Searches for new resonances decaying to W, Z & H bosons

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For ATLAS and CMS collaborations

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Motivation

- Many BSM theories predict new heavy states that can decay into SM bosons

Heavy vector triplet (HVT)

- **Simplified model used to describe the phenomenology of new resonances with a small number of parameters**
- **Contains heavy (spin 1) W'/Z' that couple to SM:**
  - bosons: $c_H g_V$
  - fermions: $(g^2/g_V)c_F$

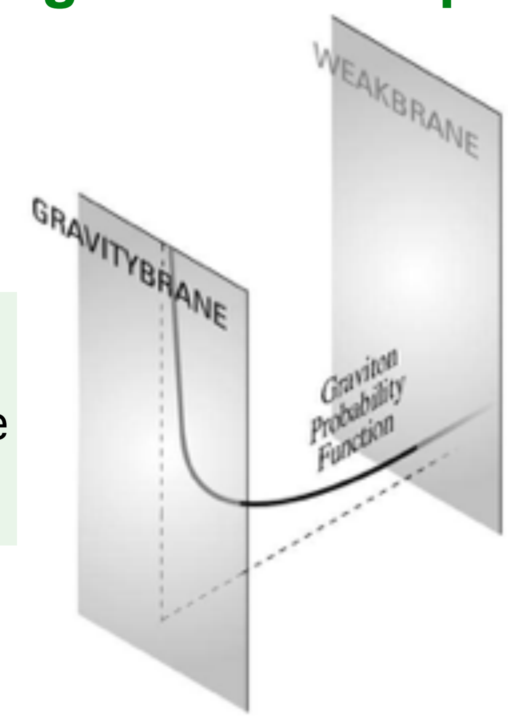
g: SM SU(2) coupling
g_V: V' interaction strength
c_H, c_F: interactions with bosons/fermions

- 2 scenarios [JHEP09(2014)060]
  - A (g_V=1): comparable couplings to fermions and bosons (e.g. Sequential SM; strongly constrained by searches in fermion final states)
  - B (g_V=3): fermionic couplings suppressed, **decays to bosons dominate** (e.g. Composite Higgs)

Warped extra dimensions

- **Possible solution to the hierarchy problem & flavor structure**
- **Kaluza-Klein graviton G (spin 2)**
- Bulk Randall-Sundrum scenario:
  - all SM fields propagate in the bulk
  - **couplings to light fermions/γ suppressed**

k: dimensionless coupling, the curvature of the extra dimension

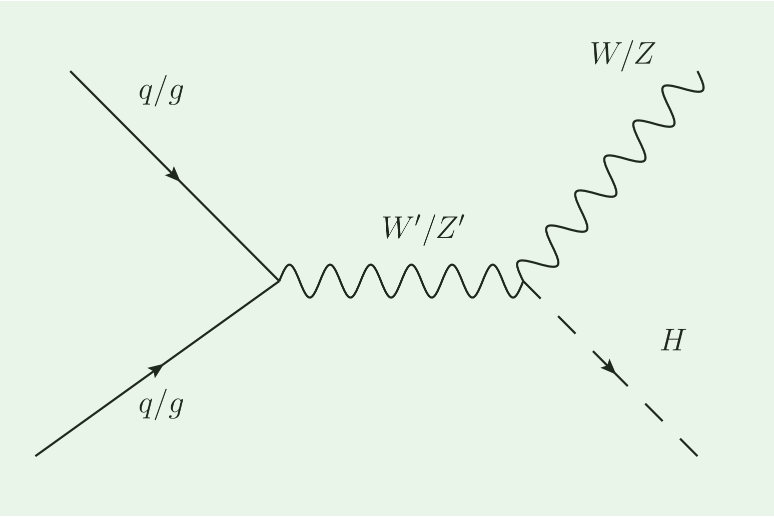


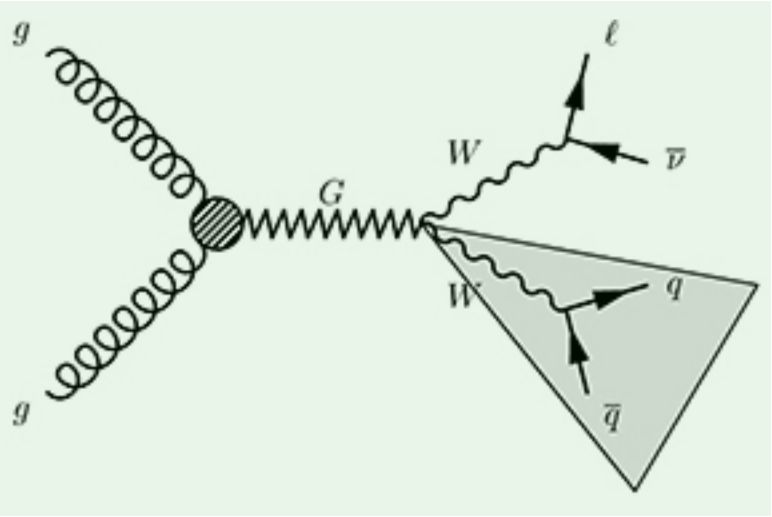
Final sates

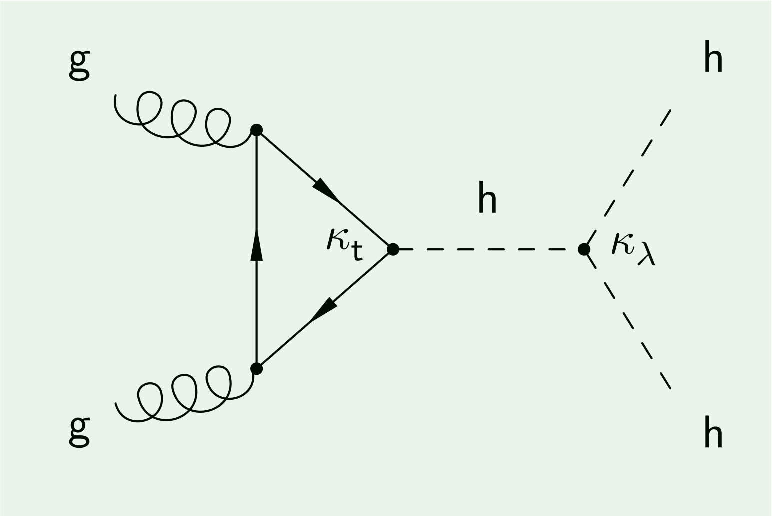
- Many searches in diboson channels in all possible final states
- In this talk will focus only on couple of recent results with 15-36 fb^{-1} of the 13 TeV data (final states in **red**)
  - See also talks: *Searches for additional Higgs bosons* (M. Xiao), *Latest results on di-Higgs production with ATLAS/CMS* (H. Fox/D.M. Morse), *High mass searches* (S. Mukherjee), *Searches for diboson resonances in ATLAS/CMS* (A. Oh, H. Huang)…

ATLAS public results   CMS public results

Channel	Final states
WW / WZ / ZZ	**qqqq**, **ℓℓνν**, ℓℓqq, ννqq, ℓνℓν, 4ℓ, ℓνqq
WH / ZH	**qqbb**, ℓνbb, ℓℓbb, ννbb, qqbb, ℓνττ, ℓℓττ, qqττ
HH	**4b**, bbVV, bbγγ, WWγγ, bbττ
γγ / Zγ	γγ, ℓℓγ, qqγ



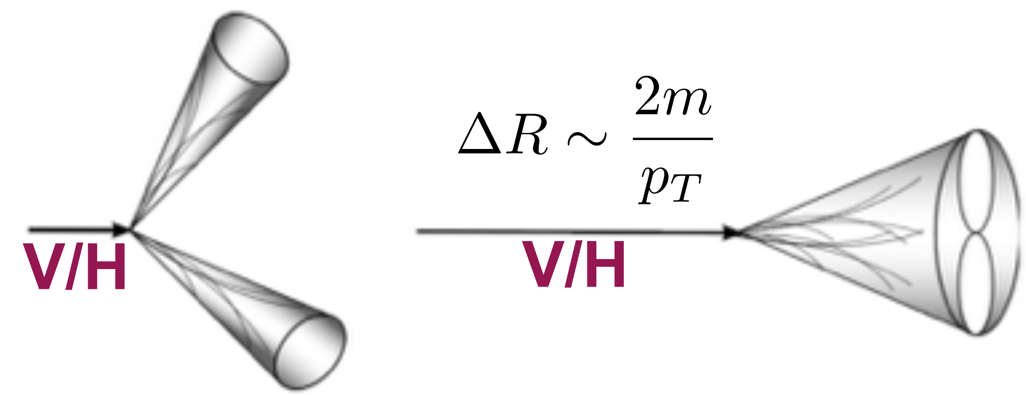




Boosted bosons

Decay topology

- Decays of massive BSM states (m(BSM) >> m(V))
  - ➡ SM bosons are boosted
  - ➡ Their decay products are collimated
  - ➡ V/H→qq: **SM boson reconstructed as a single fat jet** (R=0.8-1.0)



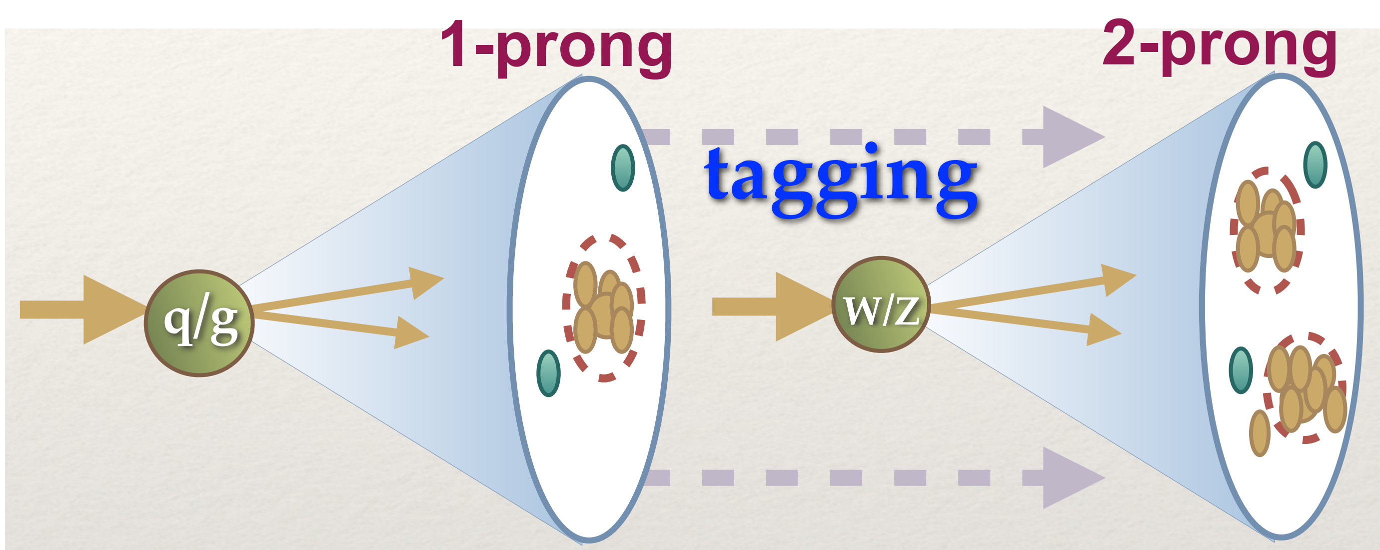
$$\Delta R \sim \frac{2m}{p_T}$$

Challenges of boosted states

- Fat jets prone to pile-up
- Main background are q/g jets from QCD jet production

