Future colliders

Freya Blekman
Interuniversity Institute for High Energies,
Vrije Universiteit Brussel, Belgium

Thanks to A. Blondel, P. Azzi,
P. Giacomelli and many
other collaborators

VRIJE
UNIVERSITEIT
BRUSSEL

Outline

- **Why?**
- **Future colliders**
  - a short overview for younger scientists (in no particular order)
- **Physics reach (highlights)**

what about detectors?

- **I will not talk about detector design but the executive summary is that there are multiple detector prototypes on the market**
- **Many more details on detectors in Nigel Watson's talk later this workshop**
- All general-purpose detectors with excellent performance at least similar but usually much better than modern LHC detectors, including excellent b and c quark tagging, **low (<1 GeV) energy photon and lepton** measurement capabilities and **high rapidity** acceptance
  - ATLAS/CMS-like but with suitable resolution, efficiency, acceptance
  - More ambitious using really cutting edge technologies such as monolithic active pixels, modern drift chambers using si-detector technology, next-generation highly granular calorimetry etc
- Both **full and fast simulation** are commonly used, while parameterized detector simulation (e.g. **DELPHES**) is also frequently used for more phenomenology-oriented studies

Why new colliders?

- Why build a better telescope?
- Why build a better microscope?

Let's focus on the physics and on **what we know**

VRIJE UNIVERSITEIT BRUSSEL

Outstanding Questions in Particle Physics *circa* 2011

EWSB
- ❑ Does the Higgs boson exist?

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of H(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Outstanding Questions in Particle Physics *circa* 2016

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ *ν* masses and and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile *ν* ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ?
  which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

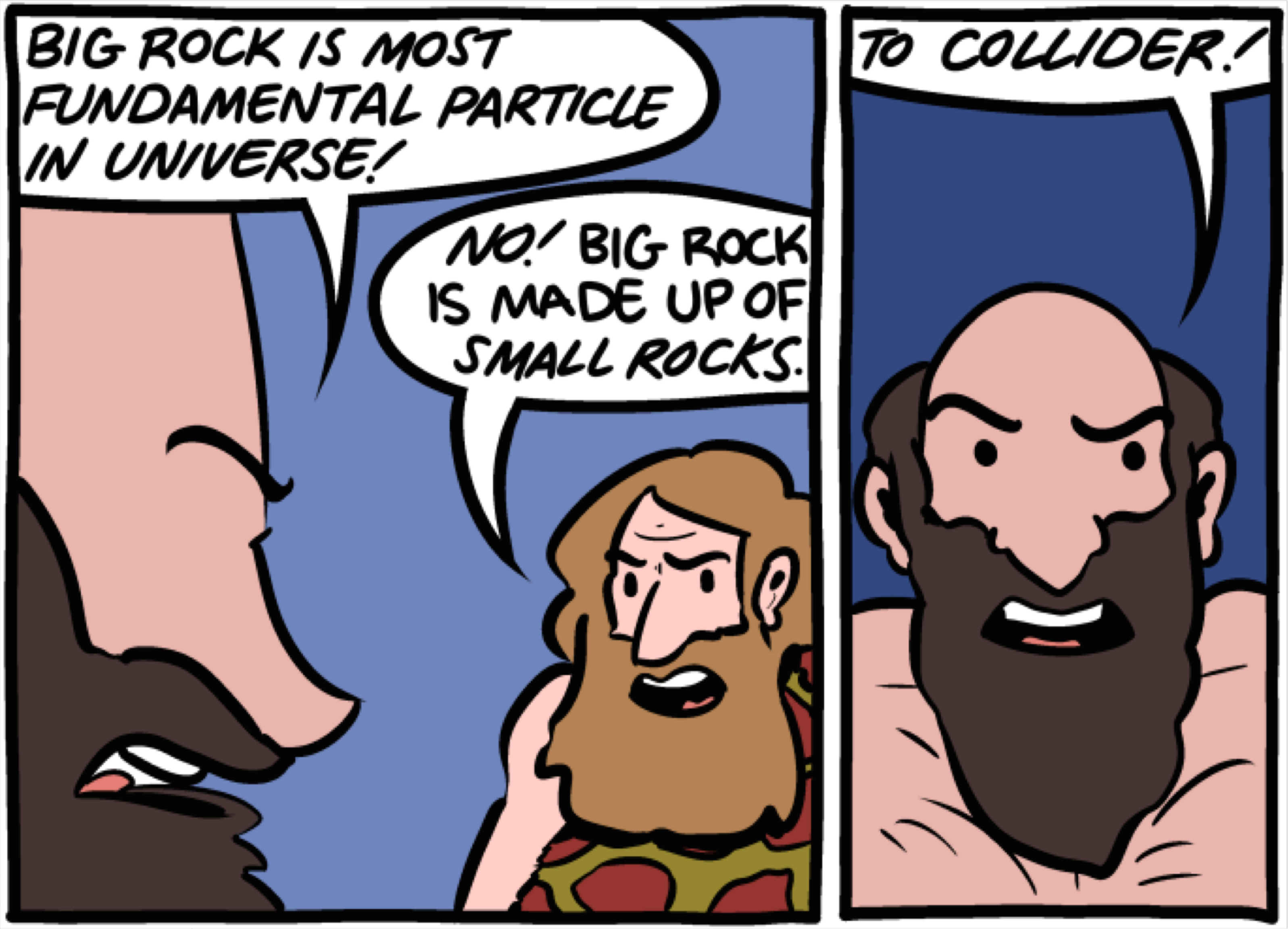
These questions are compelling, difficult and intertwined → require multiple approaches high-E colliders, neutrino experiments (solar, short/long baseline, reactors $0\nu\beta\beta$ decays), cosmic surveys (CMB, optical/IR spectroscopic and photometric), dark matter direct, indirect and astrophysical detection, precision measurements of rare decays and phenomena, dedicated searches (WIMPS, axions, dark-sector particles), …

Main questions and main approaches to address them

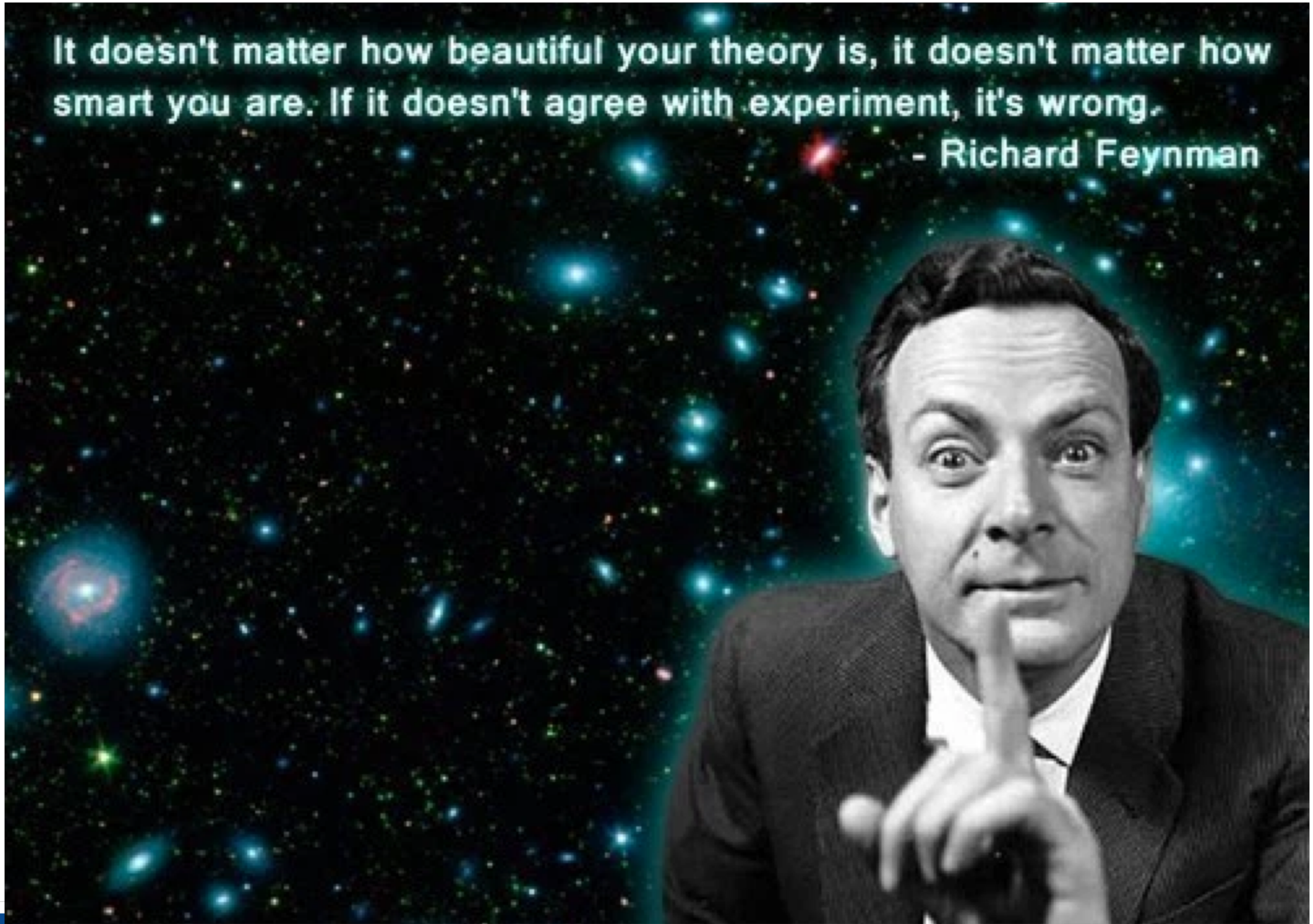
	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos			x	x	x
Dark Matter	x			x	x
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

These complementary approaches are ALL needed: their combination is crucial to explore the largest range of E scales, properly interpret signs of new physics, and build a coherent picture of the underlying theory.

Curiosity!



src: http://www.smbc-comics.com


It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.
- Richard Feynman

Future Circular Colliders at CERN

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

~16 T magnets

- ***Ultimate goal:***
  100 TeV pp-collider (FCC-hh)

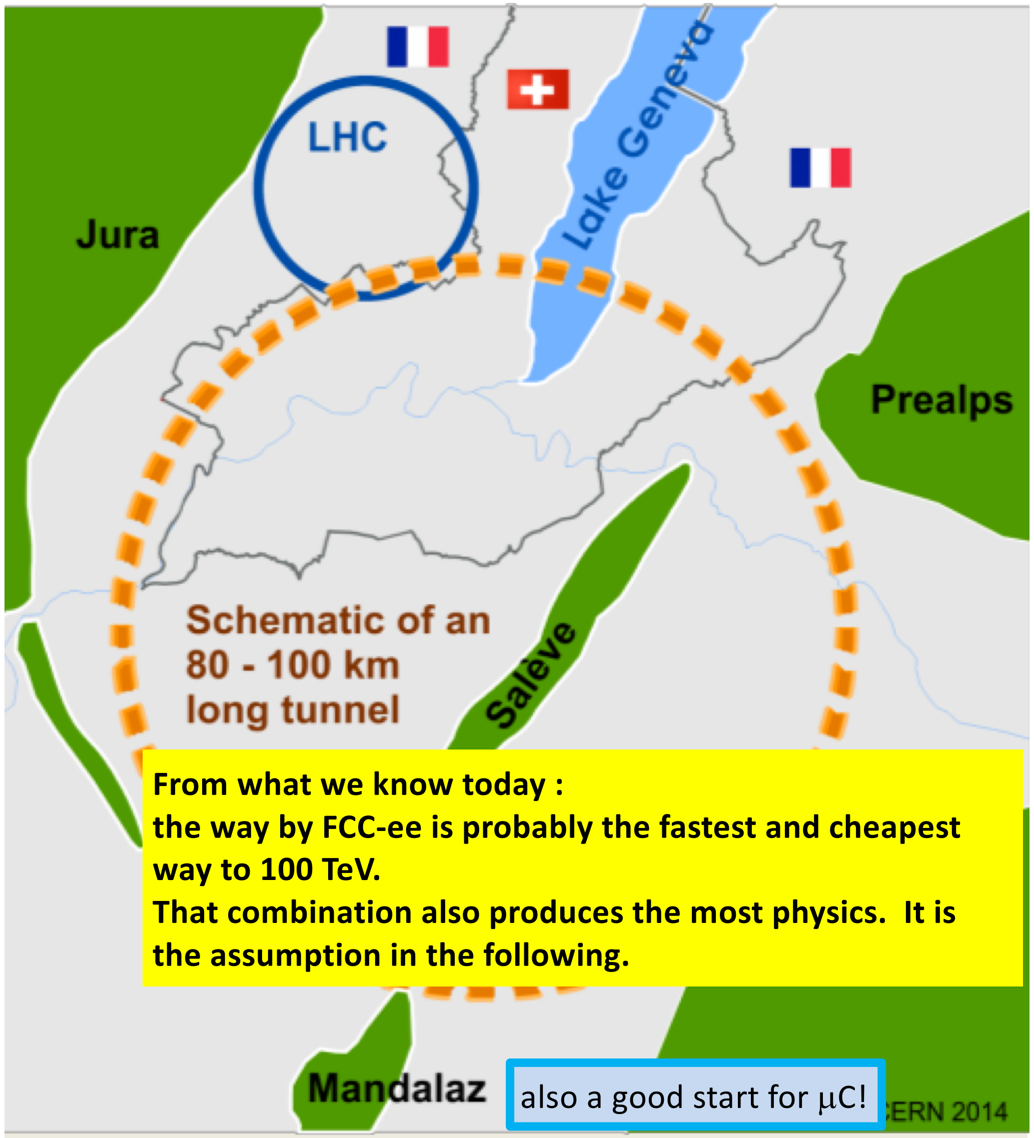
→ defining infrastructure requirements

Two possible first steps:

- ***e^+e^- collider (FCC-ee)***
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC 16T ⇒ 27 TeV***
  in LEP/LHC tunnel

Possible addition:

- ***p-e (FCC-he) option***



From what we know today :
the way by FCC-ee is probably the fastest and cheapest way to 100 TeV.
That combination also produces the most physics. It is the assumption in the following.

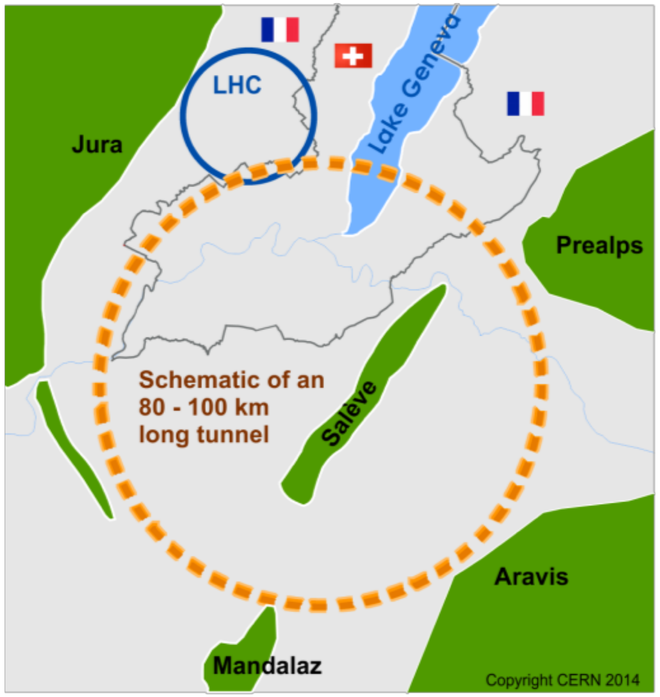
also a good start for μC!

ccelerator project"

Study kicked-off in Geneva in Feb 2014

Future Circular Collider **FCC-ee**

- High-luminosity **ee circular collider** proposed in new 80-100 km tunnel near CERN
- **Flexible** centre-of-mass-energy from **90 to 400 GeV**
- **Top physics run at 365 GeV**
- Schedule (and physics) **complementary to LHC** and in synergy with upgrade to FCC-hh (pp @ 100 TeV)

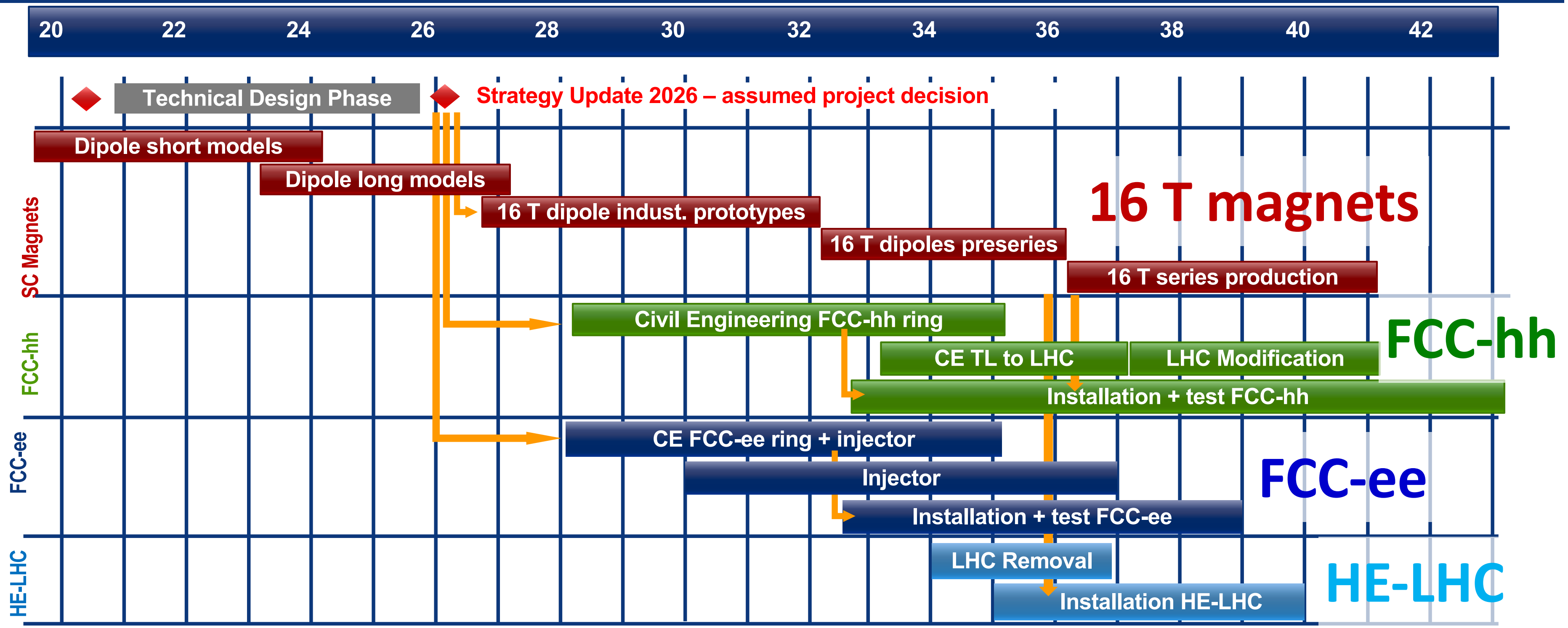


- With precision measurements, 20-50 fold improvement on many SM parameters such as
  - m_Z m_W m_{top} $\sin^2\theta_W^{eff}$ R_B, α_{QED} α_S, top and Higgs couplings
- Potential to directly or indirectly **discover** BSM physics
  - Understand BSM through quantum effects in loops
  - DM as invisible decay of H as Higgs factory
  - FCNC in Z and ttbar, flavour physics
  - Very diverse exotica programme

