Particles and Pixels:

The Beauty of the Higgs and the quest to determine the shape of the Higgs potential

Brian Moser (CERN)

Séminaires de Physique des Hautes Energies, IPHC Strasbourg

13/10/2023

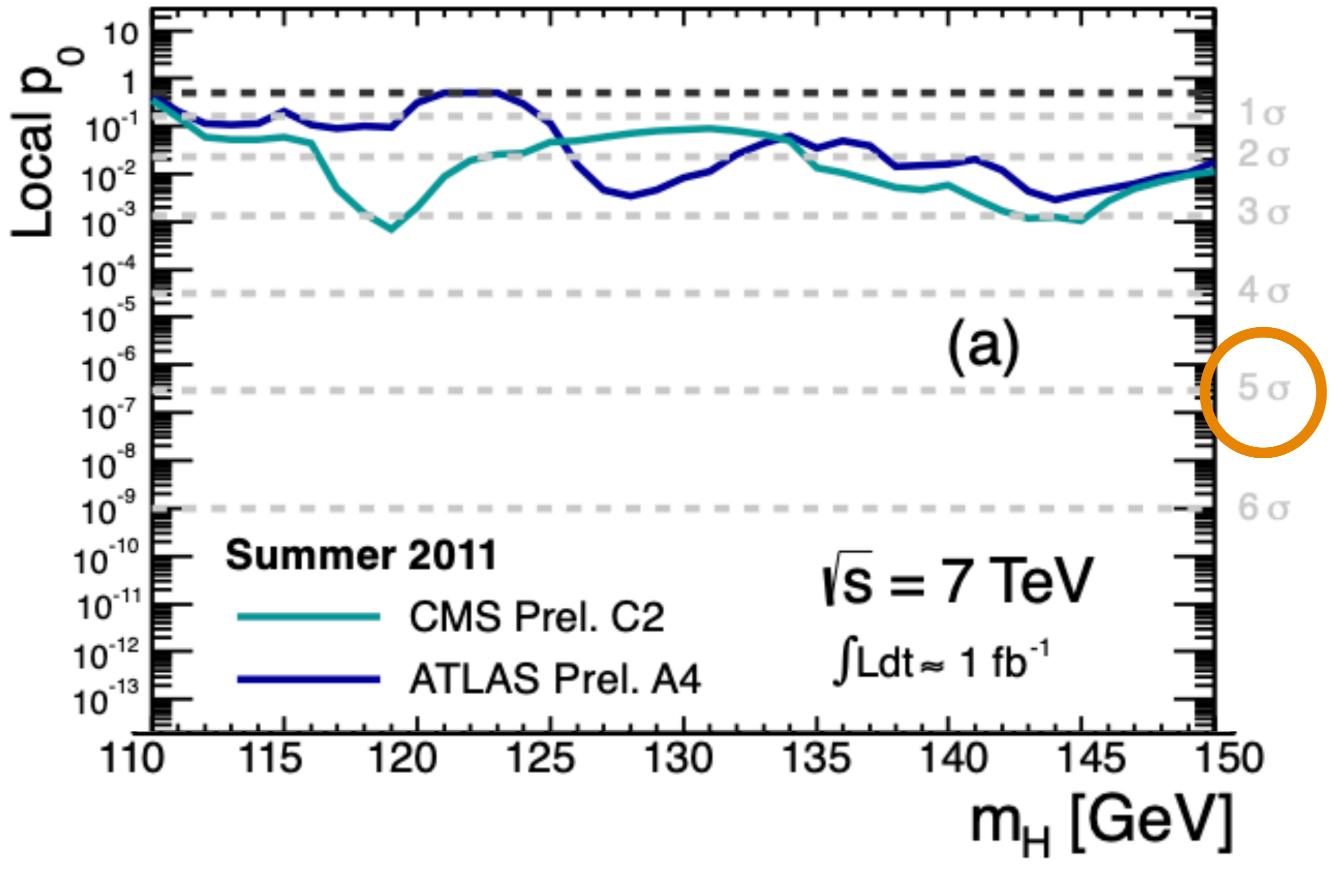
ATLAS EXPERIMENT

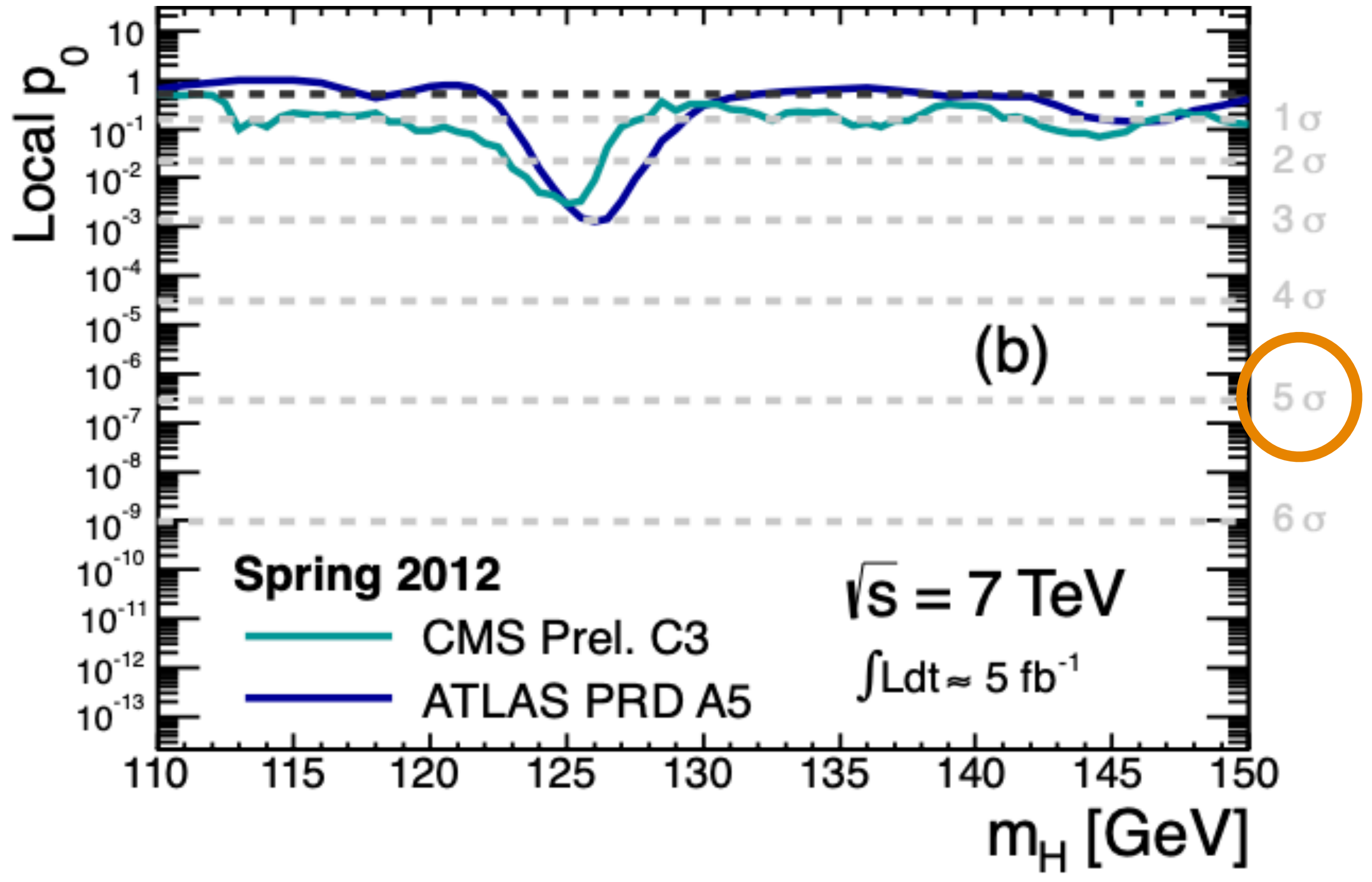
CERN

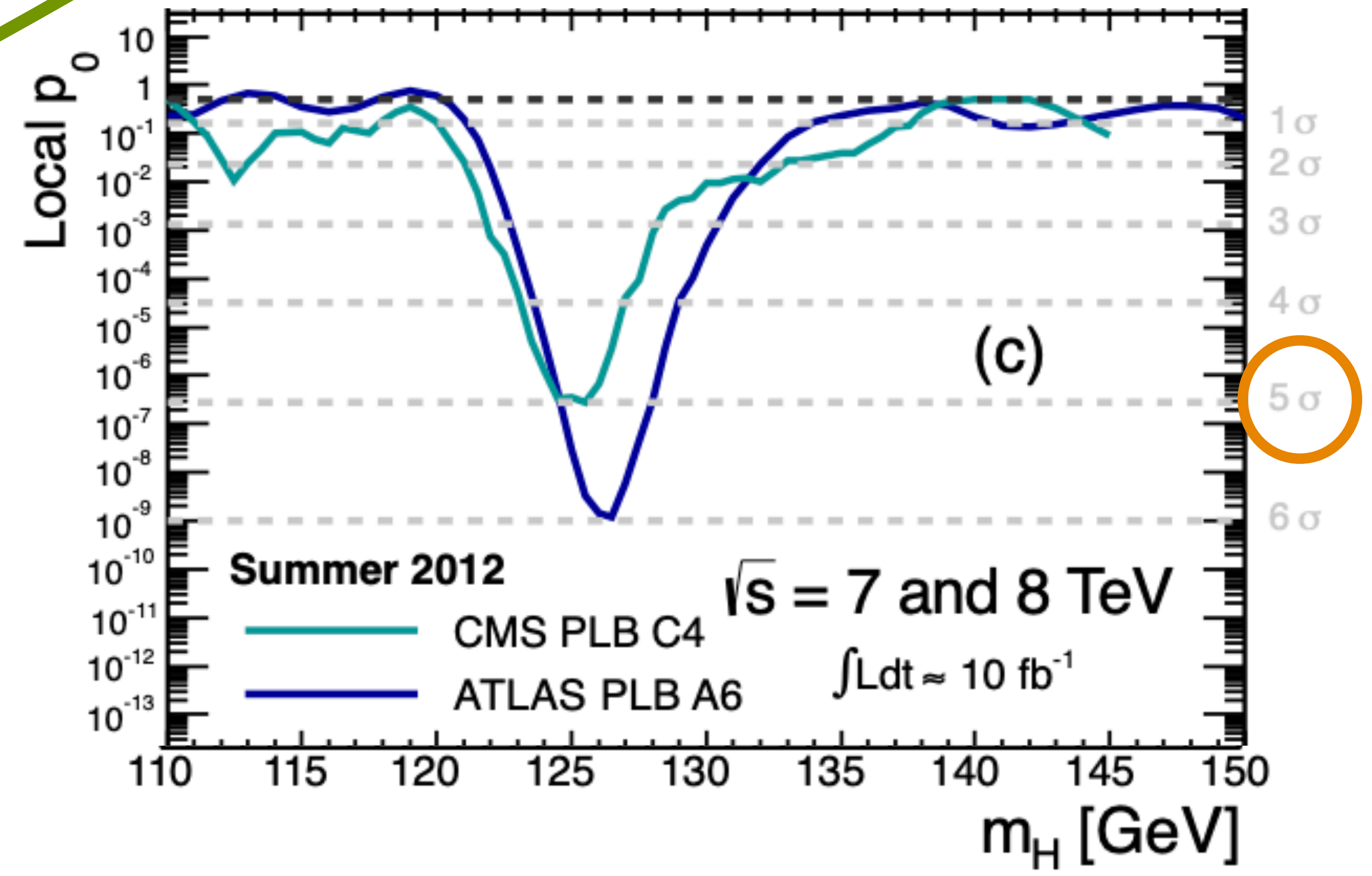
The discovery of a new particle

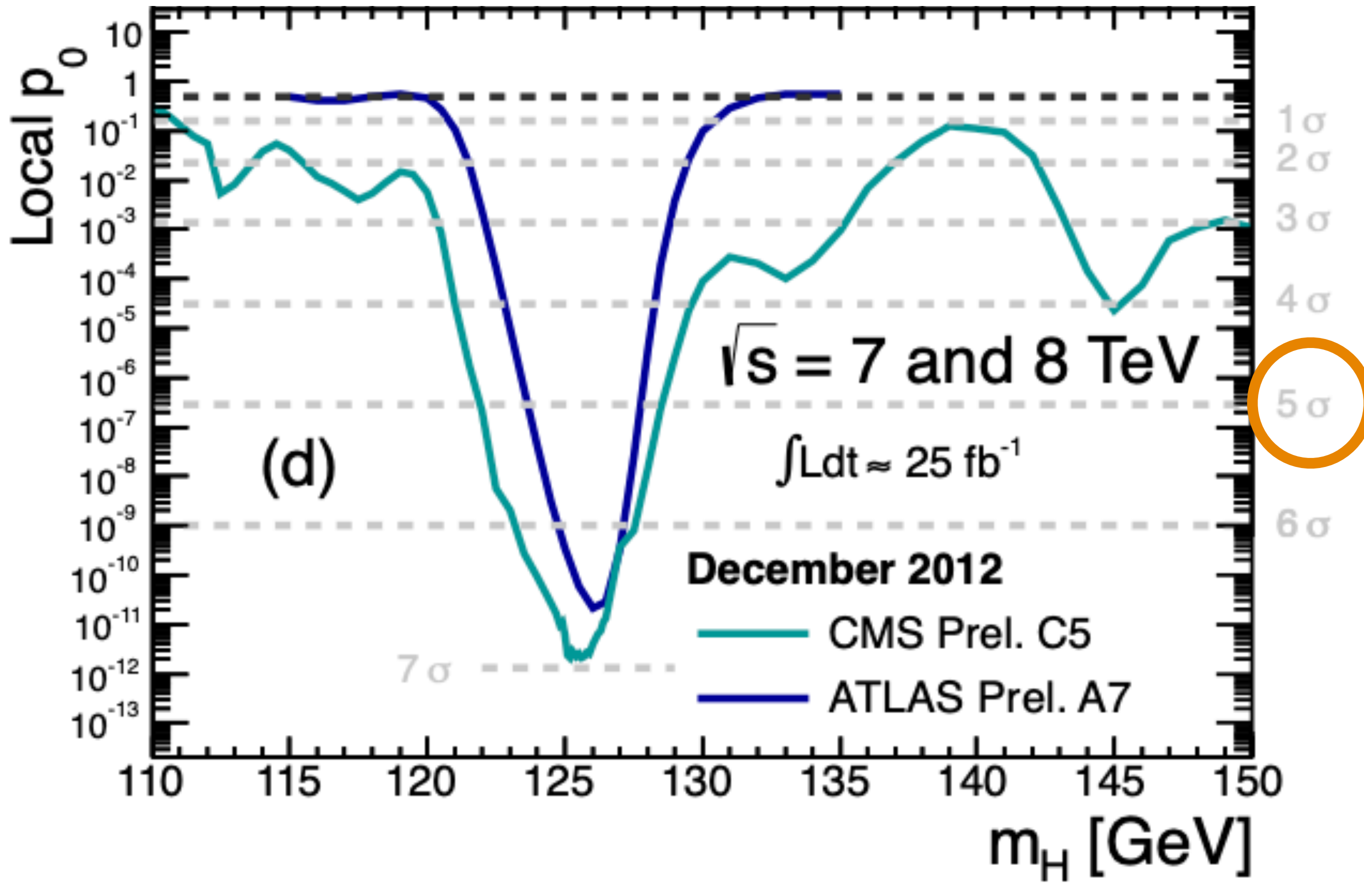
Combining
H→γγ
H→Z*Z→4l
and later adding
H→W*W→2l2v

[PDG 2013]









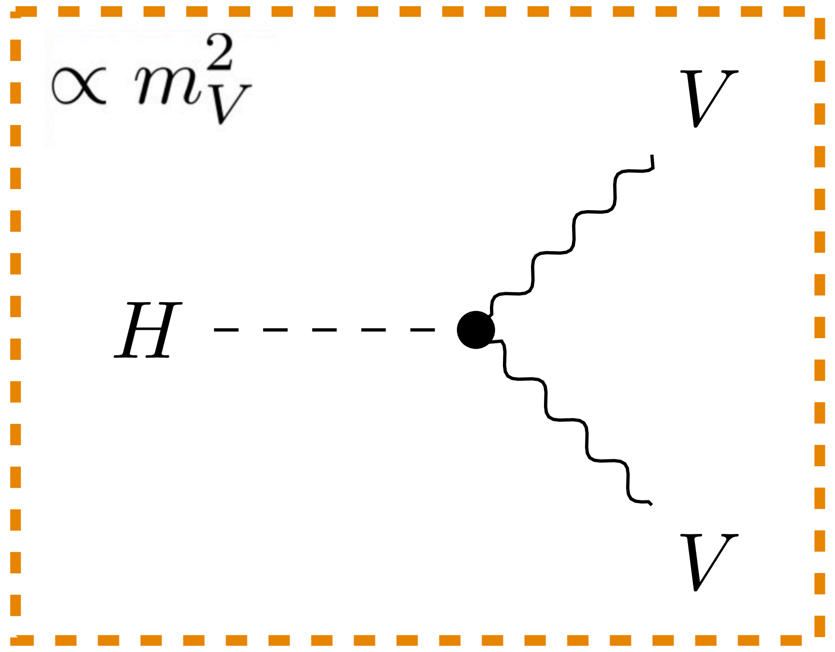
Steadily increasing discrepancy at m_H ~ 125 GeV

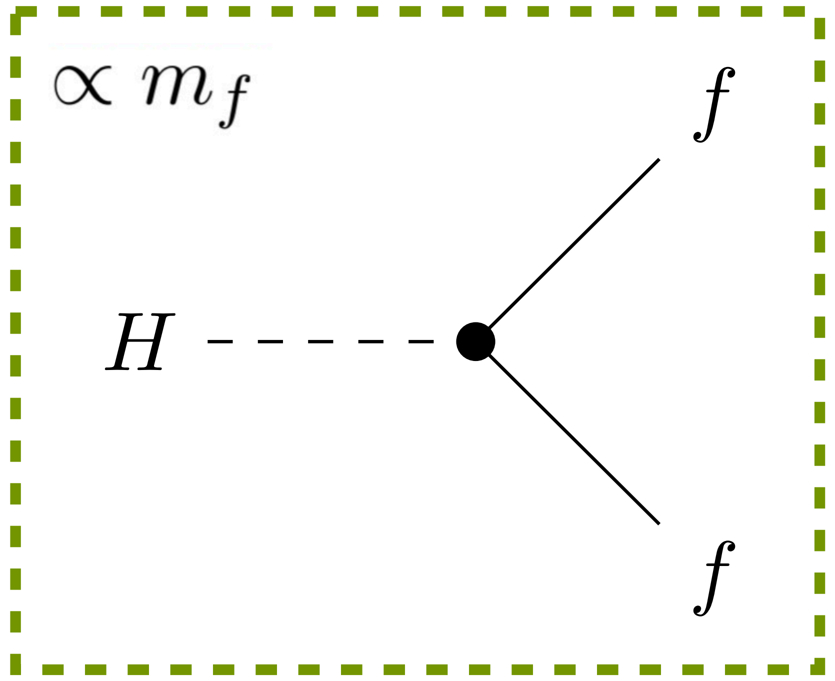
A textbook discovery!

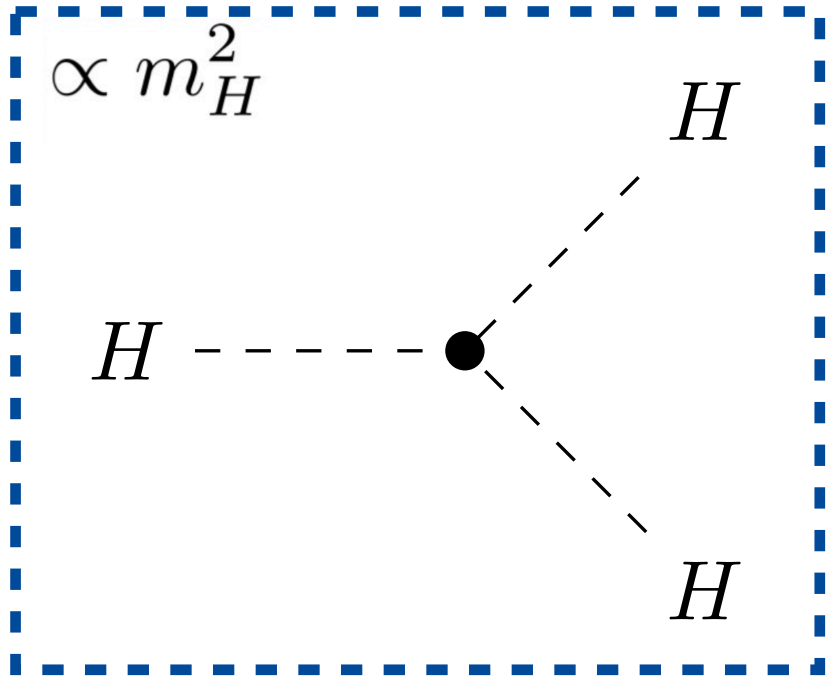
discovery (or observation) => Z > 5 σ

It’s all about that Higgs!

- **15 out of the 19** free parameters of the Standard Model are connected to the **Higgs boson**



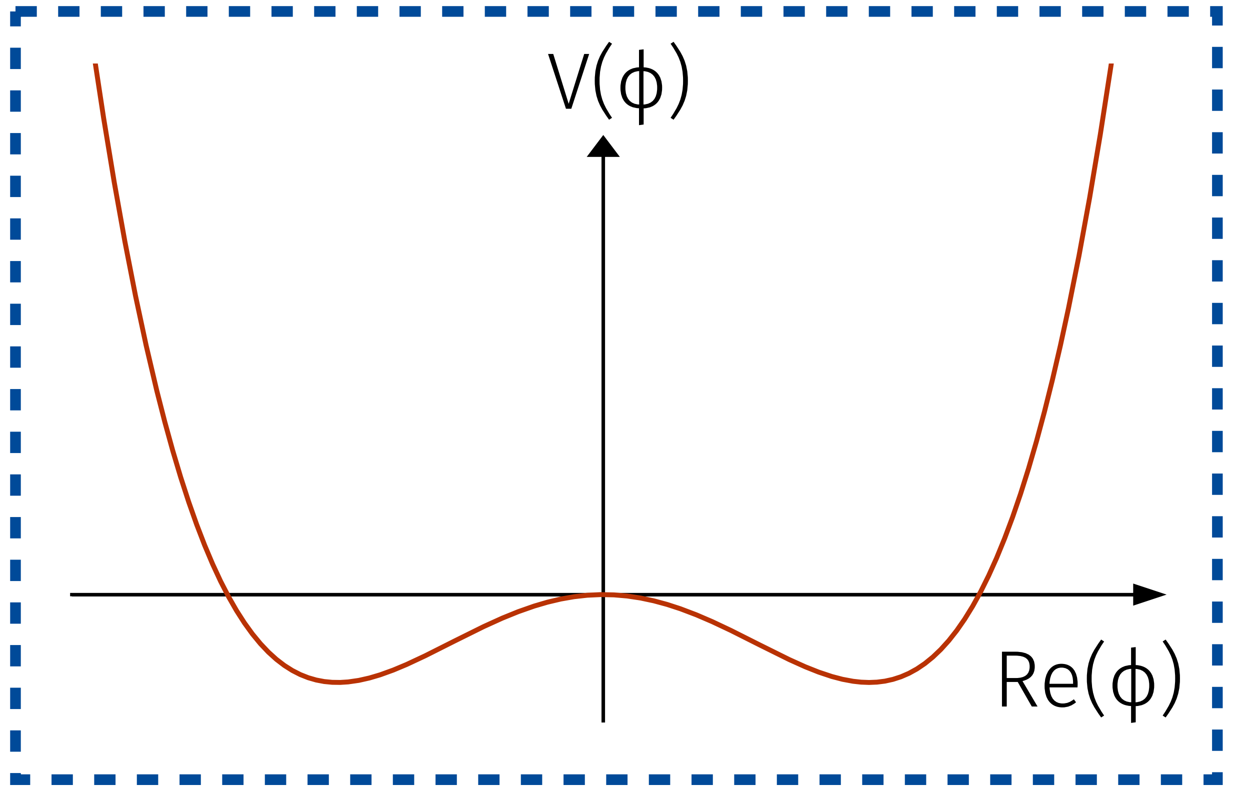




$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \boxed{|D_\mu\phi|^2} \boxed{+ \mu^2(\phi^\dagger\phi) - \lambda(\phi^\dagger\phi)^2} + \boxed{y_{ij}\psi_i\phi\psi_j + \mathrm{h.c.}}$$

BEH mechanism

Yukawa terms



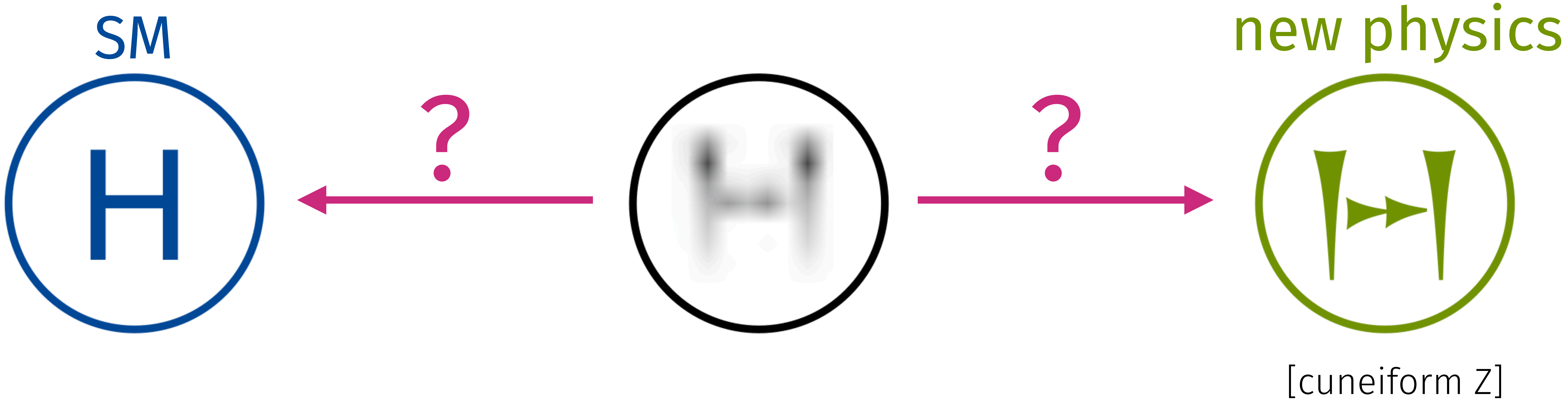
The Higgs boson couples directly to all massive particles of the SM
→ **incredibly rich phenomenology**

Our experimental picture of the Higgs boson

2nd generation?
~ evidence for Hμμ

Higgs couplings to 3rd gen. fermions with **20% precision**

1st generation?



CP-nature of the couplings?

Higgs couplings to (heavy) vector bosons with **10% precision**

Higgs potential?

Only data can tell → we need to increase the resolution of our picture of the Higgs boson!

Standard Model Effective Field Theories

EFT is a **systematic tool** to talk about the precision of measurements and quantify new physics

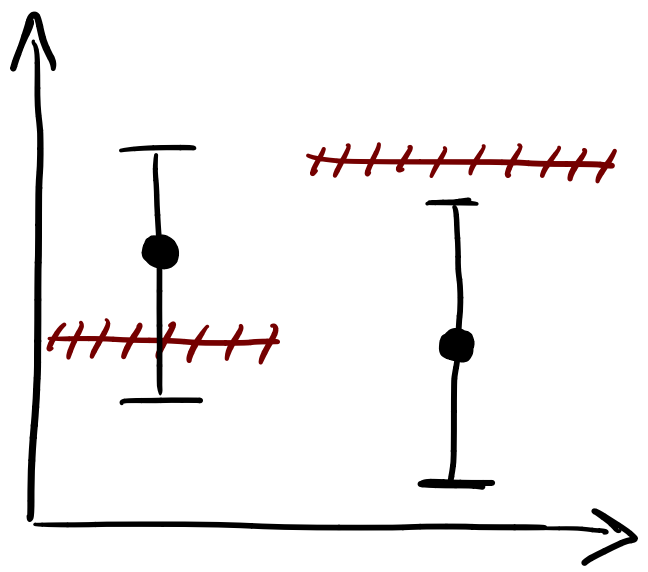
Wilson coefficients = free parameters

76 assuming U(3)^5 flavor symmetry

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} \mathcal{O}_i^{(6)}$$

scale of new physics

Measurements

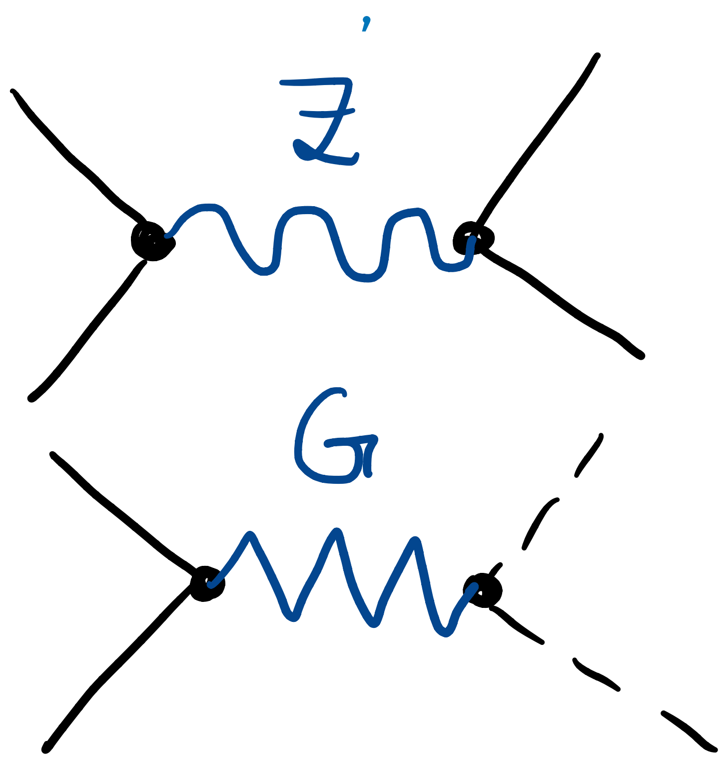


EFT interpretations

Limits

$$\mathcal{L}_6 = \sum_i c_i \, \mathcal{O}_i^{(\mathrm{dim}=6)}$$

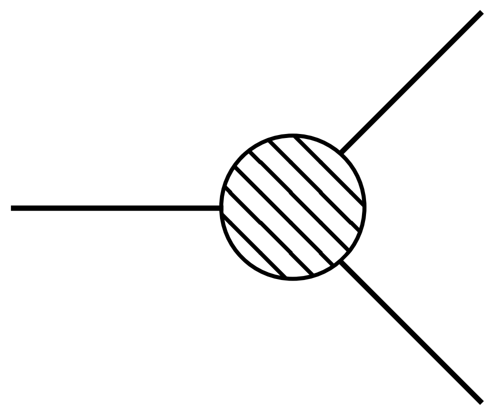
UV complete models

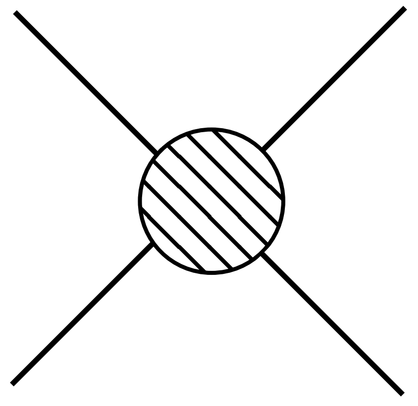


Precision versus energy

EFT: Modification of existing vertices + addition of (new) effective vertices

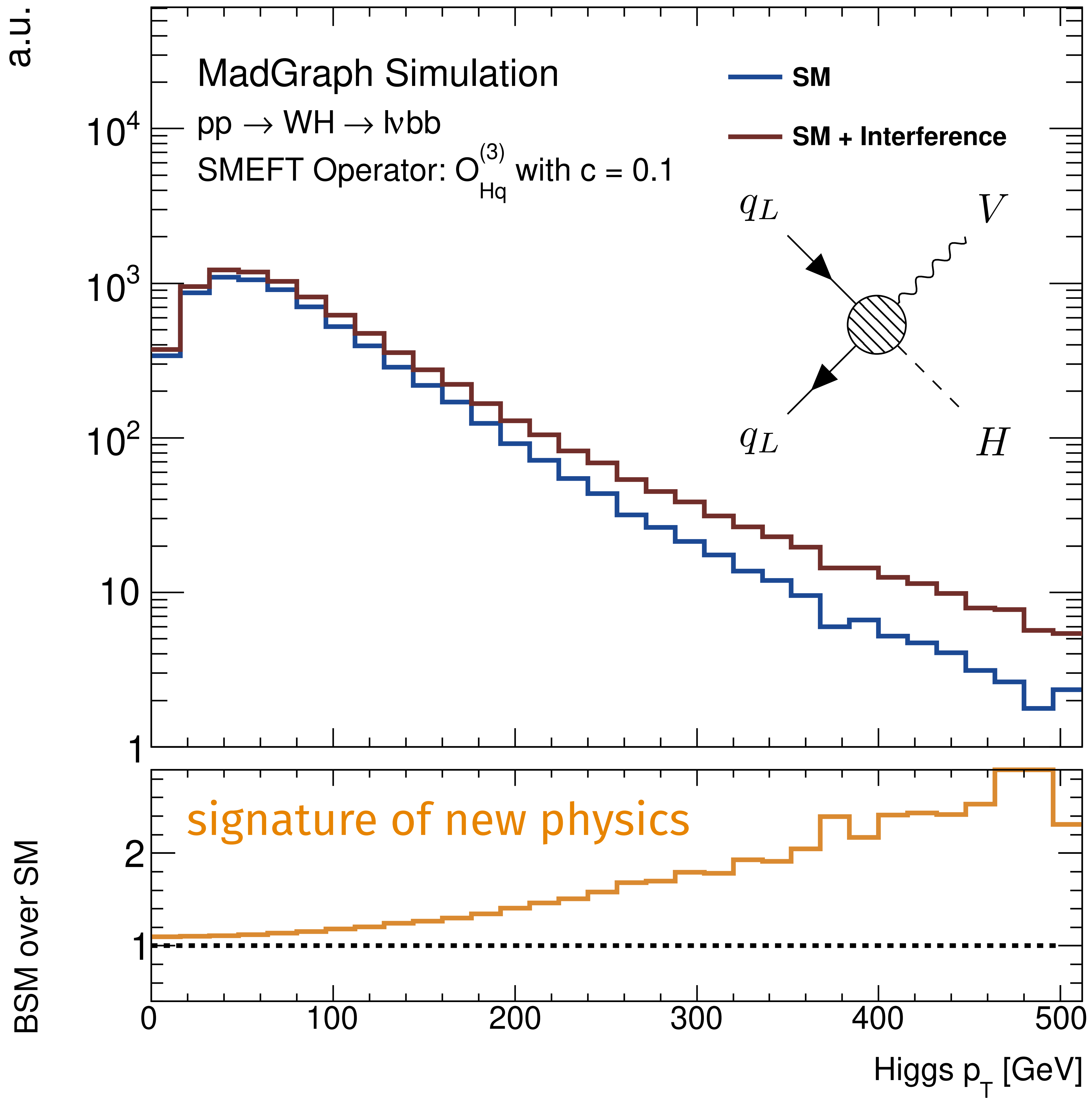
Precision vs. **Energy**





$$\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2 \qquad \delta O_Q \sim \left(\frac{Q}{\Lambda}\right)^2$$

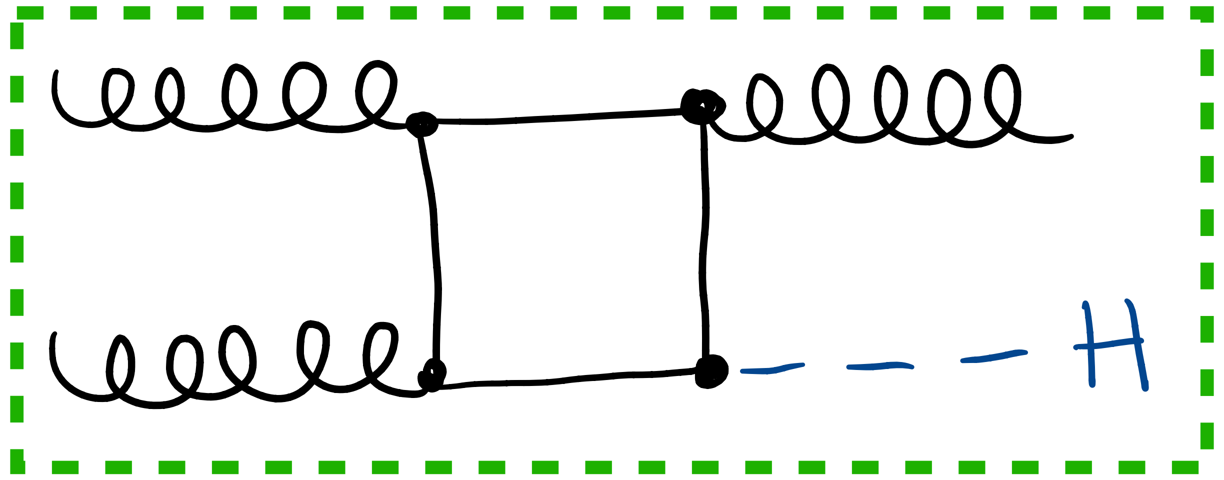
$$0.3\% \ @ \ 100\,\text{GeV} \quad \sim \quad 30\% \ @ \ 1\,\text{TeV}$$



High energy offers unique opportunities!

