Search for heavy ZZ resonances in the $\ell\ell vv$ and 4ℓ final states

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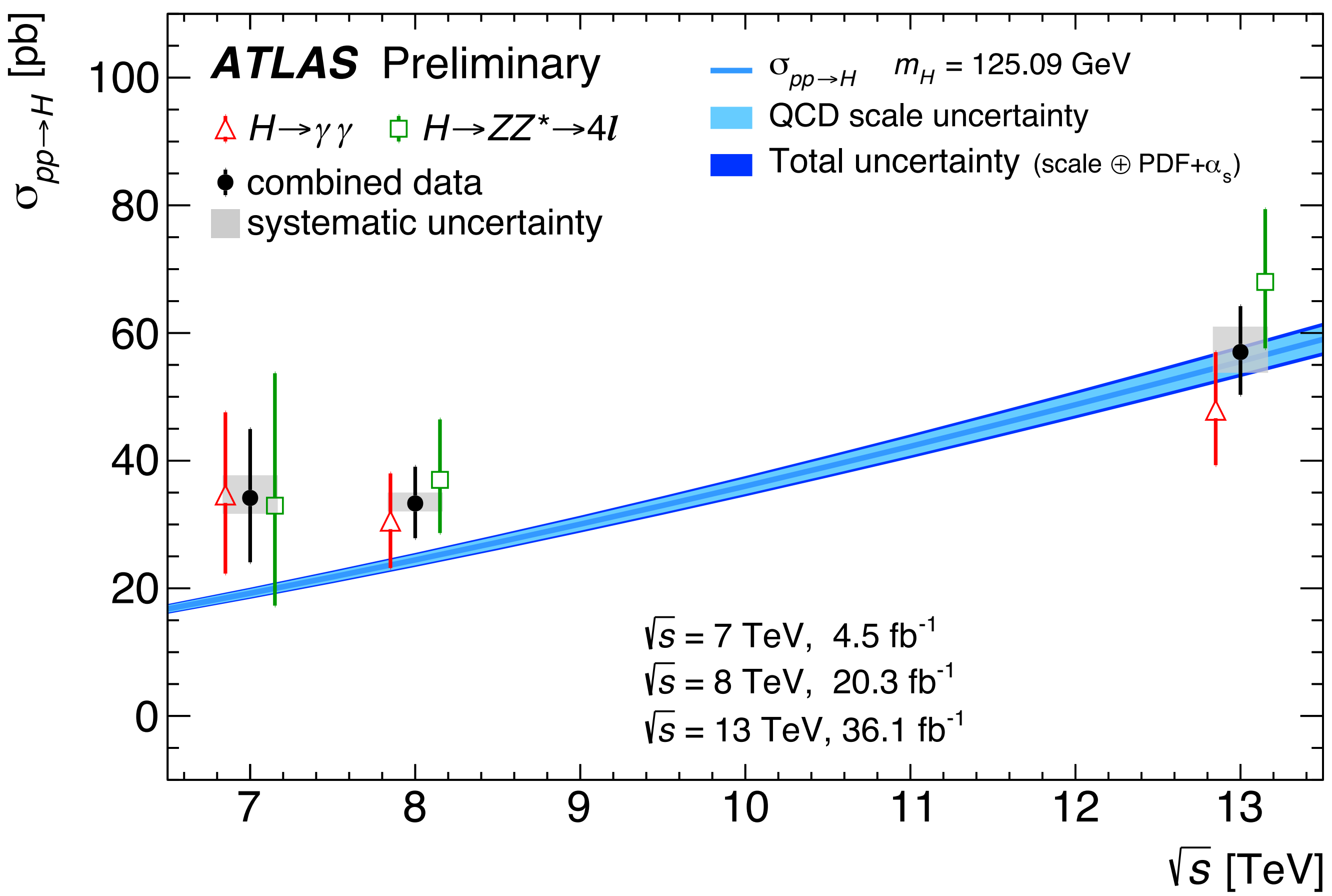
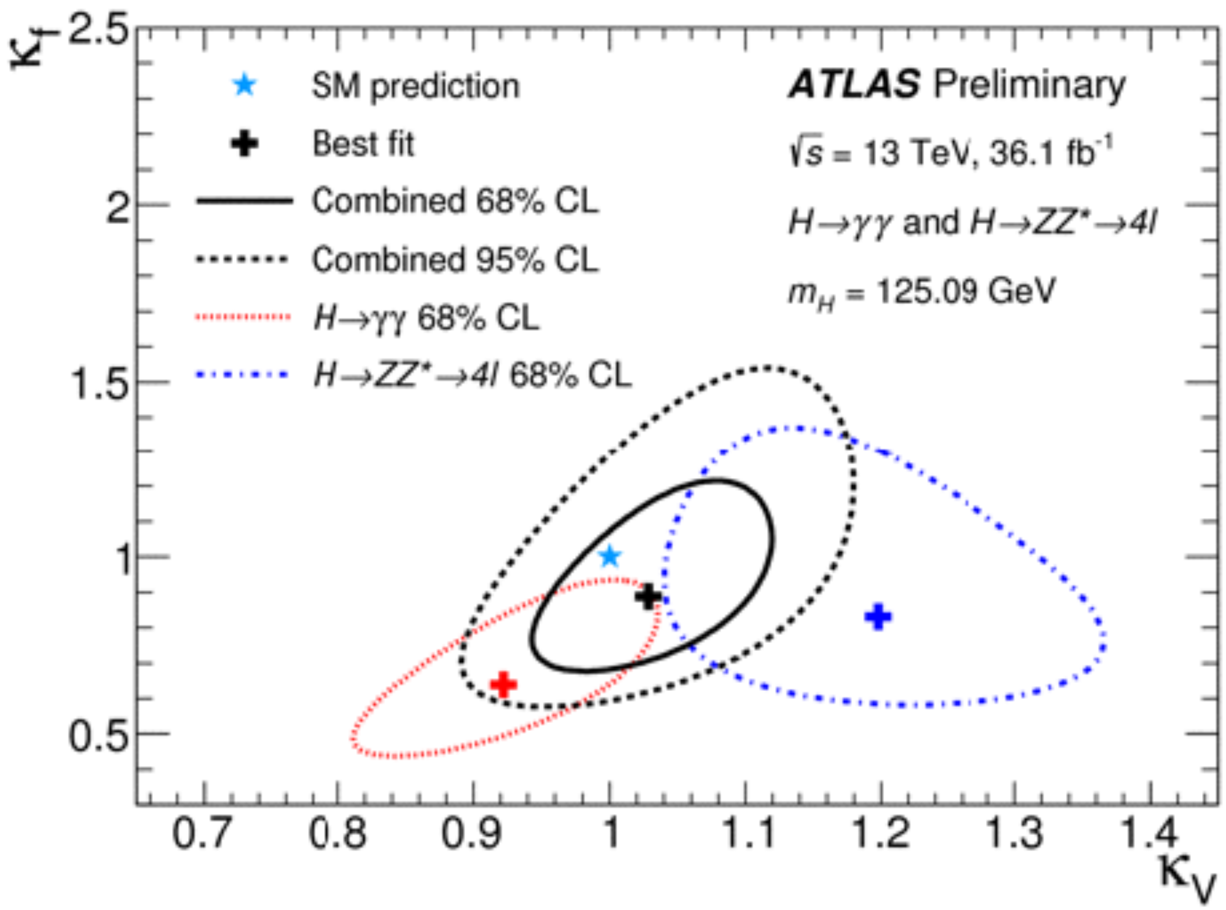
Measurements of the SM Higgs boson.

ATLAS-CONF-2017-047





- Excellent agreement entails the success of the SM and places stringent constraint on theories beyond SM.
- Current experimental results cannot rule out the possibility that it is part of an extended Higgs sector.
- Typical benchmark model is **CP-conserved 2HDM** (two-Higgs-doublet-models).

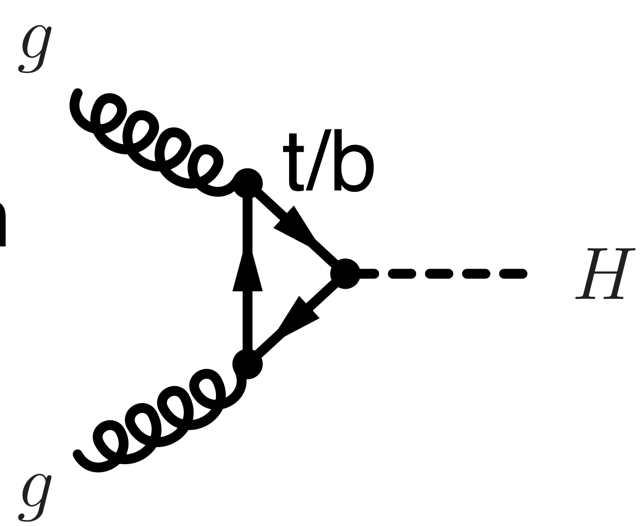
2HDM interpretation

	ϕ_1	ϕ_2
Type I	u,d,l	
Type II	u	d,l
flipped	u,l	d
lepton-specific	u,d	l

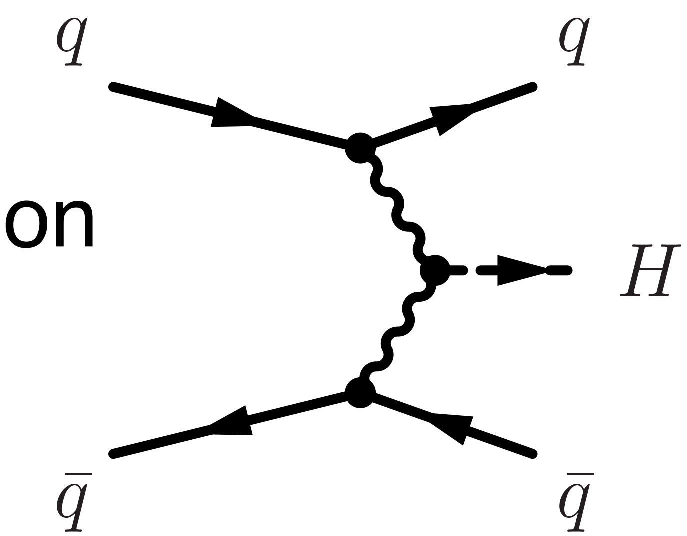
- Introduce two Higgs doublets: ϕ_1 and ϕ_2.
- Spontaneous symmetry breaking results in 5 Higgs bosons:
  - CP-even (h, H); CP-odd (A), charged Higgs ($H^{+/-}$).
- Free parameters in the physics basis:
  - masses of all Higgs bosons.
  - ratio of vacuum expectation values: $\tan\beta = v_2/v_1$.
  - Higgs mixing angle in the CP-even sector α, $H^{SM} = \sin(\beta-\alpha)h + \cos(\beta-\alpha)H$.
- **m_A, $m_{H+/-}$,** is assumed to be heavy enough that H won't decay to them.
- Coupling modifiers:
  - **$\kappa(h,V) = \sin(\beta-\alpha)$, $\kappa(H, V) = \cos(\beta-\alpha)$**.
  - $\kappa(H, t) = -\sin(\beta-\alpha)/\tan\beta + \cos(\beta-\alpha)$.
  - TypeI: $\kappa(H, b) = \kappa(H, t)$
  - TypeII: $\kappa(H, b) = \sin(\beta-\alpha)\tan\beta + \cos(\beta-\alpha)$.

