EXPERIMENTAL OPPORTUNITIES AND CHALLENGES AT FUTURE LEPTON COLLIDERS

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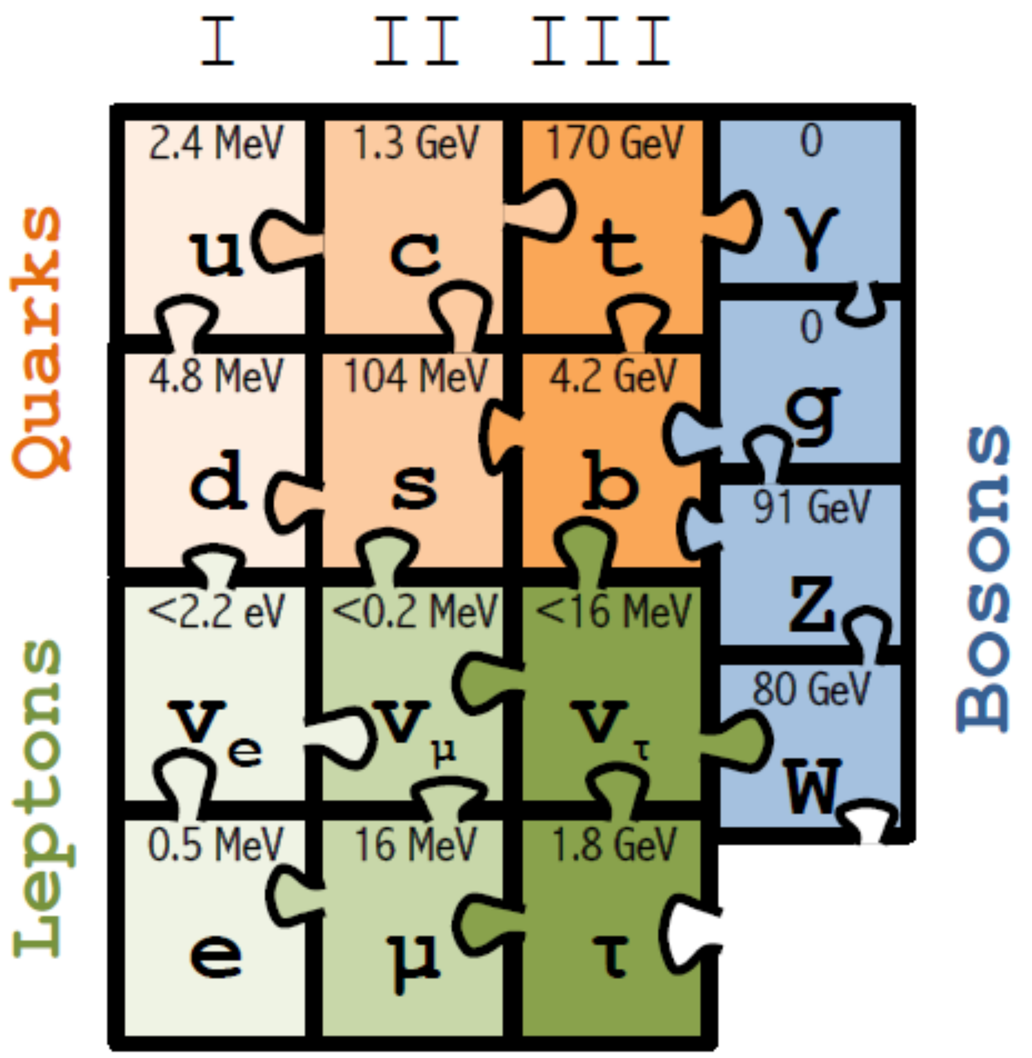
YETI Lectures 06/07/2021

Many thanks to all the colleagues' presentations I used for inspiration

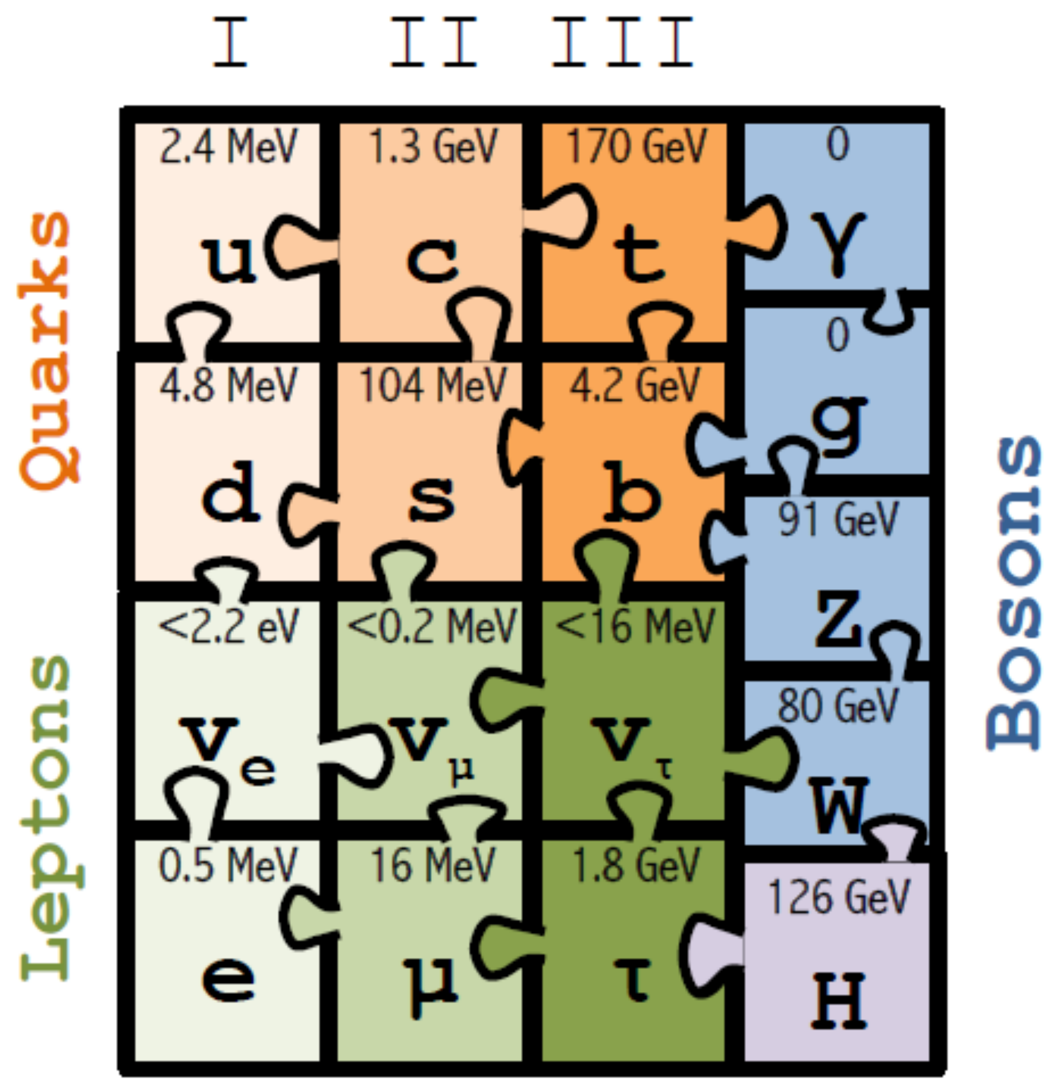
THE PHYSICS LANDSCAPE

- Particle Physics has arrived at an important moment of its History:

1989-1999:
Top mass predicted
(LEP mZ and ΓZ)
Top quark observed
at the right mass
(Tevatron, 1995)
Nobel Prize 1999
(t'Hooft & Veltman)



1997-2013:
Higgs mass cornered
(LEP EW + Tevatron mtop , mW)
Higgs boson observed
at the right mass
(LHC 2012)
Nobel Prize 2013
(Englert & Higgs)



  - It looks like the Standard Model is complete and consistent theory
  - It describes all observed collider phenomena – and actually all particle physics (except neutrino masses)
    - Was beautifully verified in a complementary manner at LEP, SLC, Tevatron, and LHC
    - EWPO radiative corrections predicted top and Higgs masses assuming SM and nothing else
  - With mH = 125 GeV, it can even be extrapolated to the Plank scale without the need of New Physics.
- Is it the *END* ?

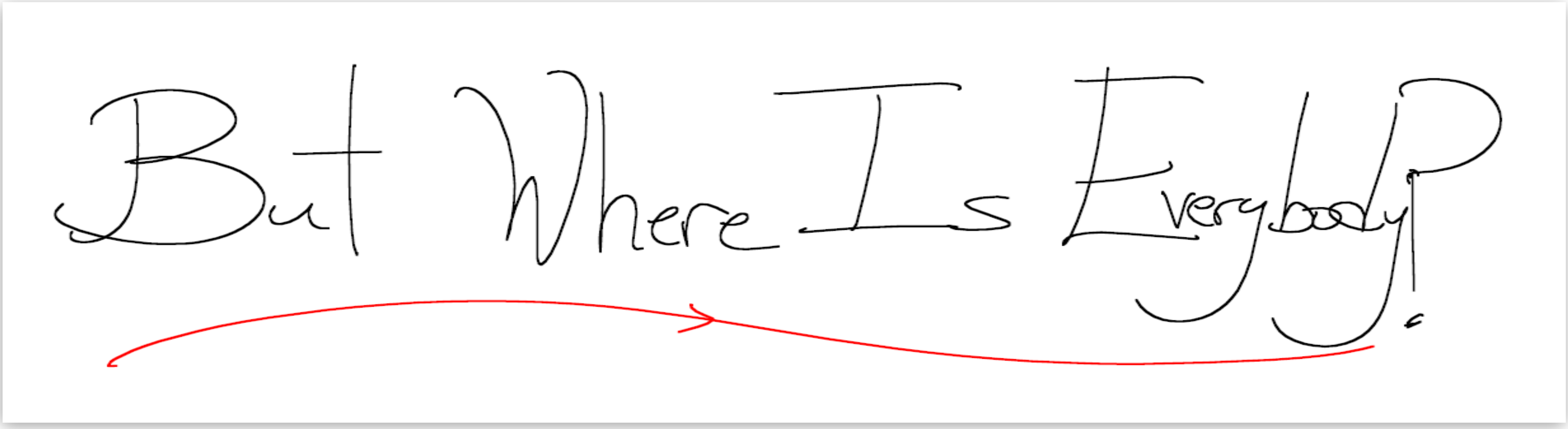
WHY NEW COLLIDER(S) / EXPERIMENTS?

- We need to extend mass & interaction reach for those phenomena that SM cannot explain:
  - Dark matter
    - SM particles constitute only 5% of the energy of the Universe
  - Baryon Asymmetry of the Universe
    - Where is anti-matter gone?
  - Neutrino Masses
    - Why so small? Dirac/Majorana? Heavier right-handed neutrinos? At what mass?

These facts require Particle Physics explanations

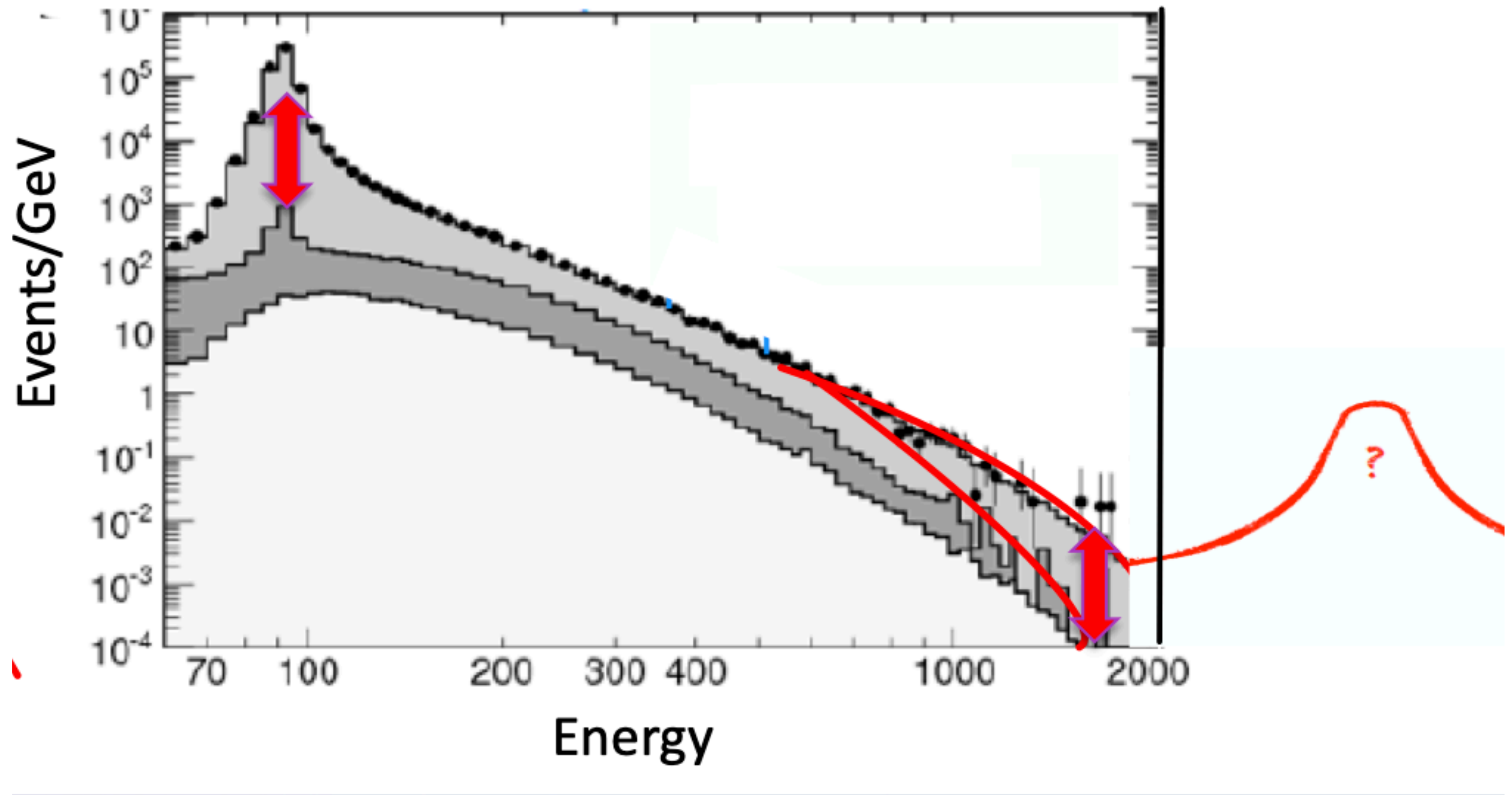
We must continue our quest, but HOW ?

- Possible experimental ways include:
  - Direct search for and observation of new particles (with any mass and any coupling to SM particles)
  - Observation of new phenomena (such as neutrino oscillations, CP violation …)
  - Measurements of deviations from precise predictions (such as top and Higgs mass predictions from loops)



WHICH WAY TO GO?

- Is new physics at larger masses ? Or at smaller couplings ? Or both ?
  - No experimental hints as to the origin of these observed (unexplained) phenomena
  - No theoretical hints that would point to one direction more than another
- Only way to find out: go look, following the historical approach:
  - Direct searches for new heavy particles ⇒ Need colliders with larger energies
  - Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles ⇒ Need colliders / measurements with unprecedented accuracy



- Energy: direct access to new resonances
- Precision: indirect evidence of deviations at low and high energy.

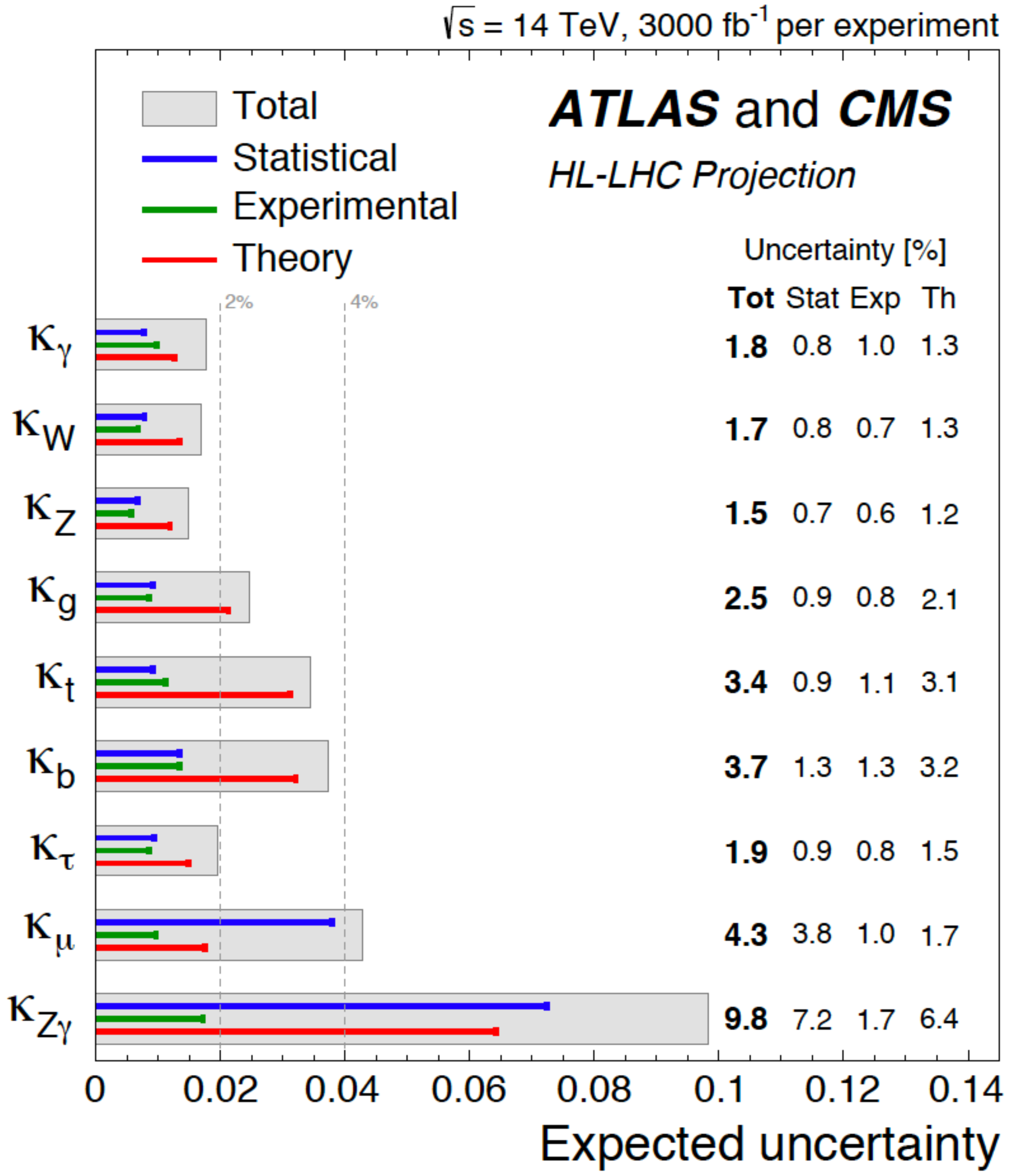
WHICH TYPE OF COLLIDER?

- The next facility must be versatile with a reach as broad and as powerful as possible – as there is no specific target

More SENSITIVITY, more PRECISION, more ENERGY

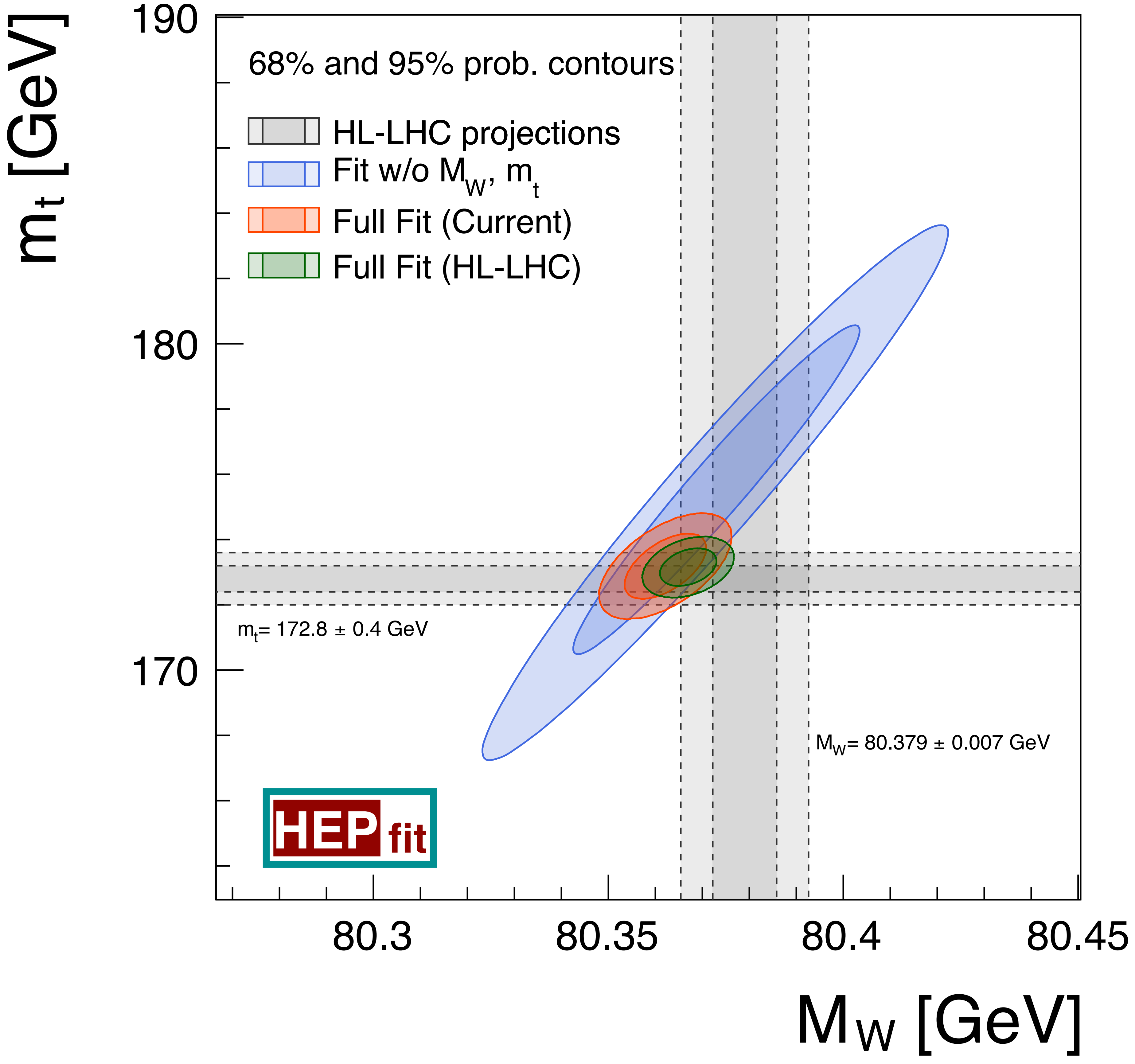
- Several Future Lepton Colliders proposed to answer these demands:
  - Largest luminosity
  - highest parton energy
  - synergies and complementarities between ee and pp, etc

AFTER HL-LHC



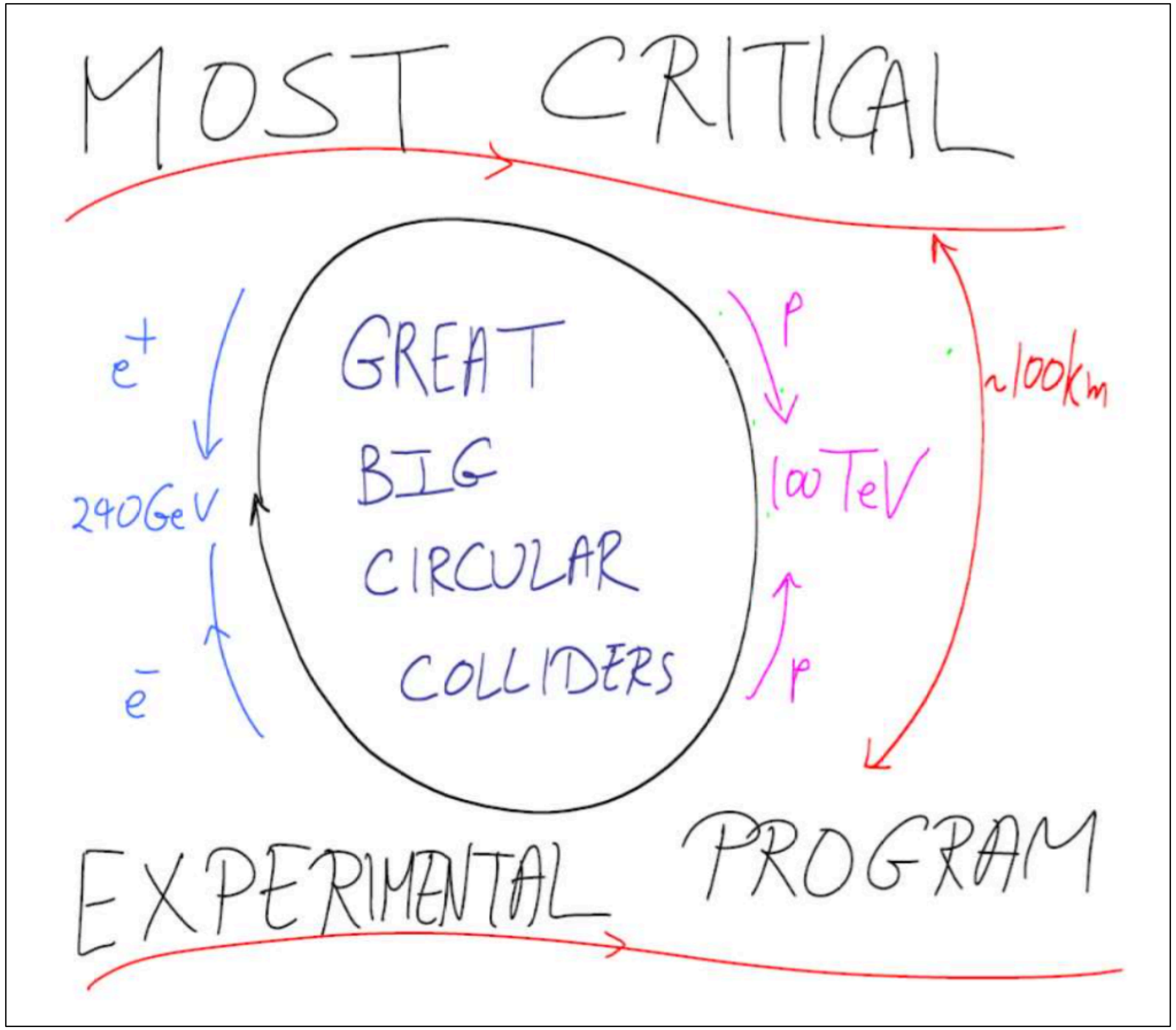
Uncertainty [%]

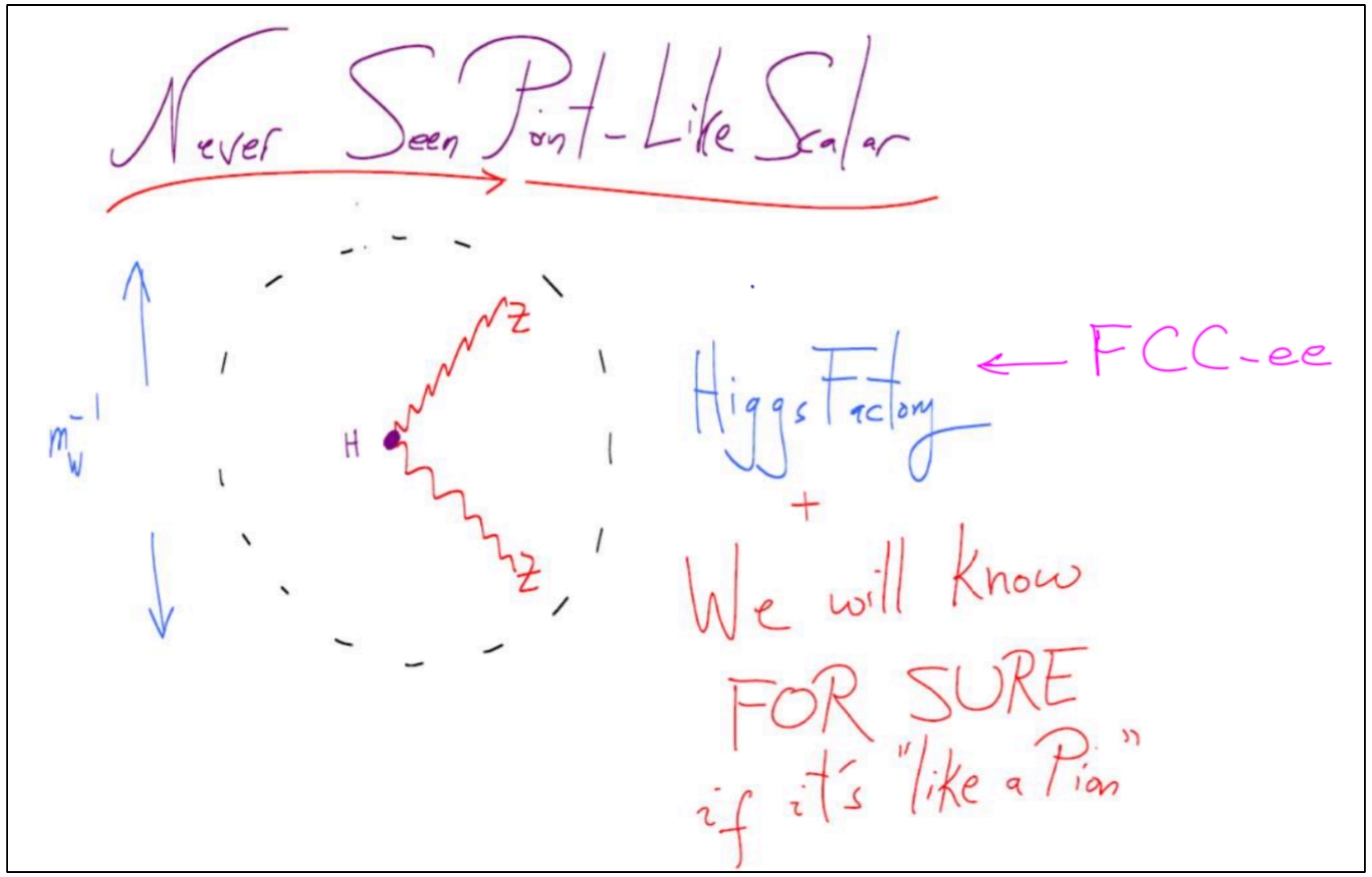
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

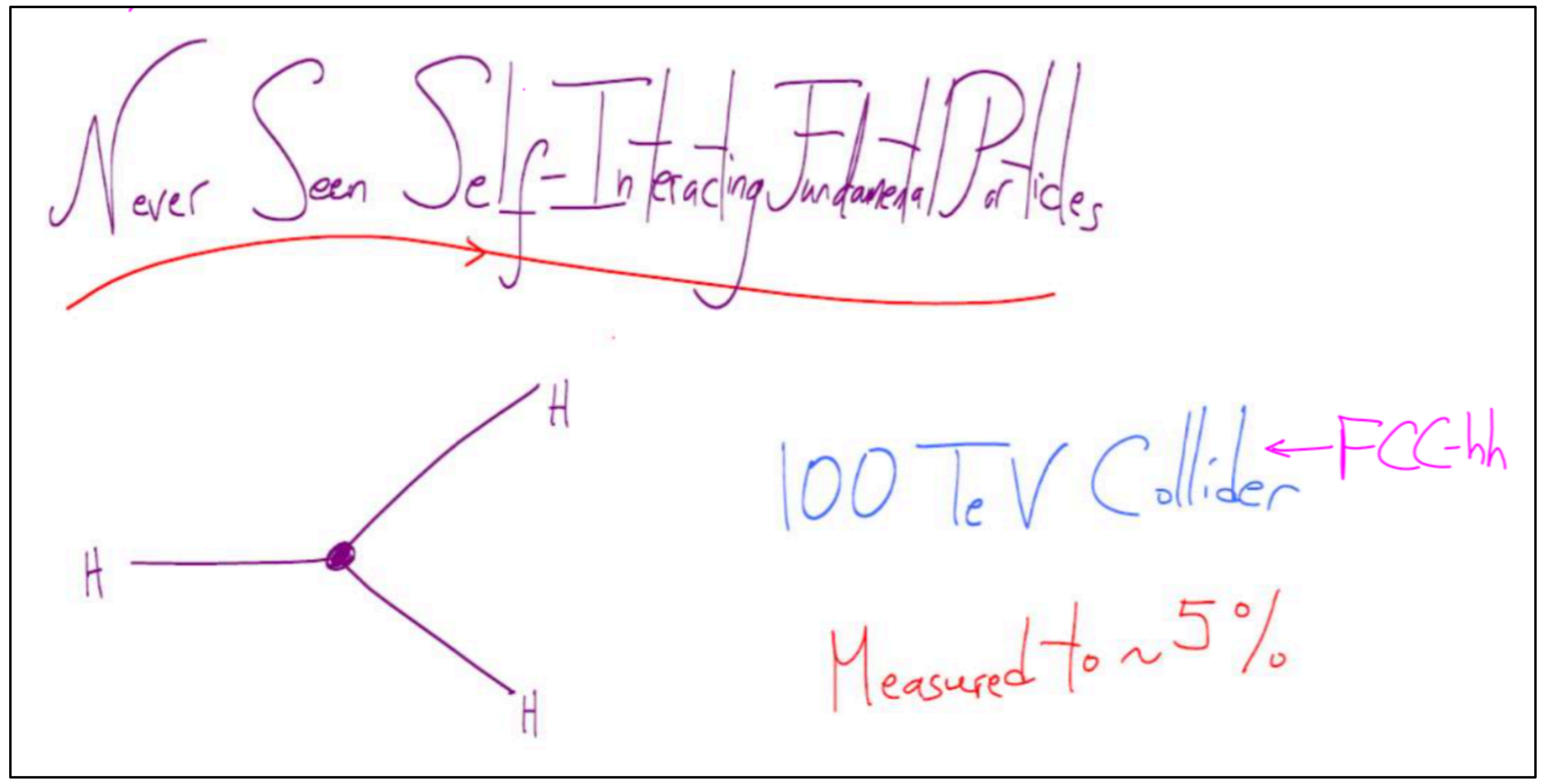


- ➤ Careful studies and projections for the physics at the HL-LHC we have shown:
  - ➤ we have designed amazing detectors that will be able to fully mitigate the 200PU conditions
  - ➤ uncertaintities on Higgs couplings of the order of 2-4% and top mass about ~200MeV
  - ➤ This precision might still not be sufficient to show the effect of new physics…

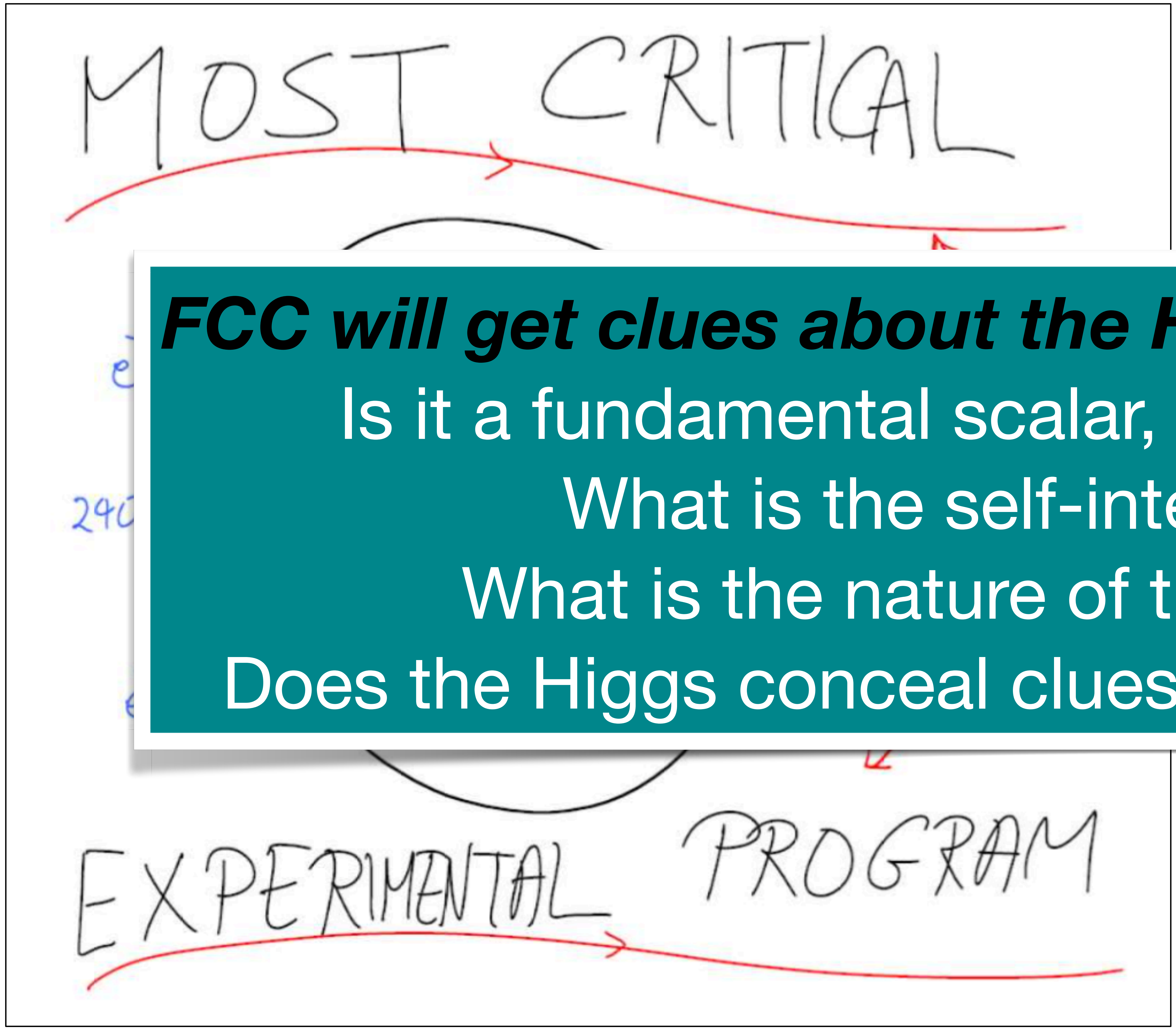
A CONCRETE TARGET: THE HIGGS BOSON

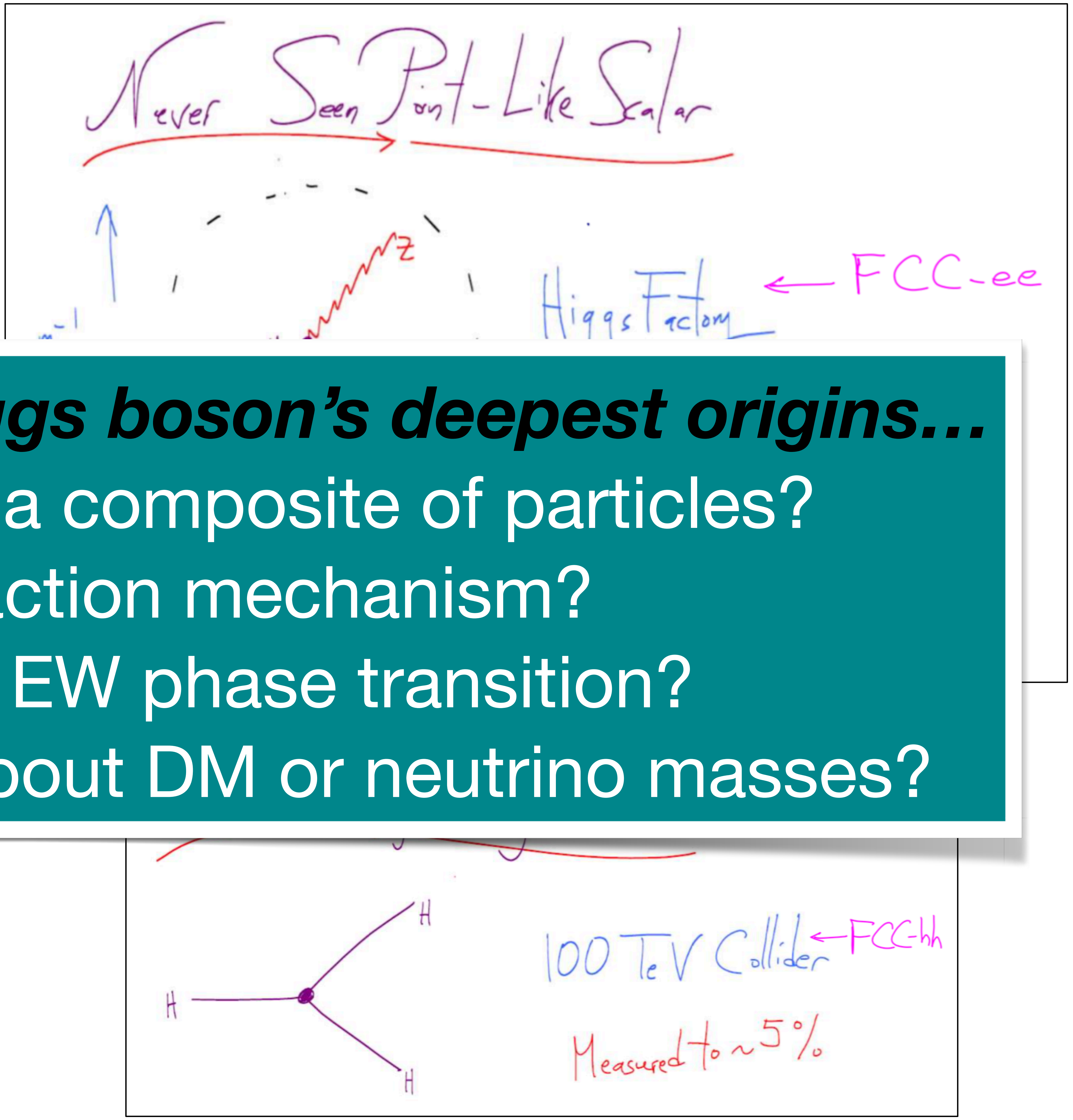






A CONCRETE TARGET: THE HIGGS BOSON





FCC will get clues about the Higgs boson's deepest origins…

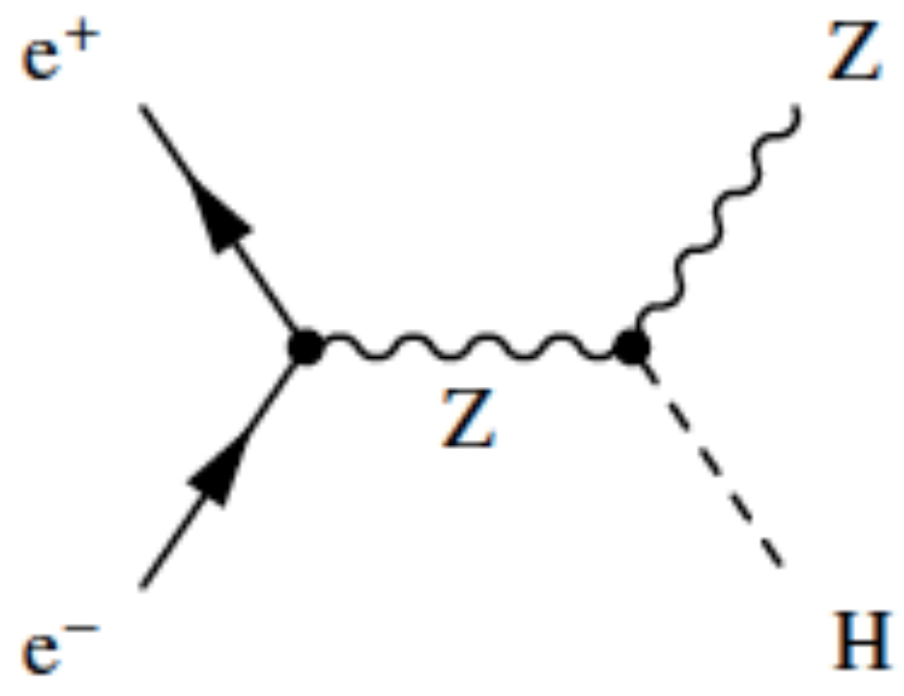
Is it a fundamental scalar, or a composite of particles?

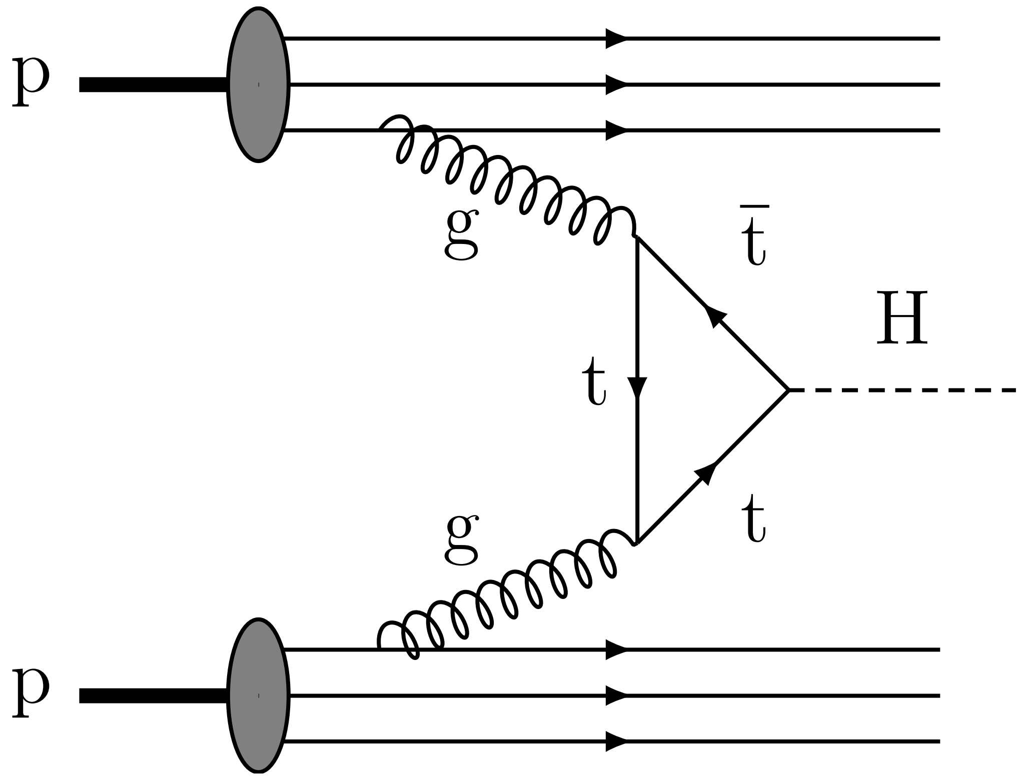
What is the self-interaction mechanism?

What is the nature of the EW phase transition?

Does the Higgs conceal clues about DM or neutrino masses?

e^+e^- VS pp COLLISIONS - THE BASICS





e^+e^- collisions

e^+/e^- are point-like

→ Initial state well defined (*E*, ***p***), polarisation

→ High-precision measurements

Clean experimental environment

→ Trigger-less readout

→ Low radiation levels

Superior sensitivity for **electro-weak states**

- At lower energies (≲ 350 GeV) , **circular** e^+e^- colliders can deliver **very large luminosities.**
- Higher energy (>1TeV) e^+e^- requires **linear** collider.

p-p collisions

Proton is compound object

→ Initial state not known event-by-event

→ Limits achievable precision

High rates of QCD backgrounds

→ Complex triggering schemes

→ High levels of radiation

High cross-sections for **colored-states**

High-energy **circular** pp colliders feasible

Which Machine(s)?

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

- $\sqrt{s}$ limited by synchroton radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)

Linear

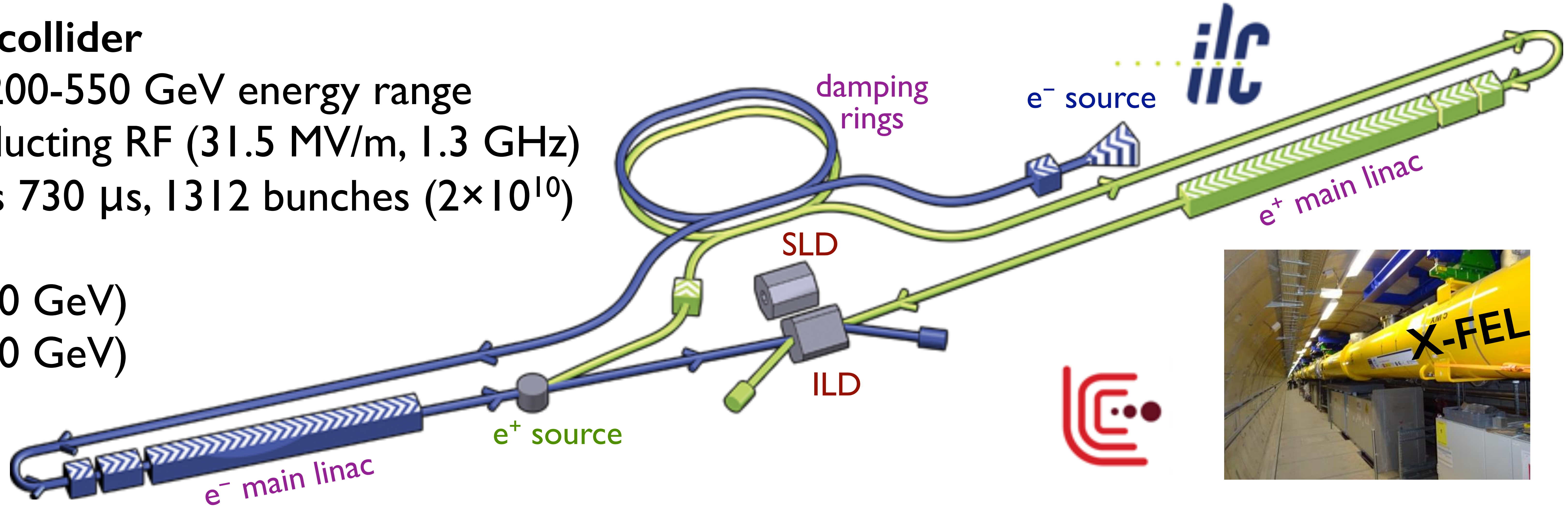
- easier to upgrade in energy
- easier to polarize beams
- large beamsthralung
- “greener”: less power consumption

INTERNATION LINEAR COLLIDER (ILC)

Linear e^+e^- collider

in the 200-550 GeV energy range

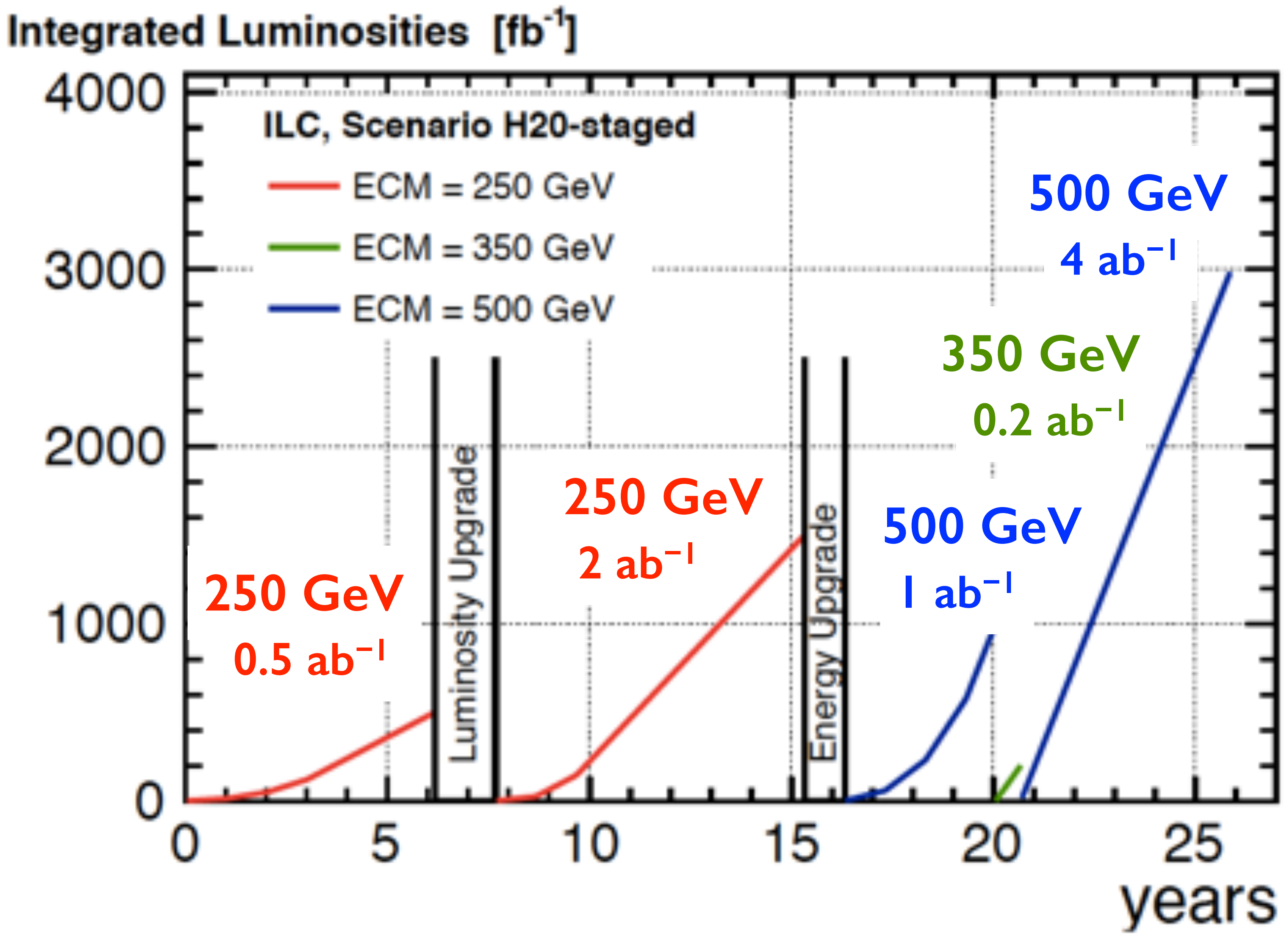
- super conducting RF (31.5 MV/m, 1.3 GHz)
- 5 Hz, trains 730 μs, 1312 bunches (2×10^{10})
- footprint:
  20 km (250 GeV)
  31 km (500 GeV)



ILC TDR (2013)
ILC-250 Physics Case (2017)

Staging scenario

- $\sqrt{s}$ = 250 GeV
- optimised luminosity: $\mathcal{L} = 1.5\times10^{34}$ cm^{-2}s^{-1}
- ±80% (±30%) e^- (e^+) beam polarisation
- (LR, RL, LL, RR) = (45%, 45%, 5%, 5%)



Strong effort by Japanese community to host ILC

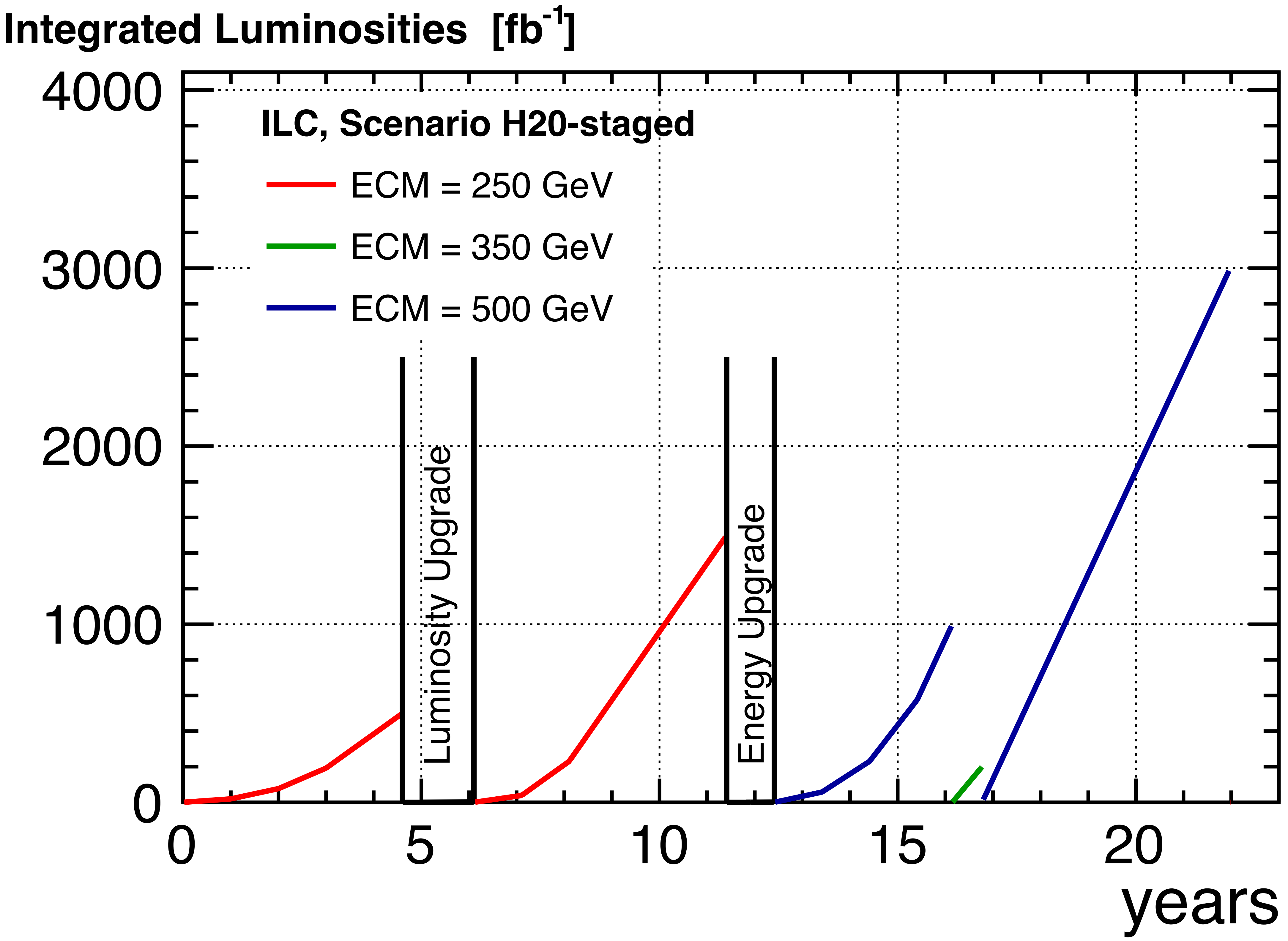
ILC « pre-Lab » in place in Europe

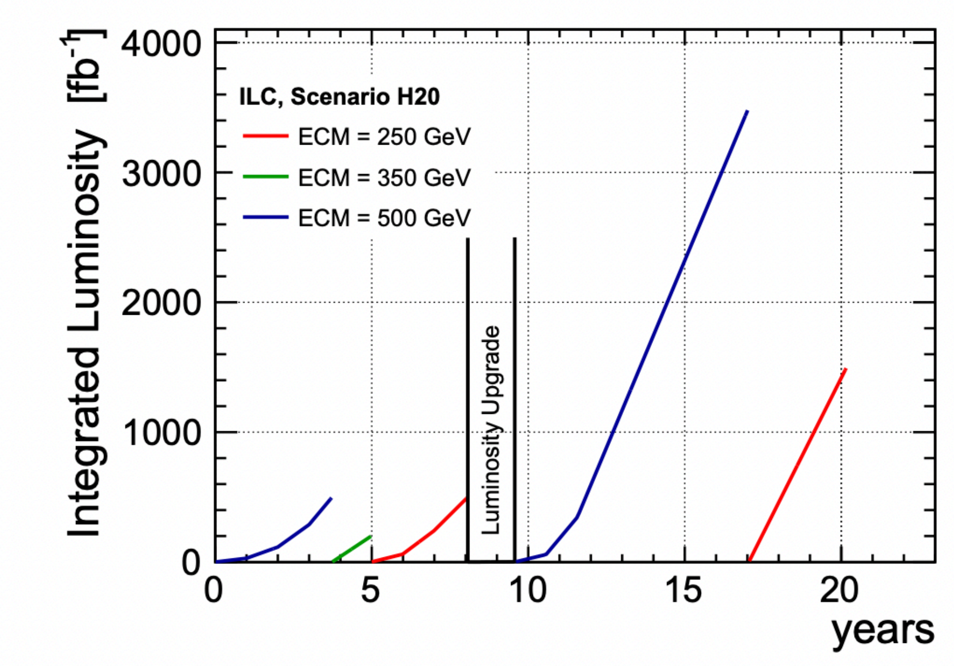
ILC RUN PLAN

	$\int \mathcal{L}dt$ [fb^{-1}]			
$\sqrt{s}$	G-20	H-20	I-20	Snow
250 GeV	500	2000	500	1150
350 GeV	200	200	1700	200
500 GeV	5000	4000	4000	1600

	fraction with sgn($P(e^-), P(e^+)$) =			
	(-,+)	(+,-)	(-,-)	(+,+)
$\sqrt{s}$	[%]	[%]	[%]	[%]
250 GeV (2015)	67.5	22.5	5	5
250 GeV (update)	**45**	**45**	5	5
350 GeV	67.5	22.5	5	5
500 GeV	40	40	10	10

$\sqrt{s}$	1 TeV	90 GeV	160 GeV
$\int \mathcal{L}dt$ [fb^{-1}]	8000	100	500





Nominal Running Program

ILC

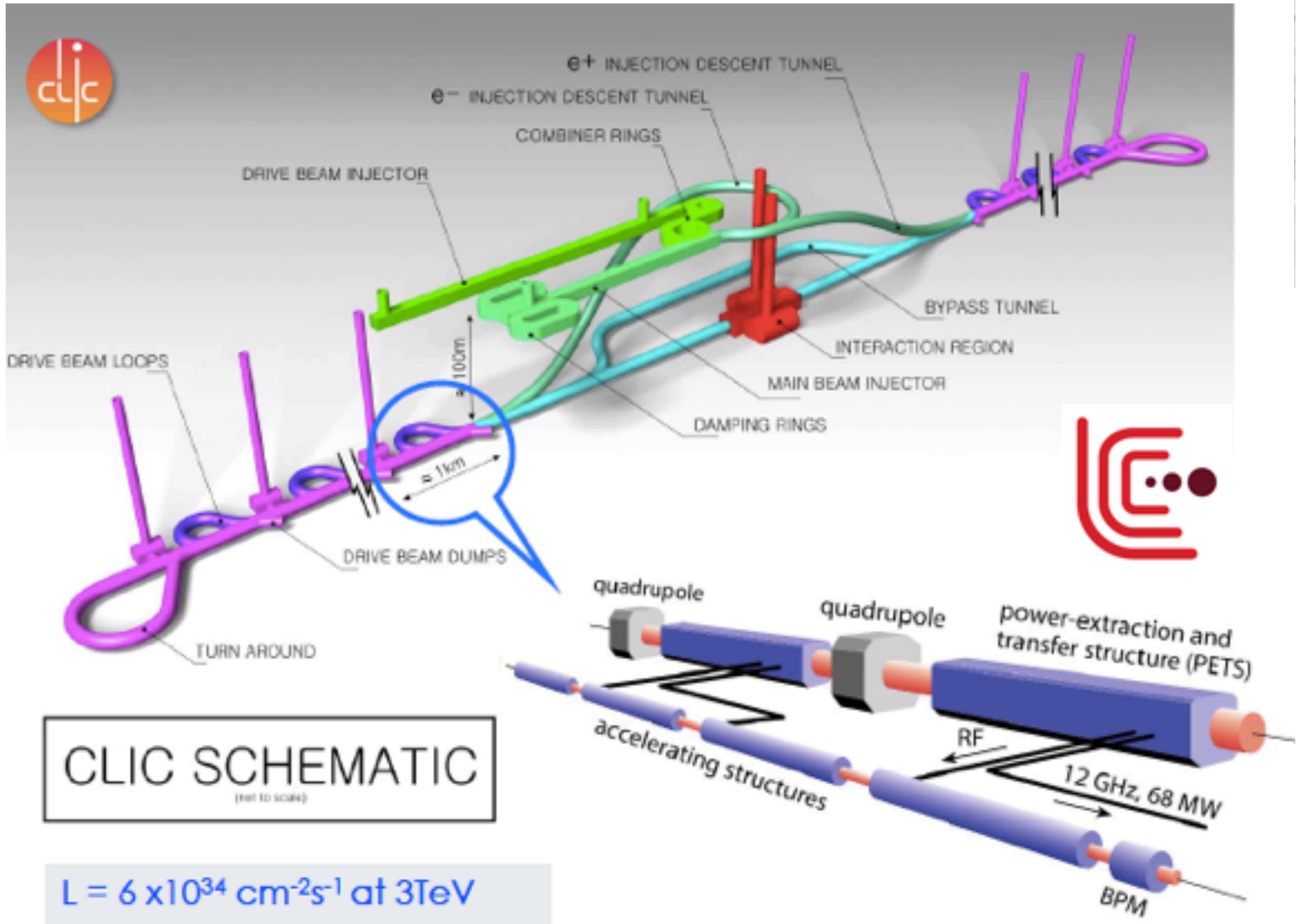
- Originally designed for √s = 500 GeV, recently re-optimized for 250 GeV
  - Supported by 25 years of R&D and innovation
    - Complete technical design report delivered in 2013
      - In principle, ready for construction as soon as decision is taken
  - Machine has many technological challenges
    - ~10 km-long, high-gradient (31 MV/m), RF system
    - A very low β^* optics delivering small beam spot sizes at high intensity
      - Still to be demonstrated to be achievable
    - A positron source with no precedent
      - Performance cannot be verified before the construction is complete
    - A green-field project
  - Can deliver data to only one detector at a time
  - In principle upgradeable to √s = 1 TeV
    - And possibly more : CLIC or *plasma acceleration* later in the same tunnel (?)
  - No design to run at the Z pole

COMPACT LINEAR COLLIDER (CLIC)

Linear e^+e^- collider at CERN

in the up-to multi-TeV energy range

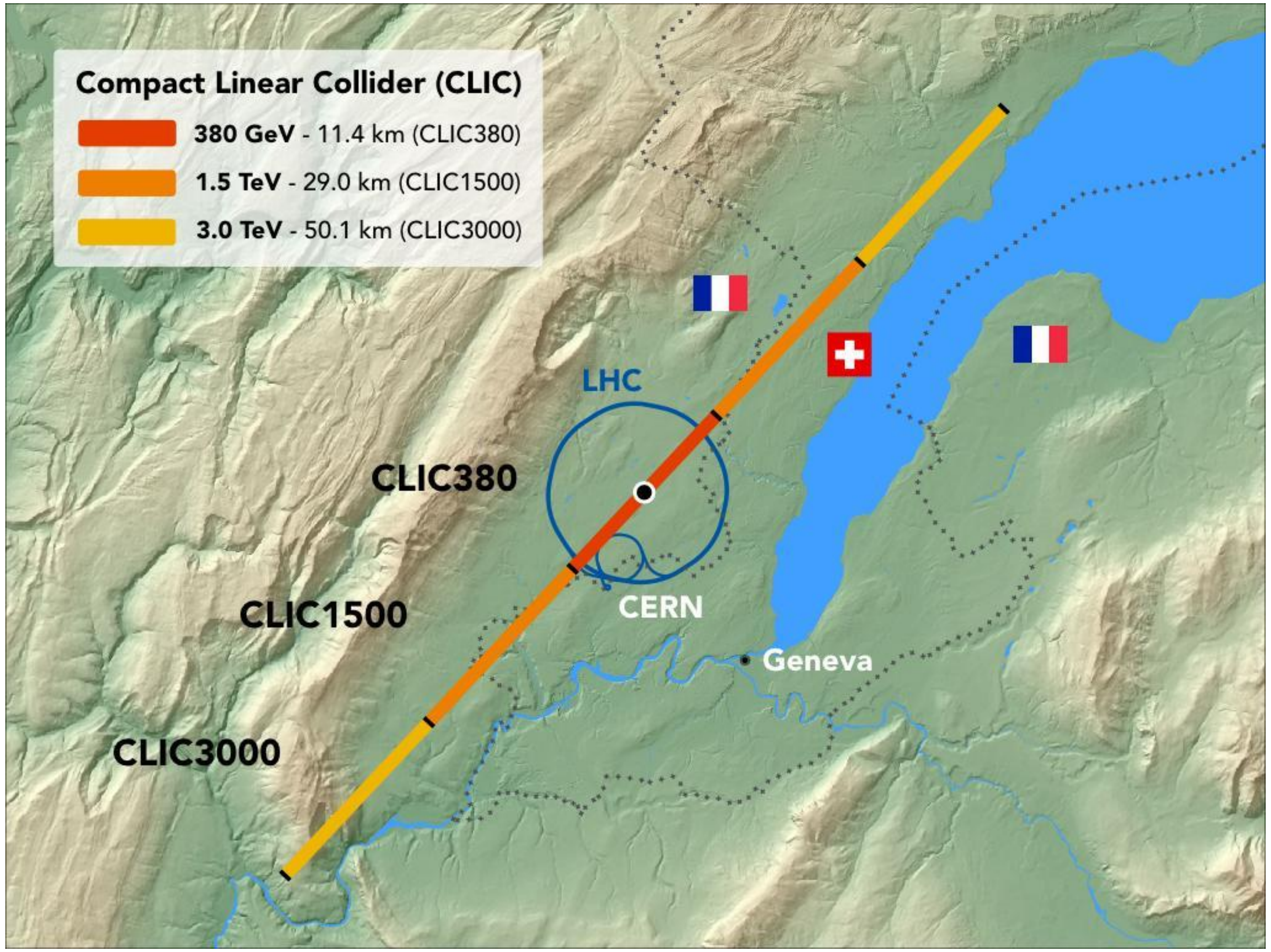
- normal conducting high-frequency RF (X-band, 12 GHz)
- e^- drive beam for RF power generation



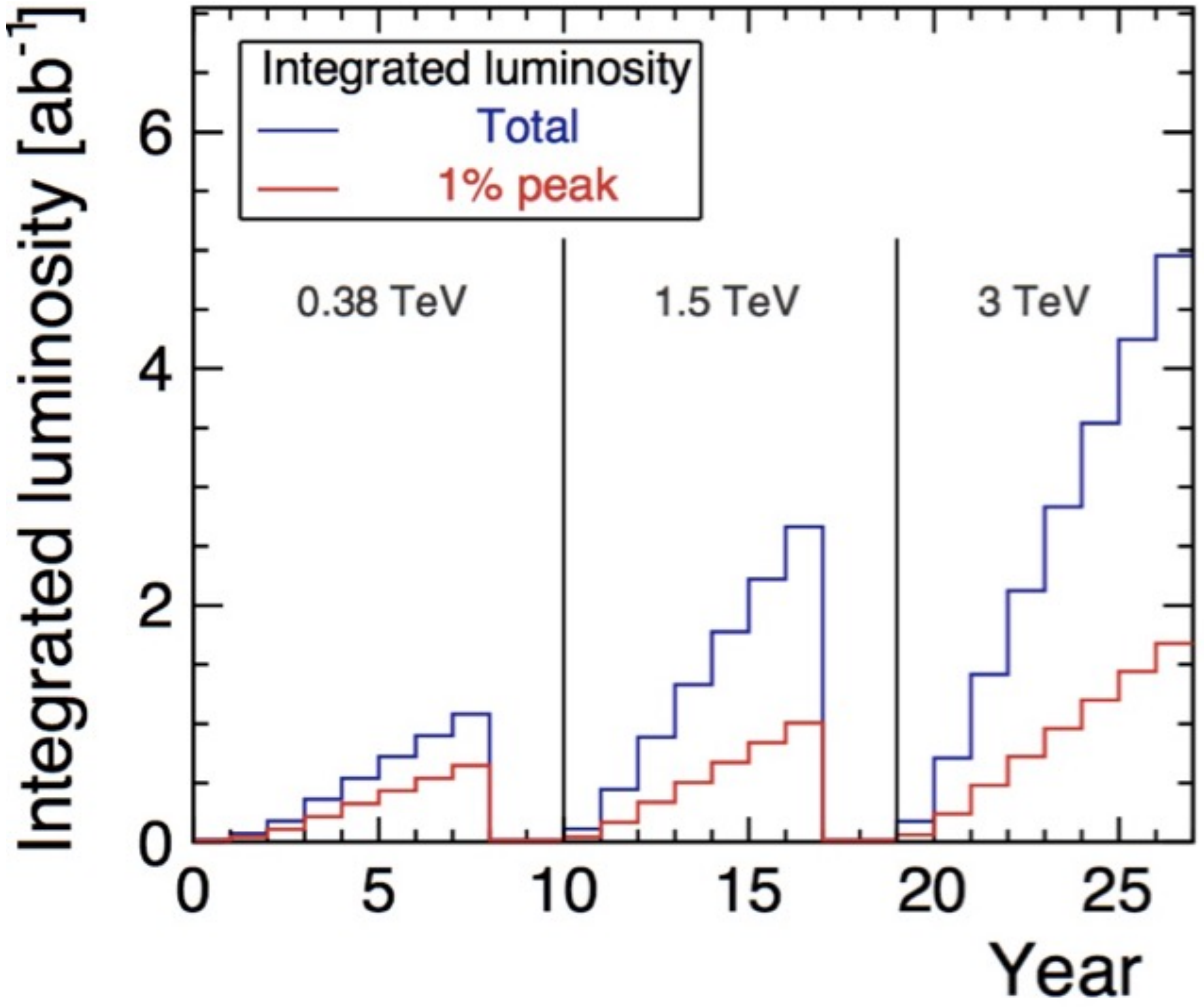
CLIC SCHEMATIC
(not to scale)

