The hunt for Higgs boson pairs at ATLAS: current status and perspectives

Experimental Particle Physics seminar, University of Bern (January 25th 2023)

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Outline

1. **Introduction**
   1. The Higgs boson
   2. The Higgs potential role in the universe evolution
   3. Higgs-boson pair production
2. **ATLAS Run 2 HH searches ($b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$)**
   1. The ATLAS detector and object reconstruction
   2. The Run 2 $HH \to b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ searches
   3. Run 2 combination and non-resonant constraints
   4. Heavy resonance searches ($X \to HH$)
   5. H+HH combinations
3. **Future prospects for HH measurements (Run 3 and HL-LHC)**
   1. Run 3 ATLAS improvements (reconstruction and triggers)
   2. Expected sensitivities at the HL-LHC (3000 fb^{-1})
4. **Conclusions and outlook**

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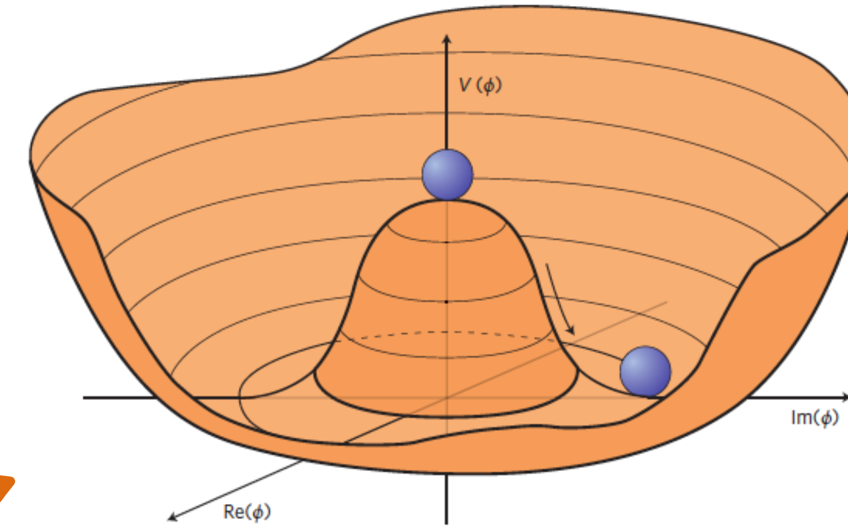
Introduction (1)

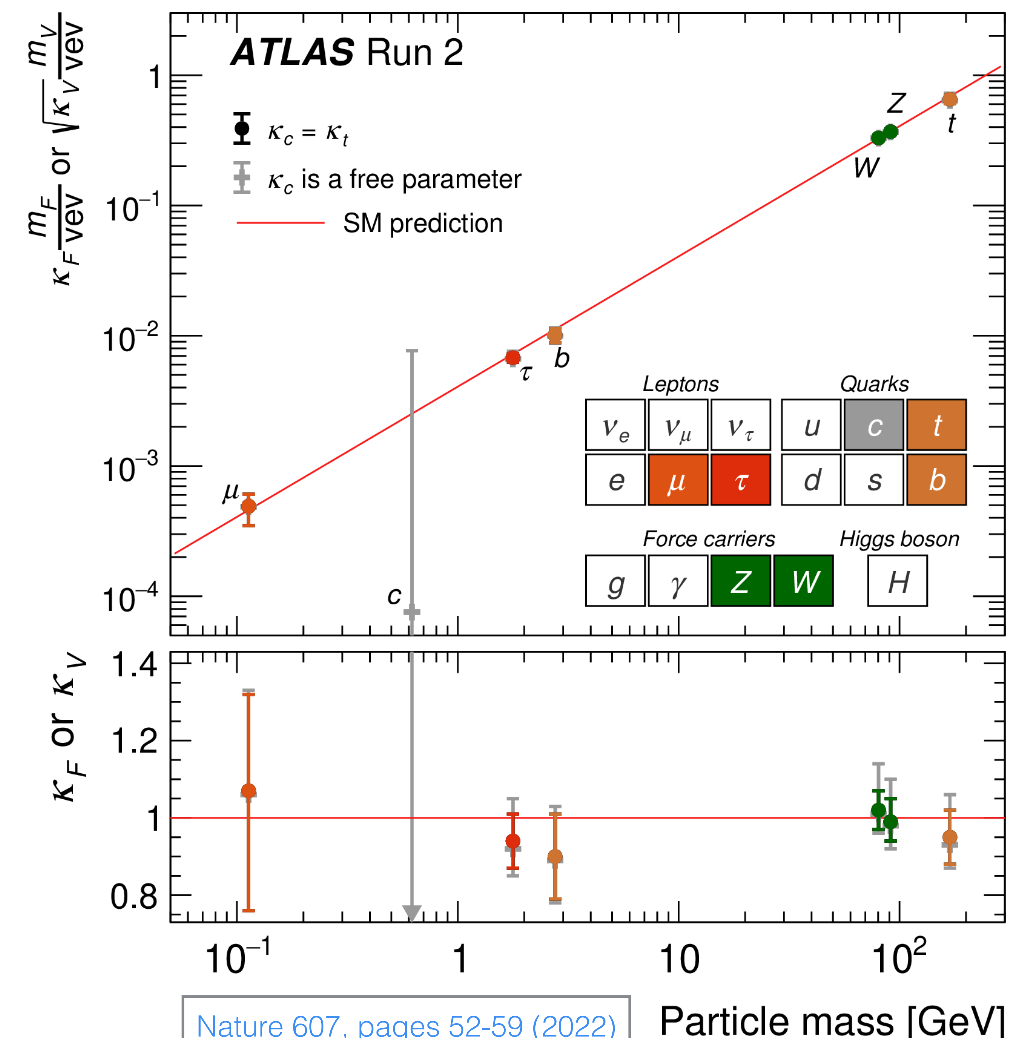
The Higgs boson discovery

- In 2012, nature brought us a new scalar particle: the **Higgs boson.**
  - In the Standard Model (SM), vacuum state of $V(\phi^\dagger\phi)$ breaks electroweak (EWK) symmetry

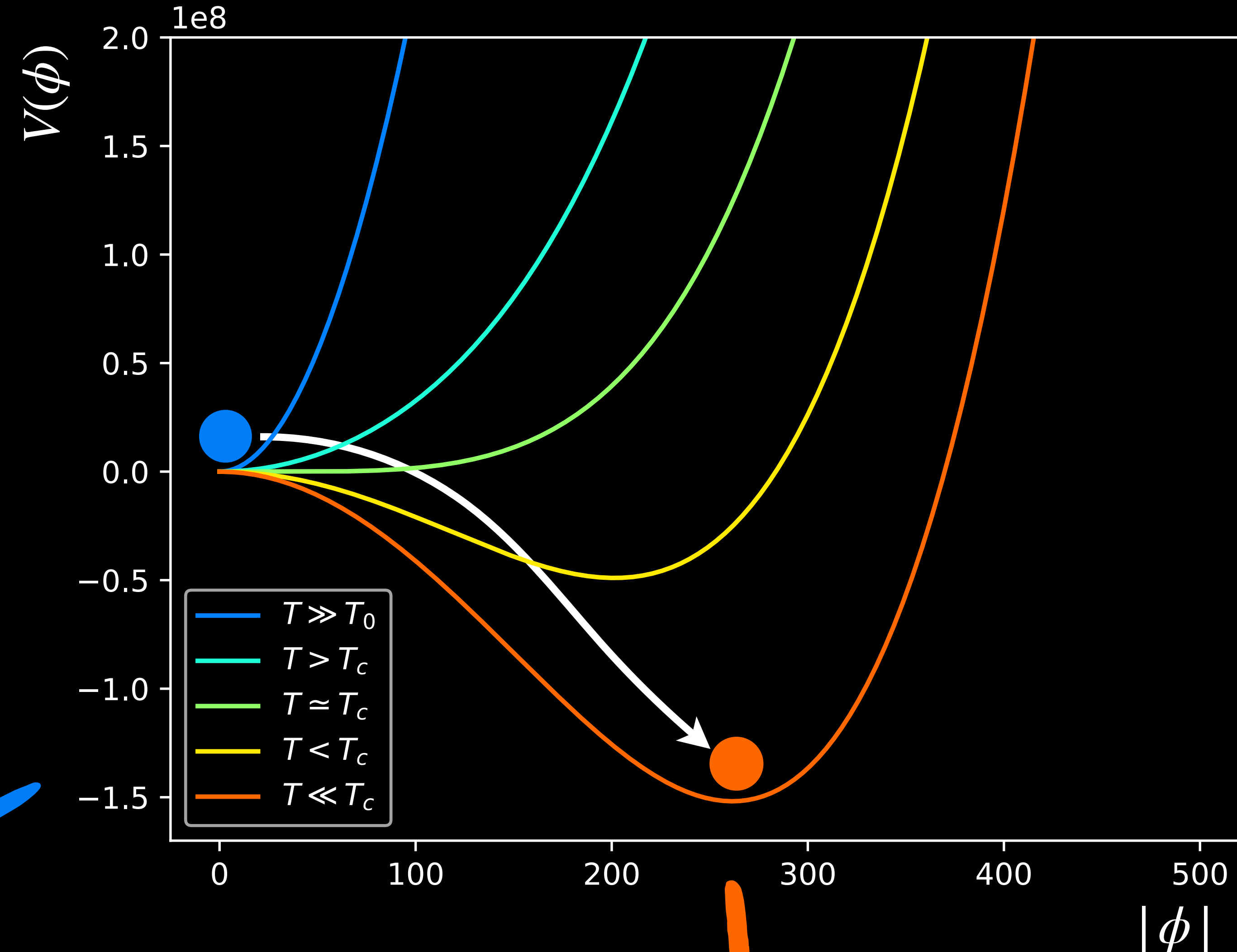
$$\boxed{V(\phi^\dagger\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2}$$



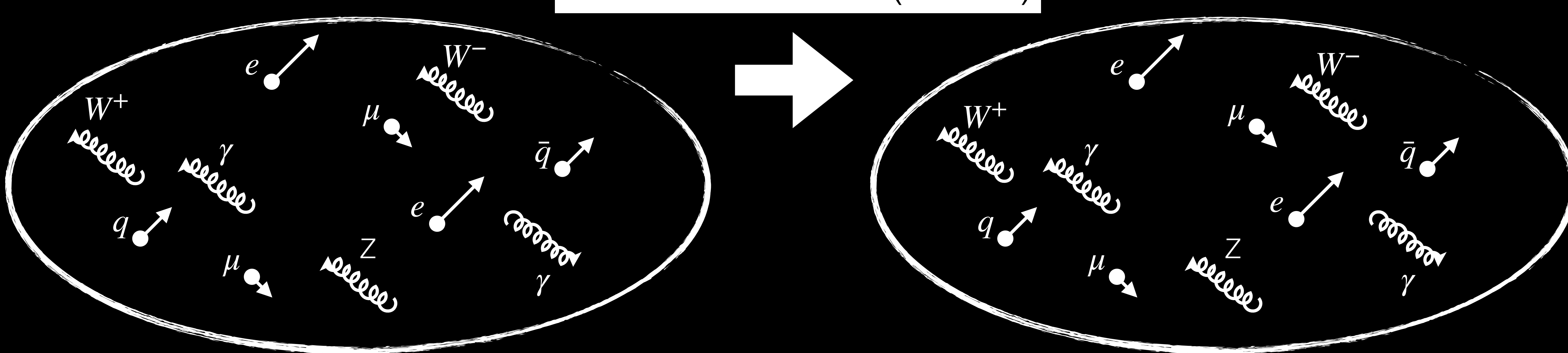
  - Weak bosons (W/Z) and fermions **acquire masses**.
  - The Higgs boson **mass observed at** ~ 125 **GeV**.
- So far, **all observed couplings (W,Z,b,t,τ) are consistent with SM** Higgs!



- The Higgs discovery also established that a **second order electroweak phase transition (EWPT) happened** in the early phases of the universe.
  - **<u>Unique process,</u>** different than the standard matter freeze-out!



Electroweak
Phase Transition (EWPT)



Massless universe ($\nu = 0$)

Massive universe ($\nu \neq 0$)

So, have we learned everything about the Higgs?

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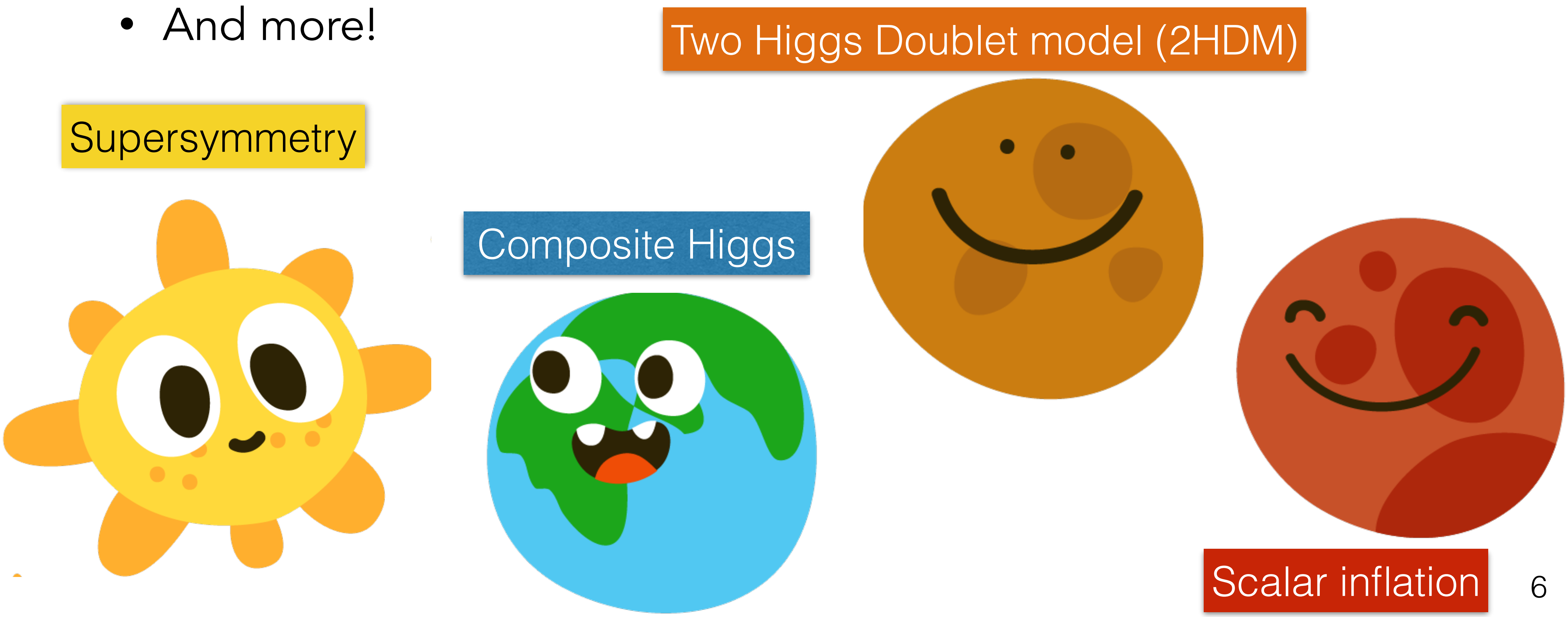
The Higgs questions

What do we still have to understand about the Higgs?

- **No**, we haven't learned everything about the Higgs!
- The simple existence of the Higgs in the SM **makes it really puzzling:**
  - Are there **more Higgs bosons**?
  - Why is the **Higgs mass so small**?
  - Did the the **Higgs potential alone trigger EWSB**?
  - And more!



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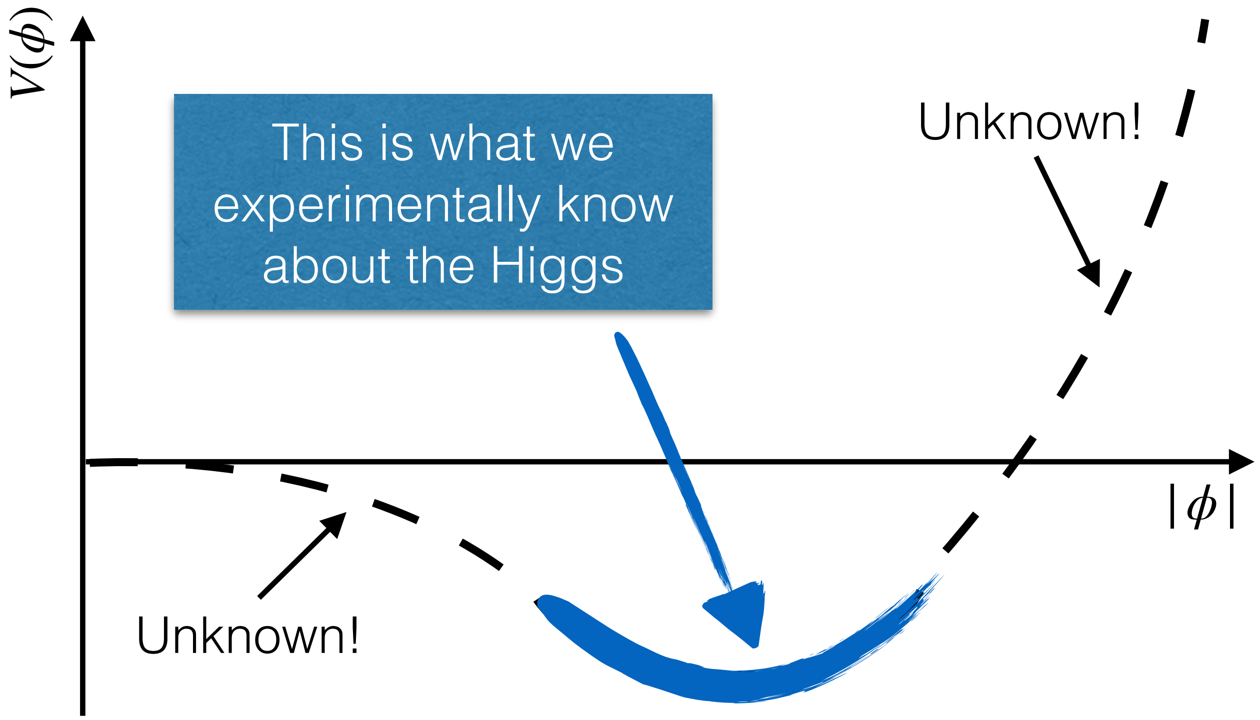
Is this **effectively the SM Higgs boson**?

The Higgs minimum and the potential shape

- So far, we only **established where the minimum of the Higgs potential is.**



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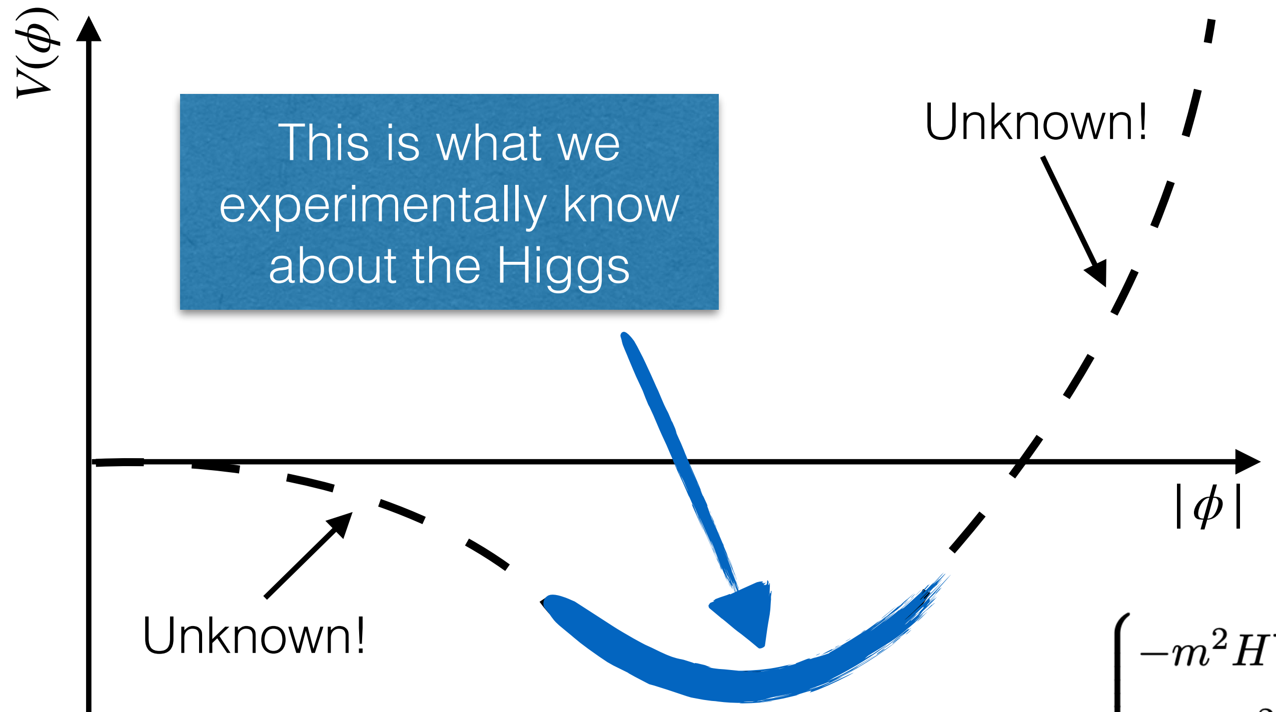
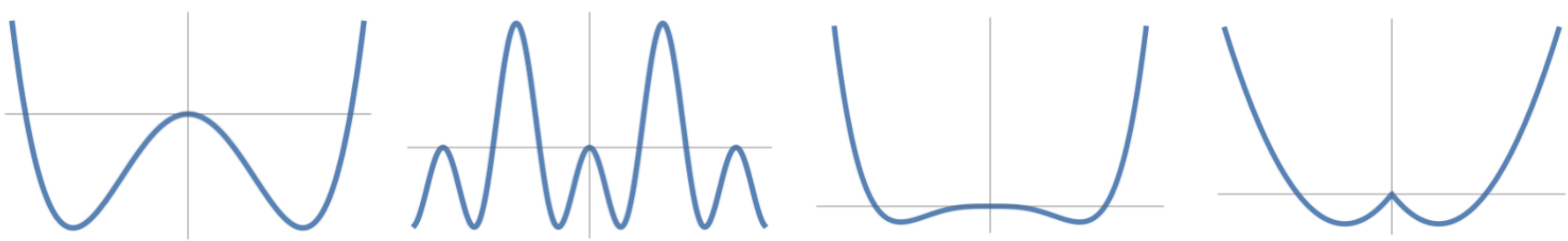


Different potential shapes could explain the same physics we see now!

$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2}(H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

arxiv:1907.02078



Landau-Ginzburg Higgs **Nambu-Goldstone Higgs** **Coleman-Weinberg Higgs** **Tadpole-Induced Higgs**

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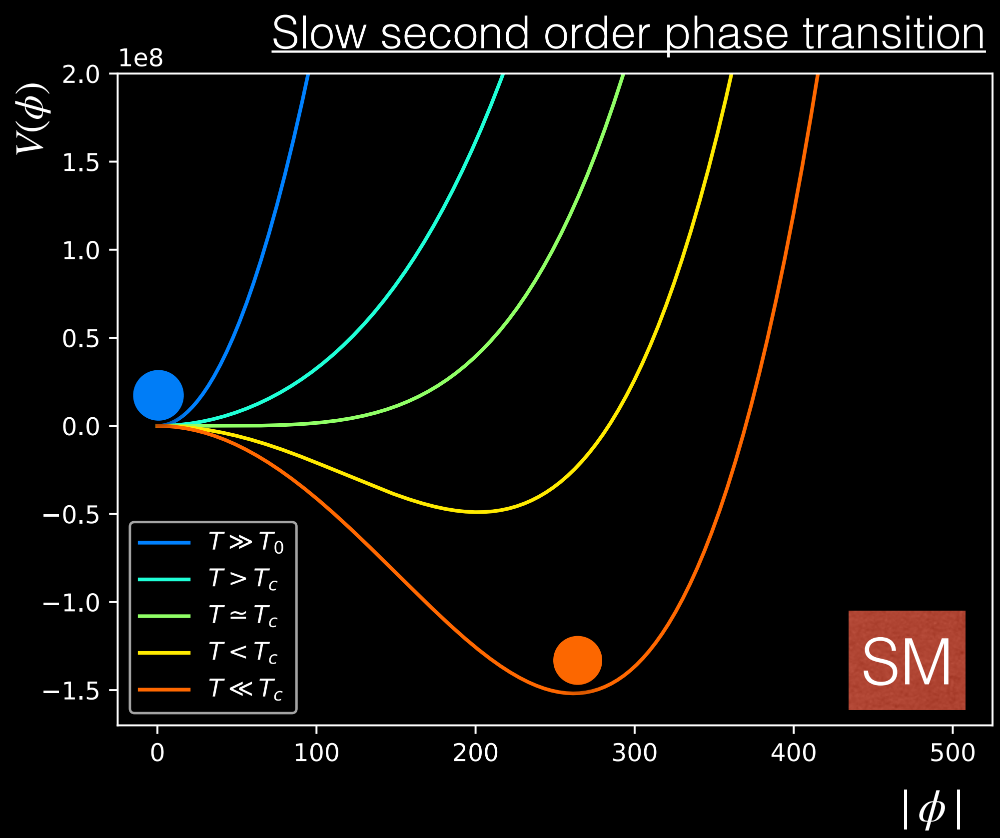
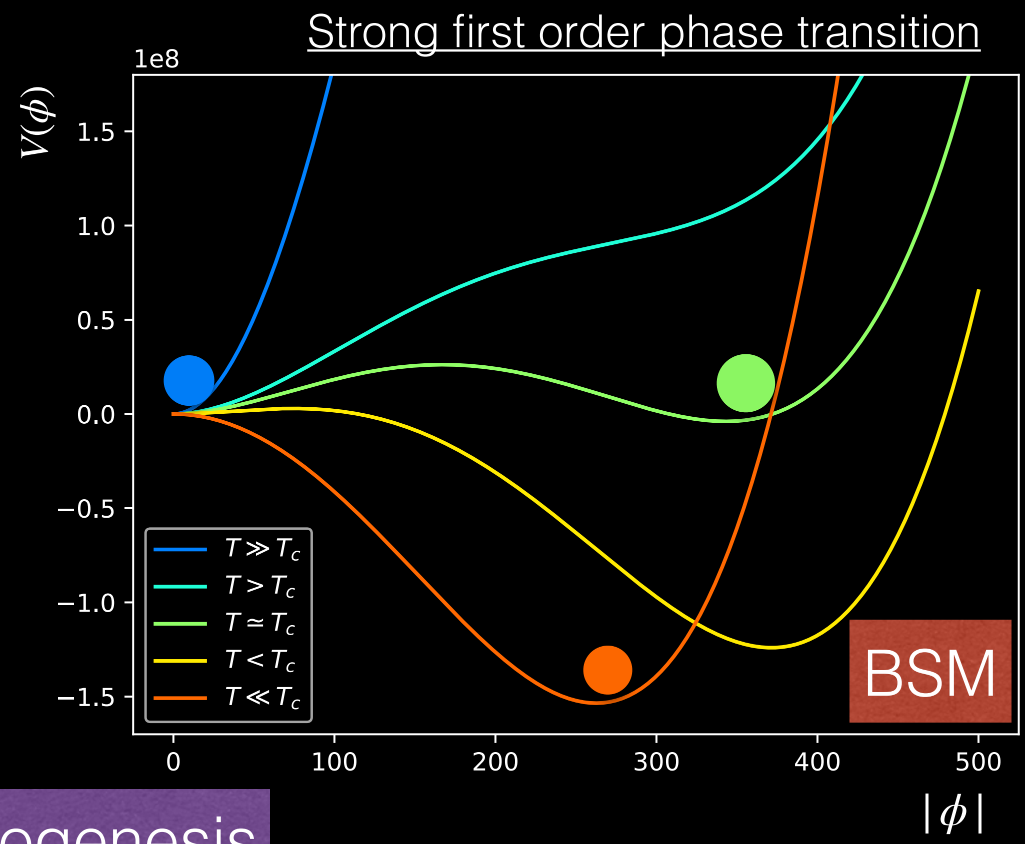
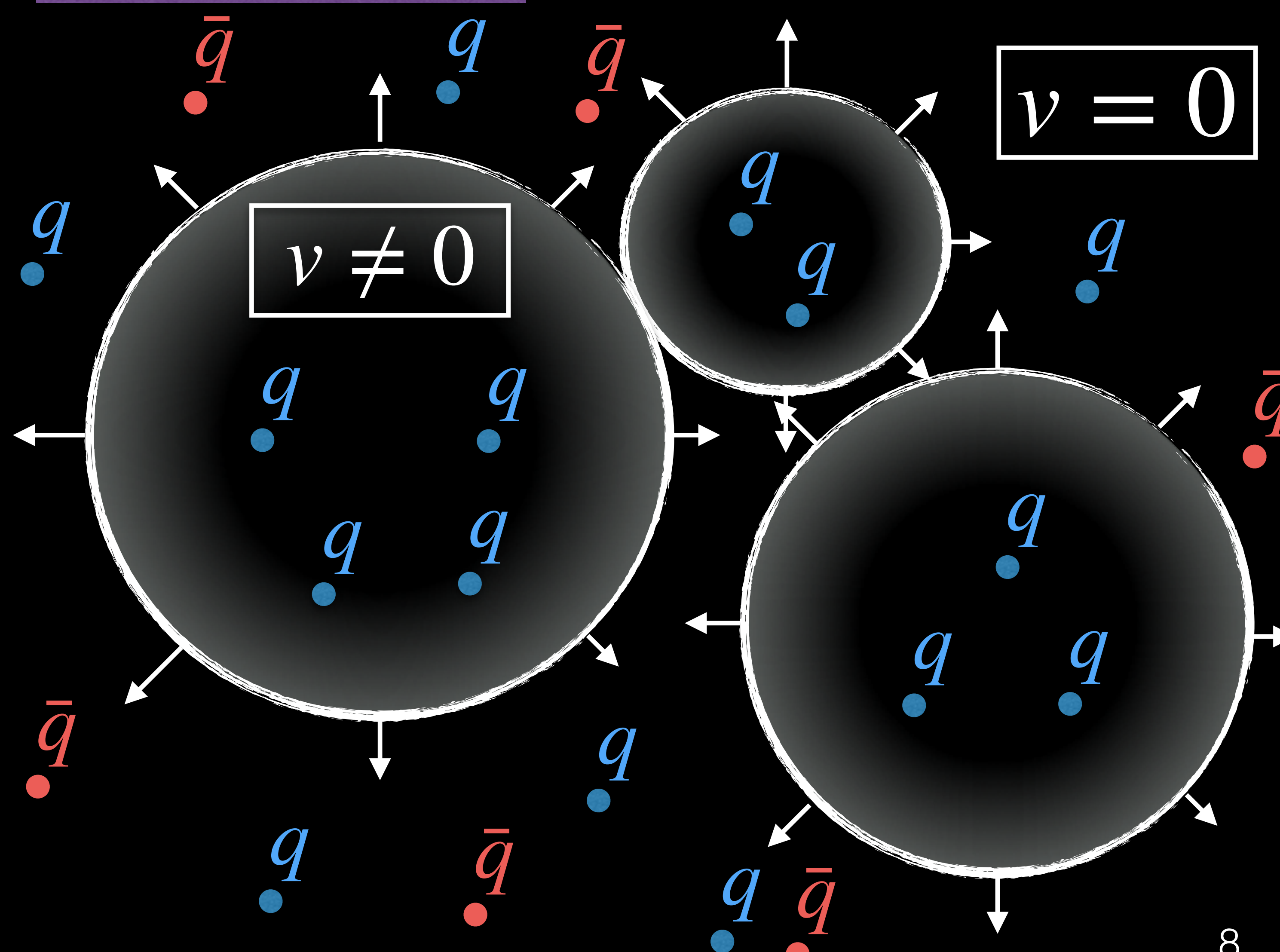




- **BSM effect in the Higgs potential could explain the matter-antimatter asymmetry** of the universe.
  - BSM physics acting on the Higgs potential would enable EWK bubble nucleation.

EWK baryogenesis



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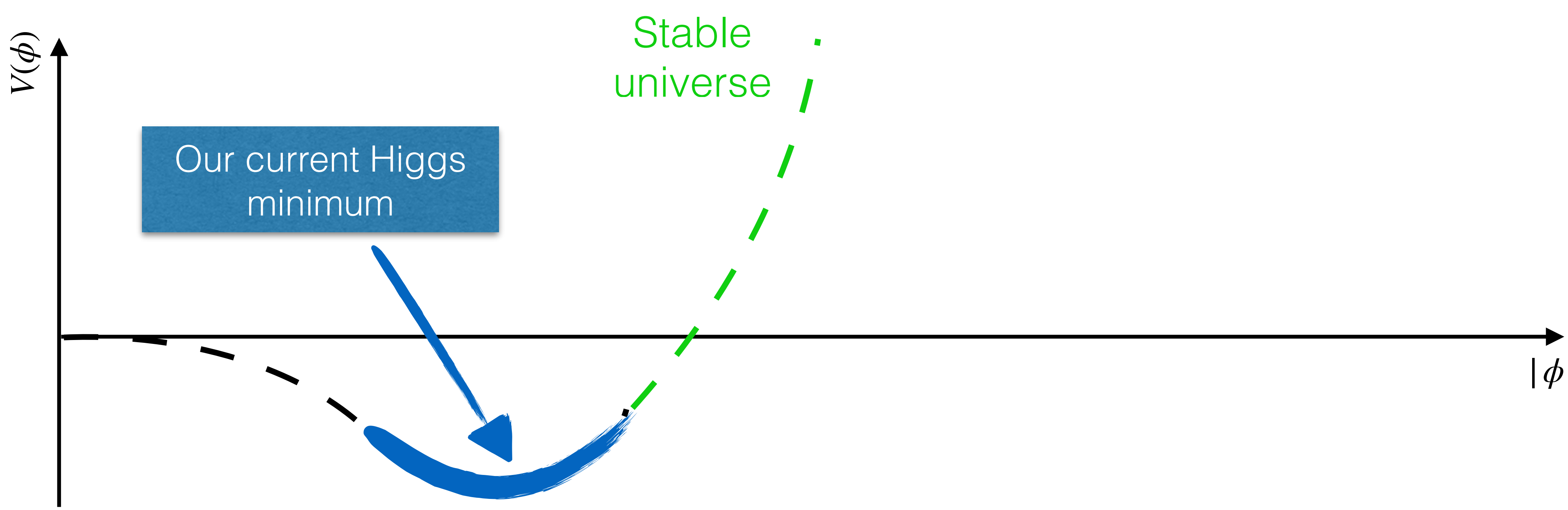
Is the Higgs vacuum stable?

