Higgs boson pair production at LHC

Overwiew of the most recent results and HL and FCC projections

Angela Taliercio

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Once upon a time

Once upon a time

2008 — Start of the run1!

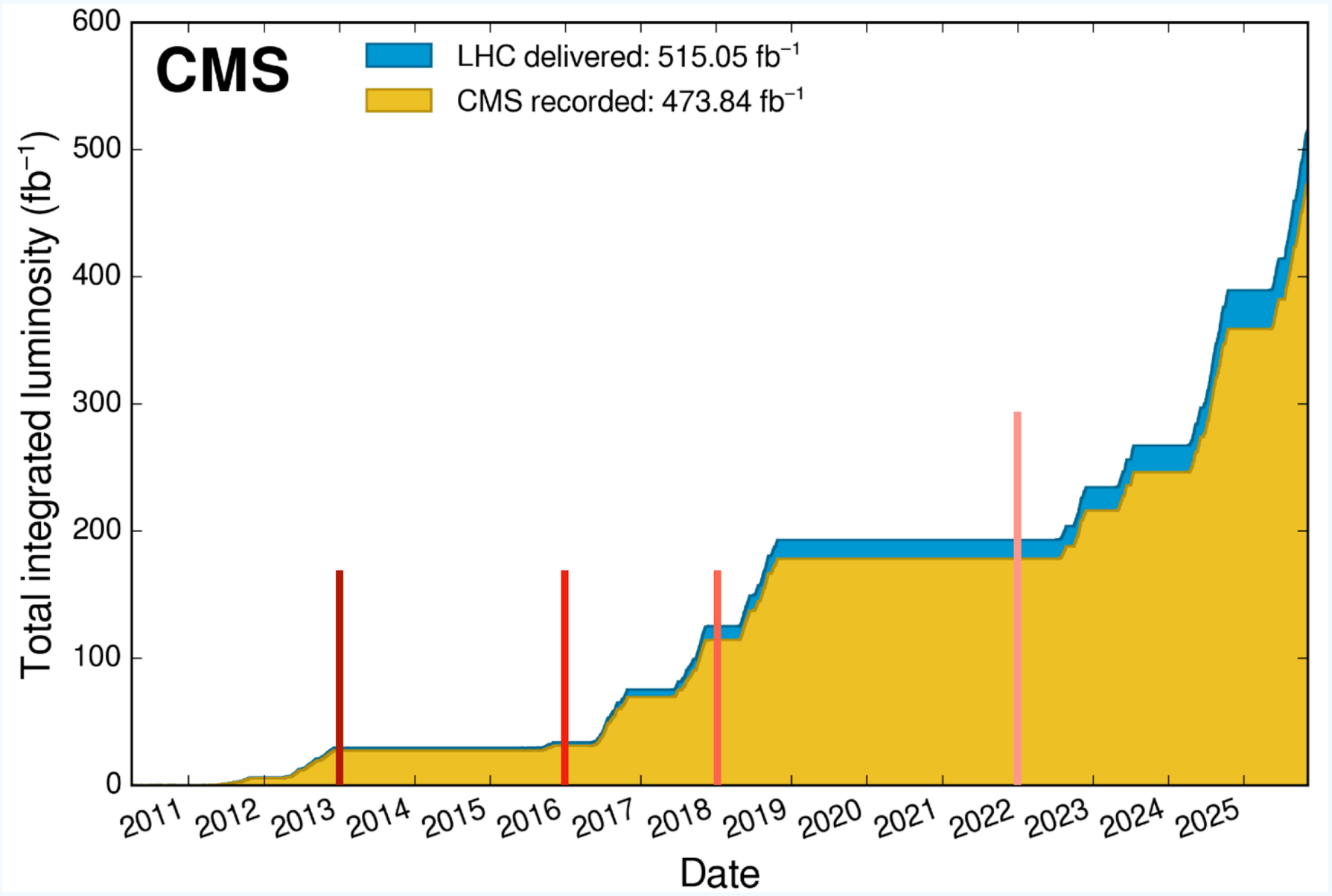
2012 — End of run1 + Higgs boson discovery (5fb^{-1})

2016 — Start of run2

2018 — End of run2

2022 — Start of run3

2026 — End of run3



Total luminosity collected is ~474 fb^{-1} rouhgly a factor 100 more than waht we had for the Higgs discovery!!

What do we do with this enormous amount of data????

Once upon a time

2008 — Start of the run1!

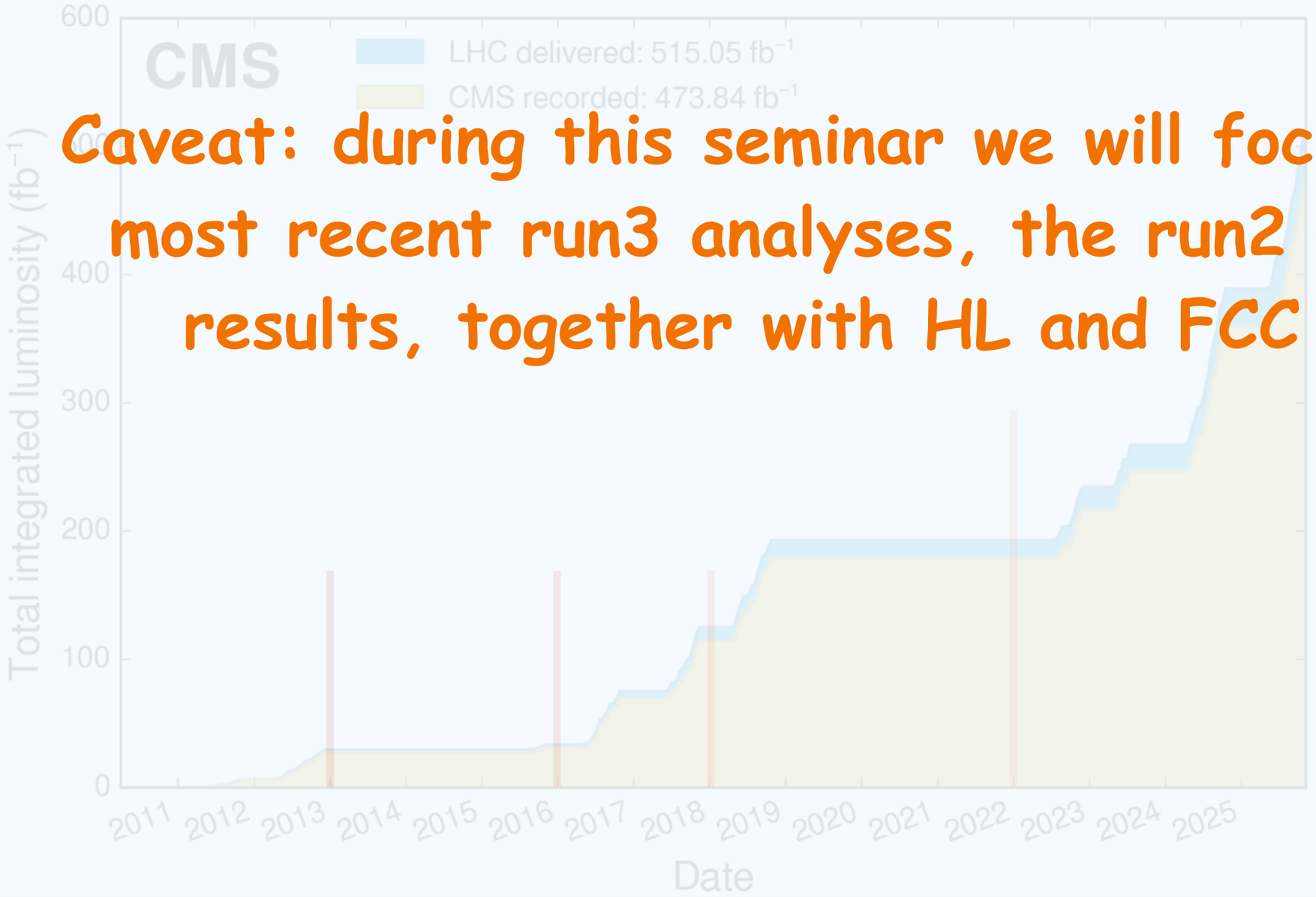
2012 — End of run1 + Higgs boson discovery ($5fb^{-1}$)

2016 — Start of run2

2018 — End of run2

2022 — Start of run3

2026 — End of run3



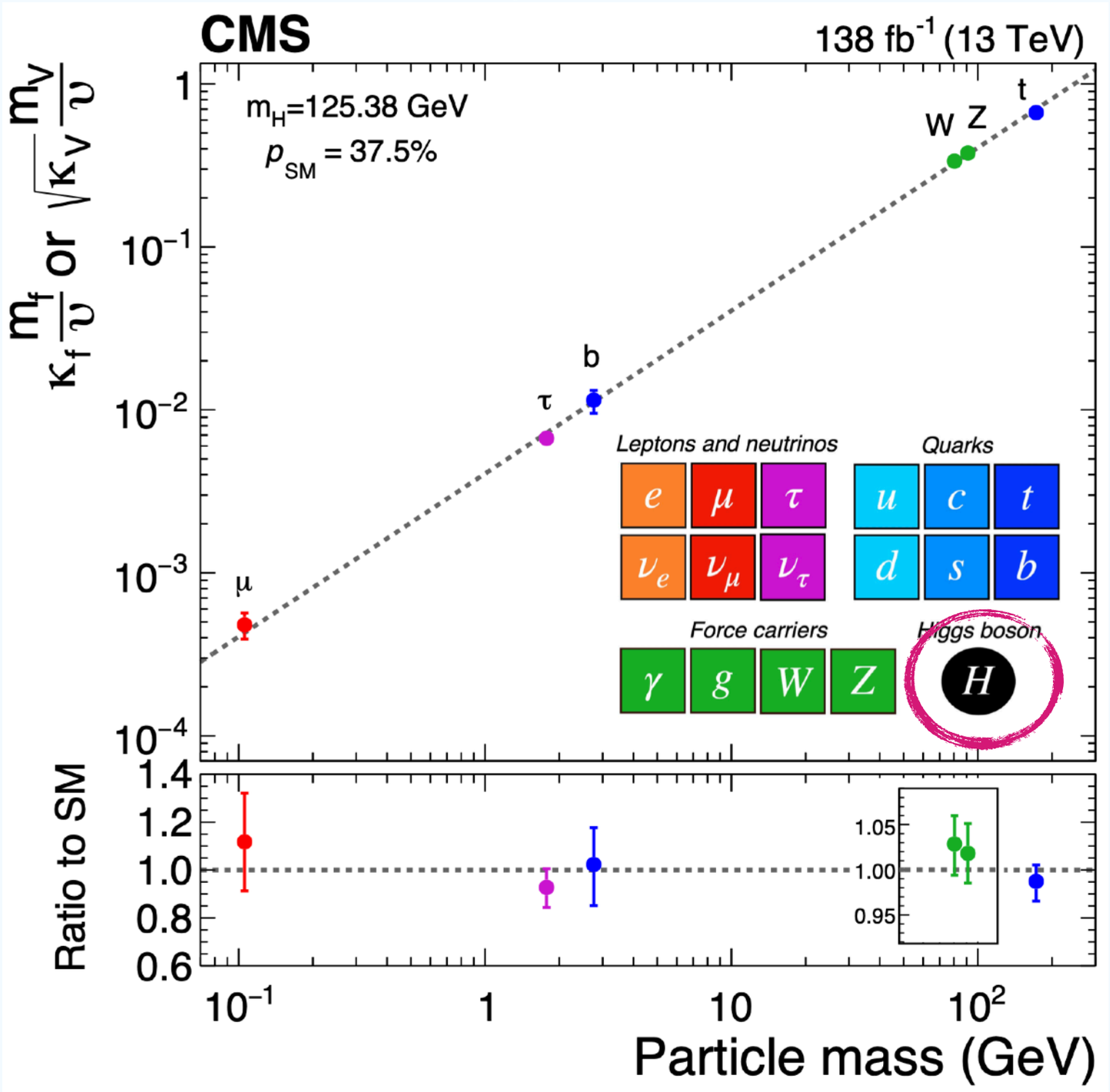
Total luminosity collected is ~474 fb^{-1}

Caveat: during this seminar we will focus only on the most recent run3 analyses, the run2 combinoation results, together with HL and FCC prjections

What do we do with this enormous amount of data????

Higgs properties

$$L_\phi = (D^\mu\phi)^+(D_\mu\phi) - \sum_f g_f(\bar{\psi}_L\phi\psi_R + h.c.) - V(\phi)$$



Main Higgs properties:

- masses to vector bosons
  - from vev and the gauge couplings
- masses of the fermions
  - from Yukawa coupling

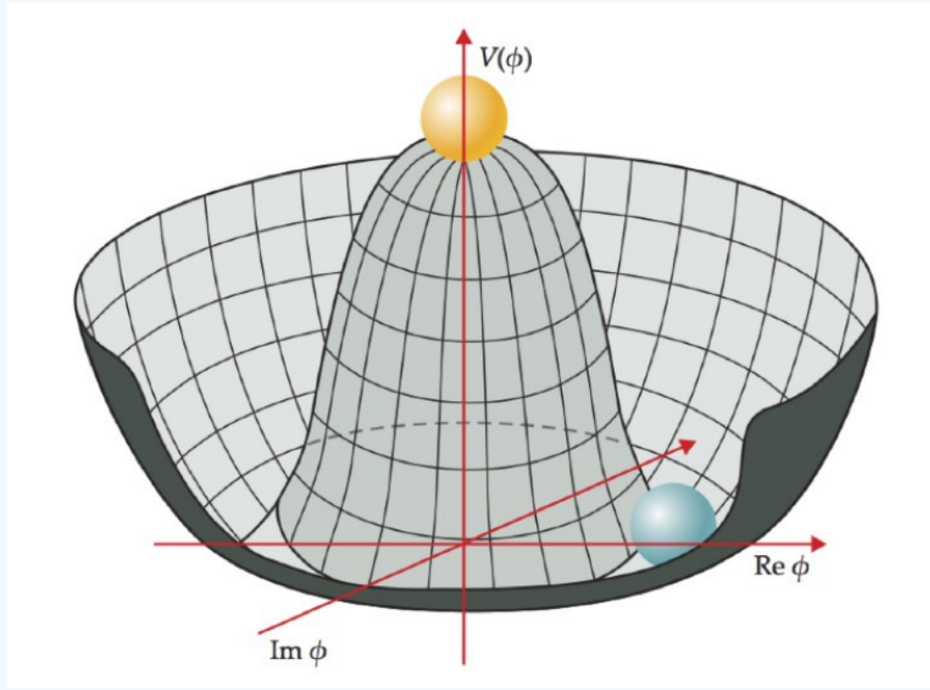
What is this plot telling us???

- **SM is very solid…**
- **We are missing the Higgs**

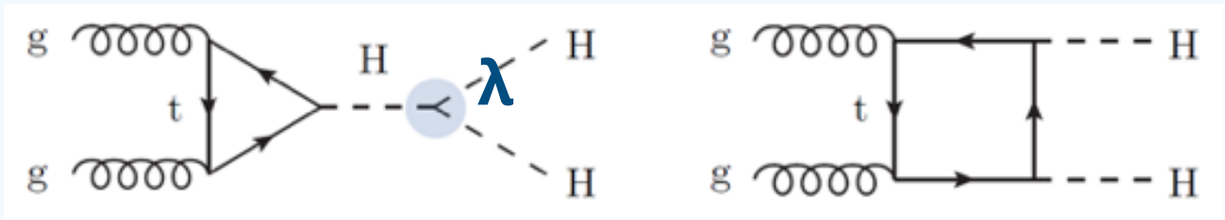
Introduction: HH production in the SM

Higgs SM potential

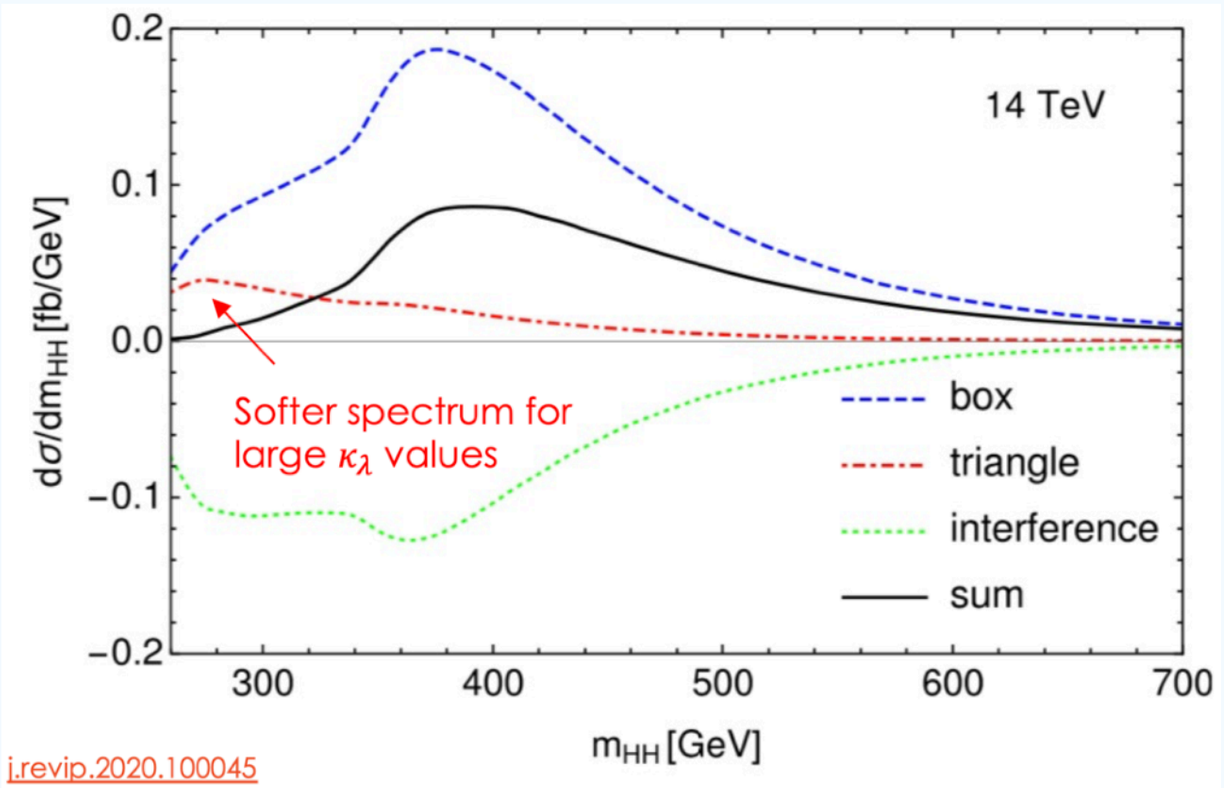
$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$



It is produced with



Destructive interference between the two dyagrams



j.revip.2020.100045

Very tiny cross section —> very challenging analyses

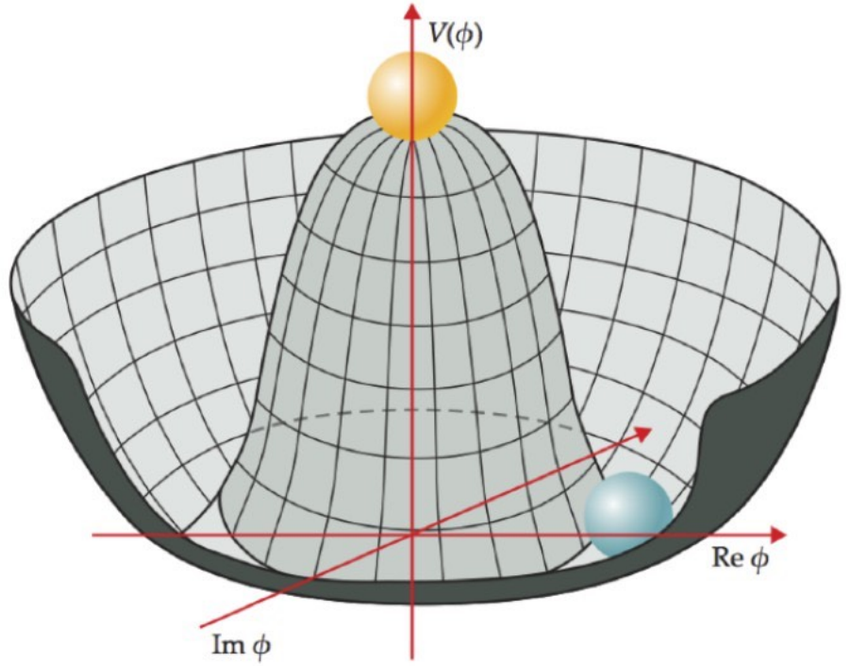
$$\sigma_{SM}^{HH} = 31.05^{+5\%}_{-7\%}\ \text{fb}\ (\text{scale} \oplus \text{PDF} \oplus \alpha_S \oplus \text{m}_\text{t})$$

Why is it that so important???

Introduction: HH production in the SM

In Standard Model destructive interference of triangle and box contributions → tiny cross section → Experimentally very challenging

$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

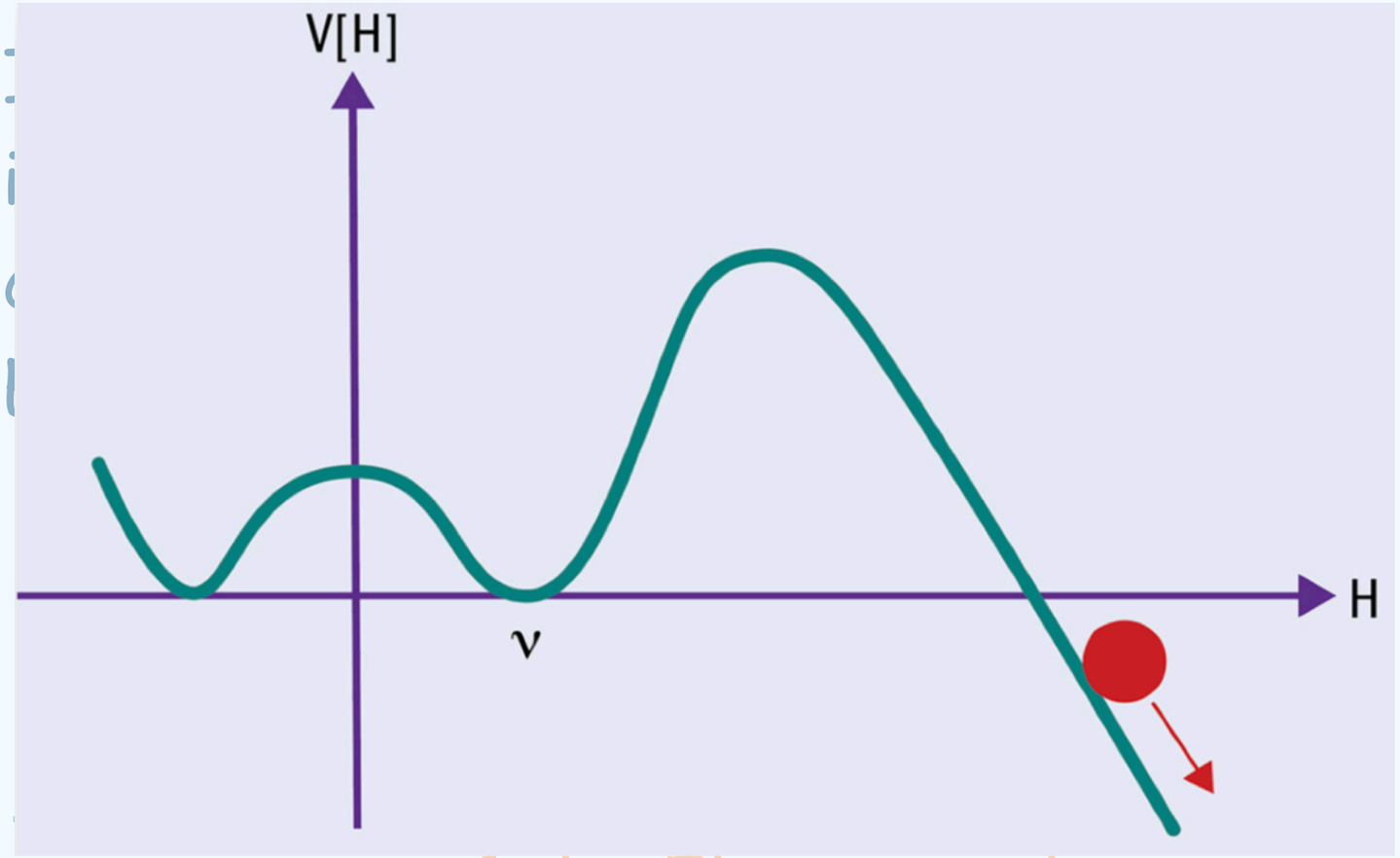


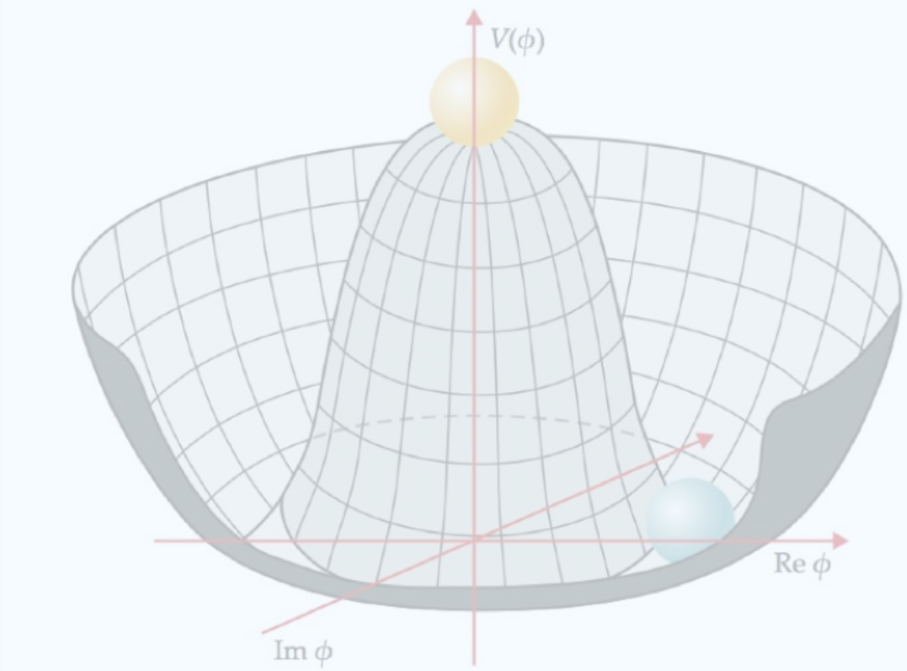
The direct measure of λ is a strong test of the Electroweak Symmetry Breaking (EWSB) mechanism

Deep fundamental questions

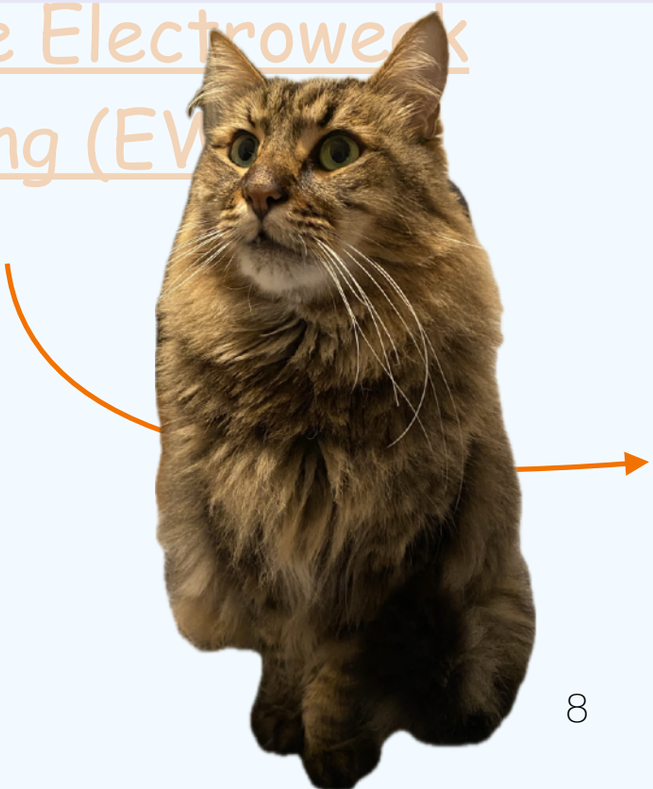
- **What is the order of the EW phase transition?**
- **What is the fate of the Universe? Is it stable?**

Introduction: HH production in the SM





strong test of the Electroweak Symmetry Breaking (EWSB) mechanism



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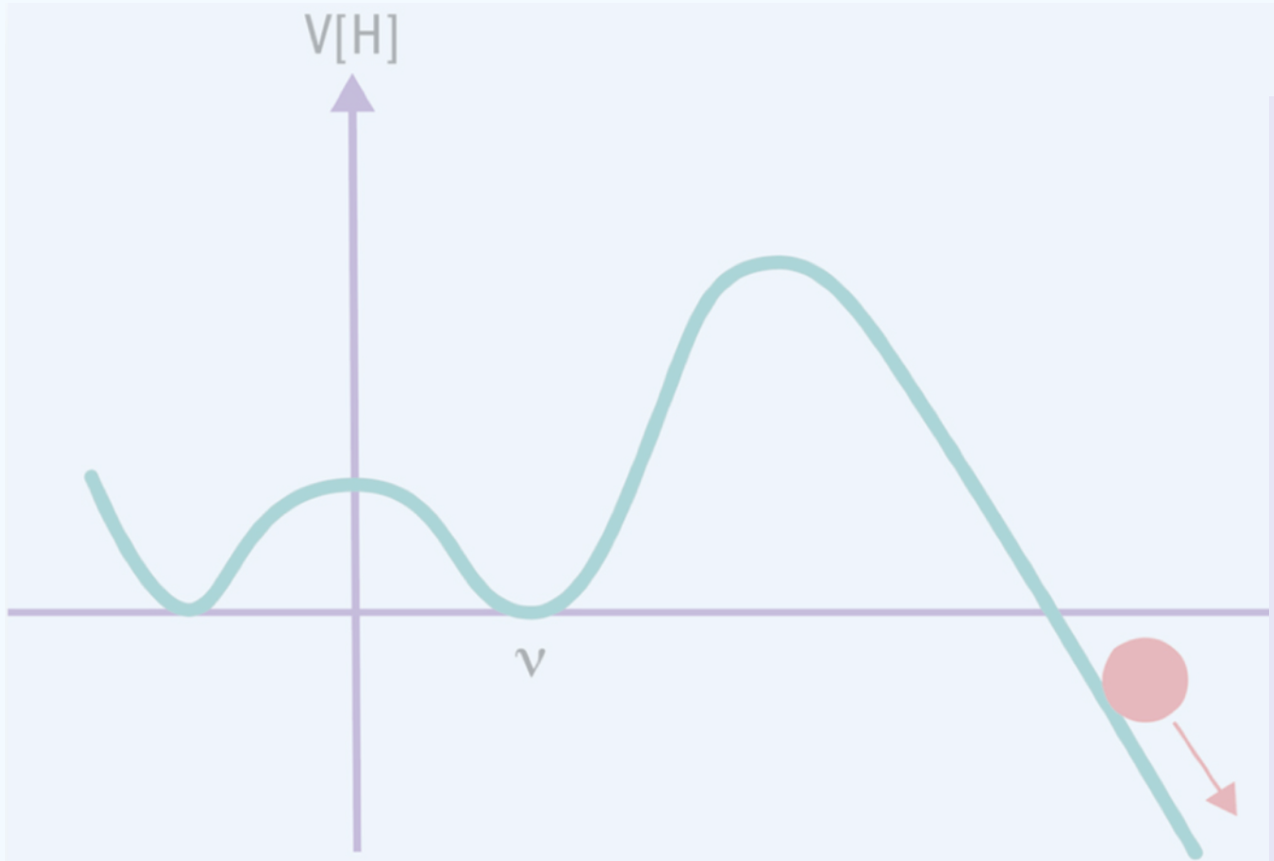
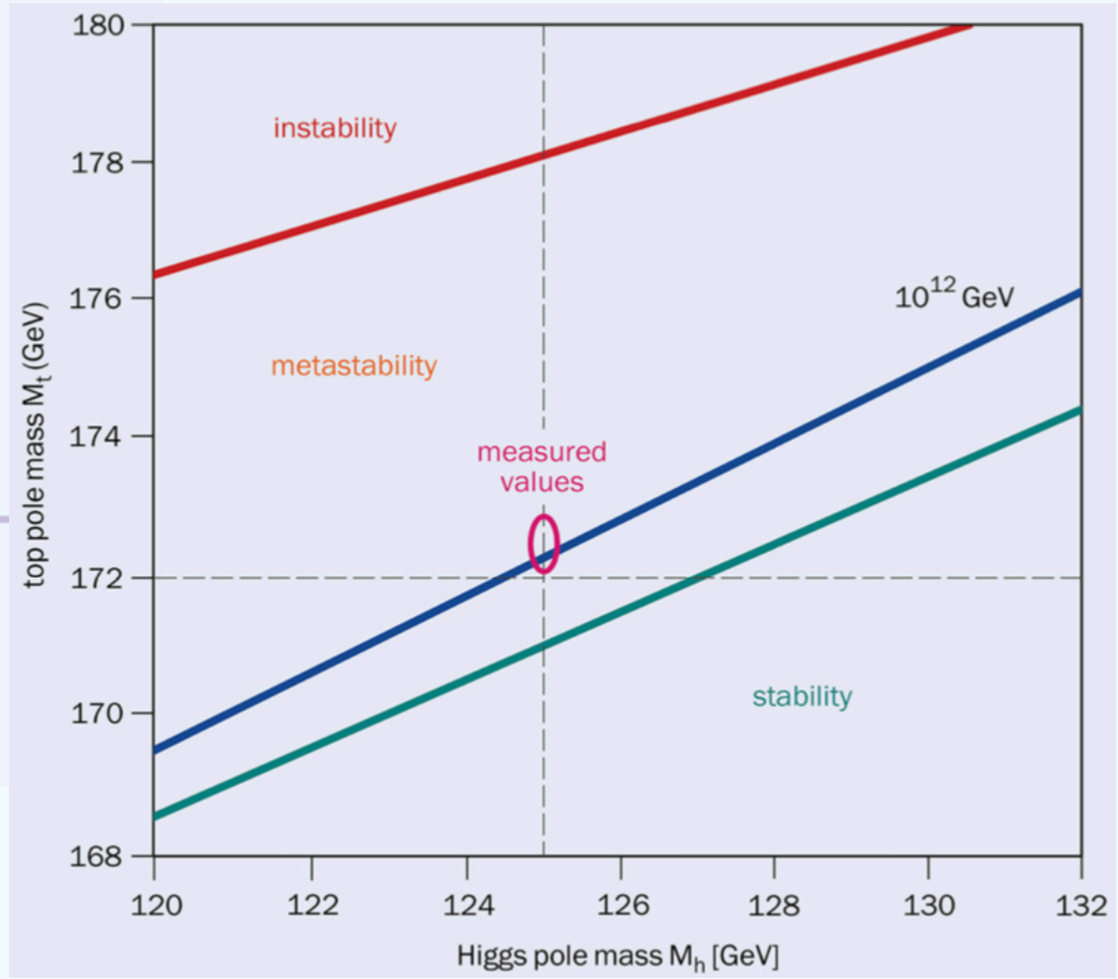




- What is the order of the EW phase transition?
- What is the fate of the Universe? Is it stable?

