European Strategy for Particle Physics

PARALLEL 1 / **Electroweak physics**

# Overall assessment of projects (including HL-LHC inputs)


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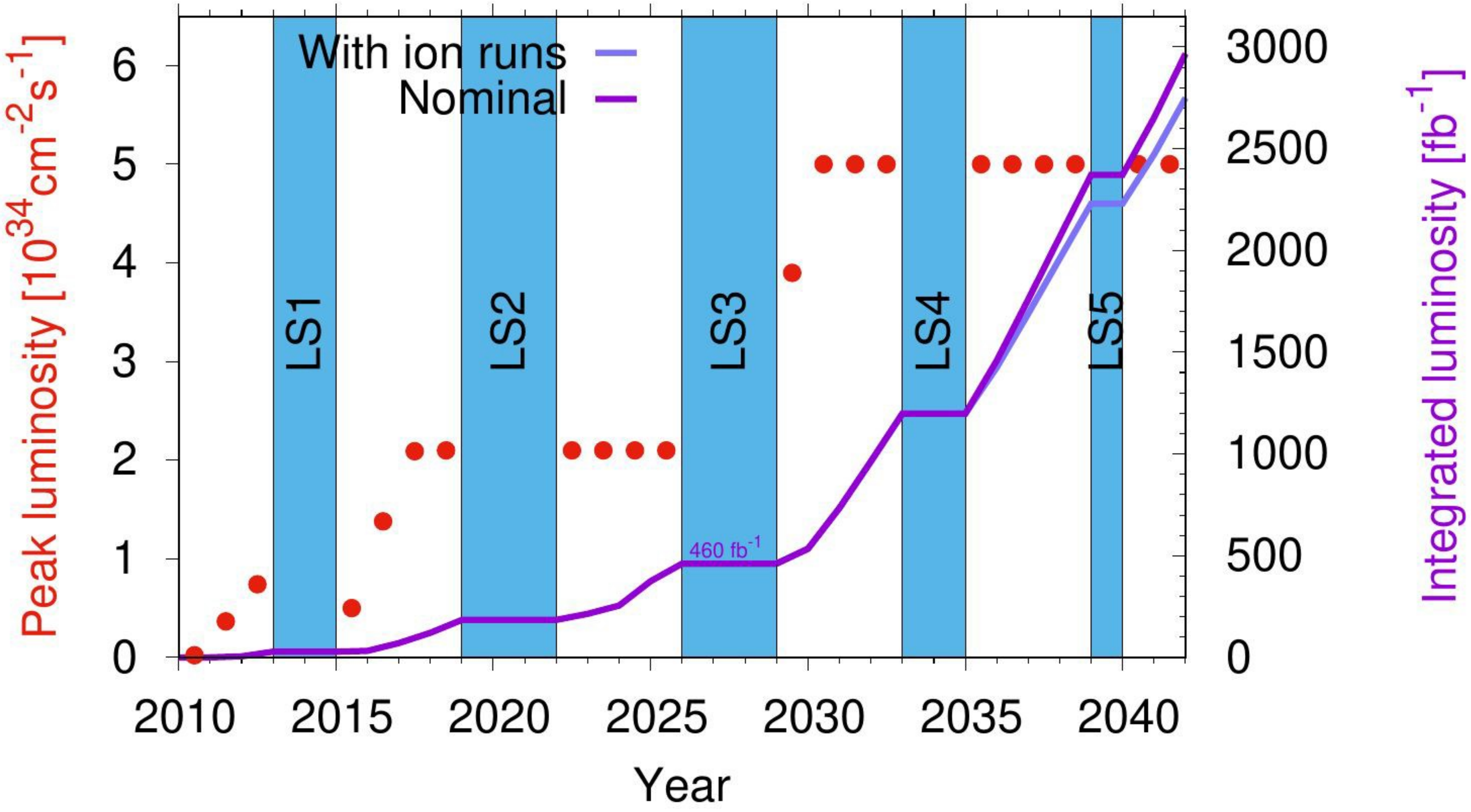
23-27 **JUNE** 2025 **Lido di Venezia**

# Introduction

- 3x increase of peak luminosity
  - Data equivalent to **3000 $fb^{-1}$ in 10 years of operation**
  - **Upgraded CMS** detector to cope with higher pileup and radiation damage




~ 36.7M HH events at 3000 $fb^{-1}$ for CMS+ATLAS

~ 367M signleH events at 3000 for CMS+ATLAS $fb^{-1}$

Lots of statistics → precise measurements

# Introduction

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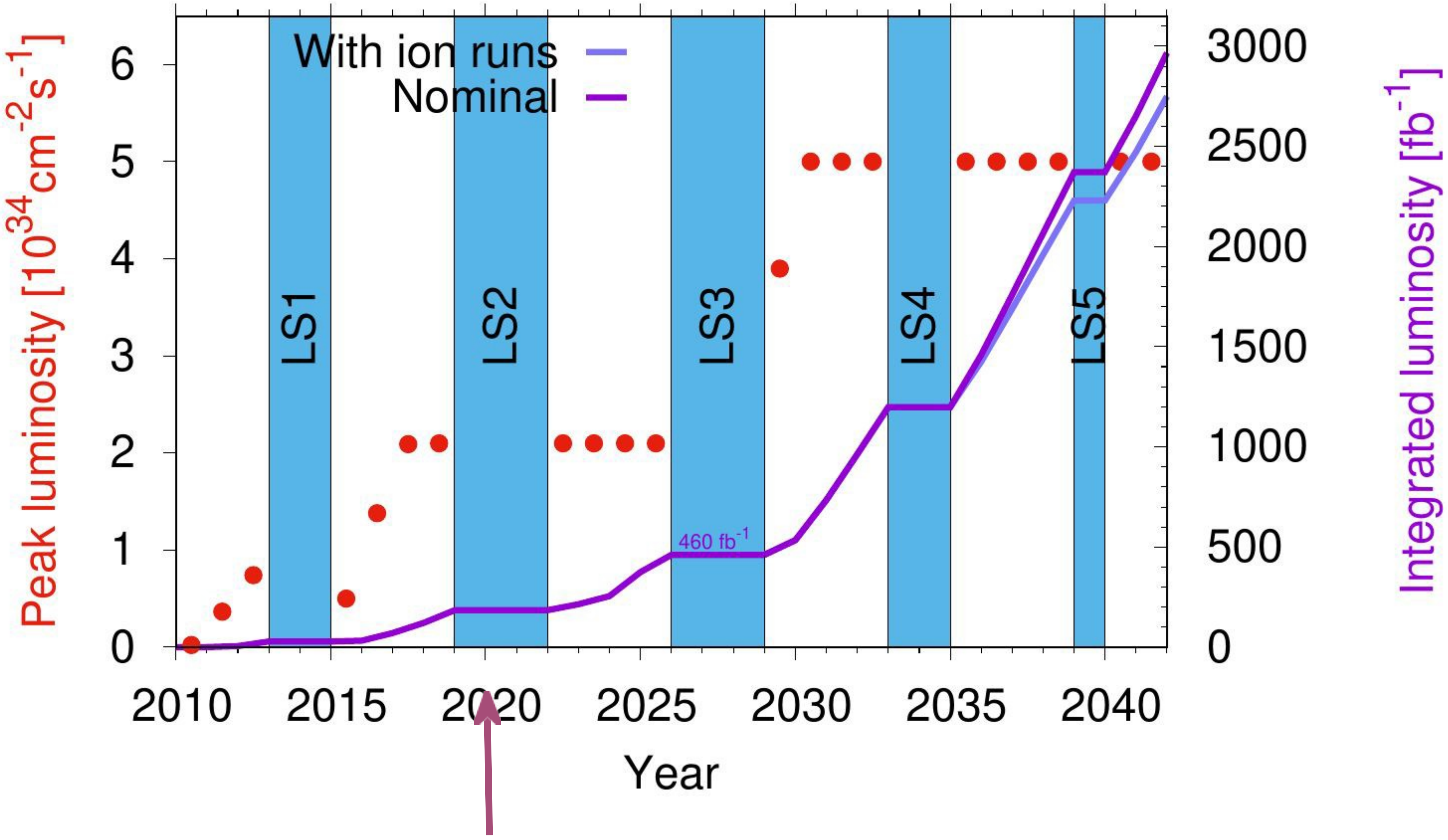
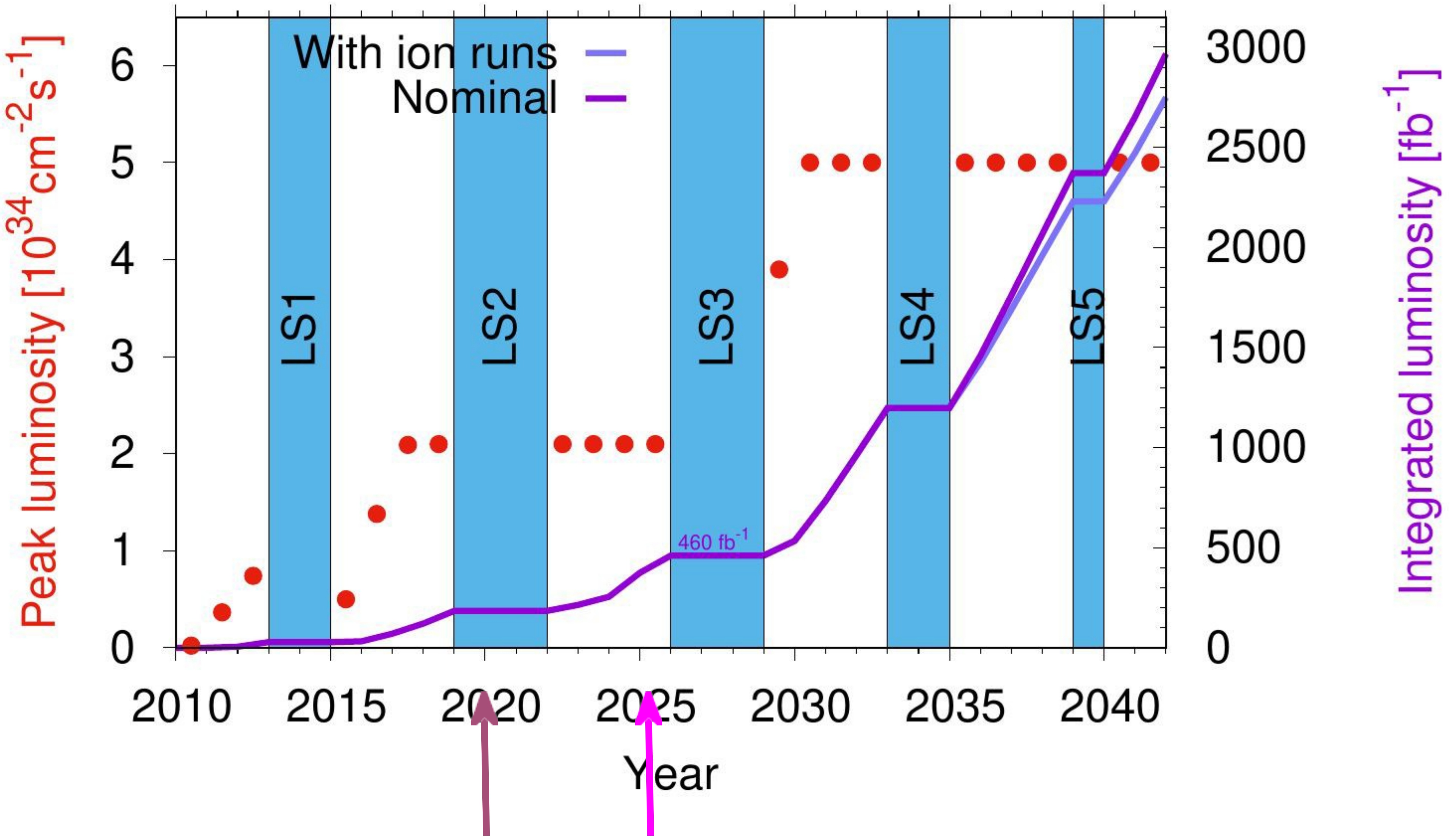



- **European Strategy for Particle Physics is the cornerstone for Europe's long-term decision making process**
- Last update from 2020
  - Priority on the successful completion of the High-Luminosity LHC over the coming decade
  - Higgs factory as the highest priority to follow the LHC

# 2025 ESU update - updated HL-LHC projections

- **We want to emphasize the unique opportunity that HL will give:**
    - more lumi + new analysis technique explored in the past 5 years