VRIJE UNIVERSITEIT BRUSSEL

Possible Timeline of the FCCs

Technical Schedule for each of the 3 options



schedule constrained by 16 T magnets & CE

→ earliest possible physics starting dates

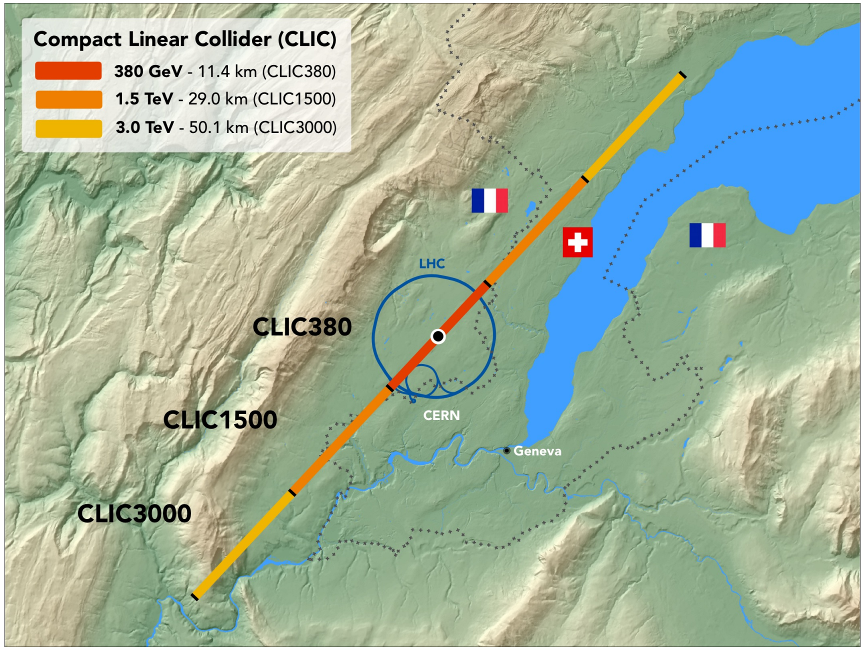
- **FCC-ee: 2039**
- **FCC-hh: 2043**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

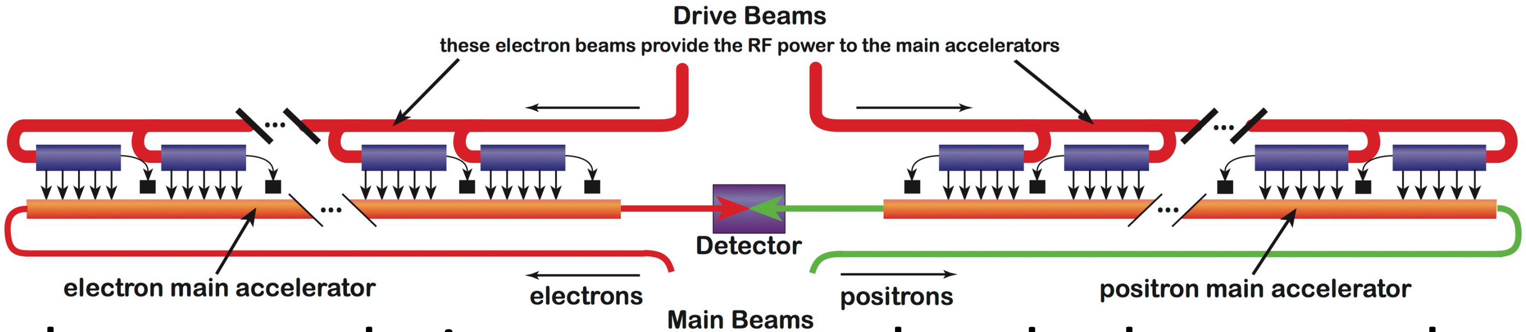
VRIJE UNIVERSITEIT BRUSSEL

CLiC: Compact Linear Collider

- Future e+e- collider with access to >=TeV sqrt(s)

Energy scenarios (staged)	
sqrt(s) [GeV]	Integrated luminosity [fb^{-1}]
380	**500**
350 (top scan)	**100**
1500	1500
3000	3000



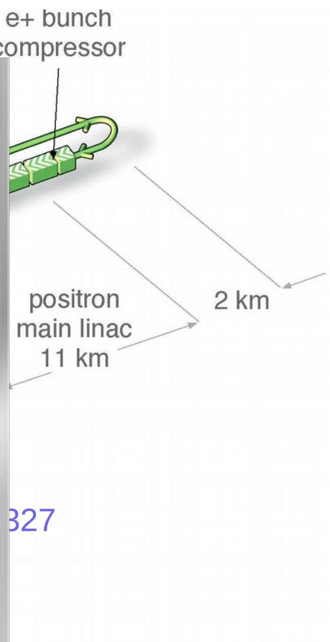


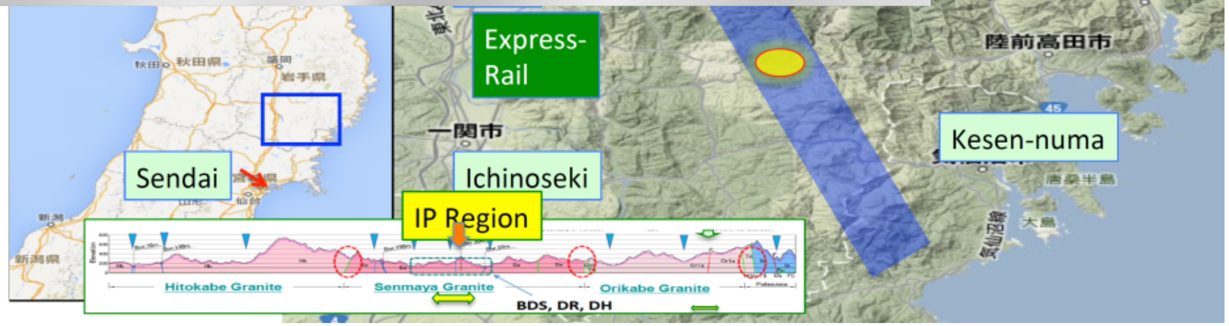
- Accelerator techniques are novel and rely on two beam acceleration involving gradients over 100 MV/m!

VRIJE UNIVERSITEIT BRUSSEL

International Linear Collider **ILC**

- **ILC250**
  initial (
  GeV:
  impor
  - Pre
    don
    inte
  - 250
    dire
- **ILC250**
  impres
  Higgs
- **Is upgradable in energy to study ttbar**

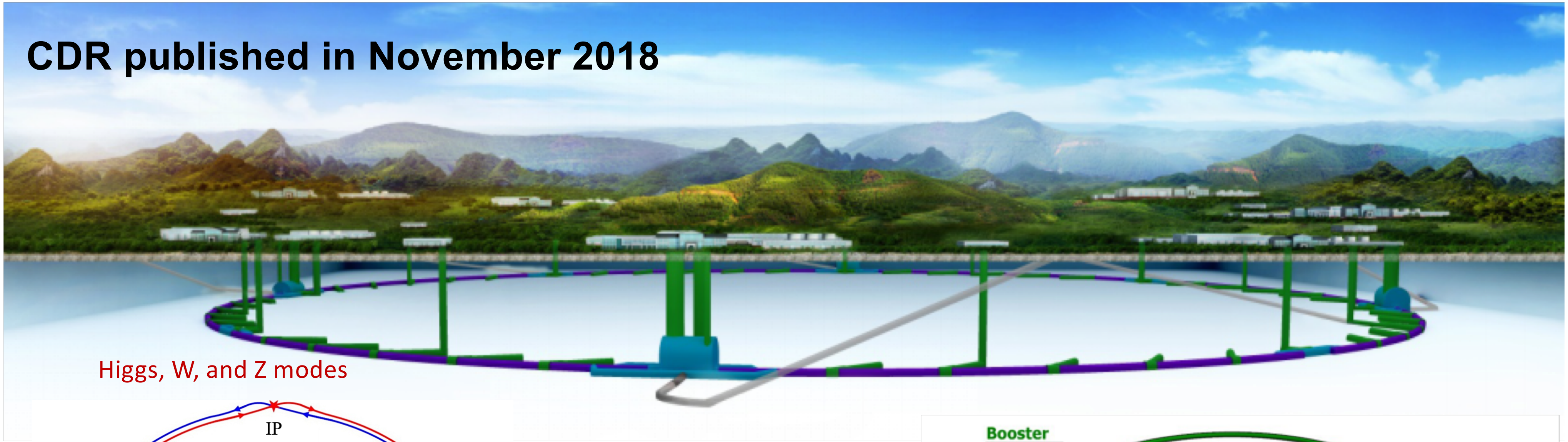




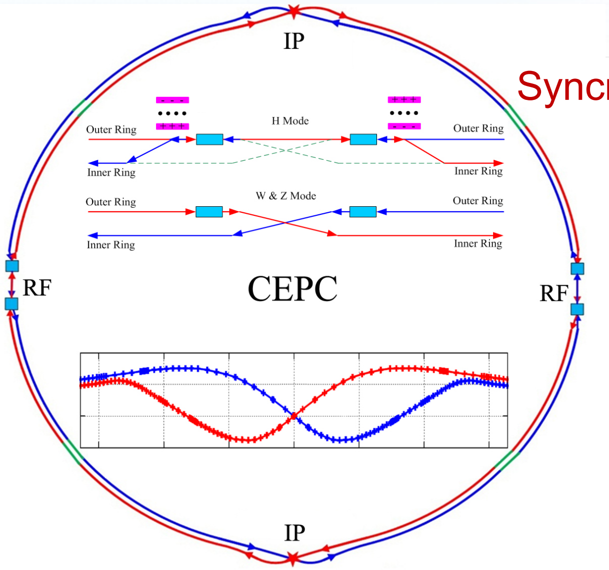
VRIJE UNIVERSITEIT BRUSSEL

Circular colliders: CEPC

CDR published in November 2018

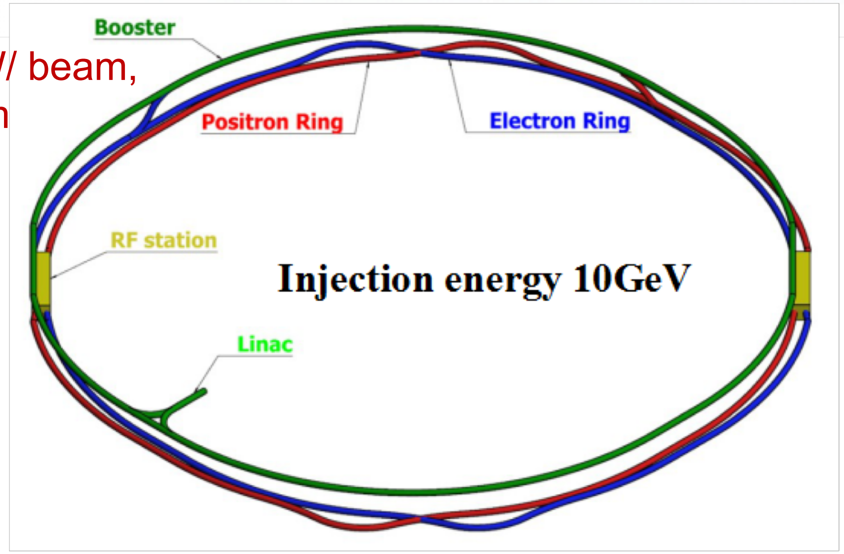


Higgs, W, and Z modes



CEPC collider ring (100km)

Syncrotron Radiation power 30MW/ beam, upgradable to 50MW/beam



CEPC booster ring (100km)

Center of mass energy **91** - **240** GeV

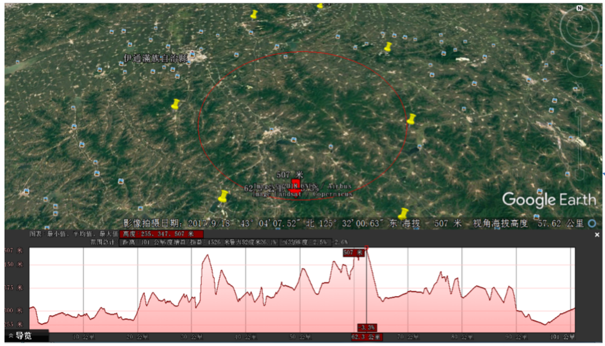
Max. luminosity (√s=240 GeV) **3 x 10^{34}** $cm^{-2}s^{-1}$

Later install SPPC (pp collider) √**s** = **100-120** TeV

VRIJE UNIVERSITEIT BRUSSEL

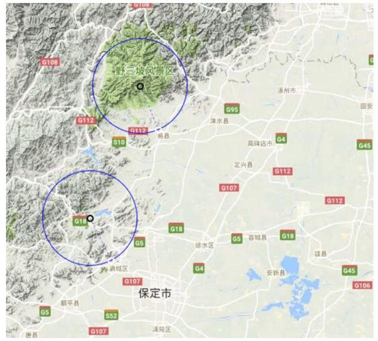
CEPC Site Selections

Huanghe Company participated

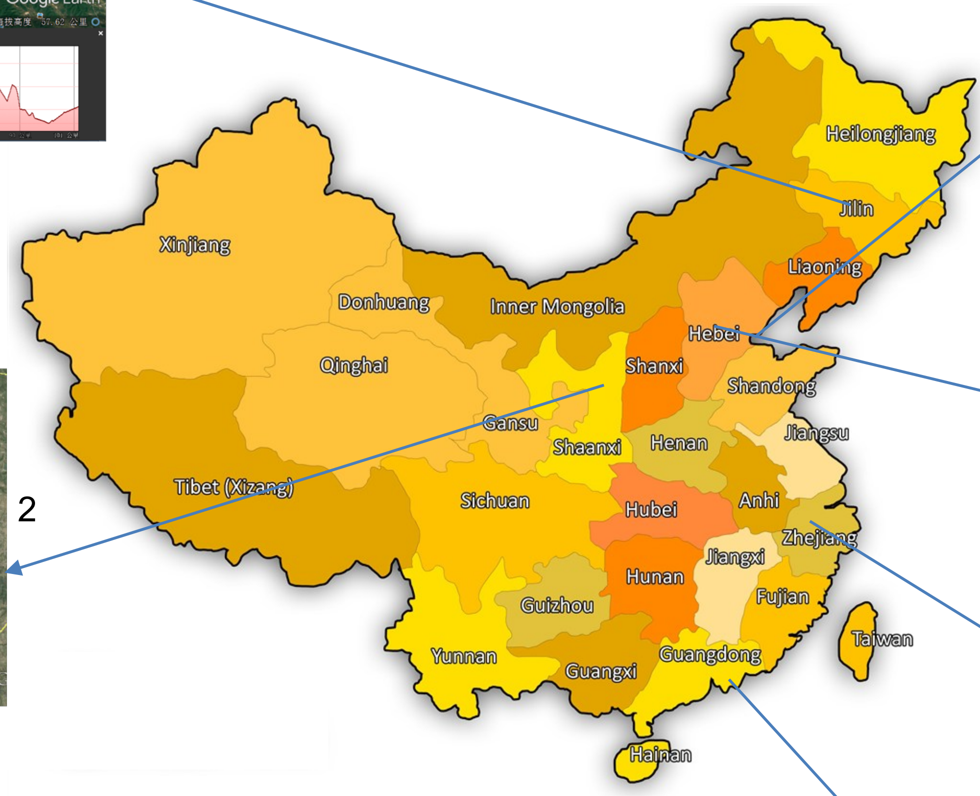


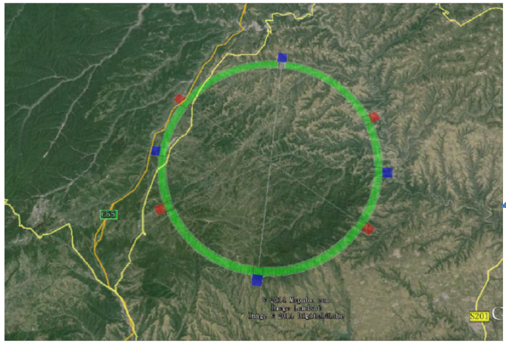
6

1

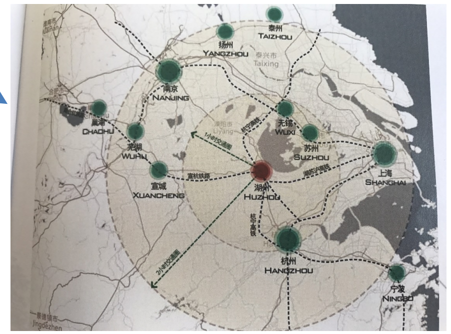


4





2



5

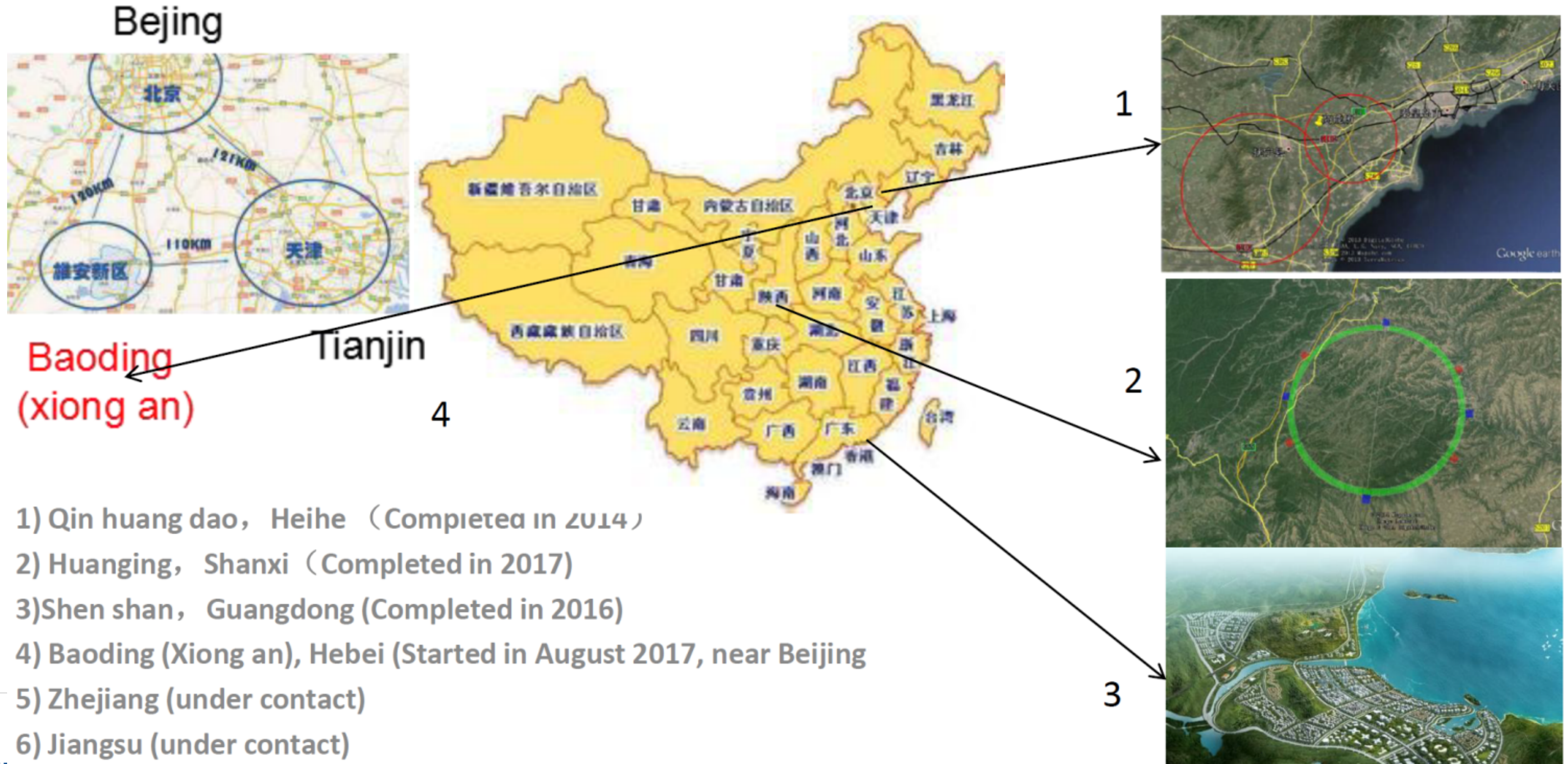
- 1) Qinhuangdao, Hebei Province（Completed in 2014）
- 2) Huangling, Shanxi Province（Completed in 2017)
- 3) Shenshan, Guangdong Province(Completed in 2016)
- 4) Baoding (Xiong an), Hebei Province (Started in August 2017)
- 5) Huzhou, Zhejiang Province (Started in March 2018)
- 6) Chuangchun, Jilin Province (Started in May 2018)

CEPC

- Studies for site ongoing
- Qing Huang Dao “Site 1” (close to Beijing) is used for studies CDR
- Top quark runs currently part of potential upgrade

Lumi.	Higgs	W	Z	Z(2T)
$\times 10^{34}$	2.93	11.5	16.6	32.1

Source: X. Lou, ICHEP18 plenaries



VRIJE UNIVERSITEIT BRUSSEL

Source: X. Lou, ICHEP18 plenaries

Paths to realizing the e^+e^- collider(s)

ILC ILC250 is ready 

n from the Japanese government

"The 2018 Asian Li is being held in Fukuoka, Japan from 28 May to 1 June. A **imously endorsed stressing the scientific importan e government to declare interest in hosting the project** he European Strategy Group, which supported Europea pdate in 2013, needs input by the end of 2018 if the I eport."

