European Strategy for Particle Physics

PLENARY: Electroweak Physics

The Electroweak physics landscape beyond the LHC: Open questions and exploration at future colliders

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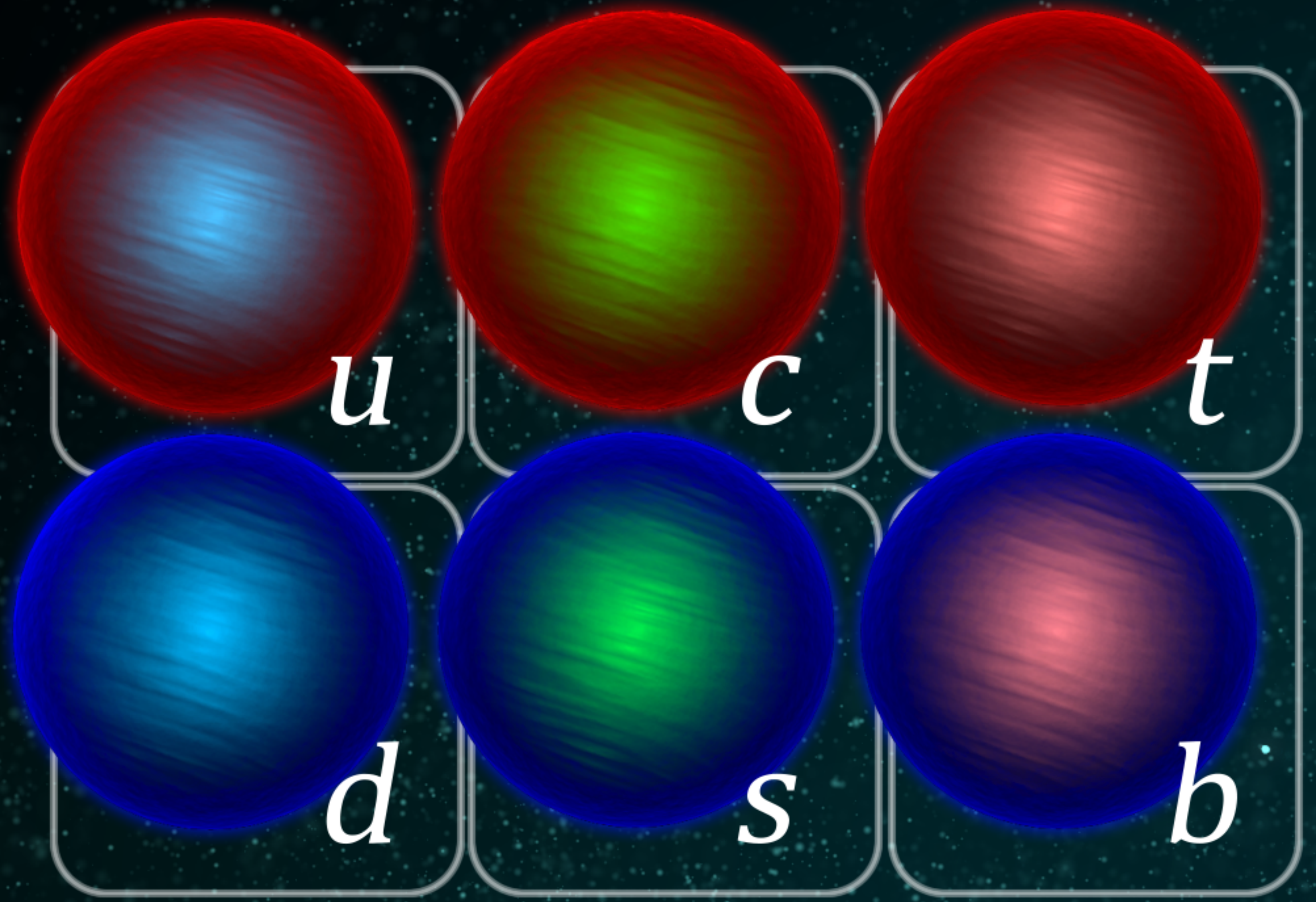
23-27 JUNE 2025 Lido di Venezia

The physics we are after

What we need to get there?

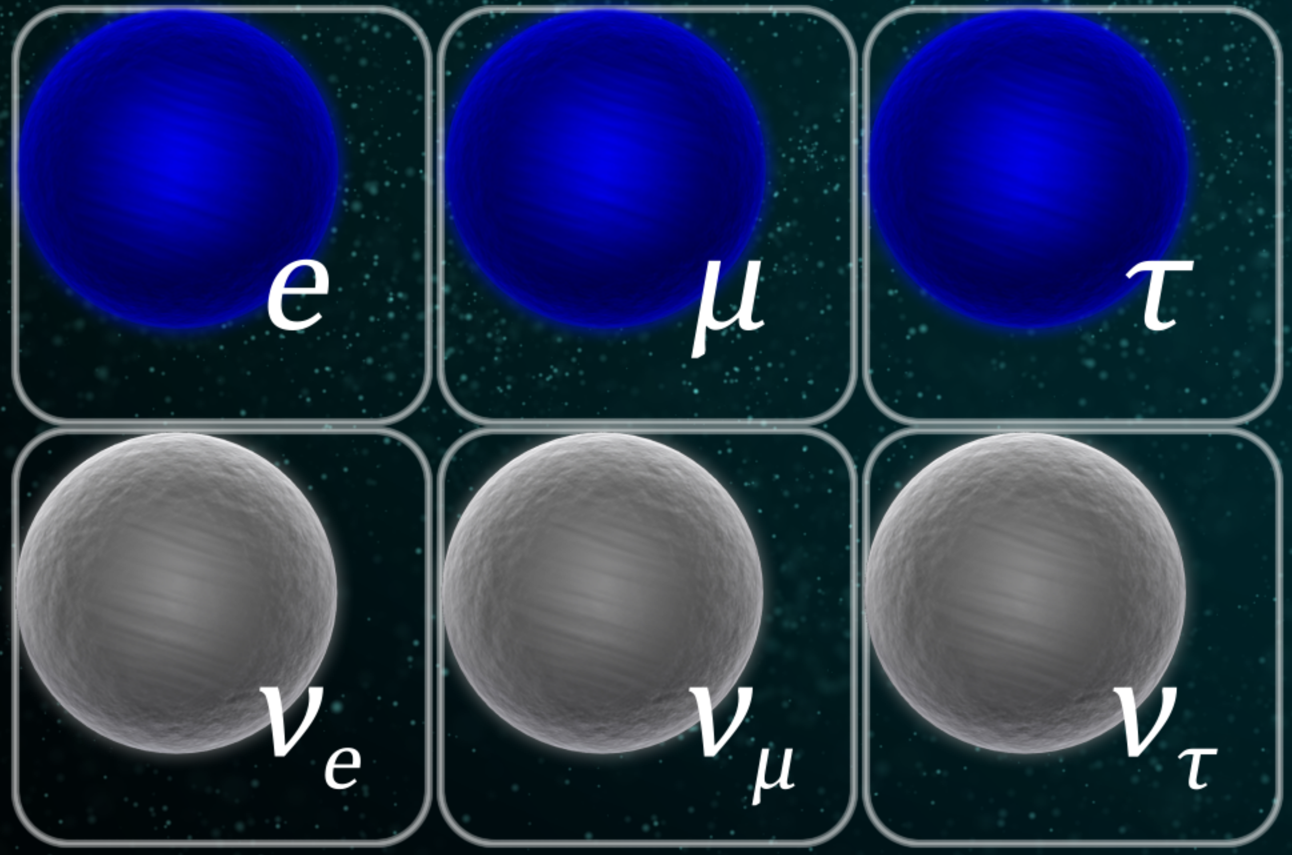


Breaking electroweak symmetry

Evolution of the cosmos

Establish the Higgs mechanism

Origin of flavour



Composite Higgs?

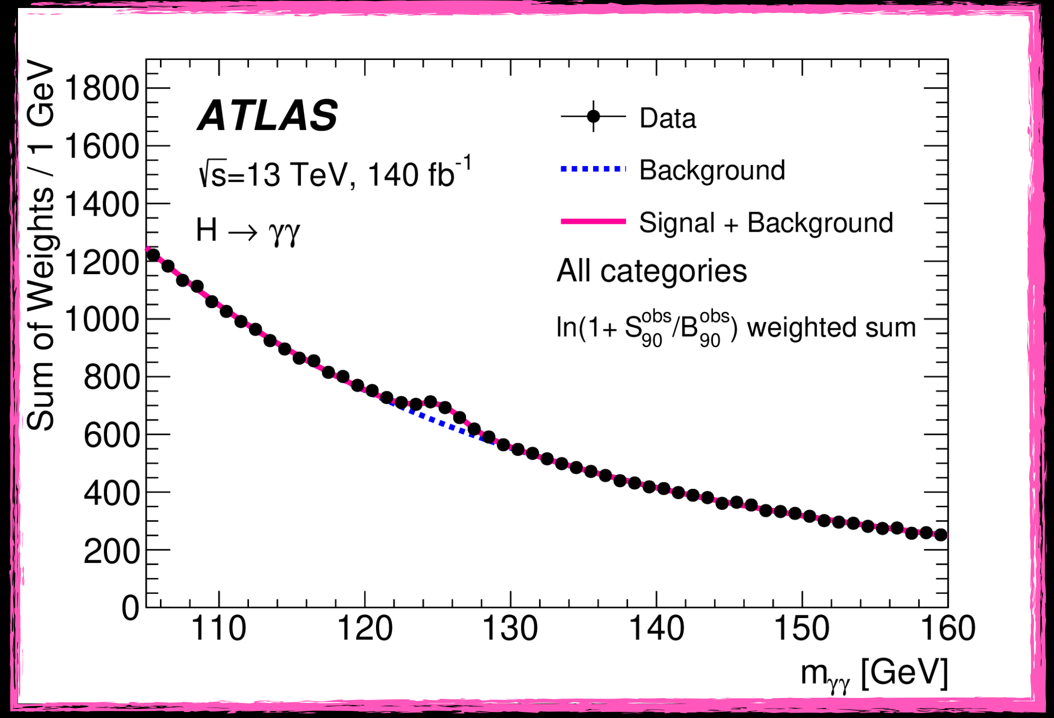
Additional phenomenon?

Stability of the Universe

Additional particles?