How to reach high energy?

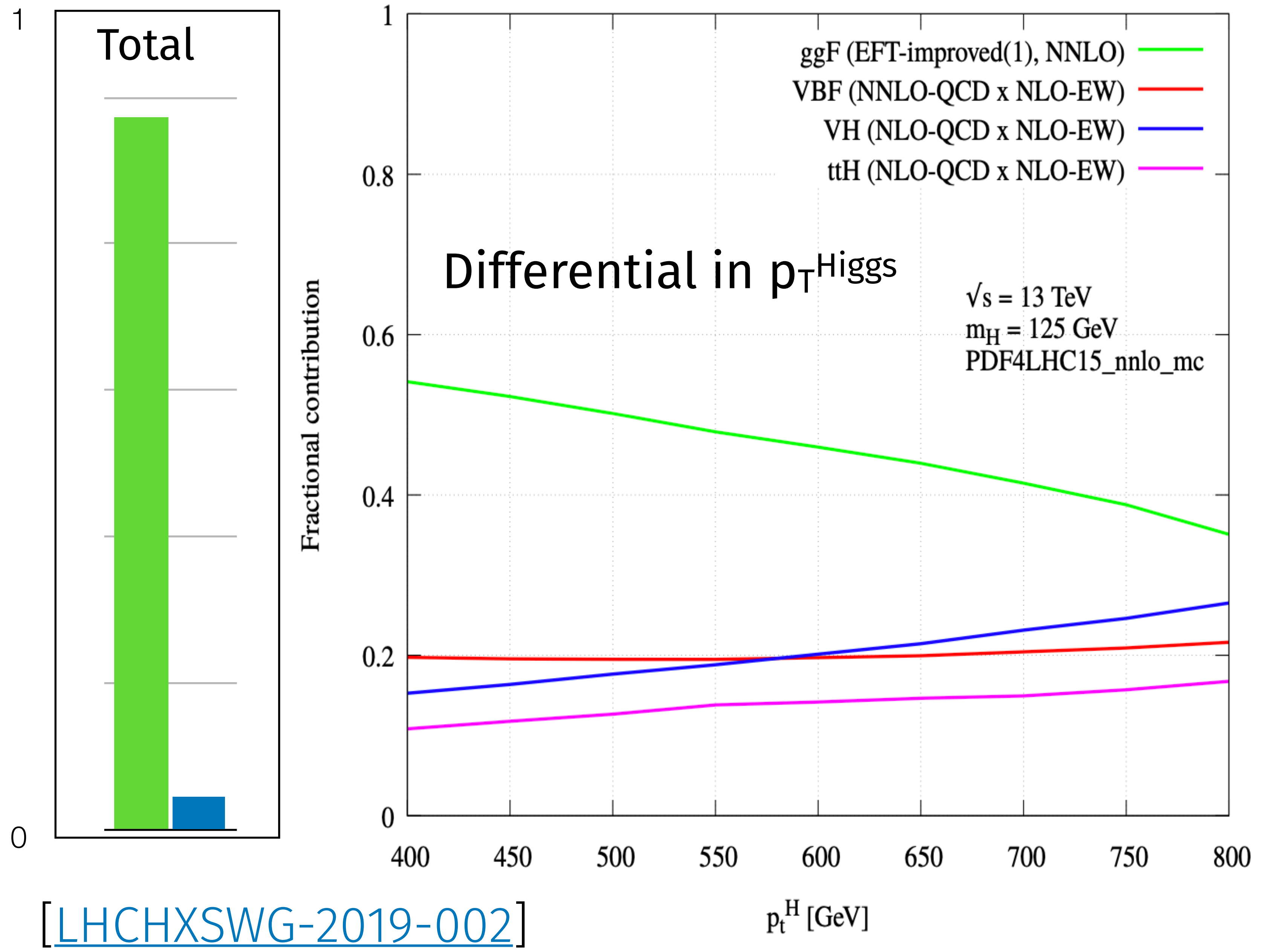
- Focus on **H→bb decay** as it has the largest **BR of ~ 58%**
- Which production mechanism?



Gluon-Gluon Fusion:

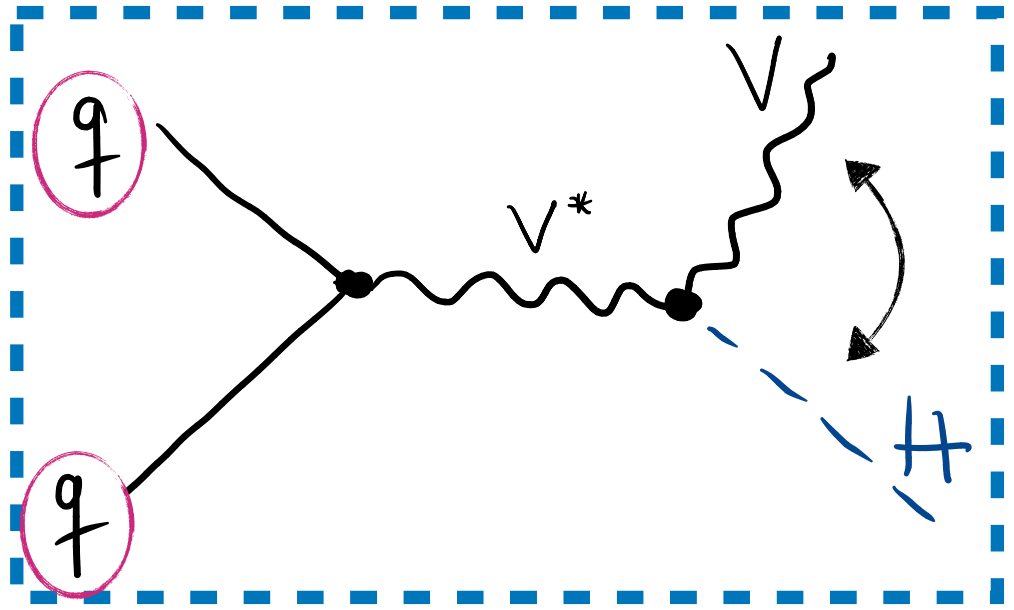
- Huge cross-section
- Huge multi-jet background
- Triggering on high p_T jets possible

rel. contribution to total Higgs production XS



[LHCHXSWG-2019-002]

Today



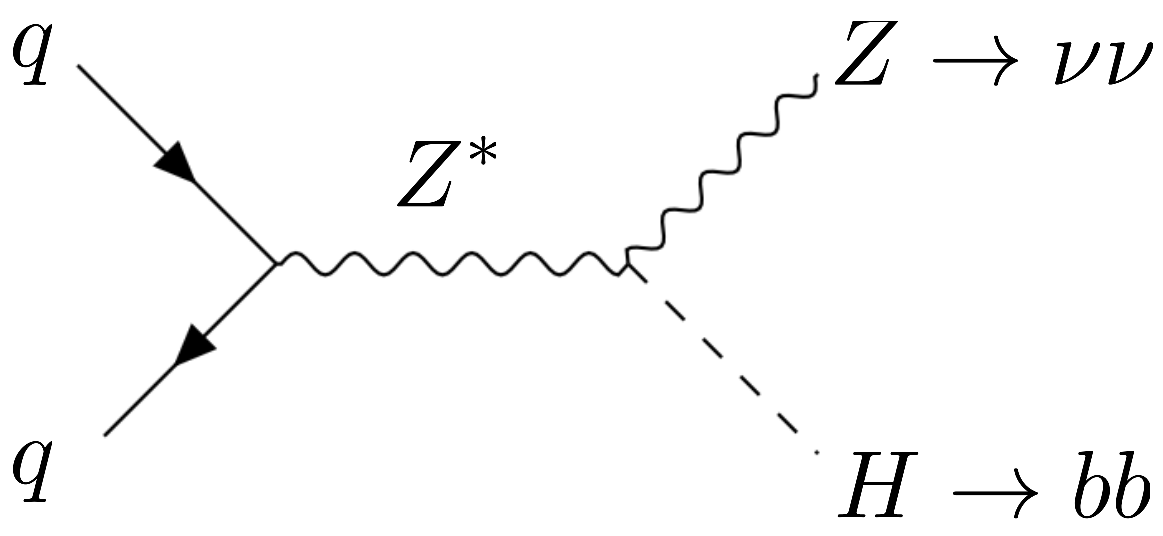
Higgs Strahlung (**VH**)

- Leptonic V decays to trigger and improve S/B
- Main search channel
- p_T^H > 0 at LO already, only limited by PDF suppression
- Harder p_T^H spectrum than Σ bkgs

On the vector boson reconstruction

- **3 main channels** depending on the charged lepton categories $[\ell = e, \mu]$

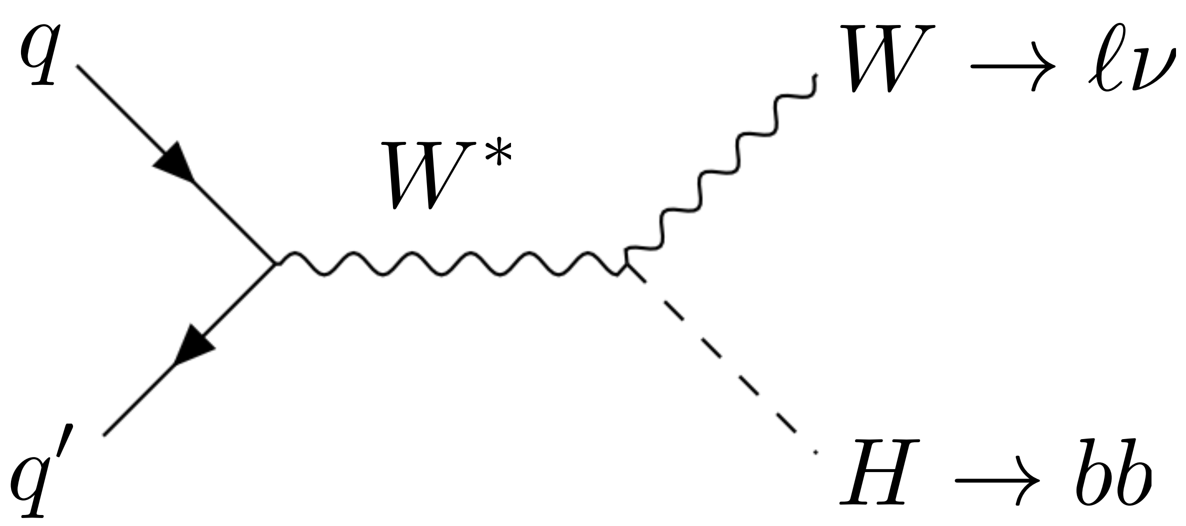
0-lepton channel



BR = 20%

- Mainly Z→νν with some W→τν

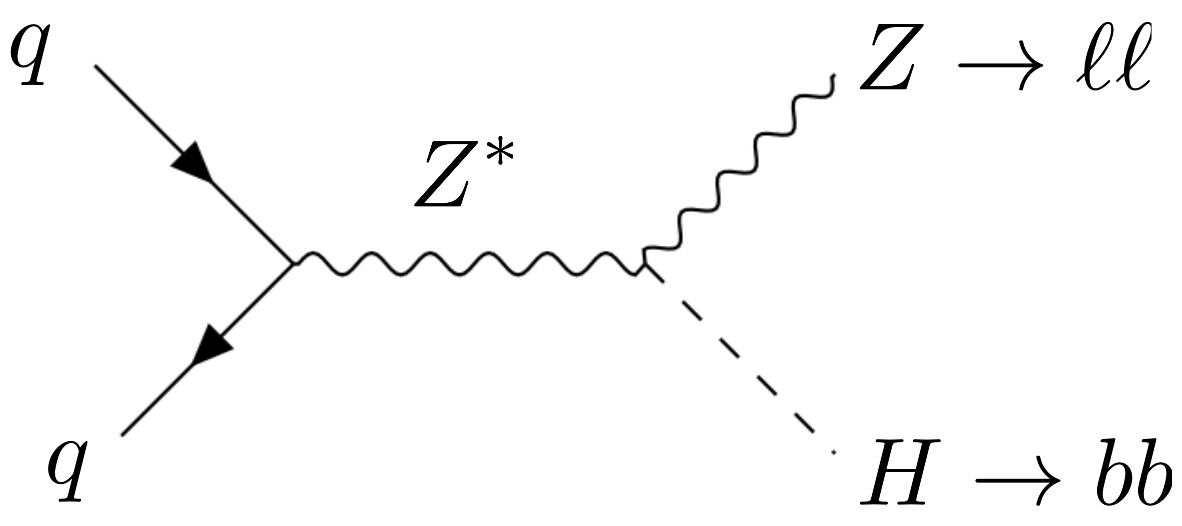
1-lepton channel



BR = 22%

- Mainly W→lν

2-lepton channel

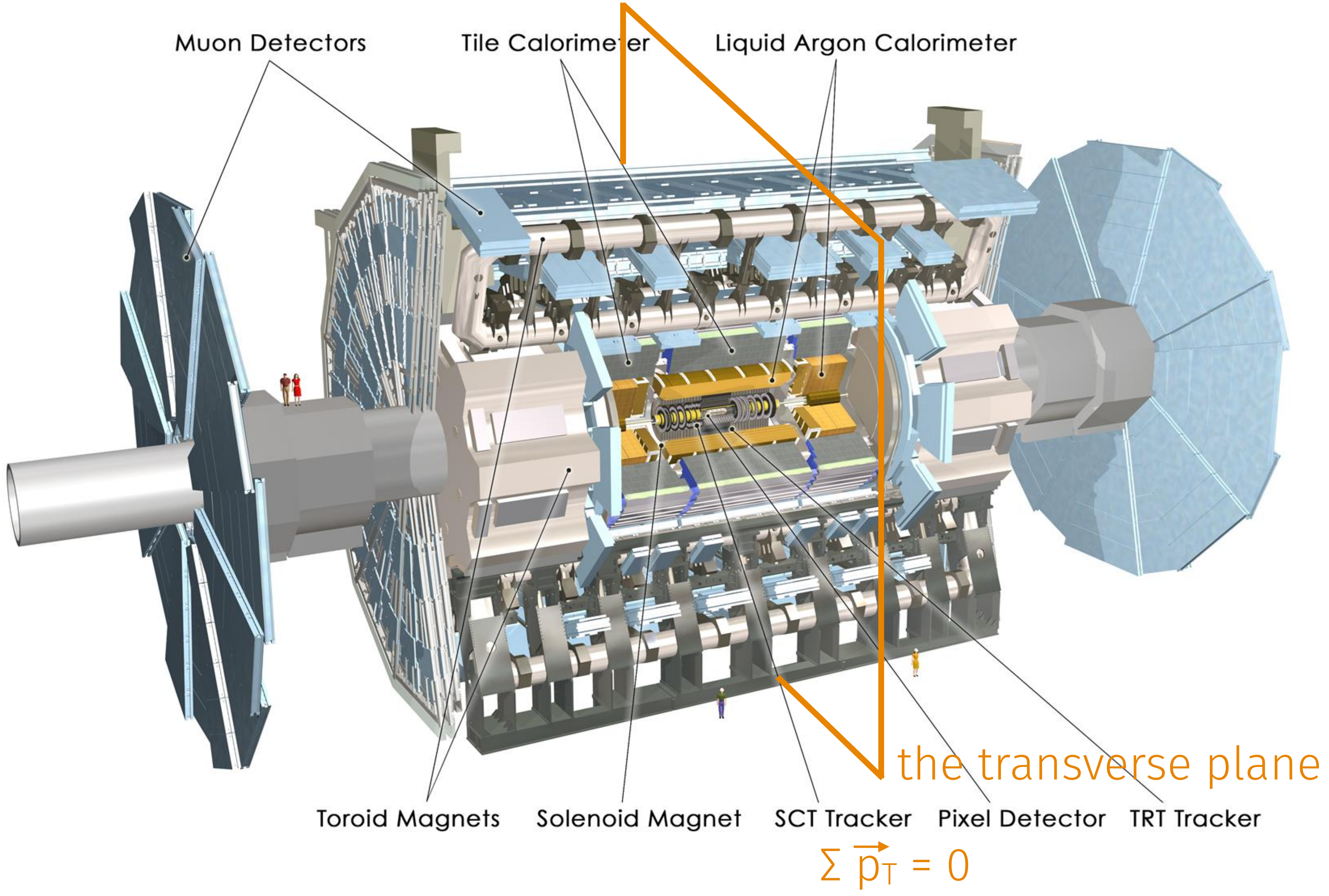


BR = 7%

- Mainly Z→ll

A Toroidal LHC ApparatuS

- Layered detector encapsulating interaction point: central tracker inside of a solenoid, calorimeters and an independent muon spectrometer with superconducting toroids

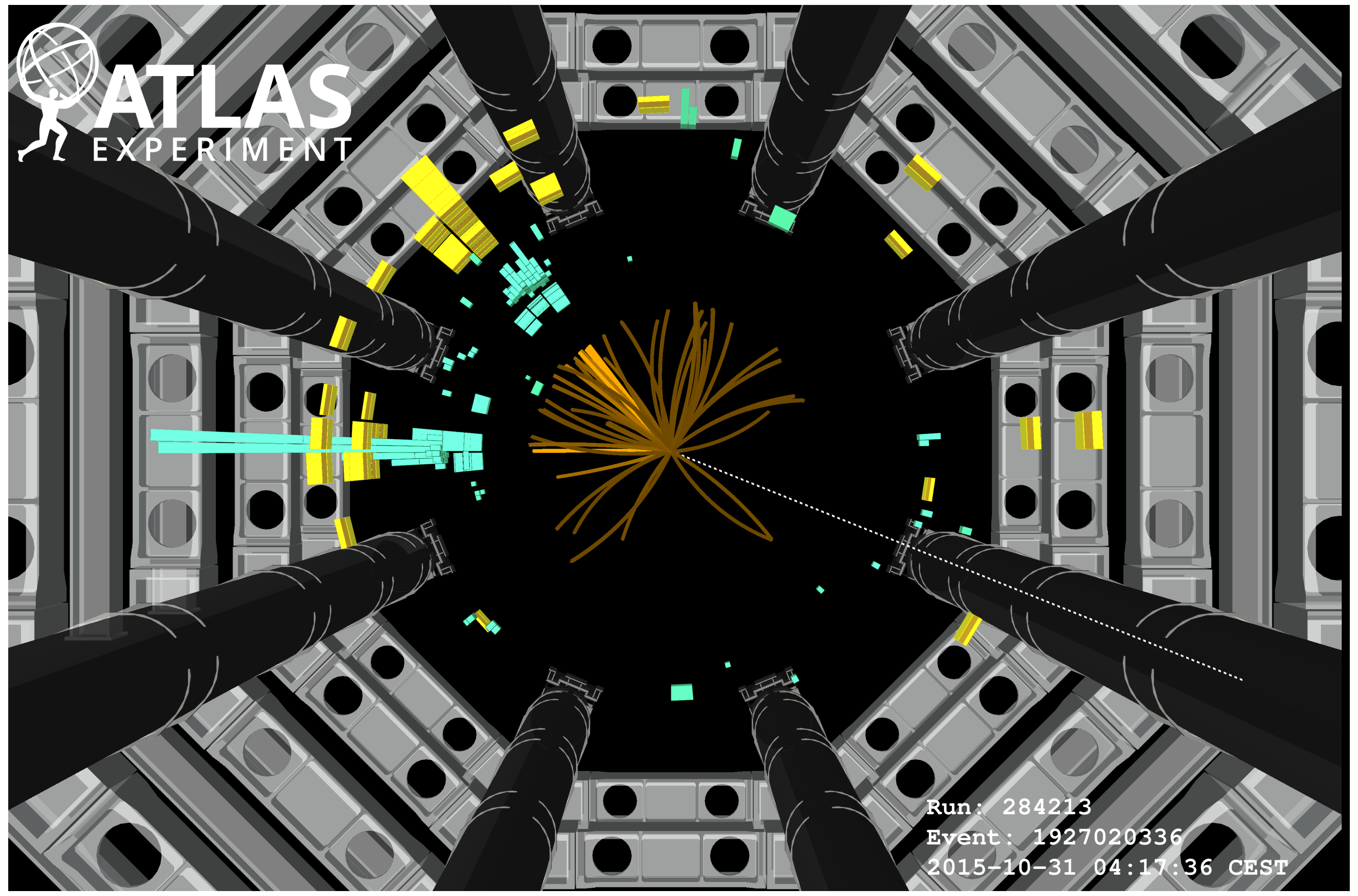


- Fast triggering on interesting signatures [**leptons, MET**]
- Precise reconstruction of:
  - collision vertices
  - photons and **electrons**
  - **muons**
  - taus
  - **jets**
  - **missing transverse momentum (MET)**
- Identification of **heavy flavor jets**

On the vector boson reconstruction

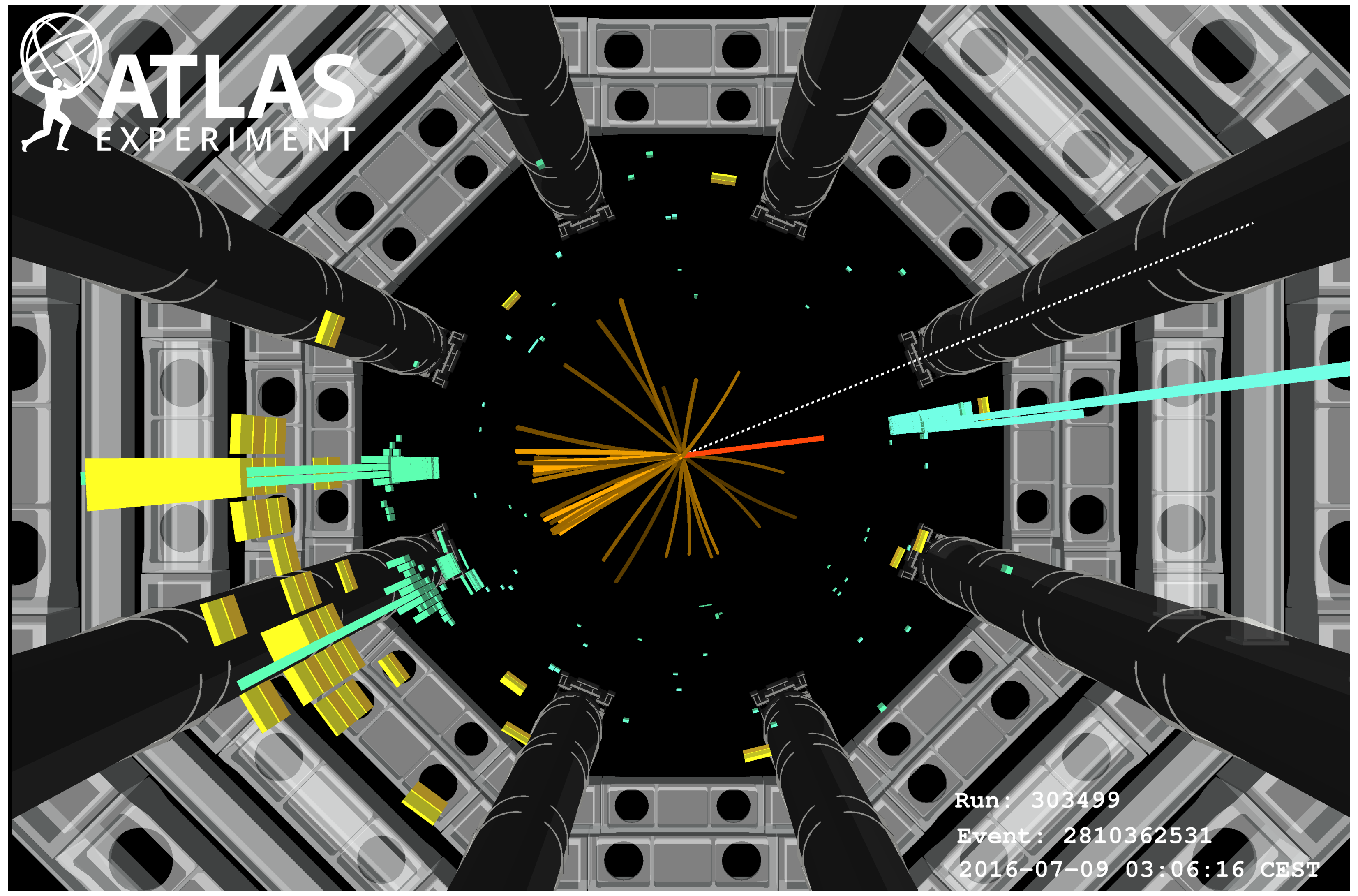
- **3 main channels** depending on the charged lepton categories

0-lepton channel



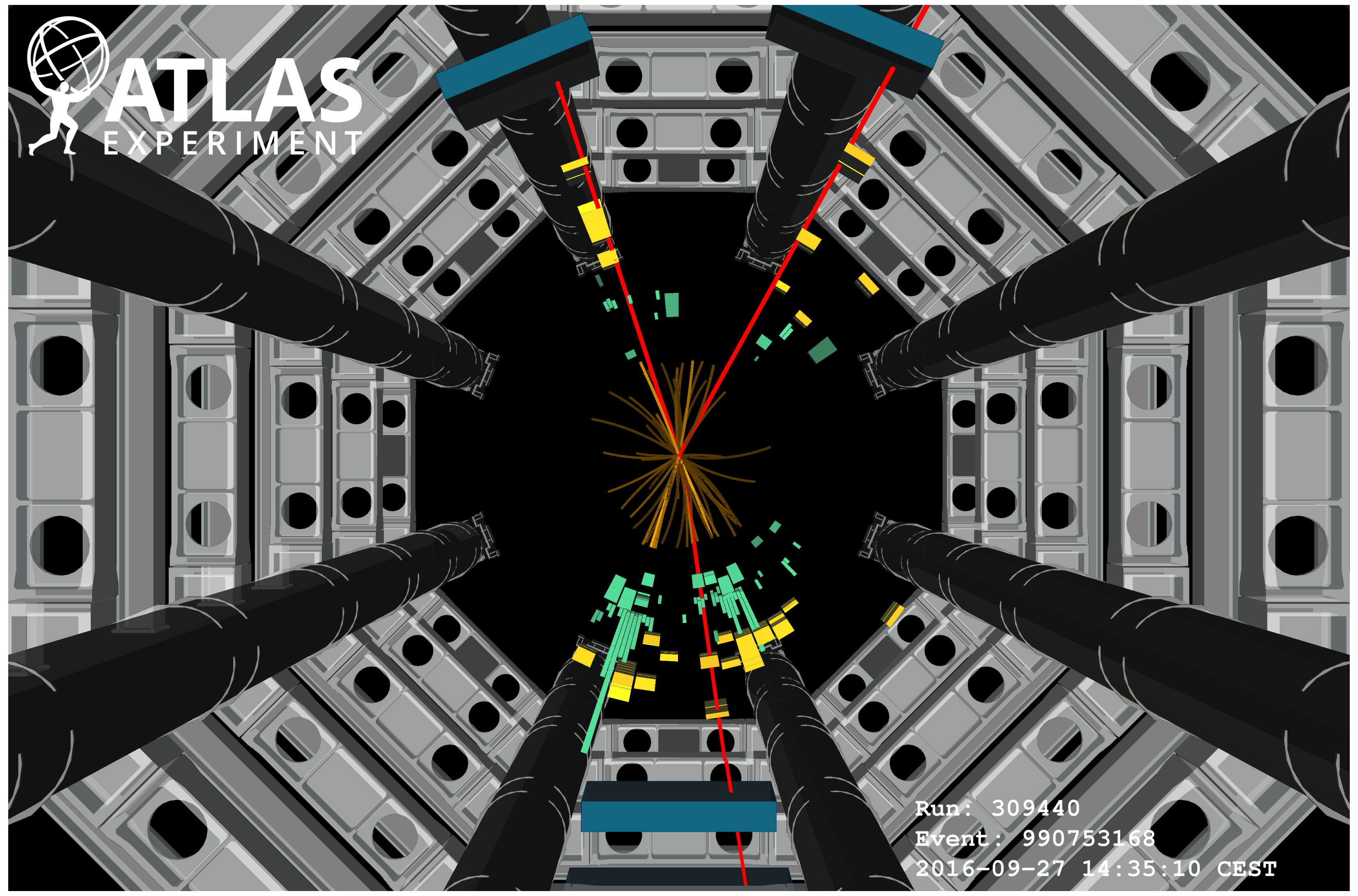
- Mainly $Z \to \nu\nu$ with some $W \to \tau\nu$
- p_T^Z = missing transverse energy (MET)

1-lepton channel



- Mainly $W \to l\nu$
- $p_T^W = p_T(\text{MET + lepton})$

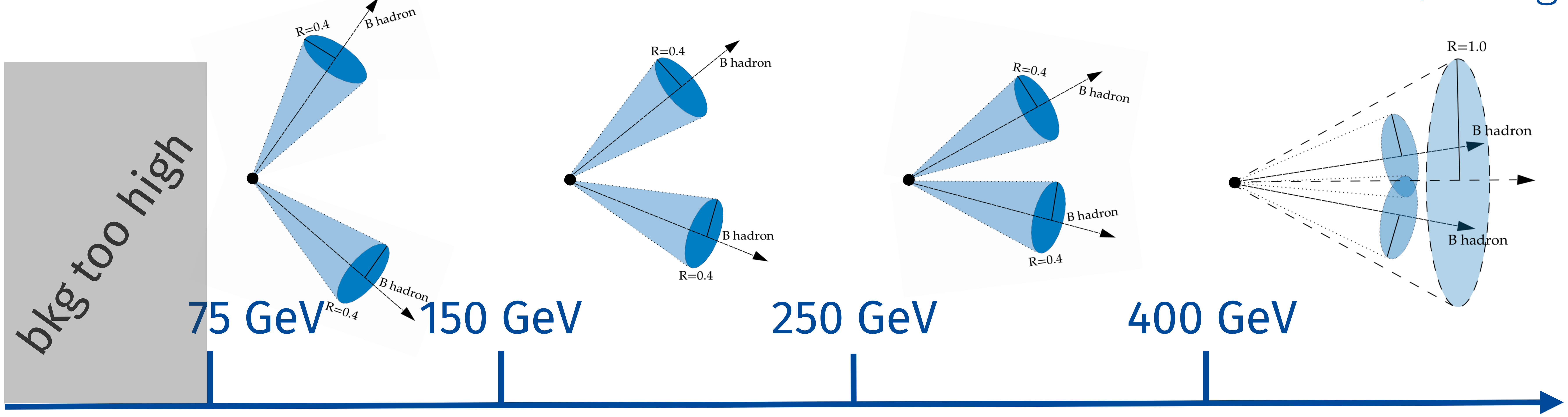
2-lepton channel



- Mainly $Z \to ll$
- $p_T^Z = p_T(\text{lep, lep})$

On the Higgs boson reconstruction

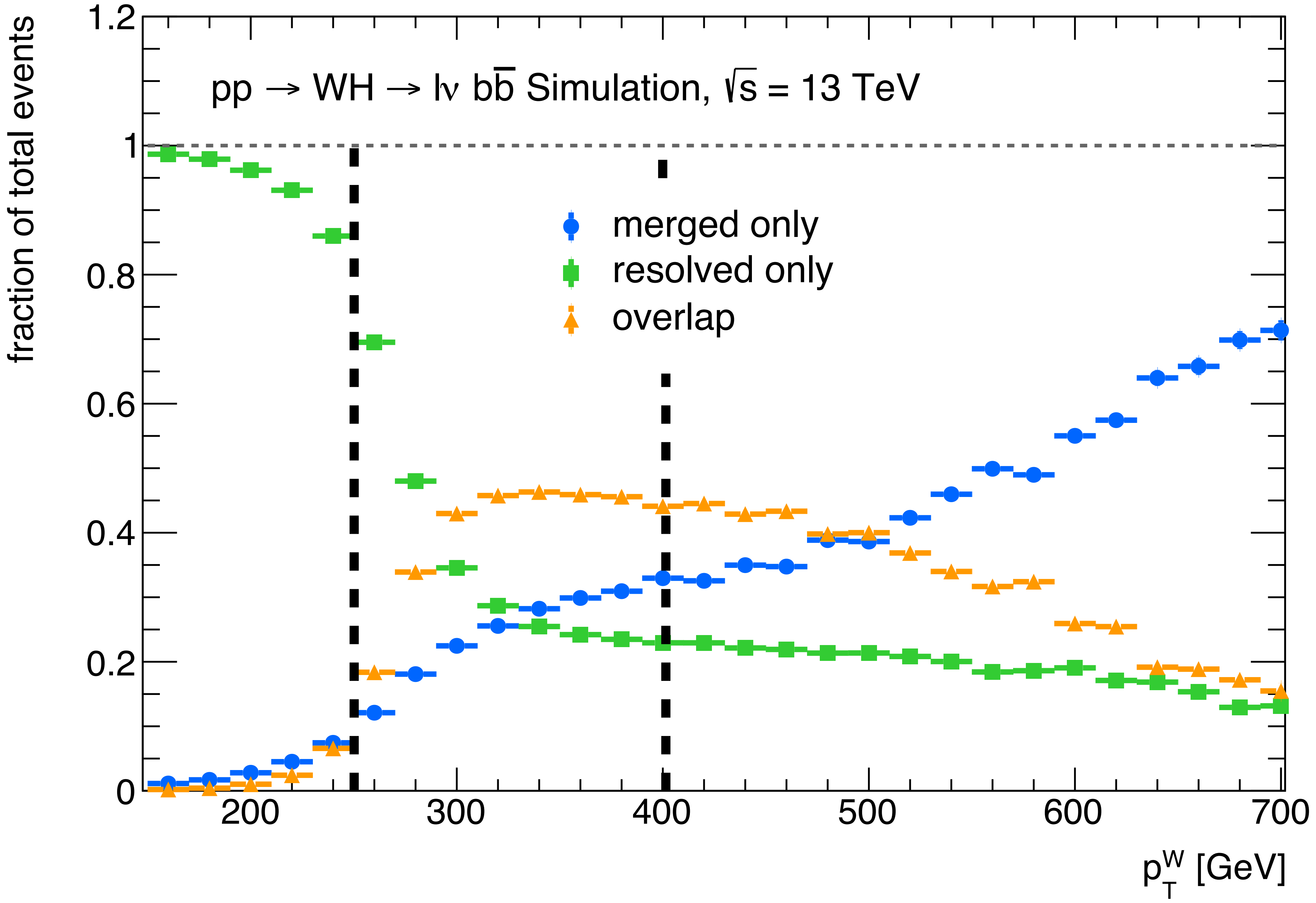
"Resolved" "Boosted"/"Merged"



$$\Delta R(b_1, b_2) \sim \frac{2m_H}{p_{\mathrm{T}}^H}$$

Vector boson p_T ($\sim$ Higgs p_T)