Is the Higgs going to destroy our universe?

- Fermions (in particular tops) **contribute to the Higgs potential** with a negative sign.



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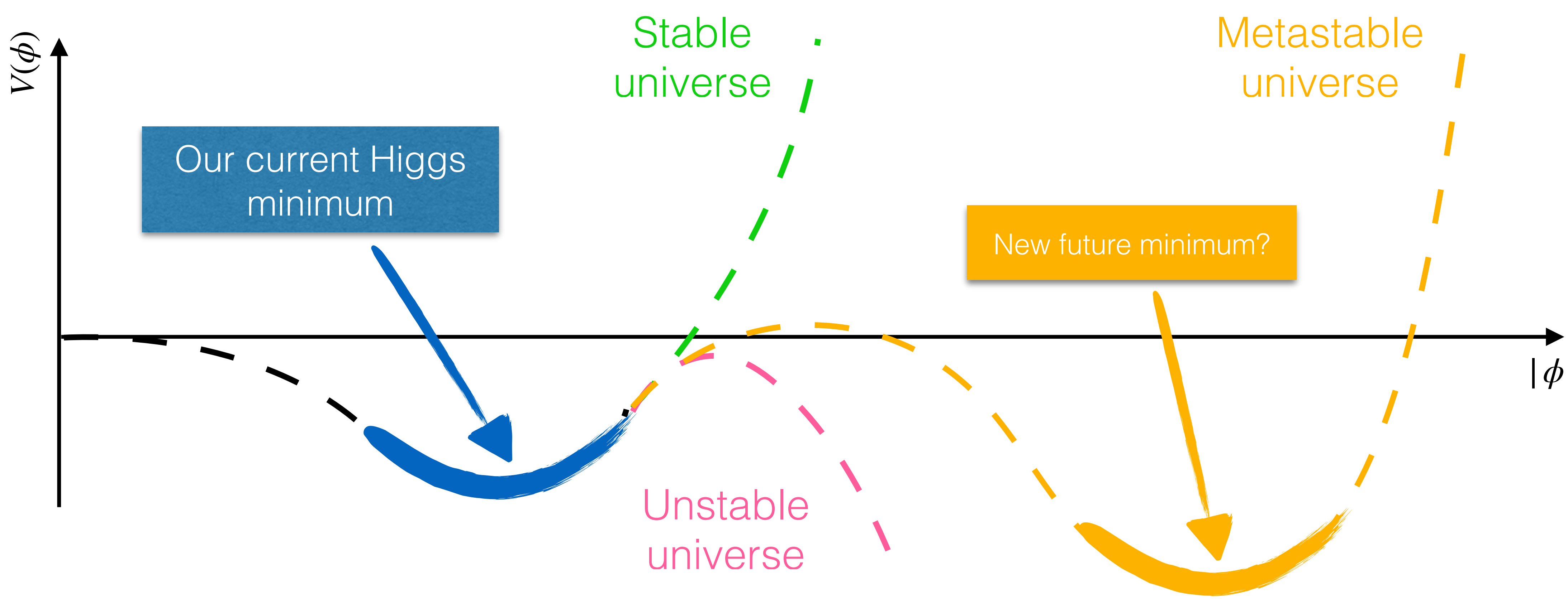

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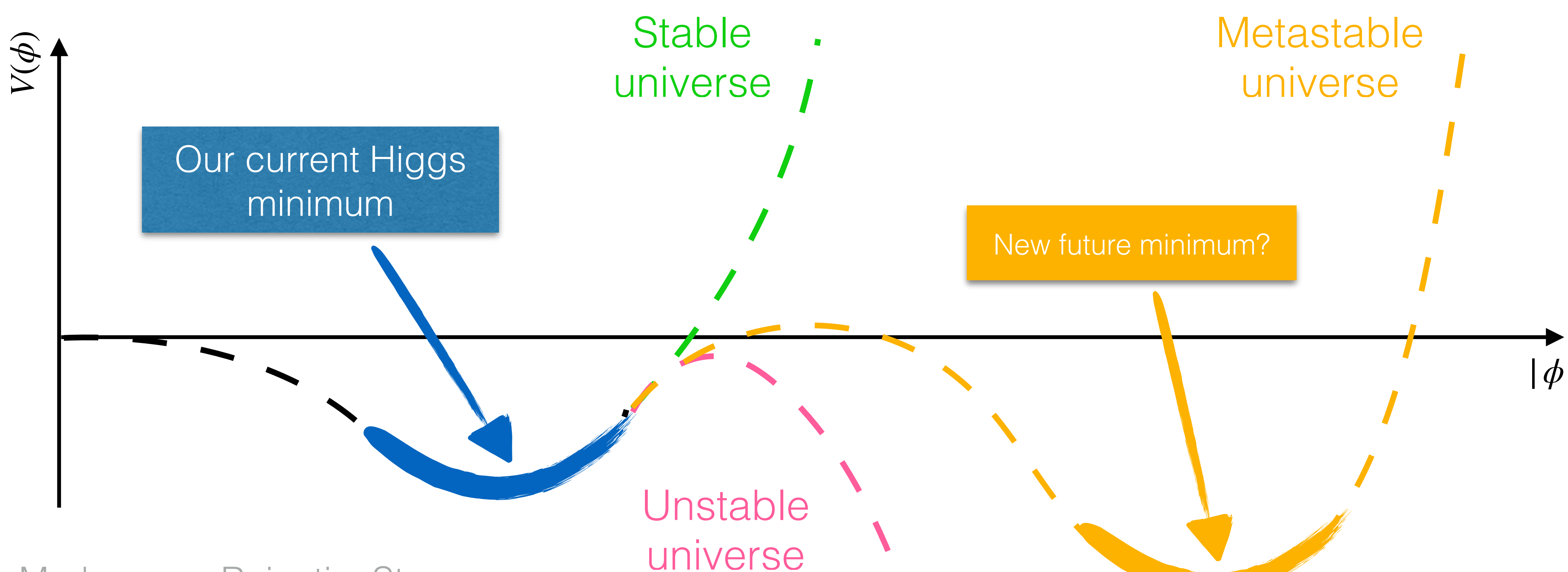

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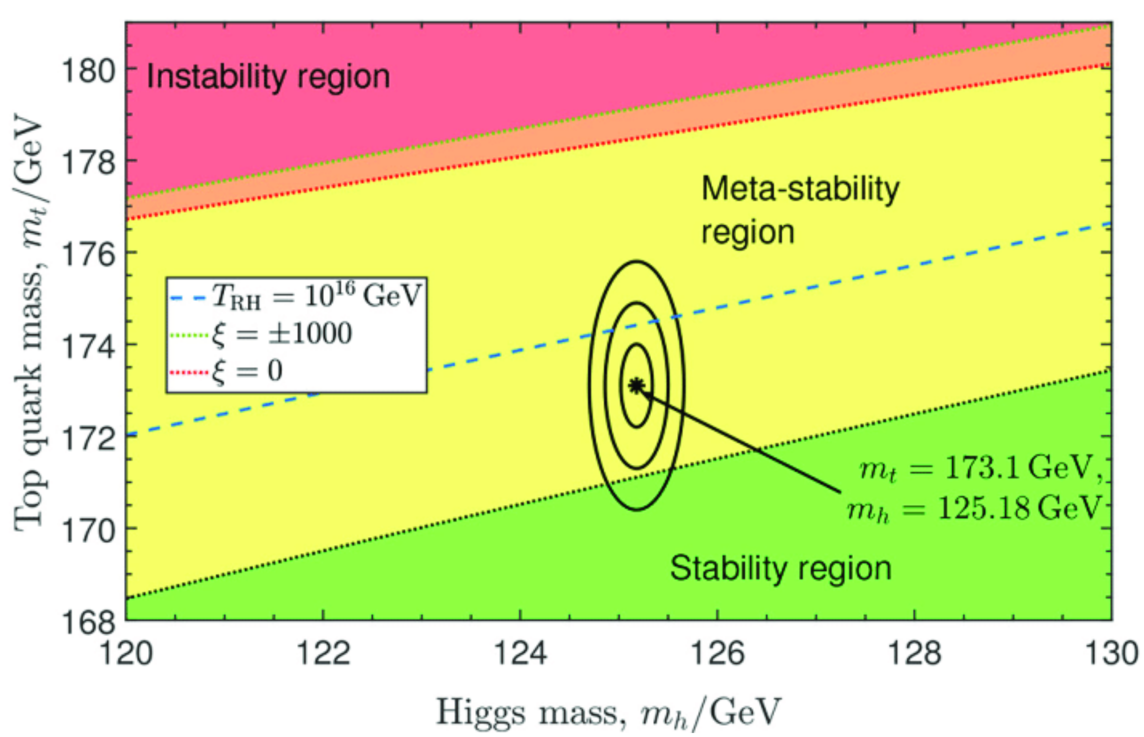

Current measurements suggest that we live in a **metastable** universe!

However, universe **decay expected in a larger time the current universe age** 😎

But it will eventually decay 😢

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Measuring **the Higgs potential is crucial** to fully understand EWSB, and also how the **universe began** and it might **finish**!

But so… **how can we measure the Higgs potential?**

How to measure the Higgs potential

Multiple-Higgs events

We need to access the λ parameter of the Higgs potential.

$$\boxed{V(h) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \simeq \frac{1}{2}m_h^2h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots}$$

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Tells us where the minimum of the potential is

$\Rightarrow m_H = \sqrt{2\lambda} v \approx 125$ GeV means $\lambda_{SM} \approx 0.13$

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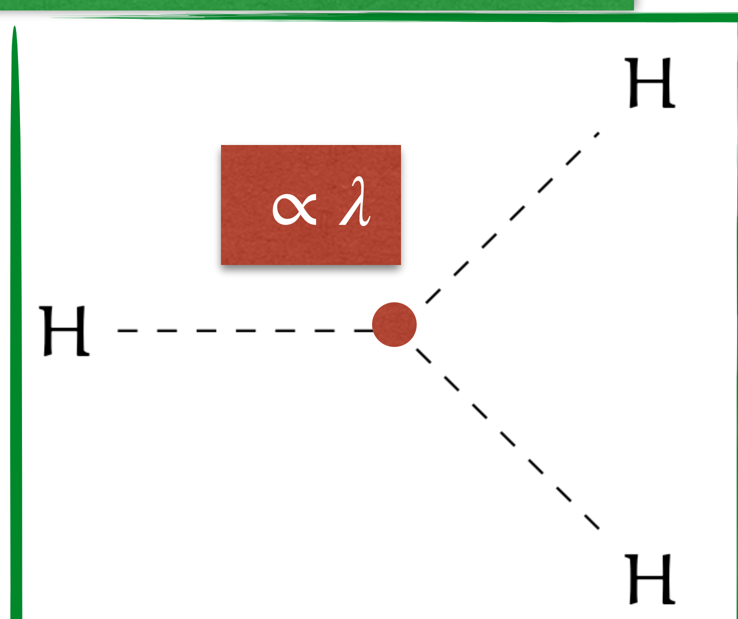
Trilinear Higgs self-coupling



Access to λ through **3-Higgs interactions**

We generally look more at κ_λ rather than λ directly

$$\boxed{\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}}$$

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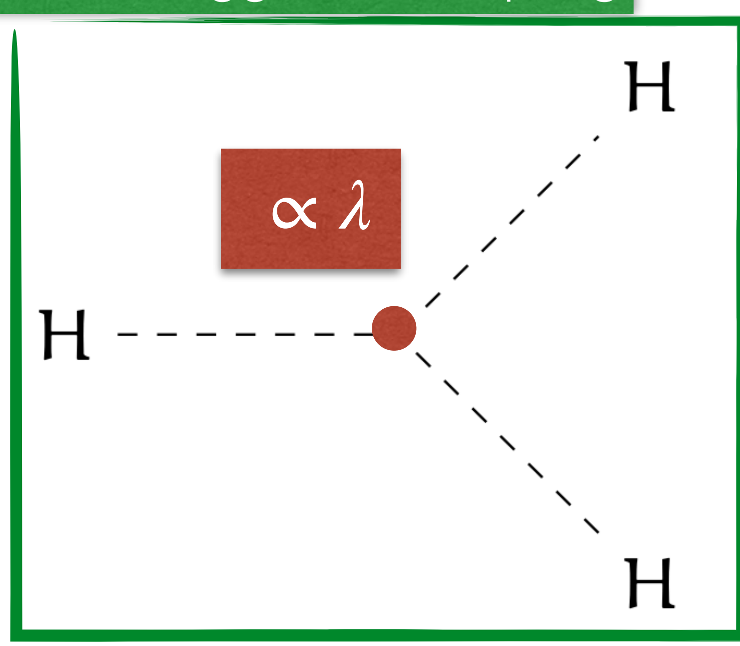
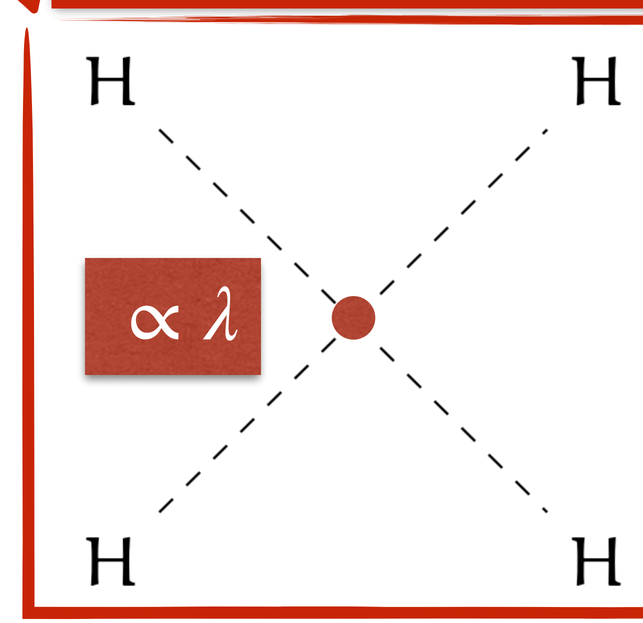


Access to λ through **3-Higgs interactions**

Quadrilinear Higgs self-coupling



Out of the reach of (HL)-LHC (and even most of future collider scenarios)

We generally look more at κ_λ rather than λ directly

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

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HH production at the LHC

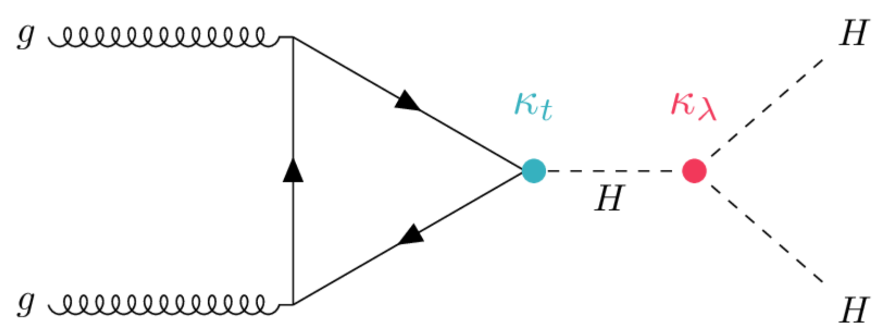
Non-resonant HH production

Gluon-gluon fusion (ggF)

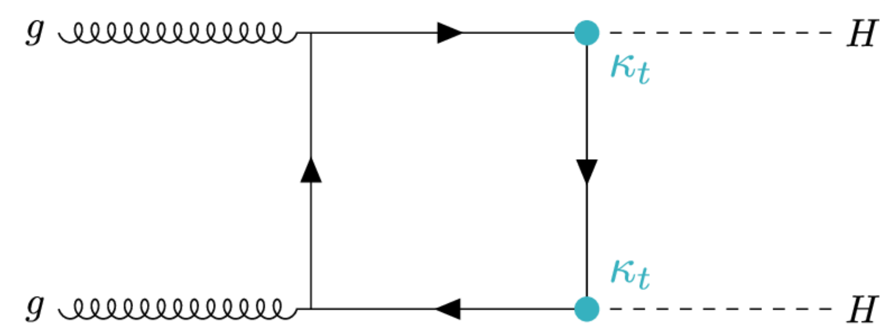
- Destructive interference leads to small cross-section:

$\sigma_{\text{ggF}} = 31.05$ fb → 1 HH event every 1000 single-H events!

Triangle diagram

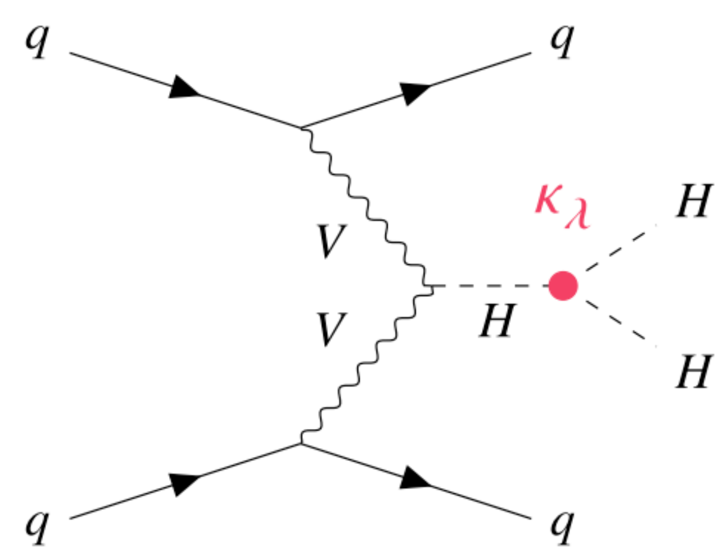


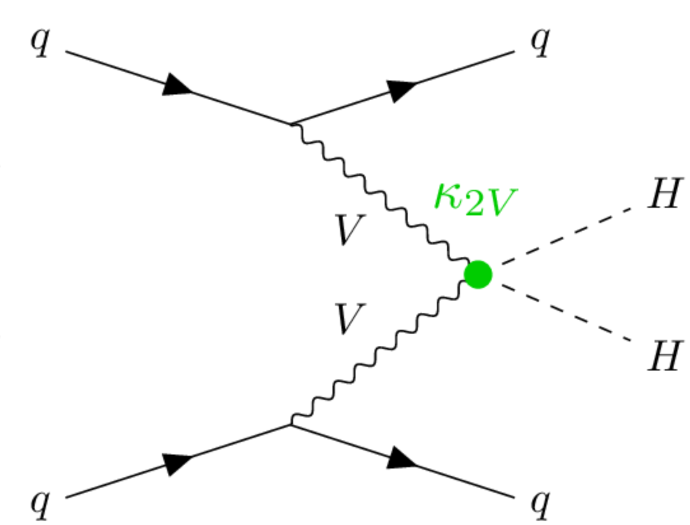
Box diagram



Vector-boson fusion (VBF)

- Signature: 2 Higgs + 2 quarks close to the LHC proton beams.
- Access to κ_λ, but also to **VVHH process** (never measured!) which could provide test **of SM unitarity via measurement of** k_{2V}.
- **Very tiny** cross-section: $\sigma_{\text{VBF}} = 1.72$ fb





$$\kappa_{2V} \equiv \frac{c_{2V}}{c_{2V}^{SM}}$$

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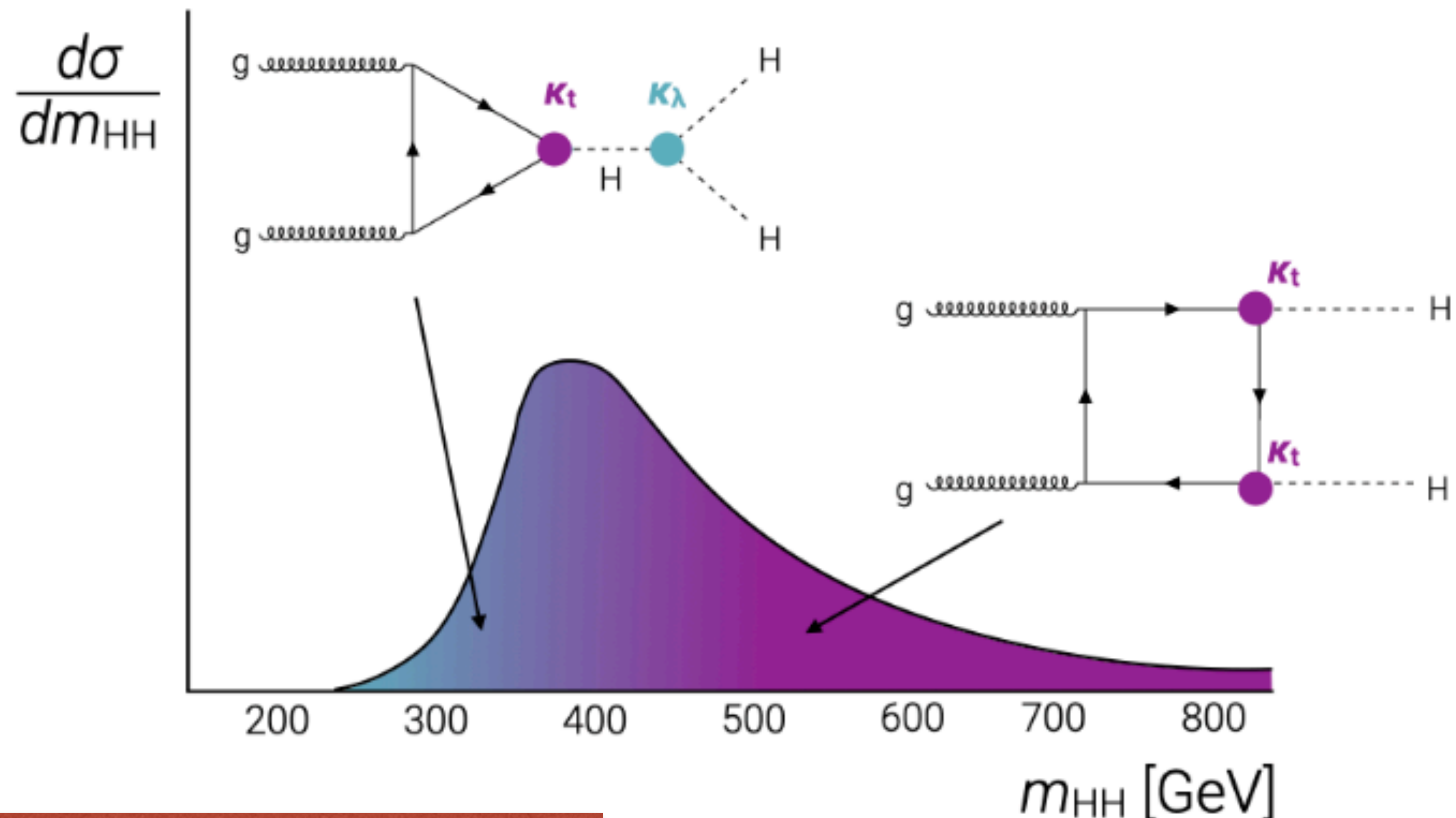
Challenges of HH production at the LHC

The unbearable lightness of HH

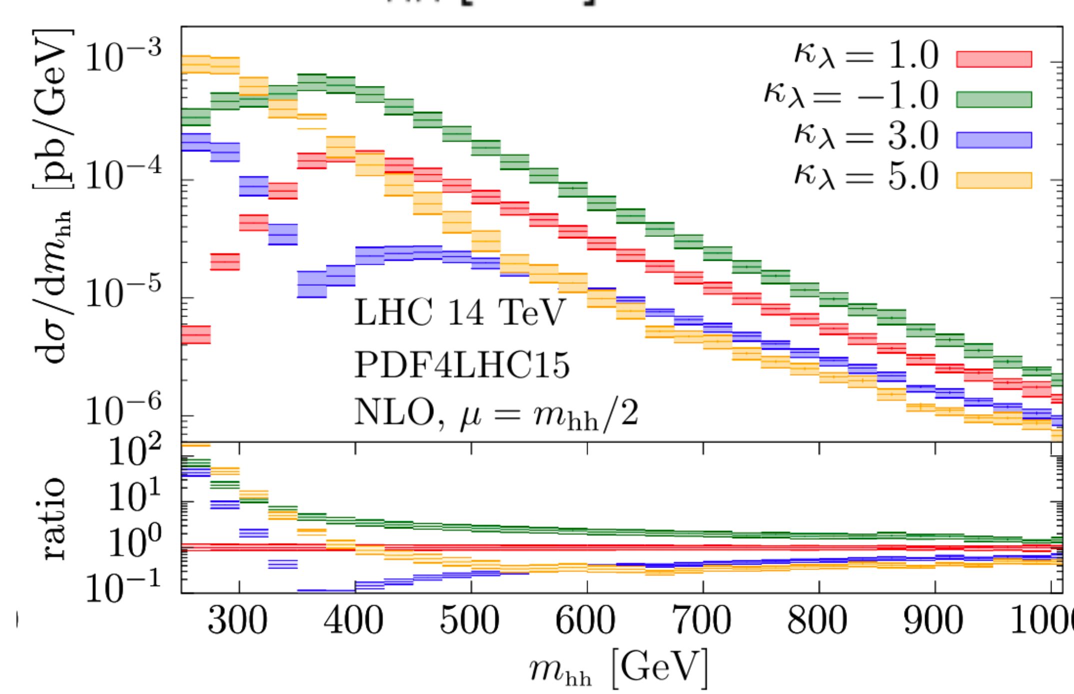
Not only small cross-section, **but also complex signal kinematic** due to diagram interference!



arXiv:1903.08137

Impact of κ_λ more visible in soft part (i.e. low p_T) of the m_{HH} spectrum

Access low m_{HH} events is hard due to soft Higgs kinematics!



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The HH final states

- With $\sigma(HH) \approx 31$ fb and $\mathscr{L}^{int} = 139\ \text{fb}^{-1}$, **~4k HH events produced** in the LHC Run 2.
    - **Maximal sensitivity requires multiple analysis channels** targeting different decays.

First Higgs decay ← ; Higher BR

Second Higgs decay ↑

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Most sensitive ATLAS channels covered in this talk.

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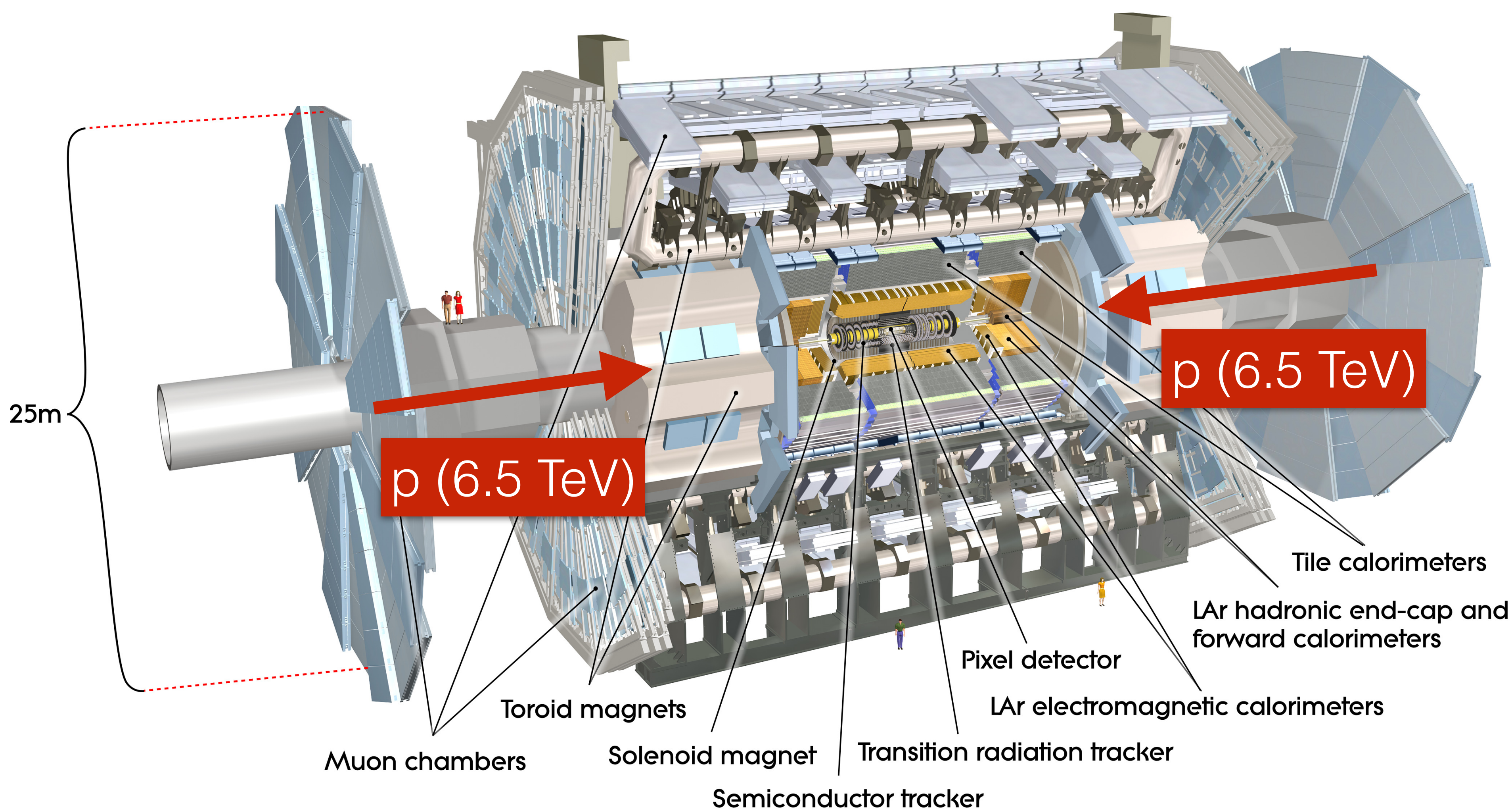
A Toroidal LHC ApparatuS (ATLAS)

The kind giant

- Different (independent) sub-detectors:
  - **Inner Detector:** providing tracking for charged particles.
  - **Calorimeters:** electromagnetic (ECAL) and hadronic (HCAL), providing the energy measurement of neutral and charged particles.
  - **Muon detectors:** providing muon measurements.
- **Trigger and Data Acquisition system:** selection of interesting collisions (events).