General analysis strategy in event selections

Gluon-fusion (ggF)



Vector boson fusion (VBF)



- First define an **inclusive signal region**.
- To enhance the sensitivity on the VBF production, VBF-like category is defined by looking for **VBF signatures:** two forward jets, leading to large m_{jj} and $\Delta\eta_{jj}$.
    - llvv: $m_{jj} > 550$ GeV and $\Delta\eta_{jj} > 4.4$. ATLAS-CONF-2017-058
    - 4l: $m_{jj} > 400$ GeV and $\Delta\eta_{jj} > 3.3$.
- Events in inclusive SR containing the VBF signatures are classified to VBF-like category, otherwise to the ggF-like category.

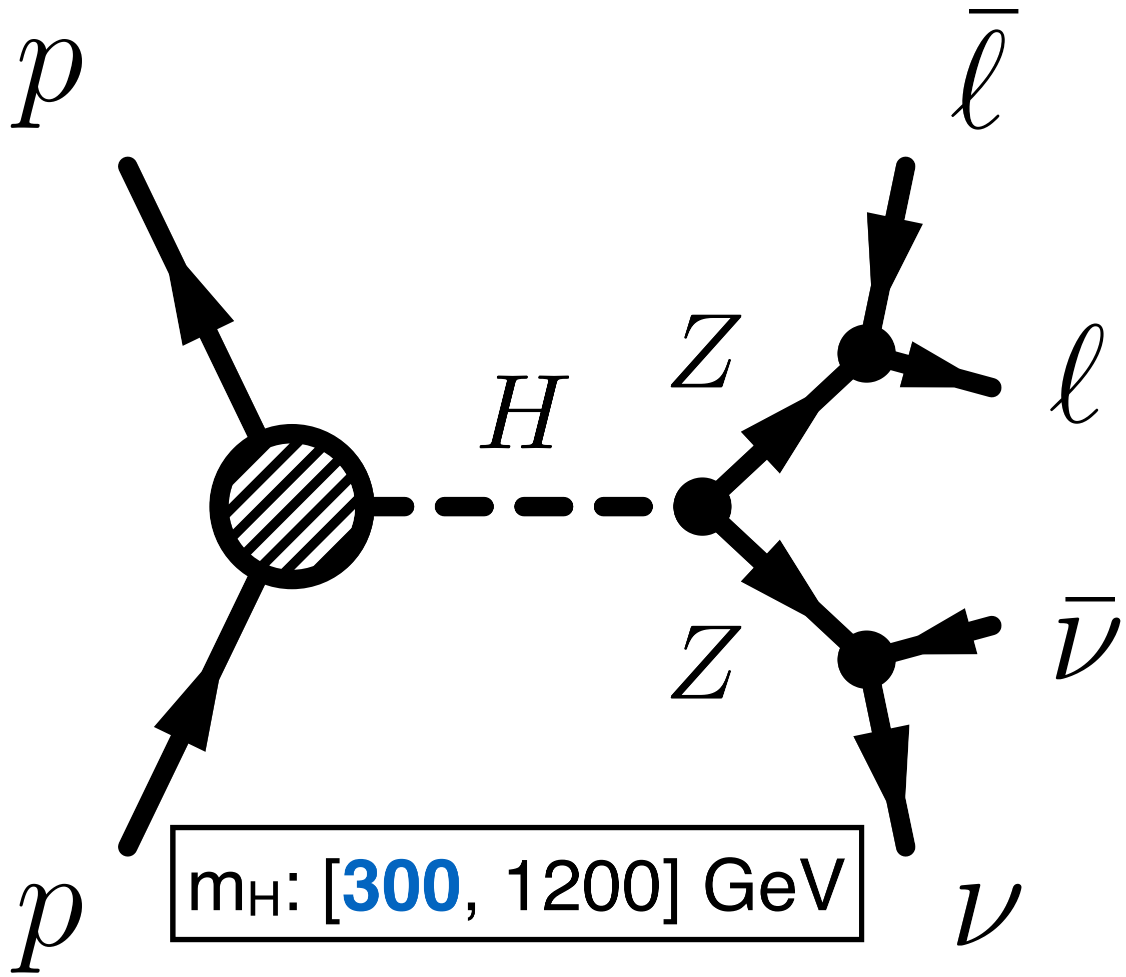
$\ell\ell\nu\nu$ analysis

- Search for the events with **two leptons** originating from a on-shell Z and **large missing transverse momentum** E_T^{miss}.
- Interesting signature, can result from different phenomena, depending on the origin of E_T^{miss}. ATLAS-CONF-2017-040
    - Dark matter: mono-Z, Invisible Higgs (ZH) or **Z→$\nu\nu$**.
- **Large branching ratio,** good sensitivity in the high mass region.
- Due to different resolution and background composition of electrons and muons, the events are classified into **ee and mm channels**.
- Look for excesses in the transverse mass:

$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_{\mathrm{T}}^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2}\right]^2 - |\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$$

Inclusive signal regions

Single electron/muon trigger, ε ~ 99%.



m_H: [**300**, 1200] GeV

$m_{\ell\ell}$ in [76, 106] GeV.

$\Delta R(\ell,\ell) < 1.8$

$\Delta\phi(\ell\ell, E_T^{miss}) > 2.7$

$E_T^{miss} > 120$ GeV.

$\Delta\phi(\text{jet}, E_T^{miss}) > 0.4$

$E_T^{miss}/H_T > 0.4$

$| p_T^{miss,jet} - p_T^{ll} | / p_T^{ll} < 0.2.$

No third lepton, no bottom-quark tagged jets!

Background composition

1. **qqZZ (~55%)**: simulated by PowHeg, corrected to NNLO QCD and NLO EW calculation.
2. **ggZZ (~4%)**: simulated by gg2VV in LO QCD calculation, corrected with NLO k-factor of 1.7 ± 1.0.
3. **WZ (~32%)**: simulated by PowHeg, using a k-factor of 1.29 derived from 3l control region (CR) to correct the overall normalization predicted by MC simulation.
4. **Z+jets (~6%)**: data-driven, use **Boolean** ABCD method.
5. **WW/tt/Zττ (~3%)**: data-driven using the **eμ** control region.

Results for $\ell\ell\nu\nu$

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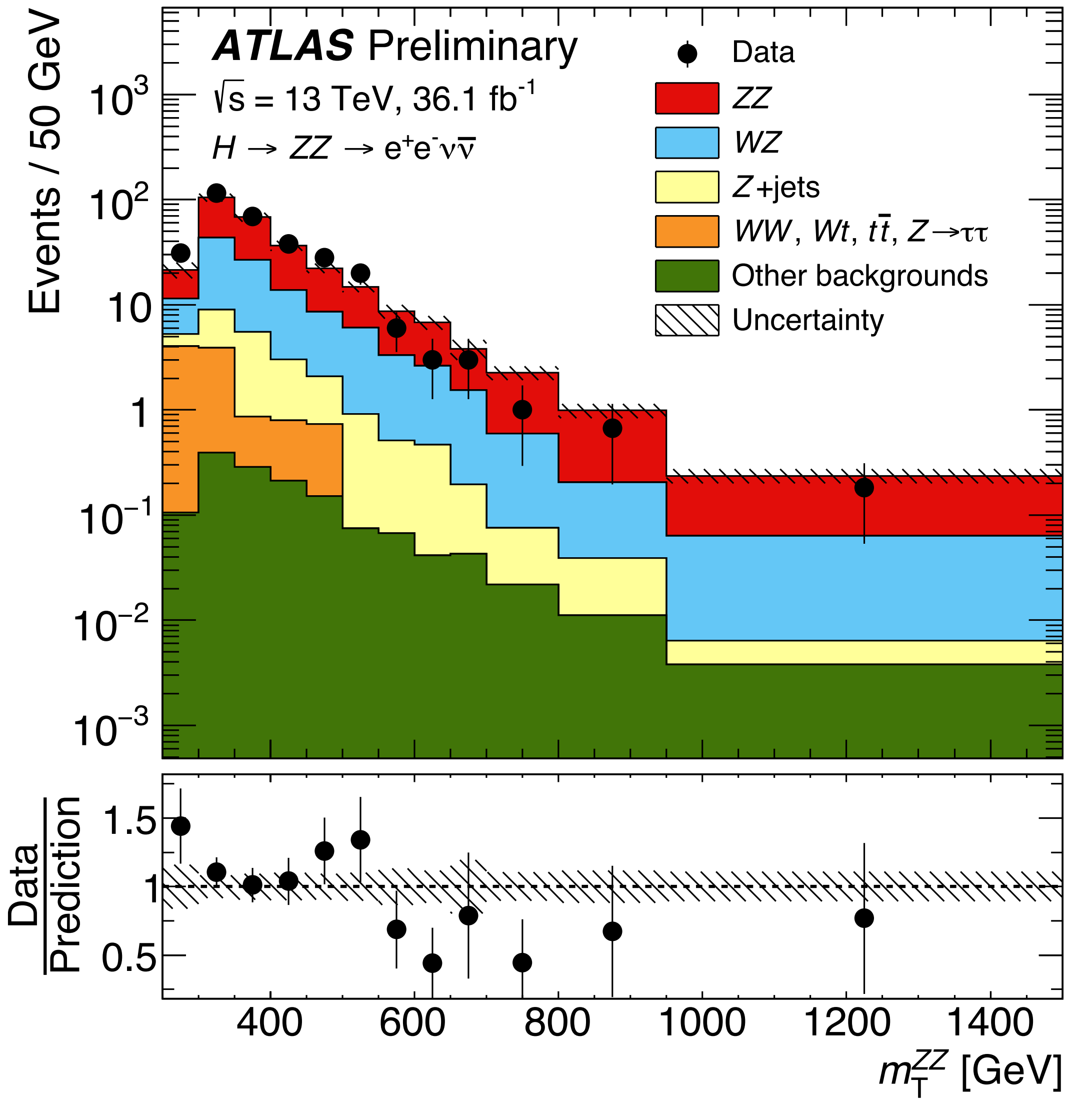
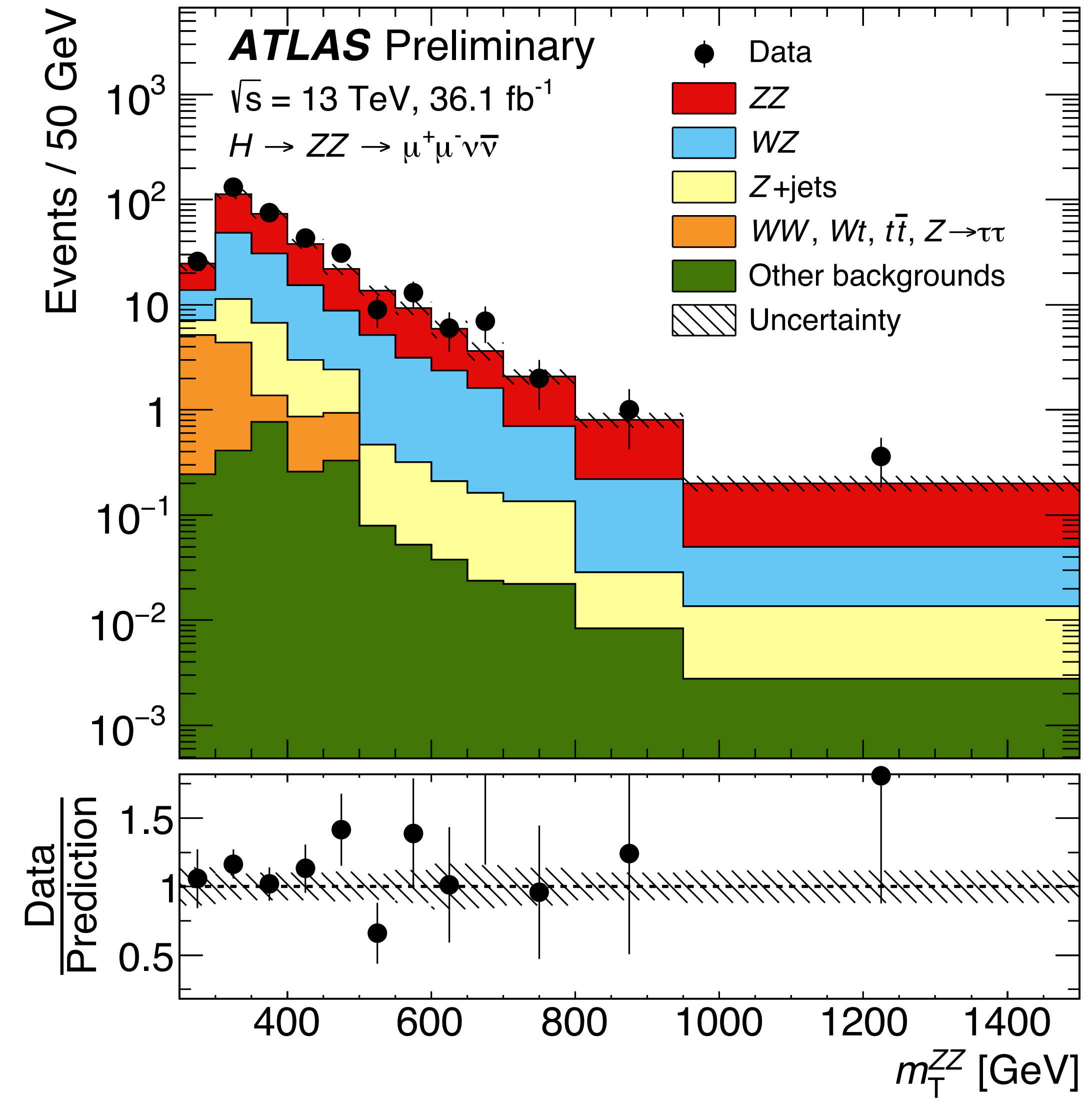