L = 6 x10^{34} $cm^{-2}s^{-1}$ at 3TeV
Beam power 30MW at 3TeV

Beam polarisation: (±80%, ∓80%)
LR / RL = 50% / 50%



CLIC RUN PLAN



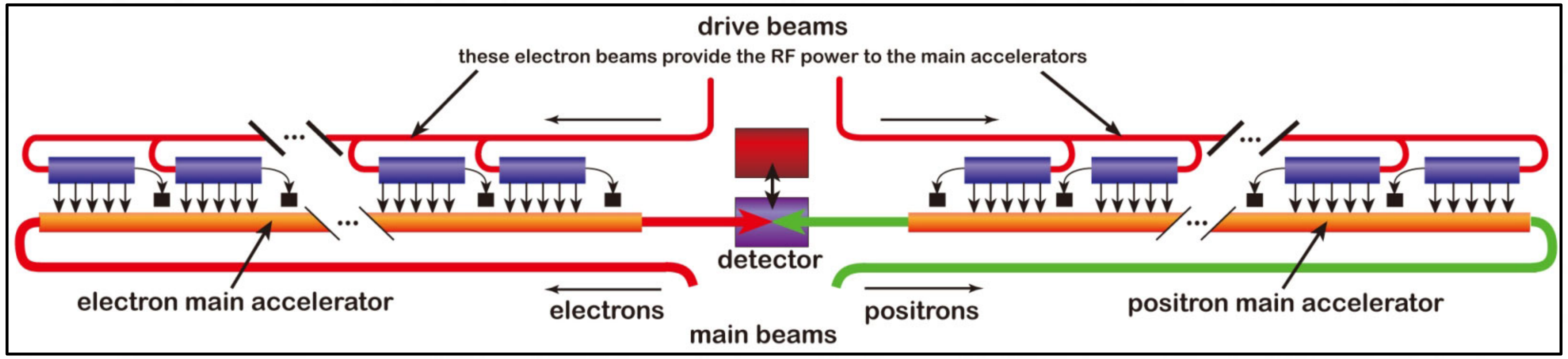
Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	increased from
1	0.38 (and 0.35)	1.0	0.5+0.1ab^{-1}
2	1.5	2.5	1.5ab^{-1}
3	3.0	5.0	3ab^{-1}

Electron polarisation enhances Higgs production at high-energy stages and provides additional observables

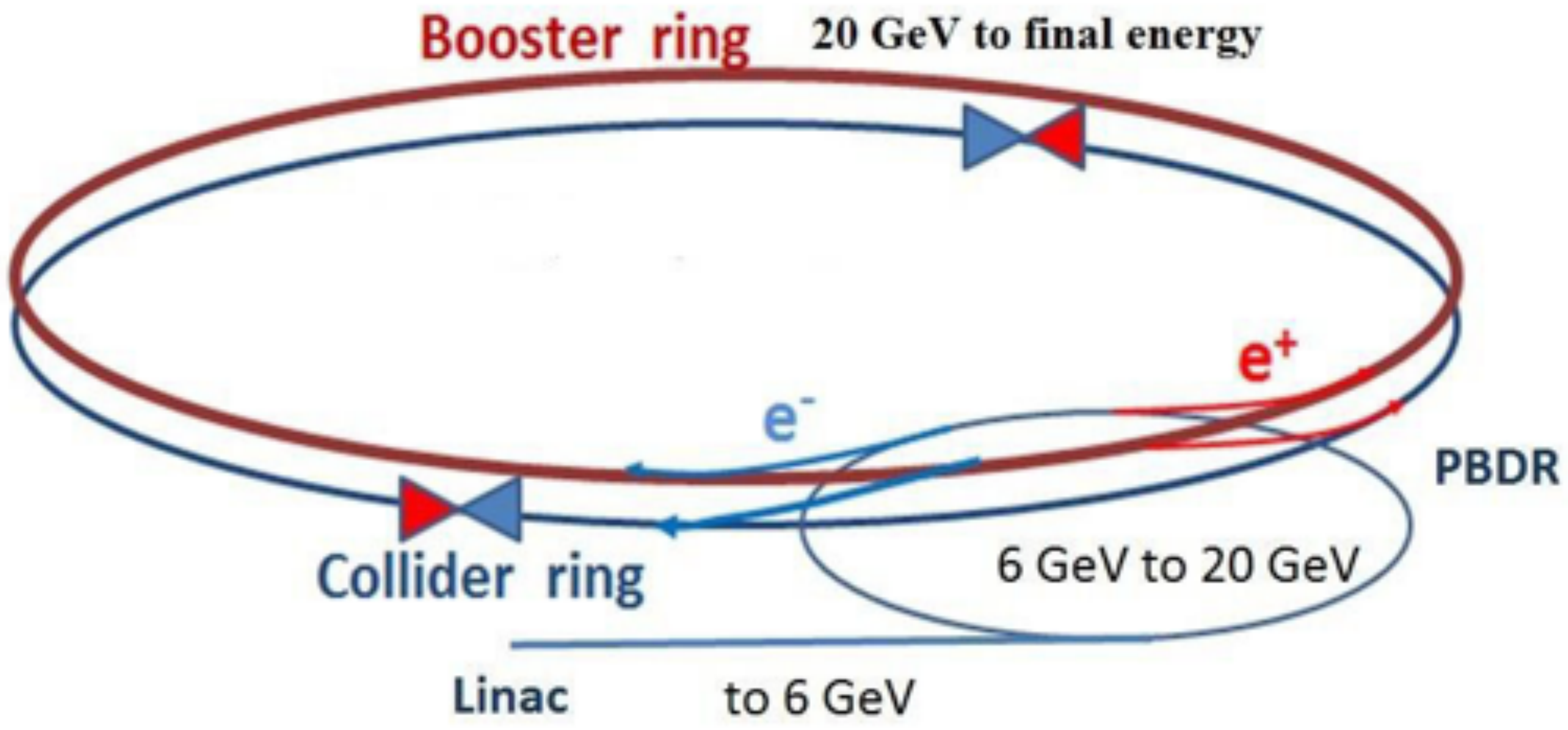
Baseline polarisation scenario adopted:
electron beam (–80%, +80%) polarised in ratio
(50:50) at $\sqrt{s}$=380GeV ; (80:20) at $\sqrt{s}$=1.5 and 3TeV

CLIC

- Designed to reach the highest possible energies in e^+e^- collision
- In staging scenario, forseen to cover the three energy points $\sqrt{s}$ = 380, 1500, and 3000 GeV
  - More than 30 years of innovation and R&D
    - Very high acceleration gradient, 100 MV/m, from a 2-beam acceleration scheme
      - demonstrated via CLIC Test Facilities
    - Conceptual Design Report delivered in 2012
  - A number of technological challenges common with ILC
    - Very low β^* optics delivering small beam spot sizes at high intensity
    - Positron source with no precedent
  - Can deliver data to only one detector at a time
  - No design to run at the Z pole



FCC-ee CIRCULAR COLLIDER



First-phase machine in the **100-km tunnel** built to host eventually FCC-hh

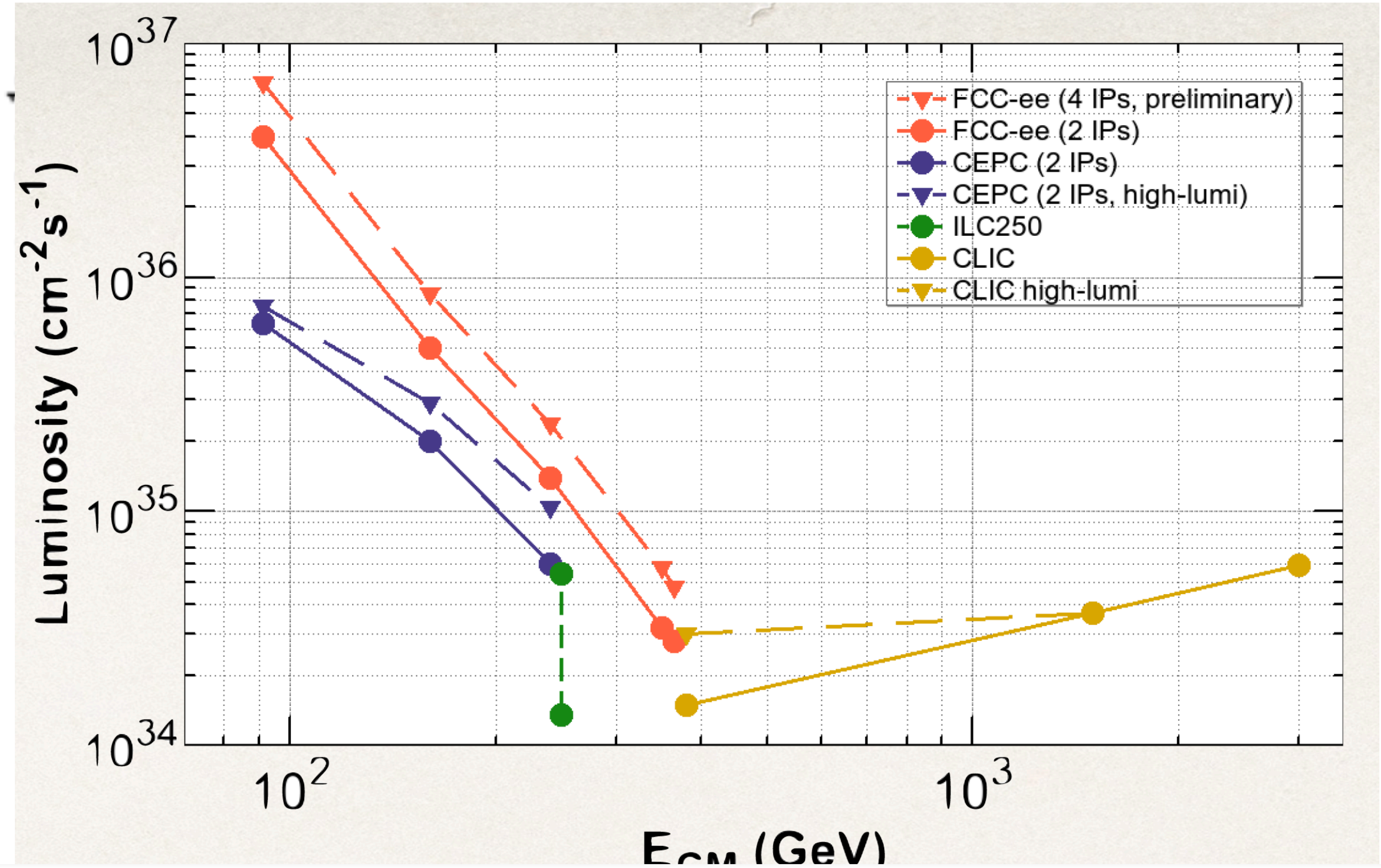
Luminosity limited by SR
- top-up injection (once per minute)
- 50 MW power/beam
- 2 interaction points

RF system: high-current → high gradient
3 sets of RF cavities

	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
WW	0.44	2000	147
ZH	2.0	393	29
top	10.9	48	5.4

Asymmetric optics with beam crossing angle of 30 mrad

FCC-ee CDR fall 2018

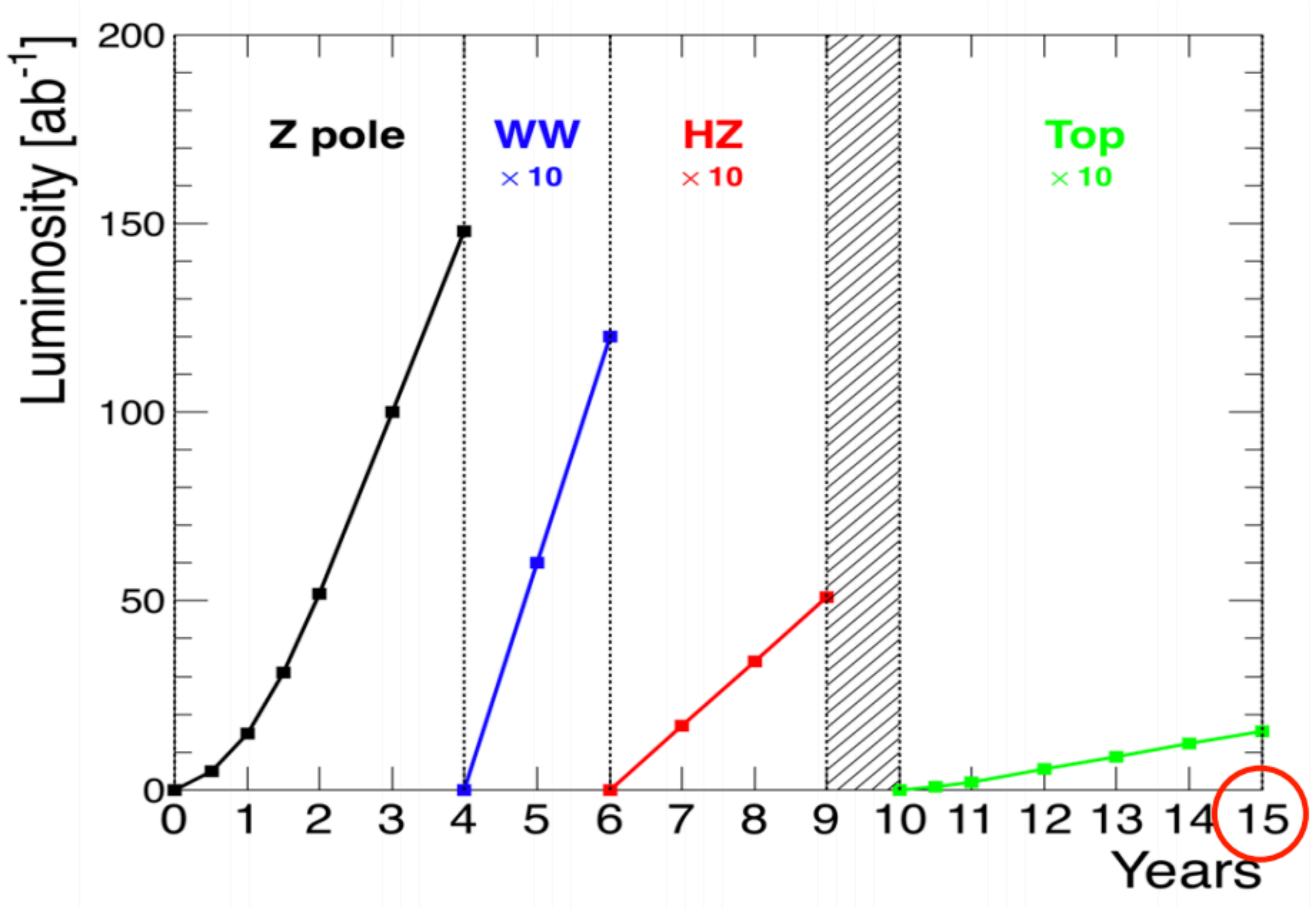


CC producing all the heaviest particles of the Standard Model

FCC-ee RUN PLAN

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics		√s uncertainty
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays	LEP x 10^5	<100keV
FCC-ee-W	2	158-162	12	10^8 WW events	LEP x $2 \cdot 10^3$	<300keV
FCC-ee-H	3	240	5	10^6 ZH events	Never done	~2MeV
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events	Never done	~5MeV

- Total running time 14(+1)years (~LEP)
  - longer shutdown to install the 196 RF for operation at the top threshold

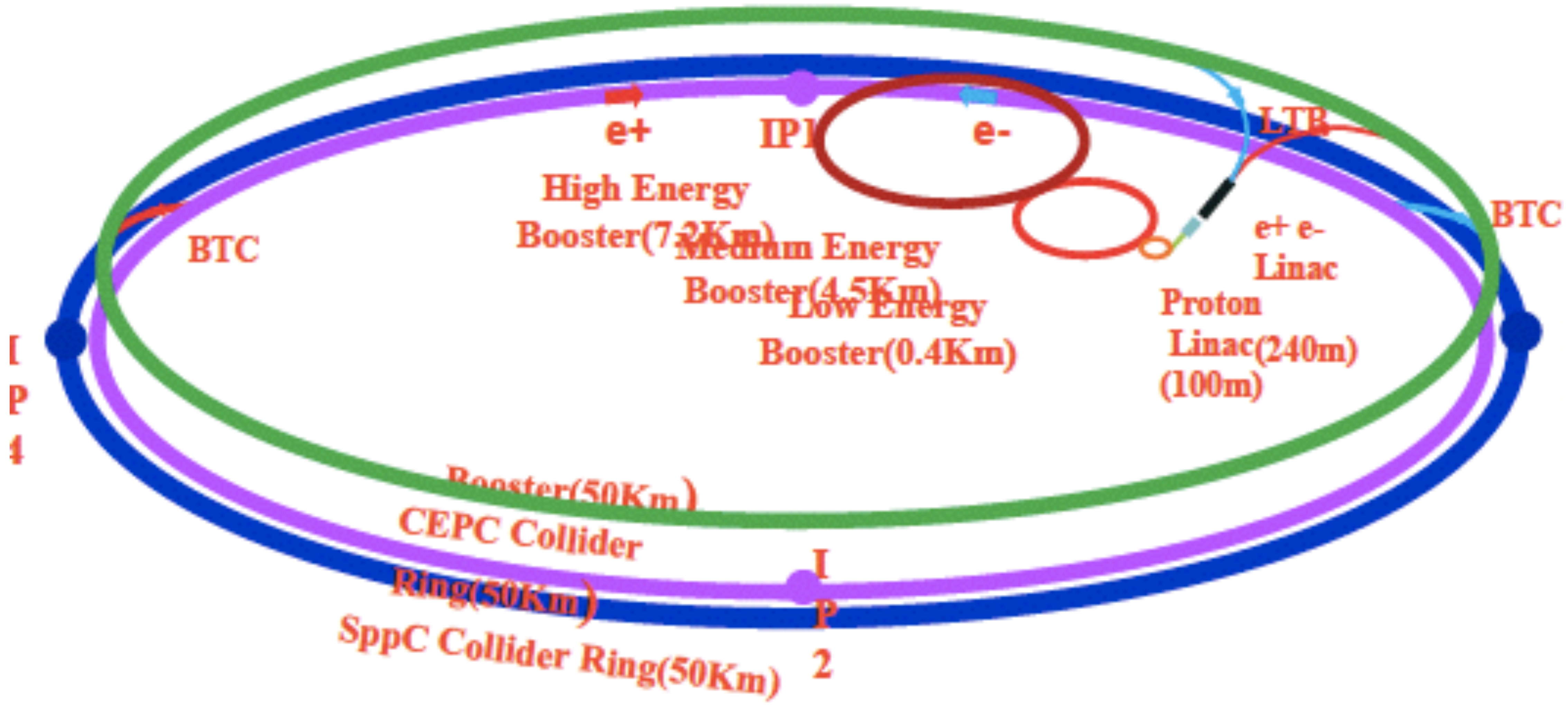


The FCC-ee unique discovery potential is multiplied by the access to the four heaviest particles of the Standard Model in its energy range

FCC-ee

- Designed as highest luminosity Z, W, H, and top factory ($\sqrt{s}$=88-365 GeV)
  - Relatively young project: about six years old
    - Lots of progress – very solid design study (2014-2018)
      - Technology ready… on paper
      - Conceptual Design Report (CDR) published early this year
  - This machine has at least as many technological challenges as linear colliders
    - A high-power (200 MW), high-gradient (10 MV/m), 2 km-long, RF system
    - Loads of synchrotron radiation (100 MW) to deal with
    - A booster (for top up injection), and a double ring for e^+ and e^-
    - Optics with very low β^*, and large momentum acceptance
    - Transverse polarization for beam energy measurement
    - Two (possible four) experiments to serve
    - … and much more
  - Supported by 50 years of experience and progress with e^+e^- circular machines
    - Most of the above challenges starting to be addressed at SuperKEKB
      - FCC-ee will build on this experience
  - First step towards a 100 TeV proton-proton collider

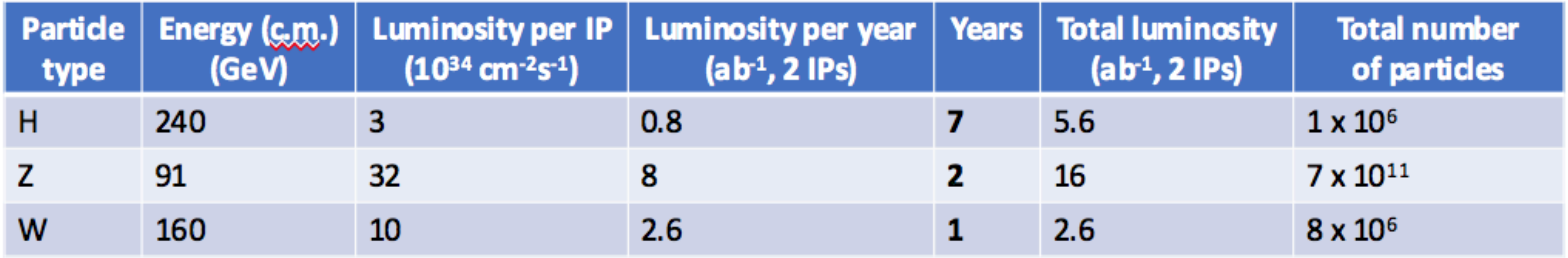
CEPC (CHINESE ELECTRON-POSITRON COLLIDER)



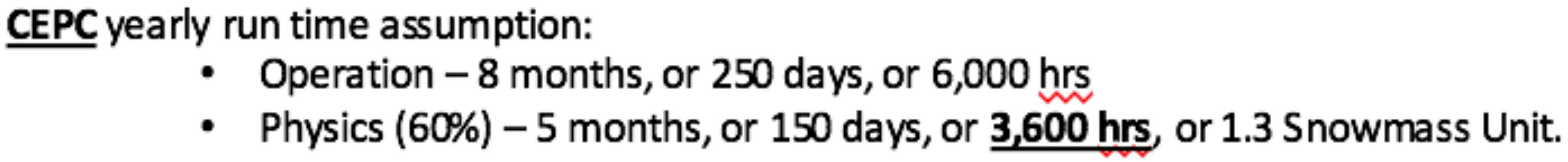
Project similar to FCC-ee in China

- two colliding rings and a booster
- $\sqrt{s}$ = 90-240 GeV

  - Hosted in a 100-km tunnel which could eventually host a 70-TeV pp collider
  - several possible sites

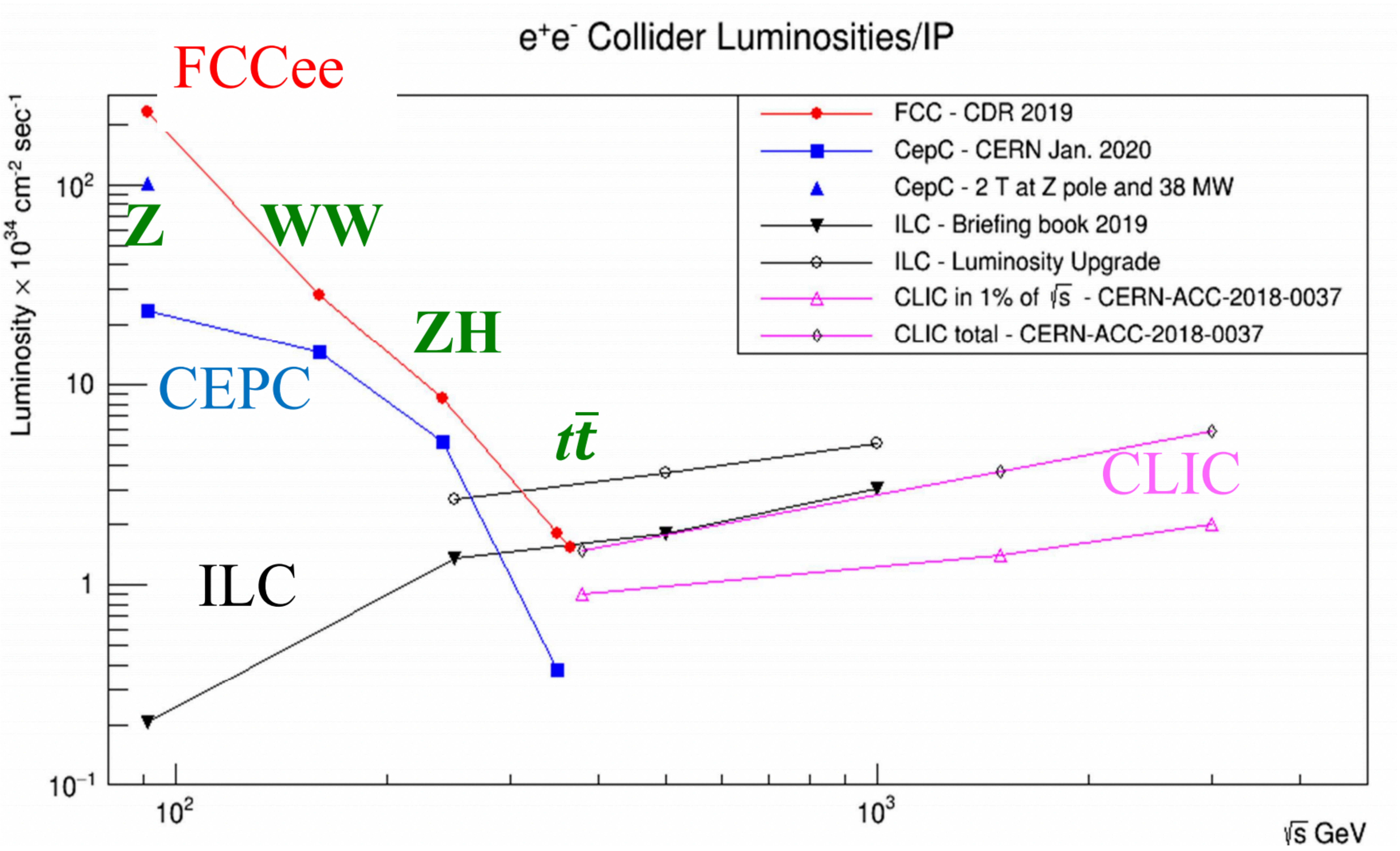


Particle type	Energy (c.m.) (GeV)	Luminosity per IP (10^{34} cm^{-2}s^{-1})	Luminosity per year (ab^{-1}, 2 IPs)	Years	Total luminosity (ab^{-1}, 2 IPs)	Total number of particles
H	240	3	0.8	**7**	5.6	1×10^6
Z	91	32	8	**2**	16	7×10^{11}
W	160	10	2.6	**1**	2.6	8×10^6



CEPC yearly run time assumption:

- Operation – 8 months, or 250 days, or 6,000 hrs
- Physics (60%) – 5 months, or 150 days, or **3,600 hrs**, or 1.3 Snowmass Unit.


e+e- Collider Luminosities/IP
FCCee
Z
WW
ZH
$t\bar{t}$
CEPC
ILC
CLIC
Luminosity × 10^34 cm^-2 sec^-1
10^2
10
1
10^-1
10^2
10^3
√s GeV
FCC - CDR 2019
CepC - CERN Jan. 2020
CepC - 2 T at Z pole and 38 MW
ILC - Briefing book 2019
ILC - Luminosity Upgrade
CLIC in 1% of √s - CERN-ACC-2018-0037
CLIC total - CERN-ACC-2018-0037

OVERALL STATISTICS

Energies (1^{st} col.) in GeV, luminosities (2^{nd} col.) in ab^{-1} . Yellow = in baseline plan

ILC

GigaZ	0.1	$5\ 10^9$ Z
WW	0.5	$3.5\ 10^6$ WW

250	2	750k H
tt	0.2	150k tt

500	4	1.5 M H 3 M tt

FCC

Numbers for two IPs

TeraZ	150	$5\ 10^{12}$ Z
WW	12	$5\ 10^7$ WW

125	10/y	ee → H

240	5	1M H
tt	1.5	1M tt

CEPC: same luminosity as FCC at ZH ; lower at lower √s ; no plan yet to run at the top threshold.

CLIC

GigaZ	0.1	$5\ 10^9$ Z

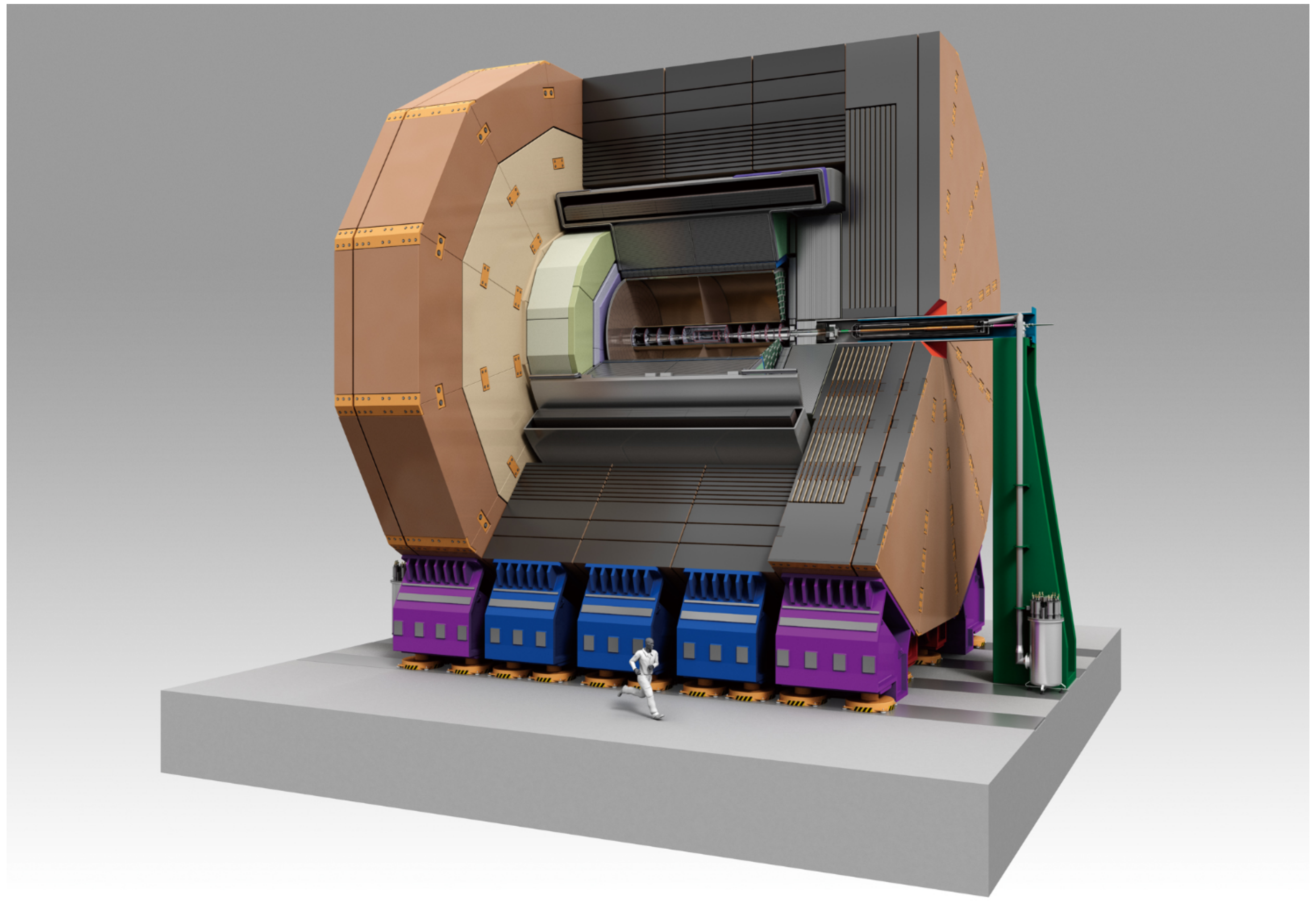
tt	1	160k H 700k tt

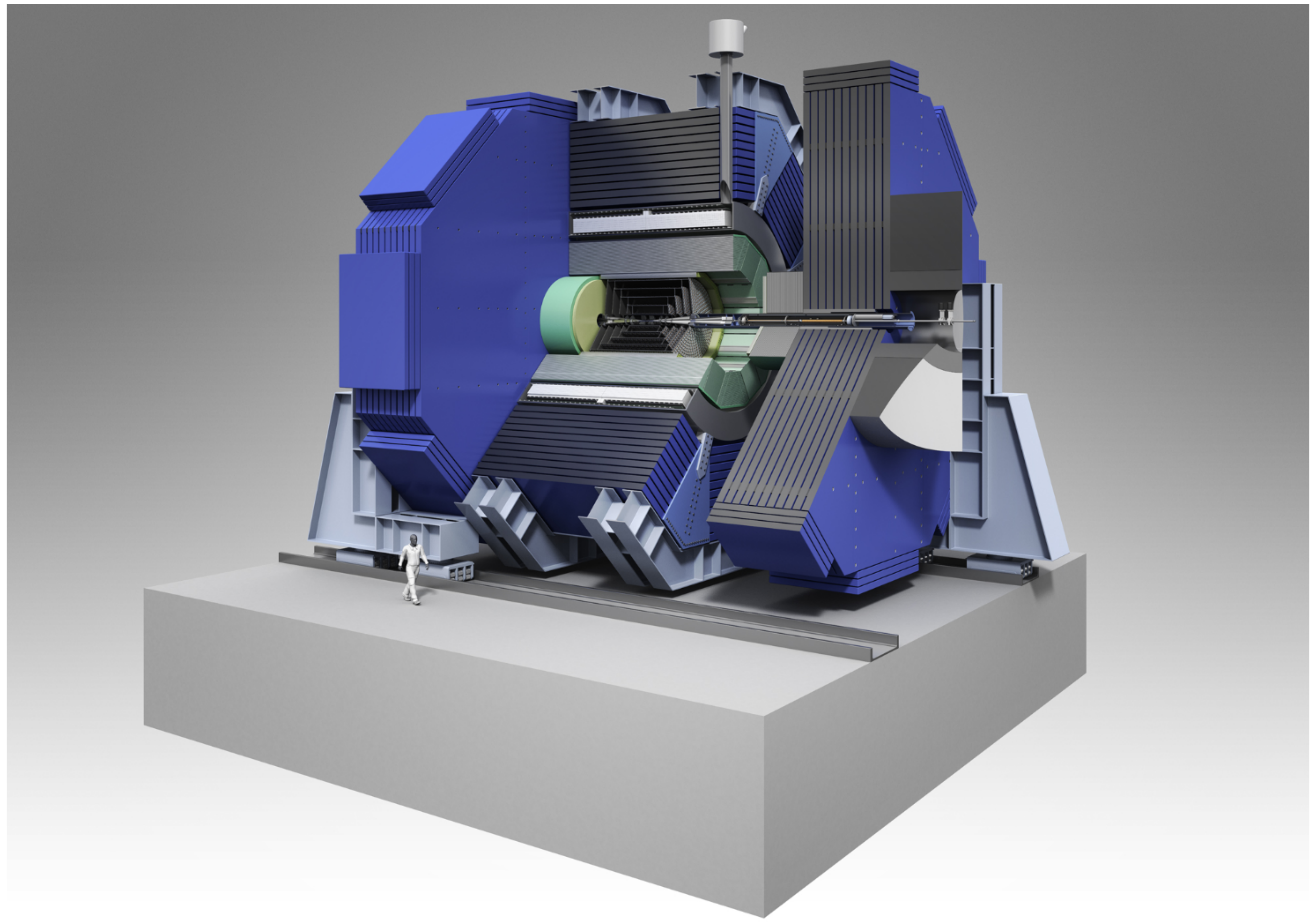
1500	2.5	1M H 400k tt
3000	5	3.3M H 300k tt

O(1 M) of Higgs, O(1 M) of tt
Trillions / Billions of Z

ILC DETECTORS

Designed for Particle Flow Calorimetry:
- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Low mass trackers → reduce interactions / conversions



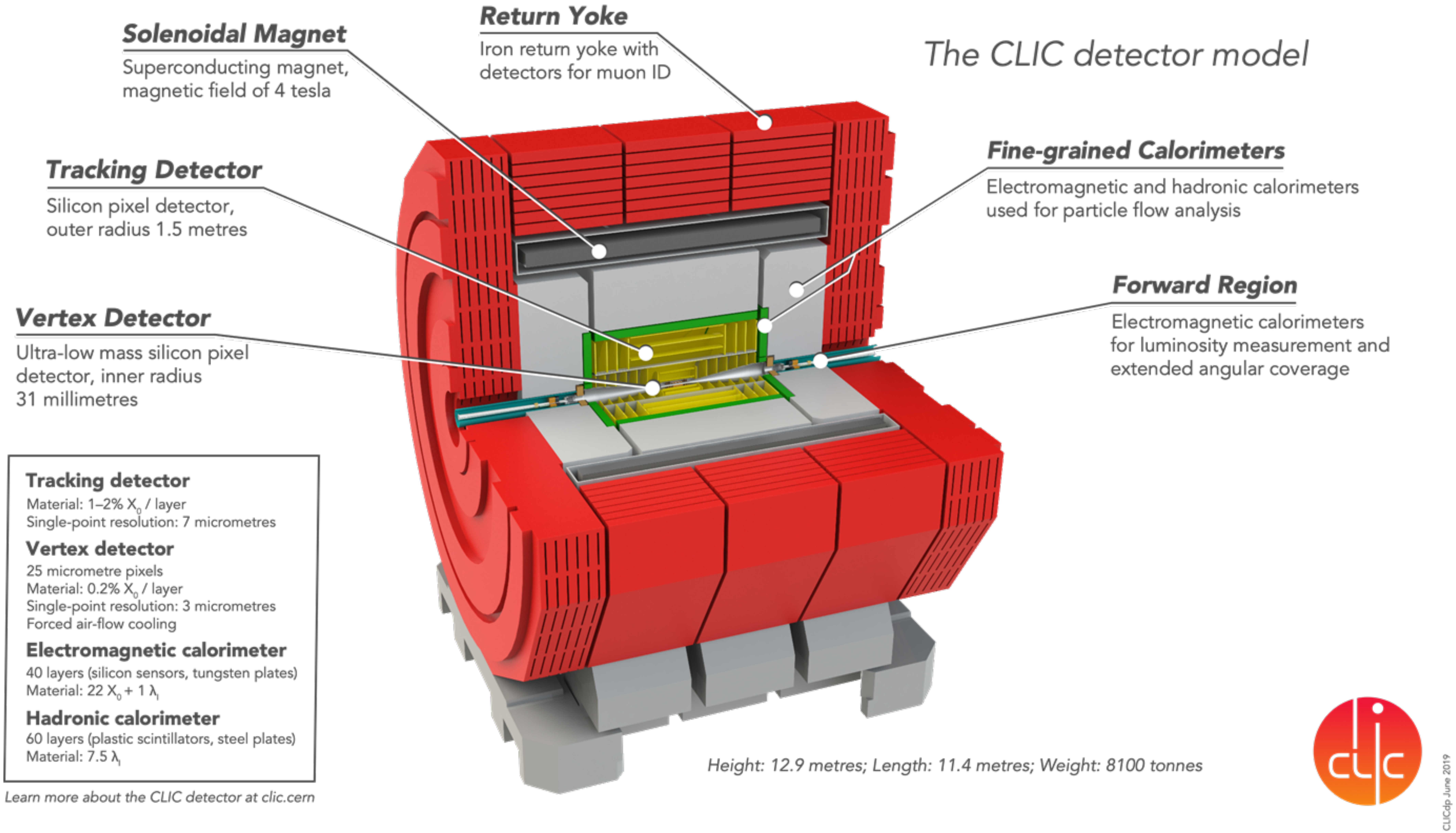


ILD (International Large Detector):
- TPC+silicon envelope, radius: 1.8 m
- B-field: 3.5 T

(small option: 1.46 m / 4 T recently studied)

SiD (Silicon Detector):
- Silicon tracking, radius: 1.2 m
- B-field: 5 T

CLD - CLIC DETECTOR



The CLIC detector model

Solenoidal Magnet
Superconducting magnet, magnetic field of 4 tesla

Return Yoke
Iron return yoke with detectors for muon ID

Tracking Detector
Silicon pixel detector, outer radius 1.5 metres

Vertex Detector
Ultra-low mass silicon pixel detector, inner radius 31 millimetres

Fine-grained Calorimeters
Electromagnetic and hadronic calorimeters used for particle flow analysis

Forward Region
Electromagnetic calorimeters for luminosity measurement and extended angular coverage

Tracking detector
Material: 1–2% X_0 / layer
Single-point resolution: 7 micrometres

Vertex detector
25 micrometre pixels
Material: 0.2% X_0 / layer
Single-point resolution: 3 micrometres
Forced air-flow cooling

Electromagnetic calorimeter
40 layers (silicon sensors, tungsten plates)
Material: 22 X_0 + 1 λ_I

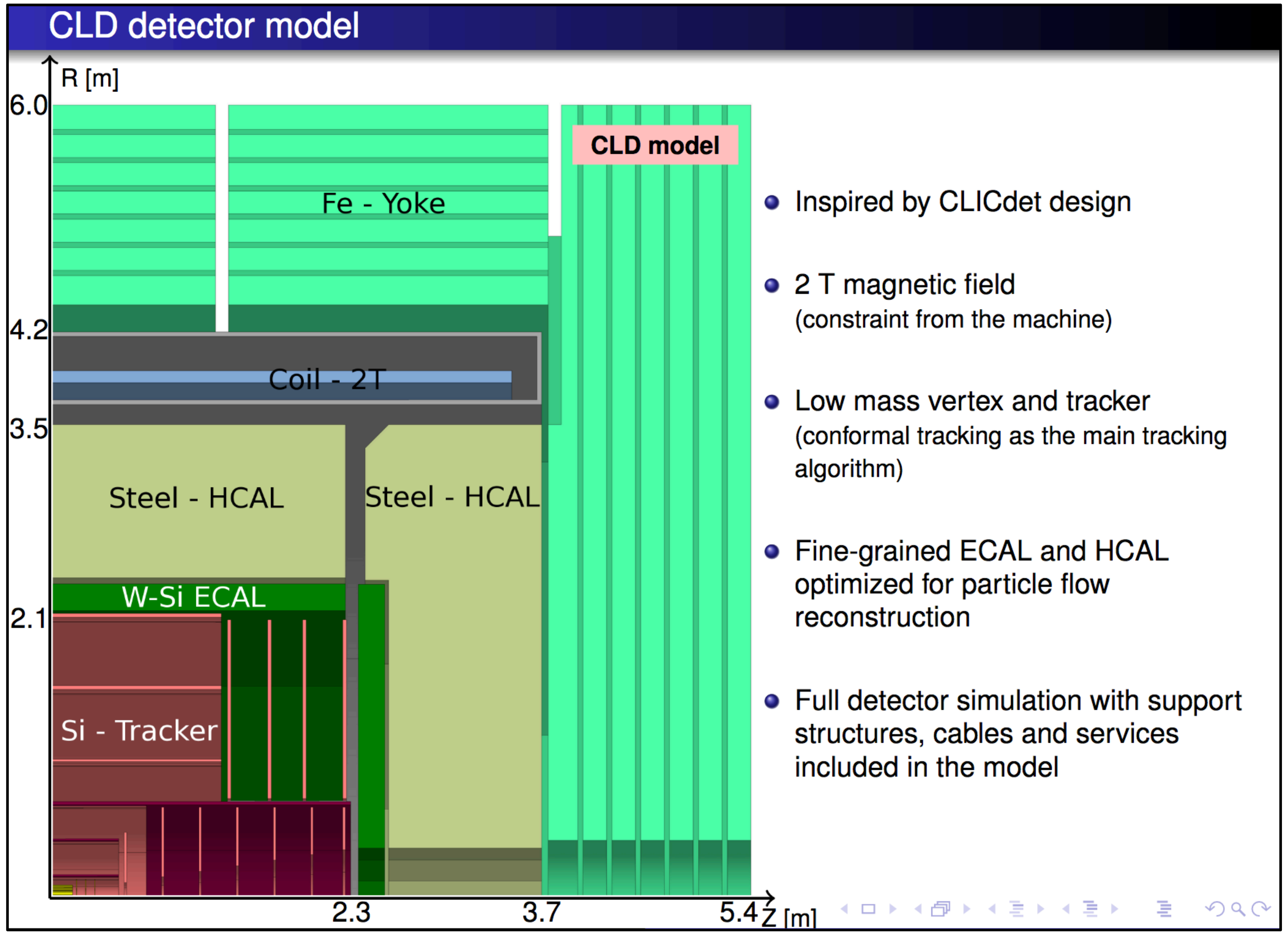
Hadronic calorimeter
60 layers (plastic scintillators, steel plates)
Material: 7.5 λ_I

Learn more about the CLIC detector at clic.cern

Height: 12.9 metres; Length: 11.4 metres; Weight: 8100 tonnes

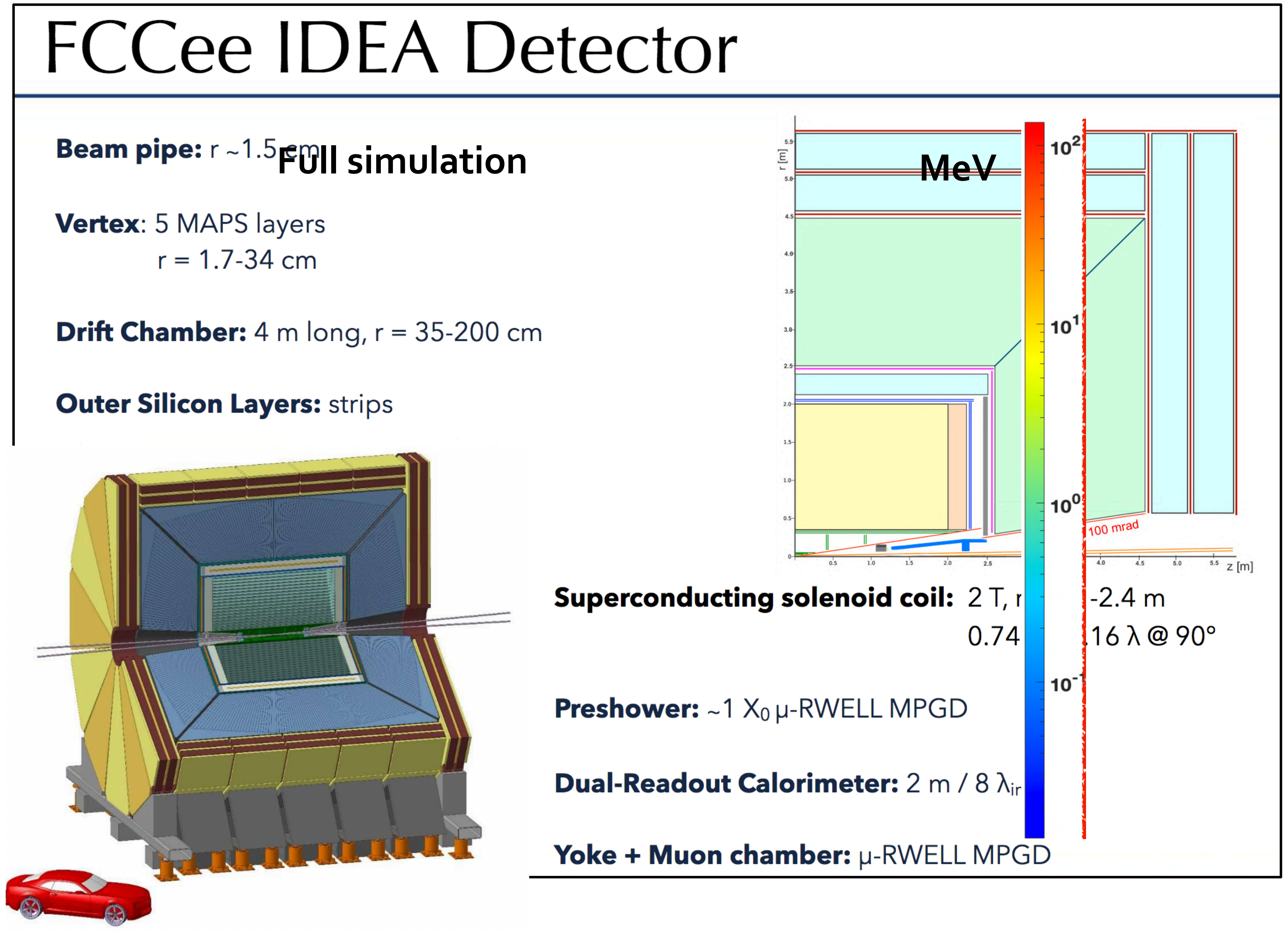
DETECTOR CONCEPTS FOR FCC-ee: CLD’ & IDEA

- It was demonstrated that detectors satisfying the requirements are feasible. Two options considered for now with complementary designs
  - physics performance, beam background, invasive MDI event rates…



CLD detector model

- Inspired by CLICdet design
- 2 T magnetic field (constraint from the machine)
- Low mass vertex and tracker (conformal tracking as the main tracking algorithm)
- Fine-grained ECAL and HCAL optimized for particle flow reconstruction
- Full detector simulation with support structures, cables and services included in the model



FCCee IDEA Detector

Beam pipe: r ~1.5 cm

Vertex: 5 MAPS layers
r = 1.7-34 cm

Drift Chamber: 4 m long, r = 35-200 cm

Outer Silicon Layers: strips

Superconducting solenoid coil: 2 T, r -2.4 m
0.74 16 λ @ 90°

Preshower: ~1 X_0 μ-RWELL MPGD

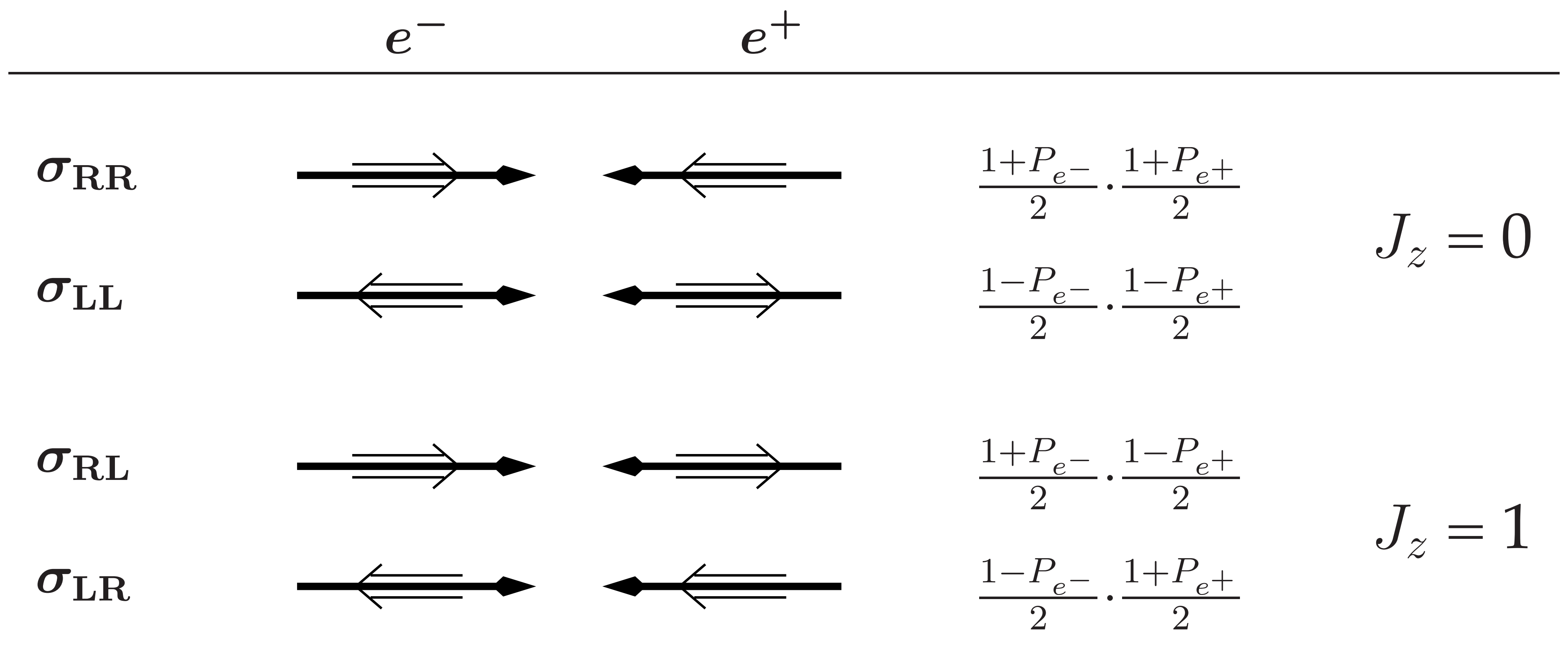
Dual-Readout Calorimeter: 2 m / 8 λ_{ir}

Yoke + Muon chamber: μ-RWELL MPGD

IMPACT OF BEAM POLARISATION AT A LC

Beam polarisation is crucial for investigating observables like left-right asymmetries, which have a high sensitivity for discriminating between different realisations of the underlying physics and for the determination of chiral quantum numbers.

The polarisation of both the electron and the positron beams yields four distinct sets of observables instead of only two observables for the case where only the electron beam is polarised.



Most important reactions can be studied with opposite-sign polarisation, but the two like-sign polarisation configurations provide additional information that can be unique.

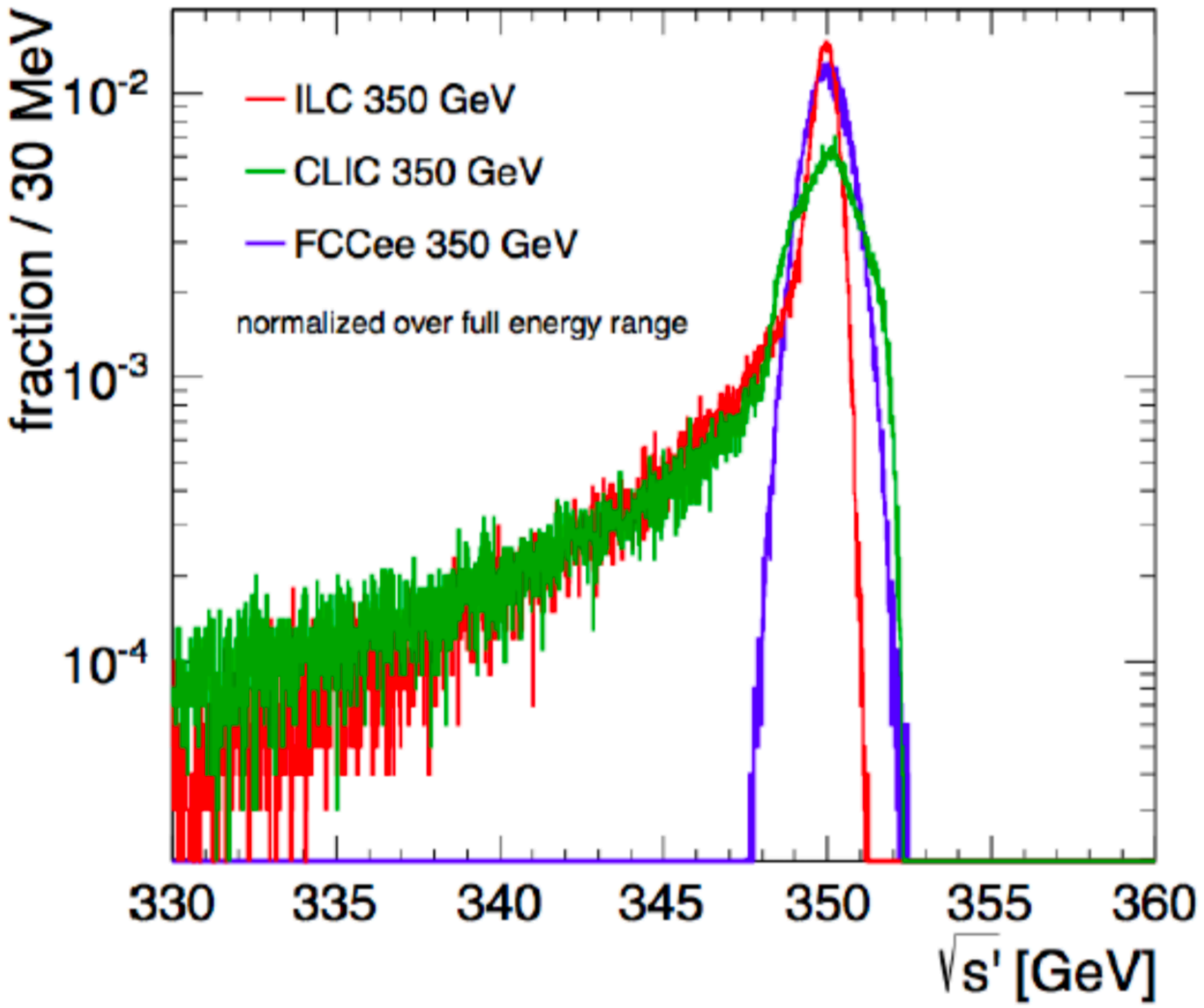
⇒ Enhancement of effective luminosity and sensitivity to rare processes

Linear Collider physics, Georg Weiglein, LCWS2021, 8th Linear Collider Physics School, 03 / 2021 16

CENTER OF MASS ENERGY AND LUMINOSITY SPECTRUM

- Need to know < √s > precisely
    - Key systematics for all mass measurements, and all EW observables.

- And the distribution of √s, i.e. :
    - basically the (gaussian) beam-energy spread (BES) for a circular machine
    - the luminosity spectrum for a linear collider
        - Large tail because of beamstrahlung



- FCC-ee, Z peak and WW threshold: exquisite precision on < √s > (100 keV at the Z, 300 keV at WW) thanks to quasi-continuous resonant depolarisation (RDP) measurements [5]
  - very powerful, unique to circular machines
  - allows a measurement of M_Z to 100 keV

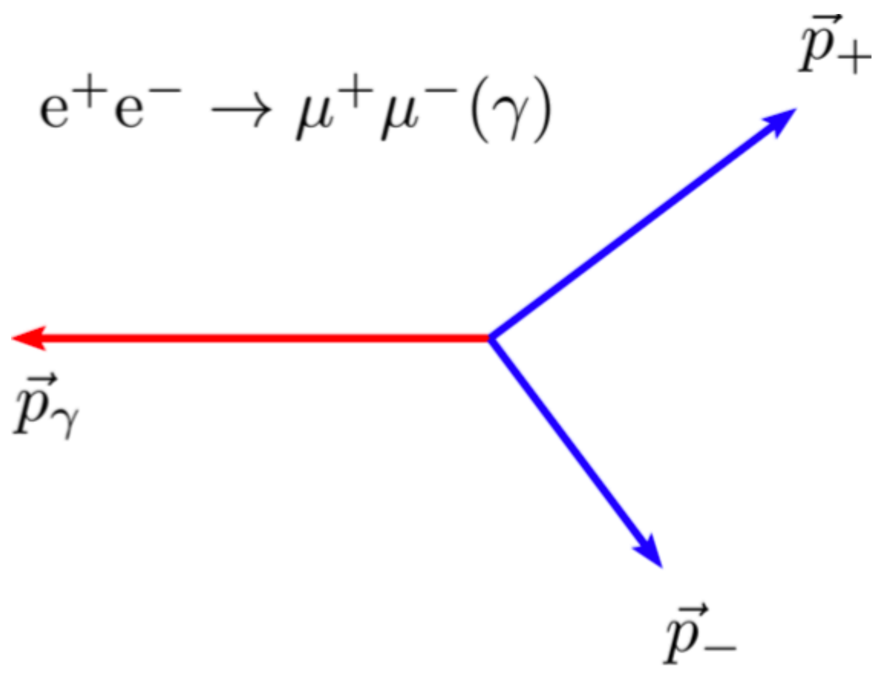
- Circular at higher √s, and linear : exploit kinematic constraints of ee → ff (γ)
  - also used at circular machines to determine the BES

CONSTRAINING THE √s FROM $ee \to ff(\gamma)$ EVENTS

- Above the Z peak: radiative return events, cf LEP2 : $\boxed{s = m_Z^2 \times \frac{\sin\vartheta_1 + \sin\vartheta_2 + |\sin(\vartheta_1+\vartheta_2)|}{\sin\vartheta_1 + \sin\vartheta_2 - |\sin(\vartheta_1+\vartheta_2)|}}$
  - Depends only on angles
  - Can use Z → qq in addition to Z → ll
  - At FCC, can be used to determine < √s > (~ 2 MeV) at 240 GeV
    - method can be calibrated at 160 GeV against the RDP meas.
  - At 350-365 : complement with ZZ and WW events, expect O(5 MeV)

- Or, using muon momenta in (all) μμ(γ) events : [6]

$$\boxed{\sqrt{s} = E(\mu^+) + E(\mu^-) + E(\gamma) \text{ with } E(\gamma) = p(\gamma) = |\,\mathbf{p}(\mu^-) + \mathbf{p}(\mu^+)\,|}$$



Measure $\sqrt{s_p}$ using,
$(|\vec{p}_+|, |\vec{p}_-|, |\vec{p}_+ + \vec{p}_-|)$

"s_p" method, developed at ILC
Much better statistical power with a good muon momentum resolution (not limited by the width of the Z).
Stat potential with ILC/FCC tracker momentum resolution:
Δ√s ~ 230 MeV per diμ event when p(μ) ~ 50 GeV
- i.e. negligible stat error at 240 - 250 GeV for LC / CC
- syst uncertainty given by the absolute p scale

Key = tracker momentum calibration.

THE HIGGS

INTERESTING HIGGS PHYSICS GOALS FOR ee COLLIDERS VS LHC

~~ significant steps in precision study of Higgs properties ~~

(1) Higgs kinematic parameters: m_H and Γ_H

↠ reduce parametric uncertainties in xs and BR

↠ control the fate of EW vacuum within the SM

↠ constrain new physics models (e.g. MSSM)

(2) Precise and model-independent access to Higgs couplings

↠ <1% level

↠ identification of correlation patterns among deviations

↠ indirect test of extended Higgs sectors/composite nature

↠ ultimate test of naturalness

(3) Access to decays modes that are background dominated @ LHC

↠ bb/cc/gg

↠ exotic decay modes (⤷ portal models of Dark Matter)

(4) Constraints on Higgs flavor violating couplings

↠ shed light on the origin of fermion masses and flavours

ROLE OF HIGGS FOR BSM SEARCHES

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

Measuring Higgs couplings to 1%
=
Probing Higgs structure to 1/10th of its Compton wave-length

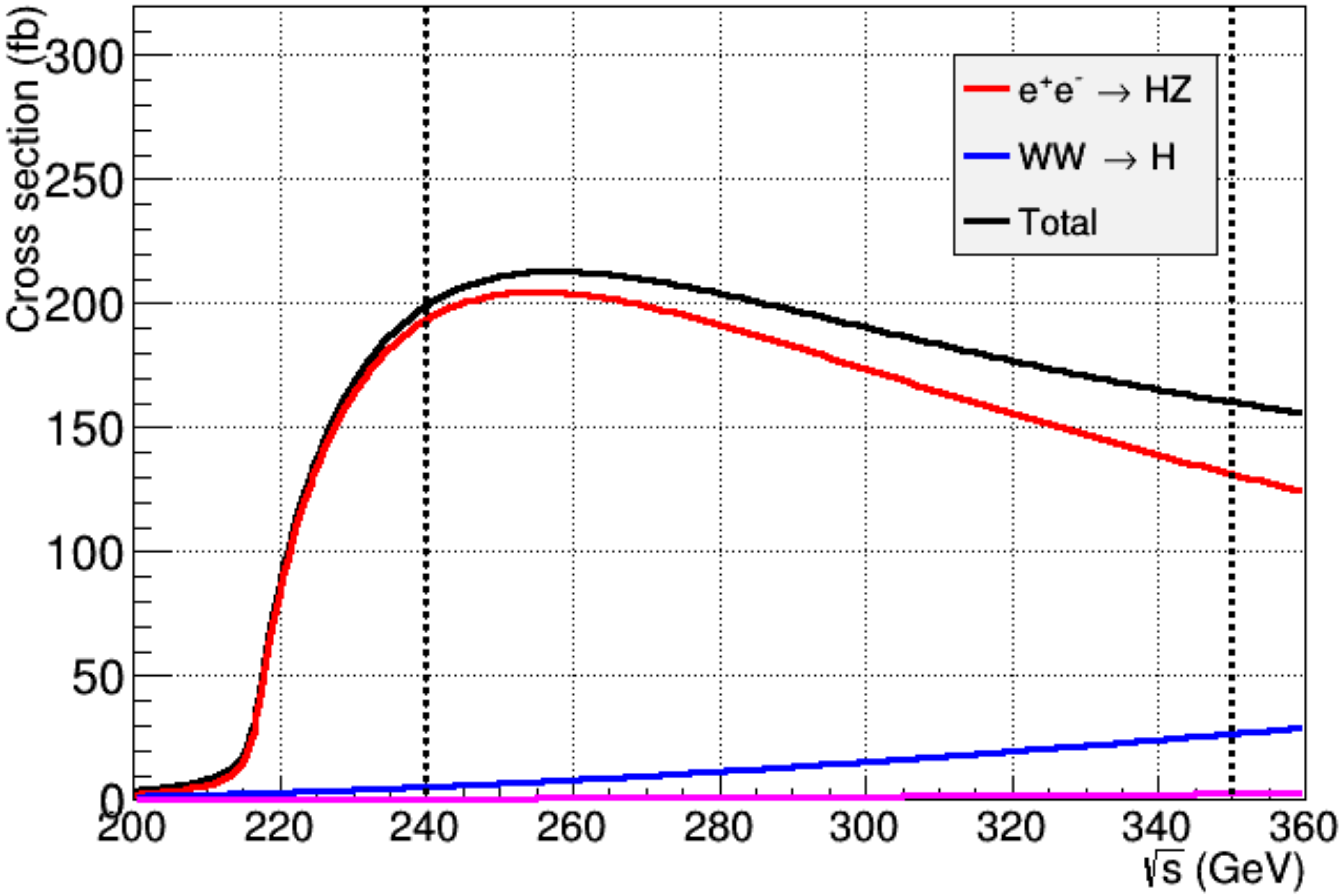
i.e. learning if the Higgs is an elementary particle!

