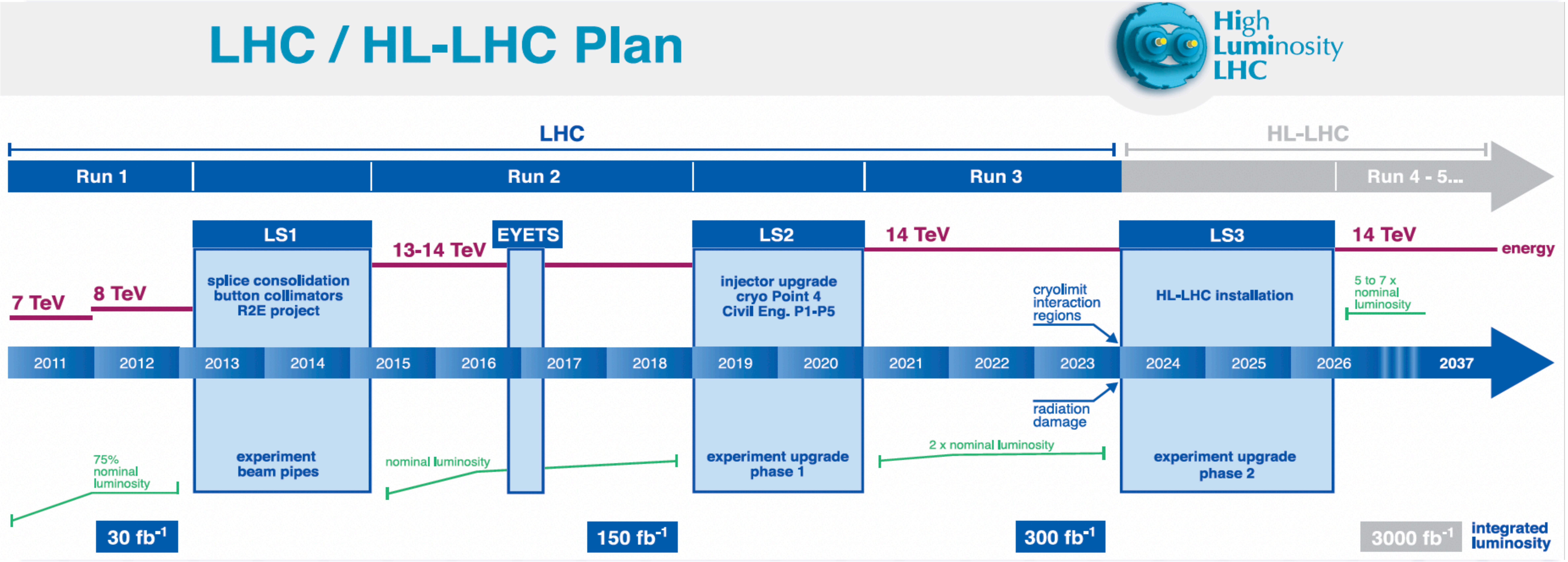
Perspectives pour les hautes énergies (HE-LHC et FCC-hh)

Giacomo Ortona (INFN)

INFN

What's expecting us



HL-LHC will work until 2037. What after?

Main goals: Extend HL-LHC reach in pp and PbPb, probe **new physics** at high mass, **diHiggs**

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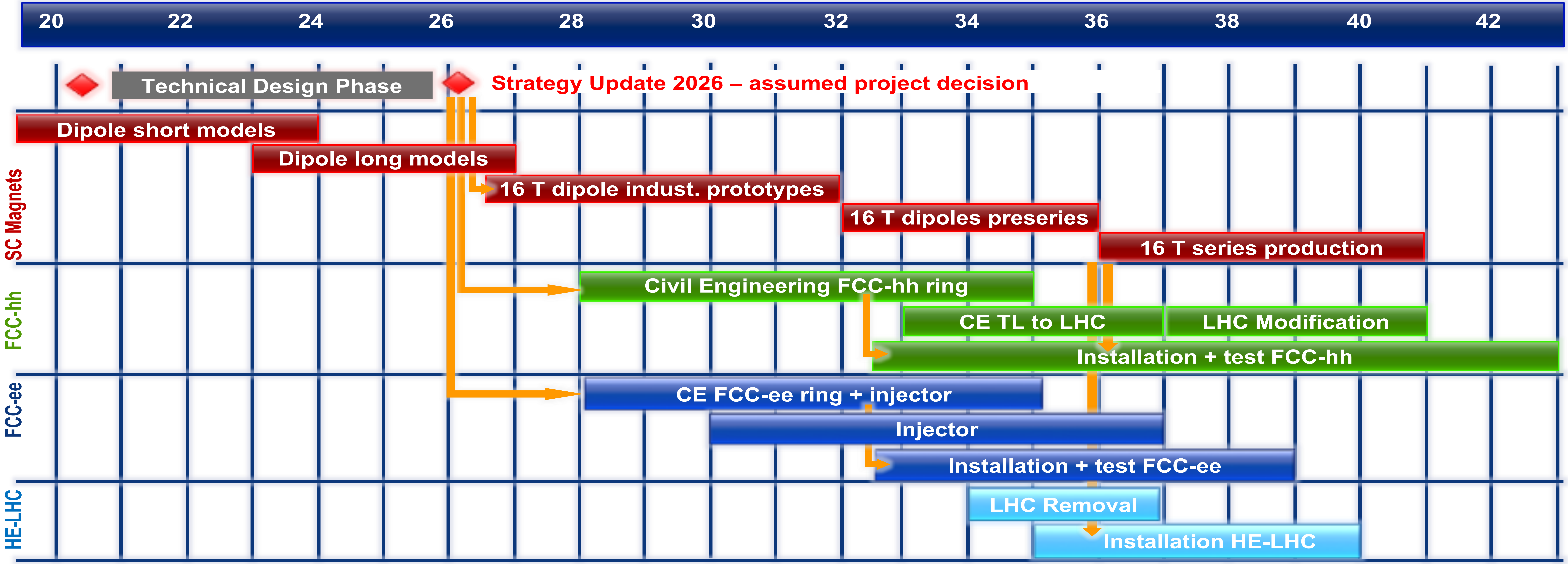

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Main goals: Extend HL-LHC reach in pp and PbPb, probe **new physics** at high mass, **diHiggs**

HE-LHC: intermediate infrastructure between HL-LHC and FCC with a center of mass energy of **27TeV**

- Using the same tunnel of HL-LHC, but FCC class magnets of 16T
- 8 years construction (post HL), ~20 years of operation
- 5 times more integrated luminosity wrt HL-LHC (15ab^{-1}), 2 IPs (CMS+ATLAS)

The FCC

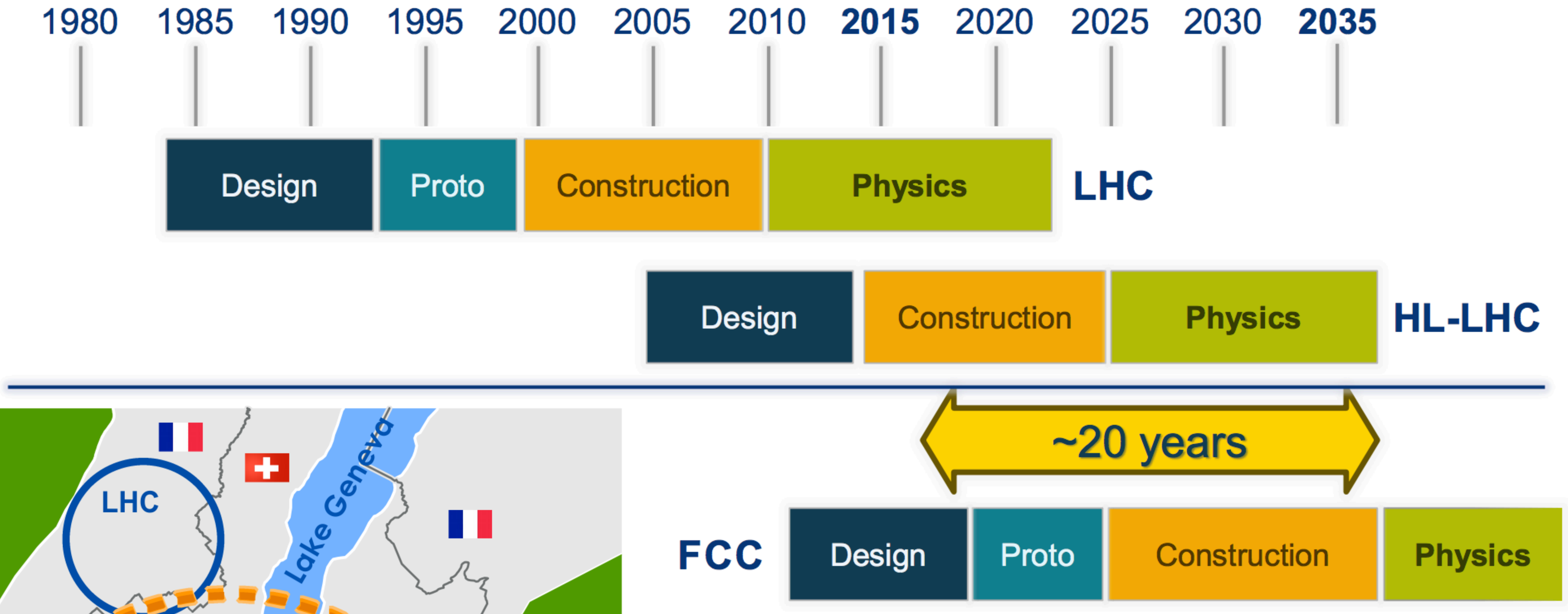
100 km circular collider capable of ee, pp, and AA collisions with 4 IPs

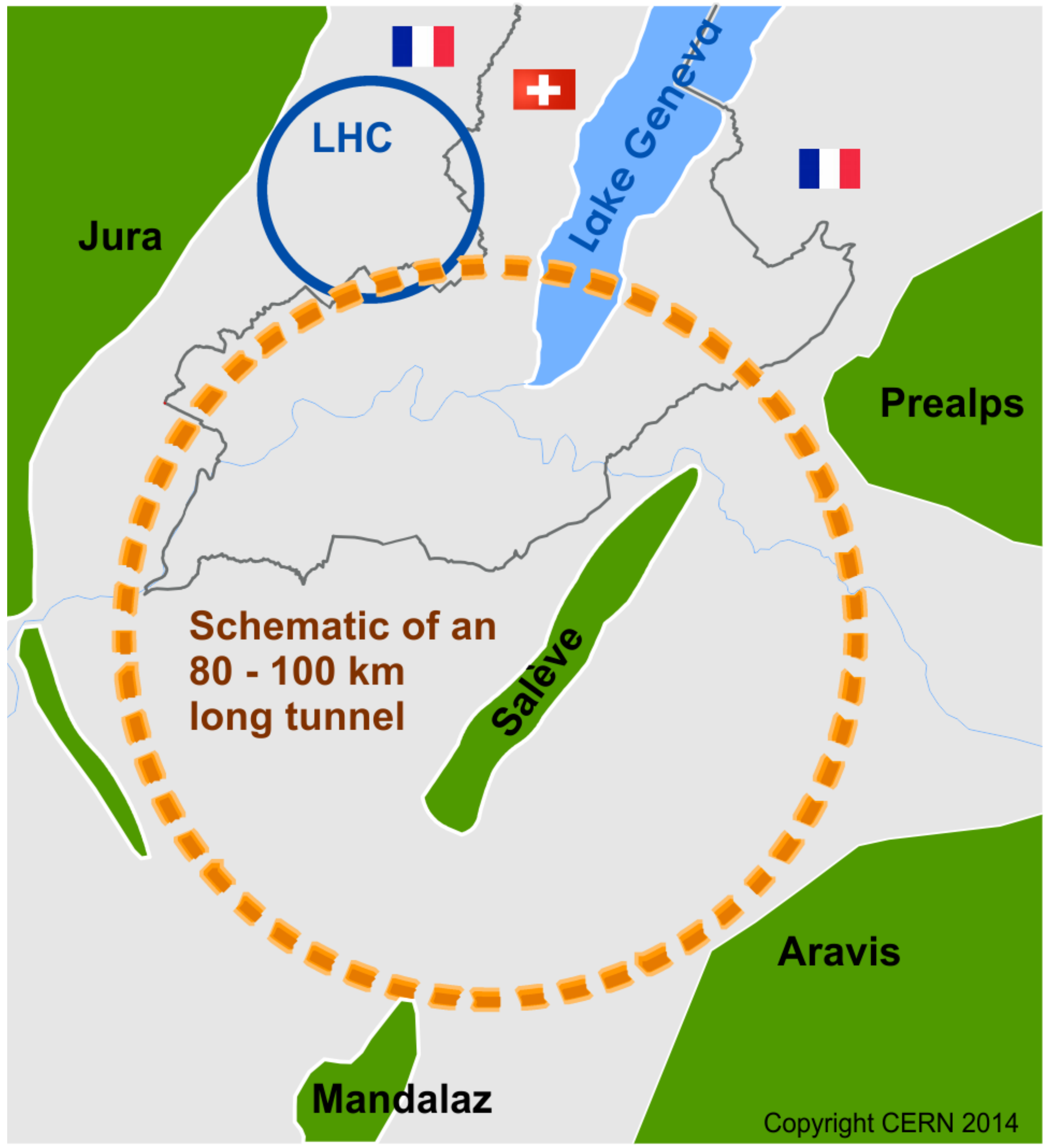
100TeV energy for pp

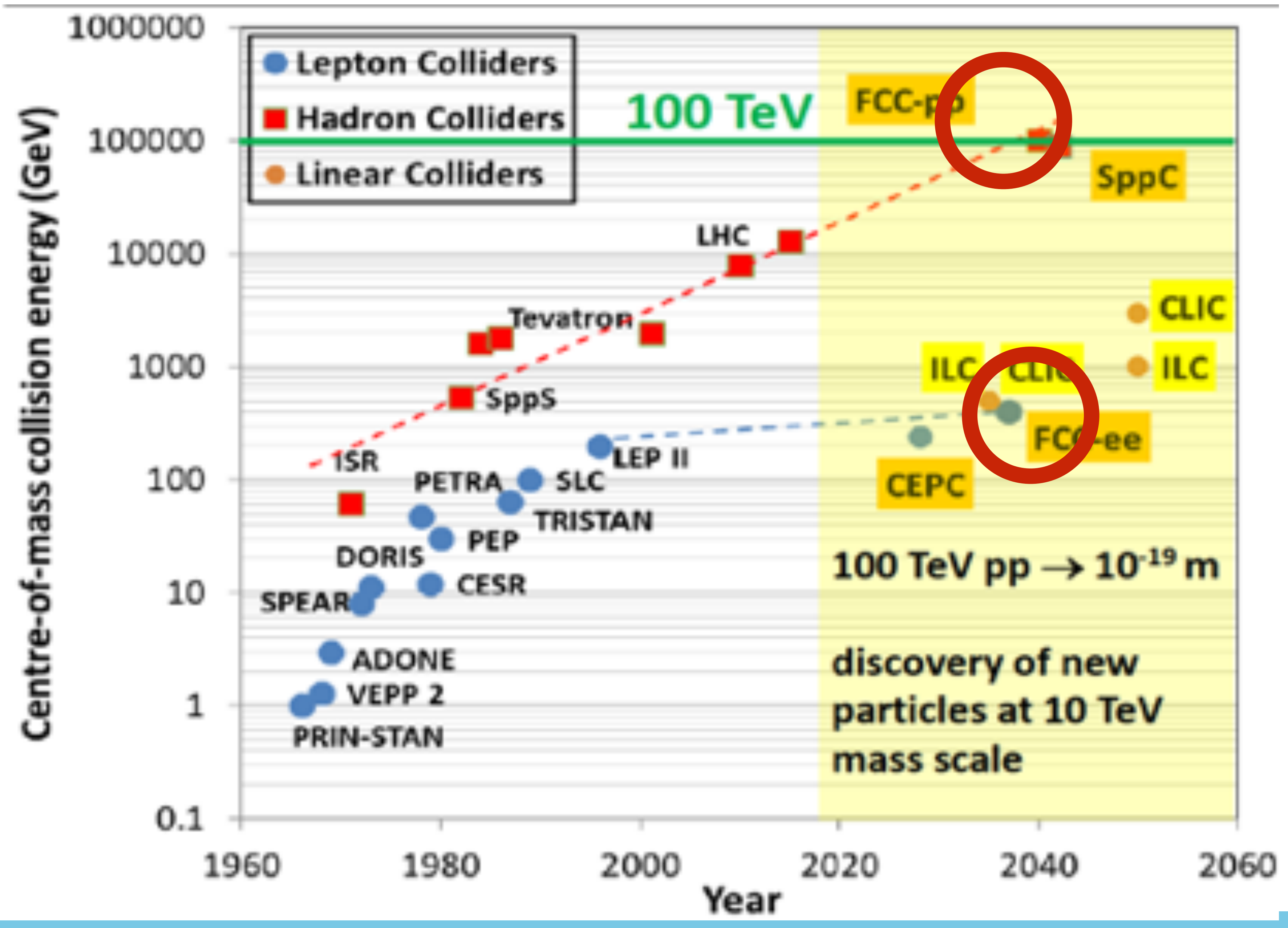
Goals:

- **probe NP up to 30TeV**
- **O(1%) precision in the measurement of the SM couplings**
- **Including Higgs self-coupling**
- **Precision measurement of the Z and top mass poles (in ee)**

10-15 years of operations as e-e before moving to p-p







Physics program

Report on the Physics at the HL-LHC and Perspectives for the HE-LHC

Collection of notes from ATLAS and CMS

CERN-LPCC-2019-01

The ATLAS and CMS Collaborations

February 26, 2019

The CMS, ATLAS, and FCC collaborations performed a thorough investigation of the future colliders physics potential

The final HL/HE-LHC report consists of 1377 pages, and FCC CDR of 4 volumes

Covering:

- Standard Model physics (top, W/Z, FCNC, EWK fit, VBS)
- Higgs (couplings, width, x-sections, H→light, self coupling, exotic Higgs decays, top-Yukawa)
- BSM exploration (New resonances, dark matter, MET, Majorana ν,…)
- Flavour physics (B decays, LFV, CP violation)
- Heavy ions (flow, R_{AA}, jet quenching, quarkonia and HF,…)
- Accelerator and detector performances

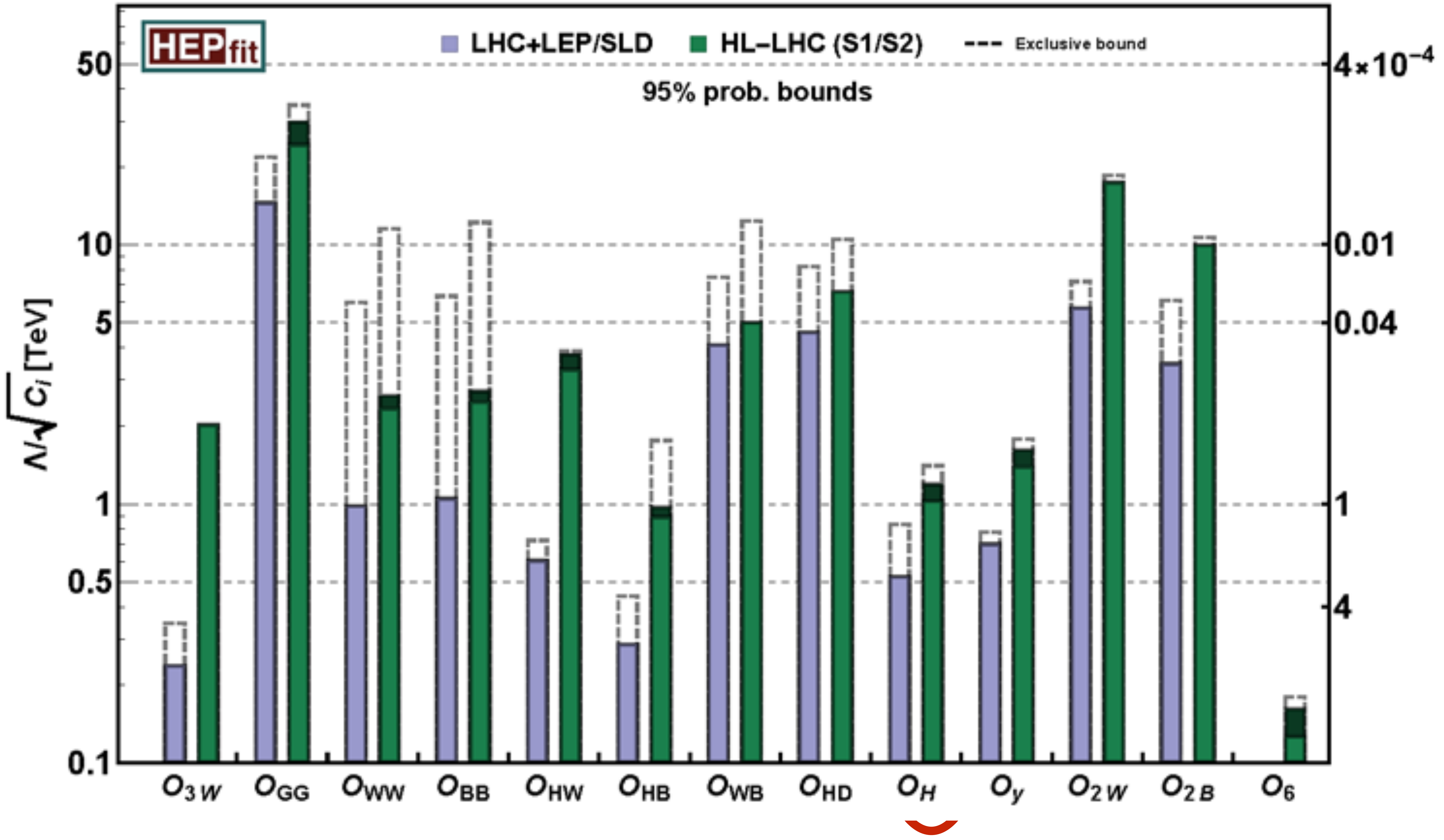
EWK physics: EFT

EWK and Higgs measurement can be used to set indirect constraints on BSM, using the formalism of Effective Field Theories

- SM Lagrangian is supplemented with **dimension-6** operators Oi $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$
- Exploiting the fact that heavy BSM dynamics can still have an impact on processes at smaller energy, via virtual effects.
- Allows to systematically parametrize BSM effects and how they modify SM processes.

Global fit to observables in Higgs physics, as well as diboson and Drell-Yan processes.

- The fit includes all operators generated by new physics that only couples to SM bosons.
- O_H: Anomalous H coupling via modified Higgs propagator. Sensitive to NP up to 25TeV, compositeness up to 2TeV



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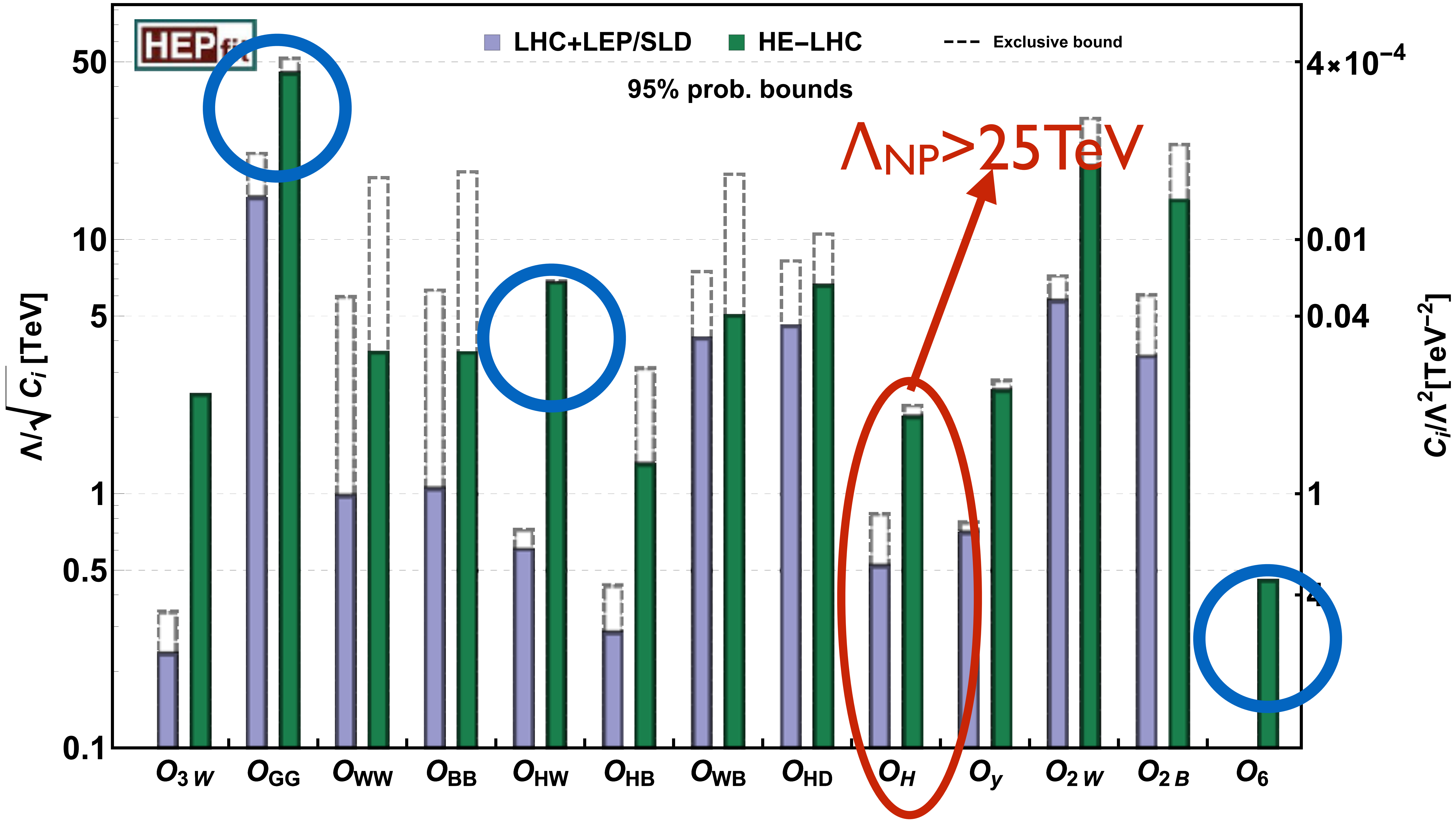
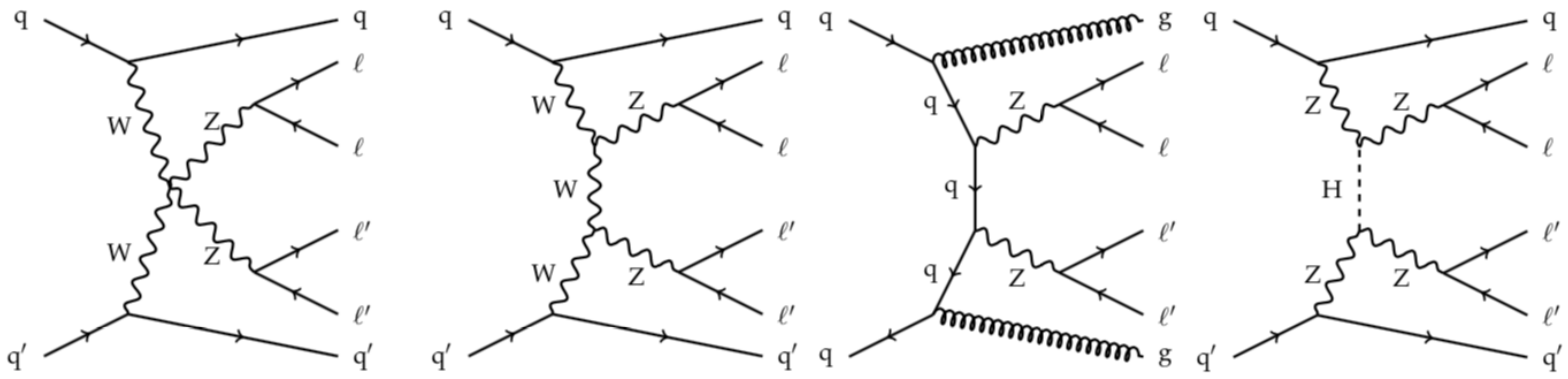


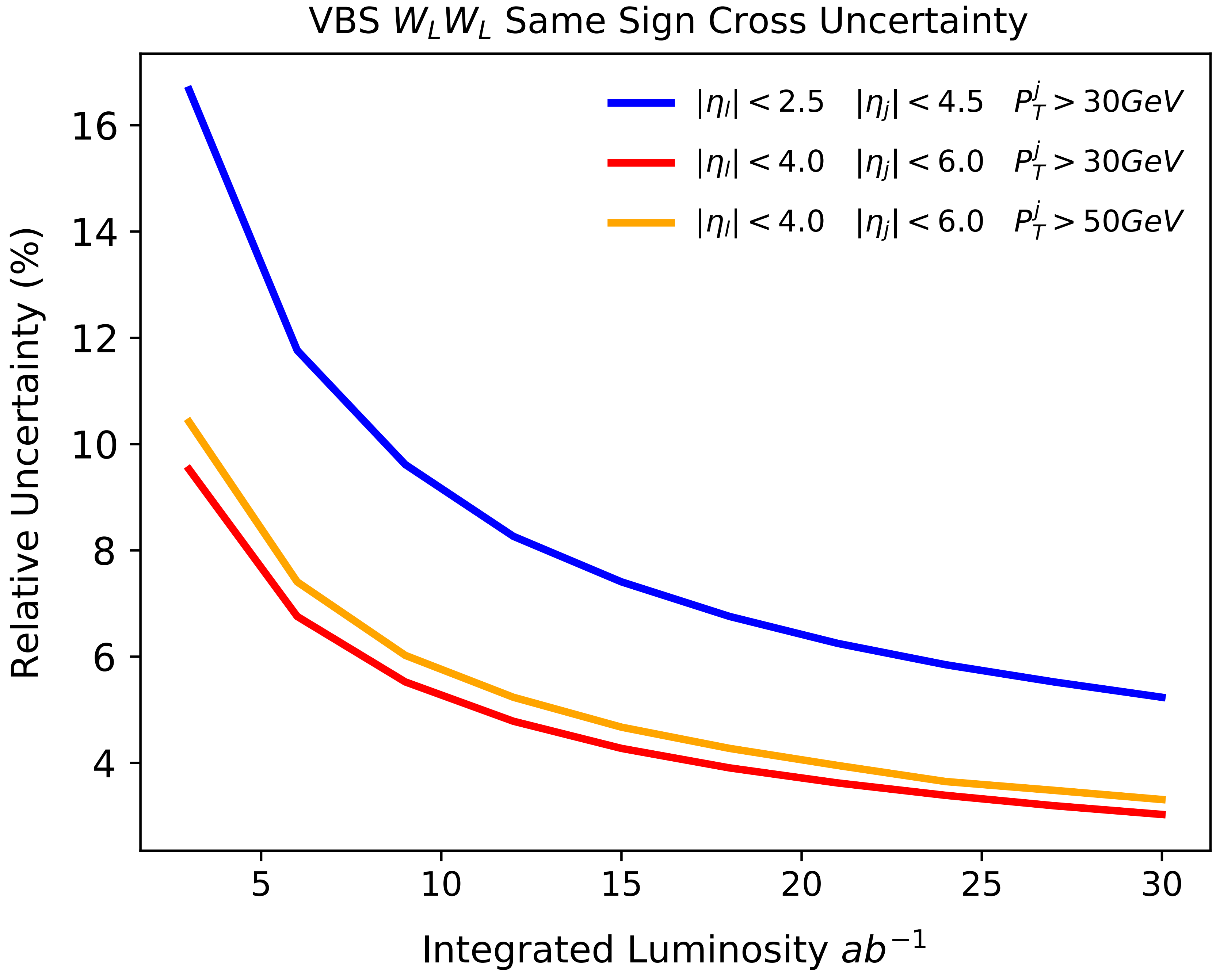
SM physics: VBS

Great importance to test the mechanism of EW symmetry breaking:

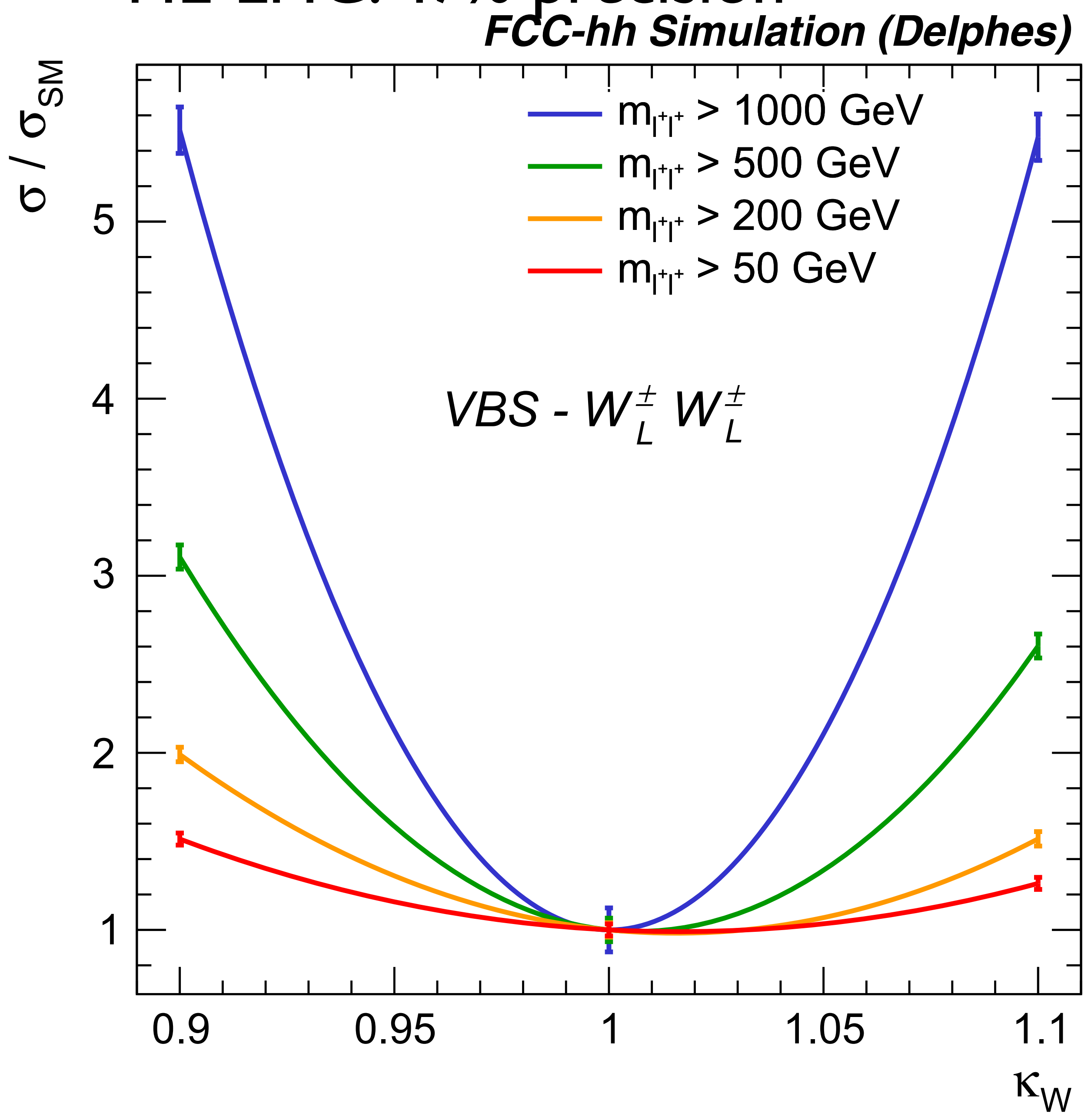
- If the discovered Higgs boson contributes fully to EWSB→ the scattering of longitudinal weak gauge bosons would not grow strong at high energies
- if the 125.5 GeV Higgs boson is only partially responsible for EWSB, and the rest is very heavy, then the VV scattering could get strong for a range of energies
- Can signal the presence of anomalous couplings and NP at energy scales beyond the reach of direct resonance production.