- mT distributions in inclusive signal region before the fit.
- Expected background: 612.6 ± 36.7 while observed: 681, compatibility is about 1.5 σ.
- In VBF category, expected 4.6 ± 1.0, while observed 9, compatibility is about 1.6 σ.

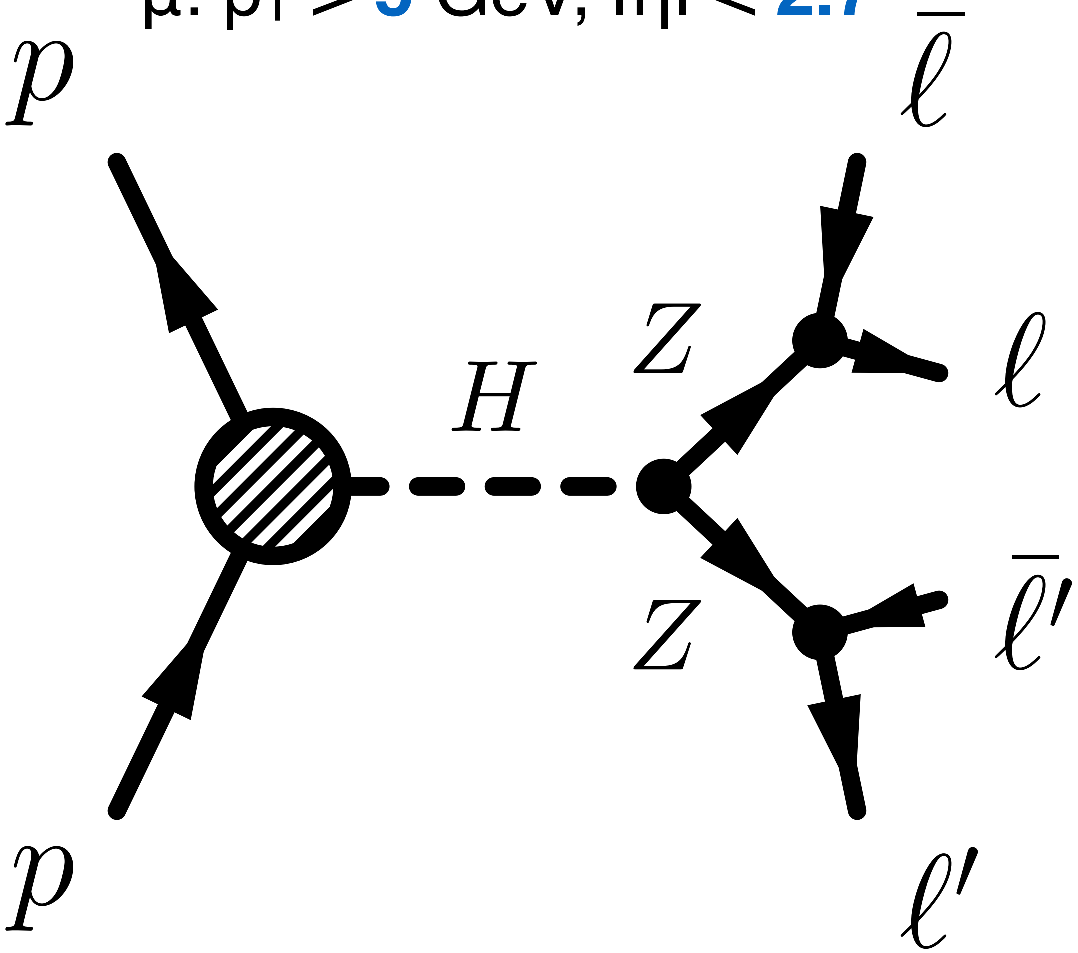
4ℓ analysis

- Search for the events with **four leptons** originating from two on-shell Zs.
- Events are classified into 4e, 4μ, 2e2μ and VBF-like categories.
- Experimental features include:
  - **Excellent mass resolution**:
    - 38 GeV (4μ) and 16 GeV (4e) for m_H = 1 TeV.
  - Challenge is to **maximize the acceptance**.
- Look for excesses in the four-lepton invariant mass.
- Search range for mH is [**200**, 1200] GeV.

Inclusive signal regions

e: $E_T > 7$ GeV, $|\eta| < 2.47$

μ: $p_T >$ **5** GeV, $|\eta| <$ **2.7**



Fire electron/muon triggers, $\varepsilon = 98\%$.

only one quadruplet: lepton pair closest (m_{12}) and second closest (m_{34}) to the pole mass of Z.

$50 < m_{12} < 106$ GeV, $50 < m_{34} < 115$ GeV for $m_{4l} > 190$ GeV

J/ψ veto, isolation and small impact-parameters criteria on leptons, χ^2/NDF in the vertex fit.

Further improvement on mass resolution:

1. Add final-state-radiation photons
2. Apply Z-mass constraint on **both Zs**.

→ **15%** improvement.

Background composition

1. **qqZZ (~85%)**: simulated by **Sherpa** (NLO for 0/1 jet, LO for 2/3 jets), with NLO EW corrections applied.

2. **ggZZ (~10%)**: simulated by Sherpa in LO QCD, apply NLO correction of 1.7 ± 1.0.

3. **qqZZjj EW (~2%):** simulated by Sherpa, important for VBF-like category (15%).

4. **Z+jets/tt/WZ (~2%)**. from data-driven methods. The uncertainty is about 20%.

5. **ttV/VVV(~1%)**: from MC simulations.

Results for 4ℓ

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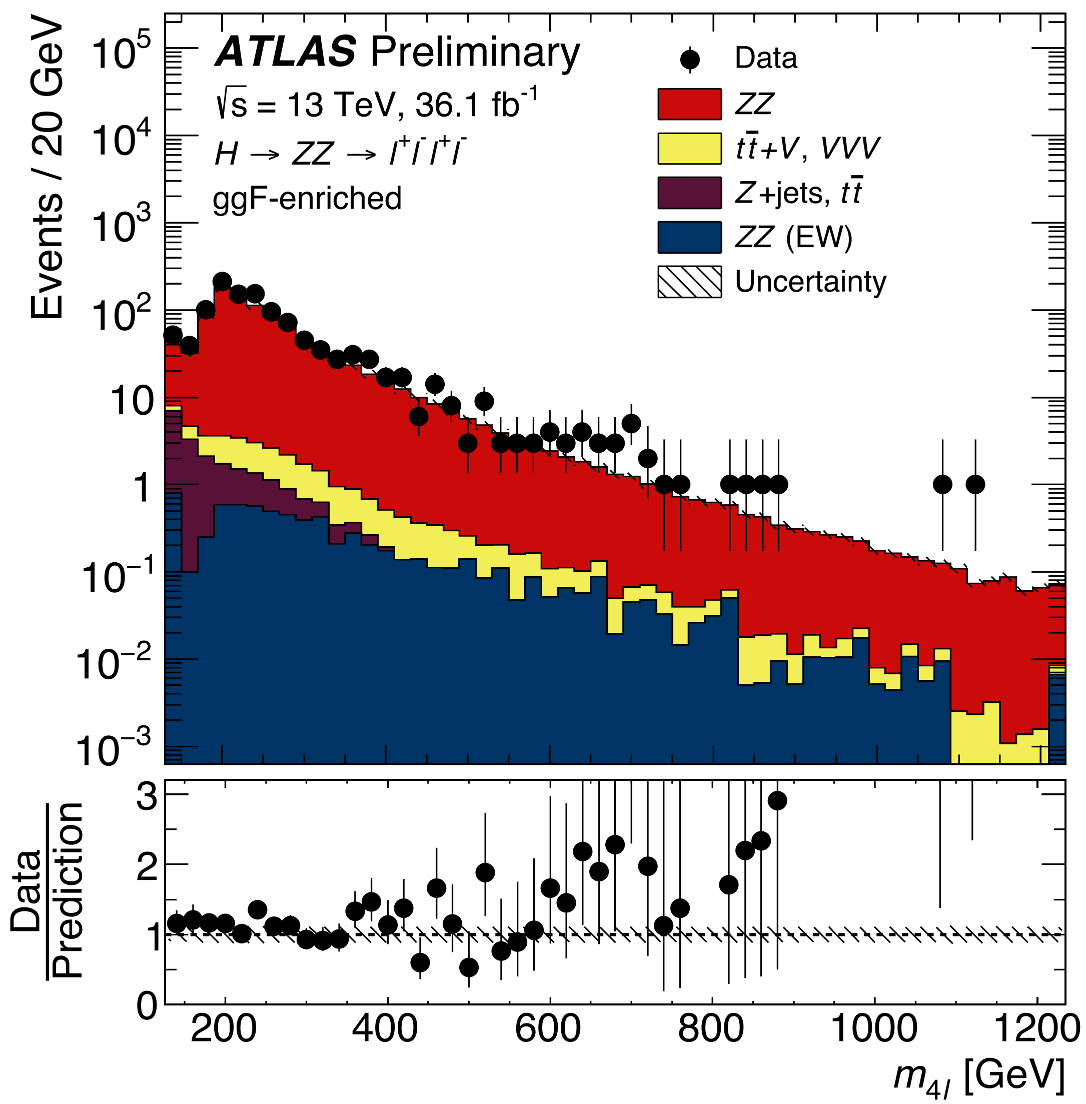