CLIC Can be implemented at CERN, as an international project, after completion of the LHC.

FCC-ee Can be implemented at CERN, as an international project, after the LHC.

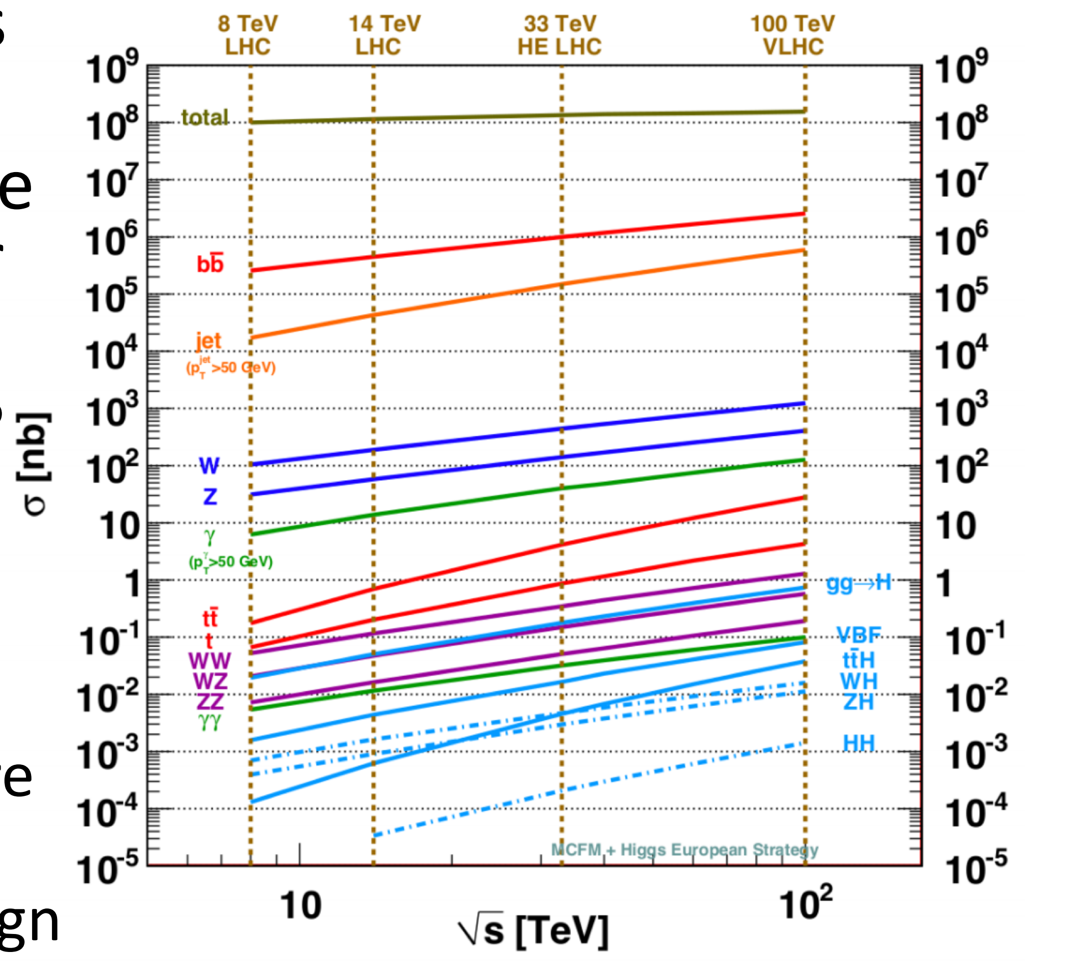
CEPC: **Chinese Government：”actively initiating major-international science project…”**

国发〔2018〕5号（2018.3.14）http://www.gov.cn/zhengce/content/2018-03/28/content_5278056.htm

- focuses on "**frontier science, large-fundamental science , global focus, international collaboration, …**"
- by year 2020，3-5 projects will be chosen to go into "preparatory stage", among which 1-2 projects will be selected. More projects will be selected in later years.
- **This is a likely path to realize CEPC.**

FCC-hh: 100 TeV proton-proton collider

- Nigel Watson will discuss more
- Physics- and analysis-wise this machine very similar to LHC – but with larger cross sections/better S/B ratio
  - parton luminosities!
  - And BIG analysis challenges: almost everything boosted, more forward production
  - But for that you can design a detector that can do that



FCC-hh discovery potential highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

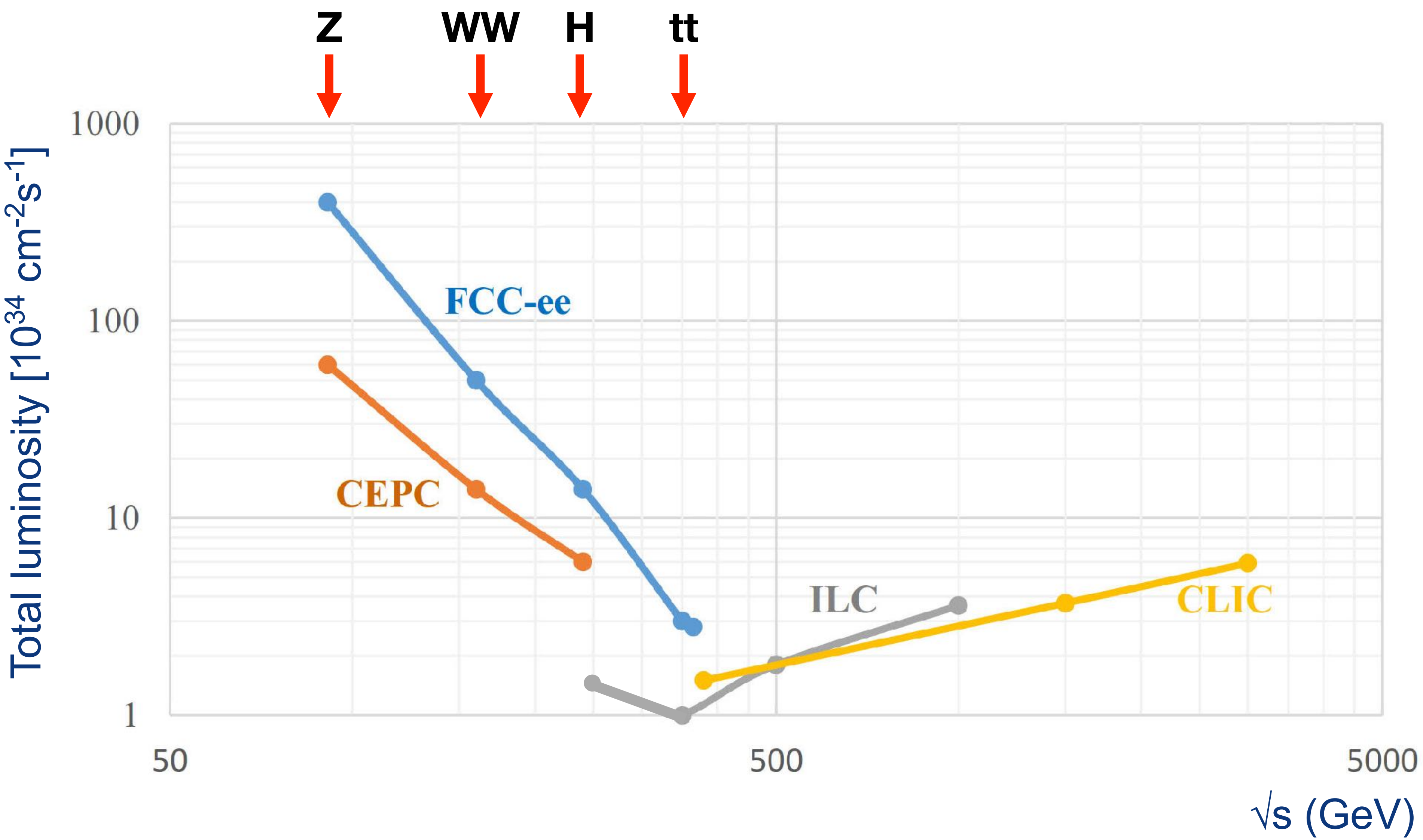
FCC-hh physics is dominated by three features:

- **Highest center of mass energy** $\rightarrow$ **a big step in high mass reach!**
  - ex: strongly coupled new particles up to >30 TeV
  - Excited quarks, Z', W', up to ~tens of TeV
  - Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV
    Sensitivity to high energy phenomena in e.g. WW scattering

- **HUGE production rates** for single and multiple production of SM bosons (H, W, Z) and quarks
  - Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau$/ZZ, ttH/ttZ @<% level
  - Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling
  - detection of rare decays $H \rightarrow V\gamma$ ($V = \rho, \varphi, J/\psi, \Upsilon$, Z…)
  - search for invisibles (DM searches, RH neutrinos in W decays)
  - renewed interest for long lived (very weakly coupled) particles.
  - rich top and HF physics program

- **Cleaner signals for high P_t physics**
  - allows clean signals for channels presently difficult at LHC (e.g. $H \rightarrow bb$)

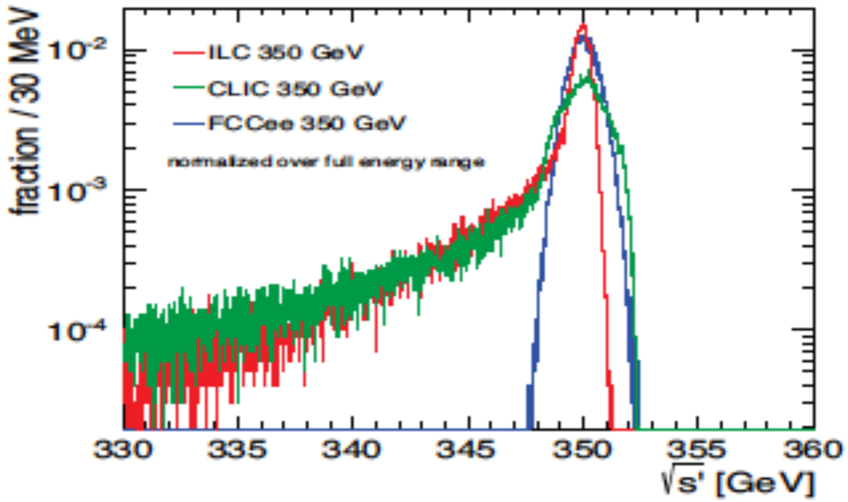
Future lepton colliders luminosities

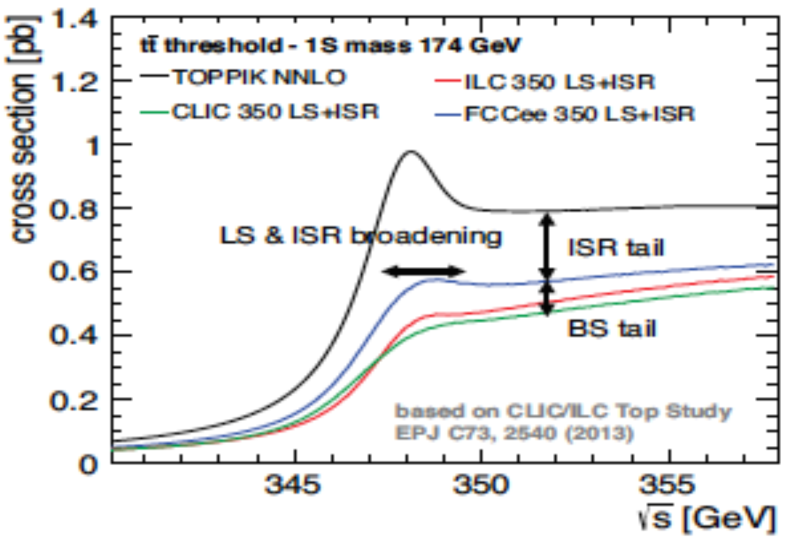


Clear advantage in luminosity for circular colliders vs. linear colliders.
Linear colliders (CLIC) have higher energy reach, but less than a pp collider.

Collider: does it matter which one?

- The **threshold shape** is affected by ISR and luminosity profile
  - Width of turn-on affected by width luminosity peak
  - Possibility to shift below threshold energy means reduction in effective cross section

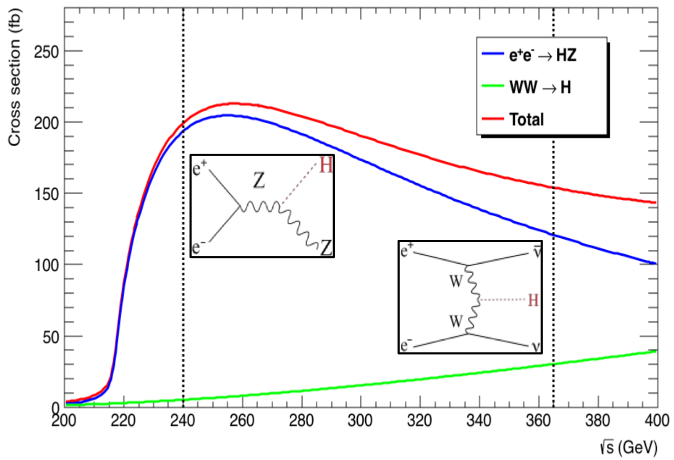


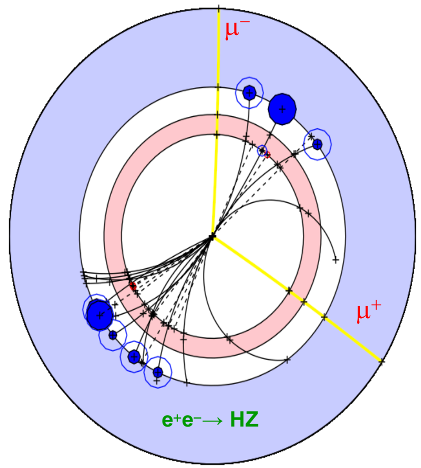


- Both **sample size** and knowledge of **uncertainty centre-of-mass** create important uncertainties
- ISR/luminosity profile sharper for circular machines
- can be optimised for expected physics performance

Circular e^+e^- colliders: FCC-ee, CepC

- **Basic measurements similar for all e^+e^- colliders**
  - **Some differences in experimental conditions**



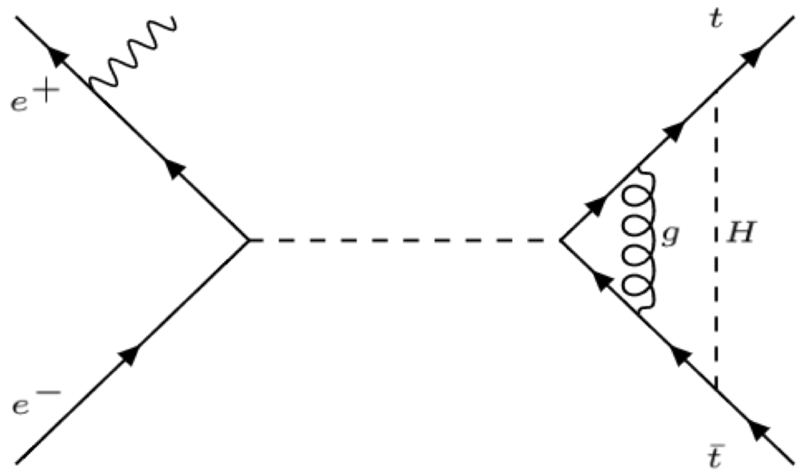


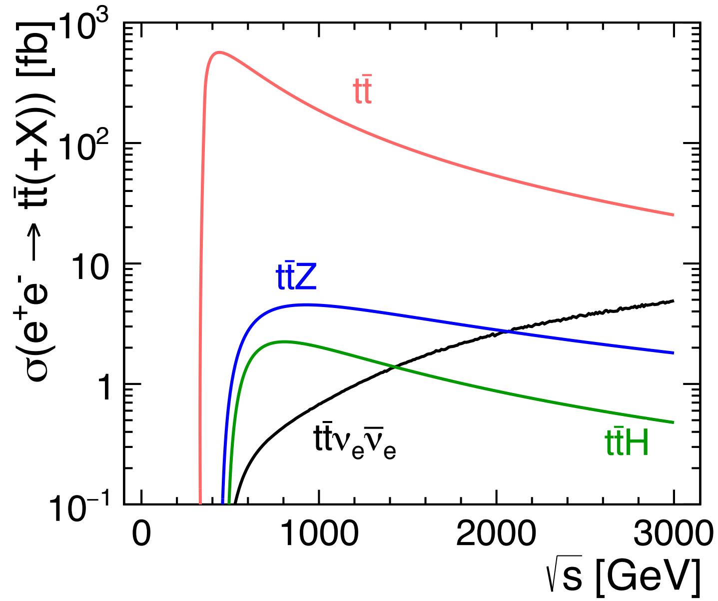
- **$e^+e^- \to HZ$ at $\sqrt{s}$ = 240-250 GeV : Higgs boson are tagged with a Z and $m_{Recoil} = m_H$**
  - Measure σ_{HZ} ($\propto g_{HZ}^2$) independently of H decay: absolute determination of g_{HZ}
  - Measure $\sigma_{HZ} \times BR(H \to \text{invisible})$ and many exclusive decays $\sigma_{HZ} \times BR(H \to XX)$
  - Infer Higgs width Γ_H from $\sigma_{HZ} \times BR(H \to ZZ)$ ($\propto g_{HZ}^4/\Gamma_H$)
  - Fit couplings g_{HX} from $BR(H \to XX)$ and Γ_H in a model-independent manner
- **$e^+e^- \to HZ$ completed with WW fusion at $\sqrt{s}$ = 350-365 GeV at FCC-ee**
  - Improves all precisions, especially on g_{HW} and Γ_H
  - First glance at top Yukawa coupling λ_t and Higgs self coupling λ_H (next slides)