FCC-hh will provide the chance to measure the VBS longitudinal component with a few percent precision.



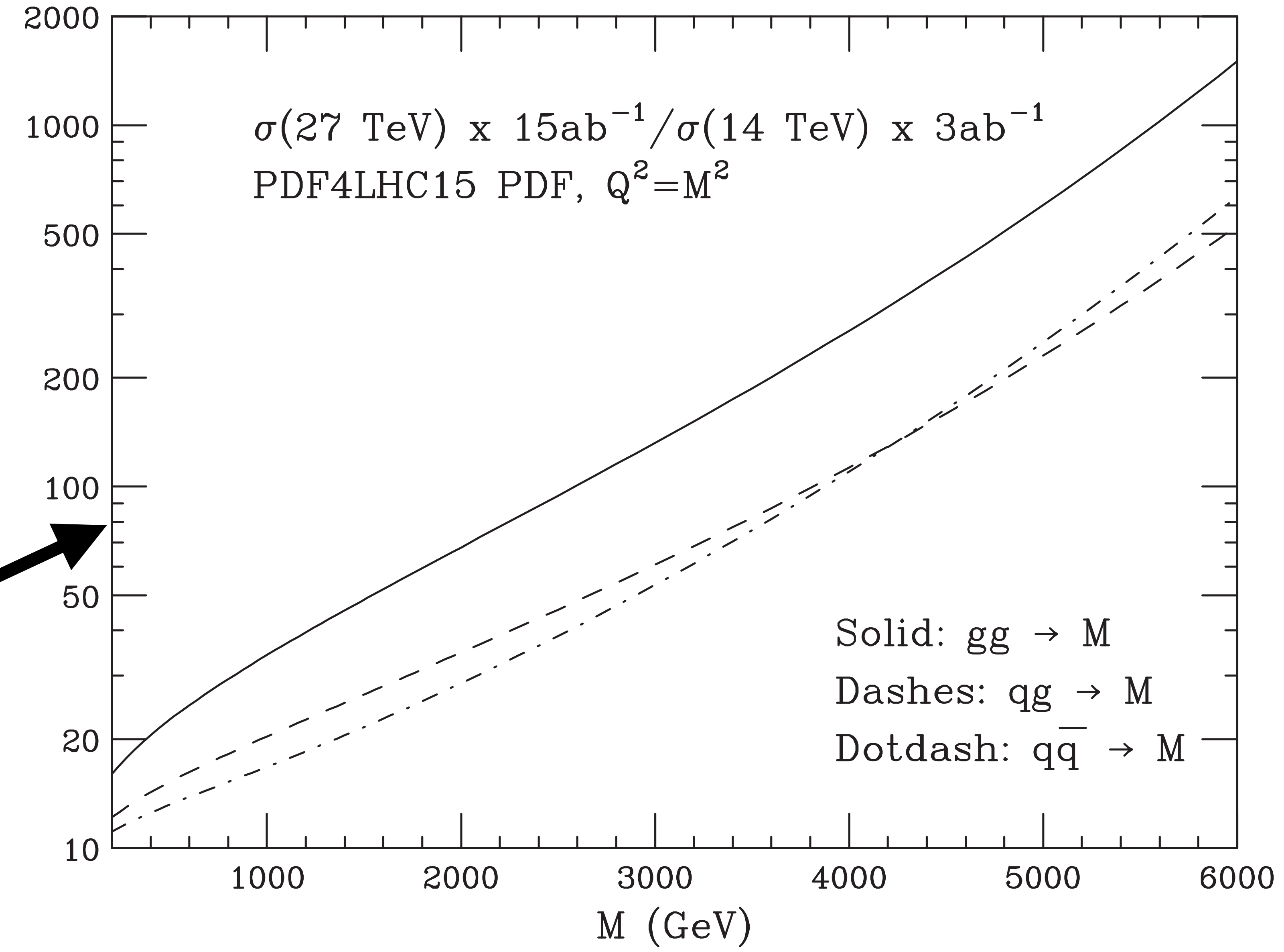


HL-LHC: 47% precision



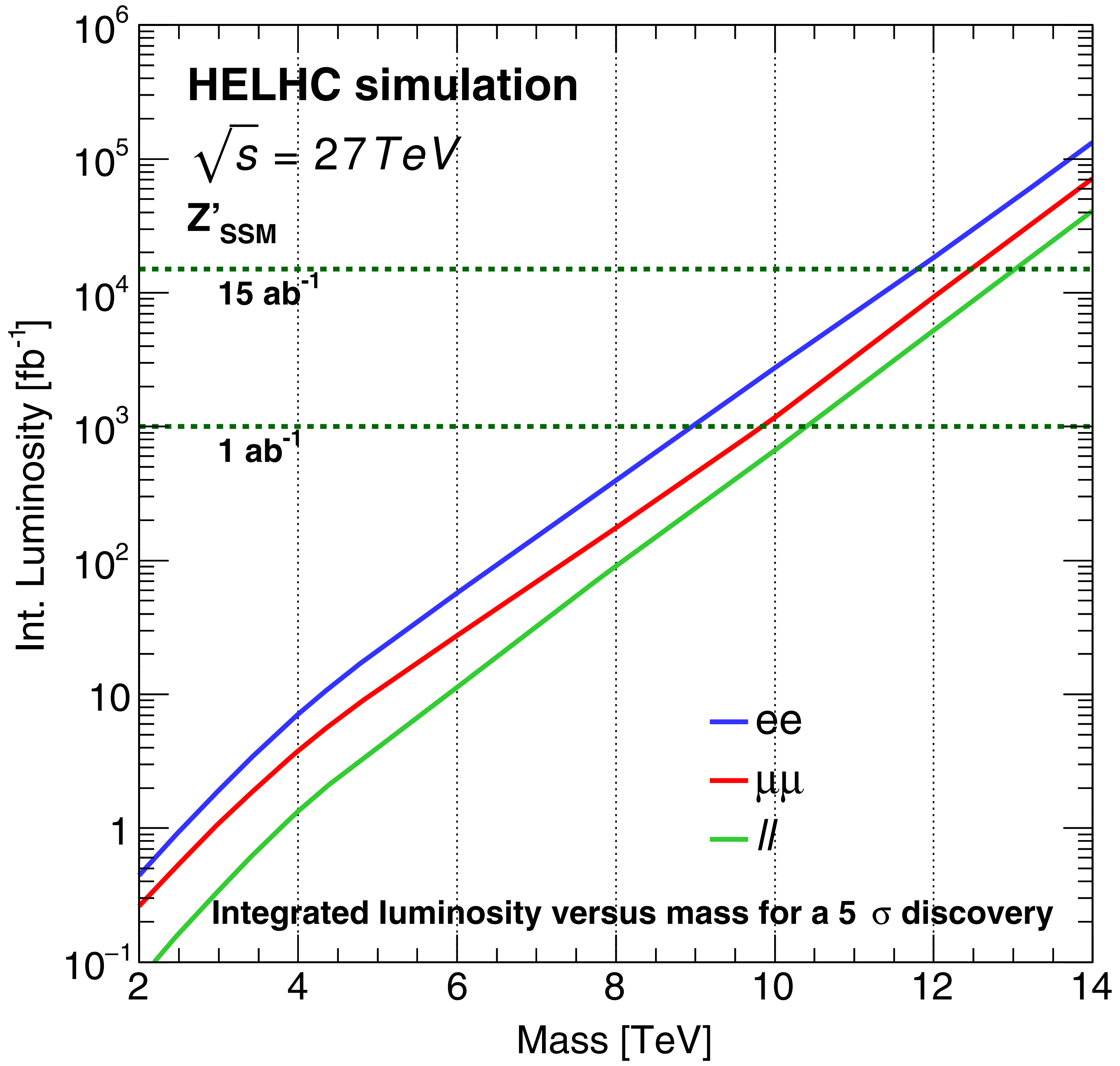
Search for new massive particles

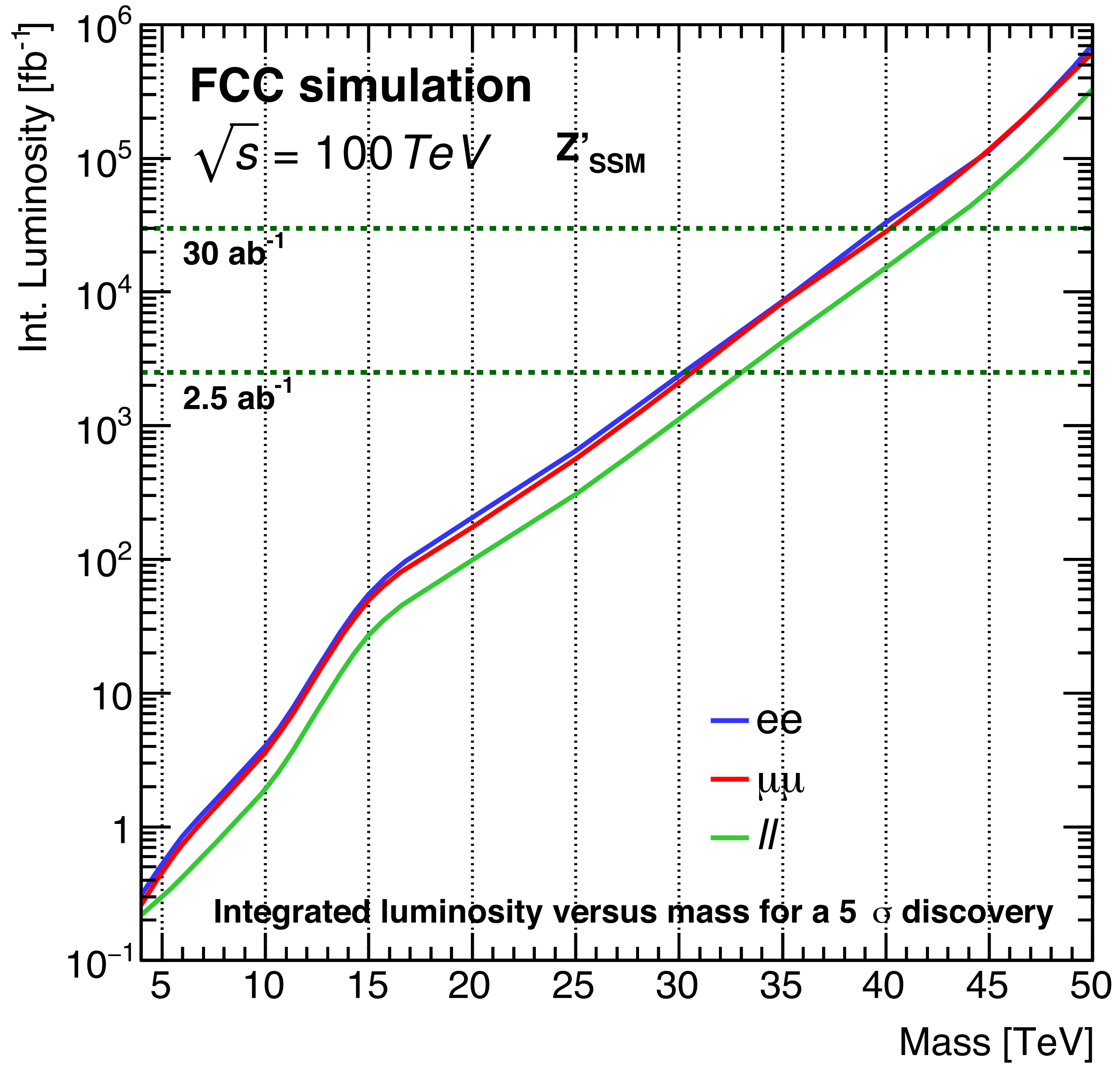
Process	HE-LHC (FCC-hh)		
	95%CL limit (TeV) 15 (30) ab^{-1}	5σ reach (Tev) 1 (2.5) ab^{-1}	5σ reach (TeV) 15 (30) ab^{-1}
$Z'_{SSM} \to e^+e^-/\mu^+\mu^-$	13 (40)	10 (33)	13 (43)
$Z'_{SSM} \to \tau^+\tau^-$	6 (14)	3 (12)	6 (18)
$Z'_{FA} \to \mu^+\mu^-$	4 (25)	– (10)	2 (19)
$Z'_{TC} \to t\bar{t}$	10 (28)	6 (16)	8 (23)
$G_{RS} \to WW$	8 (28)	5 (15)	7 (22)
$Q^* \to jj$	14 (43)	10 (36)	12 (40)



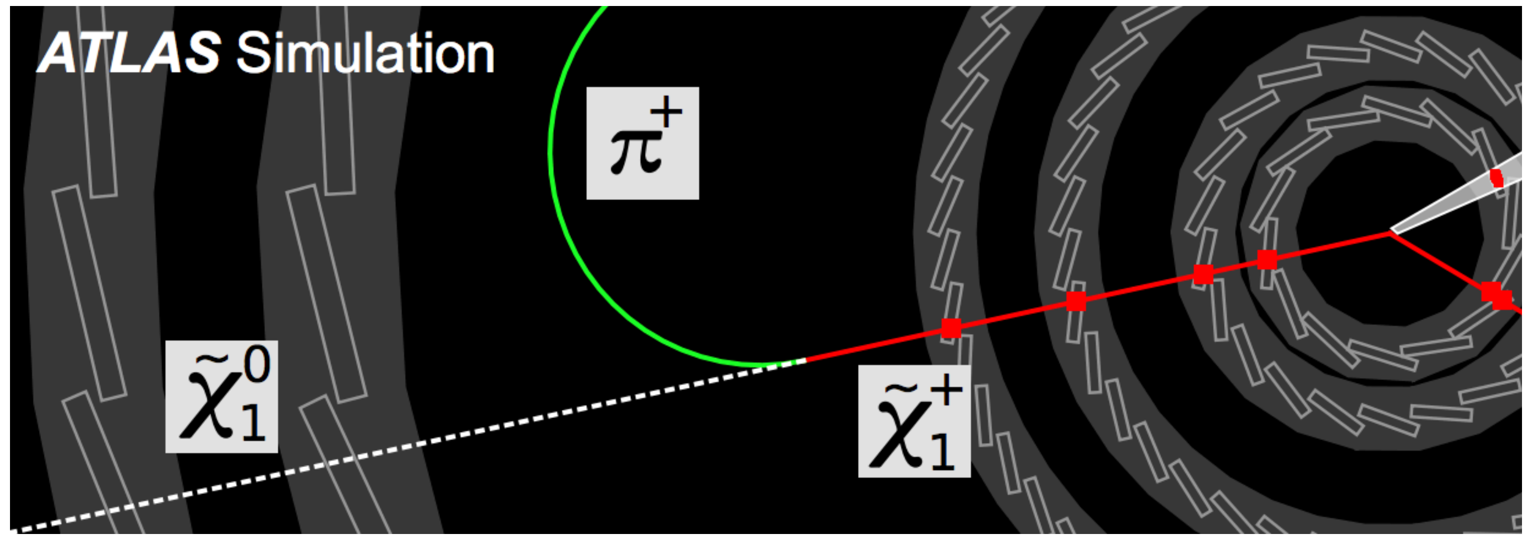
The cross-section for massive particles production is strongly dependent on the available center-of-mass energy

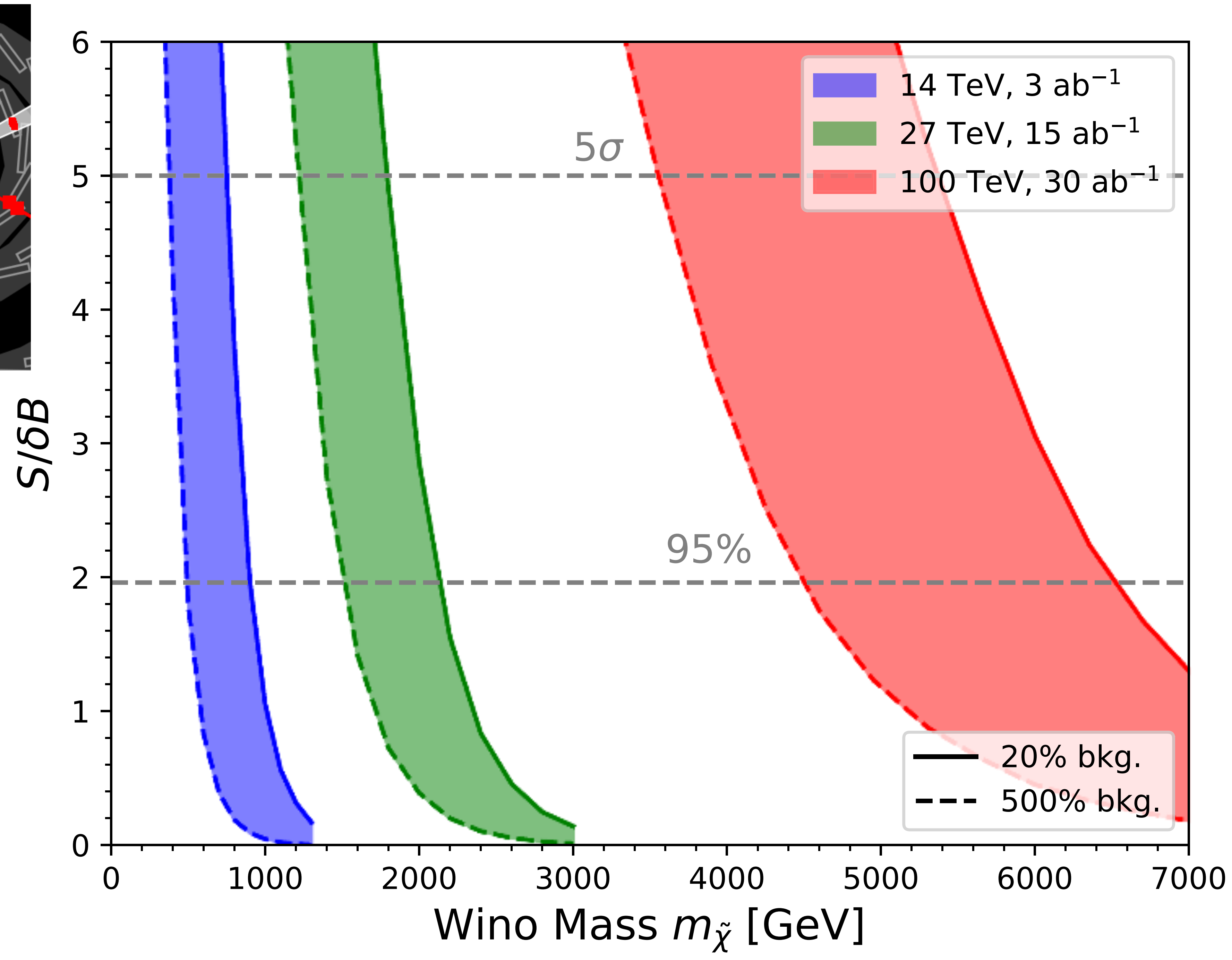
- At high mass, x-sections grow by several orders of magnitude
- Expect to be able to exclude (or discover!) particles up to **O(10TeV)** in the s-channel at HE, and 3 times more at FCC
- SSM=Sequential Standard Model. Used as benchmark to assess discovery potential

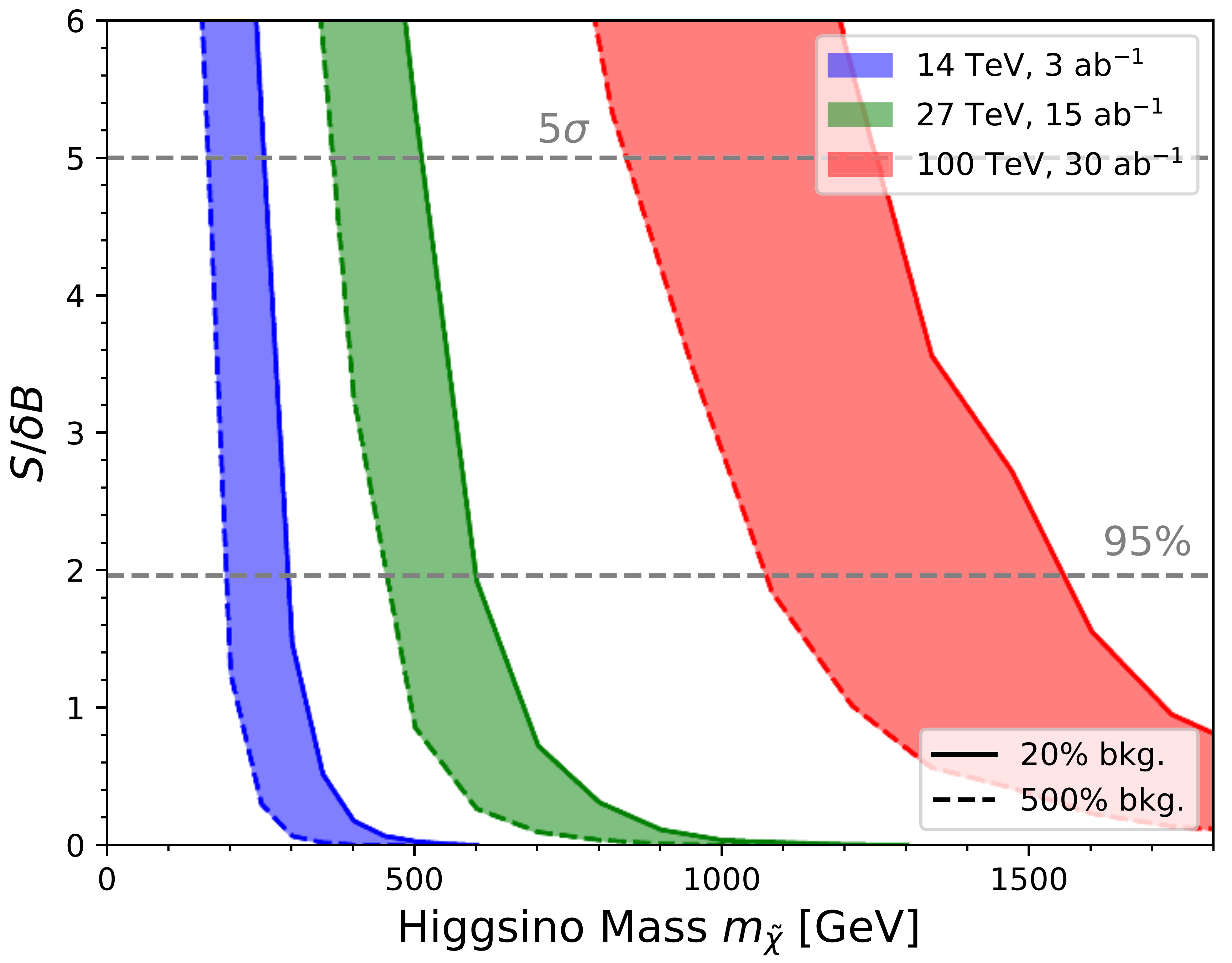




WIMPs and DM





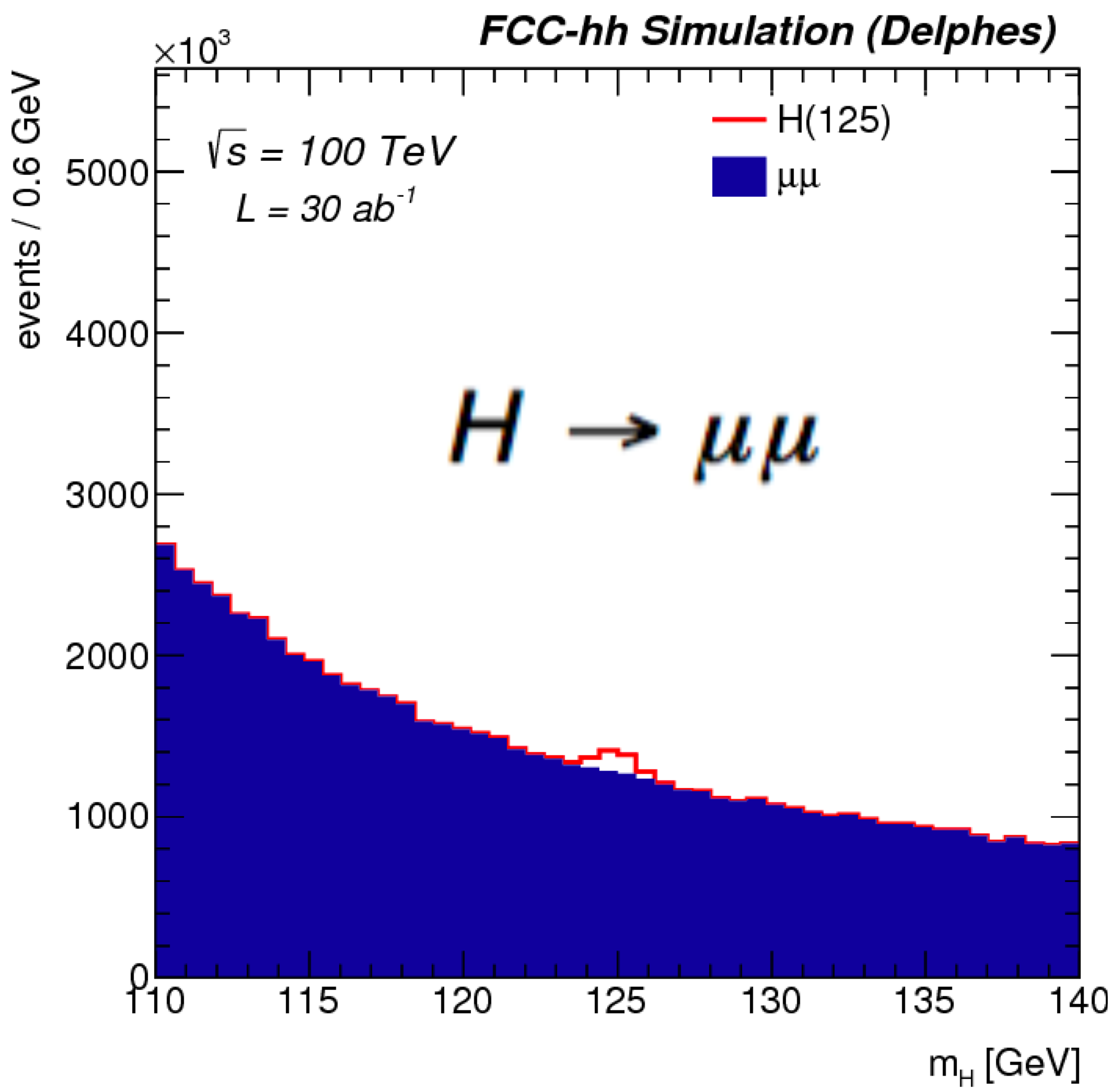


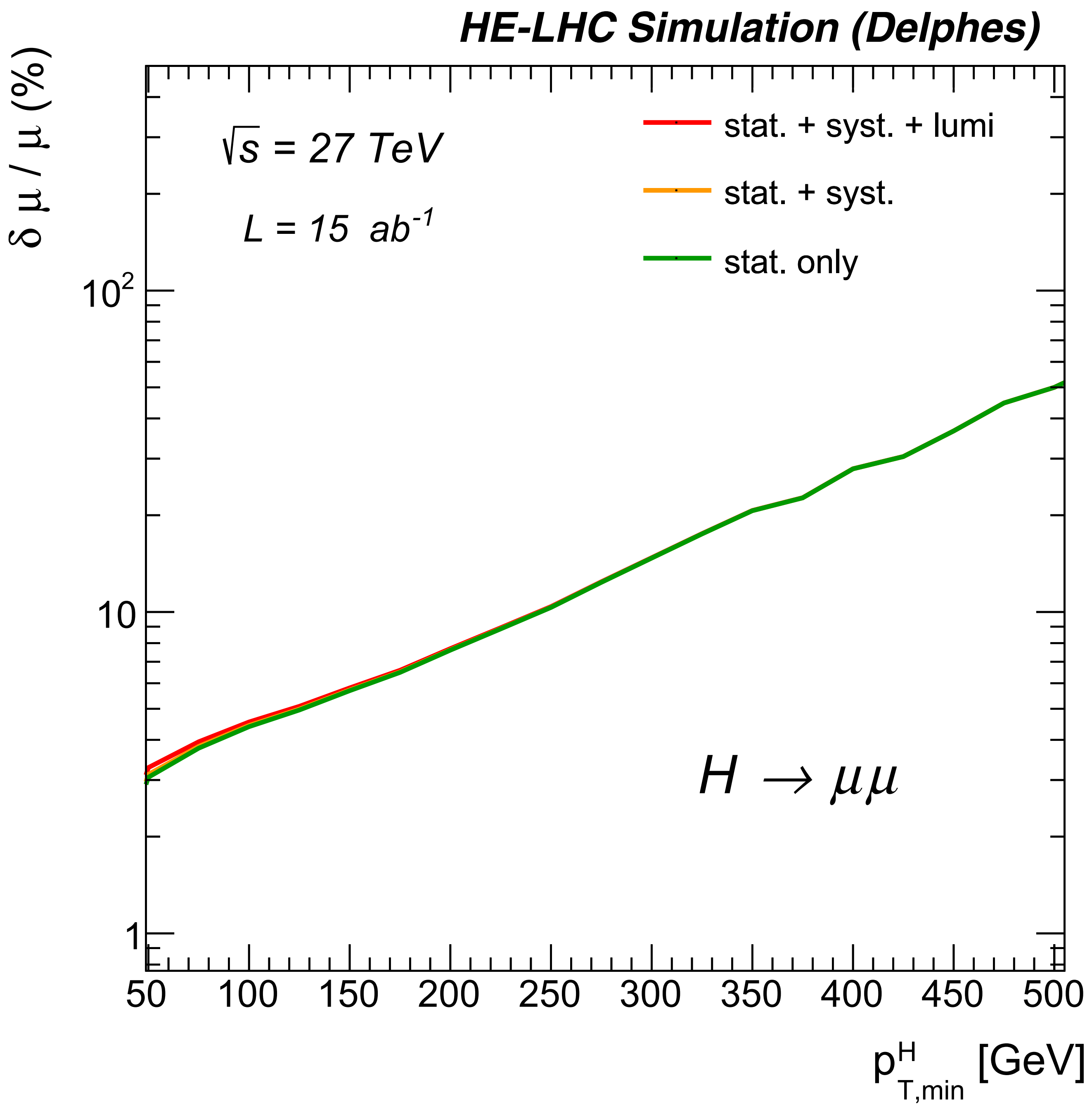
HE-LHC roughly doubles the expected range of HL-LHC in the DM and new particles searches, like WIMPs