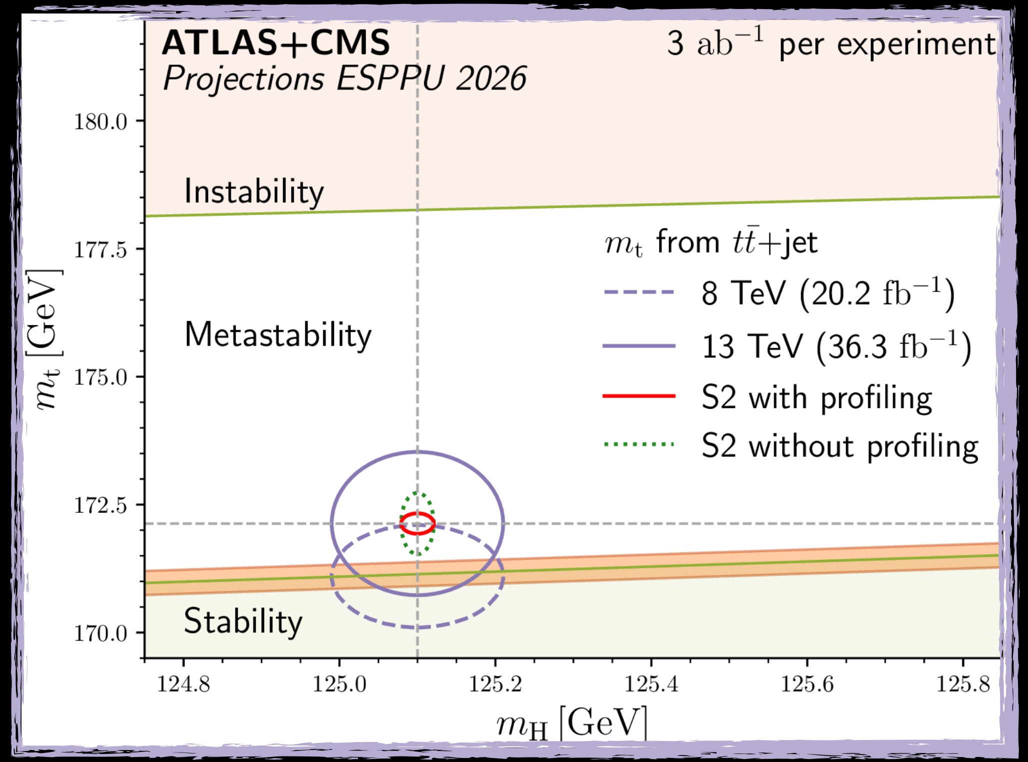
Matter and Antimatter asymmetry

Breaking Electroweak symmetry



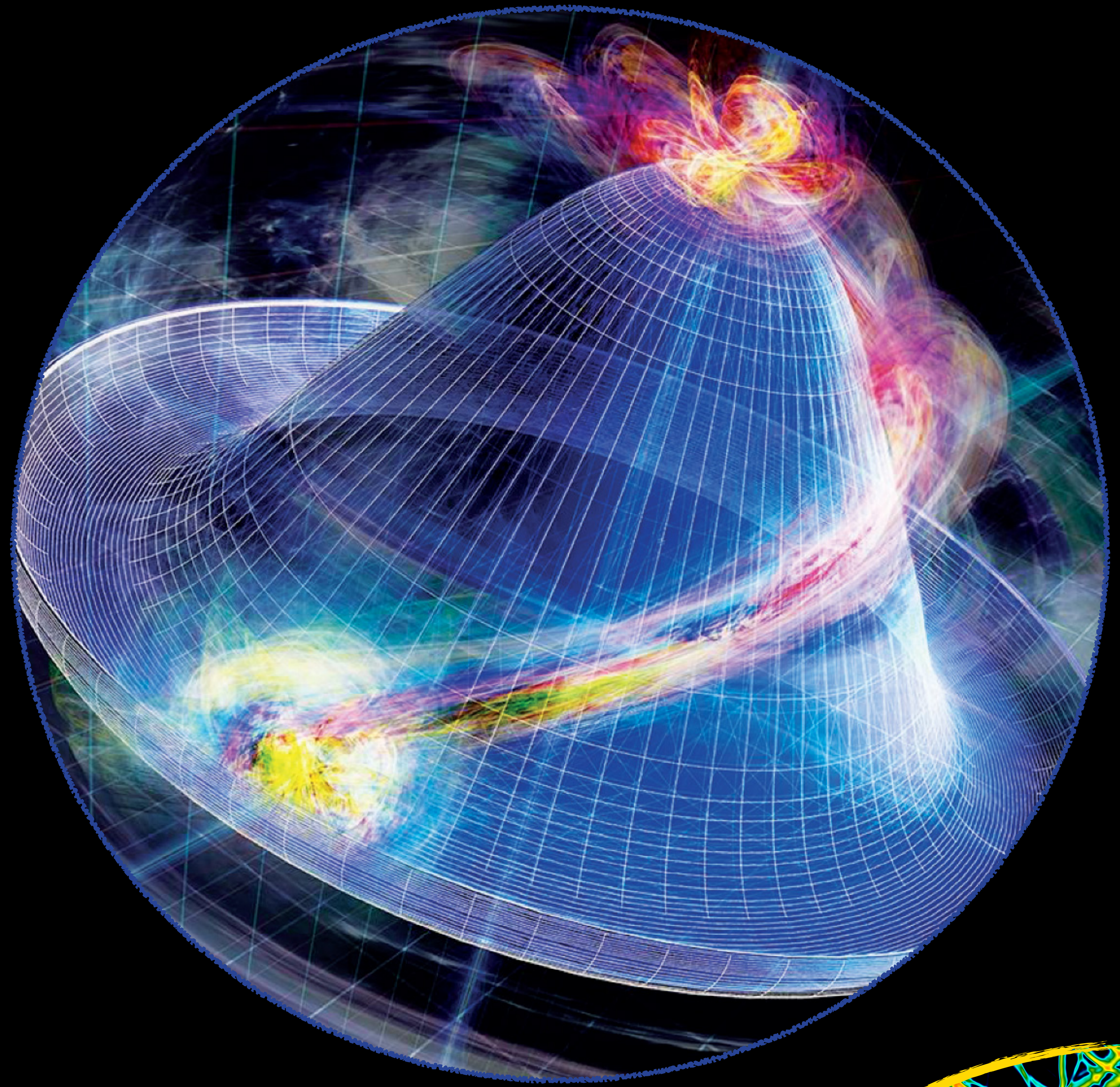
Precision Higgs

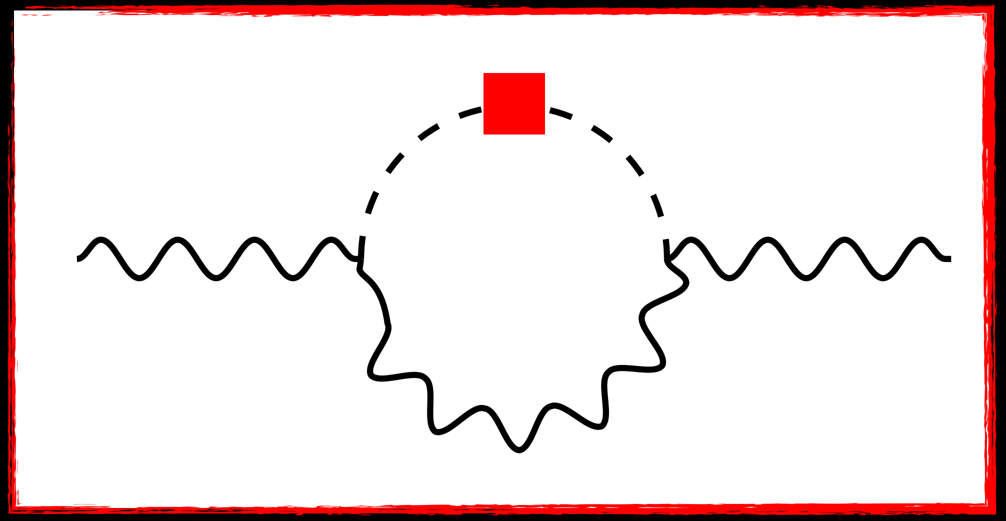
Precision Masses

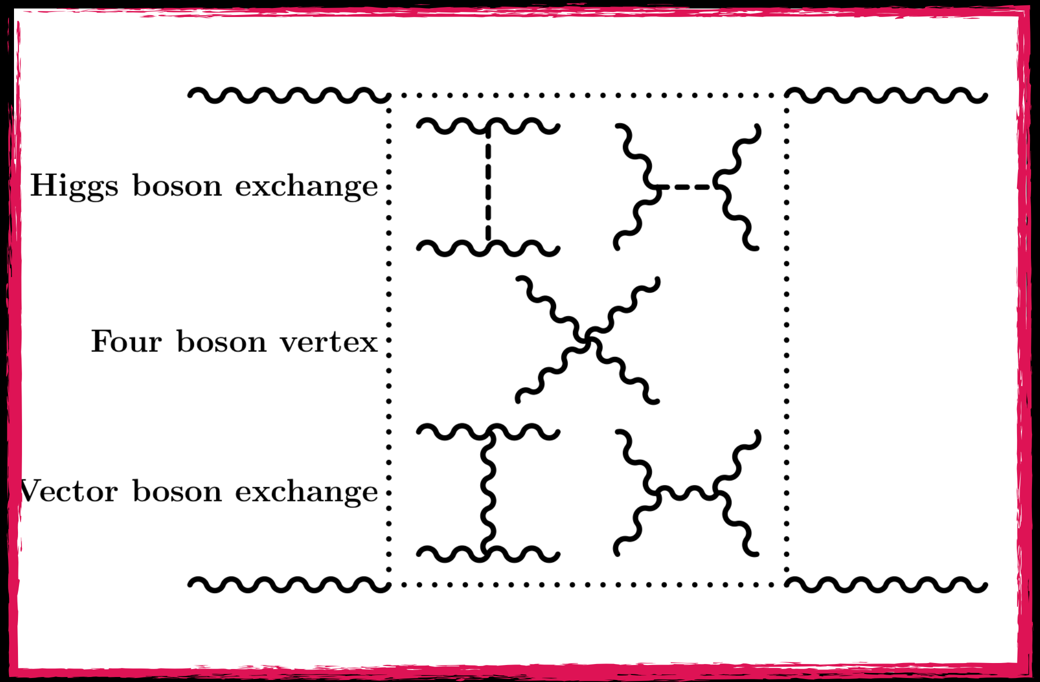


Precision Top

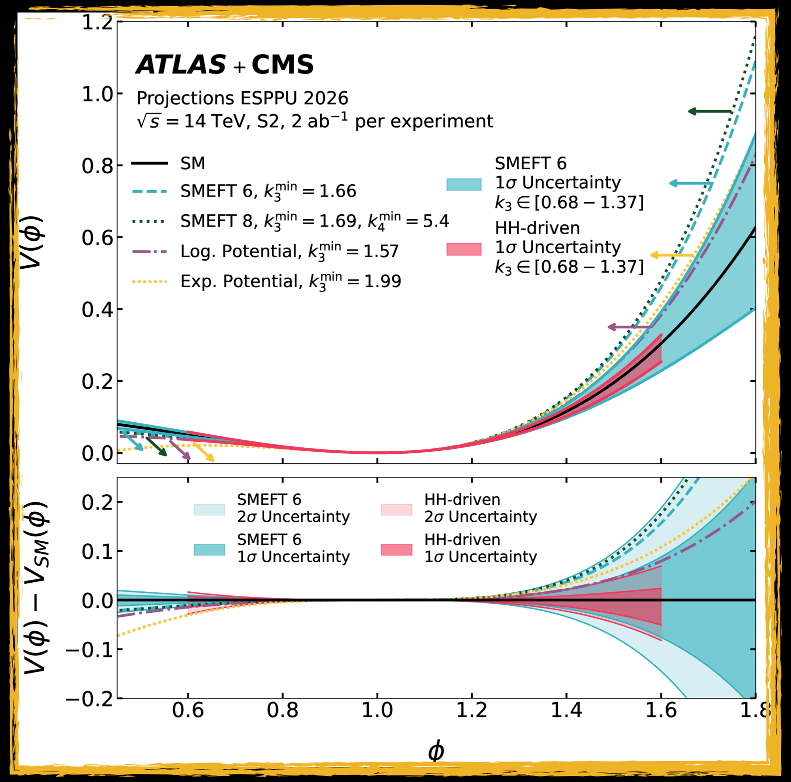
SM consistency tests



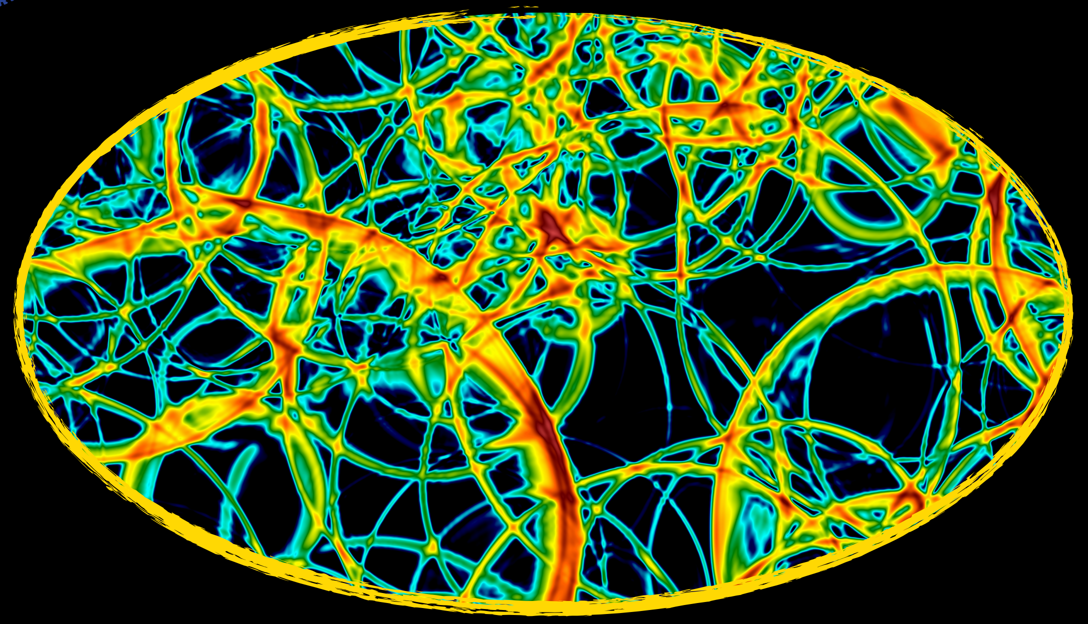




Vector boson polarisation



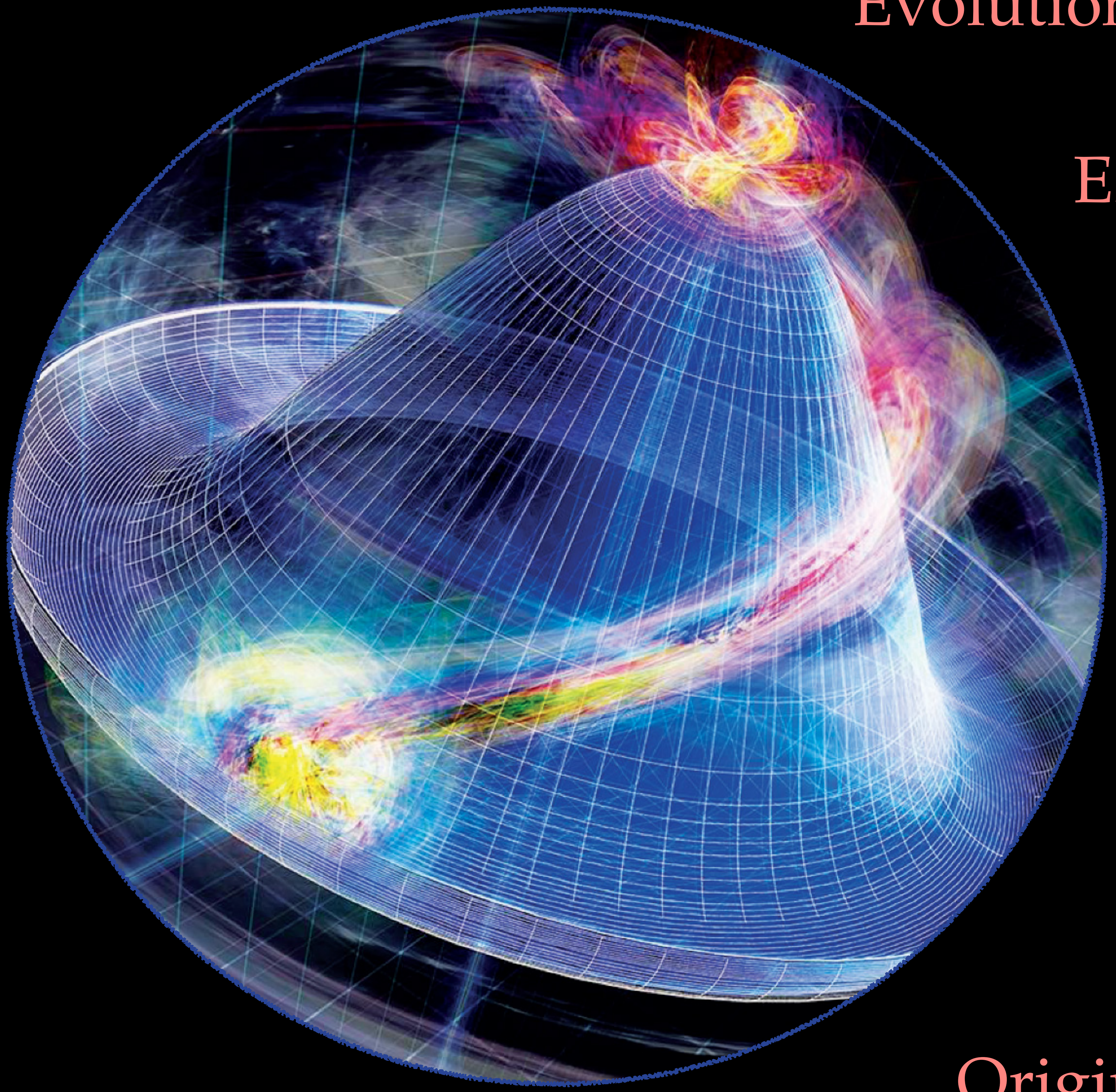
Higgs self-coupling



Extended Higgs sector

Outline

- Higgs couplings
- Top
- Higgs self-coupling
- Weak couplings



Breaking electroweak symmetry

Evolution of the cosmos

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Additional phenomenon?

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Matter and Antimatter asymmetry