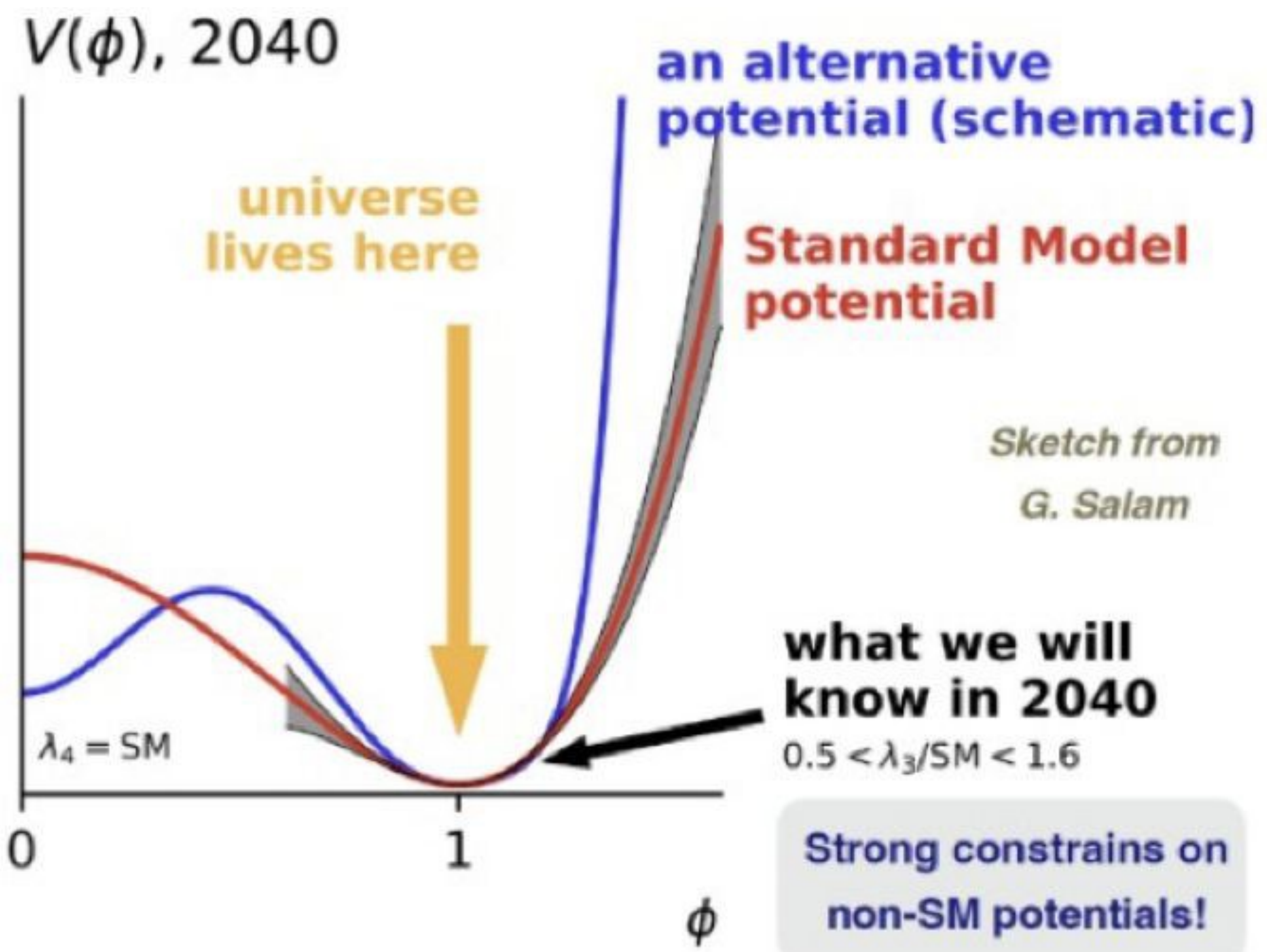
unique update the expected precision on the Higgs couplings



# 2025 ESU update - updated HL-LHC projections

- **We want to emphasize the unique opportunity that HL will give:**
  - update the expected precision on the Higgs couplings
  - establishing the shape of the electroweak vacuum
  - stability of the universe

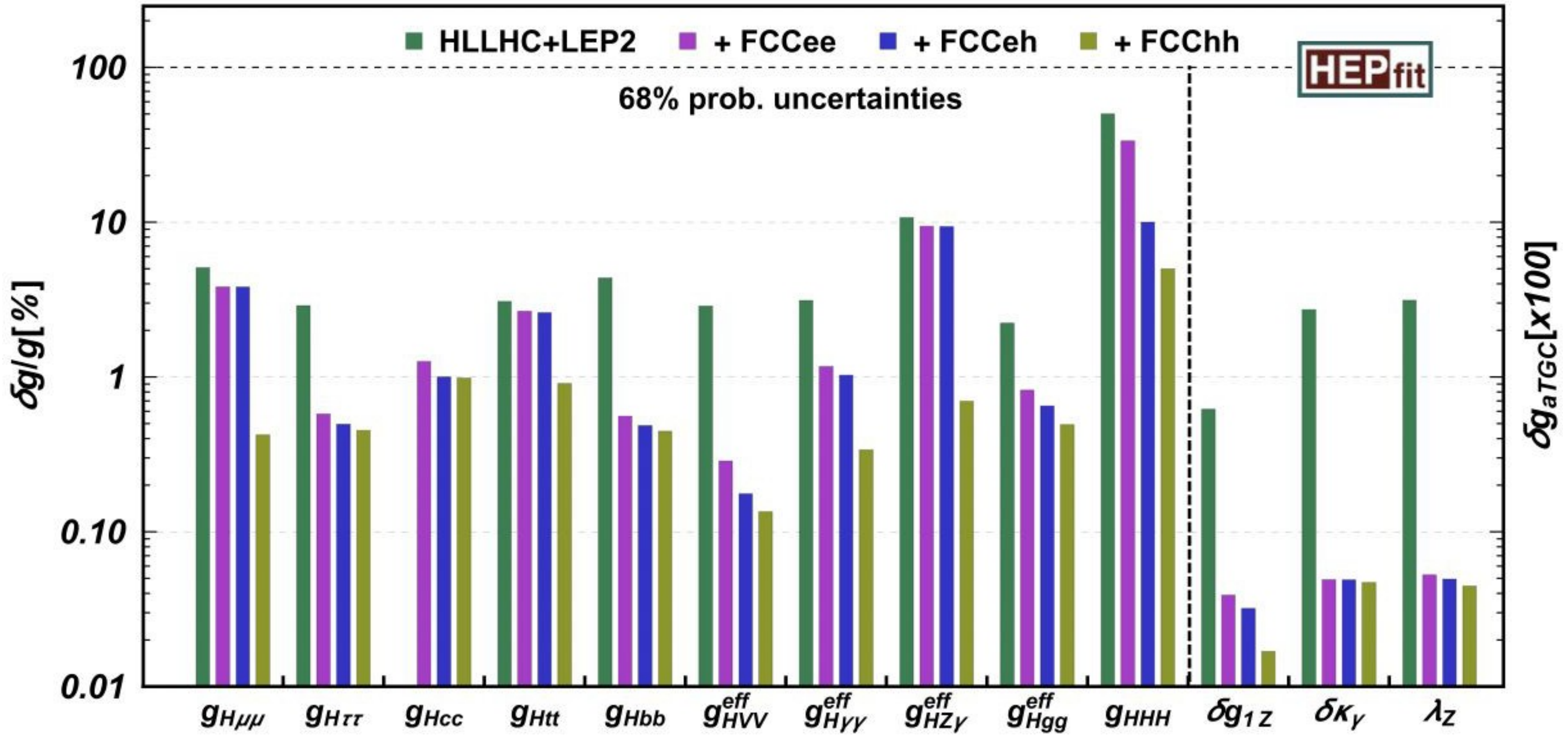
First attempt to give a proper answer to those questions




Strong constrains on non-SM potentials!

# Single H projections - what's improved in HL?

- HL is still going to be the best machine for Zγ, μ and ttH coupling determination for the next decades years (until FCC-hh)




*Phys. Rev. Lett. 132 (2024) 221802

# Single H projections - what's improved in HL?

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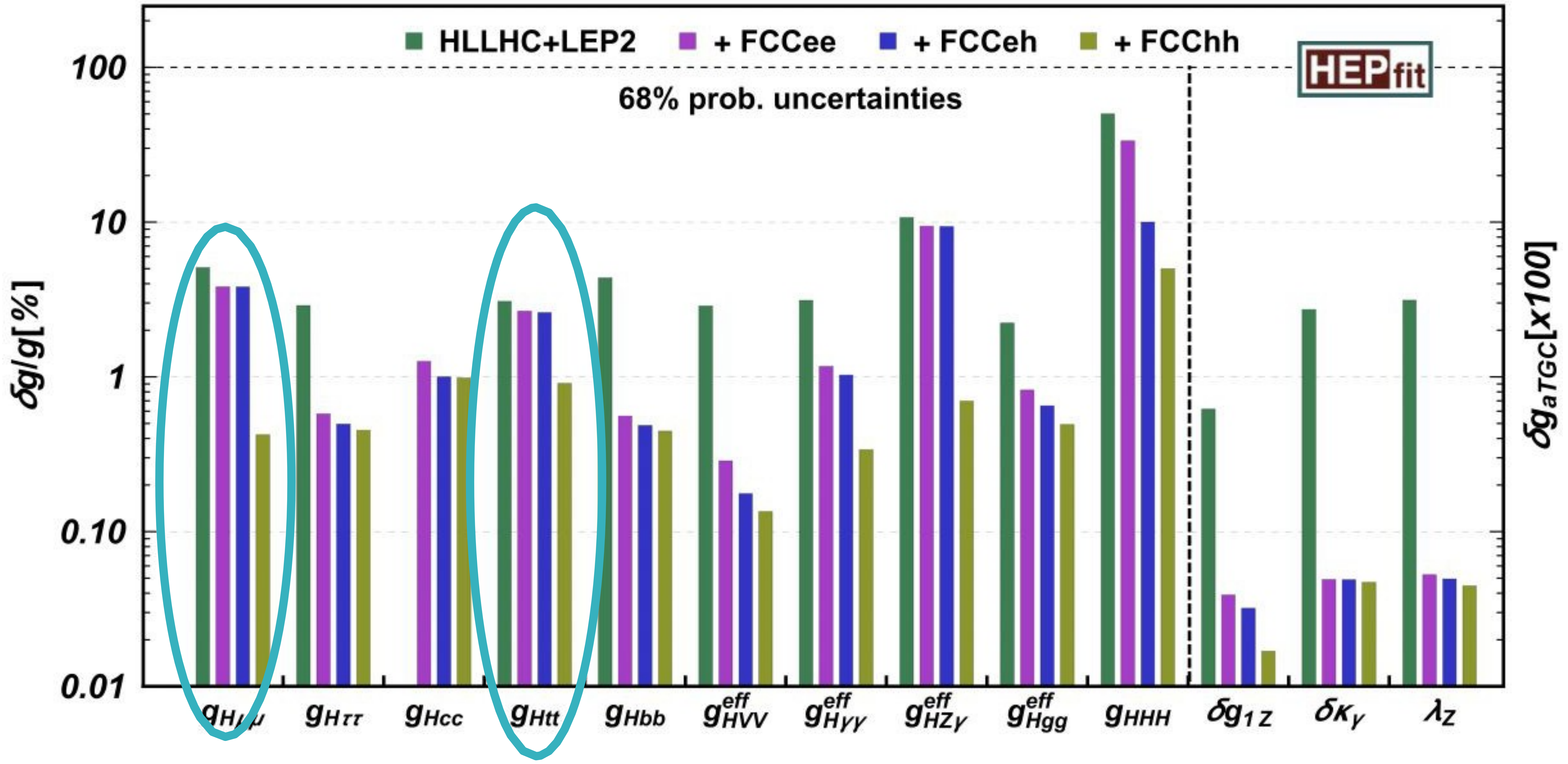



- optimize both the inclusive measurement of the signal strength (especially in the rare channels)

*[Phys. Rev. Lett. 132 (2024) 221802]