Introduction: HH production in the SM

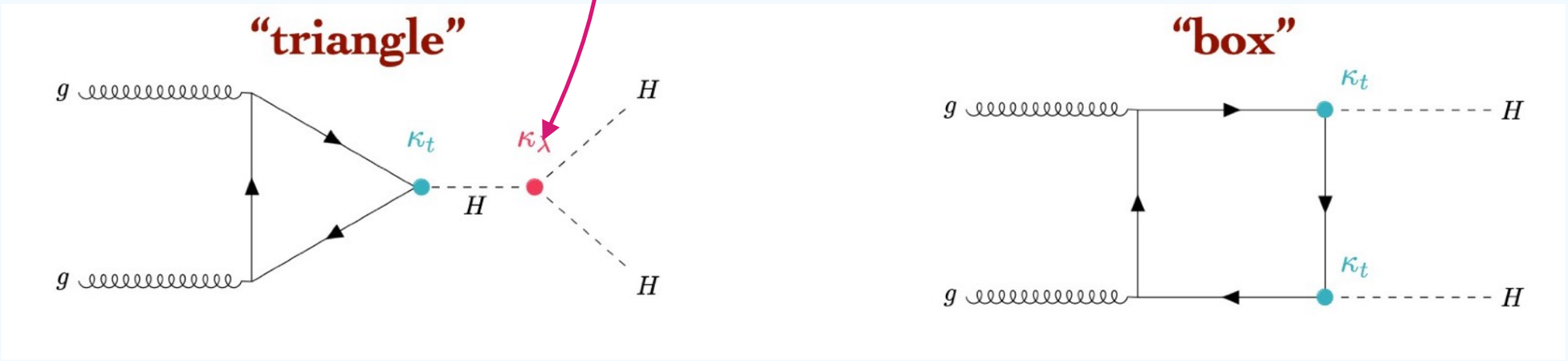
The direct measure of λ is a strong test of the SM prediction (λ~0.13 from theoretical SM prediction)

$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

- HH gluon-gluon fusion production (around 4000 events produced in the full RunII)

$$\sigma_{ggF}^{HH} = 31.05^{+2\%}_{-7\%}\ fb\ (scale \oplus PDF \oplus \alpha_S \oplus m_t)$$

*remark:
κ_X is a coupling modifier: $\kappa_X = c_X/c_{SM}$ Where c is the coupling



Gives a direct handle on the k_λ paramenter + k_t dependence in the box diagram

Introduction: HH production in the SM

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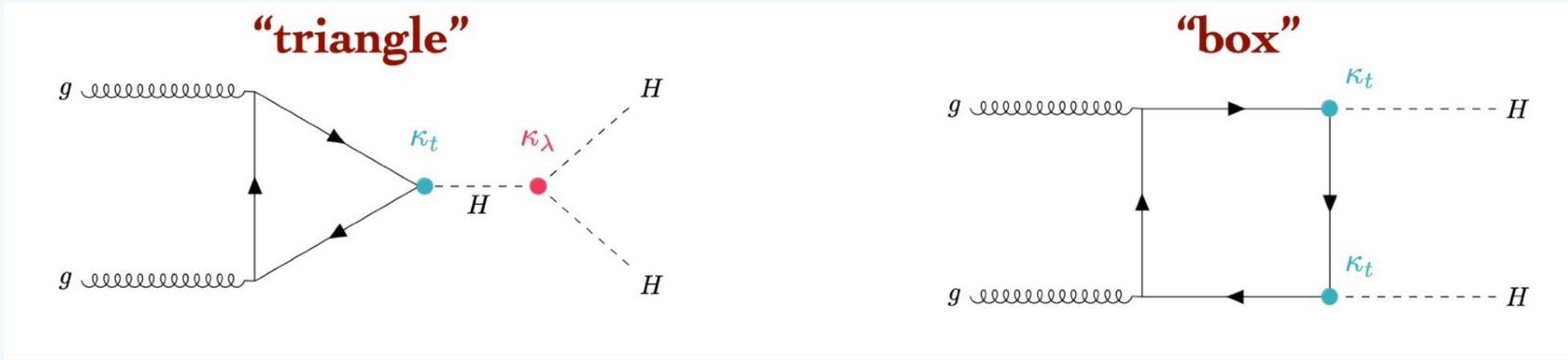

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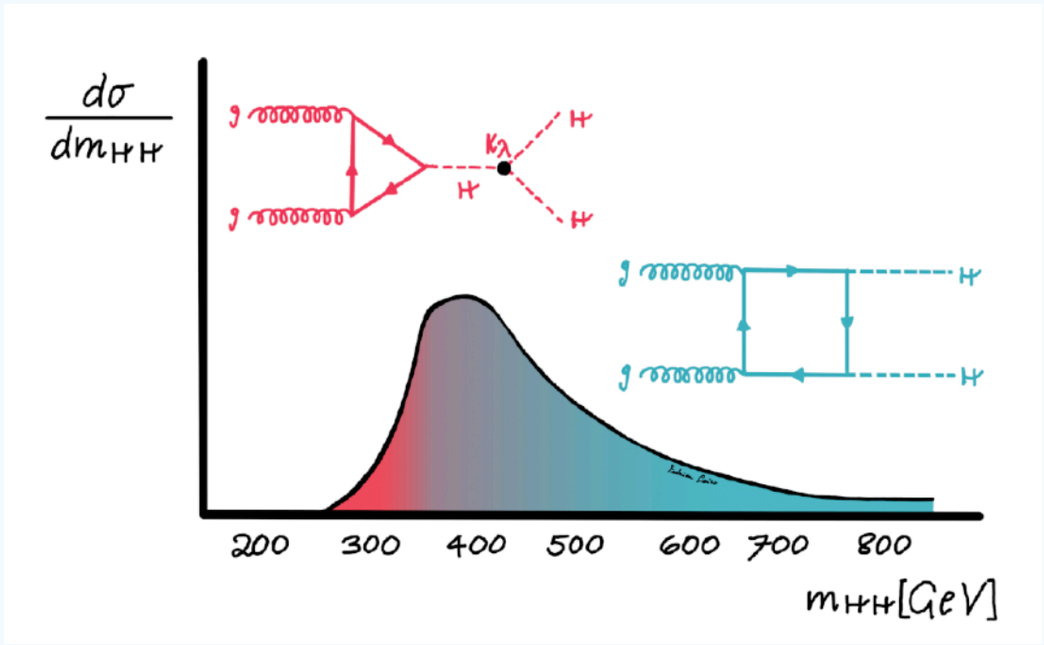
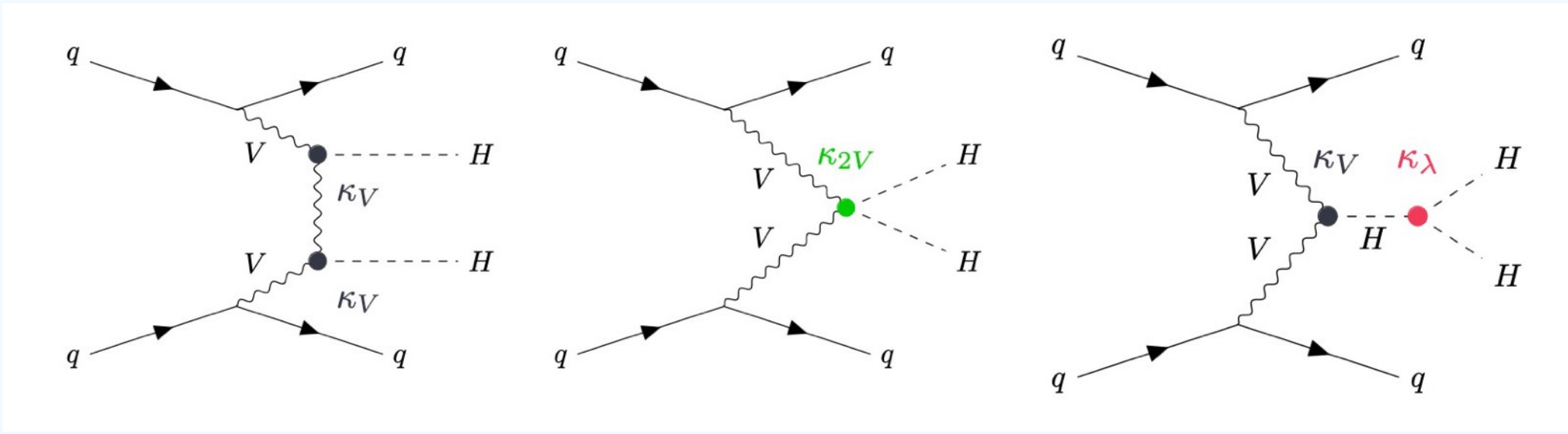


- Di Higgs kinematic strongly dependent on k_λ
- Different m_{HH} ranges can be explored to be sensitive at different physics scenarios

Introduction: HH production in the SM

- HH VBF production (around 300 events produced in the full RunII)

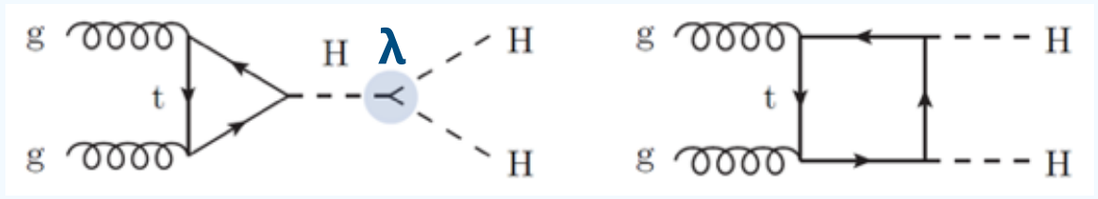
$$\sigma_{VBF}^{HH} = 1.73 \pm 0.04 \; fb \; (scale \oplus PDF \oplus \alpha_S \oplus m_t)$$



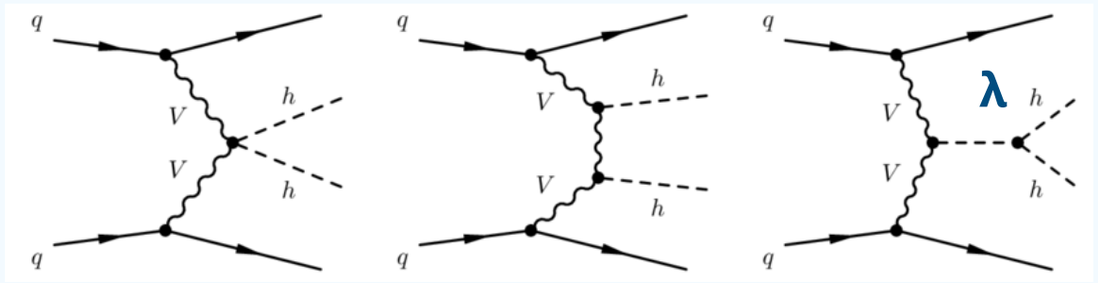
VBF production mode is less dominant but gives a direct handle on the k_V and k_{2V} couplings

