Higgs Precision at the HL-LHC and the FCC

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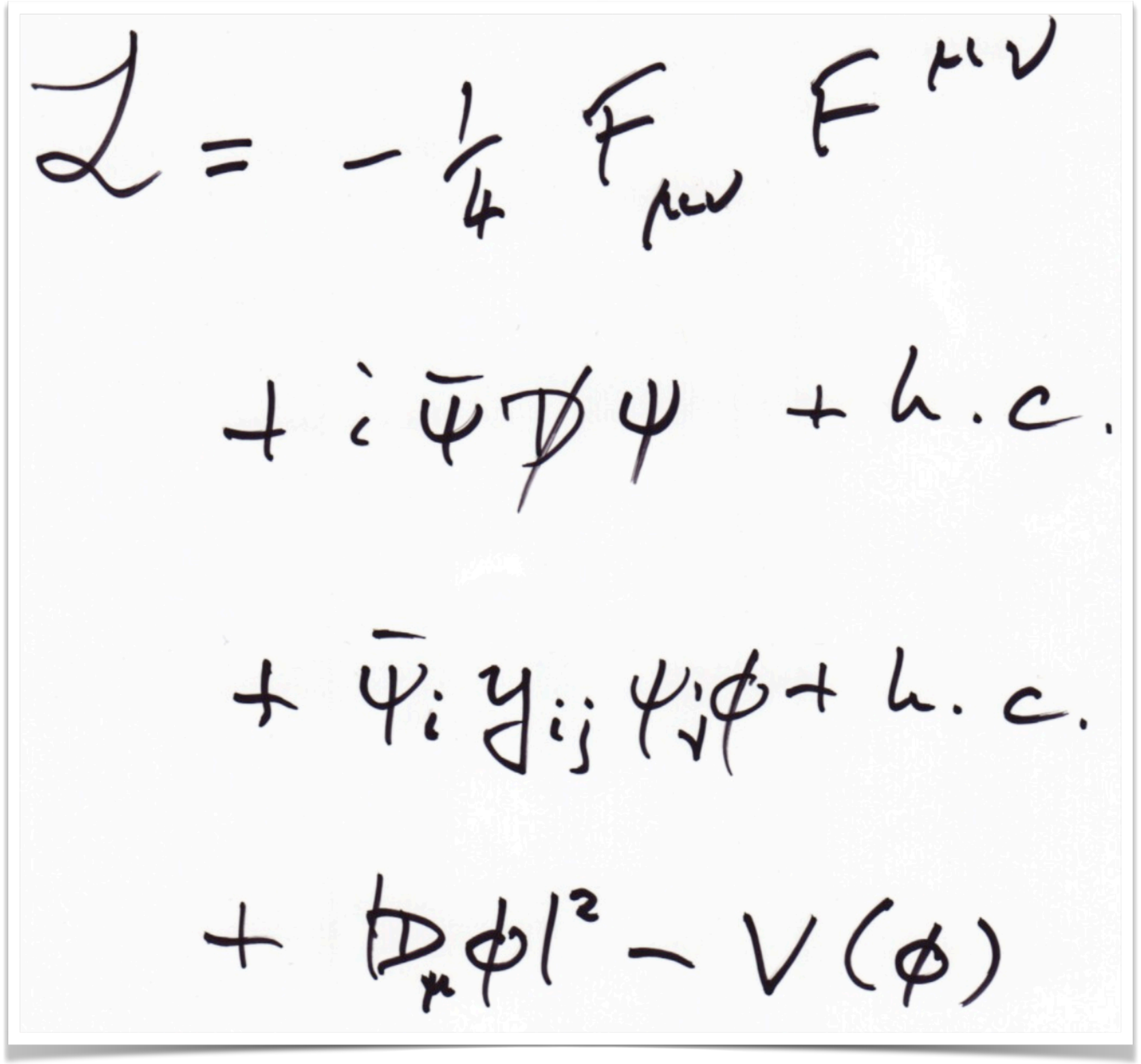
CERN

Zurich Pheno Workshop 2024

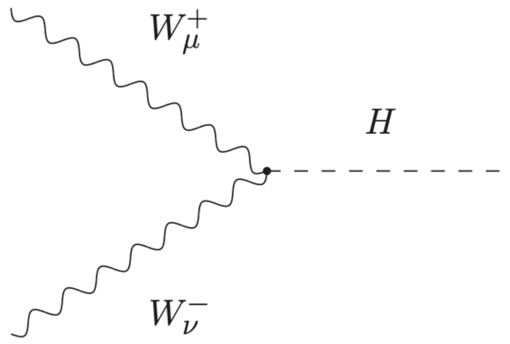
The Higgs sector

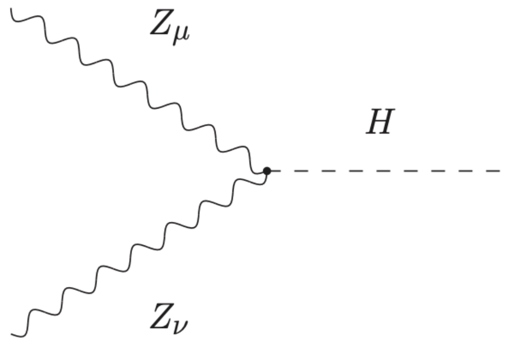


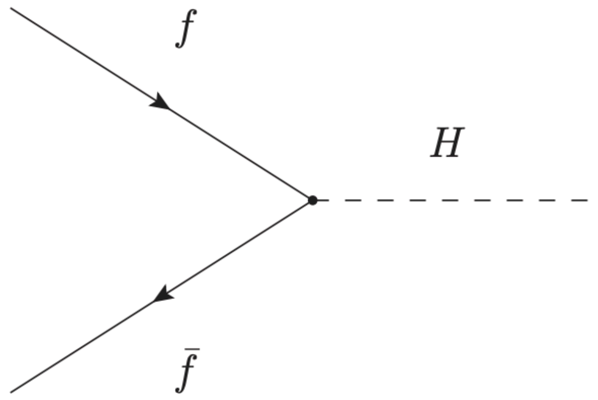
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

gauge couplings:

$$\frac{2M_W^2}{v}$$



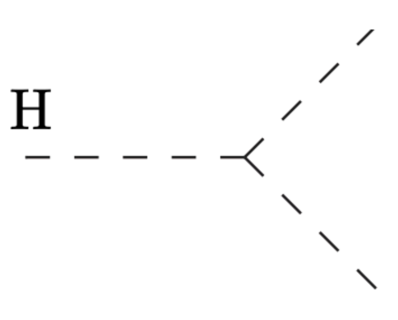




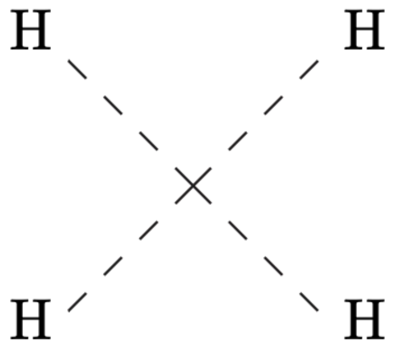
$$\mathcal{L}_{H-f} = -\sum_f \frac{m_f}{v} \bar{f} f H$$

fermion couplings

Higgs potential



$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

Outline

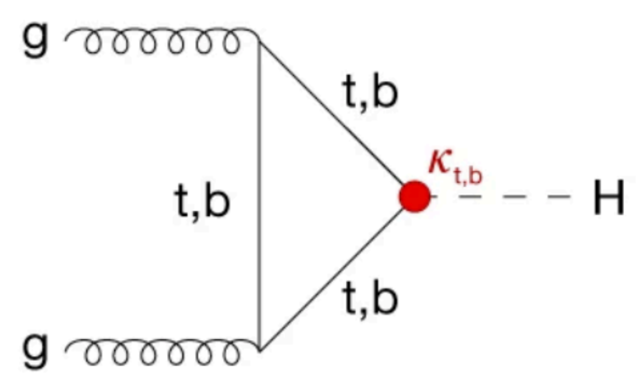
- Where we are (LHC - Run II)
  - Where we will be (Run III - HL-LHC)…

- Higgs measurements at the FCC-ee:
  - Production and decays
  - Higgs couplings
  - Higgs properties (mass, width)

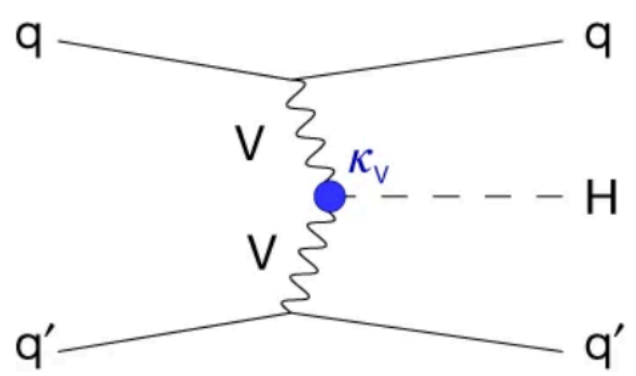
- Higgs measurements at the FCC-hh:
  - rates at 100 TeV vs 14 TeV
    - threshold vs boosted production
  - Single/double Higgs measurements

Higgs Production and decay at the LHC

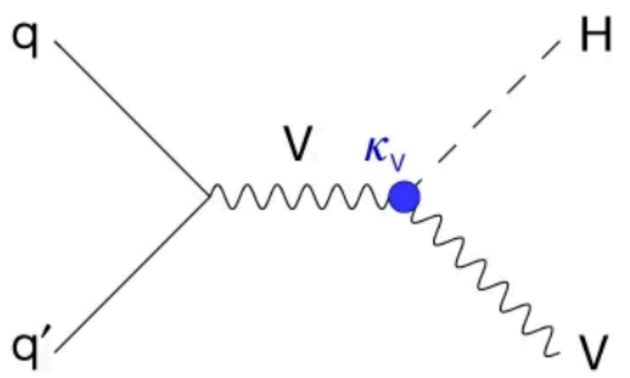
production



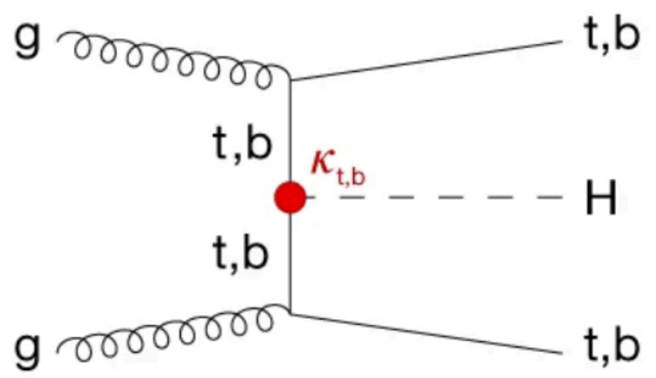
ggF ~ 87%



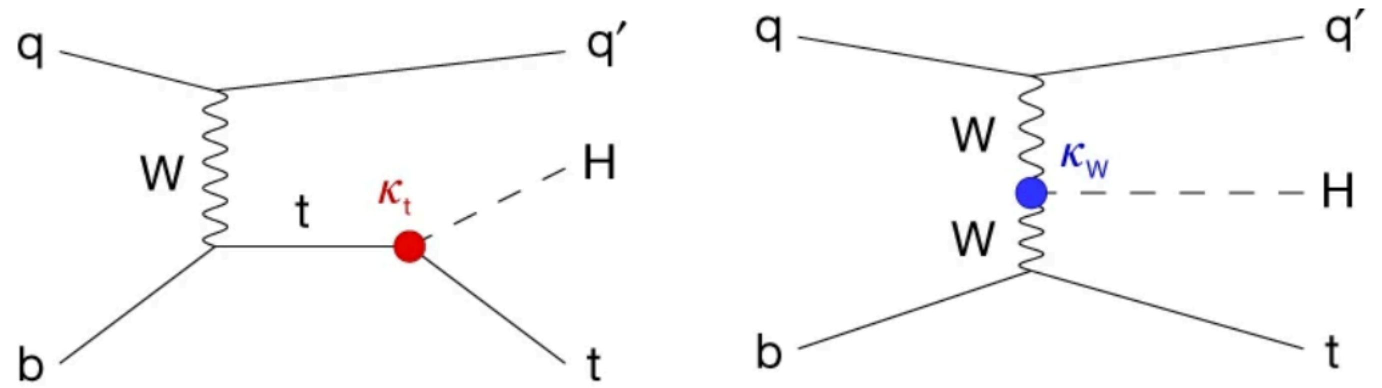
VBF ~ 7%



VH ~ 4%



ttH ~ 1%
bbH ~ 1%



tH ~ 0.1%

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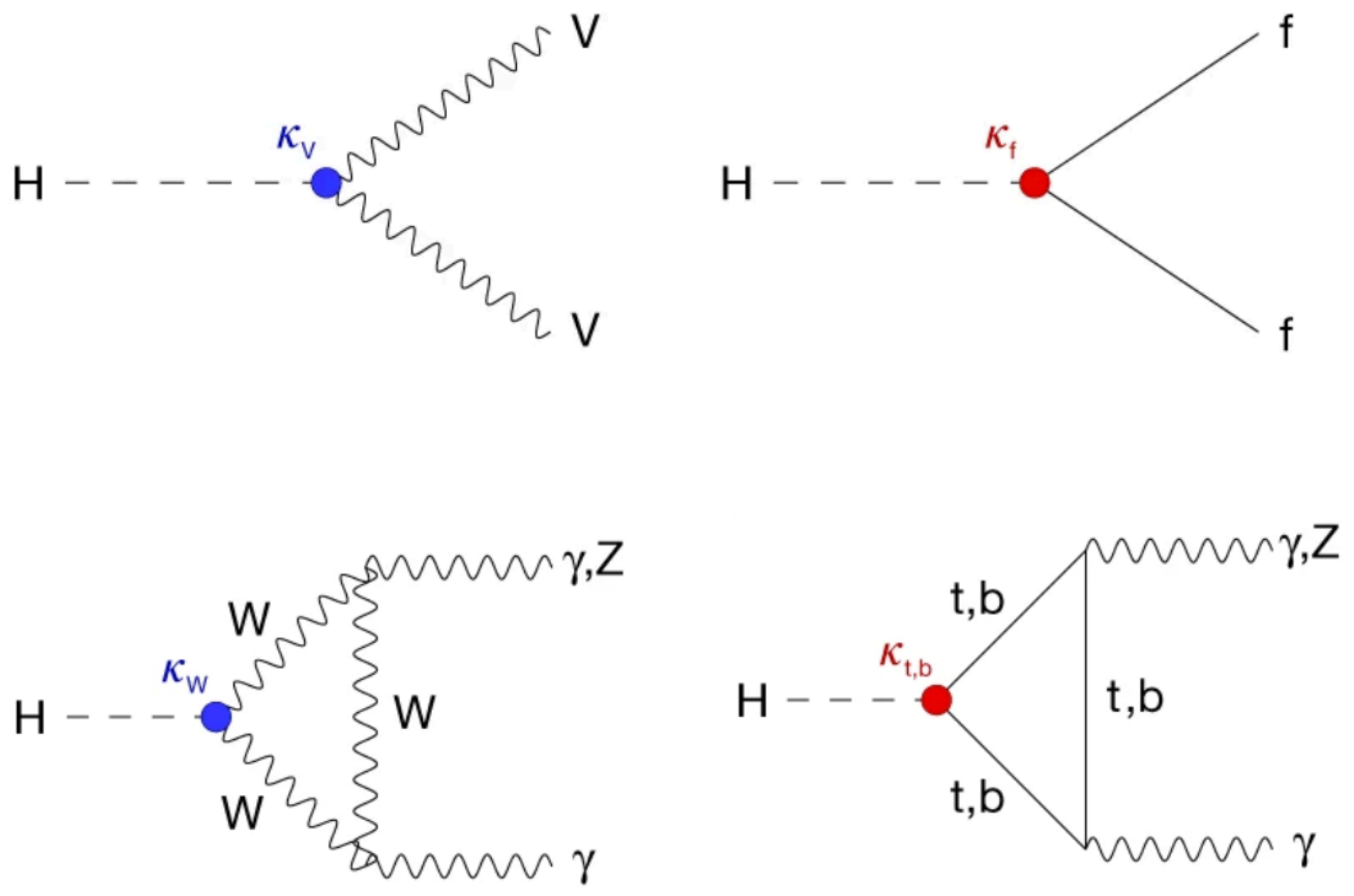
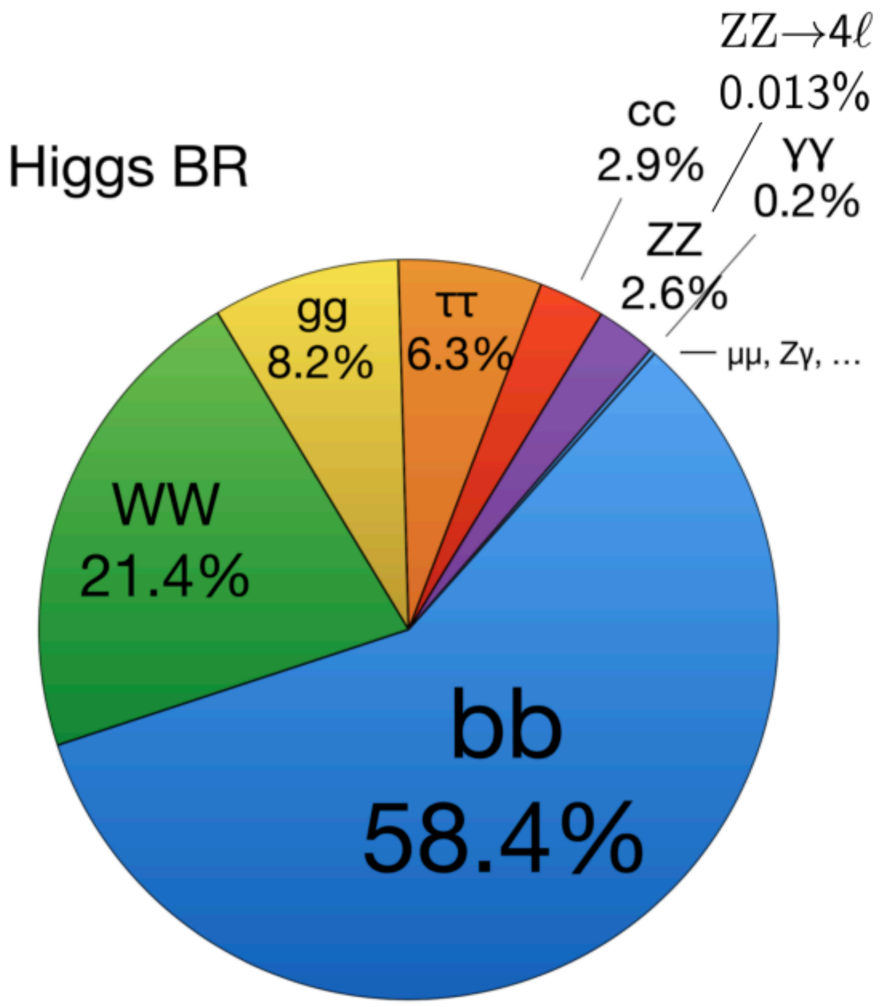
decay



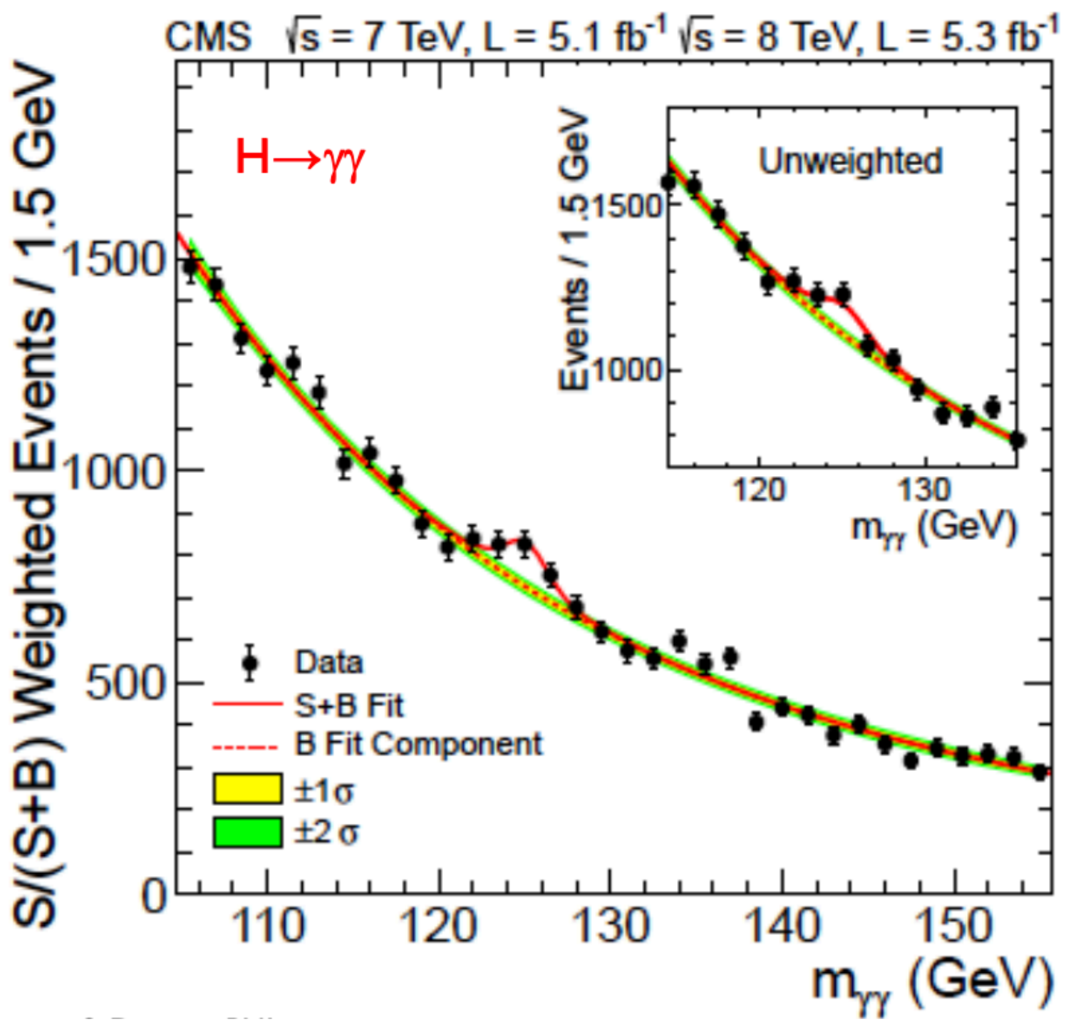


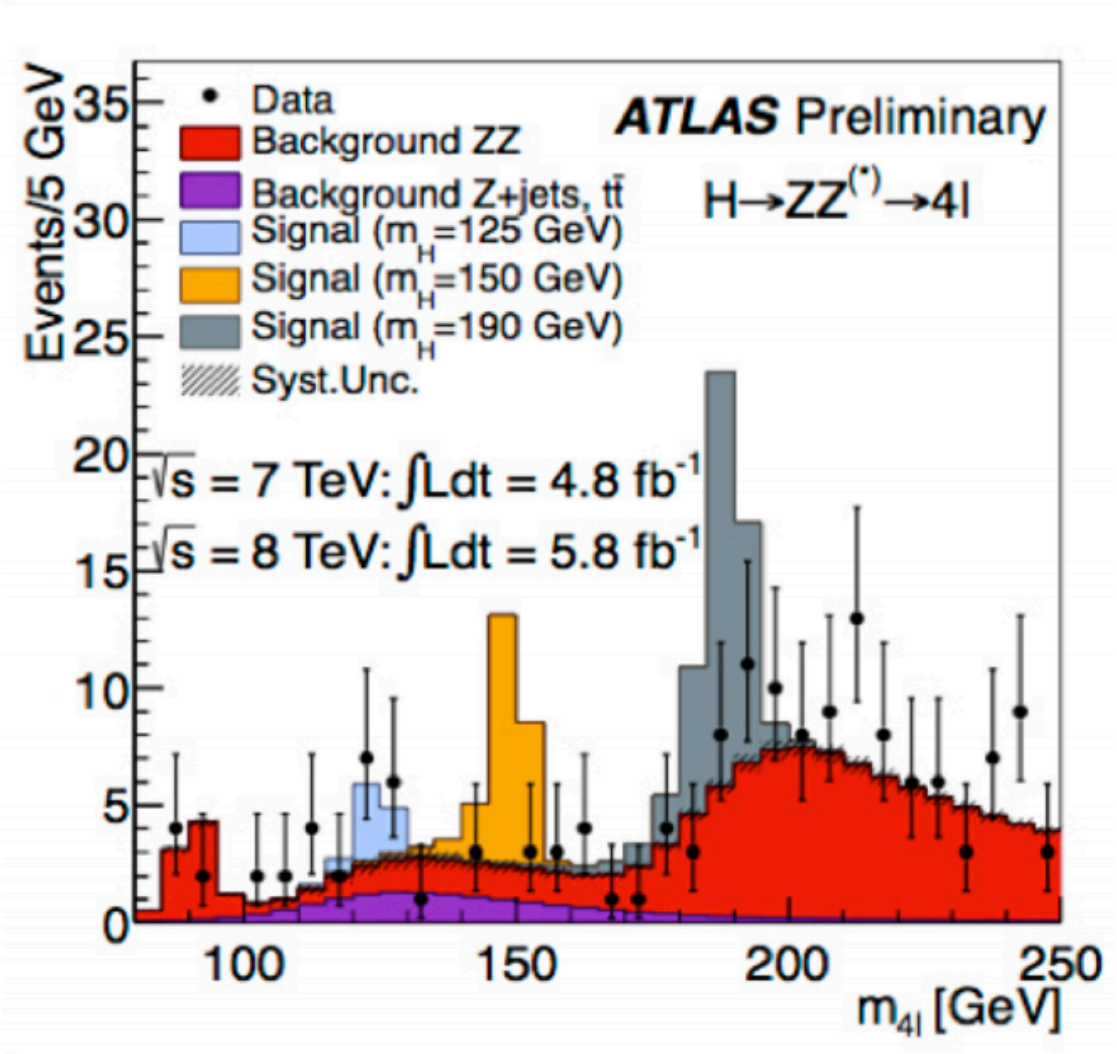
Clean decay modes:

γγ

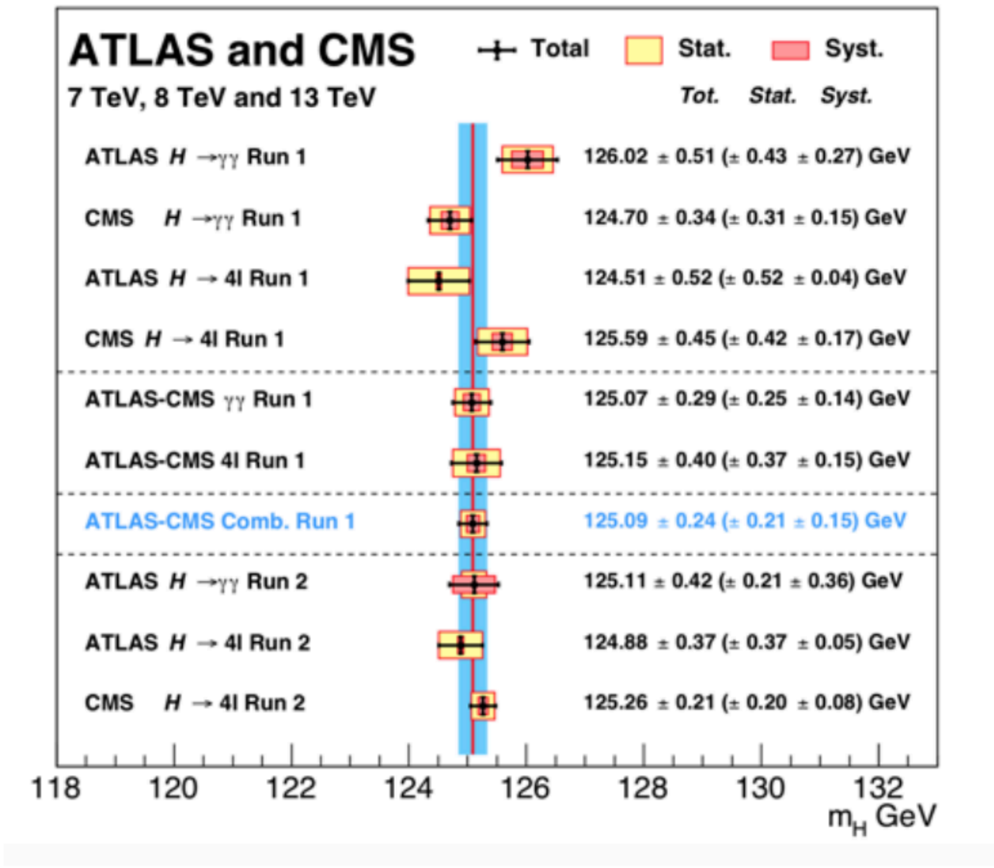
ZZ* → 4l

Present state of affairs





Higgs mass

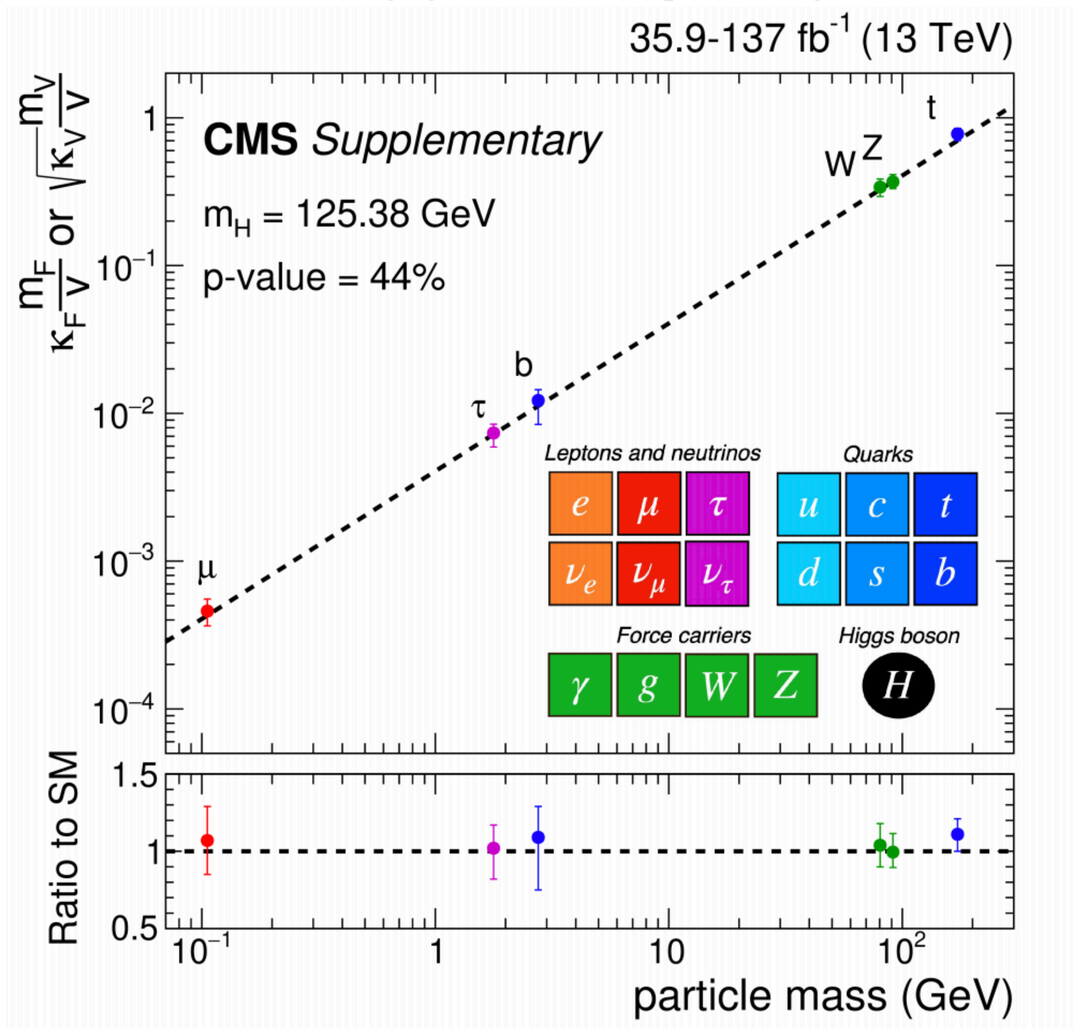


2012 — Discovery

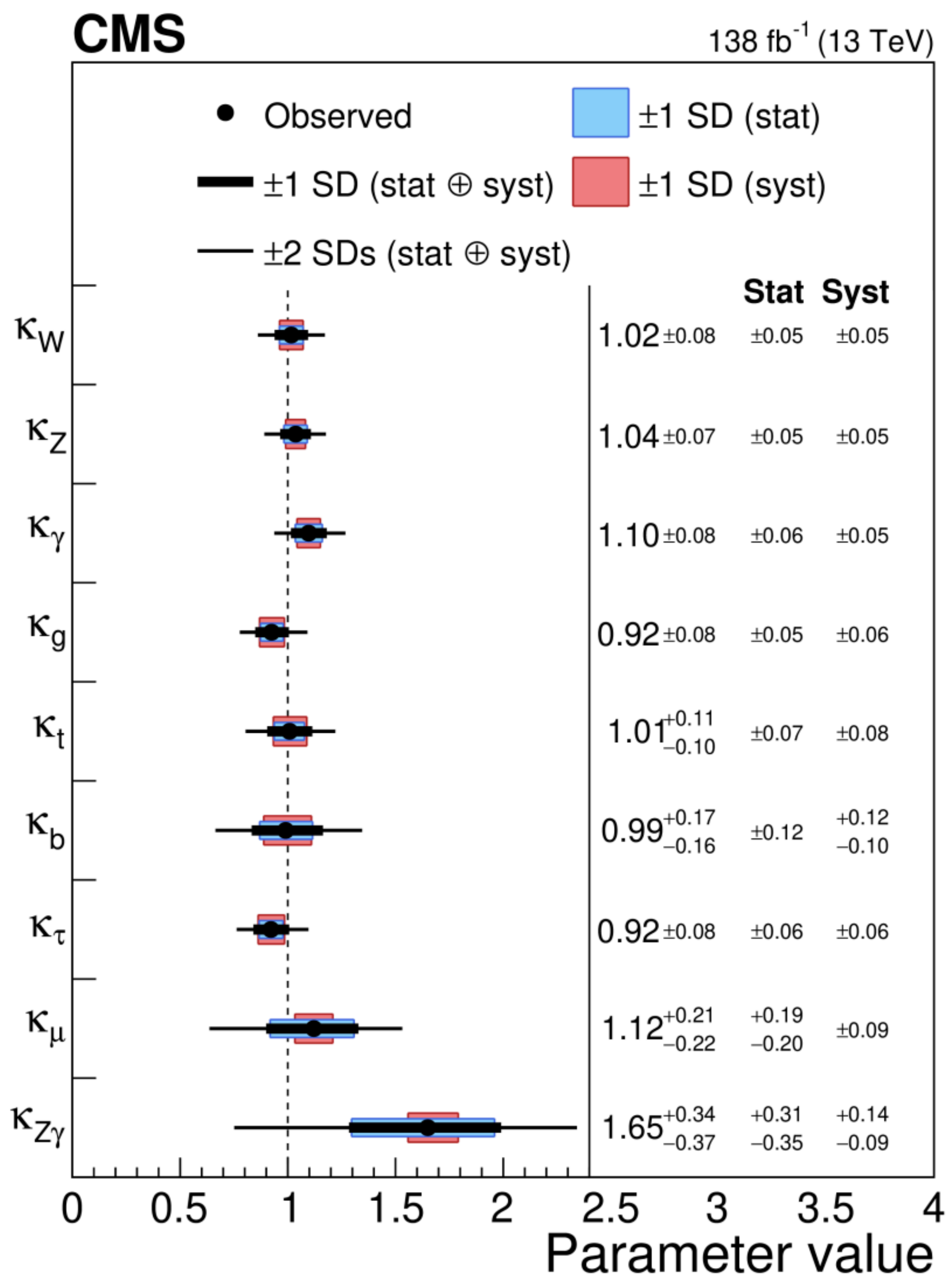
↓

> 2023 — Precision

Higgs couplings



Higgs couplings in Run 2



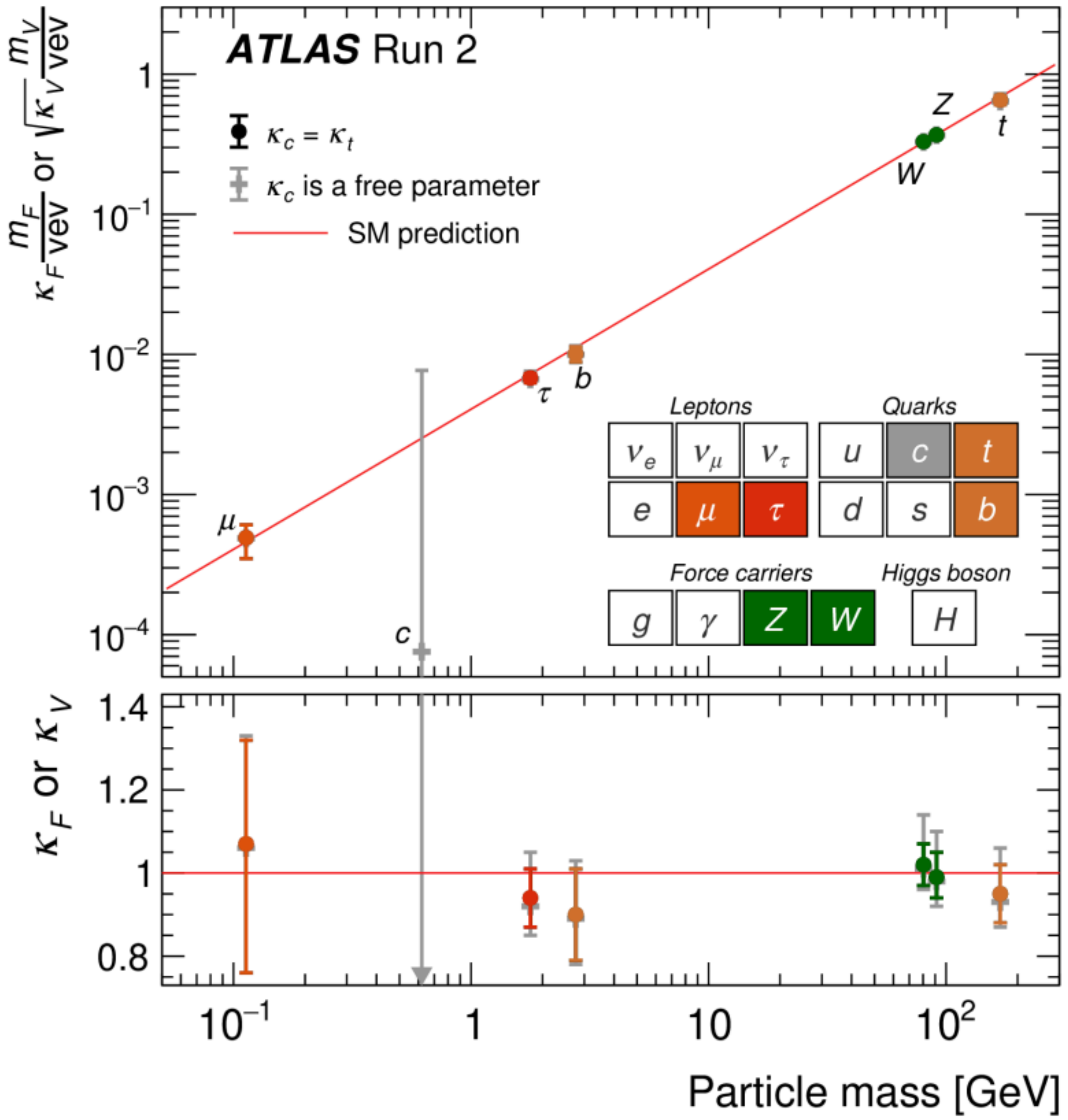
Today ~ 150 fb^{-1} /exp.

- **$\kappa_{W/Z}$, κ_γ, κ_g, κ_τ ~6-8%**
- **κ_t, κ_b ~10%**
- **κ_μ ~20%**
- **$\kappa_{Z\gamma}$ ~40%**

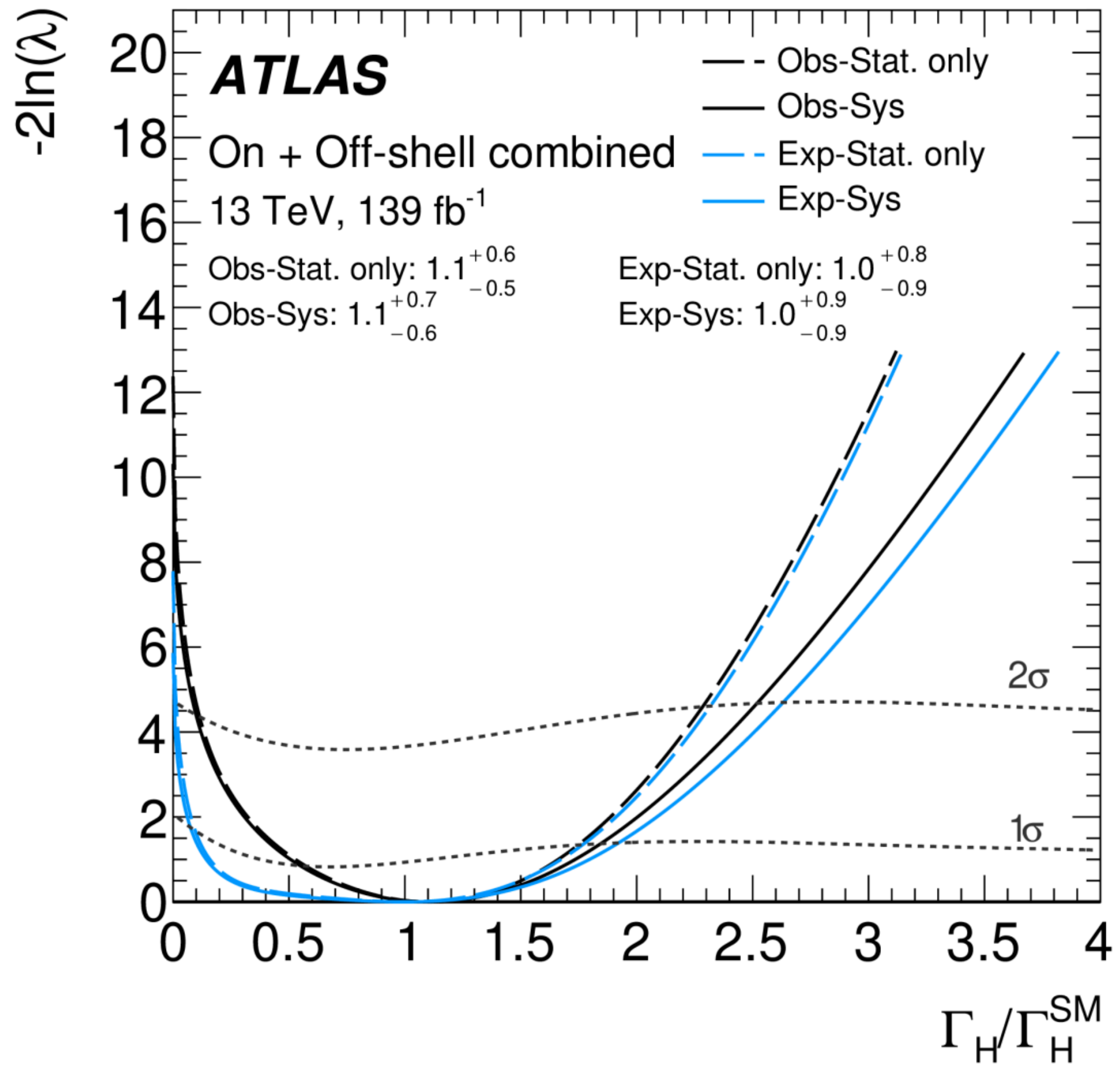
Gauge-Higgs: ✅

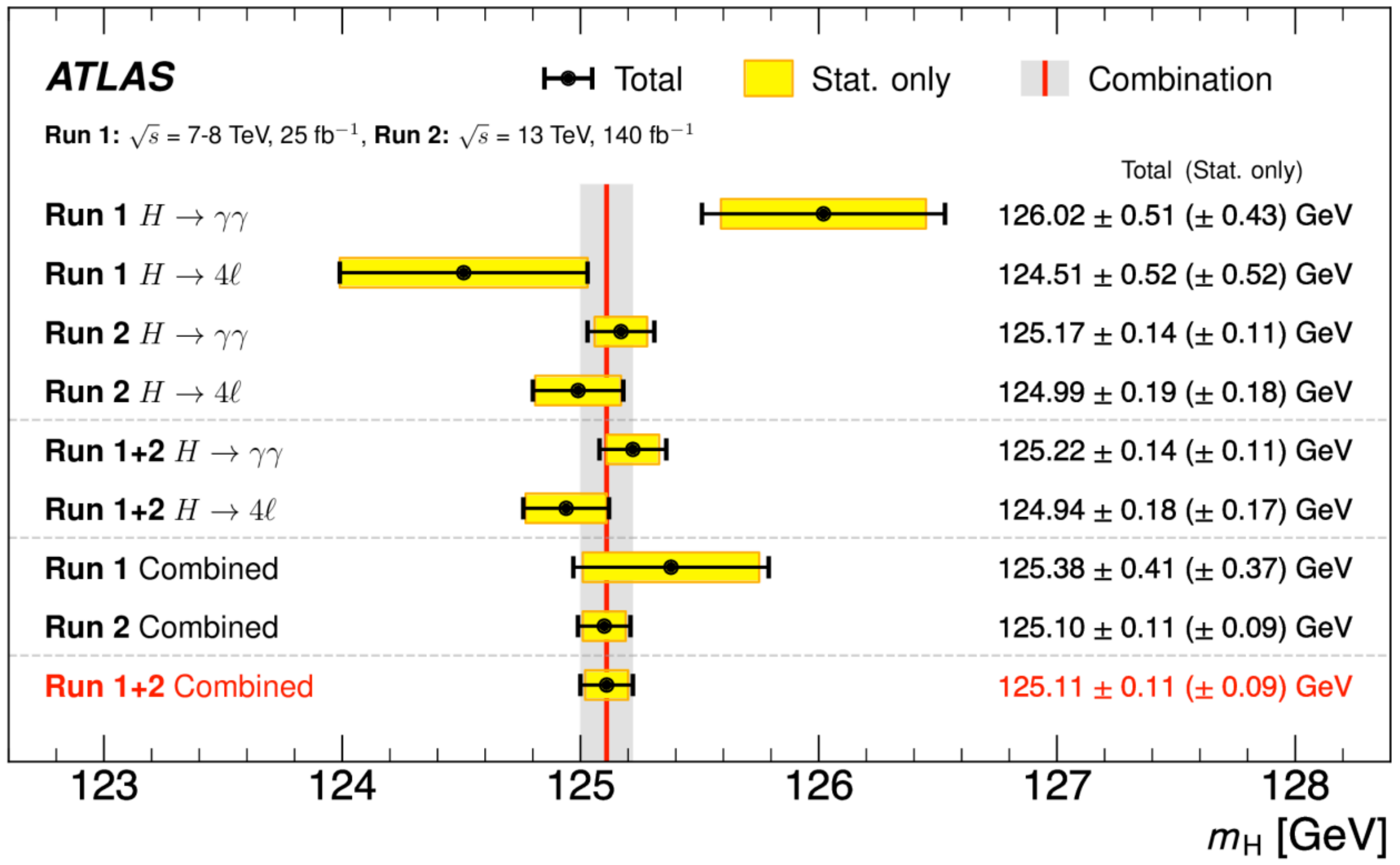
III generation: ✅

II: next?



Higgs mass and width





$\Gamma_H = 4.1 \pm 3.7$ (stat) MeV

$\sigma(\Gamma_H) \sim \Gamma_H$

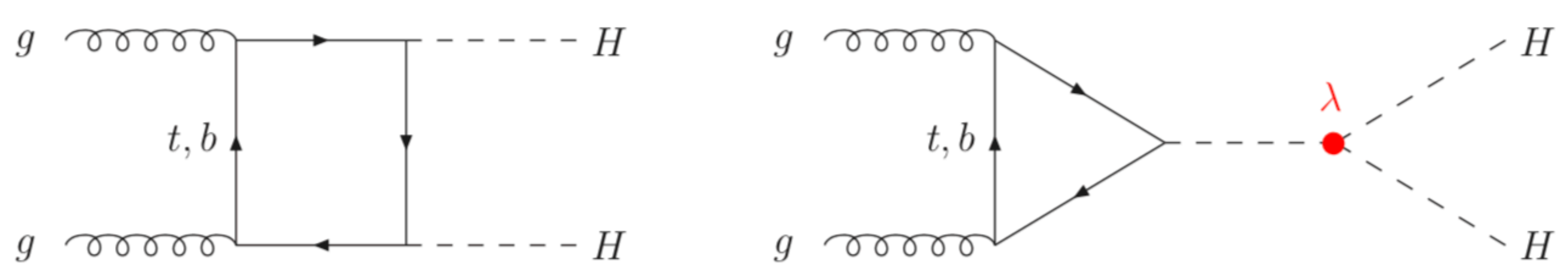
~100%

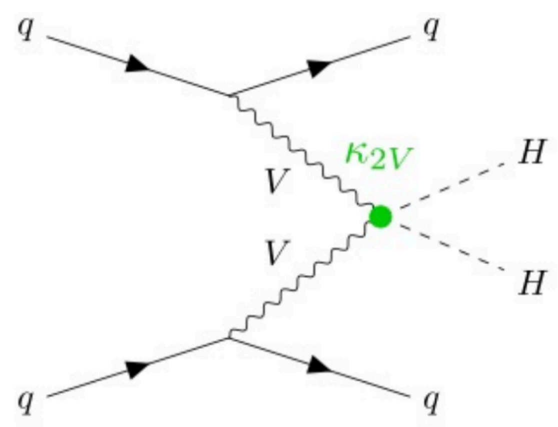
$m_H = 125.04 \pm 0.12$ (stat.) $\pm\ 0.05$ (syst.) GeV

$\sigma(m_H) \sim 100$ MeV

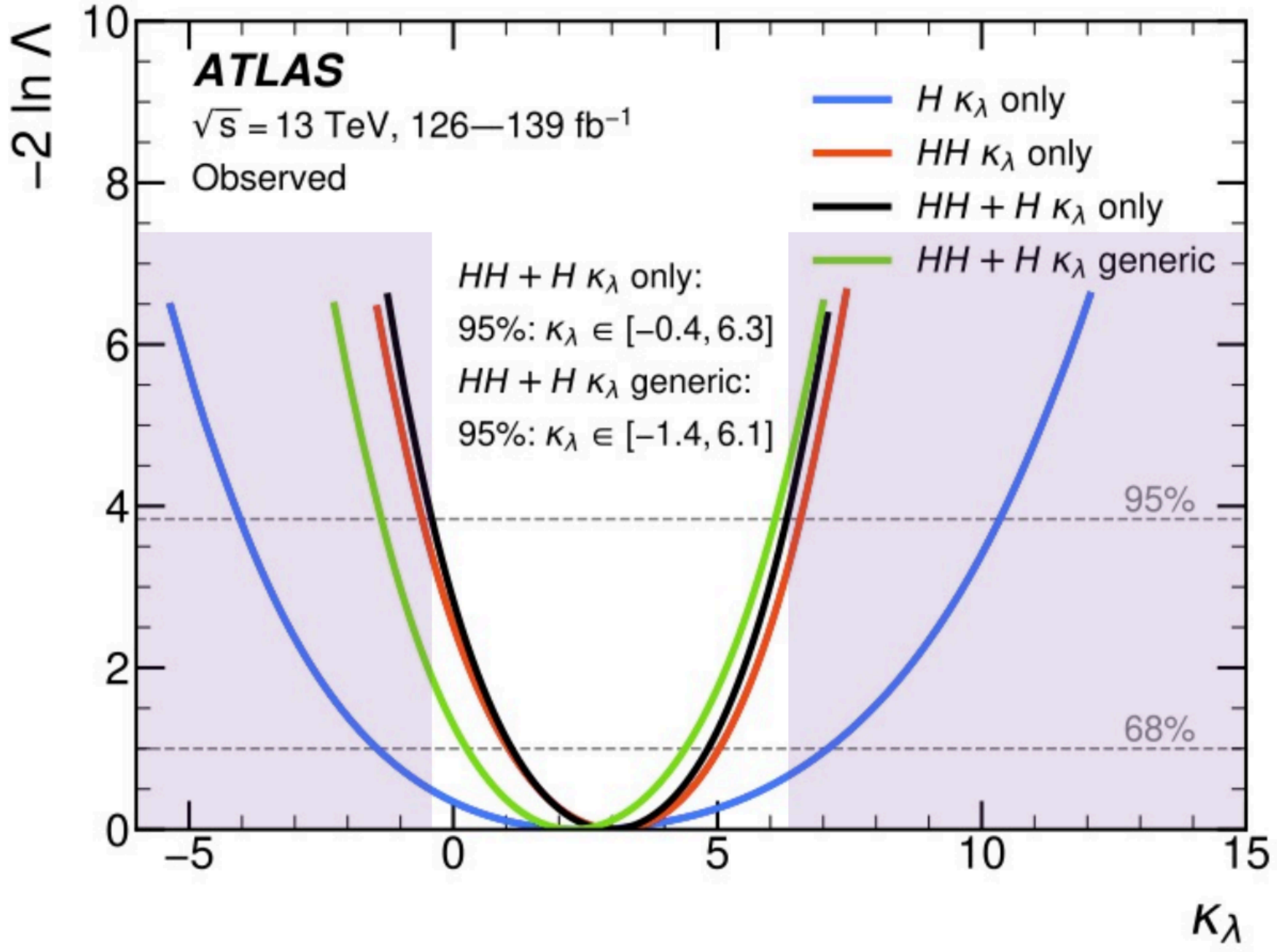
~ 0.1%

Higgs self-coupling(s)

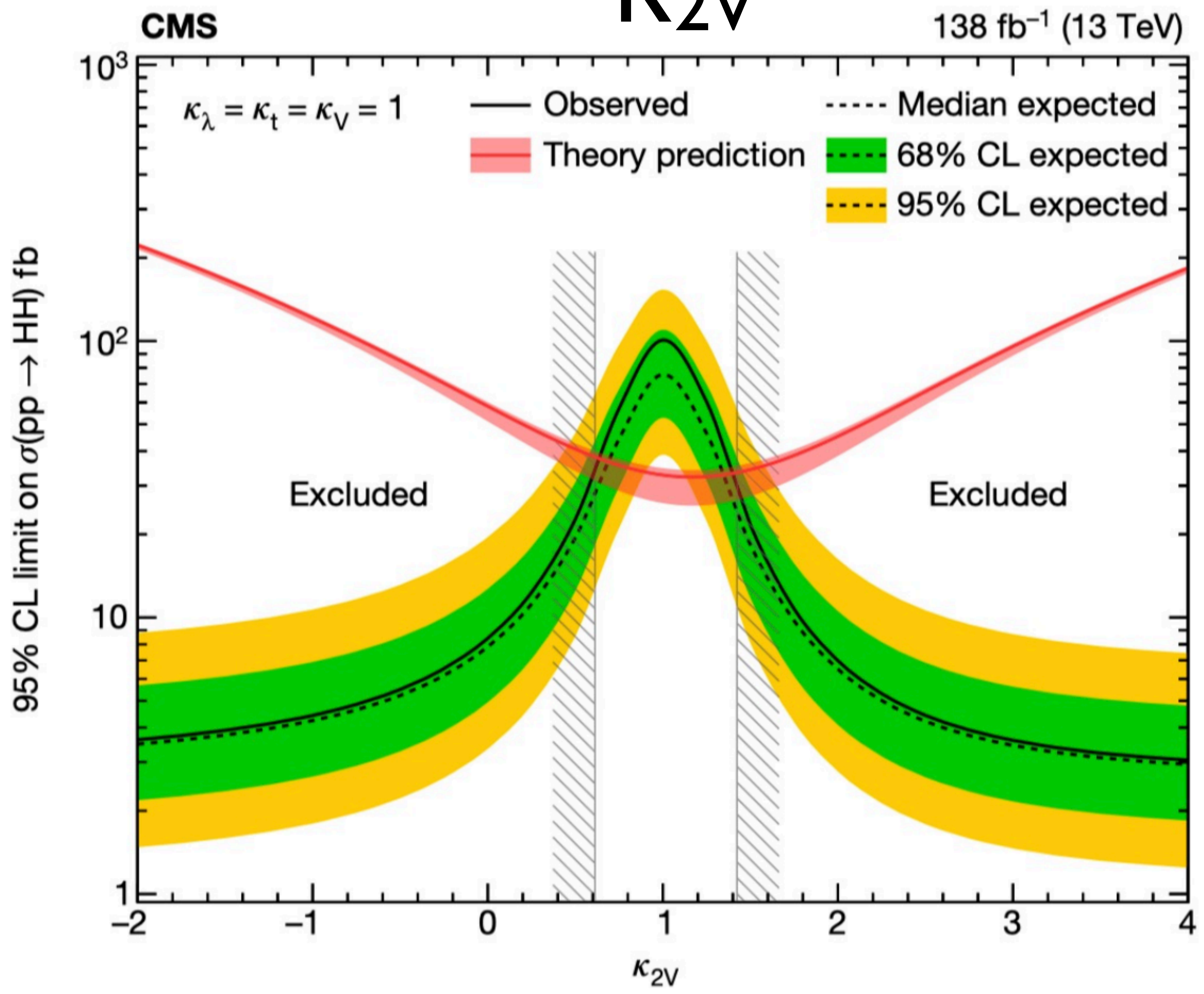




κλ



κ2V



$\mu_{HH} < 3$
$1 < \kappa_\lambda < 6$

@95% CL

$\kappa_{2V} = 0$ excluded

Timeline

time

log(L)

Run 2/3

$\sqrt{s}$ = 13 - 13.6 TeV

2025

0.3 ab^{-1}

HL-LHC

$\sqrt{s}$ = 14 TeV

2045

3 ab^{-1}

FCC-ee

$\sqrt{s}$ = 240 - 365 GeV

2070

(10 ab^{-1})

FCC-hh

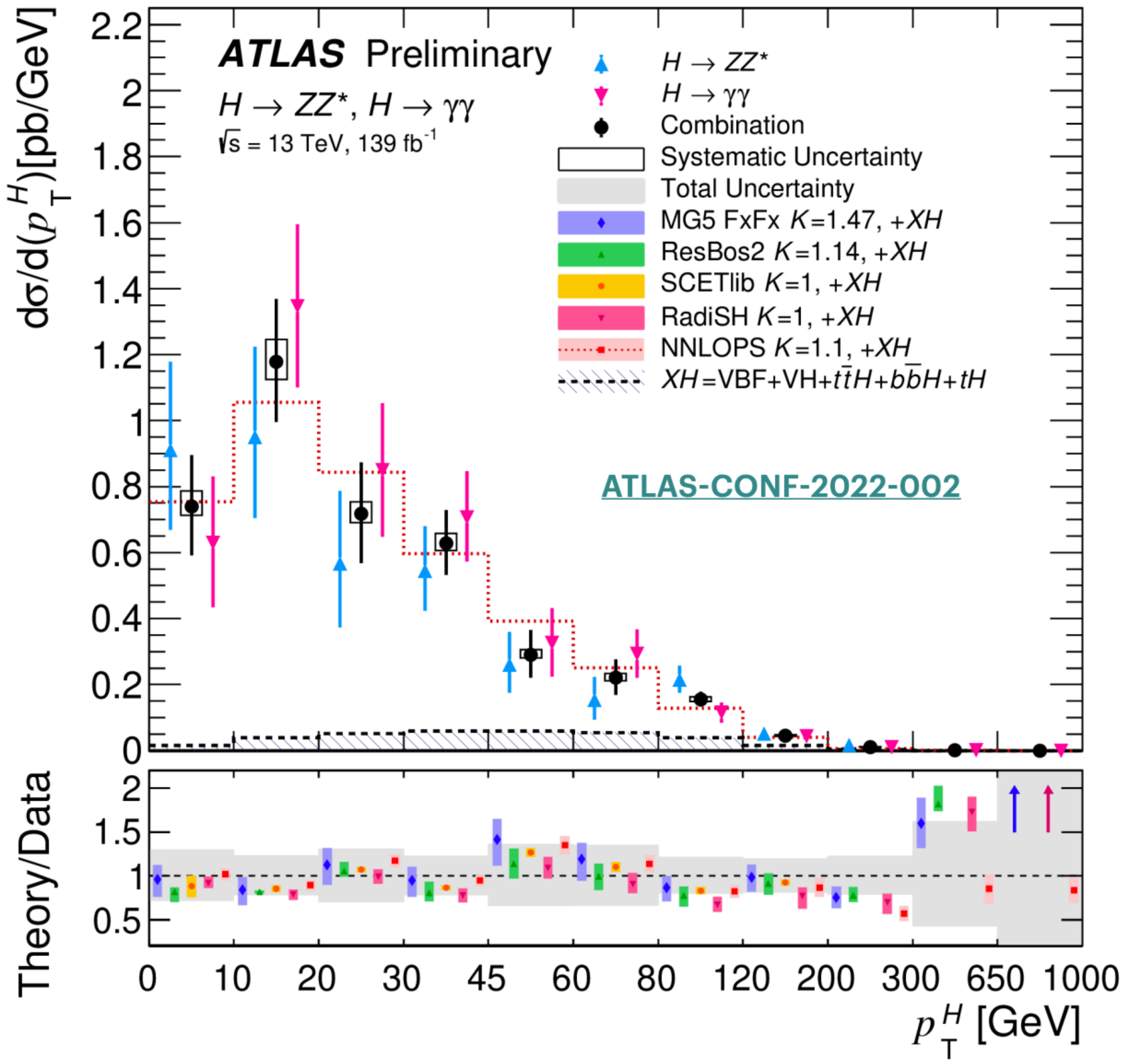
$\sqrt{s}$ = 100 TeV

30 ab^{-1}

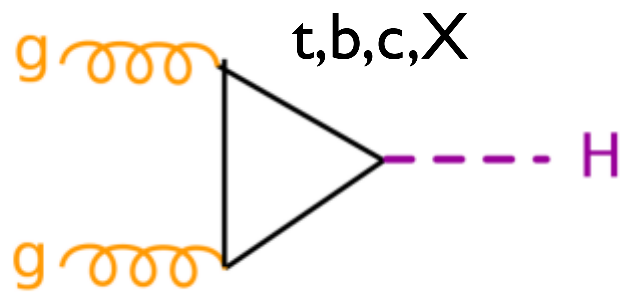
we are here

accessed only **5%** of the LHC dataset

Differentials (dσ/dp$_T$)



QCD modelling

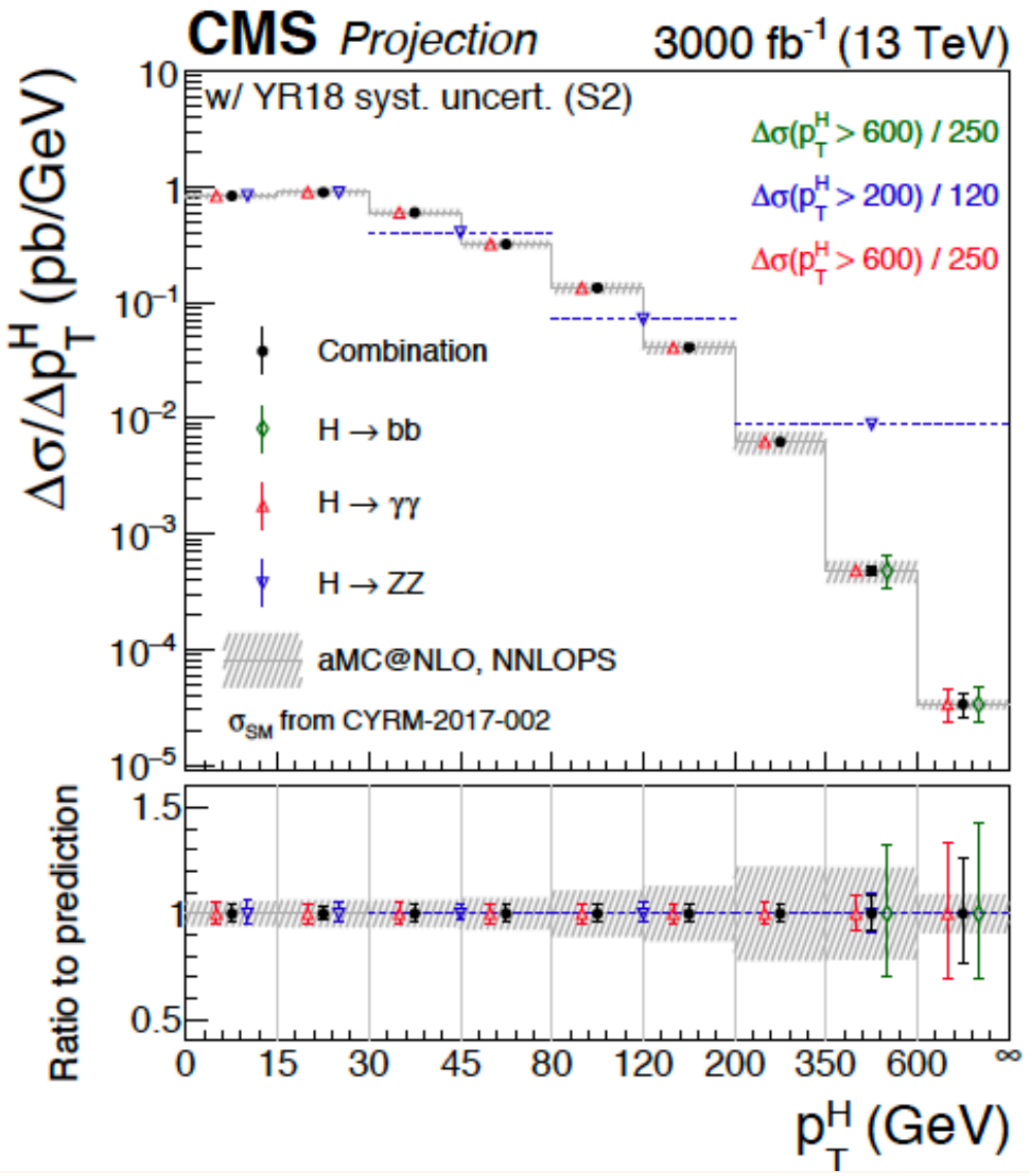


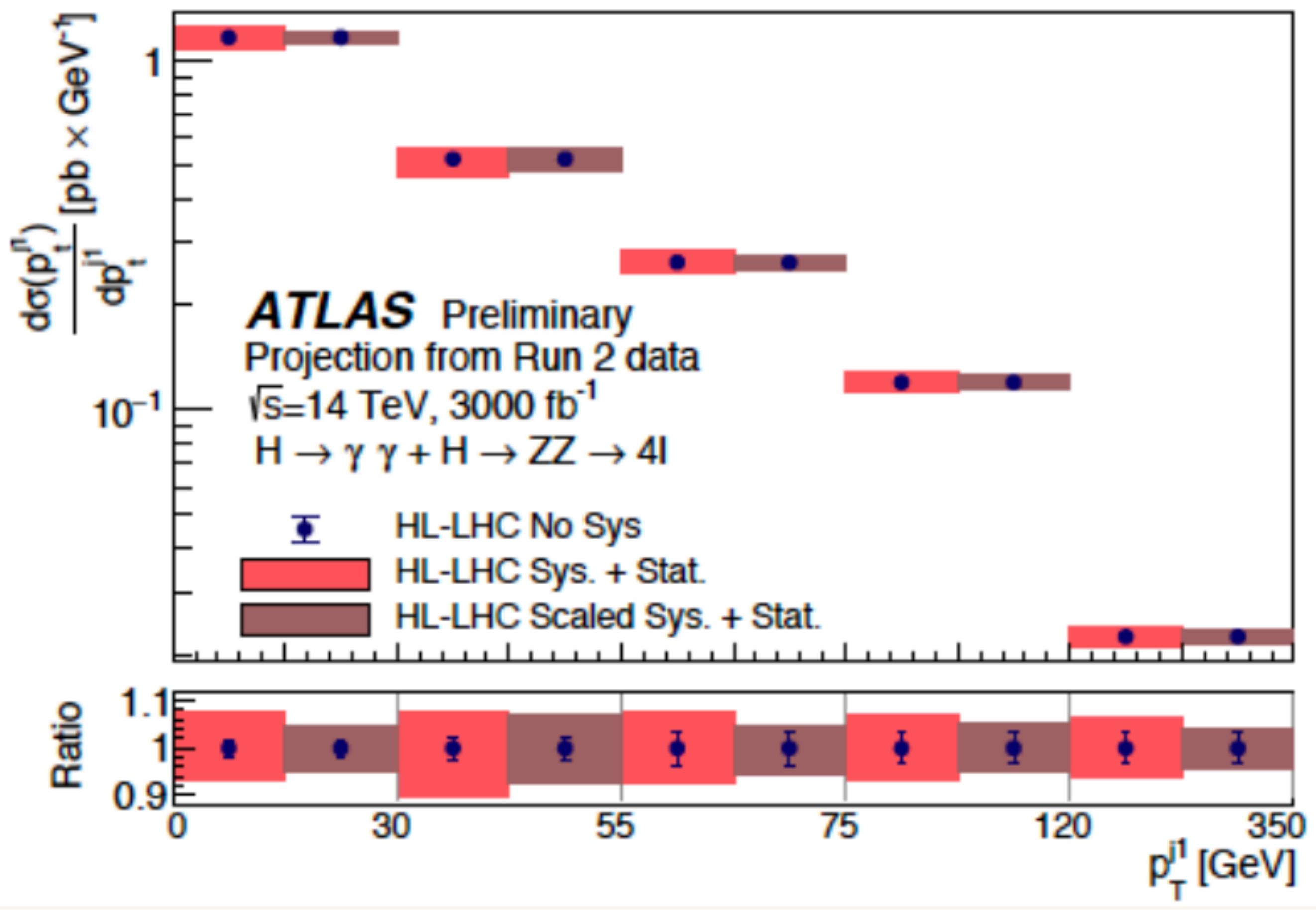
BSM?