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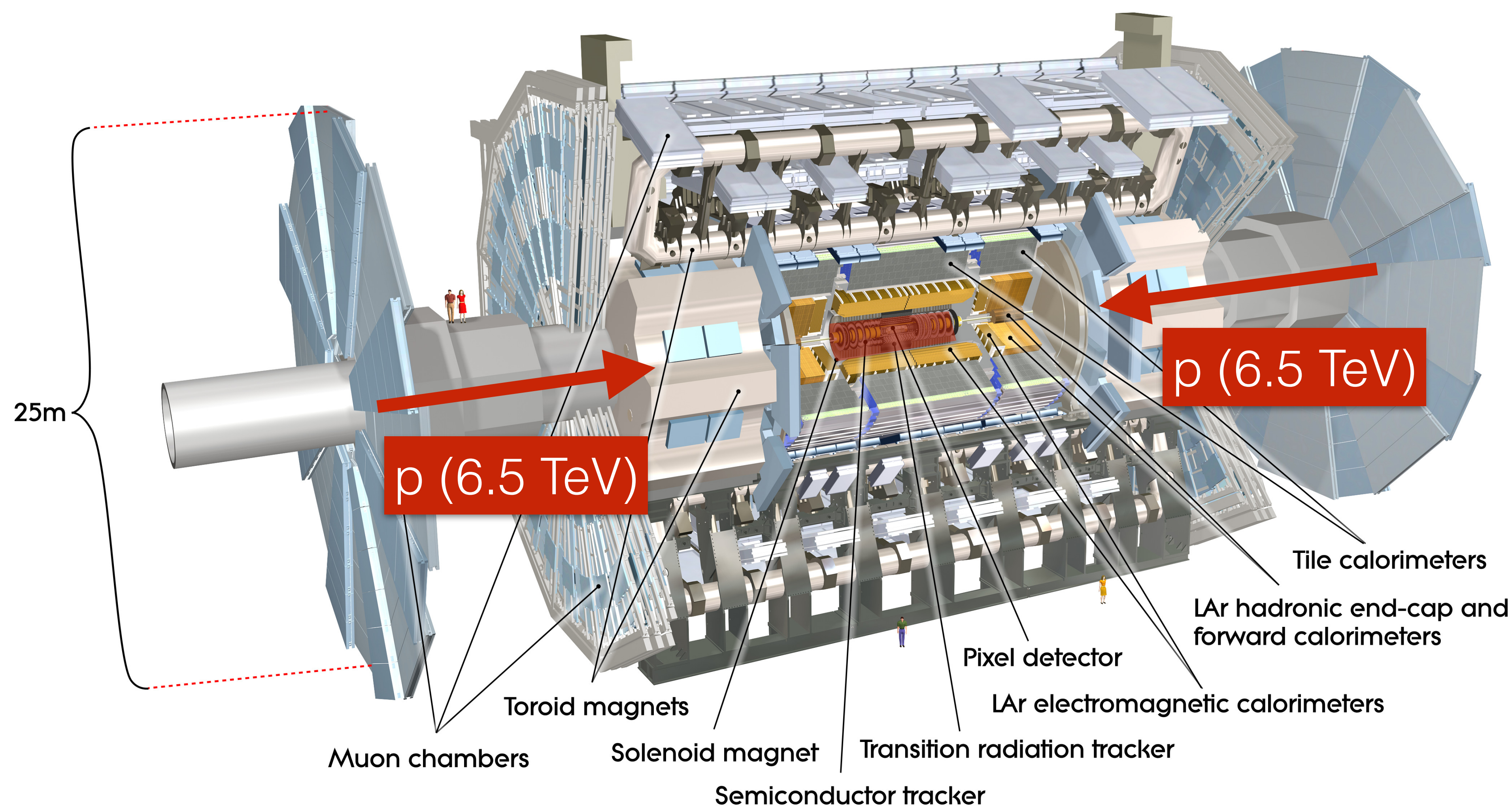

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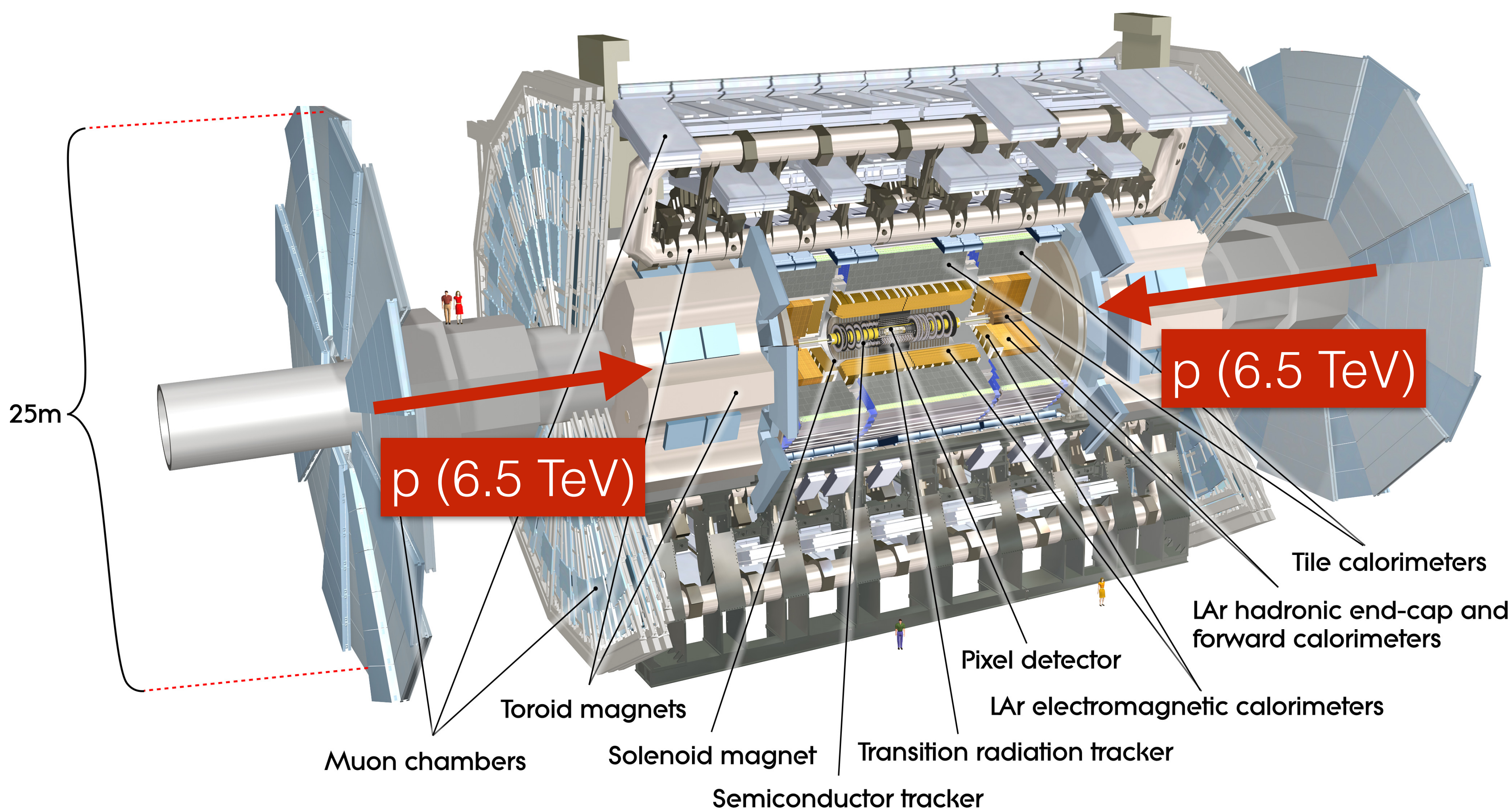

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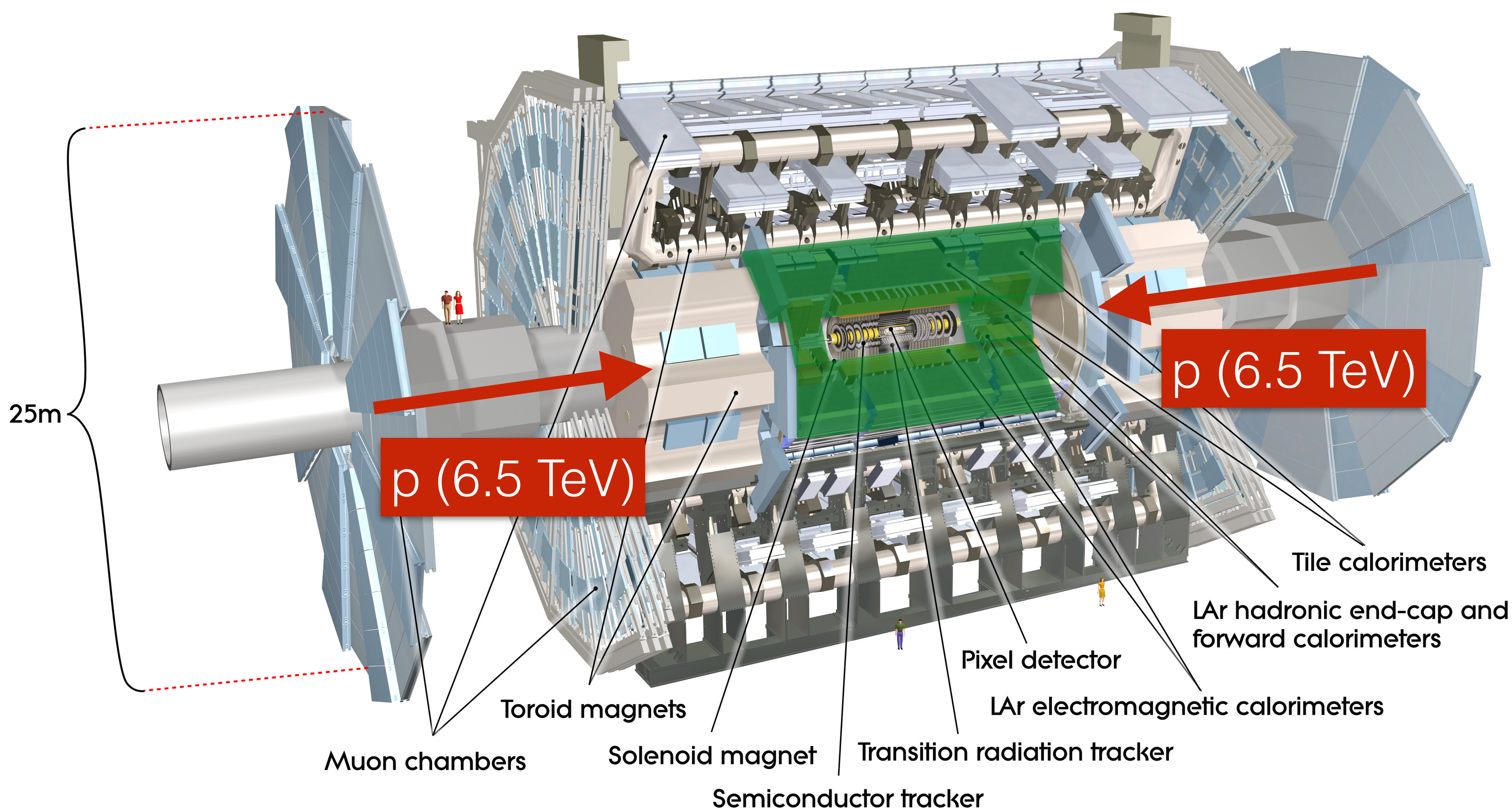

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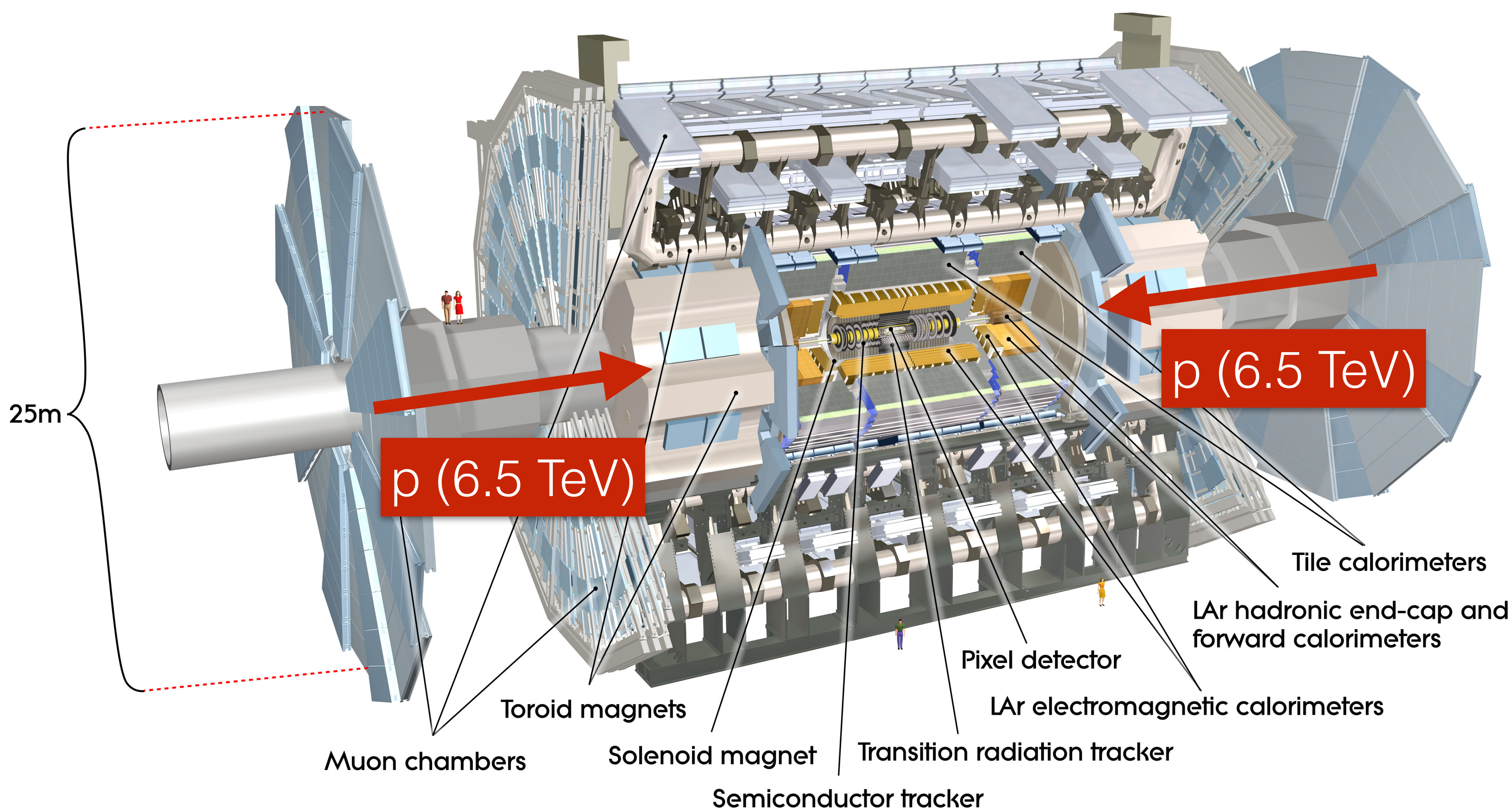

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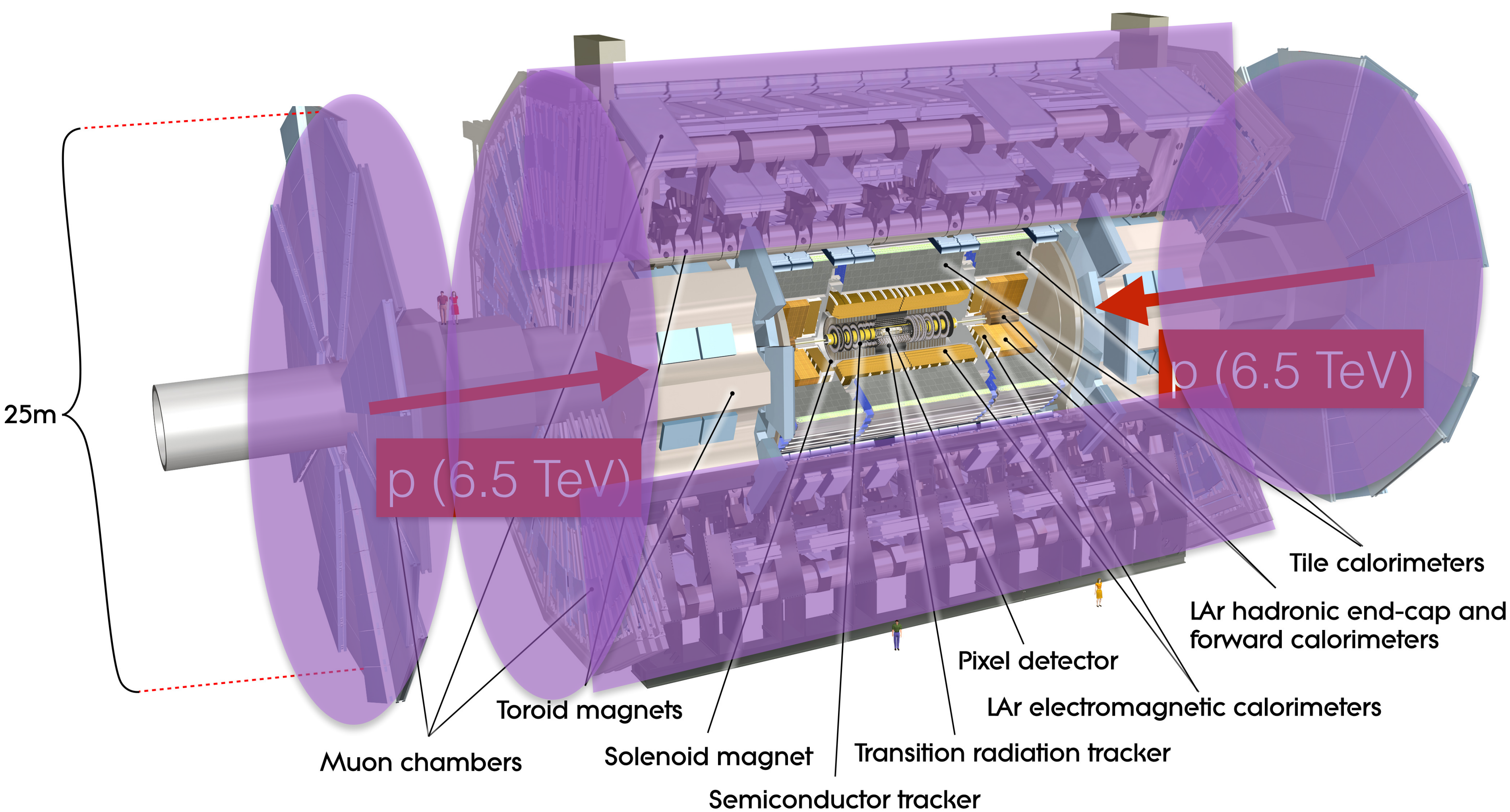

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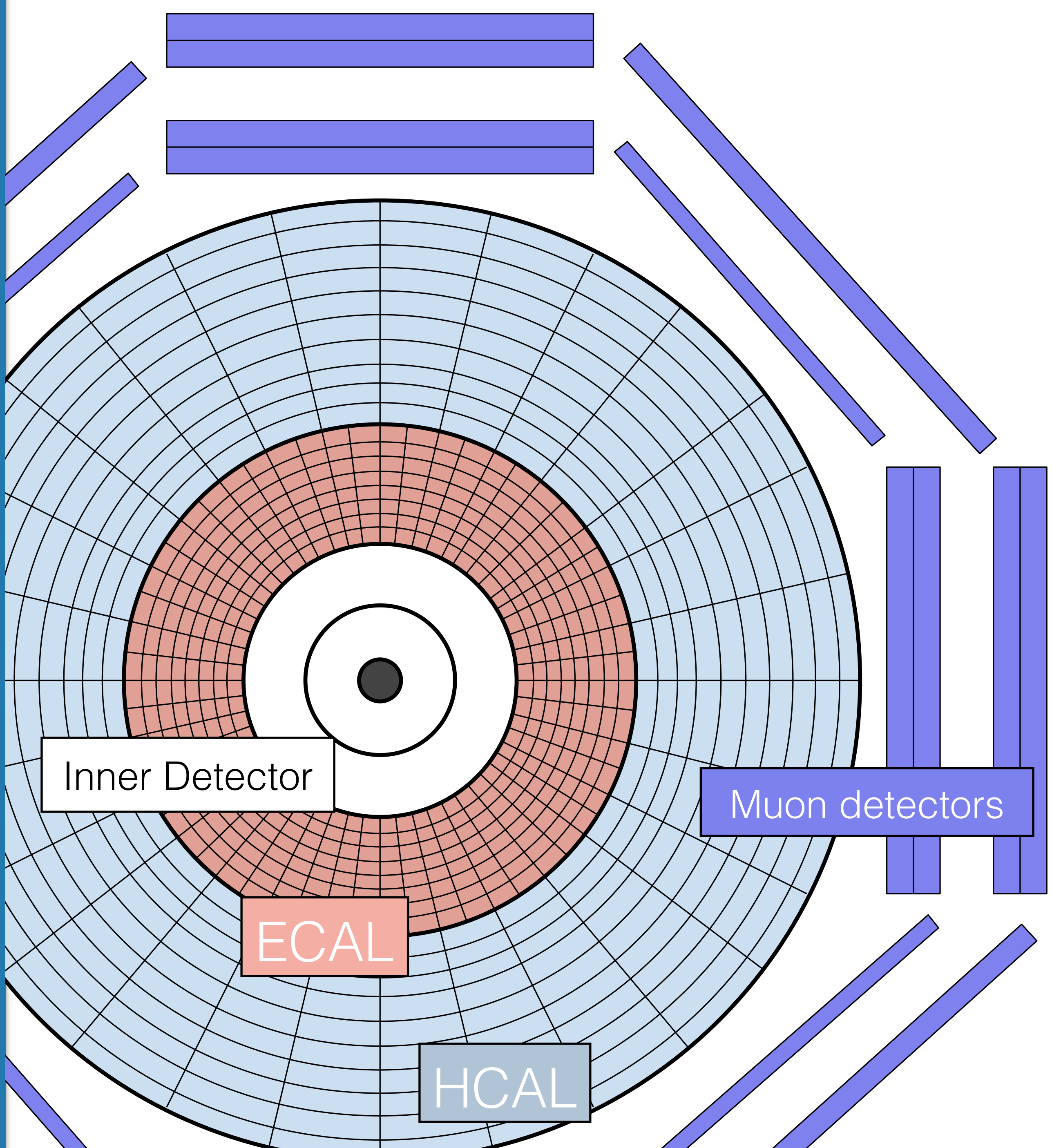
HH final state reconstruction

To observe HH decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we **need to identify b-quarks, τ-leptons and photons.**



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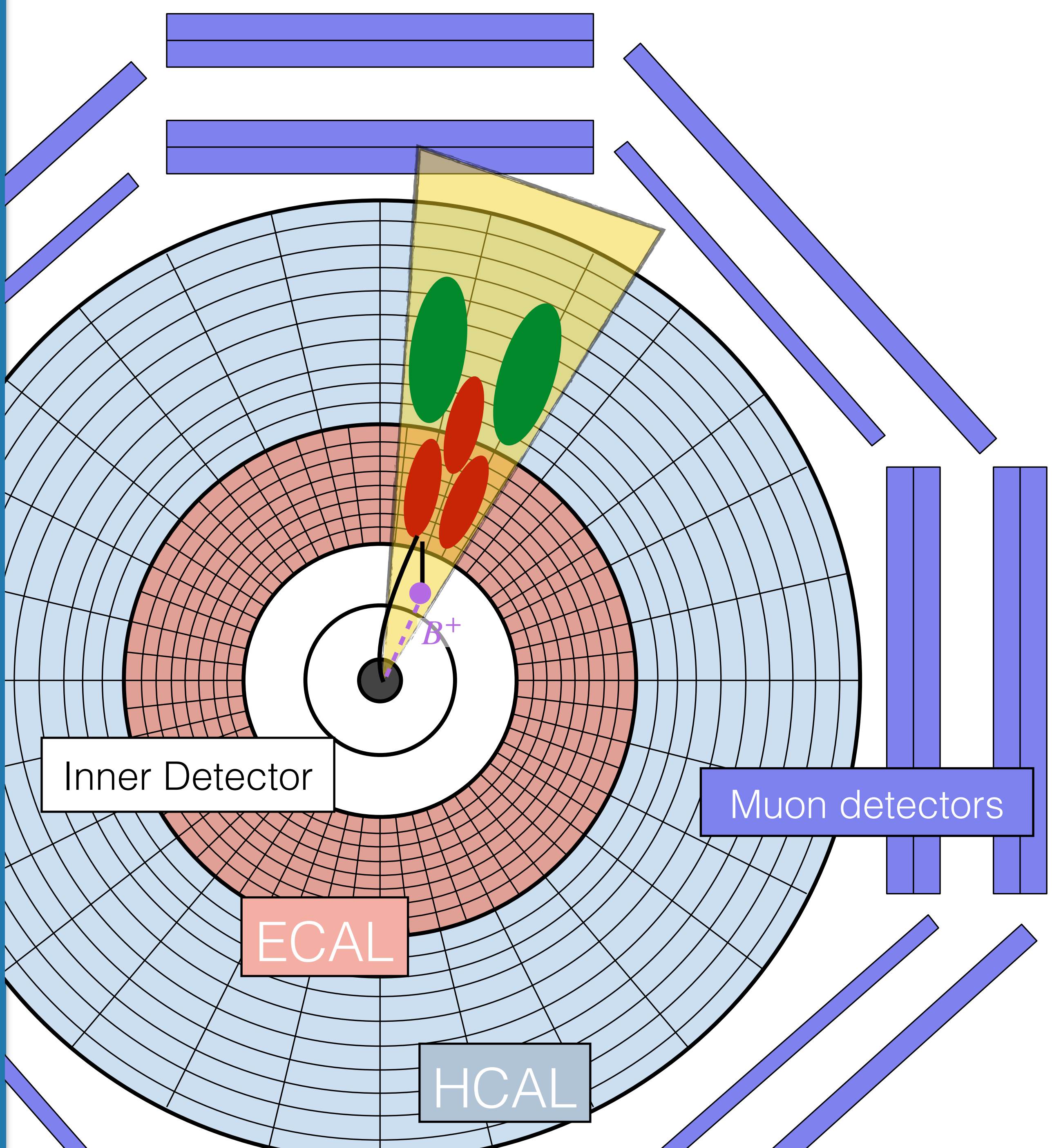

- b-jets: collimated **spray of particles** containing a **displaced vertex** (B-hadron decay).
  - Machine Learning **b-tagging algorithms** (e.g. DL1r) for identification.

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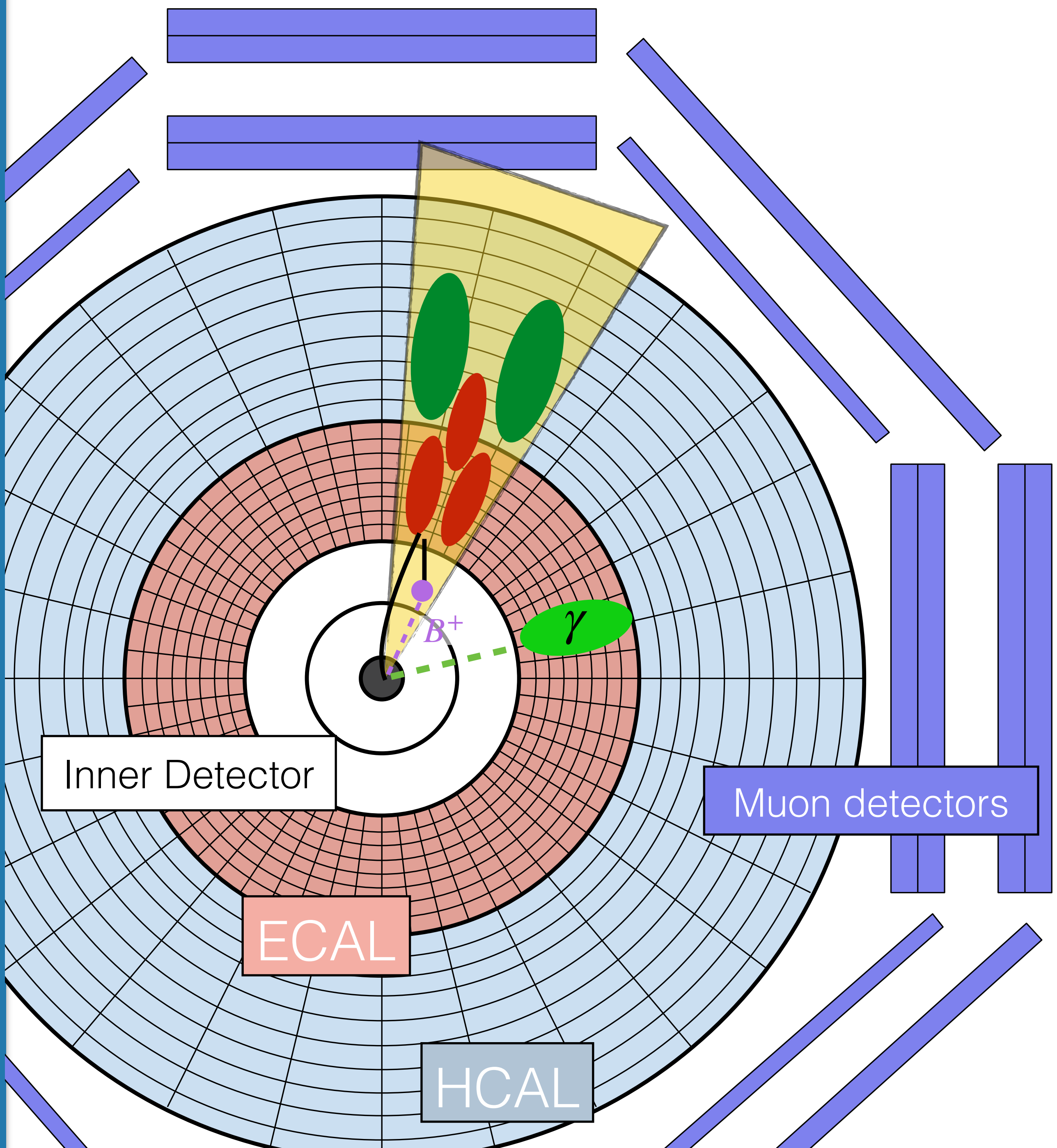

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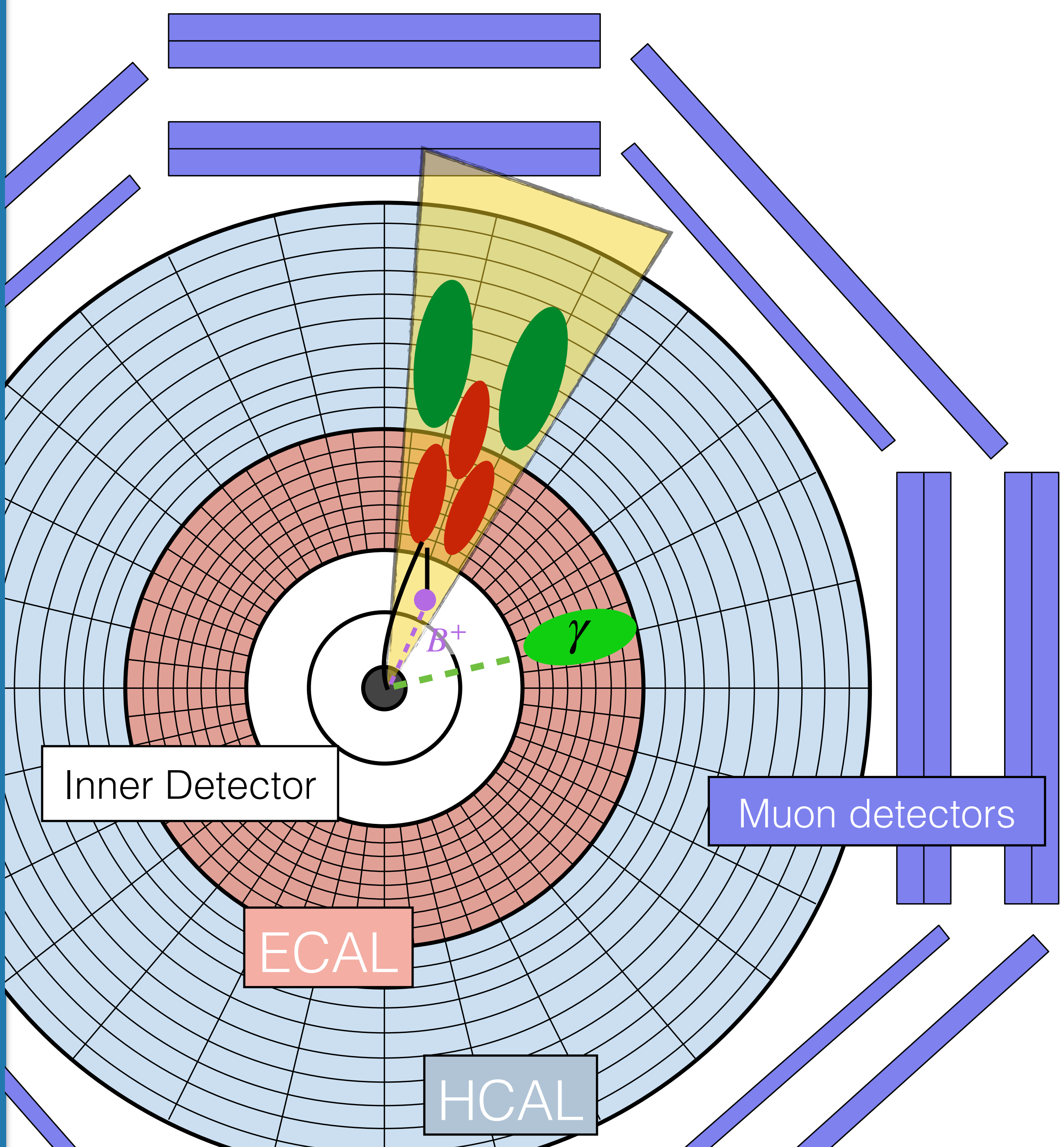

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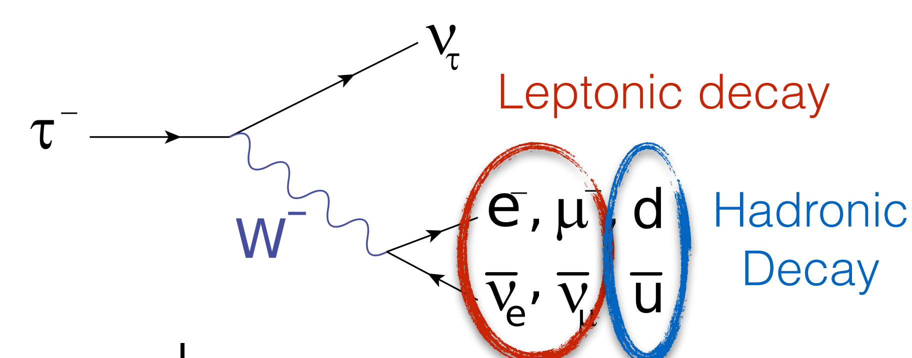

- Taus: ν_τ plus
  1. Hadronic τ (τ_{had}): **jet** with low number of tracks identified with τ tagger.
  2. Leptonic τ (τ_{lep}): **muon** (μ) or **electron** (e)

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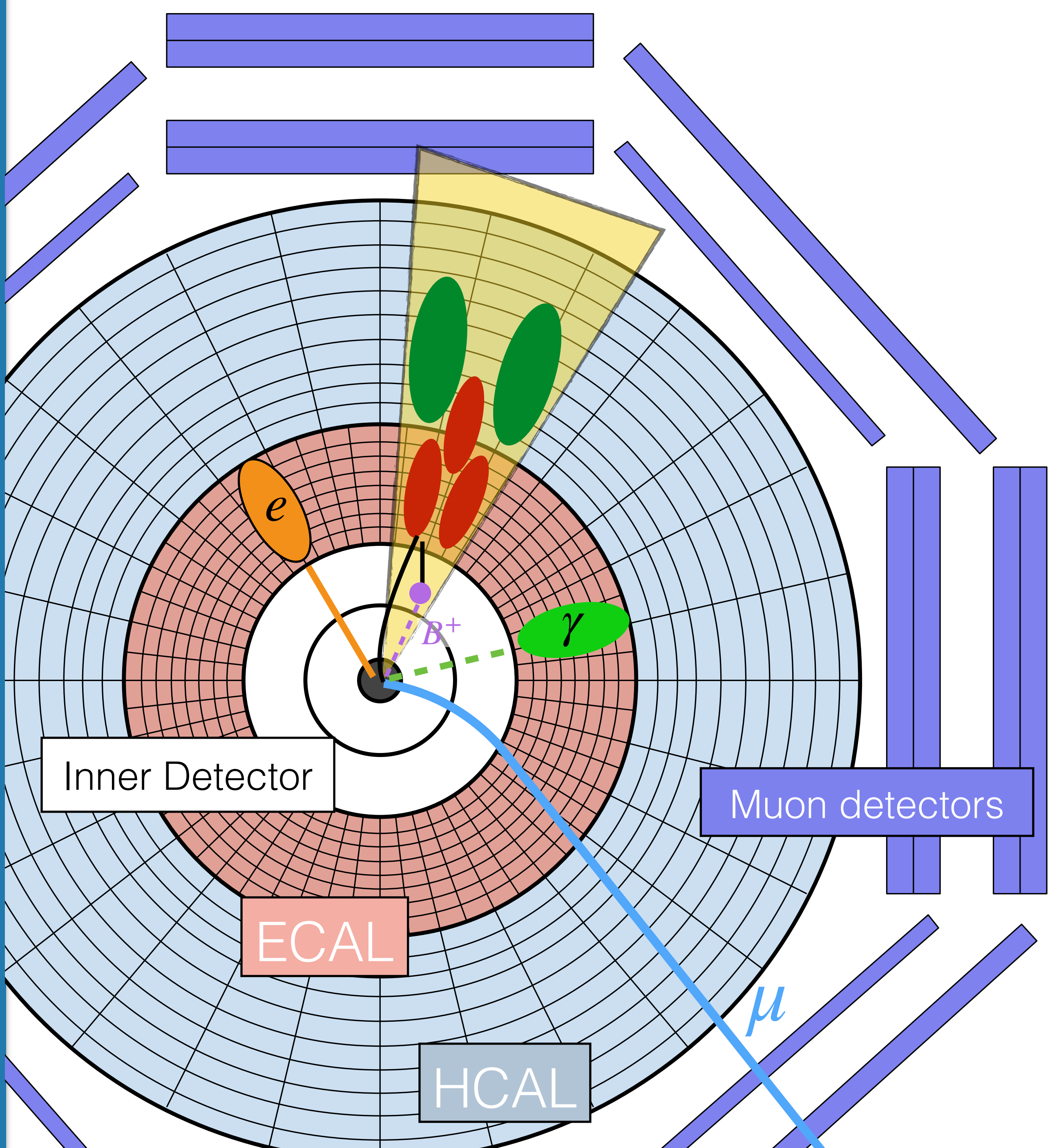
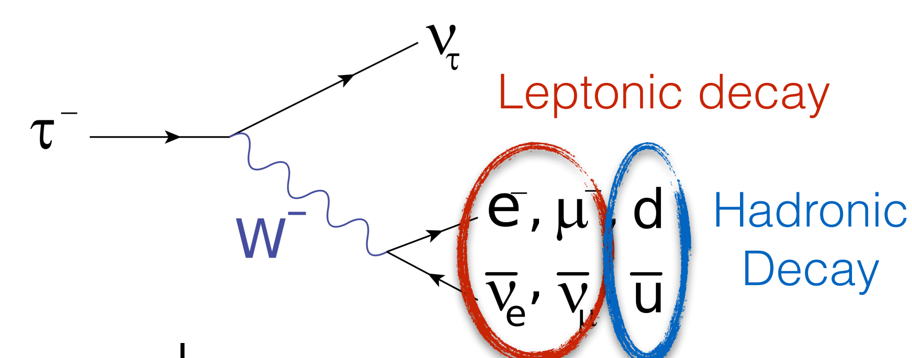
HH final state reconstruction

To observe HH decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we **need to identify b-quarks, τ-leptons and photons.**



- b-jets: collimated **spray of particles** containing a **displaced vertex** (B-hadron decay).
  - Machine Learning **b-tagging algorithms** (e.g. DL1r) for identification.
- Photons: isolated **ECAL energy deposit without associated track**.