# Single H precision - H > Zγ and H > μμ

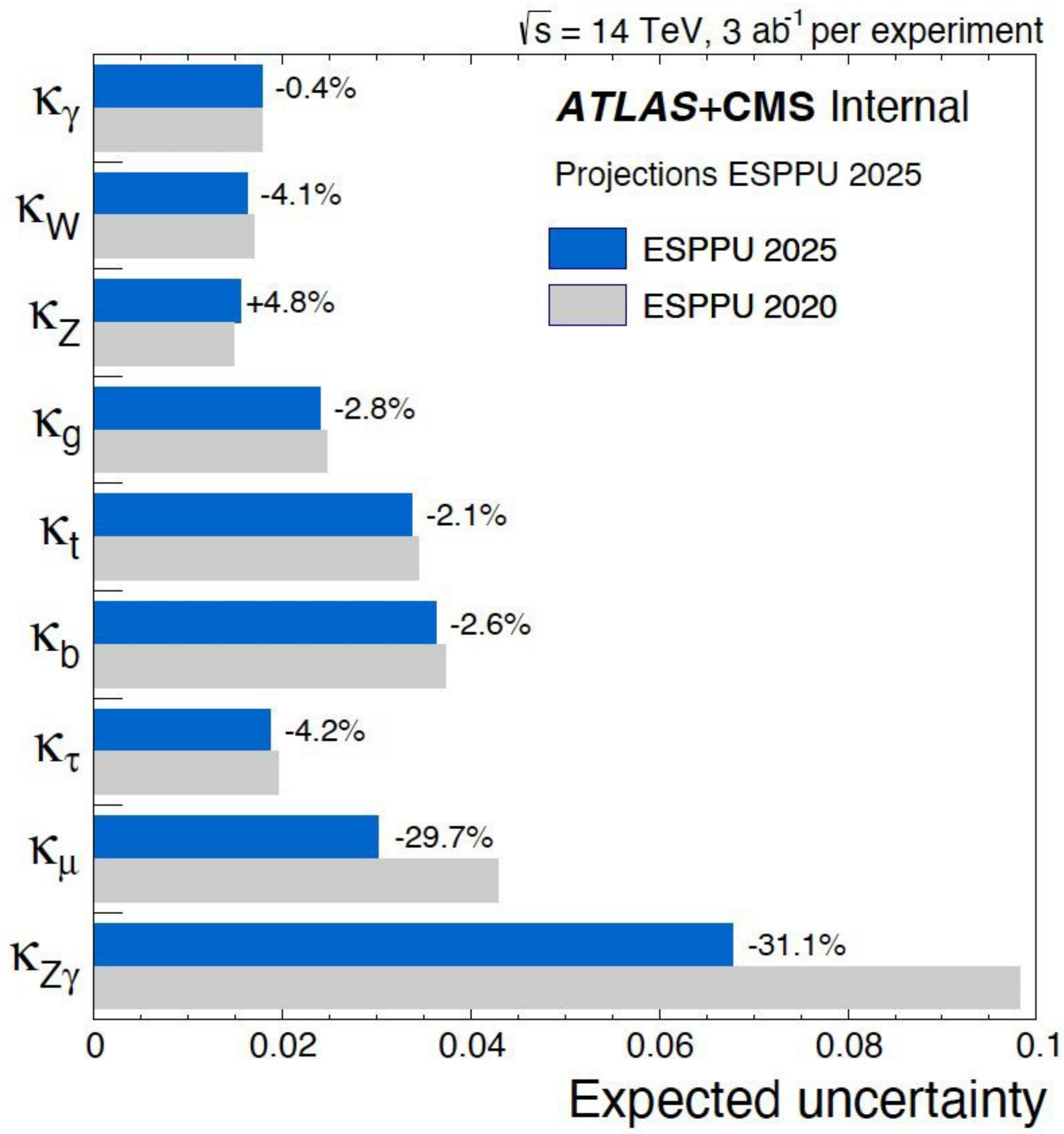
- At present, unmeasured Higgs coupling
- Relation between $H \to Z\gamma$ and $H \to \gamma\gamma / H \to ZZ$ ratios is sensitive to new physics
- The determination of the $H \to Z\gamma$ signal is heavily limited by statistical uncertainties
- The $H \to \mu\mu$ decay is the most promising channel for measuring Higgs boson interactions with second generation fermions

| $\mathcal{L}$ | | $\delta\mu[\%]$ $H \to Z\gamma$ | $\delta\mu[\%]$ $H \to \mu\mu$ |
|---|---|---|---|
| $2\ \mathrm{ab}^{-1}$ | ATLAS | 21 | 13 |
| | CMS | 23 | 8.4 |
| | ATLAS+CMS | 15 | 7.1 |
| $3\ \mathrm{ab}^{-1}$ | ATLAS | 17 | 11 |
| | CMS | 19 | 7.0 |
| | ATLAS+CMS | 14 | 5.9 |

Single experiment discovery will be reached at the intermediary stages of the HL-LHC

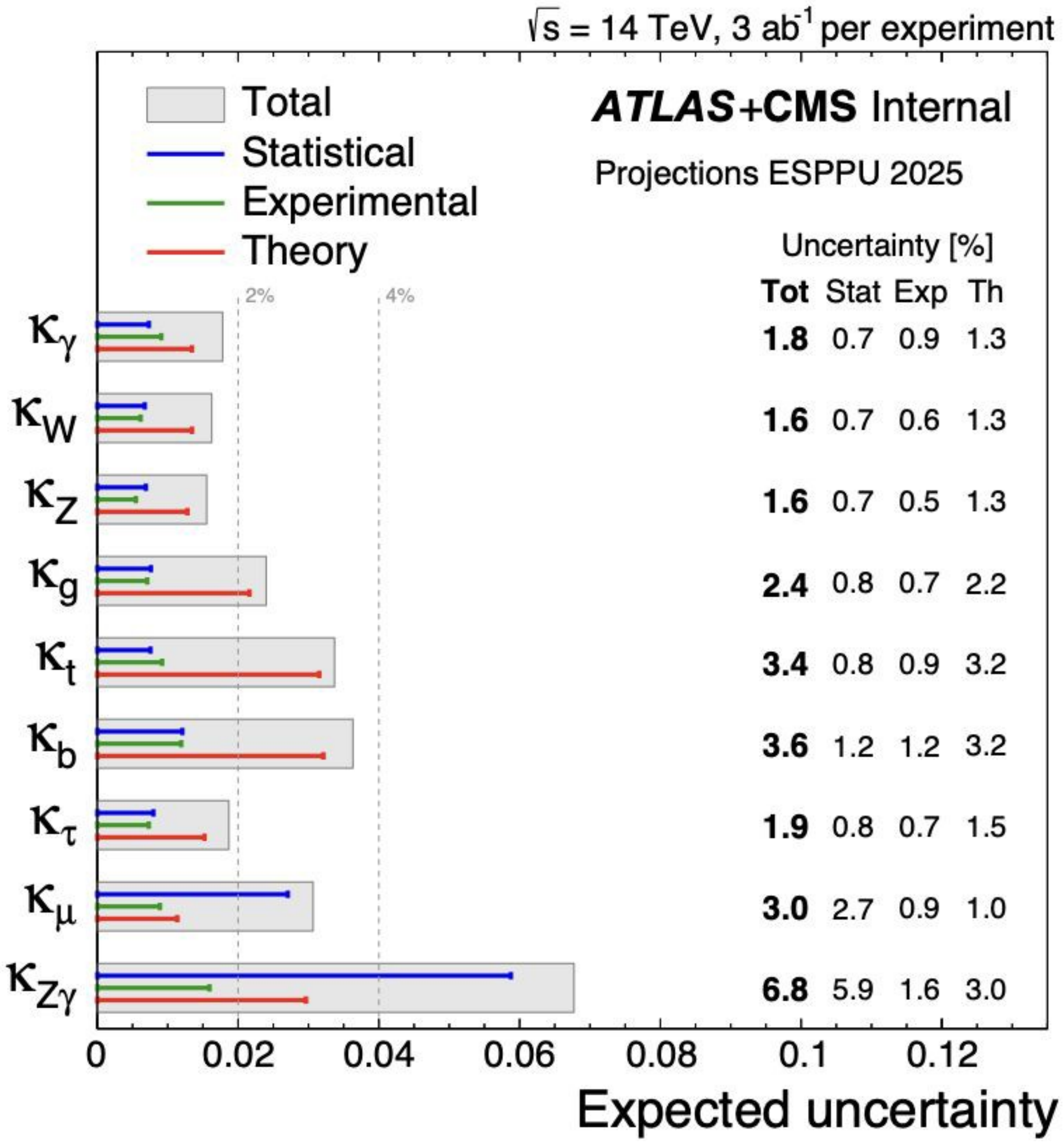
# Single H precision - Higgs couplings

- The precision of $\kappa_\mu$ and $\kappa_{Z\gamma}$ improves by 30%, wrt old projections
- Z coupling worsen wrt 2020 because less aggressive assumptions on the theory uncertainty were made this year



# Single H precision - Higgs couplings

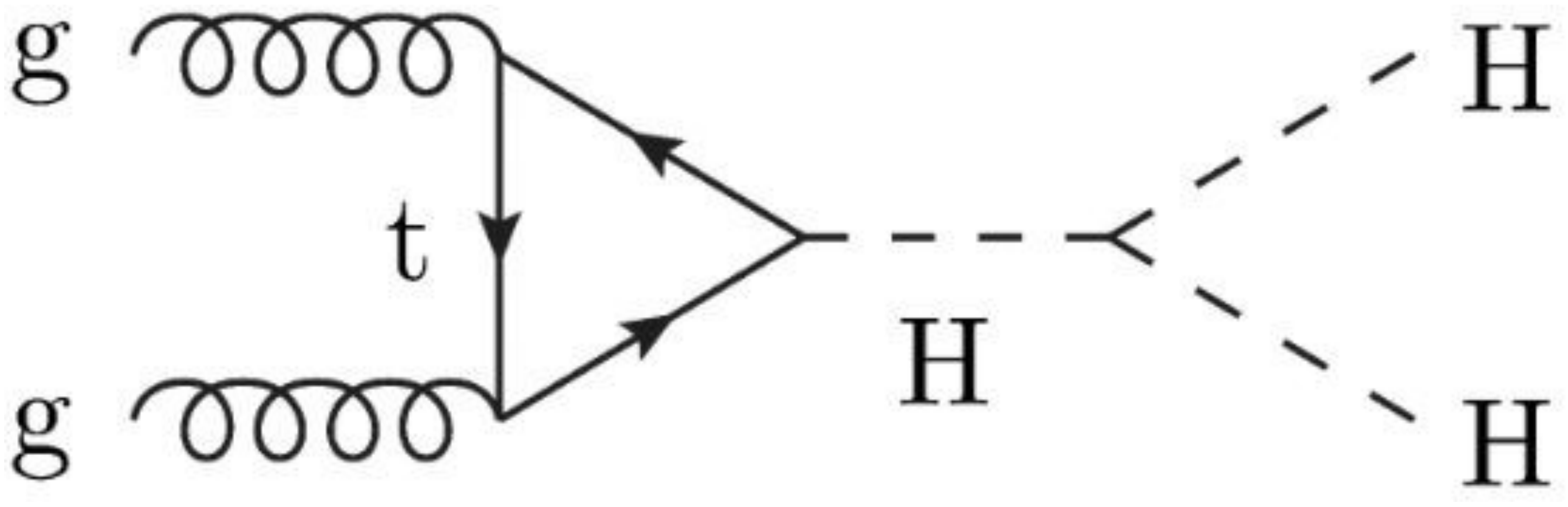
- The precision of $\kappa_\mu$ and $\kappa_{Z\gamma}$ improves by 30%, wrt old projections
- Theory uncertainties are dominating
  - if driven by experimental precision, we could reach a further factor 2 improvement

