Let's Discover Higgs Boson Pairs at High Luminosity LHC

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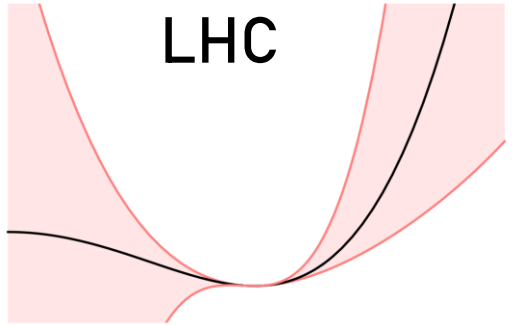
Louis D'Eramo

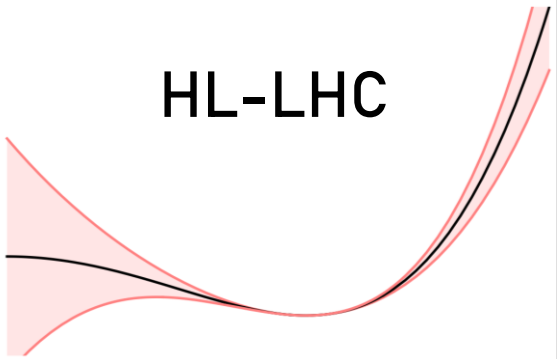
HH A CENTRAL PIECE IN PHYSICS

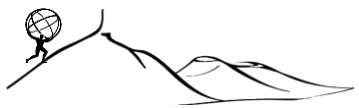
RESULTS COULD IMPACT COSMOLOGY

- **A central piece in SM**
  - 15 free parameters are affected by the Higgs potential (over 19)

N.Craig,
R. Petrossian-Byrne







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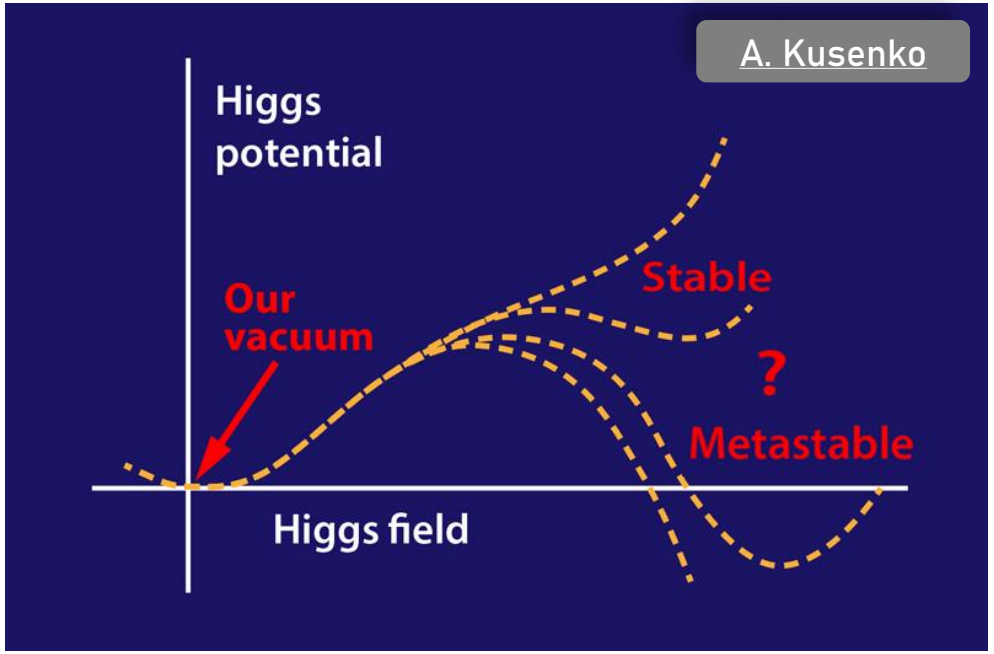
- **Ensure (or not) the stability of our univers**
  - Or what happen if the most famous Mexican hat is not a so mexican



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Our univers seems to be metastable according LHC data

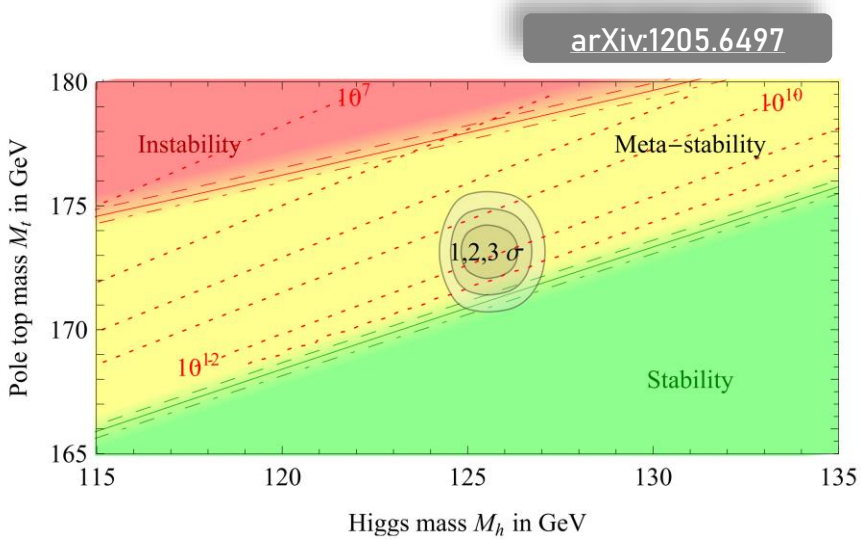
Cosmology predict that our univers have to be stable
$arXiv:0710.2484$