The High-Lumi LHC

The upcoming Higgs factory

Run 1

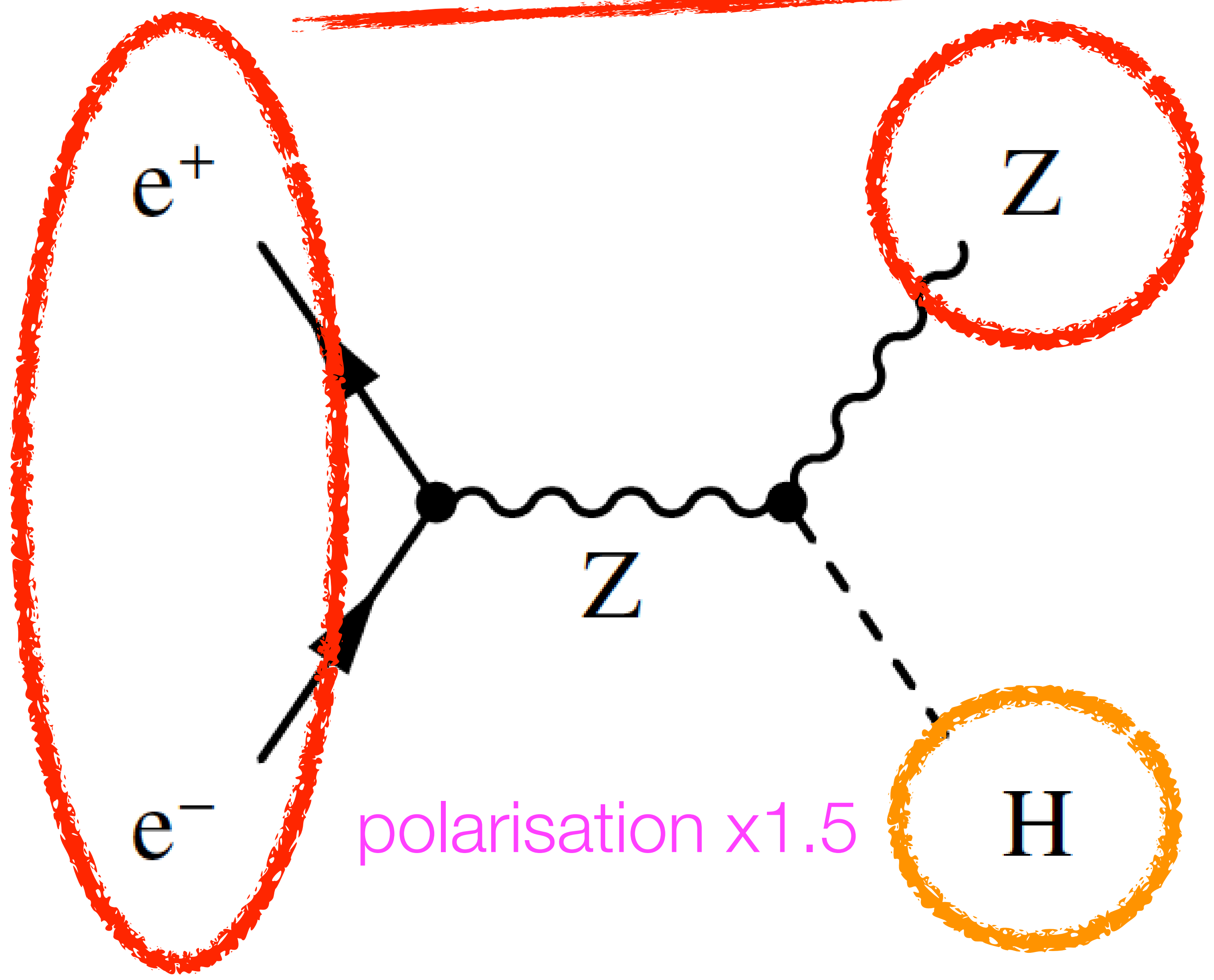
Run 2

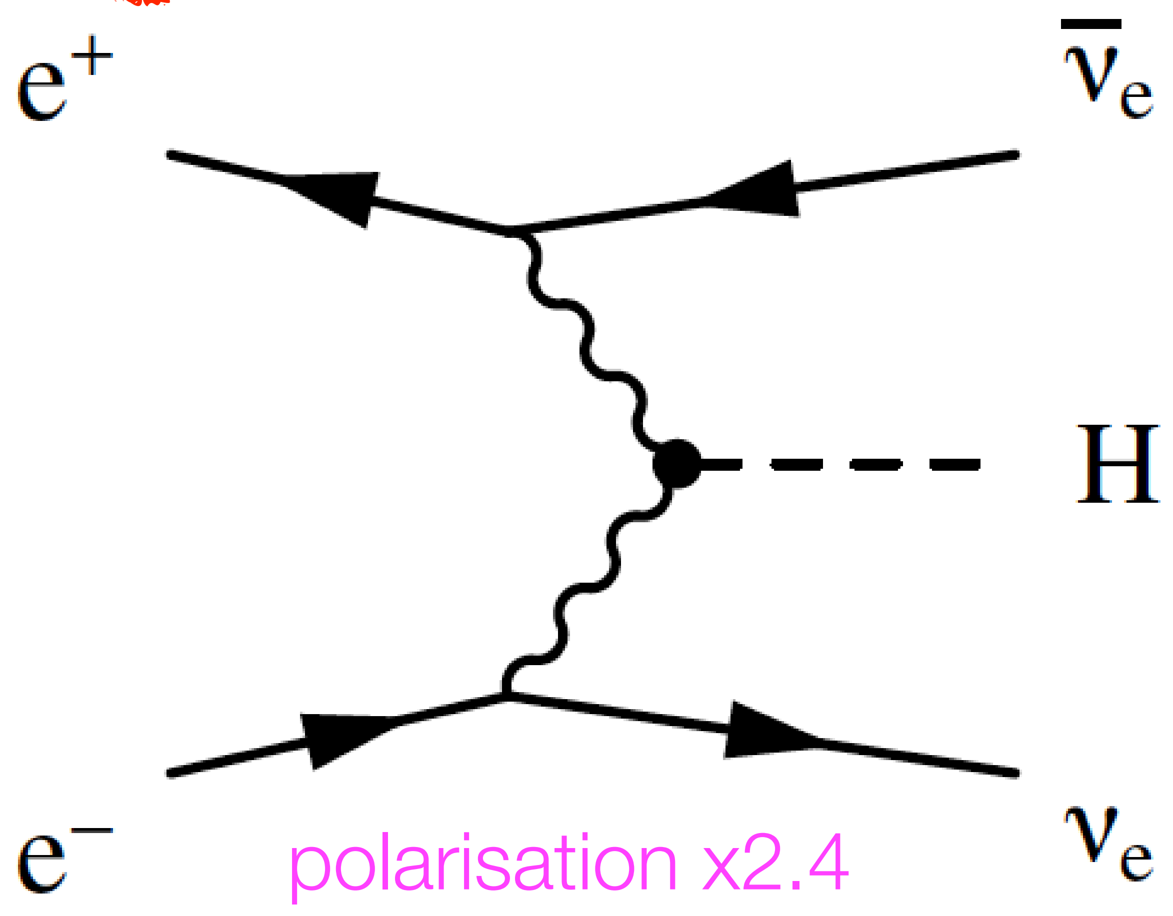
Run 3: We are here

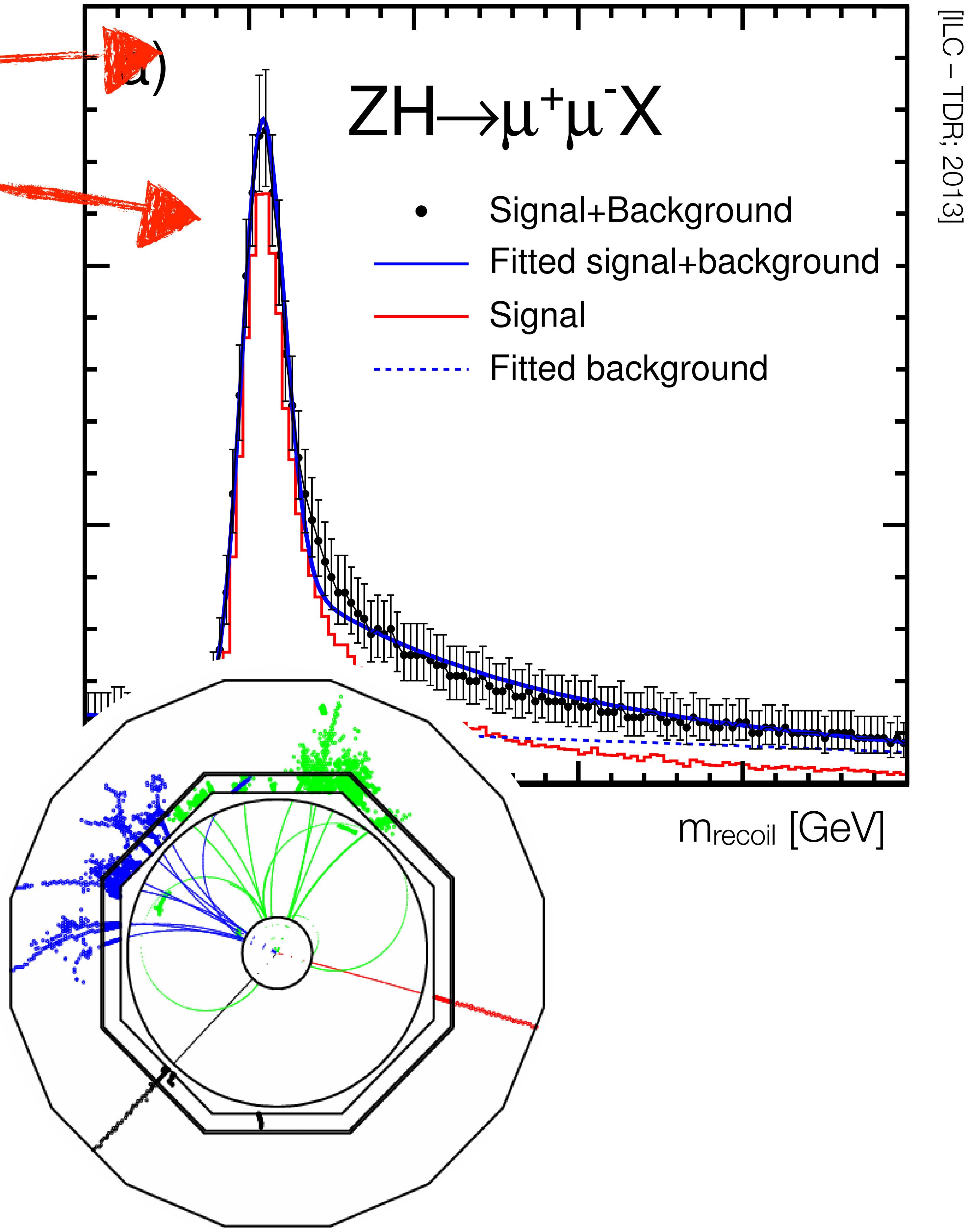
HL-LHC: 14 TeV
6000 fb-1 (ATLAS+CMS)

	# of exp.	Z-pole (91.2 GeV)	WW (160 GeV)	Higgs (230-250 GeV)	Top (365 GeV)	Higher energy
FCC-ee	4	205 ab^{-1} (total, all IP) 4 years (of operation)	19 ab^{-1} 2 years	11 ab^{-1} 3 years	3 ab^{-1} 5 years	—
Linear collider	2	0.07 ab^{-1} 1 years	—	3 ab^{-1} 3 years	CLIC: 4.4 ab^{-1} 10 years	550 GeV: 8 ab^{-1} 1 TeV+: 4-8 ab^{-1} 10 years
LEP3	2	53 ab^{-1} 5 years	5 ab^{-1} 4 years	2.5 ab^{-1} 6 years	—	—
FCC-hh	4	—	—	—	—	84.6 TeV 30 ab^{-1}
LHeC	1	—	—	—	—	1.2 TeV 1 ab^{-1} 6 years
Muon	2	—	—	—	—	3-10 TeV 1-10 ab^{-1} 8 years

Higgs Production: electron-positron colliders







Total Cross Section:
[from recoil mass]

$$\sigma(ee \to HZ) \propto g^2_{\mathrm{HZZ}}$$

Exclusive Production:
[from individual H-decays]

$$\sigma(ee \to HZ) \times BR(H \to XX) \propto g^2_{\mathrm{HZZ}} \cdot \frac{g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

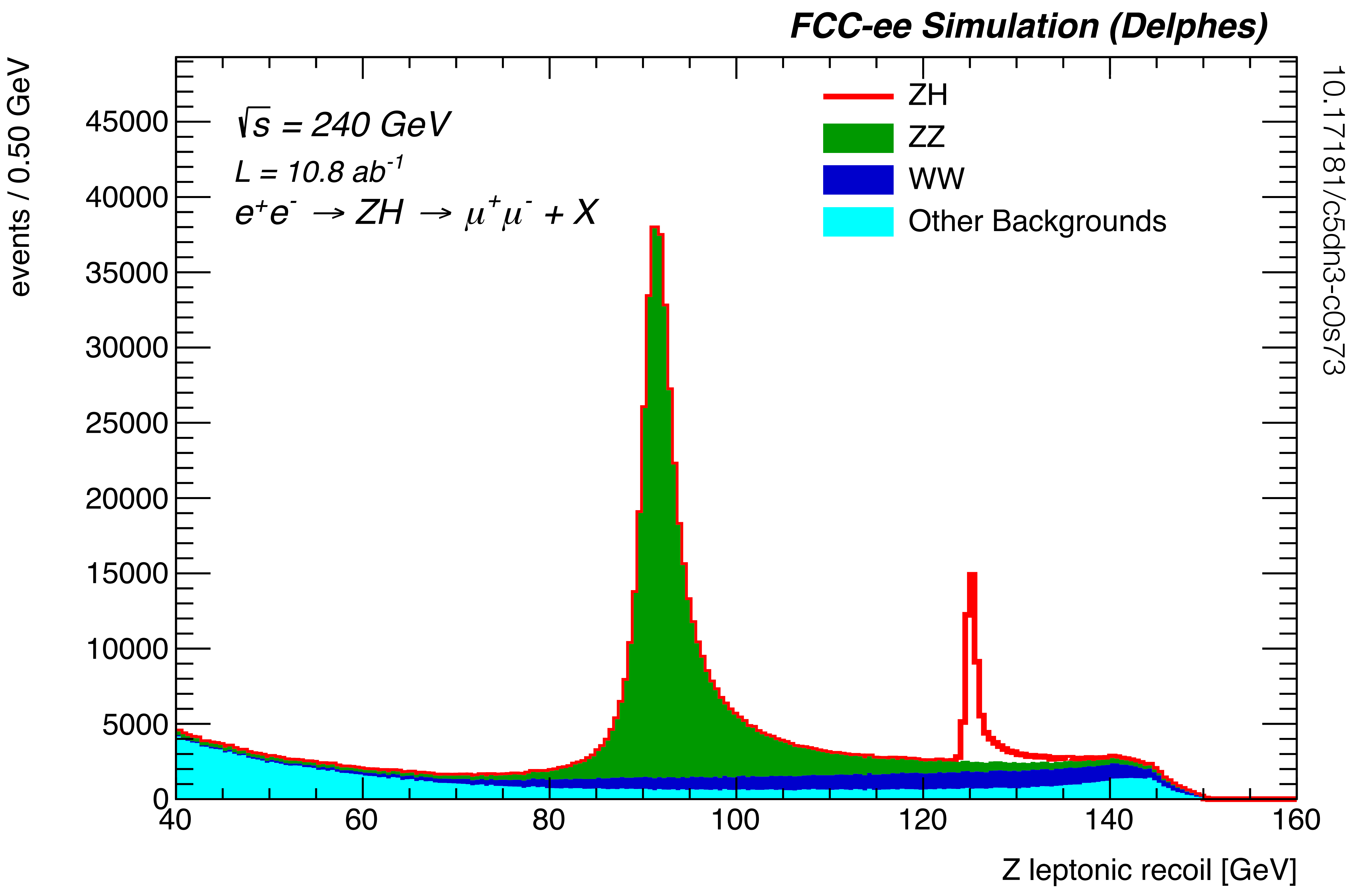
Total Width:
[from individual H-decays]

$$\Gamma_H \propto \frac{(\sigma_{e^+e^- \to ZH} \times BR_{H \to ZZ^*})^2}{\sigma_{e^+e^- \to ZH}}$$

With the width (Γ_H), everything follows…

Higgs total cross section and width

Precision on total xsect:
0.3% FCC, 0.8% LC, 0.6% LEP3



- Assumes that
  - Statistical uncertainties dominate
  - Backgrounds controlled to better than 1% (and large control samples available to constrain them)
  - All experimental and luminosity uncertainties are smaller than statistical uncertainties
  - Theory uncertainties from missing higher orders - extensions of existing methods likely sufficient to make them subdominant

Higgs at electron-positron machines

HL-LHC: 21 MeV
FCC-ee: 3 MeV
Linear collider: 12 MeV
LEP3: 15 MeV

Higgs mass estimates

‘Stats dominated’ sets the design requirements on detector performance: momentum resolution, jet energy resolution, impact parameter resolution etc

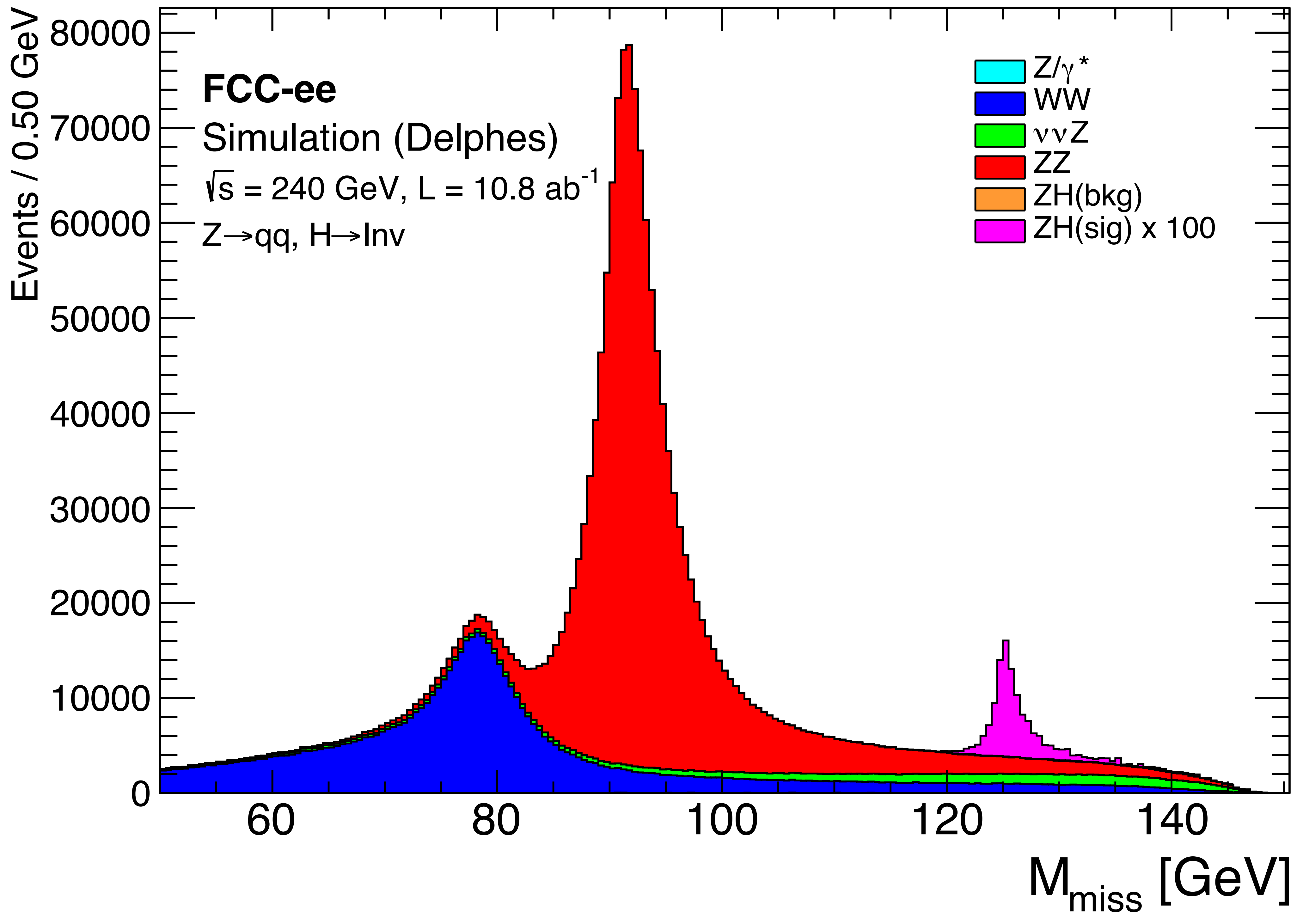
Take the challenge!