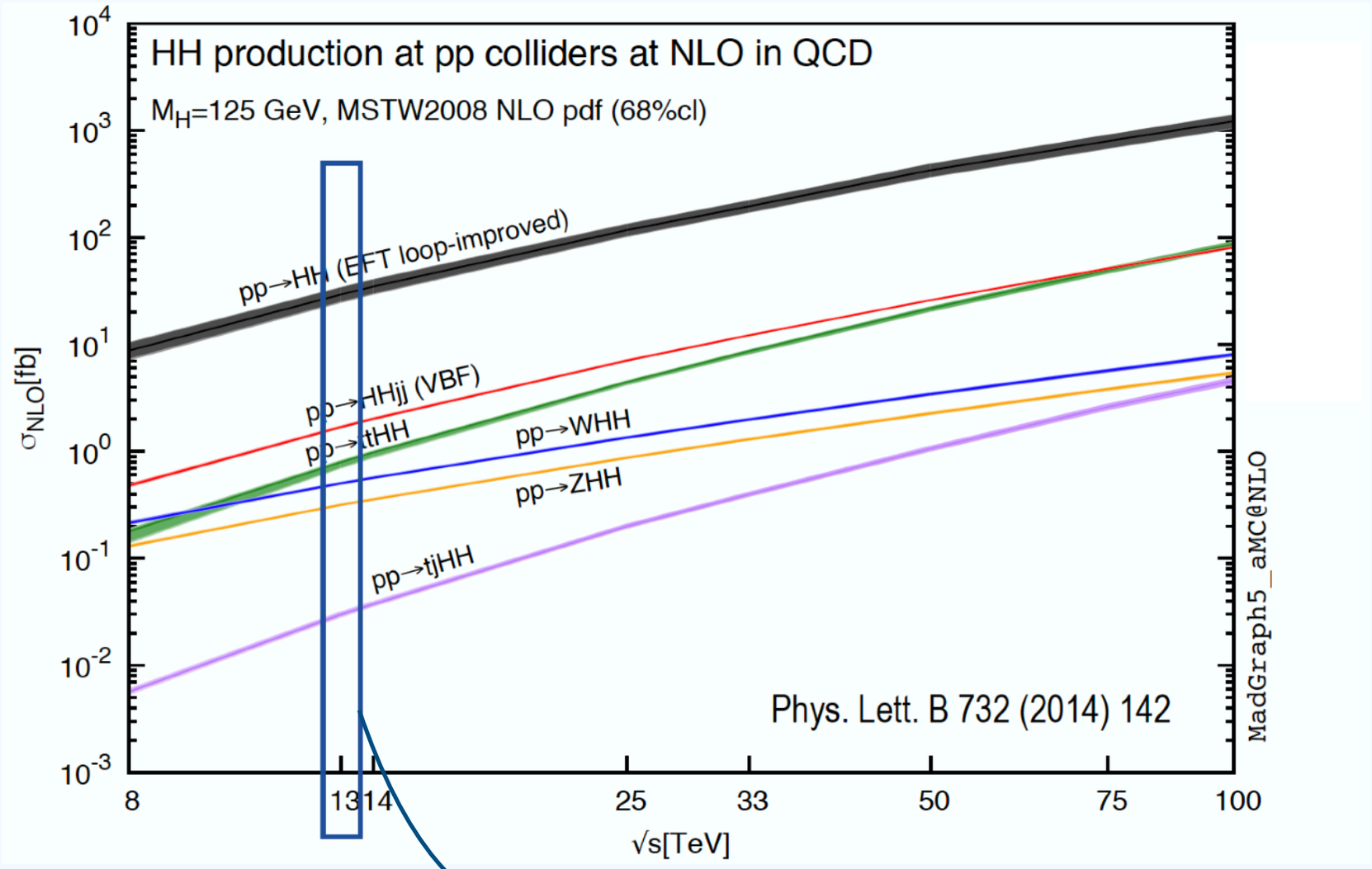
Introduction: HH production in the SM

HH gluon-gluon fusion production



HH VBF fusion production

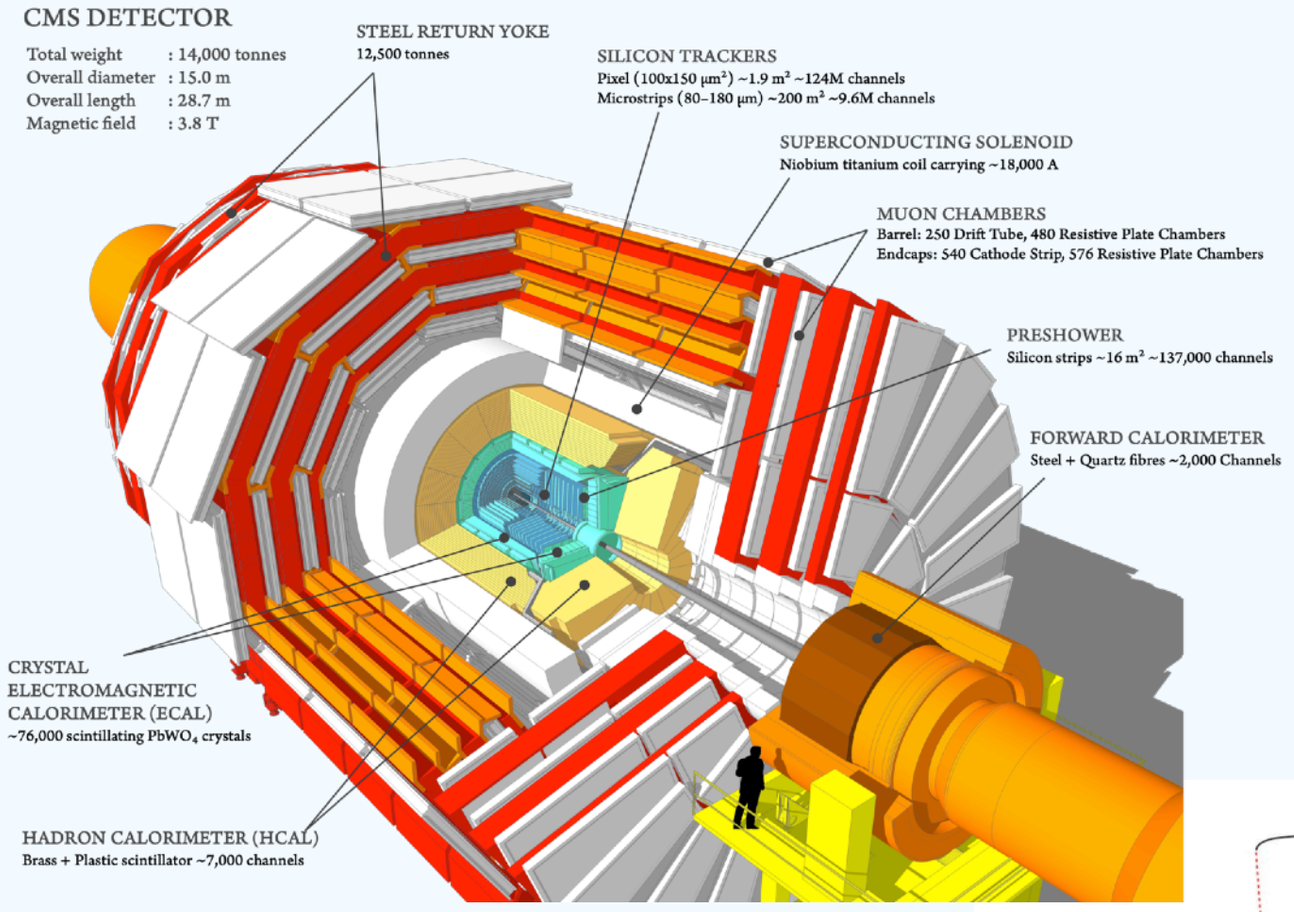


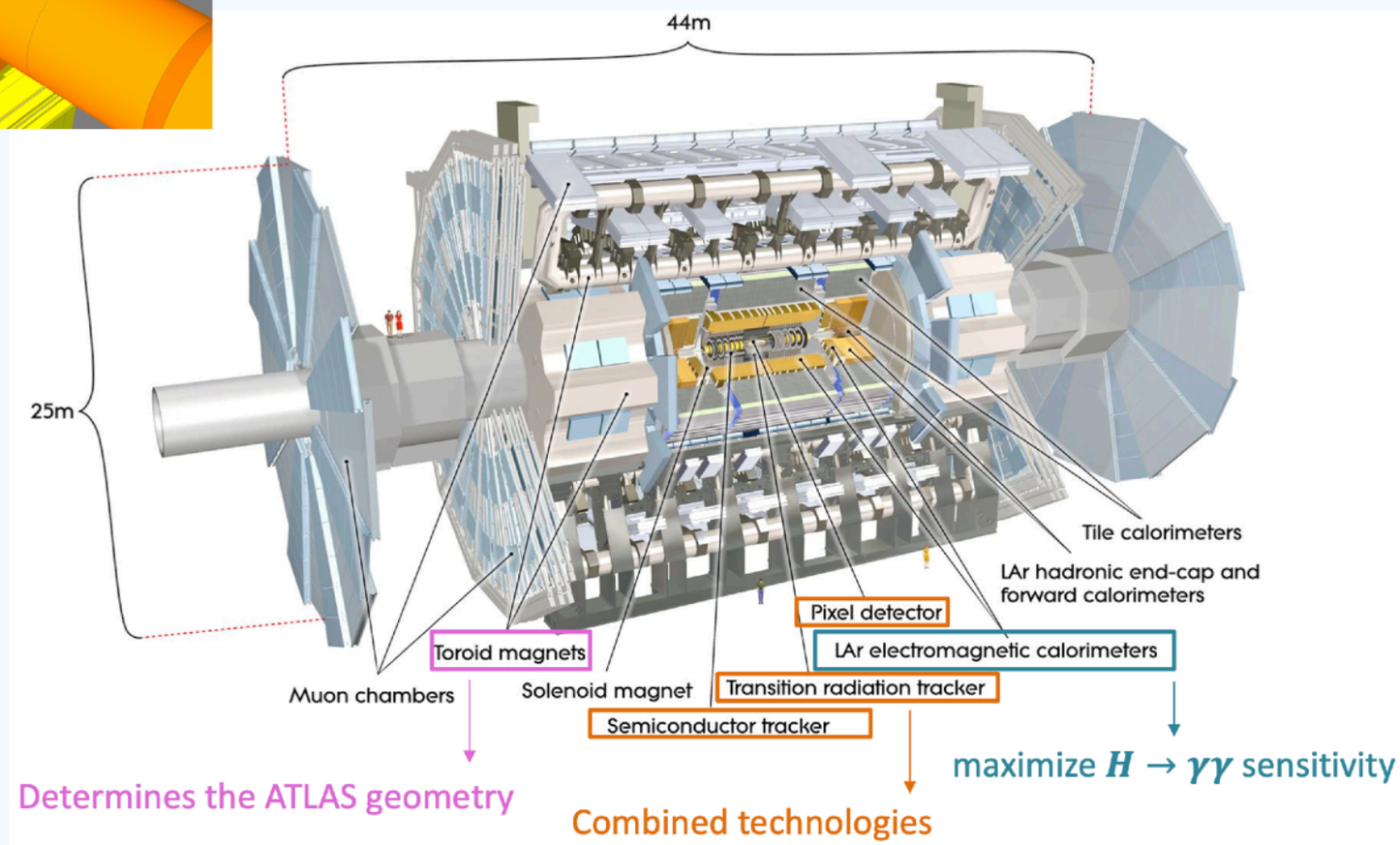


- **Gluon fusion:** dominant production mode

- **Large destructive interference → tiny cross section**

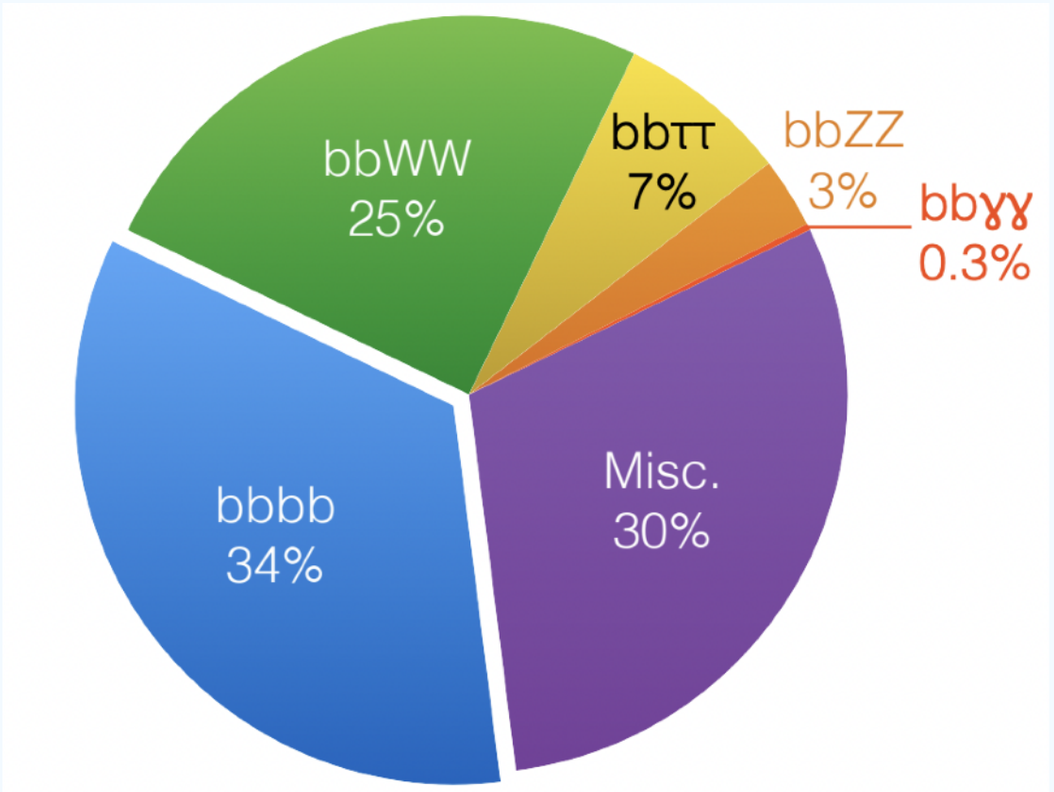
CMS and ATLAS experiments



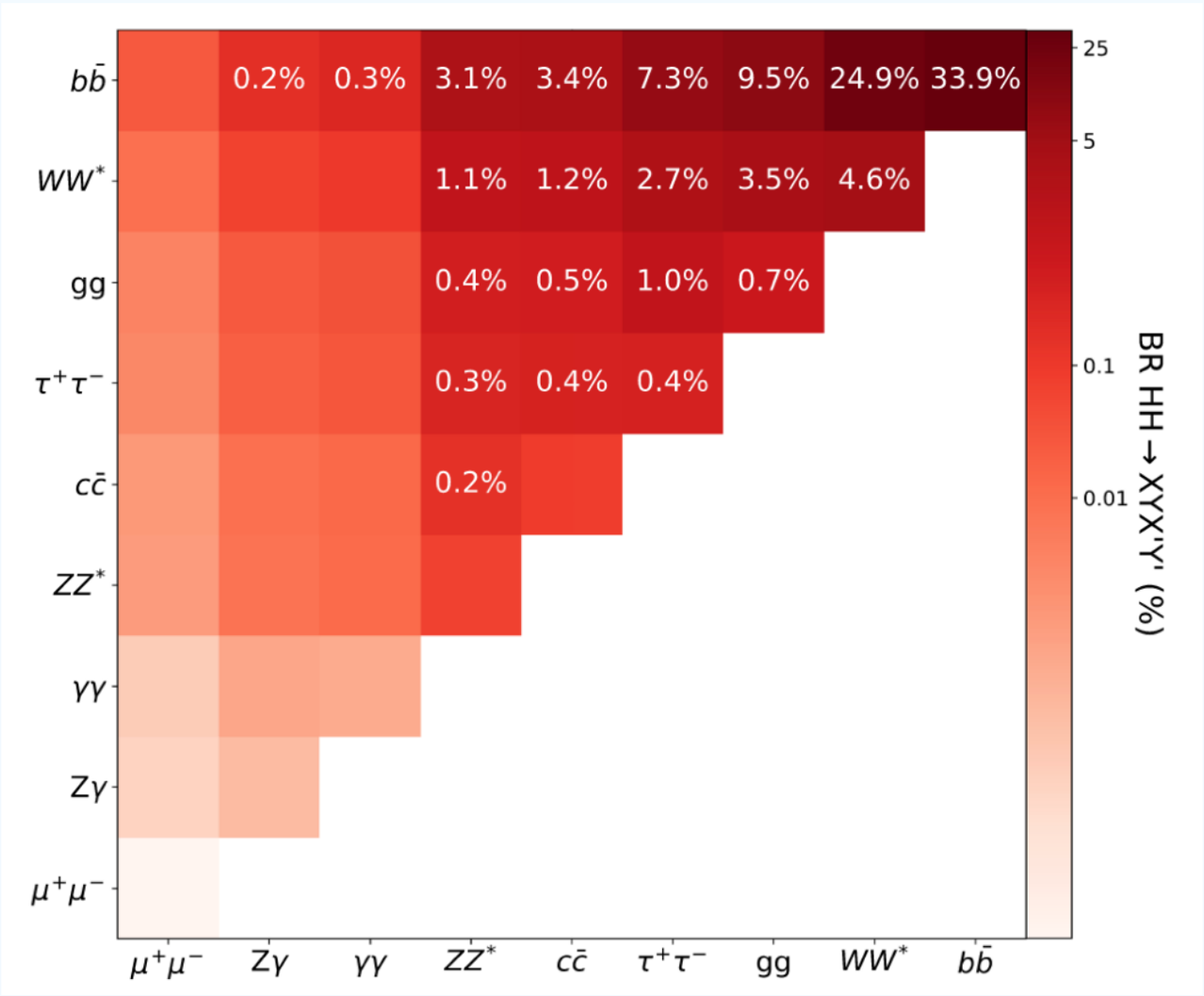


HH searches in CMS

H -> XX



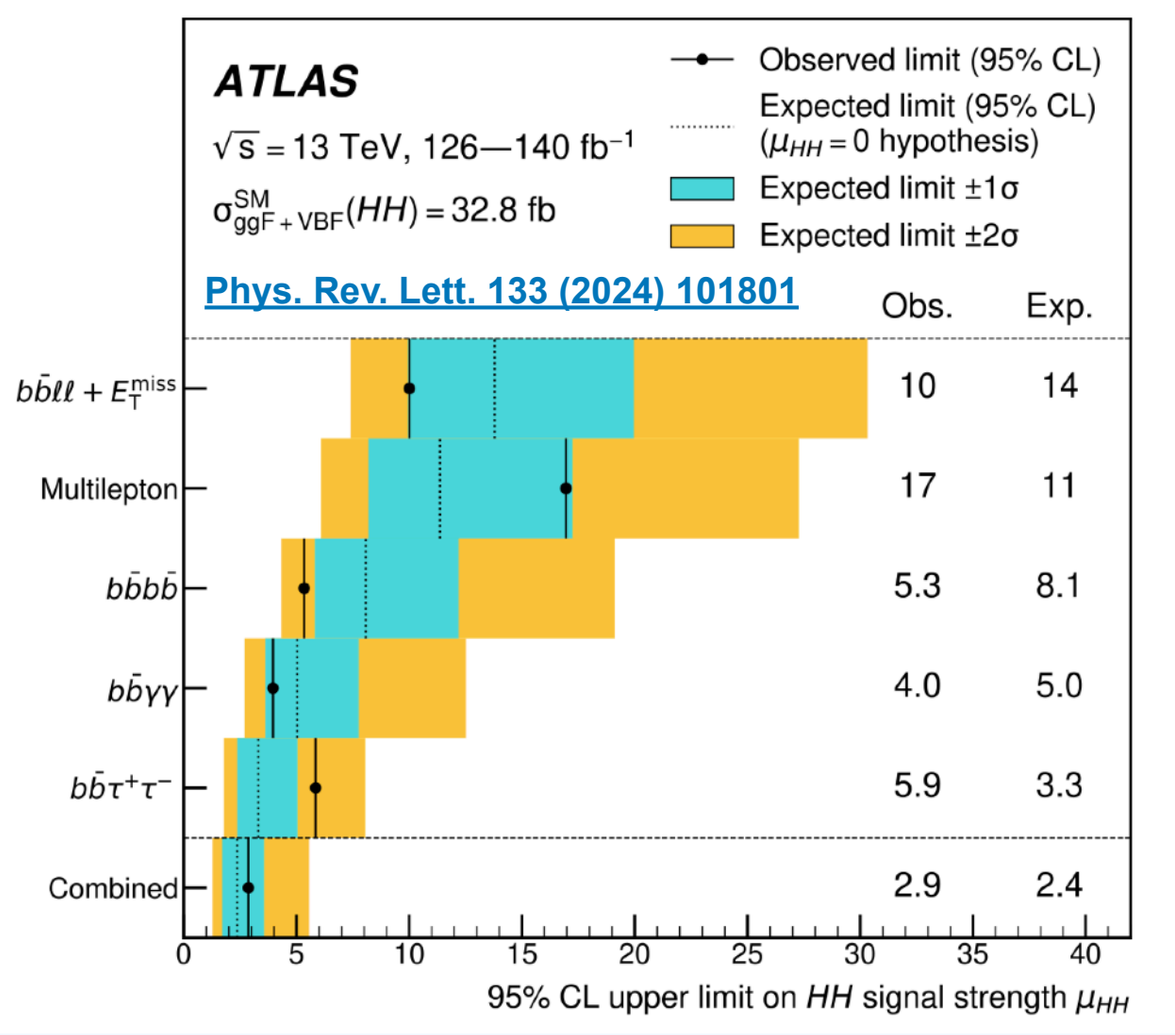
bbγγ, bbττ, 4b most promising channels

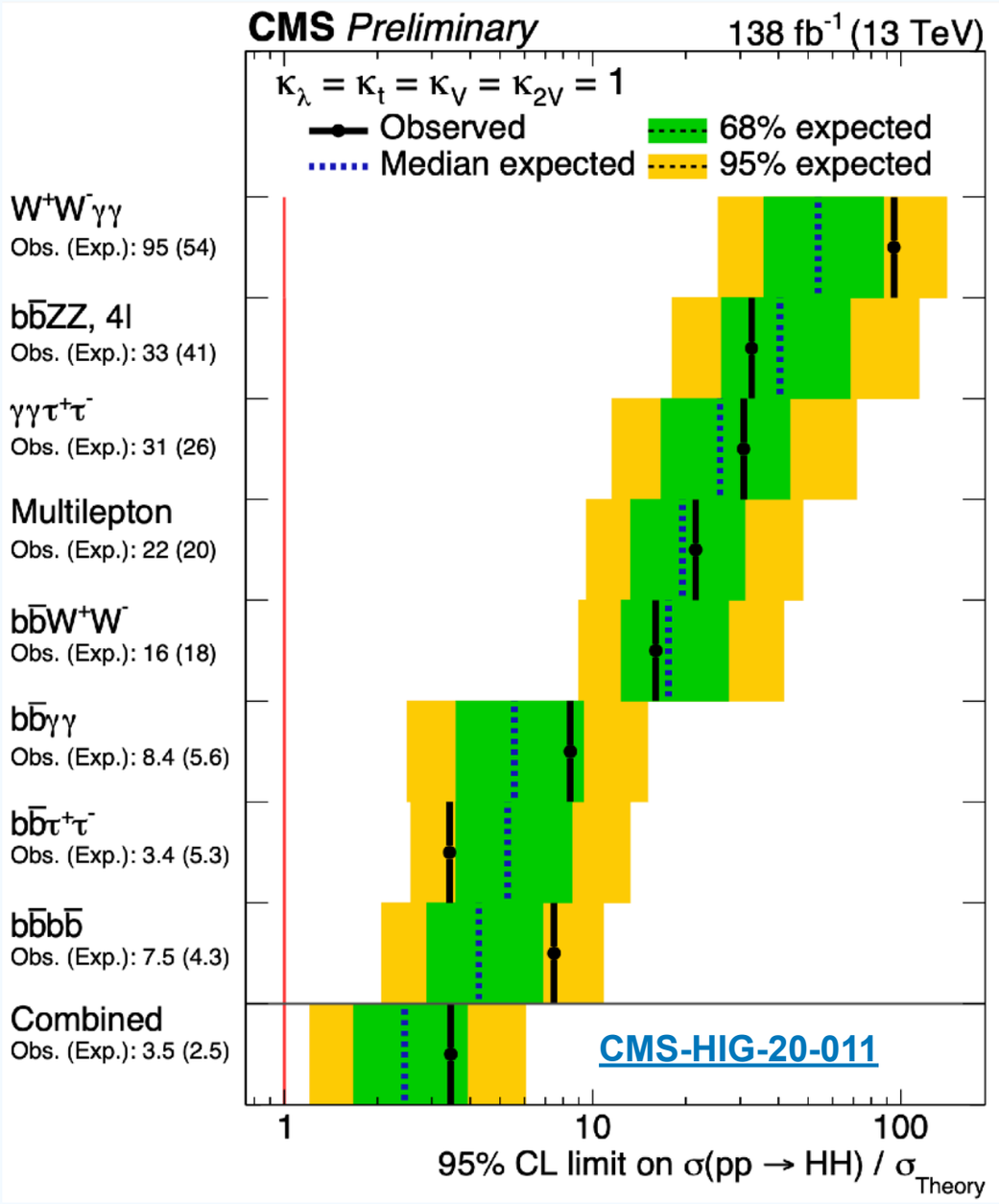


HH production cross-section

Limit on the HH cross-section relative to its SM prediction (**signal strength μ**) is shown in those plots:

- 'Golden channels' are 4b, bbγγ, bbττ
- ATLAS combination leads to 2.9xSM (exp 2.4xSM), CMS combination leads to 3.5xSM (exp 2.5xSM)





- Also limits on the VBF production mode available, both experimet are sensitive to ~90xSM

CMS + ATLAS combination

Limit on the HH cross-section relative to its SM prediction (**signal strength μ**) is shown in those plots:

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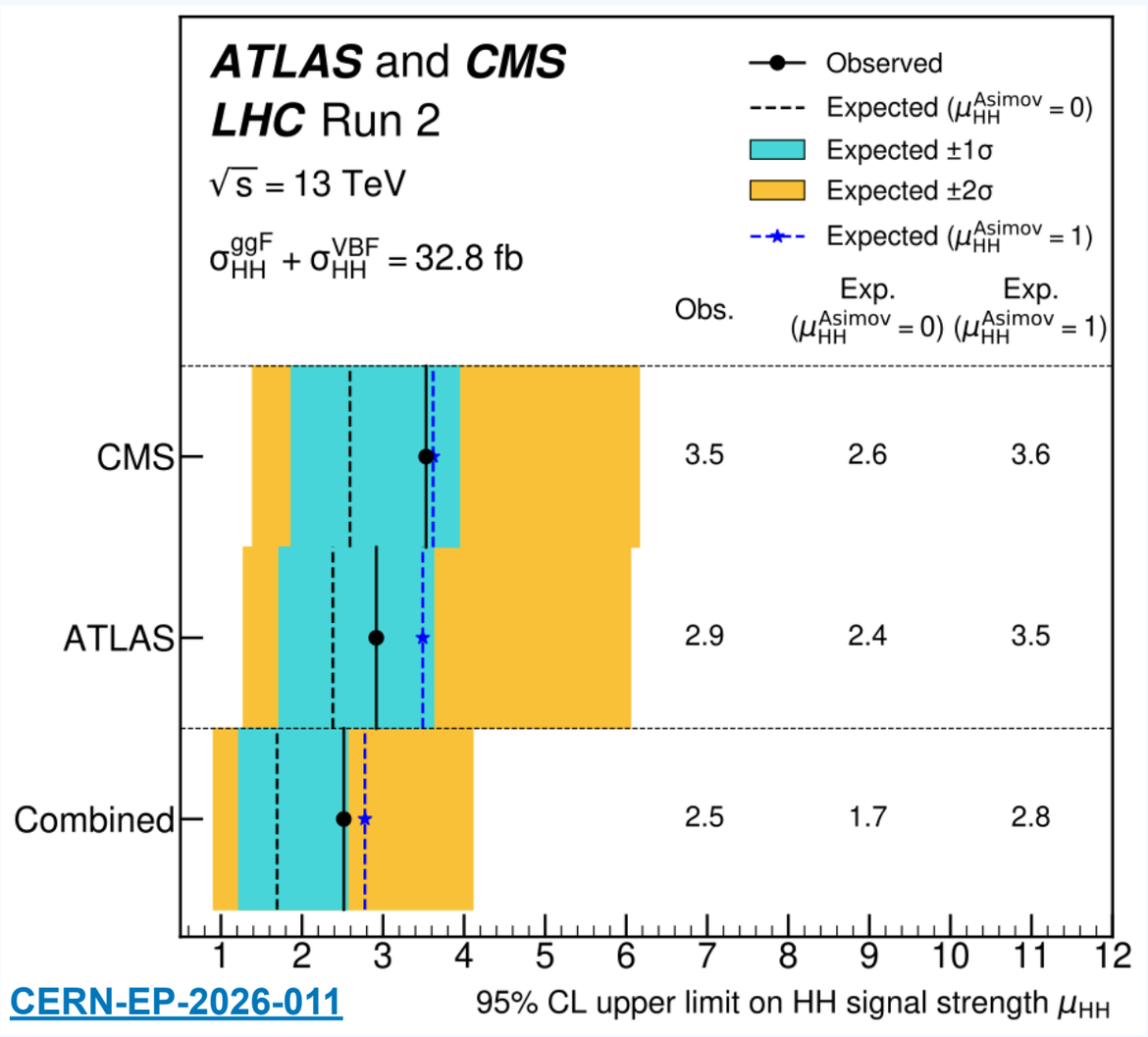


CERN-EP-2026-011

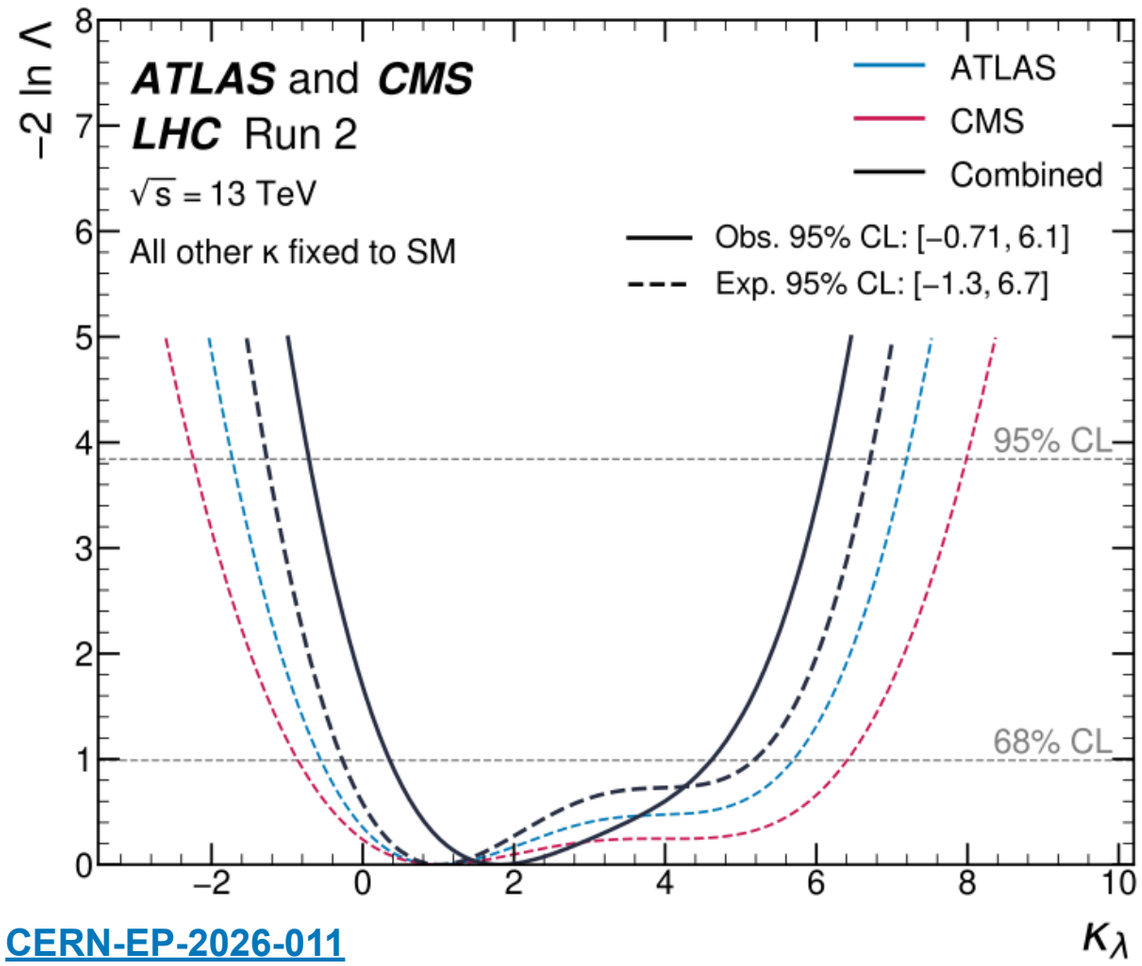
Observed significance = 1.1
Expected significance = 1.3
for the SM HH signal

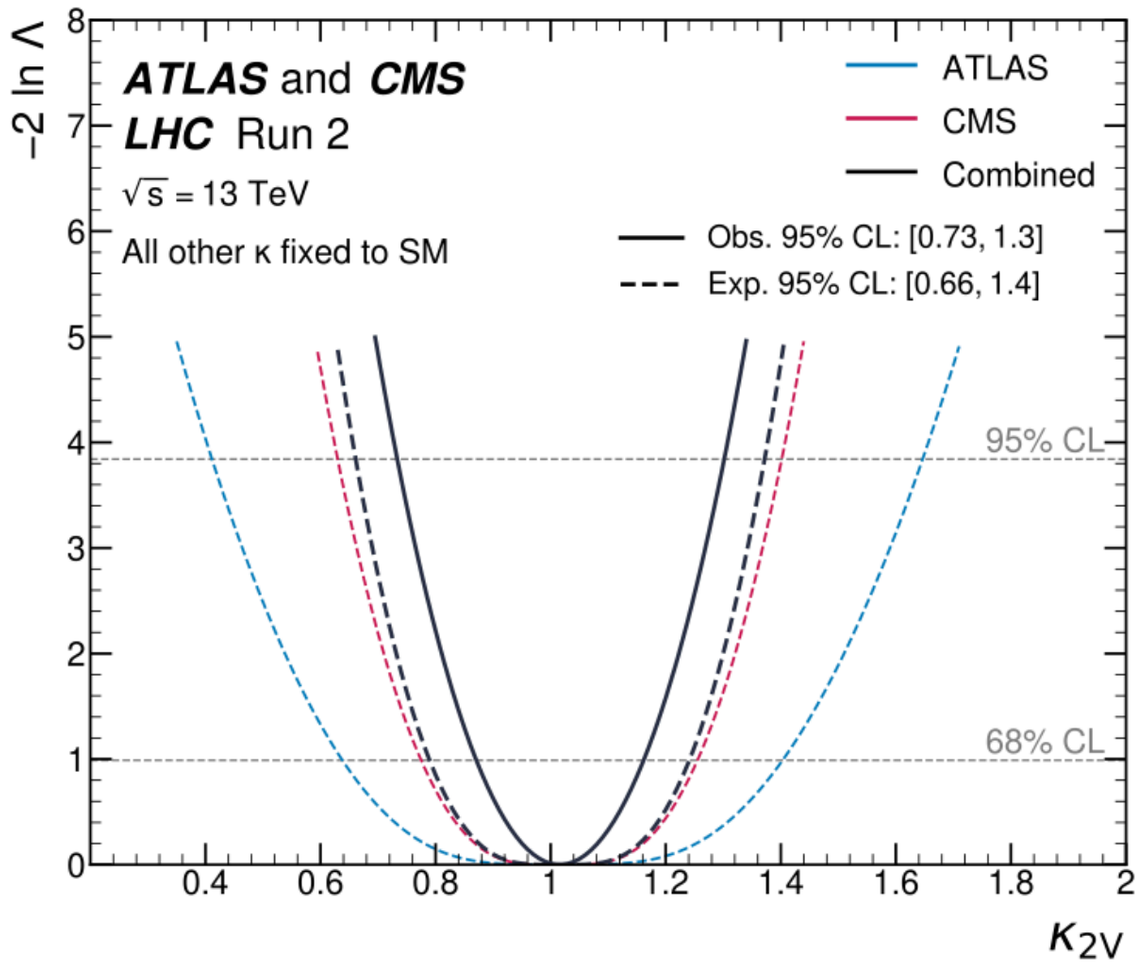
And this is 'only' with ~138fb^{-1} at the end of the run we expect at least 500fb^{-1} per experiment…

CMS + ATLAS combination

Both collaborations provided results for k_λ, k_t and k_{2V} relative results

- k_λ scan dominated by bbγγ and bbττ
- k_{2V} scan dominated by 4b boosted signature



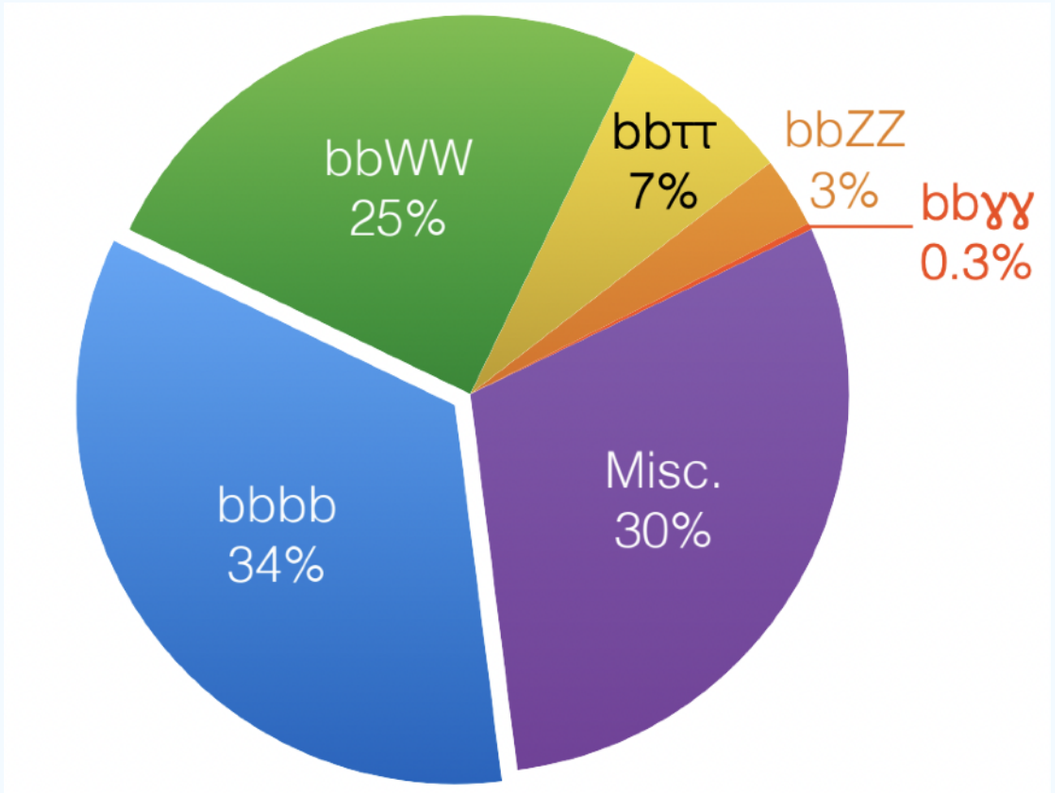


CERN-EP-2026-011

Constrain on the k_λ [−1.4, 6.6] obs - CMS
Constrain on the k_λ [−1.3, 7.2] obs - ATLAS

Constrain on the k_{2V} [0.66, 1.4] obs - CMS
Constrain on the k_{2V} [0.57, 1.5] obs - ATLAS
k_{2V} = 0 excluded at >6σ from both collaborations

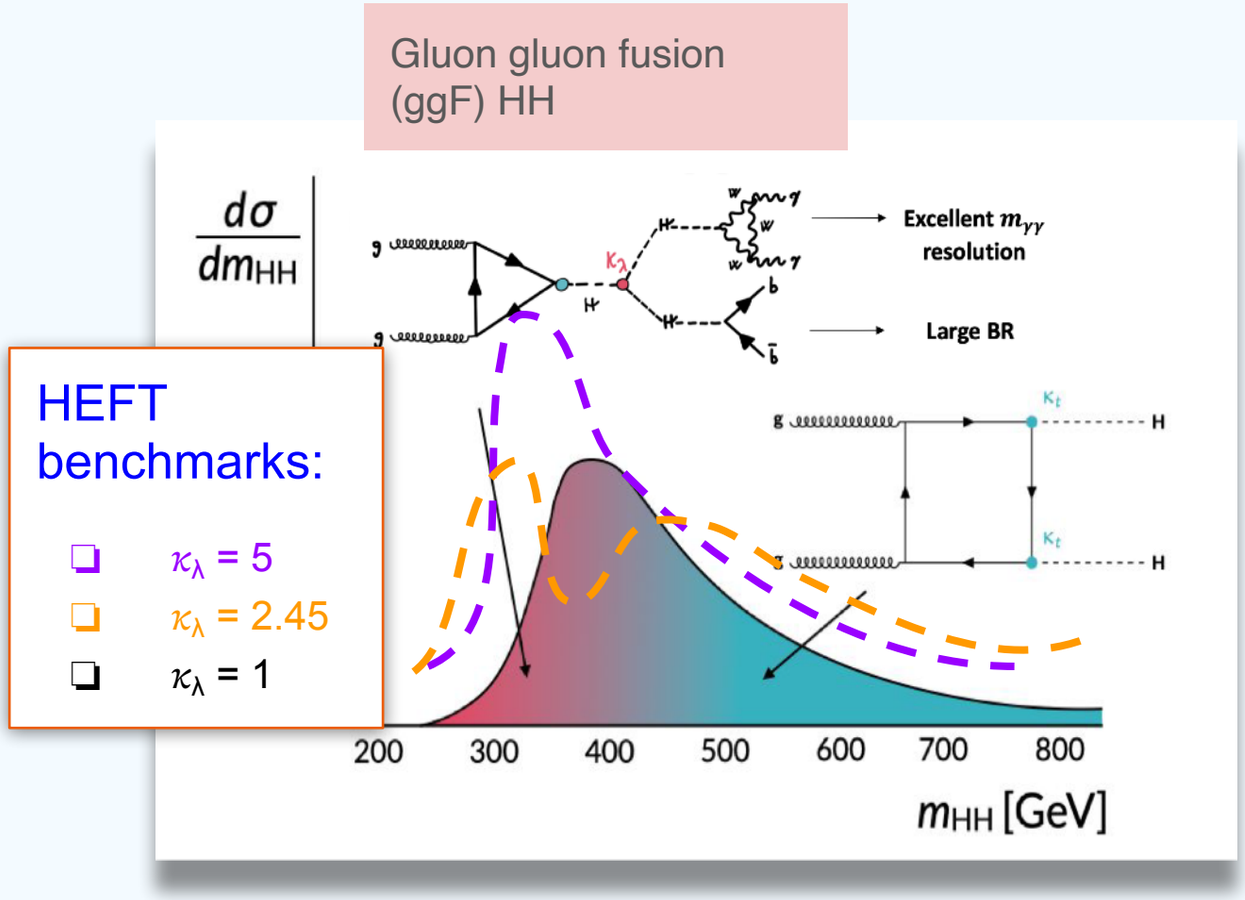
bbγγ in a nutshell



Tiny branching ratio ~0.26%, still a golden channel

Easy to trigger, good mass resolution (~1-2%), high S/B

Gluon gluon fusion (ggF) HH



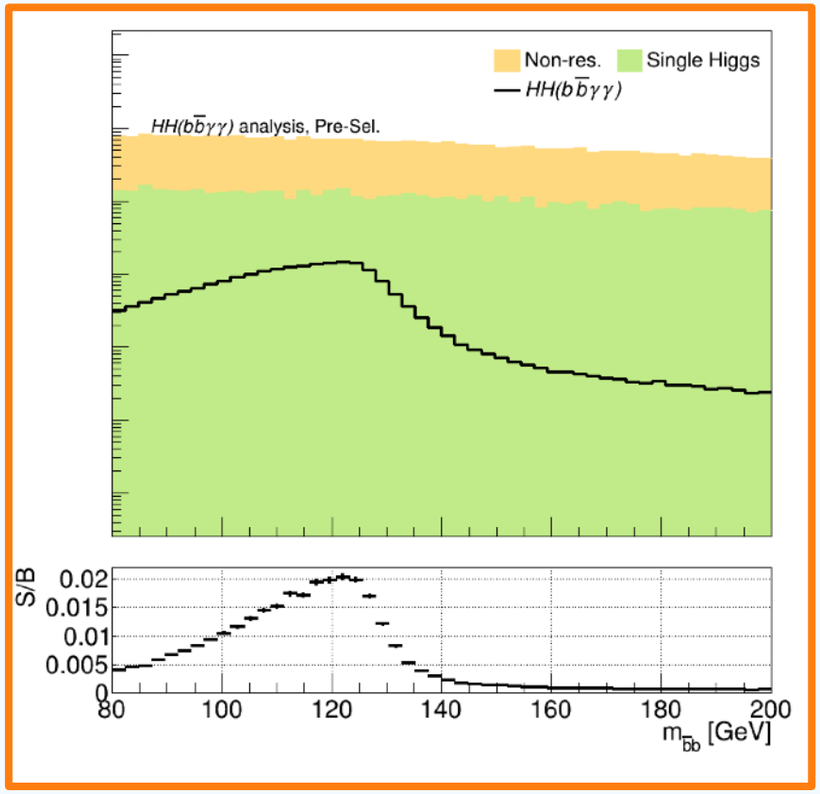
Triangle diagram dominates at low M_{HH}

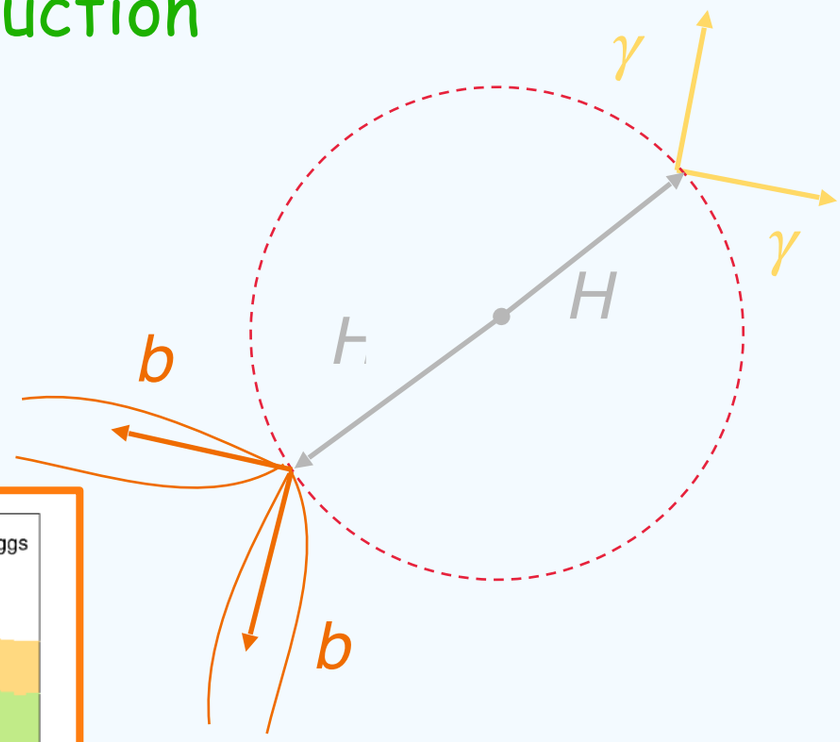
⇒ Excellent sensitivity to variations in κ_λ

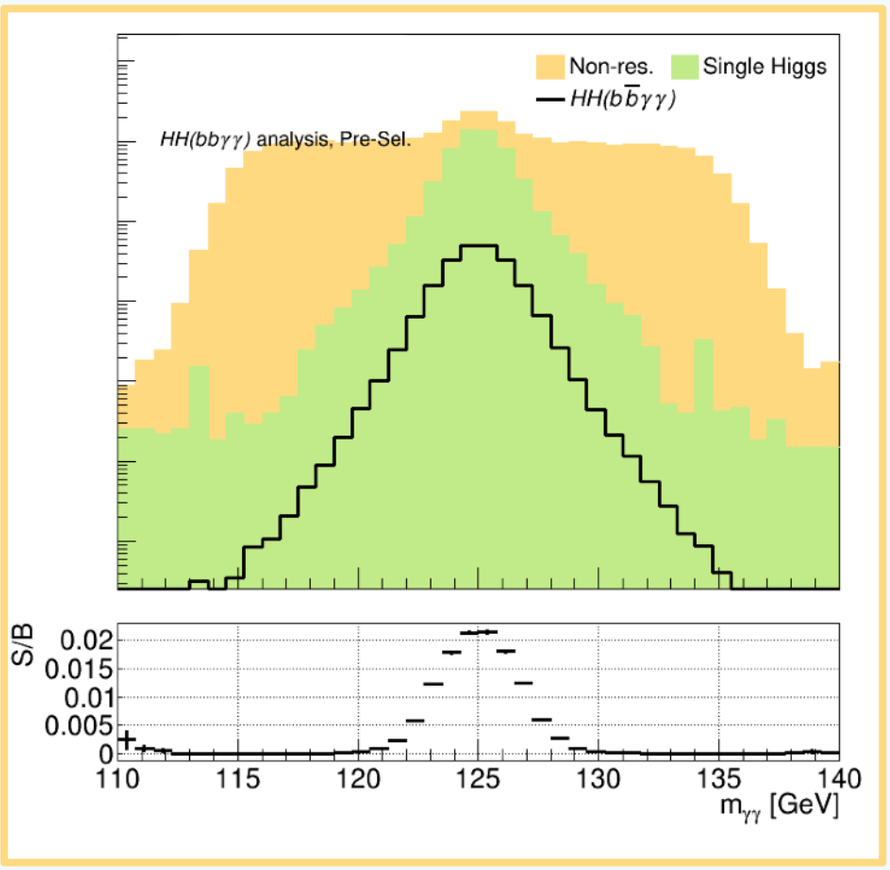
bbγγ in a nutshell

Backgrounds:

- Non-resonant QCD: γγ+jets and γ+jets
- Single Higgs production







Mass resolution is extremely good, there are mainly two approaches to this analysis:

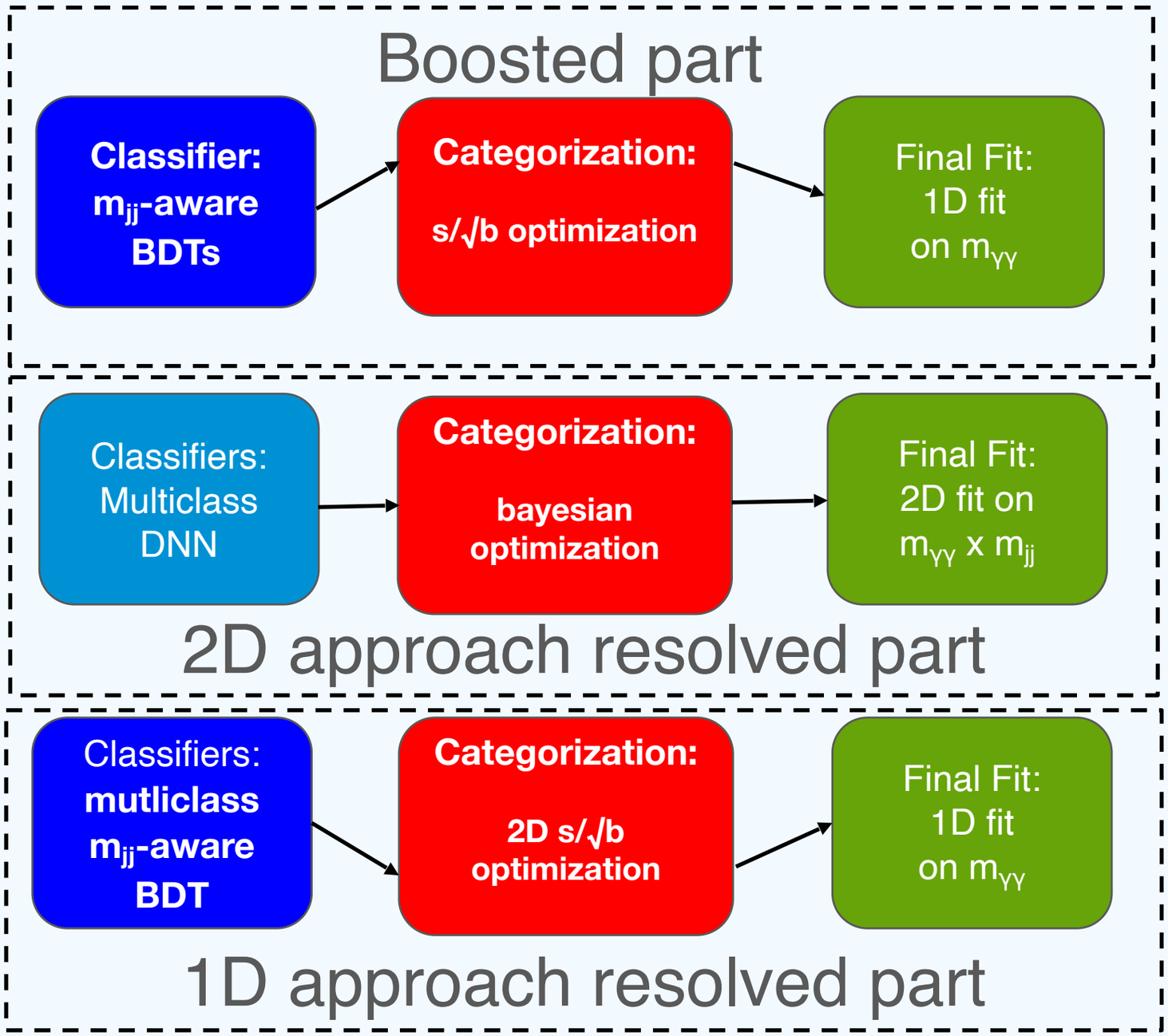
- Use the m_{jj} informations as input in a DNN and fit the $m_{\gamma\gamma}$ only (1D approach — ATLAS)
- DNN agnostic from mjj, fit simultaneously $m_{\gamma\gamma}$, m_{jj} (2D approach — CMS)

bbγγ analysis strategy: CMS

Two complementary approaches

- 1D approach:
  - multivariate BDT in which the m_{jj} information is explored at the ML level
  - Fit of $m_{\gamma\gamma}$
- 2D approach:
  - multivariate DNN, agnostic from m_{jj}
  - Fit simultaneously ($m_{\gamma\gamma}$ and m_{jj})

- **Boosted category** that complements both fitting approaches



CMS-PAS-HIG-25-007

bbγγ analysis strategy: CMS

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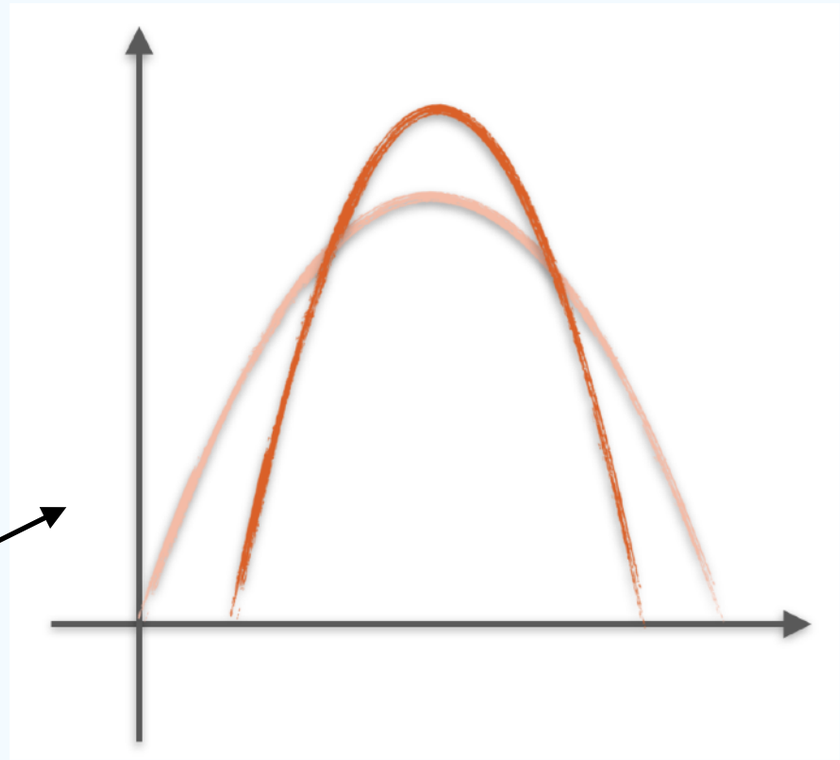


Custom mbb regression implied in this channel → improvement of ~10% in the resolution

- Boosted category that complements both fitting approaches

bbγγ analysis strategy: classifiers

Single DNN model with 4 output classes:

- Nonresonant bkgs (Data driven QCD + γ+jets, γγ+tt/jets)
- ttH
- Other single H bkgs (ggH, bbH, VBFH, VH)
- Single: SM ggHH

Preprocessing:

- mγγ/mjj - decorrelation to allow for a 2D fit.

Architecture:

- 5 hidden layers, 1024 neurons each, ELU activation

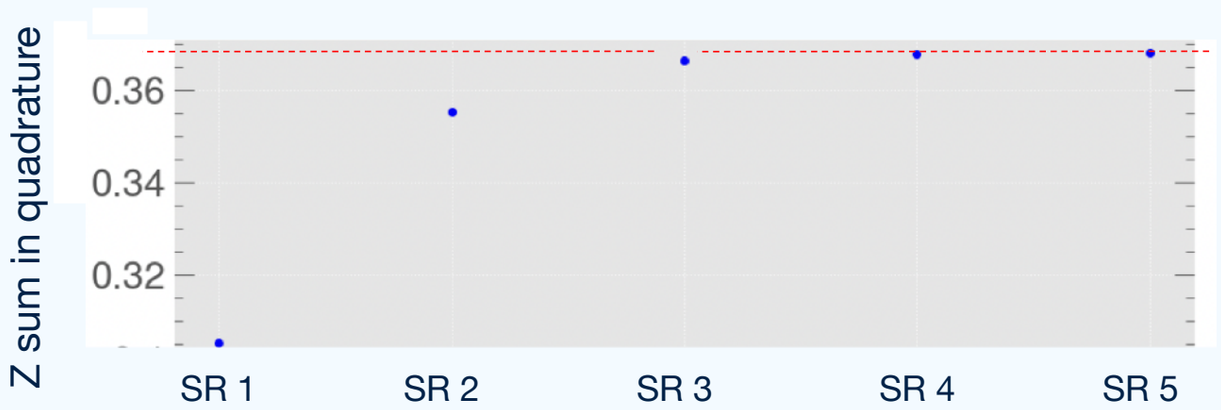
bbγγ analysis strategy: categorization

Signal Region optimization

- Maximise the asymptotic significance (Z) computed purely by MC samples + Data driven estimate

$$Z = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]}$$

- **Sequentially optimising** the SR boundaries, by choosing lower-cuts (upper-cuts) for the ggF HH score (to reject other processes)
  - Progressively add more SRs until the summed-in-quadrature significance plateaus



➡ Cumulative significance plateaus after 3 SRs

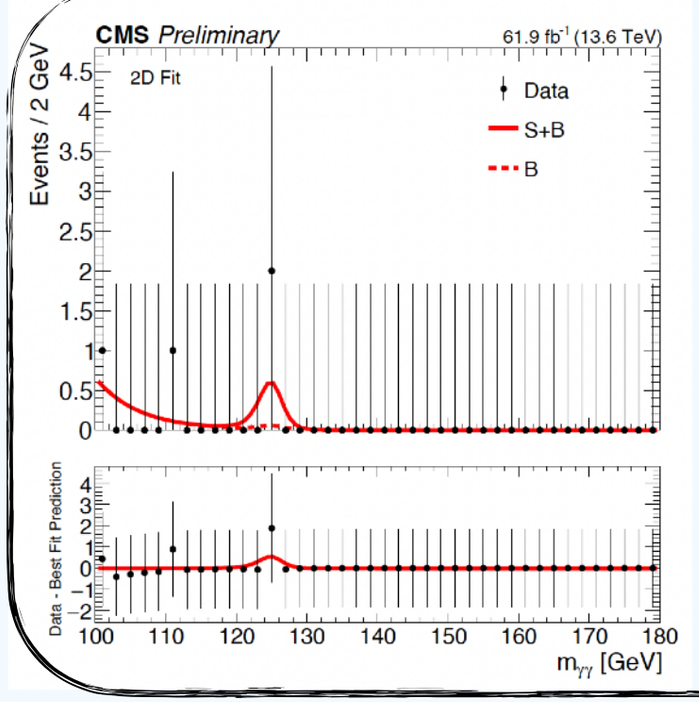
bbγγ final fits

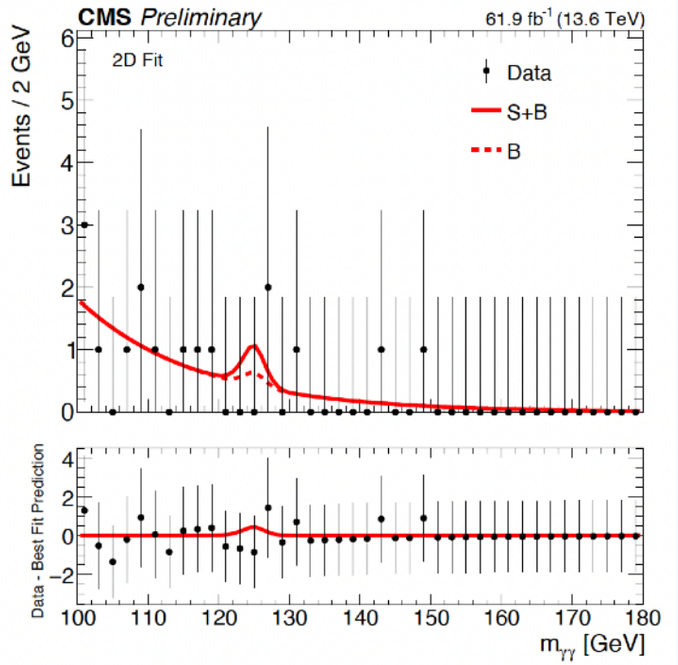
For the resolved topology we perform:

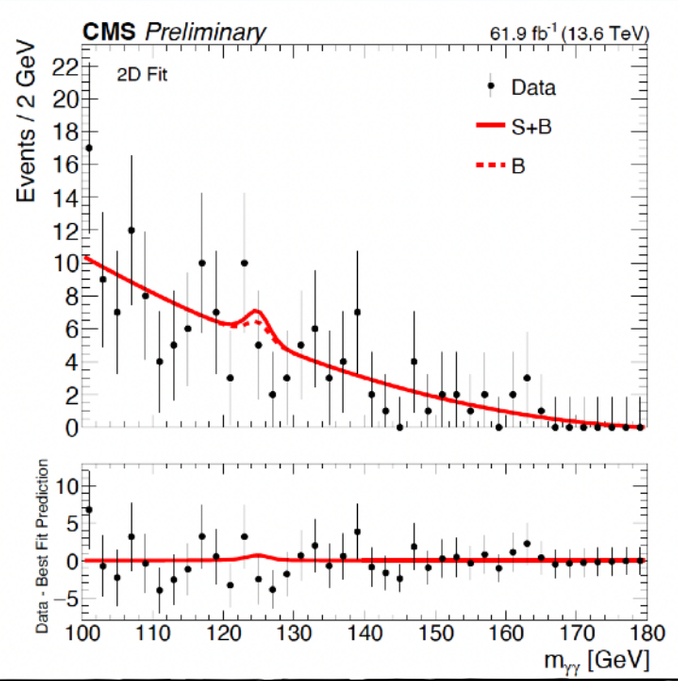
- Fit in the $m_{\gamma\gamma}$ leg:
  - Non-resonant background: family of smoothly falling functions + envelope method
  - Resonant bkg + signal: fitted with sum of gaussians
- Fit in the m_{bb} leg:
  - Non-resonant background: family of smoothly falling functions + envelope method
  - ttH + VH + signal: fitted with sum of gaussians
  - VBFH + singleH: fitted with an exponential

bbγγ postfits

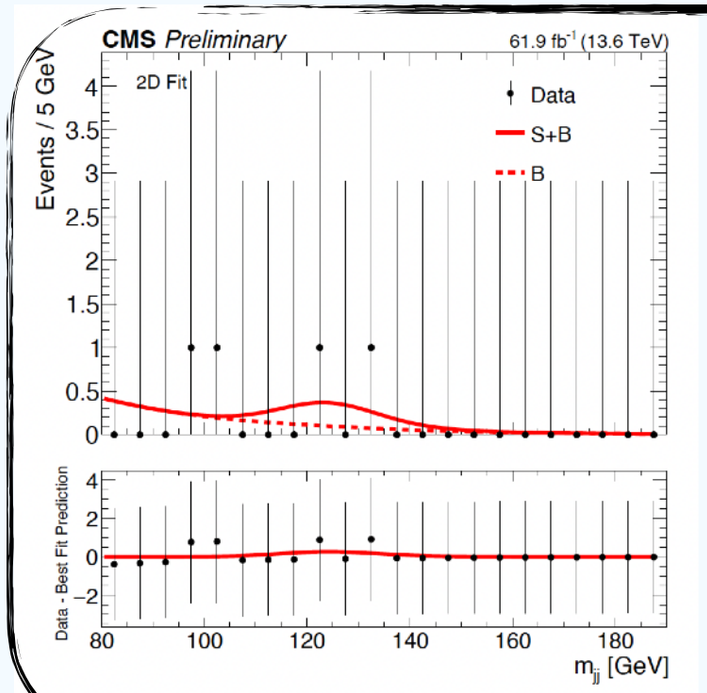
For the resolved topology we perform:

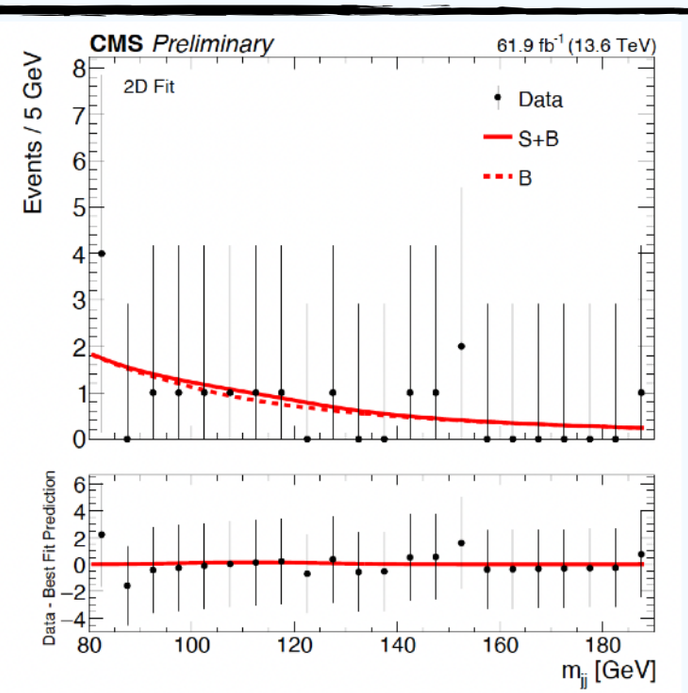


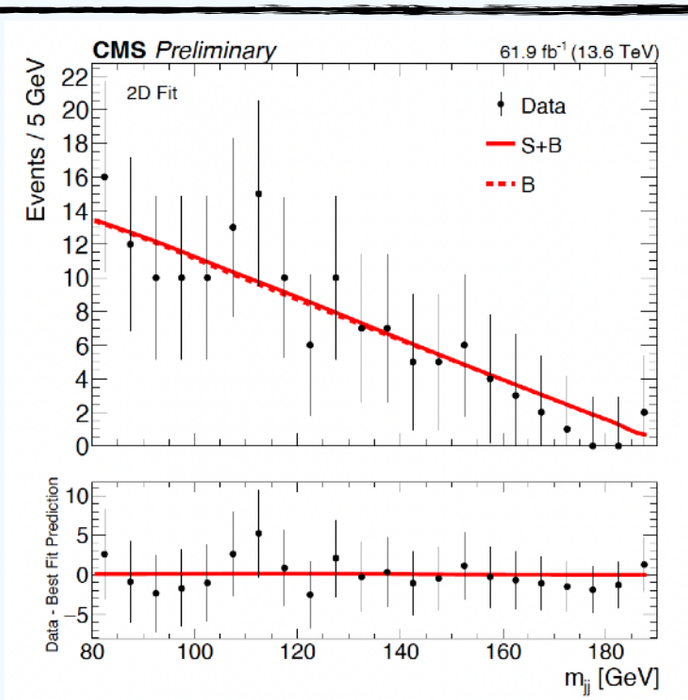




$m_{\gamma\gamma}$ leg







mbb leg

Less sensitive

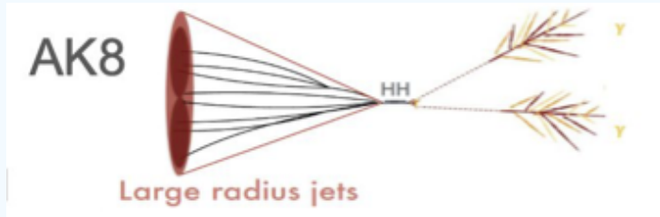
CMS-PAS-HIG-25-007

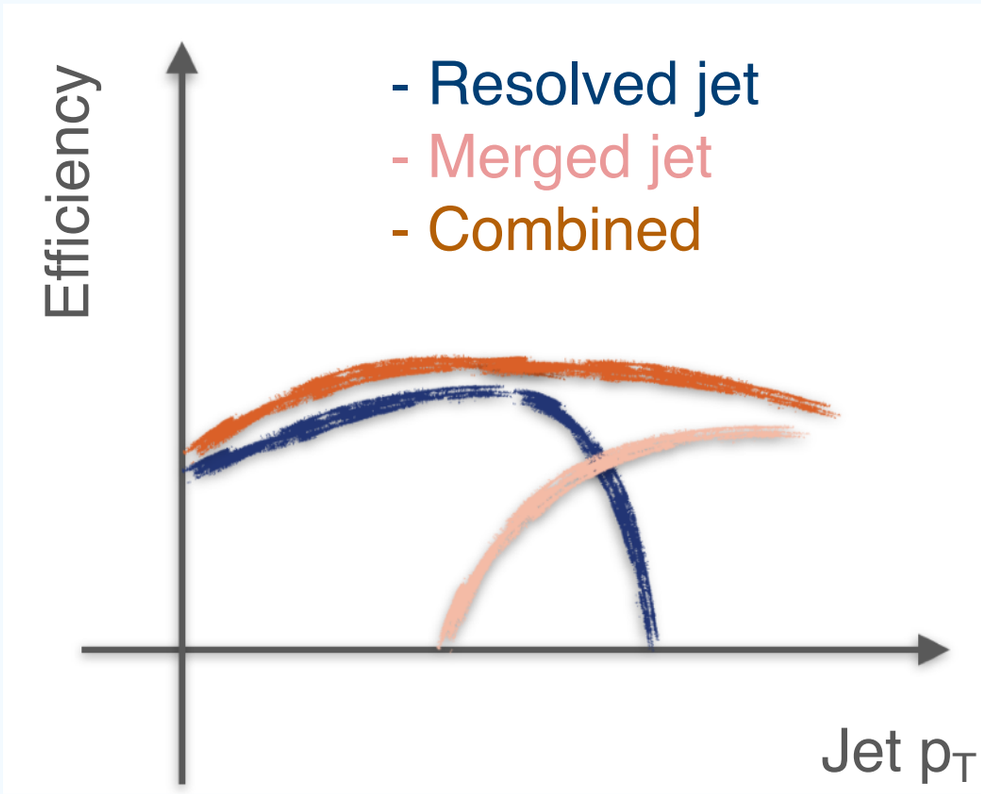
bbγγ analysis strategy: boosted category

- The boosted Higgs tagging can significantly enhance significance, and it represents a **novelty** wrt previous CMS/ATLAS HH→bbγγ results

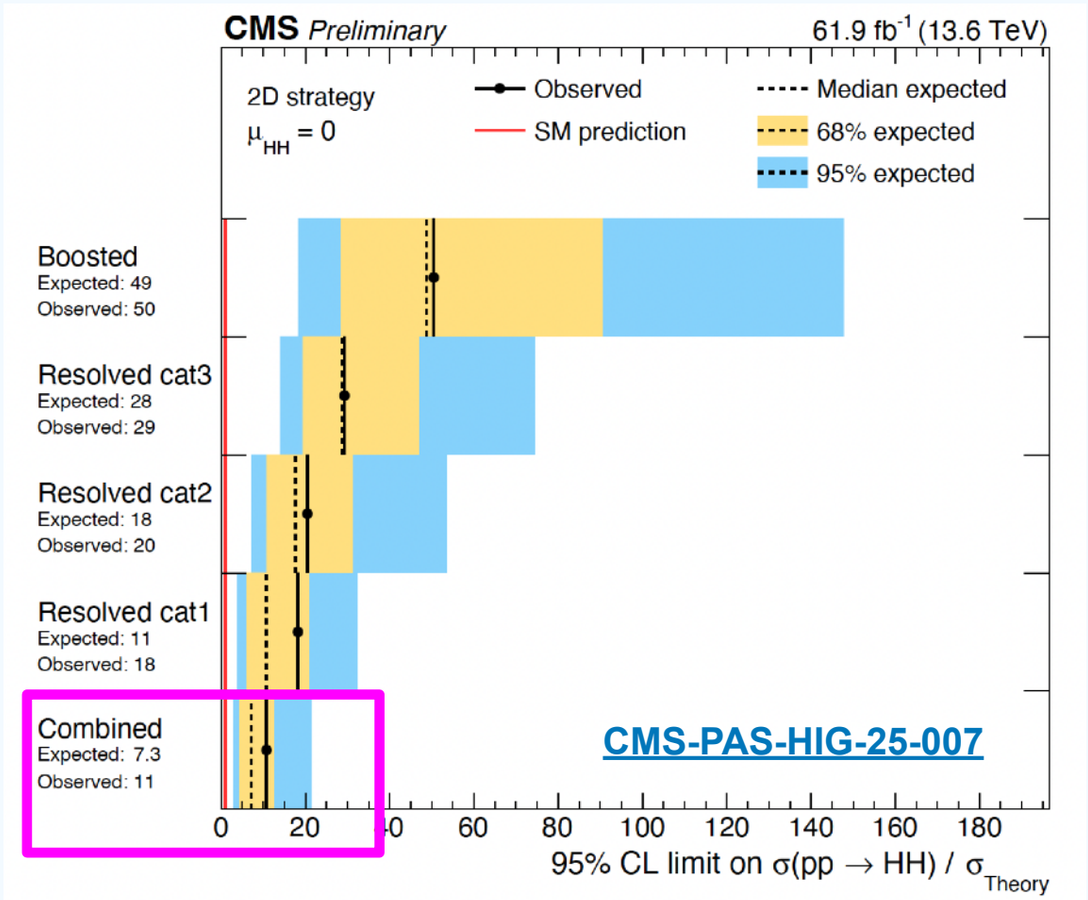
- We investigated the potential sensitivity gains from having a separate boosted Higgs category

- "boosted aware" categorization procedure
  - Boosted category prioritized over resolved → (merged jet reconstruction of takes precedence over resolved reconstruction if an event can be reconstructed in both ways)





bbγγ analysis strategy: results UL

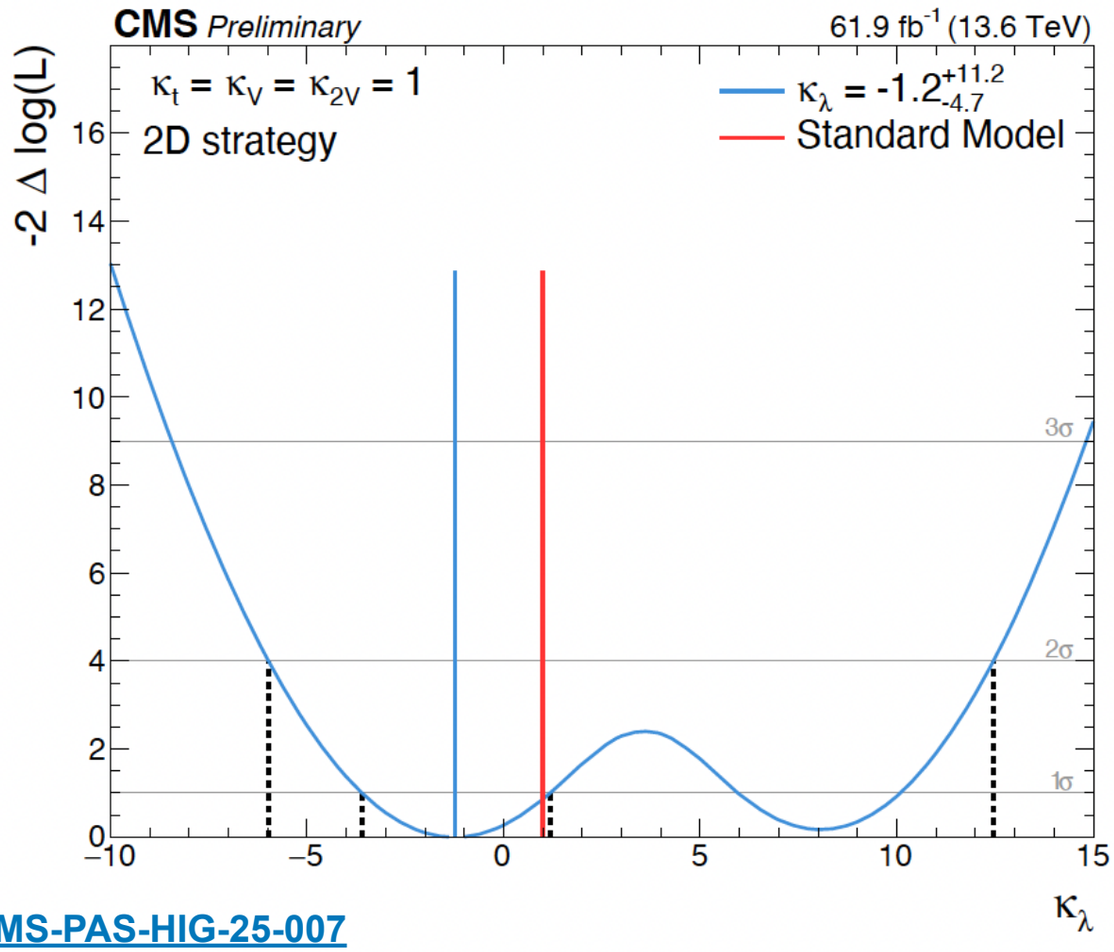


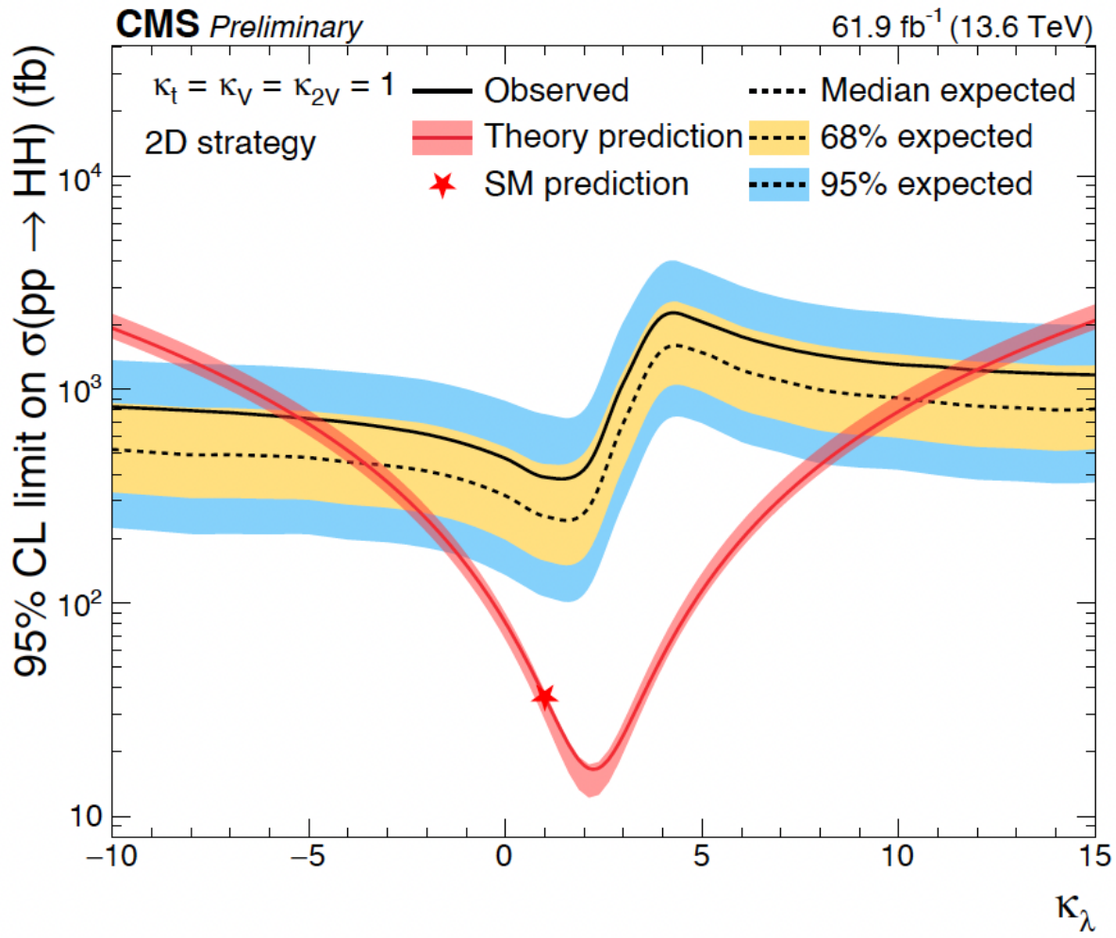
- Sensitivity of the 3 signal region category is shown together with their combination
- Upper limit of **11 (7.3) x SM**

*bbgg Run2 (138 fb-1) result 7.7 (5.2) obs (exp) xSM with >2x lumi, very promising results

*Largest source of systematic uncertainty is the HH theory uncertanty

bbγγ analysis strategy: results k_λ scan





CMS-PAS-HIG-25-007

Allowed κ_λ ranges

- Observed $\kappa_\lambda \in [-5.2, 12.0]$
- Expected $\kappa_\lambda \in [-3.6, 10.5]$

bbγγ analysis strategy: summary

- With this early run3 results we achieved 7x SM with just half of the dataset implied in run2 → very promising result!!!

What's new????