Analysis at lepton colliders

crash course for a hadron collider physicist

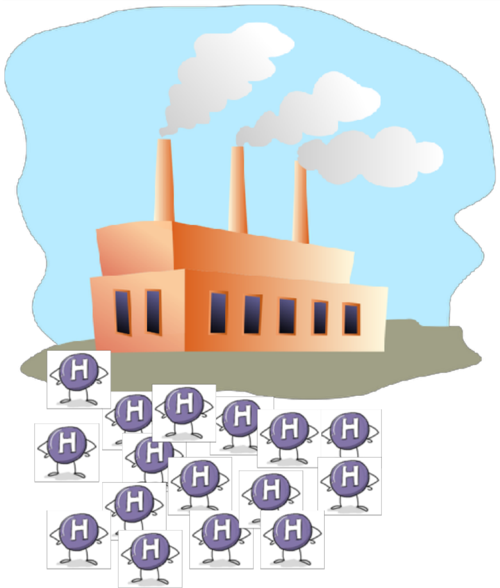
- At lepton colliders, measurement of photons from ISR can be used to **accurately measure centre-of-mass** of each event
- Triggers are not really an issue typically
- Relatively **few backgrounds that are SM-based (few 'fake' backgrounds)ß**
- Strategy jet reconstruction is very different: typically fitting all information in event for the expected jet multiplicity
  - And different jet reconstruction algorithms
  - So effectively *always* 4 jets in HH->bbbb, ttbar->l+jets, etc

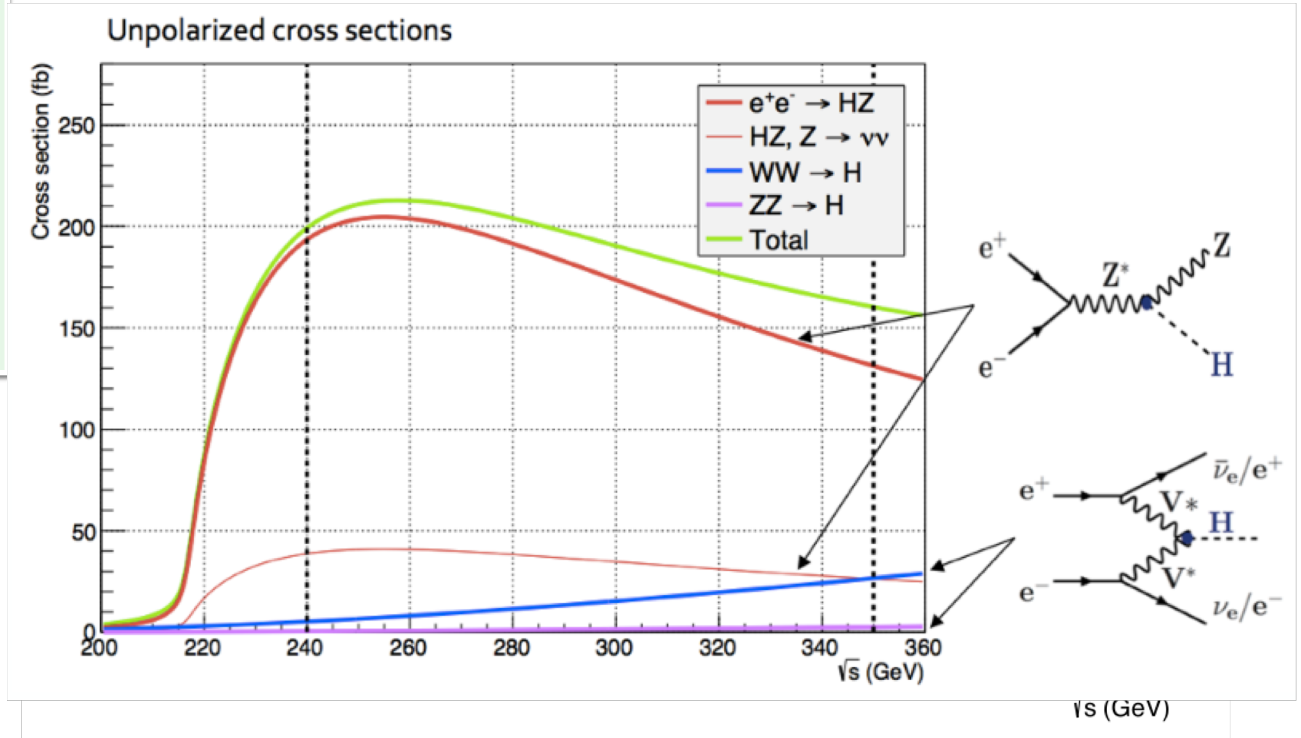




Higgs width at FCC-ee (or CPEC)

FCC-ee
5 ab-1@240 GeV
~1.5 ab^{-1}@365 GeV





	FCC-ee 240 GeV	FCC-ee 365 GeV
Total Integrated Luminosity (ab^{-1})	5	1.5
# Higgs bosons from $e^+e^- \to HZ$	1,000,000	180,000
# Higgs bosons from fusion process	25,000	45,000

Higgs Factory!

VRIJE UNIVERSITEIT BRUSSEL

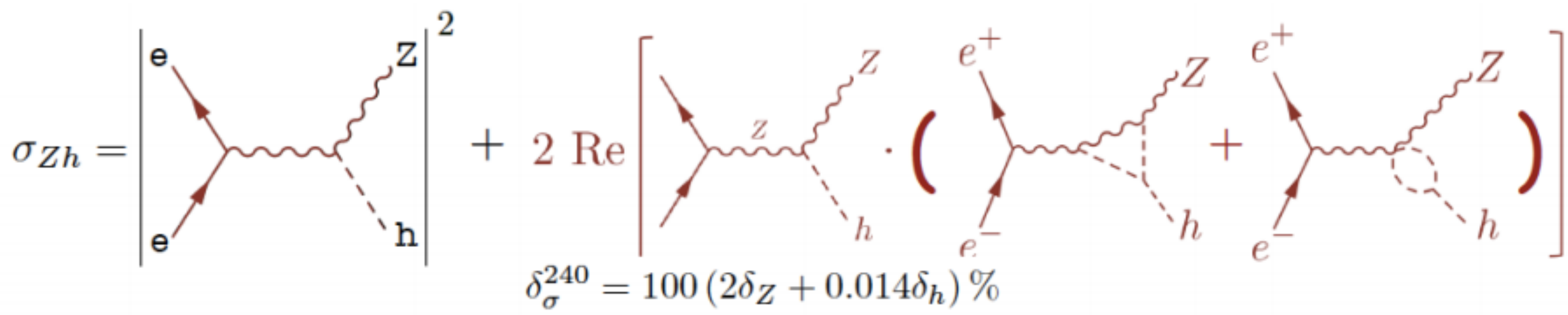
Comparison with other e^+e^- colliders

- Just from the sheer number of Higgs bosons, CPEC and FCC-ee have a clear gain beyond other ee colliders

Collider	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	7	6	7	3	4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	1.5
δm_H (MeV)	0.1	14	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$ (%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.68
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$ (%)	6.2	1.9	4.2	1.9	1.4	1.4	0.80
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	3.8
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
BR_{invis} (%)$_{95\%CL}$	SM	< 0.3	< 0.6	< 0.5	< 0.15	< 0.3	< 0.25
BR_{EXO} (%)$_{95\%CL}$	SM	< 1.8	< 3.0	< 1.6	< 1.2	< 1.2	< 1.1

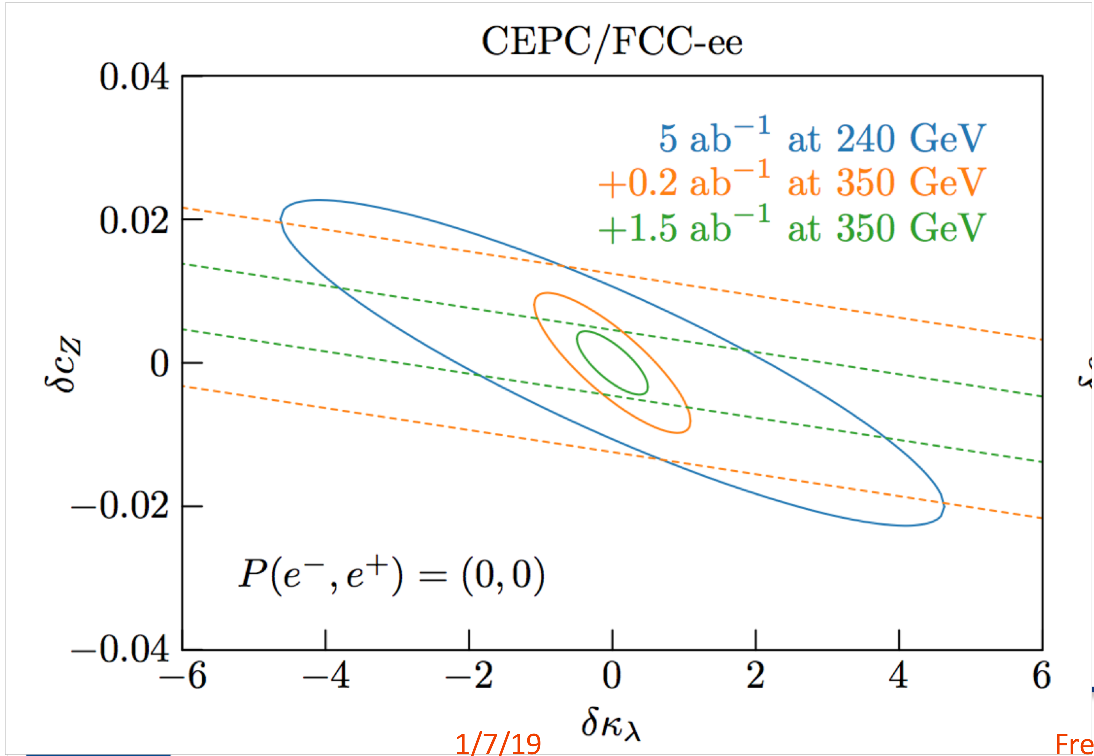
Green = best
Red = worst

Higgs self-coupling



Very large HZ datasets allow g_{ZH} measurements of extreme precision

Indirect and model-dependent probe of Higgs self-coupling



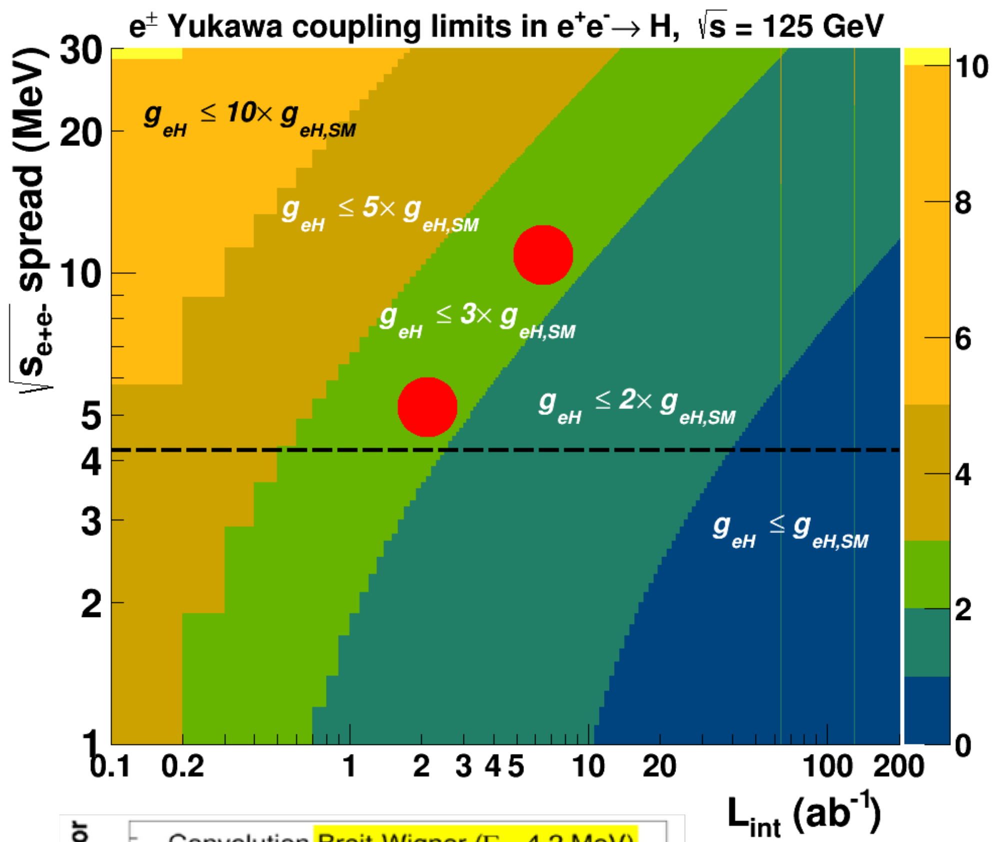
A precision on $\delta\kappa_\lambda$ of ±40% can be achieved, and of ±35% in combination with HL-LHC.

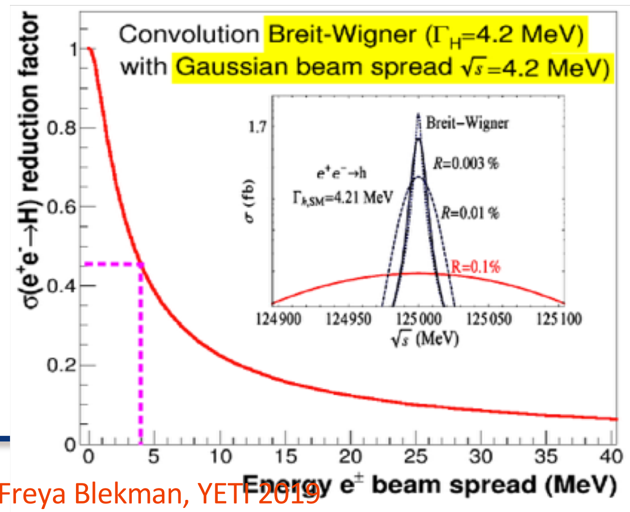
If c_Z if fixed to its SM value, then the precision on $\delta\kappa_\lambda$ improves to ±20%

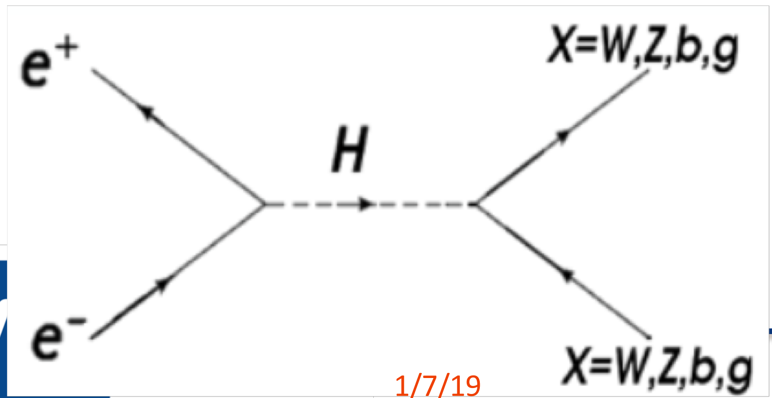
electron Yukawa coupling

s-channel Higgs production

- unique opportunity for measurement close to SM sensitivity
- highly challenging; $\sigma(ee \to H) = 1.6$ fb;
- various Higgs decay channels studied
- studied monochromatization scenarios
  - baseline: 6 MeV energy spread, L = 2 ab^{-1}
  - optimized: 10 MeV energy spread, L = 7 ab^{-1}
  - limit ~3.5 times SM in both cases