- Search for missing tracks compatible with W-ino and Higgs-Iso
- Can be complementary to indirect probes (astronomical, cosmic rays). The combination of HE-LHC and indirect measurement should probe a large part of the WIMP phase space
- FCC-hh should put the final word, probing O(TeV) masses for the WIMP (although is a moving target)

Higgs physics: signature channels

	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390



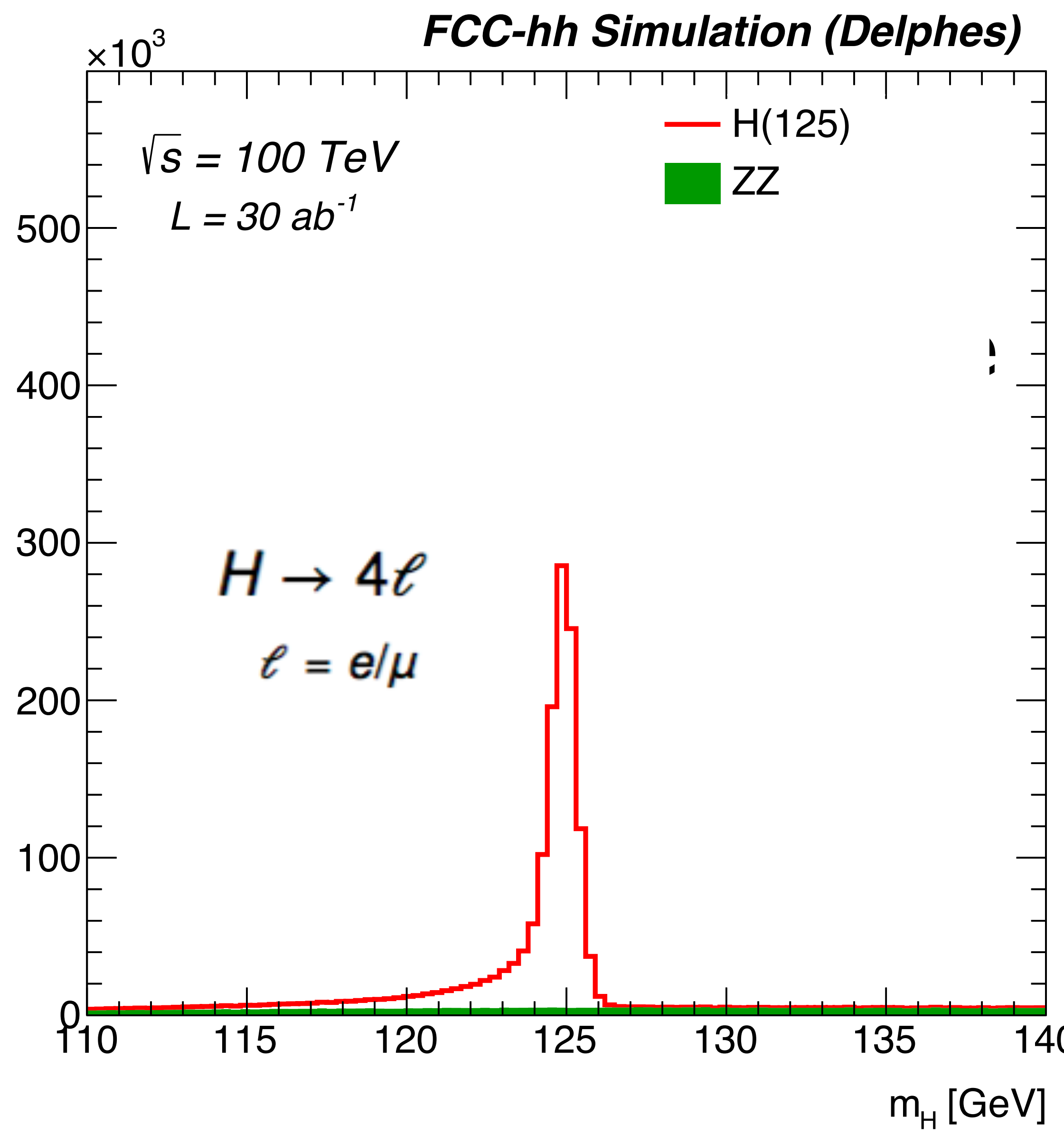


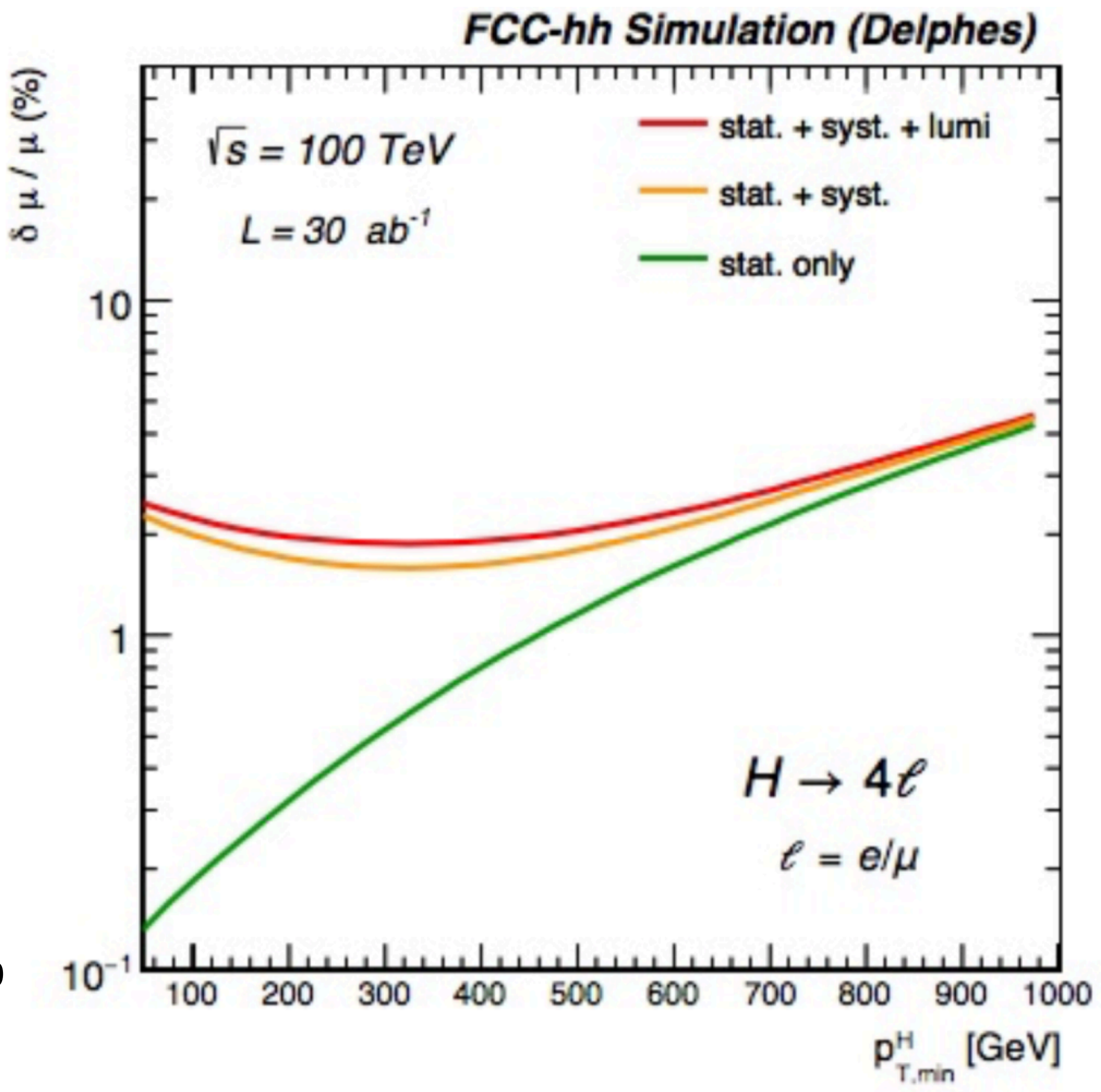
Large H production (180xHL-LHC, 14xHE-LHC) cross-section at FCC-hh allows for a significant production of rare events such as Hμμ

Excellent precision in the rare channels

Profiting of the boosted system, HZZ is almost background free

Large systematics effects at low p_T

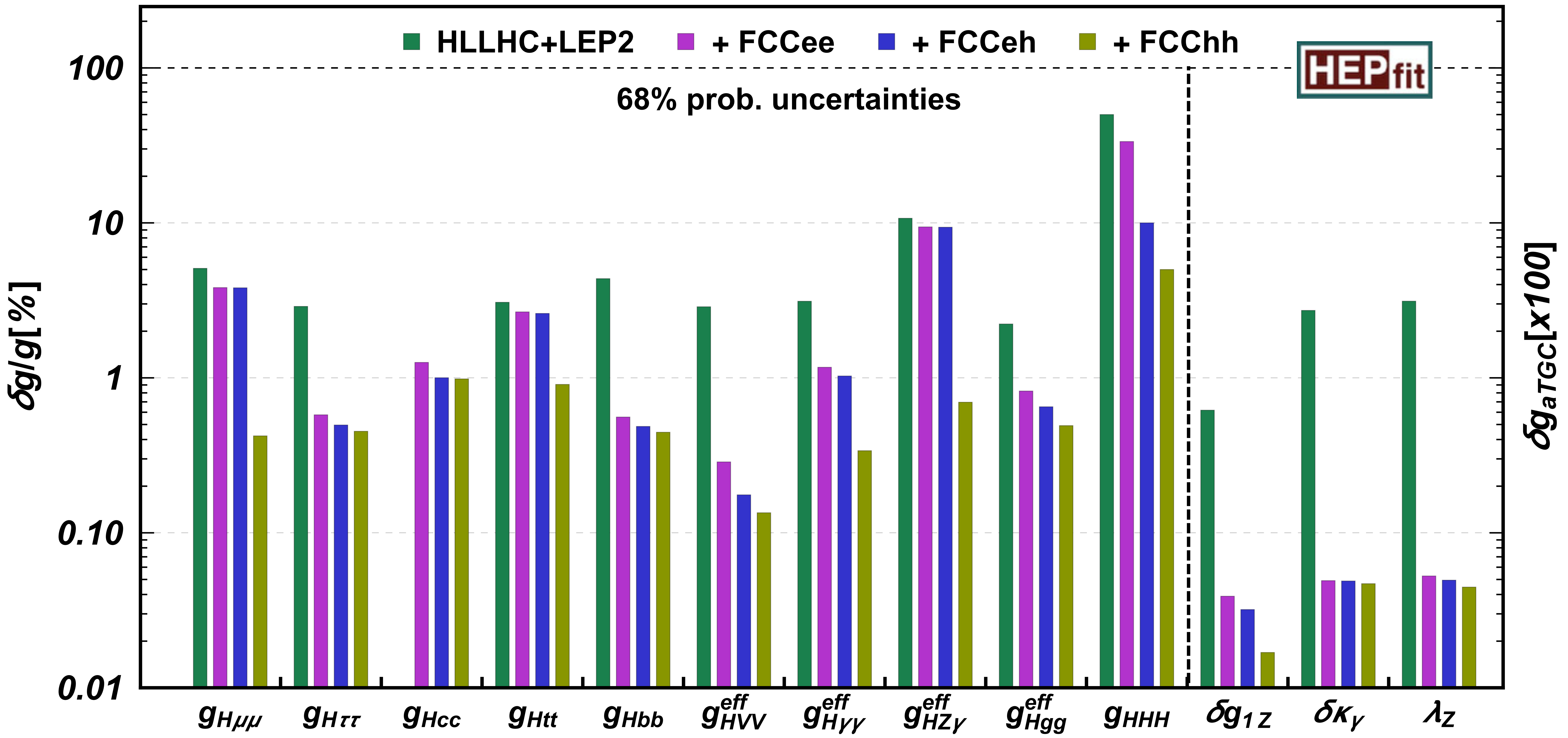


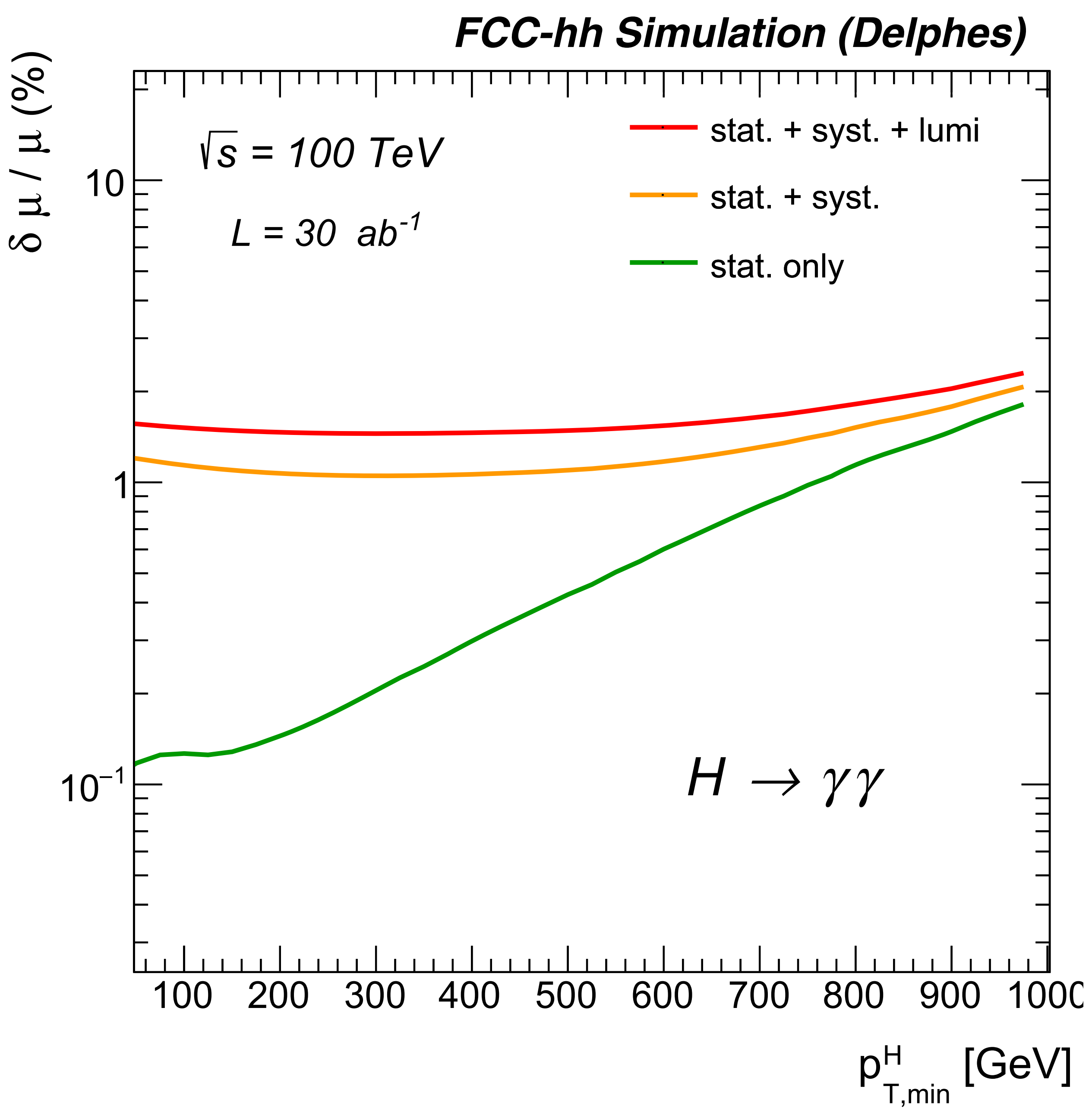


Higgs physics: Couplings at FCC

Better than 1% precision can be reached for almost all couplings

Large improvements at FCC-hh on Hμμ, HZγ, HHH



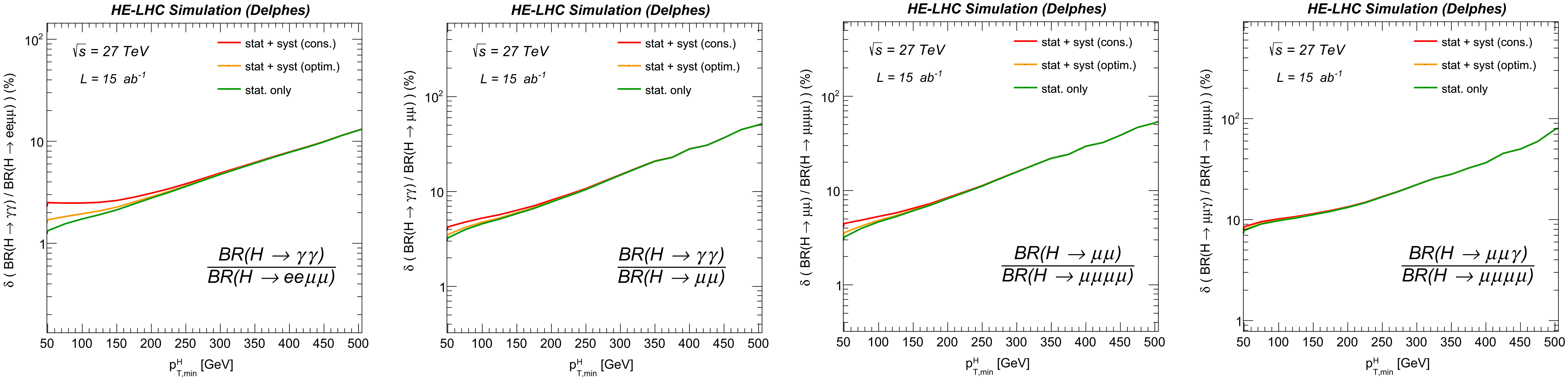


Observable	Parameter	Precision (stat)	Precision
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.5%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.2%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.9%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.6%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)\mathrm{B}(\mathrm{H} \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%

Higgs physics: Ratios of BRs at HE-LHC

	$gg \to H$	WH	ZH	$t\bar{t}H$	HH
N_{27}	2.2×10^9	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
N_{27}/N_{14}	13	12	13	23	19

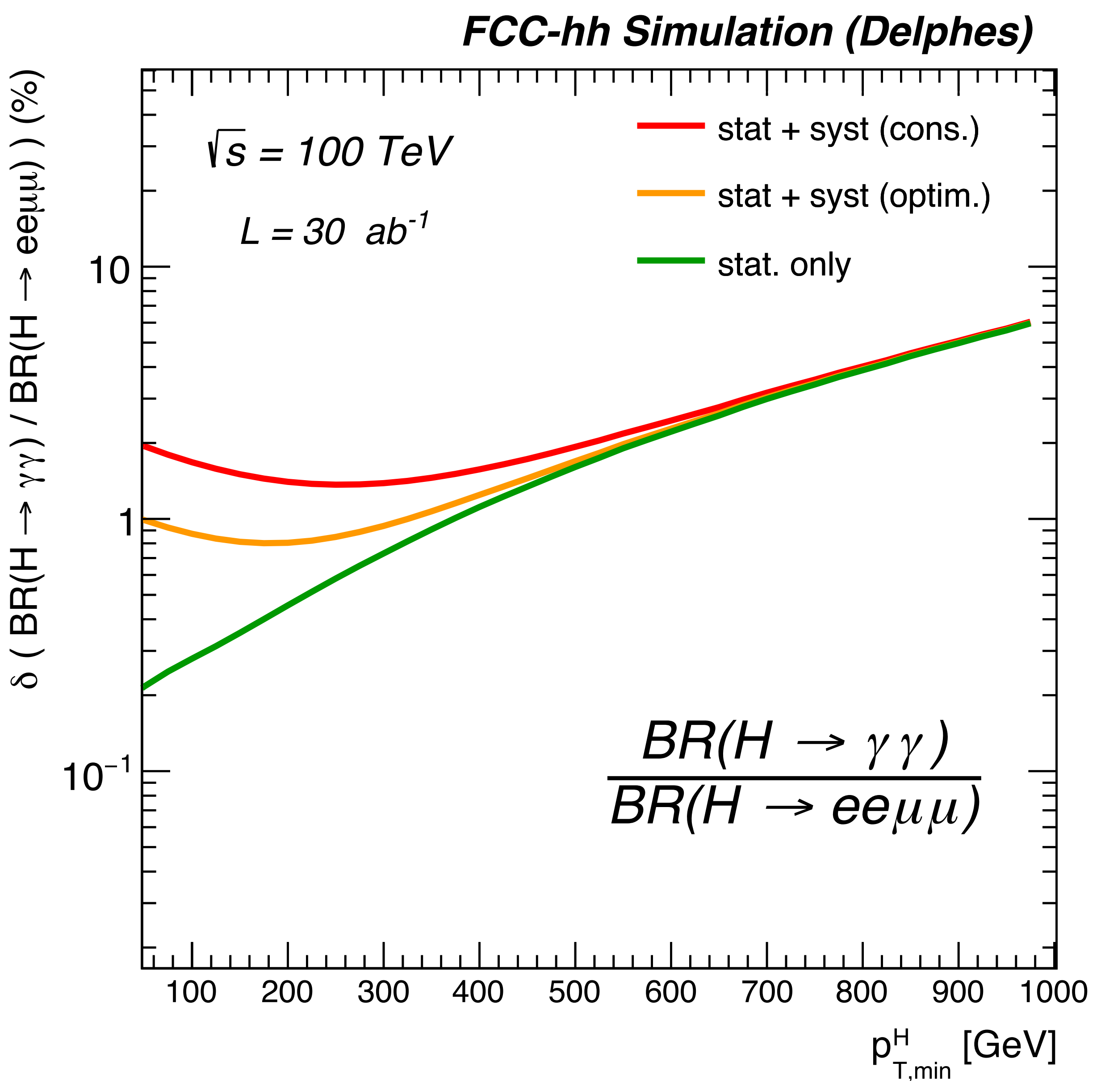
- Target of **few % uncertainty** is feasible.
- $15ab^{-1}$ expected → **x10-x25 increase in Higgs production**, especially significant in rarer production modes (ttH, HH)
- 1-5% precision on BR ratio for different processes
- Still statistically limited

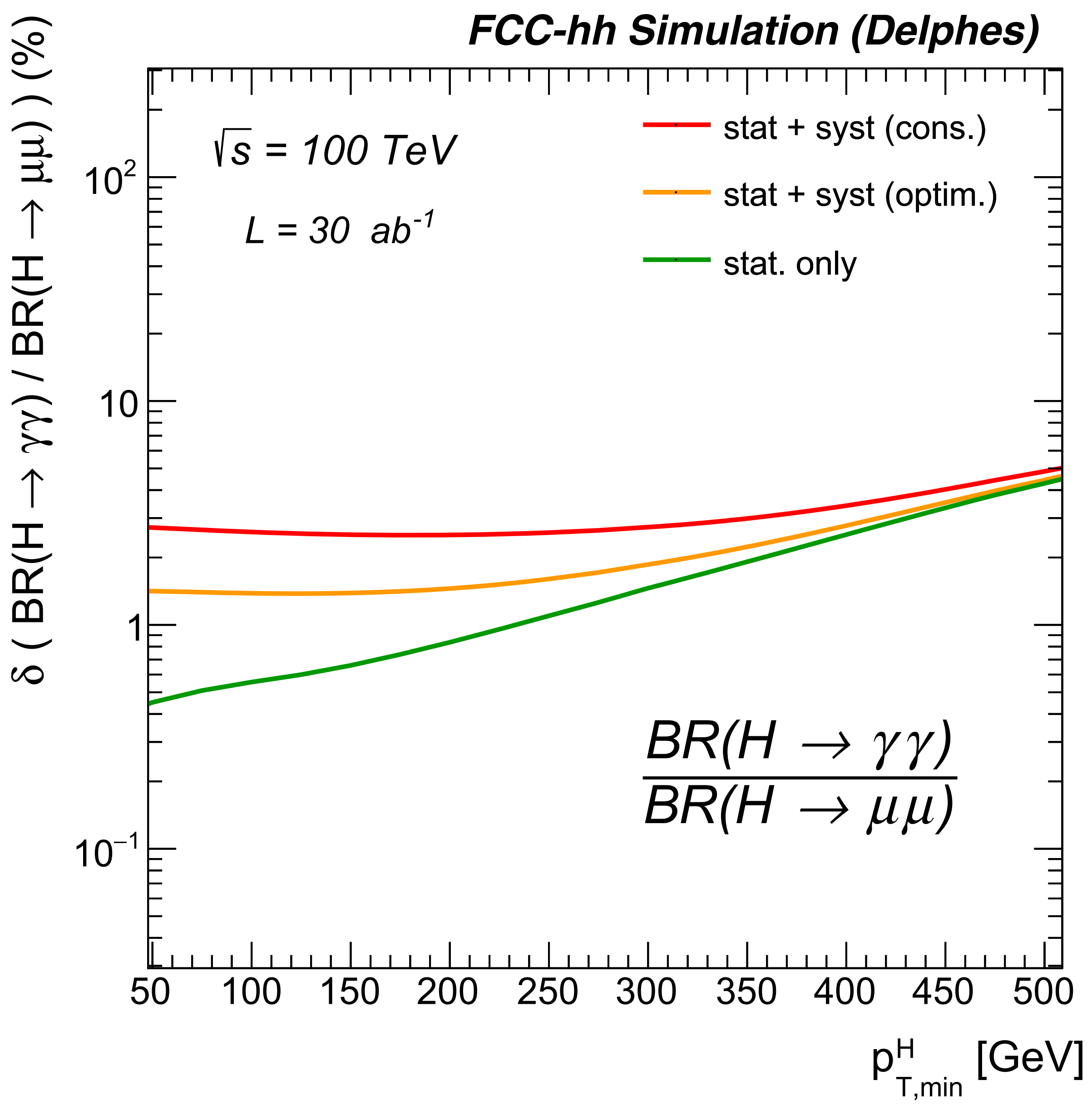


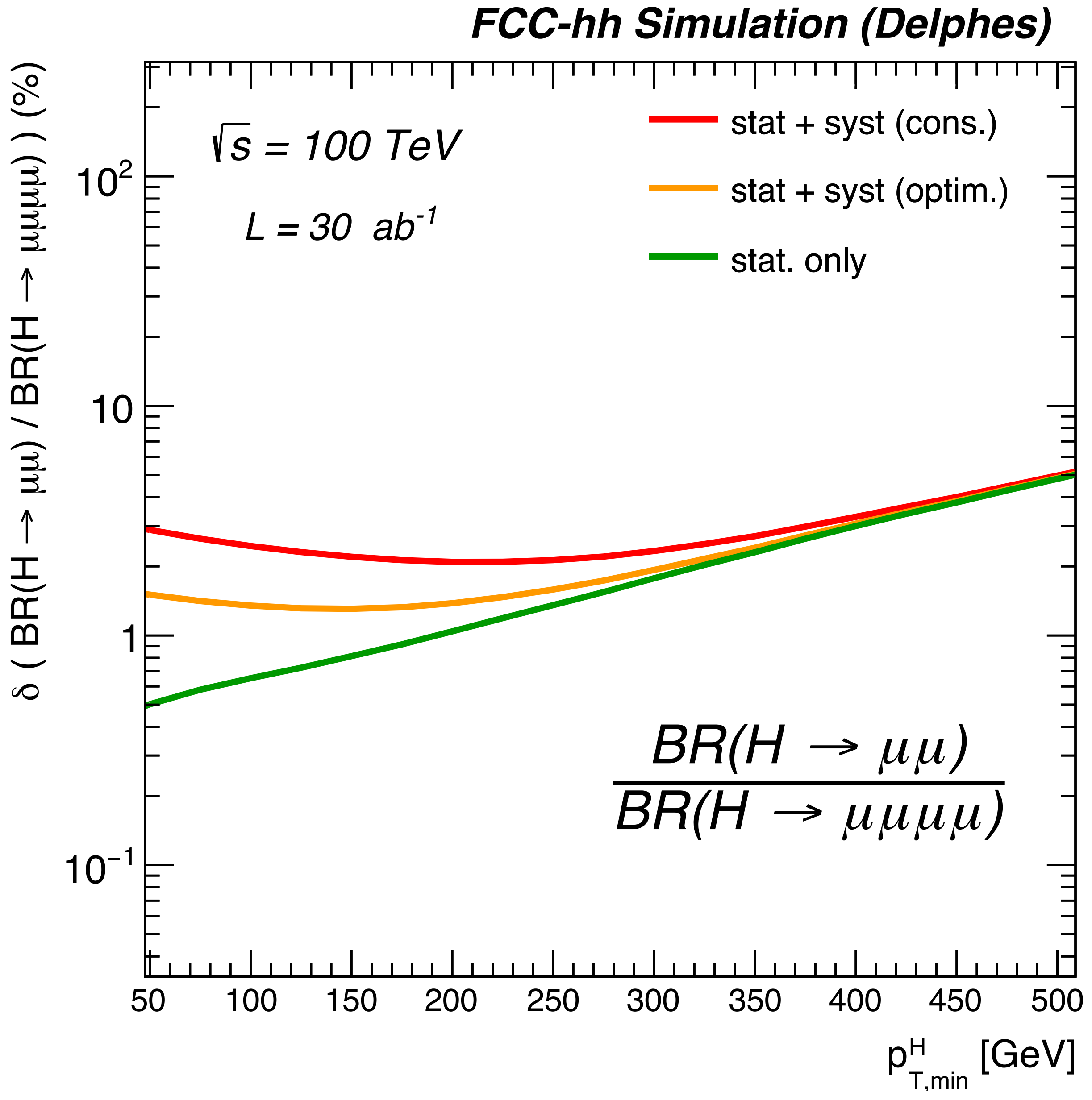
Higgs physics: Ratios of BRs at FCC-hh

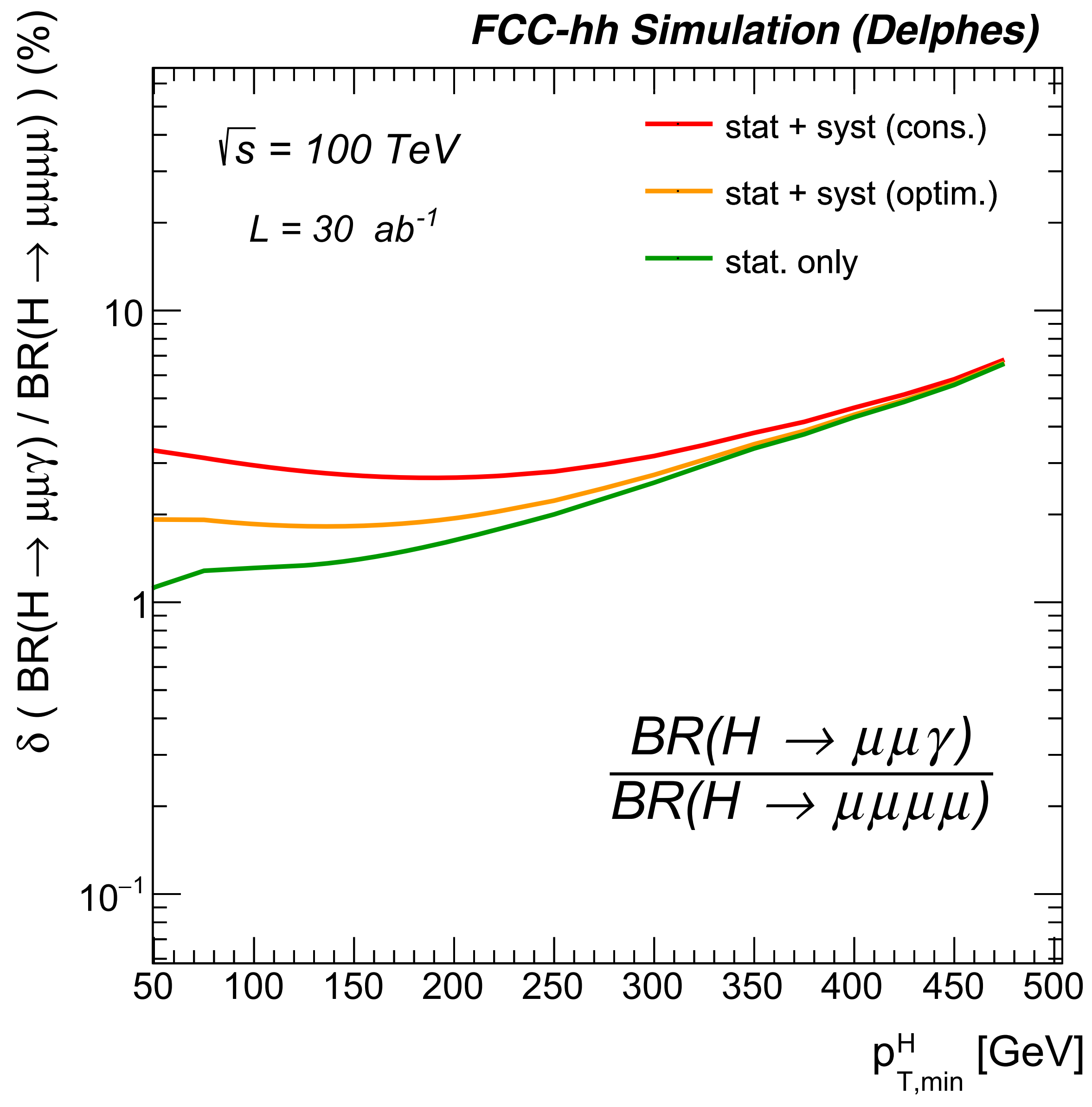
Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$R = \mathrm{B}(\mathrm{H} \to \mu\mu)/\mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2\mu)$	$\delta R/R$	0.29%	1.4%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu\gamma)/\mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta R/R$	0.58%	1.8%
$R = \sigma(t\bar{t}\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to b\bar{b})/\sigma(t\bar{t}\mathrm{Z}) \times \mathrm{B}(\mathrm{Z} \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H} \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

- 1% precision on almost all H parameters
- Systematics important at low p_T, still statistically limited at high p_T

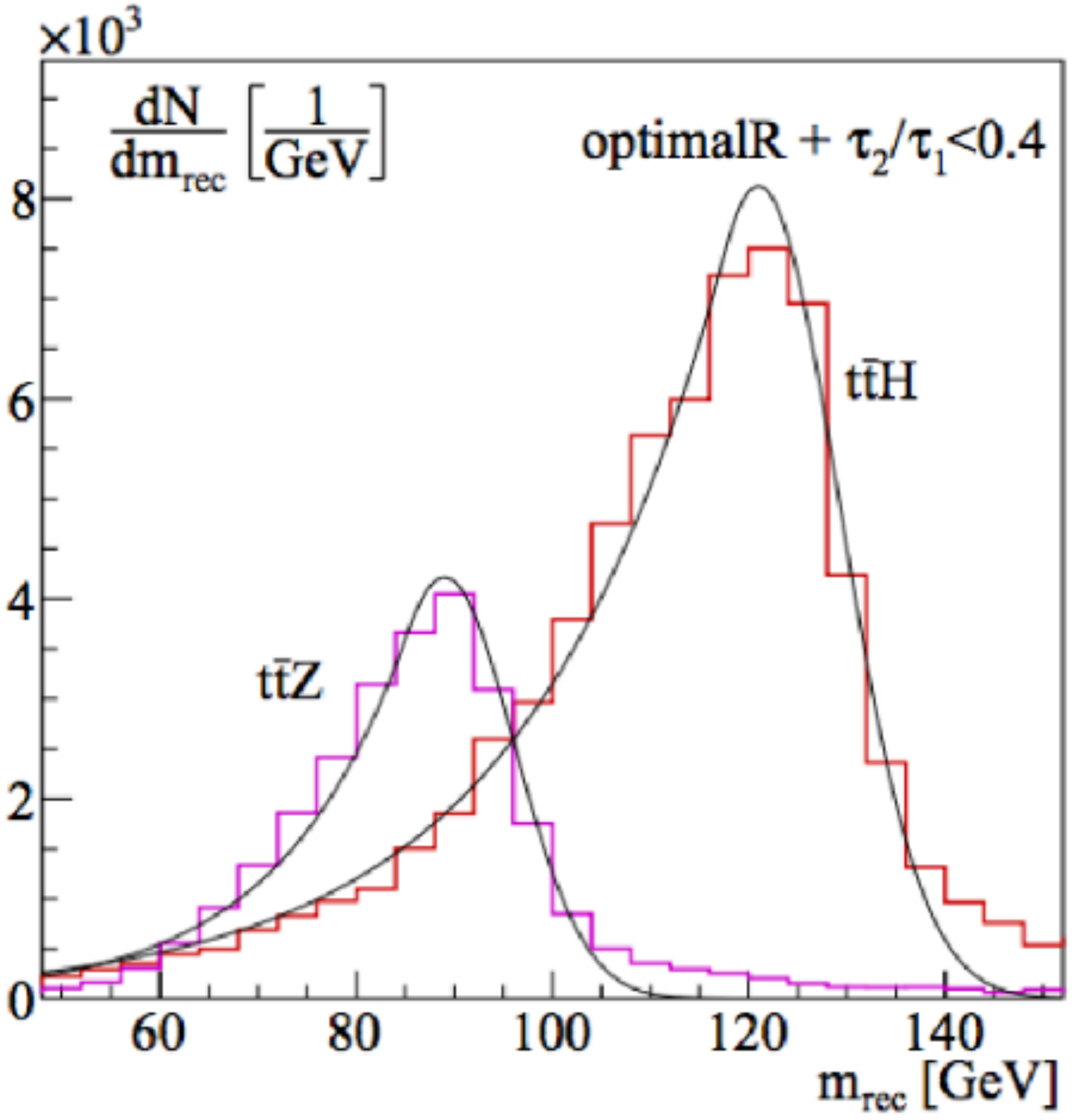








Higgs and Top at FCC



top-Yukawa can be measured at FCC-hh from the ratio σ(ttH)/σ(ttZ)

- In H/Z→bb decay in the boosted regime, semi-leptonic channel
- Simultaneous fit of double Z and H peaks
- Most uncertainties cancel out in ratio
- Assumes precision measurement of Higgs width and top-Z coupling from FCC-ee

FCC-hh can probe the Higgs couplings and the top-Yukawa at 1% level of precision.