better experimental handle

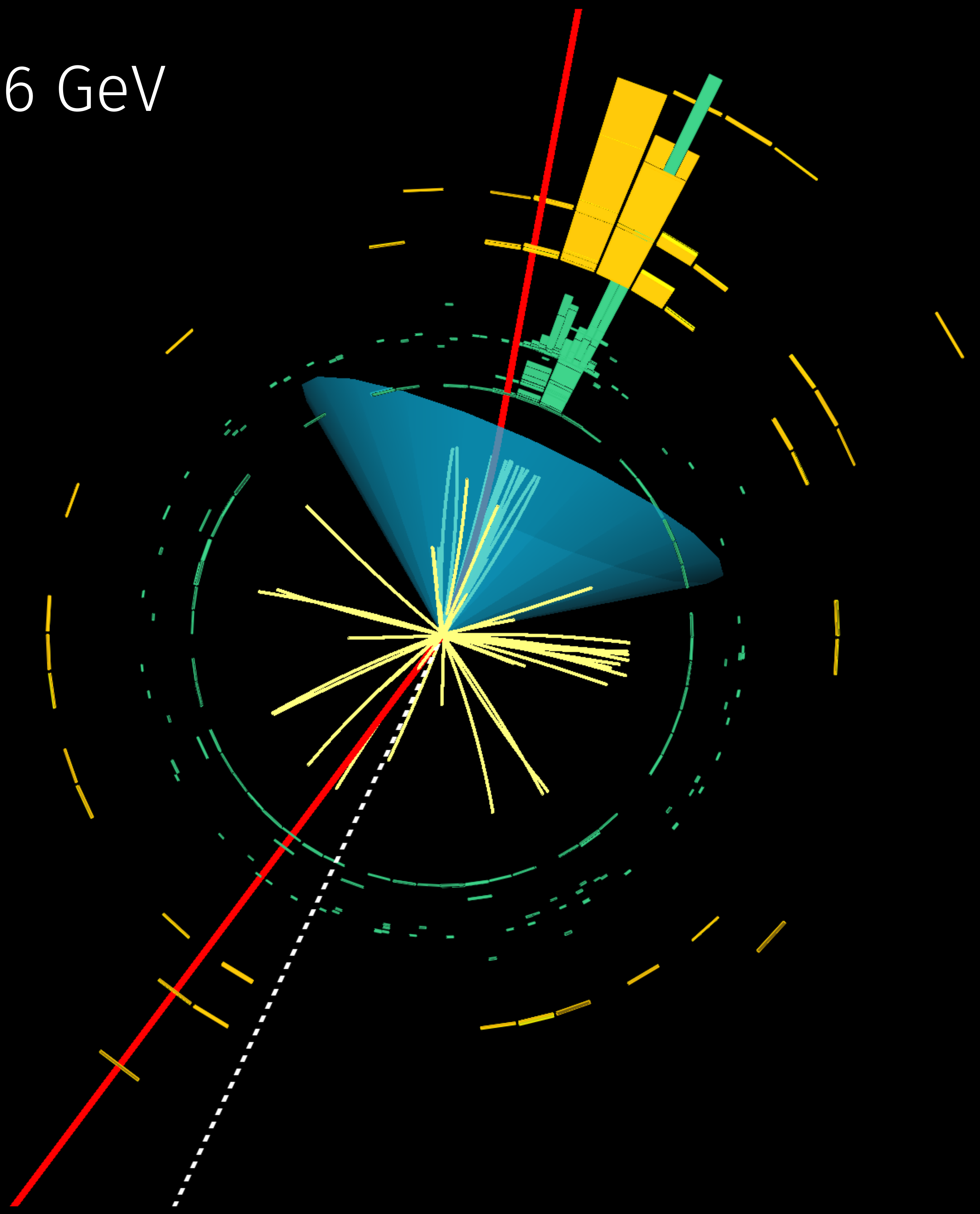


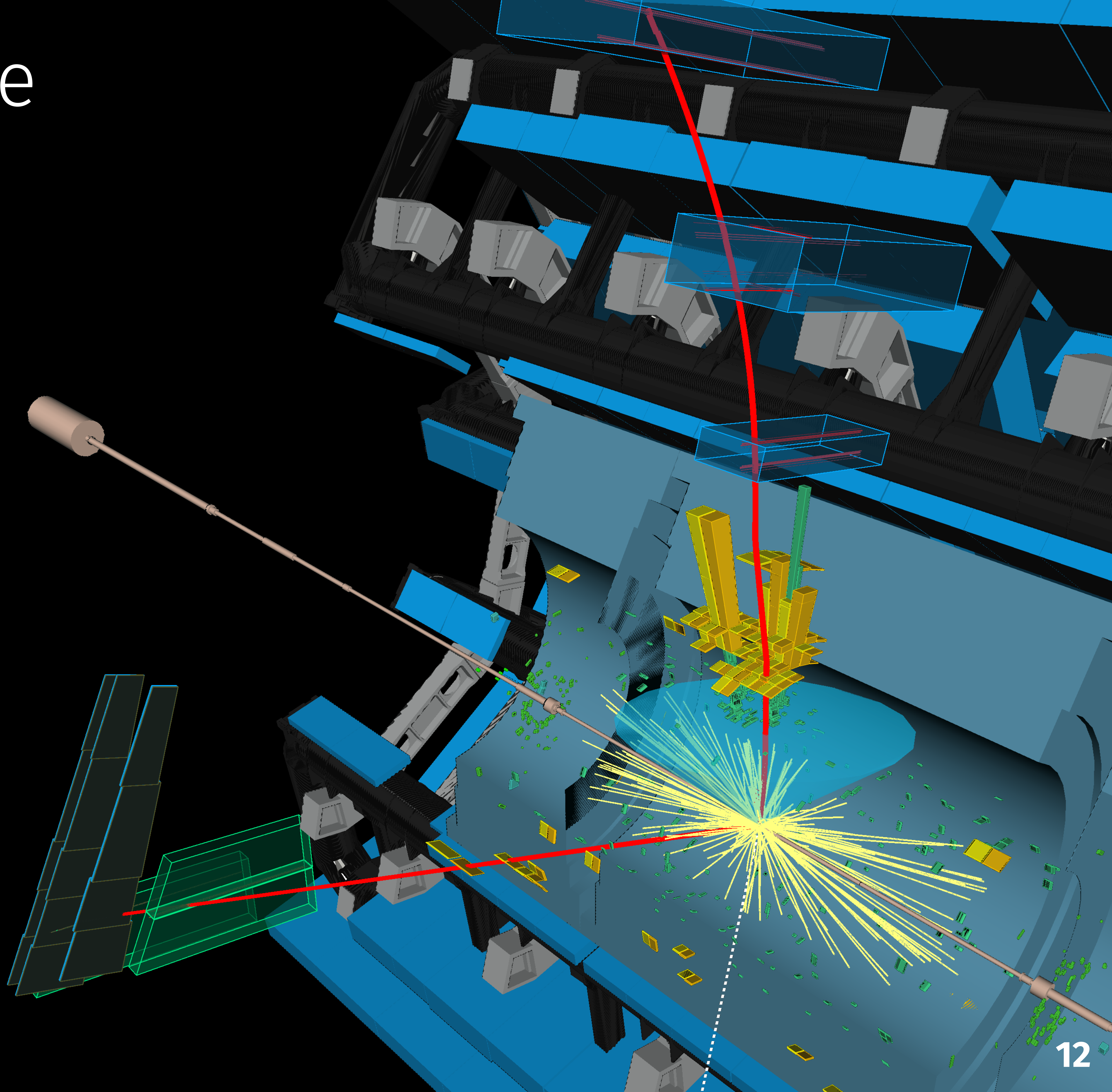
A boosted VH candidate

$pp \to WH \to \mu\nu bb$

$p_T^V \sim 1$ TeV

$m_J = 116$ GeV

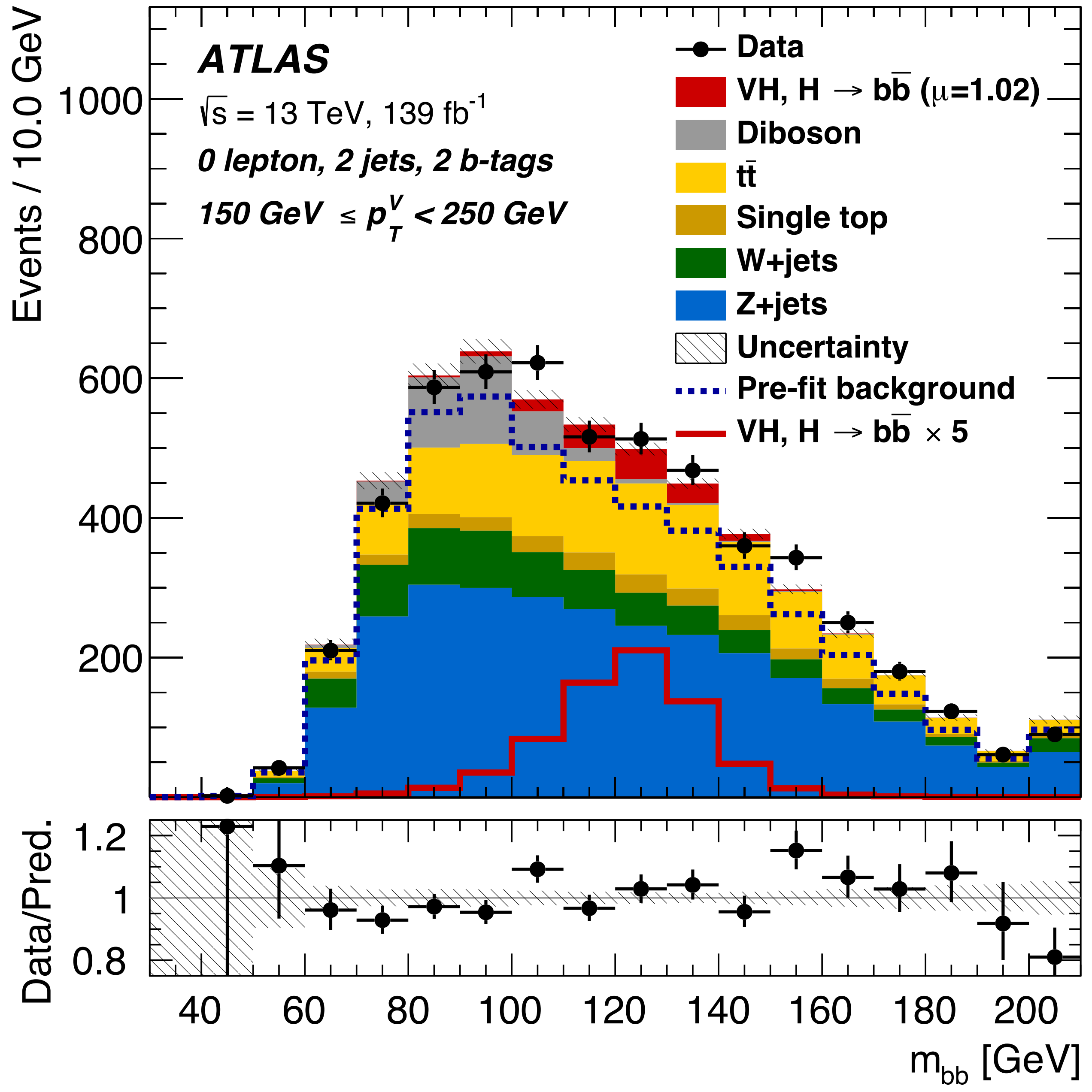




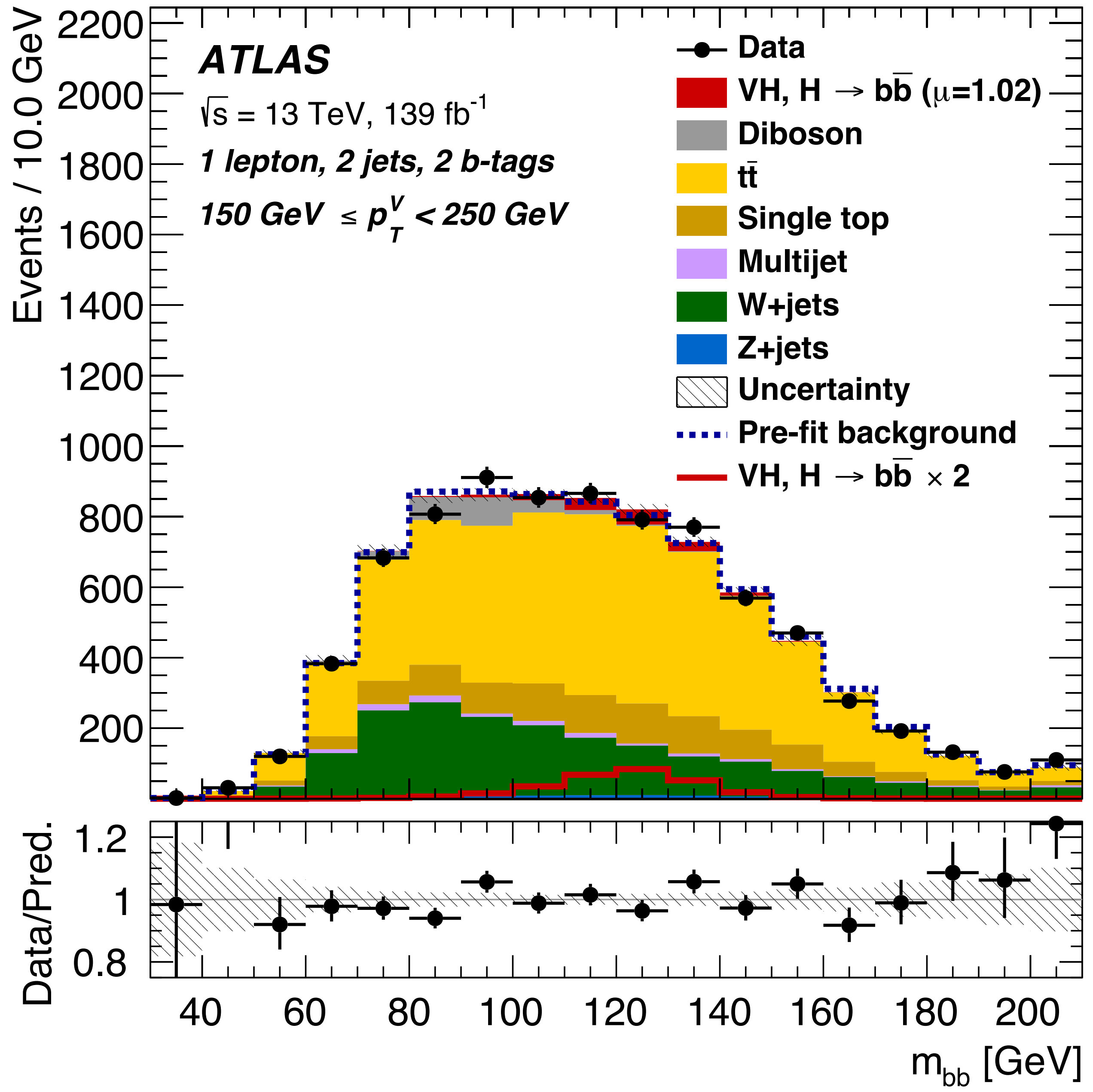
Backgrounds, backgrounds everywhere

- Resolved uses BDTs to separate signal from background, boosted uses the large-R jet mass

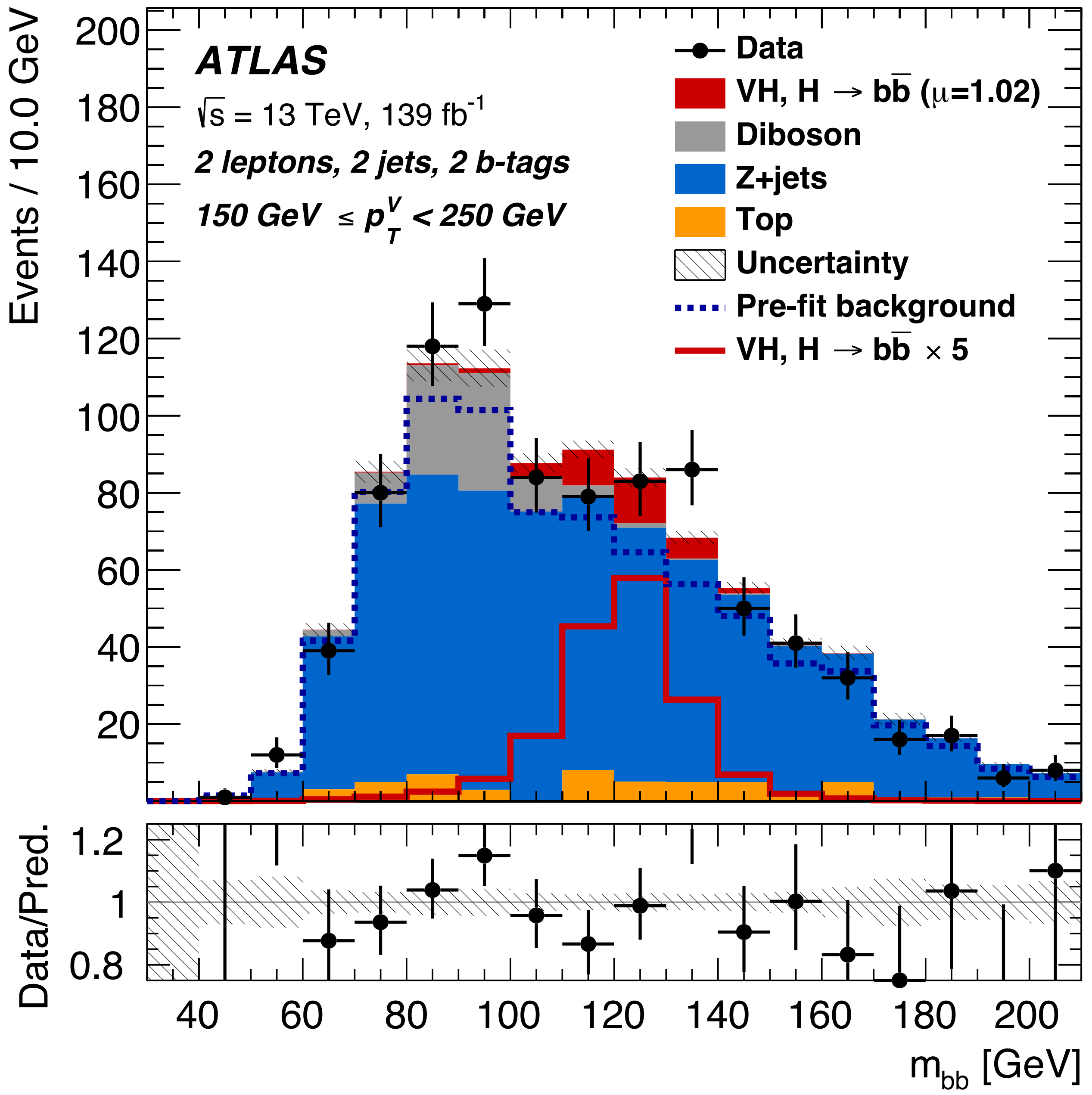
0-lepton channel



1-lepton channel



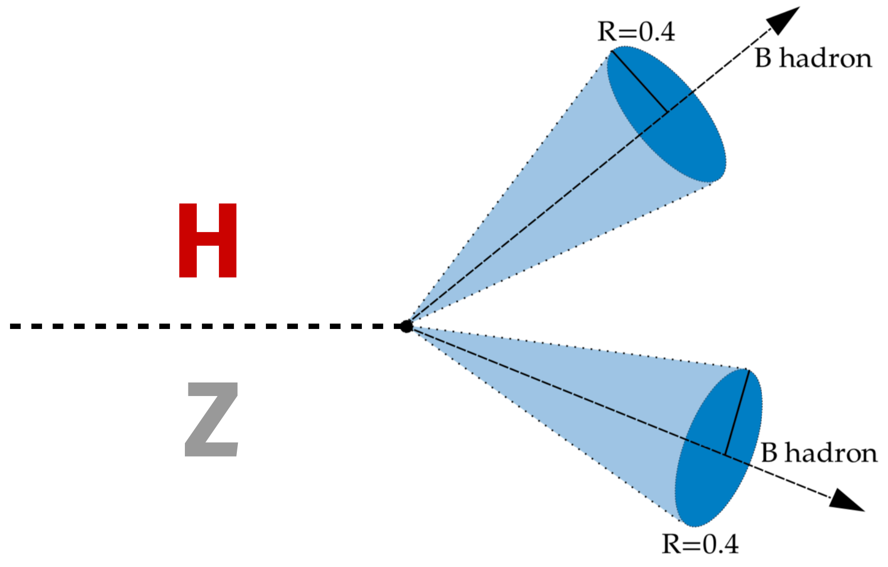
2-lepton channel



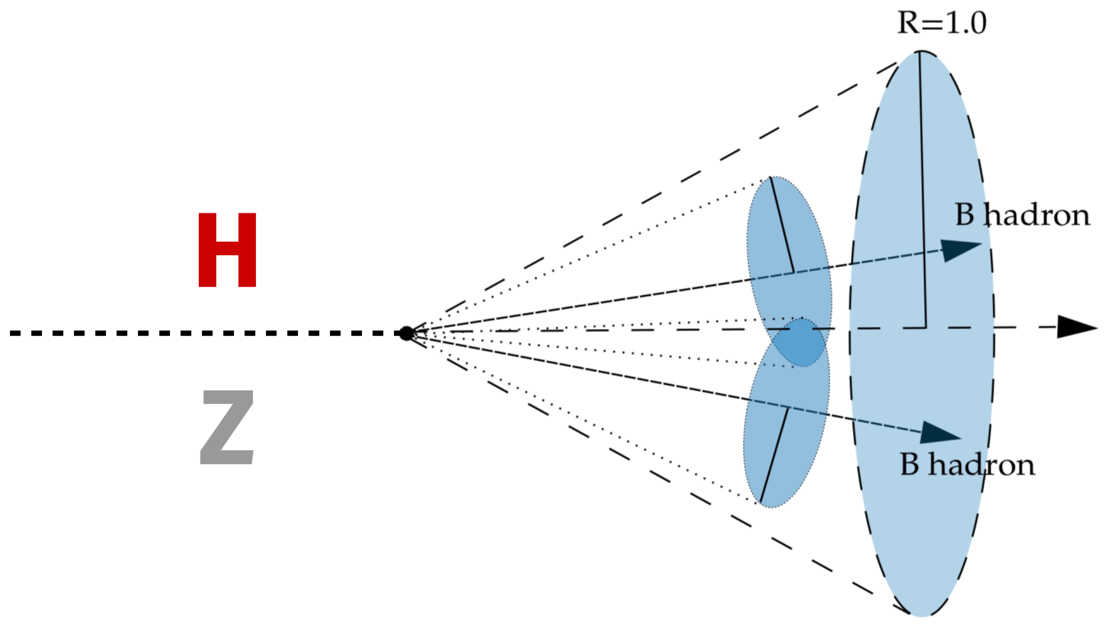
Main backgrounds:

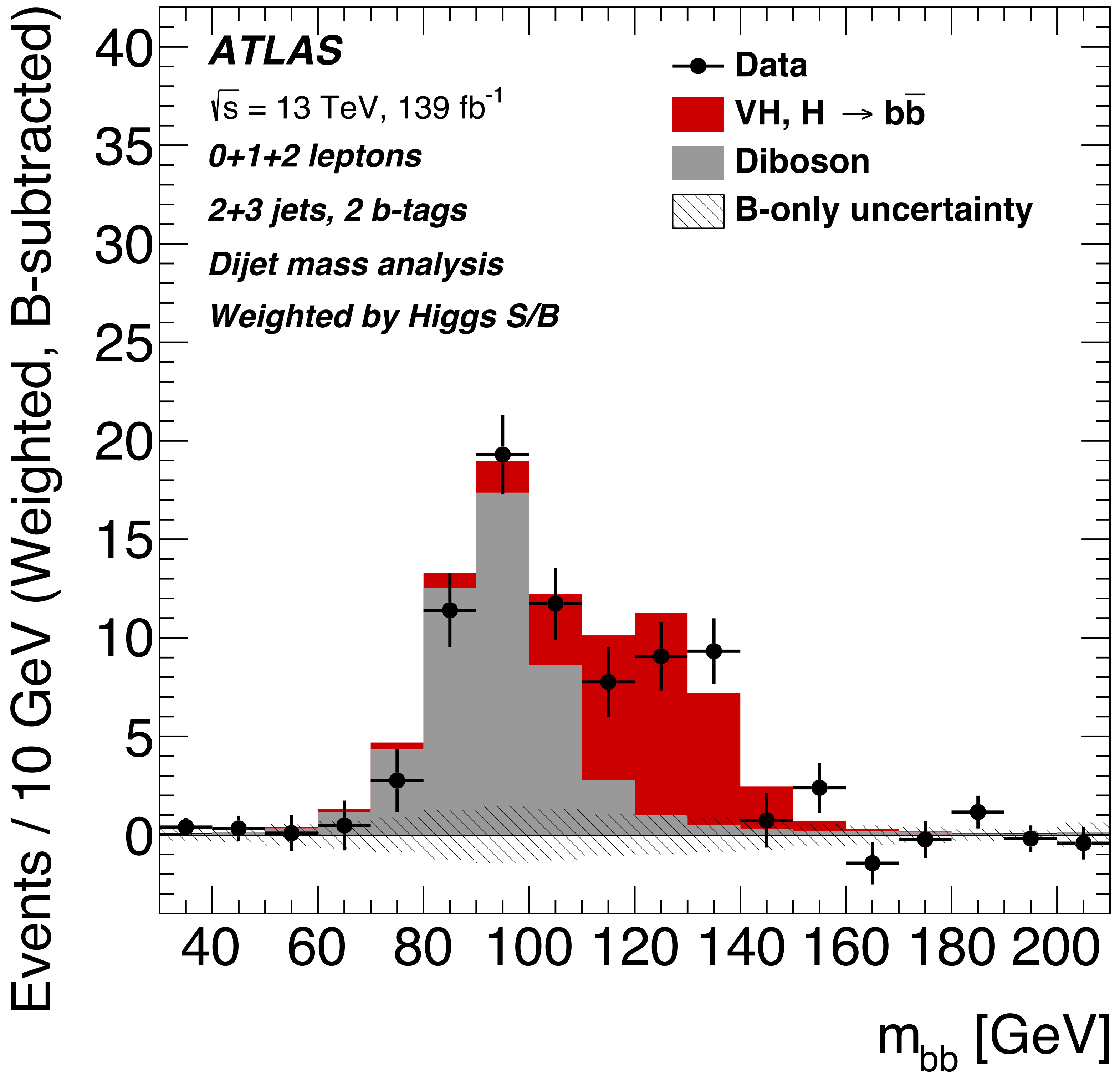
- 0-lepton: **ttbar**, **W+jets**, **Z+jets**
- 1-lepton: **ttbar**, **W+jets**, **single top**
- 2-lepton: **Z+jets**, **diboson**

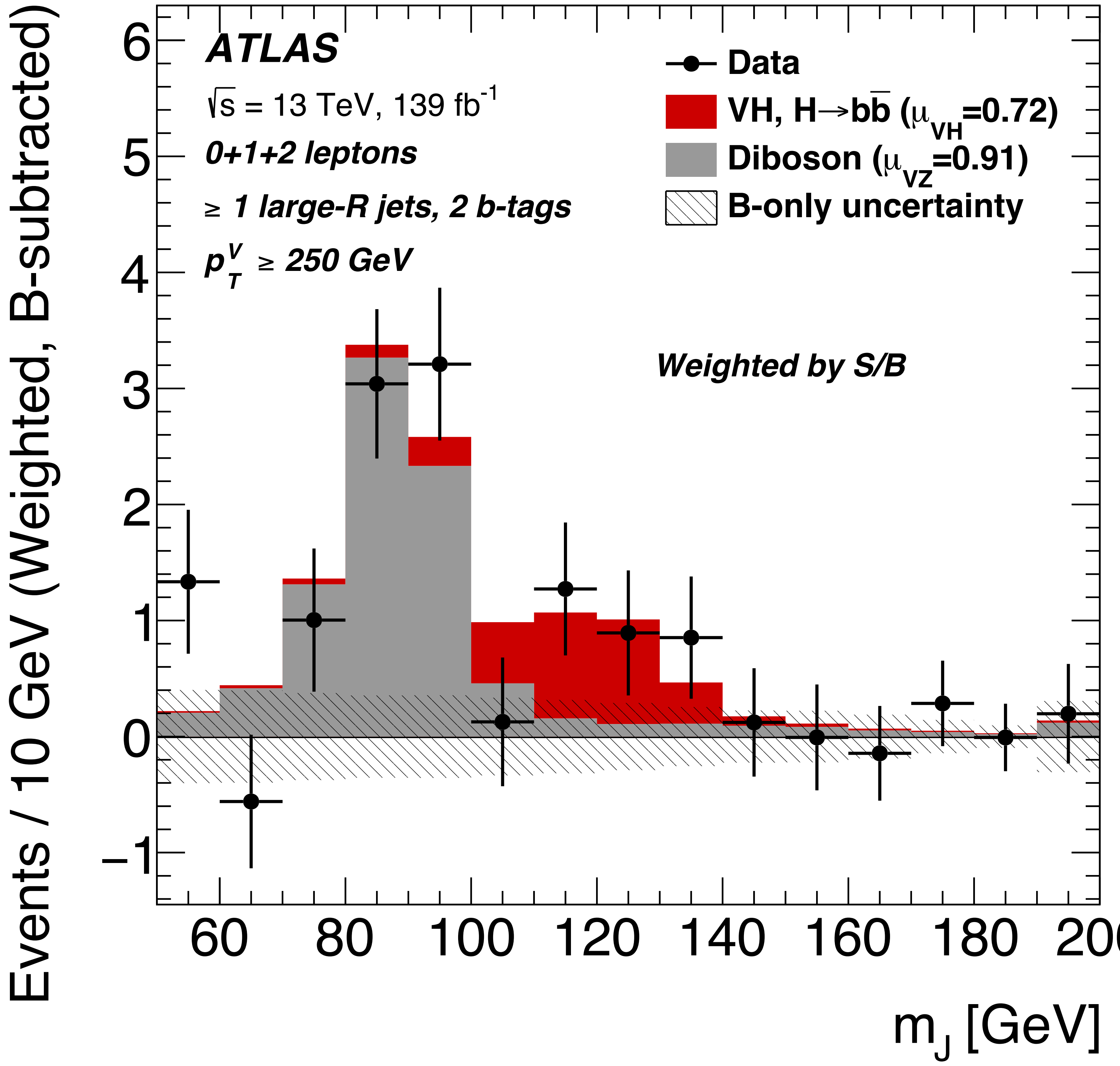
Results



$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\text{observed}}}{(\sigma \cdot \mathrm{BR})_{\text{expected}}}$$







$$\mu^{bb}_{VH} = 1.02^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.})$$

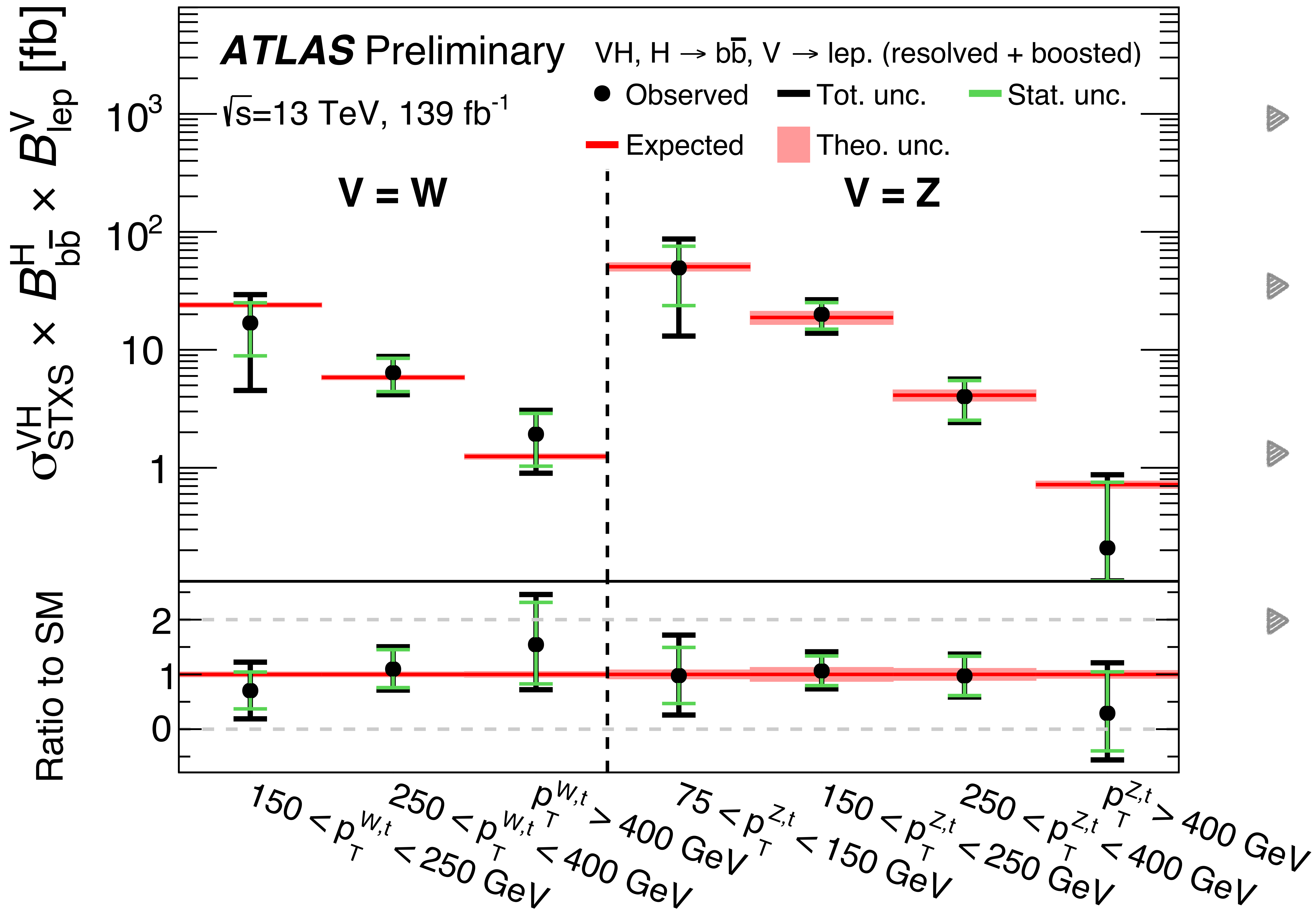
$$\mu^{bb}_{VZ} = 0.93^{+0.16}_{-0.13} = 0.93^{+0.07}_{-0.06}(\text{stat.})^{+0.14}_{-0.12}(\text{syst.})$$

$$\mu^{bb}_{VH} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$$

$$\mu^{bb}_{VZ} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.})$$

[caveat: overlap not removed between these results, see next slide for that]

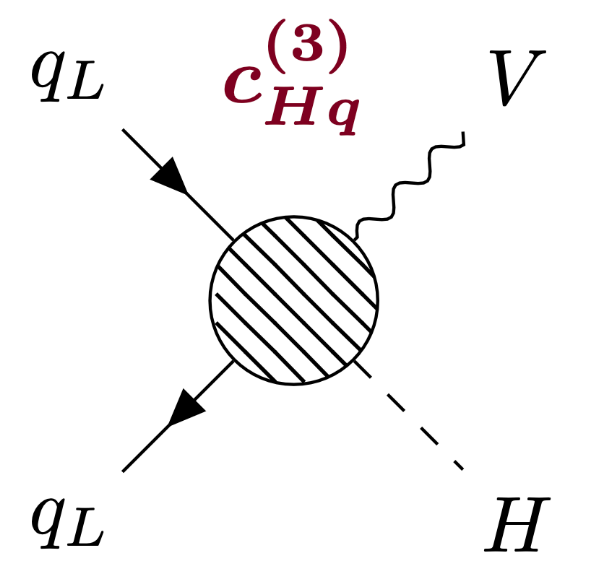
Putting it all together: differential cross-sections



- VH cross-sections measured in 7 bins of the vector boson p_T
- Agreement with SM predictions within uncertainties
- Relative uncertainties ranging from 30% to 300% depending on the bin
- Most of the bins are statistically limited → more data!

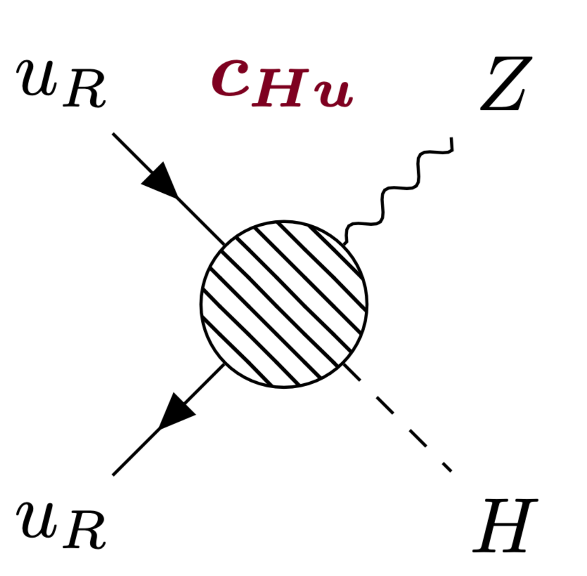
Which effects do we constrain?

