Science & Technology Facilities Council

Imperial College London

Higgs Couplings:

The expected reach of HL-LHC and prospects beyond that

UK input to the European Particle Physics Strategy Update - Durham

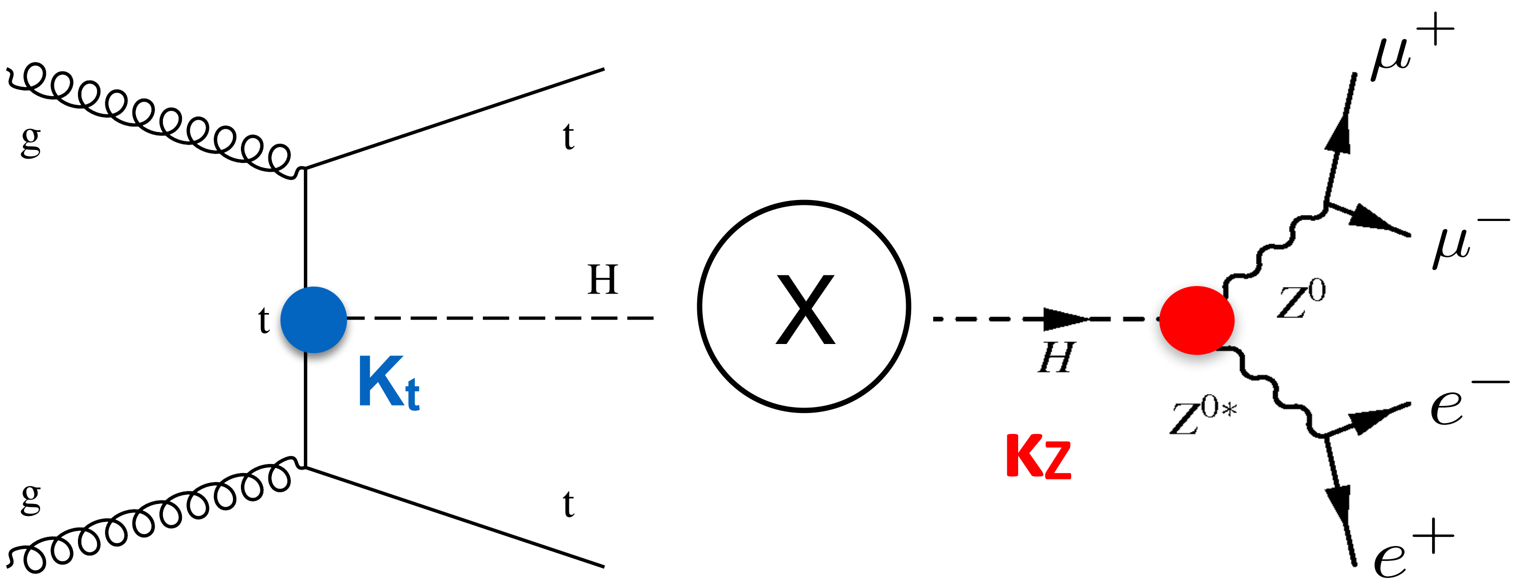
Nicholas Wardle

17/04/2018

Higgs couplings

At LHC we measure are the rates in different Higgs production and decay channels*. At LO, we express them as functions of the coupling modifiers…

$$\sigma(i \rightarrow H \rightarrow f) = \sigma_i(\boldsymbol{\kappa}) \cdot \frac{\Gamma^f(\boldsymbol{\kappa})}{\Gamma_H}$$



$$= \sigma_{\rm SM}({\rm tt}H) \cdot B_{\rm SM}(H \rightarrow {\rm ZZ}) \cdot \frac{\kappa_{\rm t}^2 \kappa_{\rm Z}^2}{\kappa_H^2}$$

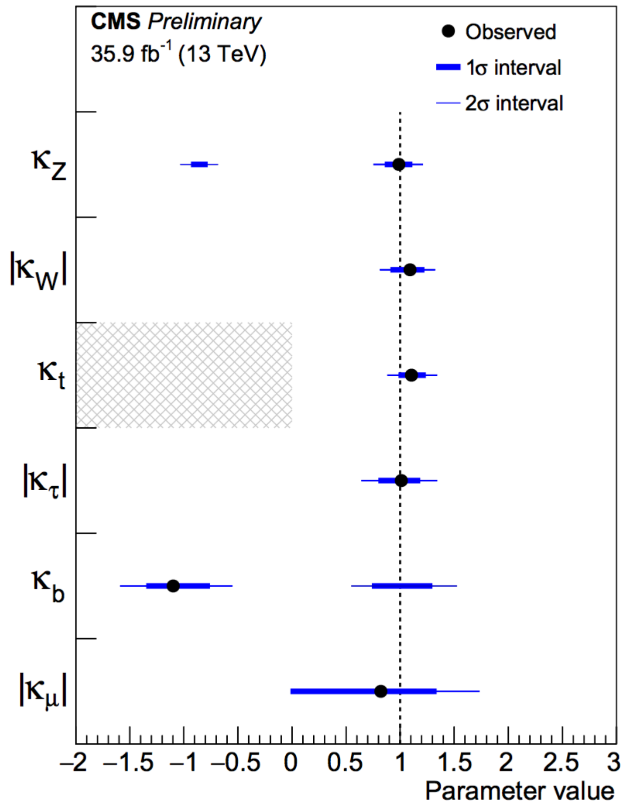
Always make some assumption to avoid degeneracy of scaling all couplings vs scaling total width e.g….

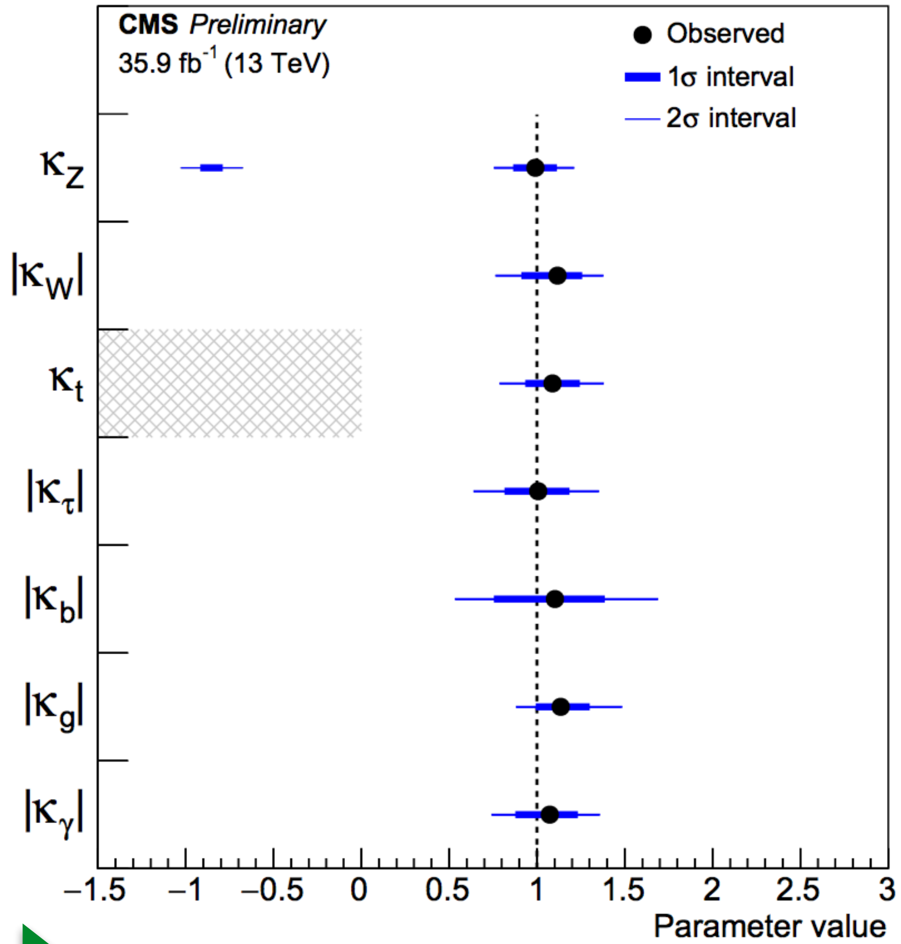
$$\Gamma_H(\boldsymbol{\kappa}) = \kappa_H^2(\boldsymbol{\kappa}) \cdot \Gamma_H^{SM}$$

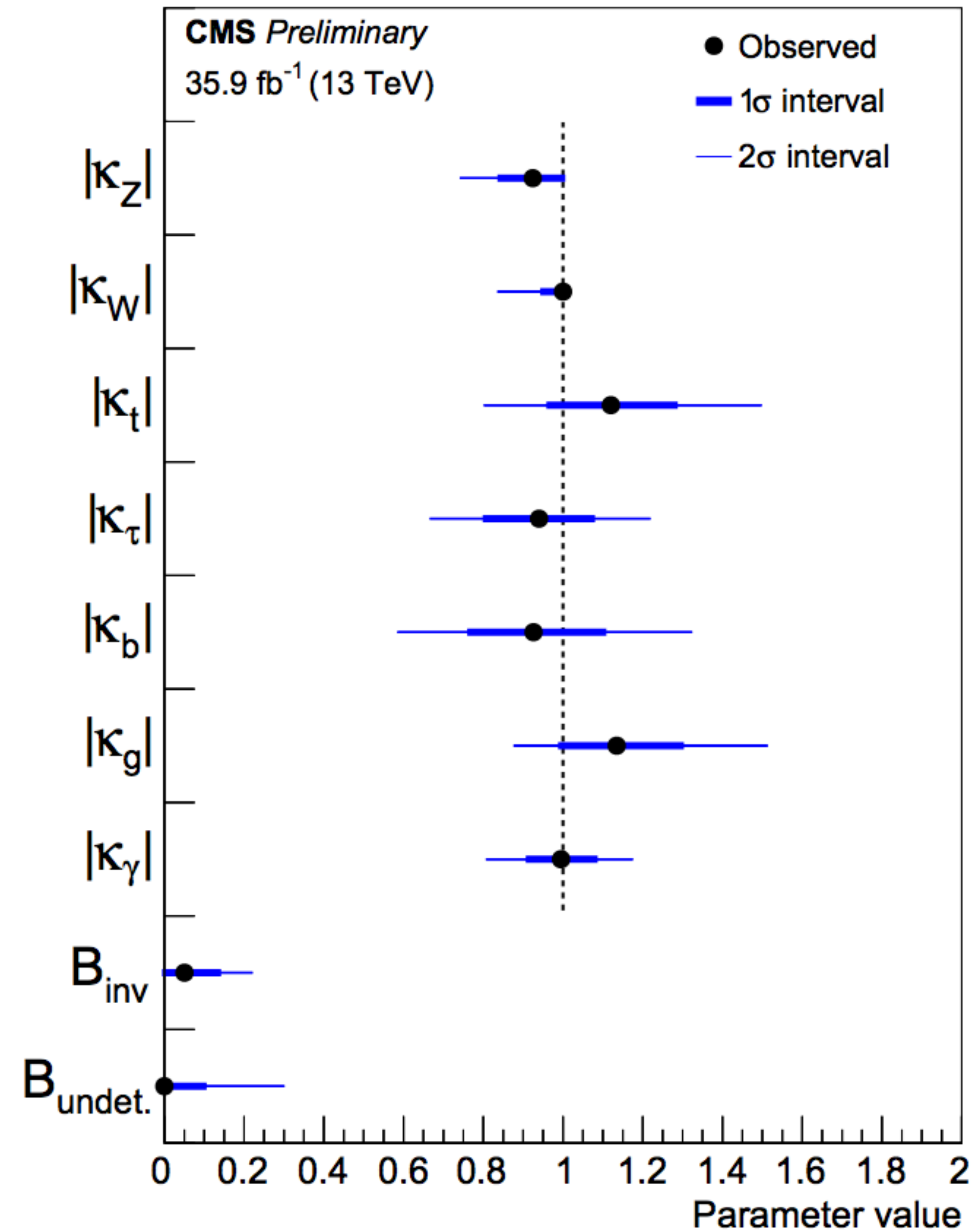
*usually expressed as ratios to SM expectations

Higgs couplings

13 TeV (36fb-1)
CMS-HIG-17-031







+ NP in loops

+ H—>other/NP

Typical scenarios in which LHC extract couplings

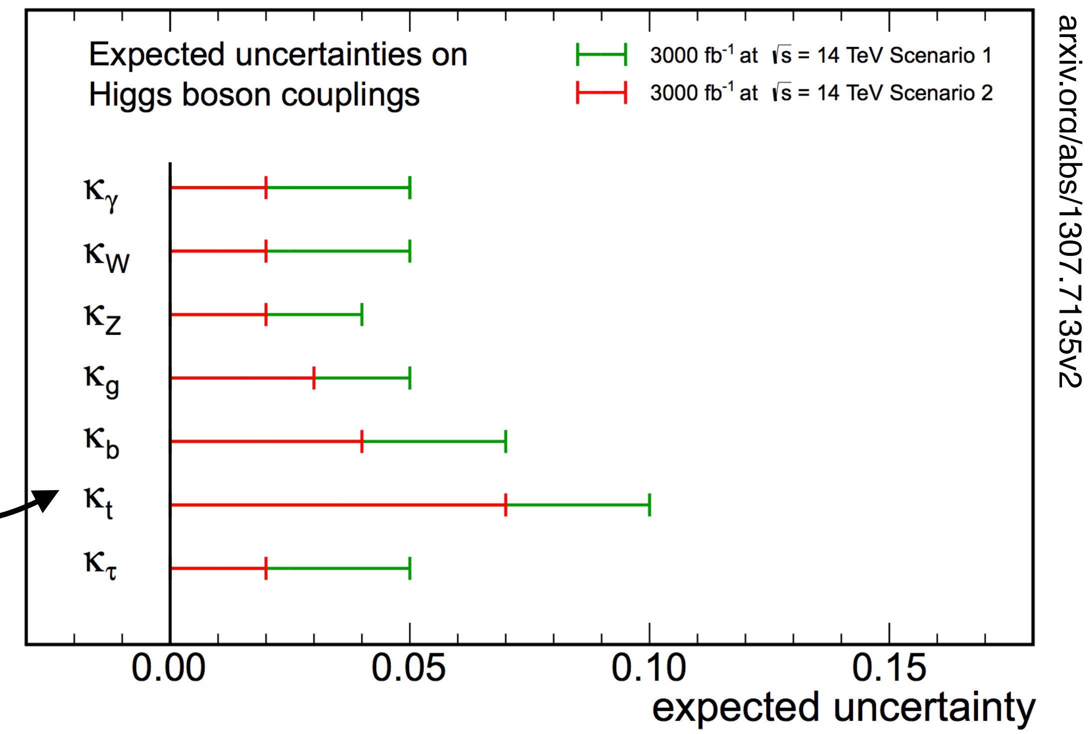
HL-LHC Projections

Coupling projections based on Run-1 combinations assuming

- Similar detector + trigger performances
- Different scenarios for theory uncertainties

S1: Sys uncertainties unchanged
S2: TH. Sys x 1/2, others scale as sqrt(L)

CMS Projection



ATL-PHYS-PUB-2014-016

	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
	All	Half	None	All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Full/half and no theory uncertainties

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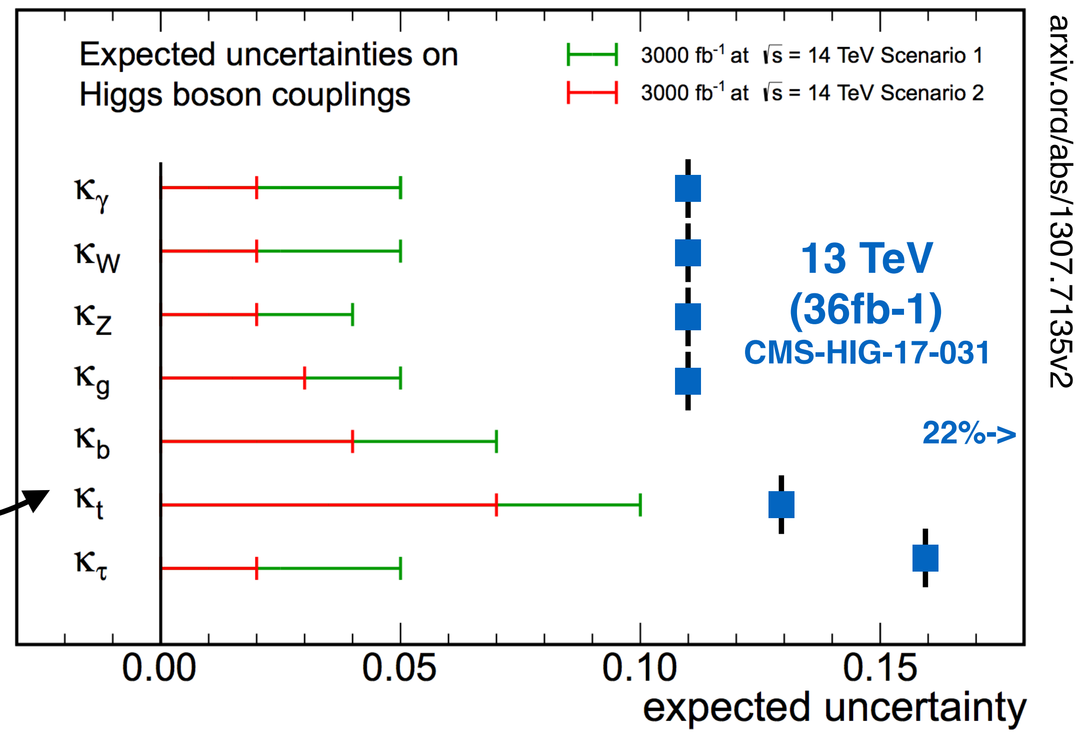

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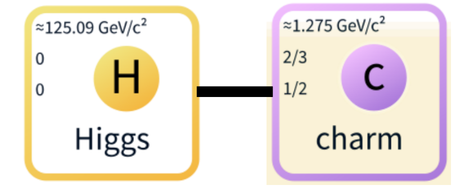
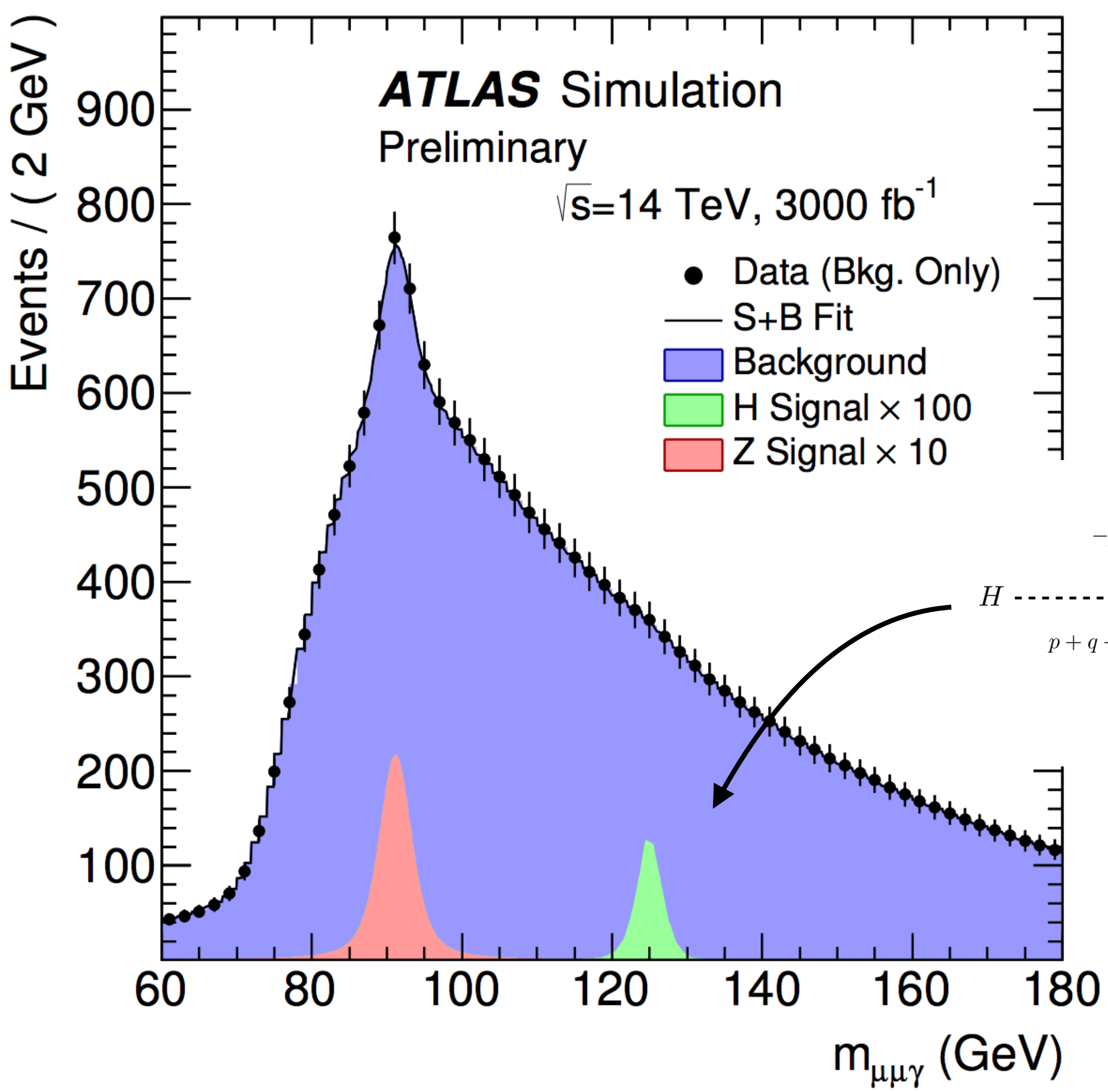
Full/half and no theory uncertainties

HL-LHC Projections

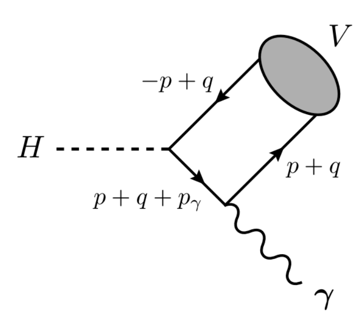


Observation of 2nd generation couplings a major goal of the (current and future) Higgs programme

ATL-PHYS-PUB-2015-043



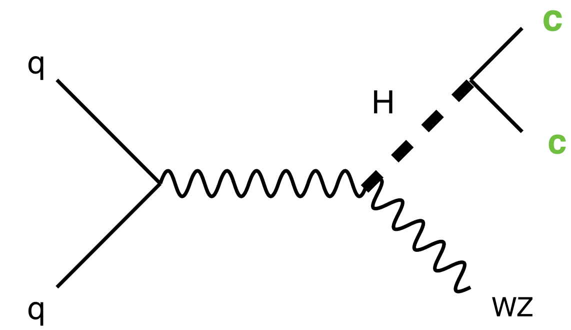
	Expected branching ratio limit at 95% CL		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	Cut Based	Multivariate Analysis	Cut Based
300 fb^{-1}	185^{+81}_{-52}	153^{+69}_{-43}	$7.0^{+2.7}_{-2.0}$
3000 fb^{-1}	55^{+24}_{-15}	44^{+19}_{-12}	$4.4^{+1.9}_{-1.1}$
	Standard Model expectation		
	$\mathcal{B}(H \to J/\psi\gamma)$ [10^{-6}]		$\mathcal{B}(Z \to J/\psi\gamma)$ [10^{-7}]
	2.9 ± 0.2		0.80 ± 0.05

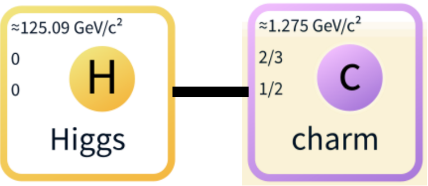


Projection assumes

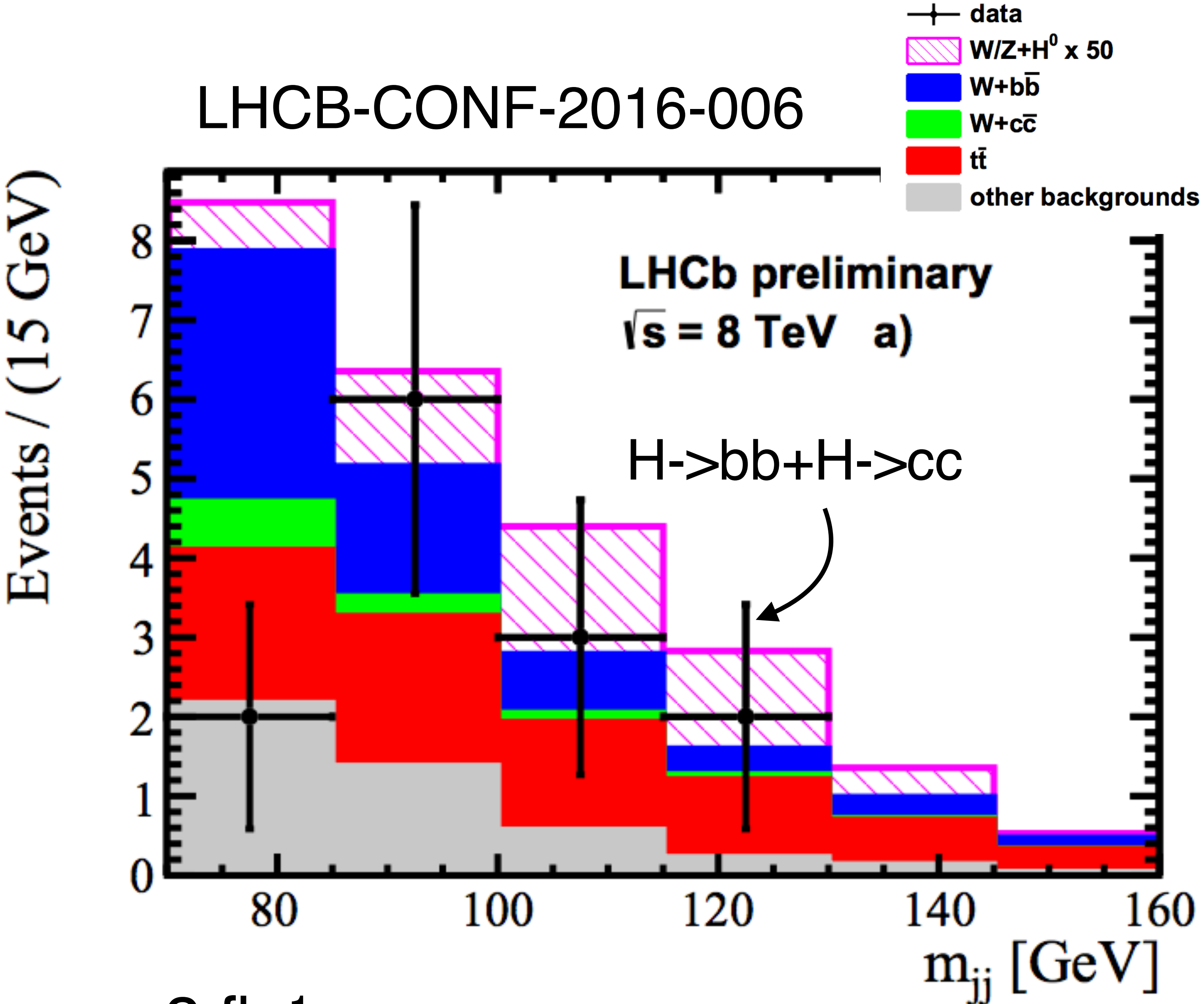
- Similar lepton and the photon reconstruction as in Run1
- Background distribution understood at ~5% level