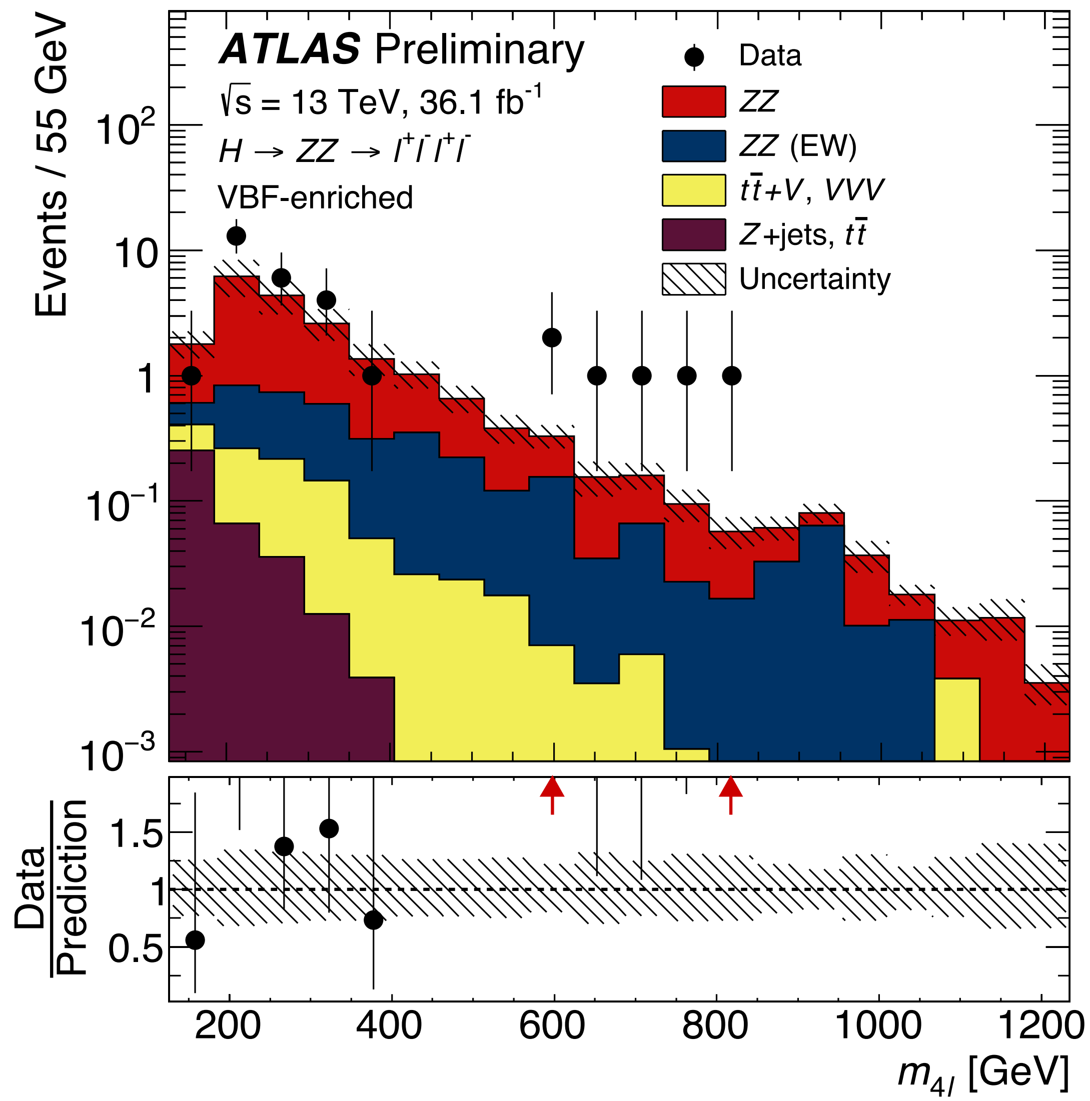

- A 3.6 (2.2) σ local (global) excess at ~240 GeV (mostly from 4e channel).
- A 3.6 (2.2) σ local (global) excess at ~700 GeV (excluded at 95% CL by llvv).
- In VBF category, expected 19.5 ± 8.0 while observed 31 events, compatibility: 1.2 σ.

Combination of 4ℓ and $\ell\ell vv$

- **correlation schemes** for systematic uncertainties:
  - the uncertainties coming from the same source are either fully correlated or anti-correlated.
- Combined yields:
  - expected events: 1643 ± 164, observed 1870, 1.3 σ.
- **Interpretations**:
  - Narrow width approximation (NWA)
  - Large width assumption (LWA)

NWA interpretation

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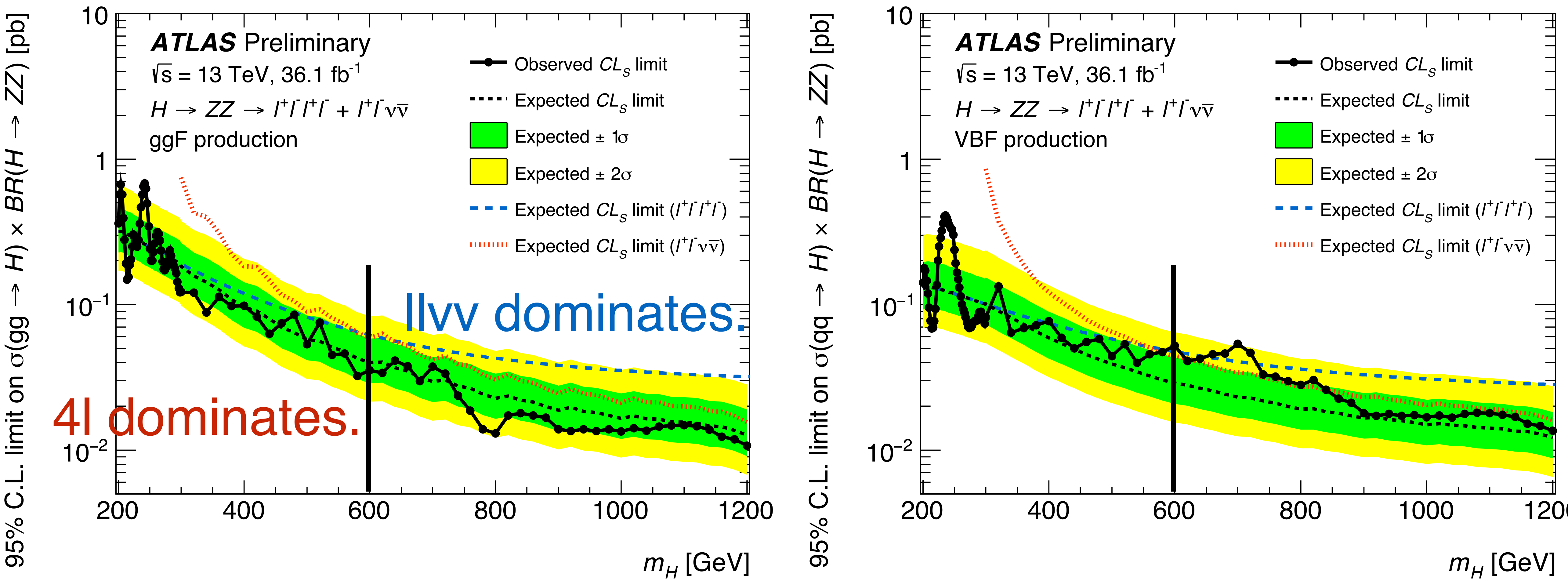

- When setting limits on ggF (VBF), VBF (ggF) is profiled.
- Compared to the limits published in Run 1 EPJC(2016), the expected limit is significantly extended depending on m_H.
- A ~2 (< 1) σ local (global) excess is observed at about 700 GeV.