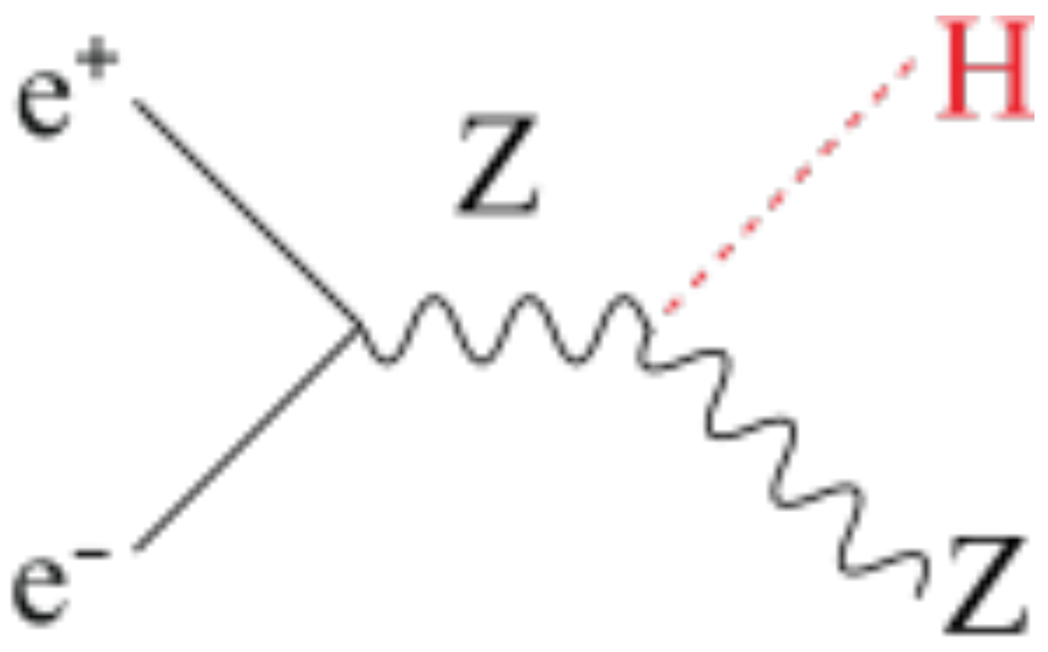
Higgs precision program is very much wanted to probe BSM physics

1% is also a magic number to probe naturalness of EW sector

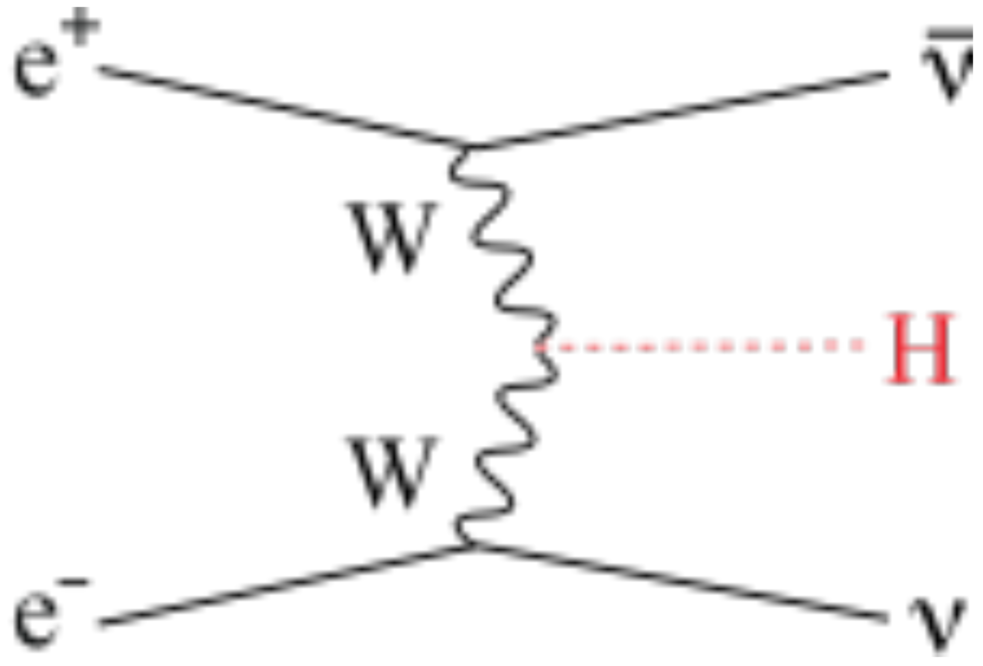
HIGGS PRODUCTION AT LEPTON COLLIDERS

- Higgsstrahlung: e+e- → ZH: $\sigma \sim 1/s$, dominant up to ≈ 450 GeV
- WW fusion: $e^+e^- \to H\nu_e\nu_e$: $\sigma \sim \log(s)$, dominant above 450 GeV. Large statistics at high energy
- Higher energy running points useful also to improve Higgs measurements (width and self-coupling)





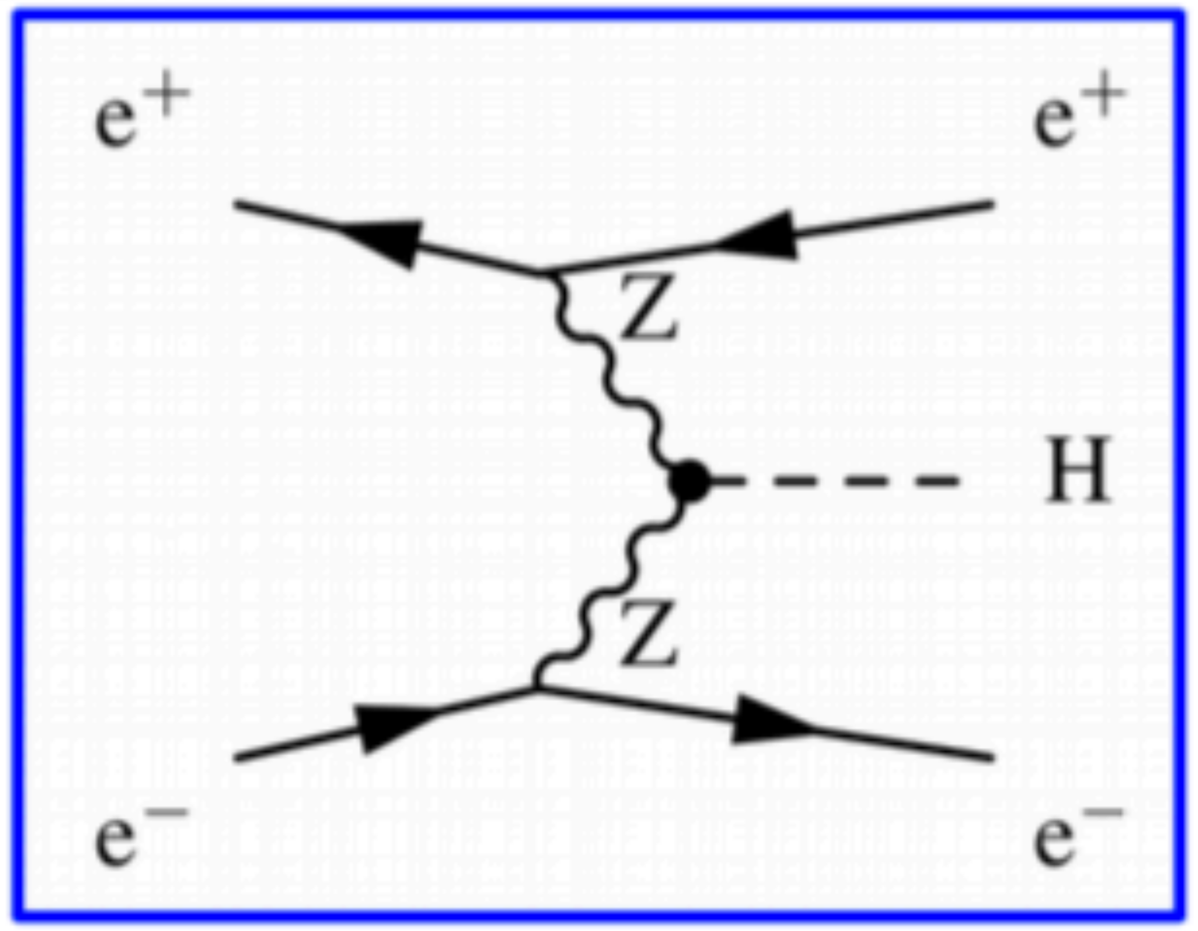
Higgs-strahlung



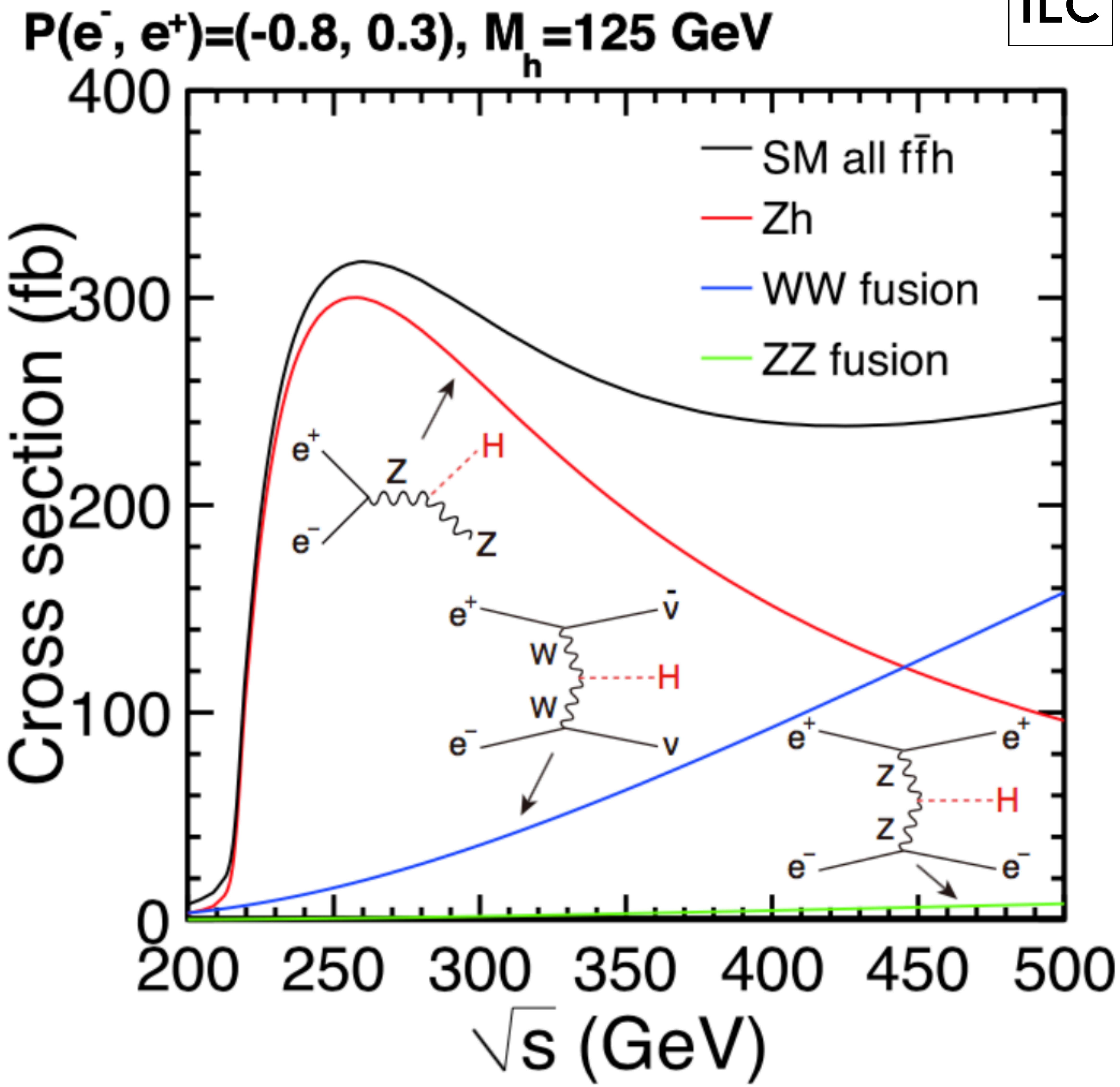
Boson fusion

EFFECT OF POLARIZATION ON HIGGS PRODUCTION (ILC,CLIC)

- Higgs-strahlung cross section multiplied by
  - $1 - P^{-}P^{+} - A_e \times (P^{-} - P^{+})$
- Boson fusion cross section multiplied by $(1-P^{-}) \times (1+P^{+})$



ILC

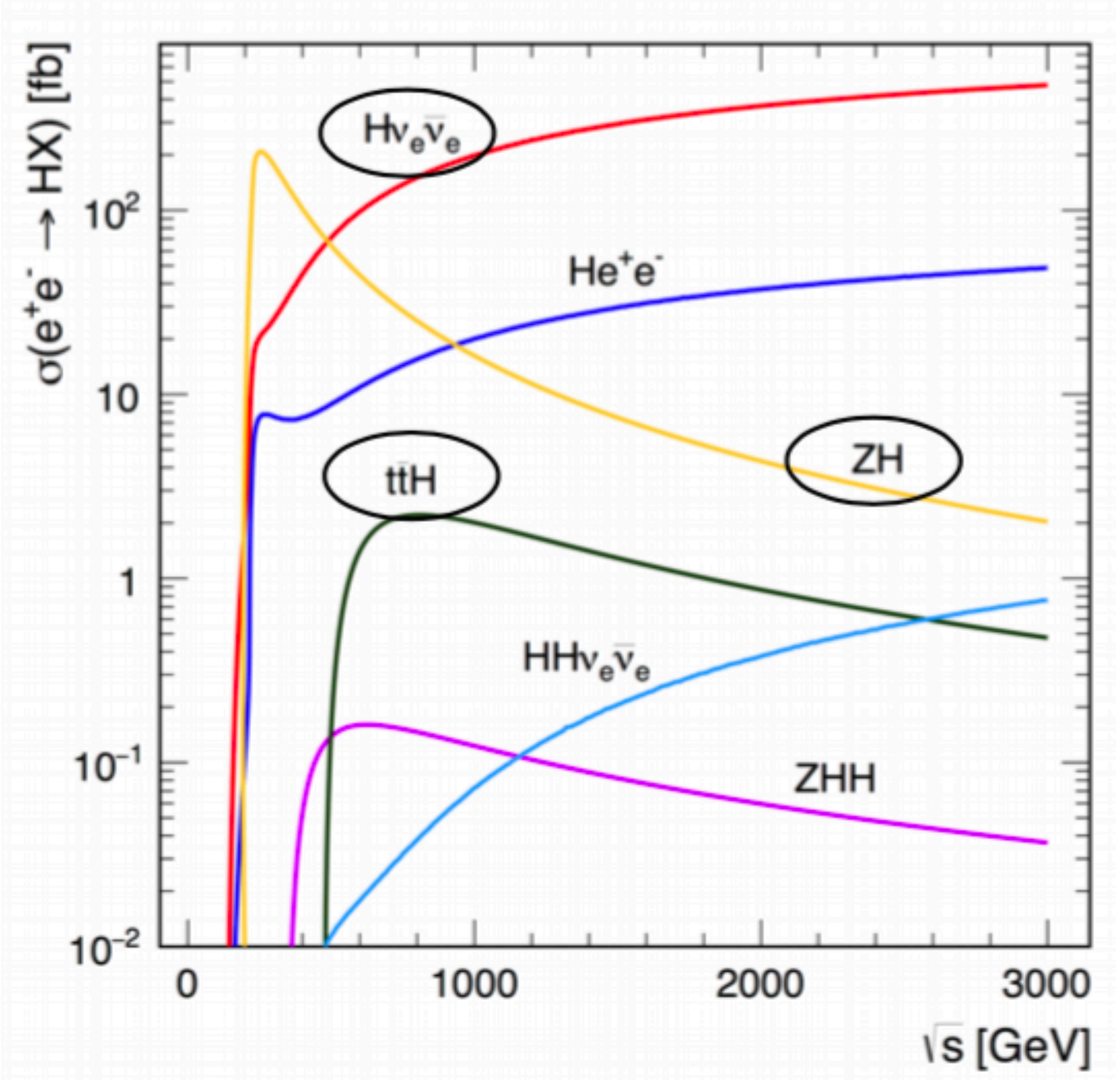


MORE ON POLARIZATION

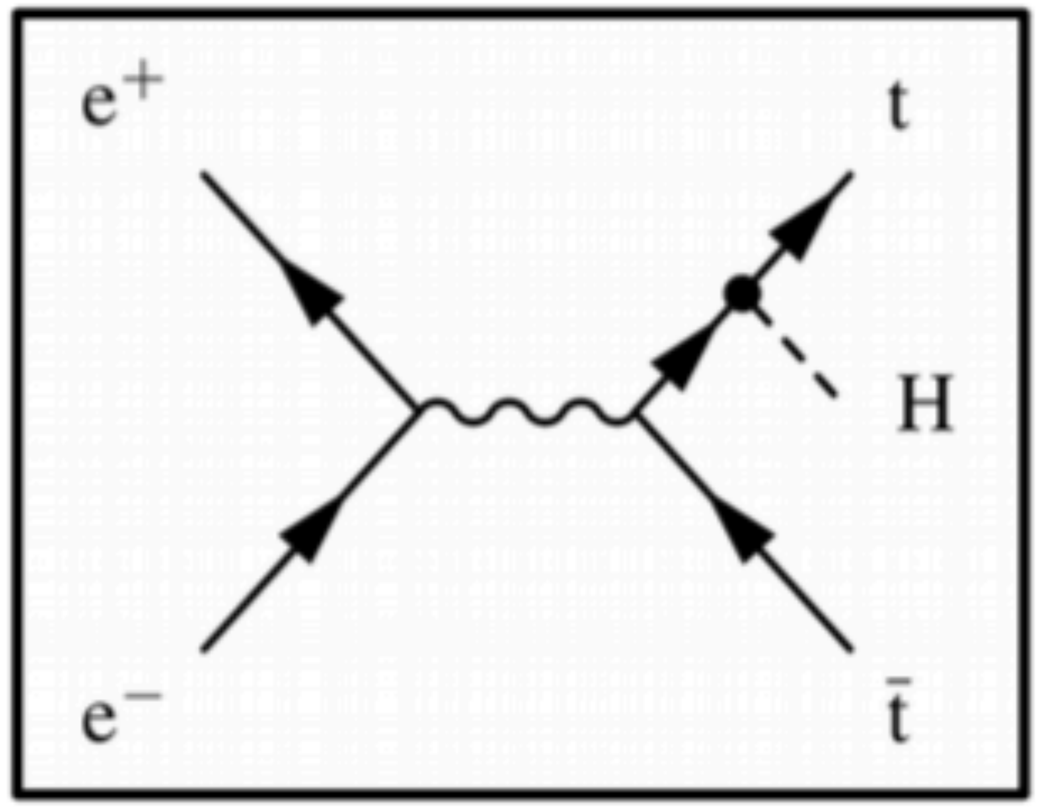
- At a circular collider the beams won't be longitudinally polarized
  - if attempted, with difficulty and money, could reach only 30% for e+, with a 50-fold loss in luminosity at the Z
- The effect of polarization on Higgs production at $\sqrt{s}$=240/250 GeV increases the σ_{HZ} cross section by 1.4(1.08) in $e_L^- e_R^+$($e_R^- e_L^+$) configuration
  - backgrounds also increase, but polarization helps separate production processes
  - marginal/no effect on k-fit
- EFT fits benefits marginally of the polarization to constrain additional operators
  - At CC the constraints come from the EW precision measurements
  - An additional energy point at $\sqrt{s}$=365 compensate the need for polarization
- For CC the gains from polarization are not worth the induced luminosity loss

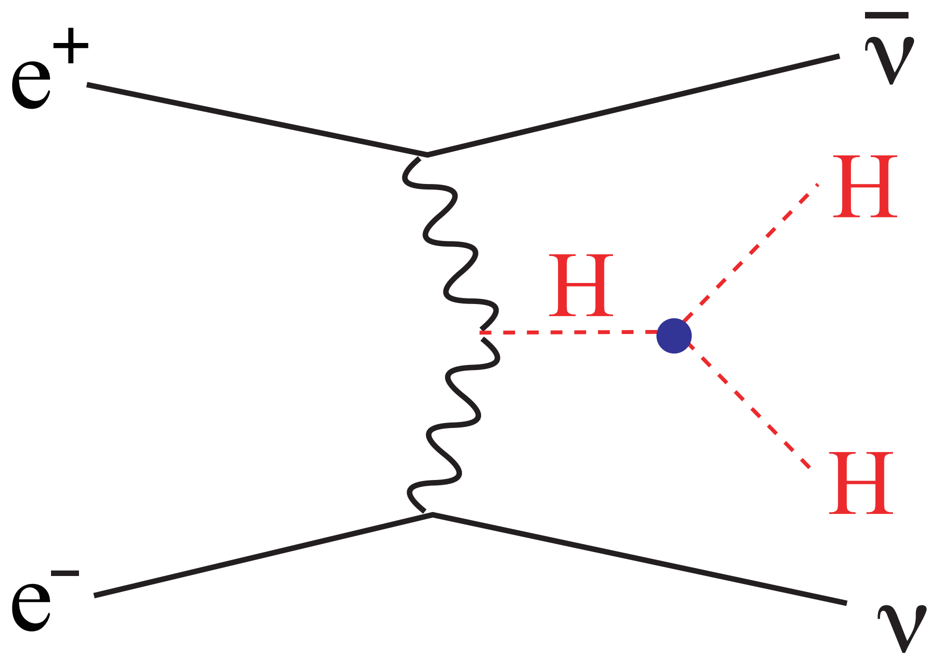
see arXiv.1906.02963

HIGGS PRODUCTION AT HIGHER ENERGIES



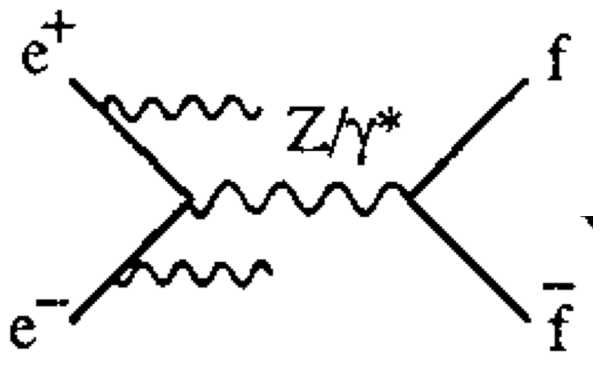
- ttH production: $e^+e^- \to$ ttH
  - Accessible $\sqrt{s} \geq 500$ GeV, maximum ≈ 800 GeV
  - Direct extraction of top Yukawa coupling
- ZHH and $HH\nu_e\nu_e$ production
  - From $\sqrt{s}=500$ GeV (ZHH) and ≈800 GeV ($HH\nu_e\nu_e$), dual Higgs production
  - Sensitivity to Higgs self coupling





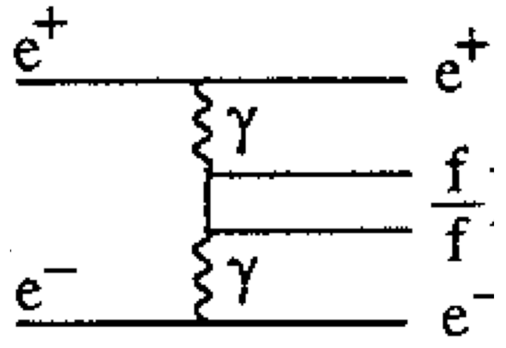
HIGGS PHYSICS BACKGROUNDS

- Physics backgrounds are "small": examples at $\sqrt{s}$=240GeV
  - "Blue" cross sections decrease like 1/s
  - "Green" cross sections increase slowly with s



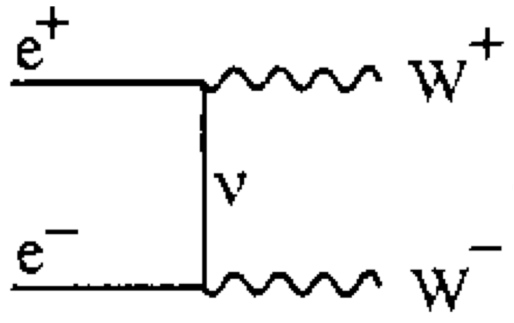
$e^+e^- \to q\bar{q}, l^+l^-$

60 pb



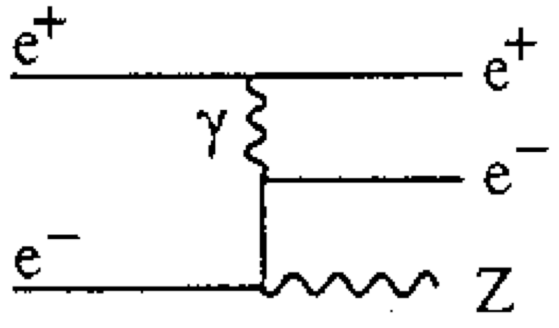
$\gamma\gamma \to q\bar{q}, \ell^+\ell^-$
m > 30 GeV

30 pb



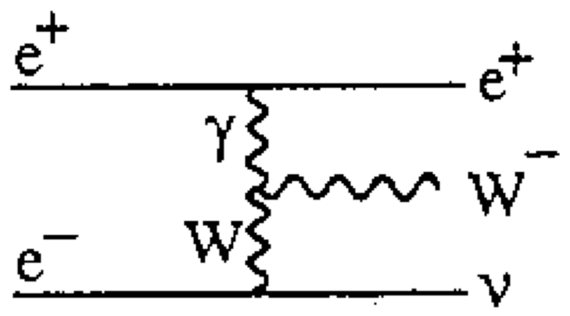
$e^+e^- \to W^+W^-$

16 pb



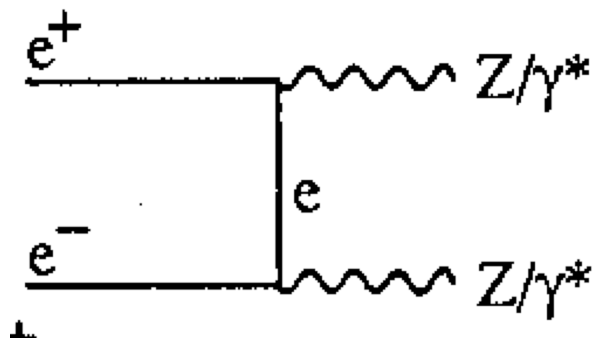
$e^+e^- \to Ze^+e^-$

3.8 pb



$e^+e^- \to We\nu$

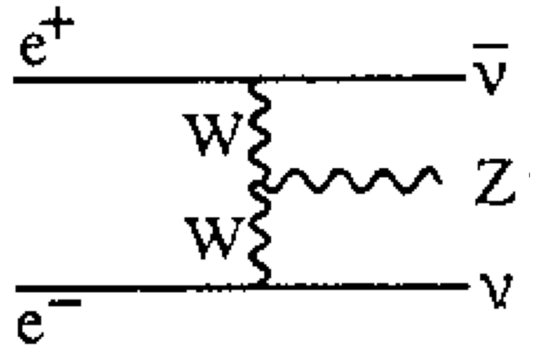
1.4 pb



$e^+e^- \to ZZ$

1.3 pb

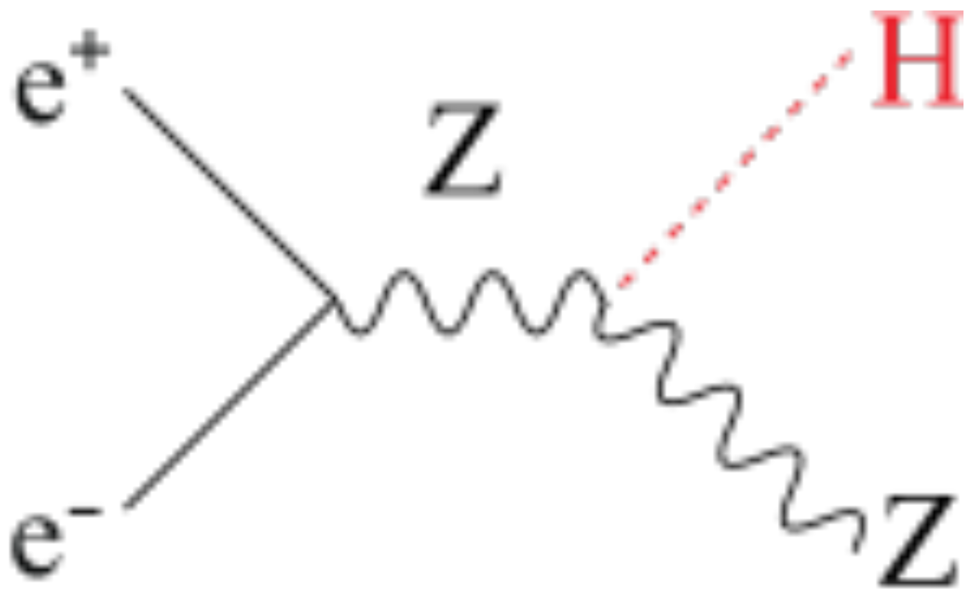
Add $e^+e^- \to t\bar{t}$
for $\sqrt{s}$ > 345 GeV



$e^+e^- \to Z\nu\bar{\nu}$

32 fb

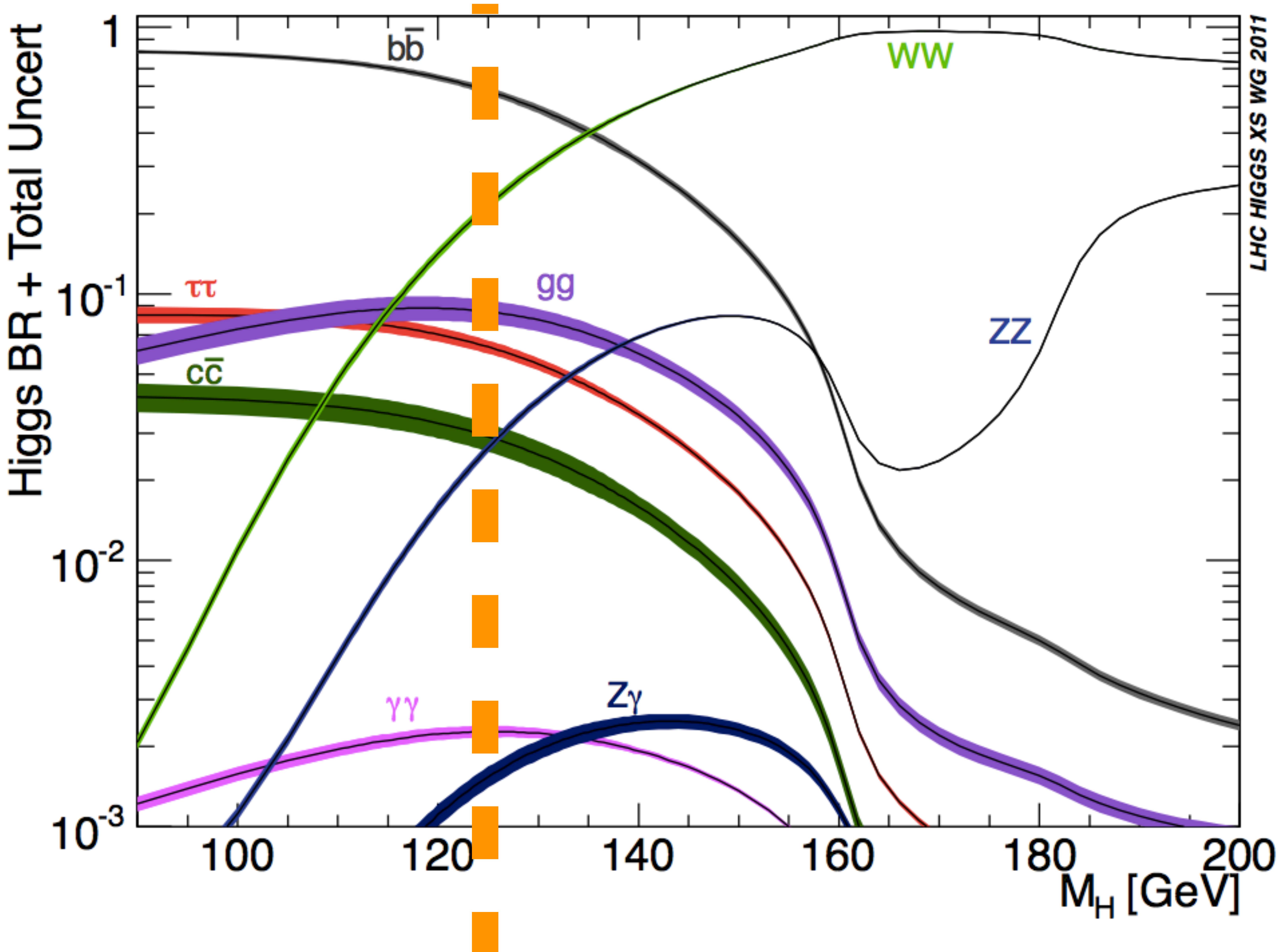
0.6 pb

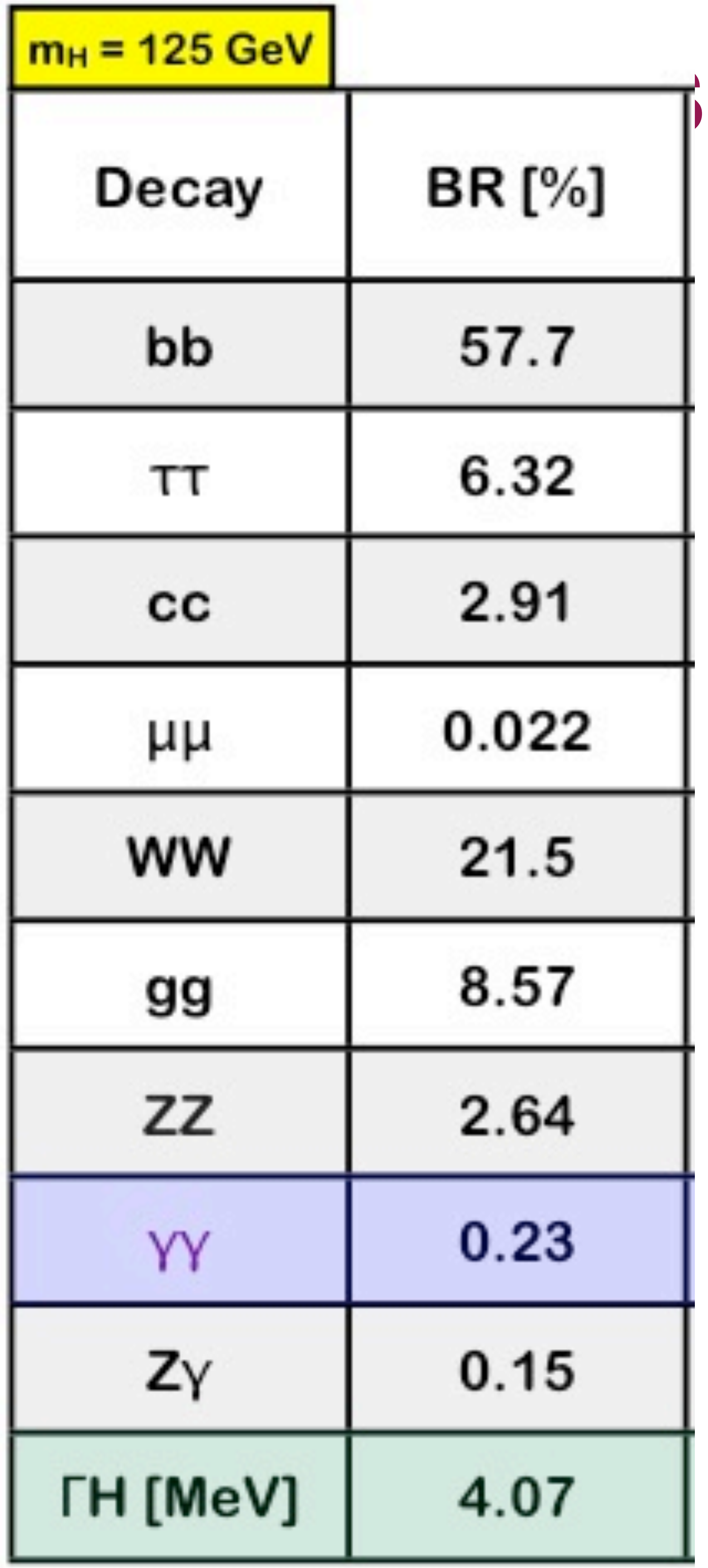


200 fb

- **Only one to two orders of magnitude smaller**
  - **vs. 11 orders of magnitude in pp collisions**
    - **Trigger is 100% efficient**

HIGGS DECAYS



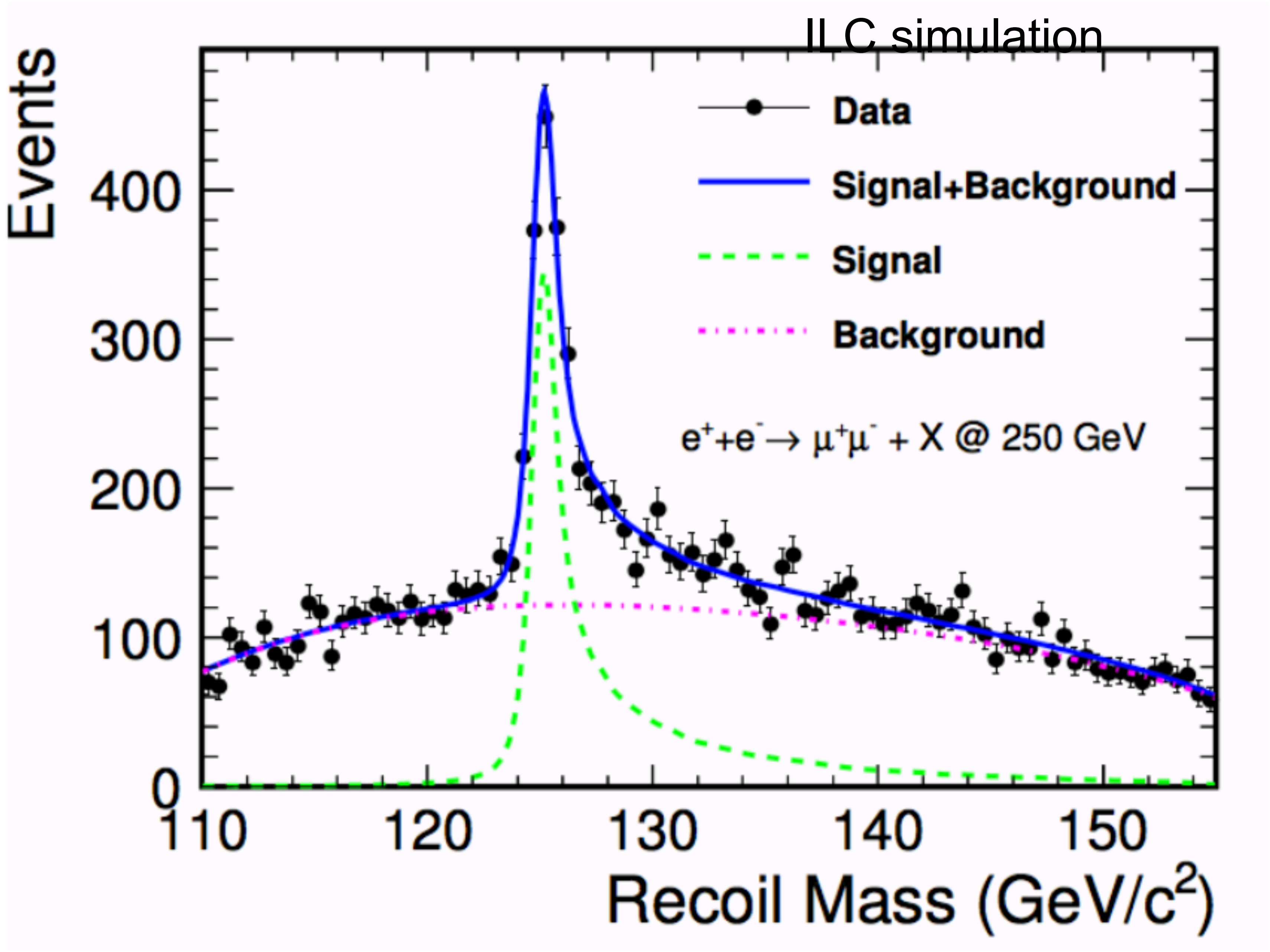


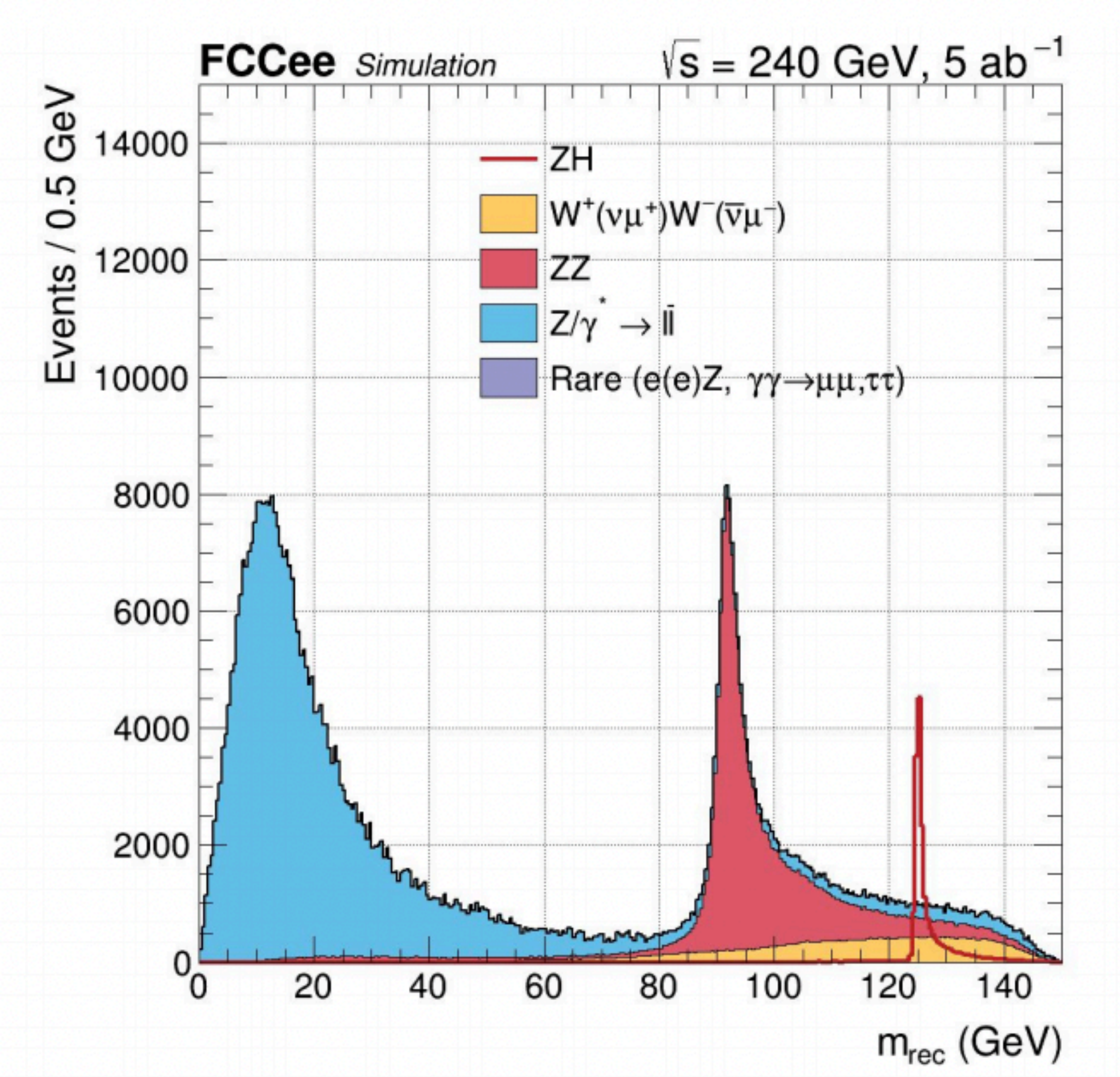
m_H = 125 GeV

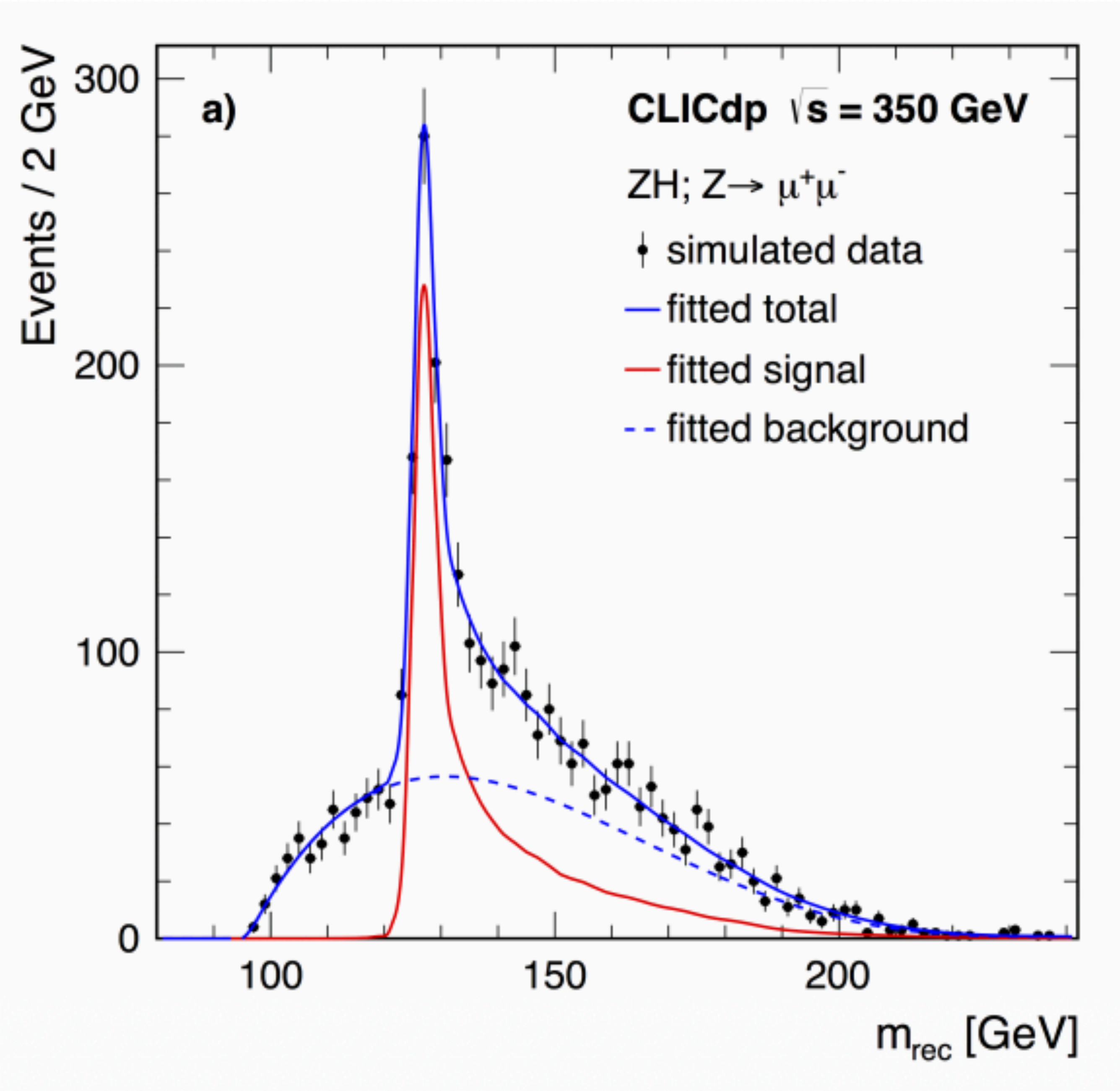
Decay	BR [%]
bb	57.7
ττ	6.32
cc	2.91
μμ	0.022
WW	21.5
gg	8.57
ZZ	2.64
γγ	0.23
Zγ	0.15
ΓH [MeV]	4.07

MODEL-INDEPENDENT MEASUREMENT OF σ_{HZ} AND g_{HZZ}

- The Higgs boson in HZ events is tagged by the presence of the Z → e+e–, μ+μ–
- Select events with a lepton pair (e+e–, μ+μ–) with mass compatible with m_Z
  - Apply total energy-momentum conservation to determine the “recoil mass”
    $$M_{H^2} = s + M_Z^2 - 2\sqrt{s}(p_{\mu^+} + p_{\mu^-})$$
  - Plot the recoil mass distribution – resolution proportional to momentum resolution
  - No requirement on the Higgs decays: measure σ_{HZ} × BR(Z→ e+e–, μ+μ–)
- Provides an absolute measurement of g_{HZZ} and sets required detector performance

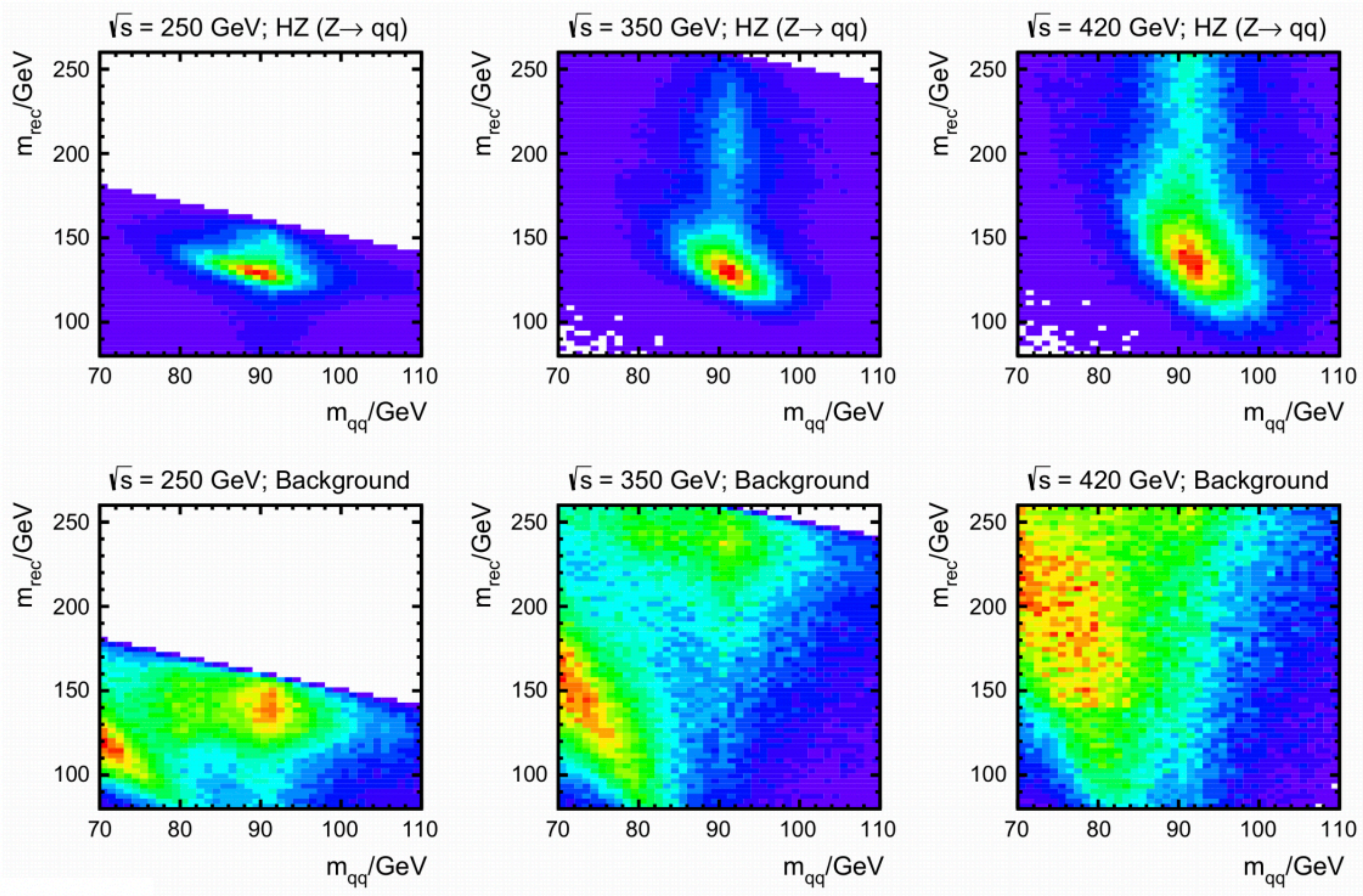






RECOIL METHOD WITH HADRONIC Z DECAYS (CLIC)

$\sqrt{s}$ = 250 GeV: **$\sqrt{s}$ = 350 GeV:** **$\sqrt{s}$ = 420 GeV:**

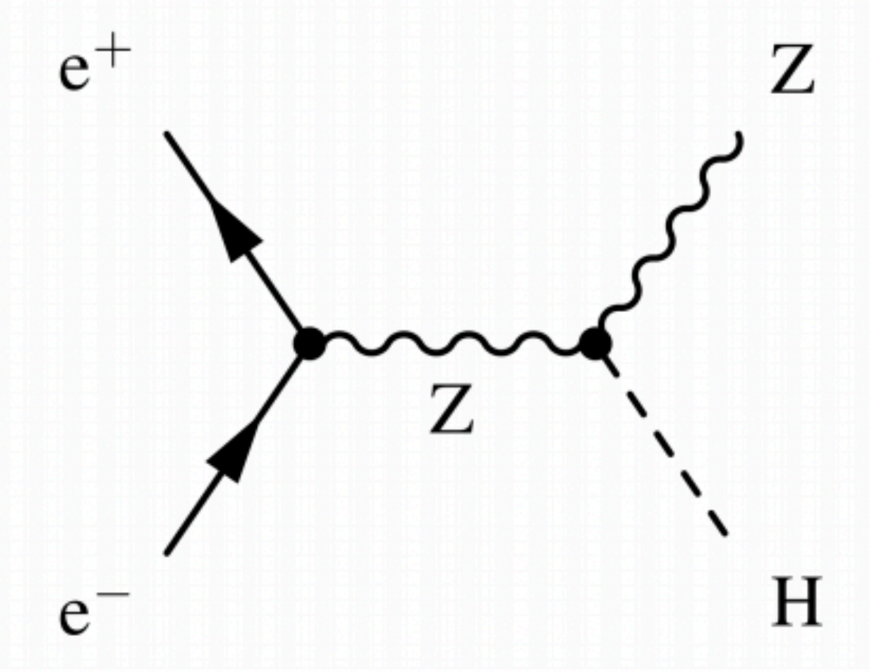


$\sqrt{s}$ [GeV]:	L_{int} [fb^{-1}]:	σ(ZH) [fb]	Δσ(ZH)
250	1000	136	±2.58%
350	1000	93	±1.27%
420	1000	68	±1.86%

Hadronic Z decays provide the best sensitivity at 350 GeV

Optimisation study for the first CLIC stage (together with top physics):

- At 250 GeV the background is more signal-like
- At 420 GeV the cross section is lower and the jet energy resolution is worse



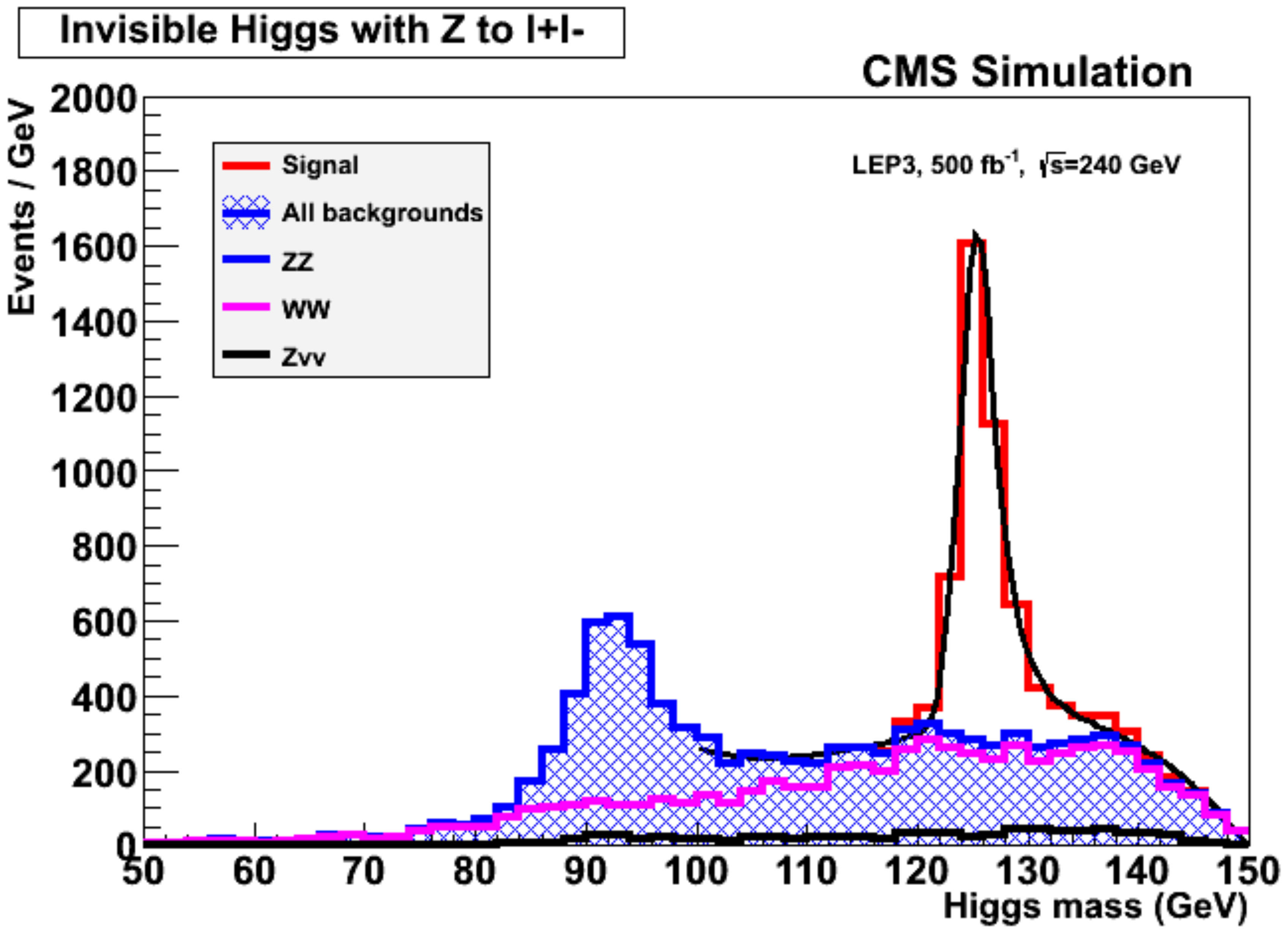
Eur. Phys. J. C 76, 72 (2016)

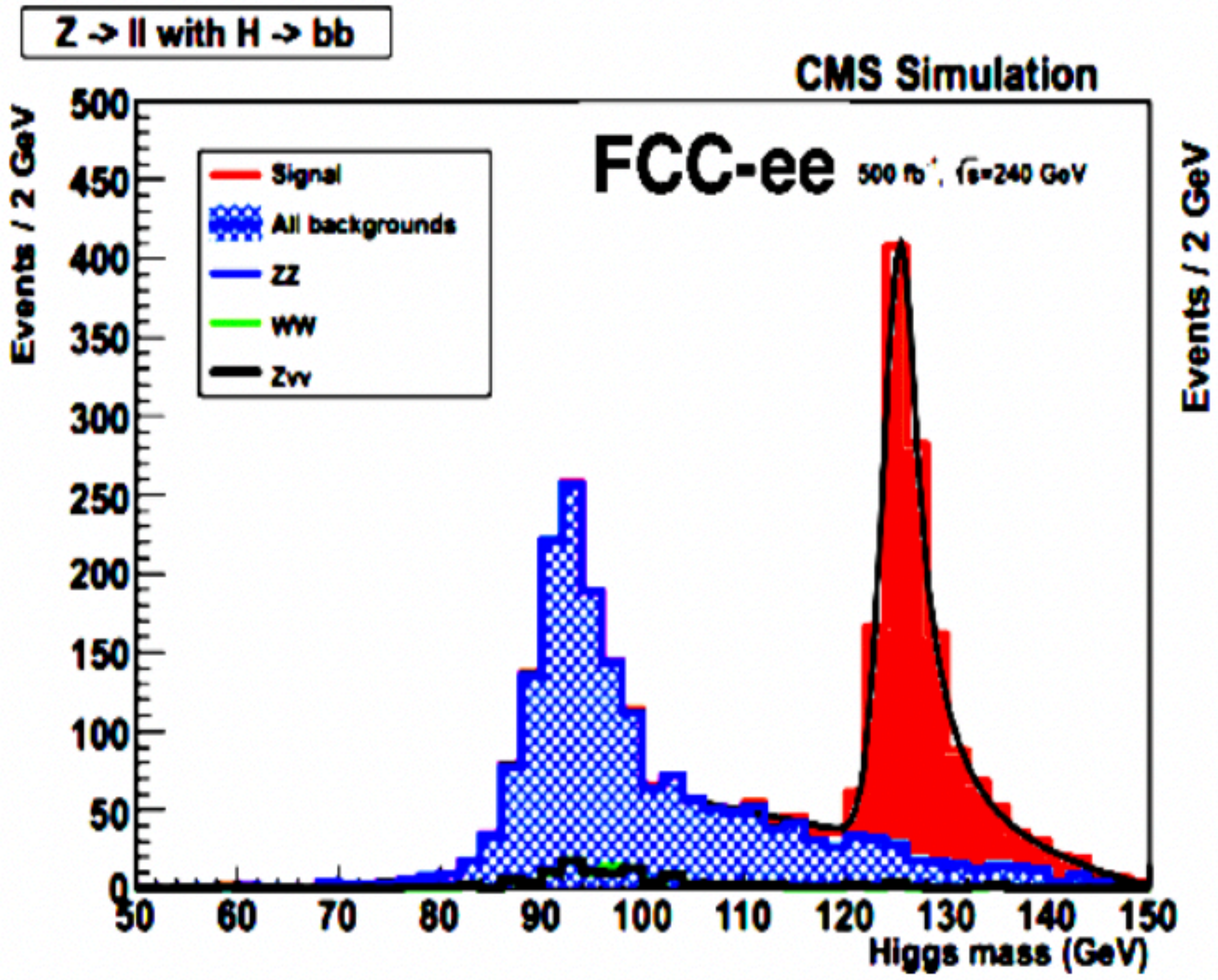
MEASURING THE HIGGS DECAY BR

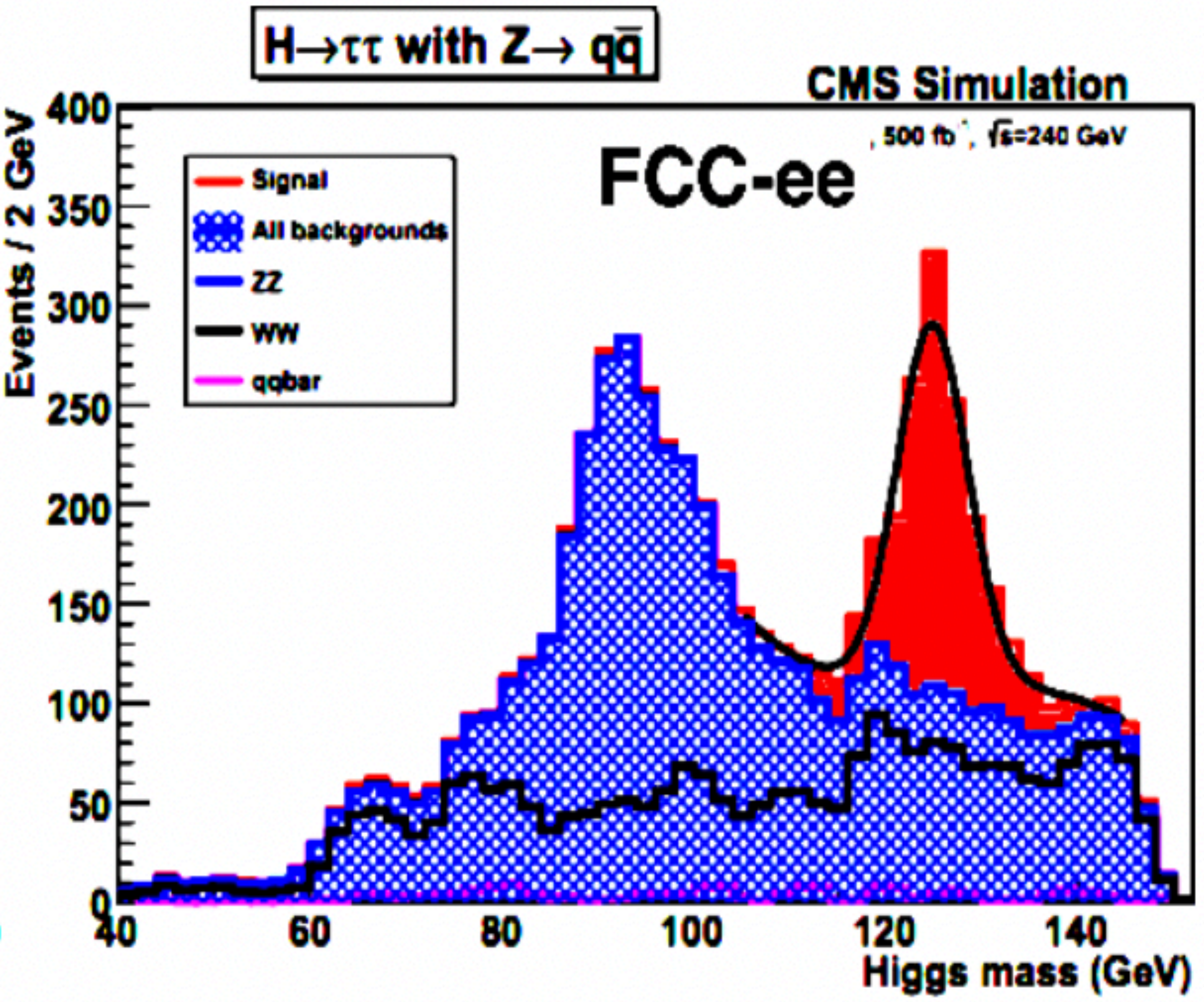
- Repeat the procedure for all possible final states
  - For all exclusive decays, YY, of the Higgs boson: measure $\sigma_{HZ} \times BR(H \to YY)$
    - Including invisible decays: event containing only the lepton pair with correct (m_{miss}, m_{recoil}), otherwise empty
  - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics [detector requirements]
  - For the WW fusion mode (Hνν final state): measure $\sigma_{WW \to H} \times BR(H \to YY)$

$ZH \to \ell^+\ell^-$ + nothing, 0.5 ab^{-1}

BR(H → invis) = 100%





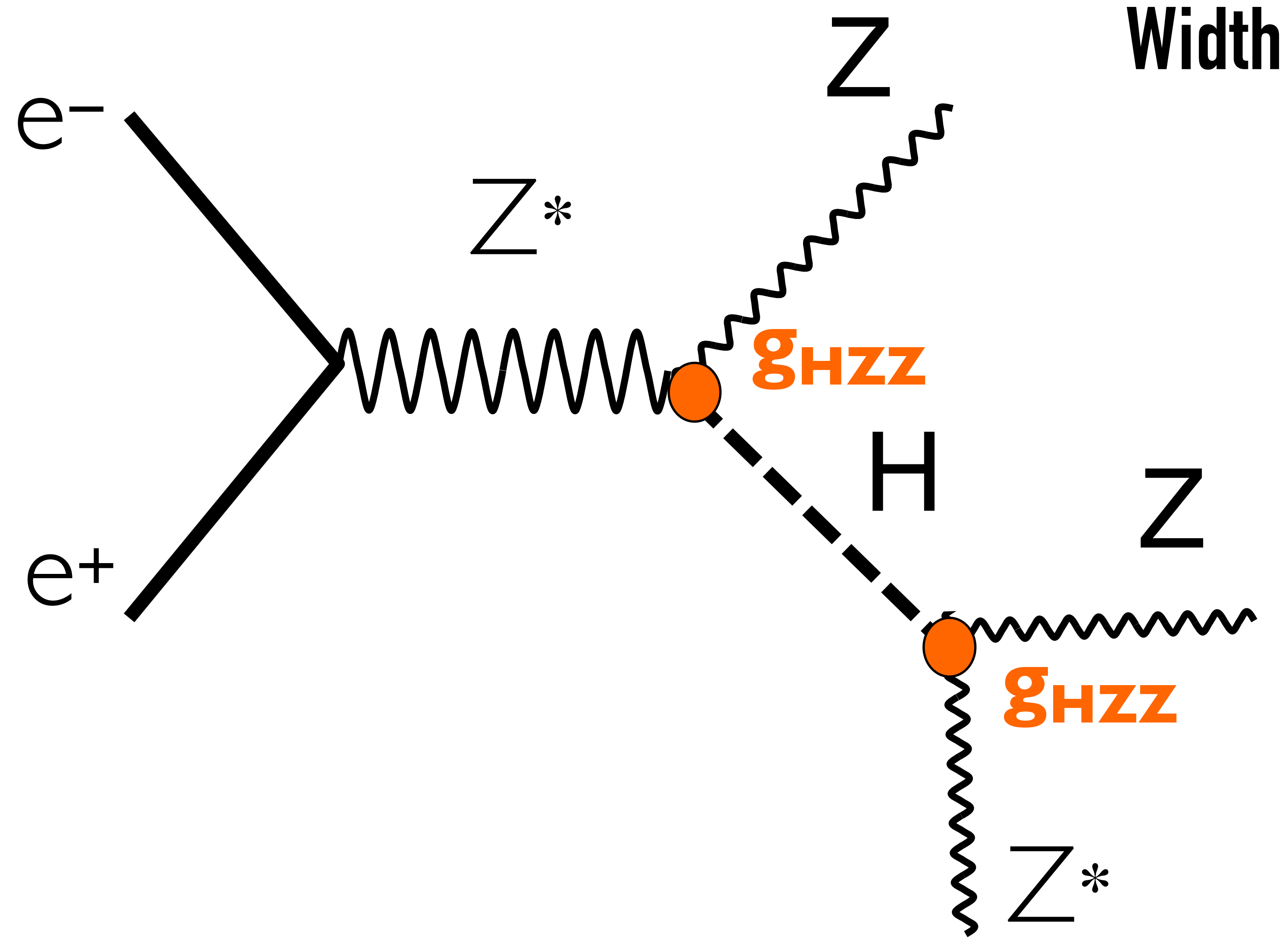


HIGGS WIDTH

- ➤ Model independent determination of the total Higgs decay width down to 1.3% with runs at √s=240 and √s=365 GeV
- ➤ To extract couplings from BR need the total width

ee →HZ & H → ZZ at √s = 240 GeV

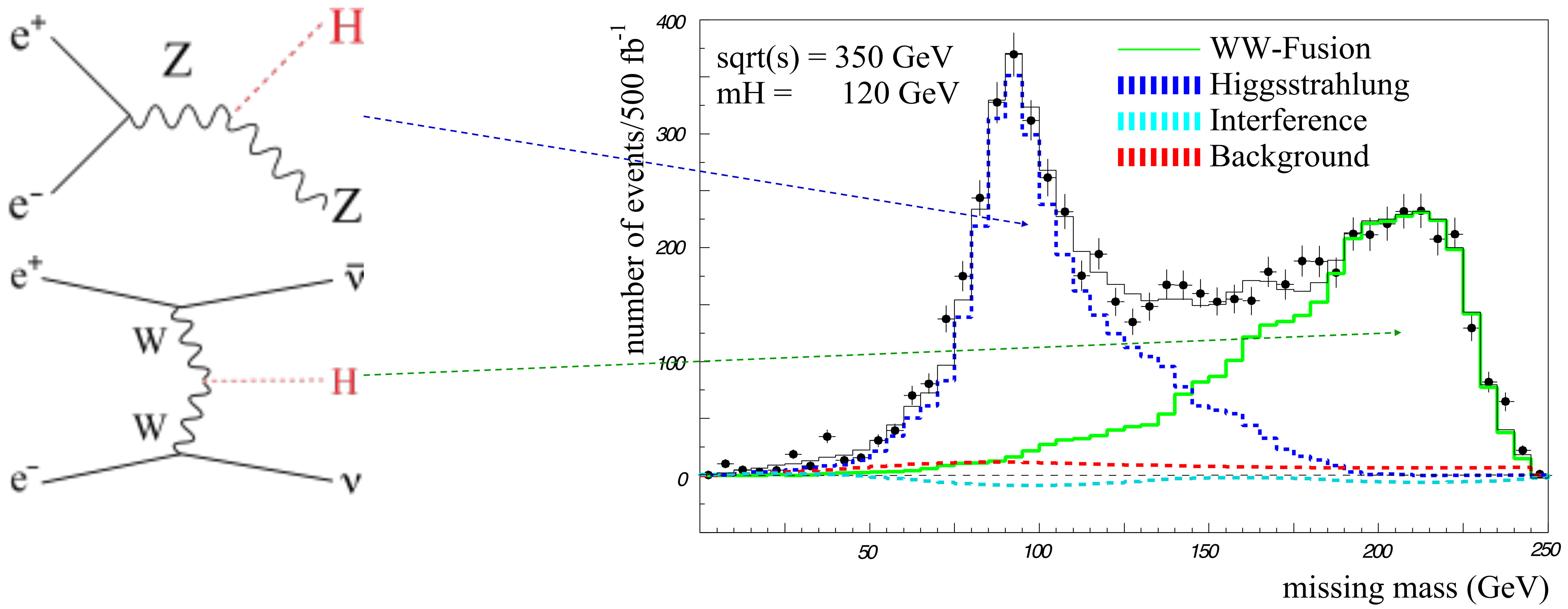
Width to Couple of %



- ❖ **σ_{HZ} is proportional to g_{HZZ}^2**
- ❖ **BR(H → ZZ) = Γ(H → ZZ) / Γ_H is proportional to g_{HZZ}^2/Γ_H**
  - ▪ **σ_{HZ} × BR(H → ZZ) is proportional to g_{HZZ}^4/Γ_H**
- ❖ **Infer the total width Γ_H**

Width to 1%

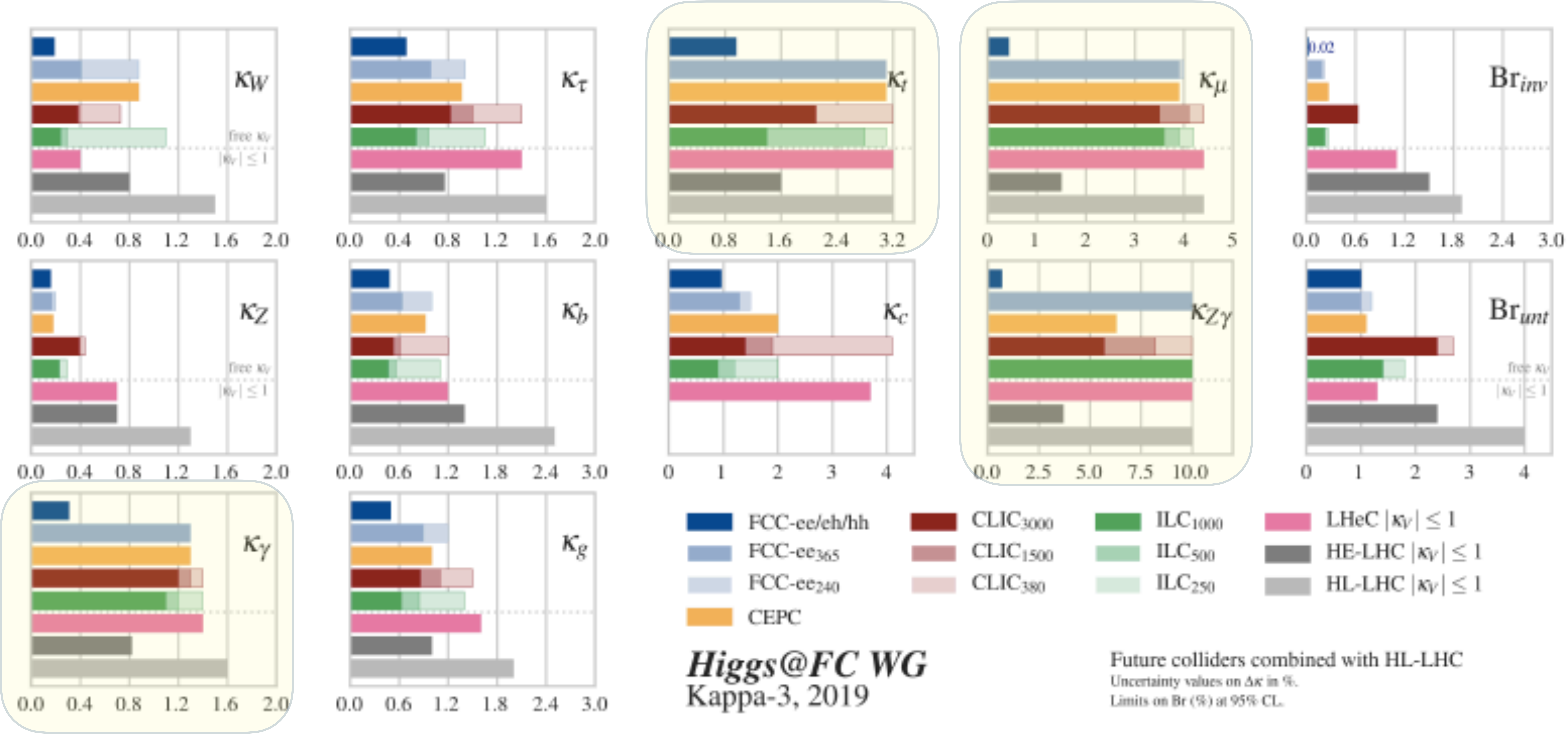
WW → H νν→ bbνν at √s = 365 GeV



$$\Gamma_H \propto \frac{\sigma_{WW\to H}}{BR(H\to WW)} = \frac{\sigma_{WW\to H\to b\bar{b}}}{BR(H\to WW)\times BR(H\to b\bar{b})}$$

HIGGS COUPLINGS

- Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.



