Search for high-mass Higgs bosons using the ATLAS detector

38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

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CHICAGO

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for the ATLAS Collaboration

Overview

This talk:

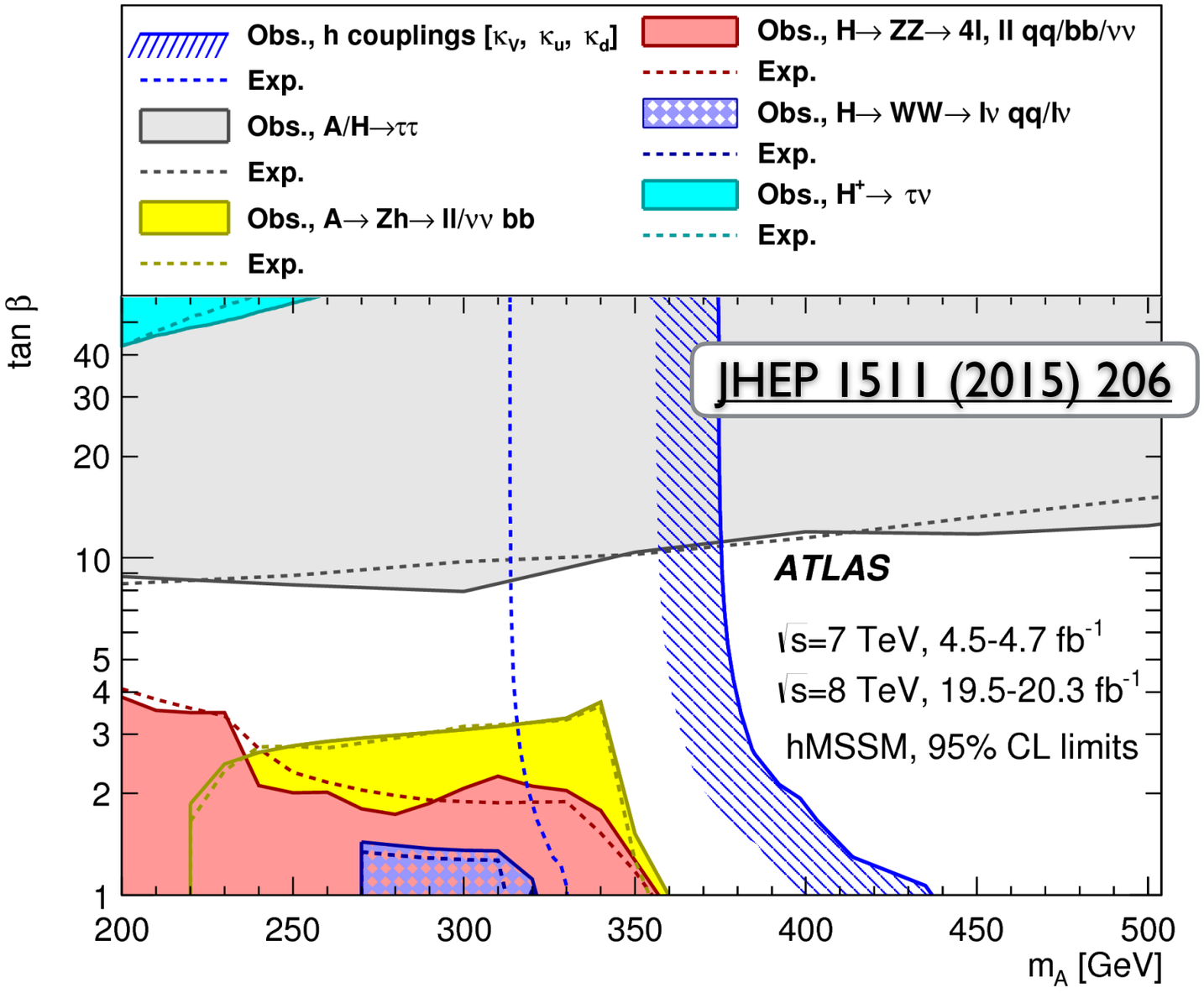
- High-mass H → VV searches in ATLAS
  - All new with LHC data from 2015-2016!

Other ATLAS talks on high-mass Higgs-boson searches:

- High-mass di-photon resonance searches:
  - ➡ Bruno Lenzi ("Joint Beyond the Standard Model & Higgs", Friday at 9:00am)
- High-mass Zγ resonance search:
  - ➡ Giovanni Marchiori ("Higgs Physics: 6", Friday at 5:50pm)
- High-mass Higgs decaying into fermions:
  - ➡ Trevor Vickey ("Higgs Physics: 6", Friday at 6:10pm)
- Charged Higgs-boson searches:
  - ➡ Carl Gwilliam ("Higgs Physics: 7", Saturday at 9:15am)

Introduction

- The 125 GeV Higgs is consistent with SM predictions
- But: could be one of multiple BSM Higgs bosons
- Many possible BSM scenarios that extend the Higgs sector, e.g.,
  - Additional Higgs-doublet, i.e., 2HDM
    - predicts 5 physical Higgs bosons: h, H, A, H^+, H^-

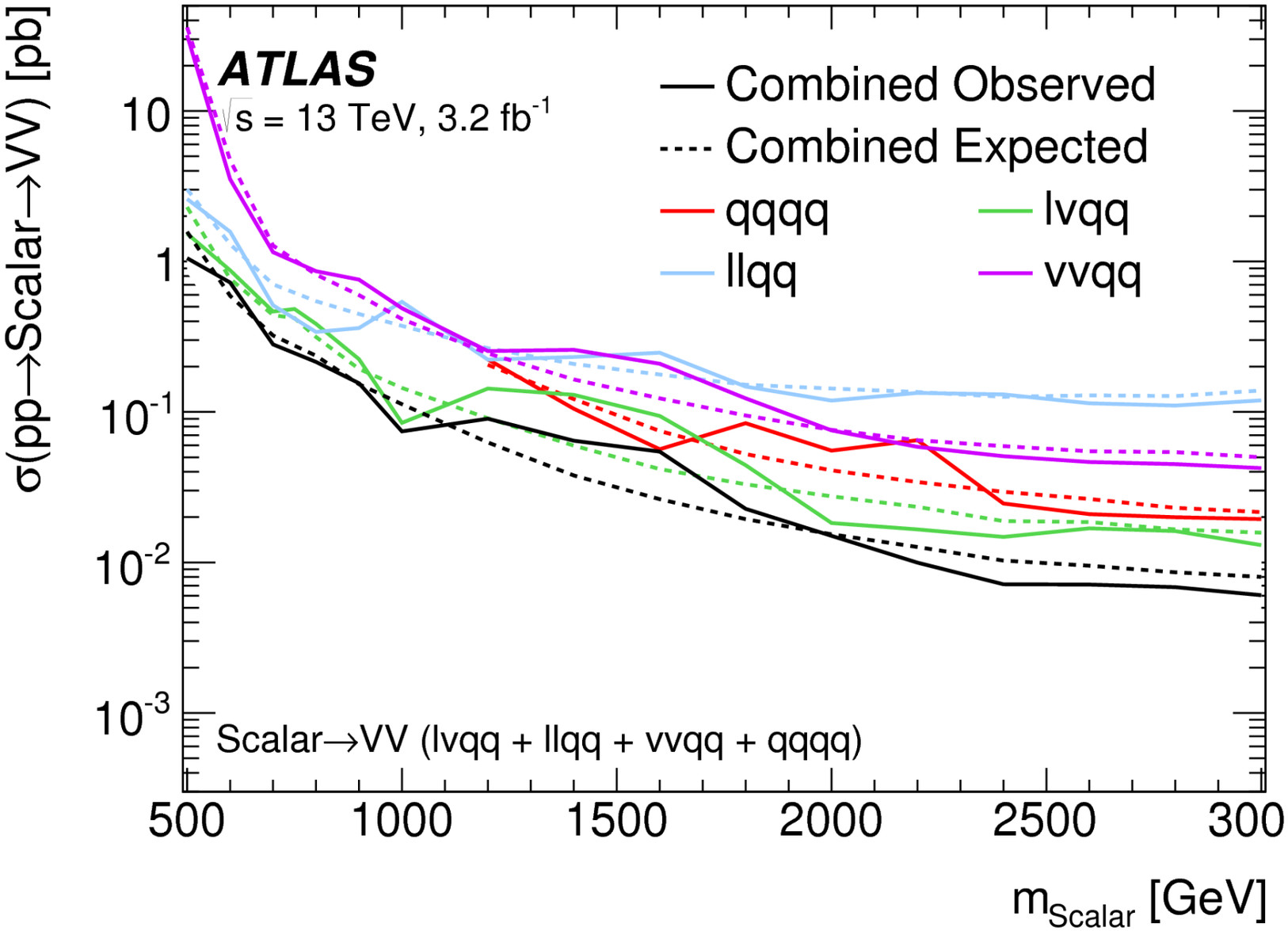


ATLAS Limits with 2015 Data

arXiv:1606.04833

Combined results with 3.2 fb^{-1} of $\sqrt{s} = 13$ TeV data:

- $H \rightarrow VV$ search in hadronic and semi-leptonic final state
- 500 — 3000 GeV



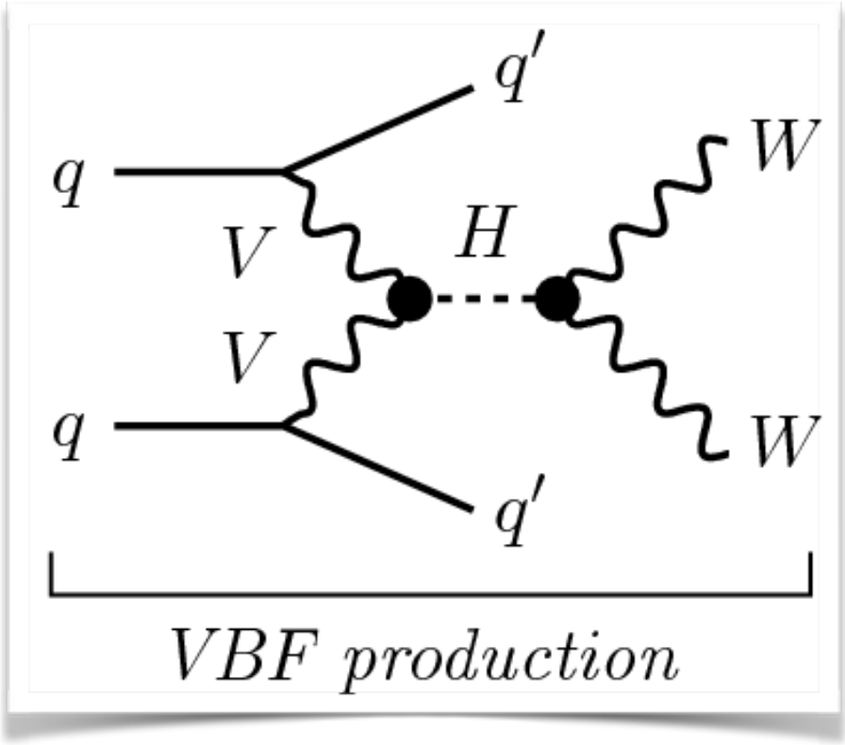
$H \rightarrow WW \rightarrow l\nu l\nu$

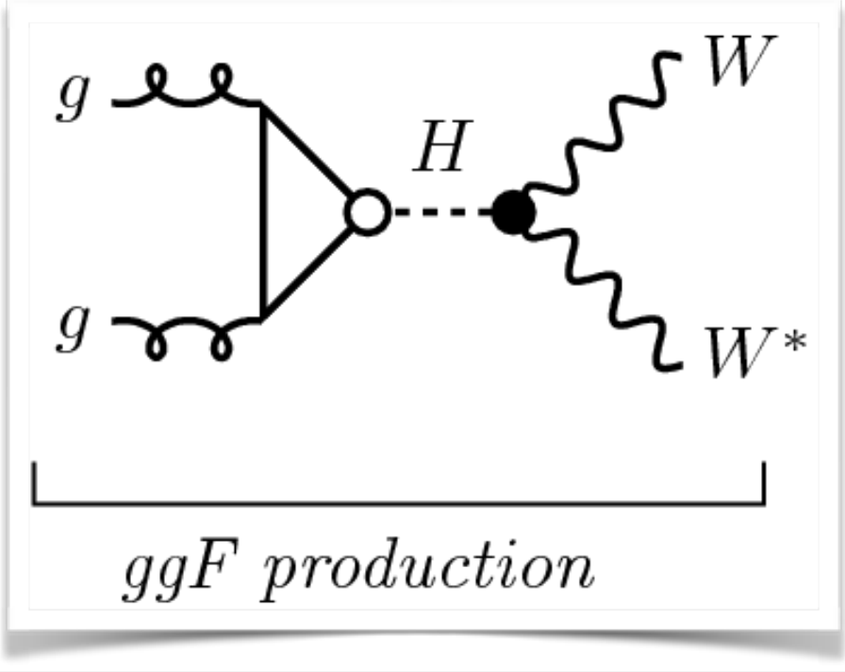
ATL-CONF-2016-074

$H \rightarrow WW \rightarrow l\nu l\nu$

Analysis strategy:

- Fully-leptonic, different-flavor
  $H \rightarrow WW \rightarrow l\boldsymbol{\nu}l\boldsymbol{\nu}$ (l = e,**μ**)
- Vector-boson fusion
  - ≥2 jets with $m_{jj} > 500$ GeV and $|\boldsymbol{\Delta}y_{jj}| > 4$
  - 1 jet with $|\boldsymbol{\eta}_j| > 2.4$ and $\min(|\boldsymbol{\Delta\eta}_{jl}|) > 1.75$
- Gluon-fusion:
  - Everything that remains
- Likelihood fit with Top and WW data control regions

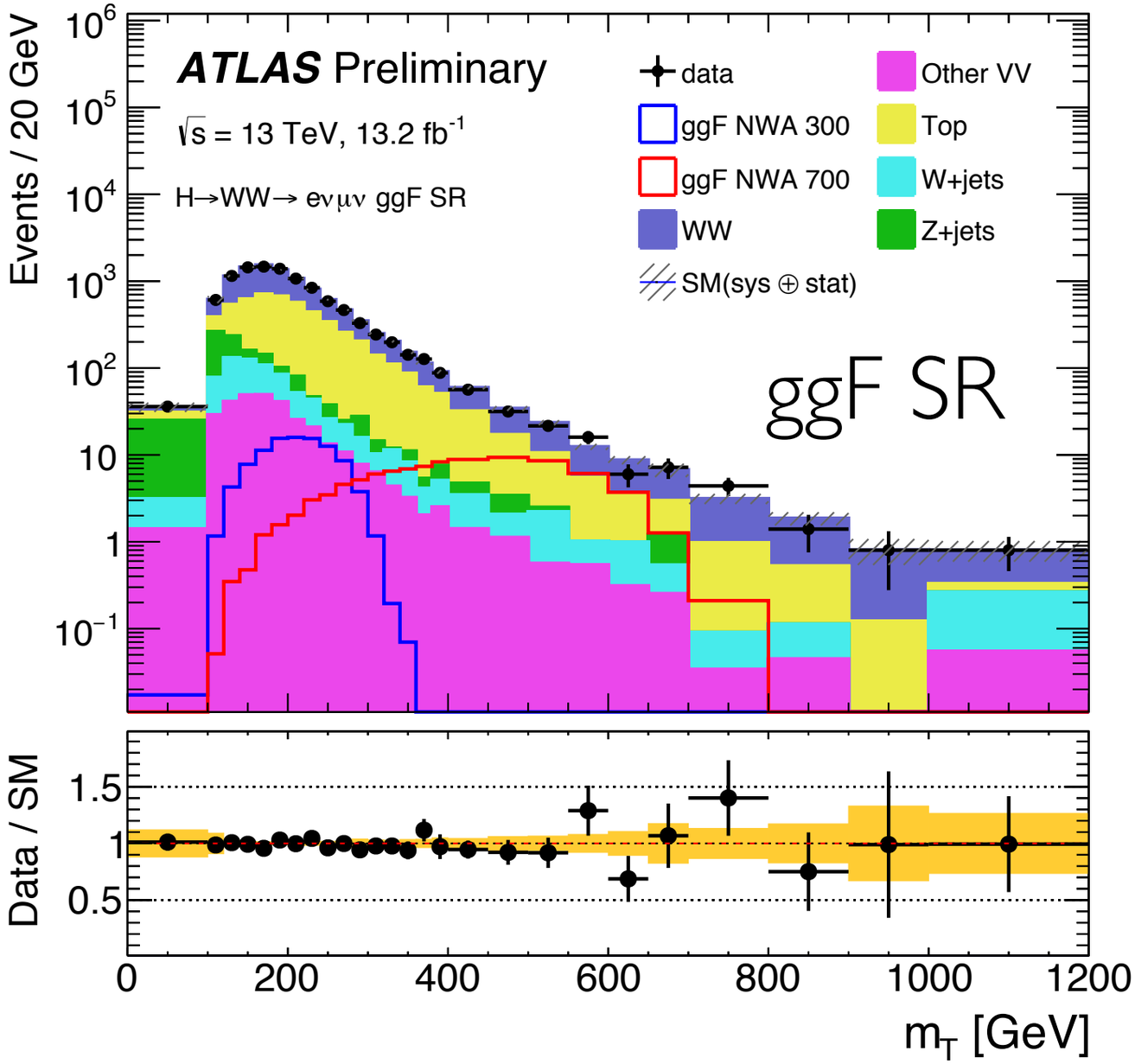


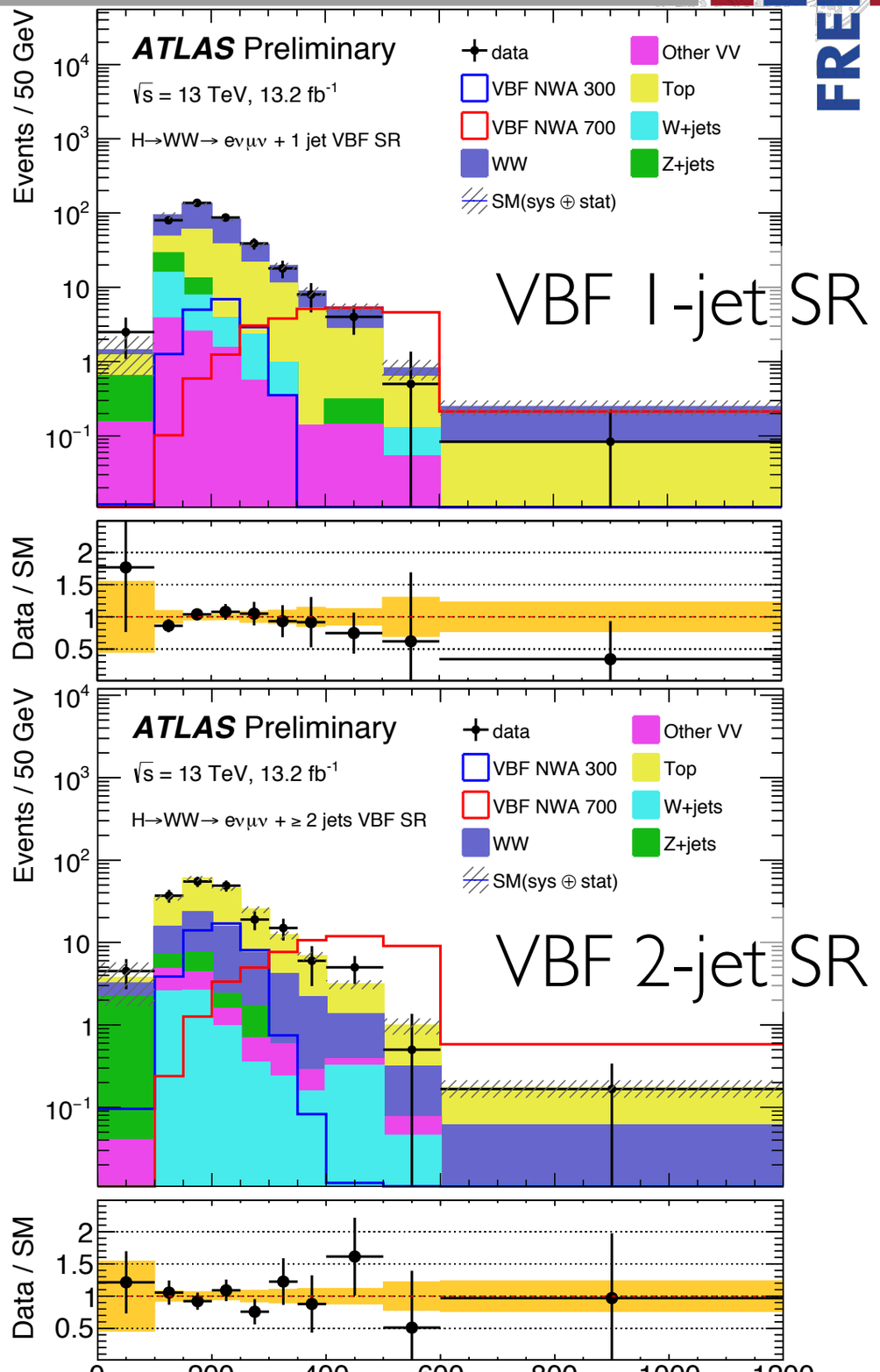


H → WW → lvlv

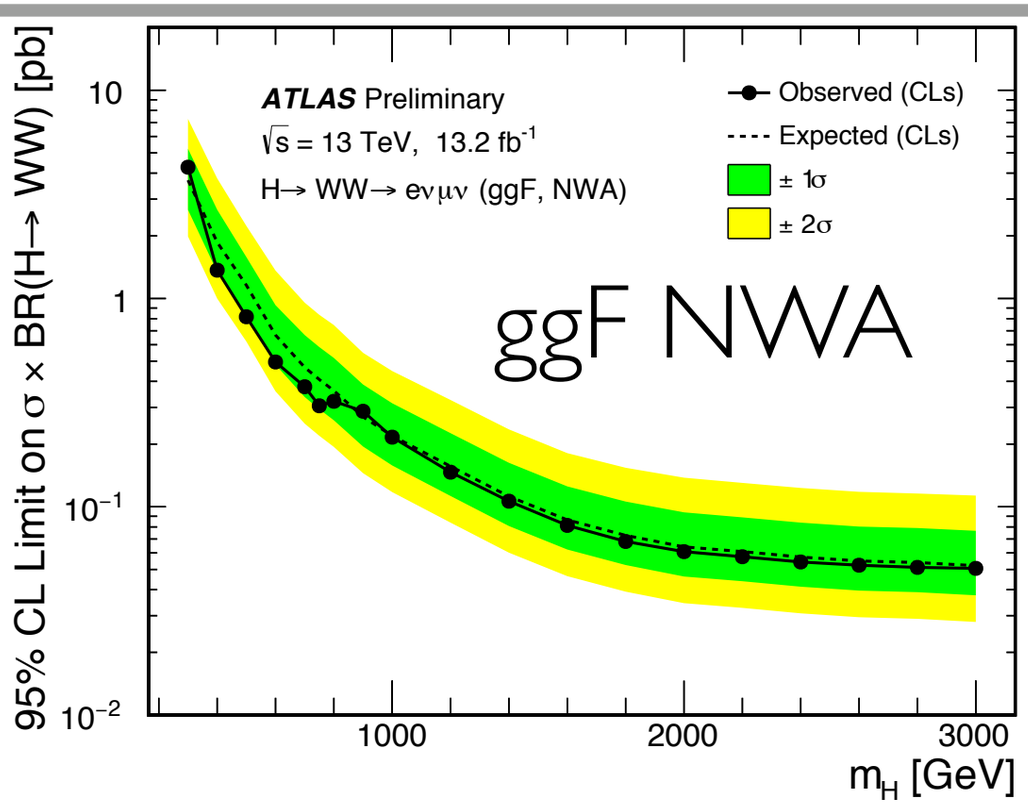
Signal regions:

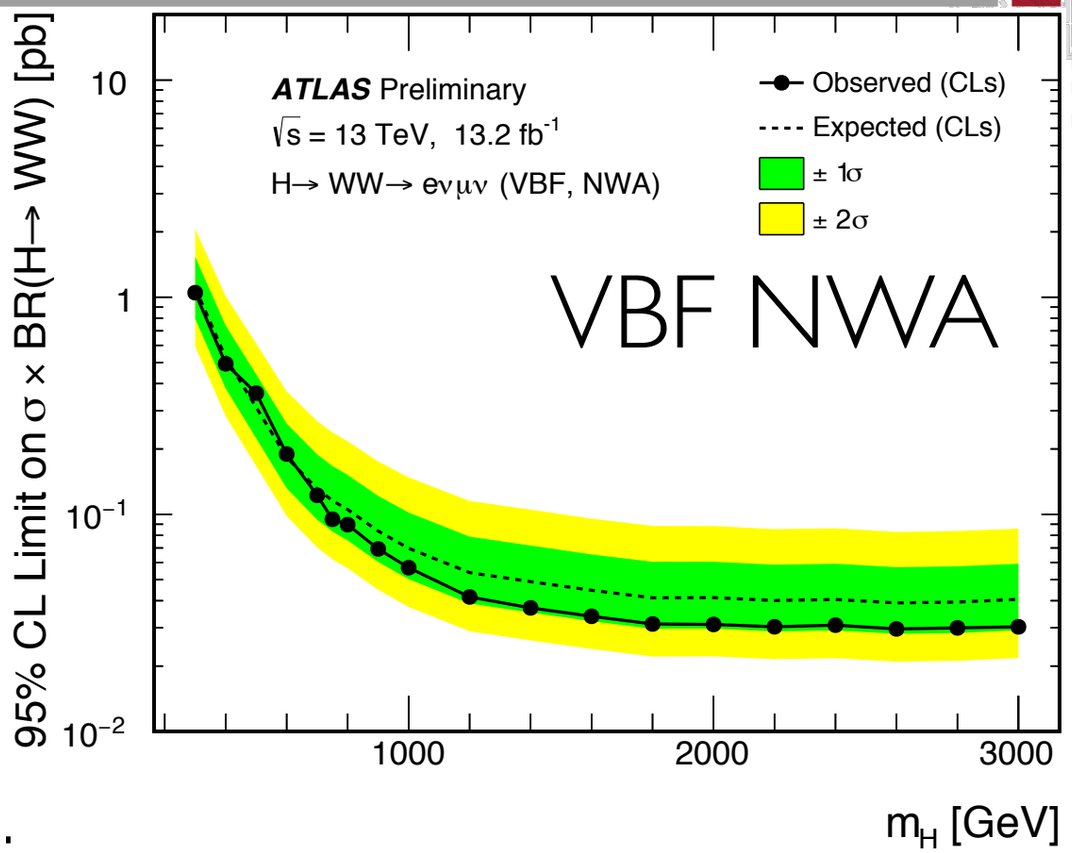
- No significant excess observed

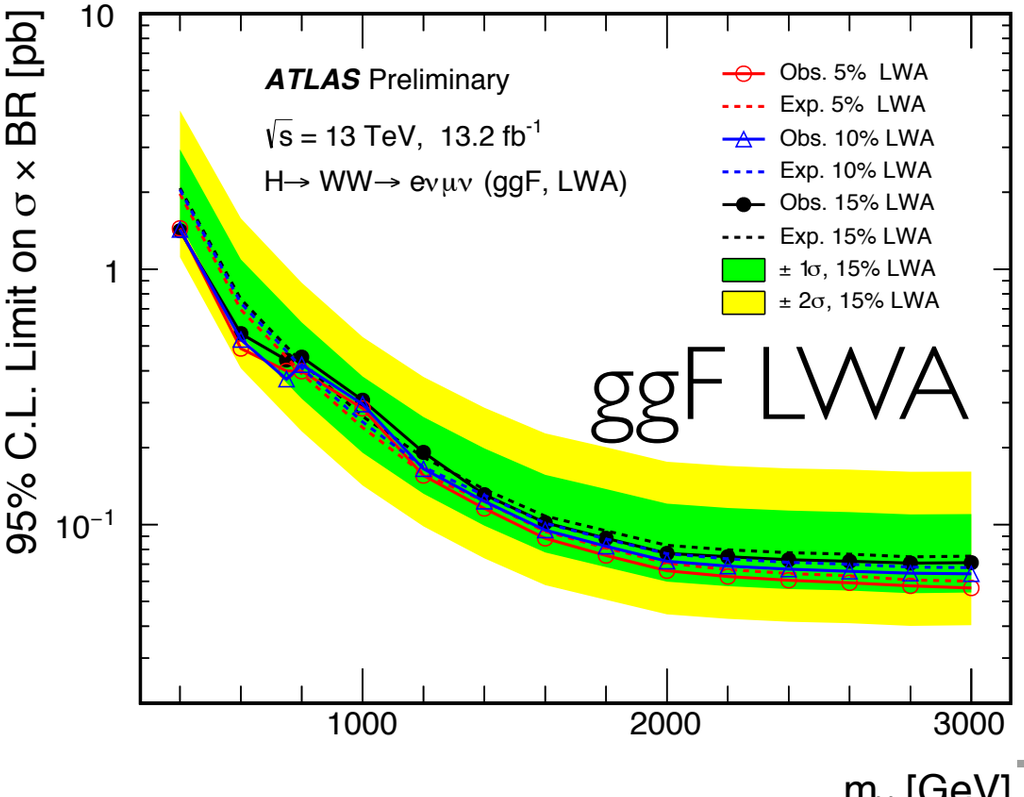




H → WW → lνlν







Results:

- Narrow-width-approximation
  - ggF and VBF
  - 300 — 3000 GeV
- Large-width-approximation
  - ggF with 5%, 10%, and 15% widths
  - 400 — 3000 GeV
- At low-mass: better than previous *combined* limit

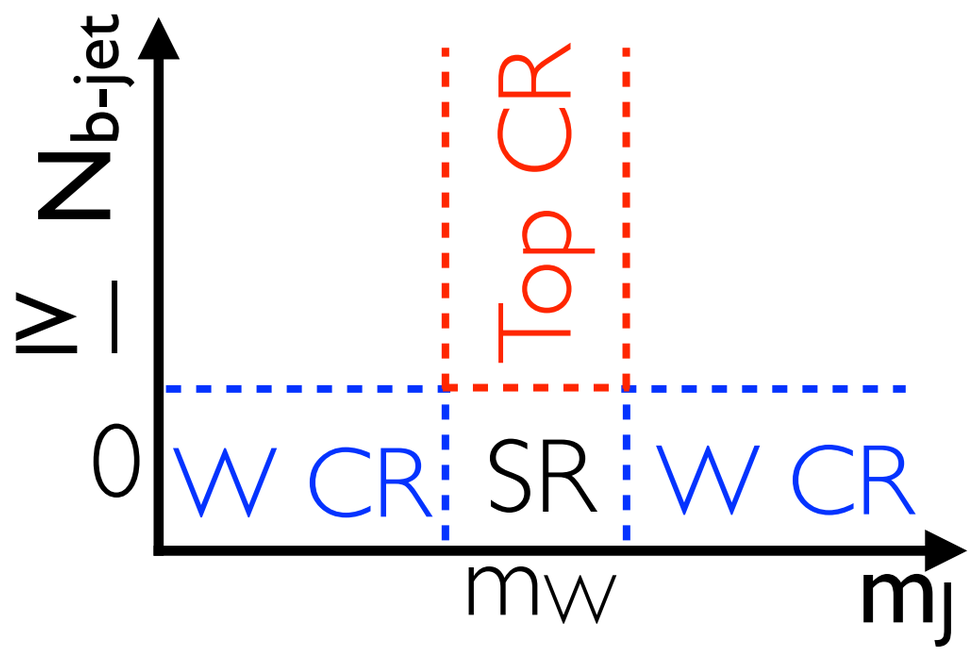
$H \rightarrow WW \rightarrow lvqq$

ATL-CONF-2016-062

H → WW → lνqq

Analysis strategy:

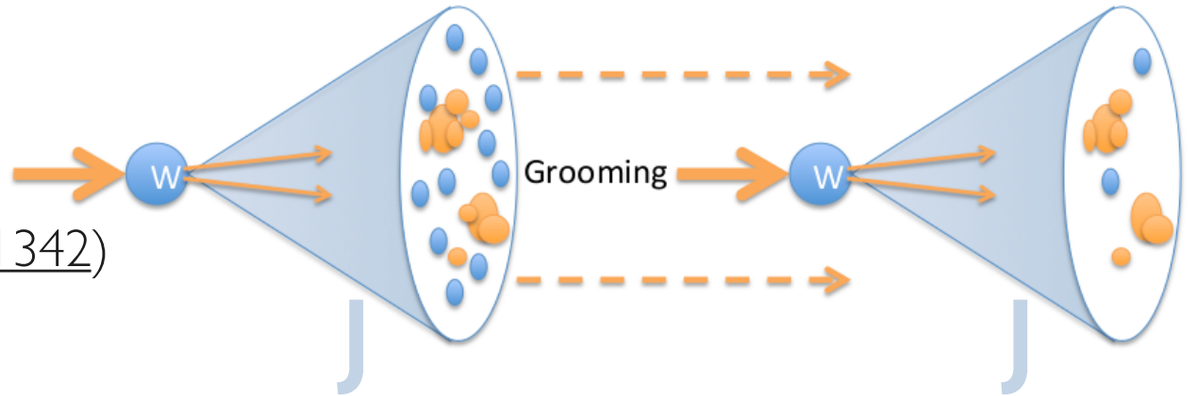
- e or **μ** + missing-E_T
- Highly-boosted W → qq system:
  - reconstruct as one large-R jet "J"
- Likelihood fit with dedicated control regions for normalizations of main backgrounds from data:
  - W+jets
  - Top



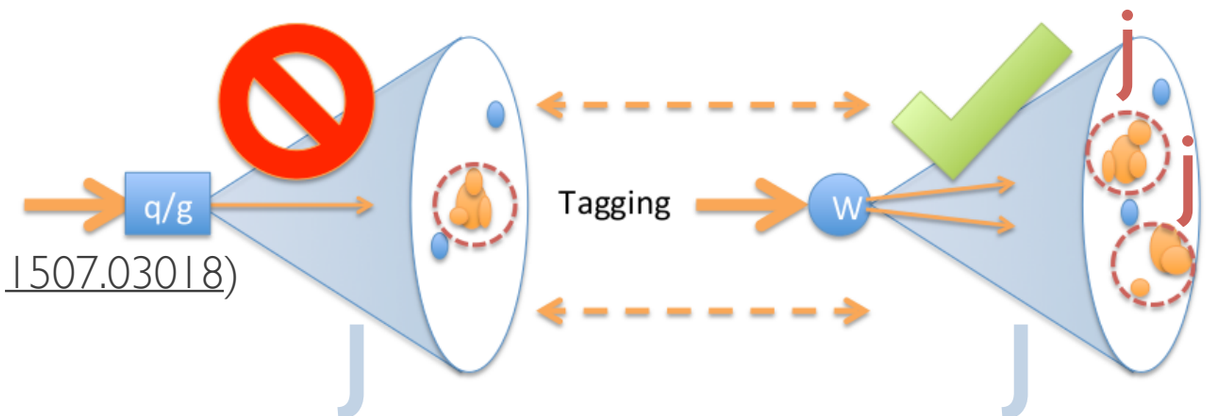
Interlude: large-R Jets

Highly-boosted W → qq system:

- **Reconstruct** as one "merged" large-R jet "J"
  - Anti-k_t with R=1.0
- **Grooming**:
  - Minimize impact of low-energy deposits from additional p-p collisions (pileup)
  - For analyses presented here: "Trimming" (arXiv:0912.1342)
    - re-cluster with k_t R=0.2
    - remove sub-jets with p_T(sub-jet)/p_T(jet) < 5%



- **Vector-boson tagging:**
  - m_J within ±15 GeV of m_V
  - Sub-structure consistent with two-prong decay
    - Use jet sub-structure variable $D_{2,\beta=1}$ (arXiv: 1409.6298, 1507.03018)
  - Typical working-point: **ε**=50%, QCD rejection ~50



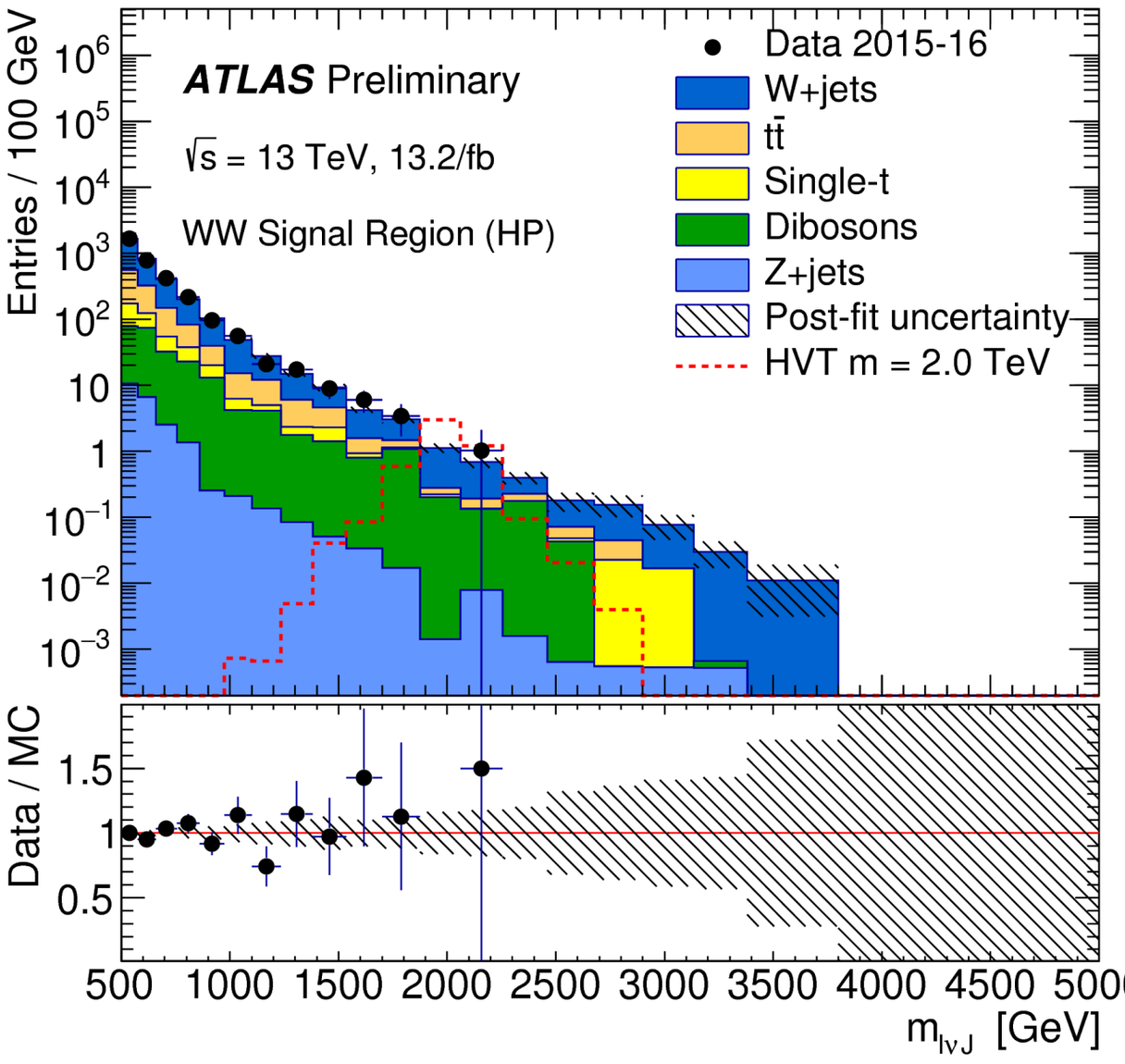
For H → WW → lνqq analysis:

- Define two categories:
  - High-purity: pass $D_{2,\beta=1}$ selection
  - Low-purity: fail $D_{2,\beta=1}$ selection (+10-30% of signal efficiency)

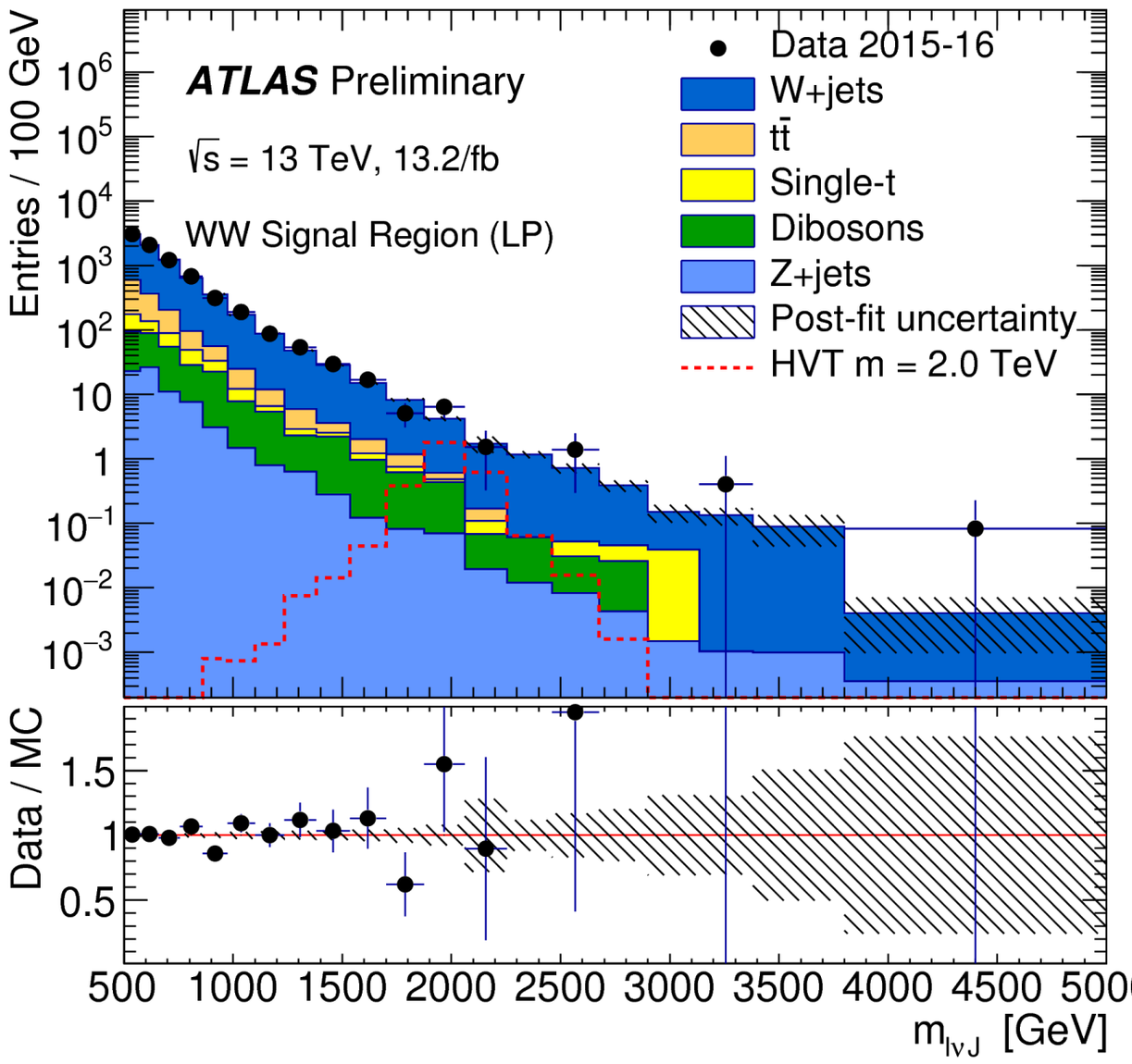
Graphics courtesy of Alex Martyniuk

H → WW → lvqq

Signal regions:



High purity

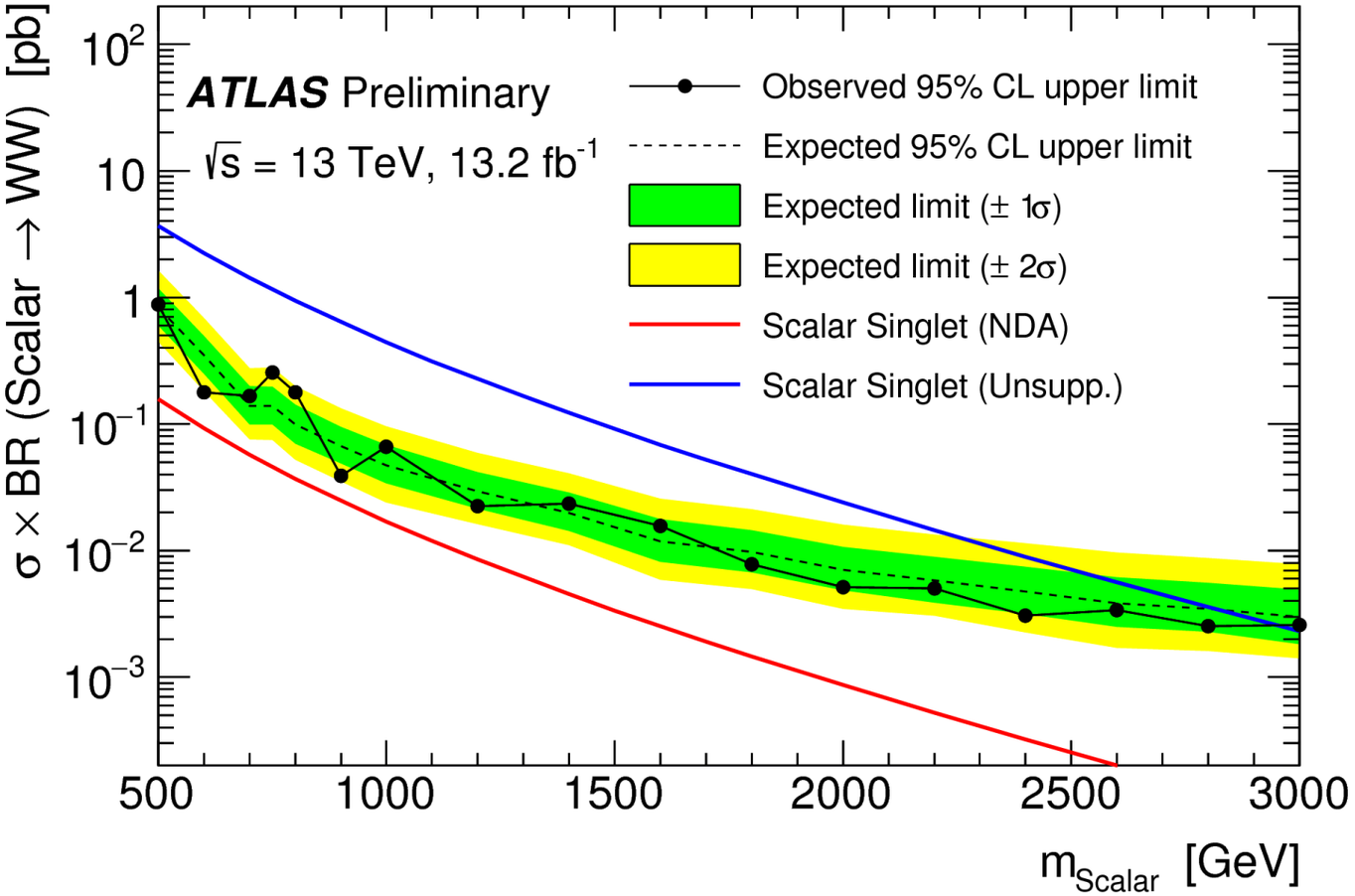


Low purity

H → WW → lvqq

Results:

- 3-4 times better limits w.r.t. Moriond 2016
- CP-even scalar singlet model interpretation (JHEP 1603 (2016) 144)
  - Unsuppressed coupling to gluons
    BR(Scalar → WW) = 59% (m_S = 500 GeV), 70% (m_S = 2 TeV)
  - Naive dimensional analysis: smaller gg → Scalar coupling, but BR(Scalar → WW) > 99%



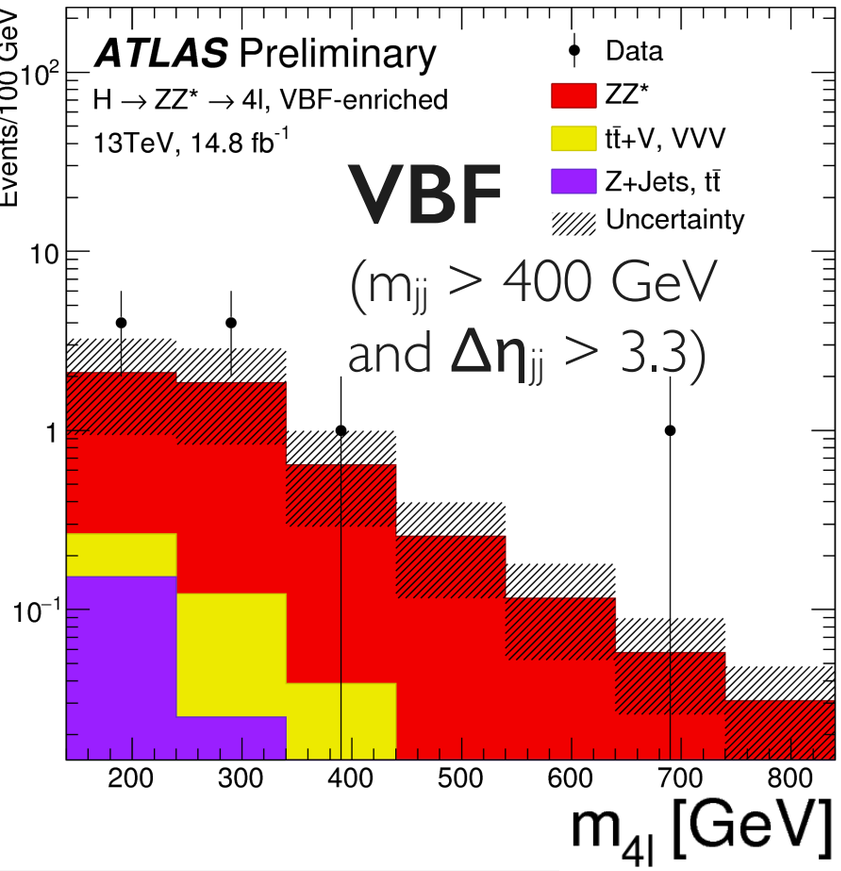
$H \rightarrow ZZ \rightarrow llll$

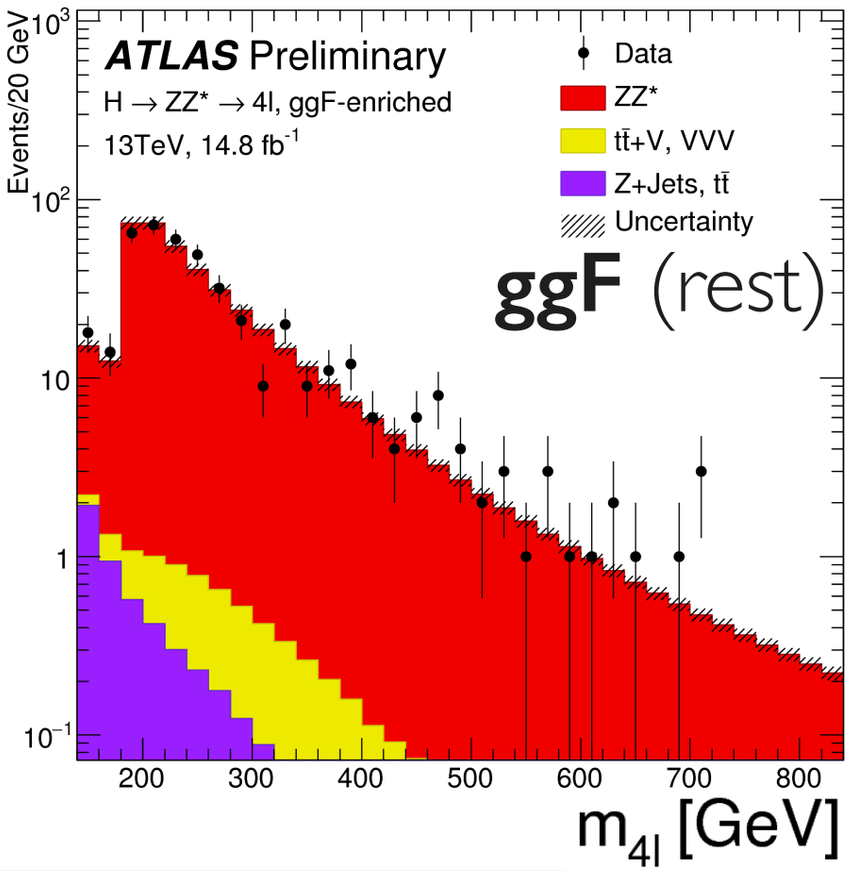
ATL-CONF-2016-079

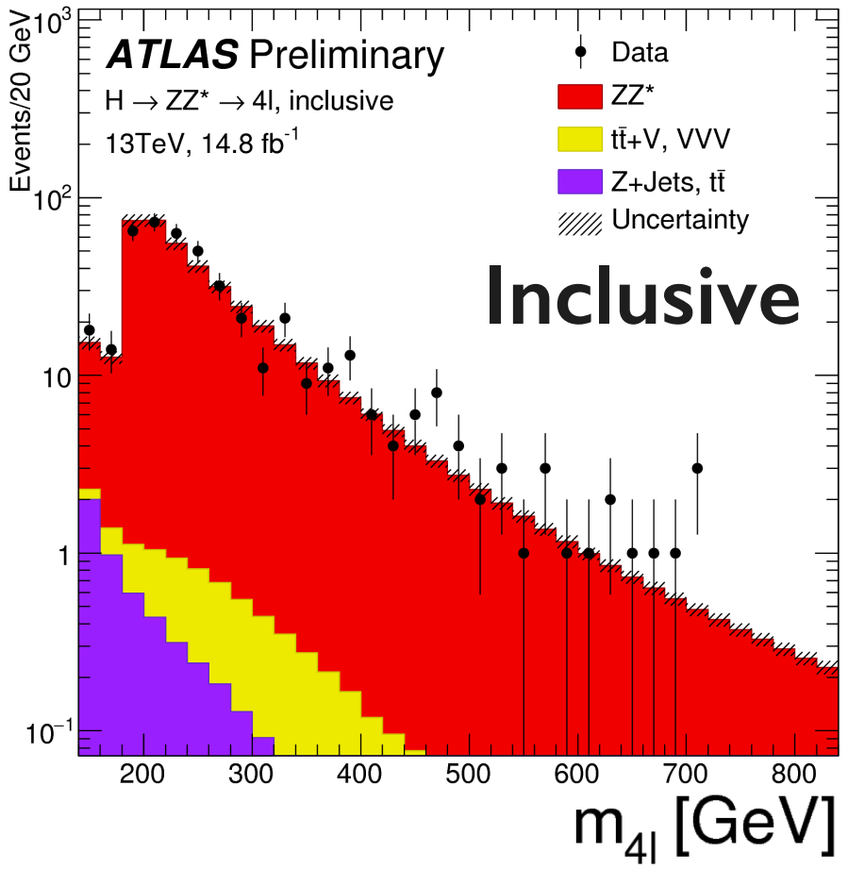
$H \rightarrow ZZ \rightarrow llll$

Analysis strategy:

- Same selection as SM H_{125} $H \rightarrow ZZ \rightarrow llll$ measurement — Talk by Ludovica Aperio Bella
  - require both Z on-shell
- Update of Dec. 2015 result (ATLAS-CONF-2015-059): added ggF and VBF categories
- Narrow (**VBF** and **ggF**) and large-width (**inclusive**) signals studied
  - Breit-Wigner signal shape with width: 4.07 MeV, 1%, 5%, 10%



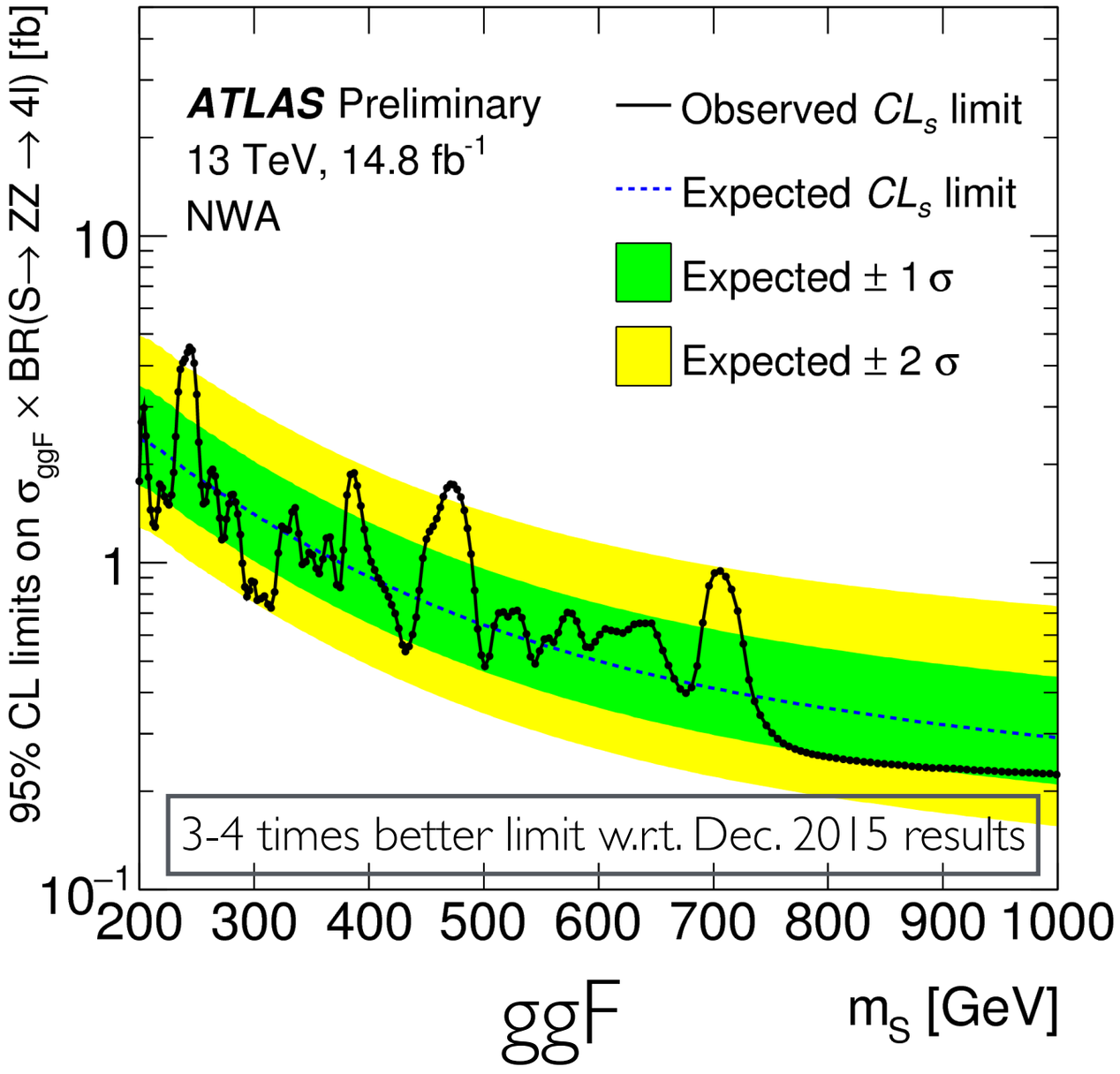


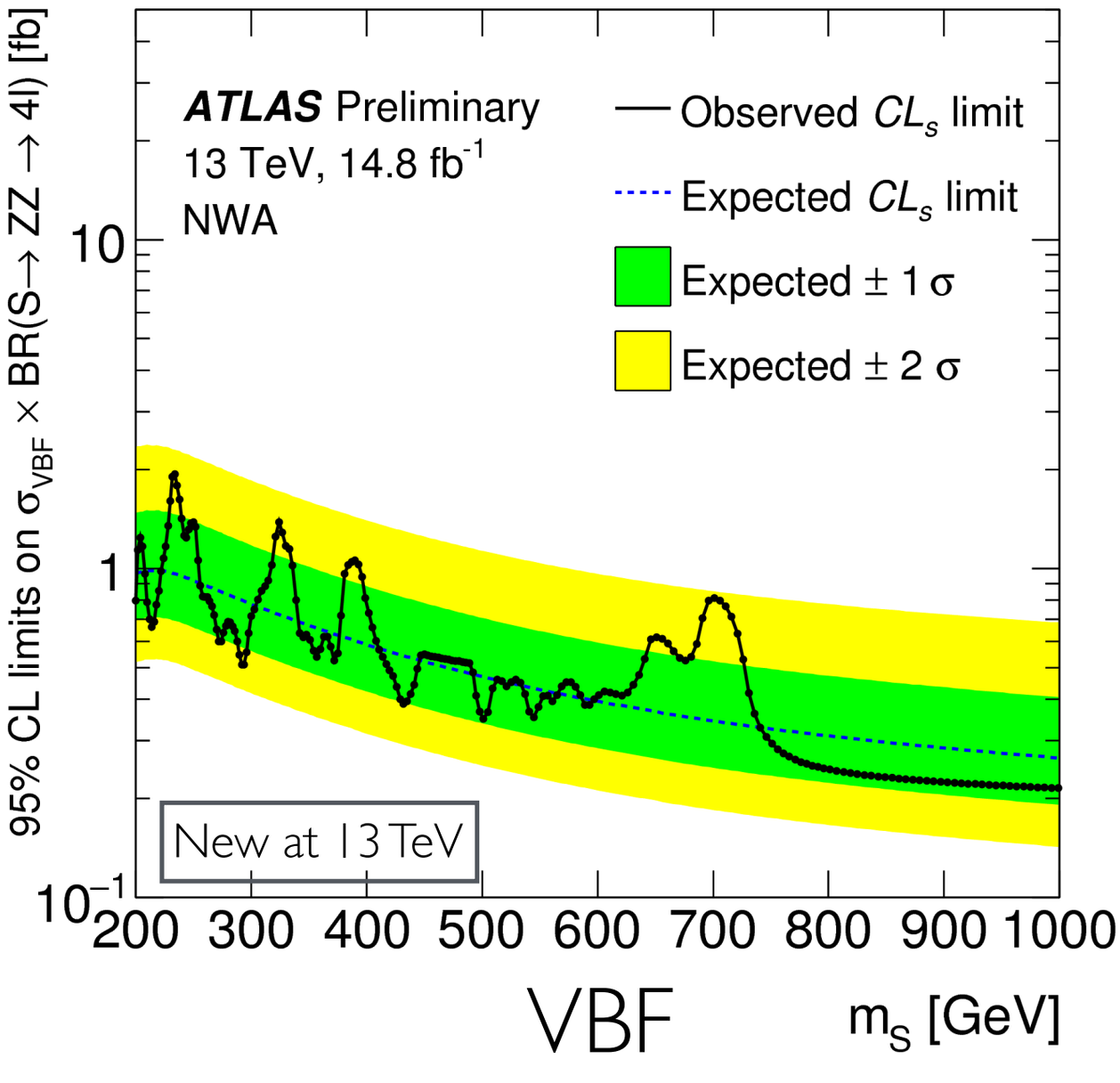


H → ZZ → llll

Results for narrow-width-approximation:

- Largest deviation near 705 GeV: 2.9σ (1.9σ) local (global)

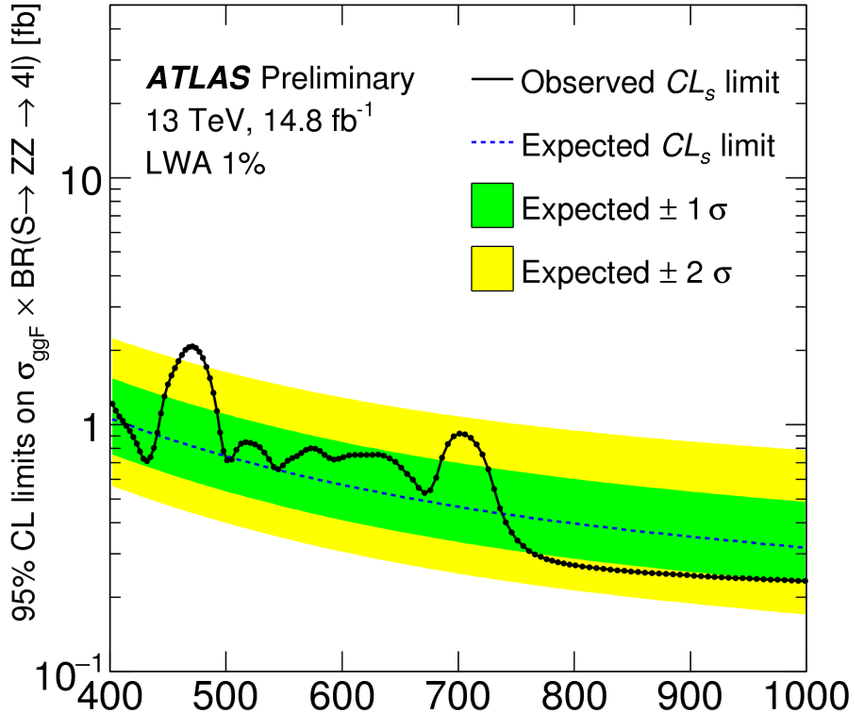




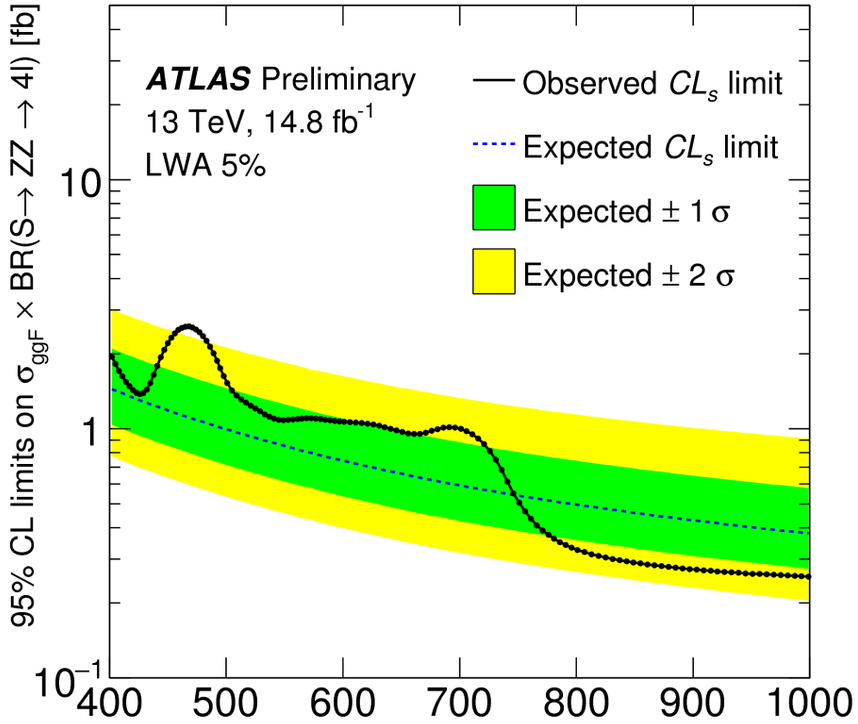
H → ZZ → llll

Results for ggF large-width-approximation:

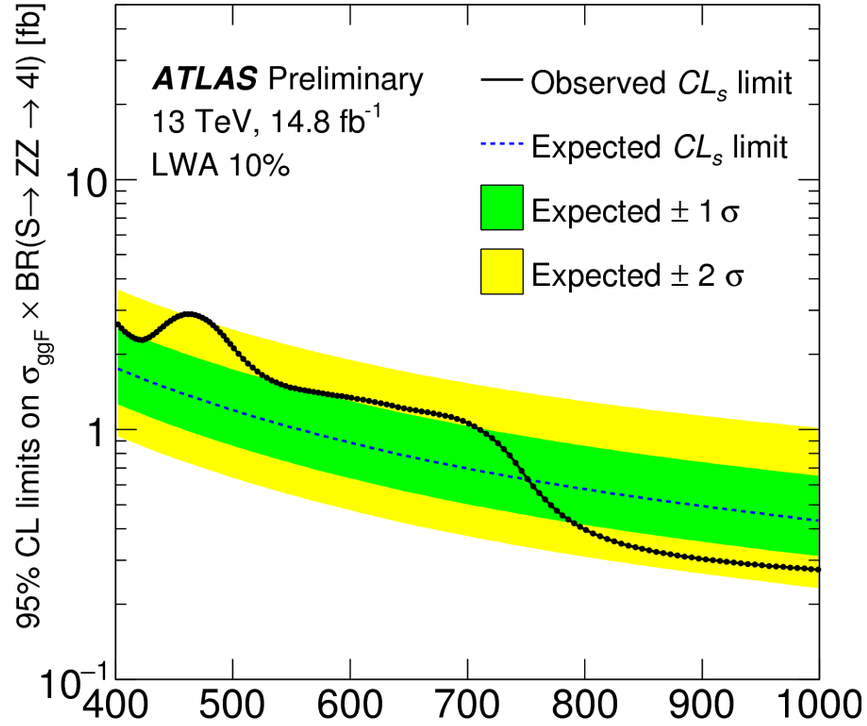
- Interference with SM background small, thus neglected
- New interpretation w.r.t. December 2015 results