Prospects for HH measurements

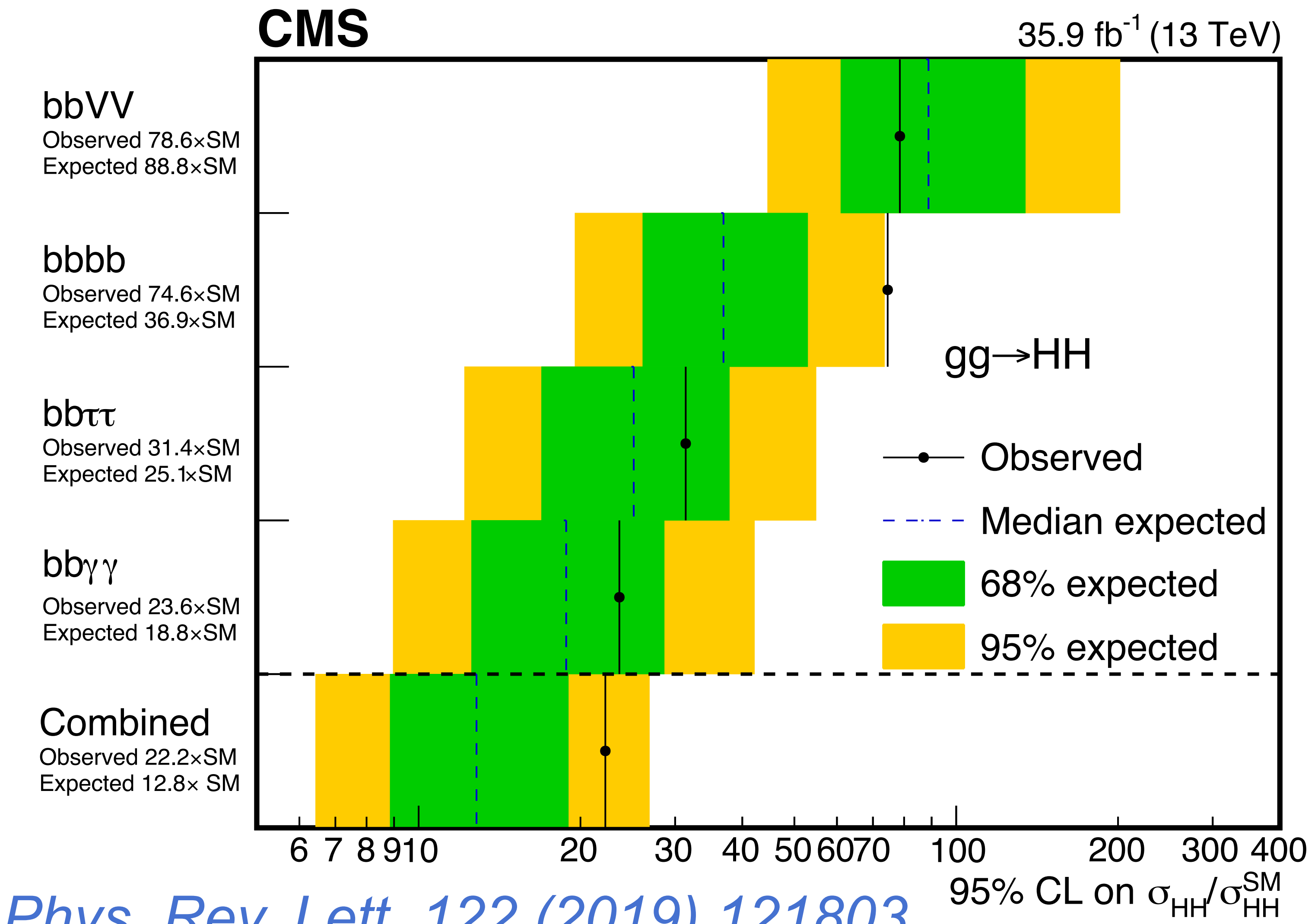
1. LHC
   - O(10)-O(2)
   - Could detect large anomalous coupling

2. HL-LHC
   - O(1)
   - Potential for evidence (3σ precision)

3. HE-LHC
   - Potential for first observation (5σ precision)

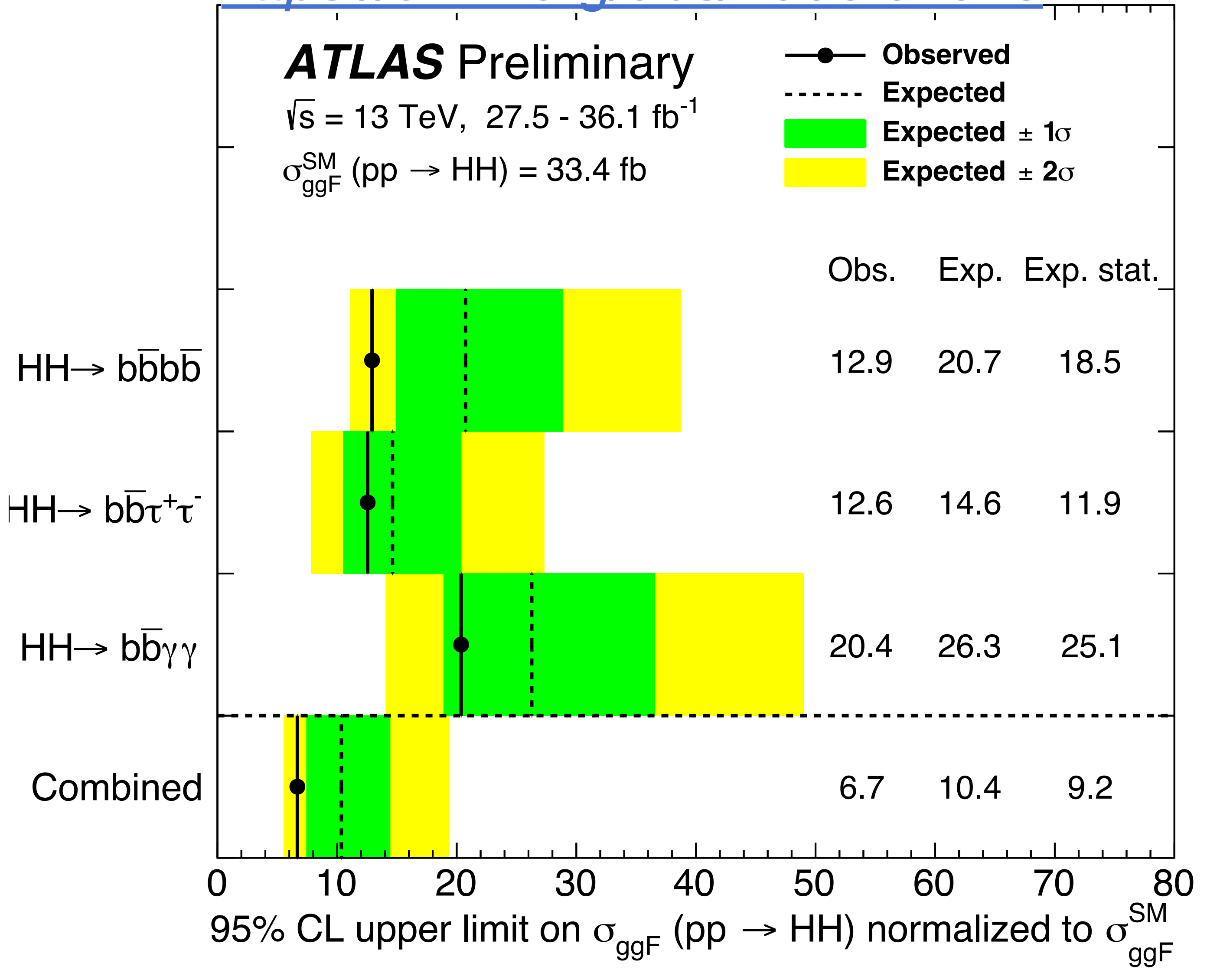
4. FCC-ee : single H couplings + indirect measurement
   - Potential for observation (5σ precision)

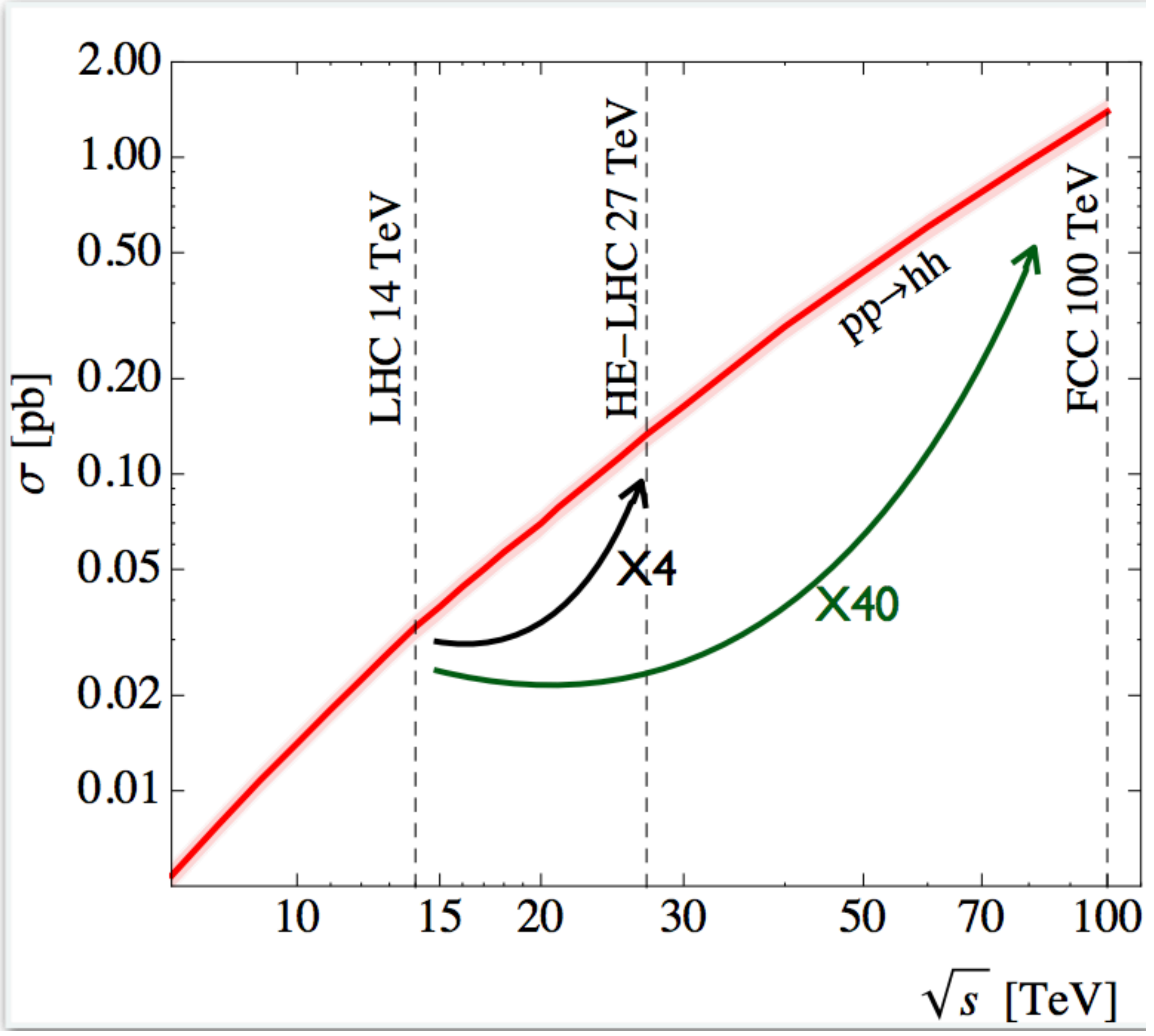
5. FCC-hh : precision measurement



Phys. Rev. Lett. 122 (2019) 121803

https://arxiv.org/abs/1906.02025

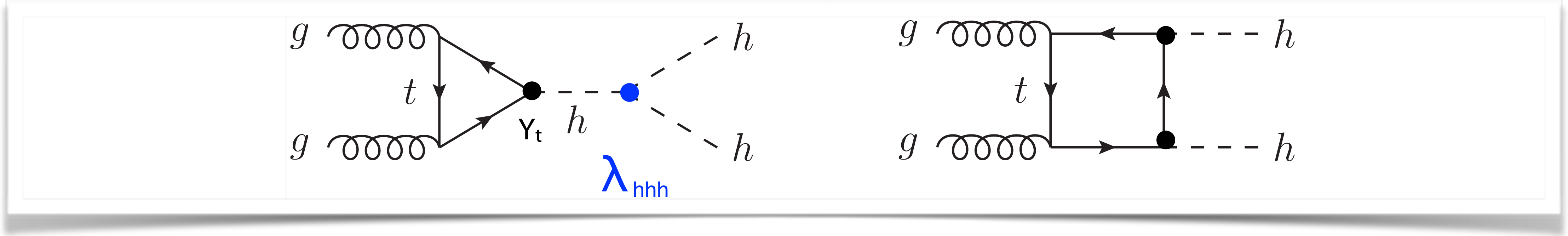




14TeV→27TeV: x4^σx5^ℒ = x20

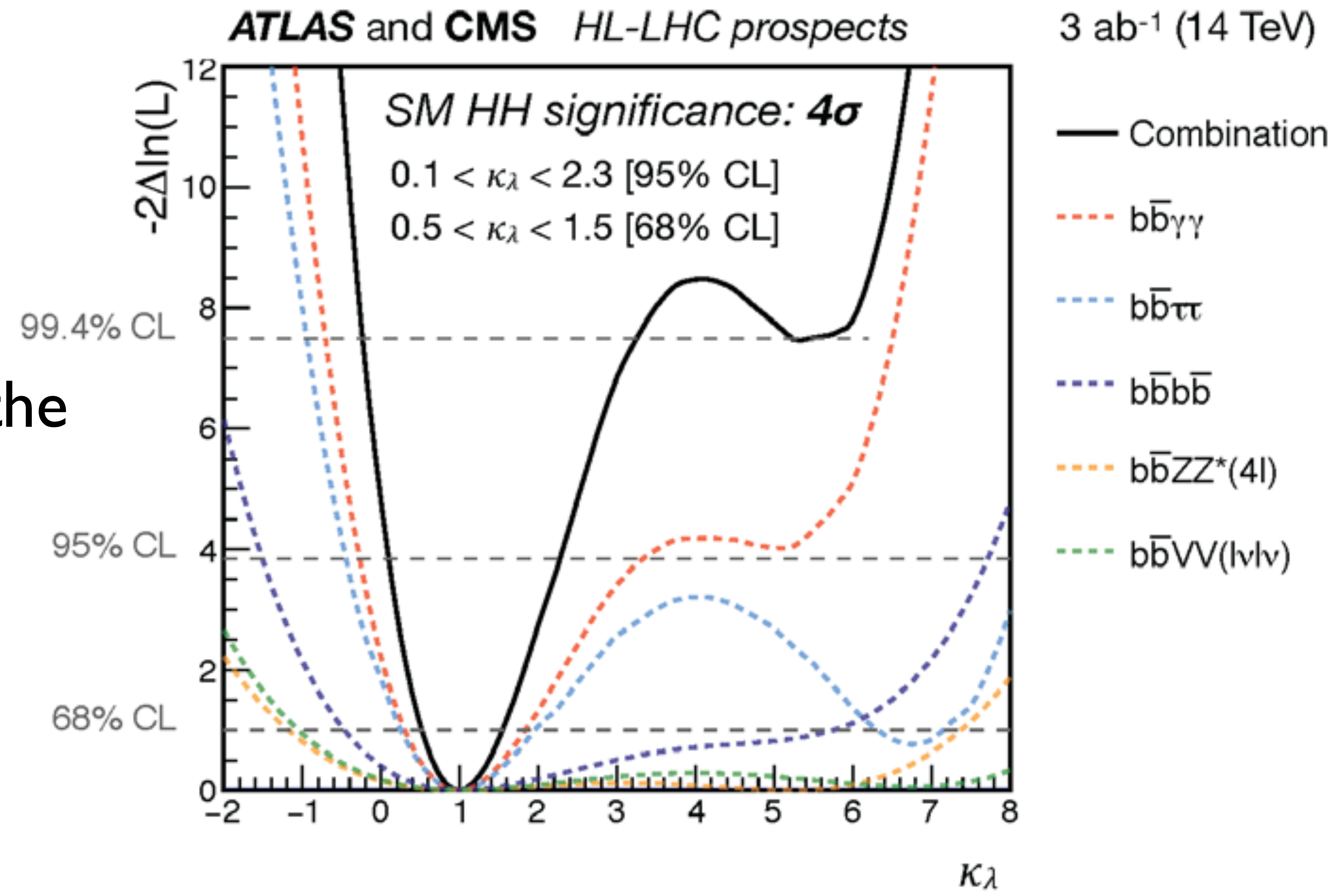
27TeV→100TeV: x10^σx2^ℒ = x20

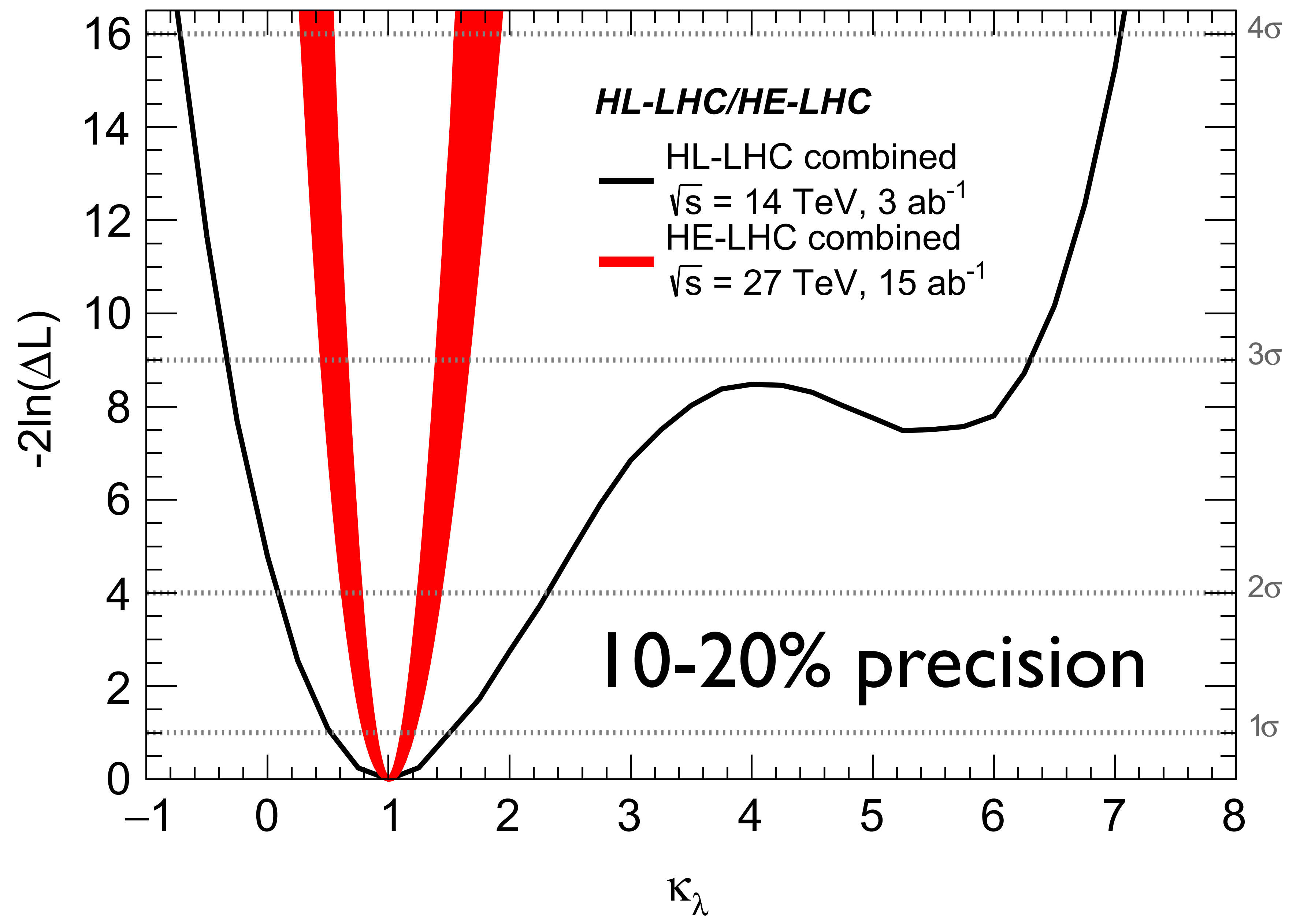
Higgs physics: HH production



The measurement of the Higgs self coupling is one of the main physics motivation for future colliders.

- The most straightforward way of measuring it is to measure the HH production cross section (warning: interference with diagrams without self-coupling!)
- Very rare process, multi-channel approach



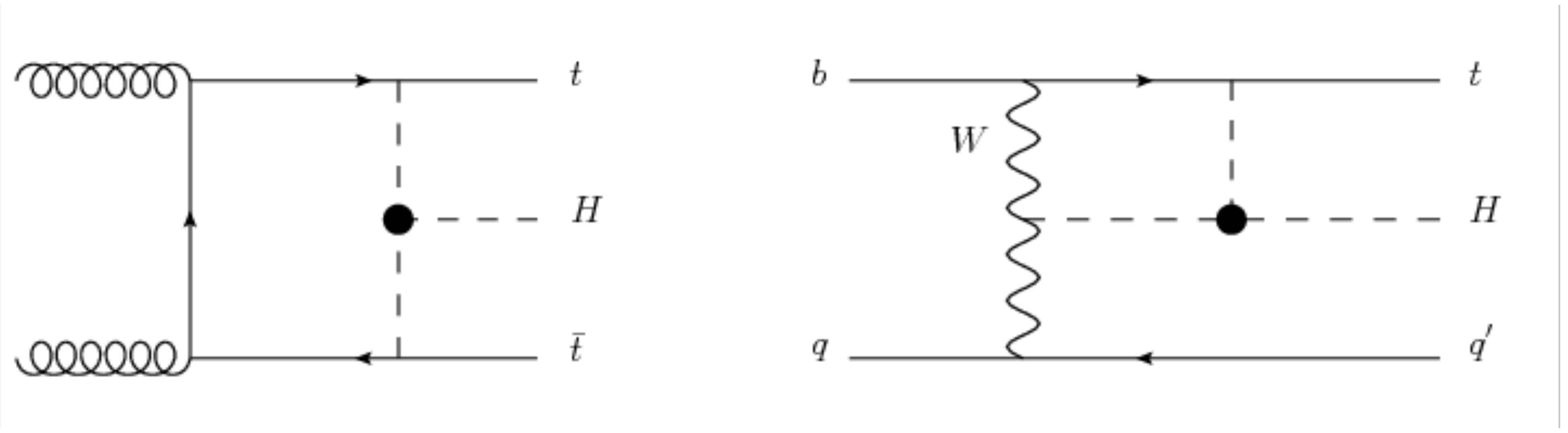


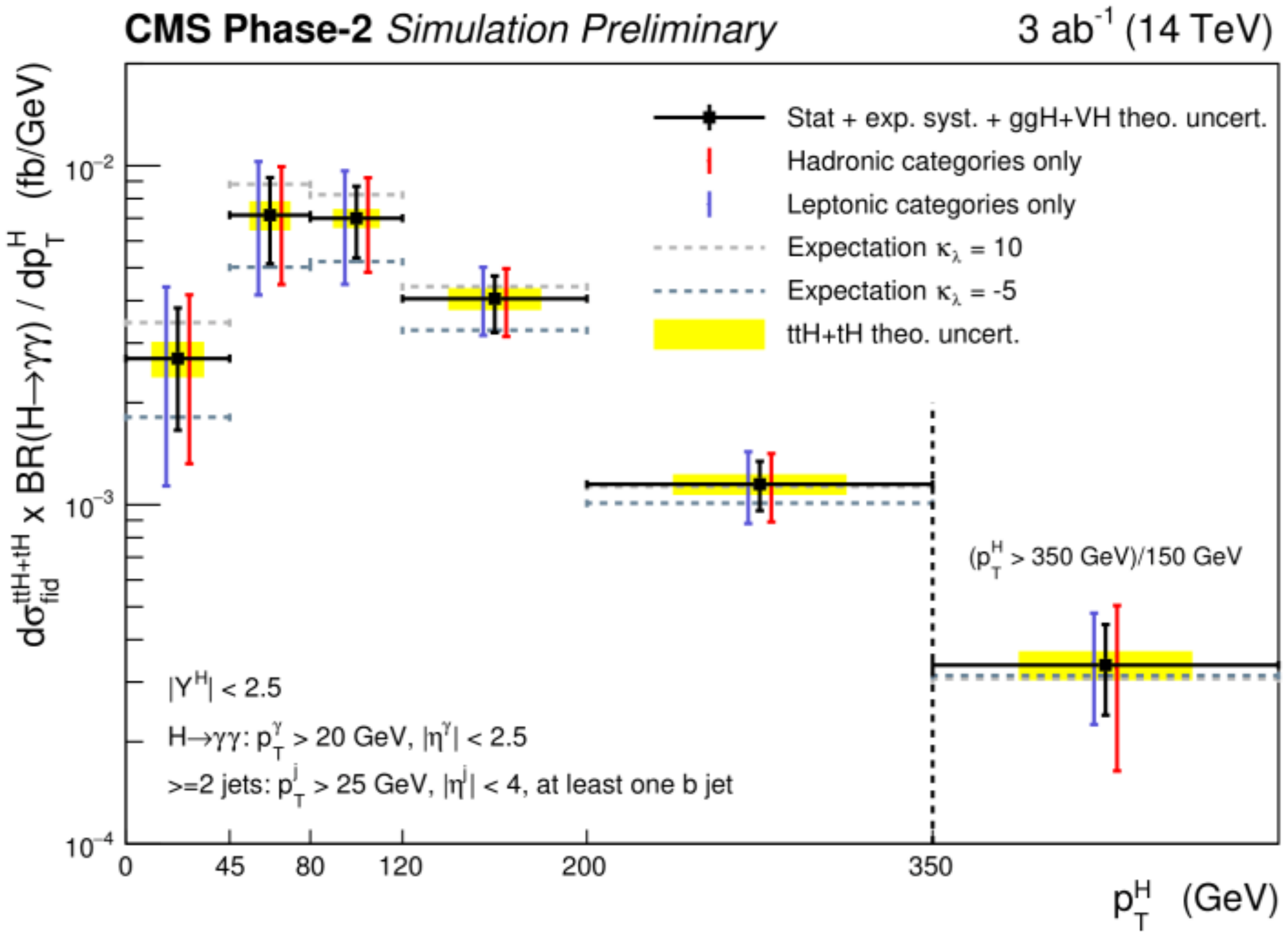
- bbγγ, bbττ are the most important channels for both experiments
- Peculiar likelihood structure. k_λ affects the kinematic and cross-section of the HH production. Using several channels removes the degeneracy.
- Potential for 3σ evidence from both experiment at $3ab^{-1}$ →4σ combining
- Discovery at HE with $15ab^{-1}$