LHC → HL-LHC

/4 stat. unc.

limited by TH precision at threshold

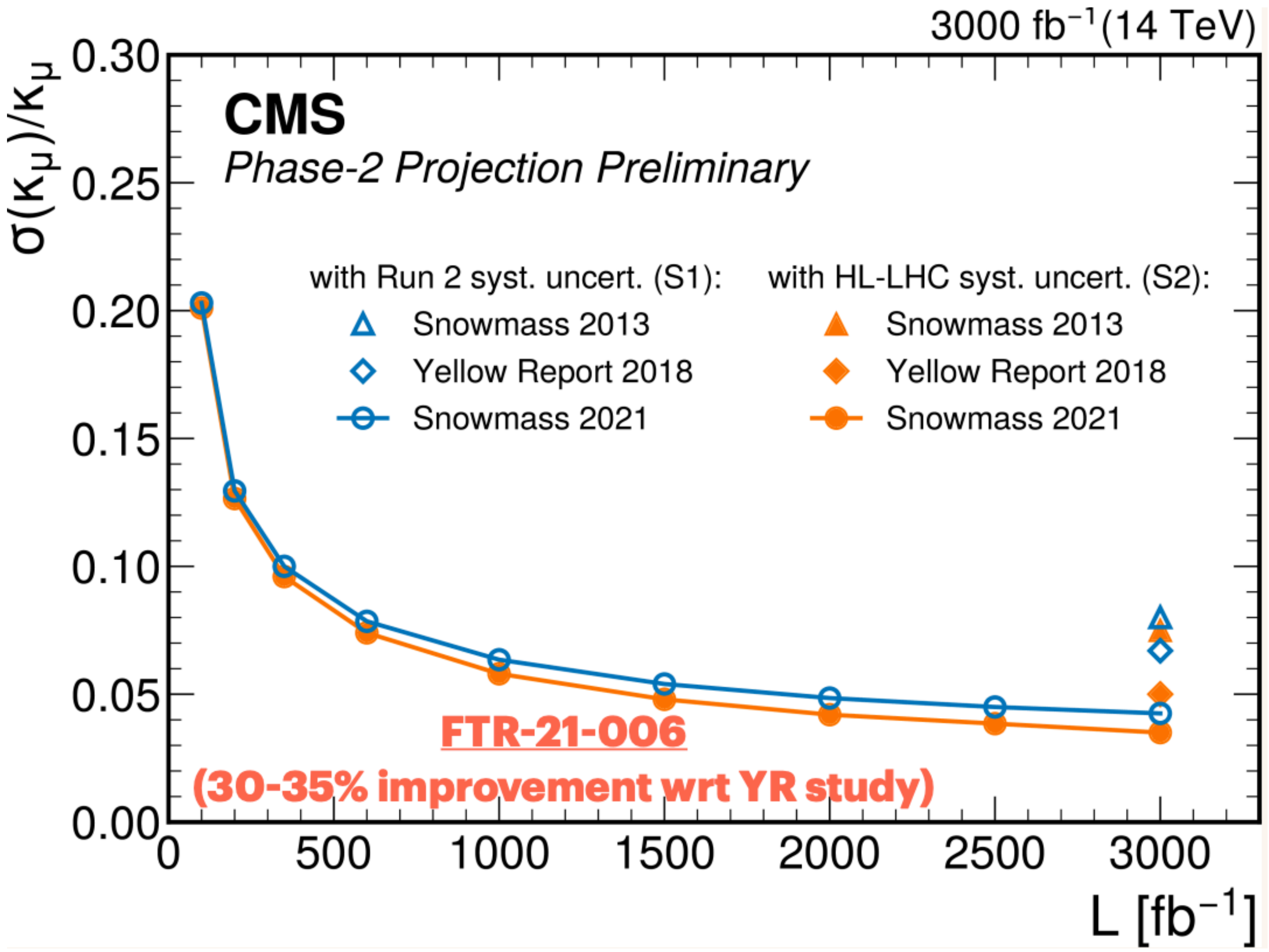




From discovery → precision total rates → differential measurements

2nd generation at HL-LHC

$H \rightarrow \mu\mu$

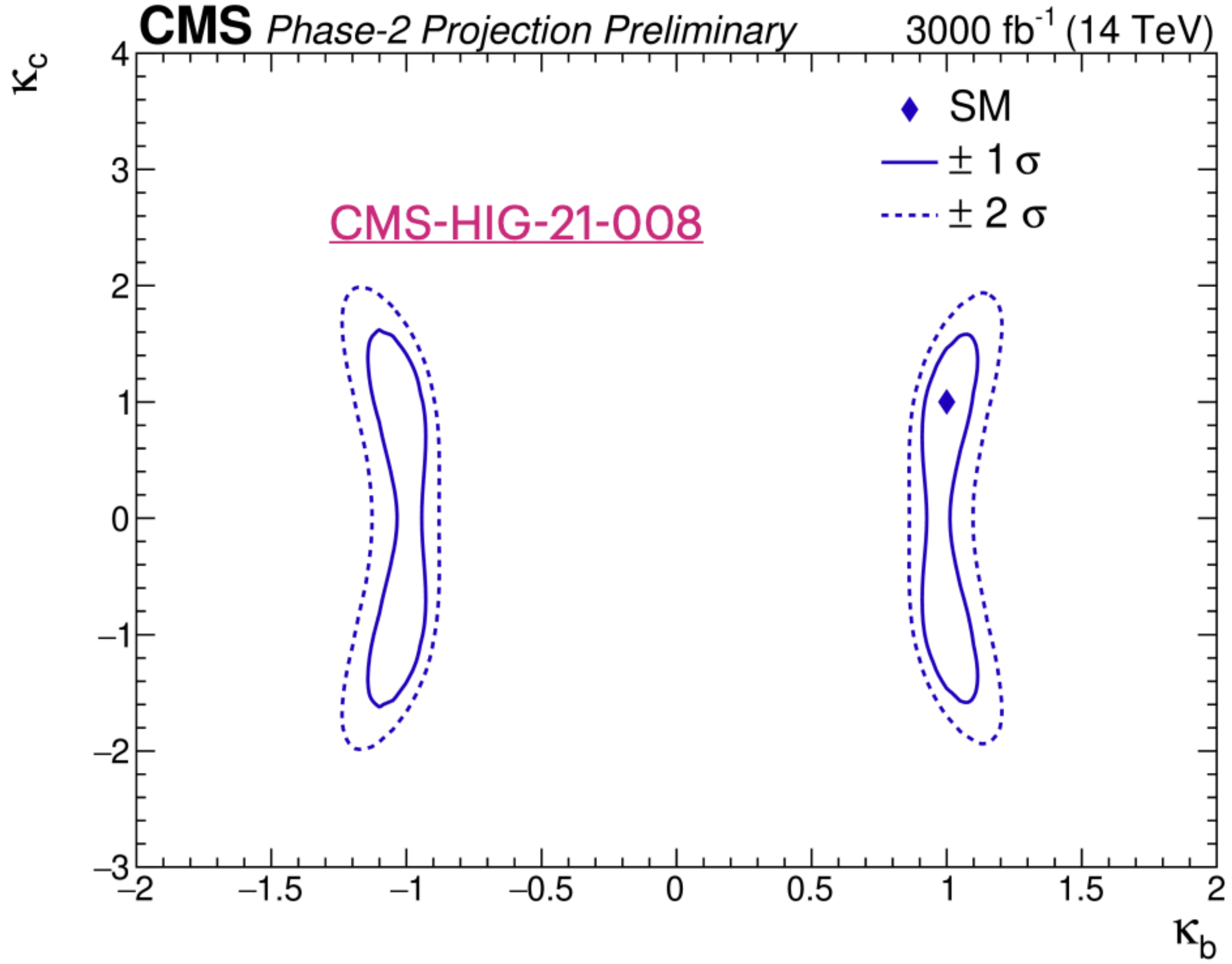


FTR-21-006

(30-35% improvement wrt YR study)

$\delta\kappa_\mu \approx$ 4-5%

$H \rightarrow cc$



CMS-HIG-21-008

$\delta\kappa_c \approx$ 100%

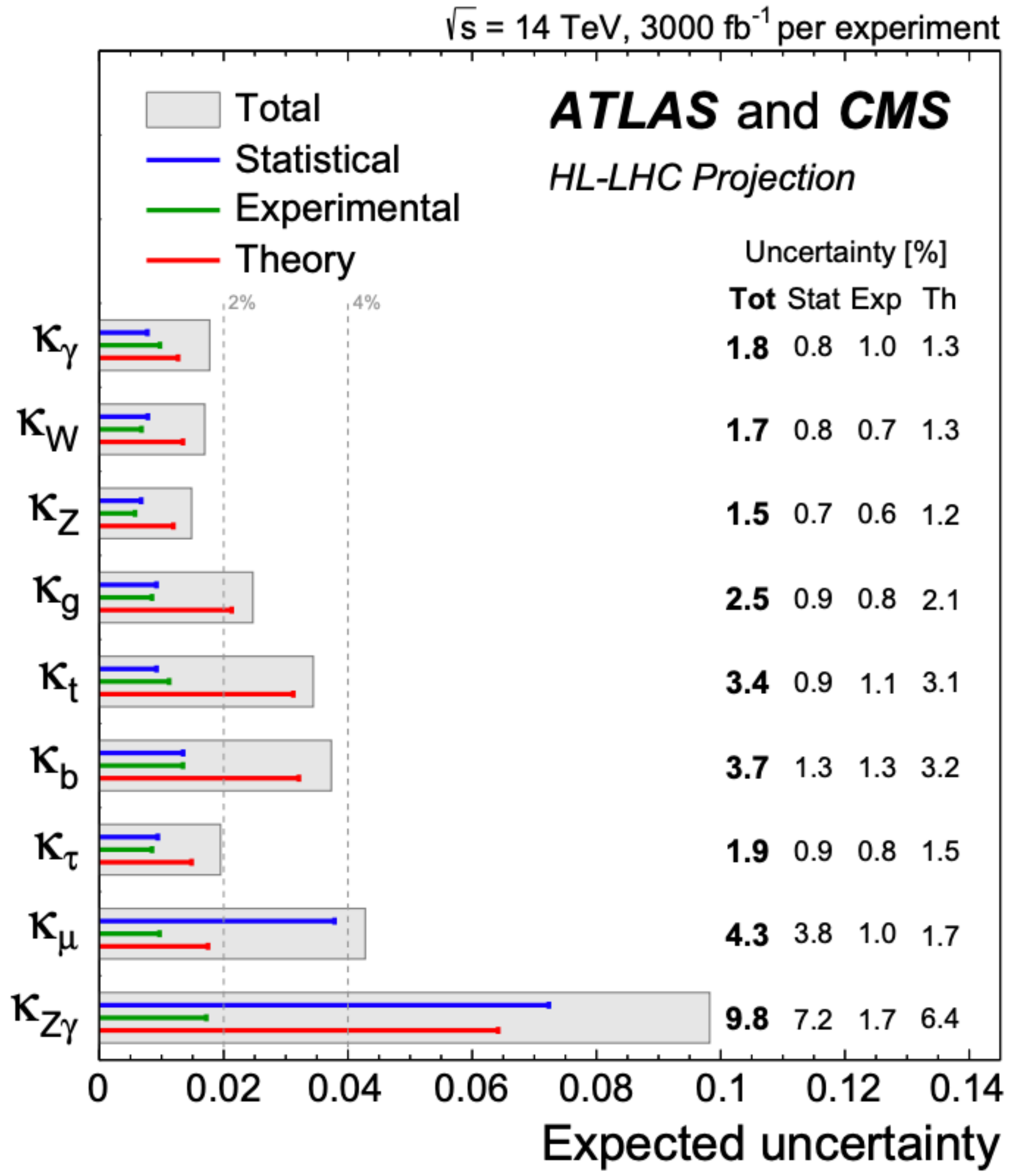
→ tracker upgrades

low mat. budget
superior vertex detectors

also $Z\gamma$ …

Higgs at HL-LHC

Higgs couplings ~ few %



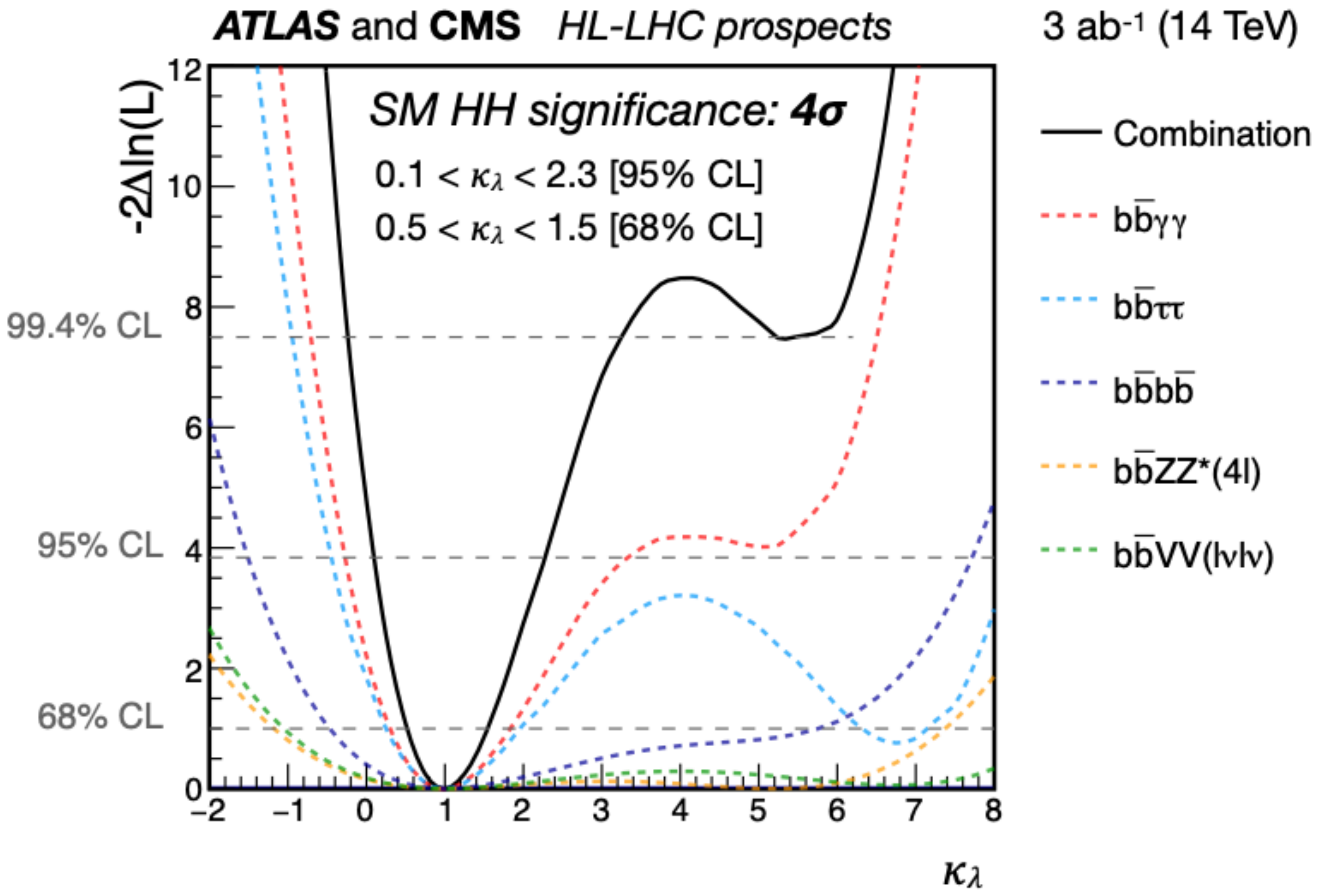
κ_V ~ 2%

κ_t ~ 3%

κ_μ ~ 5%

$\kappa_{Z\gamma}$ ~ 10%

di-Higgs evidence (4σ)
self-coupling $\delta\kappa_\lambda$ ~ 50%



Need to go beyond the LHC precision measurements:

$\delta\kappa_X < 1\%$?

- Model independence, Higgs width
- Light couplings (charm, muon)
- Invisible decays

- Self-coupling(s)
- BSM Higgs

Timeline (HL-LHC)

2025

2045

2070

time

Run 2/3

HL-LHC

FCC-ee

FCC-hh

$\sqrt{s} = 13 - 13.6$ TeV

$\sqrt{s} = 14$ TeV

$\sqrt{s} = 240 - 365$ GeV

$\sqrt{s} = 100$ TeV

log(L)

0.3 ab^{-1}

3 ab^{-1}

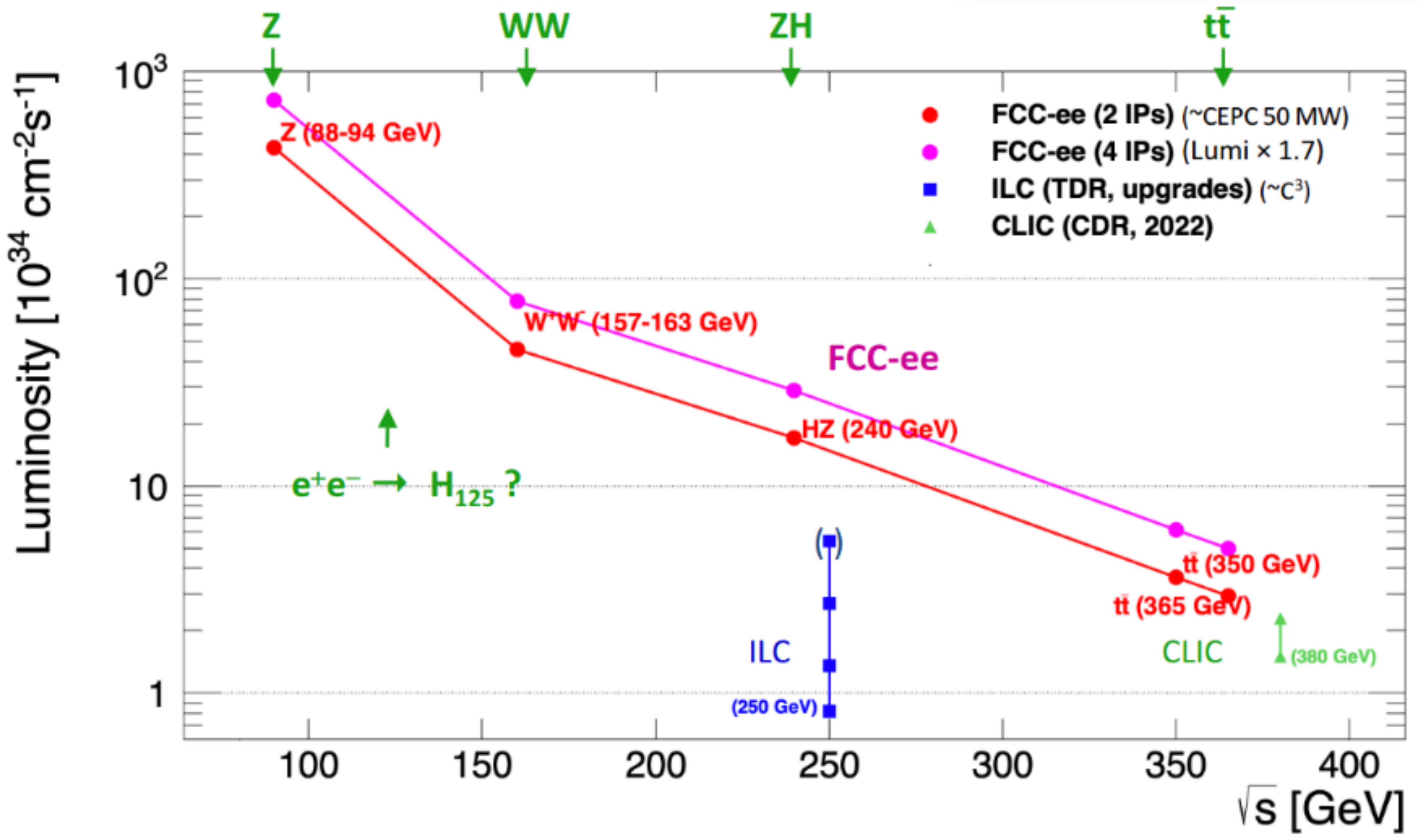
(10 ab^{-1})

30 ab^{-1}

100% of the LHC dataset

- abundant decay modes to few % level
- fully differentials in production
- partial II generation
- $\delta m_H \sim 30$ MeV and $\delta\Gamma_H/\Gamma_H \sim 25\%$
- evidence for HH production
- direct Higgs BSM reach: x1.5-2

FCC-ee program



15 (20?) years of operations

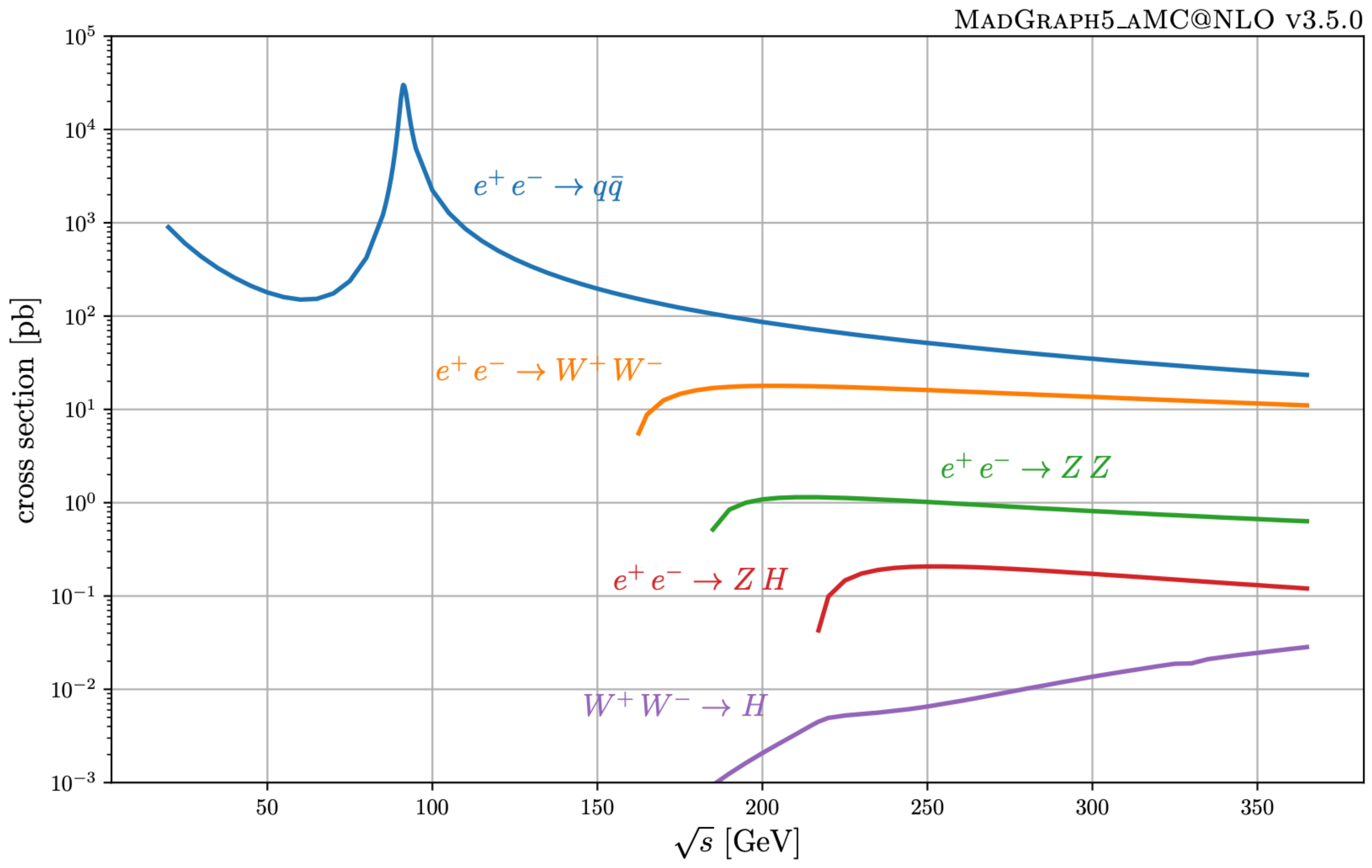
	Z pole	**? H pole ?**	**WW**	**ZH**	**ttbar**
$\sqrt{s}$ [GeV]	88 - 91 - 94	125	157 - 161	240	350 - 365
Lumi / IP $[10^{34}\ cm^2\ s^{-1}]$	182	80	19.4	7.3	1.33
Int. lumi / 4IP $[ab^{-1}$ / yr]	87	38	9.3	3.5	0.65
$\mathbf{N_{years}}$	**4**	**5**	**2**	**3**	**5**
$\mathbf{N_{events}}$	8 Tera	8 K	300 M	2 M	2 M

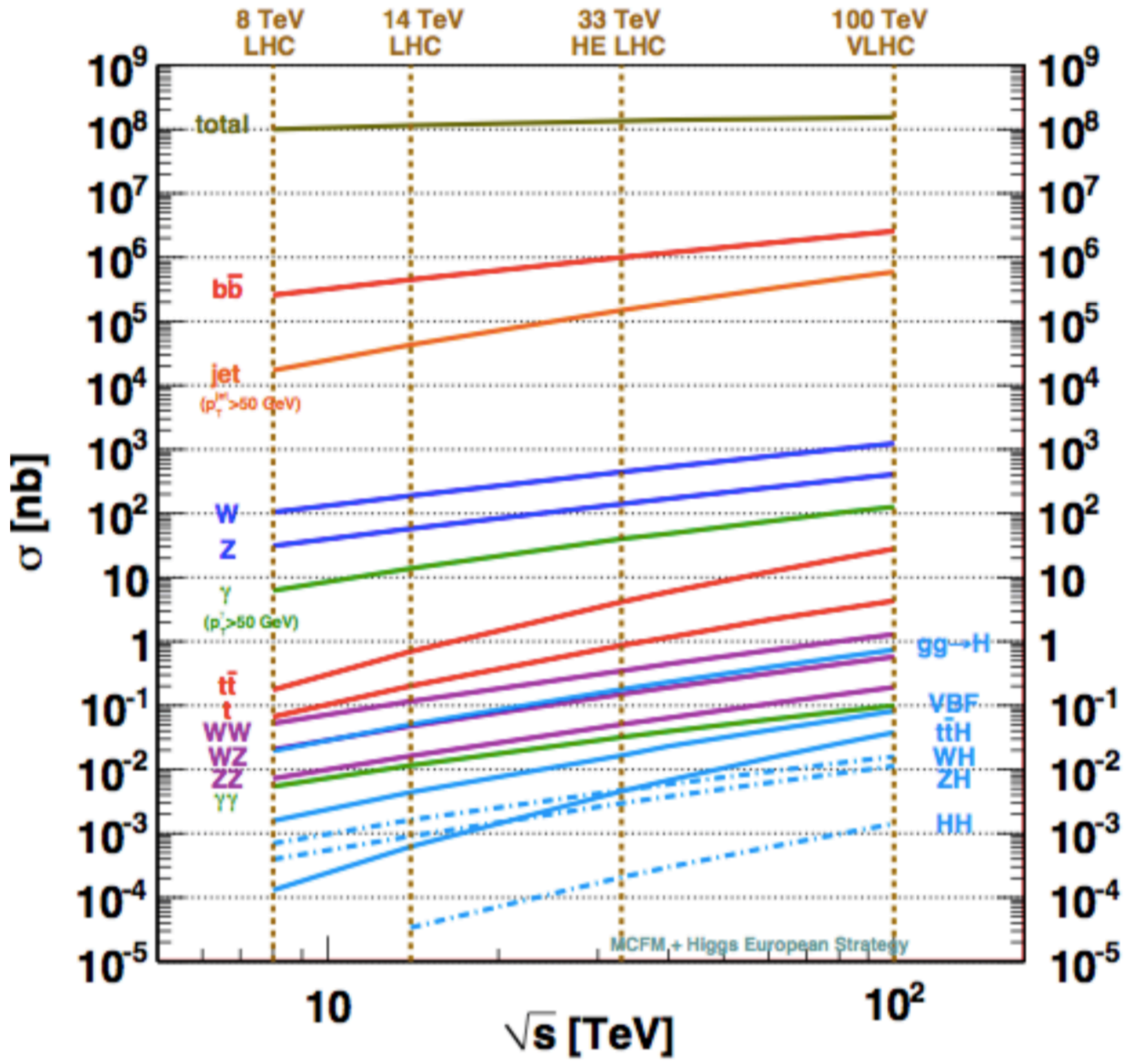
Exquisite luminosity allows for ultimate precision:

- 100K Z bosons / second
  - LEP dataset in 1 minutes
- 10k W boson / hour
- 2k Higgs bosons / day
- 3k tops / day

Physics processes

- Physics background are "small" in e^+e^-
  - s-channel ~ 1/s
  - t-channel ~ log s





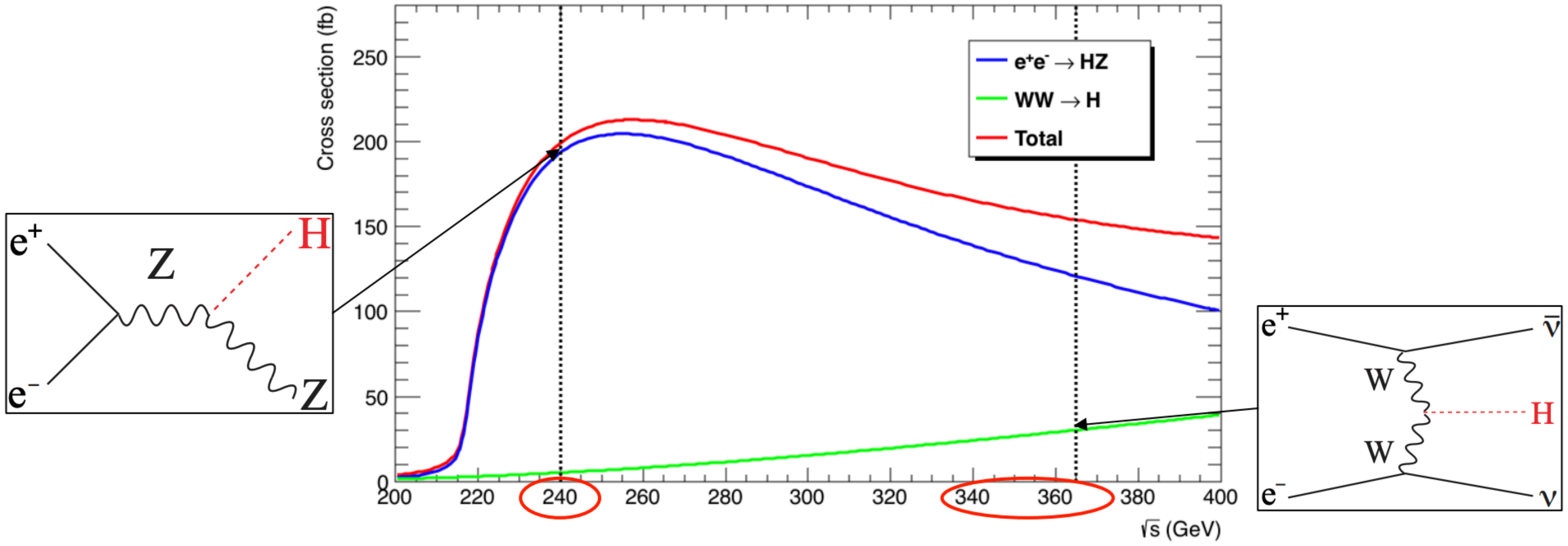
S/B **10^{-2} at e^+e^-** **10^{-10} at hadron colliders**

FCC-ee offers ideal environment for Higgs physics

large rates (> 1e6)
clean exp. environment (no UE, Pile-up, low event rate - trigger less)
Large S/B (no QCD background)
Energy, momentum constraints

Higgs at the FCC-ee

- production mechanisms
  - Higgs-strahlung
  - VBF

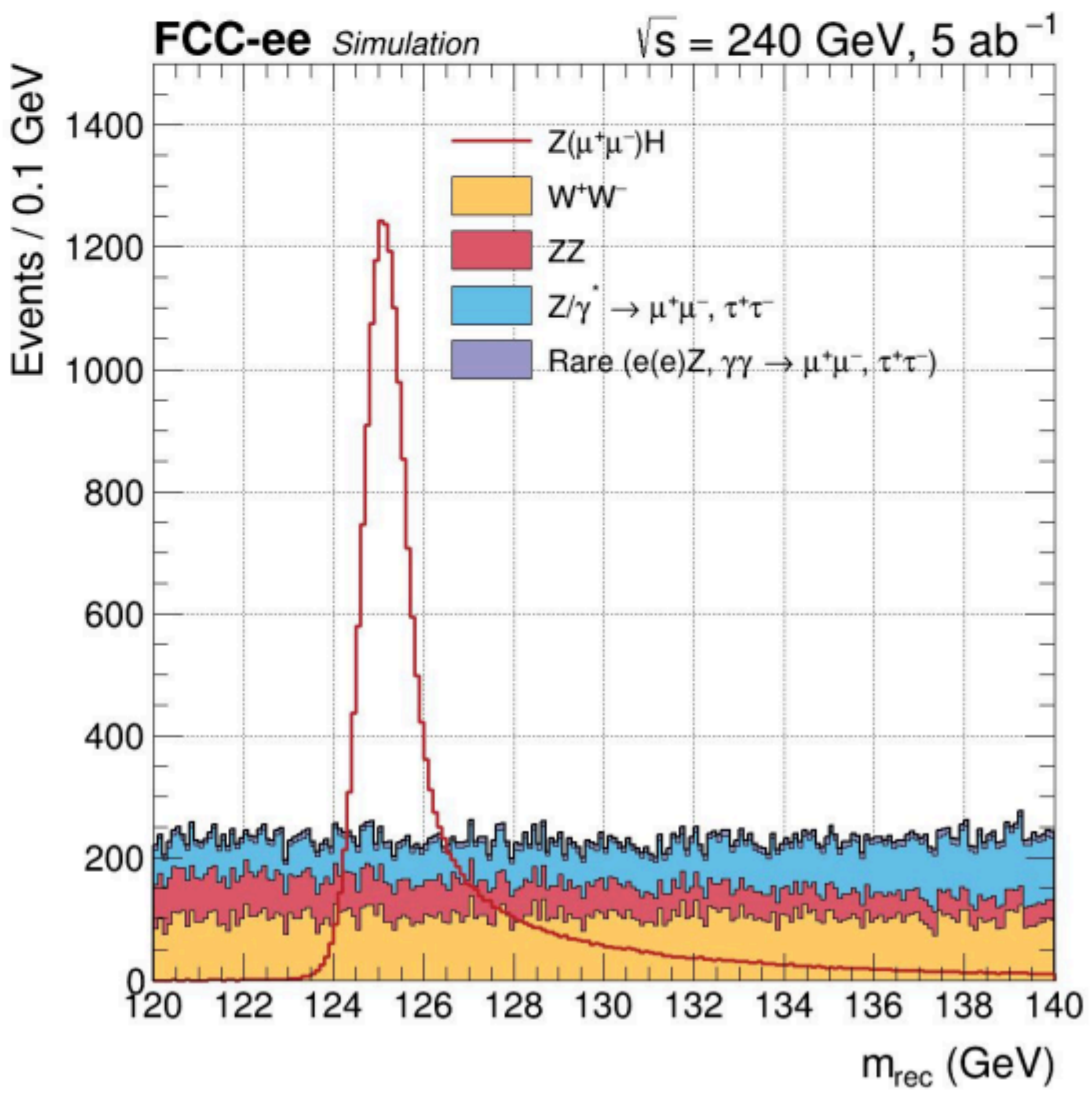


	$L = 10\ ab^{-1}$	$L = 3\ ab^{-1}$
4IP	$ZH = 2x10^6$ $VBF = 4x10^4$	$ZH = 5x10^5$ $VBF = 10^5$

Note on systematic uncertainties vs pp

- integrated lumi ~ 0.01%
- tagging efficiency, BES < 1%
- TH < 1% (no PDFs, QCD corrections are small)

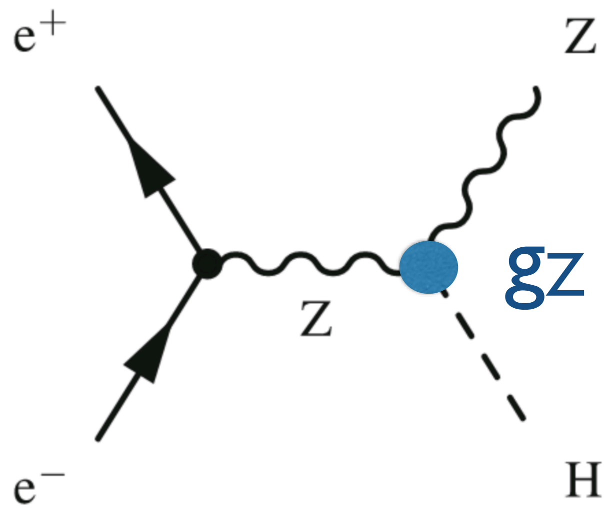
FCC-ee recoil method



Precise knowledge of center of mass allows for:

- tag the Z by reconstructing pair of leptons
- reconstruct the the recoil mass

$$m^2_{\text{recoil}} = s - 2\sqrt{s}E_{\text{di-lepton}} + m^2_{\text{di-lepton}}$$



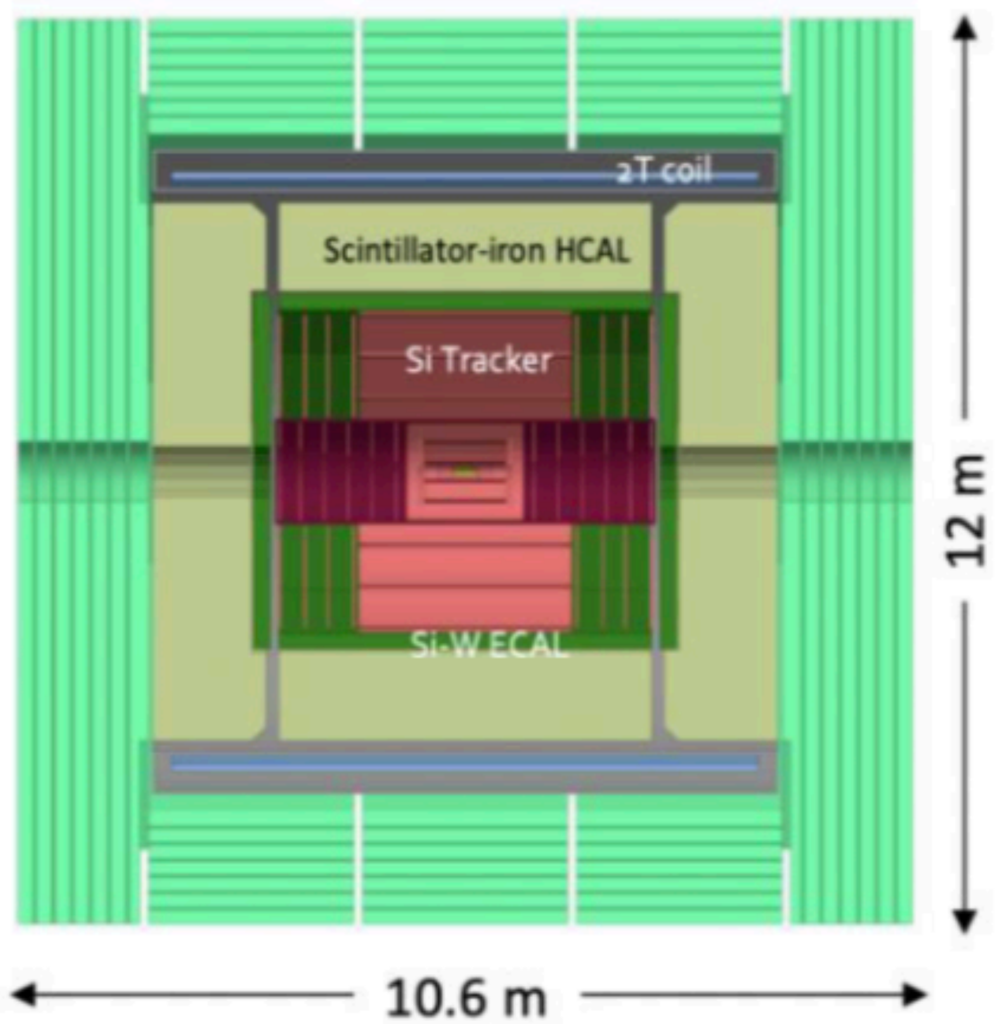
Higgs recoil mass measurement → ZH production cross section:

- 10^6 Higgs produced @ FCC-ee
  - rate ~ $\mathbf{g_Z}^{2}$ → $\delta g_Z/g_Z$ ~ 0.2 %
- Then measure ZH → ZZZ
  - rate ~ $\mathbf{g_Z}^{4} / \mathbf{\Gamma_H}$ → $\delta\Gamma_H/\Gamma_H$ ~ 1 %
- Then measure ZH → ZXX
  - rate ~ $\mathbf{g_Z}^{2}\,\mathbf{g_X}^{2} / \mathbf{\Gamma_H}$ → $\delta g_X/g_X$ ~ 1 %

Provides absolute and **model independent** measurement of g_Z coupling in e+e-

FCC-ee detectors

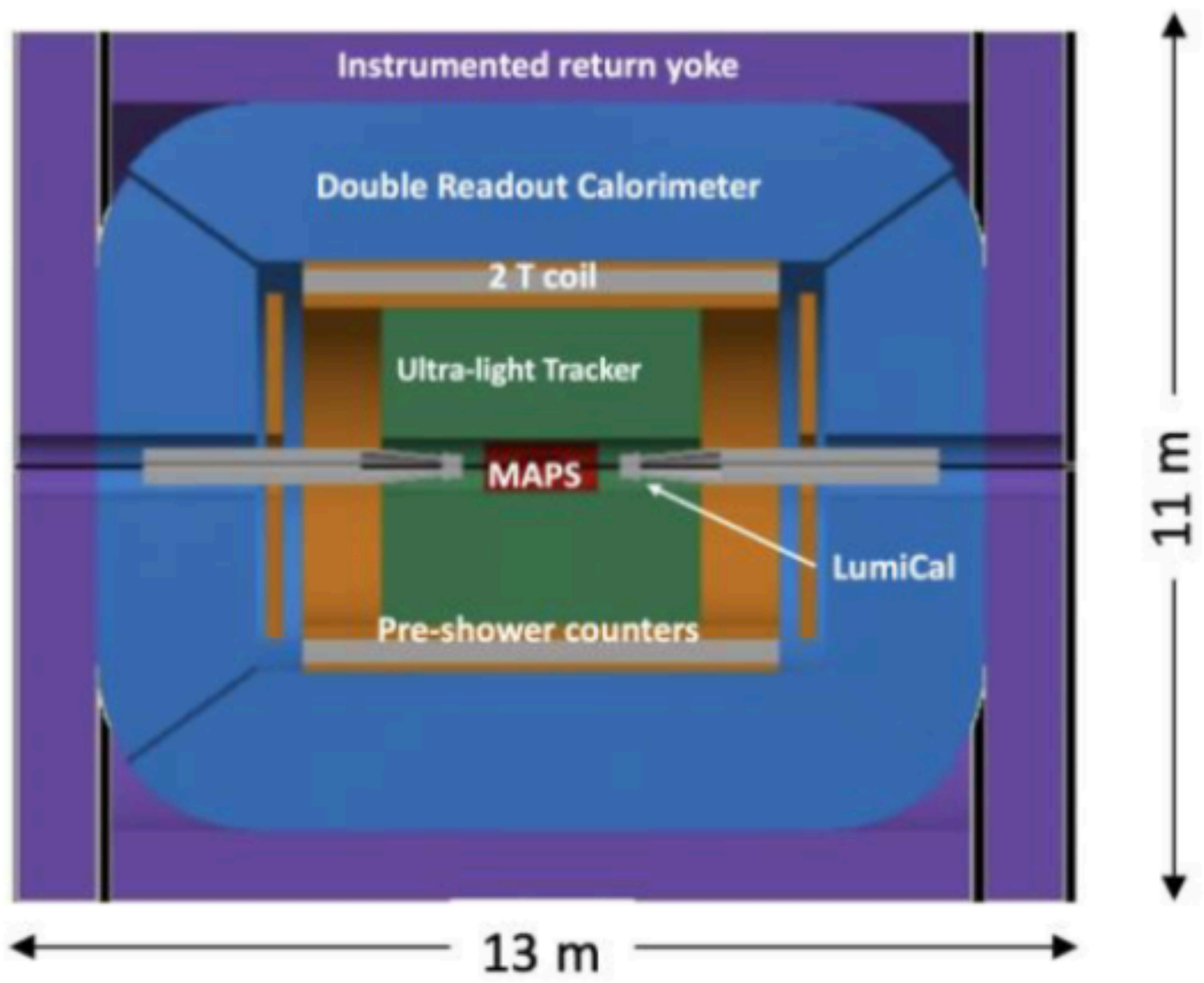
CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?

CDR

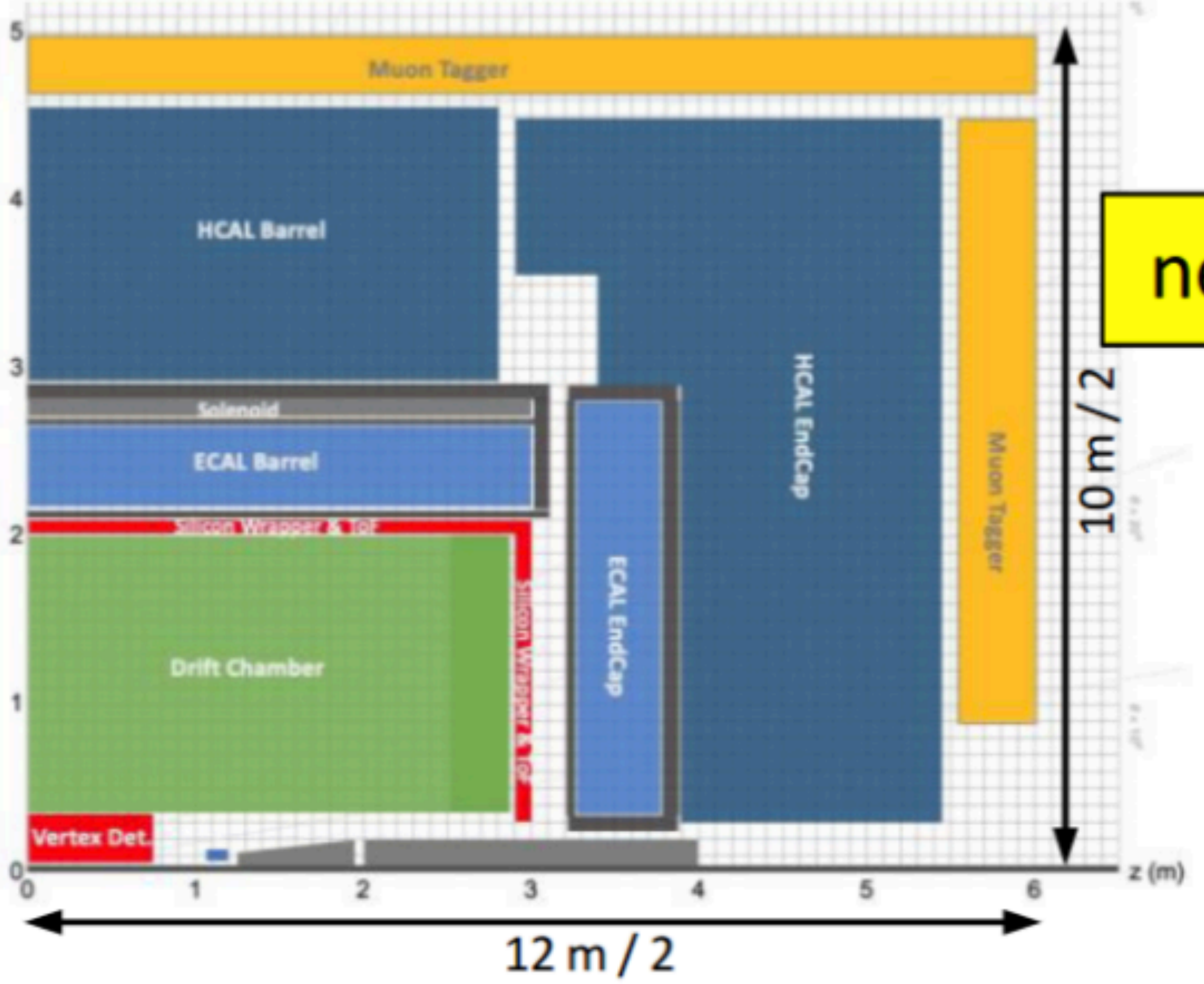
IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

new

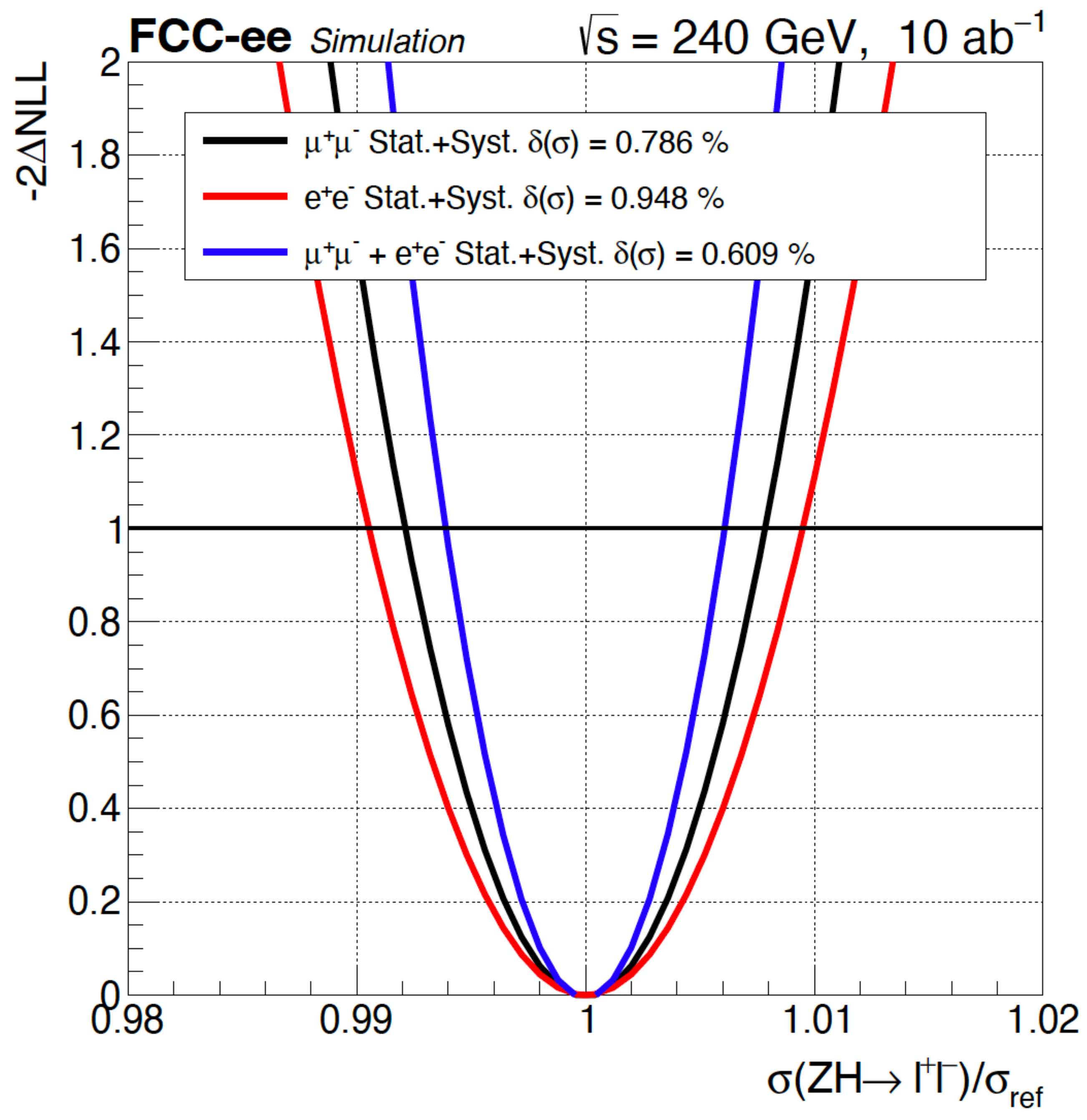


- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

Z(ll)H cross-section and mass measurements

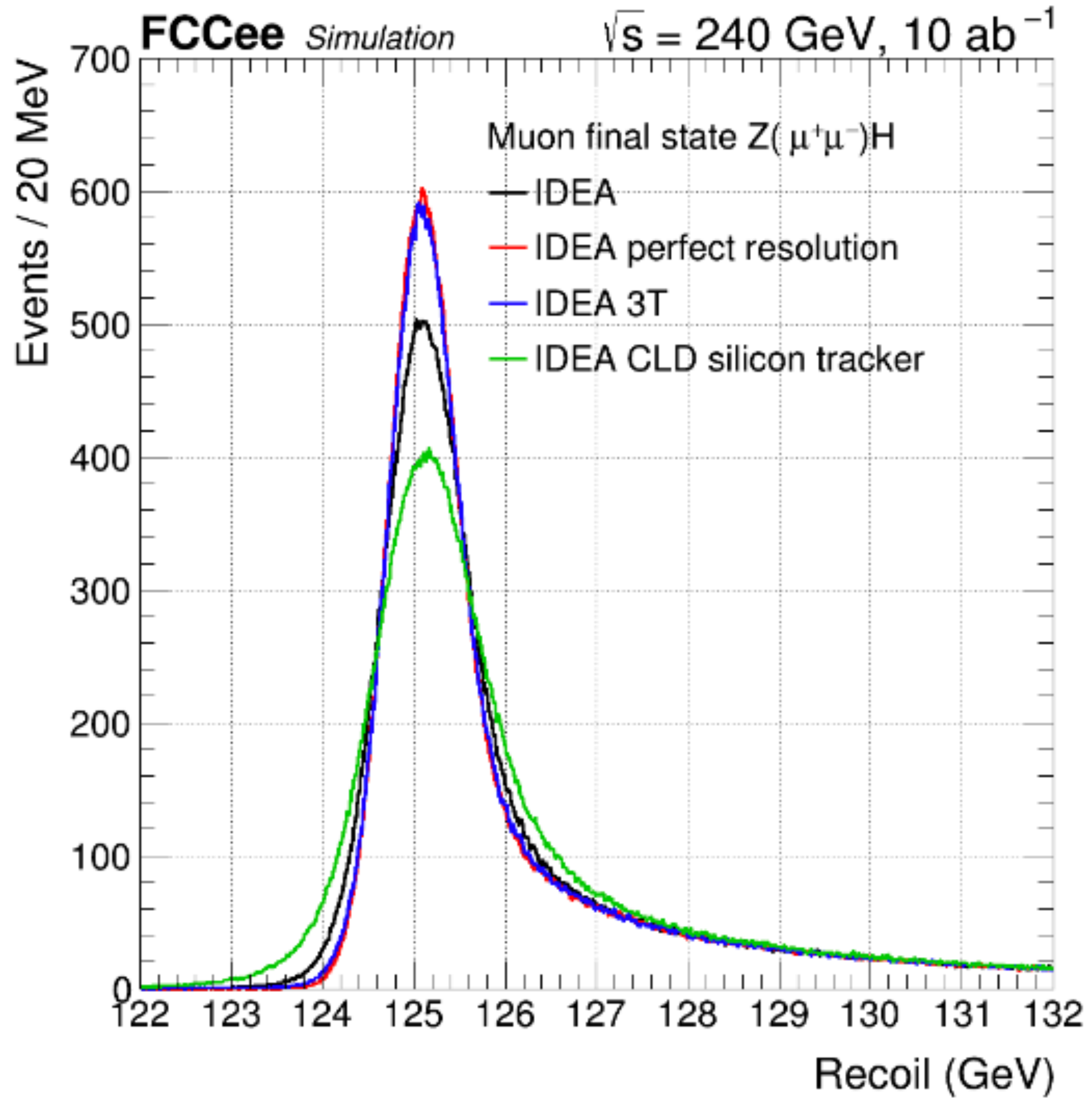
Cross-section:

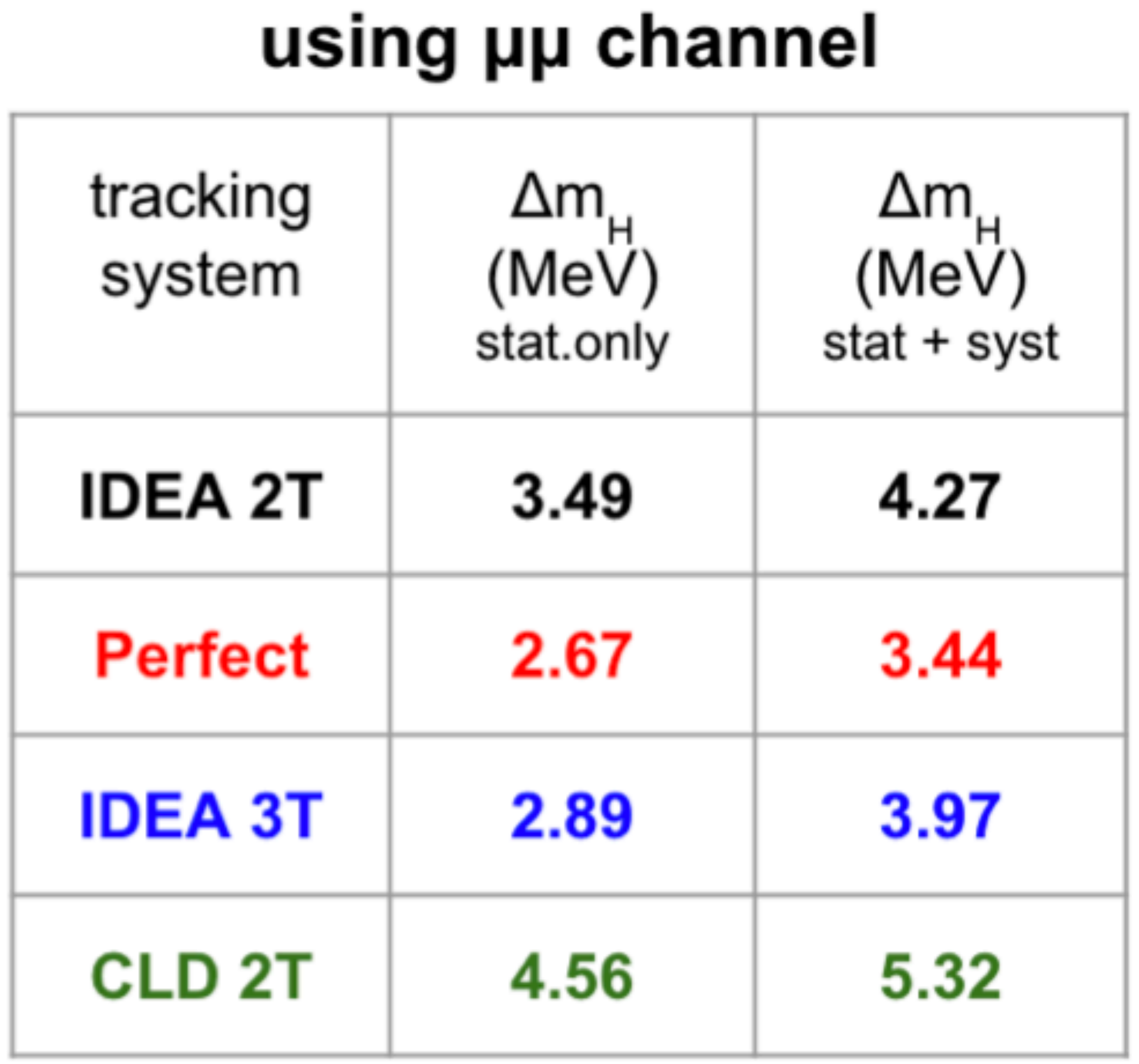
$\delta\sigma_{ZH} \sim 0.6\%$ ($\kappa_Z \sim 0.3\%$)



ToDo: HZZ (all decay) study

→ reach target of 1% on Γ_H





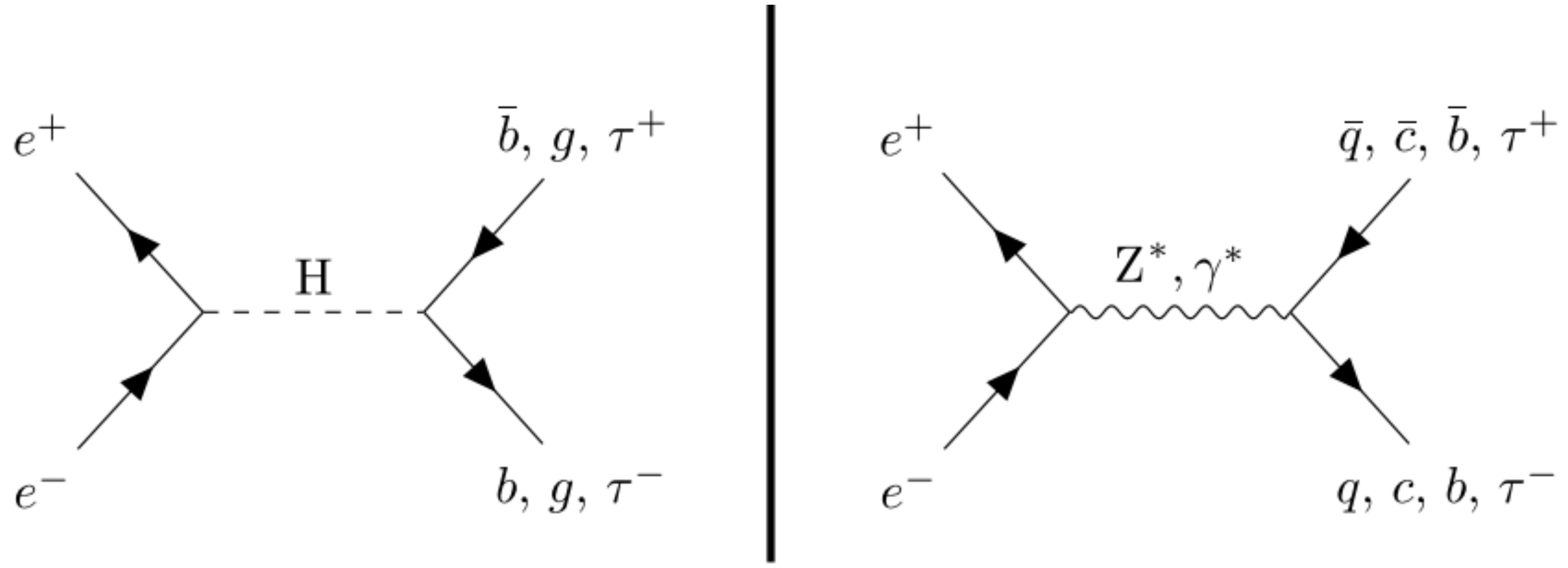
using μμ channel

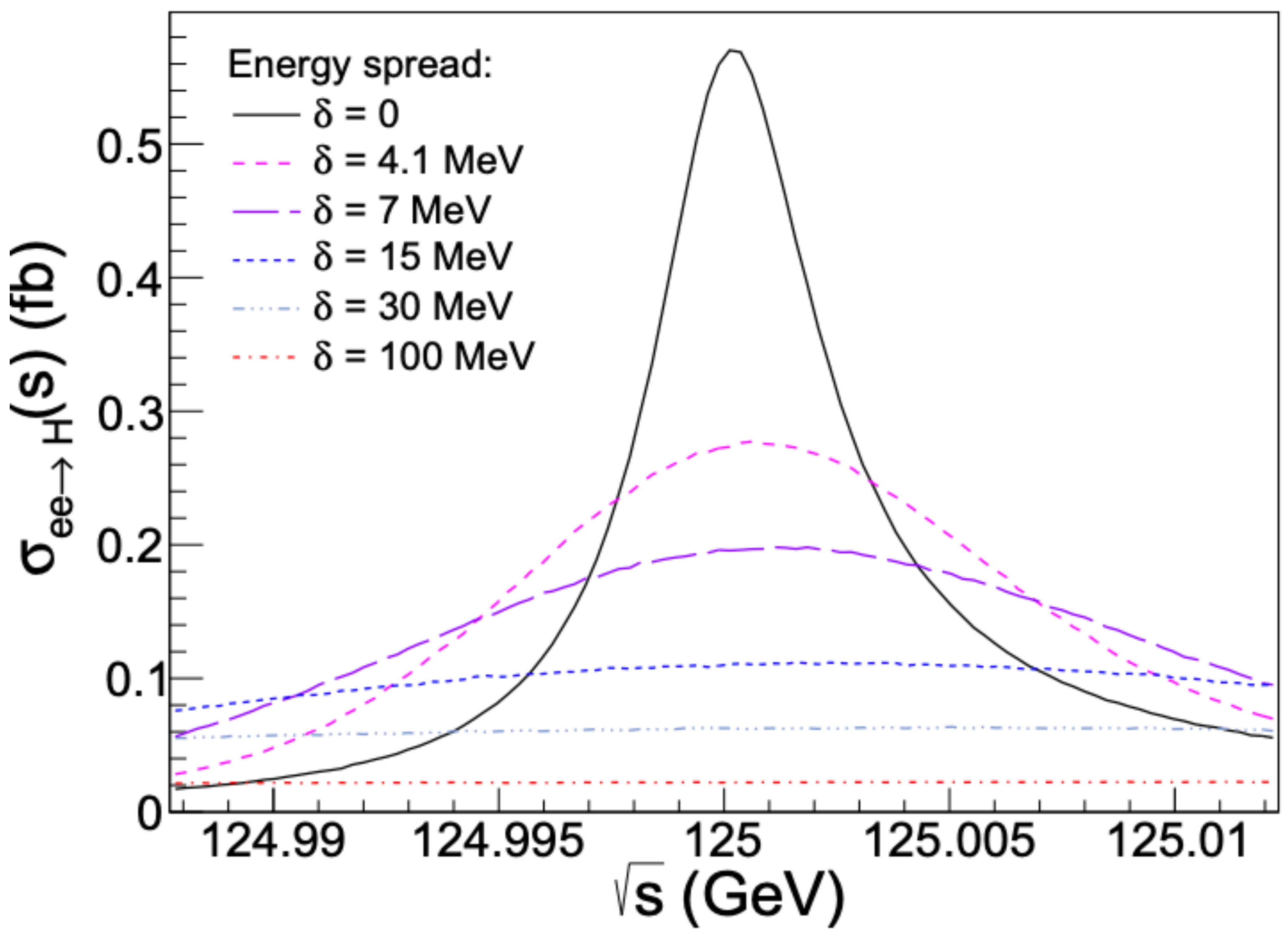
tracking system	Δm_H (MeV) stat.only	Δm_H (MeV) stat + syst
IDEA 2T	**3.49**	**4.27**
Perfect	**2.67**	**3.44**
IDEA 3T	**2.89**	**3.97**
CLD 2T	**4.56**	**5.32**

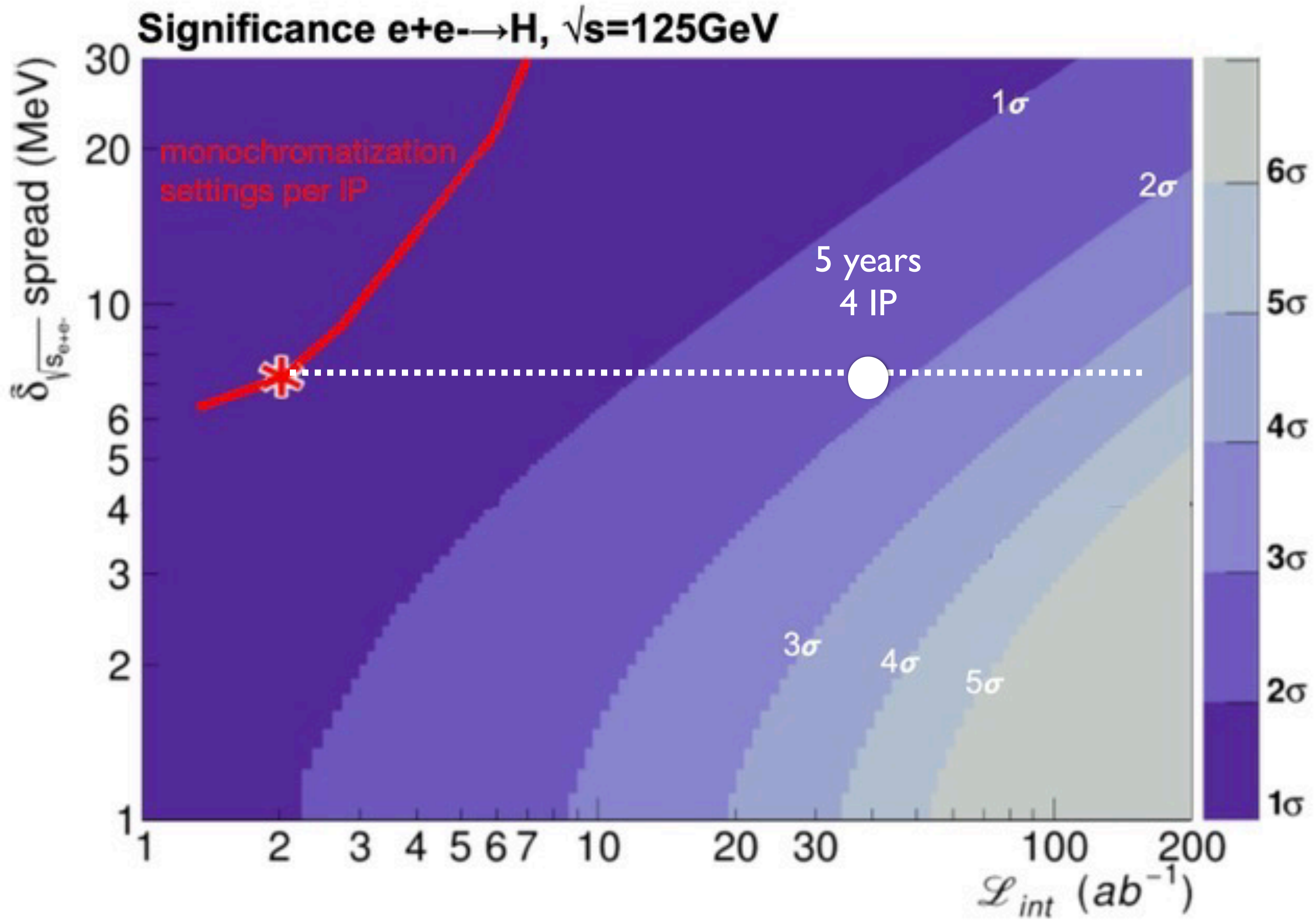
- Why measure Higgs mass:
  - input for the EW precision fit
  - O(10 MeV) need for permil precision of g_Z, g_W, $g_{Z\gamma}$
  - O(Γ_H = 4 MeV) to measure electron Yukawa

$\delta m_H \sim 2.9$ MeV (stat) + 1.9 (syst)

Electron Yukawa



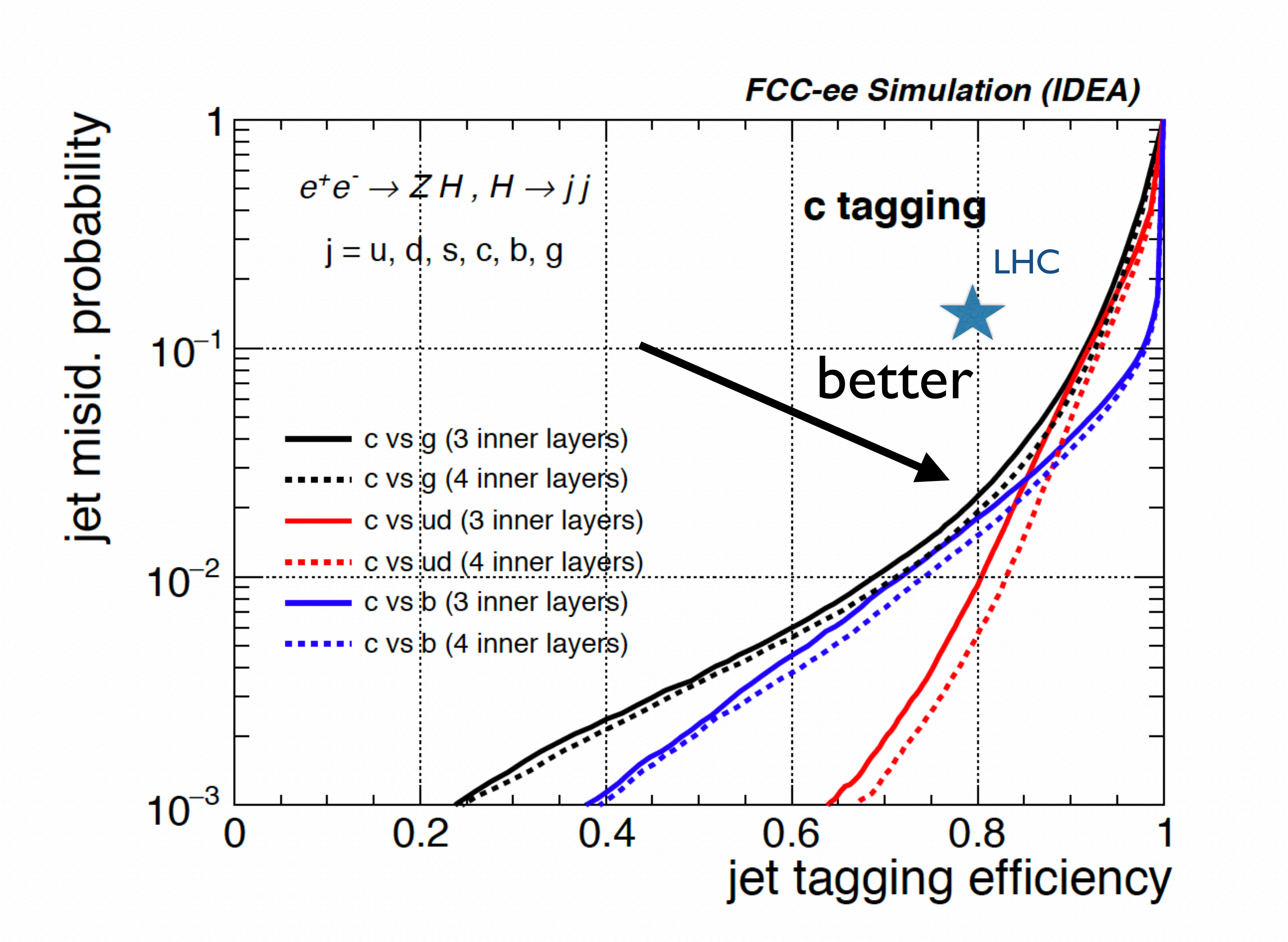




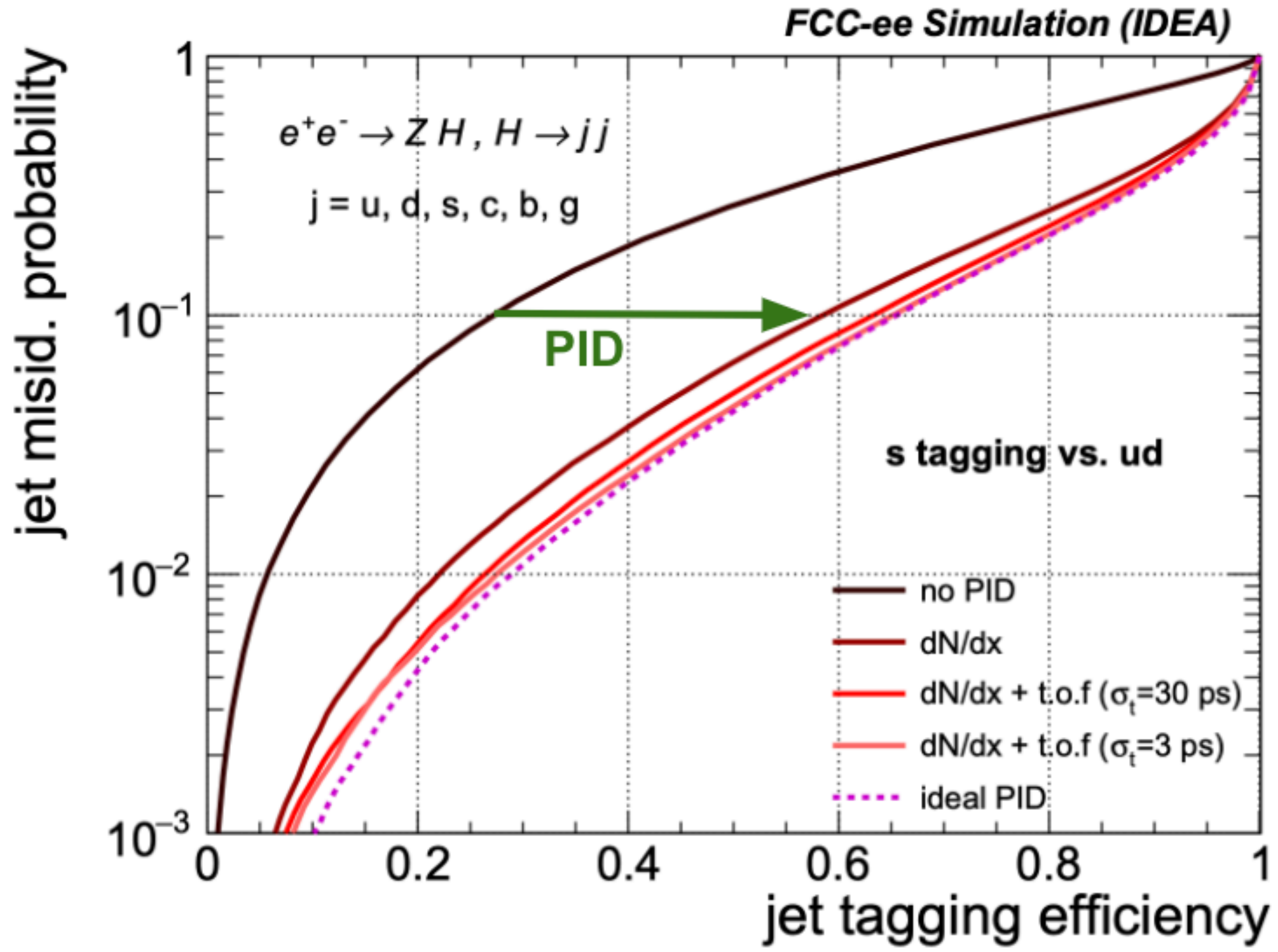
- s-channel production with beam mono-chromatisation at √s = 125 GeV
  - ISR+FSR leads to 40% + with beam spread ~ Γ_H another 45% (σ ~ 280 ab^{-1})
    - plus potentially uncertainty on the Higgs mass
    - state-of-the-art ~ 2σ with 5 years and 4 IPs
      - potentially improve with exclusive ee→gg(cc)

Higgs to hadrons at the FCC-ee

Charm-tagging



Strange-tagging

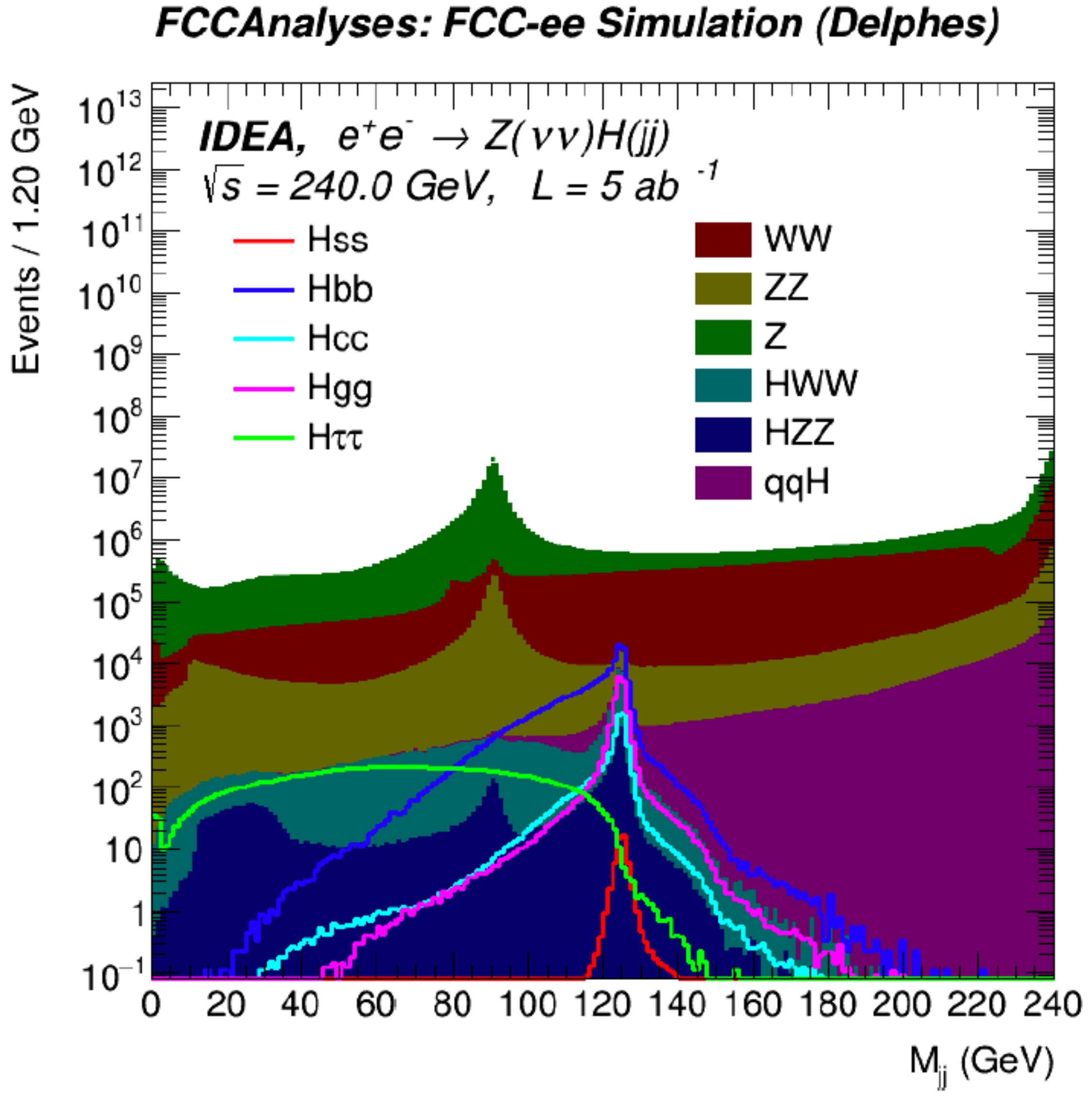


Light tracker, first measurement layer close to IP:

- excellent b/c-tagging performance
  - crucial to measure and to isolate clean H→bb/cc/gg samples

relies on particle ID
identify Kaons

2nd generation (c,s) at FCC-ee



Strategy

2D fit

(m_{vis} , m_{recoil})

→

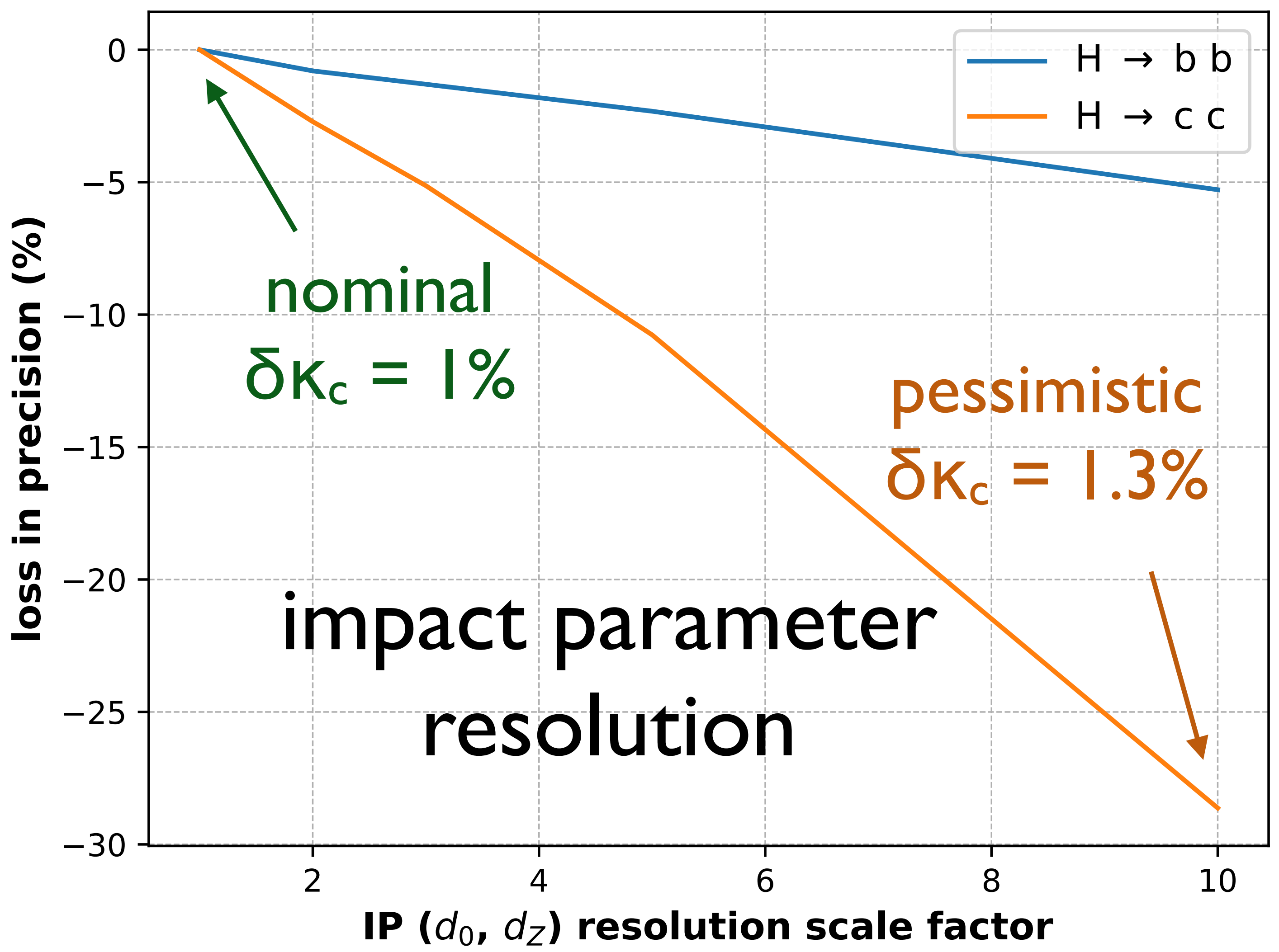
High purity with Flavour tagger

strange Yukawa: 2σ evidence

decay	δμ (%)	δκ (%)
bb	0.3	0.15*
gg	0.8	0.4
cc	2.1	**1**
ss	100	**50**

only using Z(νν) final state

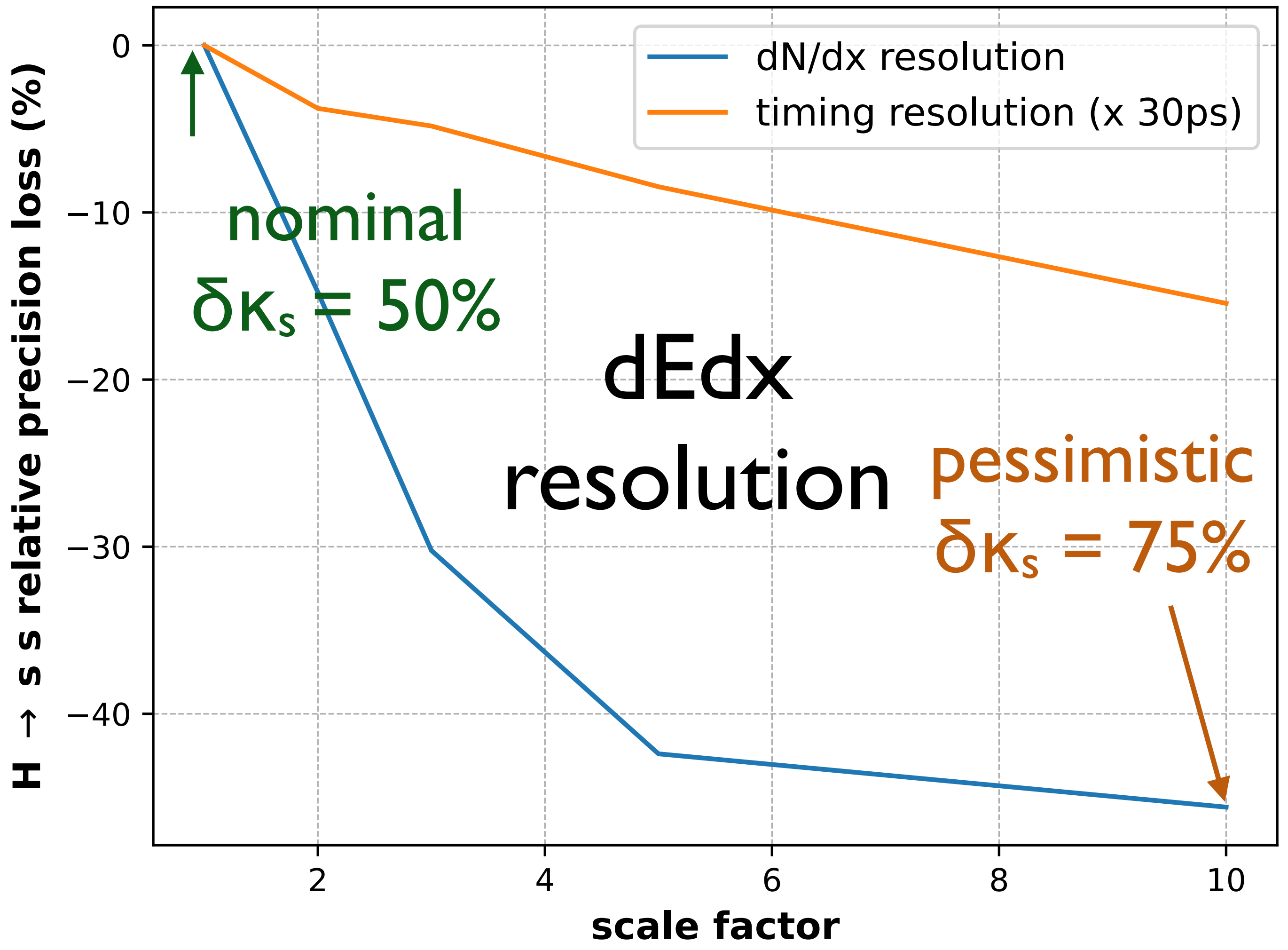
optimal detector ?



nominal
$\delta\kappa_c$ = 1%

pessimistic
$\delta\kappa_c$ = 1.3%

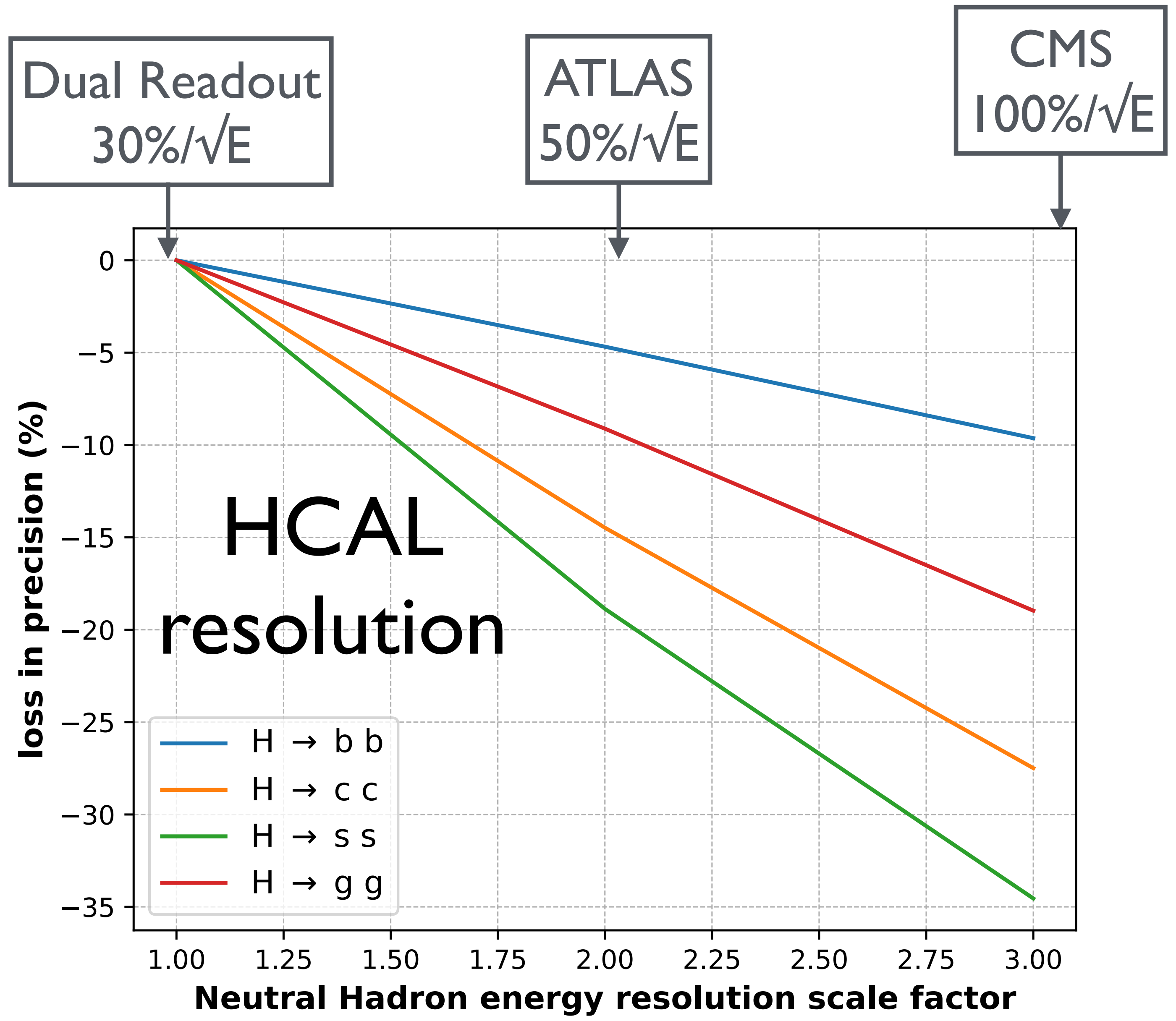
impact parameter resolution



nominal
$\delta\kappa_s$ = 50%

dEdx resolution

pessimistic
$\delta\kappa_s$ = 75%



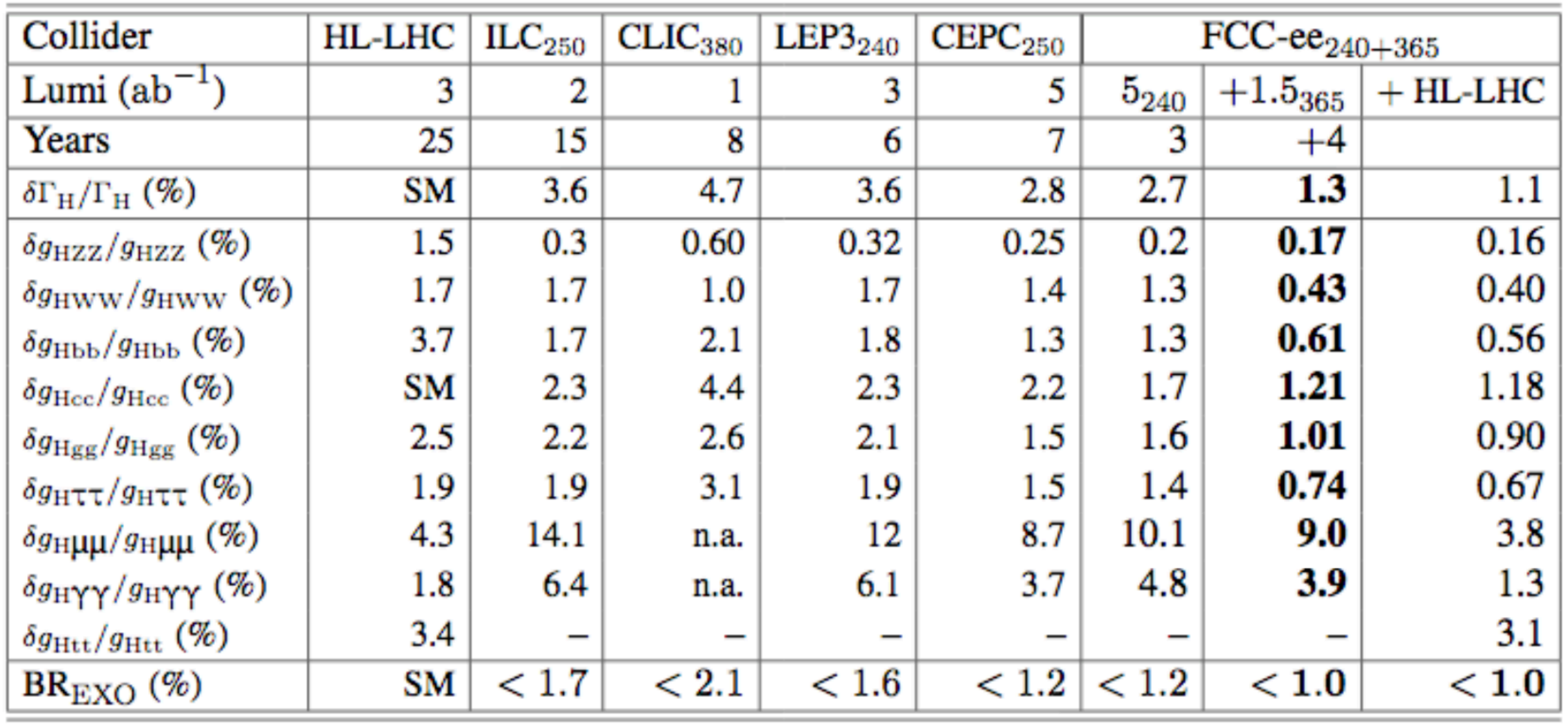
Dual Readout
30%/√E

ATLAS
50%/√E

CMS
100%/√E

HCAL resolution

FCC-ee vs. Other facilities



Collider	HL-LHC	ILC_{250}	CLIC_{380}	LEP3_{240}	CEPC_{250}	$\text{FCC-ee}_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

For abundant decay modes , FCC-ee improves upon HL-LHC by almost one order of magnitude

- both energy points (√s=240 GeV and √s=365 GeV) are important

This is only with 2 IPs !!

Timeline (FCC-ee)

2025 · 2045 · 2060 · time

Run 2/3 · HL-LHC · FCC-ee · FCC-hh

$\sqrt{s}$ = 13 - 13.6 TeV · $\sqrt{s}$ = 14 TeV · $\sqrt{s}$ = 240 - 365 GeV · $\sqrt{s}$ = 100 TeV

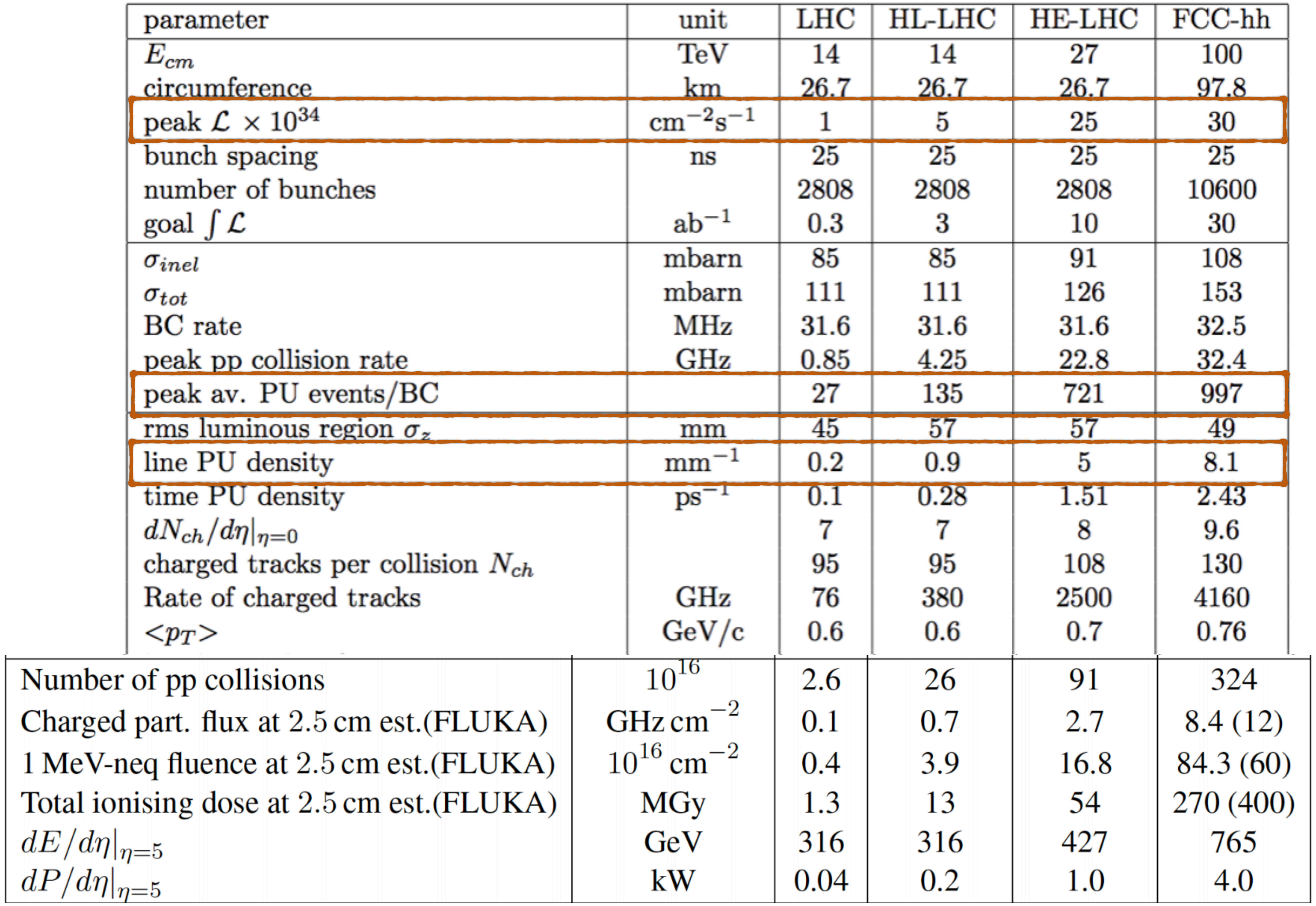
0.3 ab^{-1} · 3 ab^{-1} · (10 ab^{-1}) · 30 ab^{-1}

log(L)

- $\delta\kappa_{g,b,c,Z,W} < 1\%$
- evidence for strange Yukawa? (full II generation Yukawa)
- electron Yukawa?
- $\delta\Gamma_H \sim 1\%$, $\delta m_H \sim 3$ MeV

Machine specs and detector requirements

lumi & pile-up



parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\|_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

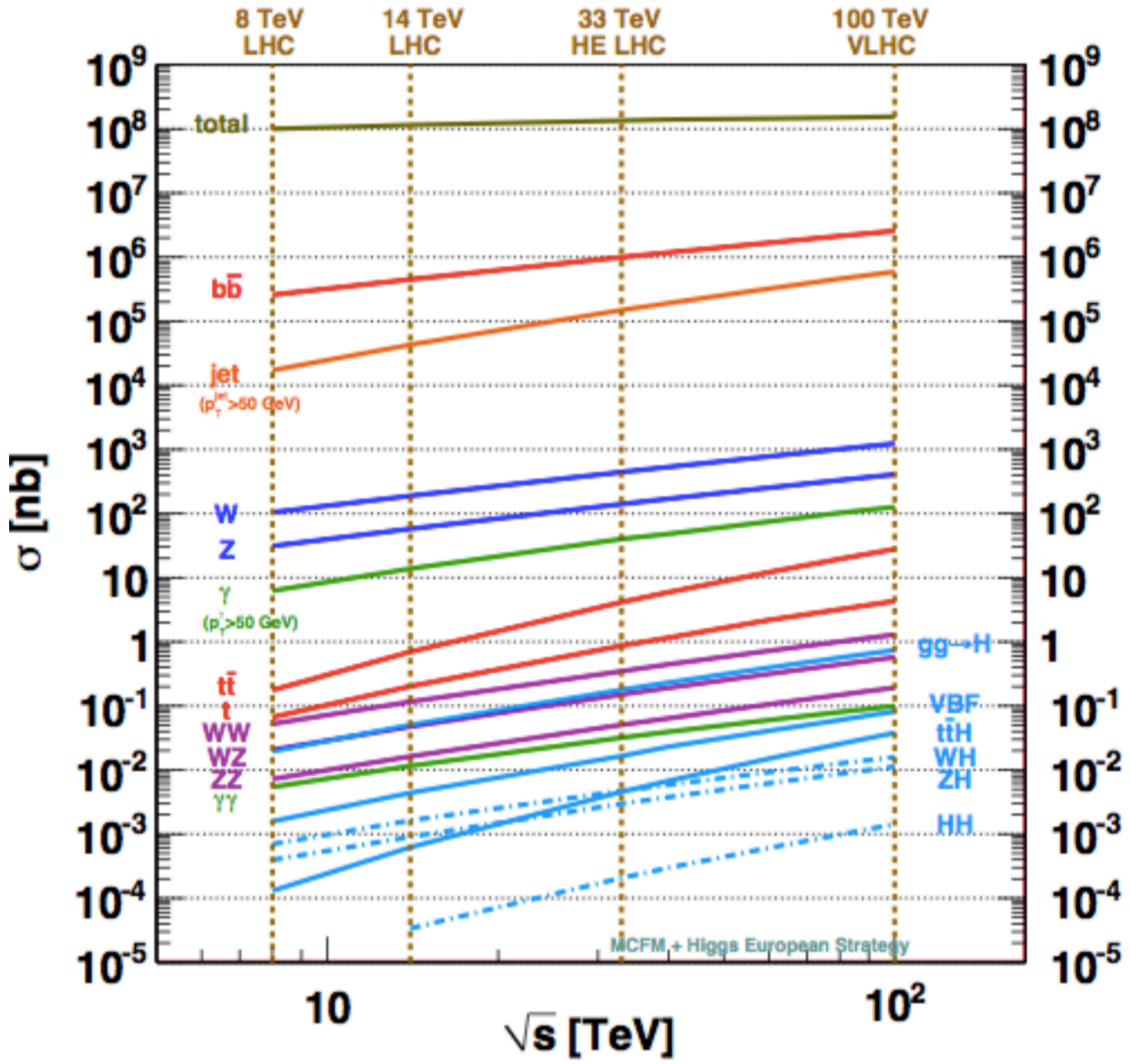
→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

but also x10 integrated luminosity w.r.t to HL-LHC

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

SM physics processes@ 100 TeV



- Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

→ Levels of pile-up will scale basically as the instantaneous luminosity.
(1000PU vs 200 PU)

- Cross-section for relevant processes shows a significant increase.

→ interesting physics sticks out more !

Rate of increase from 14 TeV to 100 TeV:

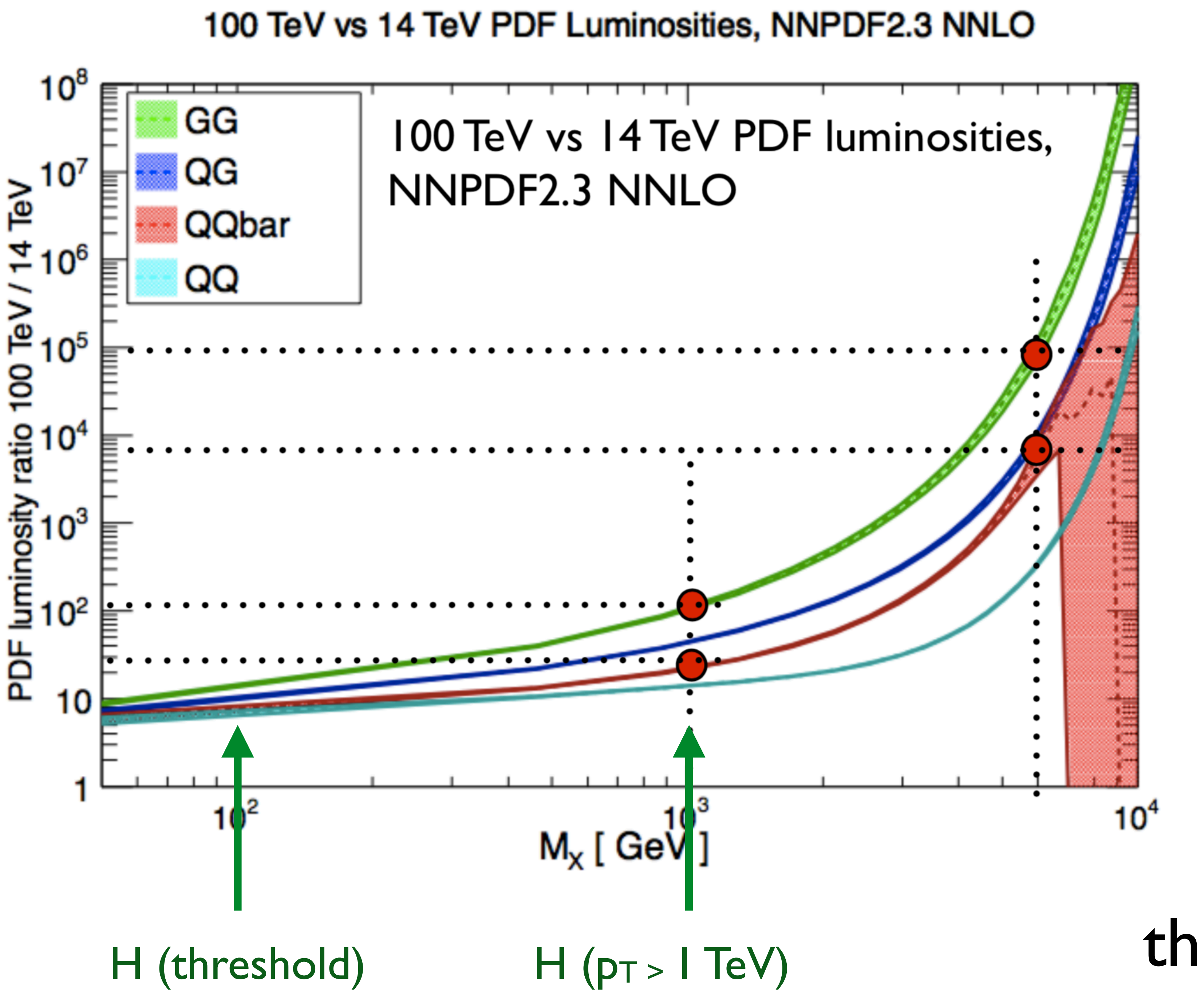
- ggH x15
- HH x40
- ttH x55
- tt x30

→ reduction of **x10-20** statistical uncertainties

Reach at high energies (III)

How does the rate of a **given process** (e.g. single Higgs production) scale from 14 TeV to 100 TeV

$$\frac{\text{cross-section } (\sqrt{s} = 100 \text{ TeV})}{\text{cross-section } (\sqrt{s} = 14 \text{ TeV})} \approx L_1 / L_2 \approx (s_2 / s_1)^a \approx (100 / 14)^{2a}$$



	σ(100)/σ(14)
ggH	15
HH	40
ttH	55
H (p_T > 1 TeV)	400

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)

Coupling measurements at ee vs hh

At pp colliders we can only measure:

$$\sigma_{prod}\, BR(i) = \sigma_{prod}\, \Gamma_i / \Gamma_H$$

→ we do not know the total width

In order to perform global fits, we have to make **model-dependent assumptions**

Instead, by performing measurements of ratios of BRs at hadron colliders:

$$BR(H\rightarrow XX) / BR(H\rightarrow ZZ) \approx g_X{}^2 / g_Z{}^2$$

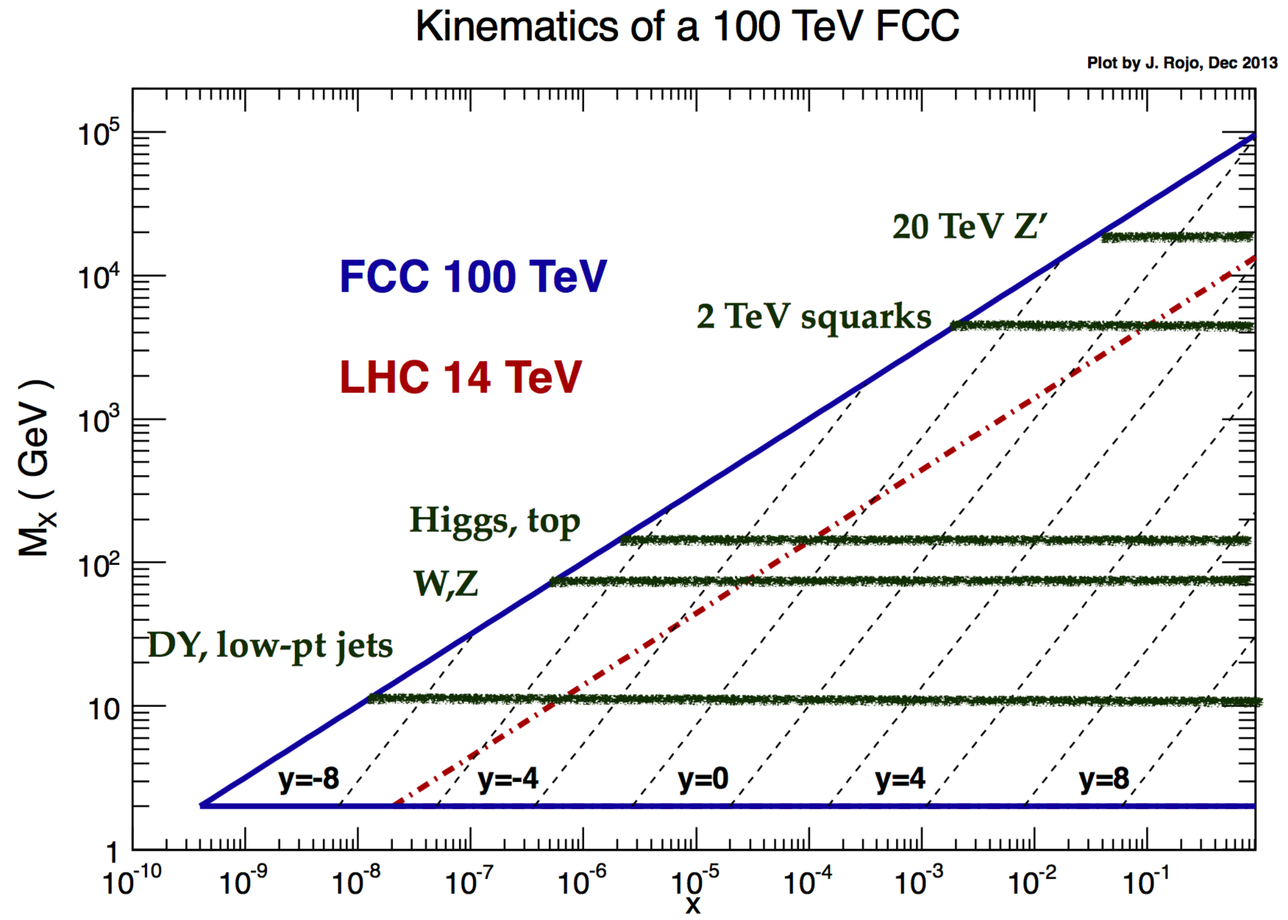
from e^+e^-

We can "convert" **relative measurements into absolute** via g_Z thanks to e^+e^- measurement