1% width



5% width



10% width

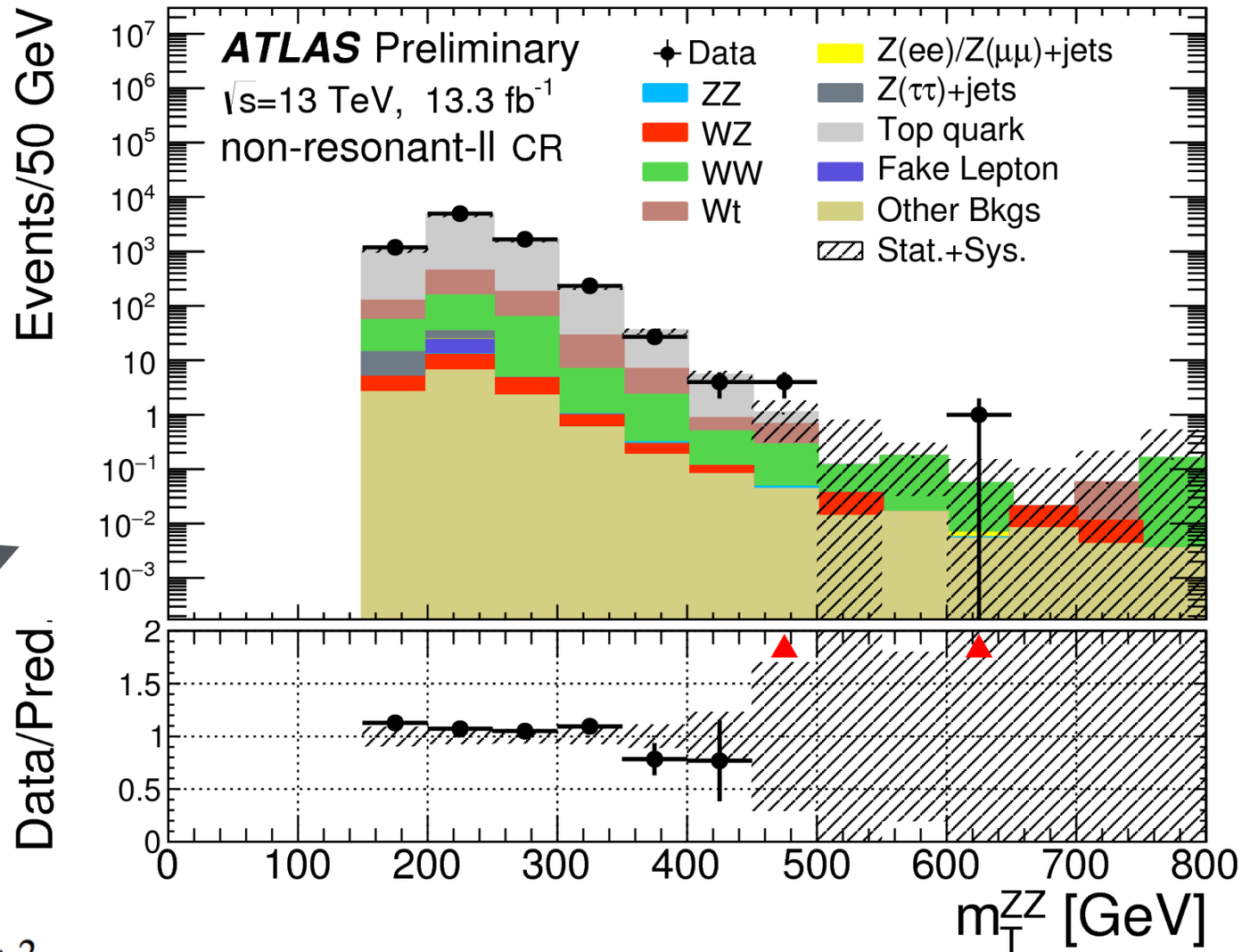
$H \rightarrow ZZ \rightarrow llvv$

ATL-CONF-2016-056

H → ZZ → llνν

Analysis strategy:

- 2 isolated leptons (e^+e^-, $\mu^+\mu^-$) consistent with originating from Z
- Large missing E_T
- Backgrounds:
  - **ZZ → llνν:** irreducible, taken from prediction
  - **WZ → lllν**: 3l control region
  - **Z+jets**: data ABCD
  - **non-resonant-ll**: eμ control region
  - **W+jets**: fake-factor from data



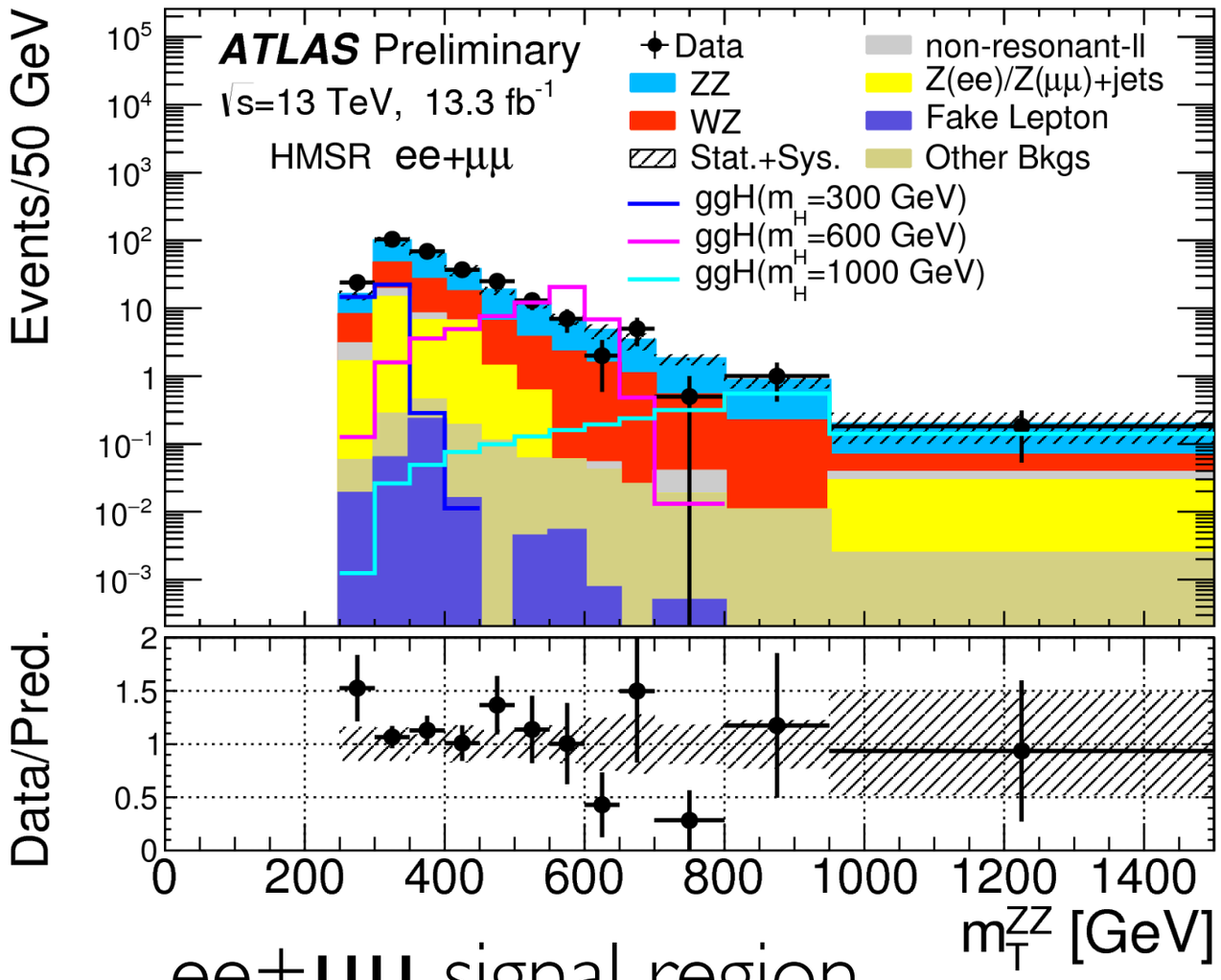
- Likelihood fit in

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

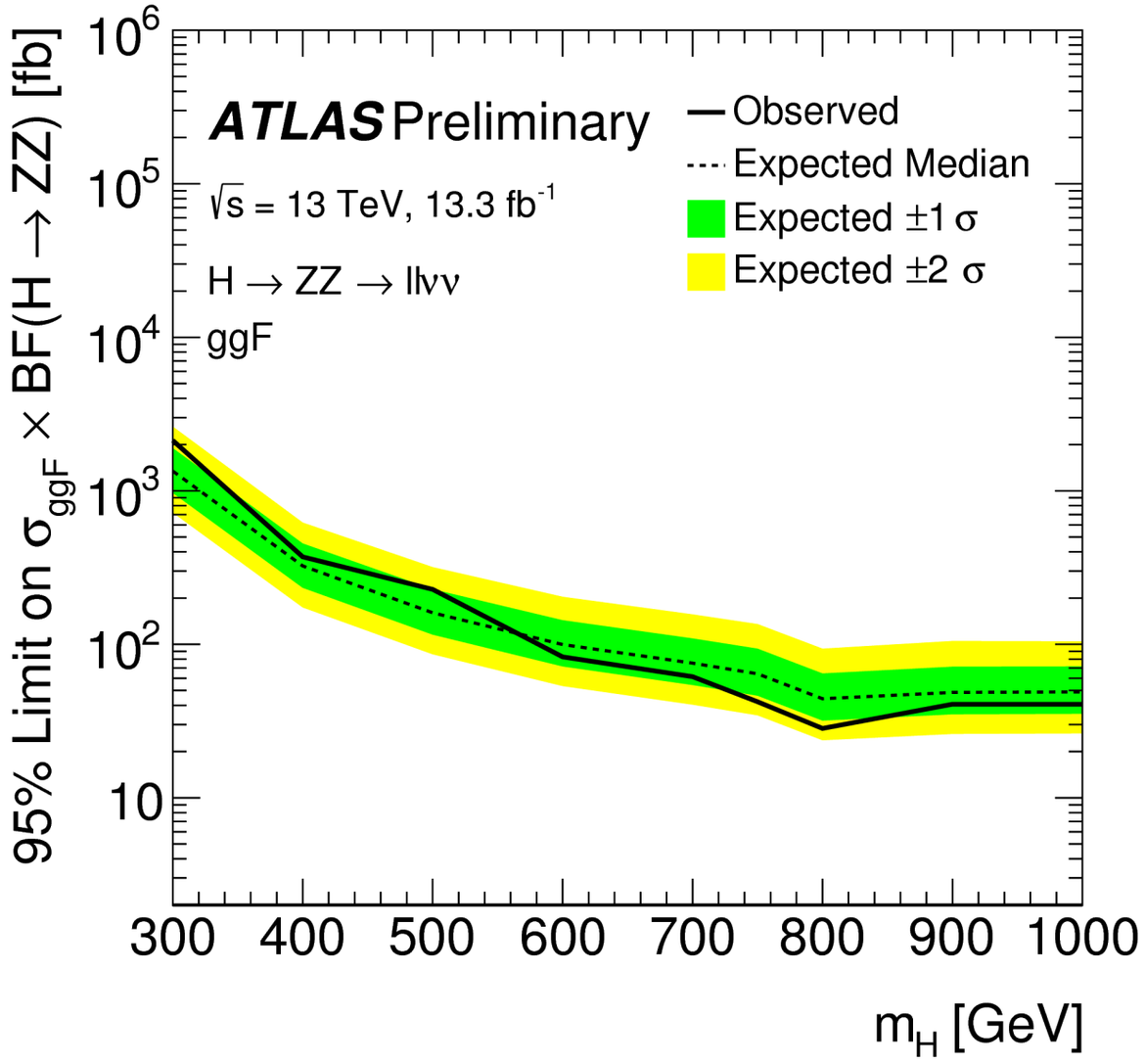
H → ZZ → llνν

Results:

- No significant excess seen ⇒ limits on ggF production
- Statistics-dominated; impact of systematics: 1-2% at 600 GeV, ~10% at 300 GeV
- Limits improved w.r.t. run 1



ee+μμ signal region



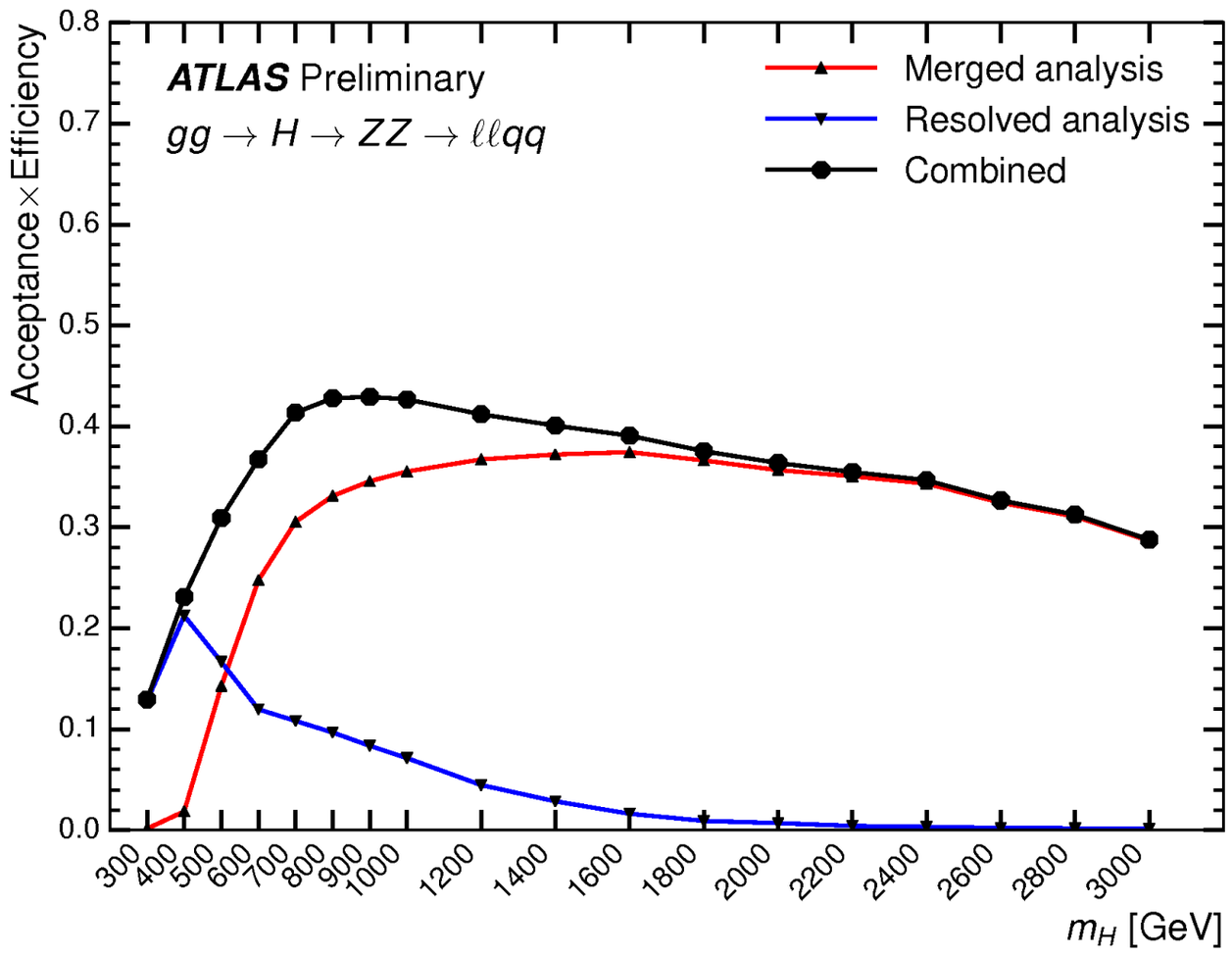
$H \rightarrow ZZ \rightarrow llqq$

ATL-CONF-2016-082

H → ZZ → llqq

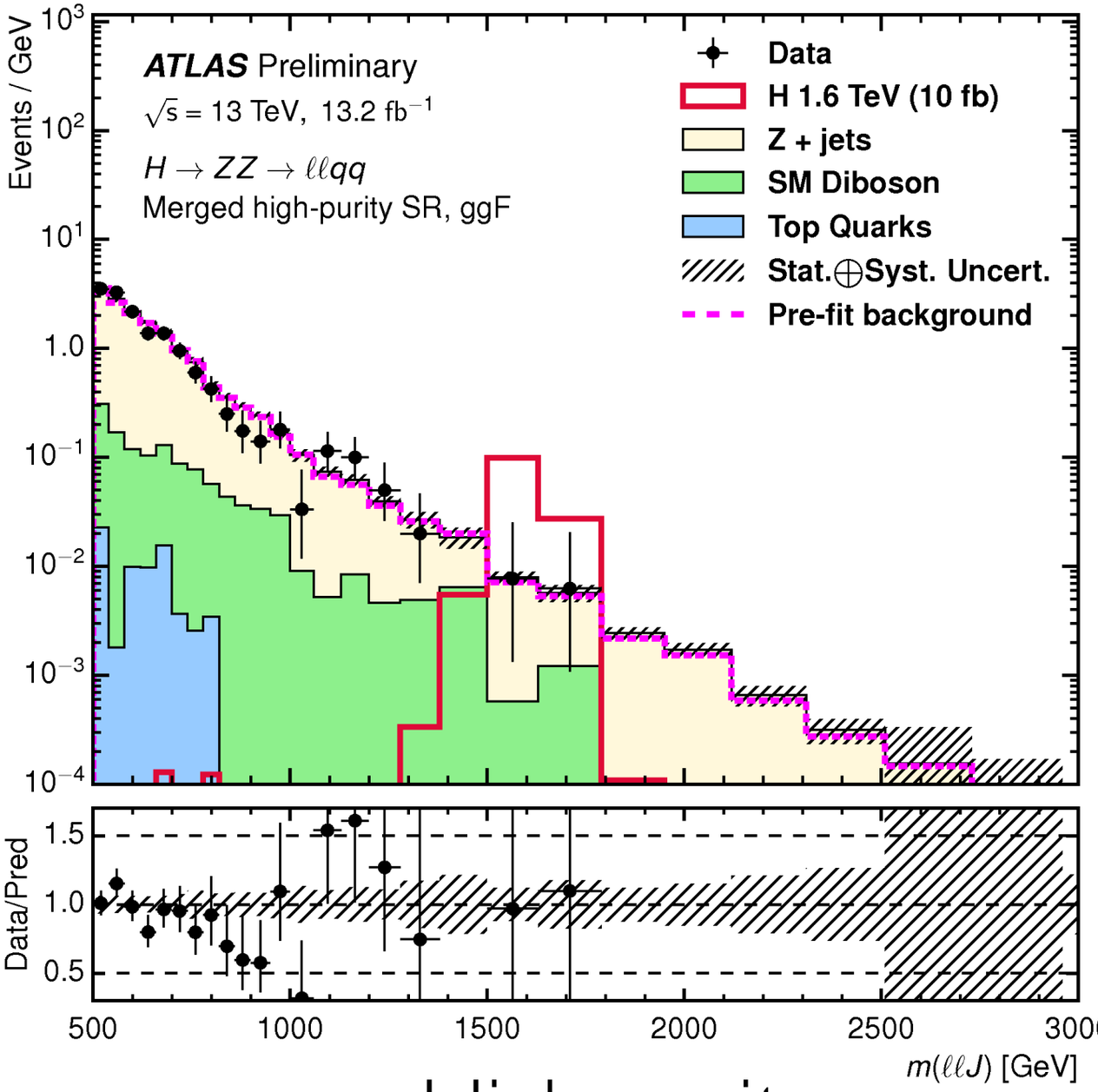
Analysis strategy:

- ggF and VBF production
- Merged large-R jet
  - high-purity (pass jet substructure selection)
  - low-purity
- Or resolved 2-jet
  - tagged (2 b-tagged jets)
  - untagged (<2 b-tagged jets)
- Resolution in m_{llJ} (m_{lljj}): 3-4%
- Data control regions:
  - Z+jets: m_J (m_{jj}) mass sideband
  - Top: e**μ** with ≥2 b-tagged jets

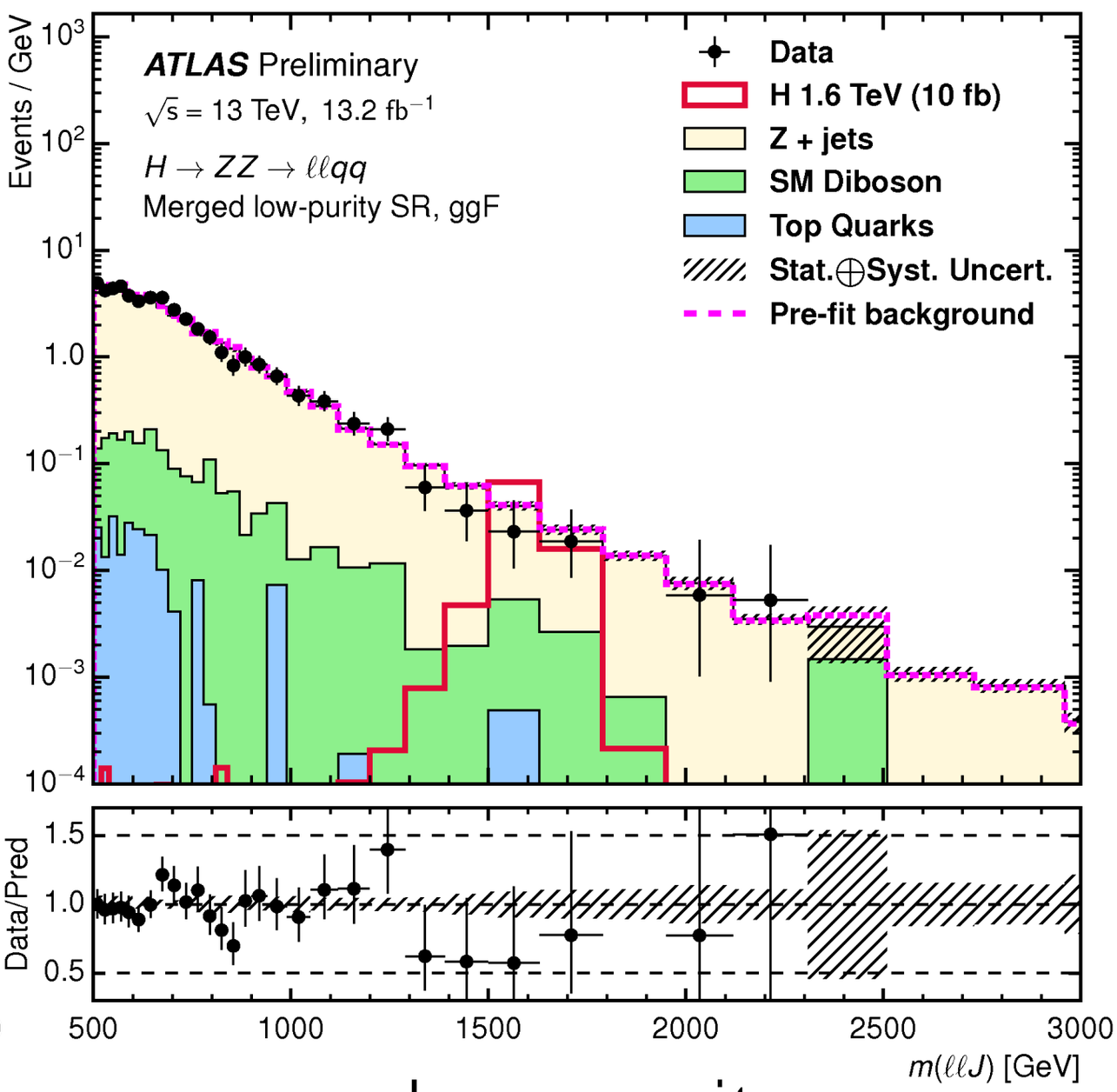


H → ZZ → llqq

Signal regions (merged Z → J):



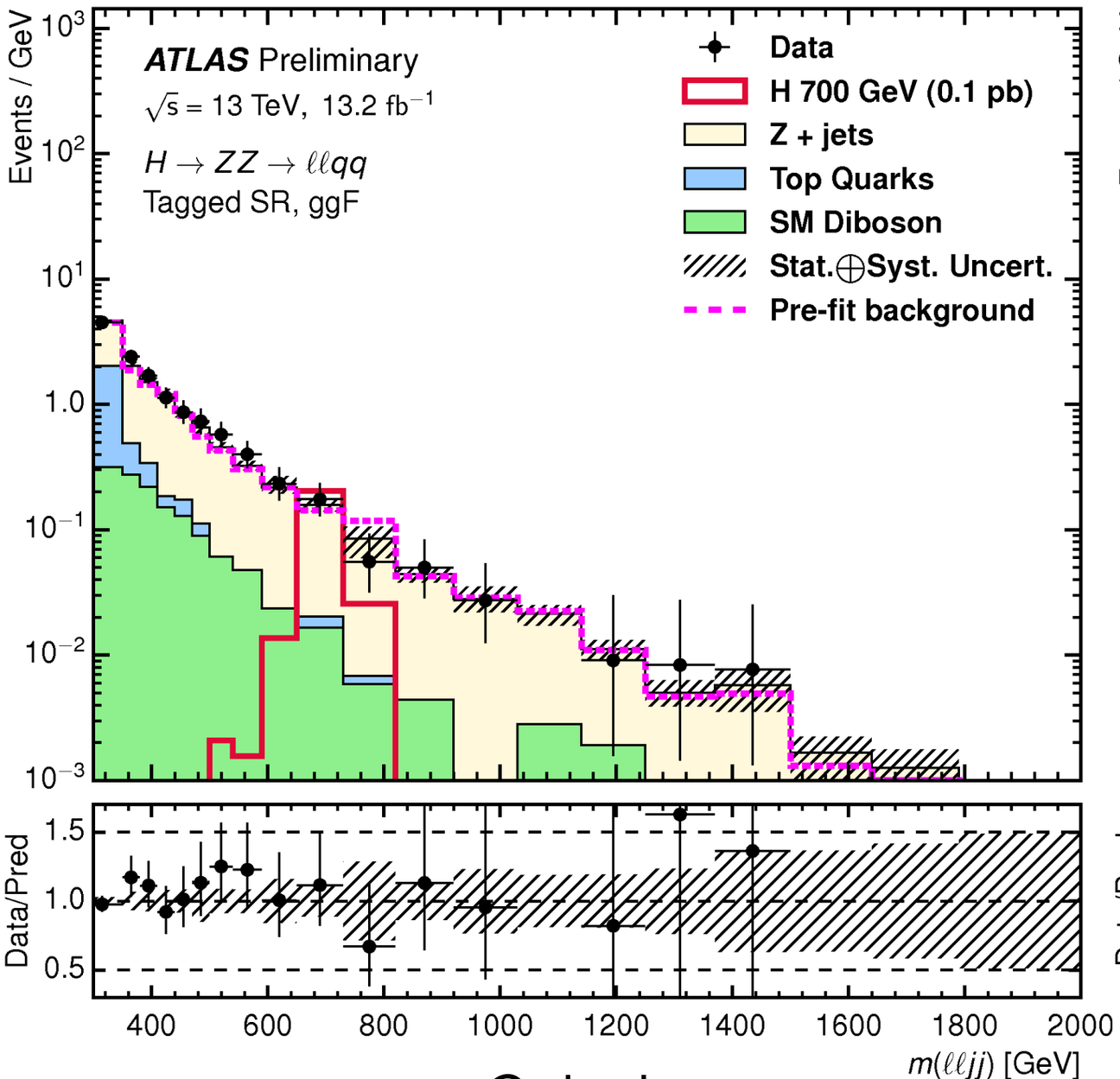
High purity



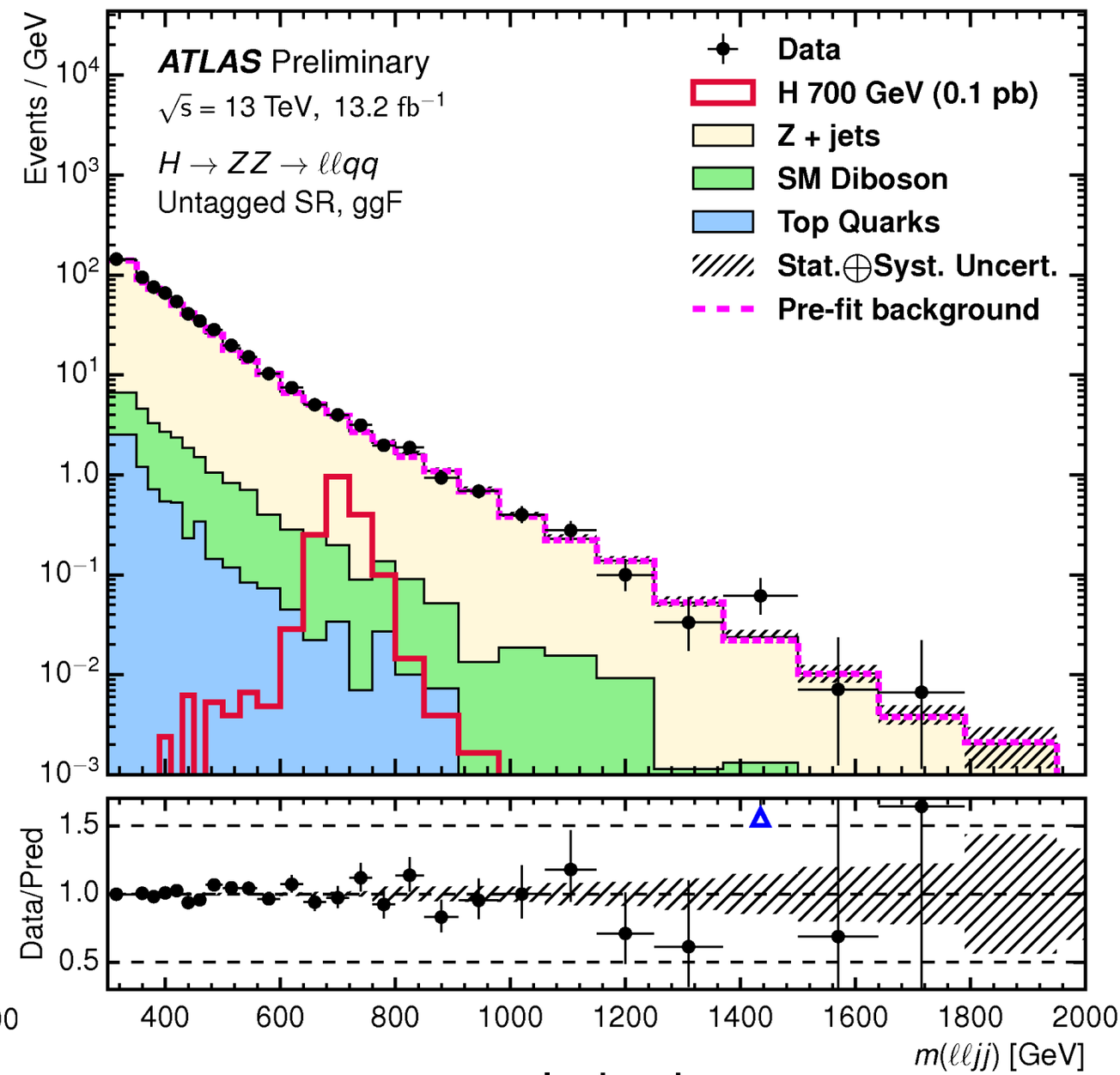
Low purity

H → ZZ → llqq

Signal regions (resolved Z → jj):



2 b-jets

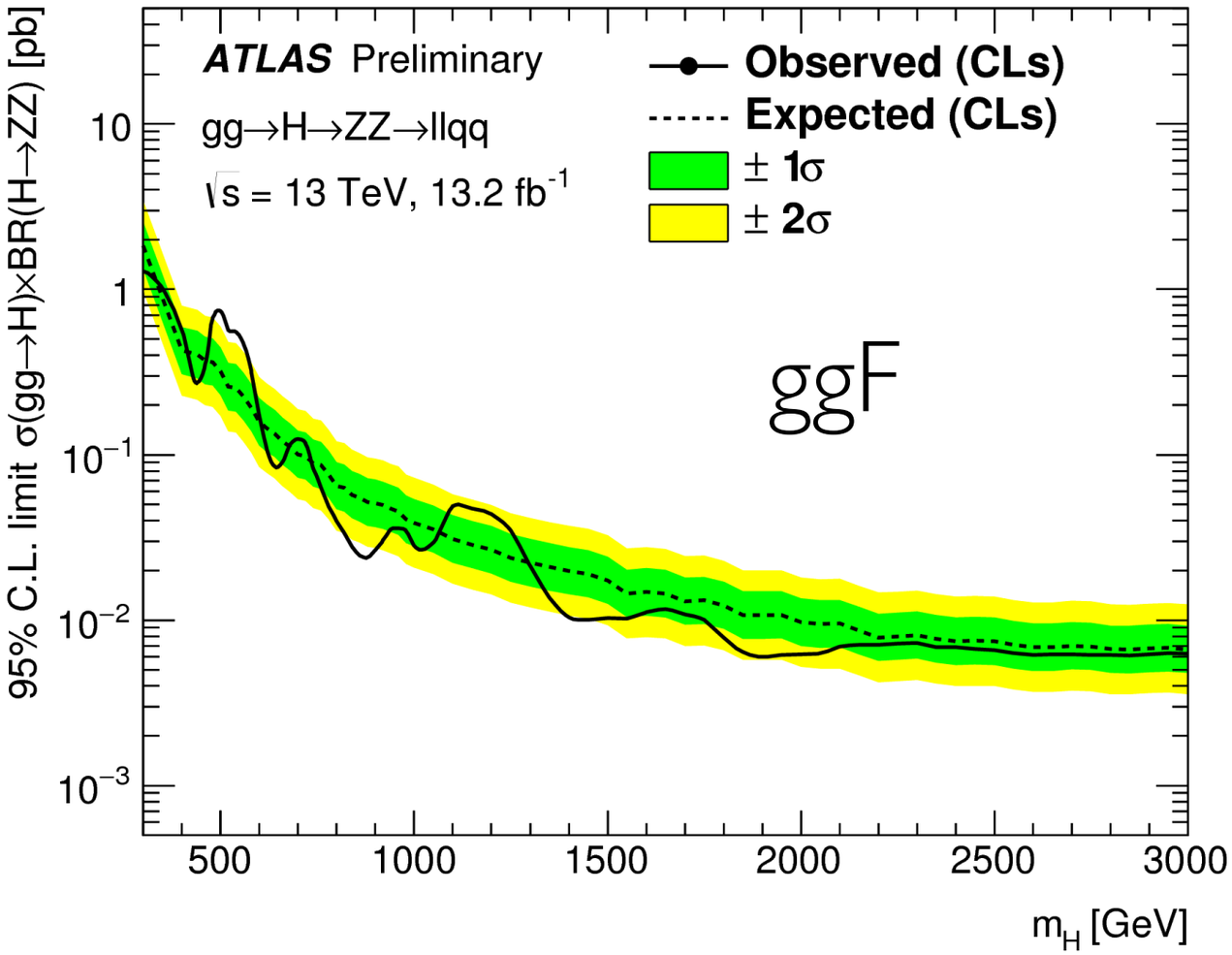


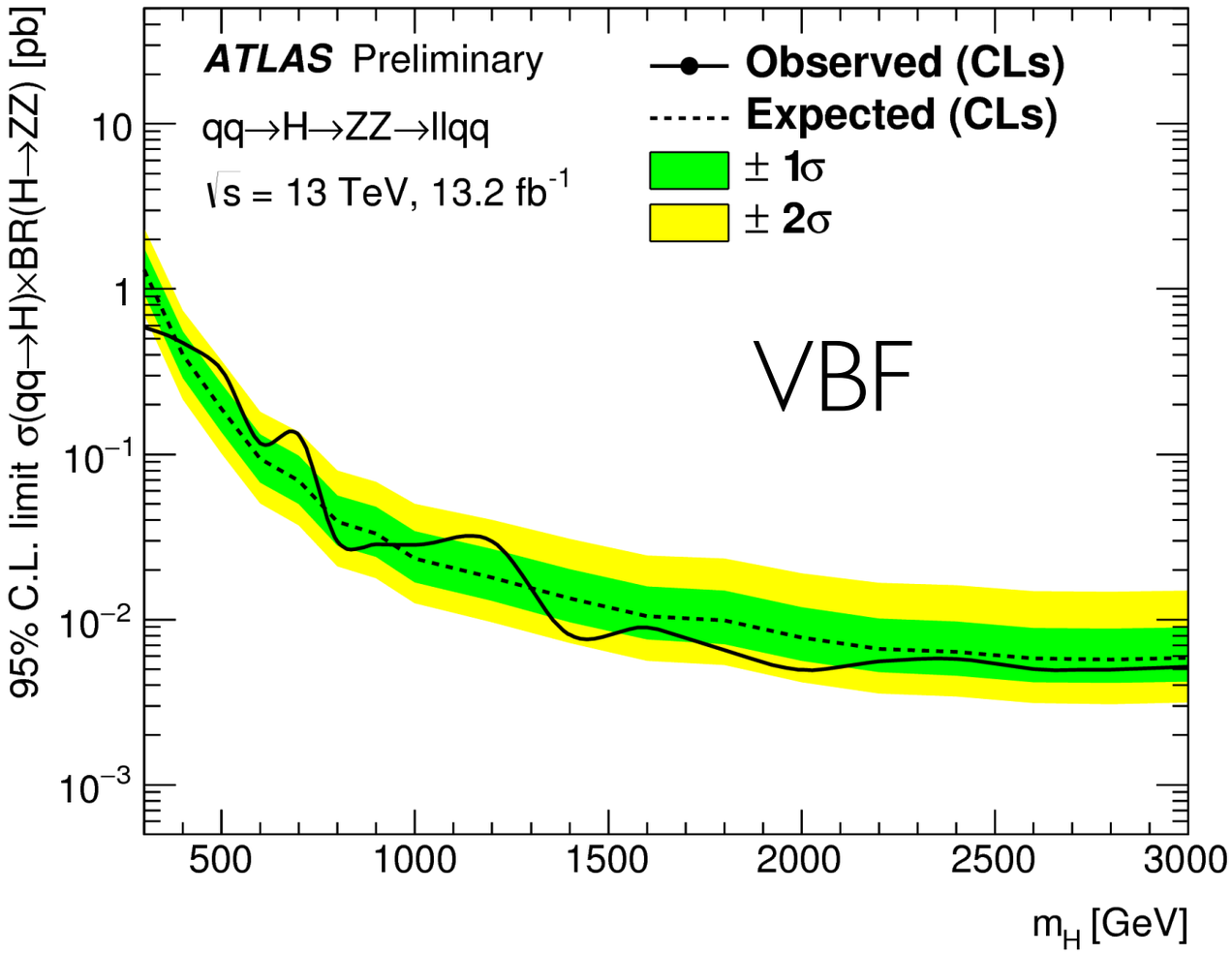
≤1 b-jet

H → ZZ → llqq

Results:

- Leading systematics: large-R jet energy scale/resolution; sub-structure variable; Z+jets modeling
- Narrow-with-approximation
- Largest excess near 500 GeV (from resolved untagged): 2.75σ (1.4σ) local (global)





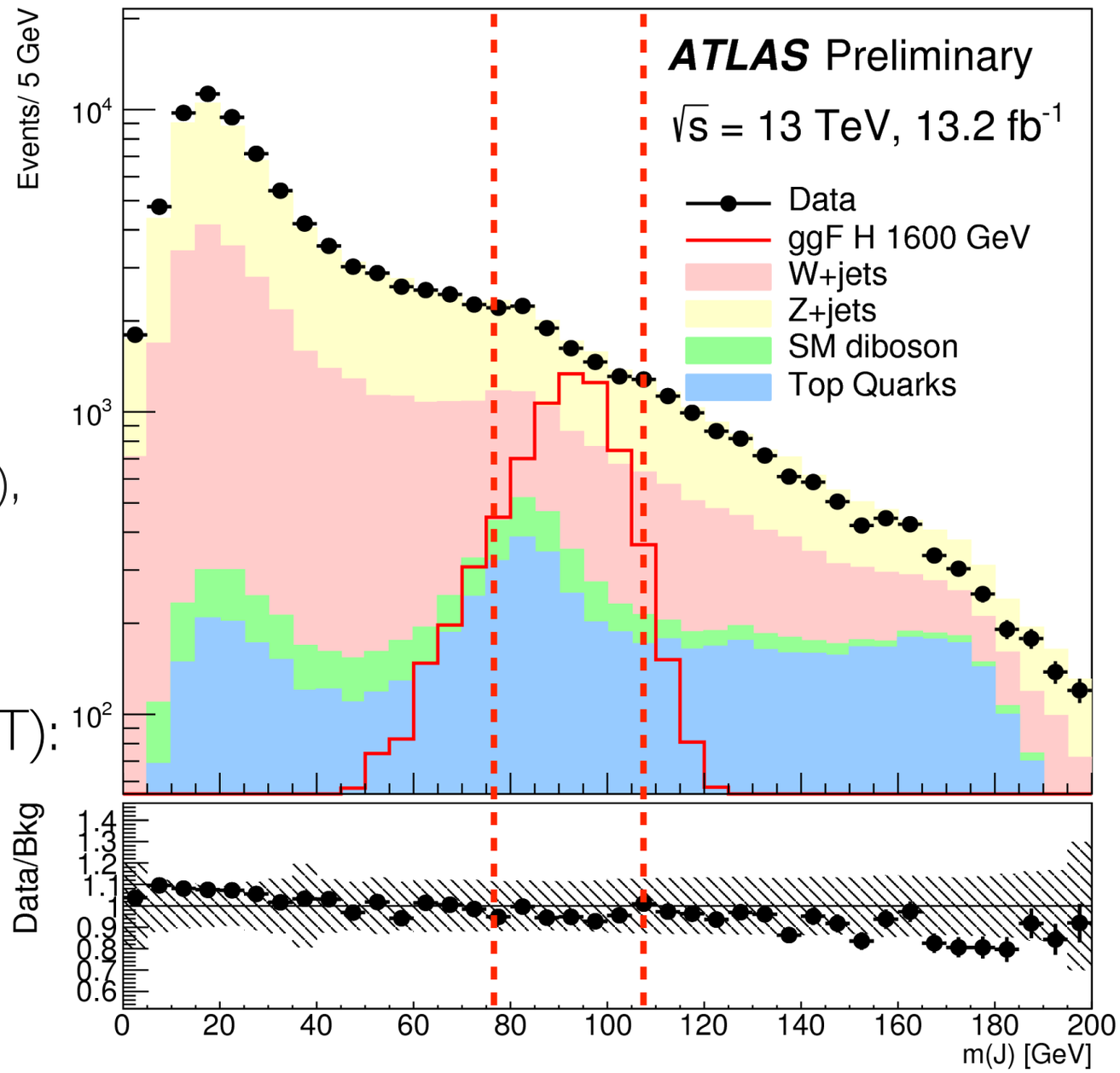
$H \rightarrow ZZ \rightarrow \nu\nu qq$

ATL-CONF-2016-082

H → ZZ → ννqq

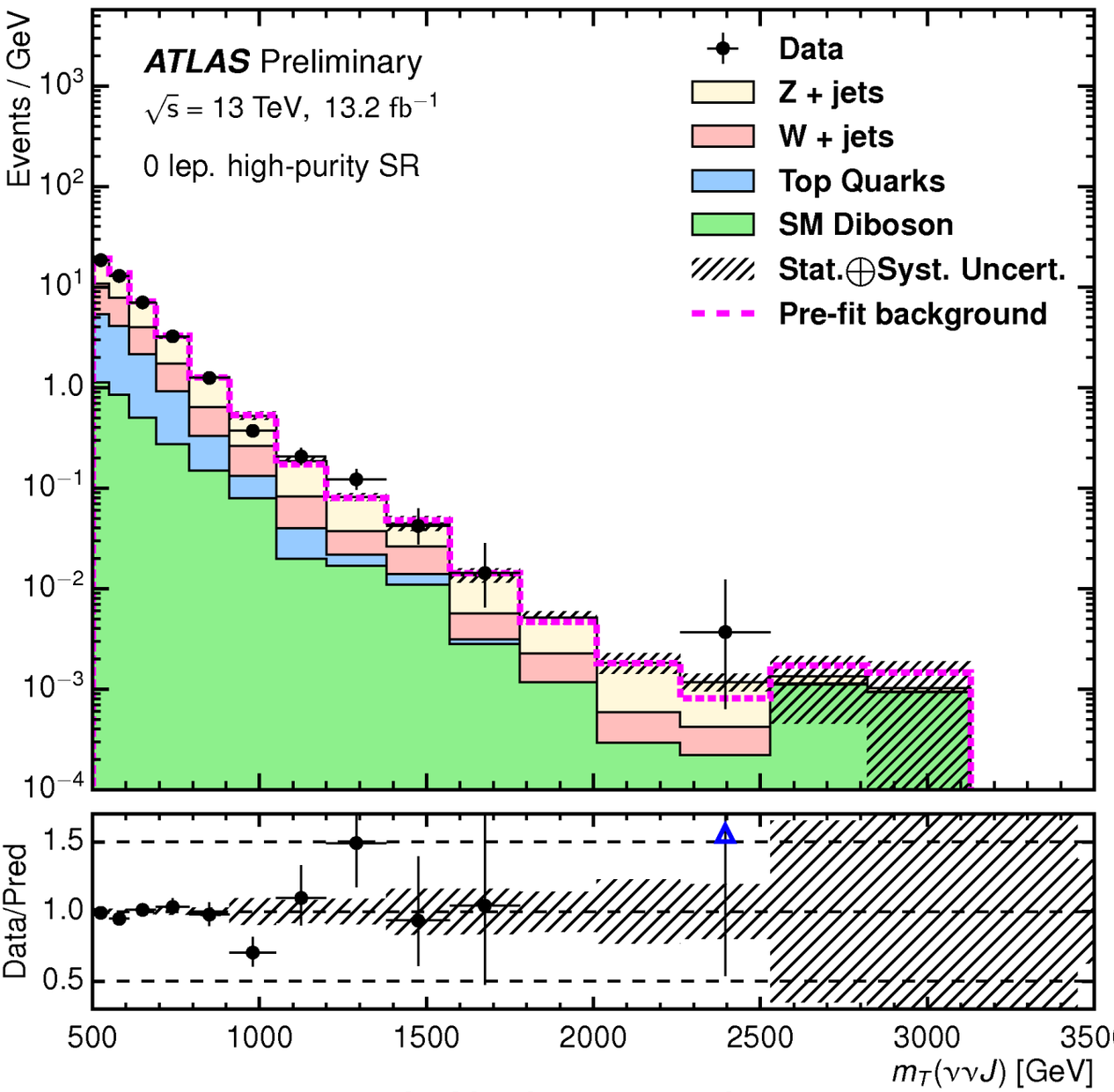
Analysis strategy:

- ggF production
  - Narrow-width-approximation
- Large missing-E_T
- Merged large-R jet
  - High-purity (pass jet substructure selection)
  - Low-purity (fail jet substructure selection), recover 10-20% signal efficiency
- Resolution in m_T: ~30%
- Data control regions (muon used in MET):
  - Z+jets: $Z \rightarrow \mu\mu$ and m_J mass sideband, separate HP and LP
  - W+jets: one μ, no b-tagged jet, m_J mass sideband
  - Top: : one μ, b-tagged jet(s), m_J near m_W

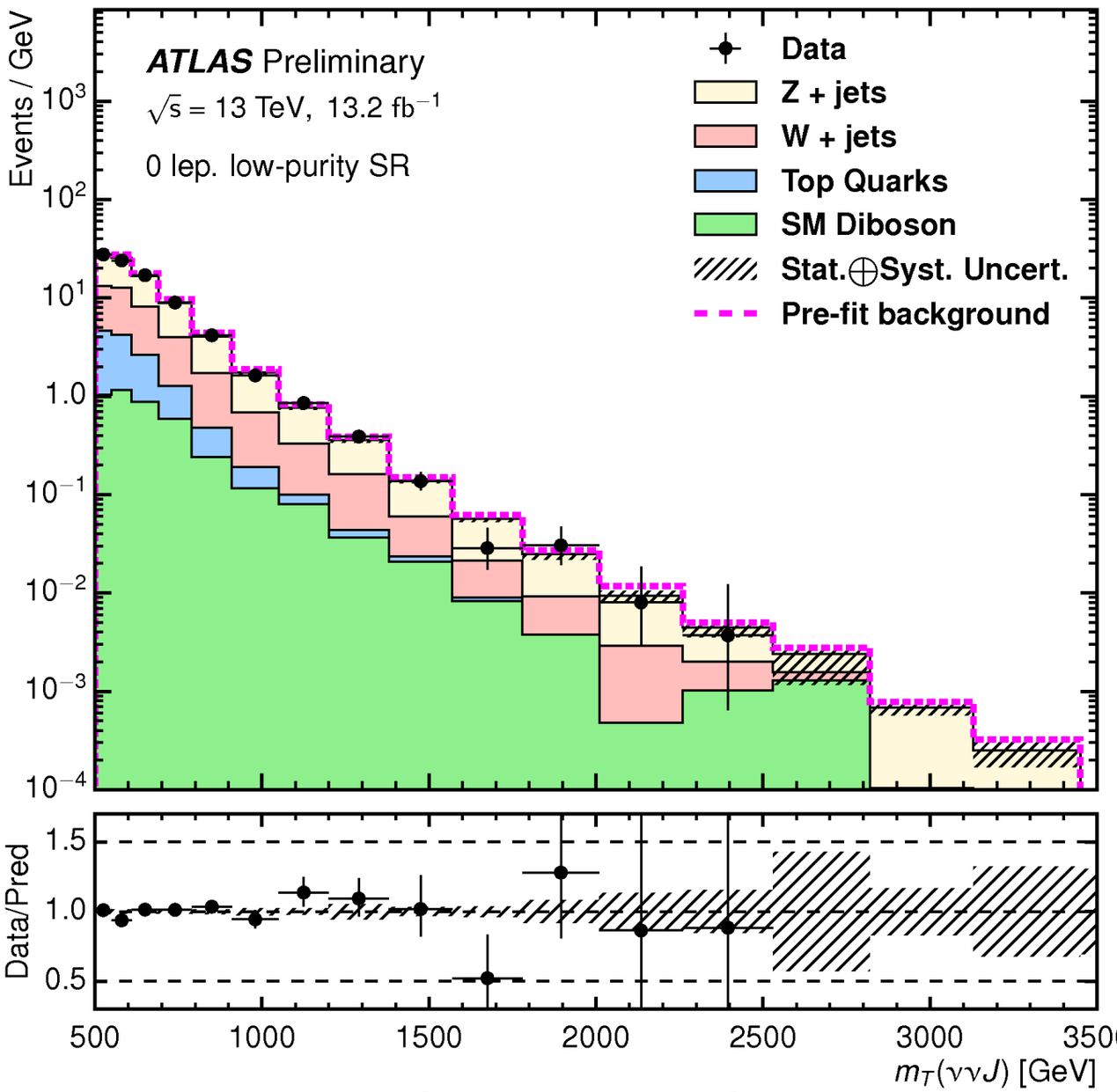


H → ZZ → ννqq

Signal regions:



High purity

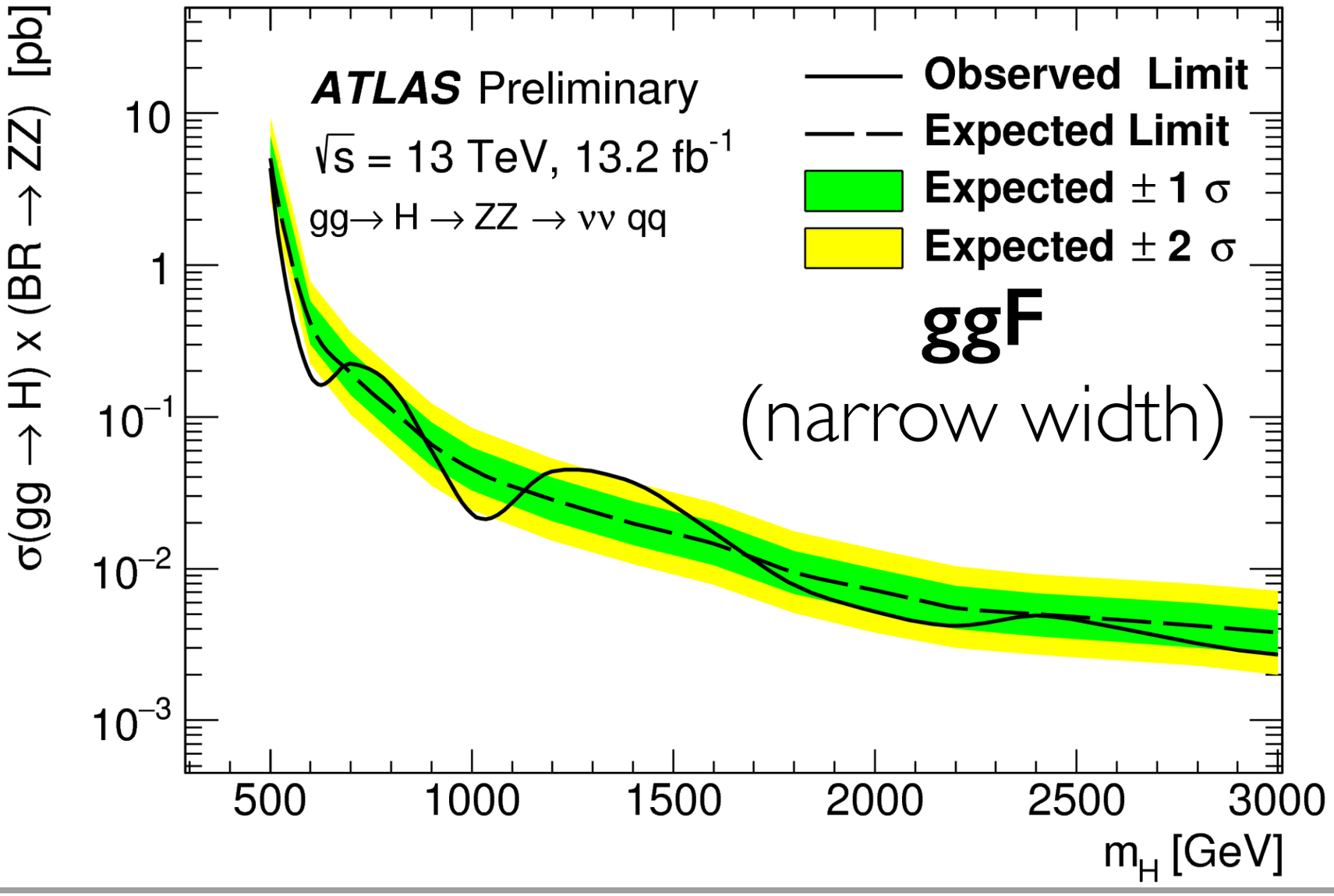


Low purity

H → ZZ → ννqq

Results:

- Leading systematics: W+jets and Z+jets modeling; large-R jet energy scale/resolution; sub-structure variable



Summary

Heavy Higgs-boson searches at $\sqrt{s} = 13$ TeV performed

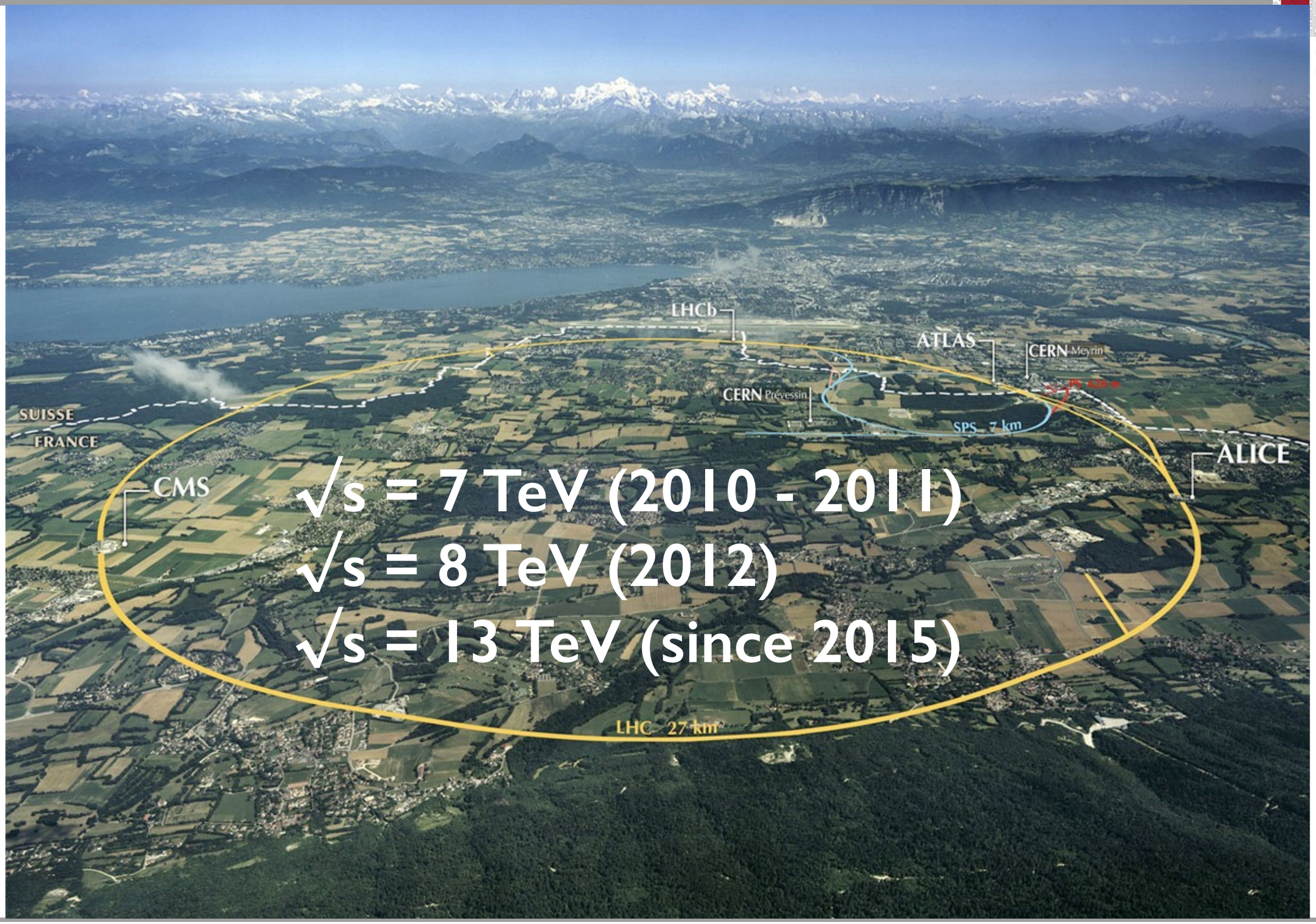
Final states WW → lvlv/lvqq and ZZ → llll/llvv/llqq/vvqq

ggF (NWA and LWA) and VBF (NWA) production probed

No significant excesses seen

Significantly improved limits on $\sigma \times$BF set
over wider mass-ranges

LHC



$\sqrt{s}$ = 7 TeV (2010 - 2011)

$\sqrt{s}$ = 8 TeV (2012)

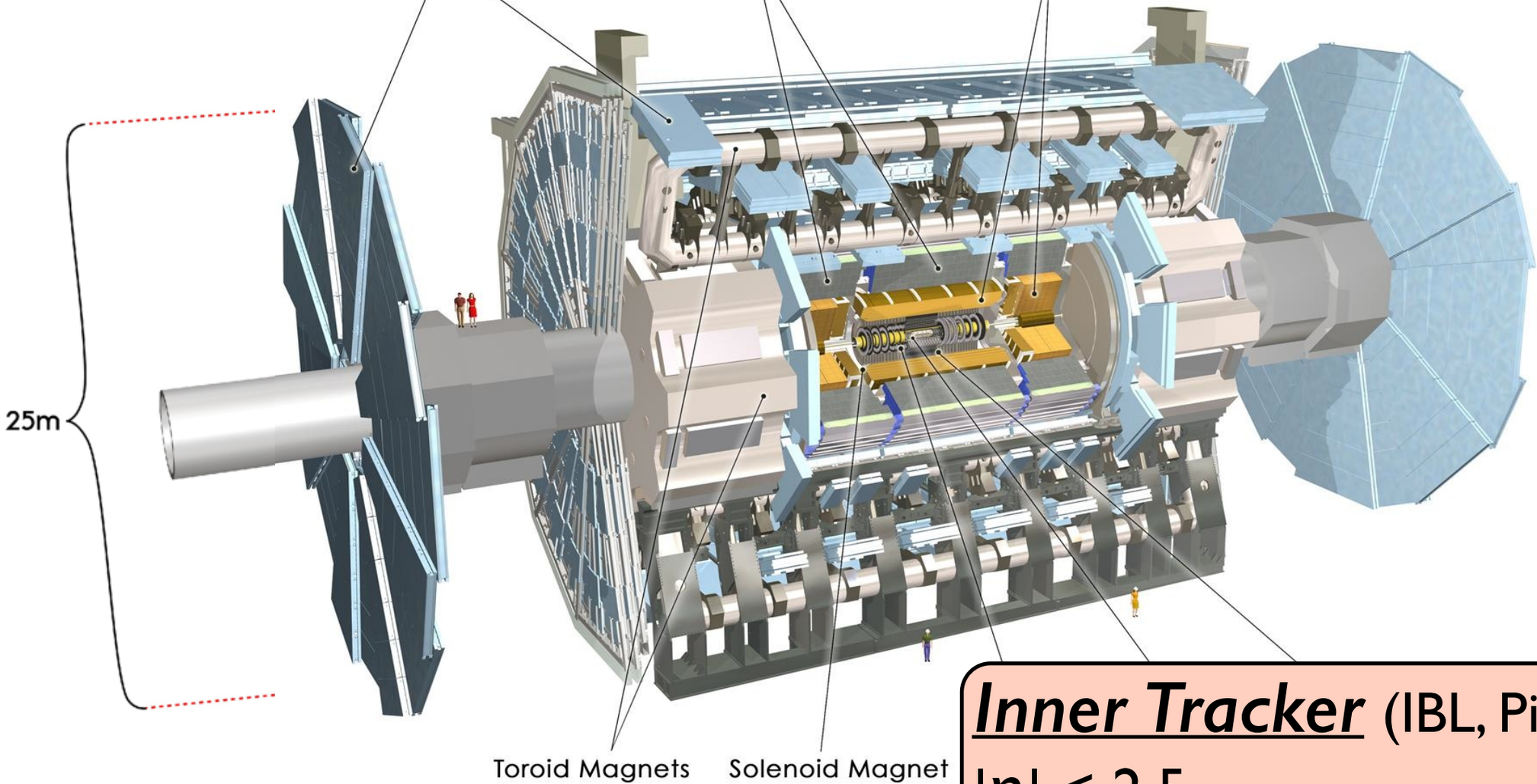
$\sqrt{s}$ = 13 TeV (since 2015)

ATLAS Detector

Muon Spectrometer
$|\eta| < 2.7$
$\sigma/p_T < 10\%$ (p_T<1 TeV)

Hadron Calorimeter
$|\eta| < 4.9$
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

Electromagnetic Calorimeter
$|\eta| < 3.2$
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

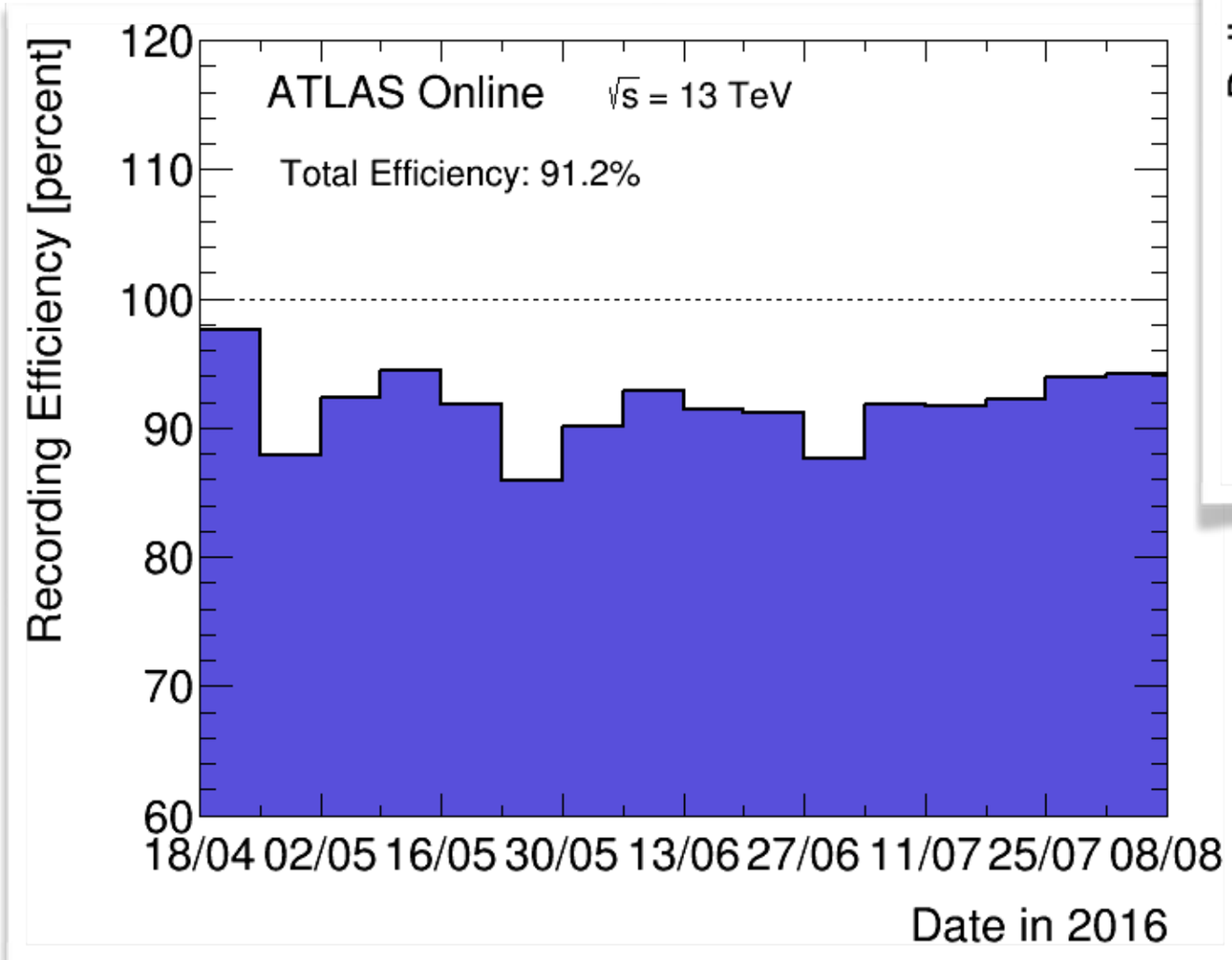


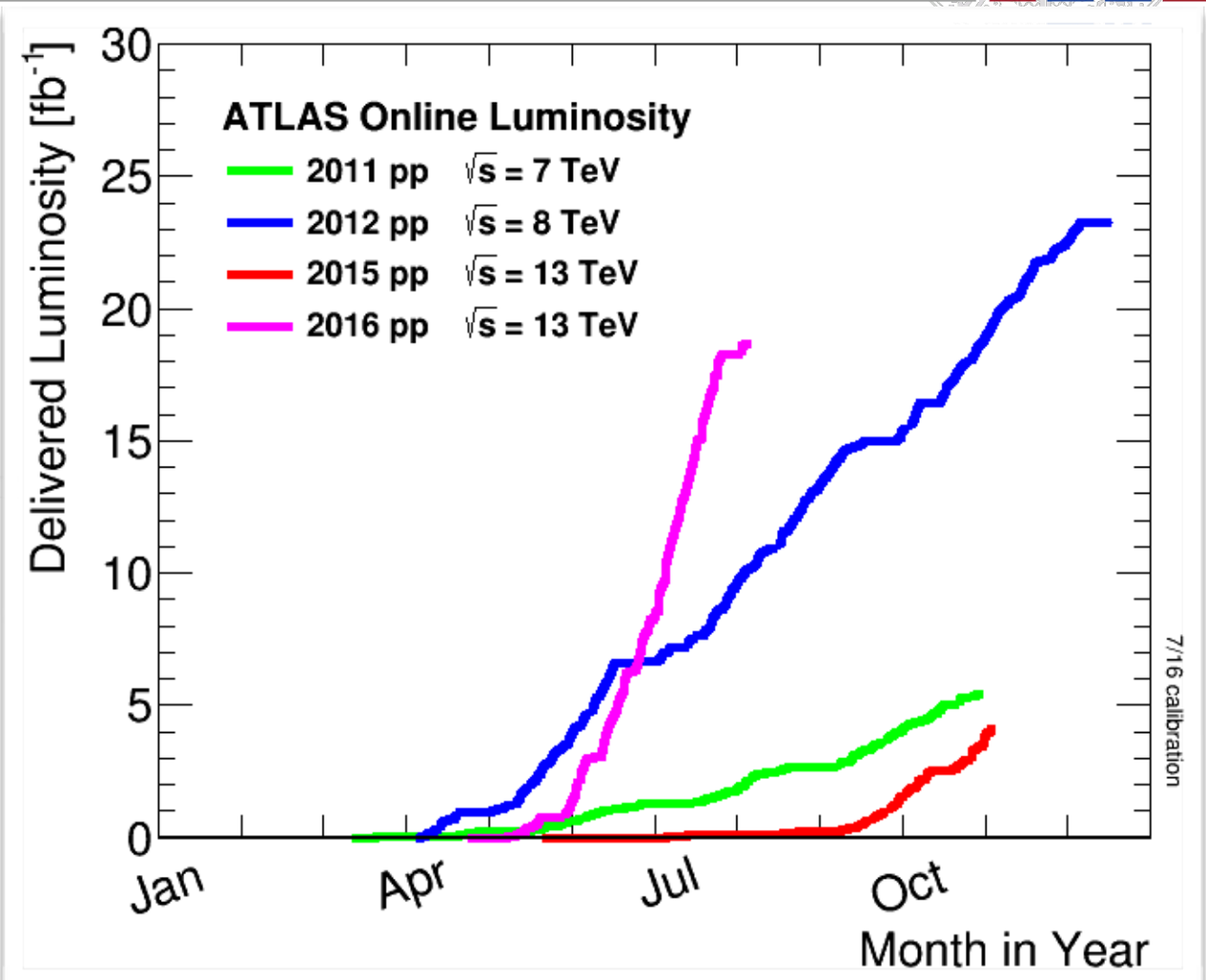
Inner Tracker (IBL, Pixel, SCT, TRT)
$|\eta| < 2.5$
$\sigma/p_T \sim 0.05\%\ p_T \oplus 1\%$

Data-taking conditions

LHC delivered excellent data!