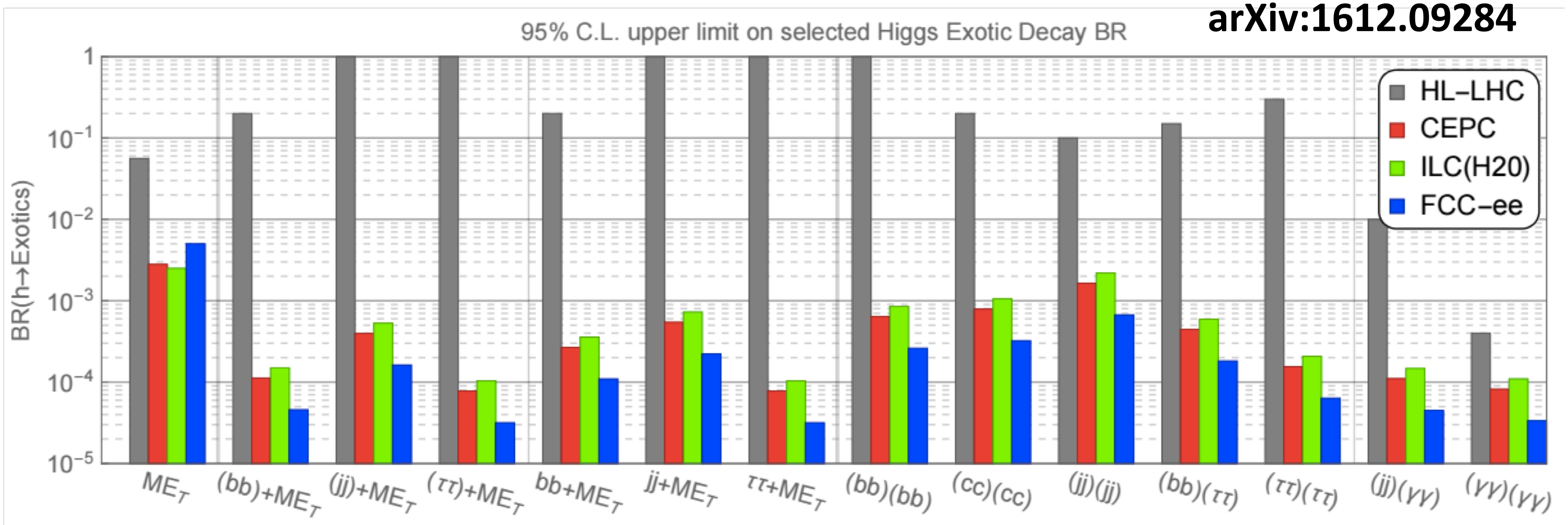




BSM Higgs

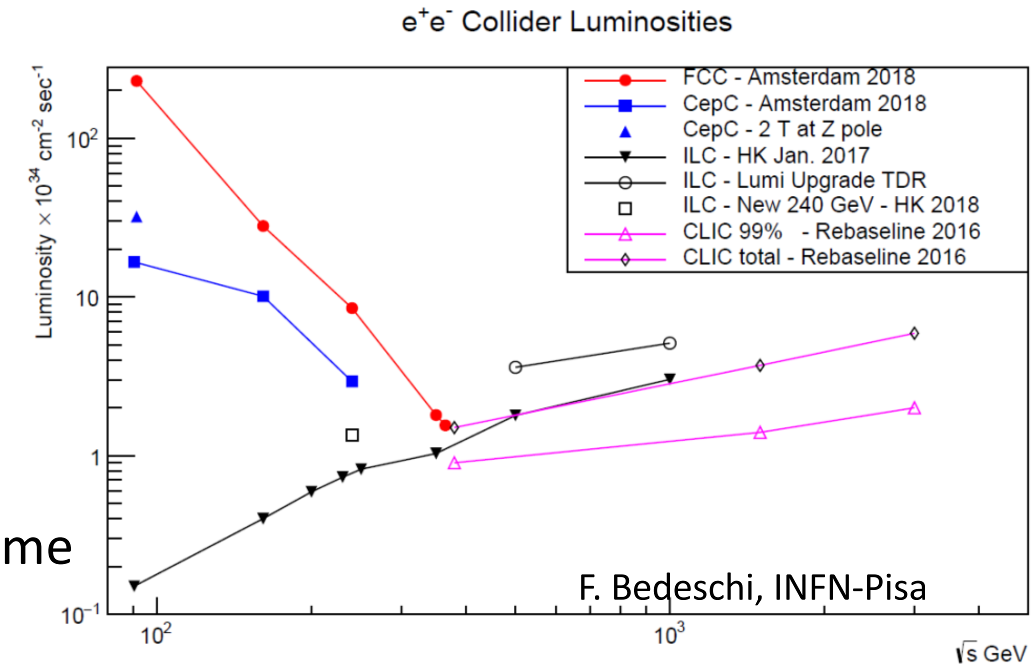
Significant improvement in most rare decay modes sensitive to exotic Higgs decay

arXiv:1612.09284



VRIJE UNIVERSITEIT BRUSSEL

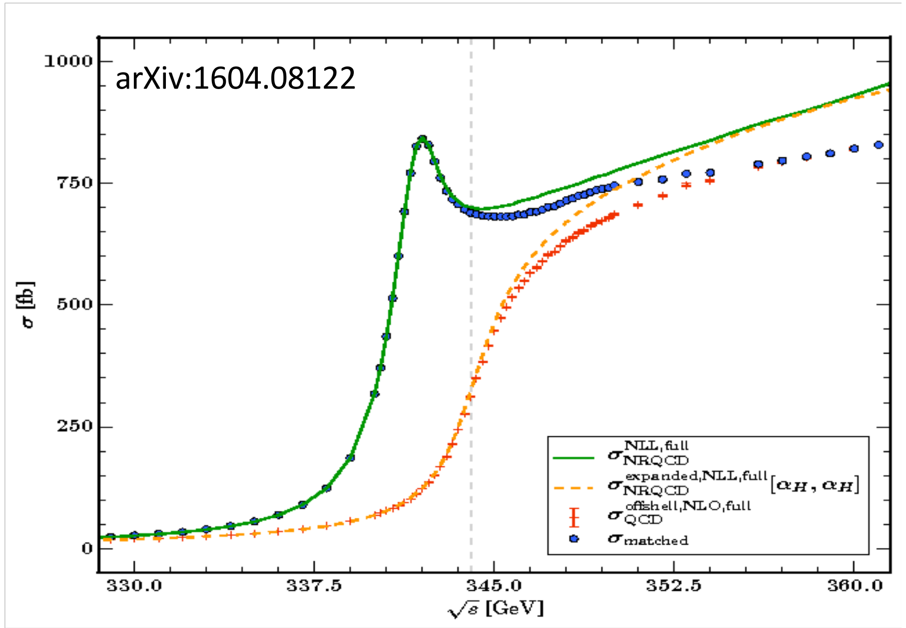
Top physics at lepton colliders

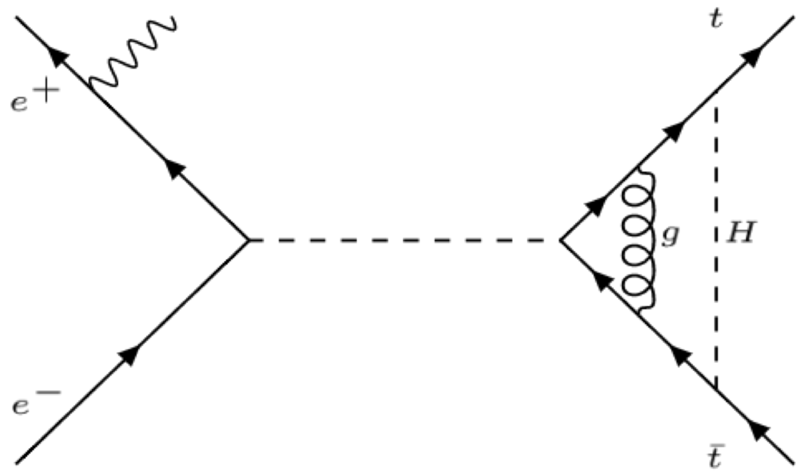


- Where/when does **top** physics come in the programs?
- @350 GeV and just above threshold @370 GeV:
  - cross section ttbar: ~0.5 pb
  - dedicated run at/around $2m_{top}$ '**Mega-Top**'
  - 2 ab^{-1} = 1M top pairs
  - Just above threshold is optimal for top electroweak couplings and other properties measurements
- Top production in the continuum (including searches) at higher energies
- **Single top quark** sample: byproduct of 240 GeV runs at H+Z mass

VRIJE UNIVERSITEIT BRUSSEL

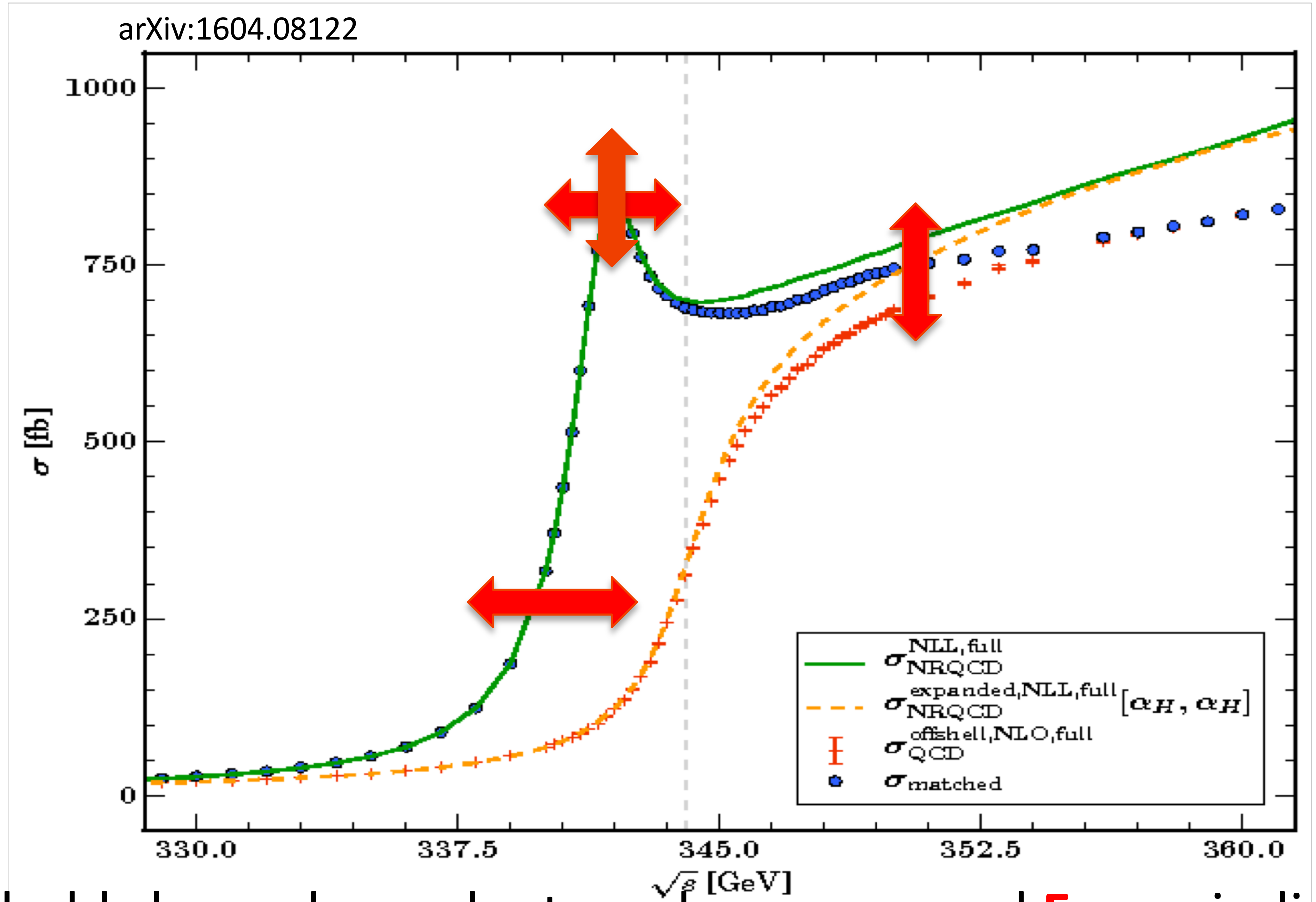
merit of m_{top} threshold scan





- Most ee colliders aim to measure α_s with unprecedented precision at Z pole and WW threshold
- Cross section shape depends strongly on top quark mass and width, α_s and Y_t
- Top mass and width can be measured directly with an accurate top cross section threshold scan
  - Improved α_s drastically improves correlations m_t, Γ_t and Y_t

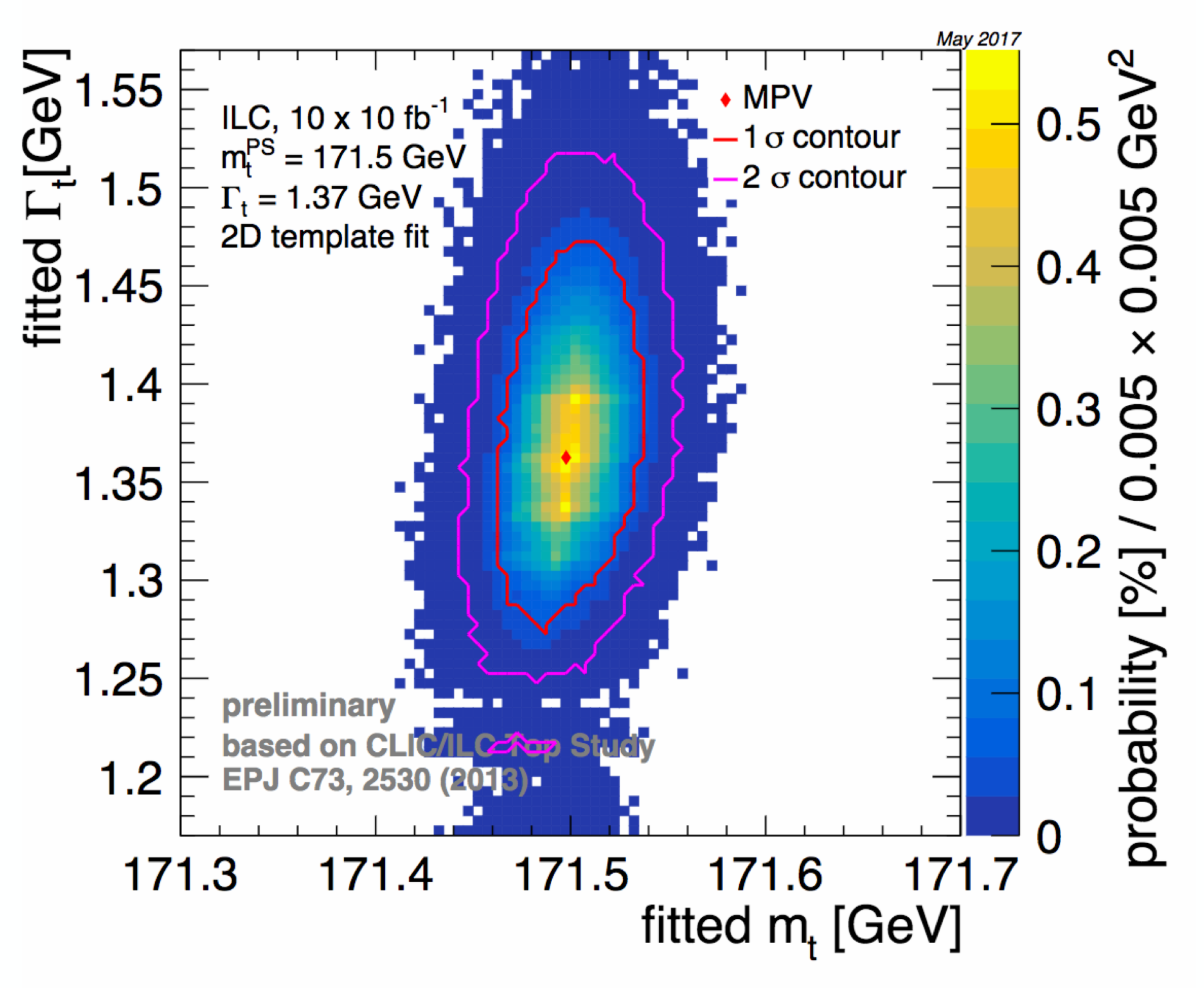
m_{top} threshold scan



- Threshold shape depends strongly on **m_{top}** and **Γ_{top}** so indirectly V_{tb}
- Size of resonance behavior at and above threshold can be used to indirectly constrain **Y_{top}**

VRIJE UNIVERSITEIT BRUSSEL

Mass and width for some ee collider scenarios



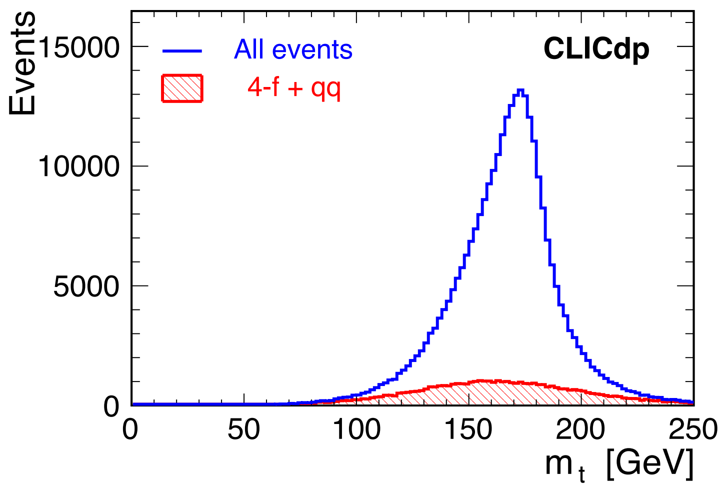
With 0.2 ab^{-1} FCC-ee can achieve following uncertainties:

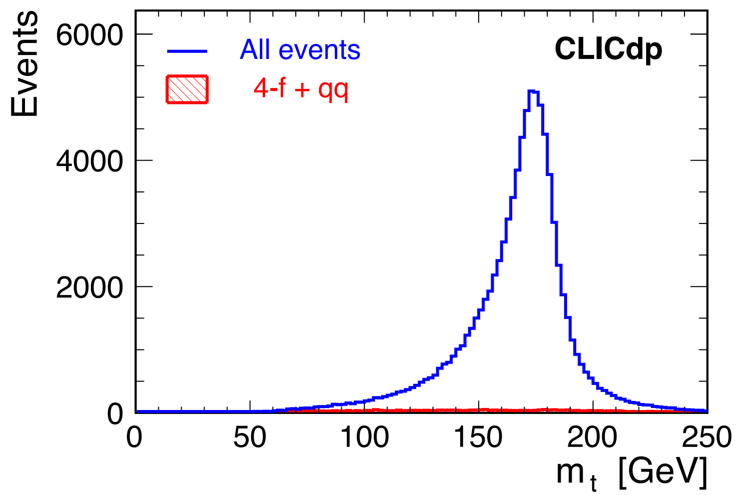
Top mass: 45 MeV
Top width: 17 MeV

F. Simon

CLIC mass measurement: direct and threshold scan

- Measurement using top mass peak possible at all CLIC scenarios
  - Highest statistics at first stage CLIC: 500 fb^{-1} at 380 GeV





- All hadronic: statistical uncertainty on mass 42 MeV
- Semi-leptonic: statistical uncertainty on mass 56 MeV

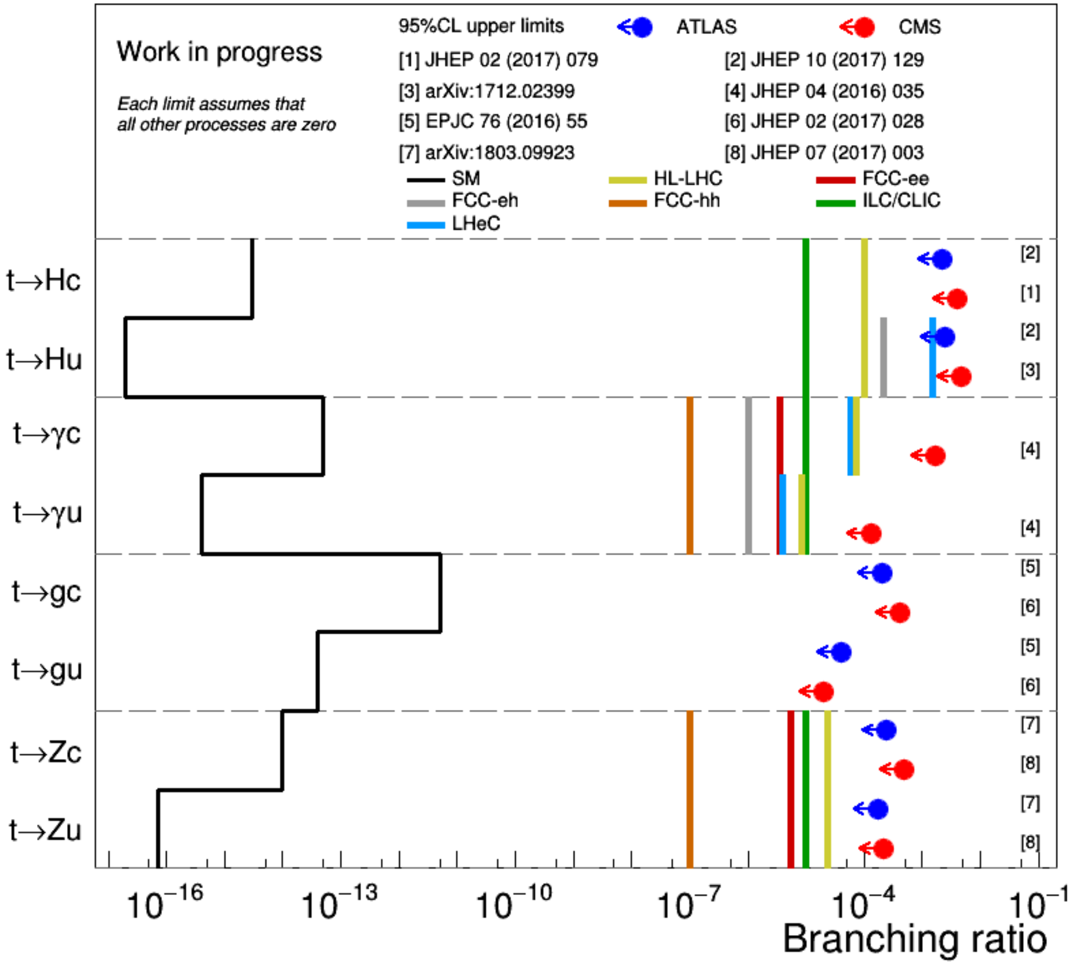
- Combination all hadronic + semi-leptonic:: 40 MeV!