Two complementary approaches explored at the same time

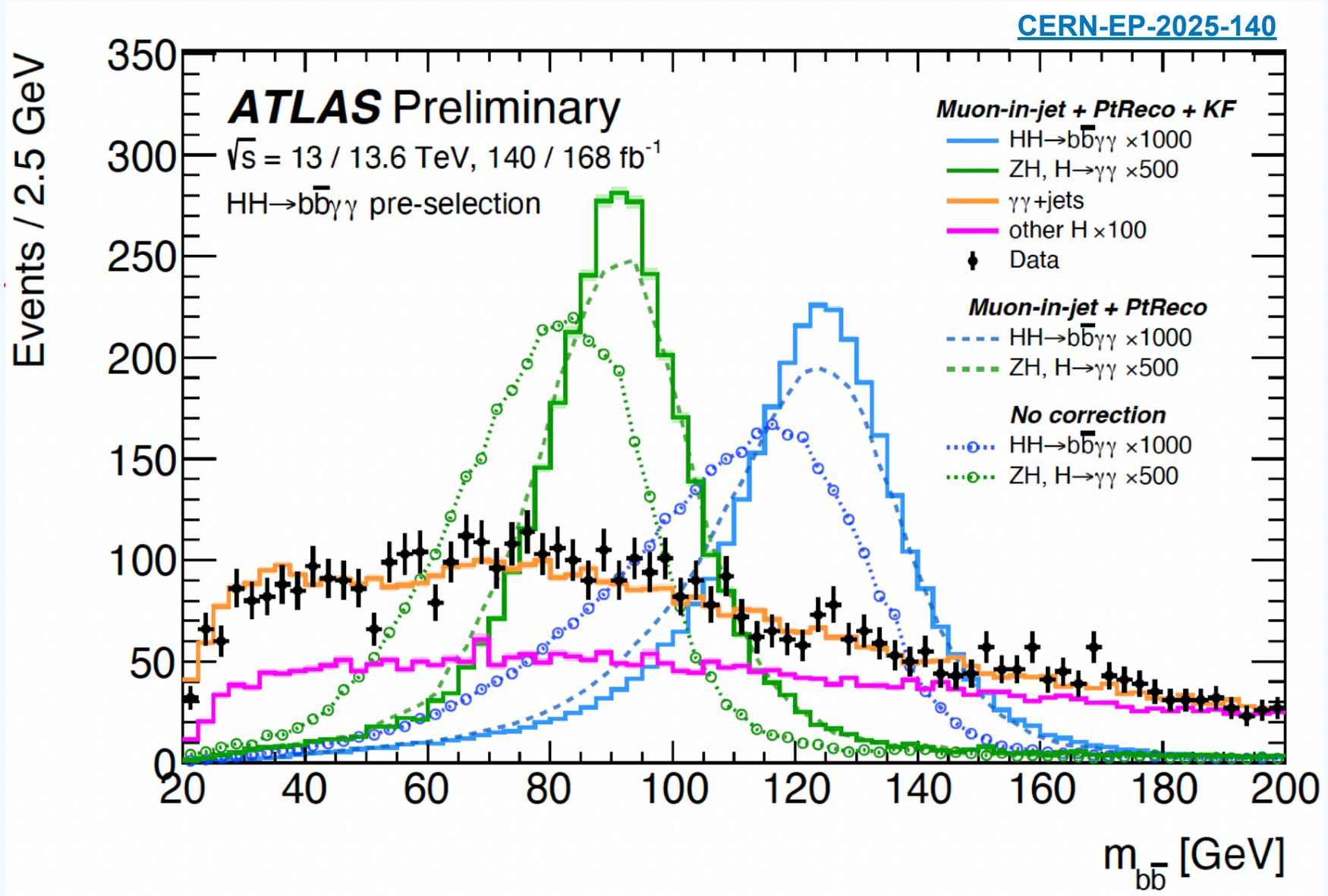
- 1D approach: multivariate BDT in which the m_{jj} information is explored at the ML level → Fit of $m_{\gamma\gamma}$
- 2D approach: multivariate DNN, agnostic from m_{jj} → Fit simultaneously ($m_{\gamma\gamma}$ and m_{jj})
- Both of them are complemented with a **boosted category**

Stay tuned!!! Many more to come!!!

bbγγ analysis strategy: ATLAS

New kinematic likelihood fit procedure introduced to improve mbb resolution.

- Jet momentum varied within experimental resolution
- Exploits momentum balance against the well-reconstructed photons
- First iteration for unbiased estimate of mbb
- Second iteration with constrained mbb to recalculate other variables

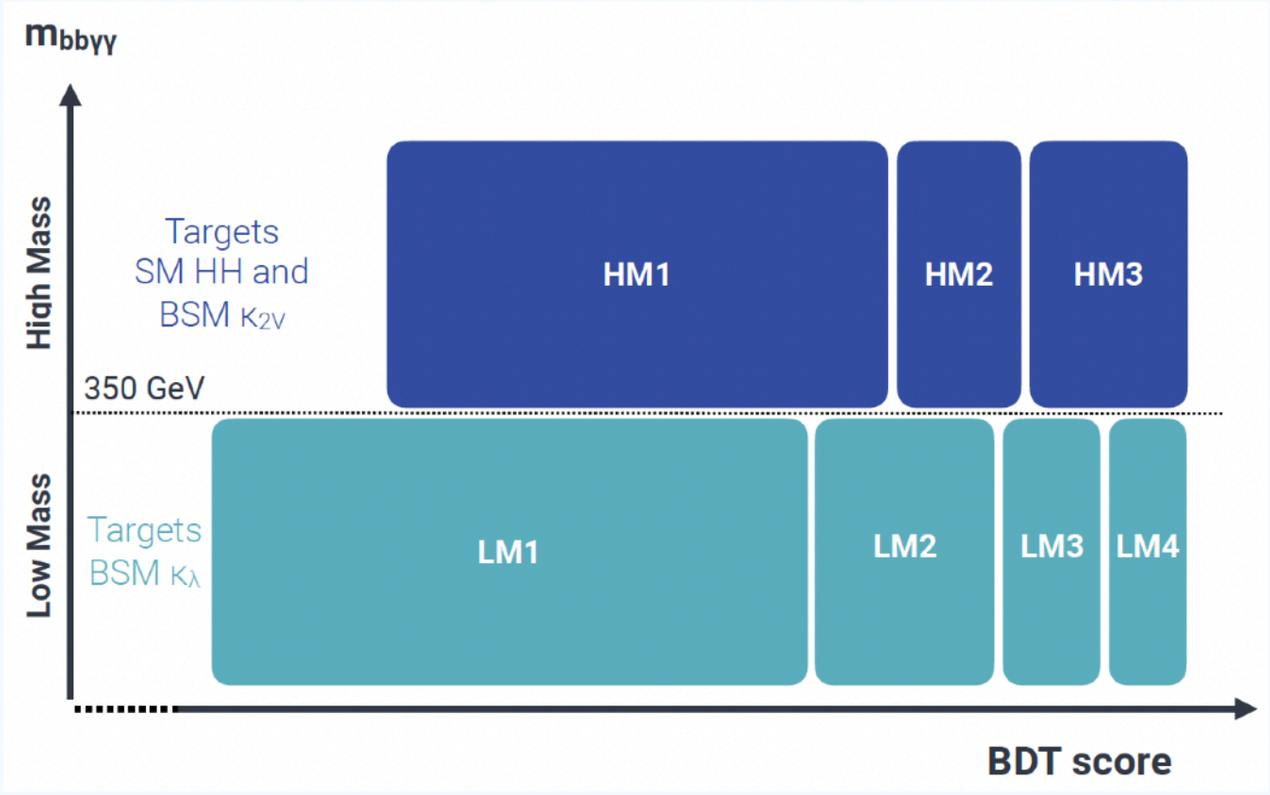


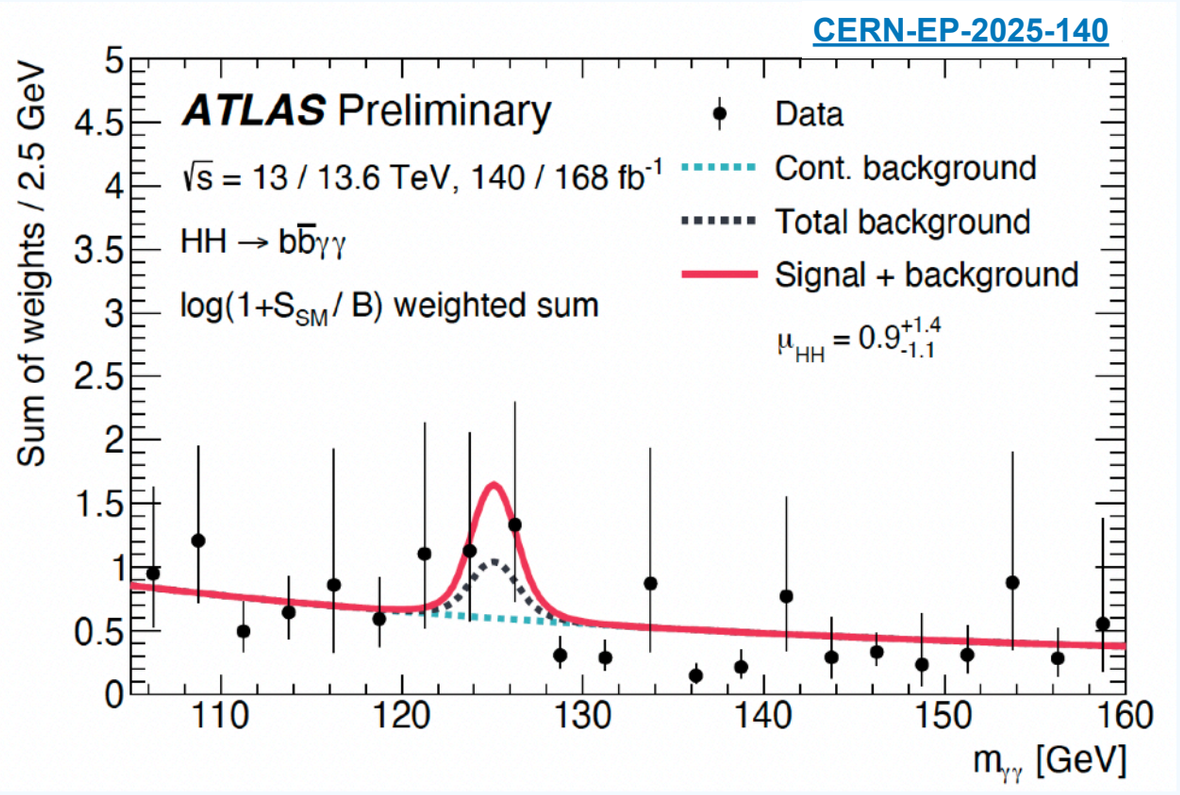
46% improvement on mHH resolution

5% improvement on expected significance

bbγγ analysis strategy: ATLAS

- Separate BDTs trained in low and high mass regions
  - Input variables : kinematics of photons, b-jets, bb-system, missing ET, HT, `single-topness'…
- Fit myy distribution in 7 signal regions based on BDT score.

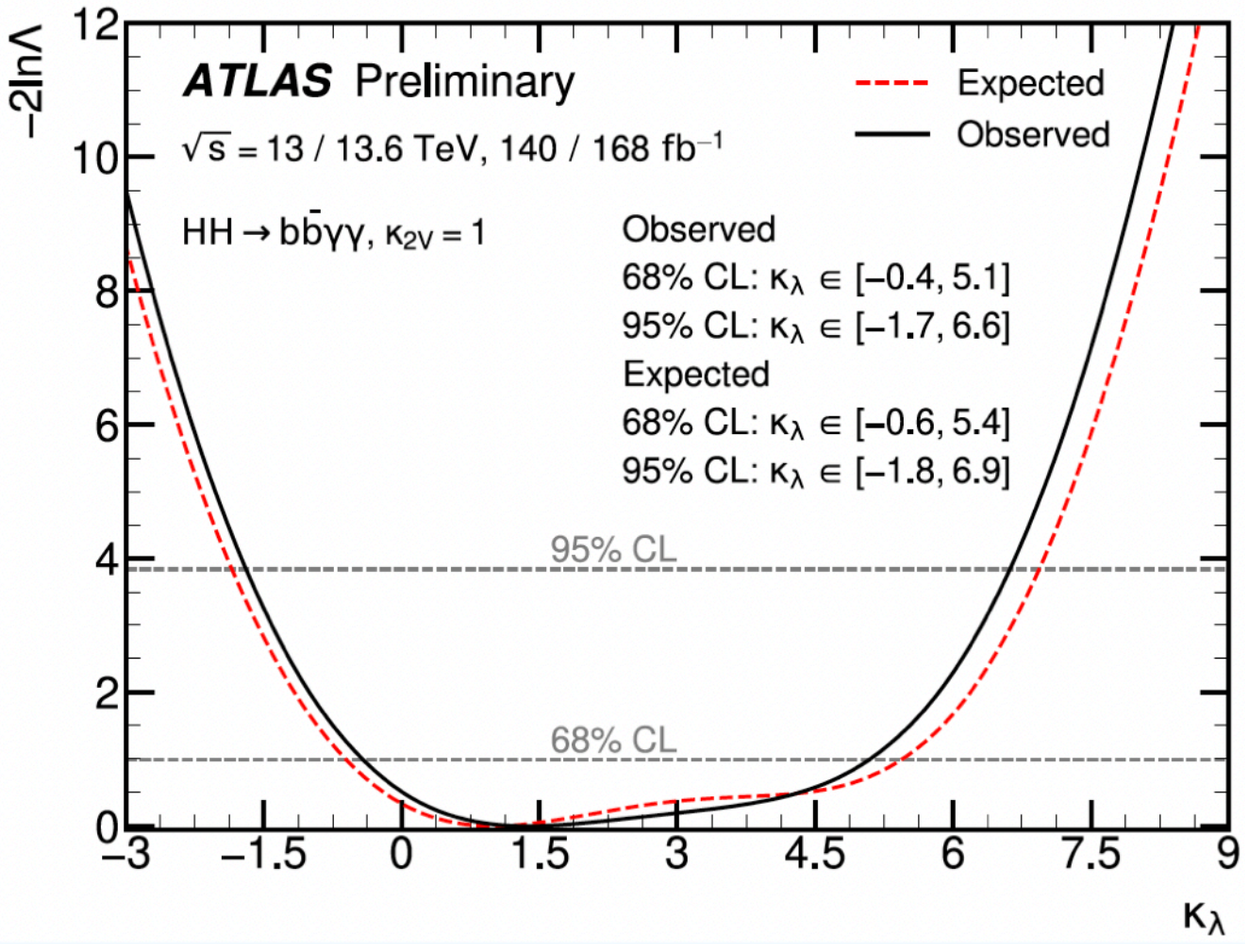


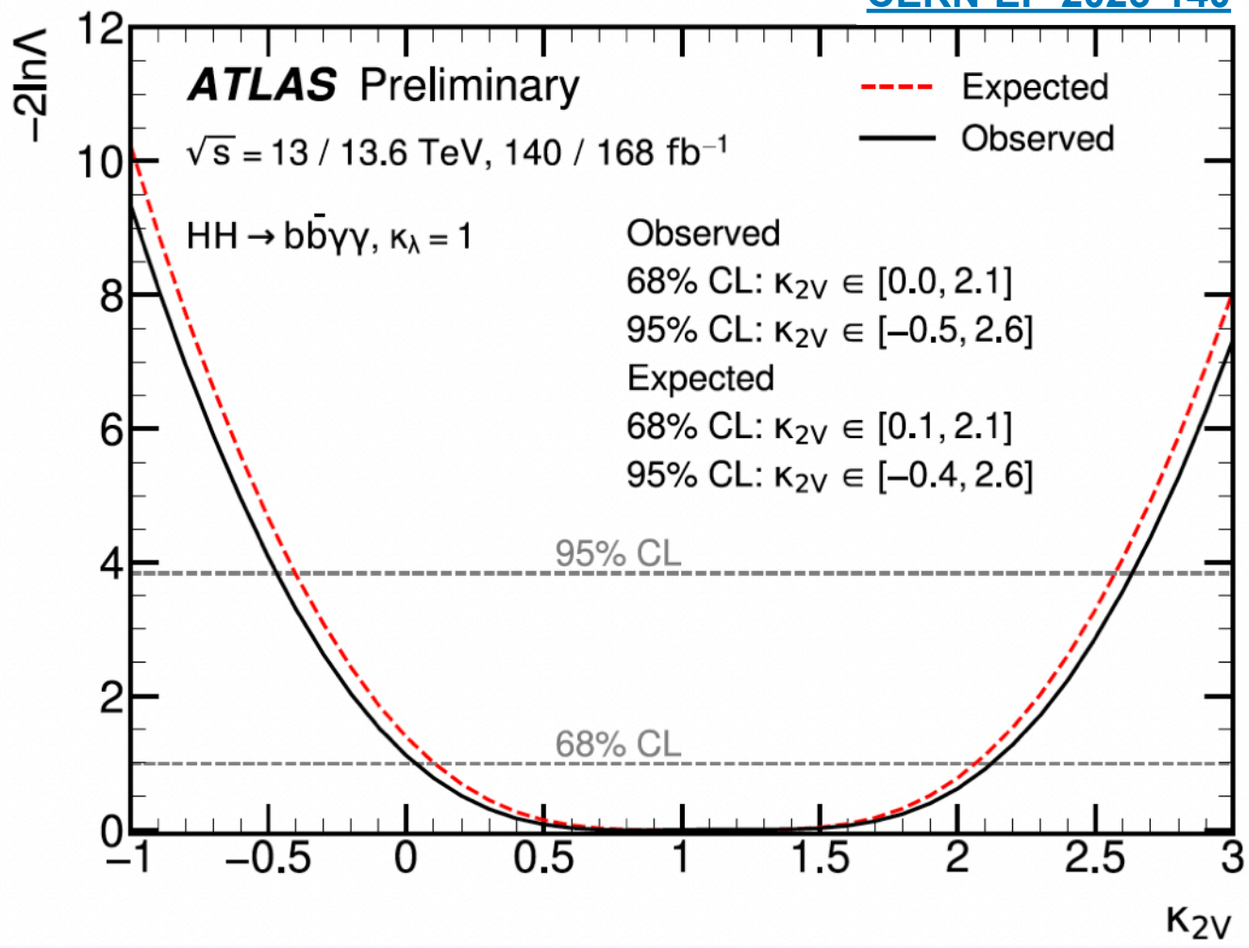


bbγγ analysis strategy: CMS

- Observed signal strength: μ_{HH} = 0.9 +1.4/-1.1
- Expected upper limit on μ_{HH} (assuming μ_{HH} = 0): 2.6 x SM

CERN-EP-2025-140





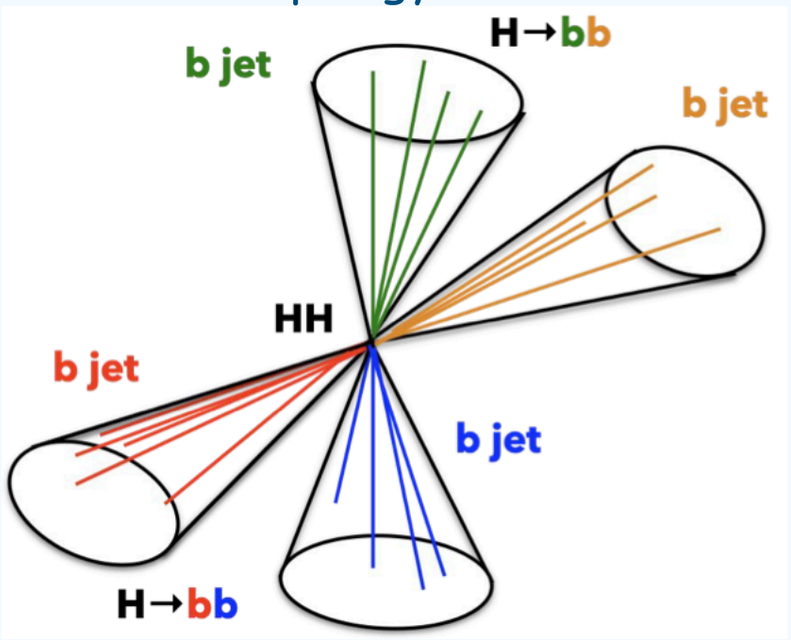
Observed significance of SM HH: 0.8σ

Expected significance: 1.0σ

bbbb analysis in a nutshell

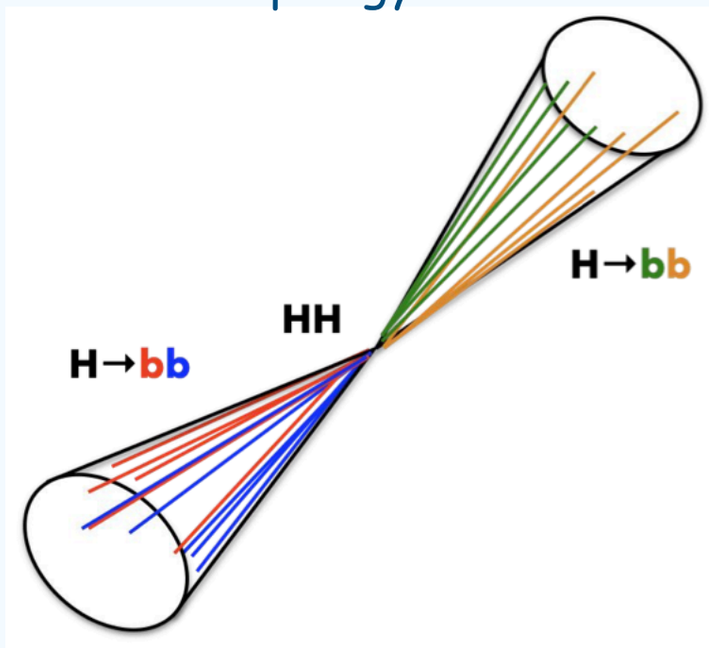
- Despite having the largest branching ratio, this channel is challenged by overwhelming QCD multijet backgrounds
- The QCD background modeled from simulation is limited and lacks higher-order corrections
- A data-driven background estimation becomes crucial for an accurate measurement

Resolved topology



- Separable H decay products (b jets)
- Reconstructed the Higgs candidates from identifie 4 b-tag jets

Boosted topology

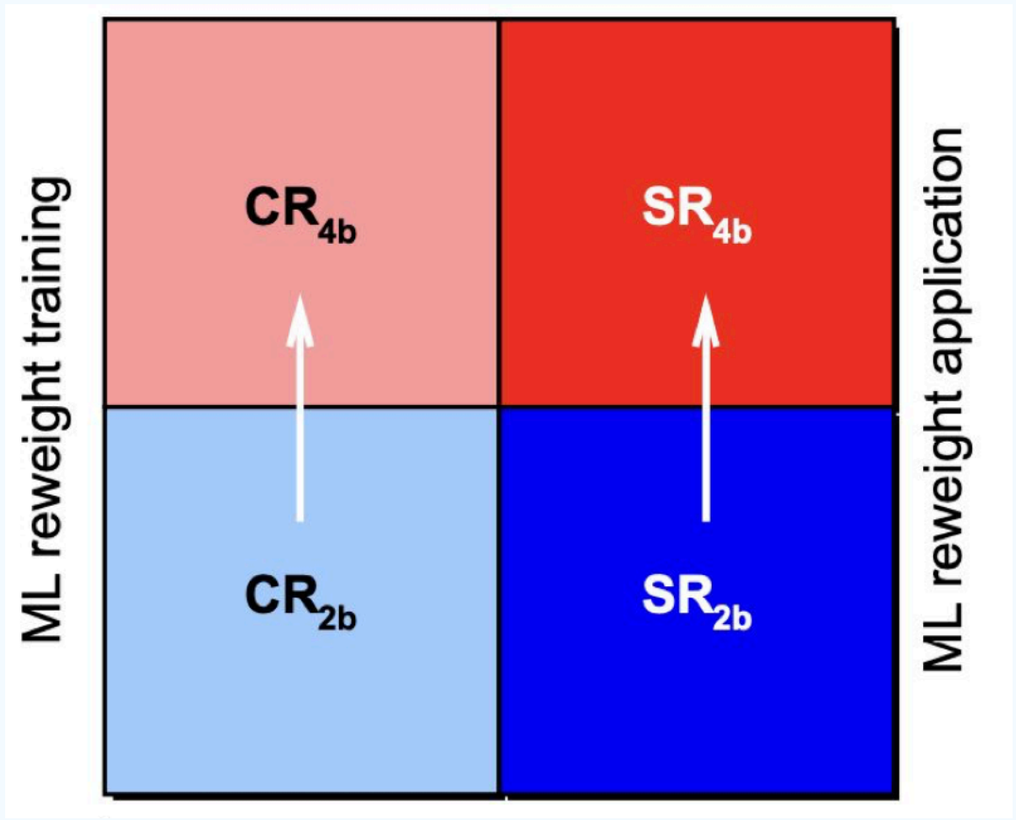


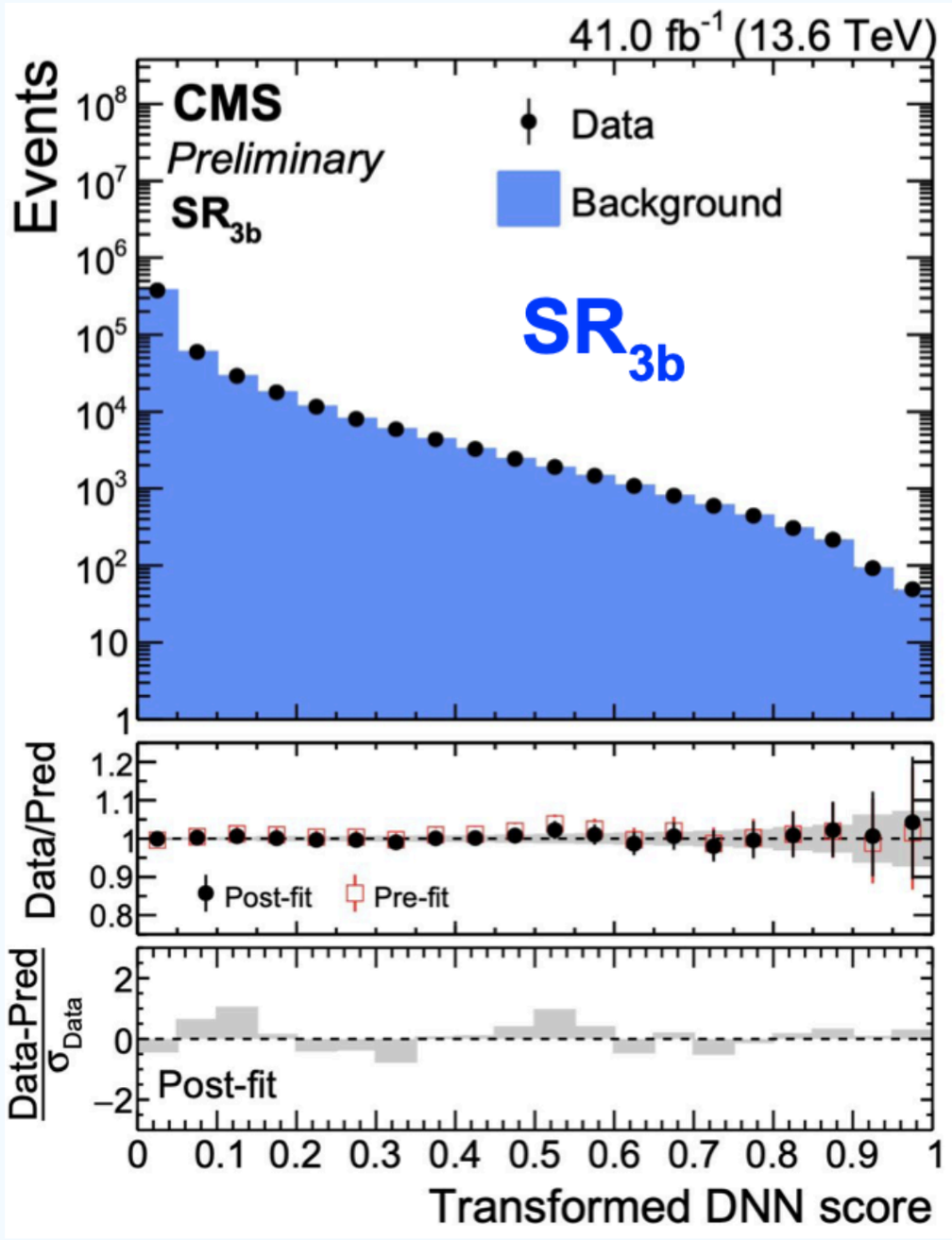
- Both the Higgs candidates are boosted
- Higgs candidates are reconstructed from two jets

bbbb analysis: data-driven bkg estimation

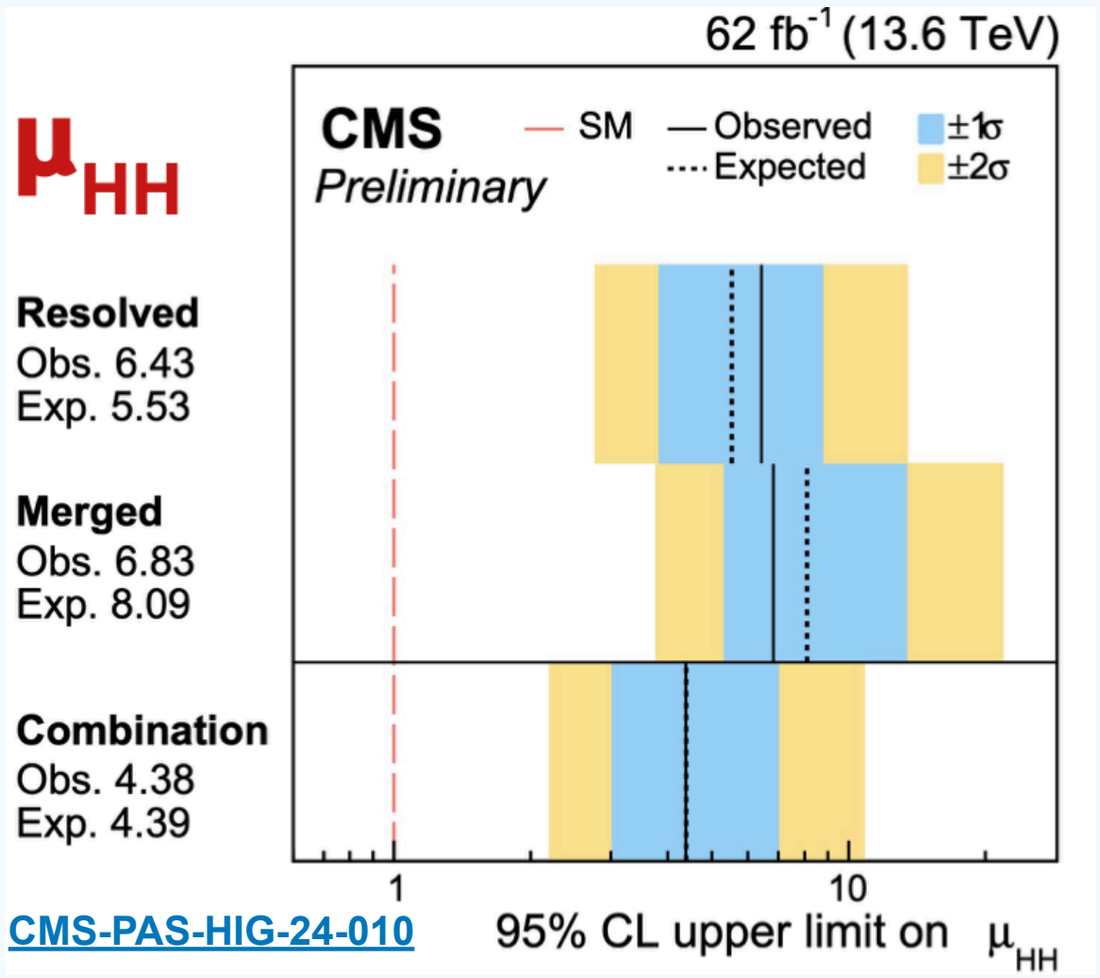
A multi-dimensional background reweighting technique, based on a DNN, is used