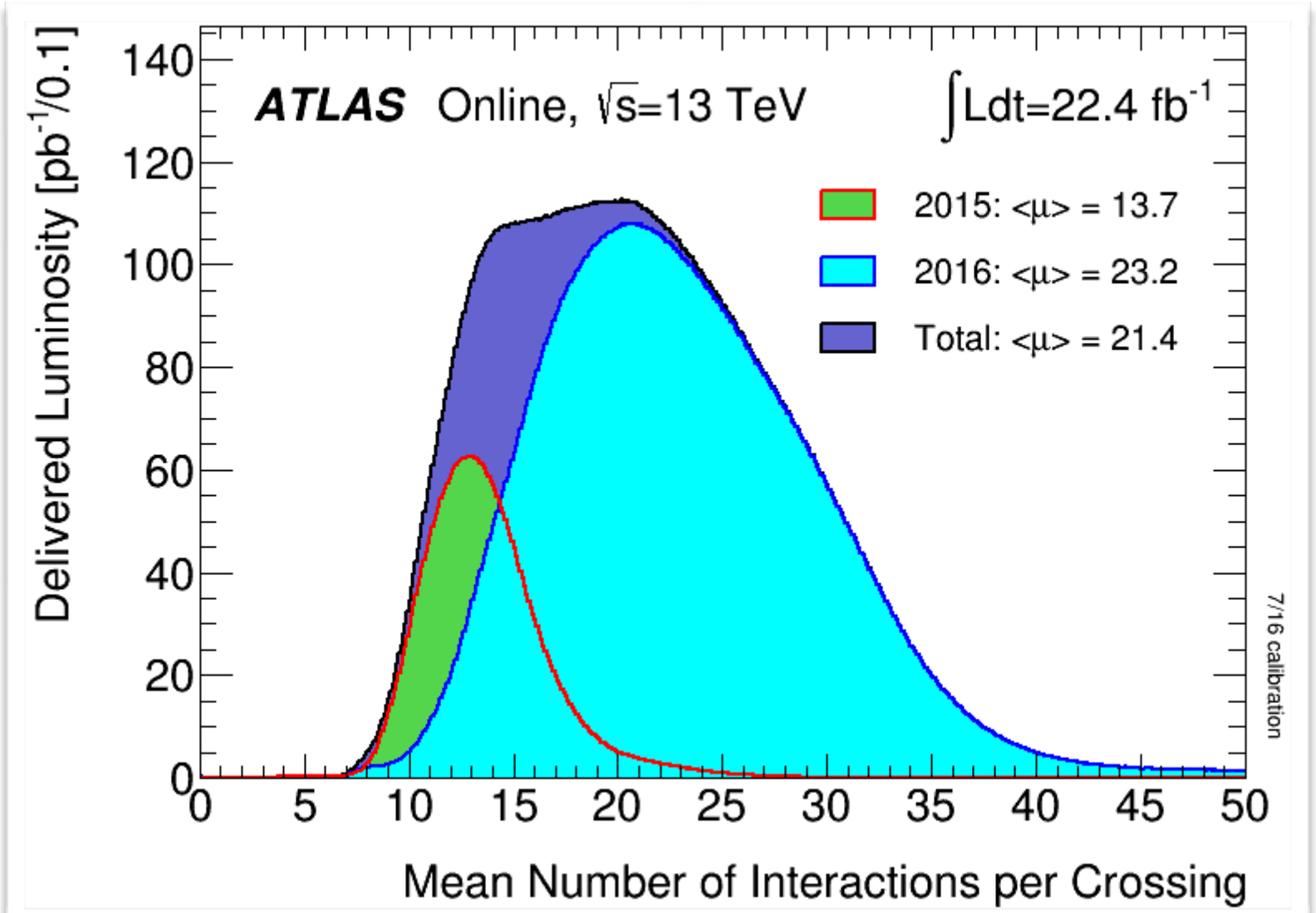
- Record peak lumi:
  $>1.2\times10^{34}$ cm^{-2} s^{-1}





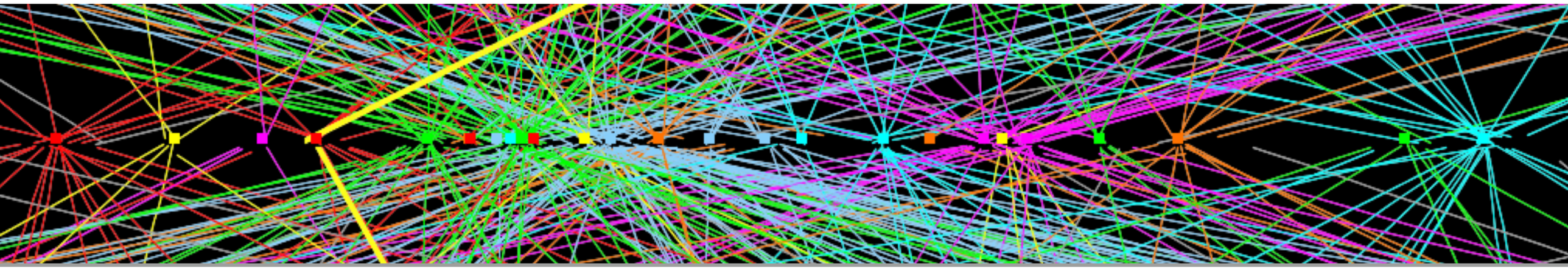
- ATLAS recorded it with very high efficiency!

Data-taking conditions

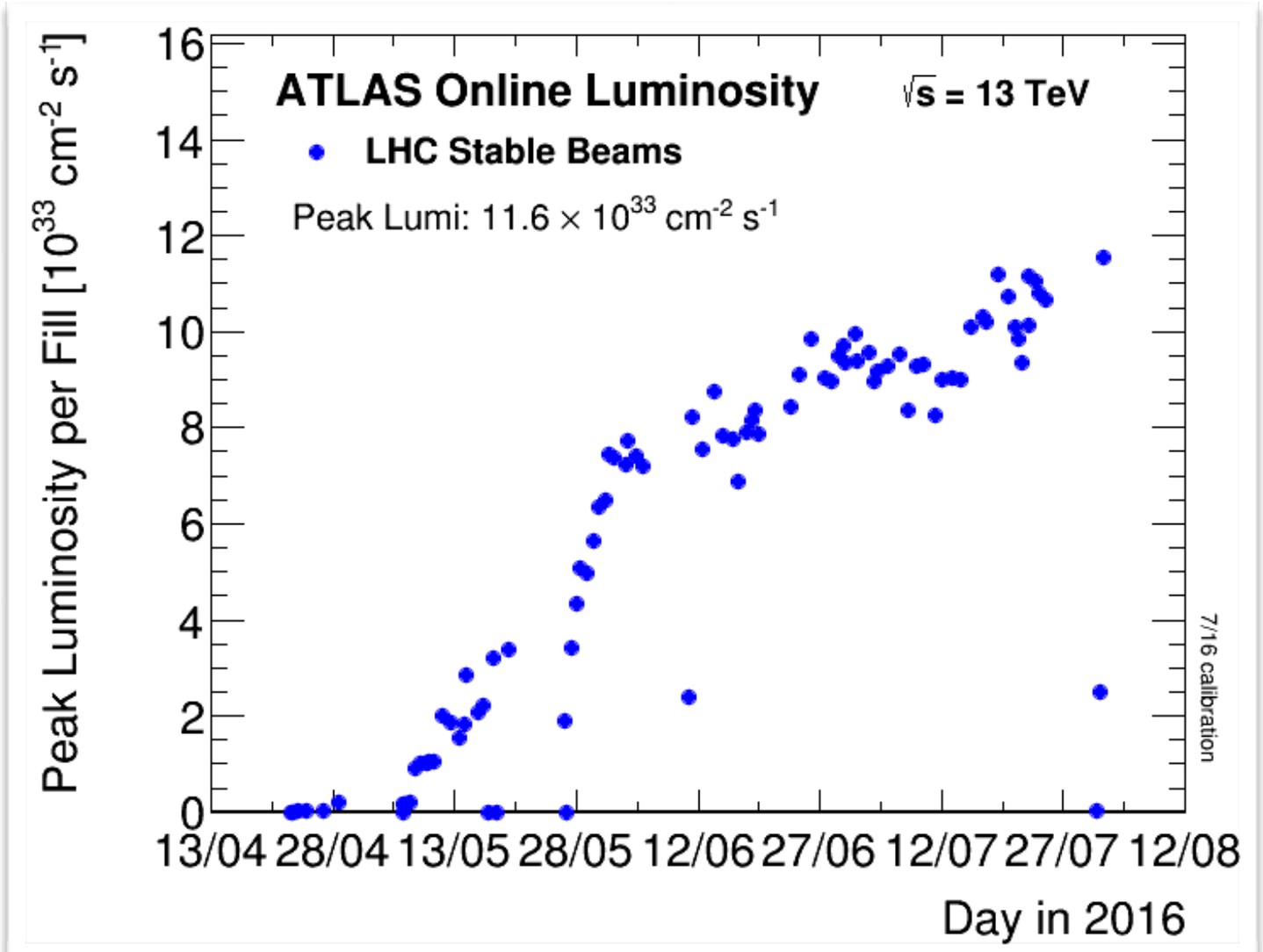


LHC conditions:

- High Luminosity comes at a price: PILEUP

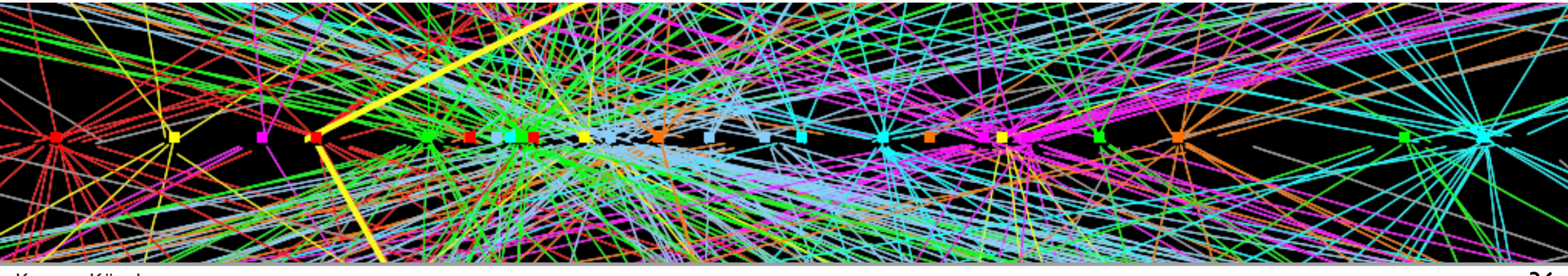


Data-taking conditions



LHC conditions:

- High Luminosity comes at a price: PILEUP



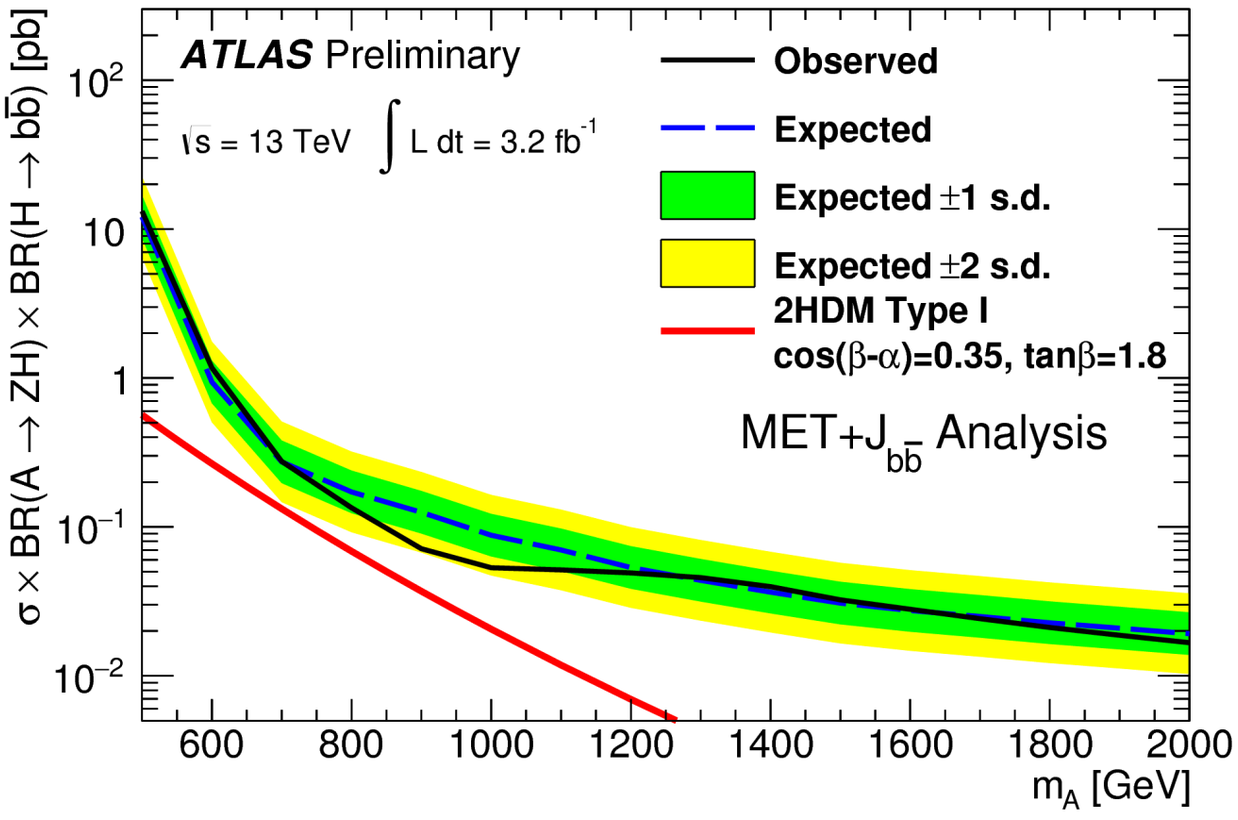
A → Zh → llbb and vvbb

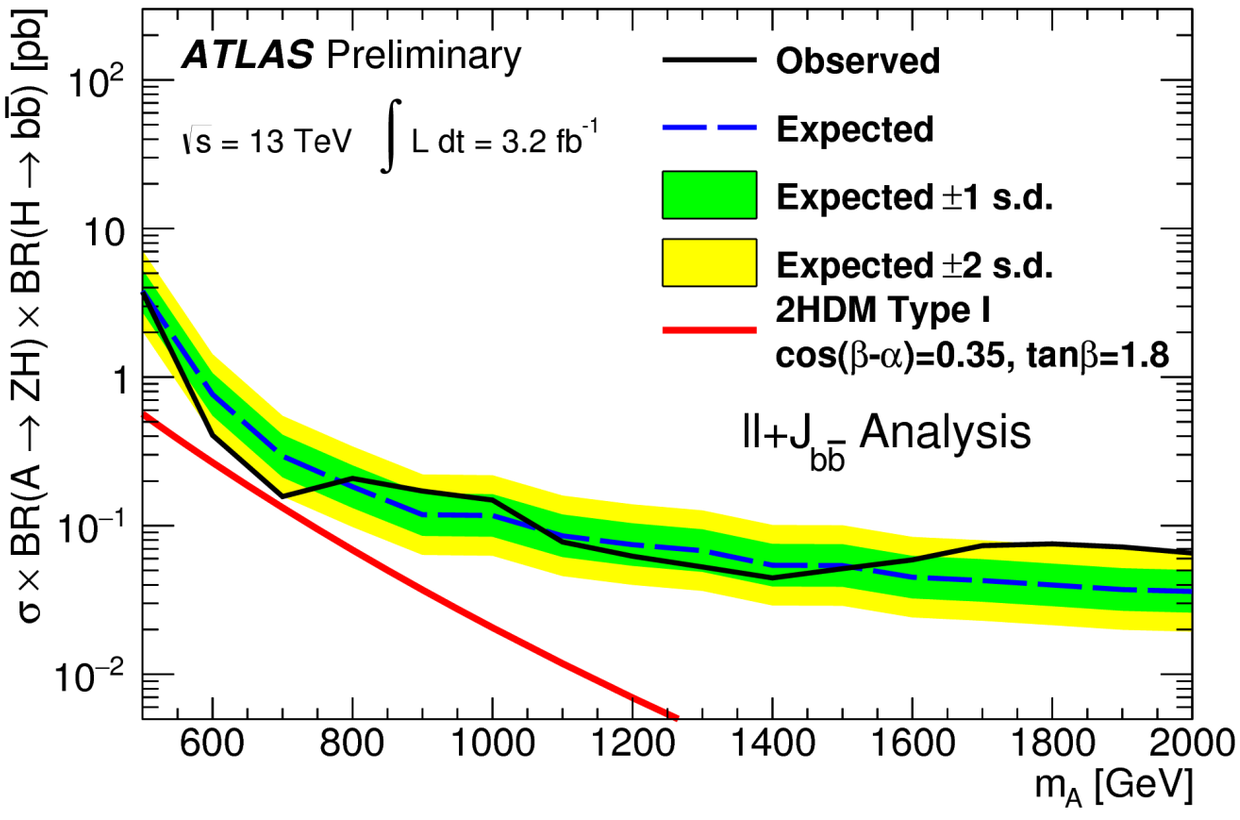
ATLAS-CONF-2015-074

A → Zh → llbb and vvbb

Analysis strategy:

- CP-odd scalar boson A search
- Large-R jet with:
  - 1 or 2 b-tags
  - 75 < mJ < 145 GeV





$H \rightarrow WW \rightarrow l\nu l\nu$

ATL-CONF-2016-074

H → WW → lvlv

- Signal regions:

Table 1: Selection cuts used in the ggF and VBF signal regions. The $\mathrm{SR_{VBF1J}}$ phase space corresponds to $N_{\mathrm{jet}} = 1$: $|\eta_j| > 2.4$ and $\min(|\Delta\eta_{j\ell}|) > 1.75$ while the $\mathrm{SR_{VBF2J}}$ phase space to $N_{\mathrm{jet}} \geq 2$: $m_{jj} > 500\,\mathrm{GeV}$ and $|\Delta y_{jj}| > 4$. These sets of cuts ensure the orthogonality with respect to the $\mathrm{SR_{ggF}}$ category.

$\mathrm{SR_{ggF}}$	$\mathrm{SR_{VBF1J}}$	$\mathrm{SR_{VBF2J}}$
Preselection cuts: $p_{\mathrm{T}}^{\mathrm{lead}} > 25\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{sublead}} > 15\,\mathrm{GeV}$, 3rd lepton veto, $m_{\ell\ell} > 10\,\mathrm{GeV}$		
$N_{b\text{-jet}} = 0$ $\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$ $m_{\ell\ell} > 55\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\mathrm{lead}} > 45\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\mathrm{sublead}} > 30\,\mathrm{GeV}$ $\max(m_{\mathrm{T}}^{W}) > 50\,\mathrm{GeV}$		
Inclusive in N_{jet} but excluding VBF1J and VBF2J phase space	$N_{\mathrm{jet}} = 1$ $\lvert\eta_j\rvert > 2.4$ $\min(\lvert\Delta\eta_{j\ell}\rvert) > 1.75$	$N_{\mathrm{jet}} \geq 2$ $m_{jj} > 500\,\mathrm{GeV}$ $\lvert\Delta y_{jj}\rvert > 4$

H → WW → lvlv

- Control regions:

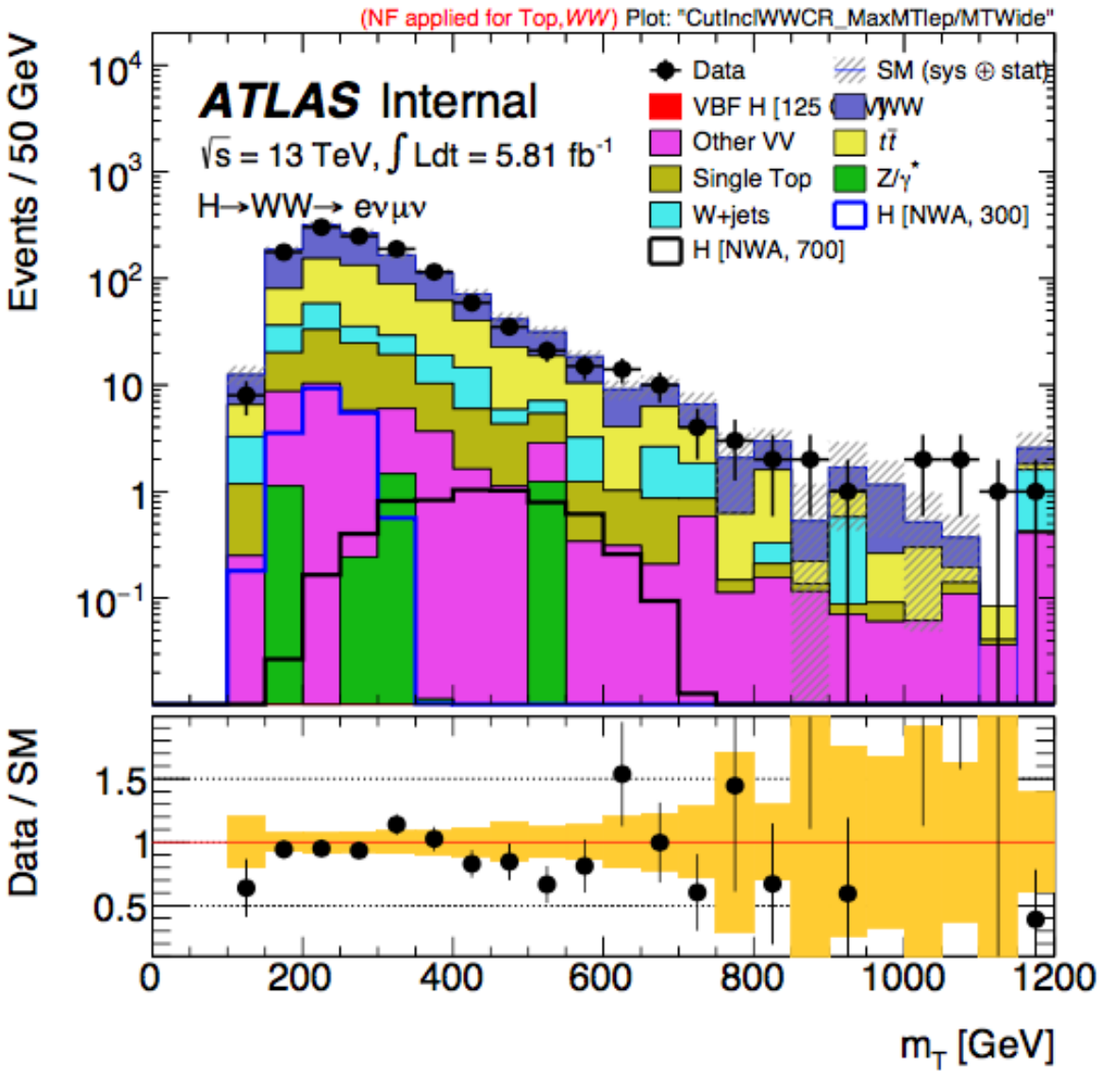
Table 2: Summary of all the selection cuts used in the ggF and VBF WW and top-quark control regions (CRs). The VBF 1J phase space corresponds to $N_{\text{jet}} = 1$: $|\eta_j| > 2.4$ and $\min(|\Delta\eta_{j\ell}|) > 1.75$ while the VBF 2J phase space to $N_{\text{jet}} \geq 2$: $m_{jj} > 500\,\text{GeV}$ and $|\Delta y_{jj}| > 4$.

WW CR_{ggF}	Top CR_{ggF}	WW CR_{VBF1J}	Top CR_{VBF}
Preselection cuts: $p_{\text{T}}^{\text{lead}} > 25\,\text{GeV}$, $p_{\text{T}}^{\text{sublead}} > 15\,\text{GeV}$, 3rd lepton veto, $m_{\ell\ell} > 10\,\text{GeV}$			
$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} \geq 1$
$\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$	$\lvert\Delta\eta_{\ell\ell}\rvert < 1.8$	($\lvert\Delta\eta_{\ell\ell}\rvert > 1.8$ or	–
$m_{\ell\ell} > 55\,\text{GeV}$		$m_{\ell\ell} < 55\,\text{GeV}$)	–
$p_{\text{T}}^{\text{lead}} > 45\,\text{GeV}$		$p_{\text{T}}^{\text{lead}} > 25\,\text{GeV}$	$p_{\text{T}}^{\text{lead}} > 25\,\text{GeV}$
$p_{\text{T}}^{\text{sublead}} > 30\,\text{GeV}$		$p_{\text{T}}^{\text{sublead}} > 25\,\text{GeV}$	$p_{\text{T}}^{\text{sublead}} > 15\,\text{GeV}$
$\max(m_{\text{T}}^{W}) > 50\,\text{GeV}$		–	–
Excluding VBF VBF1J and VBF2J		VBF1J phase space	VBF1J or VBF2J phase space

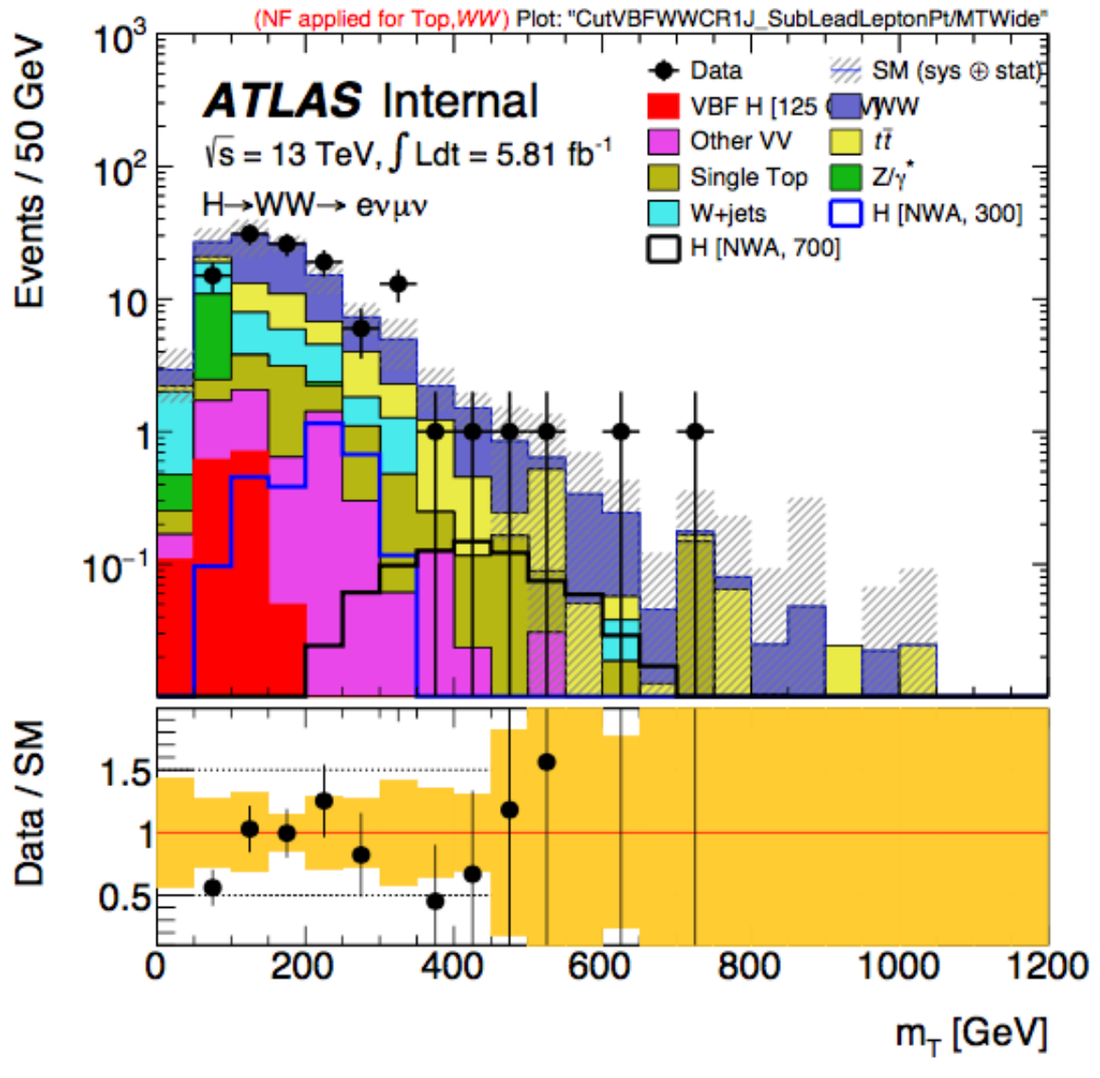
H → WW → lνlν

WW control regions:

- High $|\Delta\eta_{ll}|$



ggF

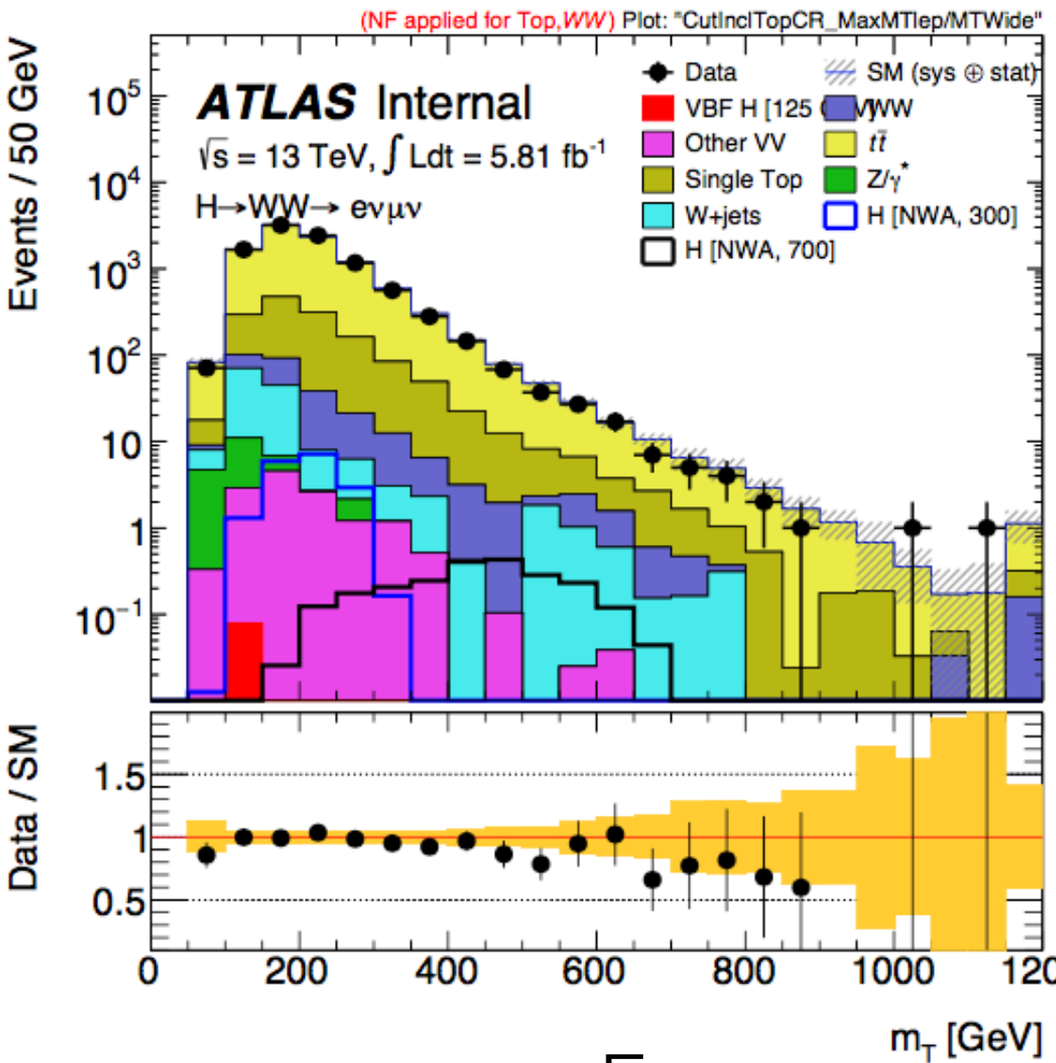


VBF 1-jet

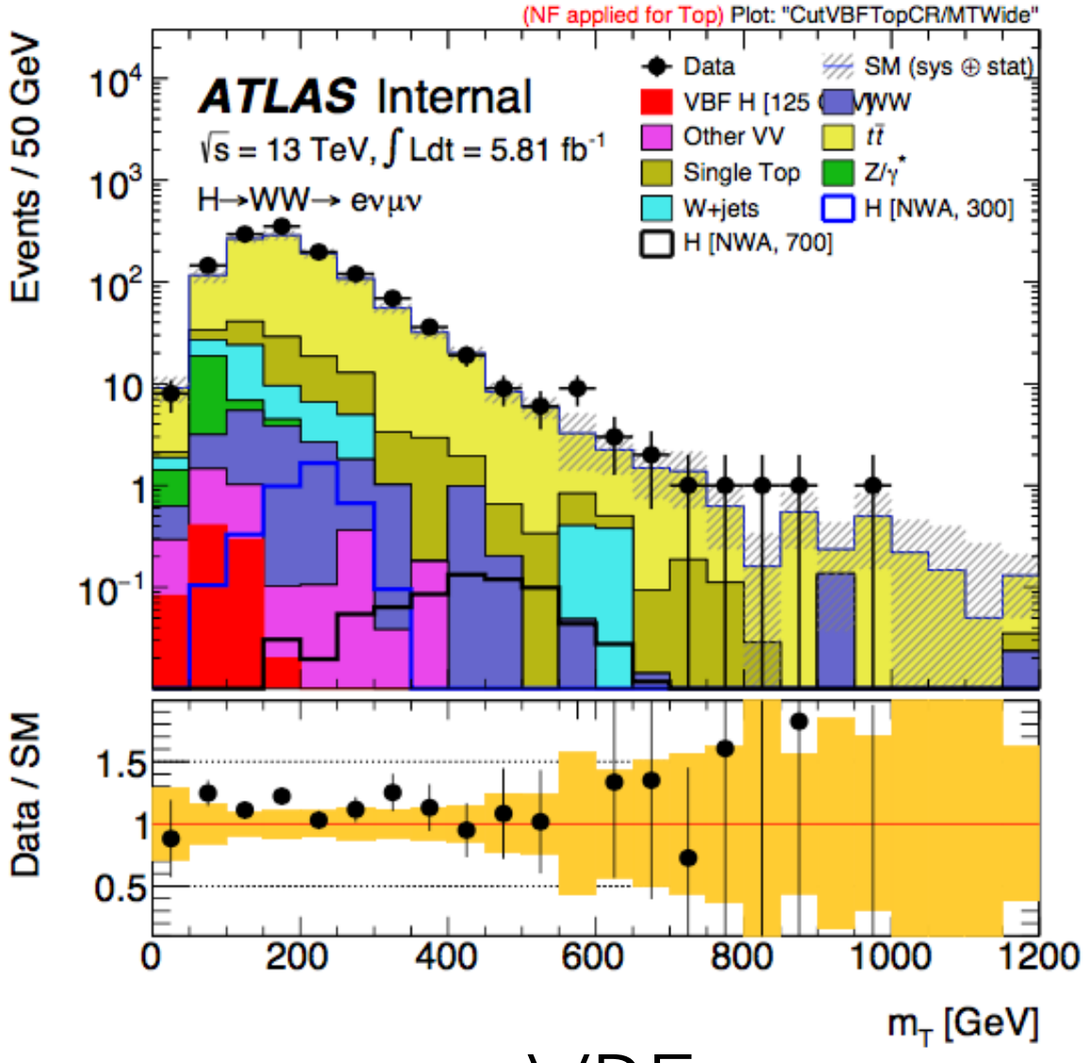
H → WW → lνlν

Top control regions:

- Require b-tagged jet



ggF



VBF

$H \rightarrow WW \rightarrow lvqq$

ATL-CONF-2016-062

H → WV → lvqq

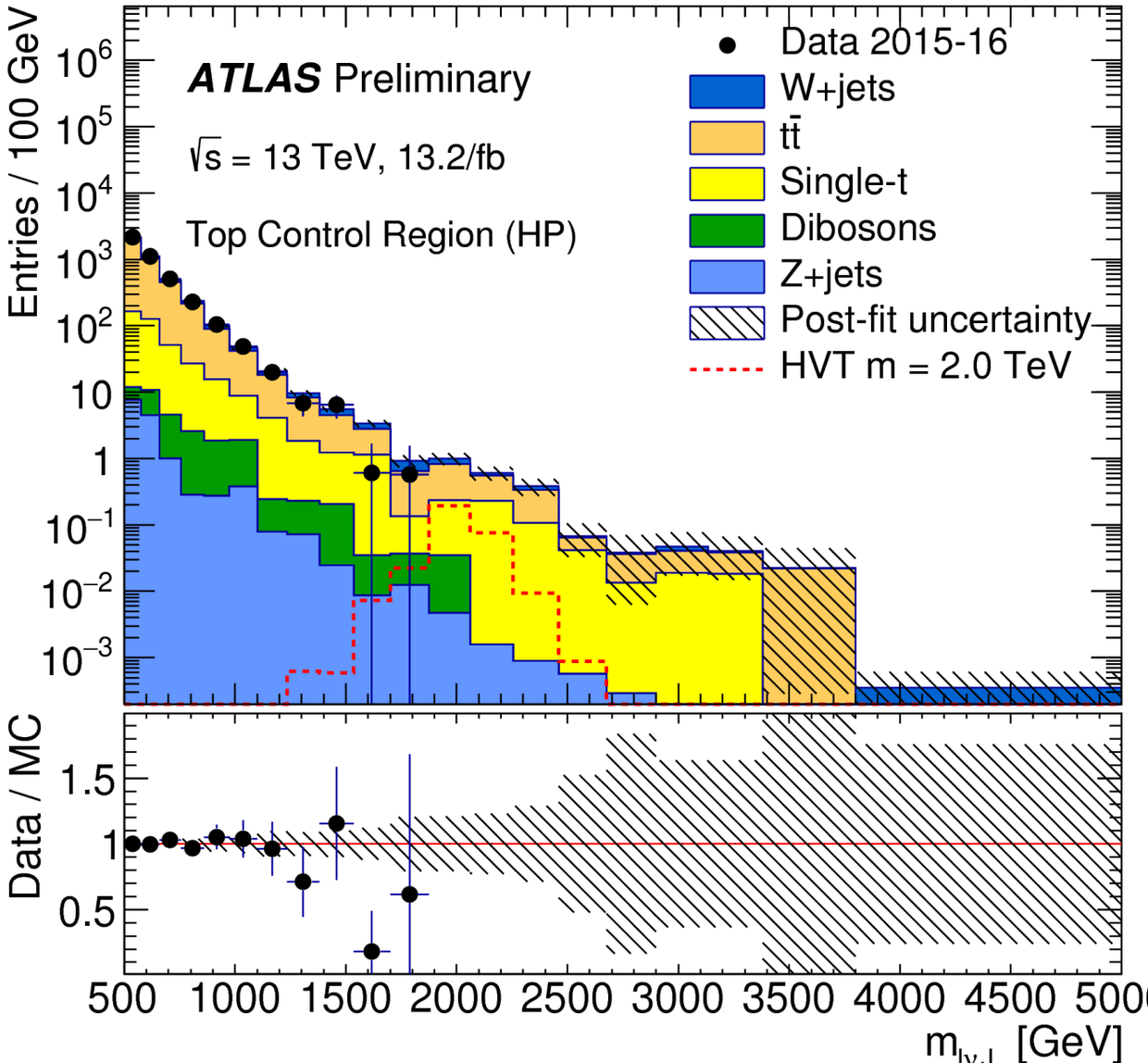
Event Selection:

Table 1: Summary of selection criteria used to define the signal region (SR), W+jets control region (CR) and $t\bar{t}$ control region, in the high-purity (HP) and low-purity (LP) categories.

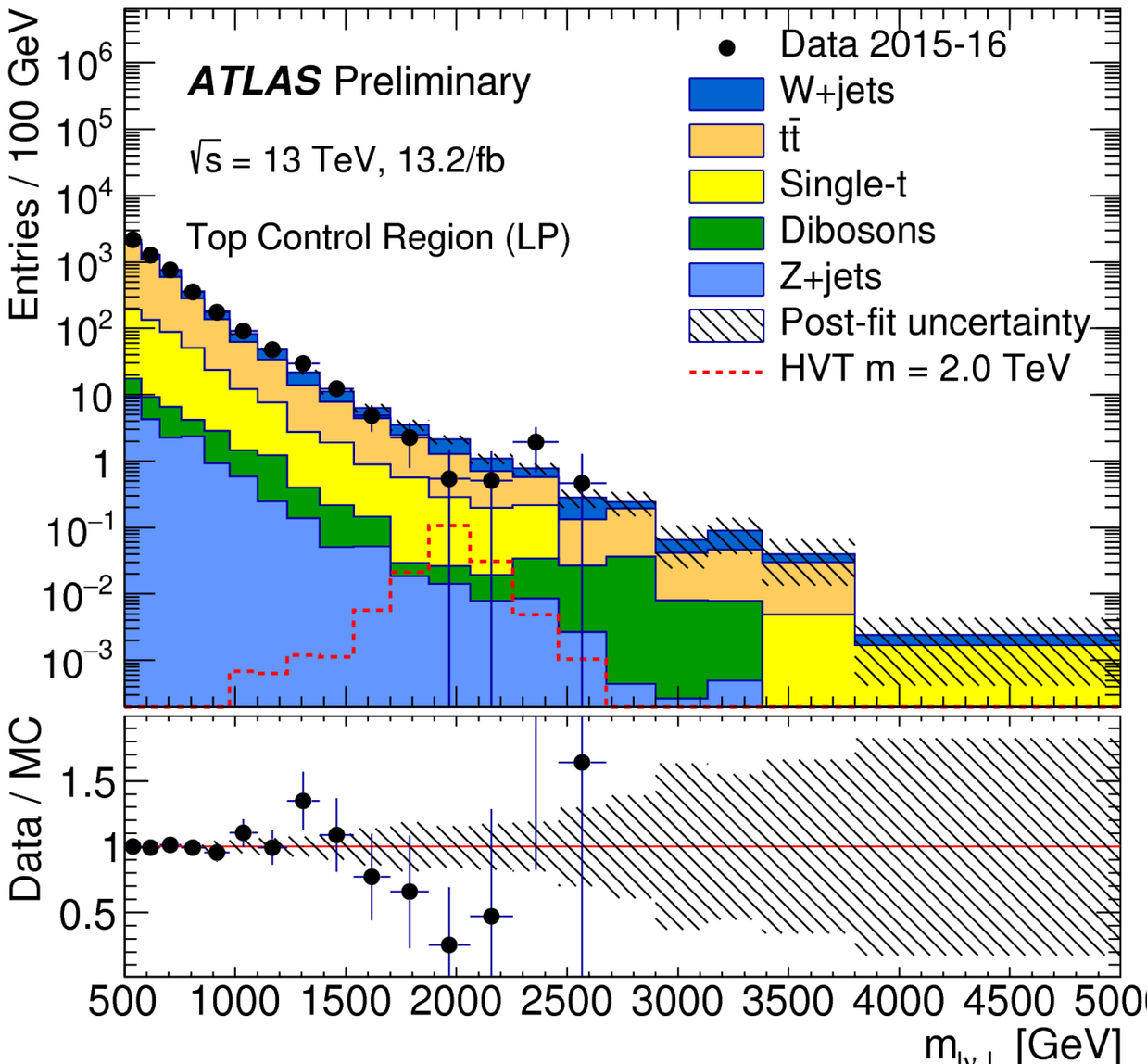
Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
$W \to \ell\nu$ selection	Number of signal leptons	1		
	Number of vetoed leptons	0		
	Number of vetoed leptons	0		
	$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 100\,GeV$		
	$p_{\mathrm{T}}(\ell\nu)$	$> 200\,GeV$		
$W/Z \to J$ selection	Number of large-R jets	≥ 1		
	Passing the $D_2^{(\beta=1)}$ cut	yes (no)	yes (no)	yes (no)
	$\lvert m_{W/Z} - m_J \rvert$	< 15 GeV	> 15 GeV	< 15 GeV
Topology cuts	$p_{\mathrm{T}}(\ell\nu)/m_{WV}$ $p_{\mathrm{T}}(J)/m_{WV}$	> 0.4		
Top-quark veto	Number of b-tagged jets	0		≥ 1

H → WW → lvqq

Top control regions:



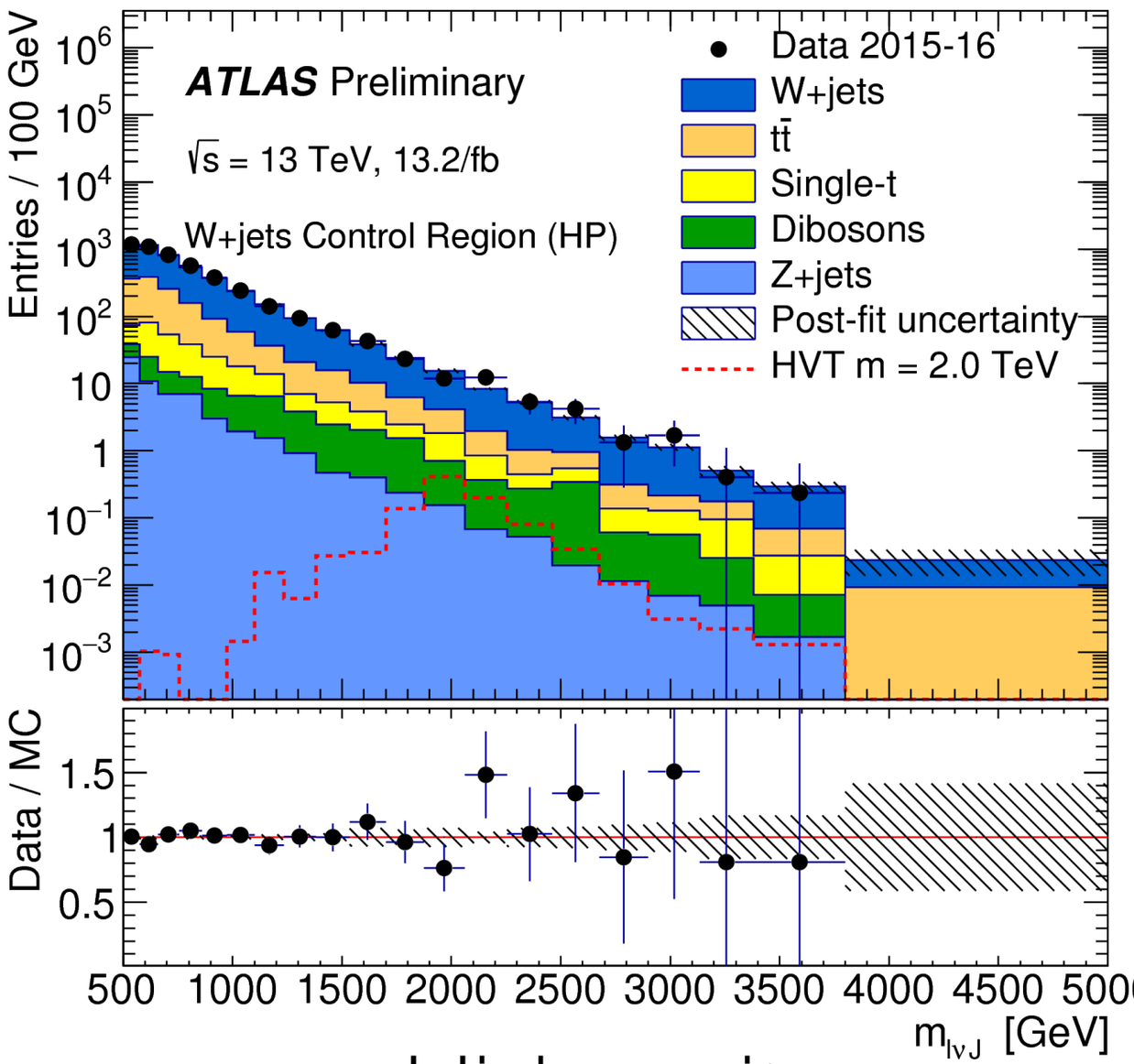
High purity



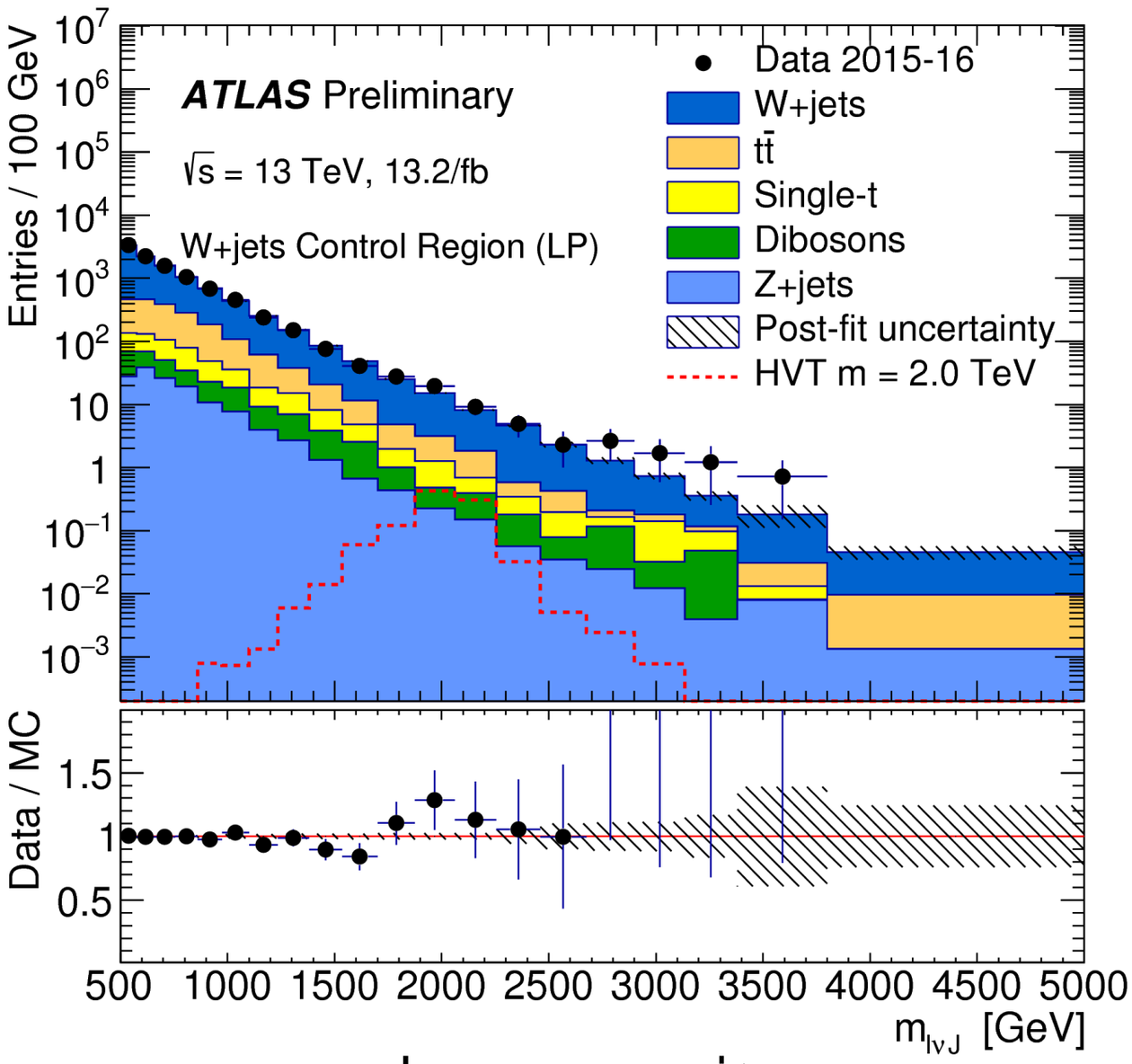
Low purity

H → WW → lvqq

W+jets control regions:



High purity



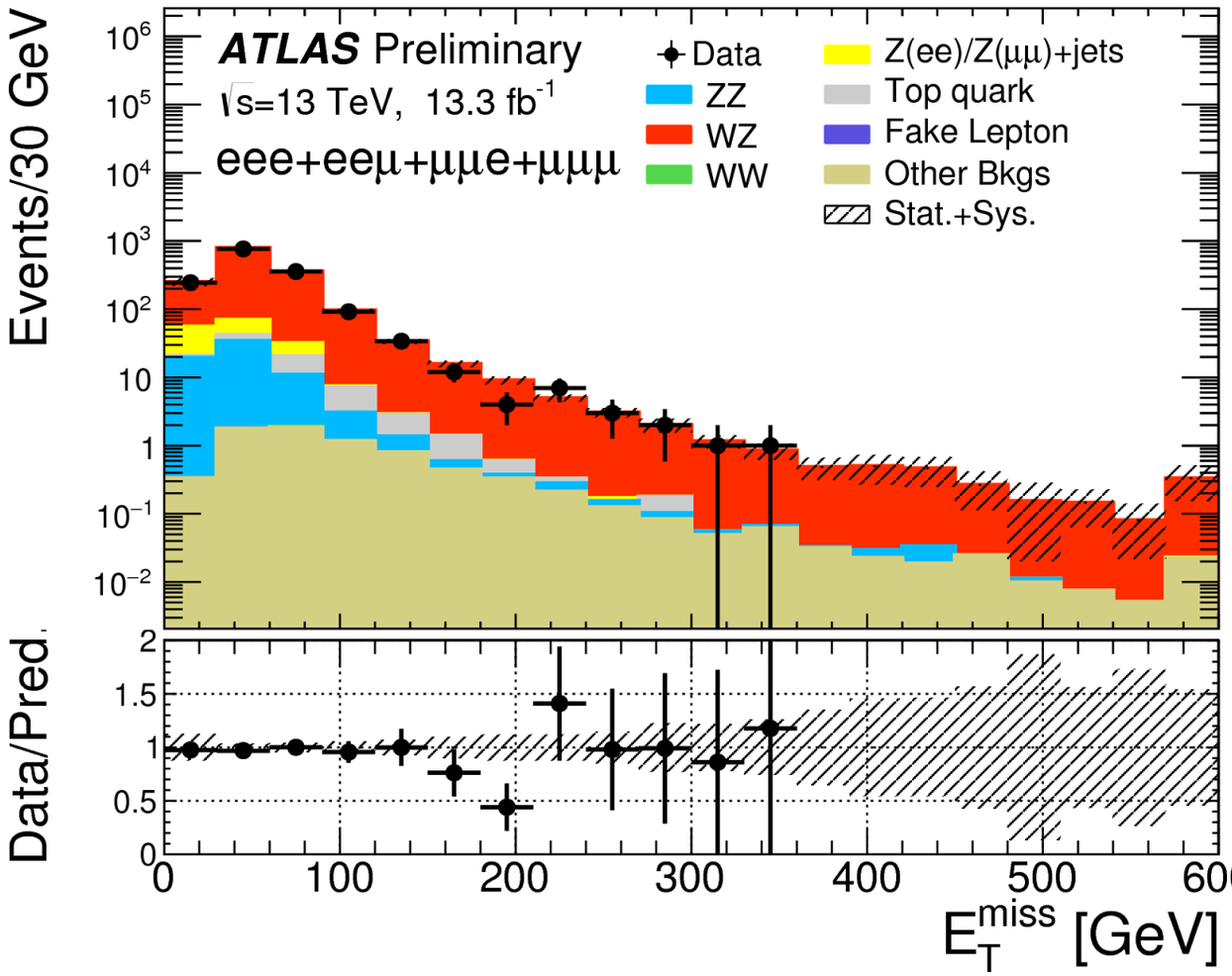
Low purity

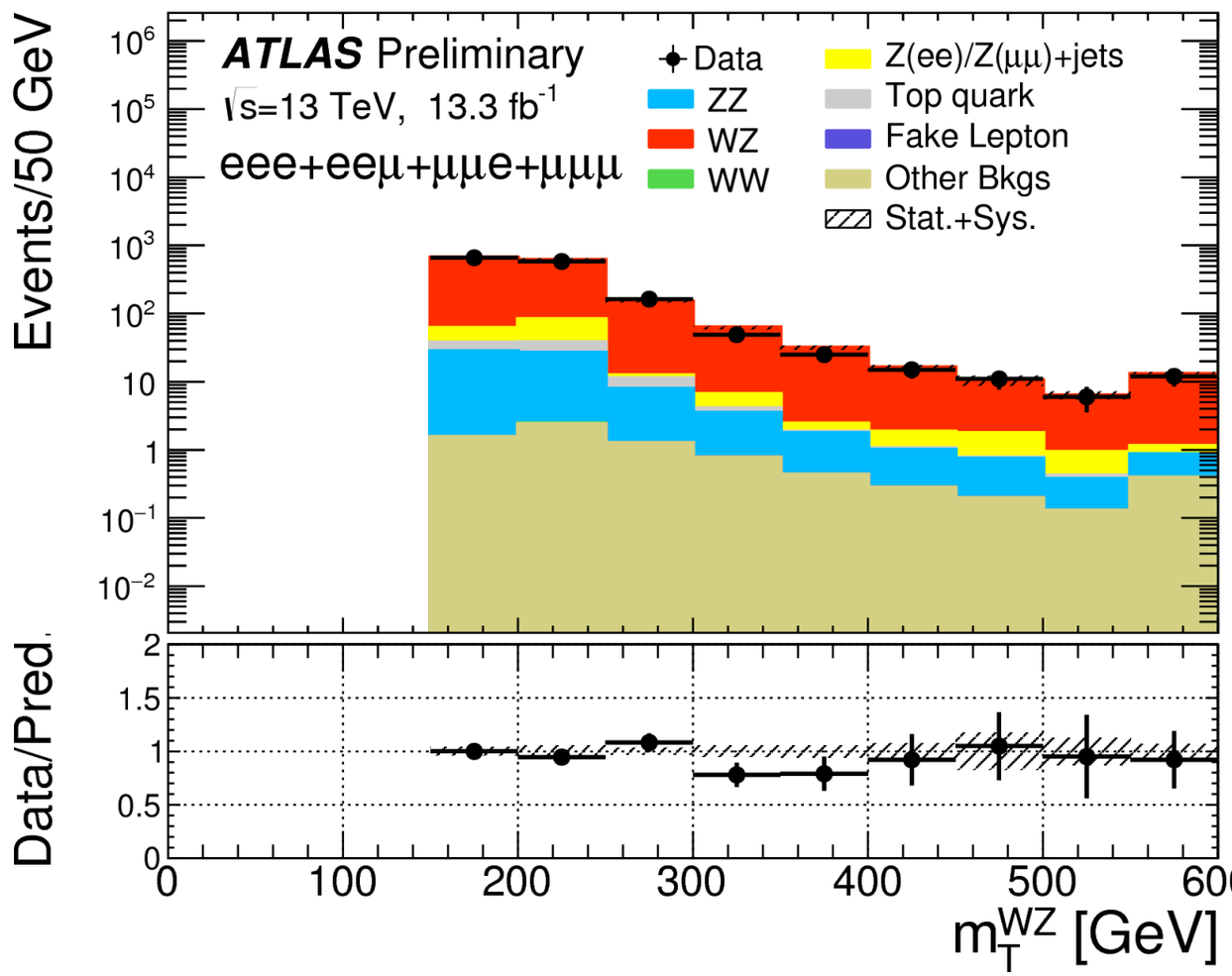
$H \rightarrow ZZ \rightarrow llvv$

ATL-CONF-2016-056

H → ZZ → llνν

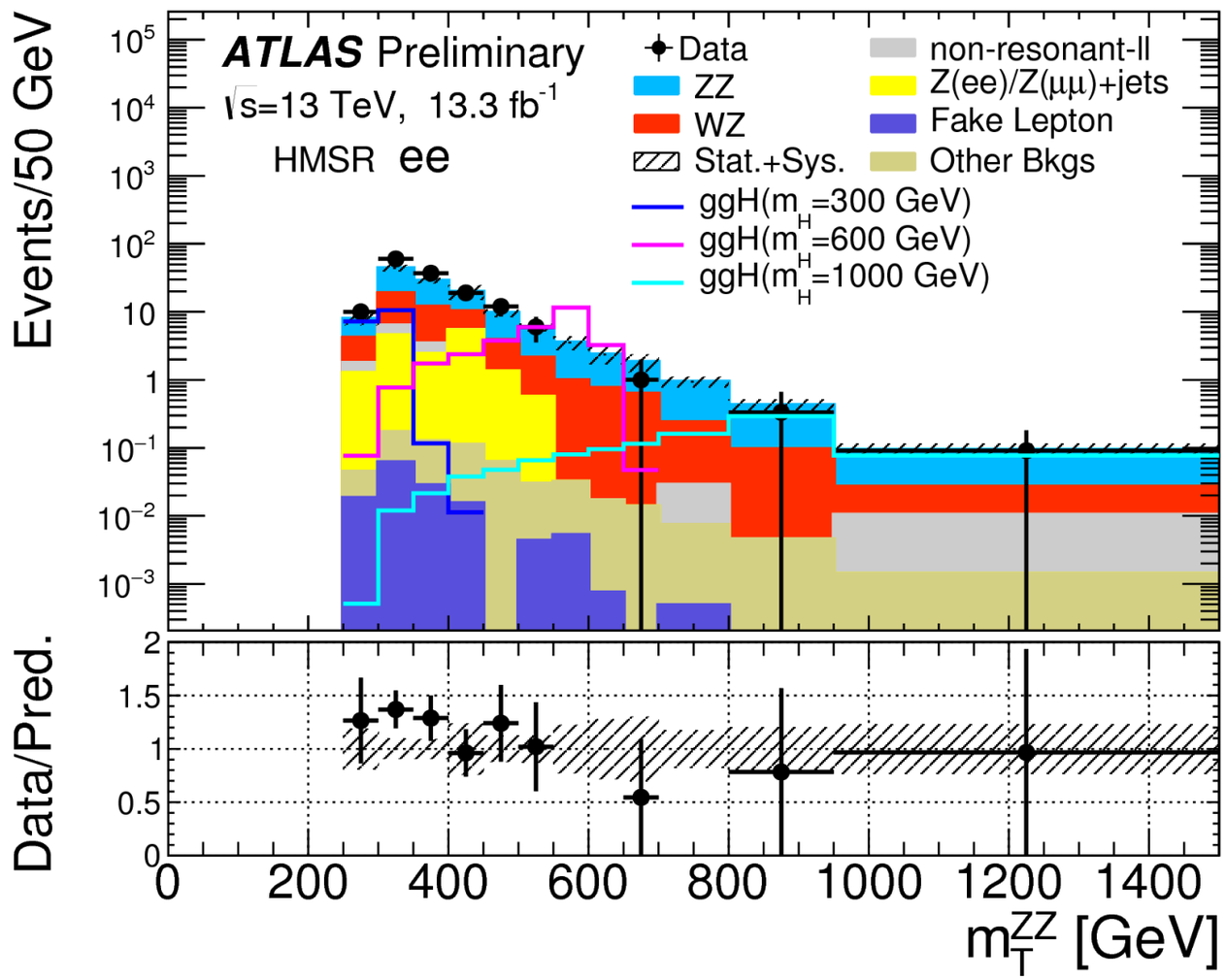
WZ control regions:

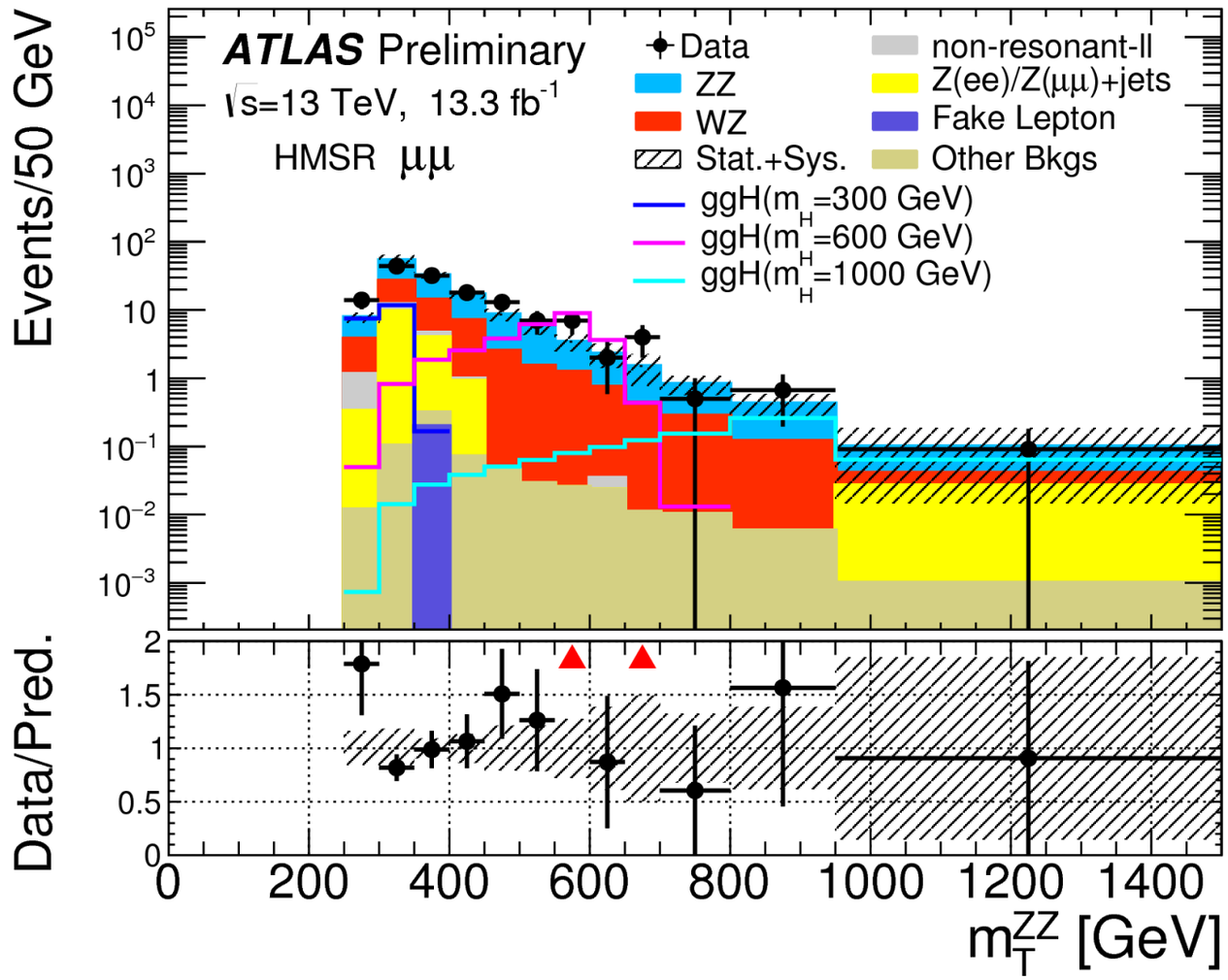




H → ZZ → llνν

Signal region (flavor split):