Reconstruction techniques

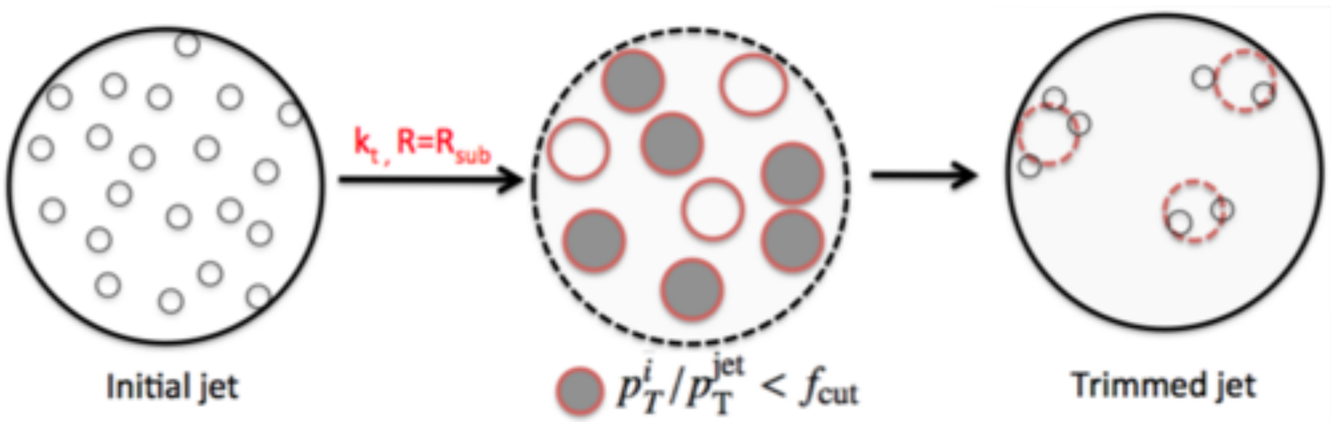
- **Jet grooming**: remove soft QCD radiation & pile-up contributions, improve the resolution of V/H-jet mass
- **Jet substructure & tagging**: discriminate between q/g-jets & V/H-jets



Jet grooming

ATLAS

- Fat jets R=1.0 (topological clusters)
- **Trimming** [JHEP02(2010)084]:
  - recluster jet constituents into sub-jets with R=0.2
  - remove sub-jets with $\frac{p_T(\text{subjet})}{p_T(\text{jet})} < 0.05$



- Jet mass computed using a combination of calo information and tracks associated with the jet (so far used in VH→qqbb)

CMS

- Fat jets R=0.8 (particle-flow)
- **PUPPI** [JHEP10(2014)059]:
  - pile-up per particle identification
  - weight describing the likelihood for each particle to originate from pileup interactions, used to rescale their 4-momenta
  - mass resolution ~10%
- **Soft drop algorithm** [JHEP09(2013)029, JHEP05(2014)146]
  - iteratively breaks the jet into 2 sub-jets dropping the softer one, until the soft-drop condition is satisfied

Jet grooming

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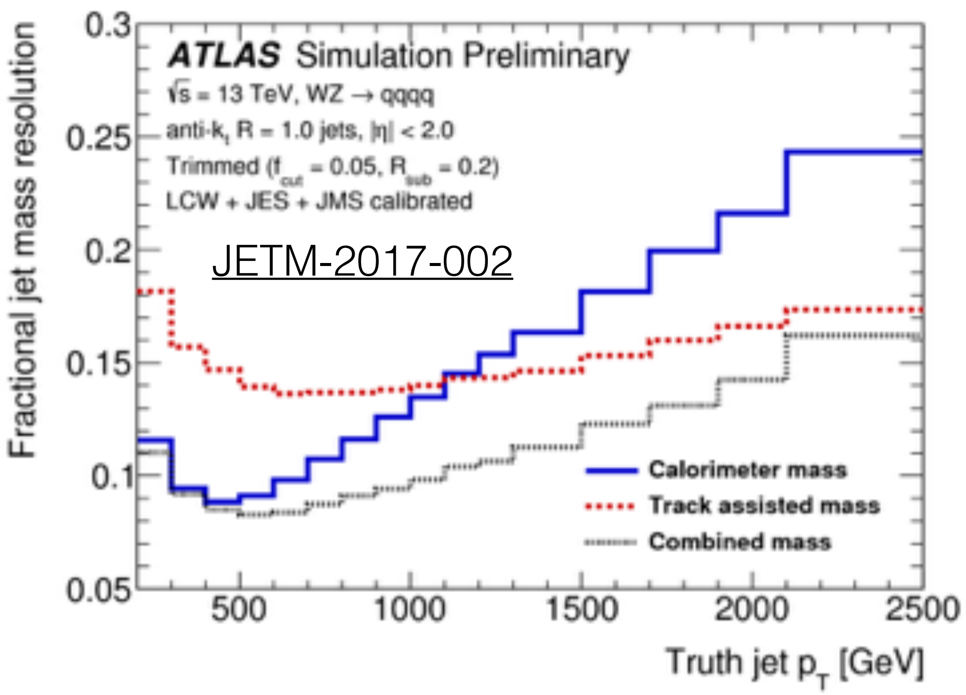

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Boosted boson tagging

ATLAS | **CMS**

H(→bb) tagging:

— fat-jet mass consistent with H-mass

ATLAS:
- 1 or 2 associated b-tagged track jets (R=0.2)

CMS:
- dedicated b-tagging discriminator to identify 2 b-quarks clustered in a single jet

W/Z tagging:

— fat-jet mass consistent with V-mass within 30-40 GeV window

ATLAS:
- Overlapping mass-windows

CMS:
- Exclusive mass-windows

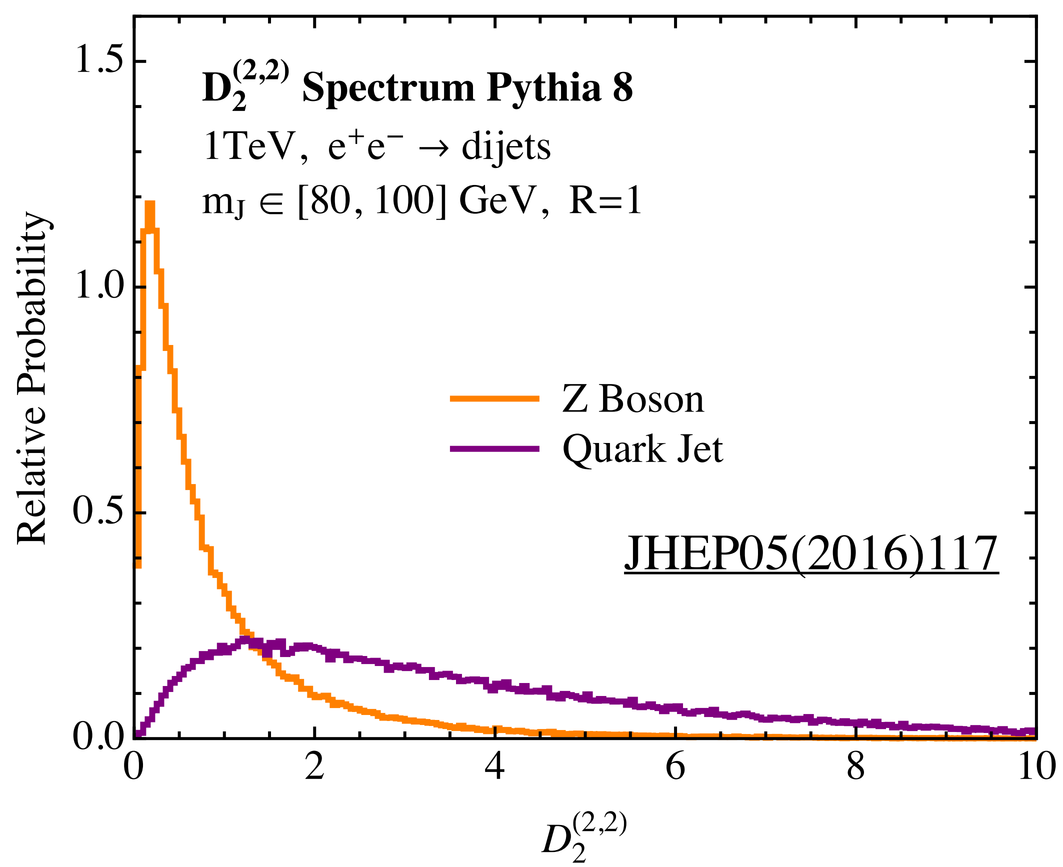
Substructure

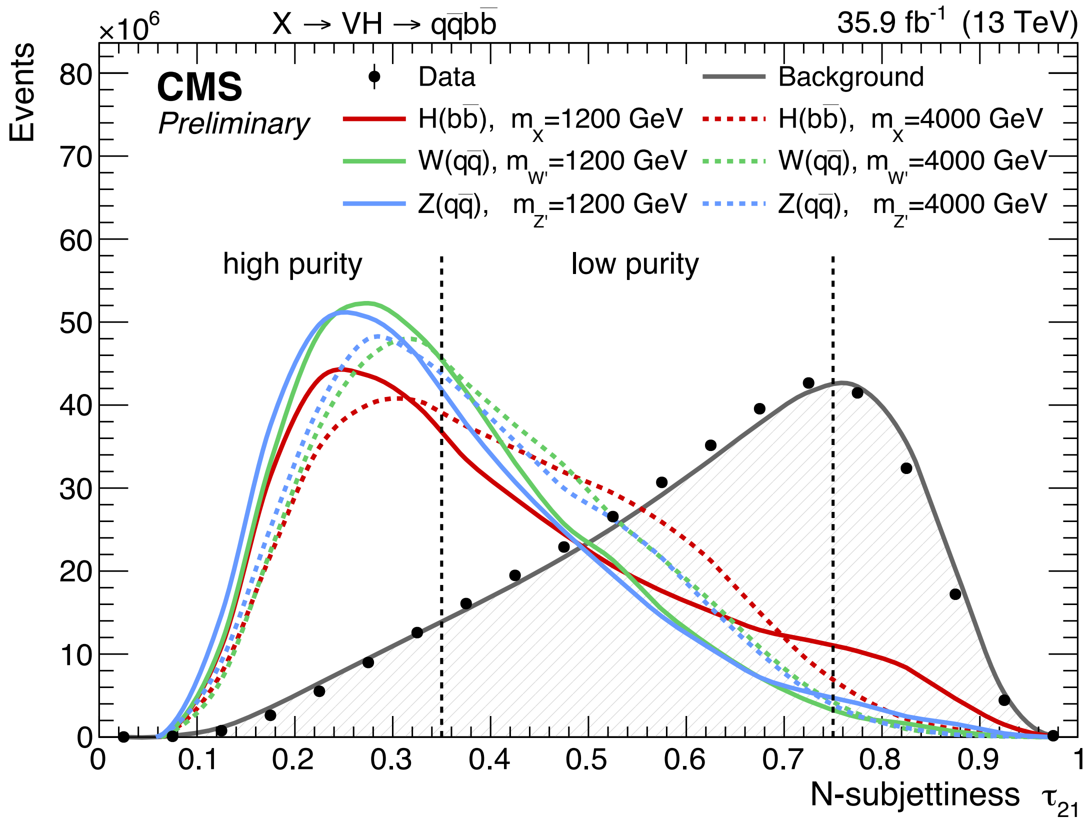
ATLAS:
- D2 (ratio of energy correlation functions) - **compatibility with a two-prong decay topology**