→ synergy between lepton and hadron colliders

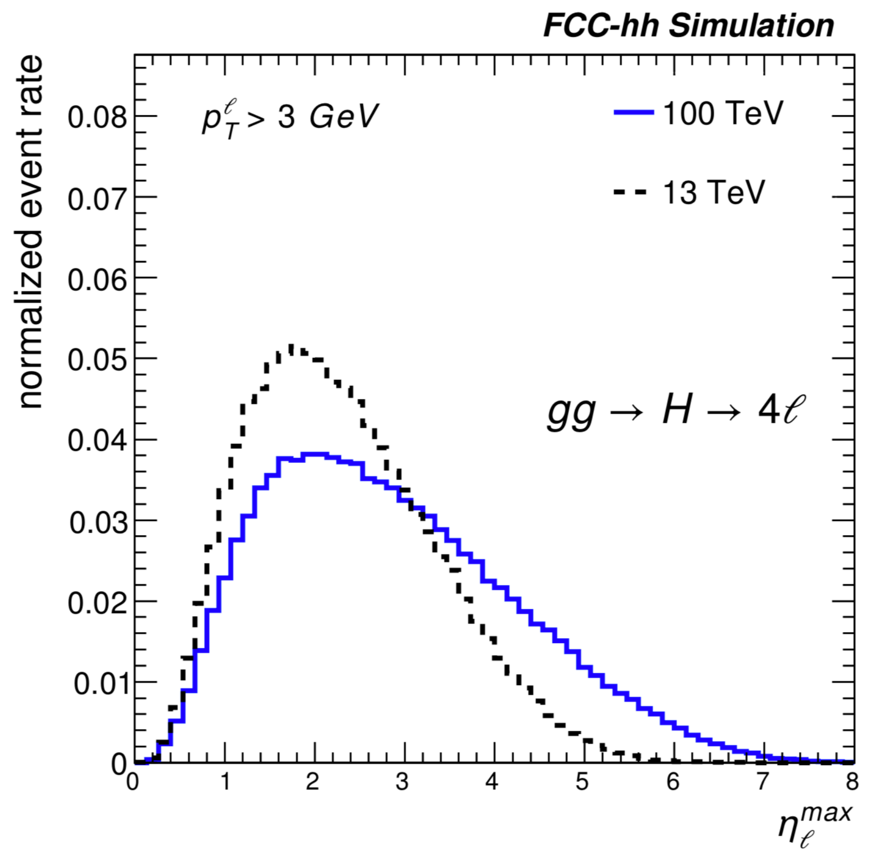
Higgs @threshold

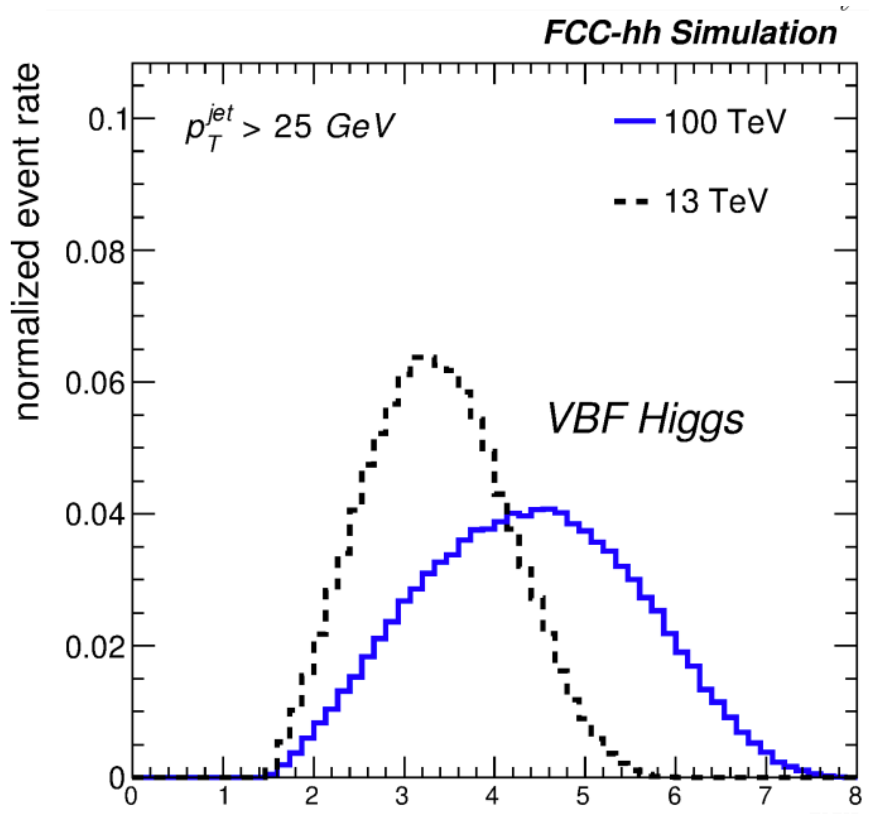
$x_{min} \sim M^2 / s$

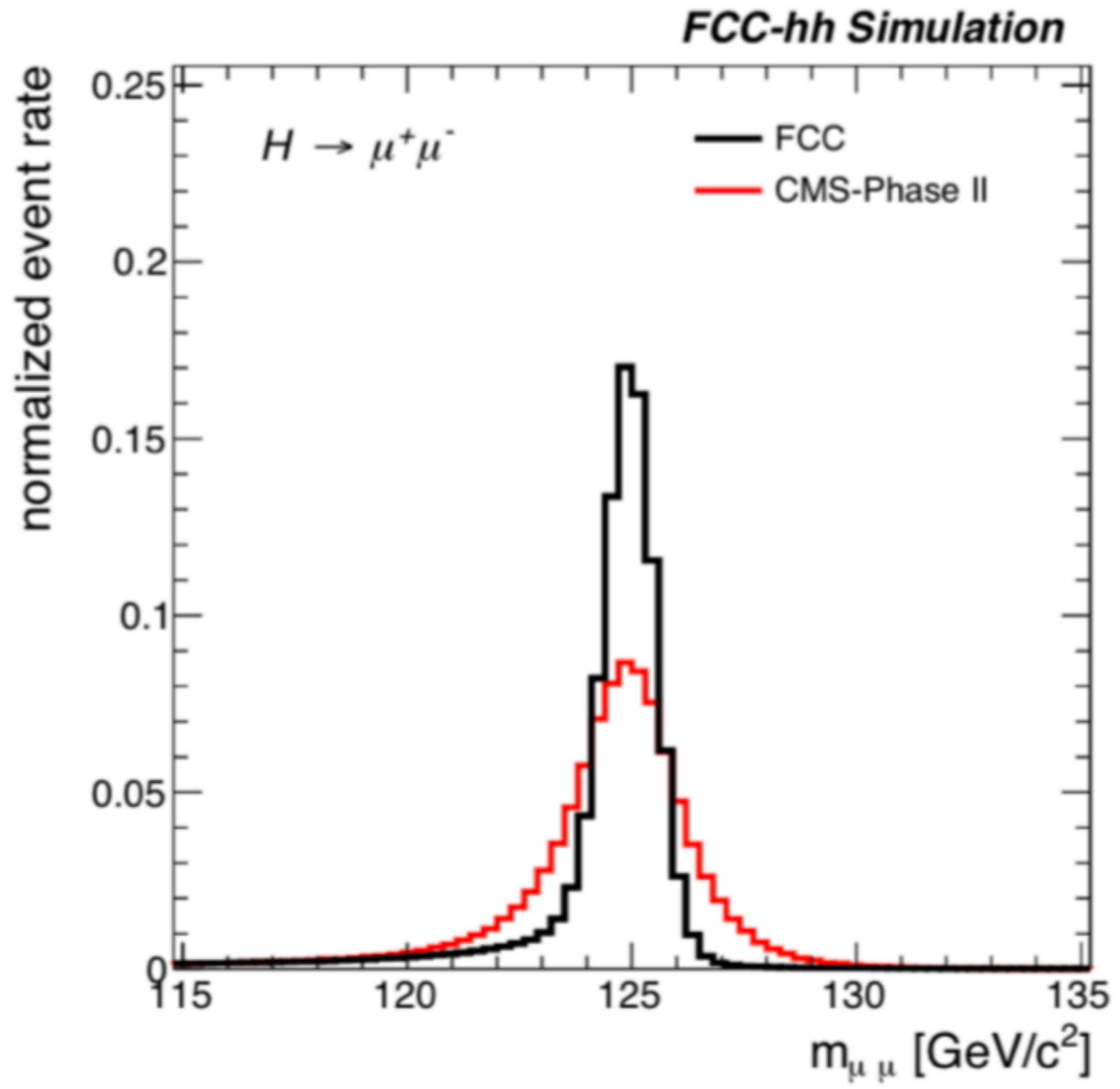


SM Physics produced at threshold is more forward @100TeV

→ in order to maintain sensitivity need **large rapidity** (with tracking) and **low p_T** coverage



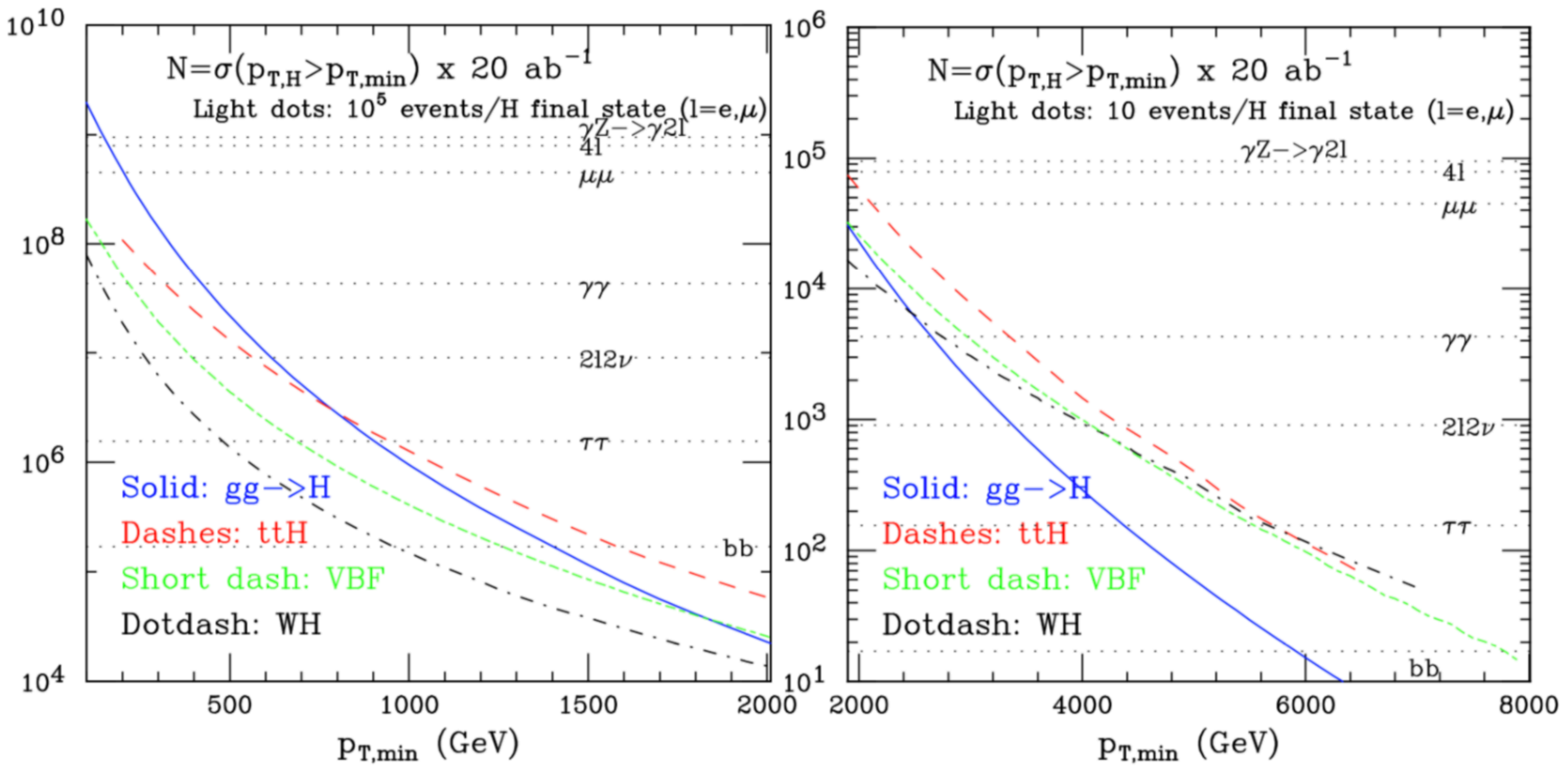




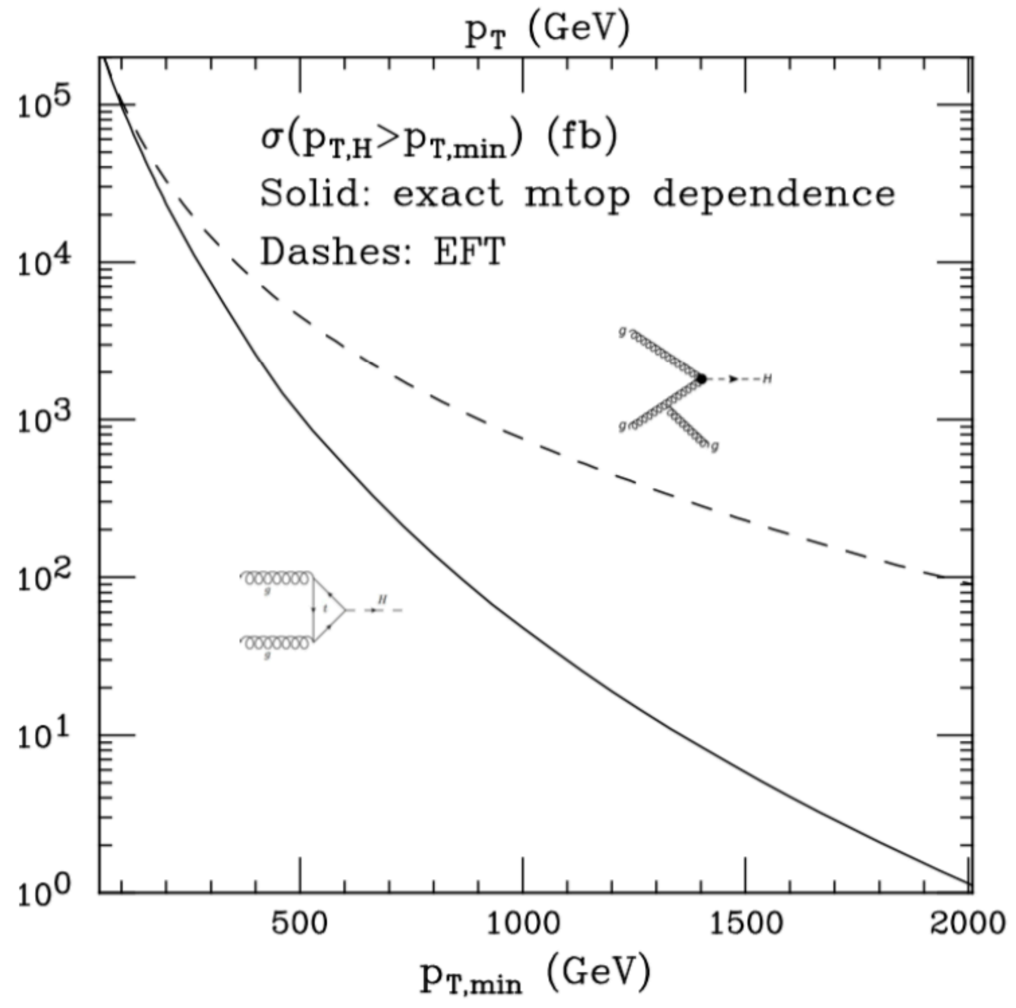
low p_T muons → resolution dominated by MS

- Goals:
  - **Precision spectroscopy** and calorimetry up to **|η| < 4**
  - Tracking and calorimetry up to |η| < 6

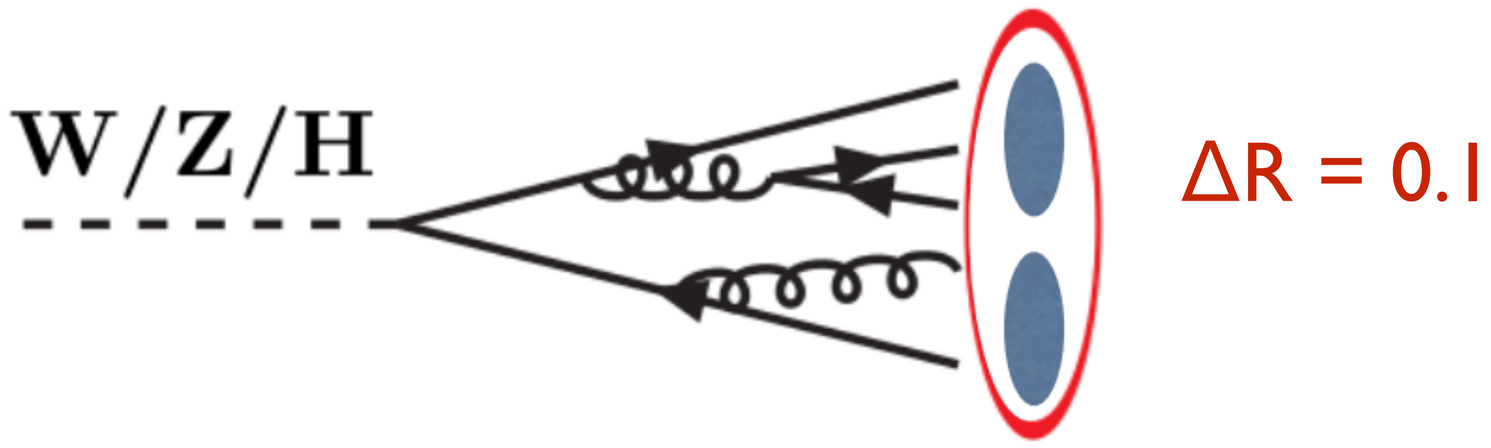
Higgs at large p_T



N(p_T > $p_{T,\,min}$)



- Huge rates at large p_T :
  - **> 10^6 Higgs** produced with p_T > 1 TeV
  - Higher probability to produce large p_T Higgs from ttH/VBF/VH at large
  - Even rare decay modes can be accessed at large p_T
- Opportunity to measure the Higgs **in a new dynamical regime**
  - Higgs p_T spectrum highly sensitive to new physics.



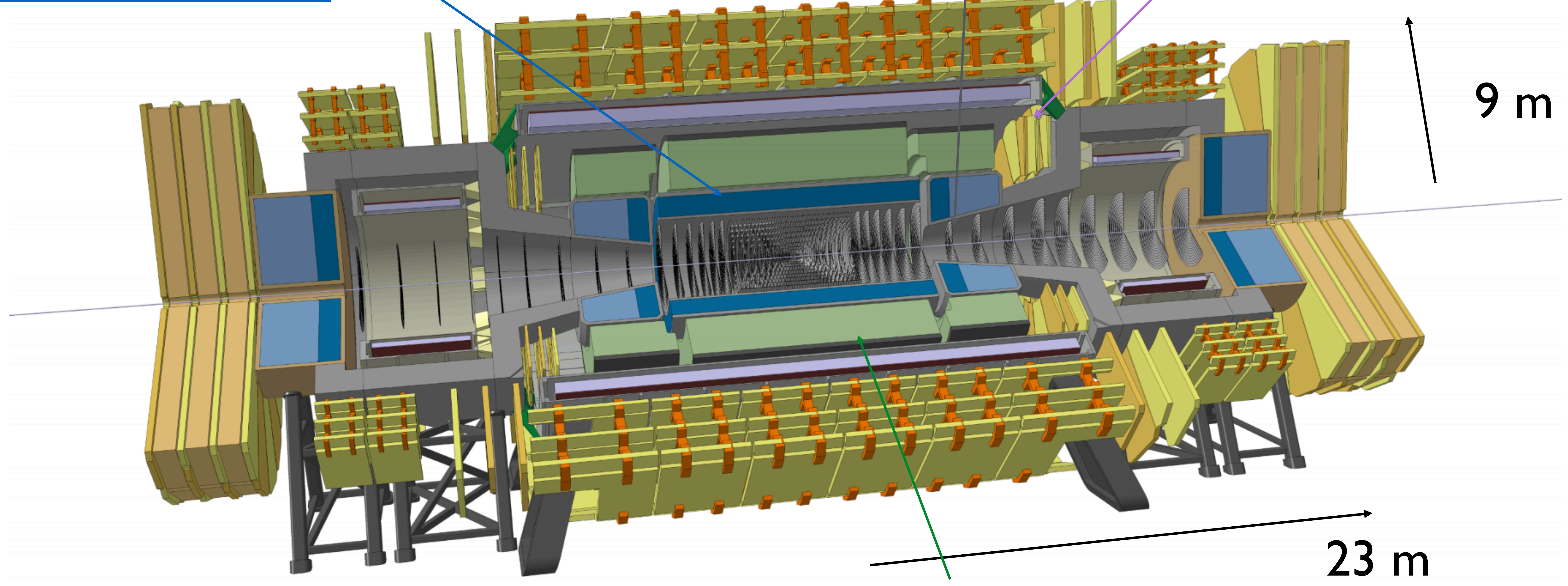
- highly granular sub-detectors:
  - Tracker - pixel:10 µm @ 2cm → $\sigma_{\eta\times\phi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\phi} \approx$ 10 mrad
- good energy/p_T resolution at large p_T:
  - σ_p / p = 2% @ 1 TeV

The FCC-hh detector

Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
$30\ X_0$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Tracker: $\sigma_{p_T}/p_T \sim 20\%$
at 10 TeV (1.5m radius)

Central Magnet +
Fwd solenoids

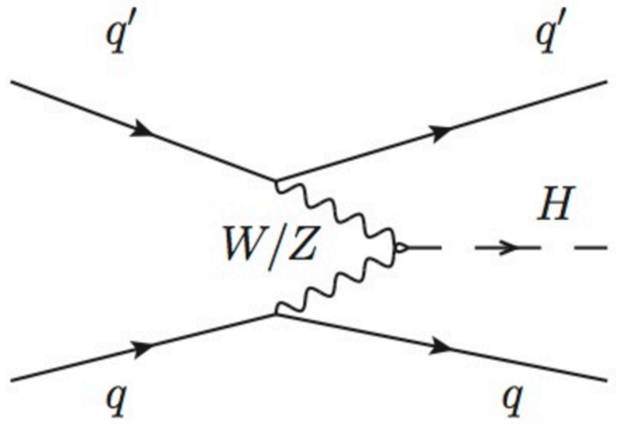


Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

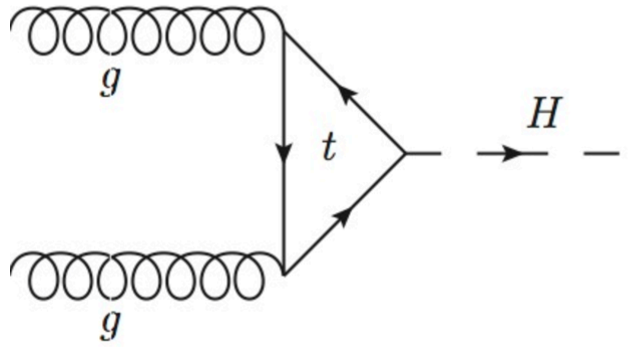
Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

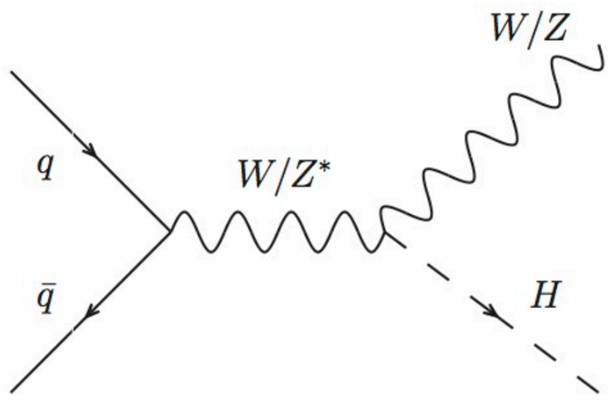
Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

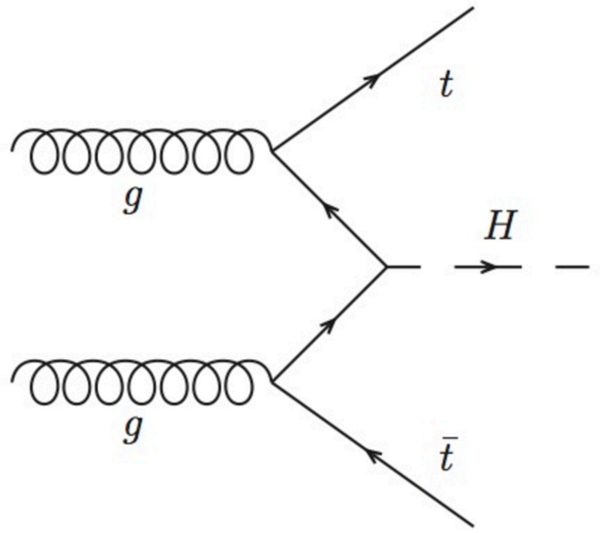
Single Higgs production @FCC-hh

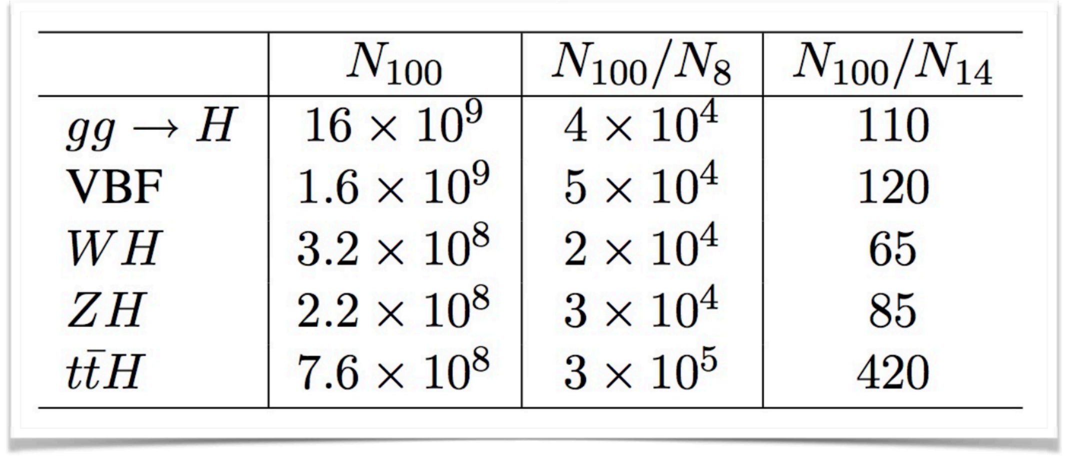


	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55









	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

Factor: 1/100 1/10

reduction in stat. unc.

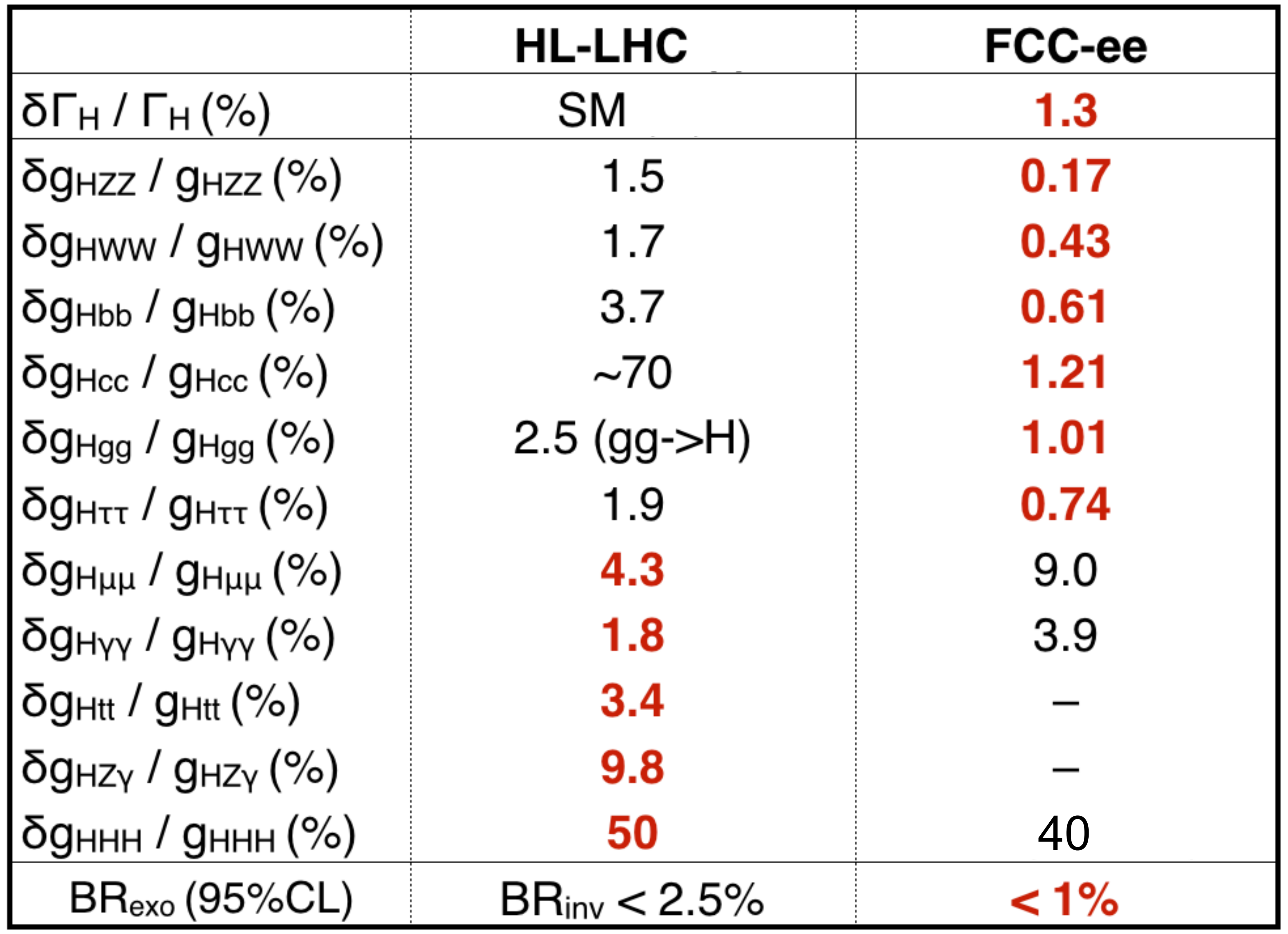
Large statistics in various Higgs decay modes allow:

- for % - **level precision in statistically limited** rare channels (μμ, Zɣ)
- in **systematics limited** channels, to isolate **cleaner samples** in regions (e.g. @large Higgs p_T) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

Why measuring Higgs @100TeV?

- 100 TeV provides **unique and complementary measurements** to ee colliders:
  - Higgs **self-coupling**
  - **top Yukawa**
  - **Higgs → invisible**
  - **rare decays** (BR(μμ), BR(Zɣ), ratios, ..) measurements will be **statistically limited** at FCC-ee

Need to improve



	HL-LHC	**FCC-ee**
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	**4.3**	9.0
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	**1.8**	3.9
$\delta g_{Htt} / g_{Htt}$ (%)	**3.4**	–
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	**9.8**	–
$\delta g_{HHH} / g_{HHH}$ (%)	**50**	40
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**

Large rates for rare modes and HH production at FCC-hh

→ complementary to e^+e^-

Top Yukawa (production)

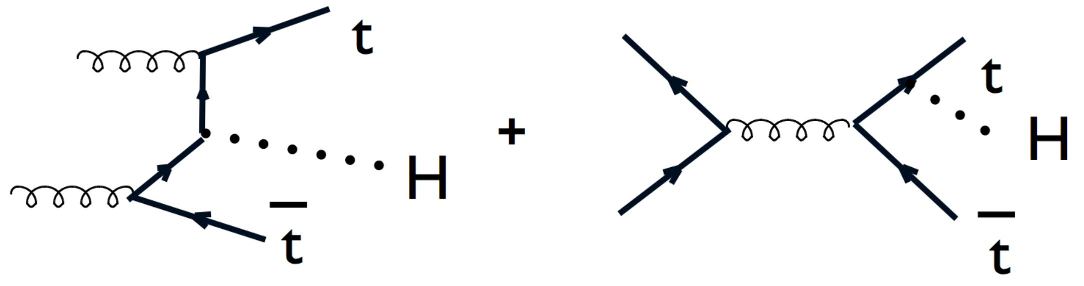
MLM, D. Jamin, C. Helsens, G. Ortona, MS

- production ratio **$\sigma(ttH)/\sigma(ttZ) \approx y_t^2\, y_b^2 / g_{ttZ}^{\ 2}$**
- measure **$\sigma(ttH)/\sigma(ttZ)$** in **$H/Z \rightarrow bb$** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

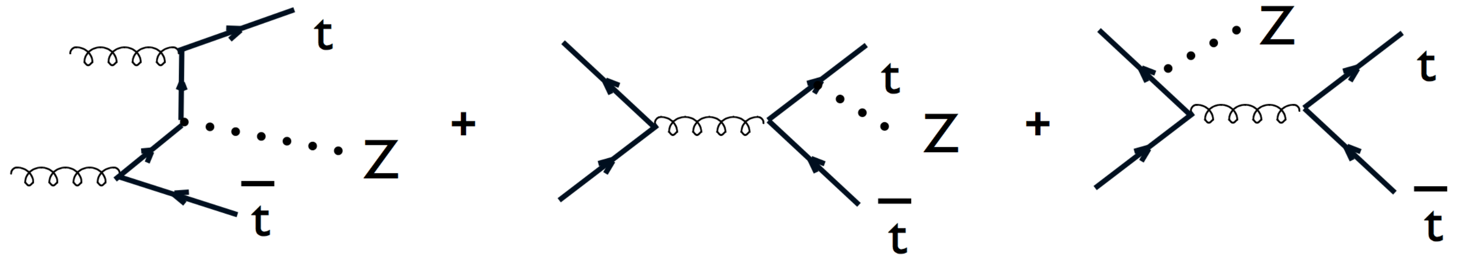
- assuming **g_{ttZ}** and **κ_b** known to 1% (from FCC-ee),

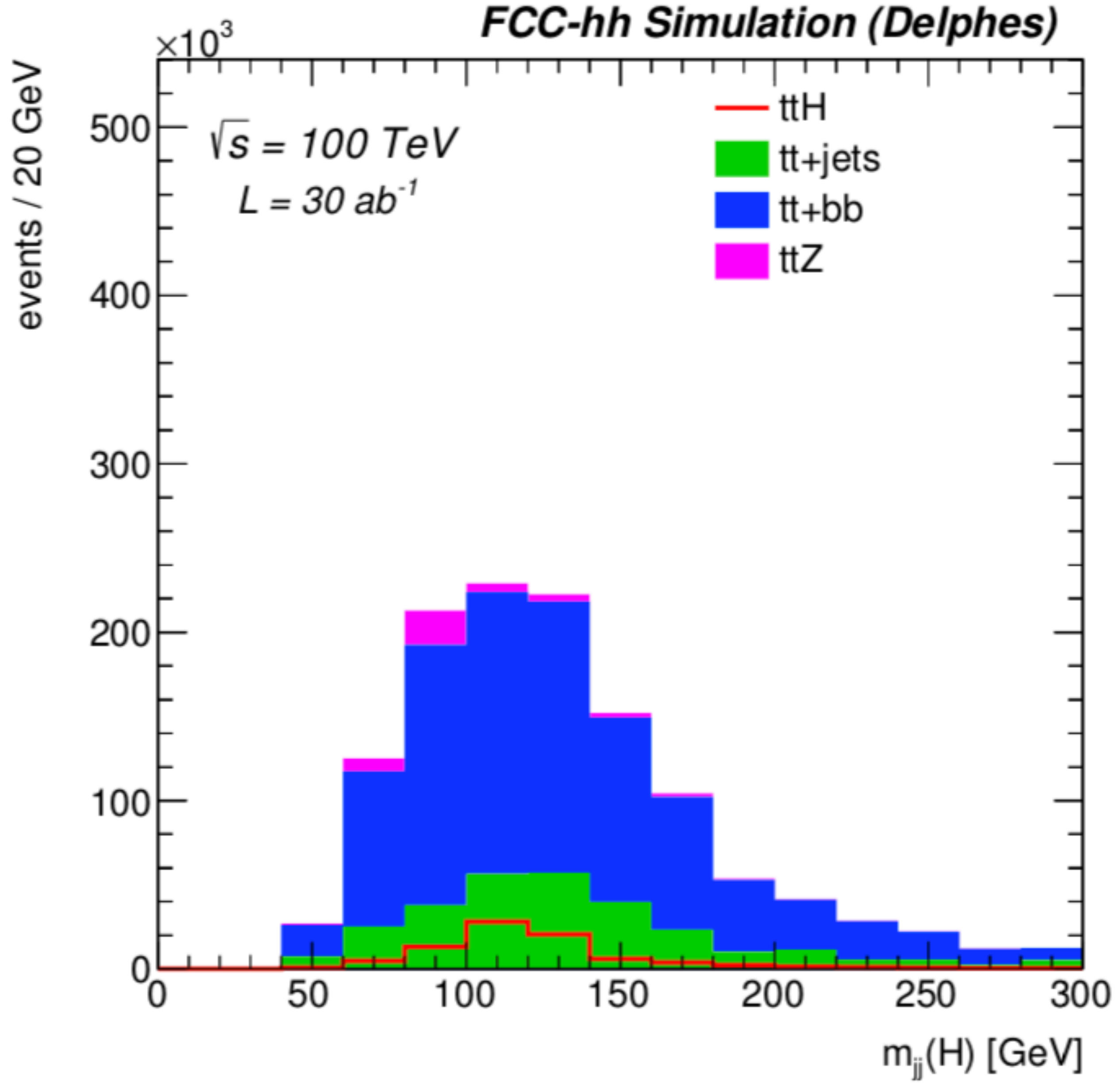
→ measure **y_t** to 1%

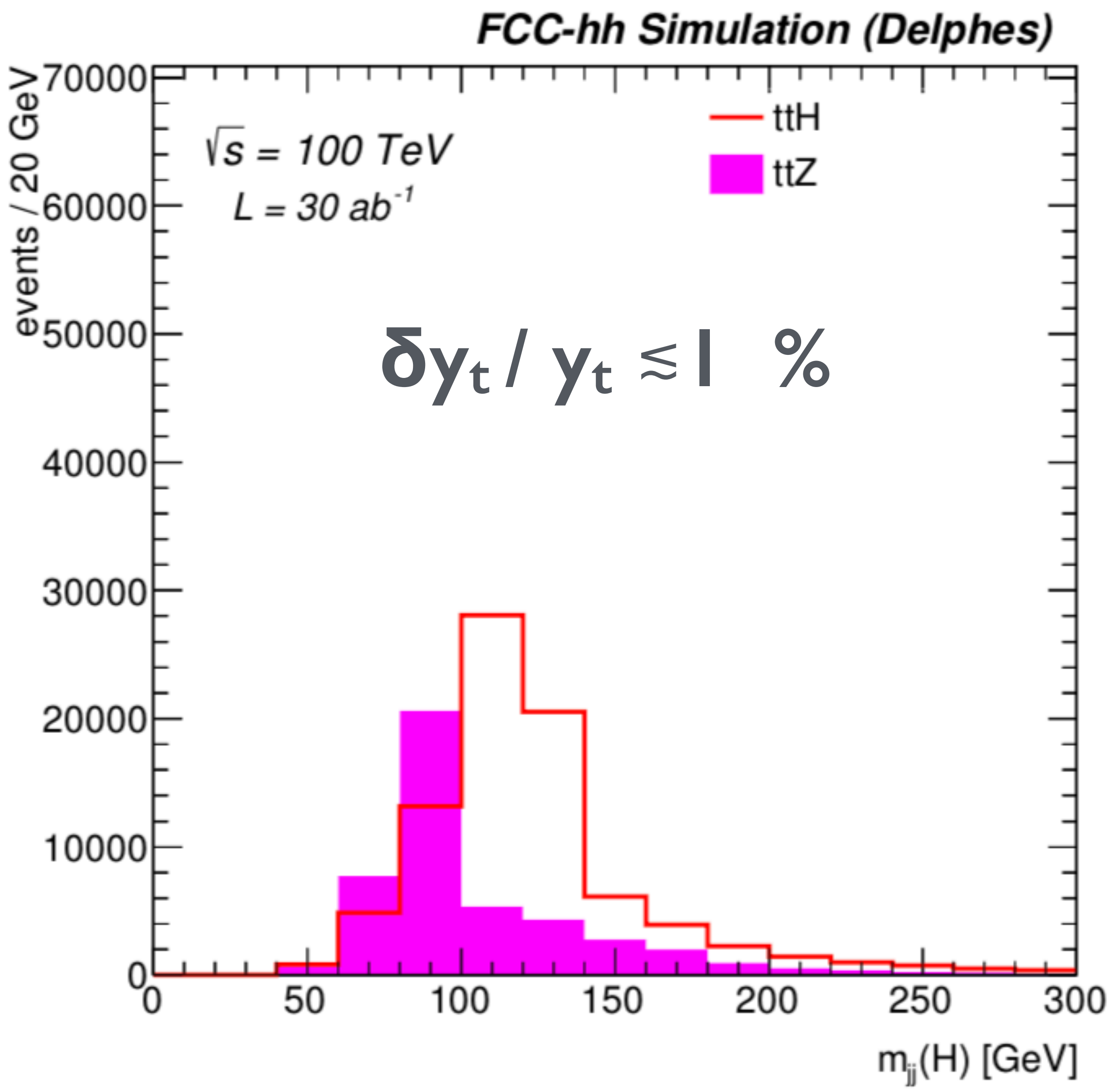
ttH



ttZ





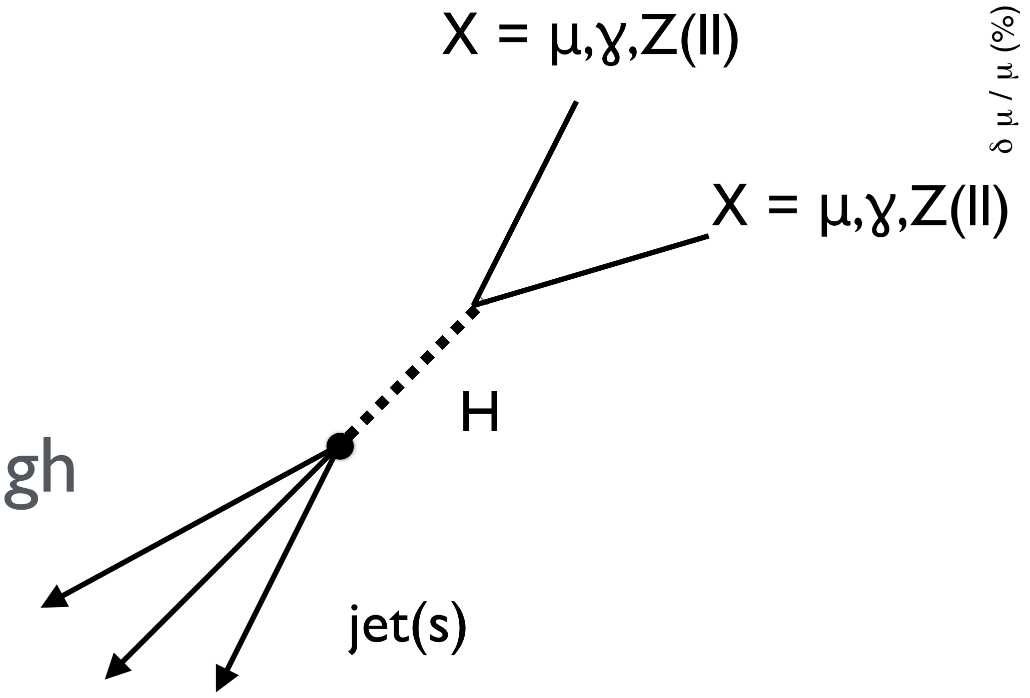


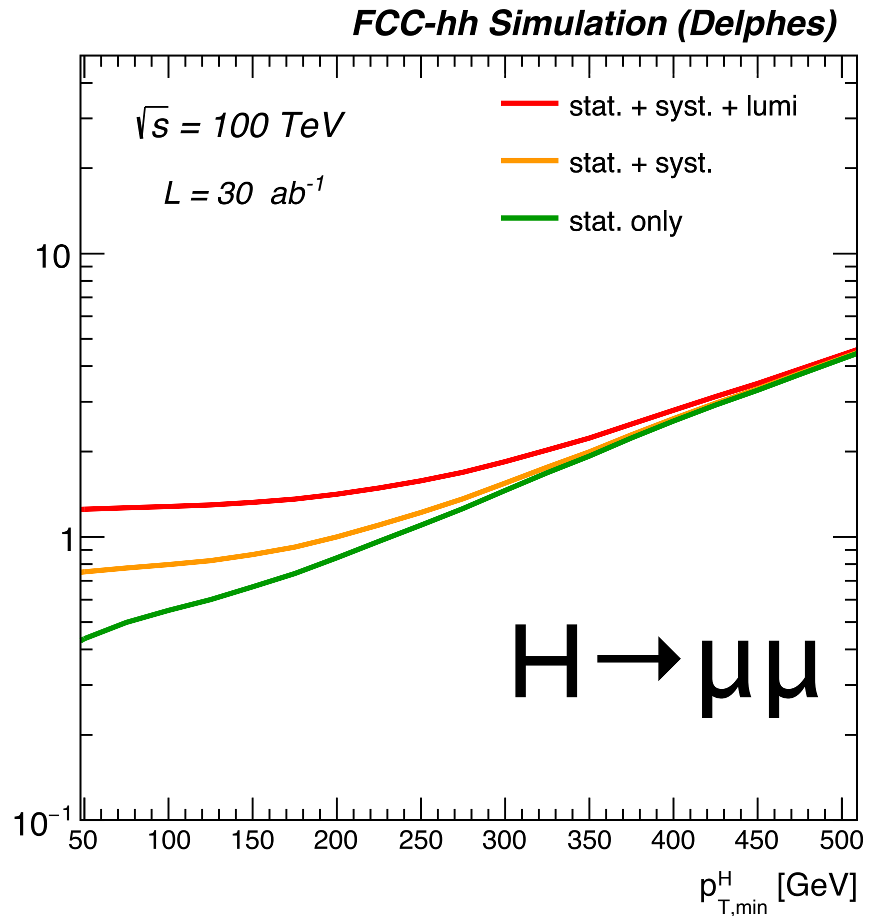
$\delta y_t / y_t \lesssim 1\ \%$

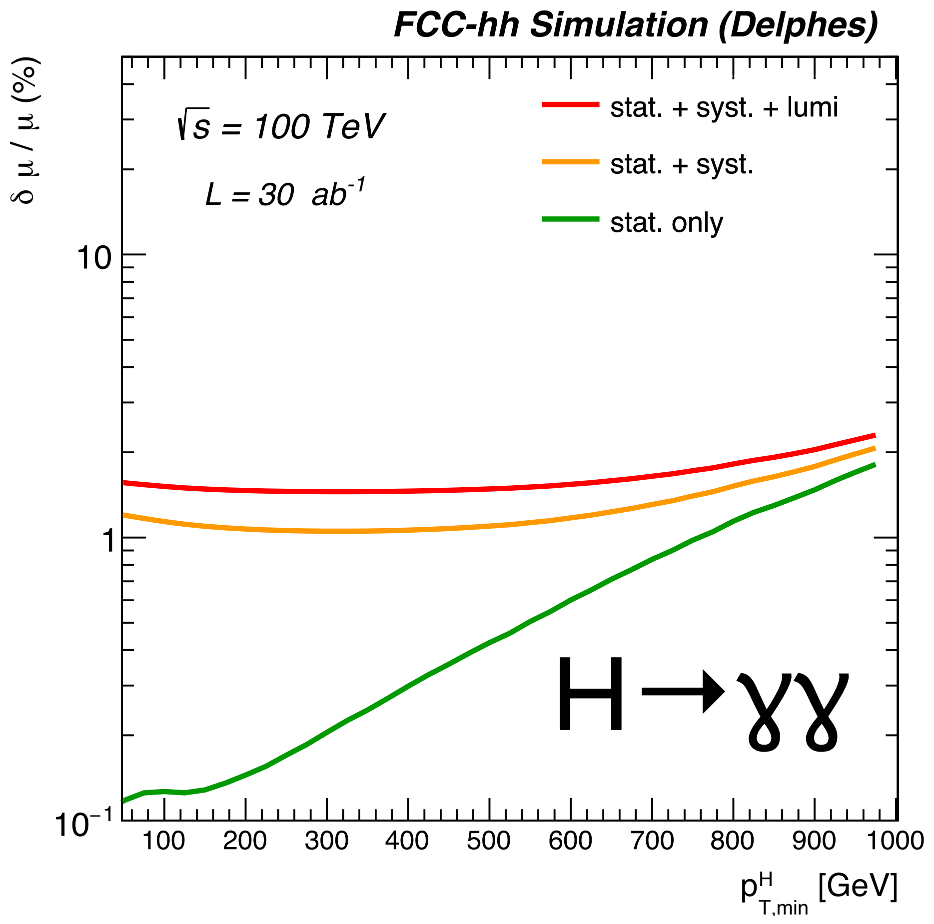
Higgs decays (signal strenth)

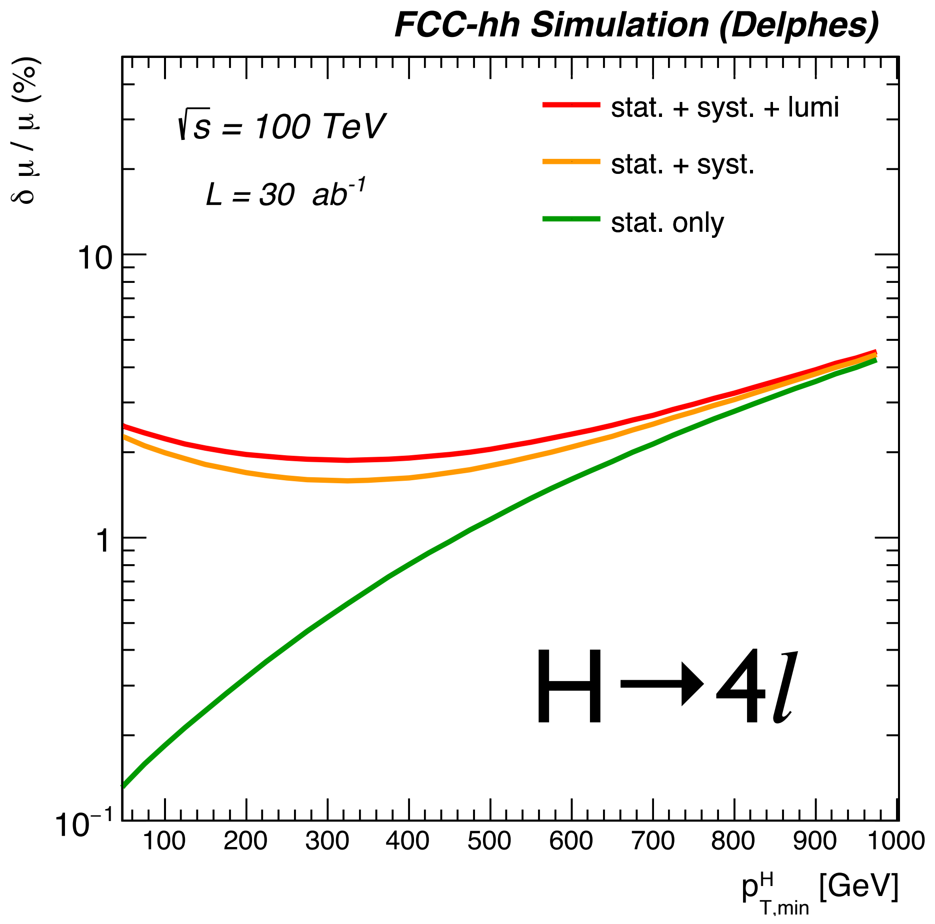
- 1% lumi + theory uncertainty
- p_T dependent object efficiency:
  - $\delta\varepsilon(e/\gamma)$ = 0.5 (1)% at $p_T \rightarrow \infty$
  - $\delta\varepsilon(\mu)$ = 0.25 (0.5)% at $p_T \rightarrow \infty$

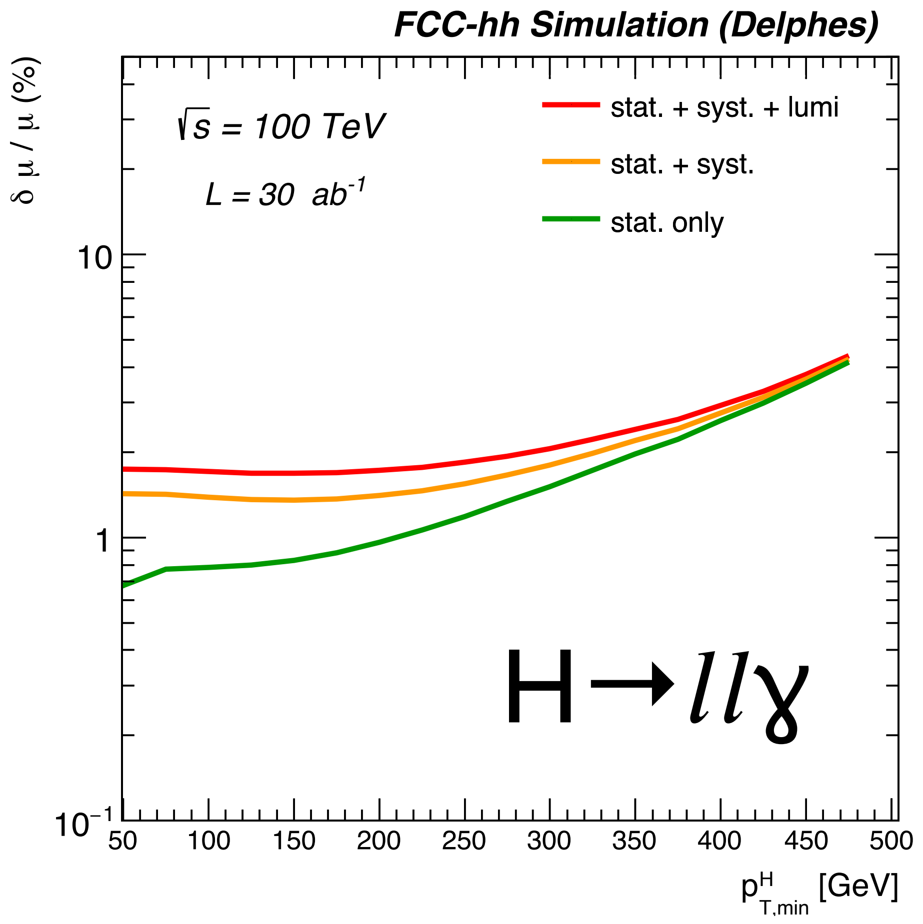
- study sensitivity as a function of **minimum p_T(H)** requirement in the **γγ, ZZ(4l), μμ and Z(ll)γ** channels
- **low** p_T(H): **large statistics** and **high syst**. unc.
- **large** p_T(H): **small statistics** and **small syst**. unc.
- **O(1-2%) precision on BR** achievable up to very high p_T (means 0.5-1% on the couplings)





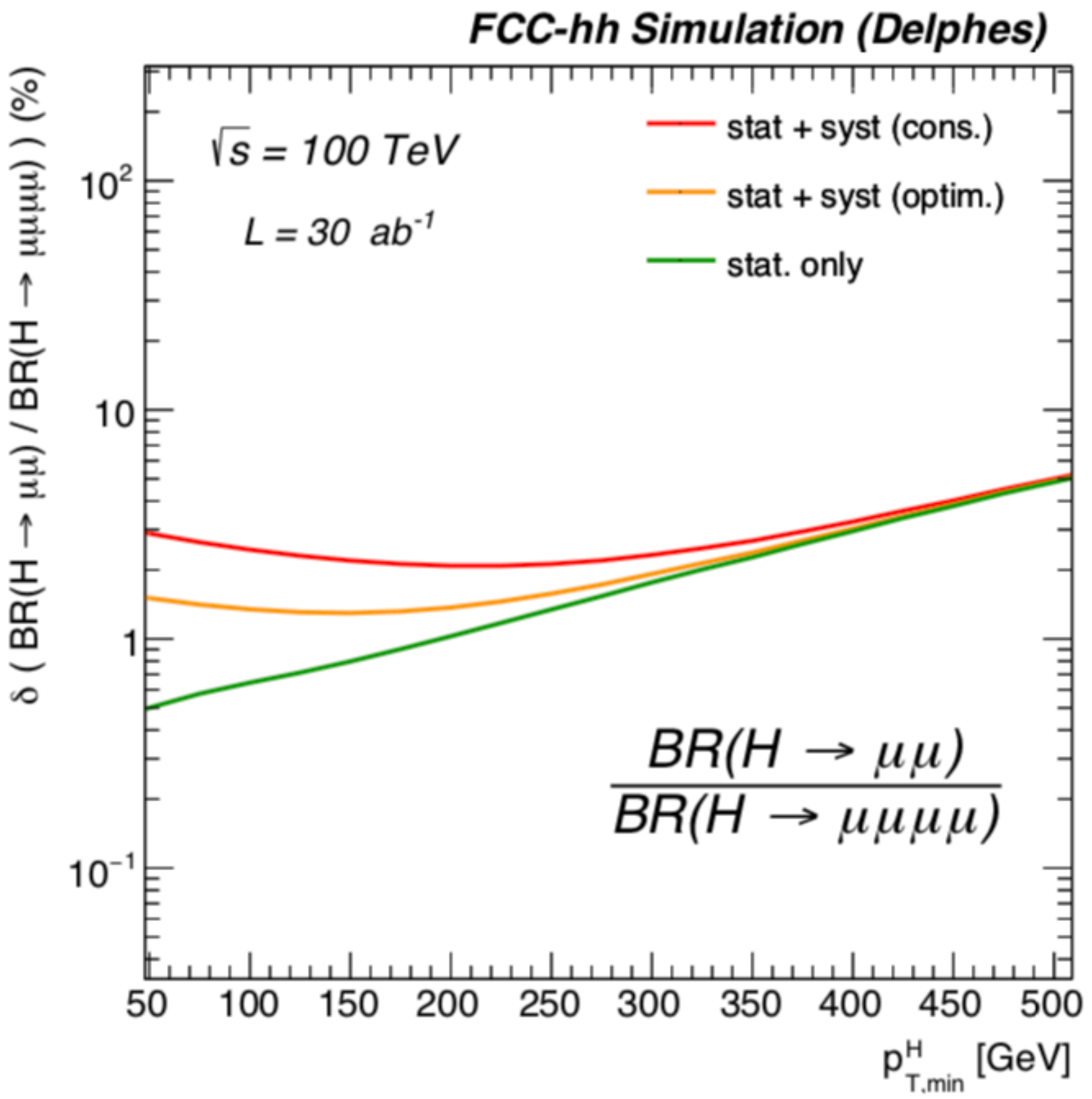


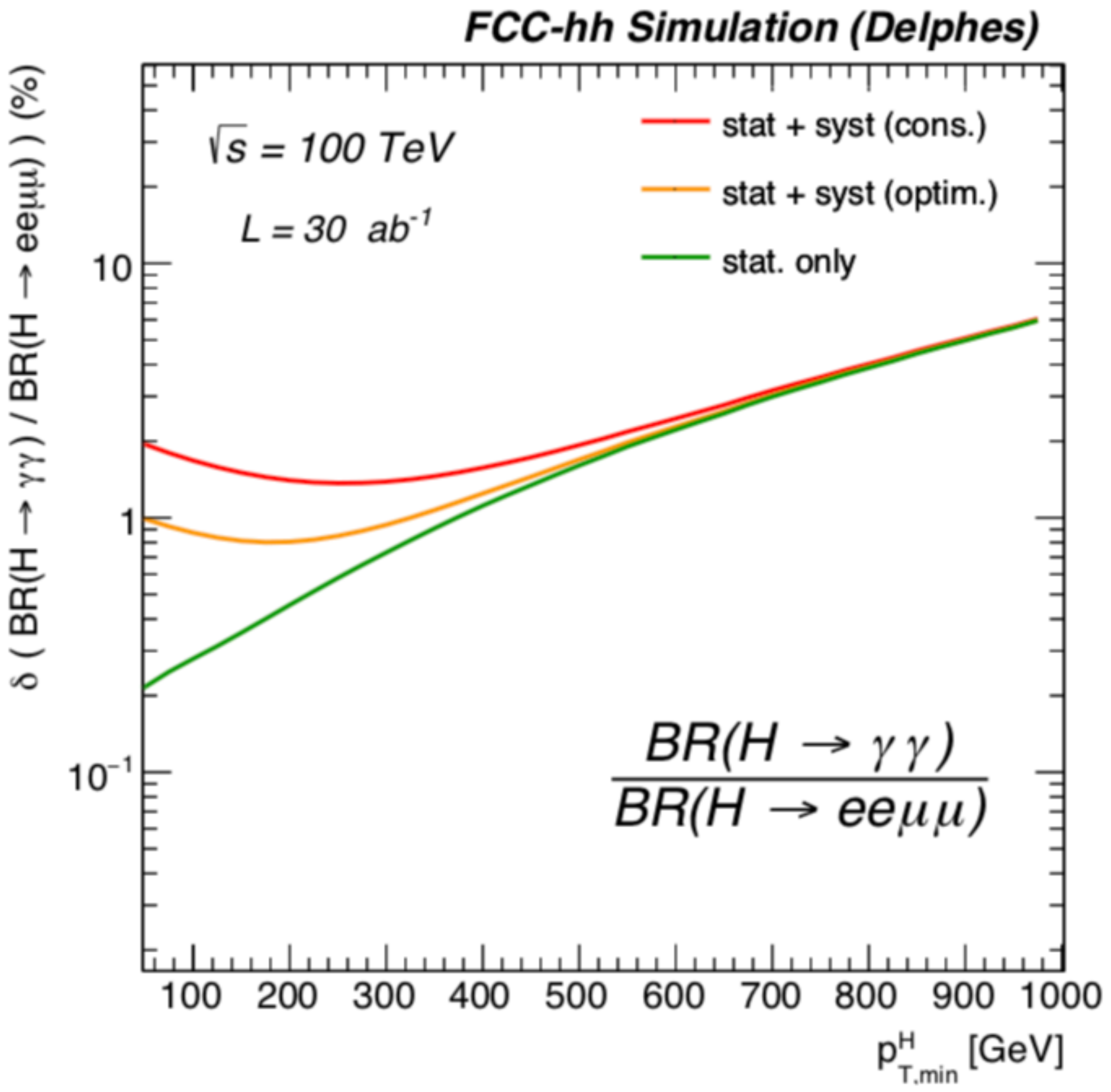




Ratios of BR(H→XX) / BR(H→ZZ)

- measure **ratios of BRs** to cancel correlated sources of systematics:
  - luminosity
  - object efficiencies
  - production cross-section (theory)
- Becomes **absolute precision** measurement in particular if combined with **H→ZZ** measurement from e^+e^- (at 0.2%)