HL-LHC Projections





LHCB-CONF-2016-006



2 fb^{-1}

σ(VH) B(H->cc) < **9.4 pb** @95%CL
(6200xSM) $|\kappa_c| < 79$

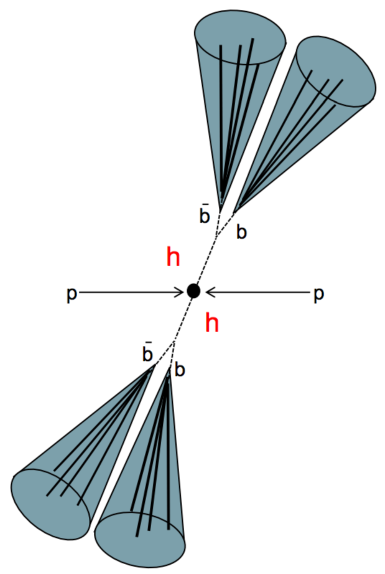
Uli Haisch

- 300 fb^{-1} at 14 TeV: $|\kappa_c| \lesssim 7$
- 30% di-c-tagging efficiency:* $|\kappa_c| \lesssim 4$
- better electron reconstruction: $|\kappa_c| \lesssim 3$
- further improvements: $|\kappa_c| \lesssim 2.2$

Projections from M. Williams

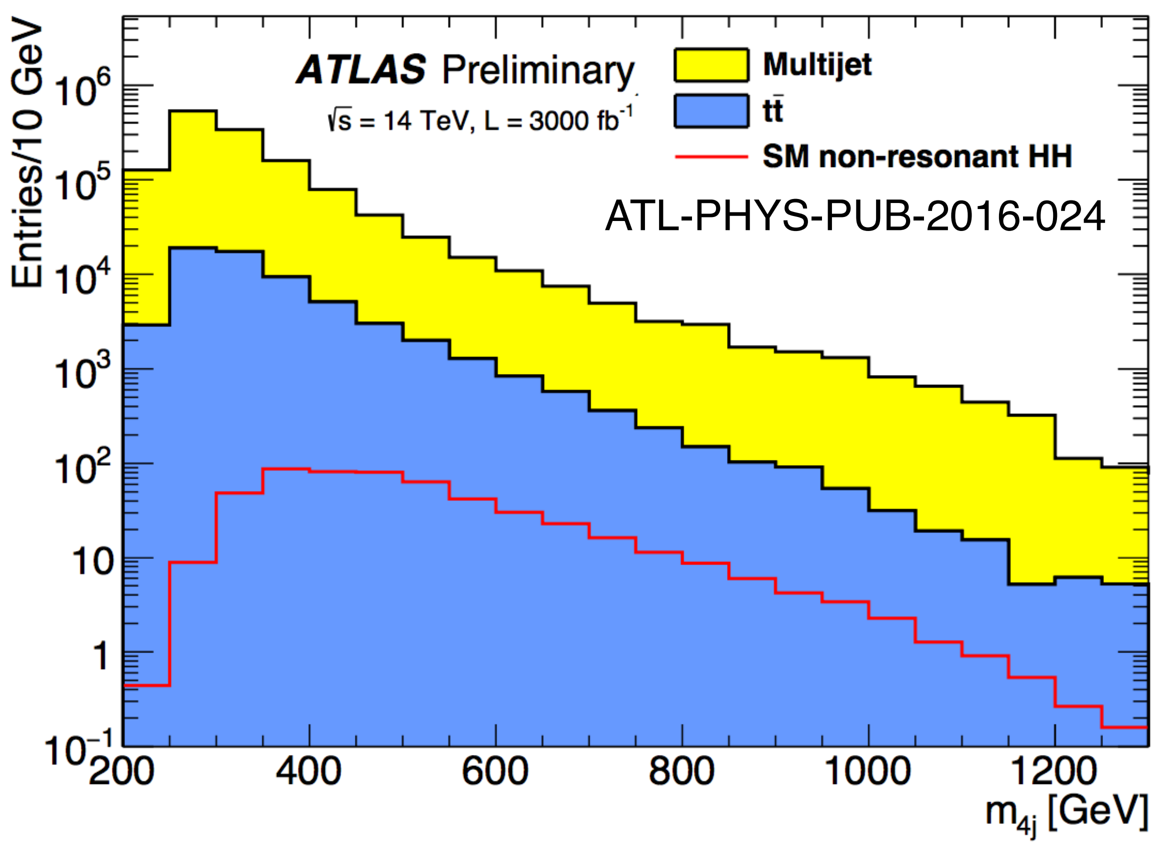
*2% @8 TeV

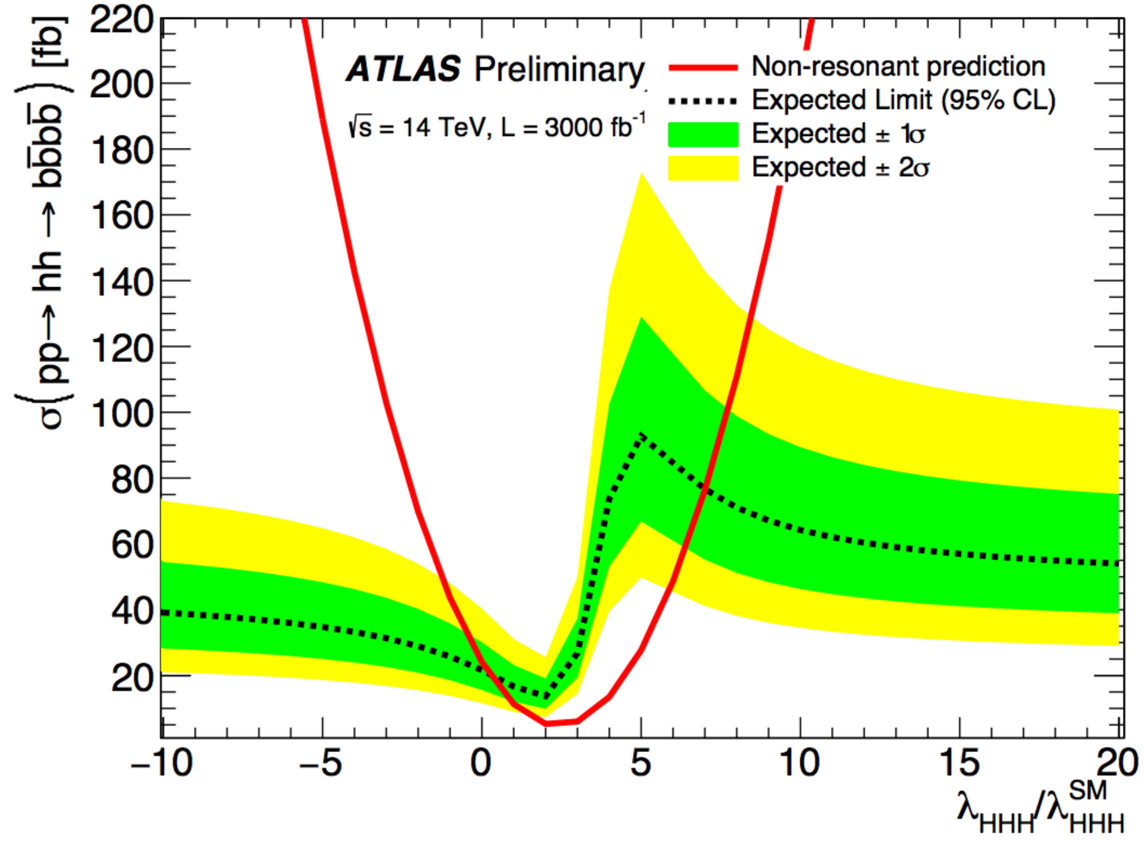
HL-LHC Projections



Target high BR Higgs boson final states at HL-LHC to maximise potential signal yield.

Eg. ATLAS H(bb)H(bb) projections based on Run2 search



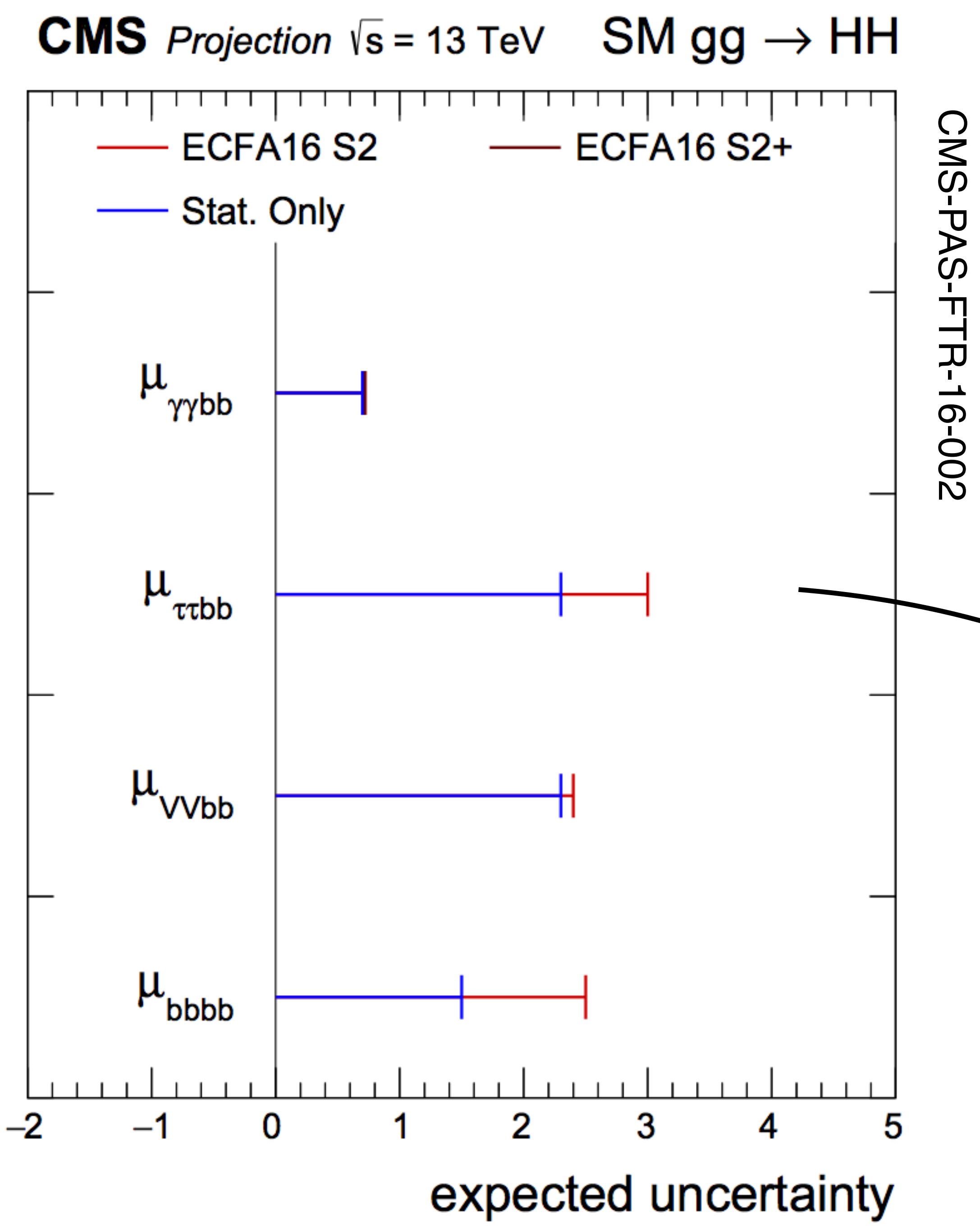


Results depend on jet pT threshold which can be achieved

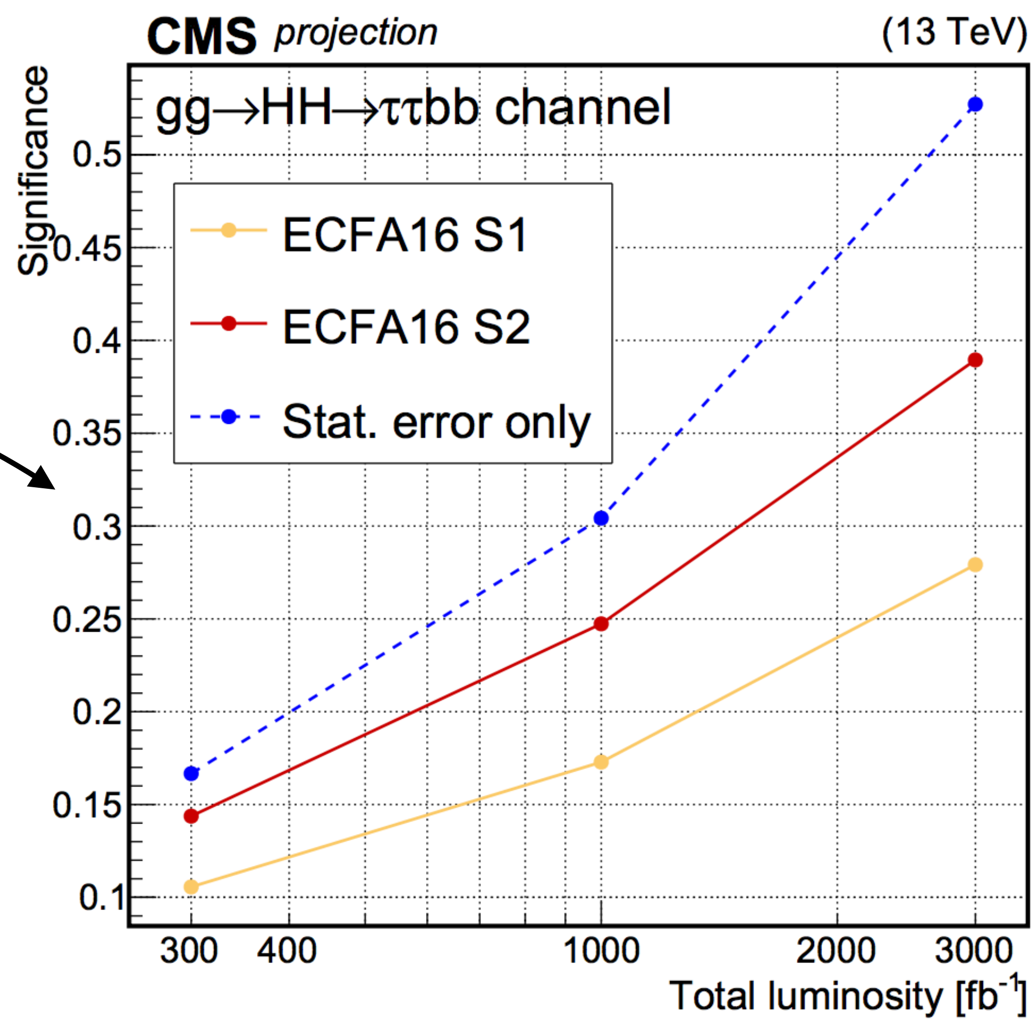
-> Raising jet p_T from 30 -> 75 worsens limit by ~2x

-> Key to understand Jet reconstruction both in the Trigger and offline

HL-LHC Projections



Similar projection of HH production from CMS based on 2015 data analyses.



HL-LHC Projections

Ongoing update of HL-LHC projections in preparation for **CERN YR18**

- Update existing projections accounting for final optimisation of HL-LHC ATLAS/LHCb/CMS detectors
- Improved analysis tools and theoretical predictions
- Combinations of ATLAS-CMS where statistics are limited
- Include HE-LHC (first experimental projections) 15fb^{-1} @ 27 TeV
- Coherent approaches for scenarios between different experiments

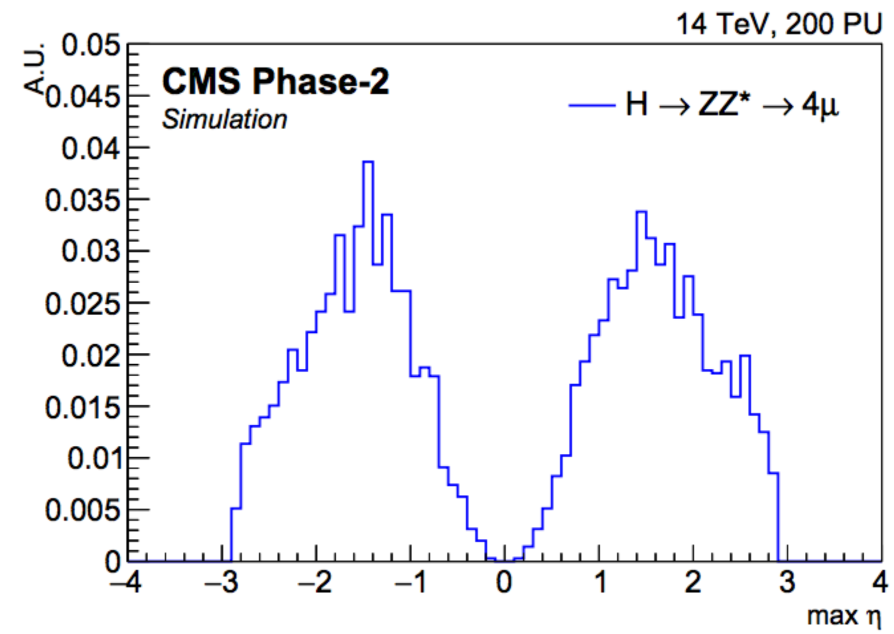
UG Tracker TDRs

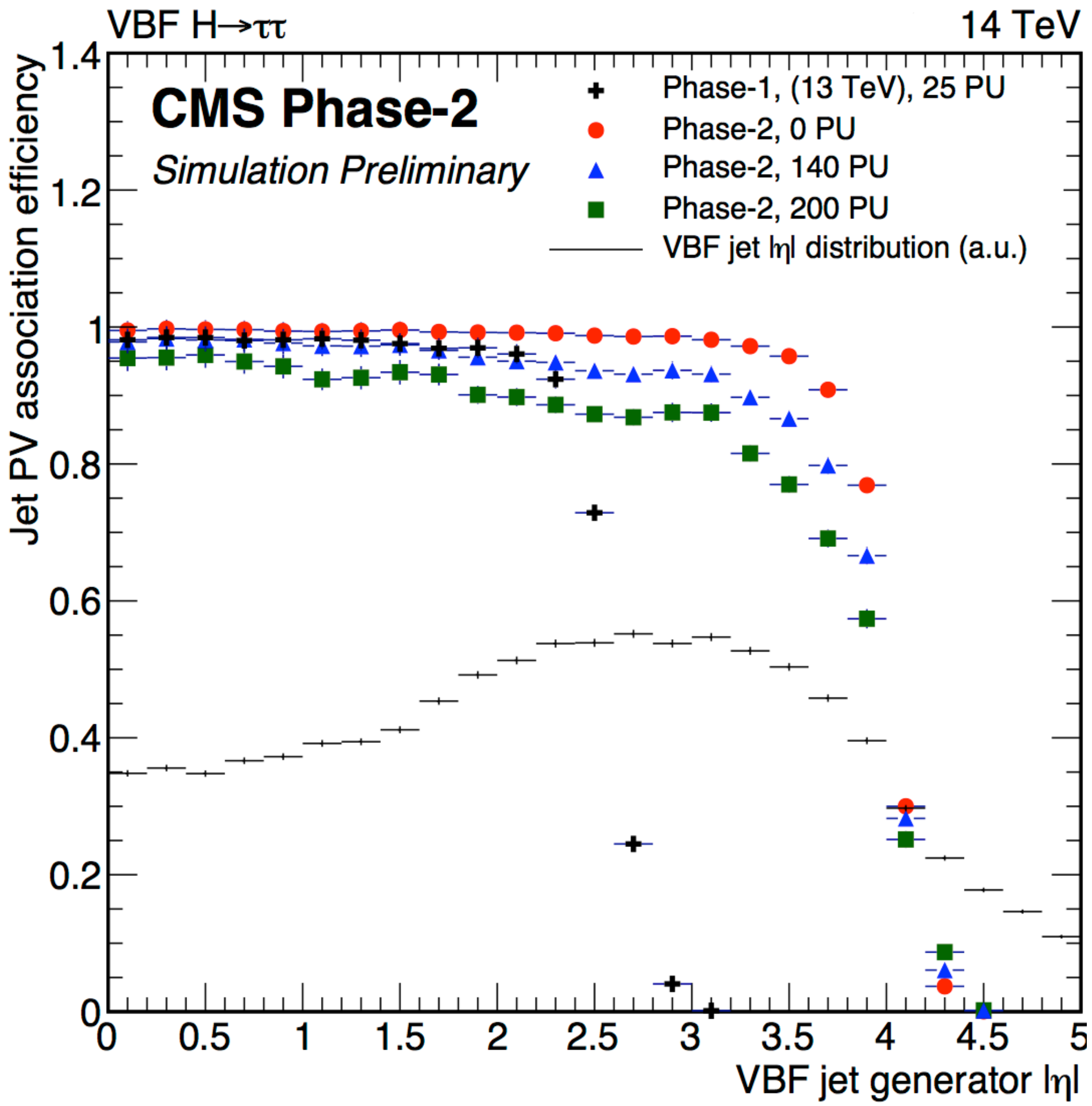
Home page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG2

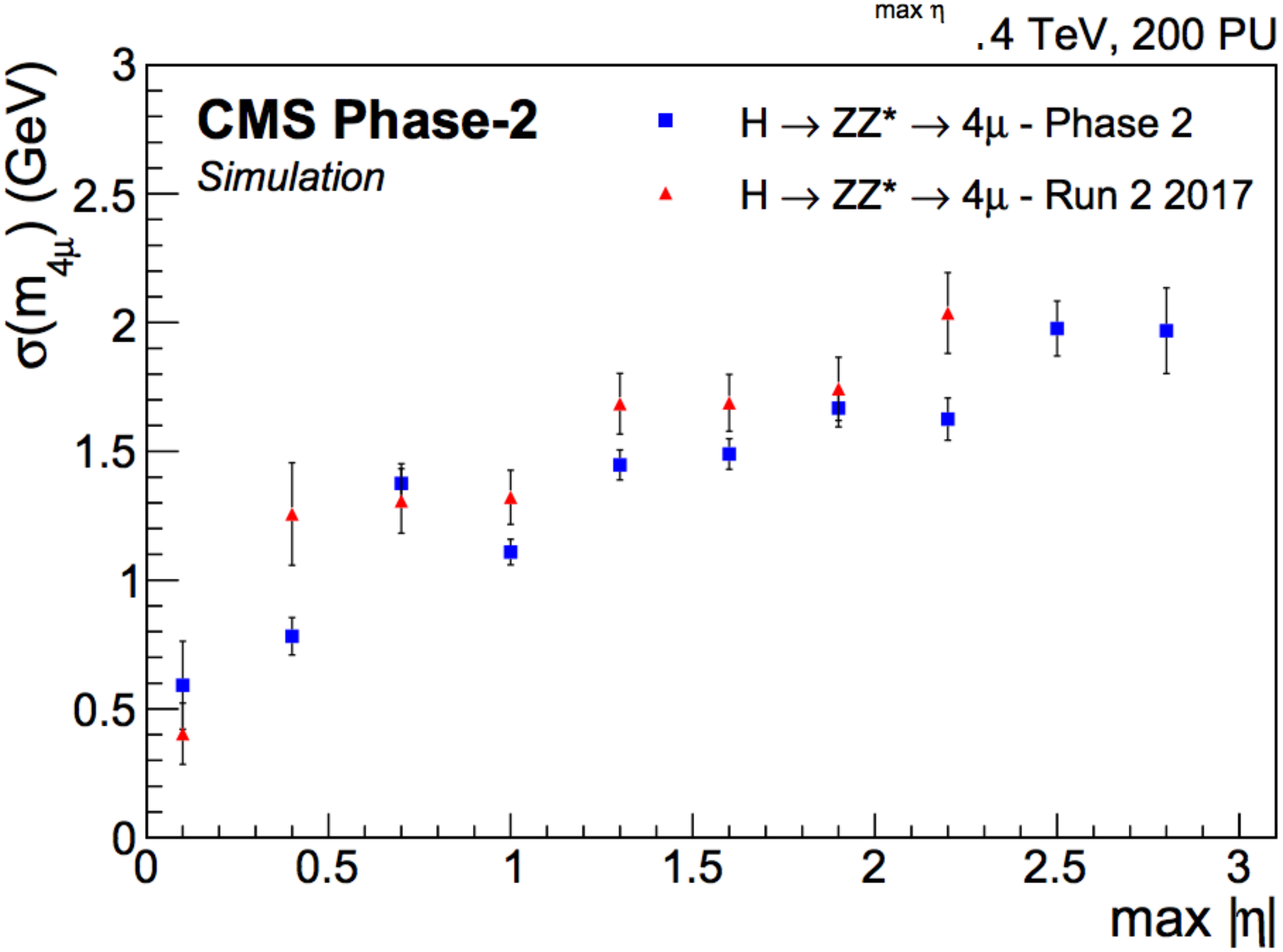
HL/HE meeting 2018 @ Fermilab https://indico.fnal.gov/event/16151/