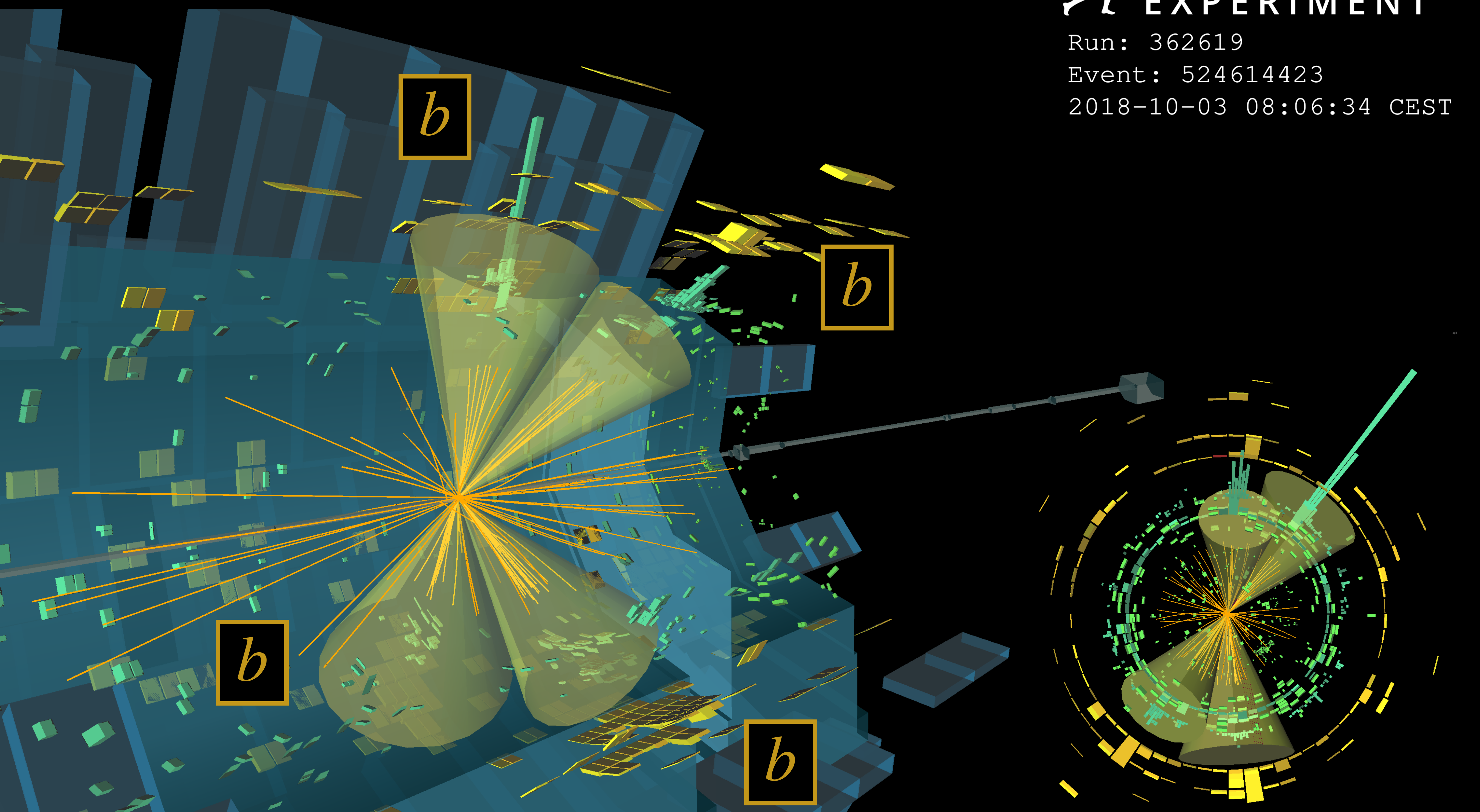


- Taus: ν_τ plus
  1. Hadronic τ (τ_{had}): **jet** with low number of tracks identified with τ tagger.
  2. Leptonic τ (τ_{lep}): **muon** (μ) or **electron** (e)

So, let’s move to the analyses!

$HH \to b\bar{b}b\bar{b}$ analysis (126 fb^{-1})

arXiv:2301.03212



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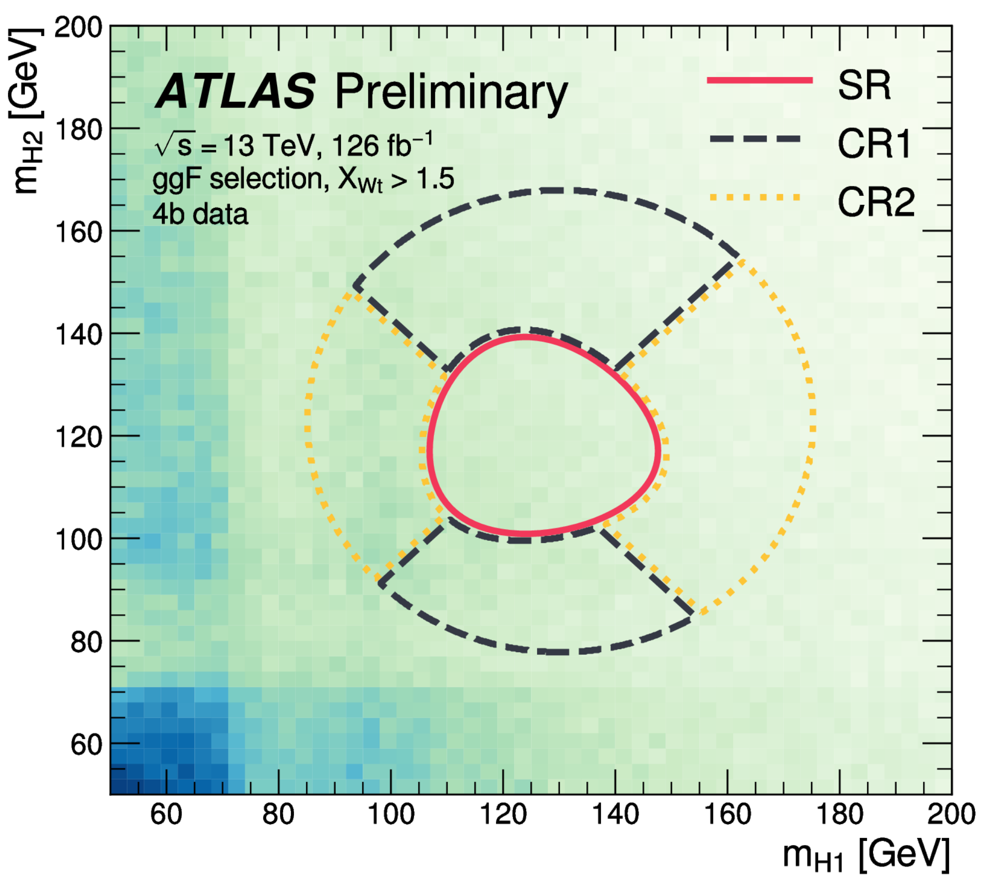
$HH \to b\bar{b}b\bar{b}$ analysis (1)

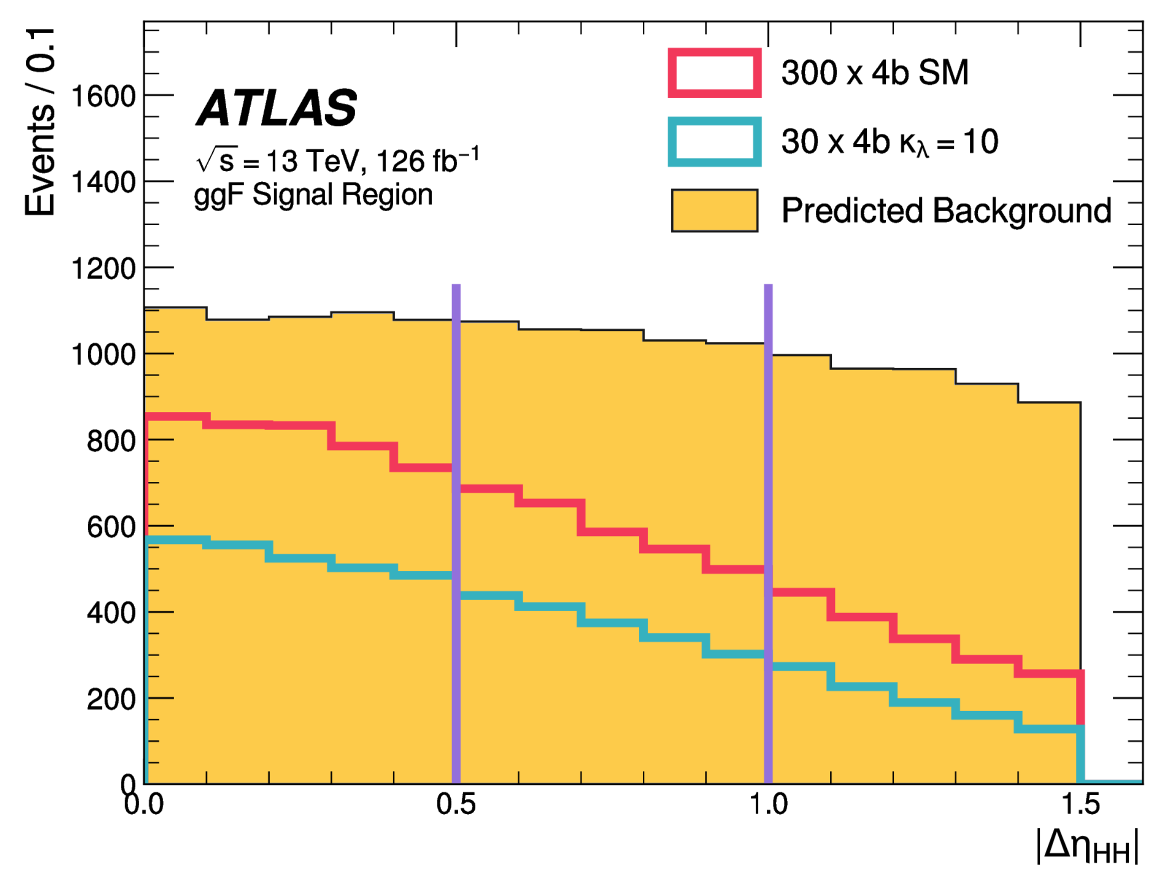
Selection and analysis categories

- **Largest HH BR** (34%), but **large multi-jet background** and challenging jet-pairing combinatorics.
- Selection:
  - Combination of **jet and b-jet triggers**.
  - At least **4 central ($|\eta| < 2.5$) b-jets** (77% eff. DL1r) for ggF.
    - VBF selection requires **two additional jets** close to the beam ($|\Delta\eta_{jj}| > 3$).
  - HH mass plane selection used for signal region (SR) definition.

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\ \mathrm{GeV}}{0.1\, m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\ \mathrm{GeV}}{0.1\, m_{H2}}\right)^2},$$

- Categories: **6 binned in ($\Delta\eta_{HH}$, X_{HH}) for ggF** and **2 binned in ($\Delta\eta_{HH}$) for VBF** to enhance signal sensitivity.

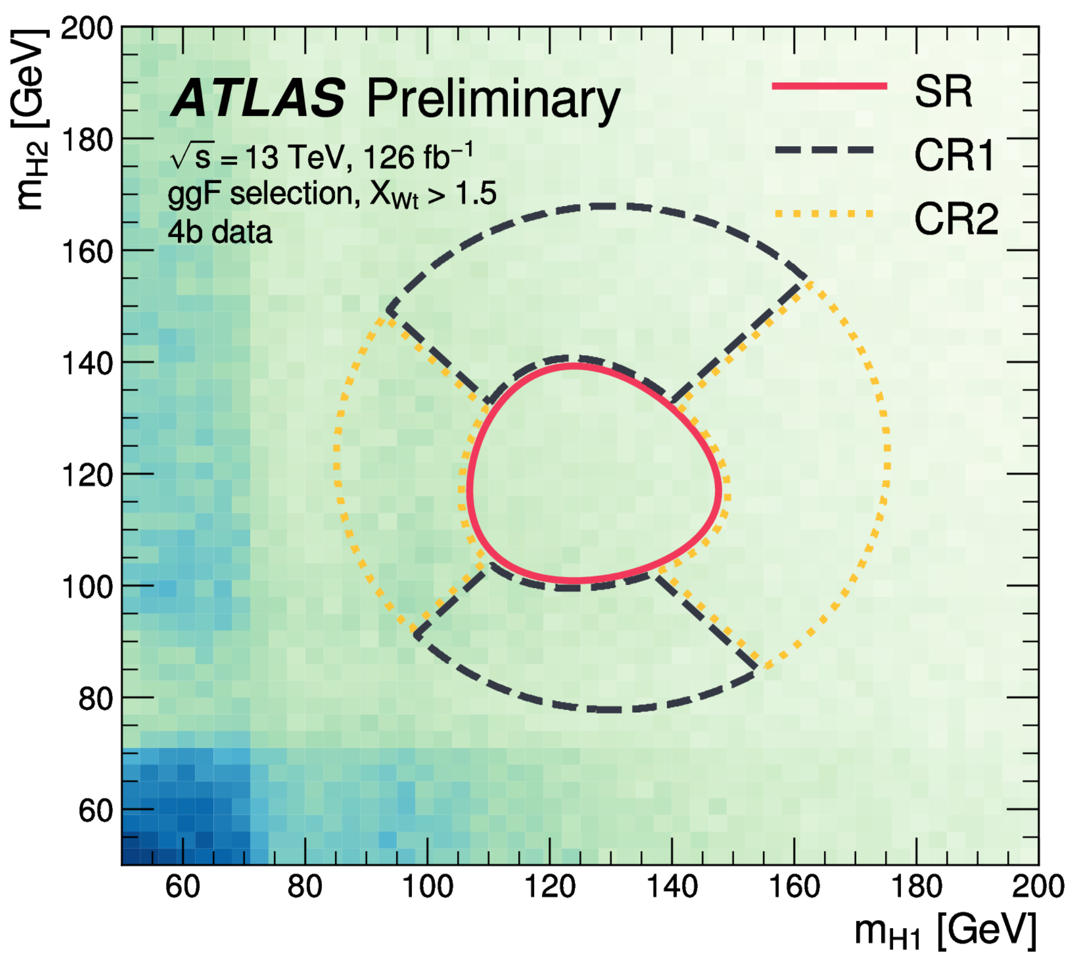


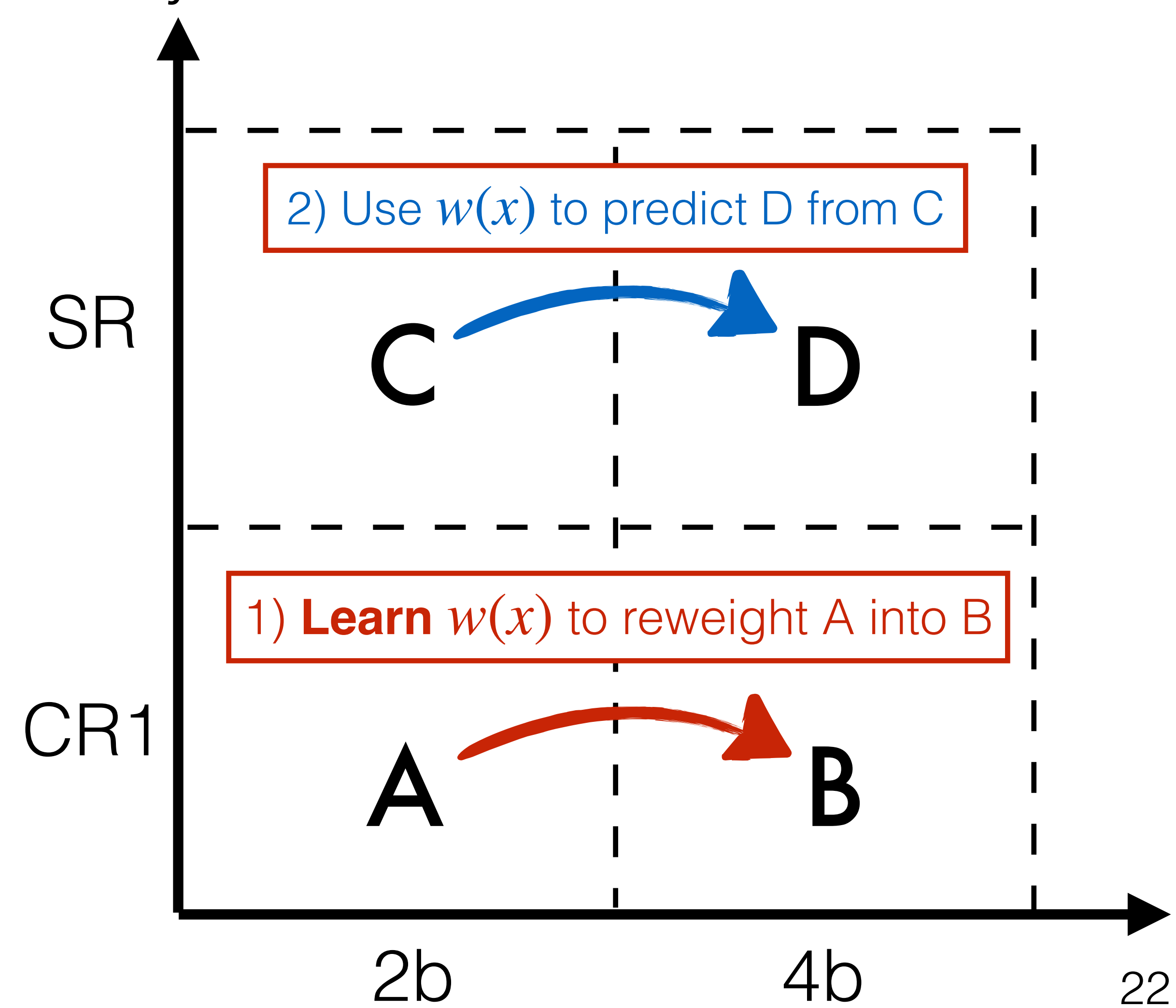


$HH \to b\bar{b}b\bar{b}$ analysis (2)

Background estimation

- Background: QCD multijet (90%) and $t\bar{t}$ (10%) estimated using a **fully data-driven** method.
  - **Machine-learning algorithm learns weight $w(x)$**, where x are different event kinematic variables, to **reweight CR1- 2b into CR1-4b** events
  - $w(x)$ **applied to SR-2b** to obtain SR-4b background estimation.
- Alternative $w'(x)$ from CR2 used to estimate systematics uncertainties.





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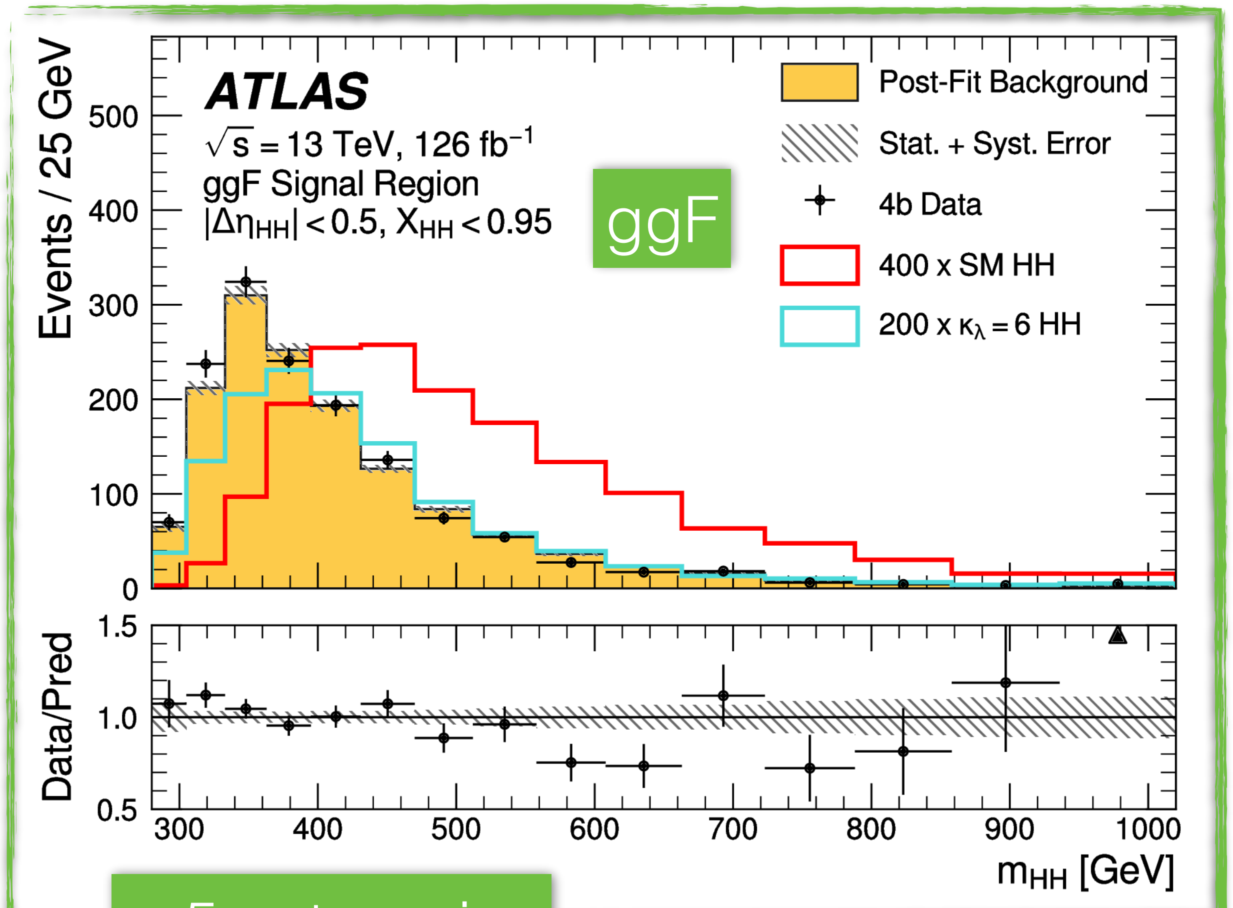
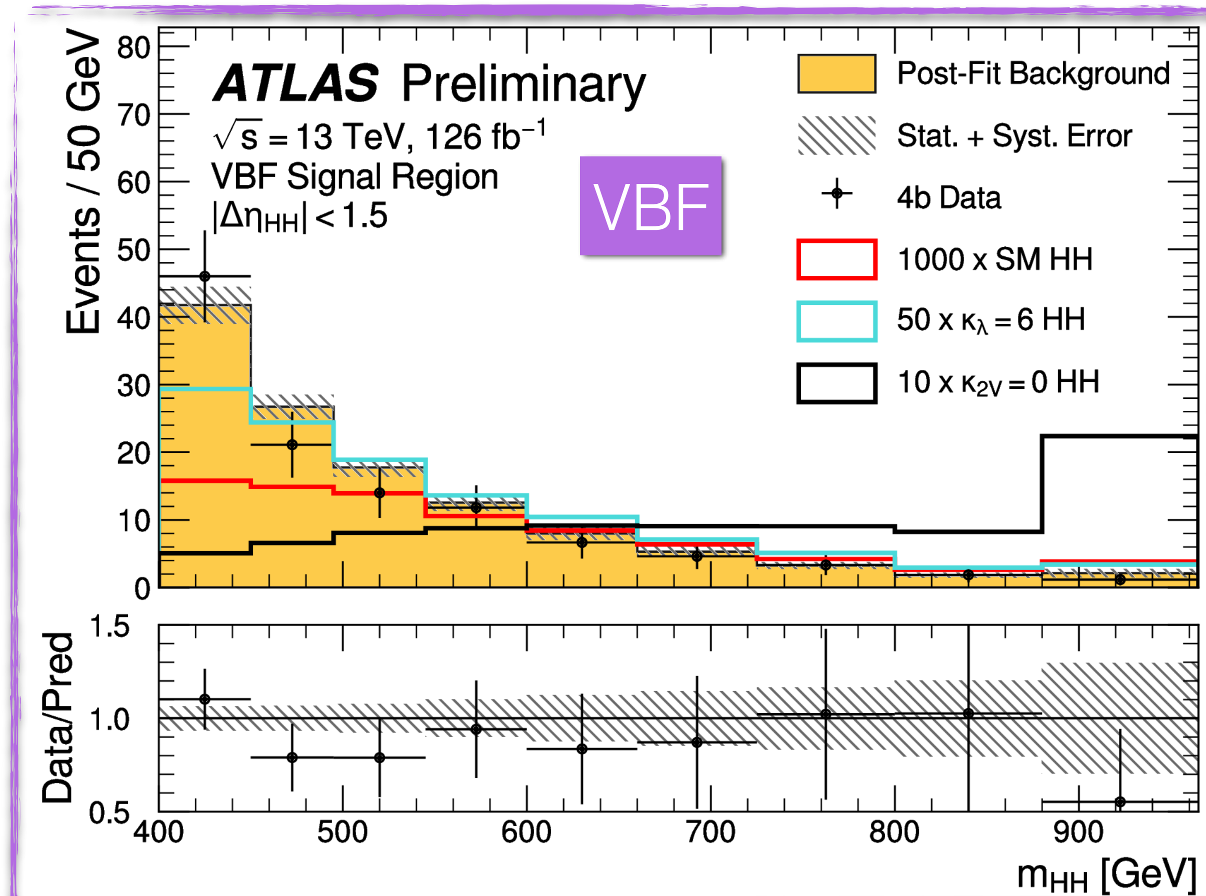
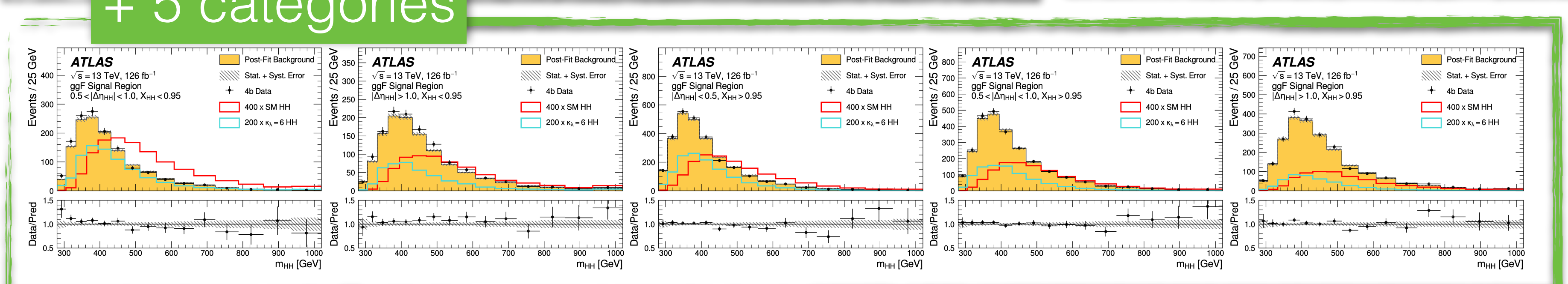
$HH \to b\bar{b}b\bar{b}$ analysis (3)

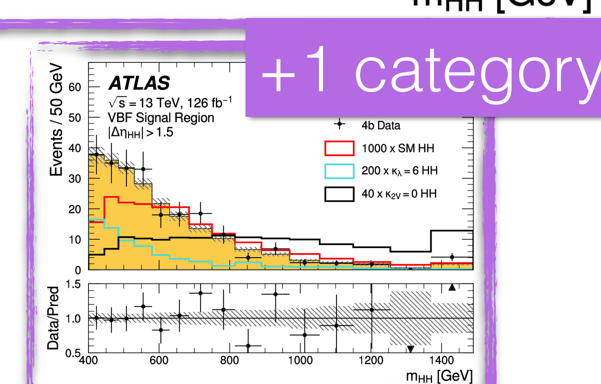
Results

Final observation: simultaneous likelihood fit of m_{HH} in all ggF and VBF categories









- **No significant excess** above SM prediction.
- Dominant uncertainties: background modelling and theoretical uncertainties of $\sigma(HH)$.

