LHC Run 3 and HL-LHC

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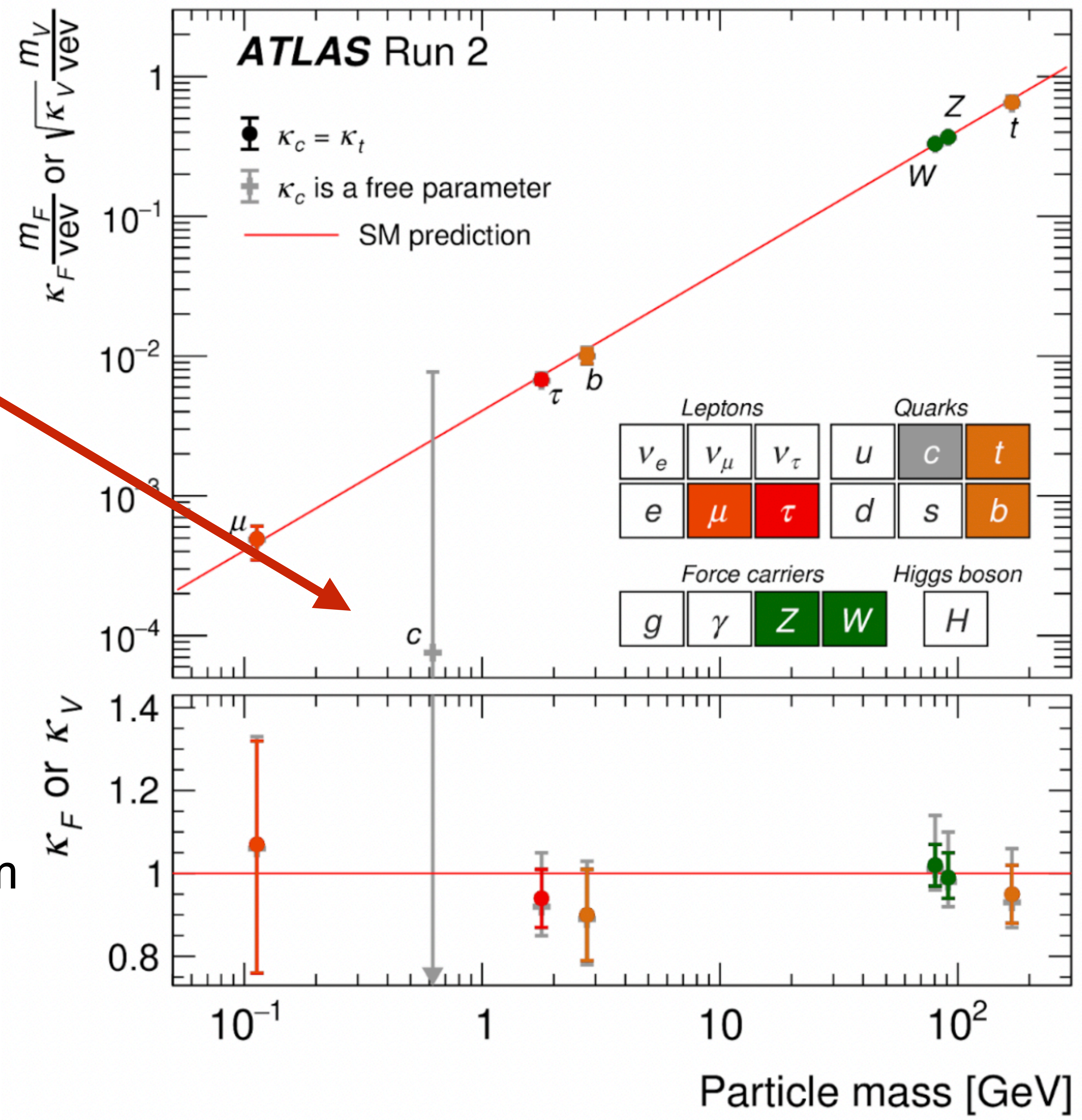
Lecture 2

Higgs couplings to 2nd generation: c quarks

Run 3 will serve as a fundamental benchmark for studying the coupling to second-generation quarks, specifically the charm quark.

Decays of the Higgs boson into a pair of c ("charm") quarks are relatively common; however, the challenge lies in accurately identifying them based on their detector signature.

When high-energy quarks transform into collimated jets of bound states known as hadrons, those originating from b or c quarks travel a finite distance before decaying (D lifetime 10^{-15} s, B lifetime 10^{-12} s)

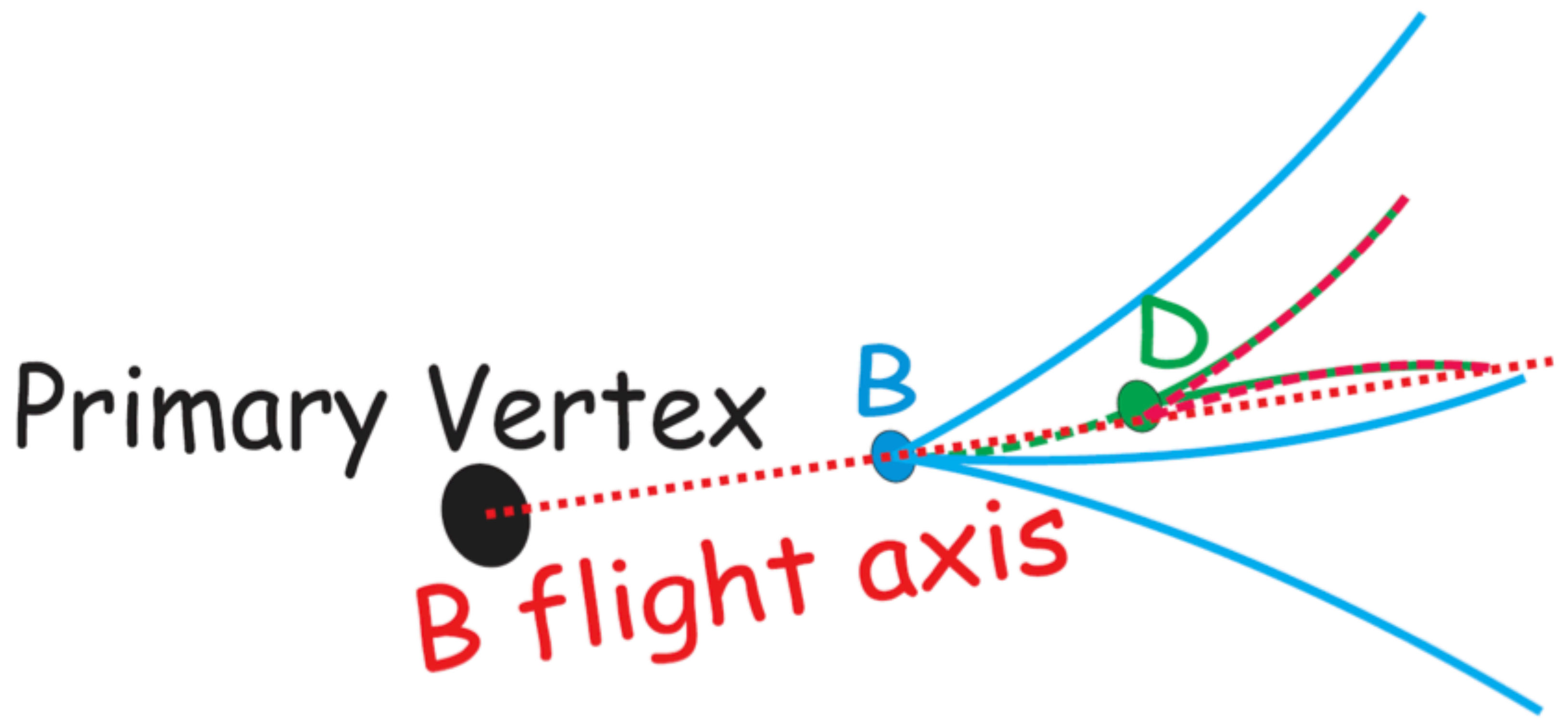


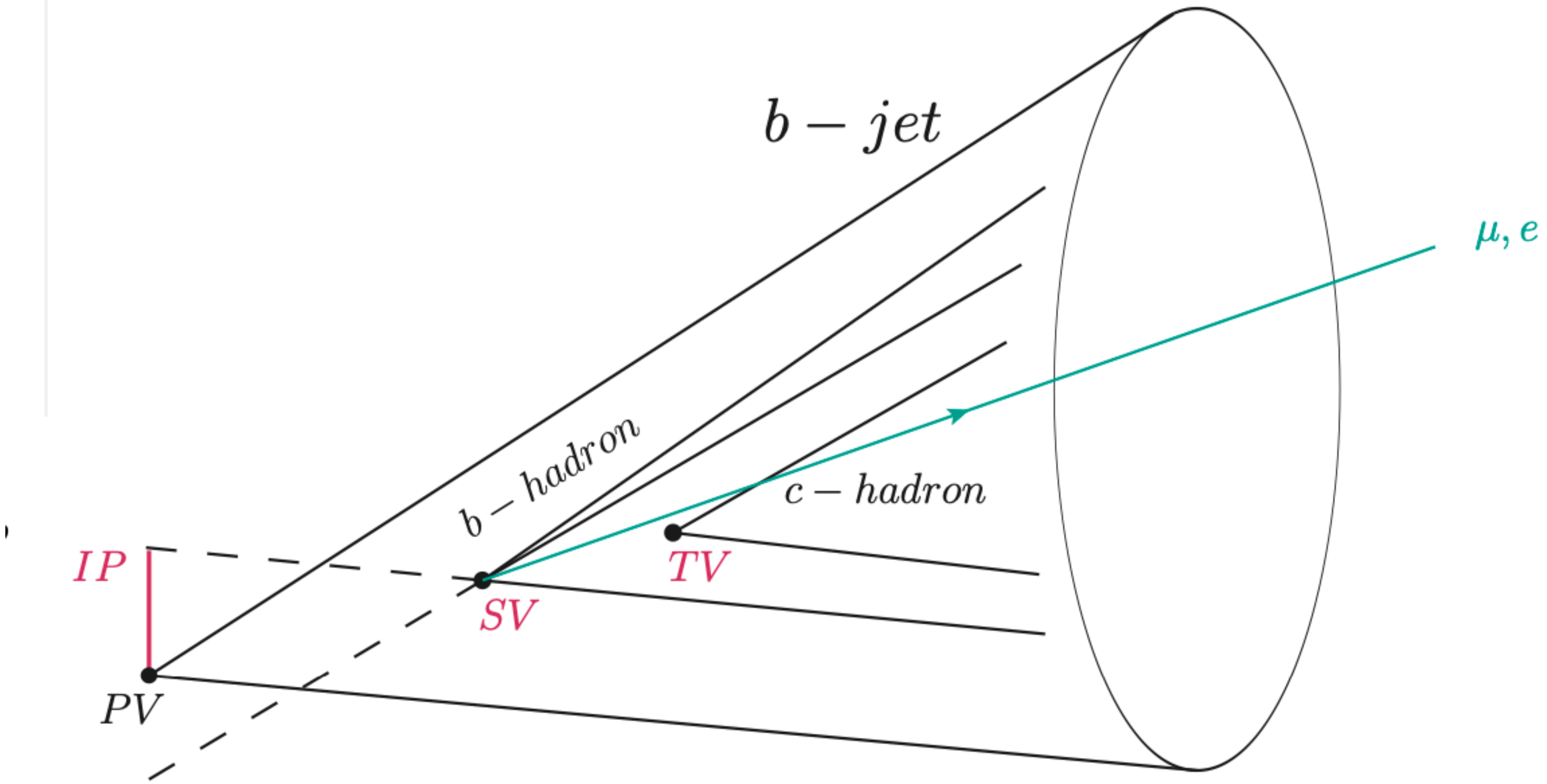
Techniques based on distance measurements have proven effective in identifying the long-lived and heavy b quarks of the third generation.

To address the more challenging scenario of the shorter-lived and lighter charm quarks, innovative analysis techniques and the utilization of boosted Higgs decays have brought the charm quark within reach for the High-Luminosity phase of the LHC. Run 3 will be instrumental in testing and establishing new analysis strategies to pave the way forward.

Flavor tagging

We tag b-hadrons and c-hadrons thanks to the fact that there is a secondary vertex

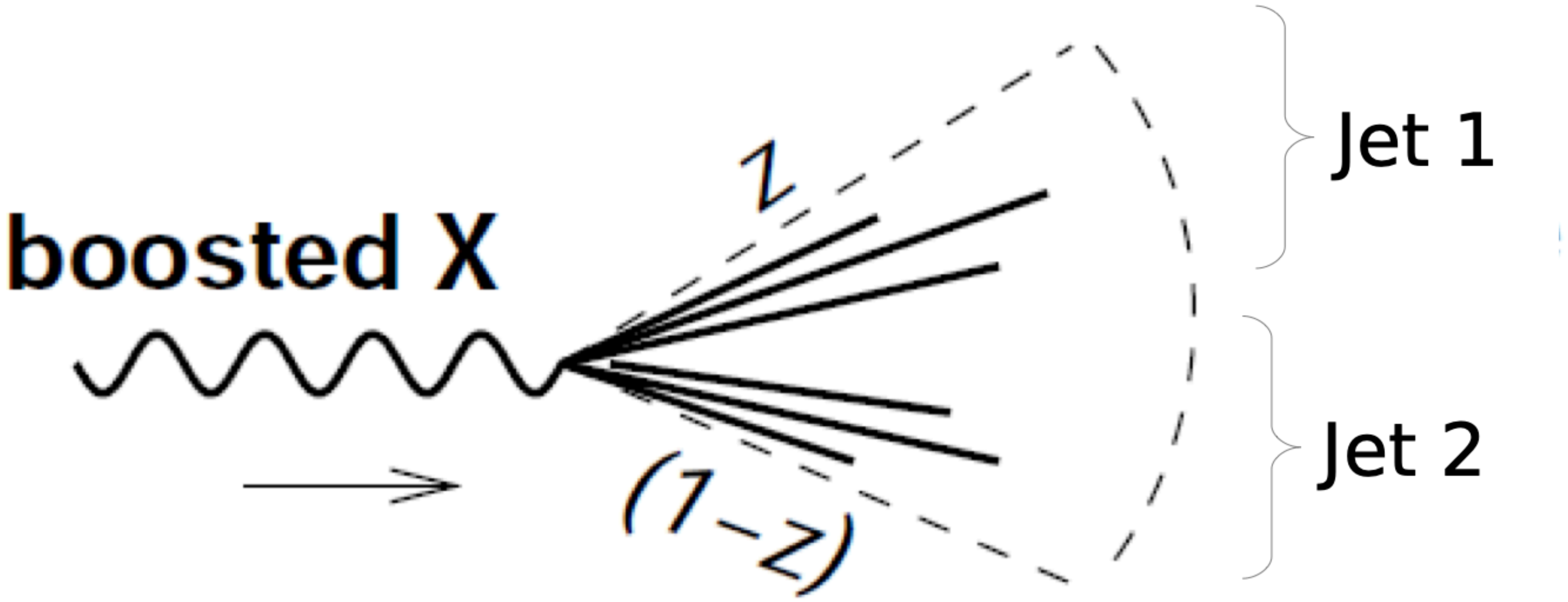




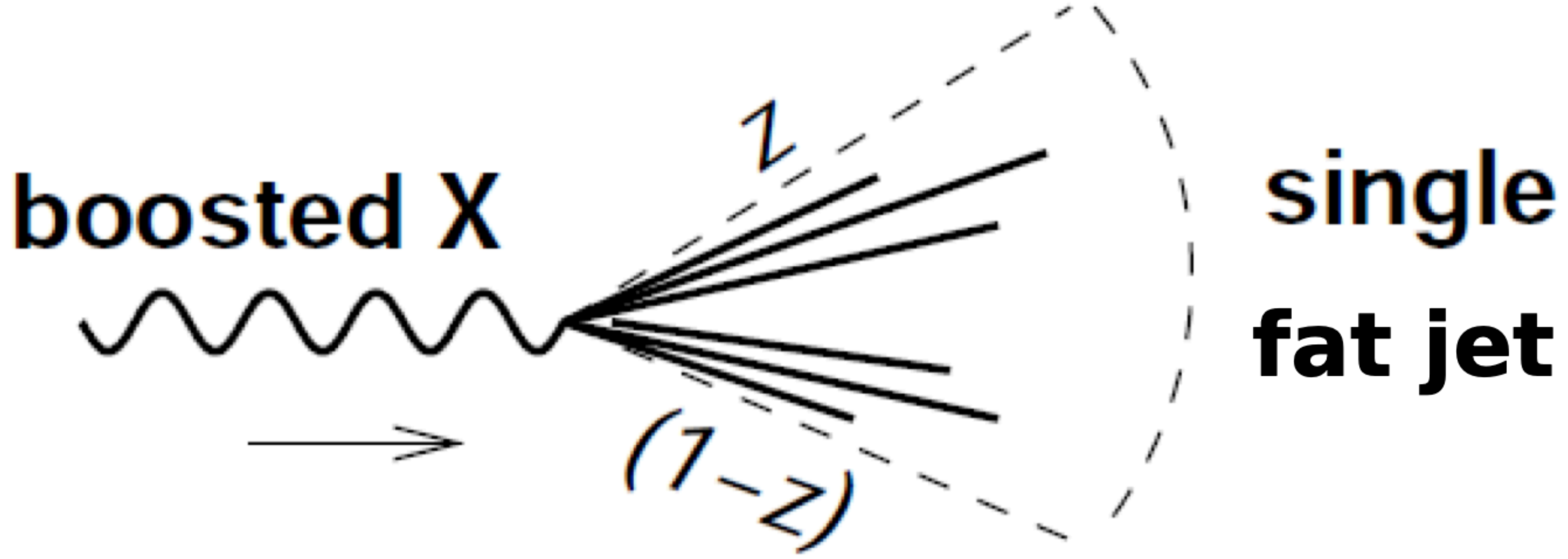
Boosted objects

At the LHC given the large center of mass energy and given that the SM particles have masses below 200 GeV, also the heaviest SM particles often acquire large momentum >> m → production of “boosted objects”

Normally we reconstruct jets with R=0.4,
if the object is boosted the jets in which it decays cannot be resolved in small r-jets

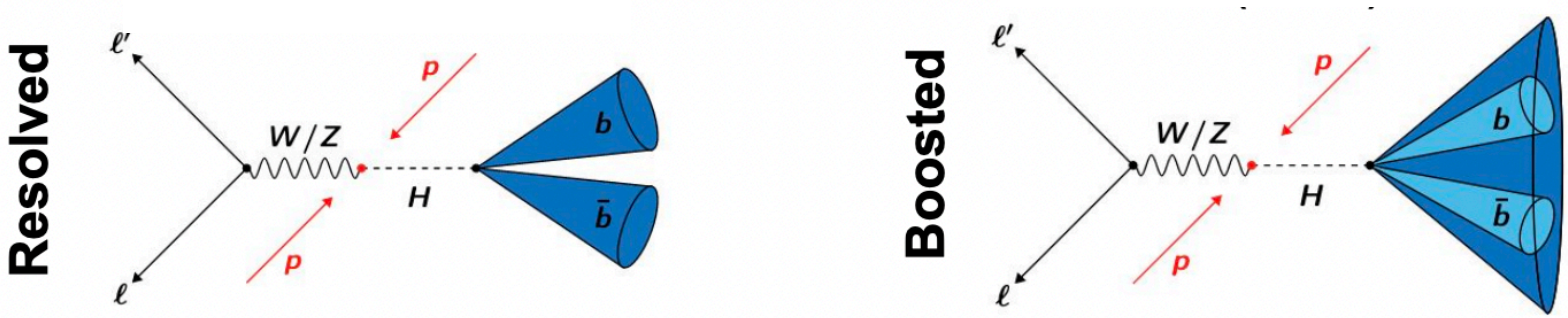


Recover sensitivity to boosted objects by developing boosted taggers, using larger R

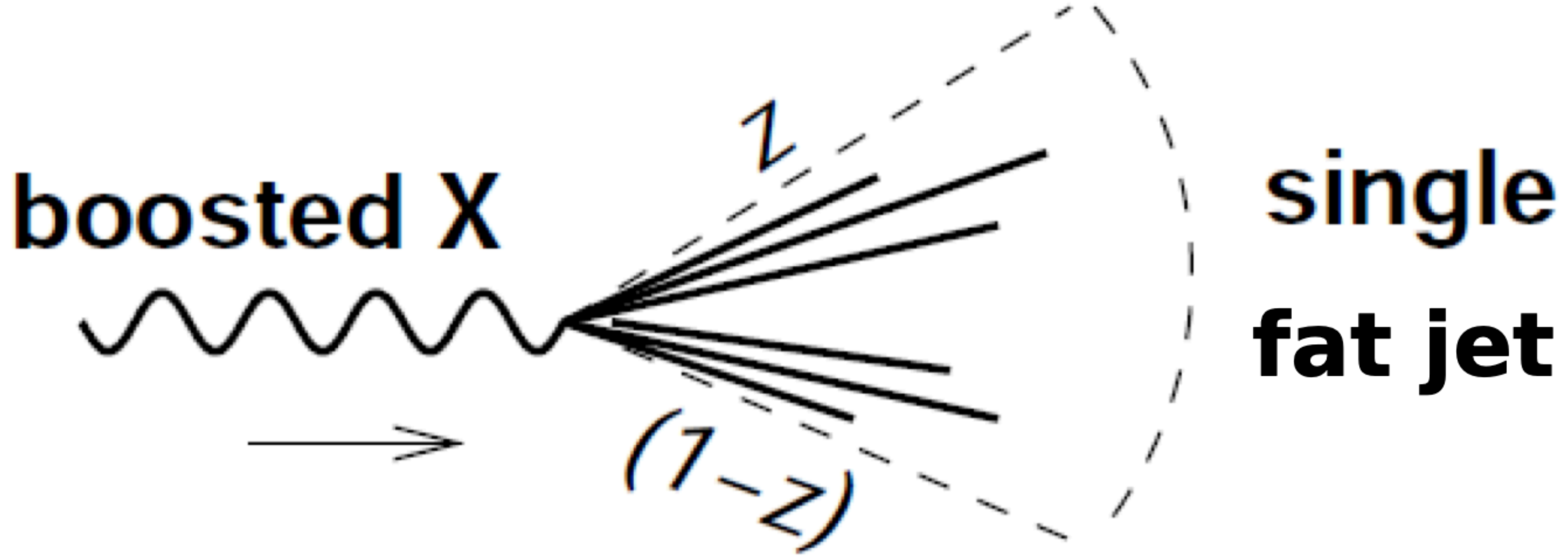


Boosted objects

At the LHC given the large center of mass energy and given that the SM particles have masses below 200 GeV, also the heaviest heaviest SM particles often acquire pT >> m → production of “boosted objects”



Recover sensitivity to boosted objects by developing boosted taggers, using larger R



Higgs boosted taggers for H→cc

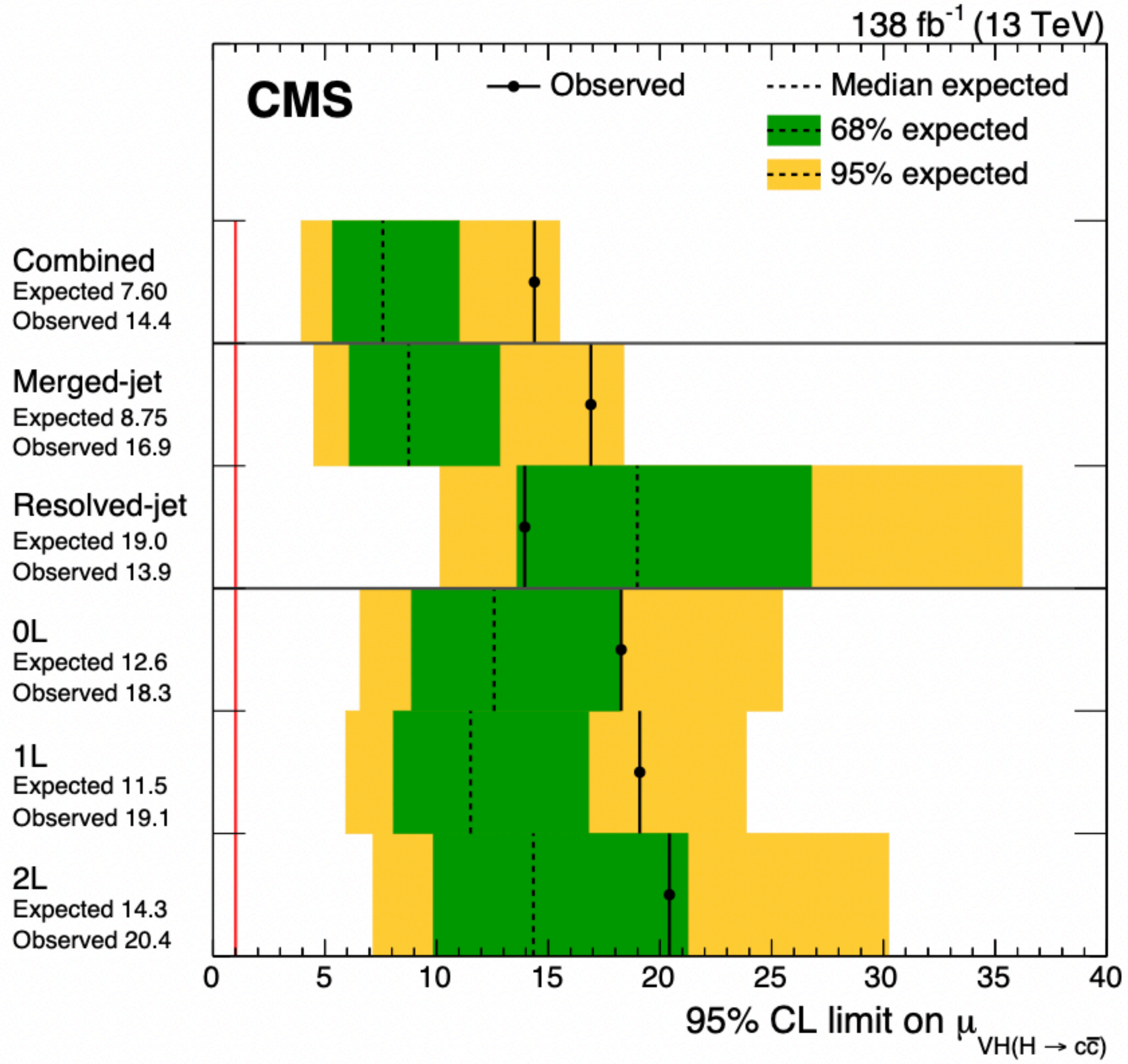
arXiv:2205.05550

Latest CMS Run 2 results (dataset 20 times smaller than HL-LHC) has sensitivity of 3.4 times the SM coupling in VH (WH,ZH) production mode. When the V has a large pT, the Higgs is boosted.

expected $|k_c| < 3.4$ observed $1.1 < |\kappa_c| < 5.5$ @95% CL

thanks to exploitation of flavour tagging + reconstruction of the m_Higgs through boosted large R-jet using modern Machine learning techniques.

HL-LHC Lumi→ Expected sensitivity↓	VH(→ cc)	
	$3\ ab^{-1}$	$2.5\ ab^{-1}$
ATLAS	-	-
CMS	1.3	1.2
Combined	1.9	1.7



Adding inclusive Higgs and the VBF production modes +various improvements could lead to first direct evidence for the Yukawa coupling of the Higgs boson to charm at HL-LHC

It is therefore extremely important as an intermediate goal of Run 3 that progress is shown by all experiments in improving their sensitivity in this channel:

Graph nets

Graph nets

- Graph nets can be neural networks operating on graphs, but can be implemented with functions very different from neural networks. arXiv:1806.01261v3
Networks acting on a “graph” rather than a vector of inputs, with output being a graph: Lot of activity on this in the past years in industry

  Here one can find open-source software library for building graph nets, with demonstrations on how to use them:
  https://github.com/deepmind/graph_nets

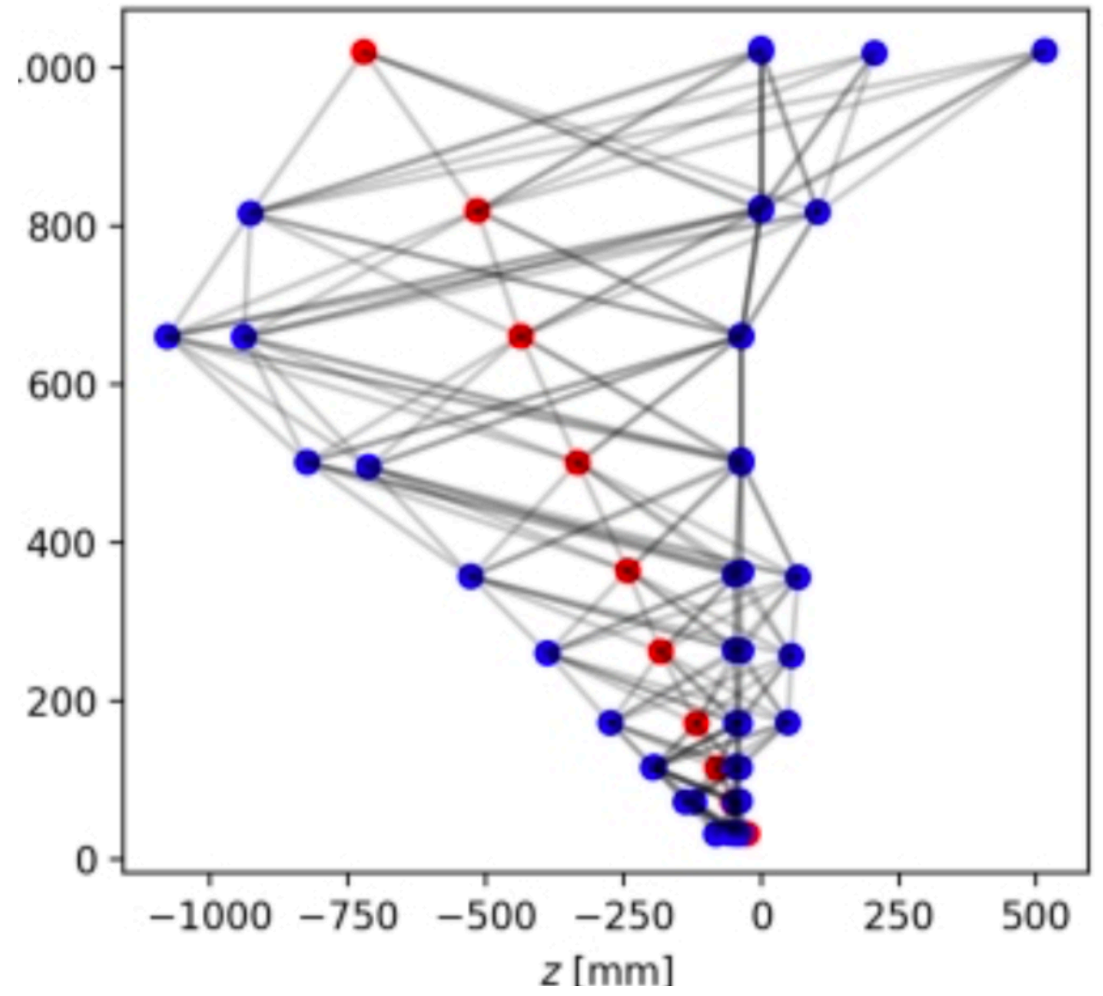
- Quite some possibile applications: they have been used already for a variety of cases:
  - to learn the dynamics of physical systems (Battaglia et al., 2016; Chang et al., 2017; Watters et al., 2017; van Steenkiste et al., 2018; Sanchez-Gonzalez et al., 2018)
  - to predict the chemical properties of molecules (Duvenaud et al., 2015; Gilmer et al., 2017)
  - to predict traffic on roads (Li et al., 2017; Cui et al., 2018)
  - to classify and segment images and videos (Wang et al., 2018c; Hu et al., 2017)
  - to perform semi-supervised text classification (Kipf and Welling, 2017)
  - in machine translation (Vaswani et al., 2017; Shaw et al., 2018; Gulcehre et al., 2018)…

Graph nets: demo

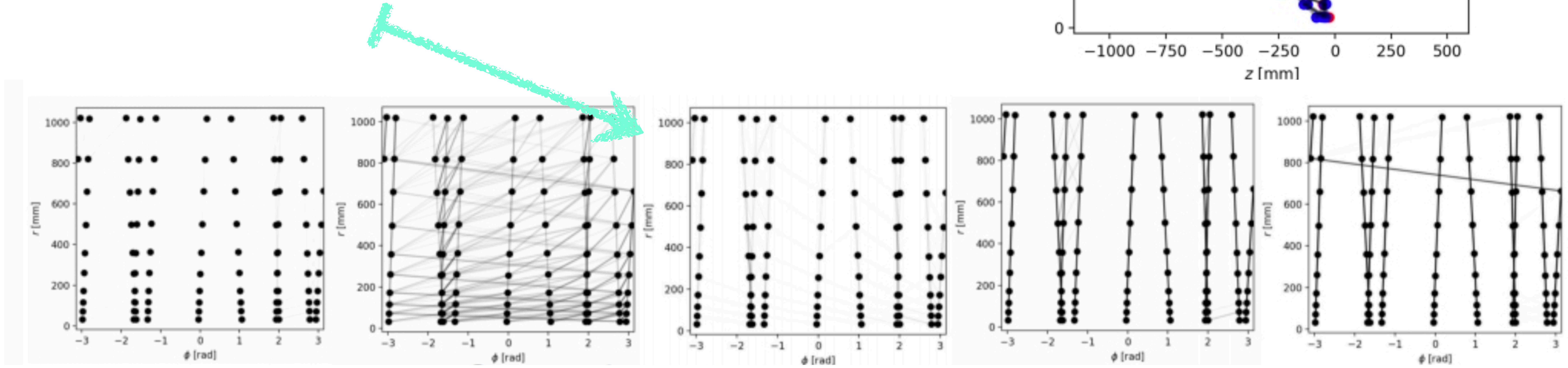
- Find the shortest path in a graph: demo: tinyurl.com/gn-shortest-path-demo
This demo creates random graphs, and trains a GN to label the nodes and edges on the shortest path between any two nodes. Over a sequence of message-passing steps (as depicted by each step's plot), the model refines its prediction of the shortest path.

Where could we apply graph-nets?

- A great improvement could be achieved by applying graph-nets to tracking
- Tracking is a very time consuming reco task at LHC (most consuming?)
- When applying graph-nets
  to track building one
  could for example use them to pair hits



Successive iterations on an event

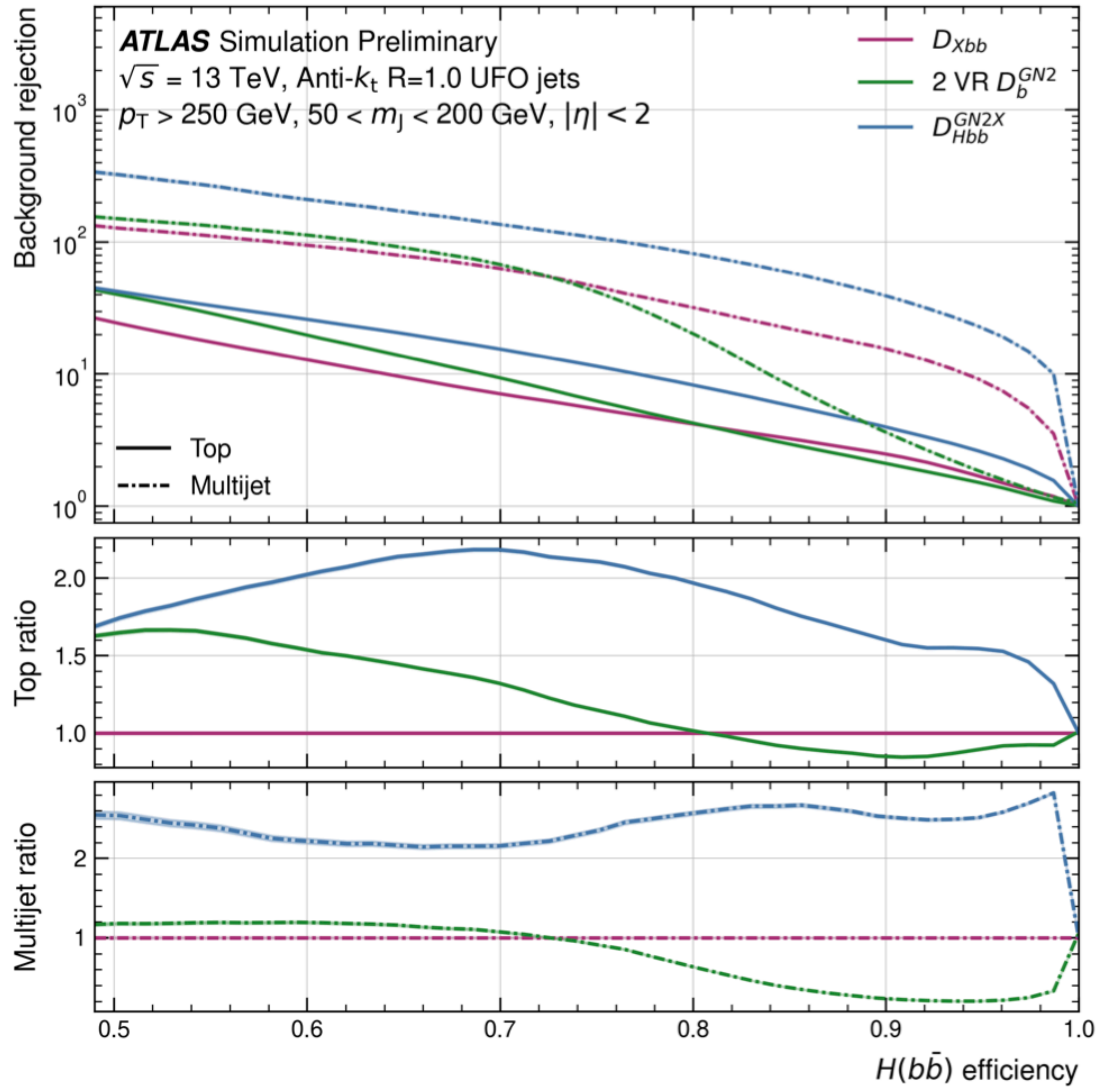


Higgs

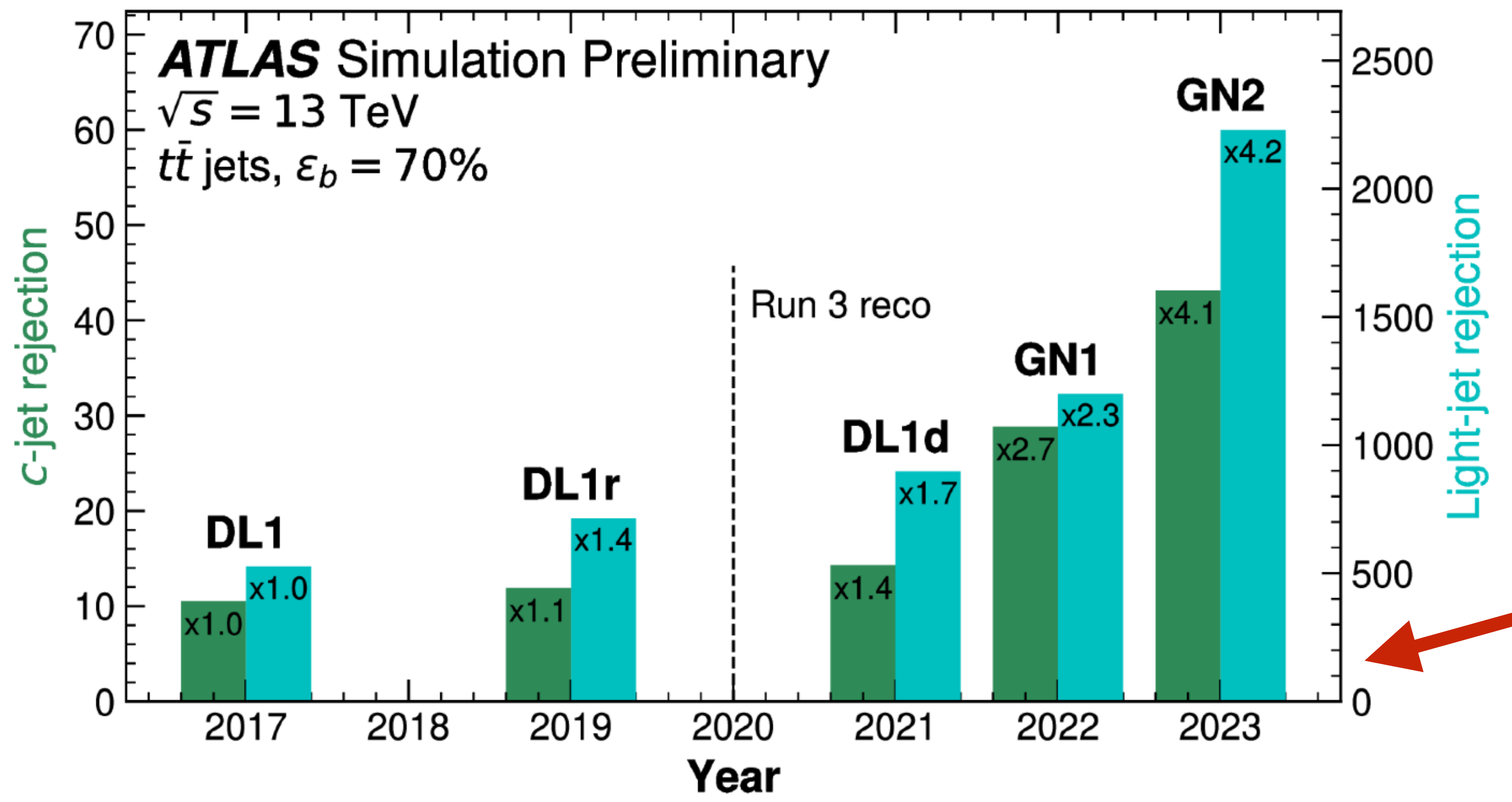
Flavor tagging in continuous evolution

Boosted H->bb/cc tagging
ATL-PHYS-PUB-2023-021

- Boosted b-tagging: new algorithm, GN2X for large-radius jets: tagging boosted H(bb) jets and H(cc) jets.



small R-jet tagging
Jet Flavour Tagging With GN1 and DL1d

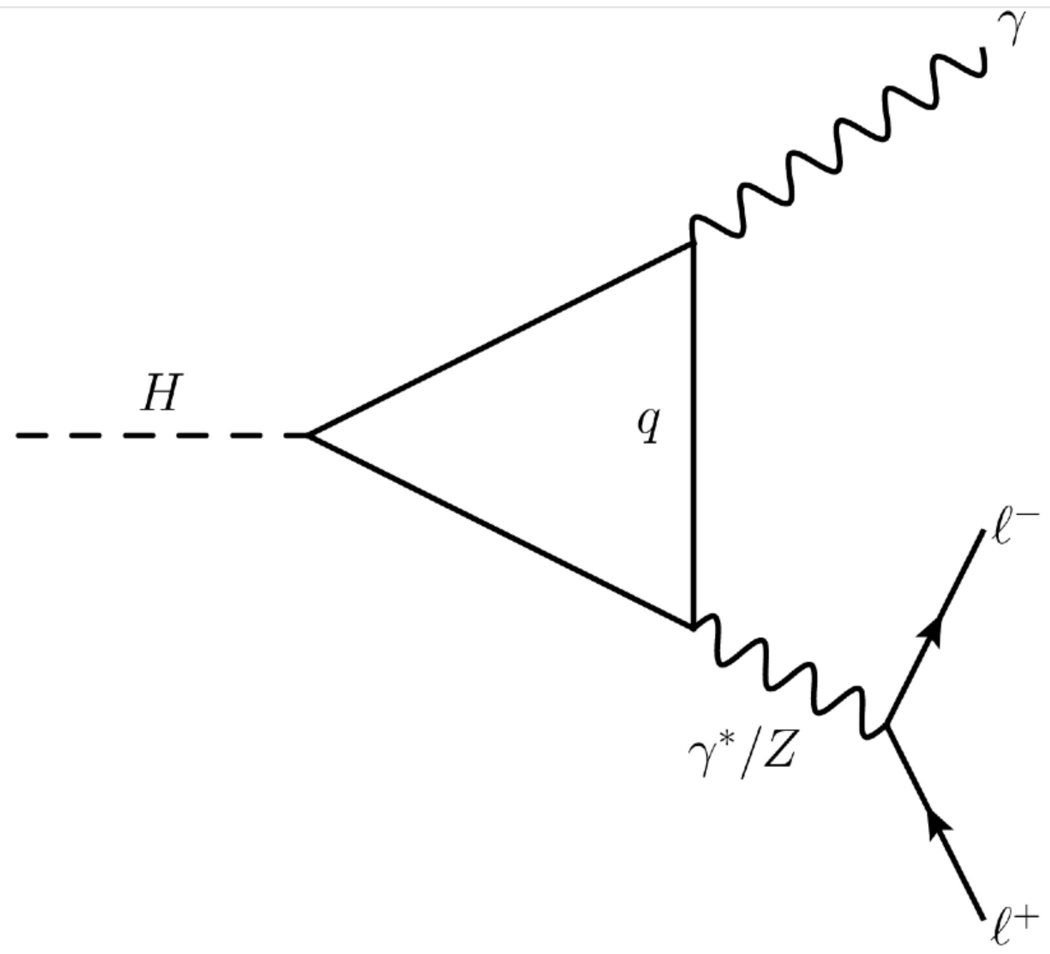


- GN2X benefits from advances in flavour tagging of small-radius jets with Graph Neural Networks (GNNs)

Rare processes: back on the envelope calculation based on SM expectations

Higgs

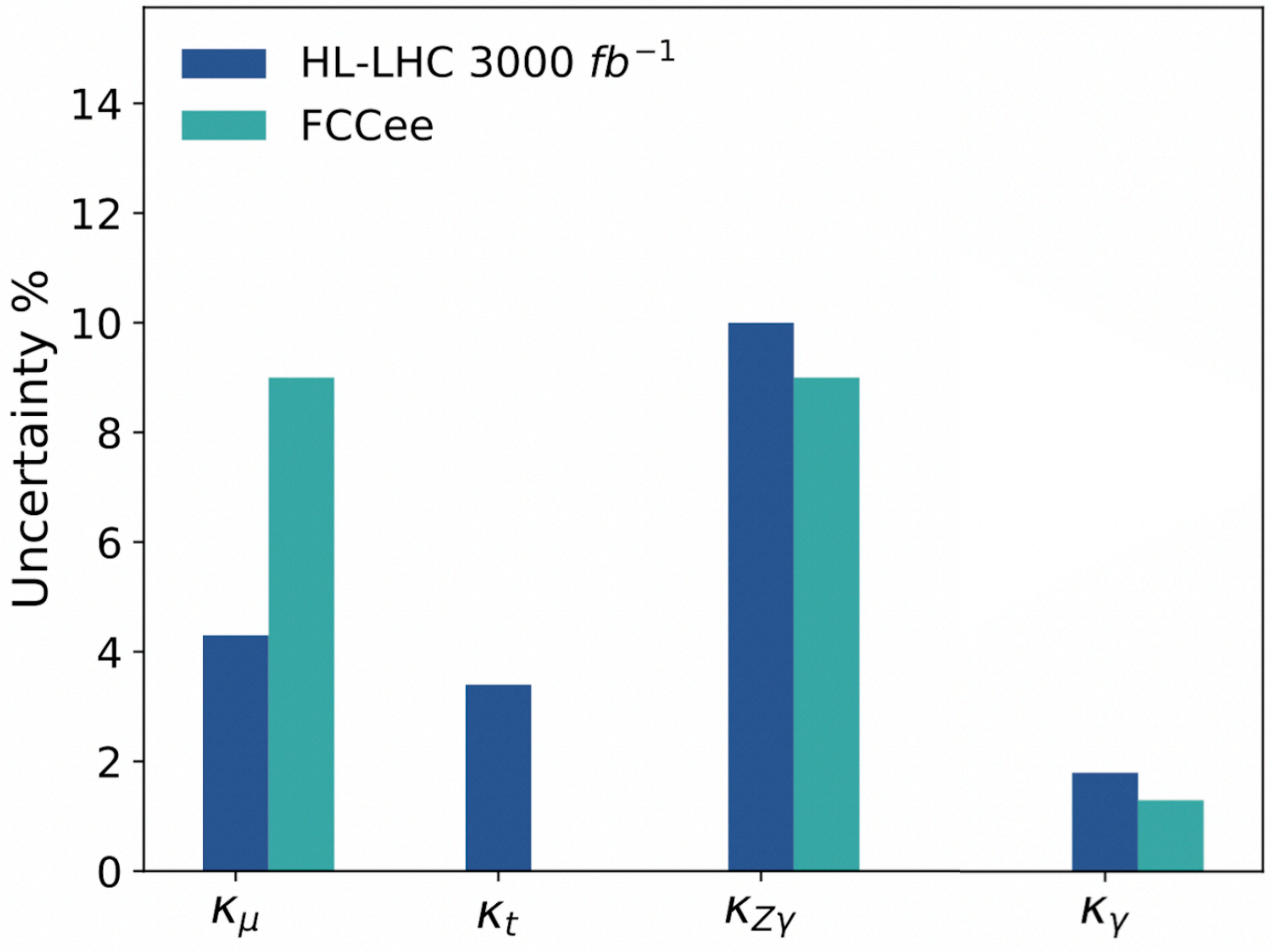
run3 Lumi→ expected sensitivity↓	H->μμ		H->γγ*		H->Zγ		HH	
	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb
ATLAS	2.8	2.6	3.5	3.3	2.0	1.9	1.2	1.1
CMS	4.2	4.0	-	-	2.0	1.9	1.3	1.2
Combined	5.0	4.8	5.0	4.7	2.8	2.6	1.8	1.6



Can reach combined observation in Run 3

γ* is a virtual particle with(non zero) mass, decays instantly to two leptons mℓℓ<30 GeV (typically <1 GeV) pT, small leptons separation ~cm (challenge for electrons)

What will the HL_LHC bring?



The ultimate precision on Higgs couplings reachable at HL-LHC and FCCee.

Improvements in experimental techniques and theoretical calculations will be needed to reach as close as possible to a O(1%) precision for all these observables.

Higgs factories cannot probe κt in a model independent way, and can only reach a O(10%) accuracy on $\kappa\mu$, κt, $\kappa Z\gamma$,through loop effects in other decays, assuming no competing new physics contributions.