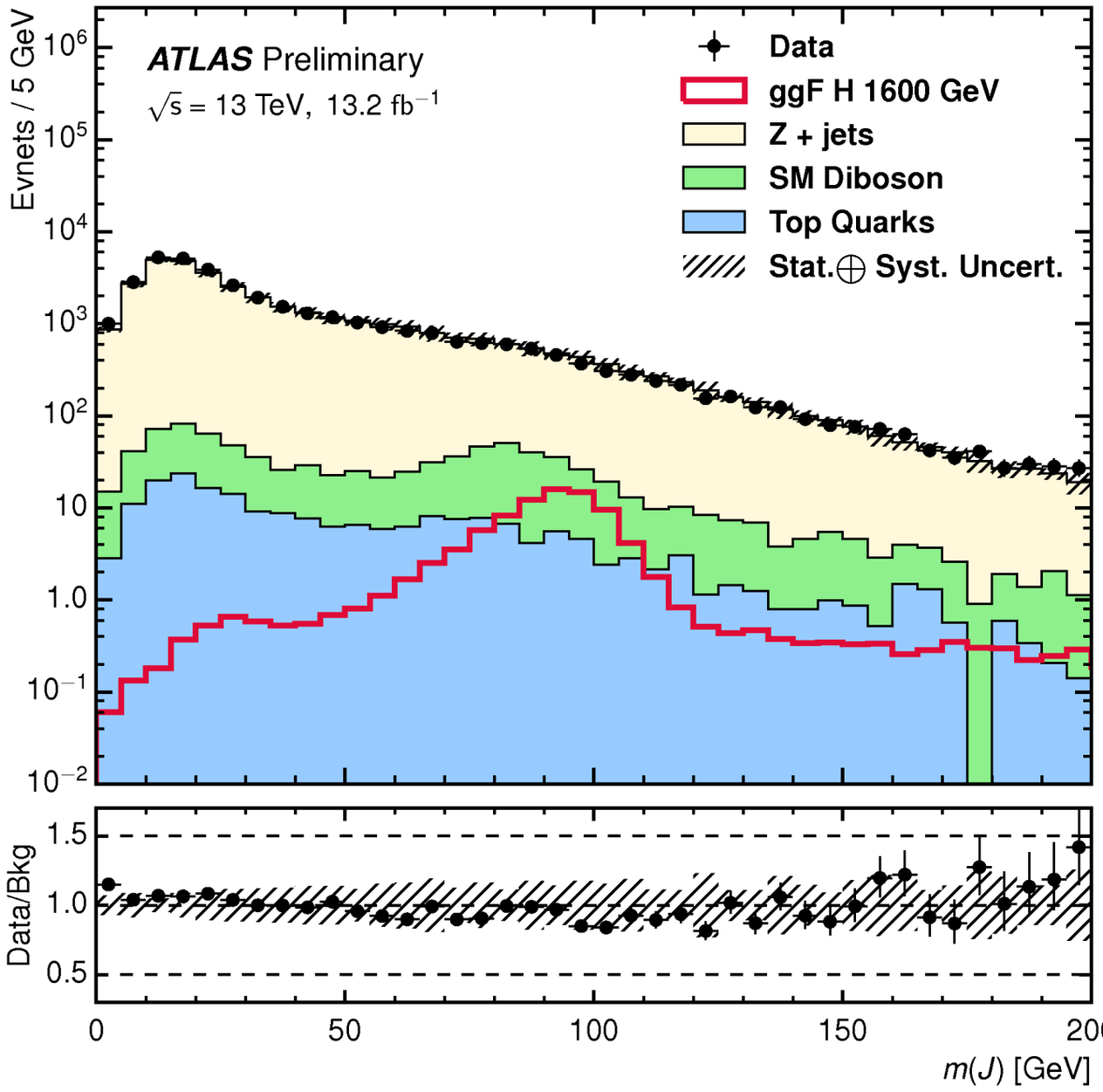


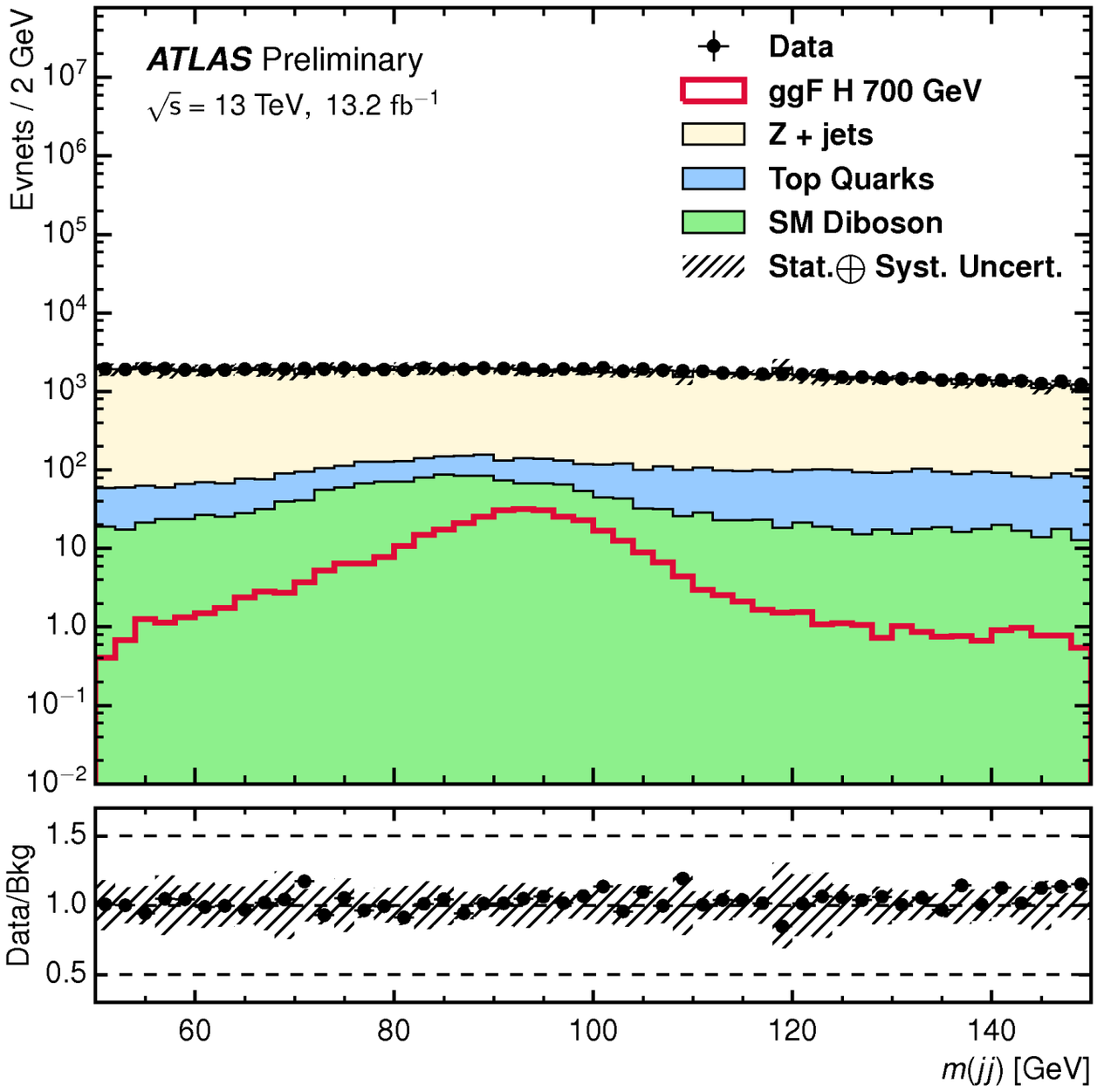
$H \rightarrow ZZ \rightarrow llqq$

ATL-CONF-2016-082

H → ZZ → llqq

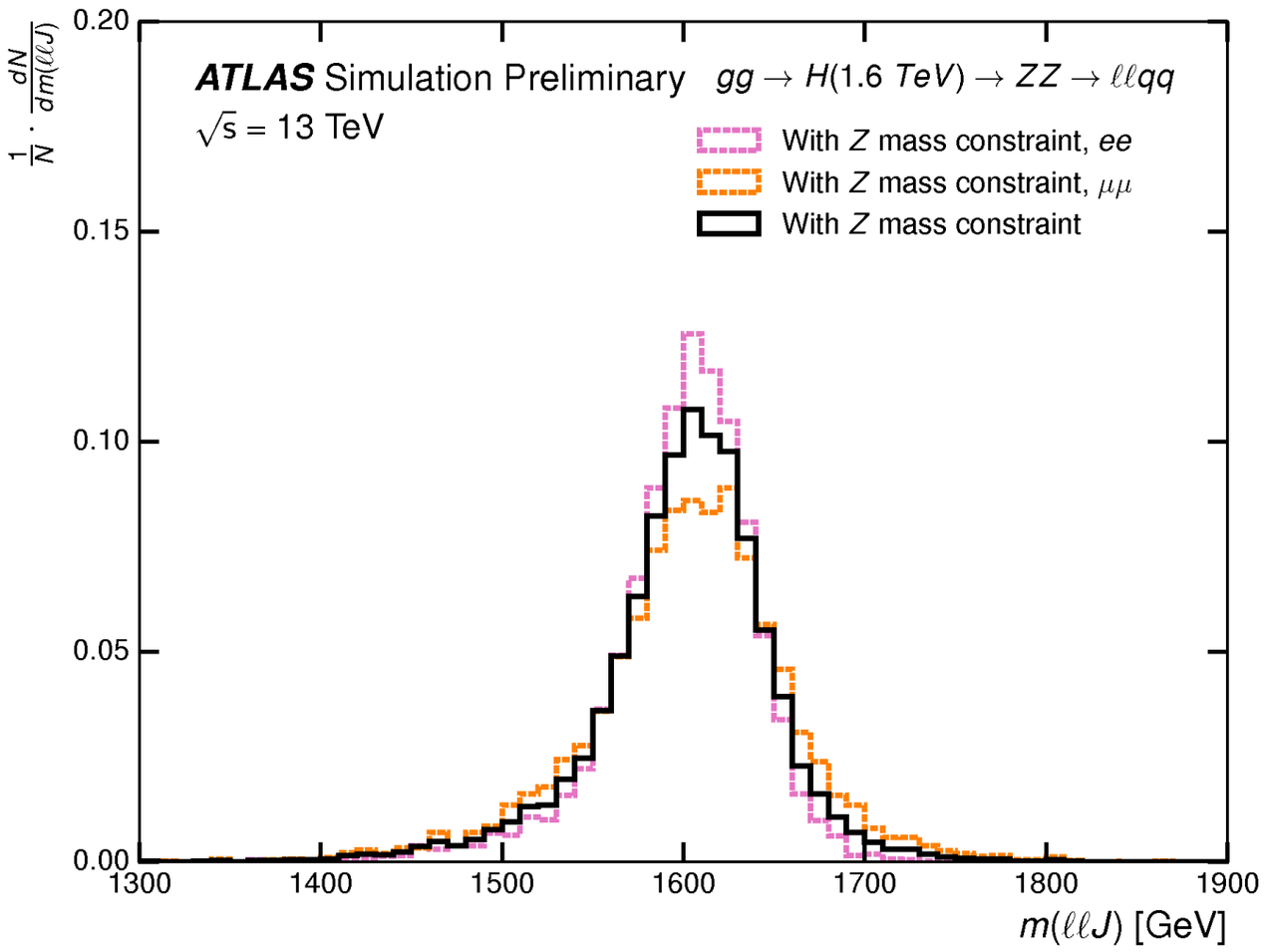
Jet-mass reconstruction:

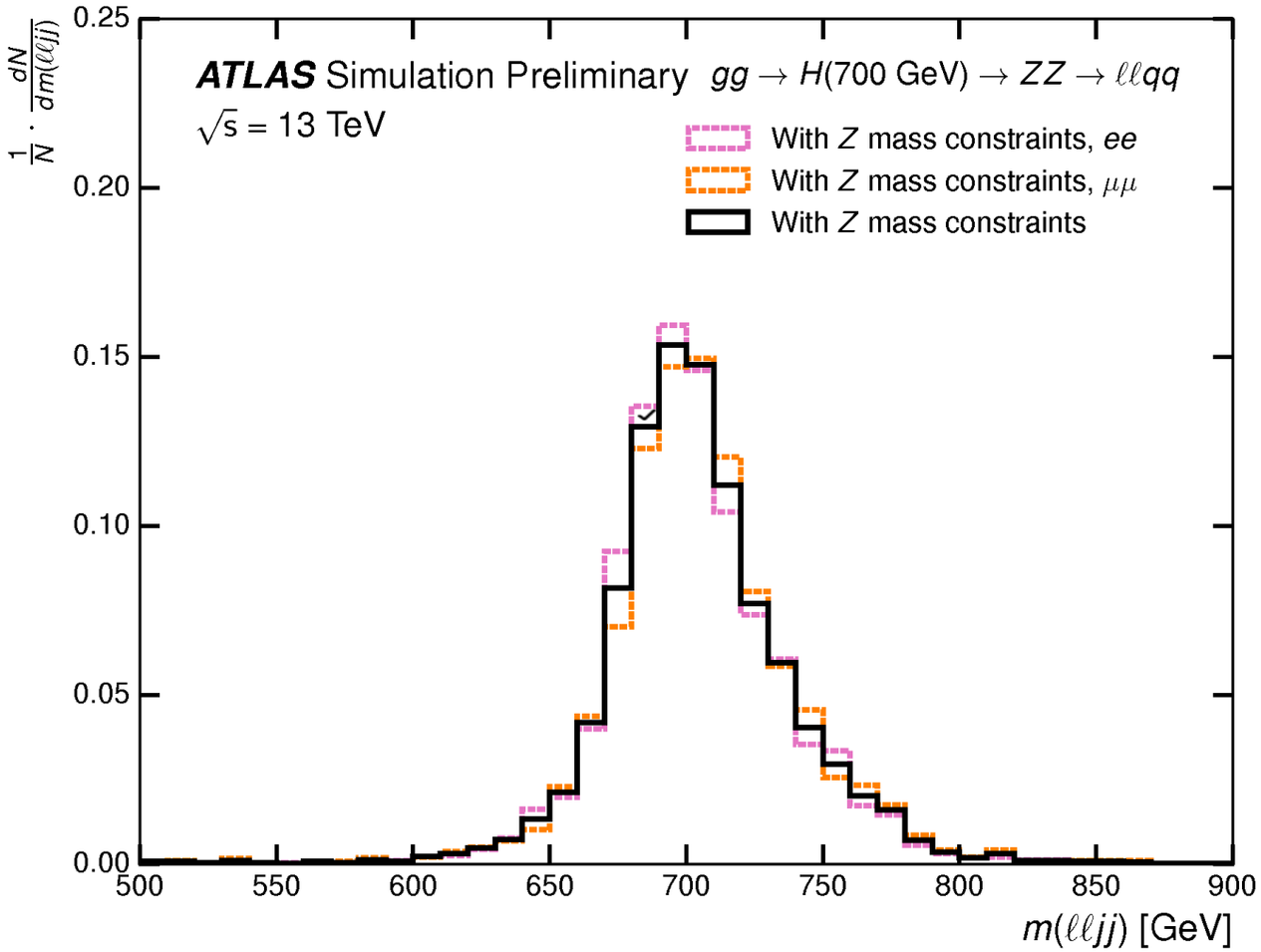




H → ZZ → llqq

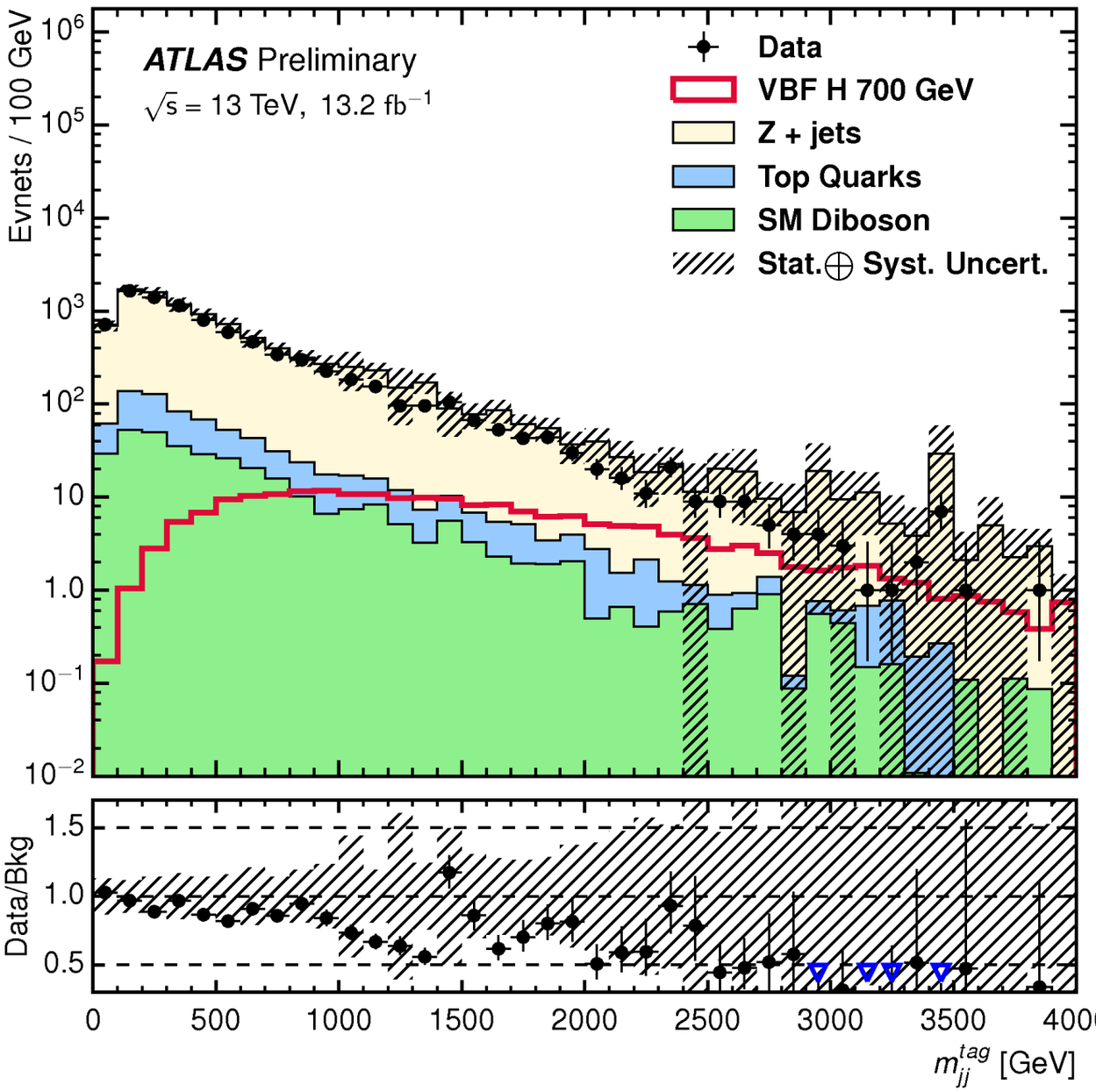
Higgs-boson mass reconstruction:

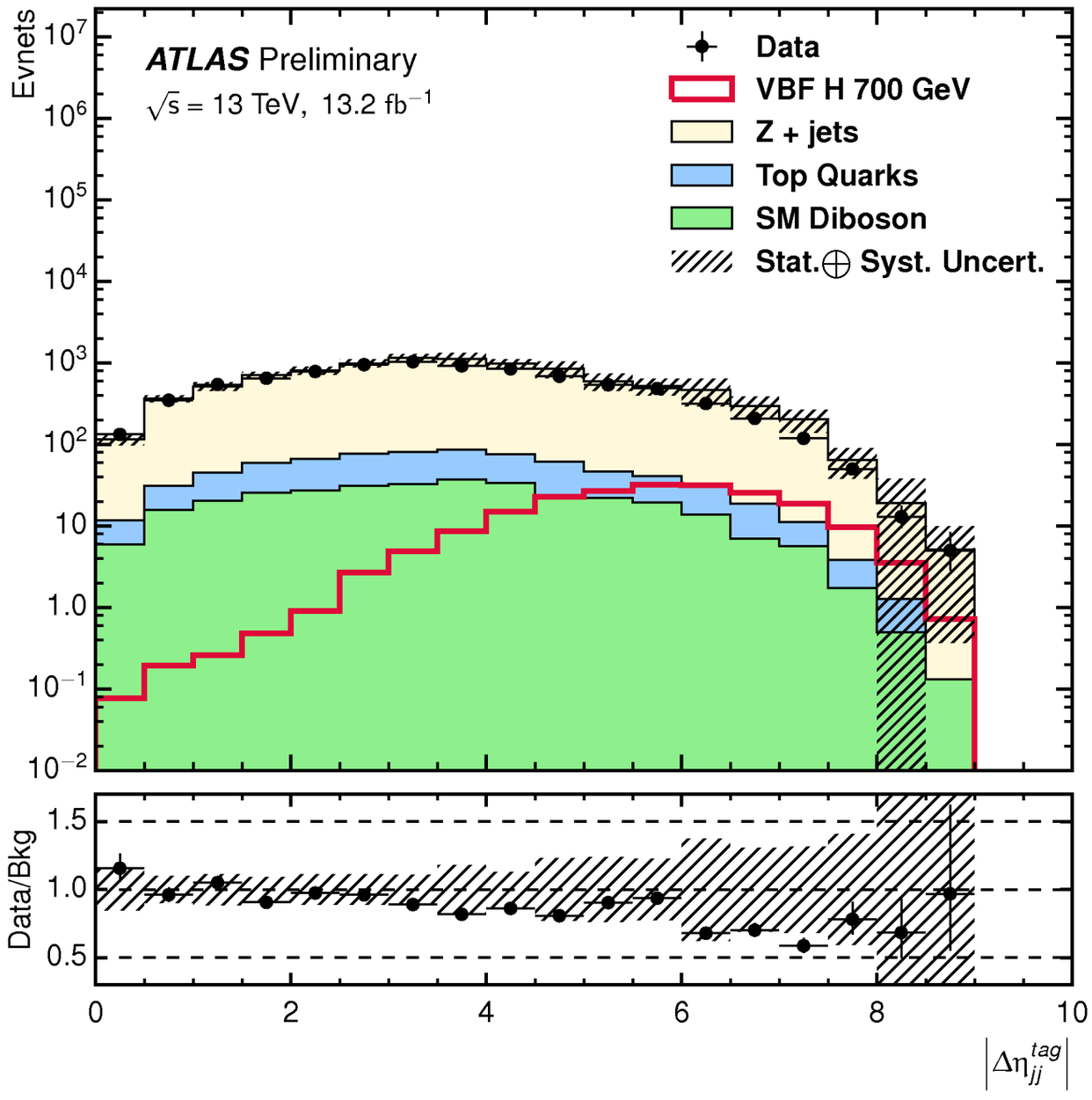




H → ZZ → llqq

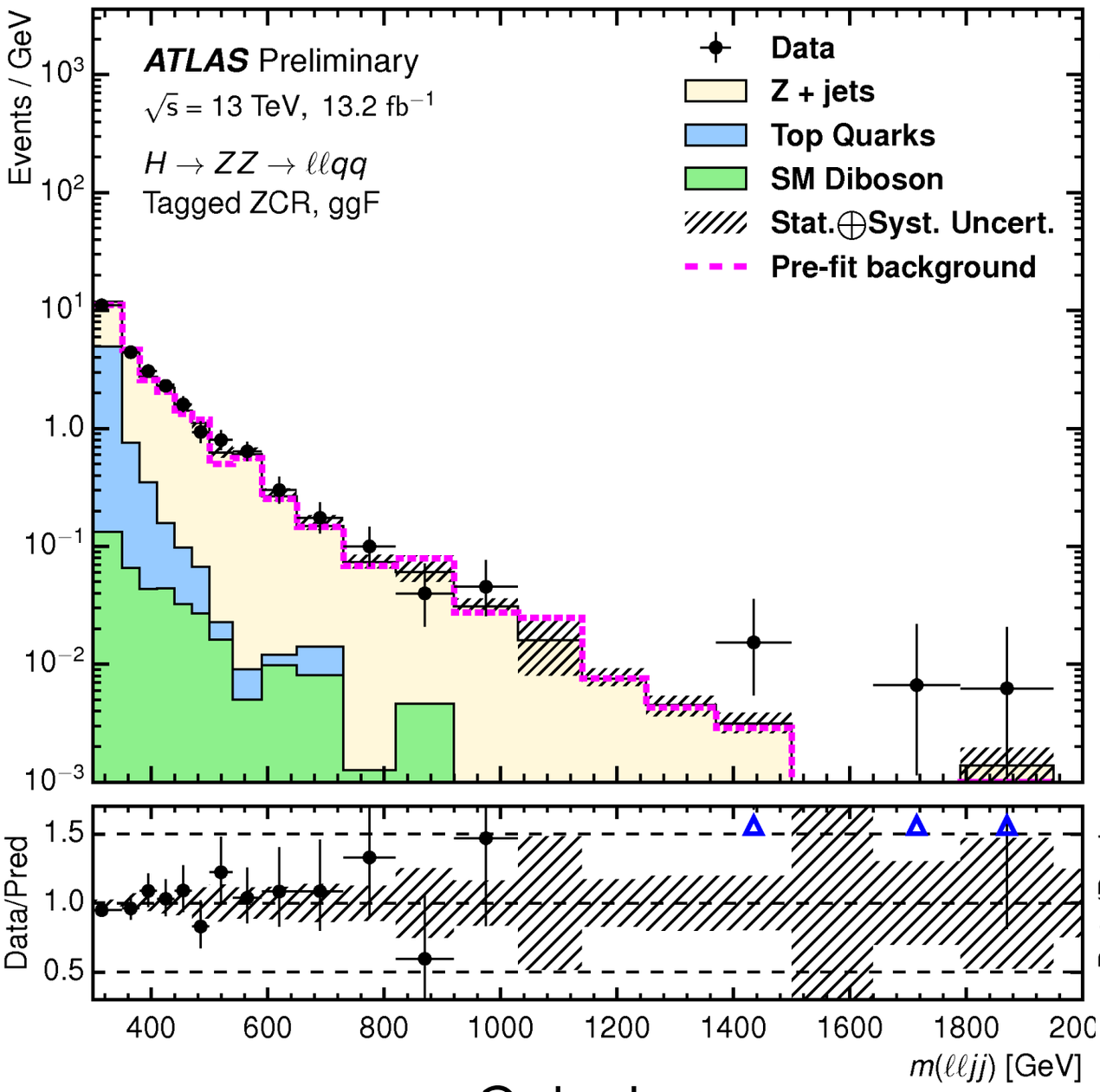
VBF topology:



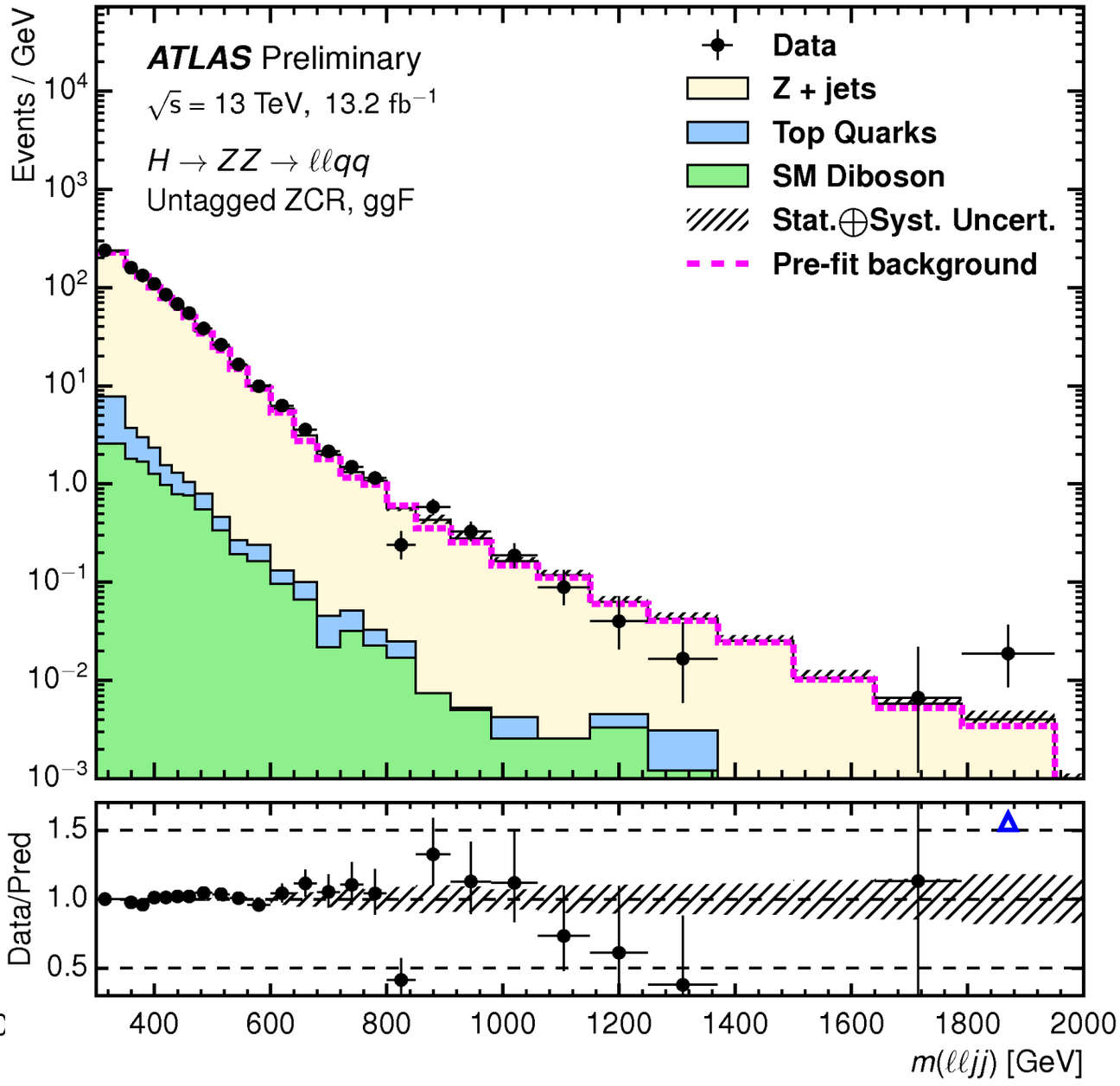


H → ZZ → llqq

Z control regions (resolved Z → jj):



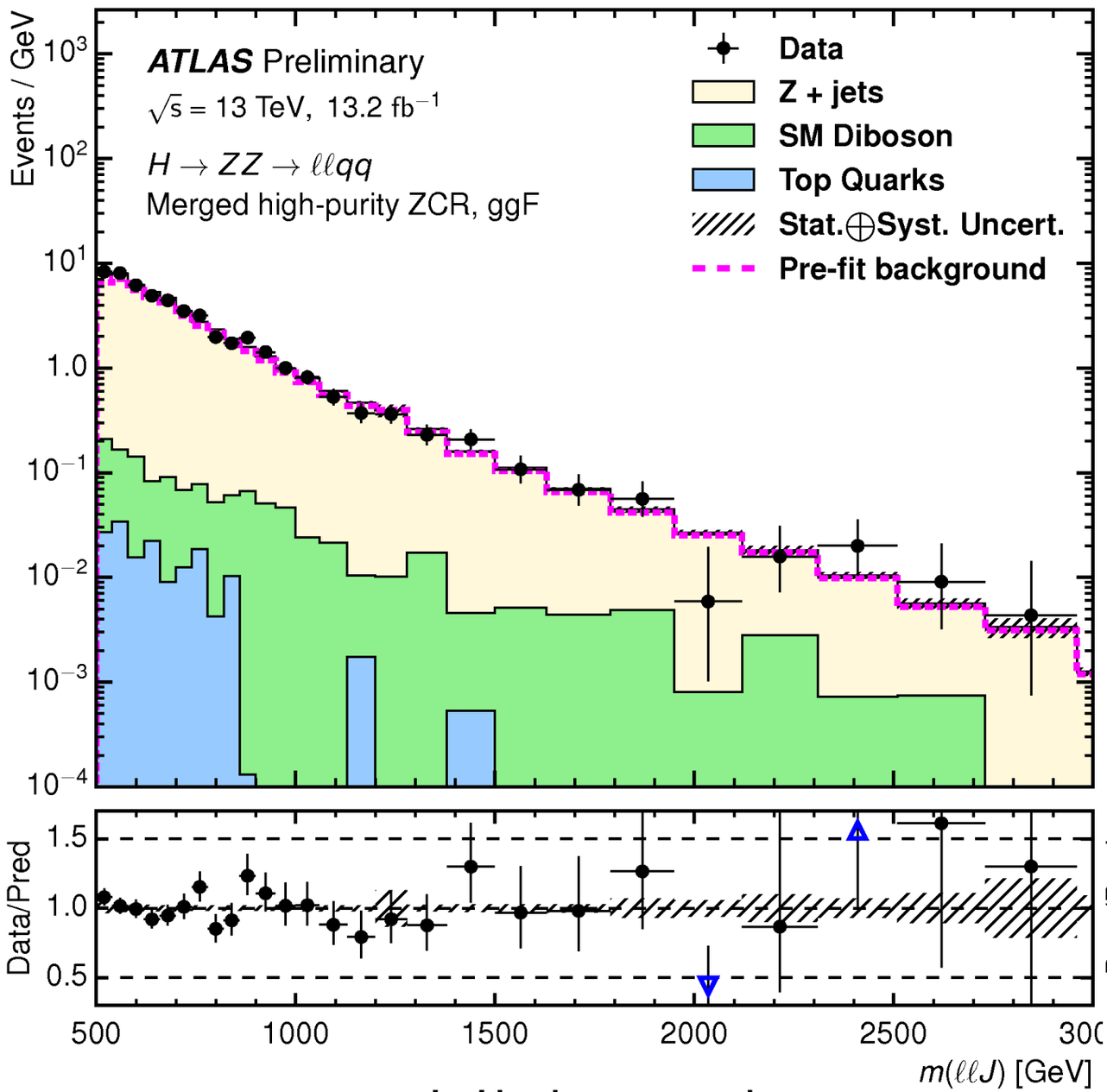
2 b-jets



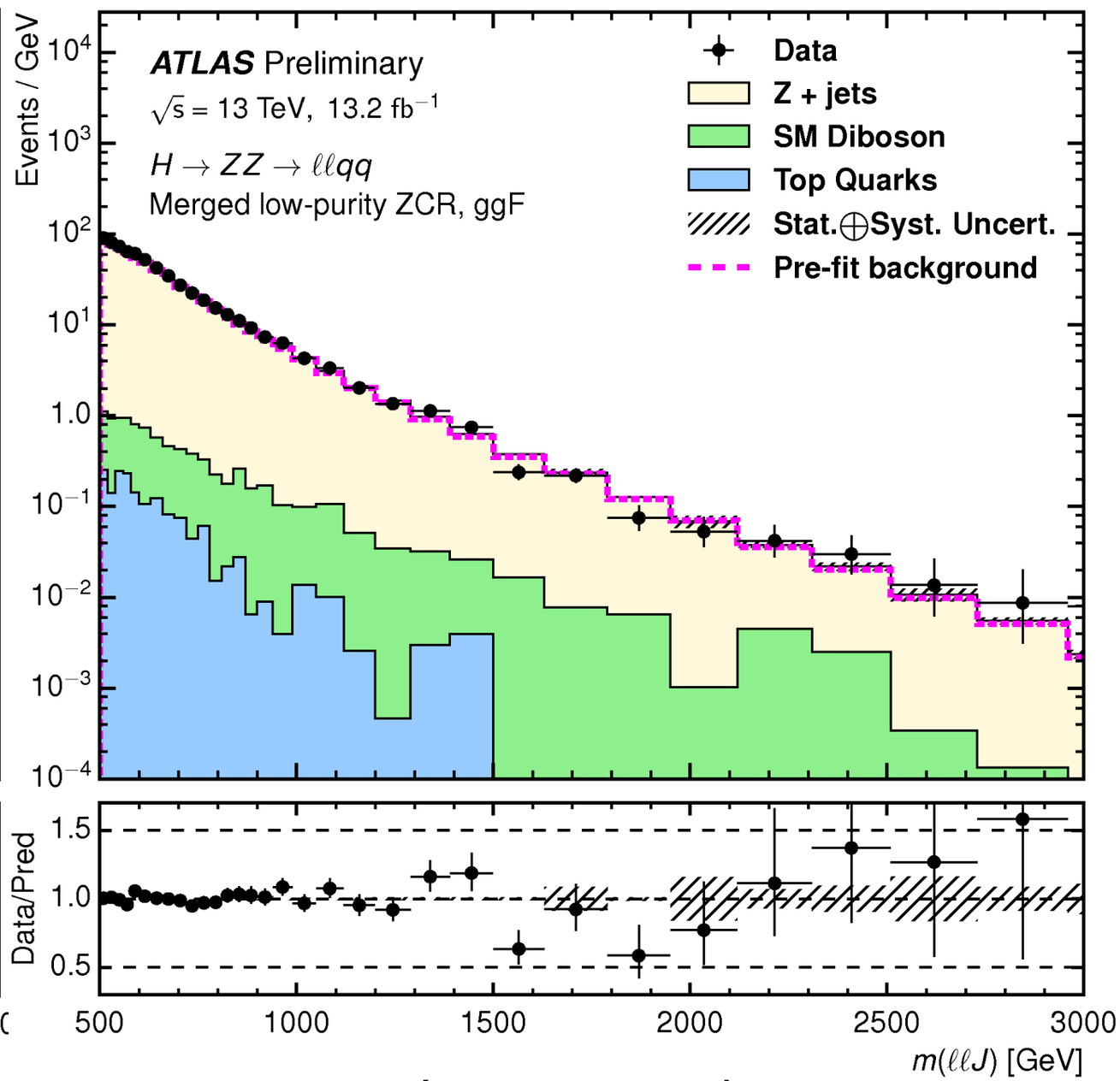
≤1 b-jet

H → ZZ → llqq

Z control regions (merged Z → J):