HL-LHC Projections

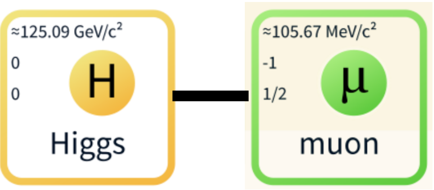
Extended inner tracking (and improved forward calorimetry) important in several channels



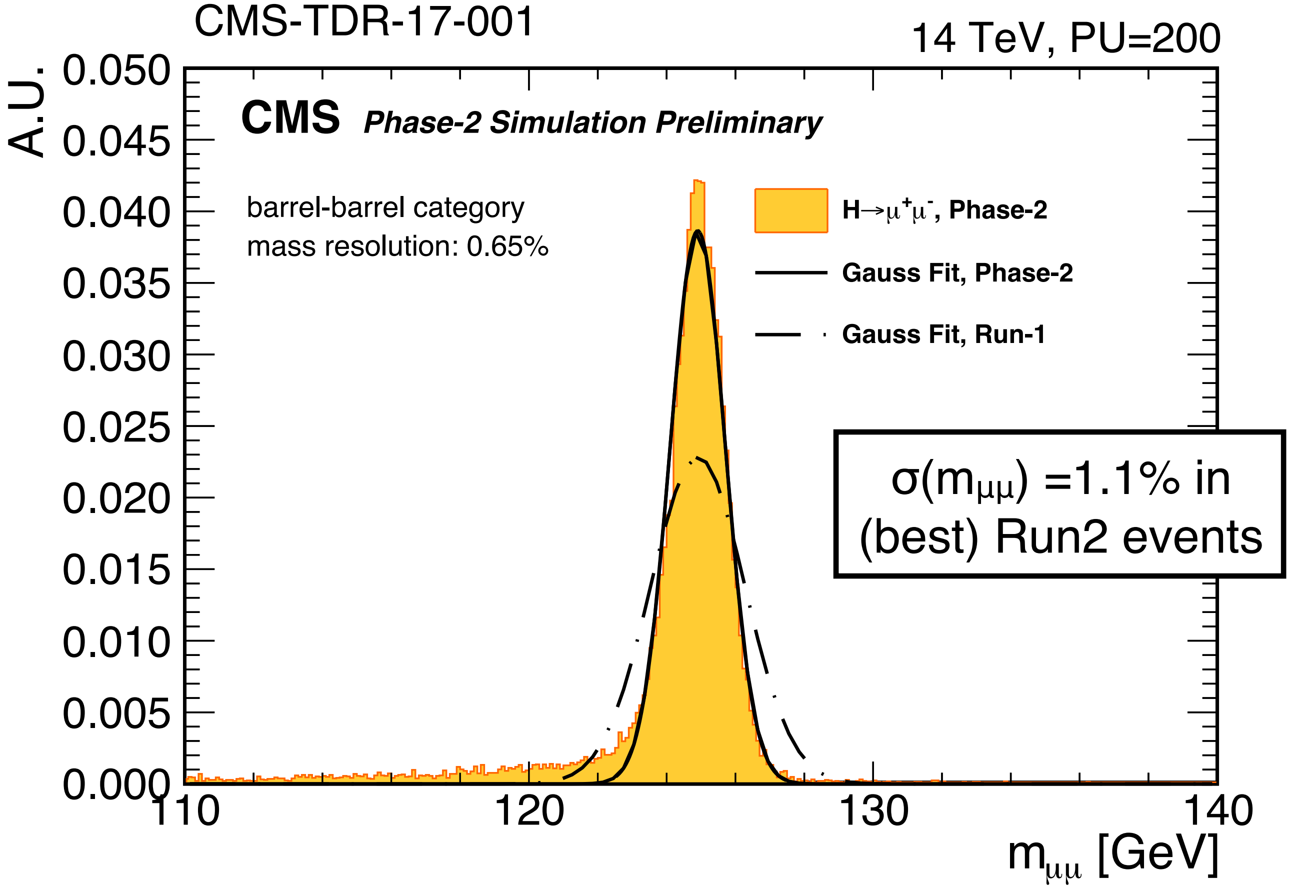


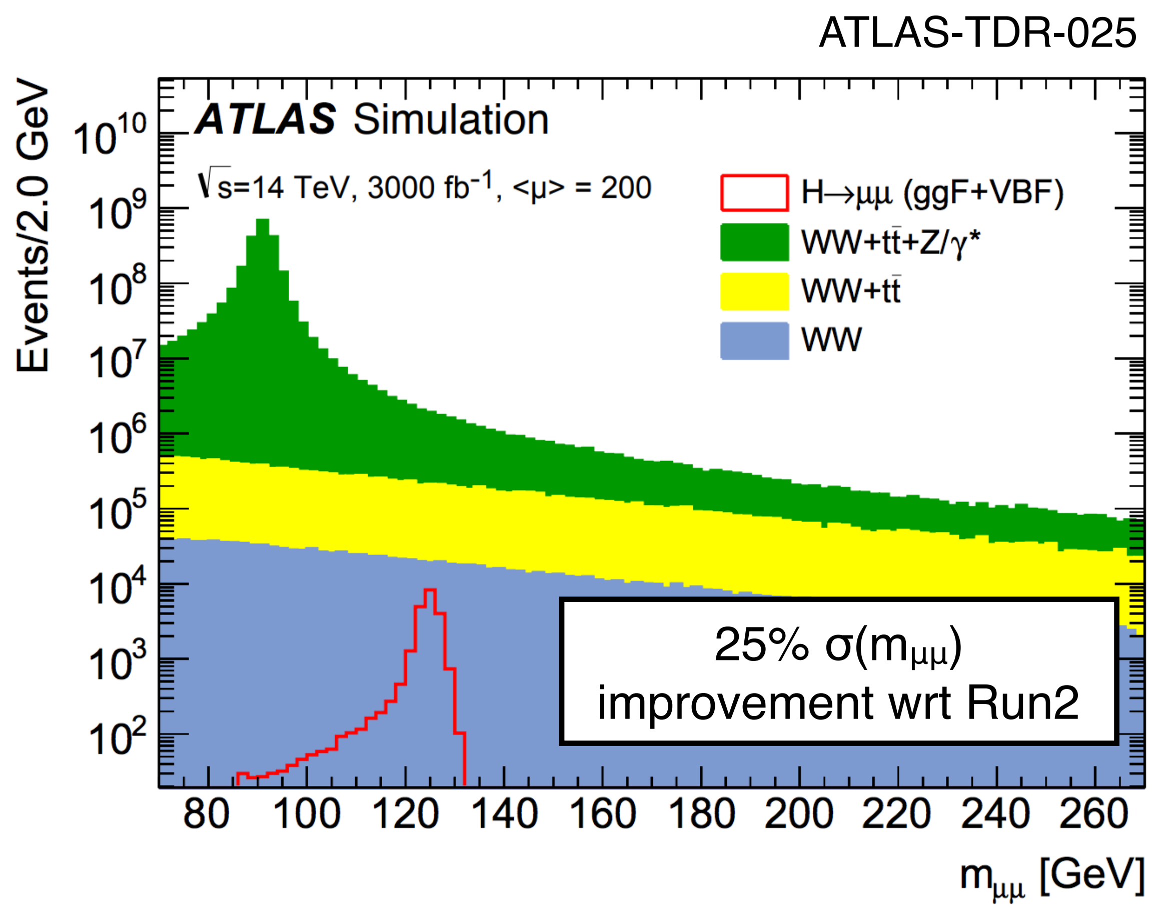


HL-LHC Projections



Dedicated studies in certain channels using knowledge of upgraded (Phase-2) detectors and PU conditions in Phase-II





Both ATLAS and CMS achieve improved $m_{\mu\mu}$ resolution with upgrade trackers

-> Sensitivity directly improved through increased S/B under peak

Future Colliders

In many cases Higgs couplings will be limited by too few statistics or (already) limited by systematic uncertainties

Higgs factories could solve these issues but there are many on the market

In the next slides, I'll try to cover the different scenarios in which Higgs couplings have been explored (from a biased viewpoint)

Future Colliders

In many cases Higgs couplings will be limited by too few statistics or (already) limited by systematic uncertainties

Higgs factories could solve these issues but there are many on the market

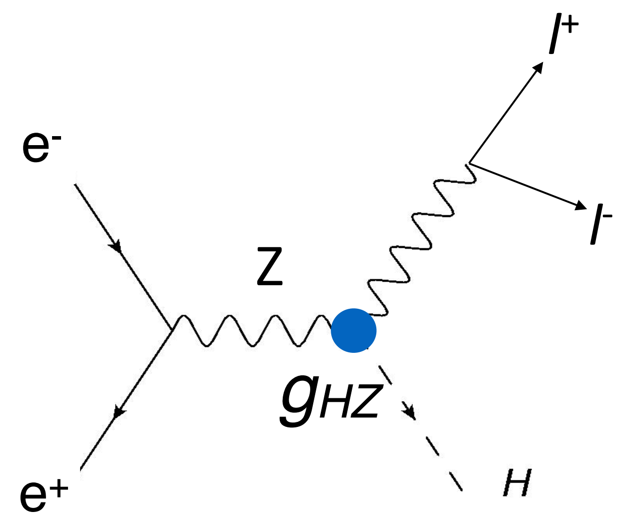
In the next slides, I’ll try to cover the different scenarios in which Higgs couplings have been explored (from a biased viewpoint)

Won’t cover muon-collider here but clearly that has the H-μ coupling advantage

Precision Couplings

Circular e^+e^- collider gives access to absolute value of couplings:

Total cross-section for ee->ZH $\approx g_{HZ}^2$



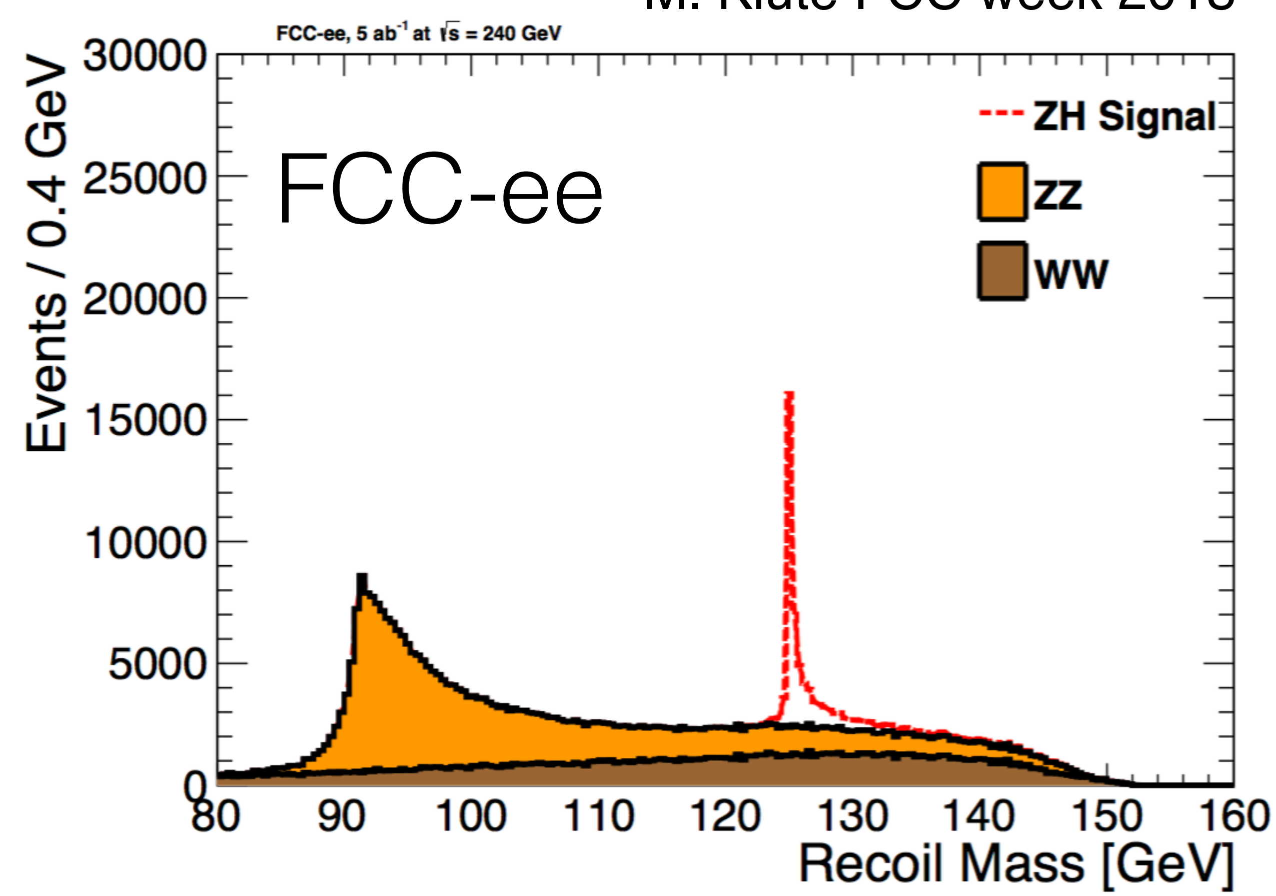
Total cross-section can be measured from "recoil mass" distribution in Z->ll final state (tag Higgs irrespective of Higgs decay)

$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{ll})^2 - |\vec{p}_{ll}|^2$$

Diboson background relatively flat under signal peak -> easy to extract total rate due to the Higgs signal

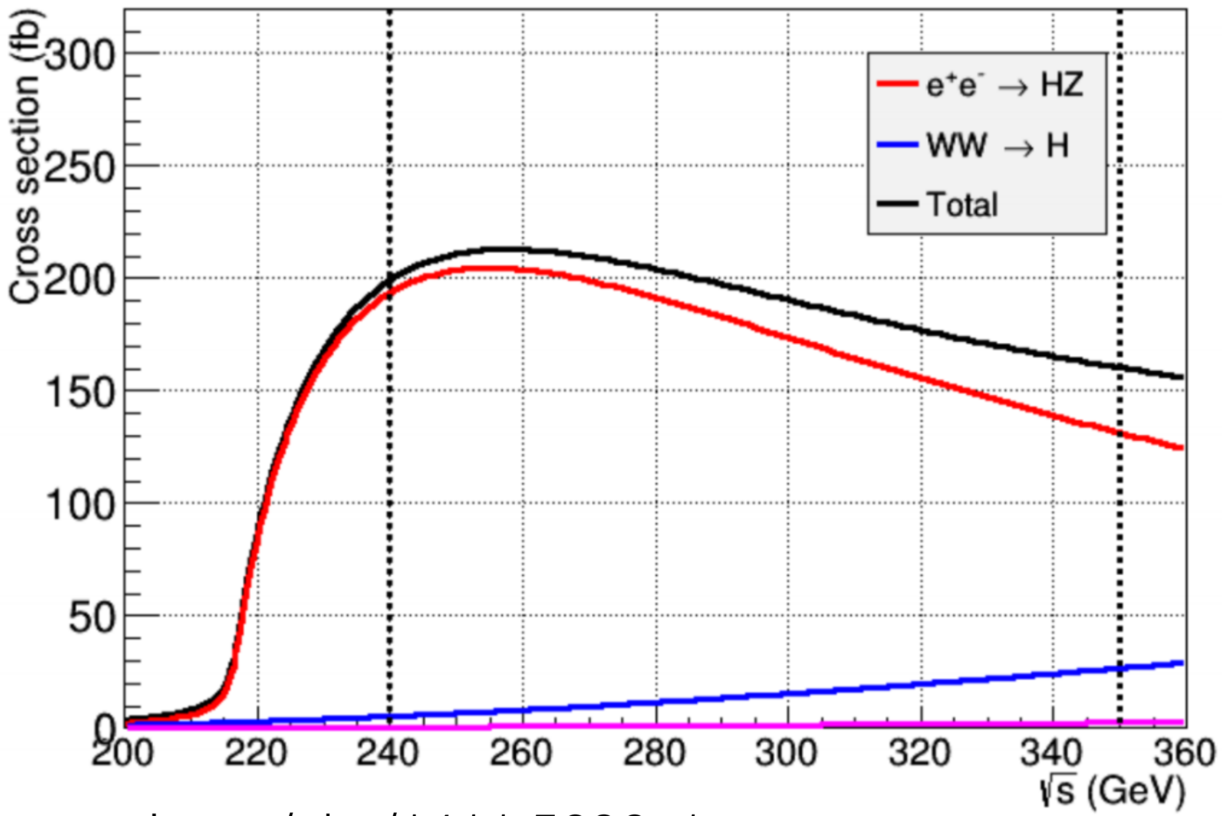
-> σ(ZH) ~ 0.7% precision from $5ab^{-1}$

M. Klute FCC week 2018

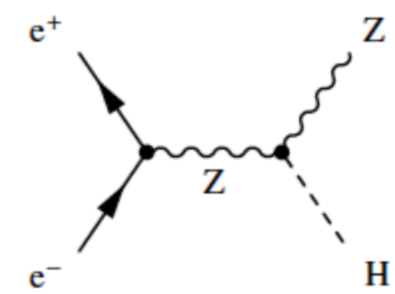


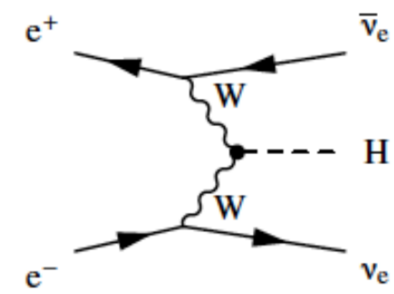
(note FCC-ee is not the only ep collider under consideration!)

Precision Couplings



arxiv.org/abs/1411.5606v1





Ratios of production mechanisms allow access to total width*

$$\frac{\sigma(ee \to ZH)B(H \to WW) \cdot \sigma(ee \to ZH)B(H \to bb)}{\sigma(ee \to \nu\nu H)B(H \to bb)} \propto \frac{g_{HZ}}{\Gamma}$$

$5ab^{-1}$@240 GeV and $1.5ab^{-1}$@350GeV

in %	FCC-ee 240 GeV	+FCC-ee 350 GeV
g_{HZ}	0.21	0.21
g_{HW}	1.25	0.43
g_{Hb}	1.25	0.64
g_{Hc}	1.49	1.04
g_{Hg}	1.59	1.18
$g_{H\tau}$	1.34	0.81
$g_{H\mu}$	8.85	8.79
$g_{H\gamma}$	2.37	2.12
Γ_H	2.61	1.55

M. Klute FCC week 2018

Determine absolute couplings from model independent fit to different Higgs final states.

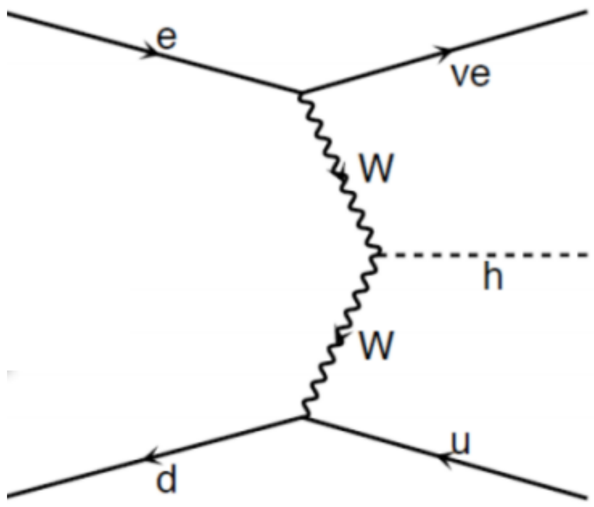
Updates to these numbers are currently in progress using improved detectors/analysis methods.

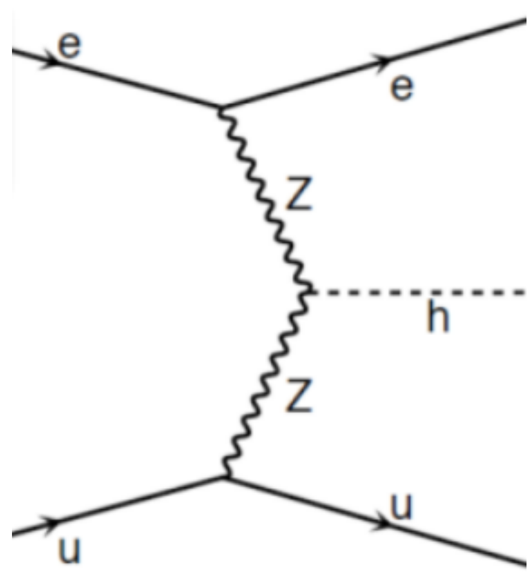
* see more from Victoria next

FCC-eh

e-p collider (60 GeV e - 50 TeV p) can reach ~similar level of precision with 2ab^{-1}

Numbers assume No invisible Higgs decays





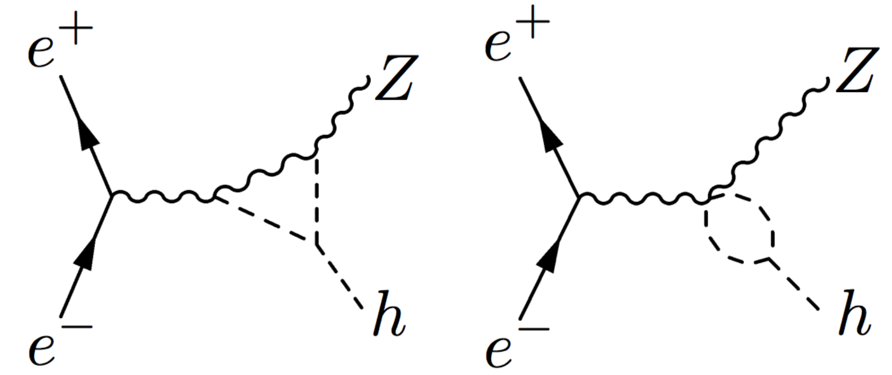
J. de Blas @ FCC week 2018

	FCC-eh
Coupling	Relative precision
κ_b	0.74%
κ_t	—
κ_τ	1.10%
κ_c	1.35%
κ_μ	—
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	—

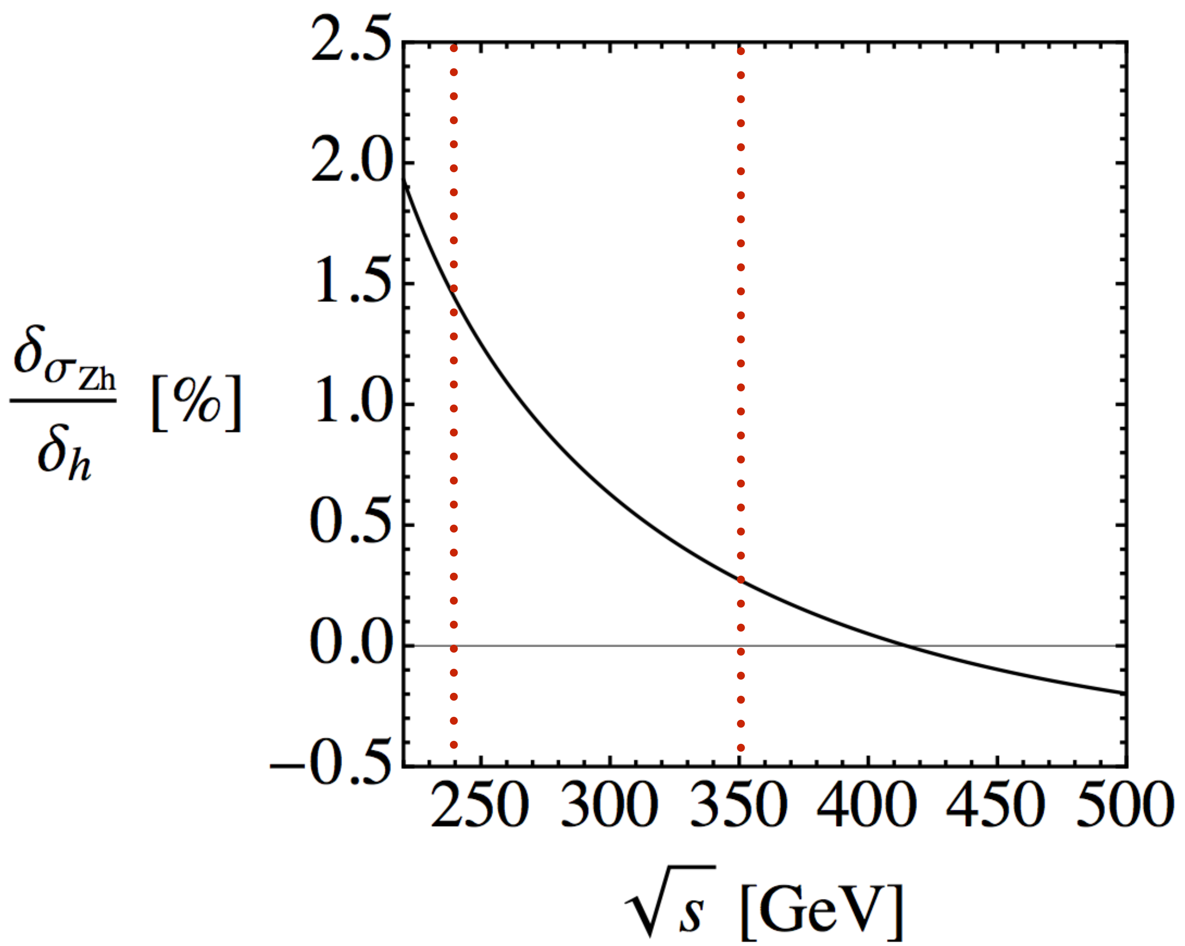
Based on recent μ analysis (Uta Klein - see here)