- Impact parameter resolution of 3um, momentum resolution of 0.1%, particle flow jet energy resolution of 2-3 GeV

Invisible, 1st/2nd generations, rare couplings

- Higgs to invisible limit of 0.05%
- Excellent b/c-tagging performance yields 1.5 (2.5)% FCCee (LC) precision for Hcc
- Some rare decays (like H→μμ) don't improve compared to HL-LHC
- FCCee: Potential access first generation
  - Needs 4 MeV precision on Higgs mass, reduce beam spread, 5 years of running

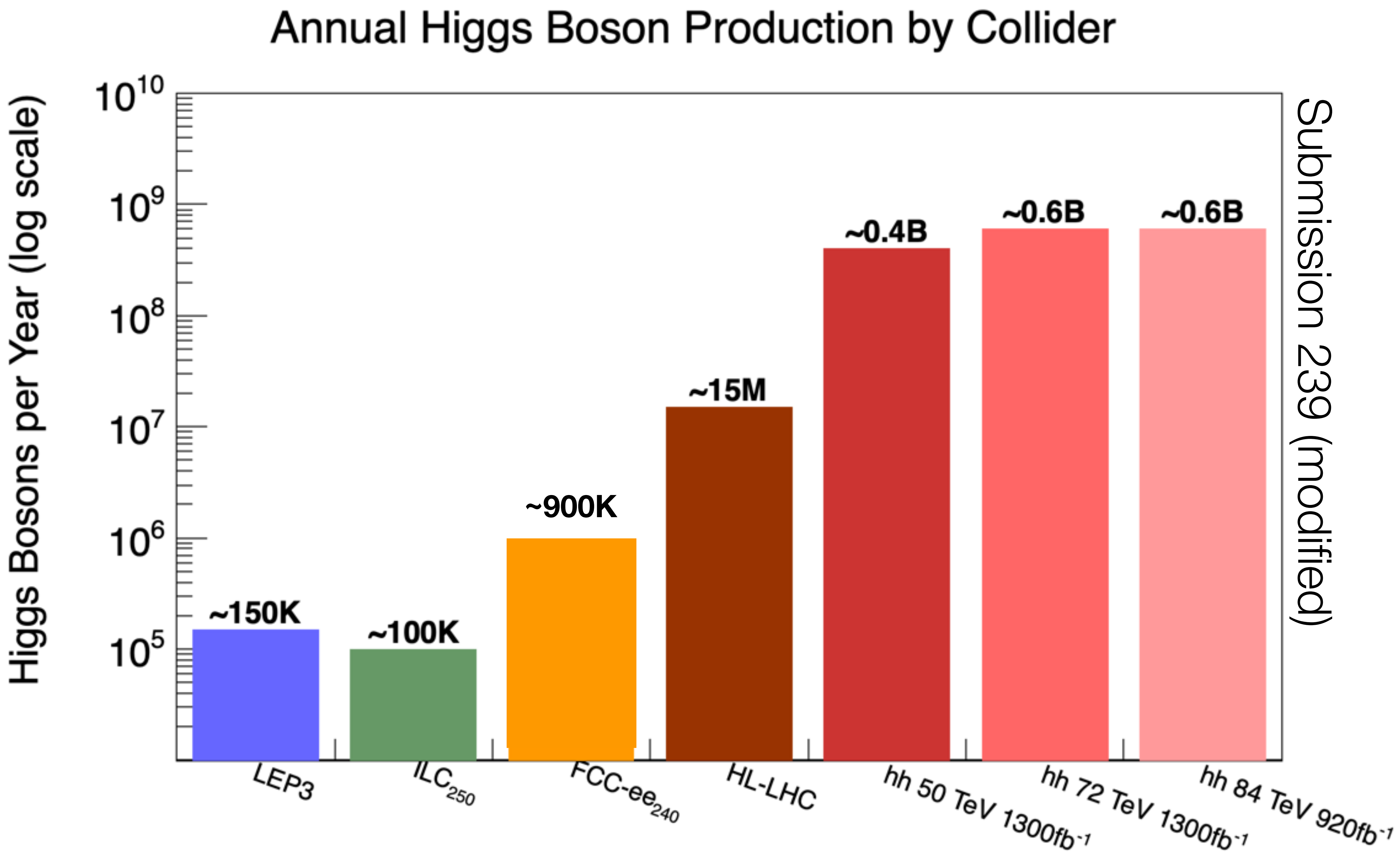
10.17181/7hbn8-3d233



Higgs to invisible example

Higgs couplings: hadron-hadron machines

- Benefit from huge samples (play-off between energy and luminosity)
- Allows for differential measurements at high pT (sensitivity to BSM)
- Use tight selection criteria and ratios to enhance signal and control systematics



Submission 239 (modified)

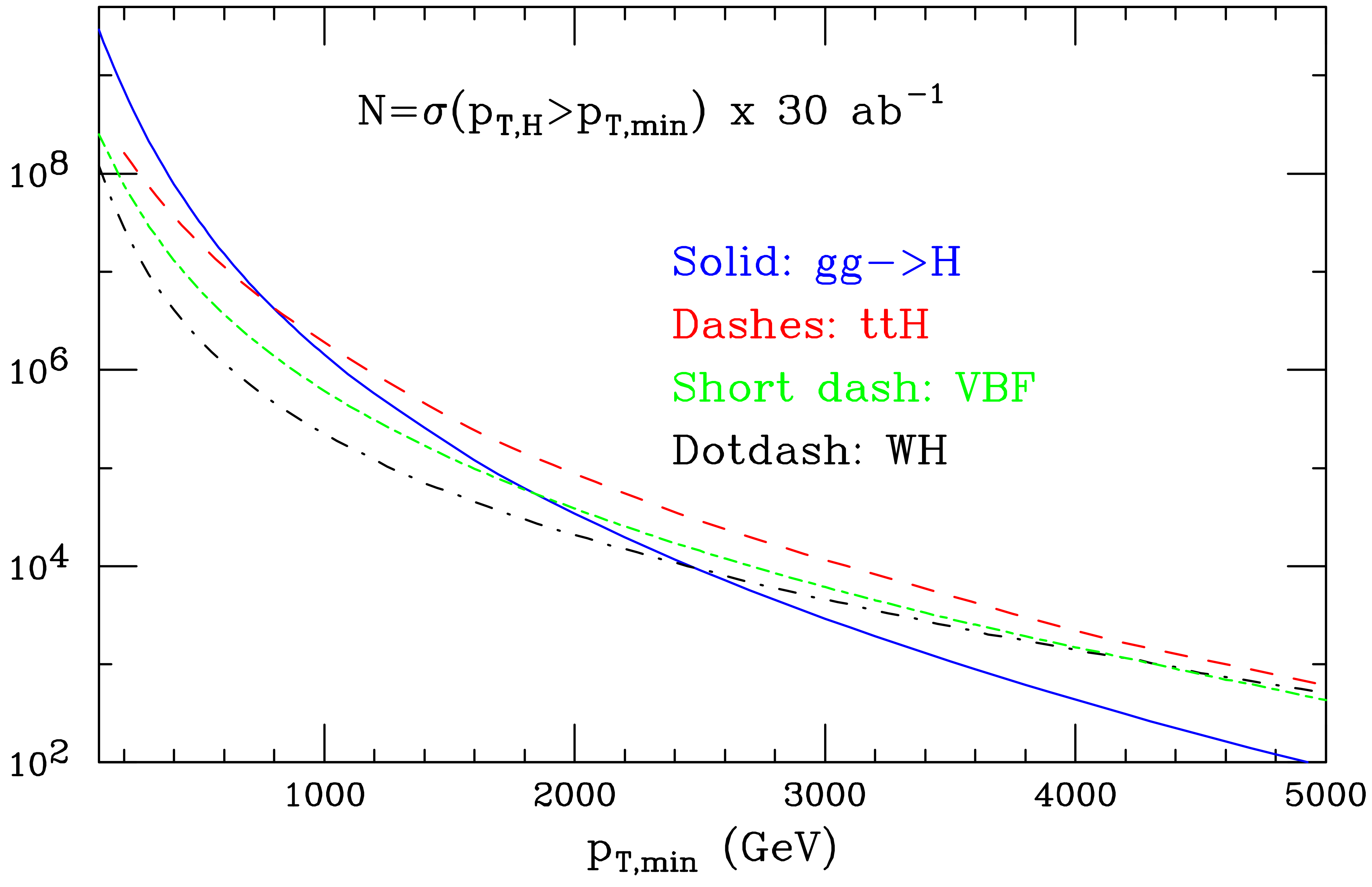
Higgs couplings: hadron-hadron machines

Take the challenge!

- Pile-up of 1000, need precise timing information at 5ps
- Assumptions and caveats:
  - Assume couplings like HZZ are measured at the per-mille level at FCCee
  - Differential information is powerful but rarely used in comparisons
  - Hadron colliders may have superior sensitivity to many energy-dependent operators - Current studies are insufficient to compare an FCChh-only option

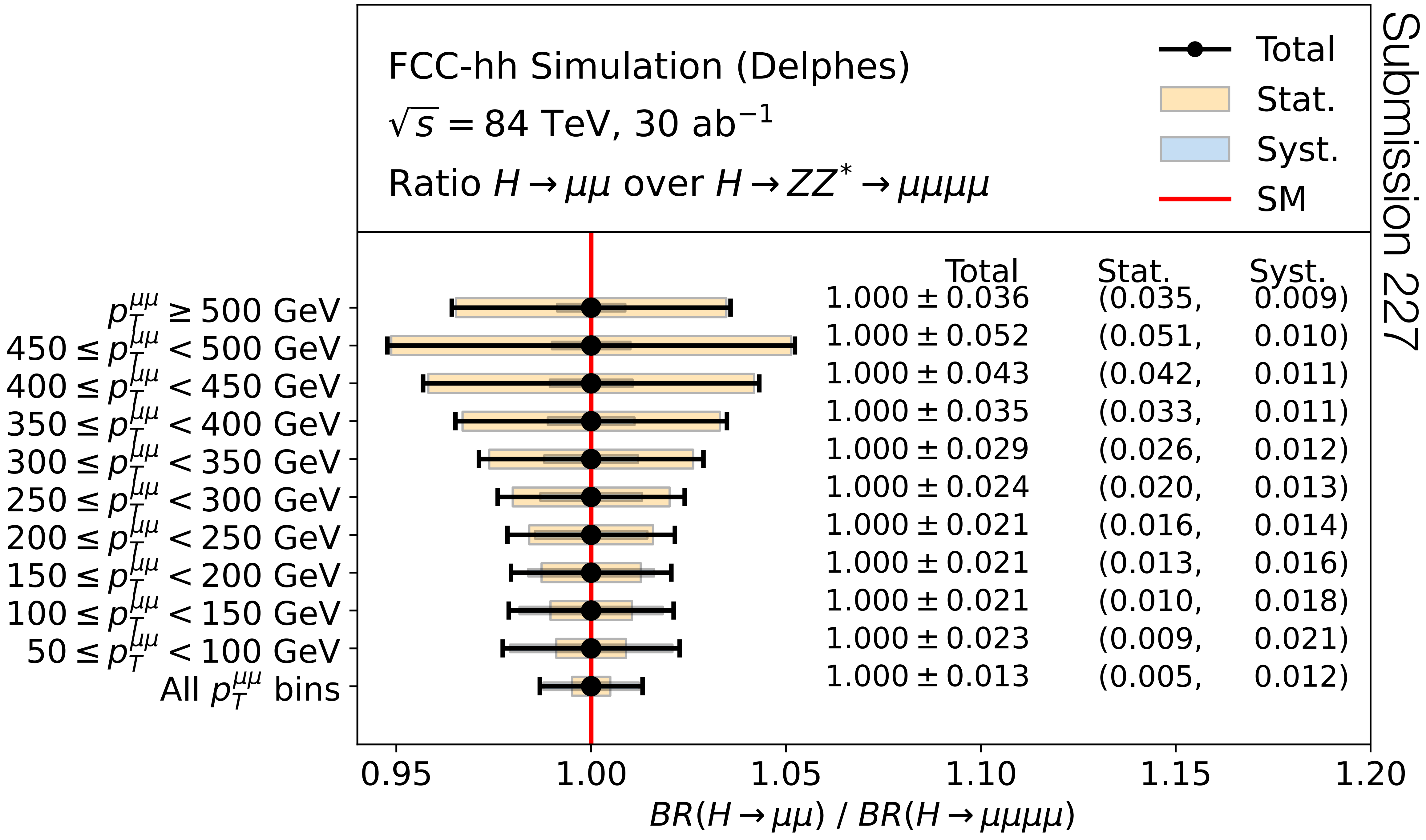
Hγγ precision:
0.3% FCChh, 1% FCCee, 2% LC

CERN-2017-003-M



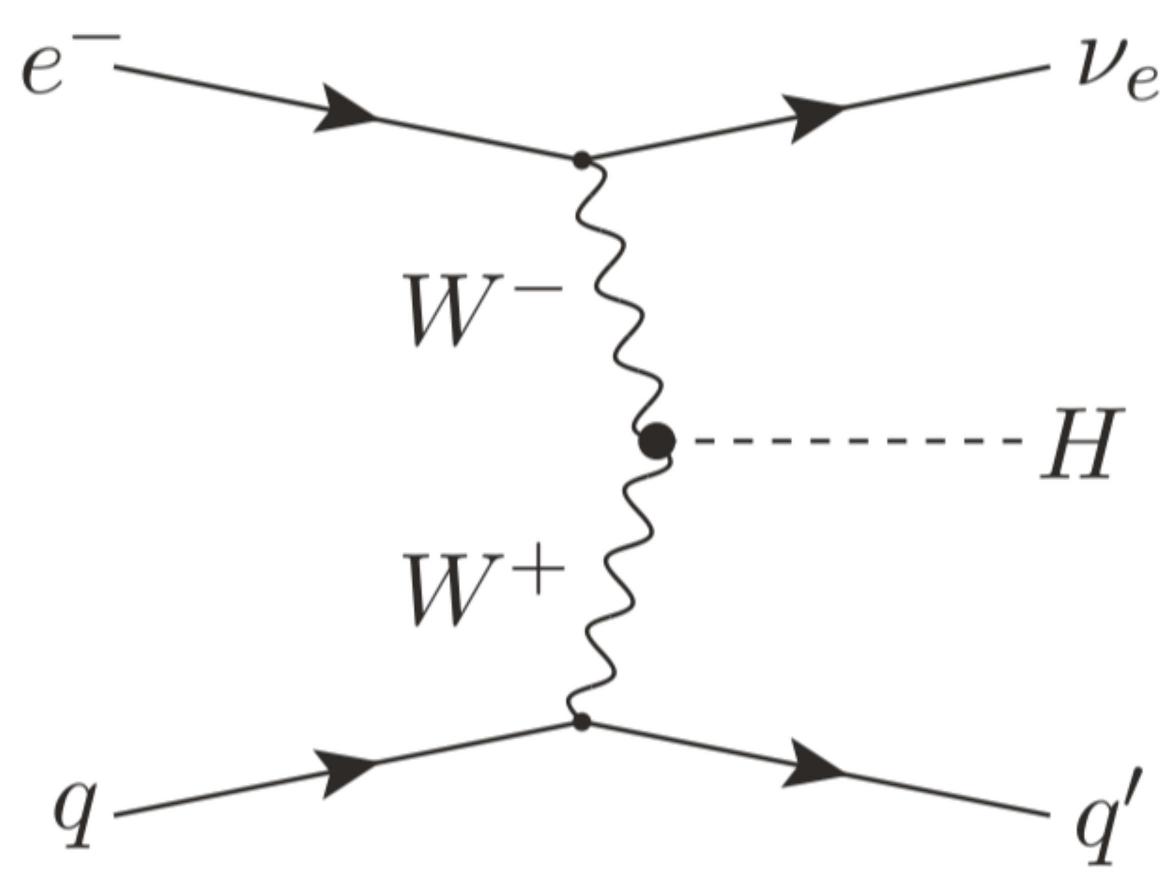
Invisible, 2nd generations, rare couplings