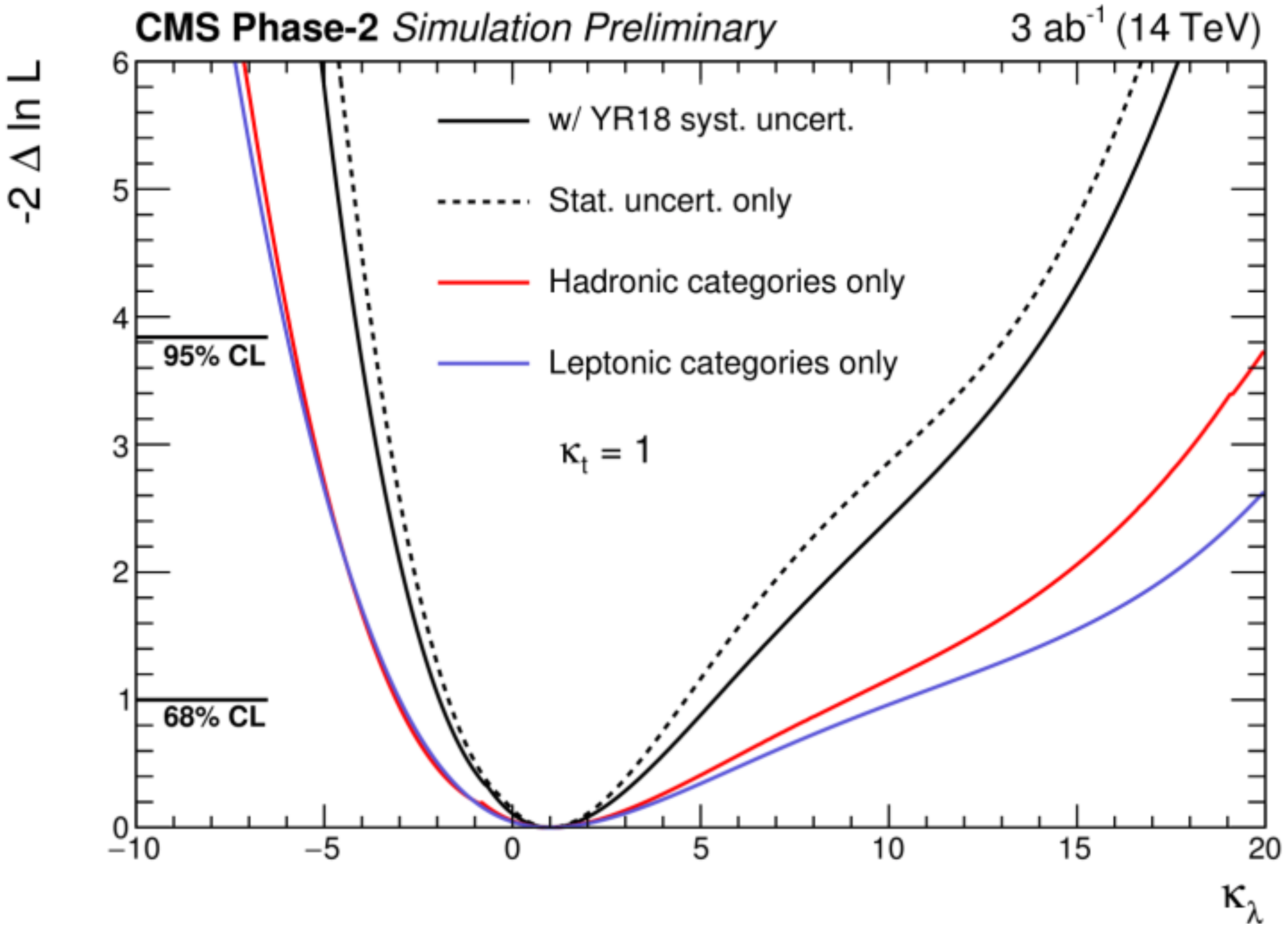
Higgs physics: Indirect self-coupling

The Higgs self-coupling can be measured from higher-order corrections to the single Higgs production

- κ_λ-dependent radiative corrections modify external Higgs boson kinematics and single-Higgs production rates
- ttH is the most sensitive production mode
- Caveat: degeneracies needs to be broken either assuming B_{BSM}=0 or combining with double Higgs measurements

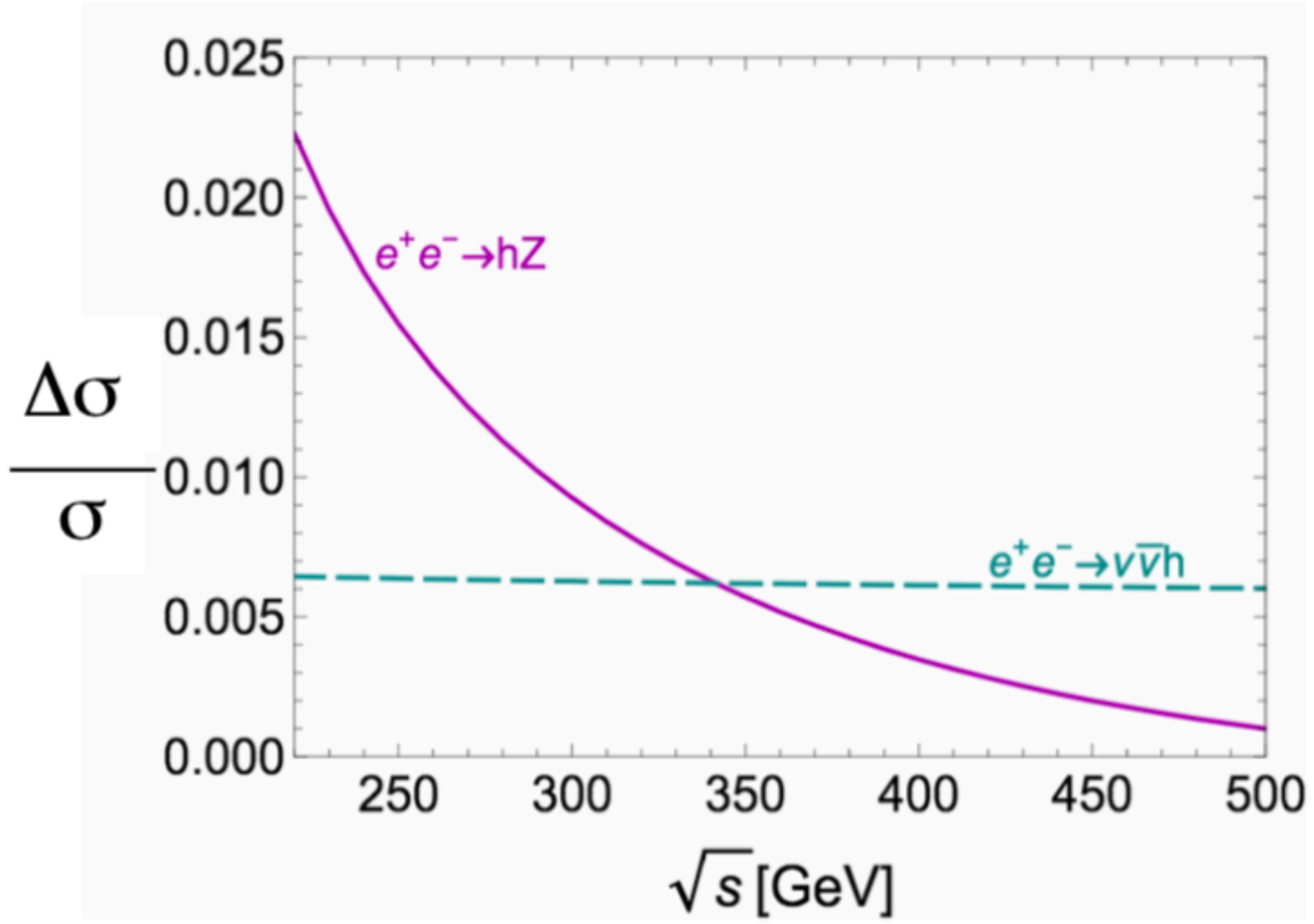






- Projections to HL-LHC sensitive to differential cross-section precision and binning
- Assuming 20-40% uncertainty on differential cross-section and all other couplings fixed to their SM value
- Not really competitive with HH, but room for improvement

Higgs trilinear coupling at FCC-ee



The same indirect approach can be exploited at FCC-ee,

If all other SM coupling fixed (in particular HHVV, HVV coupling):

- $\delta\kappa\lambda \approx 12$ % (2 IPs - baseline FCC-ee)
- $\delta\kappa\lambda \approx 9$ % (4 IPs)

Single Higgs cross section at loop level depends on HVV and HHVV:

At least two energy points needed to lift the degeneracy

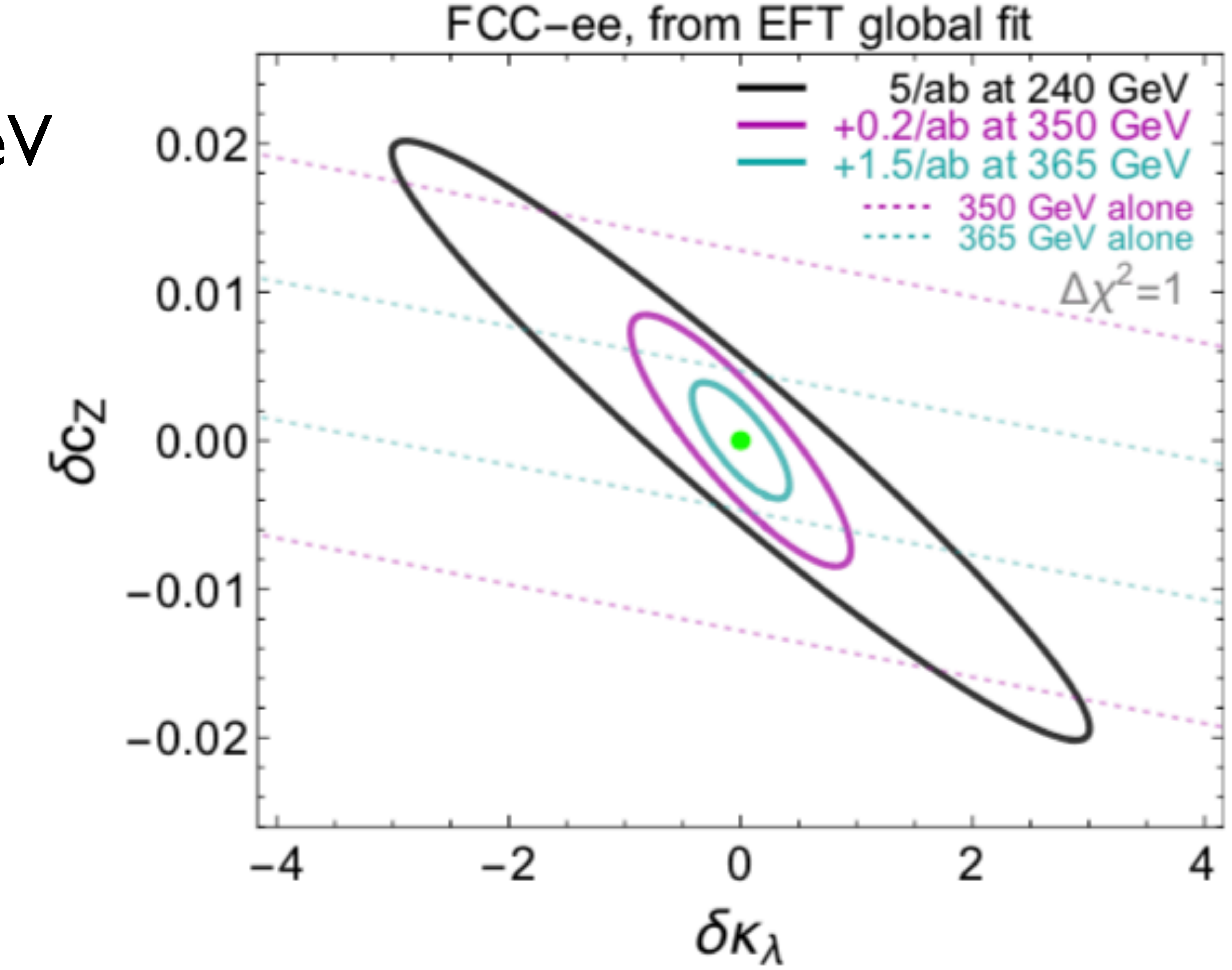
With baseline design, 2 IPs, 15 years at $\sqrt{s}$=90+160+240+350+365 GeV

- $\delta\kappa\lambda \approx 42$ % (34% combined with HL-LHC)
- To be compared with 30 years of ILC250+500

With 4IPs and 15 years of running:

- $\delta\kappa\lambda \approx 25$ % (21% combined with HL-LHC)
- To be compared with 15 years of CLIC380+1500

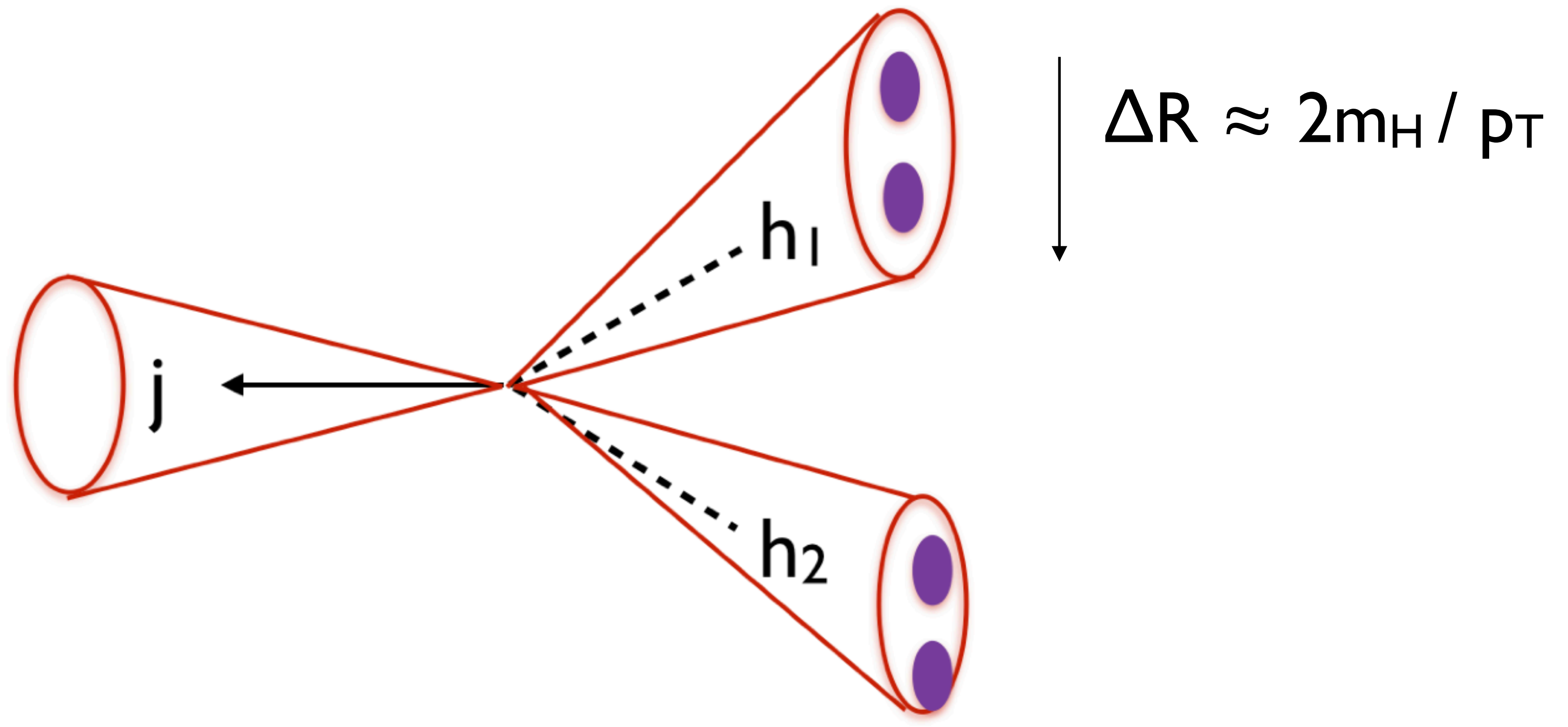
5σ sensitivity by 2050



Higgs self coupling at the FCC-hh

Same approach used as for LHC analyses/HL-LHC/HE-LHC studies

- Combination of several channels: bbγγ, bbττ, bb4l, bbbb, bbWW

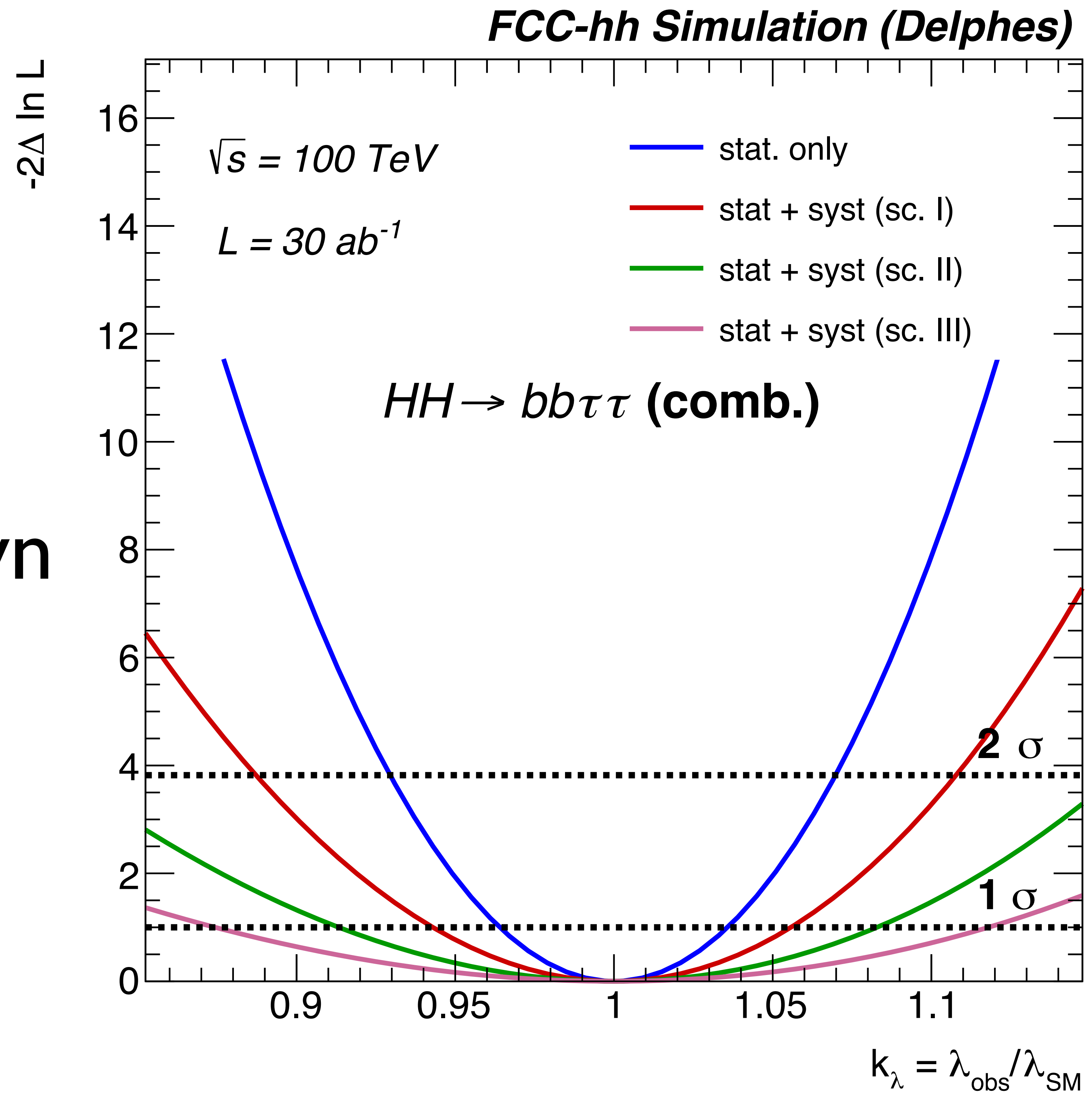


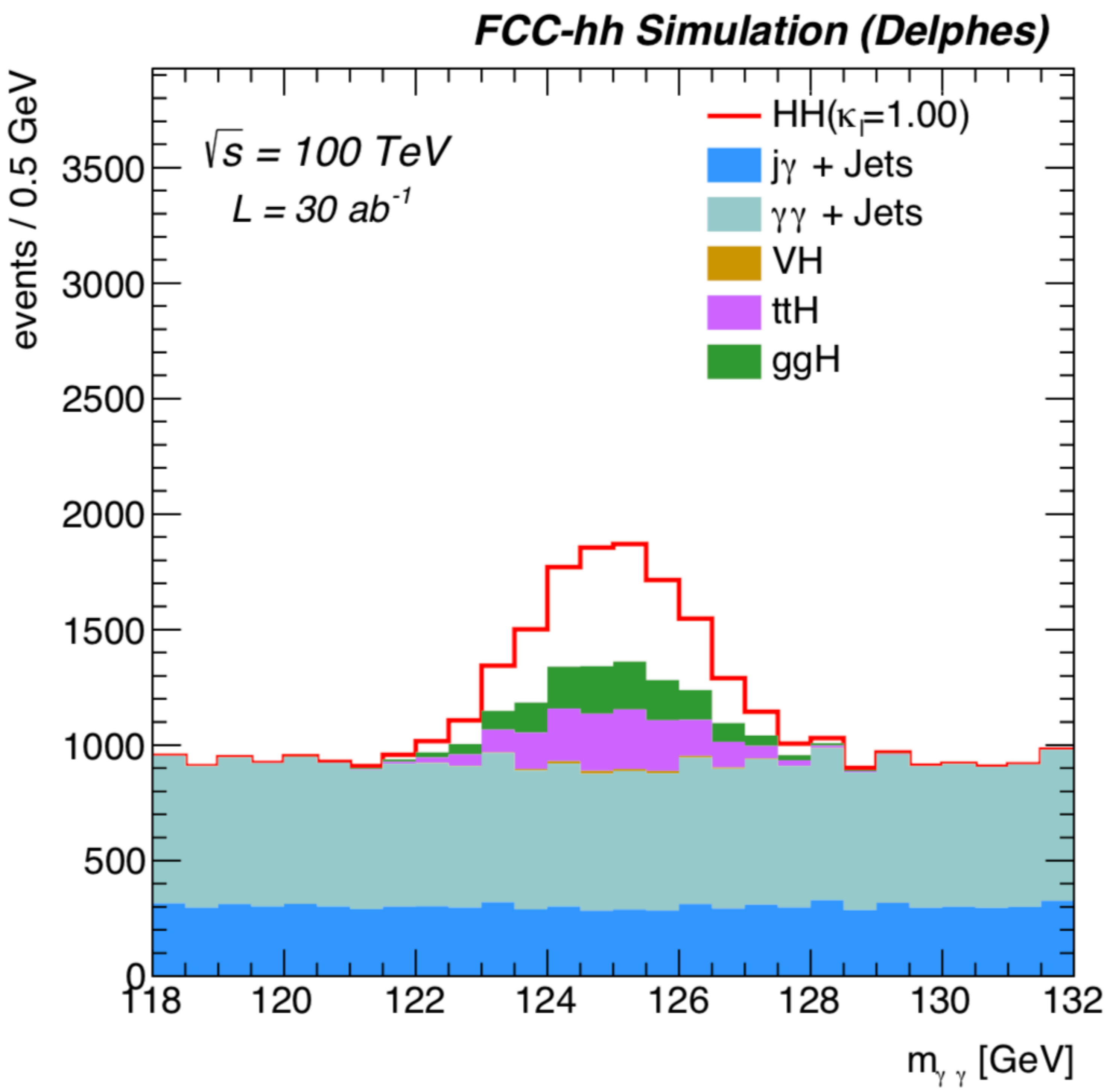
100TeV: we can profit of boosted system to reject background (for example 4b+1jet)

Projection based on Delphes simulations

- Several scenario on background rates, background estimates, and systematics uncertainties to account for large unknown factors in the detectors

We are probing the region $k_\lambda \sim 1$. Little contribution from shape information



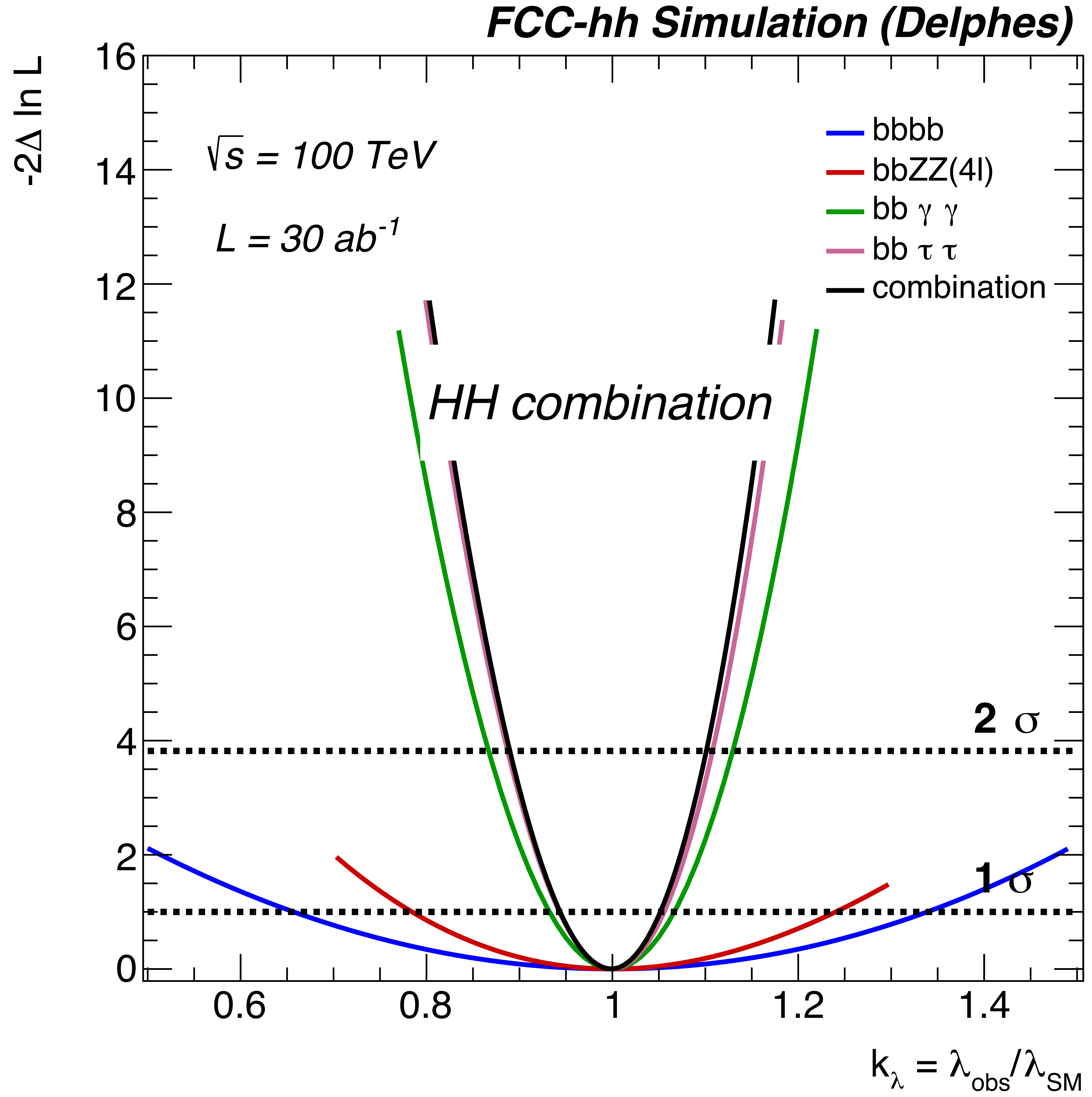


Higgs self coupling at the FCC-hh

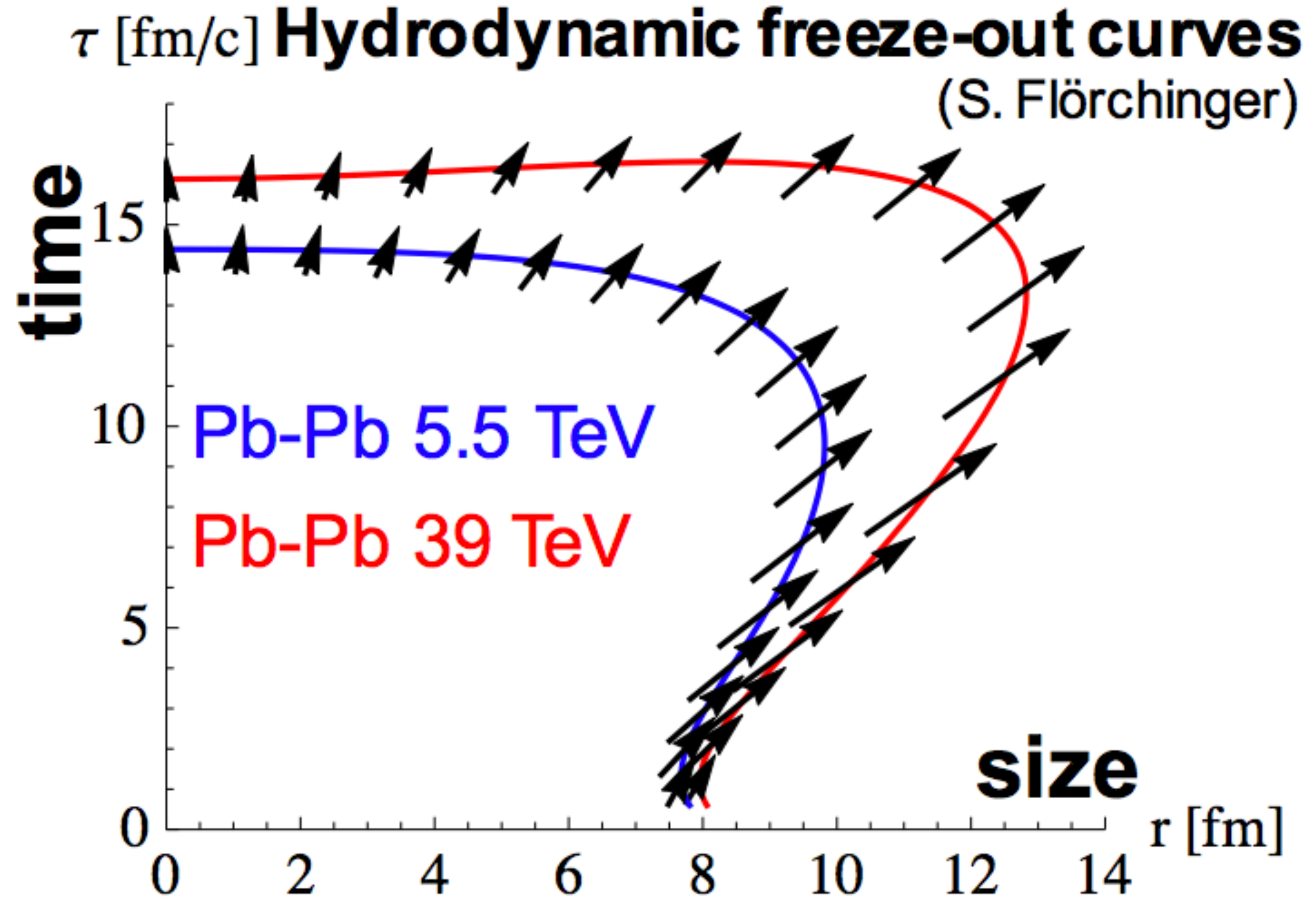
FCC-hh can reach $\delta\kappa_\lambda$(stat) ≈ 5% using double Higgs production, via:

- $b b \gamma\gamma$: $\delta\kappa_\lambda$ ≈ **5-7%**
- $b b \tau\tau$: $\delta\kappa_\lambda$ ≈ **5-10%** (using $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$)
- bb4l: $\delta\kappa_\lambda$ ≈ **10-20%**
- bbbb: $\delta\kappa_\lambda$ ≈ **20-30%**
- bbWW: $\delta\kappa_\lambda$ ≈ **40%**

Most aggressive systematic scenario for bbττ



Heavy ion and Higgs

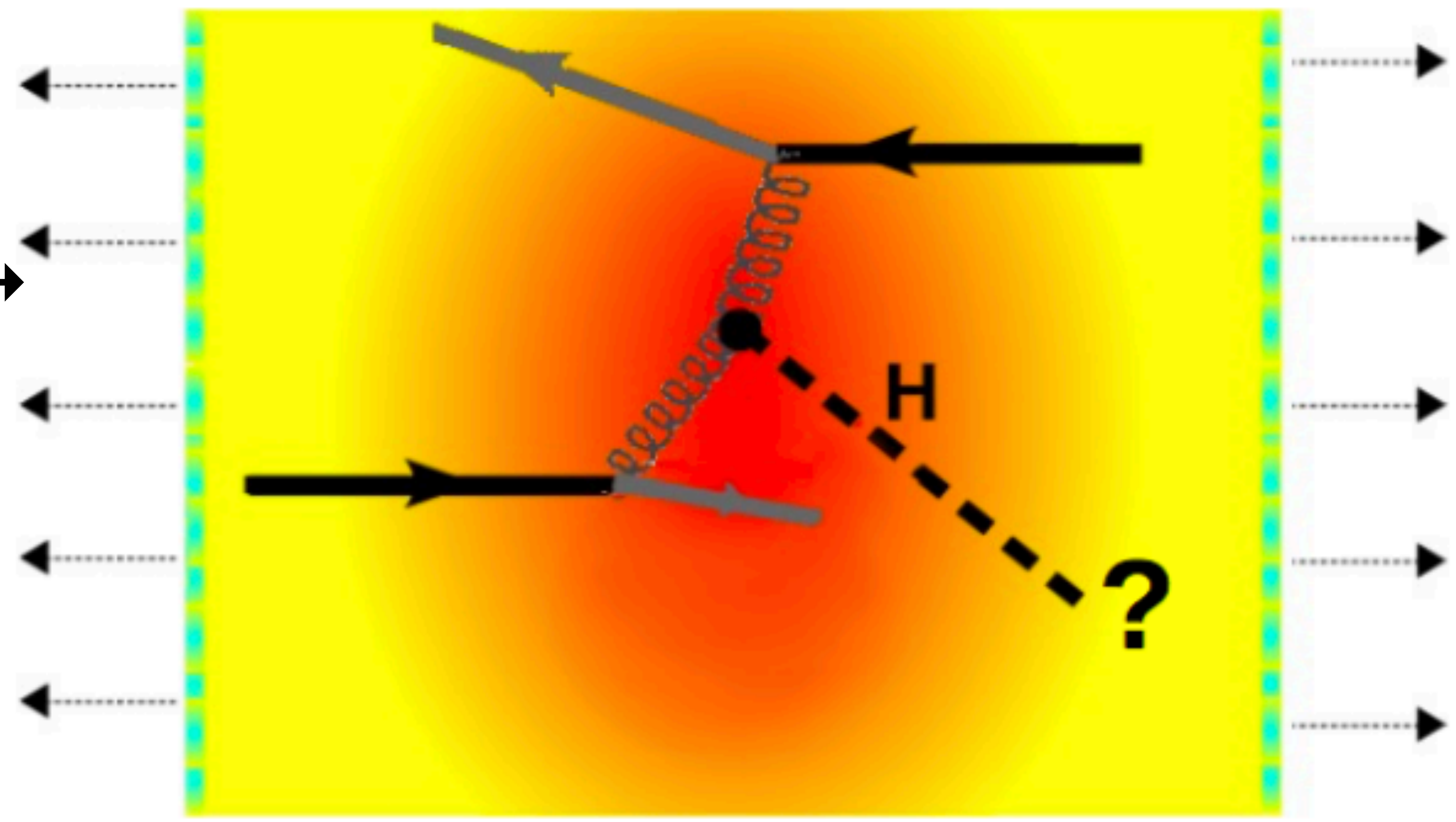


FCC-AA: PbPb collisions at $\sqrt{s_{NN}}$=39TeV ($\sqrt{s_{pN}}$=63TeV)