CMS:
- τ_N (N-subjetiness) - quantifies the **capability of clustering the jet constituents in exactly N subjets** (using PUPPI inputs) $\tau_{21} = \tau_2/\tau_1$

Boosted boson tagging

ATLAS **CMS**





Substructure

- D2 (ratio of energy correlation functions) - **compatibility with a two-prong decay topology**
- p_T dependent cut:
  - eff(V-tag) ~ 50%
  - eff (q/g) ~ 2%

- τ_N (N-subjetiness) - quantifies the **capability of clustering the jet constituents in exactly N subjets** (using PUPPI inputs)
  $\tau_{21} = \tau_2 / \tau_1$
  - eff(V-tag) ~ 50% (45%) high (low) purity
  - eff (1-prong) ~ 10% (60%) high (low) purity

WH/ZH→qqbb

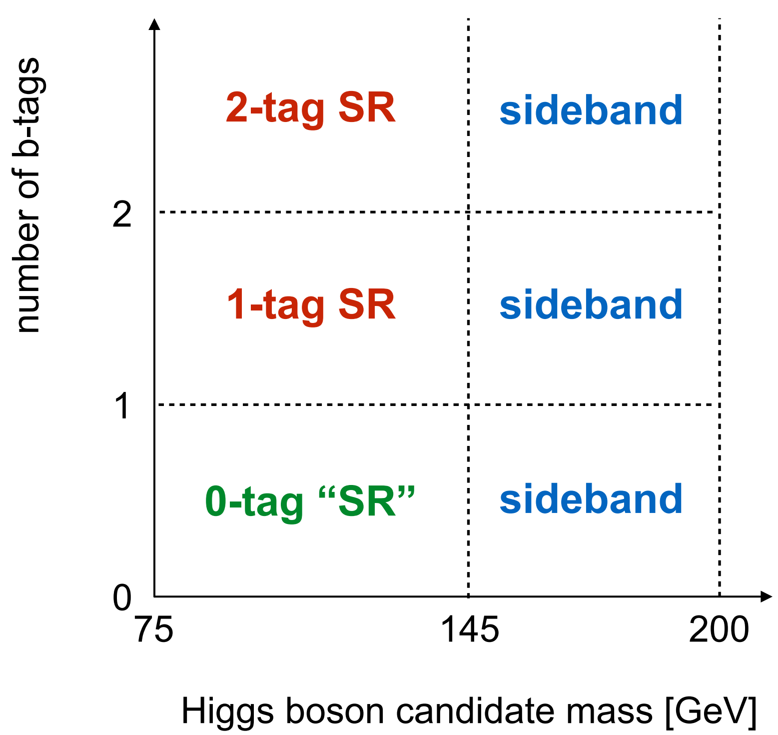
ATLAS-CONF-2017-018

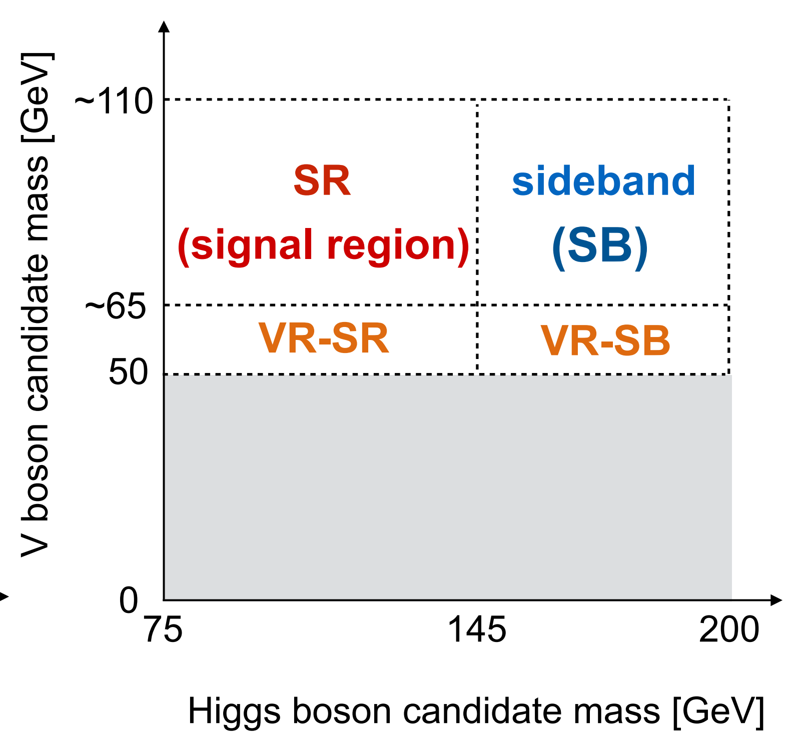
- Two fat jets: **m_{JJ}>1 TeV**
- Jet with larger mass assigned as H-candidate, the other one as V

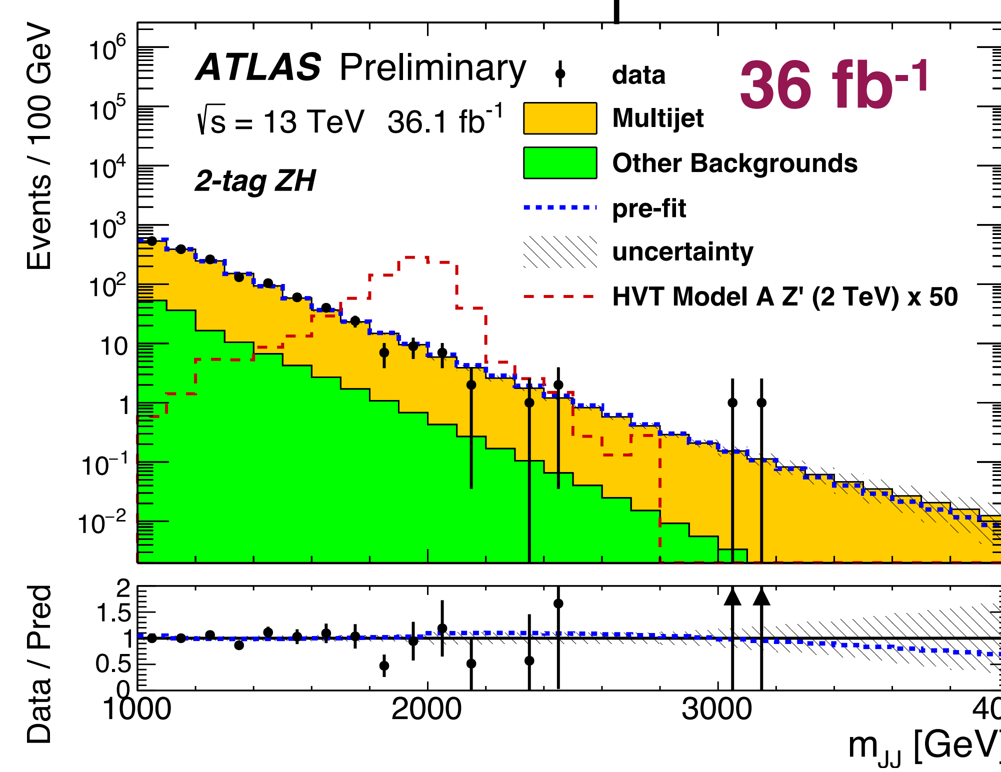
- 4 signal regions defined:
  - **1 or 2 b-tagged track jets associated with H**
  - **V-jet mass consistent with W or Z**

- **Multijet events** (~90% of the background)
  - Template extracted from the data in 0-tag "SR"
  - Corrected with kinematic reweighting (derived in the H-mass SB)
  - Normalized in the H-mass sidebands
  - Validated in V-mass sidebands (VR-SR, VR-SB)