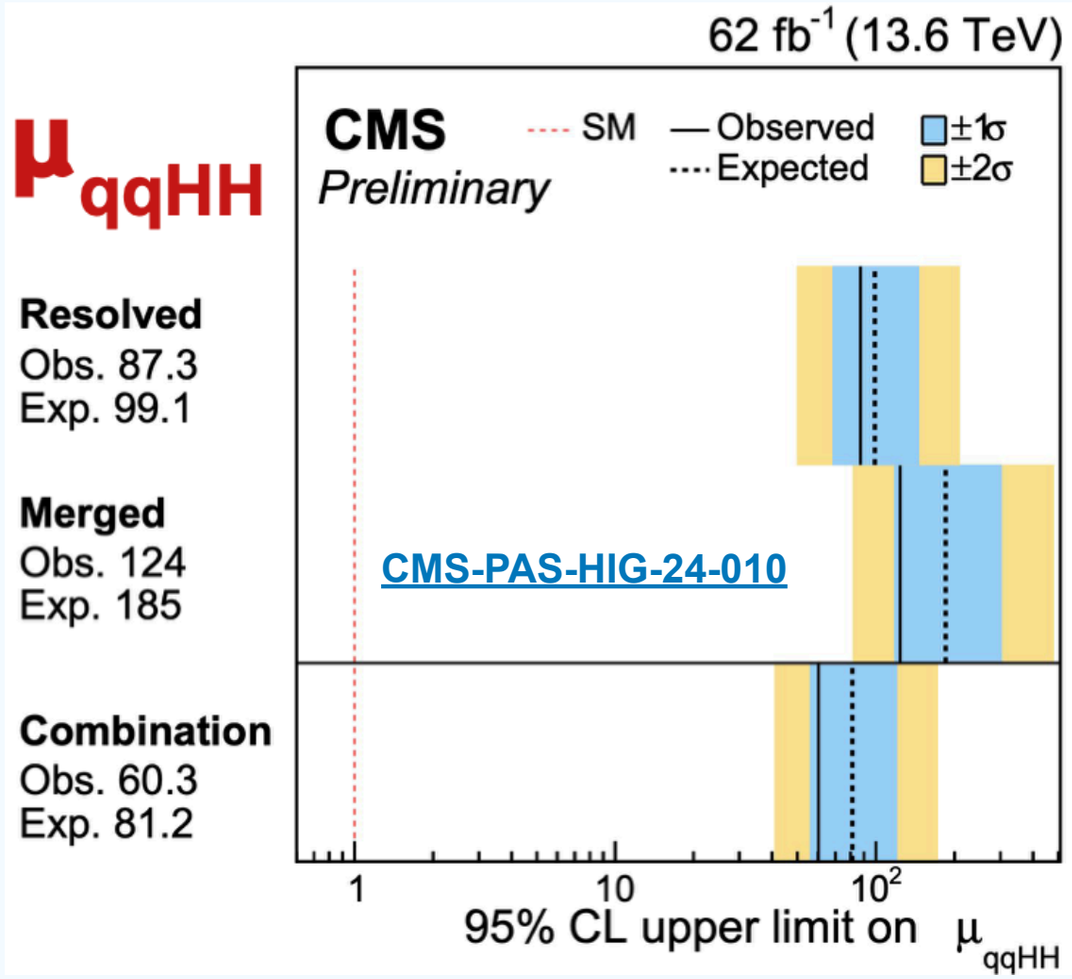
- Trained on the CR2b → CR4b
- Applied to SR2b → SR4b





bbbb analysis: results

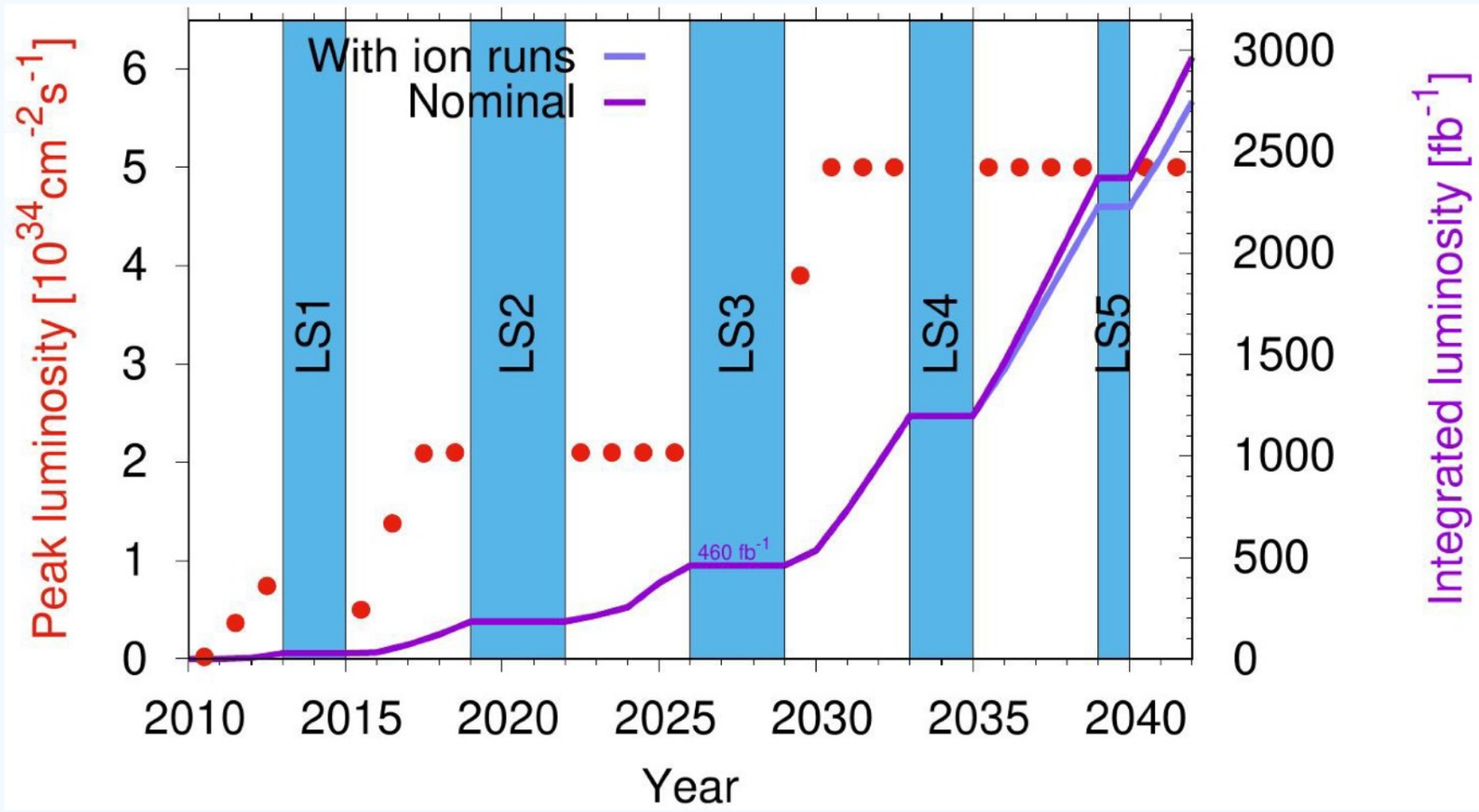




- Combining the resolved & merged 22-23 analyses, we obtain an observed (expected) upper limit of **4.4 (4.4) x SM**, including all uncertainties.
- With 62 fb-1, HH→ 4b achieves a comparable sensitivity with Run 2 (138 fb-1), and better than the Run 2 searches in bb$\gamma\gamma$ and bb$\tau\tau$

HL LHC: 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



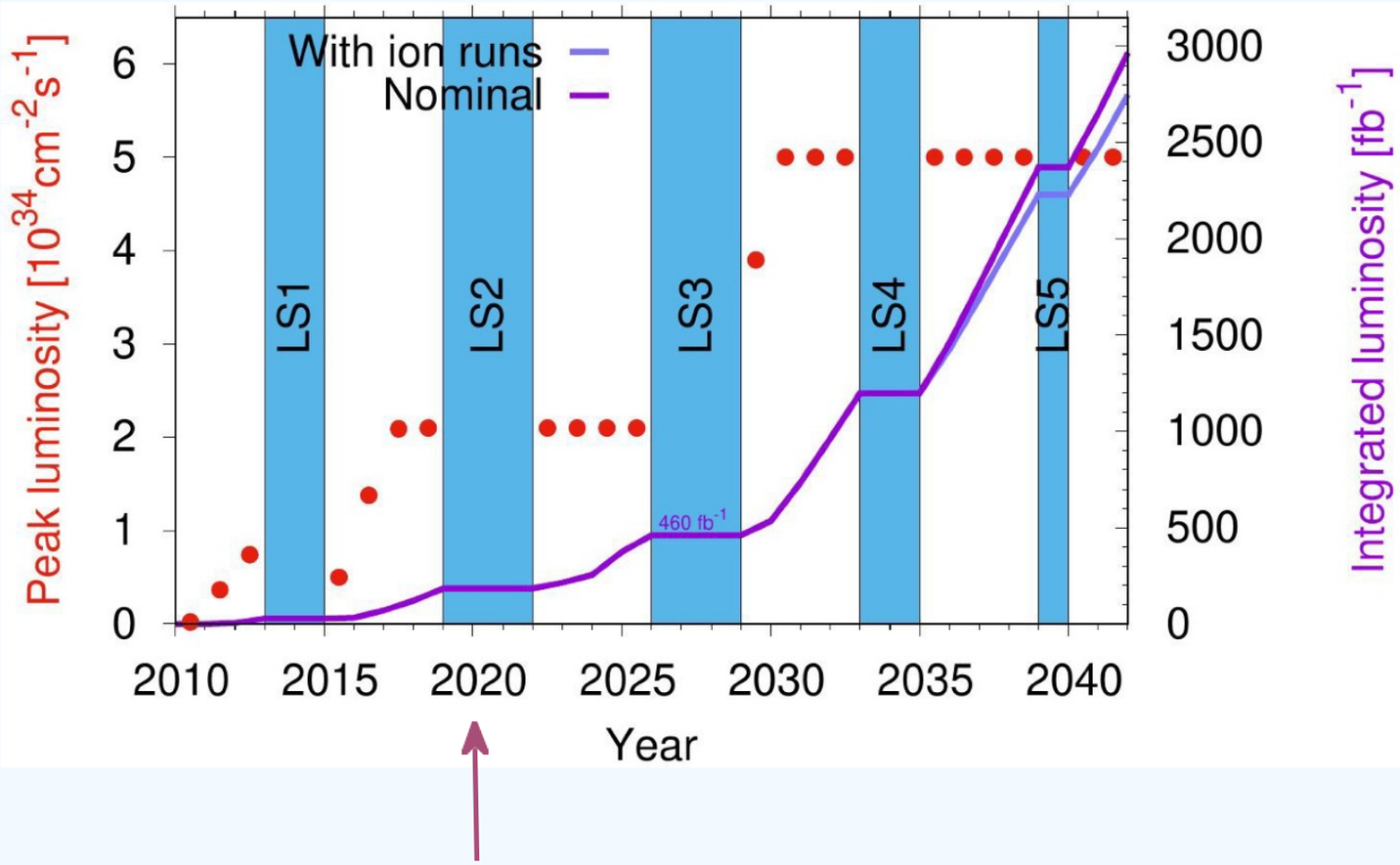
~ 36.7M HH events at 3000 fb^{-1} for CMS+ATLAS

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

Lots of statistics → precise measurements

HL LHC: introduction

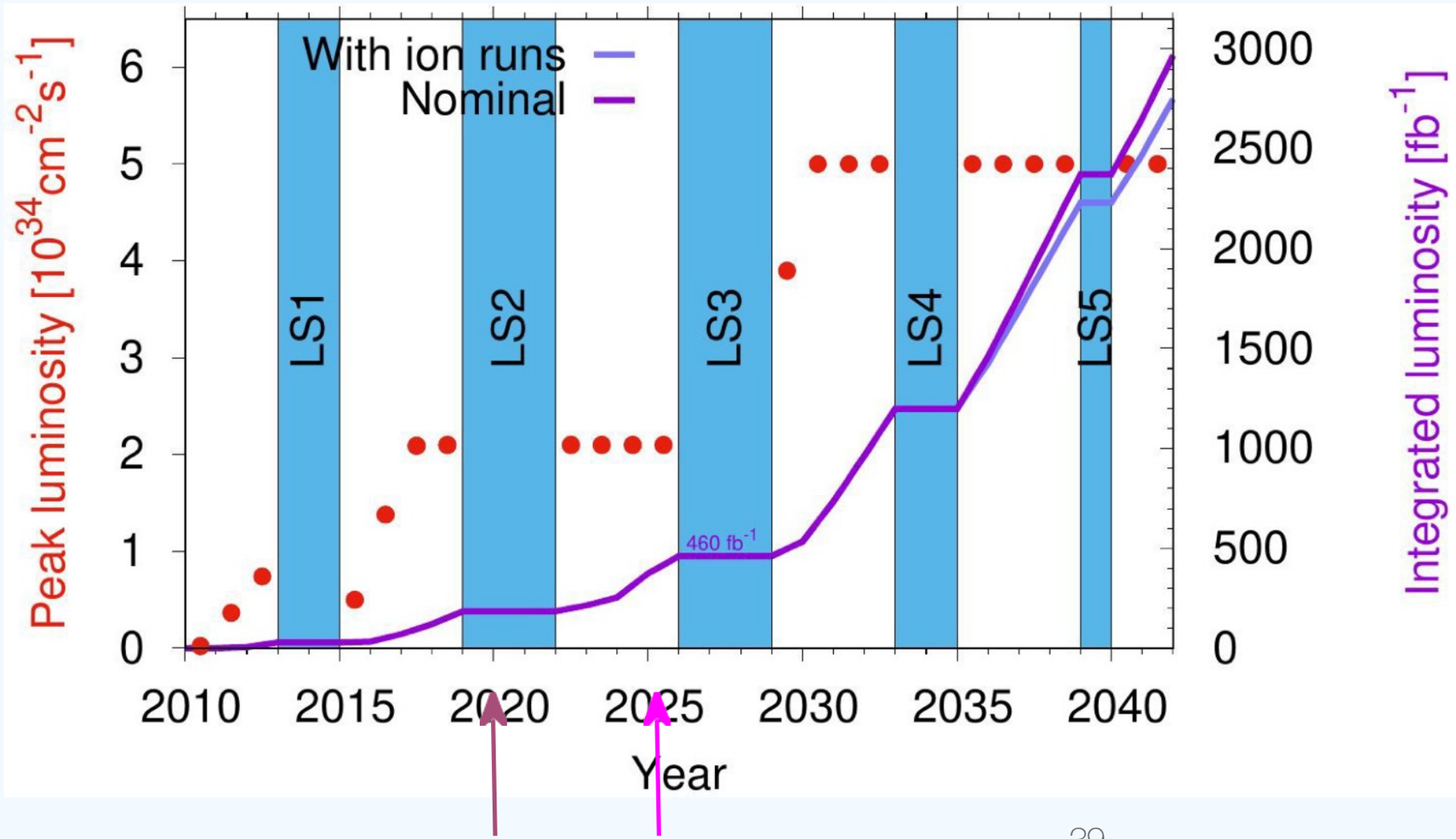
- 3x increase of peak luminosity
  - Data equivalent to **3000 fb^{-1} in 10 years of operation**
  - **Upgraded CMS** detector to cope with higher pileup and radiation damage



- **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

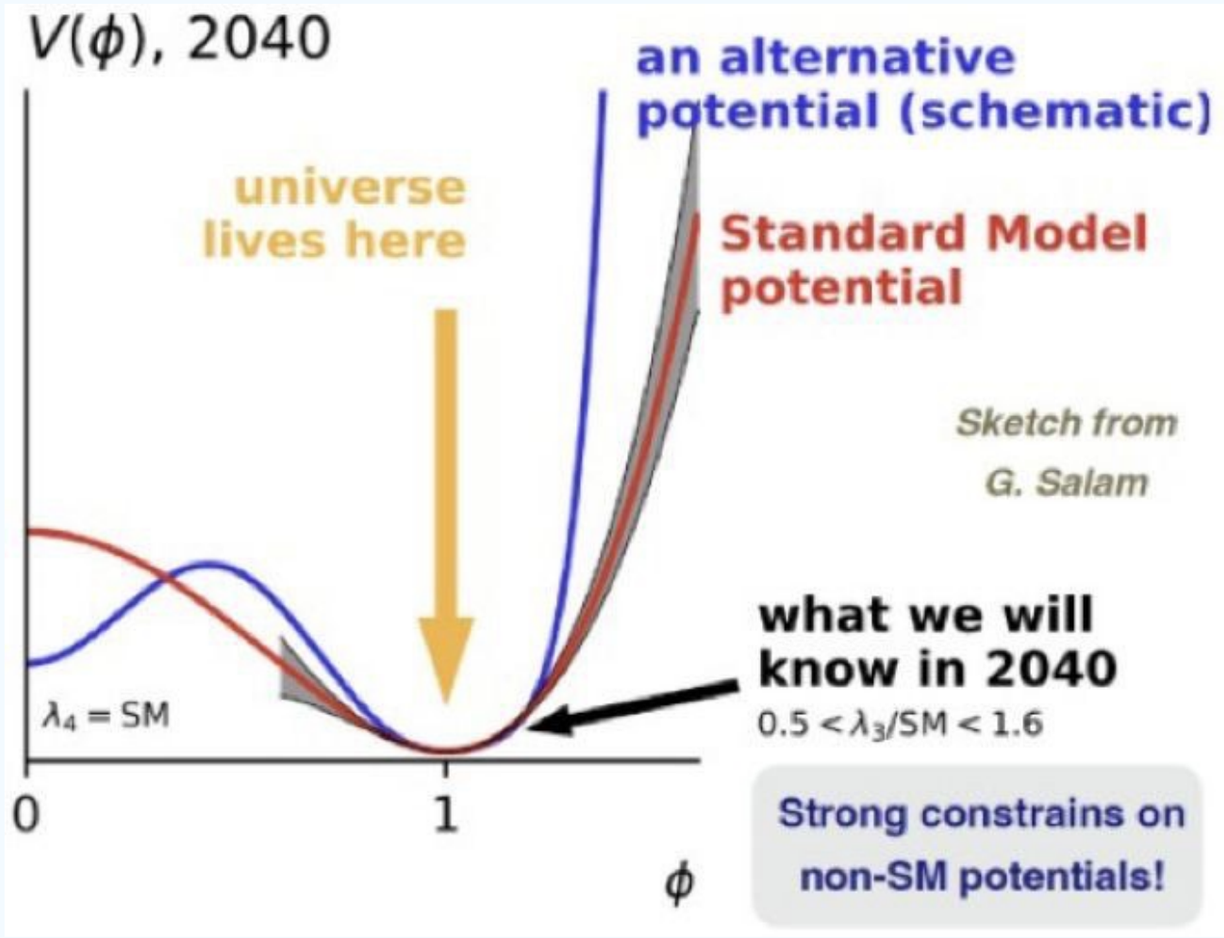
- **We want to emphasize the unique opportunity that HL will give:**
  - more lumi + new analysis technique explored in the past 5 years unique update the expected precision on the Higgs couplings



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



HH results - Significance

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

Channel	HH Significance ATLAS	HH Significance CMS
bbττ	3.8	2.7
bbγγ	2.6	2.6
4b resolved	1.0	1.3
4b boosted	-	2.2
Multilepton	1.0	-
bbℓℓ	0.5	-
Combination	**4.5**	**4.5**
ATLAS + CMS	7.60	

ATL-PHYS-PUB-2025-018 CMS-HIG-25-002

- Evidence with single experiment
- **Combined evidence >7σ**

HH results - k_λ precision

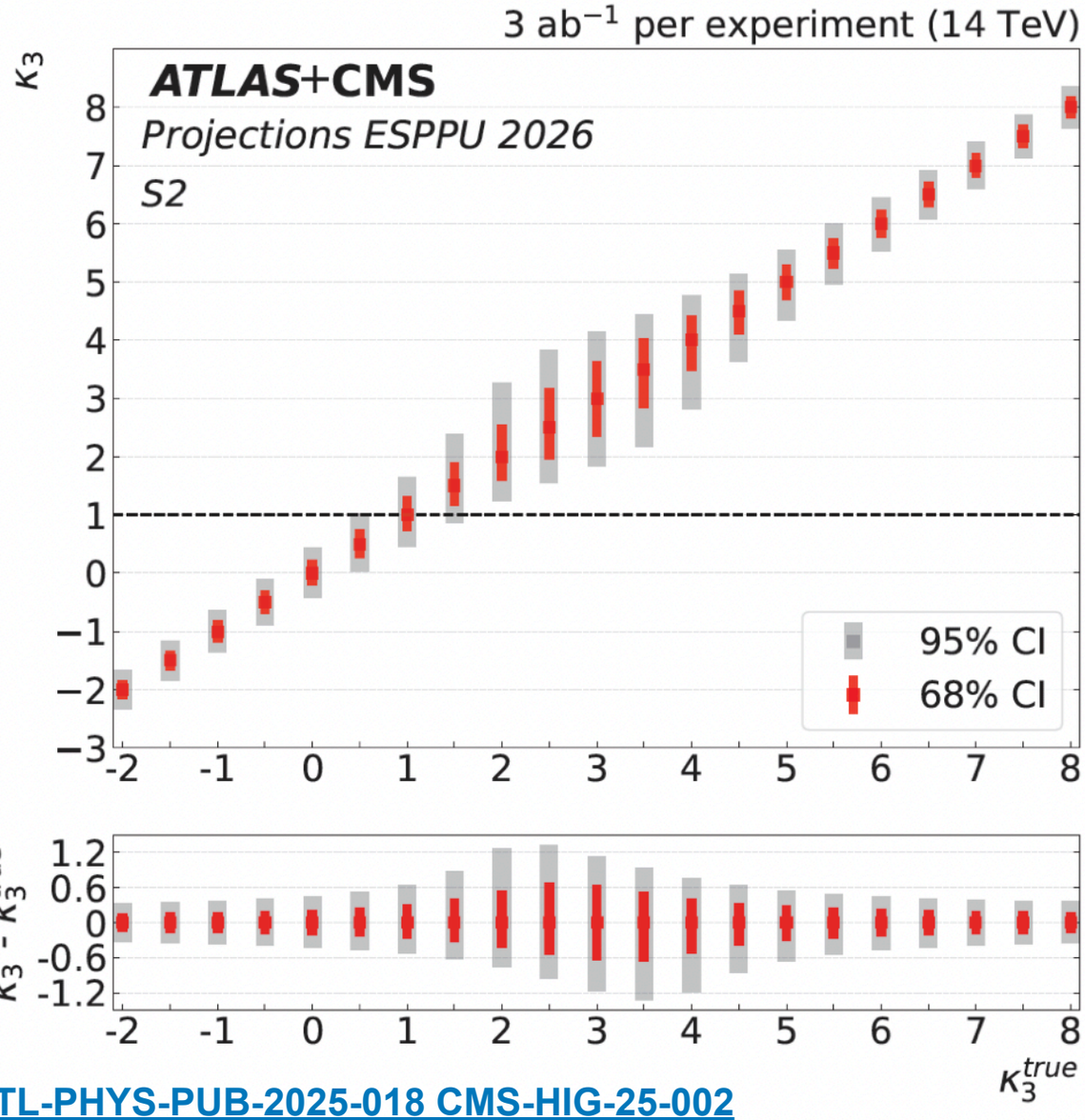
- 3000 fb^{-1} per experiment, run3 object improvement included

Channel	κ_3 precision 68% CL	κ_3 precision 68% CL
bbττ	[0.5, 1.6]	[0.3, 2.0]
bbγγ	[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]	-
bbℓℓ	[-2.1, 9.1]	-
Combination	[0.6, 1.4]	[0.6, 1.5]
ATLAS + CMS	-26/+29	

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

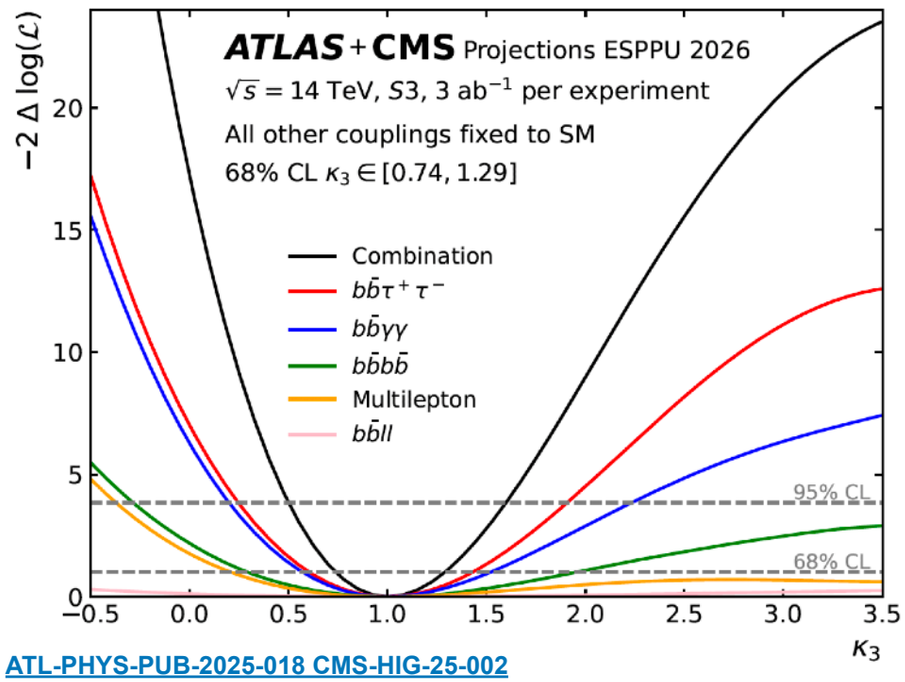
ATL-PHYS-PUB-2025-018 CMS-HIG-25-002

HH results - k_λ precision



ATL-PHYS-PUB-2025-018 CMS-HIG-25-002

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



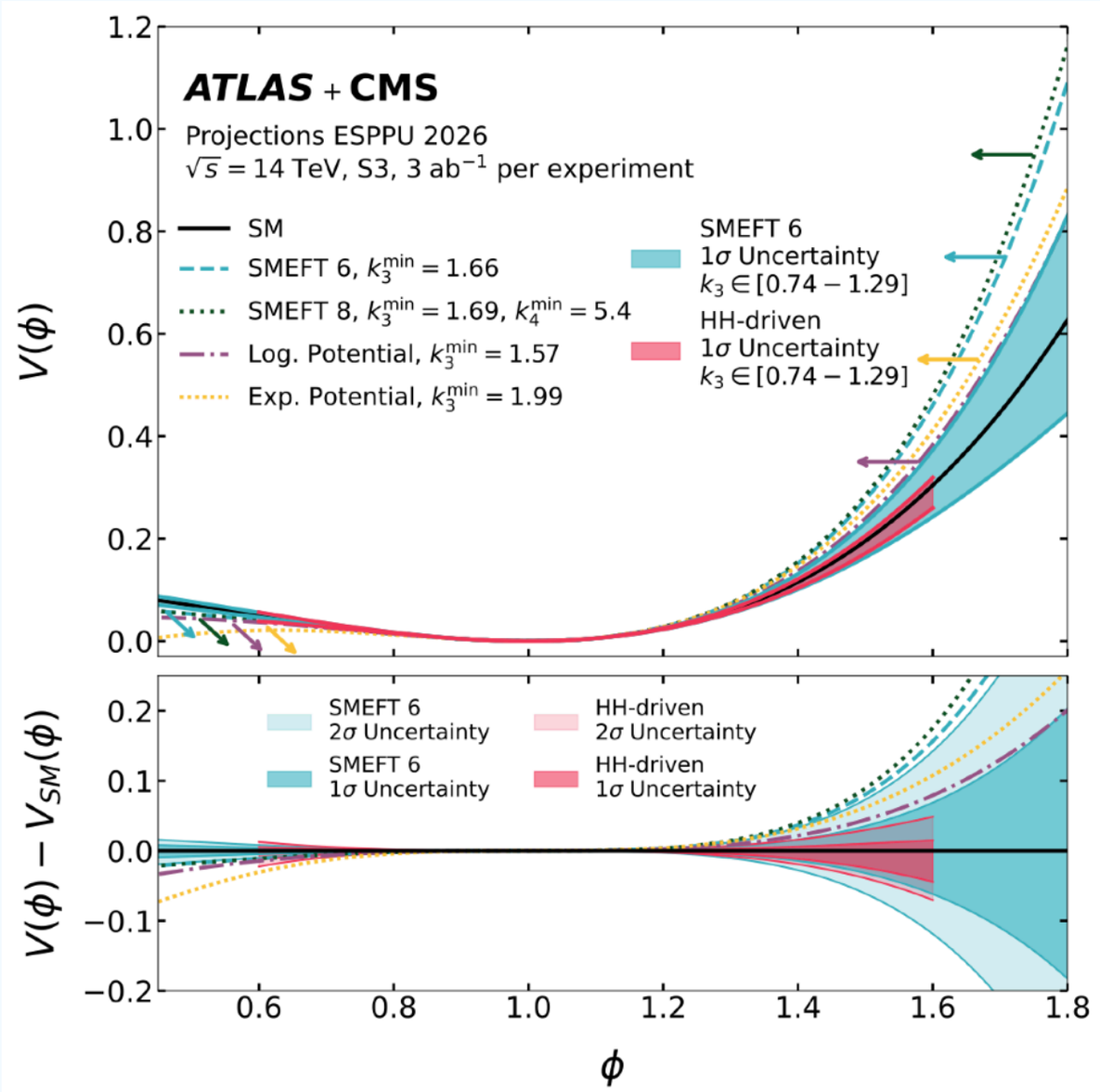
ATL-PHYS-PUB-2025-018 CMS-HIG-25-002

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

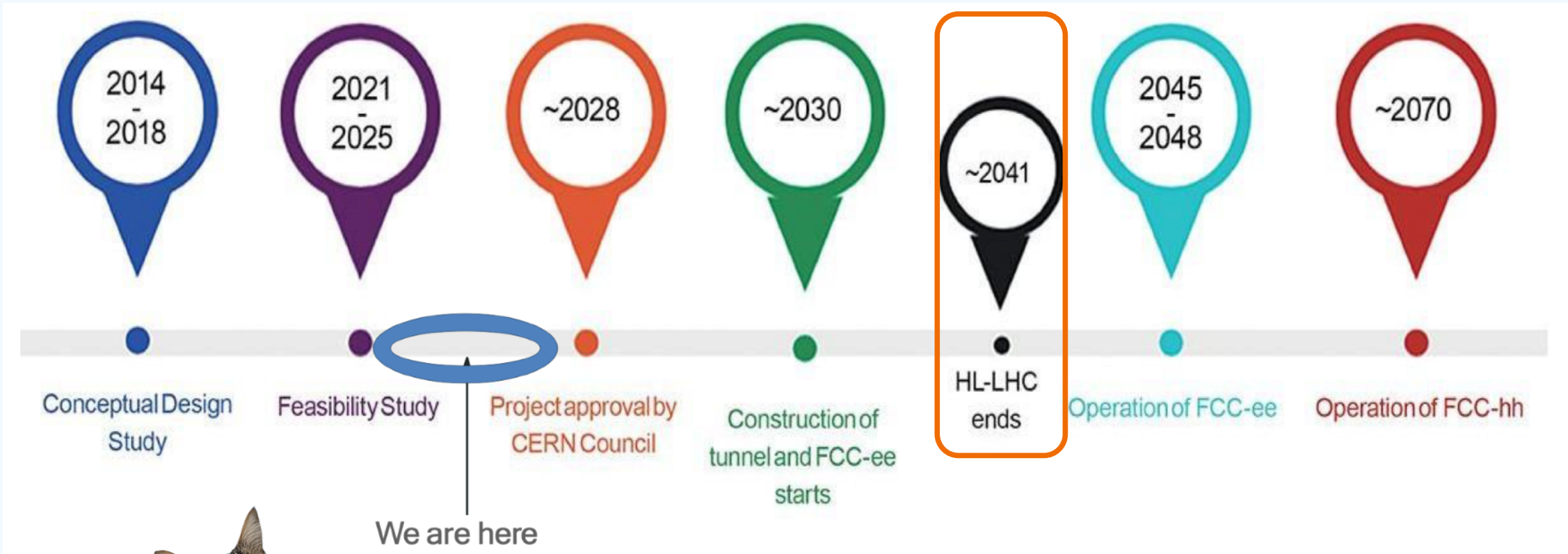
- The light blue delimits the area where a first order phase transition would be possible in a dimension 6 EFT.
  - 2σ full exclusion is reached at 3 ab^{-1} for the EFT dim 6 FOPT inducing potentials