- Larger and longer-lasting fireball (x2)
- Higher initial energy
- Shorter equilibration time

Bringing LLRCMS together: Higgs suppression in QGP

- Higgs lifetime τ_H ~50 fm/c > QGP lifetime τ~15 fm/c
- Strong interaction with QGP gluons induces decay to gg (g+H → gg) depleting its decay channels to γγ and ZZ*
- First estimate of absorption cross section: ~10 μb
- Would mean suppression by x2 in central Pb-Pb collisions



First estimate of significance with FCC reference detector:
~5 (10) σ in one Pb-Pb month with baseline (ultimate) L_{int}

Conclusions

We are already looking at the post-HL-LHC era: HE-LHC, FCC-ee, FCC-hh

- Busy schedule for the construction of the different machines
- Challenging environments, lots of detector/magnet/accelerator research to start right after HGCal

Physics goal for the moment lies on 3 main direction:

- Precision EWK sector measurements (Higgs, EFT, Z and top).
    - Most important measurement for FCC-ee
- Extending the search for new massive particles.
- Double Higgs measurements and determination of the Higgs trilinear coupling
- Plus whatever we might find at LHC and HL-LHC

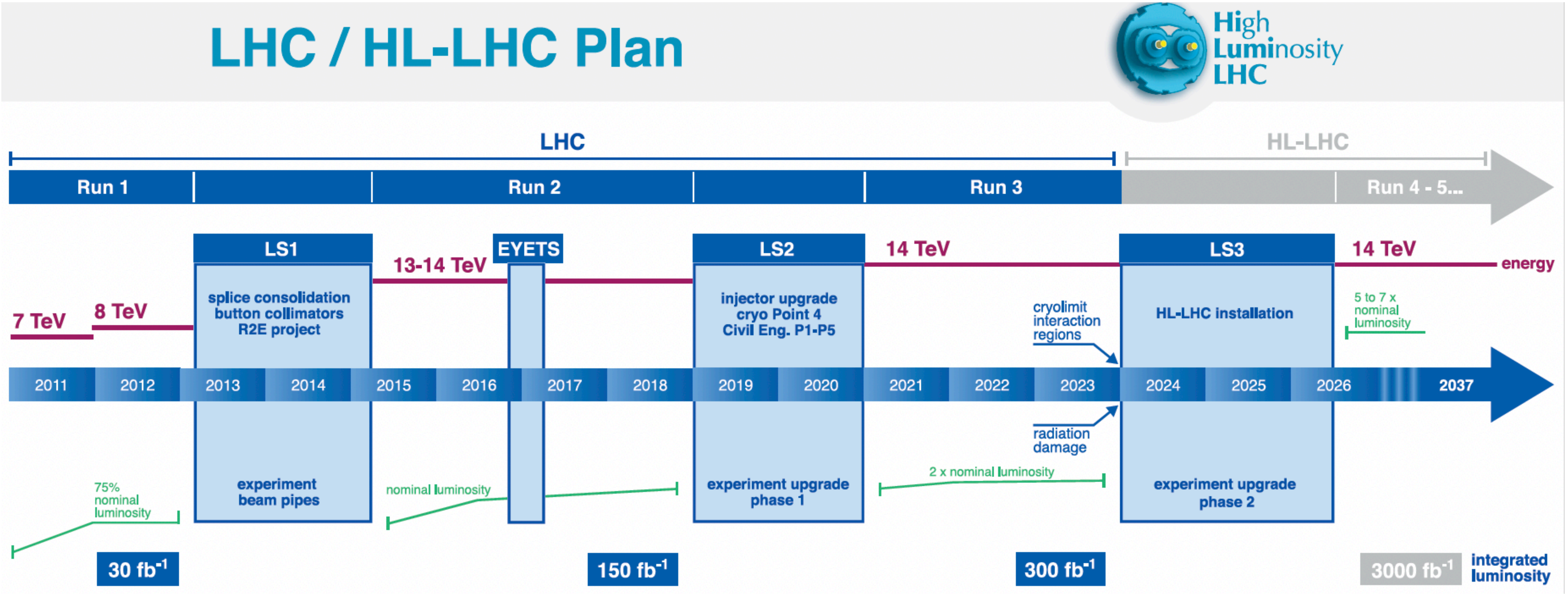
Both HE and FCC have compelling heavy ions programs

Lots of potential and complementarity in the physics programs of the 3 detectors.

LLR is already at the forefront of these programs

BACKUP

What's expecting us



2 scenarios: **baseline** $\mathscr{L} = 5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, **ultimate** $\mathscr{L} = 7.5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

At least10 years of operations: 2026-2037

Total luminosity delivered to CMS of **3ab^{-1}** (4ab^{-1} in the ultimate scenario)

Expect **140-200** interactions per bunch crossing

Barrel calorimeters: CMS-TDR-015
- ECAL and HCAL new Back-End boards.
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV.
- Lower ECAL operating temperature (8º C).

Trigger/DAQ: CMS-TDR-017, CMS-TDR-018
- Two-level L1/HLT trigger strategy
- L1: output of 750 kHz, 12.5 μs latency, include tracking and high granularity calorimeter Pflow-like information.
- HLT output at 7.5 kHz

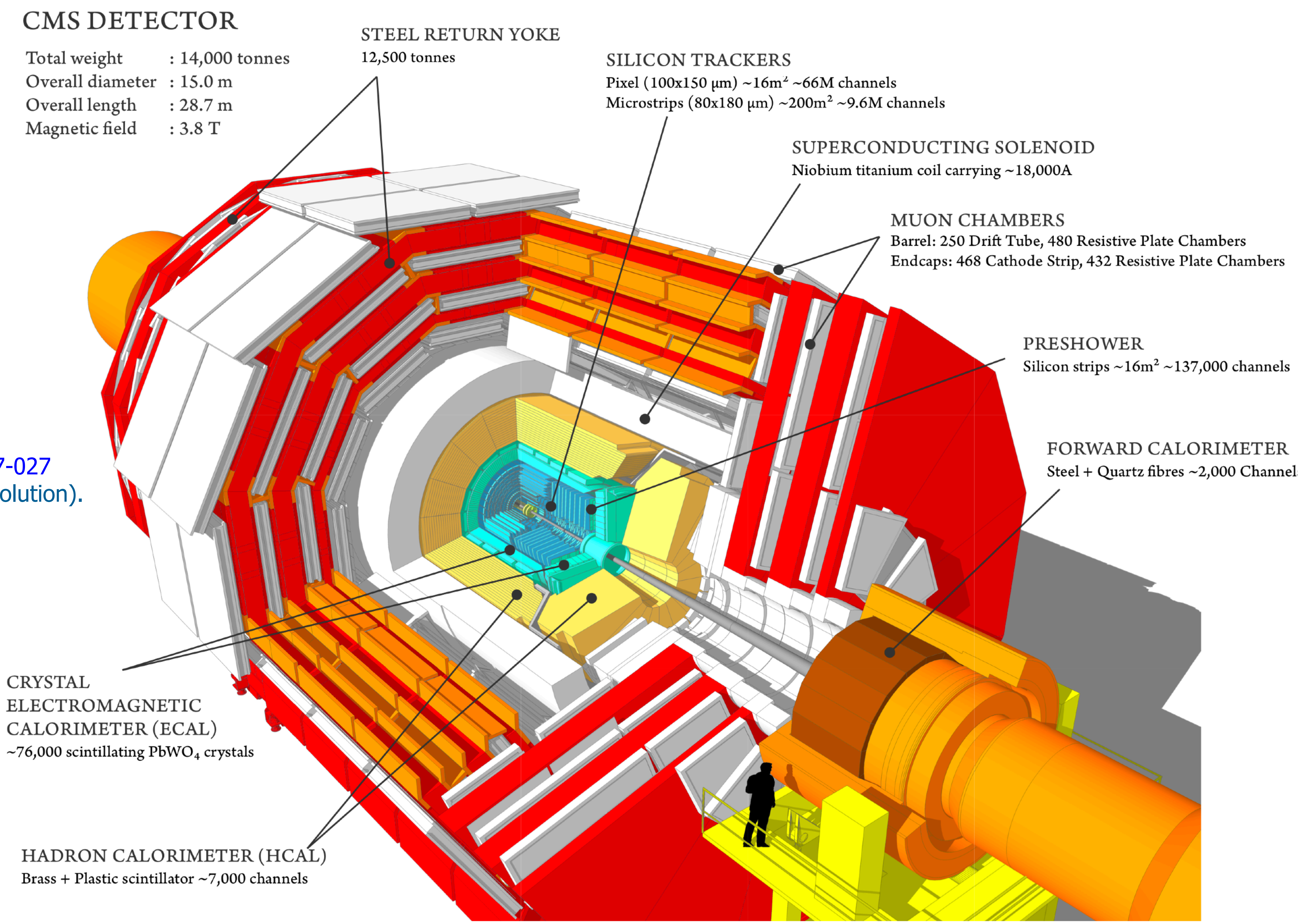
Endcap calorimeters: CMS-TDR-019
- 3D showers and precise timing.
- Si, Scint+SiPM in Pb/W-SS at -30º C.
- Rad tolerante – high granularity.

- Extend eta coverage
- Improve trigger system
- Computing: CPU and storage challenges

MIP Timing detector: CERN-LHCC-2017-027
- Reconstruct the timing of particles (30 ps resolution).
- Sensitive to minimum ionizing particles MIP.
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Muons: CMS-TDR-016
- Replace DT & CSC with new FE/BE readout.
- RPC link-board.
- Complete with new GEM/RPC for 1.6<η<2.4.
- Extended coverage to η<3.

Tracker: CMS-TDR-014
- Si-Strip and Pixels high granularity with less material.
- Design for tracking in L1-Trigger.
- Extended coverage to η<4.



Treatment of Systematic uncertainties

Systematics uncertainties are a crucial component of the projections shown today. 2 main scenarios:

S1 "Run2 systematics"

- assumes the same uncertainties of Run2, independently of luminosity

S2 "YR18 systematics"

- Theoretical uncertainties reduced by a **factor of two** with respect to the current knowledge
  - Thanks to both higher-order calculation as well as reduced PDF uncertainties (from projections of what LHC will be able to constrain)
- Statistical uncertainties reduced by a factor $1/\mathrm{sqrt}(\mathscr{L})$ with respect to the reference Run 2 analysis.
  - With a cut-off to a reasonable expected limit on uncertainty considering the upgrades

Limited number of simulated events

- Neglected under the assumption that sufficiently large simulation samples will be available.

Detector limitations

- Left unchanged (or revised according to detailed simulation studies of the upgraded detector)

Uncertainties on experimental methods

- Kept at the same value as in the latest public results available → assuming that the harsher HL-LHC conditions will be compensated by method improvements.

Uncertainty on the luminosity

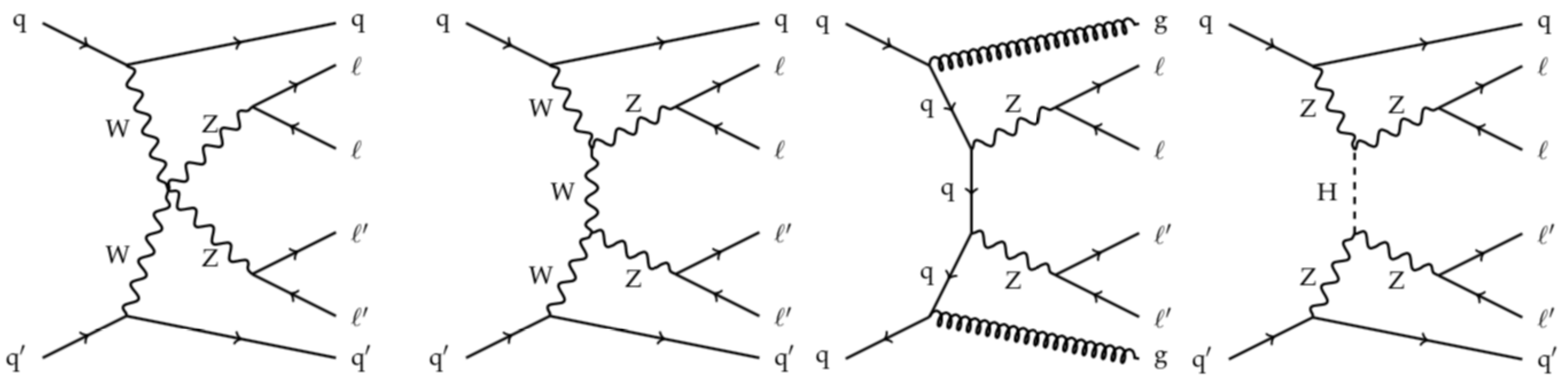
- ~ 1% level (understanding of the calibration methods, new capabilities of the upgraded detectors)

SM physics: VBS

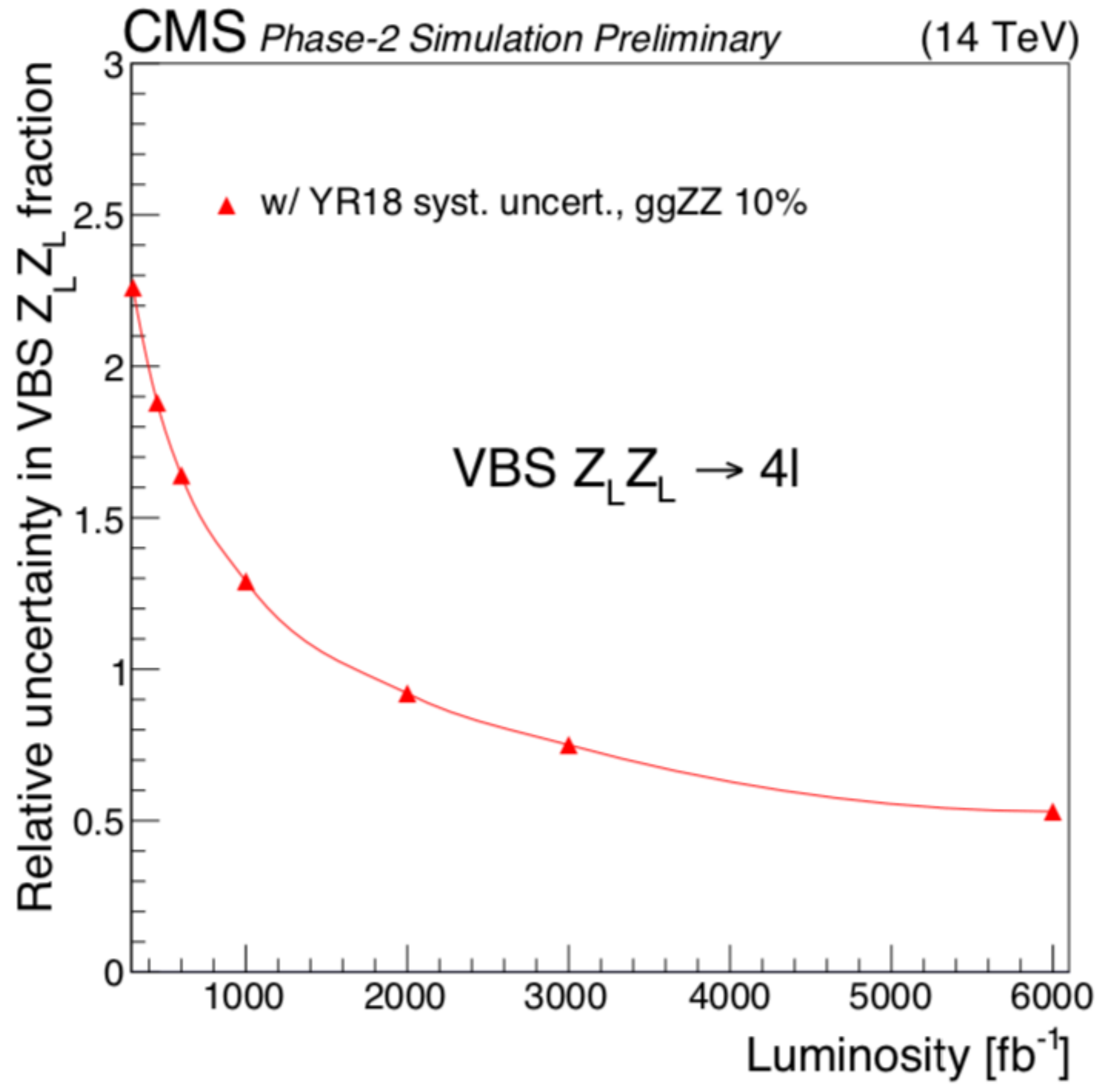
Great importance to test the mechanism of EW symmetry breaking:

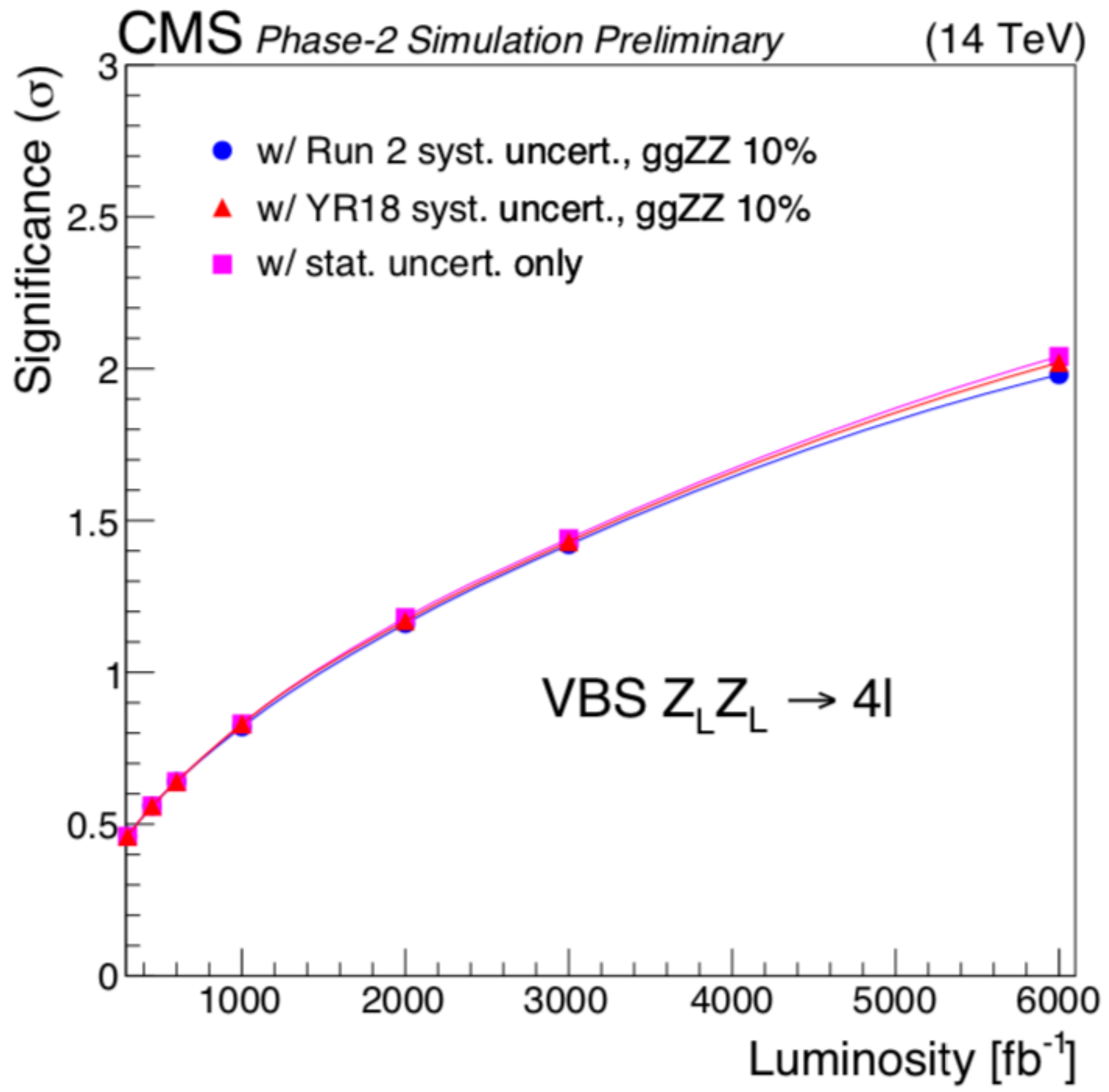
- It is still unknown whether the discovered Higgs boson preserves unitarity of the longitudinal VV (V=W,Z) scattering amplitude at all energies or if other new physics processes are involved (delayed unitarization scenario)
- Can signal the presence of anomalous couplings and NP at energy scales beyond the reach of direct resonance production.

HL-LHC will provide the chance to measure the VBS longitudinal component



Process	$W^\pm W^\pm$	WZ	WV	ZZ	WWW	WWZ	WZZ
Final state	$\ell^\pm\ell^\pm$jj	3ℓjj	ℓjjjj	4ℓjj	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	6%	6%	6.5%	10–40%	11%	27%	36%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	3.0σ	3.0σ





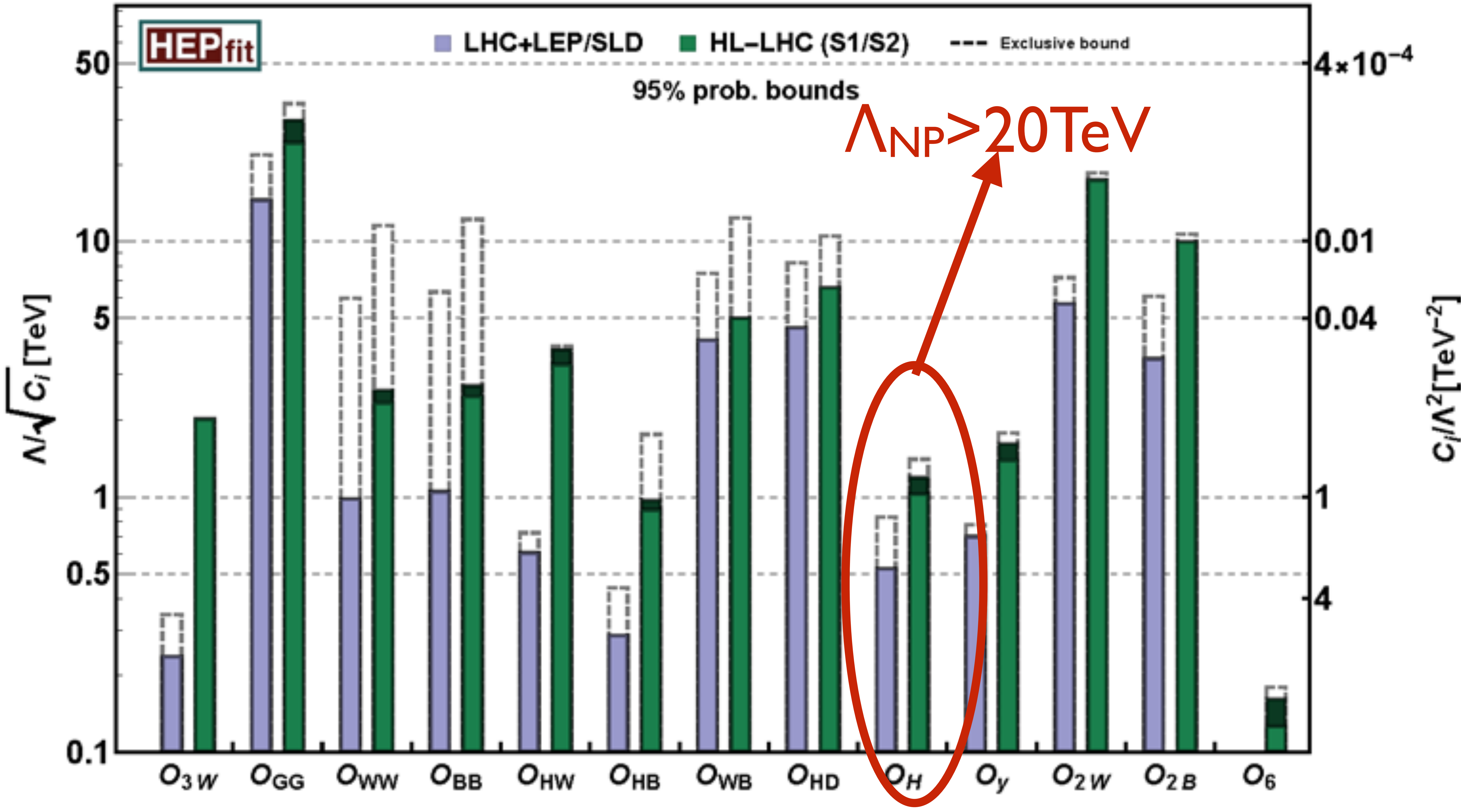
EWK physics: EFT

EWK and Higgs measurement can be used to set indirect constraints on BSM, using the formalism of Effective Field Theories

- SM Lagrangian is supplemented with dimension-6 operators Oi $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$
- Exploiting the fact that heavy BSM dynamics can still have an impact on processes at smaller energy, via virtual effects.
- Allows to systematically parametrize BSM effects and how they modify SM processes.

Global fit to observables in Higgs physics, as well as diboson and Drell-Yan processes.

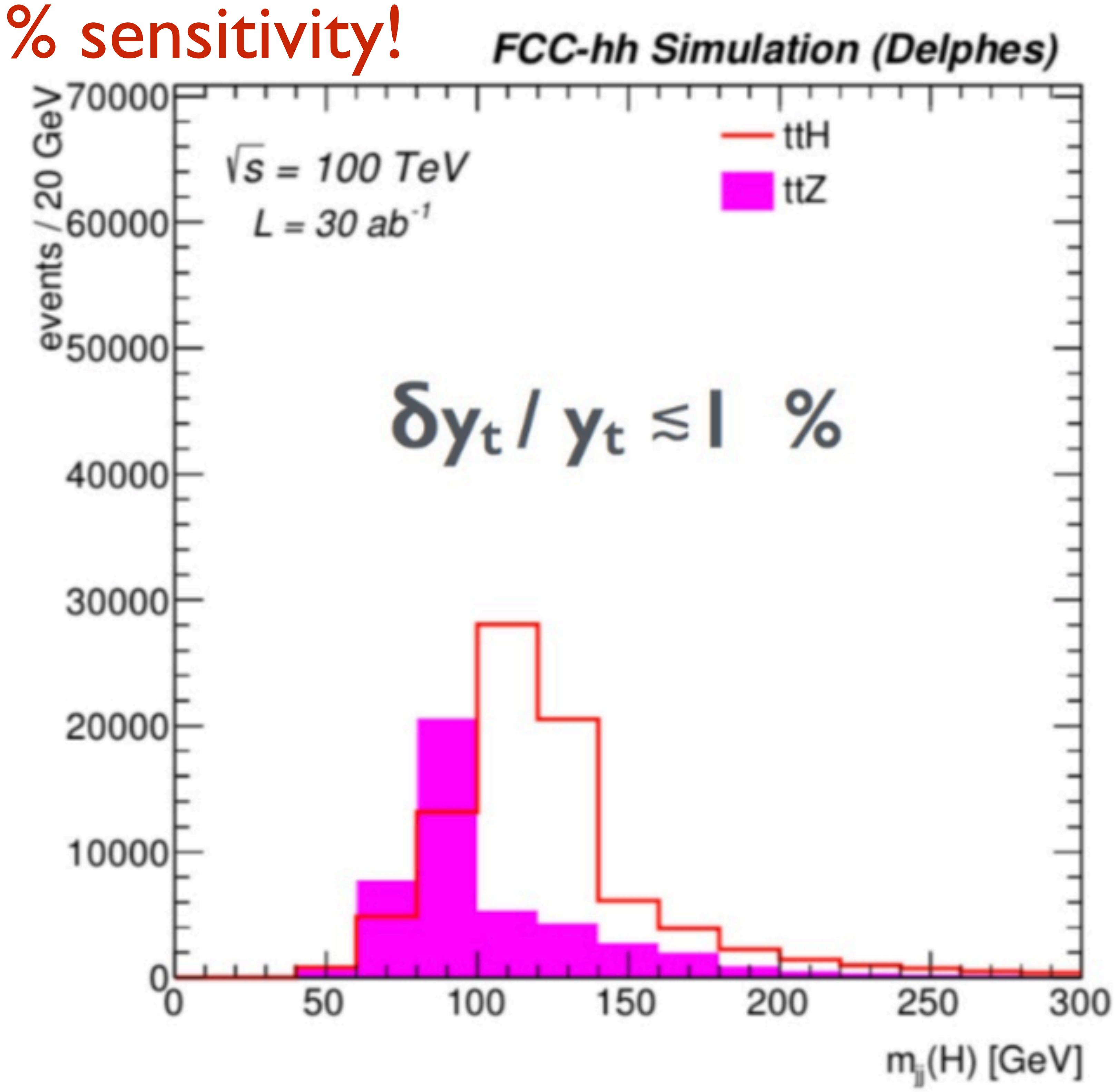
- The fit includes all operators generated by new physics that only couples to SM bosons.
- O_H: Anomalous H coupling via modified Higgs propagator. Sensitive to NP up to 20TeV, compositeness up to 1.6TeV

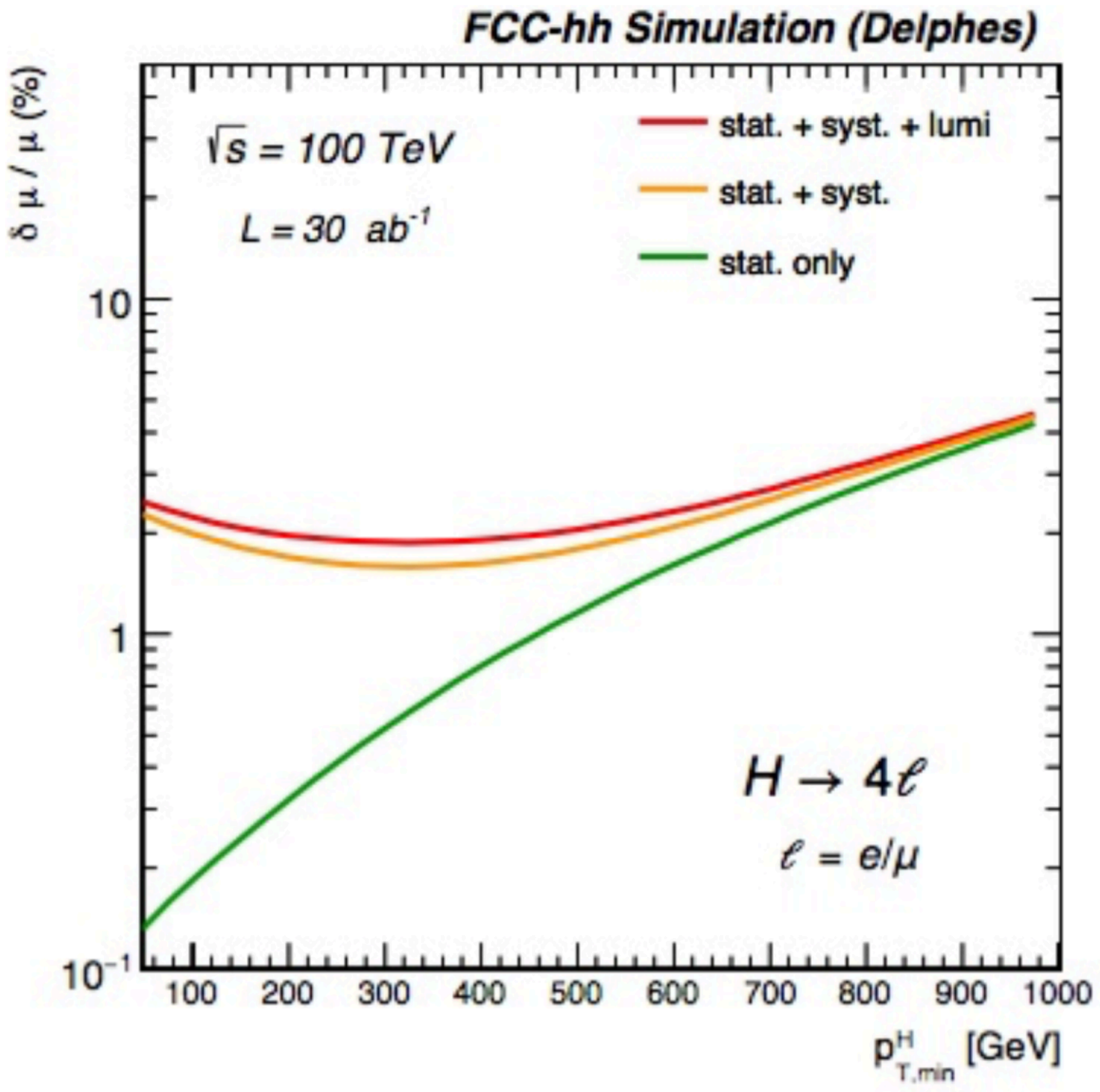


Higgs and Top at FCC

top-Yukawa can be measured at FCC-hh from the ratio σ(ttH)/σ(ttZ)

- In H/Z→bb decay in the boosted regime, semi-leptonic channel
- Simultaneous fit of double Z and H peaks
- Most uncertainties cancel out in ratio
- Reach 1% sensitivity!