Yellow highlight for those couplings best measured with FCC-hh

SUMMARY OF HIGGS MEASUREMENT PRECISIONS - KAPPAS

Coupling	HL-LHC	CEPC$_{240}$	FCCee$_{365}$	ILC$_{500}$	CLIC$_{1500}$
κ_W [%]	1.2	1.3	0.43	0.29	0.17
κ_Z [%]	1.0	0.13	0.17	0.23	0.26
κ_c [%]	SM	2.2	1.3	1.3	1.8
κ_t [%]	2.8	-	-	6.9	n.a.
κ_b [%]	2.7	1.2	0.67	0.58	0.48
κ_μ [%]	4.4	8.9	8.9	9.4	13
κ_τ [%]	1.6	1.3	0.73	0.7	1.3
κ_γ [%]	1.7	3.7	3.9	3.4	5.0
κ_g [%]	2.2	1.5	1.0	0.97	1.3
$\kappa_{Z\gamma}$ [%]	10	8.2	-	-	15
Γ_H [%]	~50	3.1	1.3	1.6	2.6
BR_{inv} [%]	$\lesssim$ 2	< 0.27	< 0.19	< 0.22	< 0.62
BR_{EXO} [%]	SM	< 1.1	< 1.0	< 1.4	< 2.4
λ_3 (sngl-H/di-H)	- / 50	17 / -	19 / -	26 / 27	40 / 36

→ **Model-independent results**

Sensitive to new physics at tree level

Expected effects < 5% / Λ^2_{NP}

1% precision needed for Λ_{NP} ~ 1TeV

Sub-percent needed for Λ_{NP} > 1TeV

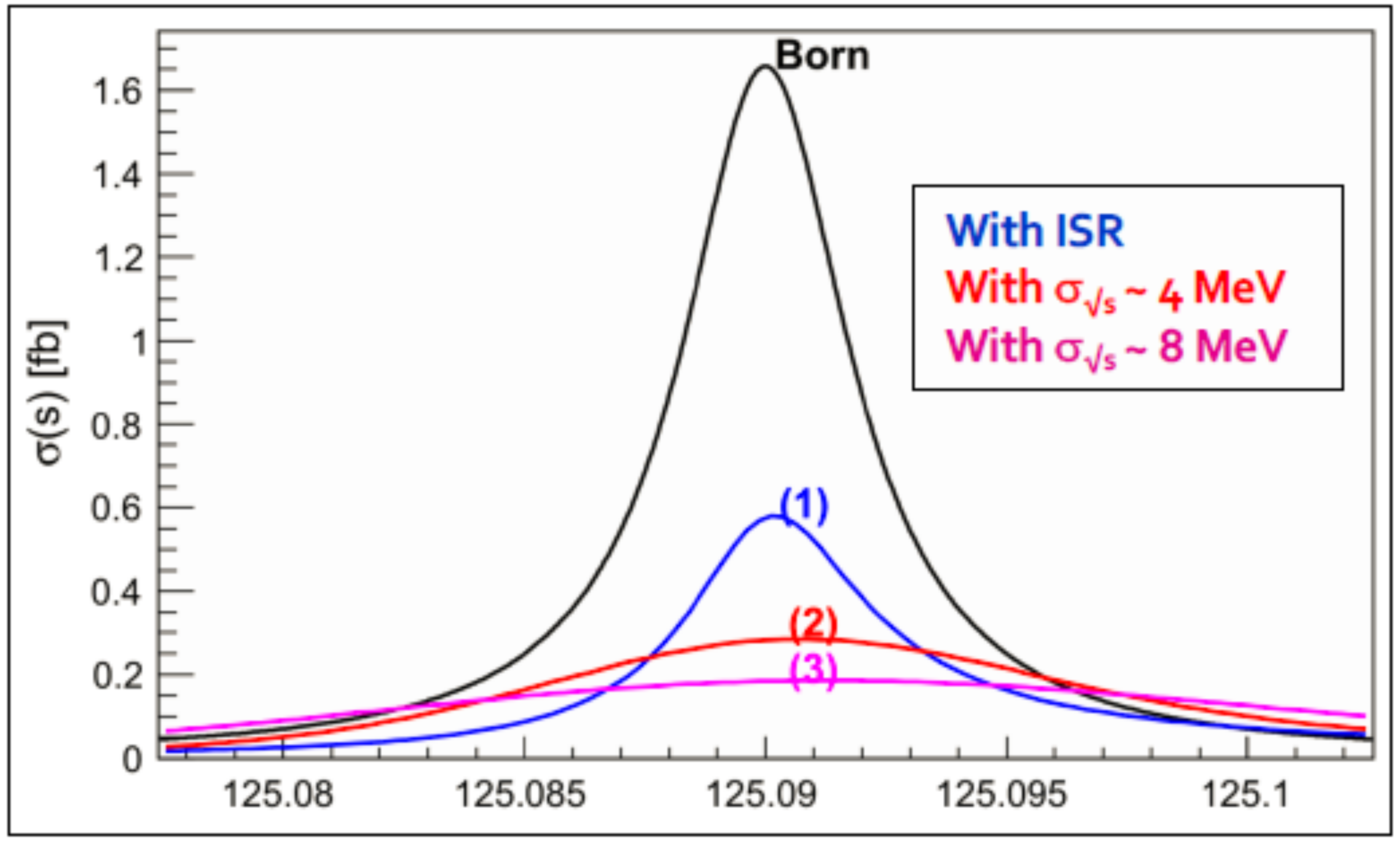
Sensitive to new physics in loops

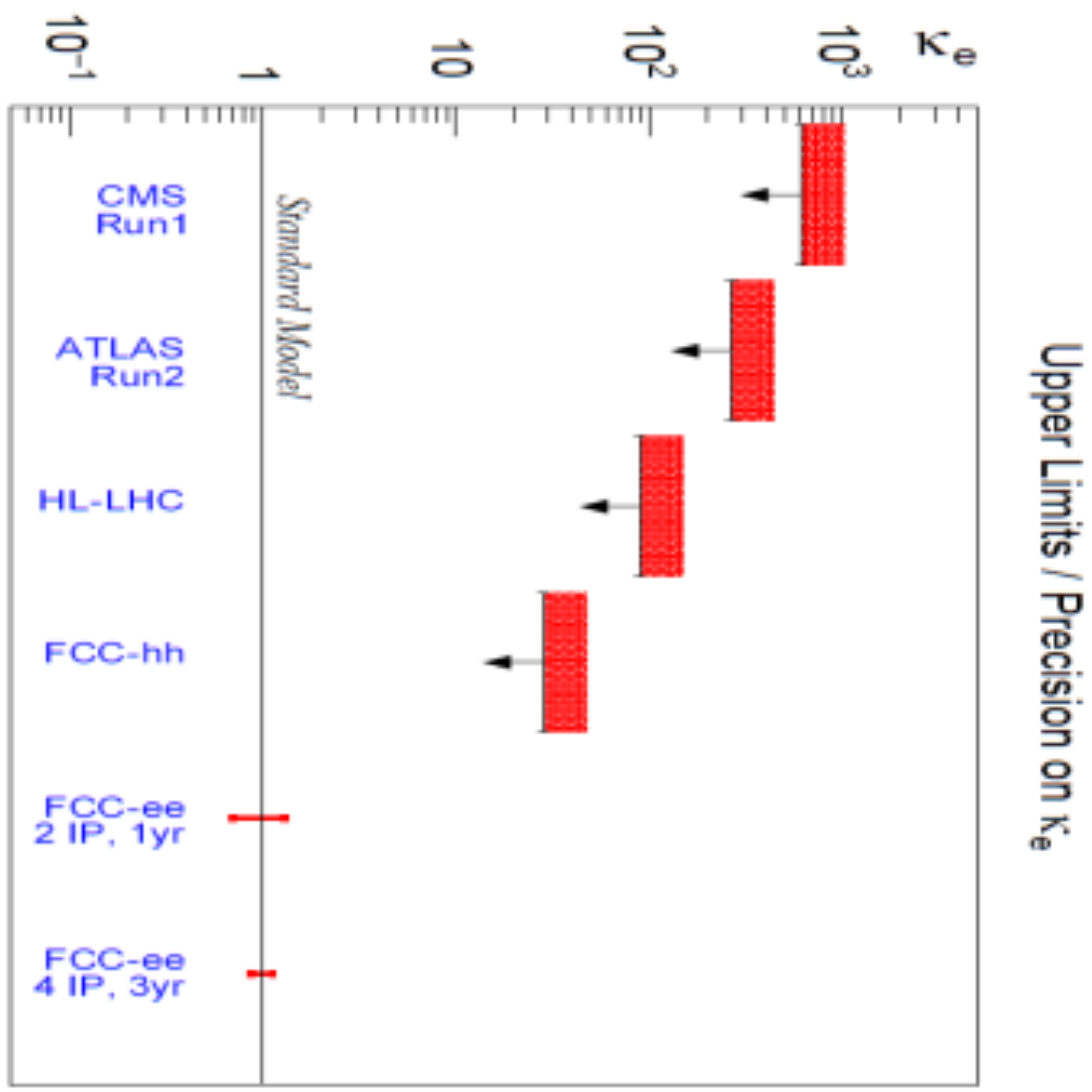
Sensitive to light dark matter particles (sterile ν, χ, …) and to other exotic decays

Higgs self-coupling

Generally, a factors of 2−10 better than HL-LHC
Plus Model Independence

SOMETHING UNIQUE: ELECTRON YUKAWA COUPLING





HUGE CHALLENGE

e+e- → H @ 125.xxx GeV requires:

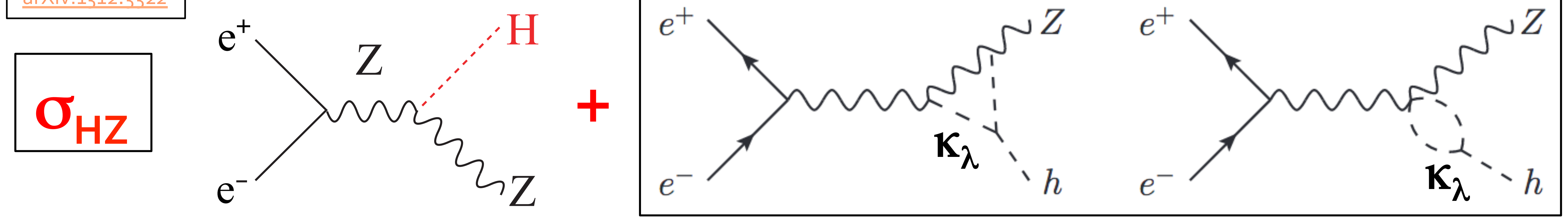
- Higgs mass to be known to <5 MeV from 240 GeV run (CEPC group almost there)
- Huge luminosity
- monochromatization (opposite sign dispersion using magnetic lattice) to reduce σECM
- continuous monitoring and adjustment of ECM to MeV precision (transv. Polar.)
- an extremely sensitive event selection against backgrounds
- a generous lab director to spend 3 years doing this and neutrino counting

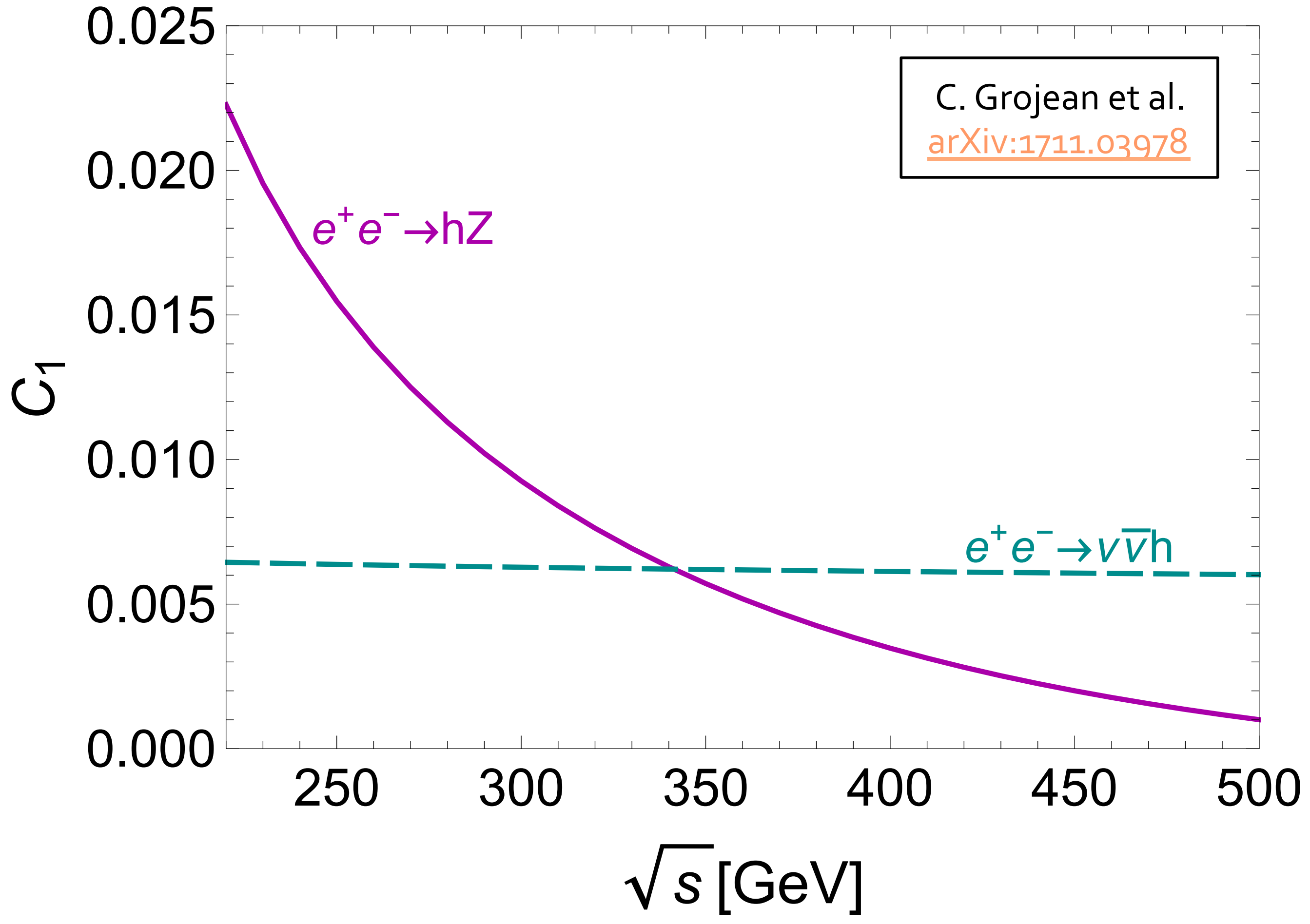
HIGGS SELF-COUPLING WITH SINGLE HIGGS

- Traditionally kλ measured in double Higgs production at higher energies. FCC-ee can profit of the significant effect on single Higgs production

Precision on kλ	
FCC-ee	33 %
FCC-ee(4IP)	24 %
FCC(ee+hh)	5 %

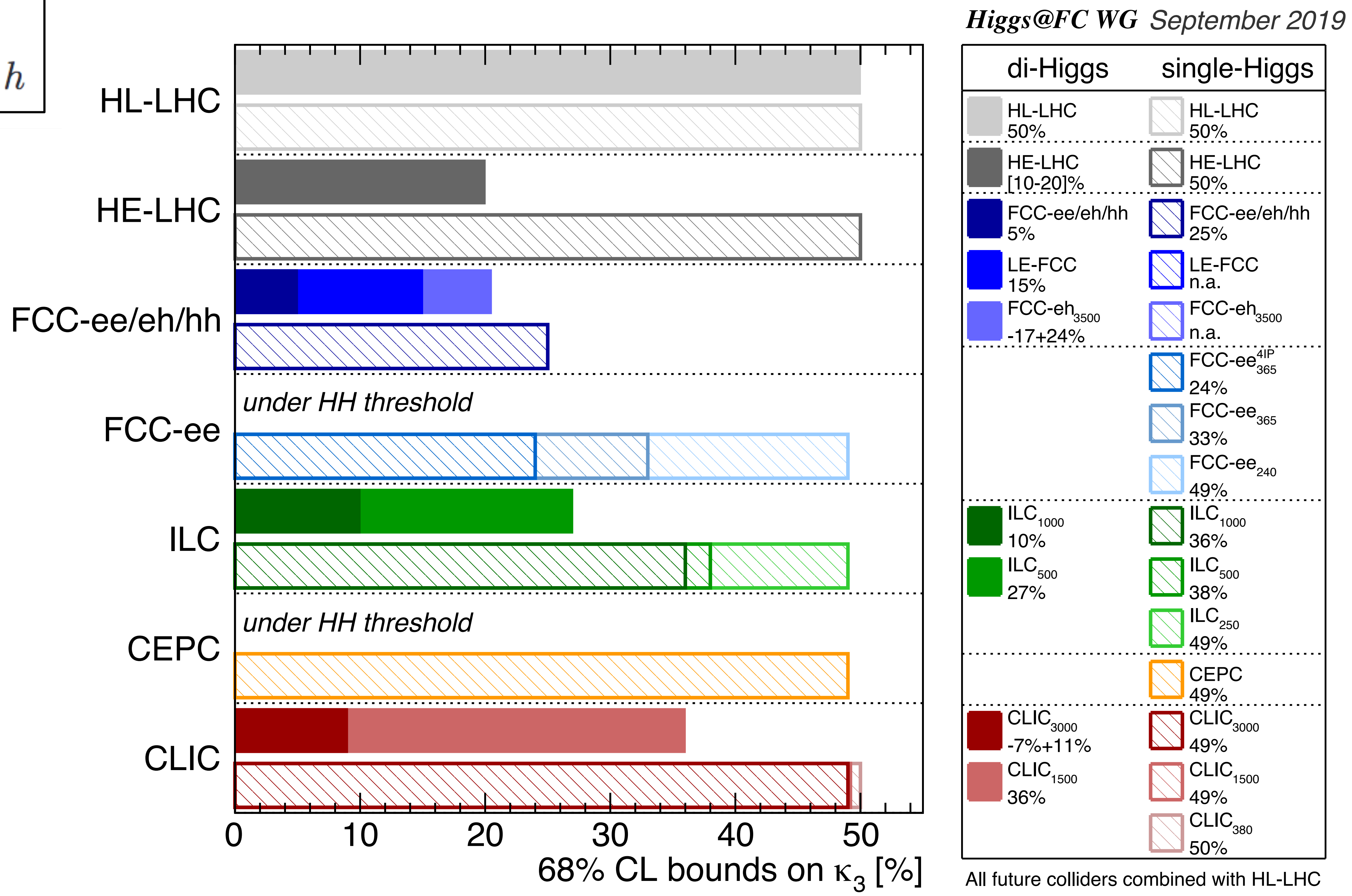
M. McCullough
arXiv:1312.3322





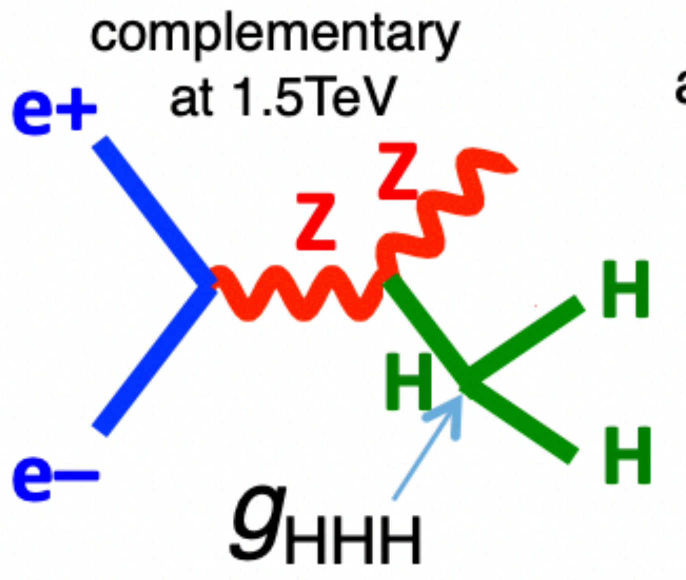
C. Grojean et al.
arXiv:1711.03978

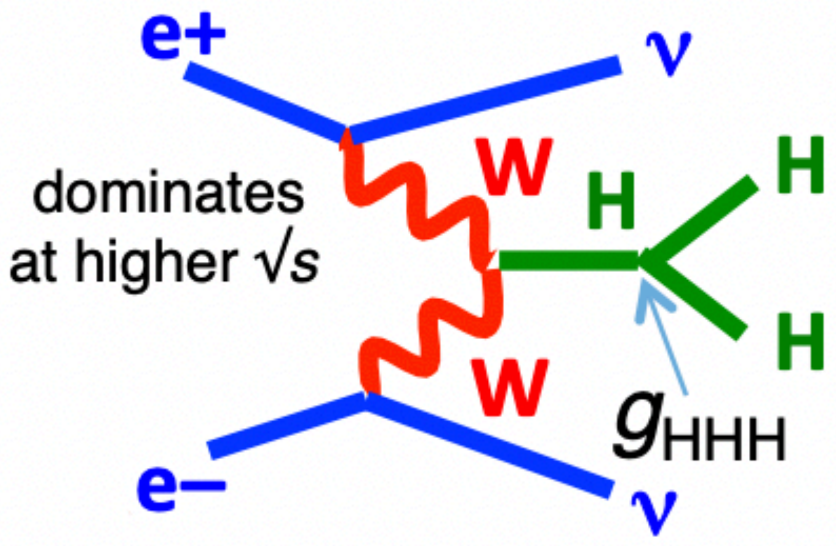
Measurements at different √s also help to lift degeneracy between processes



HIGGS SELF COUPLING WITH DOUBLE HIGGS

◆ Higgs self-coupling requires high-energy running



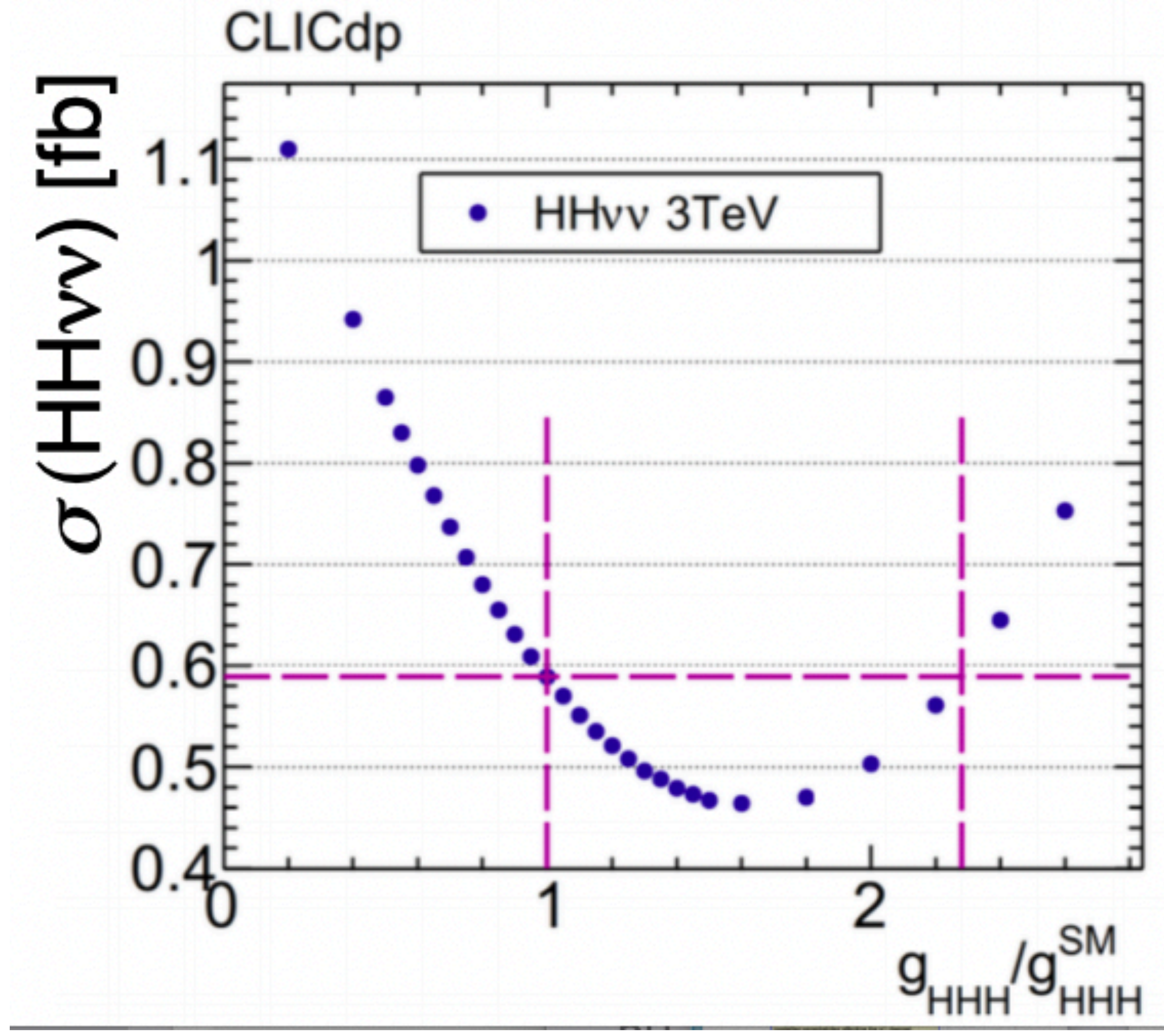


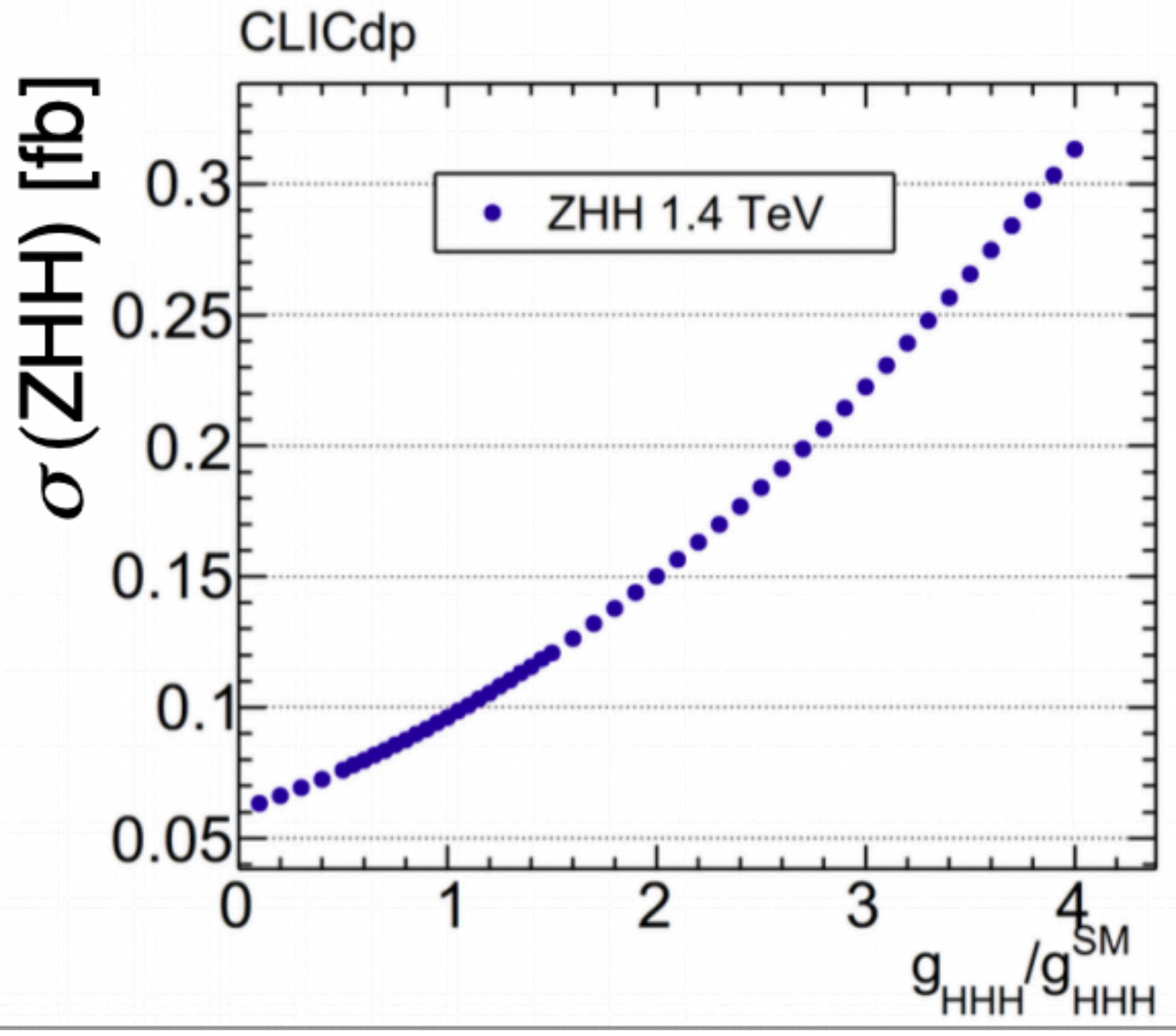
Double Higgs and self-coupling:

	1.4TeV	3TeV
$\sigma(HH\nu_e\bar{\nu}_e)$	>3σ EVIDENCE $\frac{\Delta\sigma}{\sigma} = 28\%$	>5σ OBSERVATION $\frac{\Delta\sigma}{\sigma} = 7.3\%$
σ(ZHH)	>5σ OBSERVATION	
g_{HHH}/g_{HHH}^{SM}	1.4TeV: –34%, +36% rate-only analysis	1.4 + 3TeV: –7%, +11% differential analysis

arXiv:1901.05897

◆ Direct access to two processes that behave differently with non-SM values of self-coupling:





Template fit at 3TeV using two variables: *M*(HH) differential distribution and BDT score

Gives unrivalled sensitivity to Higgs self-coupling:

$$\Delta g_{HHH}/g_{HHH} = {}^{+11\%}_{-7\%}$$

PINNING THE SM (EWK PRECISION MEASUREMENTS)

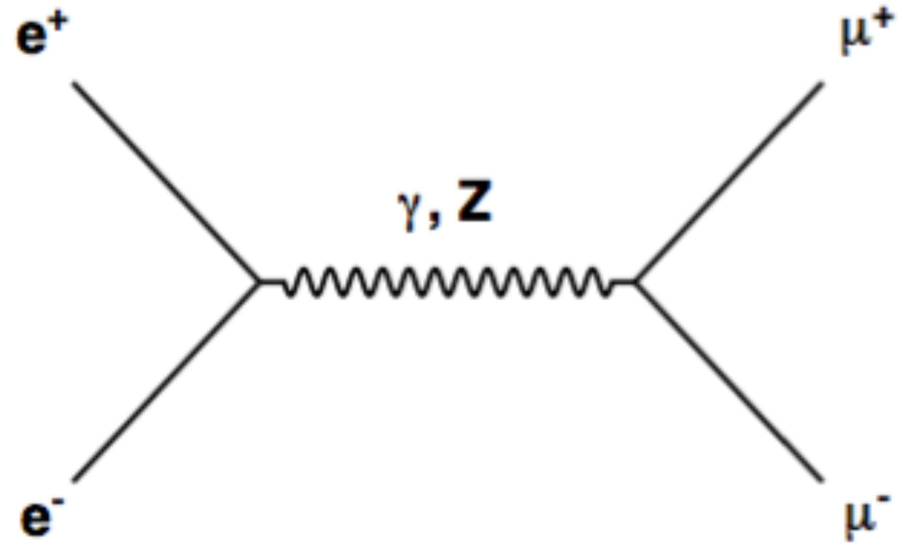
ELECTROWEAK PRECISION MEASUREMENTS

Giga/Tera-Z run ($10^9/10^{12}$Z)

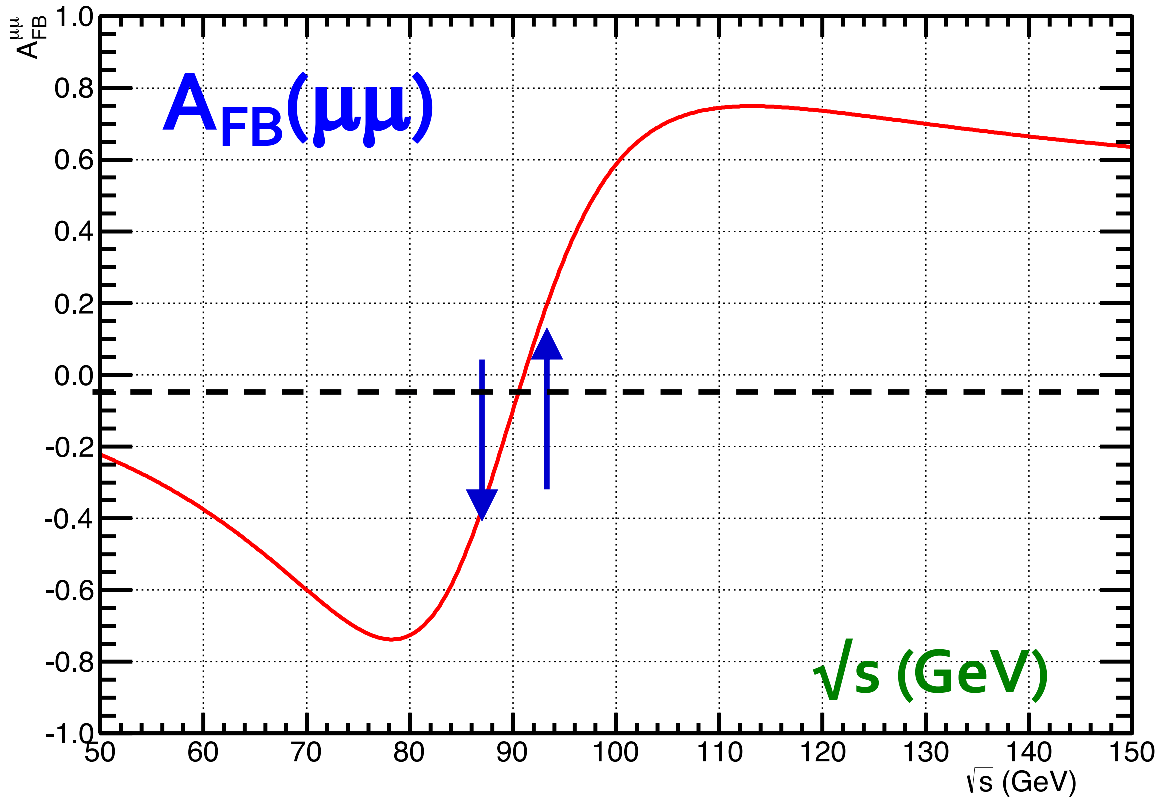
From data collected in a lineshape energy scan:

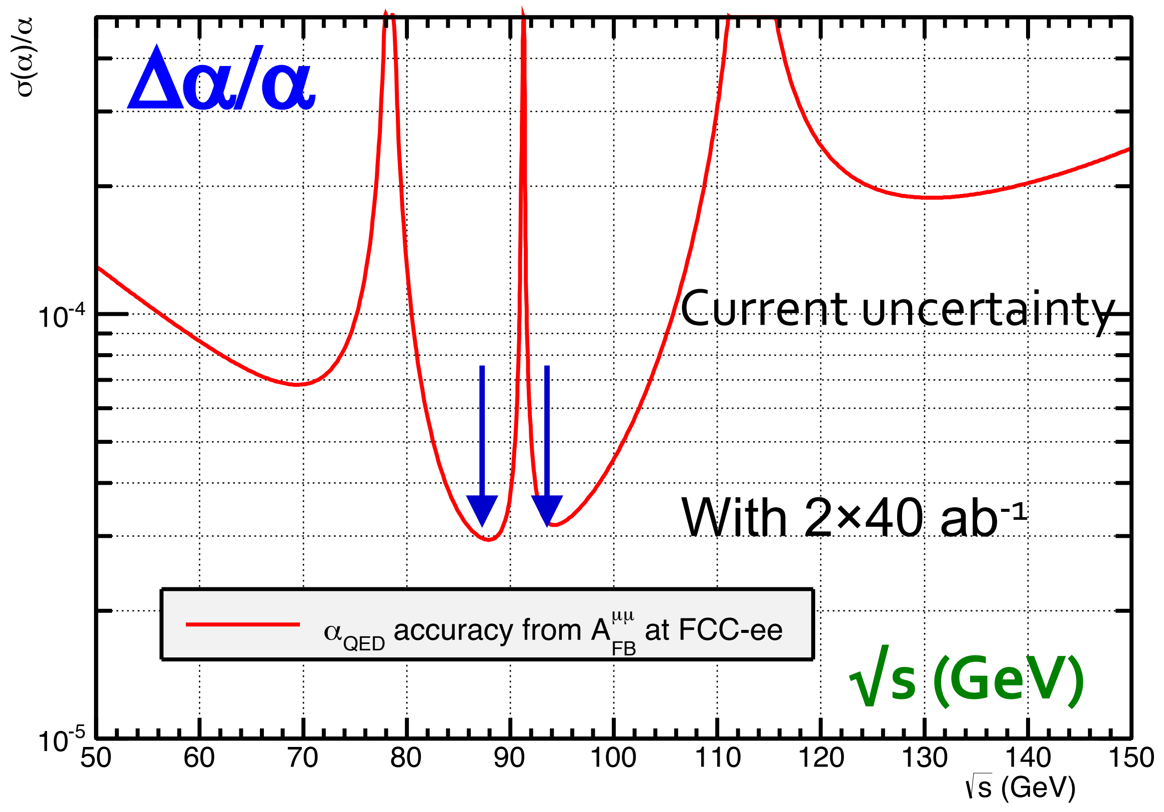
- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings, precise universality test)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)
- Tau polarization ($\sin^2\theta_{eff}$, lepton couplings, $\alpha_{QED}(m_Z^2)$)
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

- Boils down to measuring cross sections and asymmetries
  - The dominant experimental uncertainties come from the beam energy knowledge



$e^+e^- \rightarrow \mu^+\mu^-$





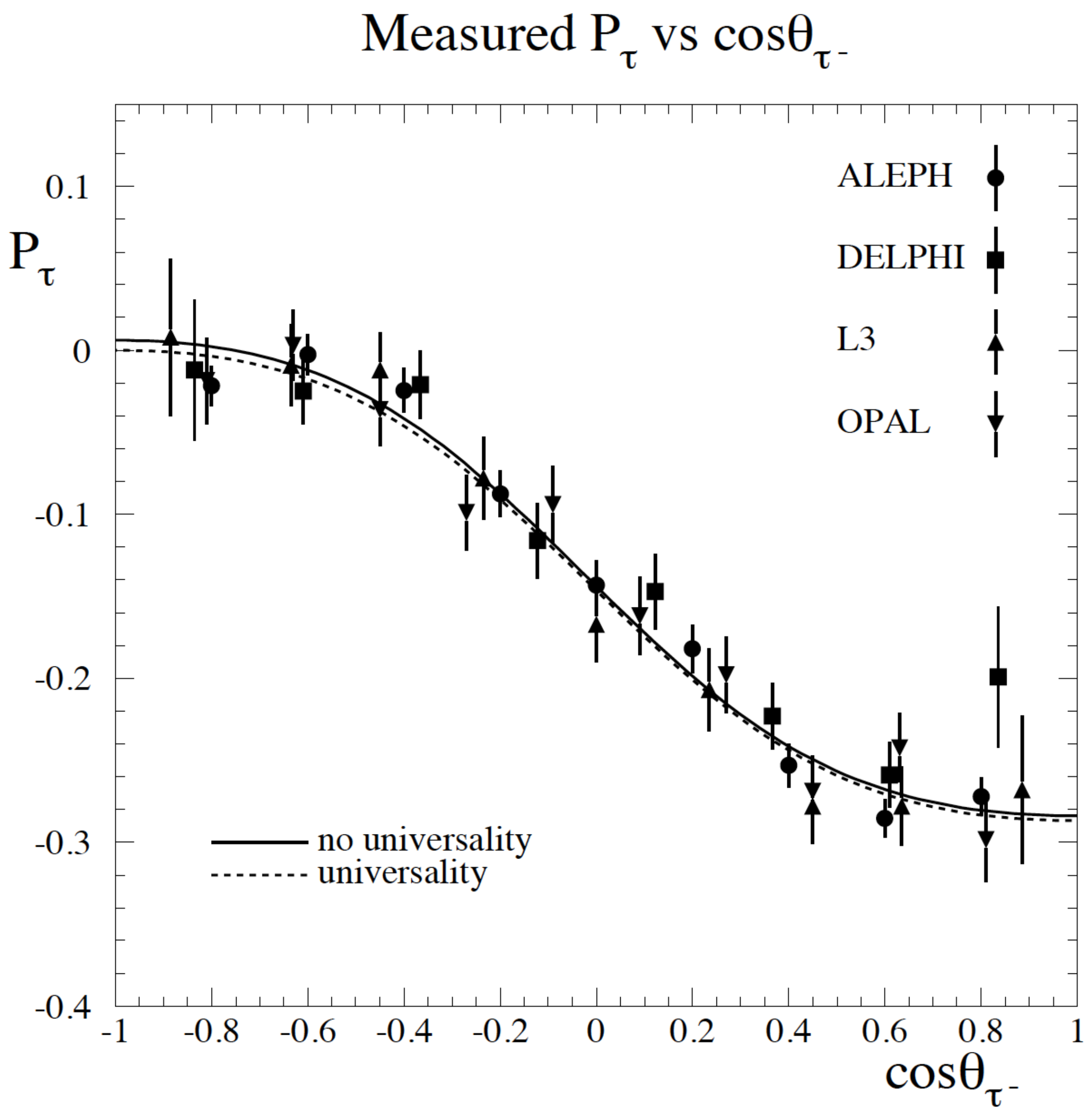
PRECISION MEASUREMENTS OF $sin^2\theta_{eff}$ FROM A_e

- If polarisation is available. Robust determination via:
  $A_e = A_{LR} = (\sigma_L - \sigma_R)/(\sigma_R + \sigma_R)$
  - Dominant syst. from the polarisation measurement, measured in situ with P+ and P-

- ILC 250, 2 ab^{-1}: 80 M hadronic Z's from radiative return: stat dominated:
  - Stat error (rel) = 10^{-3}, i.e. $\Delta(\sin^2\theta_{eff}) \sim 2\ 10^{-5}$ (~ current / 10)
- Giga-Z : 3 10^9 hadronic Z's, dominated by systematics [8]
  - Precise meas. of $\sqrt{s}$ is crucial: rel error = 1.3 10^{-4} x $\Delta\sqrt{s}$ / MeV
  - Pol: 5 10^{-4} (rel) expected from σ(2f), i.e. $\Delta(\sin^2\theta_{eff}) \sim 10^{-5}$

NB: Such precisions on $\sin^2\theta$eff call for improved M_Z, $\alpha_{QED}(M^2_z)$!!

- At FCC get A_e from the angular distribution of tau polarisation. Fit of $P(\tau)$ vs $cos\theta_\tau$. A_e much less affected by syst. Than A_τ. Should provide $\Delta sin^2\theta_{eff} = 2 - 3 \times 10^{-6}$



A_τ more demanding: e.g. systematics on ECAL scale and γ misid to be studied. Focus on ρν or $\tau \rightarrow h\nu$: avoid modelling uncertainties affecting the a1 channel.

CHALLENGES OF PRECISION MEASUREMENT OF Z COUPLING: R_l, R_b and R_c

- Dominant systematic on R_l expected to come :
  - from identification efficiencies with a few times the LEP statistics (ILC 250)
  - from the determination of the acceptance at GigaZ / FCC

$$1/R_l = \Gamma_l/\Gamma_{had}$$

$$R_{b,c} = \Gamma_{b,c}/\Gamma_{had}$$

Example, R_l at FCC: goal for $\Delta R_l / R_l = 1\text{-}5\ 10^{-5}$. Position of edge of the forward calorimeter, edge of tracking acceptance: must be known to O(10 μm).

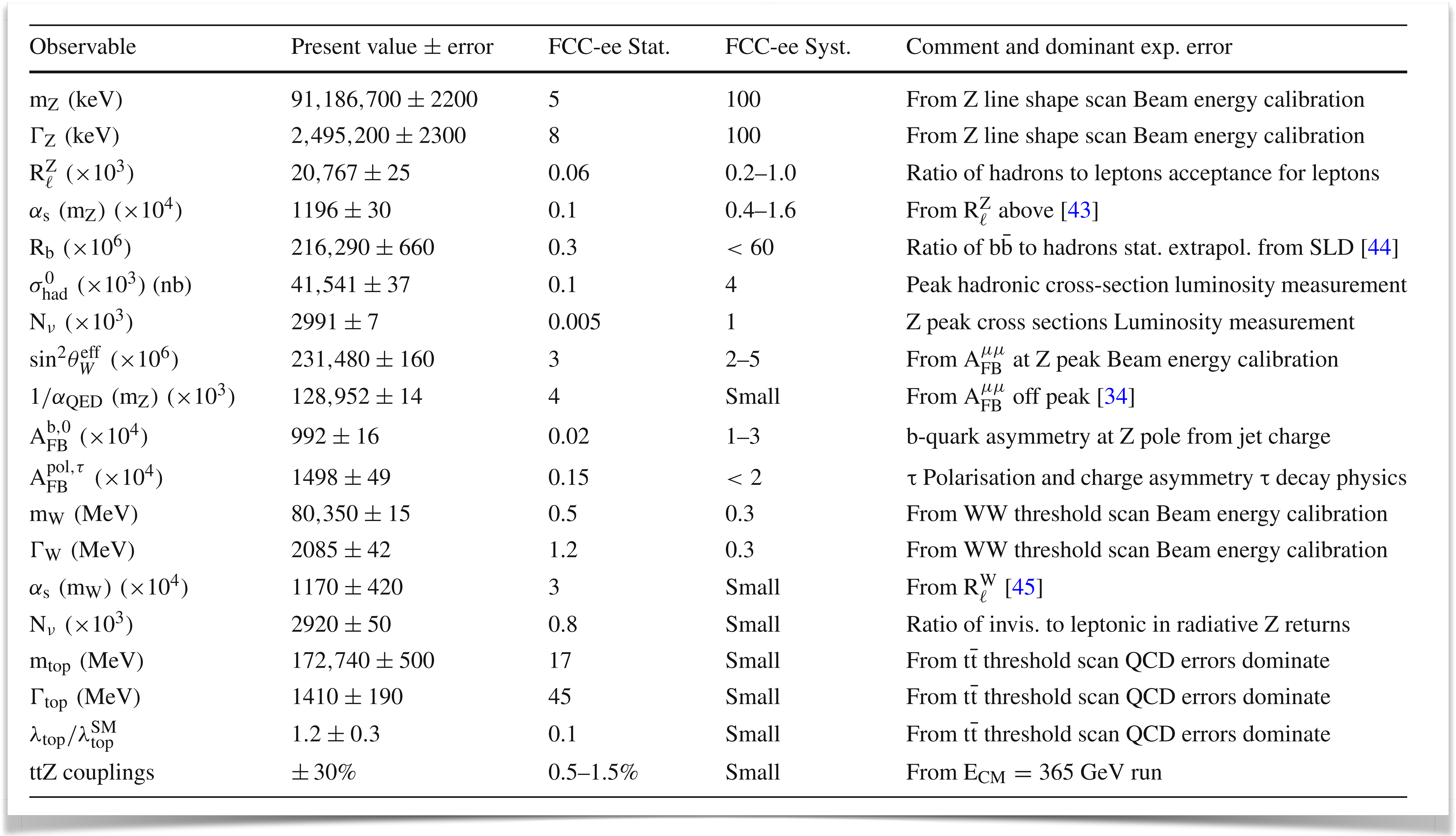
- the fwd detector must be carefully designed
  - e.g. hermetic calo, precise pre-shower in front
- will need “asymmetric” selection as done for the luminosity measurement

- Measurement of $R_{b,c}$: large statistics + improved VTX detectors w.r.t LEP / SLD allows to focus on double-tagged events. Expected systematics:
  - Hemisphere correlations: much less an issue than at LEP thanks to very small beam-spot. Further minimized with a tagger whose efficiency is independent on the b kinematics.
  - Large control samples to study effect of gluon splittings
  - Selections that minimize QCD effects

Uncertainties O(10x – 100x) better than current ones within reach: [8, 18]

$\Delta R_b / R_b \sim (0.5 – 1) . 10^{-4}$ at FCC, $(7 – 10). 10^{-4}$ at GigaZ / LC

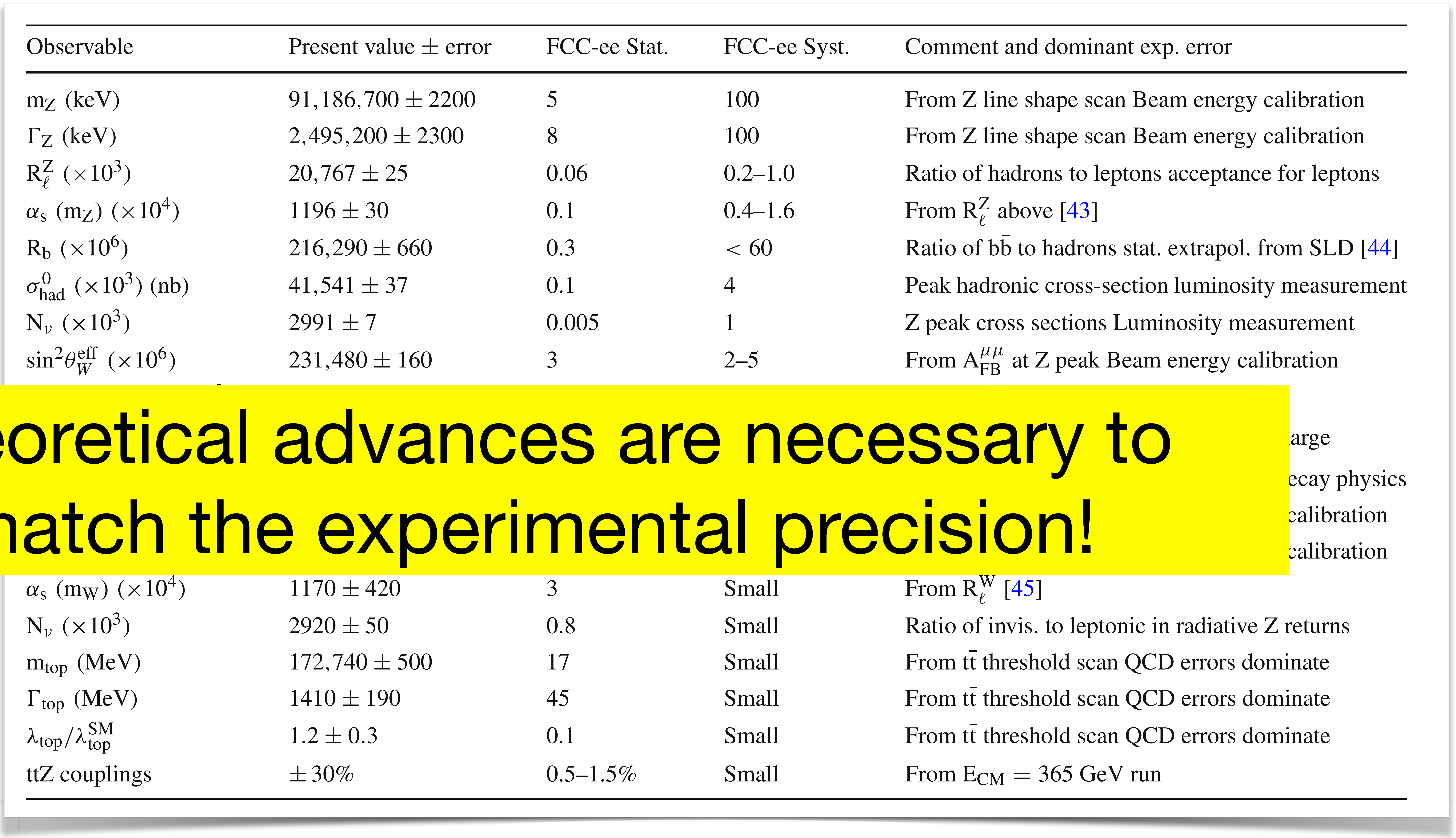
SELECTED ELECTROWEAK QUANTITIES AT THE FCC



Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91{,}186{,}700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	$2{,}495{,}200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
R_ℓ^Z $(\times 10^3)$	$20{,}767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
α_s (m_Z) $(\times 10^4)$	1196 ± 30	0.1	0.4–1.6	From R_ℓ^Z above [43]
R_b $(\times 10^6)$	$216{,}290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
$\sigma^0_{\rm had}$ $(\times 10^3)$ (nb)	$41{,}541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
N_ν $(\times 10^3)$	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{\rm eff}$ $(\times 10^6)$	$231{,}480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}$ (m_Z) $(\times 10^3)$	$128{,}952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0}$ $(\times 10^4)$	992 ± 16	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498 ± 49	0.15	< 2	τ Polarisation and charge asymmetry τ decay physics
m_W (MeV)	$80{,}350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
α_s (m_W) $(\times 10^4)$	1170 ± 420	3	Small	From R_ℓ^W [45]
N_ν $(\times 10^3)$	2920 ± 50	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	$172{,}740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410 ± 190	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5–1.5%	Small	From $E_{\rm CM} = 365$ GeV run

- In this context would need from theory full 3-loop calculations for the Z pole and propagator EWK corrections and probably 2-loop for EWK corrections to the WW cross section. Matching these experimental precisions motivates a significant theoretical effort.

SELECTED ELECTROWEAK QUANTITIES AT THE FCC



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Theoretical advances are necessary to match the experimental precision!

- In this context would need from theory full 3-loop calculations for the Z pole and propagator EWK corrections and probably 2-loop for EWK corrections to the WW cross section. Matching these experimental precisions motivates a significant theoretical effort.

THE WW THRESHOLD

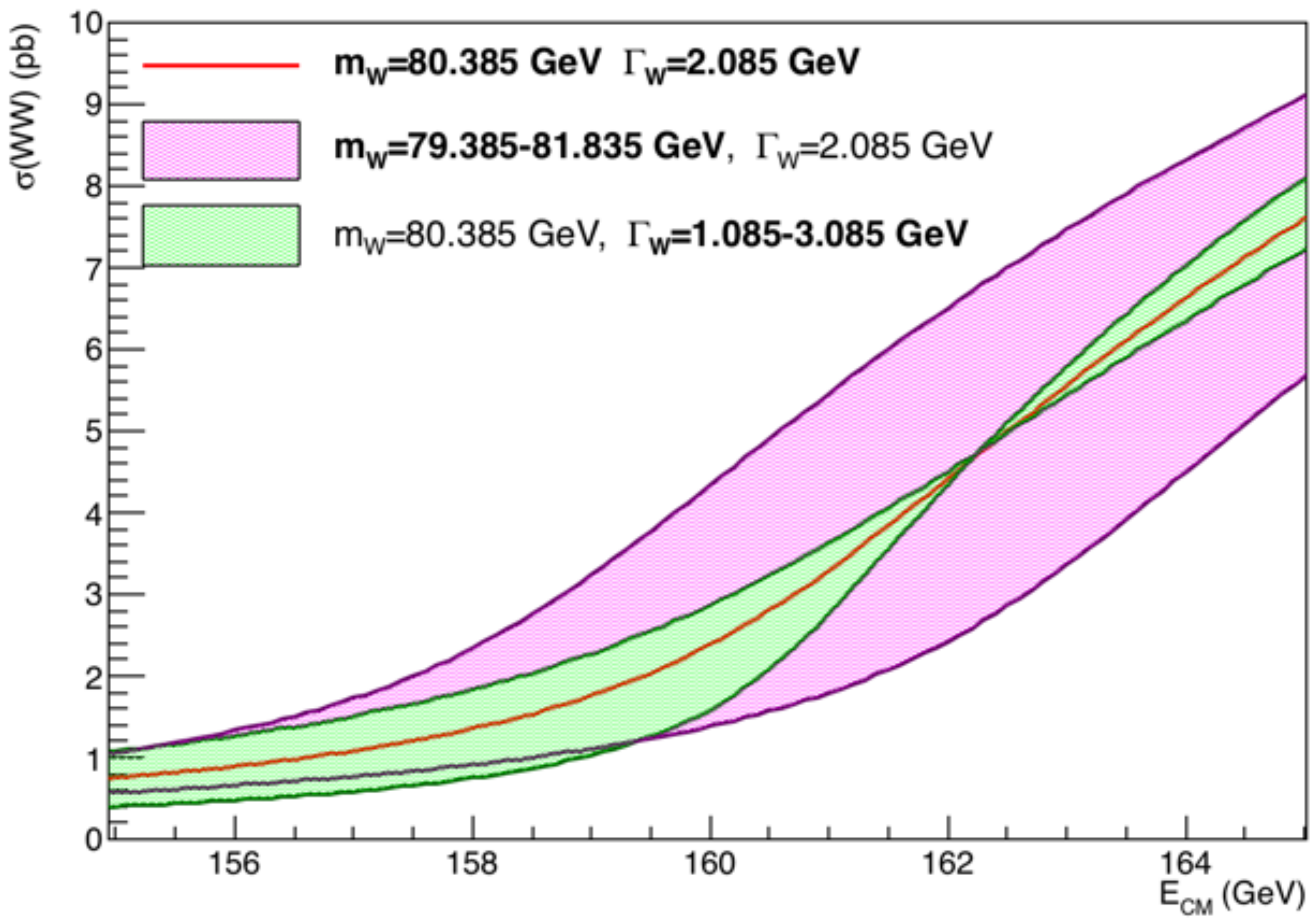
OkuWW (10^8 WW)

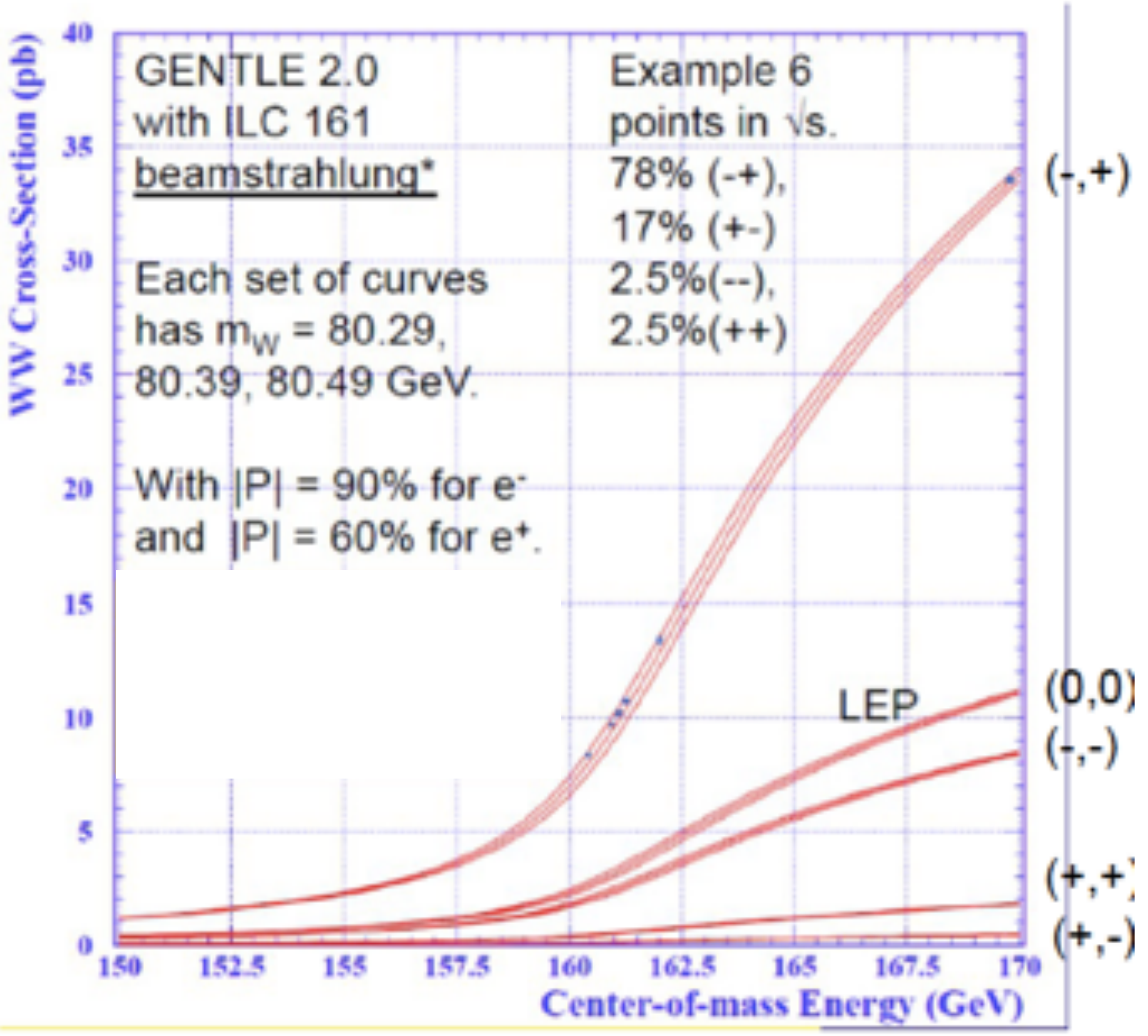
From data collected around and above the WW threshold:

- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- $R^W = \Gamma_{had}/\Gamma_{lept}$ ($\alpha_s(m^2_Z)$)
- Γ_e , Γ_μ , Γ_τ (precise universality test)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

Lumi	Collider	ΔM_W (stat.)
12 ab^{-1}	FCC-ee	400 keV
0.5 ab^{-1} w P = (90%, 60%)	ILC (not in baseline)	1100 keV [16]

➤ Sensitivity to mass and width is different as a function of √s: choosing the scan strategy to optimise both



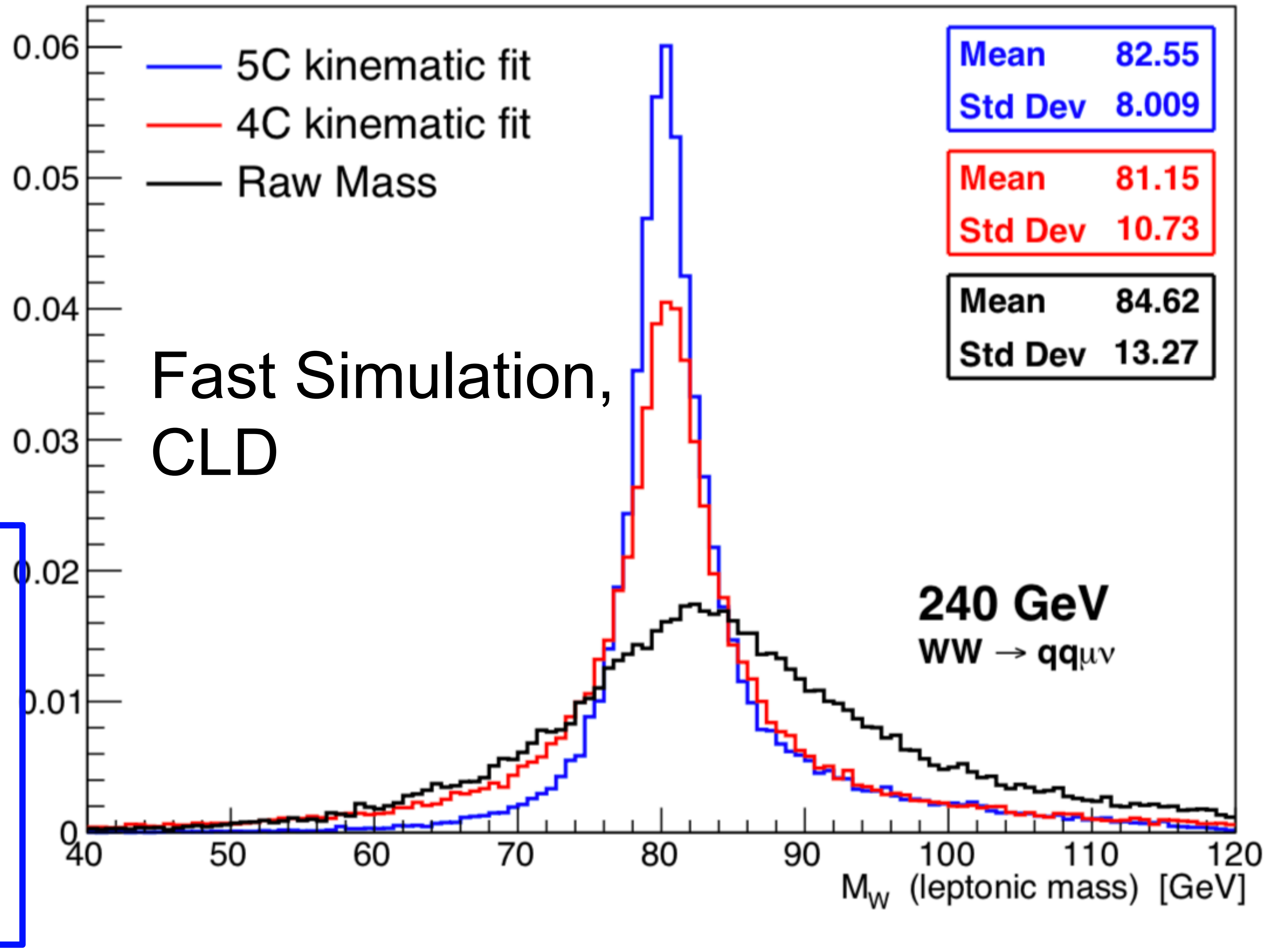


MEASUREMENT OF W MASS FROM DIRECT RECONSTRUCTION

Both at threshold and at higher √s :
M_W can be obtained from final state reconstruction.
Several methods can be contemplated.

- esp. with precise knowledge of √s, does not have to rely only on hadronic masses (JES syst.)

FCC: at threshold, precision may compete with scan – i.e. O(500 keV) - if systematic uncertainties are controlled [17].
ILC baseline : could allow a < 3 MeV measurement with 250 GeV dataset [8].

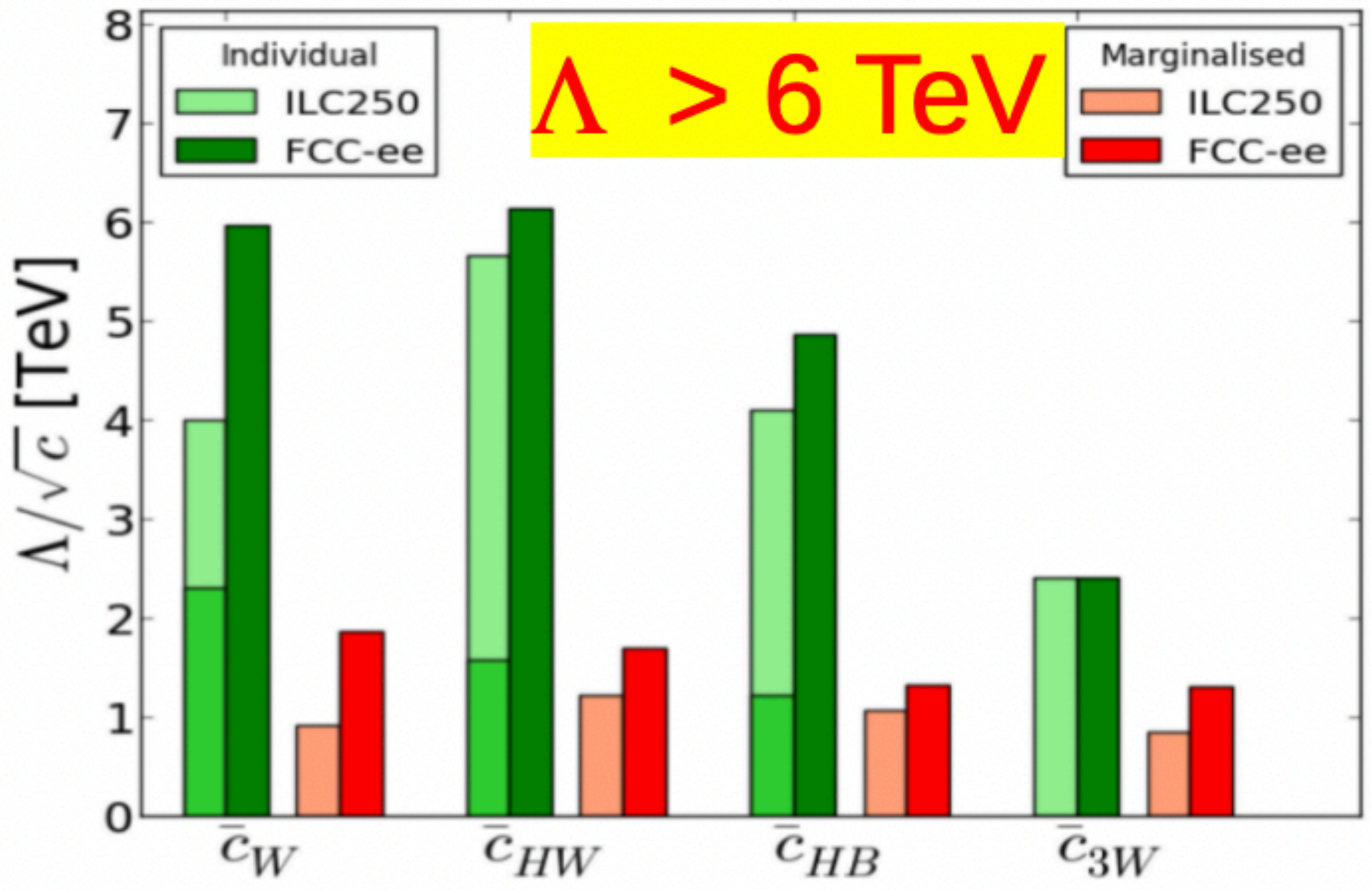


Example: Kinematic fit

- Exploit 4-momentum conservation: thanks to precise knowledge of √s
  - Δ√s at FCC 240 GeV: yet to be improved to compete with the scan !
  - Requires very good understanding of full error matrices of objects
  - Effect of ISR and beamstrahlung ?
- Hadronic channel : uncertainties from WW → had modeling ?
  - Controlled from precise measurements of frag. properties of Z → qq

INTERPLAY OF PRECISION HIGGS & EWK

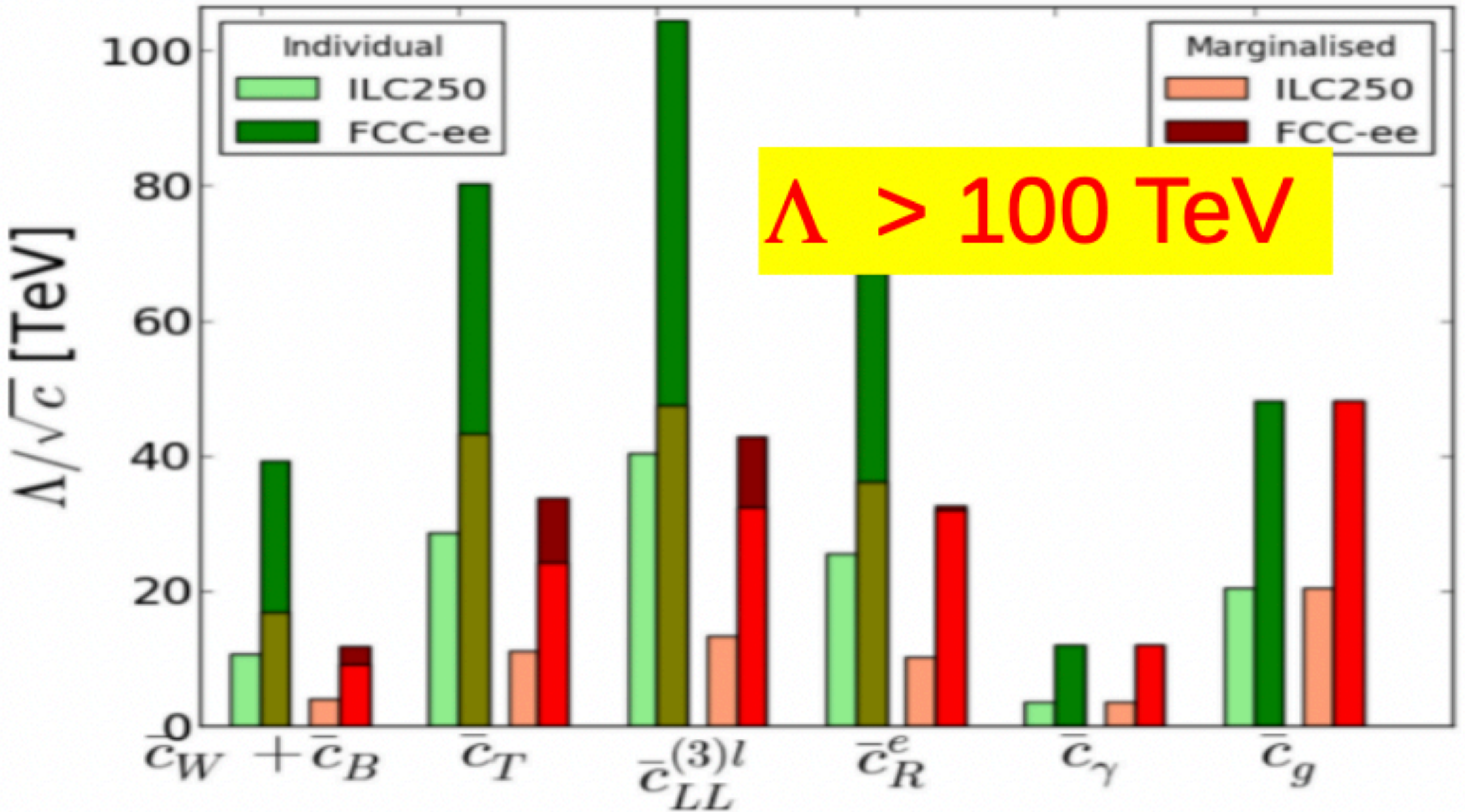
- FCC-ee Higgs measurements greatly improve scalar-coupled BSM reach.
- NP bounds from FCC-ee Higgs:



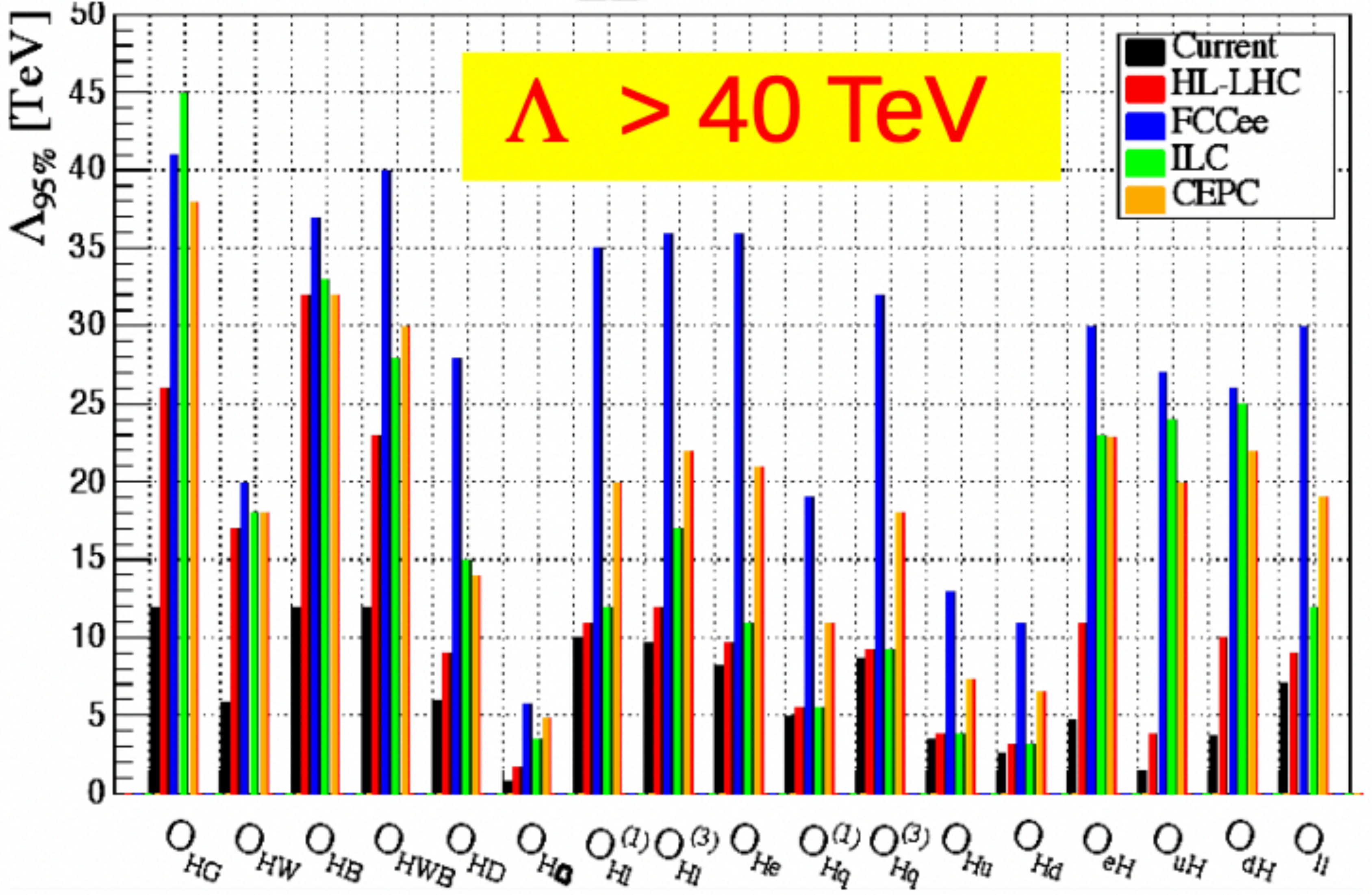
Λ > 6 TeV

[J.Ellis and T.You, arXiv:1510:04561]

- From H+EWPO combined:



Λ > 100 TeV



Λ > 40 TeV

[DeBlas et al. arXiv:1608.01509]