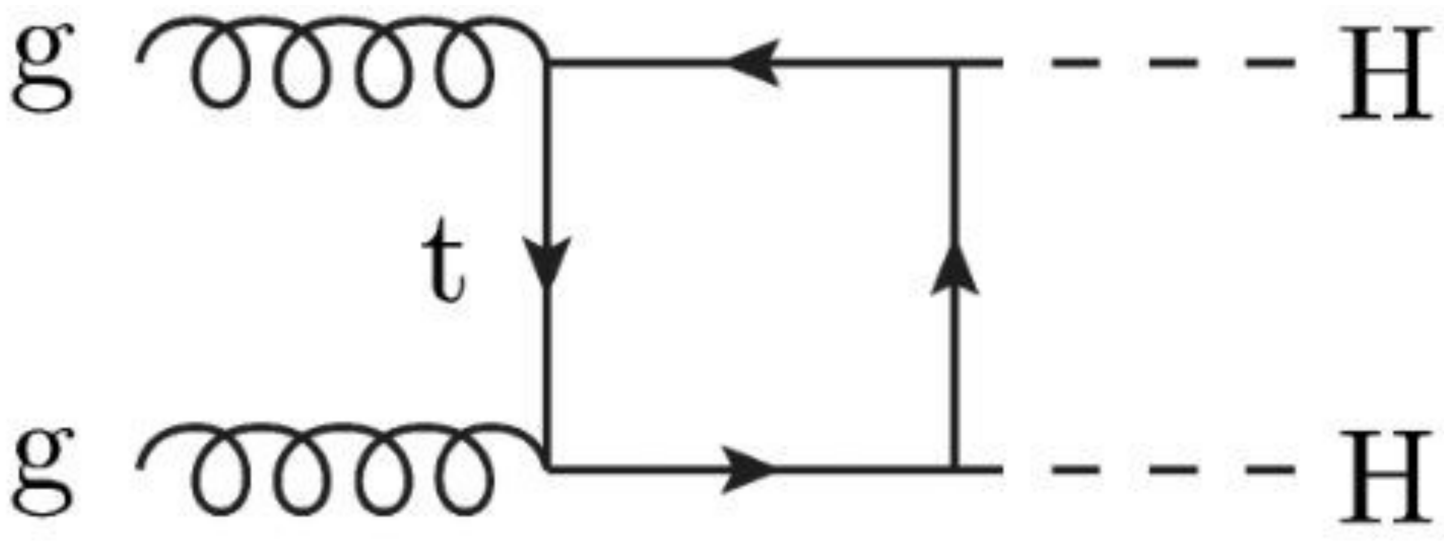


# Non-resonant HH projections

- Double H production in ggF is the most direct probe on the H potential
  - Small cross section -> process still undetected
  - Searches provide direct constraints on the H self coupling

- Test of the Electroweak Symmetry Breaking (EWSB) mechanism
- First direct measure of the $\lambda_3$ parameter -> implication for the shape of the H potential and the order of the phase transition of the universe




- Special scenario where the b-jet and hadronic tau IDs improvements confirmed by public material is extrapolated to the Run 2 results - still very conservative scenario

# HH results - Significance

- $3000\ fb^{-1}$ per experiment, run3 object improvement included

| Channel | HH Significance ATLAS | HH Significance CMS |
|---|---|---|
| $bb\tau\tau$ | 3.8 | 2.7 |
| $bb\gamma\gamma$ | 2.6 | 2.6 |
| 4b resolved | 1.0 | 1.3 |
| 4b boosted | - | 2.2 |
| Multilepton | 1.0 | - |
| $bb\ell\ell$ | 0.5 | - |
| Combination | **4.5** | **4.5** |
| ATLAS + CMS | 7.60 | |

- Evidence with single experiment
- **Combined evidence $>7\sigma$**

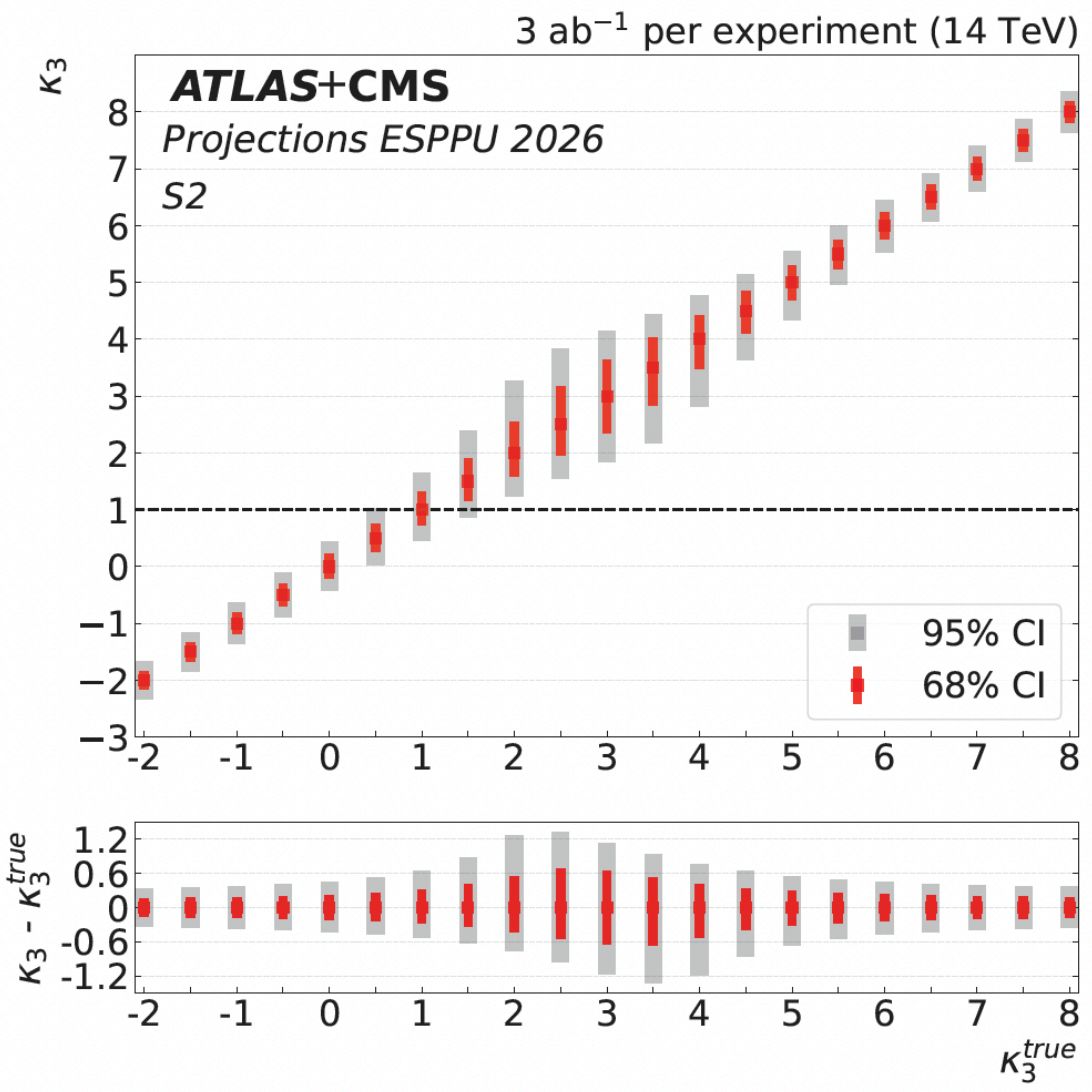
# HH results - $k_\lambda$ precision

- 3000 $fb^{-1}$ per experiment, run3 object improvement included

| Channel | $\kappa_3$ precision 68% CL ATLAS | $\kappa_3$ precision 68% CL CMS |
|---|---|---|
| $bb\tau\tau$ | [0.5, 1.6] | [0.3, 2.0] |
| $bb\gamma\gamma$ | [0.5, 1.7] | [0.4, 1.9] |
| 4b resolved | [−0.5, 6.1] | [−0.3, 7.2] |
| 4b boosted | – | [−0.4, 8.2] |
| Multilepton | [−0.1, 4.7] | – |
| $bb\ell\ell$ | [−2.1, 9.1] | – |
| Combination | [0.6, 1.4] | [0.6, 1.5] |
| ATLAS + CMS | −26/+29 | |

- ~26% precision for $k_\lambda$=1

# HH results - $k_\lambda$ precision



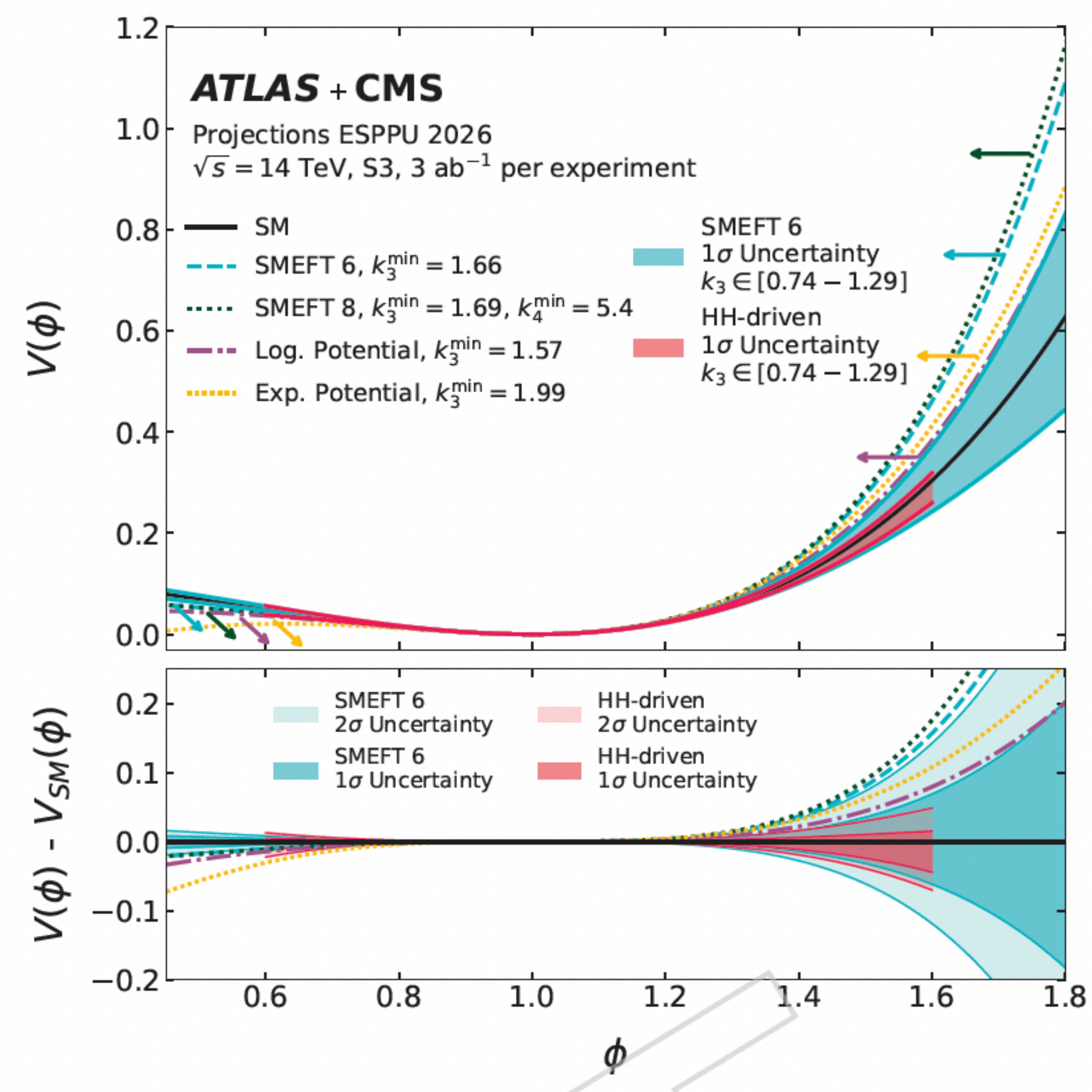

- kl scan assuming different values of kl
  - maximum interference between box and triangle diagram at 2.45 -> largest precision

# Shape of the electroweak vacuum

- Measuring the Higgs self-coupling alone is insufficient to fully determine or constrain the shape of the EWSB potential
- To provide model-independent conclusions on fundamental questions, such as whether the EWSB transition is first-order (a key element for electroweak baryogenesis) an assumption about the form of the potential is generally required:
  - dim-6 EFT
  - dim-8 EFT
  - logarithmic
  - exponential

# Shape of the electroweak vacuum

- The light blue delimits the area where a first order phase transition would be possible in a dimension 6 EFT.
  - <u>2σ full exclusion is reached at 3 ab$^{-1}$ for the EFT dim 6 FOPT inducing potentials</u>