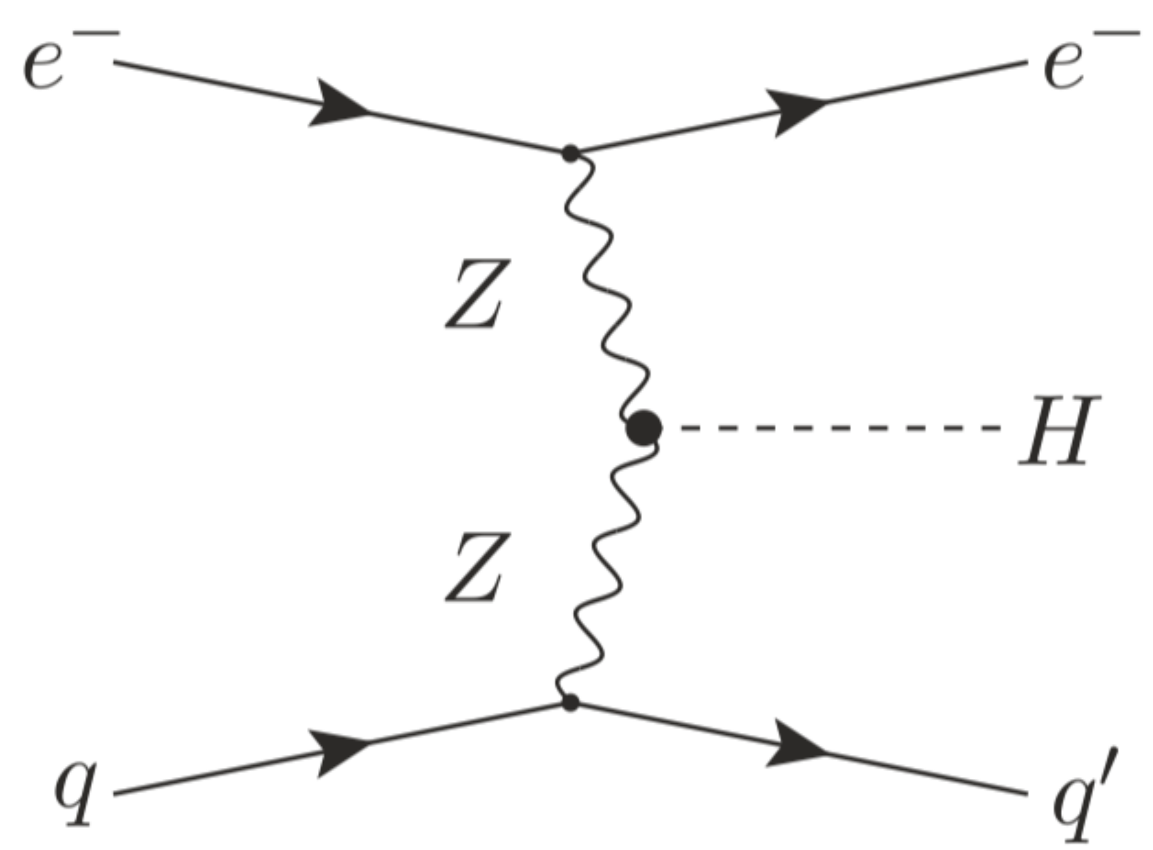
- Higgs to invisible limit of 0.02%
- Excellent sensitivity to rare decays and heavy final states
- Differential measurements of rare couplings (like H→μμ)



Uses H→μμμμ from FCCee to estimate cross section

Higgs couplings: electron-hadron

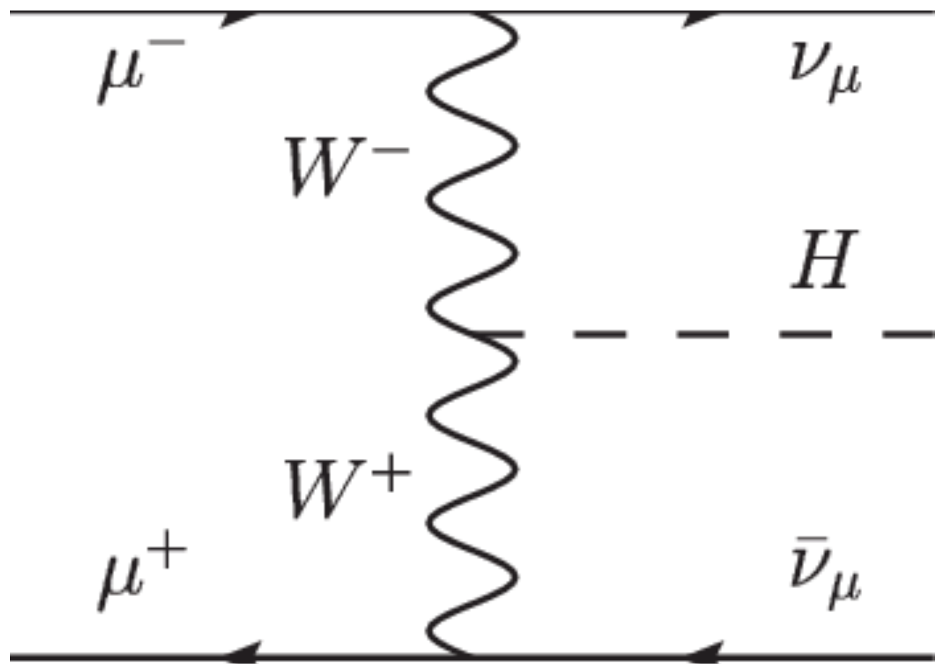


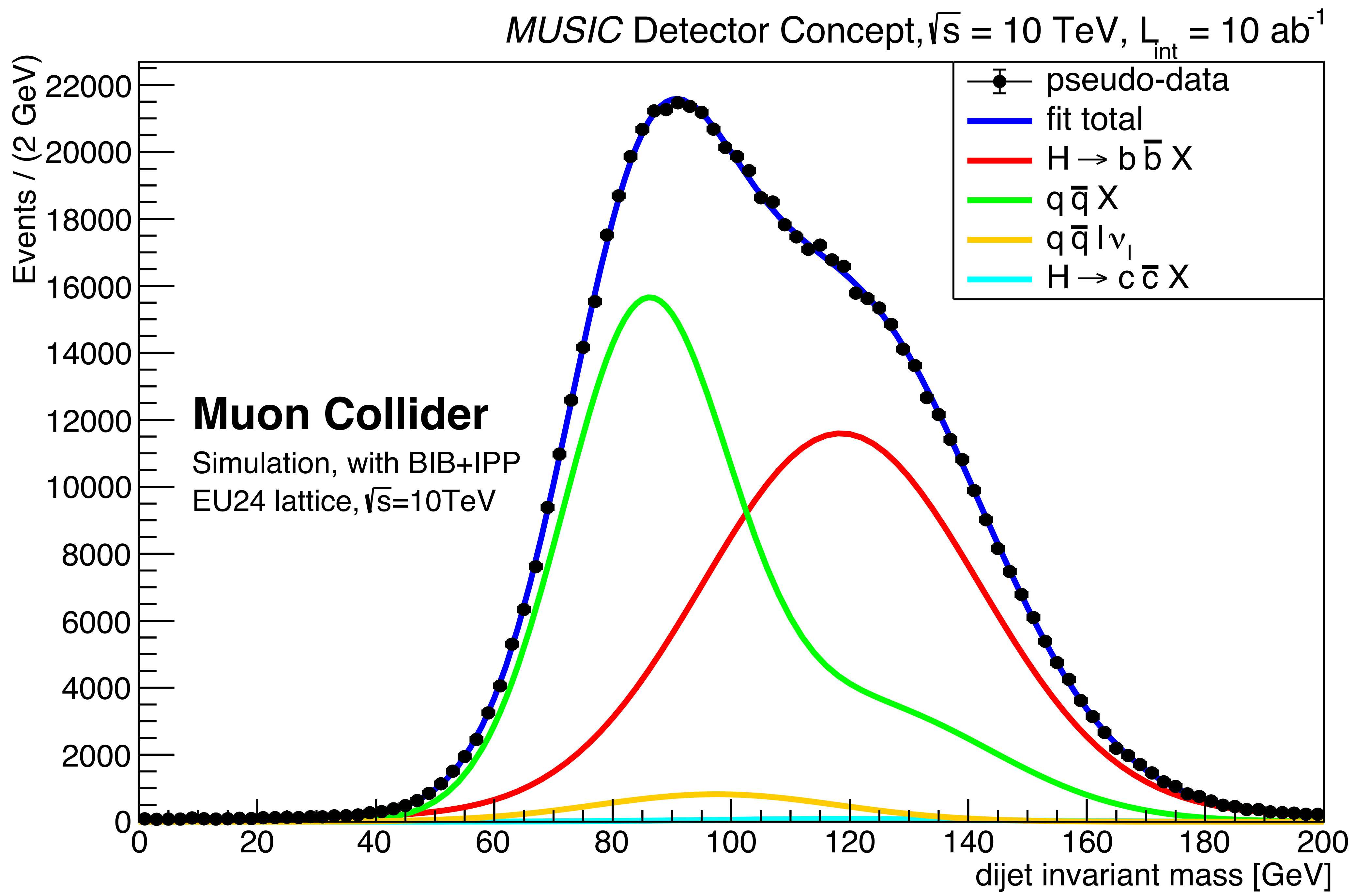


Use electron to distinguish the NC process

- Up to 50% improvement to HL-LHC Higgs couplings via better PDFs
- Strong near-term sensitivity to some Higgs coupling
    - HWW: 0.7% LHeC, 0.8% (0.3%) at FCCee 250 GeV (w/365 GeV)
    - First measurement of Hcc at 3%

Higgs couplings: muon colliders

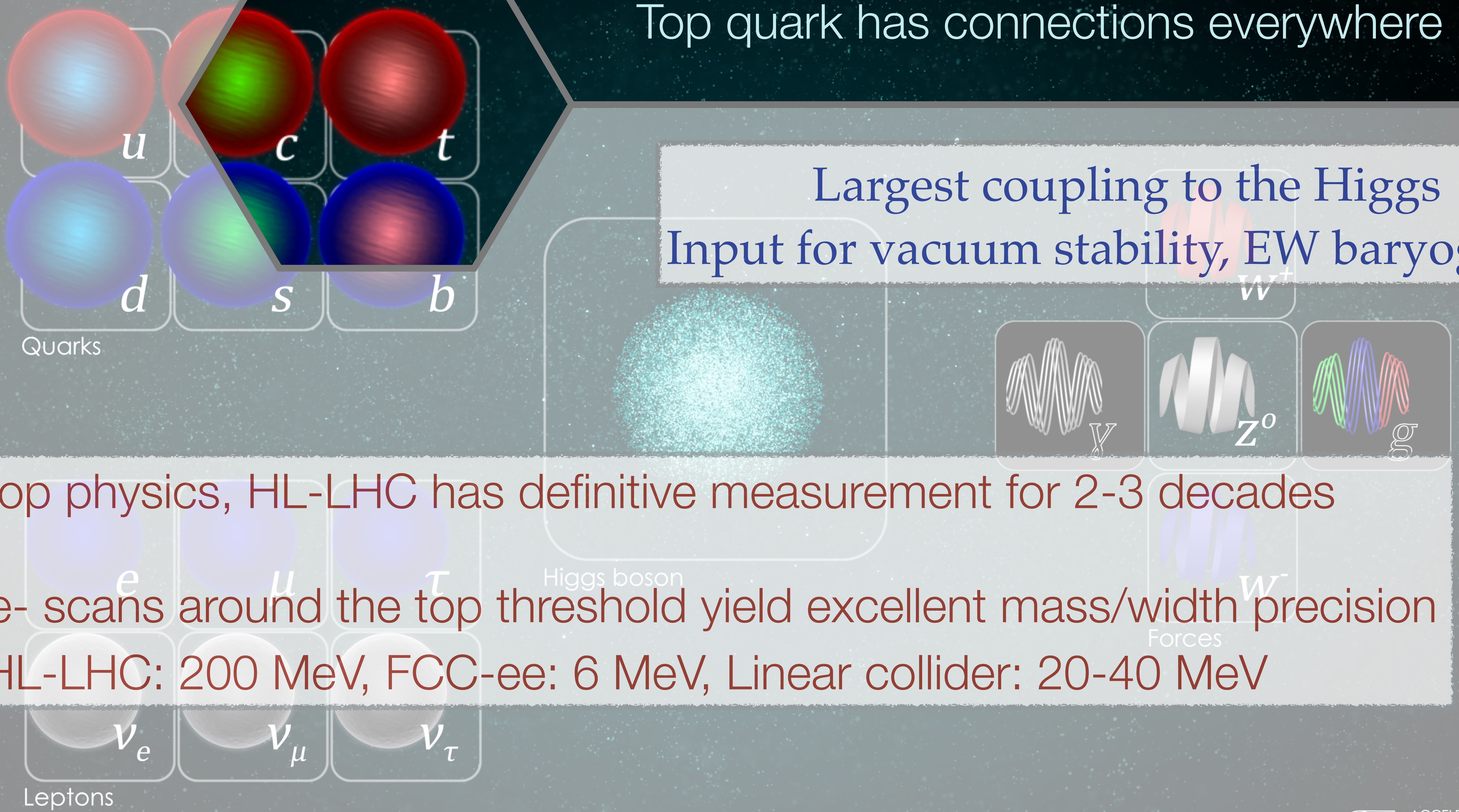




- Effectively a vector boson collider
- % to %% precision on Higgs couplings. Difficulties measuring top-yukawa. No model-independent determination of absolute couplings
- Control of beam-induced-backgrounds needed (many studies include these already)
- Challenges are forward muon tagging and increasing acceptance while mitigating beam-induced-backgrounds

Top quark has connections everywhere

Largest coupling to the Higgs
Input for vacuum stability, EW baryogensis

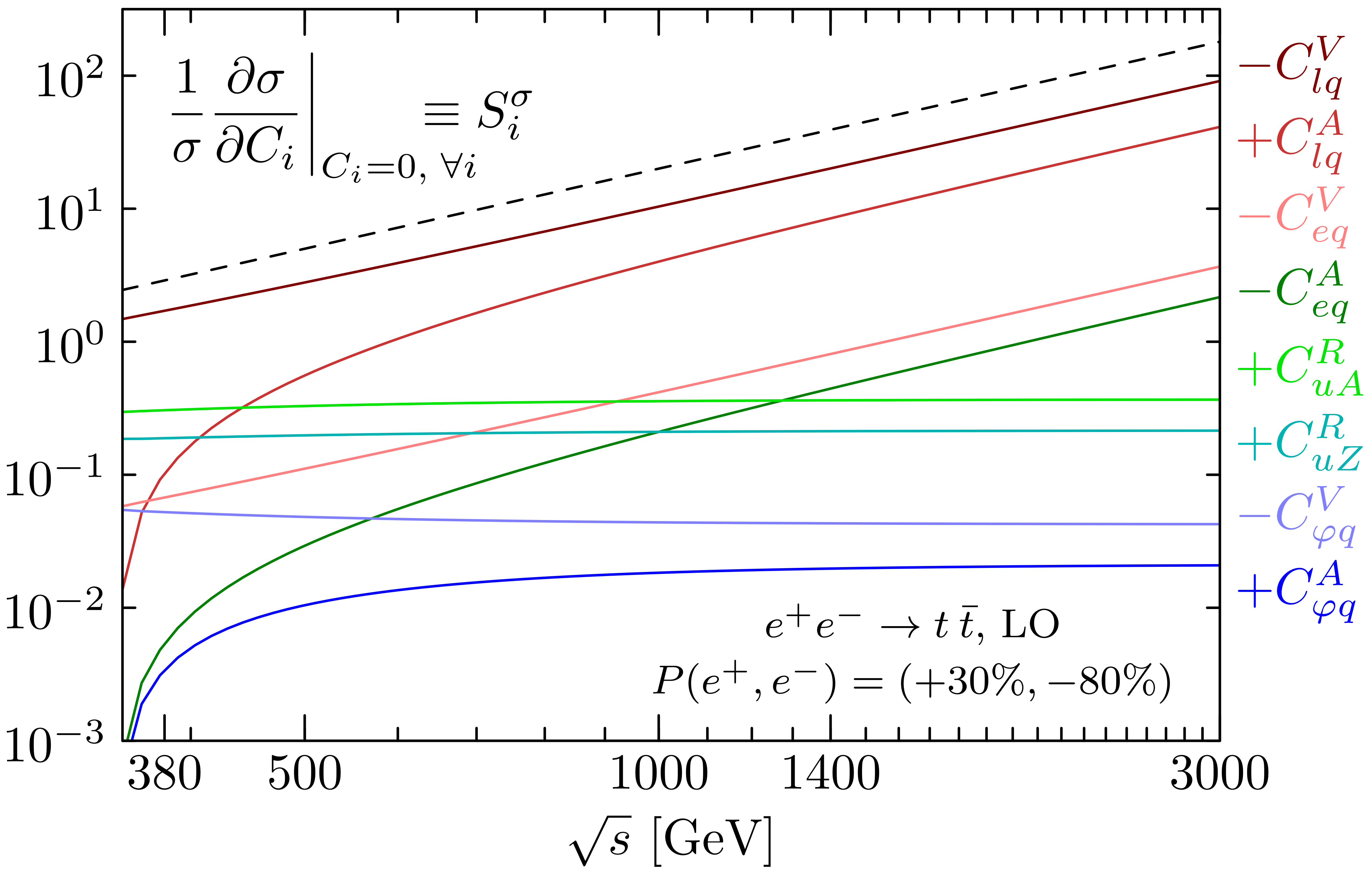


- In top physics, HL-LHC has definitive measurement for 2-3 decades
- e+e- scans around the top threshold yield excellent mass/width precision
  - HL-LHC: 200 MeV, FCC-ee: 6 MeV, Linear collider: 20-40 MeV