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

FCC-ee can probe the Higgs couplings ~% level of precision.

Further contributions from FCC-hh for rare/statistically limited channels (μμ)

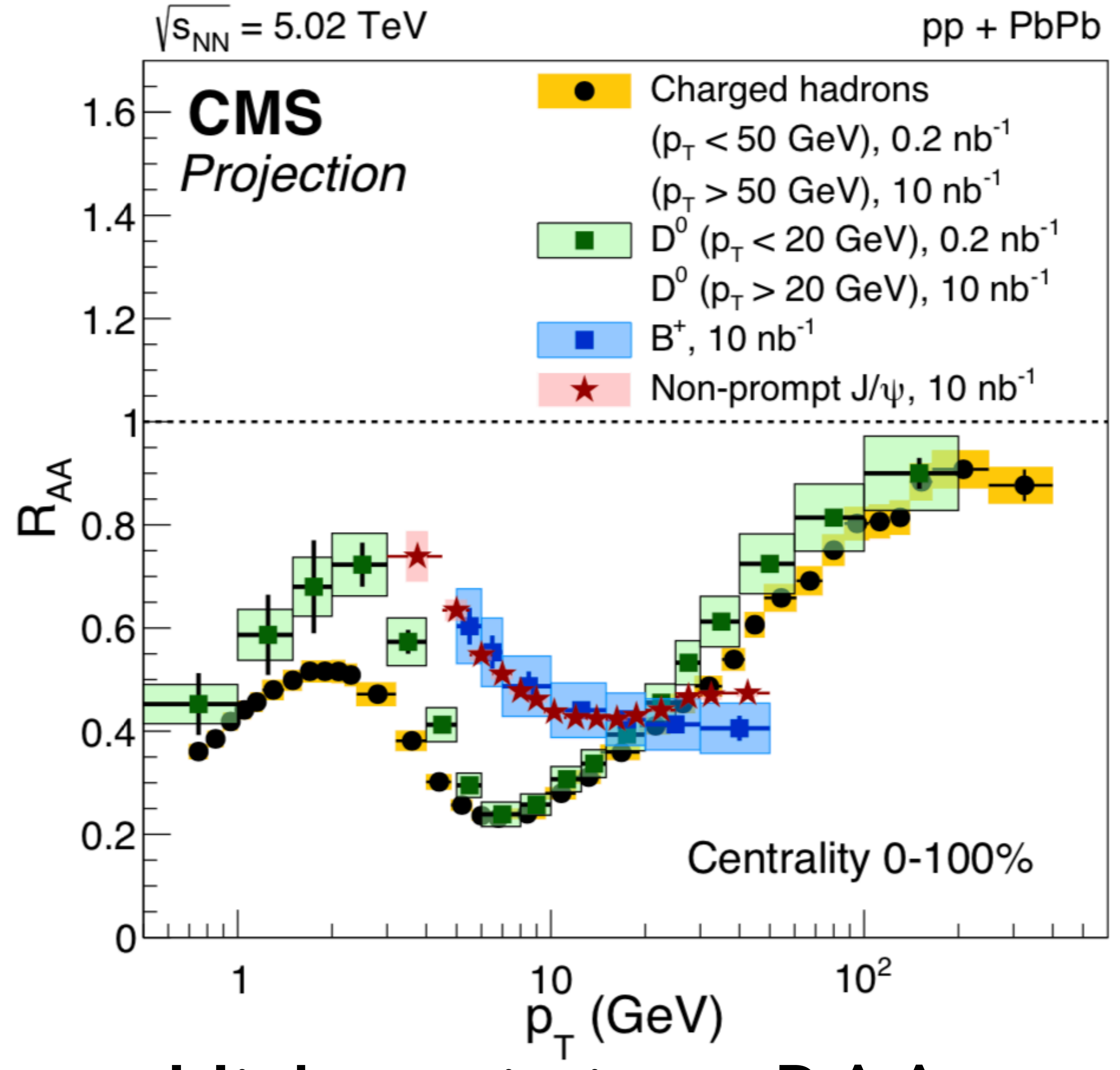
Can also measure dependence from energy and p_T

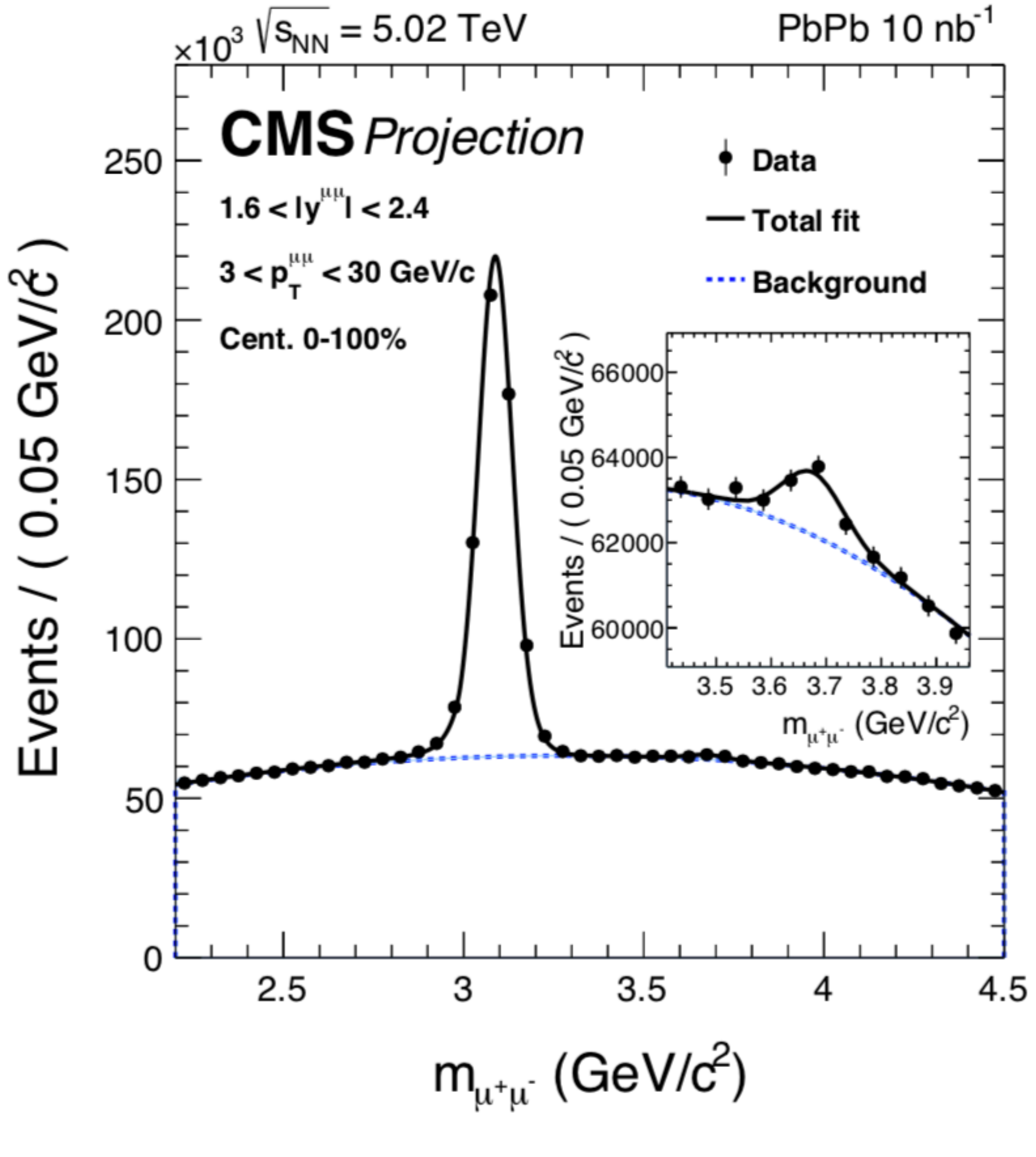
Heavy ions physics

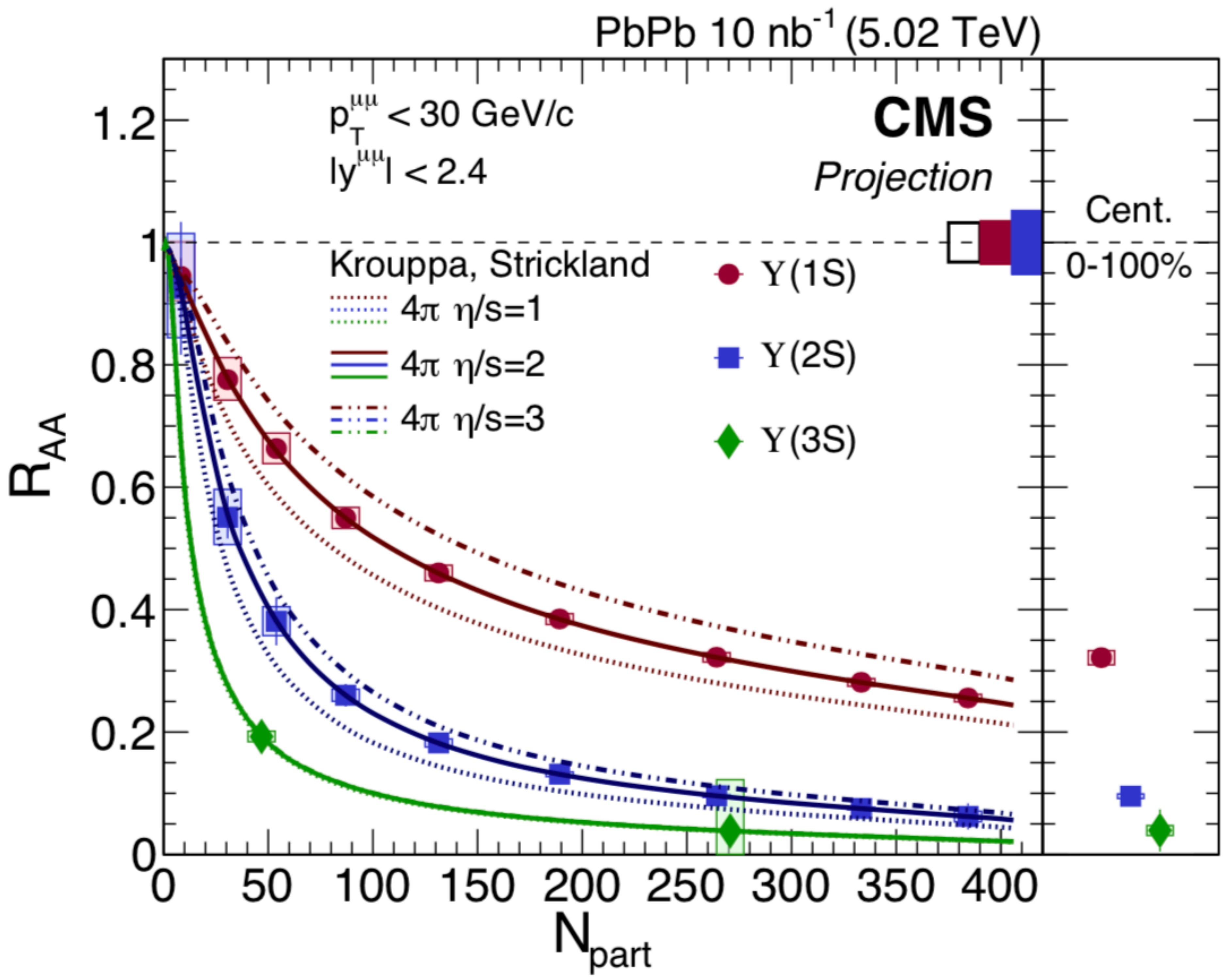
10 nb^{-1} of PbPb collisions are expected during the HL-LHC operations

Large samples of charmonia and bottomonia

- x3 reduction of systematics due to larger control samples
- Potential for first observation of Υ(3s)

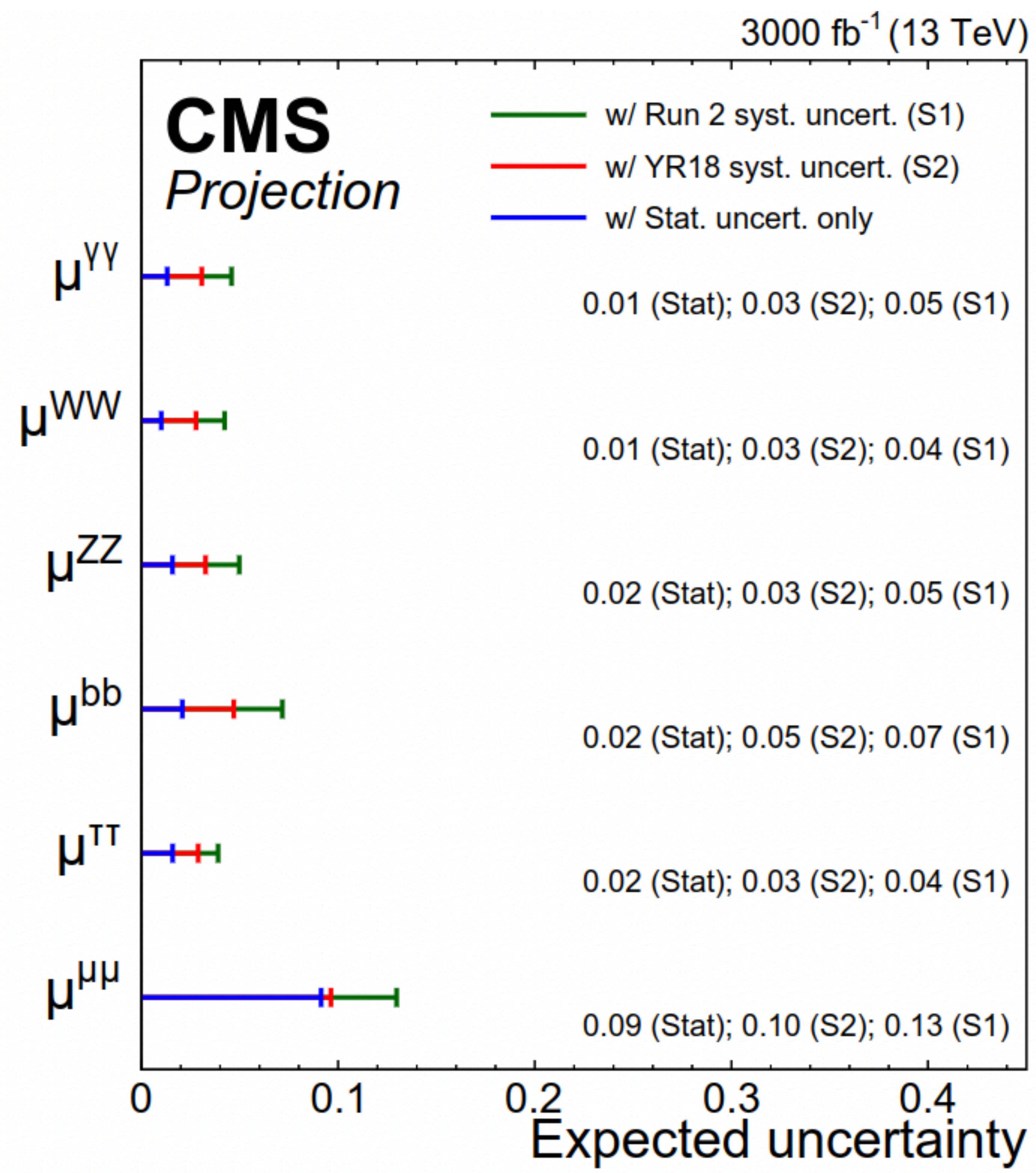


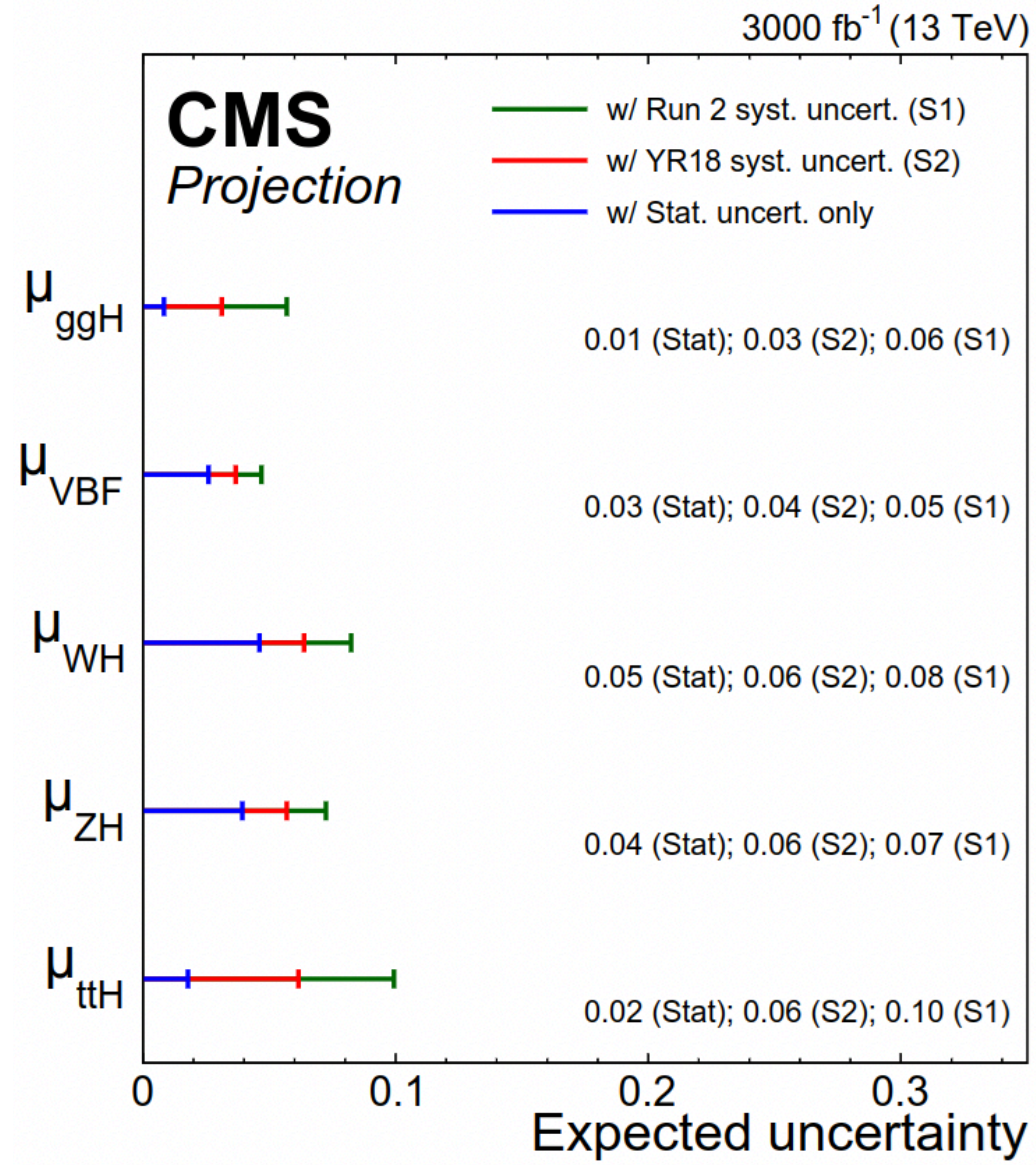


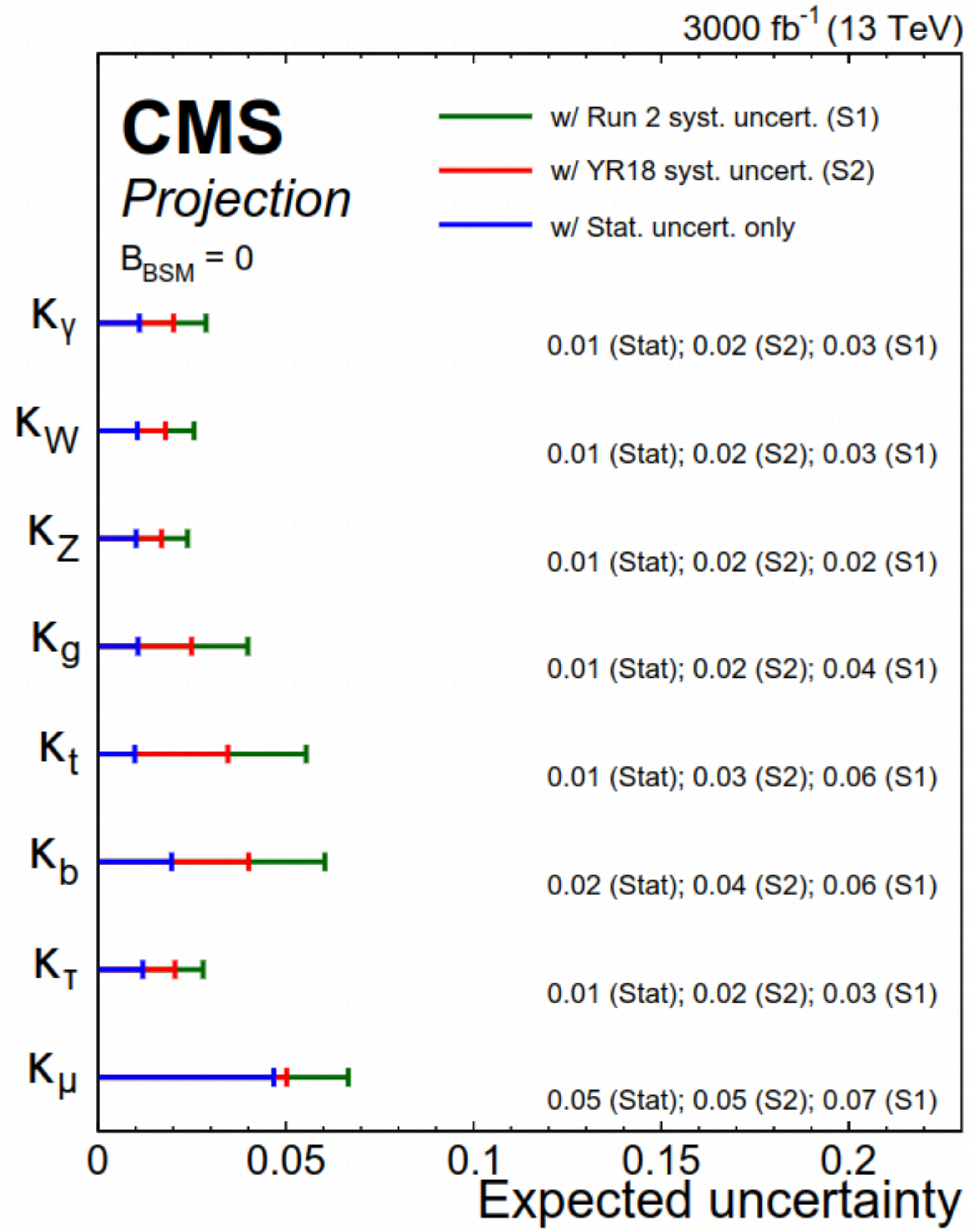


- High statistics→RAA measurement up to high pT
- low pT relies on trigger improvements and large MinBias sample

Higgs physics: couplings







- Target of few % uncertainty at end of LHC seems feasible in S2, even for k_μ
- Theory uncertainties become dominant at high lumi for most channels
- Beware: high correlations arise at 3 ab^{-1}

Higgs physics: couplings

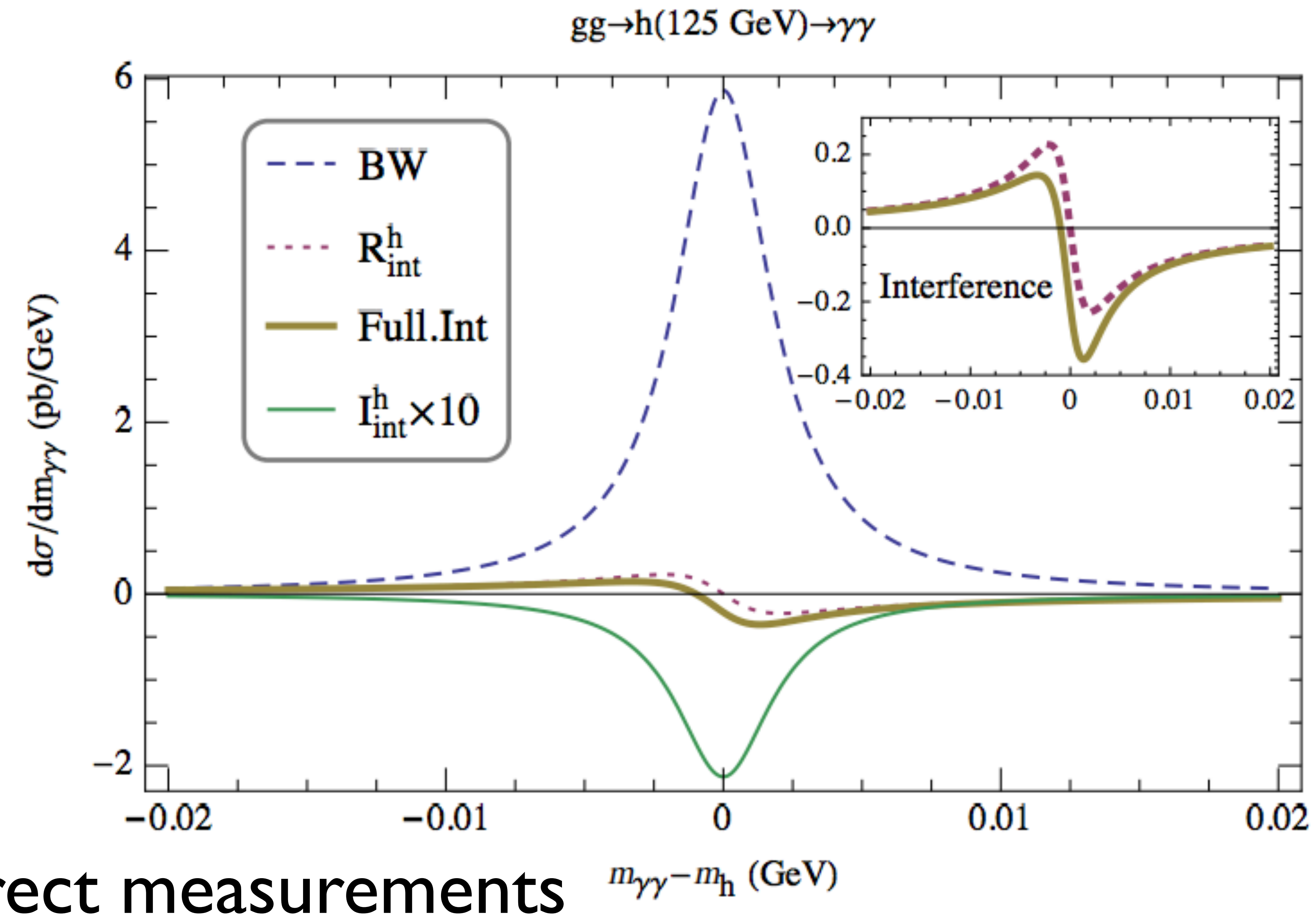
		300 fb^{-1} uncertainty [%]					3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp	Total	Stat	SigTh	BkgTh	Exp
$\mu^{\gamma\gamma}$	S1	7.9	4.1	4.8	0.3	4.8	4.6	1.3	3.5	0.3	2.6
	S2	5.6	4.1	2.7	0.3	2.6	3.1	1.3	2.1	0.3	1.7
μ^{WW}	S1	7.1	3.2	4.9	1.8	3.5	4.2	1.0	3.7	1.0	1.4
	S2	5.2	3.2	2.7	1.4	2.8	2.8	1.0	2.2	0.9	1.1
μ^{ZZ}	S1	8.5	5.1	5.1	0.4	4.5	5.0	1.6	3.5	1.9	2.5
	S2	6.4	5.1	2.9	0.3	2.7	3.3	1.6	2.1	0.7	1.7
μ^{bb}	S1	12.2	6.6	4.8	7.0	5.6	7.2	2.1	5.4	3.6	2.3
	S2	10.2	6.6	2.4	5.6	4.9	4.7	2.1	2.5	2.9	1.7
$\mu^{\tau\tau}$	S1	8.8	5.0	5.1	0.9	5.0	3.9	1.6	2.6	1.5	1.9
	S2	7.4	5.0	3.3	0.9	4.3	2.9	1.6	1.8	0.6	1.4
$\mu^{\mu\mu}$	S1	43.0	42.0	5.7	0.8	5.9	13.0	9.1	5.2	0.8	7.6
	S2	42.2	42.0	3.0	0.8	2.6	9.6	9.1	2.6	0.8	1.7

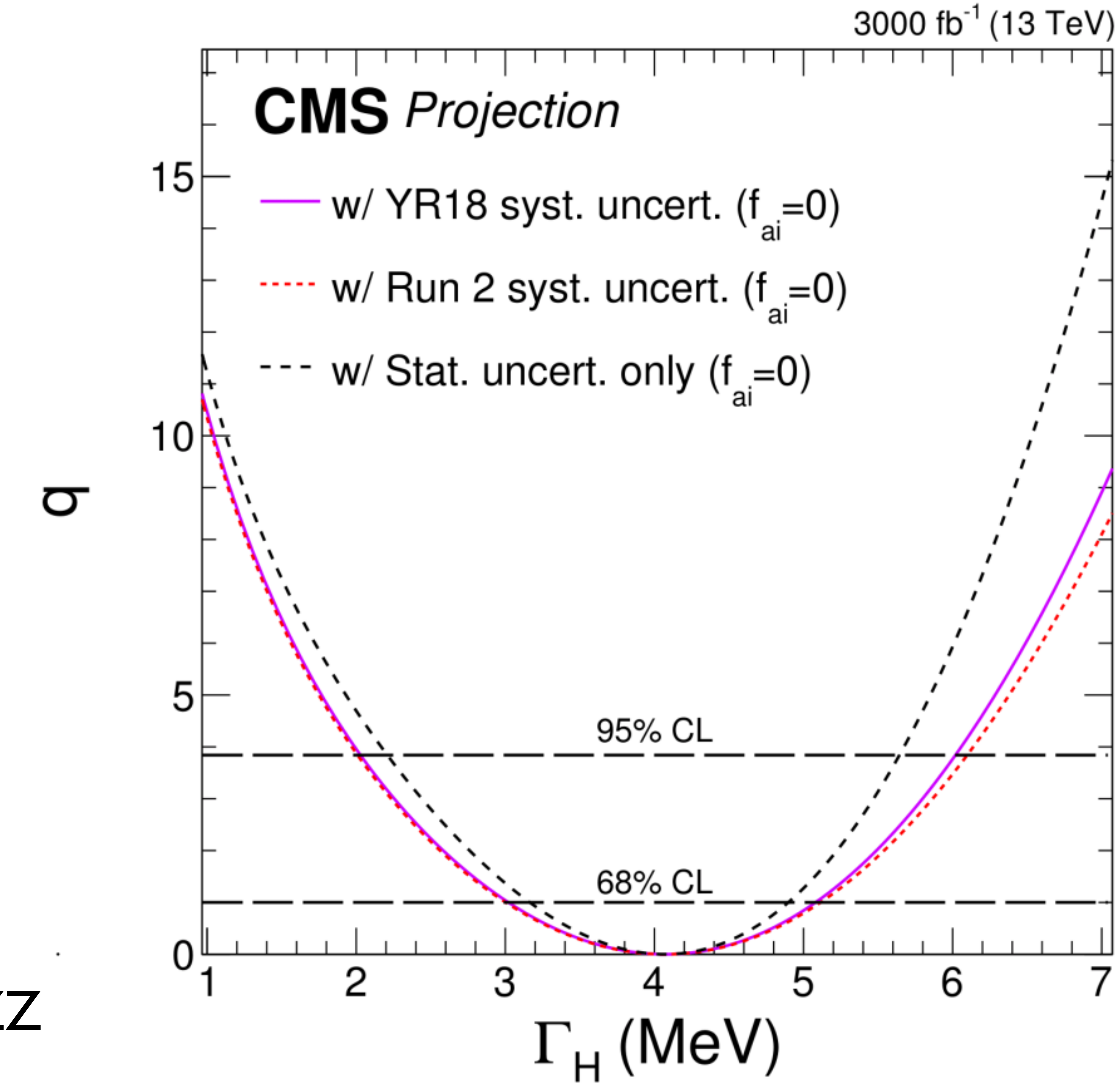
- Target of few % uncertainty at end of LHC seems feasible in S2
- Theory uncertainties become dominant at high lumi (apart from μμ)
- Beware: high correlations arise at 3 ab^{-1}

Higgs physics: width

Reminder: direct width measurement is dominated by the experimental resolution

- "Impossible" to perform at an hadron collider
- LHC results have precision of O(1GeV), we don't expect them to be different at HL-LHC





Solution: indirect measurements

- Diphoton interference causing a mass shift (ATLAS). Precision ~8-22xSM
- Indirect measurement from k-framework, assuming kV≤1, BBSM≥0. 5% precision
- Off-shell / on-shell ratio. Assuming no new particles in the HZZ loop. ~25% precision.