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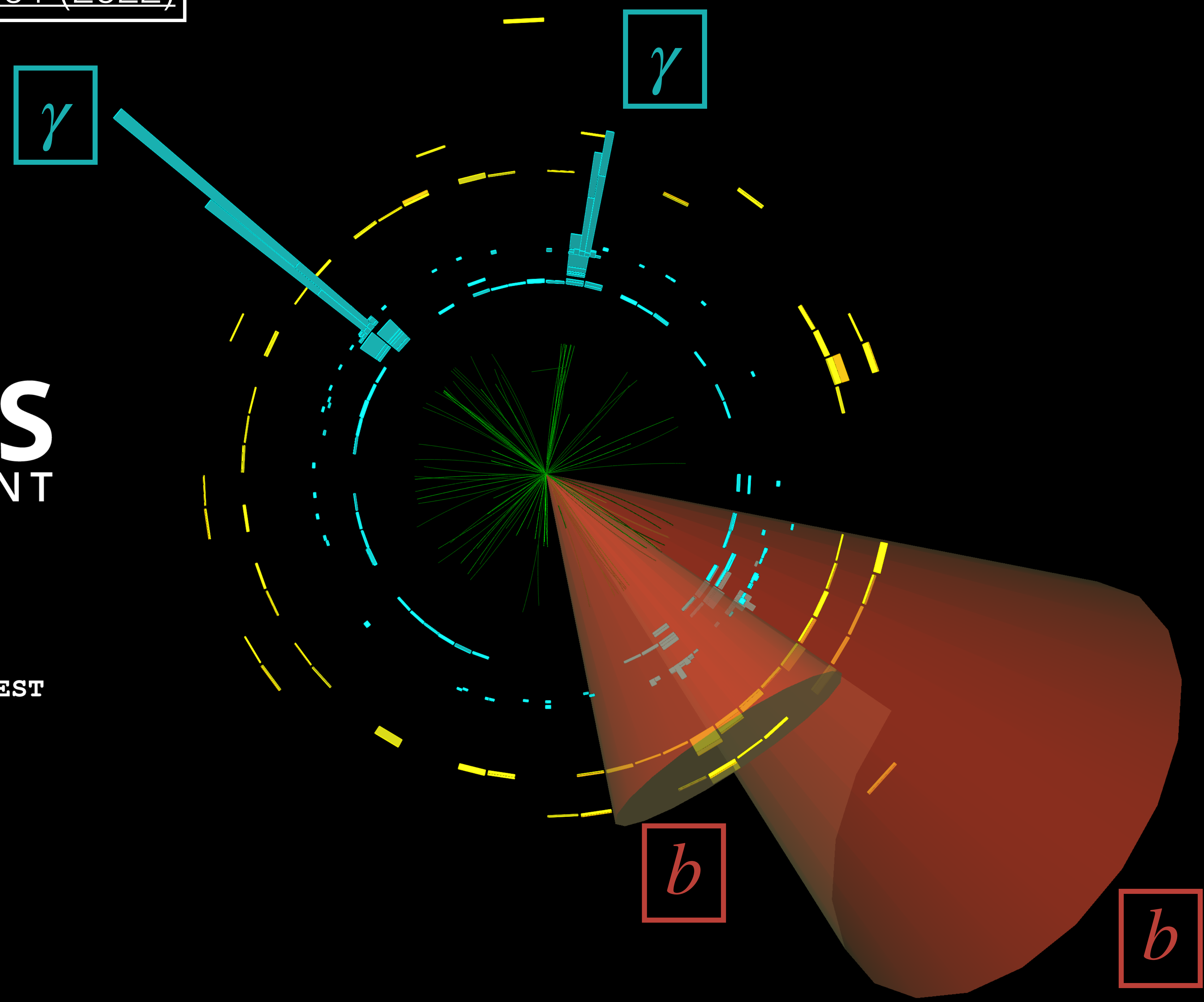
$HH \to b\bar{b}\gamma\gamma$ analysis ($139\ \mathrm{fb}^{-1}$)

Phys. Rev. D 106, 052001 (2022)

ATLAS EXPERIMENT



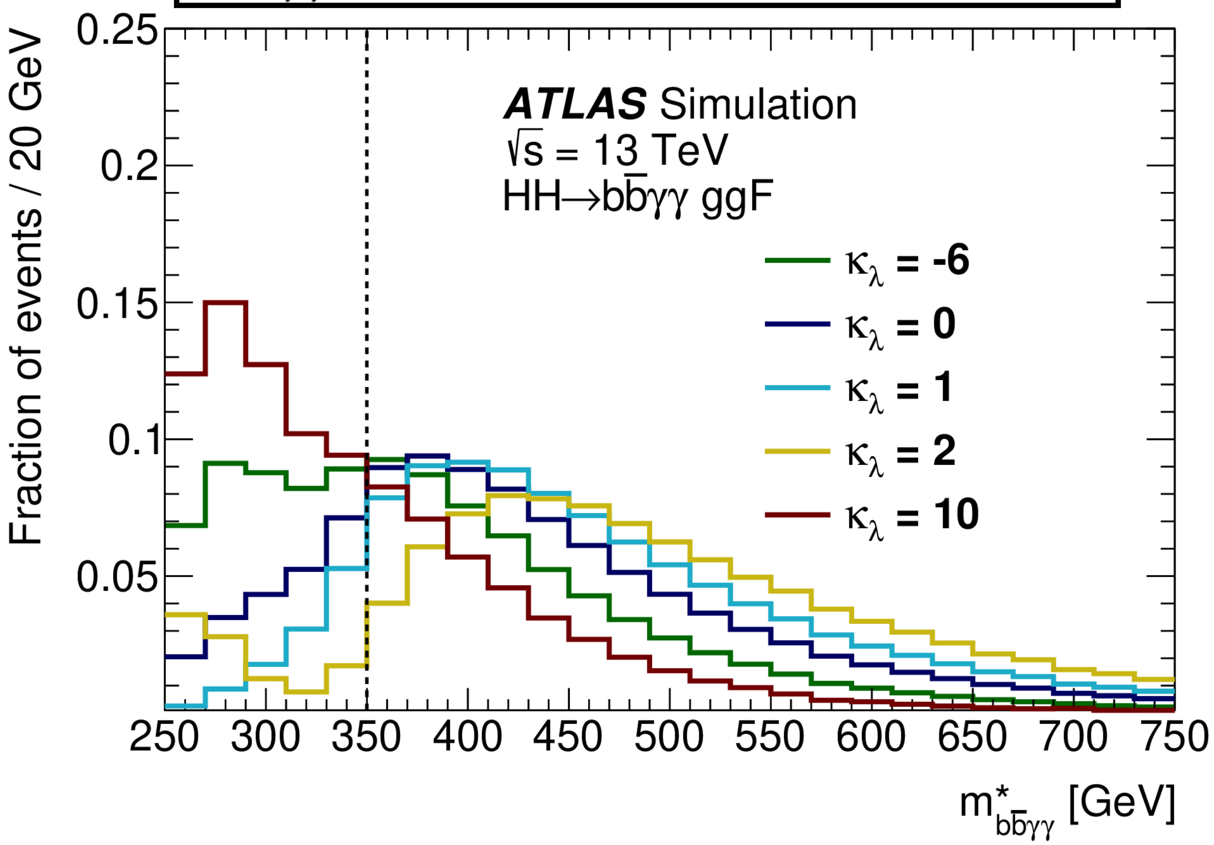
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

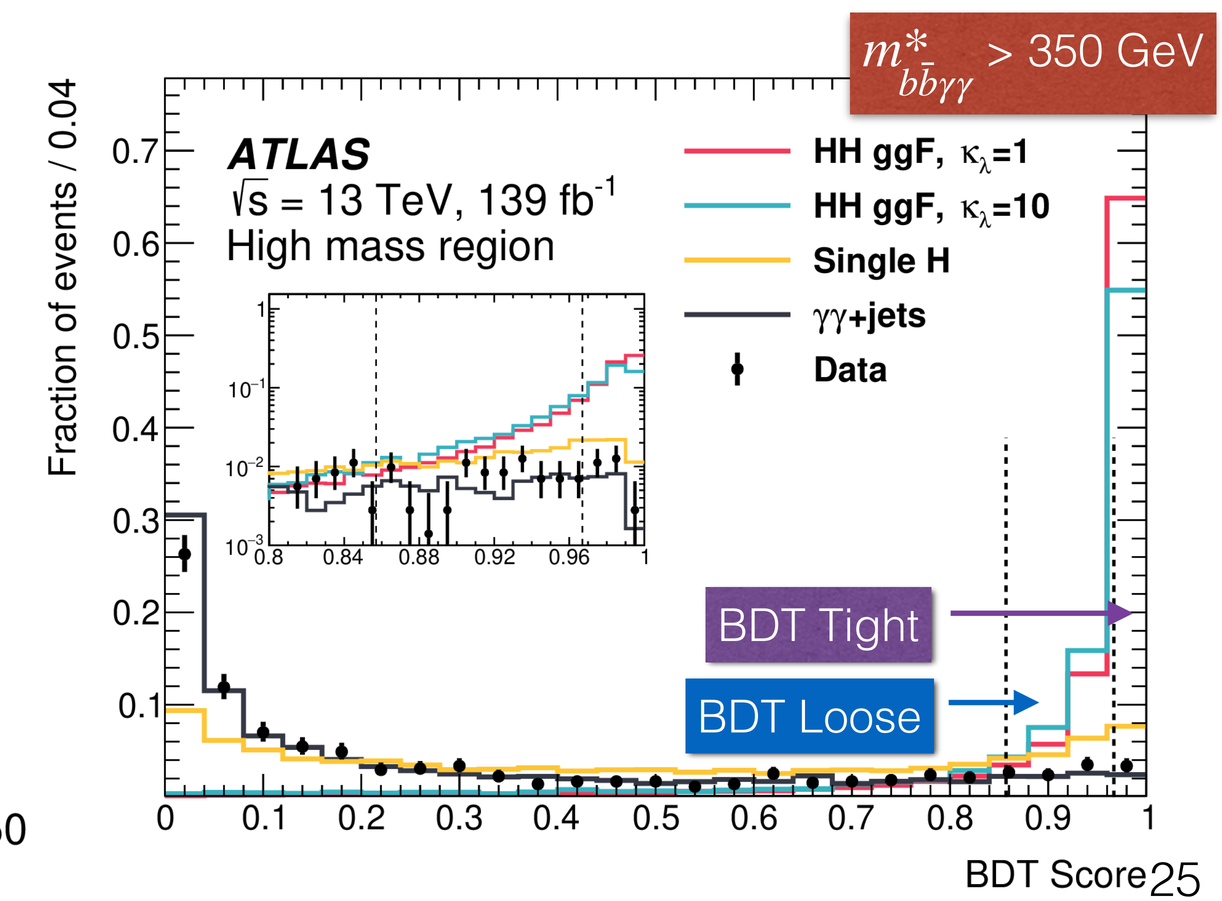
$HH \rightarrow b\bar{b}\gamma\gamma$ analysis (1)

Analysis selection and categories

- **Very tiny HH BR** (0.26%), but **excellent acceptance** ($\gamma\gamma$ triggers) and **low backgrounds.**
- Selection:
  - **Di-photon trigger** ($E_T > 35{,}25$ GeV).
  - **2 photons** + **2 b-jets** (77% eff DL1r).
  - **BDTs** to separate backgrounds and signals.
- Categories: **4 regions** split in $m^*_{b\bar{b}\gamma\gamma}$ (350 GeV) and BDT output (Loose and Tight).

$$\boxed{m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\ \text{GeV}}$$





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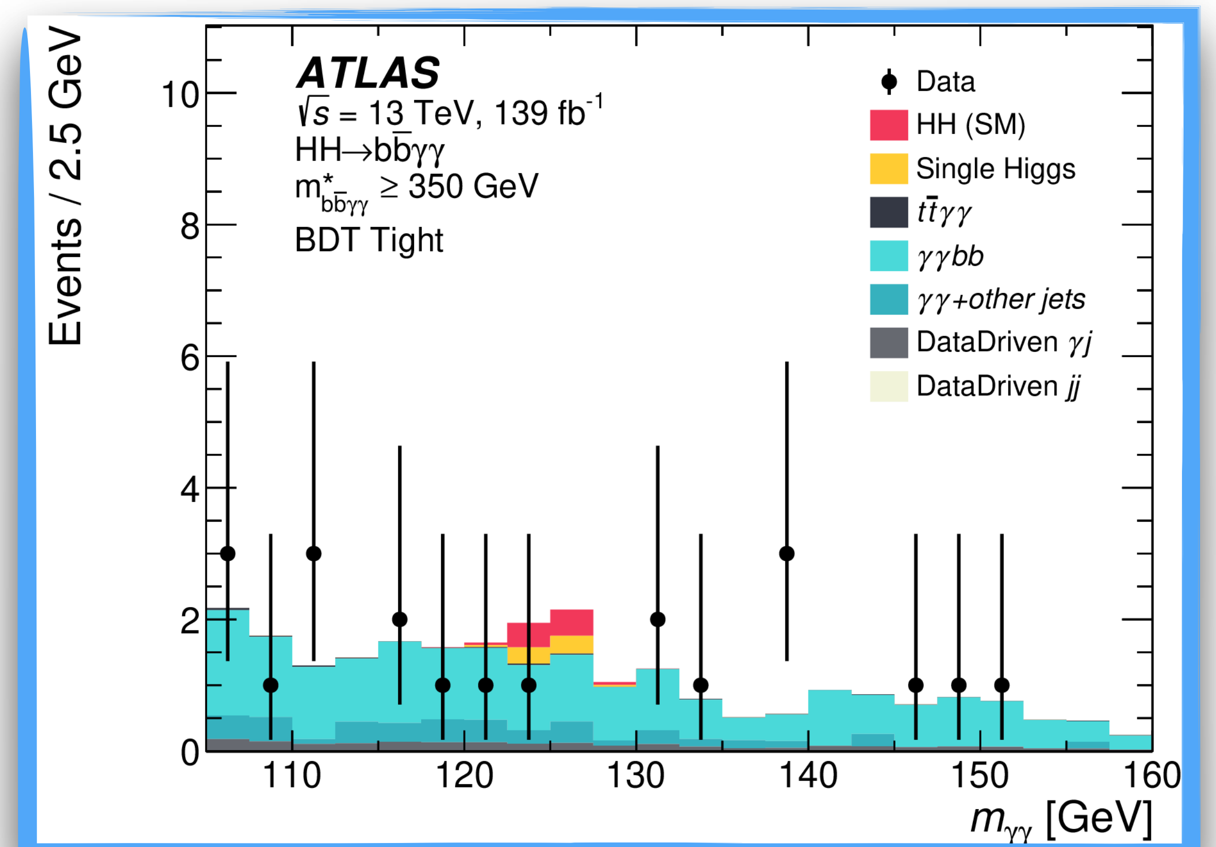
$HH \to b\bar{b}\gamma\gamma$ analysis (2)

Background estimation and results

- Main backgrounds: $\gamma\gamma$ + **jets** (MC and data-driven) and **SM** $H \to \gamma\gamma$ (MC).

Final observation: **simultaneous likelihood fit of $m_{\gamma\gamma}$** in all $m^*_{bb\gamma\gamma}$ and BDT categories.



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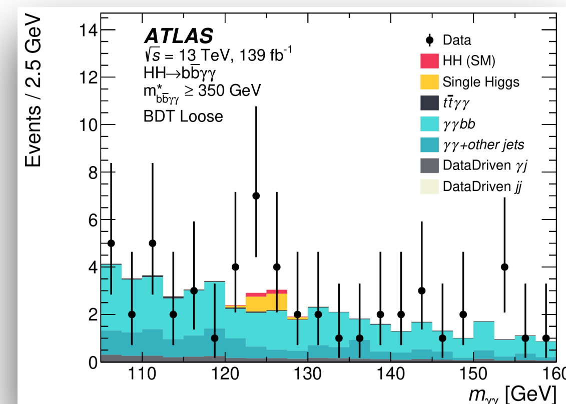

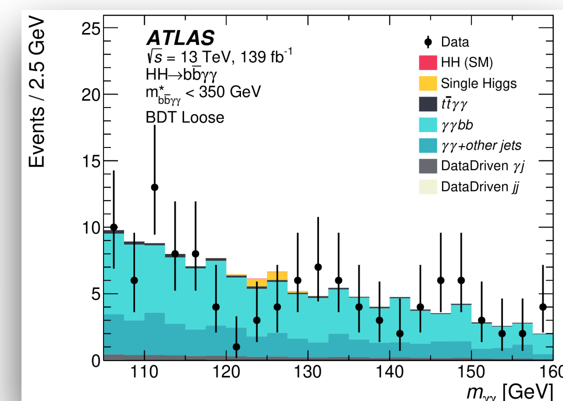

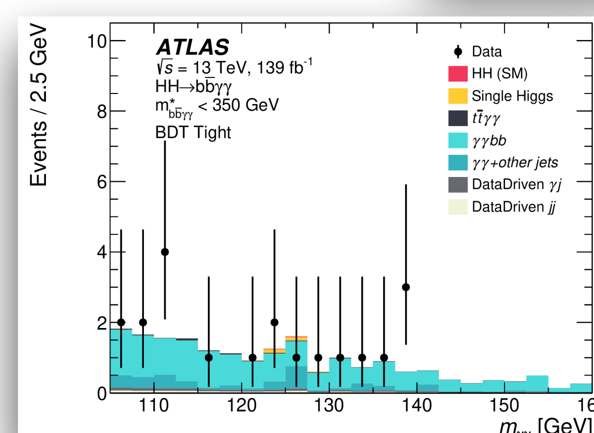

- **No significant excess** above SM prediction.
- Dominant uncertainty: data statistics

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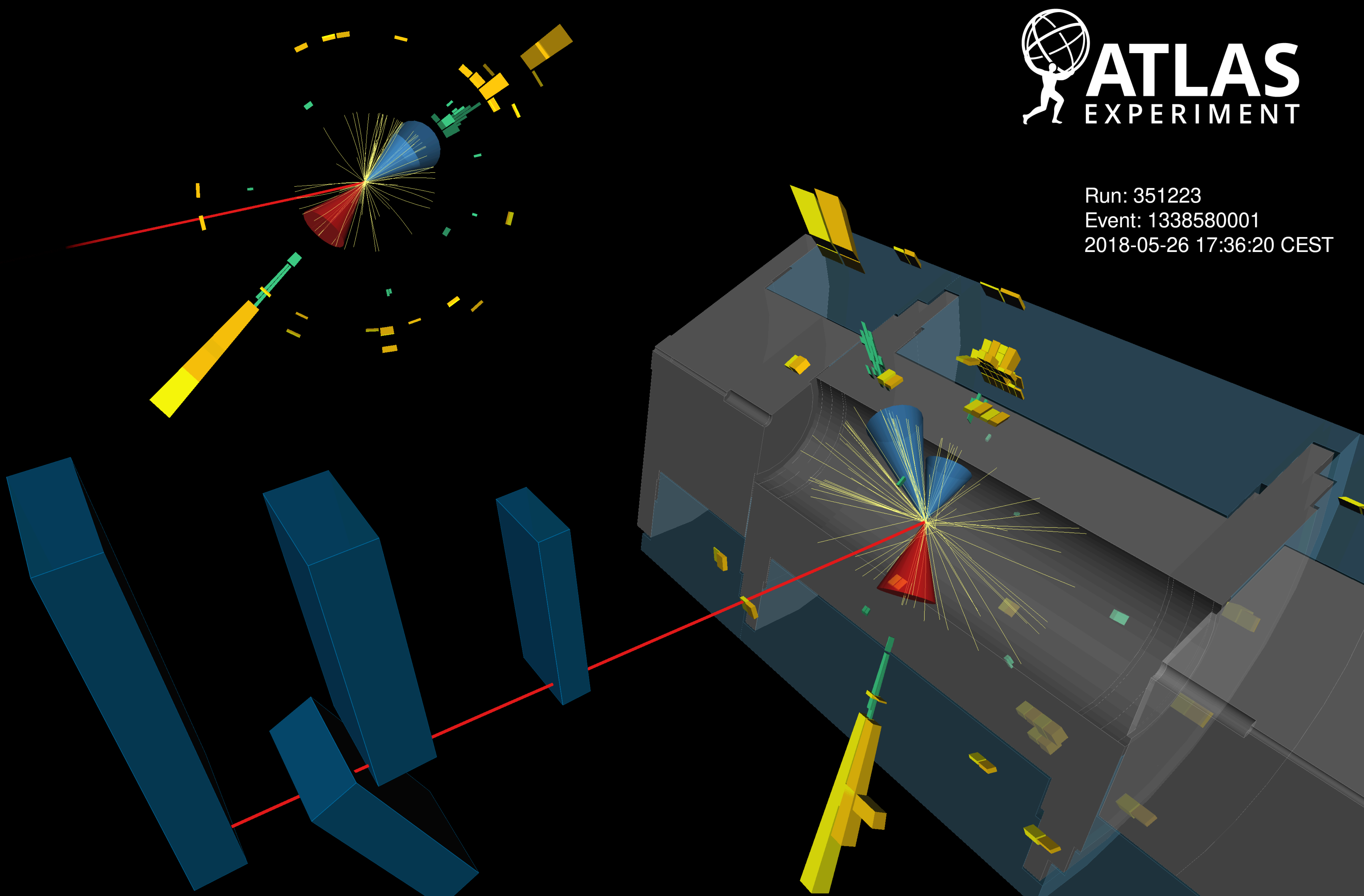
$HH \rightarrow b\bar{b}\tau^+\tau^-$ analysis (139 fb^{-1})

arXiv:2209.10910



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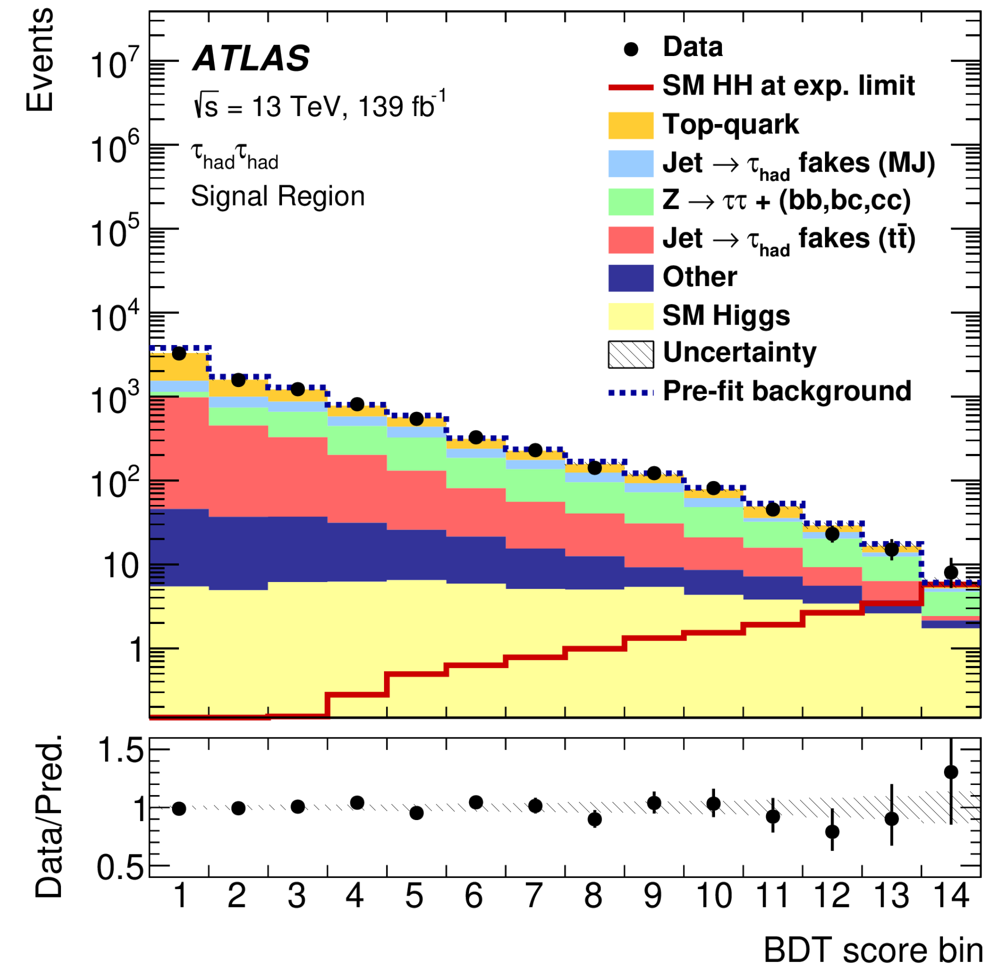
$HH \to b\bar{b}\tau\tau$ analysis (1)

Event selection and analysis categories

- **Good trade between HH BR** (7.3%) and **moderate background**.
- <u>Selection:</u>
  - **Triggers:** 1 or 2 τ leptons (τ_{had} and τ_{lep}).
  - **2 b-jets** (77% eff DL1r) and **2 τ-leptons** (τ_{had} and τ_{lep})
  - **MVA techniques** used to separate background and signals.
- **3 categories** split by τ decay mode and trigger.

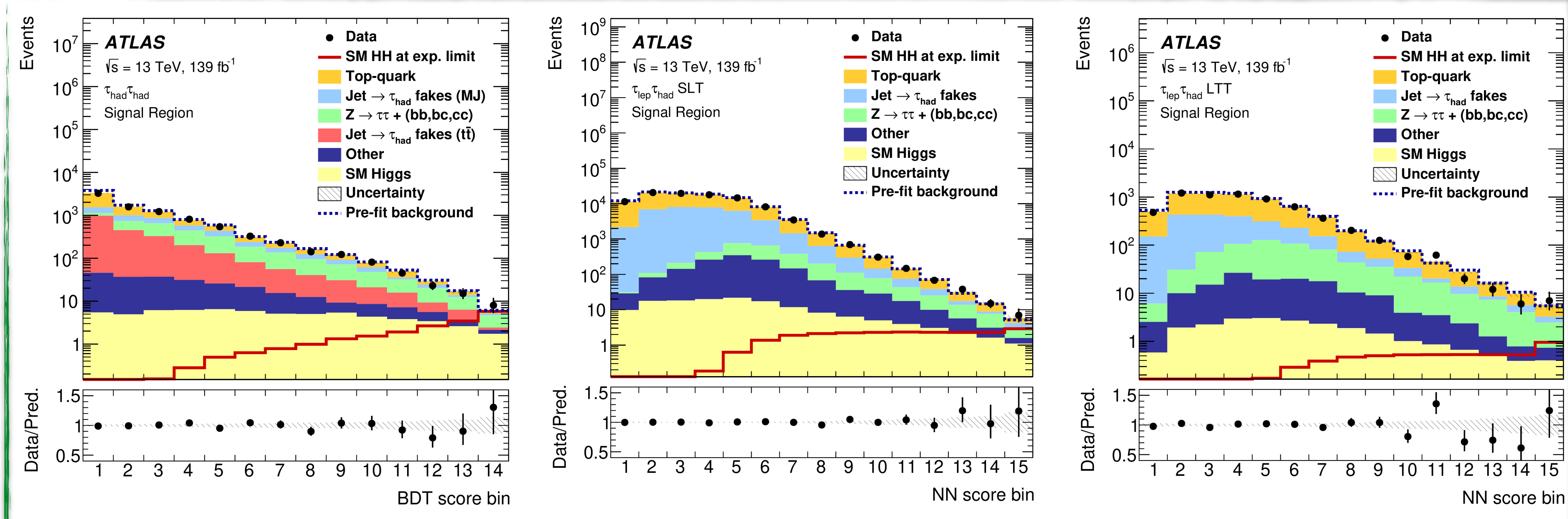


Category	Triggers
$b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$	Single-tau + di-tau triggers
$b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ SLT	Single lepton trigger (SLT)
$b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ LTT	Lepton+tau trigger (LTT)

$HH \to b\bar{b}\tau\tau$ analysis (2)

Background estimation and results

- Dominant backgrounds: true τ ($t\bar{t}$ and Z+bb/bc/cc) estimated from MC simulations, fake τ ($t\bar{t}$ and multijet) from data.
- Final observation: **binned fit of MVA scores in all 3 categories**.
  - **Control region for Z+bb/bc/cc** included in likelihood fit.
  - **No significant excess** above SM prediction observed.



- Dominant uncertainties: **stat (81%)** and systematics (59%)

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Upper limits and interpretations

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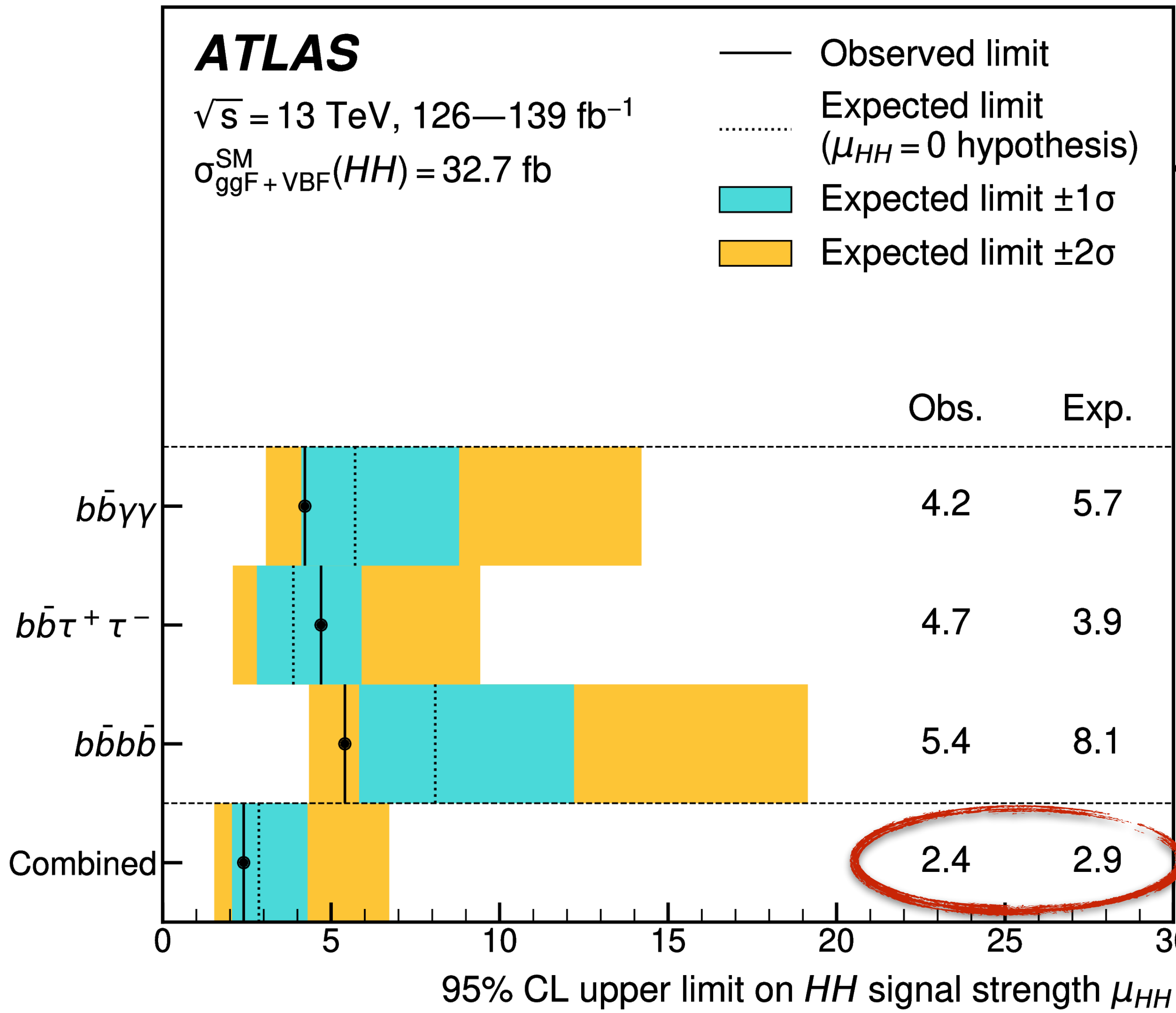
SM cross-section upper limits

Results

- Statistical **combination maximises sensitivity** to SM (and BSM) HH production

arxiv:2211.01216



$$\mu_{HH} = \frac{\sigma^{\text{obs}}(pp \to HH)}{\sigma^{\text{SM}}(pp \to HH)}$$

Currently observing $\mu_{HH}^{95\%\ \text{CL}} < 2.4$

Previous result (36 fb^{-1})

Expected: 26xSM
Observed: 20.3xSM

Expected: 15xSM
Observed: 12.5xSM

Expected: 20.7xSM
Observed: 12.9xSM

Expected: 10xSM
Observed: 6.9xSM

Large improvement (x3.5) thanks to **luminosity**, better **reconstruction** (b-jet, τ) and **analysis improvements**

Getting very close to the SM ($\mu_{HH} = 1$)!