Something should fix this stability problem

↓

Clue for Beyond the Standard Model physics

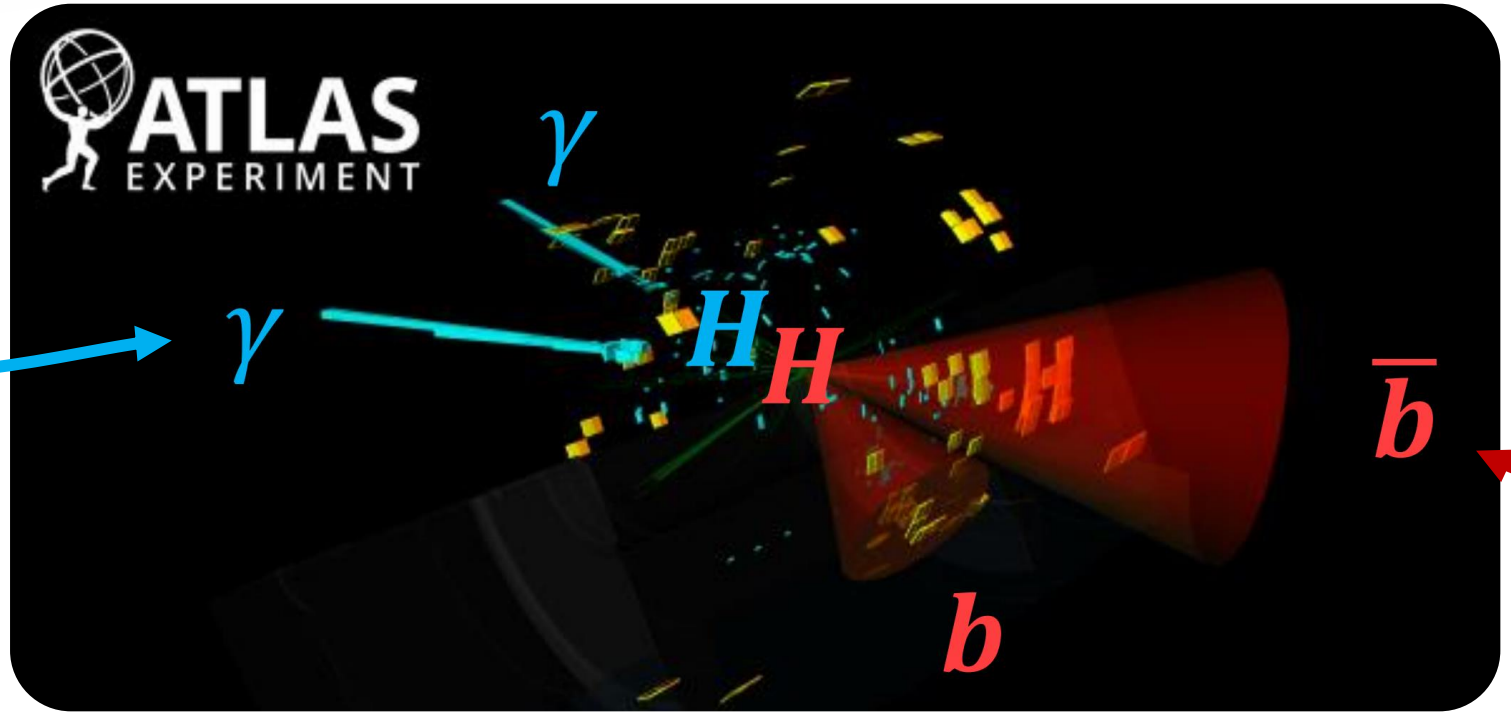
arXiv:1205.6497



THE POWER OF
$HH \rightarrow b\bar{b}\gamma\gamma$

$HH \rightarrow b\bar{b}\gamma\gamma$ CHANNEL

+ Excellent resolution ($m_{\gamma\gamma}$~$1.5 GeV$)
- Low branching ratio



- Low resolution ($m_{b\bar{b}}$~$12.7\ GeV$)
+ High branching ratio

Only 0.2% HH produced decay into
2 photons & 2 b quarks

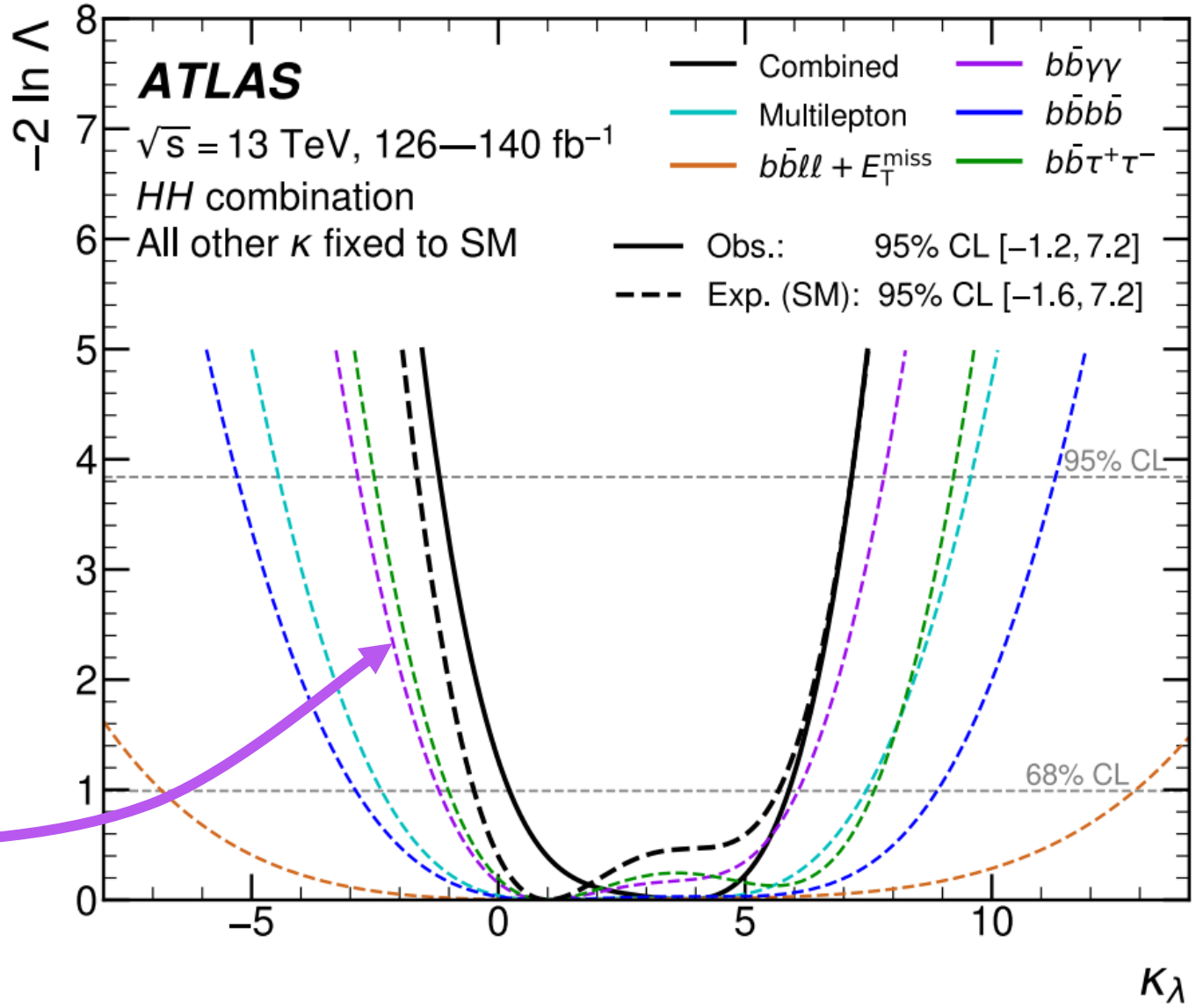
$HH \rightarrow b\bar{b}\gamma\gamma$ CHANNEL