Search for a resonance in m_{JJ} over a smoothly falling background

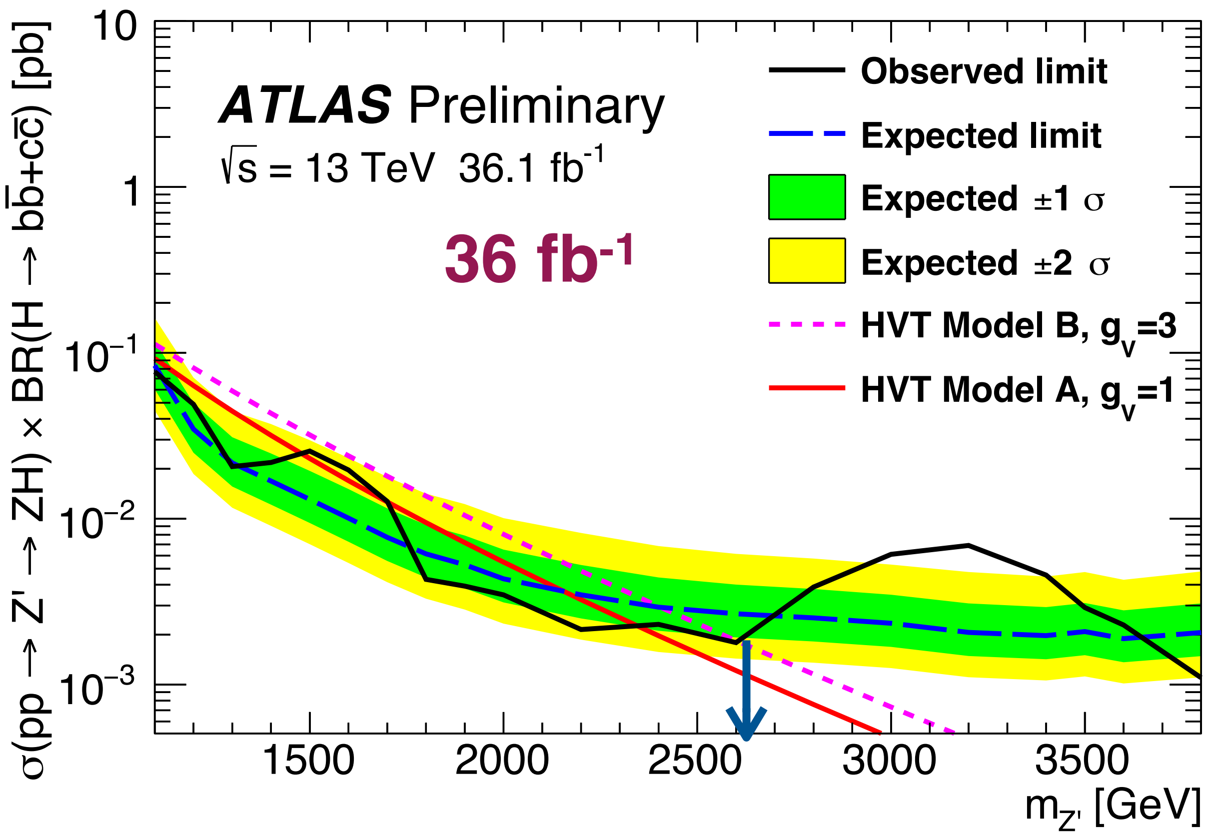


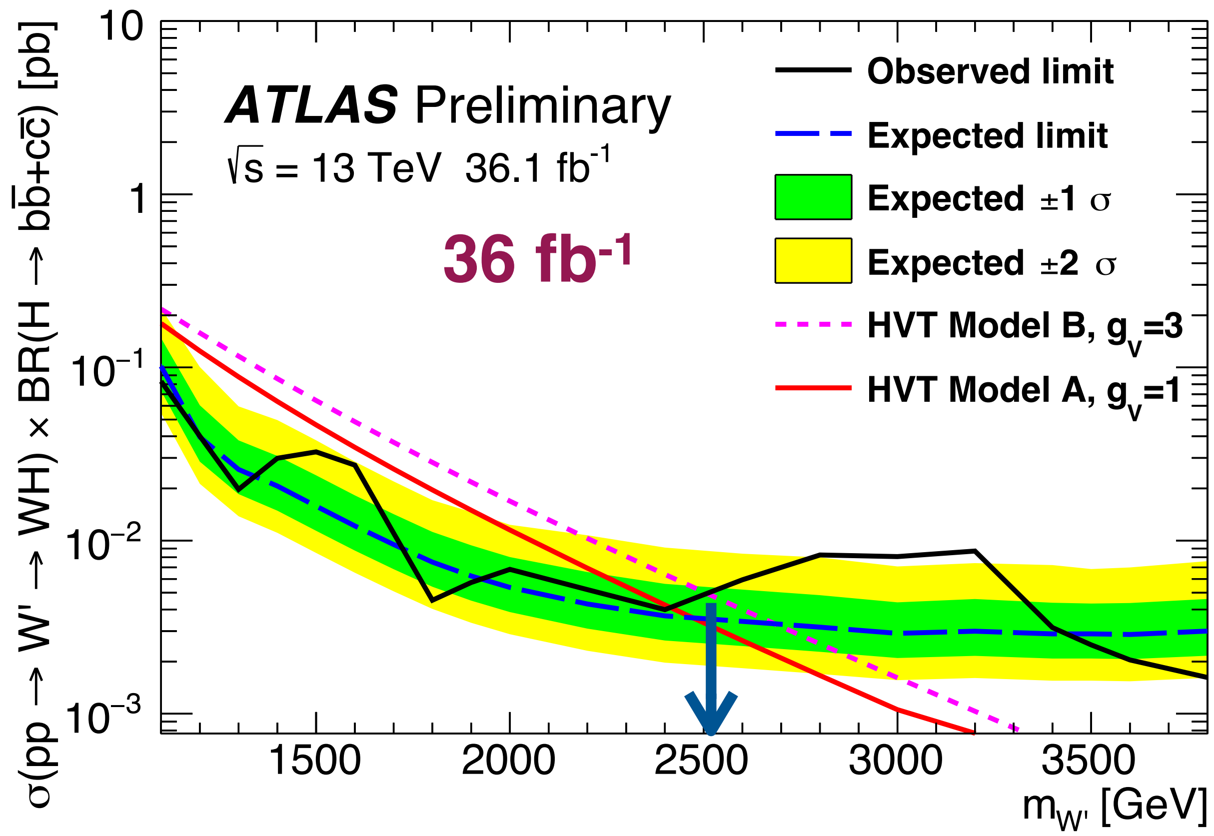


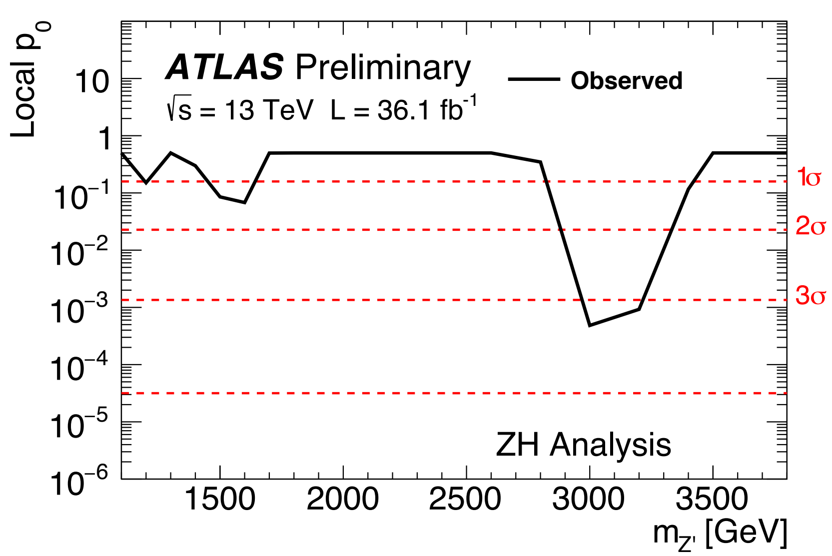


WH/ZH→qqbb

ATLAS-CONF-2017-018

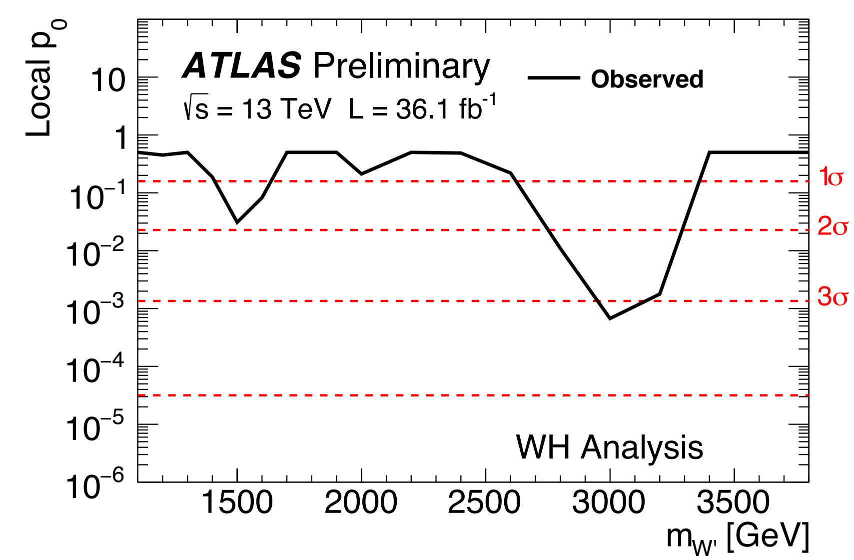






Global significance:

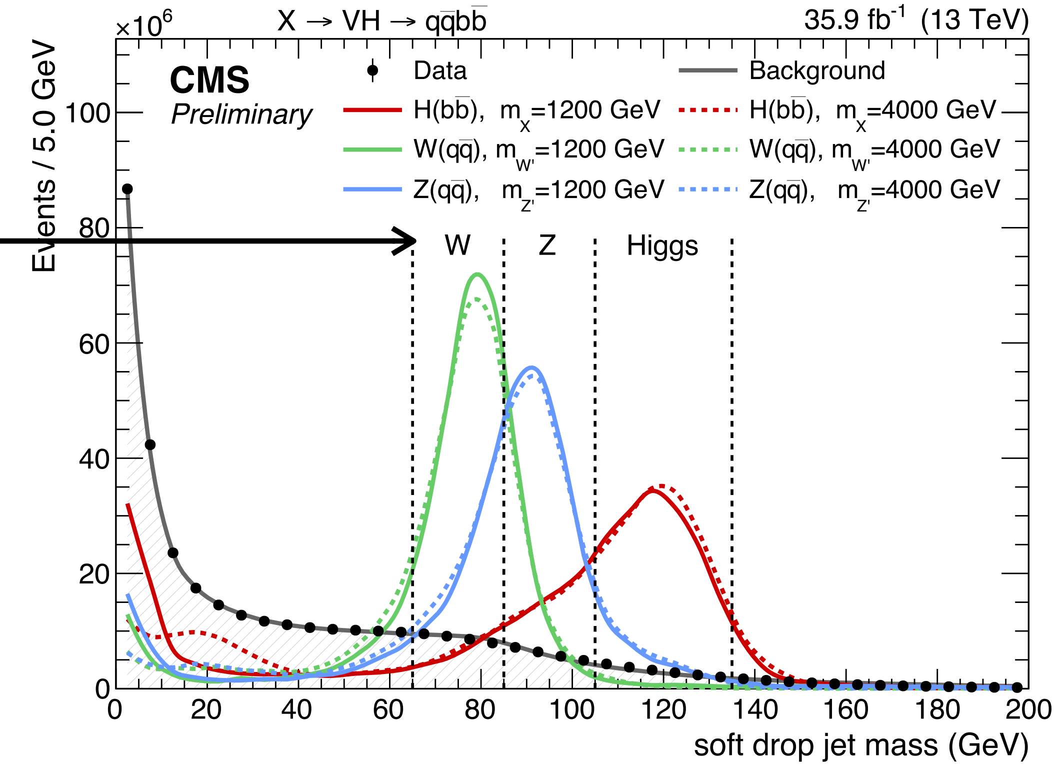
2.2 σ

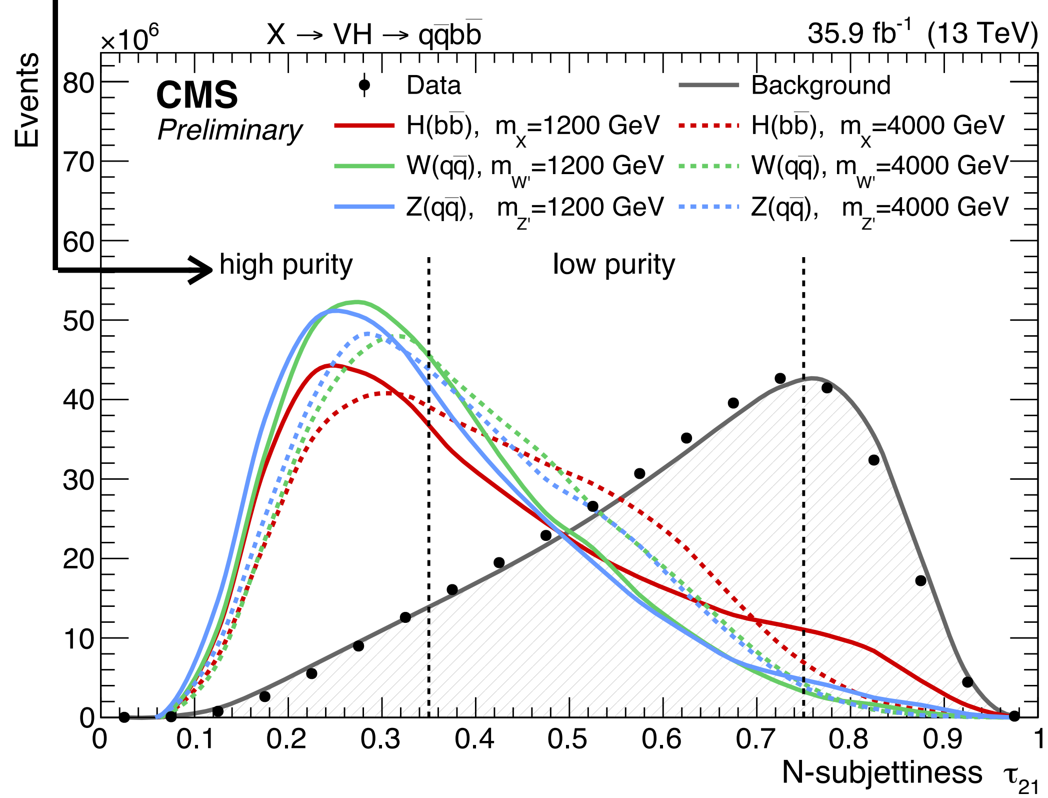


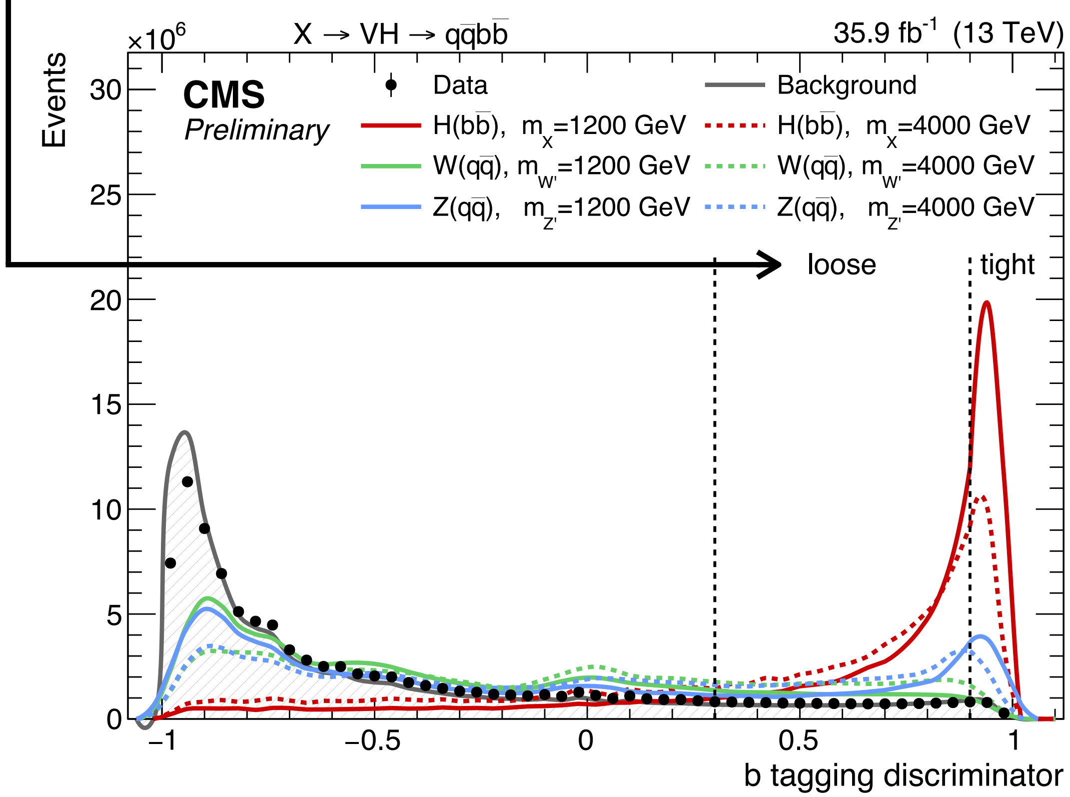
WH/ZH→qqbb

CMS-PAS-B2G-17-002

- Two fat jets: **m_{JJ}>985 GeV**
- 8 exclusive categories of events depending on:
  - **V-jet mass**
  - **H-jet b-tagging discriminator** (tight & loose)
  - $\tau_{21} = \tau_2/\tau_1$ **value for V-jets** (high & low purity)







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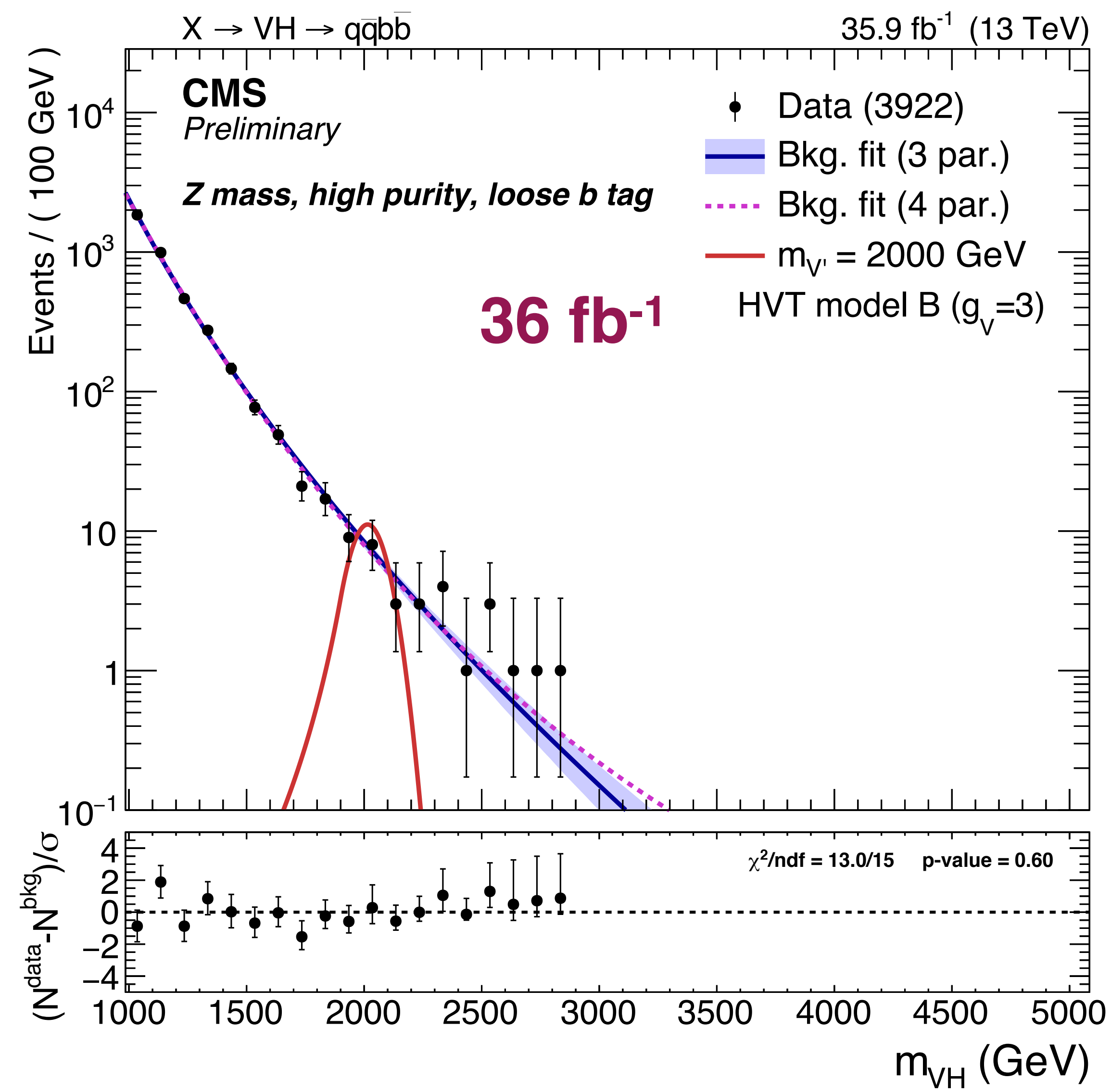
  - $\tau_{21} = \tau_2/\tau_1$ **value for V-jets** (high & low purity)
- **Multijet events** (>95% of the background)
  - Fit to the data with an analytic function
  - Validated in V-mass sidebands (40<m_V<65 GeV)



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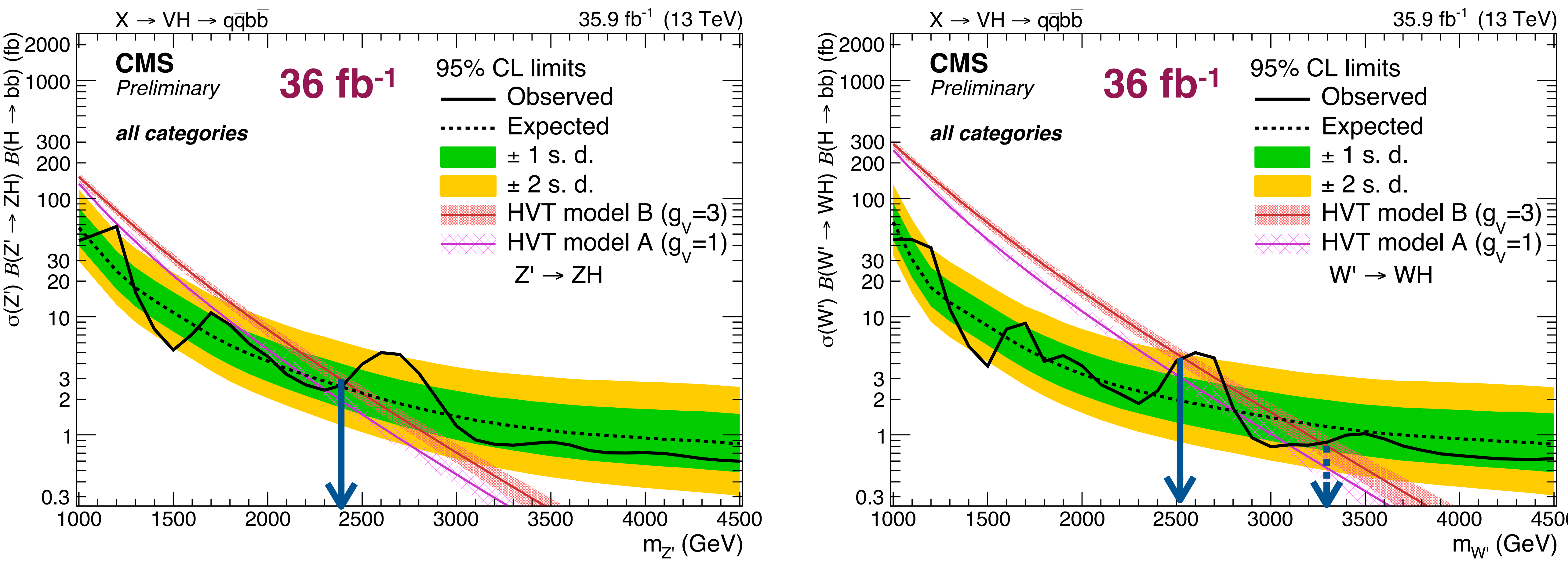