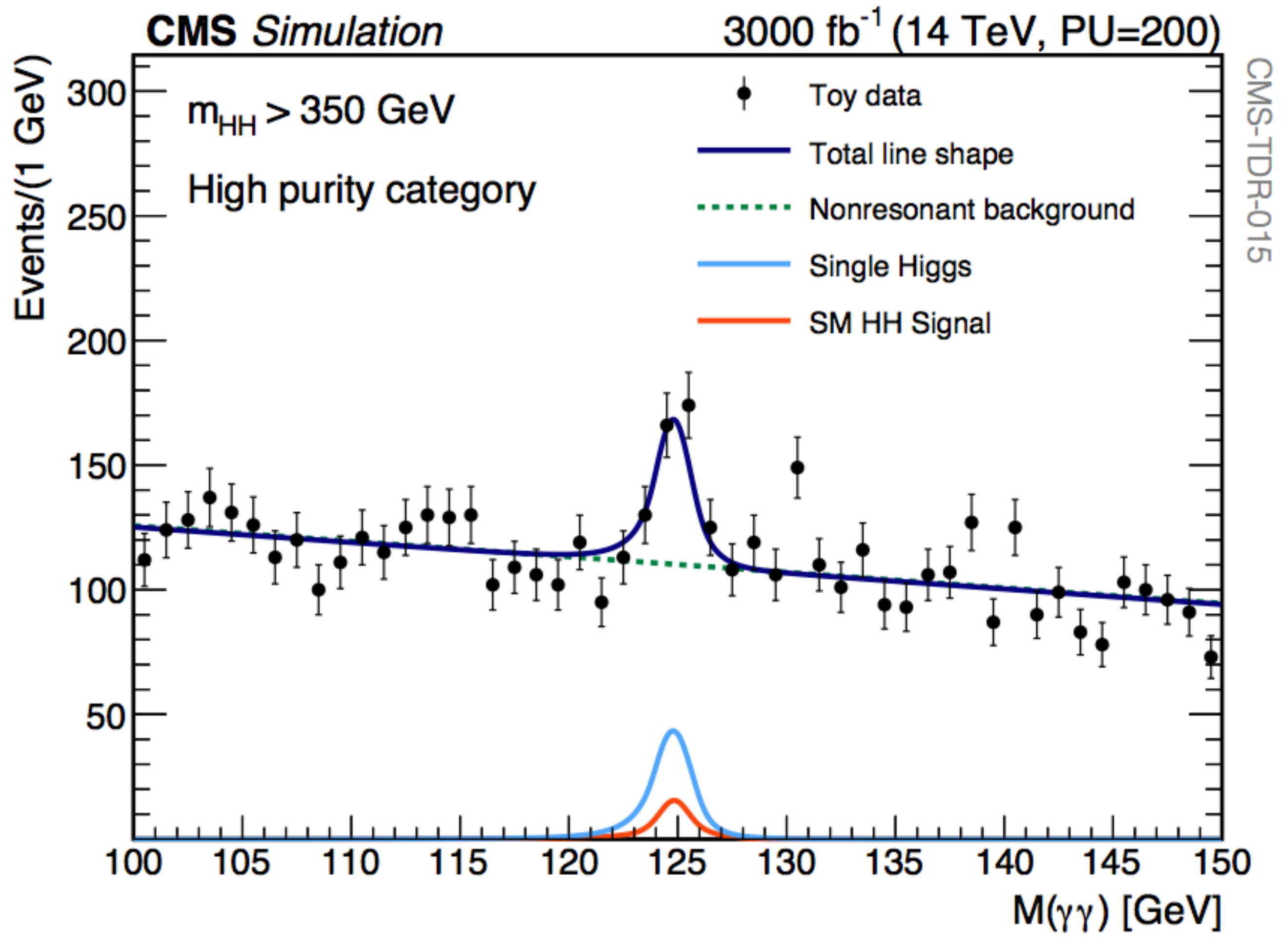




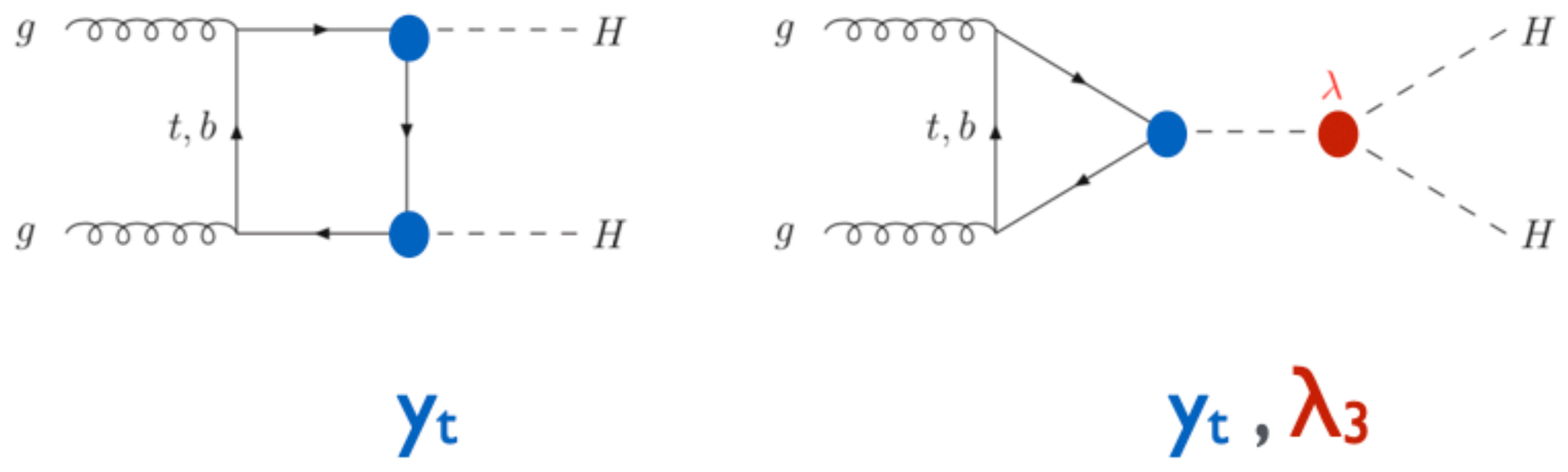
G. Ortona, MS, MLM

Higgs self-coupling

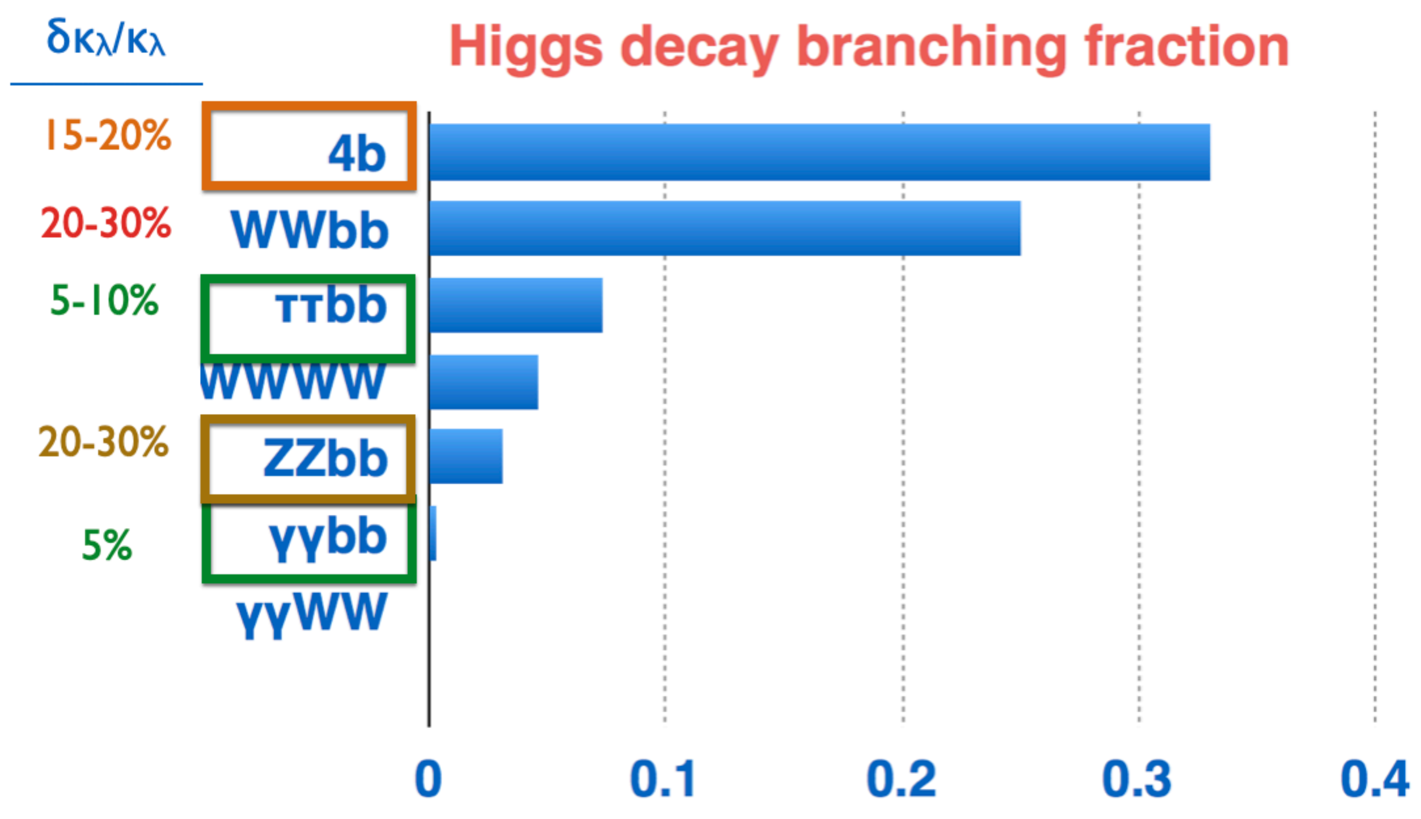
HL-LHC



gluon fusion

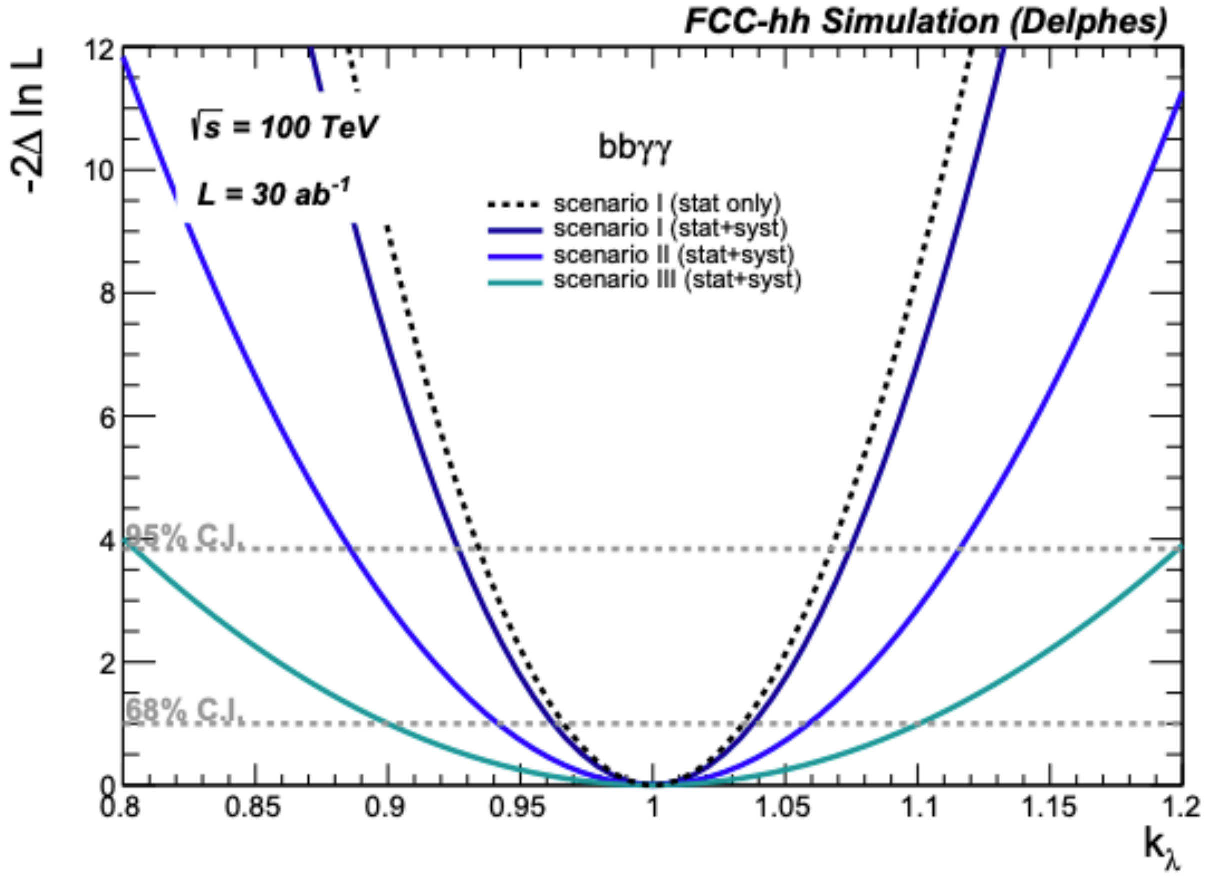


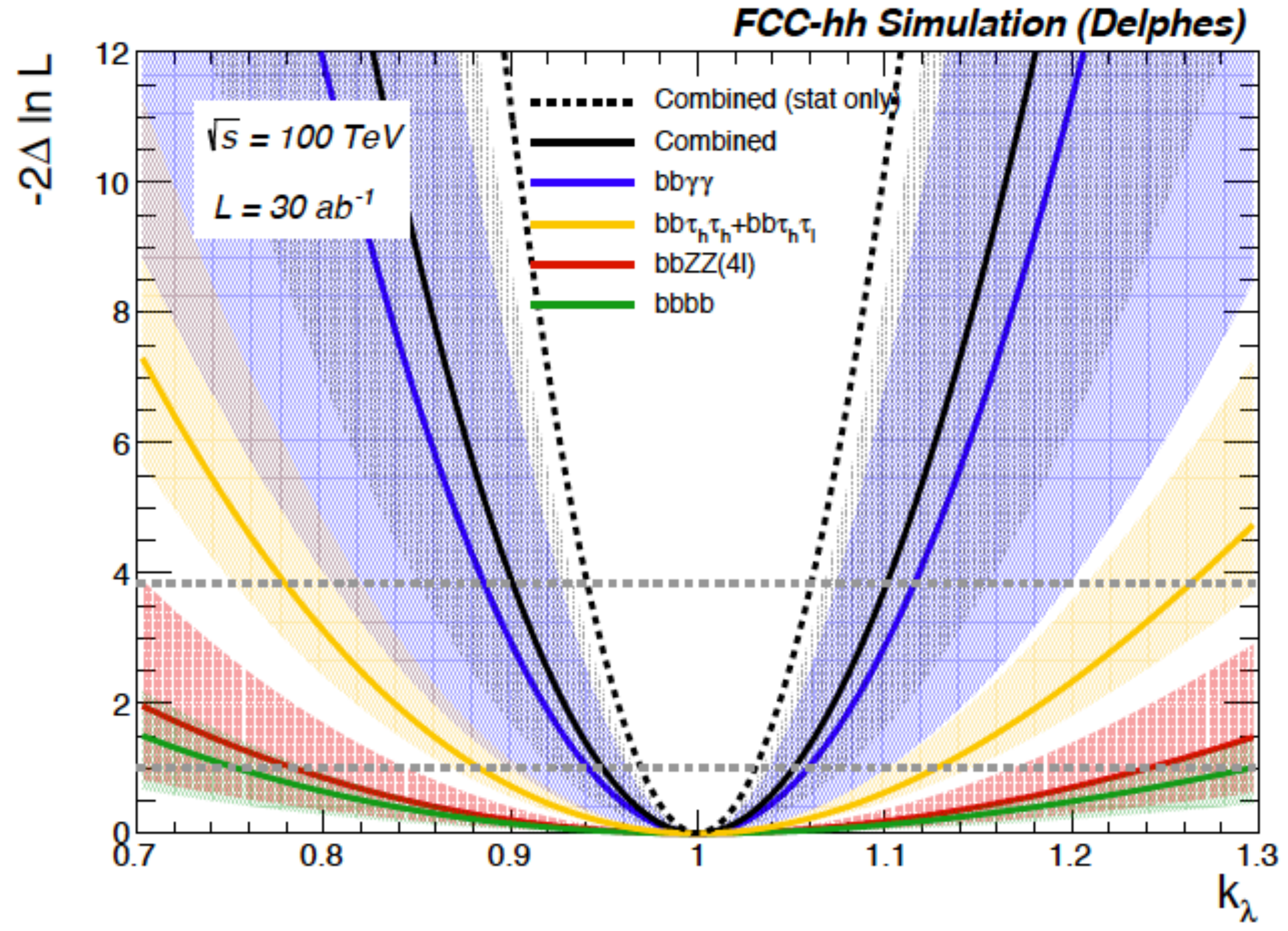
- Very small cross-section due to negative interference with box diagram
- HL-LHC projections : $\delta k_\lambda / k_\lambda \approx 50\%$
- Expect large improvement at FCC-hh:
  - σ(100 TeV)/σ(14 TeV) ≈ 40 (and Lx10)
  - x400 in event yields and x20 in precision
- main channels studied:
  - bbɣɣ (most sensitive - discussed here)
  - bbττ
  - bbZZ(4l)
  - bbbb



Self-coupling at the FCC-hh

2004.03505 [hep-ph]

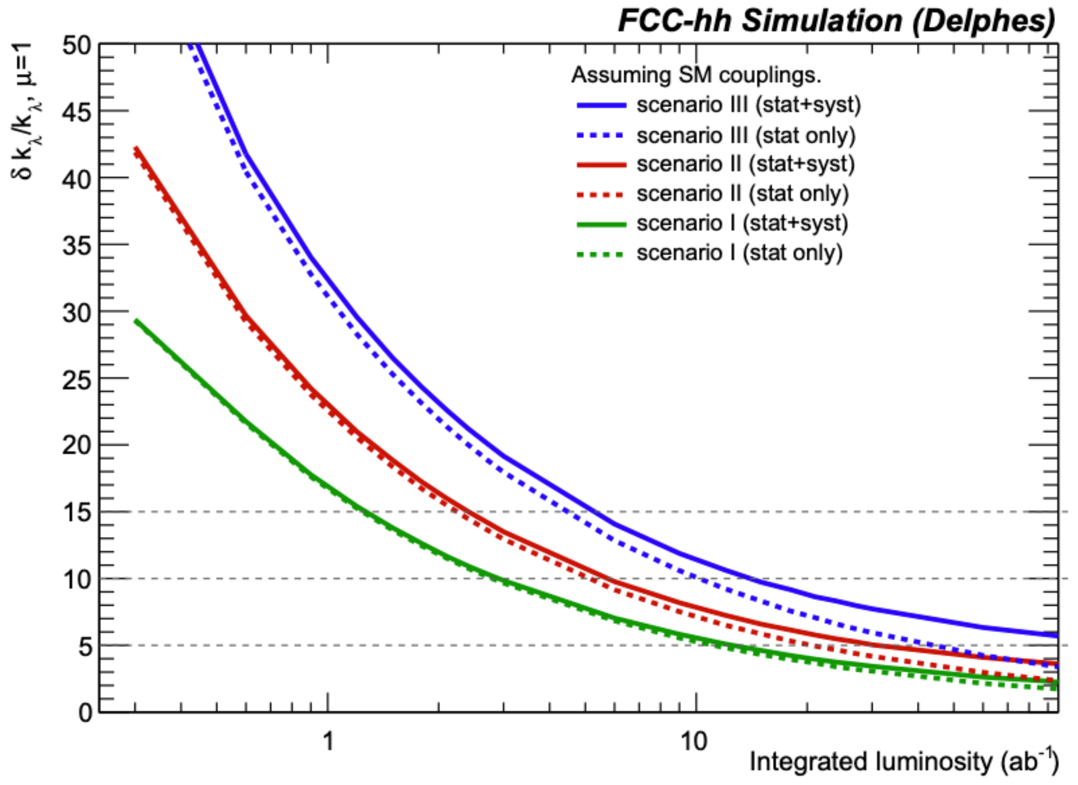


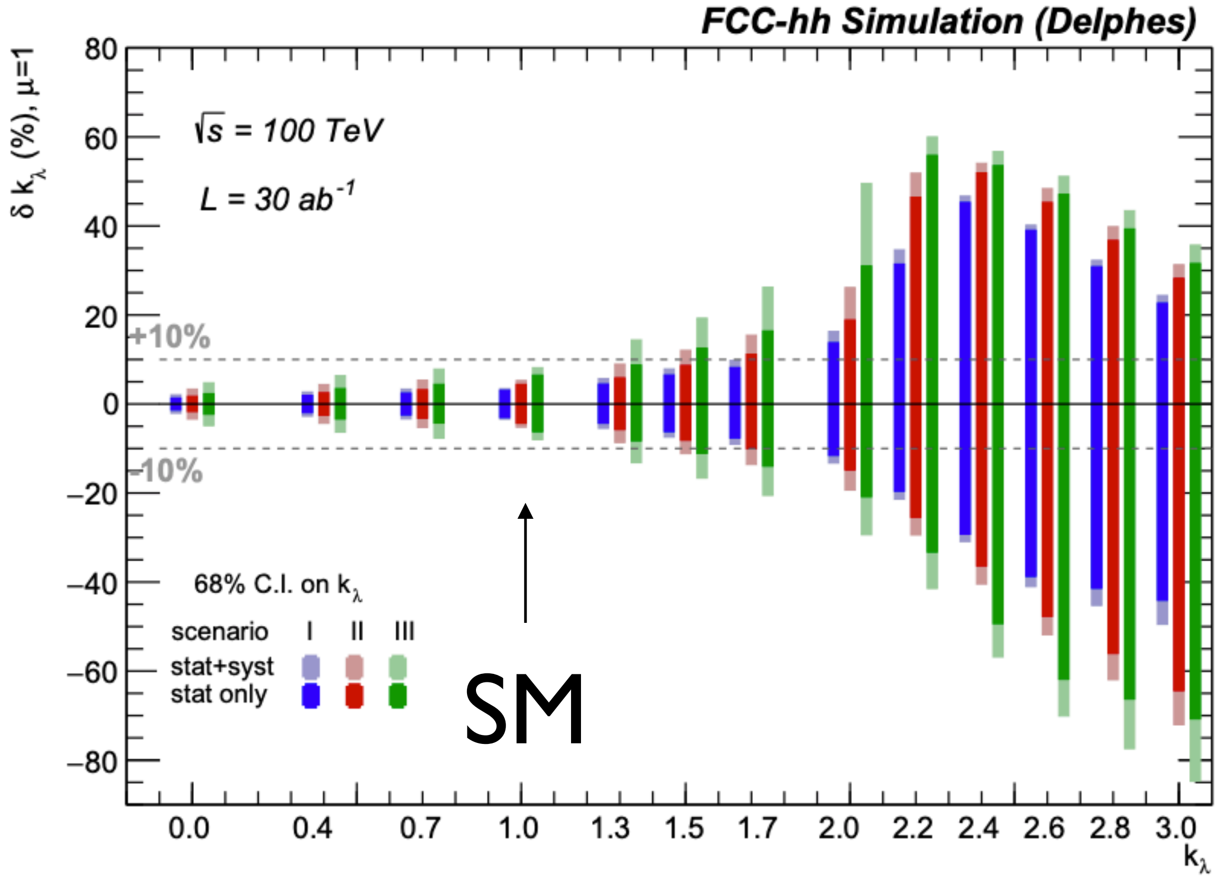


- Expected precision:

@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8

- Combined precision:
  - 3.5-8% for SM (3% stat. only)
  - 10-20% for $\lambda_3 = 1.5 * \lambda_3^{SM}$

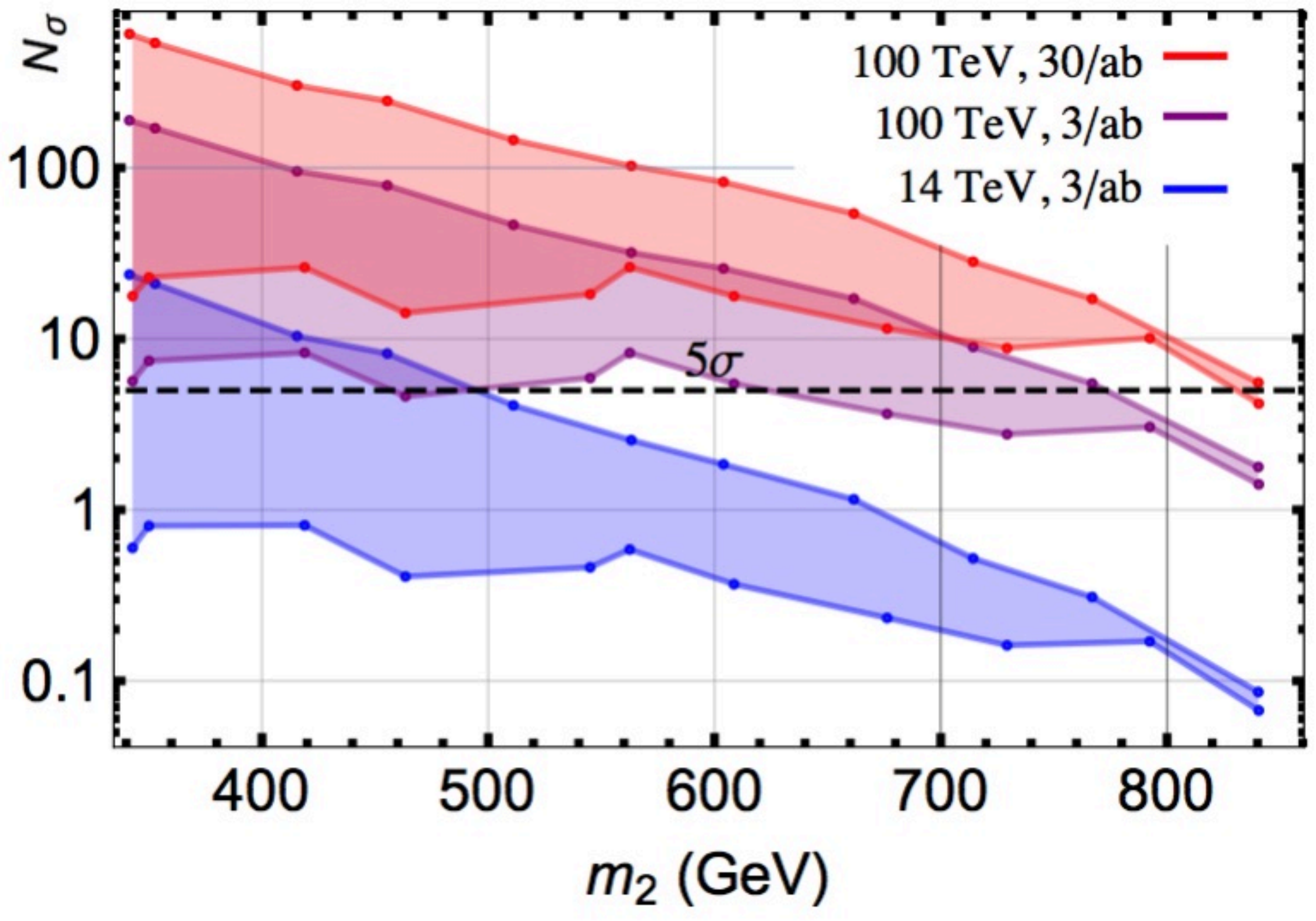




Higgs Self-coupling and constraints on models with 1st order EWPT

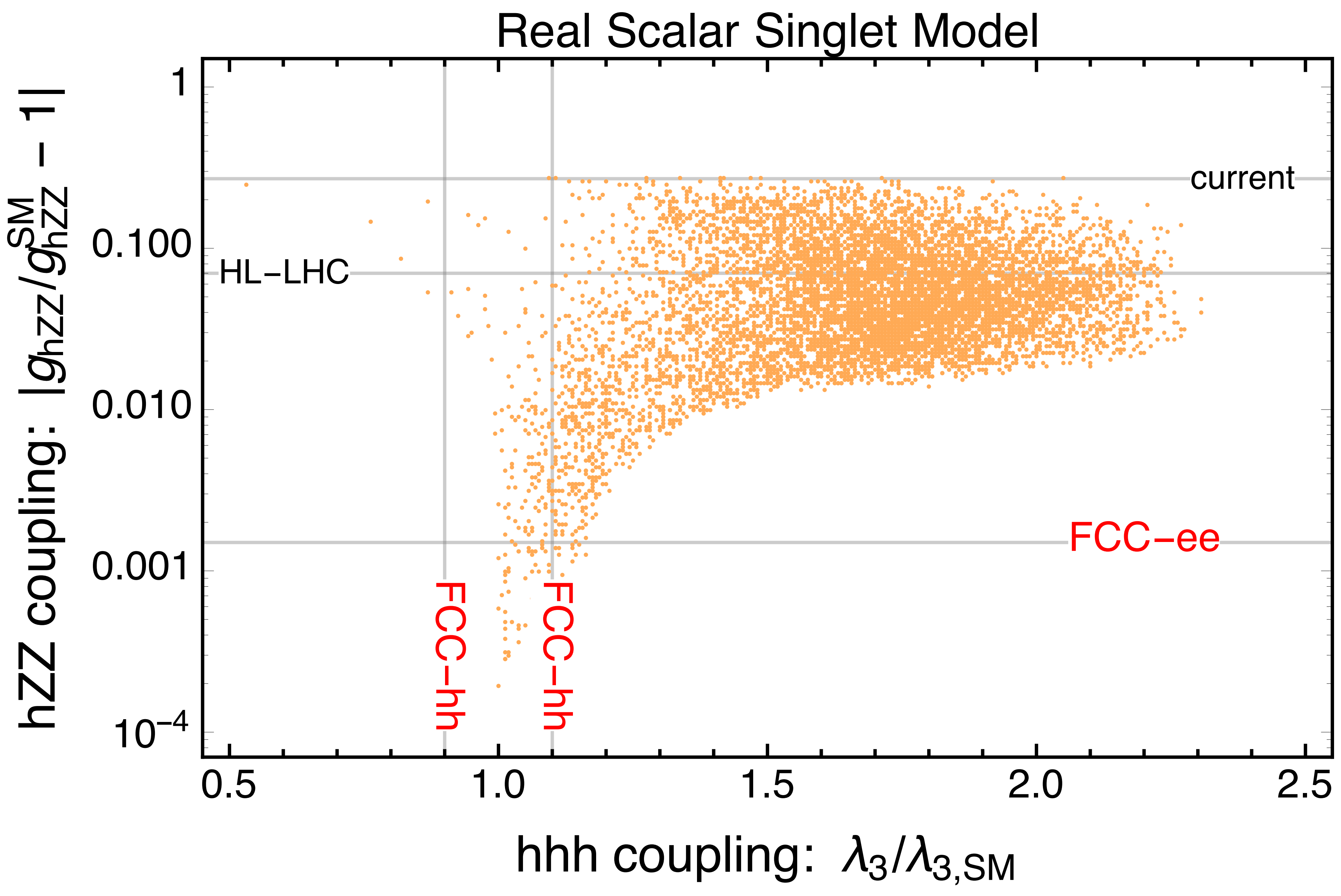
- **Strong 1st order electroweak phase transition** (and CP violation) needed to explain large observed **baryon asymmetry** in our universe
- Can be achieved with extension of SM + singlet

Direct detection of extra Higgs states



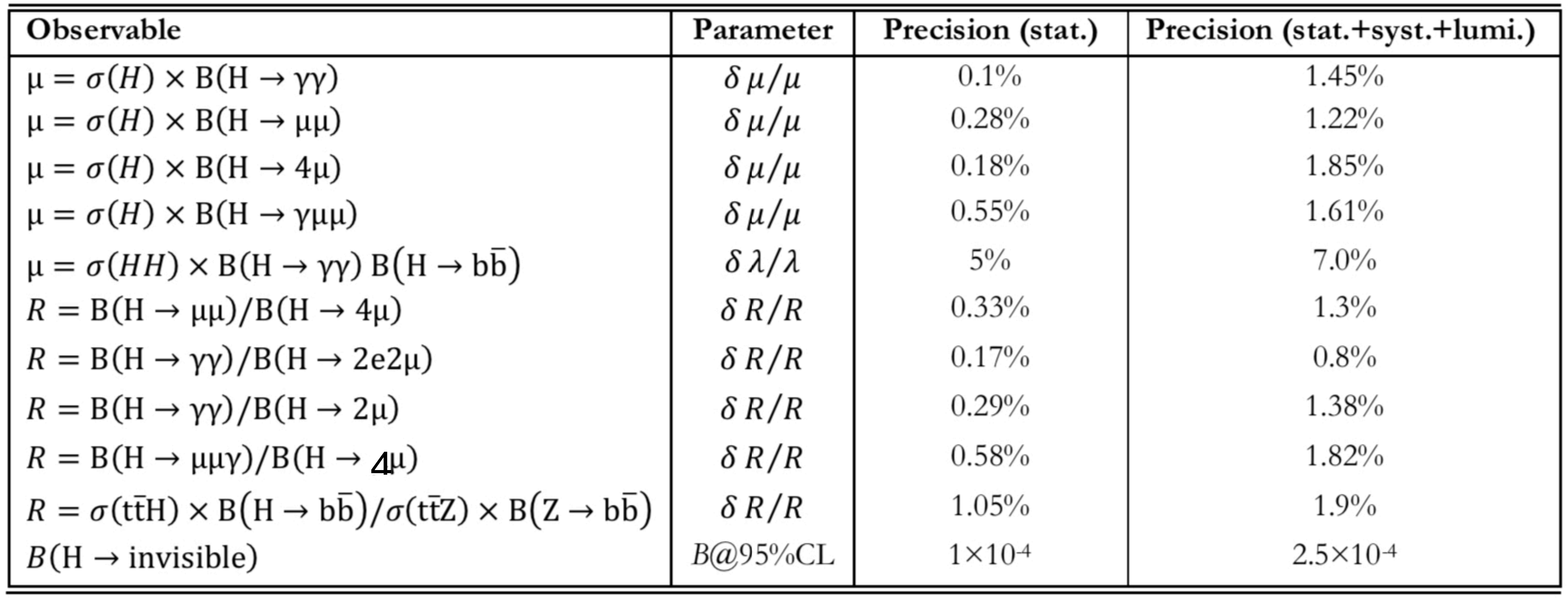
$h_2 \to h_1 h_1 \quad (b\bar{b}\gamma\gamma + 4\tau)$

Combined constraints from precision Higgs measurements at FCC-ee and FCC-hh

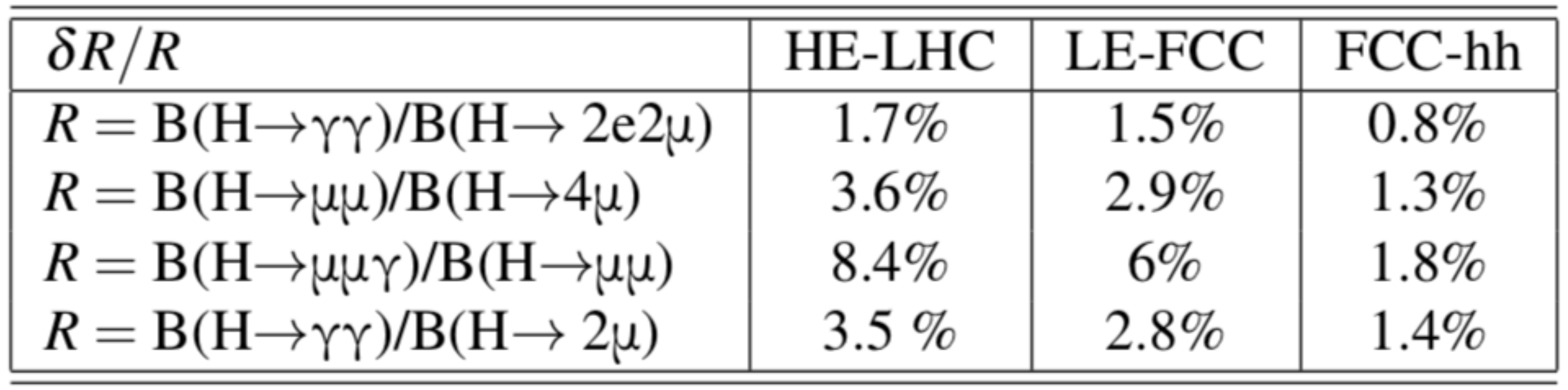


Parameter space scan for a singlet model extension of the Standard Model. The points indicate a first order phase transition.

Summary of Higgs direct measurements



Observable	Parameter	Precision (stat.)	Precision (stat.+syst.+lumi.)
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)\, B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to 4\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}



$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = B(H\to\gamma\gamma)/B(H\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = B(H\to\mu\mu)/B(H\to4\mu)$	3.6%	2.9%	1.3%
$R = B(H\to\mu\mu\gamma)/B(H\to\mu\mu)$	8.4%	6%	1.8%
$R = B(H\to\gamma\gamma)/B(H\to 2\mu)$	3.5 %	2.8%	1.4%

- **Percent level precision on σ x BR** in most rare decay channels achievable only at 100 TeV
- **Percent level precision on couplings** if HZZ coupling known from FCC-ee (to 0.2%)

Summary direct measurements

	HL-LHC	**FCC-ee**	**FCC-hh**
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 $^{(*)}$**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 $^{(*)}$**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95 $^{(**)}$**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.91 $^{(*)}$**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4l) @ FCC-ee

** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Conclusions & outlook

- The integrated FCC program allows for ultimate precision in the Higgs sector
  - Among all proposed future facilities, it is the natural next step for Higgs (and BSM) exploration

- The FCC-ee will produce 1-2 millions Higgs in a clean environment (low systematics):
  - allows for model independent measurement of Higgs couplings
  - exquisite precision in "abundant" Higgs decay channels (<1%)
    - Hints of strange Yukawa and electron Yukawa might be possible

- The FCC-hh will produce 20B Higgs and 30M Higgs pairs
  - In synergy with the FCC-ee will provide percent level precision on most Higgs couplings
    - very rare decays (H→μμ, Zɣ)
    - ttH (with ttZ from FCC-ee)
  - <5% on the Higgs self-coupling

- Still much to be done:
  - CP, Width at FCC-ee

FCC Higgs/Top group

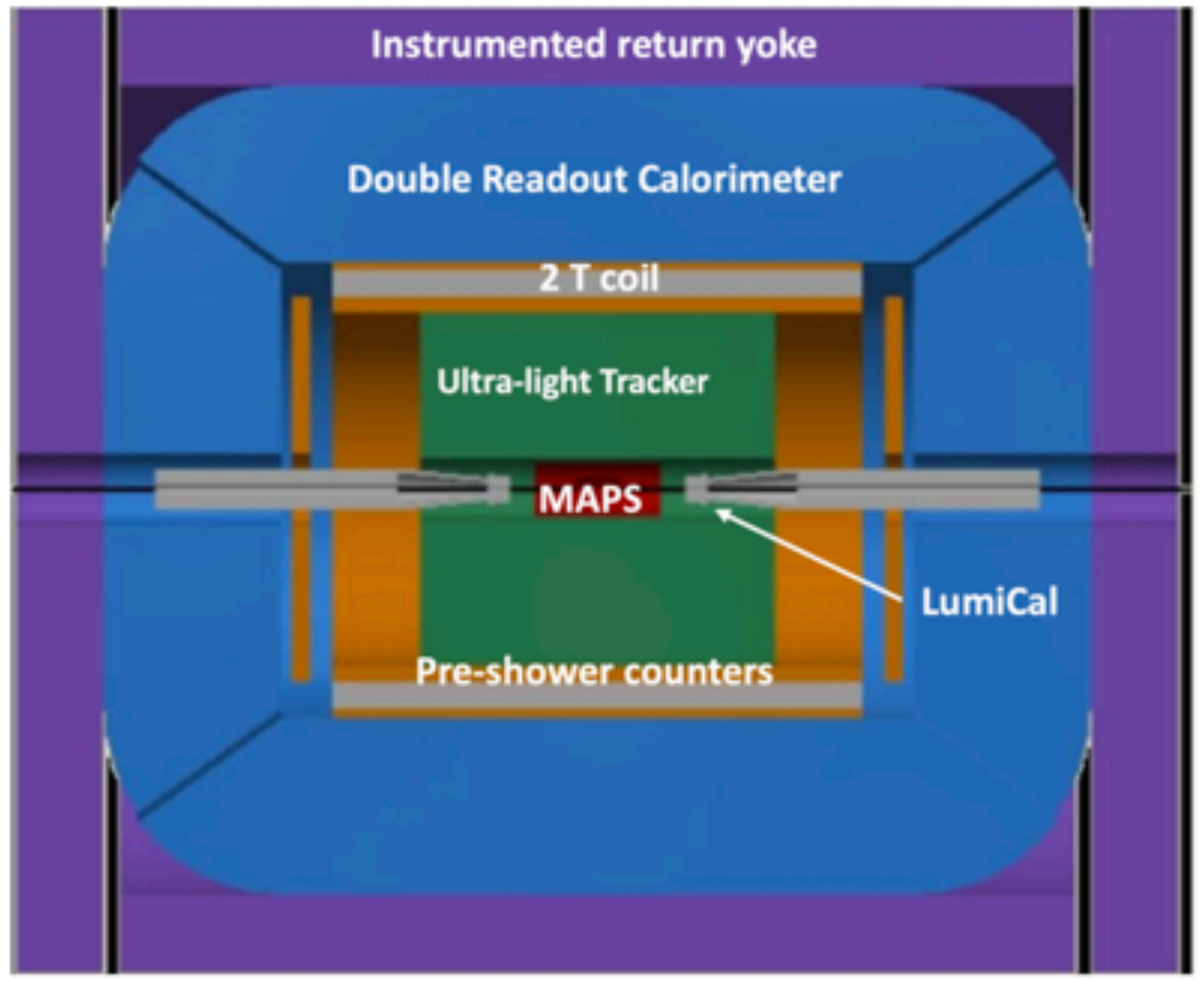
Exp: MS, J. Eysermans
TH: Gauthier Durieux, Jorge De Bras, Christophe Grojeam

FCC-PED-PhysicsGroup-Higgs@cern.ch

Backup

FCC-ee detector modeling

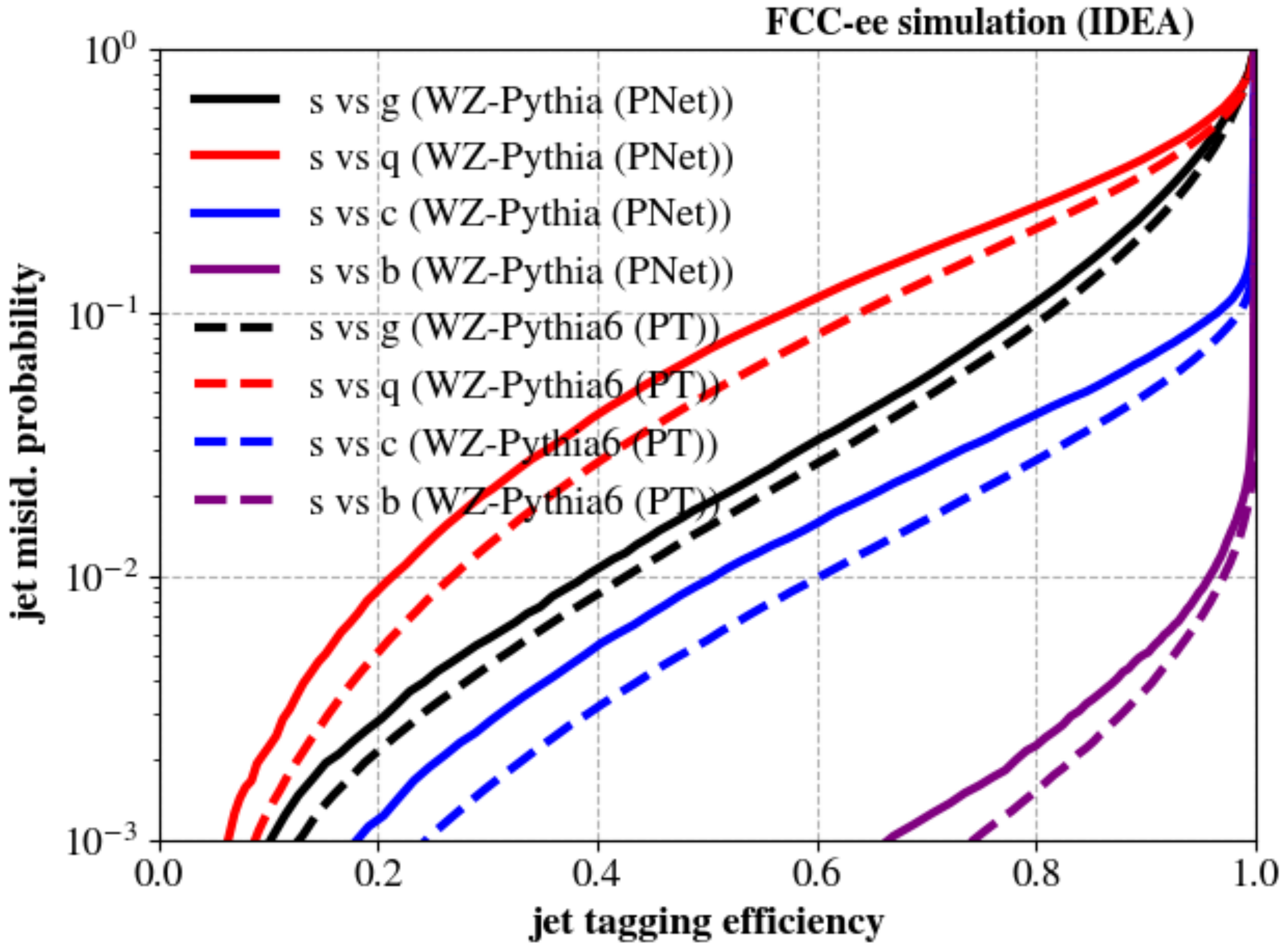
- Detector simulation baseline:
  - IDEA with Delphes
    - full track covariance reconstruction
    - particle ID (timing, charged energy loss)
    - jet tagging using Weaver/Particle NET
      - Flavors: g/b/c/s/light/tau



IDEA

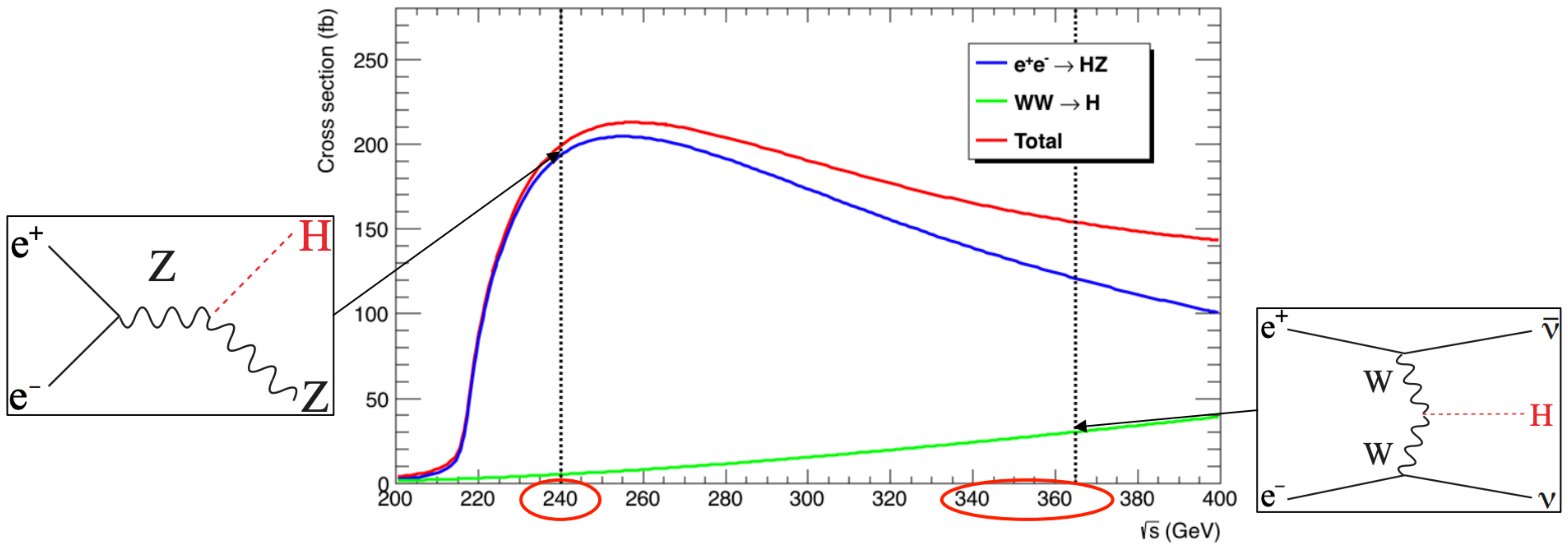
- Recent updates:
  - “Realistic” electron description
    - including brem recovery
  - smaller beampipe
  - ECAL crystal for better ele/photon performance

- Samples:
  - Wizard3+ Pythia6
  - Pythia8



http://fcc-physics-events.web.cern.ch/fcc-physics-events/FCCee/winter2023/Delphesevents_IDEA.php

FCC-ee Higgs couplings (part II)



WW fusion added value

- vvH → vvbb ~ $g_W^2 g_b^2 / \Gamma_H$
  - vvbb / (ZH(bb) ZH(WW) ~ $g_Z^4 / \Gamma_H = R$
    - Γ_H precision at 1%
- Then do vvH →vvWW ~ g_W^4 / Γ_H
  - R / vvWW ~ g_W^4 / g_Z^4
    - g_W precision to few permil

Running at the top does not simply add statistics
it exploits complementary production mode to improve constraints

BR expected precision with 2 IPs

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma \mathrm{BR})/\sigma \mathrm{BR}$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
H → any	±0.5		±0.9	
H → $b\bar{b}$	±0.3	±3.1	±0.5	±0.9
H → $c\bar{c}$	±2.2		±6.5	±10
H → gg	±1.9		±3.5	±4.5
H → W^+W^-	±1.2		±2.6	±3.0
H → ZZ	±4.4		±12	±10
H → $\tau\tau$	±0.9		±1.8	±8
H → $\gamma\gamma$	±9.0		±18	±22
H → $\mu^+\mu^-$	±19		±40	
H → invis.	< 0.3		< 0.6	

For 4 IPs, expect:
x 1.7 luminosity / statistics
x 1.3 in expected precision

Abundant statistics and high precision for:
- bb/cc/gg/WW

Limited for:
- rare decays μμ,ɣɣ, Zɣ
- HH

Higgs mass/cross-section measurements

Jan Eysermans

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$

$\Delta r \sim \ln(m_H)$
$\Delta r \sim m_t^2$
$\Delta r \sim$ new physics?

- Why measure Higgs mass:
  - input for the EW precision fit
  - O(10 MeV) need for permil precision of g_Z, g_W, $g_{Z\gamma}$
  - O(Γ_H = 4 MeV) to measure electron Yukawa

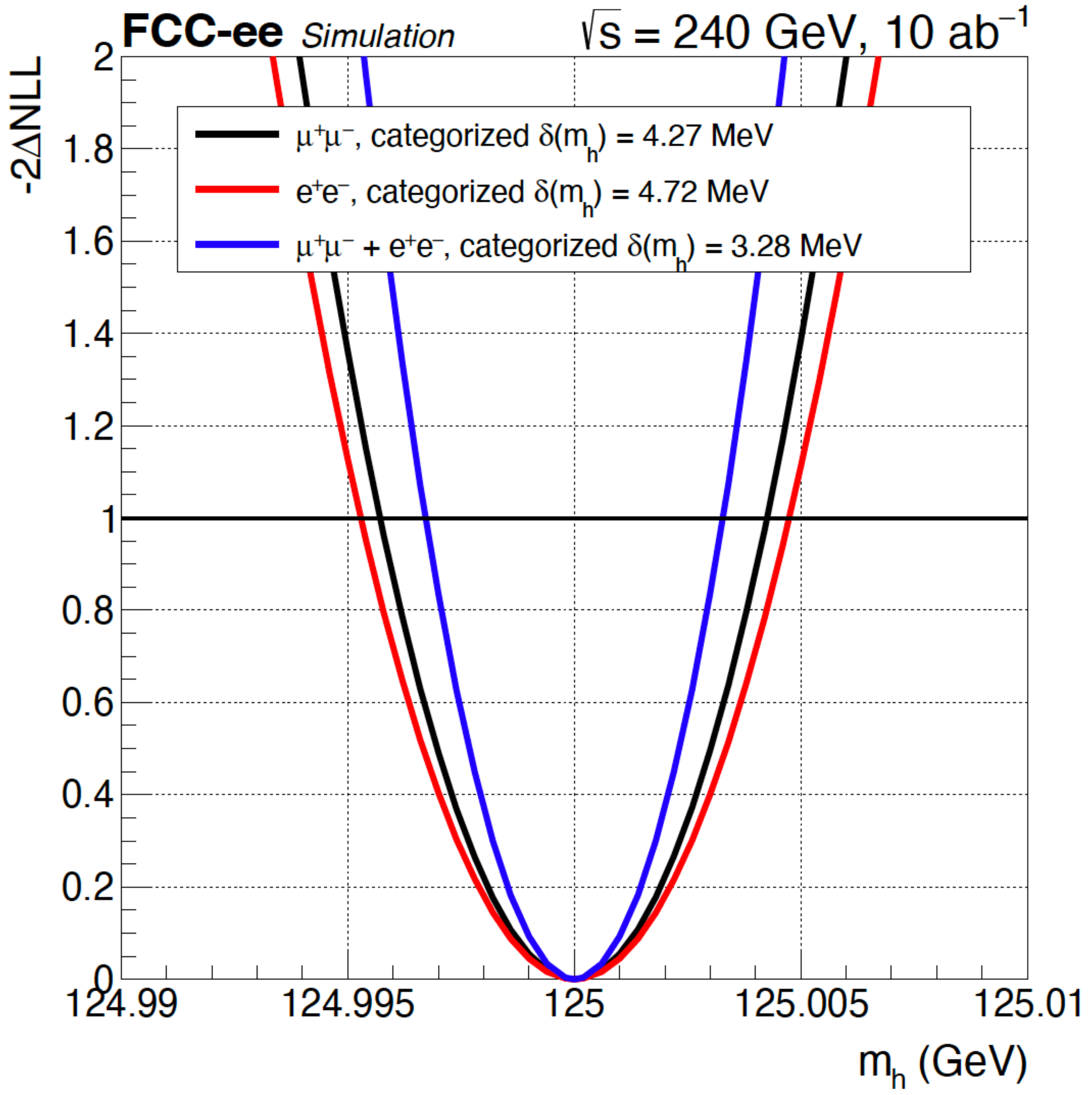
Event selection (common with sec):

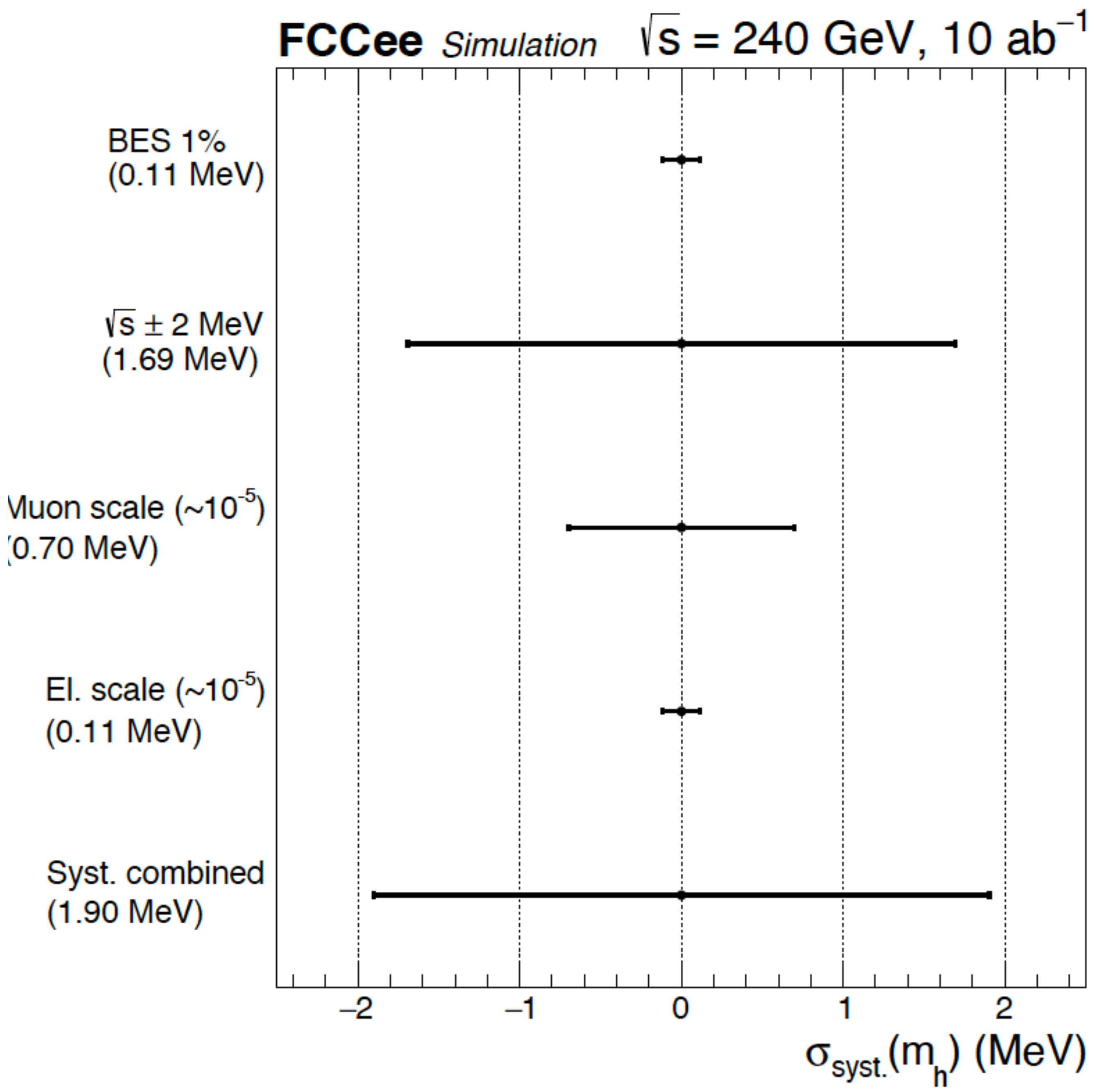
- at least 2 leptons
- tight m_Z selection [86,96] GeV
- $p(\mu\mu) > 20,70$ GeV
- measurement differential in θ

Systematics:

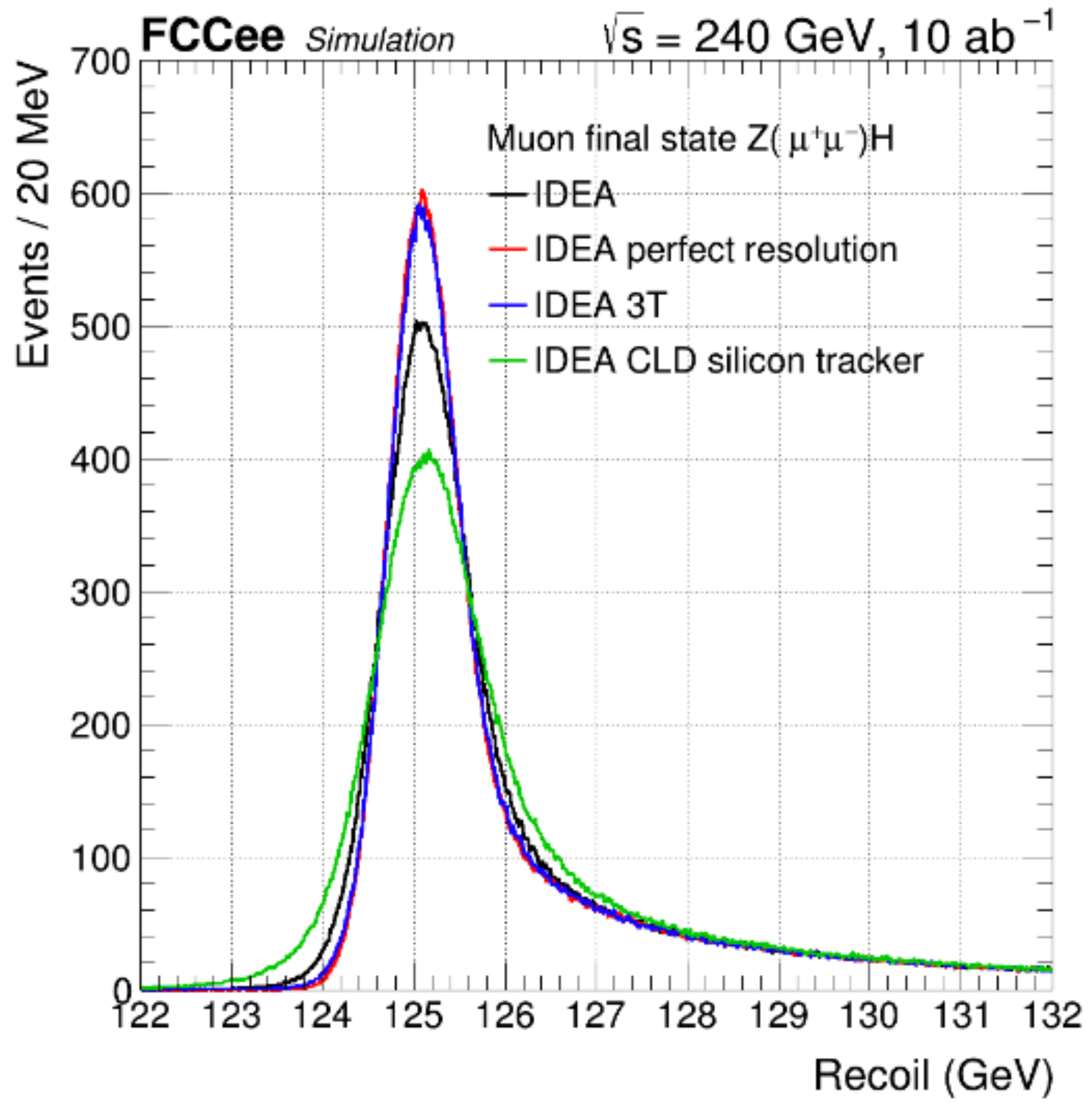
- Beam energy spread ~ **2e-03 (~200 MeV)**
- C.O.M energy ~ **2e-05 (~2 MeV)**
- Lepton scale ~ **2e-05**
- ISR ~ t.b.d