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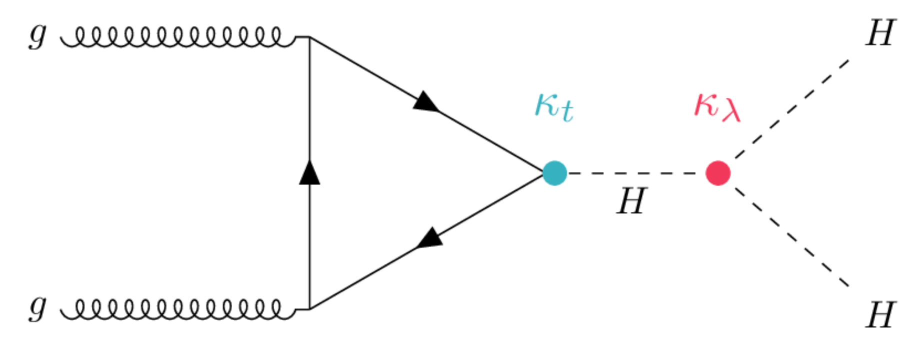
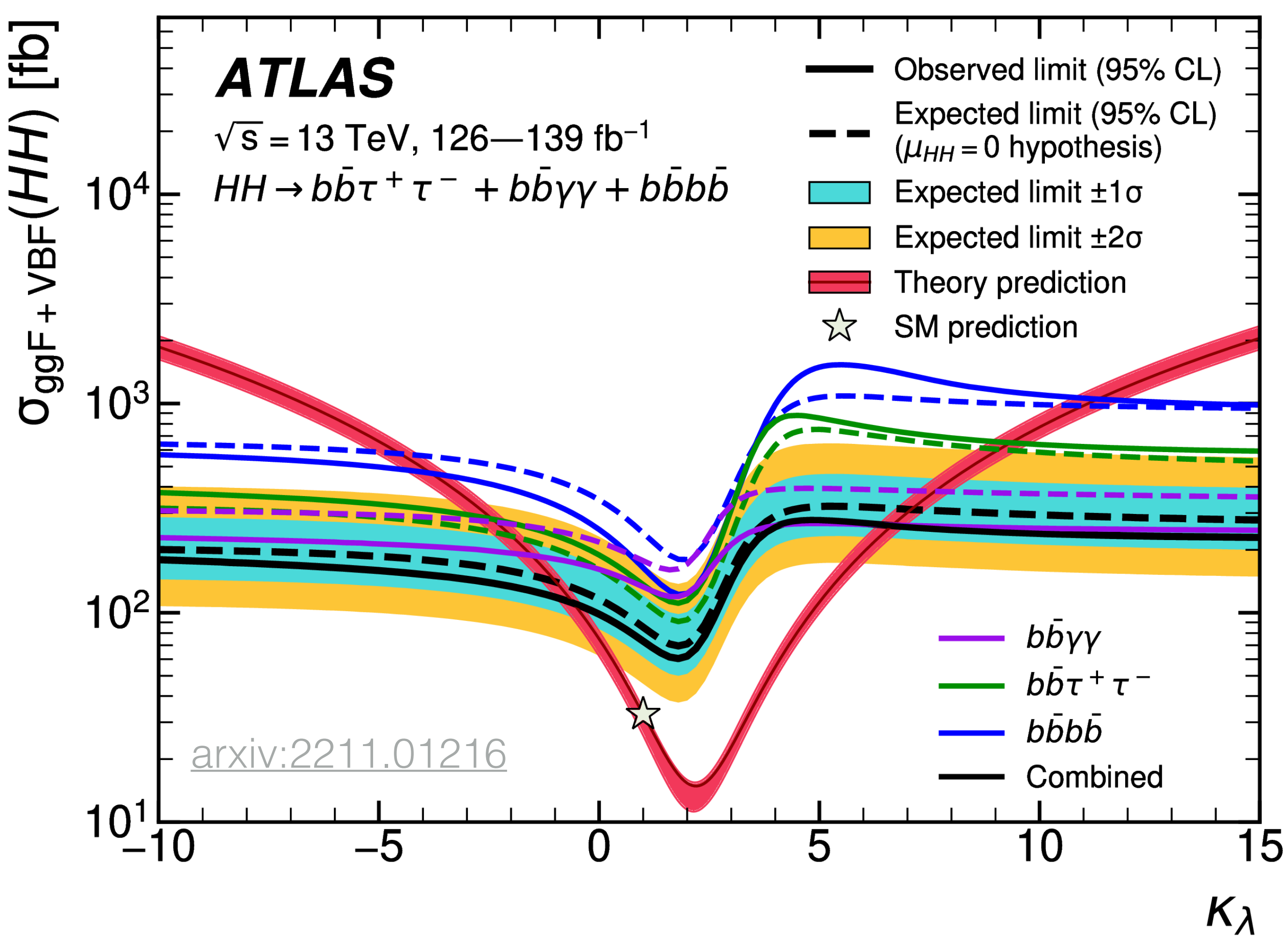
Higgs self-coupling constraints

Allowed κ_λ ranges

- **What did we learn** about the Higgs self-coupling?
- **κ_λ scan:** upper-limits on σ_{HH} assuming signal normalisation and kinematic at each value of κ_λ





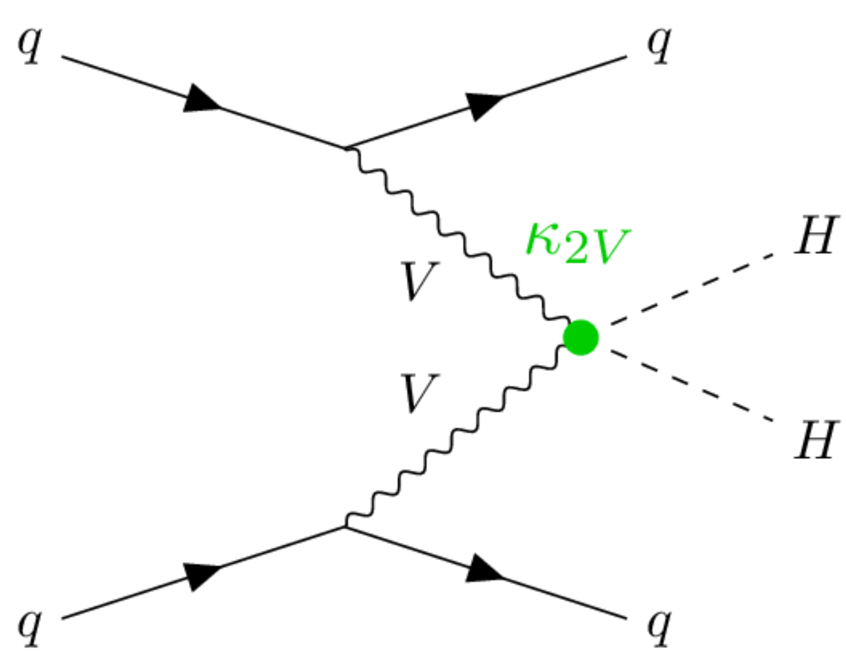
- Observed allowed κ_λ range is measured to be $-0.6 < \kappa_\lambda < 6.6$
- Previous Run 2 result (36 fb^{-1}) $-5.0 < \kappa_\lambda < 12.0$
  - **x10 improvement** on lower bound
  - **x2 improvement** on higher bound

Almost excluding $\kappa_\lambda = 0$ at 95% CL (i.e. no Higgs self-coupling)!

κ_{2V} constraints

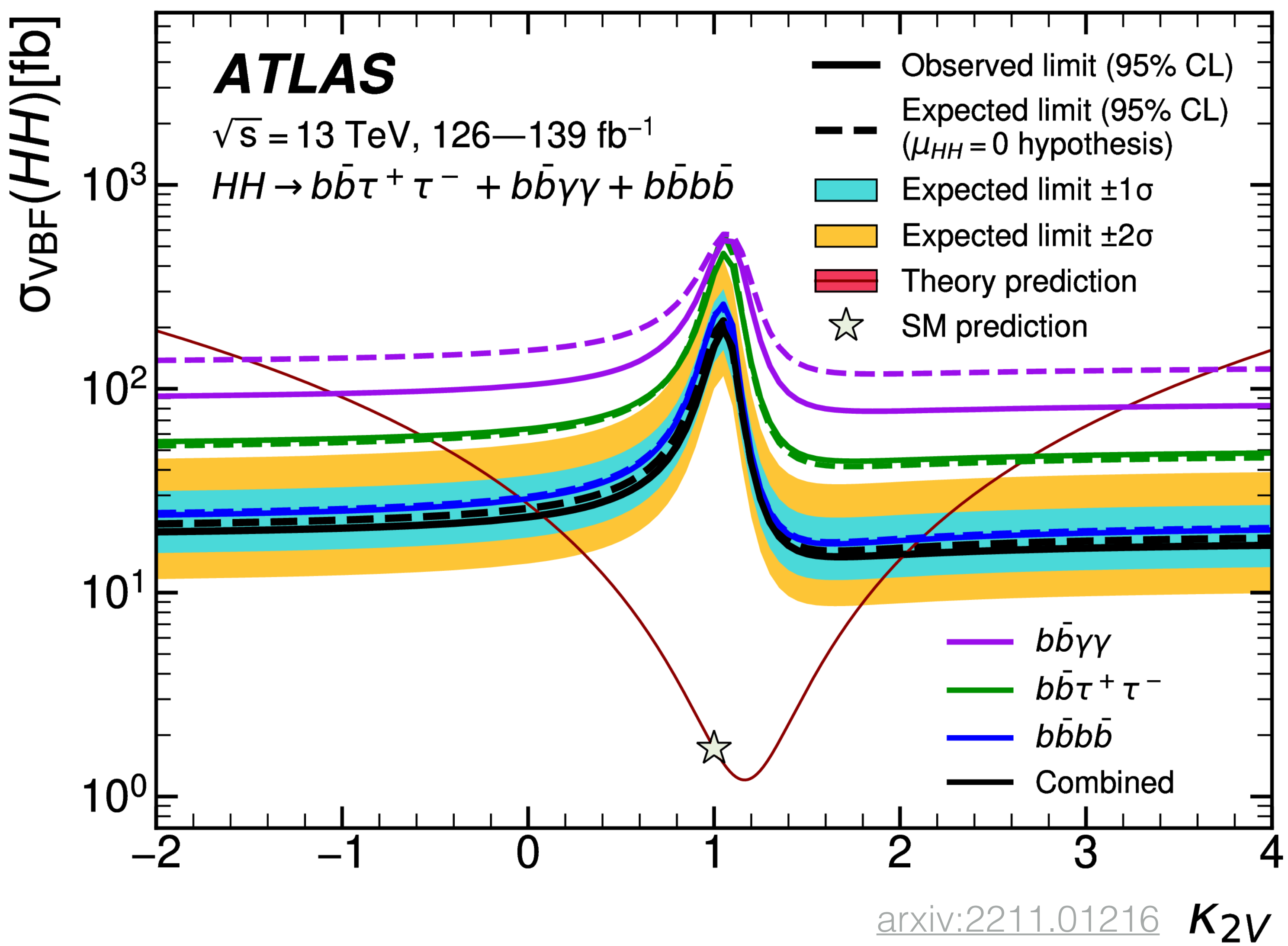
Allowed κ_{2V} ranges

- Extracted also **constraints on VVHH Higgs coupling** through scan of κ_{2V}.
  - $b\bar{b}b\bar{b}$ **has the best sensitivity** overall due to dedicated κ_{2V} categories and high BR(HH) and acceptance in VBF regime.



$\kappa_{2V} = 0$ **excluded at 95% CL** with complete Run 2 statistic $(139\ \text{fb}^{-1})$

Allowed observed κ_{2V} range: $0.1 < \kappa_{2V} < 2.0$



arxiv:2211.01216

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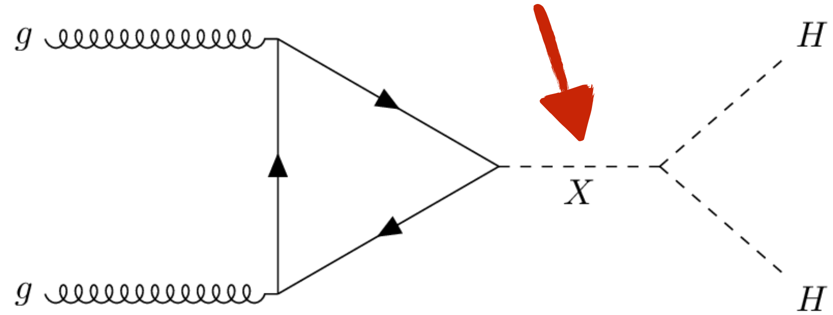
Resonant interpretation

Resonant upper limits

- BSM models also predict **possible heavy resonances decaying to HH**
  - Re-optimised analyses to target these scenarios.
- Complementarity between channels allow to obtain **optimal exclusion** across m_X.
- **No statistically significant excess** found: largest excess at $m_X = 1.1$ TeV, with local (global) significance of 3.2σ (2.1σ).

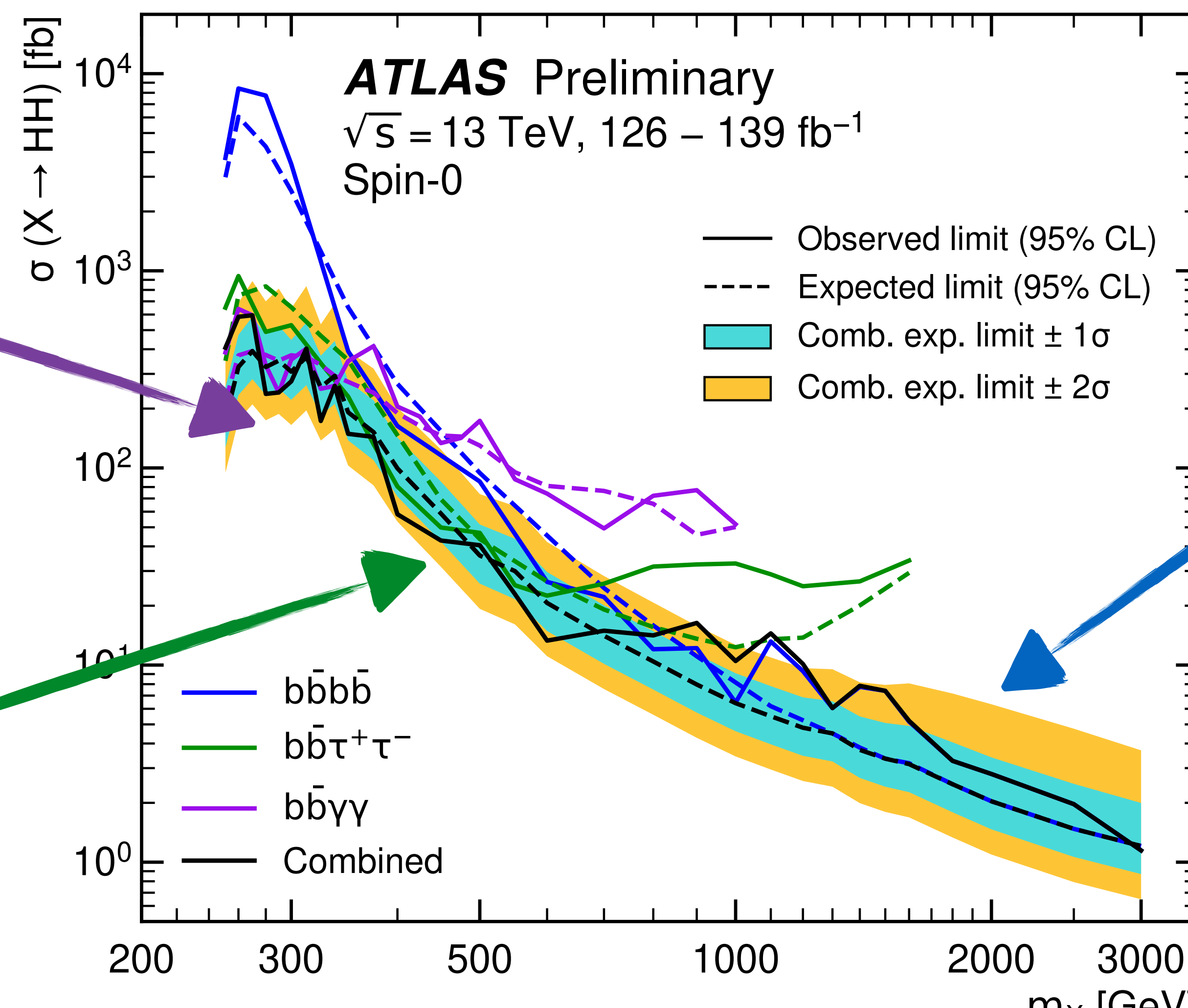
Heavy spin-0 resonance



$b\bar{b}\gamma\gamma$ dominated

$b\bar{b}\tau\tau$ dominated

$b\bar{b}b\bar{b}$ dominated



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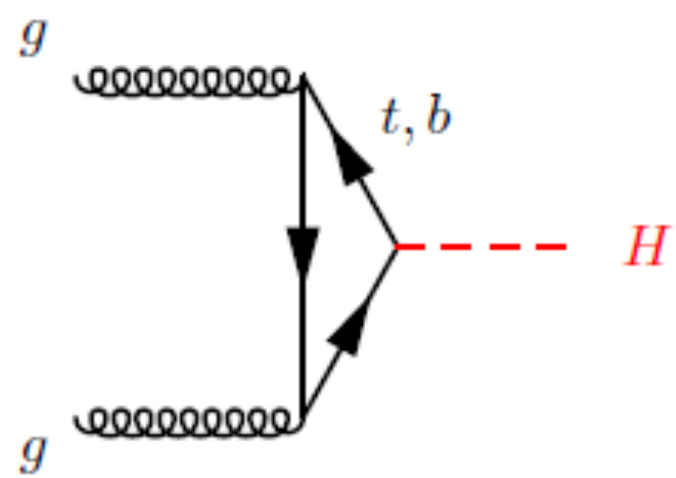
Is there a way to constrain κ_λ even further with Run 2 data?

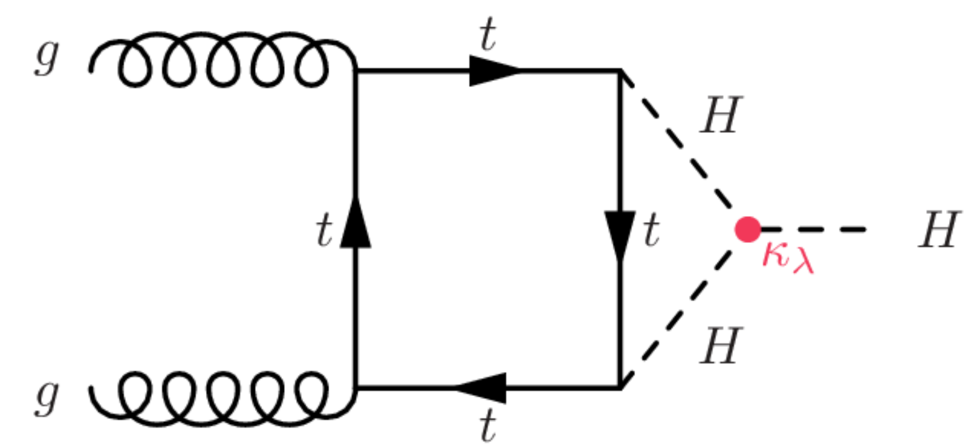
Single-Higgs contributions to κ_λ (1)

arxiv:2211.01216

Single Higgs ggF



Loop corrections make single Higgs processes also sensitive to κ_λ



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The hunt for Higgs boson pairs at ATLAS: current status and perspectives

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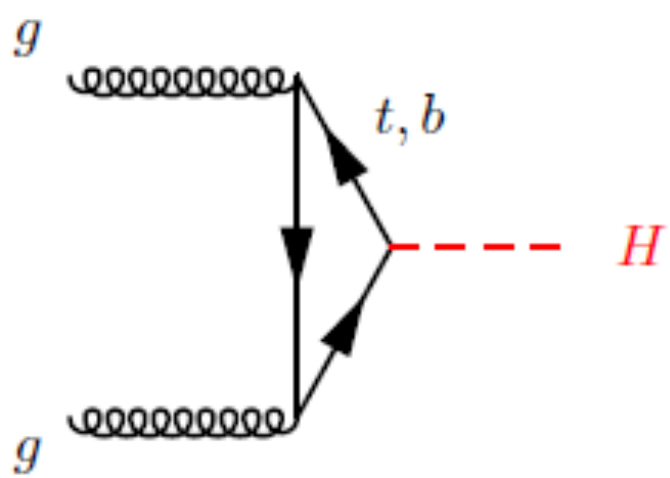
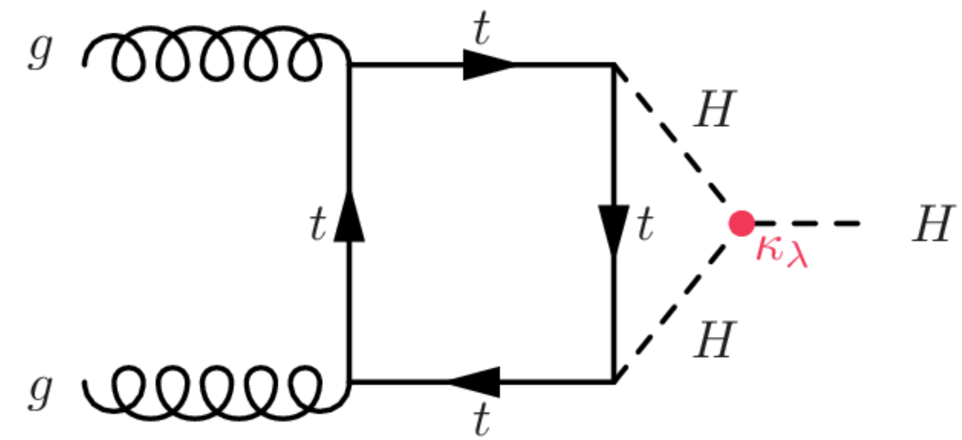
Single-Higgs contributions to κ_λ (1)

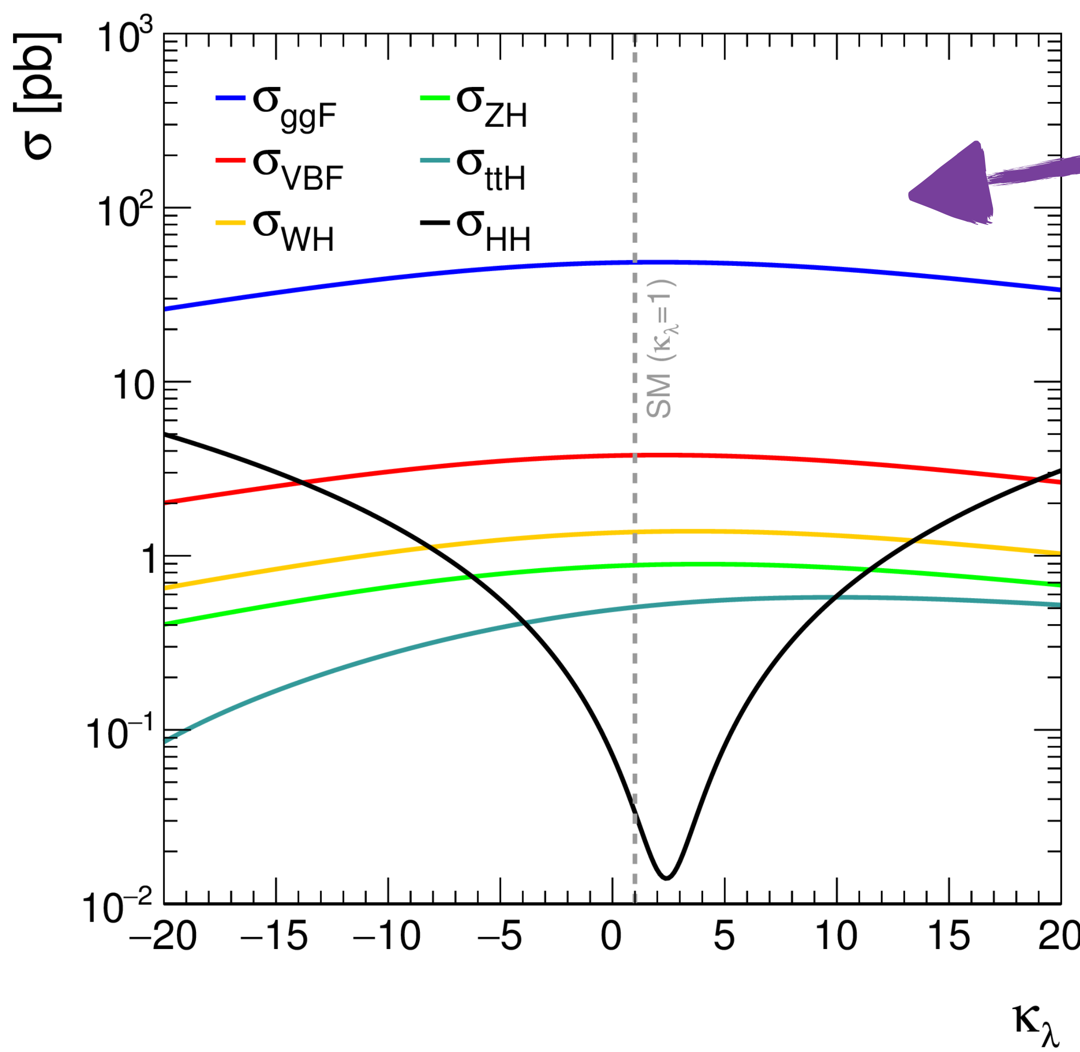
arxiv:2211.01216

Single Higgs ggF

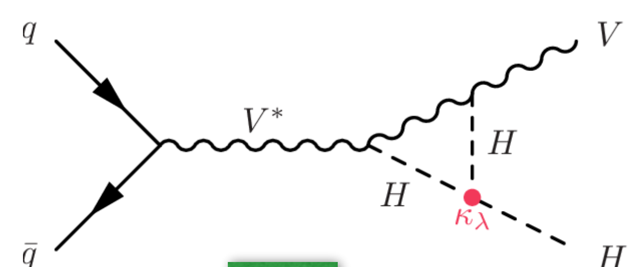


Loop corrections make single Higgs processes also sensitive to κ_λ

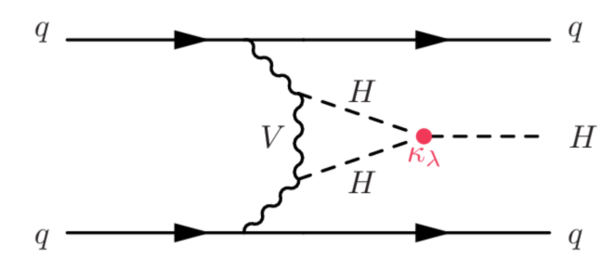




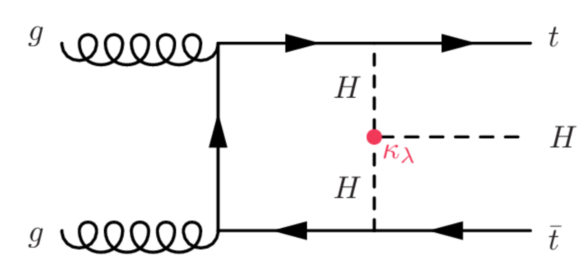
σ_{HH} more κ_λ-dependent, but larger precision on $\sigma_{\text{single-H}}$ due to high statistics.



VH



VBF

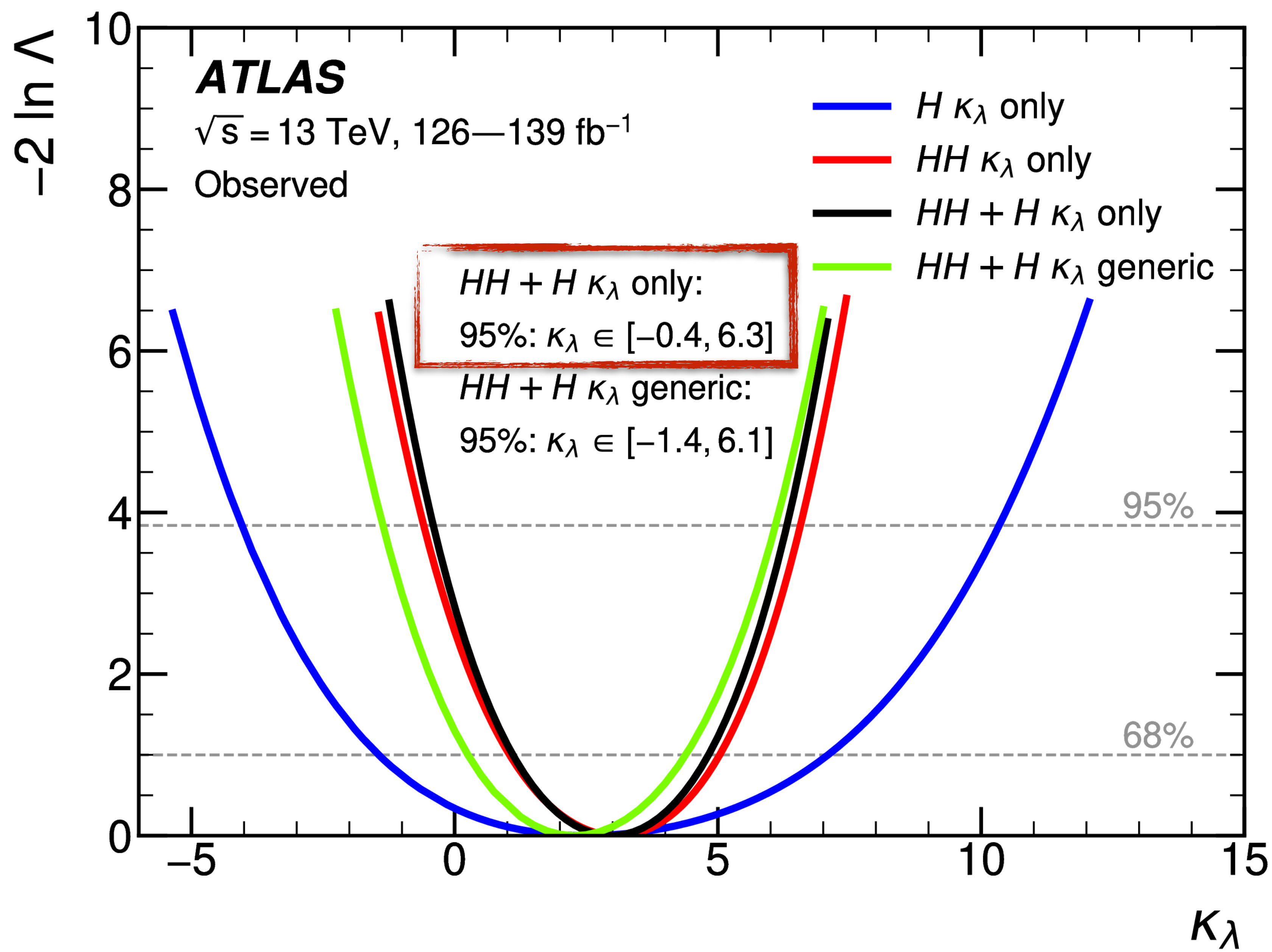


ttH

Single-Higgs constraints to κ_λ (2)

Results

- **Improvements on κ_λ constraint achieved** combining HH and single-H measurements!
    - New 95% CL allowed κ_λ range: $-0.4 < \kappa_\lambda < 6.3$



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So no unexpected Higgs self-coupling value for now.

Can we improve the precision in future?

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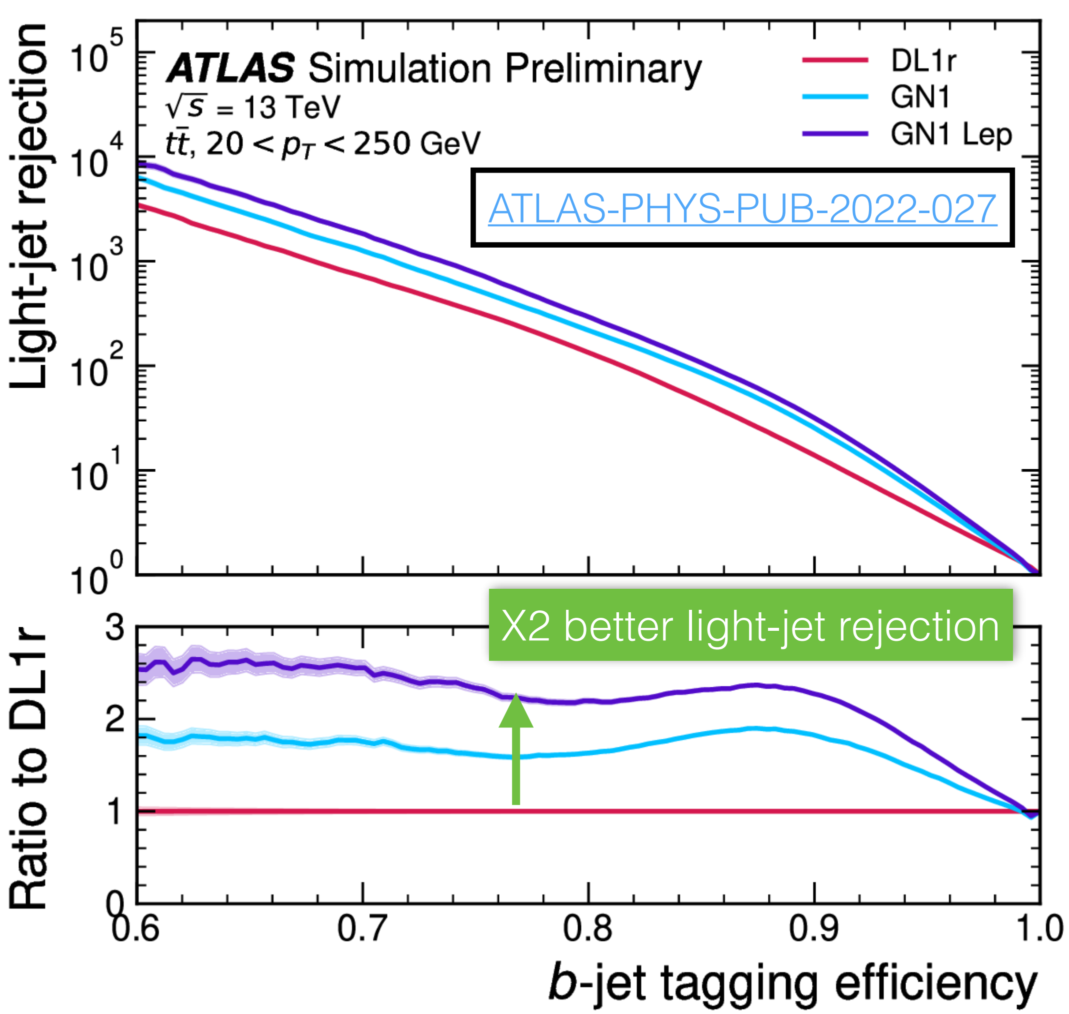
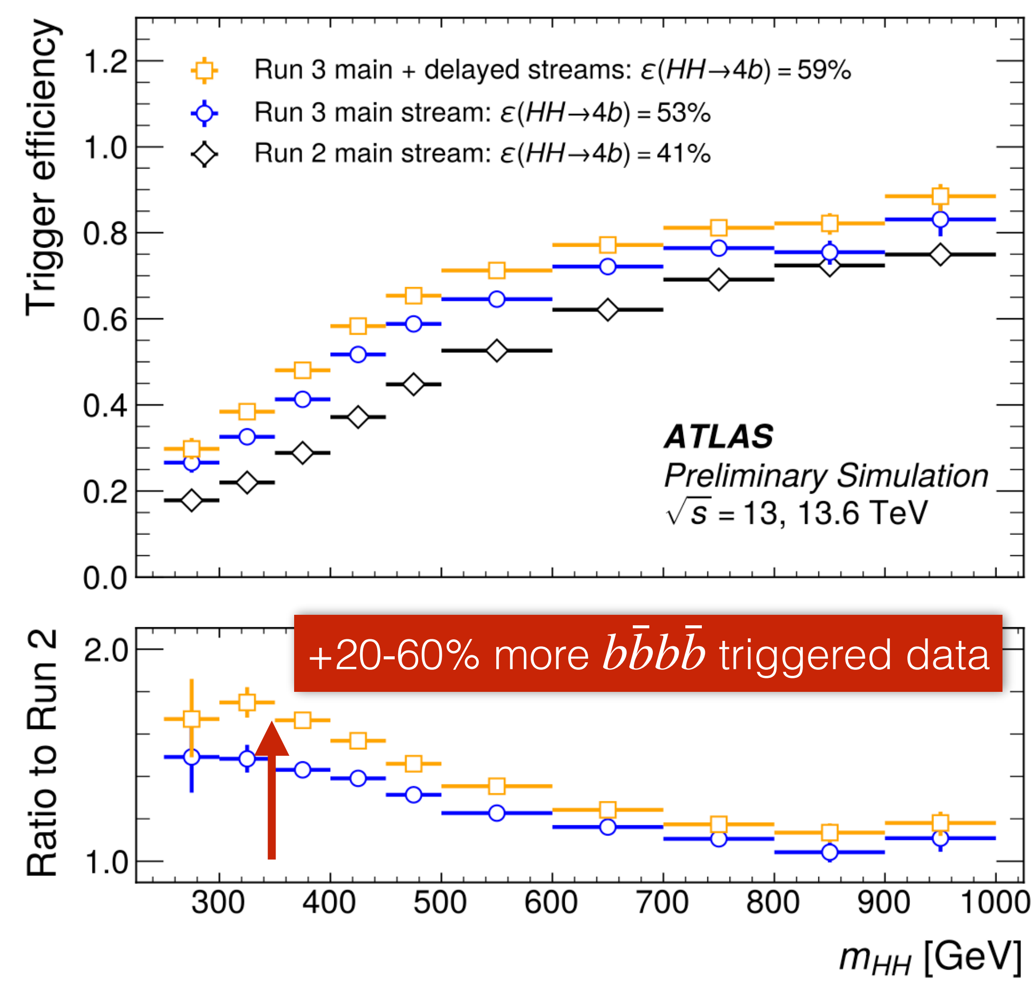
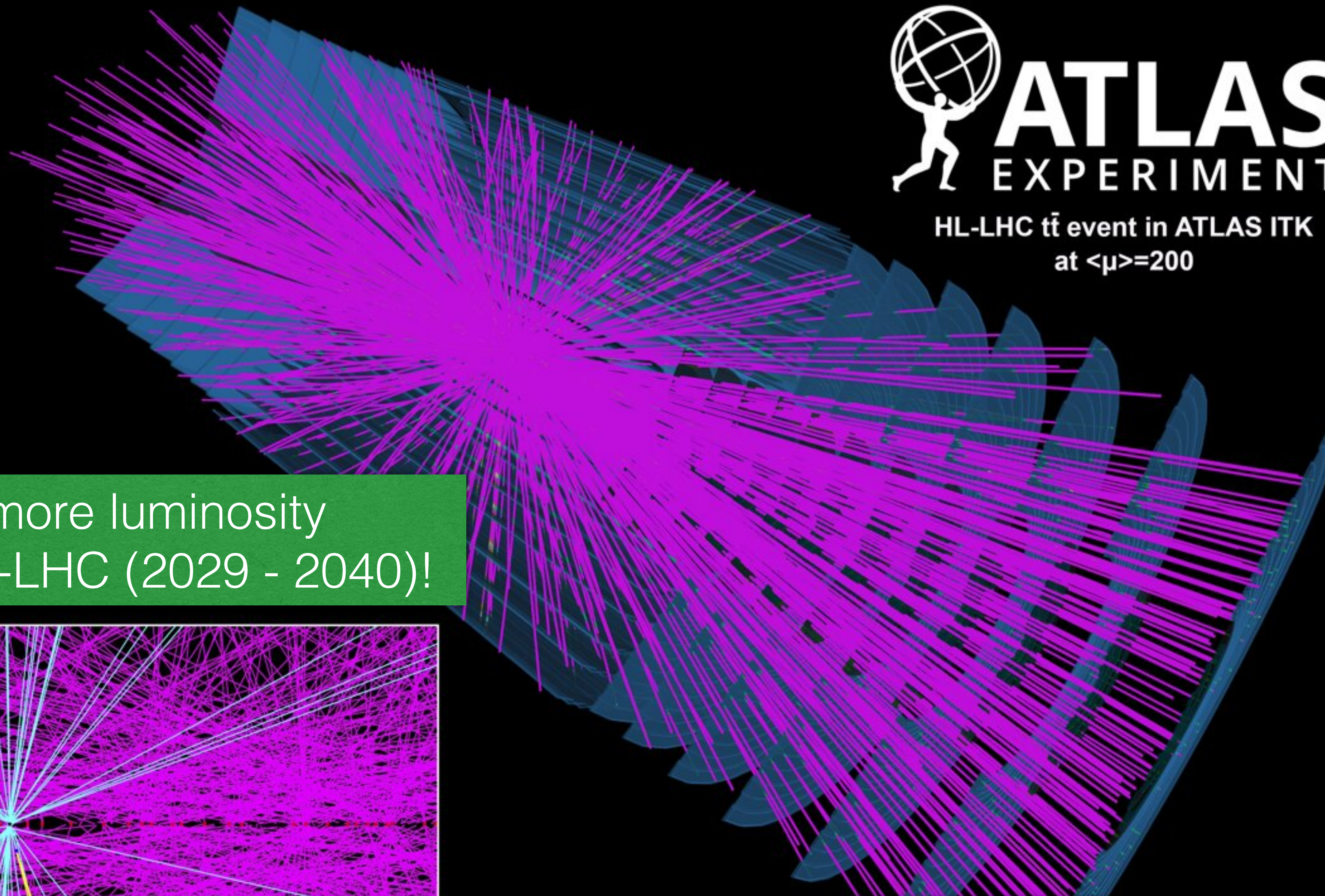
Run 3 ATLAS improvements