- **17 operators** contribute
  → not possible to constrain all at the same time
- Yukawa coupling is a simple overall scaling
  → not today
- Focus on operator with bin-dependent effect



$$H^\dagger i \overleftrightarrow{D}^I_\mu H (\bar{q}_p \tau^I \gamma^\mu q_r)$$

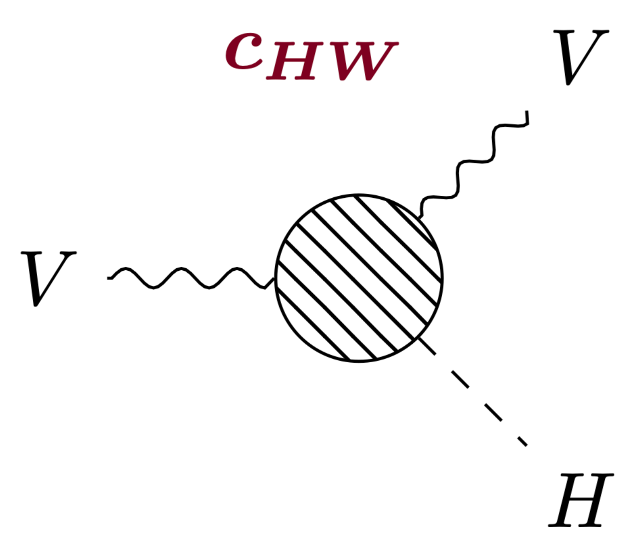
$$\sim (p_T^V)^2$$



$$H^\dagger i \overleftrightarrow{D}_\mu H (\bar{u}_p \gamma^\mu u_r)$$

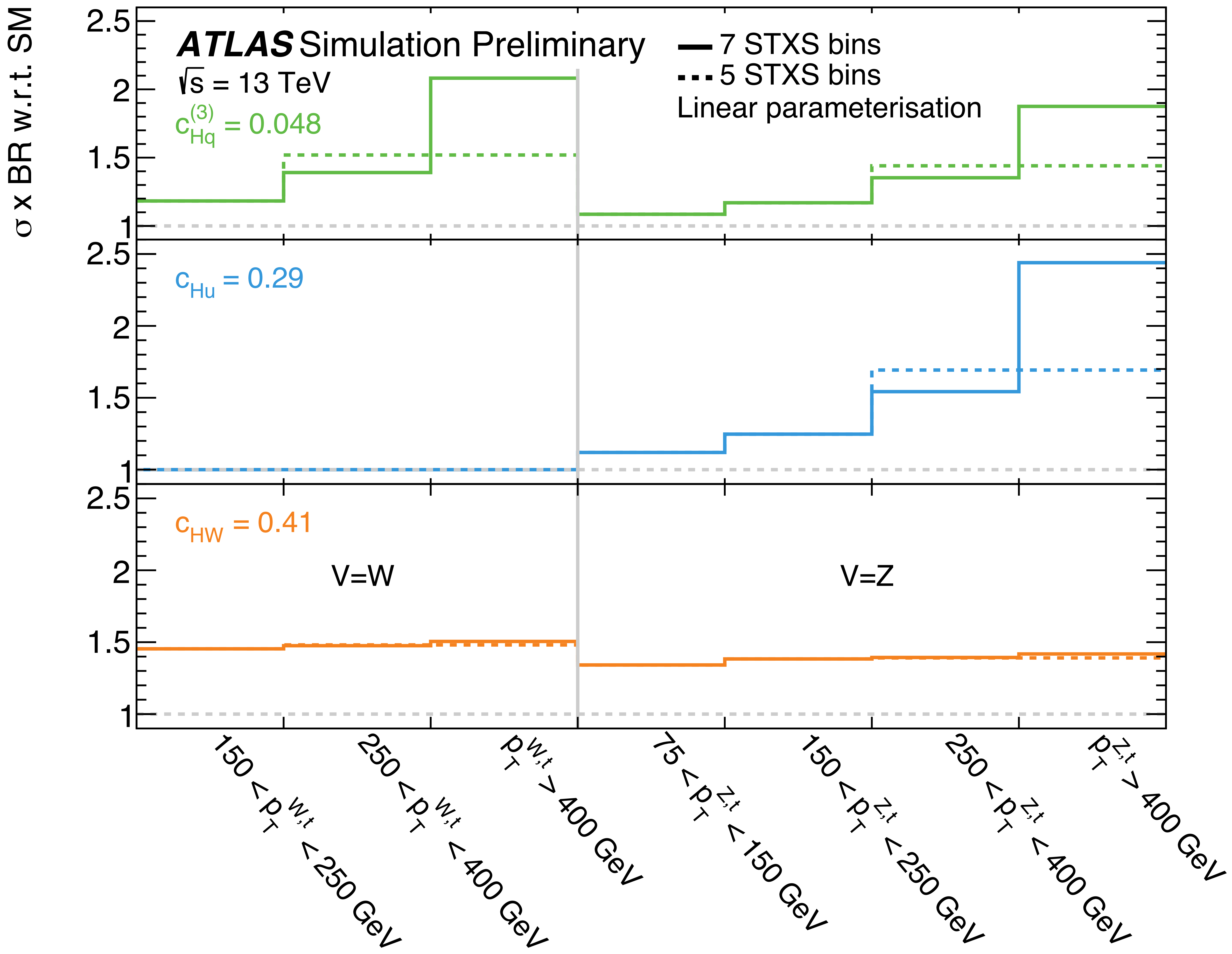
WH vs. ZH

$$\sim (p_T^Z)^2$$



$$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$$

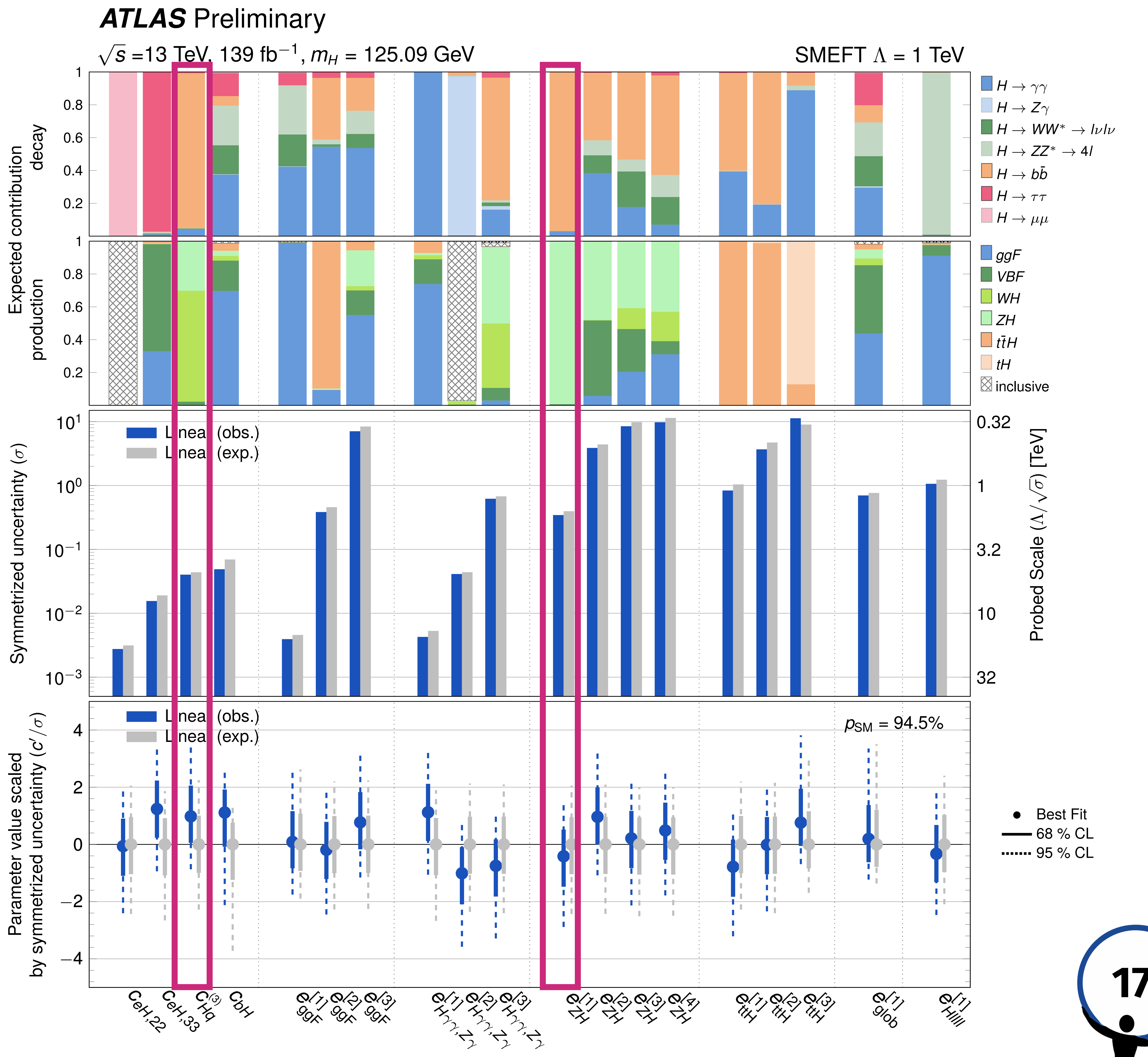
const. + linear



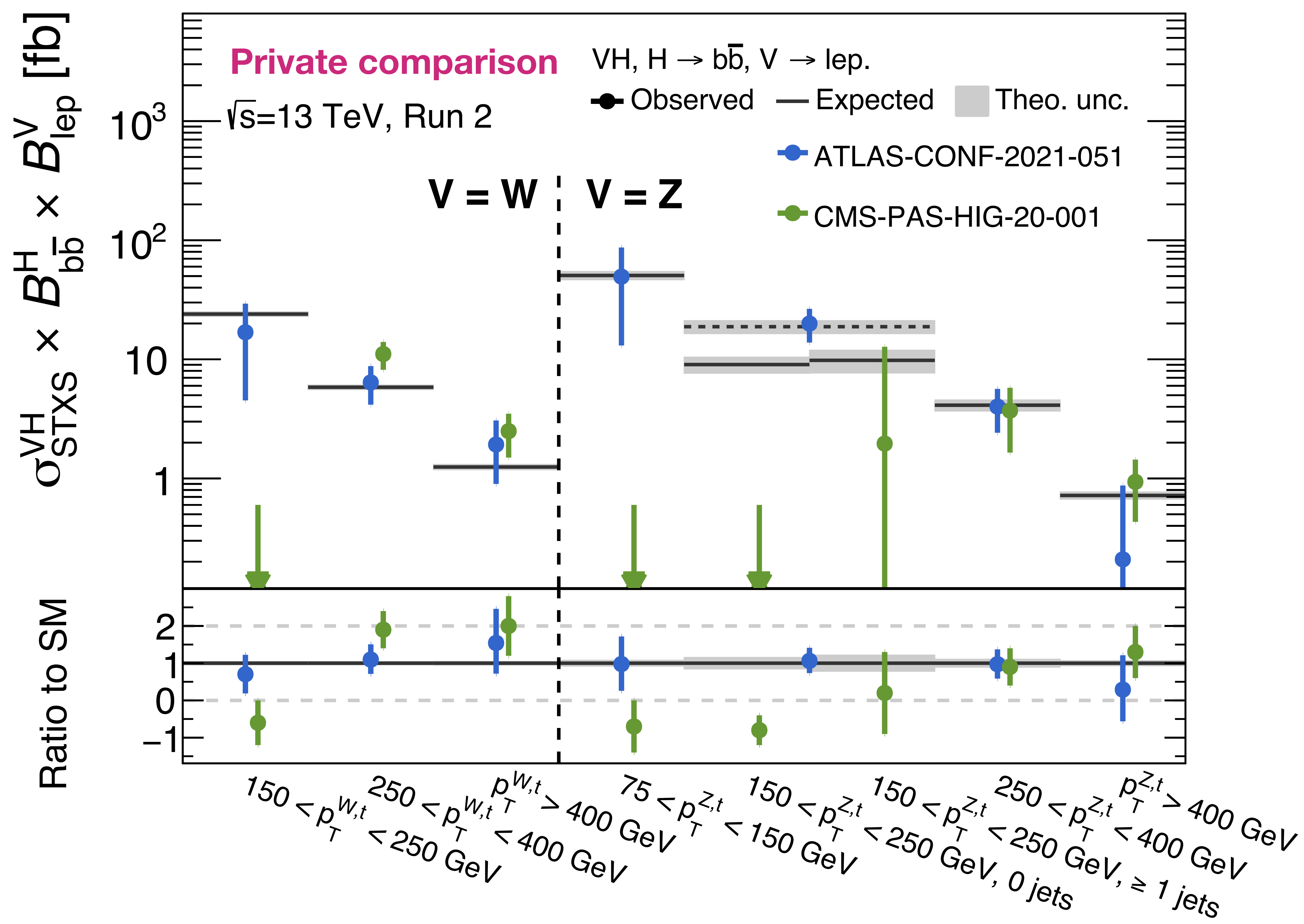
SMEFT: the bigger picture

Physically useful limits can only be obtained by combining a multitude of measurements

- VH, H→bb analysis input to the global combination of ATLAS Higgs boson measurements
- Even in global combination no sensitivity to constrain all Wilson coefficients simultaneously → Principal component analysis to determine sensitive Eigendirections
- $c_{Hq}^{(3)}$ and first ZH Eigendirection nearly exclusively determined by VH, H→bb
- **Multi-TeV scales probed**



A quick glance at the other side of the ring



ATLAS/CMS compatibility p-value ~ 0.5%

CMS/SM compatibility p-value ~ 0.0056% [~3.9σ]

Interesting tension between ATLAS and CMS (and esp. CMS with SM)
→ should keep an eye on this!

Further into the unknown: the Higgs potential

highest term even,
else any polynom. would do

arbitrary

> 0

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

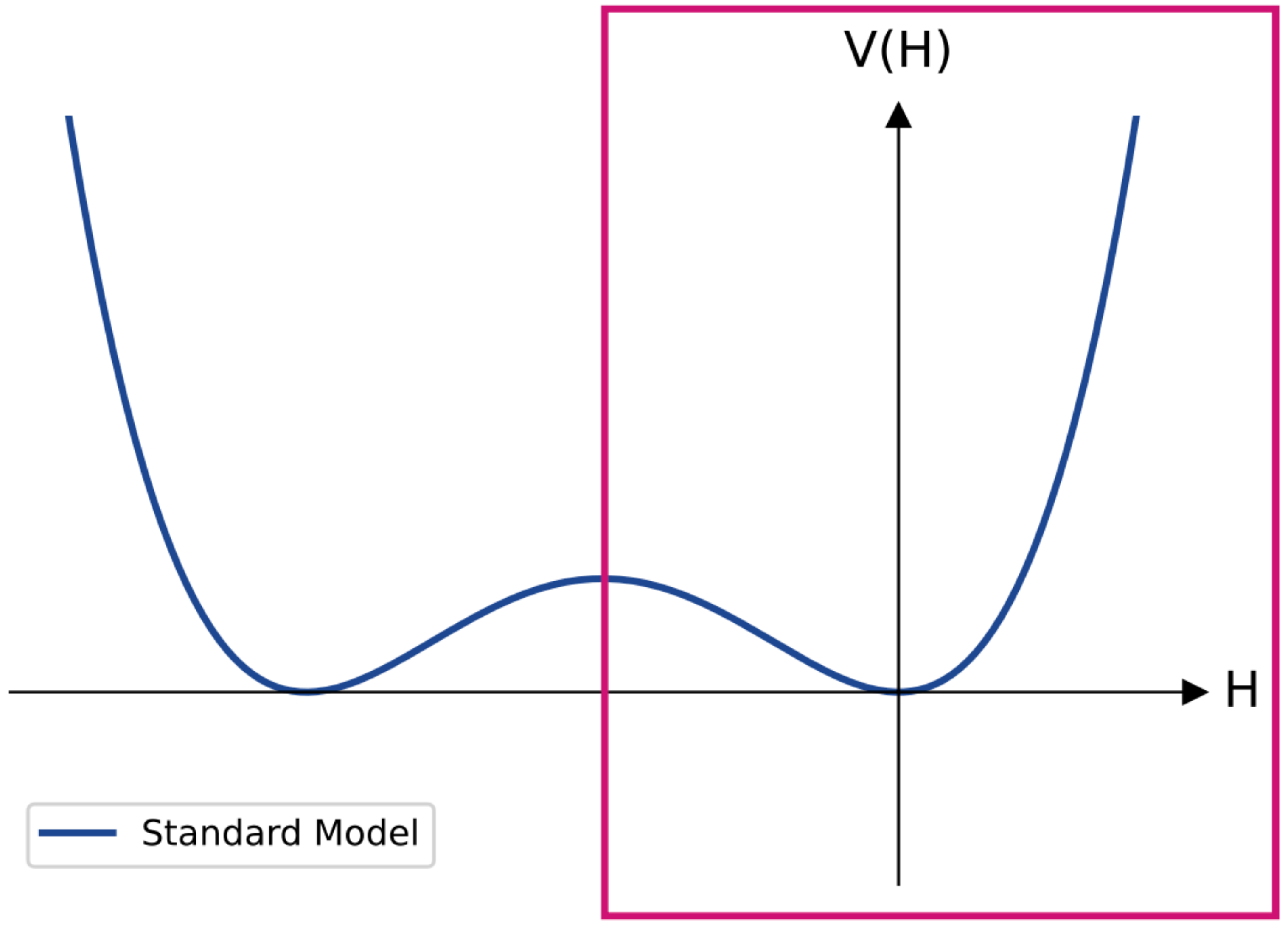
Electroweak
Symmetry
Breaking

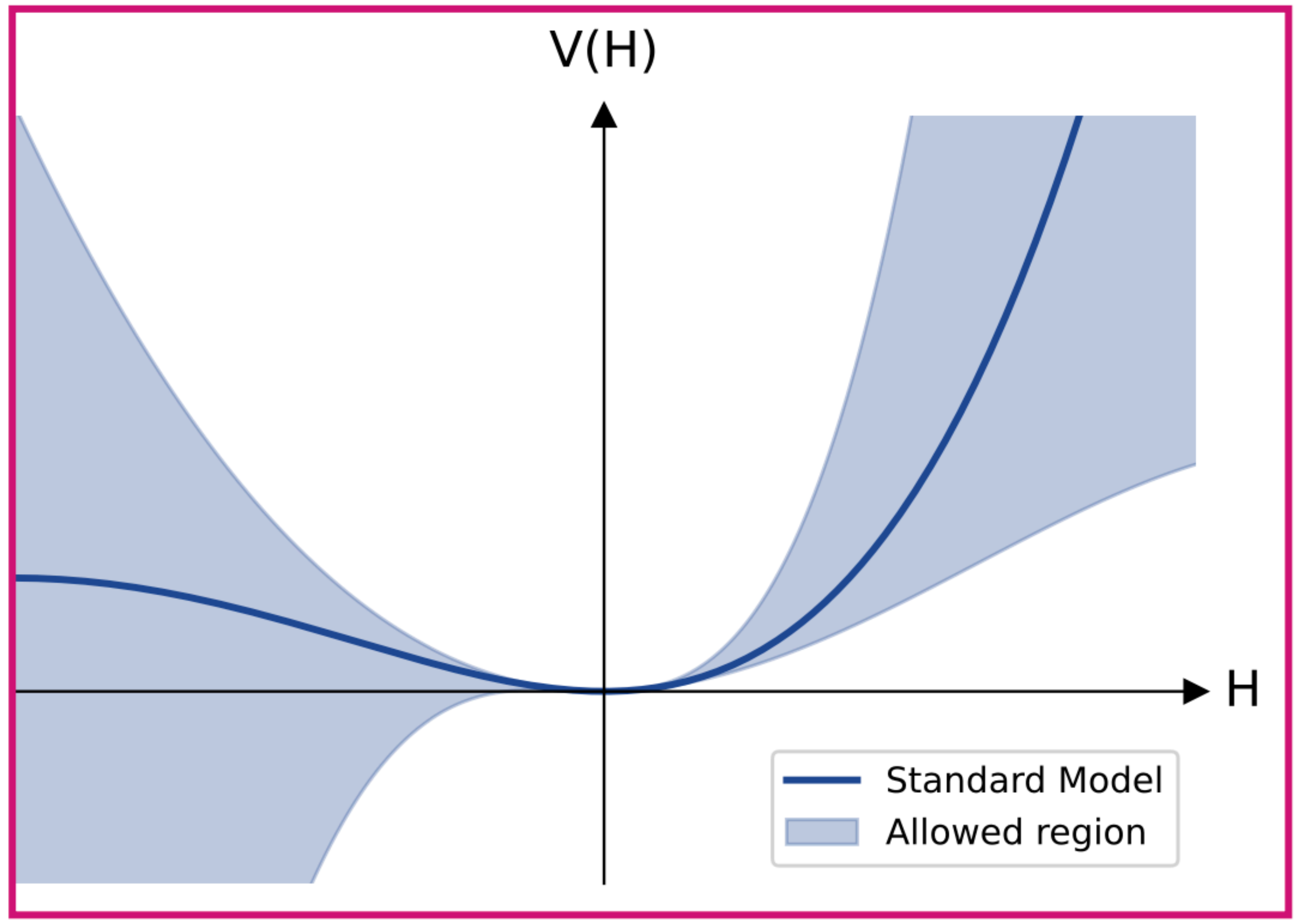
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda \text{ vev } H^3 + \frac{1}{4}\lambda H^4$$

What the SM predicts vs what we know experimentally

Where does the potential come from?

Why is it Mexican-hat shaped?

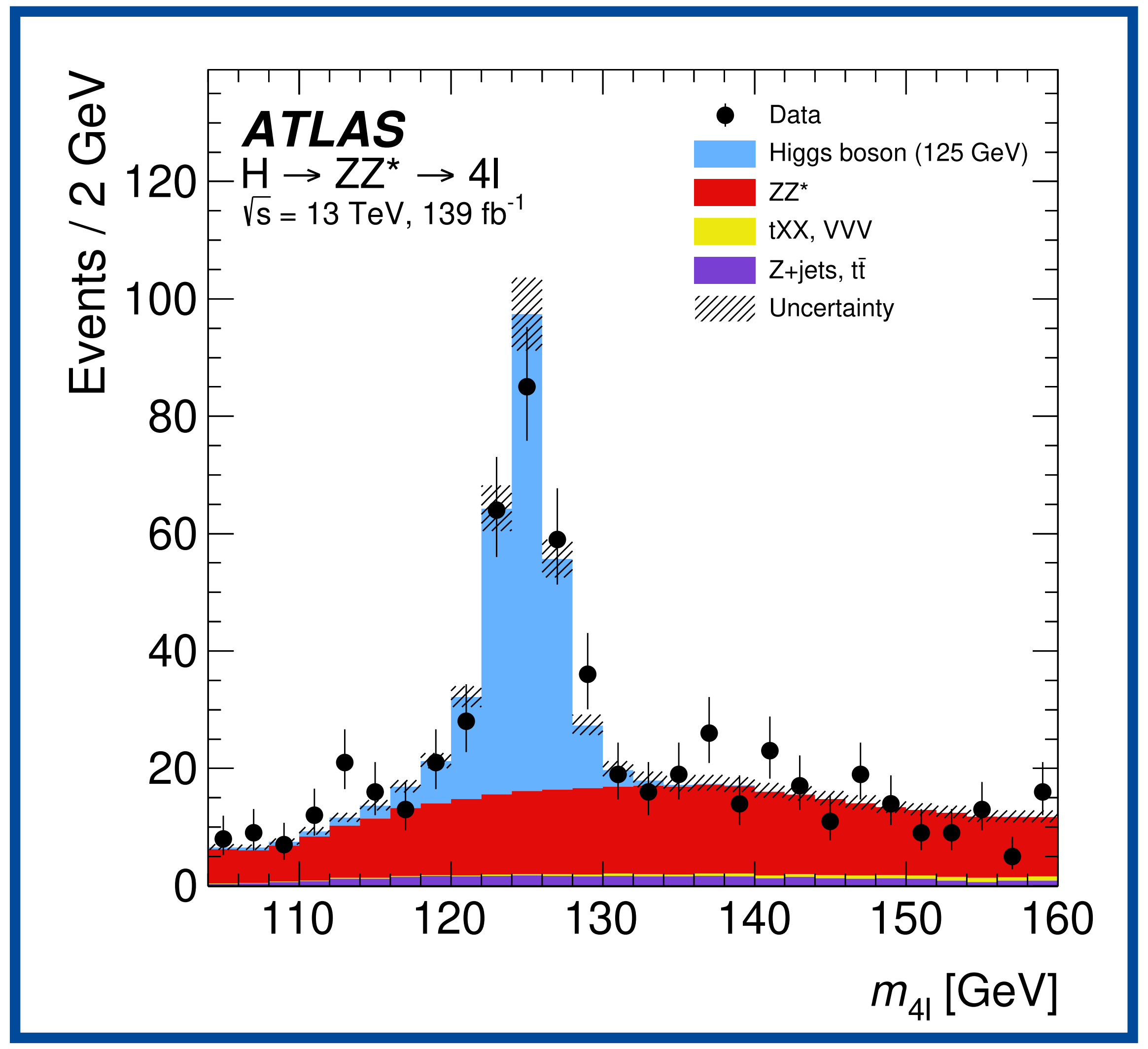


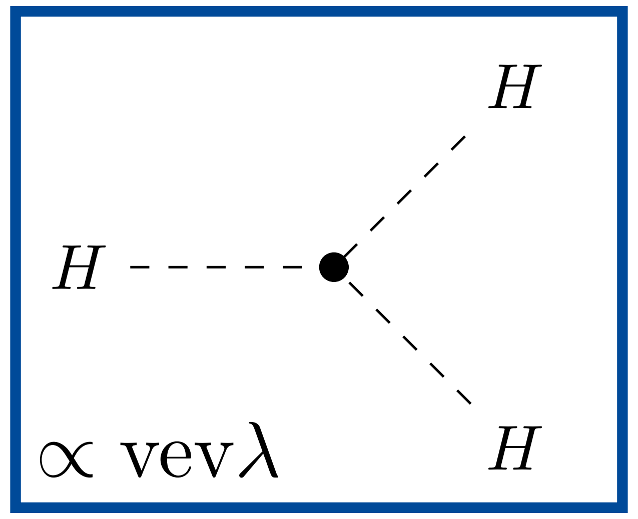


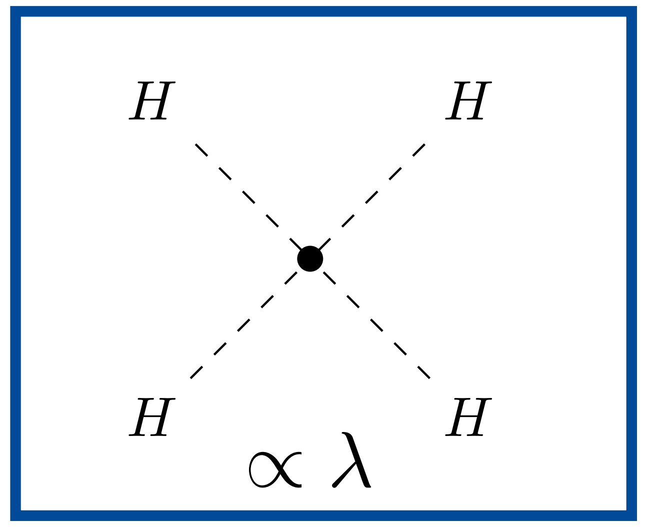
[using Run 2 ATLAS limits @ 95% CL]

Further into the unknown: the Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda \text{ vev } H^3 + \frac{1}{4} \lambda H^4$$







ATLAS H→ZZ*→4ℓ + H→γγ Run 1 + Run 2

m$_H$ = 125.11 ± 0.09 (stat.) ± 0.06 (syst.)

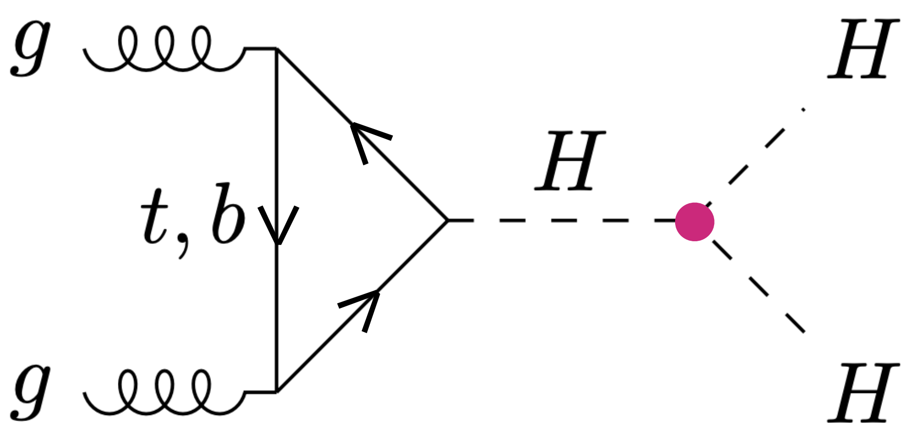
[0.09% relative uncertainty]

In the SM:

$$\lambda = \frac{m_H}{2v^2} = \frac{125}{2 \cdot 246^2} \sim \frac{1}{8}$$

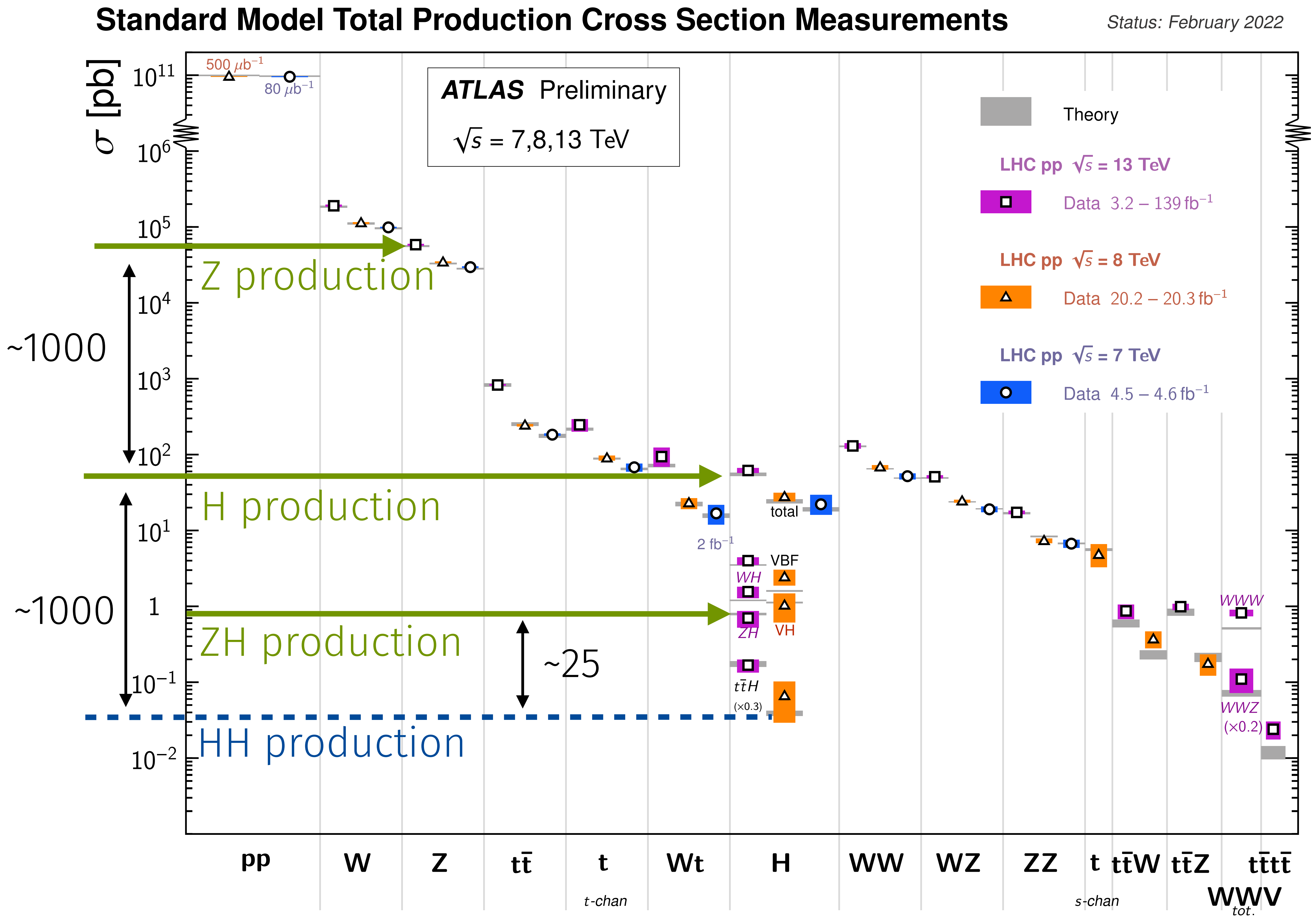
Any deviation would be a clear sign of new physics!

Measure pp→HH to determine λ:

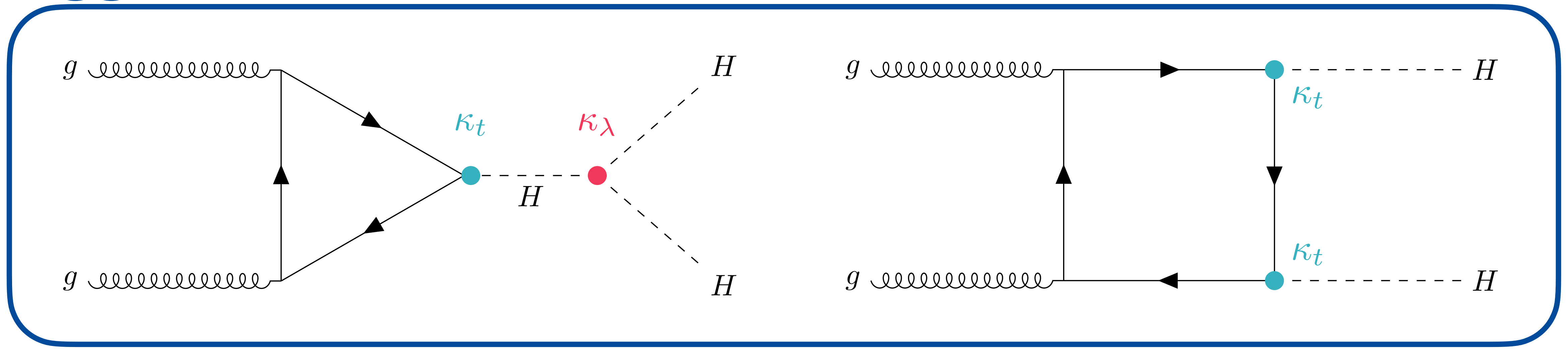


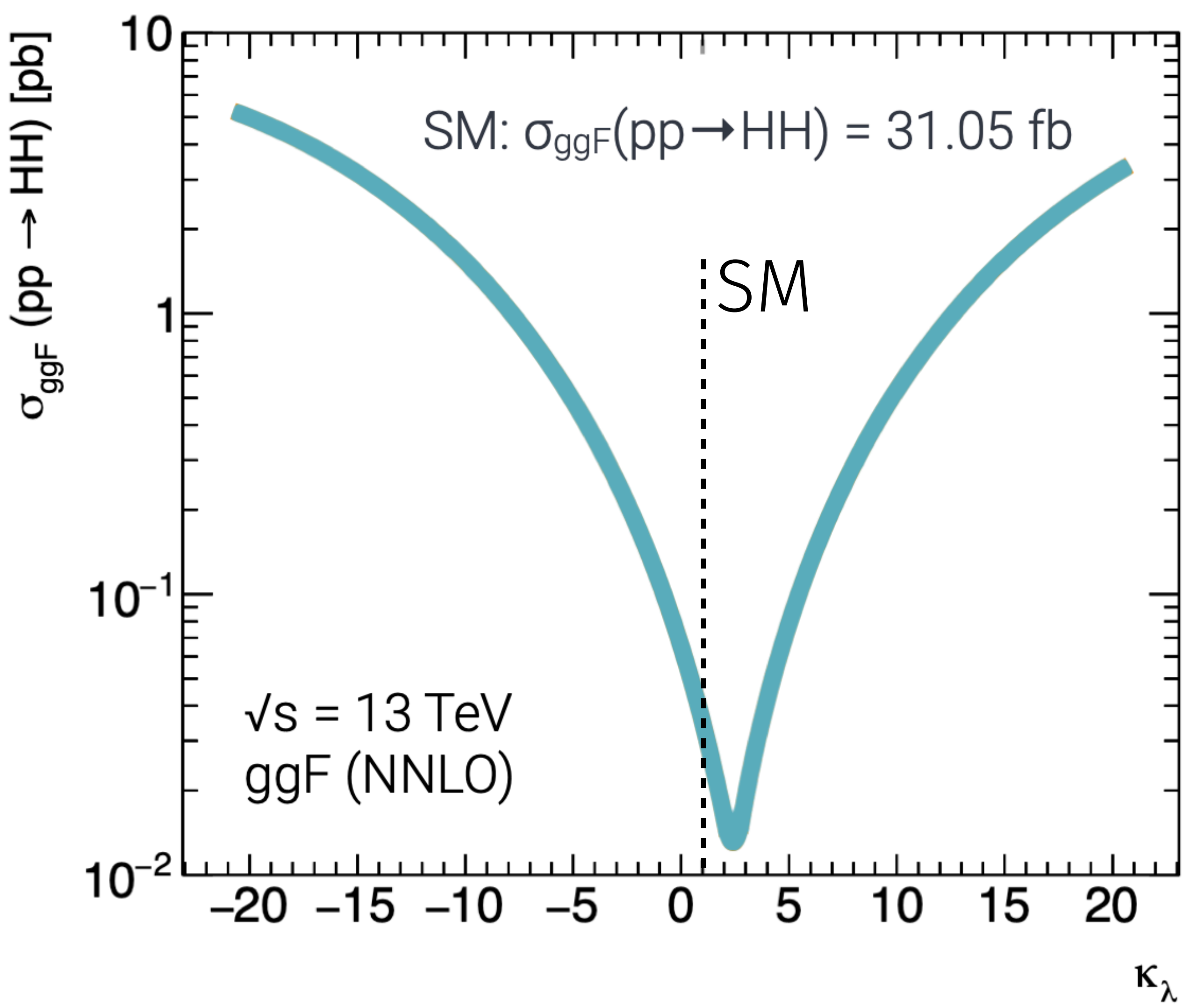
How to look for HH production?