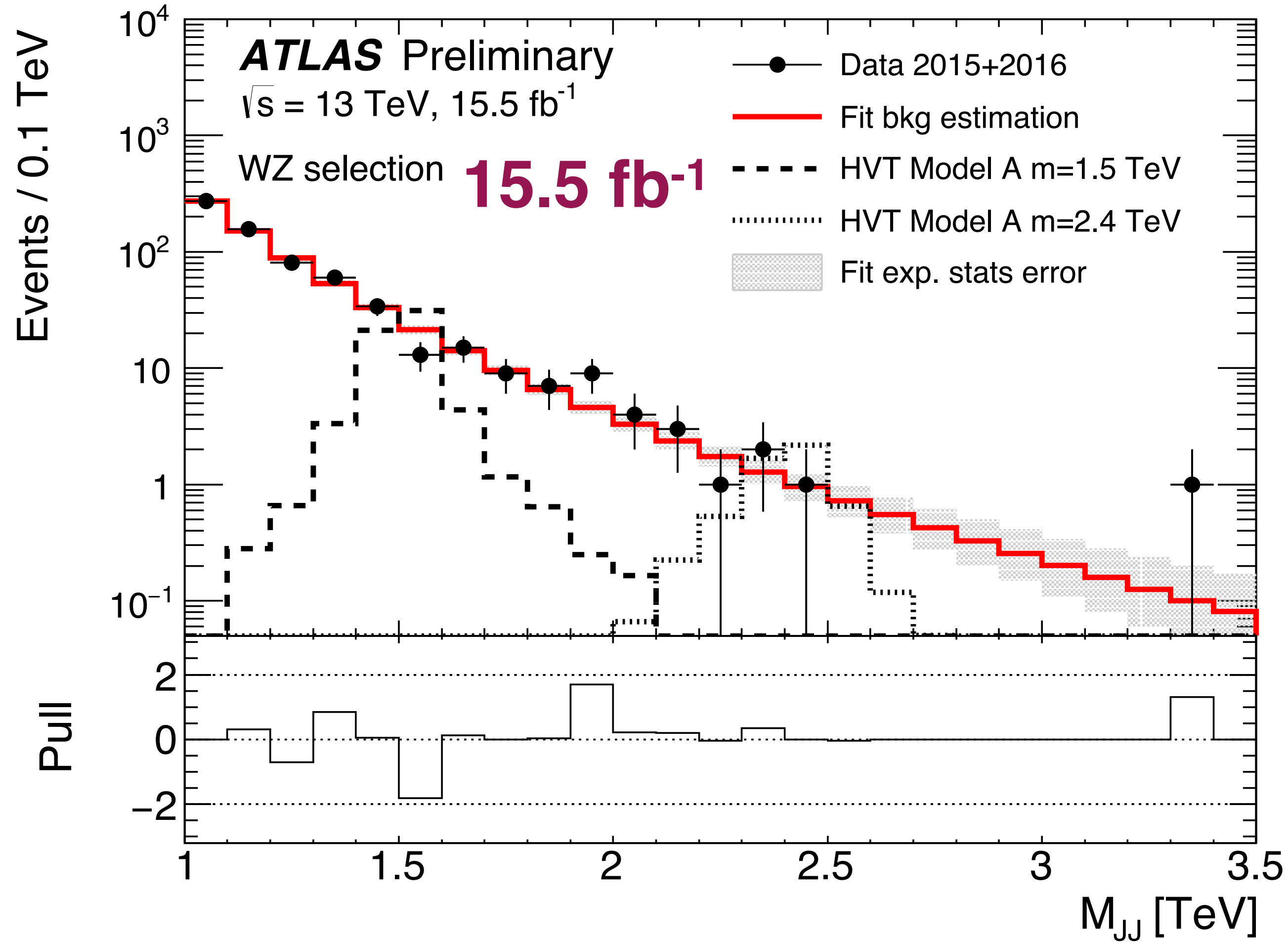
- CMS doesn't see the 3.3 σ (local) excess ATLAS observed at ~3 TeV

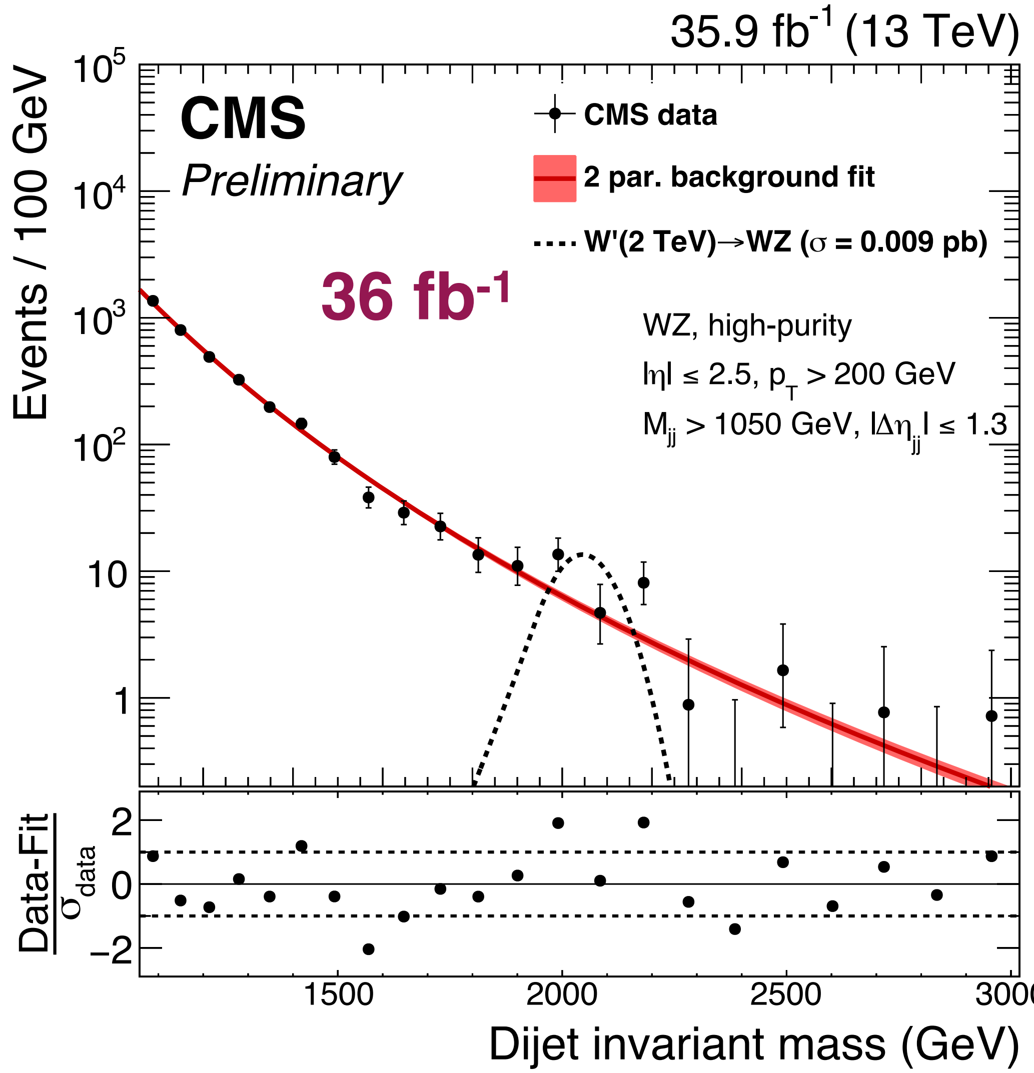
WW/WZ/ZZ fully hadronic

ATLAS-CONF-2016-055

CMS-PAS-B2G-17-001

- Two V-tagged jets: **m_{JJ}>1 TeV**
- Analysis techniques very similar to previously shown VH:
  - ATLAS: **WW/WZ/ZZ** (3 overlapping categories of events)
  - CMS: **WW/WZ/ZZ + low low/high purity based on τ_{21}** (6 categories)
  - **Background modelled with a parametric function** and validated in m_V sidebands