Higgs

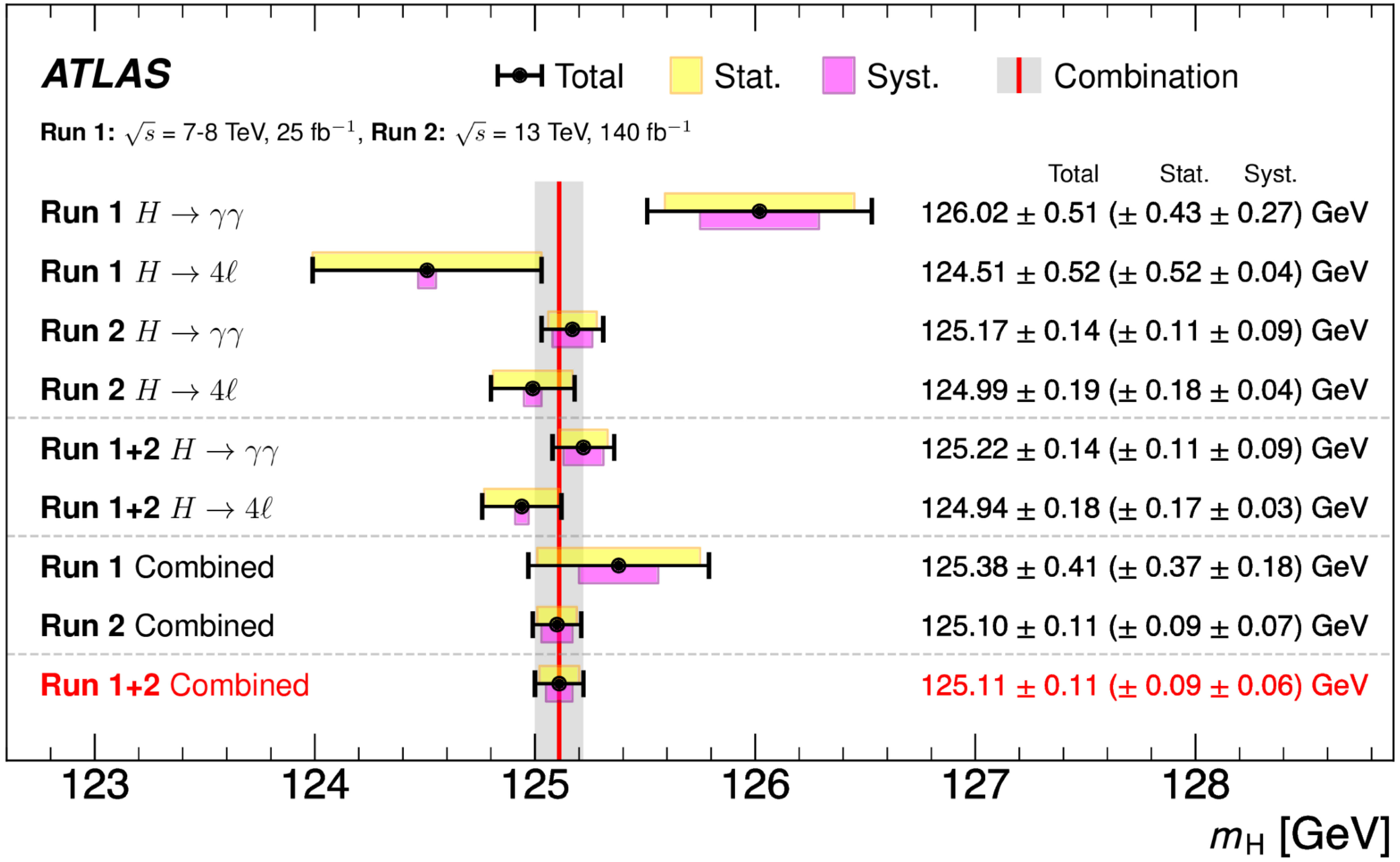
Higgs mass: great example of gain that reconstruction improvements can lead to

arXiv:2308.07216
arXiv:2308.04775

Combination of H →ZZ and H → γ γ provides:

most precise m_H measurement at 0.09%

m_H = 125.11 ± 0.11 GeV



Profits of various performance improvements:

- ~4x improvements in photon energy calibration!
  - due to 30% improvement in systematics: EM calorimeter layer calibration, measure of E lost around e/γ clusters.
  - Residual electron E scale non-linearities used for first time to constrain systematic uncertainties → further x2 improvement

➡Reduces $H \to \gamma\gamma$ systematics by factor 4:
320 MeV → 80 MeV

Higgs

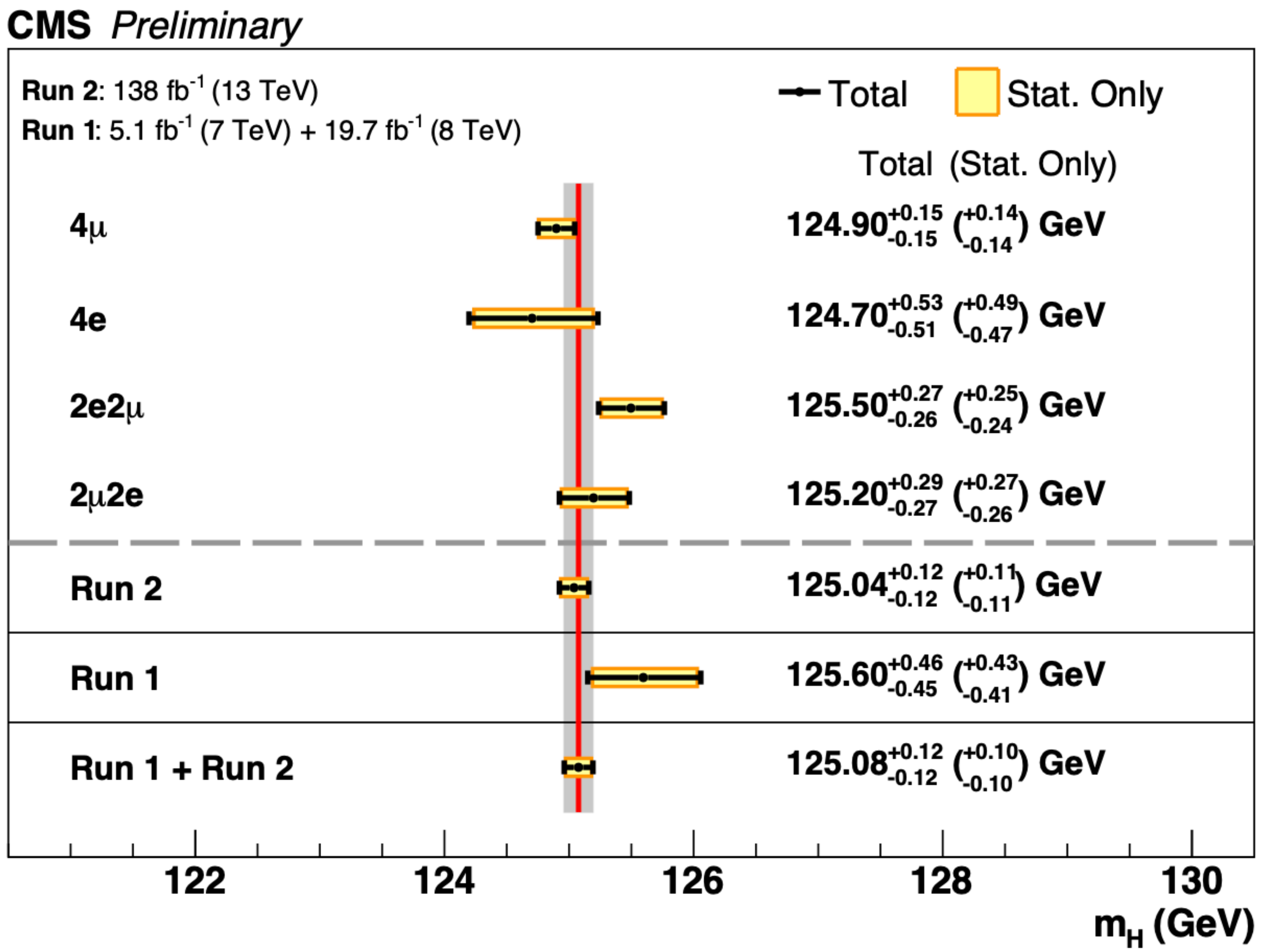
Higgs mass great example of gain that reconstruction improvements can lead to

ATLAS measures

$m_H = 125.11 \pm 0.11$ GeV

CMS measures in H->ZZ channel

$m_H = 125.04 \pm 0.12$ (stat.) ± 0.05 (syst.) GeV



Great agreement among the 2 experiments!

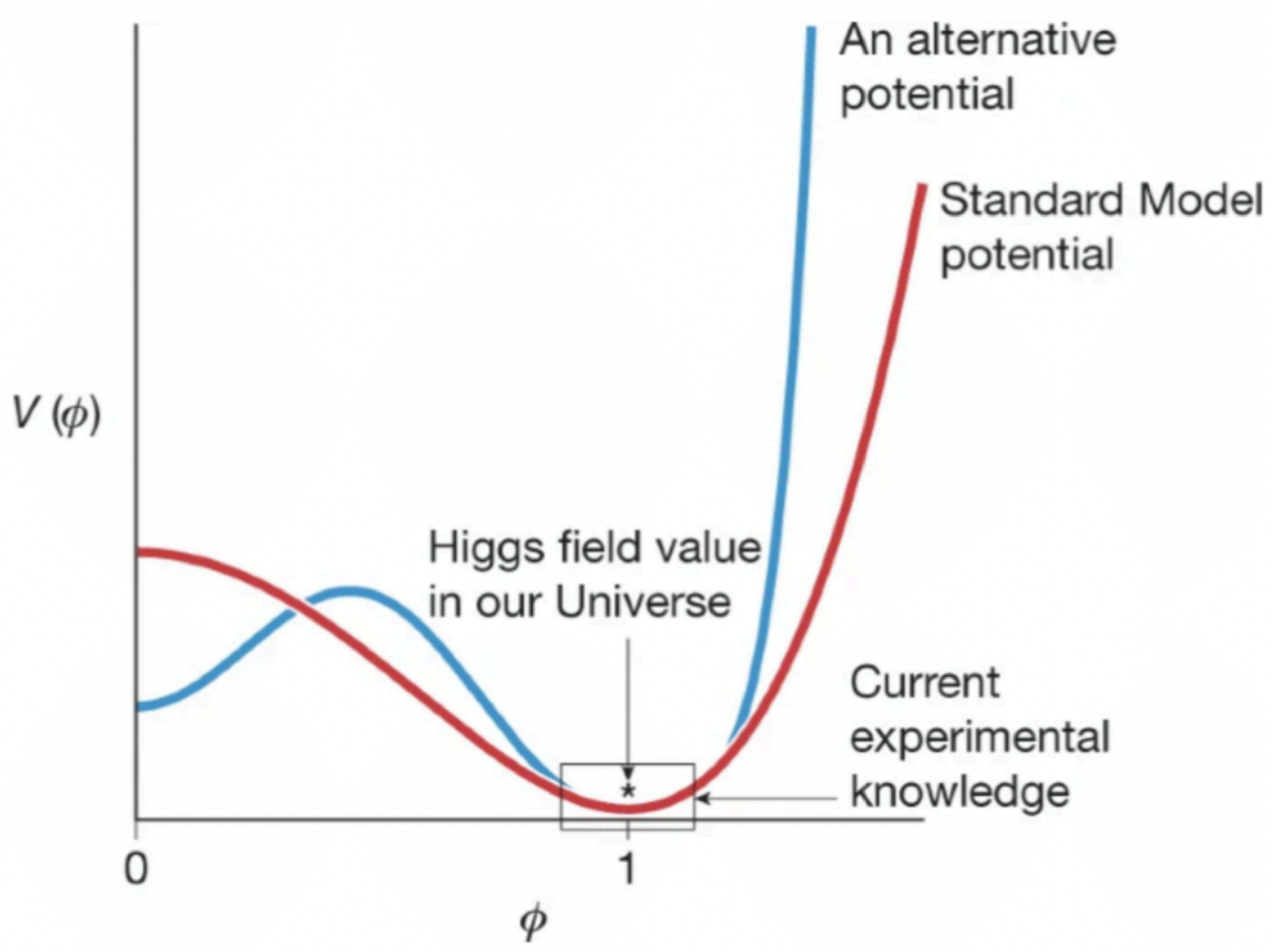
➡**CMS $H \rightarrow$ ZZ most precise single measurement**

HH

Higgs potential and self couplings

Understanding the shape of the Higgs potential is fundamental

[G. Salam, Nature 607, 41–47 (2022)]



mass term, indicating a physical particle,
the Higgs boson

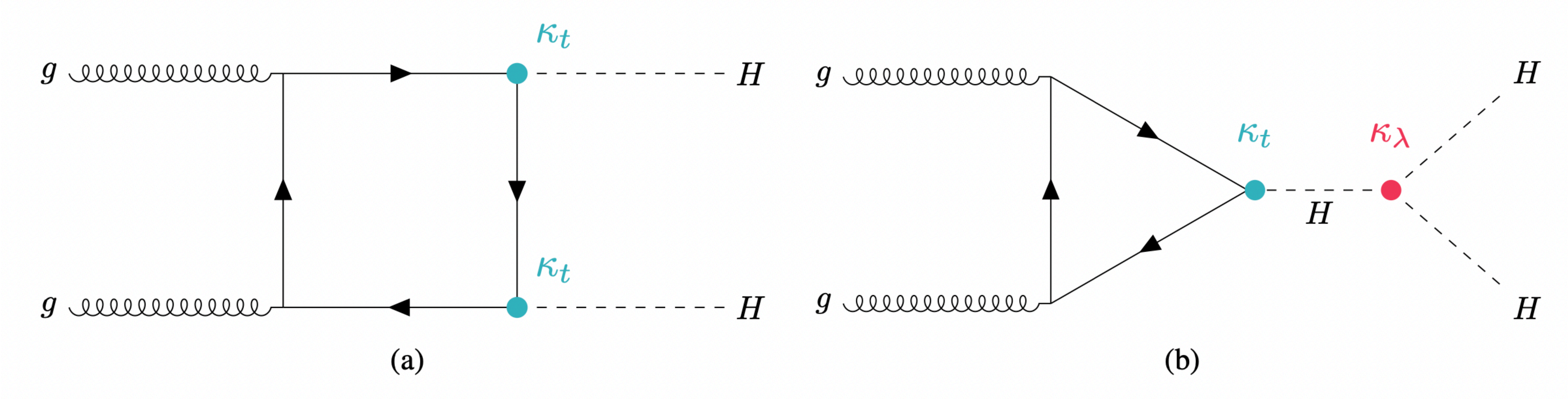
$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda v H^3 + \cdots$$

Higgs self-interaction term
direct probing of Higgs self-interaction
and the shape of Higgs potential

deviations from the SM would indicate new physics

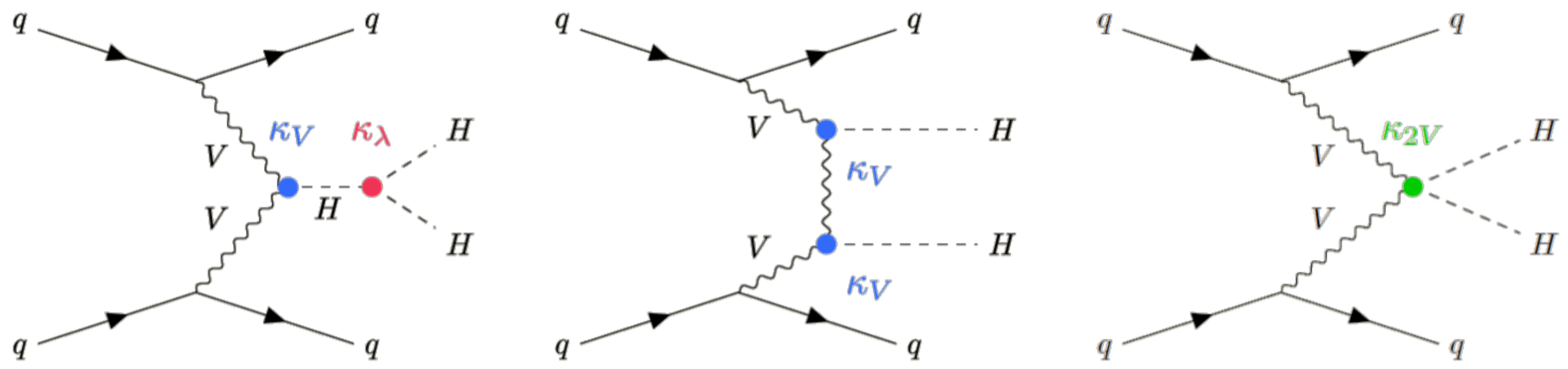
di-Higgs production at LHC

dominant production mode ggF 31 fb[13TeV] with 2 diagrams that have destructive interference



$\kappa\lambda$ = ratio of the Higgs boson self-coupling to its SM value

other dominant modes



Associated productions, HHV, HHtt have much smaller production cross-sections

HH

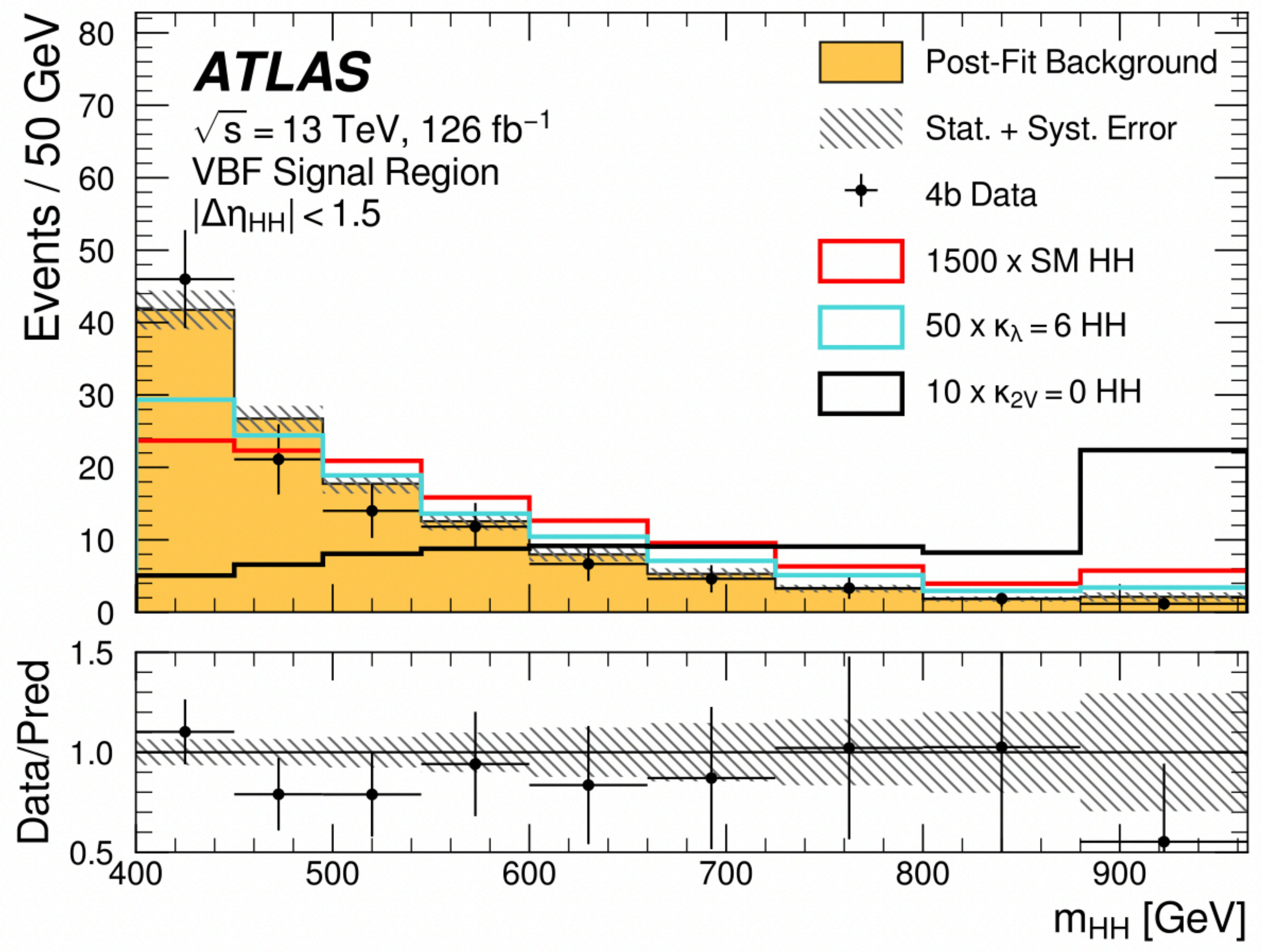
di-Higgs decay modes

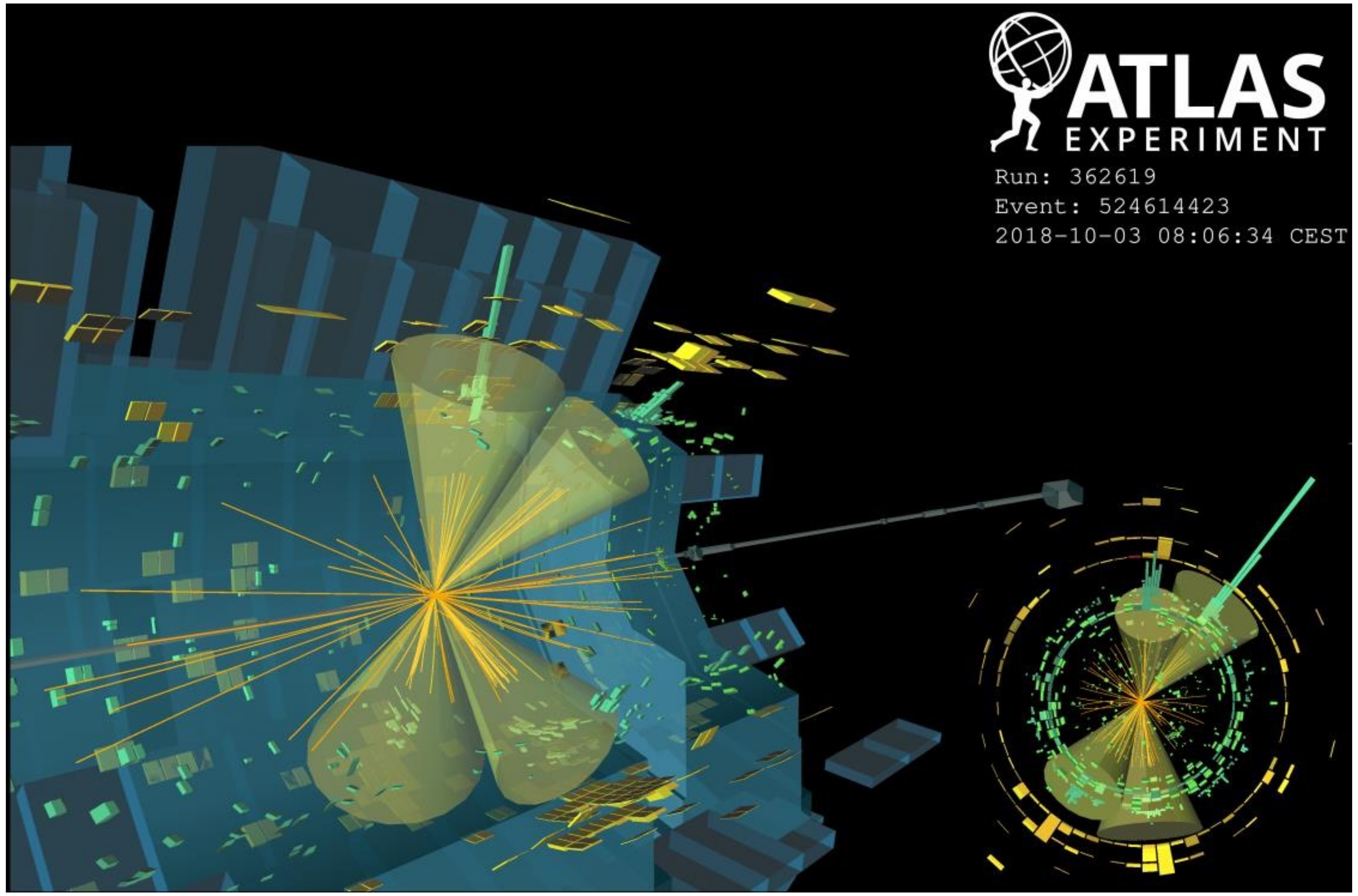
by Katharine Leney

	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%

The golden channels

HH → *bbbb*





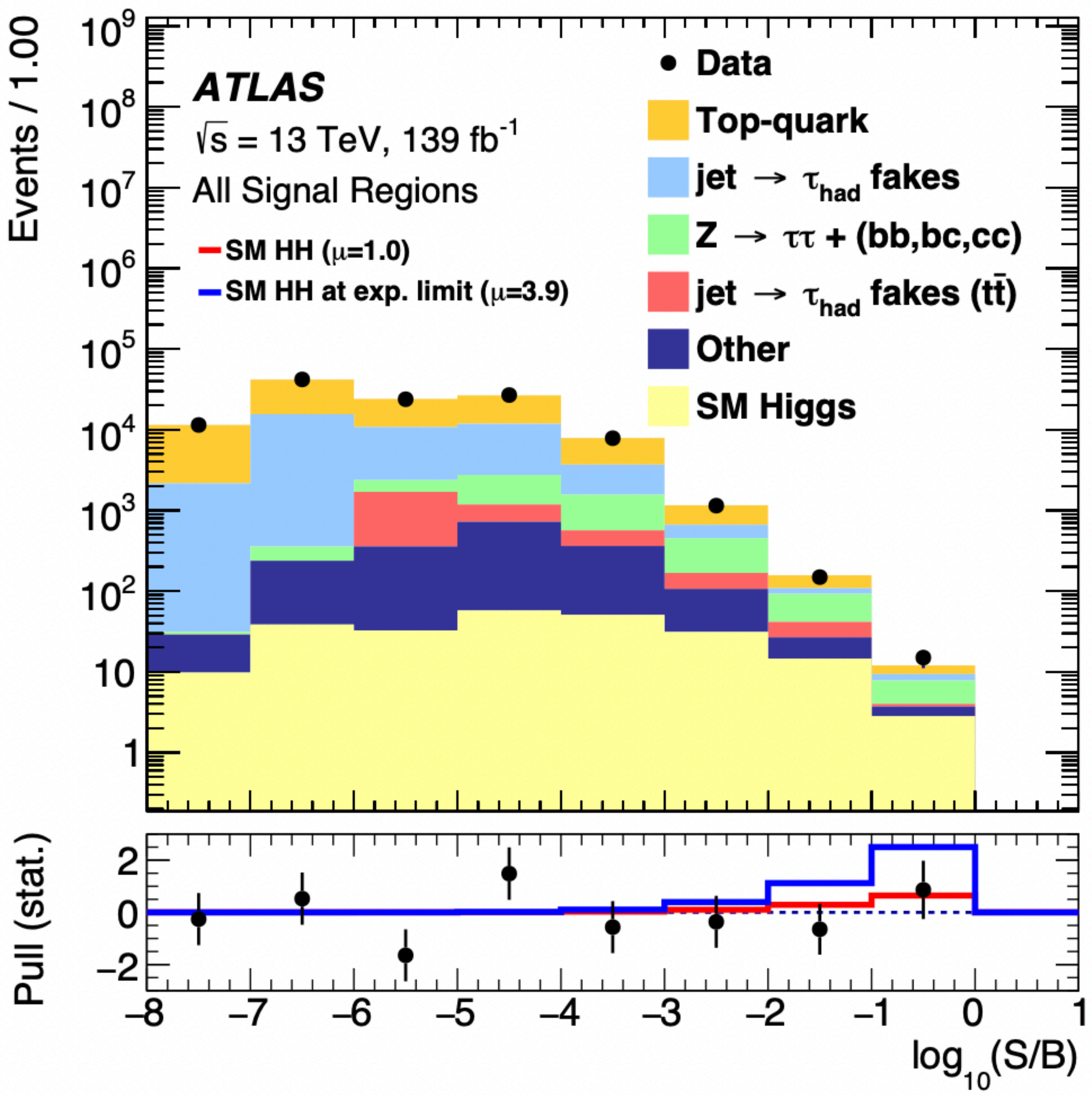
	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
μ_{ggF}	5.5	4.4	5.9	8.2	12.4	19.6
μ_{VBF}	130	70	100	130	190	280
$\mu_{\text{ggF+VBF}}$	5.4	4.3	5.8	8.1	12.2	19.1

Highest BR, sensitive to high pT of the Higgs

The sensitivity of the analyses is improved relative to previous iterations by using more sophisticated background modeling techniques, event categorization and improved jet reconstruction and flavor identification algorithms, in addition to the increased integrated luminosity of the analyzed data.

both in $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channel
and in ggf+VBF production

HH → $bb\tau\tau$



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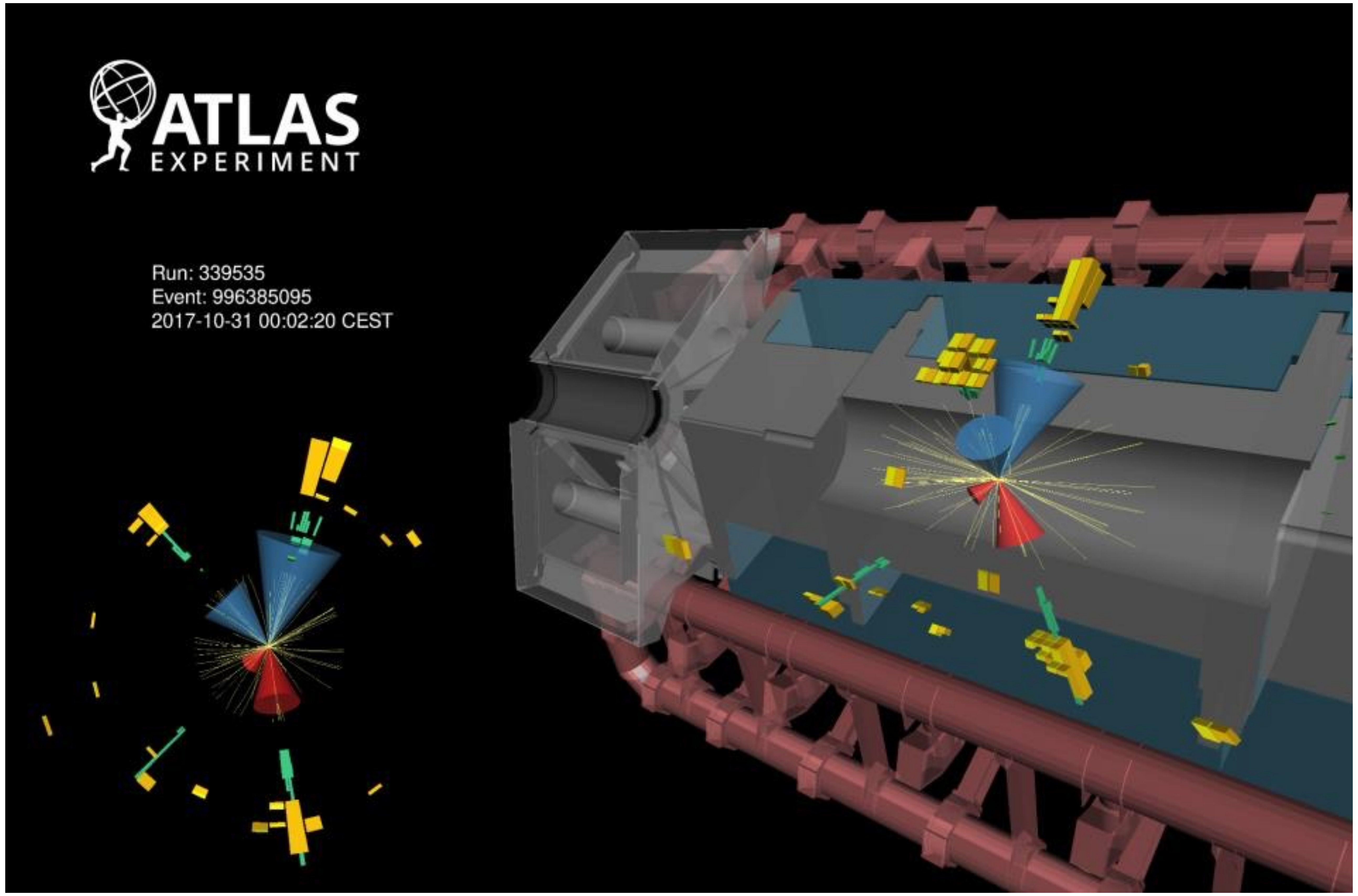
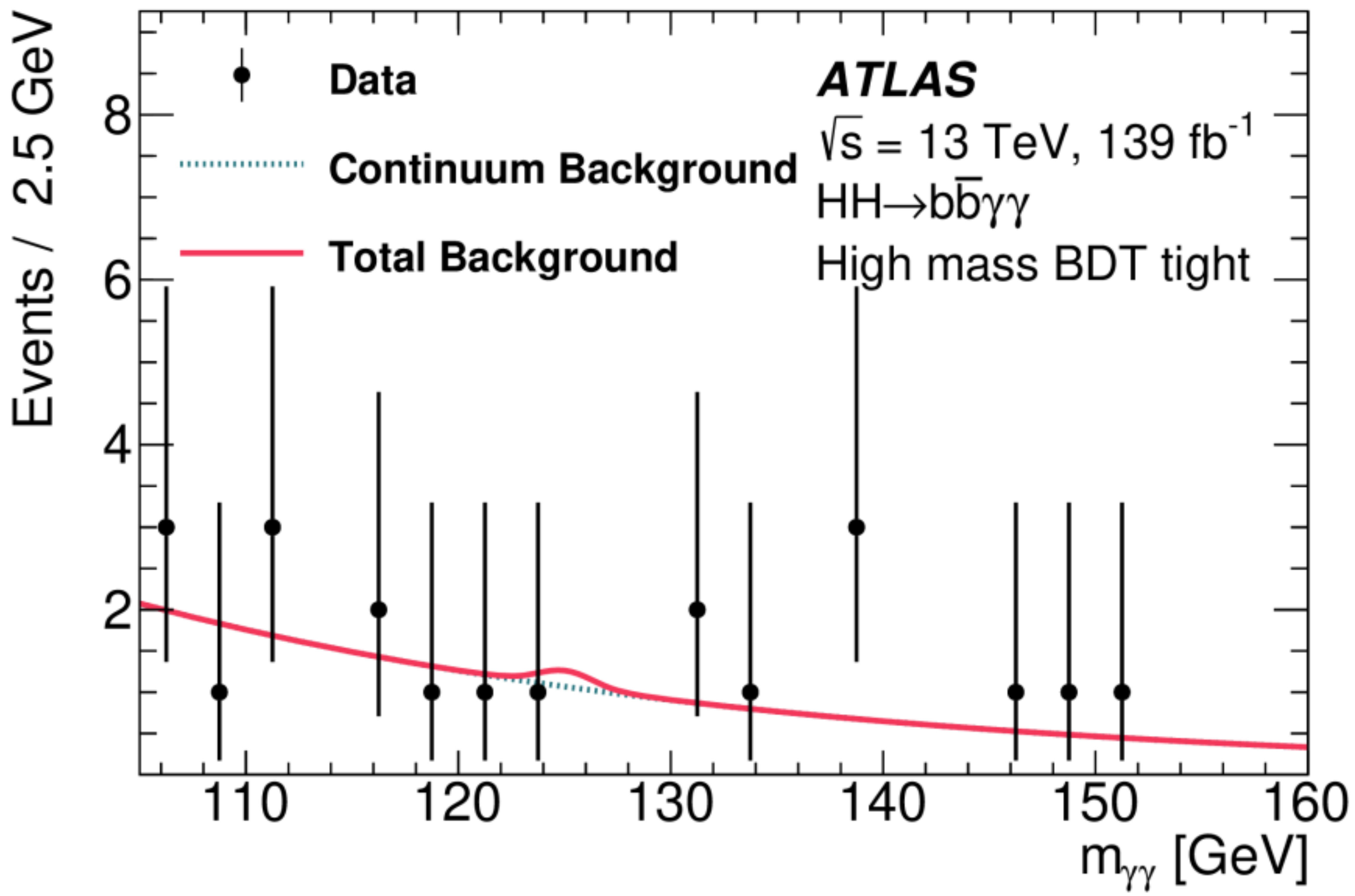
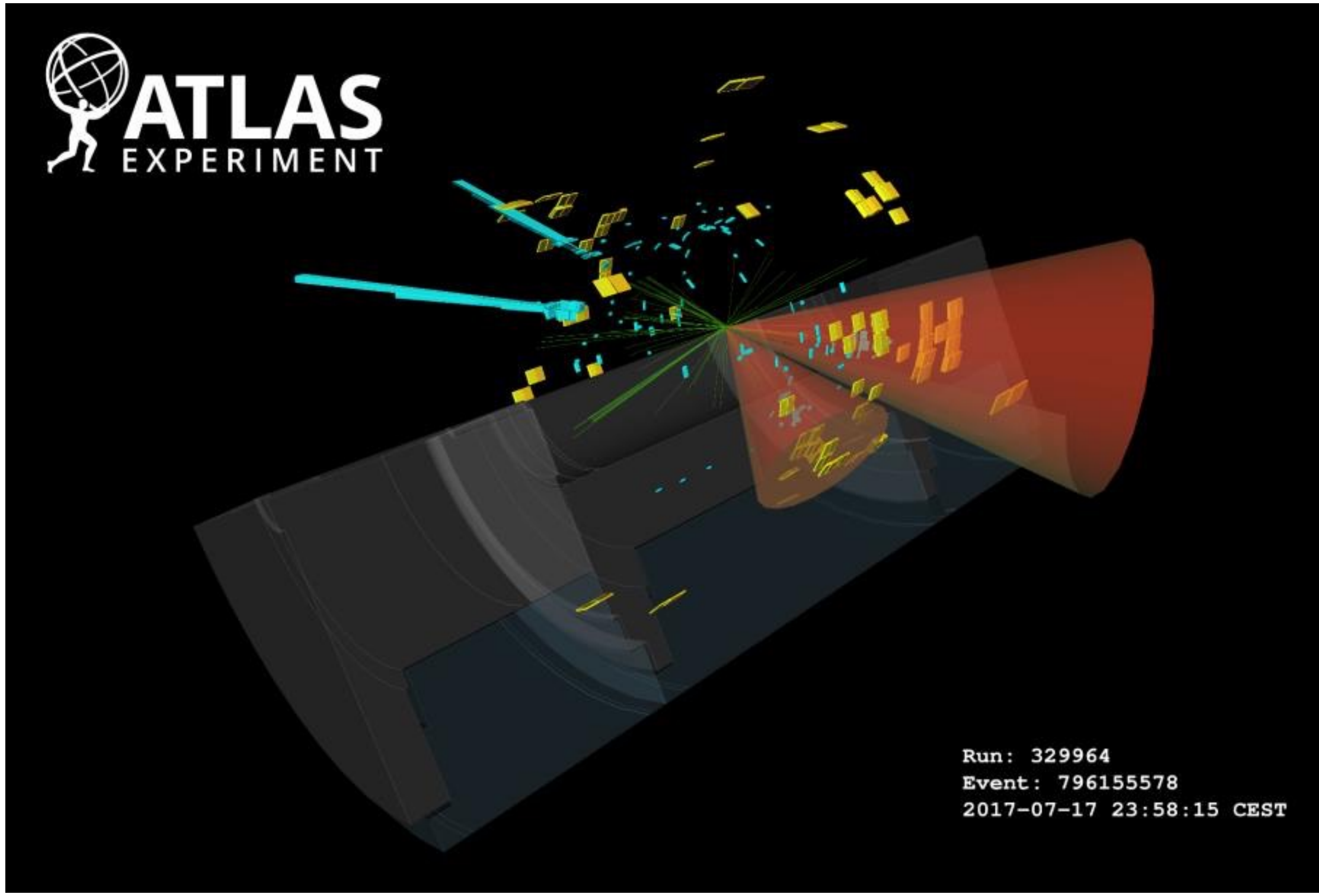


Factor 4 improvement wrt to previous version of analysis.
Half of this improvement is due to the larger dataset,
while most of the remaining sensitivity gain is due to significant improvements in the τhad-vis and b-jet reconstruction and identification.

HH → $bb\gamma\gamma$

Phys. Rev. D 106 (2022) 052001



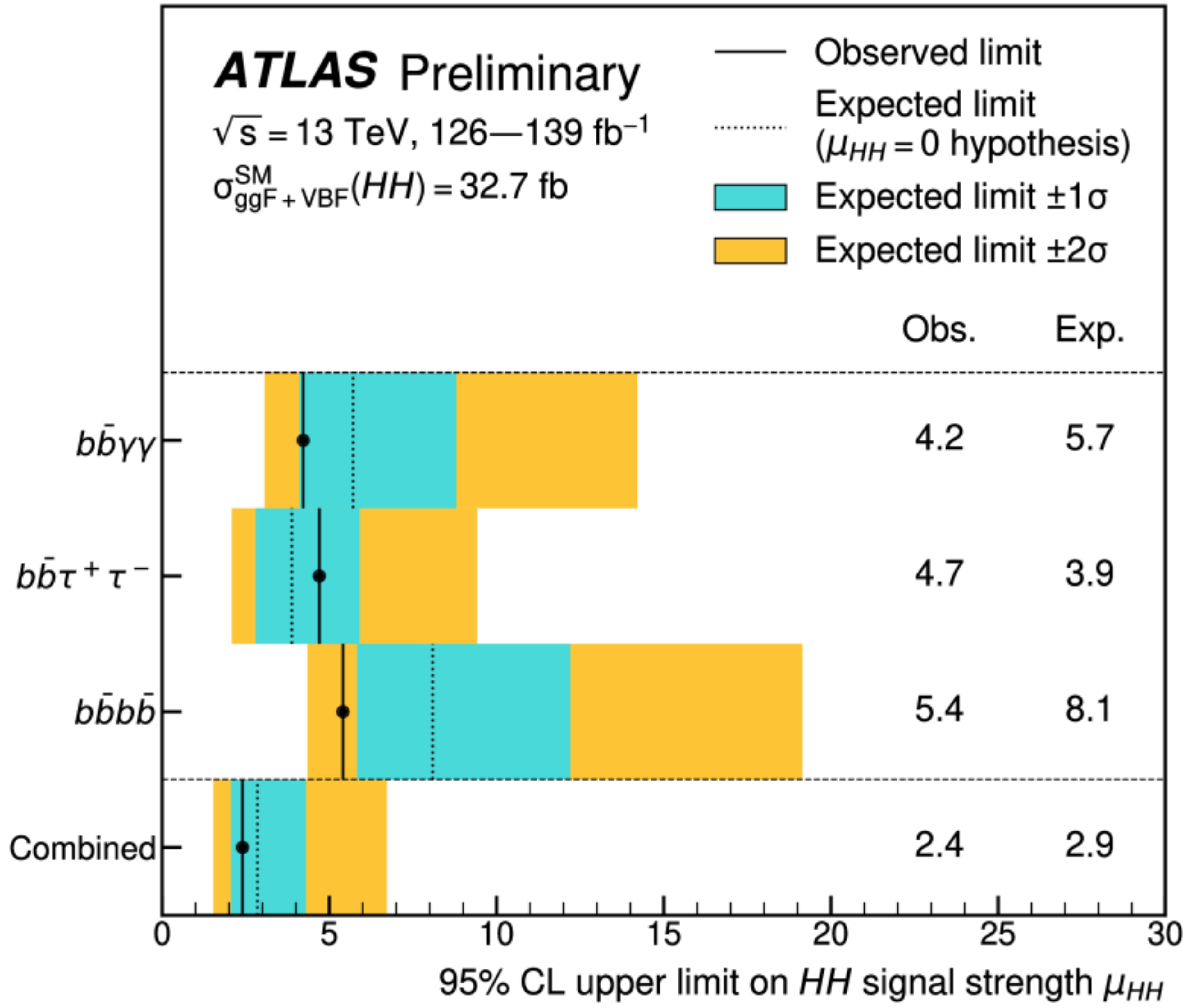


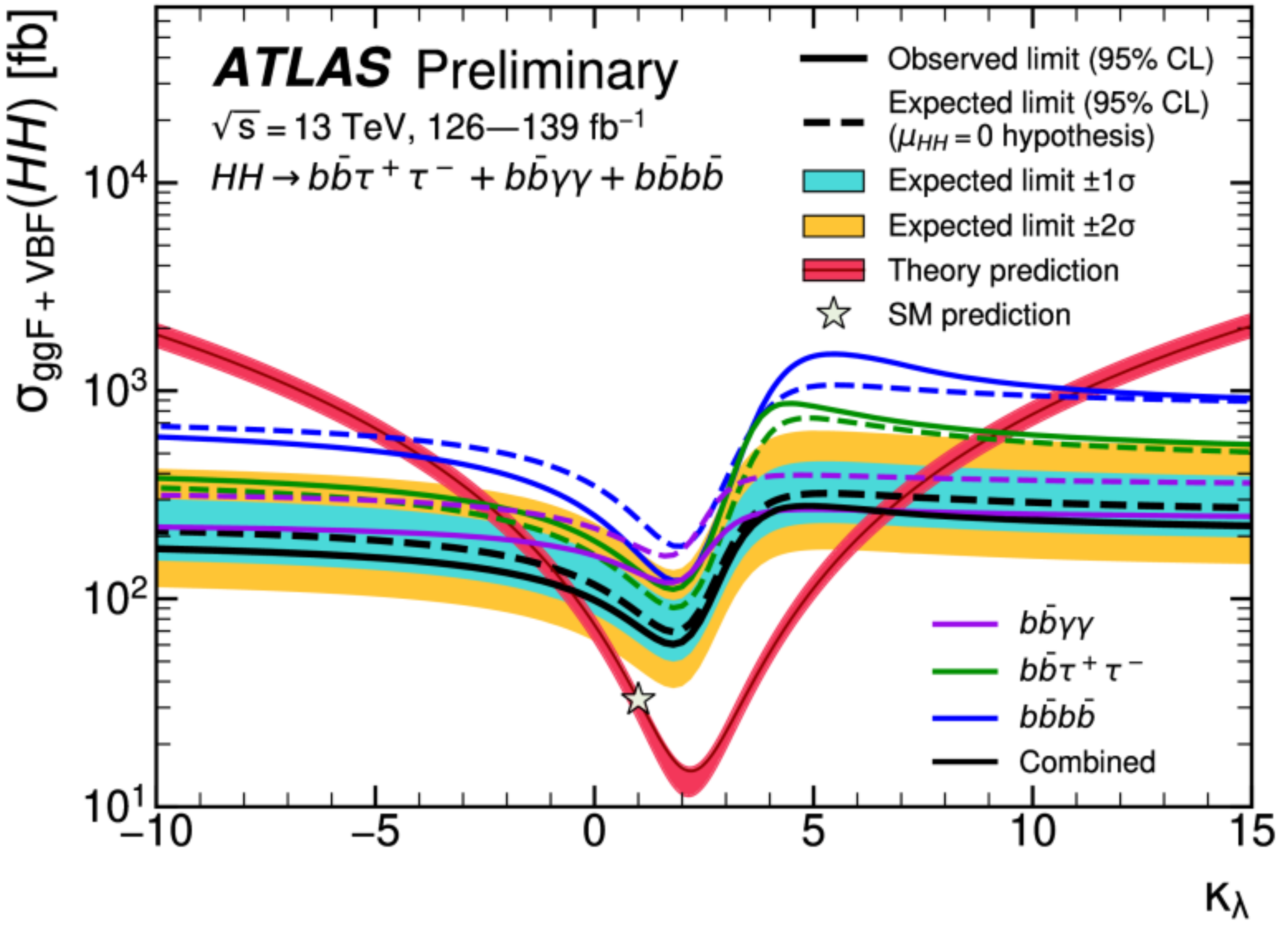
four times larger dataset, incorporates a categorization based on mbb¯γγ and multivariate event selections, and expands analyzed mass range of the resonance search to lower values.

The results improve upon the previous ATLAS limits on the HH → bb¯ γγ production cross section by up to a factor of 5 (half due to improved analysis)

Limit on on σ 4.2 (4.7) times the SM prediction @ 95% CL

HH combination





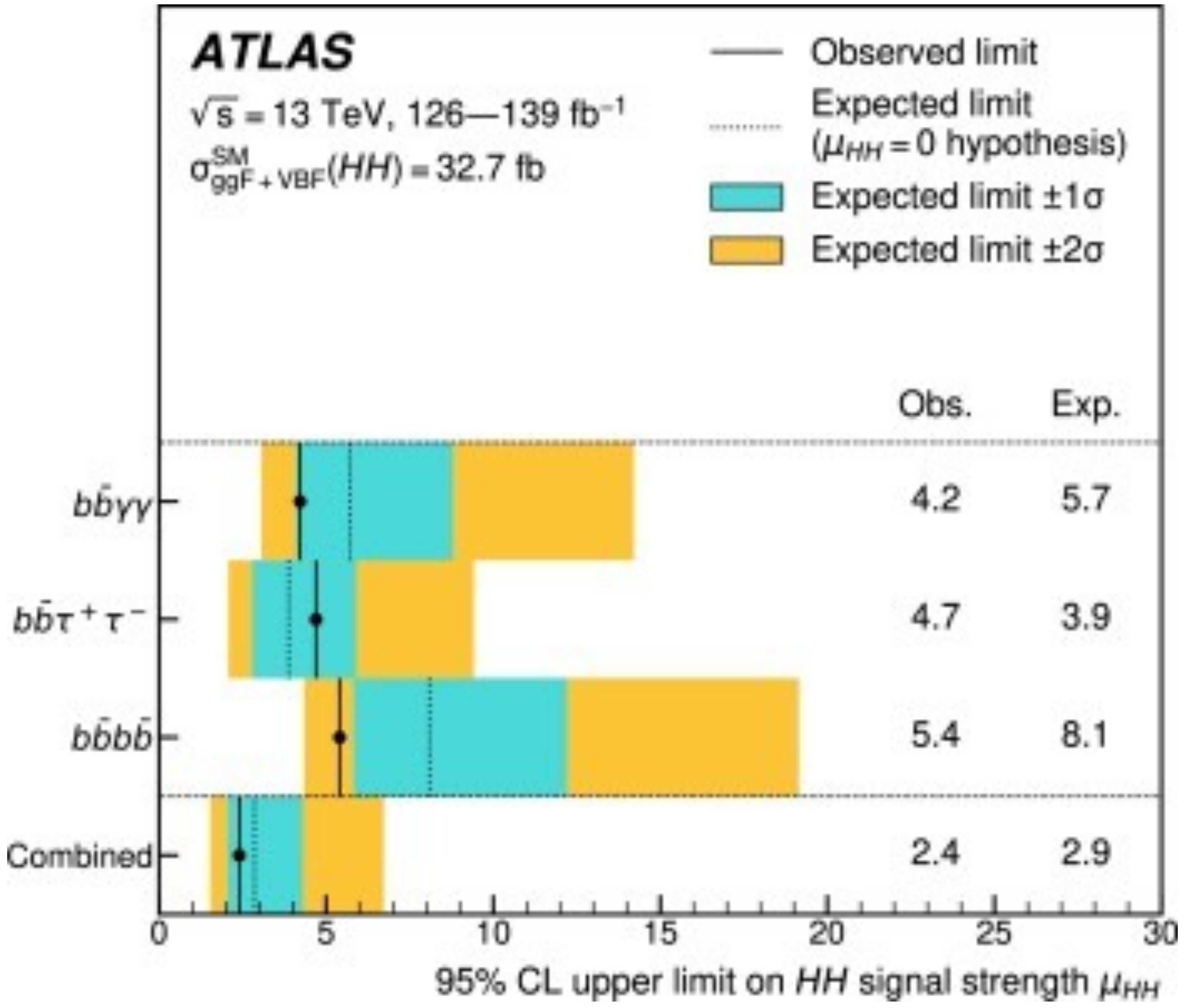
Limit on on σ 2.4 (2.9) times the SM prediction at 95% CL

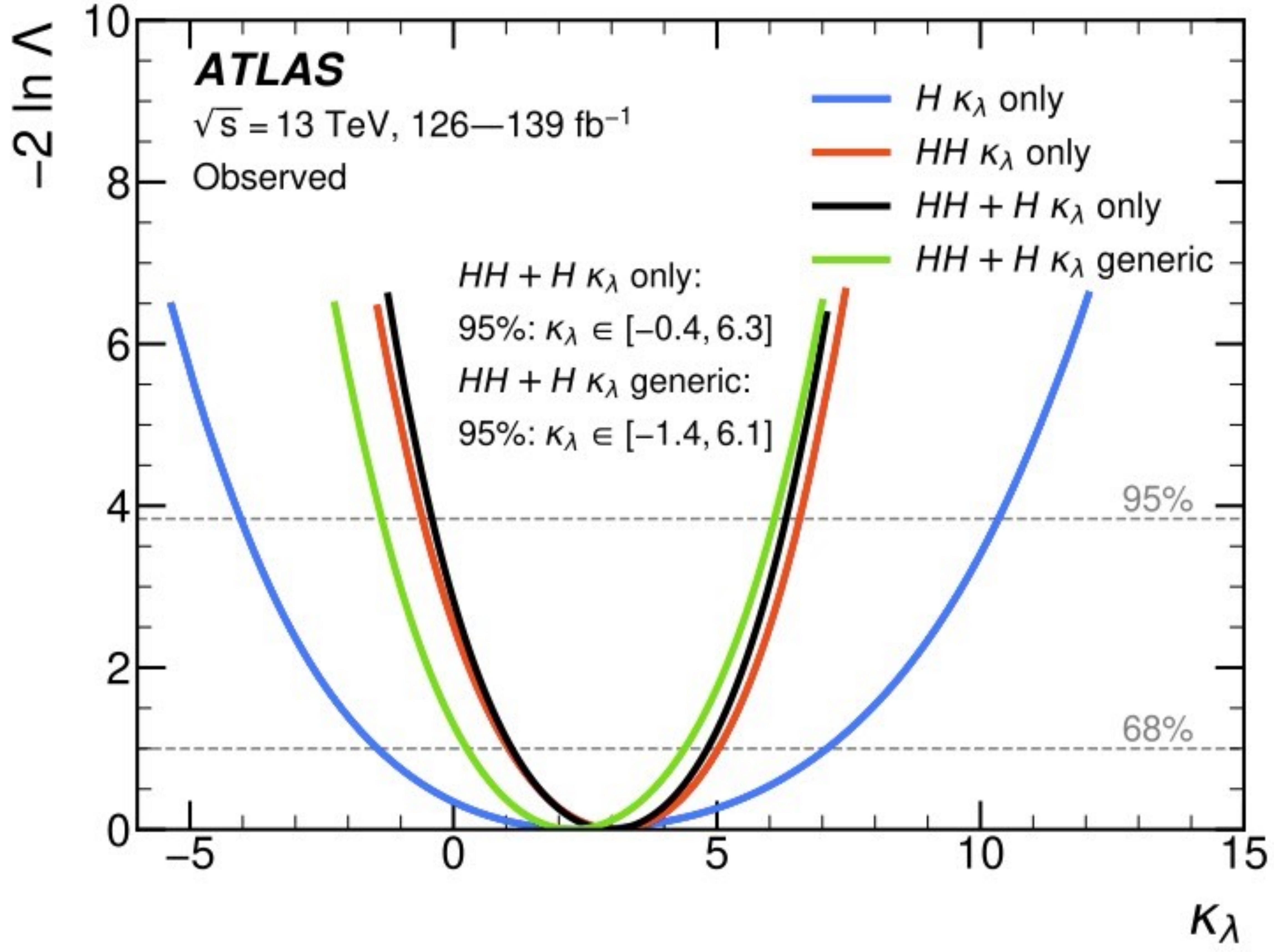
HH

Combination of di-Higgs searches

Phys. Lett. B 843 (2023) 137745

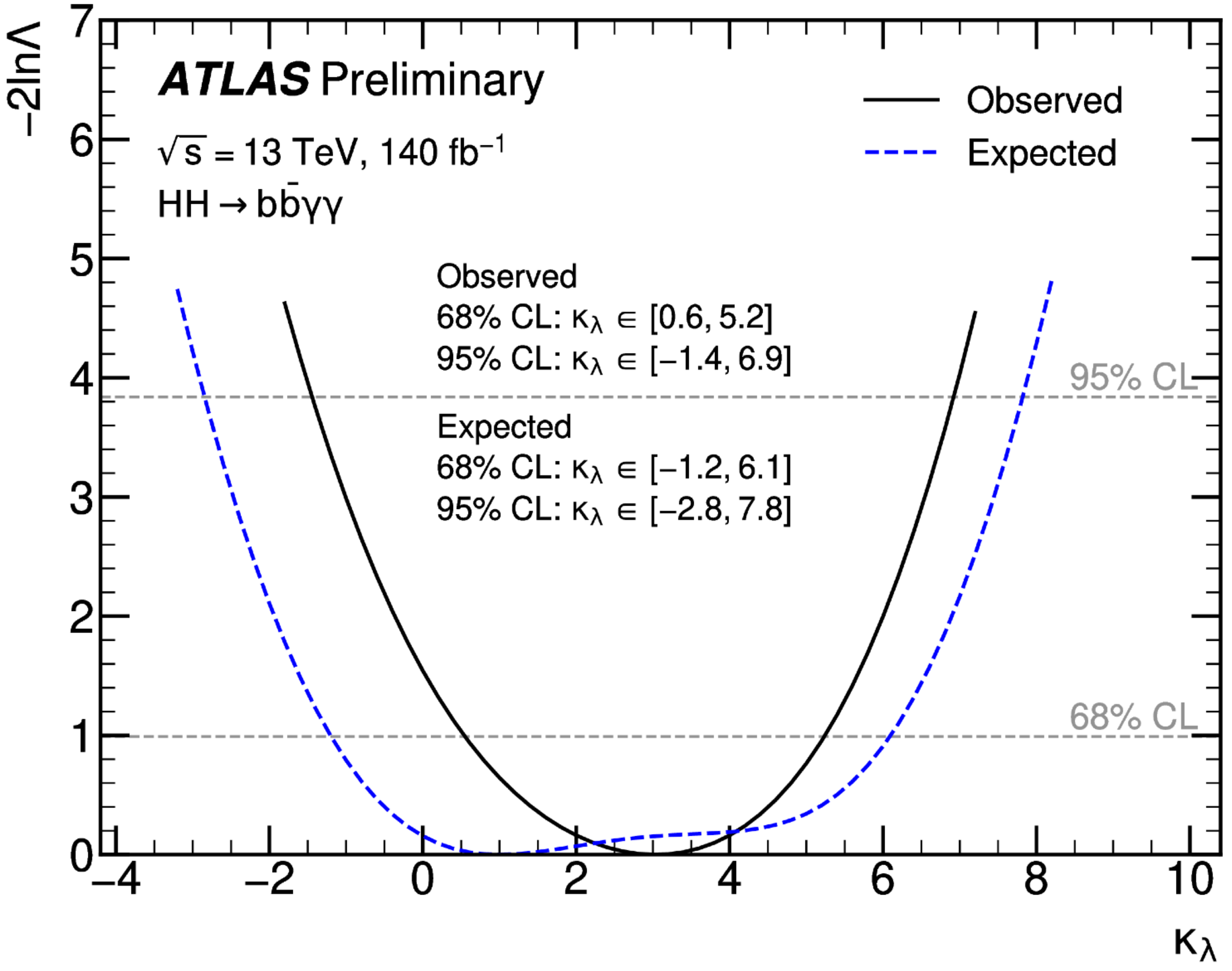
- HH → 4b, bbγγ, bbττ have been combined with single Higgs results
- μHH: 2.4×SM (2.9×SM exp.) at 95% CL
- -0.4<κλ <6.3 @95%CL (HH+H combination)



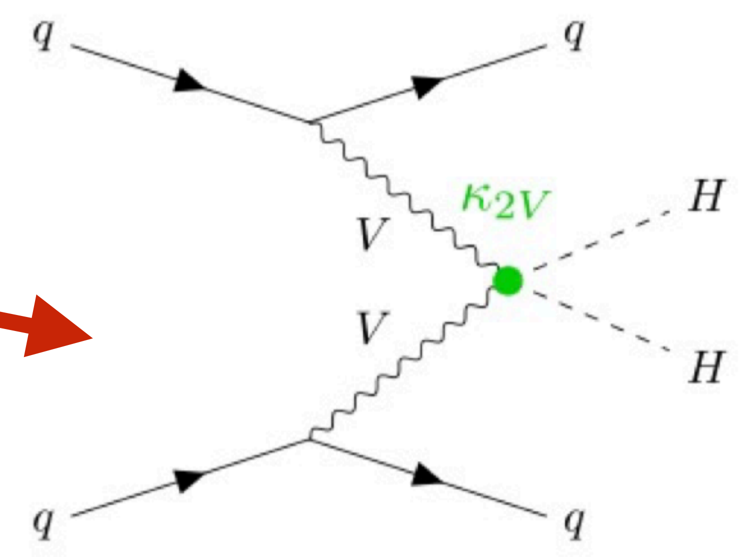


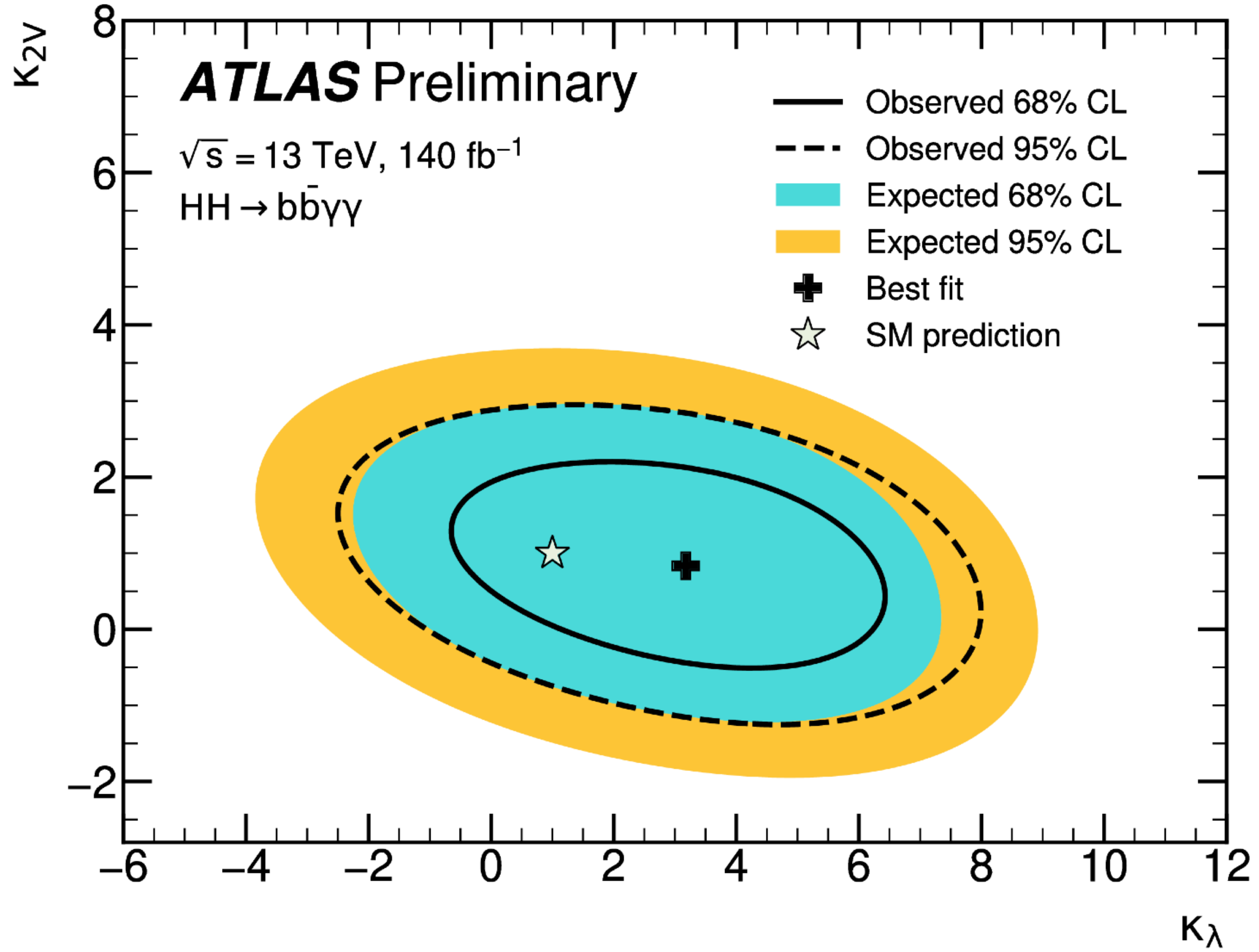
Most stringent limits to date

Further improved HH → γγbb search



- BDT used in 7categories
- sensitive to H self-coupling λ and κ_{2V}





- Expected improvement μHH (12%), κ_λ (6%), κ_{2V} (17%) (mostly owing to event categorization)
- μ_{HH}<4 @95%CL
- not including most recent improvements in b-tagging!