- Same production modes as for single Higgs production: ggF, VBF, VH, ttH, …
- Small XS → only ~ 4k HH pairs produced during LHC Run 2



ggF: σ = 31^{+2}_{-7} fb @ NNLO FT approx. [13 TeV]





$$\kappa_i = \frac{\text{measured coupling i}}{\text{SM prediction}}$$

Larger values of $|\kappa_\lambda|$ enhance the HH production cross-section significantly

Which decay channel to pick?

- Same production modes as for single Higgs production: ggF, VBF, VH, ttH, …
- Small XS → only ~ 4k HH pairs produced during LHC Run 2
- Balance needed between high signal yield and high background rejection

H_2 →

BRs	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

↓ H_1

The "golden" channels:

<u>H(→bb)H(→bb):</u>
largest BR, but huge QCD multi-jet background

<u>H(→bb)H(→ττ):</u>
moderate BR, multi-jet rejection due to presence of ττ

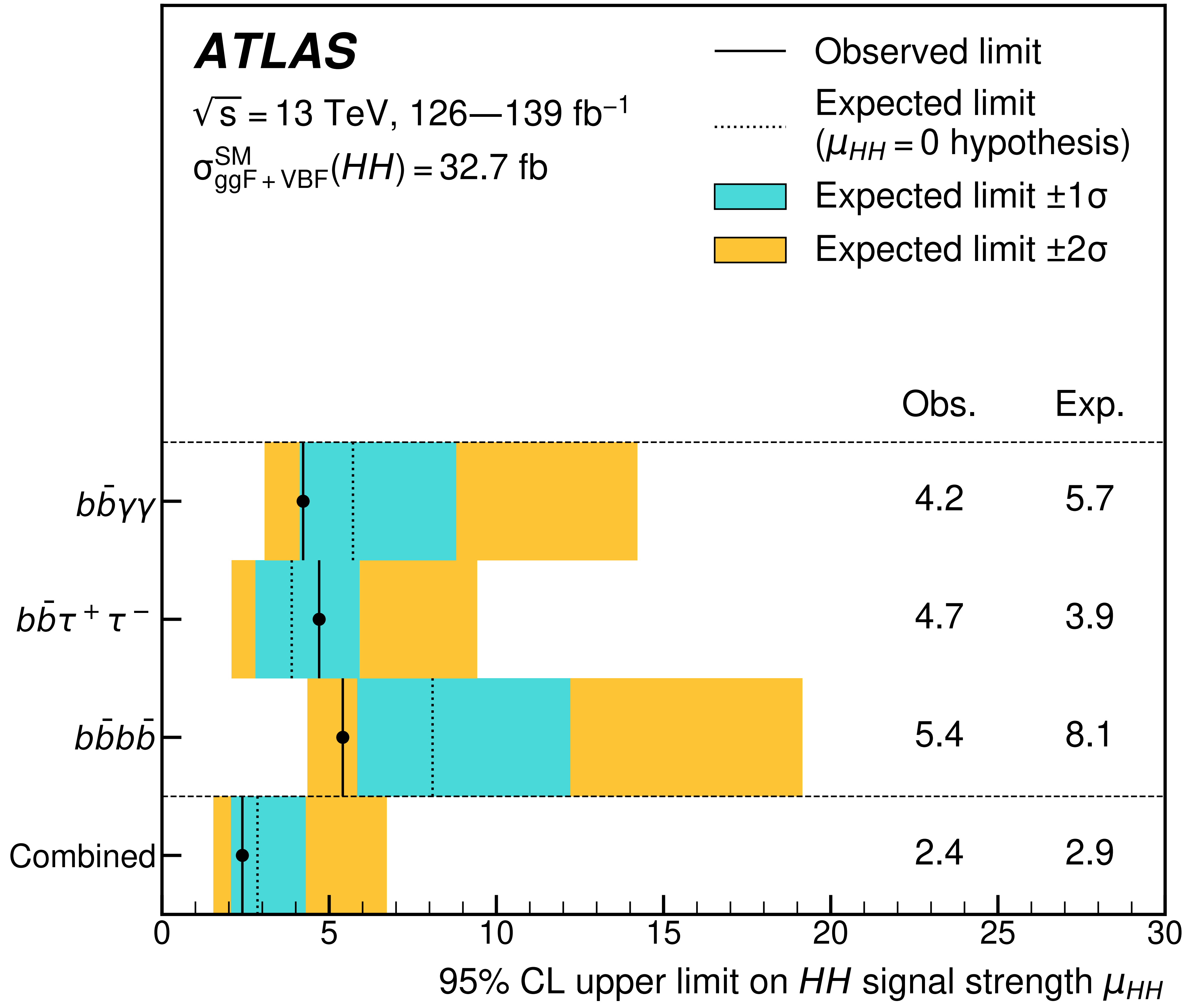
<u>H(→bb)H(→γγ):</u>
small BR, but very clean signature + benefits from $m_{\gamma\gamma}$ resolution

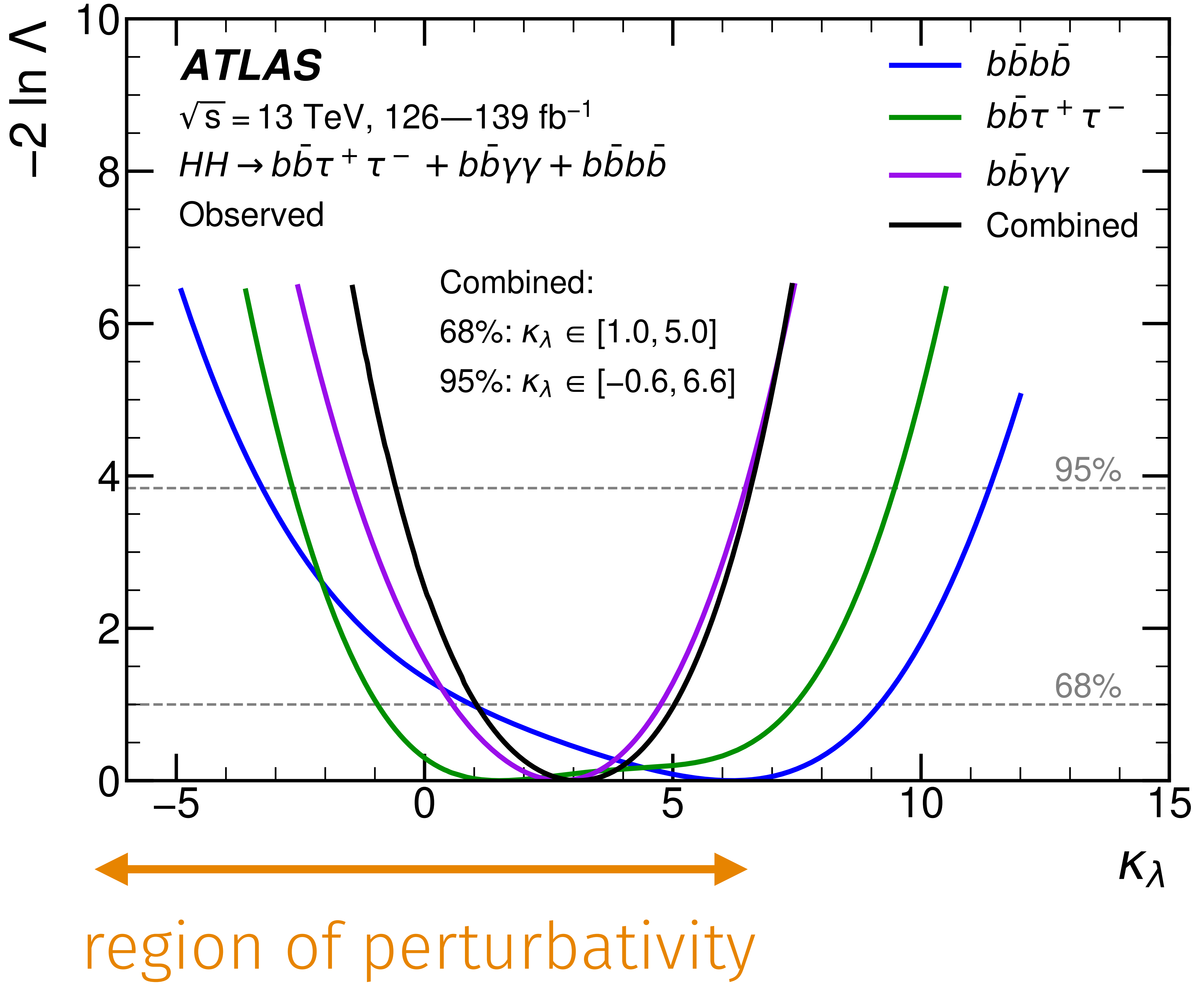
Most sensitive channels all require at least one H→bb

ATLAS Run 2 limits

pp→HH signal strength < 2.4 x SM @ 95% CL

$$\kappa_i = \frac{\text{measured coupling i}}{\text{SM prediction}}$$

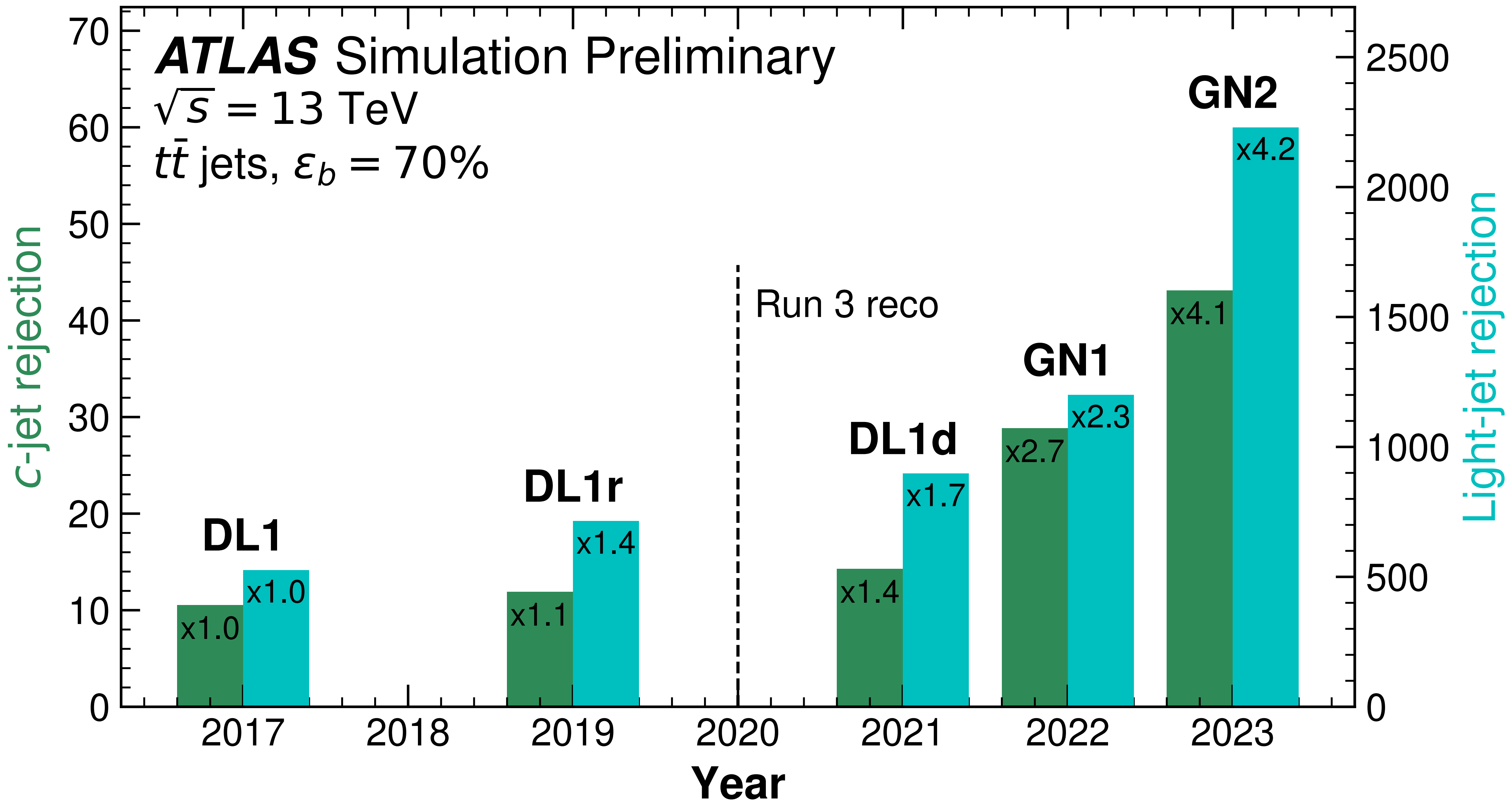


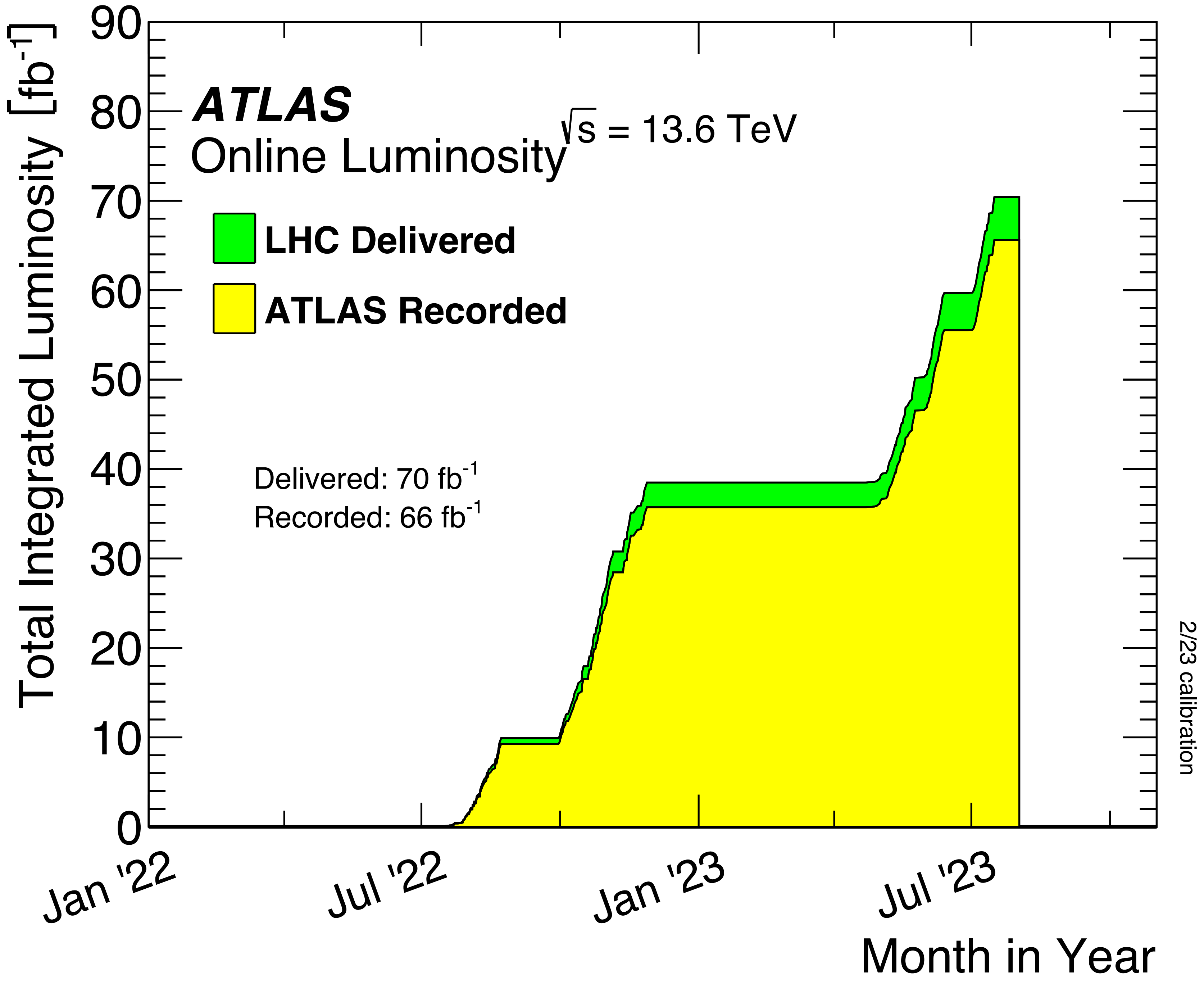


All three analyses are statistically limited!

Where do we go from here?

- Run 3 is ongoing → 66 fb^{-1} recorded at √s = 13.6 TeV so far [c.f. to 140 fb^{-1} at √s = 13 TeV in Run 2]
- σ(√s = 13.6 TeV)/σ(√s = 13.0 TeV) ~ 1.1 → 10% in signal cross-section





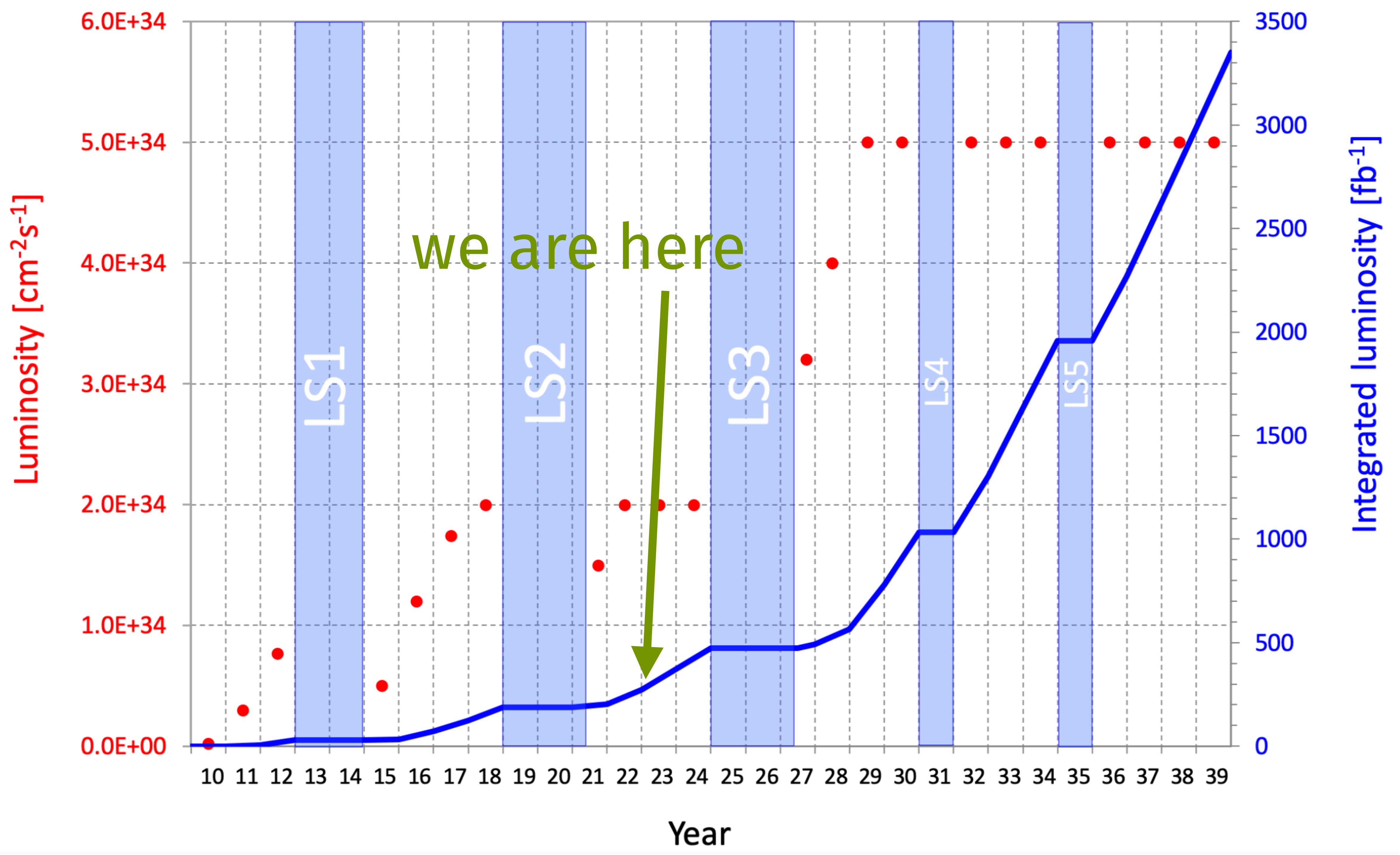
- Graph Neural networks are revolutionizing b-tagging
- New triggers with improved signal efficiencies

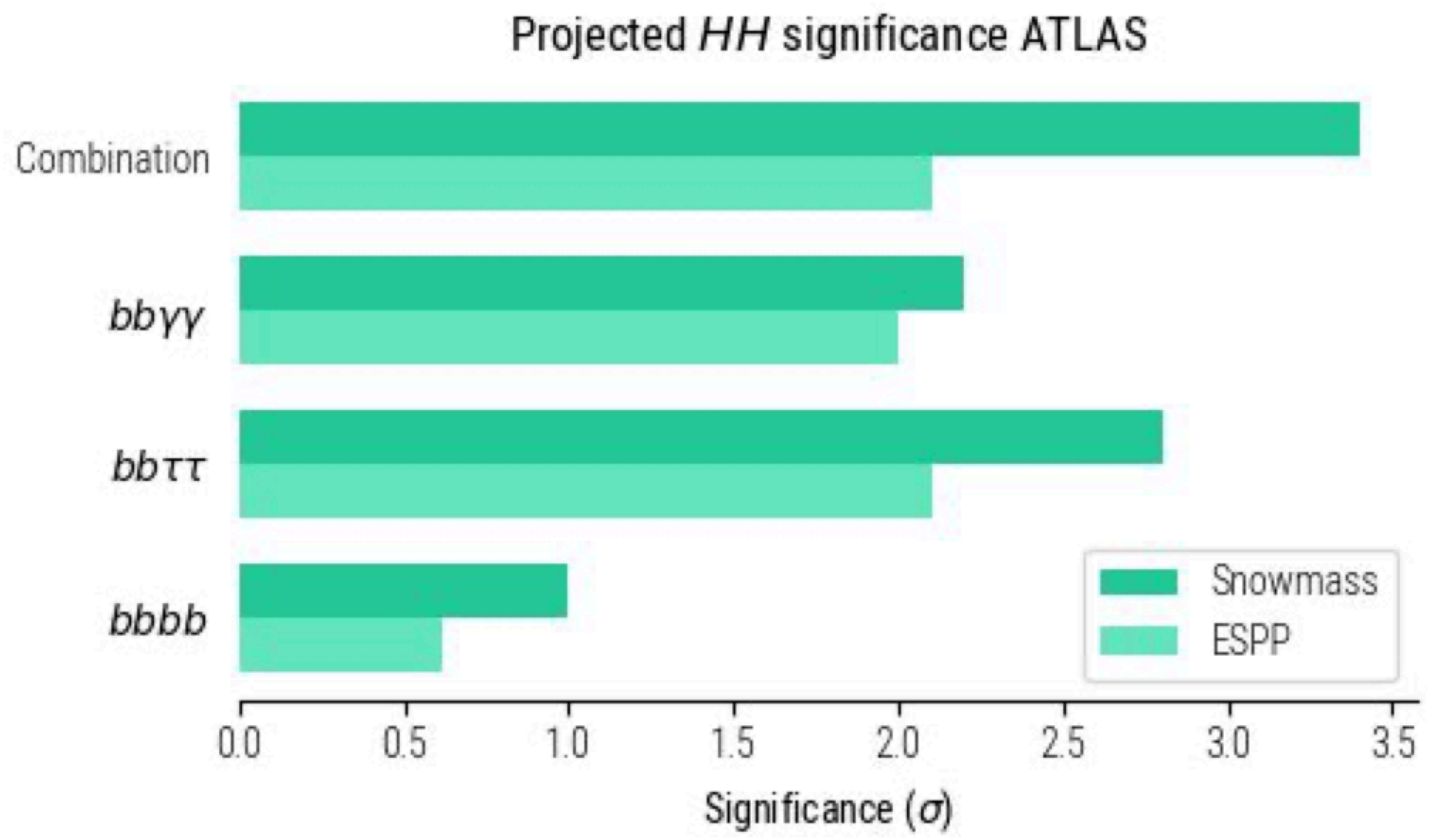
Exciting times ahead!

Further ahead: the High Luminosity LHC

- Not even 10% of the total pp collision data set taken yet (HL-LHC)

[HL-LHC Plots]



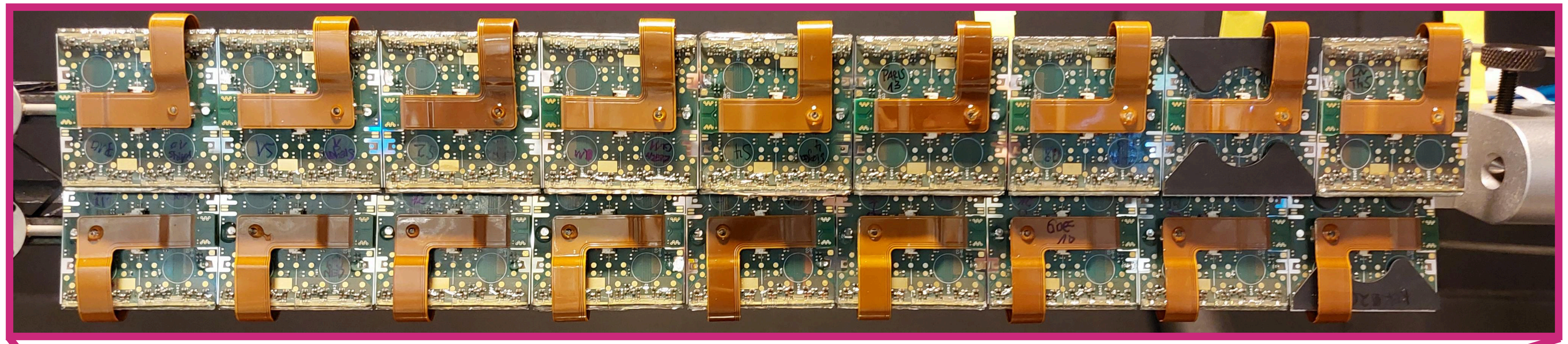


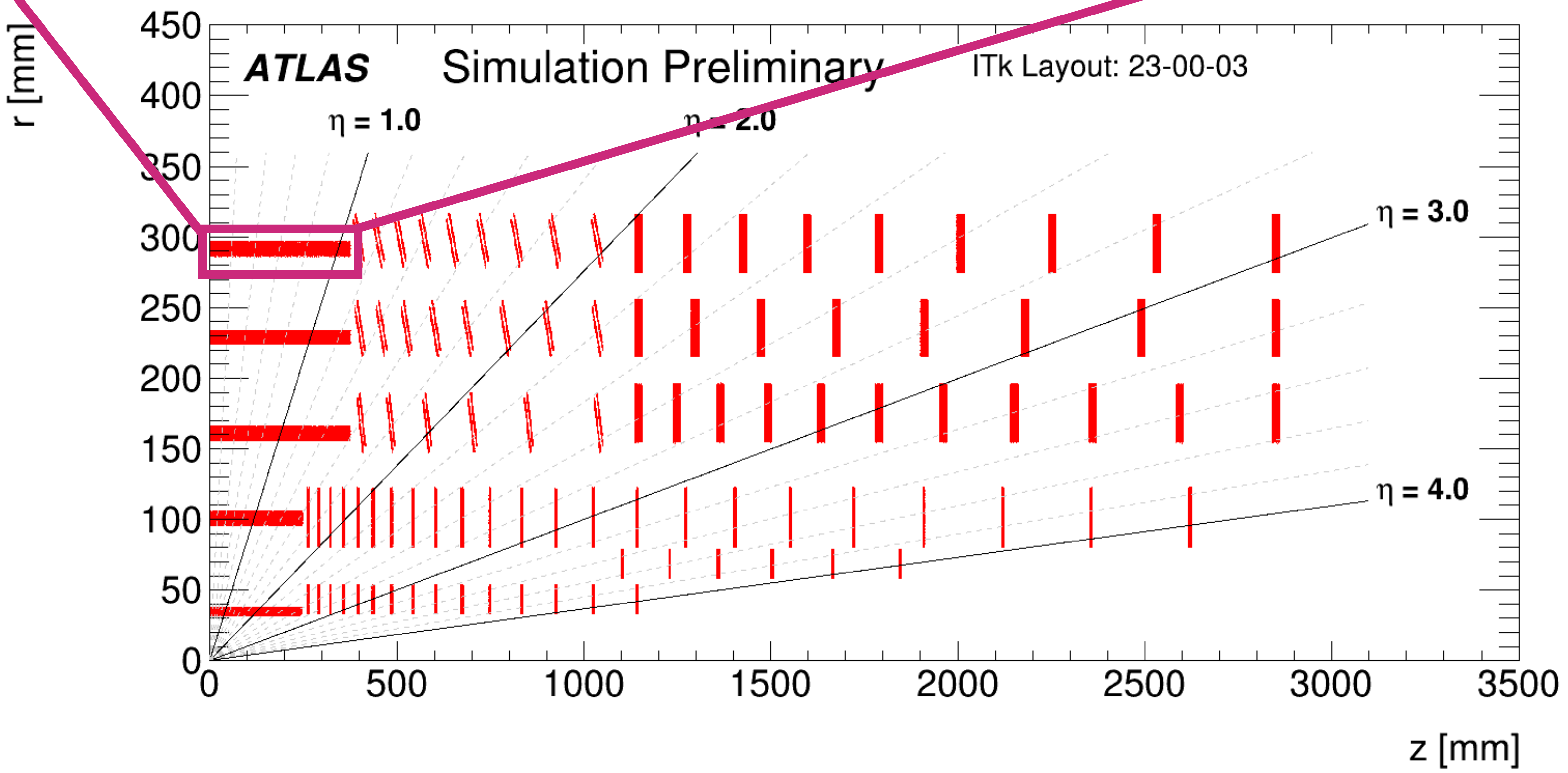
- Observation of HH production (if SM-like) seems possible with the HL-LHC data set!
- **To be able to record this data set, we need upgraded detectors!**

A new ATLAS Inner Tracker (ITk) for the HL-LHC

- Novel all-silicon tracker to replace the full ATLAS inner detector for the HL-LHC
- Increased coverage up to $|\eta| \leq 4$
- **Lower material budget** to minimize multiple scattering
- 5 innermost layers will consist of pixel detectors
- Need to withstand an unprecedented radiation exposure
- Novel serial powering scheme, CO_2 cooling, ...
- Need an intermediate step between individual modules and a full detector
  ⇨ local support prototypes

Local support prototype in the RadLab at Point 1, CERN





Material budget and multiple scattering

- Scattering described by a Gaussian core with sin(θ)$^{-4}$ Rutherford tails
  → can be described by a **double sided crystal ball** function

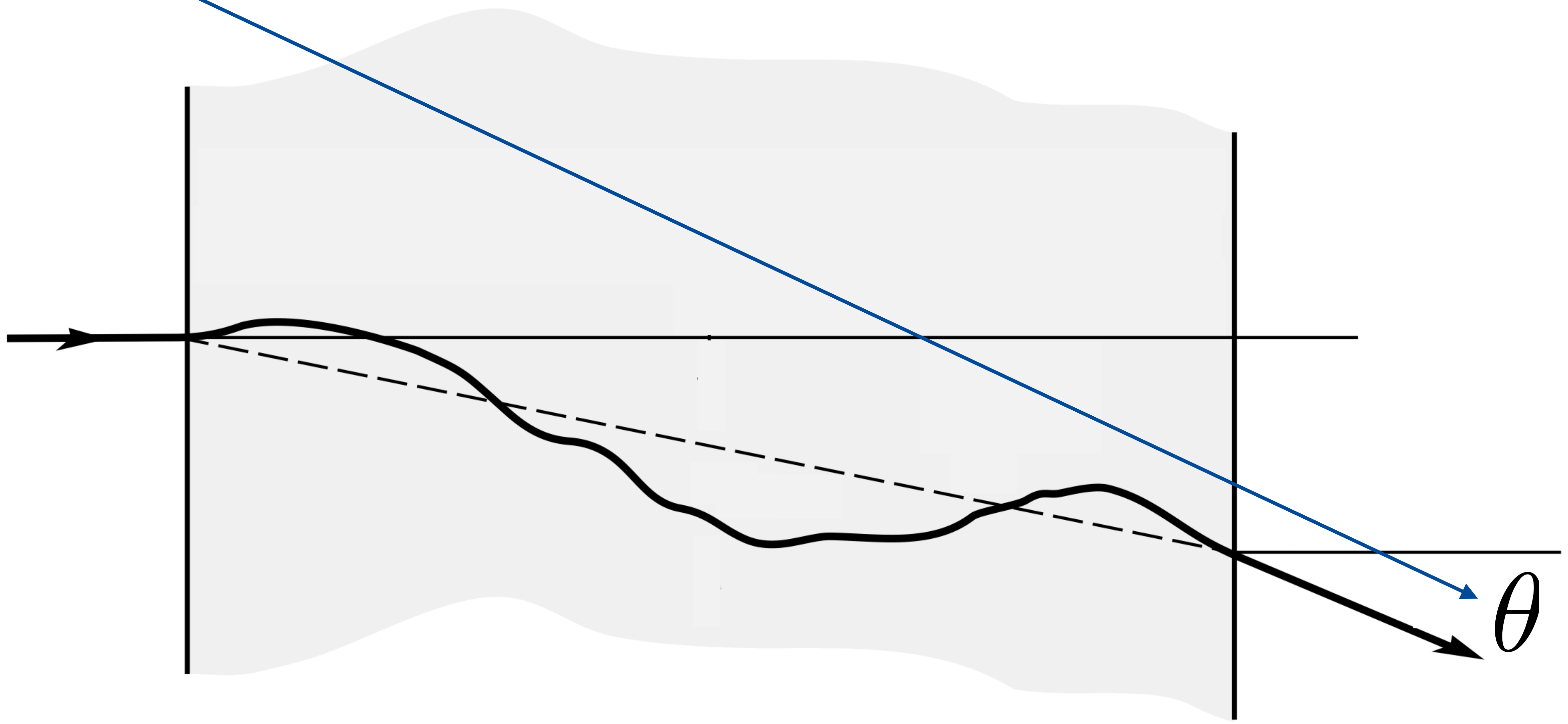
$$\theta = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{x/X_0}\left(1 + 0.038 \ln(x/X_0)\right)$$

Scatter angle
[RMS of Gaussian core]