Source

… but still constrains κ_λ the most

Best combined results on κ_λ *today*
$[-1.2, 7.2]$ *at* 95% *CL*

$b\bar{b}\gamma\gamma$ *channel*



THE HIGH-LUMINOSITY PROGRAM FOR ATLAS

ACHIEVE $\times 10$ MORE

- **Mainly designed to collect more data**

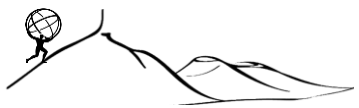
Trigger rate: 100kHz → 1MHz

Higher detection area: extend to $|\eta| < 4$

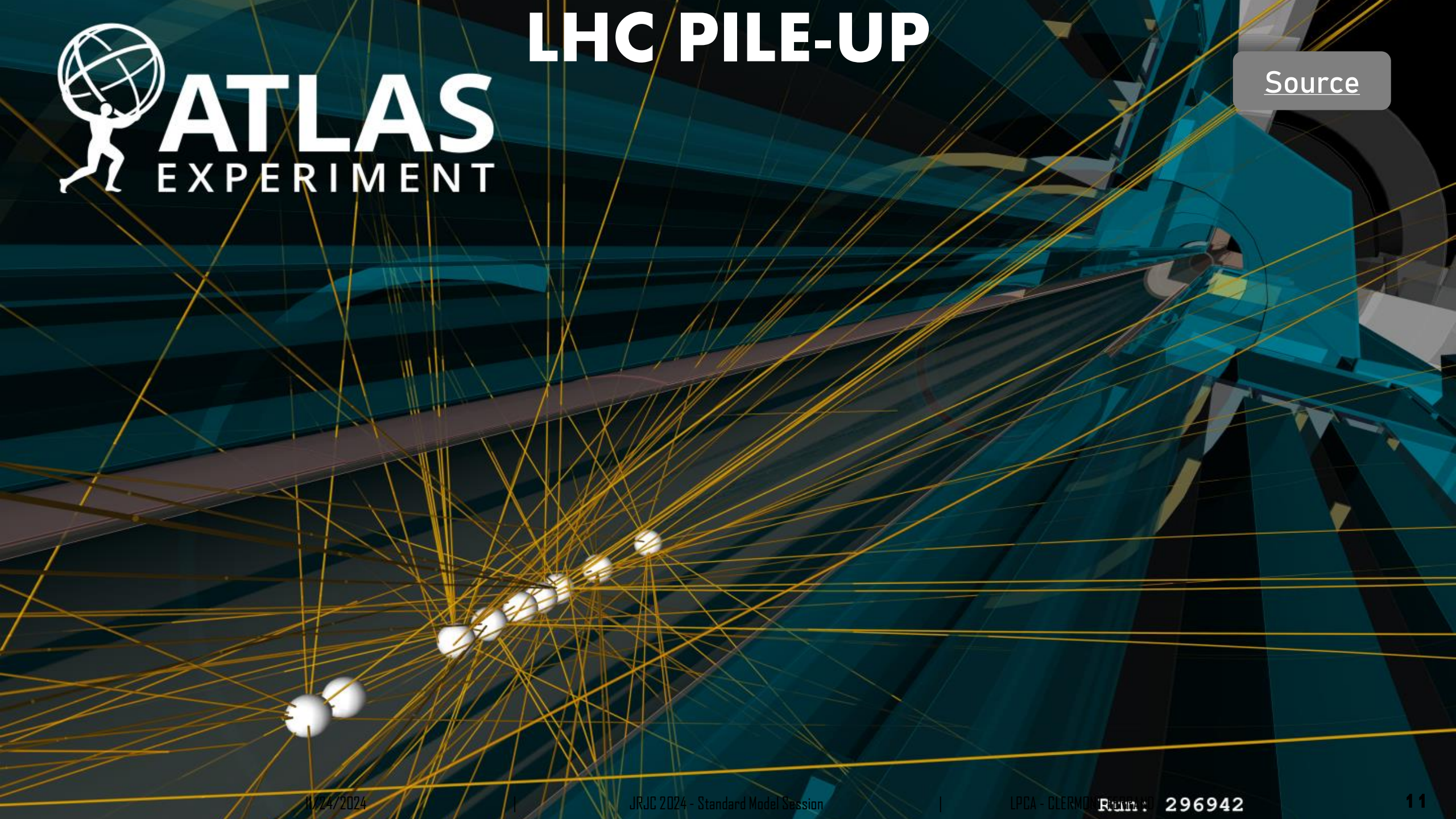
- **With a certain price**

Higher irradiations: kGy→MGy

Higher pile-up: 30→200 collisions per bunch crossing

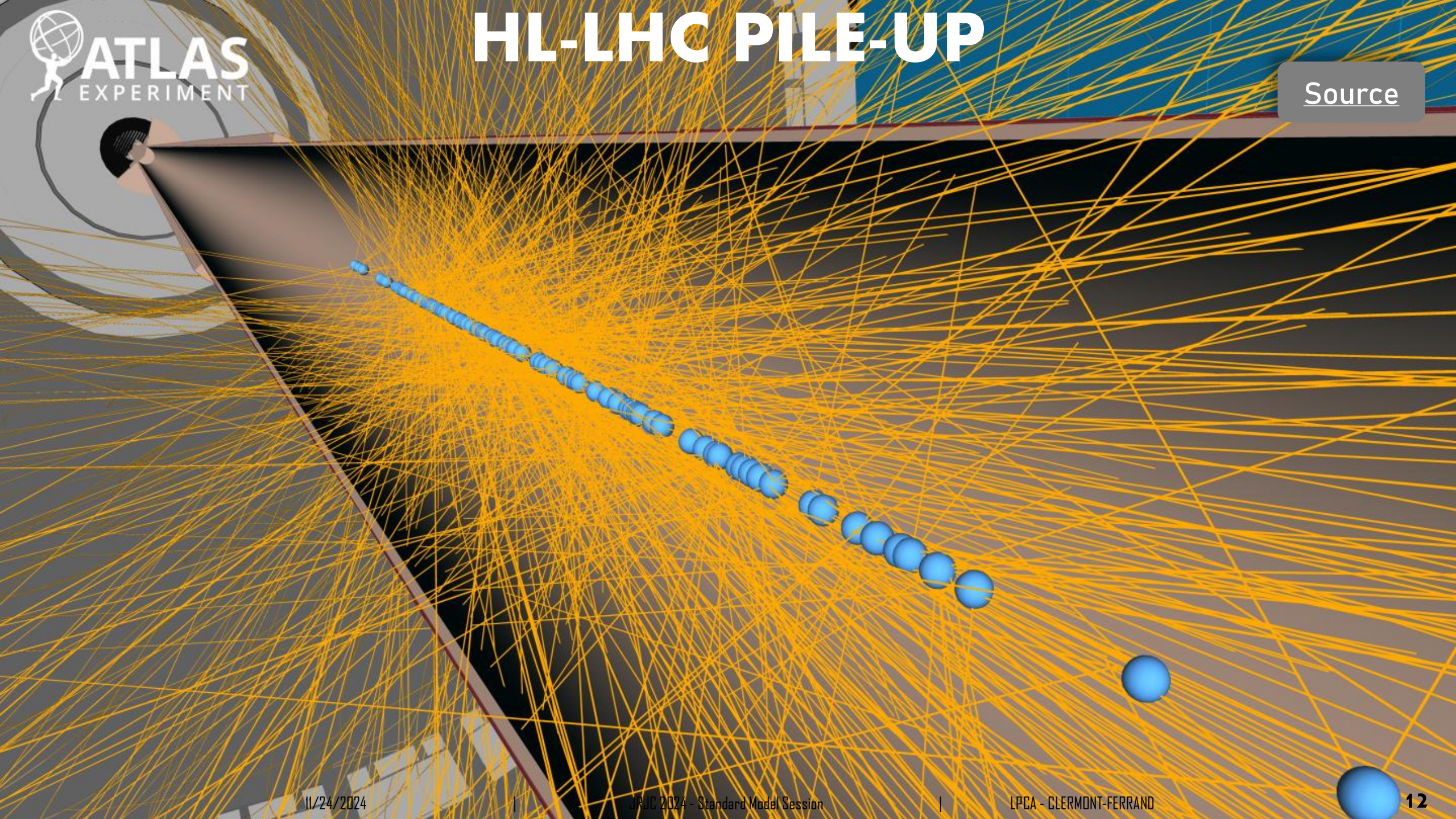


LHC PILE-UP



Source

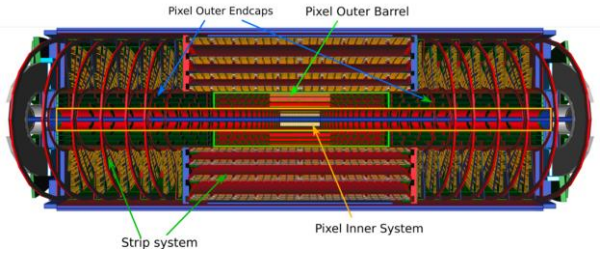
HL-LHC PILE-UP



Source

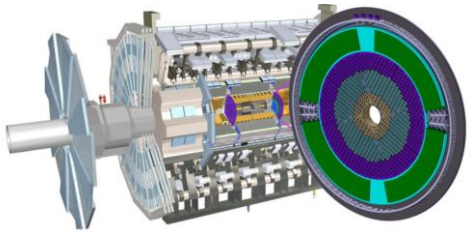
WITH THE SAME PERFORMANCES (AT LEAST…)

- **ITk: New tracking**
  - ≥ 13 hits in central region
  - 1.4 G pixels
  - $\times 2$ improvement in resolution for primary vertices



ITk TDR

- **HGTD: Timing information enter in ATLAS**
  - $50\ ps$ resolution per hit to separate collimated tracks
  - Target improvements on forward objects



HGTD TDR

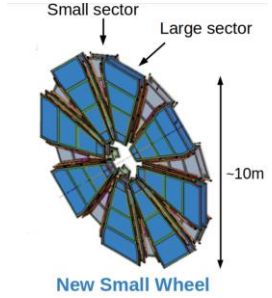
- **Trigger & DAQ**
  - Electronics/infrastructure update to handle higher flux

TDAQ TDR

- **Calorimeters**
  - New electronics (FPGA, power supplies, optical links)

Tile Calorimeters TDR
LAr TDR

- **Muon spectrometer**
  - Completely new detector (New Small Wheel, installed)
  - Improve the objects reconstruction



Muon Spectrometer TDR

WHAT WE PLAN TO OBSERVE

PROJECTION IN A NUTSHELL

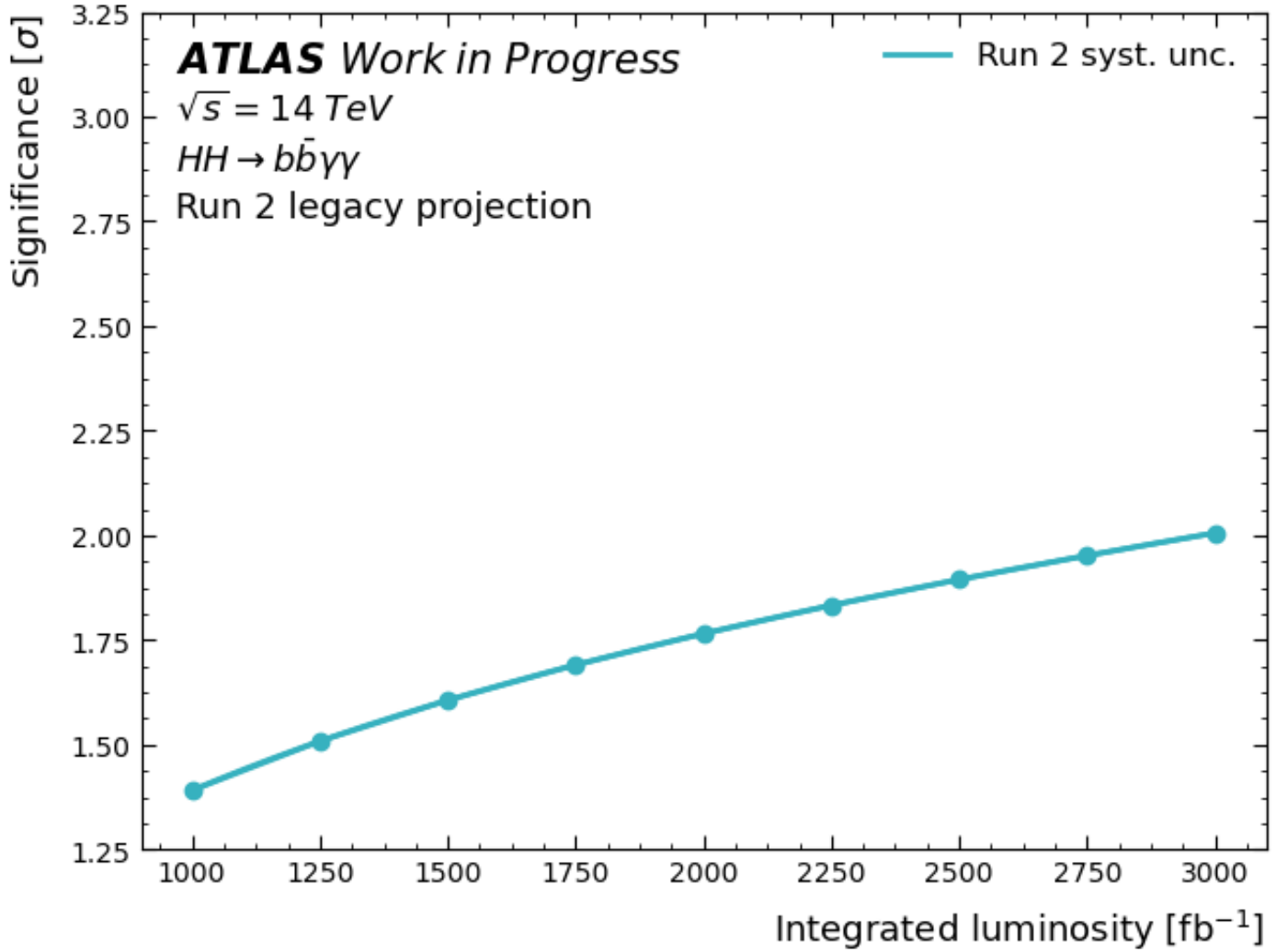
- **Starting point**
  - Run 2 $HH \rightarrow b\bar{b}\gamma\gamma$ Legacy search results (JHEP 01 (2024) 066)
- **Insert coefficients**

Scale cross-sections	Scale integrated luminosity	Scale systematics unc.
Higher energy for collisions	3000 fb^{-1} is planned	Based on different scenarios
$13\ TeV \rightarrow 14\ TeV$	$\frac{\mathcal{L}}{140\ fb^{-1}}$	*Run 2 syst./Theory halved* *Baseline/No syst.*