ATLAS-CONF-2023-050

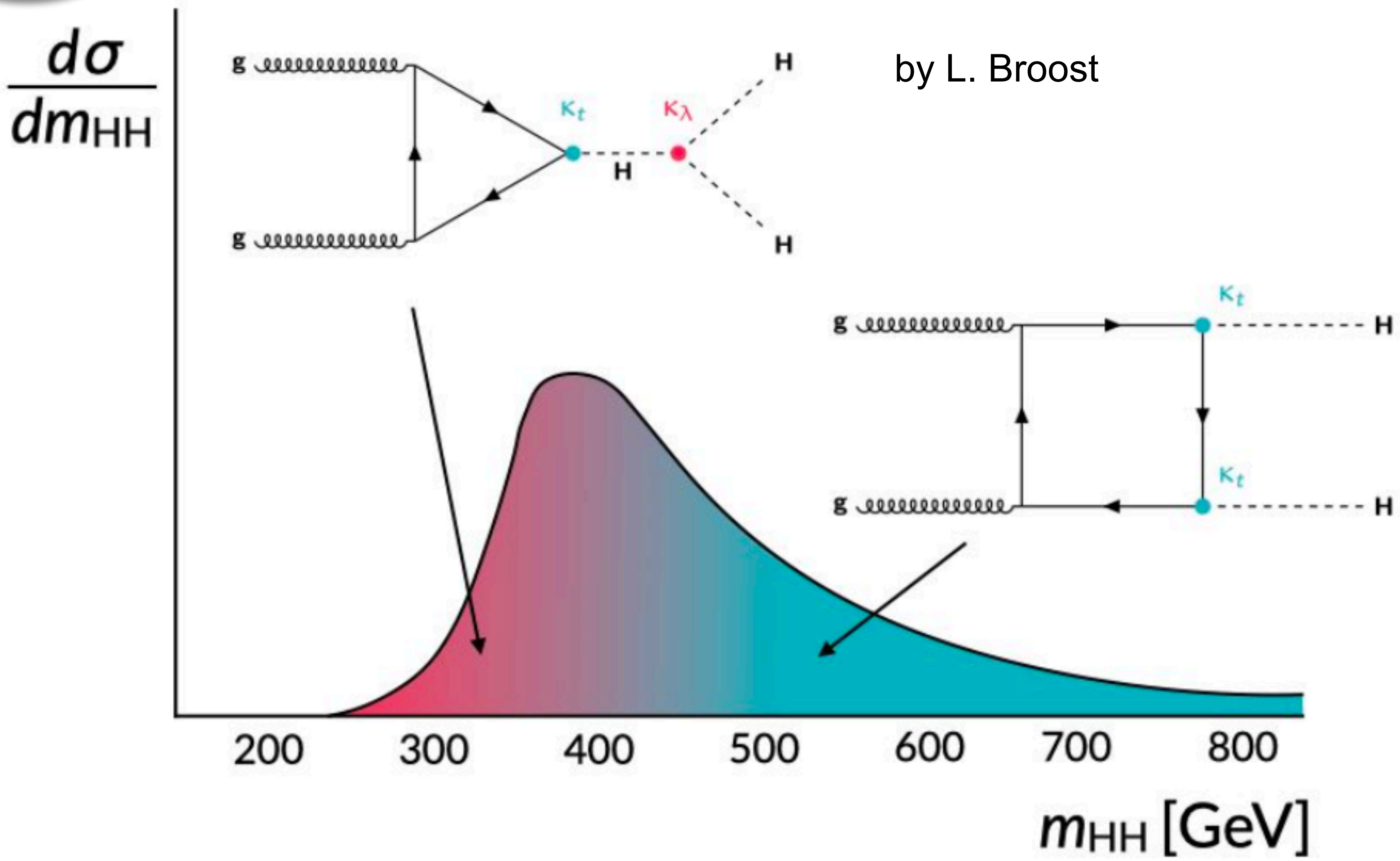
Rare processes: back on the envelope calculation based on SM expectations

HH

run3 Lumi→ / expected sensitivity↓	H->μμ		H->γγ*		H->Zγ		HH	
	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb	250 fb	200 fb
ATLAS	2.8	2.6	3.5	3.3	2.0	1.9	1.2	1.1
CMS	4.2	4.0	-	-	2.0	1.9	1.3	1.2
Combined	5.0	4.8	5.0	4.7	2.8	2.6	1.8	1.6

Doesn't include new b-taggers etc etc.

Prospects

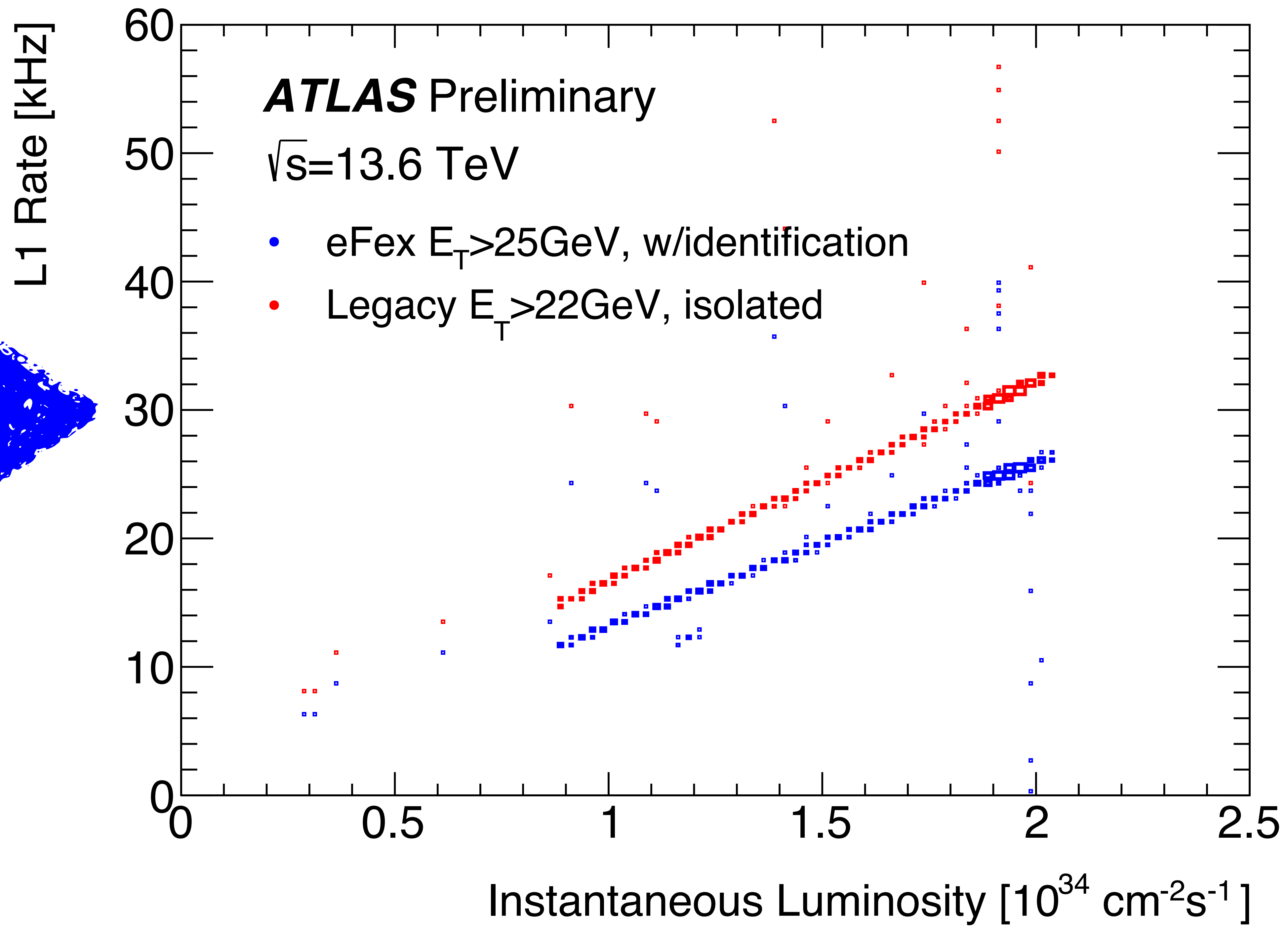


In addition to new flavor taggers, new channels etc,

the low mHH regions drives sensitivity therefore lowering thresholds including trigger is fundamental, especially for the future

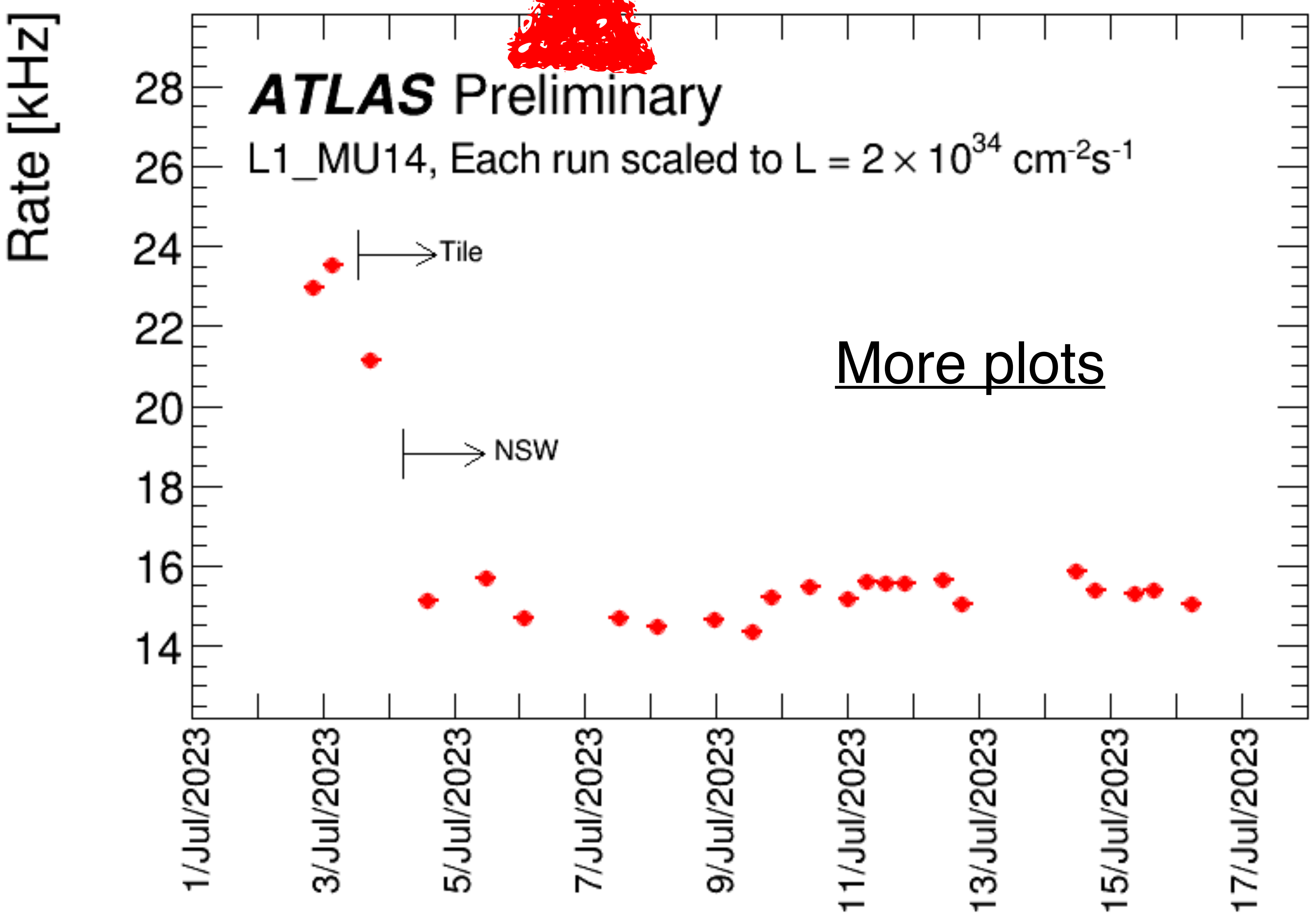
As shown at the beginning of these lectures both experiments are improving their trigger capabilities in Run3 but even more at the HL_LHC

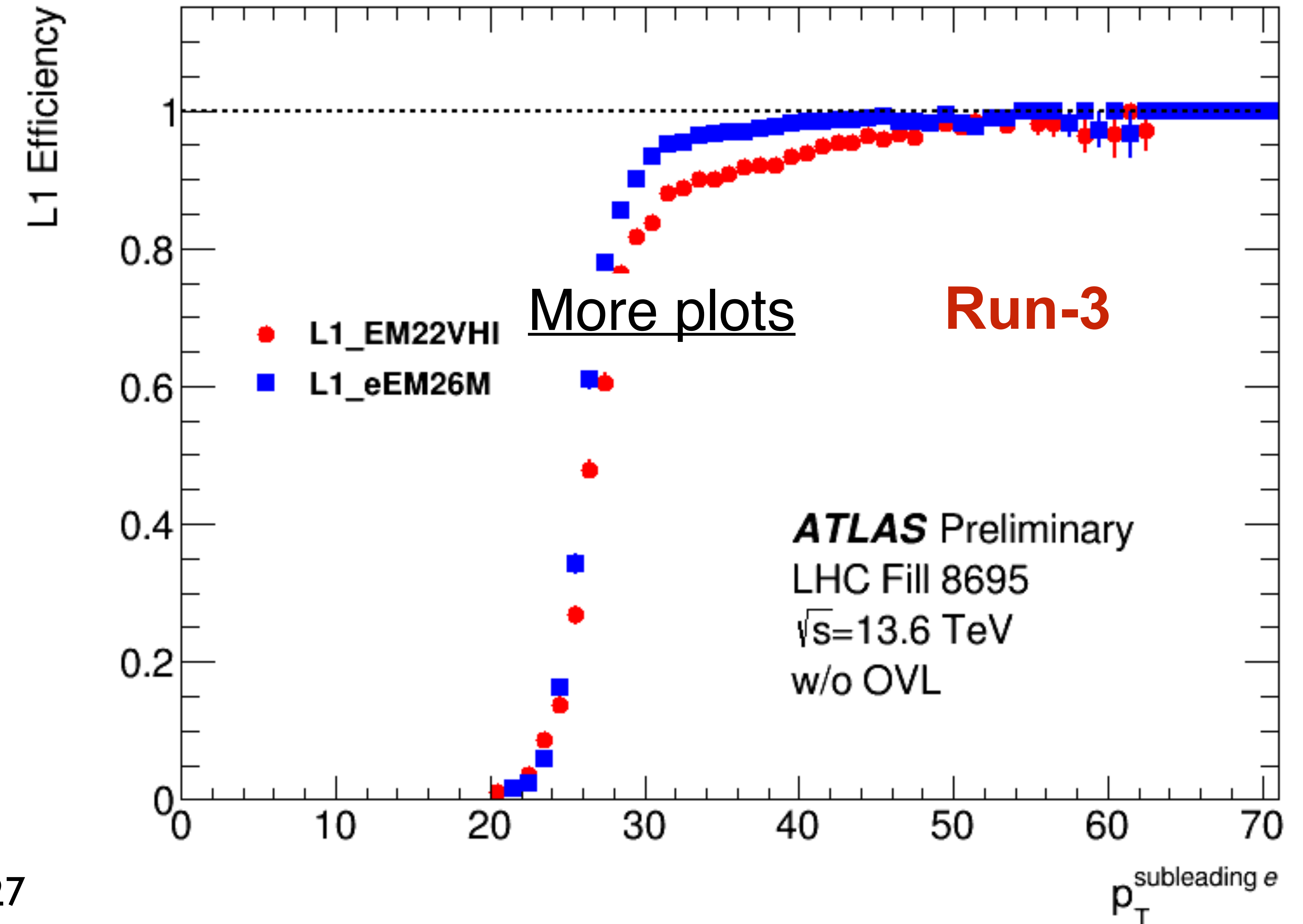
Run3 triggers, reduce rates and increase efficiencies



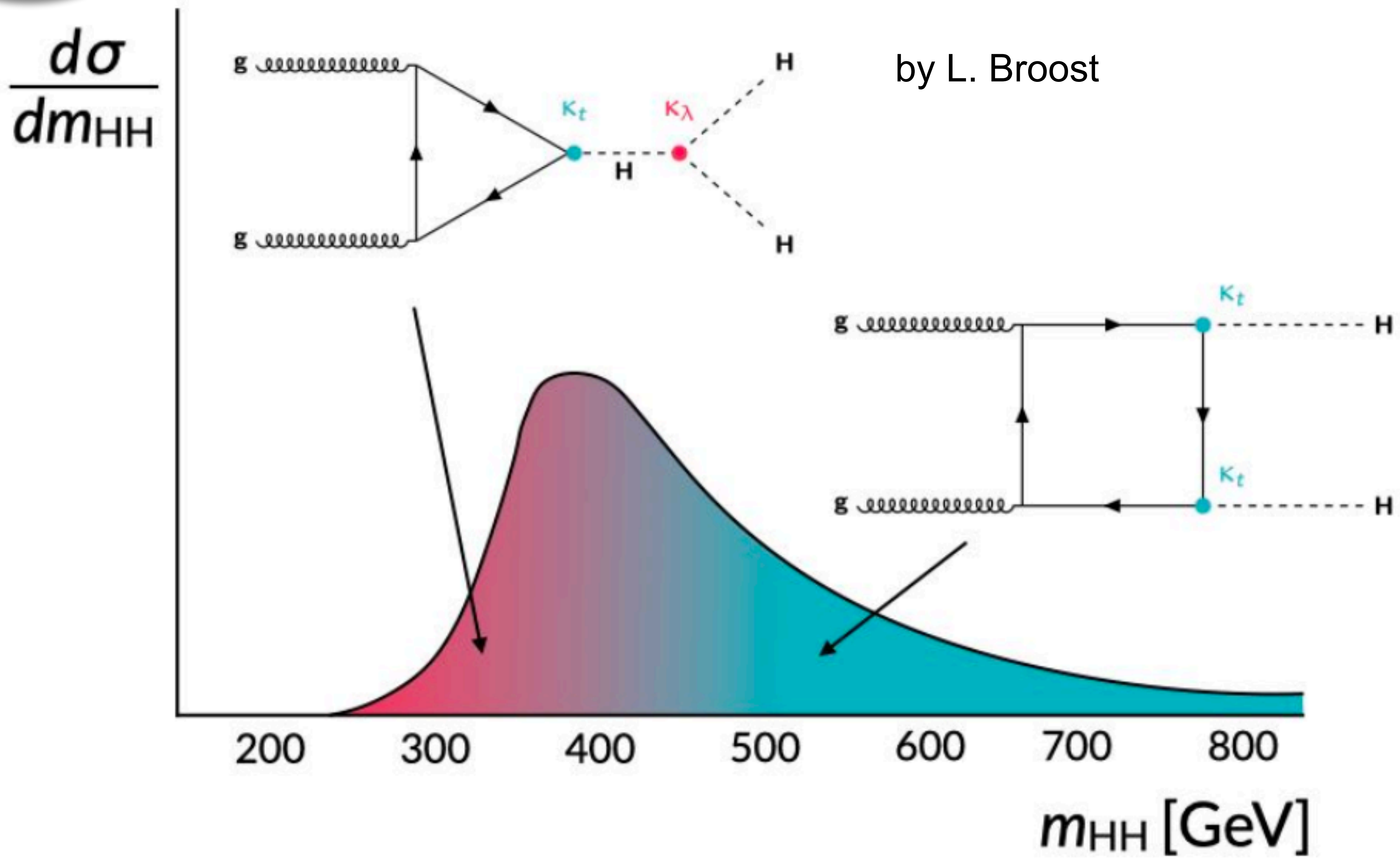
Level 1Calo single electron rates are decreased and trigger efficiencies increased

NSW and Tile calorimeter coincidences decrease significantly the muon rate





Prospects



by L. Broost

In addition to new flavor taggers, new channels etc,

the low mHH regions drives sensitivity therefore lowering thresholds including trigger is fundamental, especially for the future

As shown at the beginning of these lectures both experiments improving their trigger capabilities in Run3 but even more at the HL_LHC

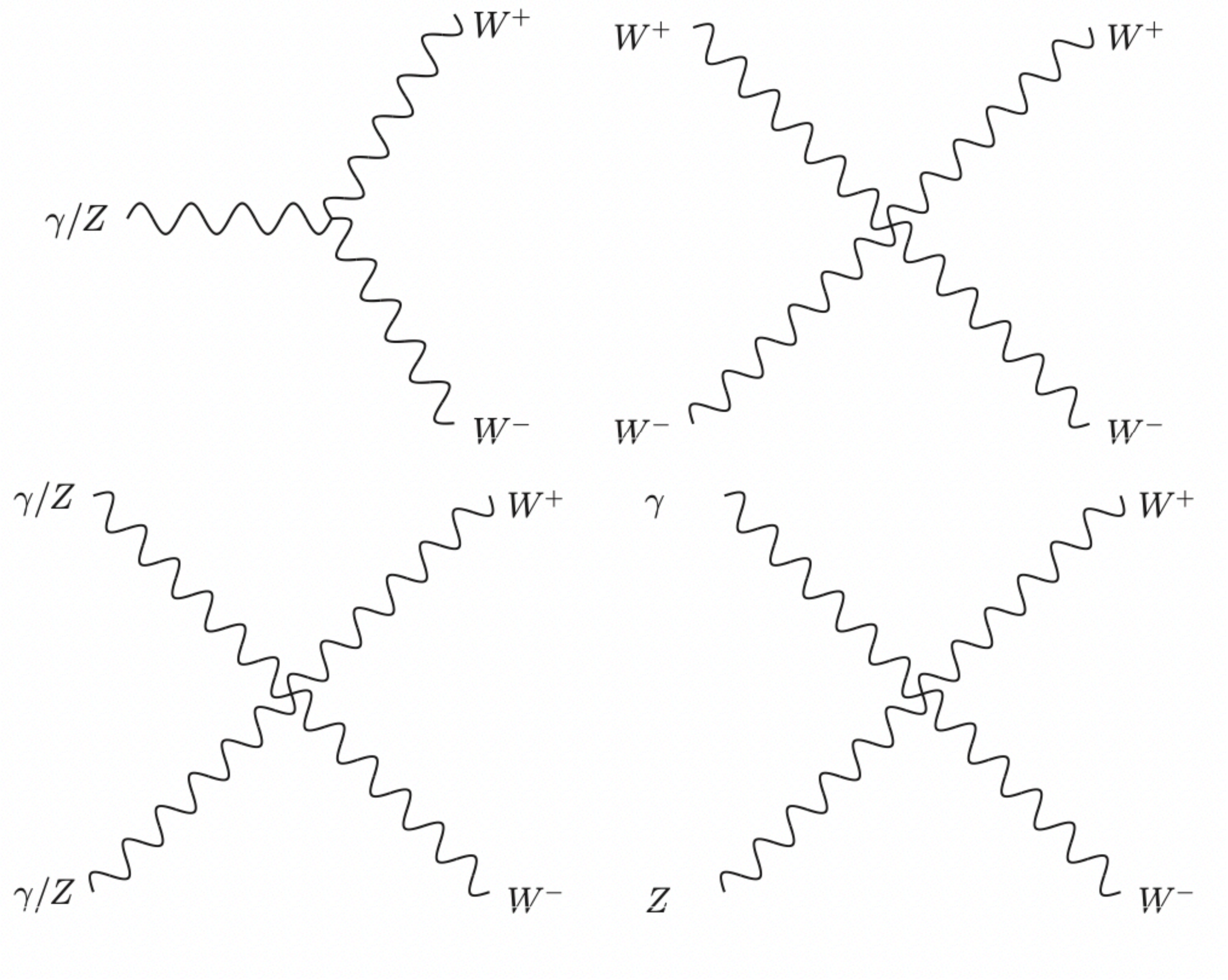
HL-LHC Lumi→ Expected sensitivity↓	HH		VH(→ cc)		VBS long. polarised	
	$3\ ab^{-1}$	$2.5\ ab^{-1}$	$3\ ab^{-1}$	$2.5\ ab^{-1}$	$3\ ab^{-1}$	$2.5\ ab^{-1}$
ATLAS	3.4	3.2	-	-	3.0	2.7
CMS	3.7	3.4	1.3	1.2	2.7	2.5
Combined	5.0	4.7	1.9	1.7	4.0	3.7

Back of the envelope calculation (no official source)

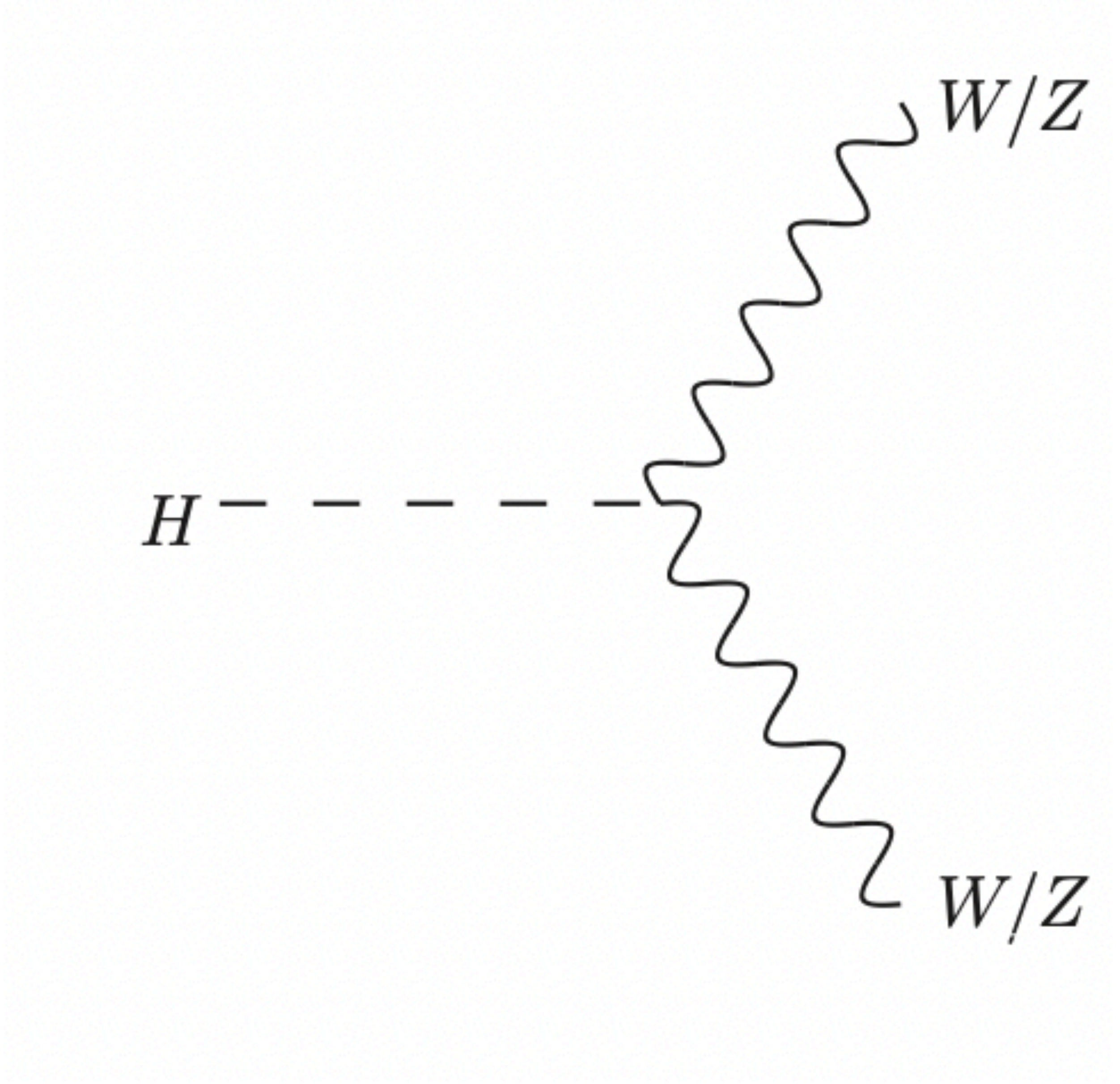
Testing the Electroweak symmetry breaking via VectorBoson Scattering: Another approach

VBS

Electroweak symmetry breaking



Self interactions of the Gauge bosons are predicted by the SM precisely

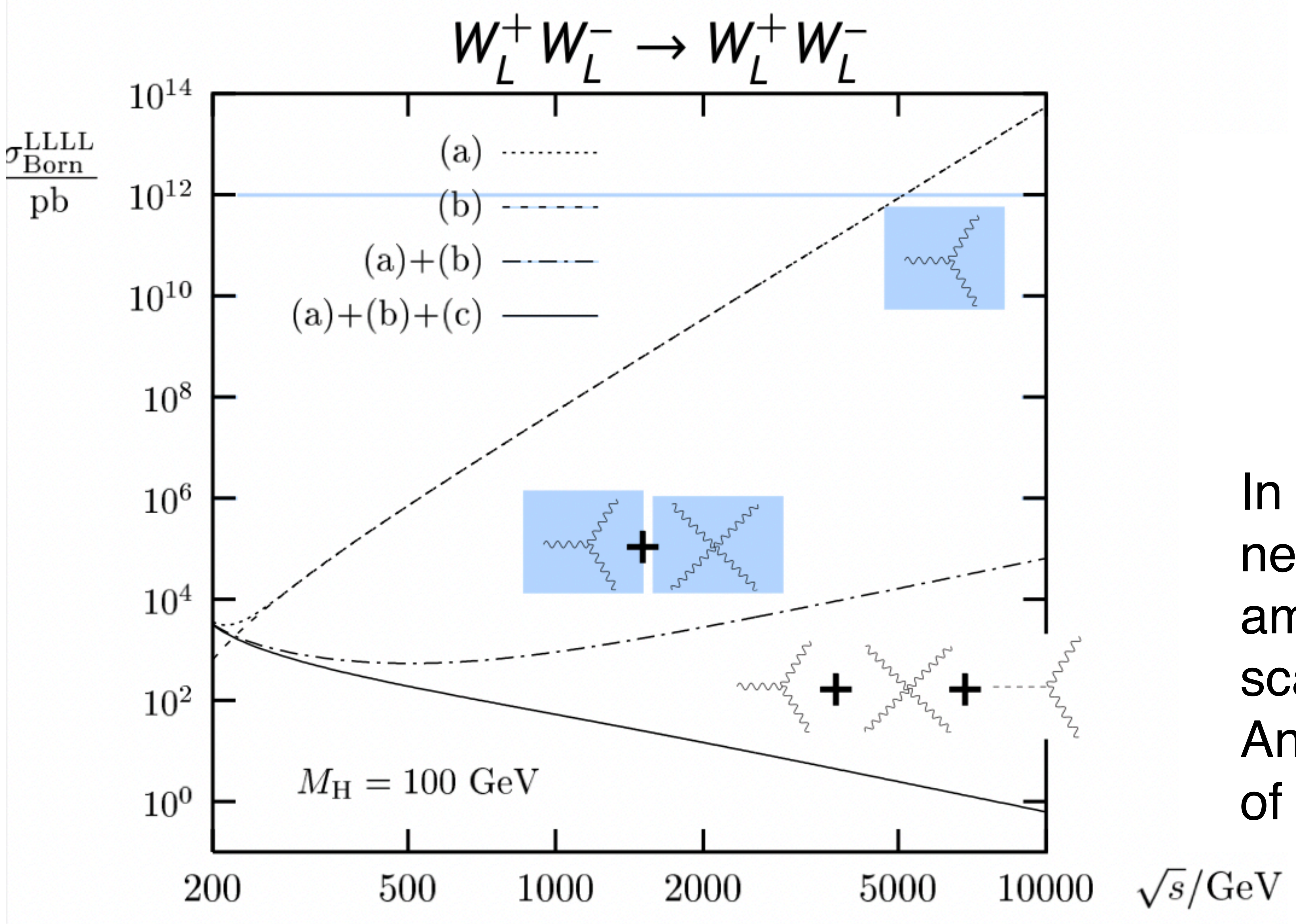


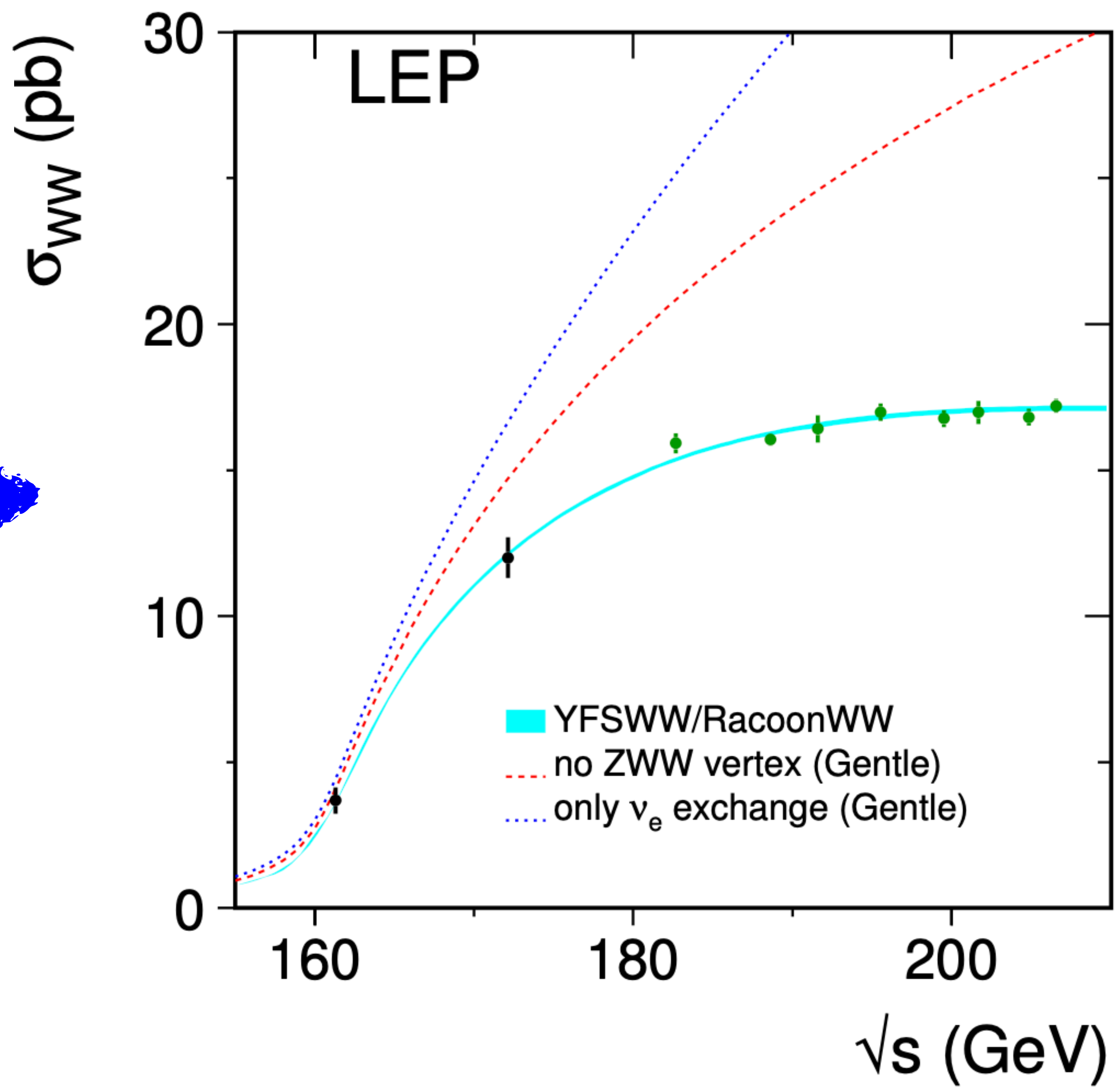
They interact even with the Higgs boson.

Electroweak symmetry breaking

Gauge-boson self interactions play a crucial role for the renormalisability of the electroweak theory

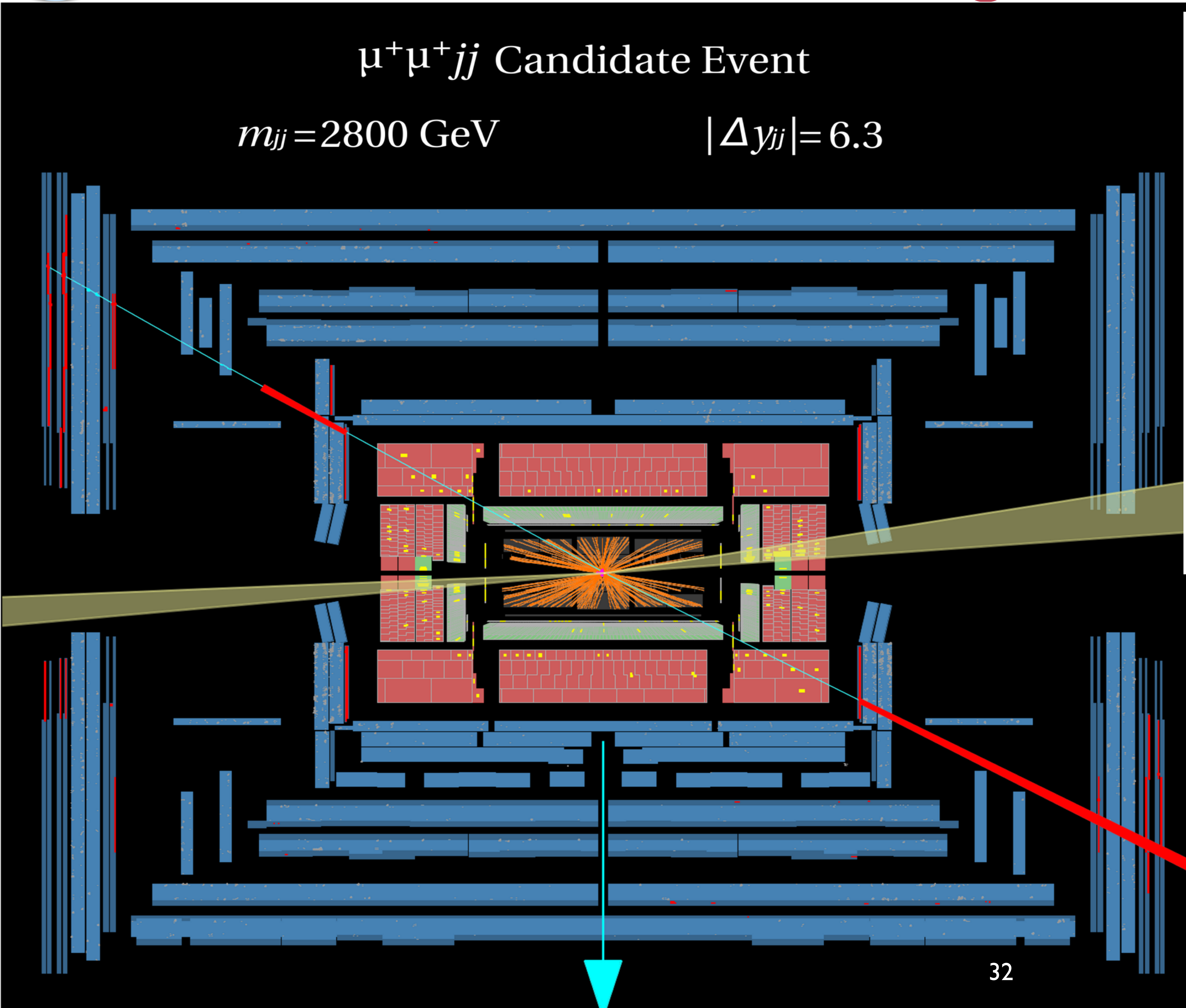
Large cancellations of divergences arising in individual diagrams are exact if couplings take the values of the SM

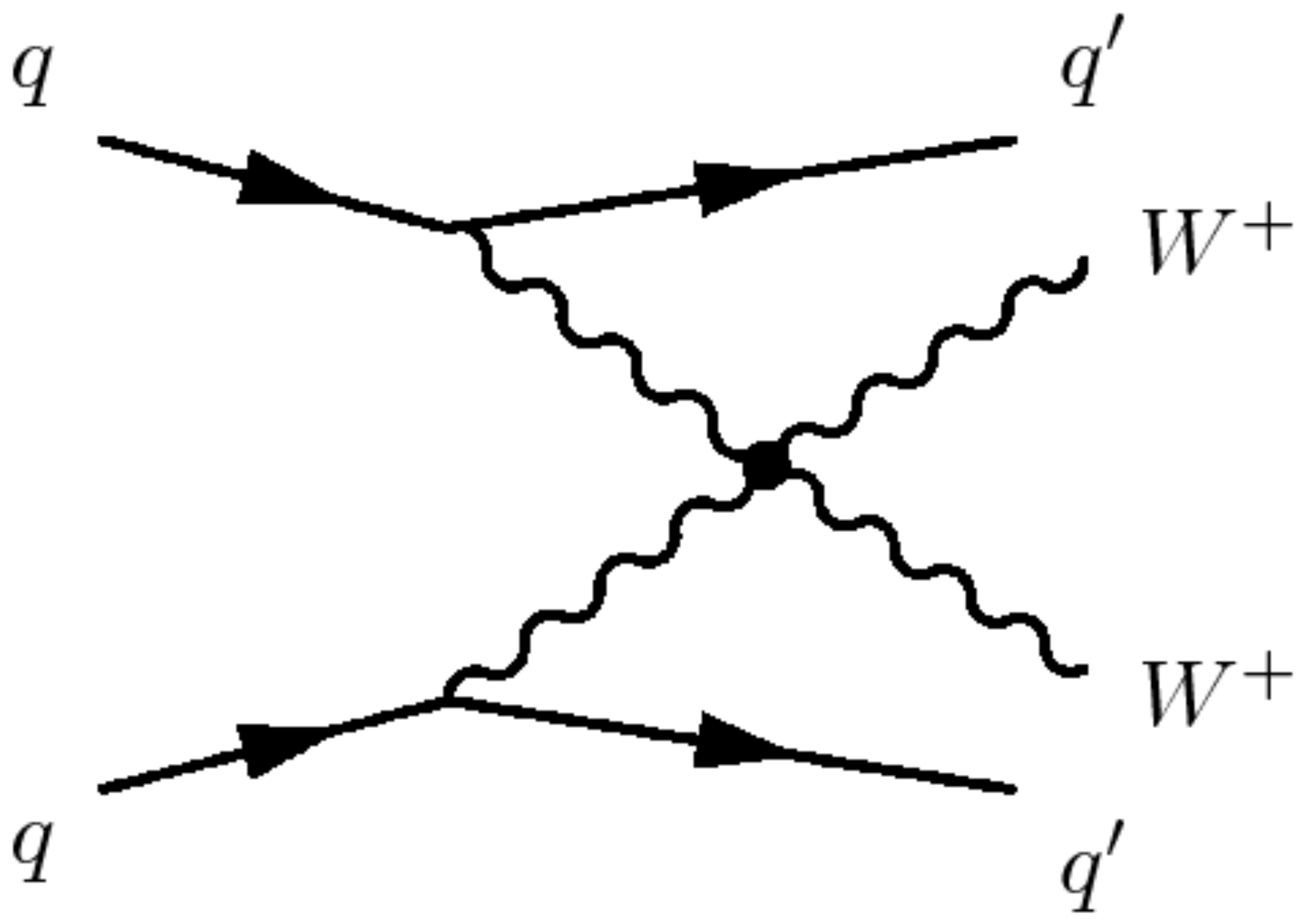




In vector boson scattering, the presence of the Higgs boson is needed to exactly cancel out the otherwise diverging scattering amplitudes at high energies and prevent unitarity violation at the TeV scale.
Any significant deviation from the predicted high-energy behaviour of vector boson scattering would point to new phenomena.