Self-coupling

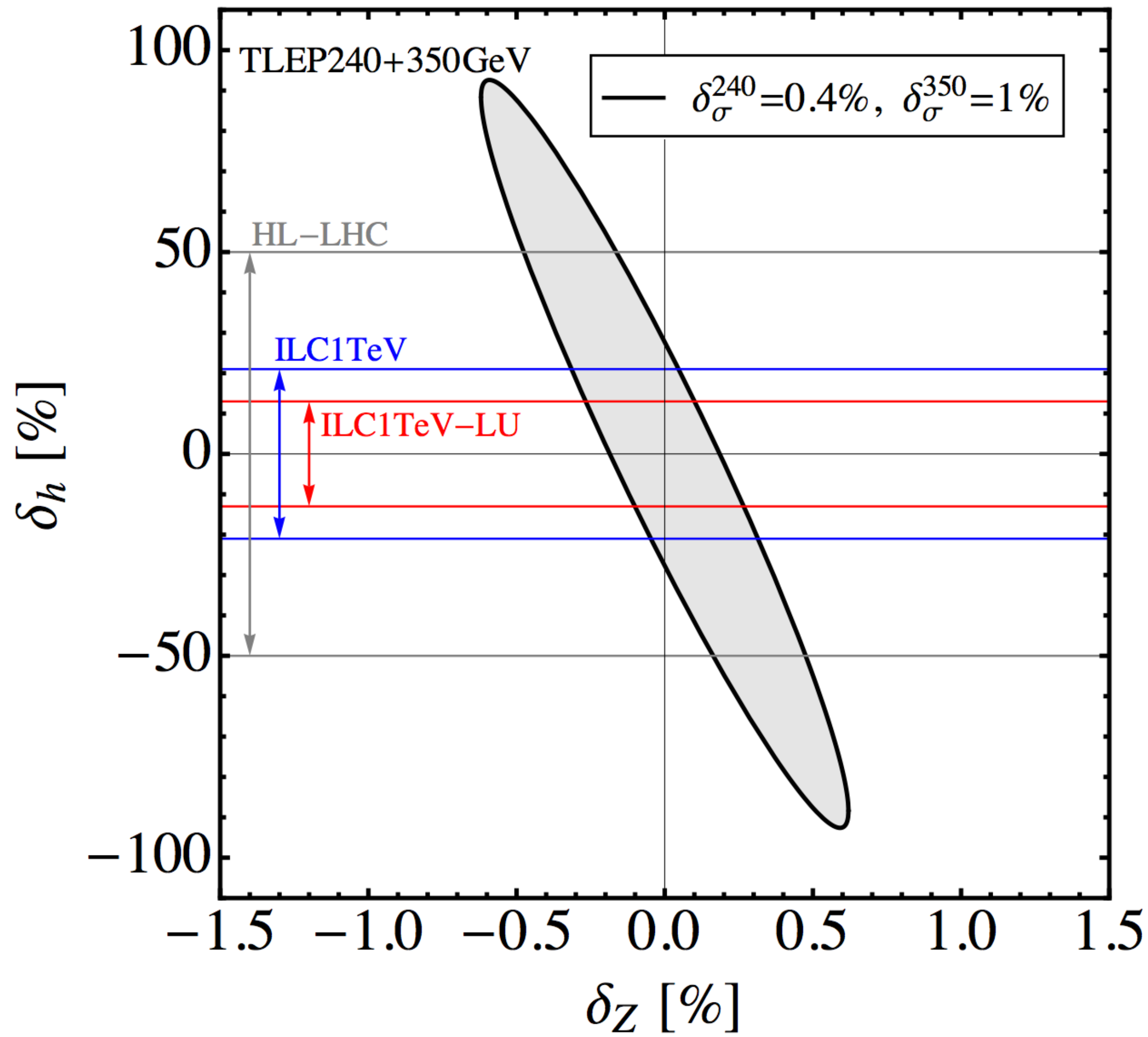
FCC-ee can also access self-coupling from precision measurement of ZH cross-section



Radiative corrections to the ZH production at the level of ~1.5% (0.3%) for COM = 240 (350) GeV



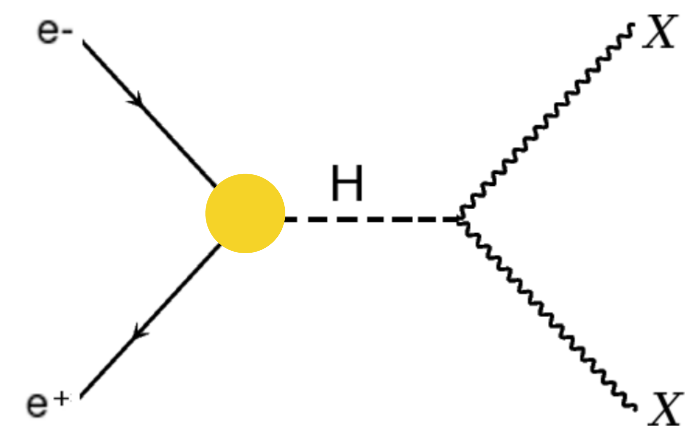
δ_h~28% achievable

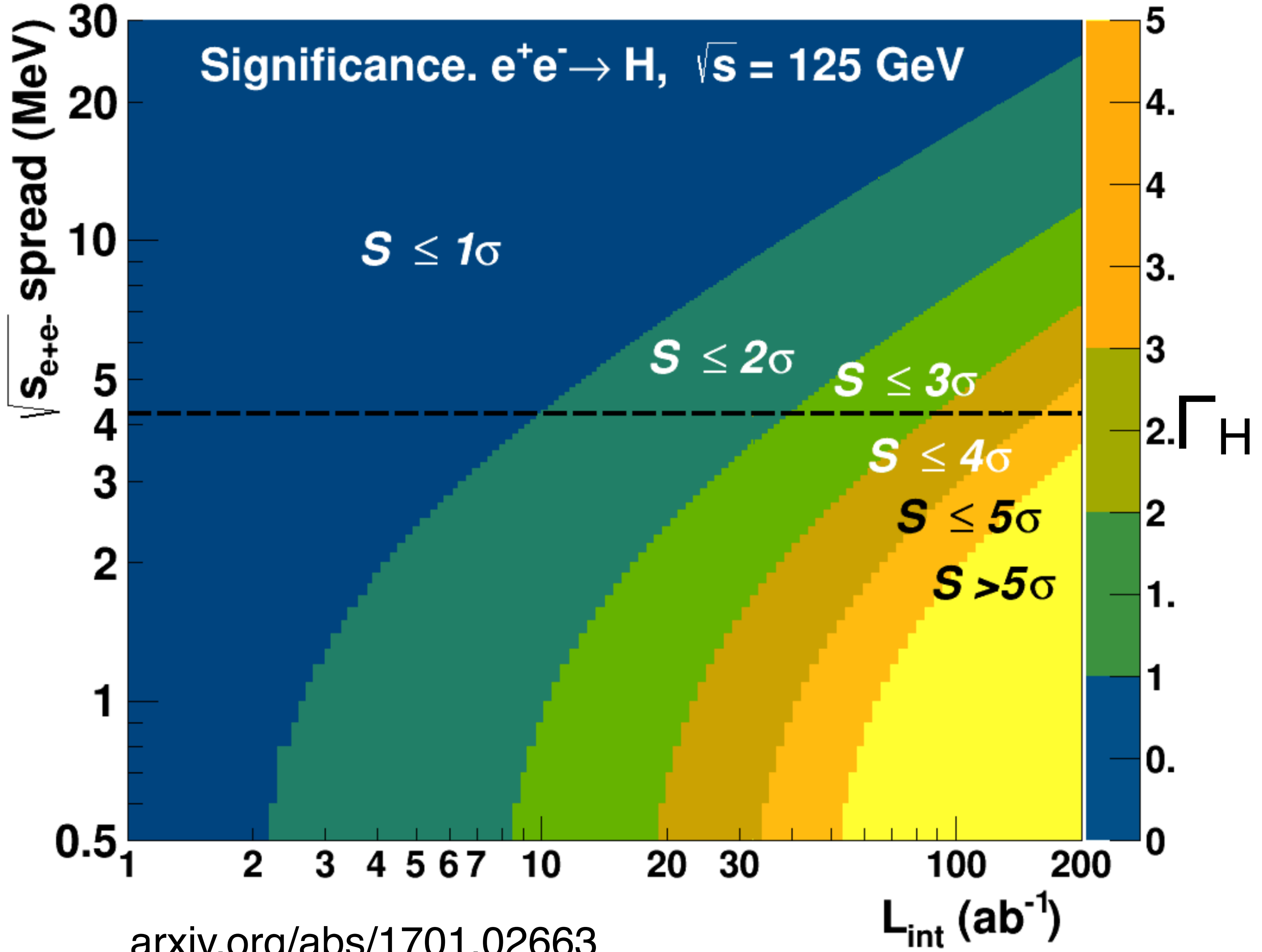


arxiv.org/abs/1312.3322

1st generation coupling

Running e^+e^- at Higgs pole gives unique access to e-H coupling (1st generation coupling)

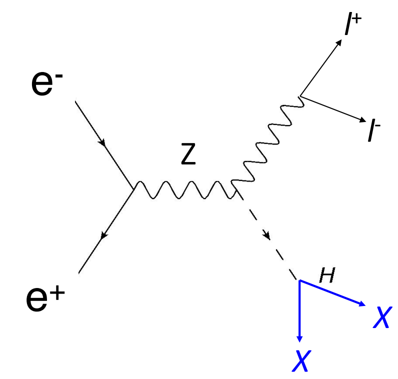




arxiv.org/abs/1701.02663

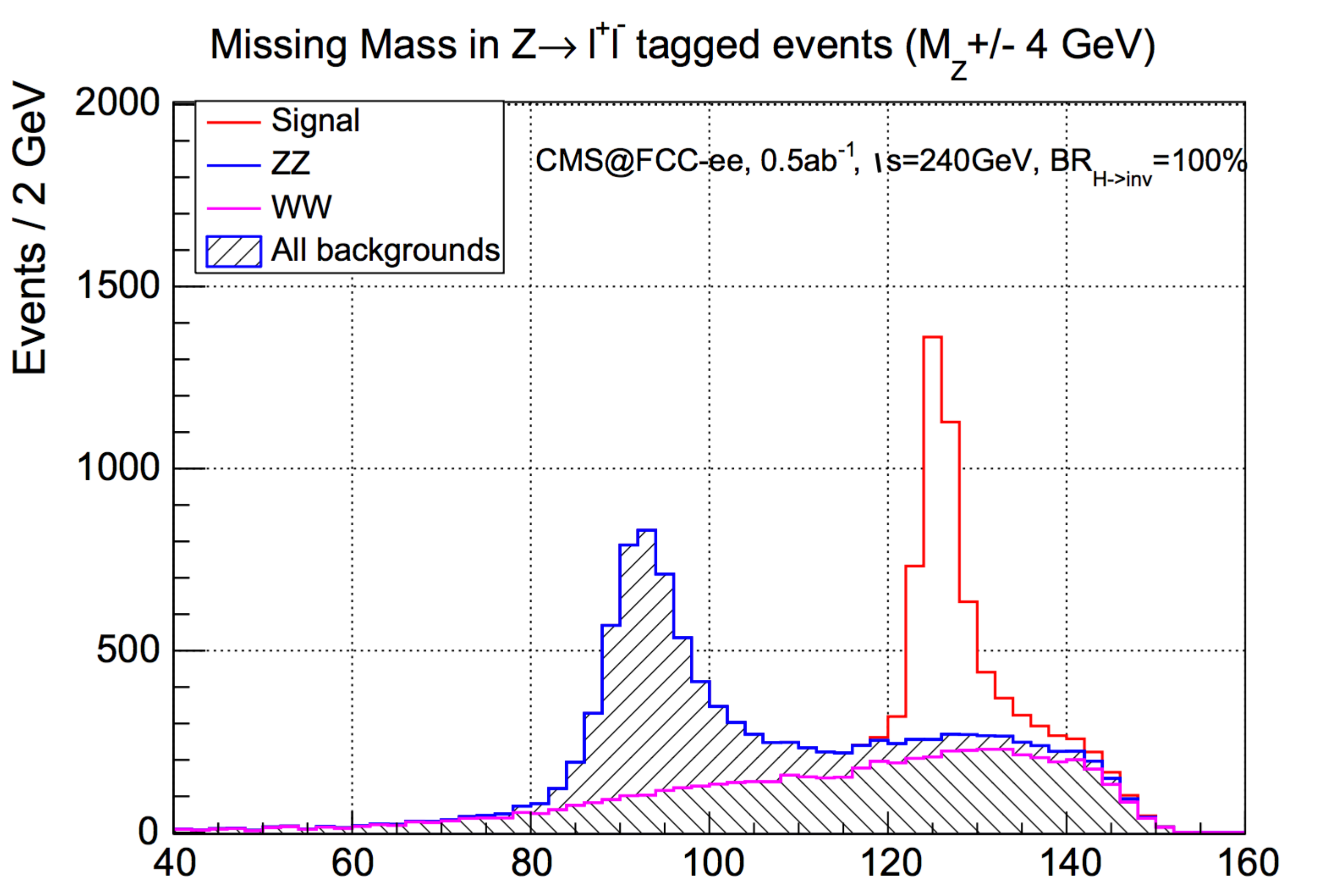
- Sensitivity studied across combining 10 Higgs decay channels
- Different beam energy spreads have been studied
- Challenge due to extremely small production in S-channel
  - $\sigma(ee \to H)$ = 290ab assuming spread~Γ_H

Invisible Higgs

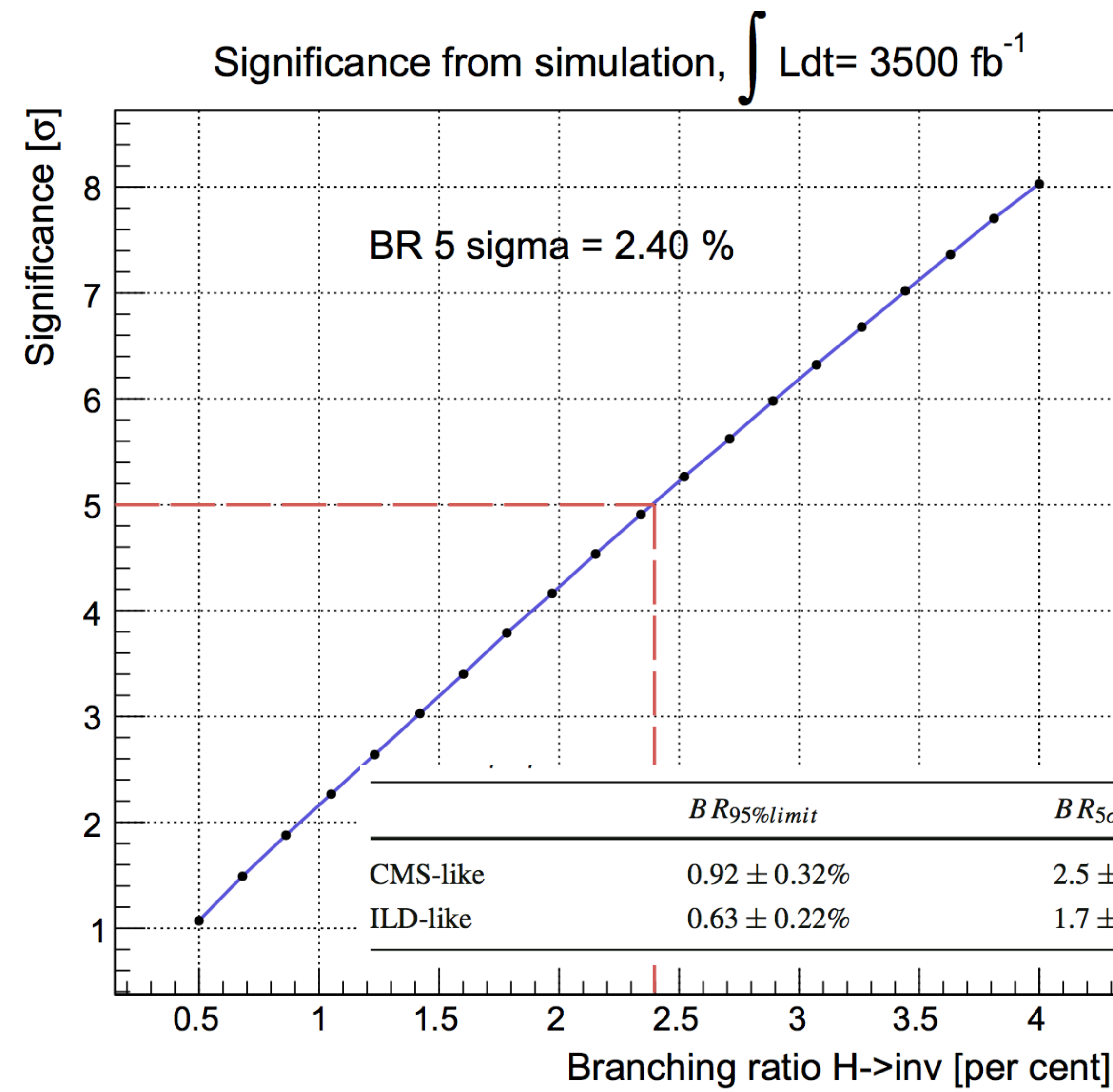


B(H->invisible) ~ 0.1% in SM (via 4ν final state)

- Enhancement possible in number of BSM scenarios (including those with DM candidates
- FCC-ee with “CMS-like” detector can observe B(H->inv) > 2.4% at 5σ
  - Studied in Z(ll)H mode
  - Assumes >85% efficiency for leptons/ photons (CMS-like)



Eur. Phys. J. C (2017) 77



	$BR_{95\%limit}$	$BR_{5\sigma}$
CMS-like	$0.92 \pm 0.32\%$	$2.5 \pm 0.2\%$
ILD-like	$0.63 \pm 0.22\%$	$1.7 \pm 0.1\%$

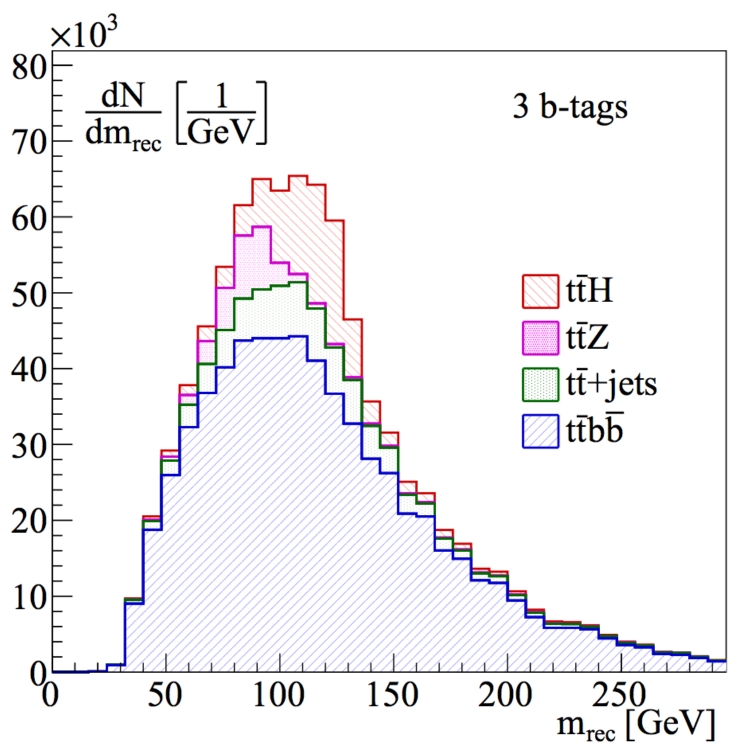
Top-Yukawa

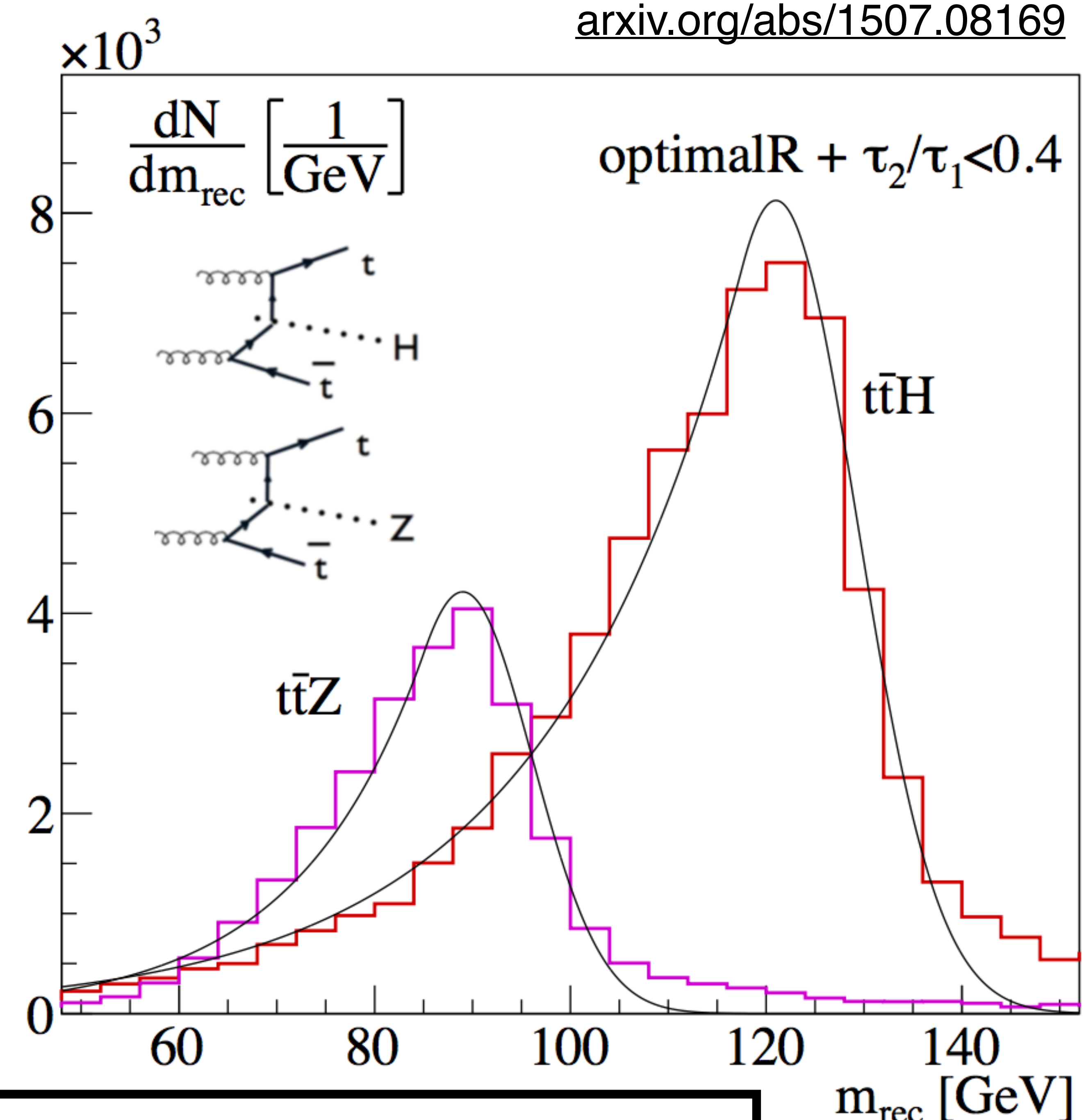
Top-Higgs coupling inaccessible at ep collider -> FCC-hh @ 100 TeV opens ttH channel

arxiv.org/abs/1507.08169

Extract H-t coupling from σ(ttH)/σ(ttZ)