# Rare Top decays

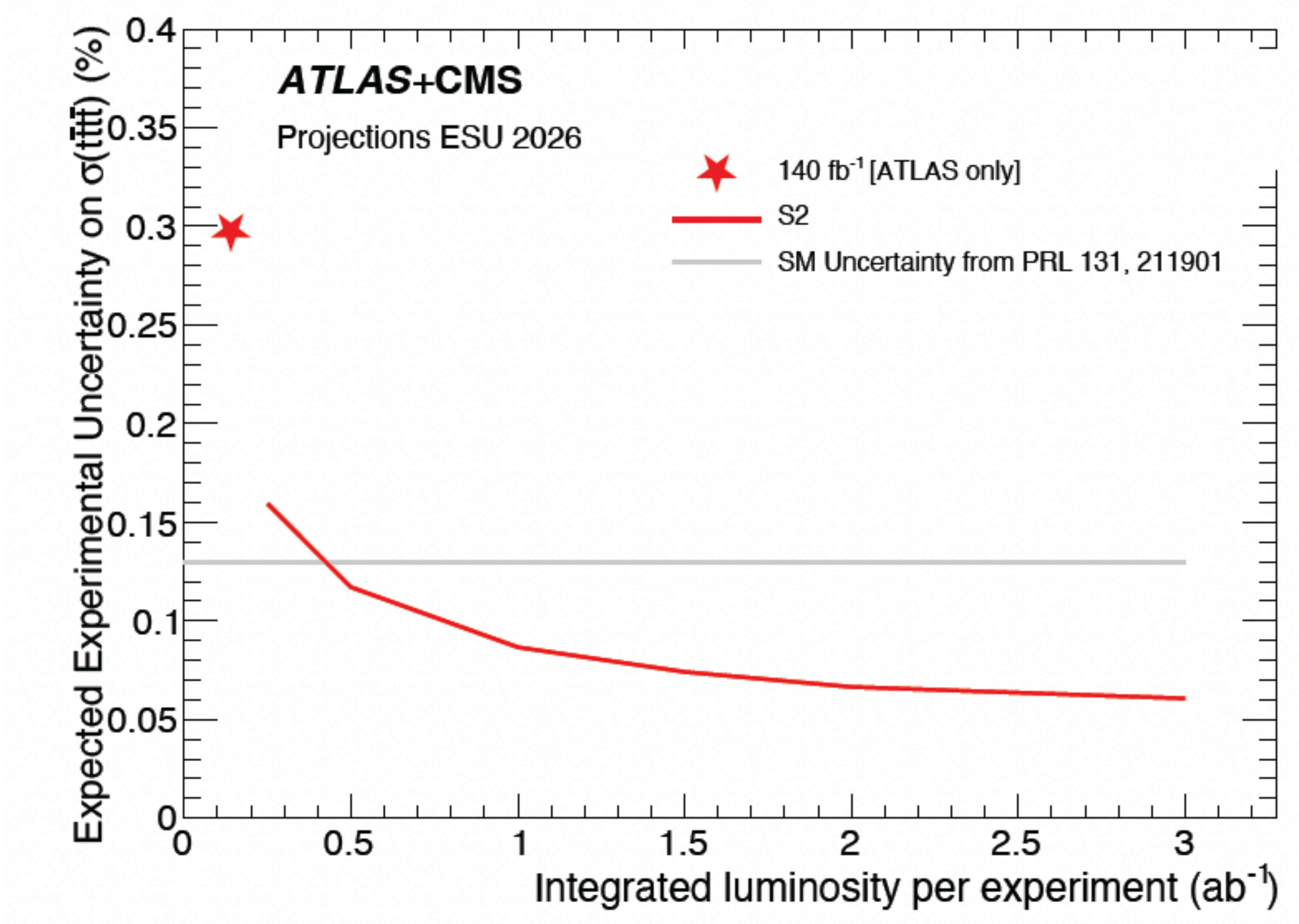
- Top quark is the heaviest mass of the SM
  - privilege connection to the scalar sector
  - exploring potential to the new physics

- Two main projections are explored:
  - tttt production
  - $tt\gamma$, $ttZ$ production

*Might be the definitive top results for a some time
(FCC might not run at the top pole)

# tttt production

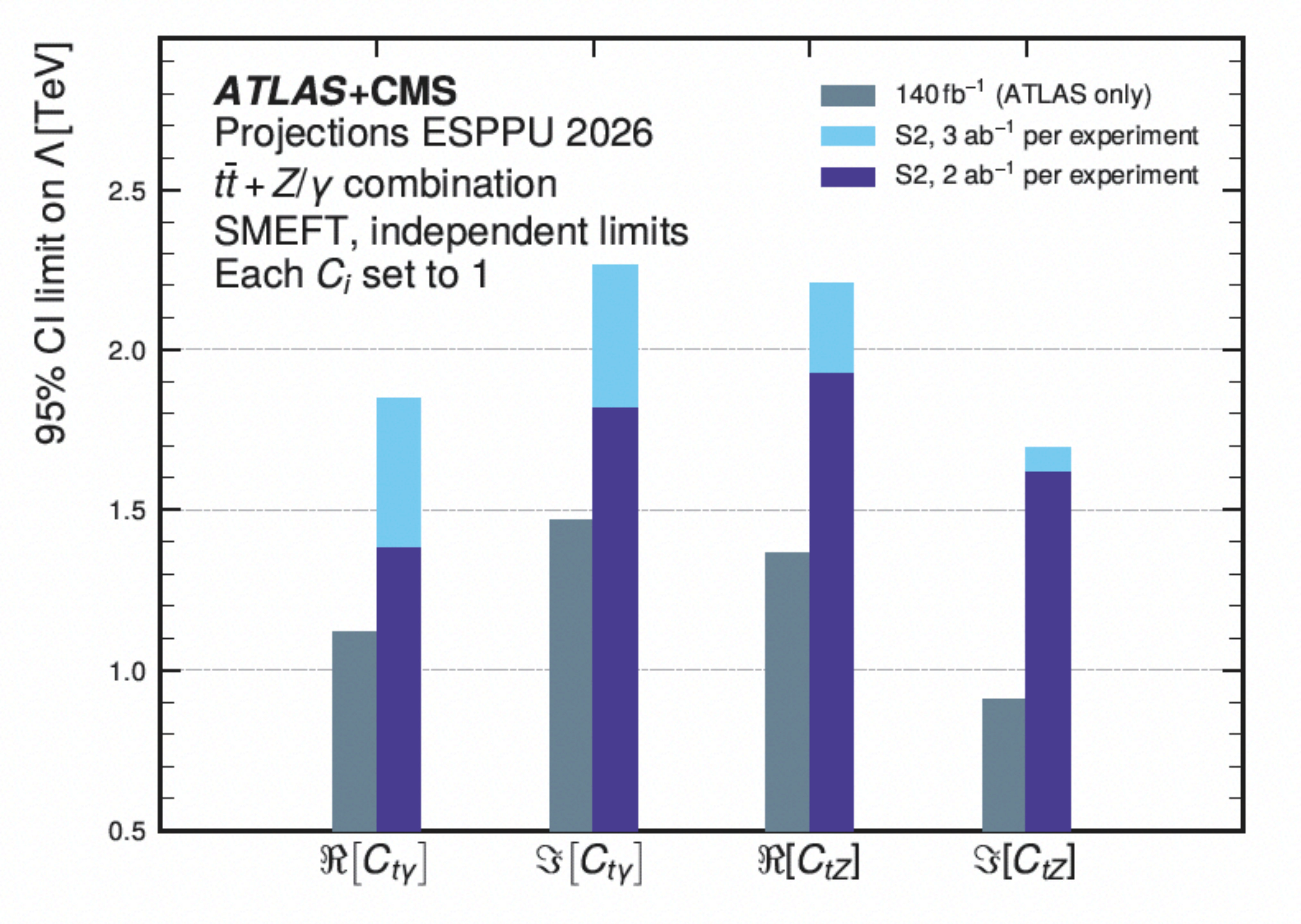
- very rare process is highly sensitive to new physics effects
- Final states with two same-charge leptons or at least three leptons are considered for this study




- Projected experimental precision in S2 is significantly smaller than the current uncertainty on the SM theoretical cross-section
- at 3 $ab^{-1}$ the expected uncertainty is can be reduced to 6%

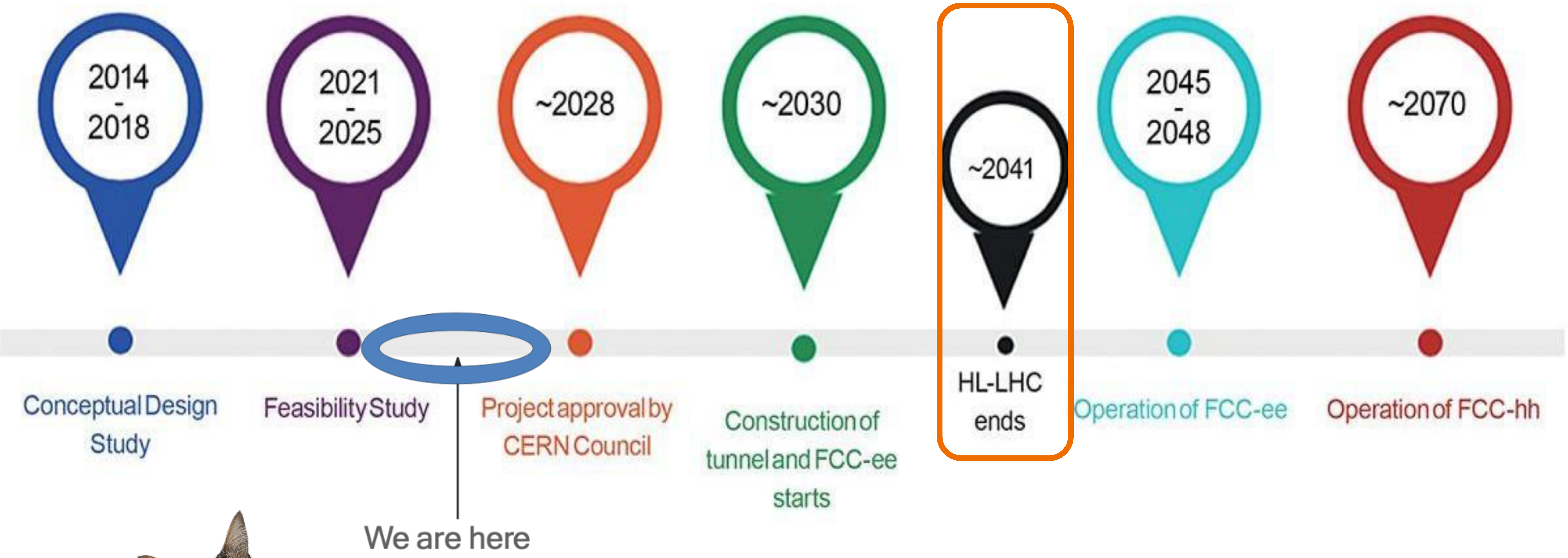
# ttγ and ttZ

- ttγ, ttZ provides a powerful probe for potential new physics effects within the framework of the SMEFT
- $p_{\gamma T}$ and $p_{ZT}$ are particularly sensitive to EFT parameters related to the electroweak dipole moments of the top quark



# What's next????

# FCC-project



2014 - 2018
2021 - 2025
~2028
~2030
~2041
2045 - 2048
~2070
Conceptual Design Study
Feasibility Study
Project approval by CERN Council
Construction of tunnel and FCC-ee starts
HL-LHC ends
Operation of FCC-ee
Operation of FCC-hh
We are here