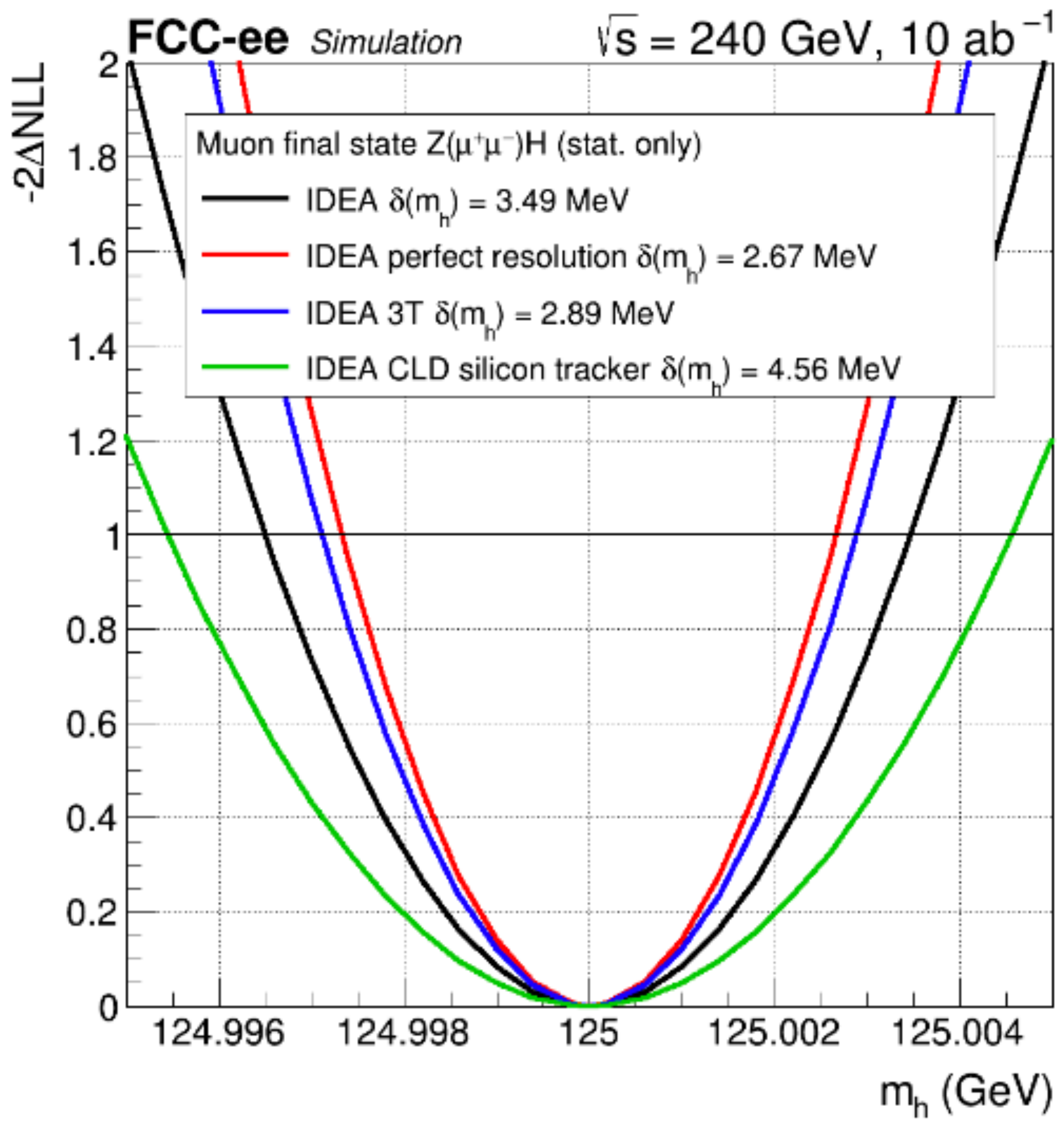
in situ from ee→ffγ events





Higgs mass measurement (detector sensitivity)



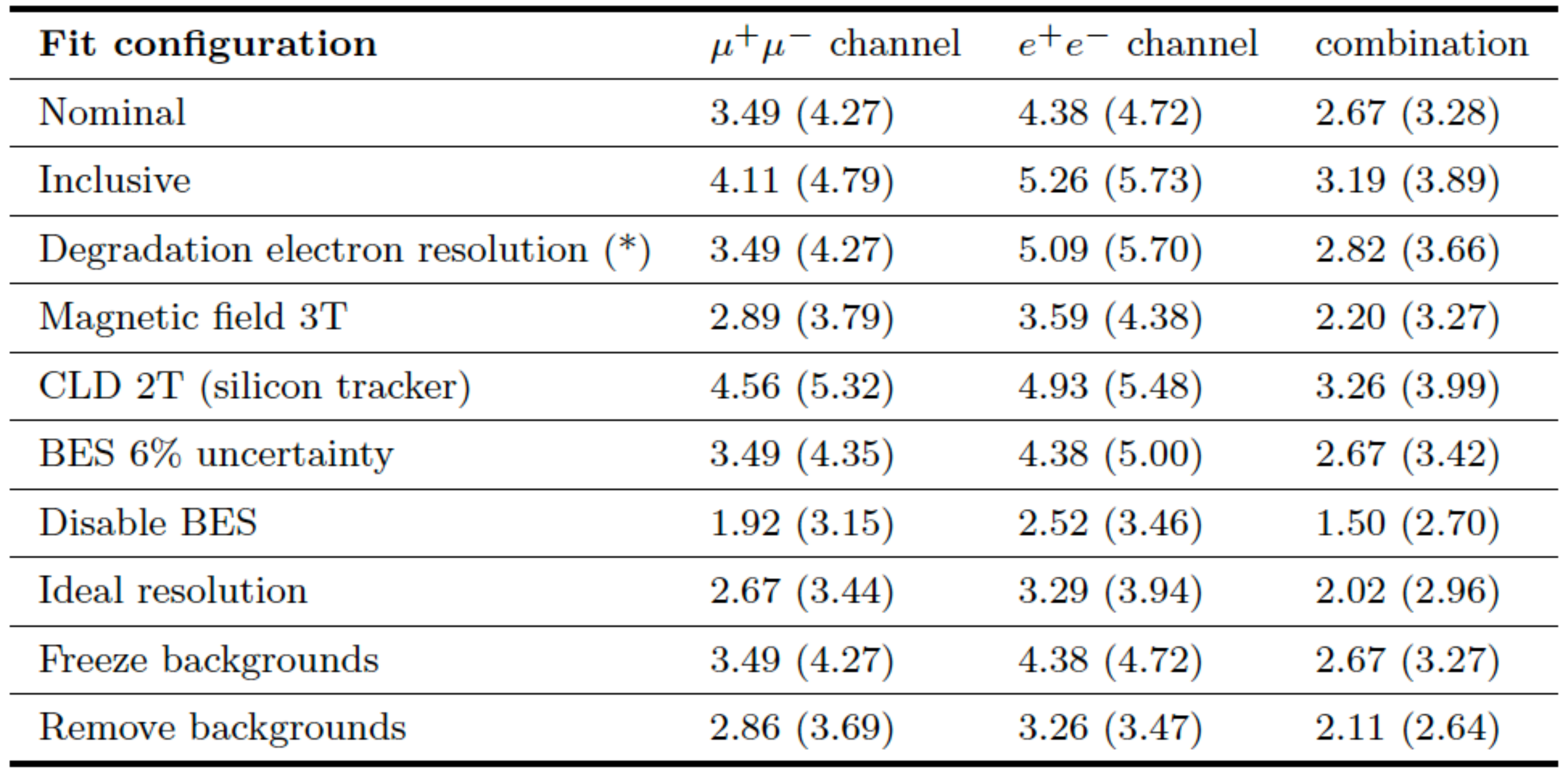


using μμ channel

tracking system	Δm_H (MeV) stat.only	Δm_H (MeV) stat + syst
IDEA 2T	**3.49**	**4.27**
Perfect	**2.67**	**3.44**
IDEA 3T	**2.89**	**3.97**
CLD 2T	**4.56**	**5.32**

~100 MeV
in ATLAS/CMS

- sensitivity dominated by the Z(μμ) final state
  - superior momentum resolution, driven by **tracking**
- track momentum resolution limits sensitivity if > beam energy spread (BES = 0.182% at 240 GeV, i.e 222 MeV)
  - multiple-scattering limit < BES
    - for CLD ~ 30% above
      - **transparent** tracker is key



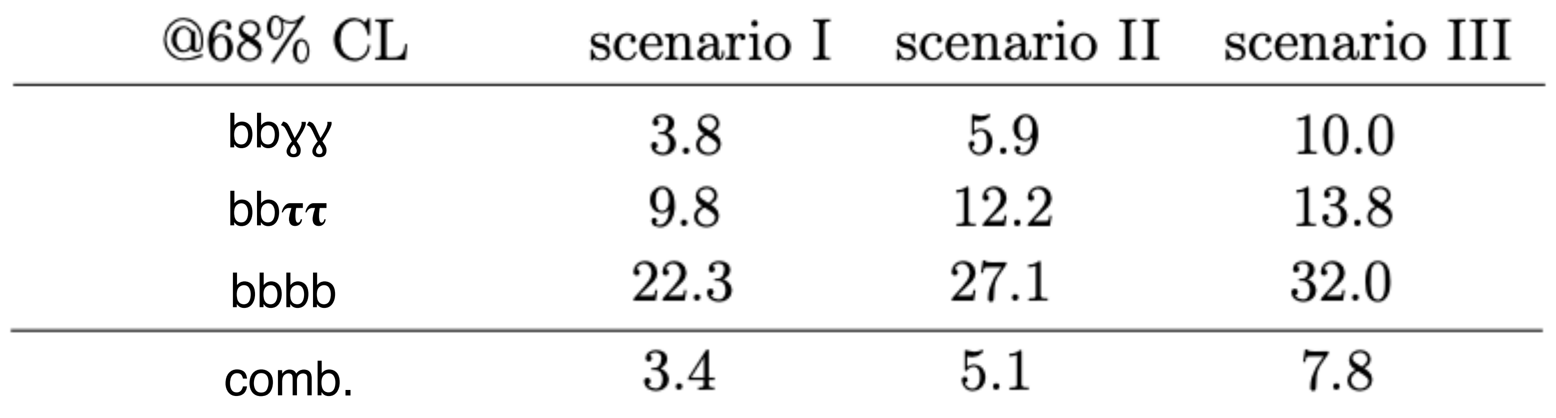
Fit configuration	$\mu^+\mu^-$ channel	e^+e^- channel	combination
Nominal	3.49 (4.27)	4.38 (4.72)	2.67 (3.28)
Inclusive	4.11 (4.79)	5.26 (5.73)	3.19 (3.89)
Degradation electron resolution (*)	3.49 (4.27)	5.09 (5.70)	2.82 (3.66)
Magnetic field 3T	2.89 (3.79)	3.59 (4.38)	2.20 (3.27)
CLD 2T (silicon tracker)	4.56 (5.32)	4.93 (5.48)	3.26 (3.99)
BES 6% uncertainty	3.49 (4.35)	4.38 (5.00)	2.67 (3.42)
Disable BES	1.92 (3.15)	2.52 (3.46)	1.50 (2.70)
Ideal resolution	2.67 (3.44)	3.29 (3.94)	2.02 (2.96)
Freeze backgrounds	3.49 (4.27)	4.38 (4.72)	2.67 (3.27)
Remove backgrounds	2.86 (3.69)	3.26 (3.47)	2.11 (2.64)

Higgs self-coupling

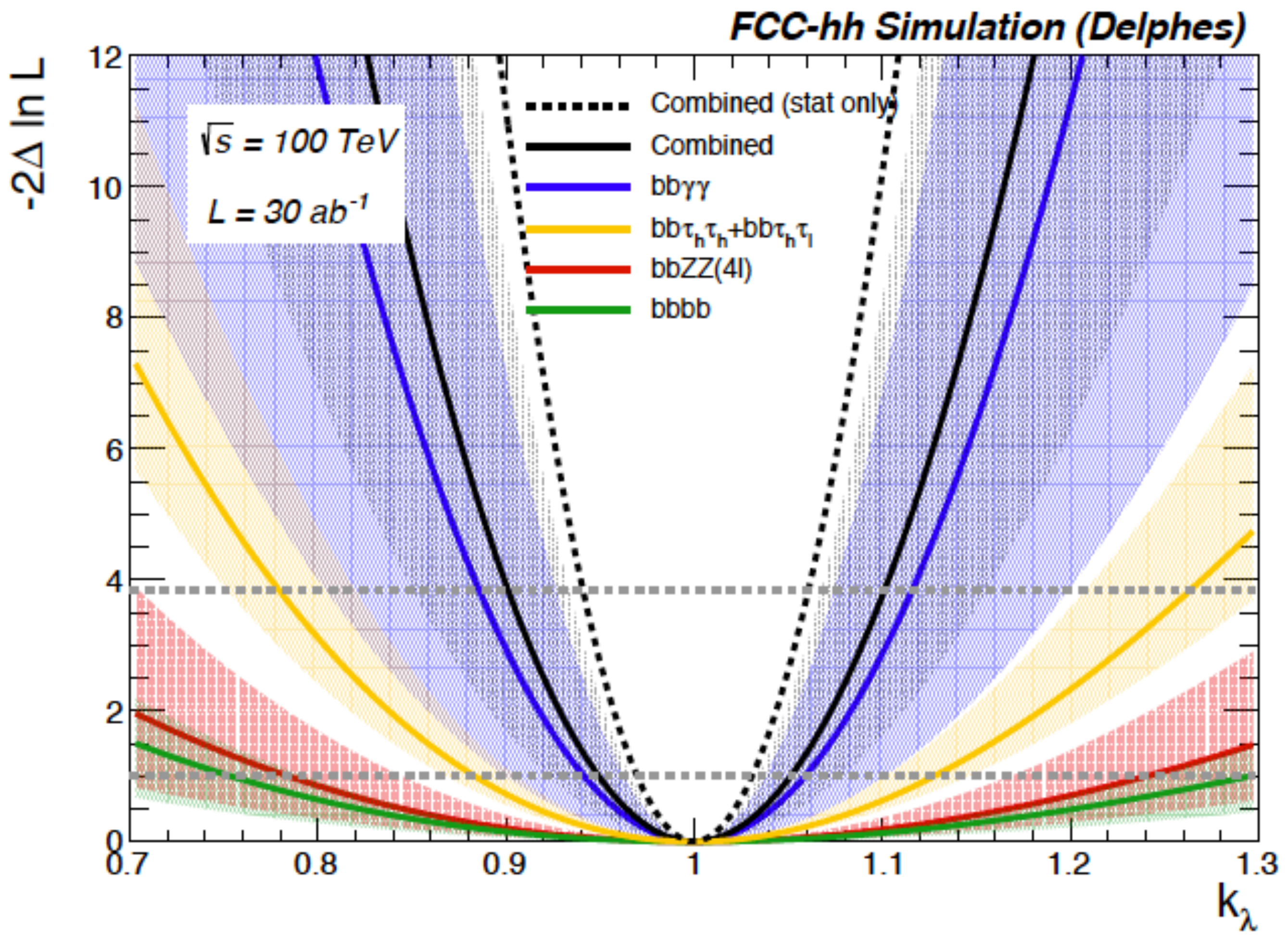
Salerno, Portales

FCC-ee:
from radiative corrections to ZH/VBF single H production
($\sqrt{s}$=240, 365 GeV)

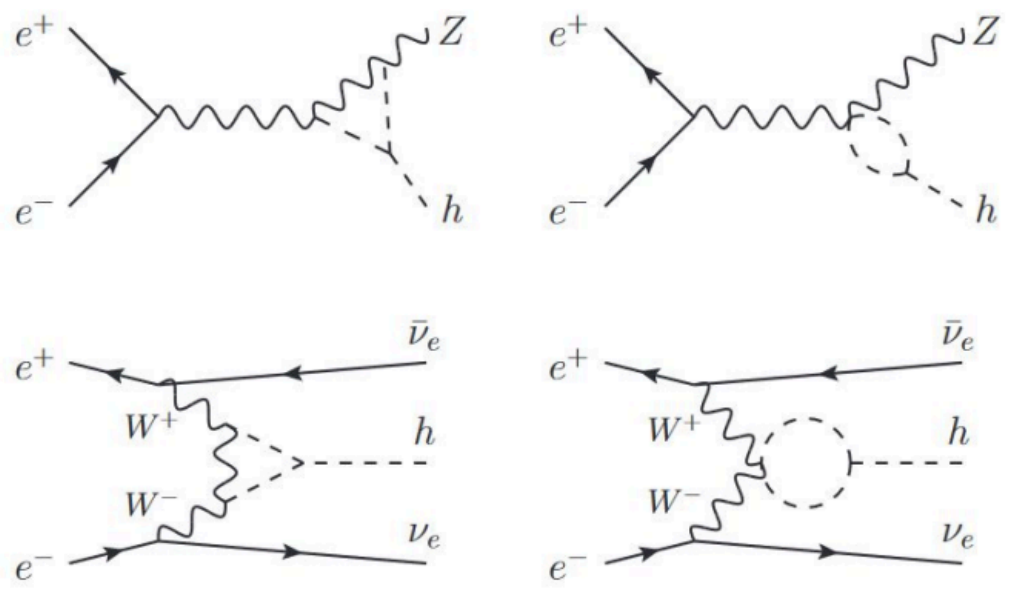
%-level precision only at the FCC-hh

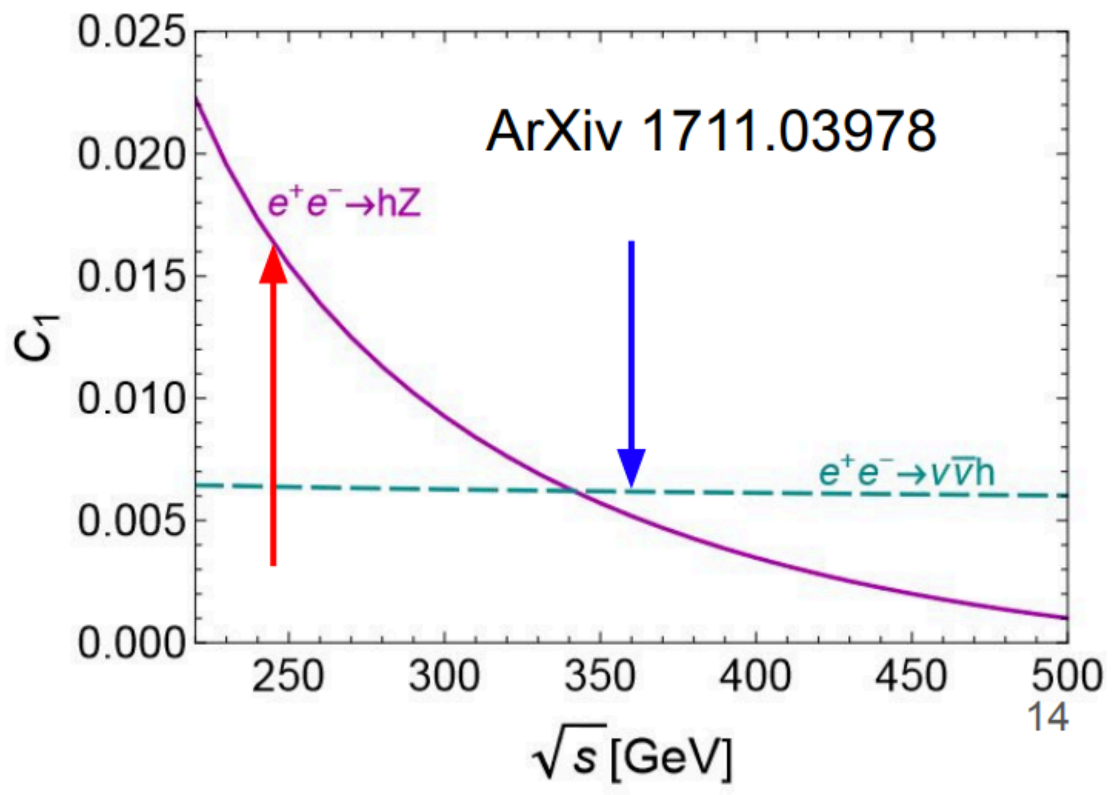


@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8

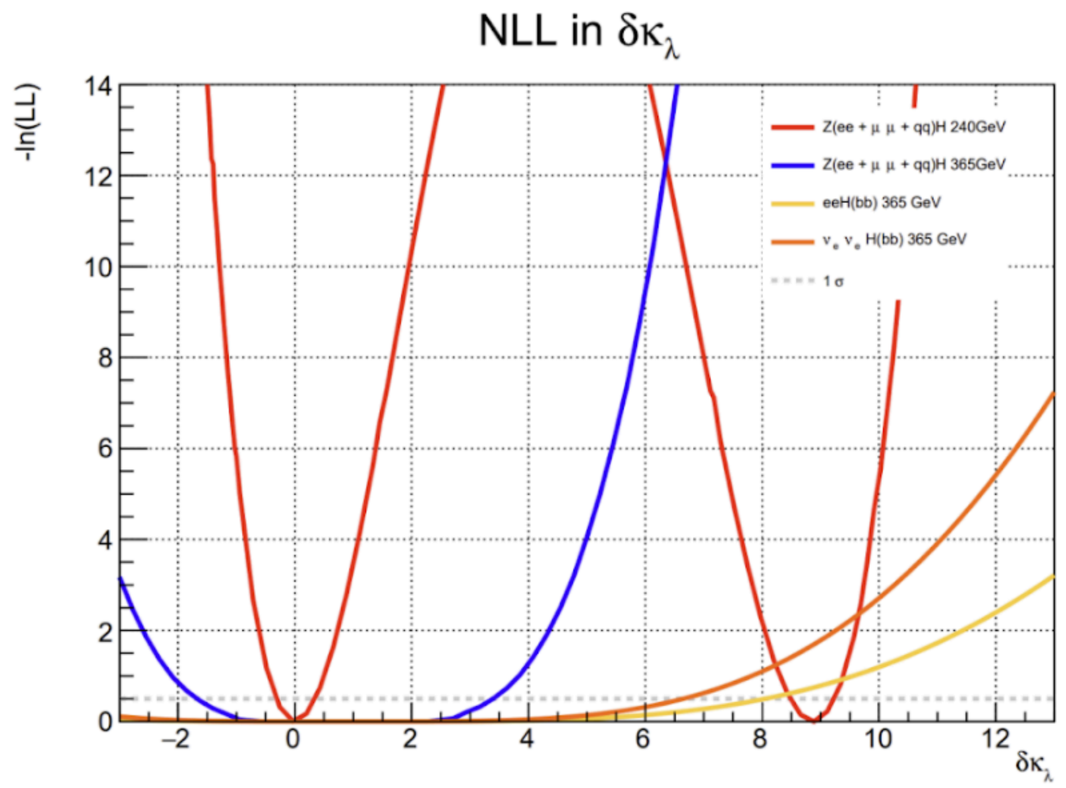


New effort started (new channel/extended parameter space/ revisited detector performance)





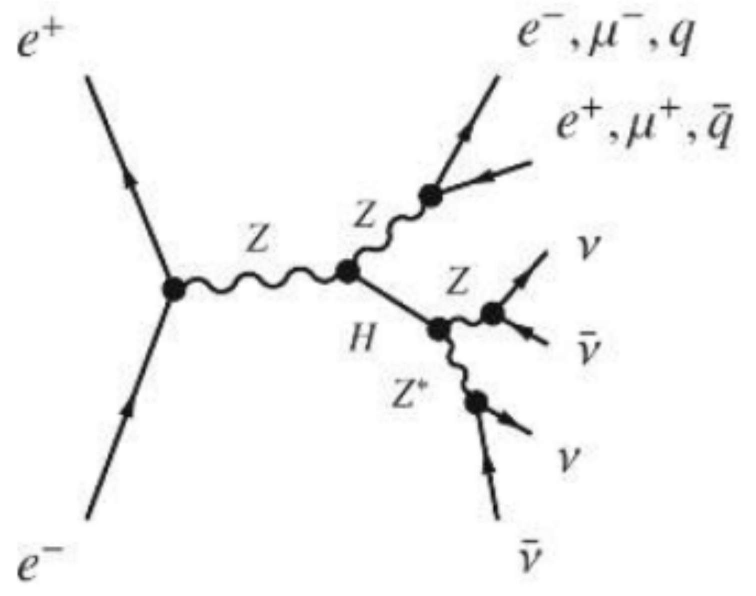
experimental analysis

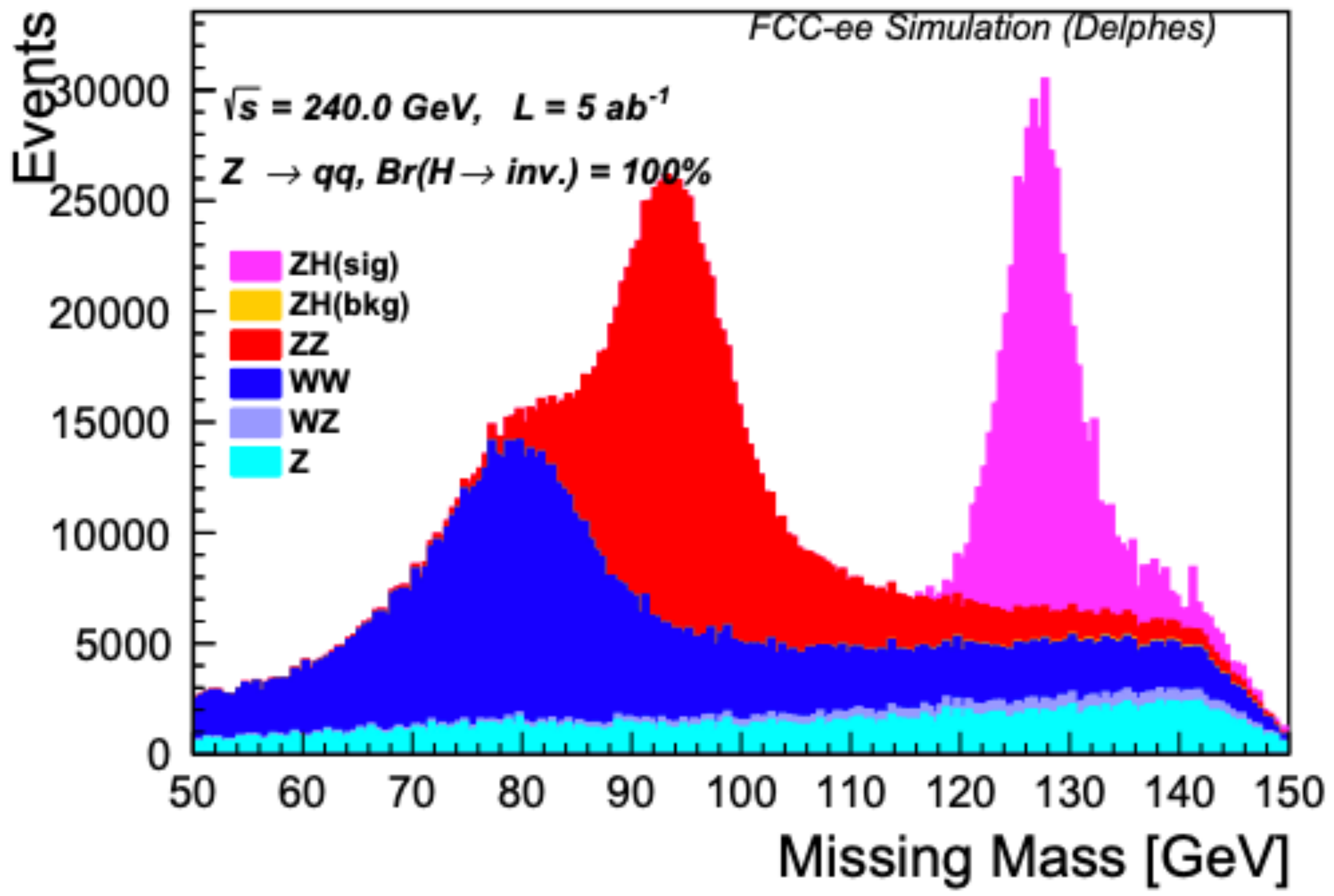


- state of the art fit to self-coupling precision:
  - 19% κλ alone vs 33% full (EFT projected) with 2IPs
  - 14% κλ alone vs 24% full (EFT projected) with 4IPs

Higgs to invisible

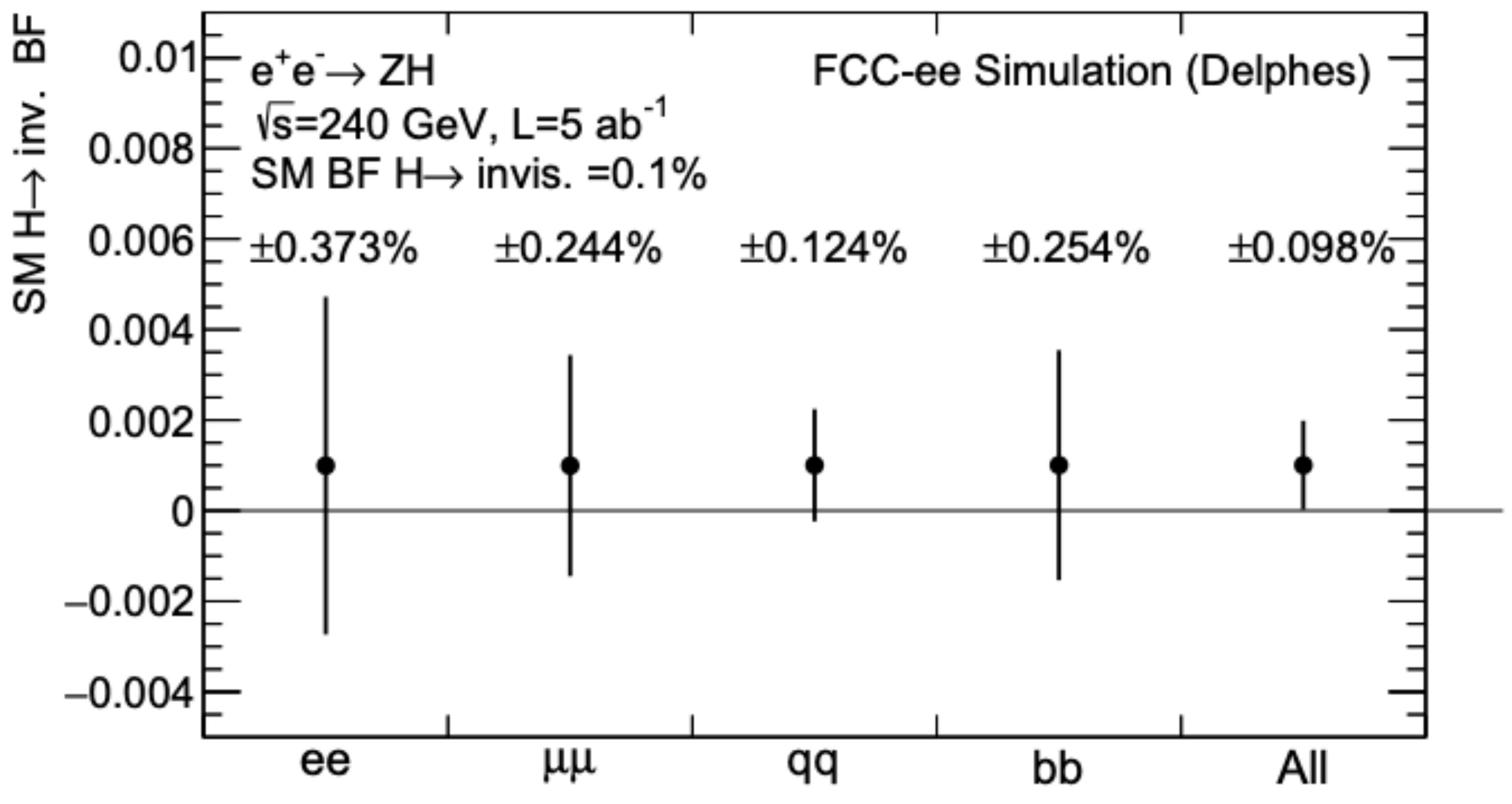
Mehta, Rompotis





- Higgs could be a portal to dark matter or other new physics
- In the SM B(H→inv) ~ 10^{-3}
- Use recoil method to reconstruct the Higgs
  - potential to improve 1 order of magnitude compared to LHC

- Event selection:
  - Split events into exactly 2e, 2μ and 0 e+μ (bb/qq)
  - Reconstruct Z from 2 leptons or M_{vis}
  - Reconstruct M_{miss} from all visible particles
  - Use distribution of M_{miss} in likelihood fit



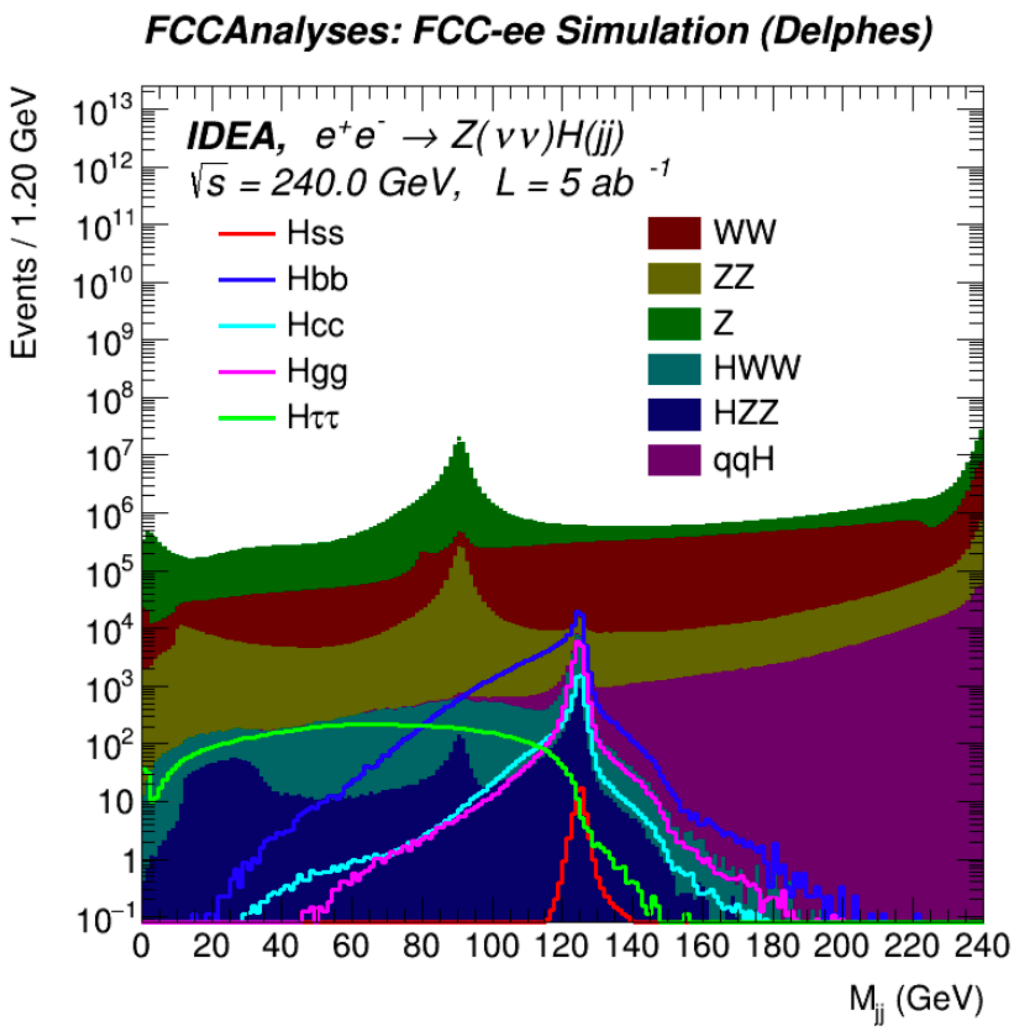
~ 100% sensitivity on SM BR(H→inv)

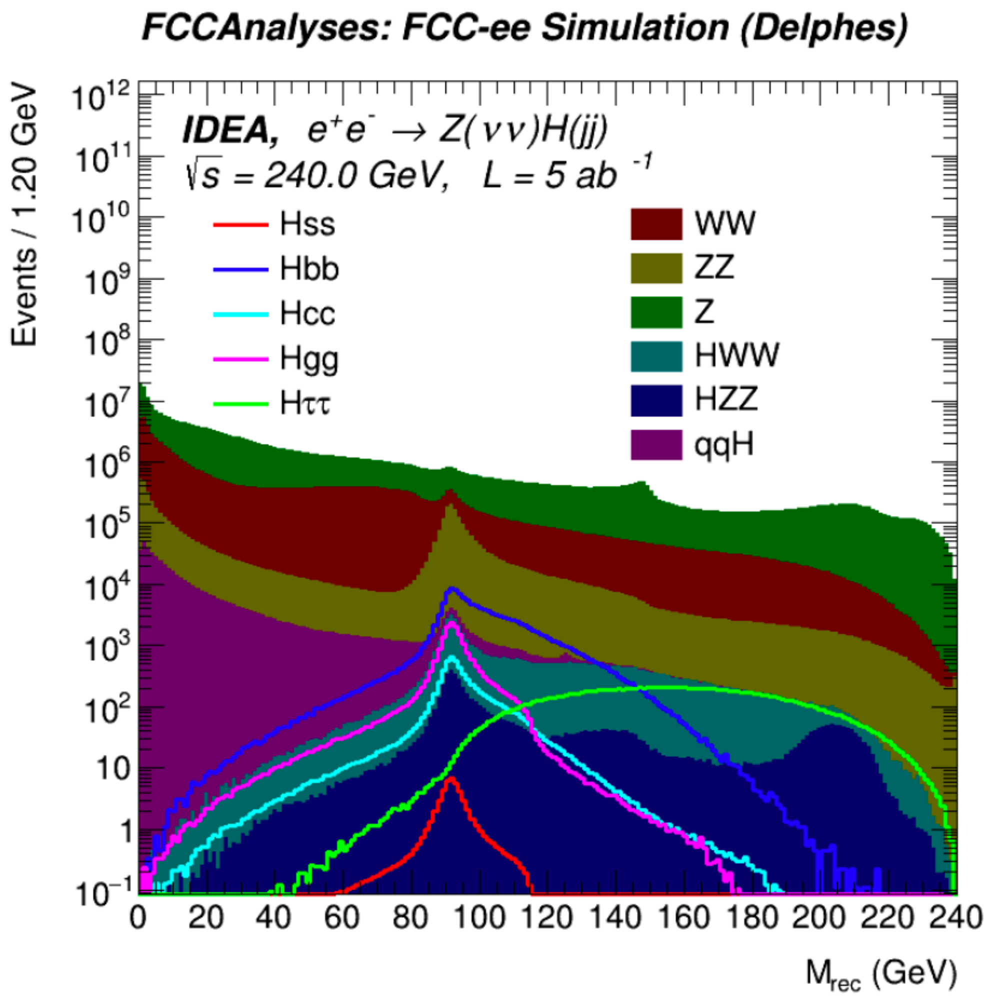
Higgs to hadrons (Z(vv))

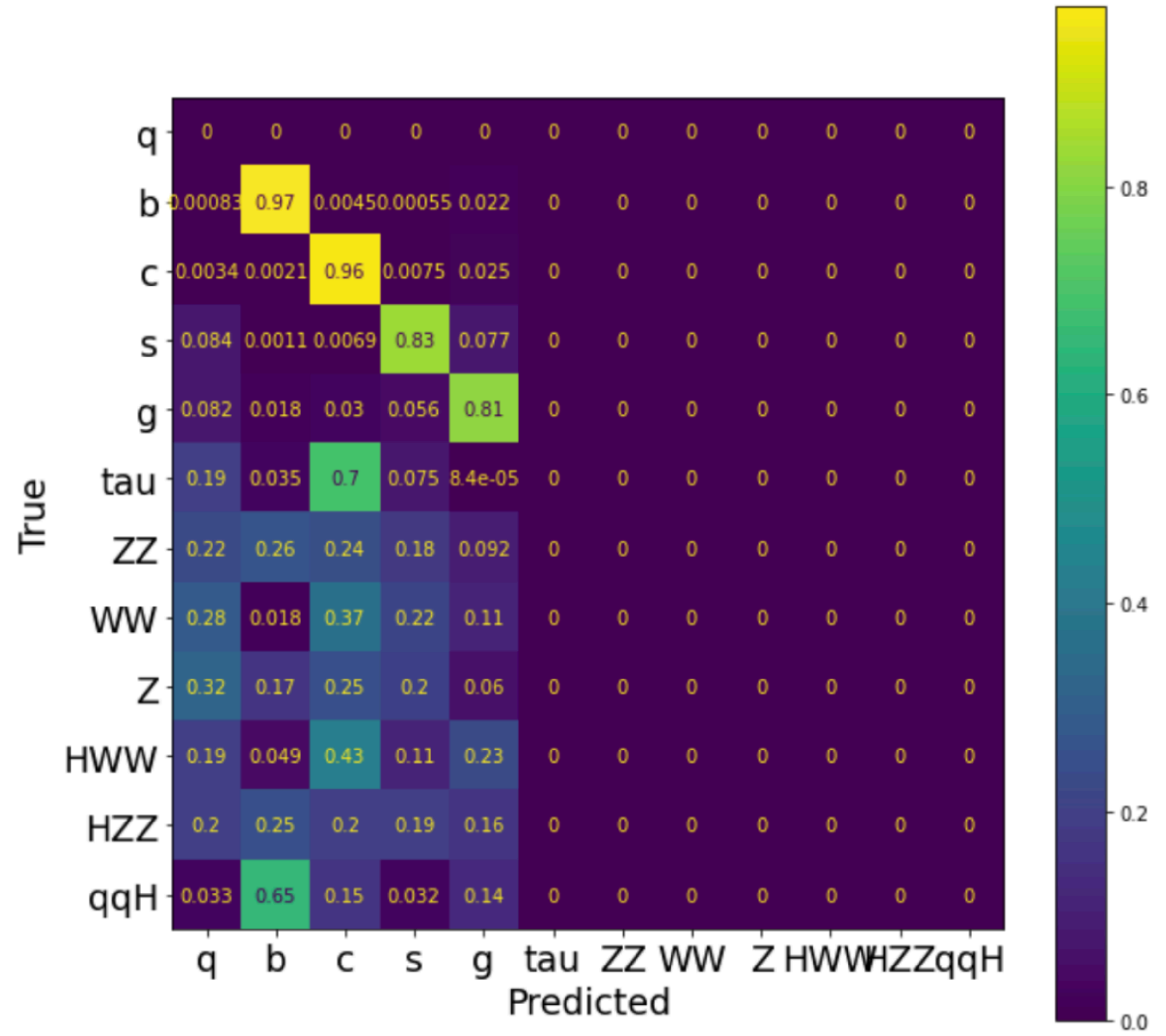
Del Vecchio, Gouskos, MS

- ee → ZH → vv j j
  - j = b, c, s, g

Final States	Cross-section [pb]	BR(H)	BR(Z)	Expected Yields
signal				
$Z(\nu\nu)H(uu/dd)$	0.201868		0.2	
$Z(\nu\nu)H(bb)$	0.201868	0.571	0.2	$1.34 \cdot 10^5$
$Z(\nu\nu)H(cc)$	0.201868	0.0291	0.2	$6.68 \cdot 10^3$
$Z(\nu\nu)H(ss)$	0.201868	$2.50 \cdot 10^{-4}$	0.2	55
$Z(\nu\nu)H(gg)$	0.201868	0.0853	0.2	$1.89 \cdot 10^4$
$Z(\nu\nu)H(\tau\tau)$	0.201868	0.0626	0.2	$1.45 \cdot 10^4$
background				
ZZ	1.35899	-	-	$6.79 \cdot 10^6$
WW	16.4385	-	-	$8.22 \cdot 10^7$
Z	52.6539	-	-	$2.63 \cdot 10^8$
$Z(\nu\nu)H(WW)$	0.201868		0.2	$4.97 \cdot 10^4$
$Z(\nu\nu)H(ZZ)$	0.201868		0.2	$6.10 \cdot 10^3$
$Z(q\bar{q})H$	0.201868			$6.82 \cdot 10^5$







True \ Predicted	q	b	c	s	g	tau	ZZ	WW	Z	HWW	HZZ	qqH
q	0	0	0	0	0	0	0	0	0	0	0	0
b	0.00083	0.97	0.0045	0.00055	0.022	0	0	0	0	0	0	0
c	0.0034	0.0021	0.96	0.0075	0.025	0	0	0	0	0	0	0
s	0.084	0.0011	0.0069	0.83	0.077	0	0	0	0	0	0	0
g	0.082	0.018	0.03	0.056	0.81	0	0	0	0	0	0	0
tau	0.19	0.035	0.7	0.075	8.4e-05	0	0	0	0	0	0	0
ZZ	0.22	0.26	0.24	0.18	0.092	0	0	0	0	0	0	0
WW	0.28	0.018	0.37	0.22	0.11	0	0	0	0	0	0	0
Z	0.32	0.17	0.25	0.2	0.06	0	0	0	0	0	0	0
HWW	0.19	0.049	0.43	0.11	0.23	0	0	0	0	0	0	0
HZZ	0.2	0.25	0.2	0.19	0.16	0	0	0	0	0	0	0
qqH	0.033	0.65	0.15	0.032	0.14	0	0	0	0	0	0	0

- Strategy:
  - Event preselection
    - lepton veto (orthogonalise)
  - build bb/cc/ss/gg orthogonal enriched categories using max sum of jet scores

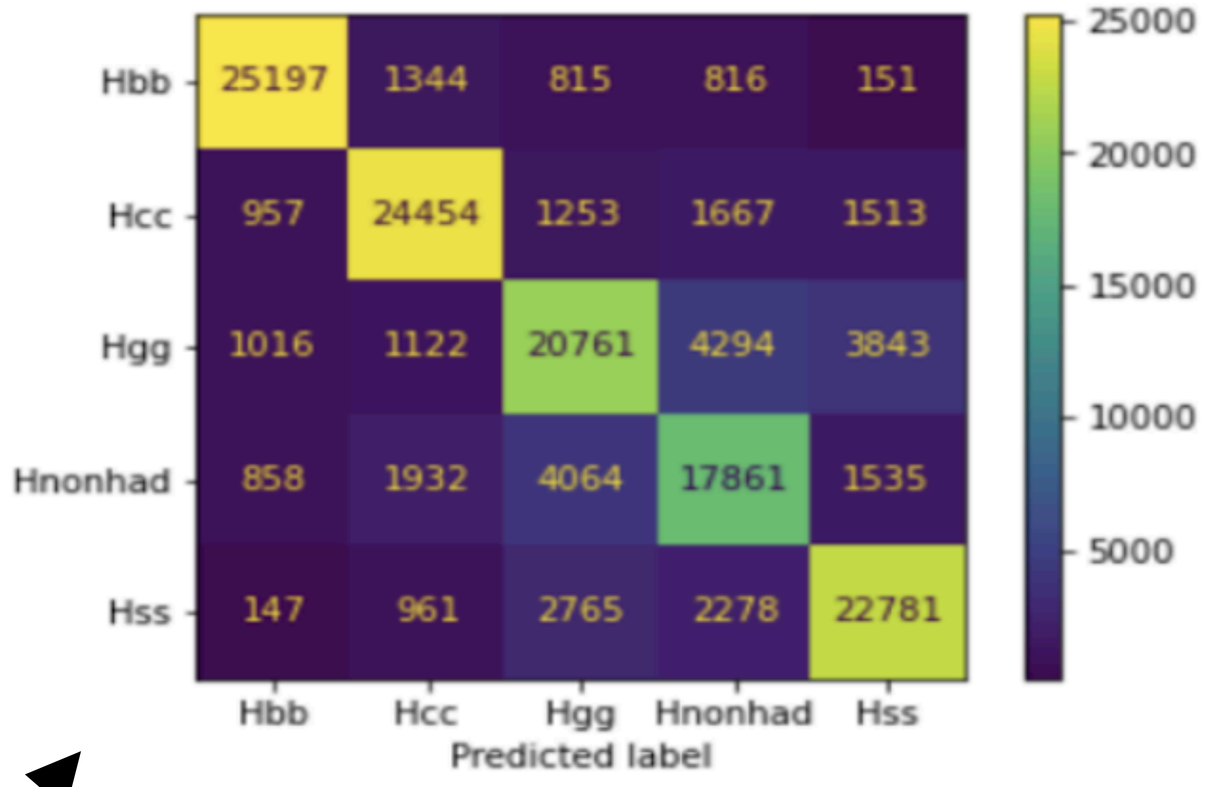
Higgs to hadrons (Z(LL))

G. Marchiori (Friday)

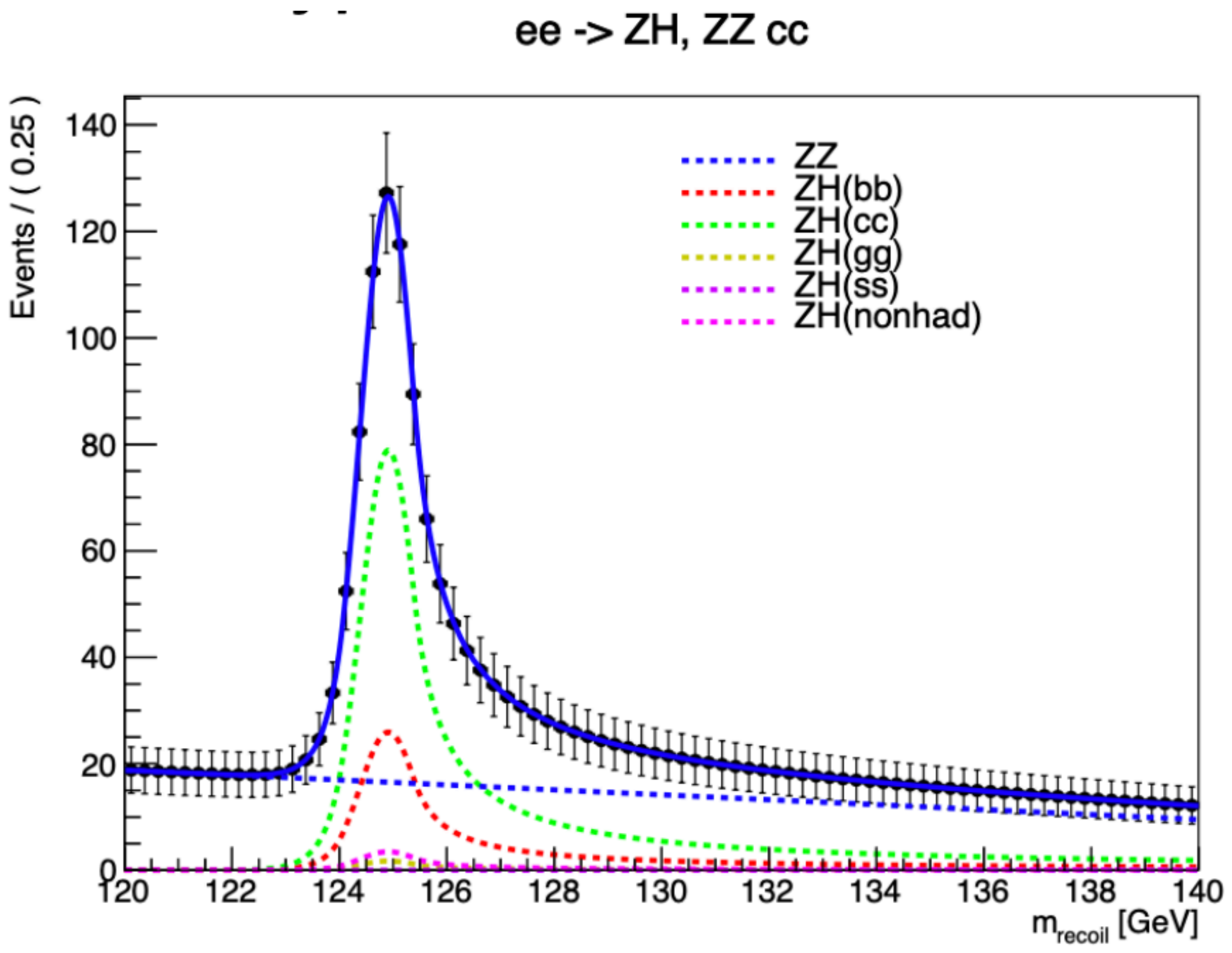
Marchiori, Maloizel

- ee → ZH → l l j j
  - j = b, c, s, g
- Event pre-selection:
  - build recoil mass

one $Z(\ell\ell)$ candidate
$m_{\ell\ell}$ in 81–101 GeV
$|\cos\theta_{\ell\ell}| < 0.8$
m_{recoil} in 120–140 GeV
m_{jj} in 100–140 GeV
$p_{\mathrm{miss}} < 30$ GeV
no leptons with $p > 25$ GeV
$d_{23} > 2,\ d_{34} > 1.5,\ d_{45} > 1.0$



	Hbb	Hcc	Hgg	Hnonhad	Hss
Hbb	25197	1344	815	816	151
Hcc	957	24454	1253	1667	1513
Hgg	1016	1122	20761	4294	3843
Hnonhad	858	1932	4064	17861	1535
Hss	147	961	2765	2278	22781



Results @10 ab^{-1}

Z(→LL)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.6	3.5	290	1.5

- Final selection and signal extraction:
  - multi-score BDT using jet tagger output to maximise purity in
    - bb/cc/ss/gg/other final states
  - simultaneous un-binned fit on m_{recoil} on 4/5 signal strength modifiers POIs

Higgs to hadrons (Z(νν))

- ee → ZH → νν j j
  - j = b, c, s, g

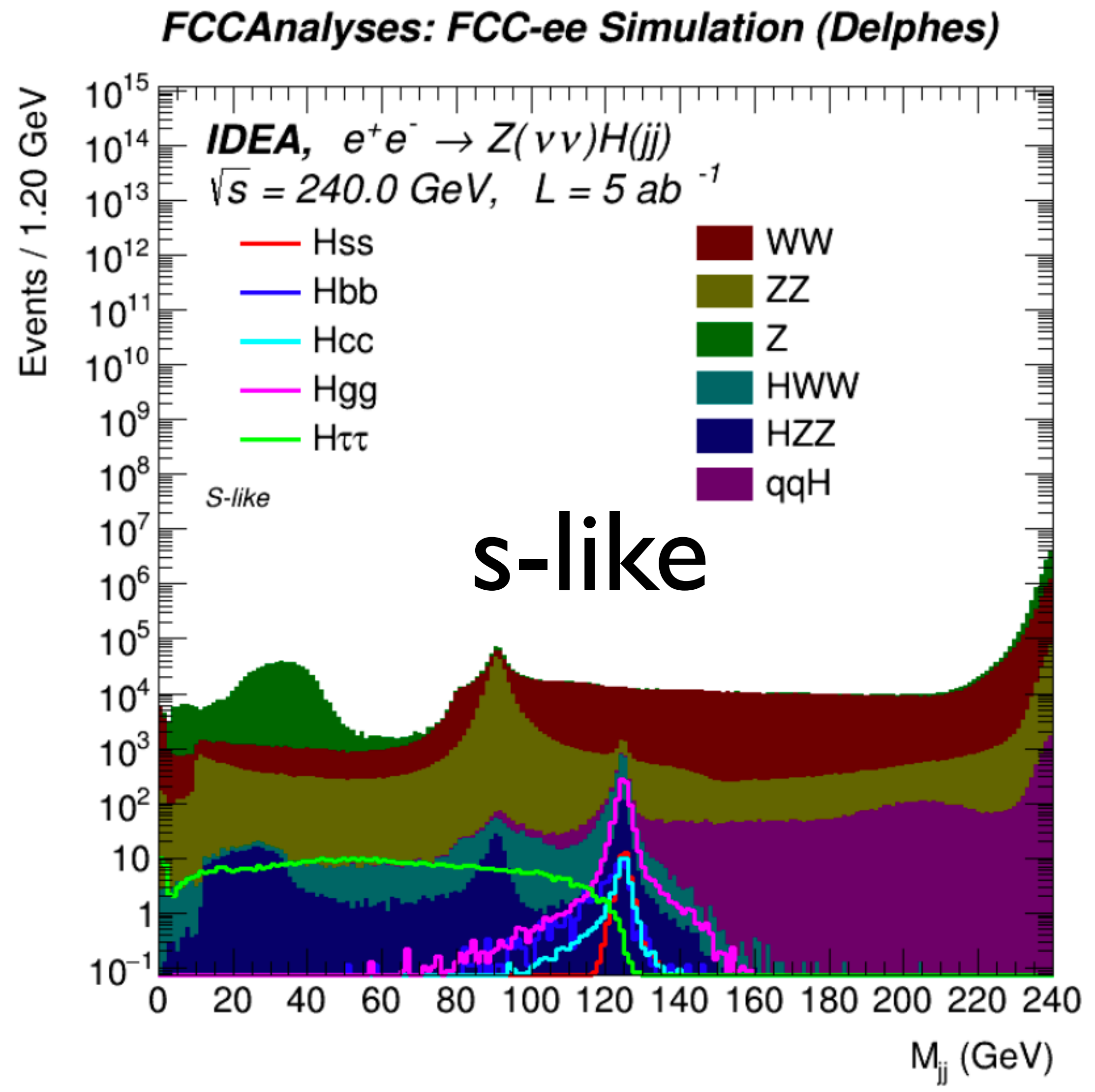
- Strategy (continued):
  - for each signal category (bb/cc/ss/gg)
    - define LP/MP/HP categories based on $s(j_1) + s(j_2)$
  - perform a 2D (m_{jj} , m_{recoil}) template fit on each of the 3x4 categories

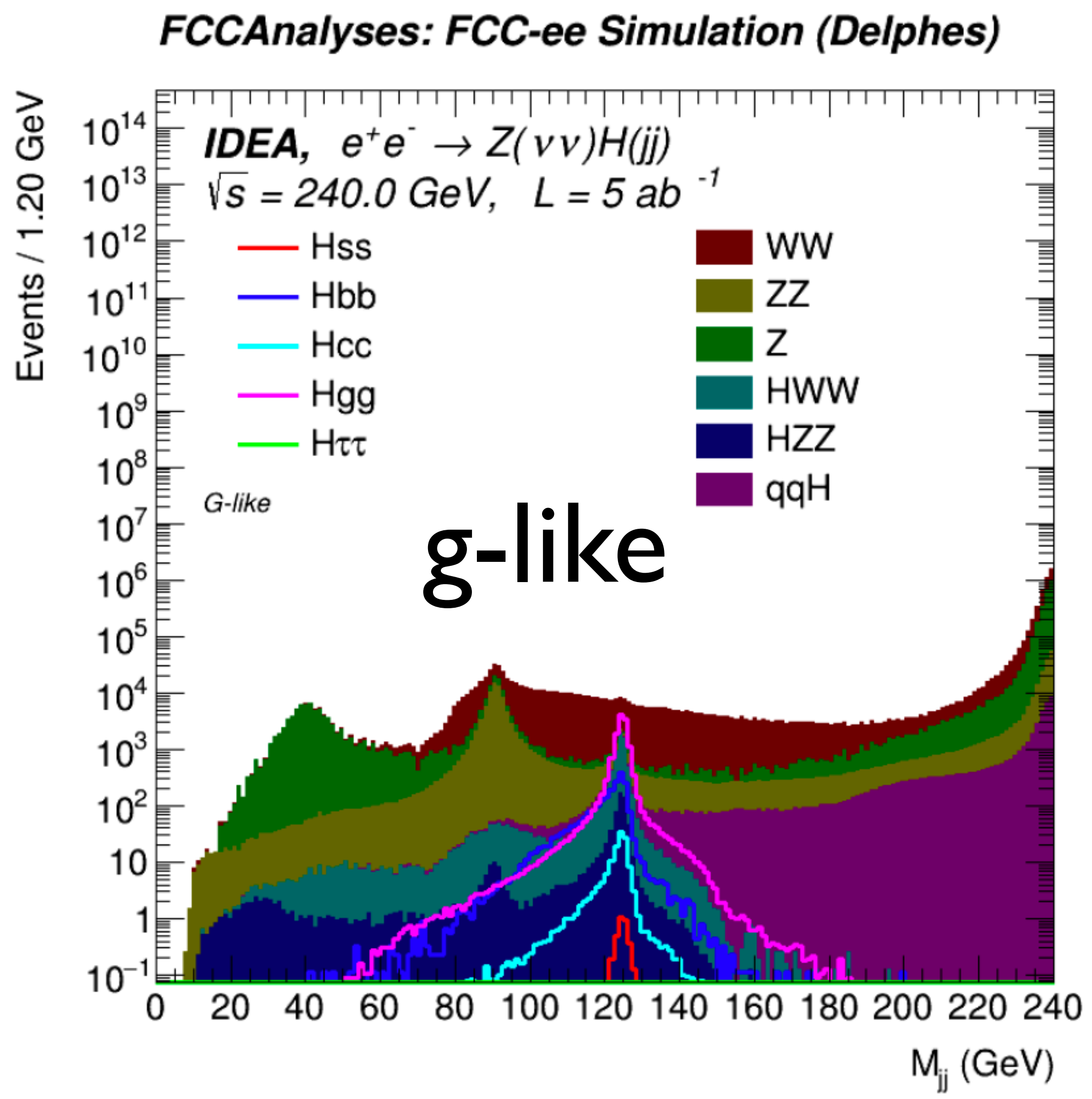
Achievable precision:

Z(→νν)H(→qq)	bb	cc	ss	gg
δμ/μ (%)	0.3	2.1	100	0.8

*$|BR_{H\to ss}|<1.3$

2x better compared to the 2L channel
All-had channel: effort started

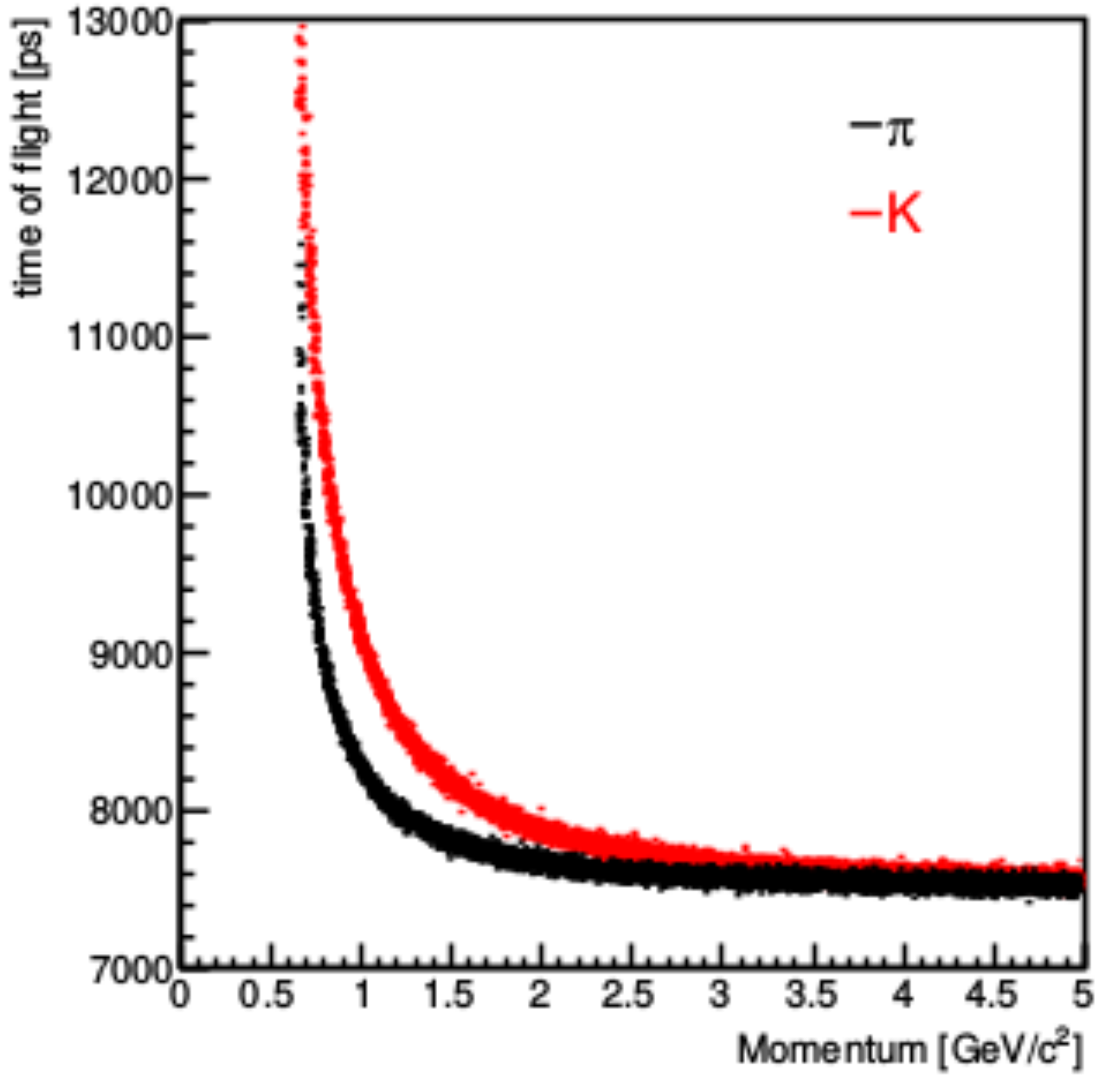


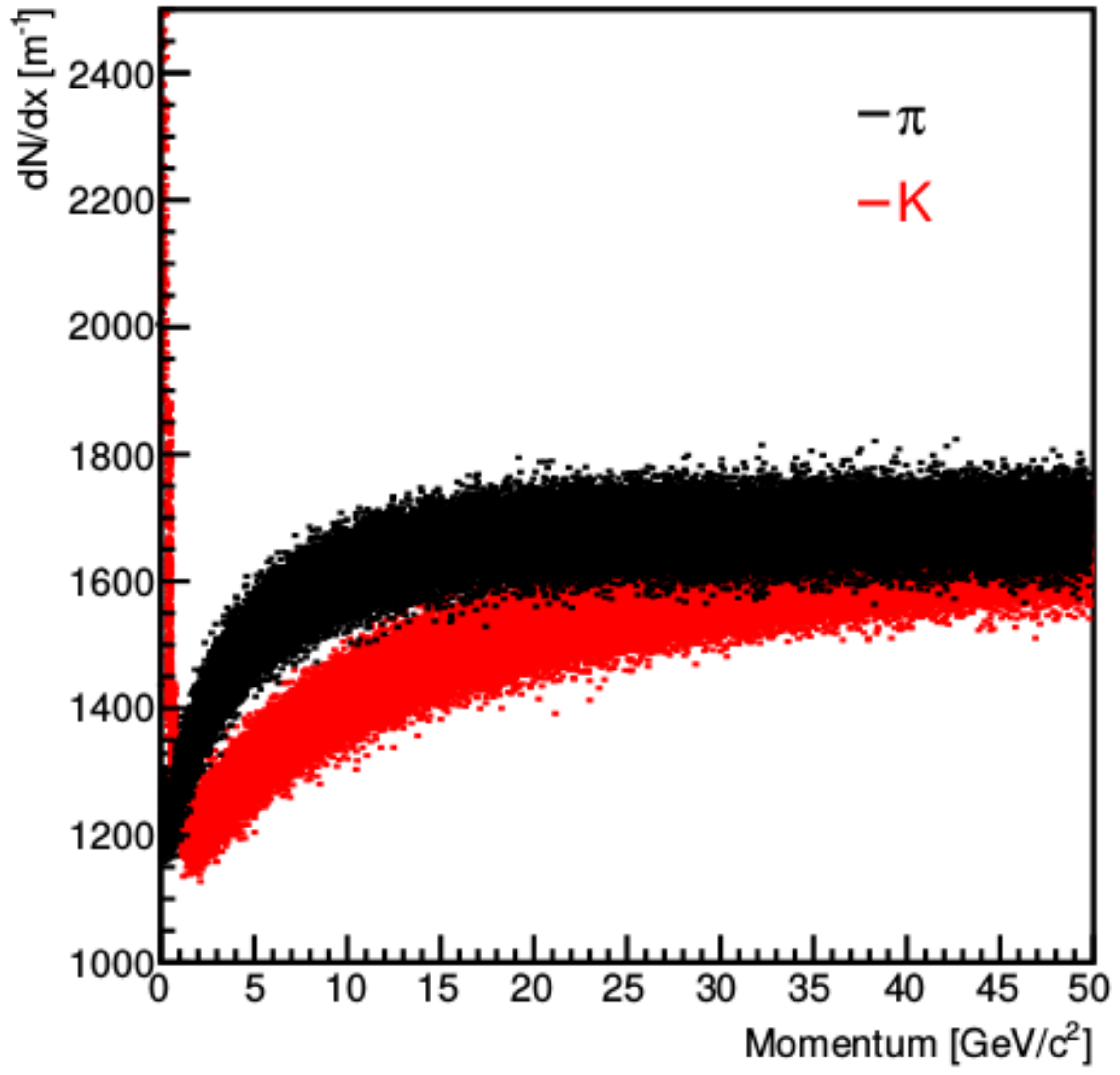


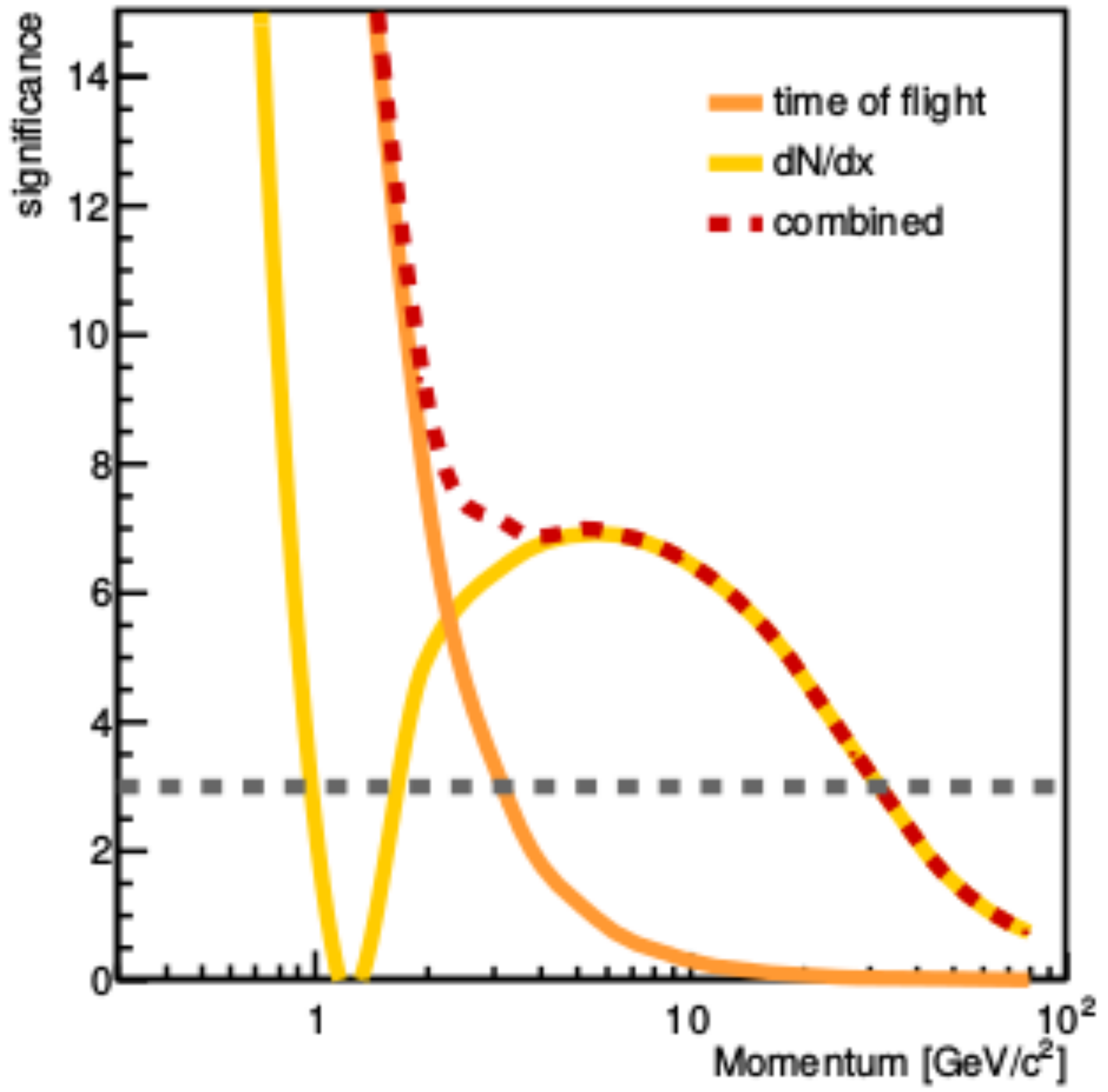
~ strange Yukawa to 50% precision seems possible …

can the fully hadronic (4j) channel help?