Top physics at threshold and beyond

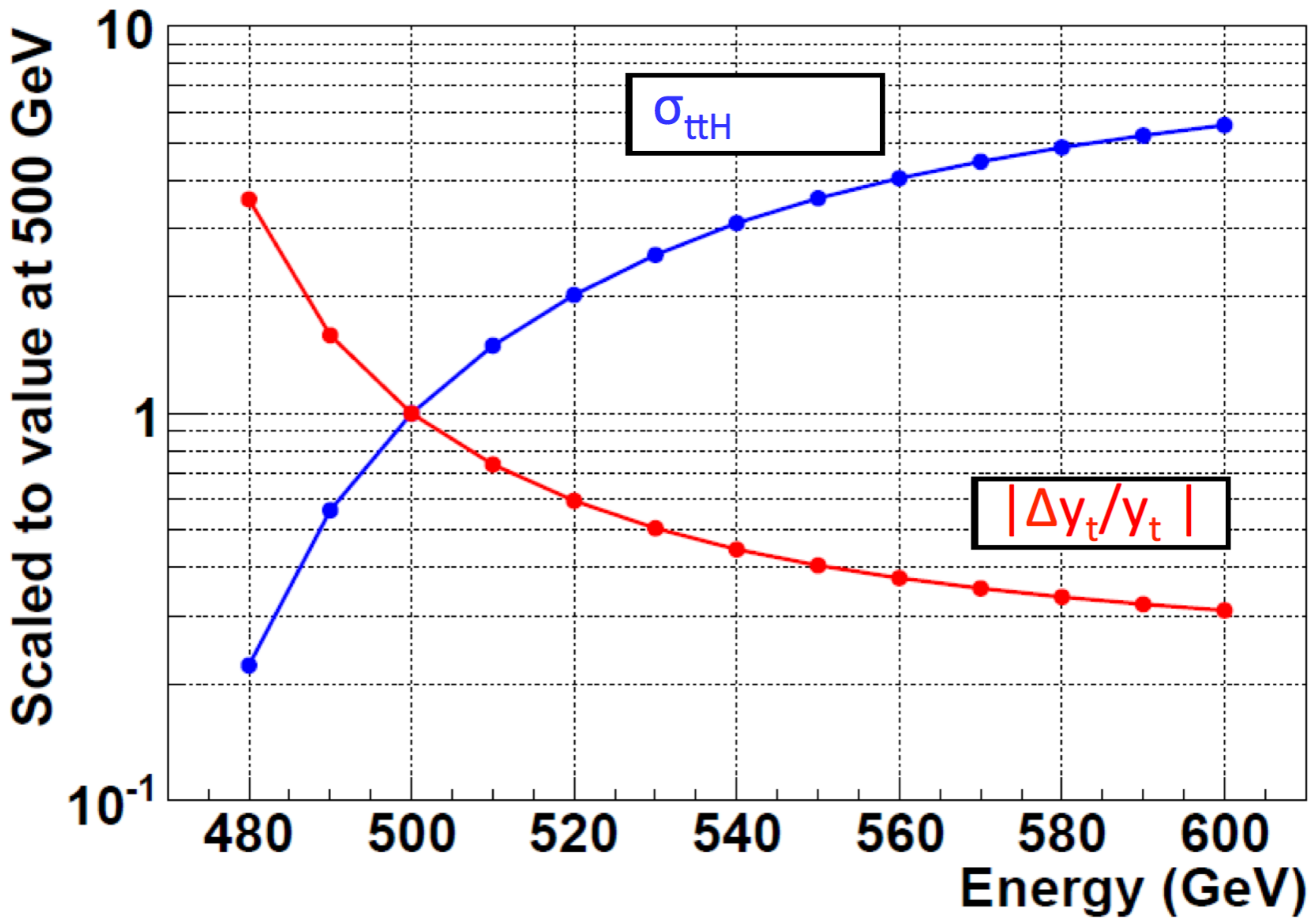
- Lepton colliders vs. hadron colliders have complementary sensitivity to top operators
    - i.e. 2-lepton+2-quark operators vs. 4-quark operators
- A large energy lever arm (i.e. LC at 550 GeV and beyond) breaks degeneracies between operators
- Runs with two beam polarization effectively doubles the number of observables and further breaks degeneracies
- Breaking degeneracies via differential observables has not been fully explored

Durieux, Perello, Vos, Zhang, JHEP 10 (2018) 168



Top physics at threshold and beyond

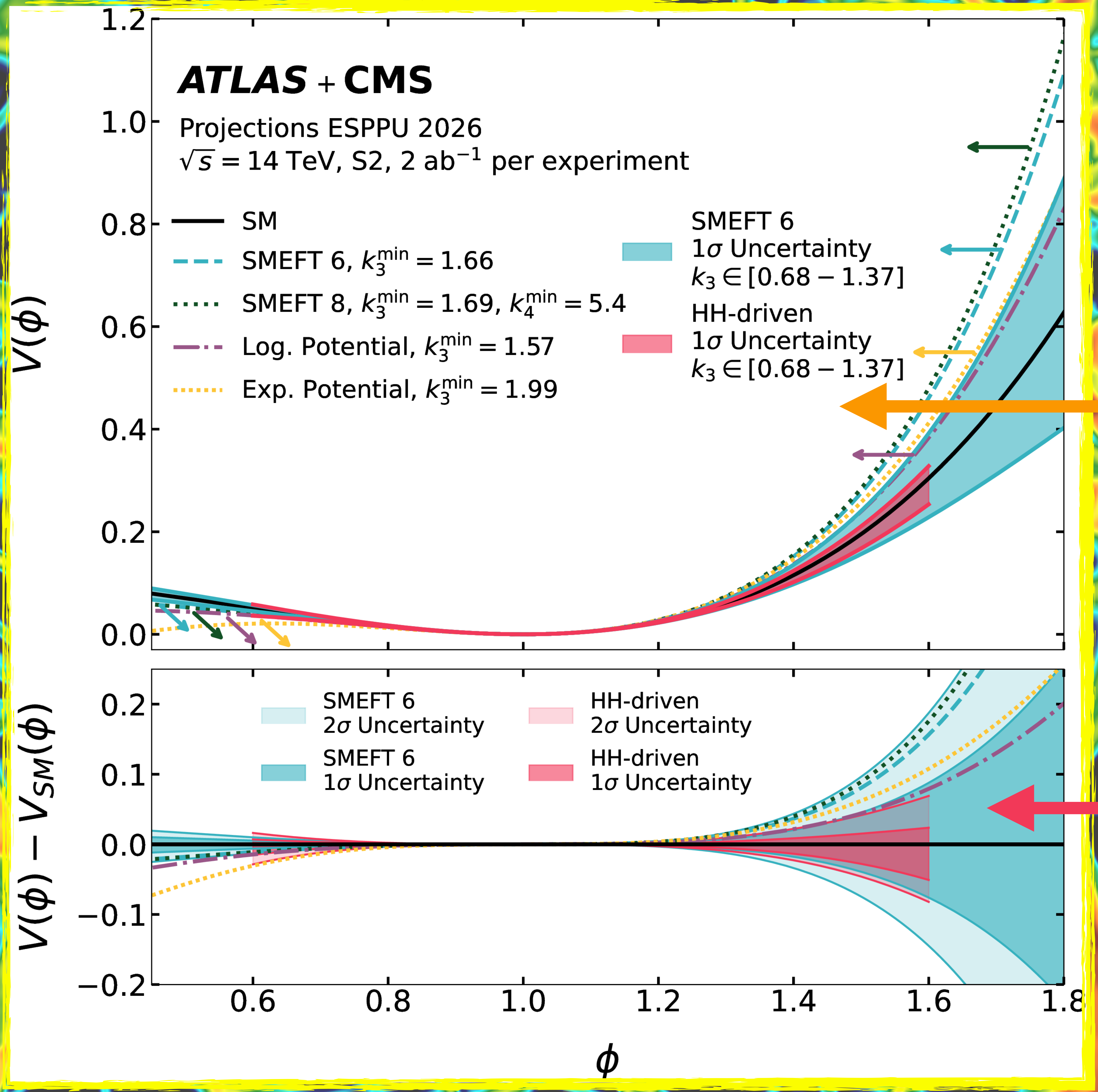
- Top Yukawa
  - At lepton colliders, ttH production opens at energies above 480 GeV
  - At hadron machines, ratios like ttH and ttZ cancel theory uncertainties, assumes ttZ coupling known to 1% from FCCee (top run)
- LHeC: can provide a series of top precision measurements, i.e. Wtb coupling



1506.07830

Challenges	• Electron/positron collider: stats limited. Implies small selection and reconstruction biases, small background uncertainties, etc. Selection efficiency close to 10% • More fundamental advancements in theory techniques and tools needed

Higgs Self-Coupling

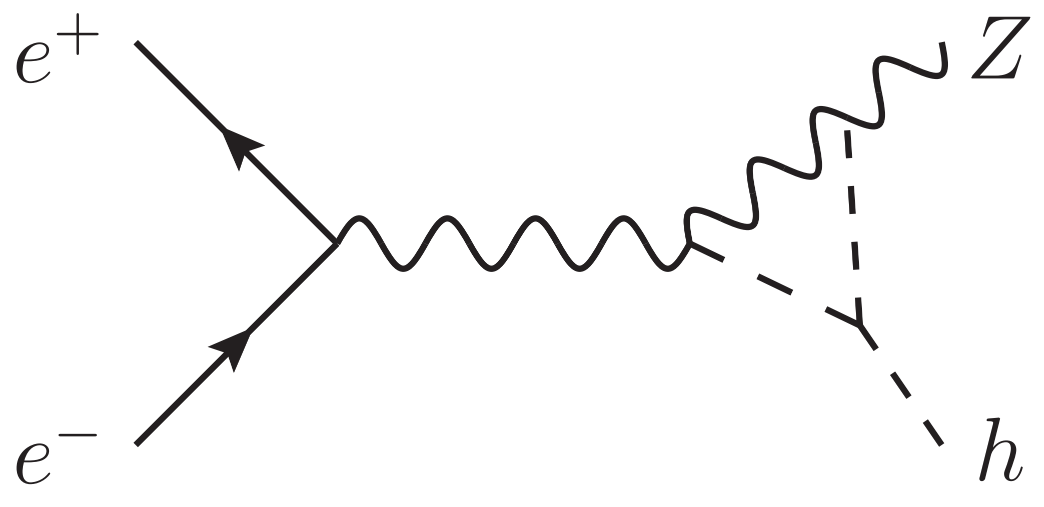


Region with strong first-order phase transition

HL-LHC expected Higgs self-coupling uncertainties

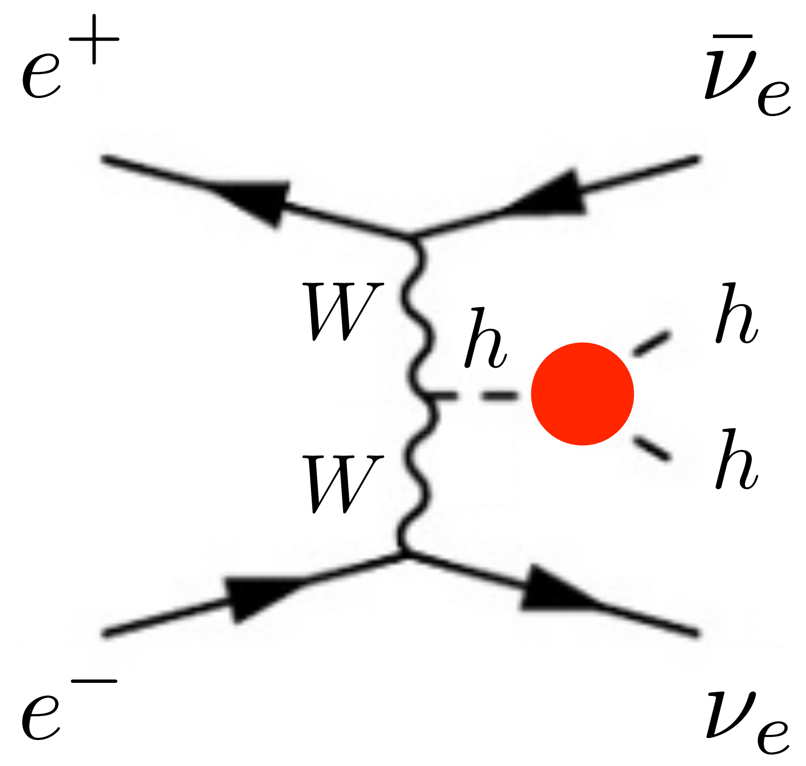
Probing Higgs Self Coupling

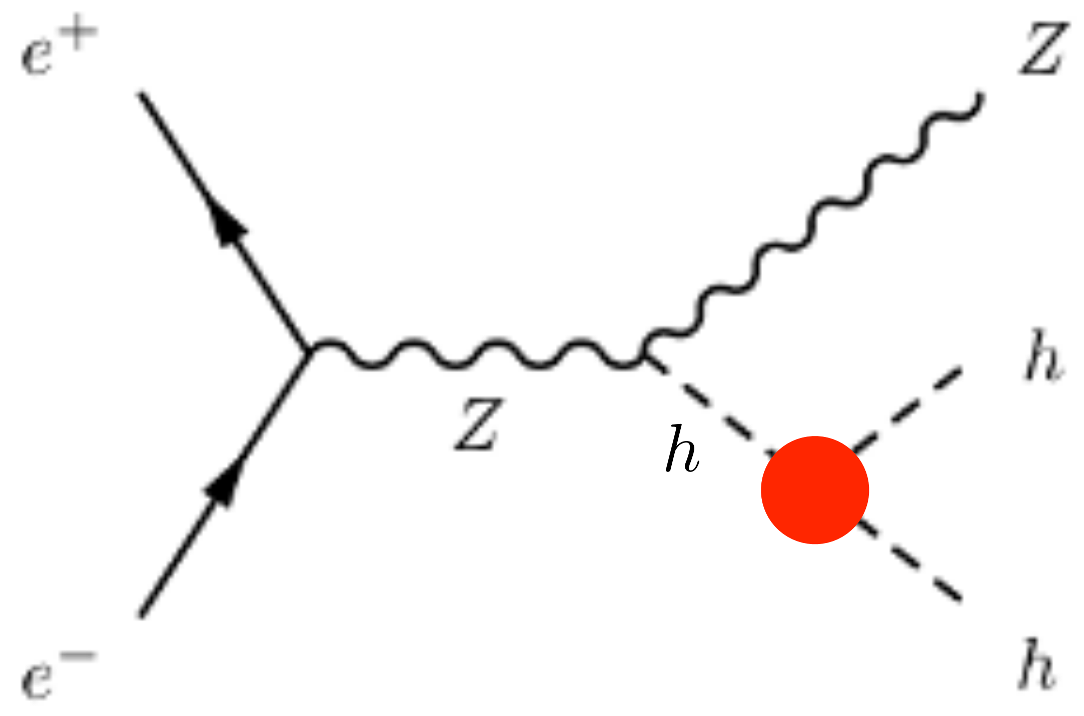
Below Higgs pair threshold via single Higgs