More data, better reconstruction and triggers

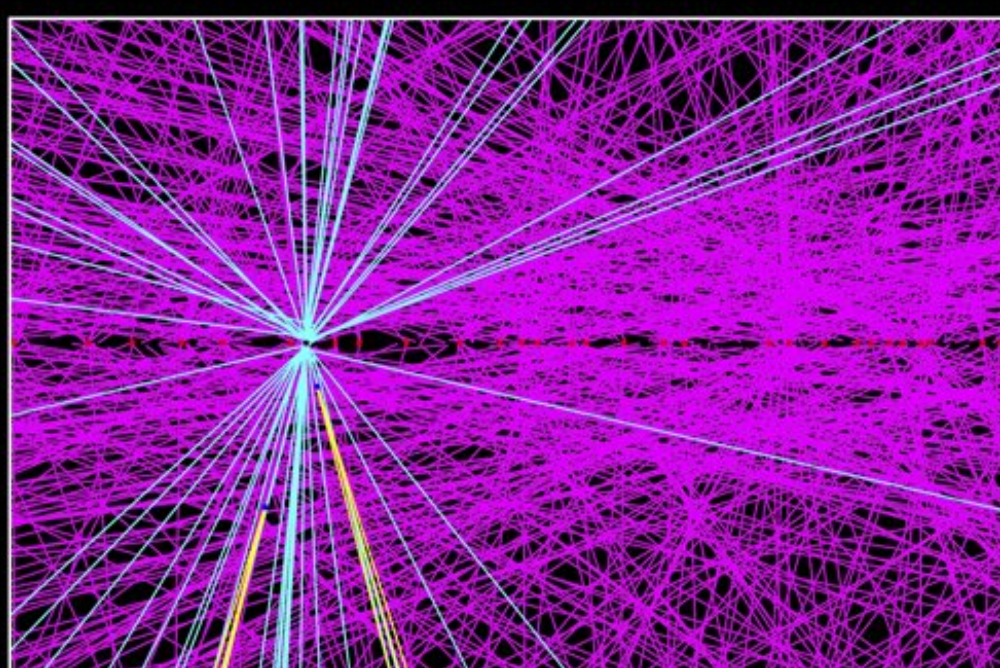
- Expect a **large number of improvements** by the end of Run 3 (2022-2025).
  - **More data** ($150 - 250\ \mathrm{fb}^{-1}$in Run 3) and +10% $\sigma(HH)$ with $\sqrt{s} = 13.6$ TeV
  - **b-tagging largely improved** with Graph Neural Networks (GN1)!
  - **Triggers significantly improved** (e.g. asymmetric $HH \to b\bar{b}b\bar{b}$ triggers)!
  - **New channels** to explore (e.g. boosted $HH \to b\bar{b}b\bar{b}$)







x 5 more luminosity
at the HL-LHC (2029 - 2040)!



Many HH events in 3000 fb^{-1} of
$\sqrt{s} = 14$ TeV of HL-LHC data!

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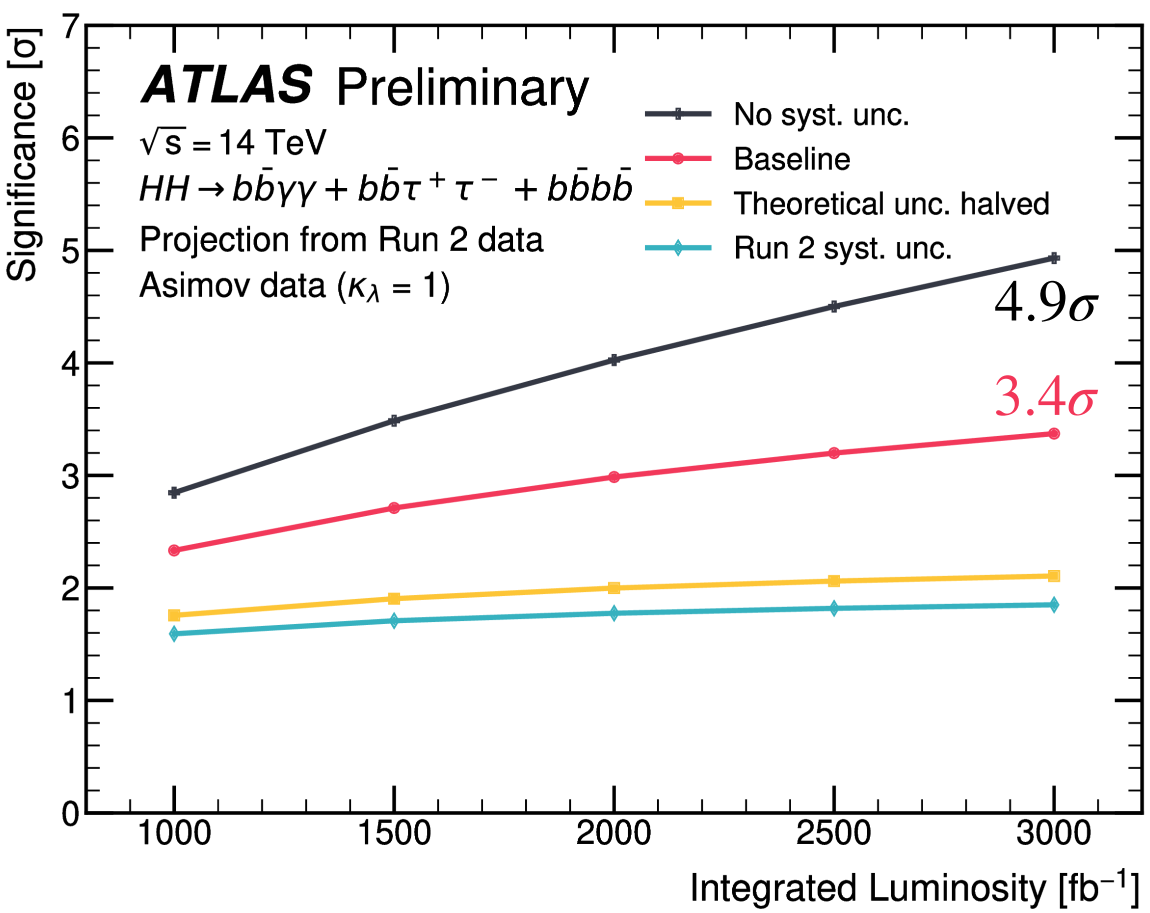
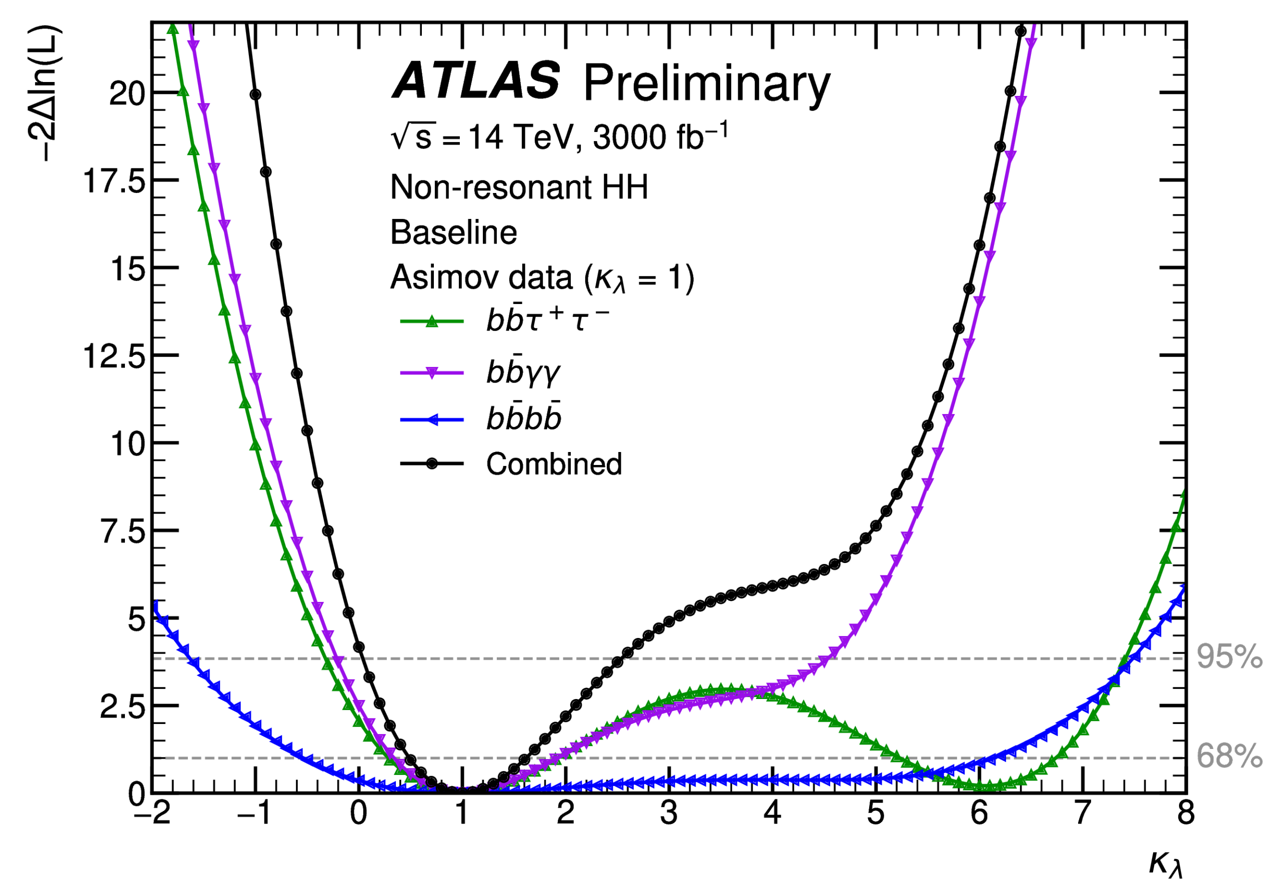
Updated HL-LHC projections for HH

ATLAS-PHYS-PUB-2022-053

- Assuming Run 2 detector performance and expected reduction of systematics, **statistical evidence (3.4σ) is expected for SM HH ($\kappa_\lambda = 1$)** with $3000\ \text{fb}^{-1}$.
  - **SM signal strength μ_{HH}^{SM}** measured with **30% precision**.
  - κ_λ **constrained to** $[0.5,1.6]$ at 68% CL.
- **Reduction of systematic uncertainties** could bring us **close to discovery** (4.9σ with stat. only). And we still have to combine with CMS! 😁





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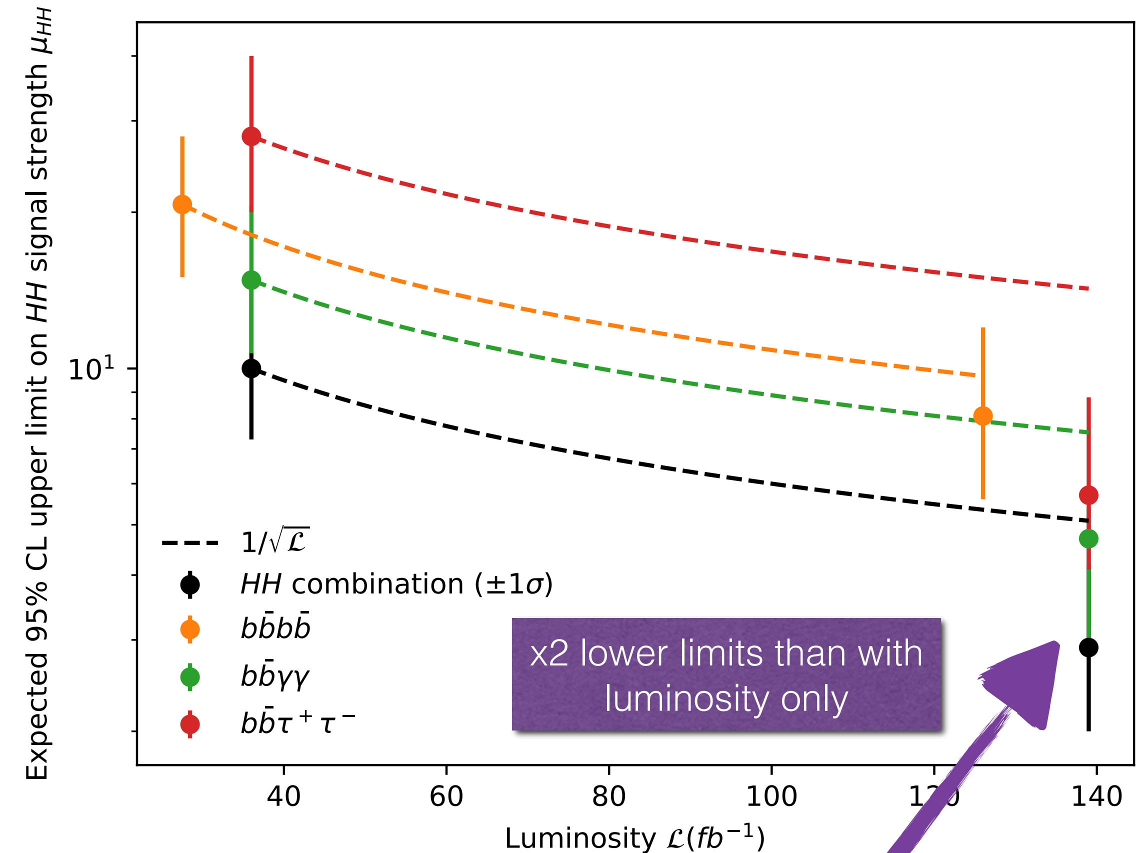
Conclusion and outlook

- The Higgs sector is **UNIQUE** and still **largely unexplored**!
    - Shape of the **Higgs potential essential** to fully understand EWSB and the evolution of the universe.

Only started to understand the Higgs!

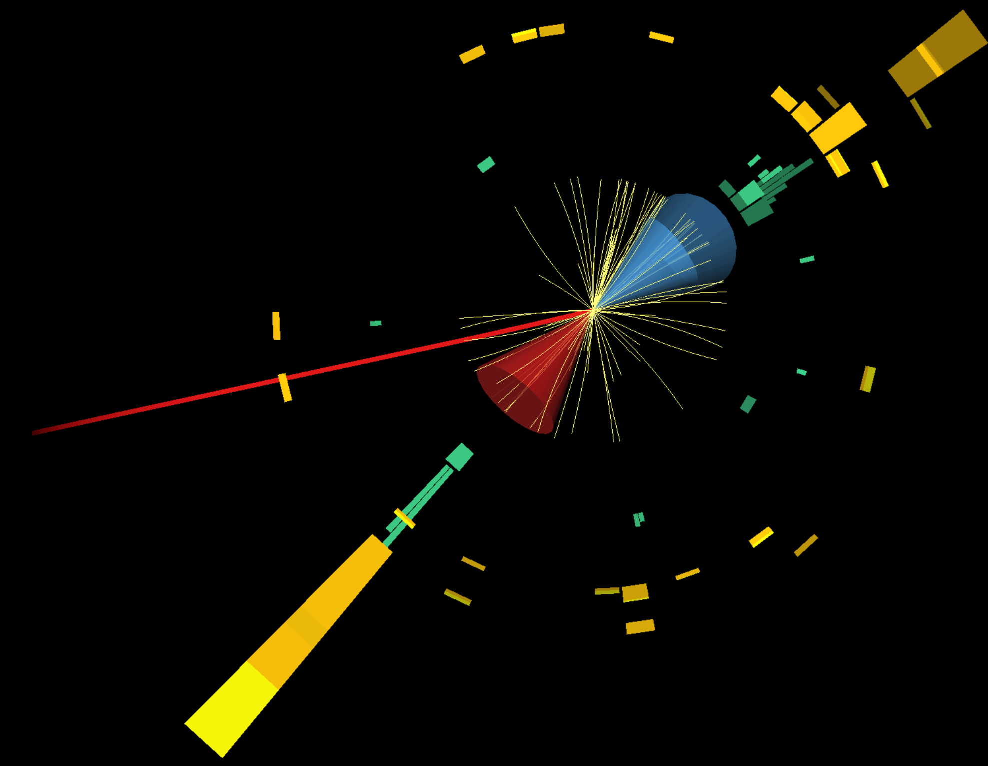
- **HH searches** at the (HL-)LHC are currently the **best tool** to constrain $V(\phi)$:
    - **Huge improvements on κ_λ constraints achieved** with Run 2 ATLAS dataset.
    - **On track to discover (5σ) HH at the HL-LHC** (ATLAS+CMS) and constrain κ_λ to $[0.5,1.6]$ at 68% CL (ATLAS only).



The human factor is important!

If something is unexpected in the Higgs, Run 3 might already reveal this to us!

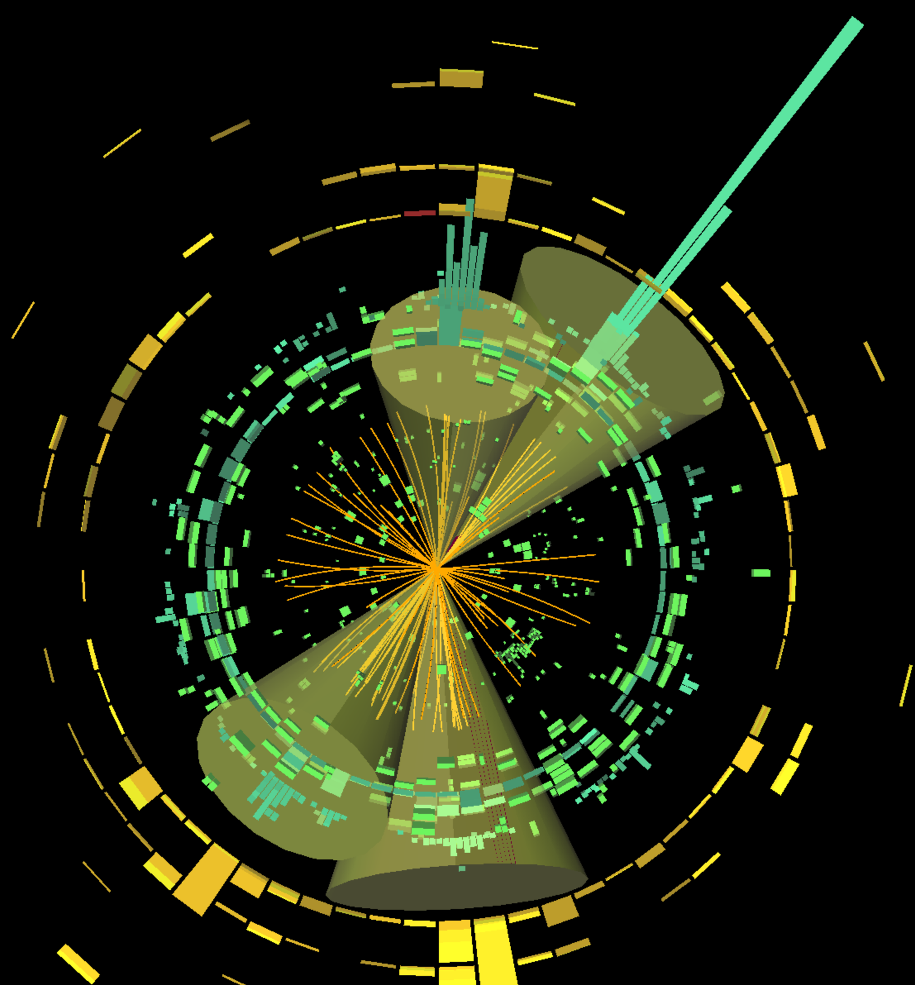
Thank you for your attention!



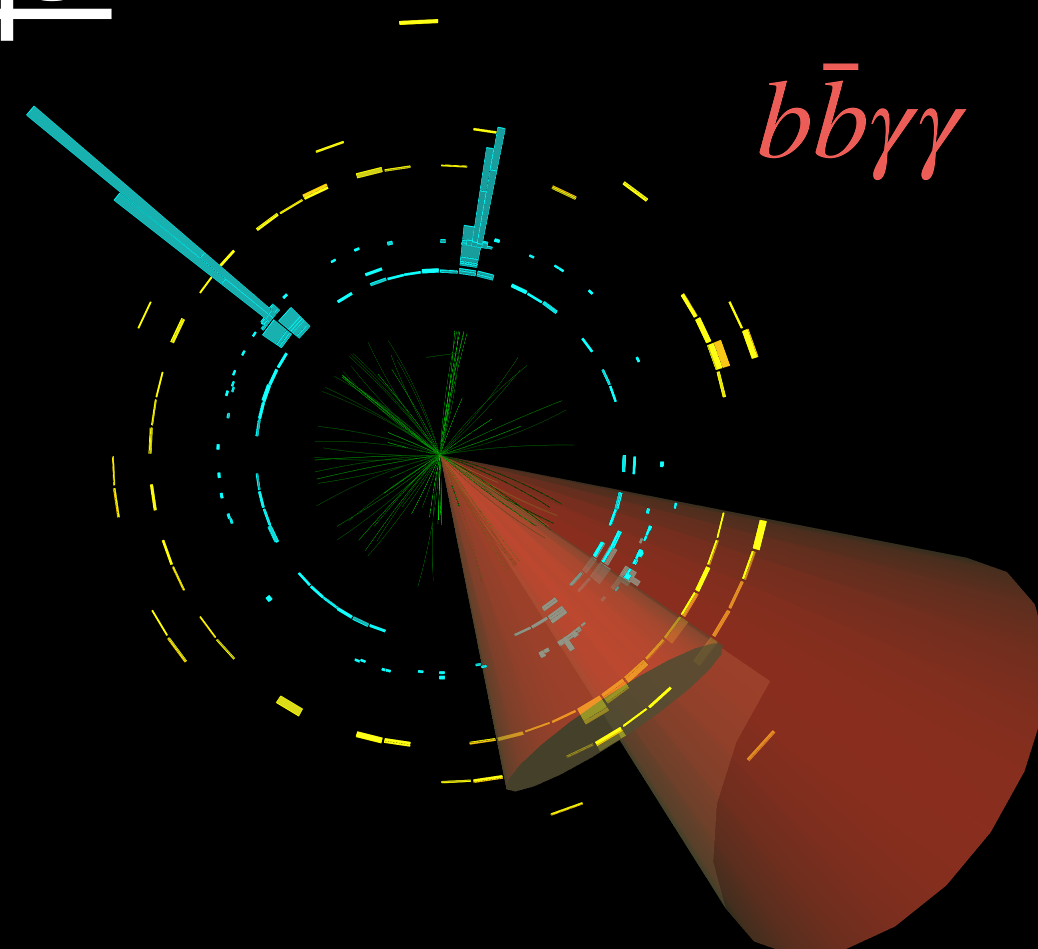
$b\bar{b}\tau^+\tau^-$

$b\bar{b}b\bar{b}$

Backup



$b\bar{b}\gamma\gamma$



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$HH \to b\bar{b}\gamma\gamma$ analysis

Additional material

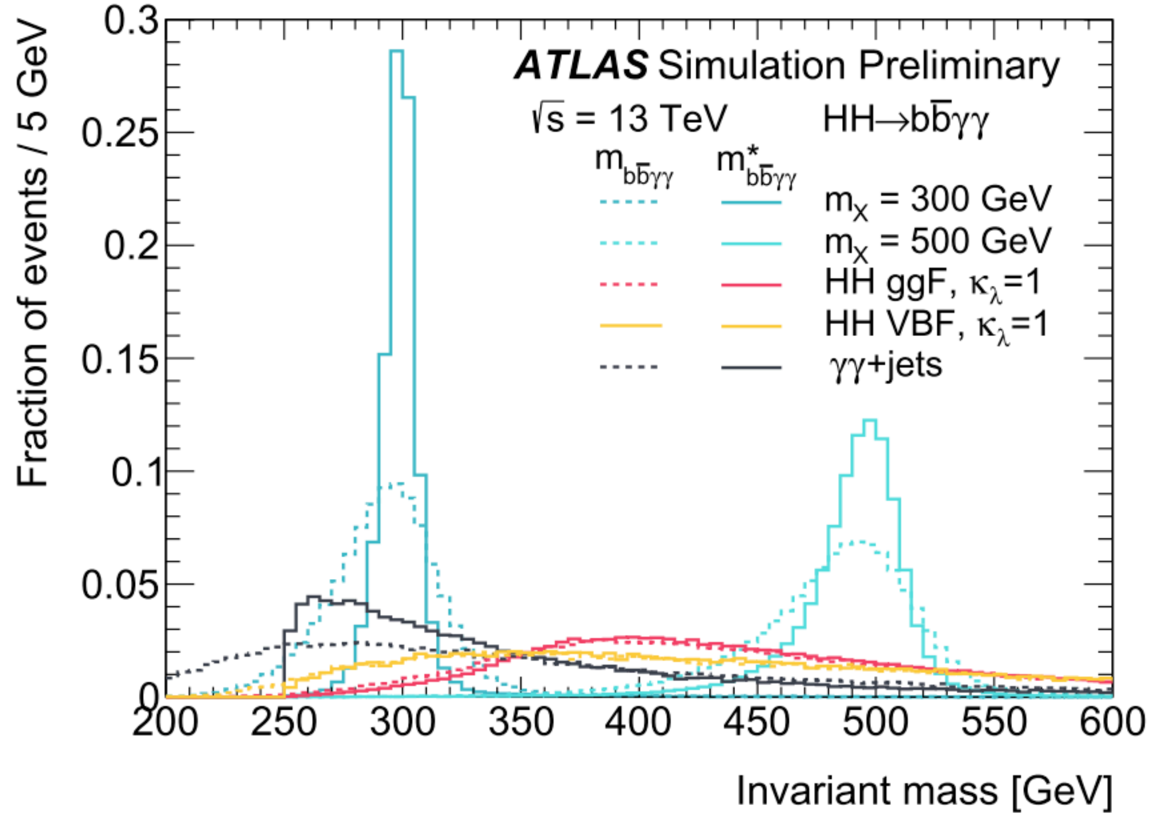

Figure 4: Reconstructed four-body mass for $m_X = 300$ GeV and $m_X = 500$ GeV resonant signal benchmarks and for the $\gamma\gamma$+jets background. Dashed lines represent the distribution of $m_{b\bar{b}\gamma\gamma}$ while solid lines represent the distribution of $m^*_{b\bar{b}\gamma\gamma}$, defined in Section 4.2.1. Distributions are normalized to unit area.