- **Estimate parameters of interest**
  - Couplings modifiers (*e.g.* Higgs self-coupling) with likelihood scans
  - Cross-section & signal strength, with an upper limit (not yet observed)
  - Significance w.r.t. to background-only hypothesis

WILL WE DISCOVER $HH \rightarrow b\bar{b}\gamma\gamma$

- **Current best results (run 2)**
  - $\sigma = 0.54$ SM significance



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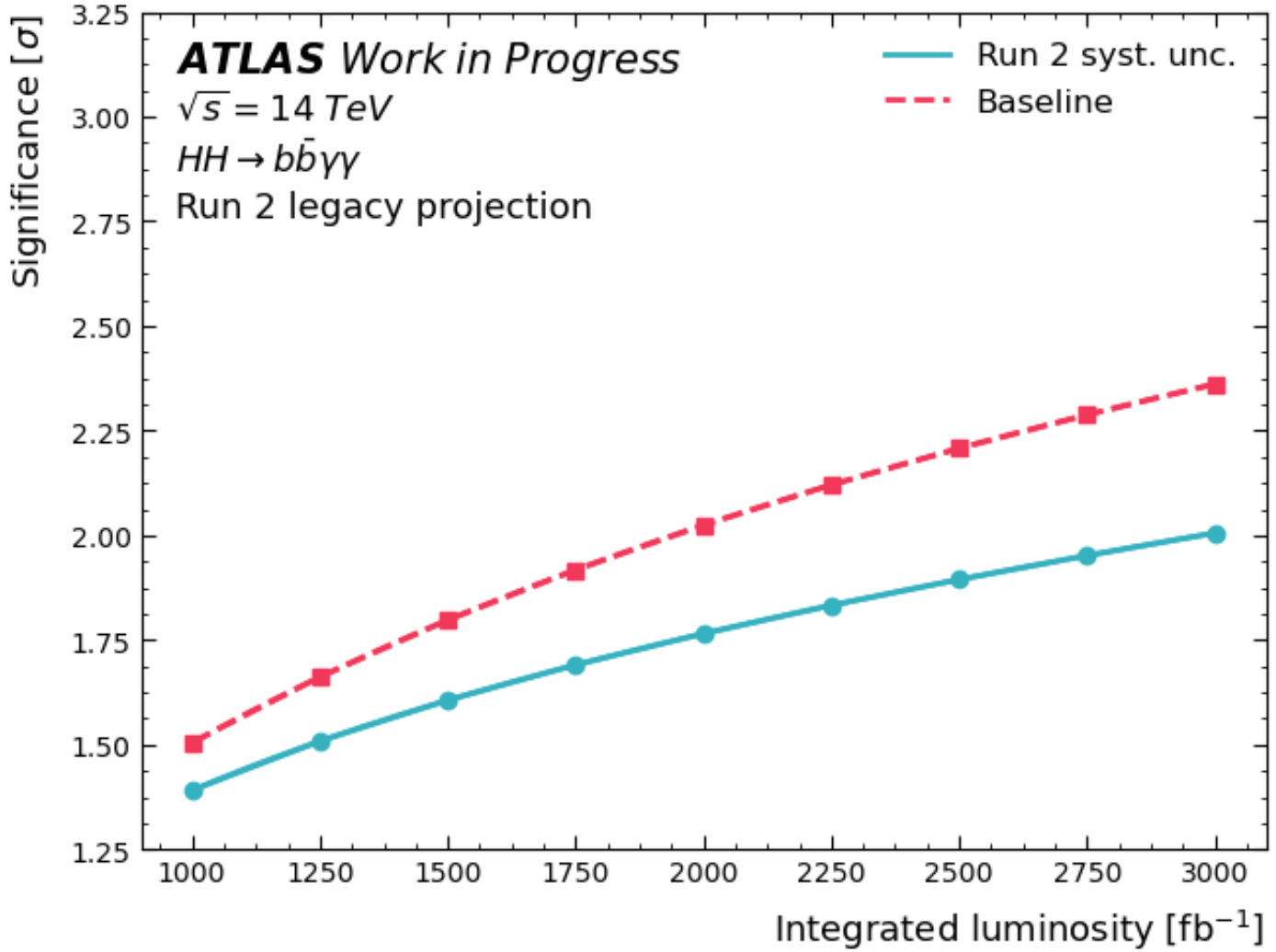

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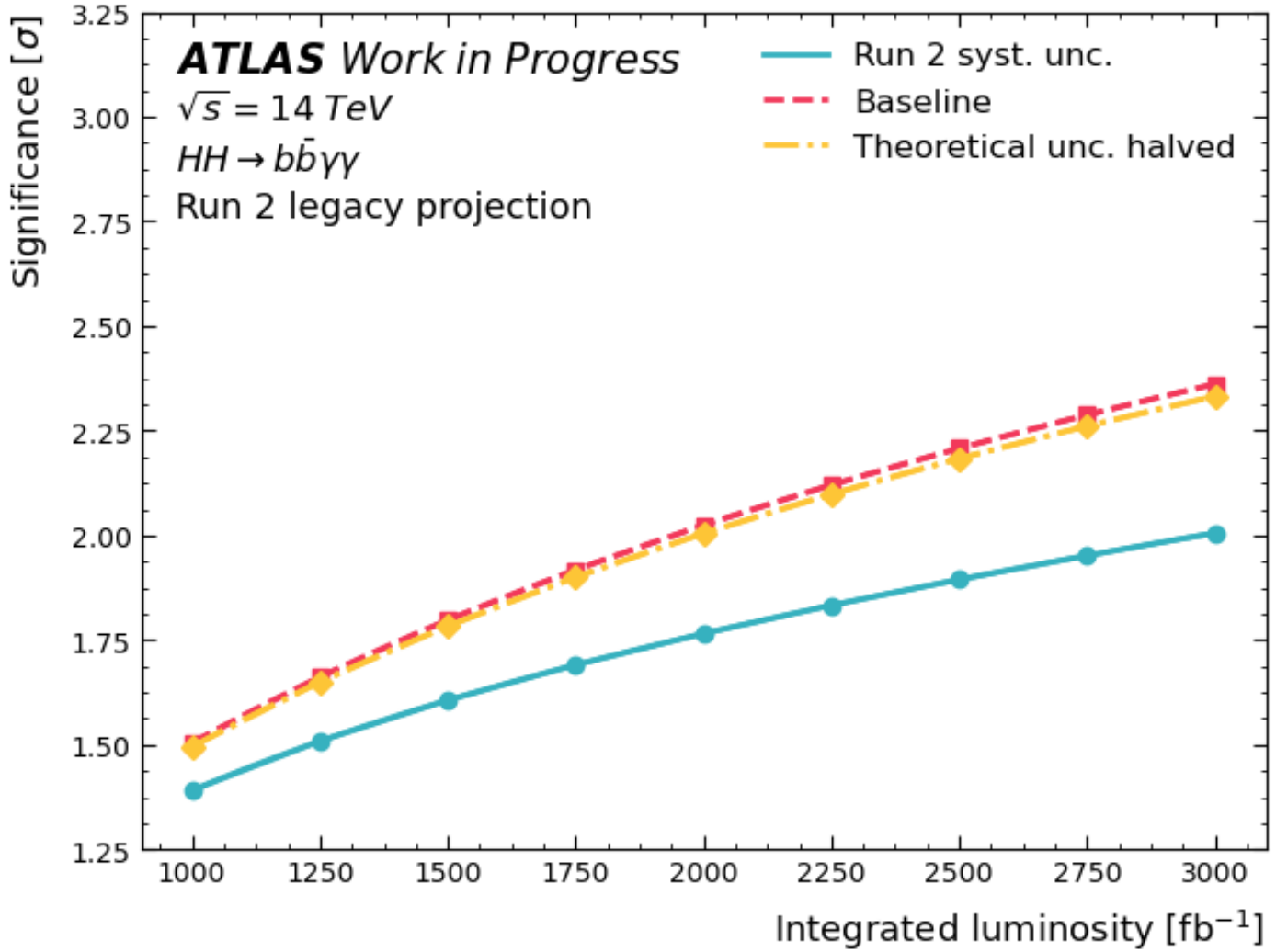
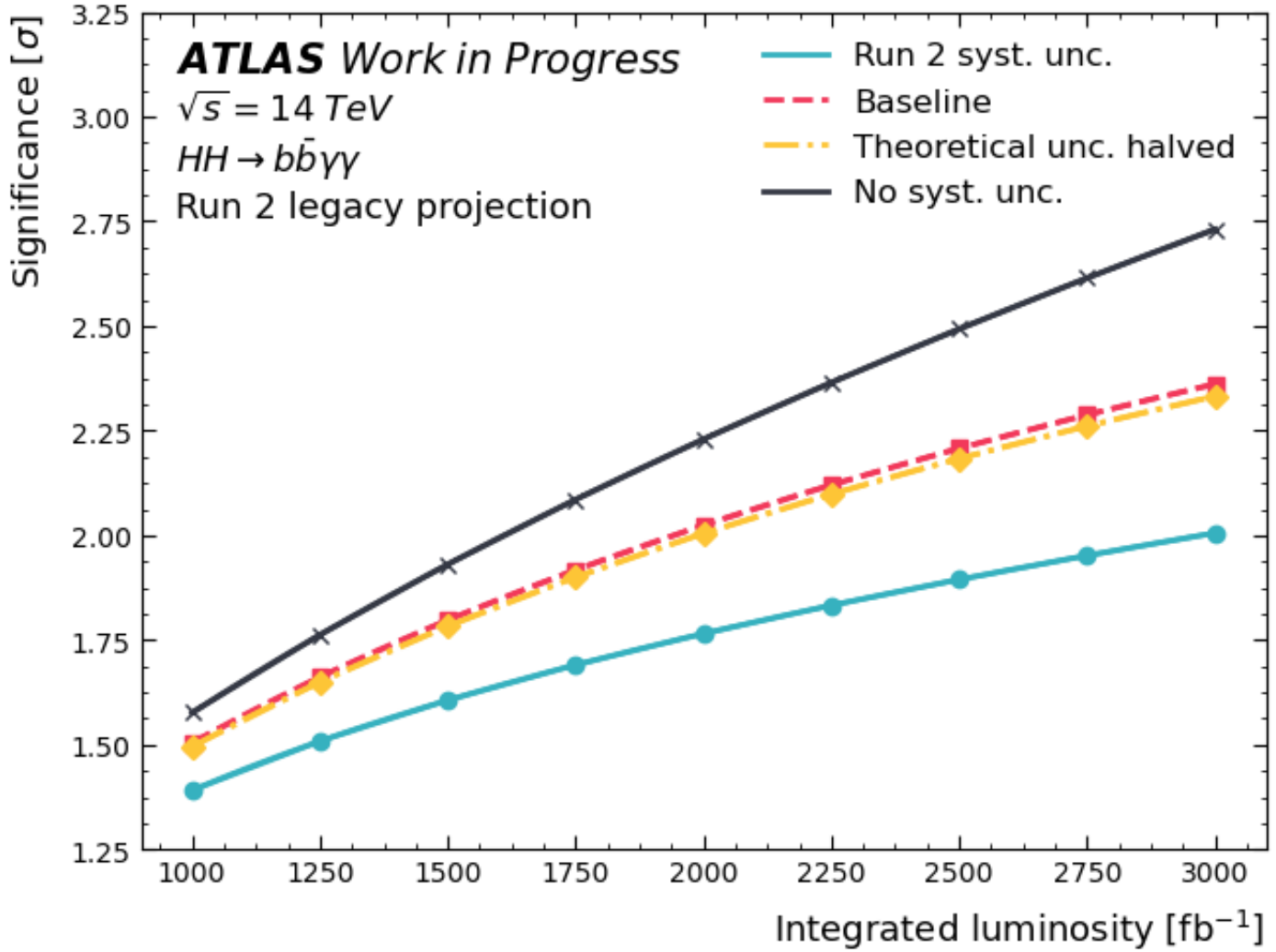