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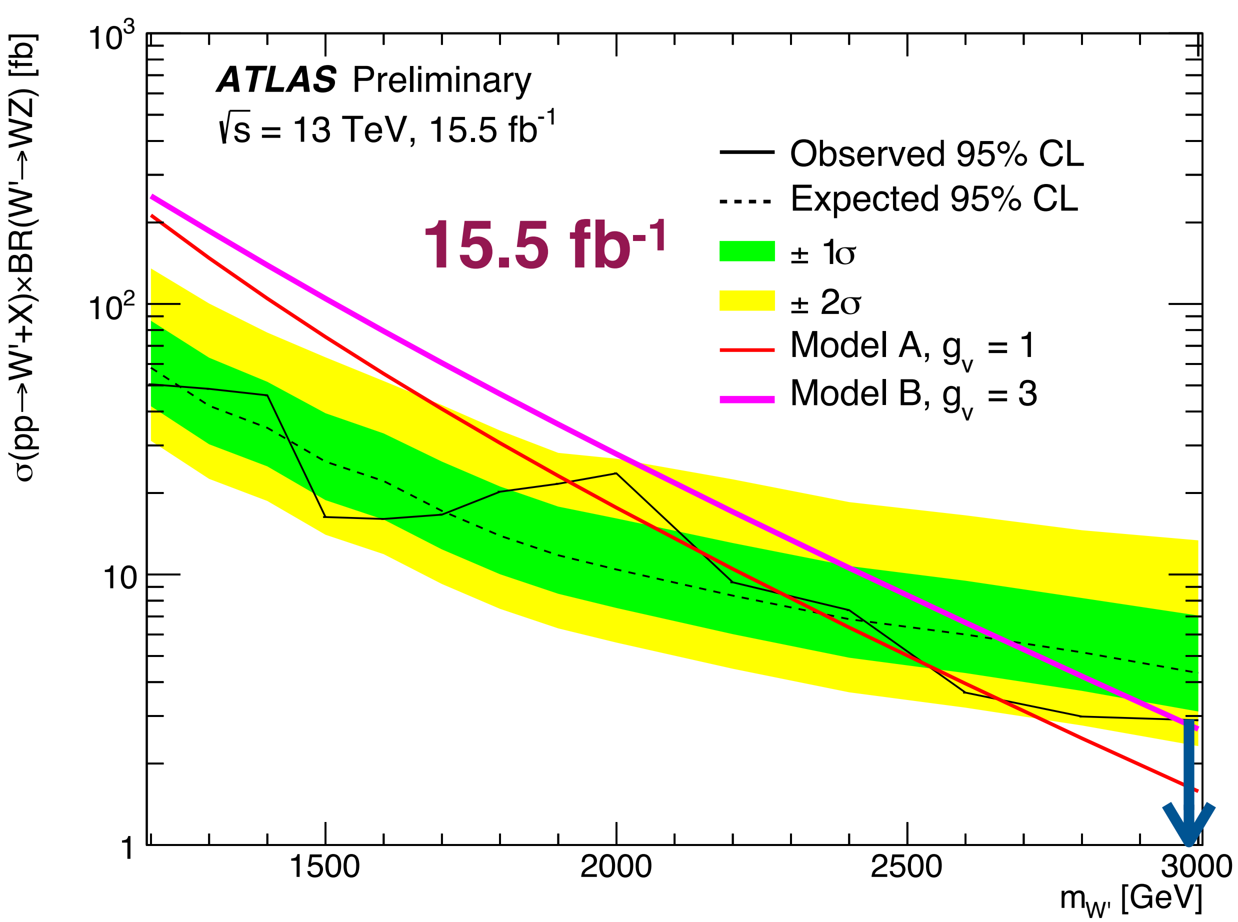
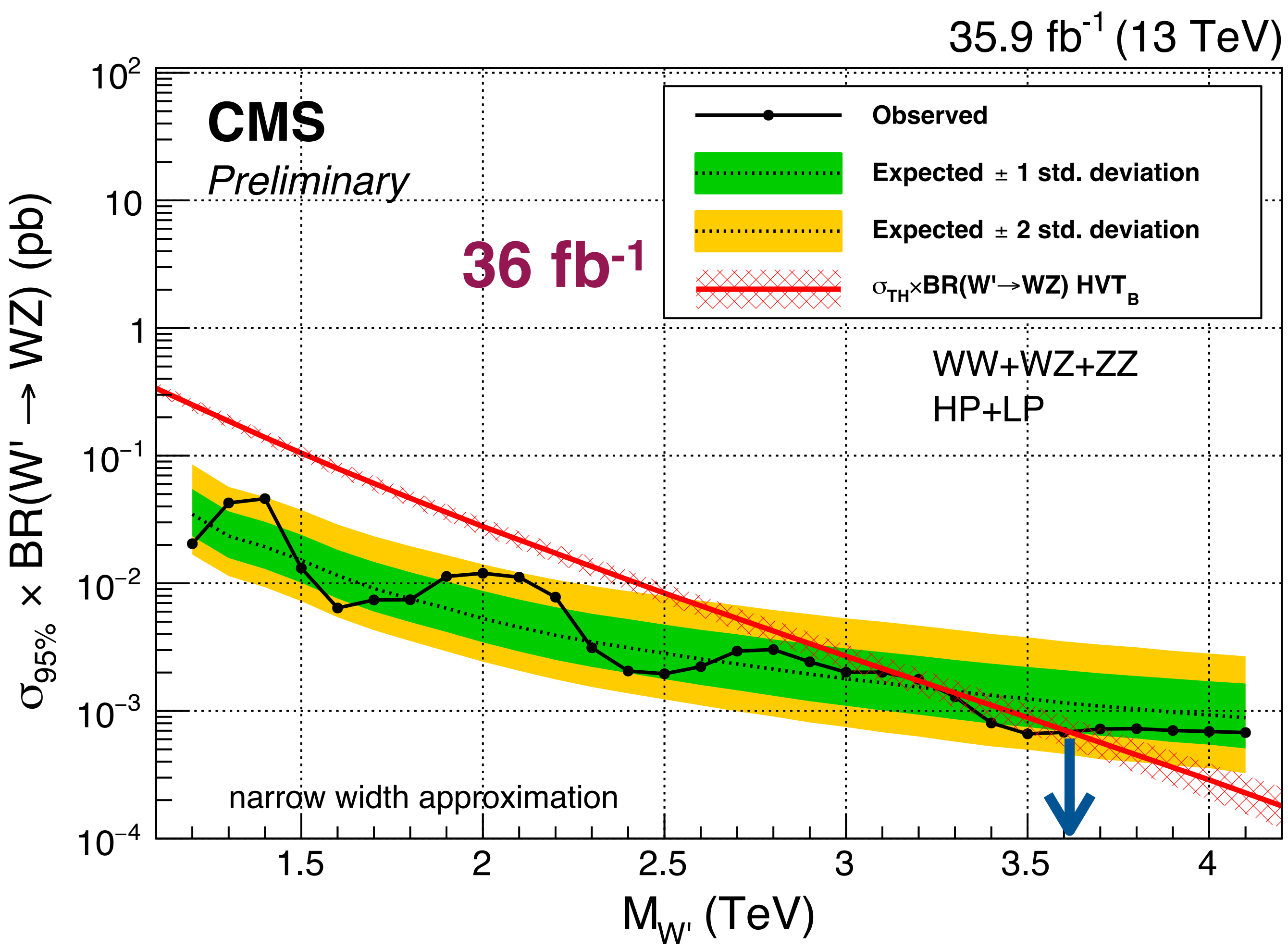
ATLAS-CONF-2016-055

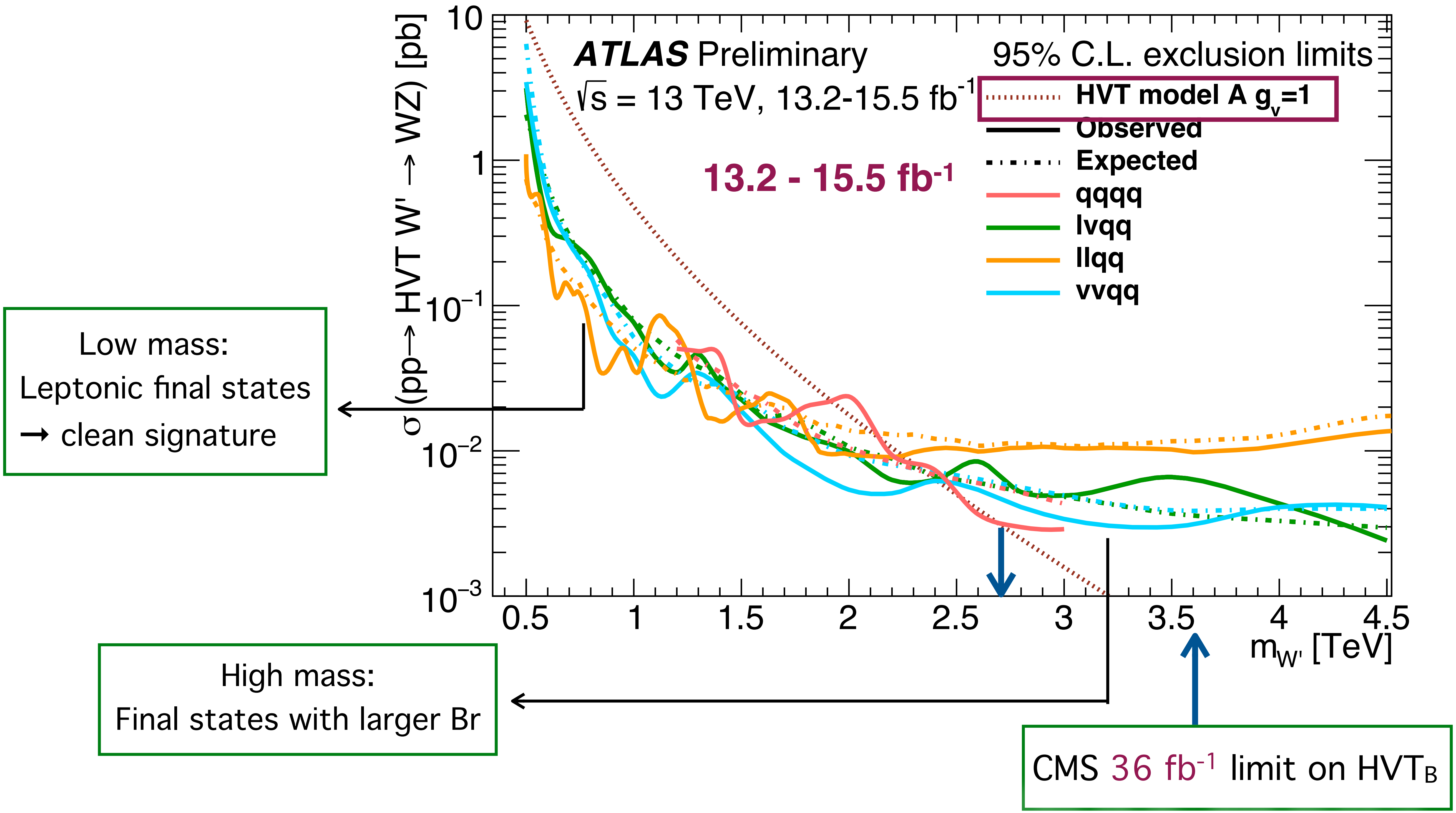
CMS-PAS-B2G-17-001





HVT - summary

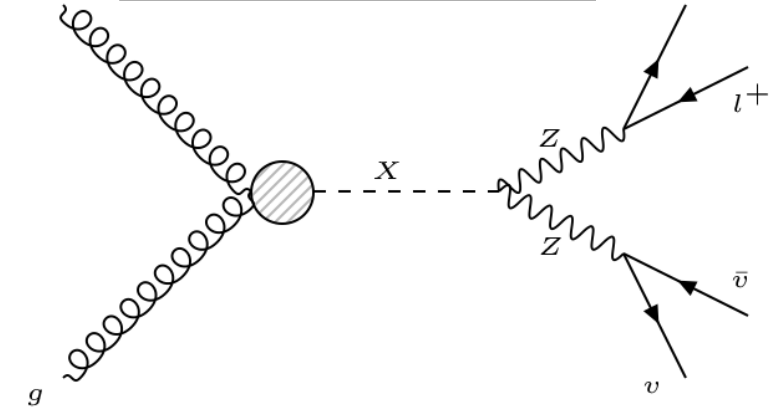
- W' → WZ: summary of limits from ATLAS
- Comparable limits with CMS combination (~2.5 fb^{-1} (13 TeV) + 19.7 fb^{-1} (8TeV), see backup)