Vector boson scattering: Probing EW symmetry





0 180 360

ϕ

ATLAS EXPERIMENT

Run Number: 207490, Event Number: 33152138

Date: 2012-07-26 04:16:35 UTC

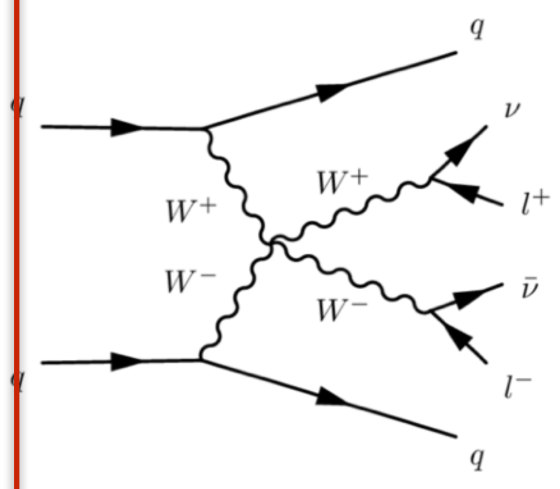
VBS+triboson to study EWK symmetry breaking

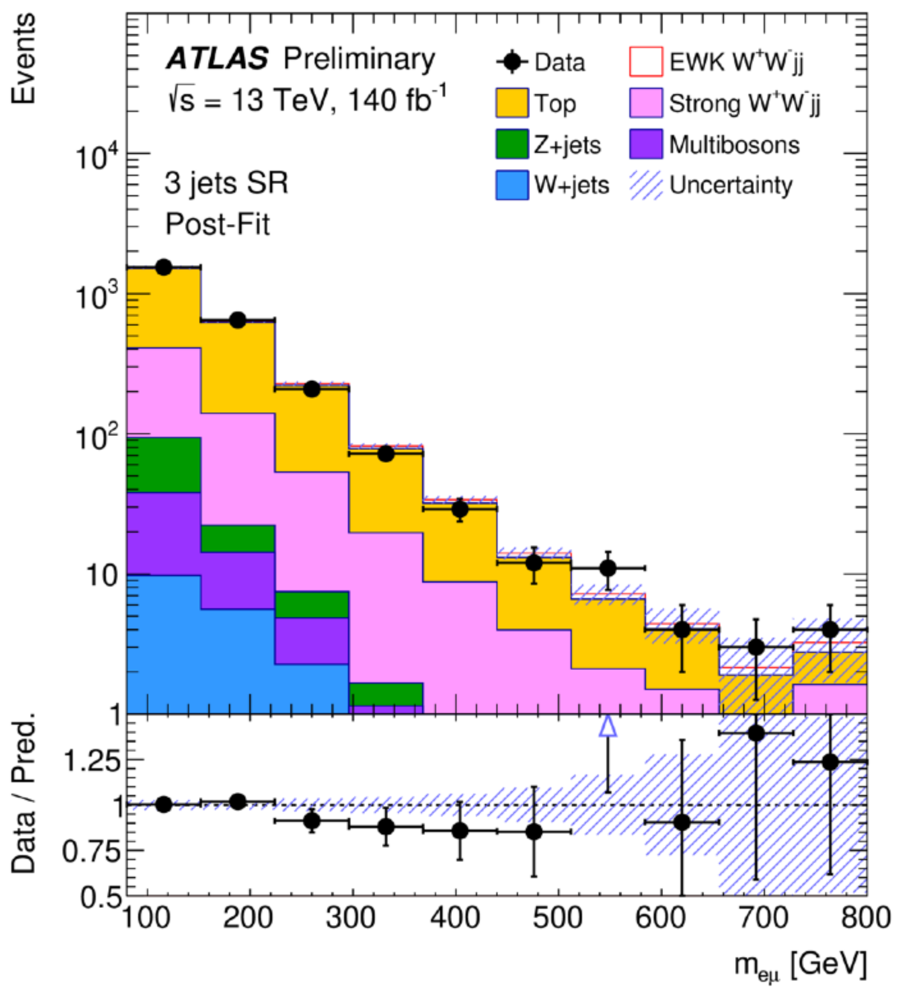
VBS

ATLAS has a broad research programme to study VBS, recent key results below

W+W-jj ATLAS observation at 7.1σ (6.2σ exp)

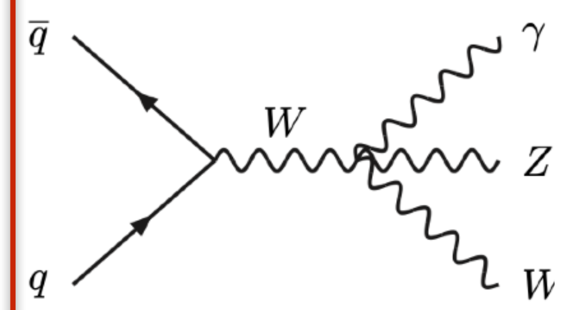
ATLAS-CONF-2023-039

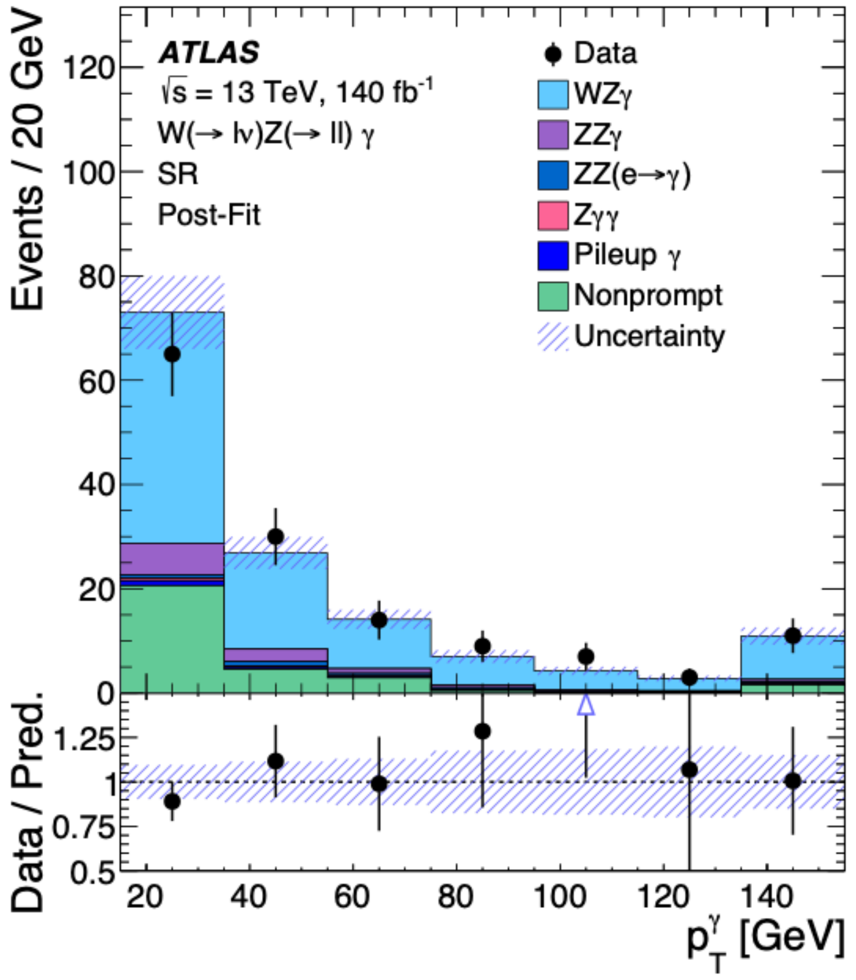




WZγ observation 6.3σ (5.0σ exp)

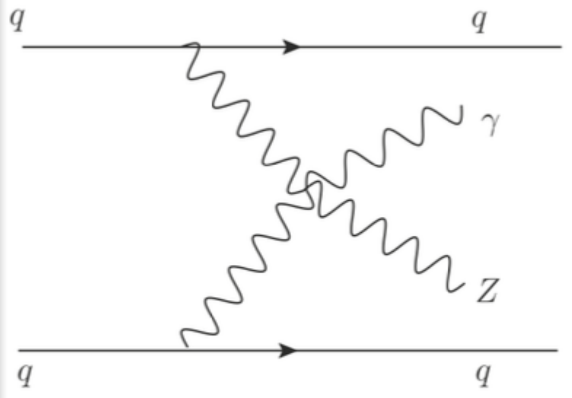
arXiv:2305.16994

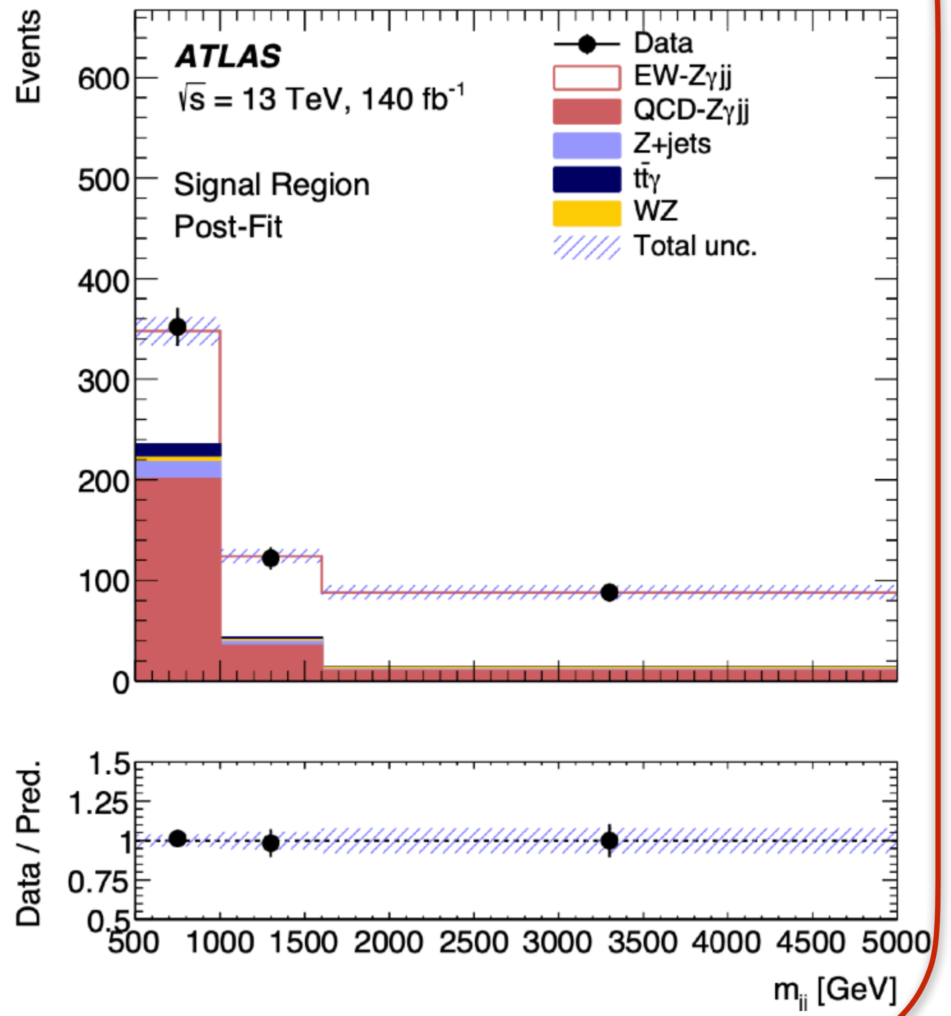




ATLAS observation of EW Zγjj

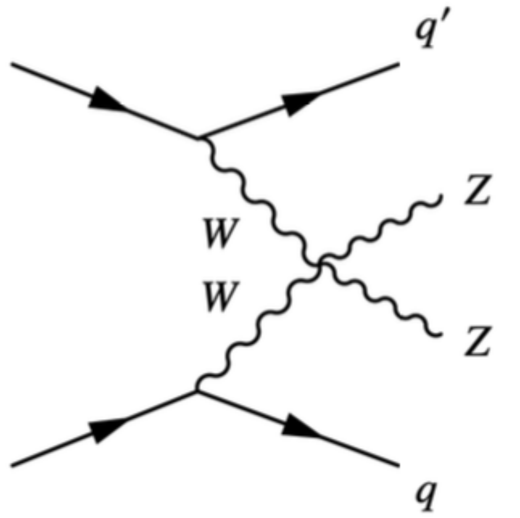
arXiv:2305.19142

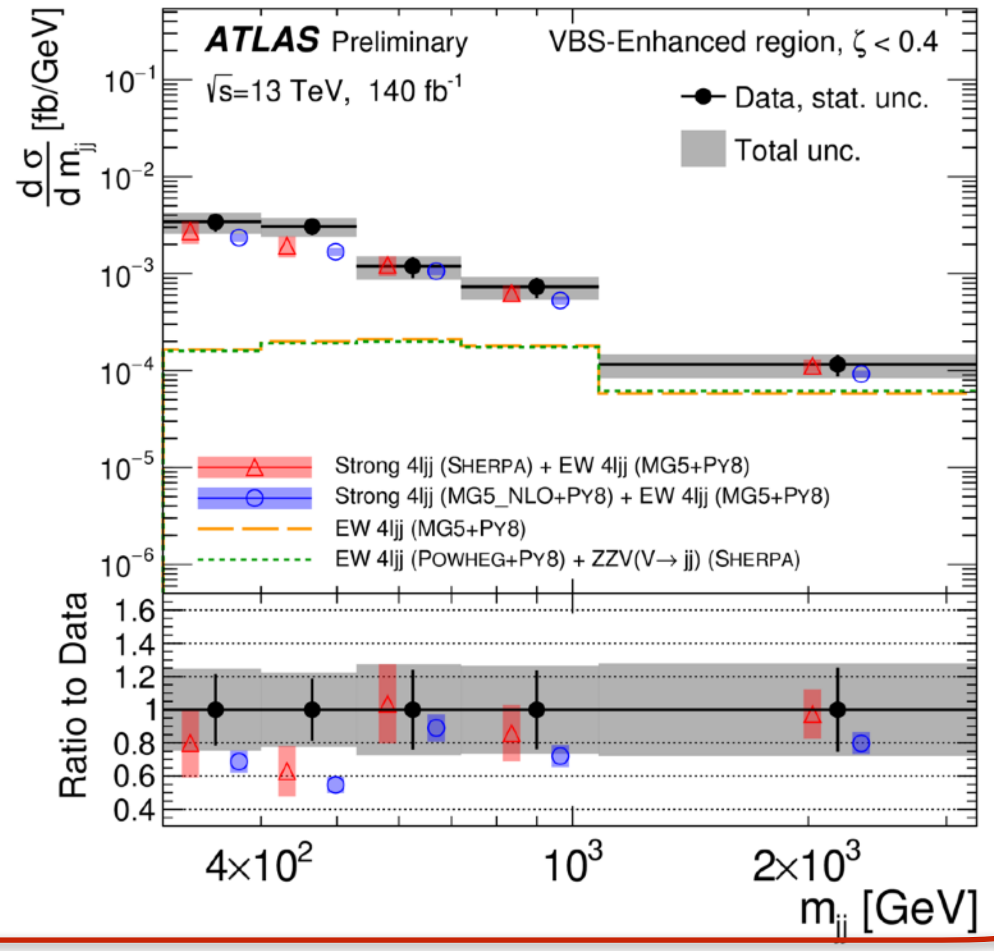




ZZjj differential distributions

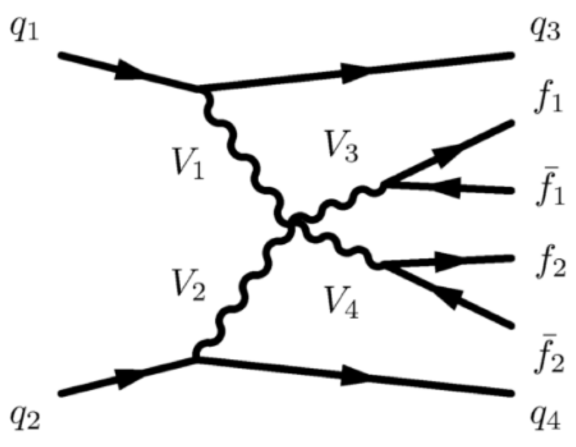
ATLAS-CONF-2023-024

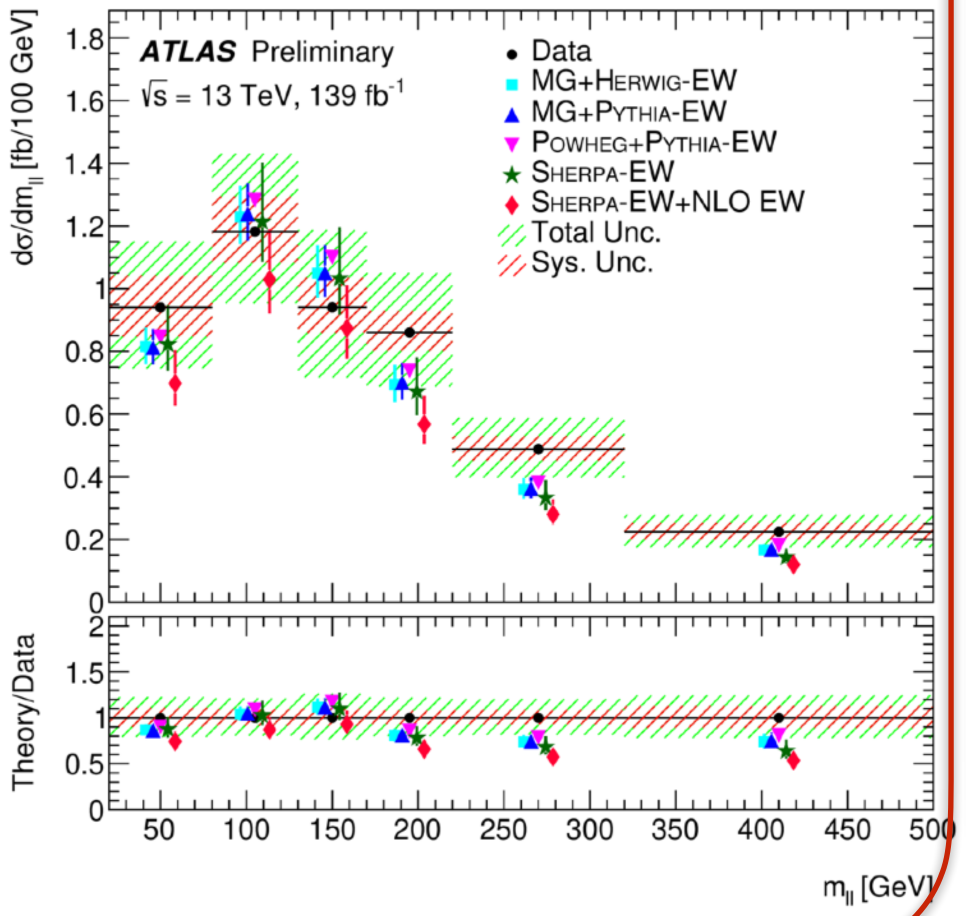




differential VBS Same Sign WWjj

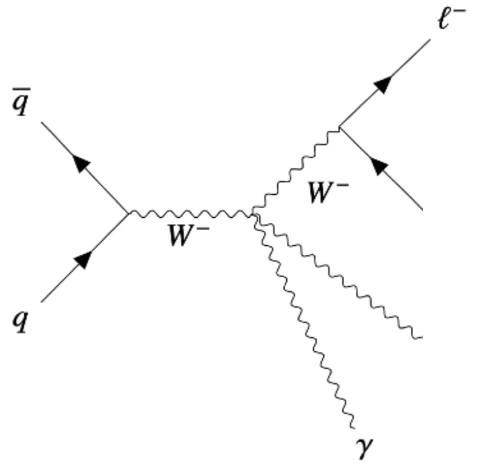
ATLAS-CONF-2023-023

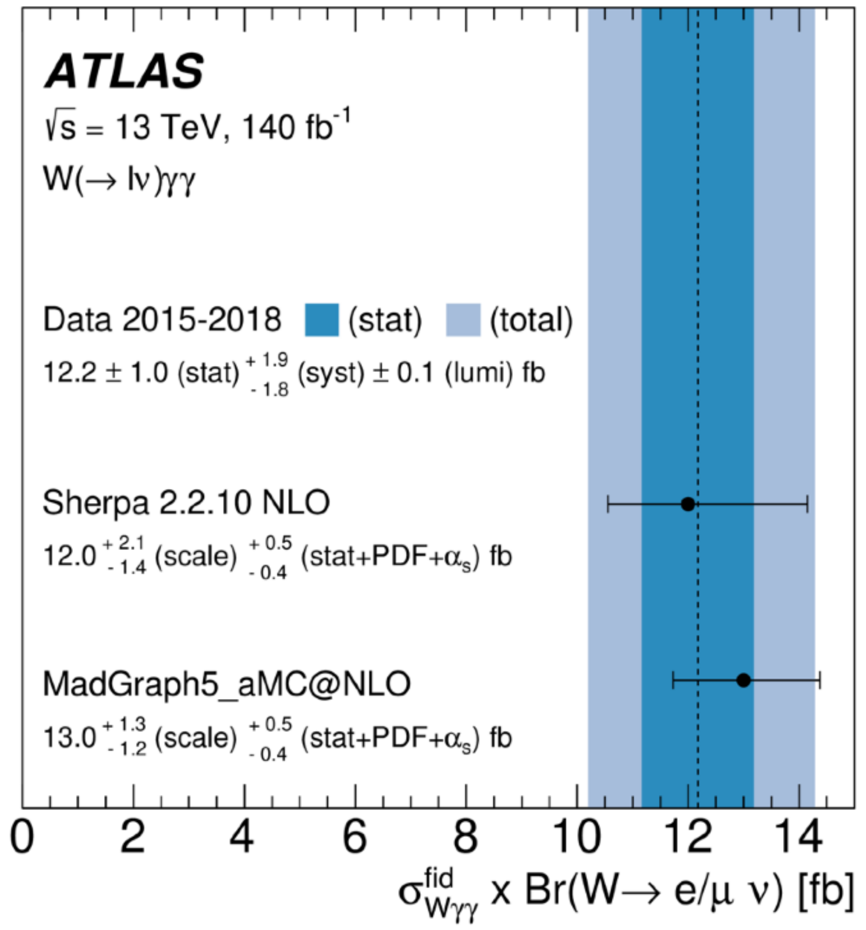




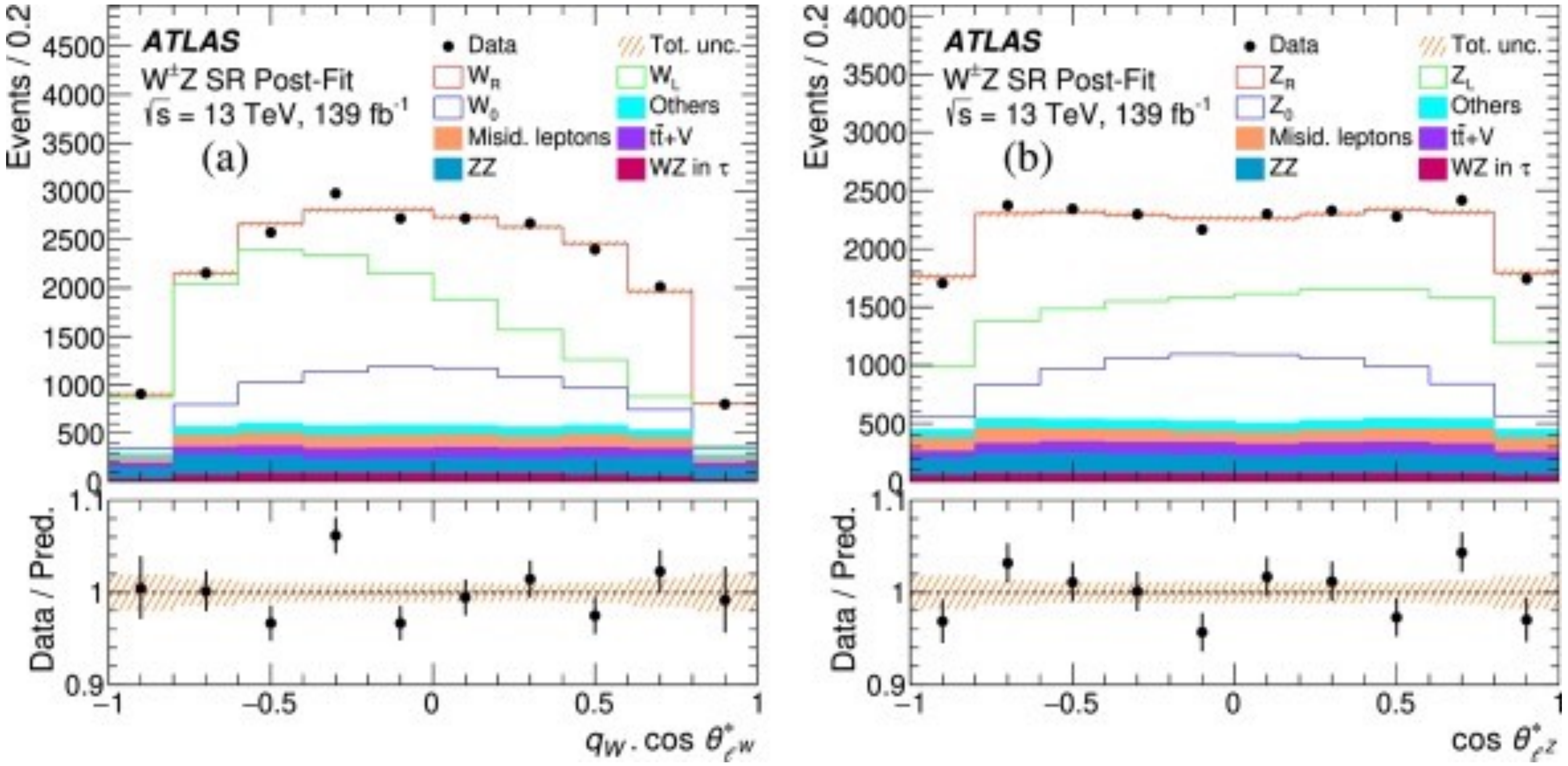
Triboson Wγγ observation 5.6σ (5.6σ exp)

arXiv:2308.03041





VBS W±Z and WW polarization



- longitudinally polarised state of weak bosons is a consequence of the non-vanishing mass of the bosons generated by the electroweak symmetry breaking mechanism.
- these measurements give insights to the way the symmetry is spontaneously broken

ATLAS observed for the first time the production of di-boson polarisation in the W±Z final state.

The most sensitive channel to probe for anomalies is the scattering of two longitudinally W bosons.

While the cross section of same-sign WW production was observed for the first time using Run 2 data,

it is one of the goals of the Run 3 program to measure the polarization

HL-LHC Lumi→ Expected sensitivity↓	VBS long. polarised	
	$3\ ab^{-1}$	$2.5\ ab^{-1}$
ATLAS	3.0	2.7
CMS	2.7	2.5
Combined	4.0	3.7

Probing new physics with precision measurements

- The absence of definitive signals indicating physics beyond the SM at the LHC suggests the possibility of a scale separation between the SM and any potential new physics at higher energies. This motivates the utilization of the **Standard Model Effective Field Theory** (SMEFT) as a valuable tool for indirectly searching for new physics in LHC data

.

- Effective Filed theories introduce new-physics states at a high mass scale Λ, significantly larger than the electroweak scale. By expanding in terms of E/Λ, where E represents the typical energy exchanged in a process, the theory provides predictions for experimental observables. This expansion is achieved through a series of operators, which are constructed as gauge-invariant combinations of SM fields with energy dimensions greater than four.

Testing the deviations from the SM via precision measurements

VBS

EFT/BSM study

- EFT and BSM interpretation using 10 year's Higgs anniversary Nature 607 (2022) 52 publication. In addition differential x-sec combined results for H → $\gamma\,\gamma$ (JHEP 08 (2022) 027) and ZZ decays (Eur. Phys. J. C 80 (2020) 942) are used as well.

Effective Field Theory parametrizes Beyond Standard Model (BSM) effects at high energies ($\Lambda \gg v$, above electroweak scale) at low energies, $E \ll \Lambda$, in terms of higher-dimensional operators in an effective Lagrangian:

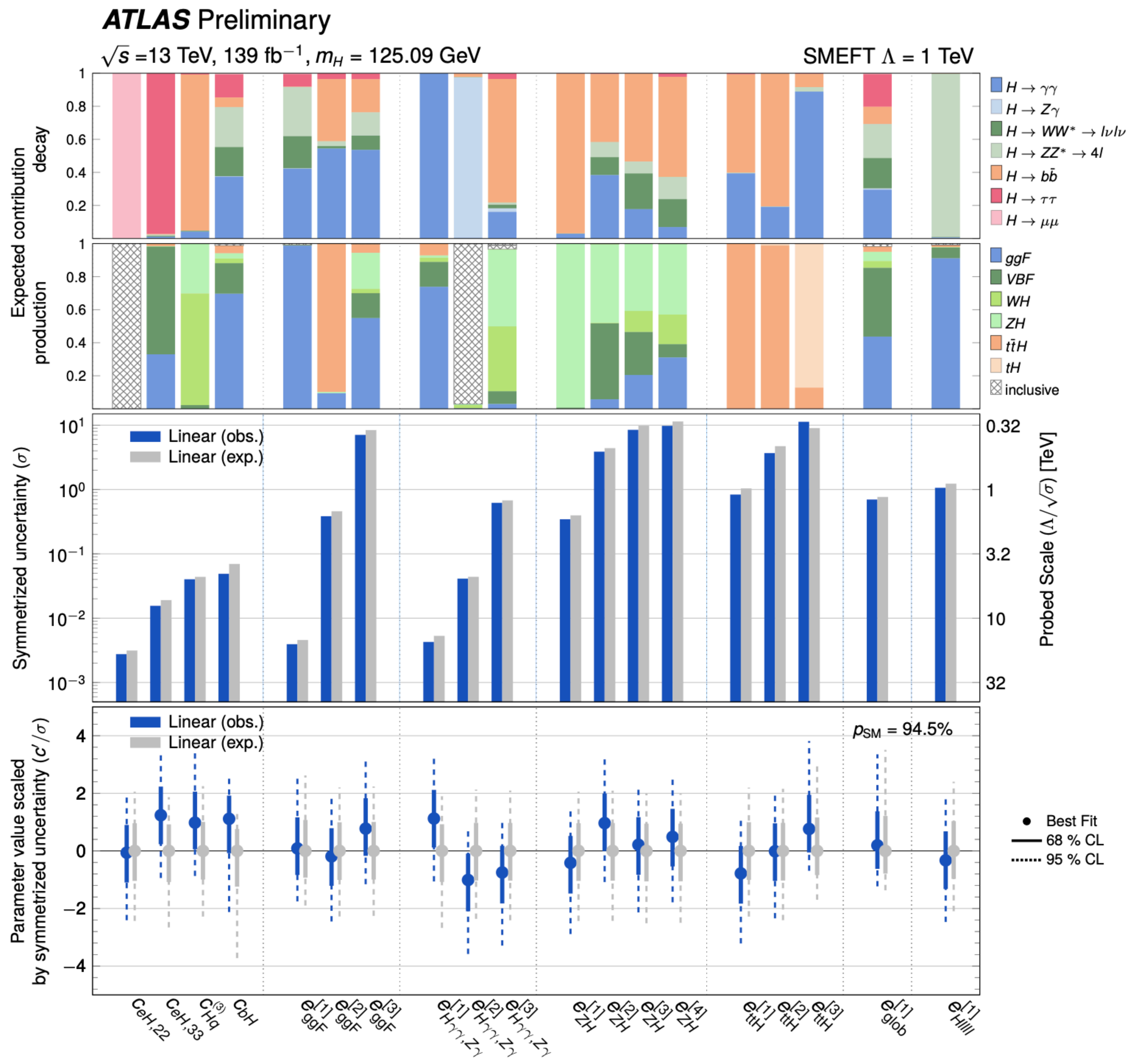
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d=8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots,$$

dimensionless Wilson coefficients of higher dimension operators

Comprehensive Higgs EFT/BSM study

- EFT and BSM interpretation using 10 year's Higgs anniversary Nature 607 (2022) 52 publication. In addition uses differential x-sec combined results for H → γ γ (JHEP 08 (2022) 027) and ZZ decays (Eur. Phys. J. C 80 (2020) 942).

ATLAS-CONF-2023-052



EFT

EFT combinations of SM and Higgs channels

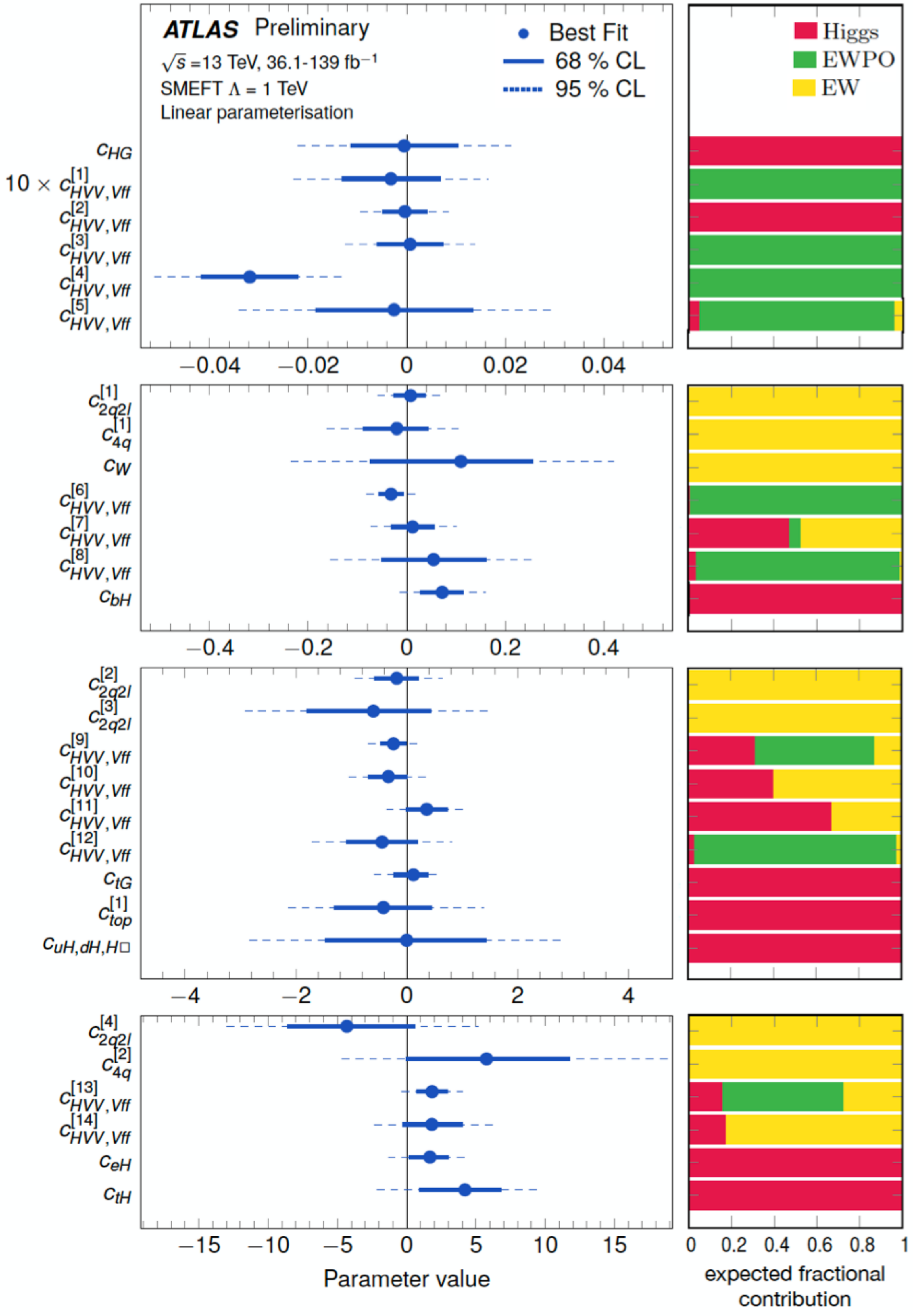
Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[10]
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139	[11]
$H \to WW^*$	ggF, VBF	139	[12]
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]
	WH, ZH	139	[14–16]
$H \to b\bar{b}$	VBF	126	[17]
	$t\bar{t}H$	139	[18]

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55$ GeV, $p_T^{\text{jet}} < 35$ GeV	$p_T^{\text{lead. lep.}}$	36	[19]
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)$ GeV	m_T^{WZ}	36	[20]
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180$ GeV	m_{Z2}	139	[21]
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000$ GeV, $m_{\ell\ell} \in (81, 101)$ GeV	$\Delta\phi_{jj}$	139	[22]

We can add also SM measurements to constrain the same operators

Planning to add also top quark

SM+Higgs EFT



The same wilson coefficients are constrained by different processes!

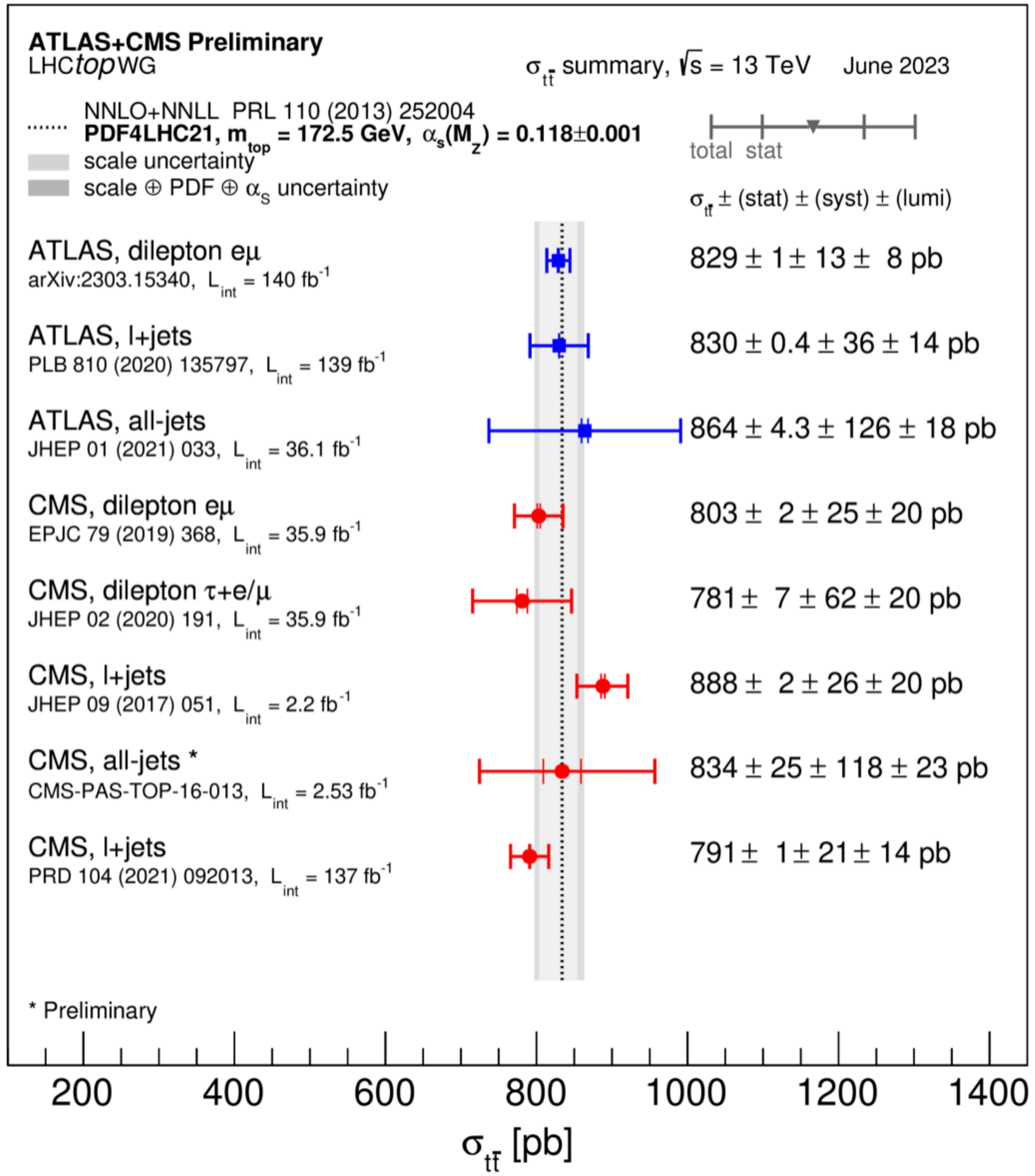
The statistical uncertinties are very large

Run 3 will be pivotal for such EFT interpretations and top+SM+higgs results will be combined,

Some more SM: top quark and more

Top quark pair production cross-section

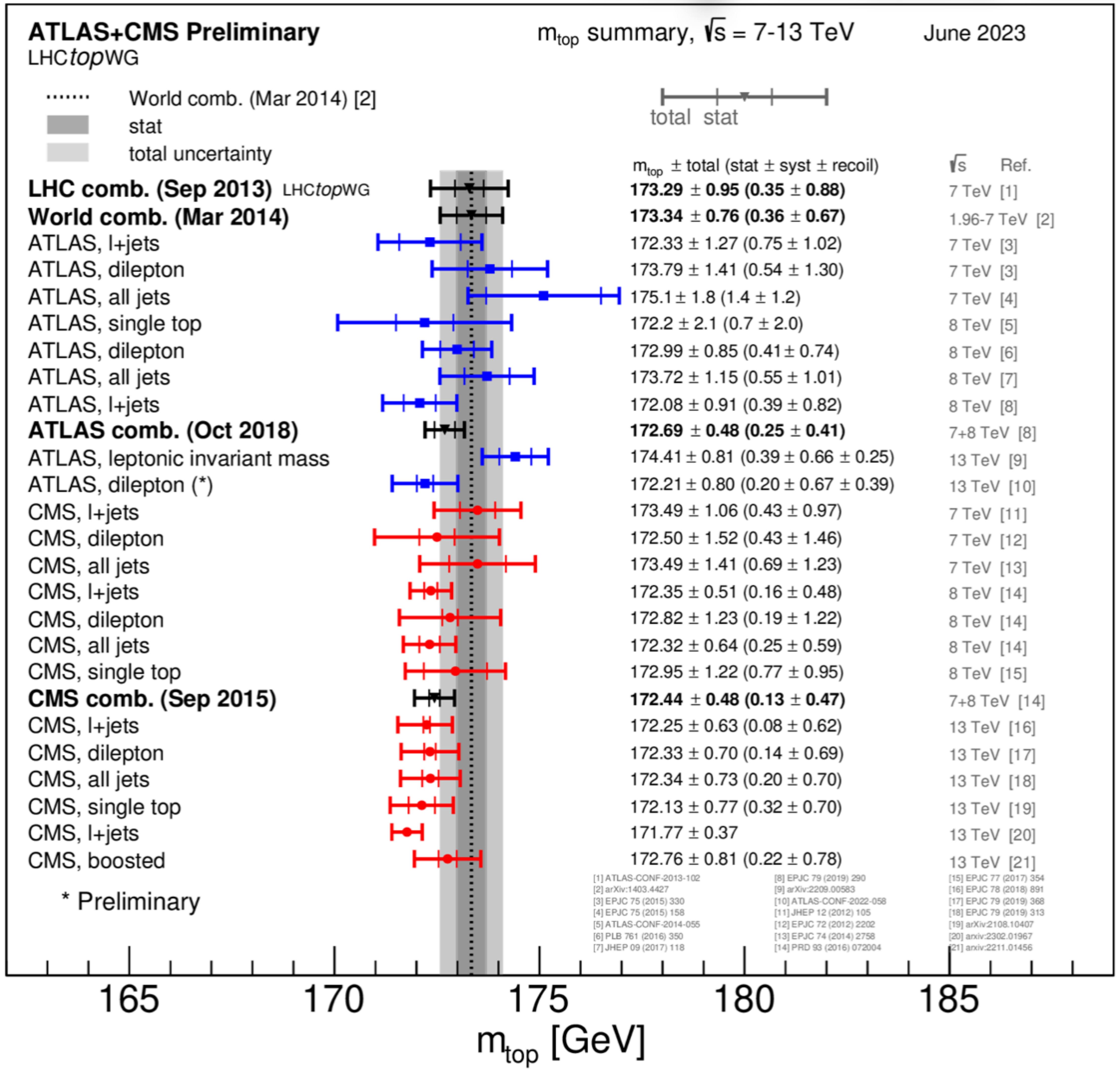
Channel	$\sqrt{s}$ [TeV]	$\int \mathcal{L}\,\mathrm{dt}$ [fb^{-1}]	$\sigma_{t\bar{t}}$ [pb]	Reference
Dilepton,ℓ+jets	5	0.257	67.5 ± 2.7	[7]
$e\mu$	7	4.6	183 ± 7	[8]
ℓ+jets	7	4.7	169 ± 7	[3]
$e\mu$	8	20.2	242 ± 9	[8]
ℓ+jets	8	20.2	248 ± 14	[9]
$e\mu$	13	140	829 ± 15	[4]
ℓ+jets	13	139	830 ± 39	[10]
all-jets	13	36.1	864 ± 127	[11]
$e\mu$	13.6	11	859 ± 29	[2]

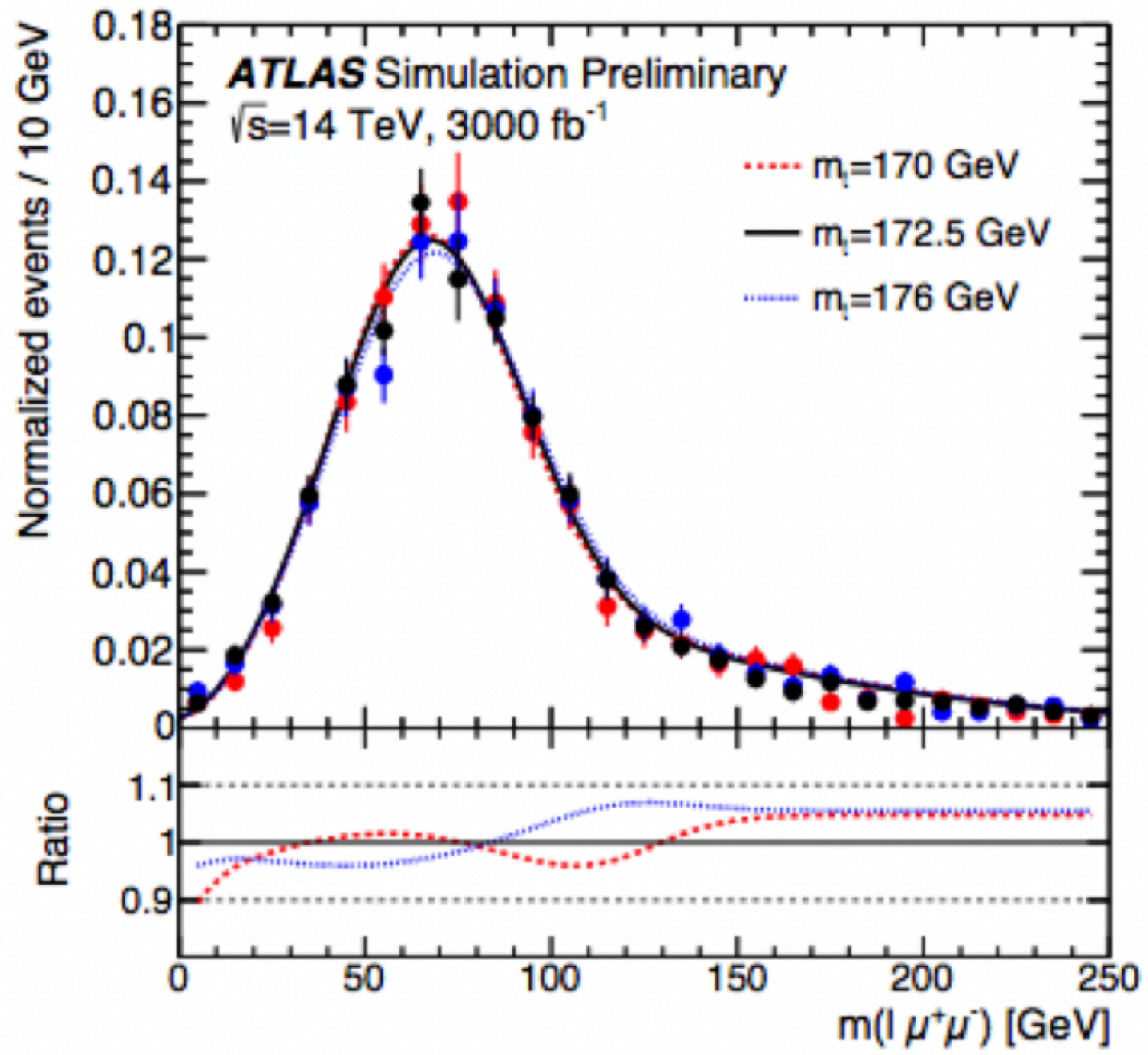


For top physics the <u>theory modelling uncertainties</u> are more important than more data in Run 3!

Generally for the top cross-section, top mass and top+X processes the top modelling uncertainties are playing a very important role, even for analyses that are statistically dominated.

Top mass measurements





The analysis will profit from high luminosity at HL-LHC and larger acceptance of the inner detector. It will be limited by jet energy uncertainty scale on mtop but $t\bar{t}$ modelling will also be relevant.

EW fit constrains m_W, m_{top} and m_H

The global electroweak fit enabled prediction of m_{top} and m_H before their discoveries:

-Measure different observables
-Calculate relations between observables

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

The W boson mass in the SM is related with the Z-boson mass, mZ, the fine structure constant, α, and the Fermi constant, Gμ
Δr includes the quantum corrections to mW, which depend m_{top} quadratically and m_H, logarithmically.

One can indirectly constrain these parameters with great precision.

By the end of the LHC, we might have results in indirect precisions of
ΔmW≈4 MeV, ΔmTop≈1.3 GeV, ΔmH≈13 GeV

The EW fits generically impose stringent constraints on any theory of electroweak symmetry breaking

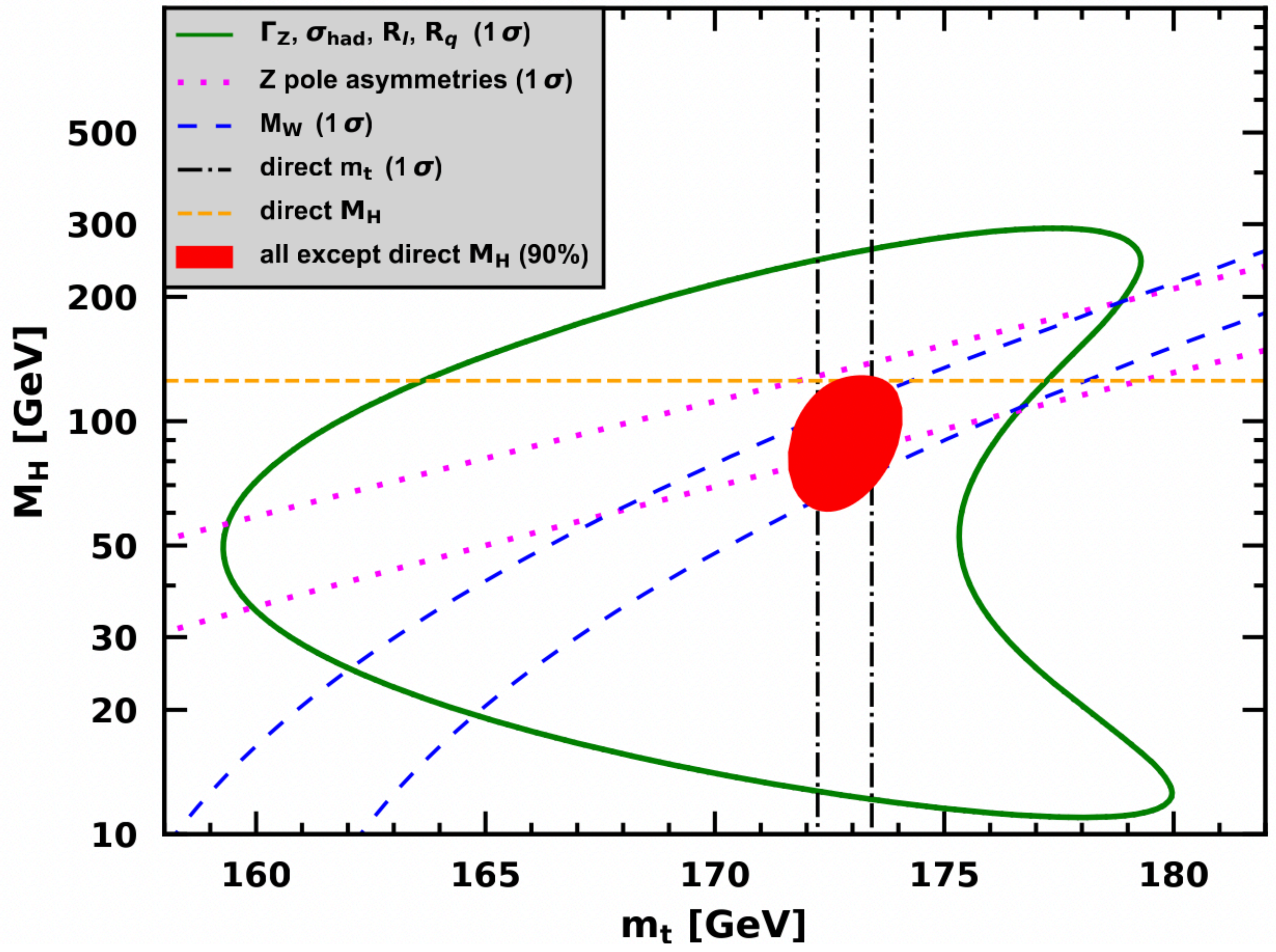
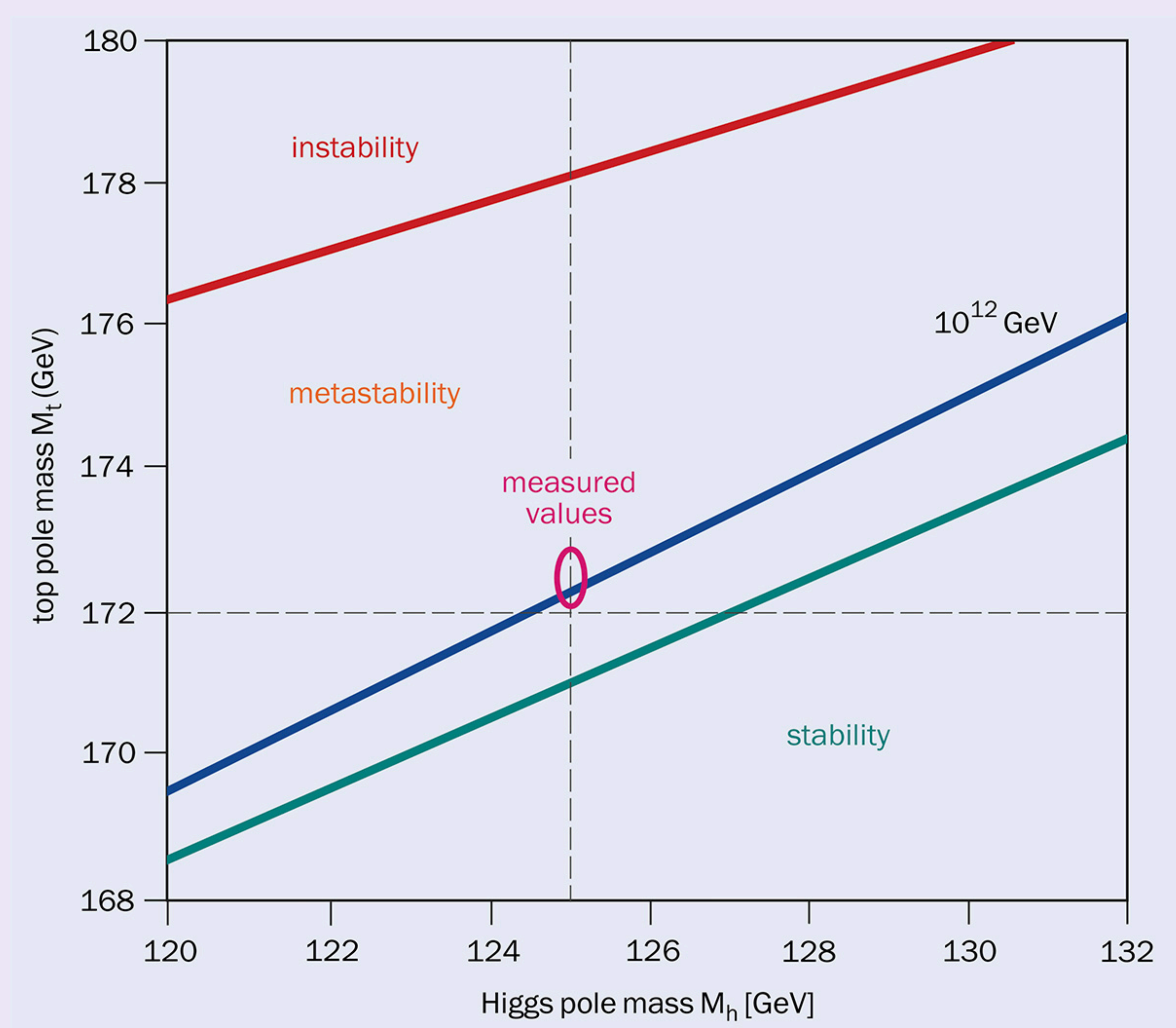


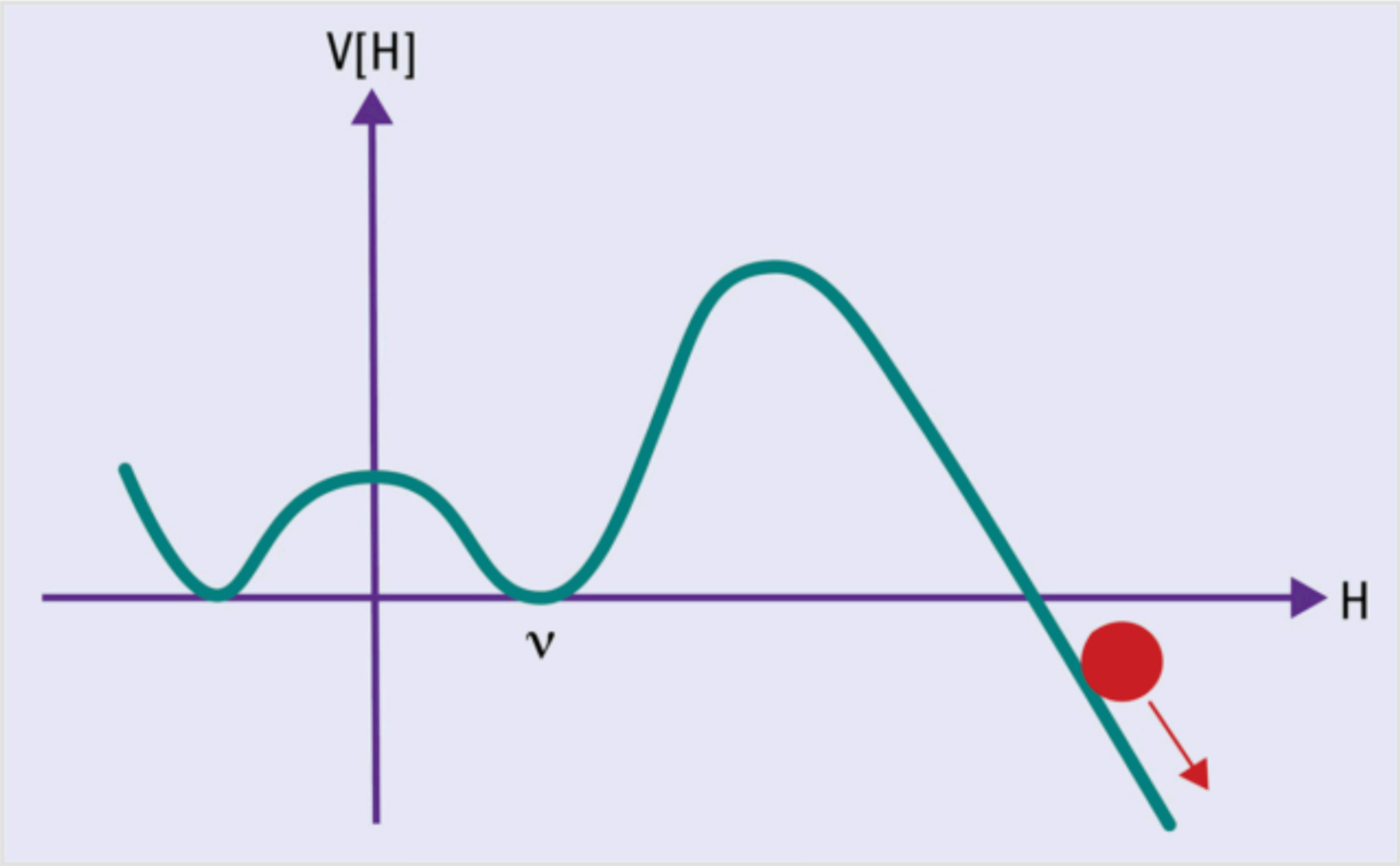
Figure 10.4: Fit result and one-standard-deviation (39.35% for the closed contours and 68% for the others) uncertainties in M_H as a function of m_t for various inputs, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. $\alpha_s(M_Z) = 0.1185$ is assumed except for the fits including the Z lineshape. The width of the horizontal dashed band is not visible on the scale of the plot.

m_{top} and m_H

Quantum effects can change the shape of the Mexican hat Higgs potential.
The Higgs field has self-interactions that make the hat turn upwards,
additional quantum effects can turn it downwards, due to interactions with the fundamental particles to which the Higgs gives mass. The top mass is the heaviest and therefore the most important.