ATL-PHYS-PUB-2025-018 CMS-HIG-25-002

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

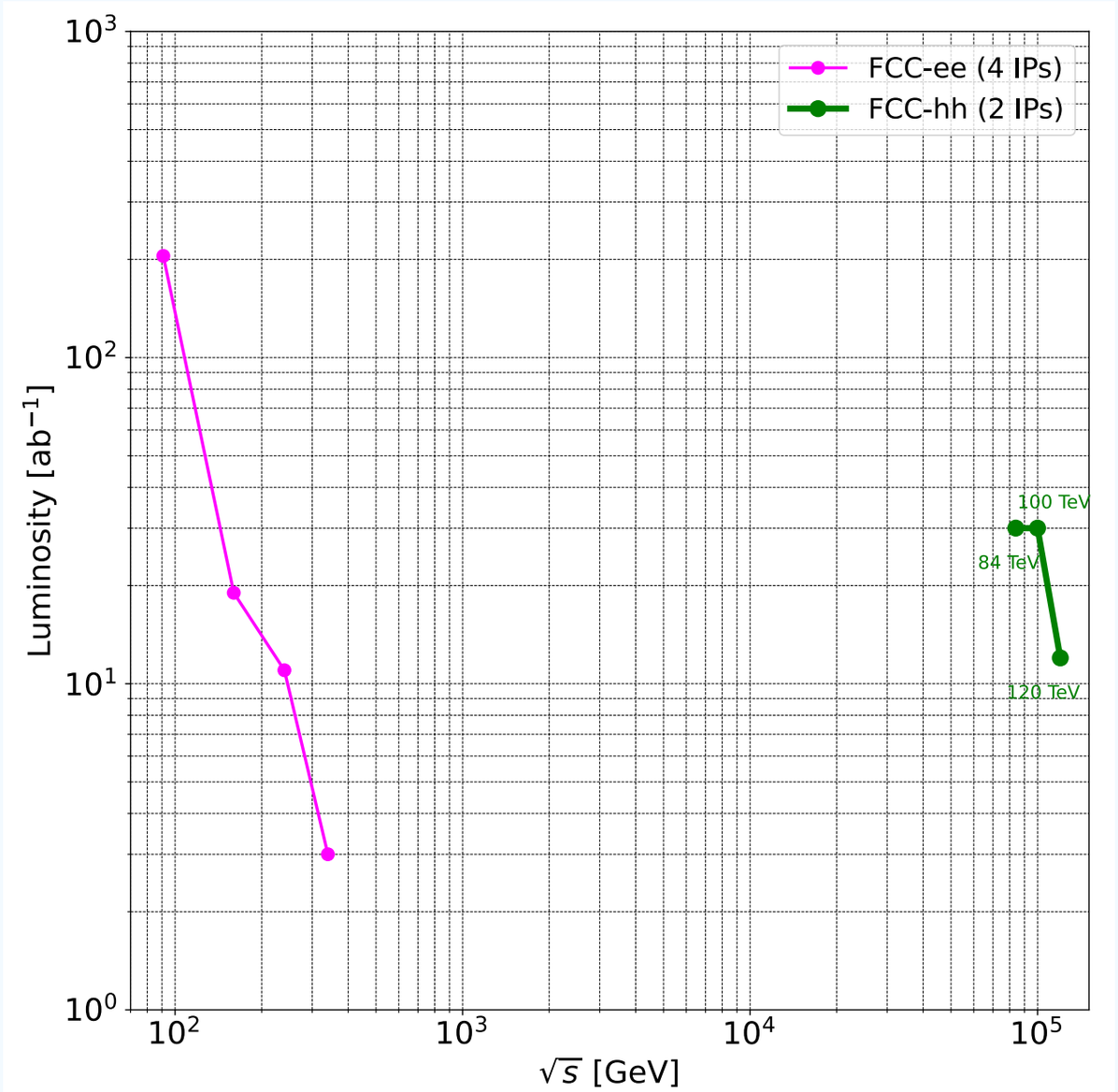
FCC-hh

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}** 100 TeV: 30 ab^{-1} 120 TeV: 12 ab^{-1}



link to the note

Re-optimized $\bar{b}b\gamma\gamma$ analysis strategy

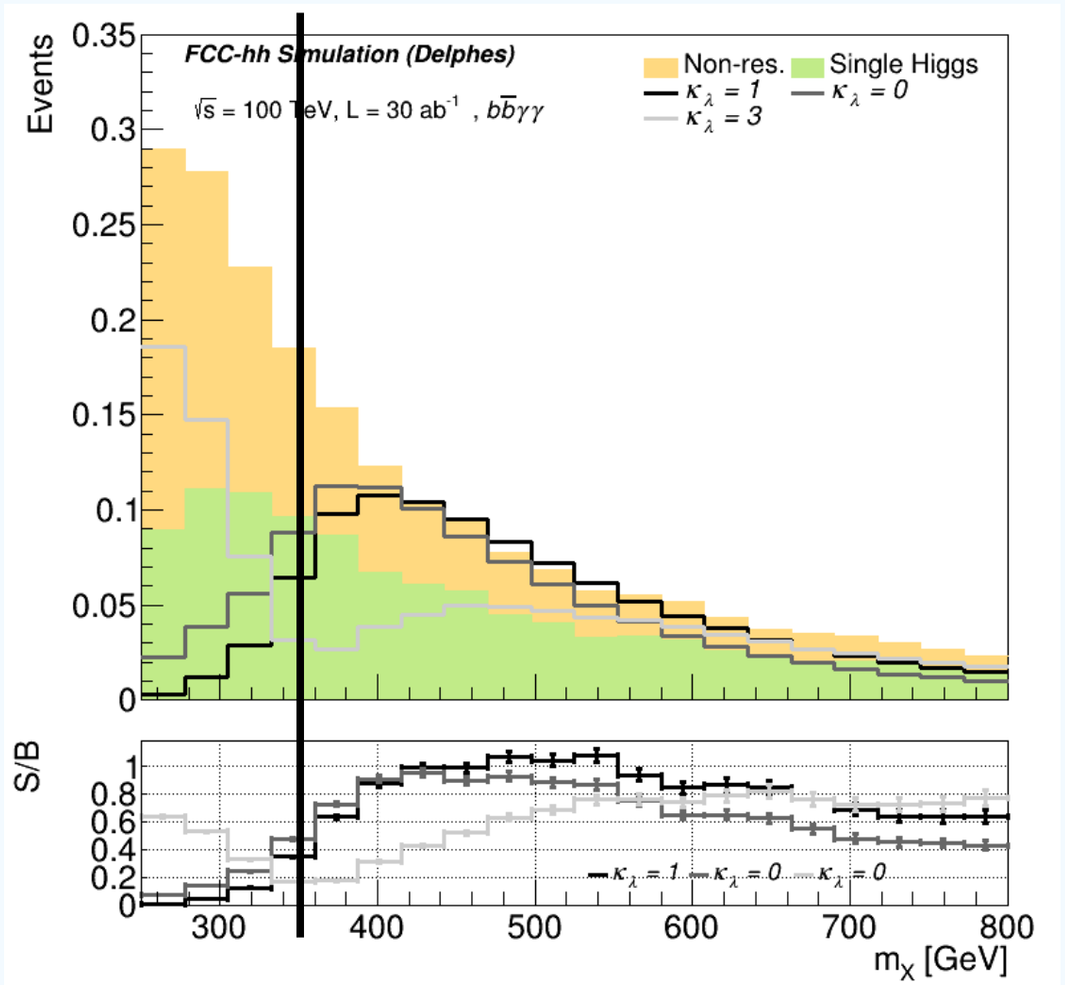
Pre-selected events

$m_X < 350$ GeV

$m_X > 350$ GeV

DNNs categorization to suppress the bkg

$$m_X = m_{\bar{b}b\gamma\gamma} - m_{\bar{b}b} - m_{\gamma\gamma} + 250\text{GeV}$$

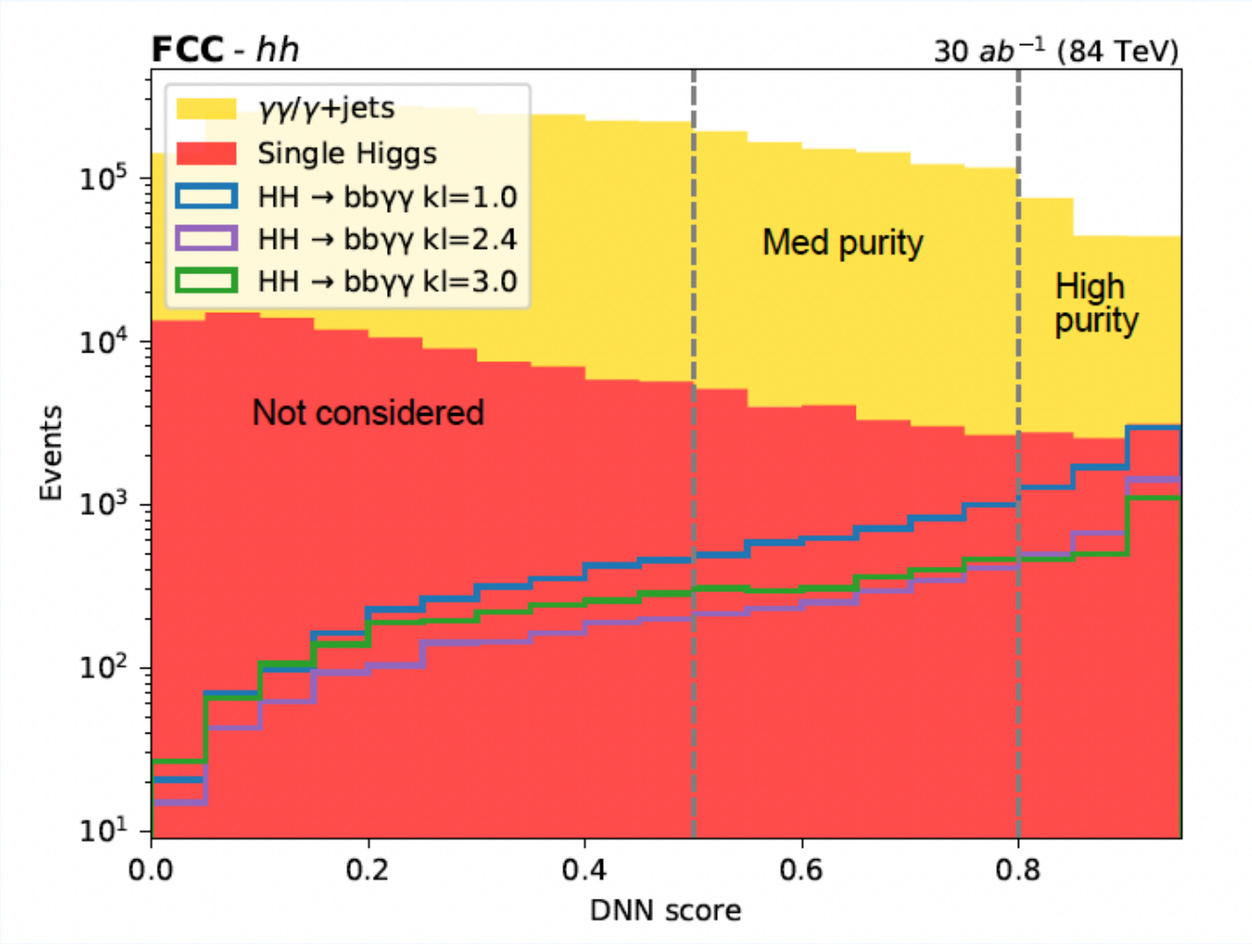


- Shape depends on κ_λ
- Region m_X < 350 GeV has low S/B for κ_λ=1 (SM) , but contributions from $\kappa_\lambda \neq 1$ (BSM) signals

link to the note

Re-optimized $\bar{b}b\gamma\gamma$ analysis strategy

Pre-selected events → $m_X < 350$ GeV | $m_X > 350$ GeV → DNNs categorization to suppress the bkg



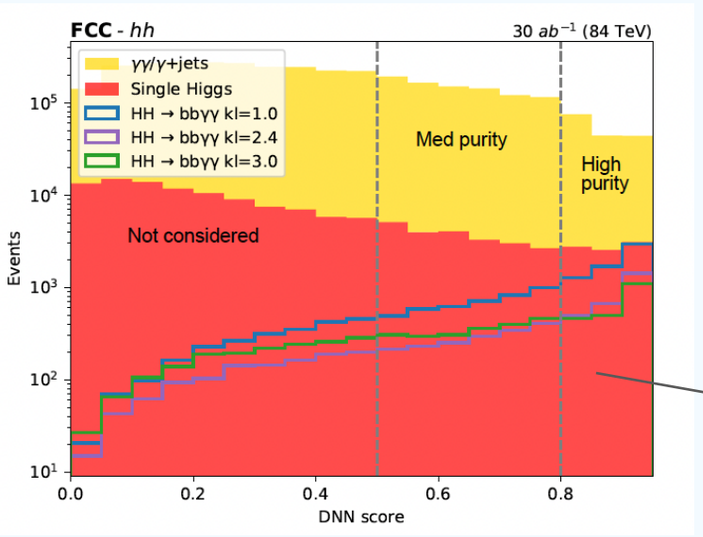
link to the note

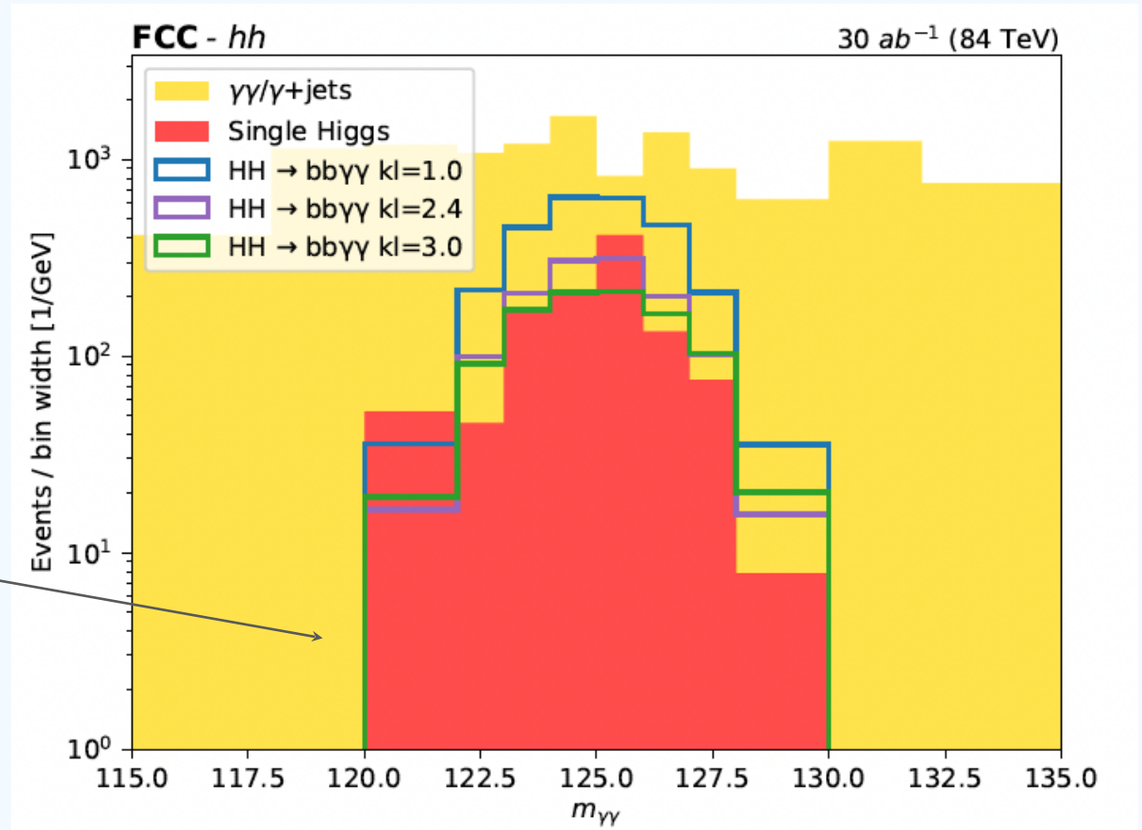
Re-optimized $\bar{b}b\gamma\gamma$ analysis strategy

Pre-selected events

DNNs categorization to suppress the bkg

Categorize based on $m_{\bar{b}b}$

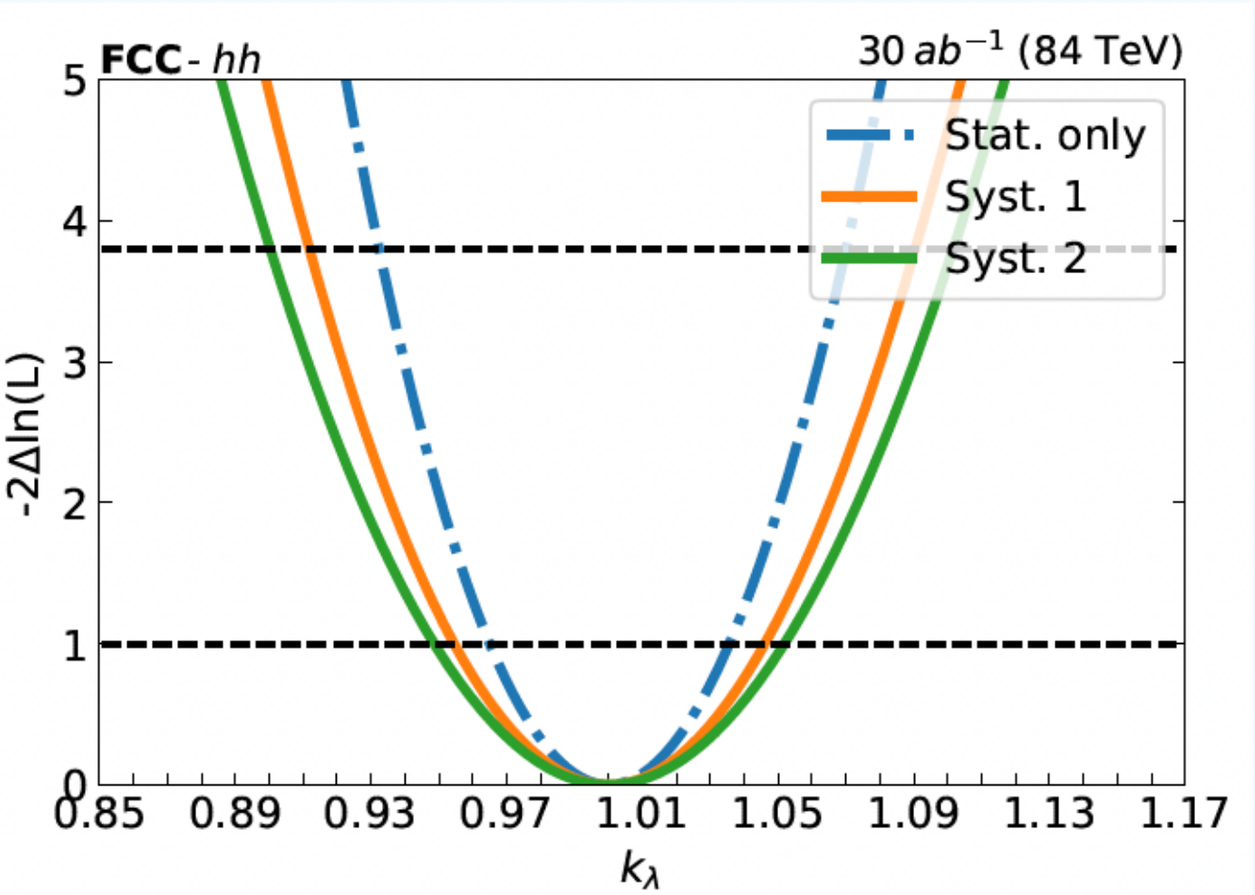


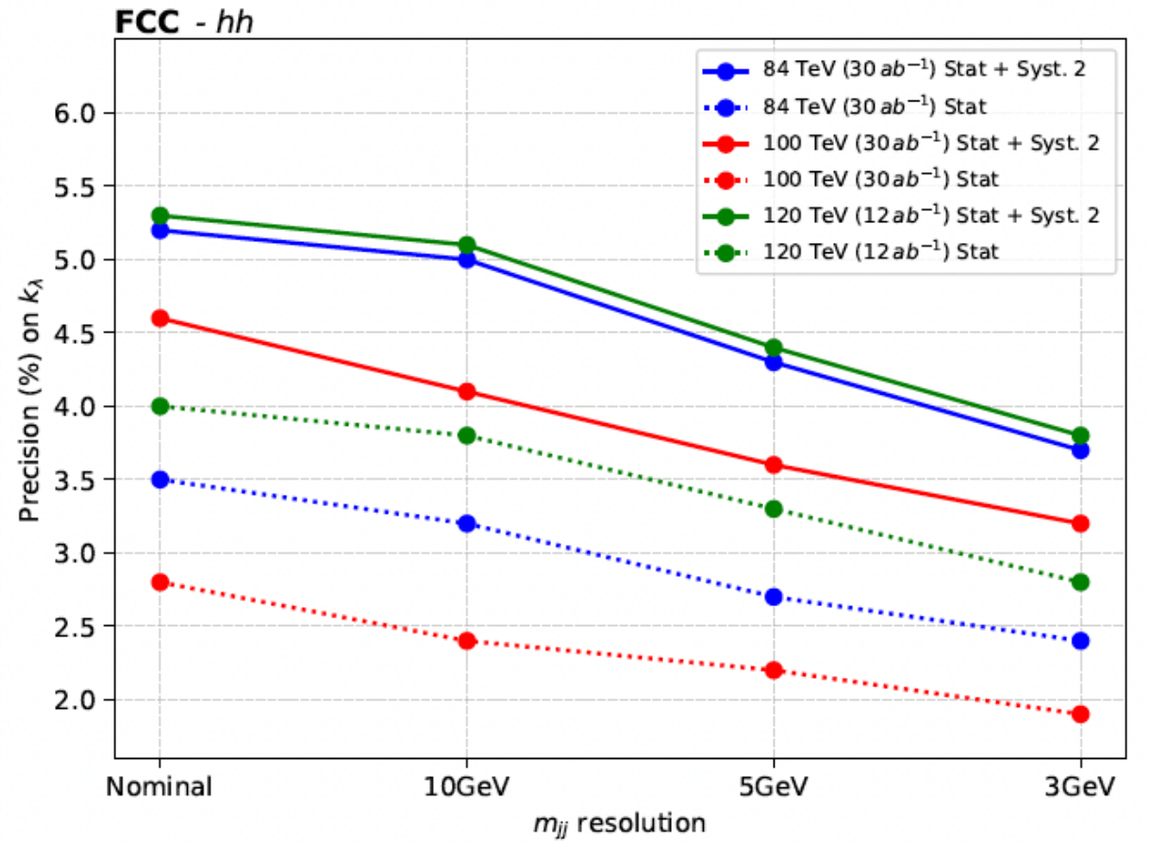


Fit $m_{\gamma\gamma}$

FCC-hh new results

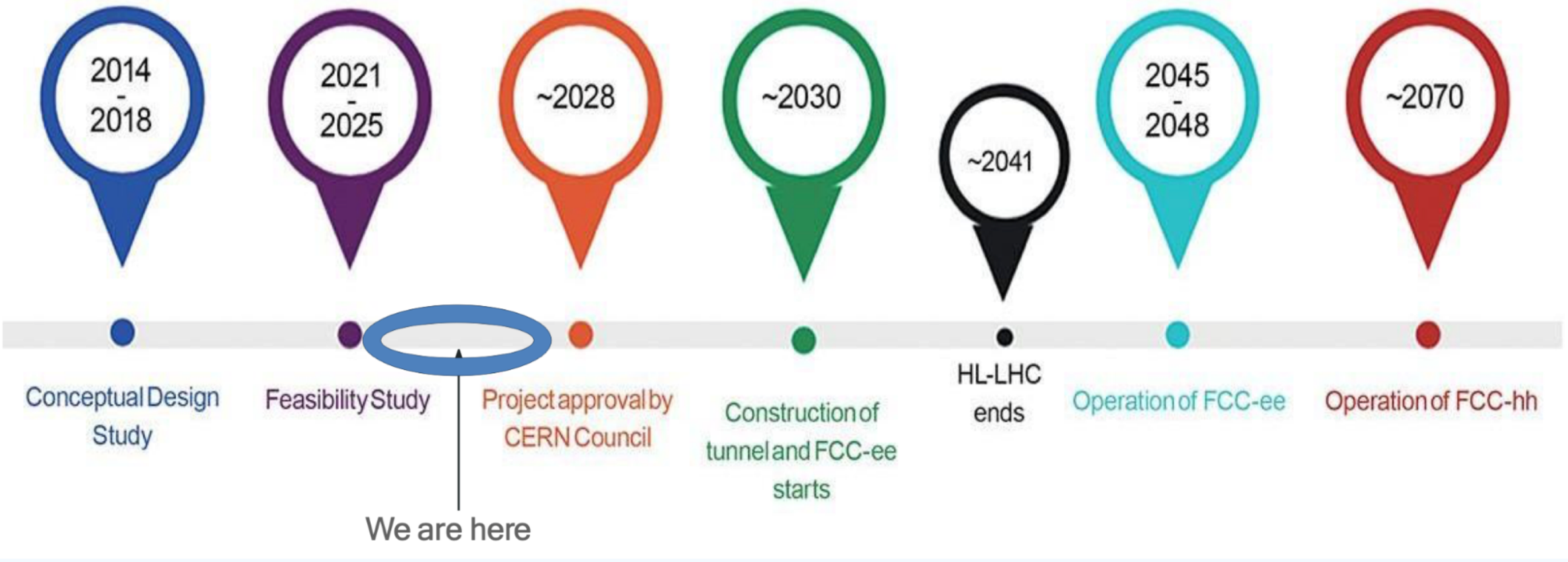
- Precision on kl at 84 TeV (st only and syst scenarios) on the left
- Precision on kl as a function of the the mjj resolution on the right

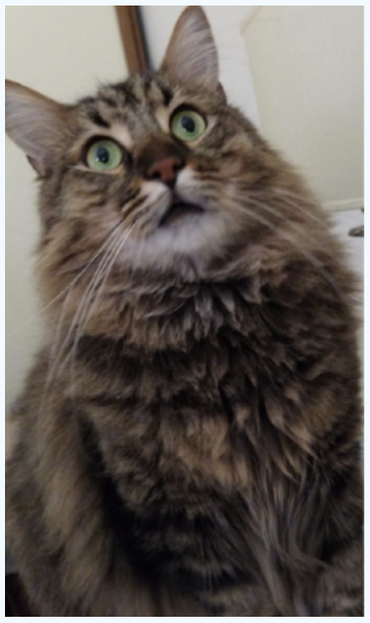




link to the note

Conclusions



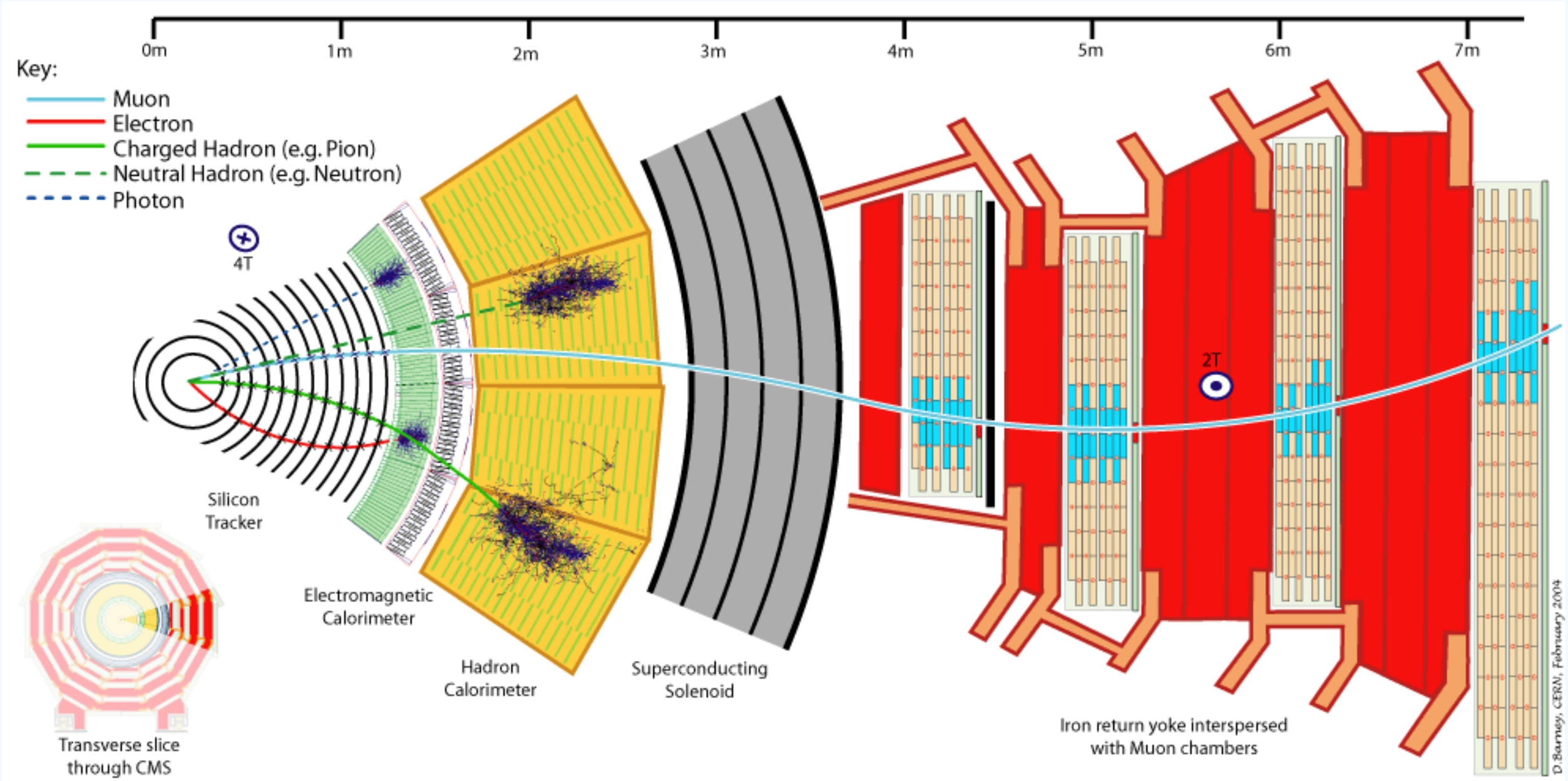


- ATLAS and CMS program on diHiggs is extremely exciting and is performing behiond expectations
- Looking forward for the run3 combination!

Many more to come!!