2HDM interpretation: tanβ vs cos(β-α), m_H = 200 GeV

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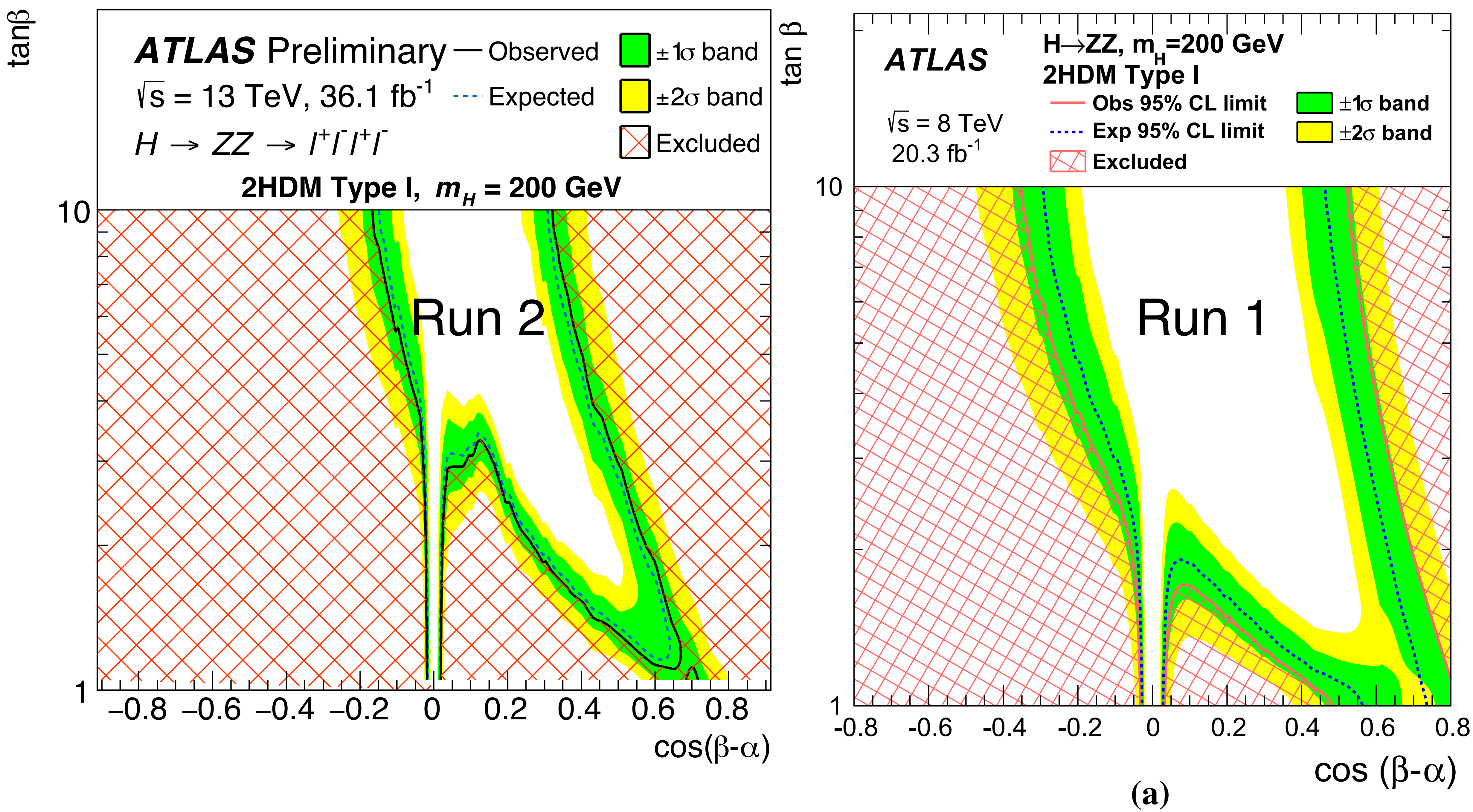
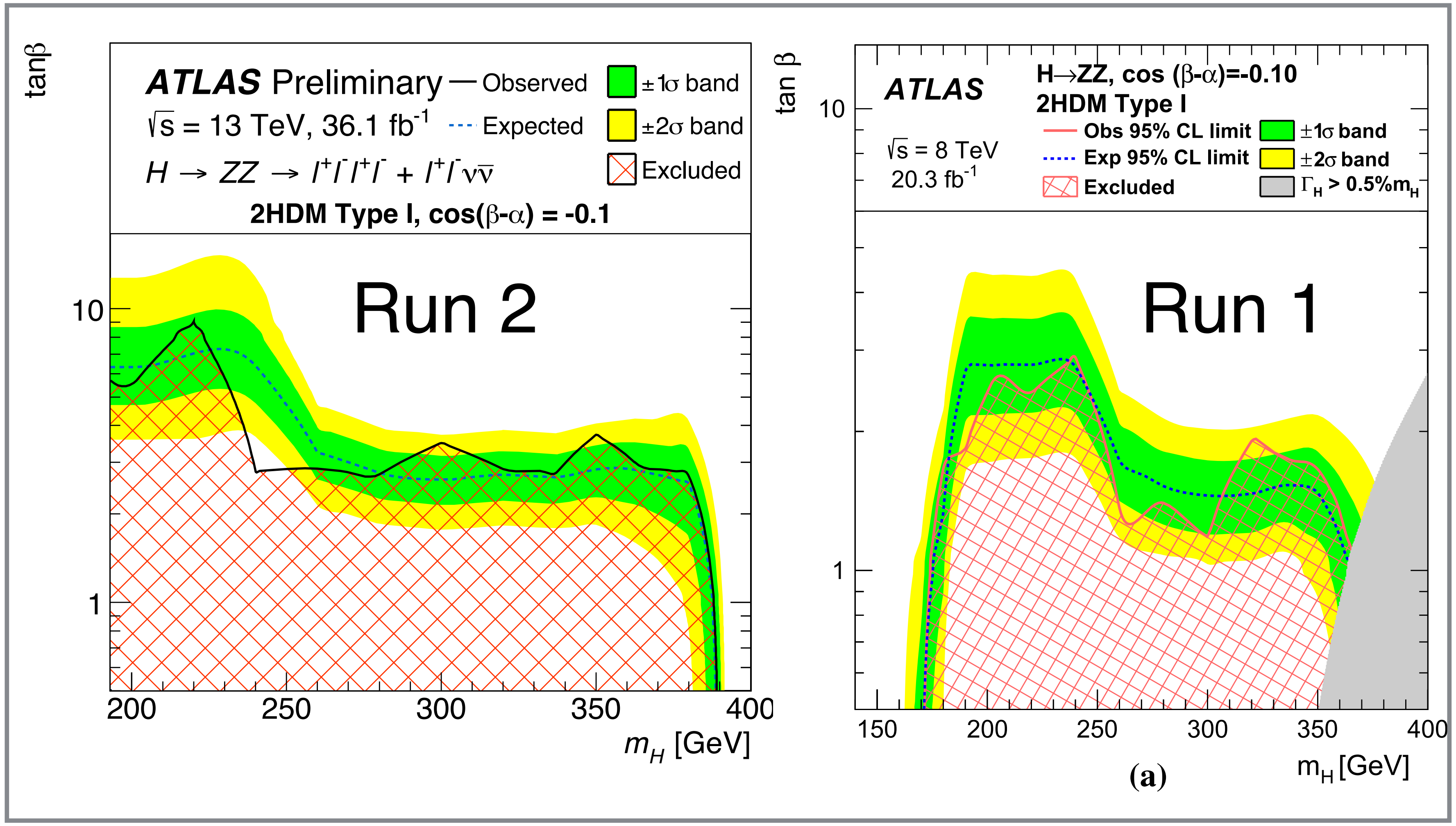
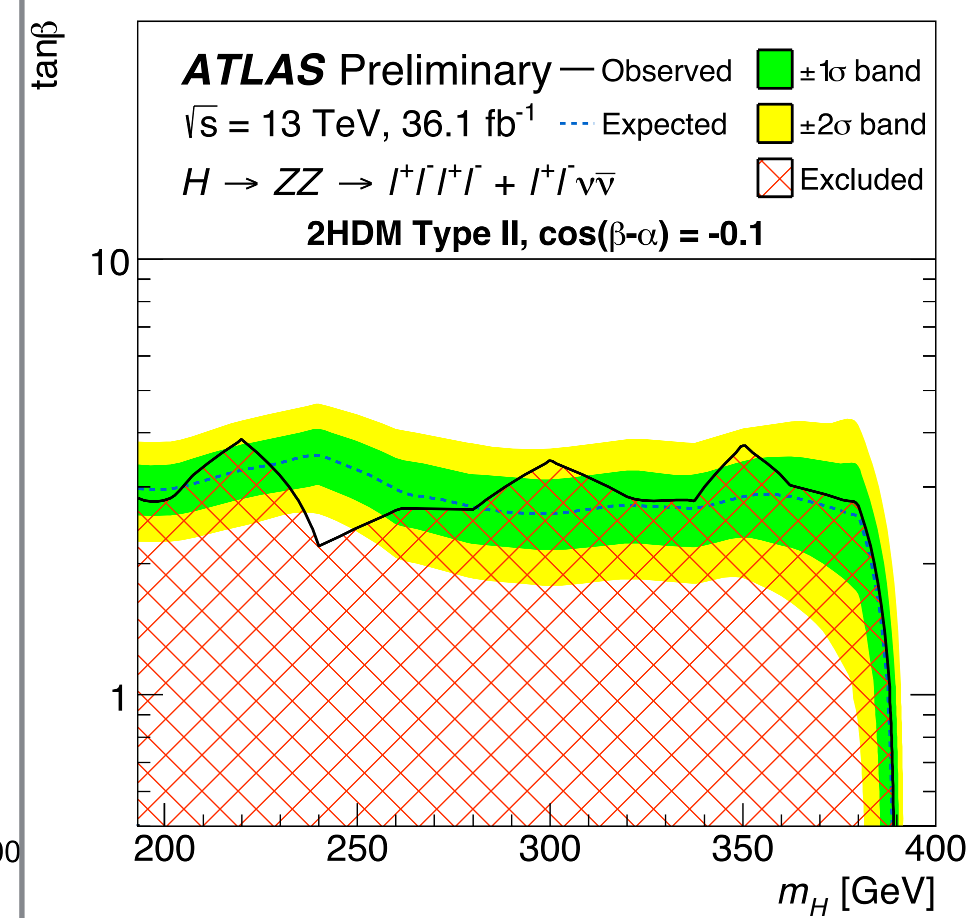
- For a given cos(β-α) and tanβ, the relative rate of σ_{ggF} and σ_{VBF} is difference, therefore the limits are re-evaluated accordingly.



2HDM interpretation: tanβ vs m_{H}, cos(β-α) = -0.1





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- Below 300 GeV only 4l contributes, above 300 GeV both 4l and llvv contribute.
- Exclusion region in 13 TeV is about 2 times better than the one in Run 1.

LWA interpretation

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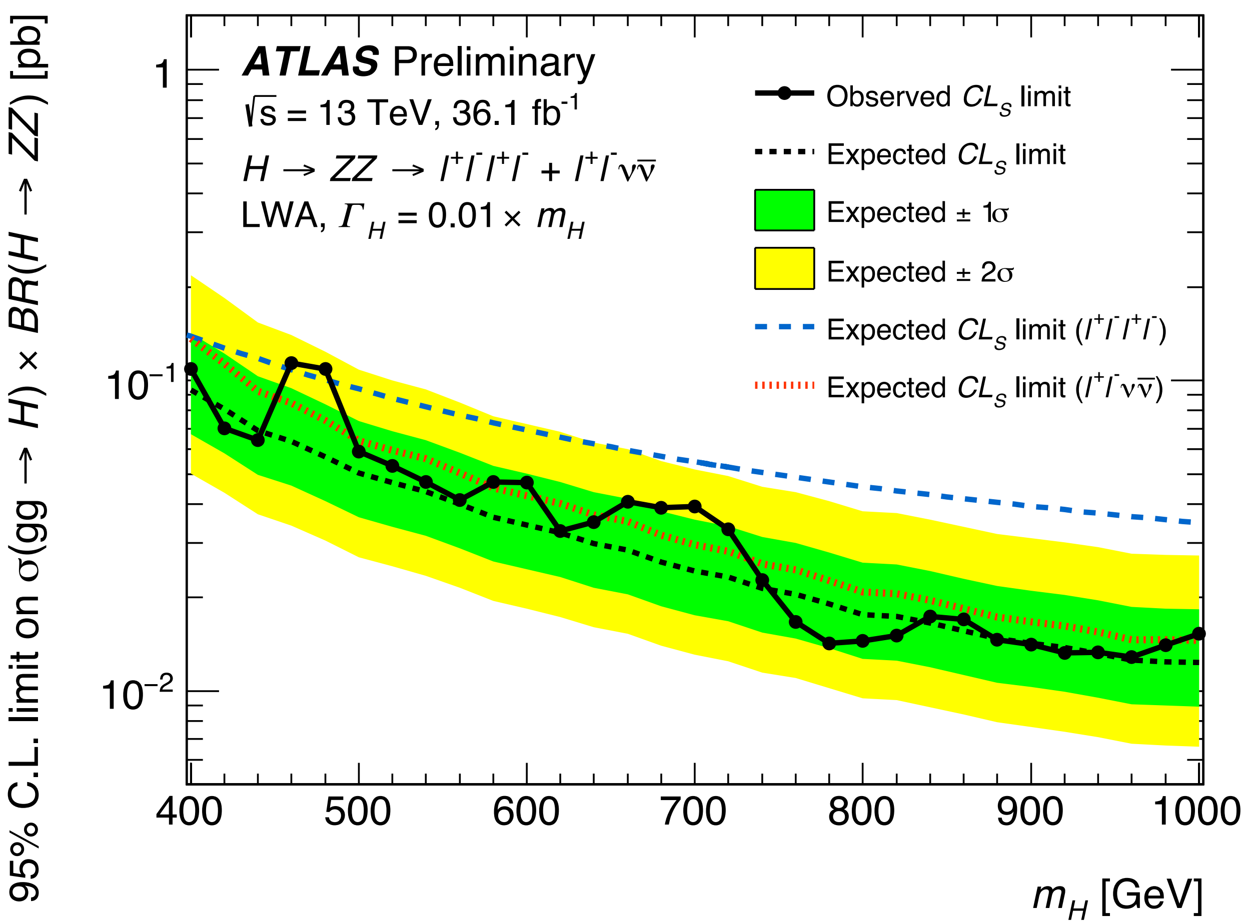
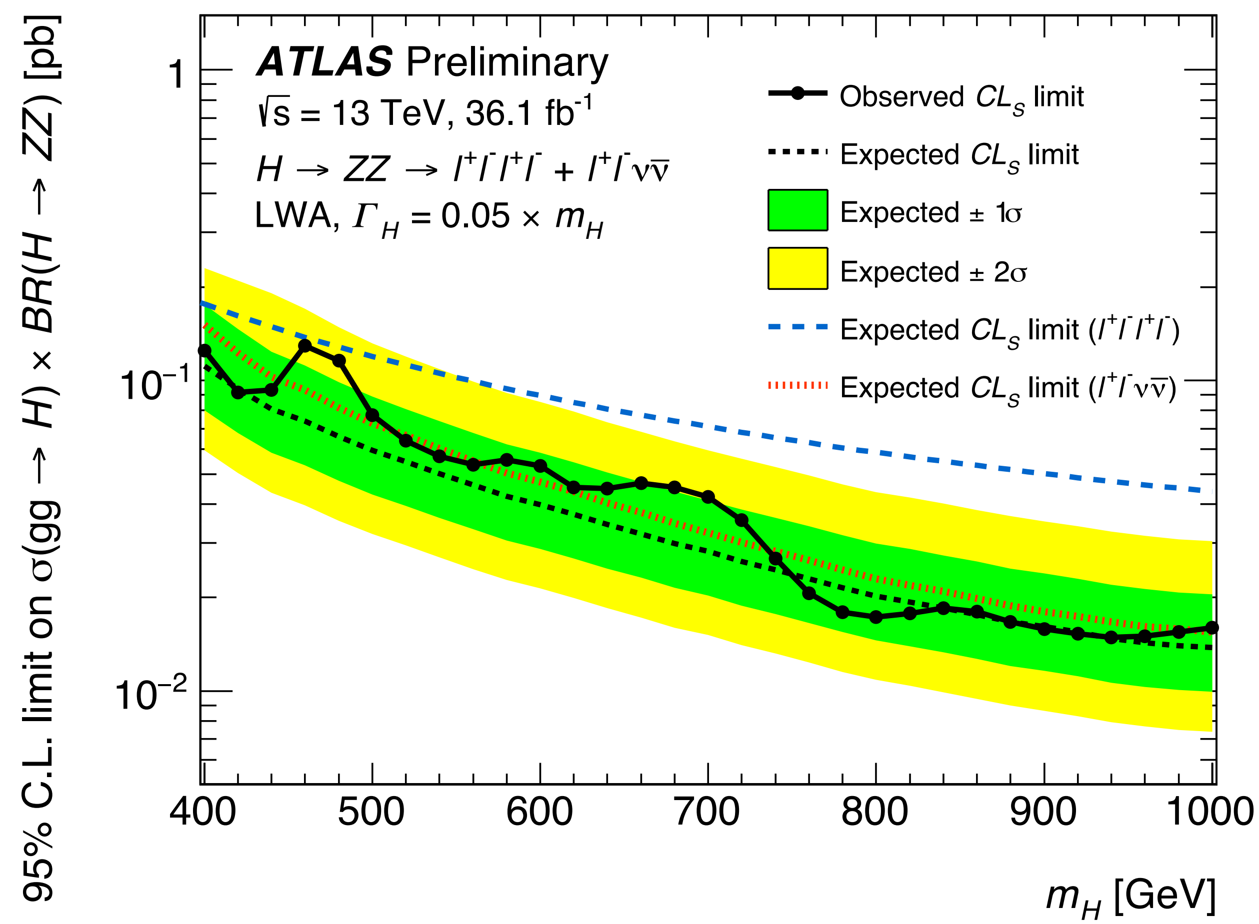