On the cusp Regions of absolute stability, metastability and instability of the SM vacuum in the m_t–m_H plane. The blue line shows where the brim of the Mexican hat turns down at 10^{12} GeV and the ellipse represents 1σ Particle Data Group values. Credit: Particle Data Group/*JHEP* **12** 089

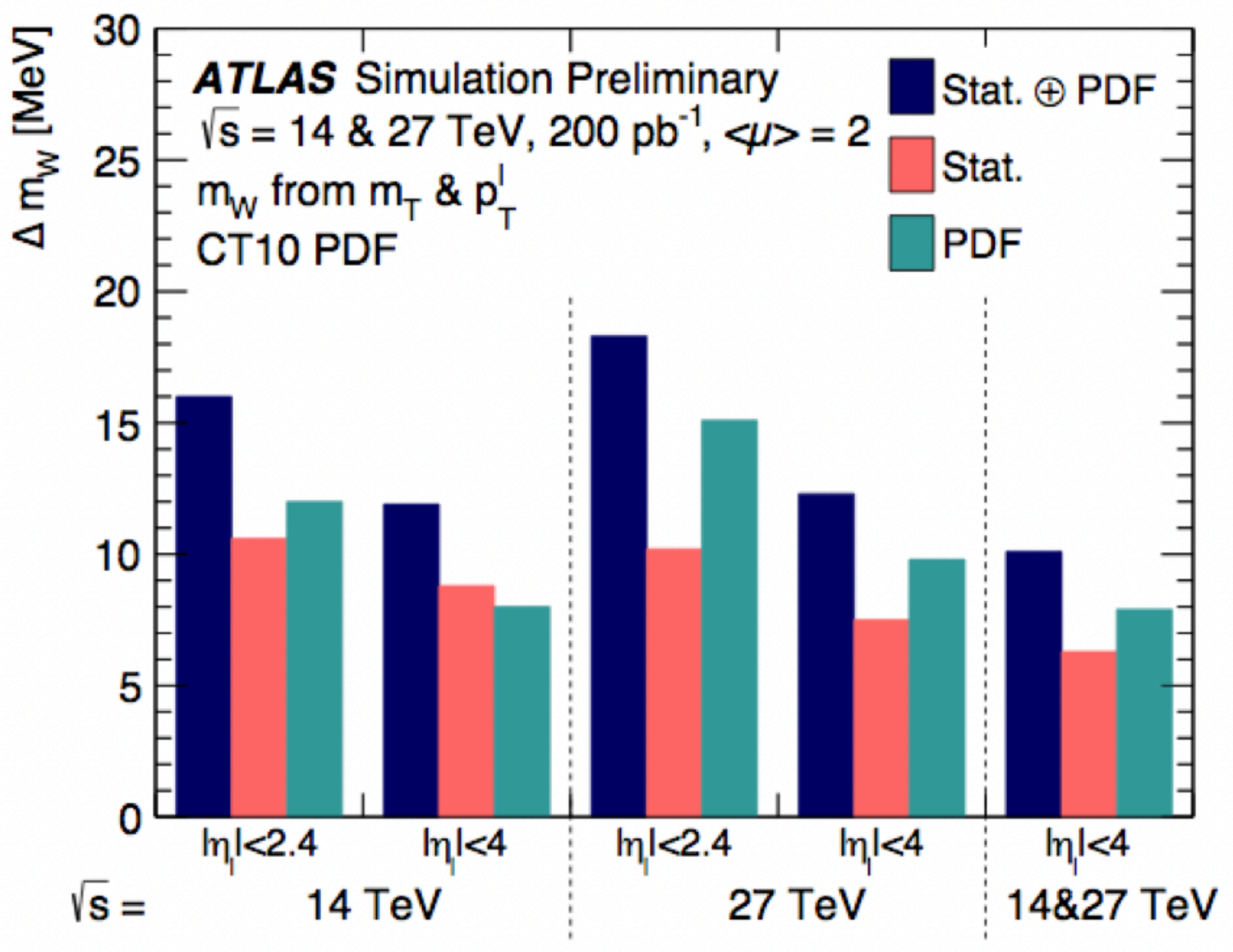


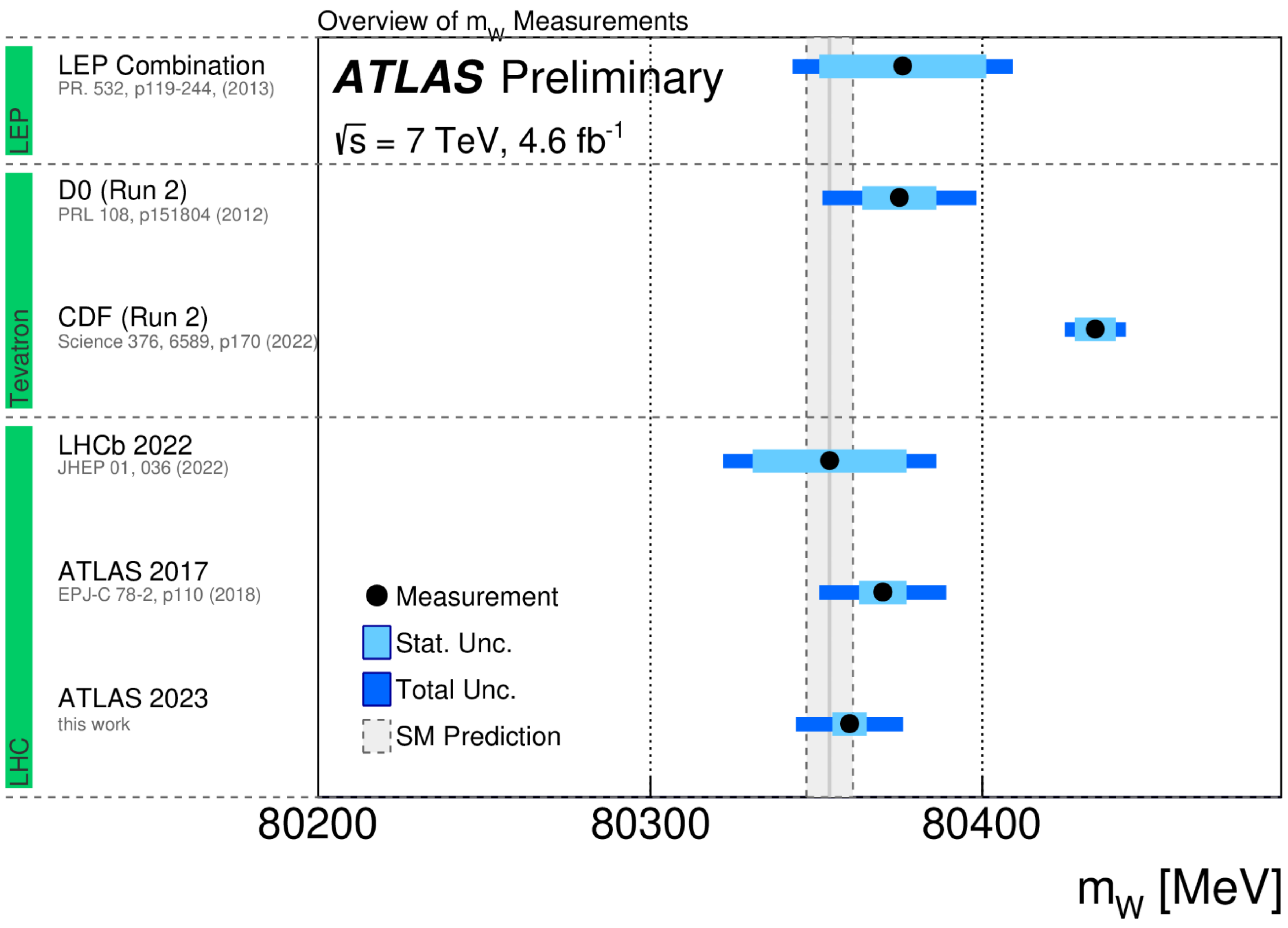
The present measurements indicate that the current minimum of the Higgs potential is not the lowest and that universe could be metastable and that it could end up in the different minimum.
New physics could stabilize the vacuum.

W mass at HL_LHC

at HL-LHC a total of 2x10[6] will be produced at the HL-LHC in 1 week

Understanding of PDFs will be crucial





- Re-analysis: new log-likelihood fit constrains systematic uncertainties with data, more modern PDFs!
- **Reduces systematic uncertainties from 18 to 15 MeV**

m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV

Compatible with SM

Errors at 10 MeV or lower will be achieved

Direct searches for New Physics

Searches: we are exploring in all directions

- dark sector
- Dark Matter
- Invisible decays
- heavy neutrinos
- Extra dimensions
- compositeness
- contact interactions
- resonances
- Long Lived Particles
- Highly ionizing particles
- Leptoquarks
- Axions
- WIMPS weakly interacting massive particles
- Supersymmetry
- vector like quarks

Strategy for Run 3 searches

- covering wider phase space
- going more model independent
- explore wider range of signatures
- exploit the new triggering features of the new detector
- exploit better reconstruction performance in particular flavor tagging large r-jets
- exploit better tracking capabilities: few examples.

Let's start with the analyses that will profit of new Triggers

Trigger Level analysis ATLAS

TLA for Inclusive Searches:TLA idea:

- Events only seen by the trigger contain compelling physics:
  - Discarded due to trigger thresholds

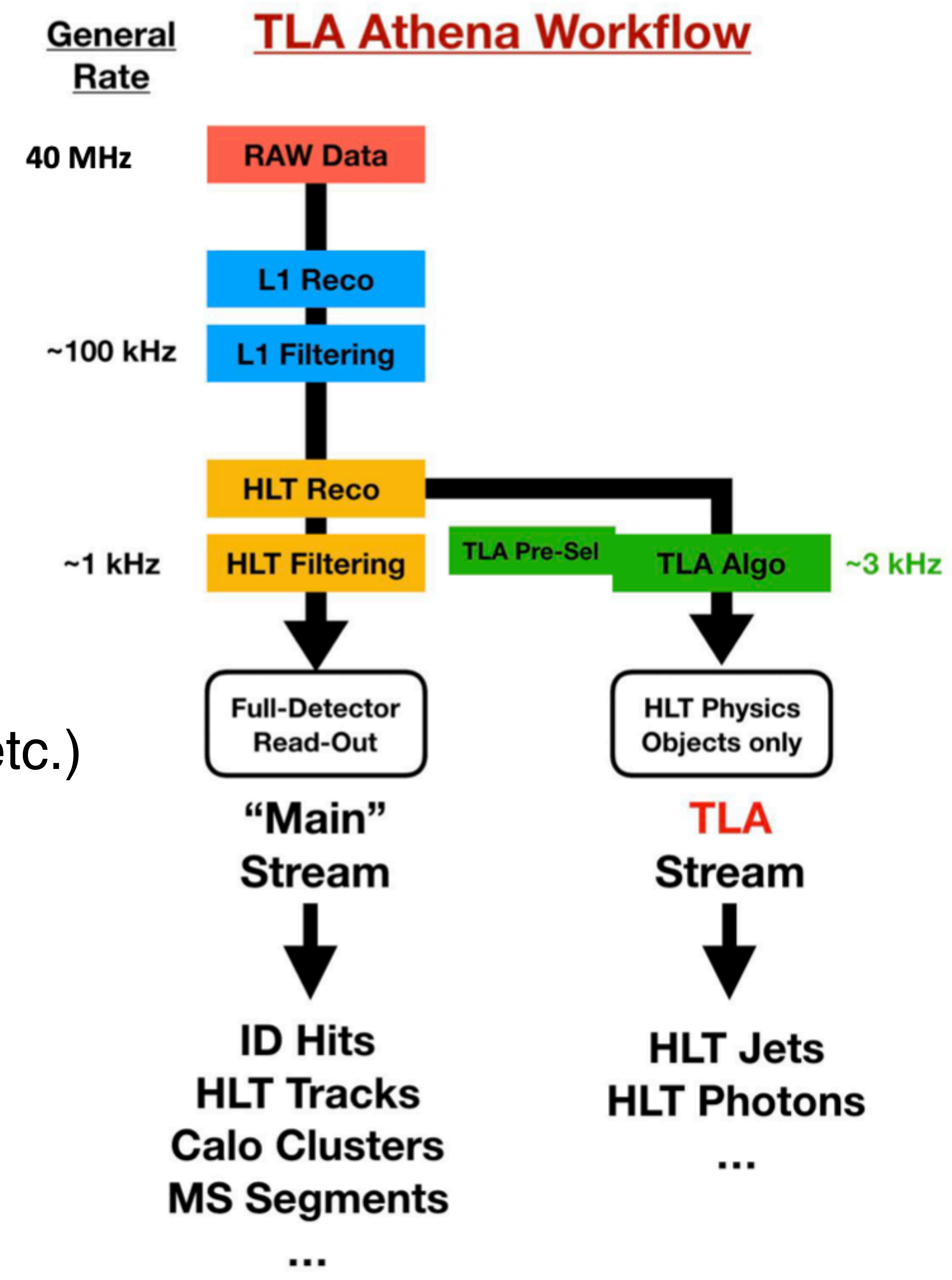
  - But already reconstructed to perform the trigger decision

Recover these events→ Store trigger reconstruction outcome

  - Run 2/3 baseline TLA:

→ SAVE ONLY RESULT OF HLT RECONSTRUCTION (HLT jets, photons, etc.)
→ No RAW data stored to output

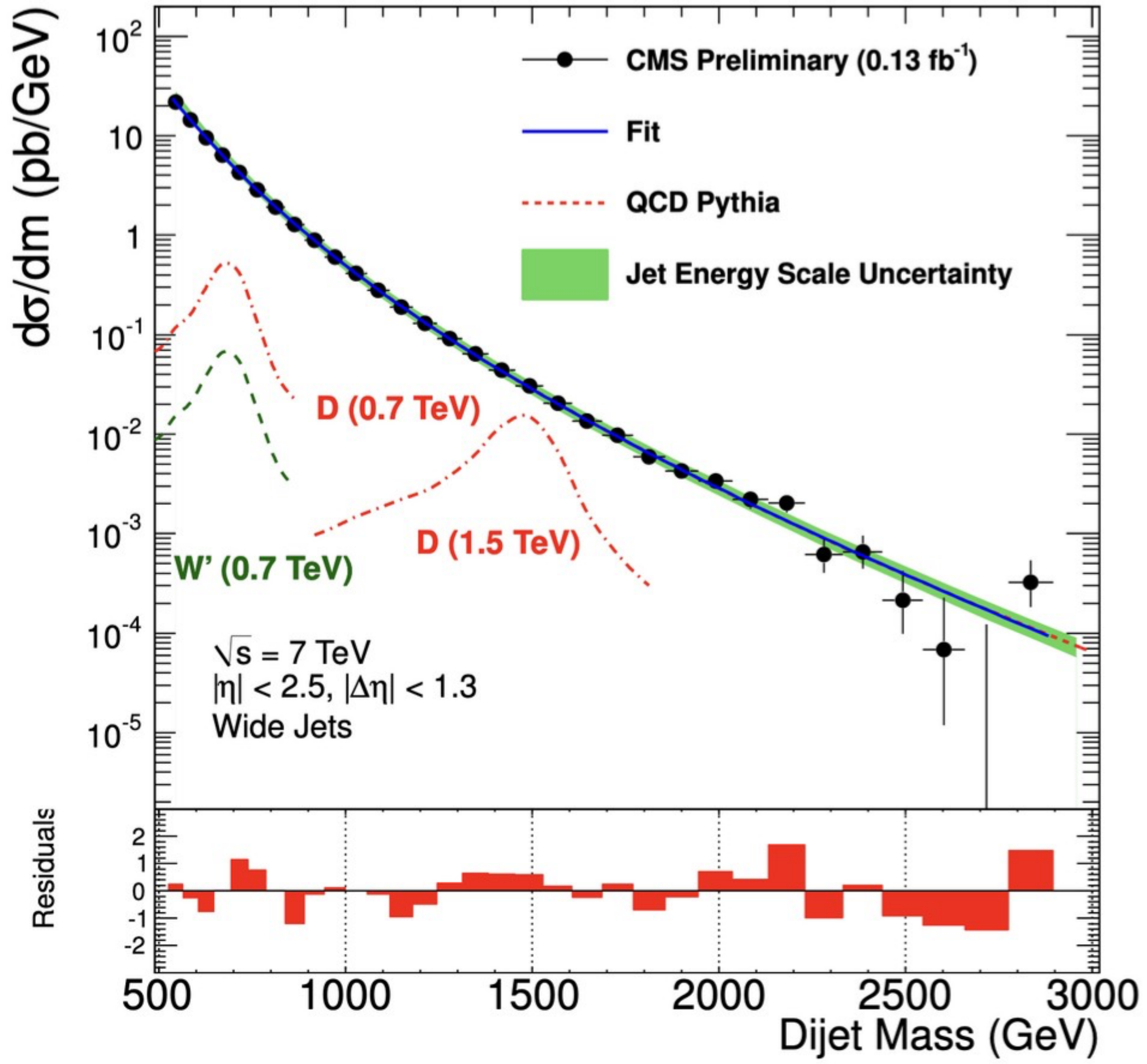
Bandwidth	= Rate	x	Event Size	
ATLAS Physics Stream	~ 1.7kHz	x	1.5MB/s	→ 3 GB/s
TLA Stream	~ 6kHz	x	4.5kB/s	→ 27 MB/s



Data-scouting in CMS (same concept)

First employed for di-jet searches by CMS in LHC Run 1

Then for many hadronic searches



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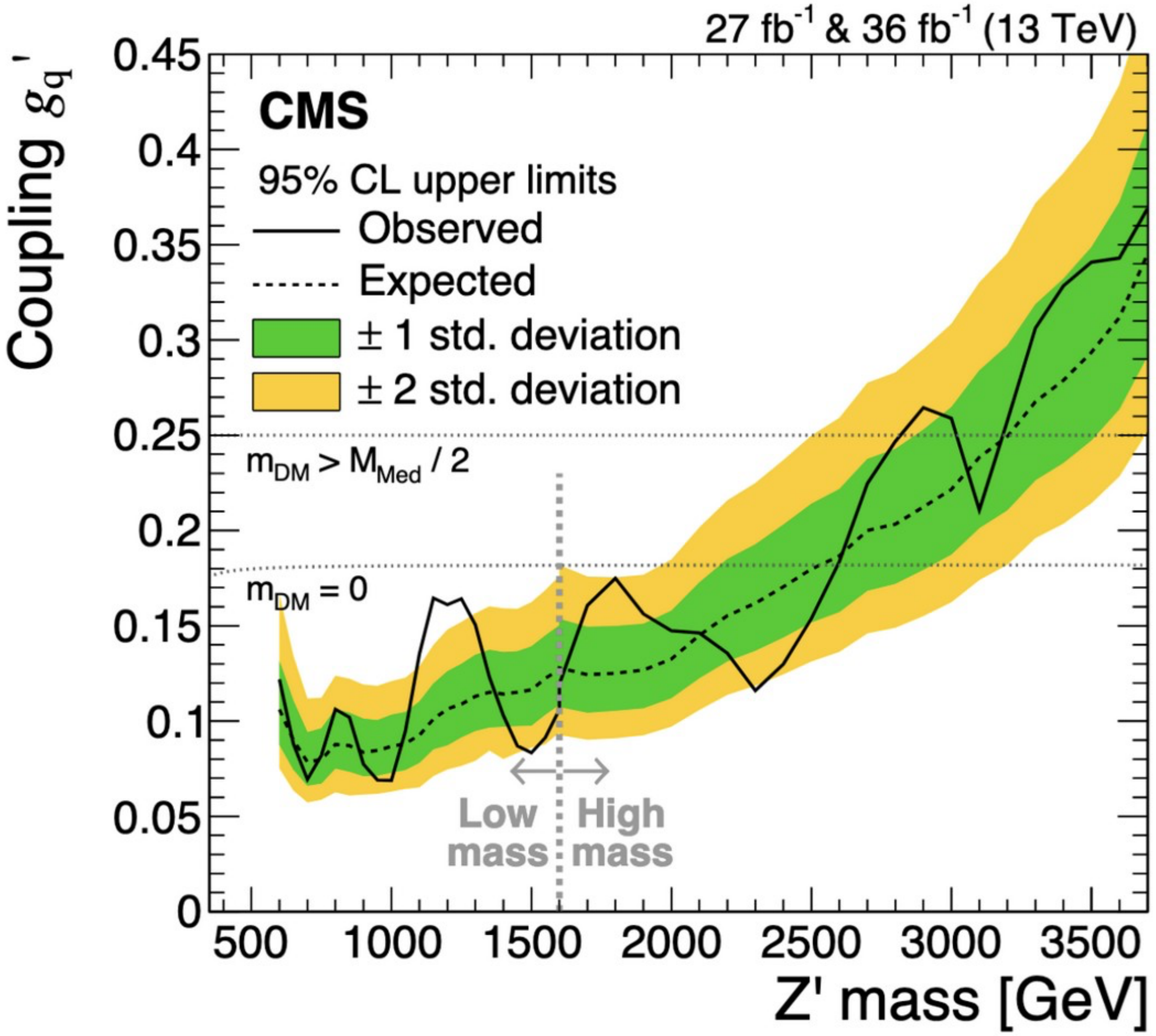
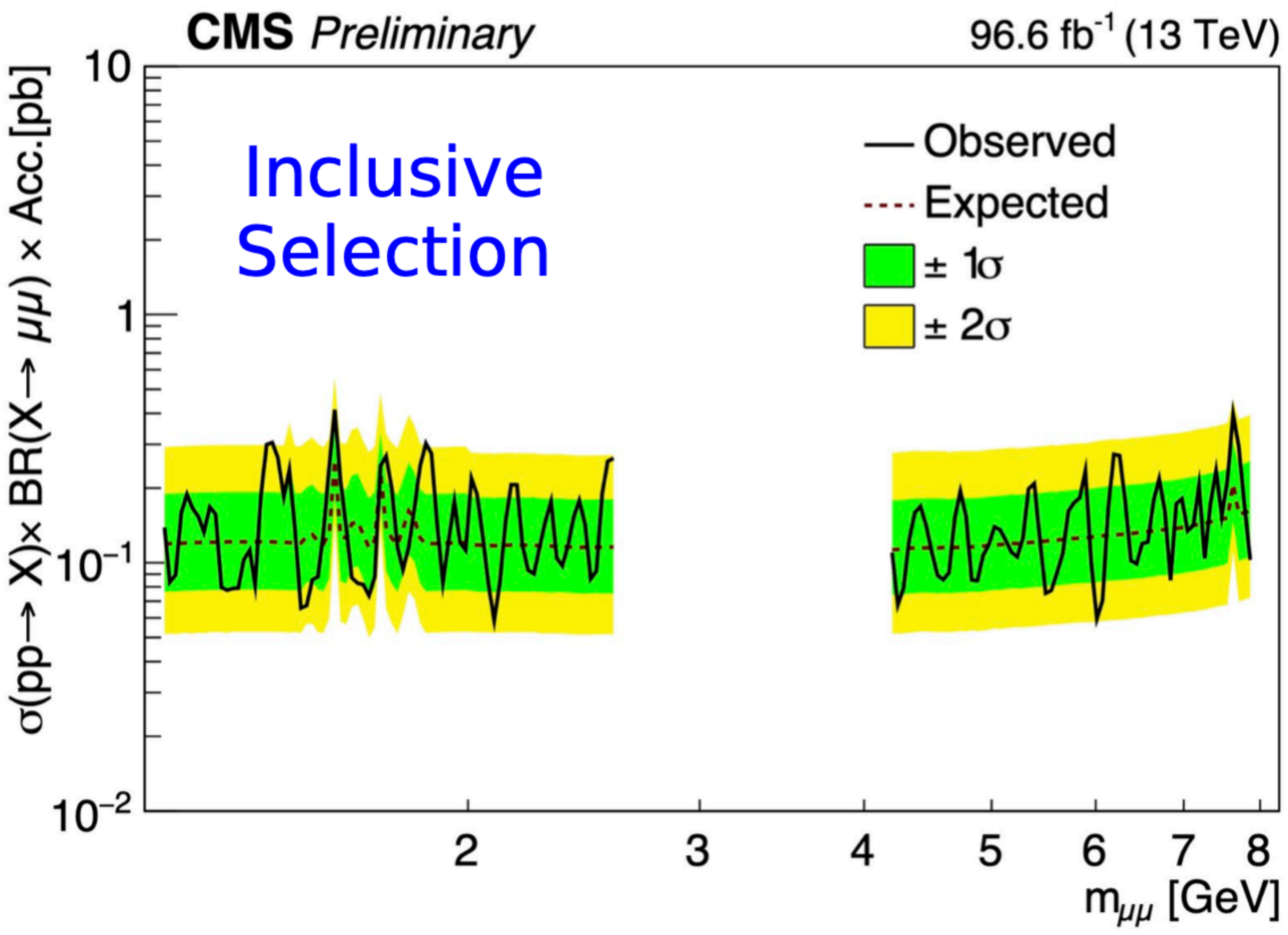
First employed for Dijet searches by CMS in LHC Run 1

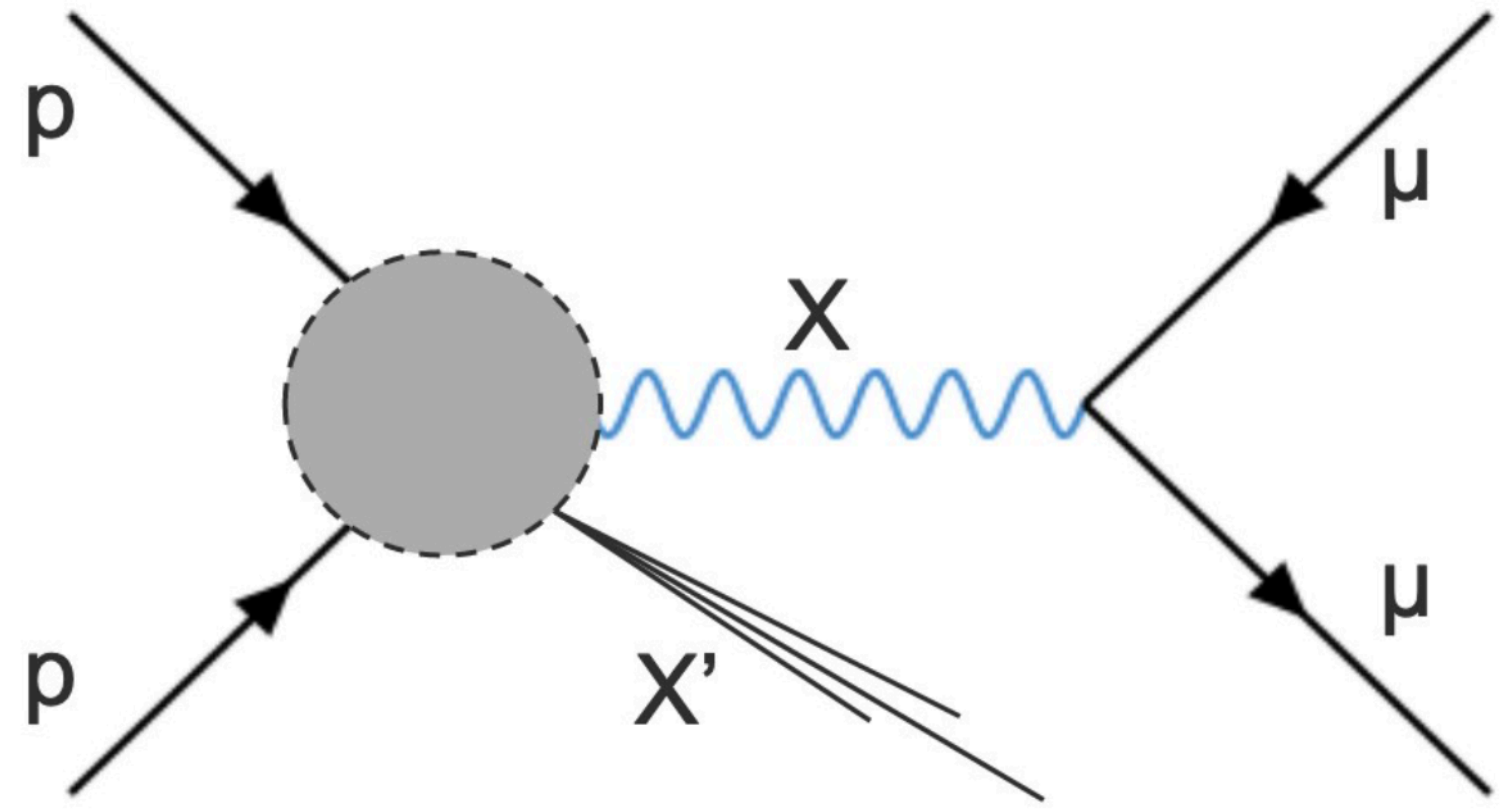


Finally CMS has it Fully commissioned for multi-muon final states

Also used for the search for unknown resonances

Bump hunt on the dimuon mass



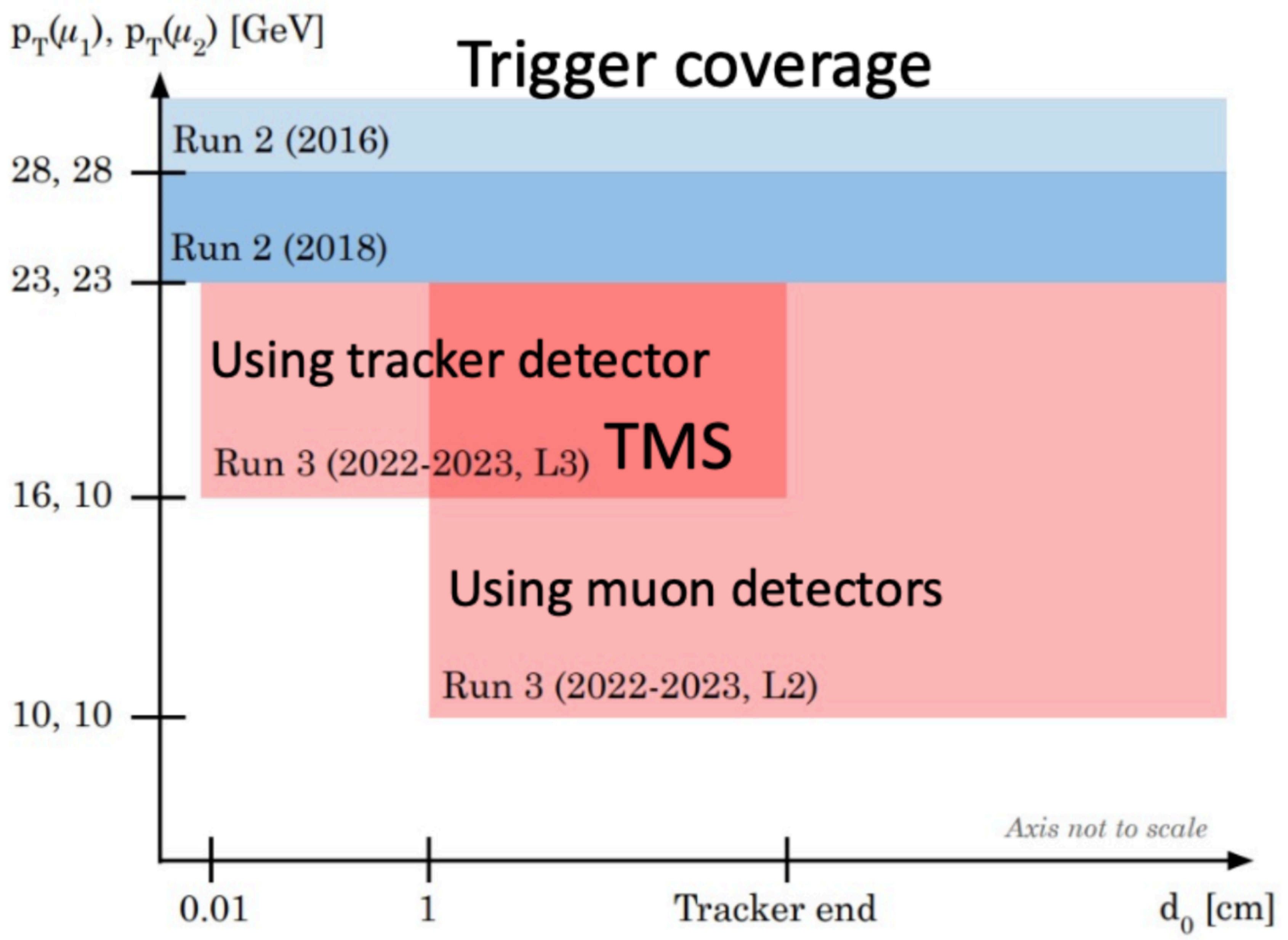


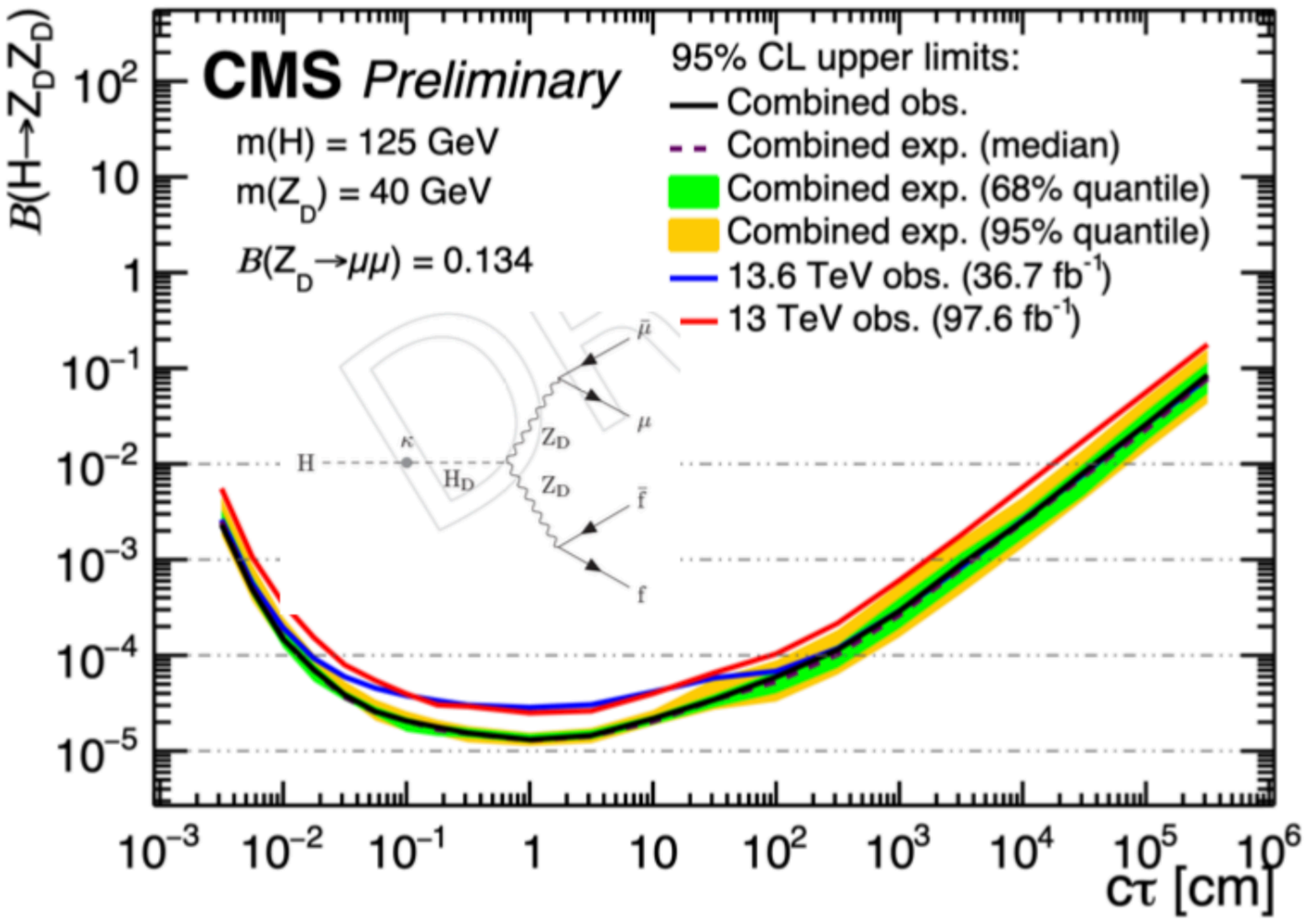
Reaches very low di muon masses!

Long Lived particles @Run 3

First search for new physics at Run 3, looking for long lived particles decaying into muon pairs: selects muon originating from a common secondary vertex spatially separated form the primary interaction point from few hundred μm to several meters.

Substancial improvement of efficiency due to improved triggers for displaced muons (and also analysis techniques)

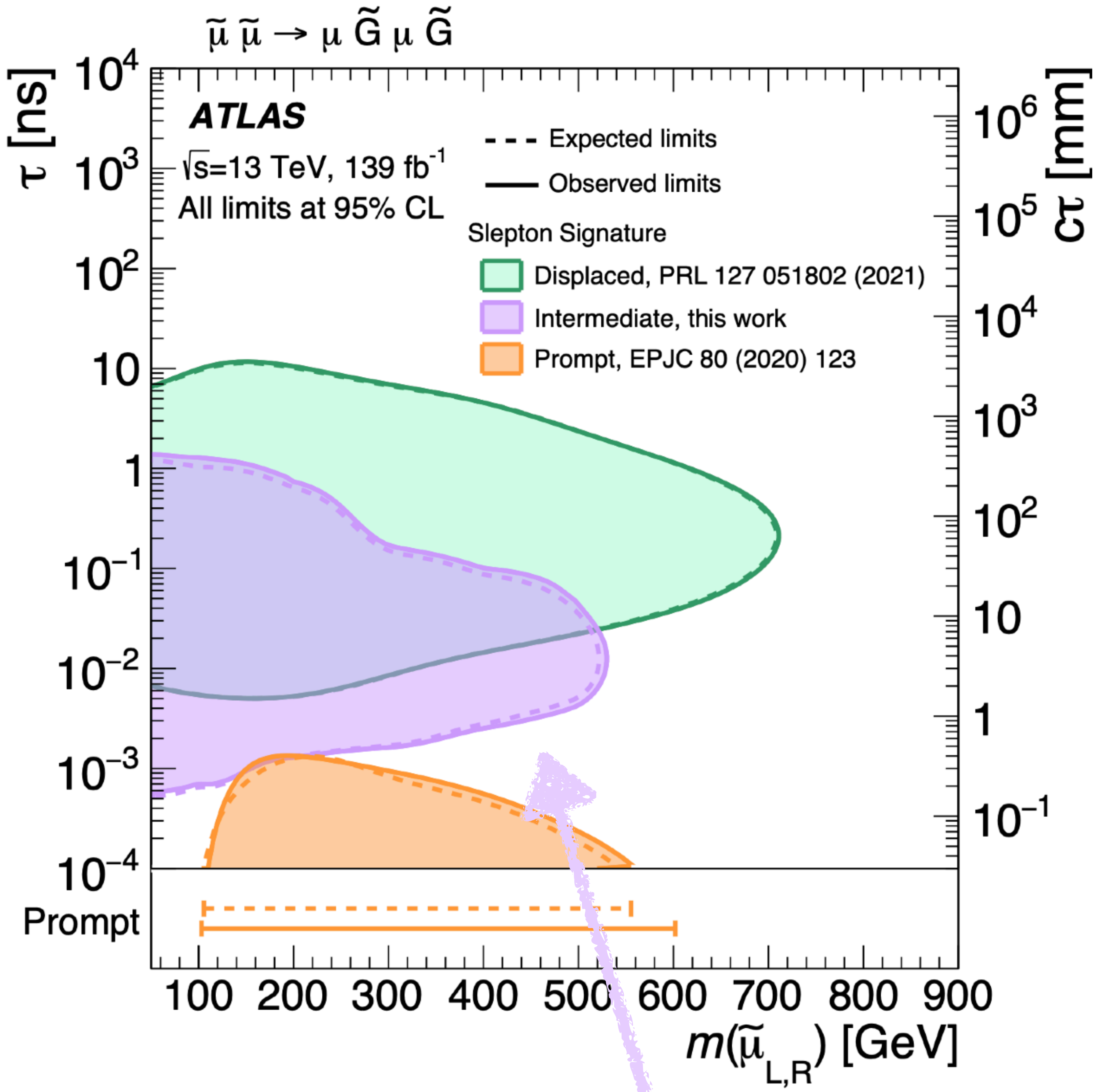




Displaced particles

https://arxiv.org/abs/2305.14931

Search for muons with small displacements



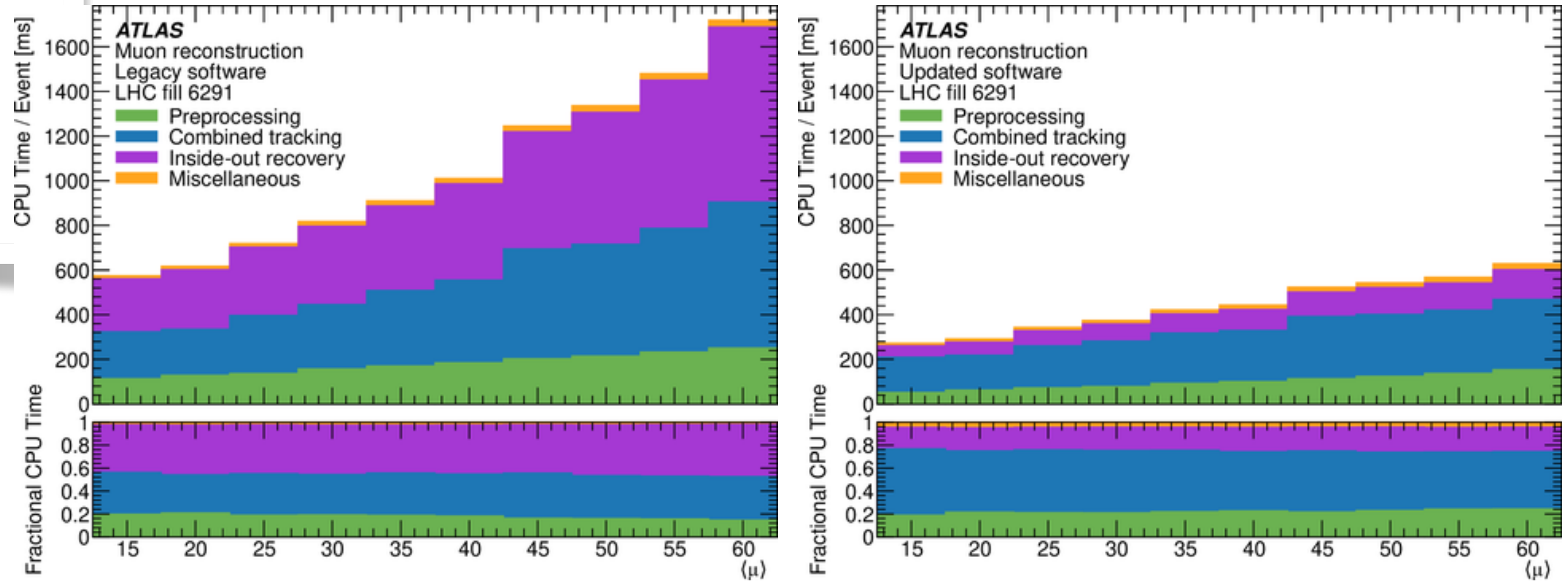
Covers phase space between prompt & displaced muons

ATLAS Tracking improved performance! arXiv:2308.09471

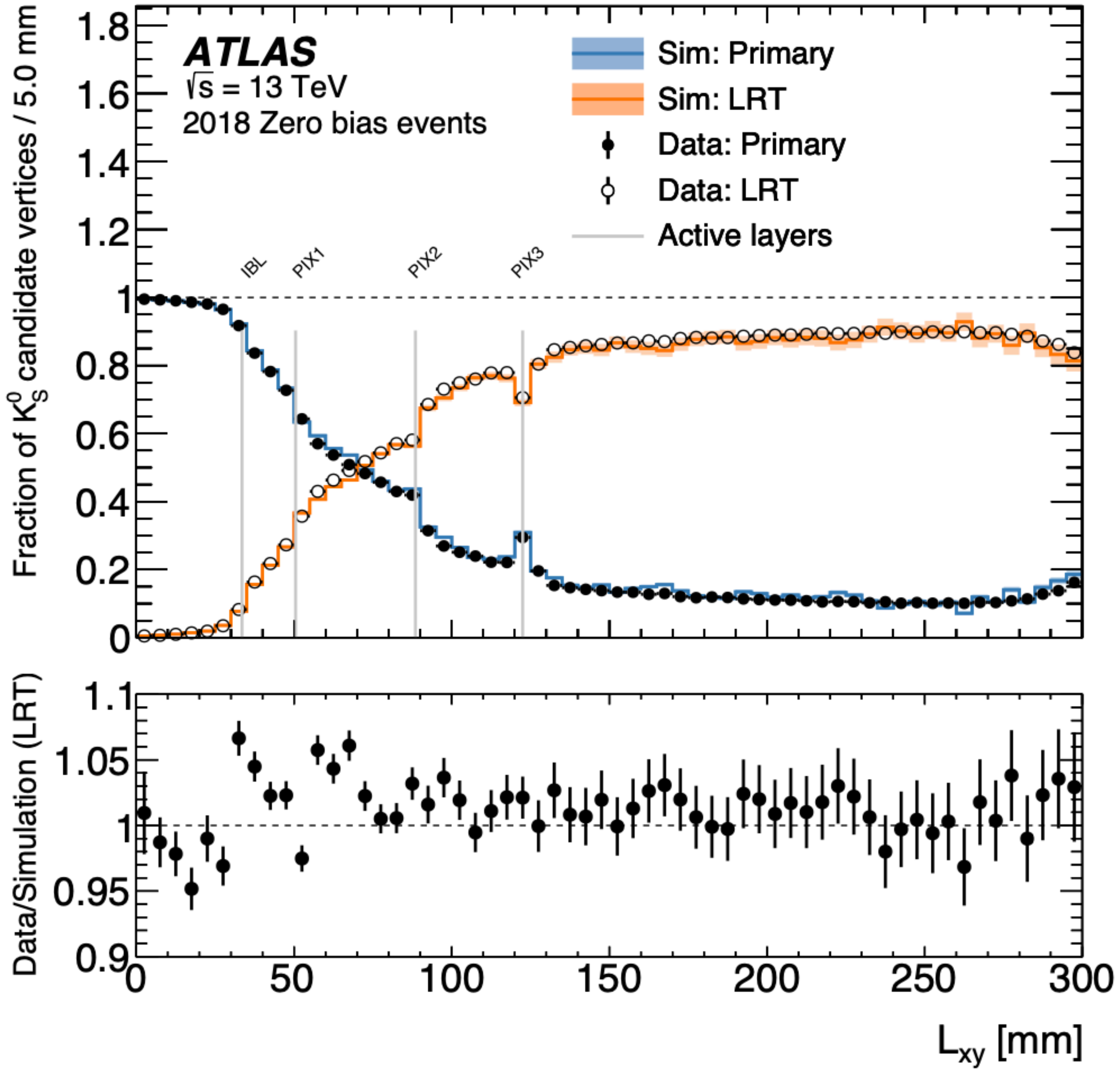
Tracking: For 60 pp collisions (⟨μ⟩)per bunch crossing:

- track reconstruction nearly 3 times as fast
- no significant reduction in reco efficiency
- large reduction in combinatorial fake tracks rate.

Legacy software | Updated software



arXiv:2304.12867



Improved Large Radius Tracking (LRT) deployed

LRT available in standard reconstruction

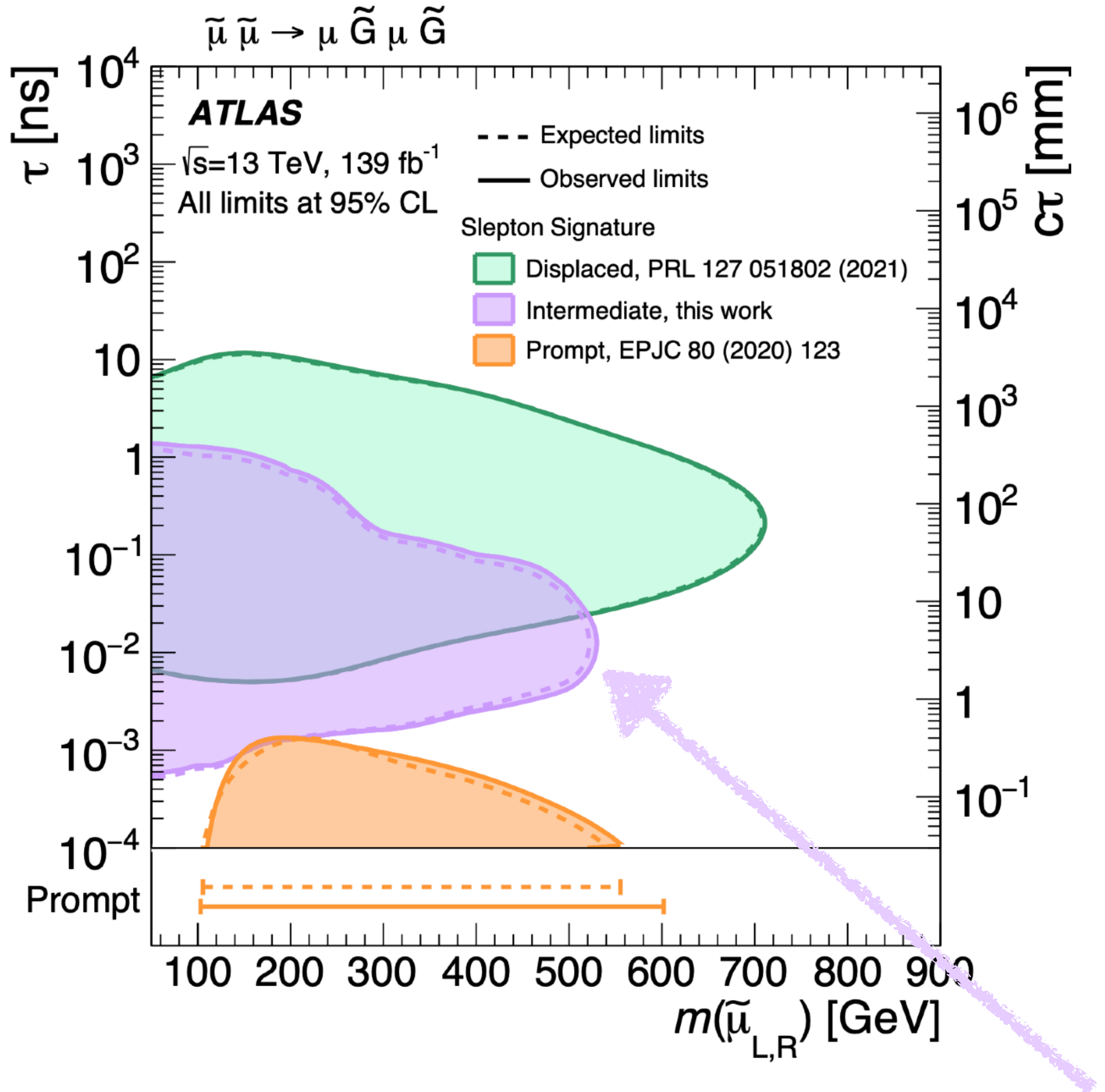
improves long lived particles searches!