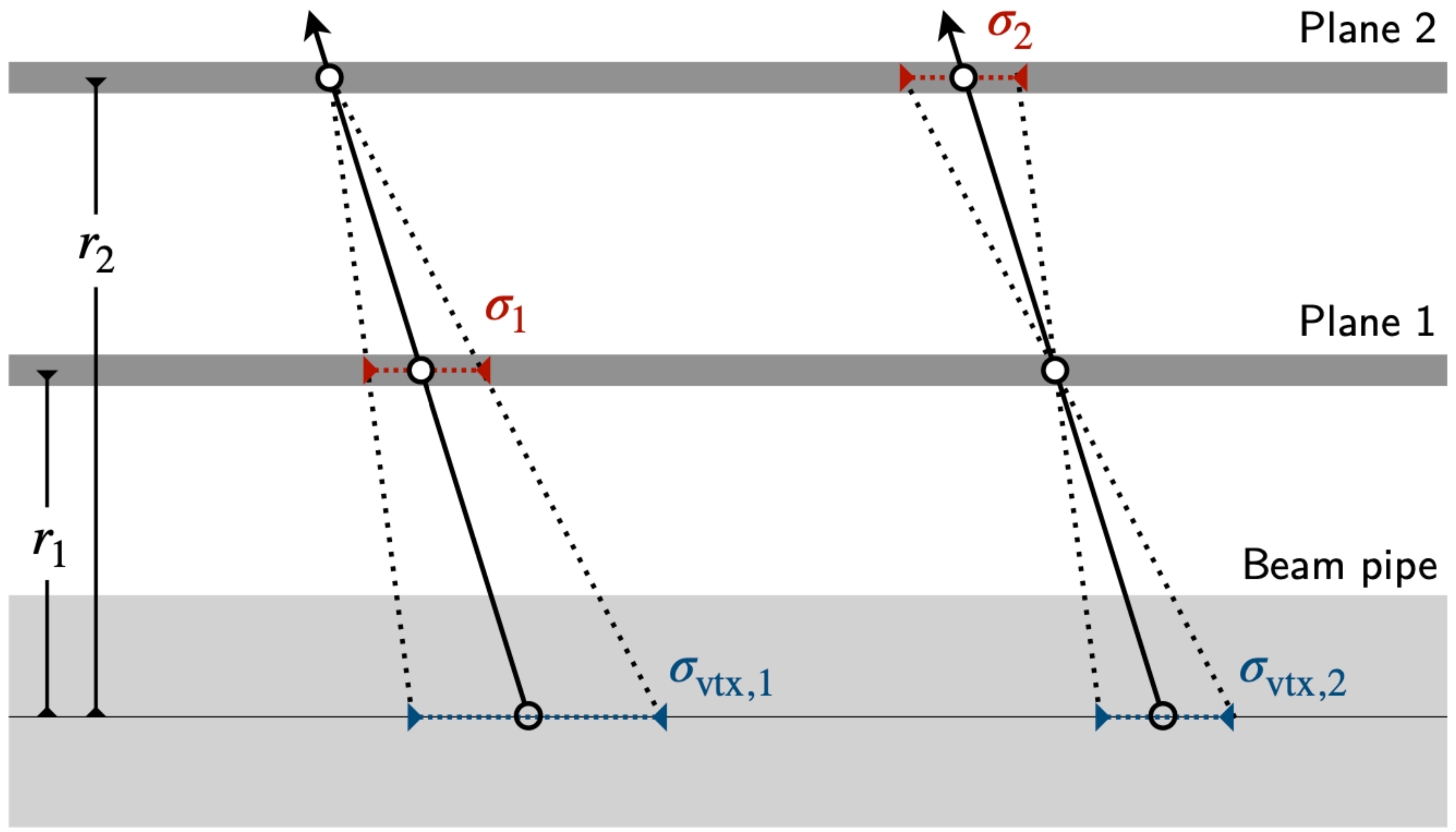
Particle energy

Particle charge

Fractional radiation length

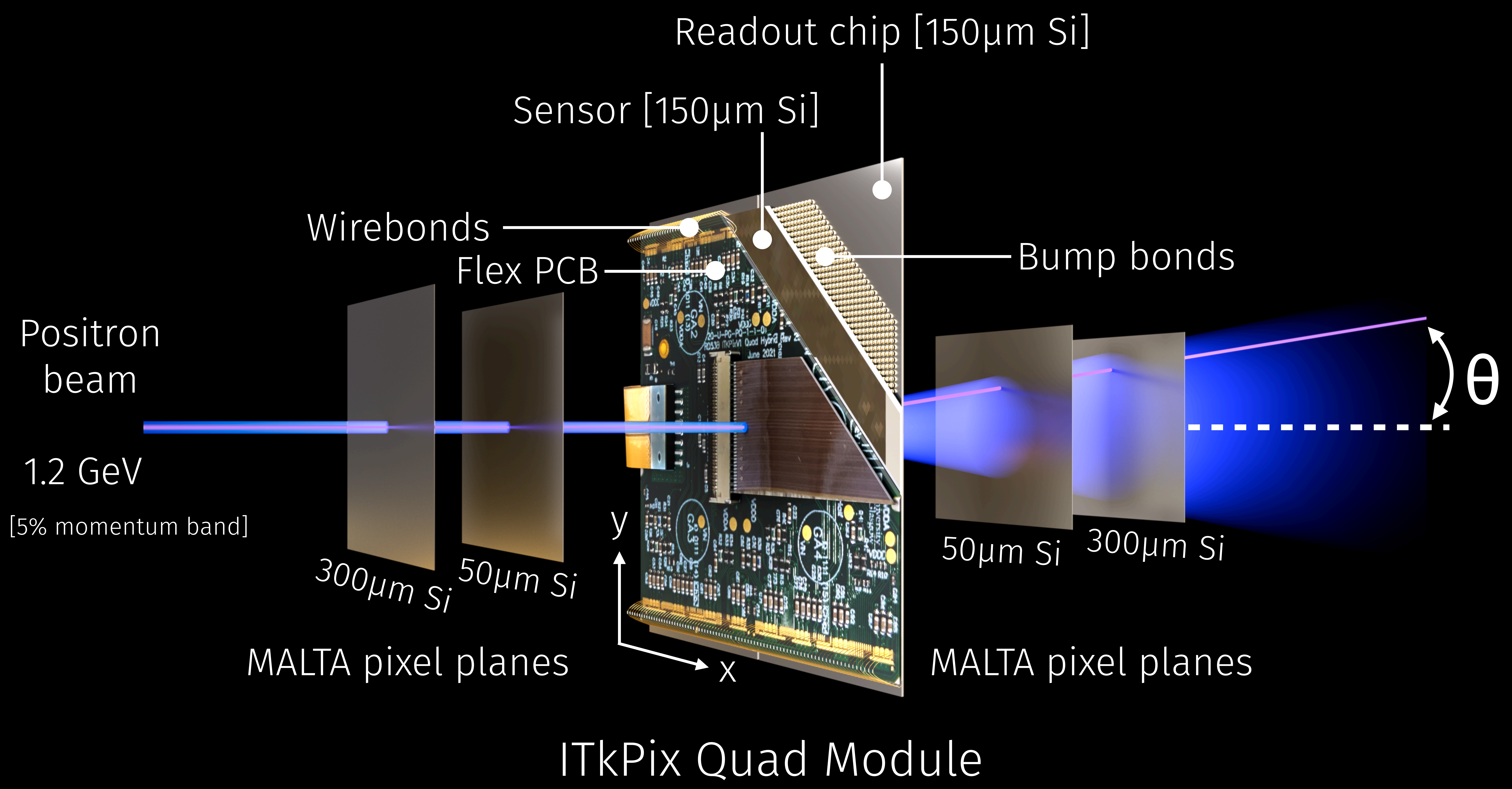


The amount of multiple scattering translates directly e.g. into an uncertainty on the vertex position



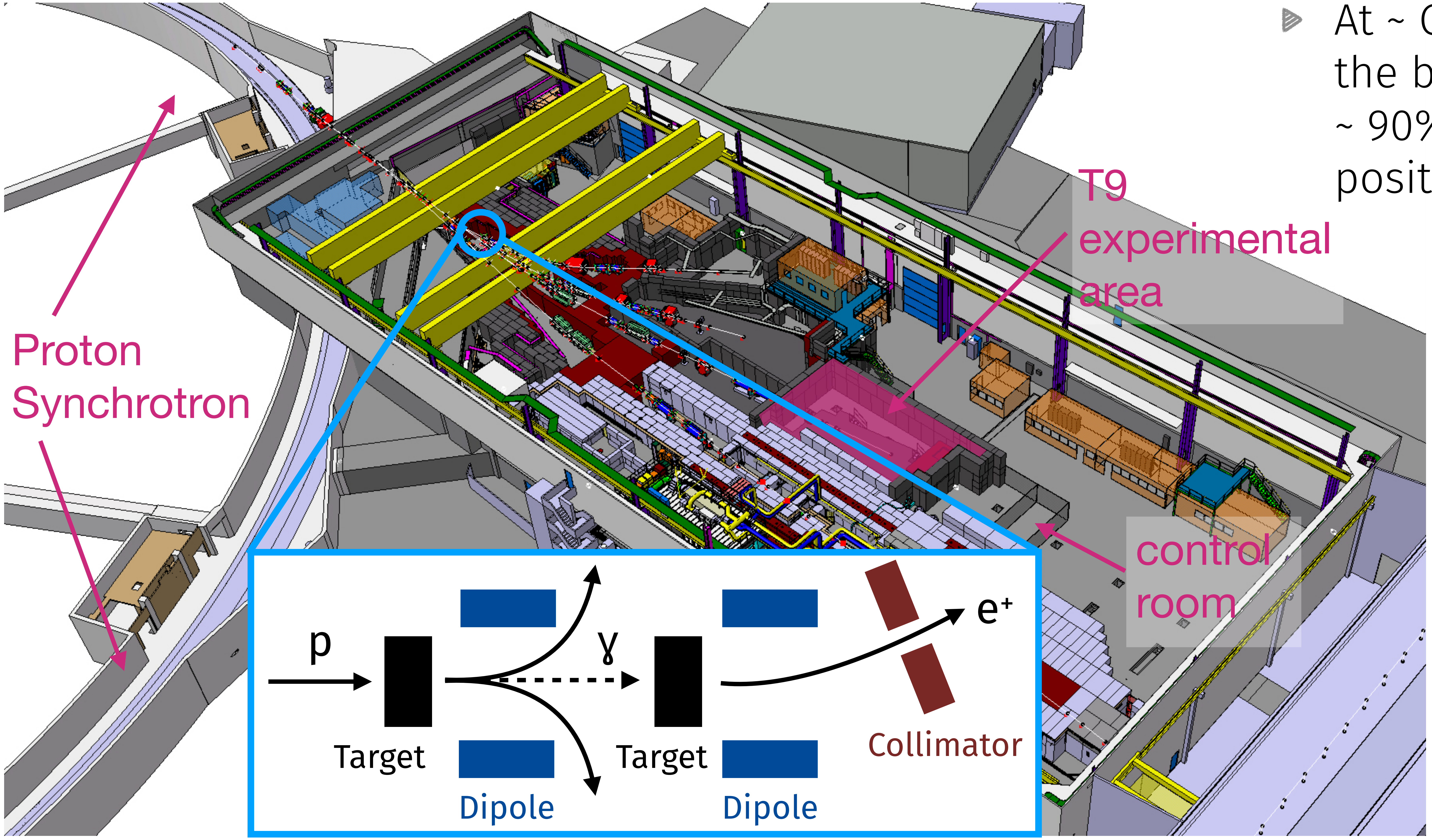
For particles with known energy we can measure the scatter angle to infer the fractional radiation length

Measuring x/X_0 using multiple scattering!



The T9 beam line at the CERN Proton Synchrotron

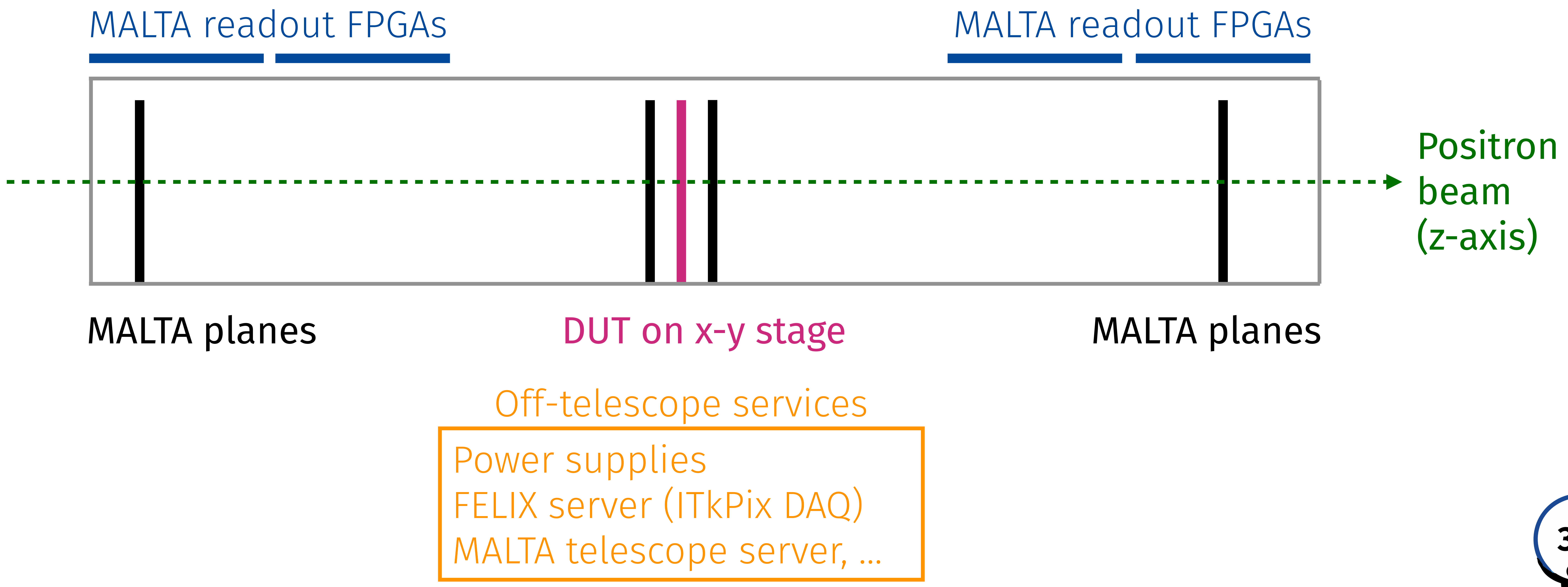
- Low energy positrons produced in a sequence of “beam hits target” starting from 24 GeV protons



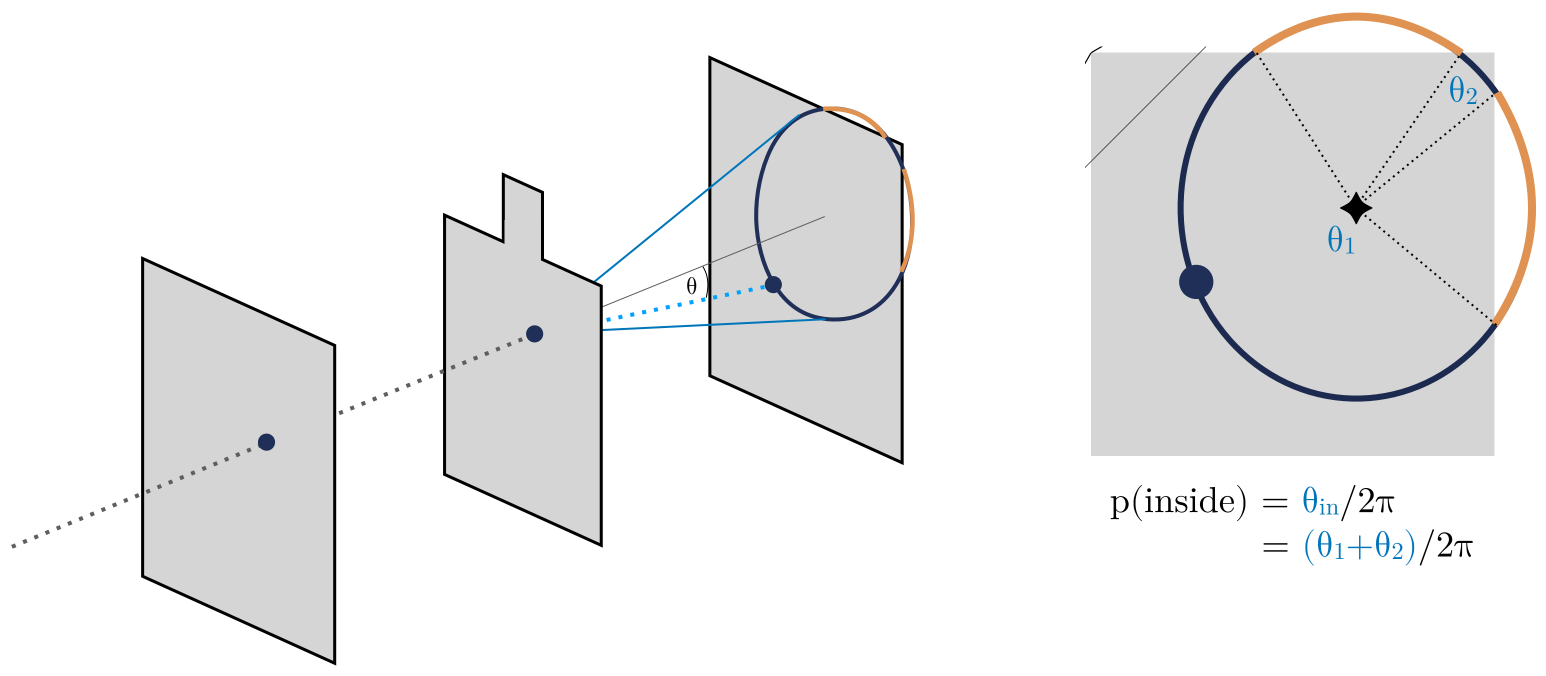
- At ~ GeV energies the beam is ~ 90%-95% positrons

Our beam telescope

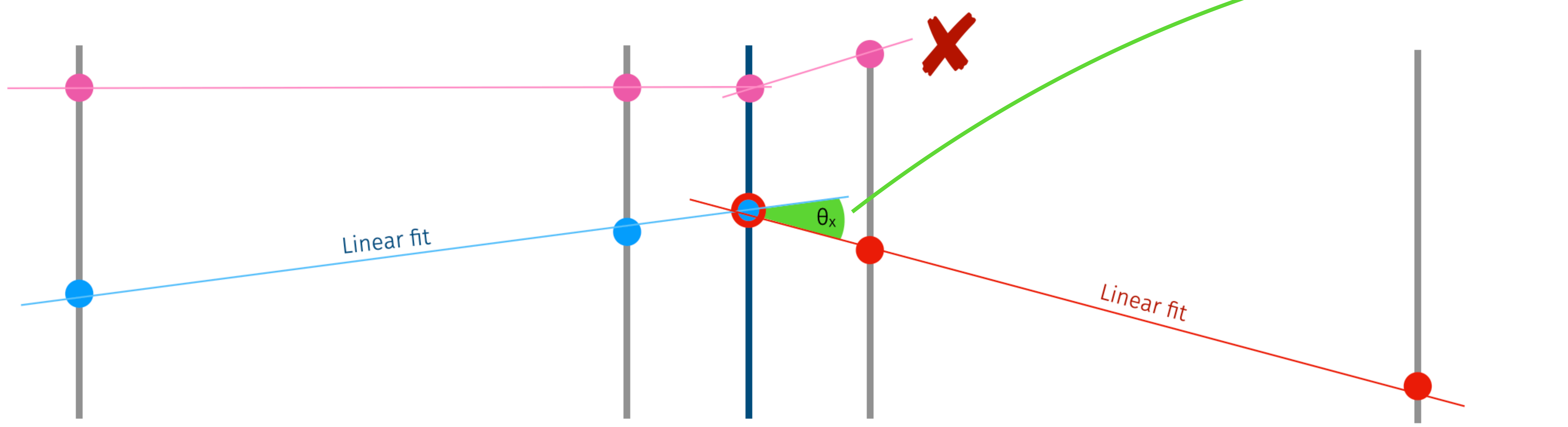
- To enable maximal flexibility with beam energy, built it as long as possible → 2m total length
- **MALTA planes** fixed in a frame made from Bosch profiles + custom 3D printed parts
- ITkPix quad sits on a linear stage and is movable in x-y-direction

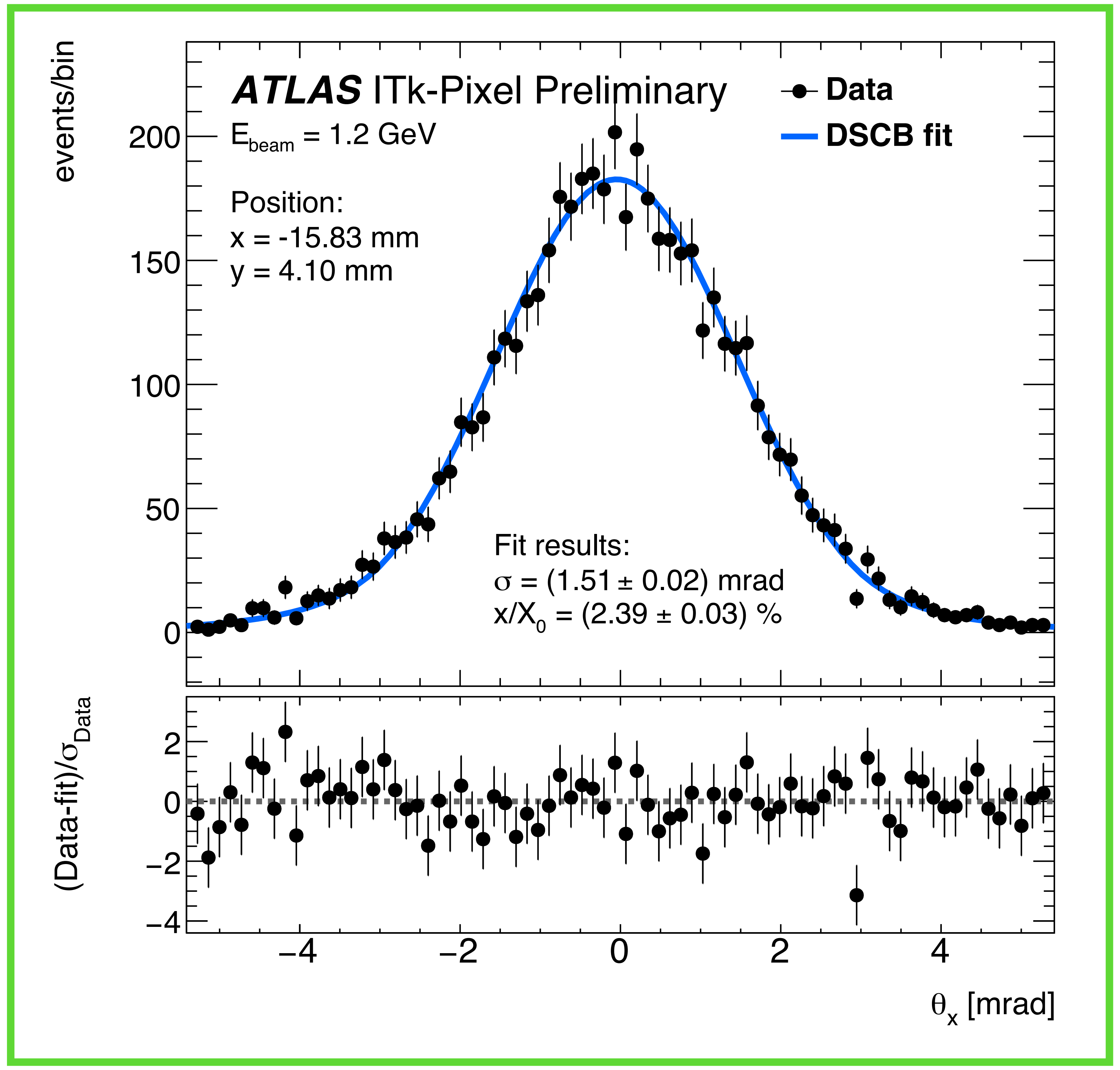


Multiplet tracking and θ fitting



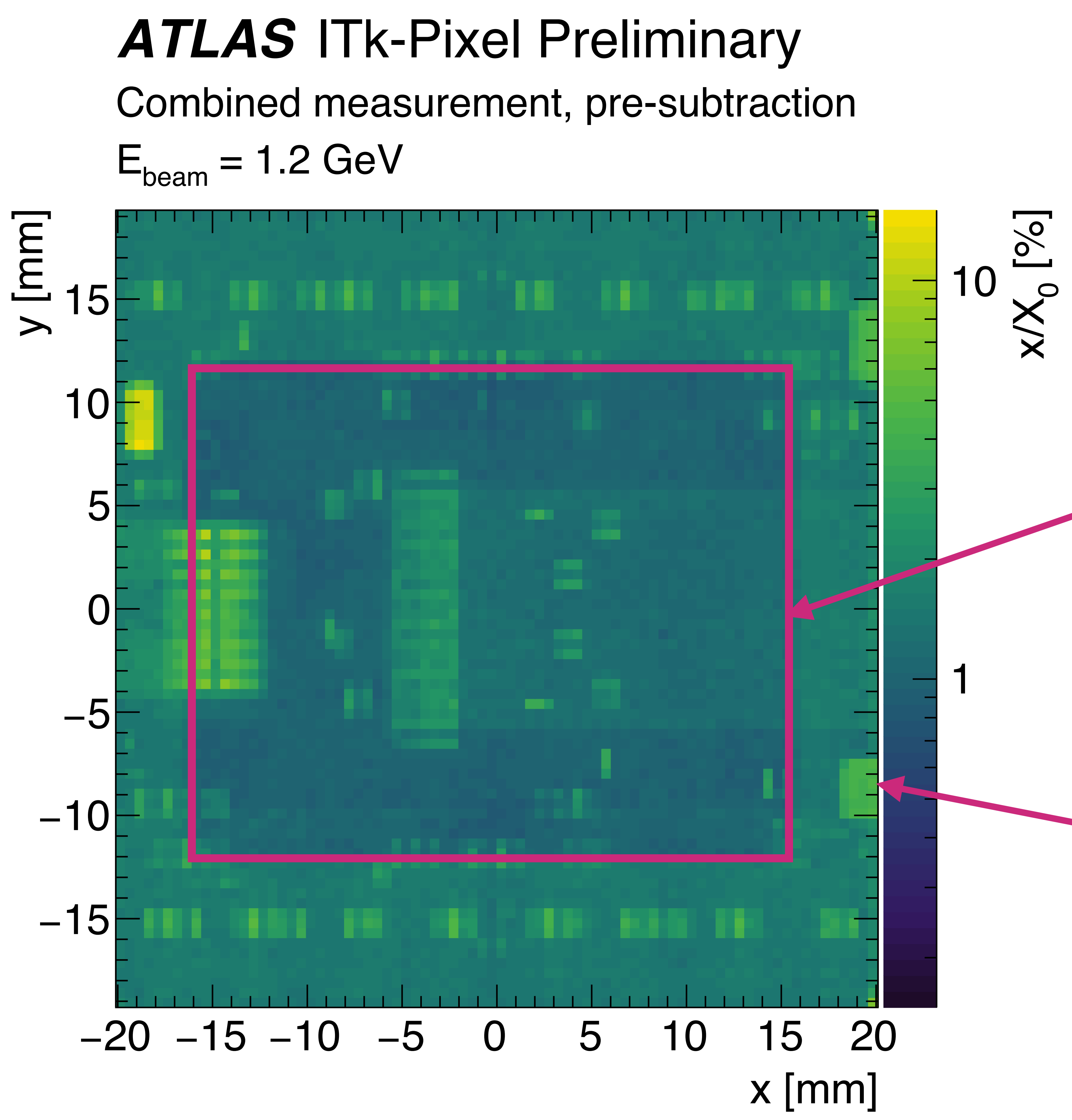
- Two separate linear fits upstream and downstream of the DUT
- Acceptance corrections for geometrical acceptance effects [small]

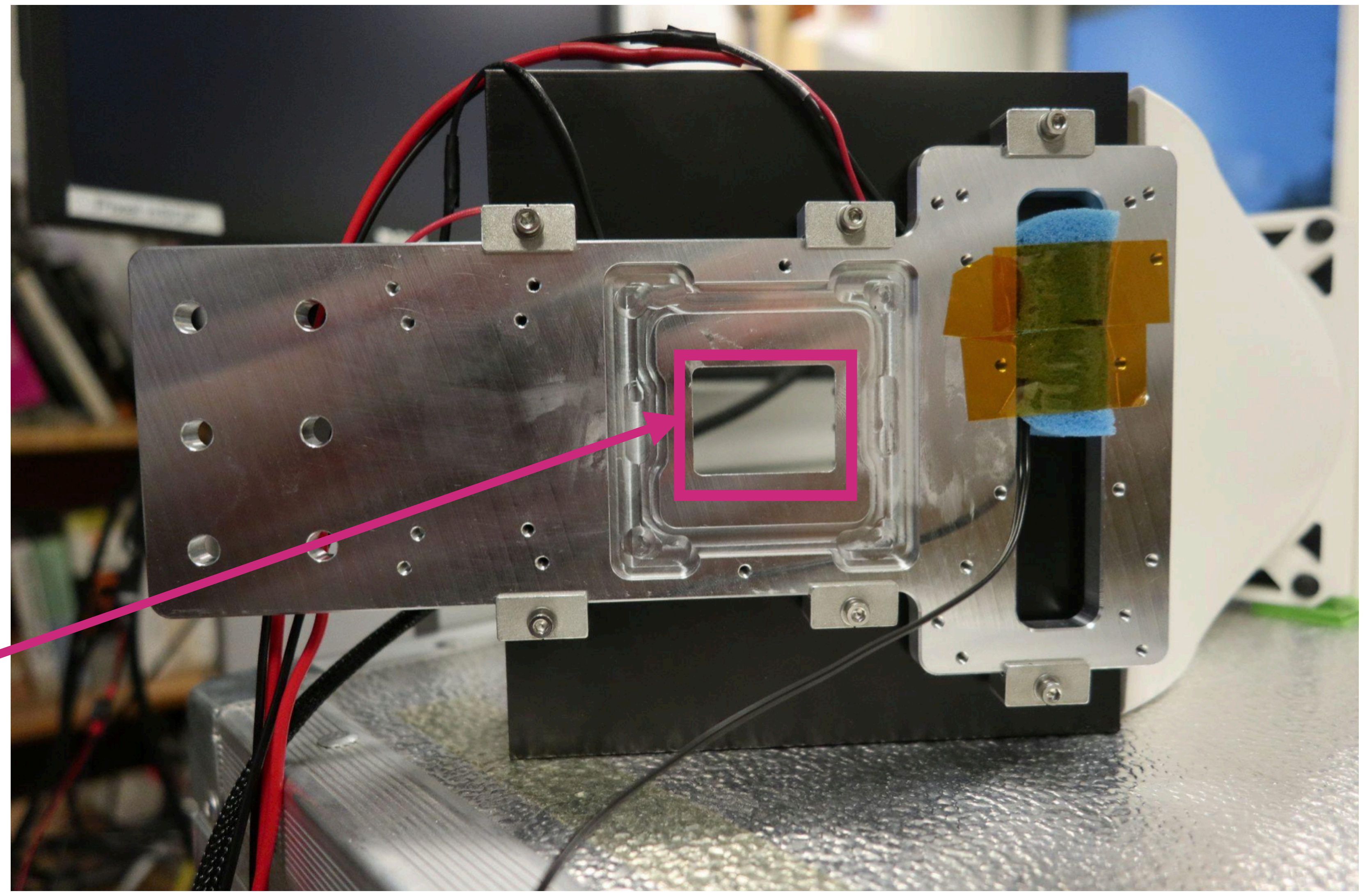


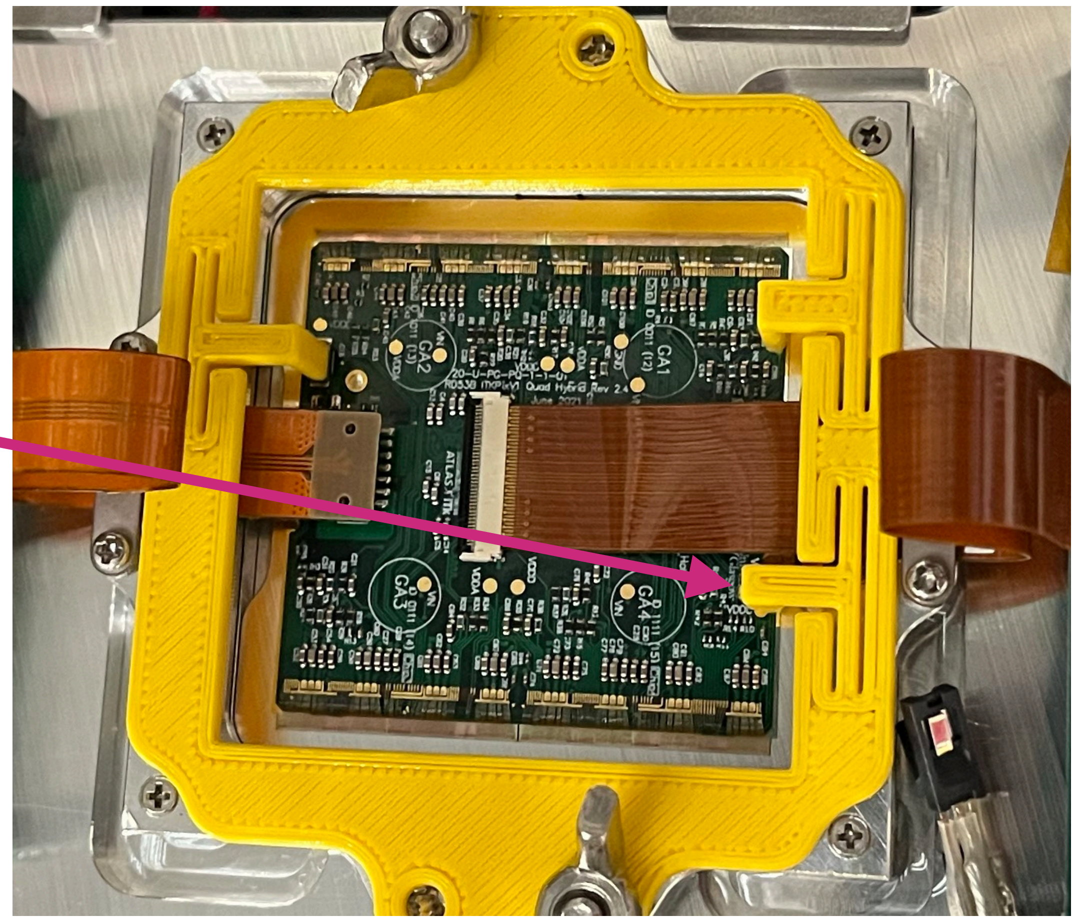


- Due to the position of the MALTA planes we do not rely on DUT information → can measure x/X_0 of anything
- Fit angle projected on x- and y-axis of the DUT → two orthogonal information that can be combined