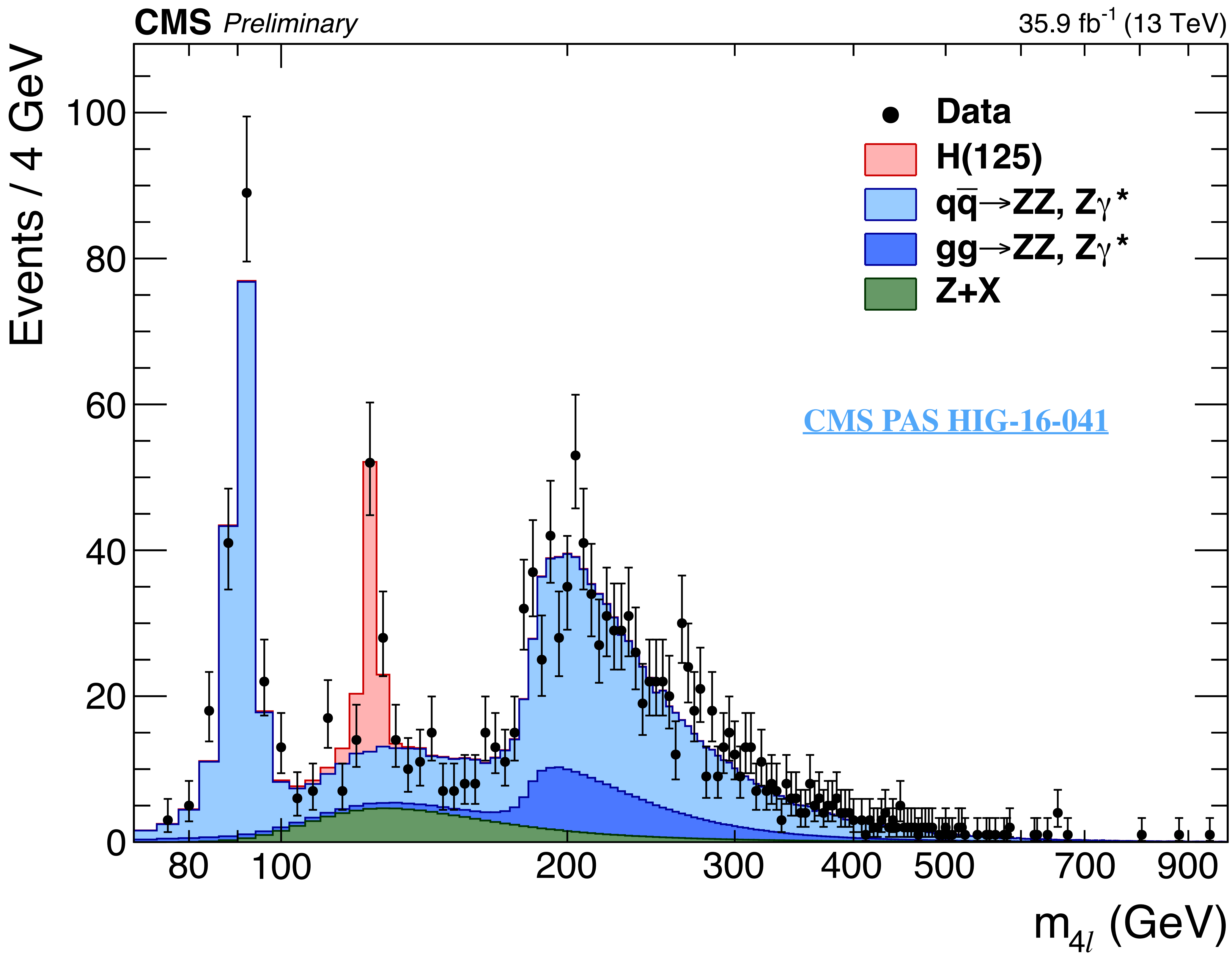
- Consider only the gluon-fusion production.
- Take into account the **interferences,** but limits are on the “signal only” cross section of the ggF production times BR(ZZ).
- Set limits on three benchmark scenarios for the width of 1, 5, 10% of the m_H.

Conclusion

- A search for heavy ZZ resonances in the $\ell\ell vv$ and 4ℓ final states has been presented.
- **The maximum deviation in data is observed at around 700 GeV with a local (global) significance of about 2 (<1) σ.**
- **Current exclusion limits in context of 2HDM are twice stringent than the one published in Run 1.**
- **Other interesting studies** can be found in the conference note [ATLAS-CONF-2017-058]

Additional Materials

CMS



CMS Preliminary
35.9 fb-1 (13 TeV)
Events / 4 GeV
0
20
40
60
80
100
80
100
200
300
400
500
700
900
m4l (GeV)
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
CMS PAS HIG-16-041

Signal modeling for NWA

- **4ℓ**: analytical function (Crystal-Ball + Gaussian) as a function of m_H.
- $\ell\ell vv$, templates obtained from MC simulation and interpolated with moment morphing for any other mass.

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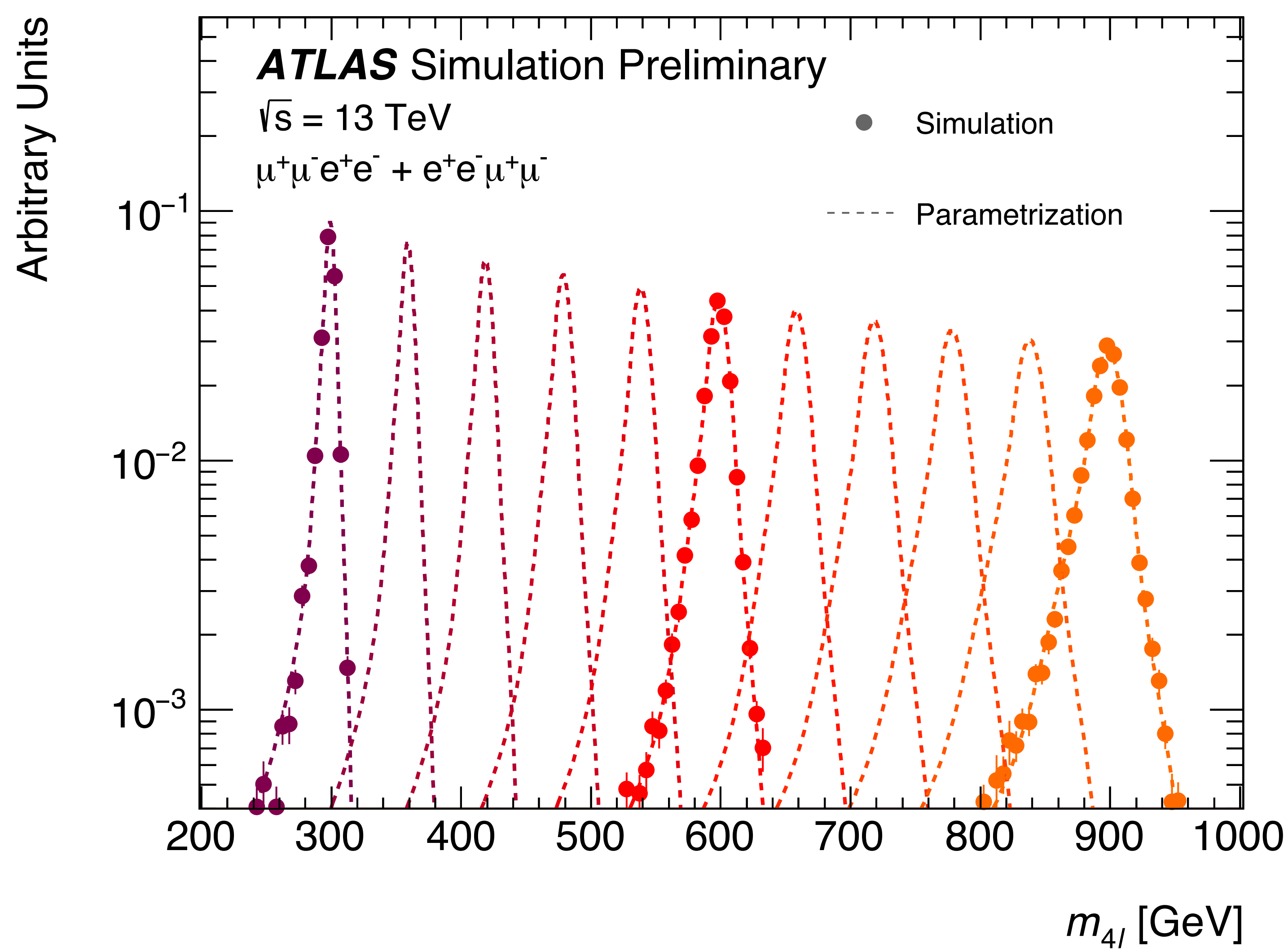

Modeling of signal and interferences.