WILL WE DISCOVER $HH \rightarrow b\bar{b}\gamma\gamma$

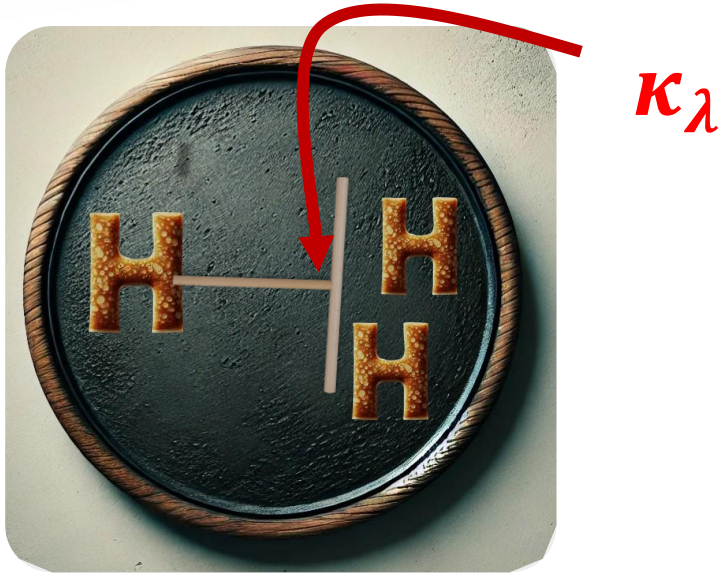
- **Current best results (run 2)**
  - $\sigma = 0.54$ SM significance
- **36 events might be detected**
  - Under SM hypothesis

$2.7\,\sigma$ significance as target for the end of HL-LHC
Near the 3σ ...



HOW MUCH WILL WE CONSTRAIN κ_λ

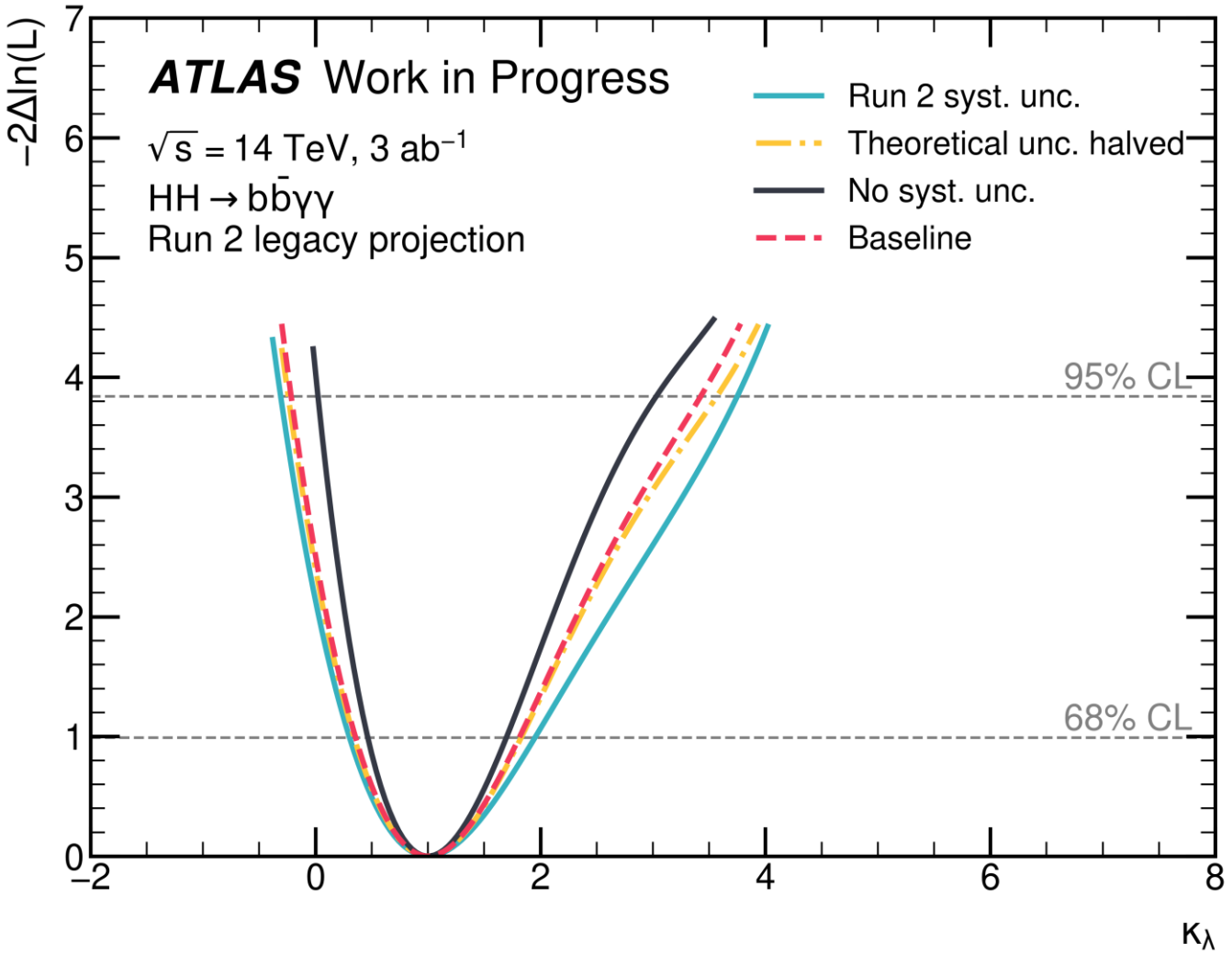
- **Run 2 results**
  - $\kappa_\lambda \in [-2.8, 7.8]$



κ_λ

- **Expected HL-LHC**

$$\kappa_\lambda \in [-0.14, 3.54]$$
$$3000 fb^{-1}$$



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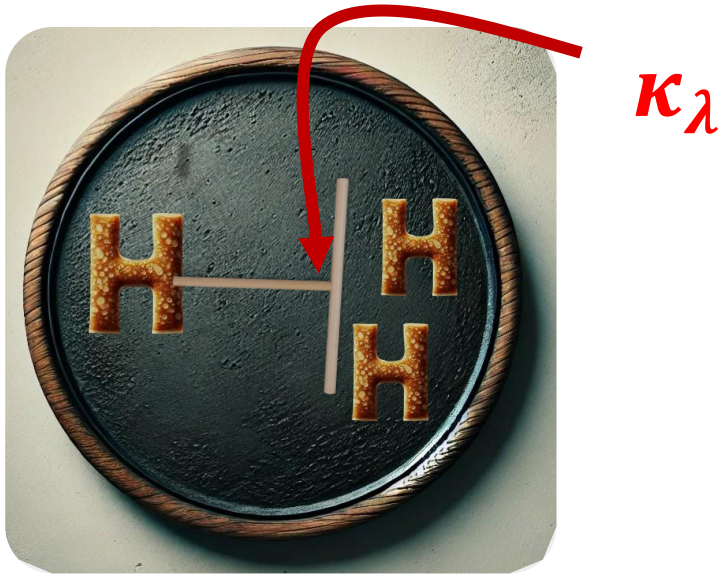