SUMMARY OF PRECISION ON HIGGS AND aTGCs

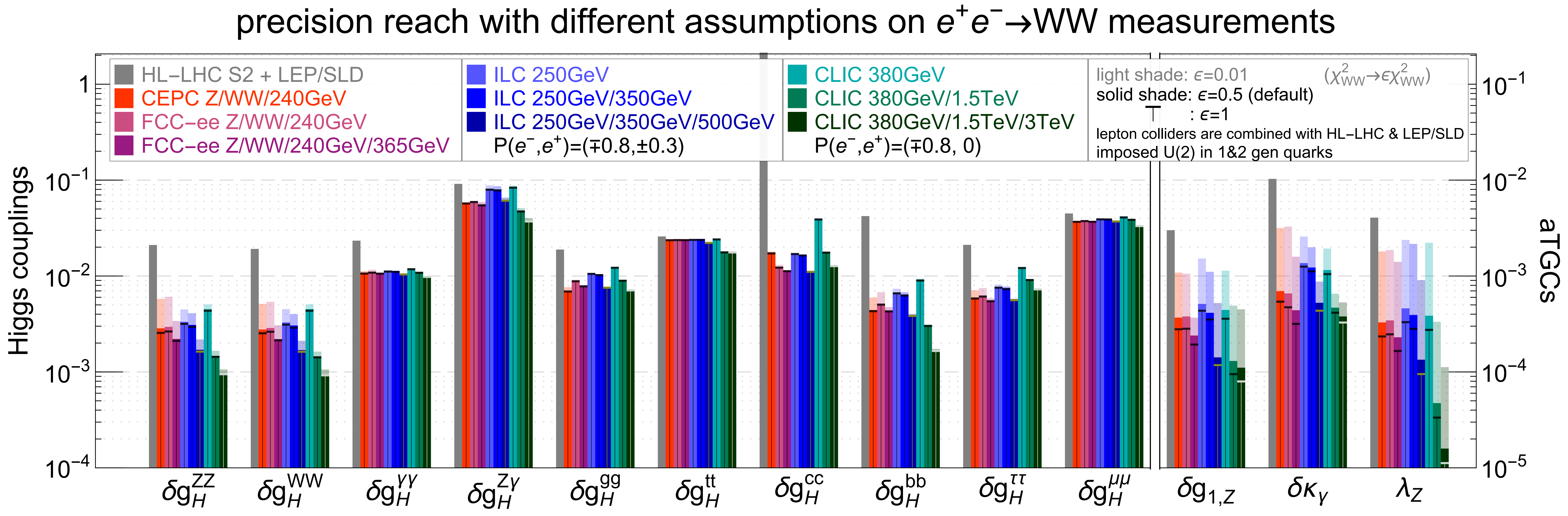
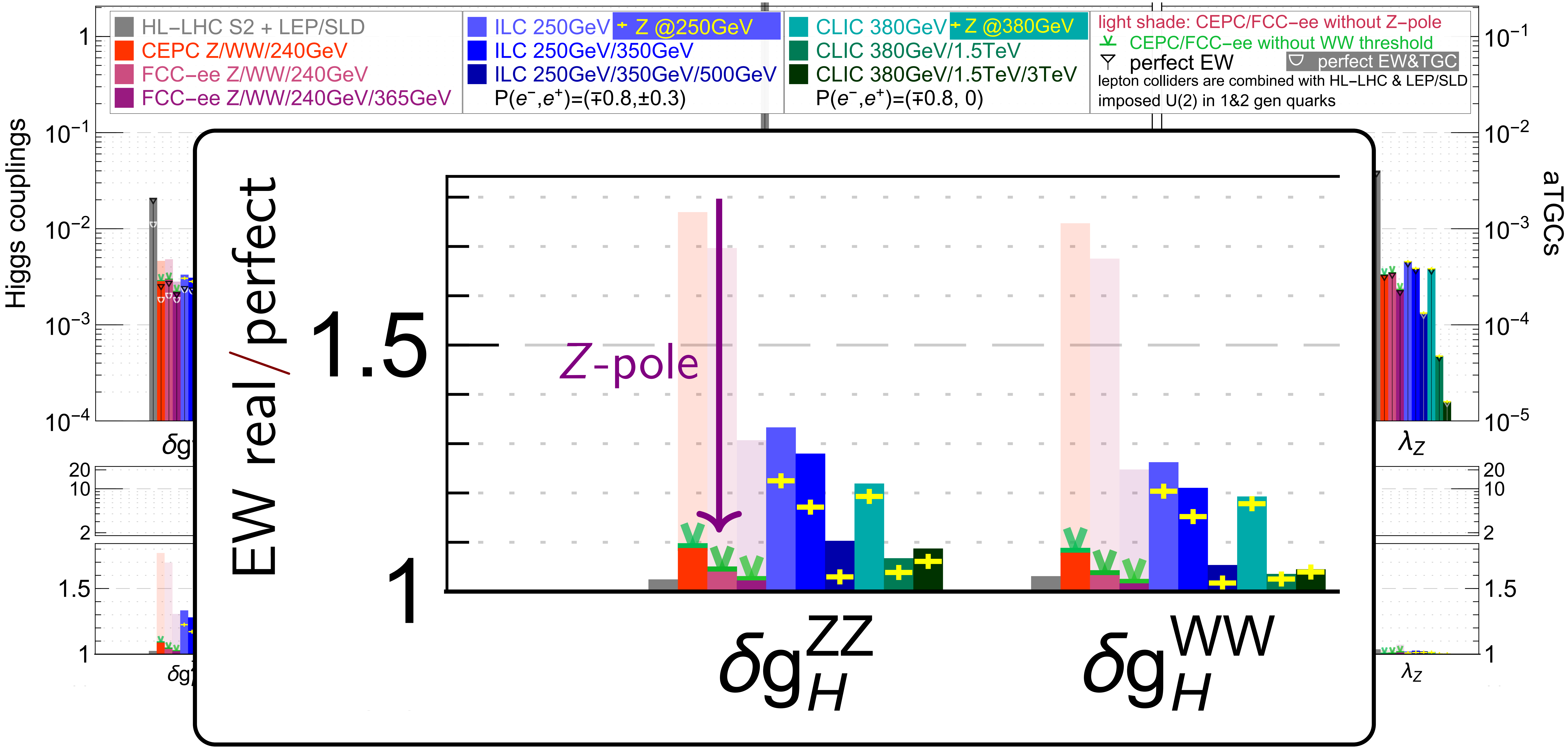

precision reach with different assumptions on $e^+e^-\to WW$ measurements

Figure 6: *Impact of diboson measurement precision on Higgs and triple-gauge couplings.*

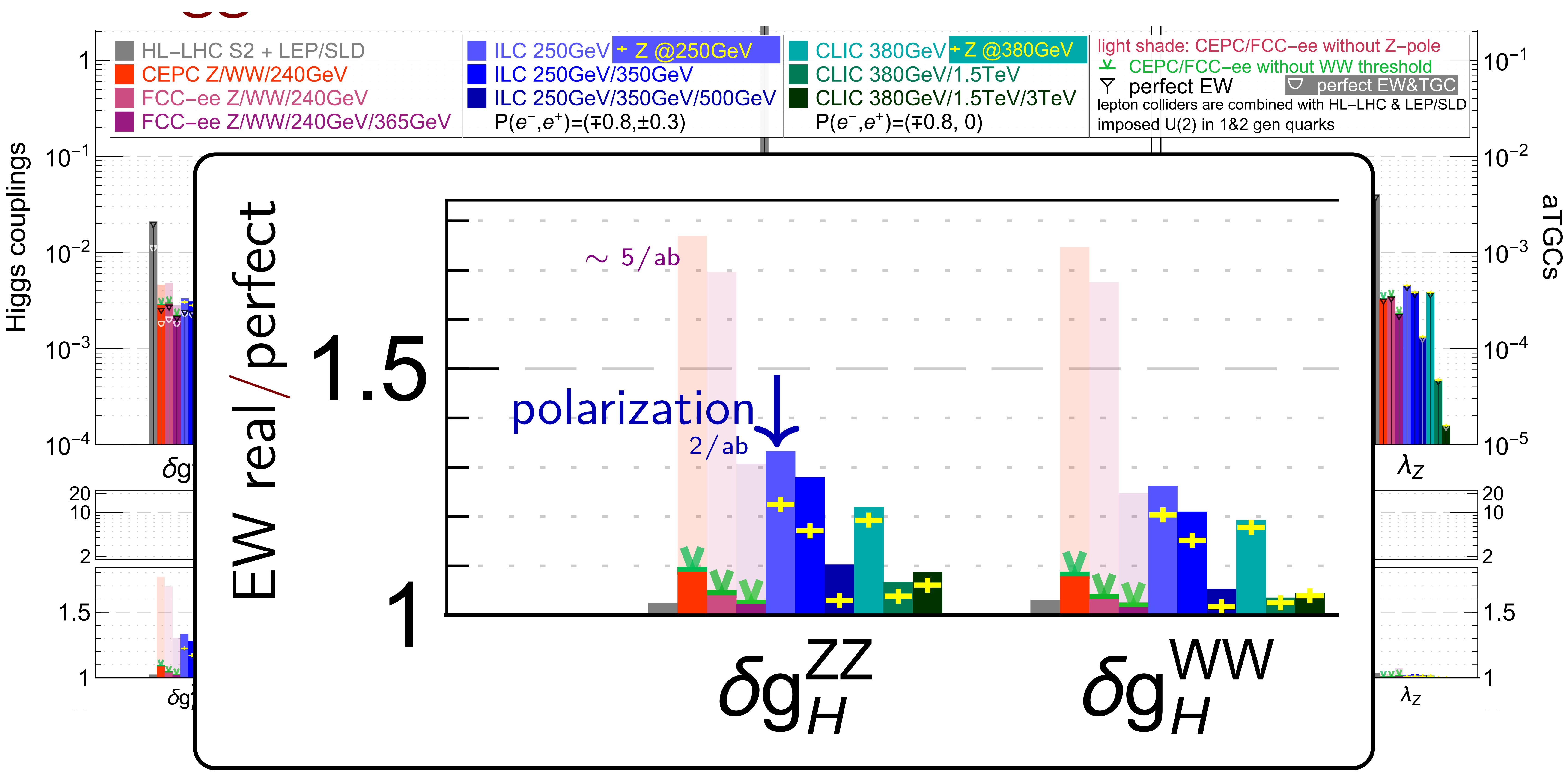
Impact of Z pole run



15 EW param. also marginalized over / assumed perfectly constrained

- *Z*-pole run has a big impact

Impact of polarization

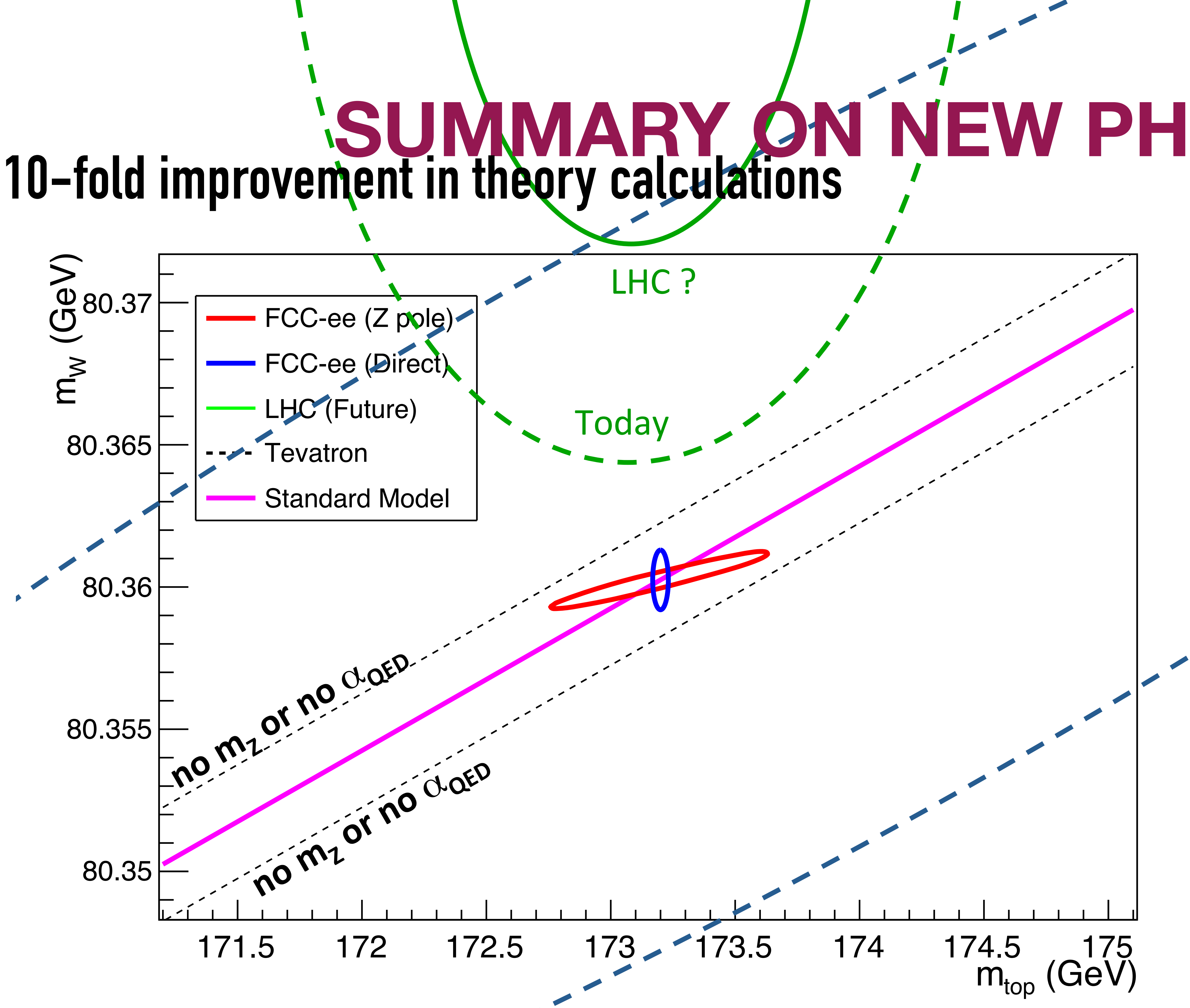


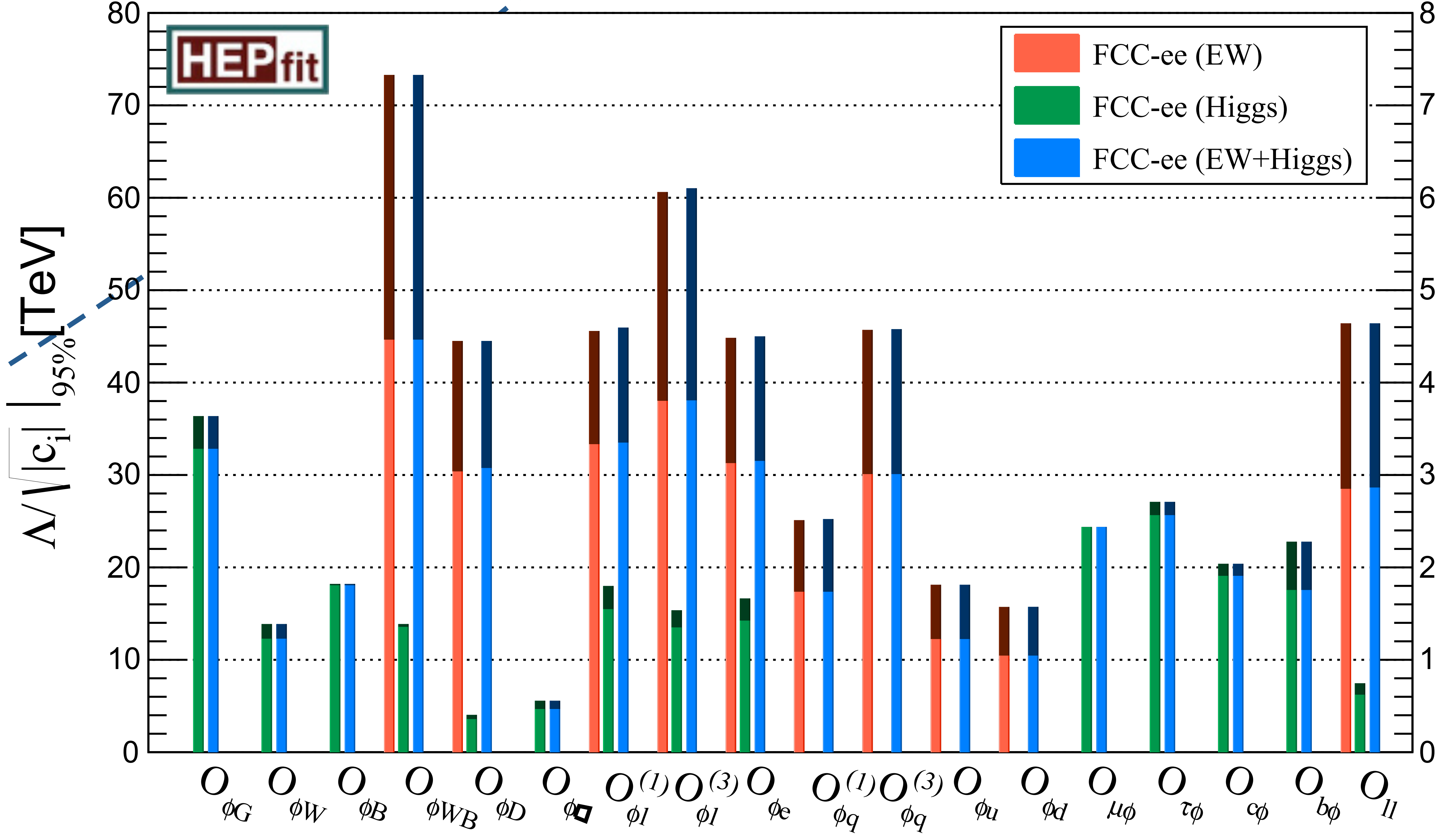
15 EW param. also marginalized over / assumed perfectly constrained

- Z-pole run has a big impact
- WW threshold run has marginal impact
- polarization helps compensating for the absence of Z-pole run

SUMMARY ON NEW PHYSICS SENSITIVITIES FROM PRECISION

Requires 10-fold improvement in theory calculations





- ➤ Fit to new physics effects parameterized by dim 6 SMEFT operators
- ➤ single operator fit can be informative
- ➤ model independent result only for global fit

What do we mean by “Sensitivity to NP up the scale of N TeV?” e.g.

$$\frac{c}{\Lambda^2} \sim \frac{g_{\rm NP}^2}{M_{\rm NP}^2} < 0.01\ {\rm TeV}^{-2} \longrightarrow M_{\rm NP} > 10\, g_{\rm NP}\ {\rm TeV}$$

(**Weakly coupled NP** $M_{\rm NP} > 10\ {\rm TeV}\ \ (g_{\rm NP} \sim 1)$)

- ➤ **Points to the physics to be studied with FCC-hh**

FLAVOUR

HEAVY FLAVOR PRODUCTION - COMPARISONS

Working point	Lumi. / IP $[10^{34}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}]$	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

$\sqrt{s}$=10.6GeV

- Features:
  - * clean environement
  - ~15 times Belle II anticipated statistics.
  - All species of *b*-hadrons are produced.
  - Boost* at the *Z*: topological reconstruction of the decays.
  - Effective flavour tagging efficiency can be expected at 10% level.

and also excellent displaced vertex reconstruction

Note: the comparison with the LHCb experiment is more involved since the decay modes yields depend on trigger efficiency. Performance to be compared mode by mode.

* Fragmentation of the *b*-quark: $\langle E_{X_b} \rangle = 75\% \times E_{\mathrm{beam}}; \langle \beta\gamma \rangle \sim 6.$

TERA-Z -YELDS FOR FLAVOR ANOMALY STUDIES

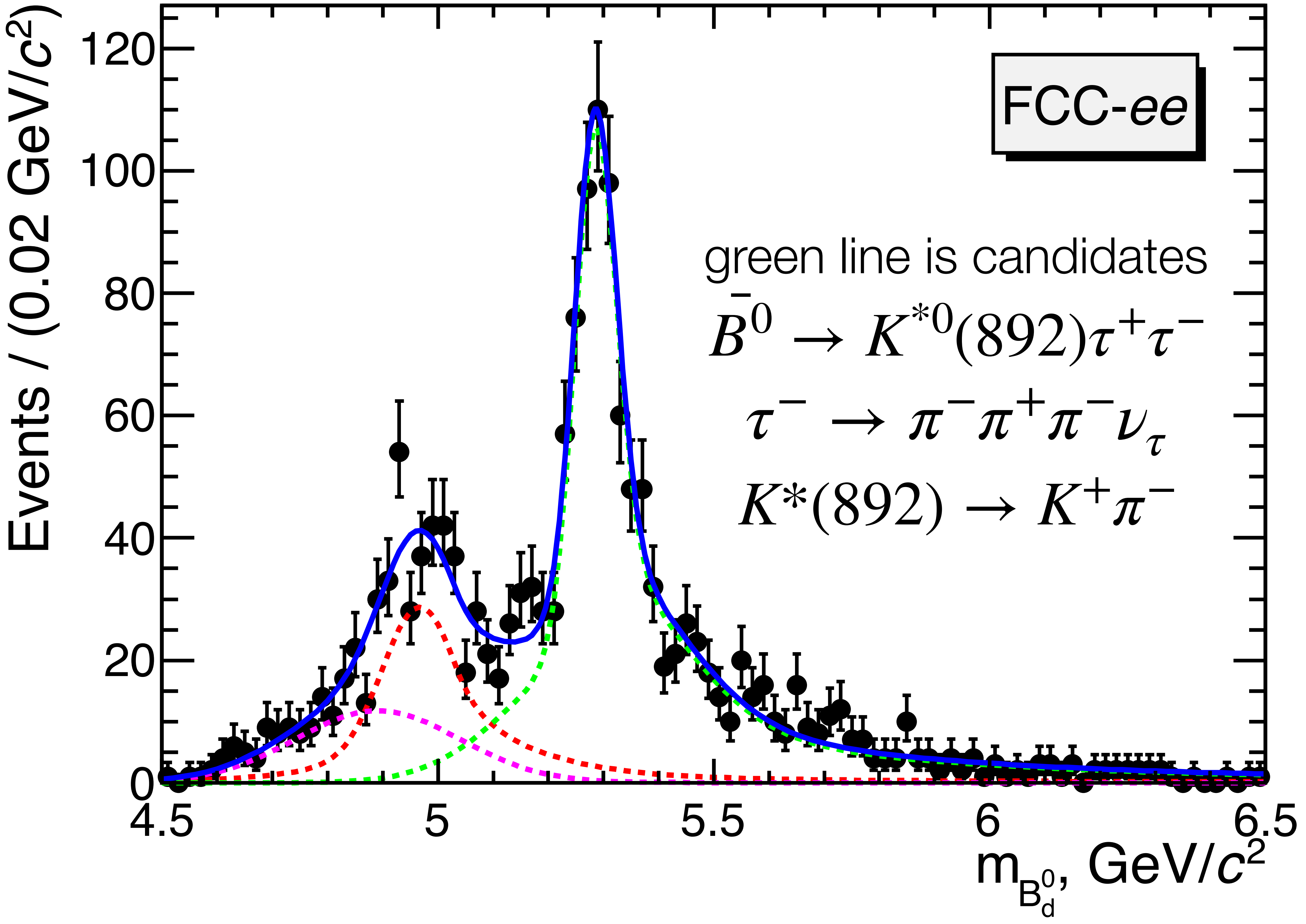
Decay mode	$B^0 \to K^*(892)e^+e^-$	$B^0 \to K^*(892)\tau^+\tau^-$	$B_s(B^0) \to \mu^+\mu^-$
Belle II	$\sim 2\,000$	~ 10	n/a (5)
LHCb Run I	150	-	~ 15 (–)
LHCb Upgrade	~ 5000	-	~ 500 (50)
FCC-ee	~ 200000	~ 1000	~ 1000 (100)

The excellent knowledge of the decay vertex, due to the multibody hadronic tau decay, allow to fully reconstruct the decay kinematics (in spite of a final-state neutrino)

👍 **Full reconstruction possible**

RARE DECAYS & FLAVOR ANOMALIES - $\bar{B}^0 \to K^{*0}(892)\tau^+\tau^-$

- Topological reconstruction of the missing energy with meas. of the decay vertices.
- Background estimates from generic double-charmed decays at SM values w/ proxies (no meas. available).
- Vertex detector can be very close to the beam pipe. Considered ILD-like vertexing performance.
- Focus here on the charged-only three-prongs decays of the taus.



green line is candidates

$\bar{B}^0 \to K^{*0}(892)\tau^+\tau^-$

$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

$K^*(892) \to K^+\pi^-$

Bottomline: several thousands of decays can be reconstructed, if the branching fraction is at SM value. *O*(5%) precision on BF. Angular analyses can be performed [arXiv:1705.11106].

The two dominant backgrounds are included: $\bar{B}_s \to D_s^+ D_s^- K^{*0}(892)(red)$ $\bar{B}^0 \to D_s^+ \bar{K}^{*0}(892)\tau^-\bar{\nu}_\tau(pink)$

Di-leptonic decays $(ex.\, B^0 \rightarrow \mu\mu, B_s \rightarrow \tau\tau)$

Again fundamental tests. Particularly important in the context the Flavour anomalies. FCC-*ee* is especially expected for $B_s \rightarrow \tau^+\tau^-$.

- More complex experimentally because of the absence of the secondary vertex to be used in topological reconstructions. Ideas to mitigate this absence, such as using the quark direction in the other hemisphere.
- Similar techniques employed as for ElectroWeak penguins with τ. That should be part of the same collective exploration.

TERA-Z - TAU PHYSICS

Visible Z decays	3×10^{12}
$Z \rightarrow \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

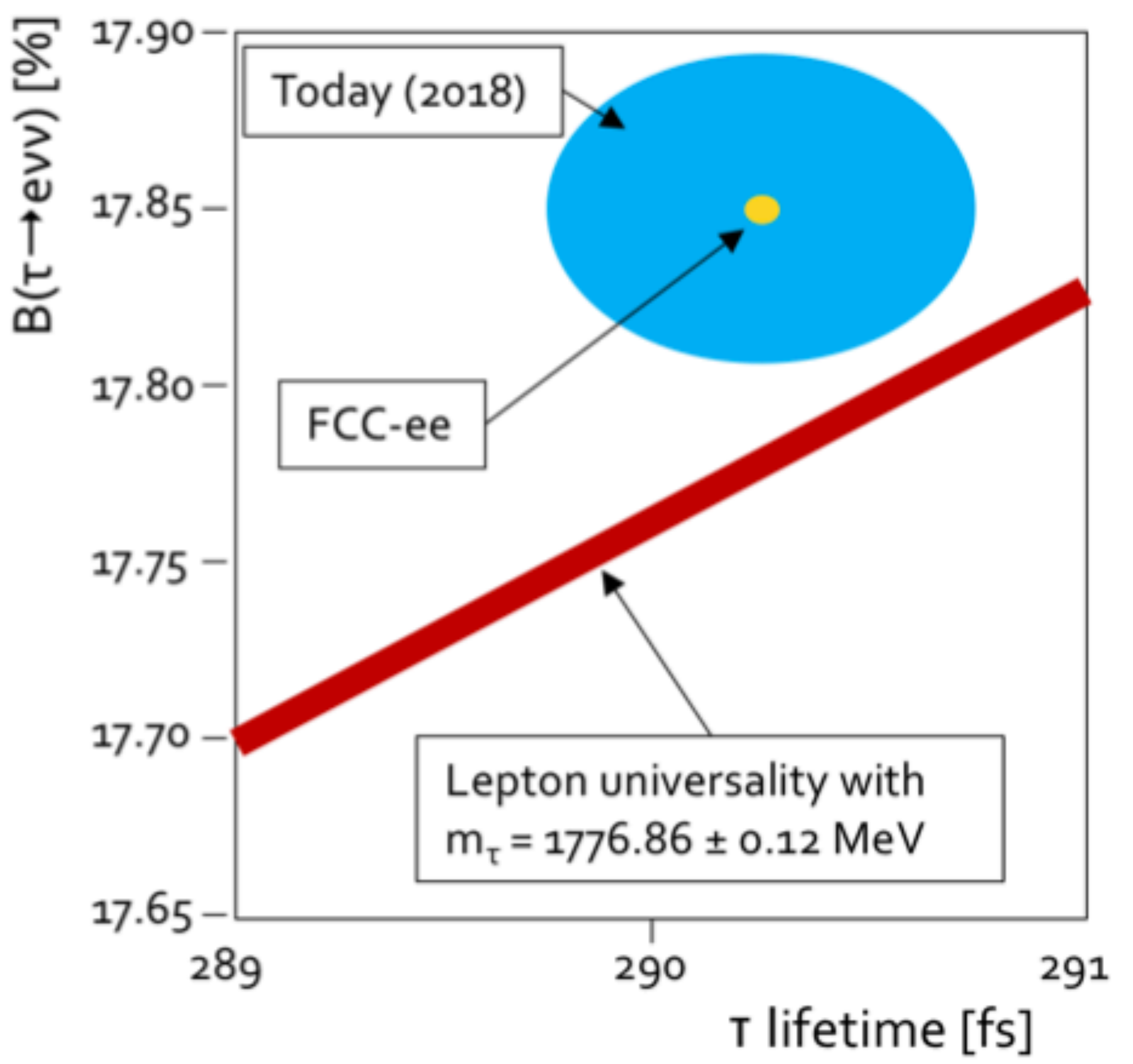
CLFV *Z* decays:

in SM $<10^{-50}$

Decay	Current bound	FCC-ee sensitivity
Z -> eμ	$0.75 \times {}^{-6}$	10^{-8}
Z -> μτ	12×10^{-6}	10^{-9}
Z -> eτ	9.8×10^{-6}	10^{-9}

CLFV *τ* decays:

Decay	Current bound	FCC-ee sensitivity
τ -> μγ	4.4×10^{-8}	2×10^{-9}
τ -> 3μ	2×10^{-8}	10^{-10}



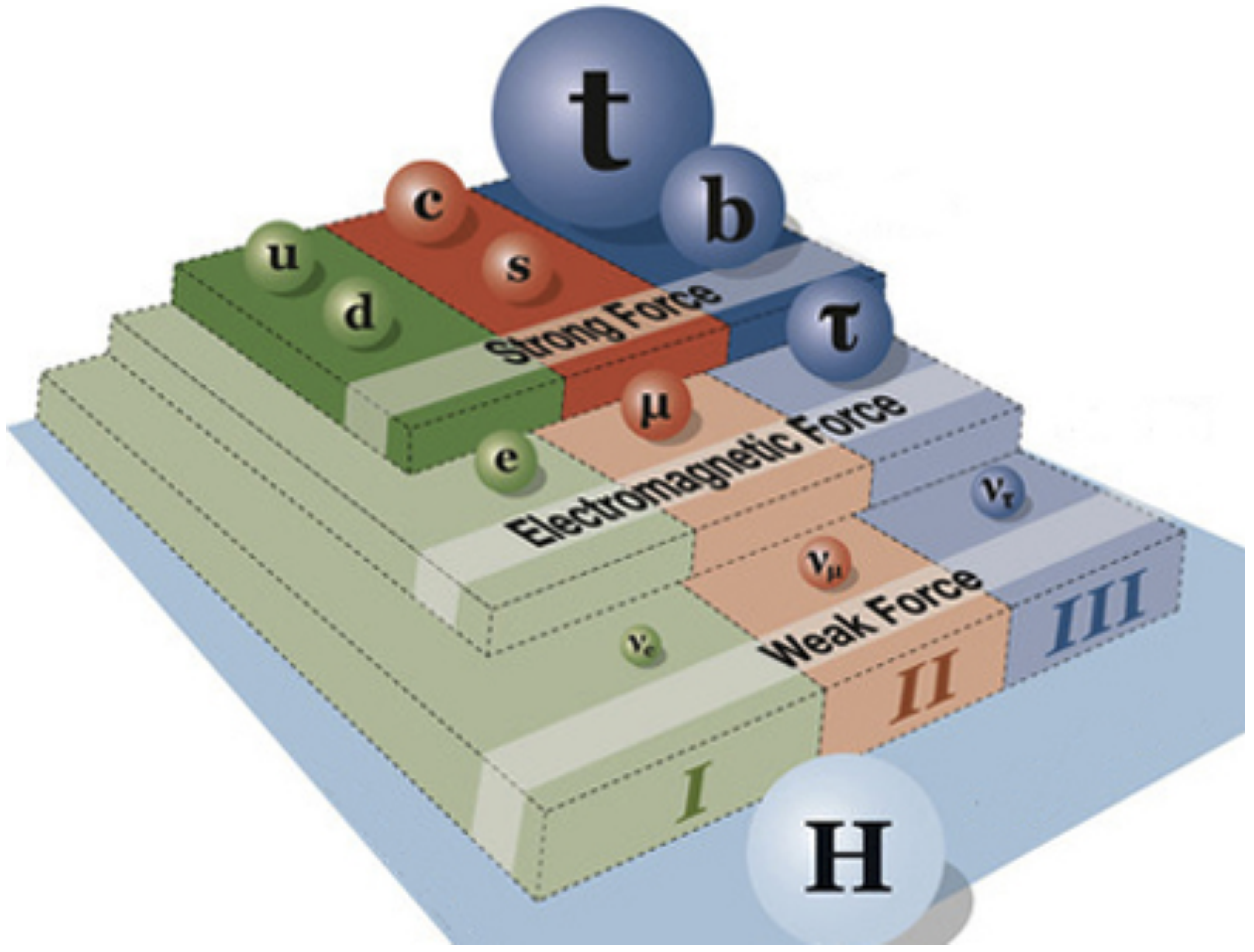
Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	1776.86 +/- 0.12	0.004	0.1
Electron BF [%]	17.82 +/- 0.05	0.0001	0.003
Muon BF	17.39 +/- 0.05	0.0001	0.003
Lifetime [fs]	290.3 +/- 0.5	0.005	0.04

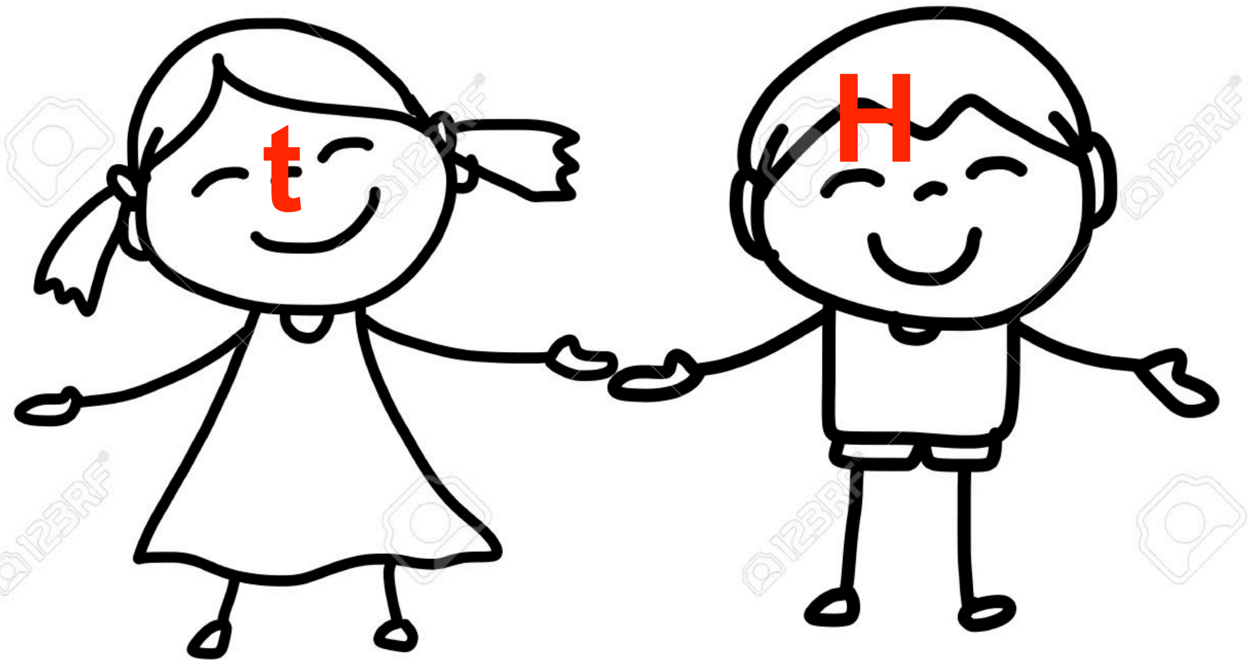
A lot more unique opportunities…

TOP PHYSICS

NEED MORE TOP PHYSICS!

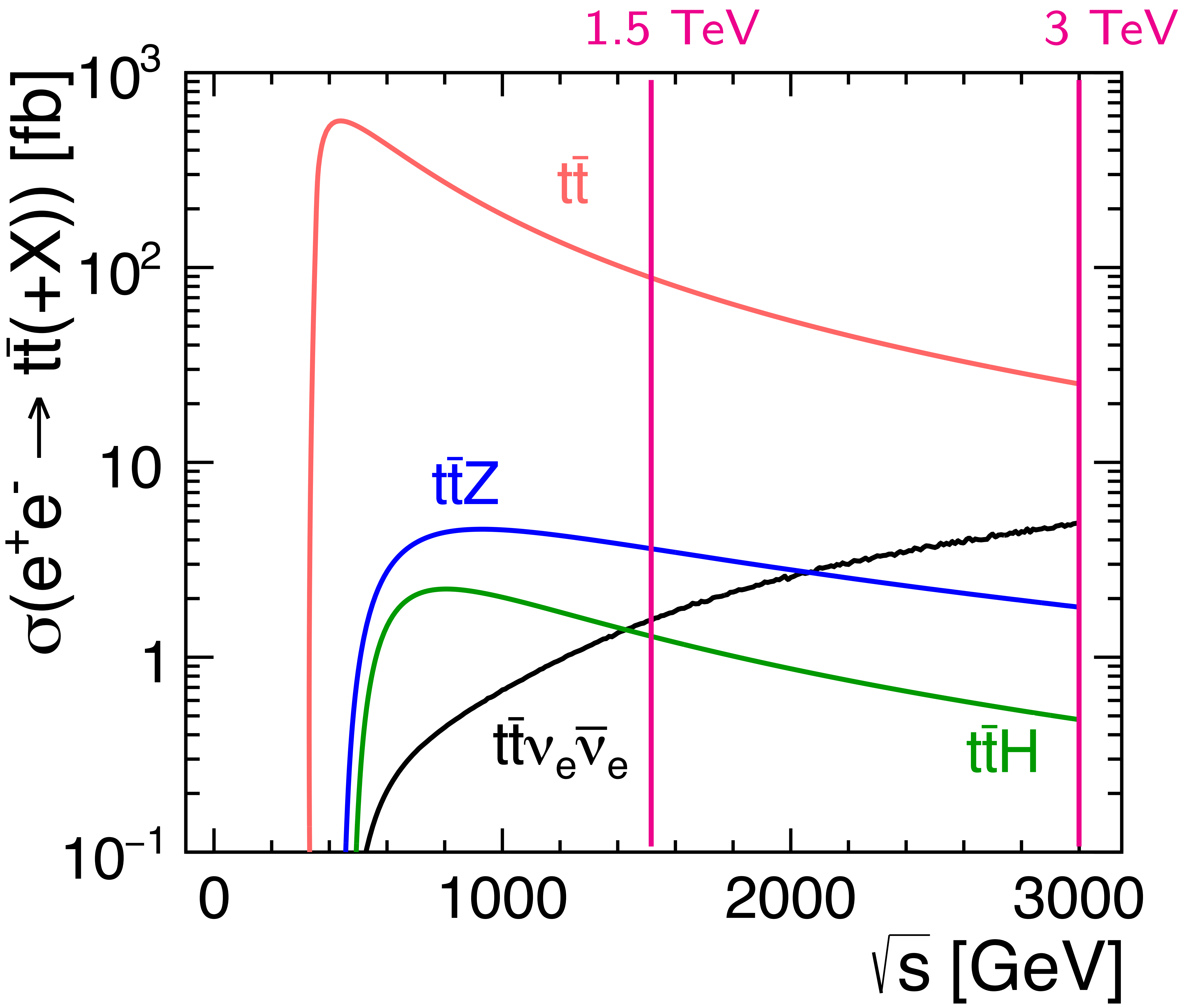
- ➤ Top being the heaviest quark (and particle) in the SM is the one that most strongly influences the Higgs and its potential
- ➤ Its mass leads to a yukawa coupling of about 1. Coincidence?
- ➤ Top mass also close to the critical value between the region where the Higgs potential is stable up to the Plack scale (or not)





Future Colliders will complete redefine the landscape of top studies and measurements: each machine providing the ultimate precision for various flagship measurements, greatly improving over HL-LHC precision studies.

TOP PRODUCTION CROSS SECTION AT LEPTON COLLIDERS



Top pair-production at and above the threshold (380 GeV)

- top-quark mass
- rare decays
- electroweak couplings

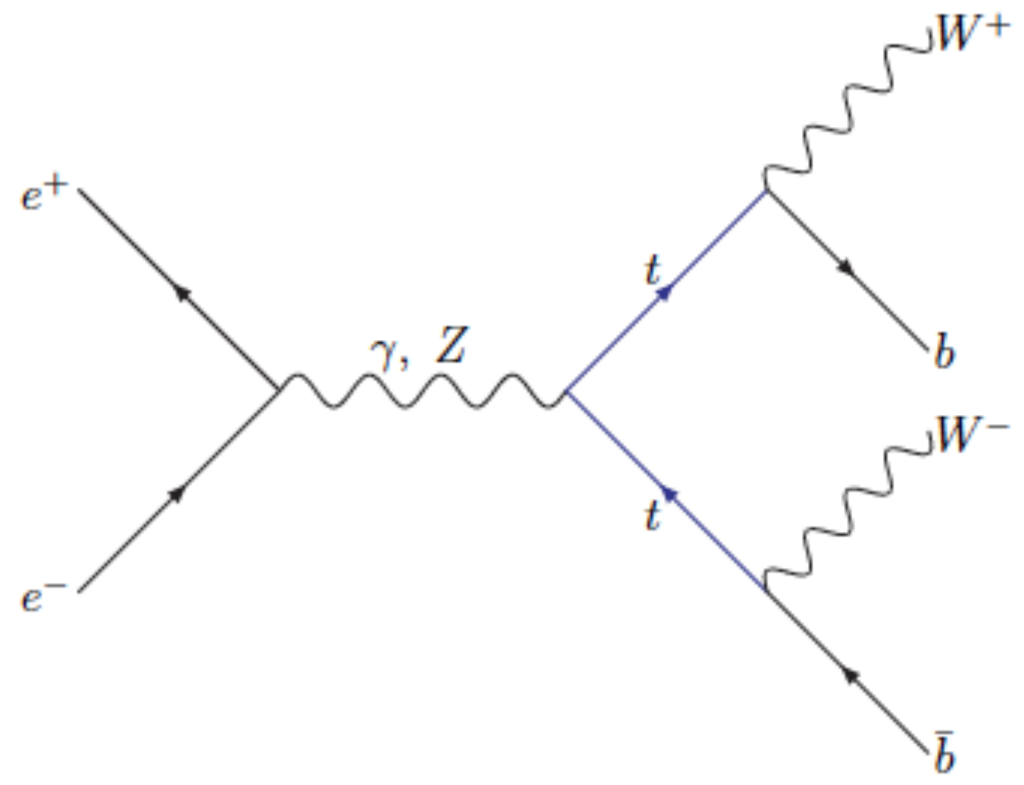
Additional processes open at high energies

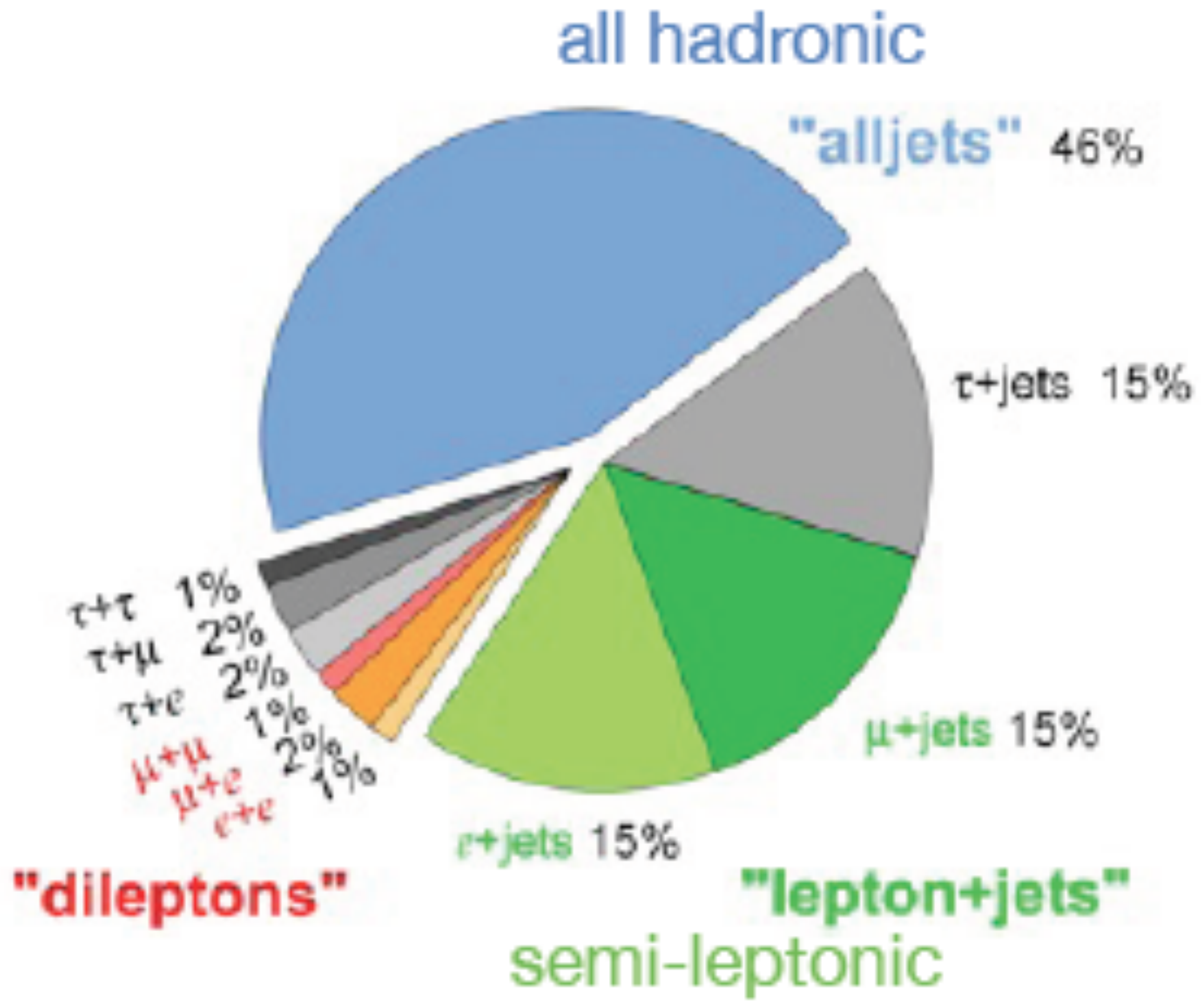
- $t\bar{t}H \Rightarrow$ Yukawa coupling and CP properties
- $t\bar{t}\nu_e\bar{\nu}_e$ vector-boson fusion $\Rightarrow$ BSM constraints

Doubled at high energy: total of over 2.8 million (anti)top quarks

TOP PRODUCTION & DECAY AT LEPTON COLLIDERS

- Top physics analysis is driven by production and decays modes
  - at lepton collider running close to threshold (or above), pair production dominates





- The decay ~100% BR in Wb
  - final states classified on the basis of the Ws decay
- at lower center of mass energies can profit of (anomalous) production of single top
  - SM cross section is tiny and basically impossible to disentangle from pair production at ee colliders

TOP PHYSICS RUNS AT FUTURE LEPTON COLLIDERS

- FCC-ee : $\sqrt{s}$= 365 GeV
- ILC: $\sqrt{s}$= 500, 1000 GeV
- CLIC: $\sqrt{s}$= 380, 1400, 3000 GeV

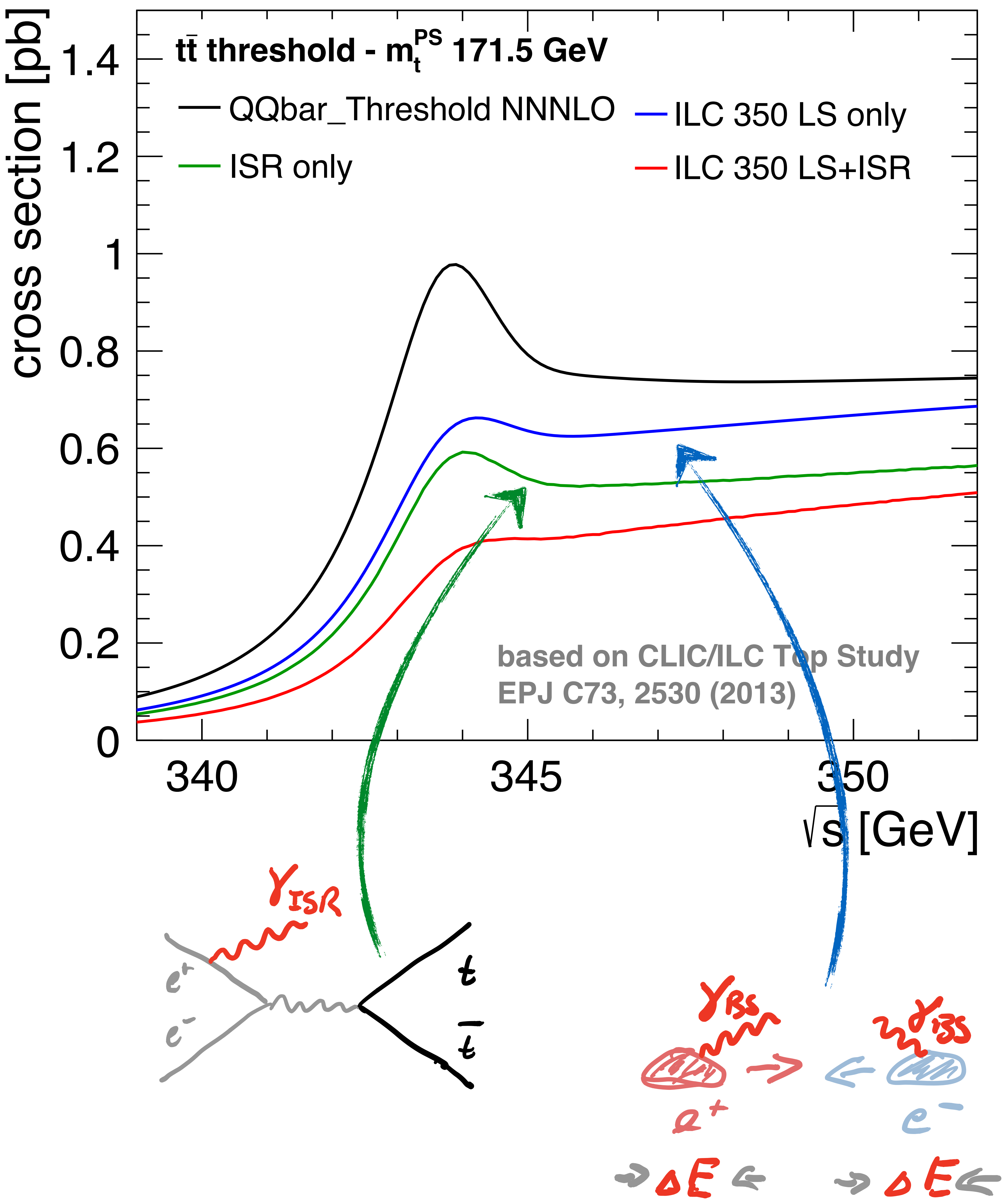
- They all include a short run at the *top threshold*

TOP QUARK AT LEPTON COLLIDERS - THE PRODUCTION

- The top quark is the only quark that has so far escaped the scrutiny of e^+e^- colliders - at the same time it may be particularly sensitive to New Physics
- Precise measurements, coupled with precise theoretical calculations, provide excellent discovery potential

- The cross section for top quark pair production in the threshold region is highly sensitive to the top quark mass and other top quark properties - and can be calculated with high precision

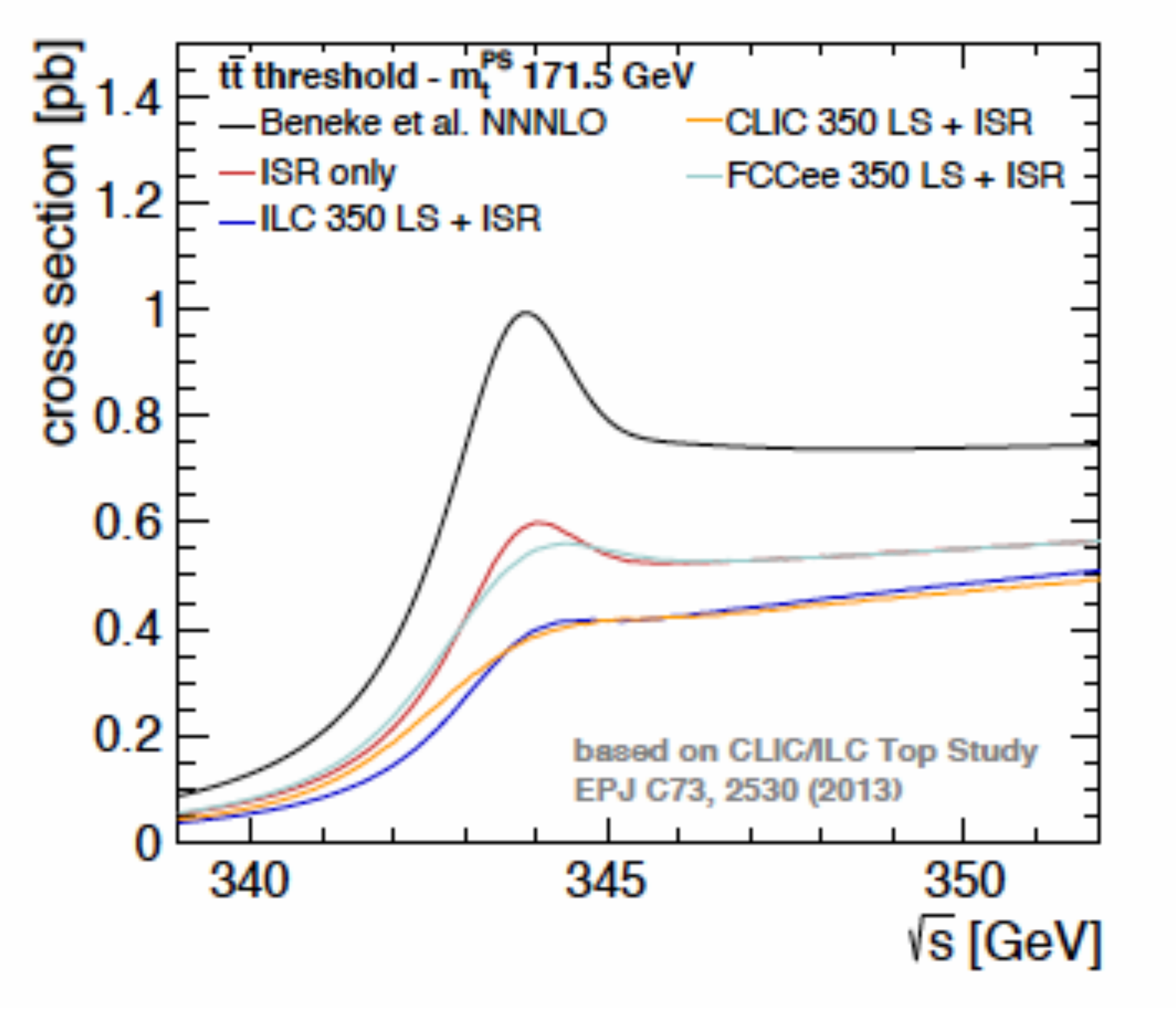
  - also depends on accelerator features
    Here: nominal ILC TDR luminosity spectrum at 350 GeV

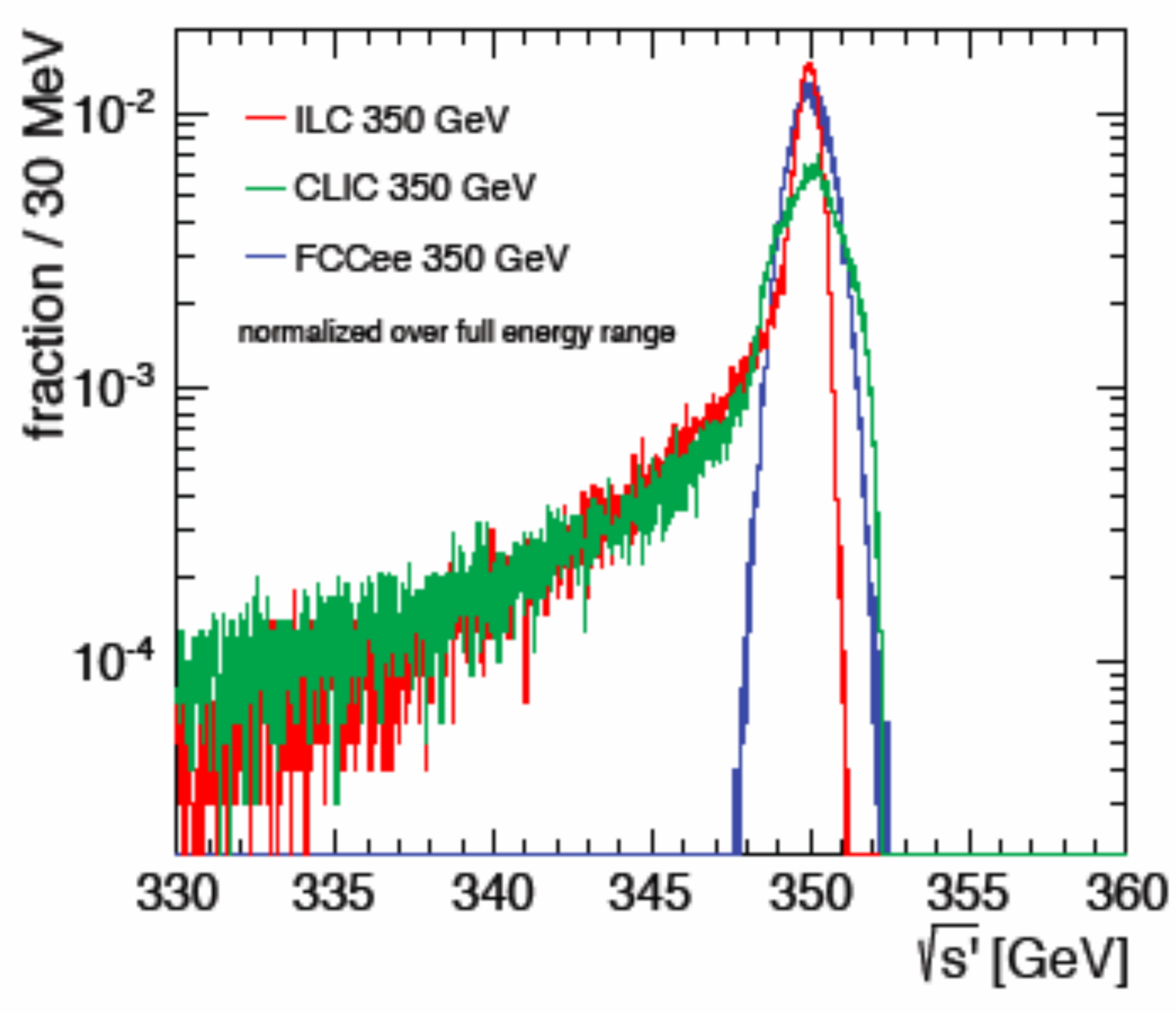


based on CLIC/ILC Top Study
EPJ C73, 2530 (2013)

THE THRESHOLD SCAN REGION

Luminosity Profile





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f top

- ➤ corresponds to about a 20% improvement in statistics compared to ILC

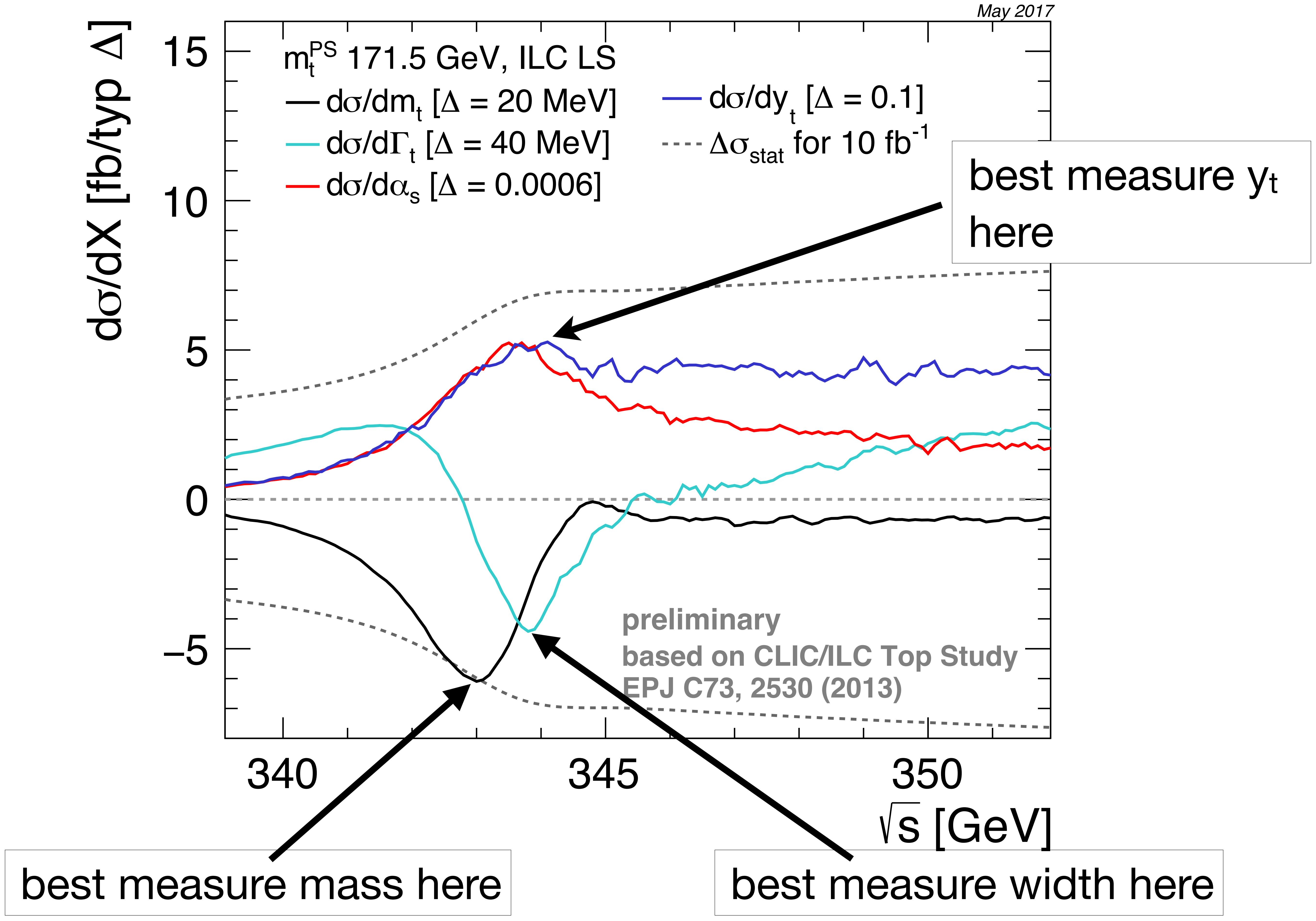
OPTIMIZING THE THRESHOLD SCAN

- Default assumption: 10 points spaced by 1 GeV, each with equal integrated luminosity
  Obvious question: **Can we do better?**

➩ The optimal way to distribute the integrated luminosity in the threshold region depends on the quantities you want to measure

Plot shows the derivative of the cross section for various parameters - to make this understandable this is normalised to typical changes of these parameters

For each of the quantities there is an optimum - if you concentrate your integrated luminosity there you get the best statistical precision



best measure y_t here

best measure mass here

best measure width here

BUT: You have to find that point!

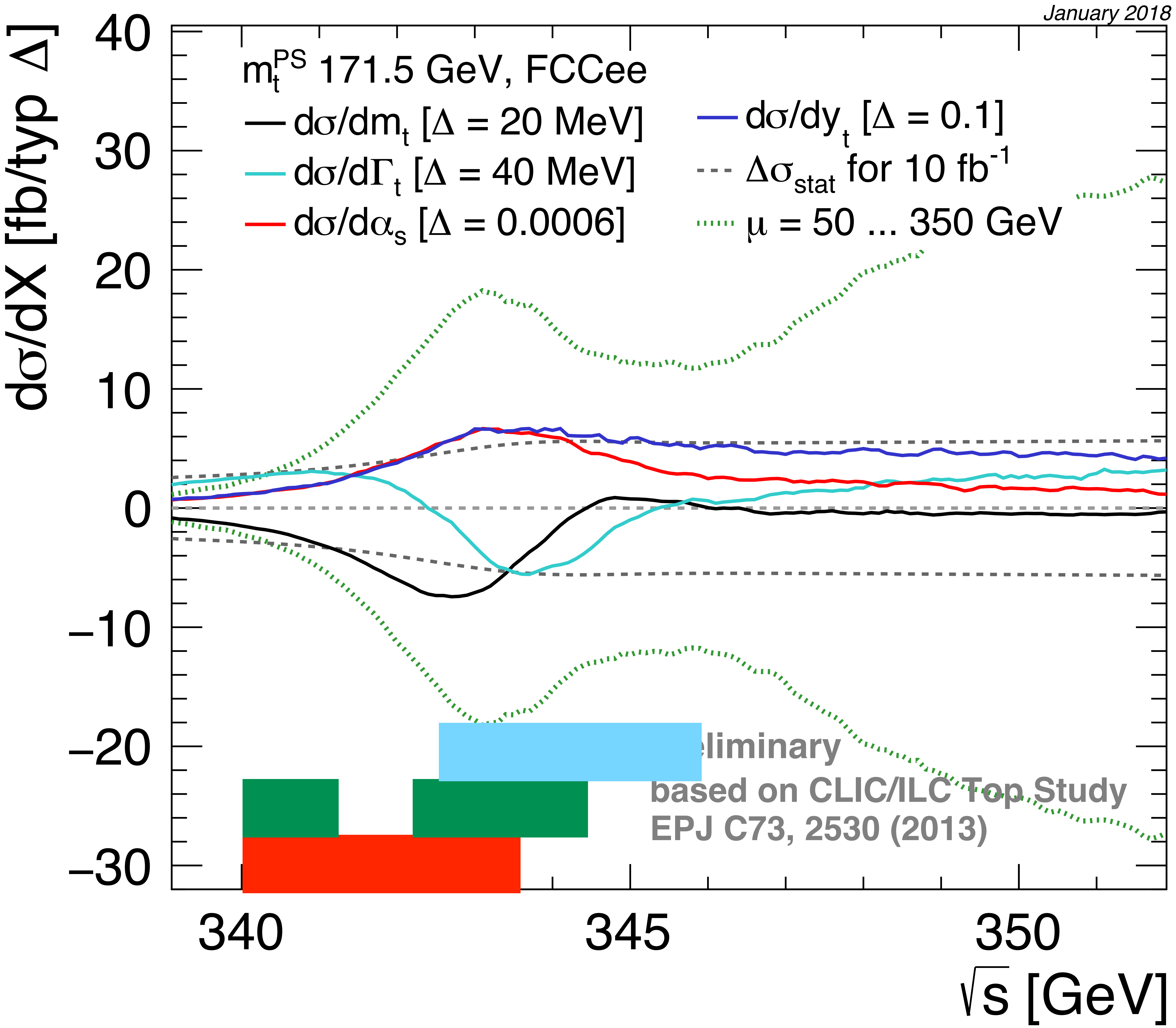
THRESHOLD SCAN REGION OPTIMISATION

sensitivity to:

🟥 mass

🟩 width

🟦 Yukawa



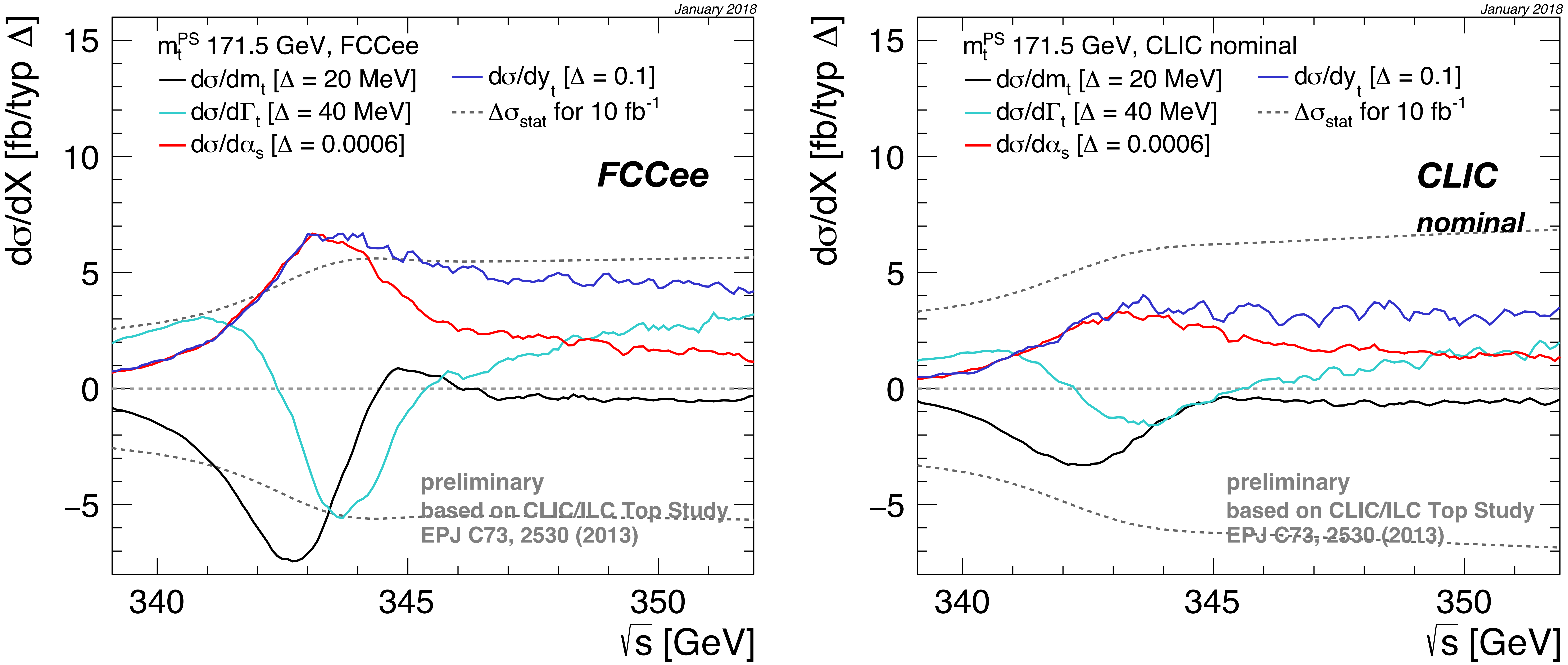
based on CLIC/ILC Top Study
EPJ C73, 2530 (2013)

EFFECT OF THE LUMINOSITY SPECTRUM

- The potential for an optimisation of the threshold scan range depends on the luminosity spectrum: A “sharper” the spectrum improves the “factorisation” of different effects on the threshold, resulting in larger improvement potential by focusing the integrated luminosity in selected regions

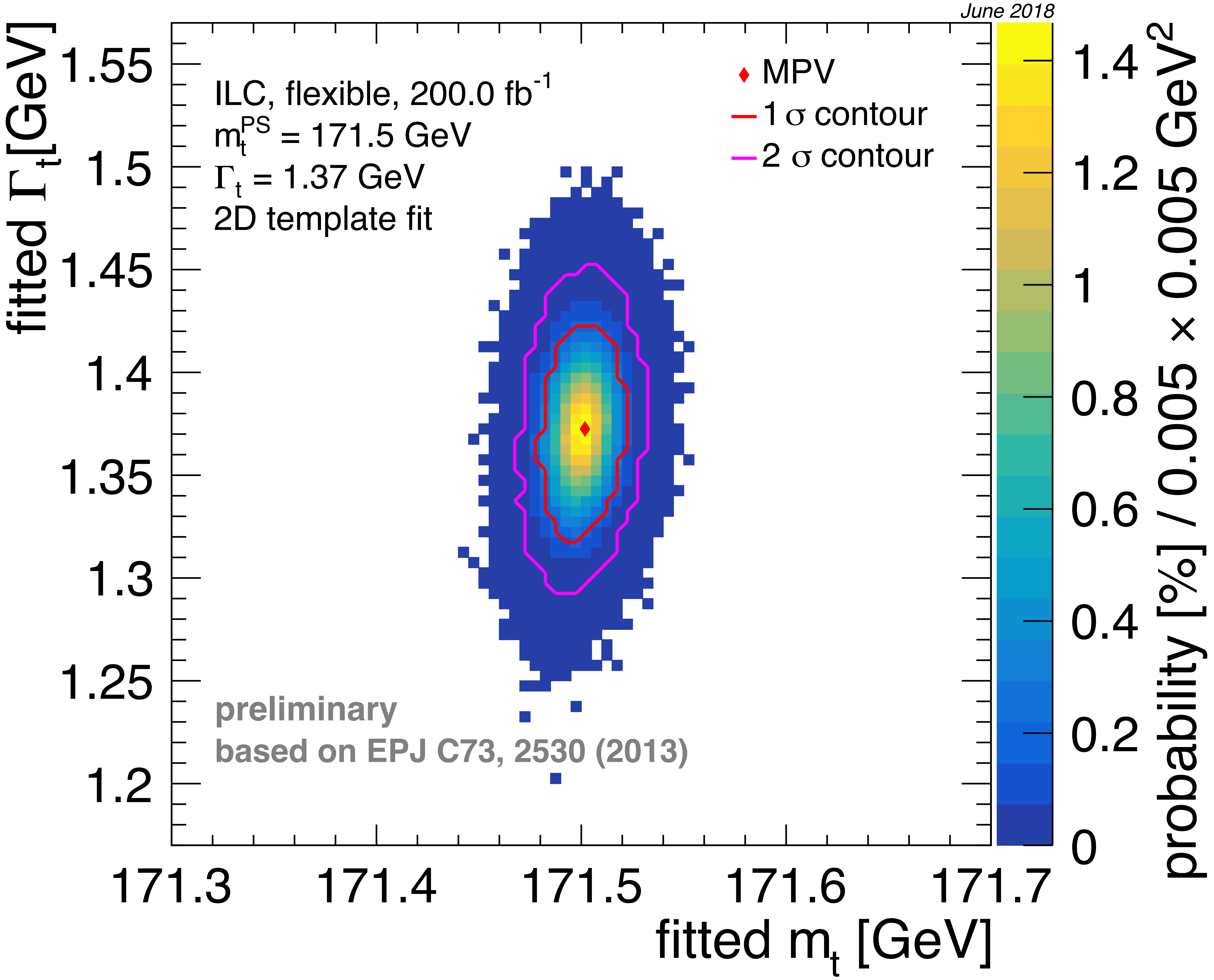
The extremes for illustration:

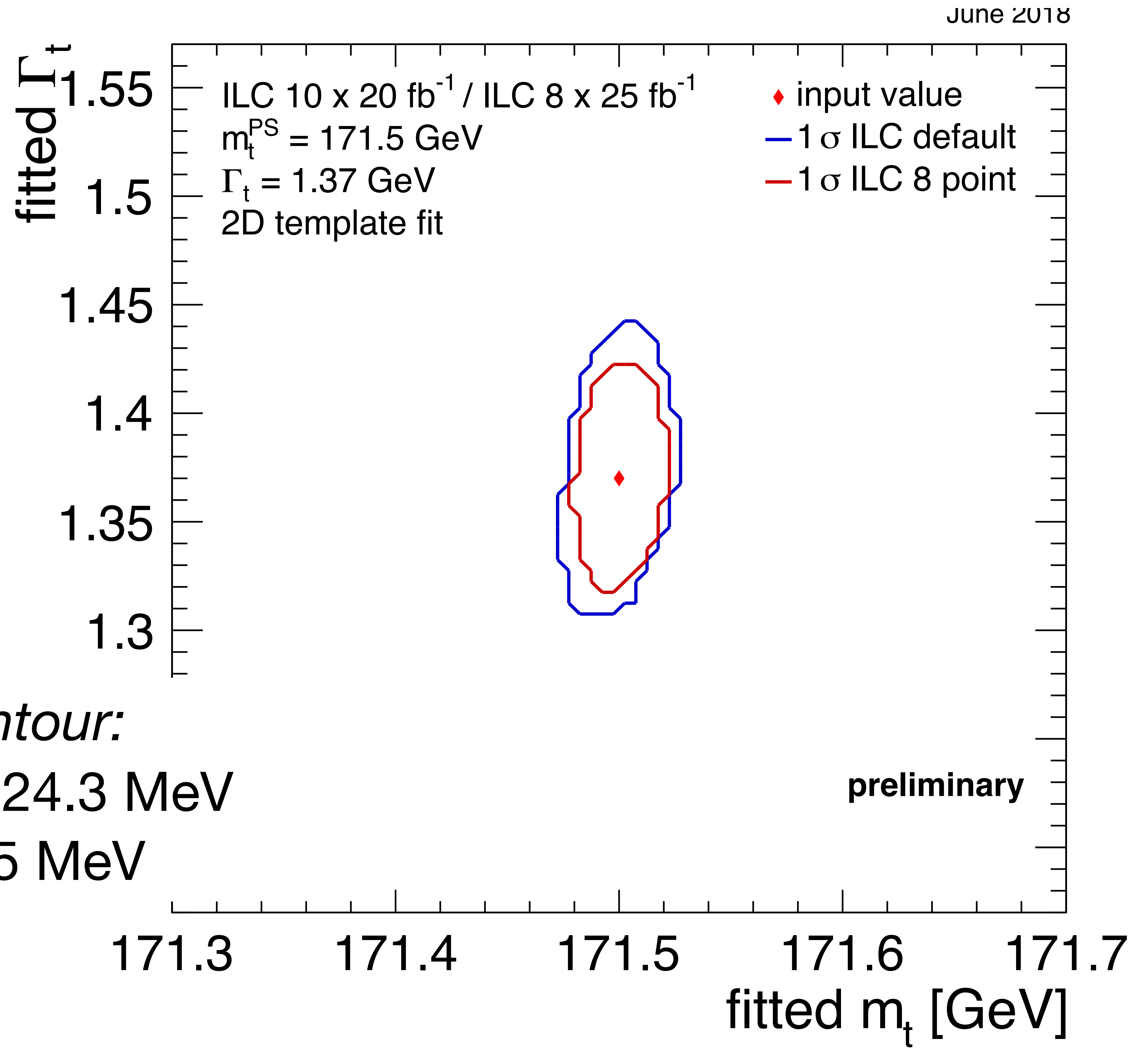
FCCee vs ***CLIC Nominal***



MASS & WIDTH: OPTIMIZED 8 POINT SCAN

- Mass only: **10.3 MeV** (stat), **-28.9 MeV** (α_s [10^{-3}]), **43.7 MeV** (theo)
- 2D Mass & Width fit





Extension of 1σ contour:

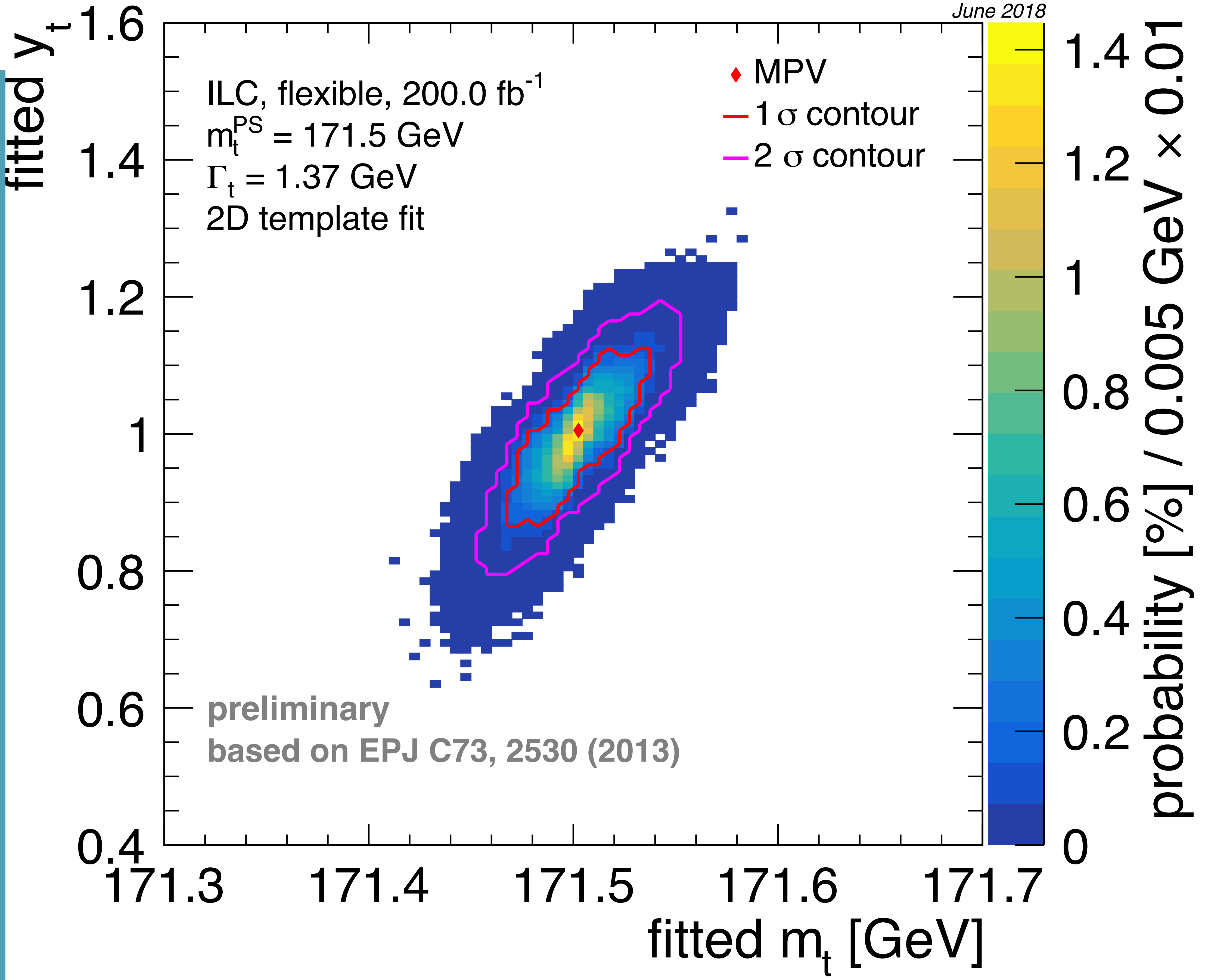
mass: +20.7 MeV, -24.3 MeV

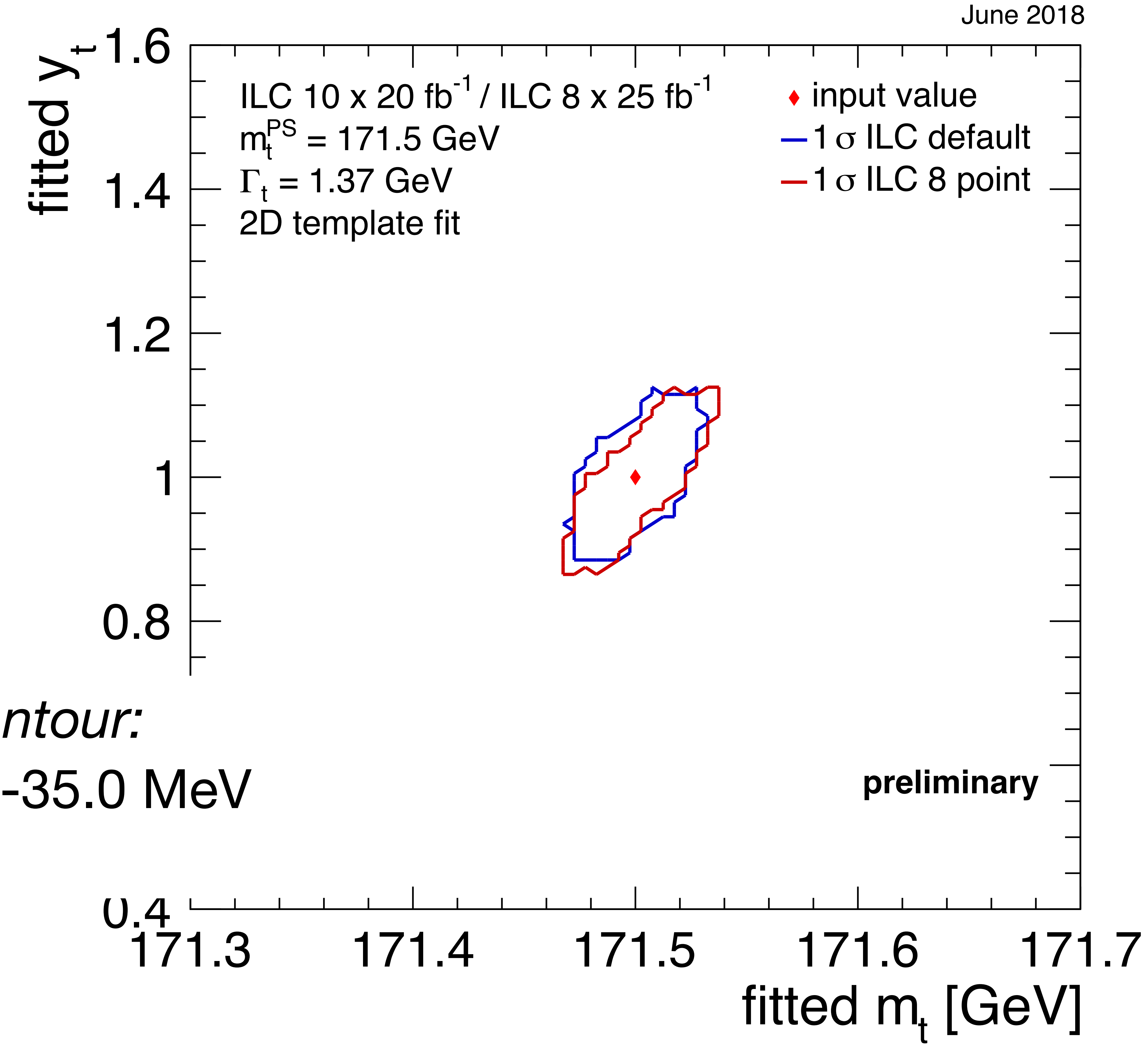
width: +50 MeV, -55 MeV

For comparison: default 10 point scan:
12.2 MeV (stat), 40.3 MeV (theo), 28.4 MeV (α_s)
2D mass: +30 MeV, - 25 MeV; 43 MeV (theo)
2D width: +80 MeV, -55 MeV; 39 MeV (theo)

MASS & YUKAWA FOR OPTIMIZED 8 POINT SCAN

- Mass only: **10.3 MeV** (stat), **-28.9 MeV** (α_s [10^{-3}]), **43.7 MeV** (theo)
- 2D Mass & Width fit





Extension of 1σ contour:
mass: +35.0 MeV, -35.0 MeV
y_t: +0.120, -0.140

For comparison: default 10 point scan:
12.2 MeV (stat), 40.3 MeV (theo), 28.4 MeV (α_s)
2D mass: +34 MeV, - 31 MeV; 42 MeV (theo)
2D y_t: 0.128, -0.112; 0.132 (theo)

GLOBAL VIEW OF UNCERTAINTIES ON TOP MASS

A multi-parameter fit can extract the PS mass with excellent precision

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^3LO QCD, arXiv:1506.06864*
Parametric uncertainty:	~30 MeV	*α_s world average, arXiv:1604.08122*
Experimental systematics:	25-50 MeV	*including LS, arXiv:1309.0372*

Exp. Syst for CC: beam energy and spread give: Δm/m~3MeV

This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

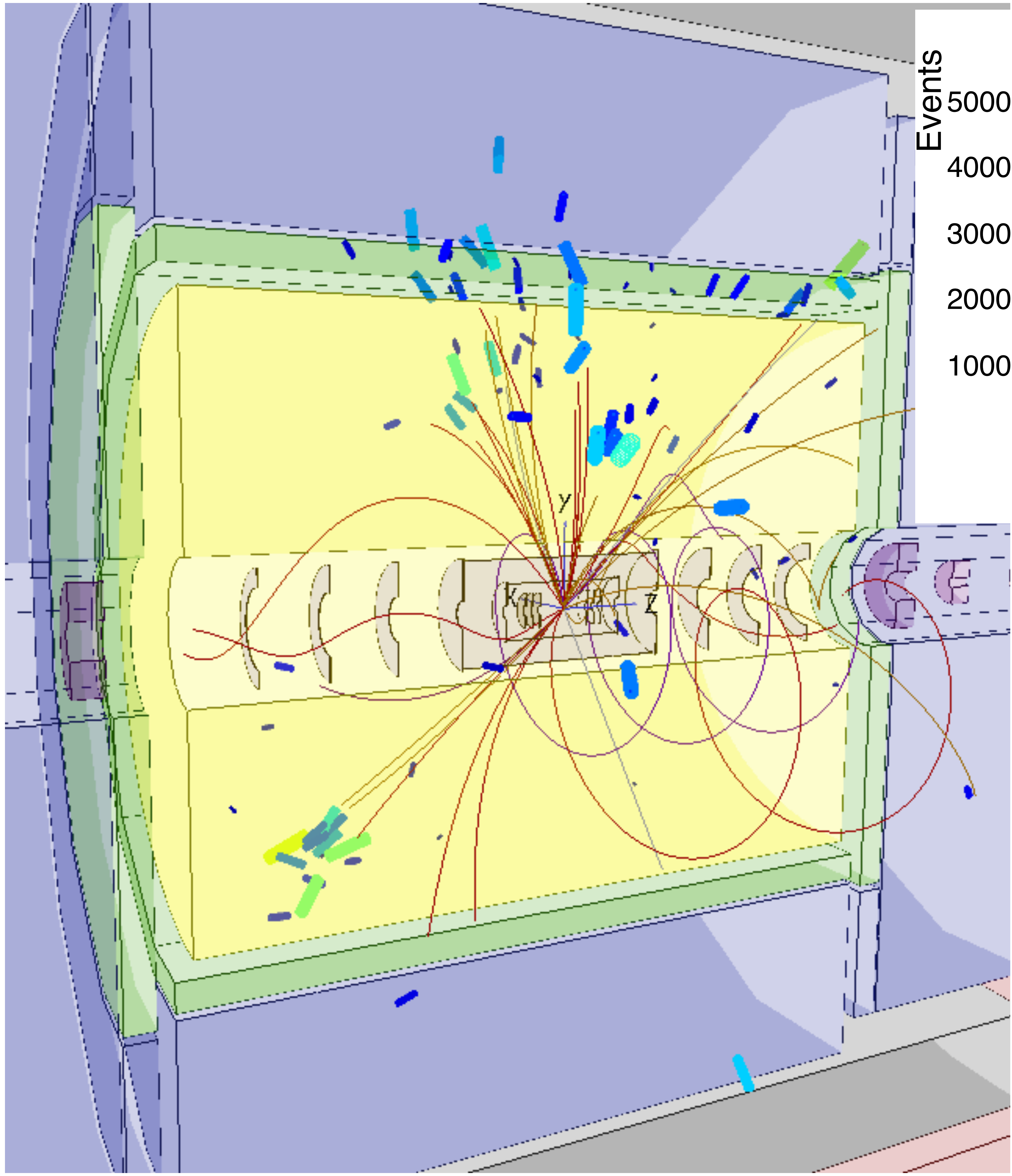
Marquard et al., PRL114, arXiv:1502.01030

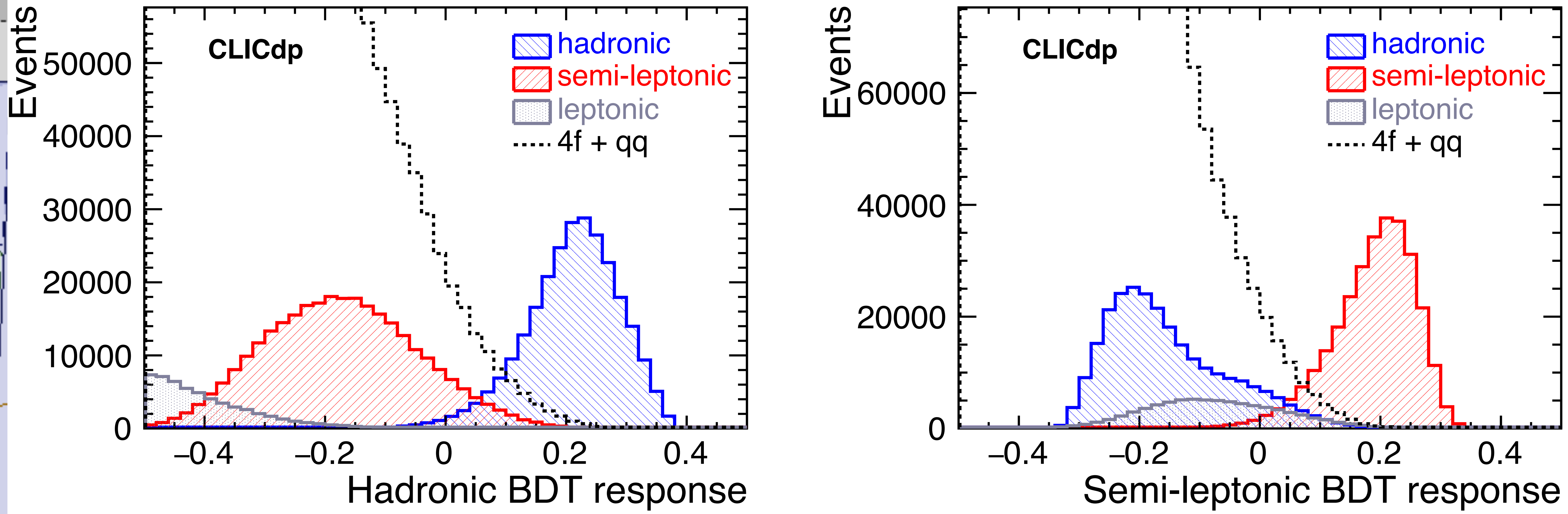
A very competitive top quark mass measurement: Nearly machine independent

$\Delta m_t \sim 50$ MeV   (= 3 x 10^{-4}, cf. Δ**m**$_b$ **~1%**)

Important: if α_s precision improves with the Z pole and WW threshold runs:
$\Delta\alpha_s < 0.0002$ then Δm/m ~5MeV
Improved α_s drastically improves correlations m_t, Γ_t and Y_t

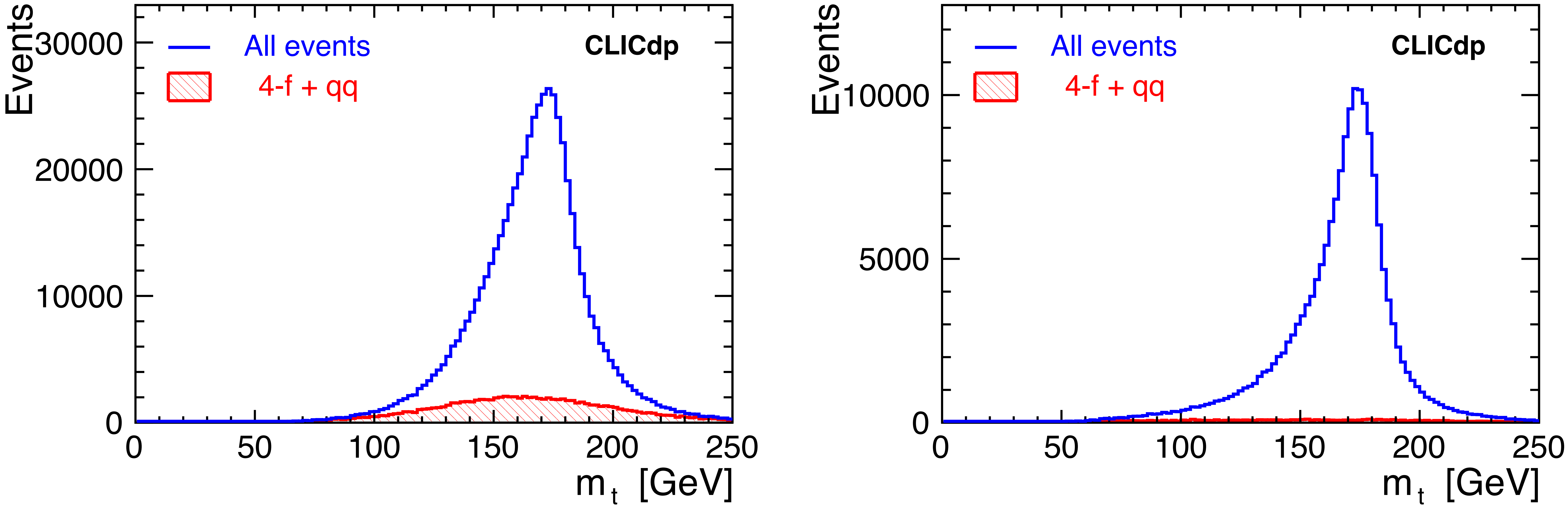
TOP MASS FROM DIRECT RECONSTRUCTION (ABOVE THRESHOLD)





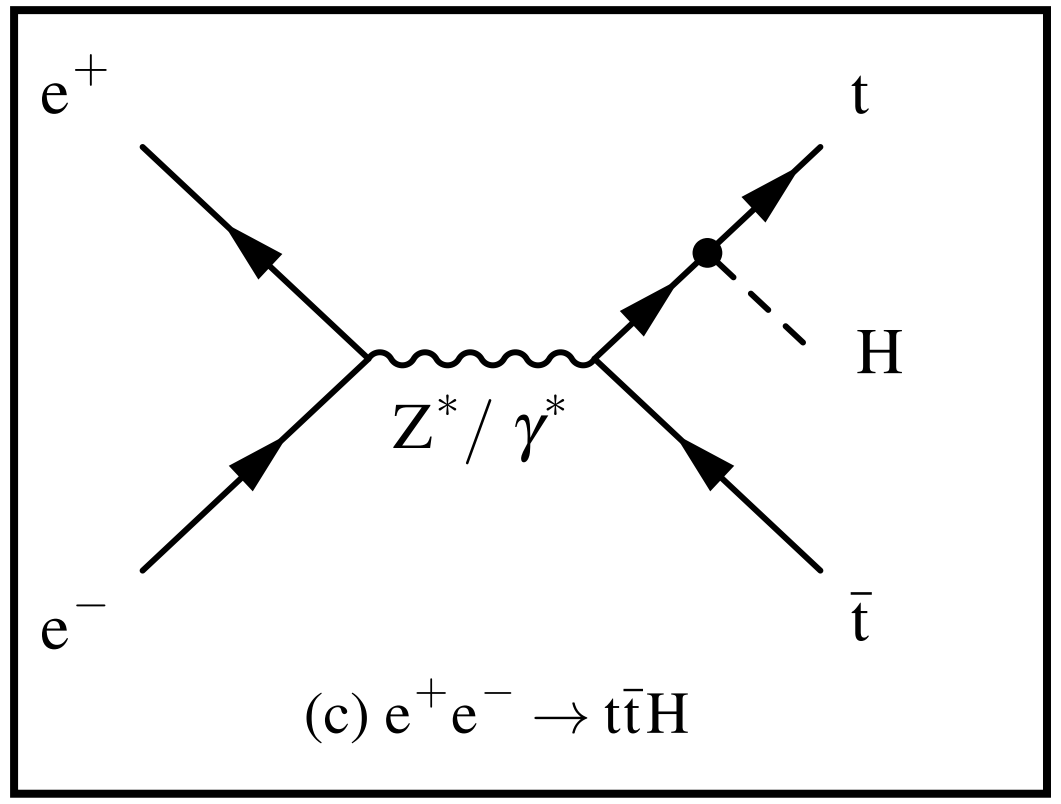
- Event selection of l+jets and all-hadronic tt events
- BDT to select from background and event classification
- Reconstruction of jets with the VLC algorithm requiring 4 or 6 jets in the final state

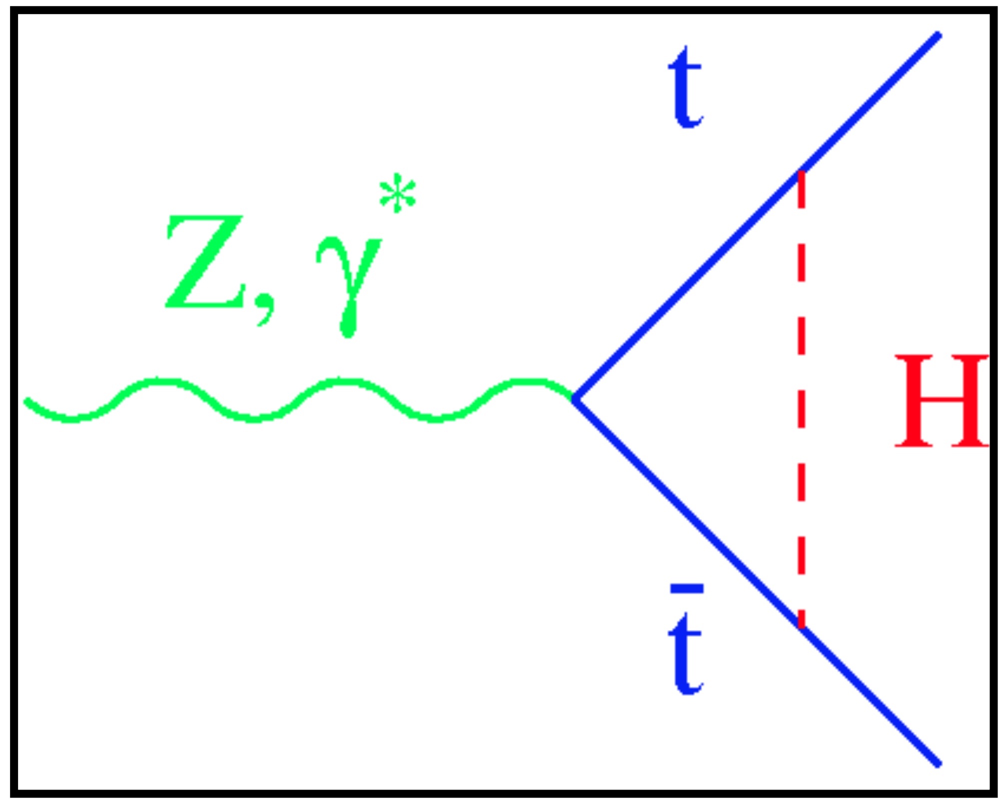
TOP MASS FROM DIRECT RECONSTRUCTION (ABOVE THRESHOLD)

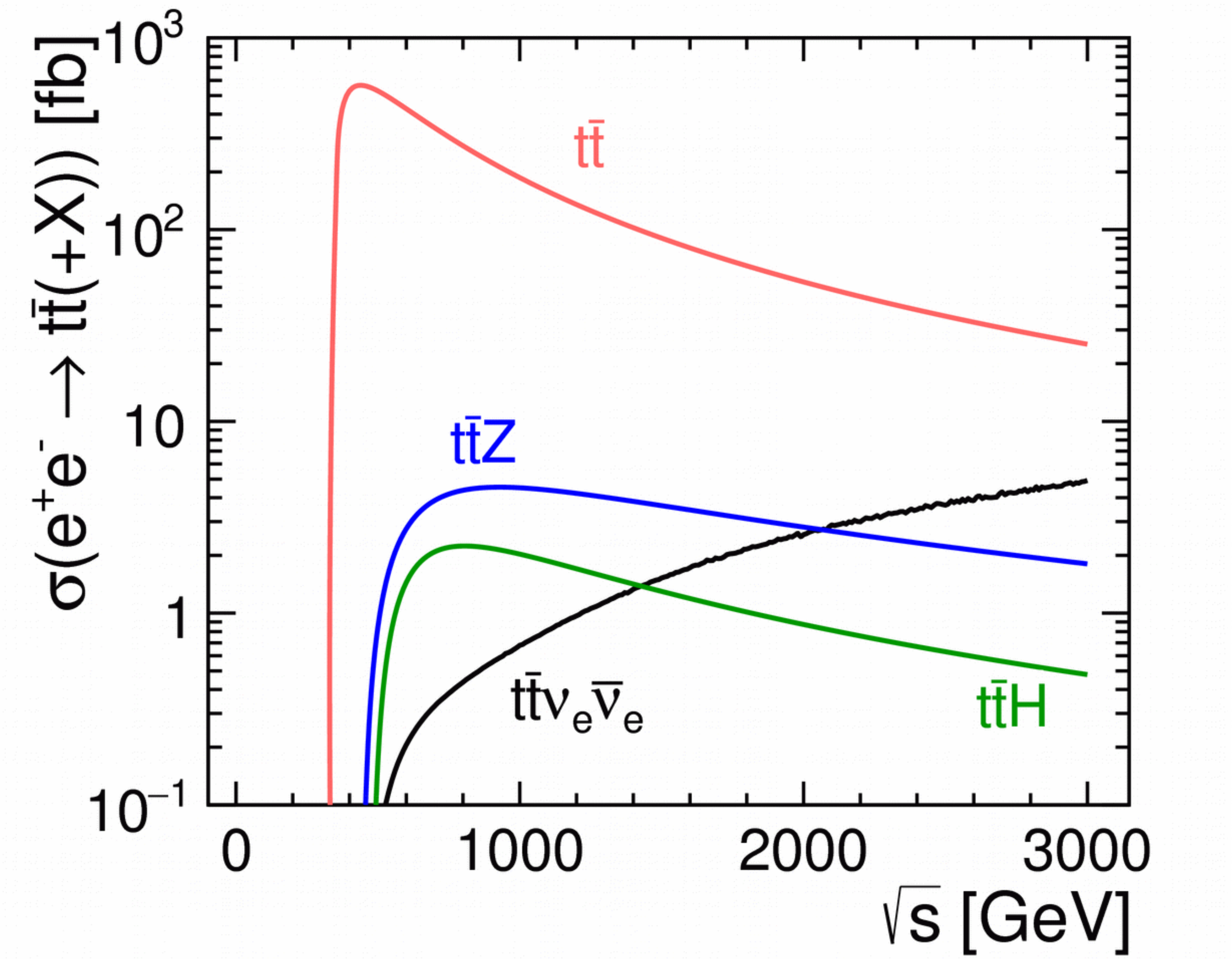


- Statistical uncertainty ~30MeV
- Systematic uncertainty from JES very important (<0.02%). Might need a run at Z pole for calibration
- Additional theory uncertainty in translation to a particular renormalization scheme of few 100 MeV (as at LHC)

THE TOP YUKAWA COUPLING







- The coupling between the top and Higgs is an extremely interesting quantity.
  - The HL-LHC is expected to reach a precision of ~7-10%. Reaching the sub-% will be a job for FCC-hh!
- ee->ttH production needs at least $\sqrt{s}$>500 GeV
- At the FCC-ee the λ_{top} is accessible only indirectly: at threshold the virtual Higgs boson exchange that can give an effect up to 9% on the cross section

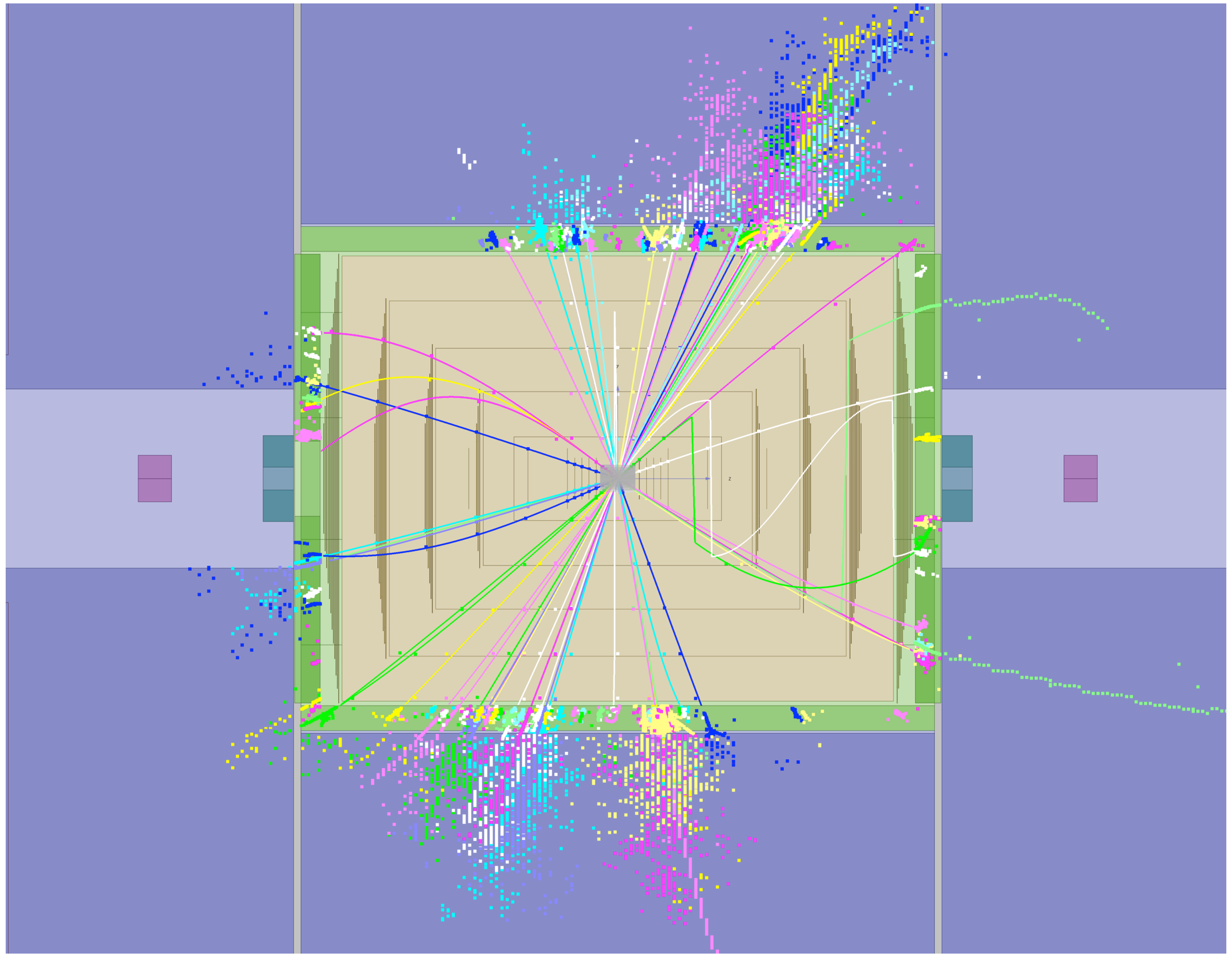
DIRECT MEASUREMENT OF TOP YUKAWA (1)

Need √s>500 GeV (ILC, CLIC)

From the measurement of the ttH production cross section

Difficult measurement:

- very low statistics
- large backgrounds
- requires perfect detector performance (6-8 jets, 4 *b*-tags)



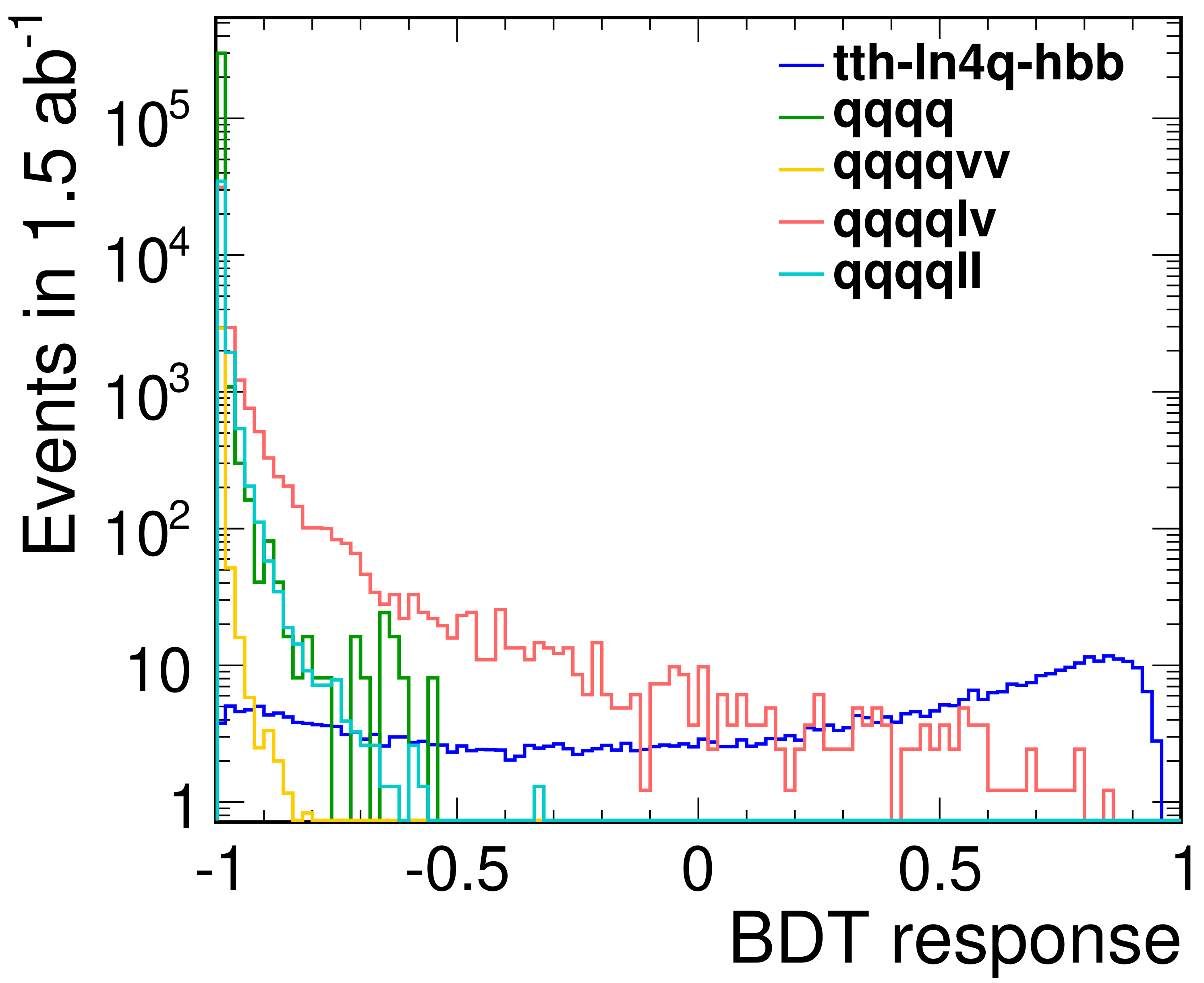
$e^+e^- \rightarrow ttH \rightarrow bbbbqq\tau\nu_\tau$

DIRECT MEASUREMENT OF TOP YUKAWA (2)

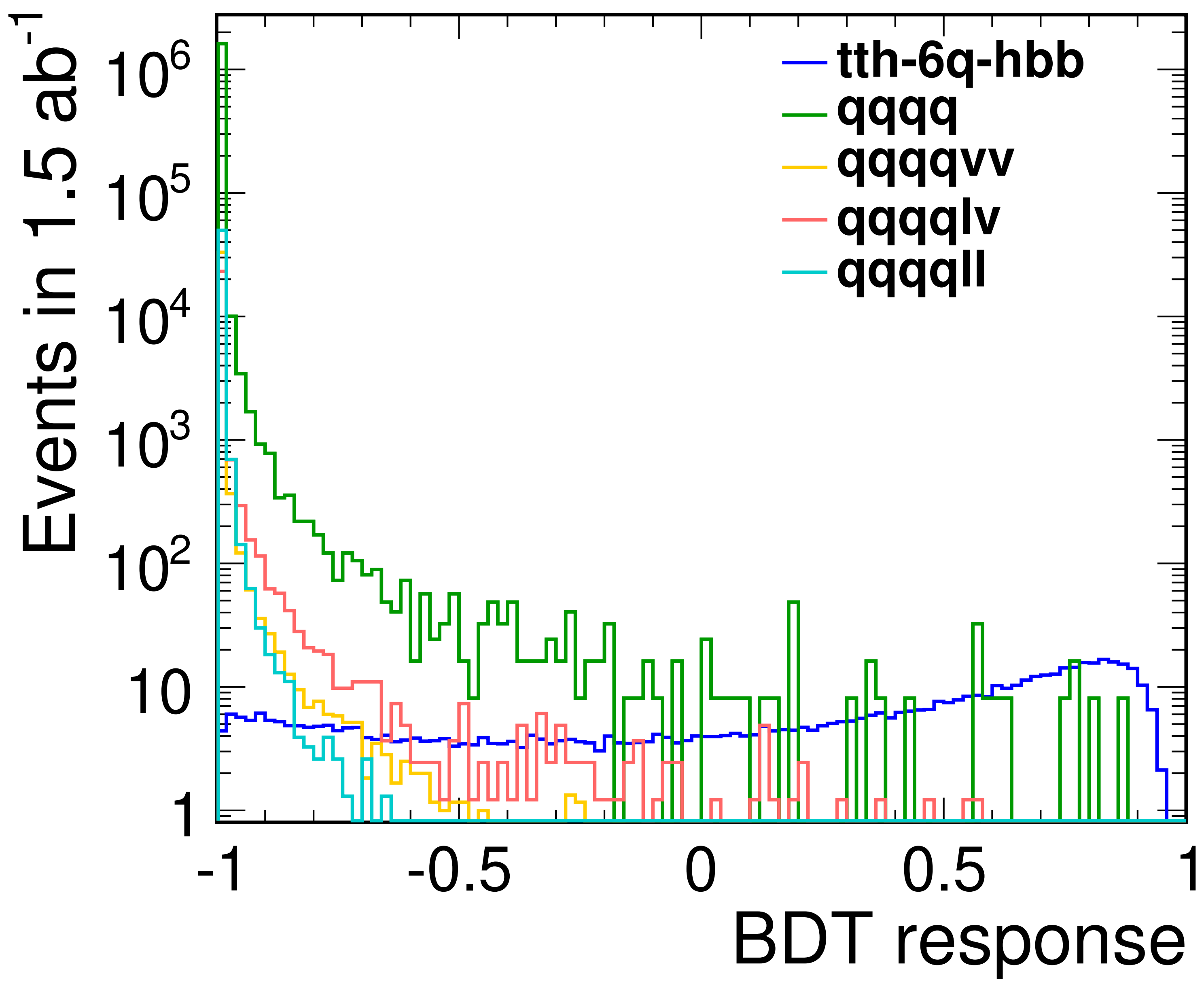
Analysis of 1.5 ab^{-1} at $\sqrt{s}$=1.4 TeV

Fully-hadronic and semi-leptonic top-quark pair decays considered
Focus on dominant Higgs boson decay channel: $H \rightarrow b\bar{b}$

Semi-leptonic event selection



Hadronic event selection



**Difficult analysis
Using BDTs to separate signal and background**

$$\frac{\Delta y_t}{y_t} = 0.503\,\frac{\Delta\sigma}{\sigma}\,.$$

Expected precision:

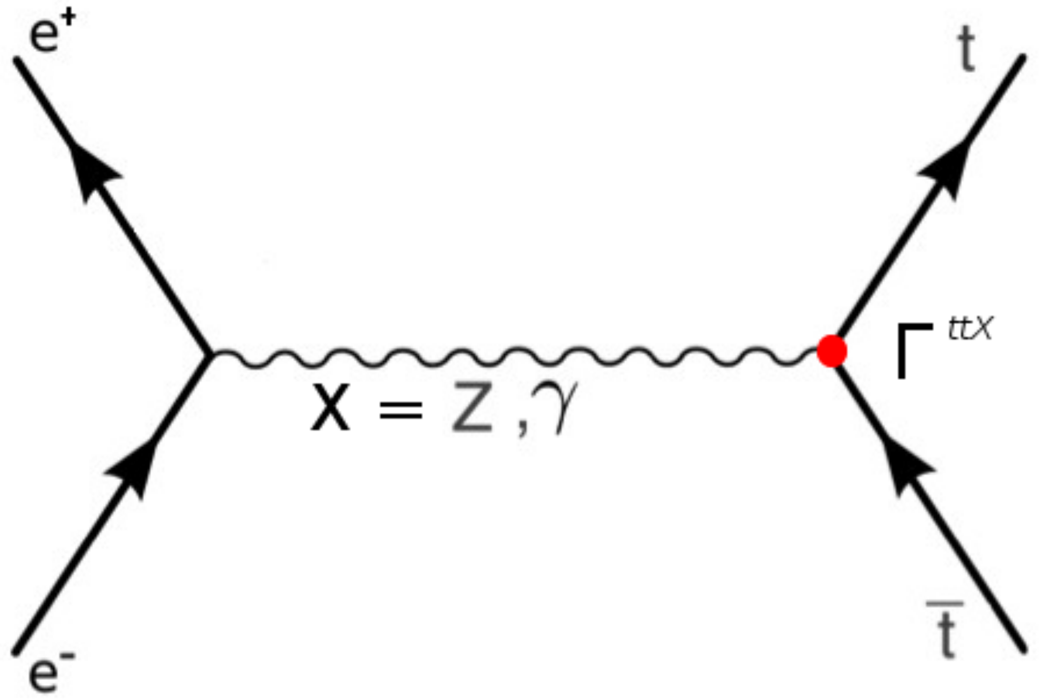
$$\Delta y_t/y_t = 3.8\,\%\,(1.5ab^{-1}, \sqrt{s} = 1.4TeV, nopol)$$

$$\Delta y_t/y_t = 2.7\,\%\,(2.5ab^{-1}, \sqrt{s} = 1.4TeV, pol)$$

TOP ELECTROWEAK COUPLINGS

Pair production provides direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics" contribution



New physics effects can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays

Additional constraints obtained by:

- using electron beam polarisation
- measurements at different $\sqrt{s}$

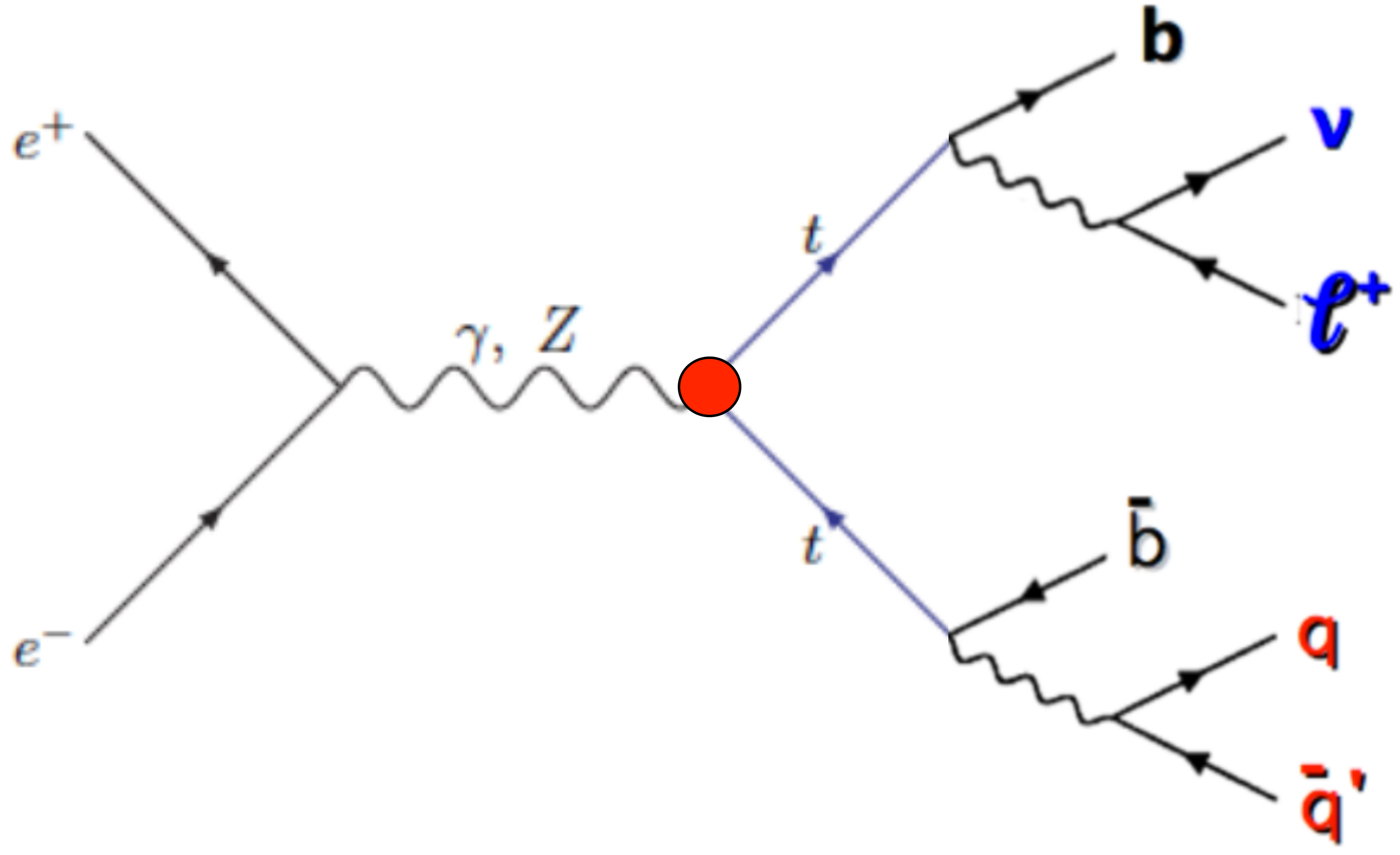
At linear colliders

(also using radiative events!)

ELECTROWEAK COUPLING OF THE TOP QUARK @CC

arXiv: 1503.01325

- Final state top quarks are produced with non-zero polarization (ttZ)
  - the top polarization and the total rate depend on the ttZ/γ couplings
  - the top polarization is maximally tranferred to its decay products $t \rightarrow Wb$
  - This affects the energy and angular distribution of these decay products
- ttZ, ttγ couplings can be enhanced in extra dimensions and (particularly) composite Higgs models



Study of the lepton energy and angular distribution as a function of √s in semi-leptonic events

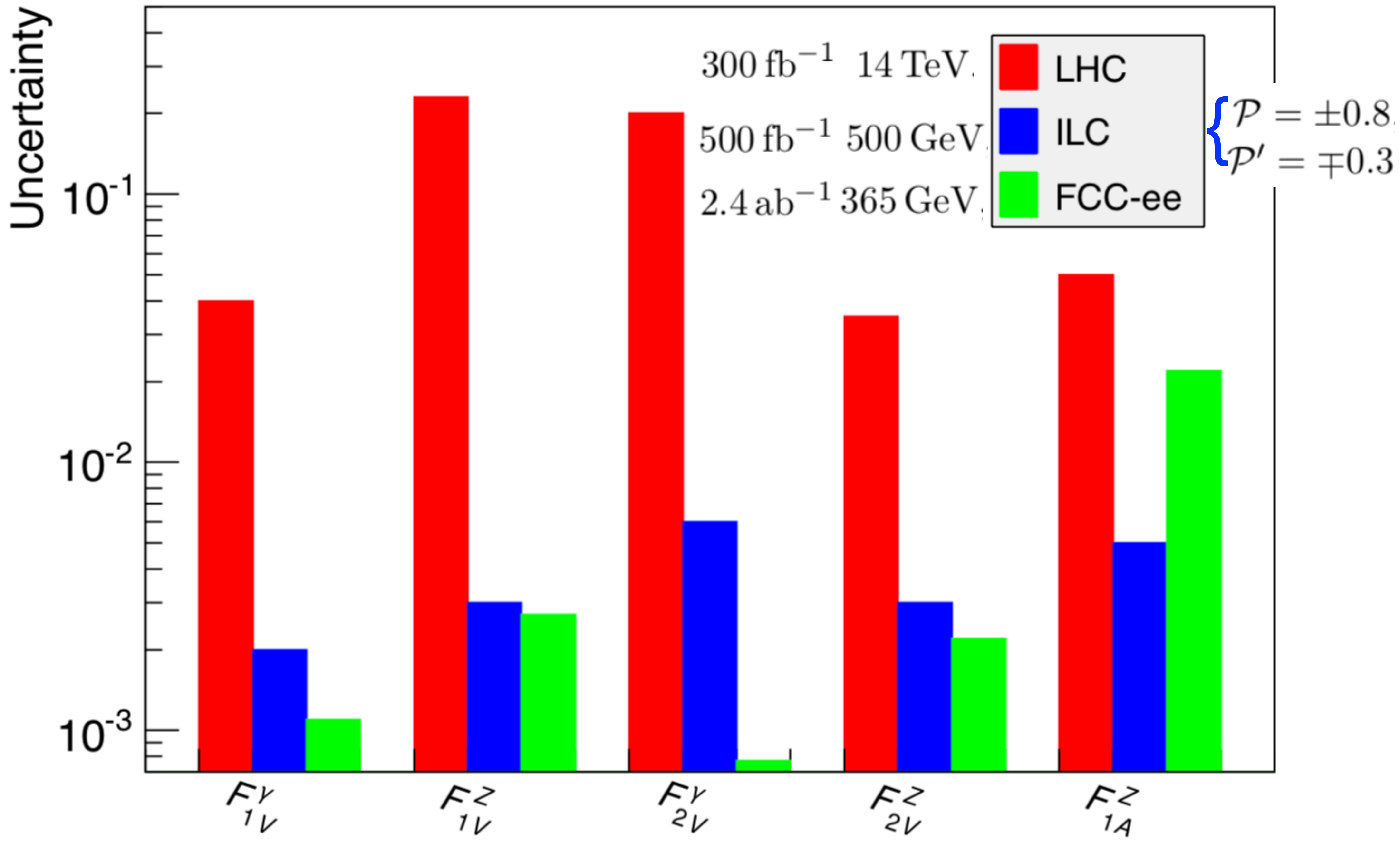
$t\bar{t} \rightarrow \ell\nu b\bar{b}q\bar{q}$

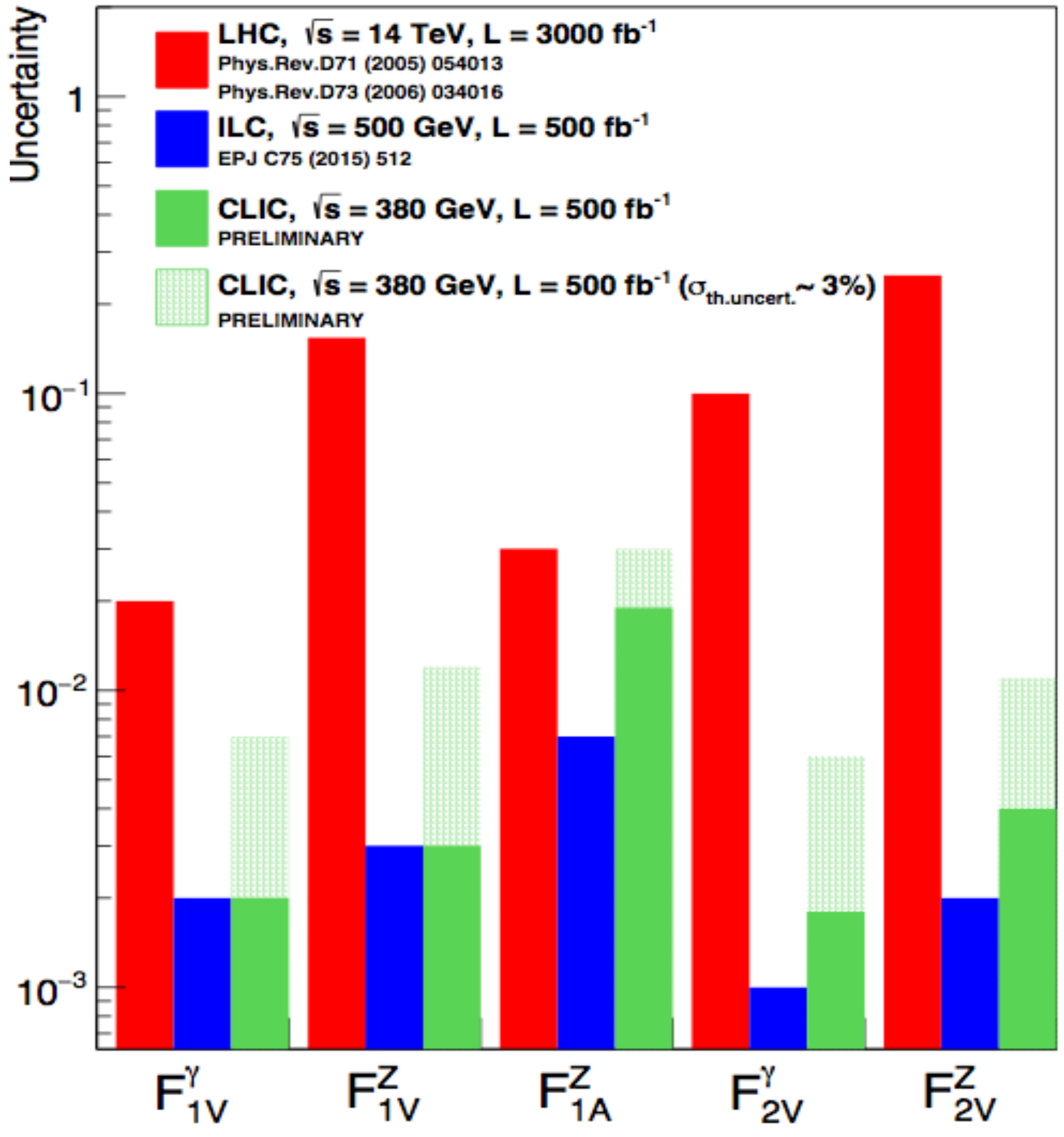
COMPARISON AMONG COLLIDERS

Higher statistics at CC compensates the polarisation of a LC

Sensitivity to BSM models

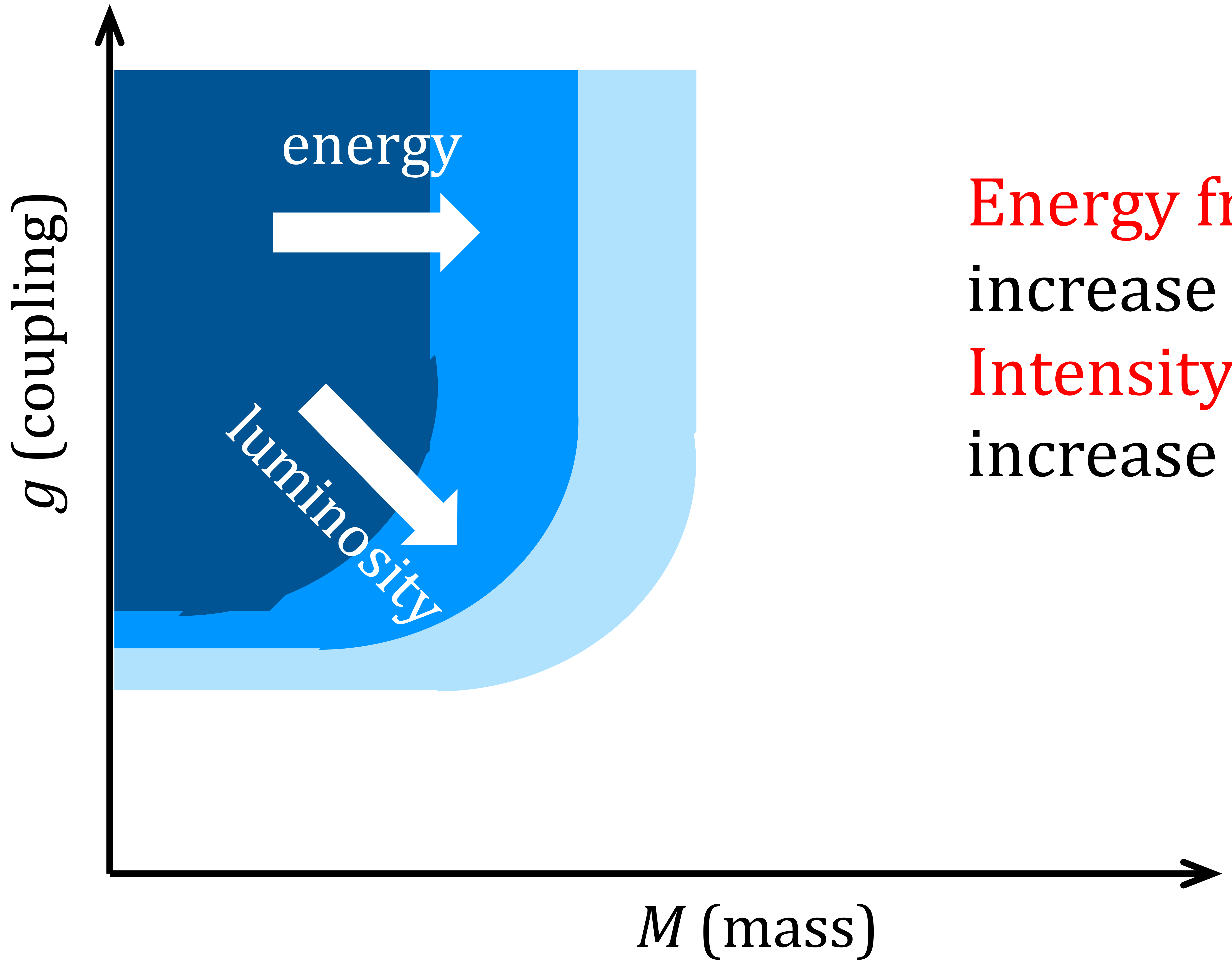
i.e. for a Z’ in Composite Higgs model up to 4TeV





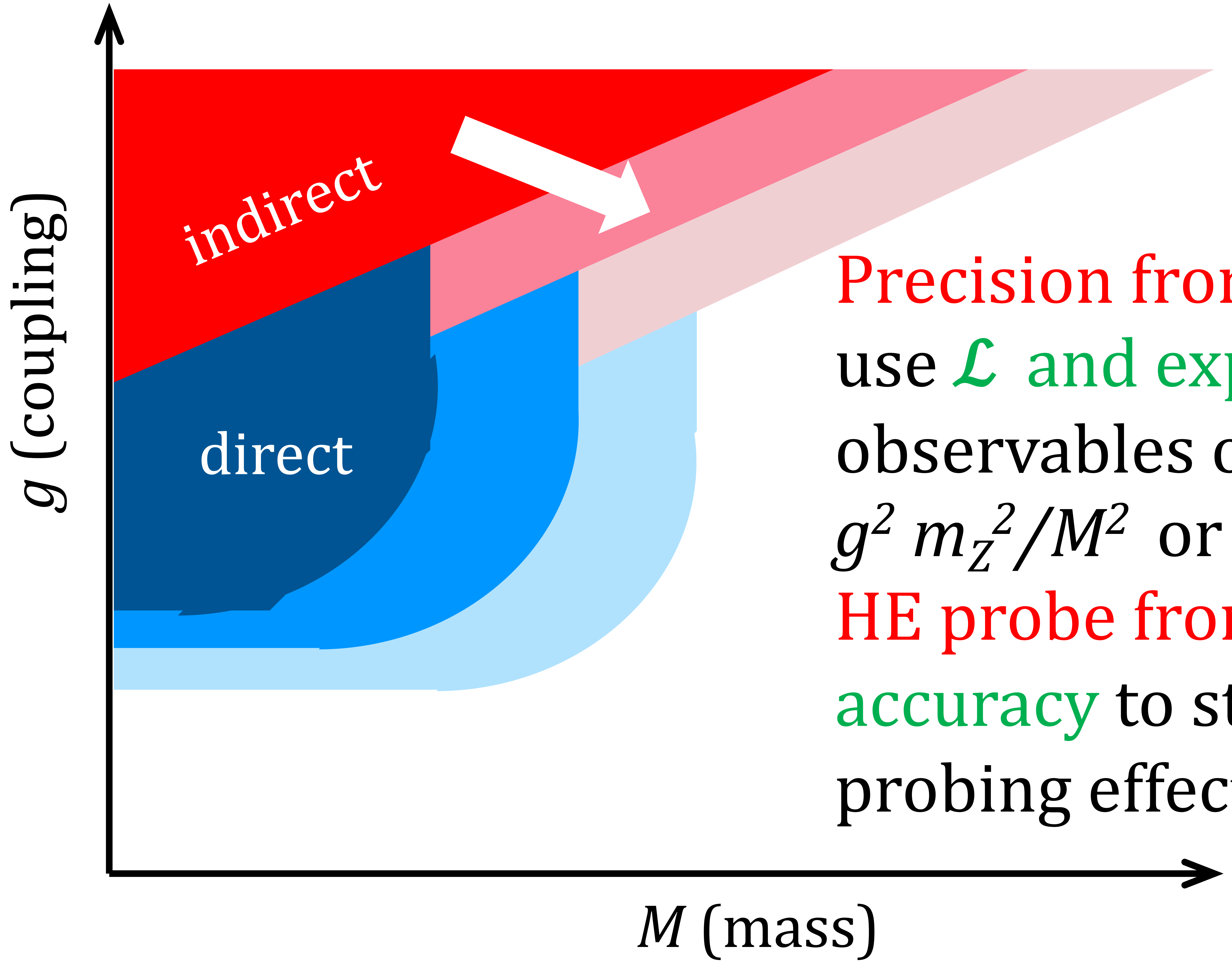
NEW PHYSICS
DIRECT SEARCHES

DIRECT SEARCHES



Energy frontier:
increase $\sqrt{s}$ to explore larger M
Intensity frontier:
increase $\mathcal{L}$ to explore smaller g

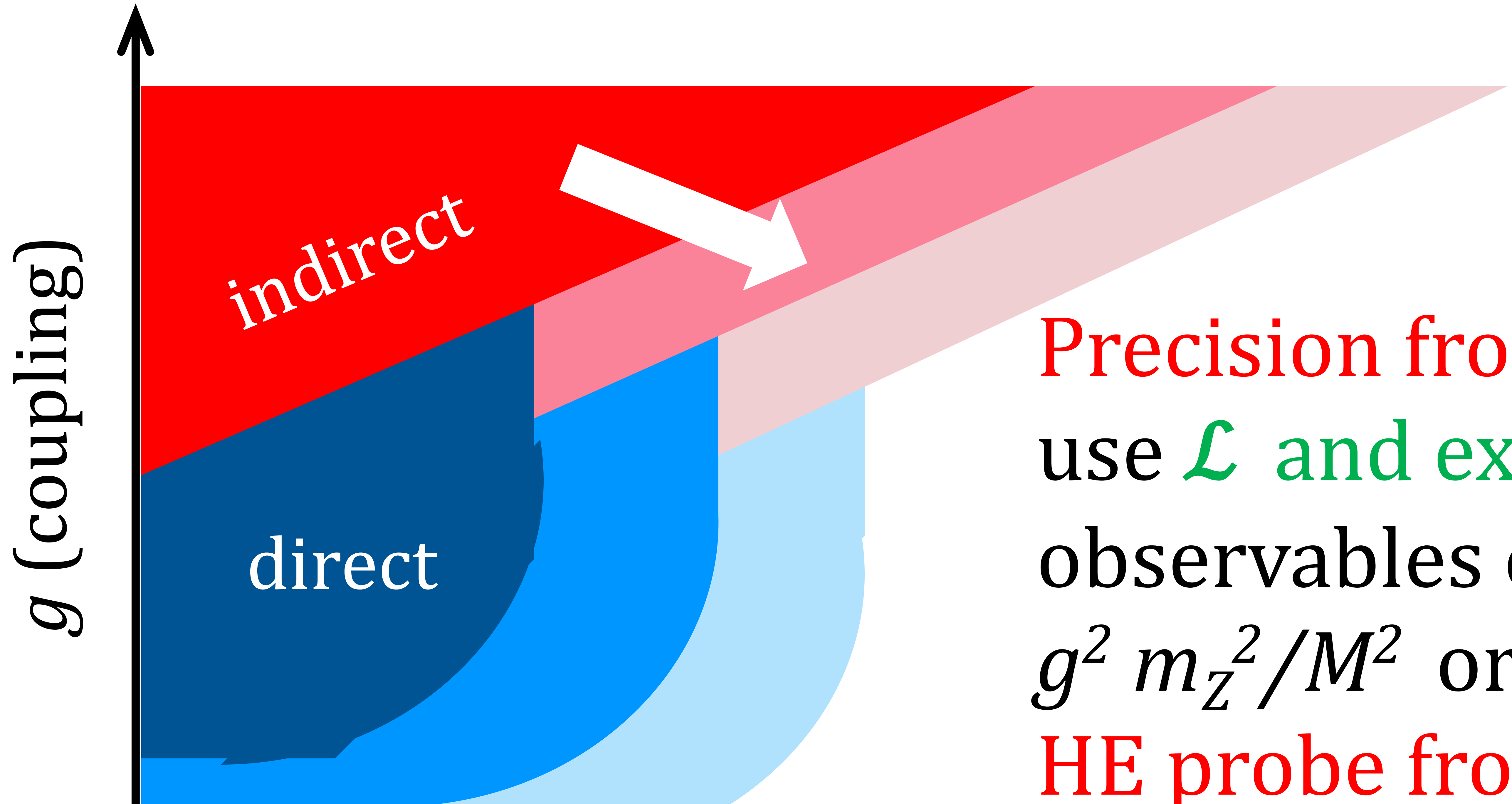
INDIRECT SEARCHES



Precision frontier:
use $\mathcal{L}$ and exp + th accuracy to study EW observables or Higgs BR, probing effects $g^2\, m_Z^2/M^2$ or $g^2\, m_h^2/M^2$

HE probe frontier: use $\sqrt{s}$, $\mathcal{L}$, and exp +th accuracy to study high-p_T processes, probing effects $g^2\, E^2/M^2$

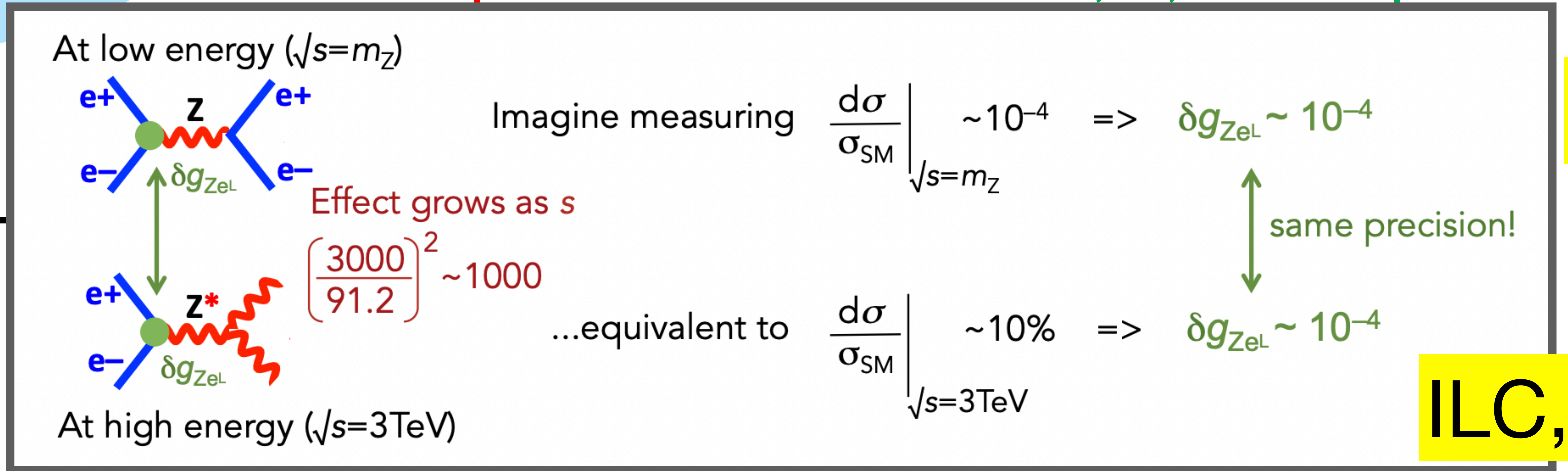
INDIRECT SEARCHES



Precision frontier:

use $\mathcal{L}$ and exp + th accuracy to study EW observables or Higgs BR, probing effects $g^2\, m_Z^2/M^2$ or $g^2\, m_h^2/M^2$

HE probe frontier: use $\sqrt{s}$, $\mathcal{L}$, and exp +th



At low energy ($\sqrt{s}=m_Z$)

Imagine measuring $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=m_Z}$ ~10^{-4} => $\delta g_{ZeL} \sim 10^{-4}$

Effect grows as s

$\left(\frac{3000}{91.2}\right)^2 \sim 1000$

same precision!