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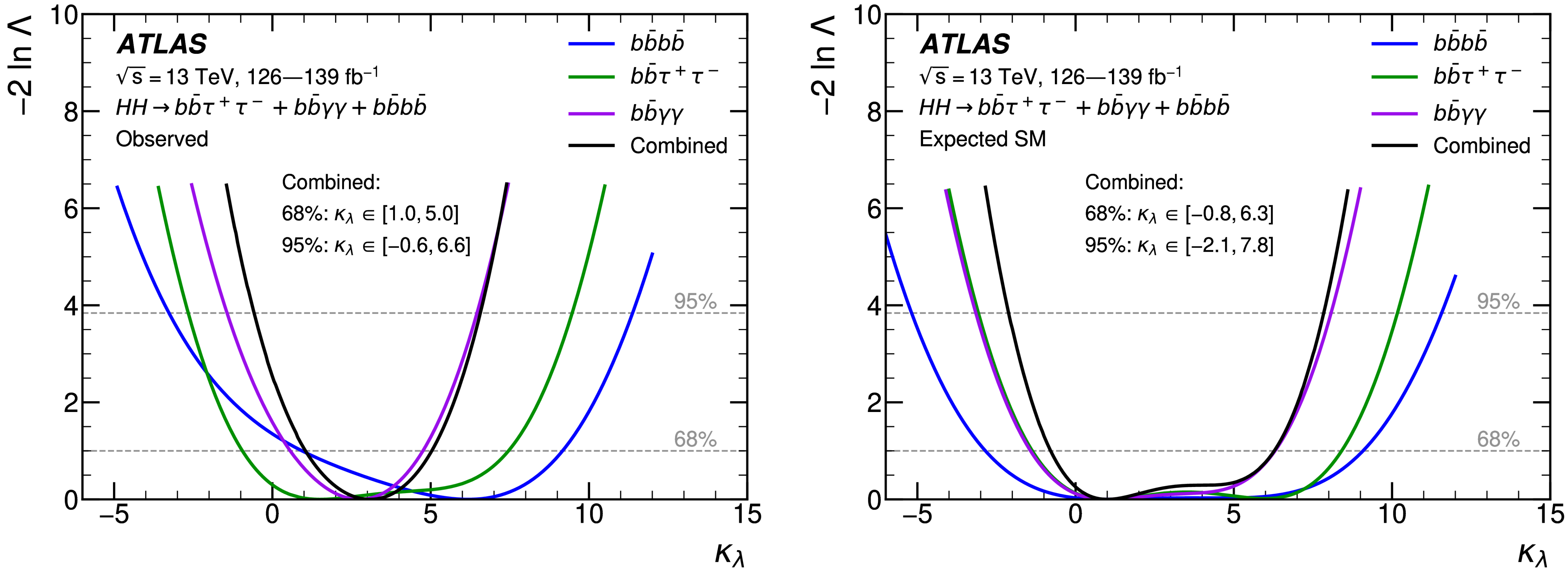
HH combined and separate likelihoods

arxiv:2211.01216



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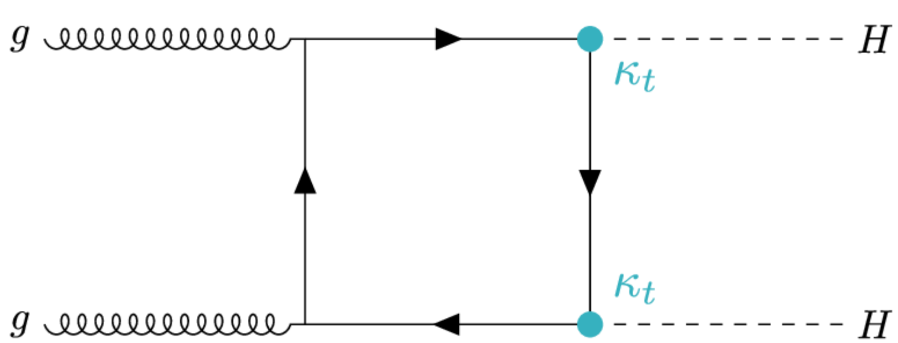
Single-Higgs constraints to κ_λ and κ_t

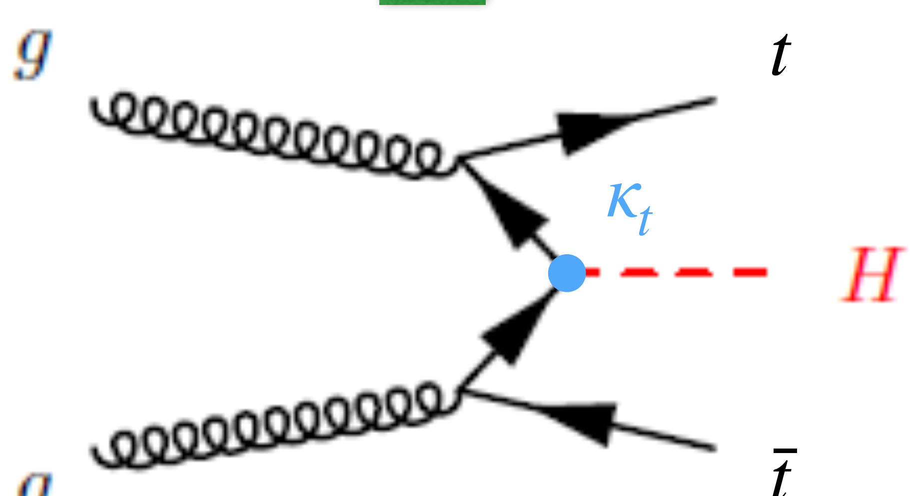
Results

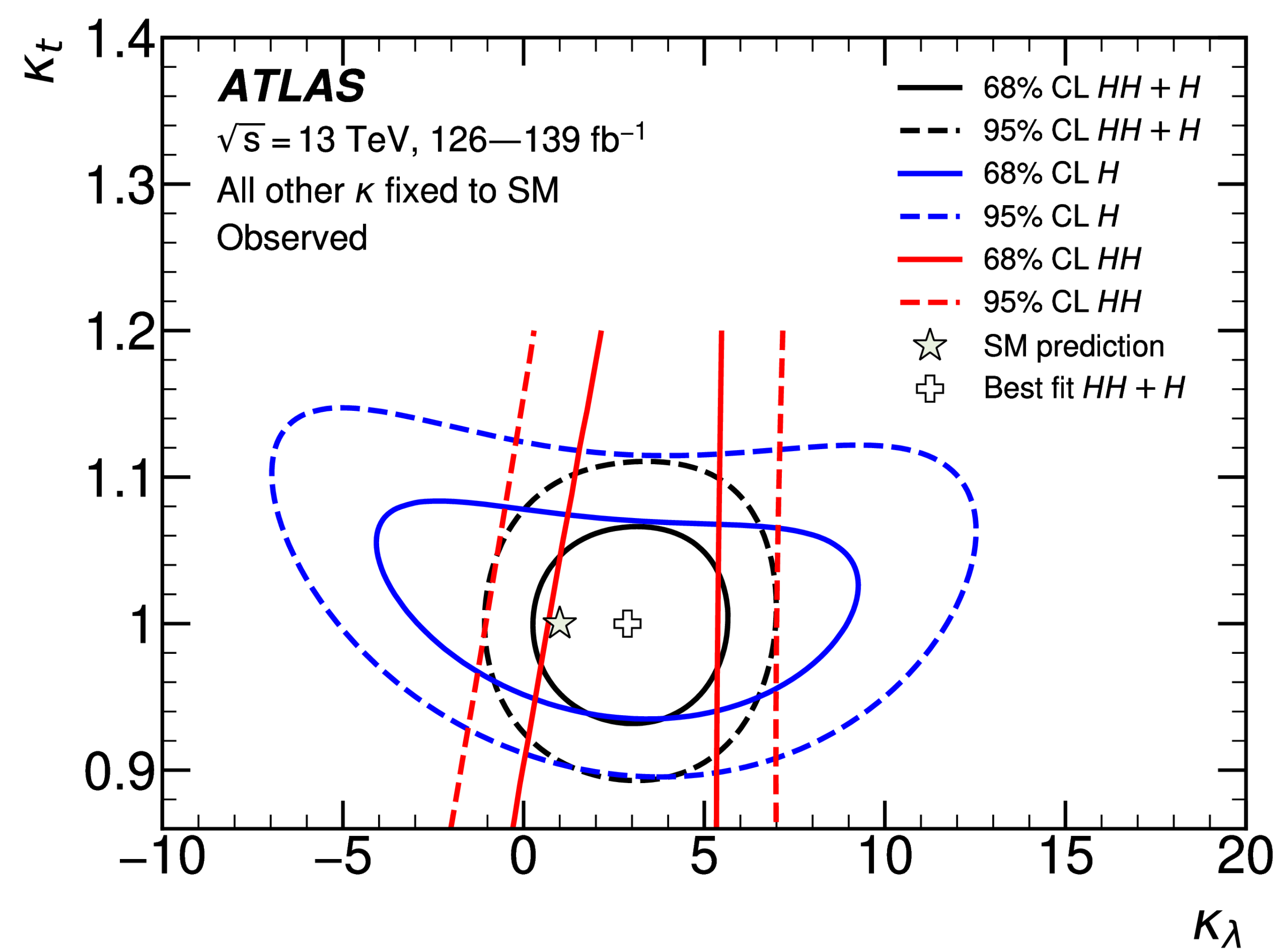
- **Combination with ttH** also **allow to constrain HH box-diagram effects** via direct measurement of κ_t

HH box diagram



ttH





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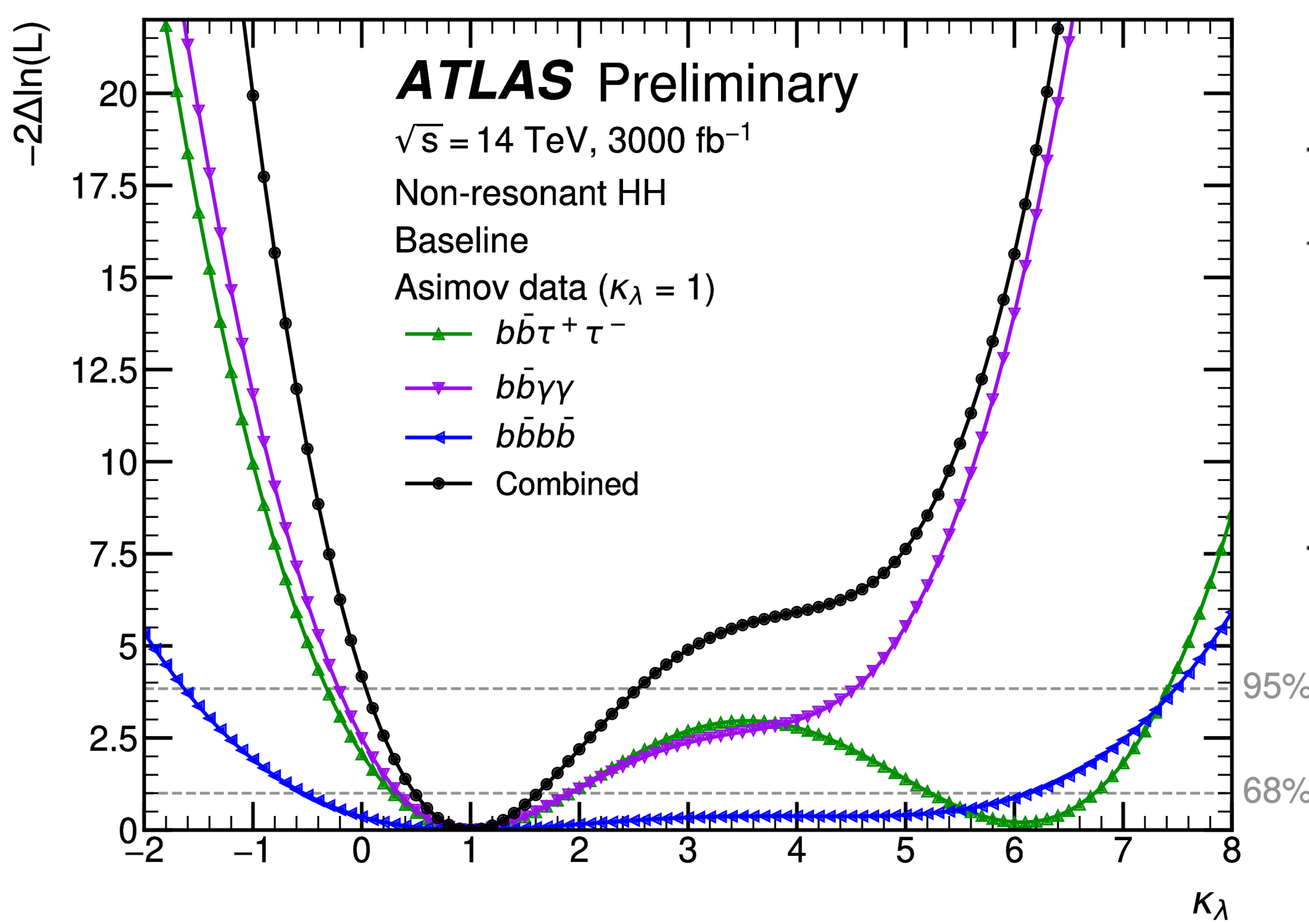
Updated projections for HL-LHC

ATLAS-PHYS-PUB-2022-053

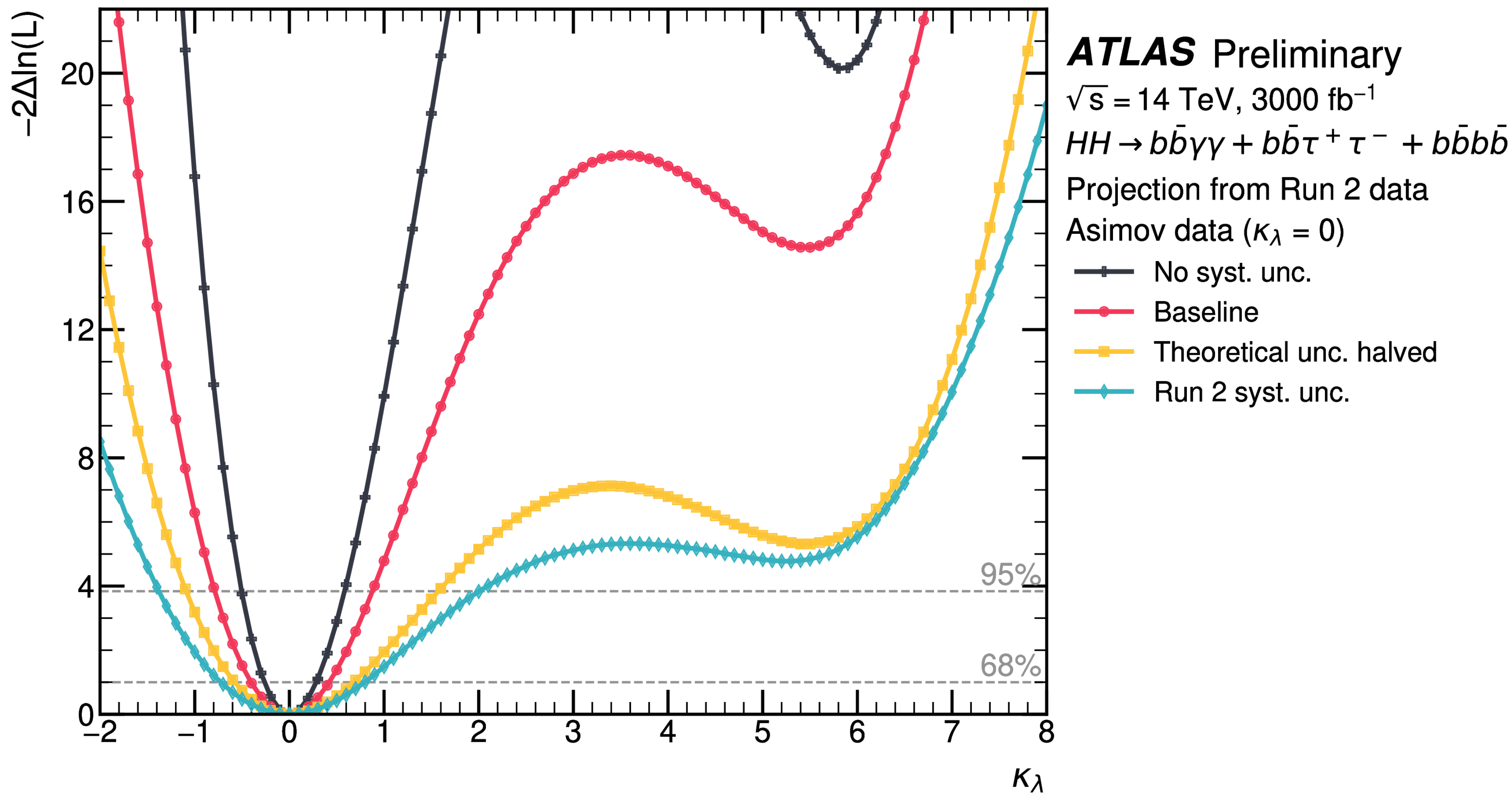
	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	$-21/+22$
Baseline	2.2	2.8	0.99	3.4	$-30/+33$
Theoretical unc. halved	1.1	1.7	0.65	2.1	$-47/+48$
Run 2 syst. unc.	1.1	1.5	0.65	1.9	$-53/+65$



Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Updated projections for HL-LHC

ATLAS-PHYS-PUB-2022-053



Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	$[-0.3, 0.3]$	$[-0.5, 0.6]$
Baseline	$[-0.4, 0.4]$	$[-0.8, 0.9]$
Theoretical unc. halved	$[-0.6, 0.7]$	$[-1.1, 1.6]$
Run 2 syst. unc.	$[-0.7, 0.8]$	$[-1.4, 2.0]$

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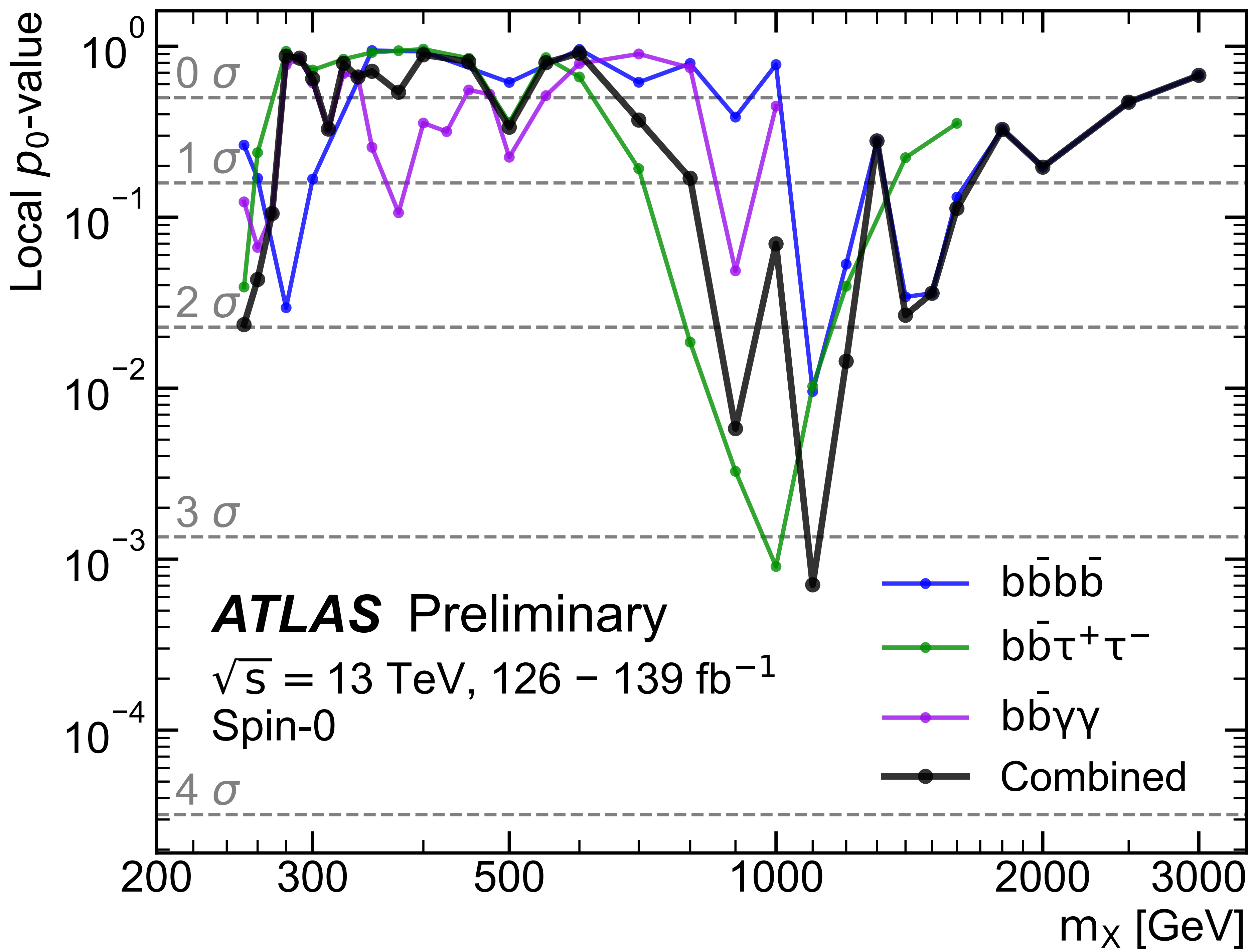
Combination p-value

Additional material (resonant)



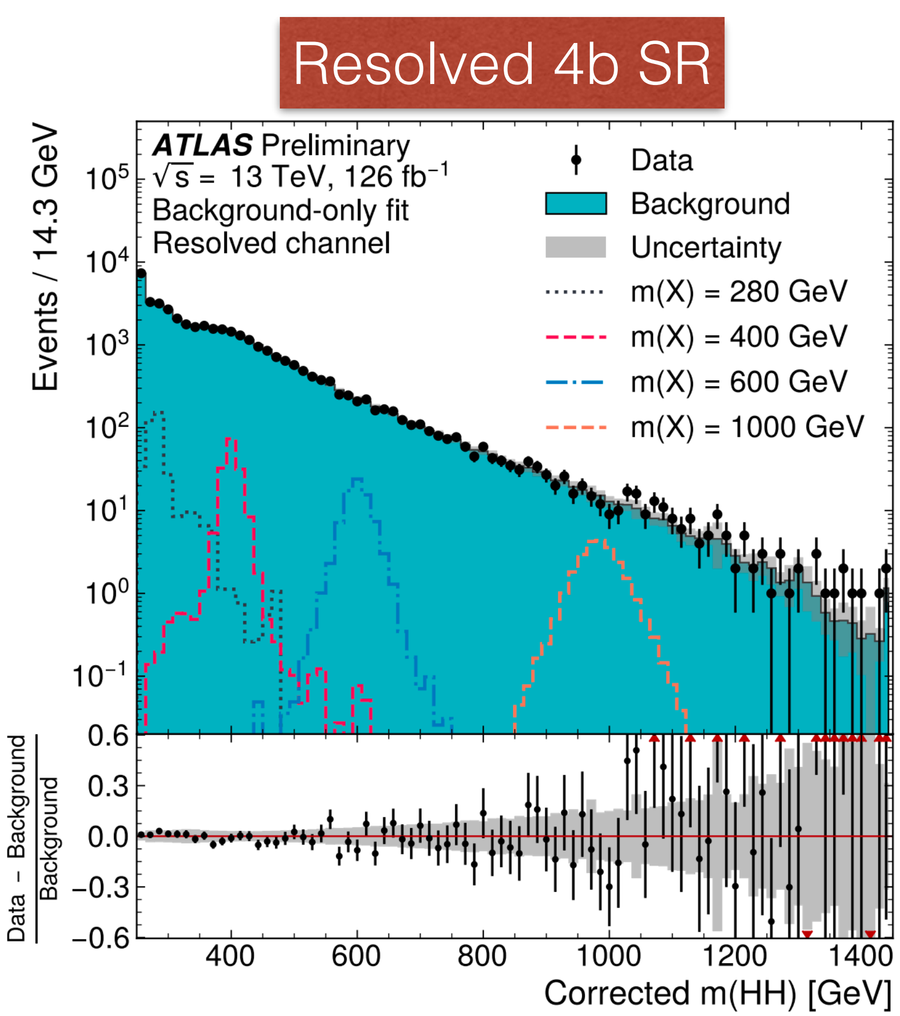
$HH \to b\bar{b}b\bar{b}$ analysis (1)

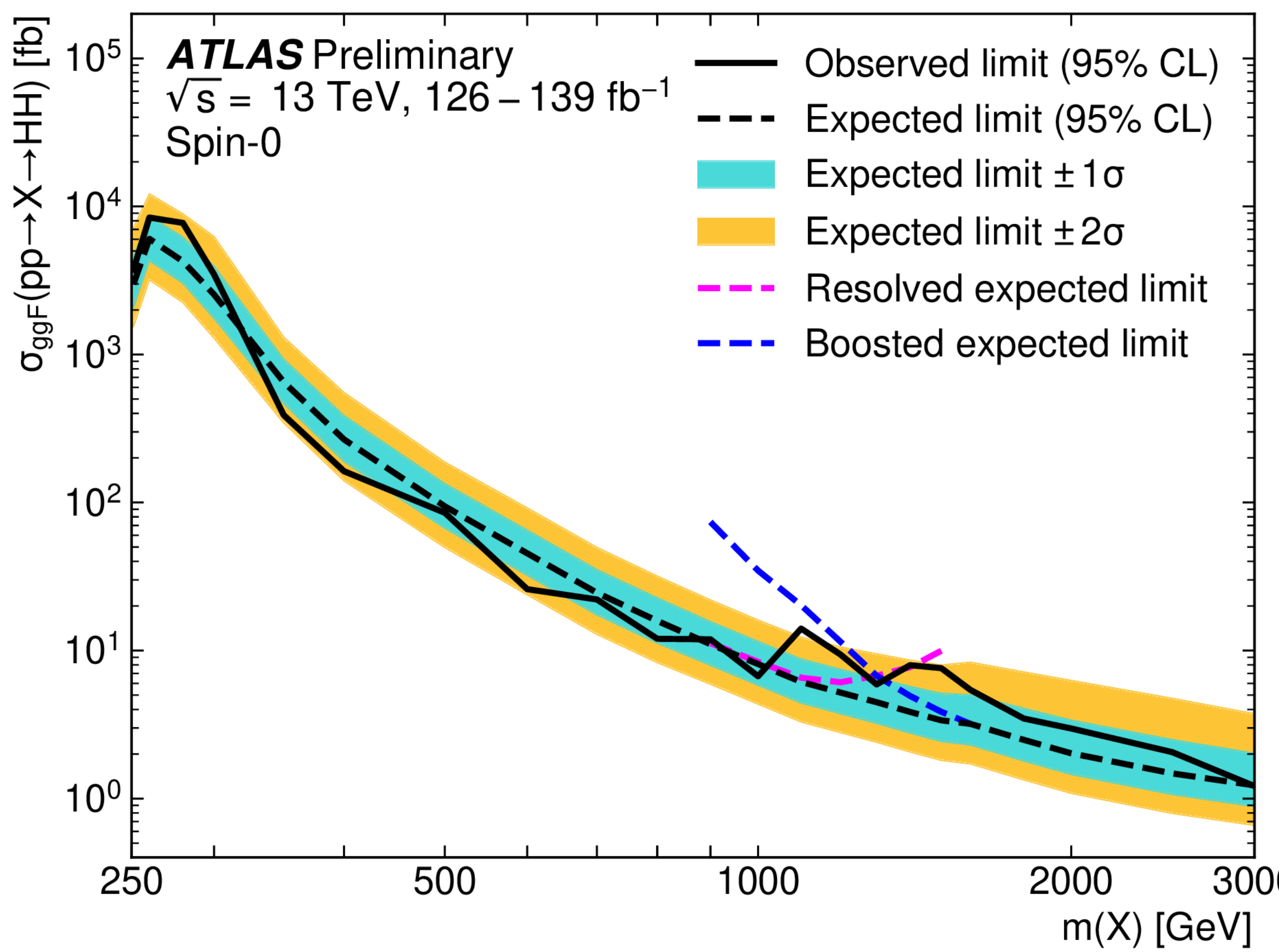
Results (resonant)

- Statistical combination of 2 analyses provided in the overlapping region (900 GeV < m_X < 1.5 TeV).
- **No significant excess** observed.
- **Largest excess at $m_X = 1.1$ TeV**

Local (global) significance at 1.1 TeV
2.6σ (1.0σ)

- **5x improvement at high mass** with respect to previous result (36 fb^{-1}): 2x due to luminosity, the rest to better reconstruction techniques.





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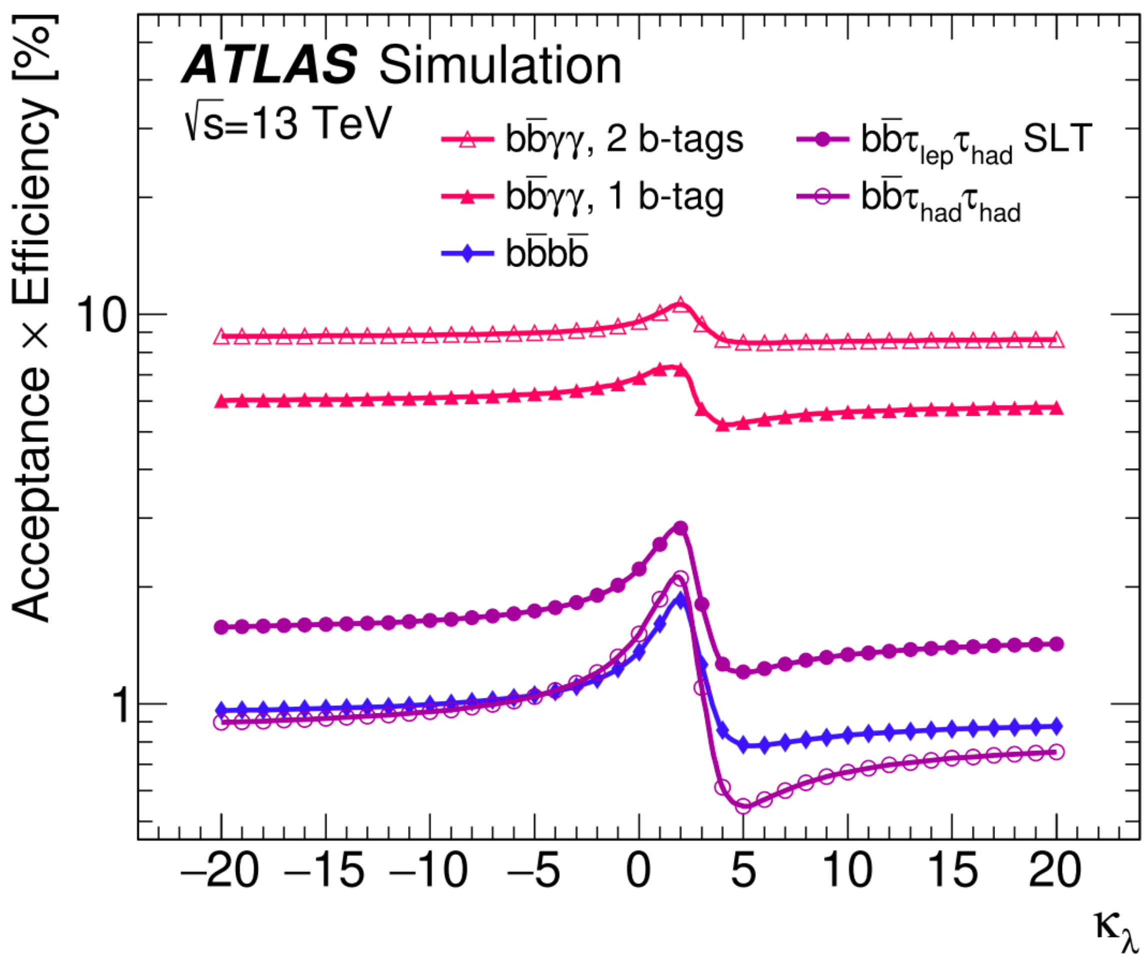
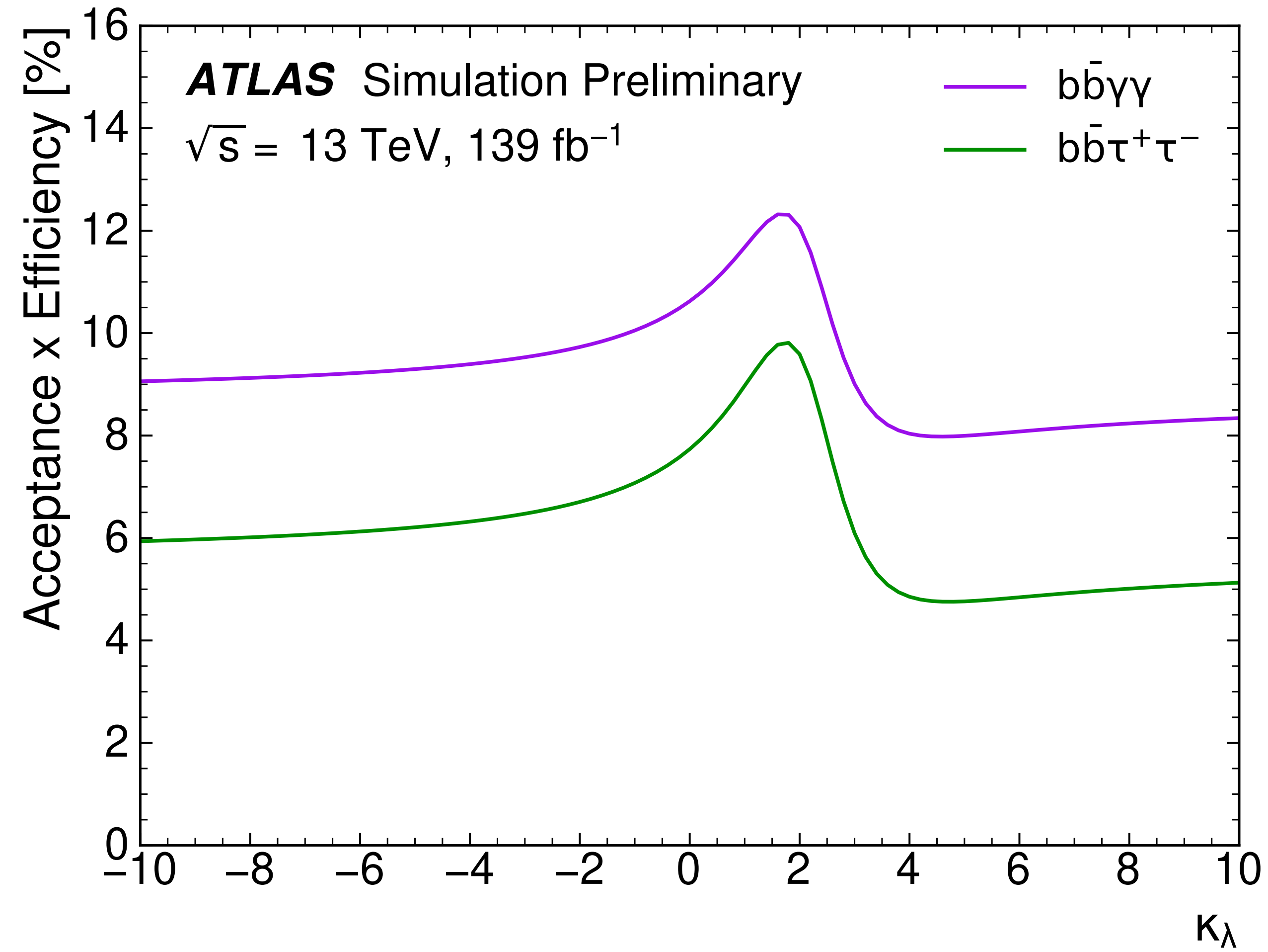
Combination acceptances vs κ_λ

Partial Run 2 combination ($36\ \text{fb}^{-1}$)



Full Run 2 combination



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κ_λ constraints at future colliders

arxiv:2209.07510

collider	Indirect-h	hh	combined
HL-LHC [77]	100-200%	50%	50%
$\mathrm{ILC}_{250}/\mathrm{C}^3$-250 [50, 51]	49%	–	49%
$\mathrm{ILC}_{500}/\mathrm{C}^3$-550 [50, 51]	38%	20%	20%
CLIC_{380} [53]	50%	–	50%
CLIC_{1500} [53]	49%	36%	29%
CLIC_{3000} [53]	49%	9%	9%
FCC-ee [54]	33%	–	33%
FCC-ee (4 IPs) [54]	24%	–	24%
FCC-hh [78]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [63]	-	15-30%	15-30%
μ(10 TeV) [63]	-	4%	4%

TABLE IX: Sensitivity at 68% probability on the Higgs cubic self-coupling at the various future colliders. Values for indirect extractions of the Higgs self-coupling from single Higgs determinations below the first line are taken from [2]. The values quoted here are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

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