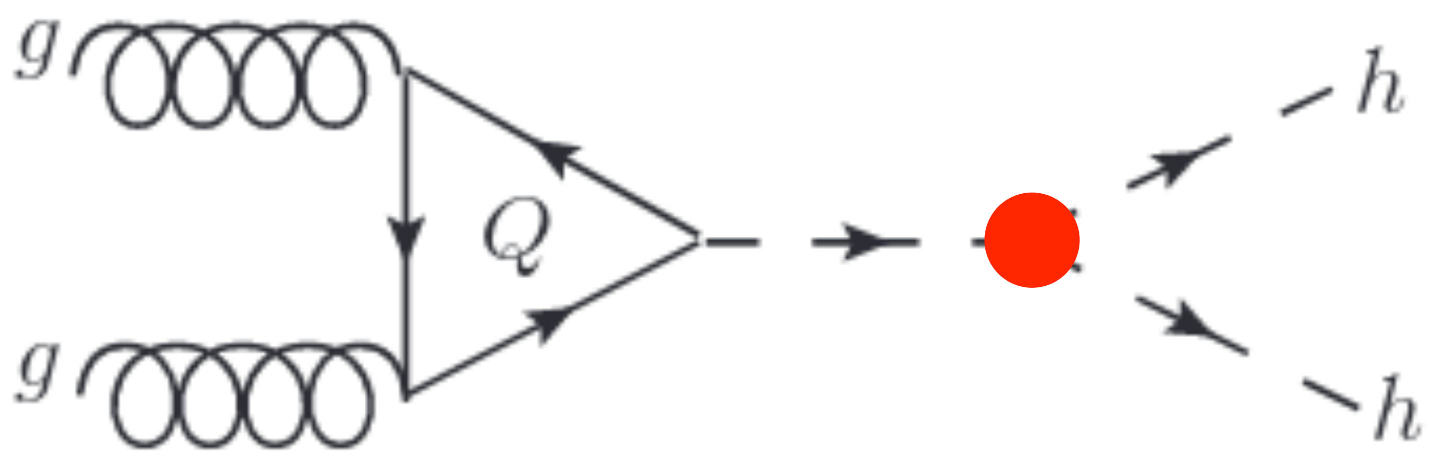
FCCee, LC at 250 GeV

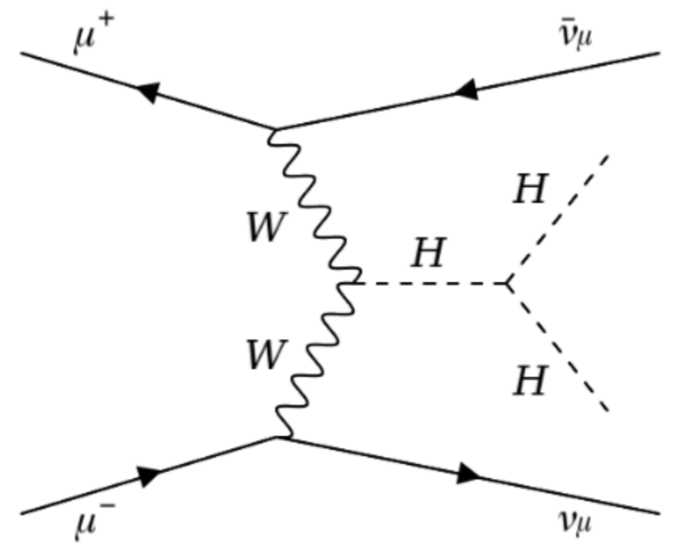
Above Higgs pair threshold via HH





LC at 550 GeV+





HL-LHC, FCChh

Muon collider

Higgs Self Coupling: electron-positron colliders

Uncertainty on λ at the SM value	HL-LHC: 27% FCCee+HL-LHC: ~15% LC (at 550 GeV): 11-18%

Challenges below threshold

- Size of the modification goes like

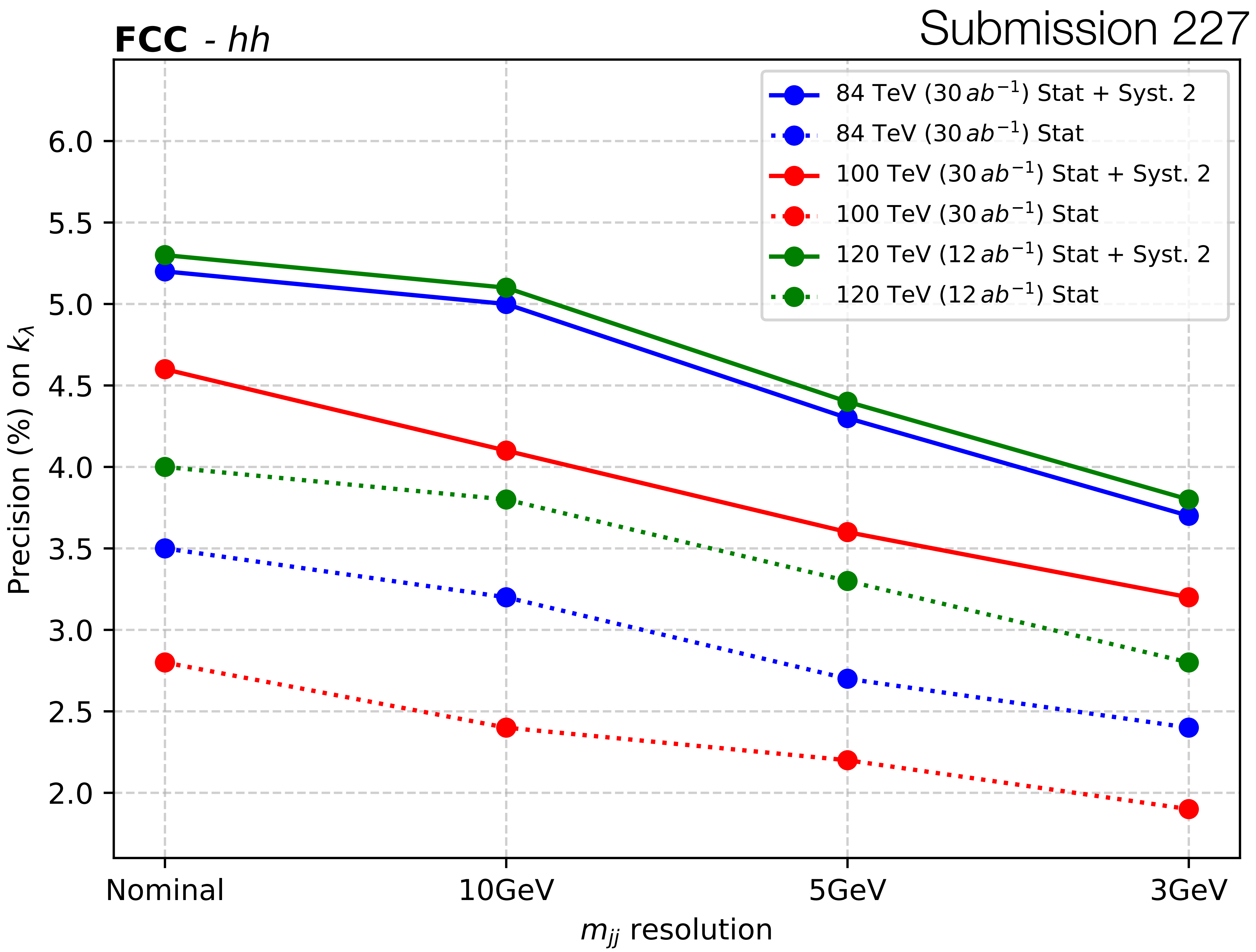
$$\sigma_{ZH}^{\mathrm{NLO}} \approx \sigma_{ZH}^{\mathrm{NLO,SM}}(1 + 0.014\,\delta\kappa_3)$$

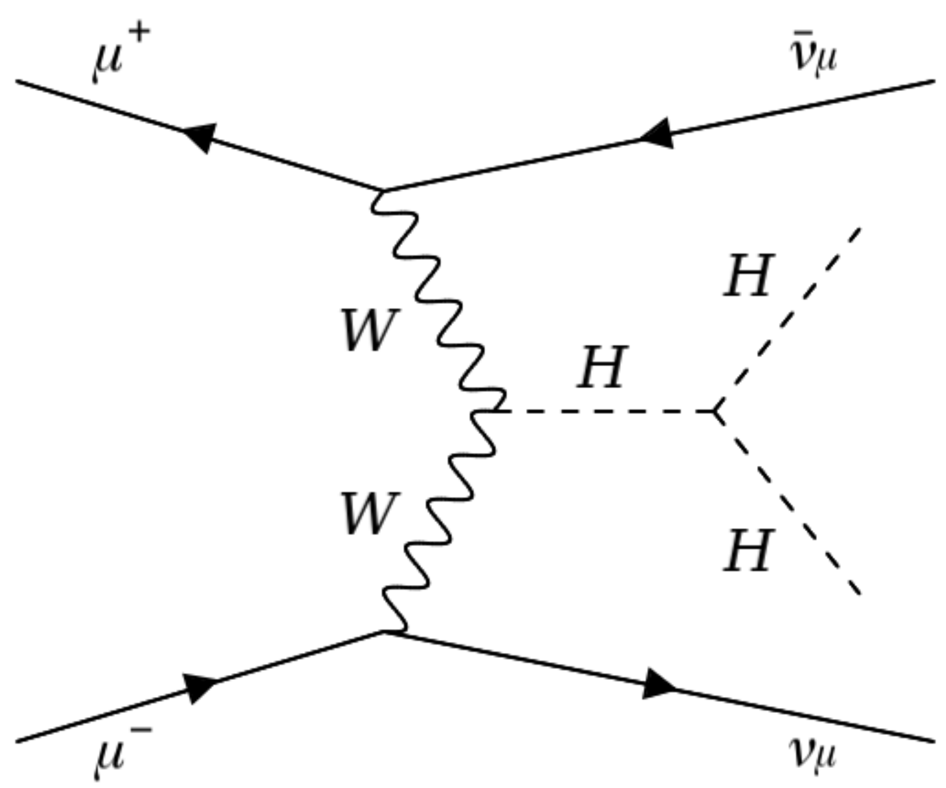
- To be competitive, ZH cross section needs to be measured with an accuracy below 1%
- Need to disentangle deviations from other possible contributions. Different center-of-mass energies helps

Challenges above threshold

- Major challenges are jet assignment, jet energy resolution and flavour tagging
- HH total production xsec sensitive to BSM besides the triple coupling. More observables are needed to disentangle
- Expected uncertainty on σ(ννHH) ≈ 22 % CLIC 1.5 TeV. Note: these have not been updated to include modern taggers, etc.

Higgs Self Coupling: Hadrons and Muons





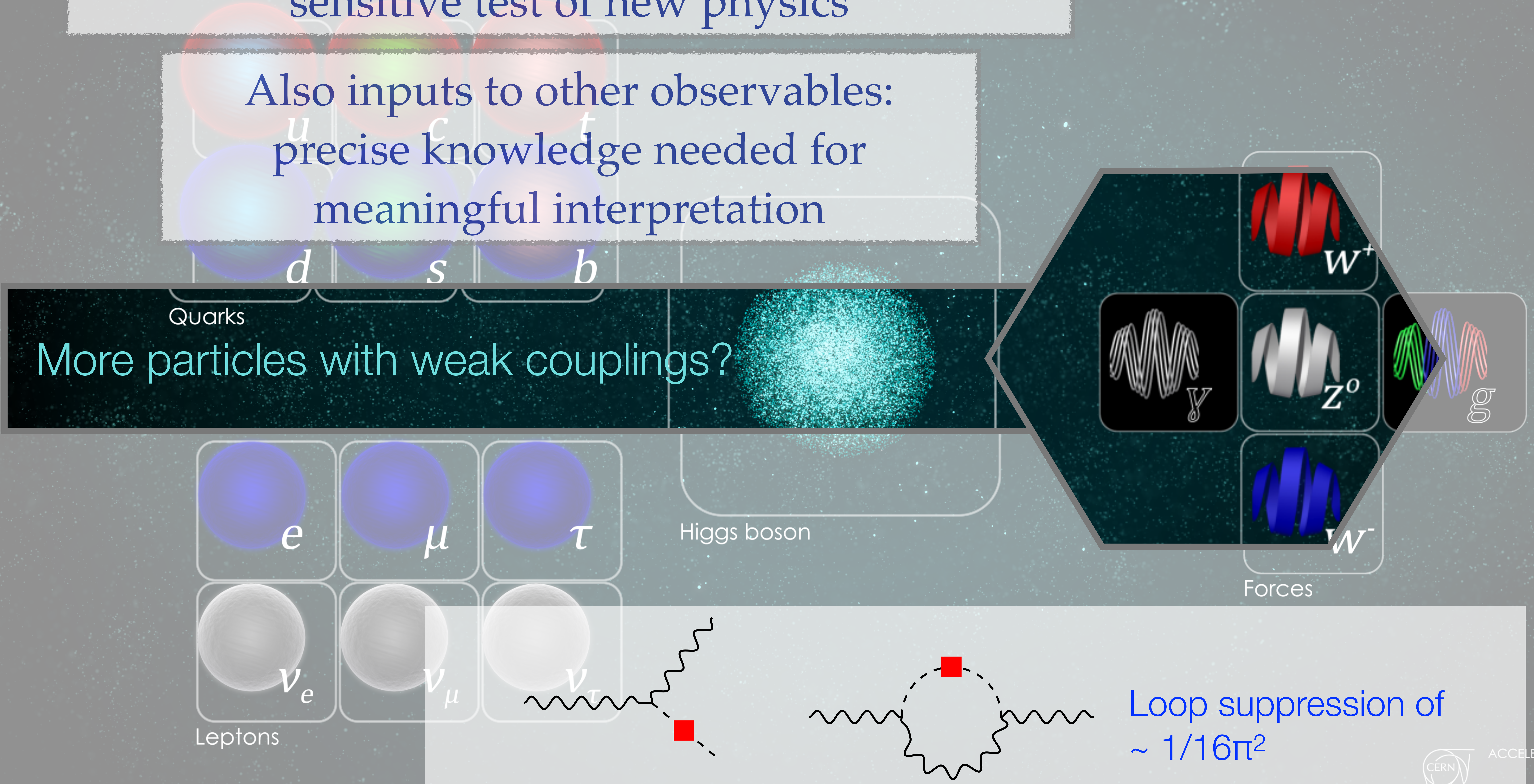
- Similar final states to hadron machines - without pile-up and QCD backgrounds

Ultimate precision of 3-5% with 30ab^{-1}

Precision of <5% at 10 TeV

SM parameters are related to each other via loops: sensitive test of new physics

Also inputs to other observables: precise knowledge needed for meaningful interpretation



More particles with weak couplings?

Loop suppression of ~ $1/16\pi^2$

Maura, Stefanek, You, arXiv:2412.14241

EW Precision measurements: electron-positron colliders

- At Z-pole
  - Z mass, width, alpha (circular only), sigma_had
  - Leptonic/hadronic asymmetries
  - Partial widths and universality tests
- At WW threshold or above:
  - W mass, width, branching ratios
- Muon colliders probe EW but via VV scattering

Left-right asymmetry for LCs (beam polarisation)

$$A_{LR} = \frac{1}{P_{\text{eff}}} \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \approx \mathcal{A}_e$$

- Direct sensitivity to Zee chiral coupling asymmetry. Chiral observables (asymmetries) are measured better at LCs by P/A_e ~ 6 for a given luminosity
- Polarisation via tau decays can also be used by both

Available to circular and linear

$$A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

Dominant uncertainties

- For the most part, systematics dominated
- Most of the systematics are limited by the statistics of the calibrations samples
    - i.e. sample size used to determine the luminosity
- More fundamental advancements in theory techniques and tools needed