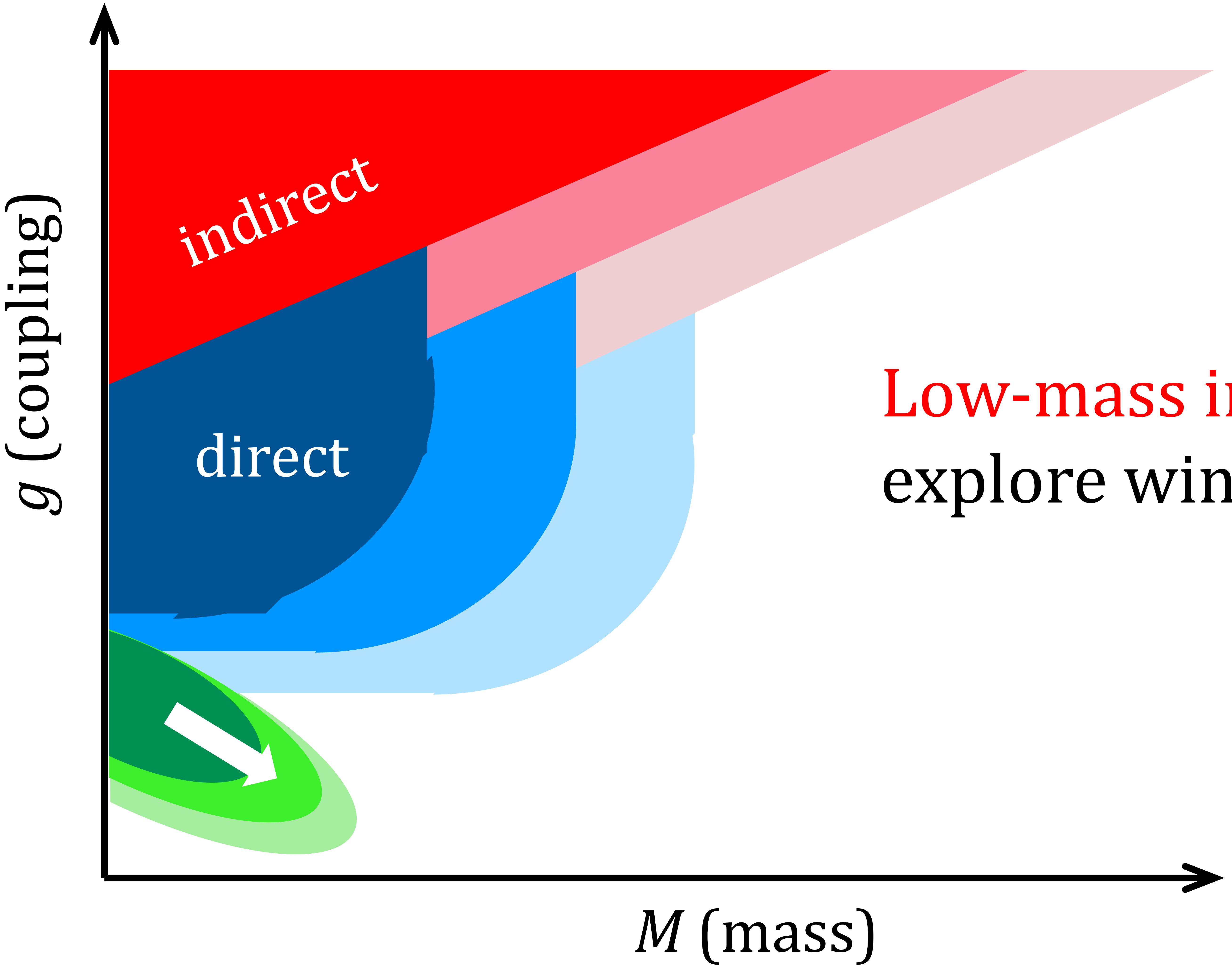
...equivalent to $\left.\frac{d\sigma}{\sigma_{SM}}\right|_{\sqrt{s}=3\text{TeV}}$ ~10% => $\delta g_{ZeL} \sim 10^{-4}$

At high energy ($\sqrt{s}$=3TeV)

FCC

ILC,CLIC

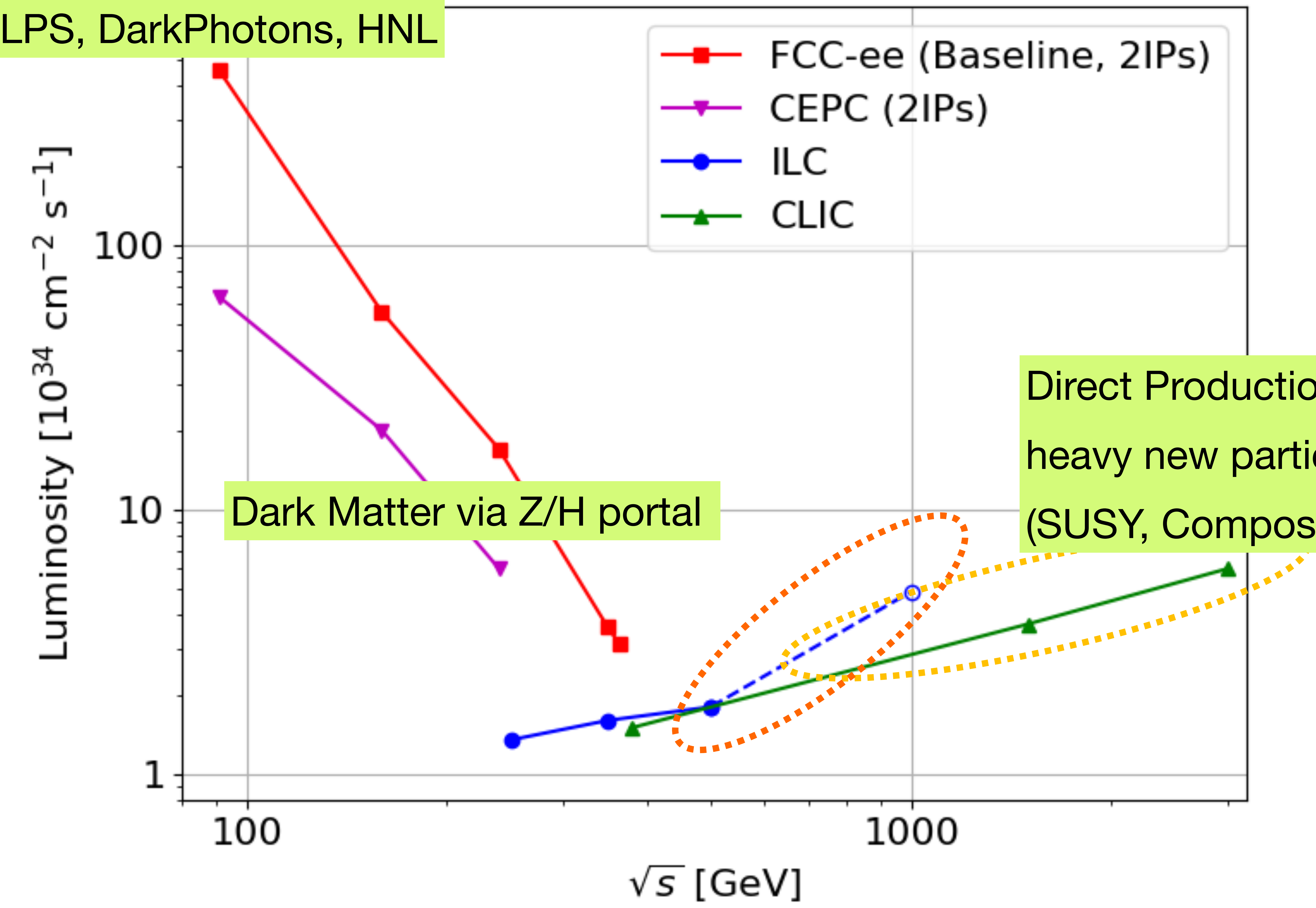
FEEBLY INTERACTING PARTICLES



Low-mass intensity frontier:
explore window at low M and low g

Tera-Z approach

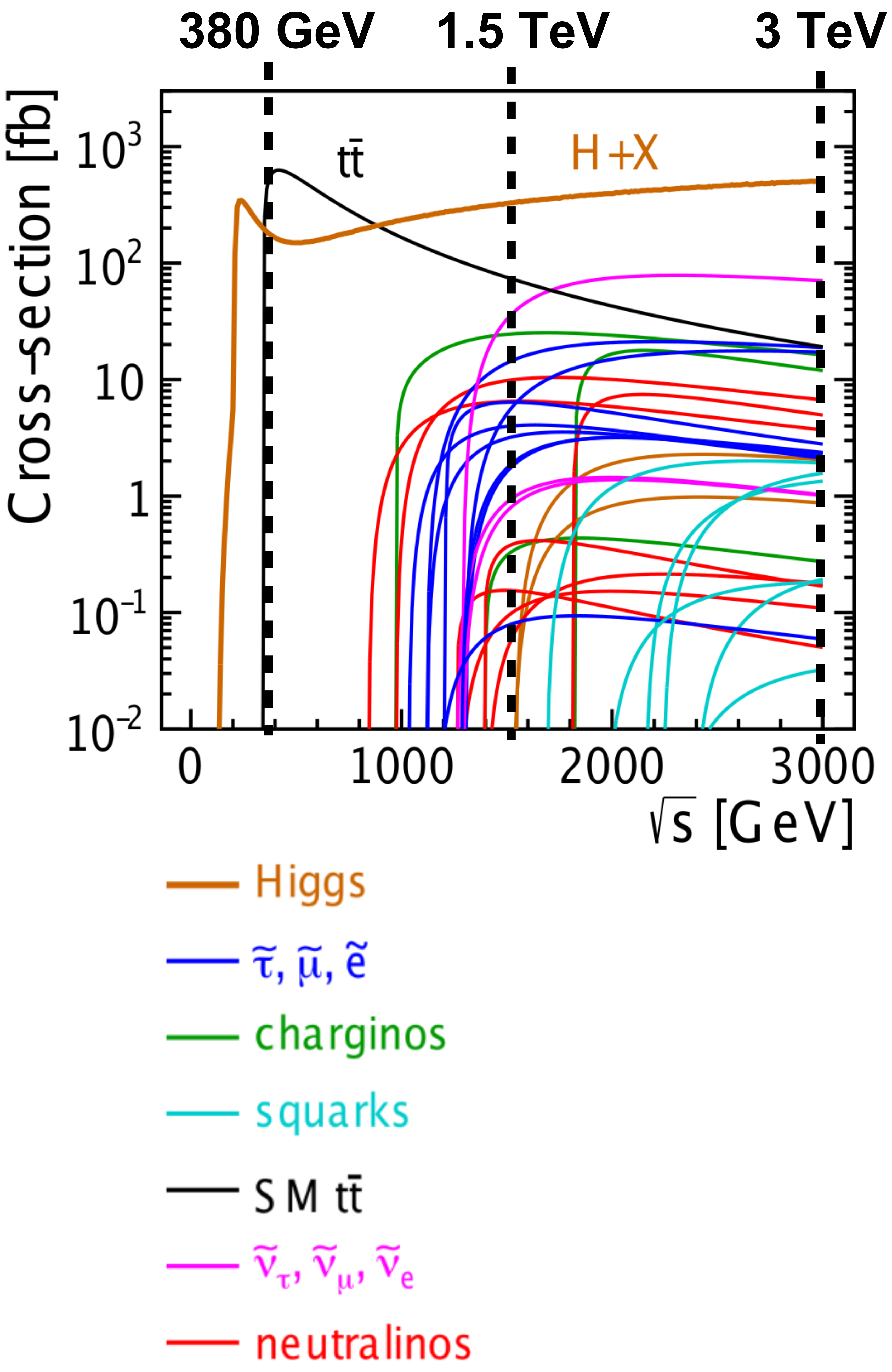
DIRECT SEARCH FOR BSM PHYSICS AT e^+e^- COLLIDERS



Feebly coupled particles:
ALPS, DarkPhotons, HNL

Dark Matter via Z/H portal

Direct Production of
heavy new particles
(SUSY, Composite Higgs,…)

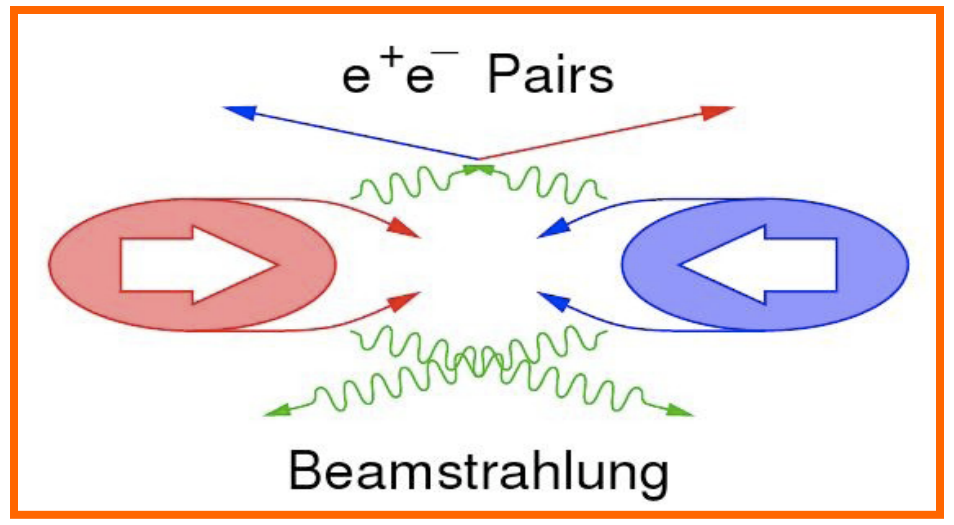


SUSY DIRECT SEARCHES AT CLIC

- Direct observation of new particles coupling to $\gamma^*/Z/W$
  - **Precision measurement** of new particle masses and couplings
  - Sensitivity often extends up to the **kinematic limit** (e.g. $M \leq \sqrt{s}/2$ for pair production)
  - Very rare processes accessible due to low background (no QCD): especially EWK states!
  - **Polarised electron beams and threshold scan** might be useful to constrain and characterise the underlying theory

CLIC ACCELERATOR ENVIRONMENT

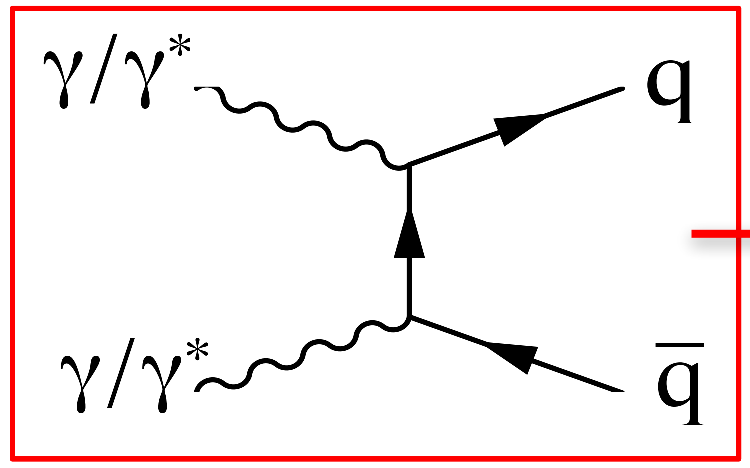
Going to higher energy comes with a price



Beam-beam background at IP:

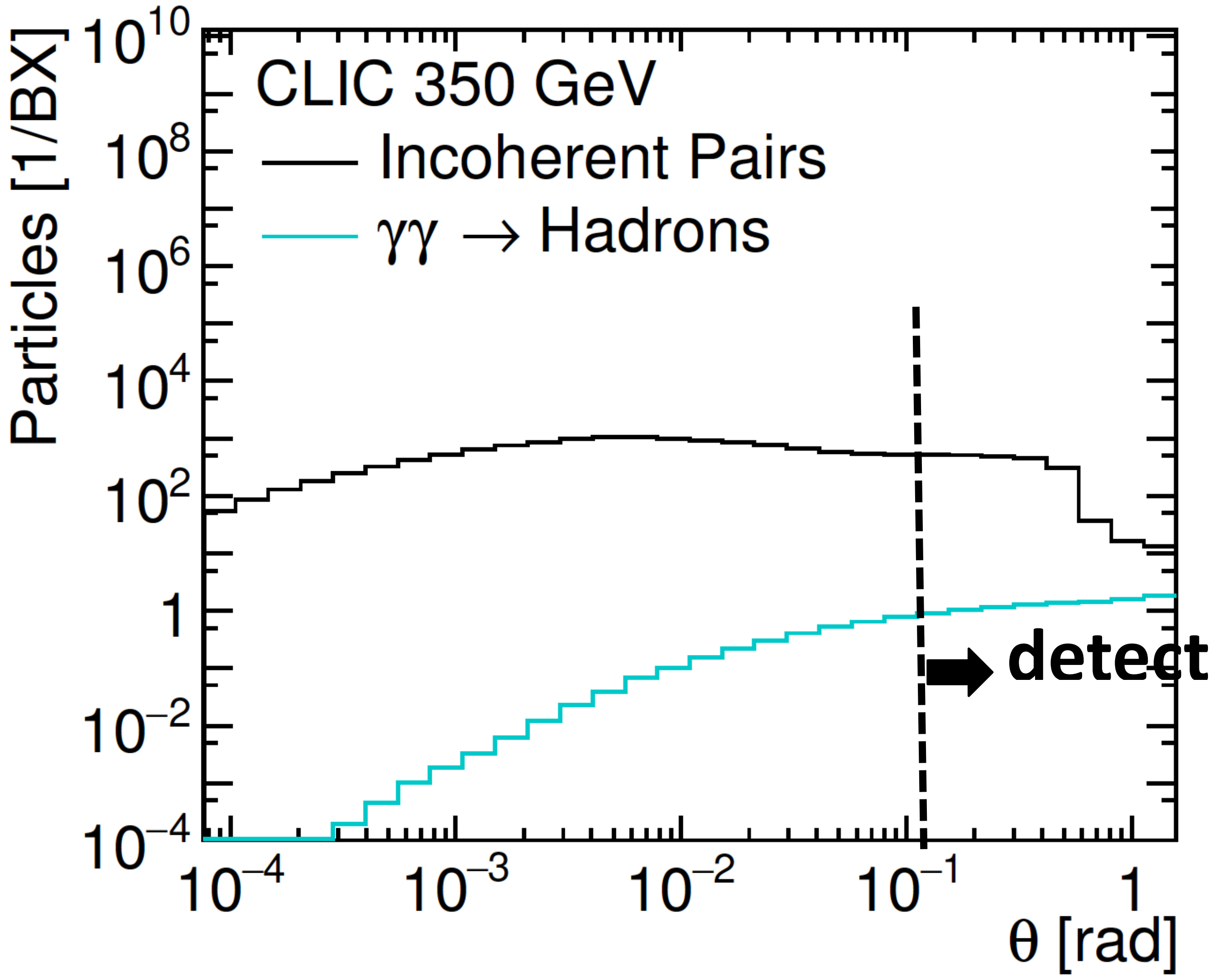
- Small beams => very high E-fields
  - ♦ **Beamstrahlung**
  - ♦ **Pair-background** → Simplified picture: Design issue (small cell sizes)
    - ♦ High occupancies

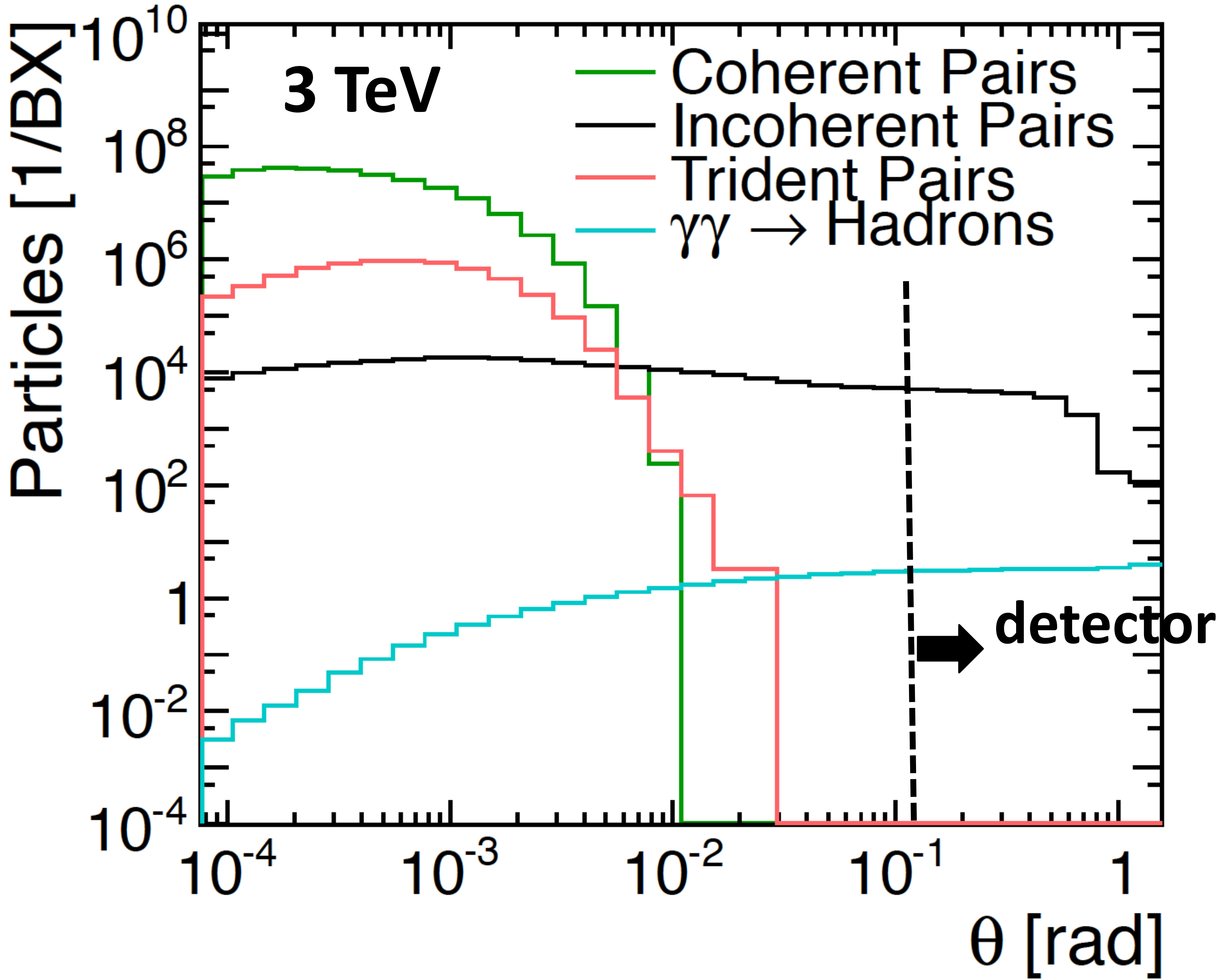
High granularity



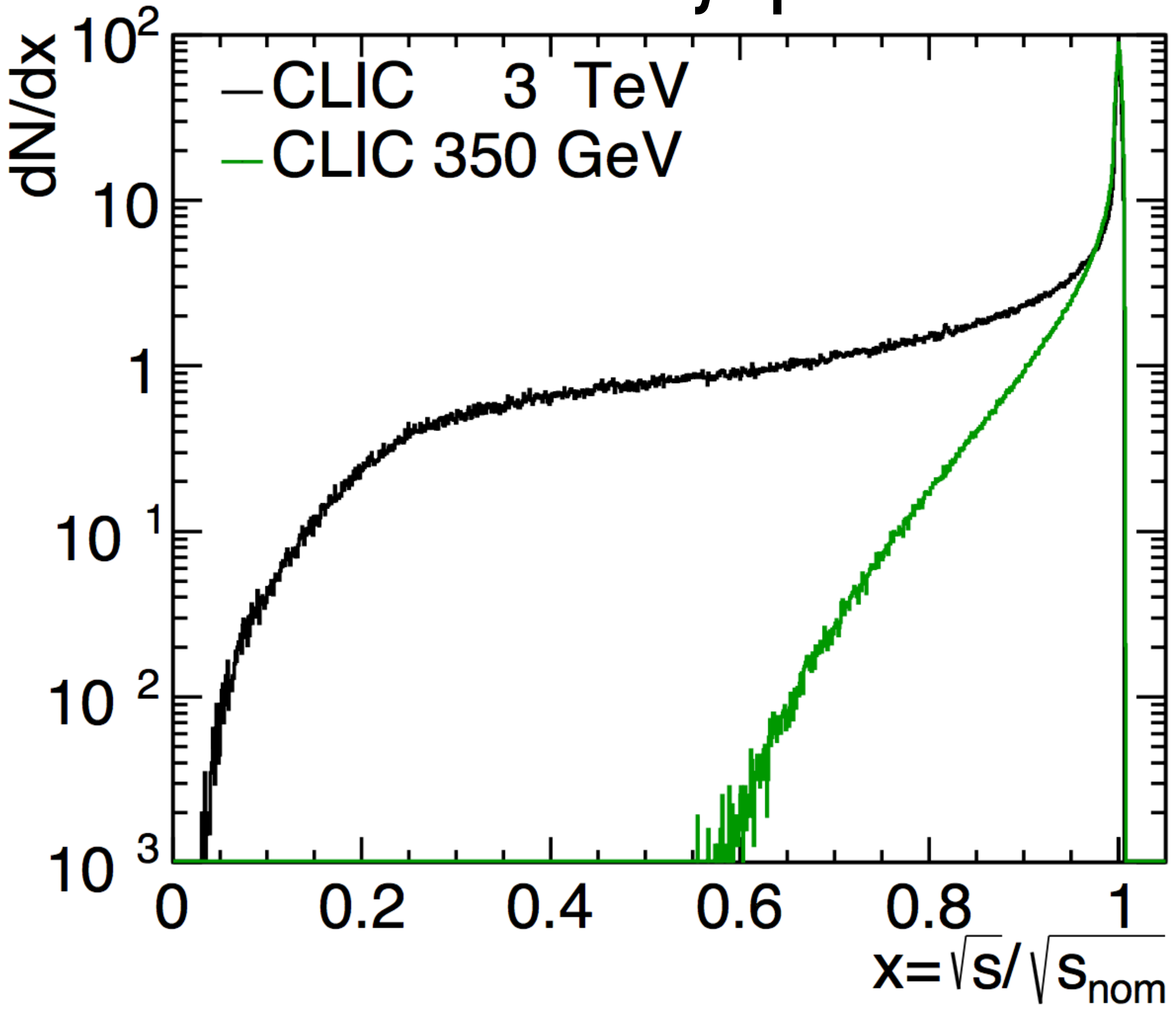
- ♦ **γγ to hadrons** → Impacts on the physics
  - ♦ Energy deposits

Needs suppression in data





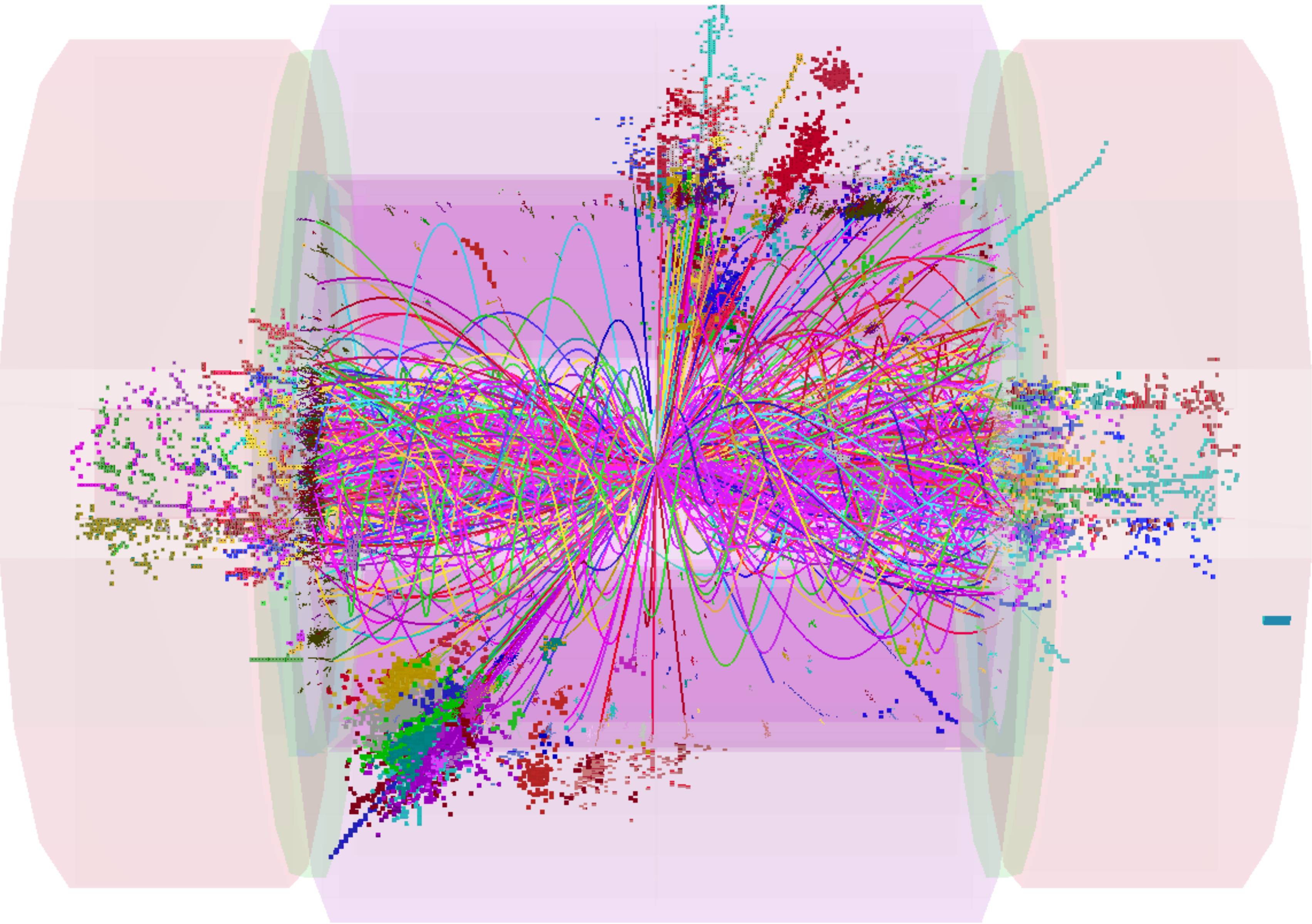
Luminosity Spectrum



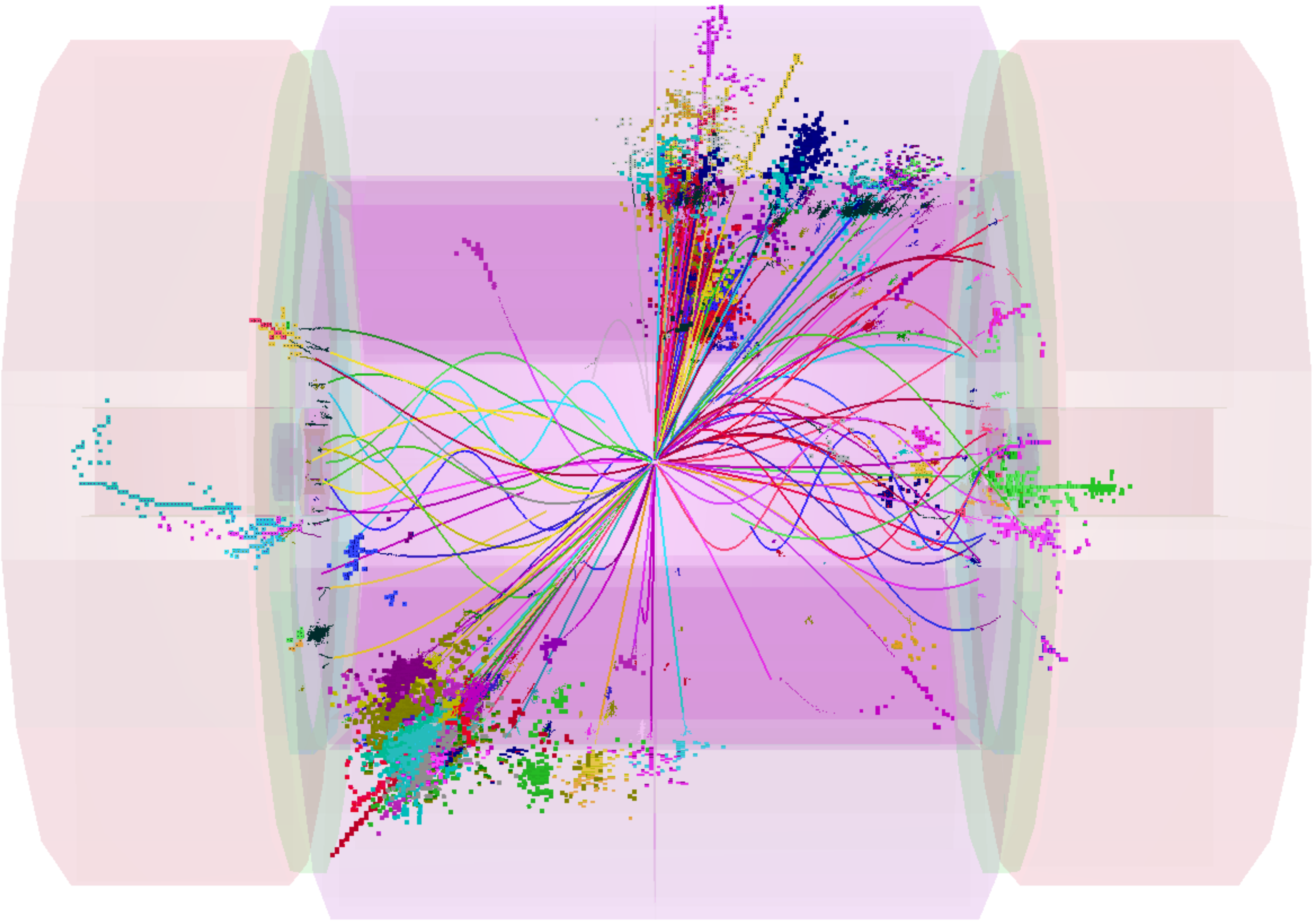
CLIC BEAM-INDUCED BACKGROUND REJECTION

Beam-induced background from γγ → hadrons can be efficiently suppressed by applying ***p_t* cuts and timing cuts on individually reconstructed particles** (particle flow objects)

1.2 TeV



100 GeV



$$e^+e^- \to H^+H^- \to t\bar{b}b\bar{t} \to 8\ \mathrm{jets}$$

1.2 TeV background in reconstruction window (>=10 ns) around main physics event

100 GeV background after tight cuts

FUTURE PROSPECTS FOR SEARCHES - SUSY

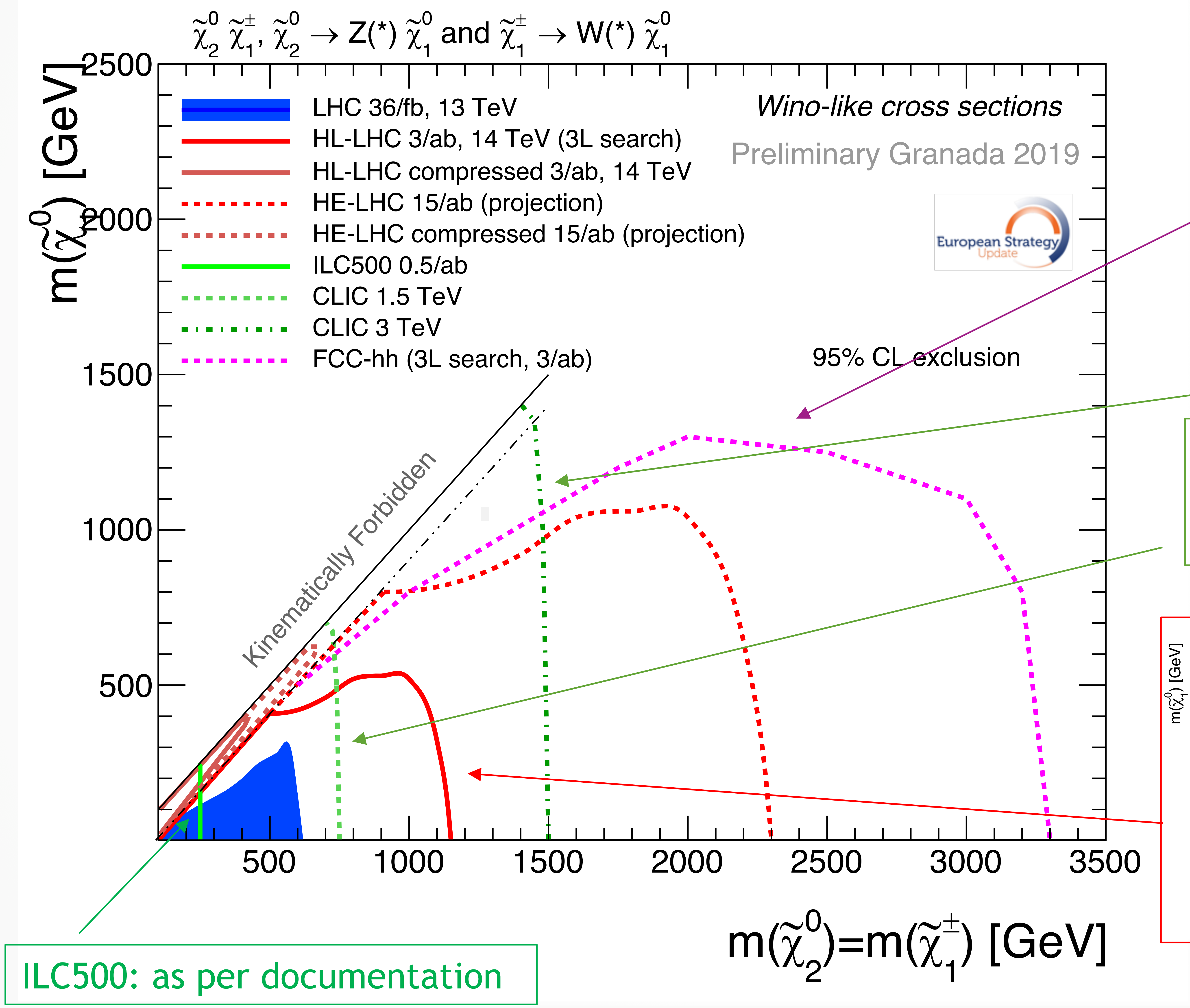
- Many variants to be considered (MSSM, NMSSM, gauge mediation, stealth…)
  - phenomenology depends on the model and sparticle mass hierarchy
- **Strong Production** (gluino, 1st and 2nd generation squarks, top squarks: dominated by hadron colliders.
- **Lepton Colliders help in the case of compressed scenarios**
- **Weak production** (charginos, neutralinos, sleptons): complementarities among colliders (compressed scenarios)
  - **Lepton colliders help for the EWKino (softer final states)**
  - R-Parity conserving SUSY considered here (i.e. R-parity prevents the decay of the lowest neutralino to SM particles, gives rise to missing energy in the final state)

SUSY - CHARGINO & NEUTRALINO PHENOMENOLOGY

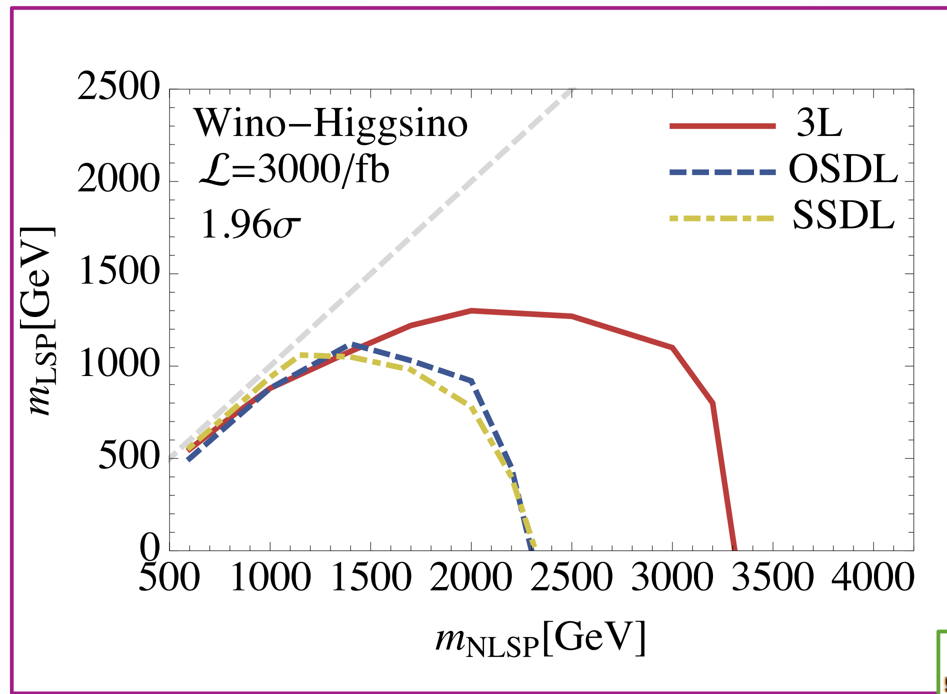
- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature

- ➤ For lepton colliders the dominant processes are $e^+e^- \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0\tilde{\chi}_1^0$.
- ➤ The large mass difference bewteen the LSP and the NSLP allows to exploit multi-leptons final states.
- ➤ Often leptons are low-pt. Compressed spectra can be exploited at hadron colliders with the use of leptons recoiling against an ISR jet.
- ➤ Lepton colliders are competitive in these cases: sensitive to $\Delta m \approx \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ as low as 1 GeV

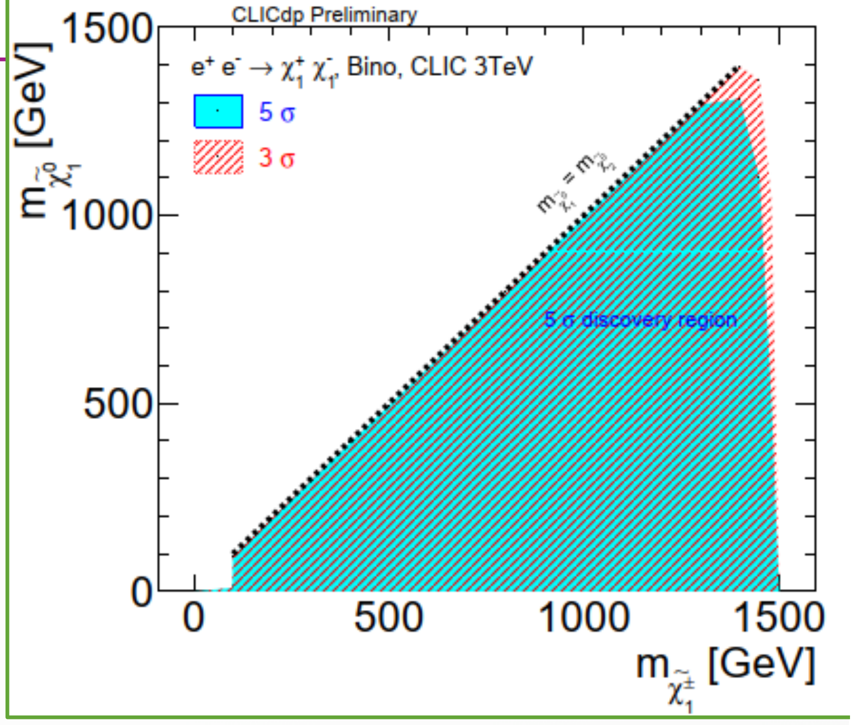
Wino-like cross section: $\chi^{\pm}_1\chi^0_2$



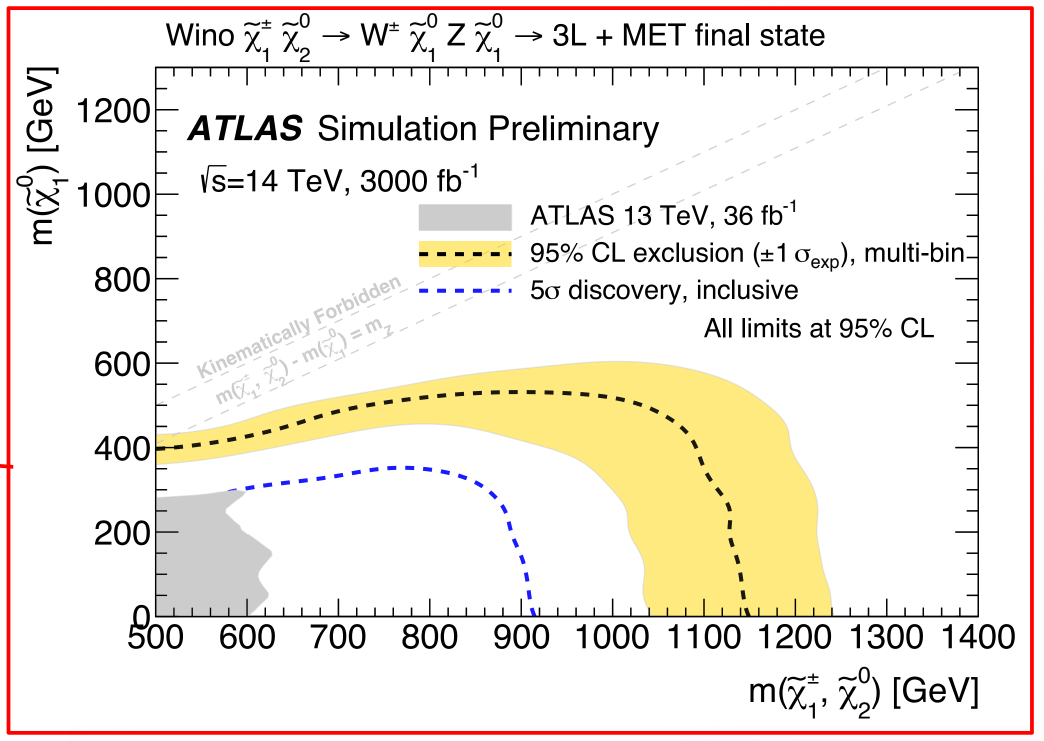
ILC500: as per documentation



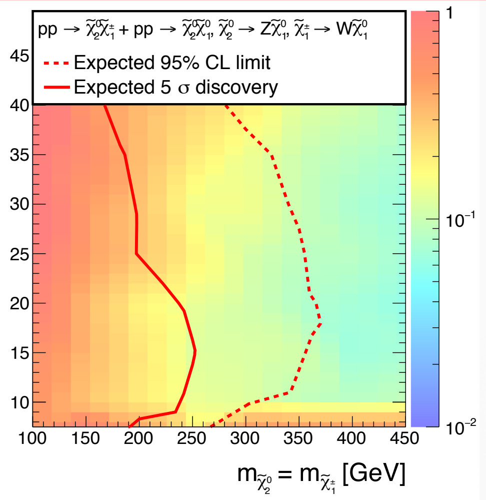
FCC-hh Contour of the 3-lepton search



CLIC: Assume reach for $\chi^+_1\chi^-_1$ and $\chi^{\pm}_1\chi^0_2$. CLIC 1.5 TeV reach / 2 up to ΔM~5 GeV



HL-LHC compressed: reinterpretation of higgsino $\chi^{\pm}_1\chi^0_2$ results



HE-LHC → projections with ColliderTool Reach

GAUGINO SEARCH @CLIC : DI-JET FINAL STATES

Chargino and neutralino pair production

$$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 W^+ W^-$$

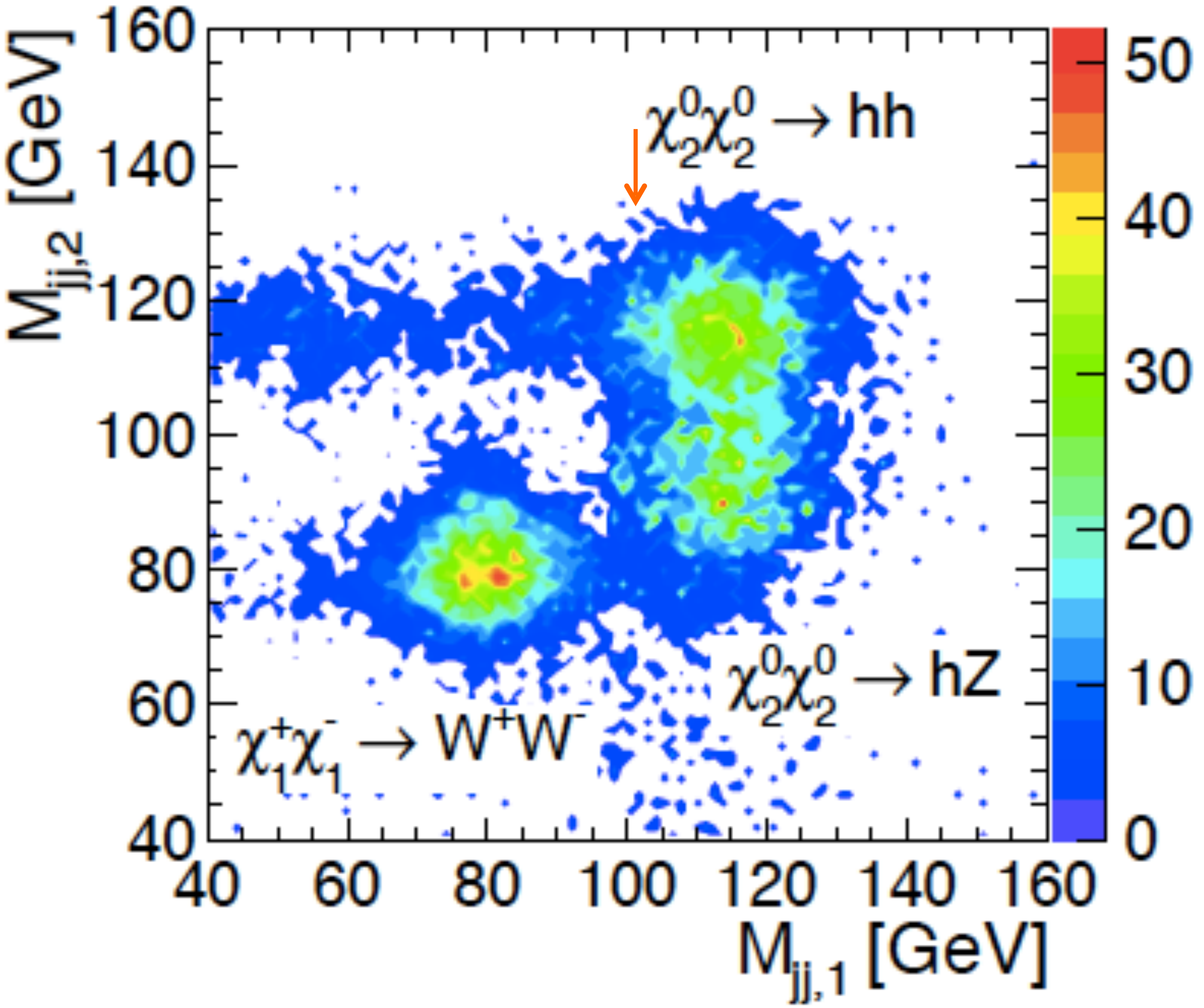
$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow hh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 82\ \%$$

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow Zh\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad 17\ \%$$

- separation using di-jet invariant masses (test of PFA)

$$m(\tilde{\chi}_1^0) = 340\,\mathrm{GeV}$$

$$m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643\,\mathrm{GeV}$$



→

$$m(\tilde{\chi}_1^{\pm}) \ :\ \pm 7\,\mathrm{GeV}$$

$$m(\tilde{\chi}_2^0) \ :\ \pm 10\,\mathrm{GeV}$$

→

use slepton study result

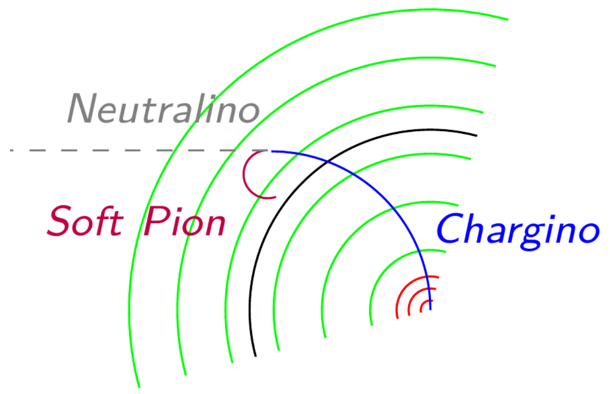
$$m(\tilde{\chi}_1^0) \ :\ \pm 3\,\mathrm{GeV}$$

result: $\Delta m/m \leq 1\%$

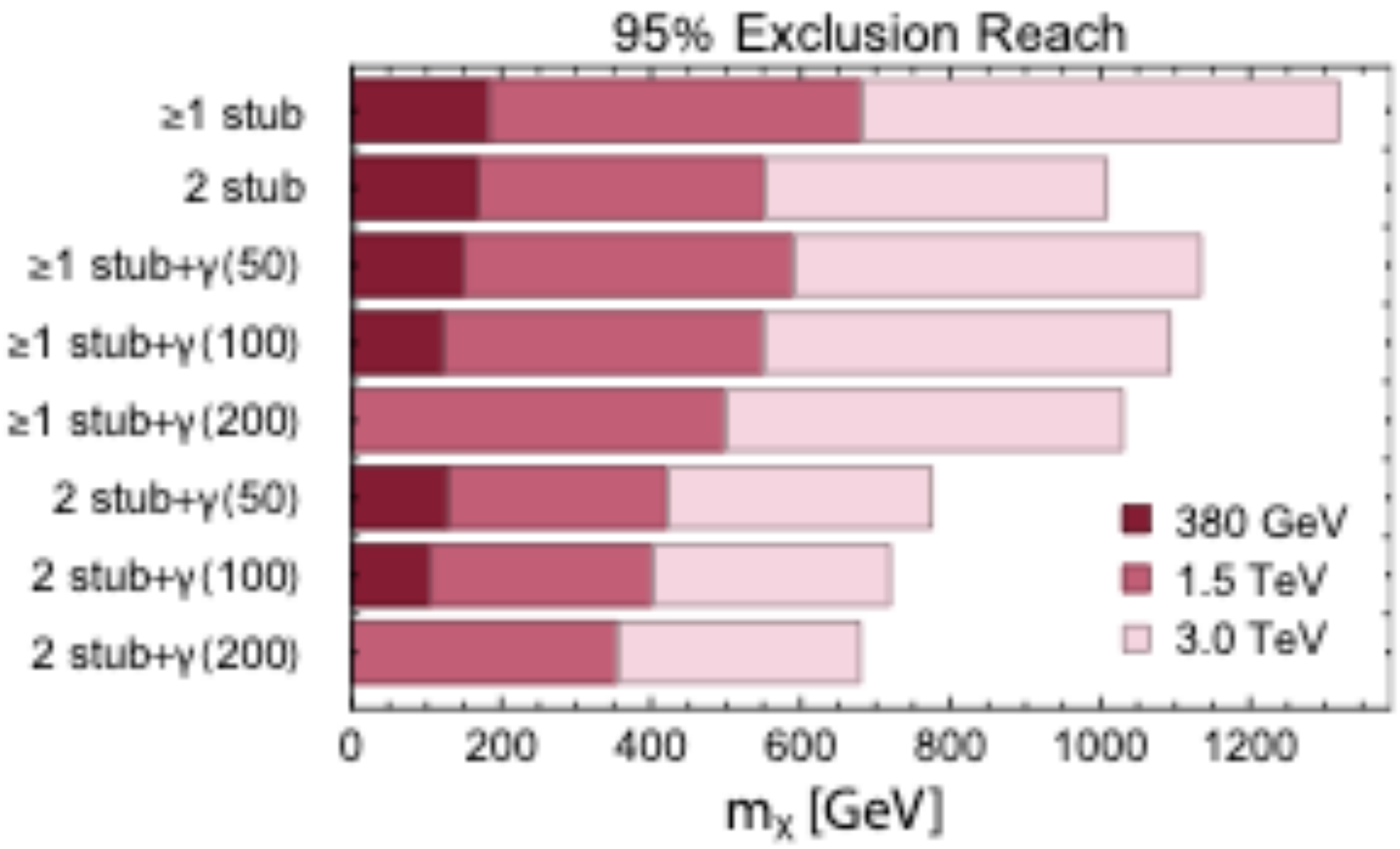
LCD-Note-2011-037

CLIC DISAPPEARING TRACK ANALYSIS

- Process: chargino pair production
- Stub tracks from charged Higgsino with a lifetime of 6.9 mm
- Decay to pion and neutralino



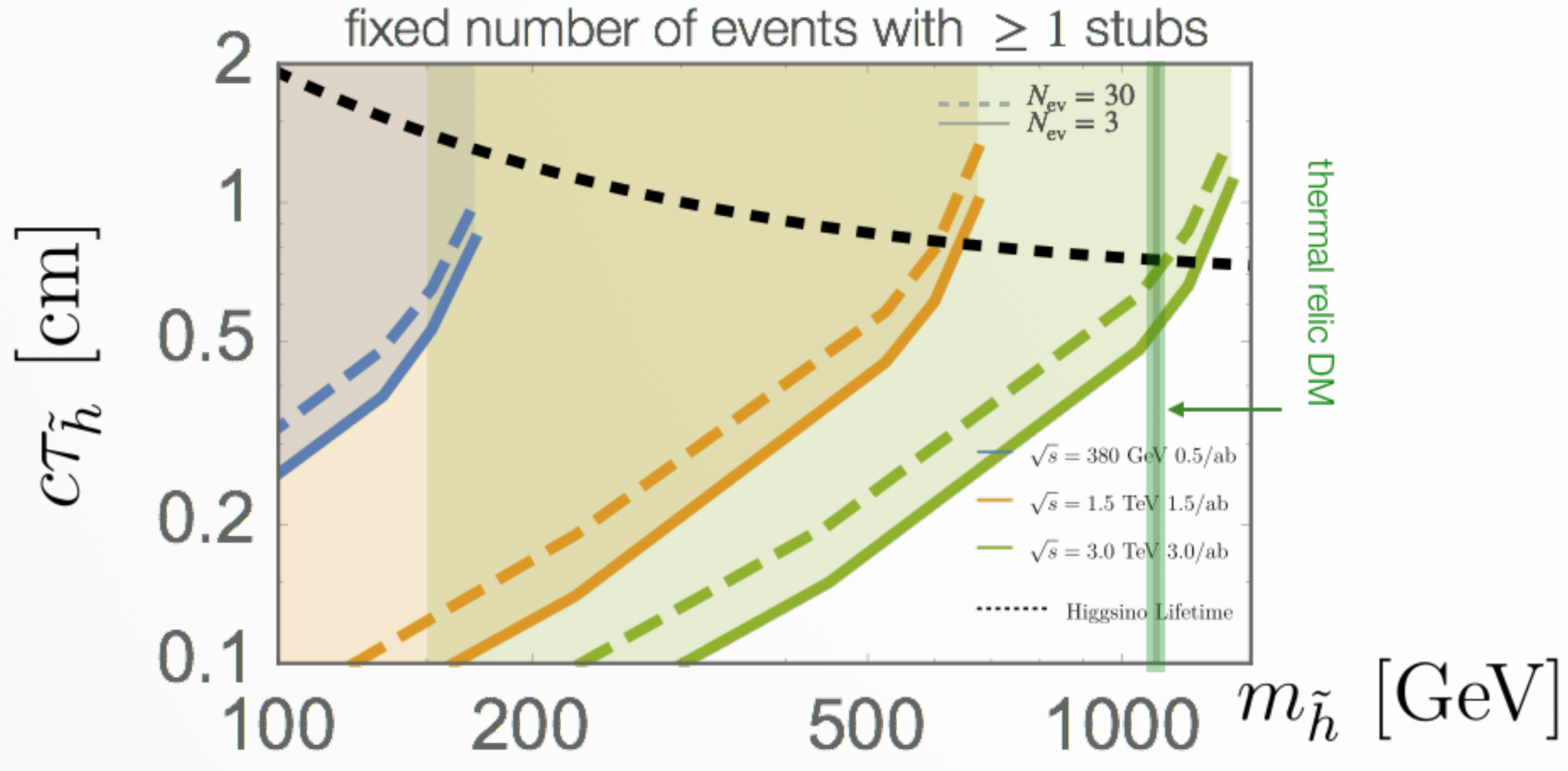
Pure higgsino case

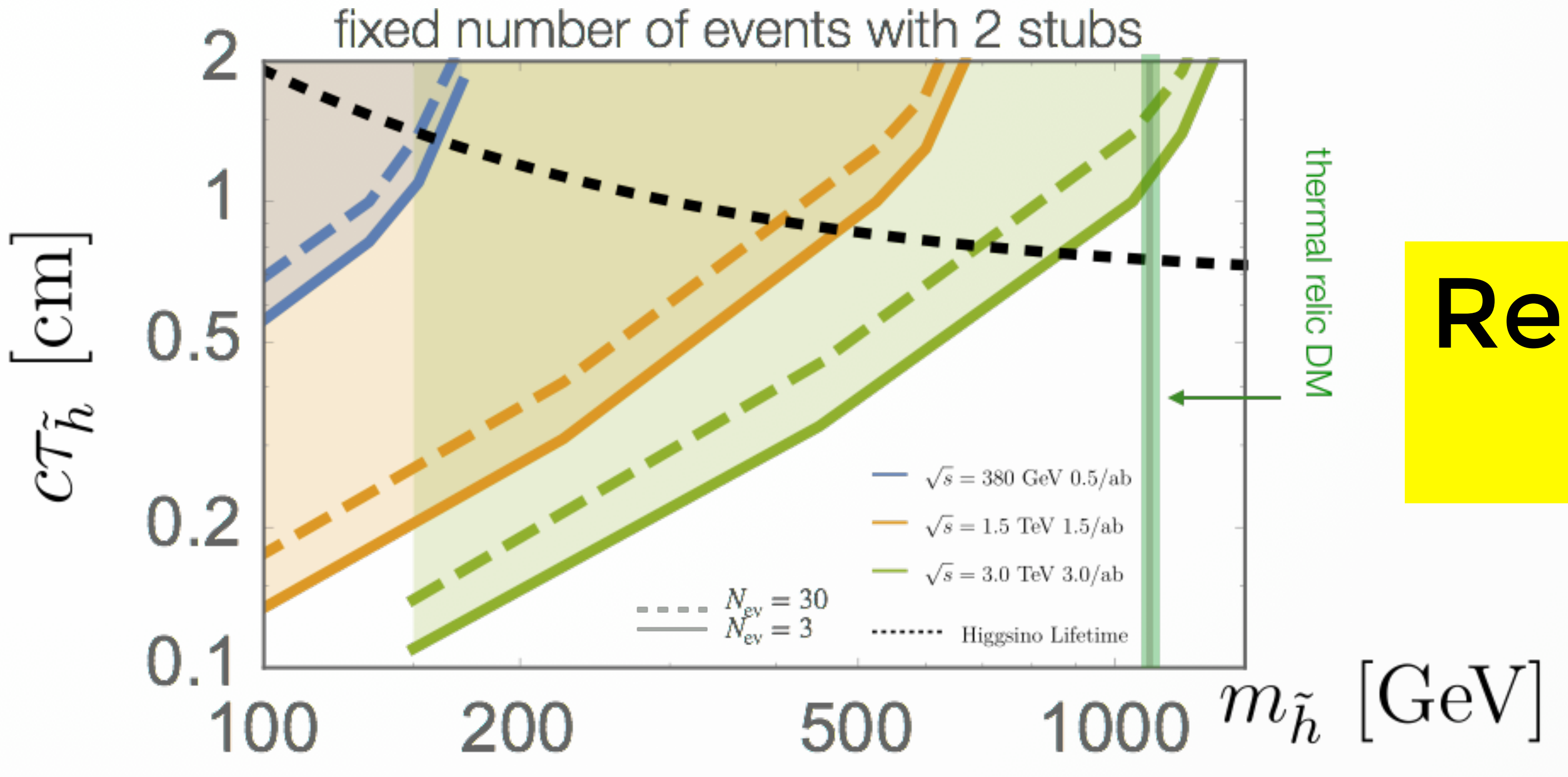


m_χ m_χ

➨ Charged stub + photon analysis

In order to be counted as a charged stub, the χ± must traverse at least 4 layers of the CLIC tracker before decaying.





Require an extra ISR photon

SUMMARY FOR DARK MATTER SEARCHES

From the ESPPU Briefing Book

Terminology applied to Dark Matter analysis taken from SUSY, but these can be considered standalone models

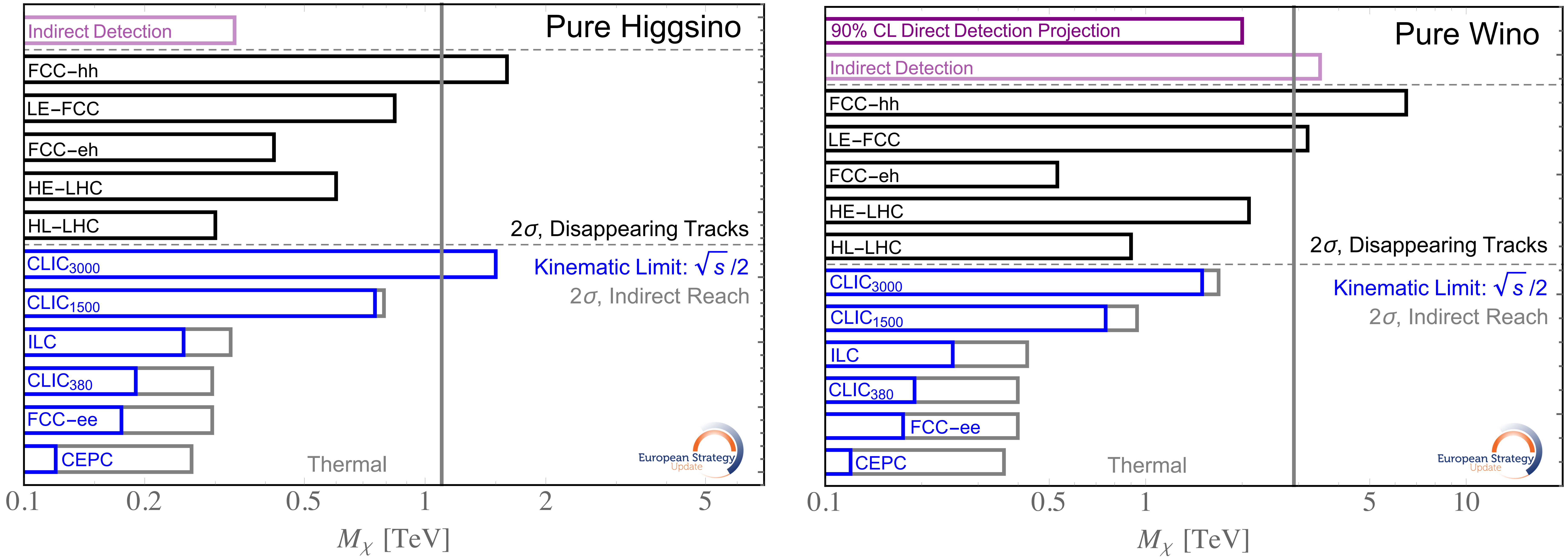


Fig. 8.14: Summary of 2σ sensitivity reach to pure Higgsinos and Winos at future colliders. Current indirect DM detection constraints (which suffer from unknown halo-modelling uncertainties) and projections for future direct DM detection (which suffer from uncertainties on the Wino-nucleon cross section) are also indicated. The vertical line shows the mass corresponding to DM thermal relic.

SUMMARY OF THE DISCOVERY REACH IN THE SUSY EWK SECTOR

- HL-LHC analyses now target also compressed scenarios with soft-lepton + ISR analyses and/or monojet
  - Good prospects, but discovery potential is limited (~ 200 GeV for higgsino-like models)
- ILC500 (→ CLIC 1.5 TeV, 3 TeV) might allow discovery in case deviations are observed at HL-LHC
  - Characterization of the EWK sector possible at e^+e^- for sparticles with masses below ~ sqrt(s)/2
- FCC-hh has certainly a high potential for EWK particles (with mass up to 3-4 TeV)
  - Together with CLIC 3 TeV, FCC-hh could go beyond ~ 1 TeV for higgsino scenarios
- Potential of monojet searches at pp colliders might be further exploited to evaluate exclusion reach. However:
  - What if a deviation in monojet final states is observed at the HL-LHC? → multiple interpretations are possible → additional EWK processes (i.e. from heavier charginos/neutralinos) must be searched for (see some examples in back-up for e+e- and pp).