CLIC has excellent top physics overview paper: 1807.02441

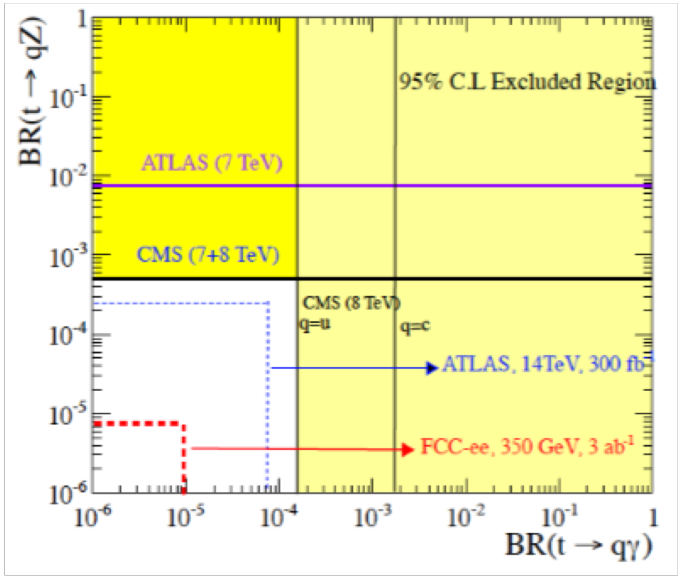
Flavour Changing Neutral Currents

- **FCNC** are one of the best handles on constraining SM/indirectly discovering BSM in the top sector
- Almost all popular BSM extensions predict **increased** rare decays of the top quark

Sensitivity FCNC: 95% CL exclusion limits



Example:FCC-ee expects to substantially improve beyond HL-LHC



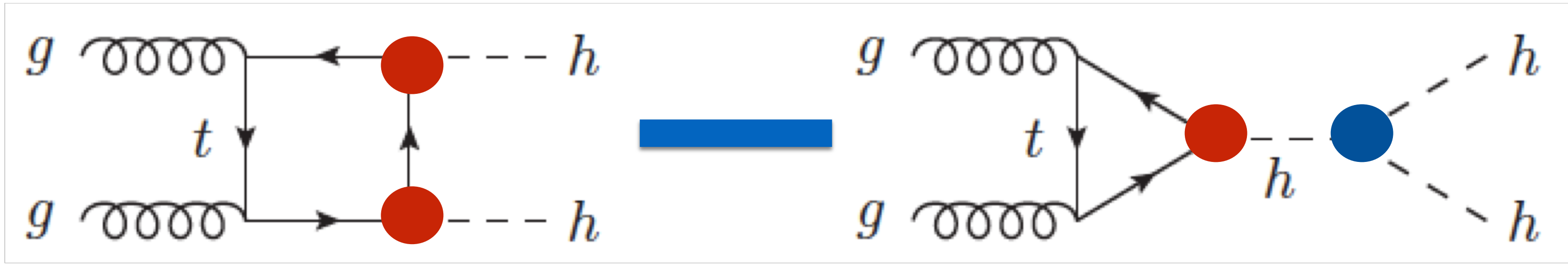
CDRs in preparation, many new/updated Numbers available soon!

Outlook

- Lepton Colliders= **Precision** physics with **BSM** sensitivity
  - Lepton colliders offer **unexplored physics** and unprecedented precision
  - **Four** potential ee machines – physics input/studies ongoing
    - CLIC and FCC-ee have ttbar in their 'standard' programme, for CPEC and ILC it is part of the upgrade planning
  - Knowledge most S**M parameters** accessible can be improved by **factors > 10** if sample is large enough
    - **Example: Top quark mass and width** can be measured down to **16 MeV** and **37 MeV** respectively, depending strongly on size of sample and accelerator scenario
- **Not all work is done – CDRs have appeared but your help is needed to make these machines happen**
  - And your opinion is even more important!
  - Many **opportunities for new ideas** for interesting short (and not-so-short) studies in collider physics

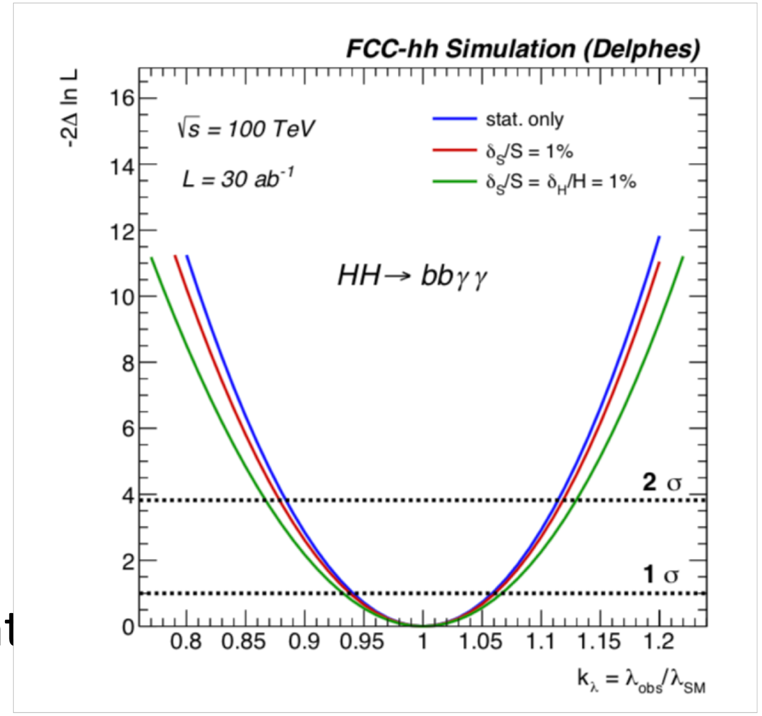
Backup

Higgs self-coupling at FCC-hh



$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

EFT Lagrangian



Enormous di-Higgs samples produced at FCC-hh

- σ(100 TeV) / σ(14 TeV) ≅ 40
- L (FCC-hh) / L (HL-LHC) ≅ 10
- Naively, factor 20 smaller statistical uncertaint

Studied a number of final states

- bbγγ most sensitive channel

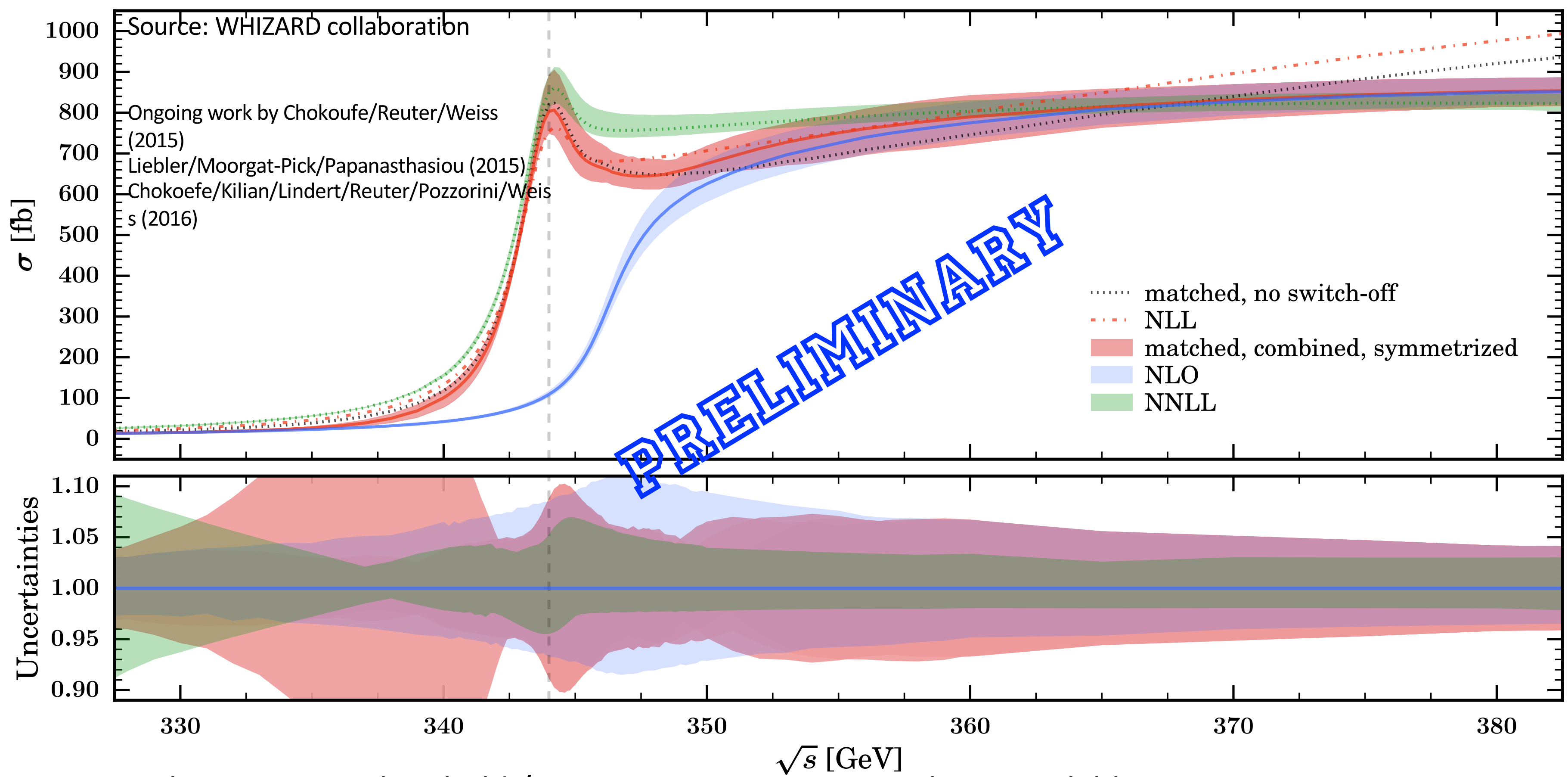
δμ ≅ 2-4%

δϰ ≅ 5%

Details in arXiv:1606.09408 and arXiv1802.01607

VRIJE UNIVERSITEIT BRUSSEL

Simulation of ee-> bWbW

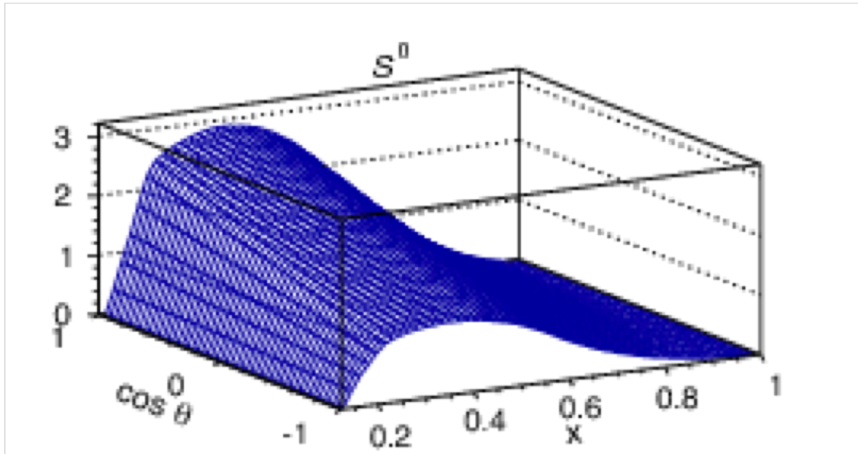


- Complete vNRQCD threshold / QCD-NLO continuum matching available
- Can in principle be reweighted to NNNLO QCD accuracy at threshold
- To do still: EW corrections, semi-leptonic/hadronic top decays, *ttH* threshold matching, top threshold matched with EWcorrections
- WHIZARD 2.6 framework for automated NLO QCD (almost) done → WHIZARD 3.0 [EW in validation]

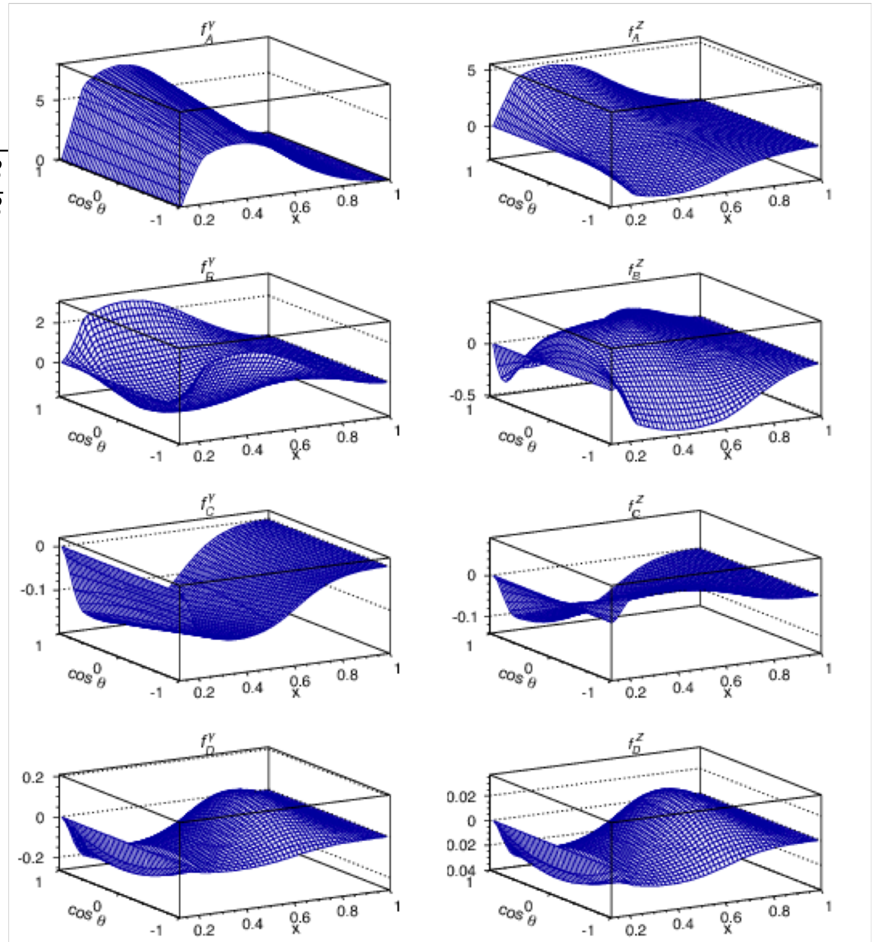
Electroweak couplings to top

$$\Gamma^{\mu}_{ttv} = \frac{g}{2}\left[\gamma^{\mu}\left\{(A_v + \delta A_v) - \gamma_5(B_v + \delta B_v)\right\} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_{\mathrm{t}}}(\delta C_v - \delta D_v \gamma_5)\right]$$

- Each contributes differently to double-differential cross section
  - Lepton angle ($\cos\theta$)
  - x (reduced lepton energy) $\quad x = \frac{2E_\ell}{m_t}\sqrt{\frac{1-\beta}{1+\beta}}$
- Sum contributions fitted to data $SM+\delta A_{Z/\gamma}+\delta B_{Z/\gamma}$



Standard Model



Angular modifications

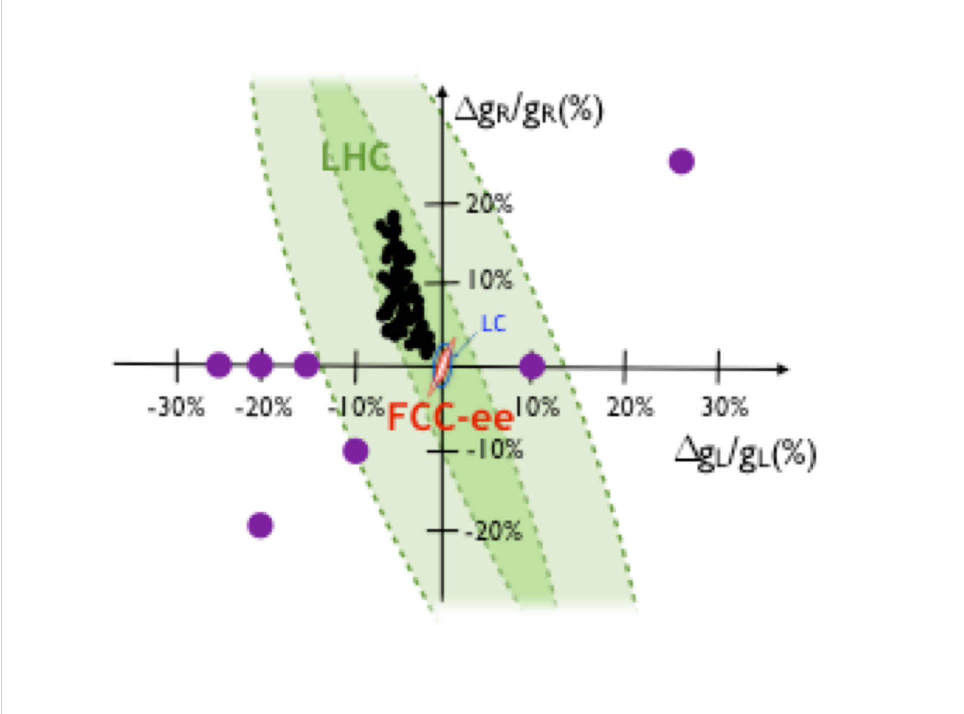
Reference: arXiv: 1503.01325

Constraining BSM with Z/γ to ttbar

- Precision measurement has great potential to constrain BSM
  - $A_{Z/\gamma}$ and $B_{Z/\gamma}$ parameters can be interpreted as g_R and g_L

$$g_L = \tfrac{g}{2}(A_z + B_z)$$

$$g_R = \tfrac{g}{2}(A_z - B_z)$$



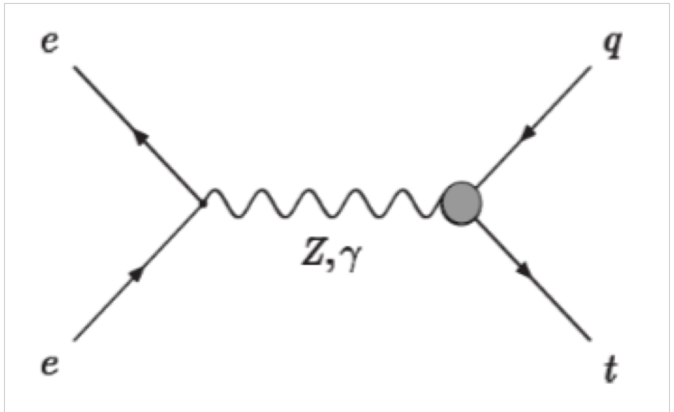
- Cross section constraint of ~2% can be used to constrain BSM well beyond LHC precisions
  - in this case Composite Higgs models