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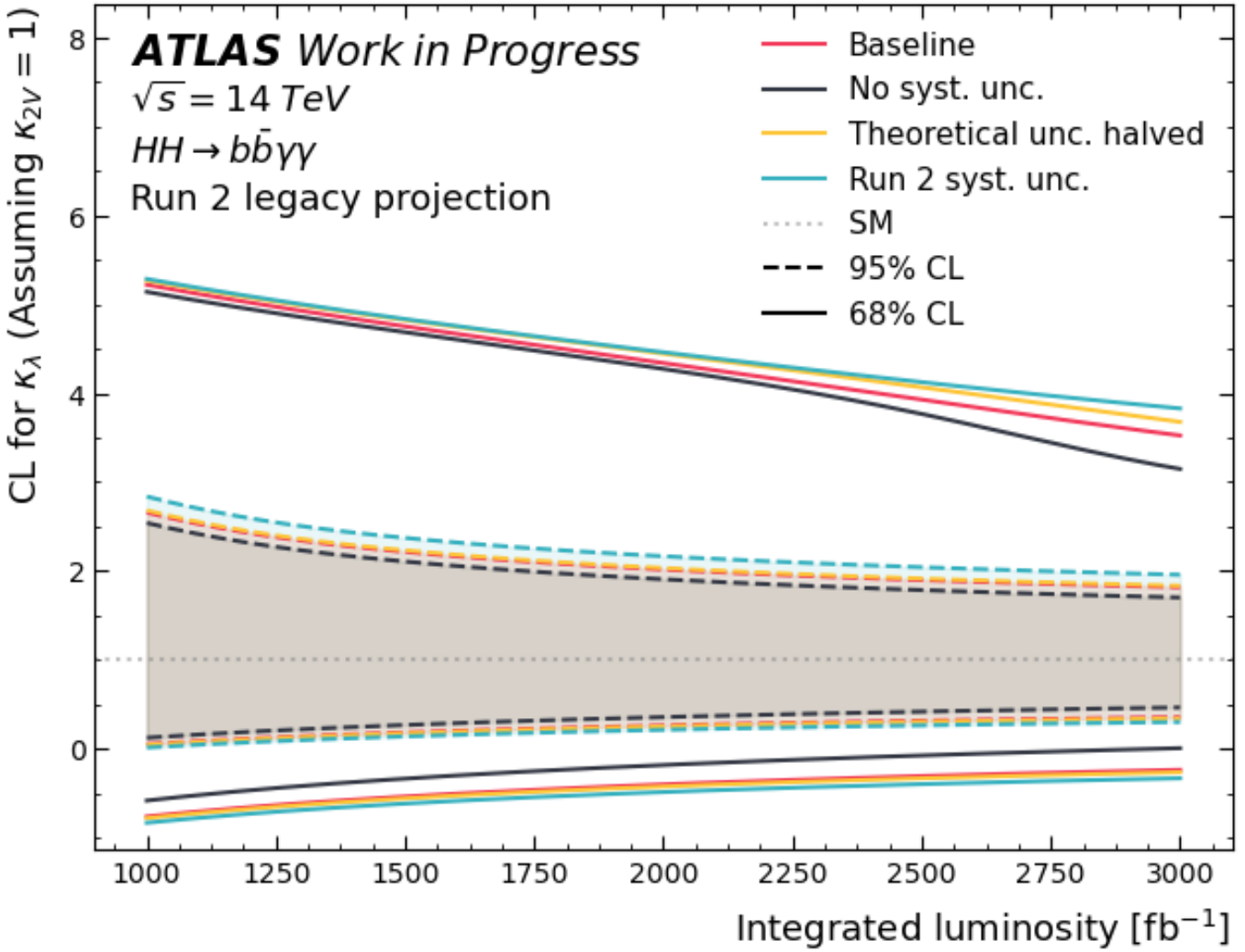
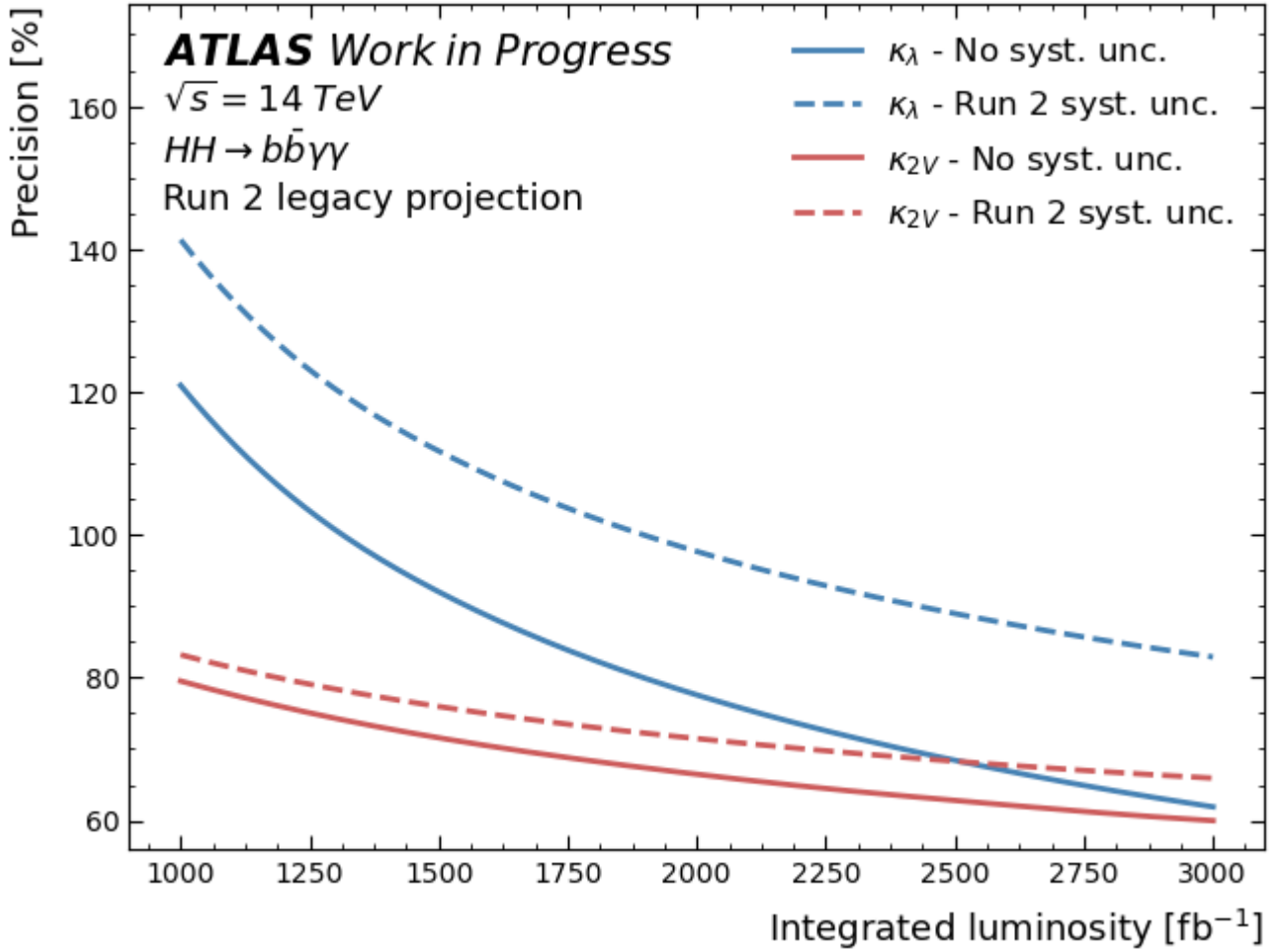