High purity



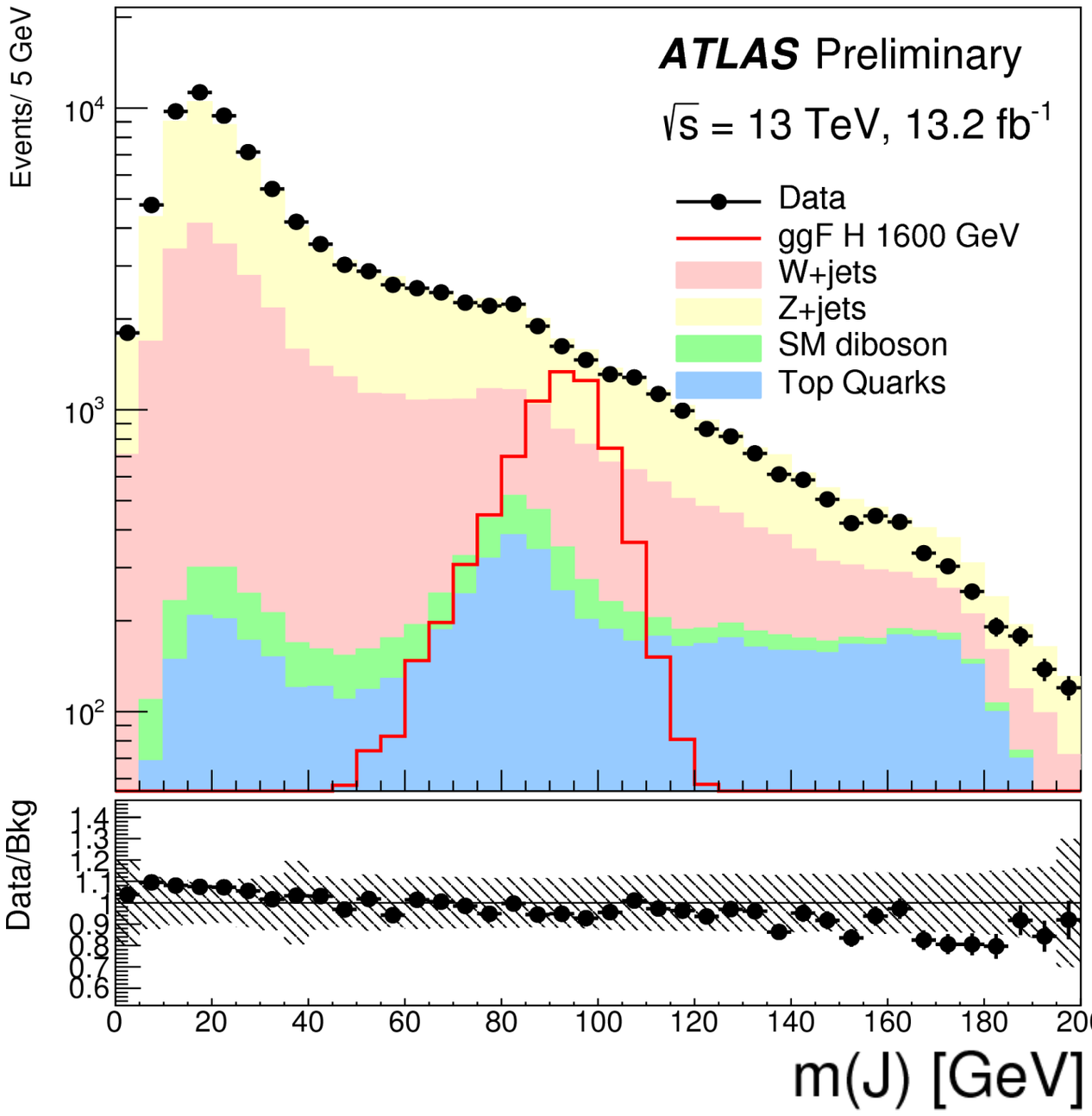
Low purity

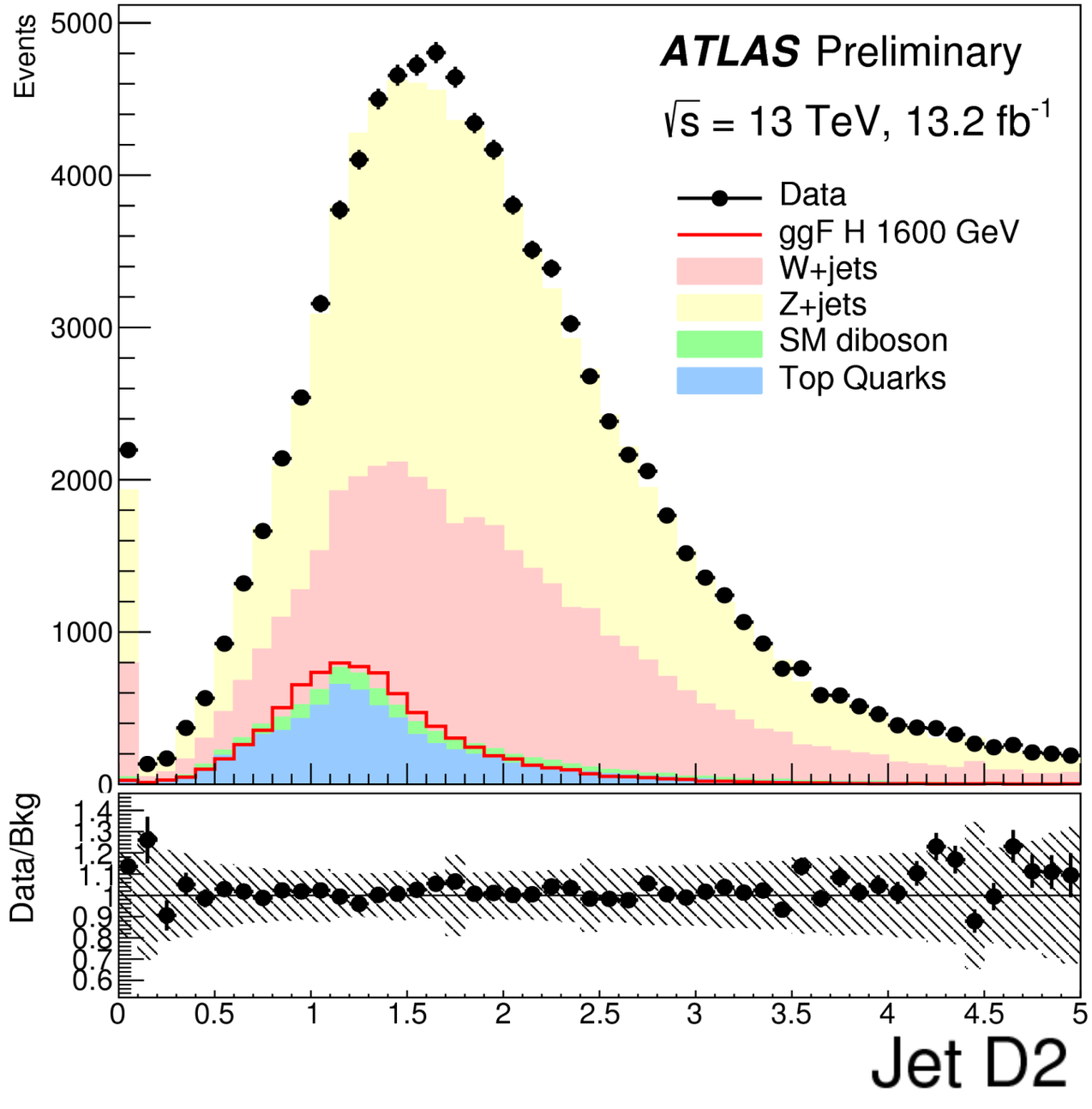
$H \rightarrow ZZ \rightarrow \nu\nu qq$

ATL-CONF-2016-082

H → ZZ → ννqq

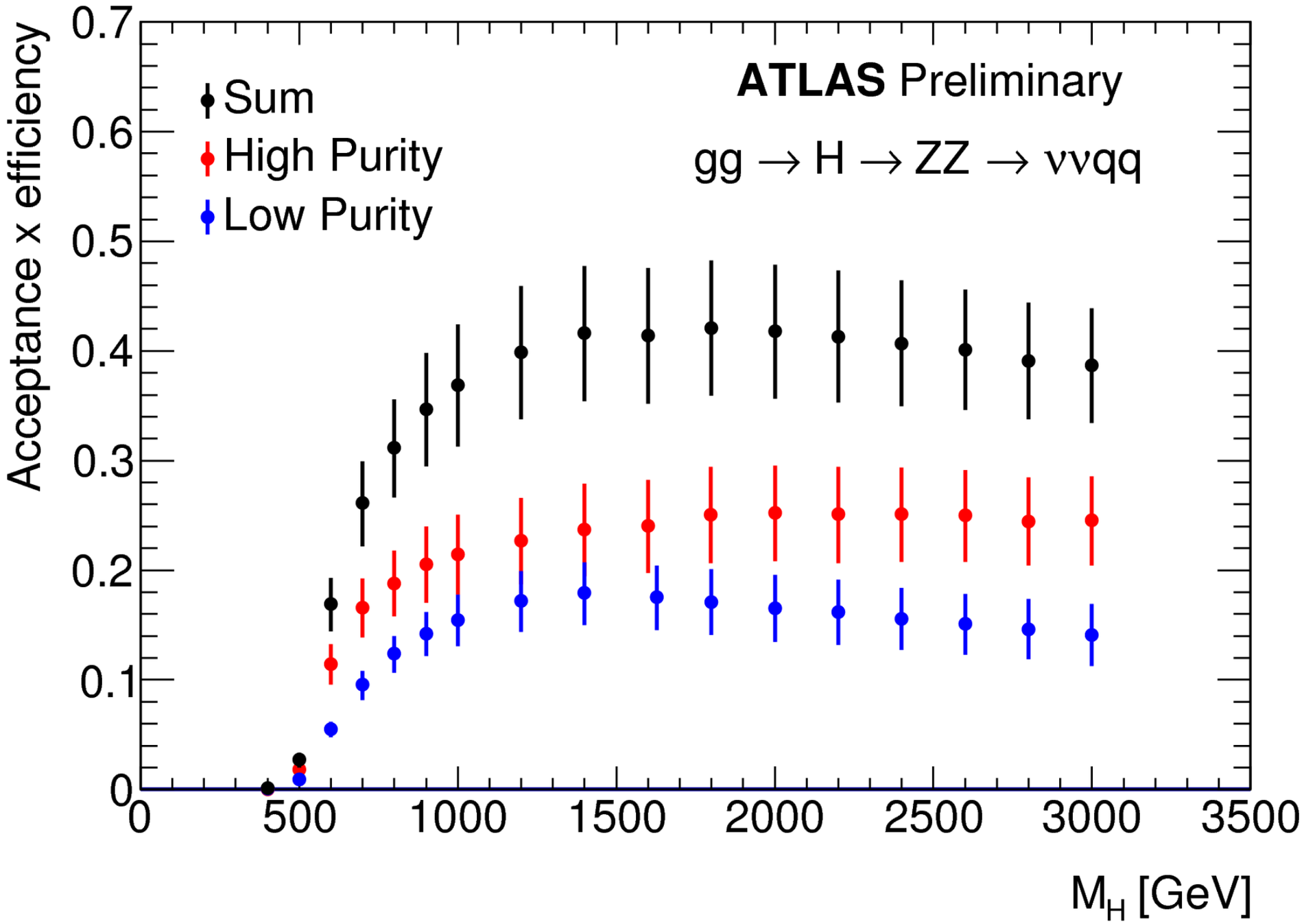
Large-R jet reconstruction:





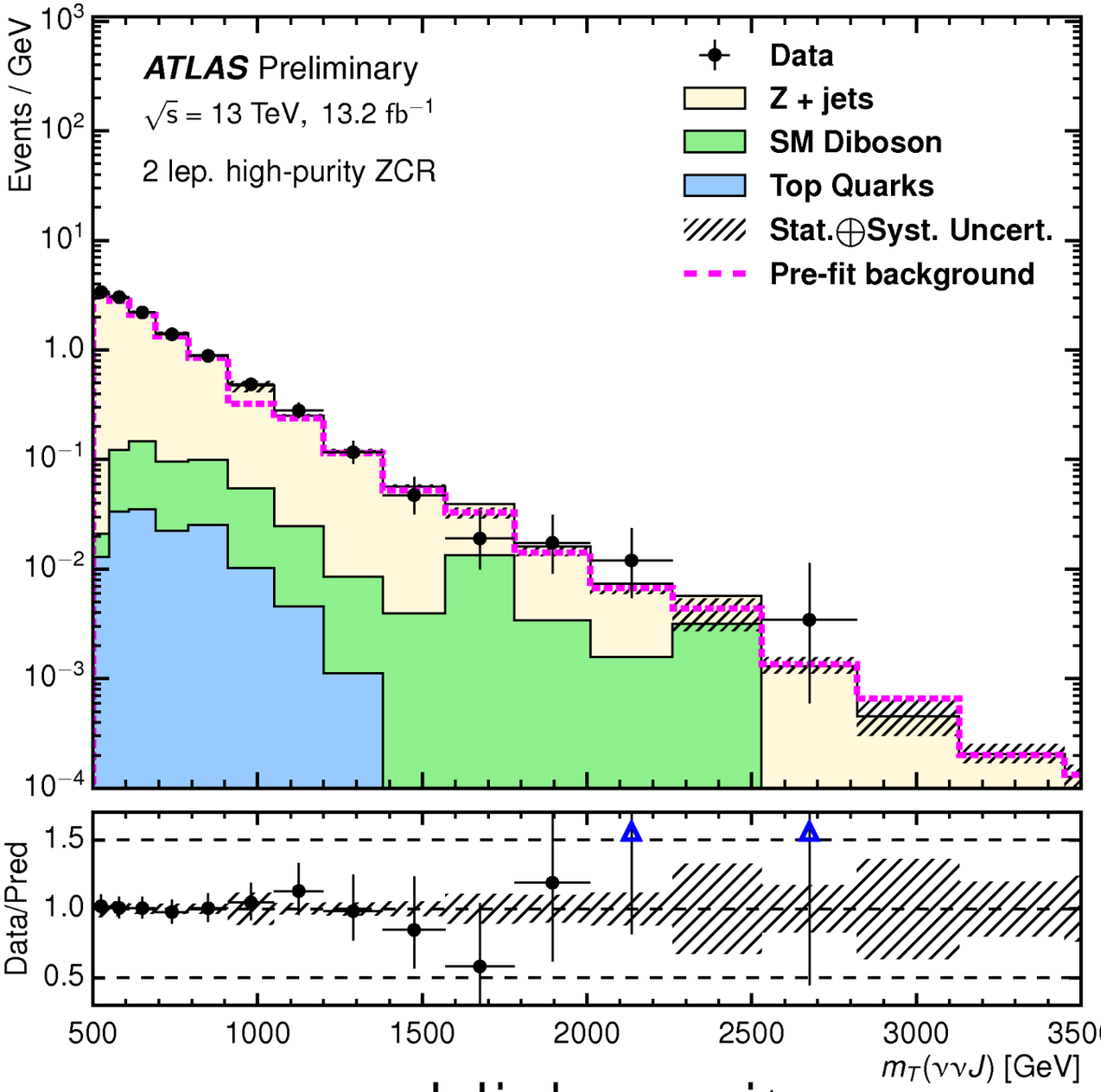
H → ZZ → ννqq

High-purity and low-purity:

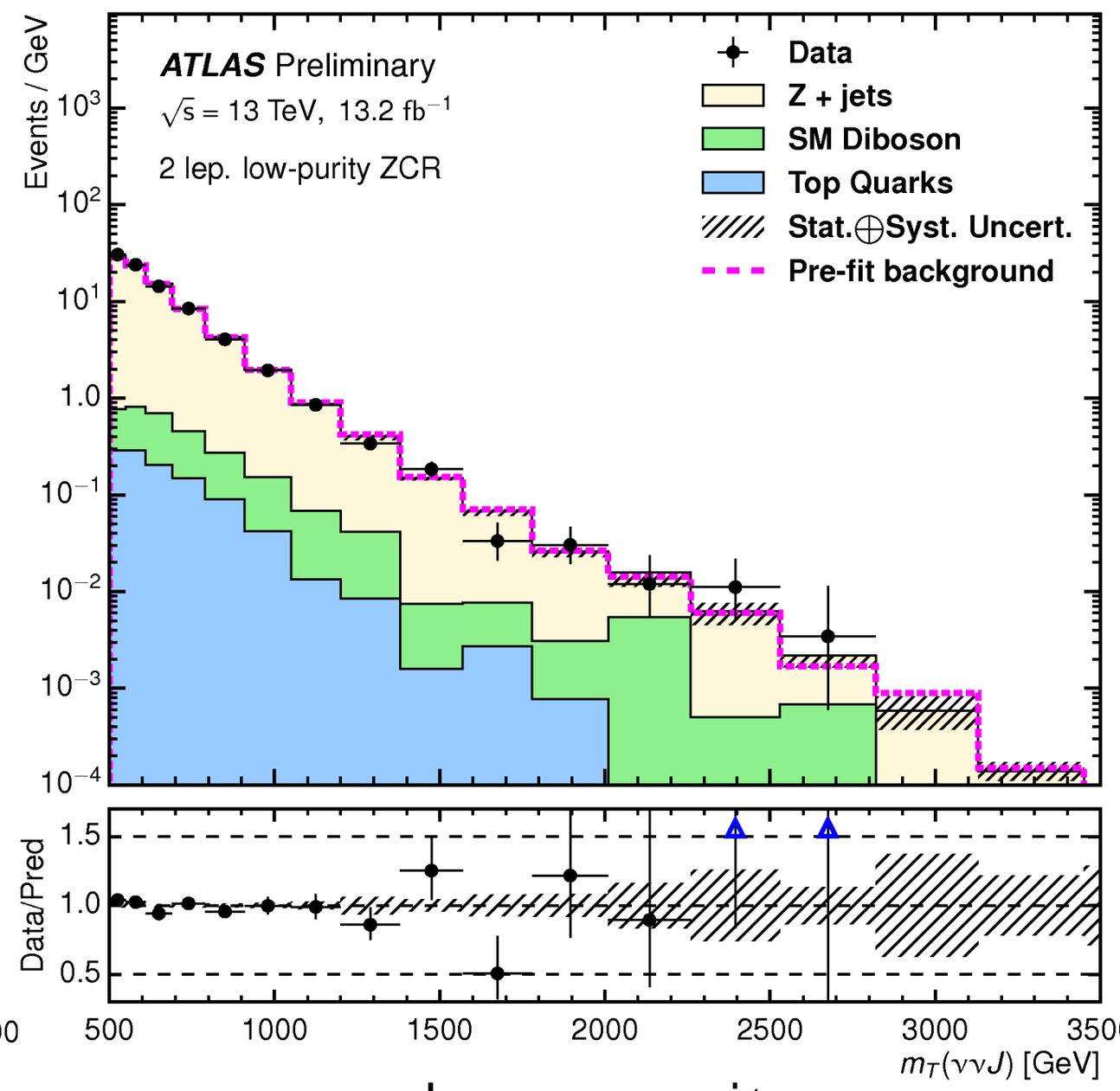


H → ZZ → ννqq

Z control regions:



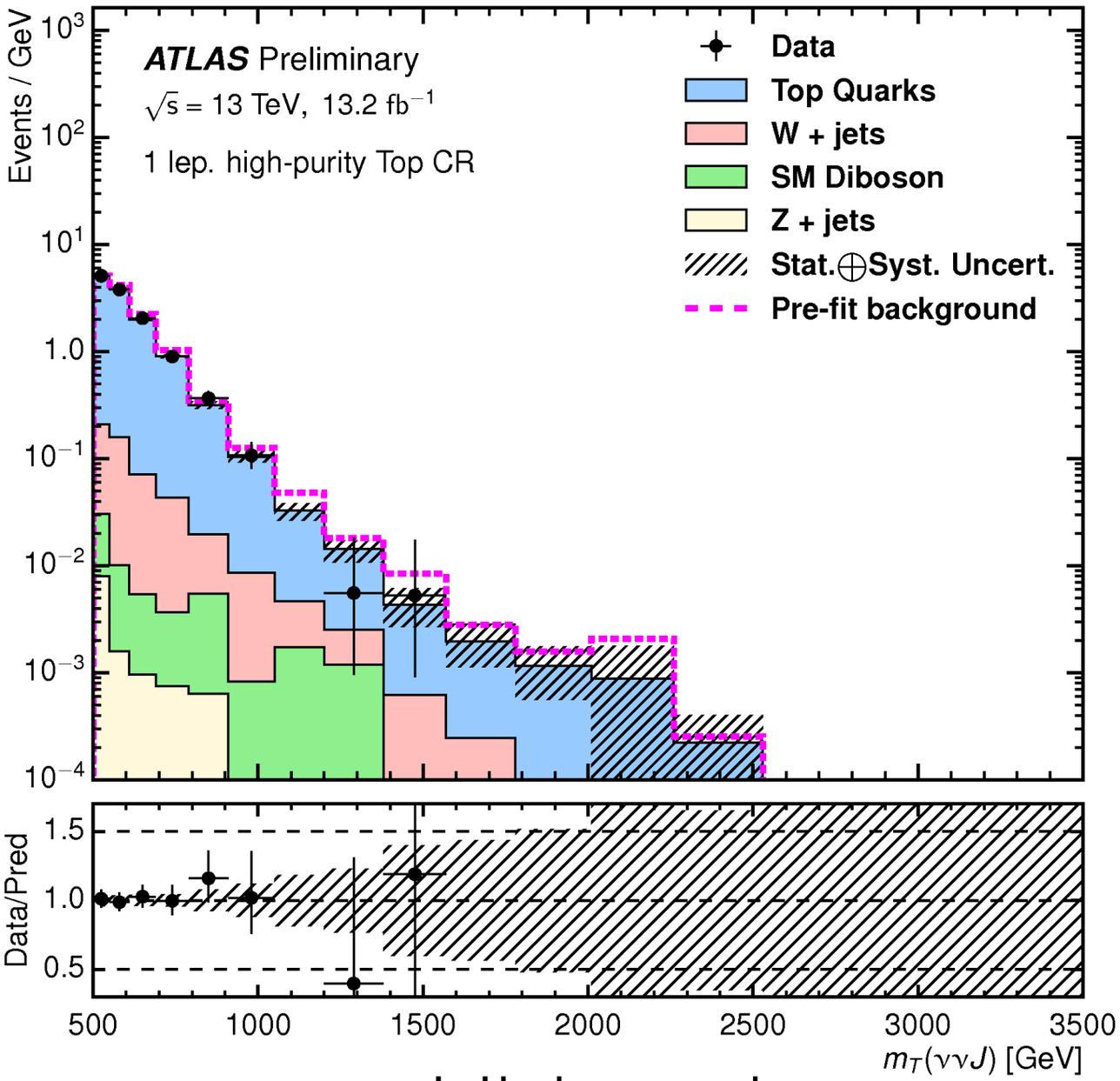
High purity



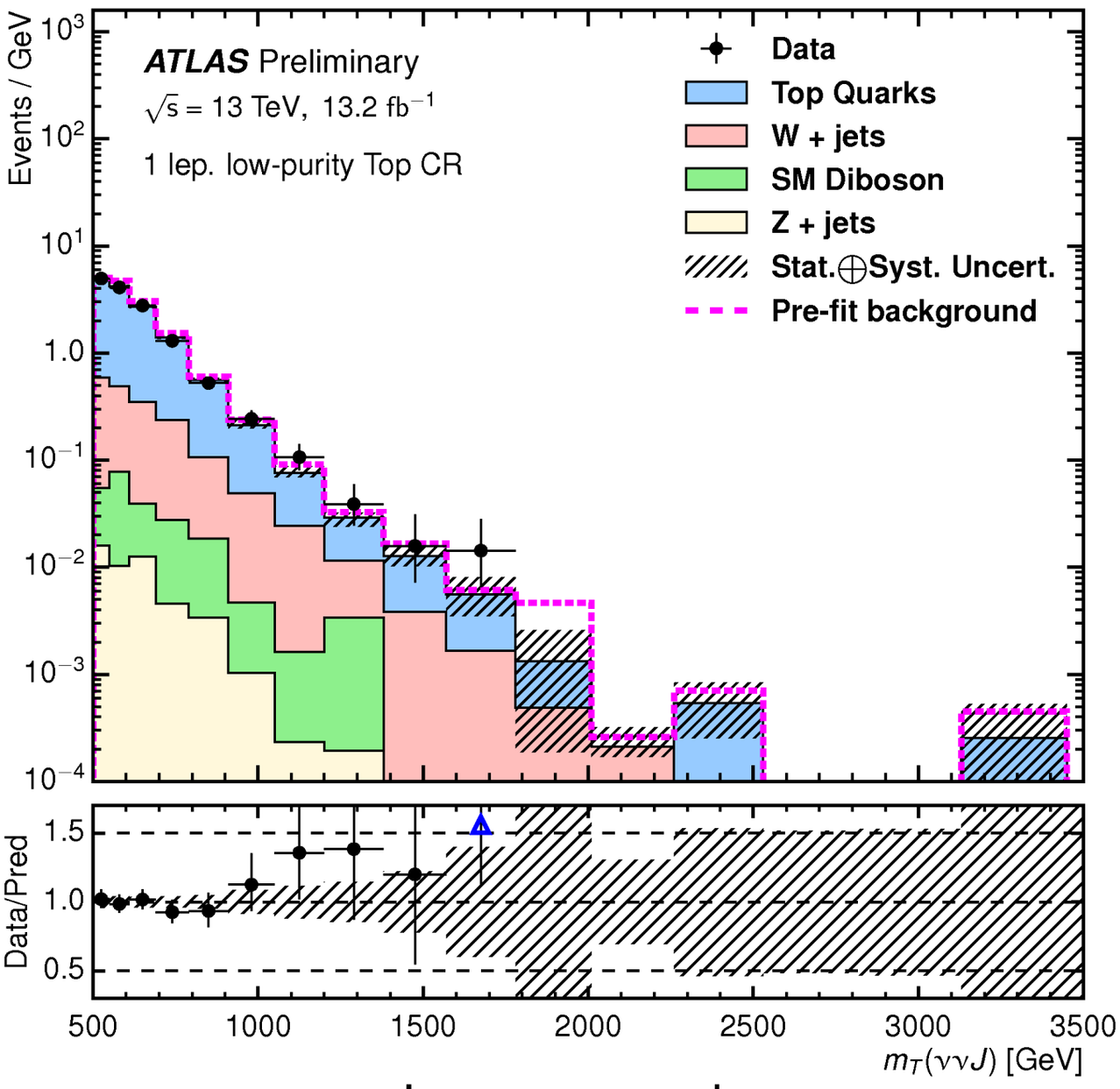
Low purity

H → ZZ → ννqq

Top control regions:



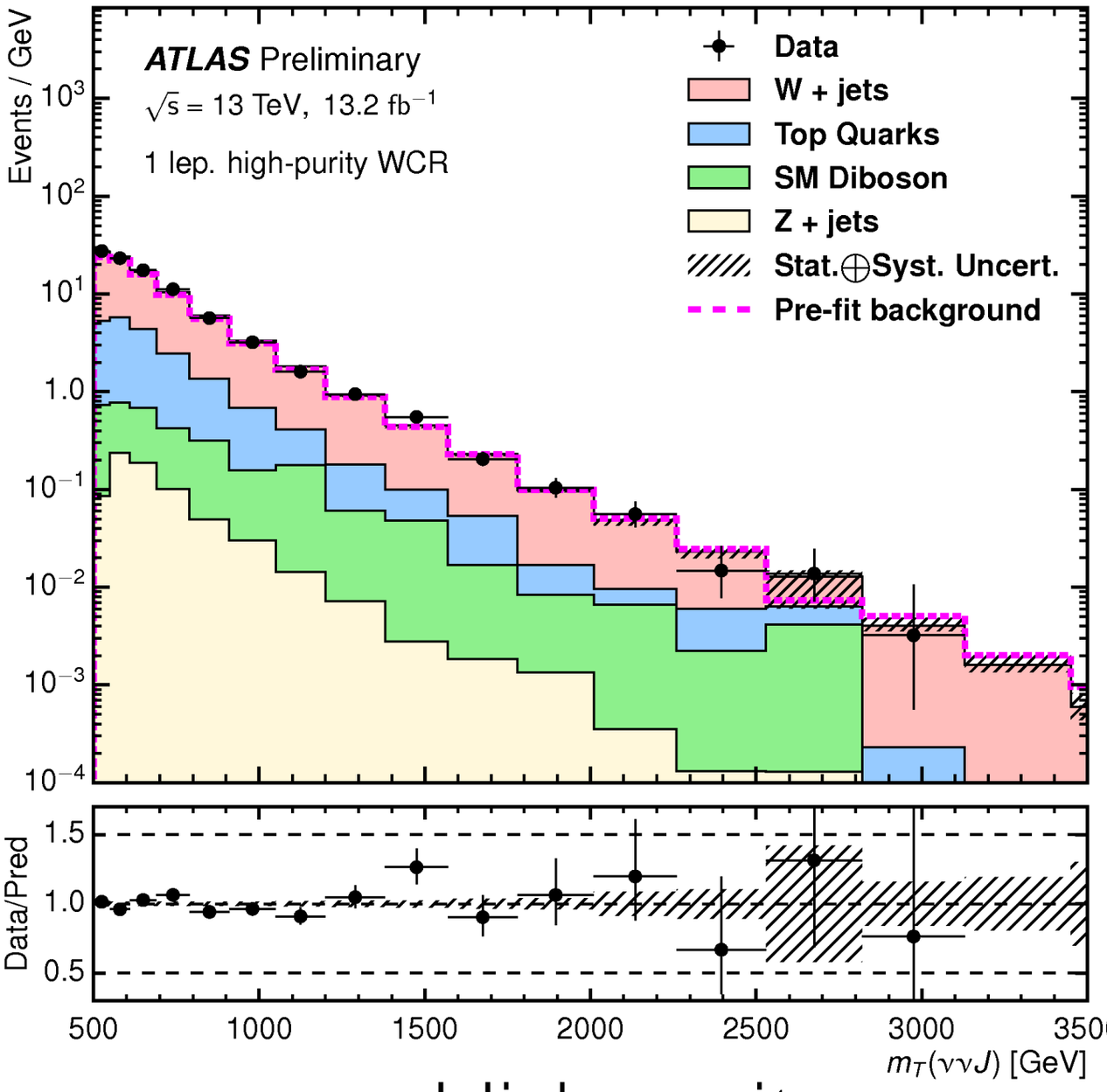
High purity



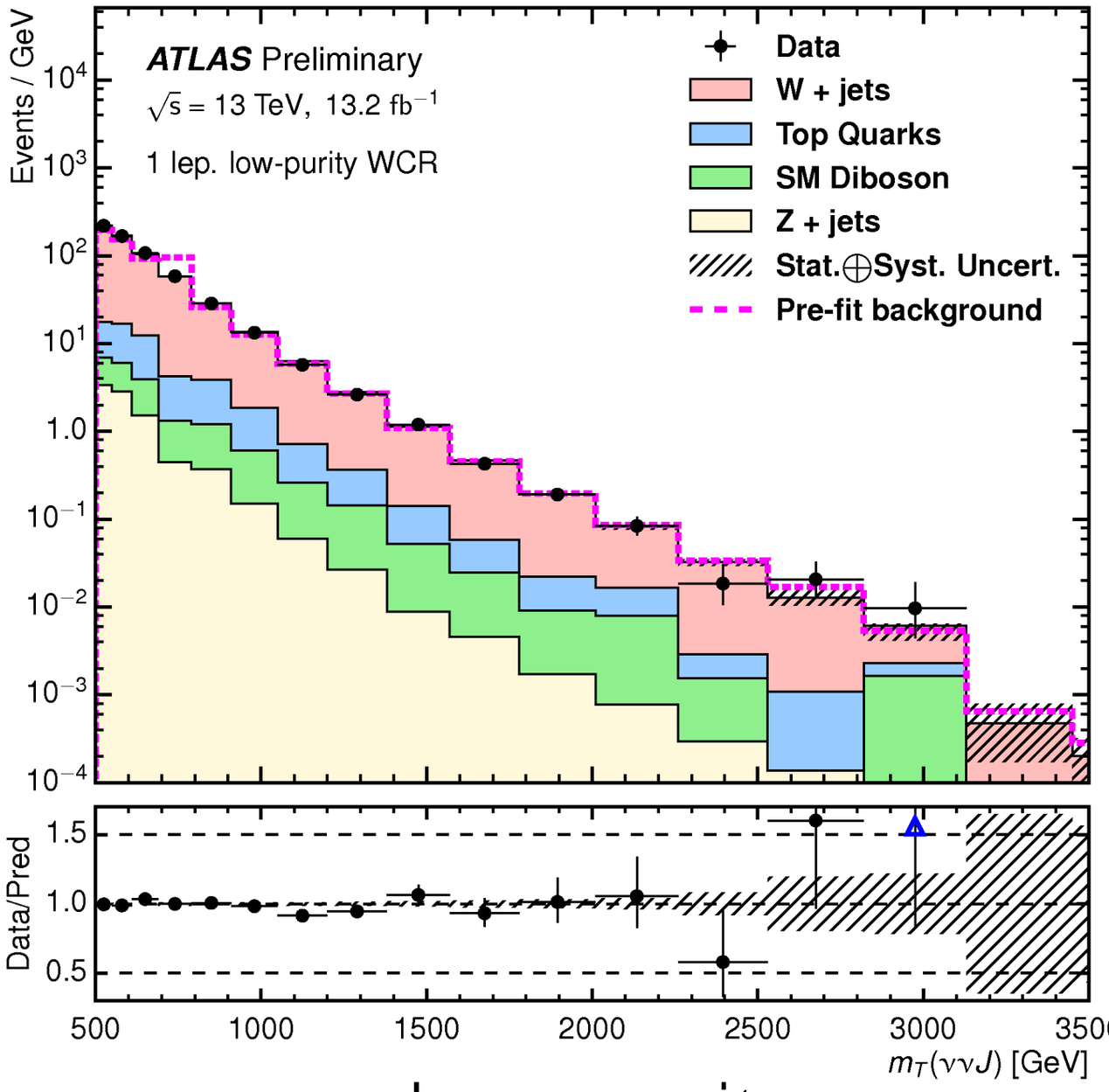
Low purity

H → ZZ → ννqq

W control regions:



High purity



Low purity