- Note: 2% uncertainty cross section depends on controlling large QCD uncertainties near threshold!
- Currently theory uncertainty at 370 GeV is about 3-4%
  - Larger at 350 GeV
  - We are not far from 2% needed

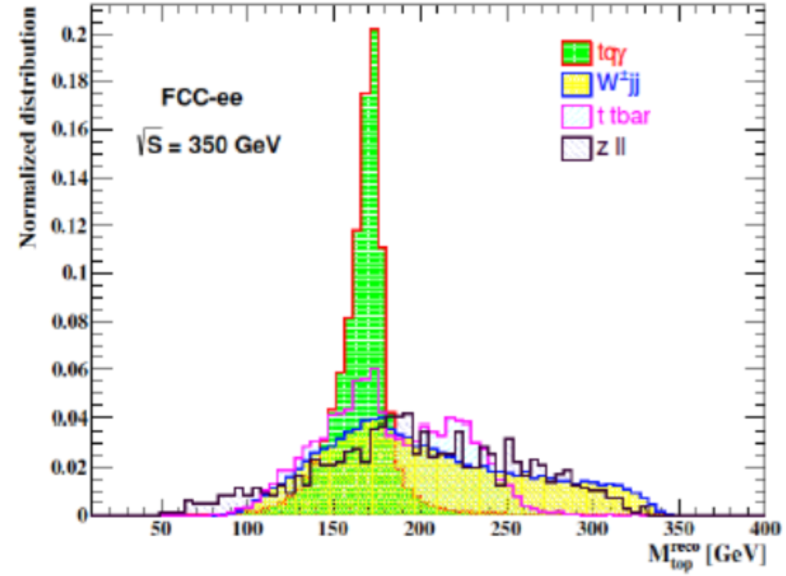
Large and pure 'MegaTop' sample good for FCNC

- In this case taking an **effective Lagrangean** approach

$$\mathcal{L}_{eff} = \sum_{q=u,c} \Big[e\lambda_{tq}\bar{t}(\lambda^v - \lambda^a\gamma^5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} qA^\mu + \frac{g_W}{2c_W}\kappa_{tq}\bar{t}(\kappa^v - \kappa^a\gamma^5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} q\, Z^{\mu\nu} + \frac{g_W}{2c_W}X_{tq}\,\bar{t}\gamma_\mu(x^L P_L + x^R P_R)q\, Z^\mu \Big] + \text{h.c.}$$



- FCNC tqZ and tqγ: top quark+light quark jet final states
  - Due to lower total mass, already **sensitivity at 240 GeV** FCC-ee run (ee --> HZ)
  - Can be analysed in **full hadronic** and **semileptonic** top decays



FCC-ee Clear distinction between tqγ and ttbar in semileptonic final state

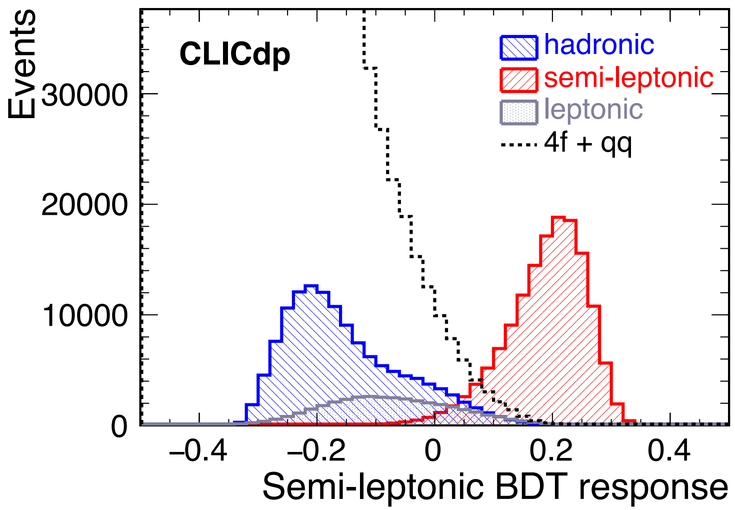
VRIJE UNIVERSITEIT BRUSSEL

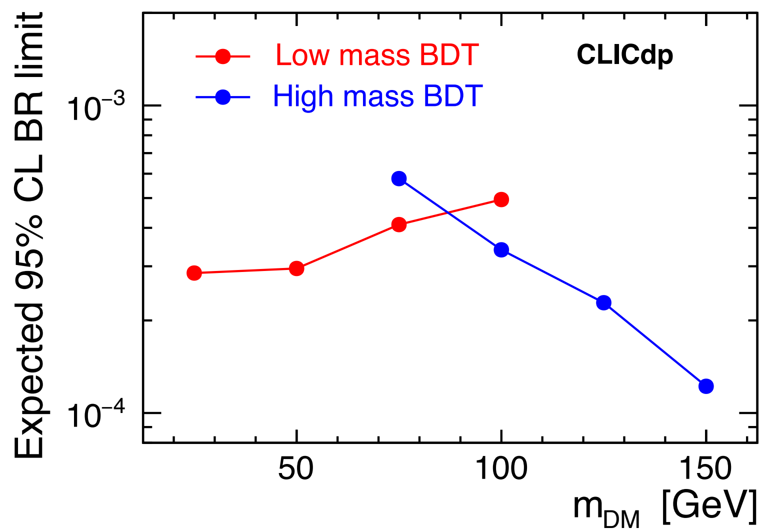
FCNC at CLIC

- Advanced analyses (including machine learning, full simulation) with 380 GeV, 500 fb^{-1} dataset

$$BR(t \to c\gamma) < 4.7 \cdot 10^{-5}$$
$$BR(t \to cH) \times BR(H \to b\bar{b}) < 1.2 \cdot 10^{-4}$$
$$BR(t \to c\not{E}) < 1.2 - 4.1 \cdot 10^{-4}$$

Event classification for $t \to cH$

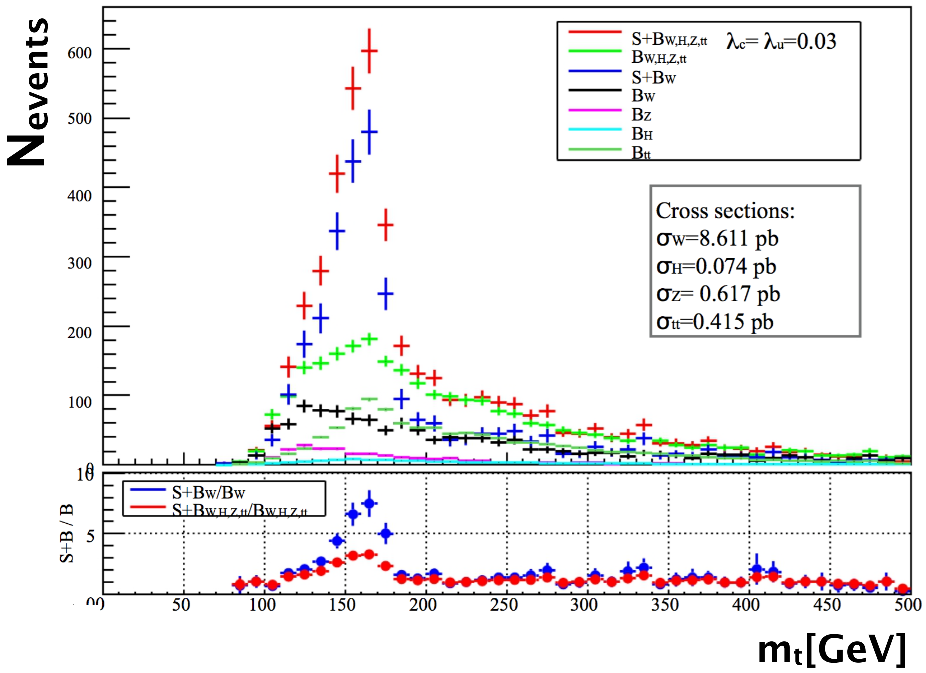


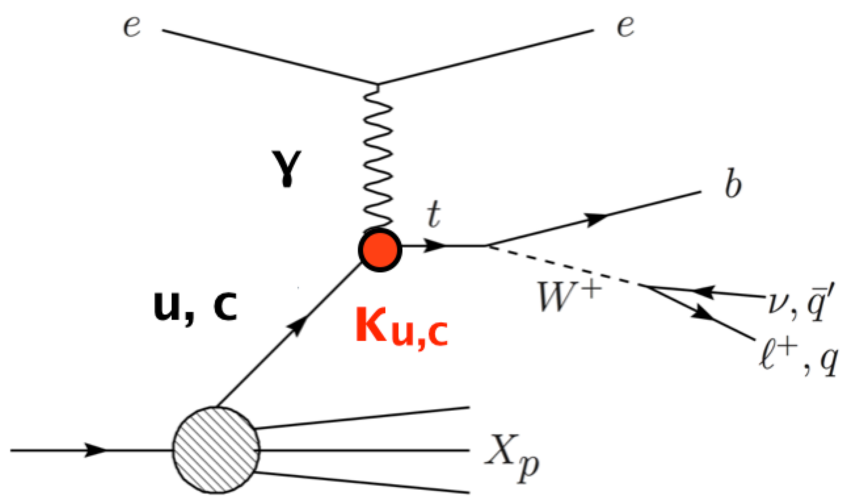


VRIJE UNIVERSITEIT BRUSSEL

Top Quarks in p-e collisions?

- Note that proton-electron collider scenarios also have top physics sensitivity
  - Particularly **FCNC** and V_{tb}

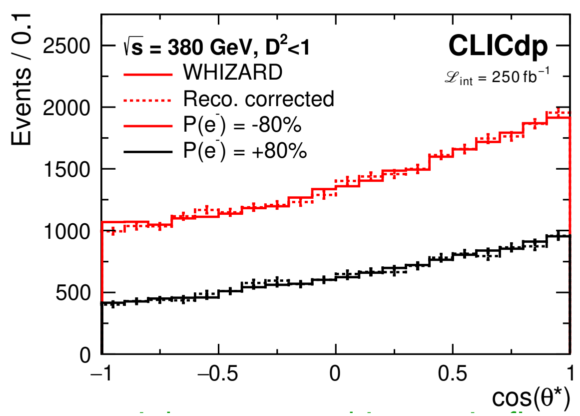




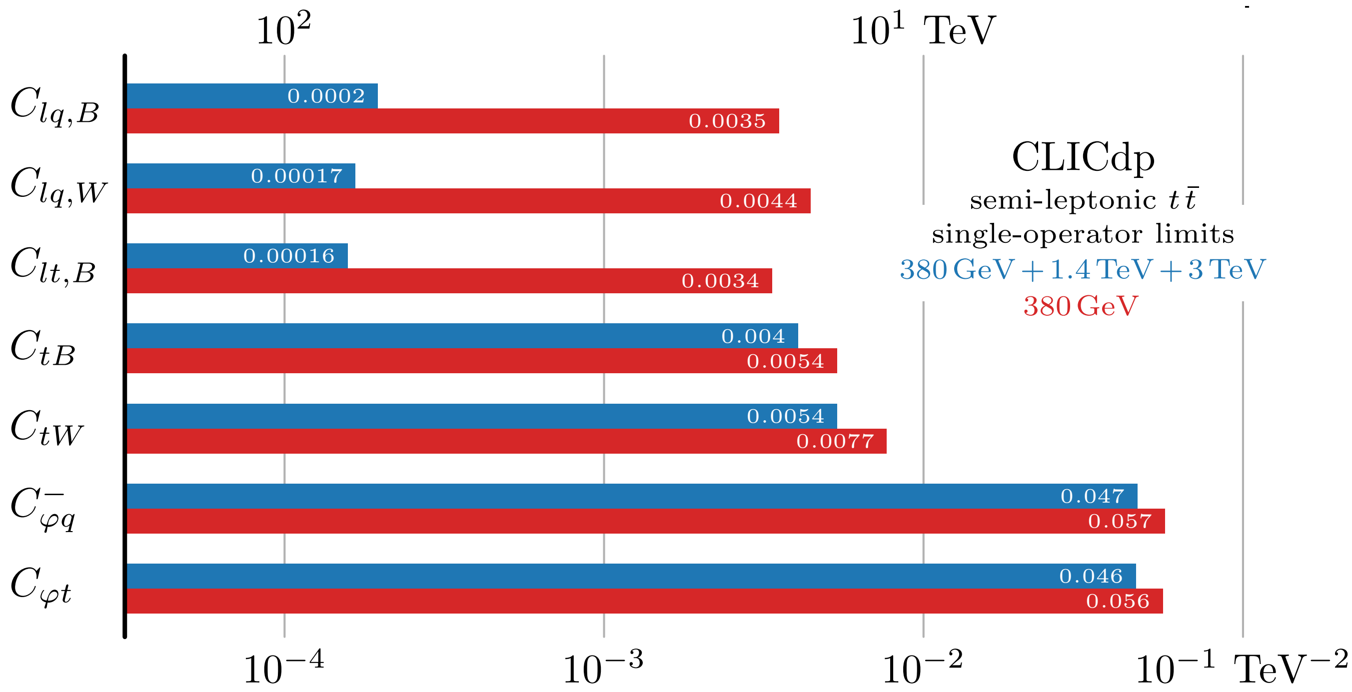
LHeC, 1 ab^{-1}	2σ	3σ	5σ
BR(t->uγ)	4.0×10^{-6}	7.5×10^{-6}	1.5×10^{-5}
BR(t->cγ)	4.0×10^{-5}	9.0×10^{-5}	2.0×10^{-4}

CLIC forward-background asymmetry

- FB-asymmetry directly derived from top quark angular distributions and used to constrain SMEFT

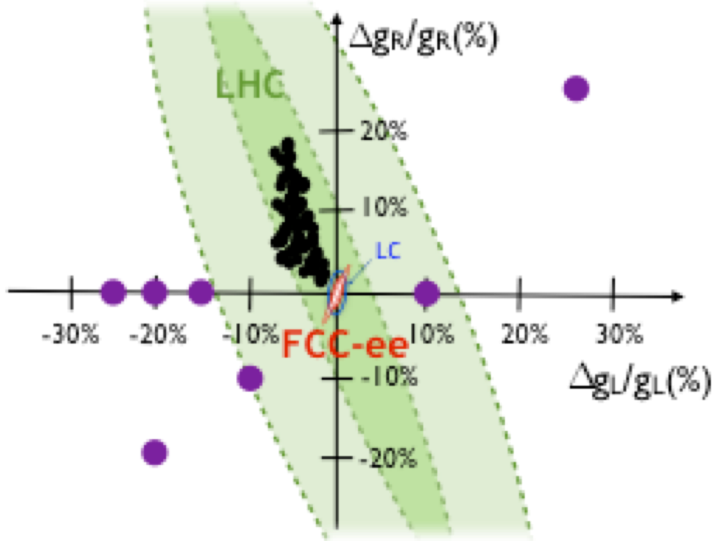


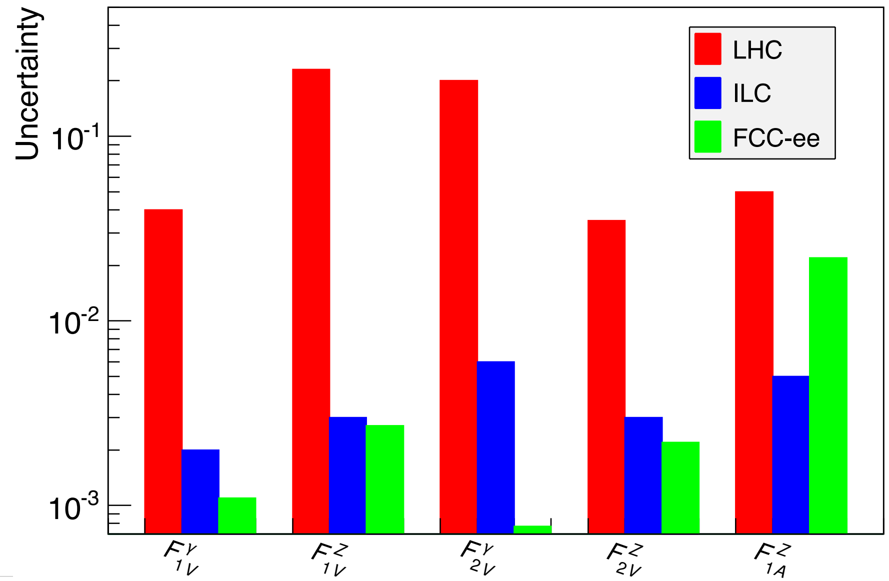
Semileptonic ttbar with tightened kinematic fit to avoid bias on angle



Electroweak couplings to top

- Fit includes conservative assumptions detector performance such as b-tagging, lepton identification and angular/momentum resolution
- Expected precision of order 10^{-2} to 10^{-3}



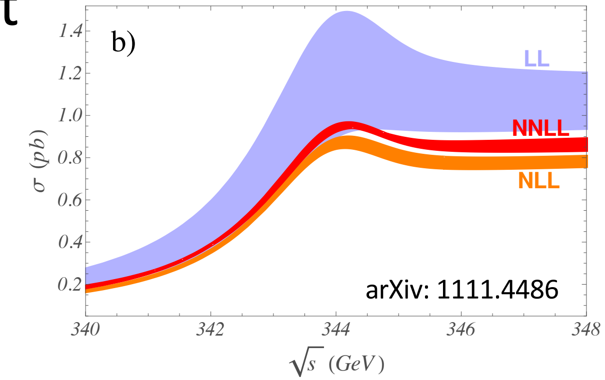


- Expected uncertainty on bounds ttZ/ttγ couplings dominated by theory uncertainty on prediction mechanism
- **Optimal centre-of-mass energy is 365-370 GeV: going for 365!**
- Also confirmed by full analysis using Whizard and assumed FCC-ee detector performance