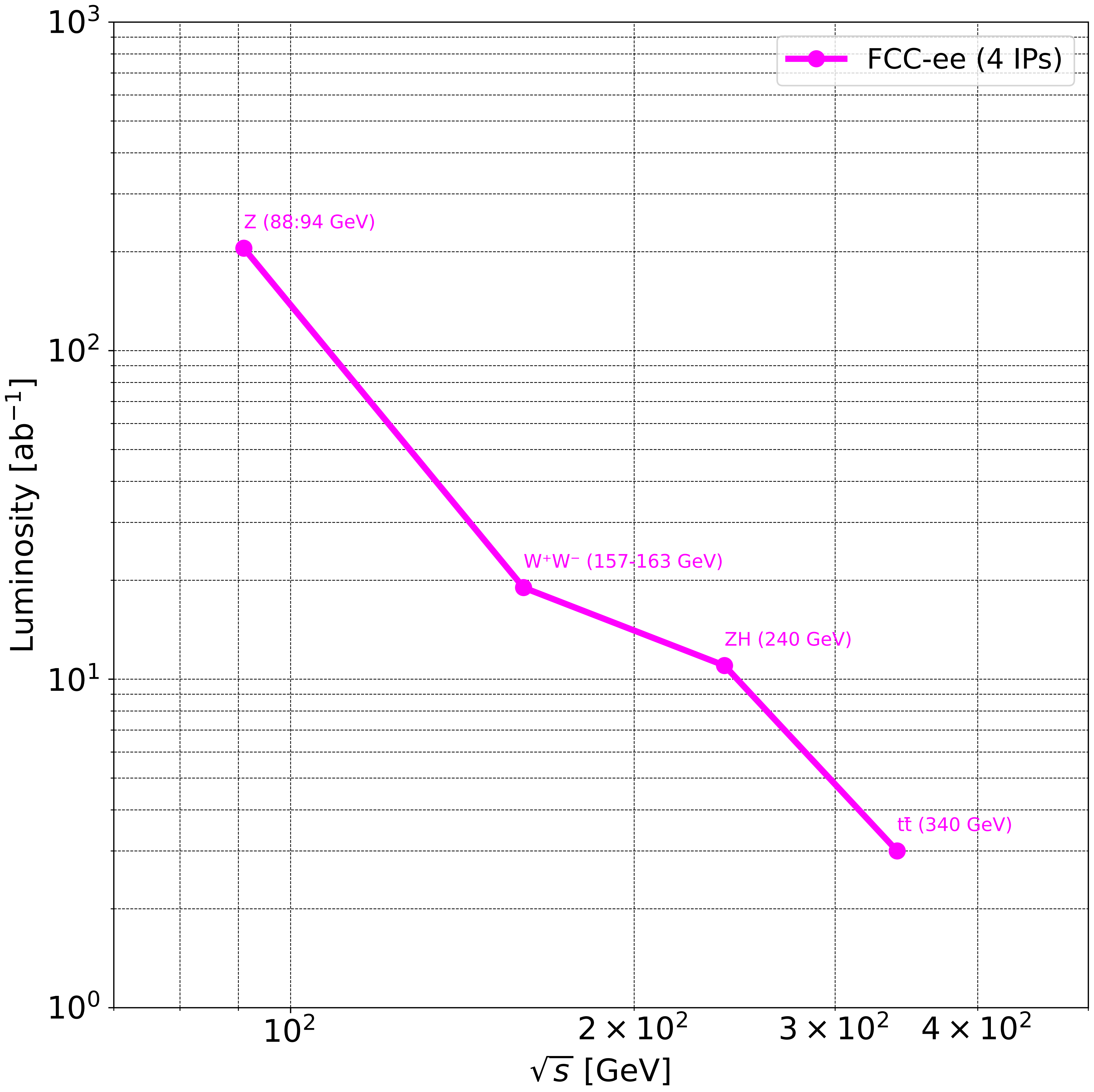

# FCC-ee

## ee collider

## FCC-ee has four phases:

- Near Z peak (91 GeV)
- Near WW threshold (163 GeV)
- Near ZH threshold (230 GeV)
- Near tt threshold (365 GeV)

| Project | IP | Z-pole (91.2 GeV) | WW (160 GeV) | Higgs (230-250 GeV) | Top (365 GeV) |
|---|---|---|---|---|---|
| FCC-ee | 4 | 205 $ab^{-1}$ 4 year | 19 $ab^{-1}$ 2 year | 11 $ab^{-1}$ 3 year | 3 $ab^{-1}$ 5 year |



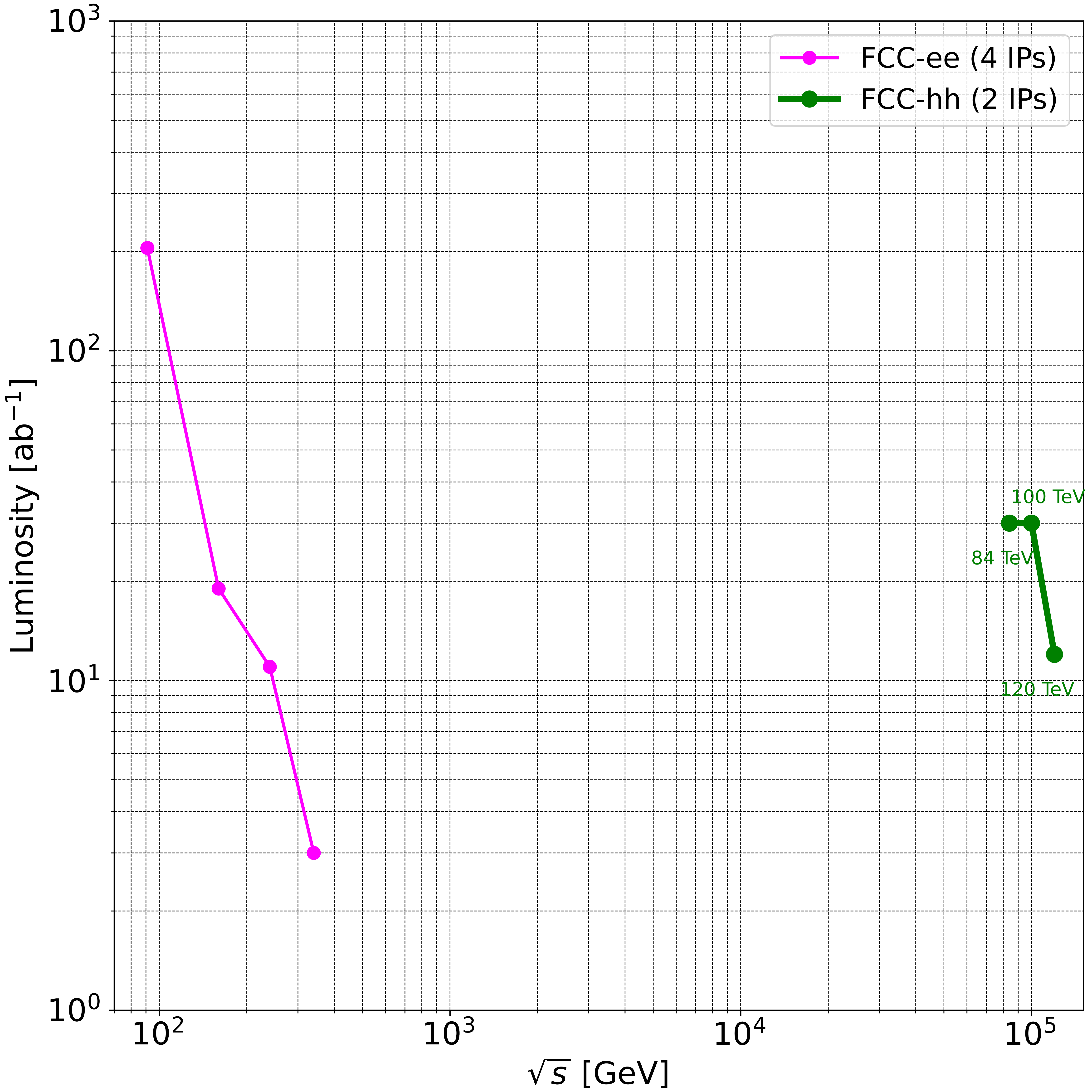
# FCC-hh

## pp collider

## FCC-hh has three baselines:

- **84 TeV (14T Magnet)**
- **100 TeV (17T Magnet)**
- **120 TeV (20T Magnet)**

| Project | IP | Higher Energy |
|---|---|---|
| FCC-hh | 2 | **84.6 TeV: 30 ab$^{-1}$**<br>100 TeV: 30 ab$^{-1}$<br>120 TeV: 12 ab$^{-1}$ |



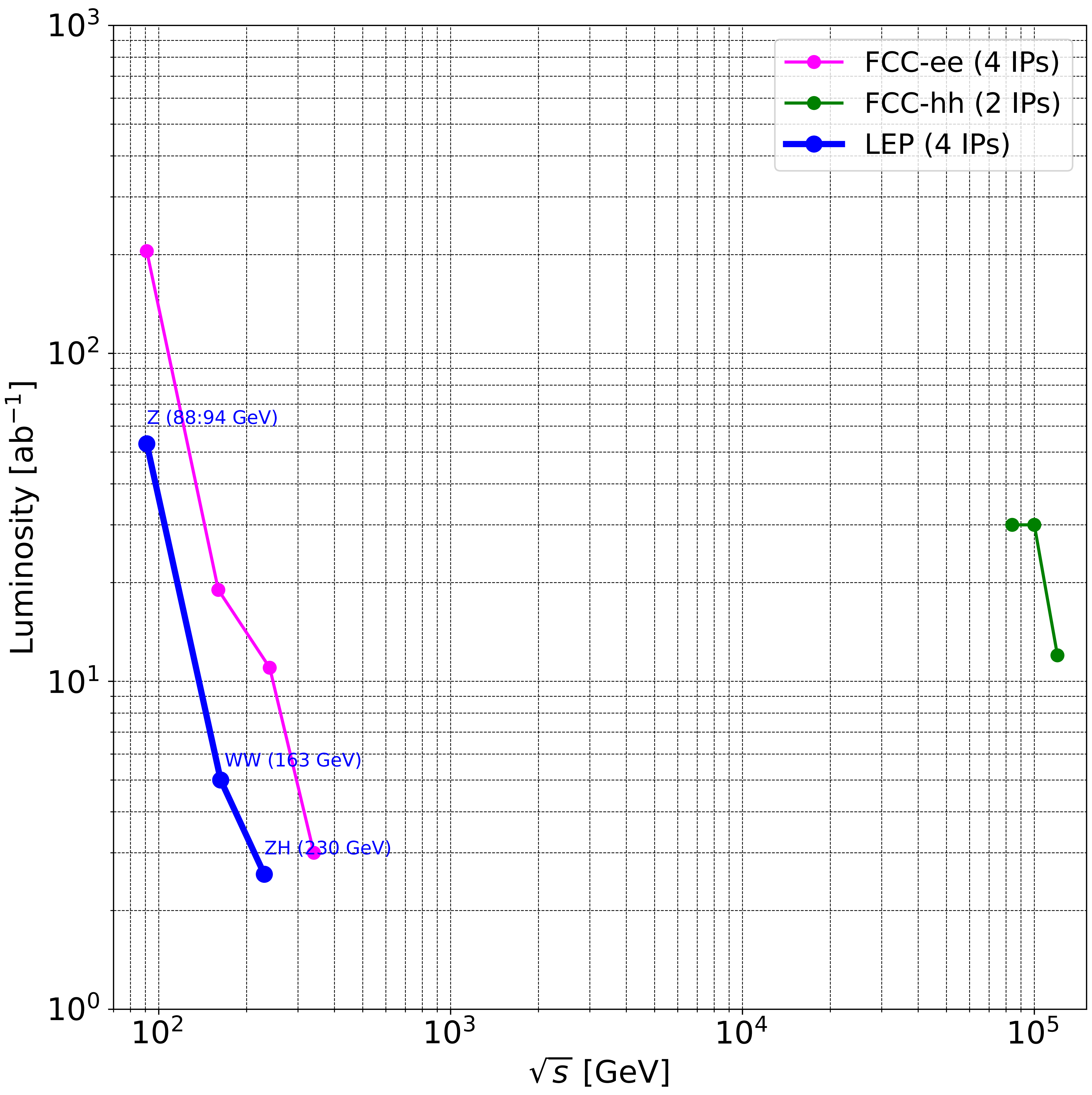
# LEP3 program

ee collider

LEP3 has three phases:

- Near Z peak (91 GeV)
- Near WW threshold (163 GeV)
- Near ZH threshold (230 GeV)

| Project | IP | Z-pole (91.2 GeV) | WW (160 GeV) | Higgs (230-250 GeV) |
|---|---|---|---|---|
| LEP3 | 2 | 53 $ab^{-1}$<br>5 years | 5 $ab^{-1}$<br>4 years | 2.5 $ab^{-1}$<br>6 years |