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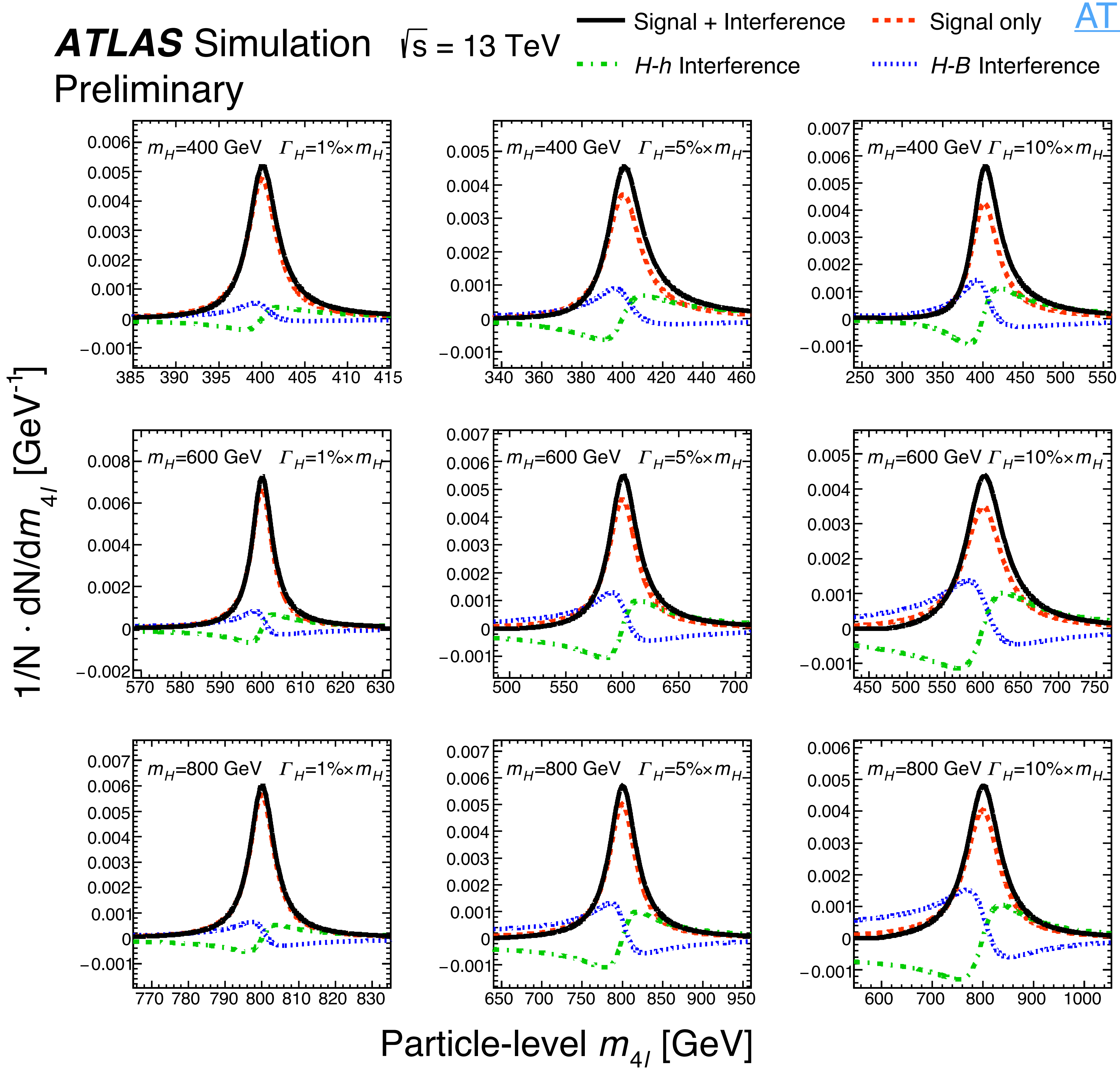

yields

Table 4: $\ell^+\ell^-\ell^+\ell^-$ search: Number of expected and observed events for $m_{4\ell} > 130$ GeV, together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

Process	ggF-enriched categories 4μ channel	$2e2\mu$ channel	$4e$ channel	VBF-enriched category
ZZ	297 ± 1 ± 40	480 ± 1 ± 60	193 ± 1 ± 25	15 ± 0.1 ± 6.0
ZZ (EW)	1.92 ± 0.11 ± 0.19	3.36 ± 0.14 ± 0.33	1.88 ± 0.12 ± 0.20	3.0 ± 0.1 ± 2.2
Z + jets/$t\bar{t}$/WZ	3.7 ± 0.1 ± 0.8	7.8 ± 0.1 ± 1.1	4.4 ± 0.1 ± 0.8	0.37 ± 0.01 ± 0.05
Other backgrounds	5.1 ± 0.1 ± 0.6	8.7 ± 0.1 ± 1.0	4.0 ± 0.1 ± 0.5	0.80 ± 0.02 ± 0.30
Total background	308 ± 1 ± 40	500 ± 1 ± 60	203 ± 1 ± 25	19.5 ± 0.2 ± 8.0
Observed	357	545	256	31

Table 5: $\ell^+\ell^-\nu\bar{\nu}$ search: Number of expected and observed events together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

Process	ggF-enriched categories e^+e^- channel	$\mu^+\mu^-$ channel	VBF-enriched category
ZZ	177 ± 3 ± 21	180 ± 3 ± 21	2.1 ± 0.2 ± 0.7
WZ	93 ± 2 ± 4	99.5 ± 2.3 ± 3.2	1.29 ± 0.04 ± 0.27
$WW/t\bar{t}/Wt/Z \to \tau\tau$	9.2 ± 2.2 ± 1.4	10.7 ± 2.5 ± 0.9	0.39 ± 0.24 ± 0.26
Z + jets	17 ± 1 ± 11	19 ± 1 ± 17	0.8 ± 0.1 ± 0.5
Other backgrounds	1.12 ± 0.04 ± 0.08	1.03 ± 0.04 ± 0.08	0.03 ± 0.01 ± 0.01
Total background	297 ± 4 ± 24	311 ± 5 ± 27	4.6 ± 0.4 ± 0.9
Observed	320	352	9

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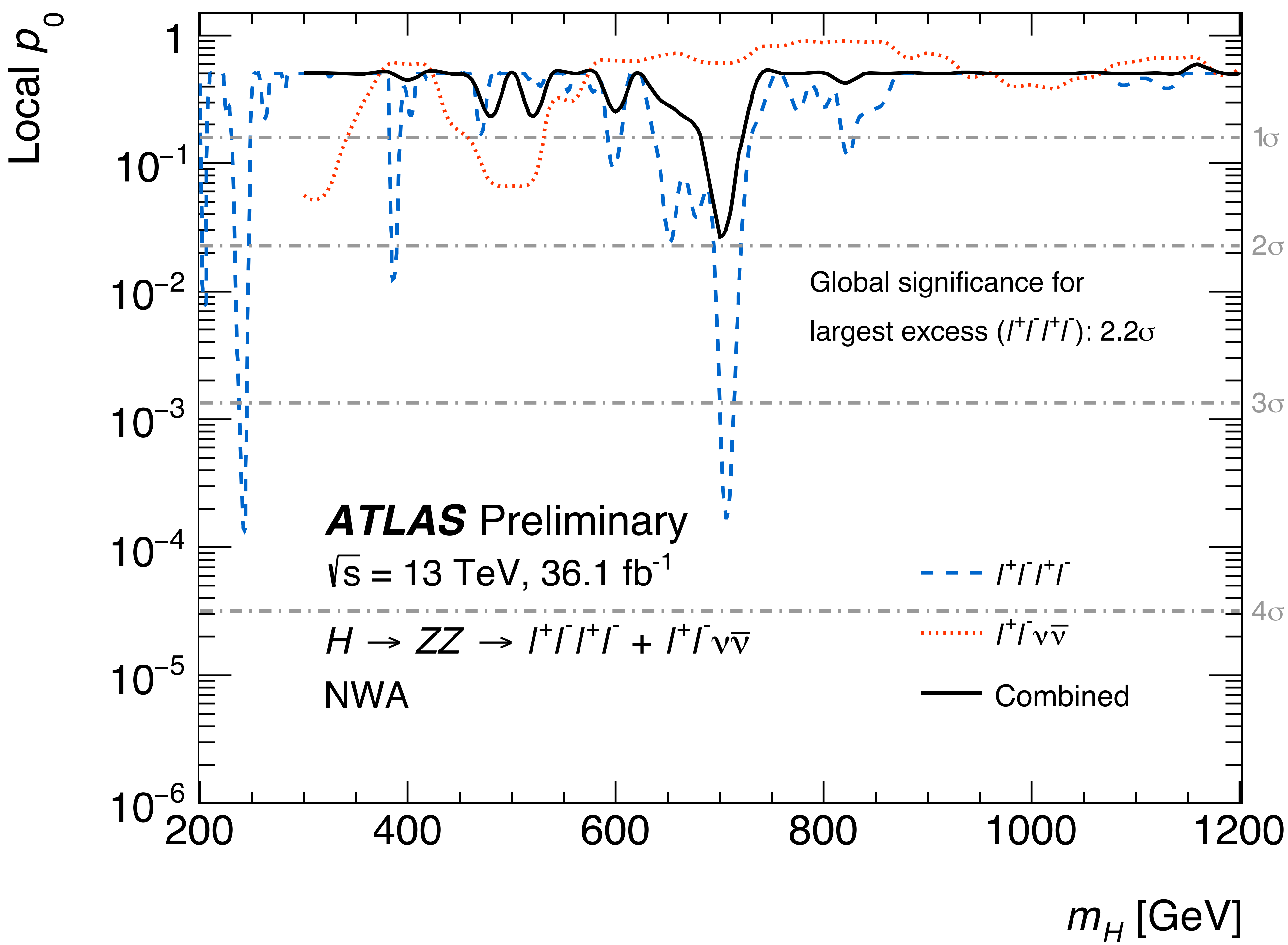

Limits on LWA

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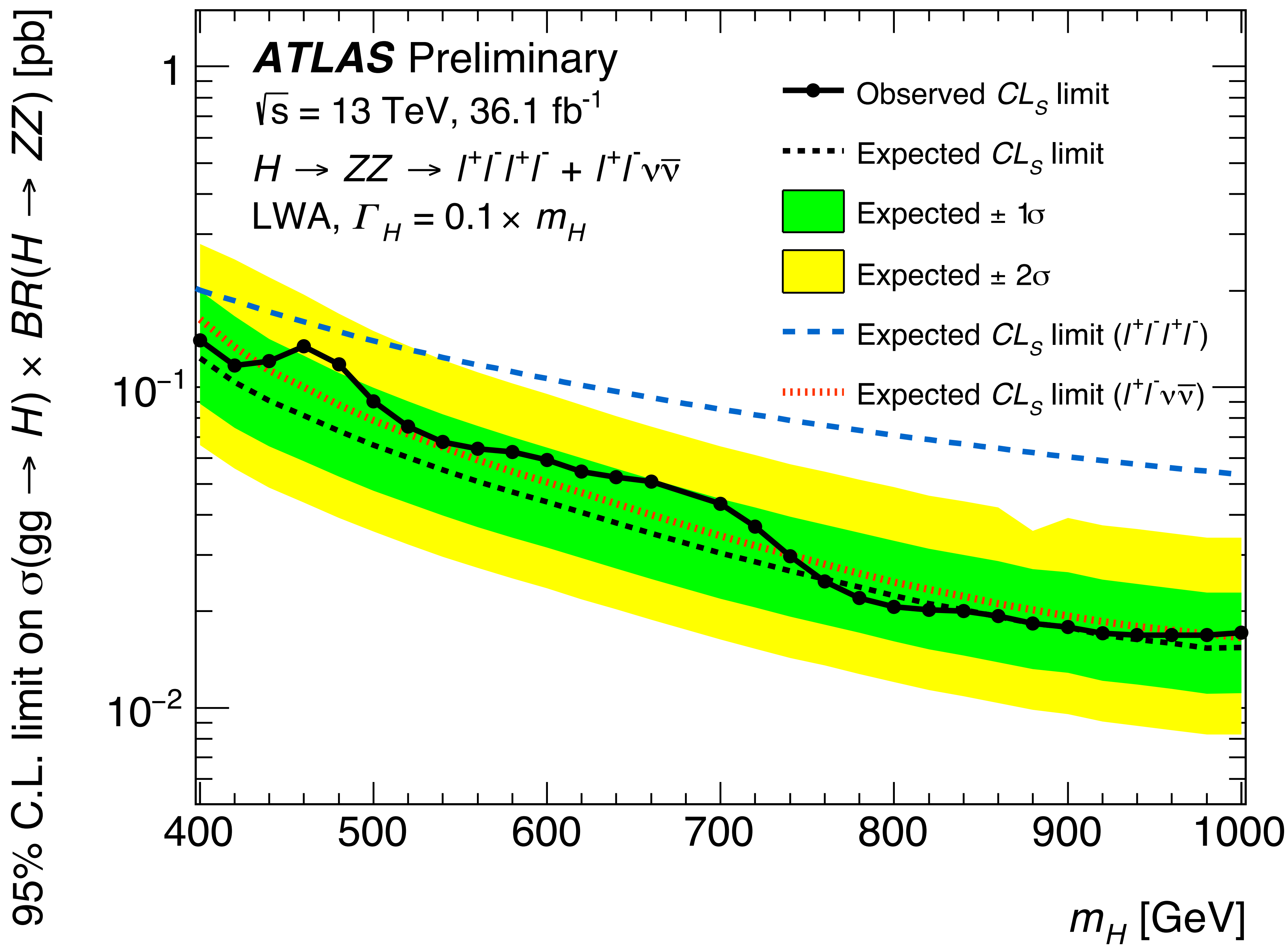


Modeling for Large Width Assumption

The Modeling for signal-only.