10×(50x) improvement in CPU usage(disk usage)
(also present at HighLevelTrigger HLT for Run 3).

Run3/HL_LHC Long Lived particles ATLAS

https://arxiv.org/abs/2305.14931

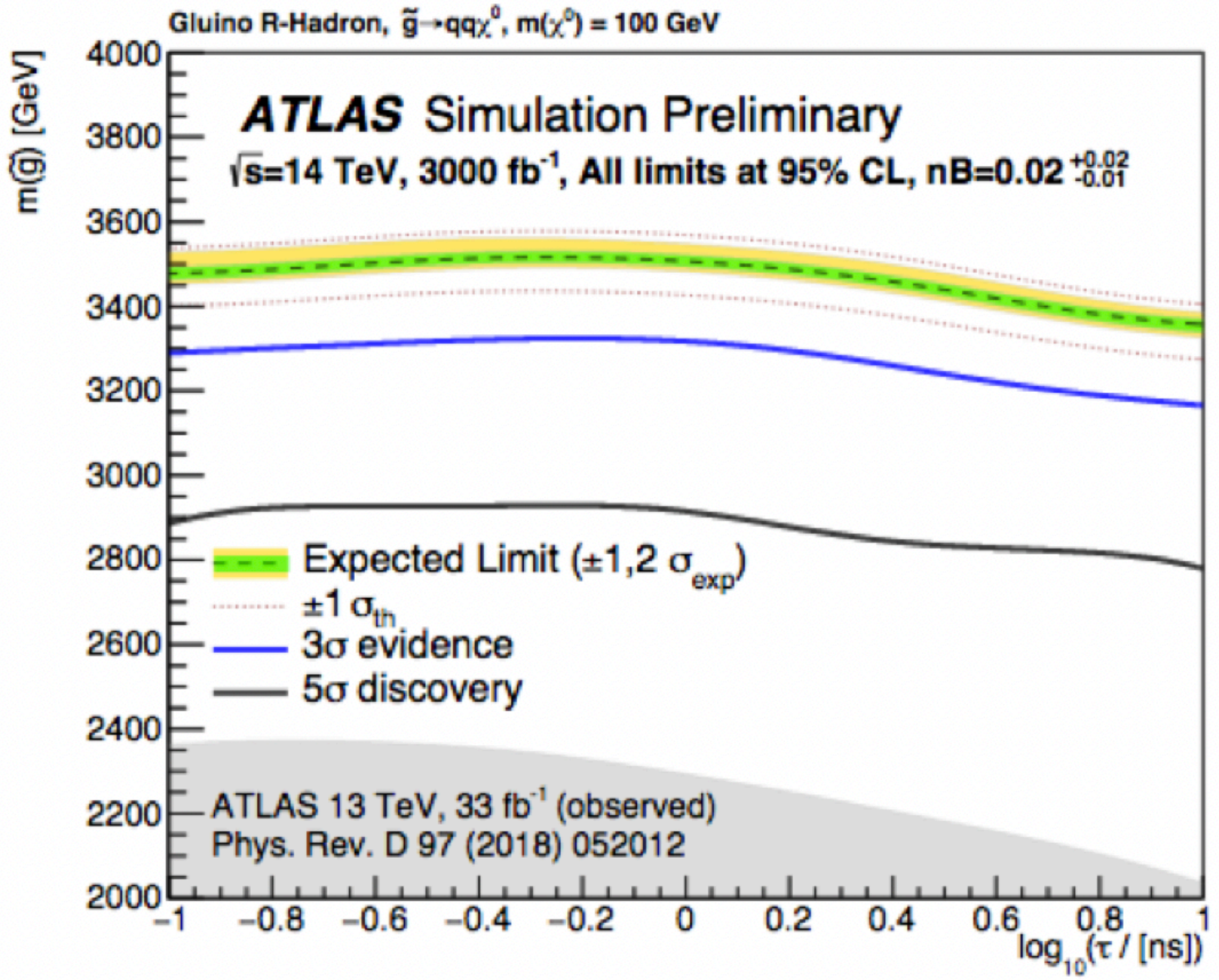
Search for muons with small displacements



Goal for Run 3: exploring uncovered phase spaces!

Covers phase space between prompt & displaced muons

HL-LHC: long-lived particles: projected sensitivity for the mass of a long lived gluino which hadronizes after production into an R-hadron, and then decays through a virtual squark into a pair of SM quarks and a neutralino. In the analysis high Emiss and one displaced T vertex are required.

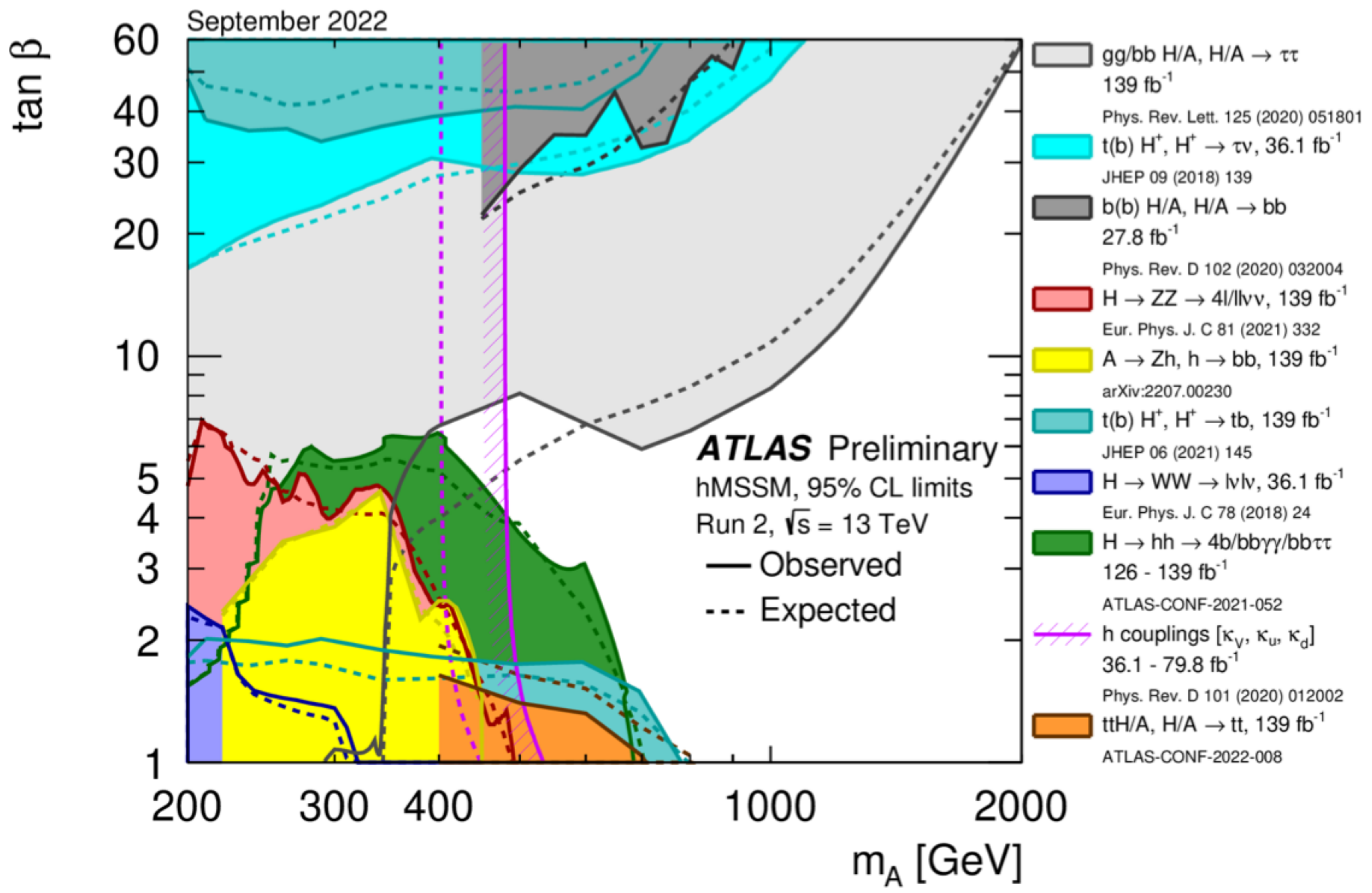


Extended Higgs sector and Supersymmetry

Strategy for Run 3 extended Higgs searches

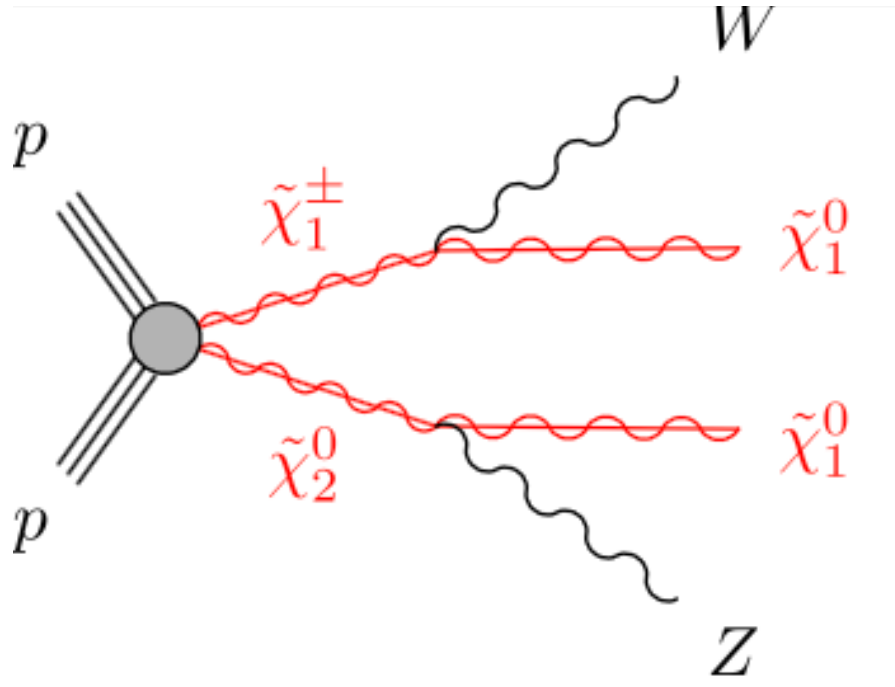
- For probing the Electroweak sector, continued searches of extended Higgs sectors are of particular interested.
- An extended Higgs sector is, for example, needed to lead to a first-order phase transition in the early universe.
- Using Run 2 data, the searches for an extended Electroweak sector have been vast, covering searches for new diboson resonances, exotic Higgs decays and direct and indirect searches for additional Higgs bosons.
- see hMSSM model exclusion: wide range and complementary of different final states and search modes, but also unexplored gaps.

- The added data of Run 3 will benefit us greatly in closing these gaps.



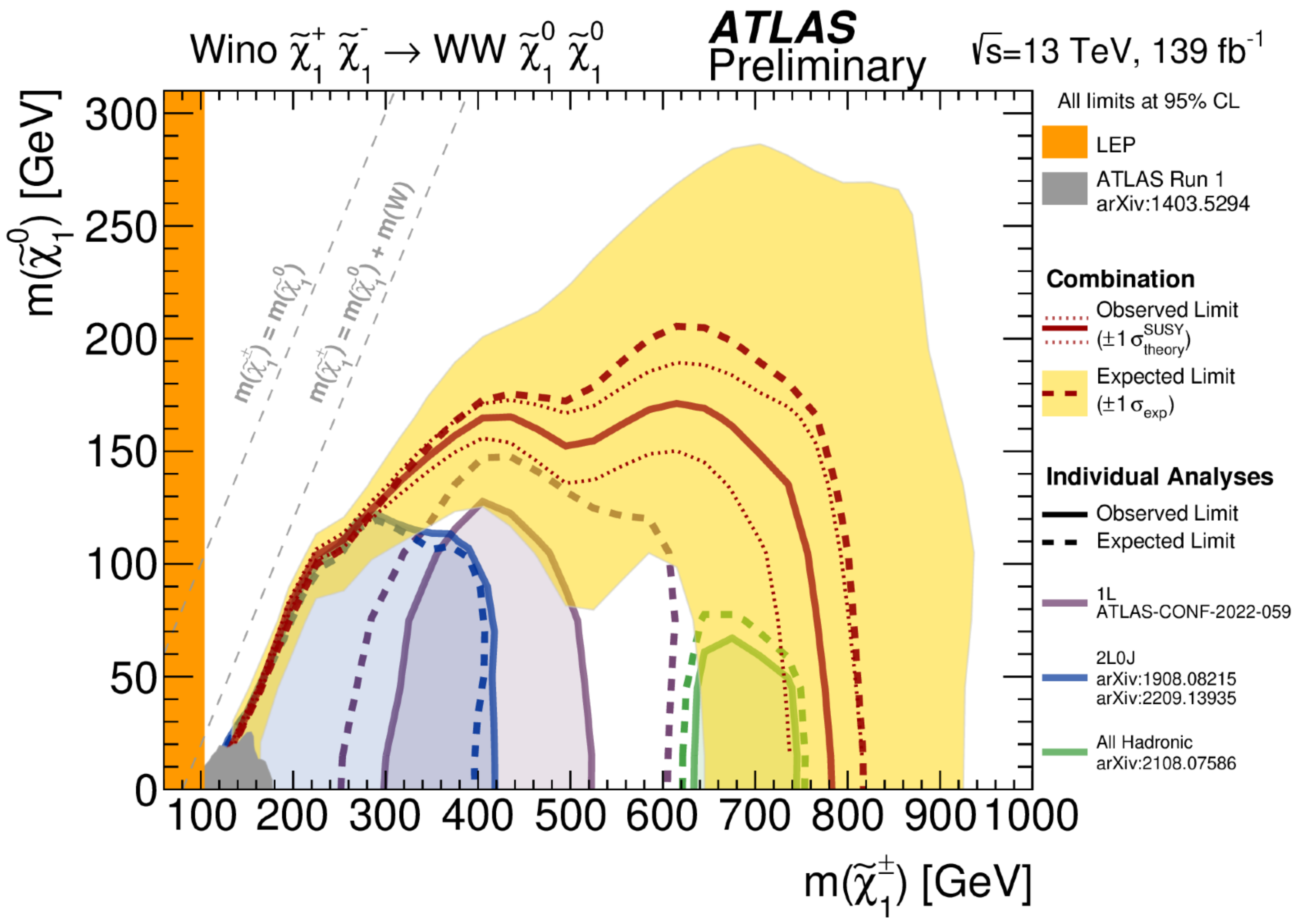
Search for ElectroWeaK SUSY

ATLAS-CONF-2023-046



- Normally in SUSY we use simplified models. Here we present
- **Statistical** Combination of multiple SUSY EWK analyses, improving exclusion limits and exclusion depth

- chargino, neutralino production decaying via W,Z



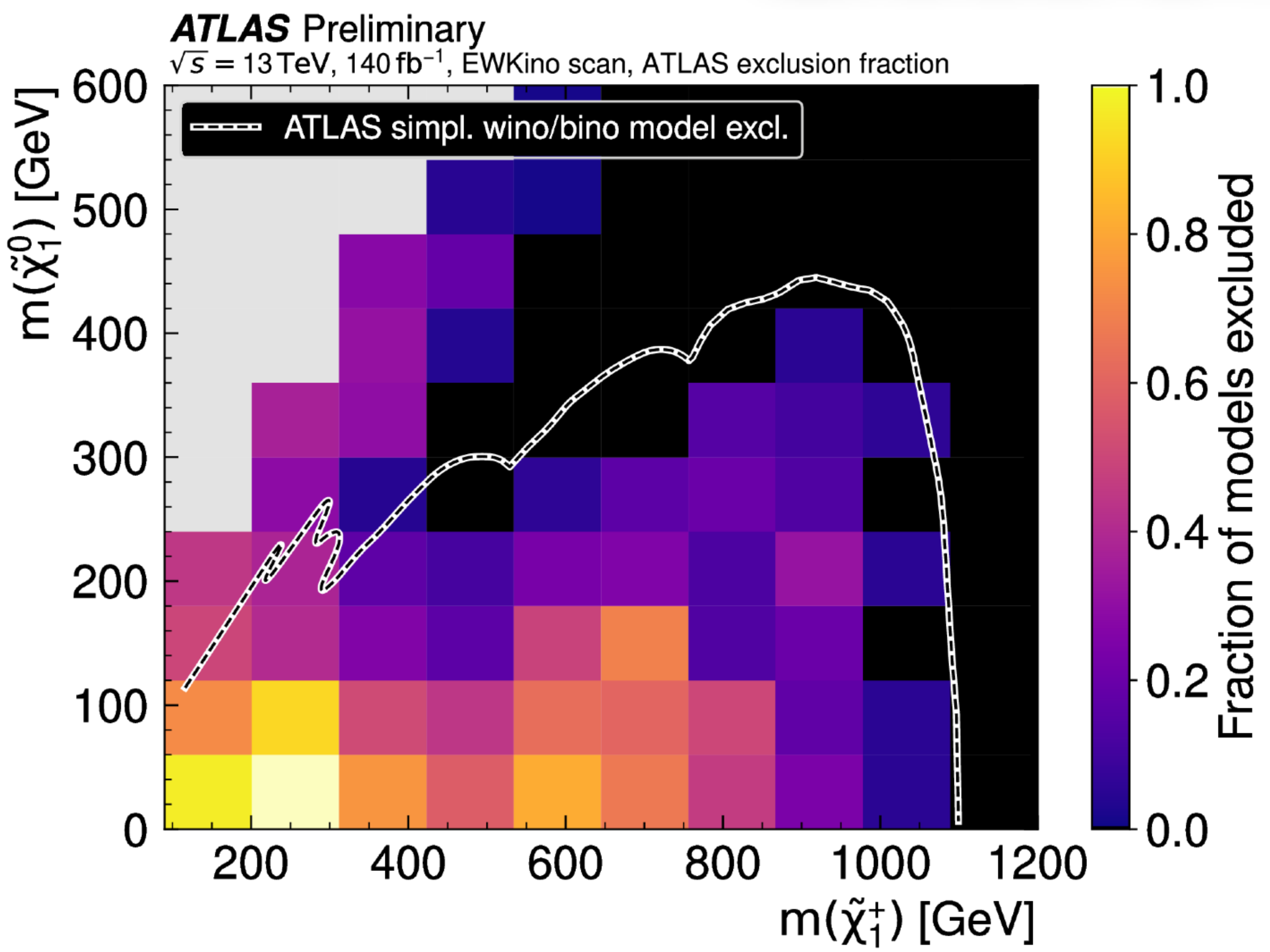
The combined result fills the gap between the individual analyses

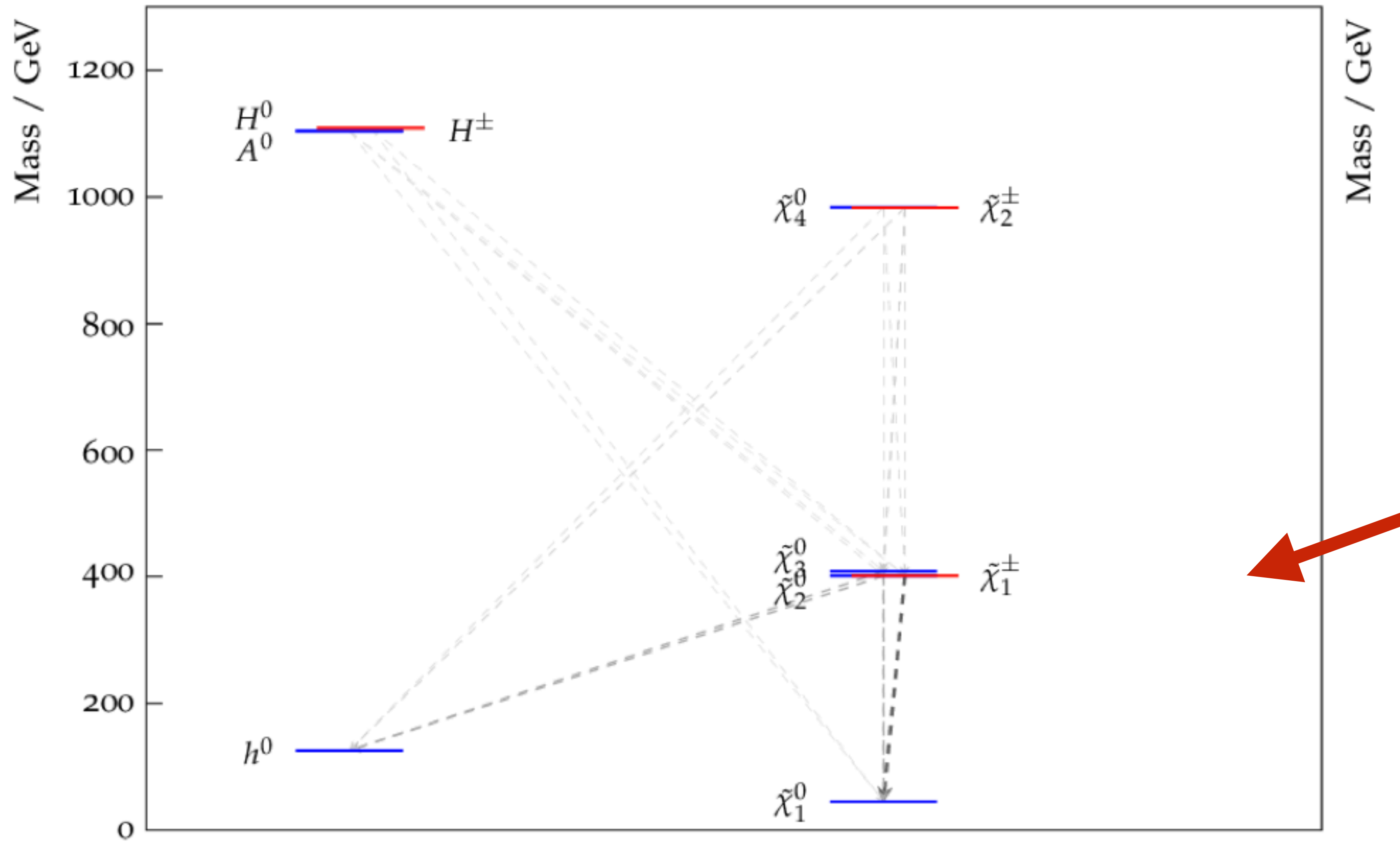
Simplified models come with shortcomings

It is mandatory to make sure that we are searching in the correct phase space

Electroweak pMSSM

ATLAS-CONF-2023-055





(a) Z/h funnel region

- scan exploring Phenomenological Minimal Supersymmetry (pMSSM) a UV complete Model (normally simplified models are used)
- imposes LHC + external constraints (LEP, flavor, precision EWK, Dark Matter)
- Almost full exclusion of low-mass χ^0_1 in regions where a low-mass neutralino would not oversaturate the dark matter relic abundance
- Example spectra for surviving supersymmetry models that are not excluded despite having a mass-spectrum within published ATLAS simplified model contours.

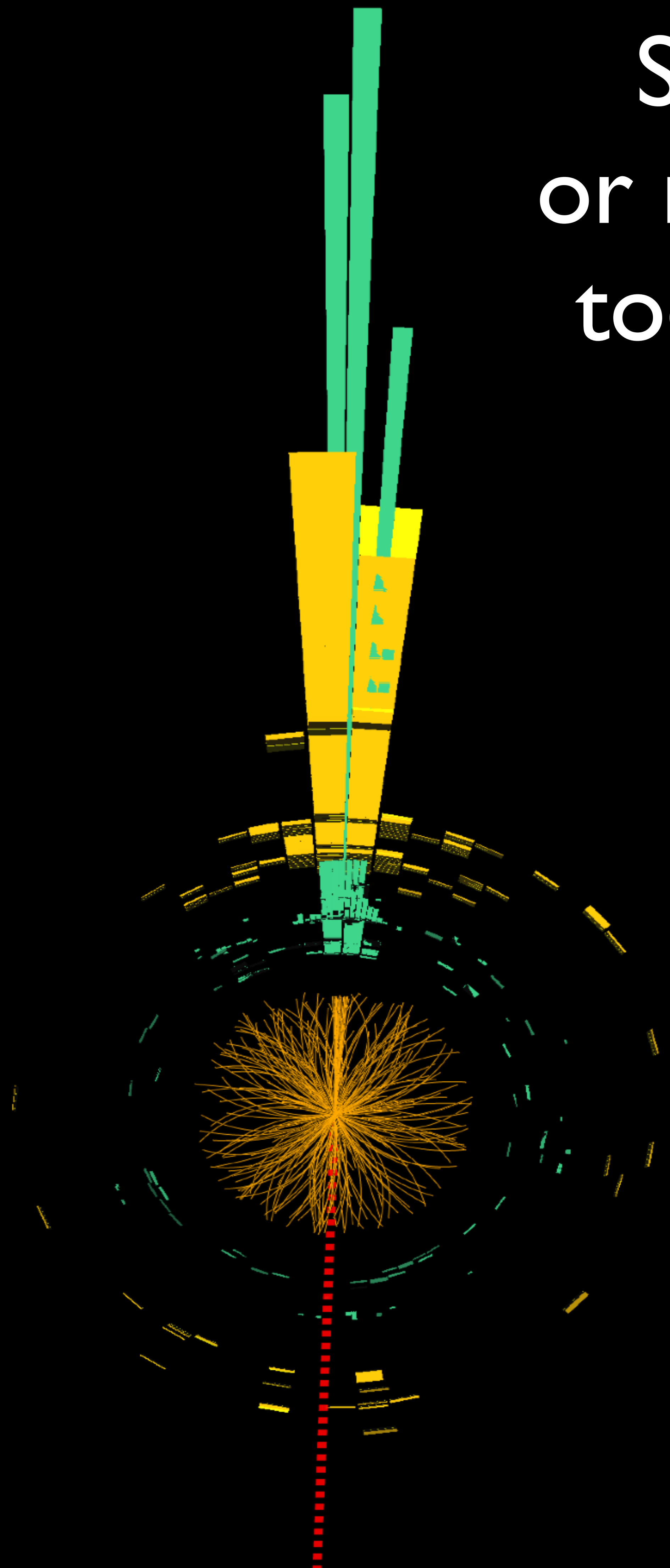
Dark matter and invisible decays

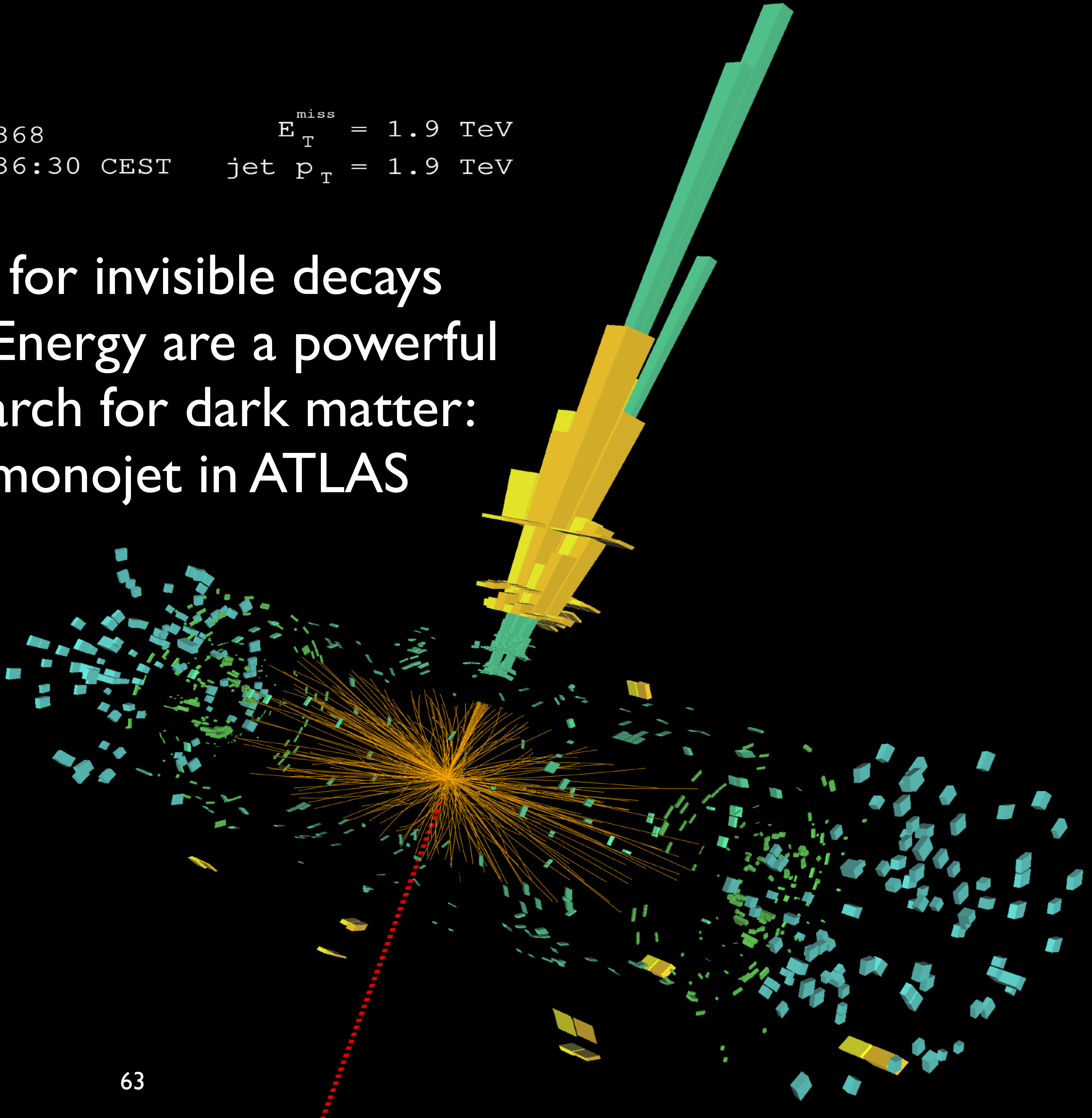
ATLAS EXPERIMENT

Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST

E_T^{miss} = 1.9 TeV
jet p_T = 1.9 TeV

Searches for invisible decays or missing Energy are a powerful tool to search for dark matter: here a monojet in ATLAS



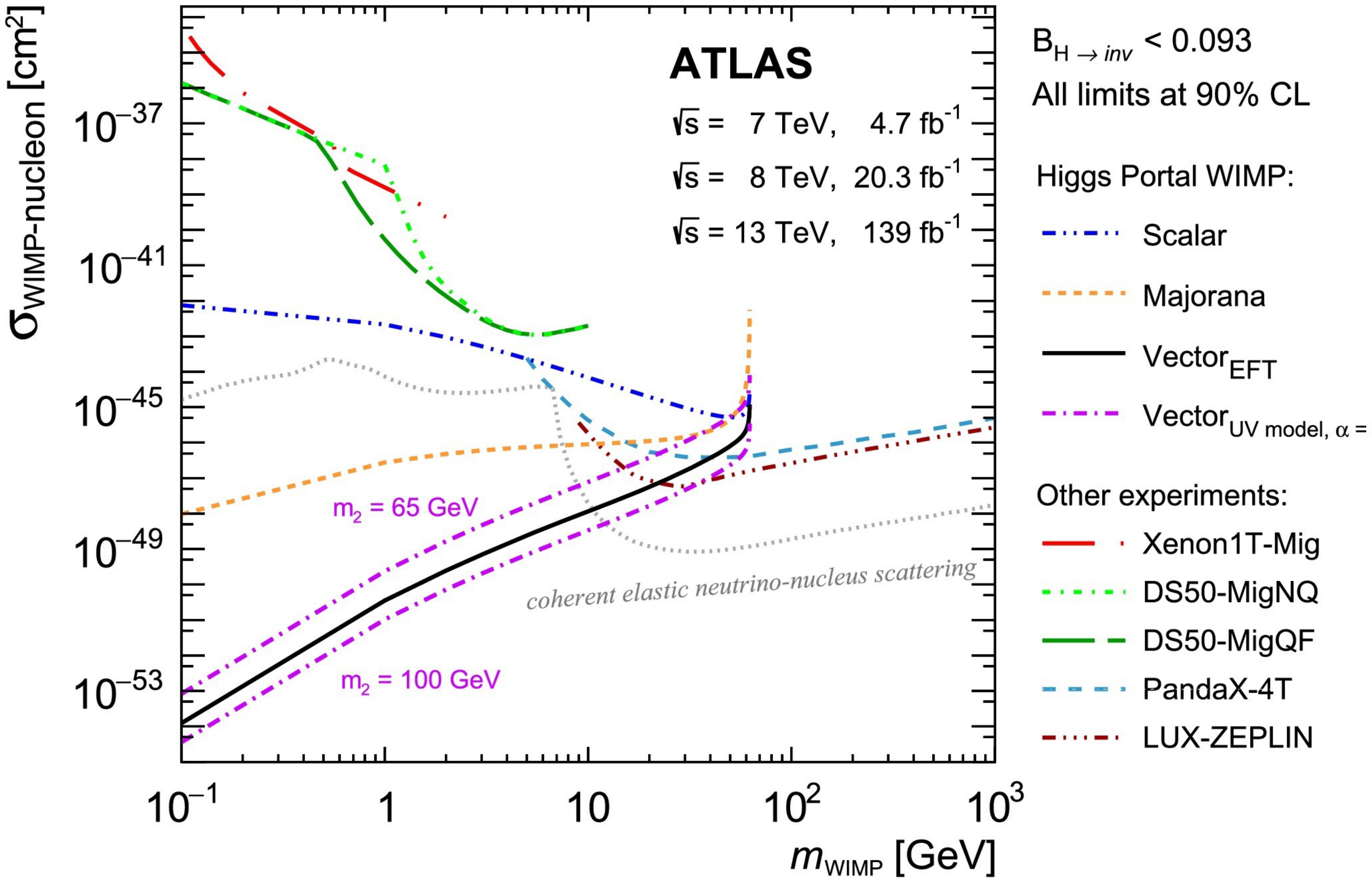


Invisible Higgs width

Phys. Lett. B 842 (2023) 137963

- SM particles get mass through the Higgs. Dark matter could behave the same way and be produced in Higgs decays
- SM Higgs invisible decays are <0.1%
- **The analysis: B(H→inv)$_{obs}$ < 10.7% @95%CL**
  B(H→inv) $_{exp}$< (7.7%) @95%CL best to date
- These results are also interpreted in the context of models where the SM Higgs boson acts as a portal to dark matter
- exclusion regions extend to very low DM mass-> very important to improve

90% CL on the spin-independent WIMP-nucleon scattering cross-section

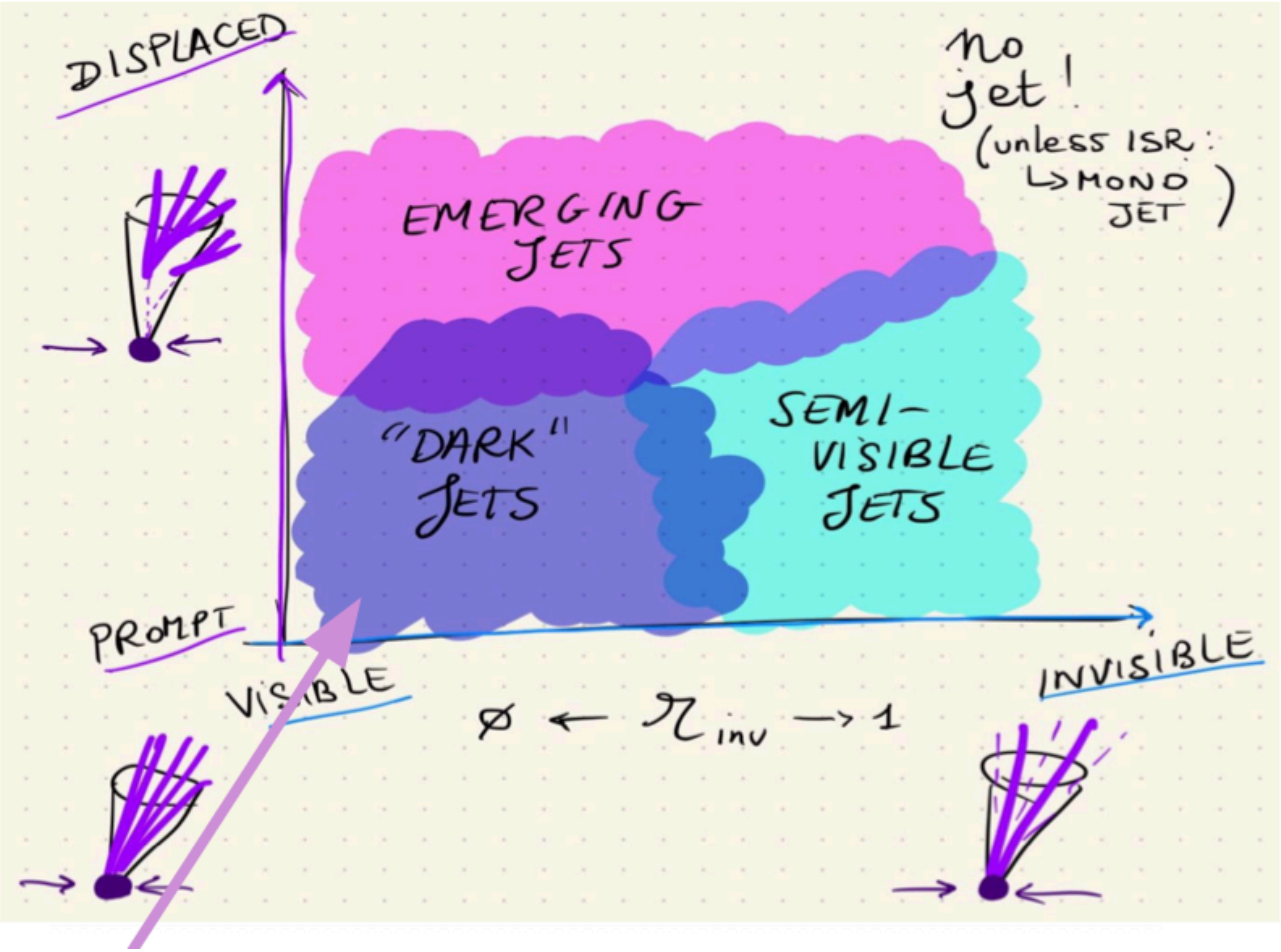


The regions above the limit contours are excluded

Dark Matter searches not only WIMPs: QCD like dark sector

QCD-like dark sector producing dark showers
Dark hadrons can decay completely or partially in a QCD-like fashion:

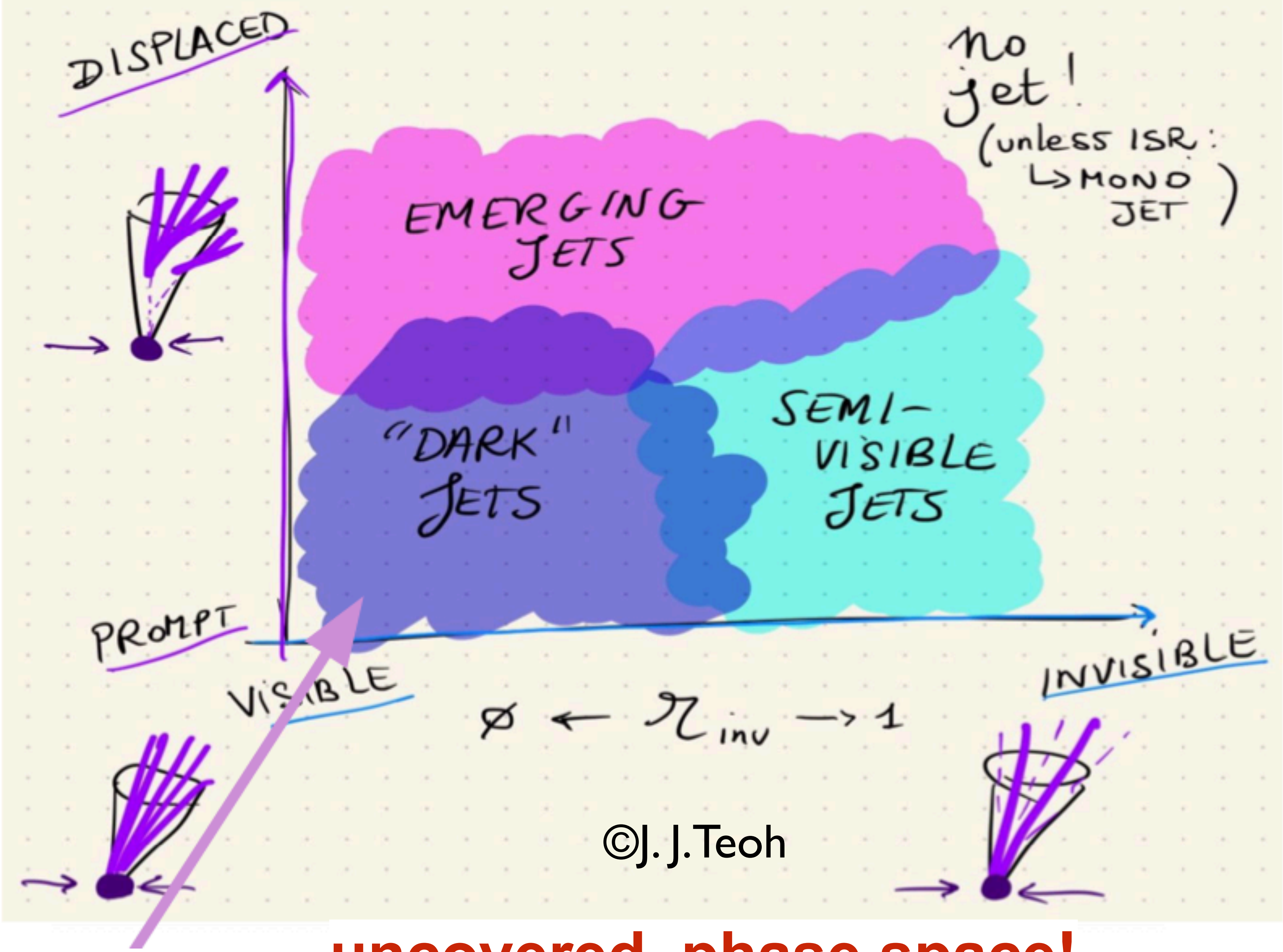
-Semi-Visible jets
- Emerging jets
- dark jets from Stable dark hadrons with unusual large R-jet dijet signatures (higher charged-particle multiplicity)



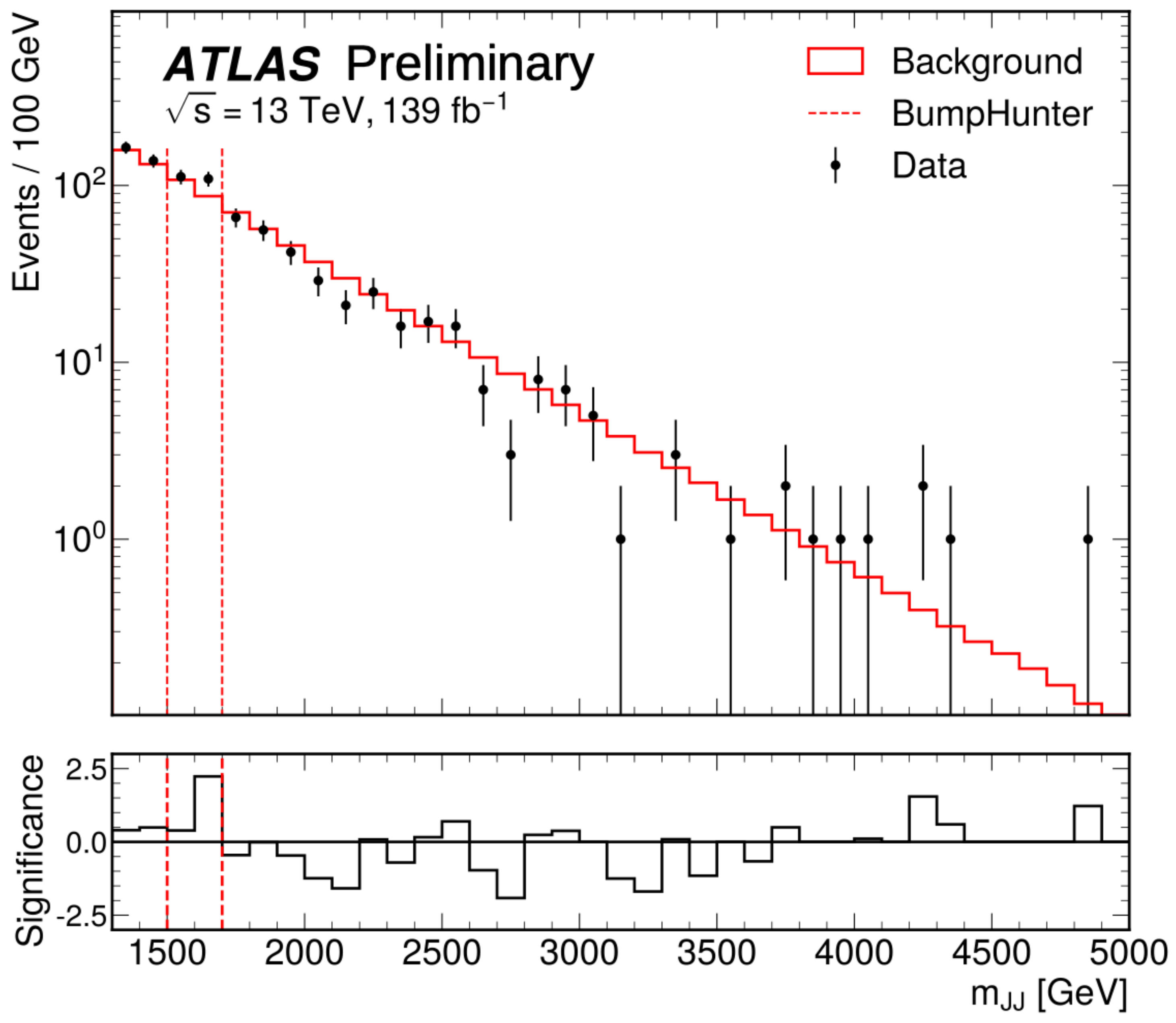
DM

Dark Matter: QCD-like dark sector linked to SM via Z′

- Stable dark hadrons with unusual dijet signatures (higher charged-particle multiplicity)
- Search for dark jets bump in the mass spectrum of two large-R jets.

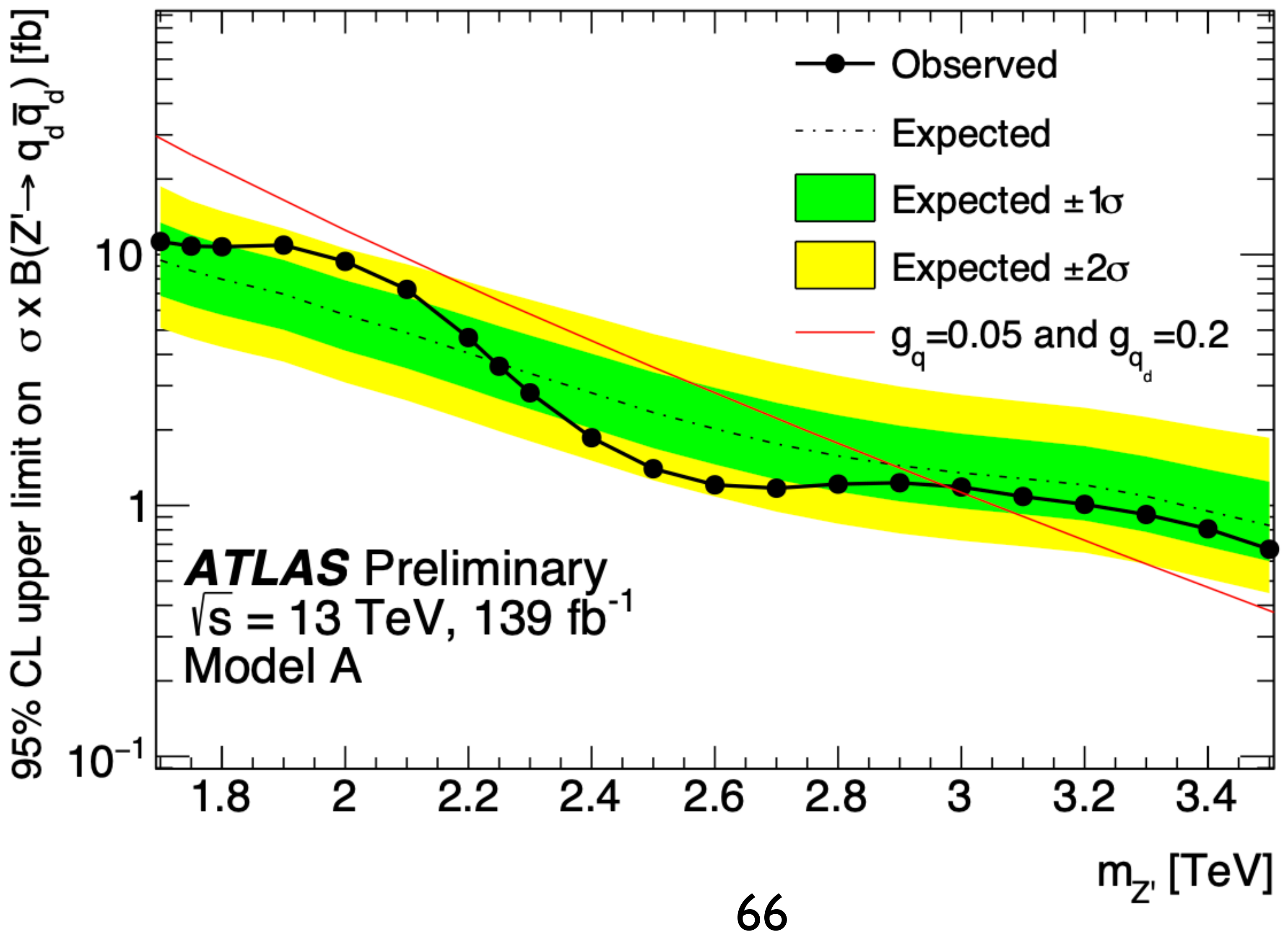


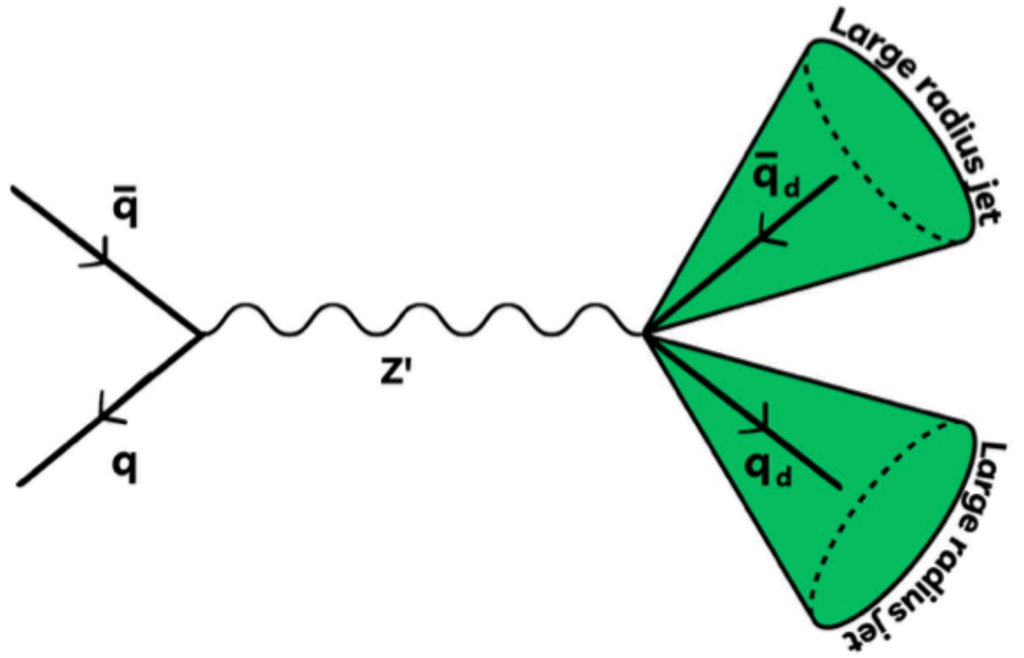
uncovered phase space!



no excess

ATLAS-CONF-2023-047



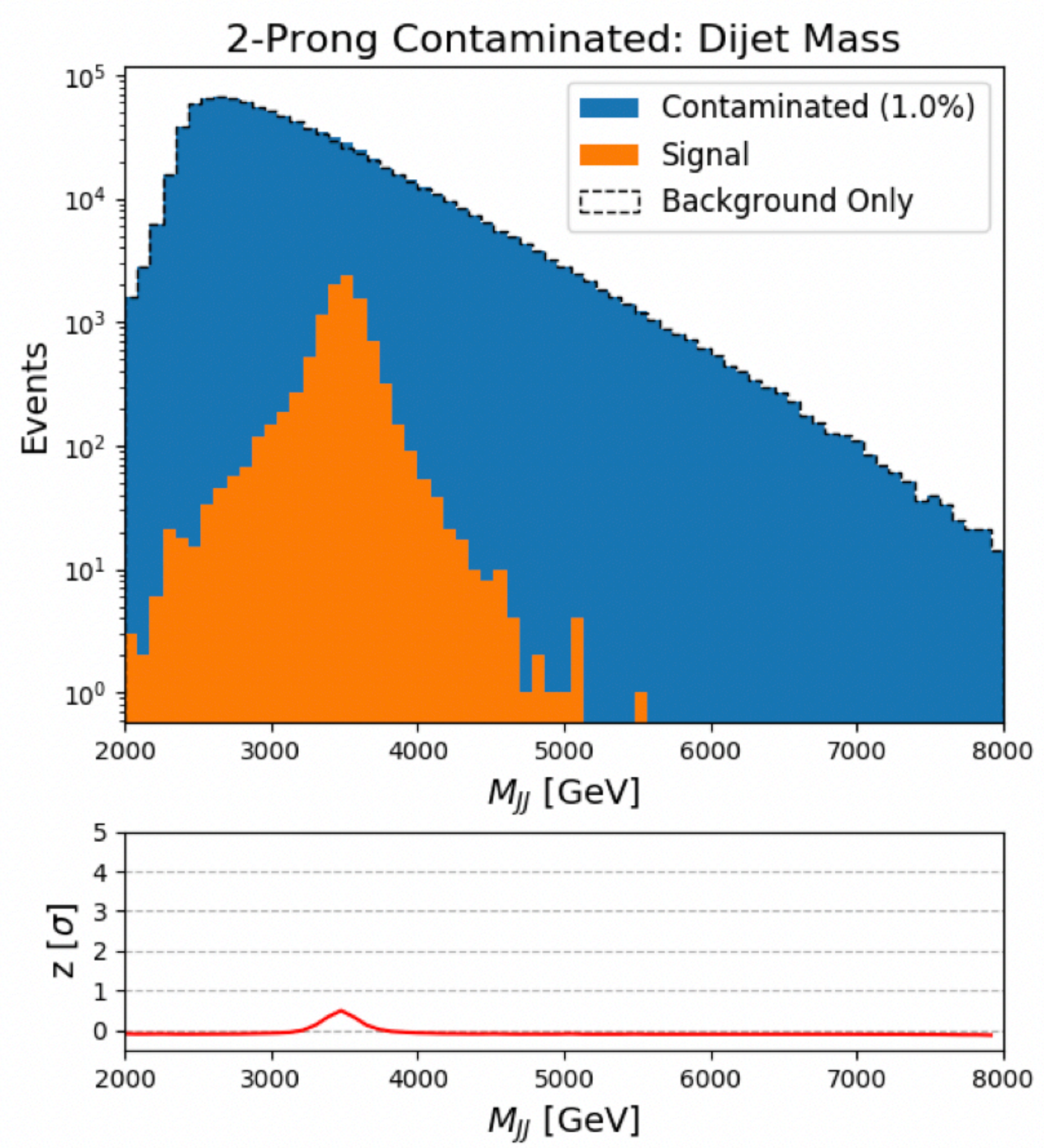


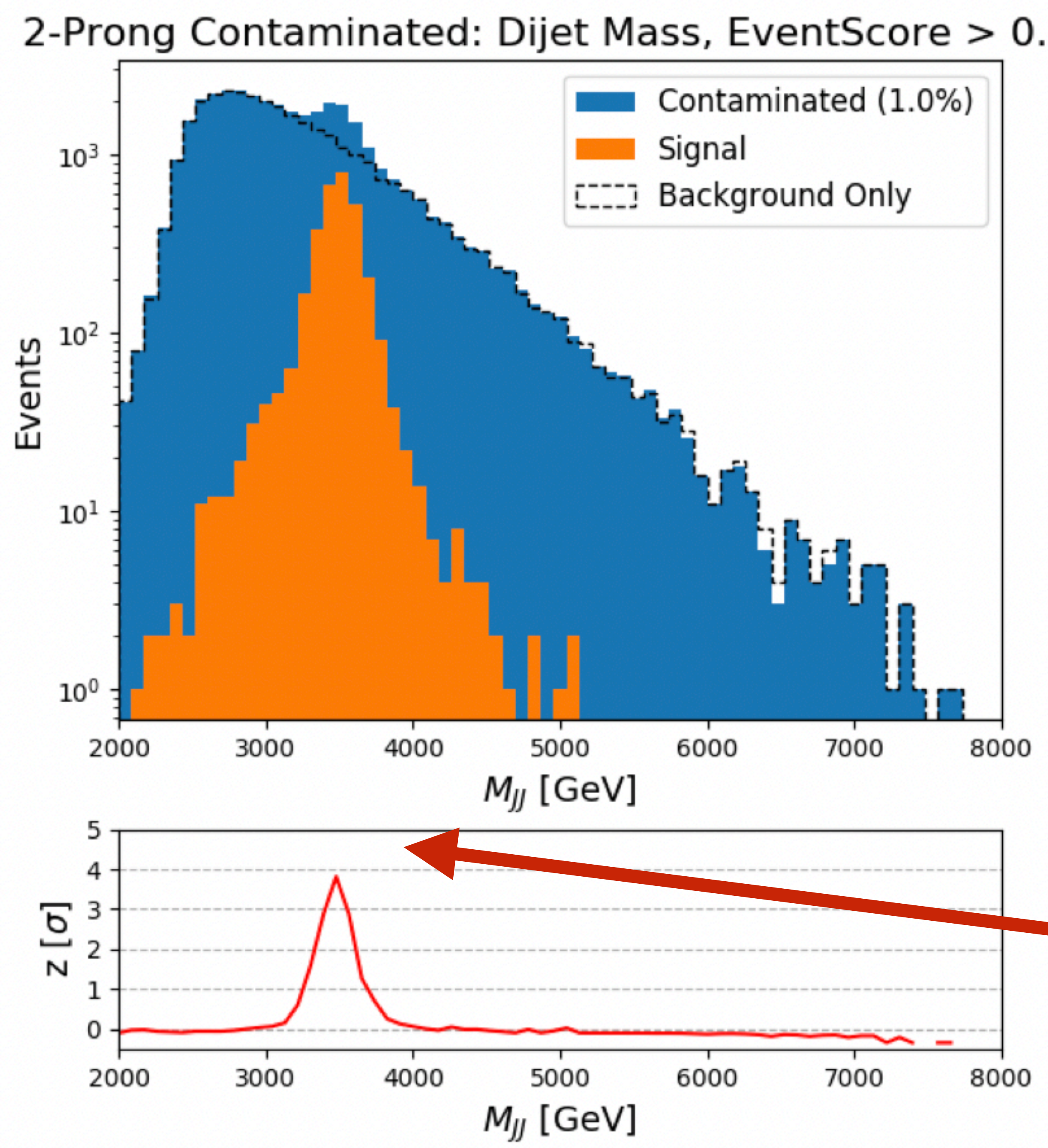
VBS

Going model independent

Anomaly detection

- Detecting anomalies using unsupervised Machine learning!
- use Model-independent discovery region introduced with novel, data-driven anomaly score (AS). For example searching for boosted hadronically decaying objects by treating them as anomalous elements of a contaminated dataset.
- the AS for example in this analysis link: is determined from fully unsupervised variational recurrent neural network (VRNN) trained over jets modeled as sequence of constituent four-vectors.