HOW MUCH WILL WE CONSTRAIN κ_λ

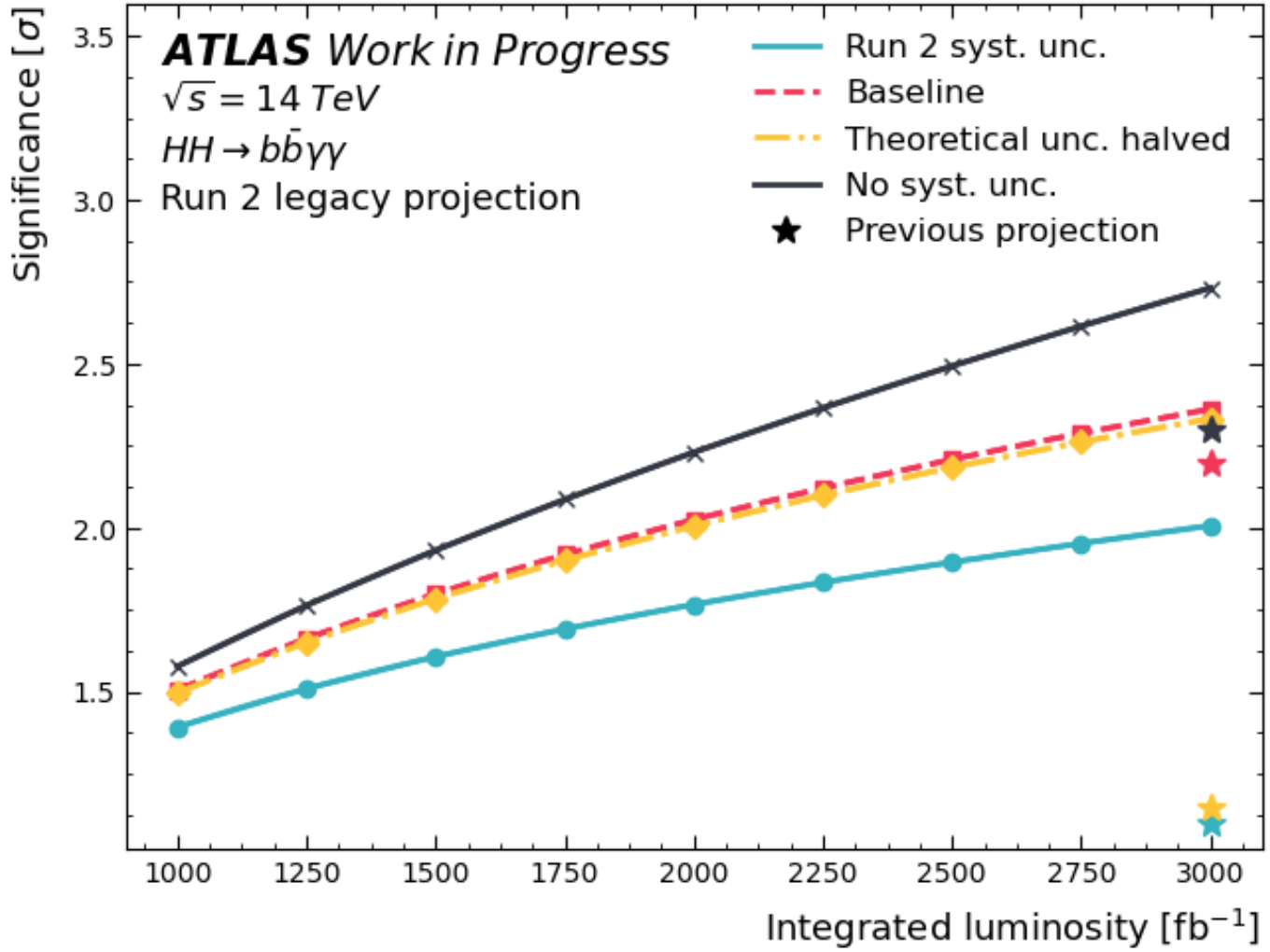
- **Definition**
  - Size of the confidence level interval from likelihood scan
  - Then, divided by 2

$$\mathbf{63\%\ precision\ on\ \kappa_\lambda}$$
$$3000\ fb^{-1}$$



THAT'S ALL?

- We always do better



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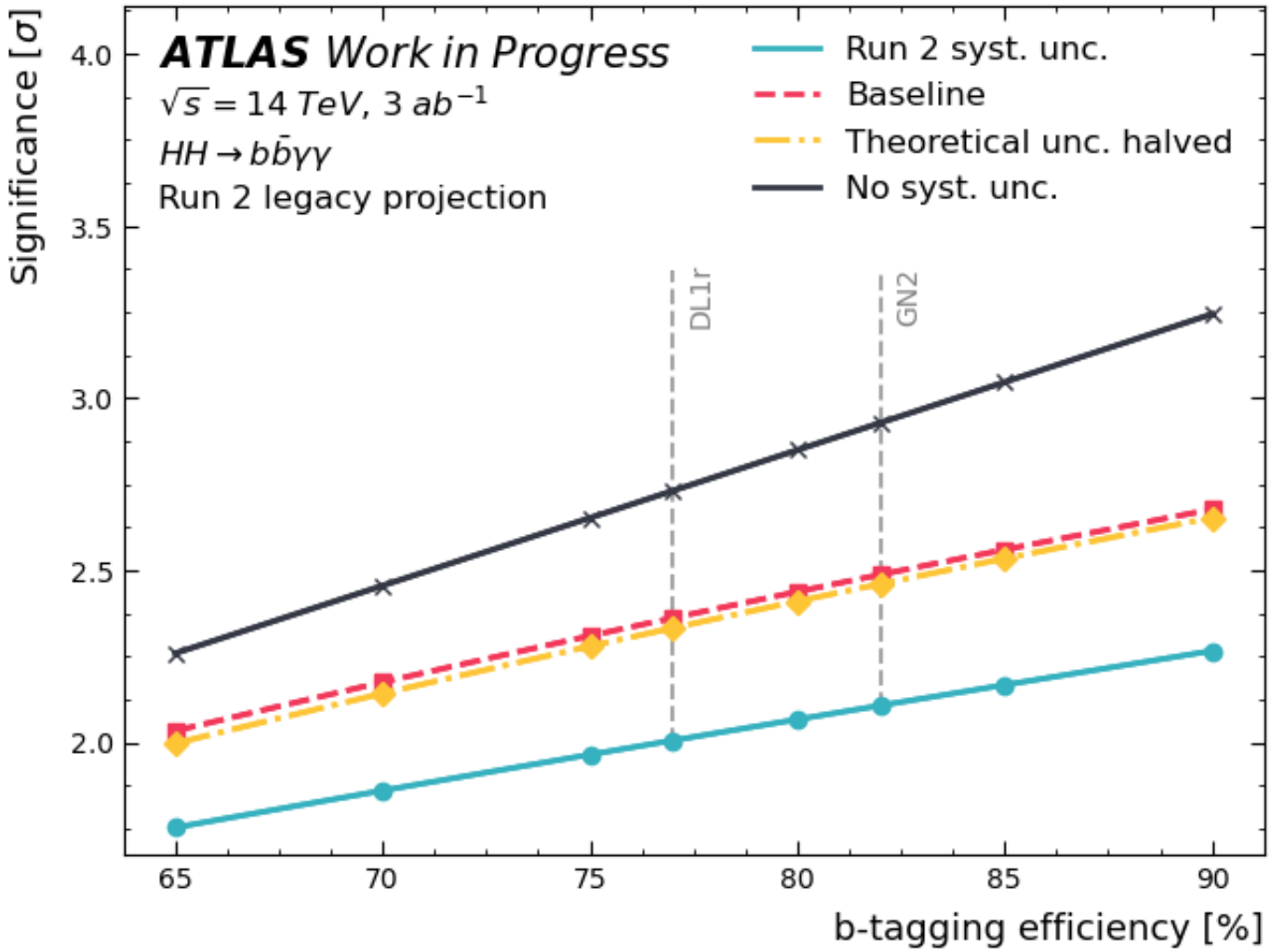
- **We always do better**
  - New algorithms to tag jets
    - Tagging jets from b-hadrons
      - Same light-jet rejection…
      - But higher efficiency

$\mathcal{O}(6\%)$ *improvement*

  - Object reconstruction will be improved
    - b-jet calibration
  - Selection Algorithm
    - What will happen when timing will be used?



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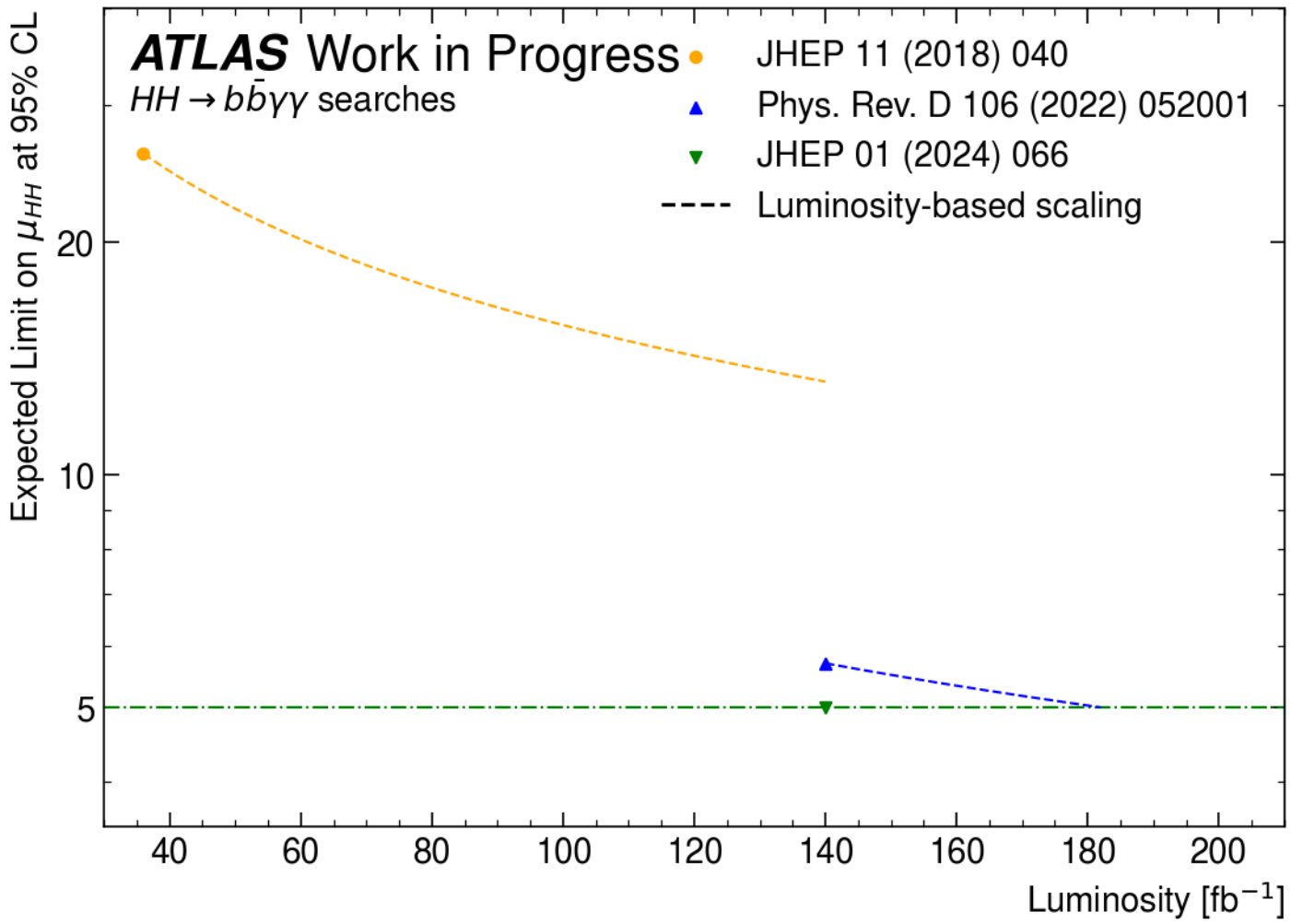
High development of ML technics