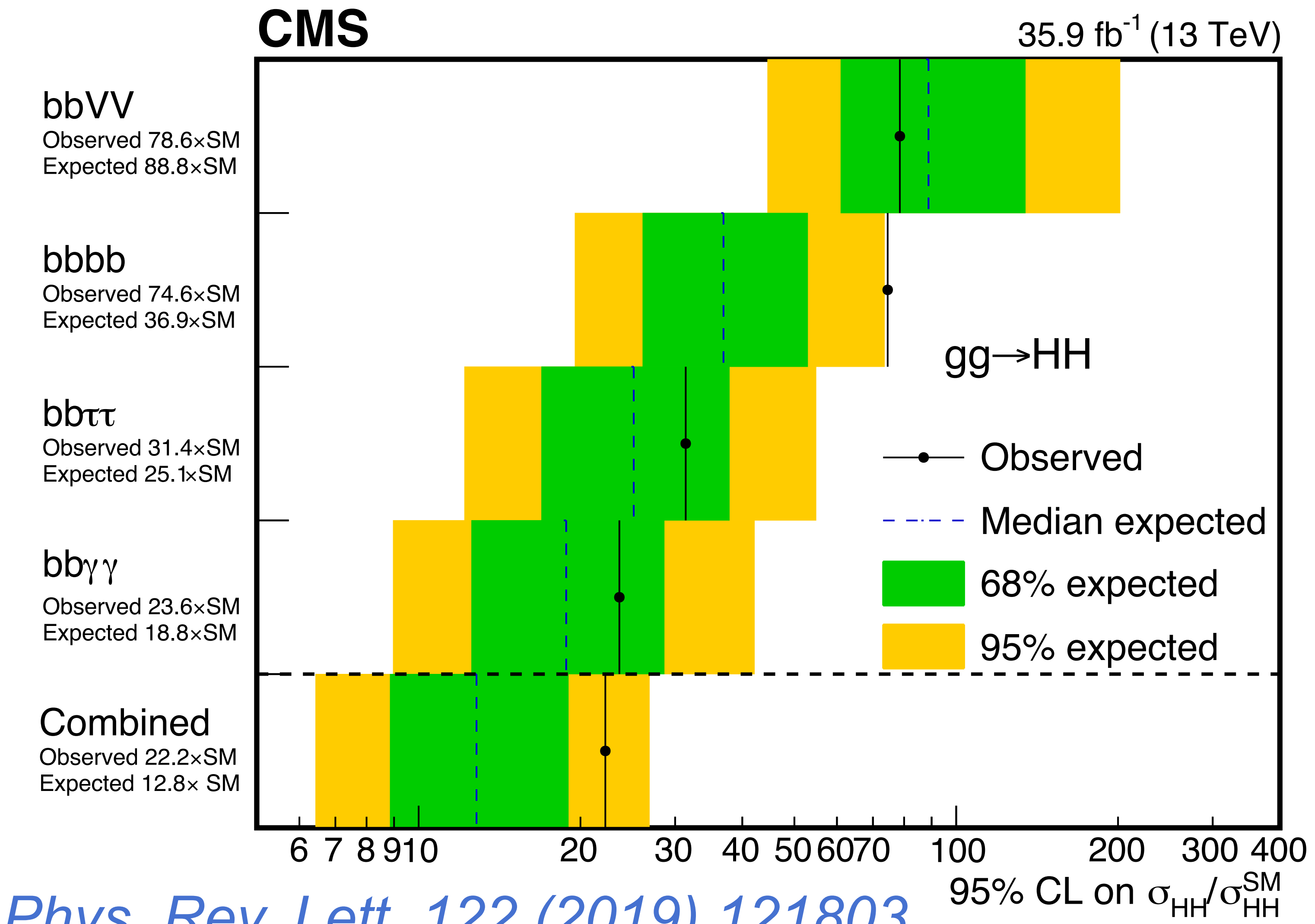
Prospects for HH measurements

1. LHC
   - O(10)-O(2)
   - Could detect large anomalous coupling

2. HL-LHC
   - O(1)
   - Potential for evidence (3σ precision)

3. FCC-ee : single H couplings + indirect measurement
   - Potential for observation (5σ precision)

4. FCC-hh : precision measurement



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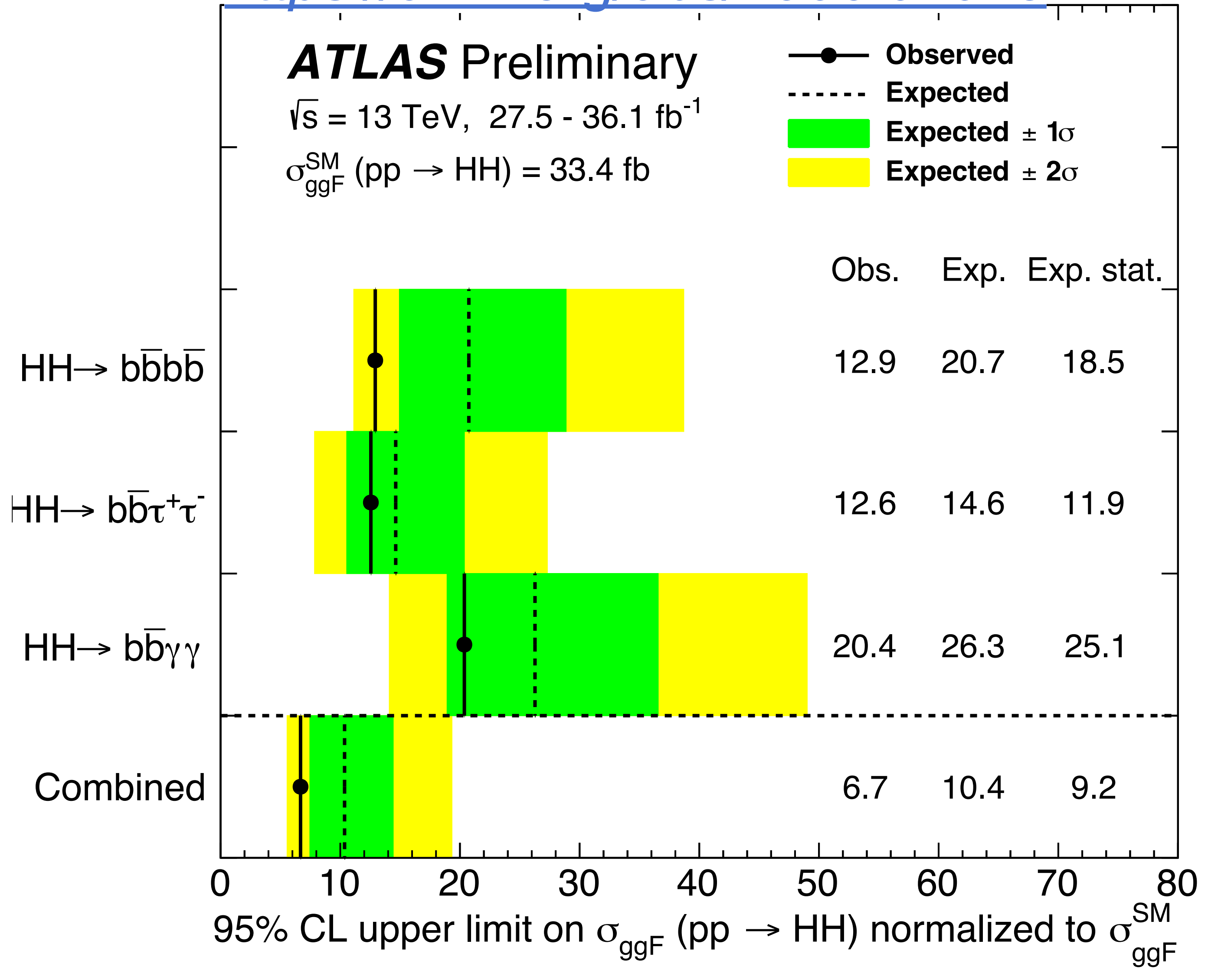
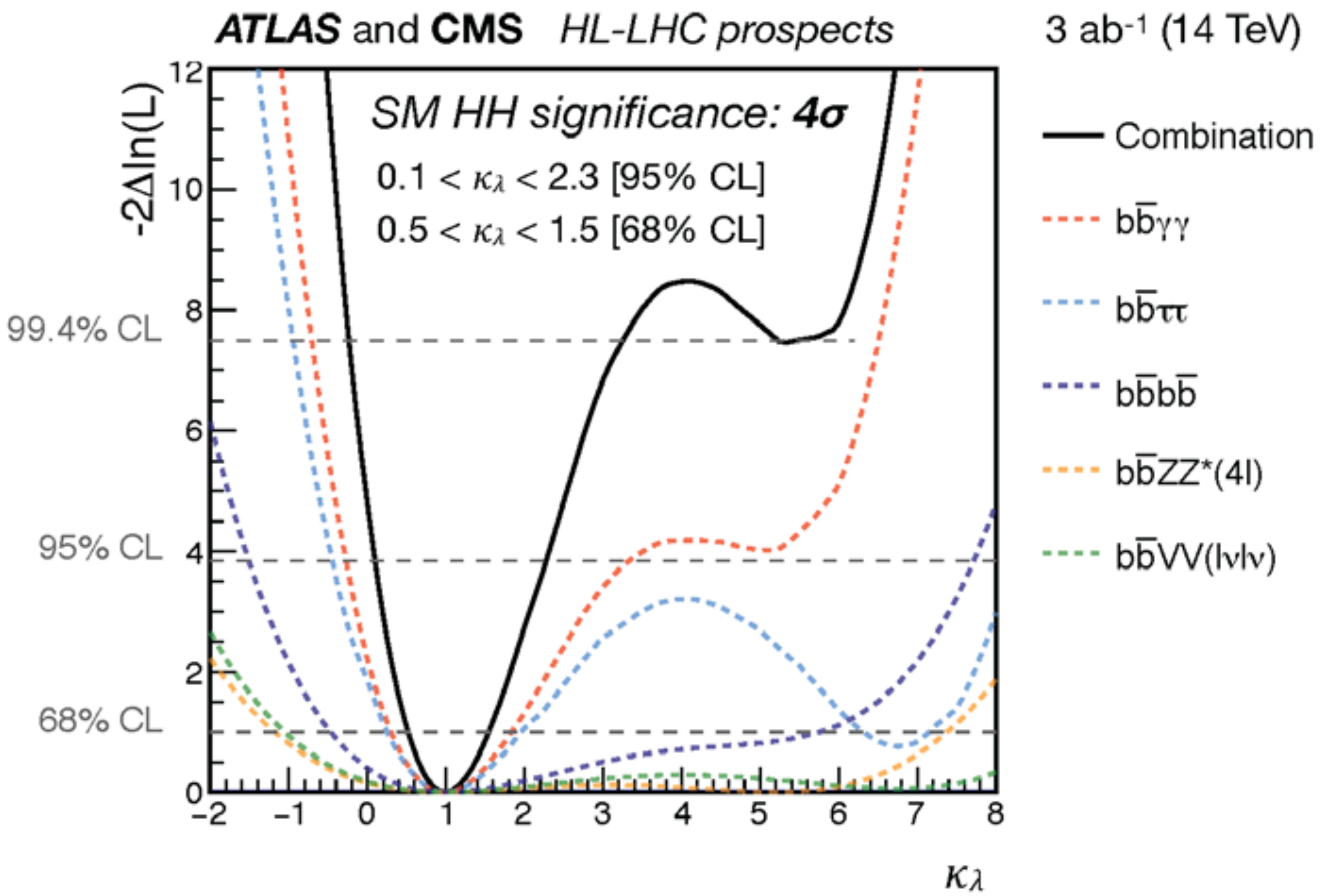
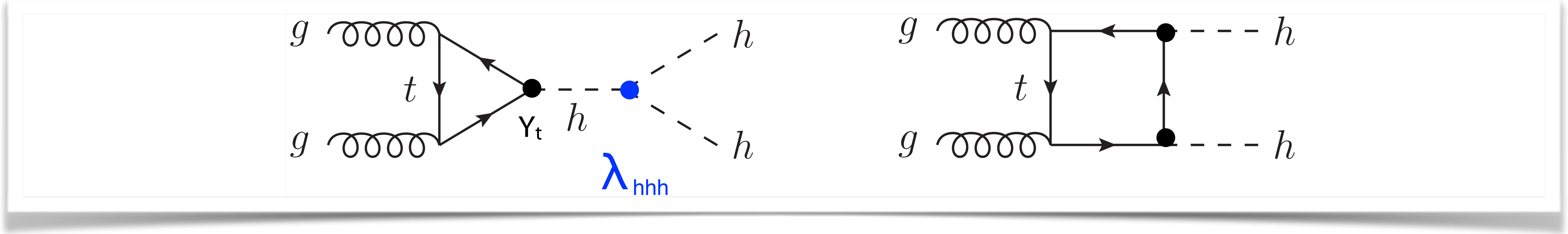
https://arxiv.org/abs/1906.02025

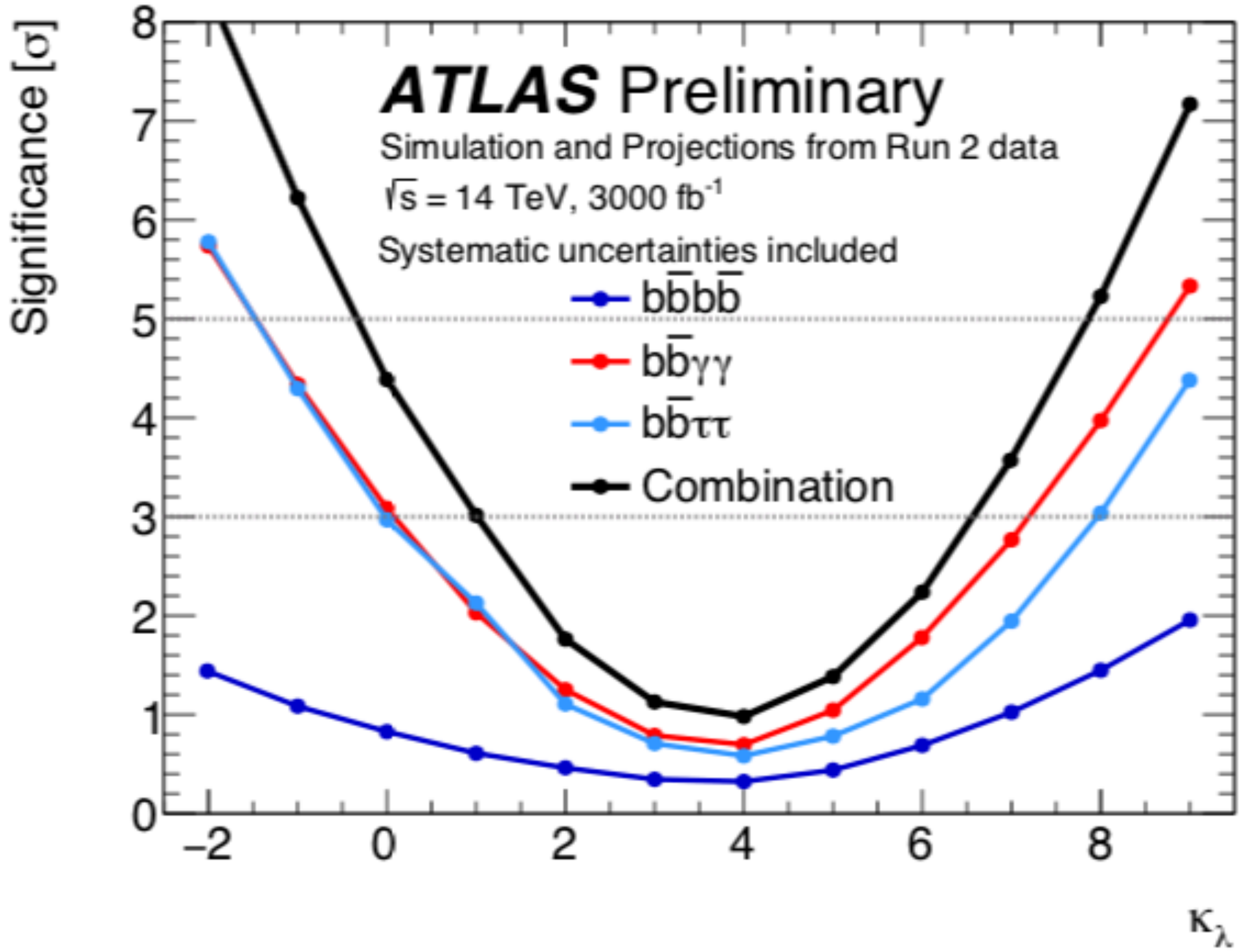


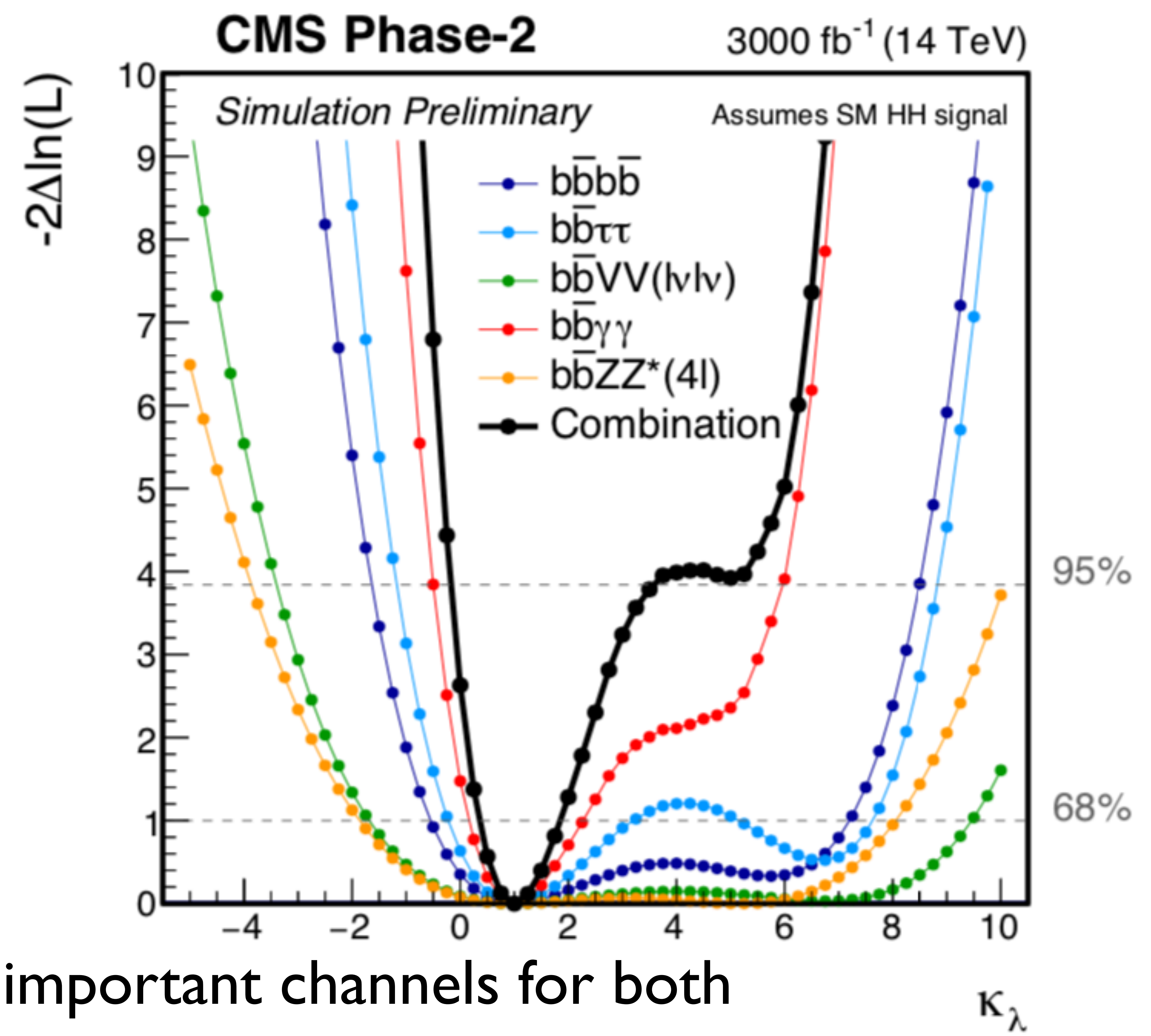


Higgs physics: HH production



- The measurement of the Higgs self coupling is one of the main physics motivation for HL-LHC.
- The most straightforward way of measuring it is to measure the HH production cross section (warning: interference with diagrams without self-coupling!)
- Very rare process, multi-channel approach

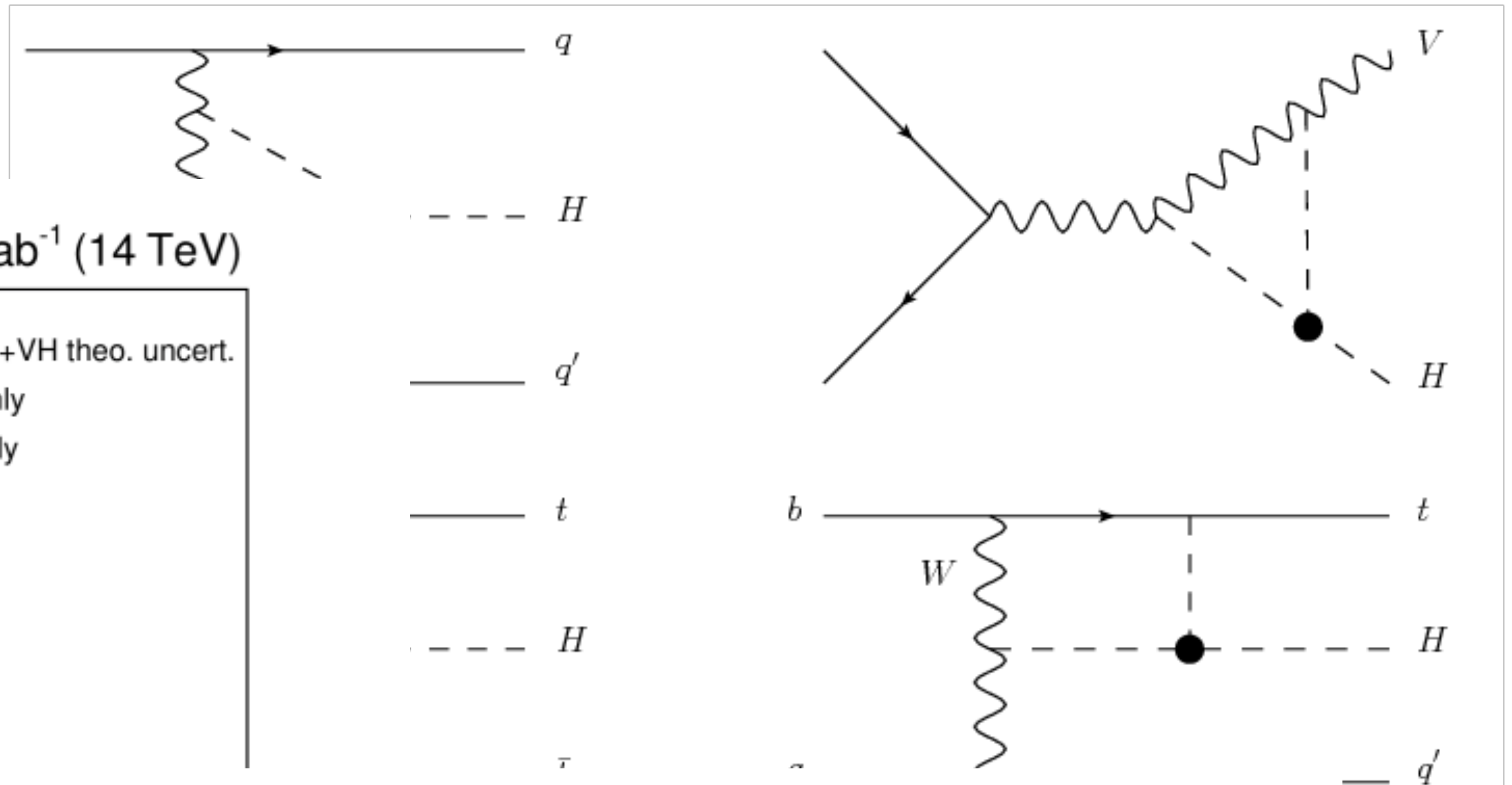


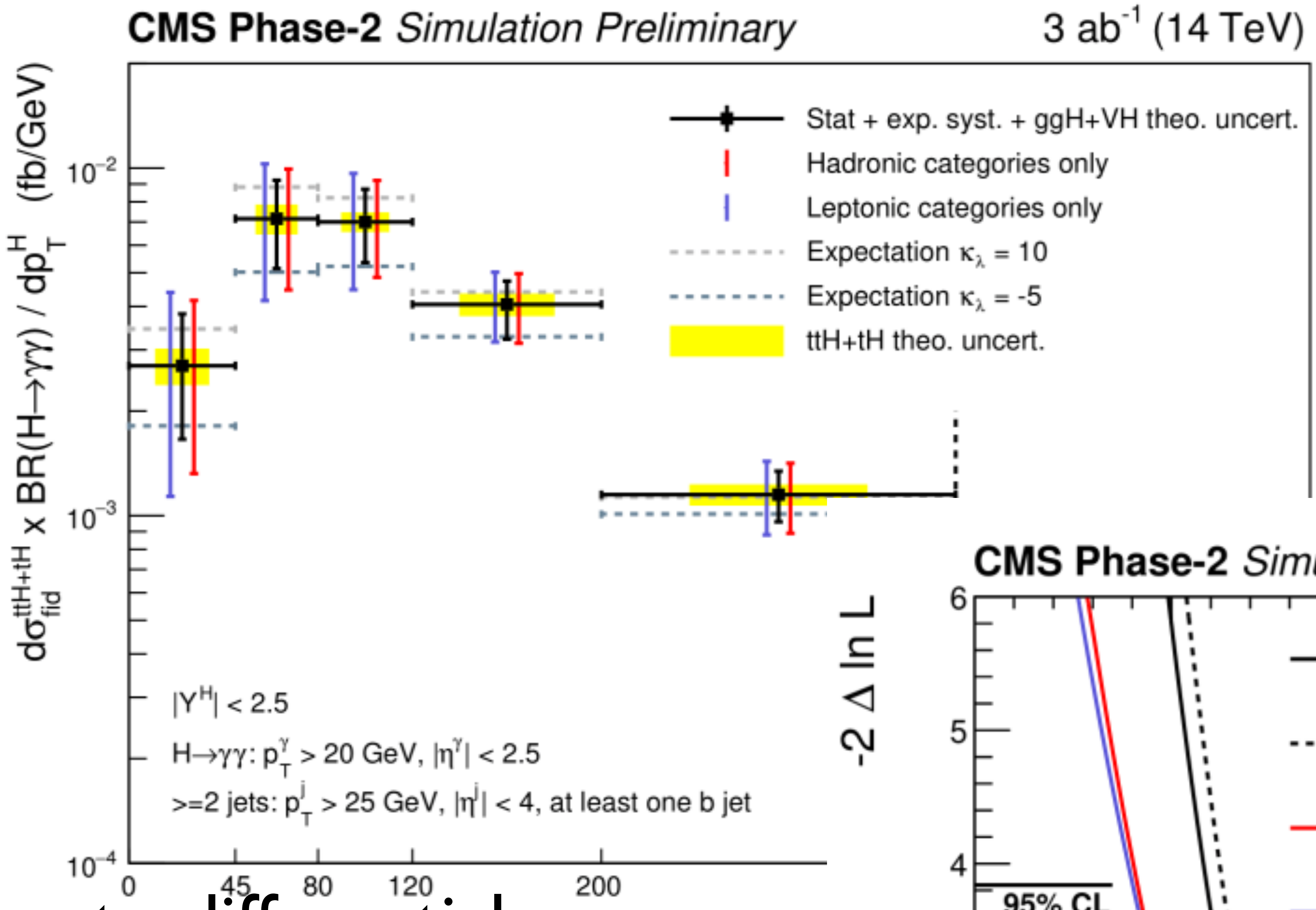


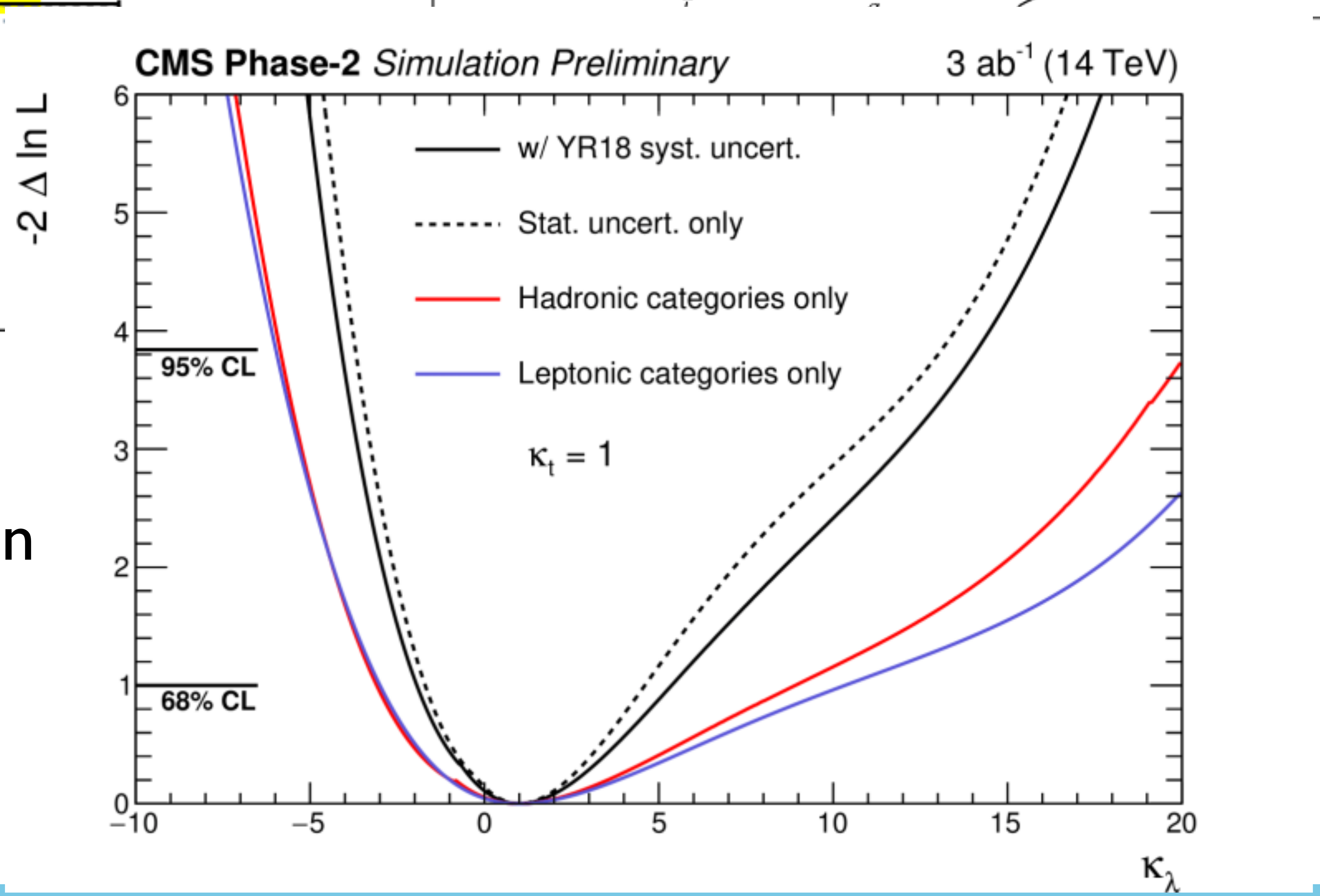
- bbγγ, bbττ are the most important channels for both experiment
- Peculiar likelihood structure. k_λ affects the kinematic and cross-section of the HH production. Using several channels removes the degeneracy.
- Potential for 3σ evidence from both experiment at $3ab^{-1}$ →4σ combining, 4.6σ in the $4ab^{-1}$ scenario!!

Higgs physics: Indirect self-coupling

- The Higgs self-coupling can be measured from higher-order corrections to the single Higgs production
- κ_λ-dependent radiative correcti boson kinematics and single-Hig
- ttH is the most sensitive produ
- Caveat: degeneracies needs to b B_{BSM}=0 or combining with doub
- Preliminary computations @LH to HH measurement.







- Projections to HL-LHC sensitive to differential cross-section precision and binning
- Assuming 20-40% uncertainty on differential cross-section and all other couplings fixed to their SM value
- Not really competitive with HH, but room for improvement