x/X_0 **before** subtracting telescope mechanics

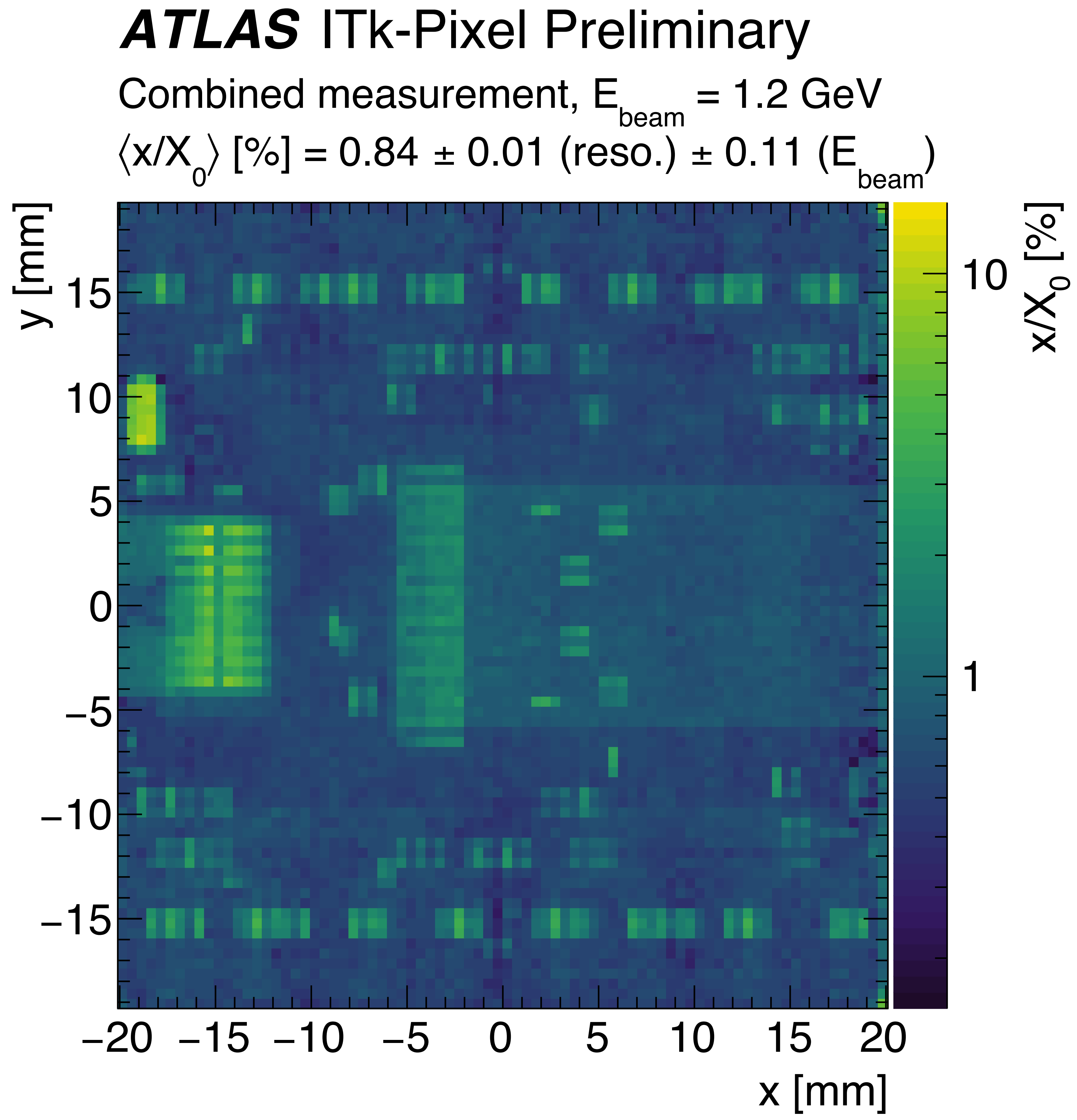


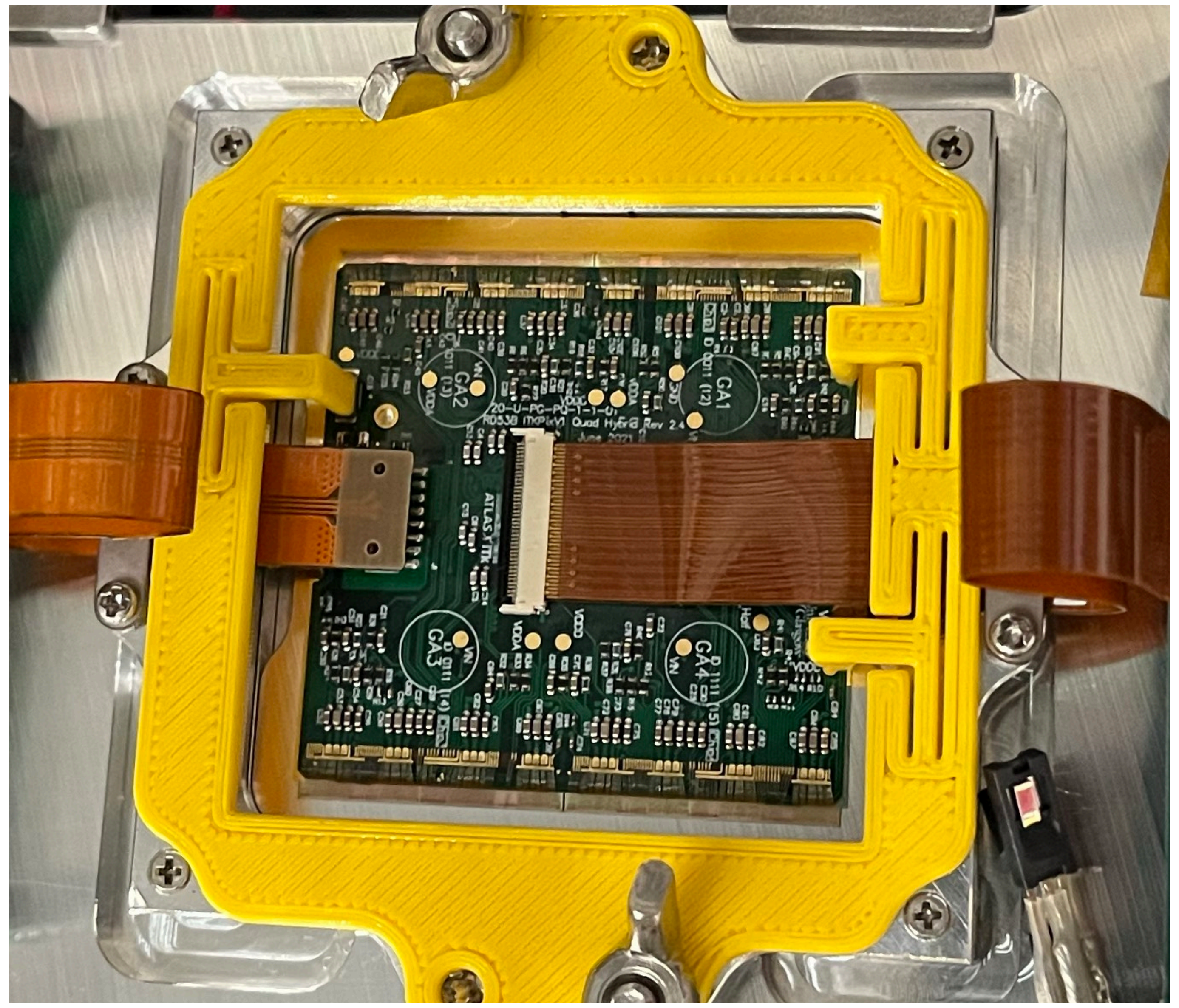


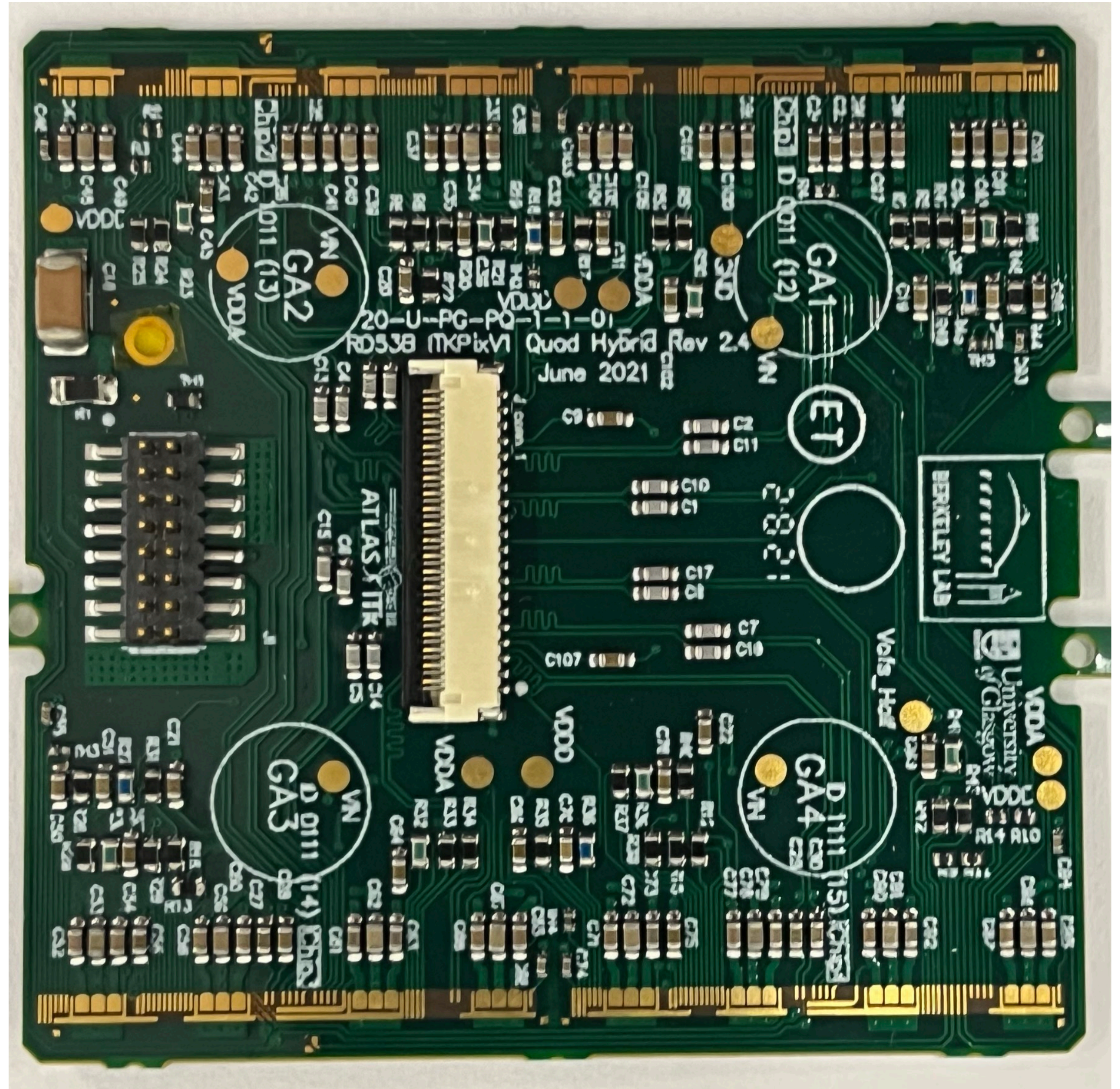


x/X_0 **after** subtracting telescope mechanics

- Material budget map of the ITkPix Quad with sub-mm resolution and 0.5 [%] stat. unc. per bin





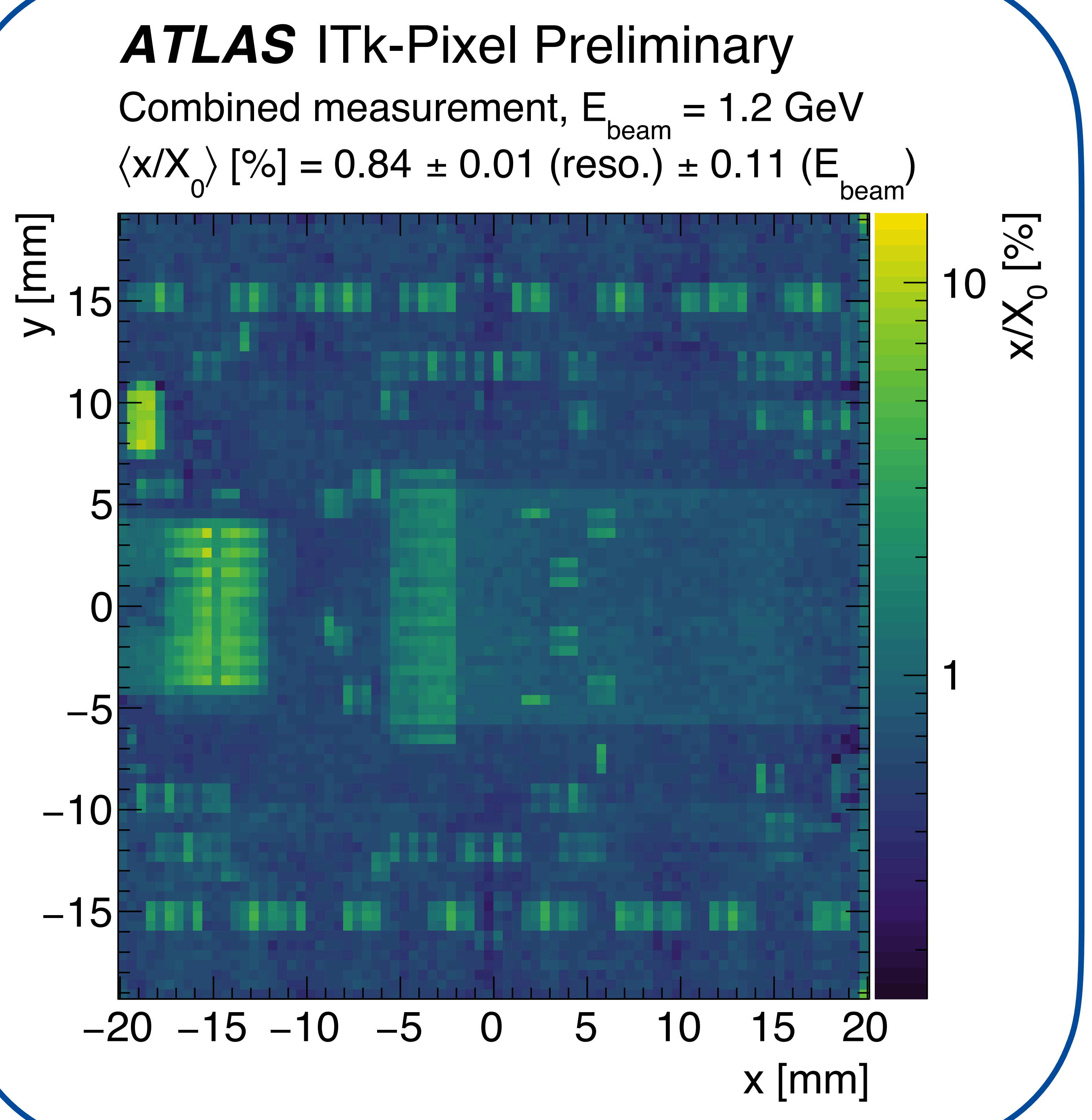


- SMD components clearly visible; largest contributors are the HV filter capacitor, data and powering connector; the data and powering pigtails are visible, too

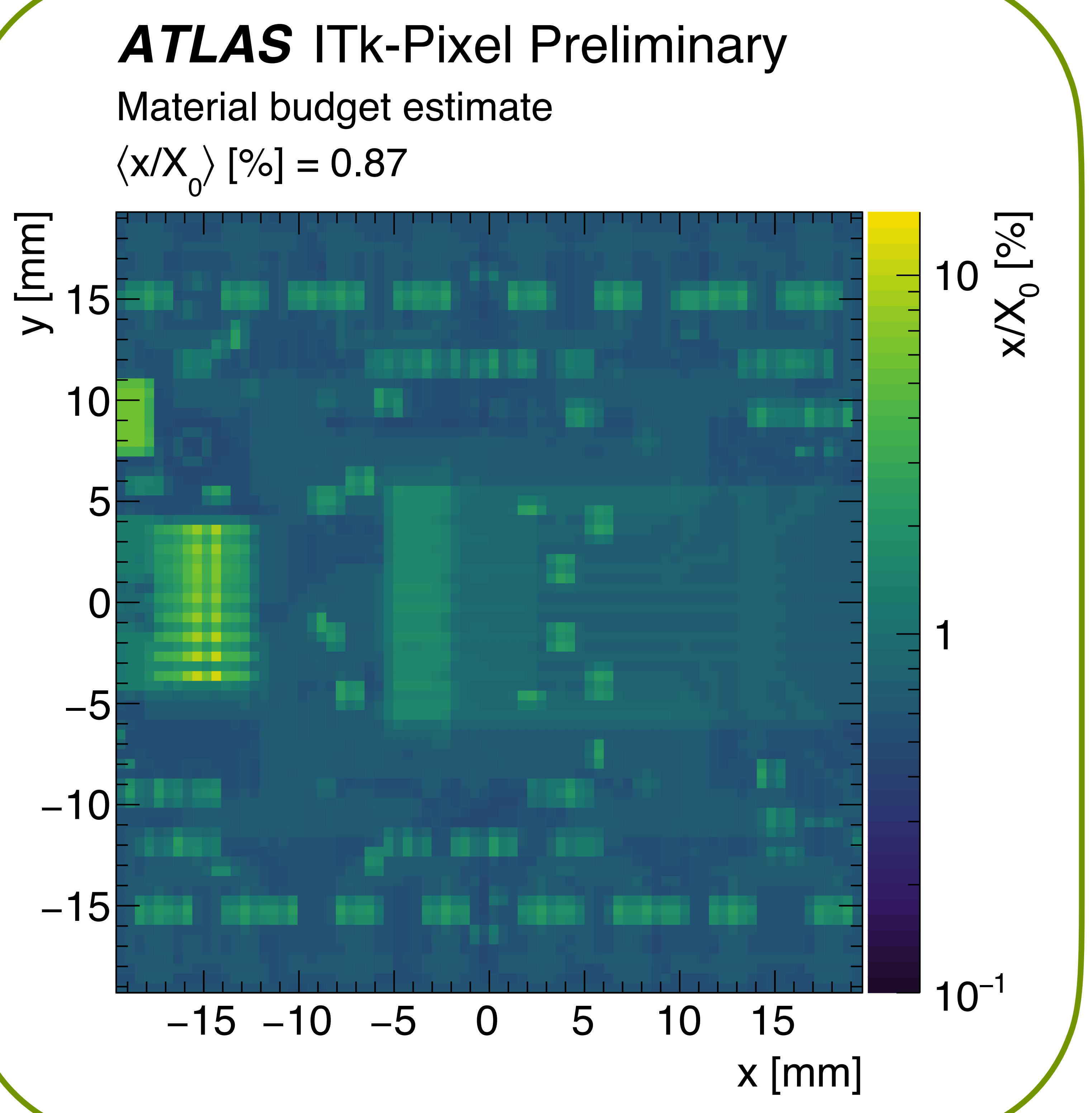
Comparison of measurement with estimate

- Estimated the material budged based on design drawings and component expectations

Measurement



Expectation



- Good agreement between the two, minor differences e.g. on the placing of the components

Next: include services!

Concluding remarks

- With the increasing LHC pp collision data set we can explore rare Higgs boson topologies with increased sensitivity to new physics scenarios

- SMEFT is a powerful tool to talk about our results …

  Which effects is an analysis sensitive to? How does it compare to other analyses?

  … and to combine our knowledge to get a global picture

- The large HL-LHC dataset awaits with exciting promises

  Will we be able to measure the self-interaction of the Higgs?

  … but also poses unique challenges

  Can we finish our detector upgrades?

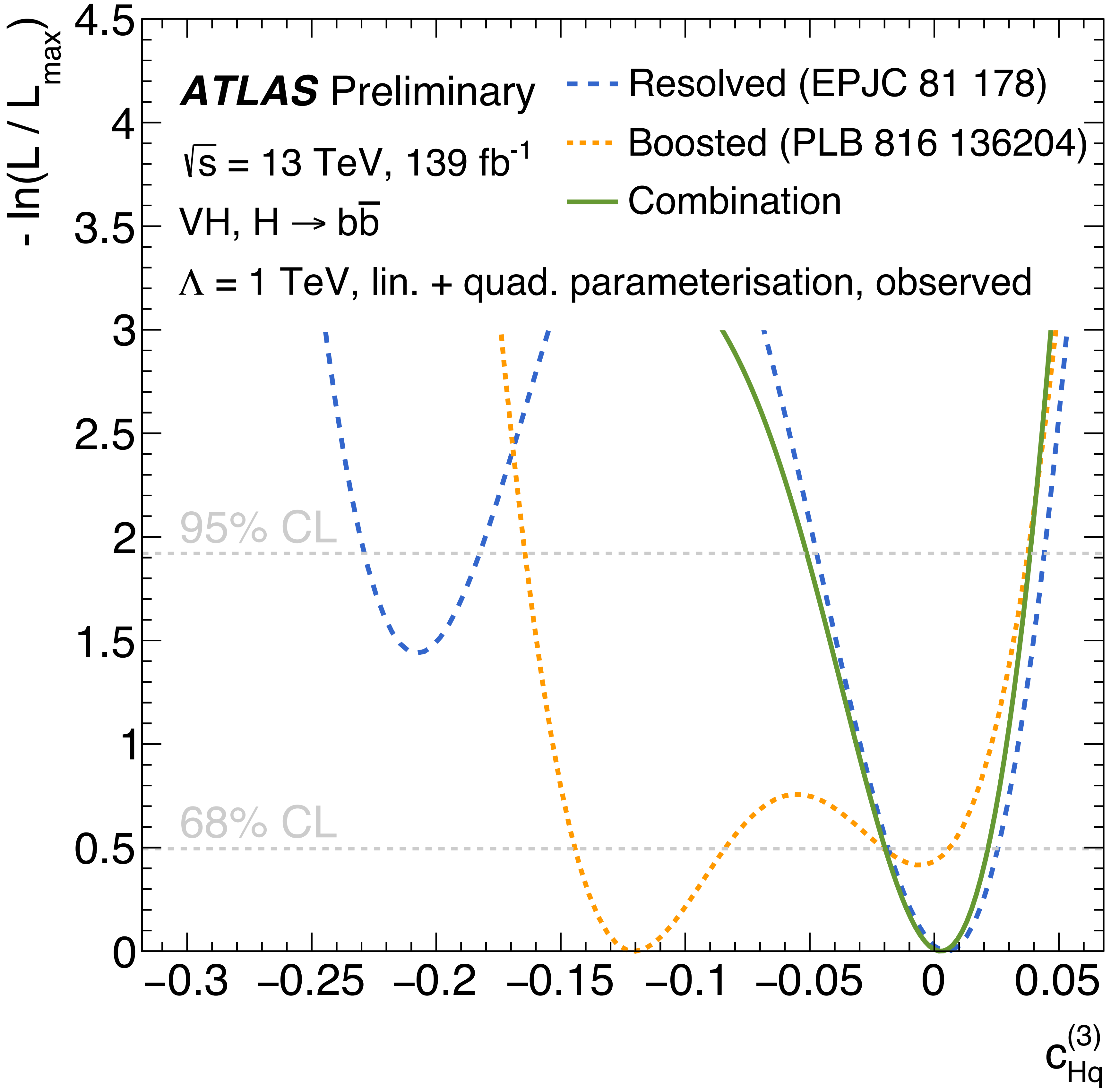
[Image: PhD comics]

Exciting times are ahead! Let's make the most out of it.

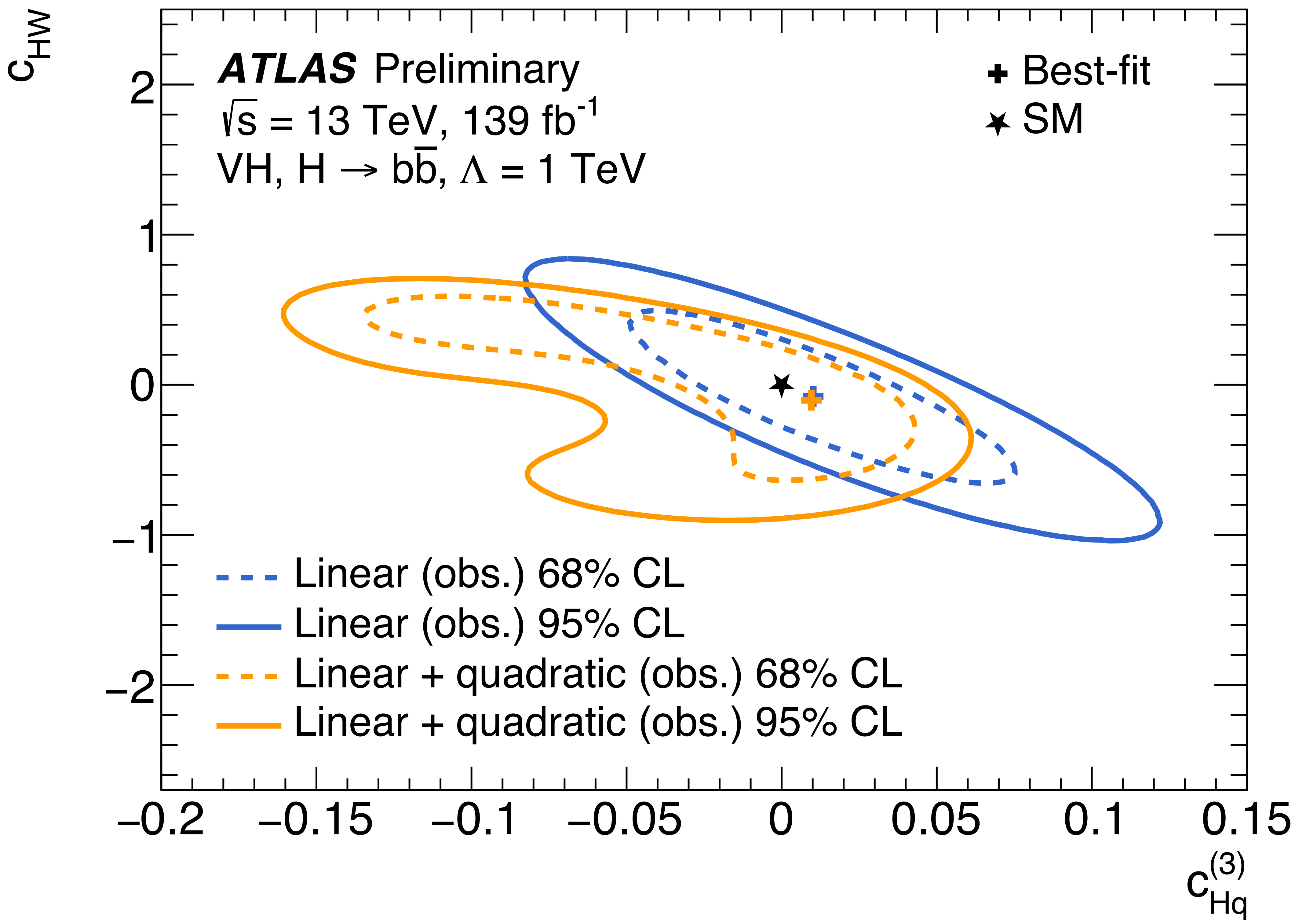
Backup

SMEFT interpretation

Single operator fit to determine analysis sensitivity



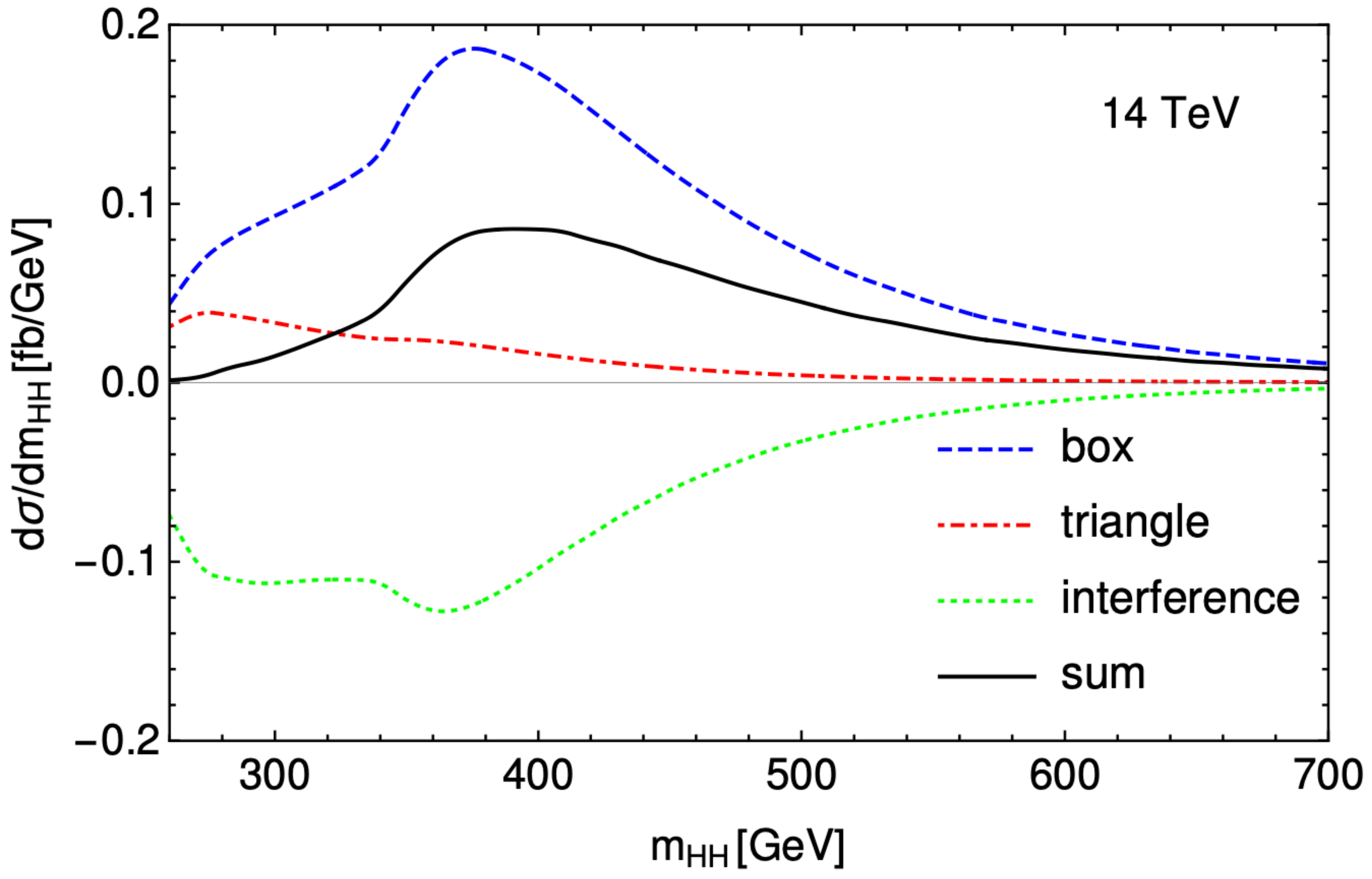
Different operators have different effects on p_T^V bins → can constrain multiple at the same time

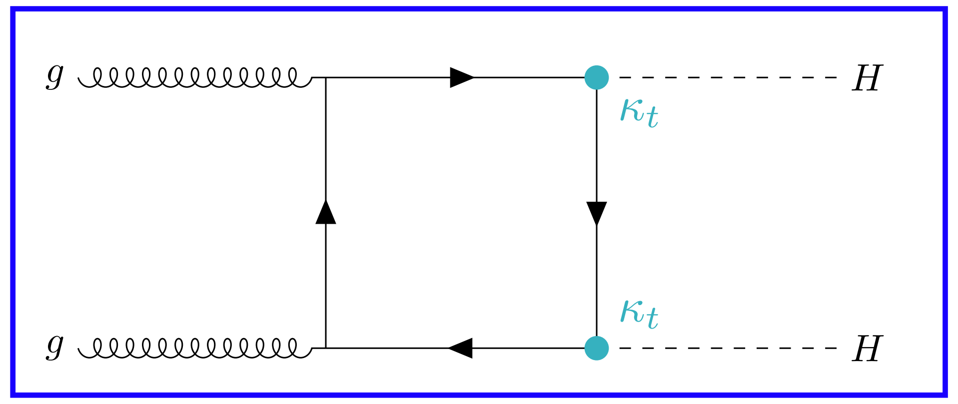


Physically useful limits can only be obtained by combining a multitude of measurements

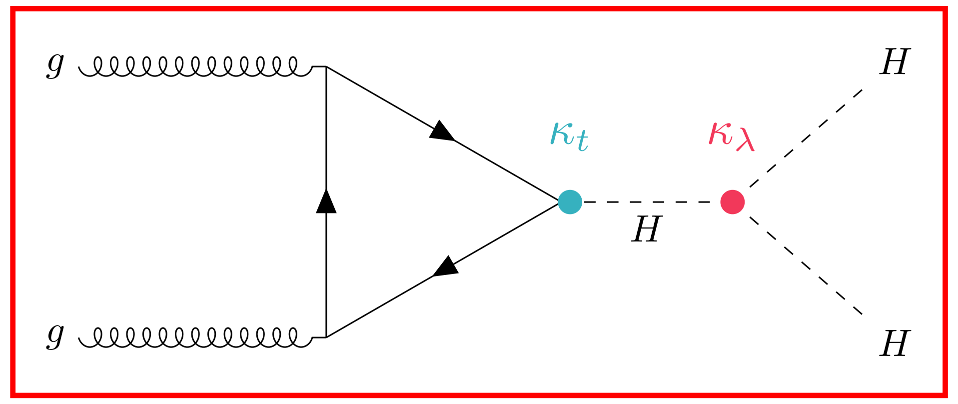
HH diagrammatics: ggF

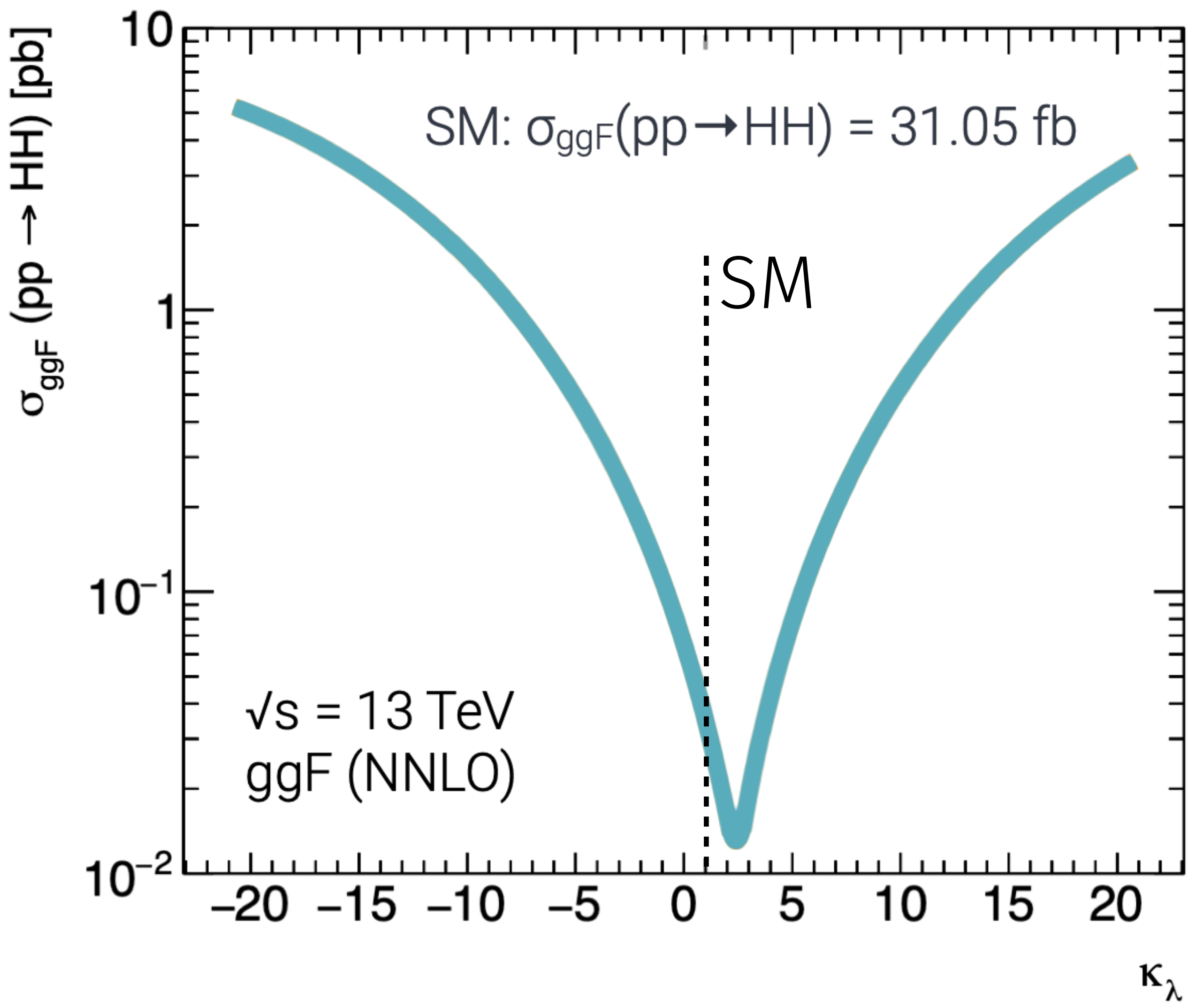
- The box and the triangle diagram interfere with each other destructively → reduction of XS