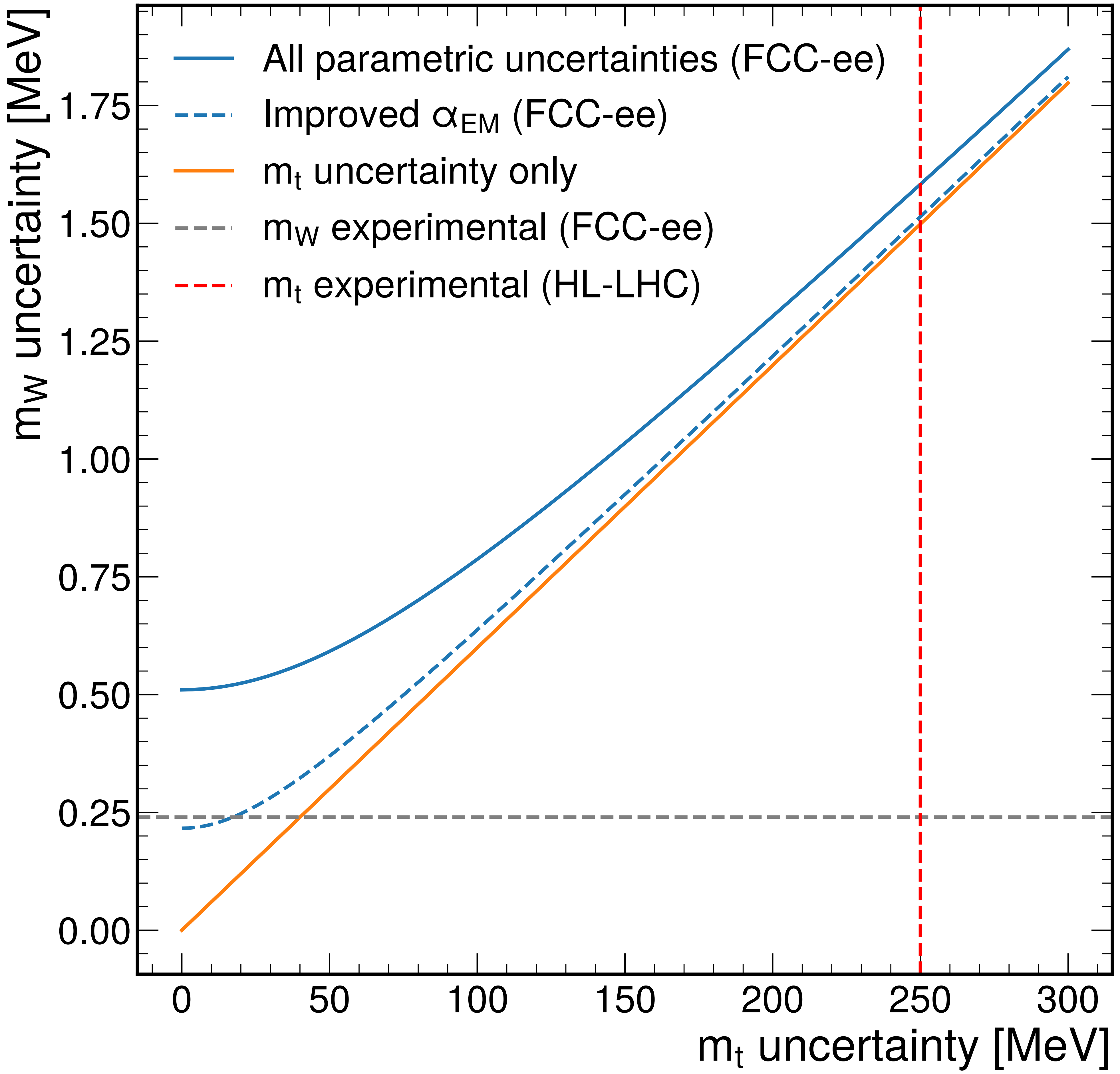
Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}}$ $(\times 10^6)$	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ $(\times 10^3)$	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z $(\times 10^3)$	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ $(\times 10^4)$	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 $(\times 10^3)$ (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ $(\times 10^4)$	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic $(\mu\nu_\mu\nu_\tau)$ BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ $(\times 10^4)$	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν $(\times 10^3)$	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

The W mass (and the Top mass)

- W mass analysis methodology varies depending on the data sample

HL-LHC: 3-5 MeV
FCC-ee: 0.2 MeV
Linear collider: 1.5 MeV
LEP3: 1 MeV
LHeC+HL-LHC: 2-3 MeV

Defranchis, de Blas, Mehta, Selvaggi, Vos
https://arxiv.org/pdf/2503.18713



FCCee

FCChh

High luminosity

Energies up to top threshold

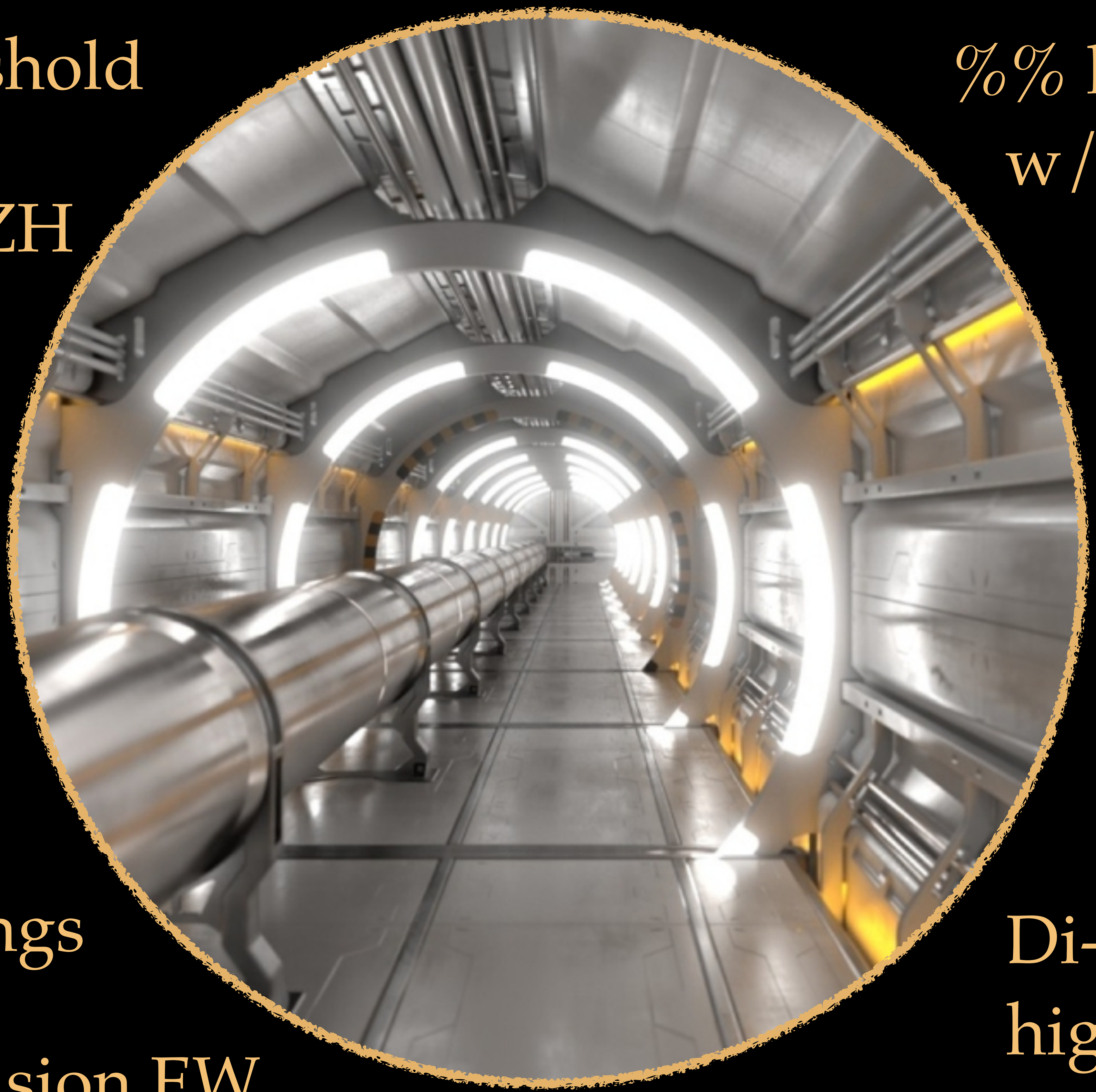
Easy transition between Z, WW, ZH

% to %% level precision on Higgs couplings (except top), stats limited

Best precision on Higgs couplings of all e+e- options

Possible 1st generation couplings

TeraZ run for precision EW



%% level precision on Higgs w/FCCee, ttH production

% level precision on Higgs self-coupling

Access to rare decays and high pT distributions with strong BSM potential

Di-boson measurements at high energy

Combined precision top results

LC 250 GeV, CLIC 380 GeV

550 GeV and 1+ TeV

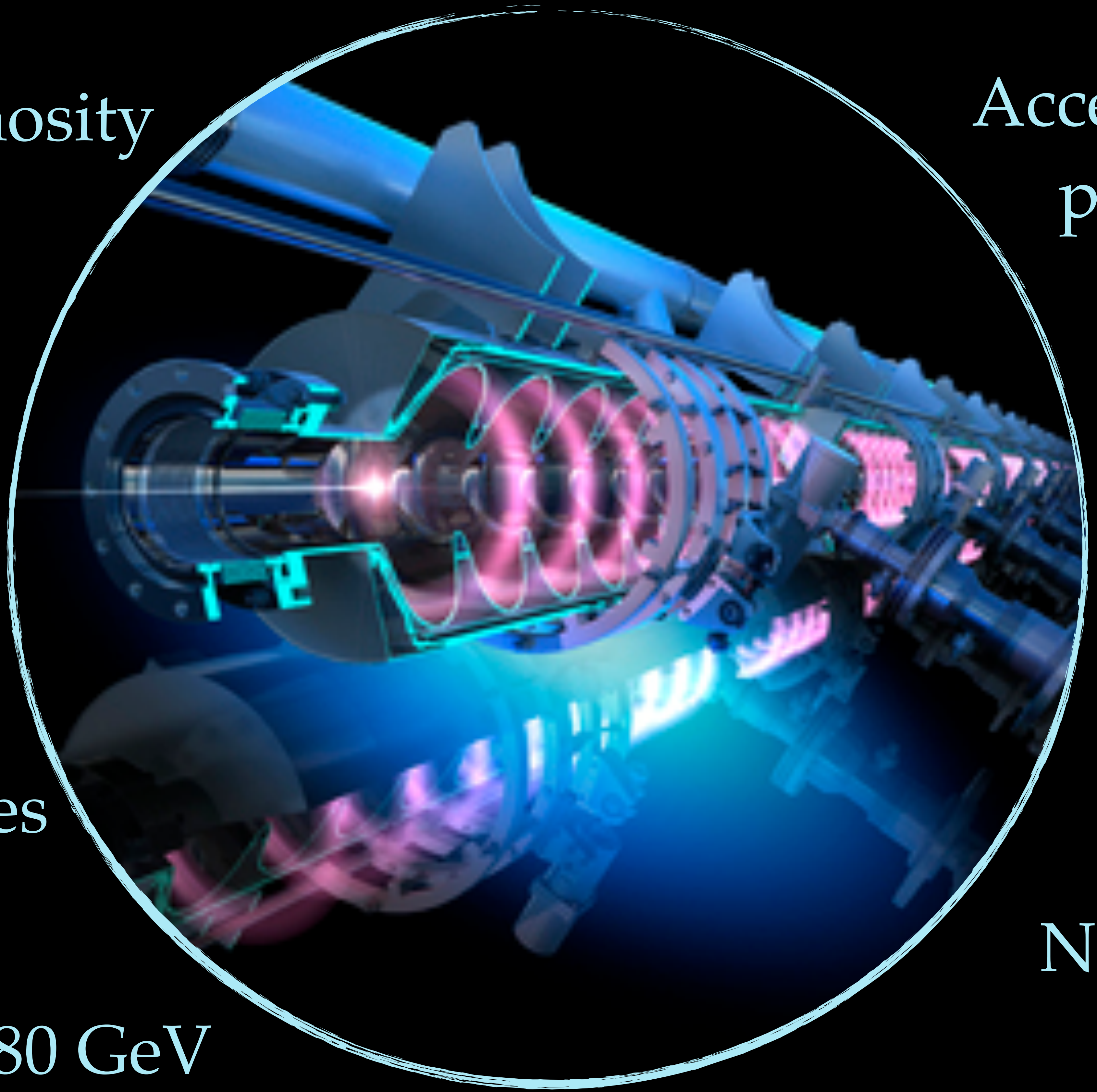
x3 ZH (x1000 Z-pole) less luminosity

Polarisation enhances sensitivity

Less precision on Higgs couplings

Less precision on EW observables

Access to top with CLIC 380 GeV



Access to direct HH and ttH production

Di-boson measurements at high energy

Excellent top progam with large energy span and polarisation

No hadron option

LEP 3

- x4 less luminosity compared to FCCee
- Short-term energy changes w/reduced lumi
- Precision Higgs couplings, worse w.r.t. FCCee
- Systematics increase for EW measurements
- No high energy run
  - Impacts Higgs width via lack of VBF H
  - No top program

FCChh

- Large luminosities and energy reach
- Excellent self-coupling sensitivity
- Sensitivity to top operators, differential distributions, di-bosons
- Reduced or no e+e- could affect Higgs results
- Insufficient inputs to compare its full sensitivity on its own

LHeC

- Improved PDFs and strong coupling
- Excellent Higgs coupling on Hcc, Hbb, HWW
- Interesting top physics (i.e. via single top production)
- Competitive near-term W mass determination

Muon collider

- Energy reach w/clean final states
- %% level precision on Higgs couplings
- Probes EW physics via high-energy processes (i.e. VV): difficult to compare at the measurement level

The physics we are after ↔ What we need to get there

Breaking electroweak symmetry

Establish the Higgs mechanism

Evolution of the cosmos

Stability of the Universe

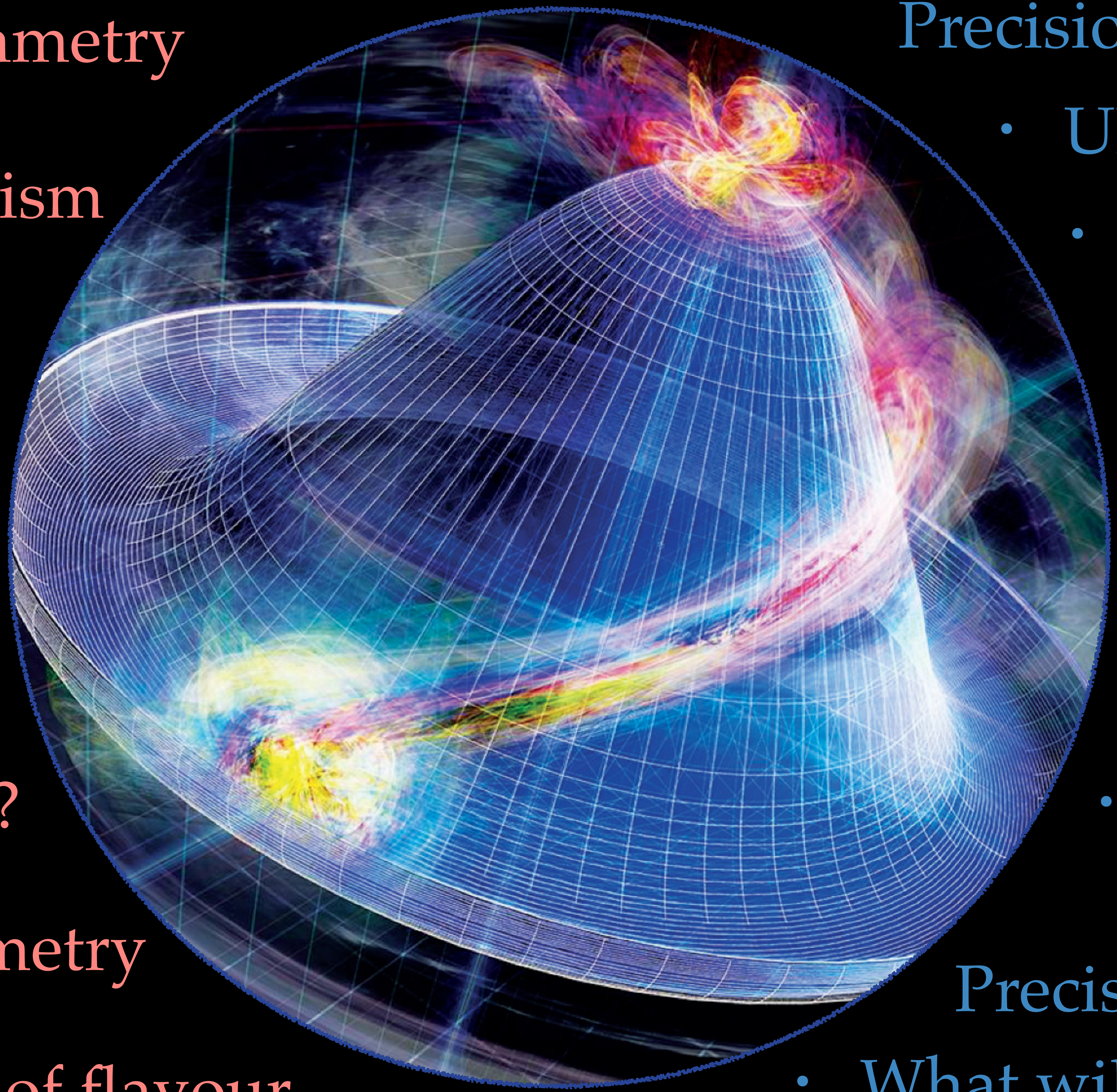
Additional phenomenon?

Additional particles?

Matter -Antimatter asymmetry

Origin of flavour

Composite Higgs?



Precision ↔ Energy

- Ultimately a BSM-specific question
- Innovation in detectors and theory needed to match data statistics

Precision ↔ Breadth

- Precise single measurements vs a broader set
- Source of new physics is unknown

Precision ↔ Flexibility

- What will the HL-LHC and future physics bring? How adaptable are these programs?

Extras

Photo Credits

- All photo credits are CERN. Exceptions below
- S5: Robert Hradil, Monika Majer/ProStudio22.ch (HL-LHC)
- 28) Linear collider