4ℓ: use analytical function to describe the truth line-shape, convolved with detector resolution.

$$\sigma_{pp\to H\to ZZ}(m_{4\ell}) = 2 \cdot m_{4\ell} \cdot \mathcal{L}_{gg} \cdot \frac{1}{|s - s_H|^2} \cdot \Gamma_{H\to gg}(m_{4\ell}^2) \cdot \Gamma_{H\to ZZ}(m_{4\ell}^2)$$

The difference in the line-shape at another mass and width comes from the **propagator**. $1/|s - s_H|^2$

$\ell\ell vv$: Reweight full-simulated signal samples to obtain mT distribution in reco. for any mass and width.

Modeling for Large Width Assumption

The Modeling for interference of (h-H), described by.

$$\sigma_{pp}(m_{4\ell}) = 4 \cdot m_{4\ell} \cdot \mathcal{L}_{gg} \cdot Re\left[\frac{1}{s - s_H} \cdot \frac{1}{(s - s_h)^*}\right] \cdot \Gamma_{H\to gg}(m_{4\ell}) \cdot \Gamma_{H\to ZZ}(m_{4\ell})$$

obtained from signal only samples by applying the following weight:

$$w(m_{4\ell}) = \frac{2 \cdot Re\left[\frac{1}{s-s_H} \cdot \frac{1}{(s-s_h)^*}\right]}{\frac{1}{|s-s_H|^2}}$$

at truth-level for 4ℓ and at reco-level for $\ell\ell vv$. For 4ℓ, it then convolves with detector resolution.

Modeling for Large Width Assumption

The Modeling for interference of (H-B), similar in 4ℓ and $\ell\ell vv$.

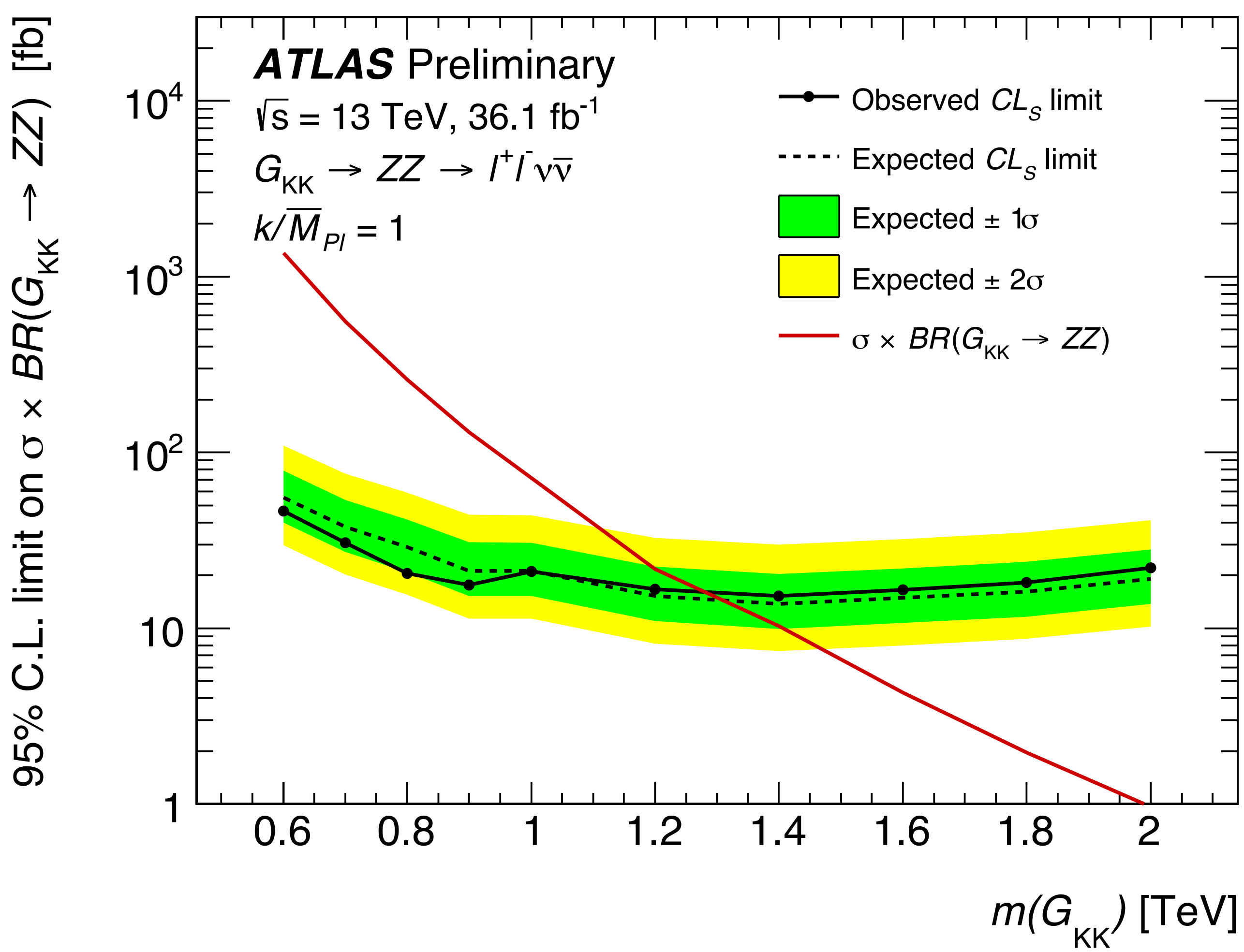
- Generated truth samples for SBI using gg2VV for $\ell\ell vv$ and MCFM for 4ℓ. From that subtract the S and B to get the interference.
- Fit the interference with following formula in m_{ZZ} with to obtain its line-shape in truth:

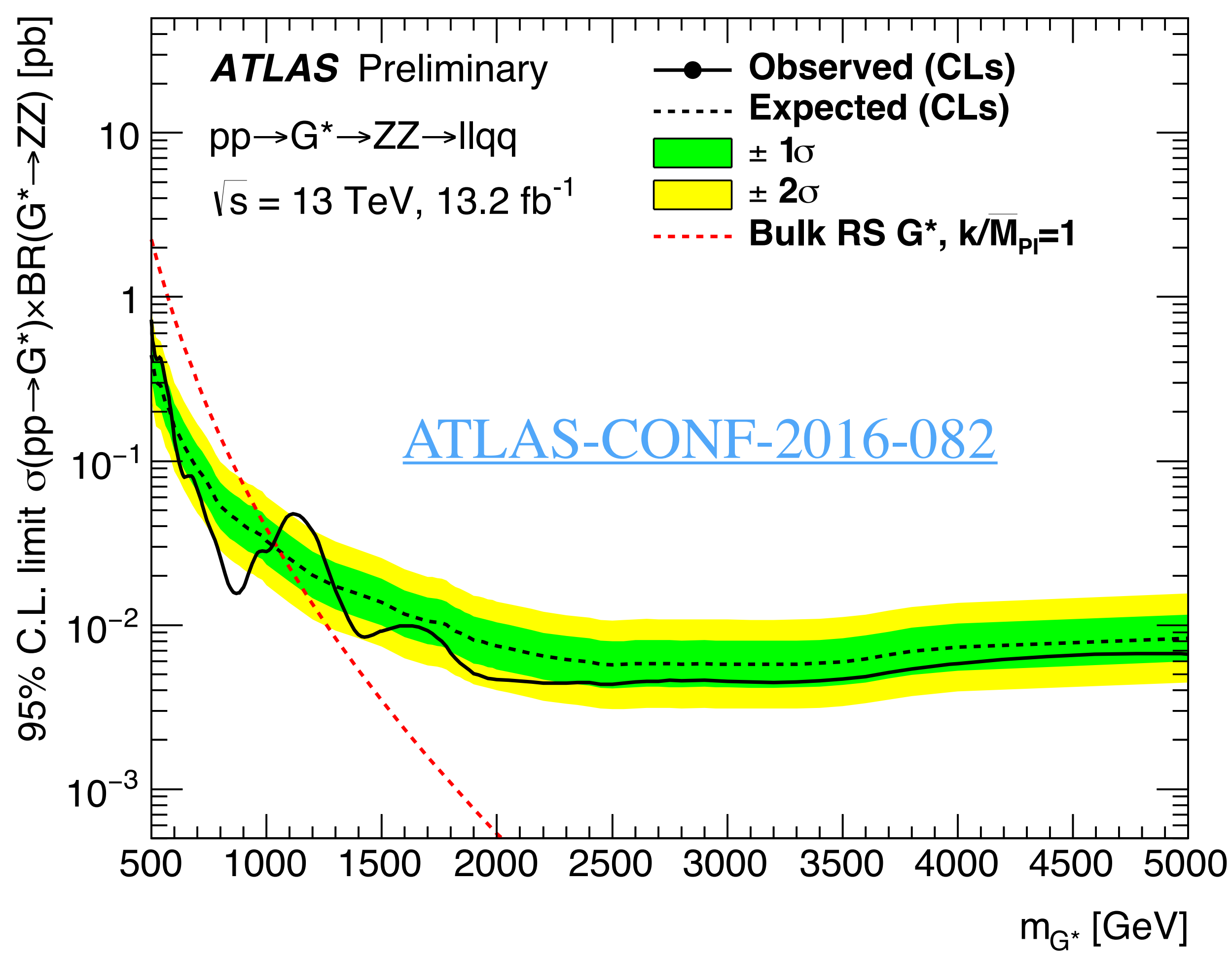
$$\boxed{\sigma_{pp}(m_{4\ell}) = \mathcal{L}_{gg} \cdot \frac{1}{m_{4\ell}} \cdot Re\left[\frac{1}{s - s_H} \cdot ((a_0 + a_1 \cdot m_{4\ell} + ...) + i \cdot (b_0 + b_1 \cdot m_{4\ell} + ...))\right]}$$

For 4ℓ, it convolves with detector resolution;

For $\ell\ell vv$, a 'c-factor' is applied to obtain the shape at reco. level.

Limits on Graviton





- llvv excludes the region of mG* < ~1.3 TeV.
- llqq+vvqq excludes the region of mG* < ~1.3 TeV.