# Linear collider

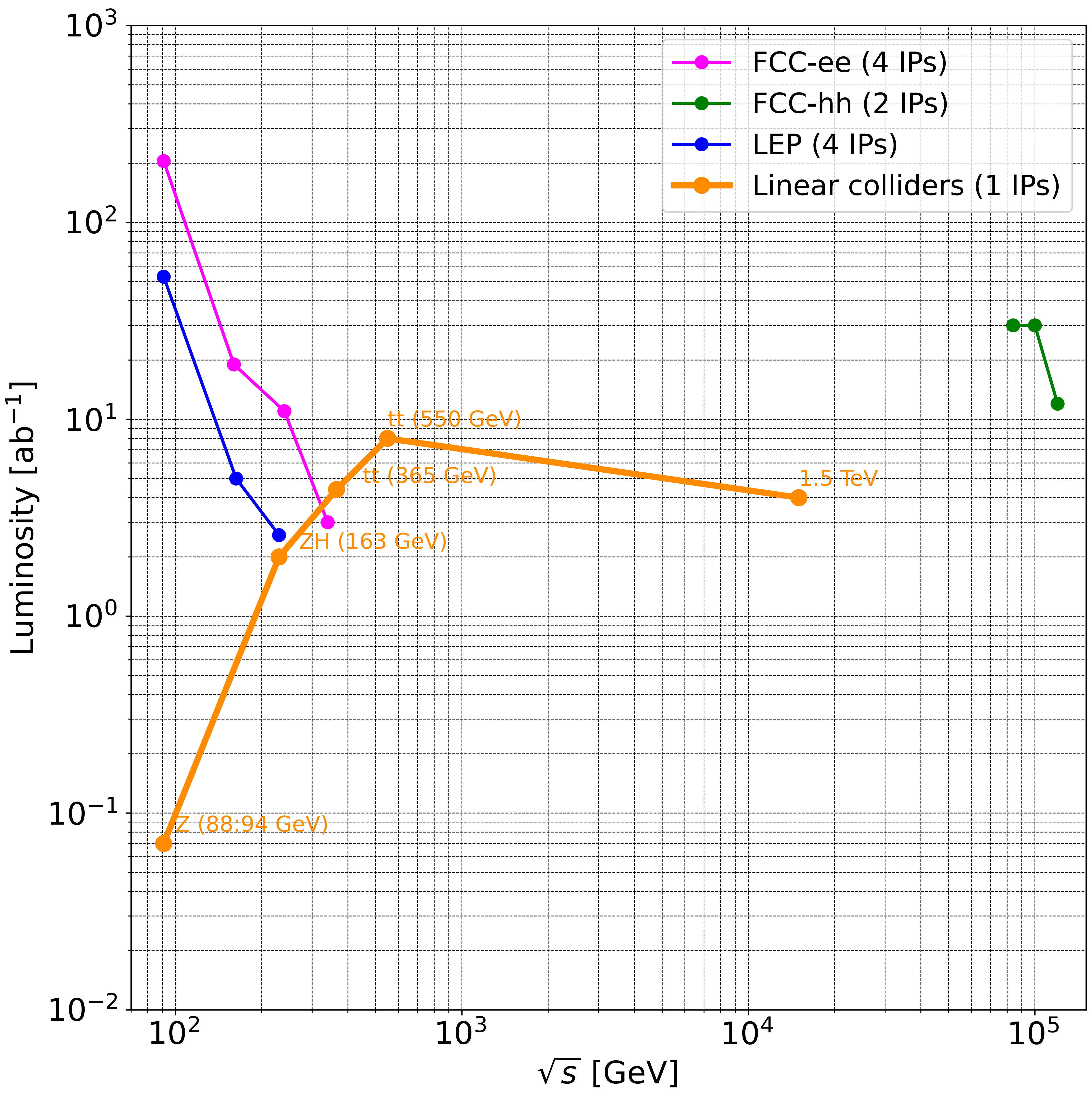
## ee collider

## Linear colliders have three phases:

- Near ZH threshold 250 GeV
- Near ttH and ZHH threshold 550 GeV
- Near vvHH threshold 1-3 TeV

## Clic:

- Near top threshold 365 GeV




| Project | IP | Z-pole (91.2 GeV) | WW (160 GeV) | Higgs (230-250 GeV) | Top (365 GeV) | Higher Energy |
|---|---|---|---|---|---|---|
| Linear colliders | 1 | 0.07 $ab^{-1}$<br>1 year | — | 2 $ab^{-1}$<br>3 years | CLIC: 4.4 $ab^{-1}$<br>10 years | 550 GeV: 8 $ab^{-1}$<br>1.5 TeV: 4 $ab^{-1}$<br>10 years |

# LHeC

## Hadron electron collider:

- 1st phase with concurrent operation of electron-hadron and hadron-hadron collisions, followed by
- 2nd phase of electron-hadroncollisions only
- Serves as a bridge between HL-LHC and the next future project

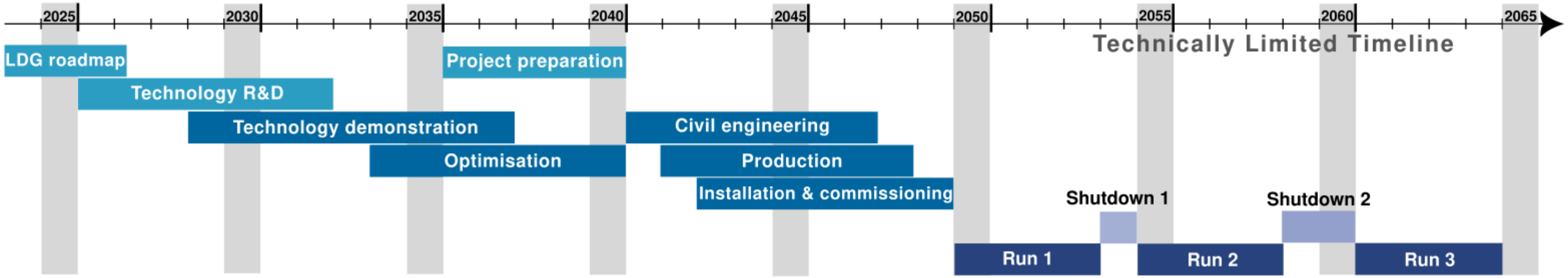
| Project | IP | Higher Energy |
| --- | --- | --- |
| LHeC | 1 | 1TeV operational for 6 years |

# Muon collider

## Muon-muon collisions

Offers a **compact, high-energy (~10 TeV) collider** combining:

- The energy reach of proton colliders
- The precision of lepton colliders




| Project | IP | Higher Energy |
|---|---|---|
| **Muon Collider** | 1 | 10 TeV: 1.1 $ab^{-1}$<br>8 year |

# Projects summary

| Project | IP | Z-pole (91.2 GeV) | WW (160 GeV) | Higgs (230–250 GeV) | Top (365 GeV) | Higher Energy |
|---|---|---|---|---|---|---|
| FCC-ee | 4 | 205 $ab^{-1}$<br>4 year | 19 $ab^{-1}$<br>2 year | 11 $ab^{-1}$<br>3 year | 3 $ab^{-1}$<br>5 year | — |
| FCC-hh | 2 | — | — | — | — | 84.6 TeV: 0.6 $ab^{-1}$ / year /IP |
| LEP3 | 2 | 53 $ab^{-1}$<br>5 years | 5 $ab^{-1}$<br>4 years | 2.5 $ab^{-1}$<br>6 years | — | — |
| Linear colliders | 1 | 0.07 $ab^{-1}$<br>1 year | — | 2 $ab^{-1}$<br>3 years | CLIC: 4.4 $ab^{-1}$<br>10 years | 550 GeV: 8 $ab^{-1}$<br>1.5 TeV: 4 $ab^{-1}$<br>10 years |
| LHeC | 1 | — | — | — | — | 1 TeV for 6 years |
| Muon Collider | 2 | — | — | — | — | 10 TeV: 1.1 $ab^{-1}$<br>8 year |

# Summary

- Updated projections for the singleH channels, massive improvement on the Zγ and μ coupling

- Updated for the HH studies:
    - 30% precision on the $k_\lambda$ determination
    - **exclude FOPT at 2σ for dim6 operators**

# Summary

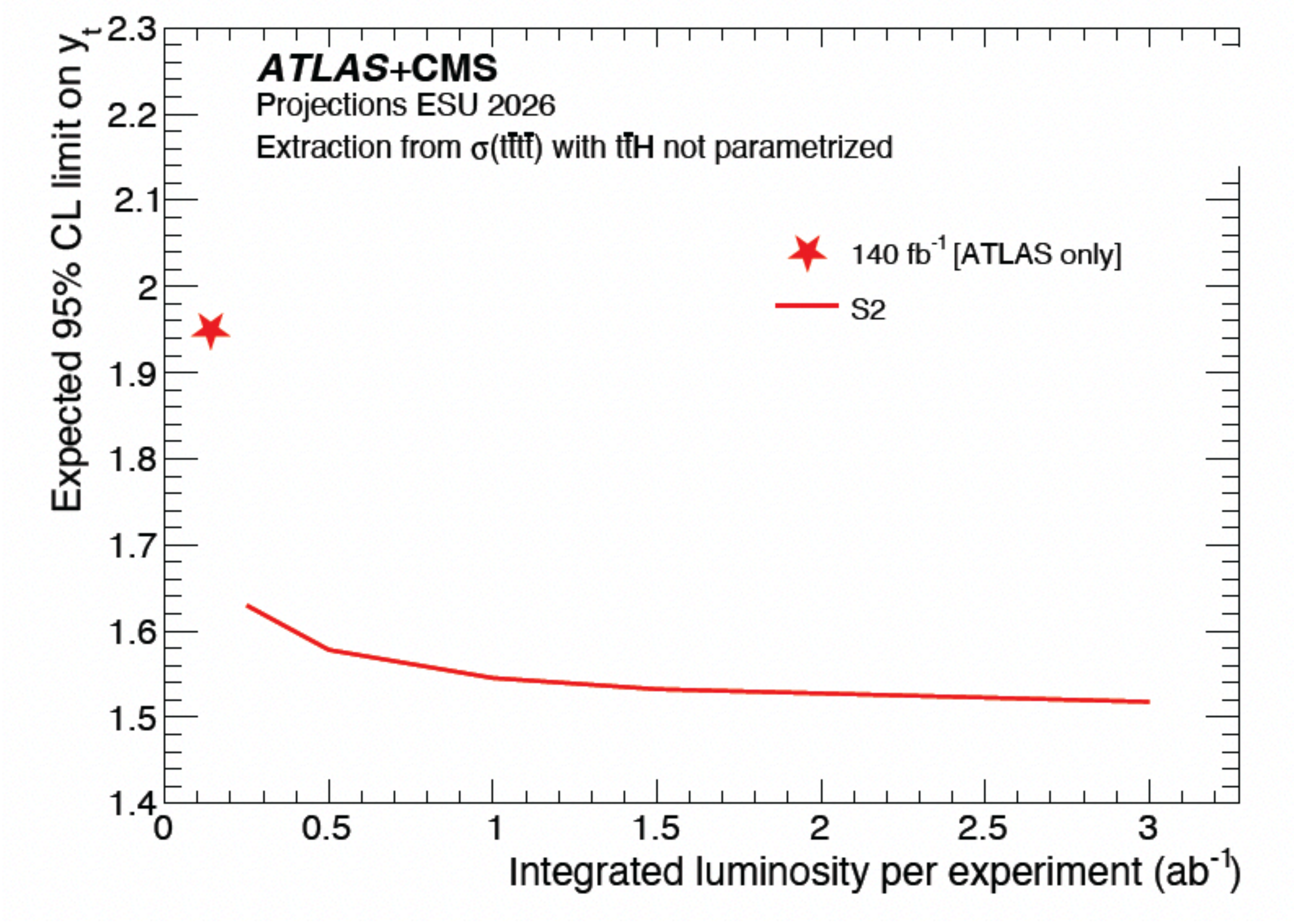
- Updated top analyses
- Prospects of several rare decays that can serve as an indirect constraint on the SM assumptions