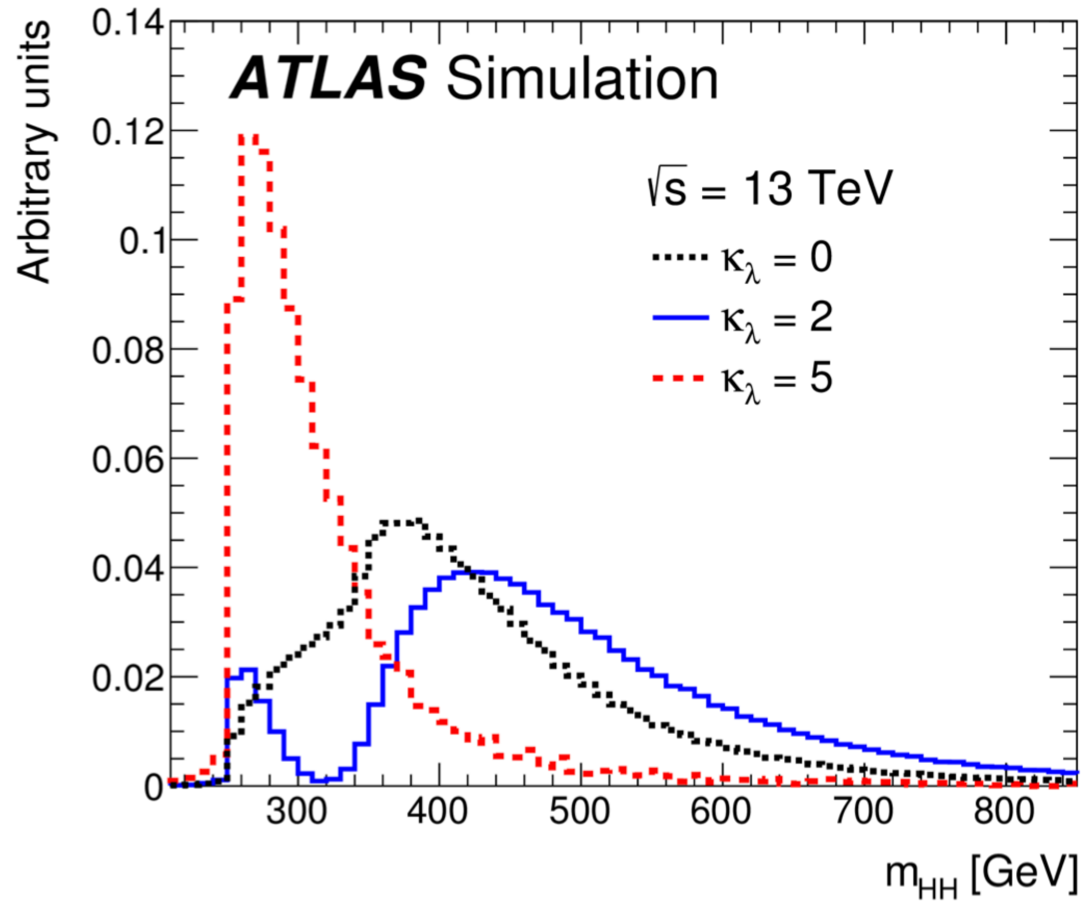




$\sigma \sim |B|^2 + |T|^2 + 2\mathrm{Re}(B^*T)$







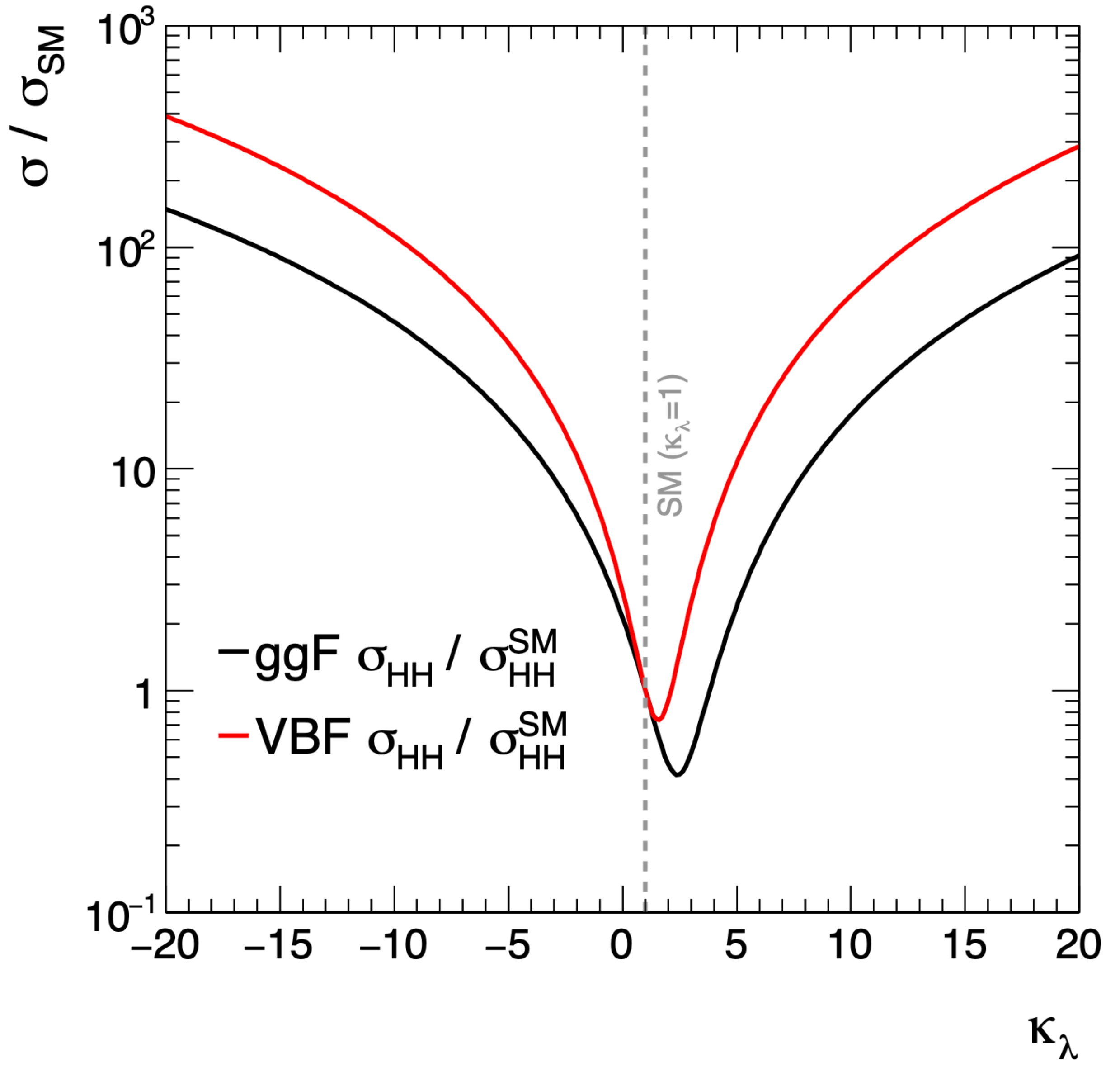
Contribution sensitive to κ_λ predominantly at low m_{HH}

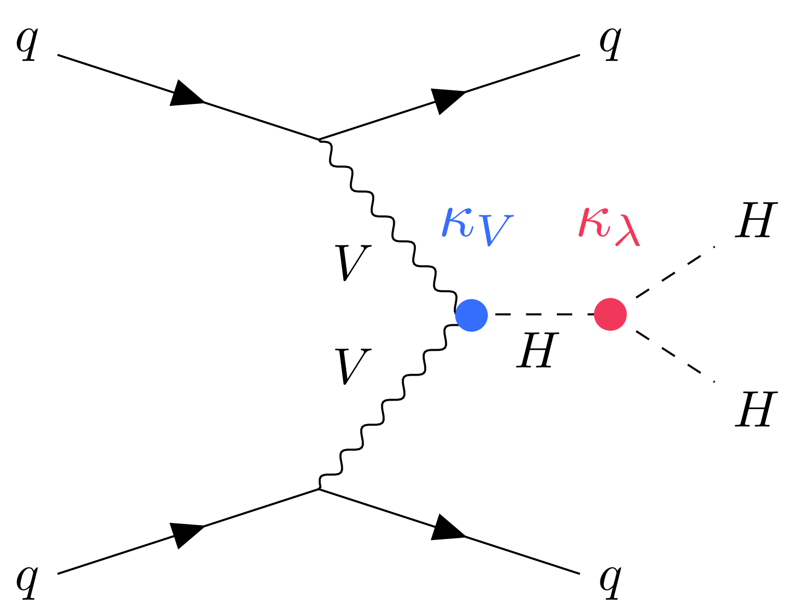
Larger values of $|\kappa_\lambda|$ enhance the HH production cross-section significantly

HH diagrammatics: VBF

- VBF HH production has ~ 6 x lower cross-section compared to ggF HH production

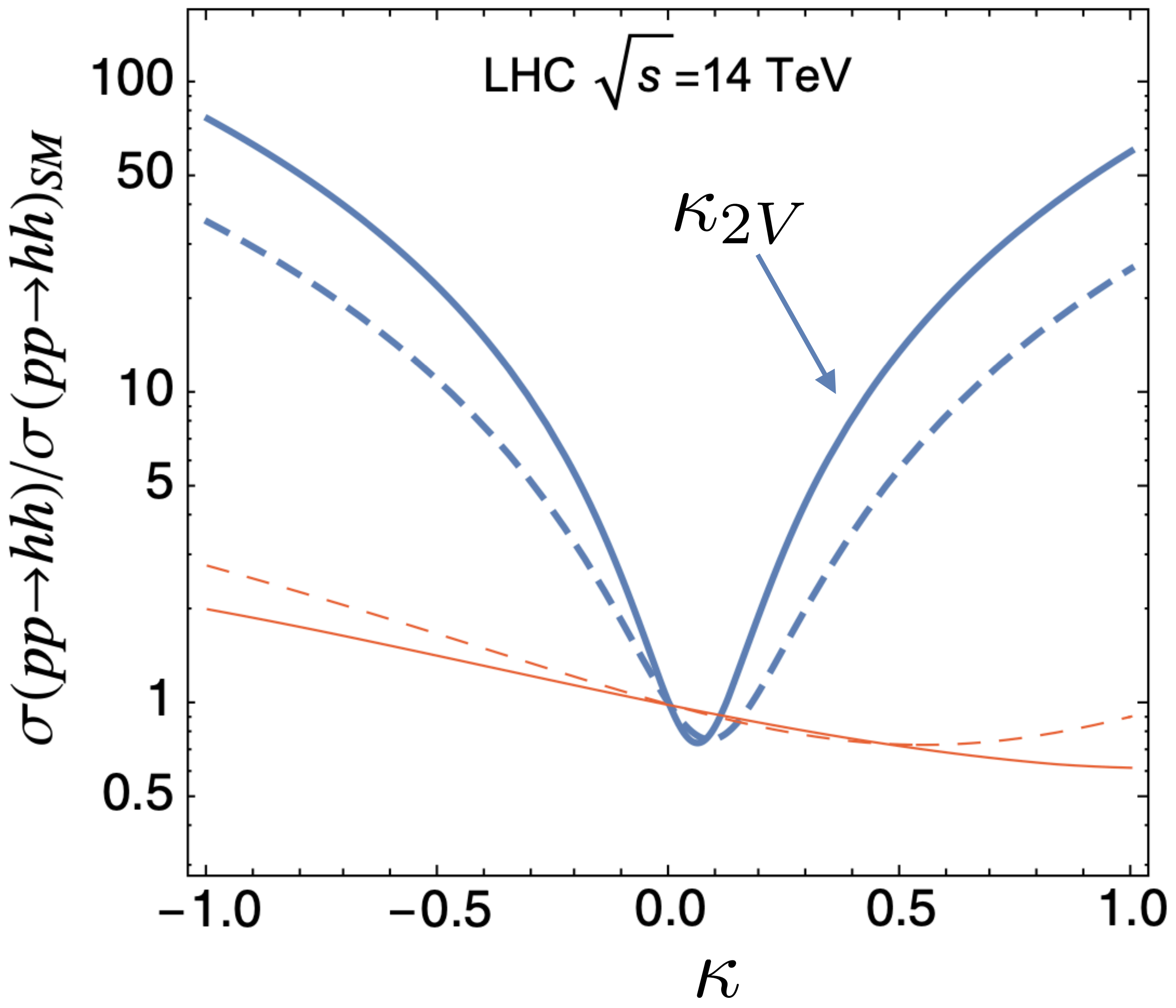
sensitive to HHH coupling

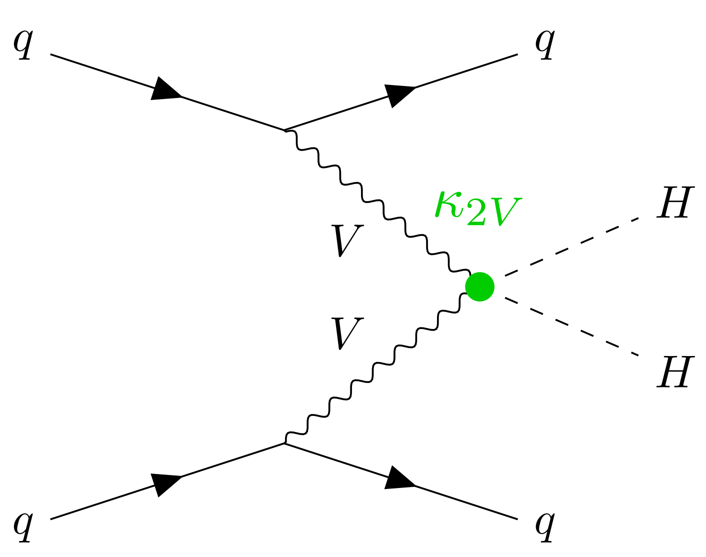




VBF HH is also very sensitive to κ_λ variations [absolute XS always below ggF HH, however]

unique sensitivity to VVHH coupling

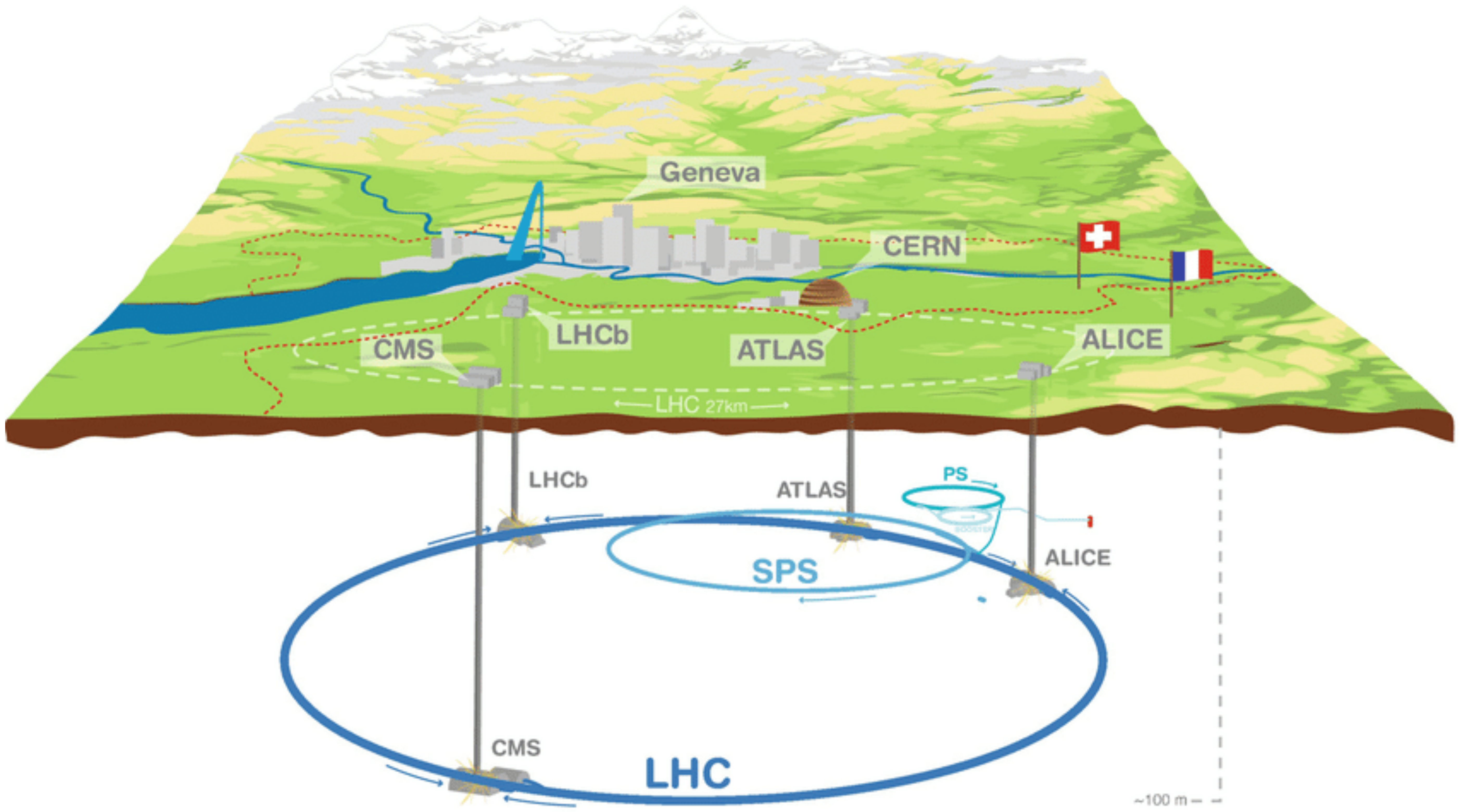




In case of a deviation in κ_V, κ_{2V} can be used to determine whether H is part of a doublet [$\Delta\kappa_V \sim 2\Delta\kappa_{2V}$]

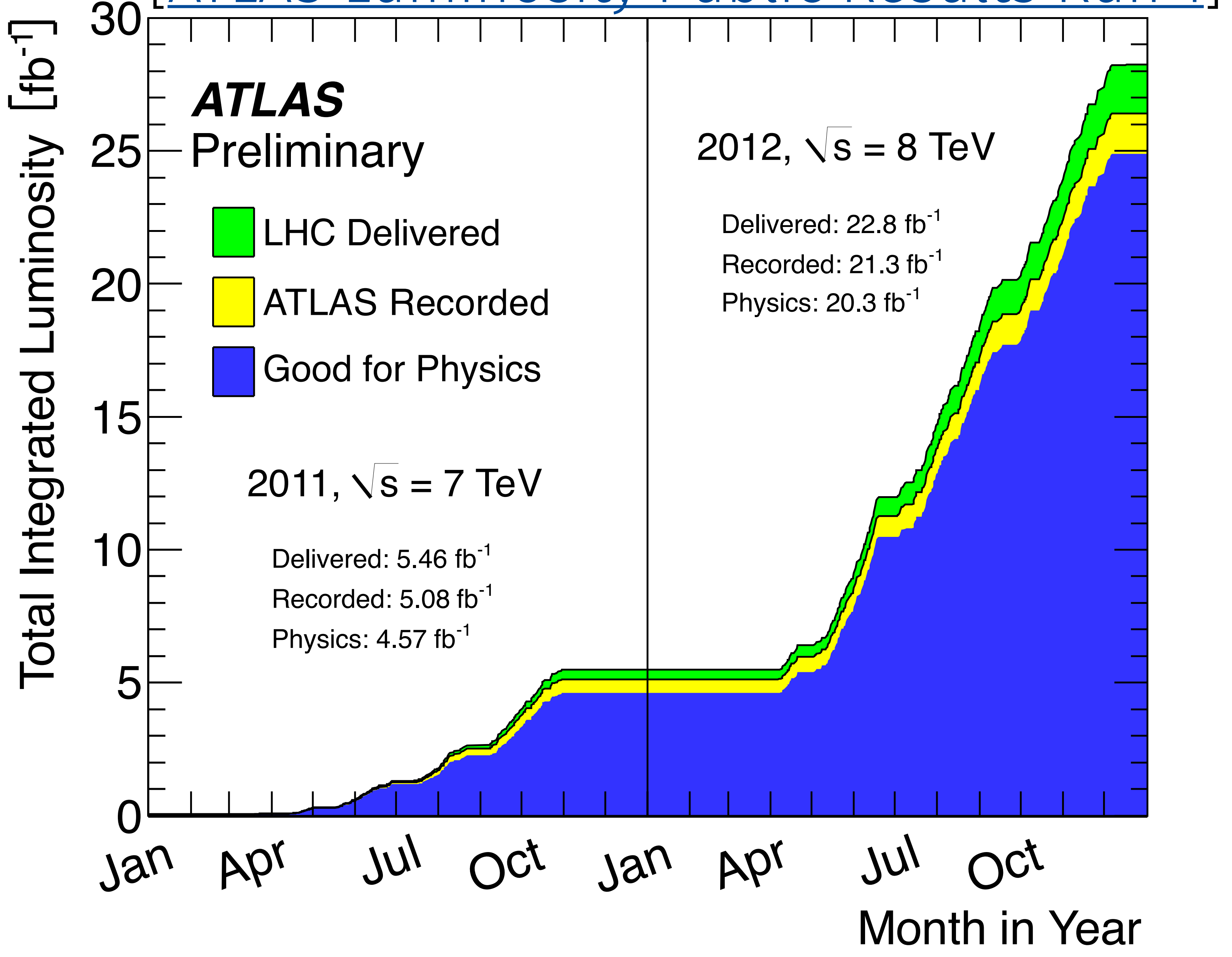
The Large Hadron Collider

- proton proton collider with a circumference of ~ 27km at CERN in the Geneva area

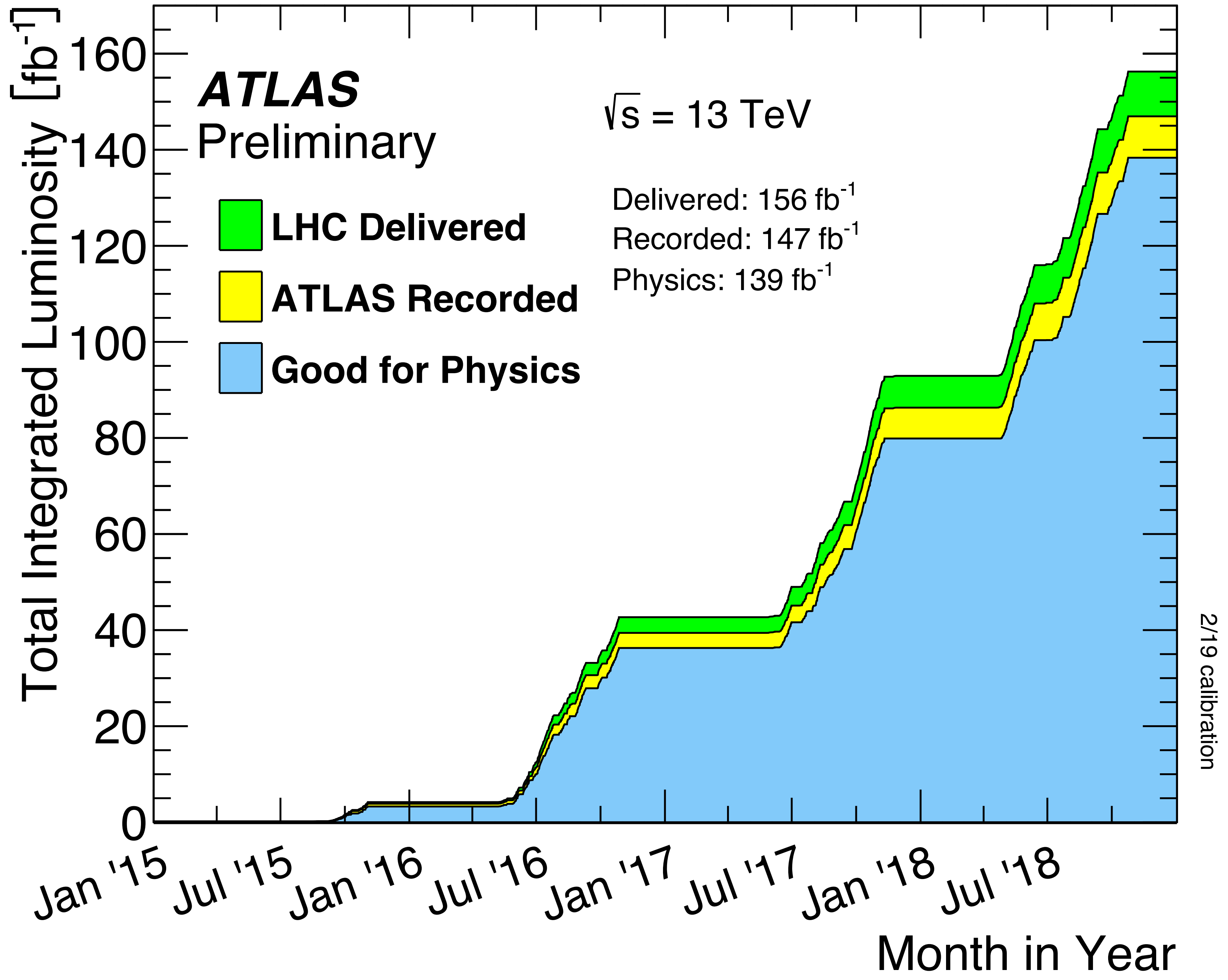


- 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV and 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV (Run 1)
- 139 fb^{-1} at $\sqrt{s}$ = 13 TeV (Run 2)

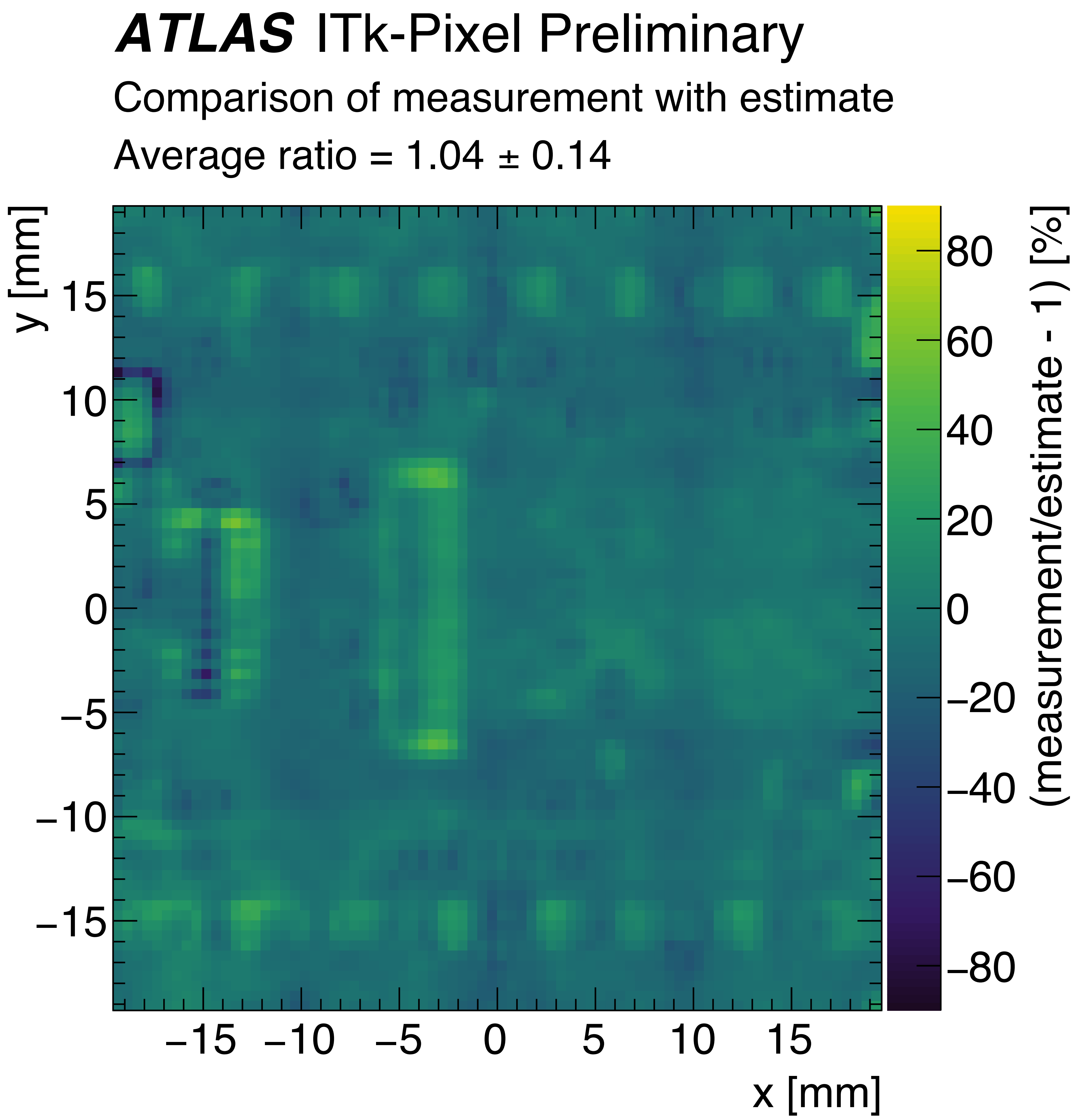
[ATLAS Luminosity Public Results Run 1]



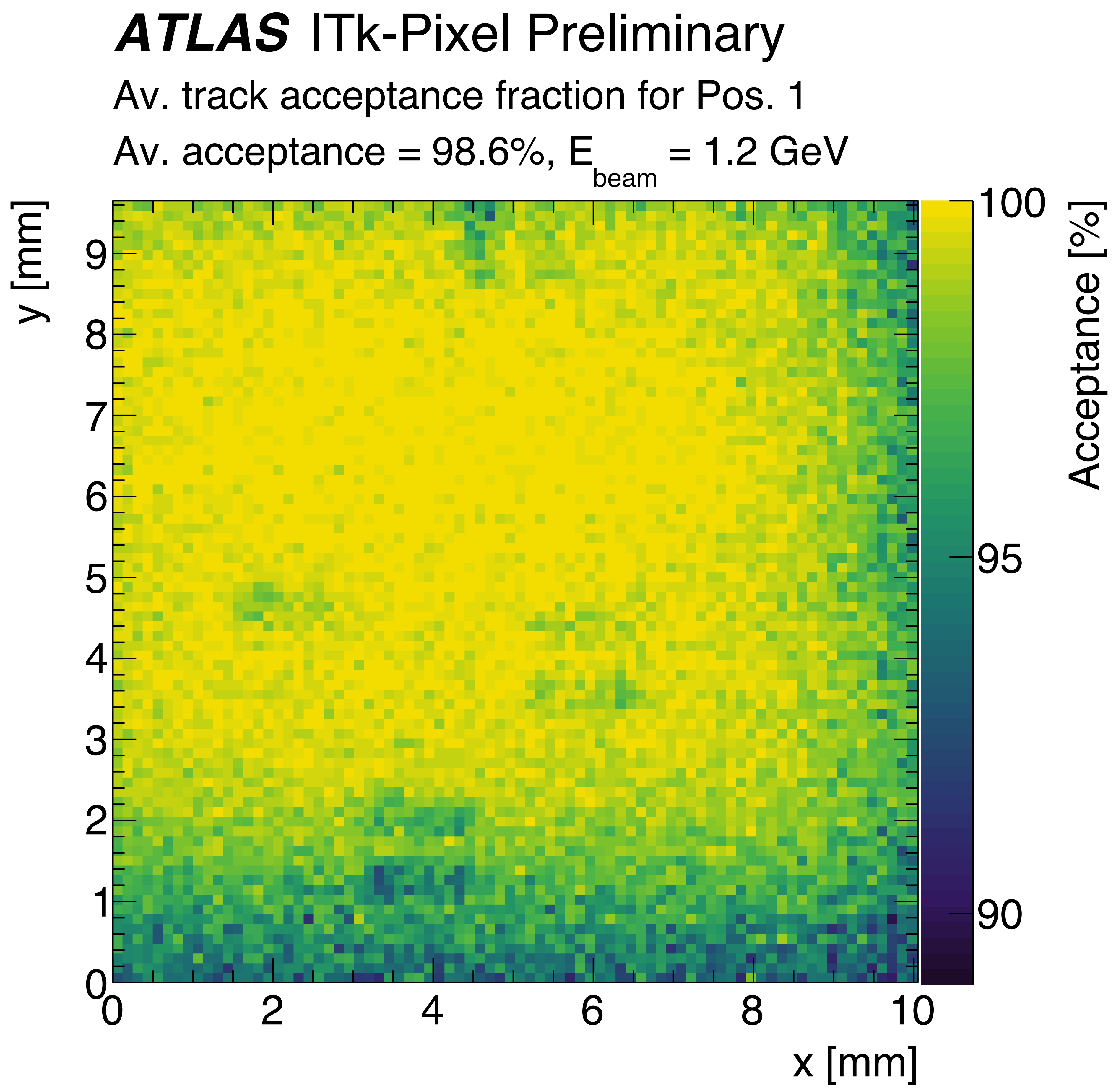
[ATLAS Luminosity Public Results Run 2]



x/X_0: Comparison of measurement with estimate



x/X$_0$: geometric acceptance fraction



Standard Model Effective Field Theories

Taylor expanding the SM in (E,vev)/Λ:

energy scale
of the process

energy scale of new physics

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4}\mathcal{O}_i^{(8)} + \dots$$

Wilson coefficients
= free parameters of the theory

operators from SM fields with higher mass dimension
(Lorentz invariance, gauge invariance, locality)

Standard Model Effective Field Theories

Taylor expanding the SM in (E,vev)/Λ:

violate L,
some violate B,
high suppression

further suppressed

19 parameters

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4}\mathcal{O}_i^{(8)} + \dots$$

1 operator type
(Weinberg operator)

Majorana ν masses
(m_ν small -> Λ_i high)

2499 parameters with ΔL=ΔB=0
+ O(300) with ΔL=ΔB=1 ⟶ proton decay -> Λ_i high

76 assuming $U(3)^5$ flavor symmetry

Allows for a systematic classification of all the possible new physics signals

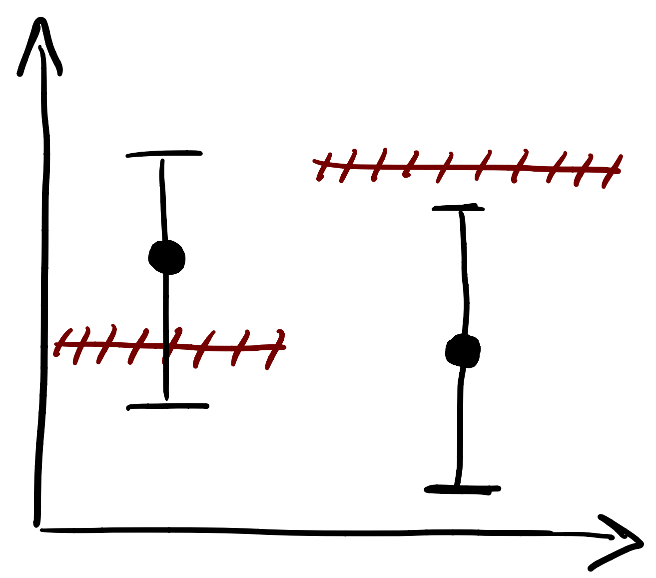
Standard Model Effective Field Theories

Taylor expanding the SM in (E,vev)/Λ:

76 assuming U(3)⁵ flavor symmetry

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda_i}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda_i^4}\mathcal{O}_i^{(8)} + \dots$$

Measurements

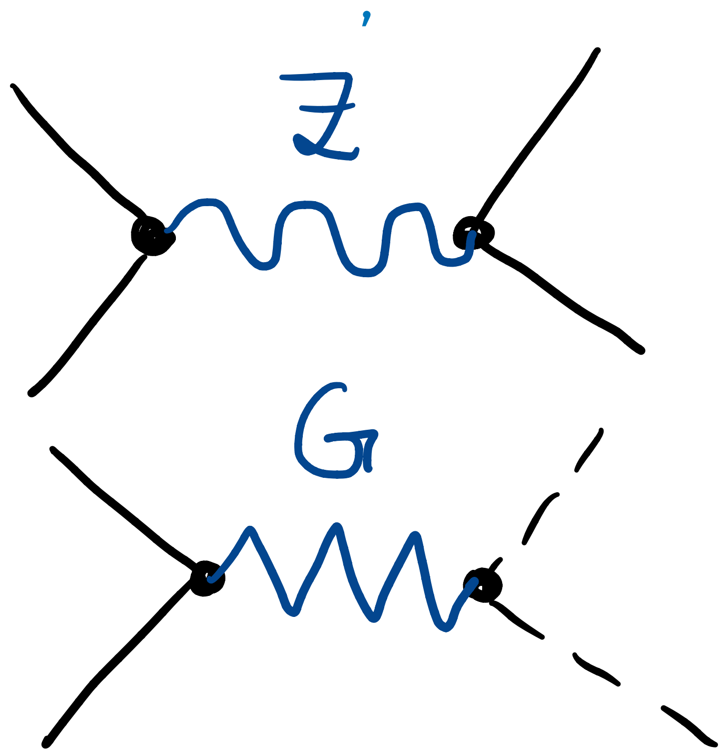


EFT interpretations

Limits

$$\mathcal{L}_6 = \sum_i c_i \; \mathcal{O}_i^{(\mathrm{dim}=6)}$$

UV complete models



A few impressions from the setup