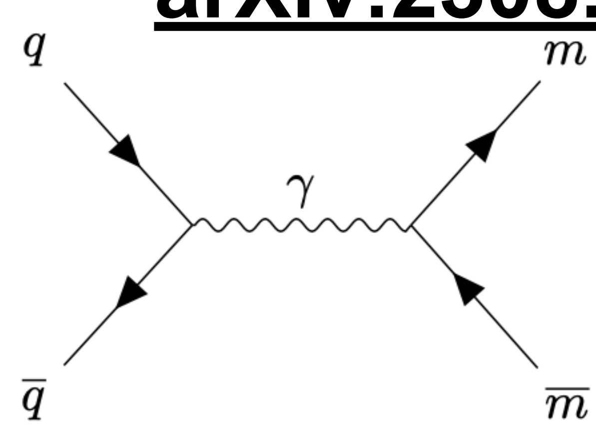
- Variational Autoencoders (VAEs) are built on the idea of standard AEs, with the extension that they are designed to perform Bayesian inference. This assumes that observed data x is generated by some hidden random variable z whose posterior distribution $p(z|x)$ is intractable. The goal of a VAE is to learn an approximate posterior distribution, $q(z|x)$, through training.
- After cutting on anomaly score

VBS

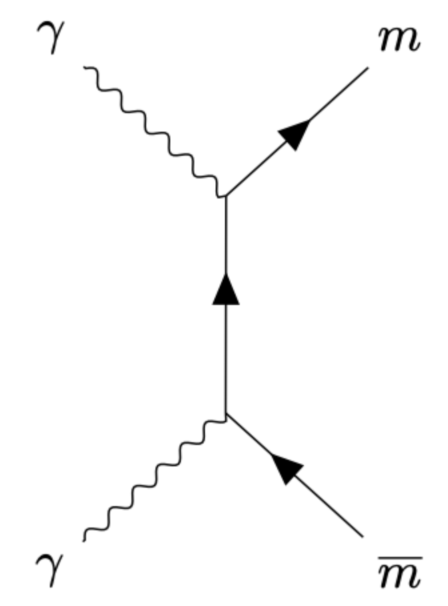
Highly Ionizing particles?

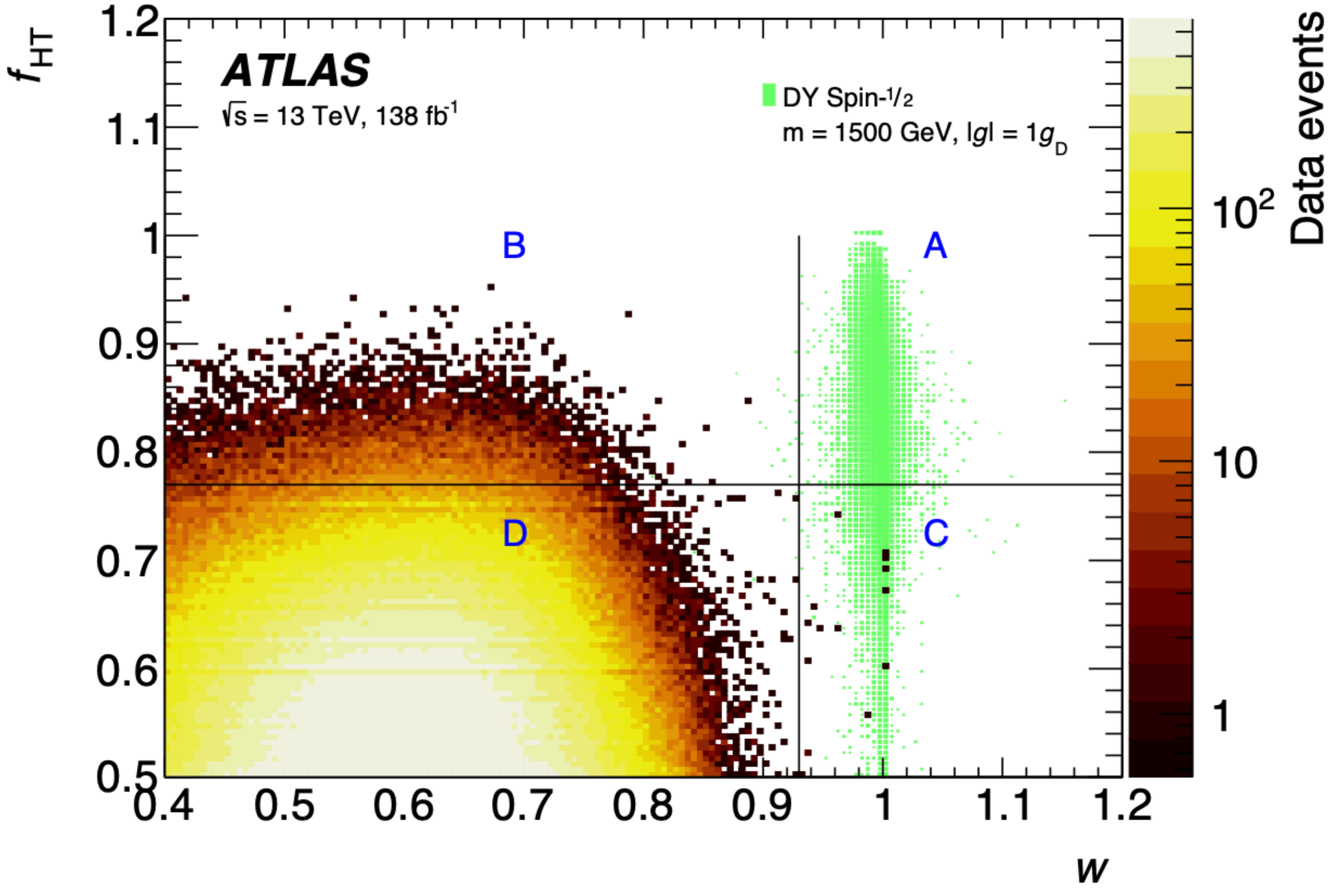
HIP Search for highly Ionising particles

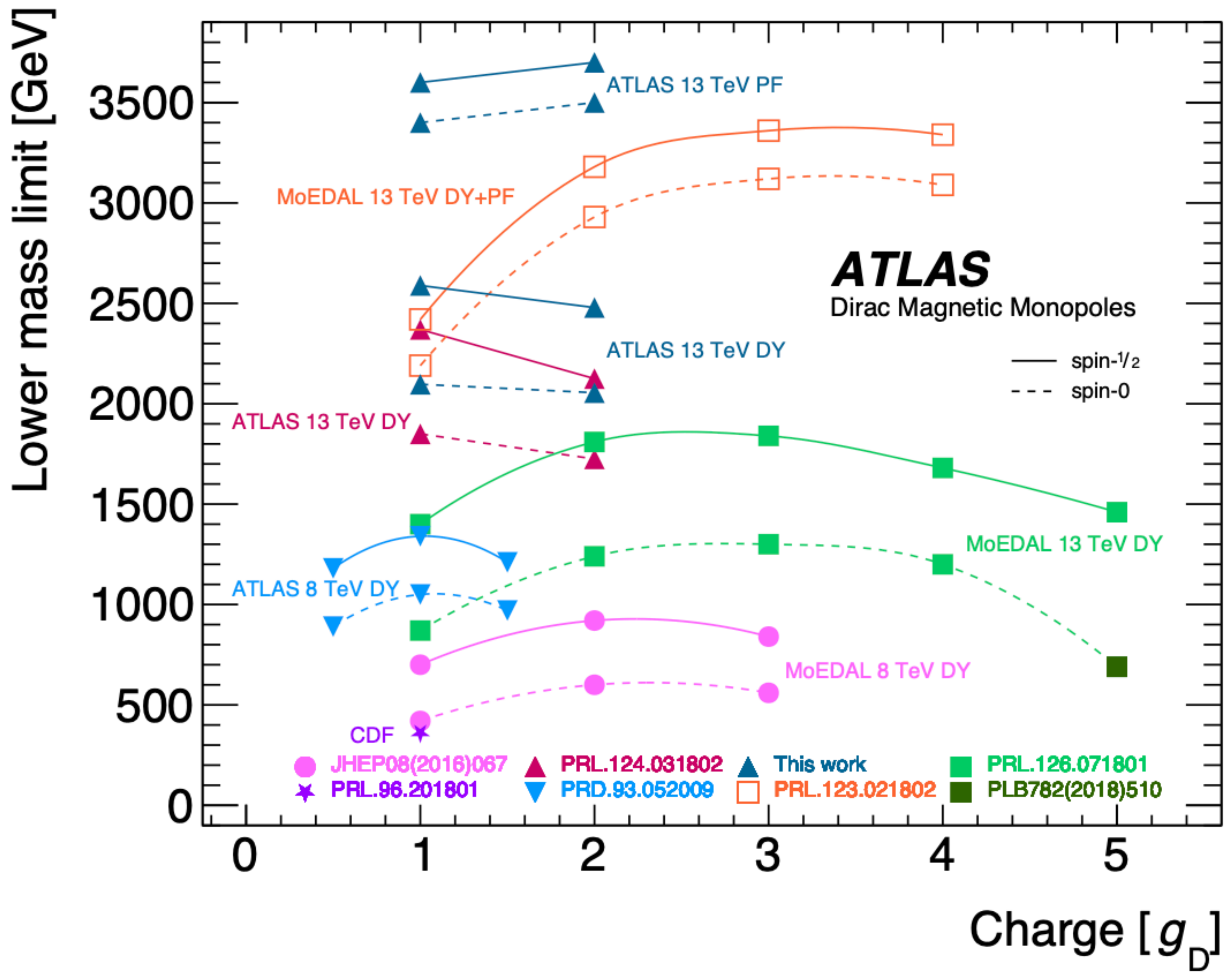
arXiv:2308.04835



- Search for magnetic monopoles and stable particles with high electric charges
- **improves by factor 3 the previous x-section limits** by ATLAS 36fb^{-1}
- first ATLAS limits on photon-fusion pair production mechanism.





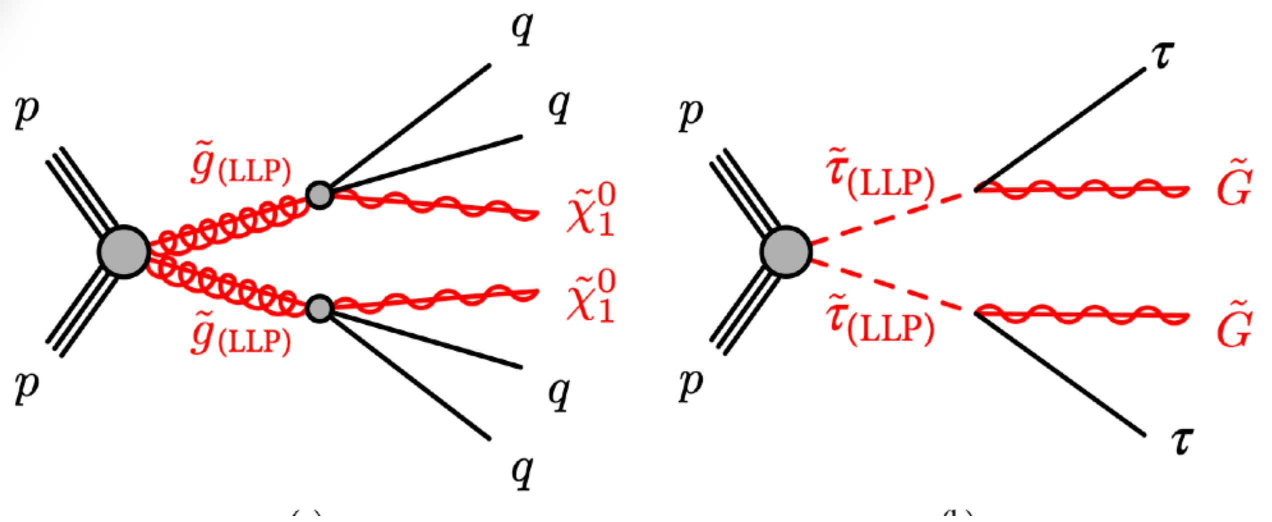


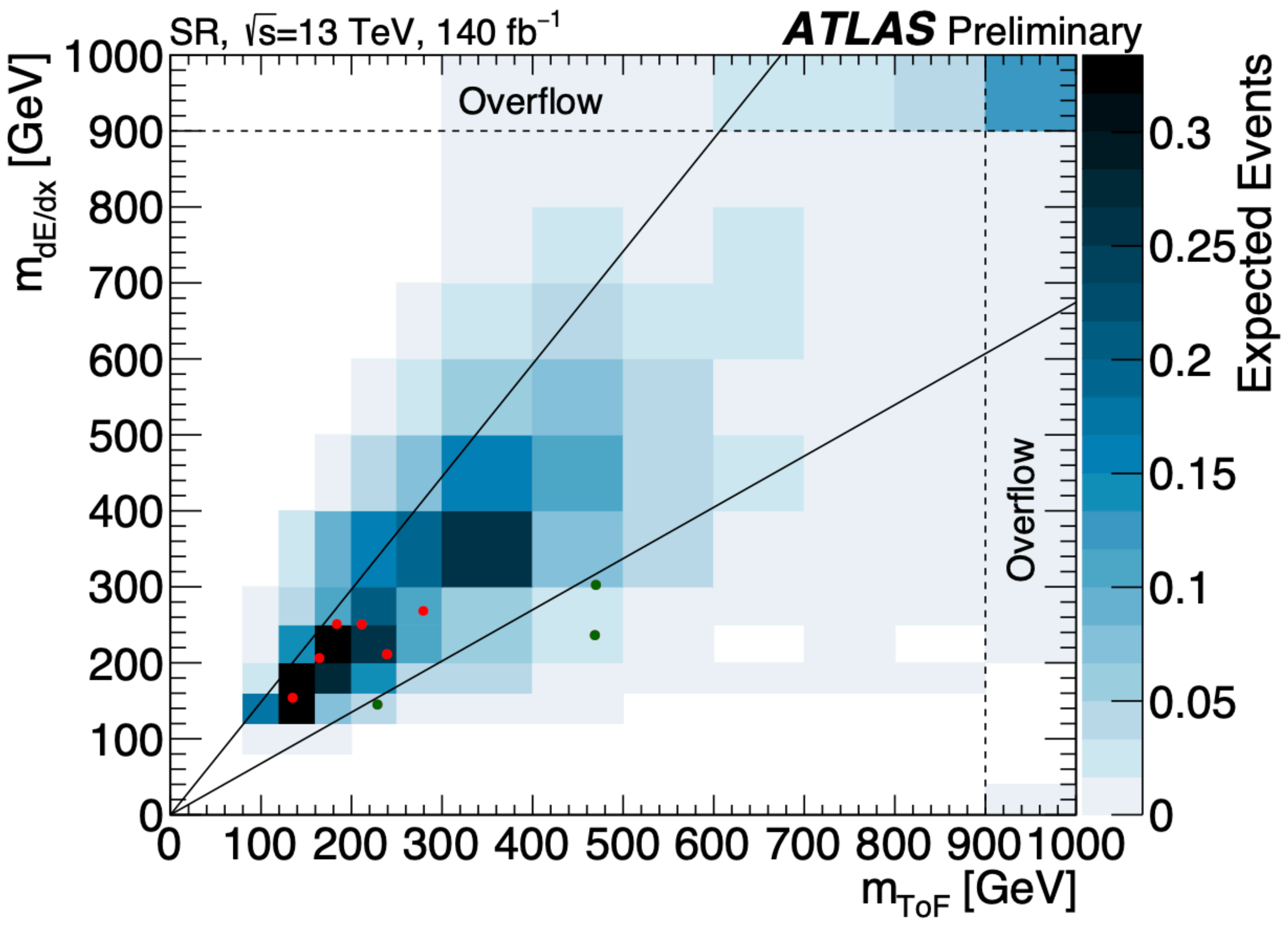
- HIPs produce TRT tracks with δ-rays ➡ many high TRT hits (HT)
- too massive to produce shower in EM calo ➡ low lateral dispersion (w)

HIP

Highly ionizing particles (large Energy deposition in pixel detectors)

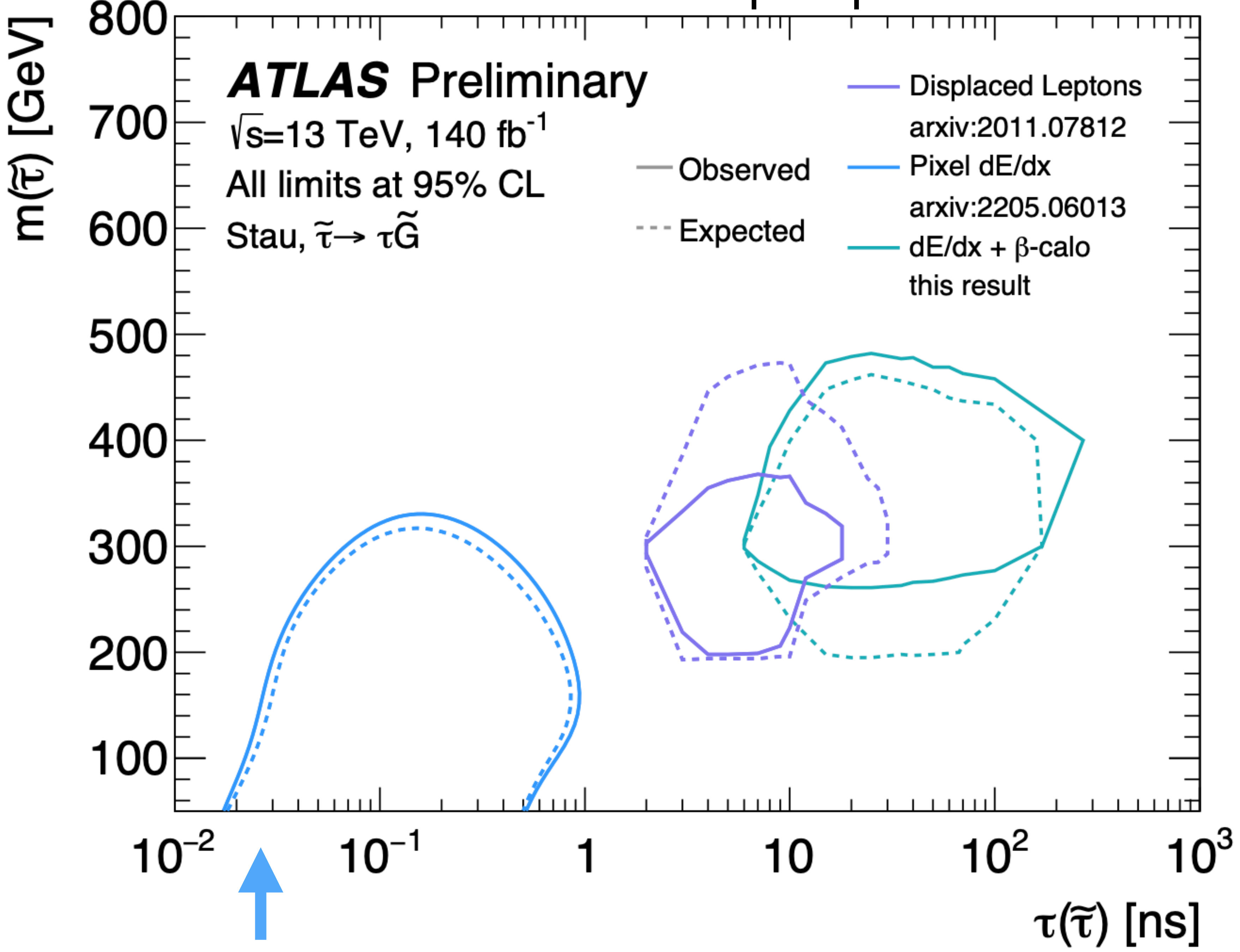
ATLAS-CONF-2023-044





- **complements previous analysis** arXiv:2022.06013 using large E depositions in pixel detector by including calorimeter ToF info
- targeting massive slow particles with high charge

stau pair production



displaced leptons

- previous analysis ->3.3 σ excess m=~1.4 TeV not confirmed to be due to slow high-mass particles particles by ToF
- **no significant excess: 6 data vs 3.7 bkg events**

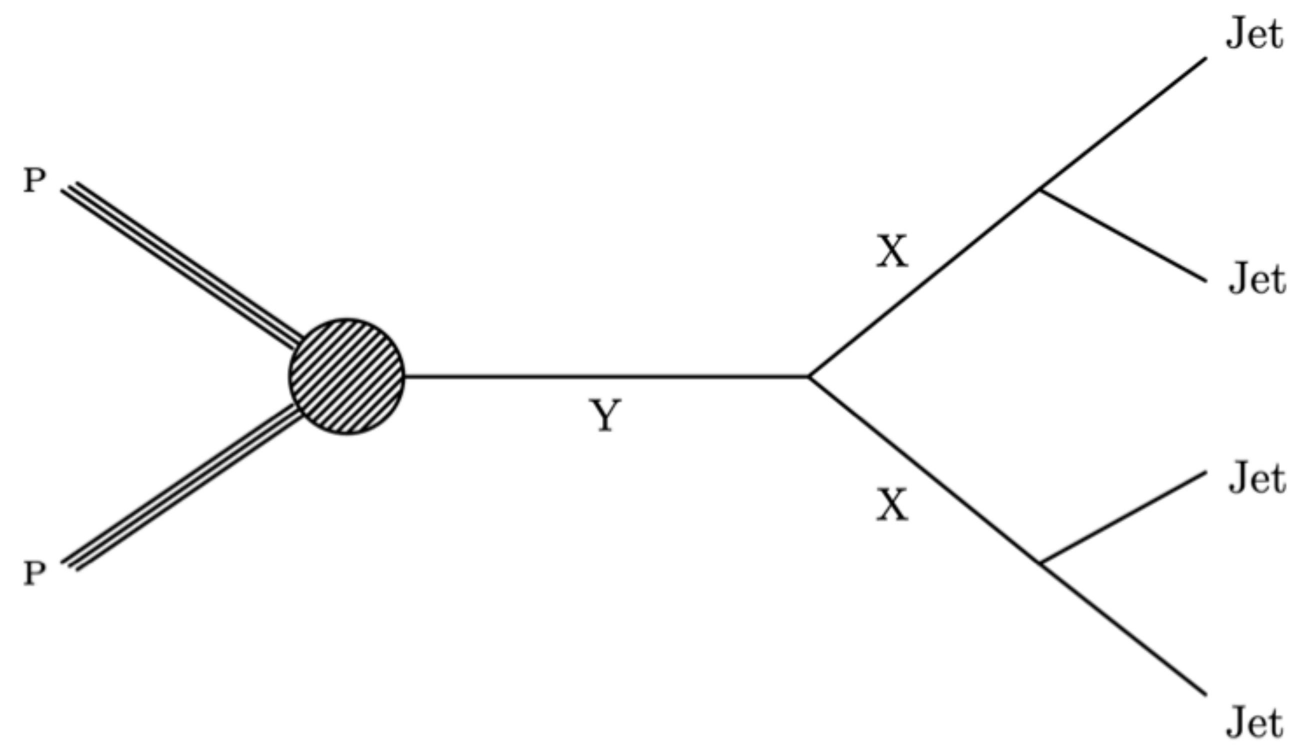
Resonances

res

Resonances: Tetrajets Y → XX → jjjj

arXiv:2307.14944

- Search for generic massive resonance Y decaying to intermediate resonances X
- Bumphunter search in m4j & di-jet average inv. mass <m2j>
- Follow up on 3.6σ CMS excess paired dijets [arXiv: 2206.09997]



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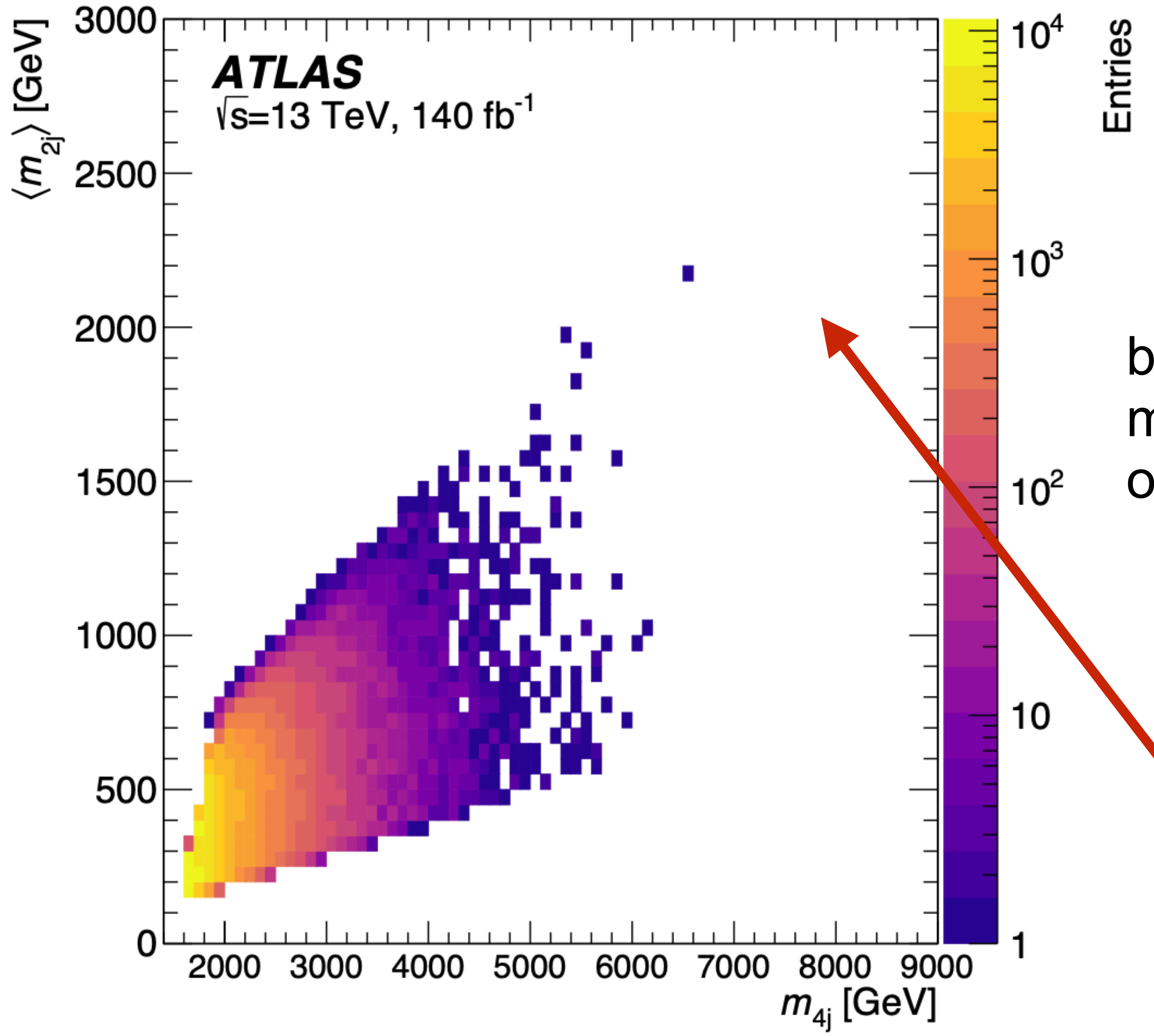
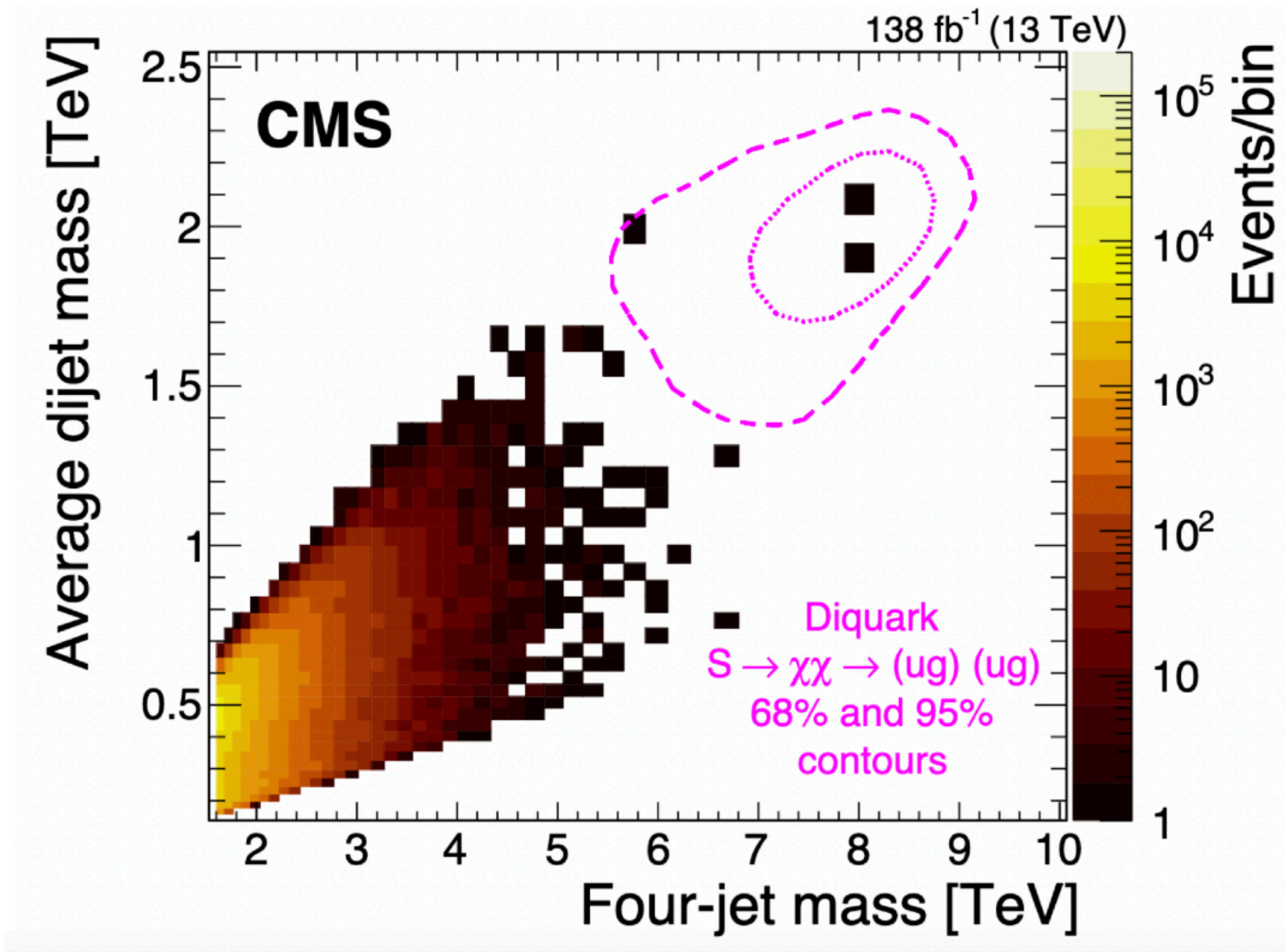
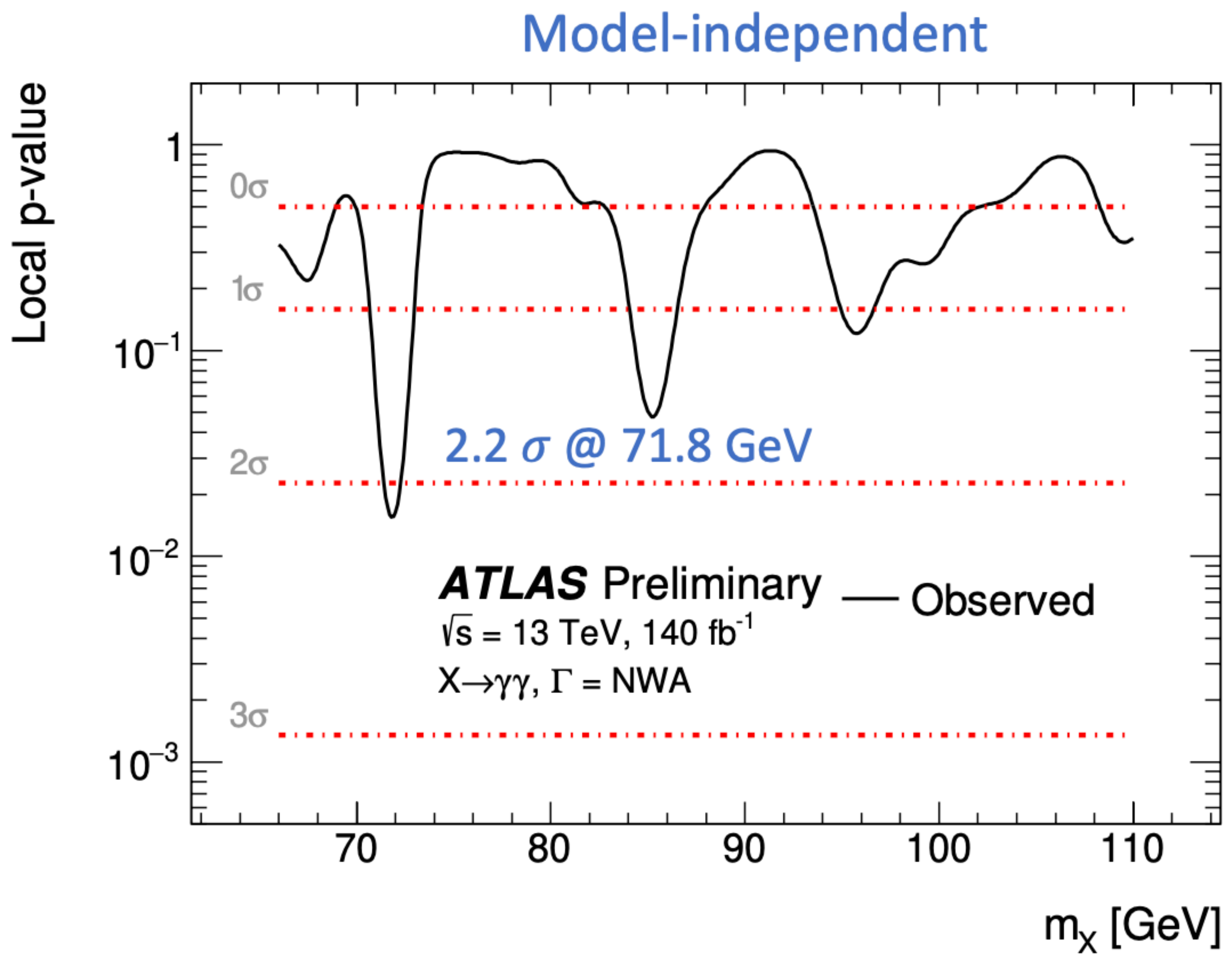


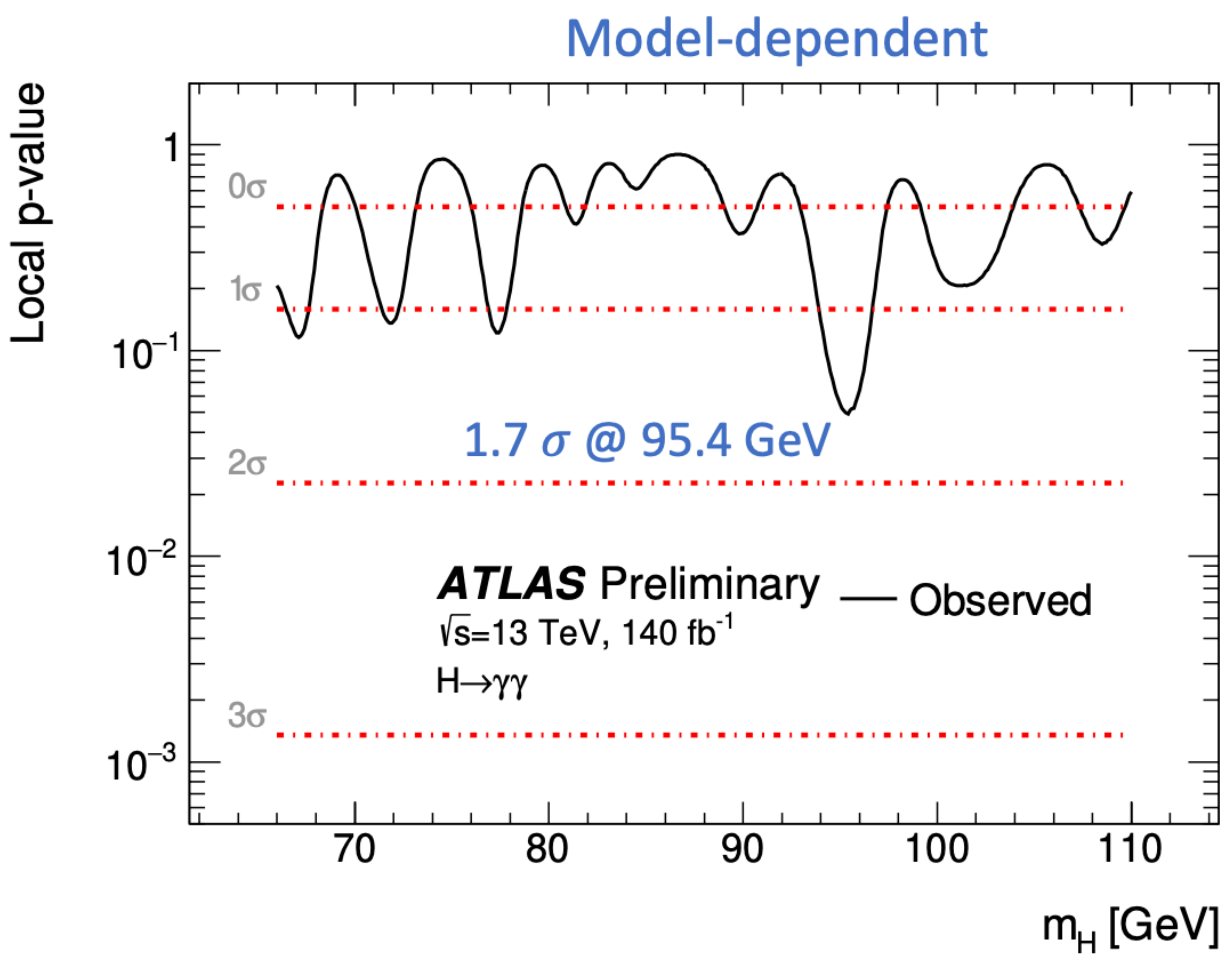
best pairing chosen minimizing quantities based on angular distributions

no excess



Low mass $h \rightarrow \gamma\gamma$

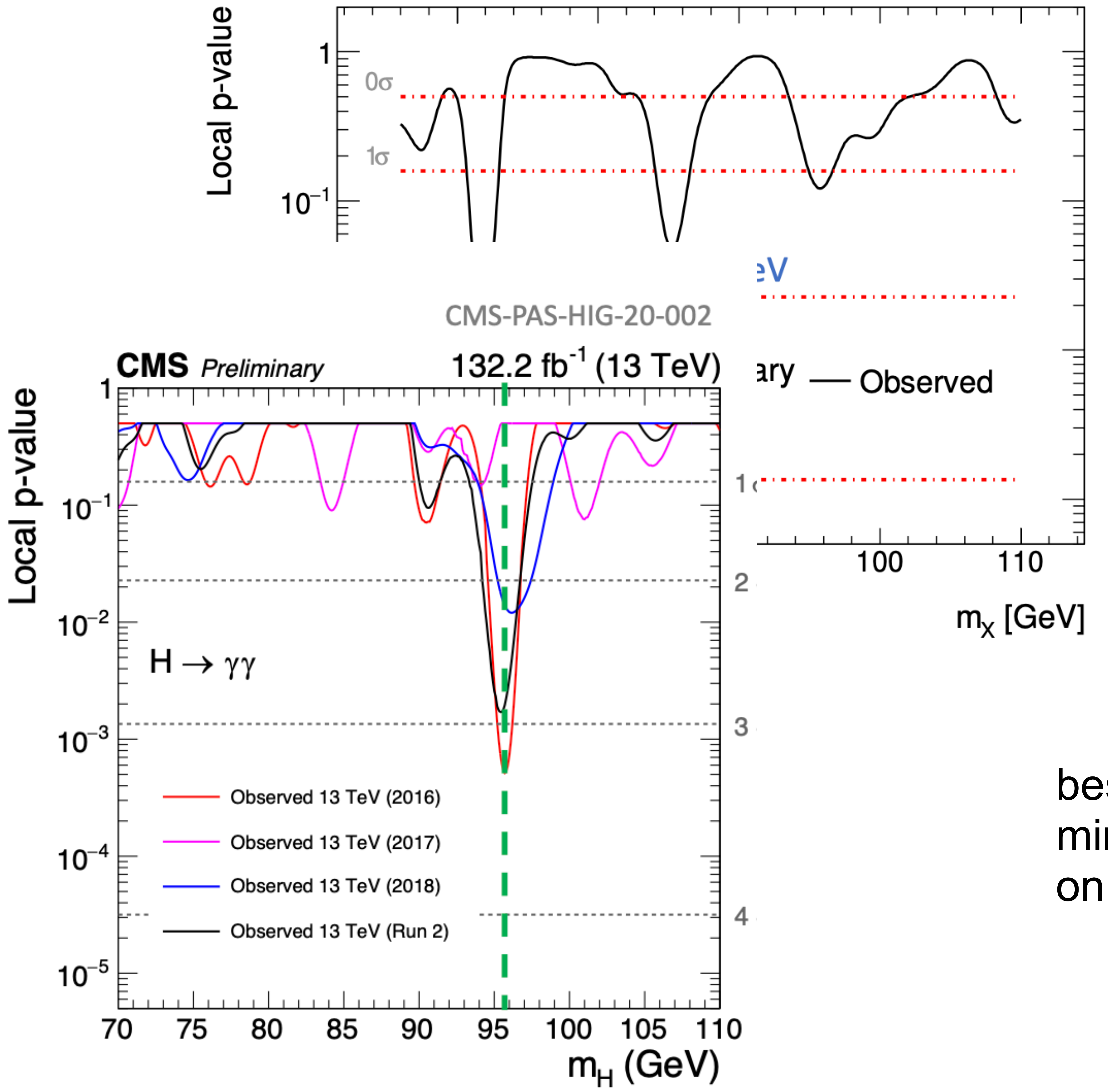




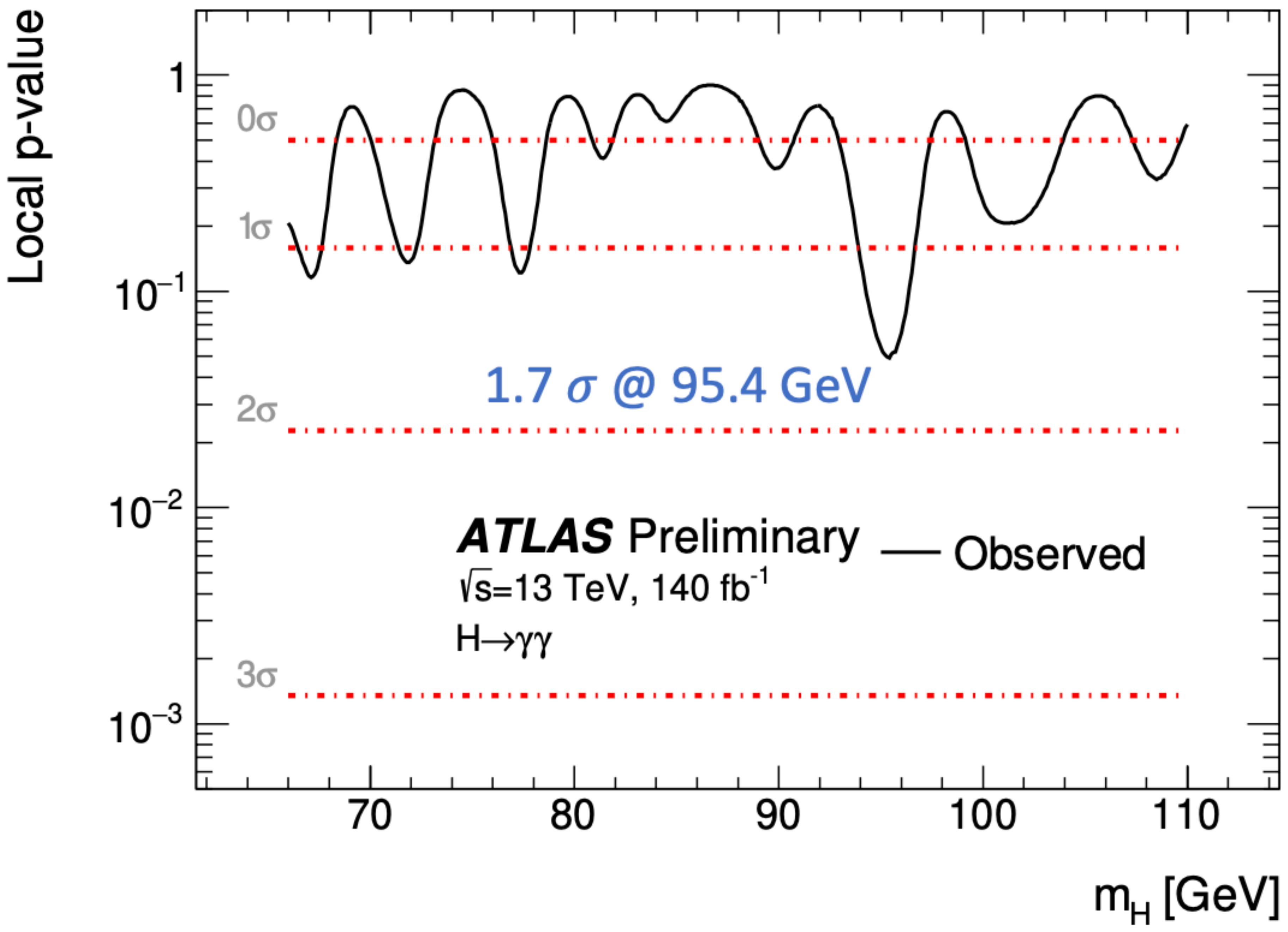
Low mass Higgs resonance could come from Axion like particles in SUSY, or from 2HDMS

Low mass $h \to \gamma\gamma$

Model-independent



Model-dependent



best pairing chosen
minimizing quantities based
on angular distributions

Conclusions

- There are many exciting searches and results behind the corner
- The efforts in improving the trigger, the analysis techniques are paying off.
- This shows that much more can be achieved, especially by exploiting even more the data
- as a tool to control or systematic errors
- Theory and experiment also have to go hand in hand
- We have great chances at Run 3 and the HL-LHC to find the clue that will lighten up the path for the search of new physics

Back-up

Several recording strategies to circumvent limitations in practice

- **New Trigger:** Develop new trigger logic to enhance selection of your signature, sufficiently selective for minimal background (↓Bandwidth = ↓Rate x Size).
  Advantage: Full detector information, unique data.

- **Delayed Stream Strategy**: Store full event data on SFOs (storage at Point 1) to reduce TIER0 bottleneck.
  Advantage: Full detector information

- **Trigger(-object) Level Analysis (TLA)**: Reduce event size 100x by recording only HLT reconstructed objects - take advantage of offline-like reco algorithms at HLT (↓Bandwidth = ↑Rate x ↓↓Size).
  Advantage: Trigger thresholds no longer limited by HLT thresholds.