- Many more details in Christian's and Michele's contributions

# Back up

# tttt production

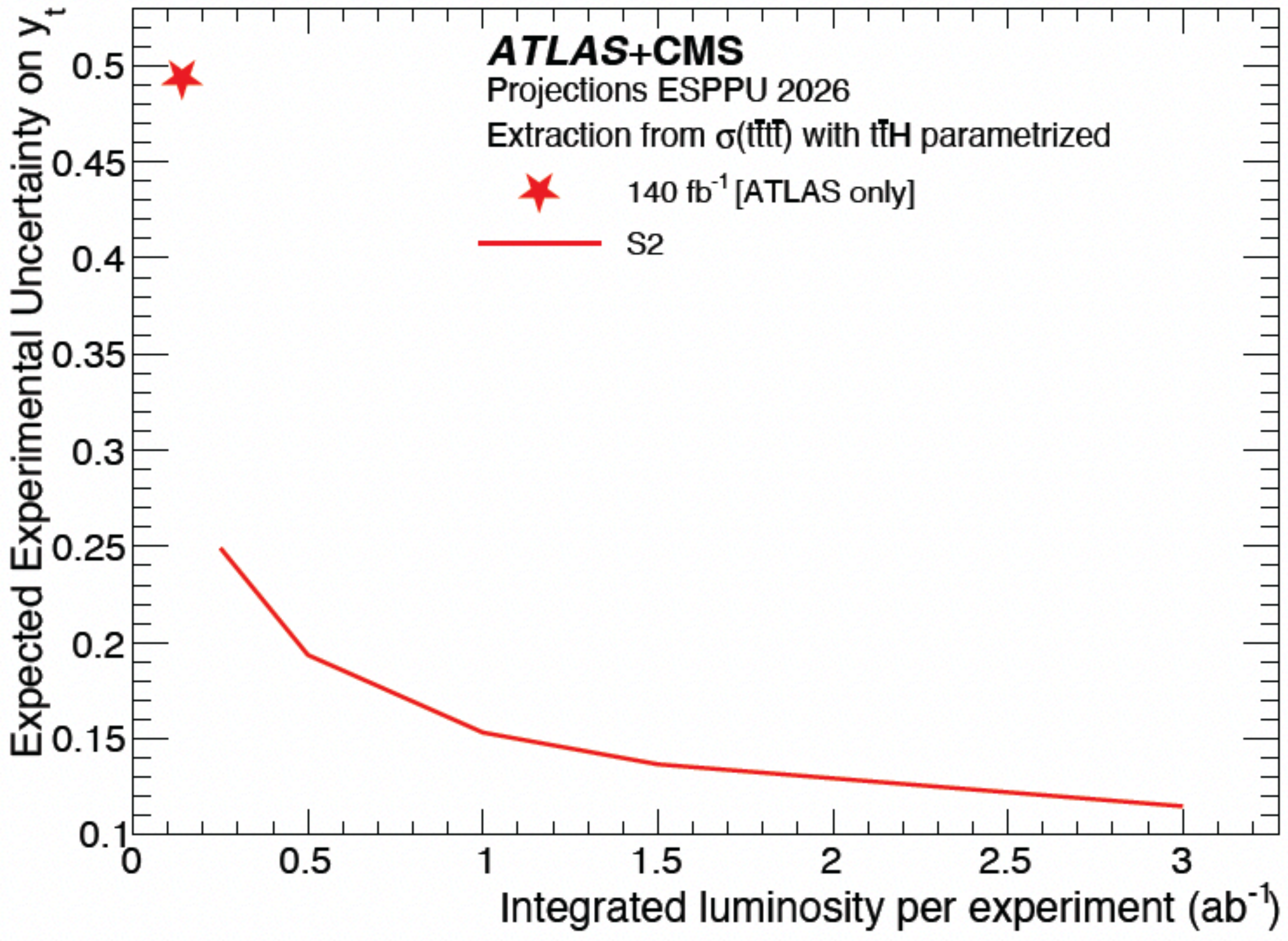
- tttt production sensitive to the top-quark Yukawa coupling
- top-quark Yukawa coupling also affects the ttH process (background for tttt production)




- Upper limit on $y_t$ are performed leaving ttH yield floating in the fit
- A limit on $y_t$ is ~1.5 is obtained in the best scenario

# tttt production

- tttt production sensitive to the top-quark Yukawa coupling
- top-quark Yukawa coupling also affects the ttH process (background for tttt production)




- Upper limit on $y_t$ are performed leaving the ttH yield floating in the fit, and parametrizing ttH events as a function of $k_t$
- Constrain comes mainly from ttH, limit on $y_t < 0.15$ is obtained in the

# Shape of the electroweak vacuum

A minimal extension of the Standard Model (SM) involves the inclusion of a new real scalar singlet, S

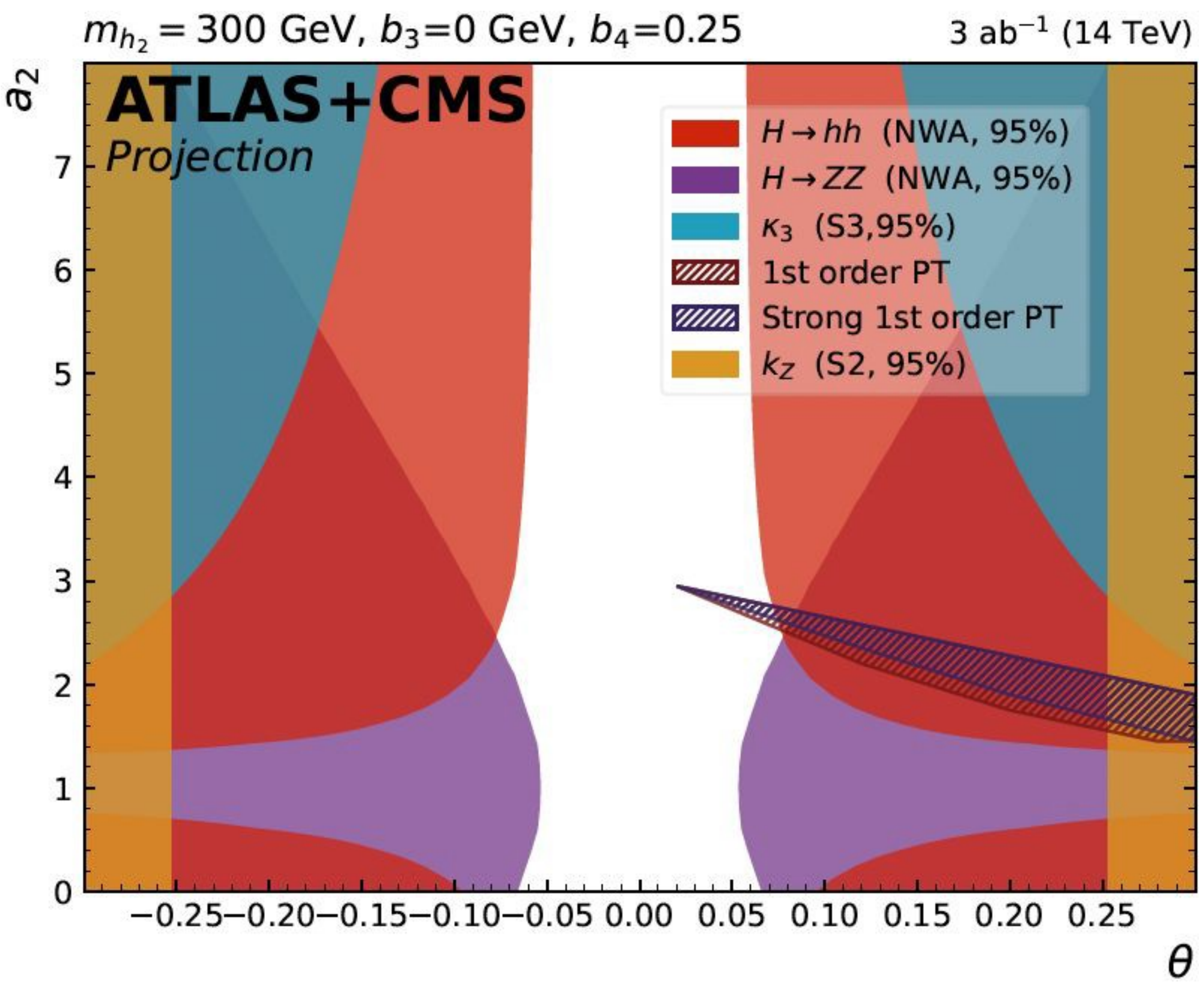
$$V(\Phi, S) = -\mu_H^2|\Phi|^2 + \lambda_H|\Phi|^4 + b_1 S - \frac{\mu_S^2}{2}S^2 + \frac{b_4}{4}S^4 + \frac{a_2}{2}|\Phi|^2 S^2 + \frac{b_3}{3}S^3 + \frac{a_1}{2}|\Phi|^2 S.$$

Effect of S:

- universal modifications of the Higgs boson couplings
- the presence of an additional scalar state can decay into HH - > modified three- and four-point Higgs self-interactions
- **The enriched scalar potential dynamics enables the possibility of a FOPT**

# Shape of the electroweak vacuum

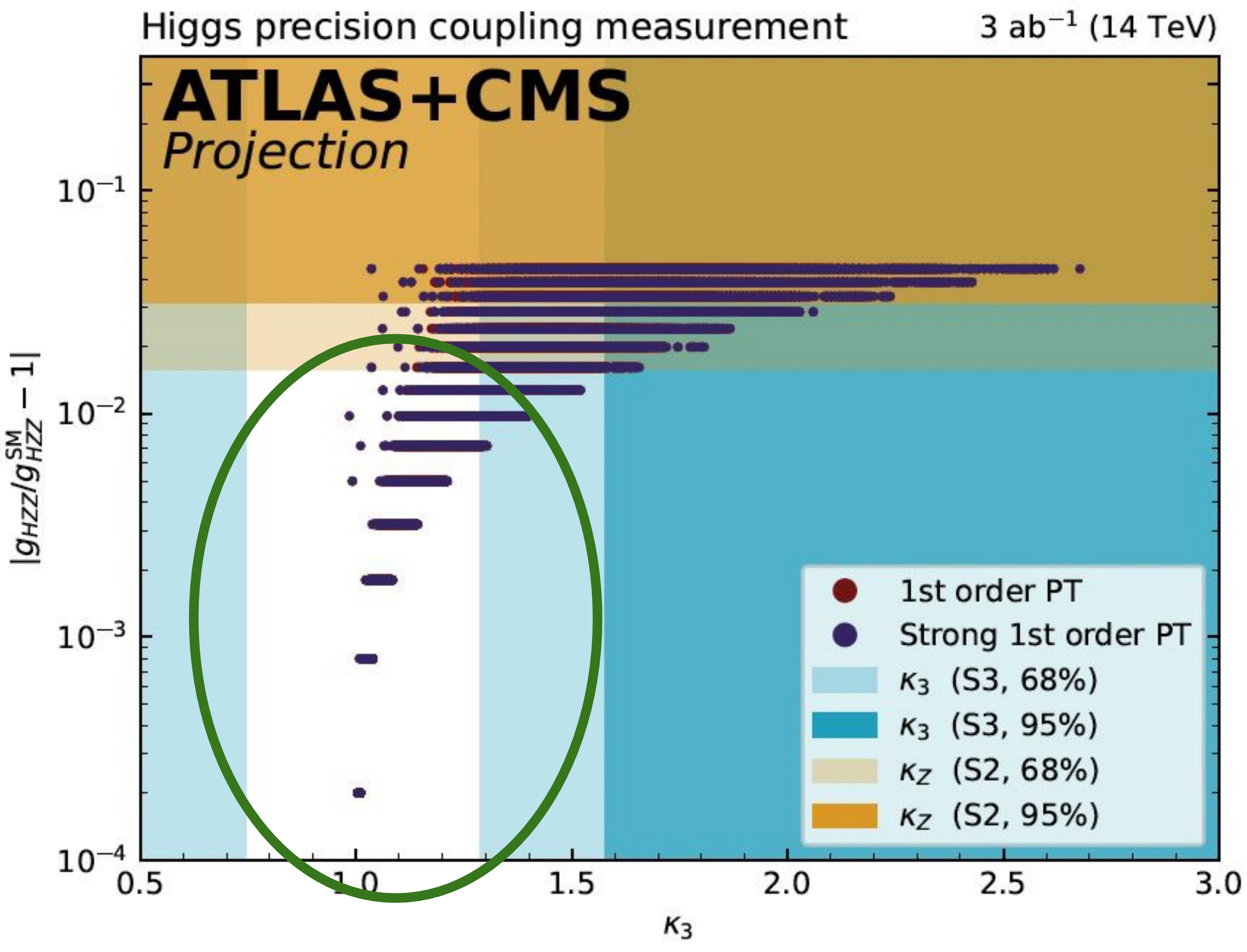
- comprehensive set of precision measurements from both experiments
  - scalar decays into vector bosons (VV) and HH
  - upper bounds on universal modifications to Higgs couplings with SM particles provide + $k_\lambda$
- **significant portion of the viable parameter space for this generic SM extension is excluded**
- two hatched regions show the regions where a first order phase transition is possible




*more plots in backup

# Shape of the electroweak vacuum

- The red and blue points show the area where a first order and a strong first order phase transition are possible
- 68% and 95% exclusion curves are displayed.
- Few possibilities for the first order phase transition




Not excluded area