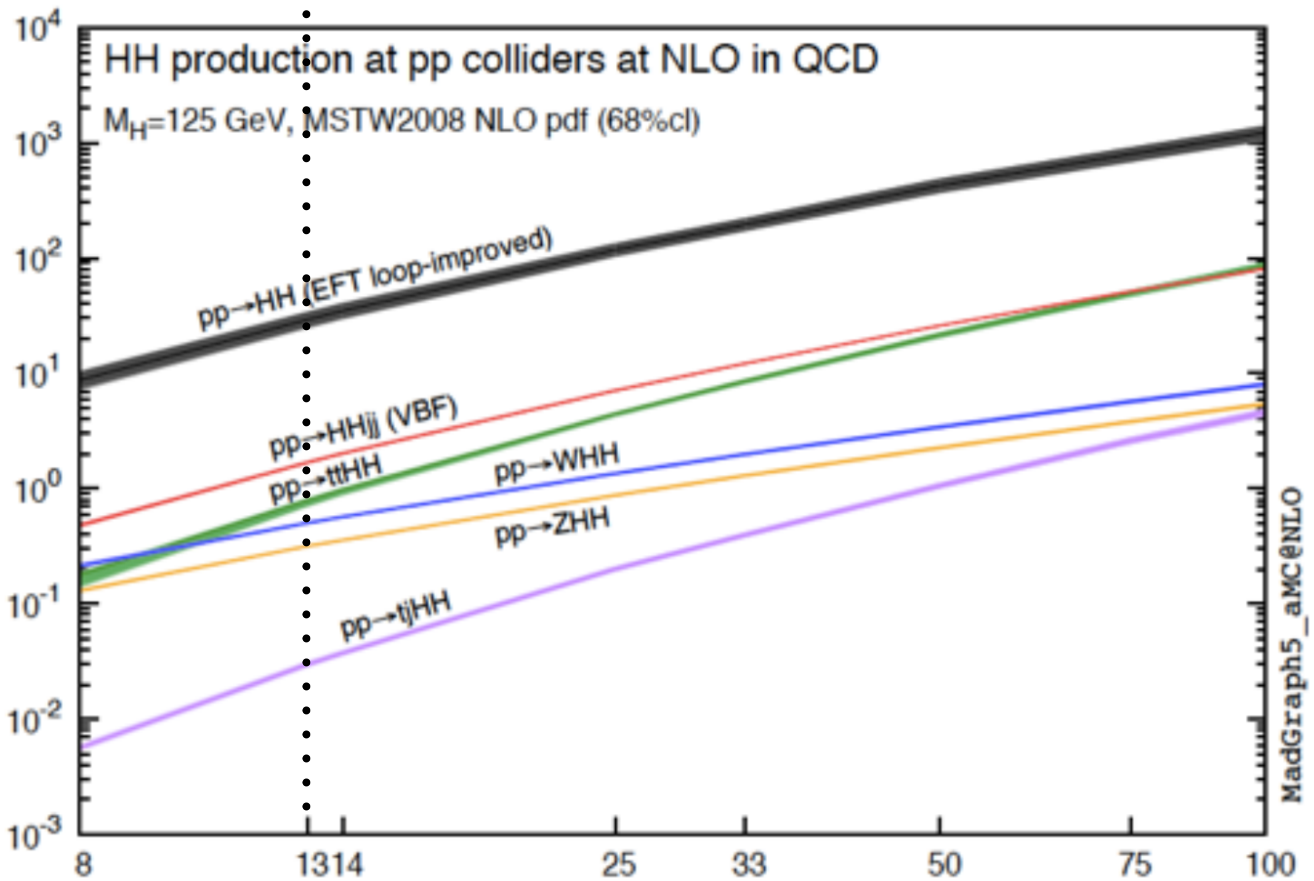
- Measure in boosted top, boosted higgs and lepton final states
- Requires precision measurement of t-Z and Γ_H from FCC-ee





~1% uncertainty for g_t from 20ab^{-1}

Double Higgs



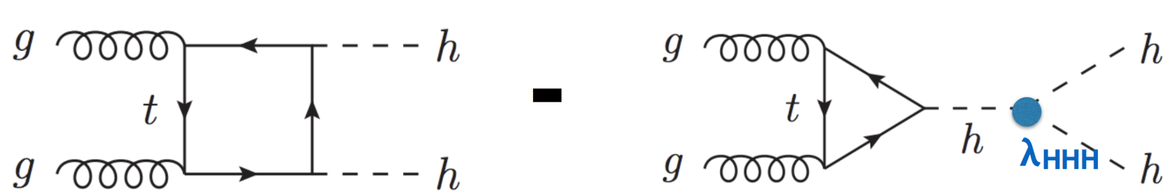
Double Higgs production cross sections increased at higher COM in pp colliders

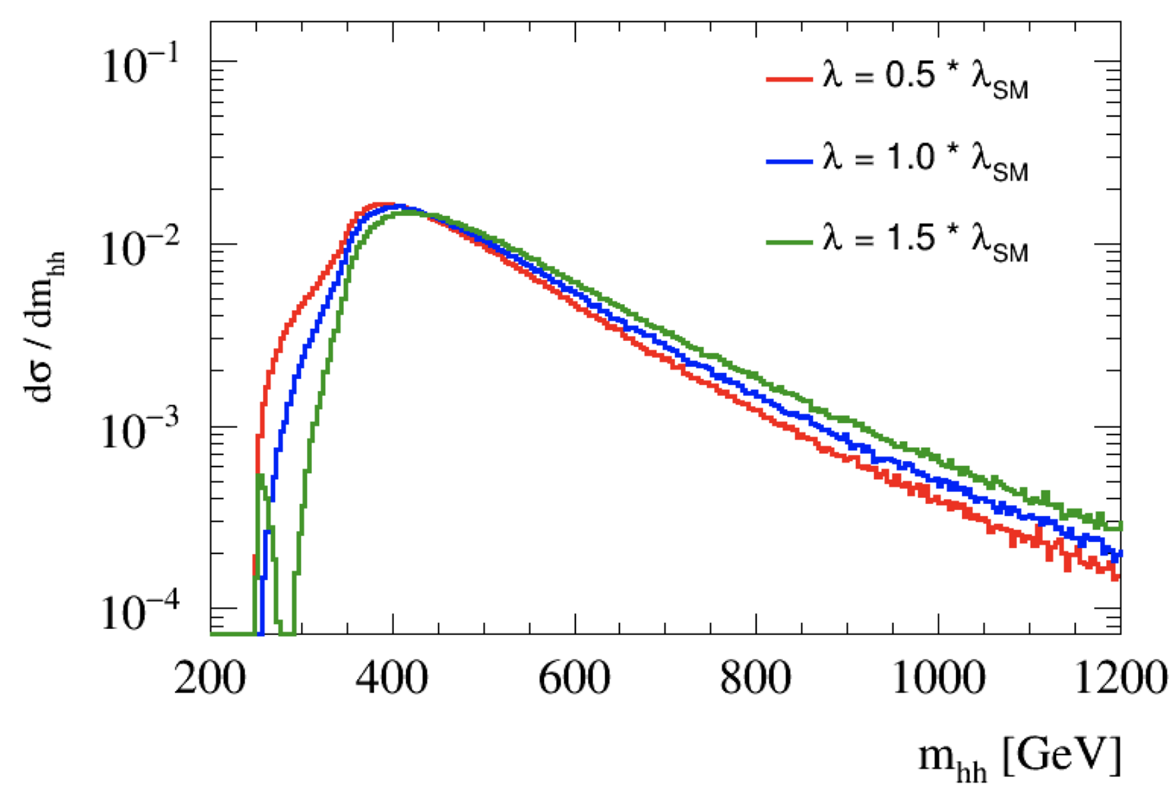
- VBF-HH and ttHH channels

~ equal at 100 TeV

Sensitivity to self coupling from distribution of m_{hh} gg-fusion

- High m_{hh} dominated by box-diagram

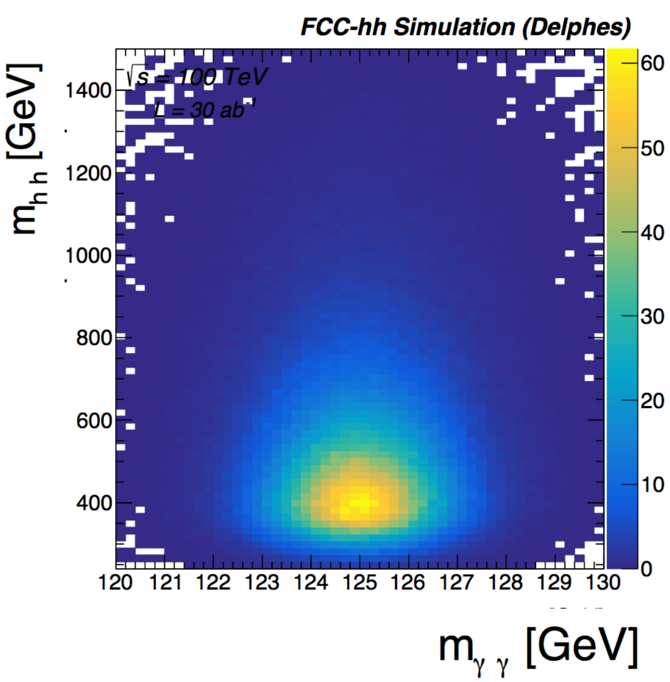


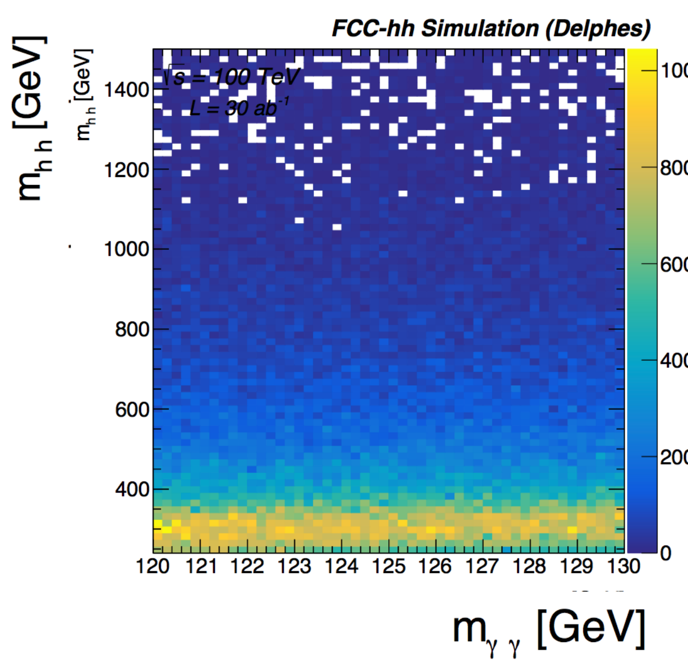


Self-coupling

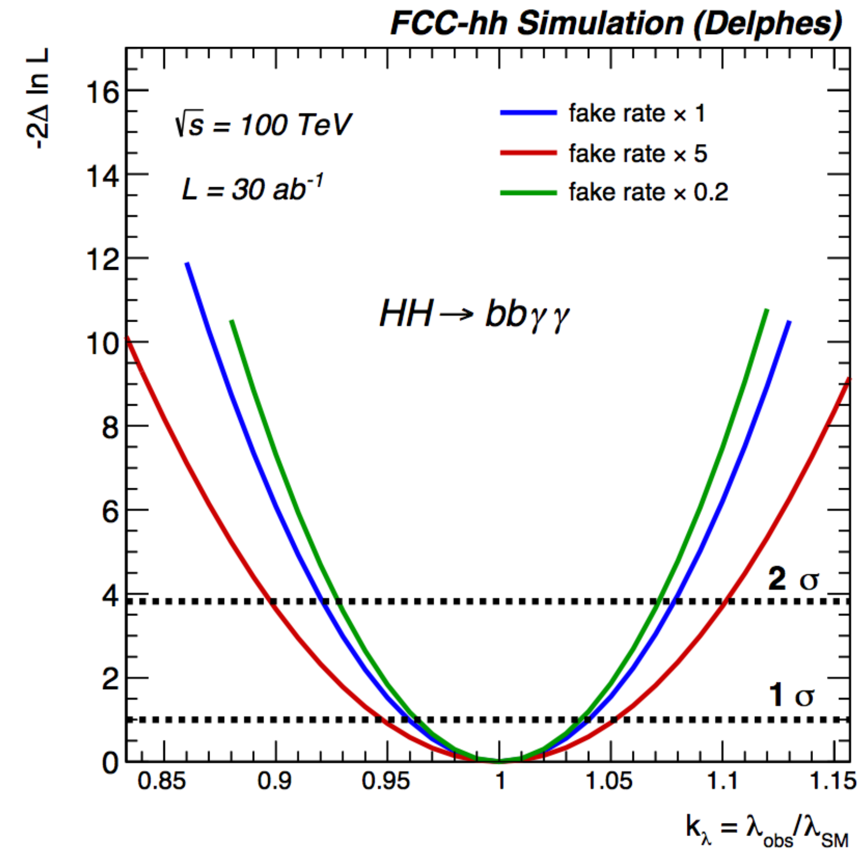
H(bb)H(γγ)

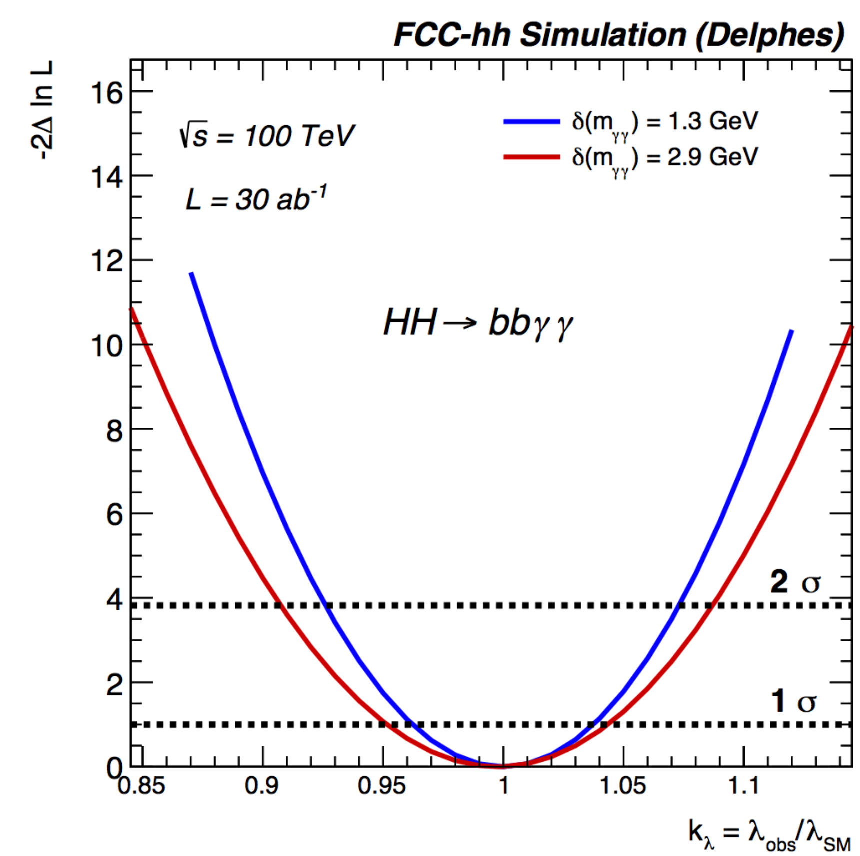
- 2D fit of m_{hh}-$m_{\gamma\gamma}$ distribution
- Dominant backgrounds from QCD (diphoton and multi jet from j->γ fakes) and ttH
- Various background rejection and object resolution scenarios considered*
- 5% precision on κ_λ could be feasible (note systematics not studied in great detail)





Similar studies for bbbb, bbττ, bbWW



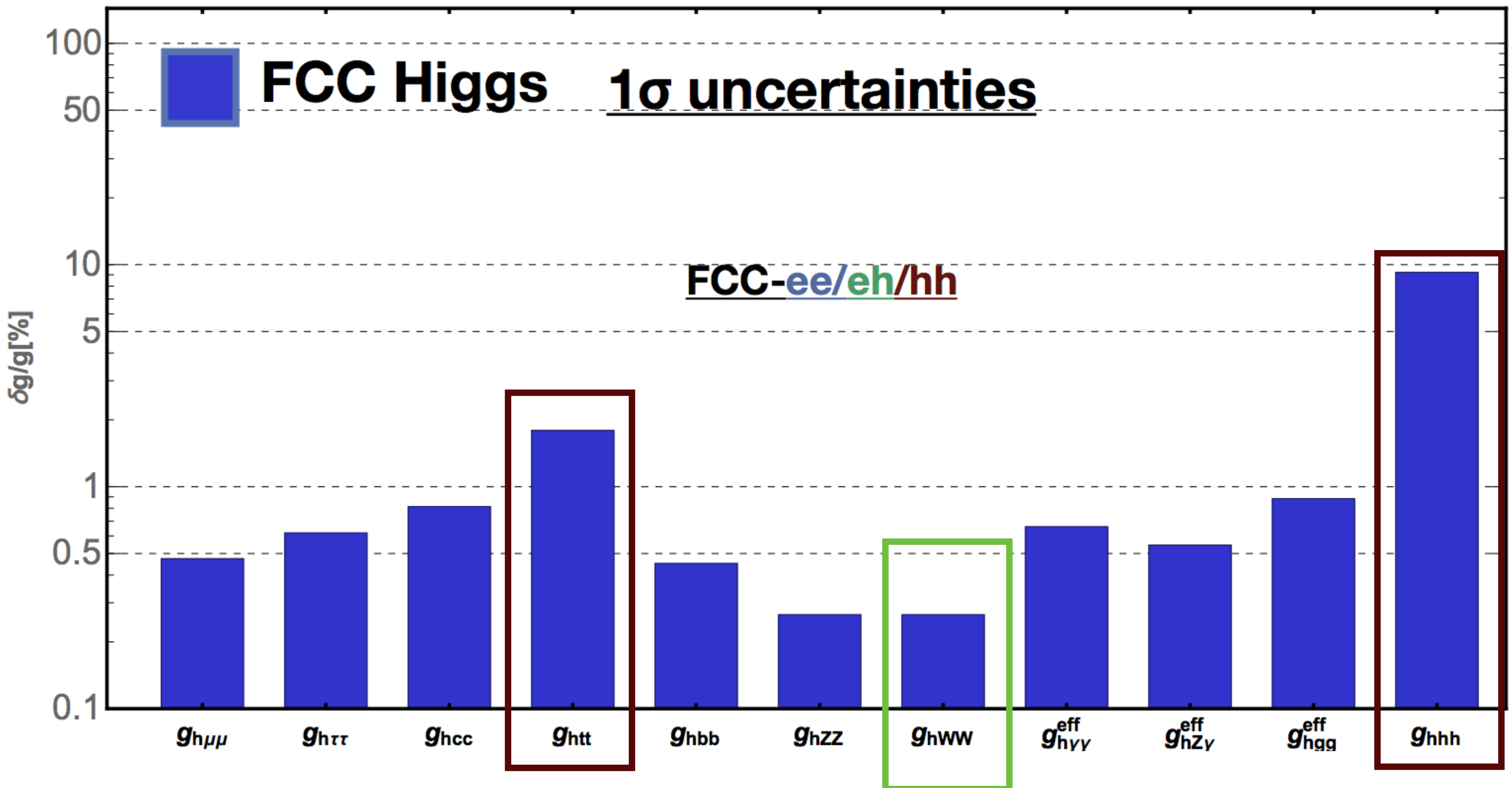


G. Ortona (FCC week 2018)

*See https://indico.cern.ch/event/656491/contributions/2915653/attachments/1628734/2595839/FCChhDetectorsExperiments.pdf for detector setup

Summary - Global fits

Ultimate sensitivity from combination across full future programme

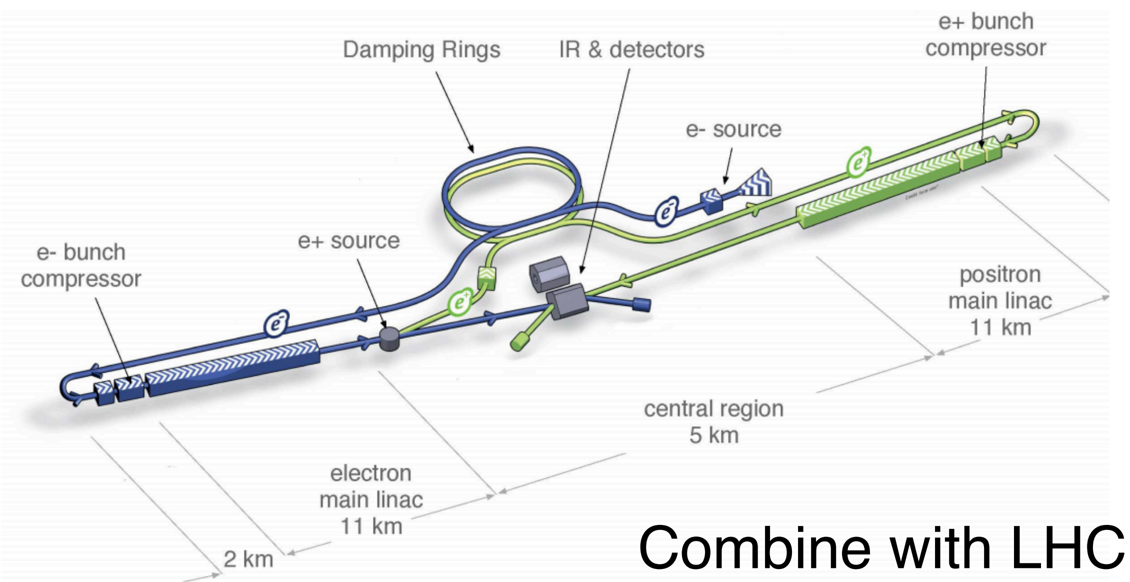


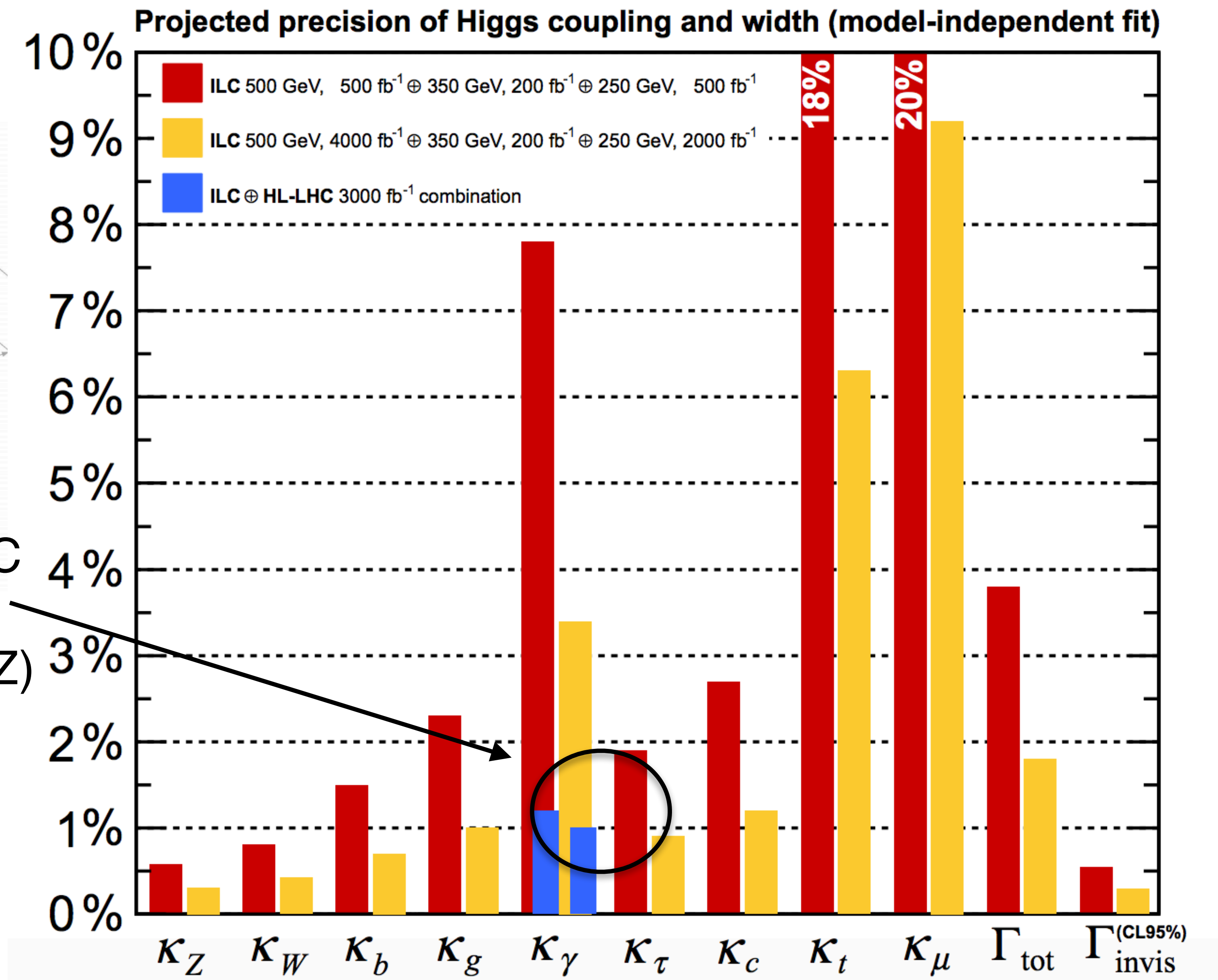
J. de Blas FCC week 2018

ILC (Very Quick Word)

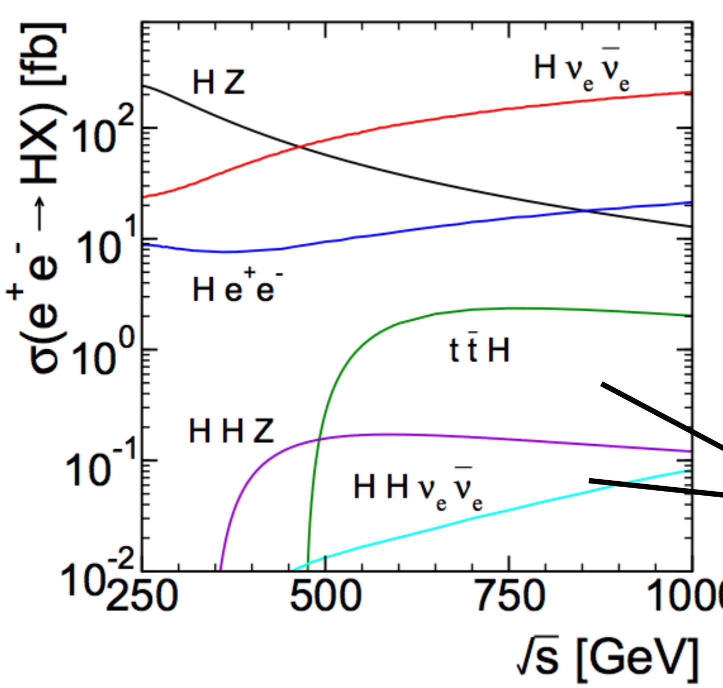
arXiv/abs/1506.05992

Competitive with FCC in several cases





Combine with LHC measurement of B(H->γγ)/B(H->ZZ)