Credit to L. Santi



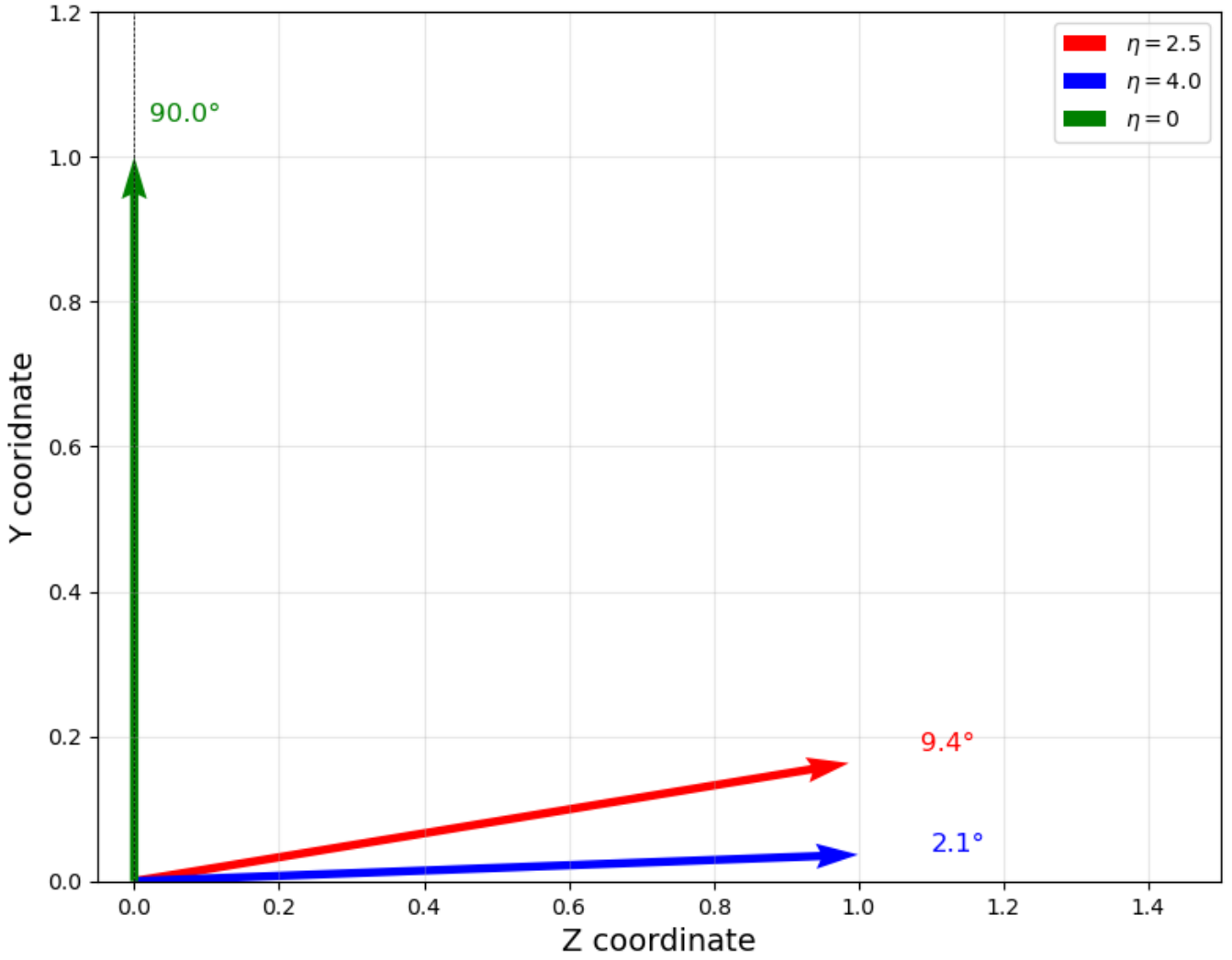
UNSUBSTANTIATED CONCLUSION

- **Higgs self-coupling is probably the most important place to look for New Physics**
- **Di-Higgs will be discovered at High-Luminosity LHC**
  - At least by combining with CMS + other channels ($b\bar{b}b\bar{b}, b\bar{b}\tau\tau, ML, \ldots$)
- **Higgs self-coupling will be constrained as never before**
  - Big chance that $HH \to b\bar{b}\gamma\gamma$ has the leading role

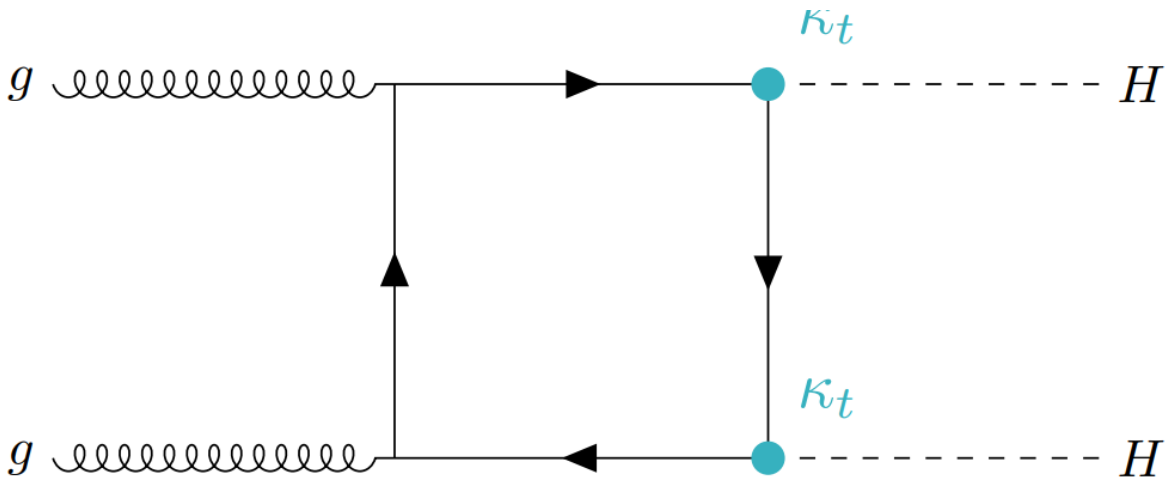
HH search if overall a global effort between many channels and experiments to make projections failed

BACKUP

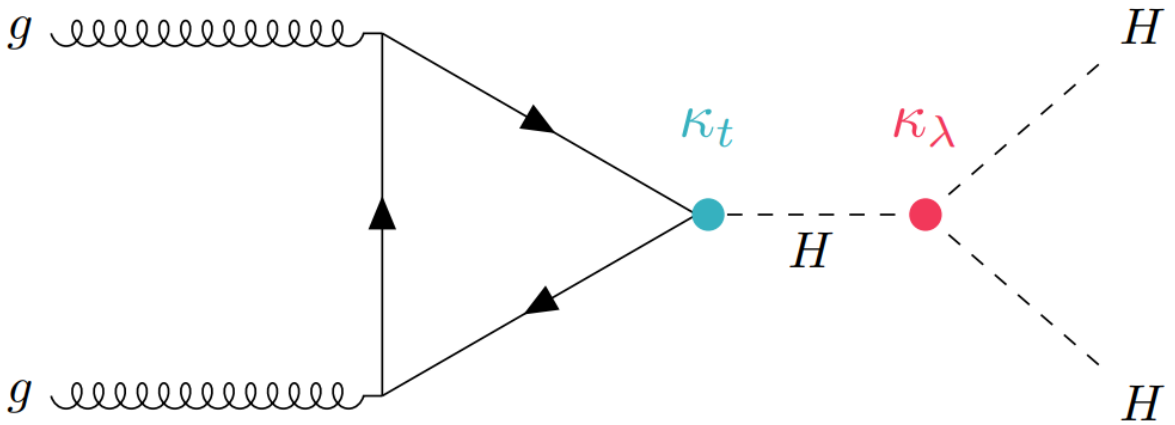
η


1.2
1.0
0.8
0.6
0.4
0.2
0.0
Y cooridnate
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Z coordinate
$\eta = 2.5$
$\eta = 4.0$
$\eta = 0$
90.0°
9.4°
2.1°

HH DIAGRAMS



(a) Box Diagram



(b) Trilinear Coupling