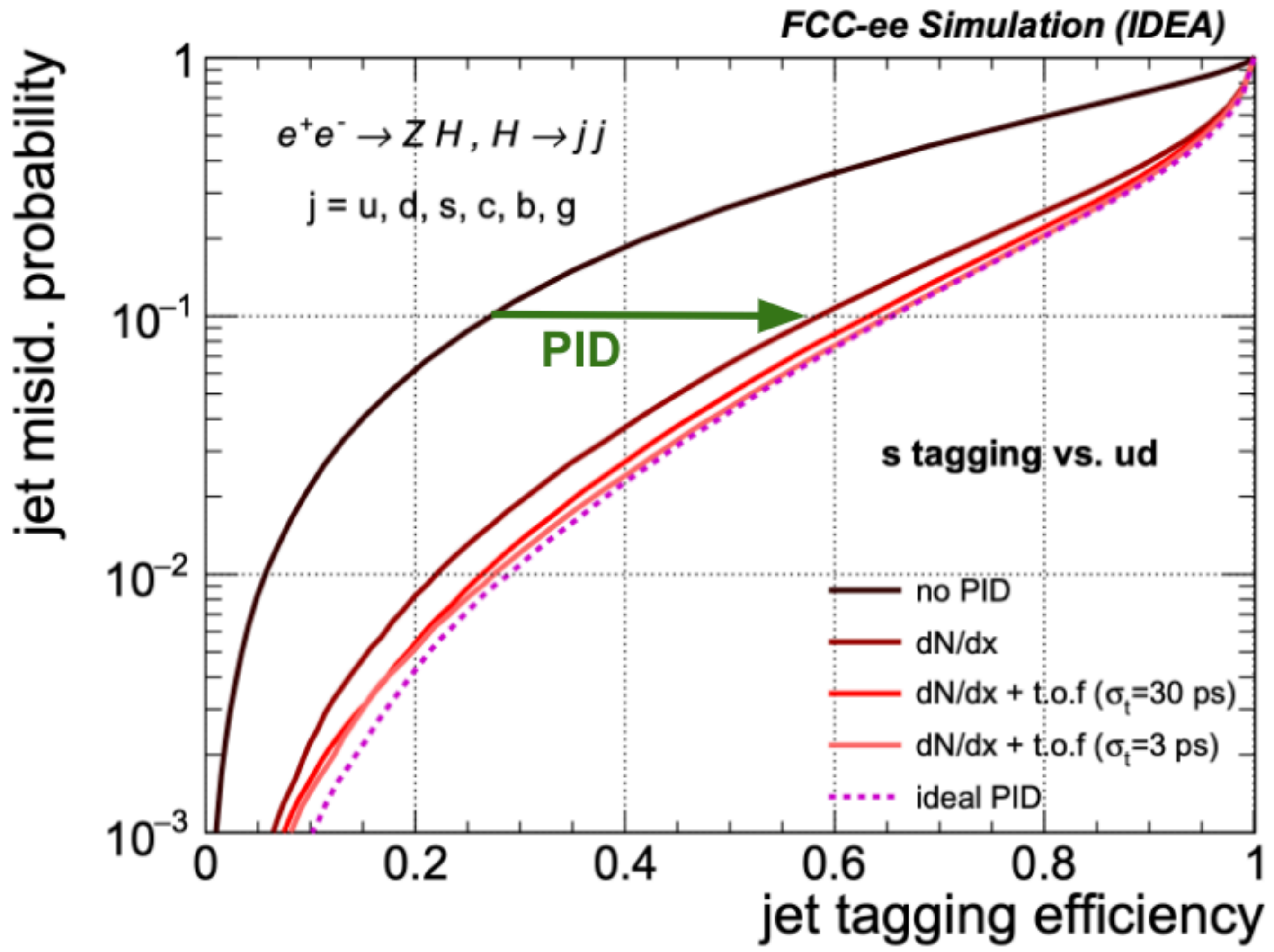
Particle ID







- Particle Id for **strange** jet identification:
  - ToF at low momenta
  - dN/dX at high momenta
- Possible to measure strange Yukawa at FCC-ee ?



H→jj (detector requirements)

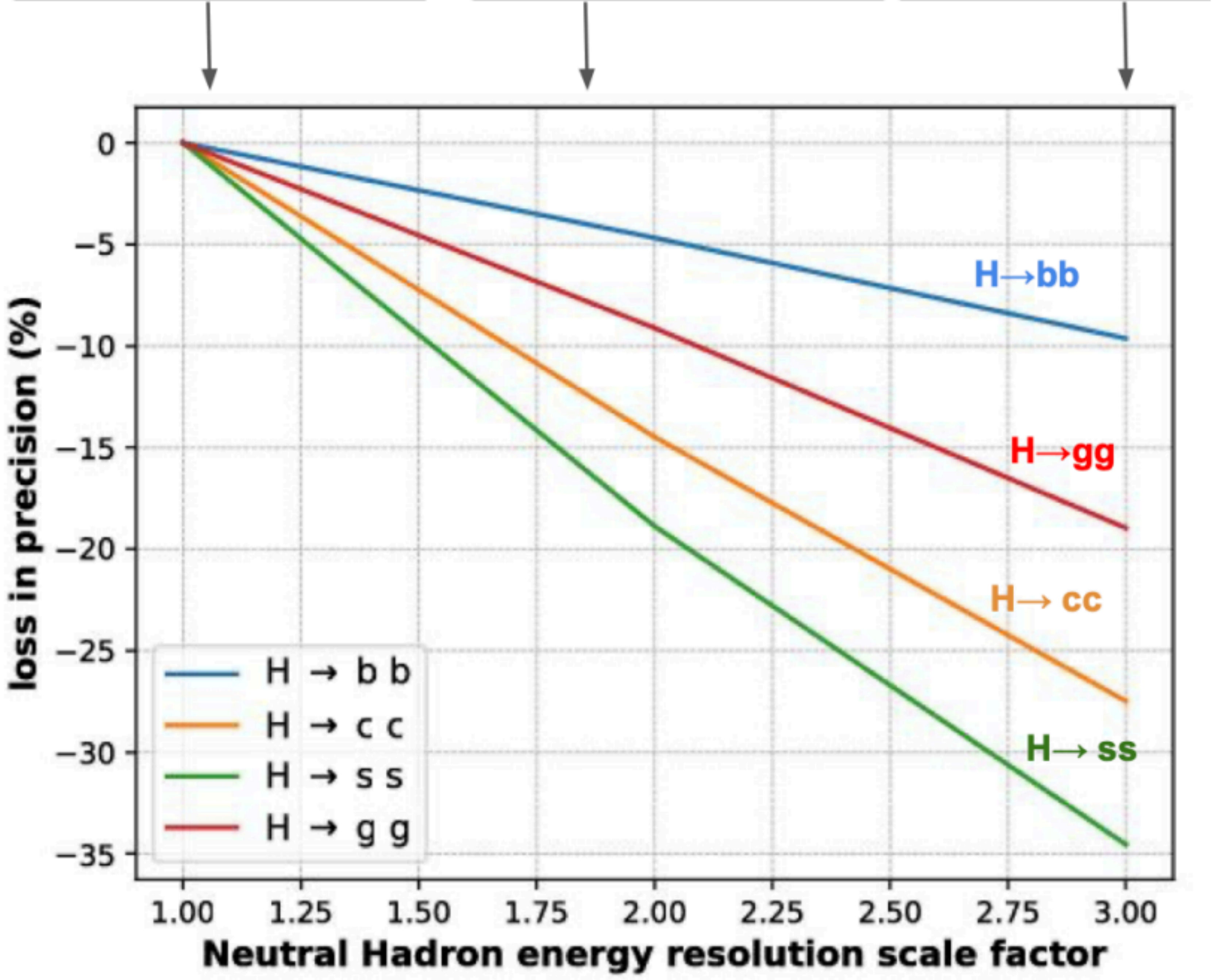
j=b,c,s,g

Neutral Hadron resolution

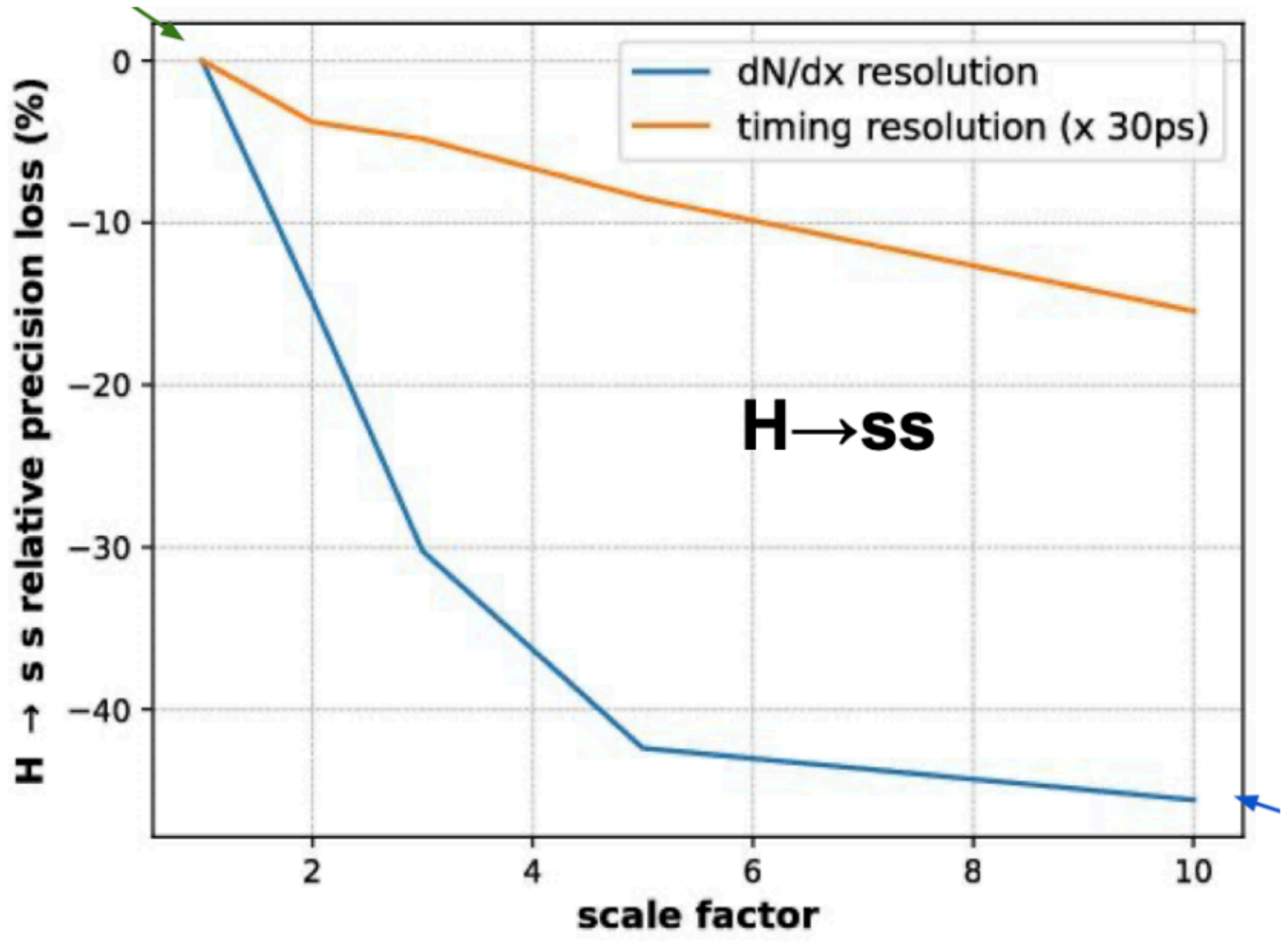
Dual Readout 30% / √E

ATLAS 50% / √E

CMS 100% / √E



PID

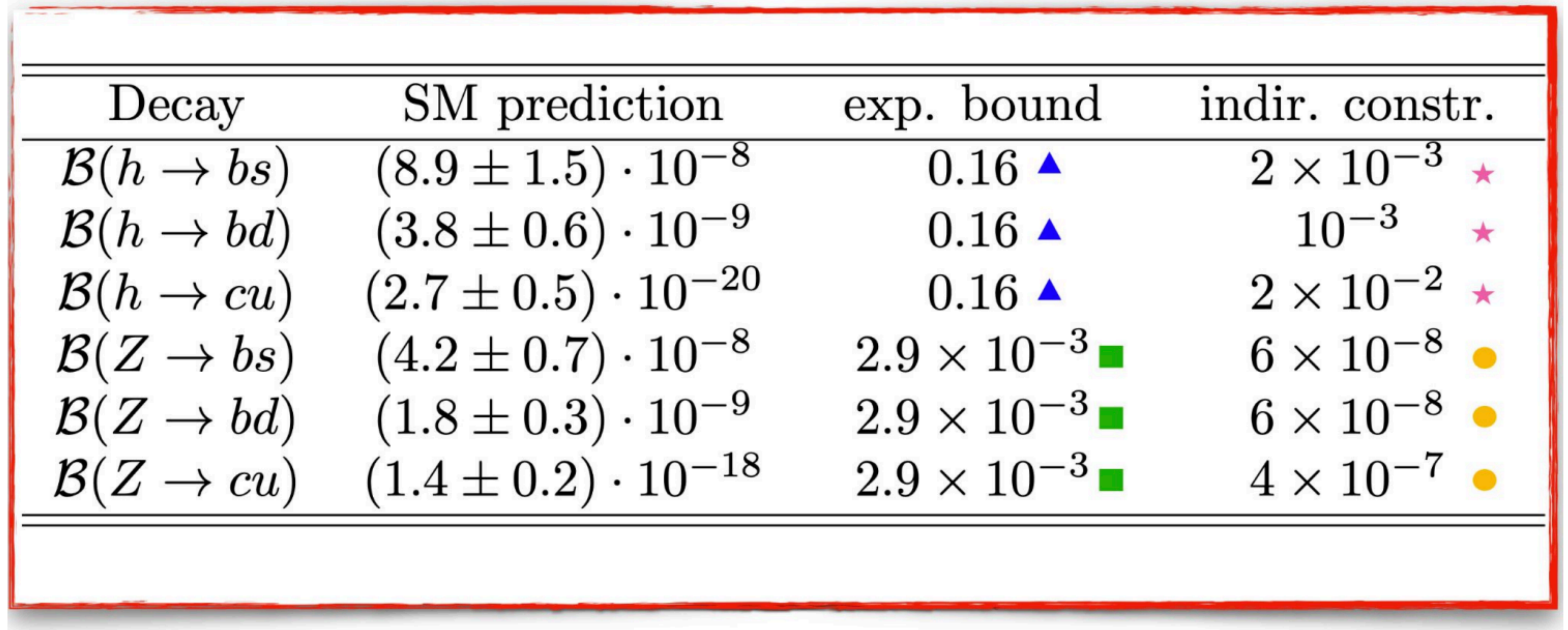


Maximise physics output in Higgs physics:

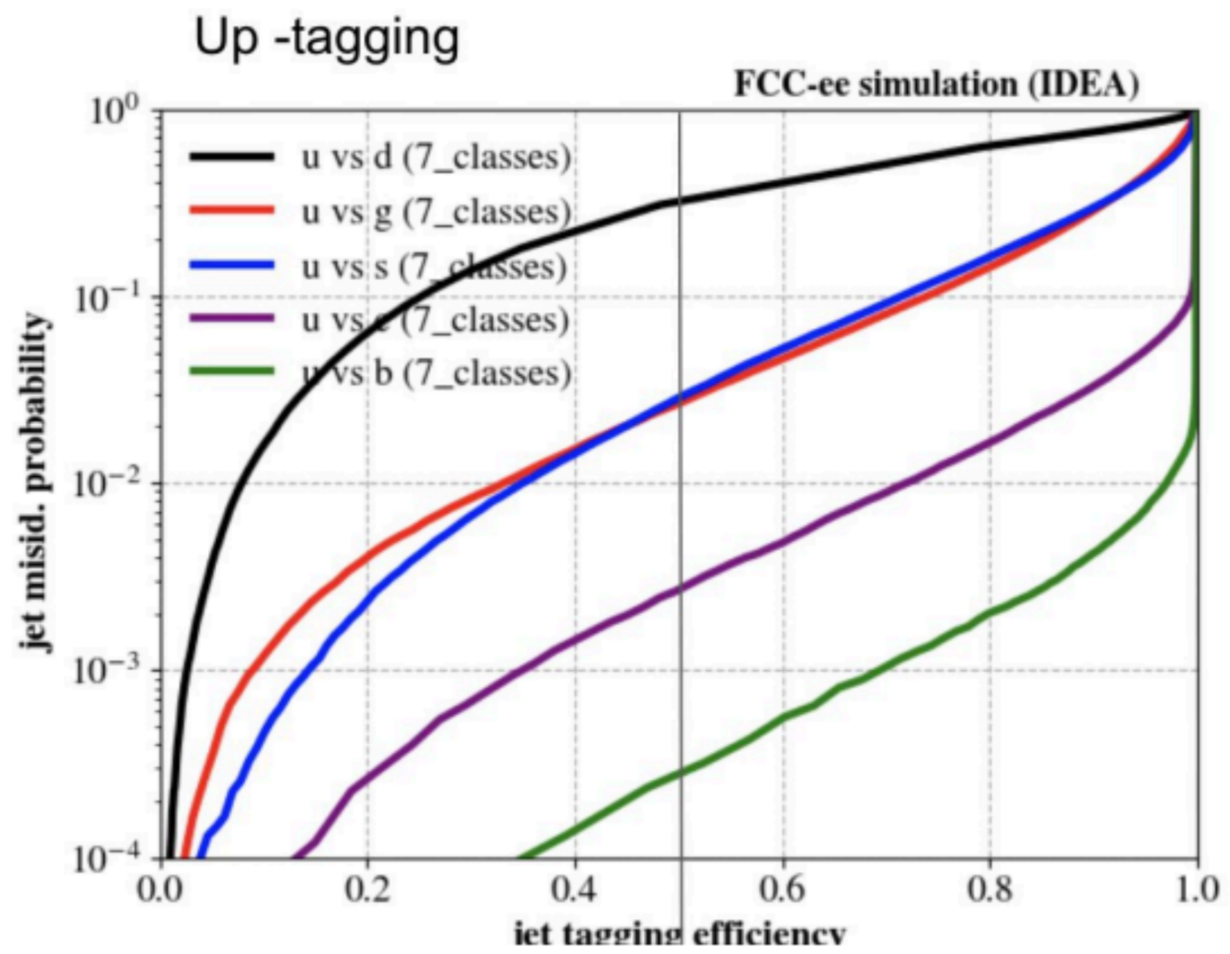
- **Hadronic resolution** critical for all H→jj
- Powerful **PID** (K/π) essential for **strange Yukawa**

Higgs to light and FCNCs at the FCC-ee

cf. Michele Tammaro



Decay	SM prediction	exp. bound	indir. constr.
$\mathcal{B}(h \to bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16 ▲	2×10^{-3} ★
$\mathcal{B}(h \to bd)$	$(3.8 \pm 0.6) \cdot 10^{-9}$	0.16 ▲	10^{-3} ★
$\mathcal{B}(h \to cu)$	$(2.7 \pm 0.5) \cdot 10^{-20}$	0.16 ▲	2×10^{-2} ★
$\mathcal{B}(Z \to bs)$	$(4.2 \pm 0.7) \cdot 10^{-8}$	2.9×10^{-3} ■	6×10^{-8} ●
$\mathcal{B}(Z \to bd)$	$(1.8 \pm 0.3) \cdot 10^{-9}$	2.9×10^{-3} ■	6×10^{-8} ●
$\mathcal{B}(Z \to cu)$	$(1.4 \pm 0.2) \cdot 10^{-18}$	2.9×10^{-3} ■	4×10^{-7} ●



Light quarks and FCNCs BRs in the SM

BR(H→uu) = 1.2e-07
BR(H→dd) = 5.5e-07

BR(H→bs) = 8.9e-08
BR(H→bd) = 3.8e-09
BR(H→sd) = 1.9e-15
BR(H→cu) =2.7e-20

→

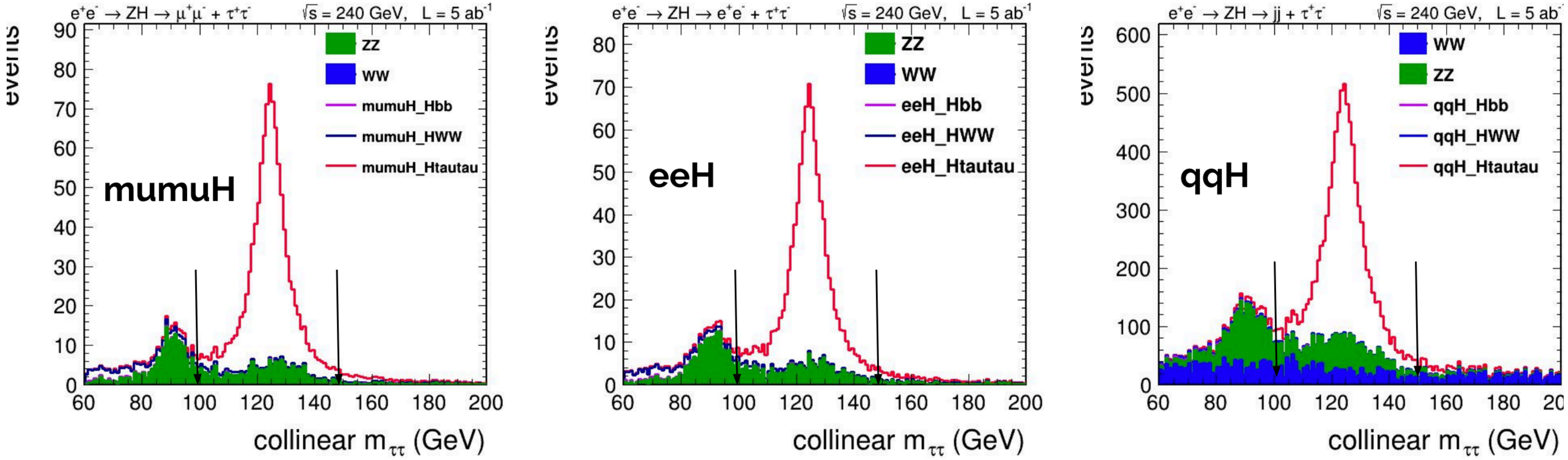
improve by 3 orders of magnitude over LHC direct bounds

BR(Huu) < 1.8e-03 @95% CL
BR(Hdd) < 1.7e-03 @95% CL

BR(Hbs) < 4.5e-04 @95% CL
BR(Hbd) < 3.3e-04 @95% CL
BR(Hcu) < 3.0e-04 @95% CL
BR(Hsd) < 9.5e-04 @95% CL

$H\to\tau\tau$

Cepeda



Restricting the results to the Collinear Mass range: 100 to 150 GeV

		TauTau	MuTau	ETau	HTauTau
Z→QQ	Signal	2741	1875	1917	6533
	Bg	1142	939	1060	3141
Z→MuMu	Signal	456	203	214	873
	Bg	63	66	55	184
Z→EE	Signal	440	206	201	847
	Bg	71	57	62	190

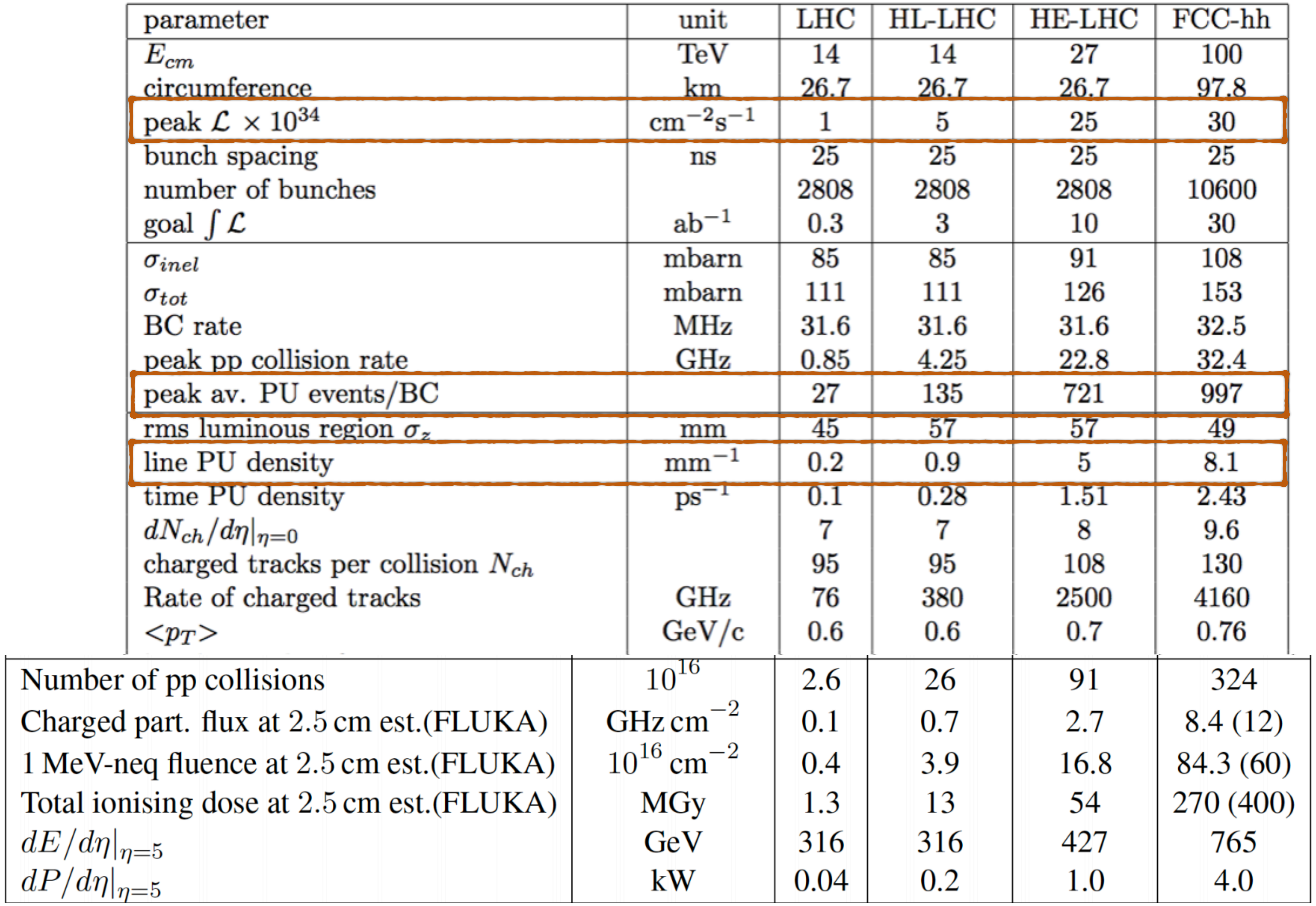
Assuming only stat uncertainty on the signal (no bg uncertainty, no syst): ~>~8253 events in 5ab-1 → 1.1% uncertainty on Δ(σ_{ZH}*Br(H→ττ)) . **Assuming 10ab-1 , 0.78% .**

Conclusions & outlook

FCC-ee parameters		**Z**	**WW**	**ZH**	**ttbar**
√s	GeV	88 - 94	157.2 - 162.5	240	350-365
Inst. Lumi / IP	10^{34} cm^{2} s^{-1}	182	19.4	7.3	1.33
Integrated lumi / 4IP	ab^{-1} / yr	87	9.3	3.5	0.65
N bunches/beam	-	10 000	880	248	36
bunch spacing	ns	30	340	1 200	8 400
L*	m	2.2	2.2	2.2	2.2
crossing angle	mrad	30	30	30	30
vertex size (x)	µm	5.96	14.7	9.87	27.3
vertex size (y)	nm	23.8	46.5	25.4	48.8
vertex size (z)	mm	0.4	0.97	0.65	1.33
vertex size (t)	ps	36.3	18.9	14.1	6.5
Beam energy spread	%	0.132	0.154	0.185	0.221

Machine specs and detector requirements

lumi & pile-up



parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\vert_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\vert_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\vert_{\eta=5}$	kW	0.04	0.2	1.0	4.0

→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

but also x10 integrated luminosity w.r.t to HL-LHC

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

Reach at high energies (I)

For more details see L.Wang lectures at IAS '17

To compute reach, we assume we need to observe given number of events:

$$N = \sigma \mathscr{L}$$

dimensional analysis

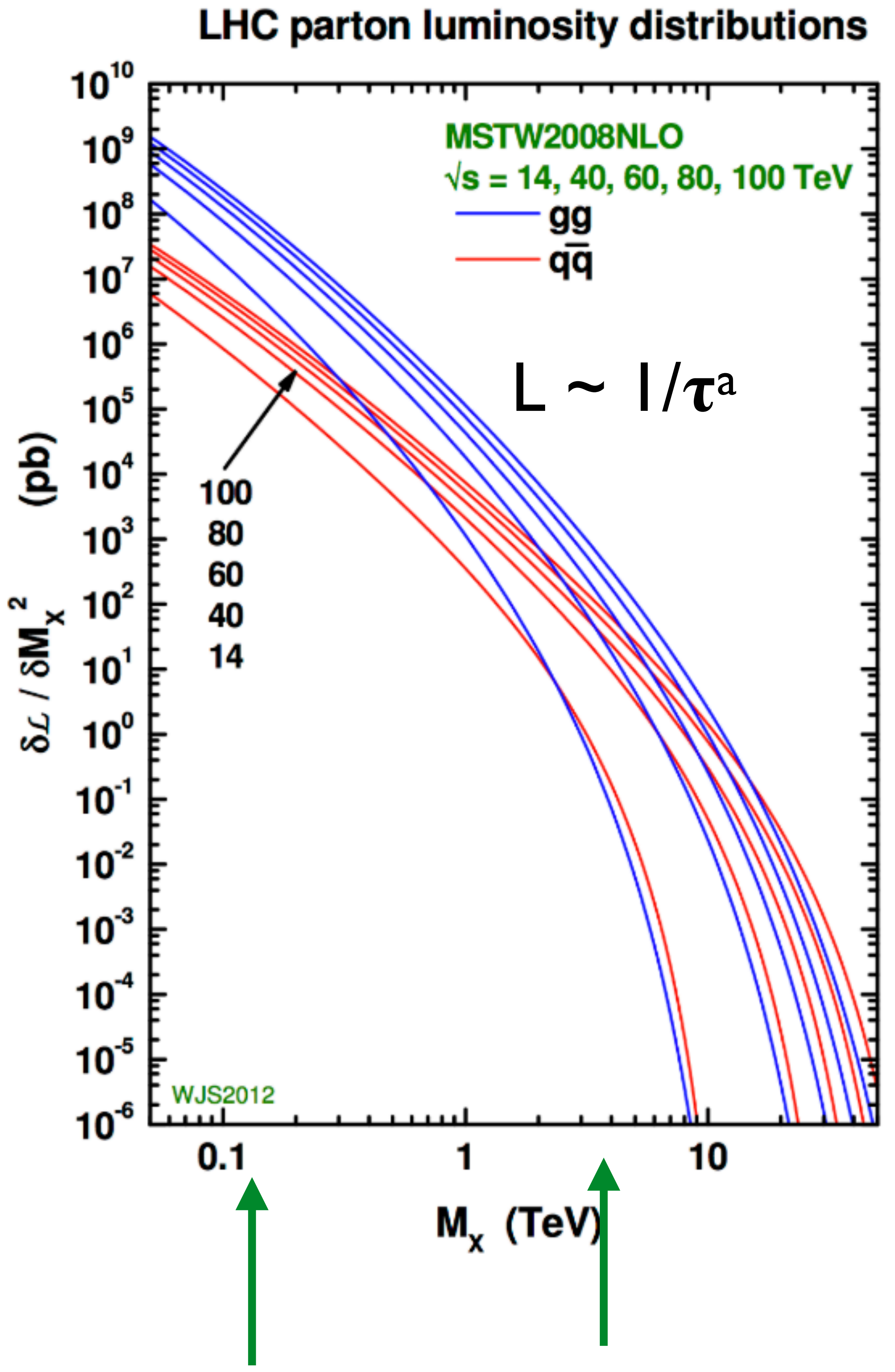
$$\sigma \sim L_{parton}(\tau) \cdot \sigma_{partonic}$$

$1/\tau^{a}$

$\tau = x_1 x_2 = M^2 / s$

$1/M^2$

assumes mostly produce at threshold

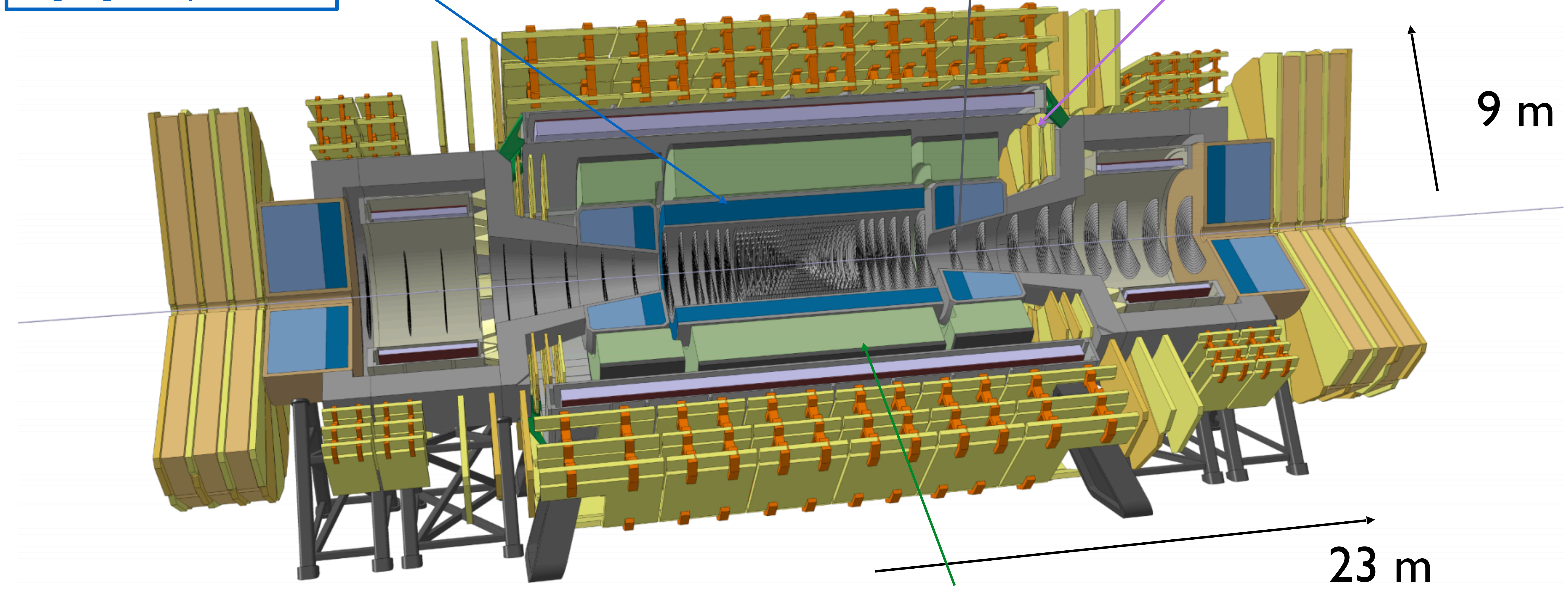


a≈2 a≈6

$\mathscr{L}$: integrated luminosity

L_{parton} : parton luminosity

The FCC-hh detector



Barrel ECAL: LAr/Pb
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\ \%$
$30\ X_0$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Tracker: $\sigma_{p_T}/p_T \sim 20\%$
at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids

Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

Higgs physics at future hadron colliders

- Large Higgs production rates:
  - access (very) rare decay modes (eg. 2nd gen,), complementary to ee colliders
  - push to %-level Higgs self-coupling measurement
- Large dynamic range for H production (in p_T^H, m(H+X) , …):
  - new opportunities for reduction of syst. uncertainties (TH and EXP)
  - develop indirect sensitivity to BSM effects at large Q^2 , complementary to that emerging from precision studies (*e.g. decay BRs*) at $Q \sim m_H$
- High energy reach:
  - direct probes of BSM extensions of Higgs sector (e.g. SUSY)
  - Higgs decays of heavy resonances
  - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)

Higgs decays: ɣɣ - ZZ - Zɣ - μμ

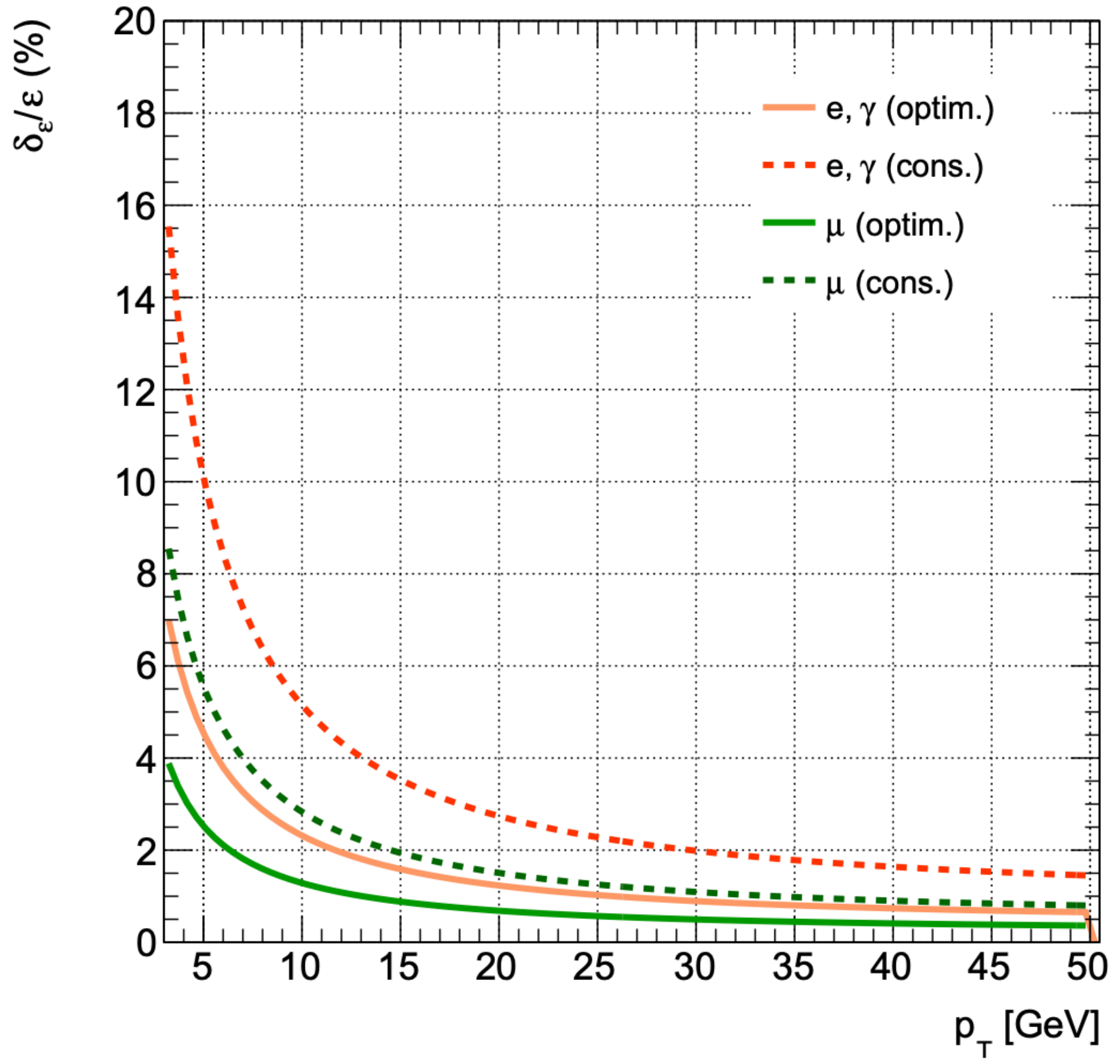
- **1% systematics on (production x luminosity)**, meant as a reference target. Assumes good theoretical progress over the next years, and **reduction of PDF+α_S uncertainties with HL-LHC + FCC-ee**.

- **e/μ/γ efficiency systematics** (shown on the right). In situ calibration, with the immense available statistics in possibly new clean channels (Z→μμɣ), will most likely reduce the uncertainties.

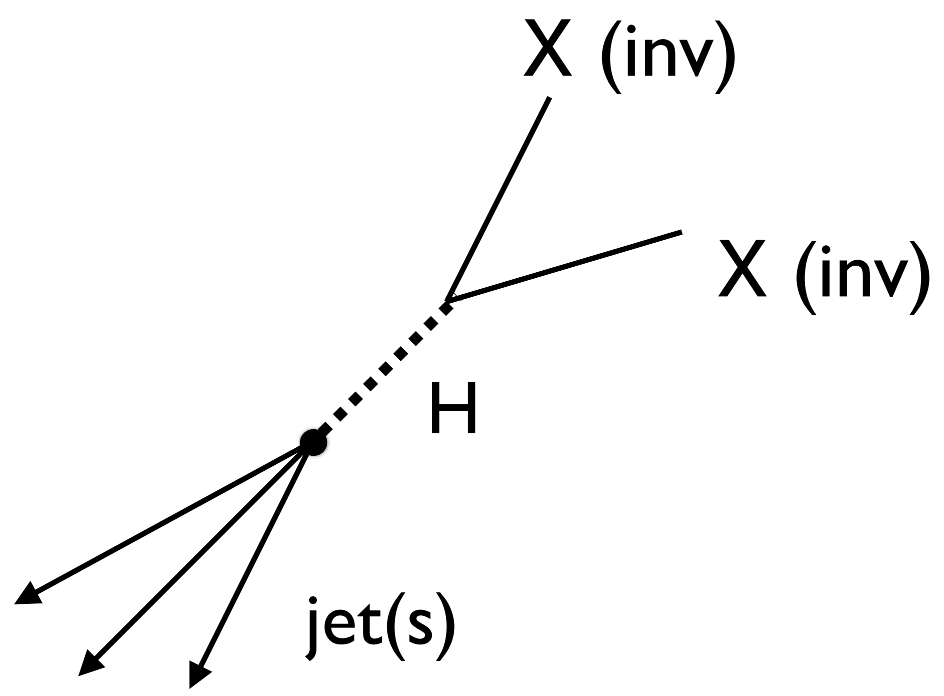
- All final states considered here rely on **reconstruction of m_H** to within few GeV.
  - **backgrounds** (physics and instrumental) to be **determined with great precision from sidebands** (~ infinite statistics)

- **Impact of pile-up**: hard to estimate with today's analyses.
  → **Focus on high-p_T objects** will help to decrease relative impact of pile-up

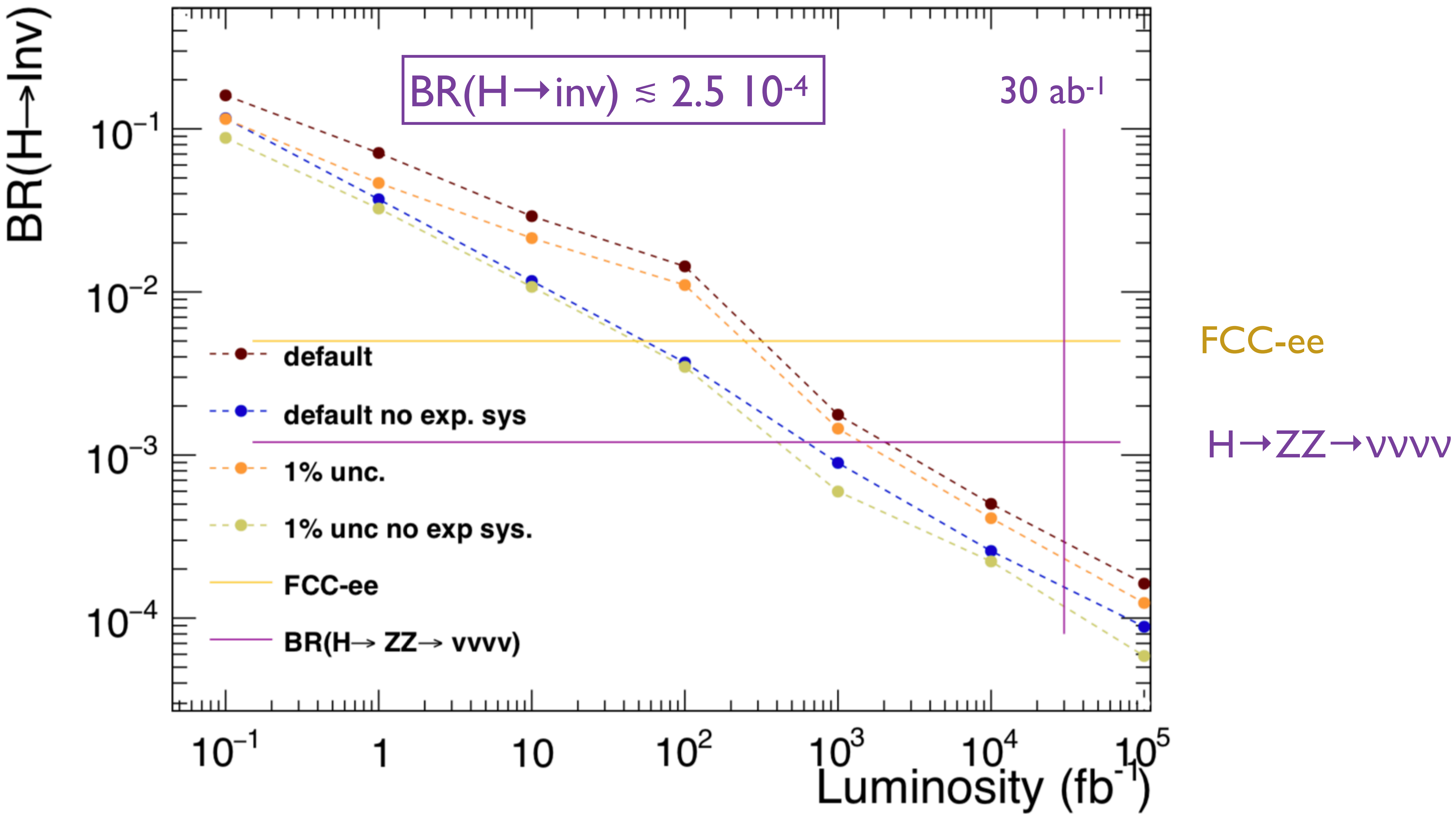
- Following **scenarios** are considered:
  - δ_{stat} → stat. only (I) (signal + bkg)
  - δ_{stat} , δ_{eff} → stat. + syst. (II)
  - δ_{stat} , δ_{eff} , δ_{prod} = 1% → stat. + syst. + prod (III)



H→invisible



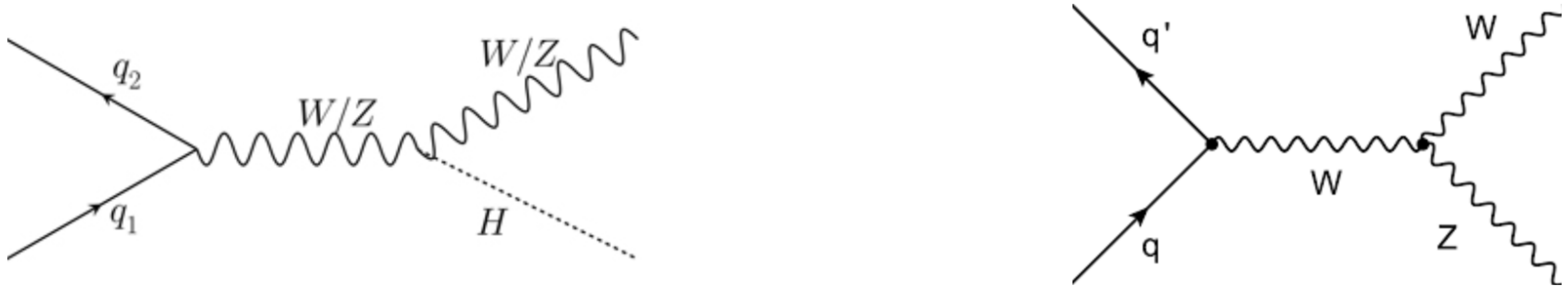
- Measure it from H + X at **large p_T(H)**
- Fit the **E_T^{miss}** spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z,W and γ spectra (low stat)
- Estimate Z→νν (W→lν) from Z→ee/μμ (W→lν) control regions (high stat).