EXTENDED HIGGS SECTOR

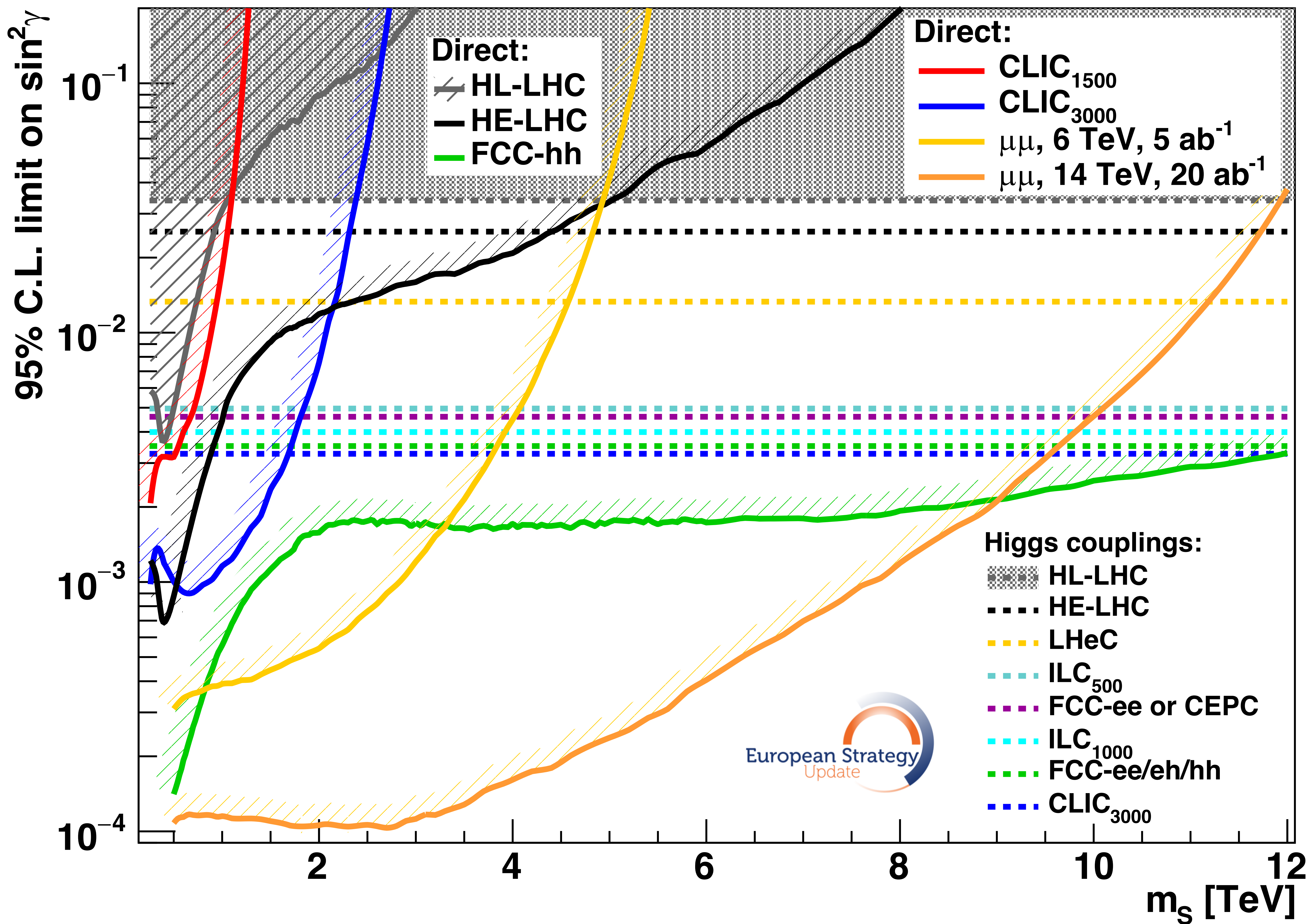
Potential for SM Higgs and a single real scalar

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS}|H|^2 S^2$$

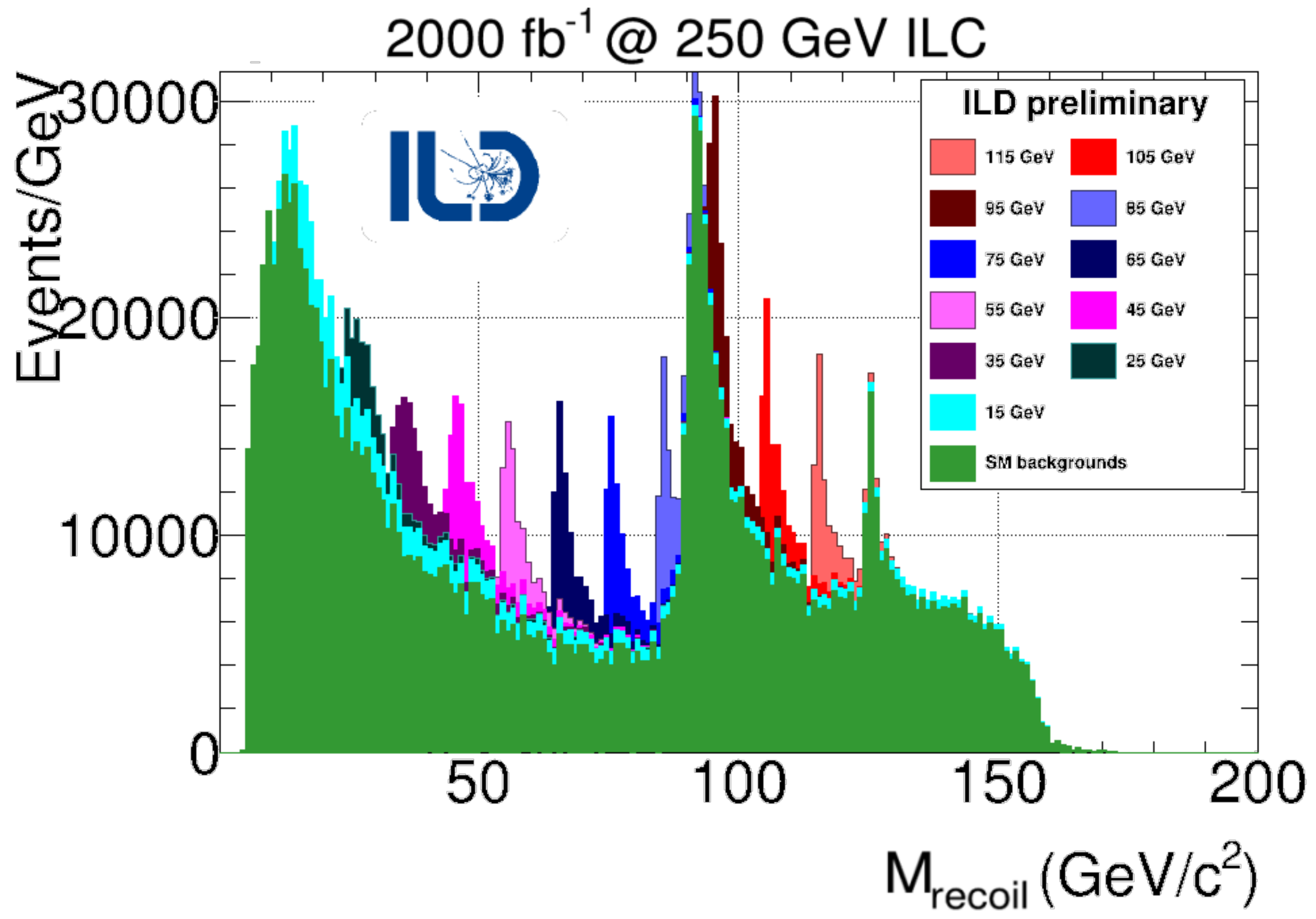
Higgs-singlet mixing:

$h = h_0 \cos\gamma + S \sin\gamma$

$\phi = S \cos\gamma - h_0 \sin\gamma$

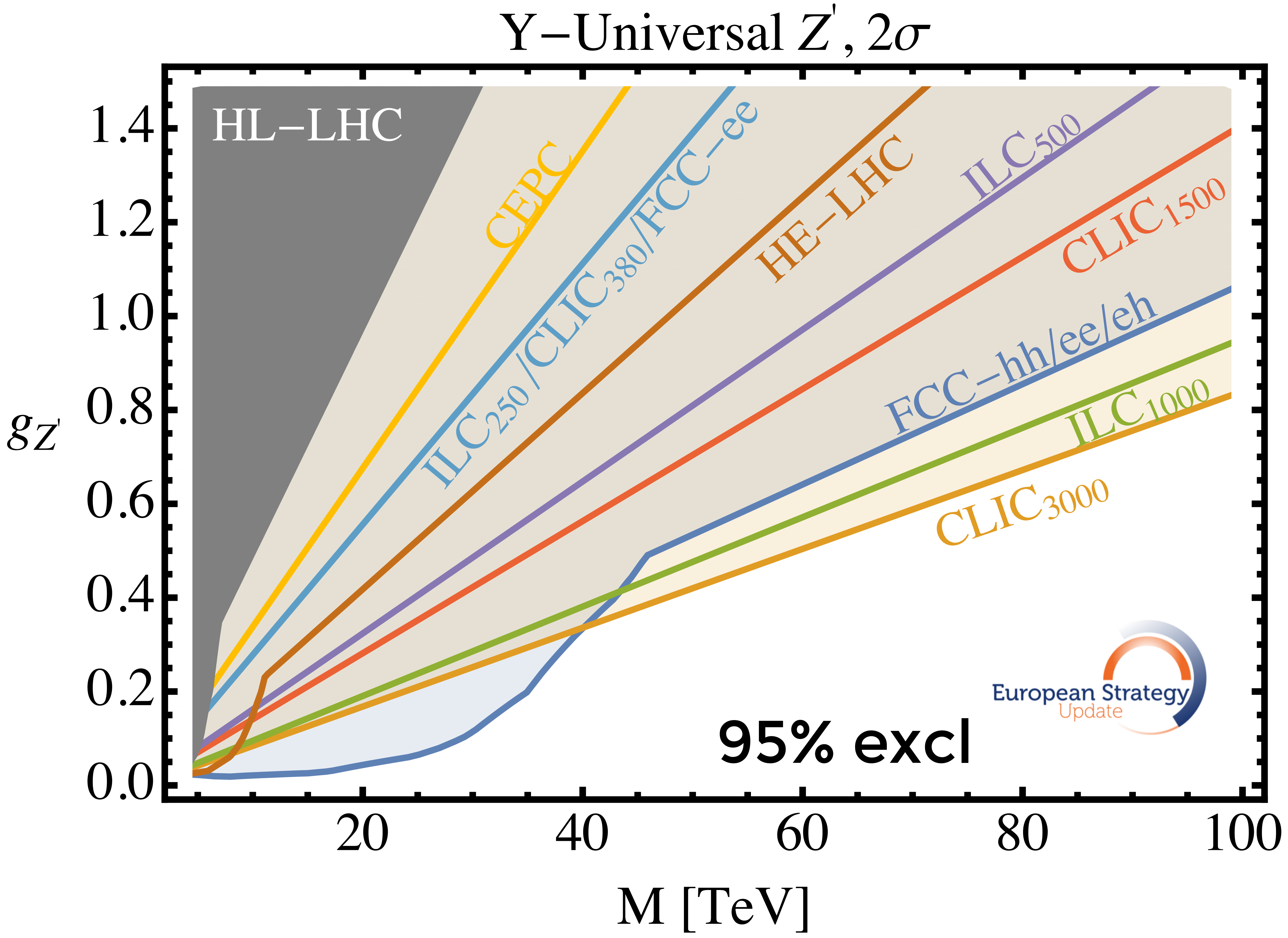


Can always be searched using the recoil technique



EXO SEARCHES - THE UNIVERSAL Z’ MODEL

- Model consists of a neutral gauge boson Z’ with mass M and charges to the SM particles equal to the hypercharge.
- The coupling $g_{Z'}$ is a free parameter.
- Model chosen by the EPSSU for comparison of future colliders as couplings to quarks and leptons are similar (also bc connected to one EFT operator that is available for all colliders)



Straight lines: indirect limits, better at higher g.
Better with higher energy machines

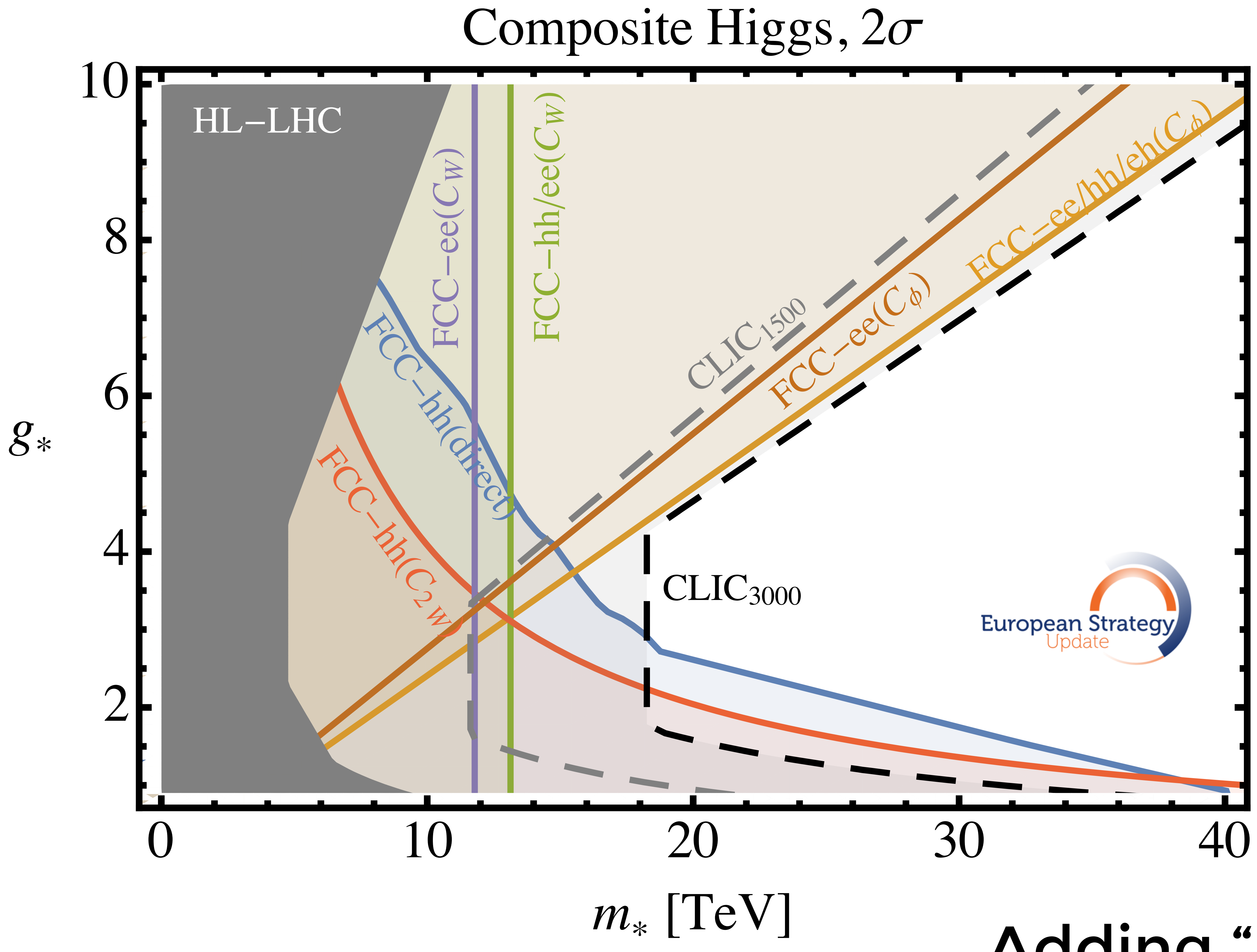
Curved contour: direct limit

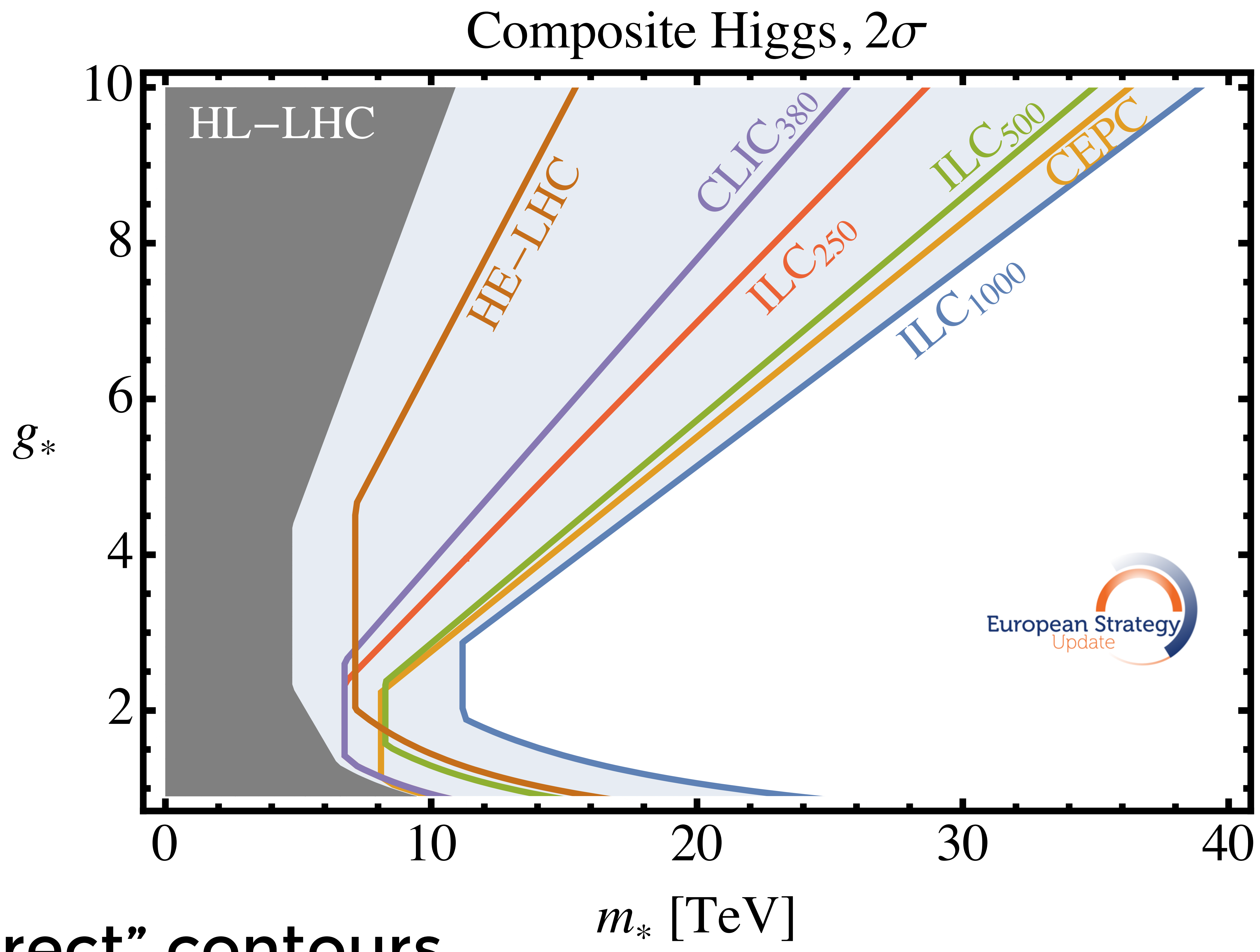
- **Strongly coupled new physics is better probed indirectly**

COMPOSITE HIGGS MODEL SUMMARY

- Higgs as a bound state of a new strongly-interacting confining Composite Sector. Parameters: mass scale m* (compositness scale) and coupling g*
- Note: $\ell_H = 1/m^*$ (« size » of the composite Higgs)

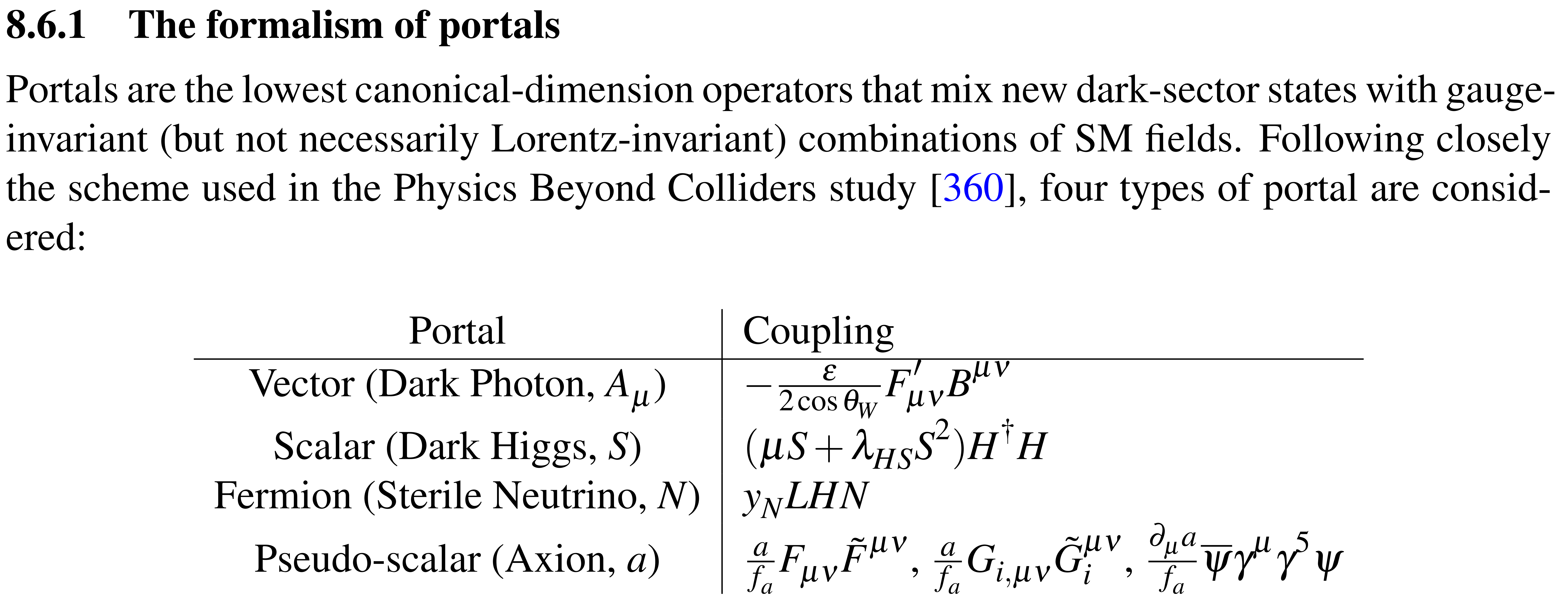
95% exclusion limits





Adding “direct” contours

DARK MATTER SEARCH - THE “PORTALS”



8.6.1 The formalism of portals

Portals are the lowest canonical-dimension operators that mix new dark-sector states with gauge-invariant (but not necessarily Lorentz-invariant) combinations of SM fields. Following closely the scheme used in the Physics Beyond Colliders study [360], four types of portal are considered:

Portal	Coupling
Vector (Dark Photon, A_μ)	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion (Sterile Neutrino, N)	$y_N LHN$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$

SUMMARY OF DARK PHOTON SENSITIVIES

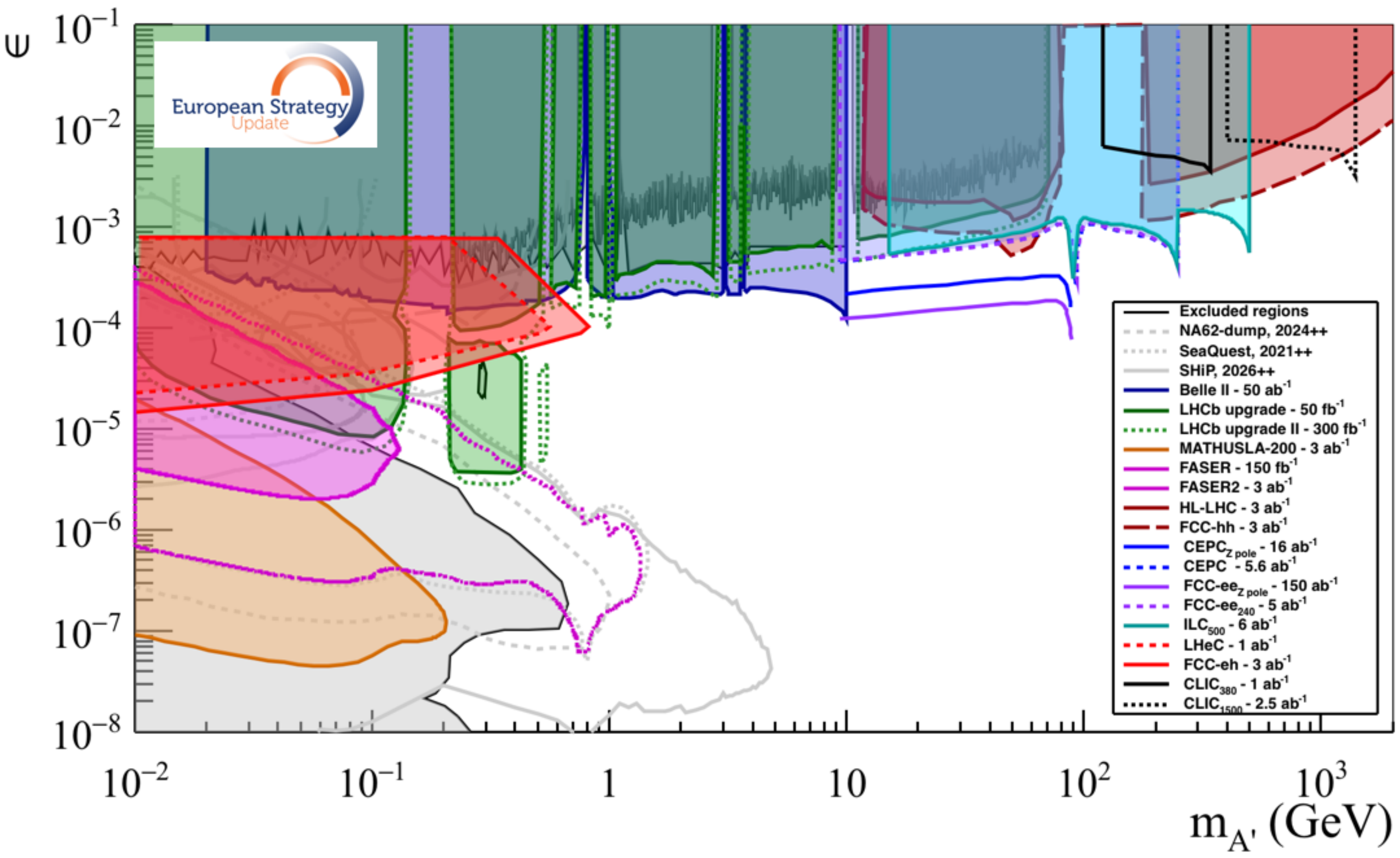
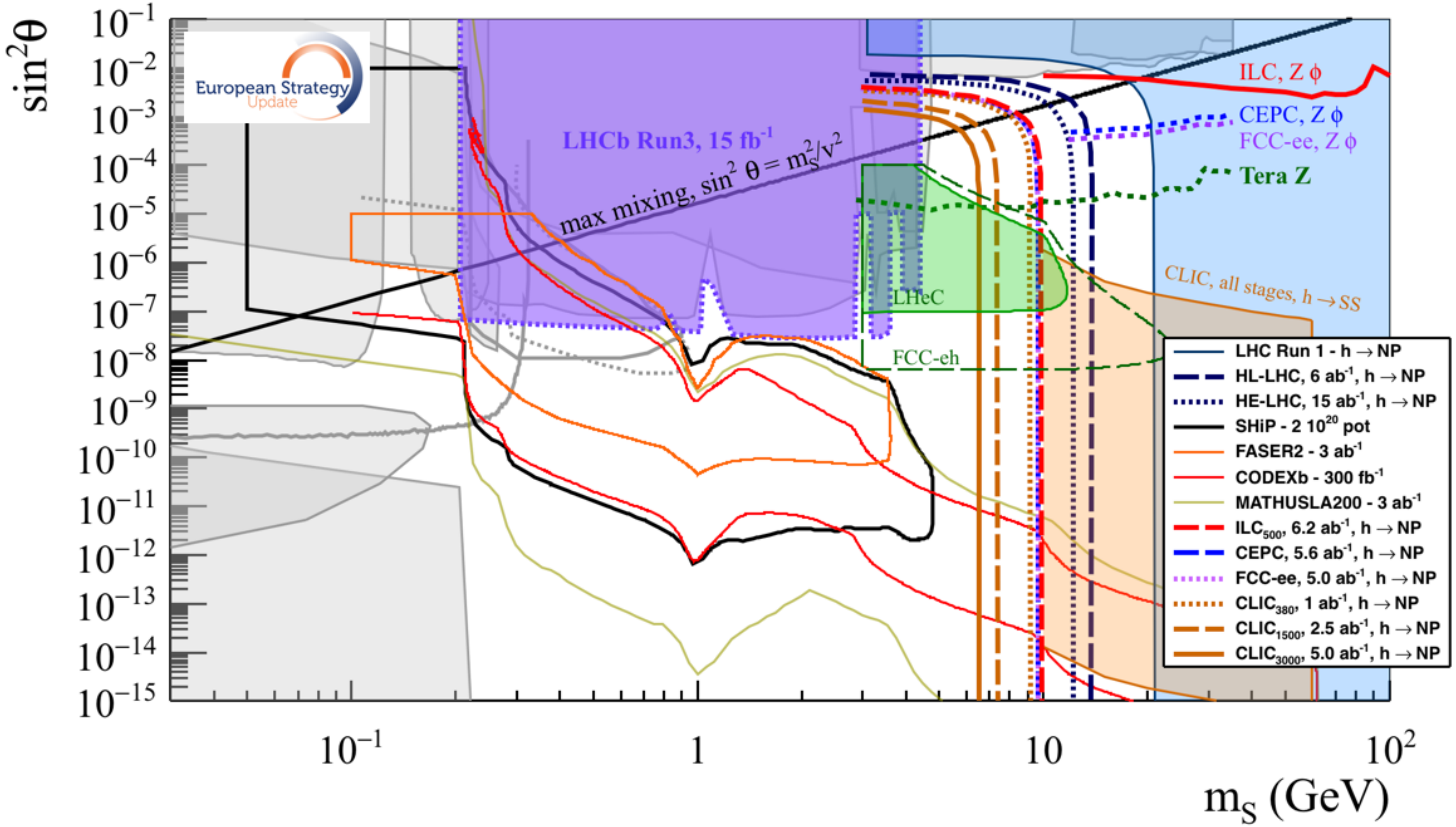


Fig. 8.16: Sensitivity for Dark Photons in the plane mixing parameter ε versus Dark Photon mass. HL-LHC, CEPC, FCC-ee and FCC-hh curves correspond to 95% CL exclusion limits, LHeC and FCC-eh curves correspond to the observation of 10 signal events, and all other curves are expressed as 90% CL exclusion limits. The sensitivity of future colliders, mostly covers the large-mass, large-coupling range, and is fully complementary to the the low-mass, very low-coupling regime where beam-dump and fixed-target experiments are most sensitive.

Dilepton resonances

Also LC can be used as "beam dump" experiment for these types of searches

SUMMARY OF DARK SCALAR SENSITIVITIES

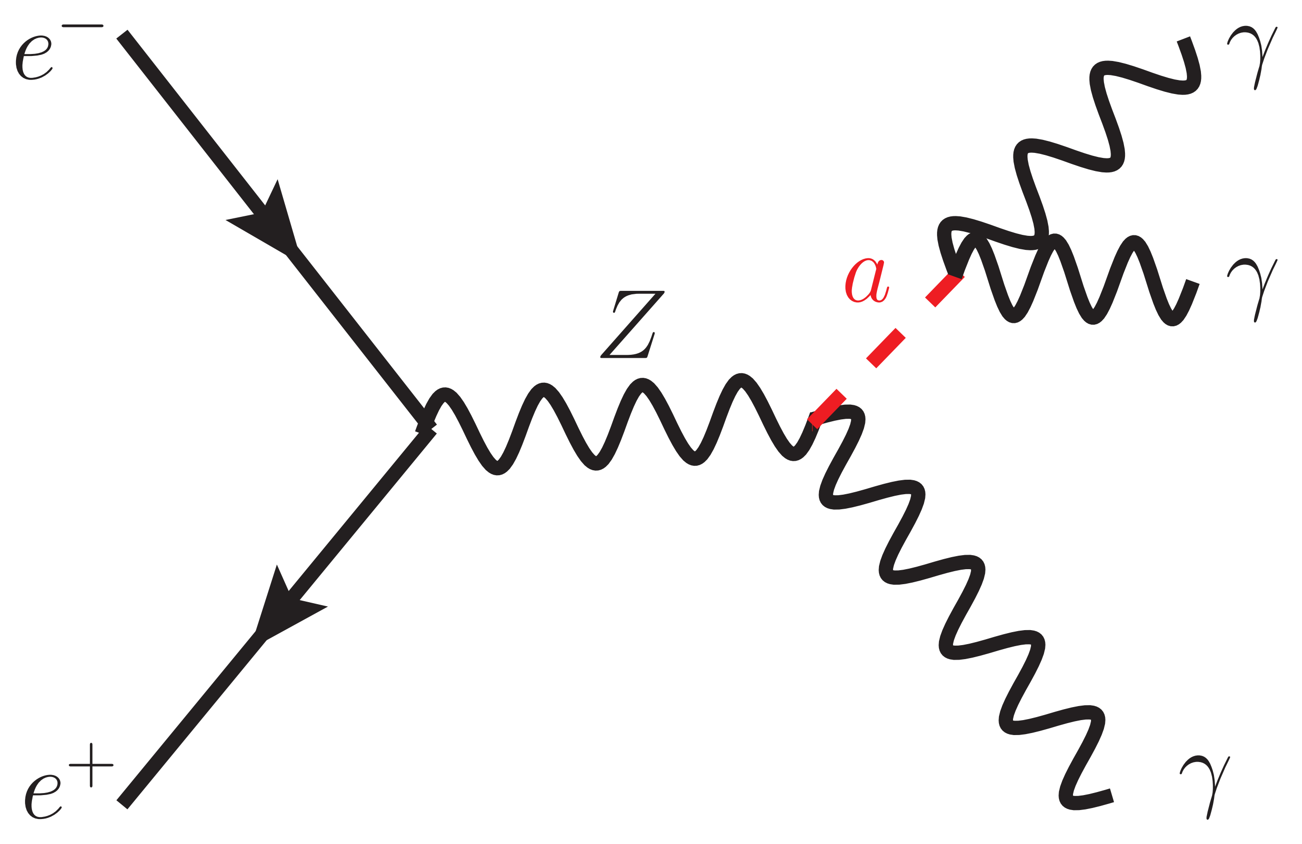


Displaced vertex+

Recoil method

Fig. 8.17: Exclusion limits for a Dark Scalar mixing with the Higgs boson. LHeC, FCC-eh, CLIC (all stages) curves and the vertical lines correspond to 95% CL exclusion limits, while all others to 90% CL exclusion limits. See text for details.

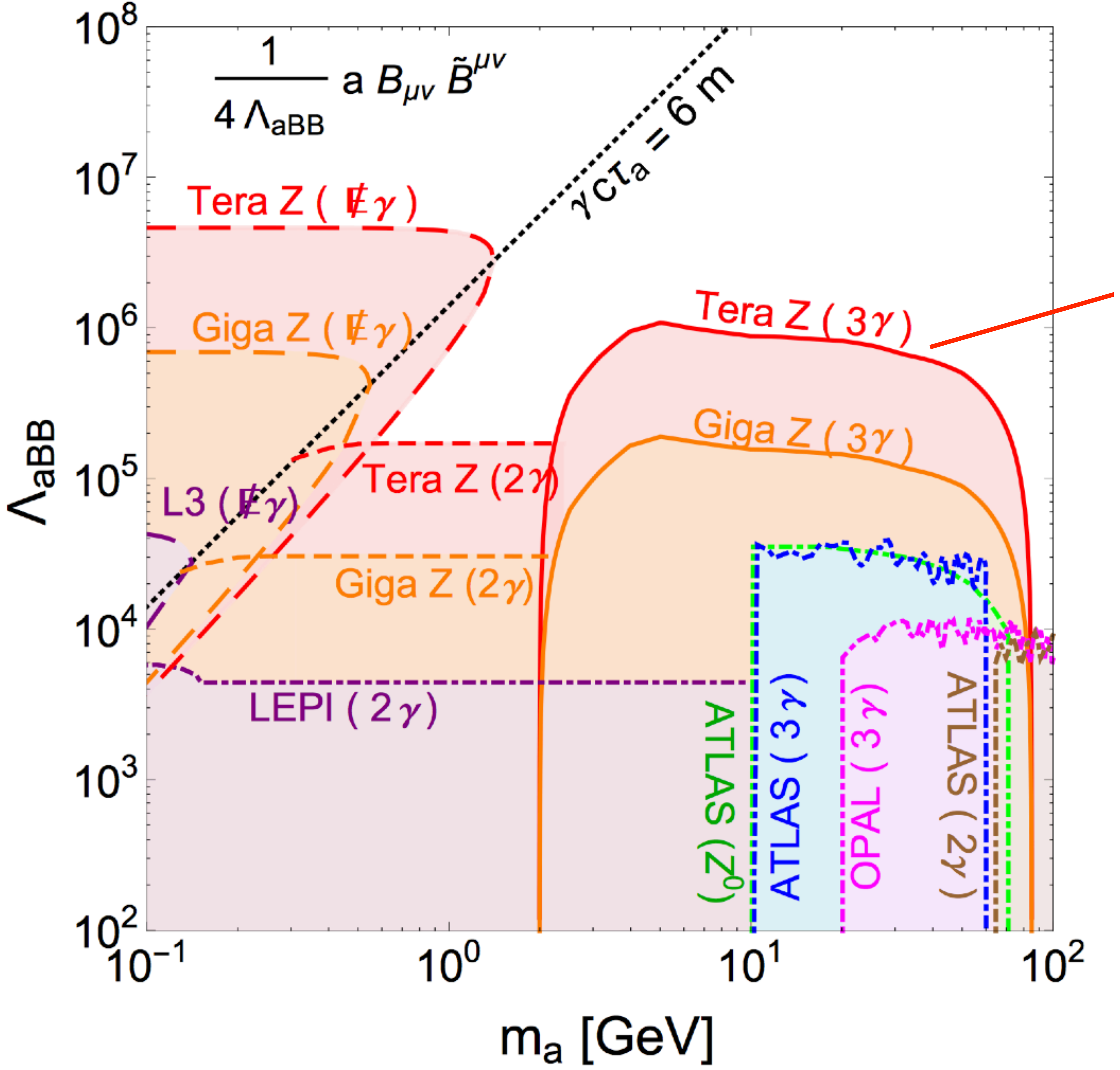
ALPS MASS AND SIGNATURES



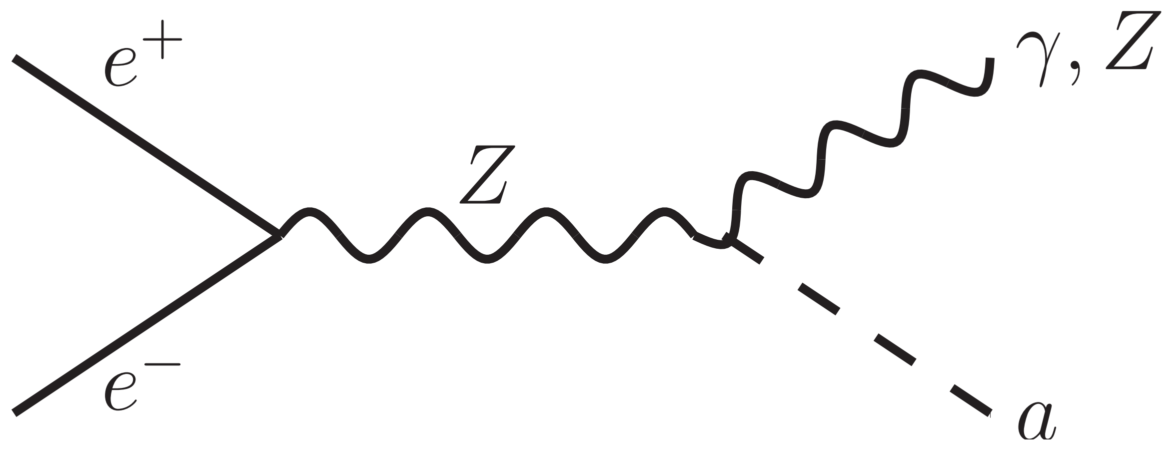
$$\mathcal{L}_{\text{ALP}} = \frac{1}{4\Lambda_{aBB}} a B_{\mu\nu} \tilde{B}^{\mu\nu} \ ,$$

- ➡ γ + E_{MISS} for very light a
- ➡ γγ for light a
- ➡ γγγ for heavier a

Liu Wang Wang Xue 1712.07237

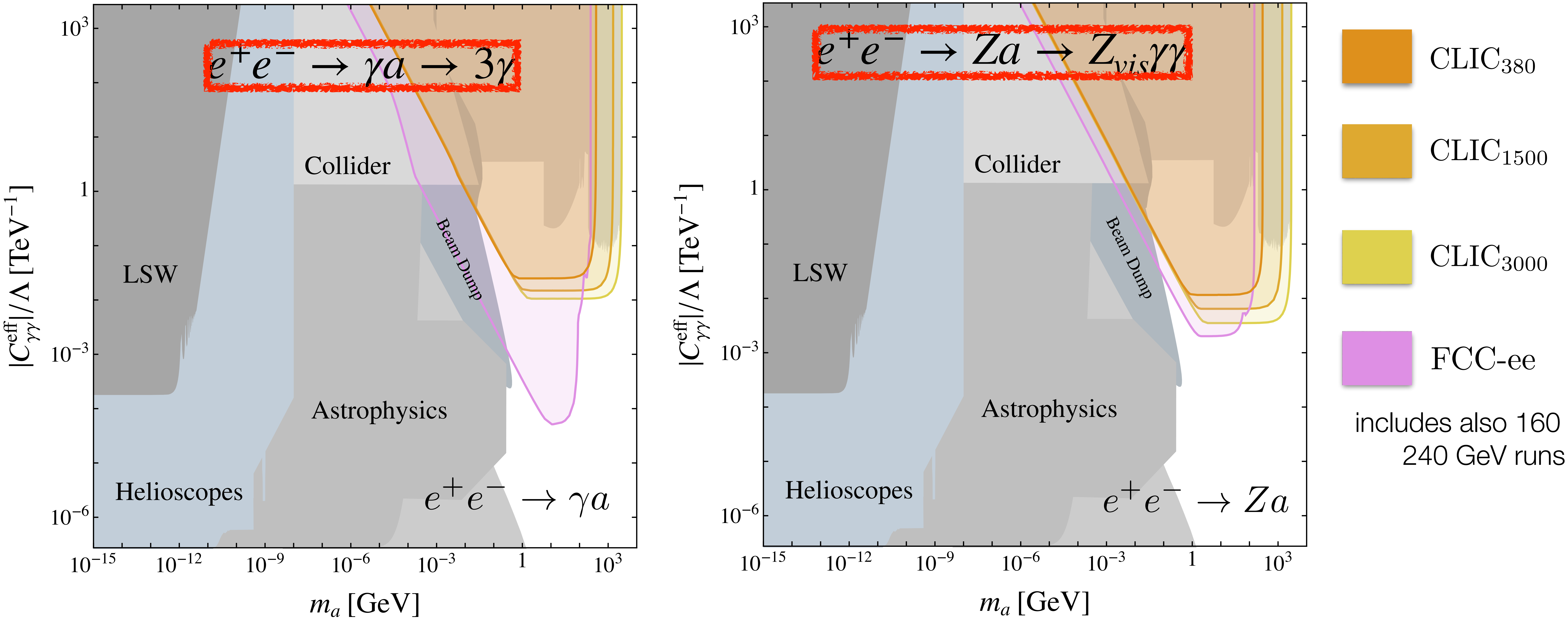


SEARCH AT FUTURE ee COLLIDERS



$a \to \gamma\gamma$ with BR=1

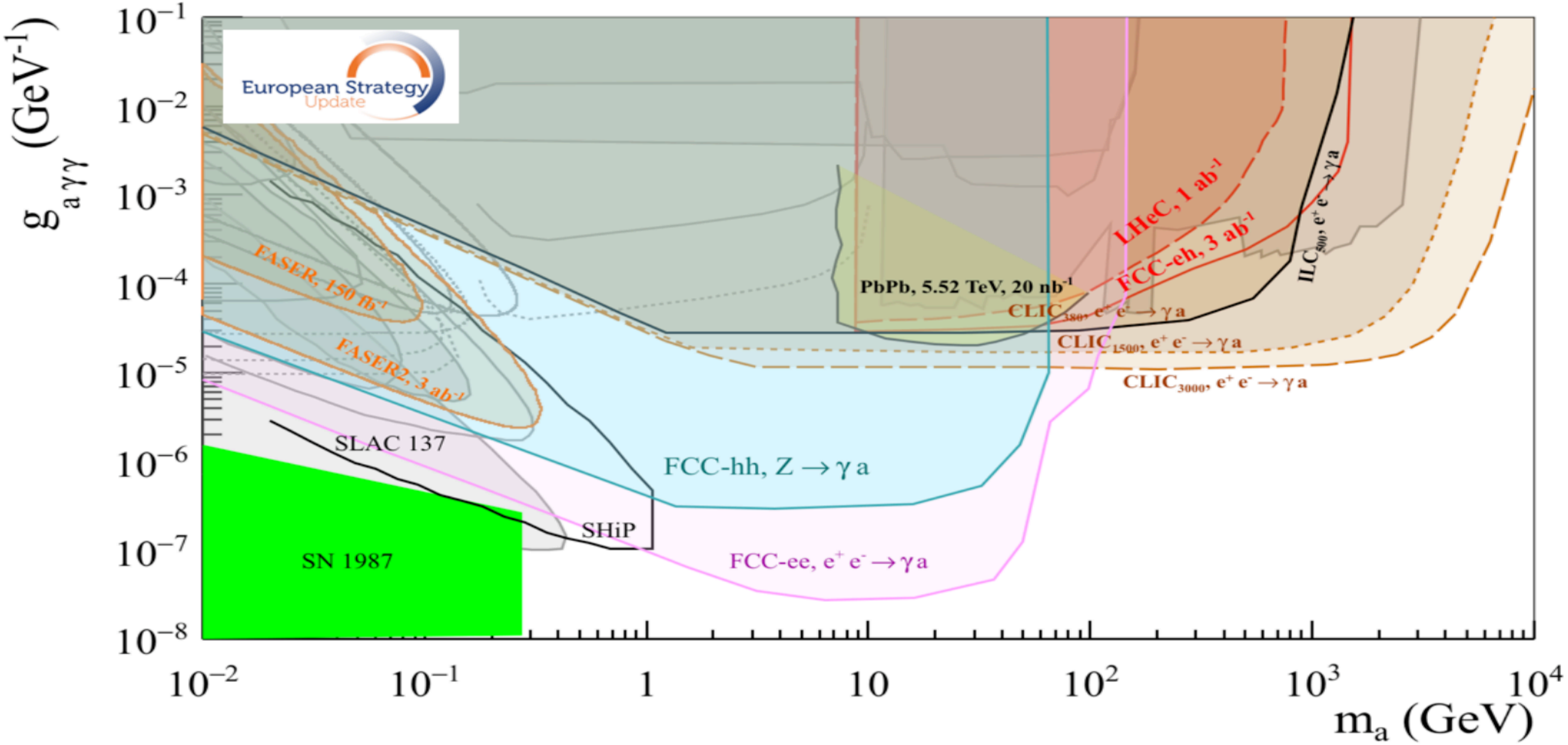
a decaying in the tracker region, before the calorimeter.



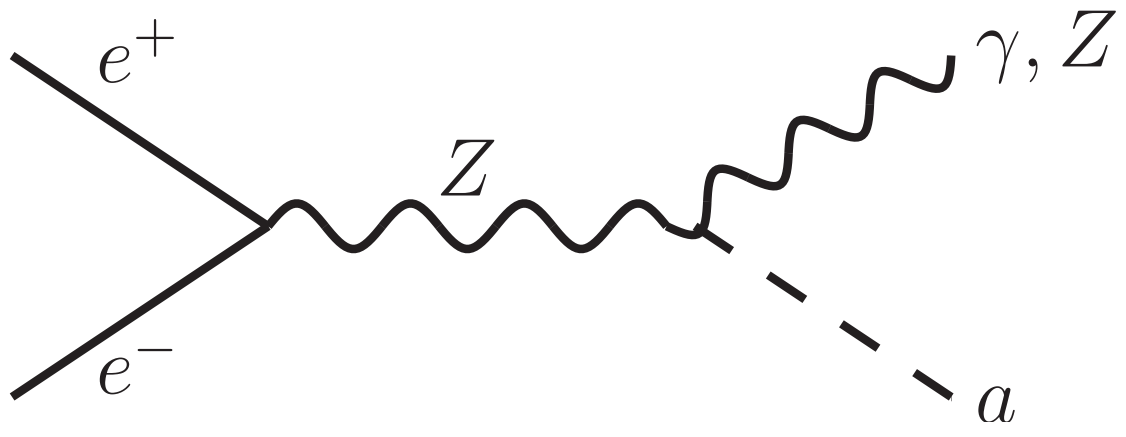
includes also 160 and 240 GeV runs

SUMMARY OF ALPS COUPLED TO PHOTONS

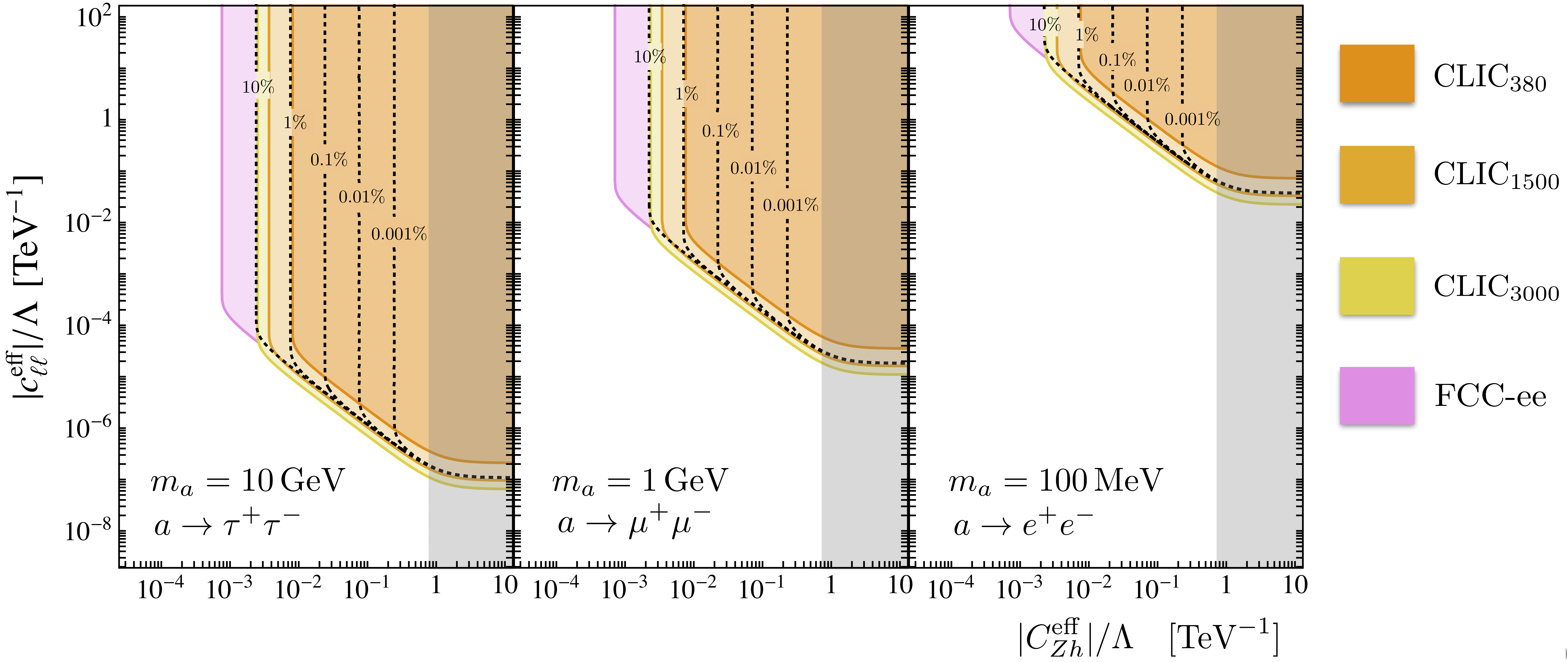
- Also for ALPS luminosity is key to the game
- Complementarity of lepton colliders at different energies
- Fertile ground for development of innovative detector ideas!



ALPS SEARCH WITH DIFFERENT FINAL STATES

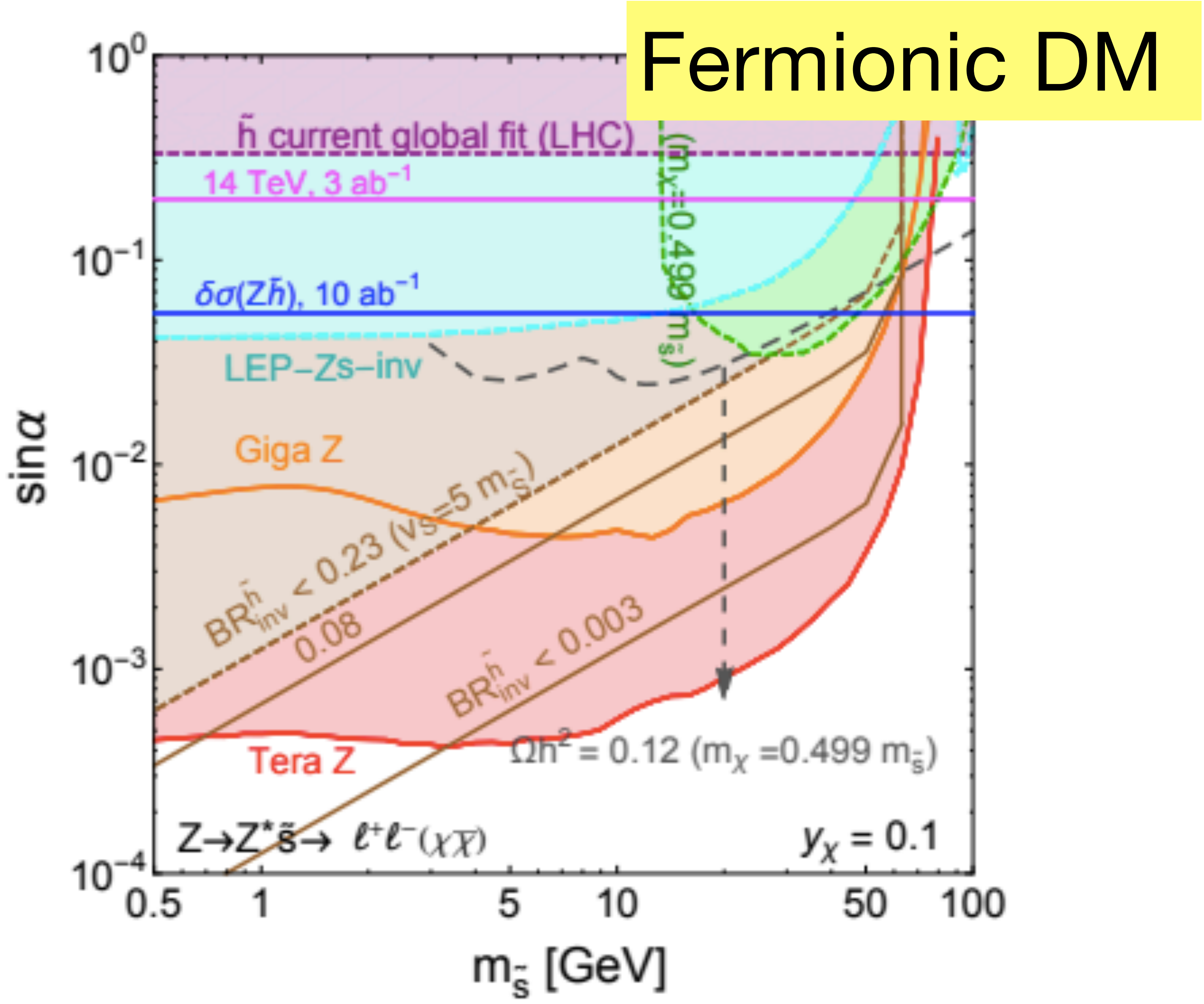


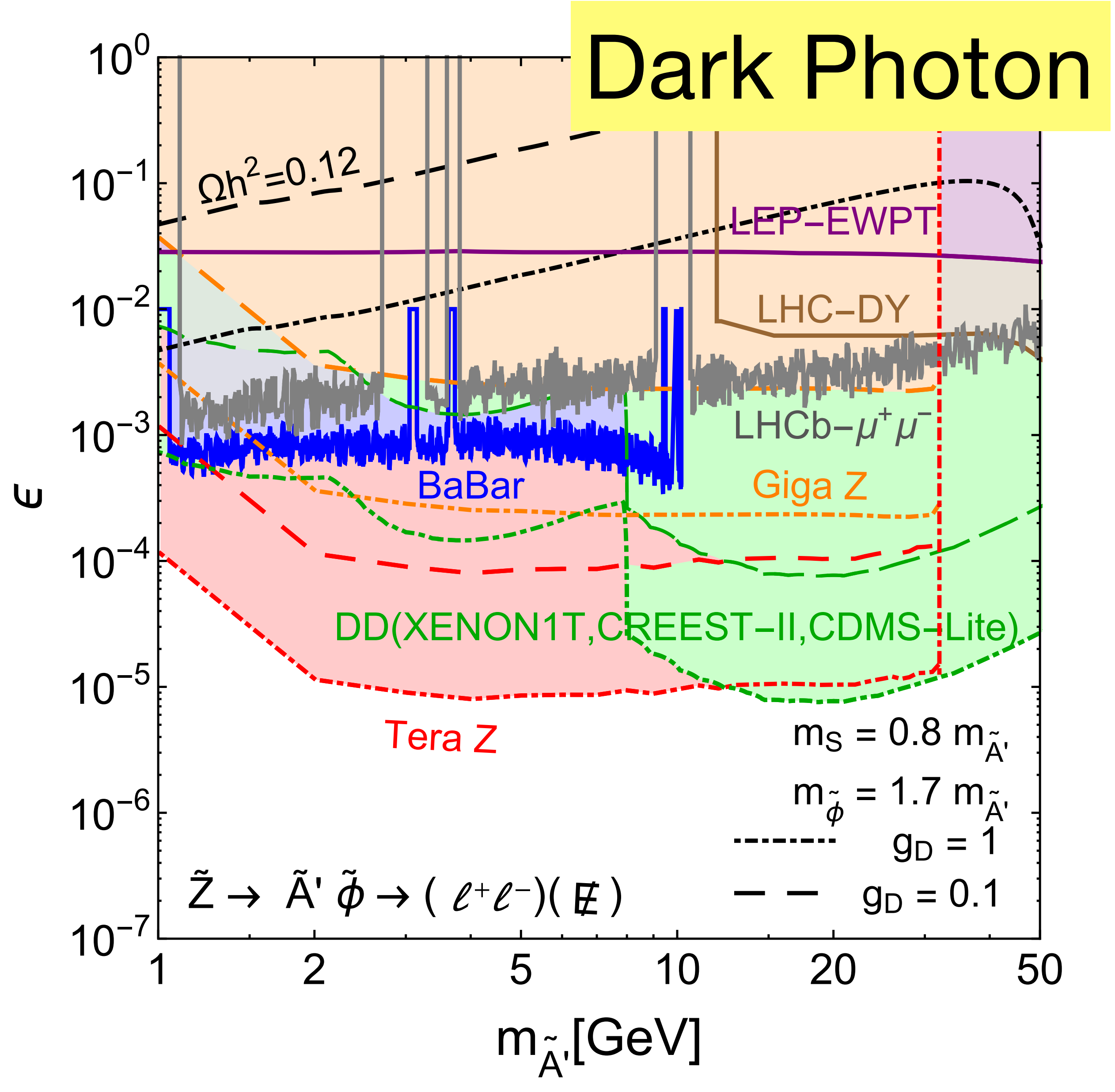
$a \to ll$

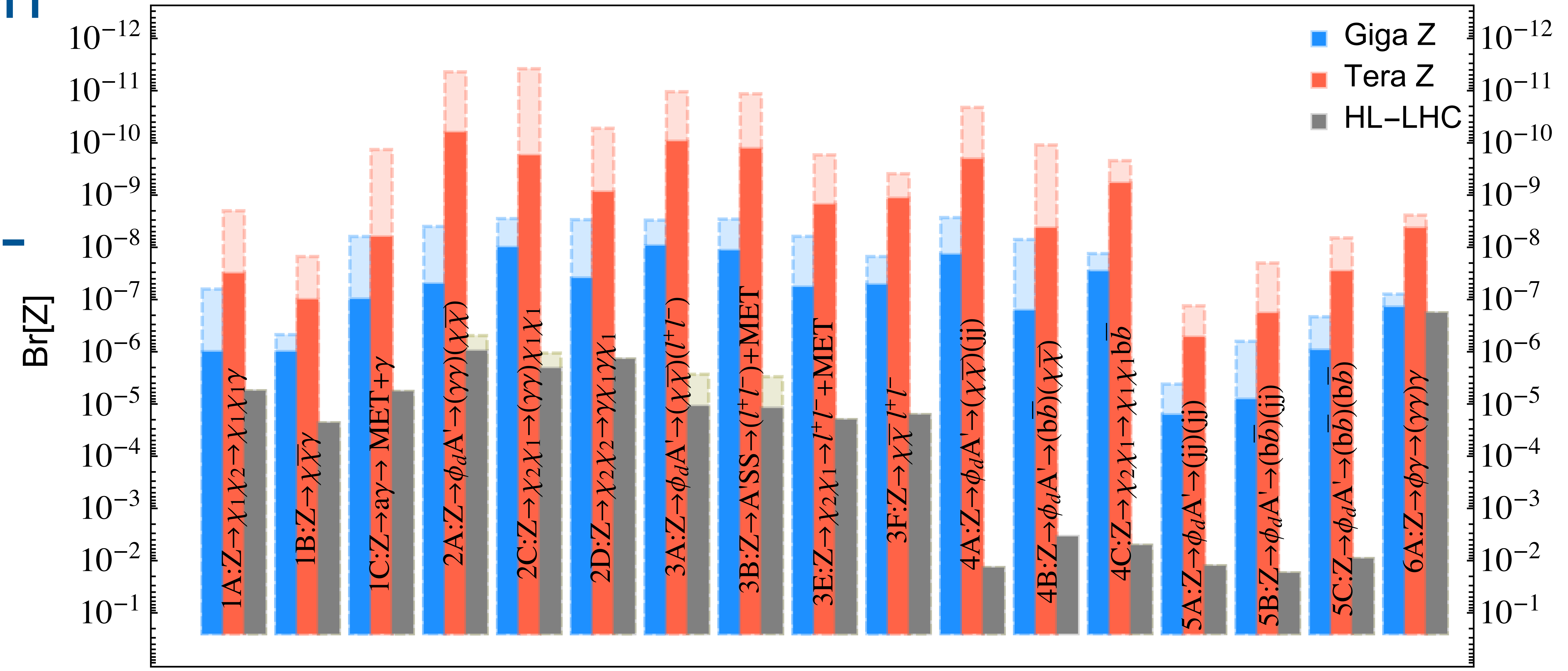


BSM DIRECT SEARCHES - Z EXOTIC DECAYS

- Several models that describe possible exotic Z decays in dark sector candidate particles have been studied
  - Nice review 1712.07237
- Complementarity between experiments depending on the parameter space
- Also comparison with HL-LHC


Fermionic DM

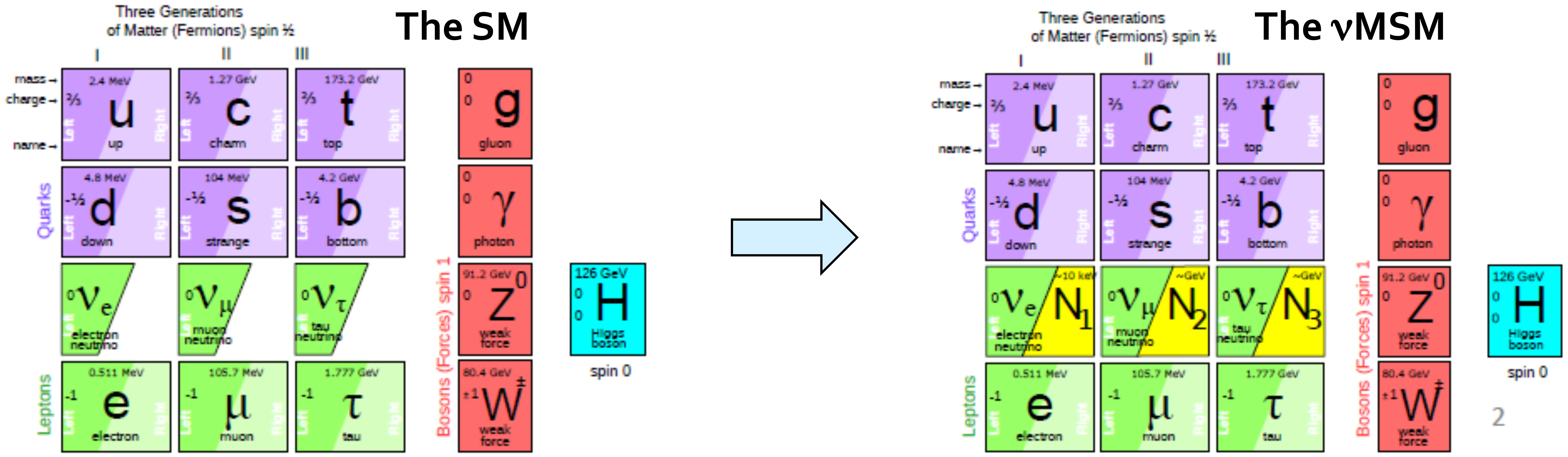

Dark Photon



SEARCH FOR HEAVY NEUTRAL LEPTONS

- ➤ Neutrino oscilations require at least two massive light/active SM neutrinos. This corresponds to an extension of the SM
- ➤ We consider the addition of right-handed fermion singlets (« sterile neutrinos » N_i)
- ➤ Interesting scenario: symmetry protected (See-Saw)
- ➤ **This extension of the Standard Model with three sterile Majorana neutrinos Ni is called Neutrino Minimal Standard Model (νMSM)**

◆ **νMSM : Complete particle spectrum with the missing three right-handed neutrinos**



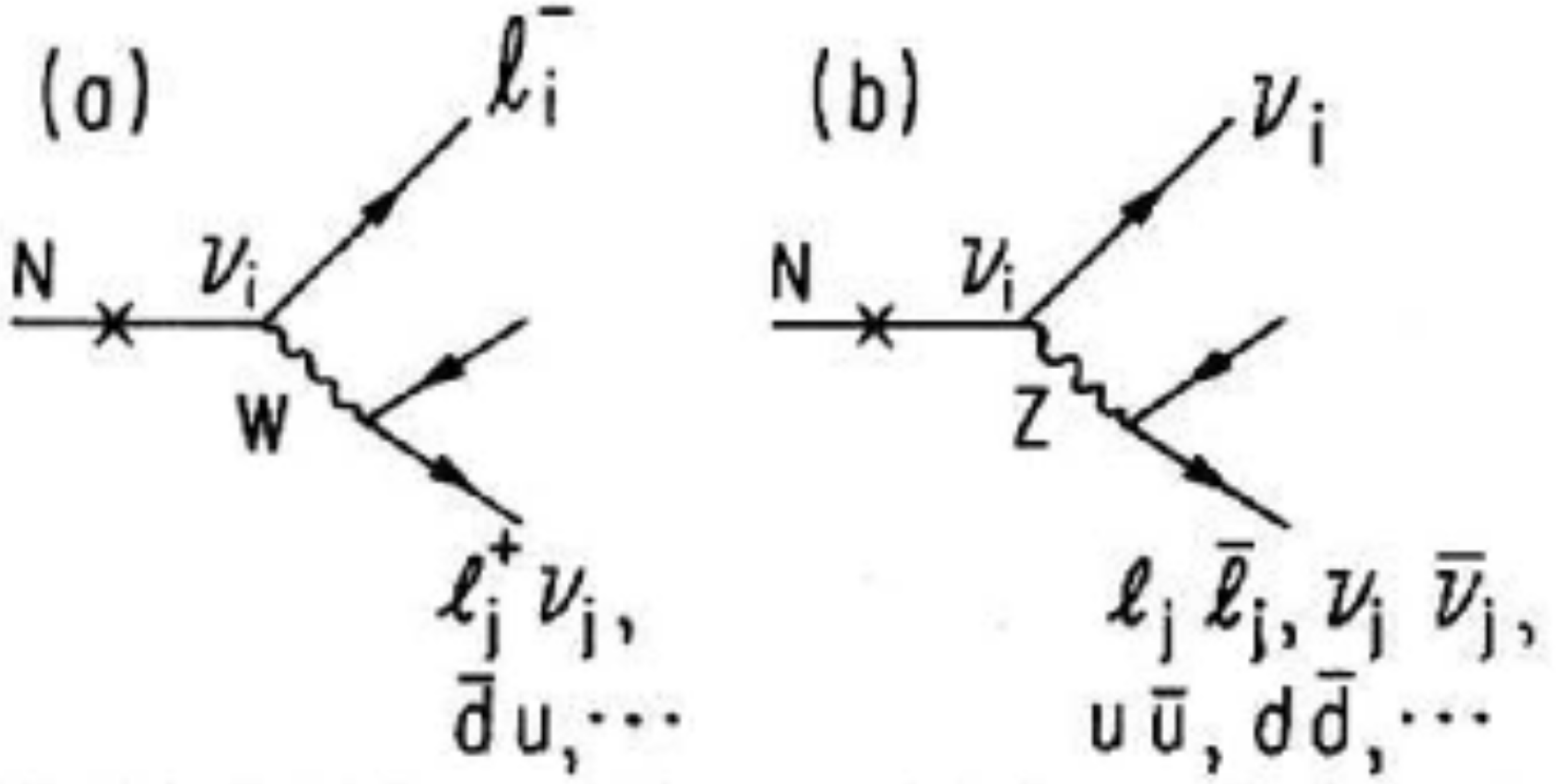
The SM

The νMSM

SEARCH FOR HNL WITH DISPLACED VERTICES

- Benchmark for detector design choices

arXiv:1411.5230
arXiv:1810.12463
arXiv:2008.13771

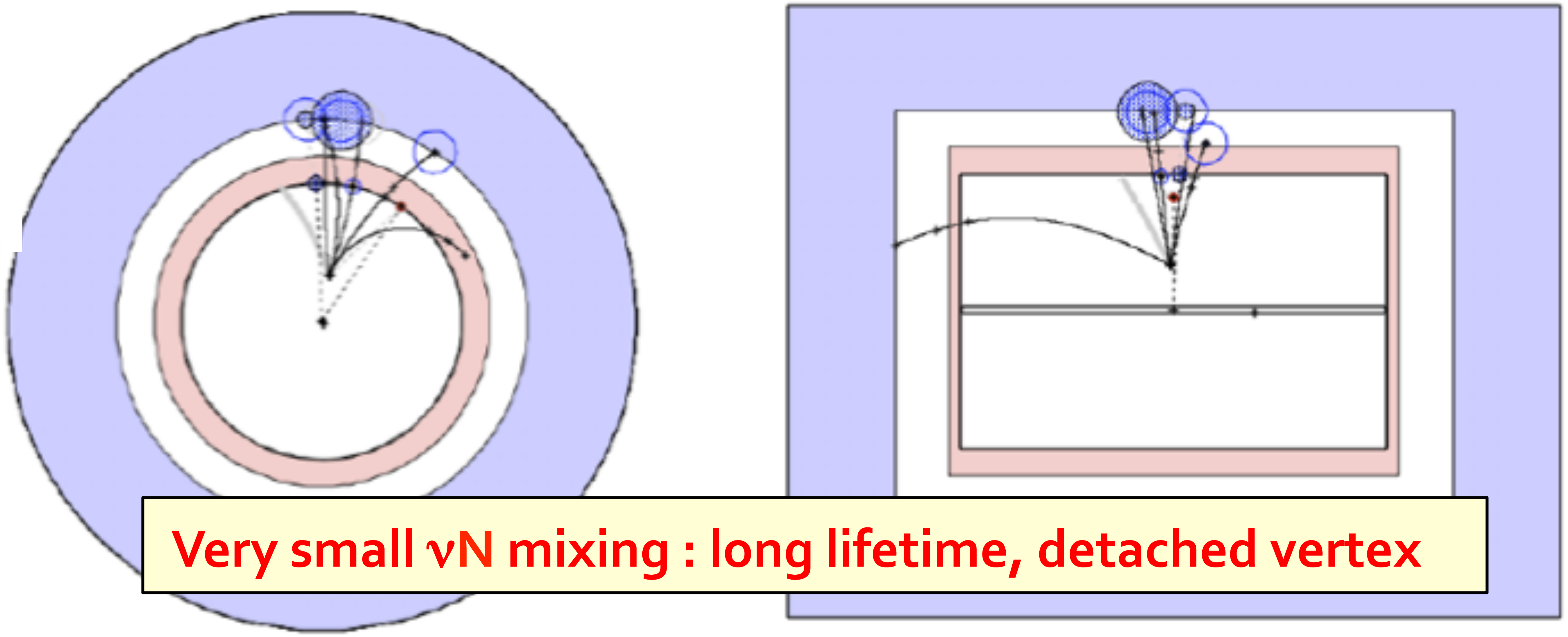


$$L \sim \frac{3\ [cm]}{|U|^2 .\ (m_N[GeV]\ )^6}$$

L~1m for m_N=50GeV and $|U|^2$=10-12

- Searched for in very rare $Z \rightarrow \nu N_{2,3}$ decays
  - Followed by $N_{2,3} \rightarrow W^* \ell$ or $Z^* \nu$

A. Blondel et al.
arXiv:1411.5230



Very small νN mixing : long lifetime, detached vertex

HNL SENSITIVITY ANALYSIS DEPENDENCE

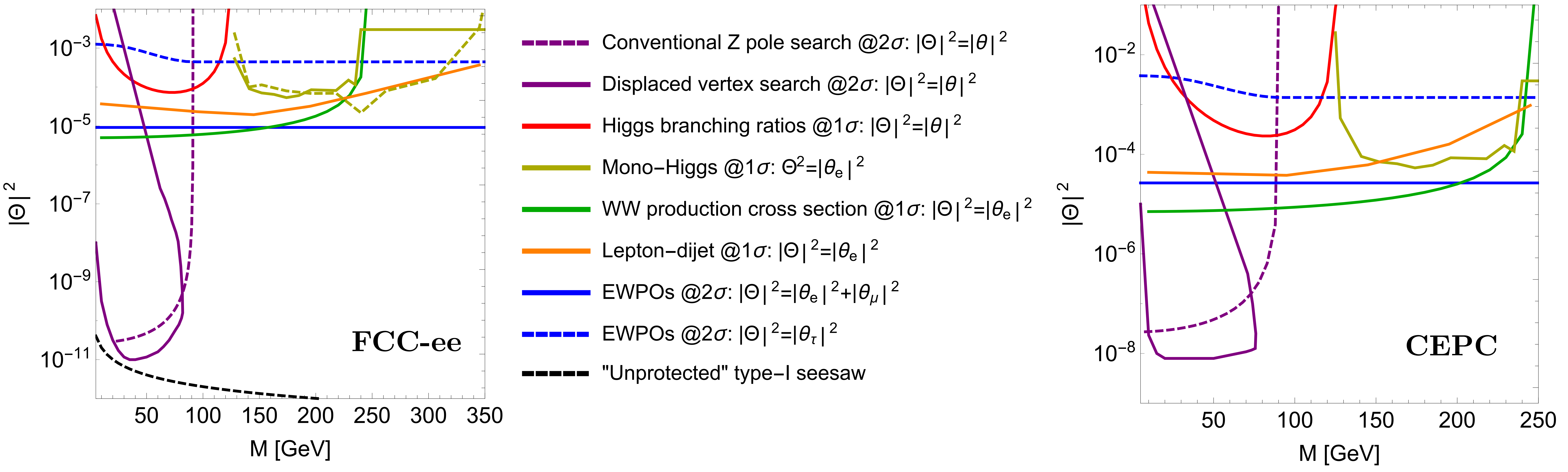
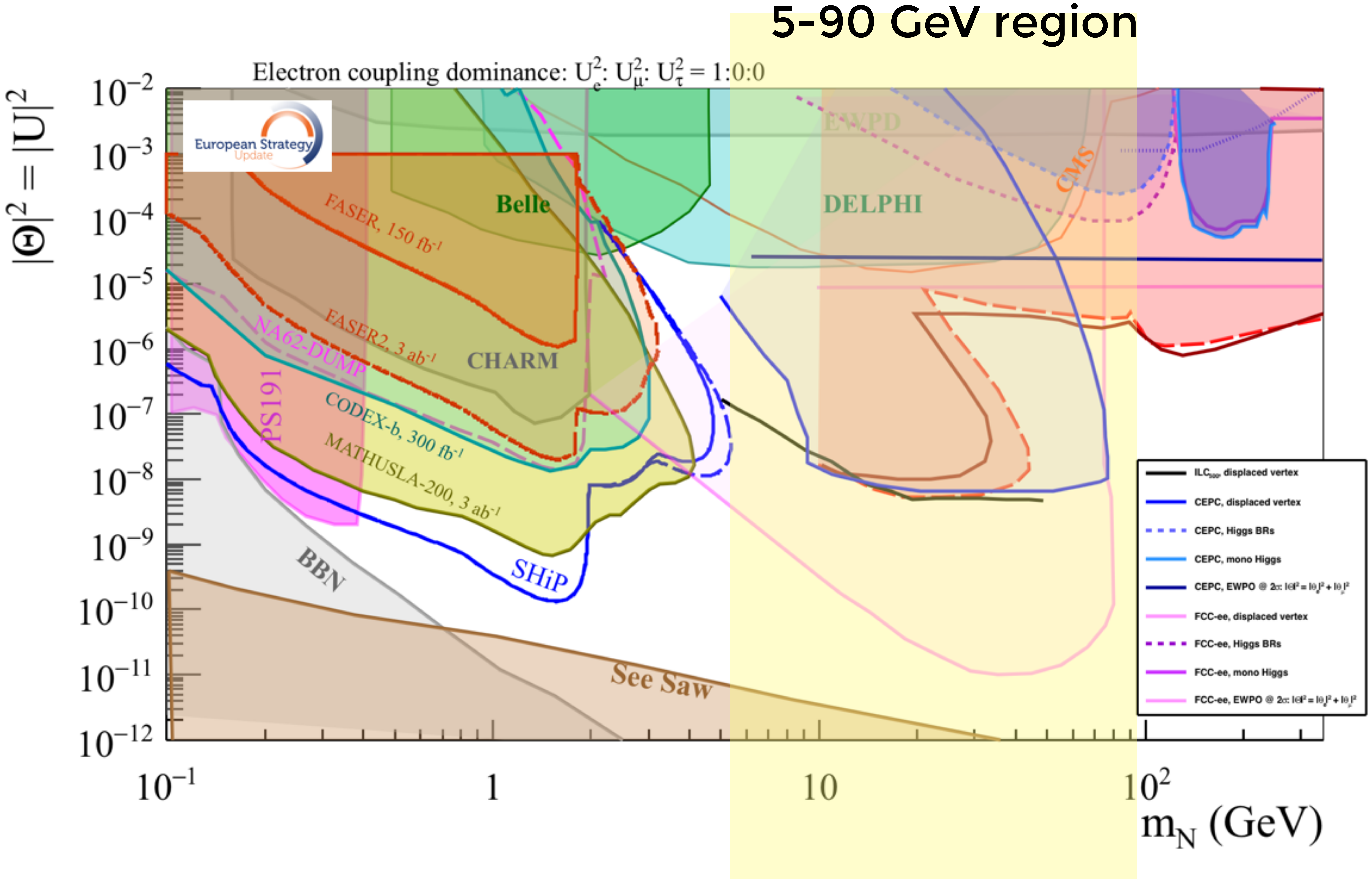


Figure 7: Sensitivities of the different signatures to the active-sterile mixing and masses of sterile neutrinos at the FCC-ee and the CEPC. For details on the signatures see text and tab. 3, for the considered modi operandi see fig. 4. See section 3.3 for a summary on the references that were used.

$|\theta|^2$ magnitude of the mixing angle

SUMMARY FOR HEAVY NEUTRAL LEPTON (MIXED WITH ν_e)



5-90 GeV region

SHIP&FCC-ee close to the leptogenesis bound

Fig. 8.19: 90% CL exclusion limits for a Heavy Neutral Lepton mixed with the electron neutrino. See text for details.

CONCLUSIONS

- Electron-positron colliders remain the best tool to **improve our knowledge of the Higgs boson and of the SM** through precise measurements and access to features not available at hadron colliders.
- They have a **unique opportunities for discoveries** of new physics inaccessible to hadron colliders
  - They are the natural step after the HL-LHC
- Four projects on the table (ILC, CLIC, FCC, CEPC) with overlaps and complementarities, strong physics case, challenging but achievable technology.
  - It is very important to understand the need of the knowledge a lepton machine can bring before jumping in a new and more powerful hadron collider at 100TeV or more (or even other options)
- Our job is to inspire the new generations with the exciting new physics and discoveries that can be made at a future lepton collider