Reference: arXiv: 1503.01325

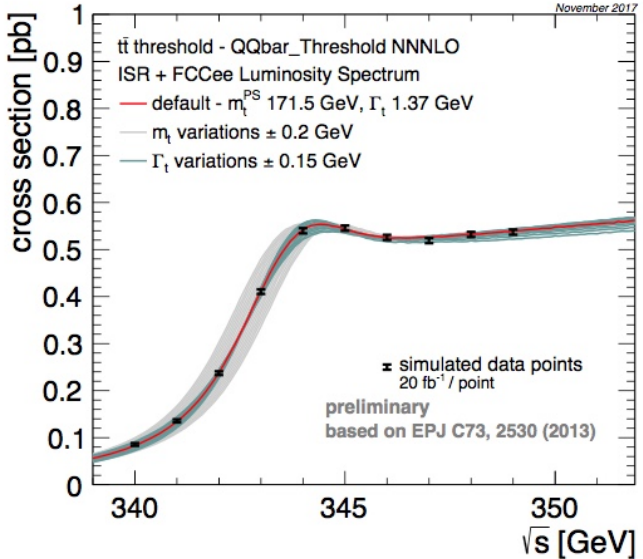
Uncertainties on m_{top}

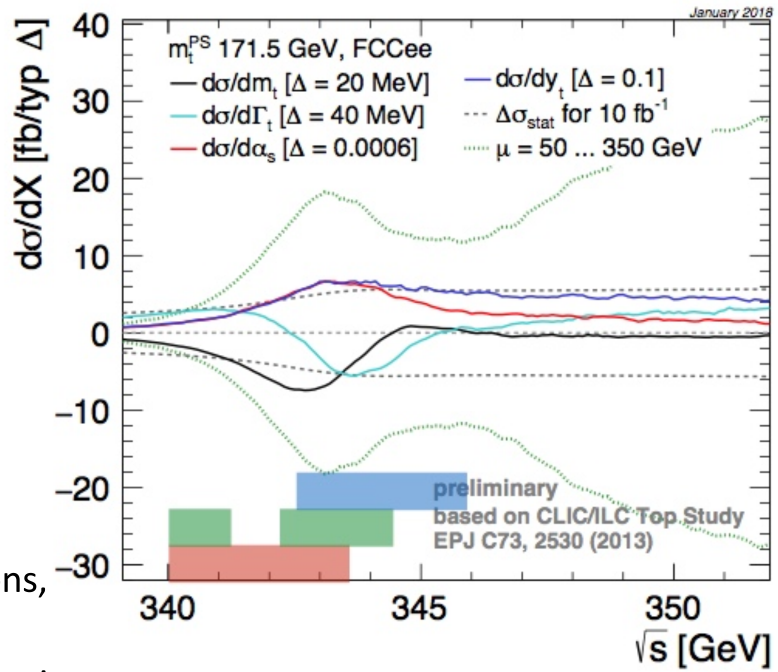
- Uncertainty due to α_S:
  - Δm_{top} = 2.7 MeV × ($\Delta\alpha_s$/0.0001) → **5.4 MeV**
  - Input measured (at FCC-ee) with precision of **$\Delta\alpha_s$ < 0.0002** using W/Z boson hadronic branching fraction
- Theory uncertainty:
  - Description shape e^+e^- to bWbW calculated at NNLL
  - Most important NNLL dependence
    - 1S-MSbar scheme top mass
  - Recent developmenst:
    - Uncertainty m_{top} **23 MeV** (parton shower level)
- Experimental (statistics) uncertainty 8-14 MeV depending on 1D or 2D fit
  - **10 MeV stat uncertainty** m_{top} within reach if theory improvement continues



Threshold scan: what part of the spectrum is sensitive to what

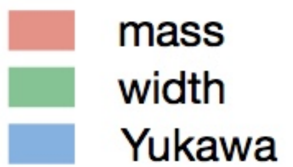
- Spectrum very sensitive to theoretical uncertainties
- One approach: look at derivative of cross section
- Has sensitivity to changes in mass, width, top Yukawa, α_S





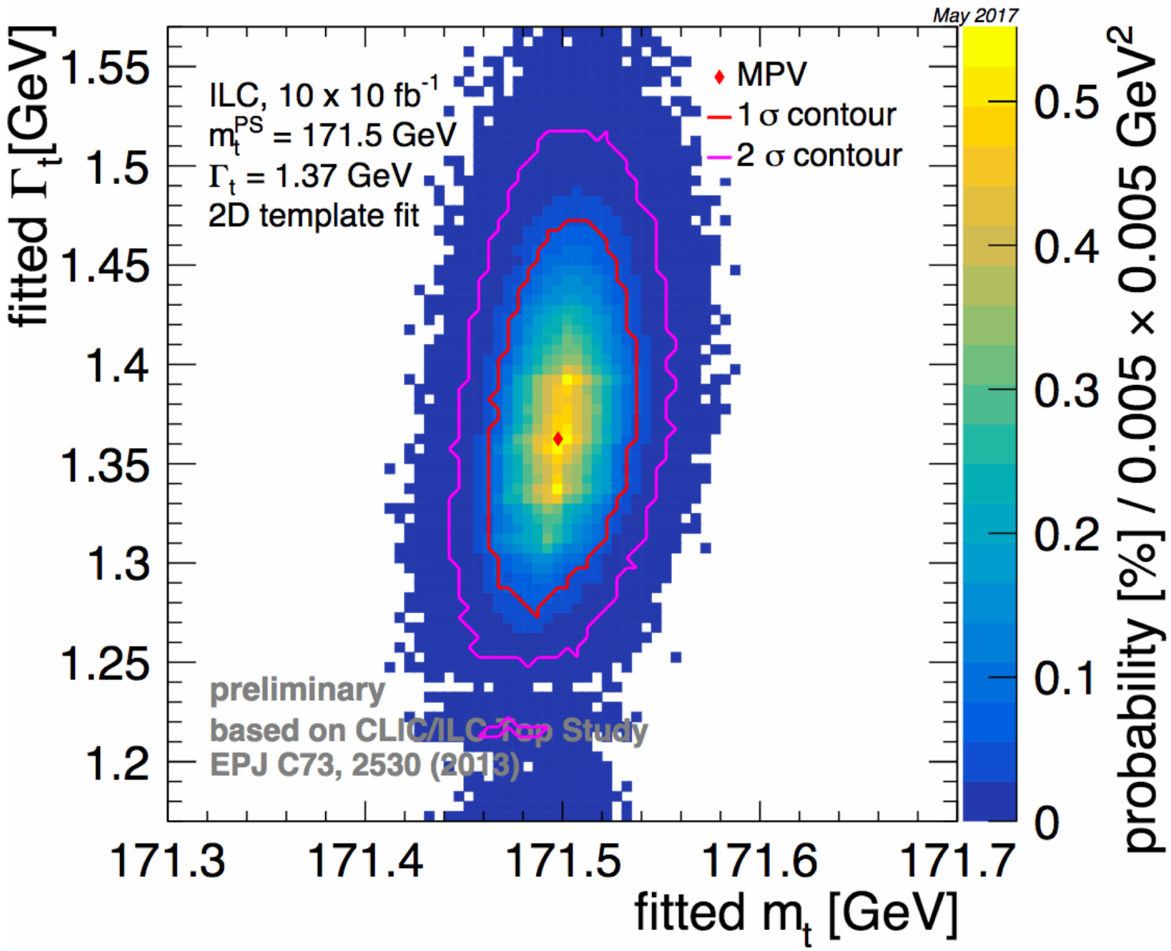
- Leads to parts of spectrum with low sensitivity to scale variations, for example
- Scale uncertainties equivalent to luminosity uncertainties: target is few per mille accuracy
- Uncertainties beam energy can shift by up to 10 MeV!

Sensitivity to



VRIJE UNIVERSITEIT BRUSSEL

Mass and width for some ee collider scenarios



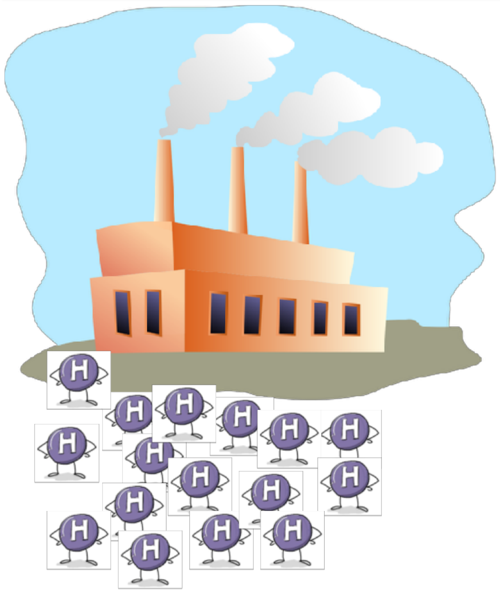
- 1D mass resolution (assuming def. Γ_t)
  18 MeV (ILC)
  21 MeV (CLIC)
  16 MeV (FCCee)
- 1D width resolution (assuming def. m_t)
  43 MeV (ILC)
  51 MeV (CLIC)
  37 MeV (FCCee)
- Extension of 1 σ contour:
  m_t +39 -35 MeV **(ILC)**
  Γ_t +90 -45 MeV
  m_t +40 -45 MeV **(CLIC)**
  Γ_t +130 -95 MeV
  m_t +35 -30 MeV **(FCCee)**
  Γ_t +95 -65 MeV

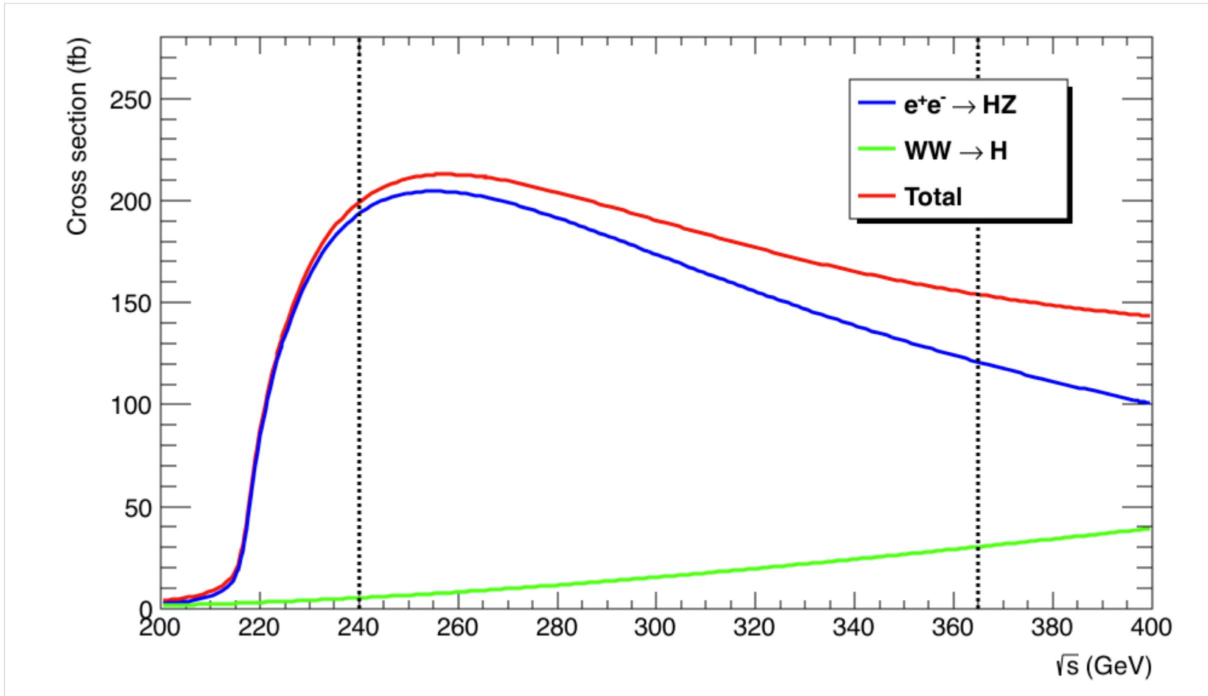
F. Simon

VRIJE UNIVERSITEIT BRUSSEL

Higgs production at FCC-ee (or CPEC)

FCC-ee
5 ab-1@240 GeV
~1.5 ab^{-1}@365 GeV





	FCC-ee 240 GeV	FCC-ee 365 GeV
Total Integrated Luminosity (ab^{-1})	5	1.5
# Higgs bosons from $e^+e^- \rightarrow HZ$	1,000,000	180,000
# Higgs bosons from fusion process	**25,000**	**45,000**

Higgs Factory!

Higgs boson couplings

Precision Higgs coupling measurements

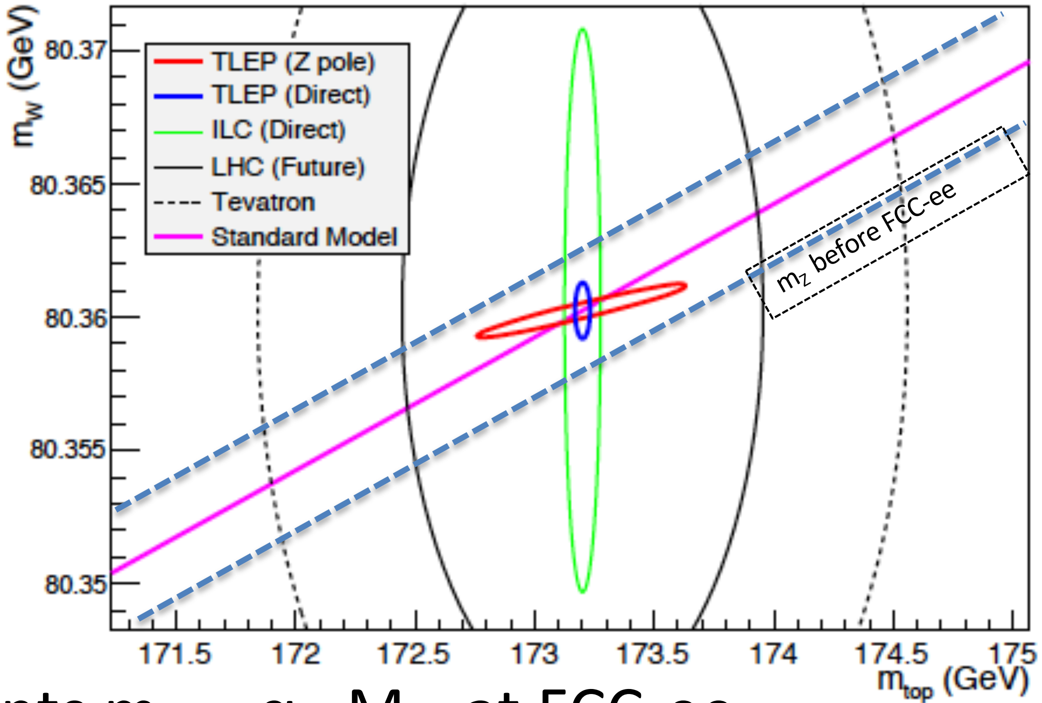
- Absolute coupling measurements enabled by HZ cross section and total width measurement
- Data at 365 GeV constrain total width
  - only used $H \to bb$ in fusion production so far
- Tagging individual Higgs final states to extract various Higgs couplings
- Couplings extracted from model-independent fit
- Statistical uncertainties are shown for 5 ab^{-1}@240 GeV and 1.5 ab^{-1}@365 GeV (from arXiv:1308.6176)
  - all measurements are under review / are being redone
  - possible improvements of 10-35% on cross section measurements

in %	FCC-ee 240 GeV	+FCC-ee 365 GeV	+HL-LHC
δg_{HZZ}	**0.25**	**0.22**	**0.21**
δg_{HWW}	**1.3**	**0.47**	**0.44**
δg_{Hbb}	**1.4**	**0.68**	**0.58**
δg_{Hcc}	**1.8**	**1.23**	**1.20**
δg_{Hgg}	**1.7**	**1.03**	**0.83**
$\delta g_{H\tau\tau}$	**1.4**	**0.8**	**0.71**
$\delta g_{H\mu\mu}$	**9.6**	**8.6**	**3.4**
$\delta g_{H\gamma\gamma}$	**4.7**	**3.8**	**1.3**
δg_{Htt}			**3.3**
$\delta \Gamma_H$	**2.8**	**1.56**	**1.3**

Several couplings improve further by doing a combined fit with HL-LHC

VRIJE UNIVERSITEIT BRUSSEL

Prospectives EWK t-W fits

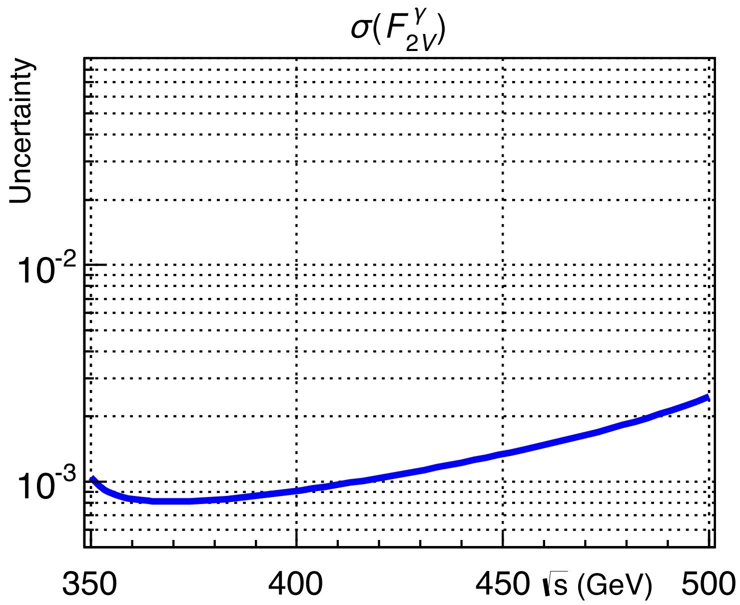


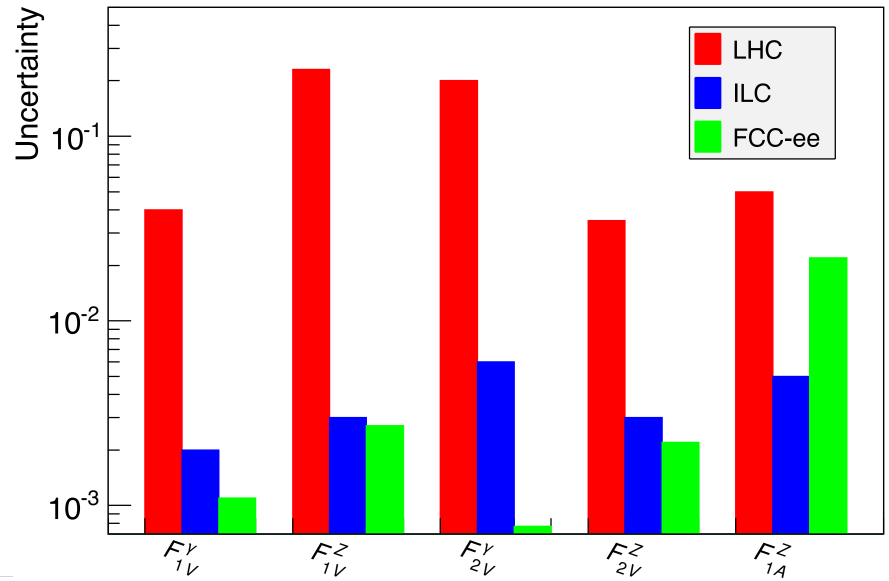
- Improvements m_{top}, α_{S}, M_W at FCC-ee
  - Would improve understanding consistency SM in top-W-H radiative corrections
- Standard Model line uncertainty dominated by Z boson mass error
  - Without FCC-ee it's 2.2 MeV!

VRIJE UNIVERSITEIT BRUSSEL

Electroweak couplings to top

- Fit includes conservative assumptions detector performance such as b-tagging, lepton identification and angular/momentum resolution
- Expected precision of order 10^{-2} to 10^{-3}





- Expected uncertainty on bounds ttZ/ttγ couplings dominated by theory uncertainty on prediction mechanism
- **Optimal centre-of-mass energy is 365-370 GeV: going for 365!**
- Also confirmed by full analysis using Whizard and assumed FCC-ee detector performance

Reference: arXiv: 1503.01325