Access to self coupling at higher COM (10% @5ab^{-1}, 16%@ 2ab^{-1} in hh->bbbb + hh->bbWW)

Summary

Precision studies of Higgs couplings remains an important goal of the Future Higgs programme

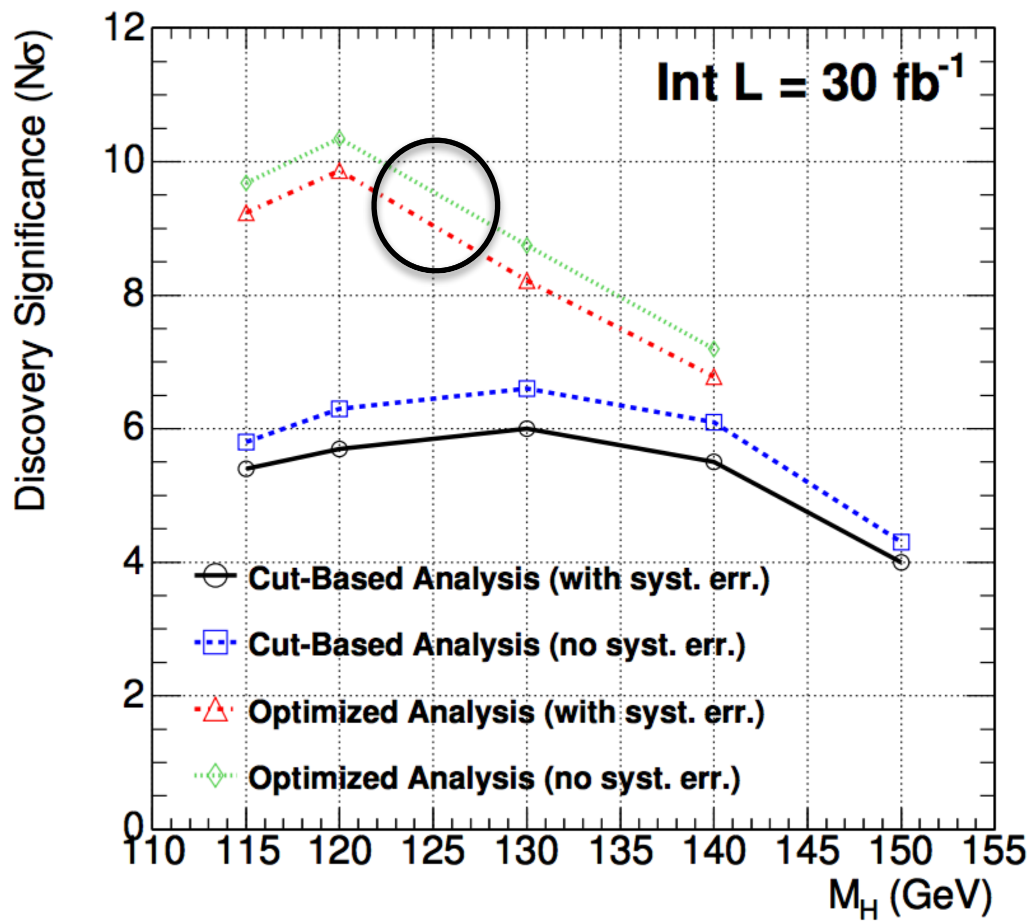
- Sensitivity limited at HL-LHC (systematics/statistical) and ultimately need to measure width for independent measurements - though most projections are outdated already!
- Higgs factories are a well studied option for precision
  - FCC-ee (or CepC) promises O(<1%) level precision in many couplings
    - CLIC/ILC can achieve similar precision - range of options for running
    - High energy (FCC-hh) picks up top-yukawa and self coupling and provides constraints on rare-decays (+ generic BSM searches for HE NP)

- Studies of physics potential / detector design are very much open and underway*
- UK should have a strong involvement in these areas for Higgs Physics
  - Where do we want to focus our attention (HL-LHC upgrades will clearly shape our future detector designs)
  - UK ATLAS and CMS groups play major roles in Higgs physics @LHC (experiment (hw/fw/analysis-sw) + theory)
    - Assuming something gets what level of involvement would we maintain now and over the next 20 yrs

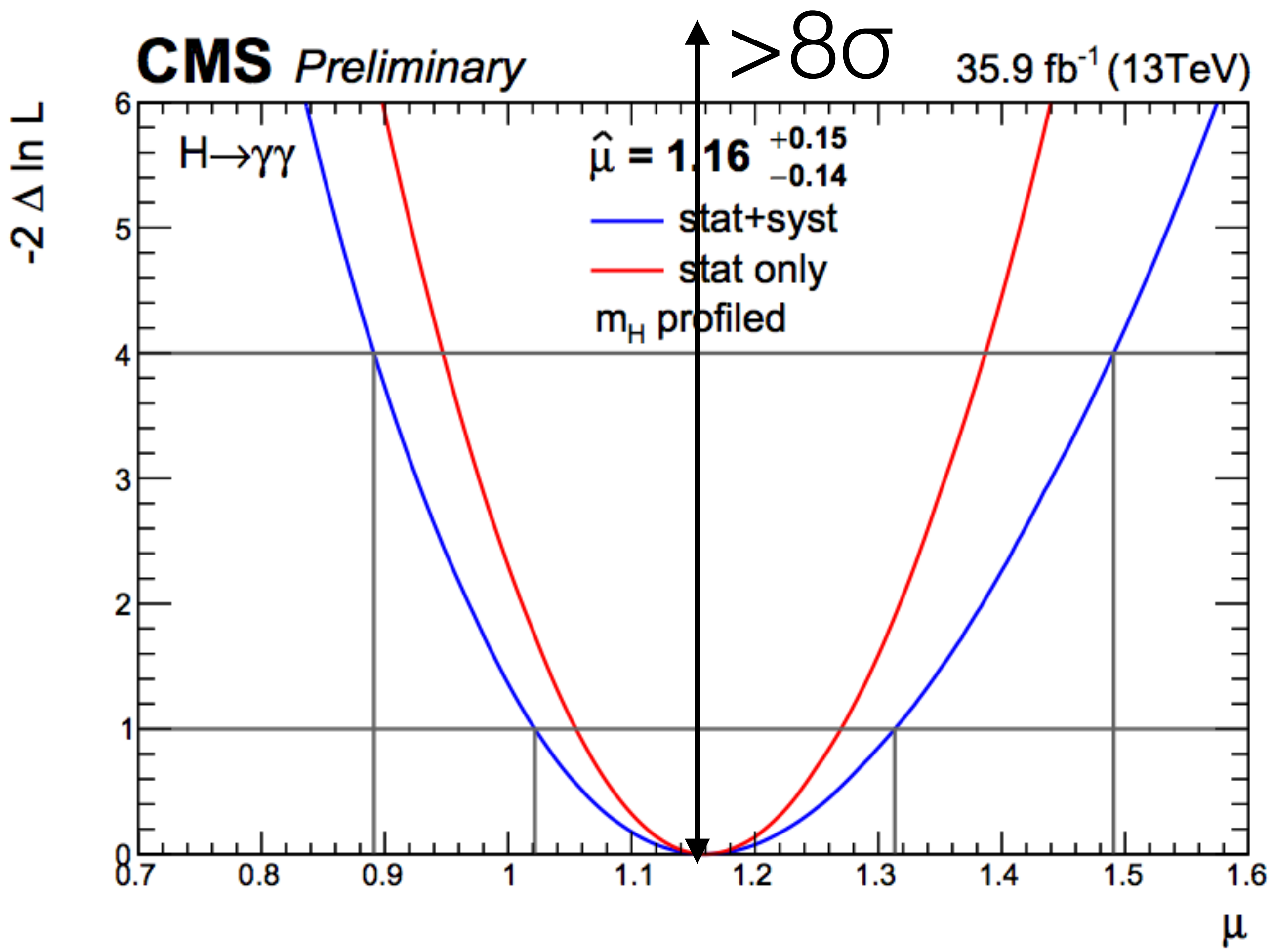
* https://github.com/FCC-hh-Framework/FCChhAnalyses/

Pinches of salt

CMS H-> γγ pTDR - 2006



CMS H->γγ@Moriond 2018

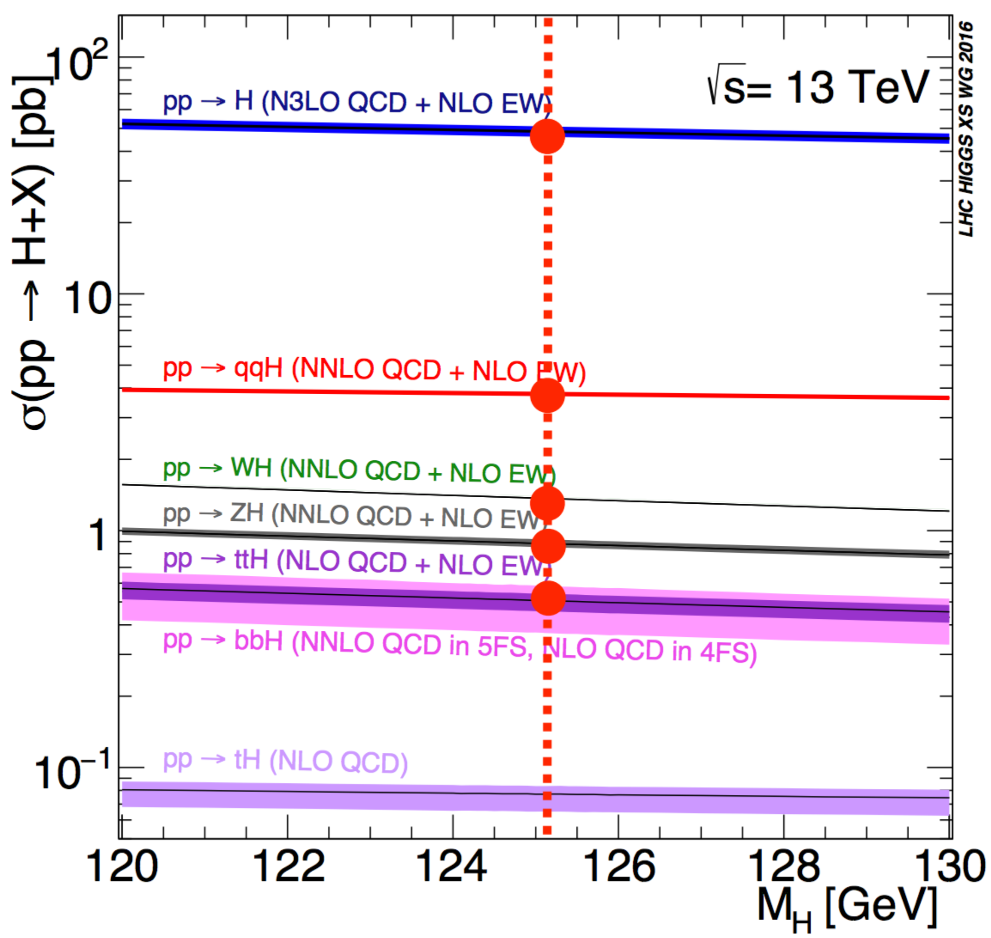


Backup Slides

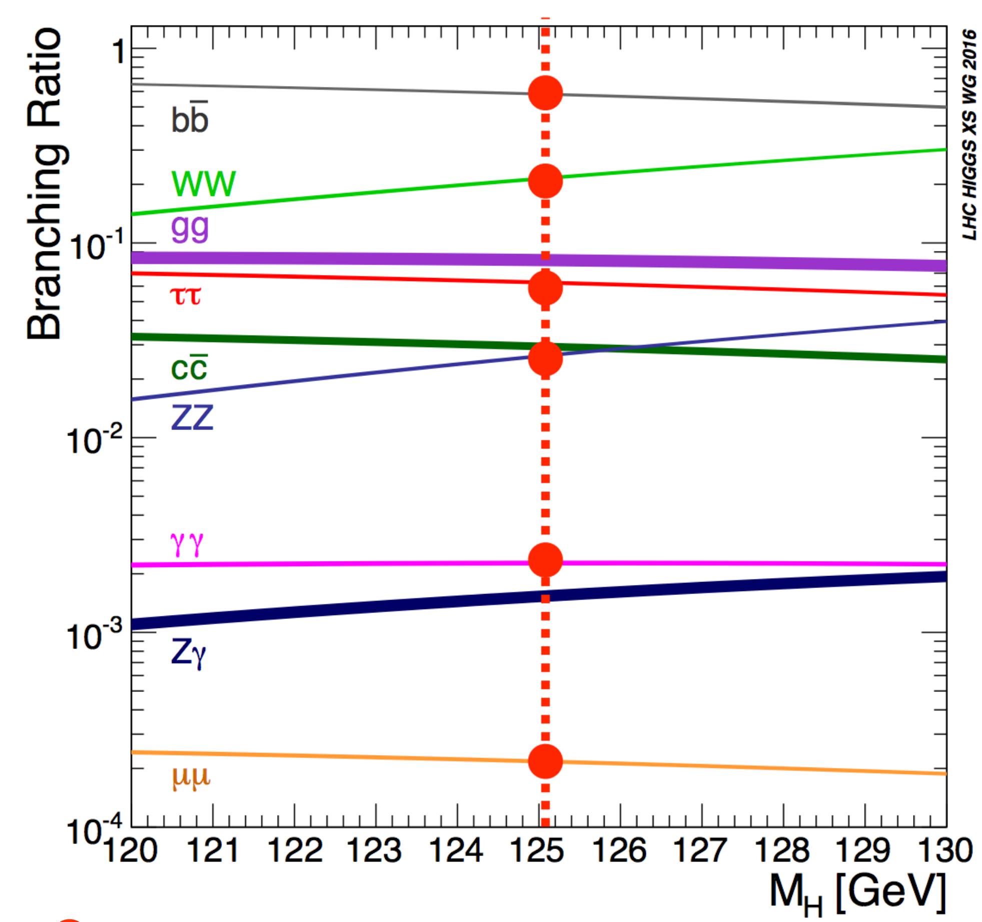
Higgs couplings

At the LHC - access to a wide range of production and decay modes which are sensitive to the Higgs boson couplings

Production

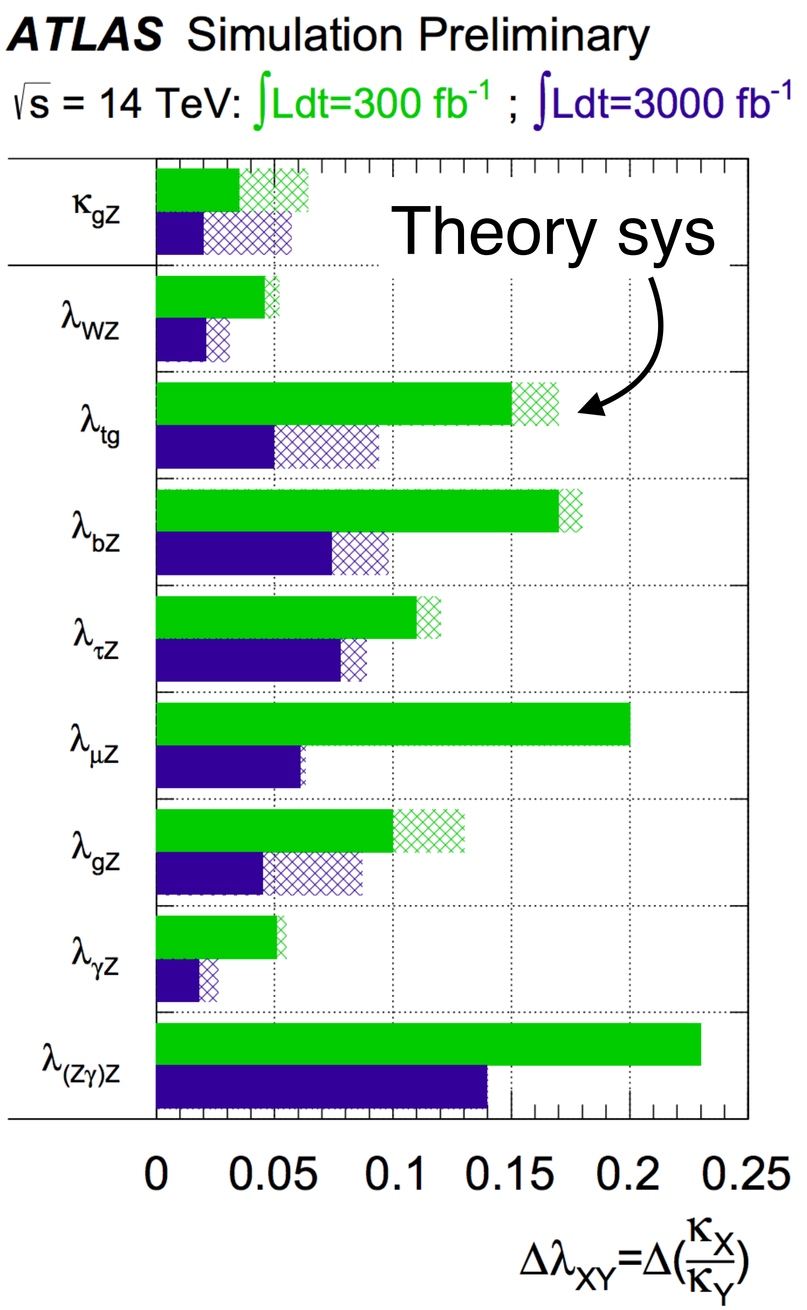


Decay



● dedicated coupling measurements

Projections



% uncertainty [S2, S1]

	L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
LHC	300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
HL-LHC	3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

ep colliders - Higgs

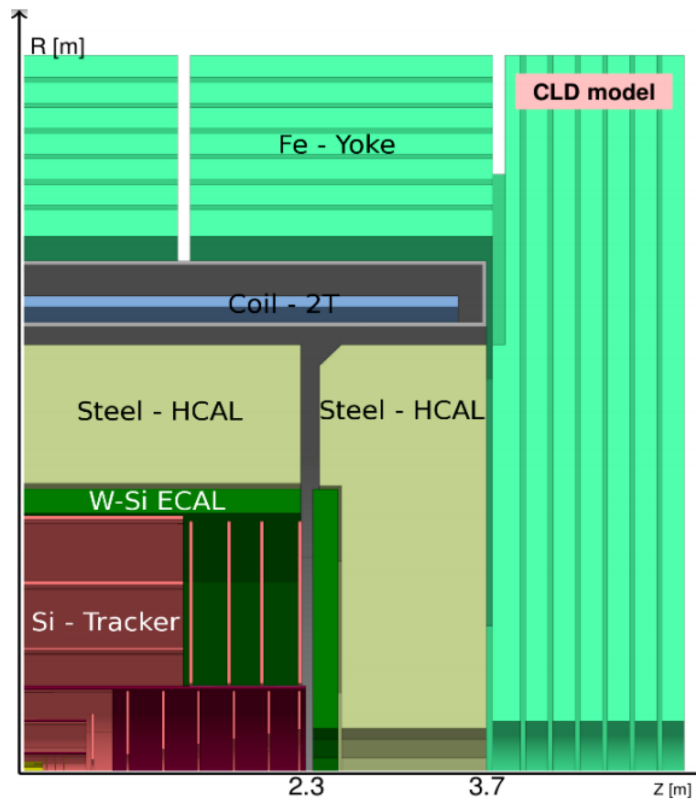
Parameter	Current* 7+8+13 TeV $\mathcal{O}$ (70 fb^{-1})	HL-LHC* 14 TeV (3 ab^{-1})	FCC-ee Baseline (10 yrs)	ILC Lumi upgrade (20 yrs)	CEPC Baseline (10 yrs)	CLIC Baseline (15 yrs)
σ(HZ)	–	–	0.4%	0.7%	0.5%	1.6%
g_{ZZ}	10%	2–4%	0.15%	0.3%	0.25%	0.8%
g_{WW}	11%	2–5%	0.2%	0.4%	1.6%	0.9%
g_{bb}	24%	5–7%	0.4%	0.7%	0.6%	0.9%
g_{cc}	–	–	0.7%	1.2%	2.3%	1.9%
$g_{\tau\tau}$	15%	5–8%	0.5%	0.9%	1.4%	1.4%
$g_{t\bar{t}}$	16%	6–9%	13%	6.3%	–	4.4%
$g_{\mu\mu}$	–	8%	6.2%	9.2%	17%	7.8%
$g_{e^+e^-}$	–	–	<100%	–	–	–
g_{gg}	–	3–5%	0.8%	1.0%	1.7%	1.4%
$g_{\gamma\gamma}$	10%	2–5%	1.5%	3.4%	4.7%	3.2%
$g_{Z\gamma}$	–	10–12%	(to be determined)			9.1%
Δm_H	200 MeV	50 MeV	11 MeV	15 MeV	5.9 MeV	32 MeV
Γ_H	<26 MeV	5–8%	1.0%	1.8%	2.8%	3.6%
Γ_{inv}	<24%	<6–8%	<0.45%	<0.29%	<0.28%	<0.97%

CMS-like detector at Fcc-ee

- Solenoid:
  - Magnetic field strength: B_Z: 3.5 T at ILD, 3.8 T at CMS.
  - Tracking radius: 1.8 m at ILD, 1.29 m at CMS.
  - Half length of field coverage: 2.4 m at ILD, 3.0 m at CMS.
- Tracking efficiency:
  - ILD: 99% for particles with $p_T > 100$ MeV and $|\eta| < 2.4$, including muons and electrons.
  - CMS: 95% for particles with $p_T > 100$ MeV and $|\eta| < 2.5$, including muons and electrons.
- Muon momentum resolution:
  - ILD: $\frac{\Delta P}{P} = 0.1\% + \frac{P_T}{10^5 GeV}$ for $|\eta| < 1$ and 10 times higher for $|\eta|$ up to 2.4.
  - CMS: between 1% and 5%.
- Electron energy resolution:
  - ILD: $\frac{\Delta E}{E} = \frac{16.6\%}{\sqrt{E[GeV]}} + 1.1\%$.
  - CMS: $\frac{\Delta E}{E} = \sqrt{E^2 * 0.007^2 + E * 0.07^2 + 0.35^2}$, E in GeV.
- Particle reconstruction efficiency:
  - ILD: 99% for e, μ and γ with $P_T > 10$ GeV.
  - CMS: 85%–95% for the same p_T range.