MLM

Standalone 100 TeV Higgs measurements

- Following the principle of **reducing** as much as possible **the impact of systematics** assumptions on future measurements, additional **ratio measurements**:



$$\sigma(\mathrm{WH}[\to\gamma\gamma]) / \sigma(\mathrm{WZ}[\to e^+e^-]) \longrightarrow G_W = g^2_{HWW} \times BR(H \to \gamma\gamma)$$

$$\sigma(\mathrm{WH}[\to\tau\tau]) / \sigma(\mathrm{WZ}[\to\tau\tau]) \longrightarrow G_\tau = g^2_{HWW} \times BR(H \to \tau\tau)$$

$$\sigma(\mathrm{WH}[\to bb]) / \sigma(\mathrm{WZ}[\to bb]) \longrightarrow G_b = g^2_{HWW} \times BR(H \to bb)$$

parton level study

p_T^{min} (GeV)	W[e]Z[e] (pb)	W[e]H (pb)	W[ℓ]Z[e] × L	W[ℓ]H[γγ] × L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E6	1.4E4	8.5E−3
150	1.0E-2	6.3E-2	6.0E5	8.7E3	1.1E−2
200	5.6E-3	3.8E-2	3.4E5	5.2E3	1.4E−2
300	2.1E-3	1.6E-2	1.3E5	2.2E3	2.1E−2

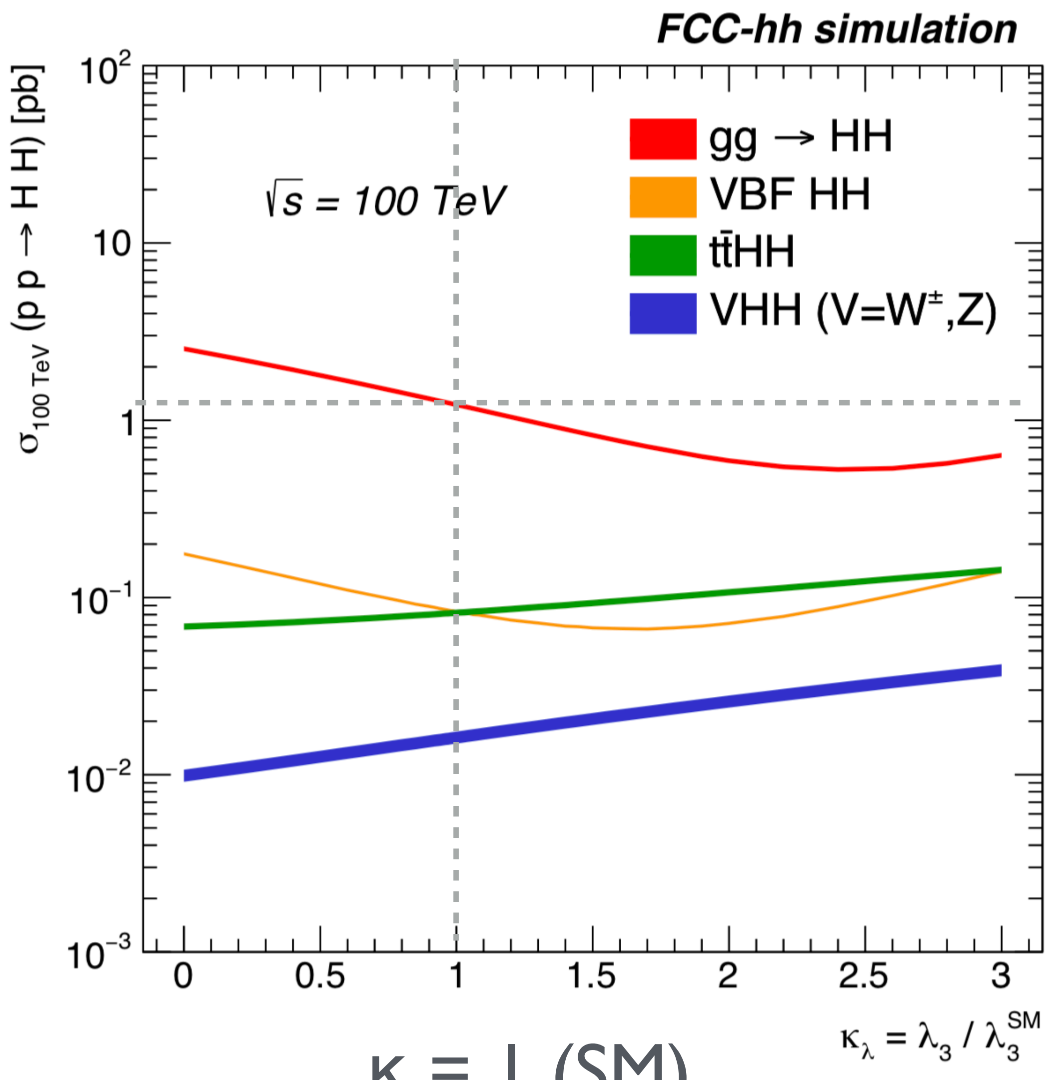
p_T^{min} (GeV)	W[e]Z[τ] (pb)	W[e]H (pb)	W[ℓ]Z[τ] $\times\varepsilon_\tau$ L	W[ℓ]H[ττ] $\times\varepsilon_\tau$ L	$\delta R/R$
100	2.1E-2	1.0E-1	1.3E5	3.8E4	5.9E−3
150	1.0E-2	6.3E-2	6.0E4	2.4E4	7.7E−3
200	5.6E-3	3.8E-2	3.4E4	1.4E4	1.0E−2
300	2.1E-3	1.6E-2			
400	9.8E-4	7.9E-3			

δG/G < 1%

p_T^{min} (GeV)	W[e]+bb (pb) $m[bb] \in m_Z$	W[e]Z[bb] (pb)	W[e]+bb (pb) $m[bb] \in m_H$	W[e]H (pb)	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_Z$	W[ℓ]Z[bb] $\times\varepsilon_b$ L	W[ℓ] bb $\times\varepsilon_b$ L $m[bb] \in m_H$	W[ℓ]H[bb] $\times\varepsilon_b$ L	$\delta R/R$
200	3.3E−2	2.5E−2	2.3E−2	3.8E−2	9.9E5	7.5E4	6.9E5	6.6E5	2.5E−3
300	1.2E−2	9.2E−3	8.8E−3	1.6E−2	3.6E5	5.5E4	2.6E5	2.8E5	3.2E−3
400	5.5E−3	4.3E−3	4.1E−3	7.9E−3	1.7E5	2.6E5	1.2E5	1.4E5	4.5E−3
600	1.7E−3	1.4E−3	1.3E−3	2.6E−3	5.1E4	8.4E4	3.9E4	4.5E4	7.8E−3
800	6.8E−4	6.2E−4	5.0E−4	1.2E−3	2.0E4	3.7E4	1.5E4	2.1E4	1.1E−2

also: $\sigma(\mathrm{Z}[\nu\nu]\mathrm{H}[\to\gamma\gamma]) / \sigma(\mathrm{Z}[\nu\nu]\mathrm{Z}[\to e^+e^-])$

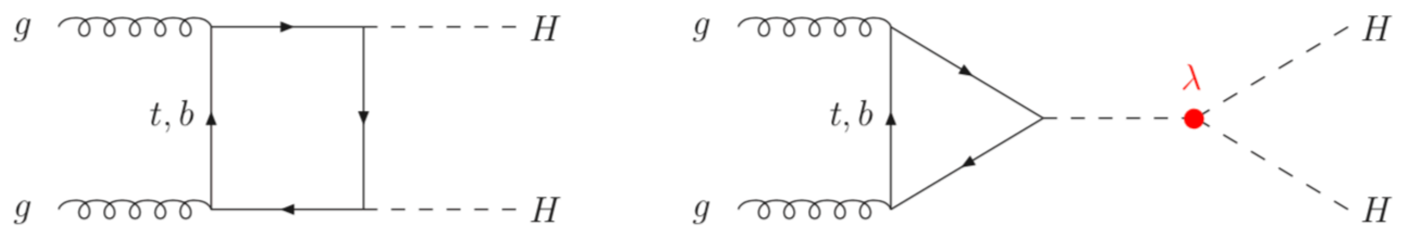
Higgs pair production at the FCC-hh



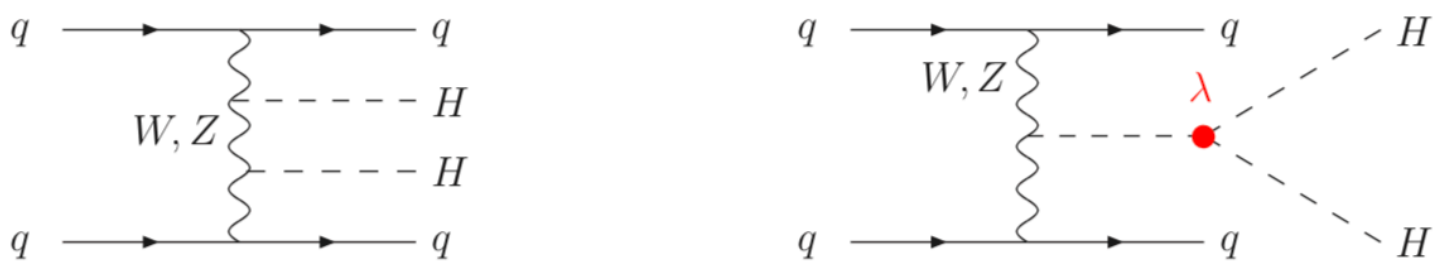
σ ≈ 1 pb

κ = 1 (SM)

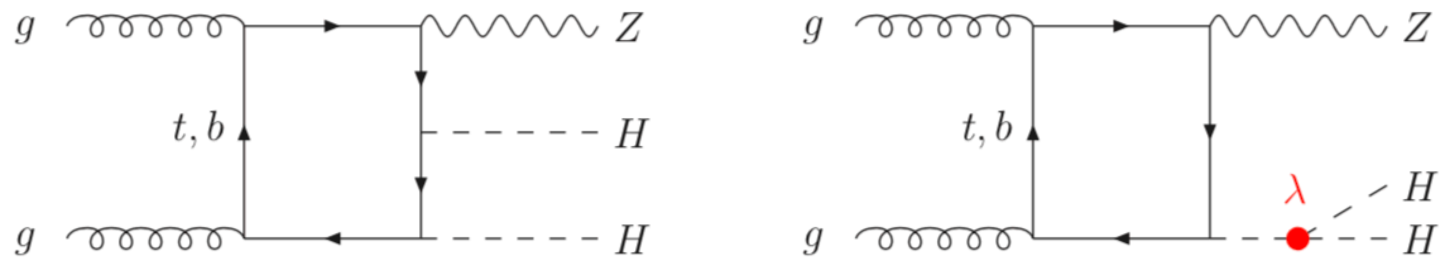
gluon fusio



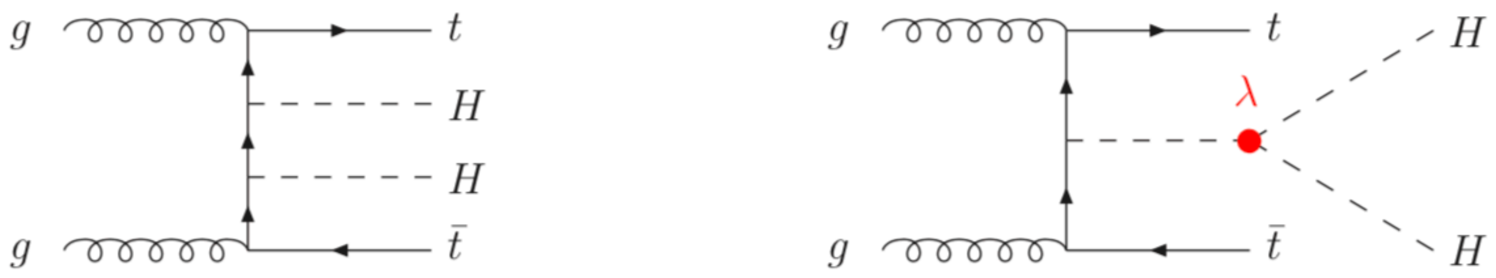
vbf HH:



VHH:



ttHH:



Expected precision:

$$\boxed{\delta_{\kappa_\lambda} = \frac{\delta_\mu}{\left.\frac{d\mu}{d\kappa_\lambda}\right|_{\text{SM}}}}$$

~1

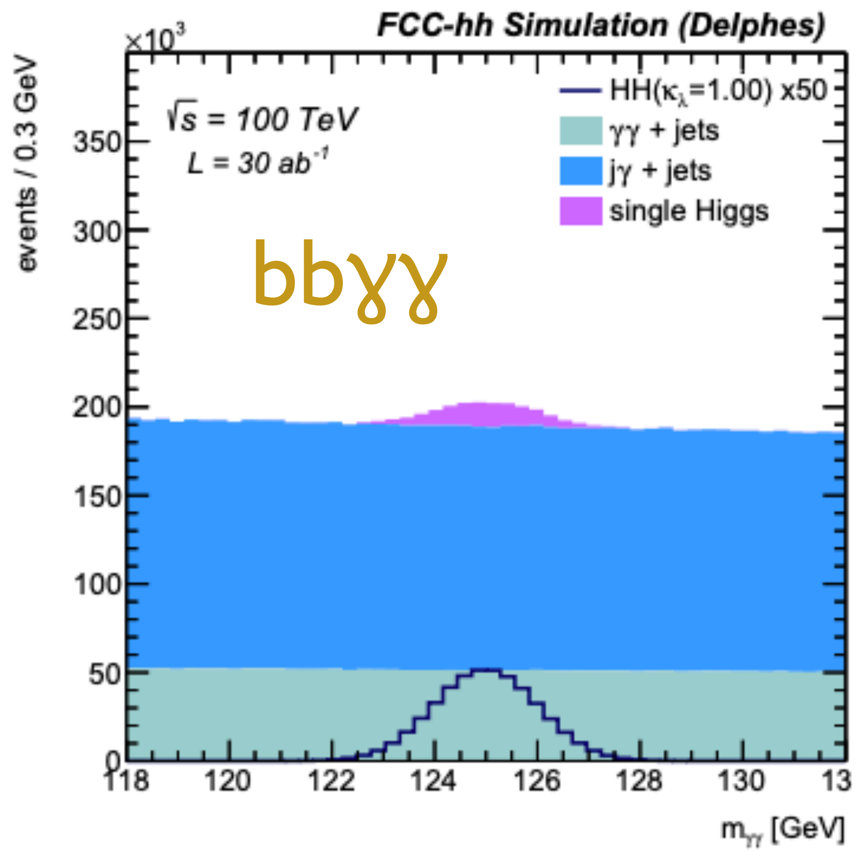
where:

$$\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$$

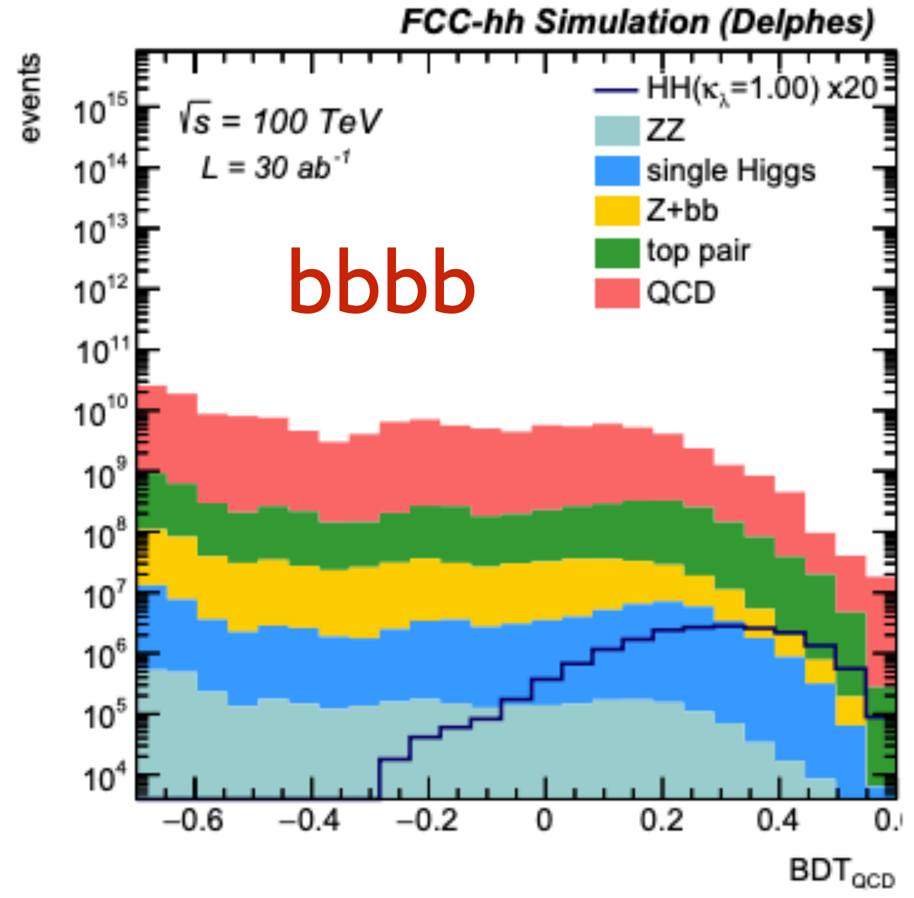
$$\mu = \sigma/\sigma_{\text{SM}}$$

Self-coupling at the FCC-hh

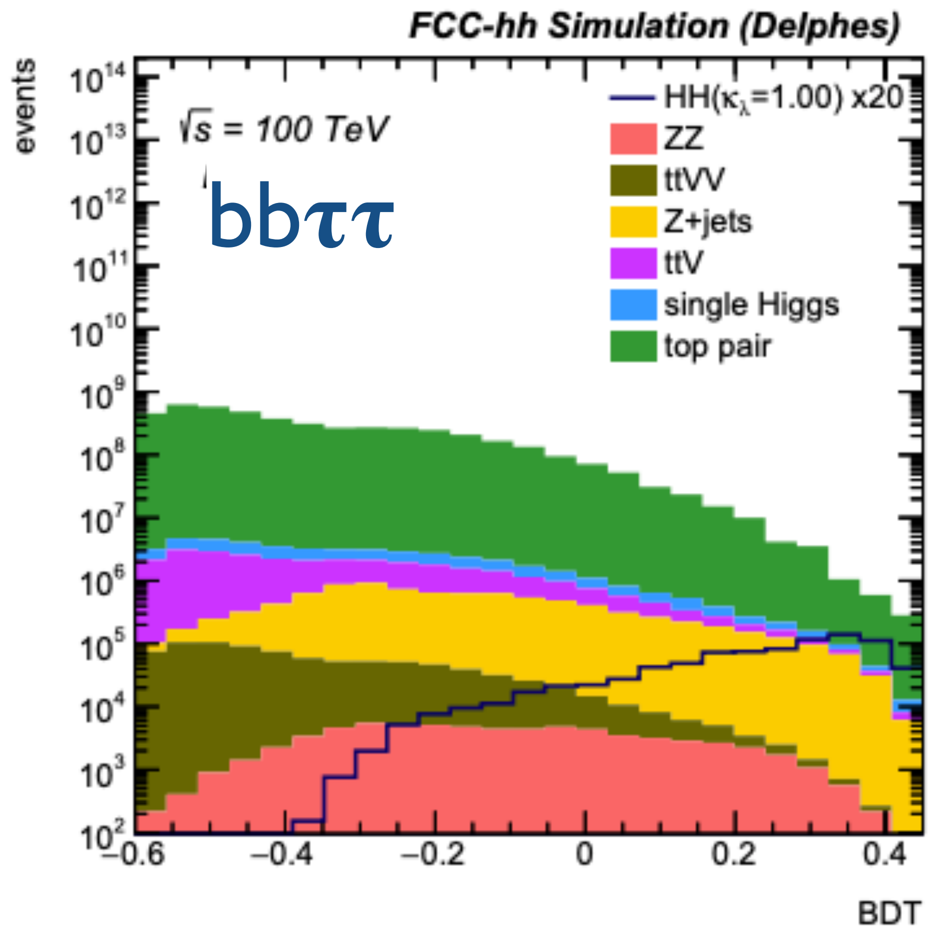
2004.03505 [hep-ph]



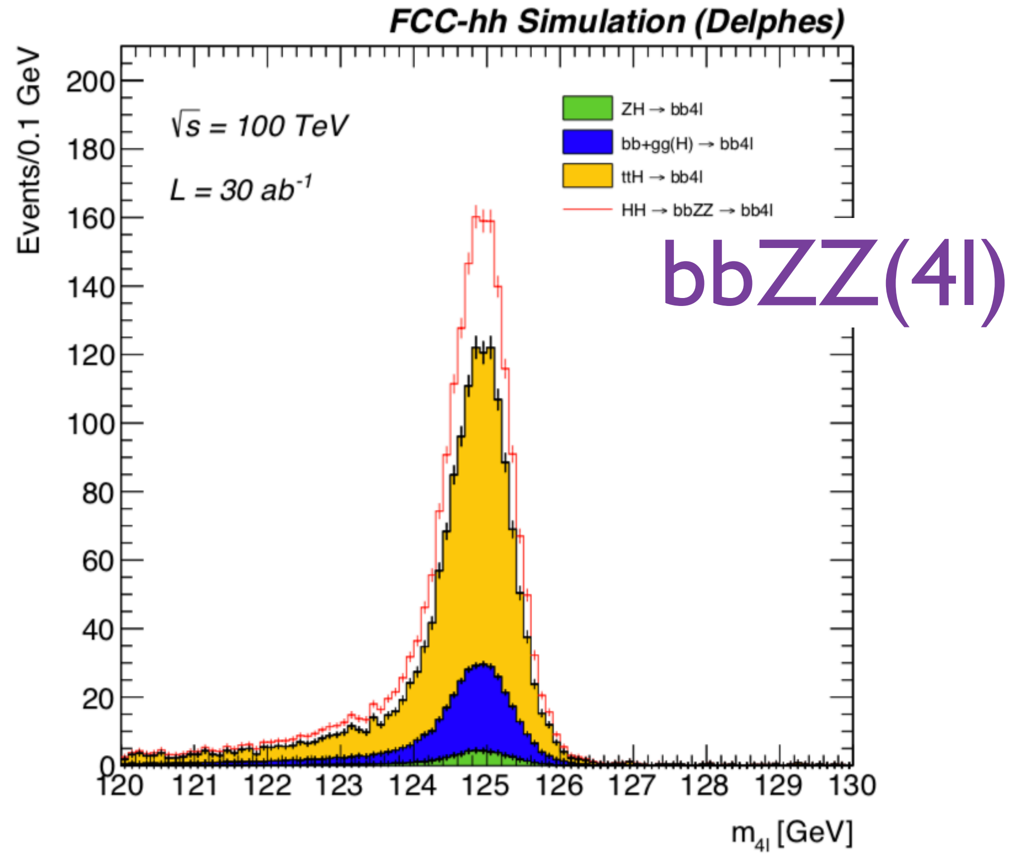
- Channels:
  - bbγγ (golden channel)
  - bbττ
  - bbbb
  - bbZZ(4l)



- Defined 3 scenarios with various detector assumptions and systematics:

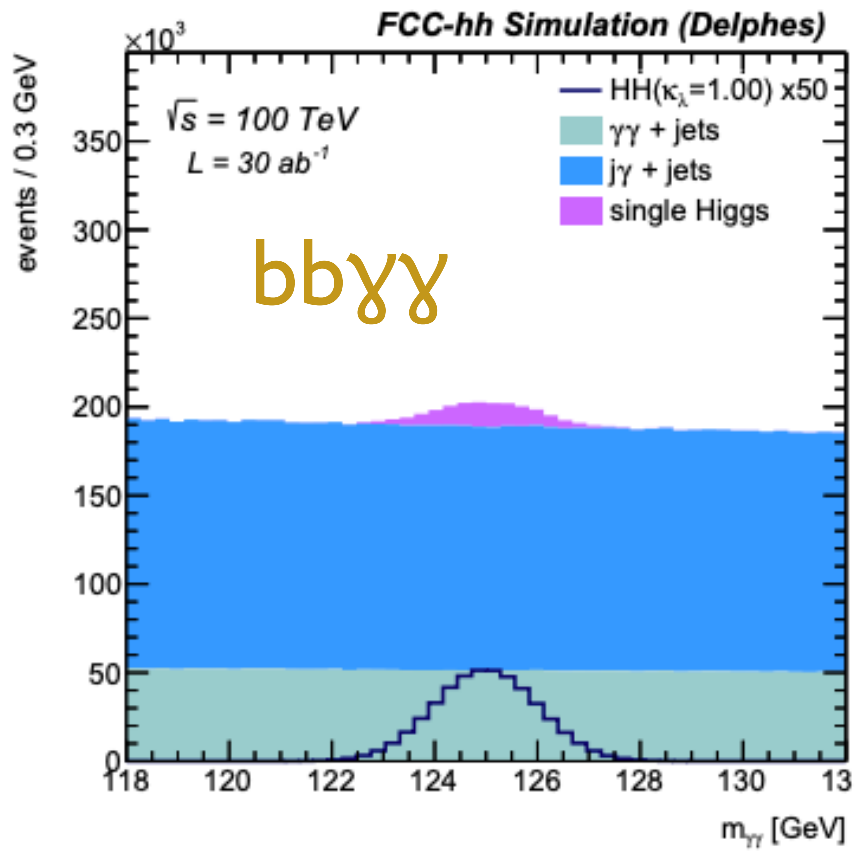


parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\rightarrow \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

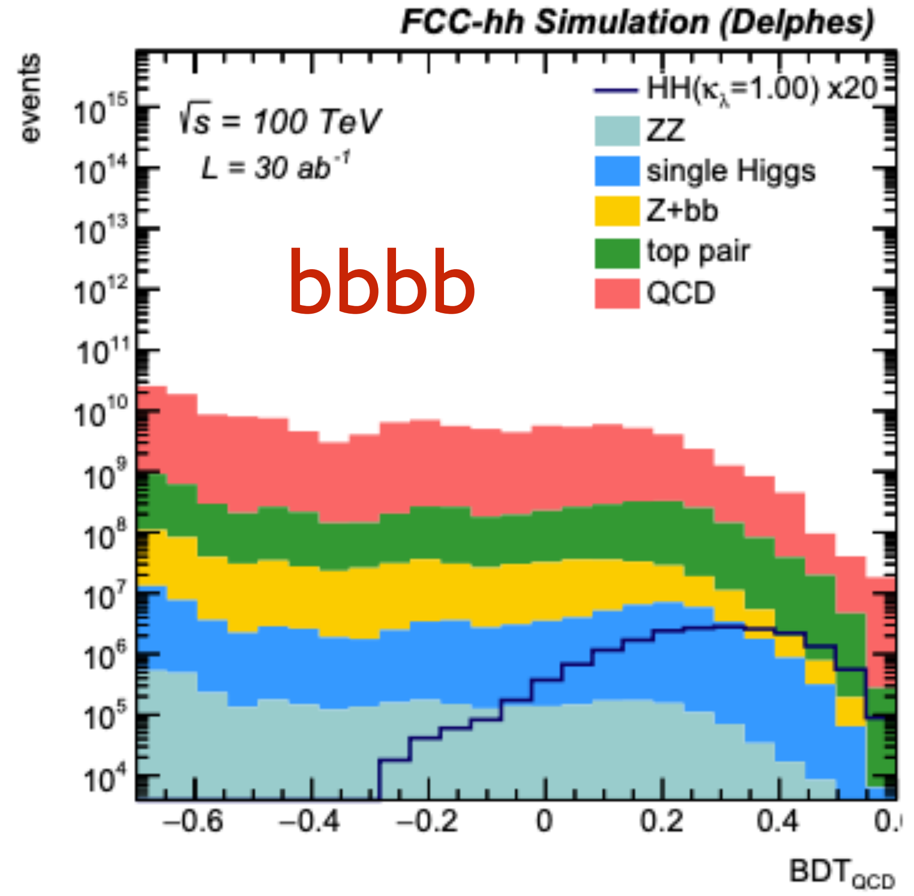


Self-coupling at the FCC-hh

2004.03505 [hep-ph]

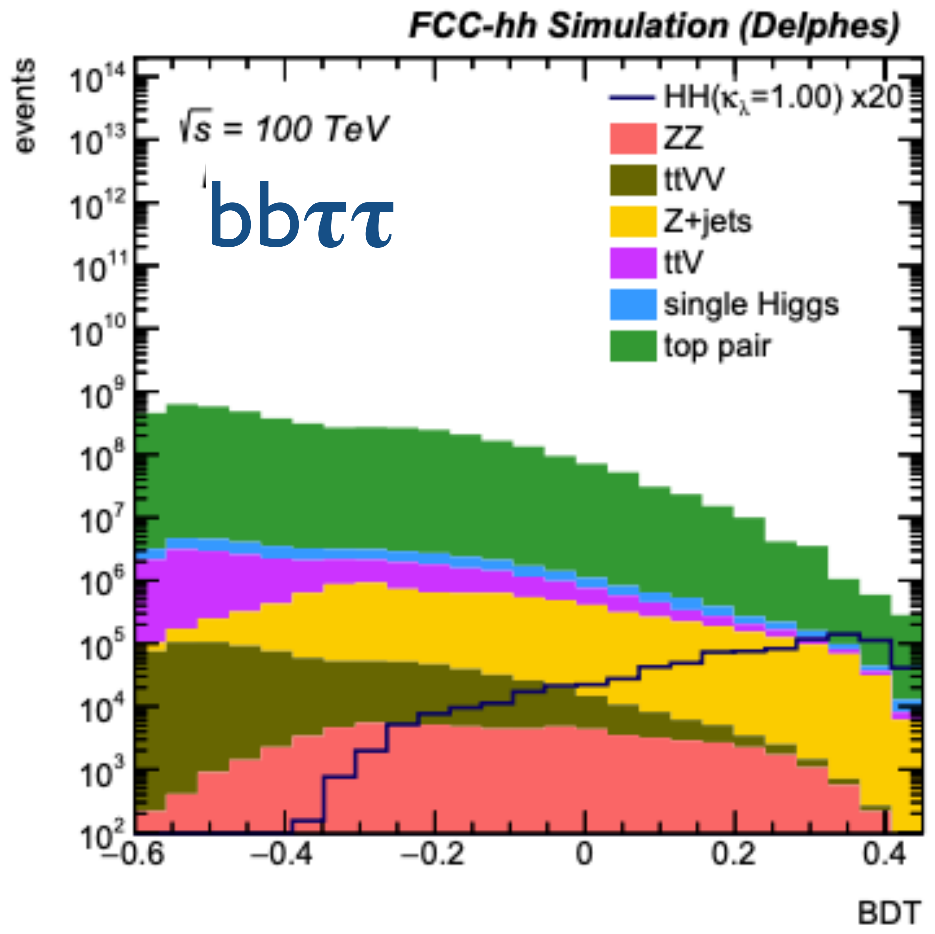


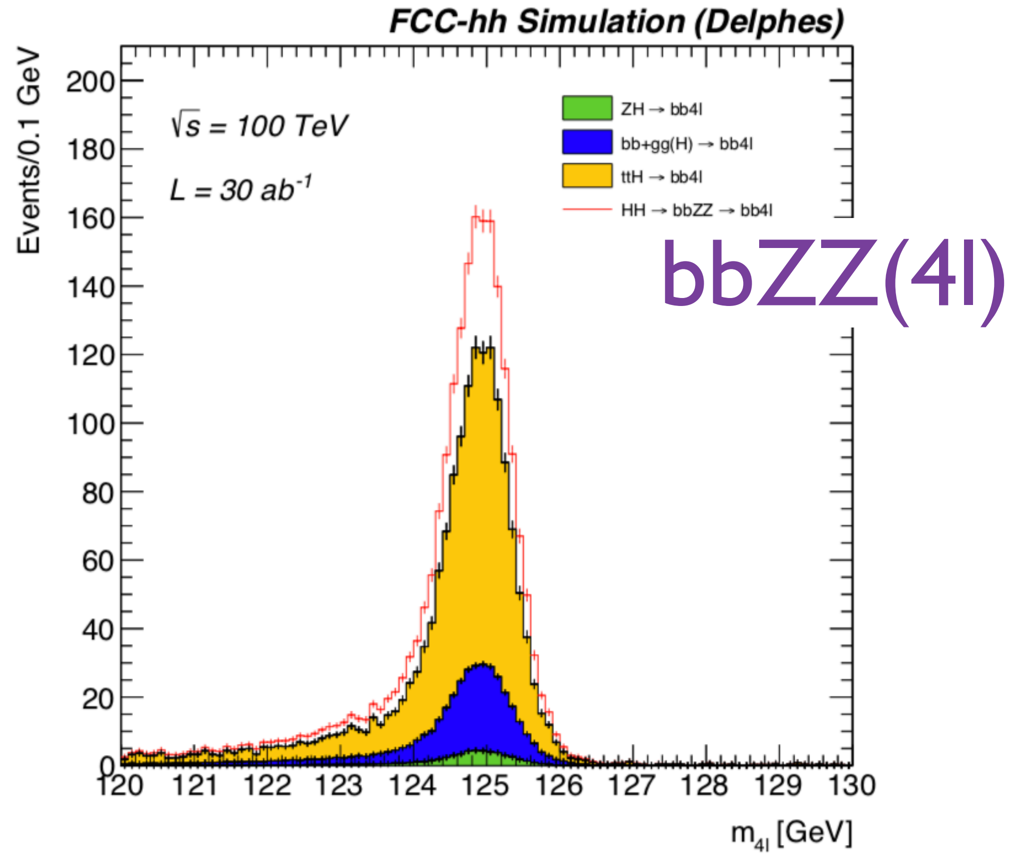
- Channels:
  - bbγγ (golden channel)
  - bbττ
  - bbbb
  - bbZZ(4l)



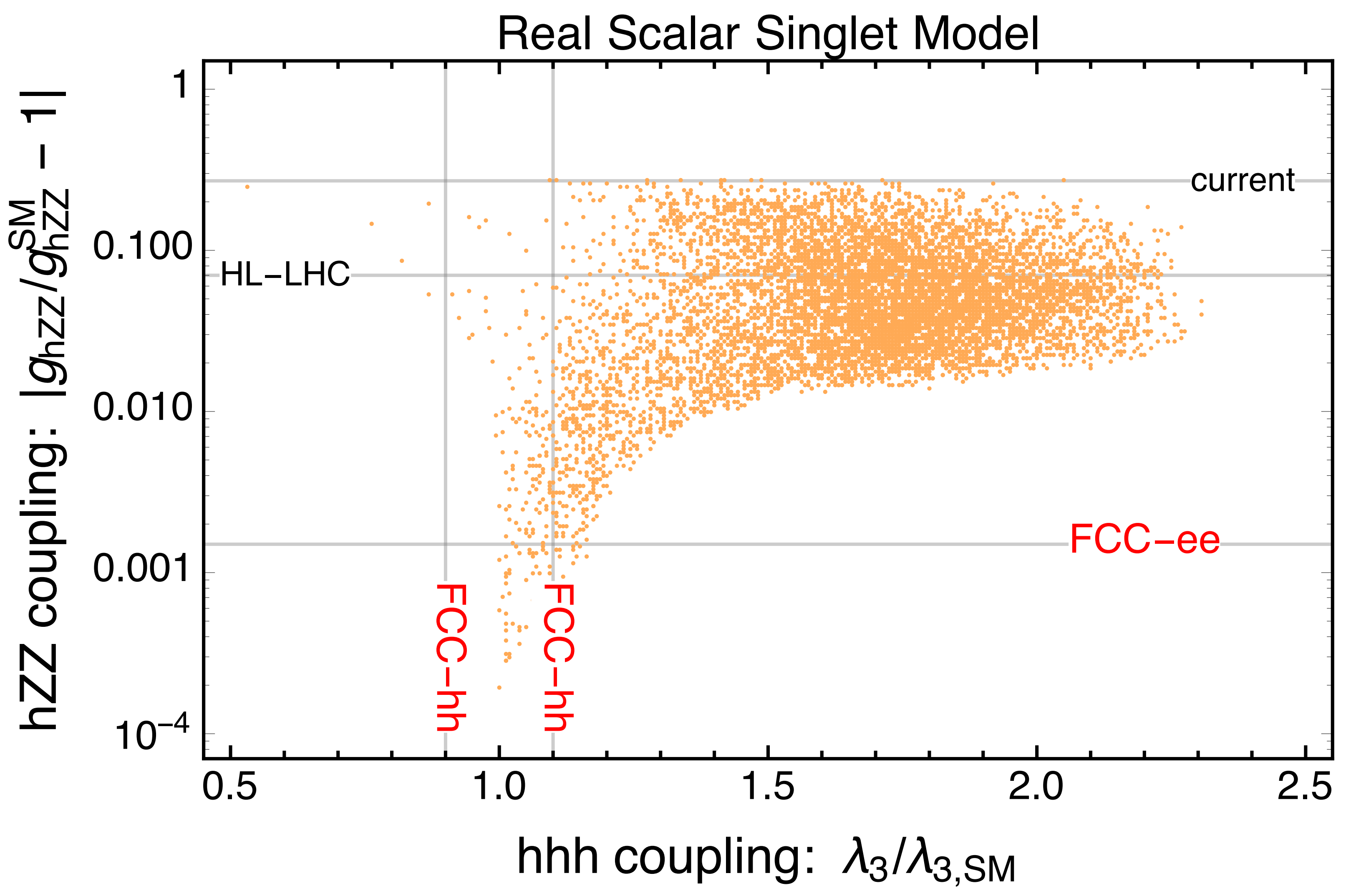
- Defined 3 scenarios with various detector assumptions and systematics:

parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\rightarrow$ γ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

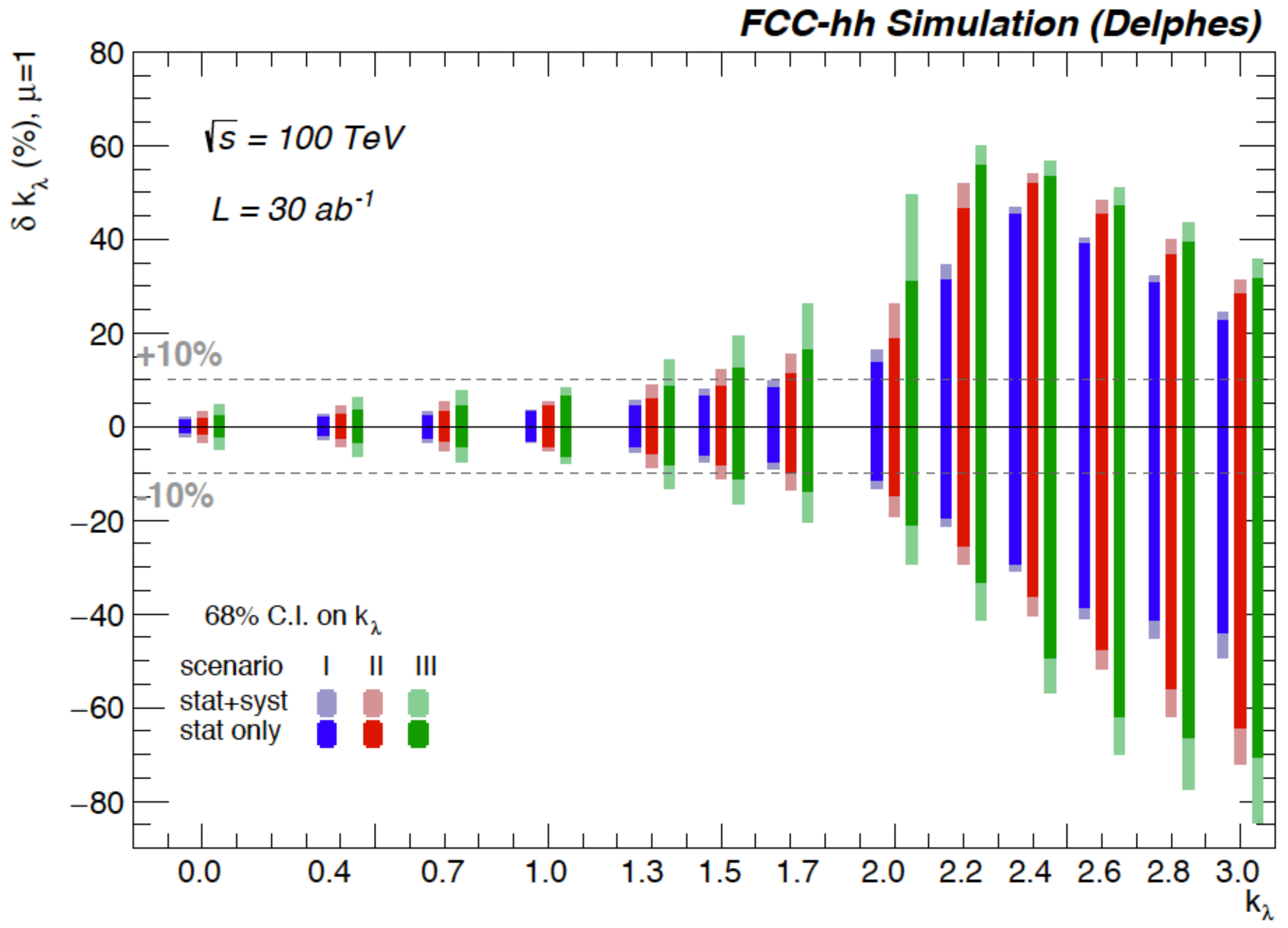




BSM sensitivity



Parameter space scan for a **singlet model extension** of the Standard Model. The points indicate **a first order phase transition**.

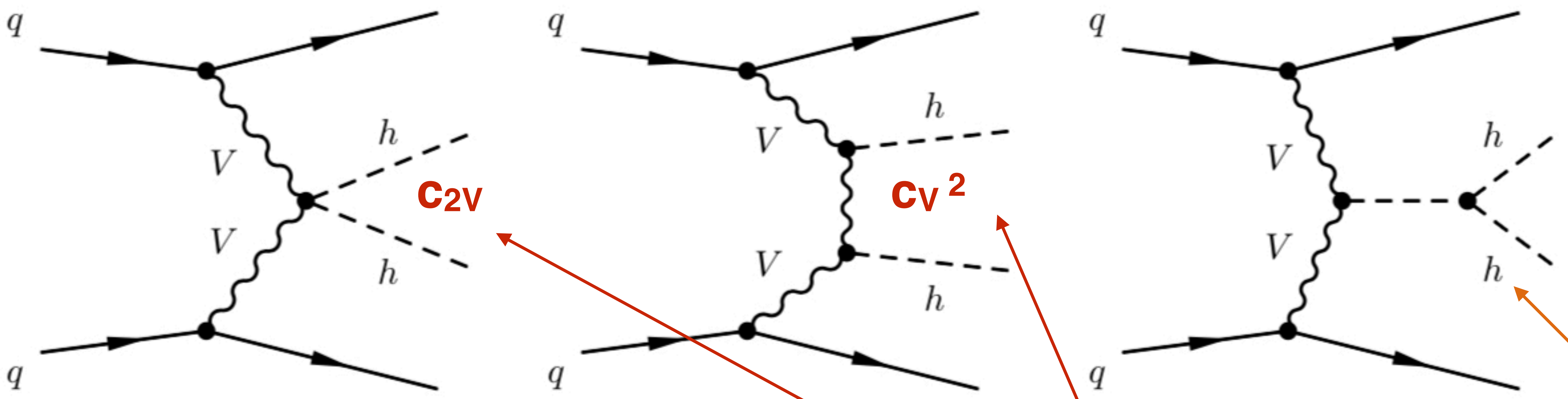


- $\delta\kappa_\lambda^{stat+syst}$ (κ_λ = 1.5) ≈ 10 %
- $\delta\kappa_\lambda^{stat+syst}$ (κ_λ = 1.7) ≈ 15 %
- $\delta\kappa_\lambda^{stat+syst}$ (κ_λ = 2.0) ≈ 20 %

CAVEAT: assumes all SM-like couplings except for trilinear

$W_L W_L \to HH$

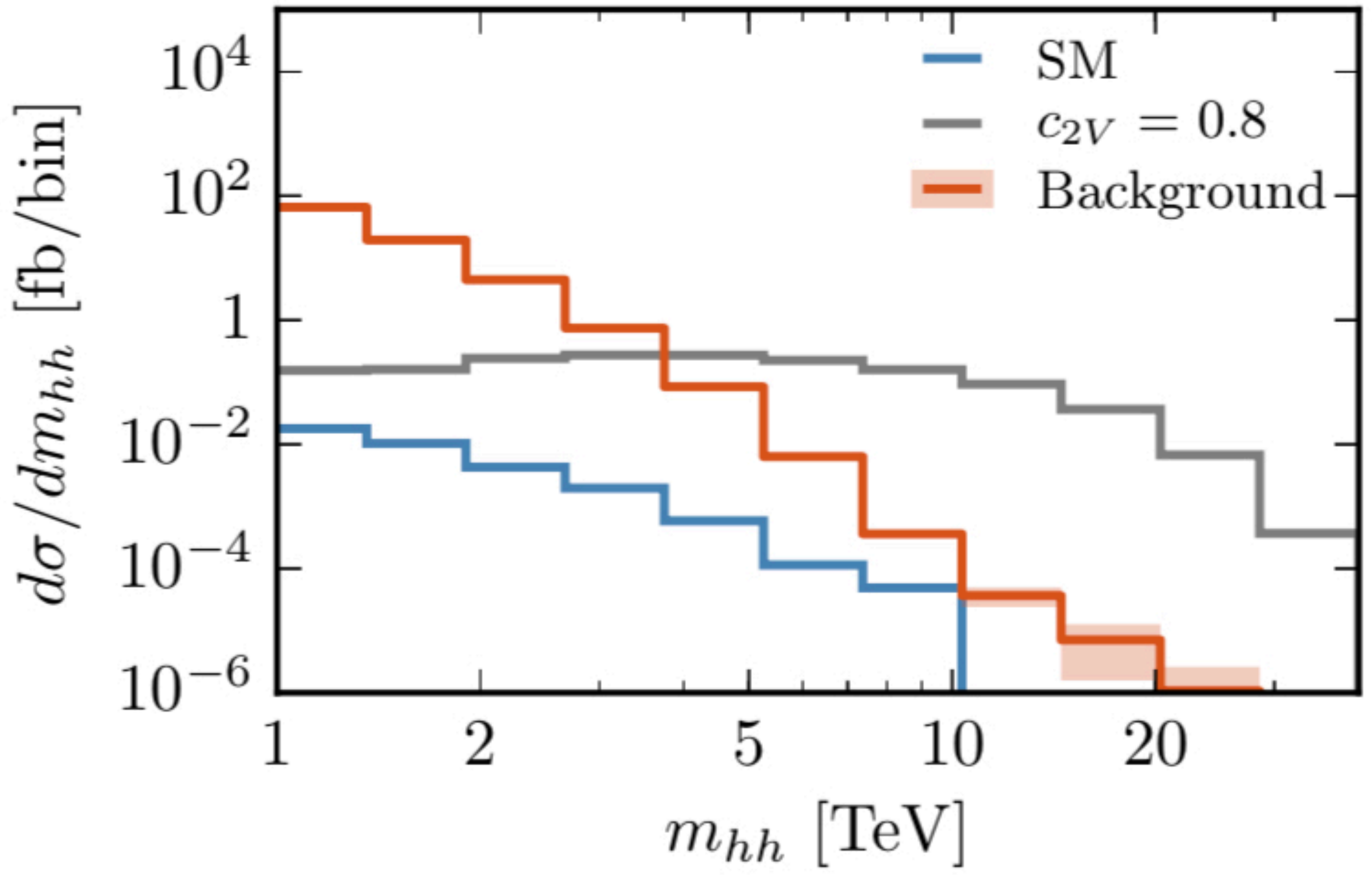
F. Bishara, R. Contino, J. Rojo

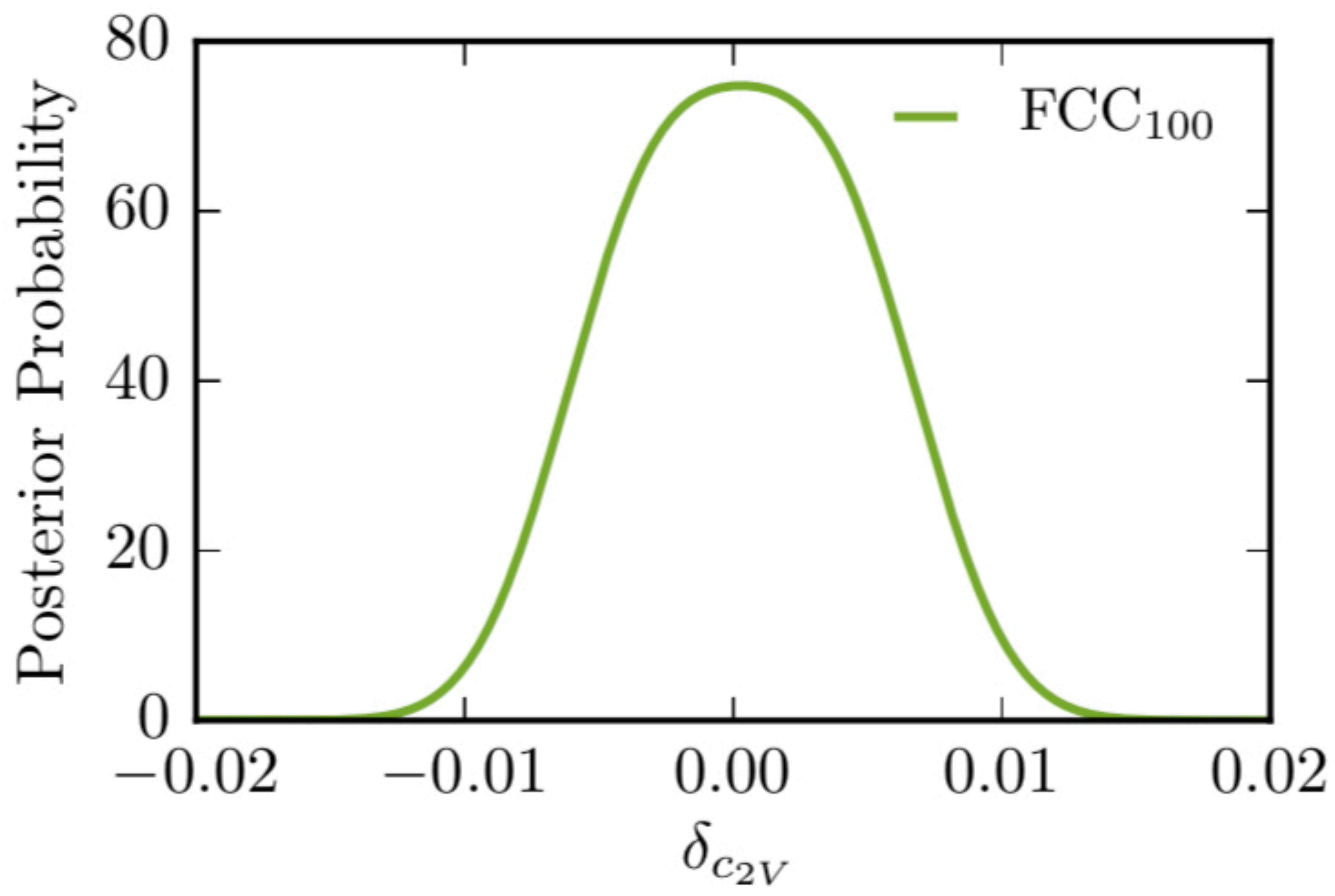


negligible at large m_{HH}

$$A(V_L V_L \to HH) \sim \frac{\hat{s}}{v^2}\underbrace{(c_{2V} - c_V^2)}_{\text{0 in the SM}} + \mathcal{O}(m_W^2/\hat{s}),$$

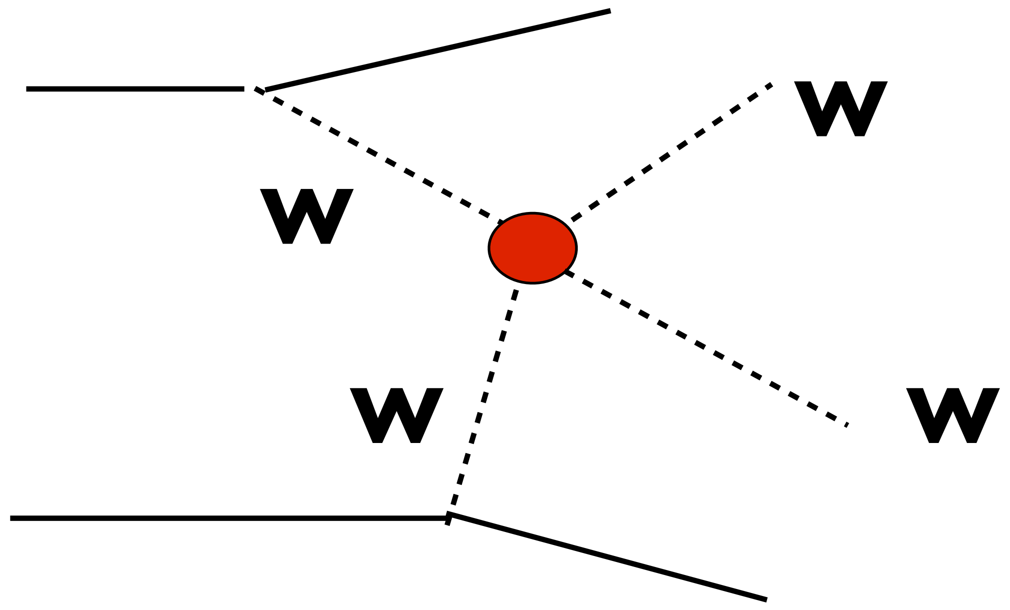
high energy behaviour driven by C_{2V} and C_V, if $\delta C_{2V} \neq 0$, grows with E





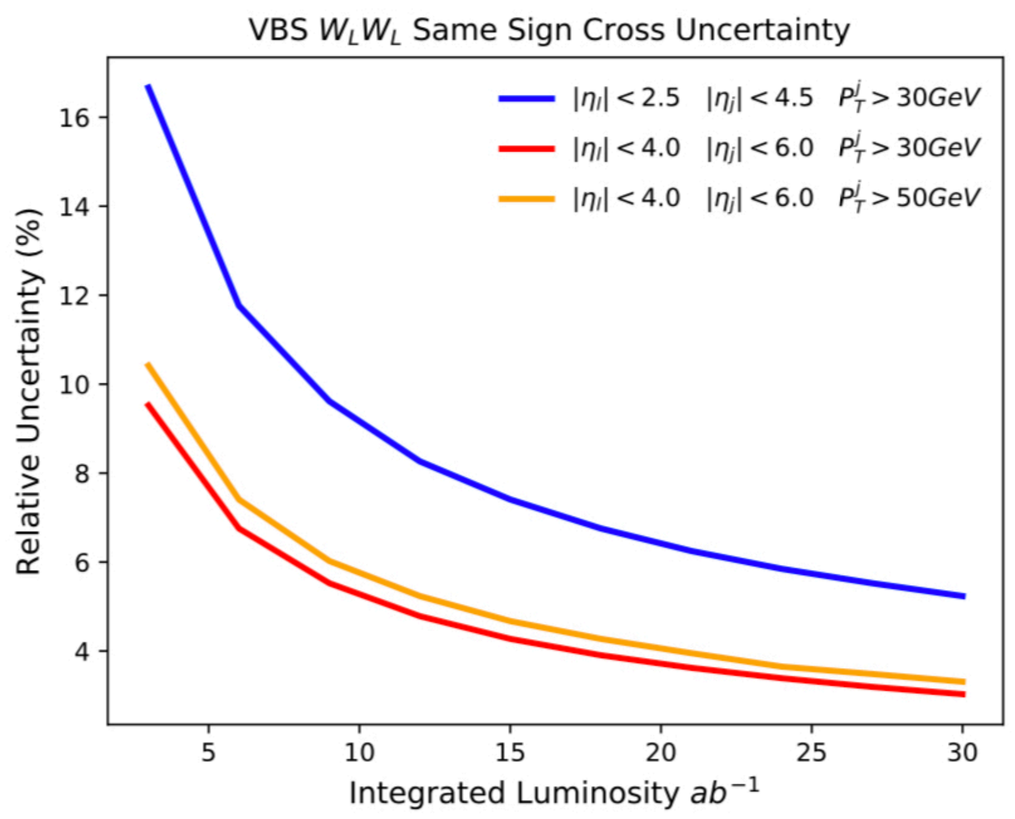
With c_V from FCC-ee, $\delta c_{2V} < 1\%$

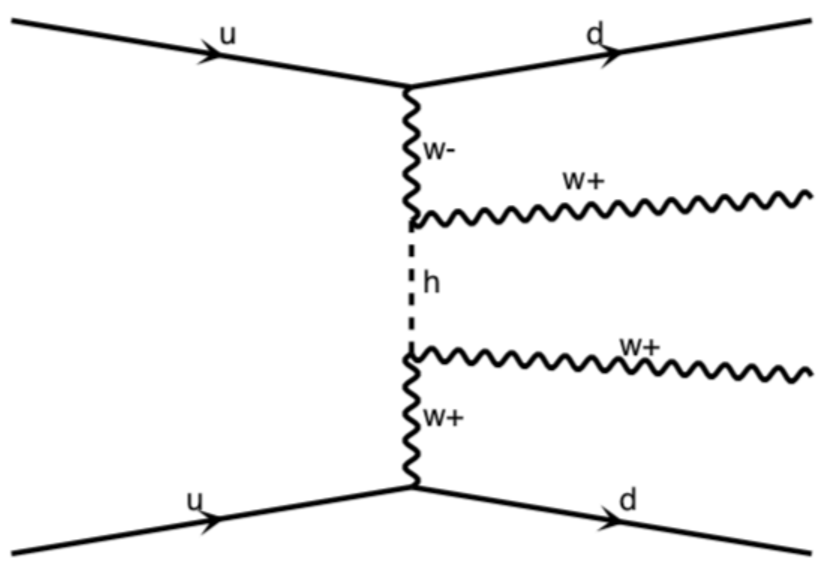
Vector Boson Scattering



large m_{WW}

- Sets constraints on **detector acceptance** (fwd jets at **$\eta \approx 4$**)
- Study **$W^{+/-}W^{+/-}$ (same-sign)** channel
- **Large WZ** background at FCC-hh
- **3-4% precision on W_LW_L scattering** xsec. achievable with full dataset (only 3σ HL-LHC)
- Indirect measurement of HWW coupling possible, **$\delta\kappa_W / \kappa_W \approx 2\%$**





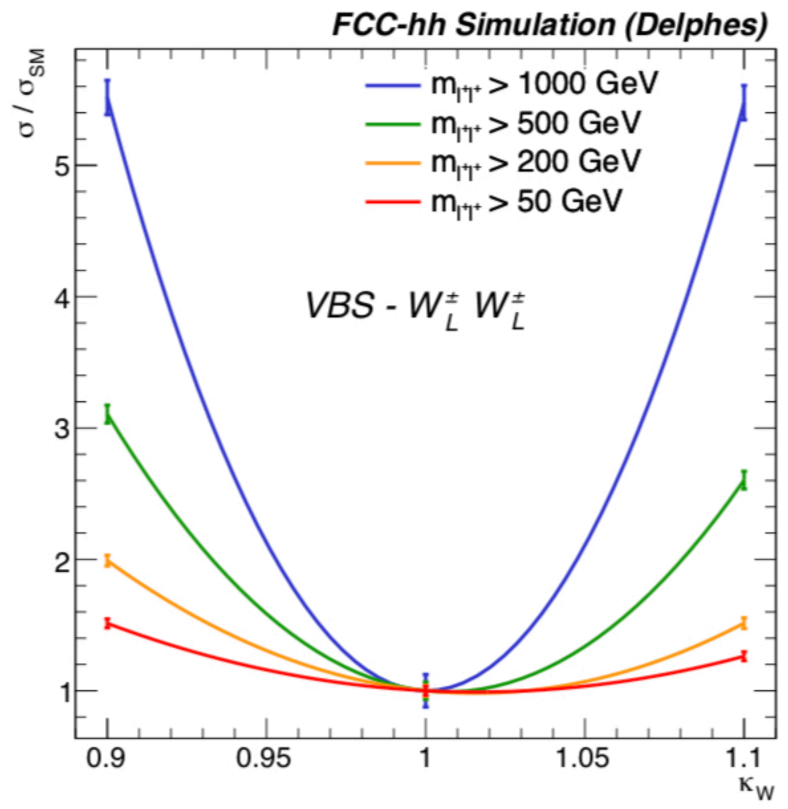


Table 4.5: Constraints on the HWW coupling modifier κ_W at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the $W_LW_L \rightarrow HH$ process.

$m_{l^+l^+}$ cut	> 50 GeV	> 200 GeV	> 500 GeV	> 1000 GeV
$\kappa_W \in$	[0.98,1.05]	[0.99,1.04]	[0.99,1.03]	[0.98,1.02]

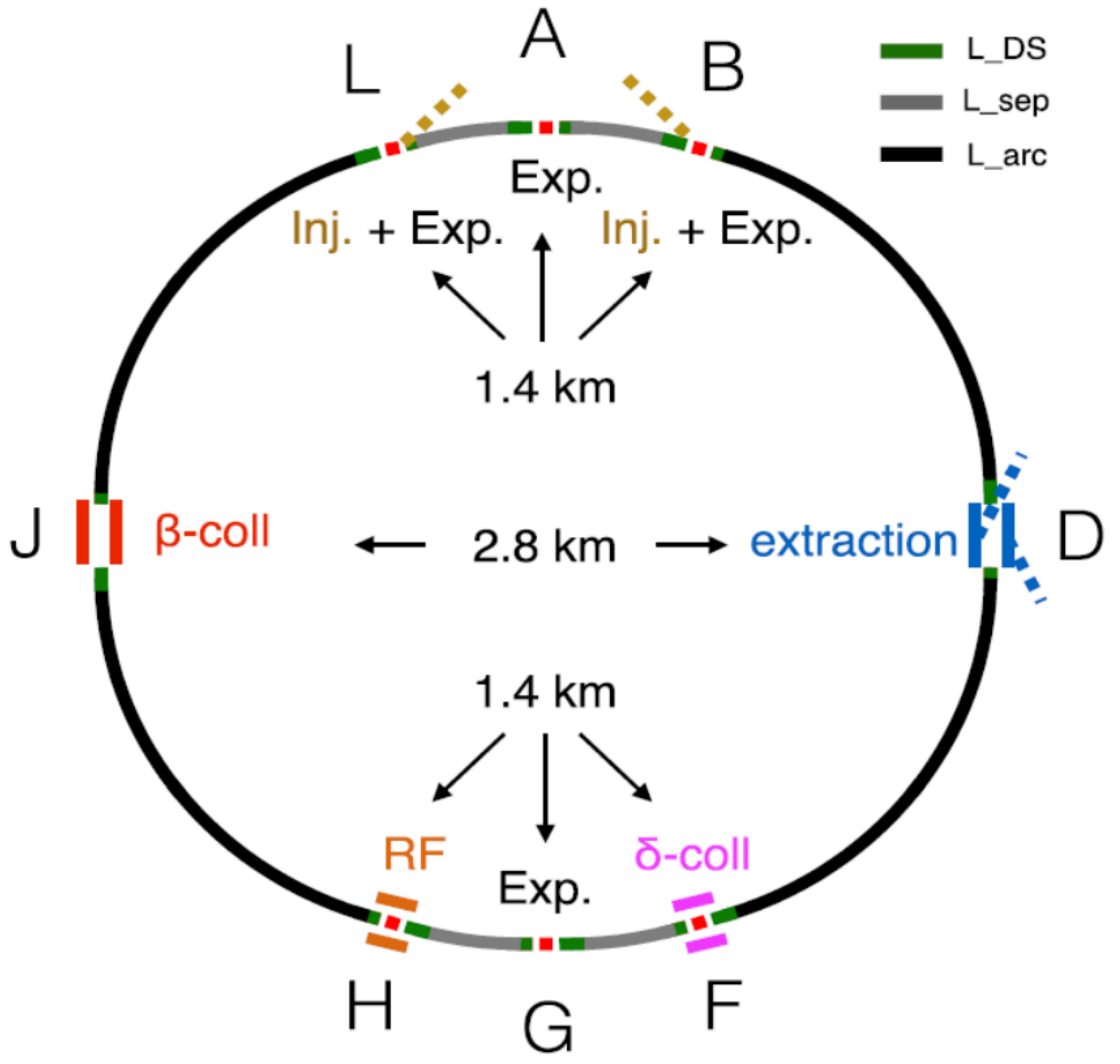
Possible future colliders: FCC-hh

- Circumference = 100 km
- Need dipoles that generate B = 16 T

$\sqrt{s}$ = 100 TeV

8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- O(20) times LHC

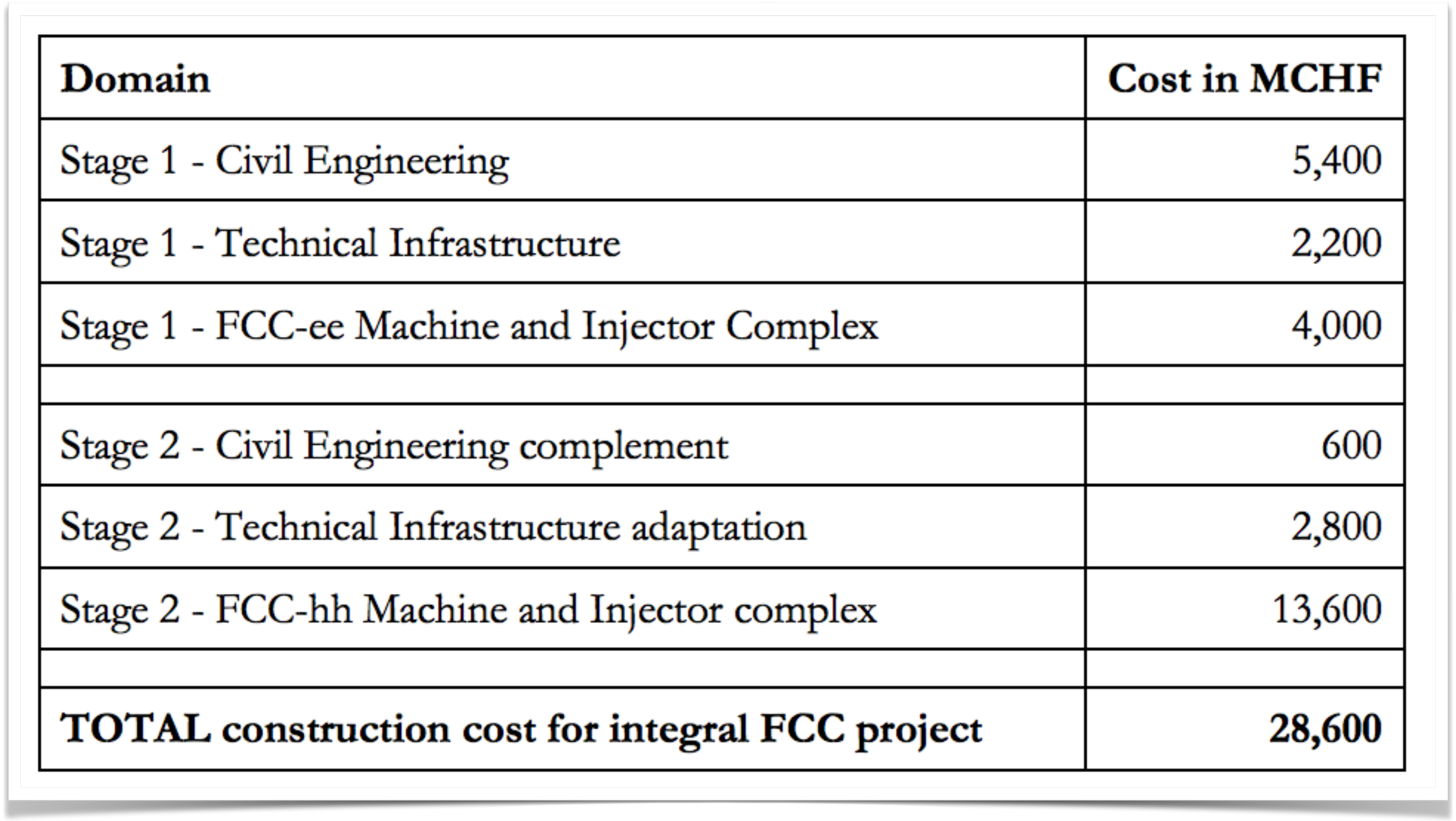
	FCC-hh Initial	FCC-hh Ultimate
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [µm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [µm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4



In its high luminosity phase, FCC-hh produces **1000 PU interactions** per bunch crossing

The FCC project (rationale)

- HL-LHC data-taking ends in 2035
- Build a 100 km tunnel
- If magnets are ready by ~ 2040 go for FCC-hh
- If not FCC-ee ~20 yrs
- then FCC-hh ~20 yrs



Domain	**Cost in MCHF**
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**

~1 espresso/year/person

- 100 km tunnel ensures HEP field activities for ~ 60 yrs
- FCC-ee → FCC-hh → FCC-xx (x=μ)
- Long term accelerator complex easier to fund on flat budget