Backup

CMS reconstruction



EFT Frameworks used in HH

- The **kappa-framework**: Modifies the couplings predicted by the SM

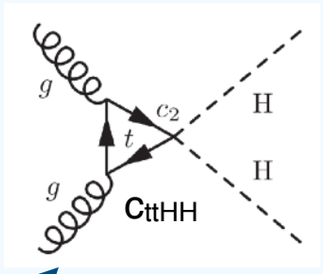
$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

- **Higgs EFT (HEFT)**: Natural extension of the kappa-framework with additional BSM couplings

- **Standard Model EFT (SMEFT)** : Similar to HEFT but the Higgs is a SM doublet adding correlations between H and HH

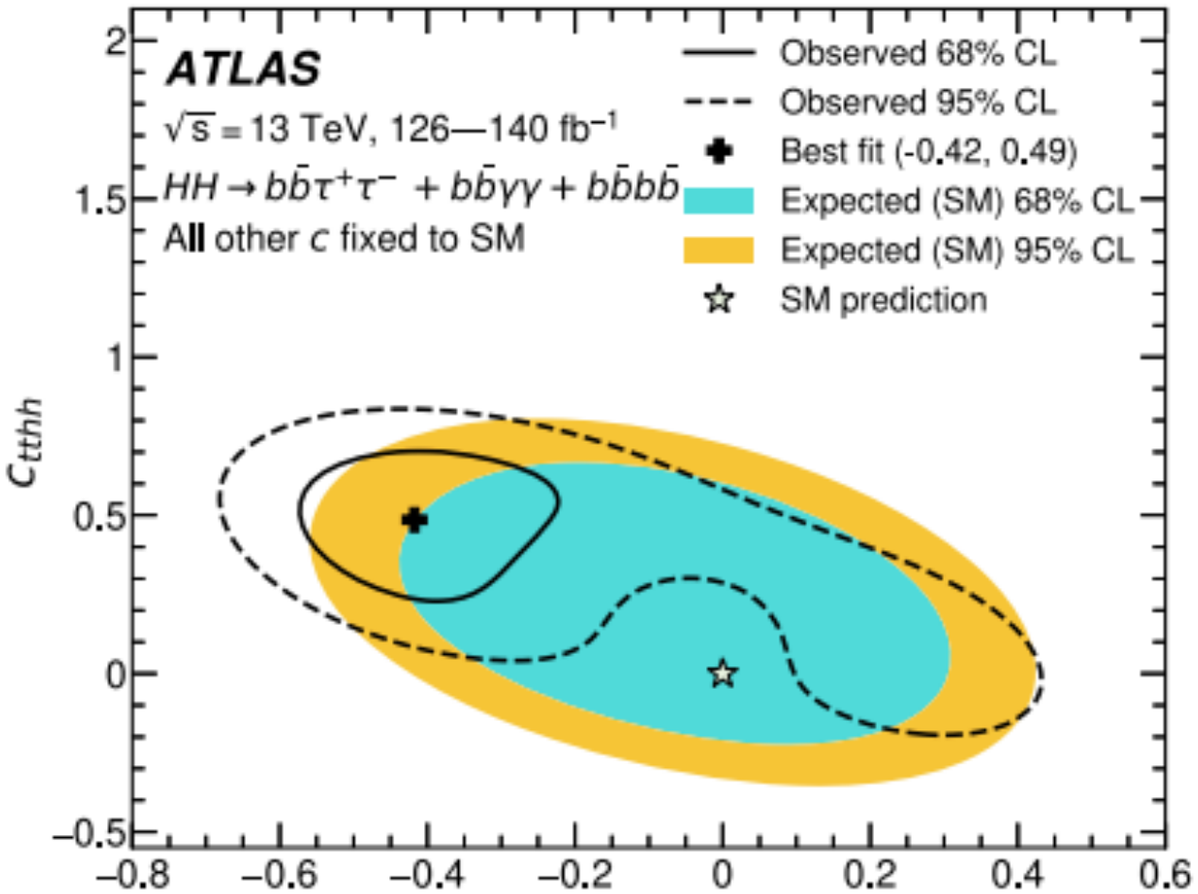
	ATLAS		CMS	
HH production	ggF	VBF	ggF	VBF
kappa-framework	✓	✓	✓	✓
HEFT	✓		✓	
SMEFT	✓	✘	✘	✘

HEFT results



Both collaborations provided results in the HEFT framework:

- **CMS new results**: c_2 scan dominated by the bbττ channel
- **ATLAS 2D scan**: c_2 vs c_{gghh}



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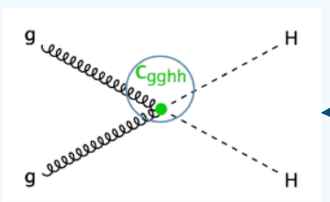
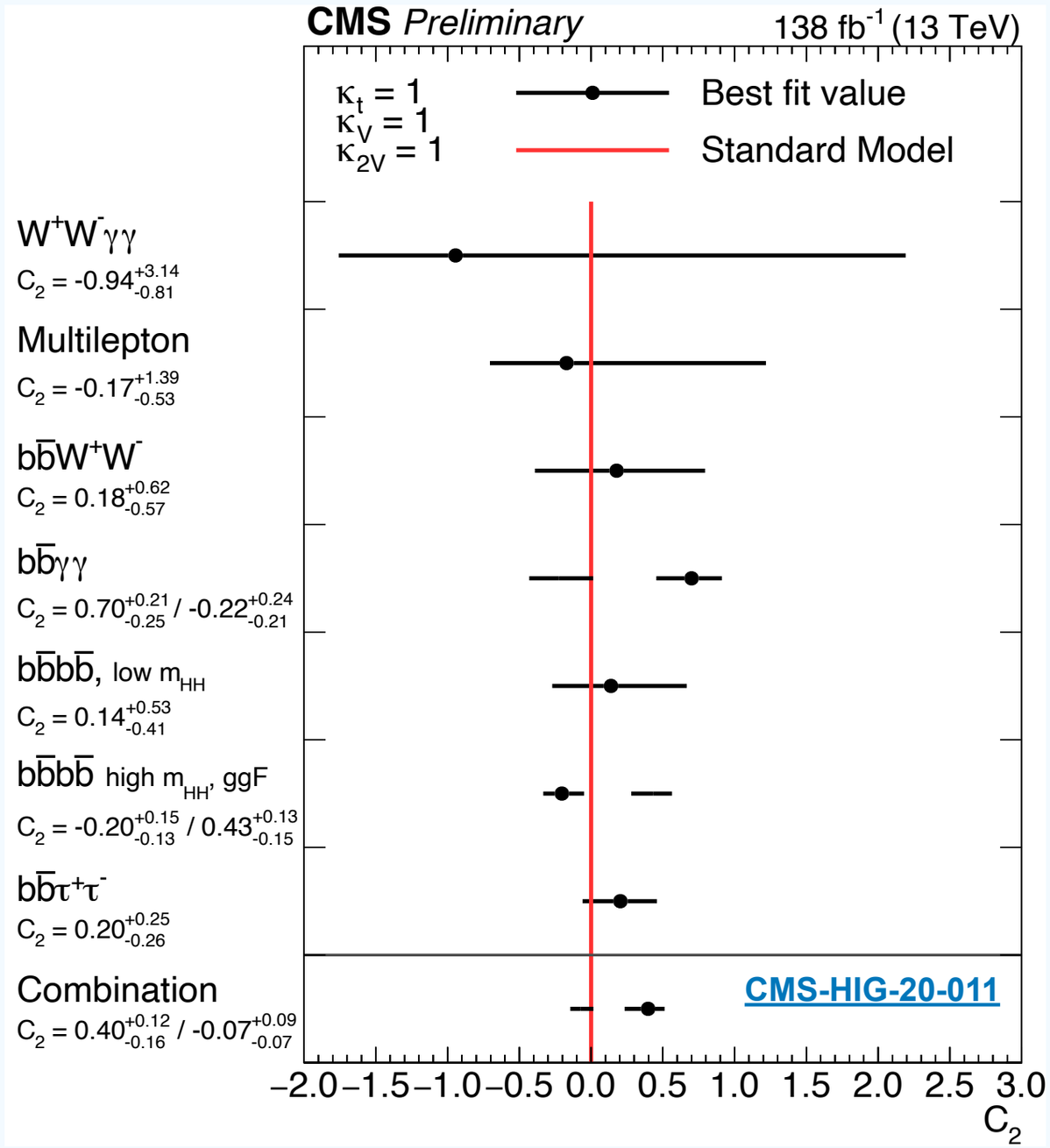
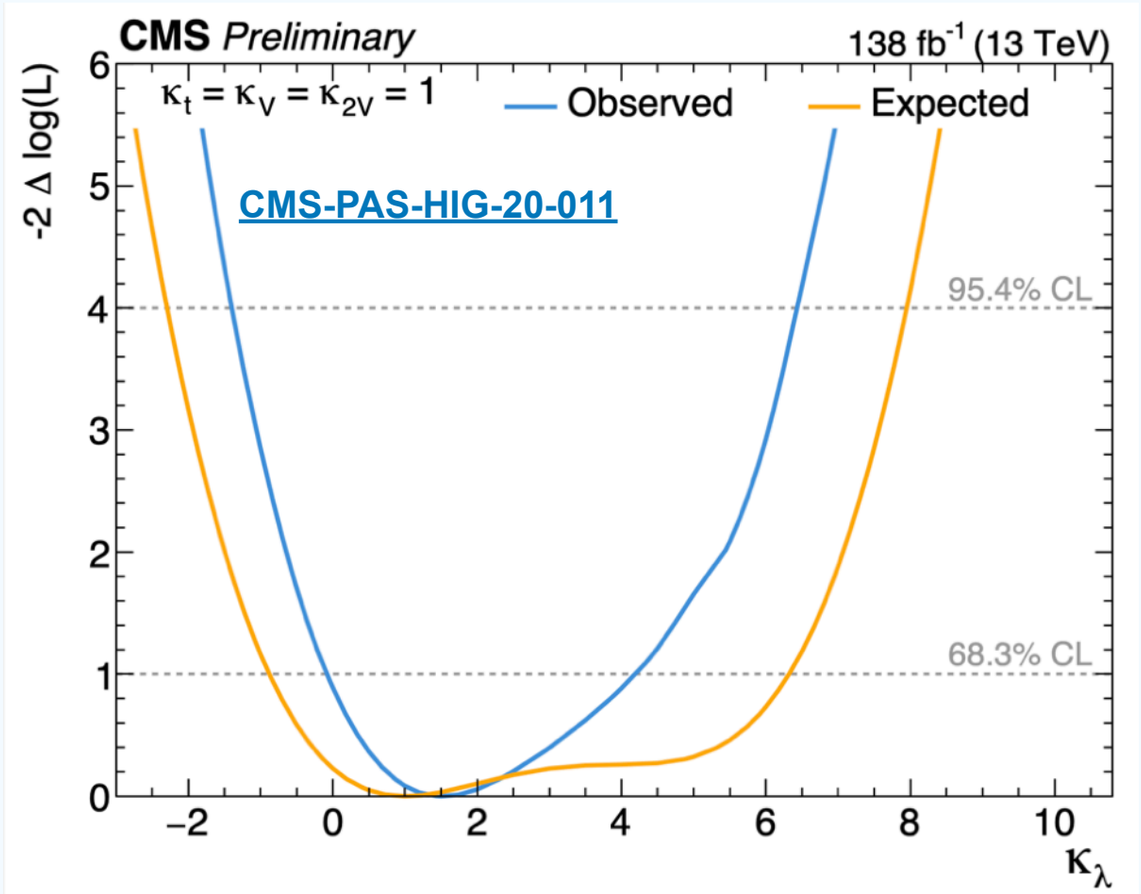




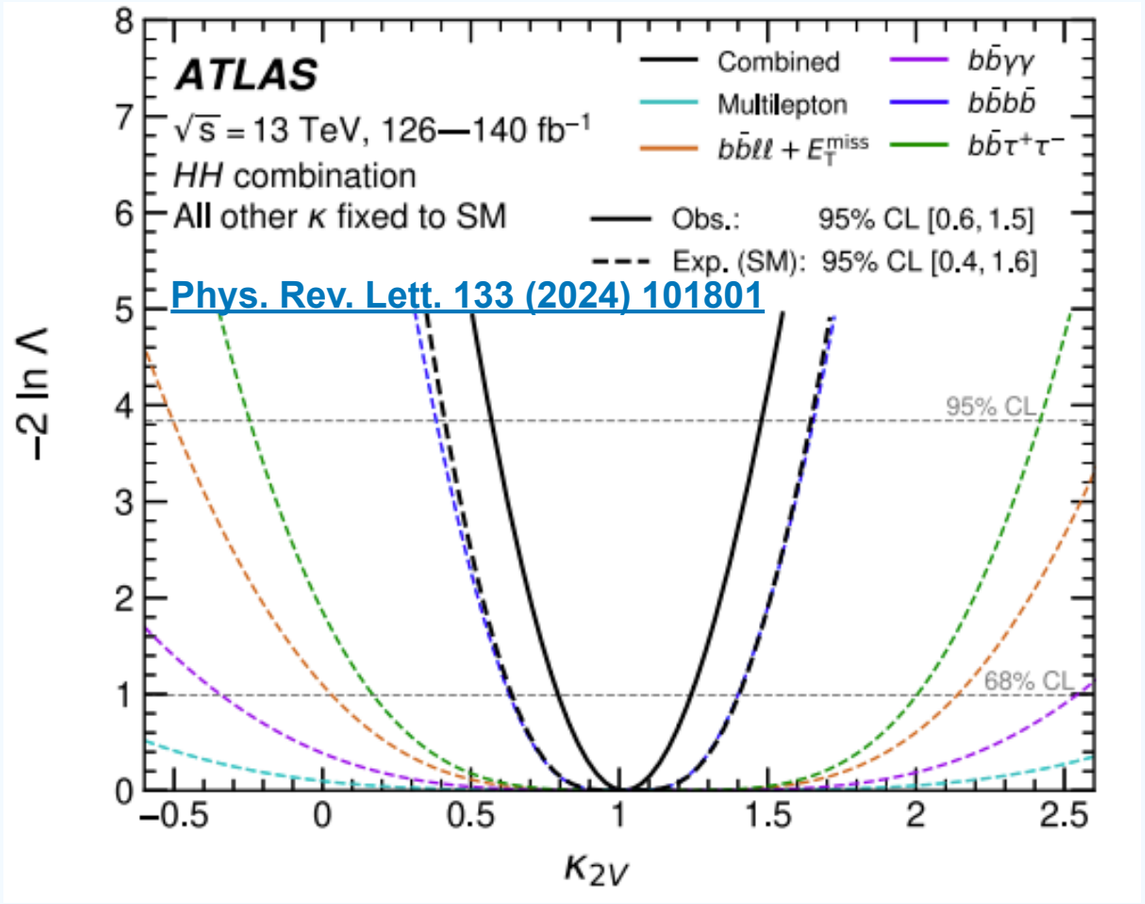
Higgs self-coupling and quartic HHVV coupling

Both collaborations provided results for k_λ, k_t and k_{2V} relative results

- k_λ scan dominated by bbγγ and bbττ
- k_{2V} scan dominated by 4b boosted signature



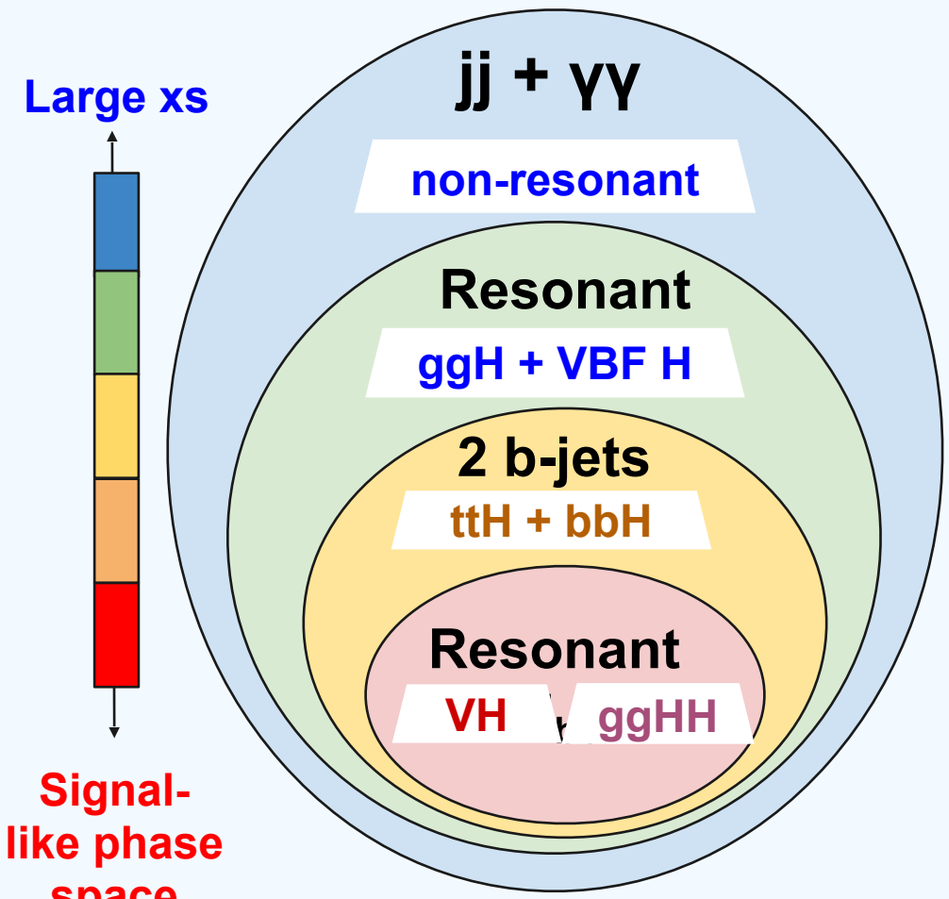
Constrain on the k_λ [-1.4, 6.4] obs - CMS
Constrain on the k_λ [-1.2, 7.2] obs - ATLAS



Constrain on the k_{2V} [0.6, 1.4] obs - CMS
Constrain on the k_{2V} [0.6, 1.5] obs - ATLAS
$k_{2V} = 0$ excluded at >6σ from both collaborations

bbγγ analysis strategy: classifiers

- Major backgrounds categorized into three different classes based on their similarity to signal kinematics:
  - Non-resonant QCD, γ(γ)+jets, ggH, VBF H
  - ttH & bbH - has true b-jets
  - V(bb)H - has m_{bb} resonance



- Single DNN model with 4 output classes:
  - Nonresonant bkgs (Data driven QCD + γ+jets, γγ+tt/jets)
  - ttH
  - Other single H bkgs (ggH, bbH, VBFH, VH)
  - Single: SM ggHH

- Preprocessing:
  - $m_{\gamma\gamma}/m_{jj}$ - decorrelation to allow for a 2D fit.
- Architecture:
  - 5 hidden layers, 1024 neurons each, ELU activation

bbγγ analysis strategy: categorization

- The Multiclass BDT provides 4 outputs: P_{signal}, P_{ttH}, P_{VH}, P_{QCD}
- We define two discriminators:

$$D_{ttH} = \frac{P_{HH}}{P_{HH} + P_{ttH}} \qquad D_{QCD} = \frac{P_{HH}}{P_{HH} + P_{QCD} + P_{VH}}$$

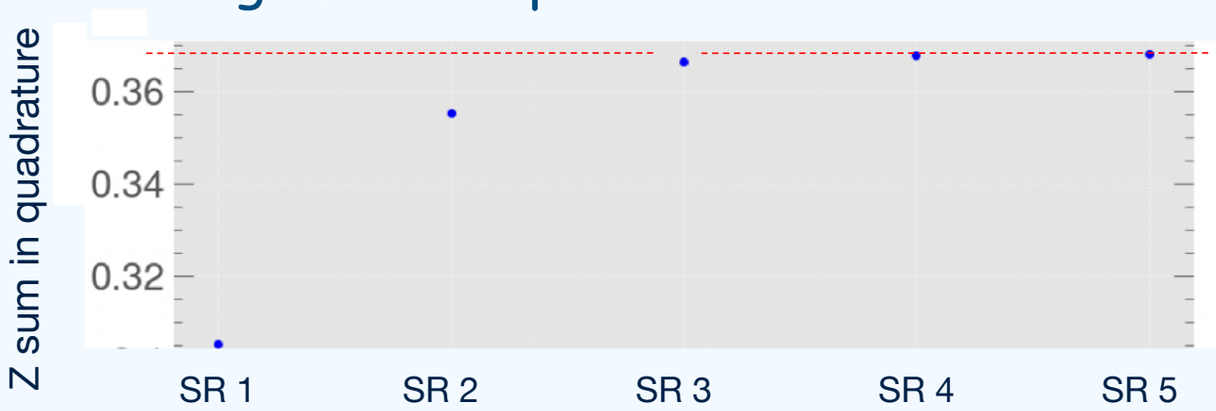
- Optimize cuts on D_{QCD} and D_{ttH} to maximize S/B
  - Start with D_{ttH} cut to achieve 85% ttH rejection.
  - Scan D_{QCD} and find max of S/B
- 3 SR category are selected
- Fit is performed on the $m_{\gamma\gamma}$ leg

Signal Region optimization

- Maximise the asymptotic significance (Z) computed purely by MC samples + Data driven estimate

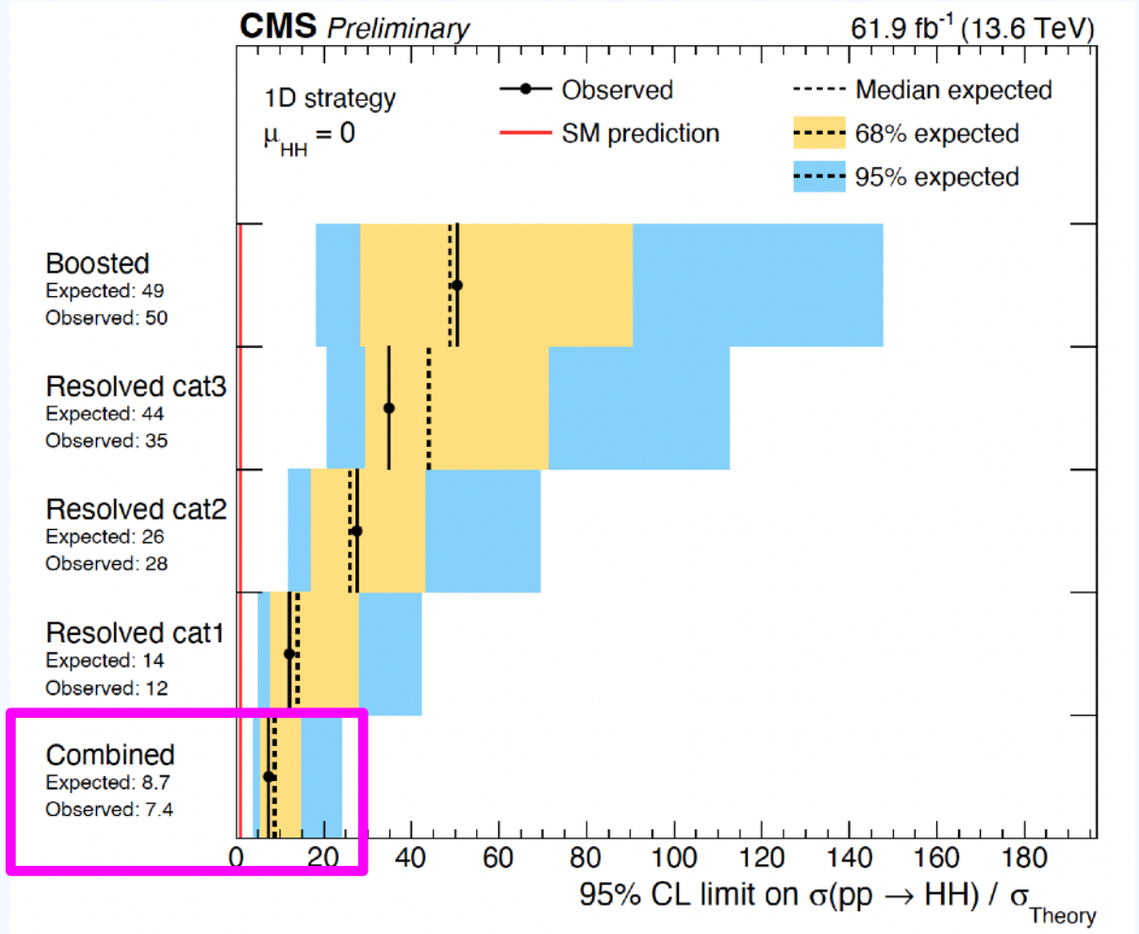
$$Z = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right) - s\right]}$$

- **Sequentially optimising** the SR boundaries, by choosing lower-cuts (upper-cuts) for the ggF HH score (to reject other processes)
  - Progressively add more SRs until the summed-in-quadrature significance plateaus

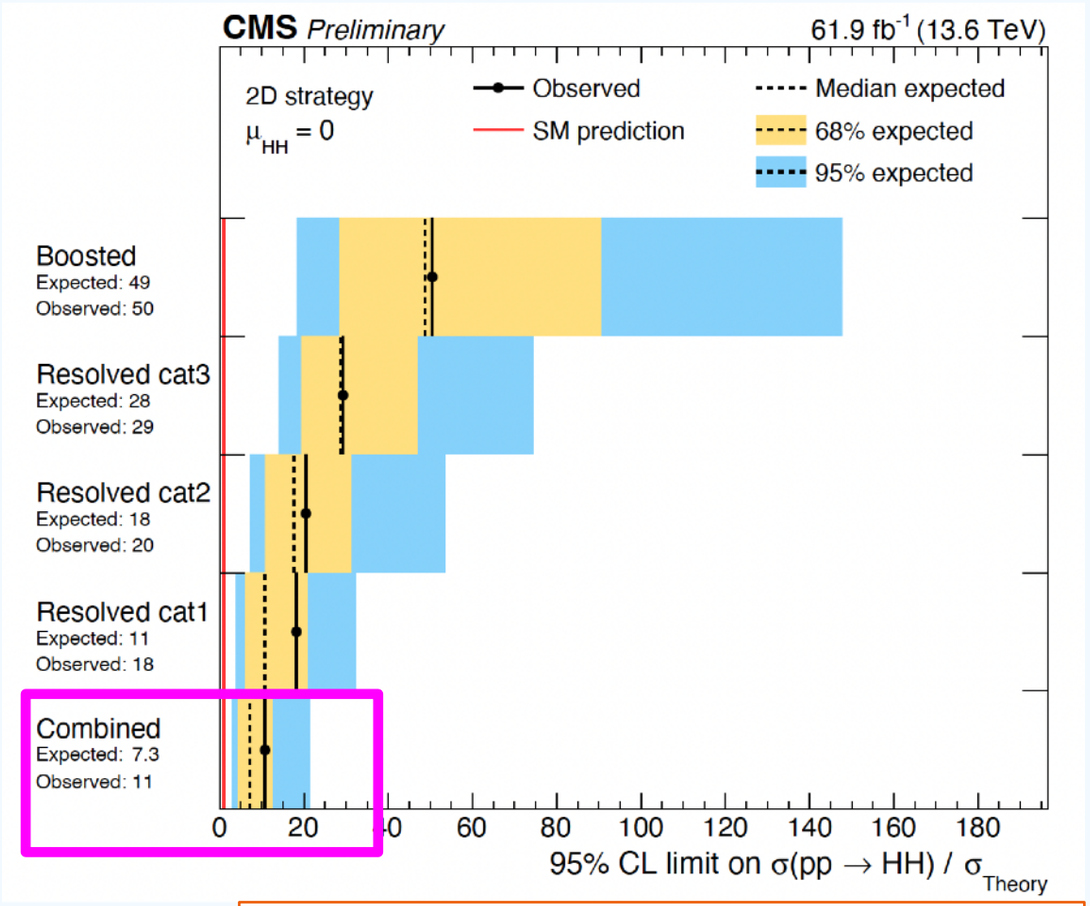


➡ Cumulative significance plateaus after 3 SRs

bbγγ analysis strategy: results UL

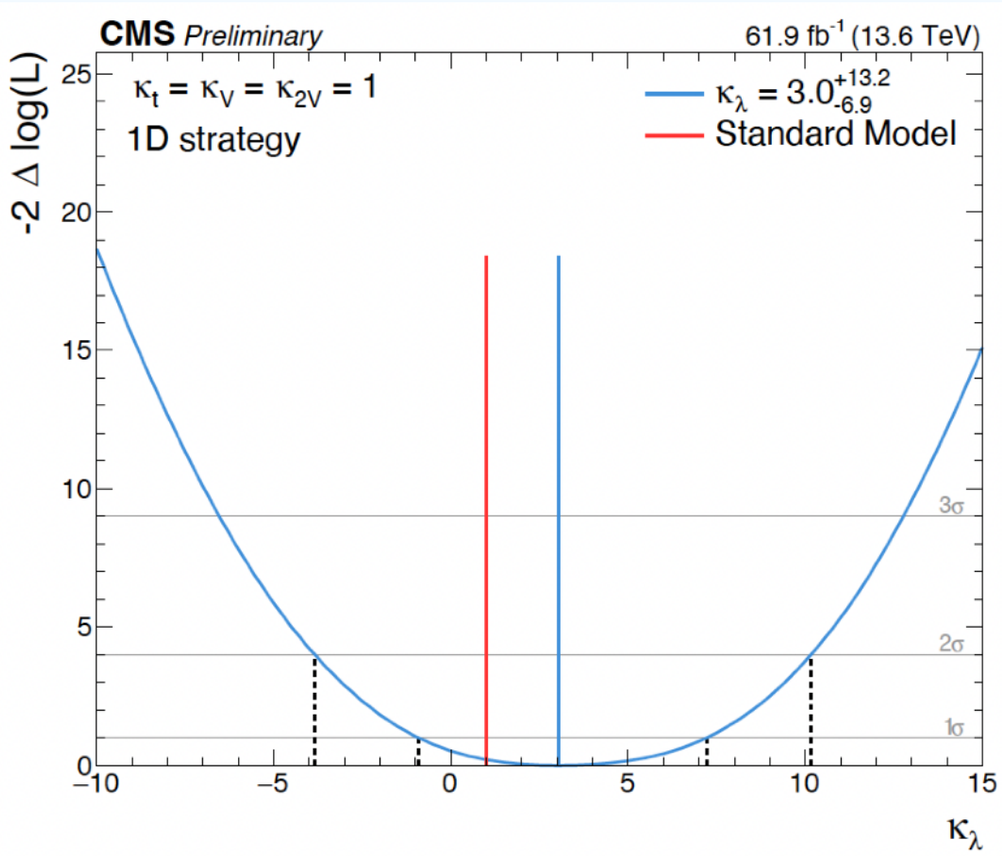


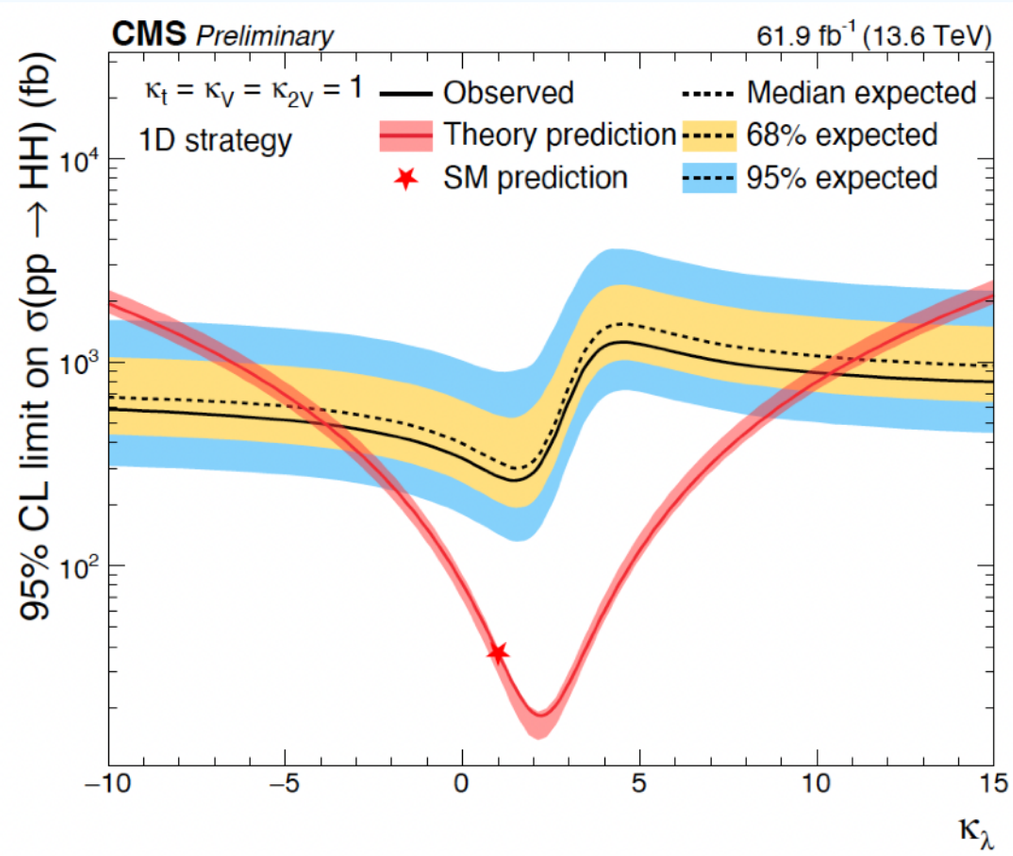
*Largest source of systematic uncertainty is the HH theory uncertanty



*bbgg Run2 (138 fb^{-1}) result 7.7 (5.2) obs (exp) xSM

bbγγ analysis strategy: results k_λ scan





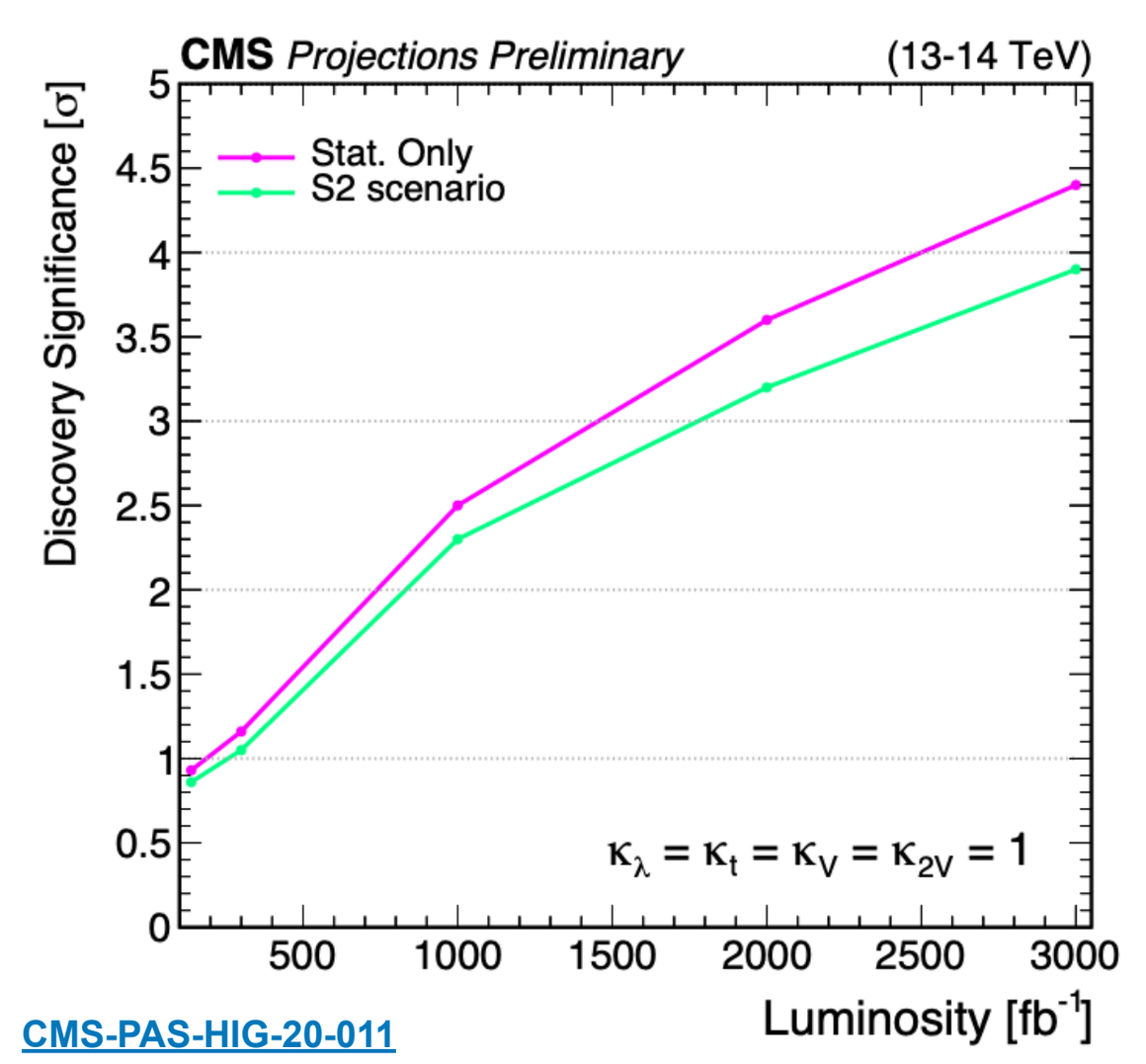
Allowed κ_λ ranges

- Observed $\kappa_\lambda \in [-3.9, 10.4]$
- Expected $\kappa_\lambda \in [-4.5, 11.1]$

HH projections: k_λ precision and significance

CMS and **ATLAS** provided projections for HL:

- evidence of HH production at the end of HL for both experiments



CMS-PAS-HIG-20-011