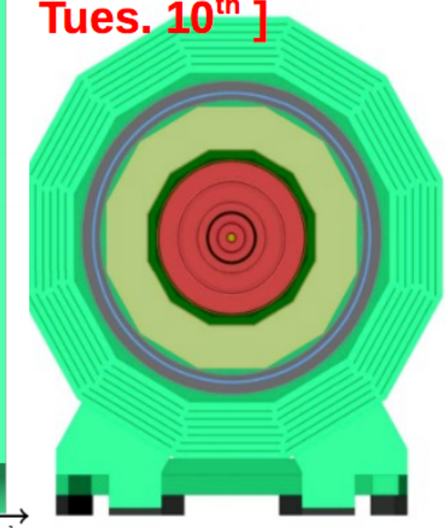
FCC-ee detectors

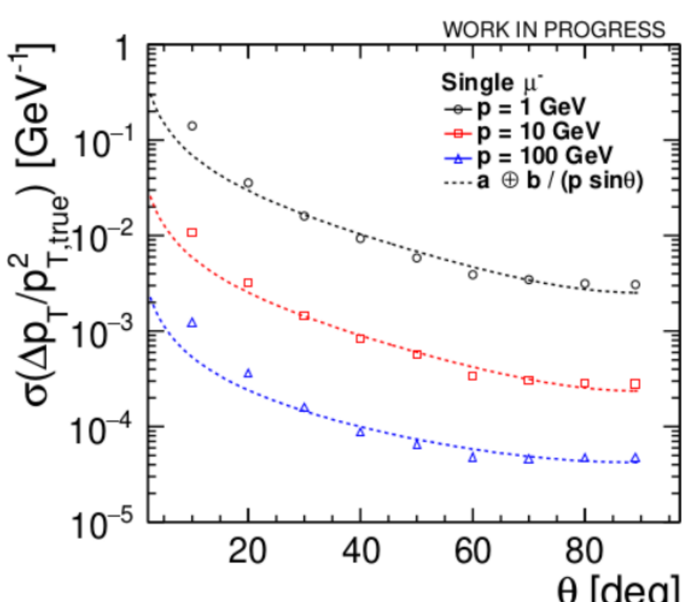
- CLD (L=10.6 m) inspired in CLIC/ILC detectors & optimized for FCC-ee conditions:
  - ► Beam pipe: ~1.5 cm (0.5% X_0)
  - ► Vertex detector: Si pixels
    3x2 double-layers (1% X_0). Point resol.: 3μm
  - ► Tracker detector: Si pixels & microstrips
    6 layers (8% X_0). Point resol.: 7x90 μm
  - ► EM & HCAL Calorimeters:
    Si-W sampling calo (22 X_0, 1λ_{int})
    Sci/Steel sampling calo (5.5 λ_{int})
  - ► B-field: 2 T (superconducting coil)
  - ► Muon system: 6 RPCs
  - ► Forward region (<150 mrad): MDI & LumiCal

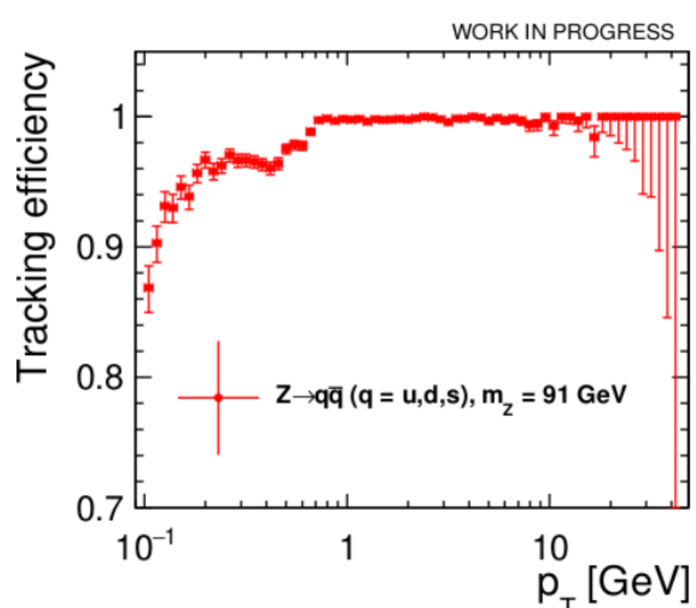


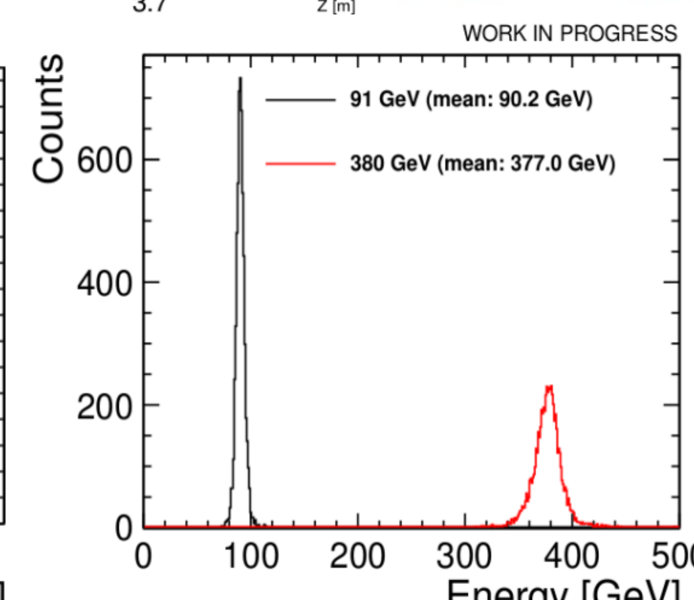
Proven concept, Performances from full simulation

[See O.Viazlo, Tues. 10th]





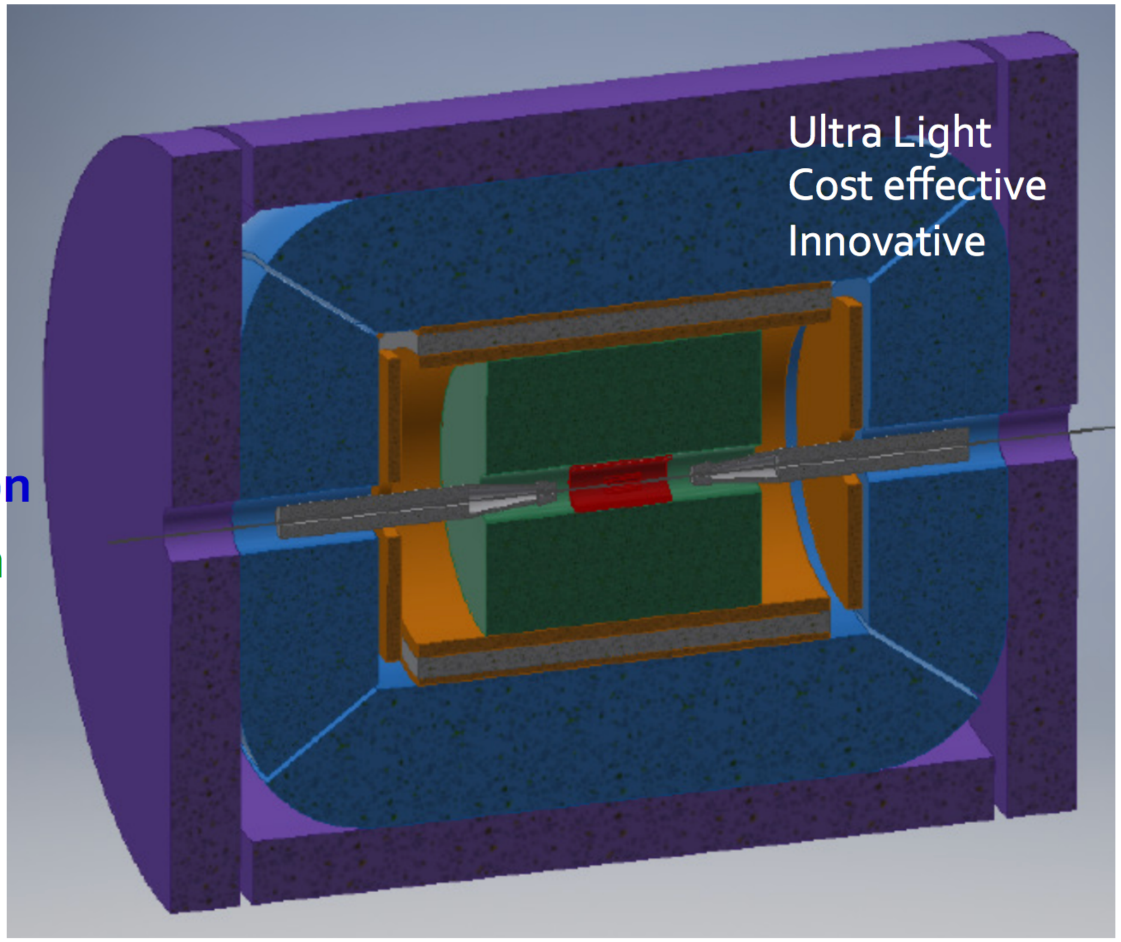




CC Week, Amsterdam, April'18 12/34 David d'Enterria (CERN)

FCC-ee Detectors

- New IDEA, a detector specifically designed for FCC-ee
  - Vertex Si detector
    - With light MAPS technology
    - 7 layers, up to 35cm radius
  - Ultra light wire drift chamber
    - 4m long, 2 m radius, 0.4% X_0
    - 112 layers with Particle ID
  - One Si layer for acceptance determination
    - Precise tracking with large lever arm
      - Barrel and end-caps
  - Ultra-thin 20-30cm solenoid (2T)
    - Acts as preshower ($1X_0$)
    - Or $1X_0$ Pb if magnet outside calo
  - Two μ-RWell layers
    - Active preshower measurement
  - Dual readout fibre calorimeter
    - 2m thick, longitudinal segmentation
  - Instrumented return yoke



Design, R&D, test beam, performance studies have started and will be continued during the FCC-ee technical design phase. Performance tailored for FCC-ee physics.

FCC-ee running

- The FCC-ee physics goals require at least
  - 150 ab^{-1} at and around the Z pole ($\sqrt{s}$~91.2 GeV)
  - 10 ab^{-1} at the WW threshold ($\sqrt{s}$~161 GeV)
  - 5 ab^{-1} at the HZ cross section maximum ($\sqrt{s}$~240 GeV)
  - 0.2 ab^{-1} at the top threshold ($\sqrt{s}$~350 GeV) and 1.5 ab^{-1} above ($\sqrt{s}$~365 GeV)

$5{\times}10^{12}$ Z
10^8 WW
10^6 HZ
10^6 $t\bar{t}$

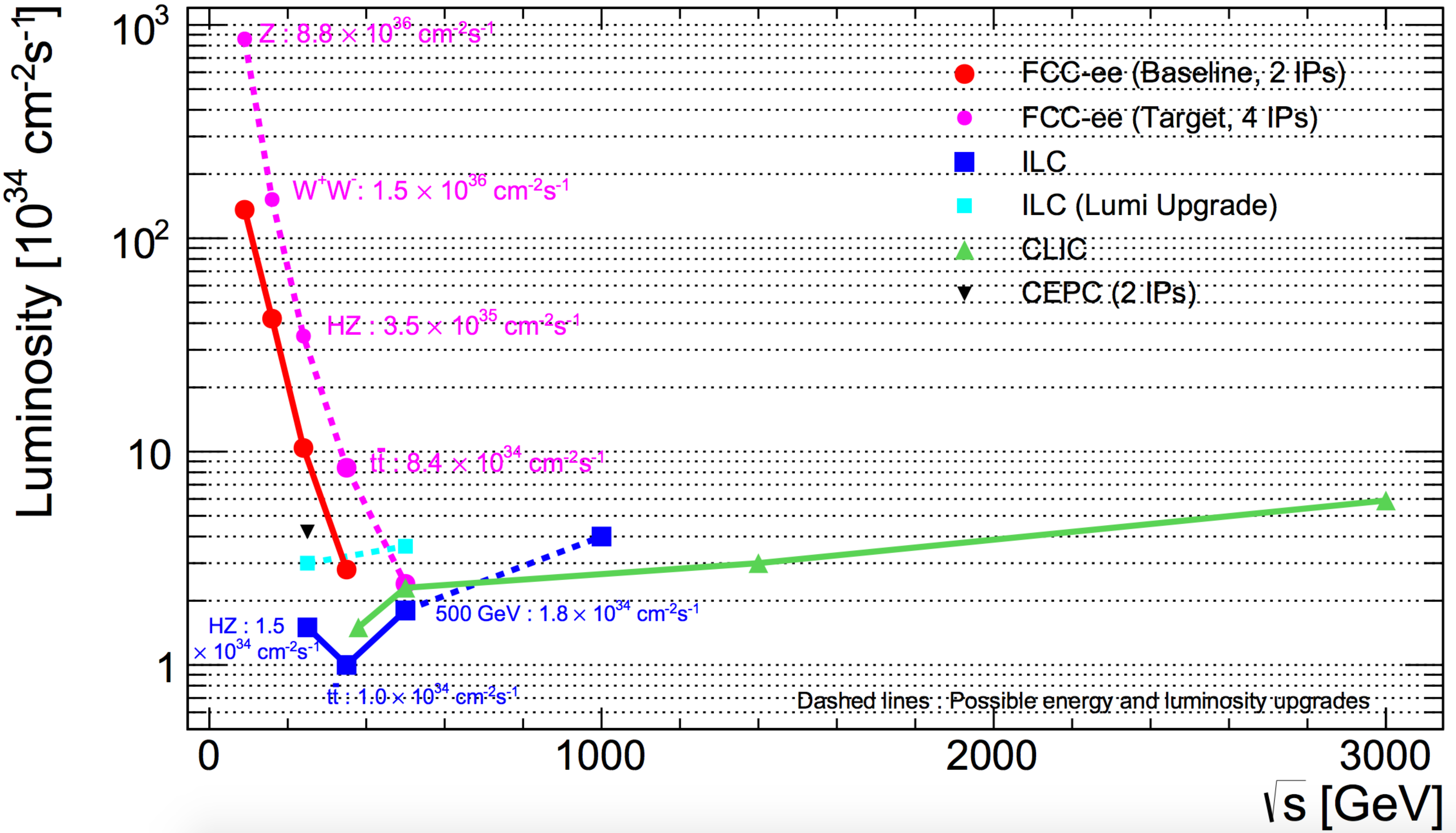
- Operation model (with 10% safety margin) with two IPs
  - 200 scheduled physics days per year (7 months – 13 days of MD / stops)
  - Hübner factor ~ 0.75 (lower than achieved with KEKB top-up injection, ~0.8)
  - Half the design luminosity in the first two years of Z operation (~LEP1)
  - Machine configuration between WPs changed during Winter shutdowns (3 months/year)

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$ threshold	365 GeV
Lumi/IP (10^{34} $cm^{-2}s^{-1}$)	100	200	13	7	1.6	1.3
Lumi/year (2 IP)	26 ab^{-1}	52 ab^{-1}	7.8 ab^{-1}	1.8 ab^{-1}	0.4 ab^{-1}	0.35 ab^{-1}
Physics goal	150		10	5	0.2	1.5
Run time (year)	2	2	1	3	0.5	4

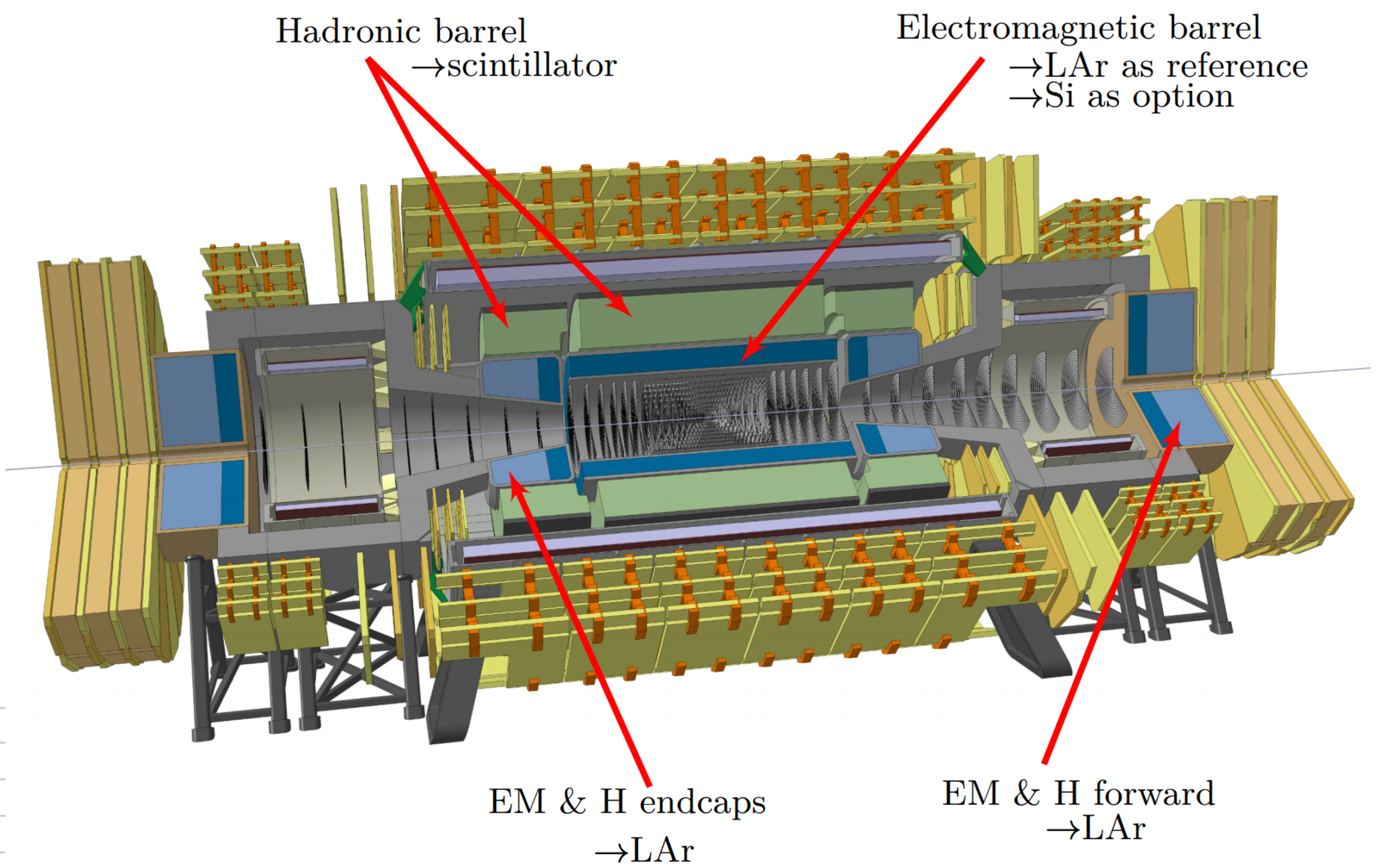
- Total running time : 12-13 years (~ LEP)

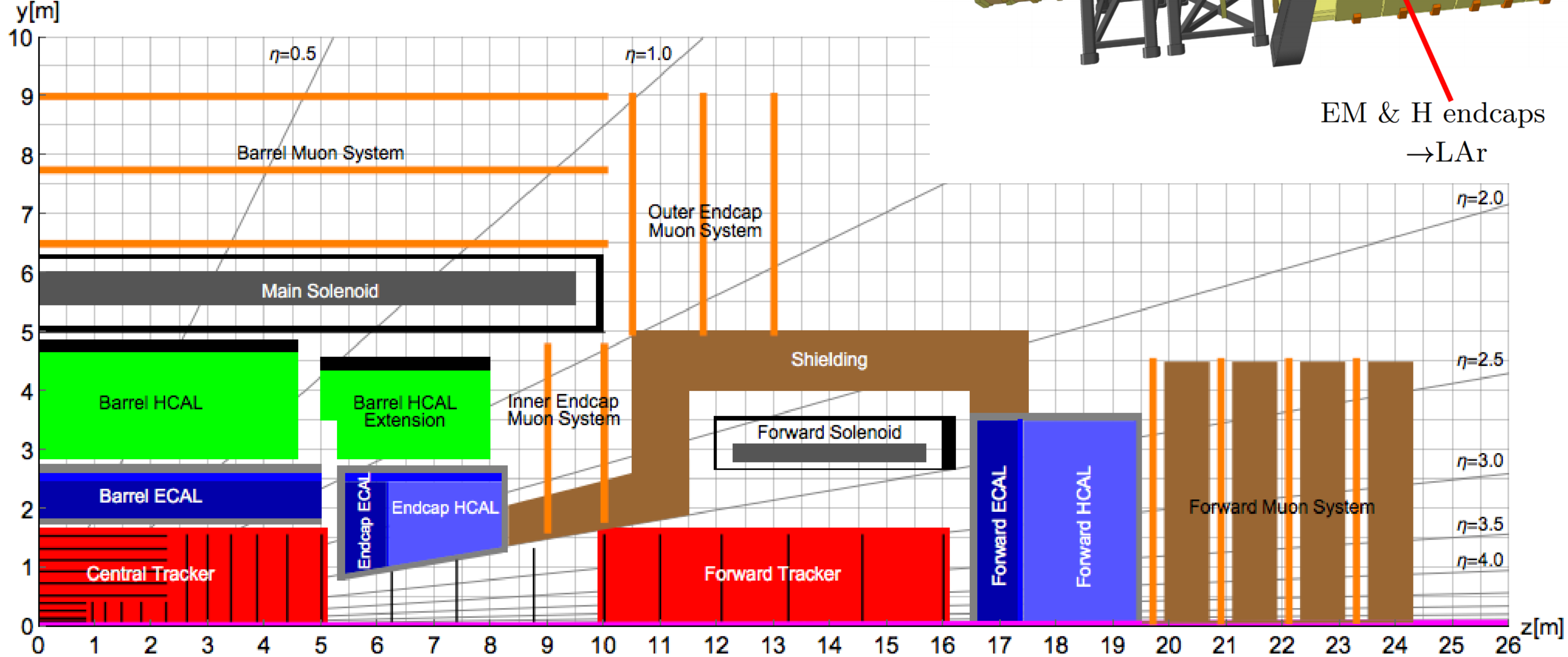
Longer shutdown: install 74 RF CMs
LEP Record: 32 in one shutdown !