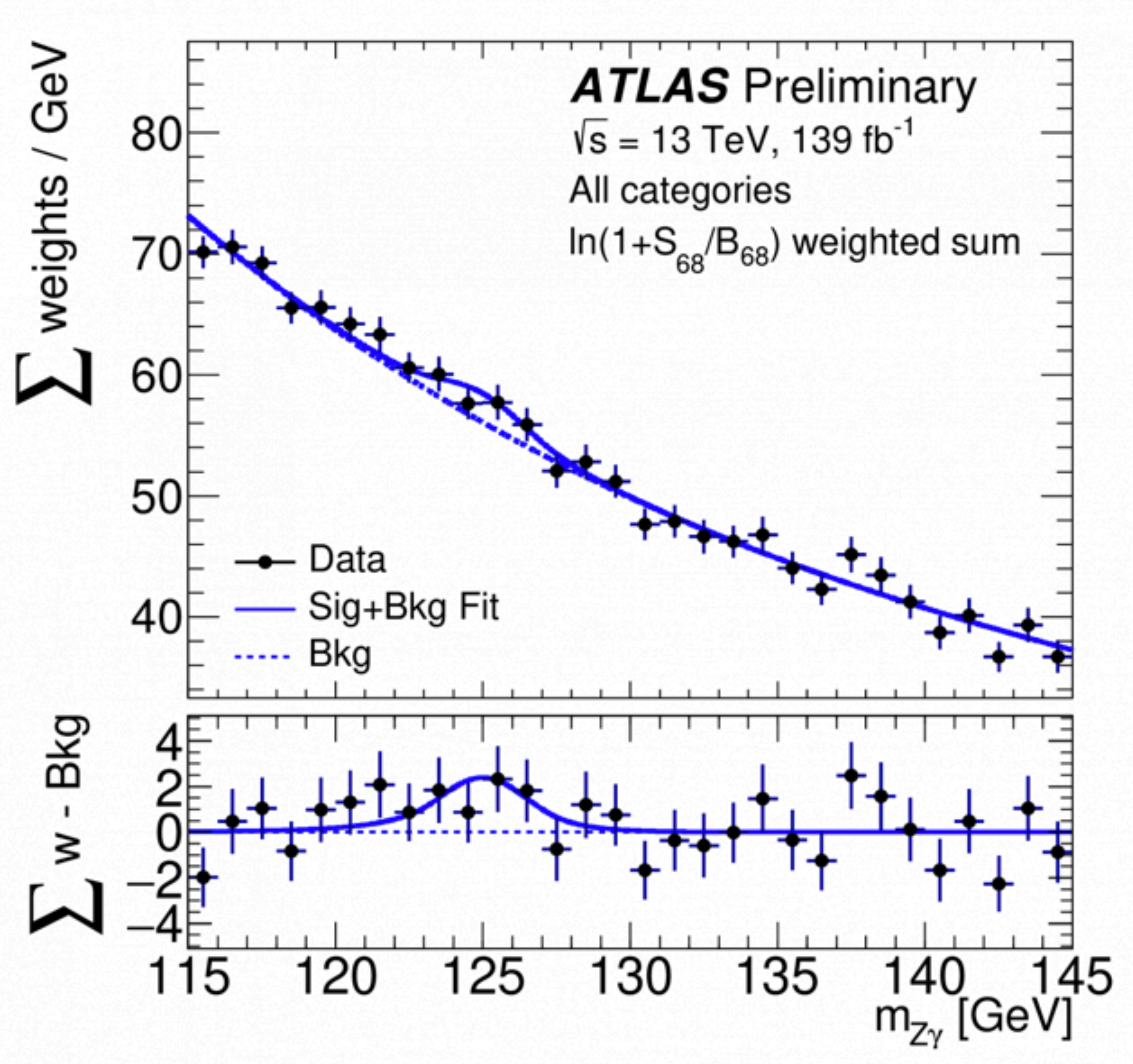
- **Partial Event Building (PEB)**: Reduce event size by recording only raw detector data in Regions Of Interest (↓Bandwidth = ↑Rate x ↓↓Size, ↓↓↓CPU).
  Advantage: CPU limitations lifted.

H → Zγ and γγ*

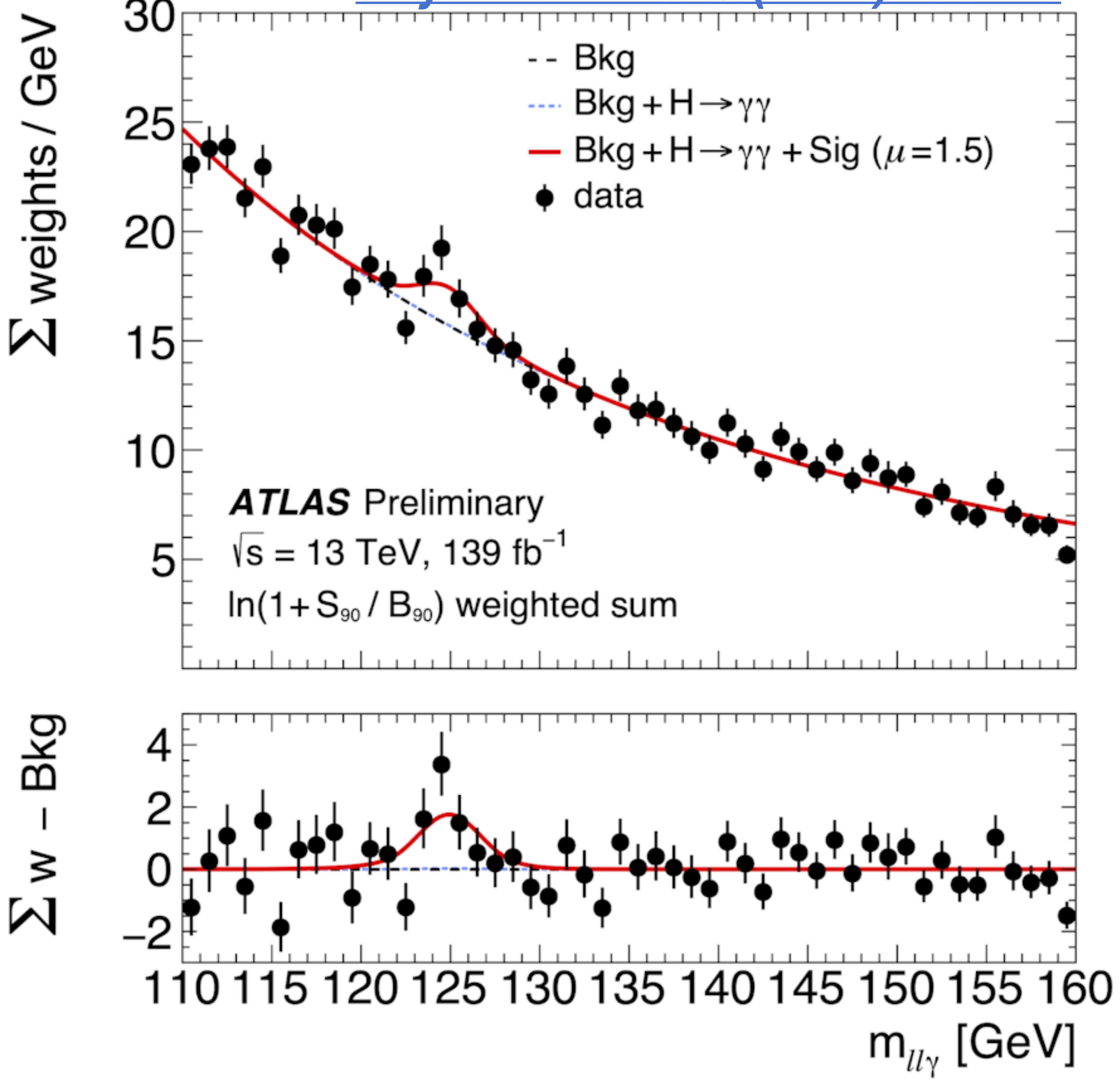
Phys. Lett. B 809 (2020) 135754

The SM predicts 0.15% of Higgs to decay to Zγ comparable to the decay to two photons (Z BR bosons decay to leptons) makes this more challenging.

- significance of 2.2σ obs(1.2σ exp)
- 95%CL upper limit at 3.6xSM obs (2.6xSM exp)



Phys. Lett. B 819 (2021) 136412



γ* is a virtual particle with(non zero) mass, decays instantly to two leptons
mℓℓ<30 GeV (typically <1 GeV)
high pT, small leptons separation ~cm
(challenge for electrons)

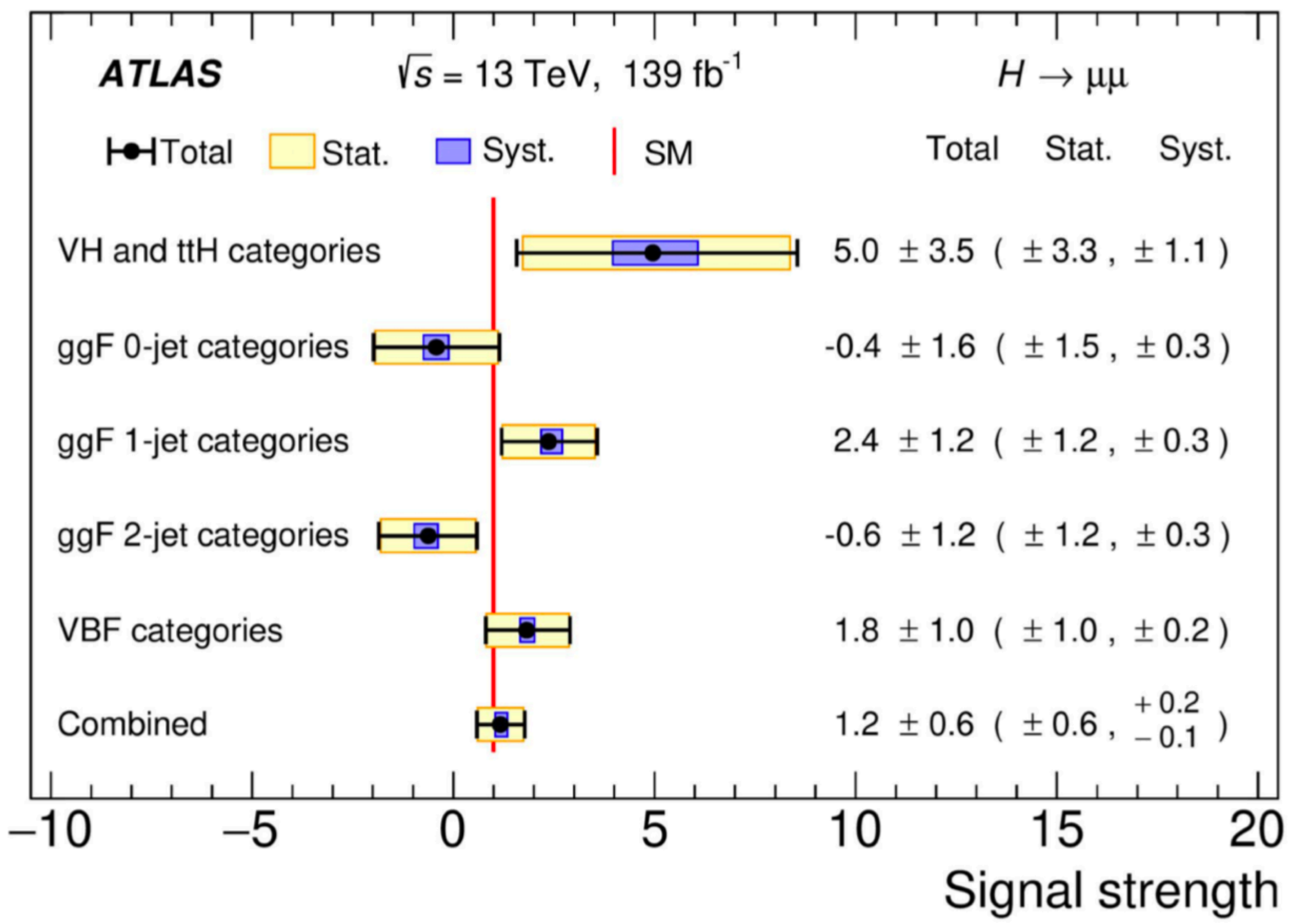
significance of 3.2 σ obs (2.1 σ exp)

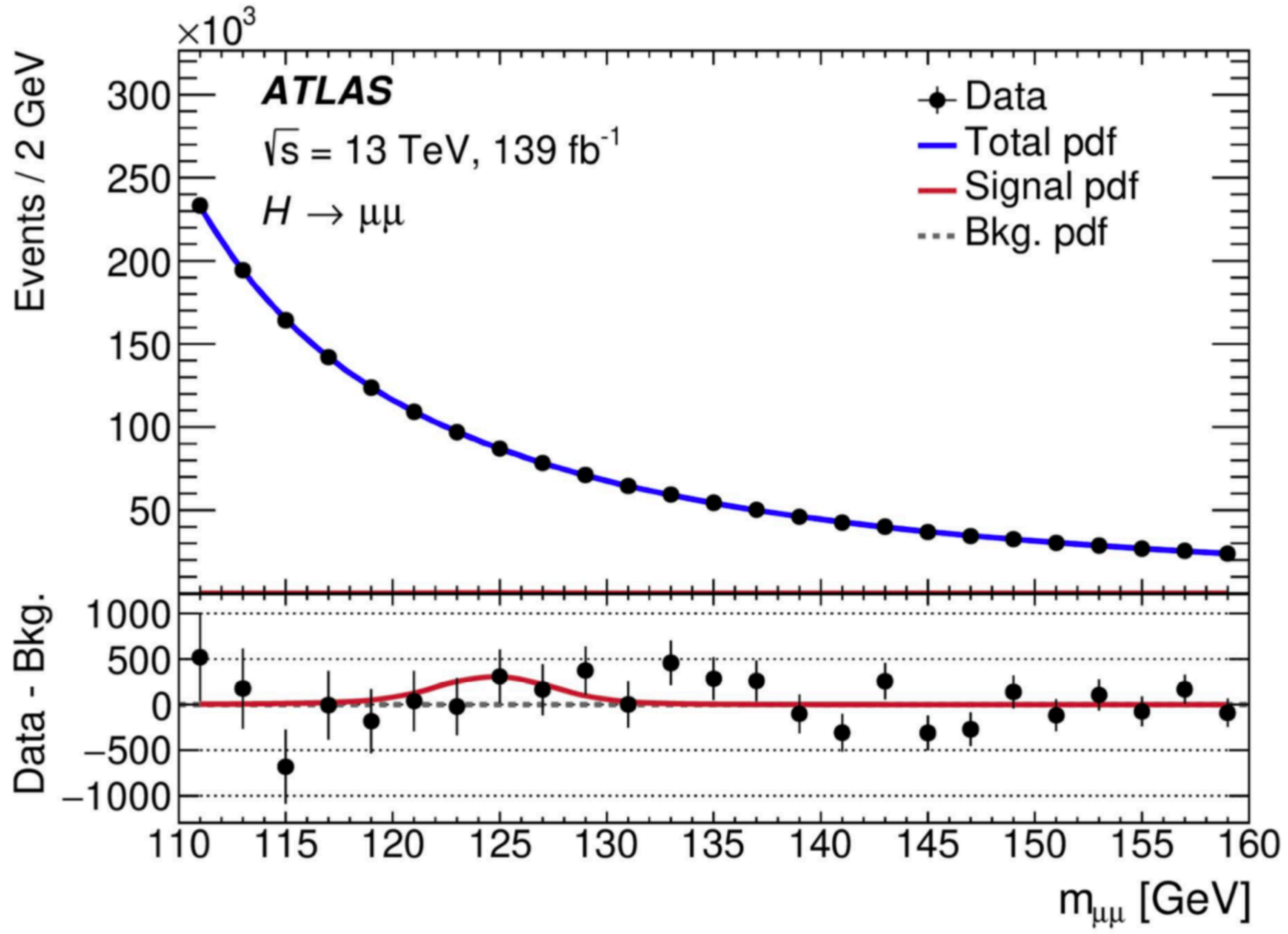
H→μμ

PLB 812(2021) 135980

Z→μμ main background
statistically limited

VBF category is the most powerful!





Observed (expected) significance of 2.0 (1.7) σ

Important in run 3: in reach 3 sigma

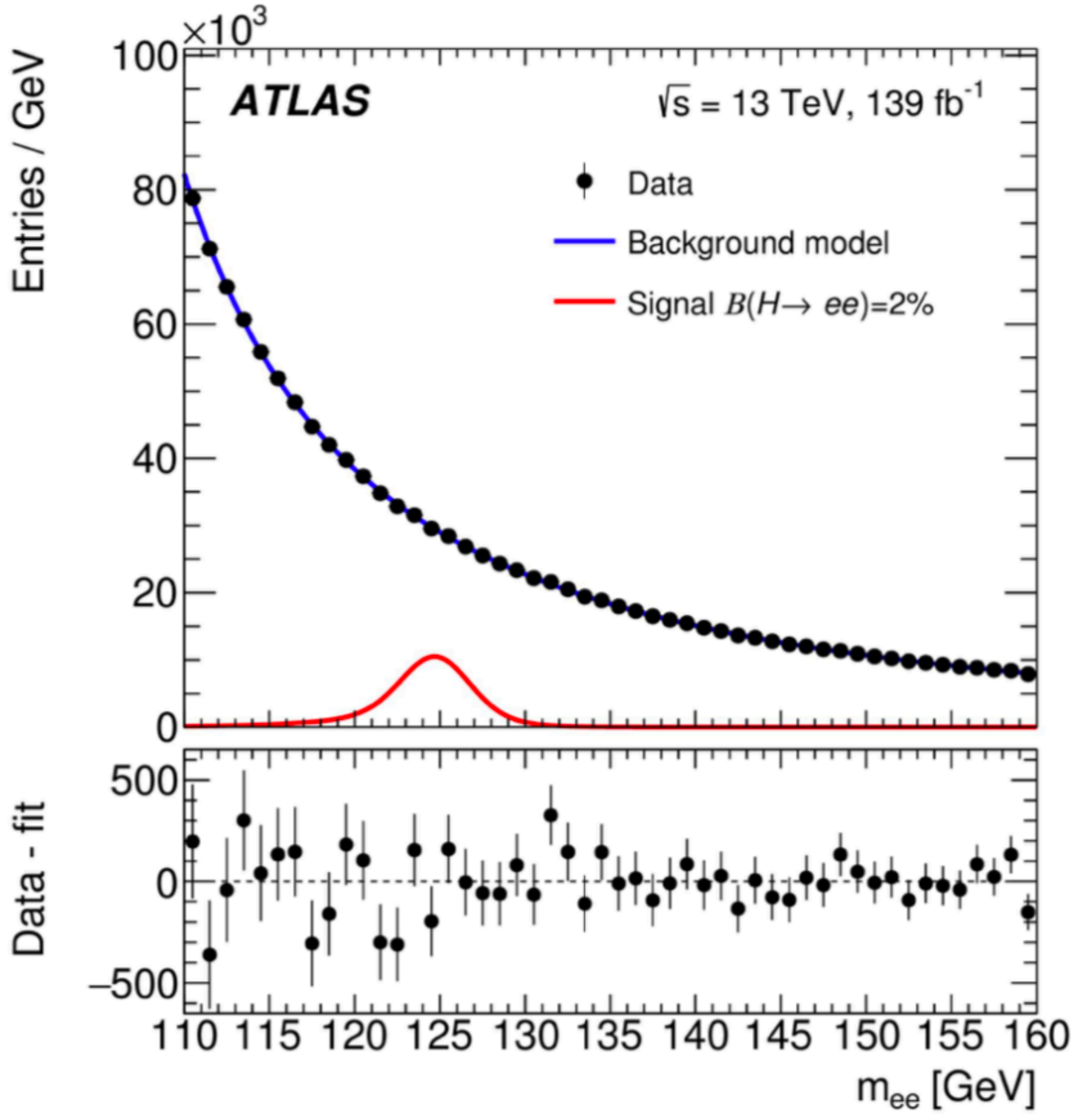
per experiment and 5 in combination.

H→ee

PLB 801(2020) 135148

Z→ee main background
statistically limited
similar analysis strategy as H→μμ

Observed (expected) limit at 95% CL:
$BR_{H->ee} < 3.6\ (3.5) \times 10^{-4}$



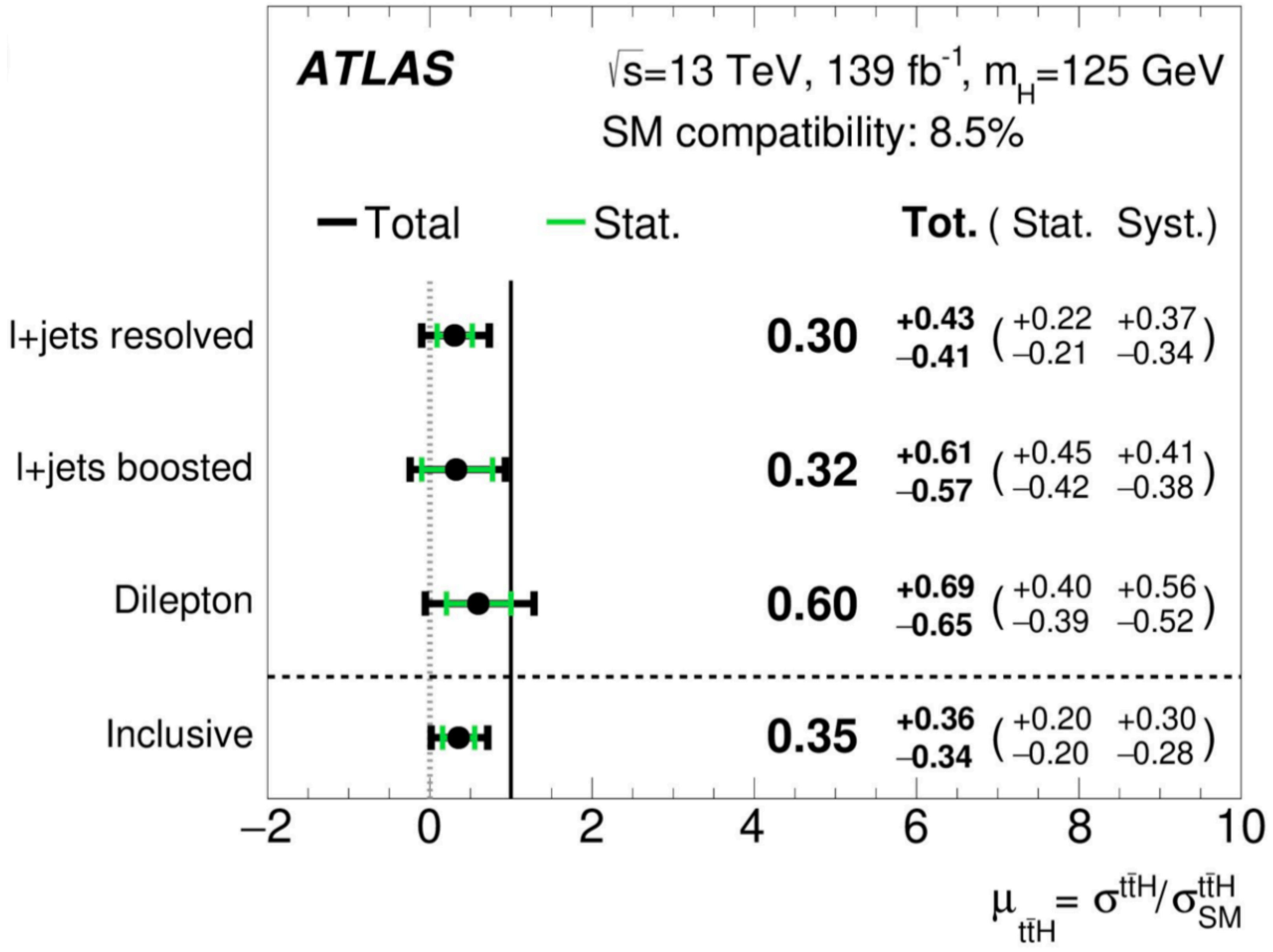
the Higgs boson is around 40,000 times less likely to decay into electrons as it is into muons

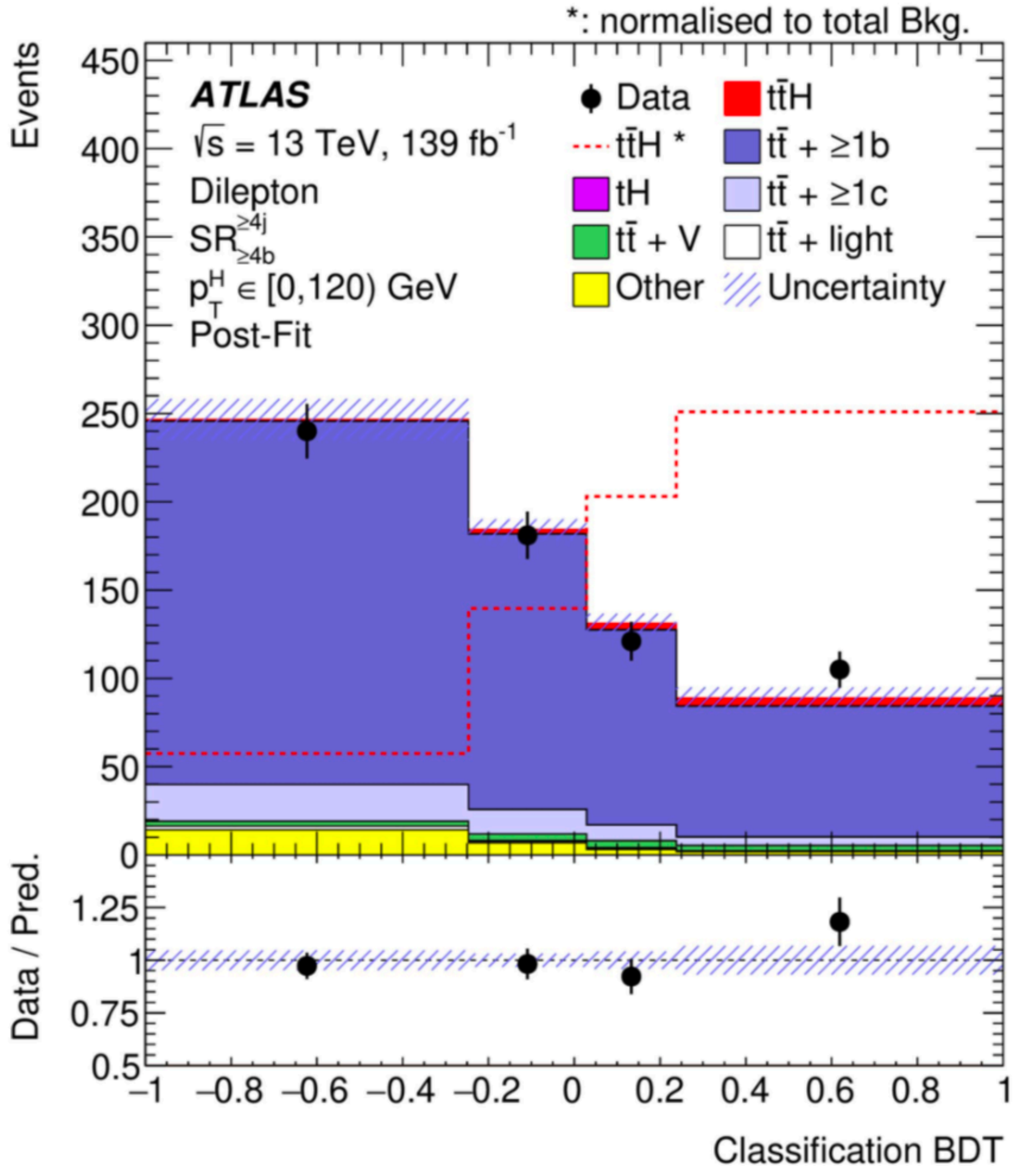
ttH(bb)

JHEP 06 (2022) 097

- The top Yukawa coupling probed with this channel, 1 or both tops decaying leptonically.
- Events classified according to the number of leptons, jets and b-jets
- Machine learning techniques to aid the signal/background discrimination

- significance of 1σ obs (2.1σ exp)

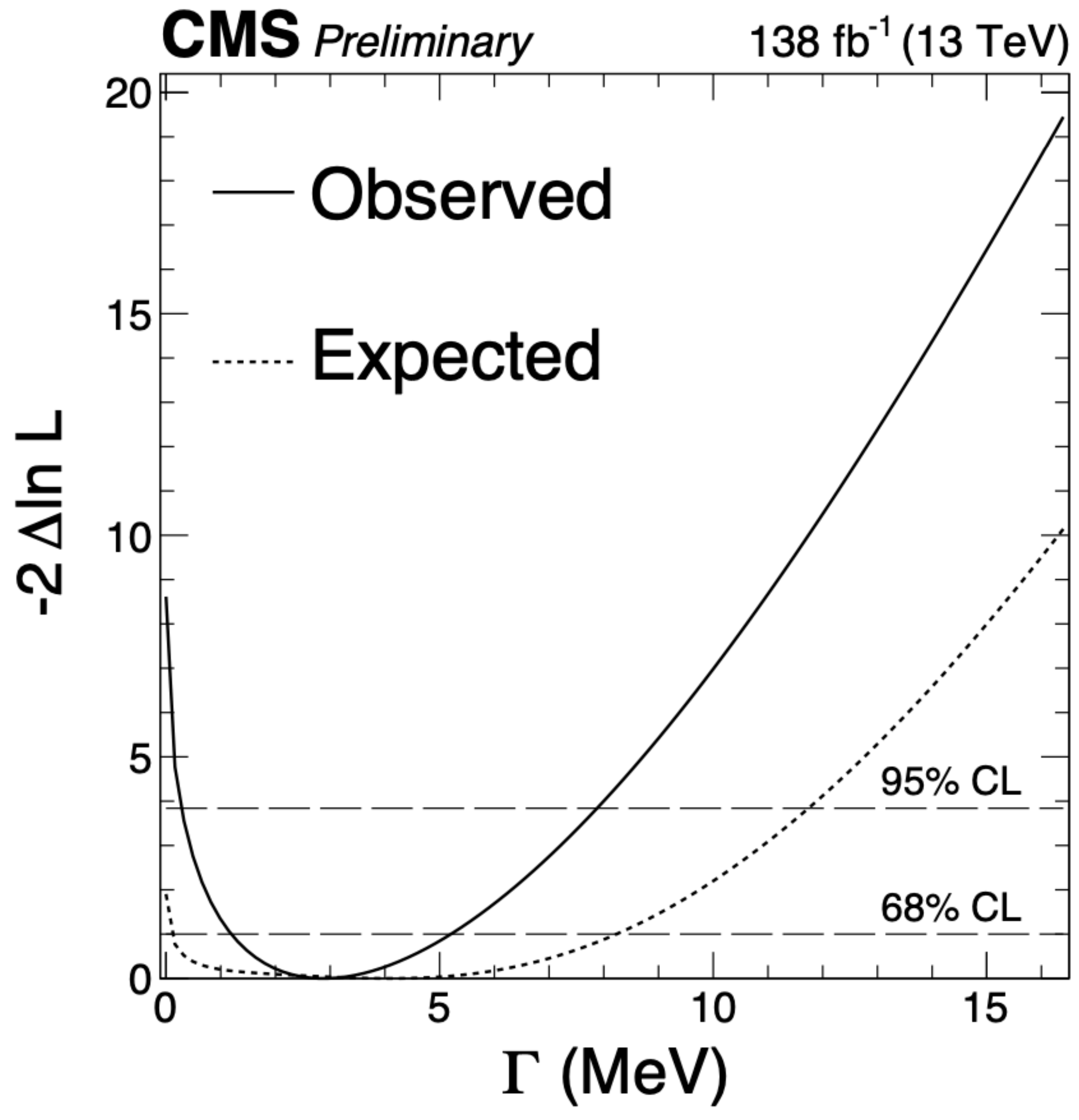




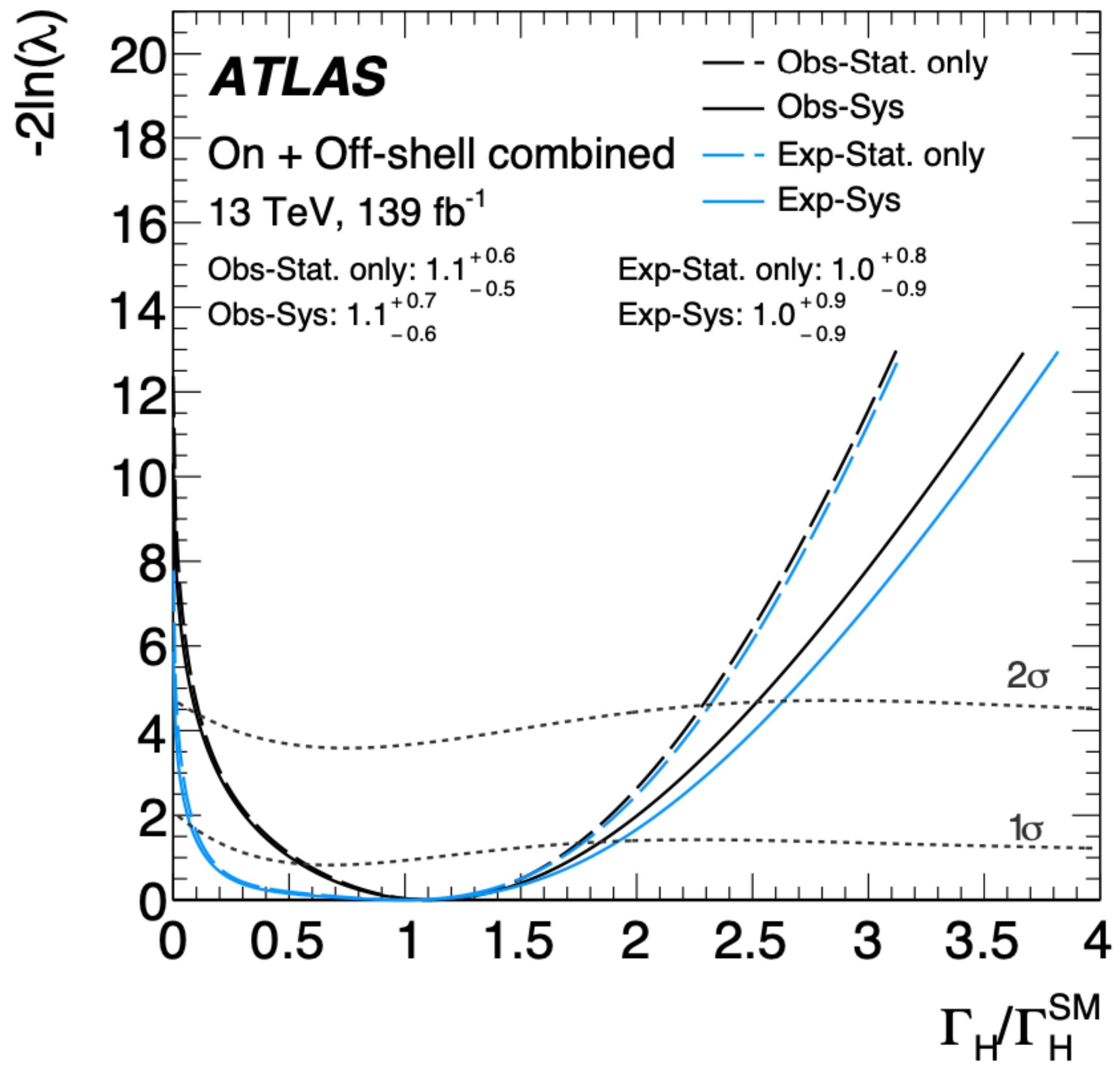
Higgs width

The best estimate of the Higgs boson total width is:ΓHHSM = 4.07 MeV

3 orders of magnitude smaller than our mass resolution

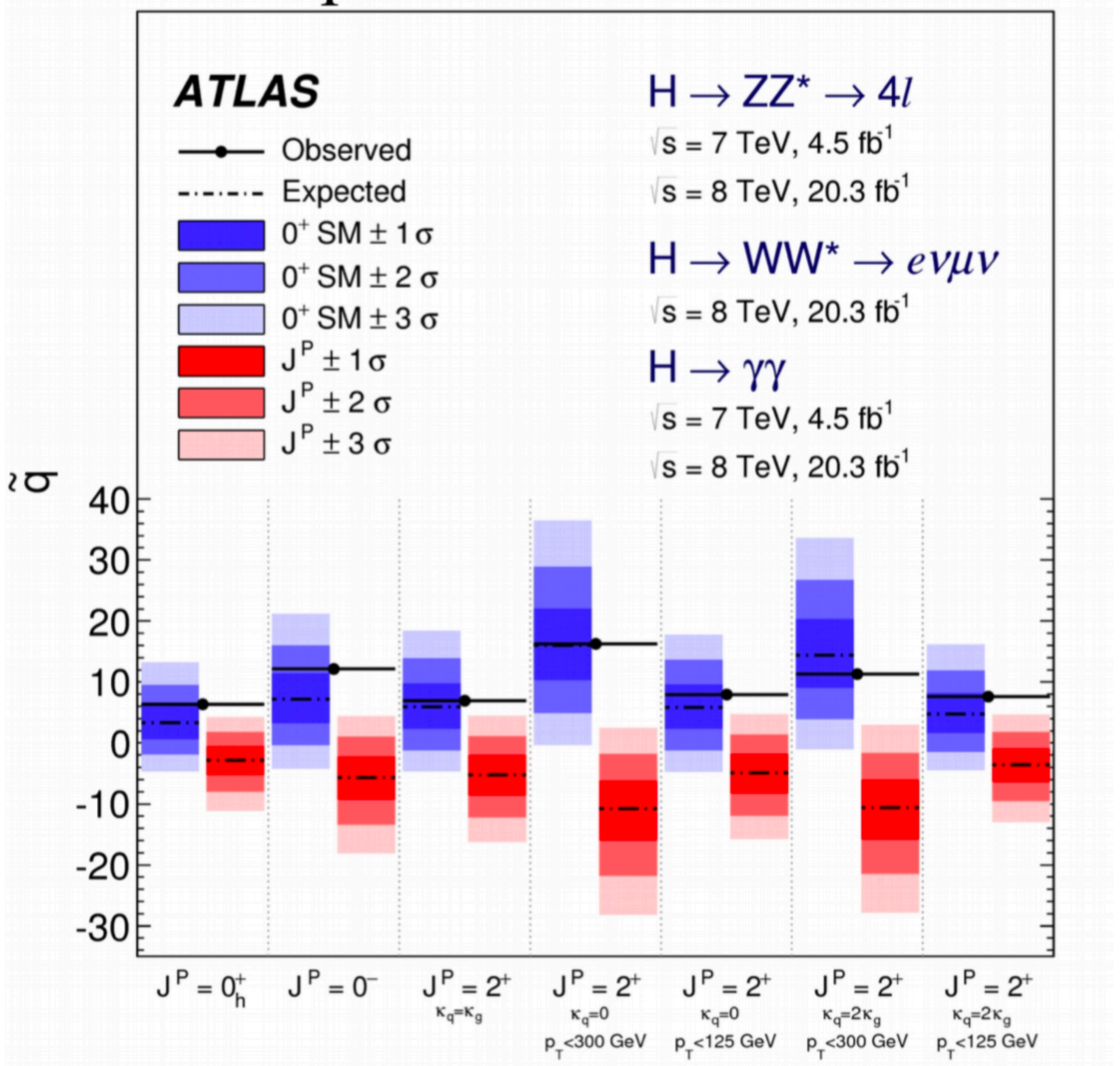


Extracted width: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV



$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

- Spin/parity: $J^{PC} = 0^{++}$
  - spin 1 and 2 excluded at > 99% CL



In bosonic couplings parametrized with higher order terms suppressed by powers of Λ (scale of new physics)

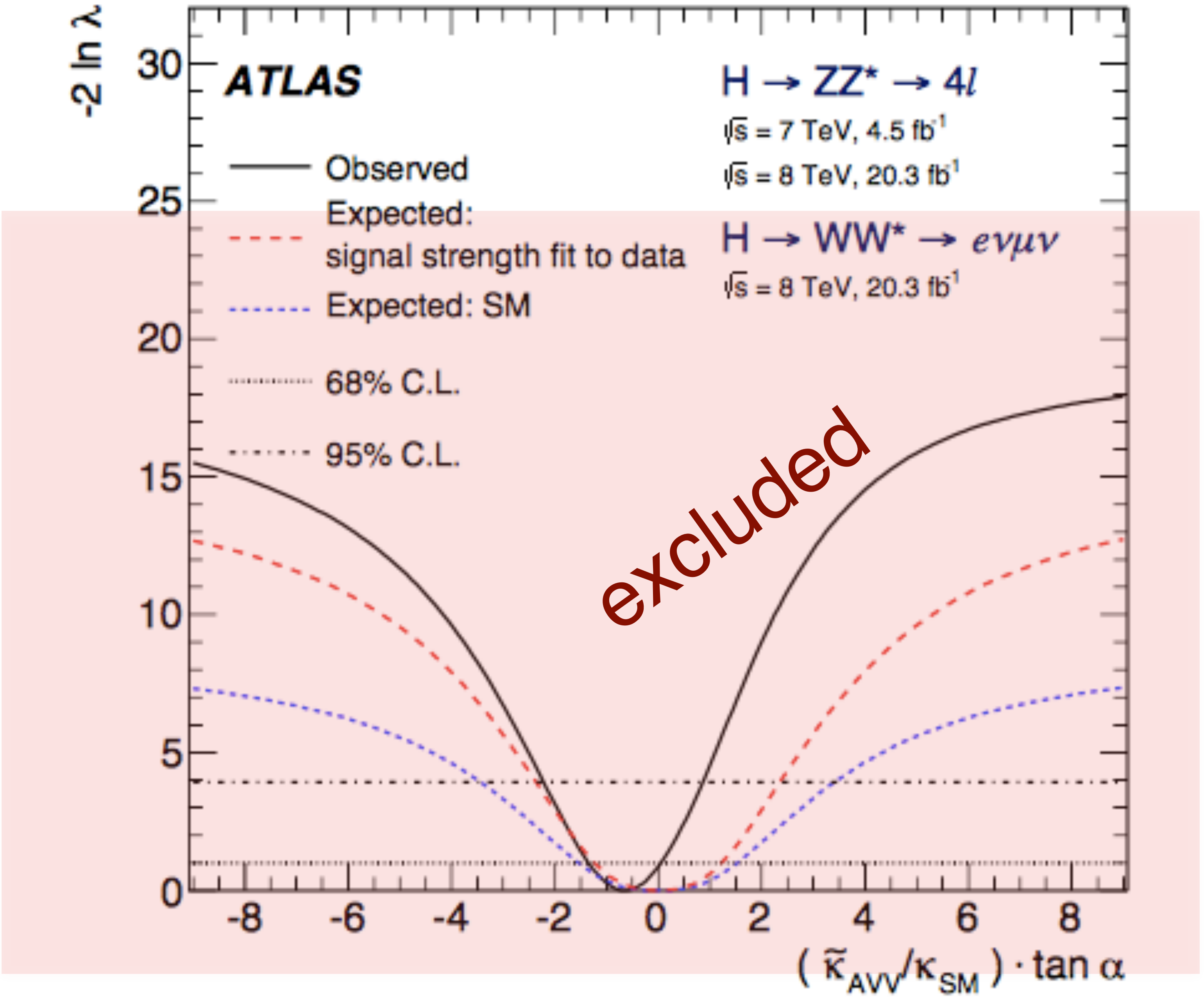
$$\mathcal{L}_{VVH} = \mathcal{L}_{VVH,SM} + \frac{1}{\Lambda^2} c\,\phi \widetilde{V}_{\mu\nu} V^{\mu\nu} + \ldots$$

CP violation

Fermionic couplings affected at tree level (more important for heavier fermions due to higher coupling)

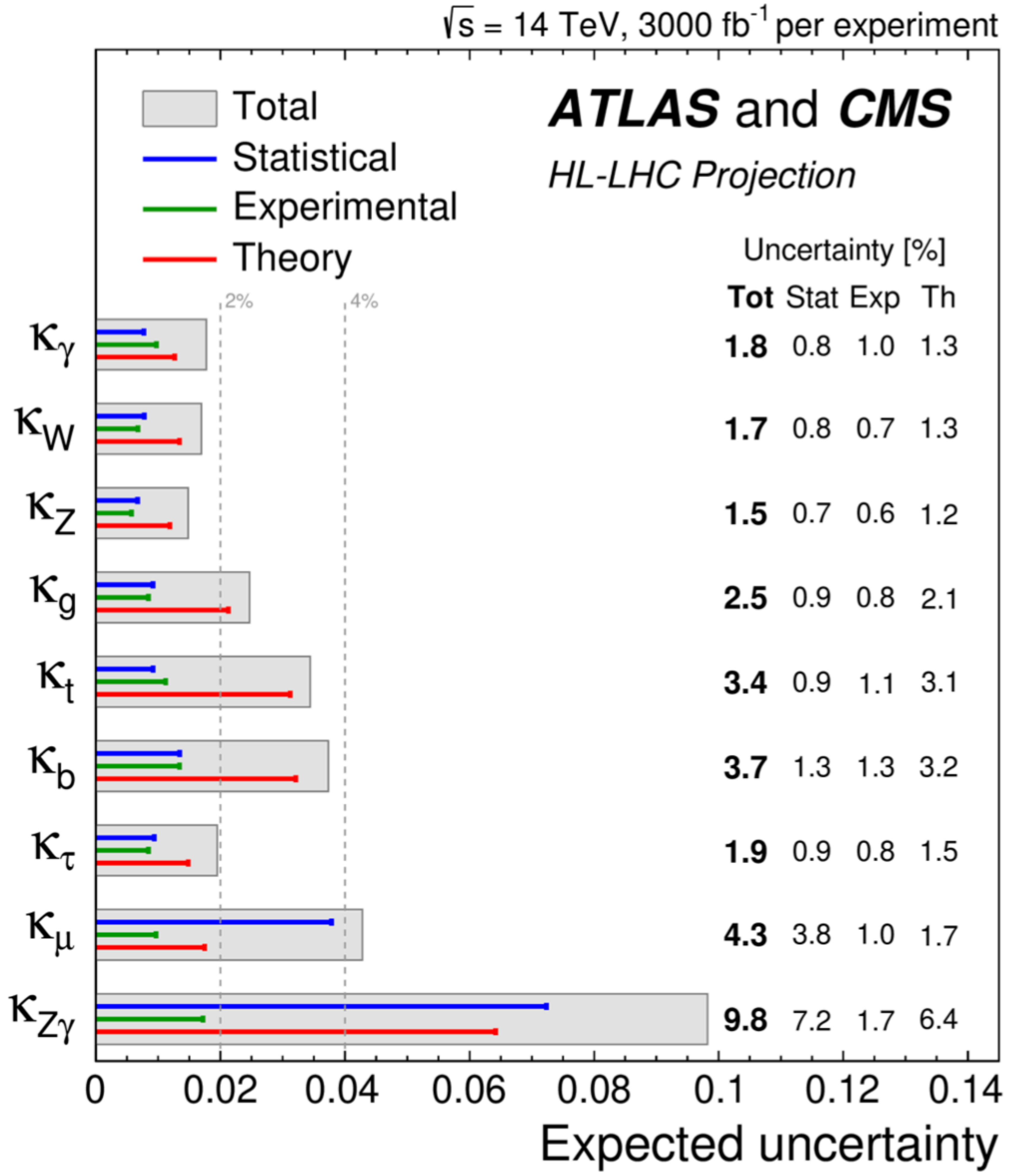
α CP- even and CP-odd mixing angle

$$\mathcal{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

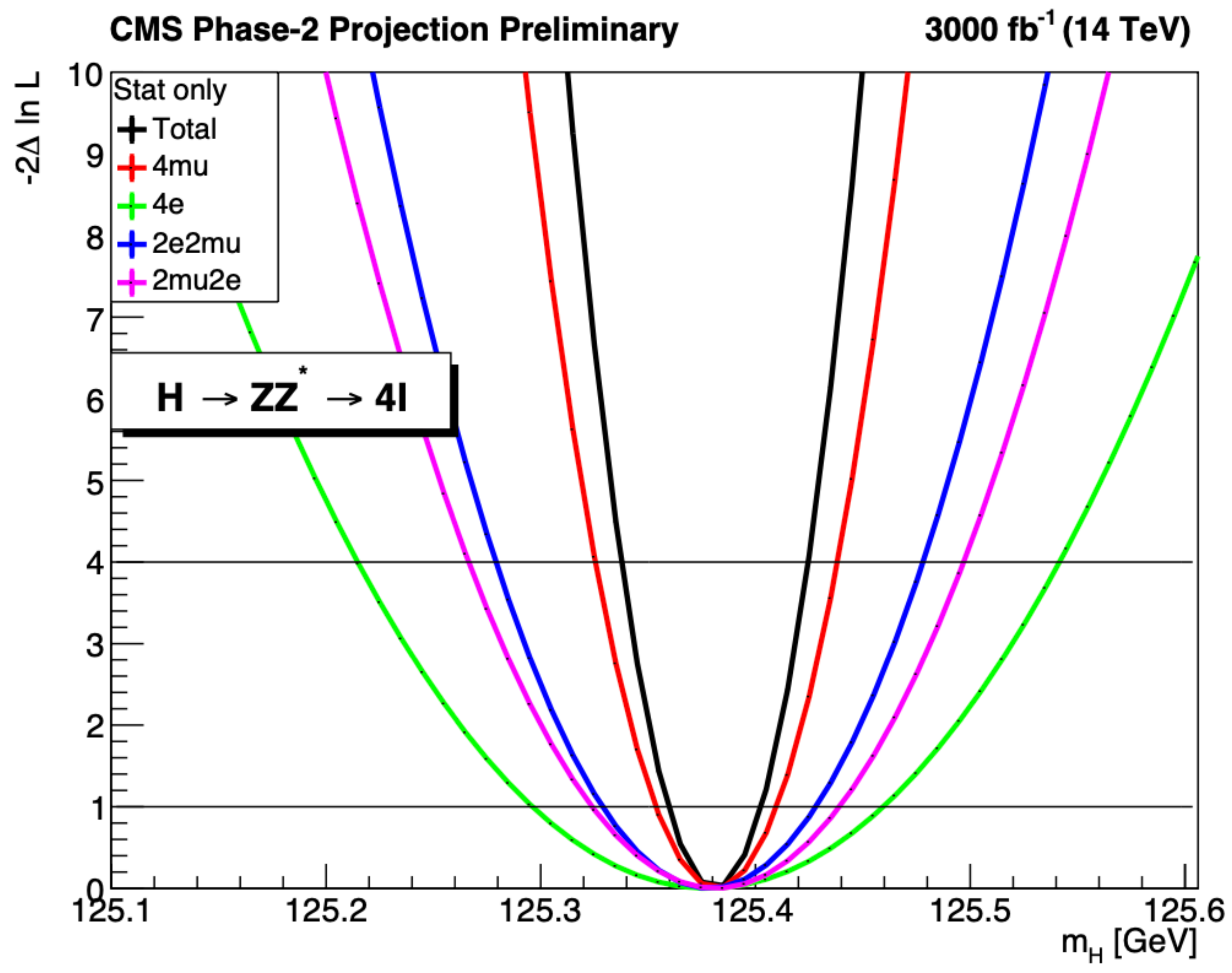


← CP odd increasing →

HL-LHC projections



The projected expected result, for mass measurement, is $m_H = 125.38 \pm 0.03[0.022(stat) \pm 0.020(syst)]$ GeV and for width is $\Gamma_H < 0.09(0.18)$ GeV at 68(95)% confidence level

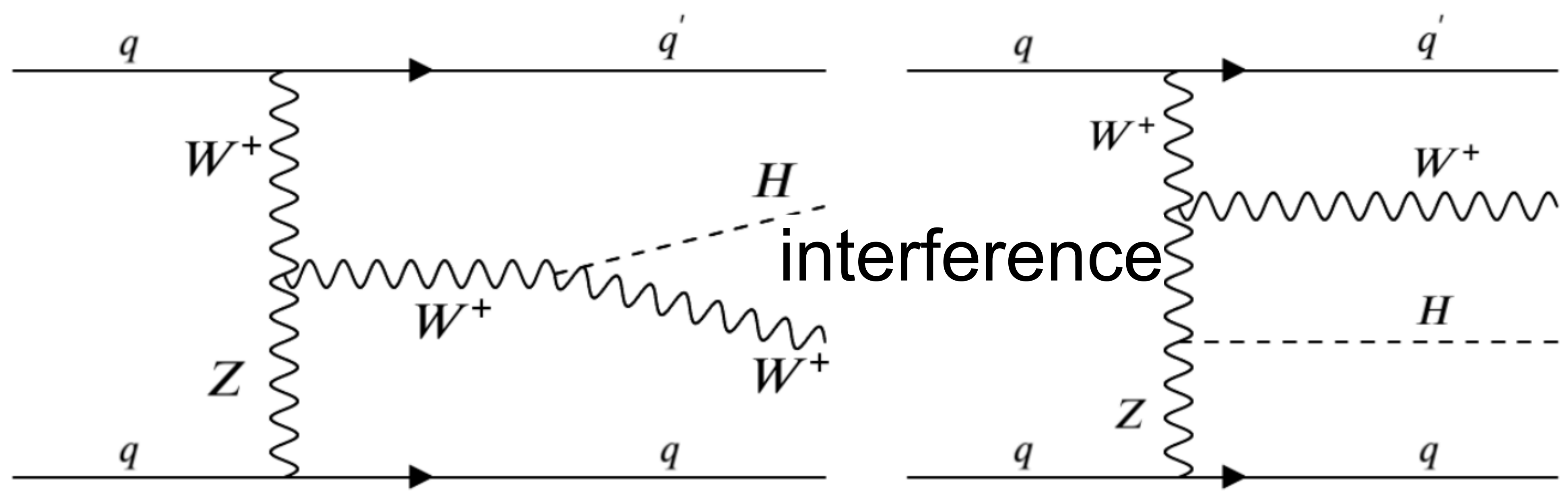


Higgs VBF,WH production sign of λWZ coupling

ATLAS-CONF-2023-057

New!

- New production mode: sensitive to sign of ratio of Higgs-W/Z couplings ($\lambda_{WZ}=\kappa_W/\kappa_Z$), (H->bb) for which we had no sensitivity before



- **Excluded λ_{WZ} = -1 at >8σ**

- Measure μ for +λ_{WZ} signal

Fit: $\hat{\mu} = 2.6^{+4.6}_{-4.5}$