FCC-ee luminosities



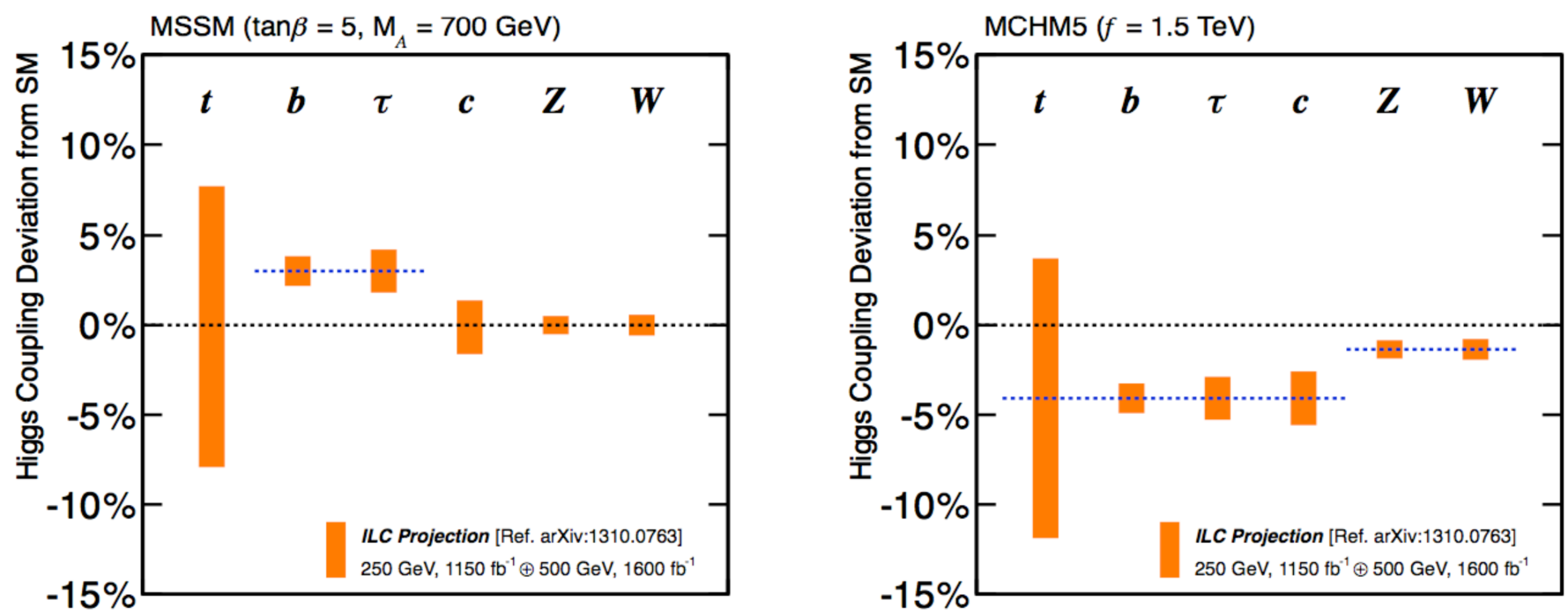
FCC-hh reference detector



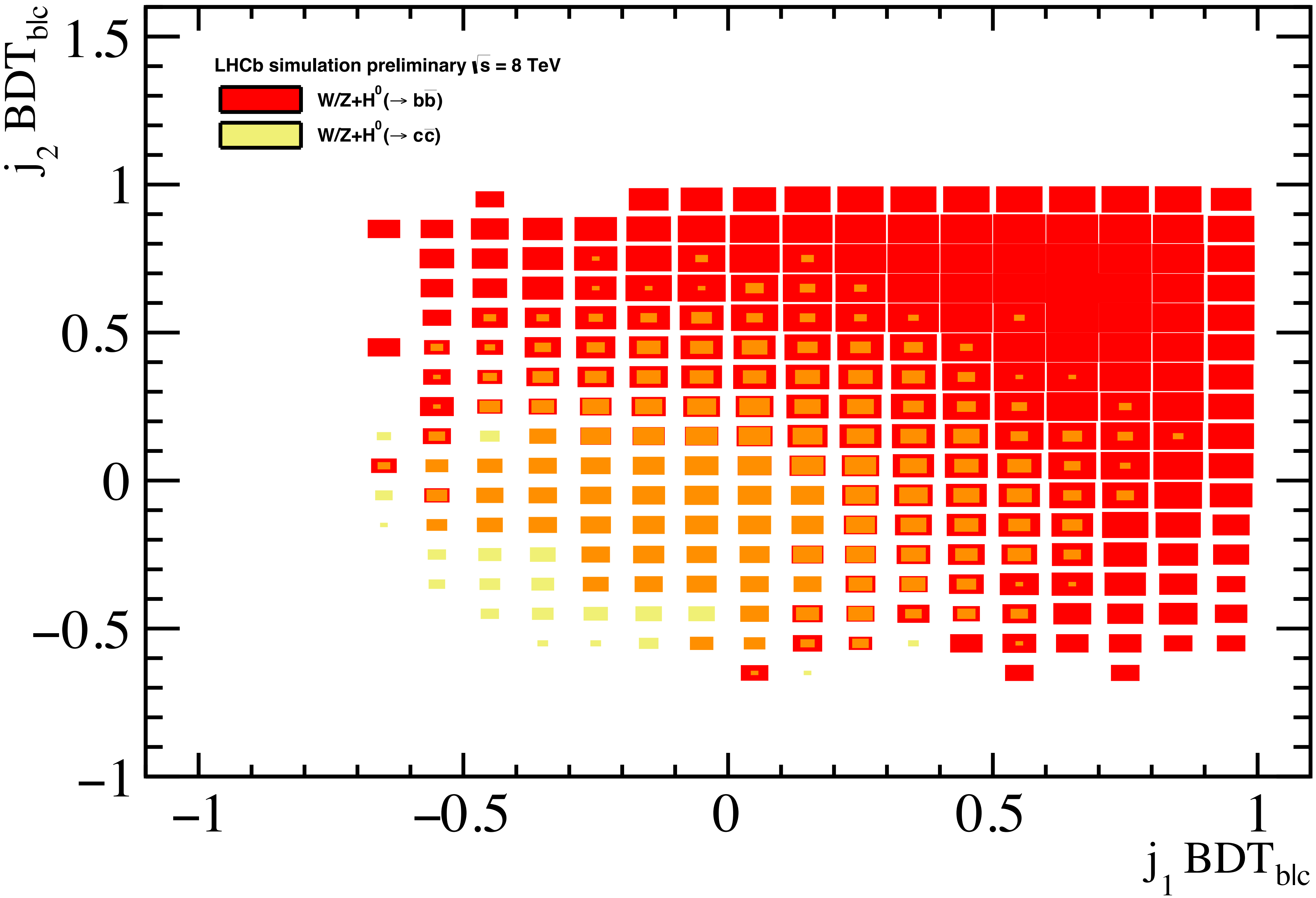


Higgs deviations

SUSY | Kanemura, Tsumura, Yagyu, Yokoya | COMPOSITE HIGGS

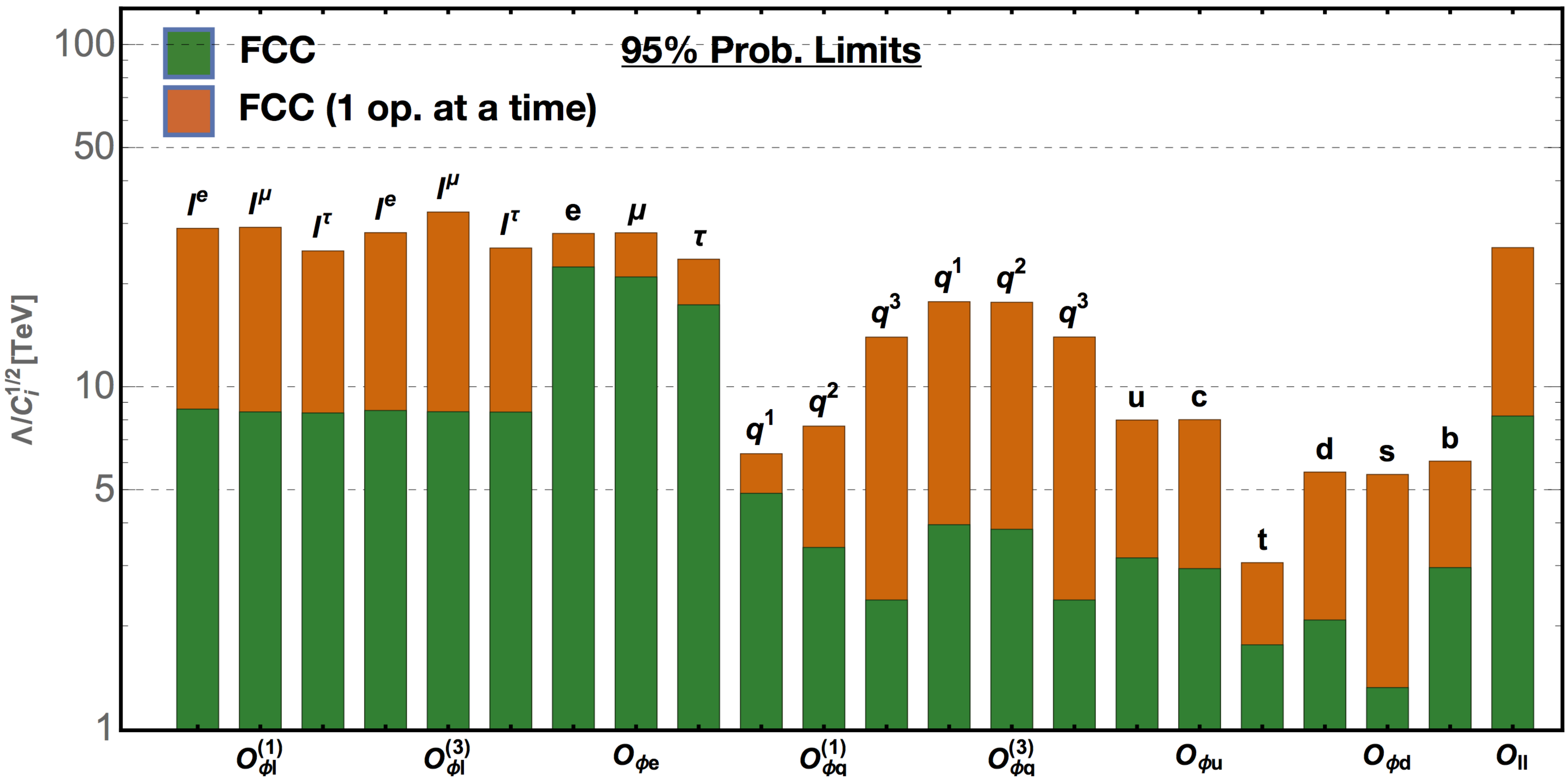


LHCb H->bb/cc


LHCb simulation preliminary √s = 8 TeV
W/Z+H^0(→ b$\bar{b}$)
W/Z+H^0(→ c$\bar{c}$)
1.5
1
0.5
0
−0.5
−1
−1
−0.5
0
0.5
1
j_2 BDT$_{blc}$
j_1 BDT$_{blc}$

Global fits

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$



Global fits

Higgs observables in terms of EFT operator bases

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\rm SM}_{\gamma\gamma}} = 1 + 2.56\,\delta c_z + 2.13\,c_{z\Box} + 0.98\,c_{zz} - 0.066\hat{c}_{z\gamma} - 2.46\,\hat{c}_{\gamma\gamma} - 0.56\,\delta y_t\,, \tag{A.6}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{\rm SM}_{Z\gamma}} = 1 + 2.11\,\delta c_z - 3.4\,\hat{c}_{z\gamma} - 0.113\,\delta y_t\,, \tag{A.7}$$

$$\frac{\Gamma_{\rm WW}}{\Gamma^{\rm SM}_{\rm WW}} = 1 + 2.0\,\delta c_z + 0.67\,c_{z\Box} + 0.05\,c_{zz} - 0.0182\,\hat{c}_{z\gamma} - 0.0051\,\hat{c}_{\gamma\gamma}\,, \tag{A.8}$$

$$\frac{\Gamma_{\rm ZZ}}{\Gamma^{\rm SM}_{\rm ZZ}} = 1 + 2.0\,\delta c_z + 0.33\,c_{z\Box} + 0.19\,c_{zz} - 0.0081\,\hat{c}_{z\gamma} - 0.00111\,\hat{c}_{\gamma\gamma}\,, \tag{A.9}$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma^{\rm SM}_{\tau\tau}} = 1 + 2.0\,\delta y_\tau\,, \tag{A.10}$$

$$\frac{\Gamma_{bb}}{\Gamma^{\rm SM}_{bb}} = 1 + 2.0\,\delta y_b\,, \tag{A.11}$$

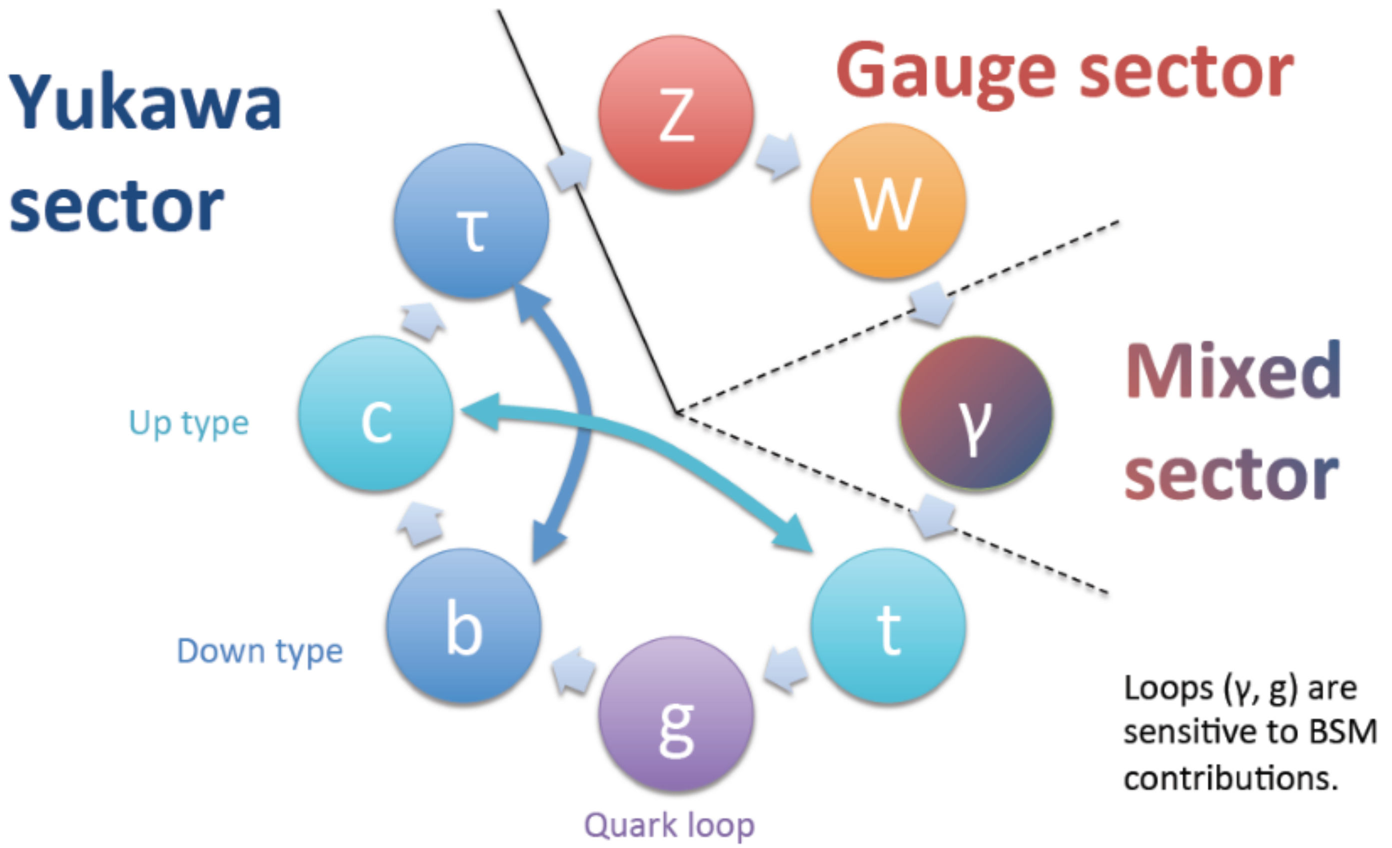
$$\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}} = 1 + 0.171\,\hat{c}_{gg} + 0.006\,c_{zz} - 0.0091\,\hat{c}_{z\gamma} + 0.15\,c_{z\Box} - 0.0061\,\hat{c}_{\gamma\gamma} + 0.48\,\delta c_z + 1.15\,\delta y_b + 0.23\,\delta y_t + 0.13\,\delta y_\tau\,, \tag{A.12}$$

Higgs couplings

In the SM, the Higgs boson couples to SM particles in proportion to their mass (or mass²)

$$g_{\mathrm{V}} = \frac{2m_{\mathrm{V}}^2}{v}$$

$$g_{\mathrm{f}} = \frac{\sqrt{2}m_{\mathrm{f}}}{v}$$



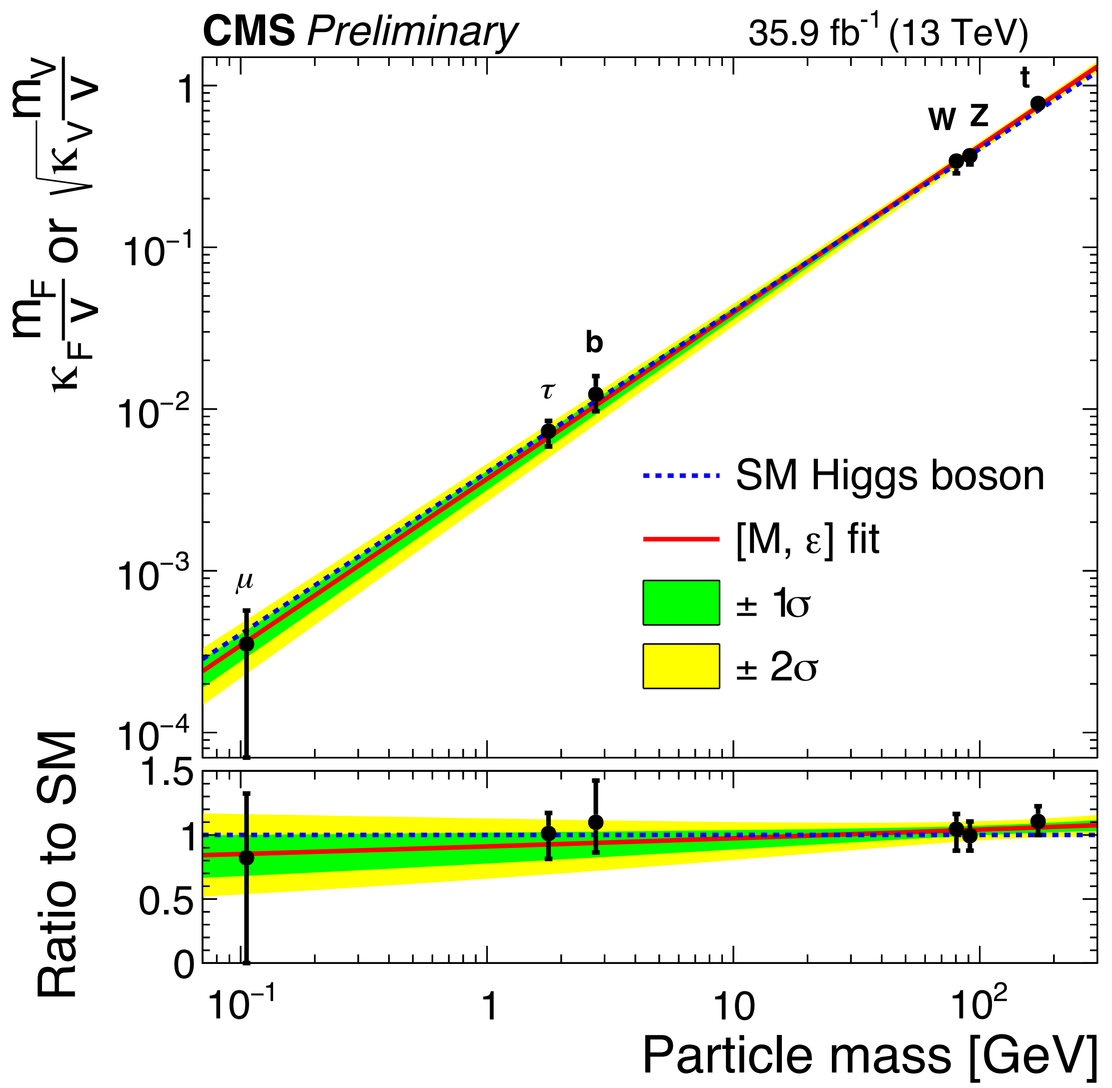
Higgs couplings

In the SM, the Higgs boson couples to SM particles in proportion to their mass (or mass^2)

We typically consider deviations from SM values -> ***κ* - coupling modifiers in LO framework**

- Assumes underlying Lorentz structure unchanged
- Often QCD NLO effects are "factorizable"
- Allows for interference effects to be probed

$$\kappa_i = \frac{g_i}{g_{i,\mathrm{SM}}}$$



Higgs Couplings

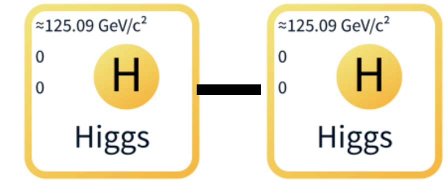
Measuring Higgs bosons couplings remain a key goal of Future Higgs measurements

- Higgs coupling measurements are good to test SM compatibility
  - Synergies with EFT approaches
- BSM contributions requite O(%) level Higgs property measurements

arXiv:1310.8361 $M_{NP} \sim$ 1TeV

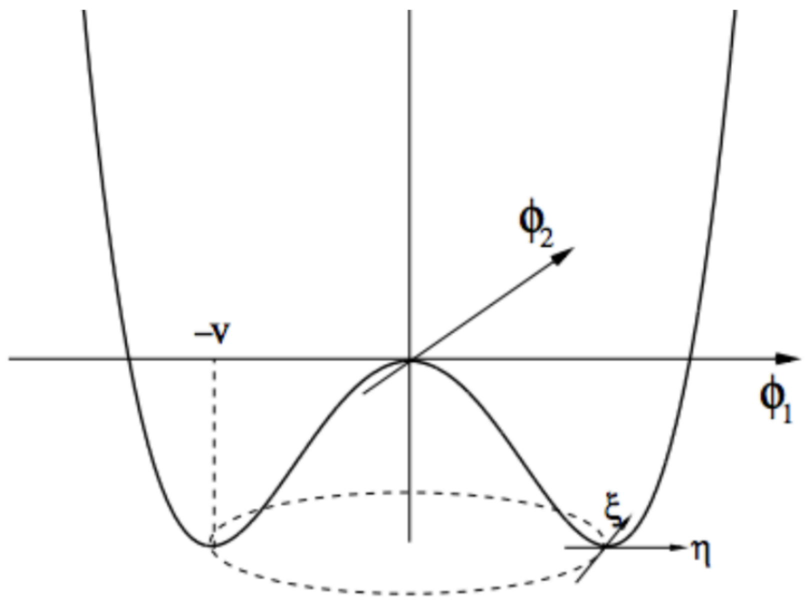
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

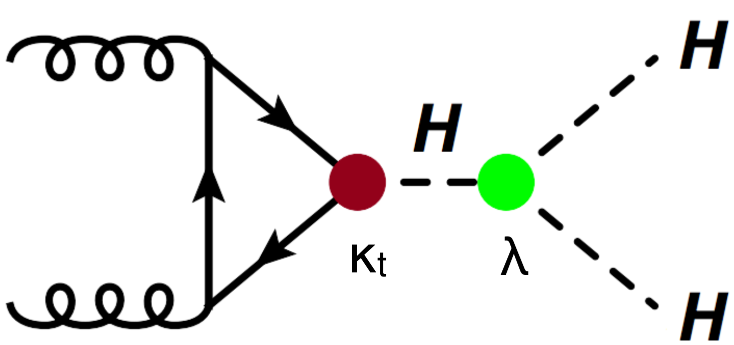
HL-LHC Projections

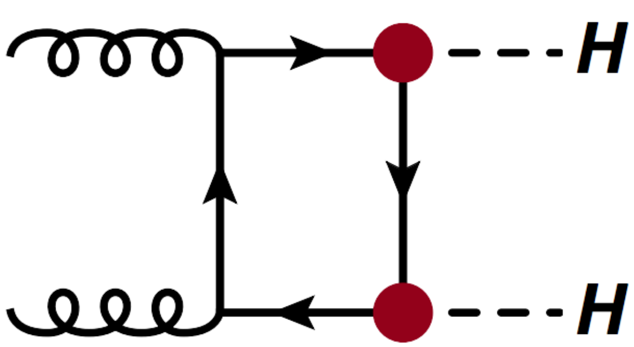


Double Higgs production important to study Higgs boson self-coupling (the Higgs potential itself!)

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4$$

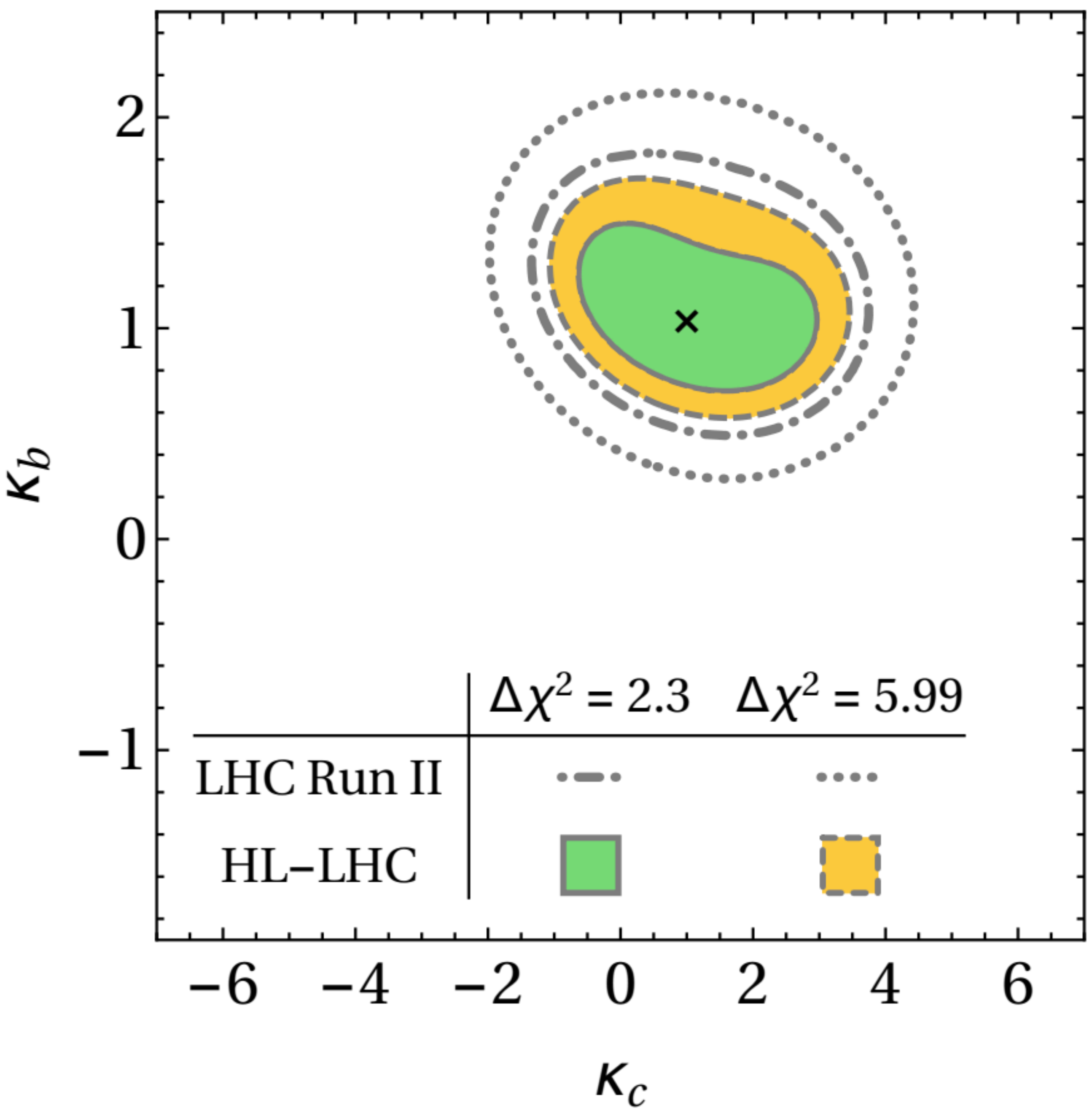




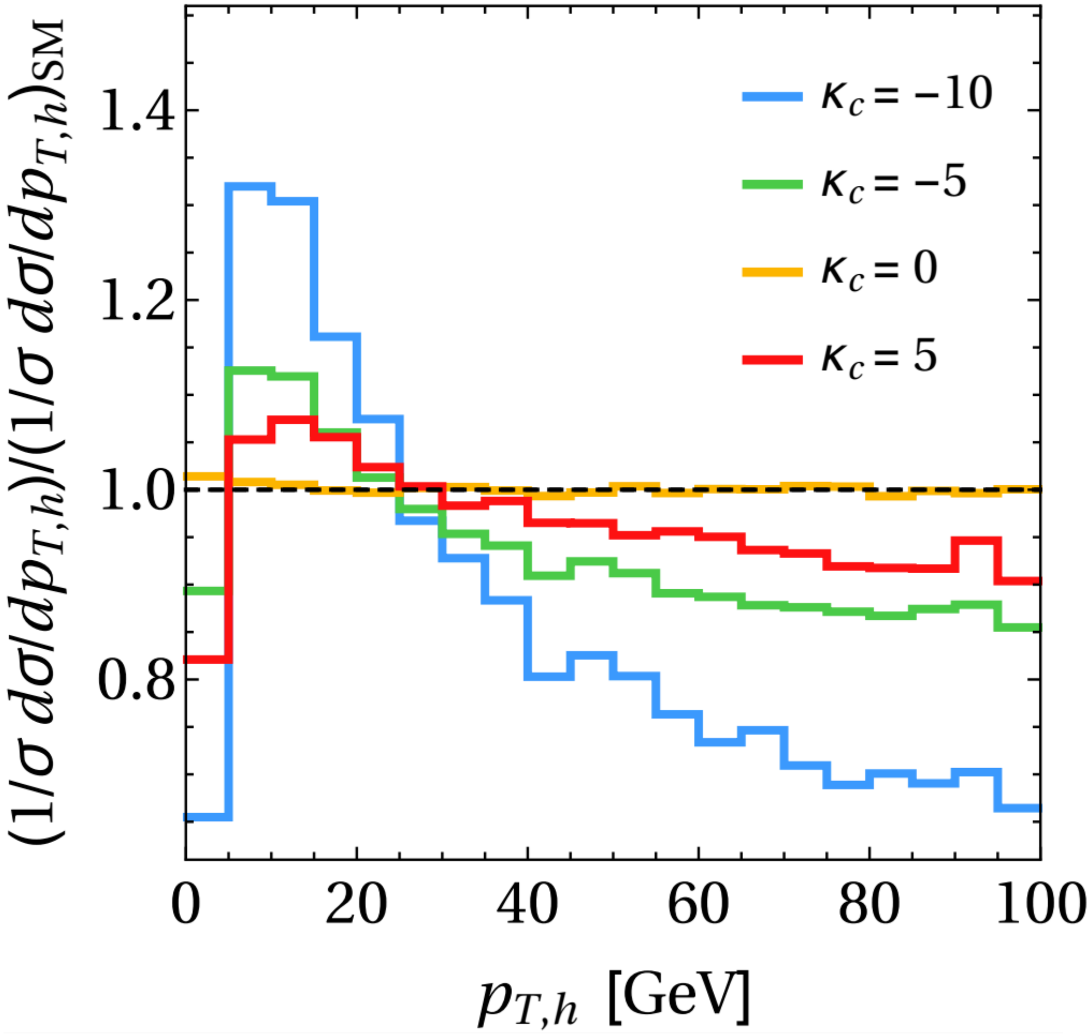


Destructive interference between leading contributions leads to very small cross section (**$\sigma_{pp \to HH}$ ~ 40fb at 13TeV**)

b-c couplings from differential



Bishara, Haisch, Monni, Re (2016) [1606.09253]



Use the Higgs pT spectrum to constrain fermion couplings

$$\frac{\kappa_{\mathrm{u}}}{\kappa_{\mathrm{d}}}$$