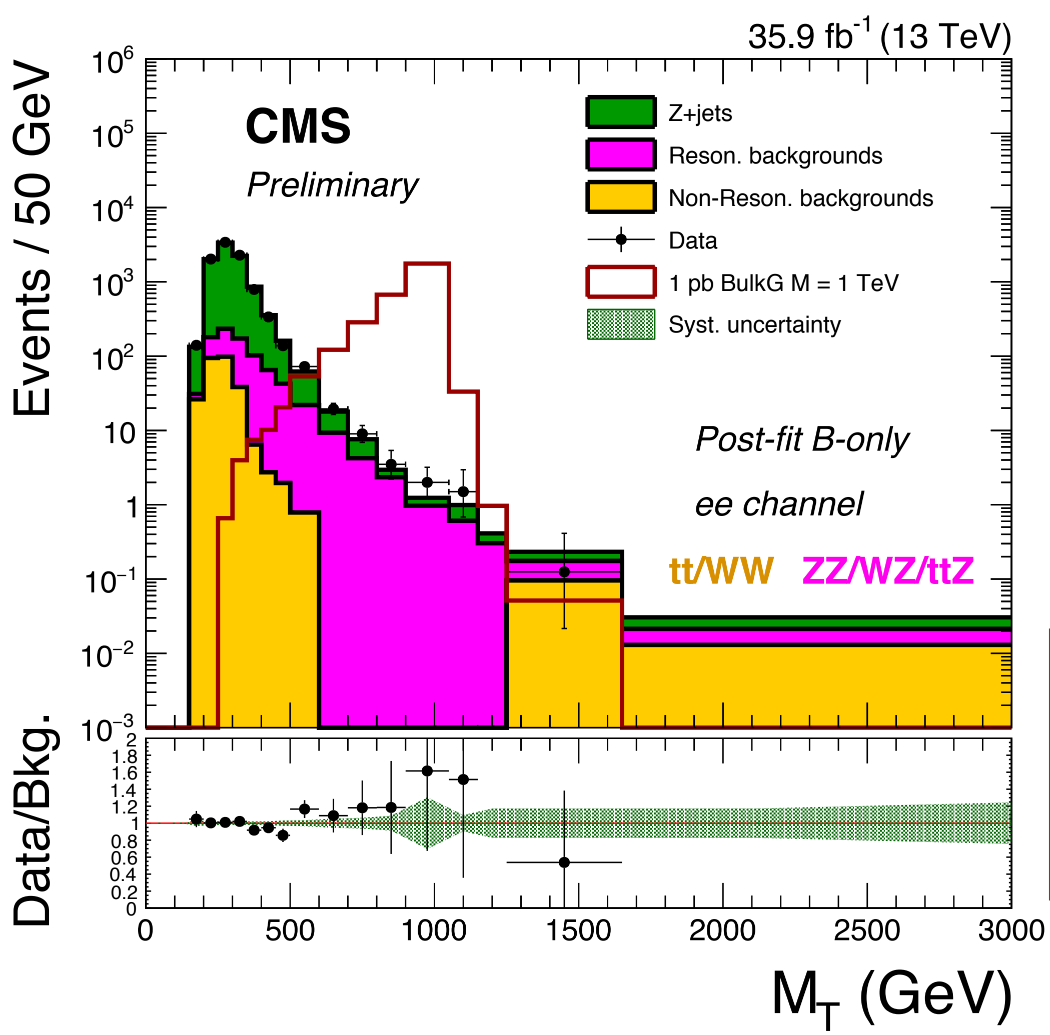


NEW ZZ→2l2ν

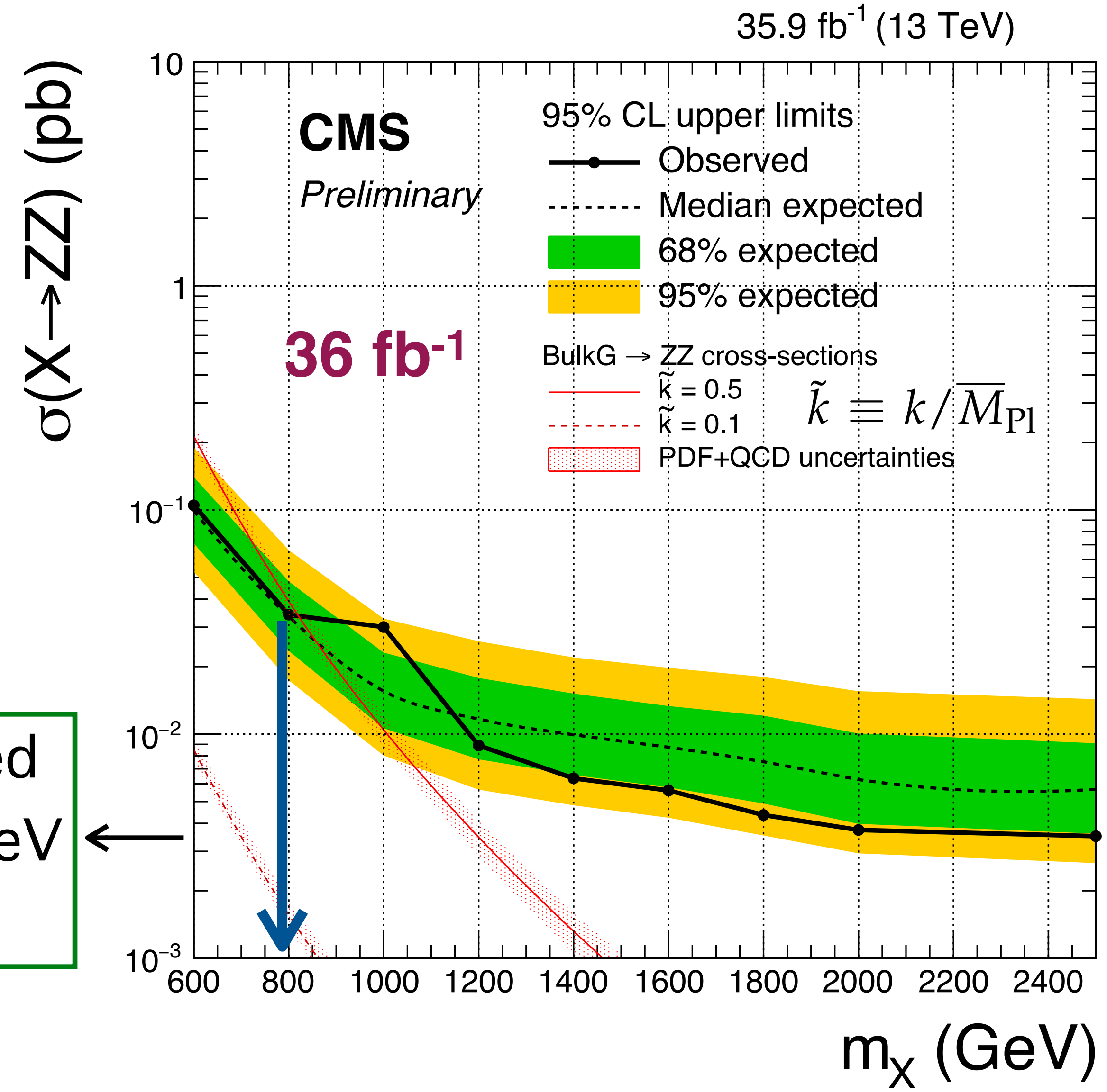
- **Large Br to llvv final state + controllable backgrounds**
- Discriminating variable: **transverse mass M_T**
- **Z+jets production** (dominant background)
  - E_T^{miss} comes from mismeasurements of jet/lepton pT
  - **Estimated from γ+jets data reweighted to reproduce the kinematics of Z+jets events**

CMS PAS B2G-16-023





Gbulk excluded below 800 GeV for $\tilde{k}$=0.5

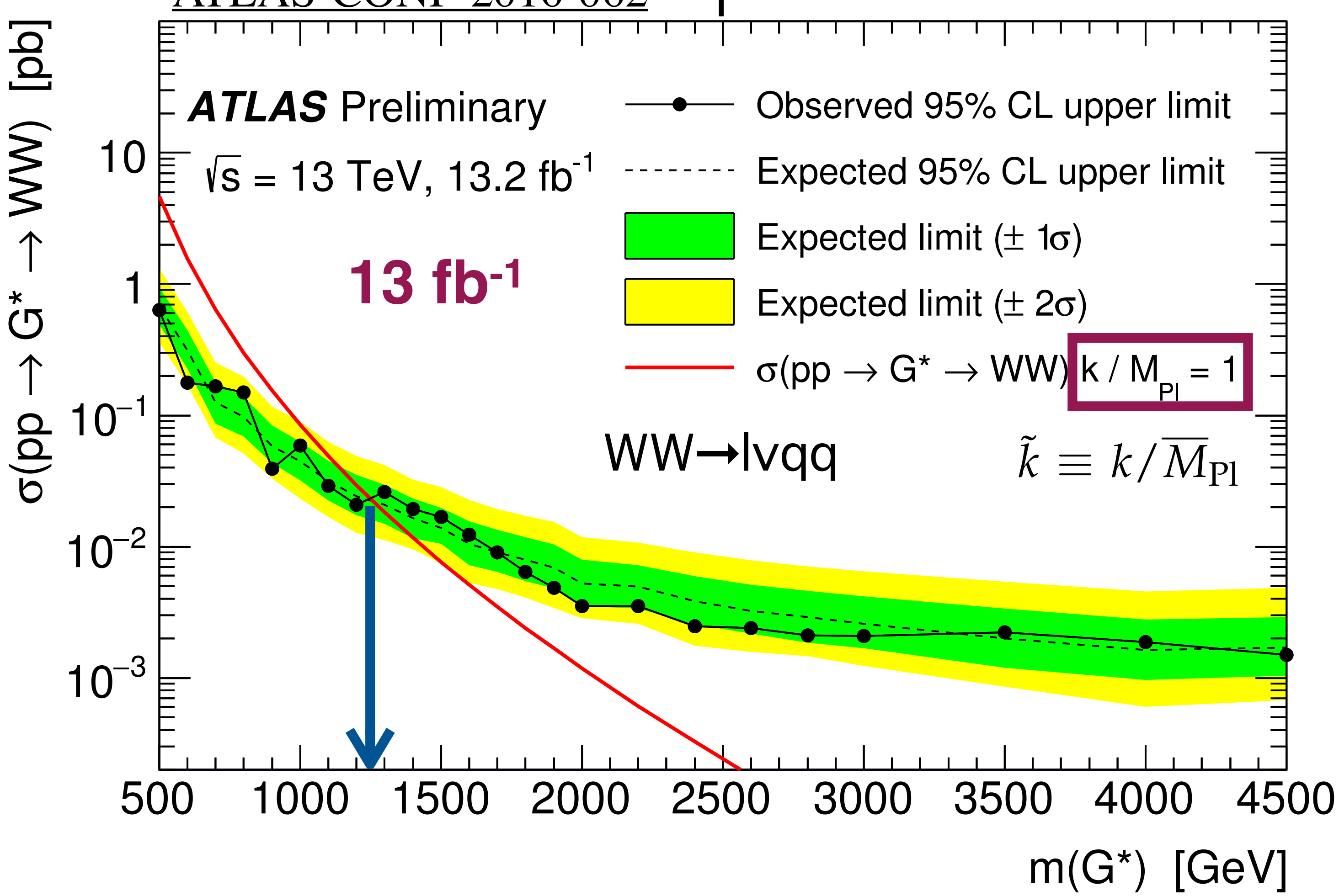


RS graviton - limits

- Currently the best limit from ATLAS on the bulk RS graviton with $\tilde{k} = 1$ coming from WW→lvqq channel

G_{bulk} excluded below 1.2 TeV for $\tilde{k} = 1$

ATLAS-CONF-2016-062



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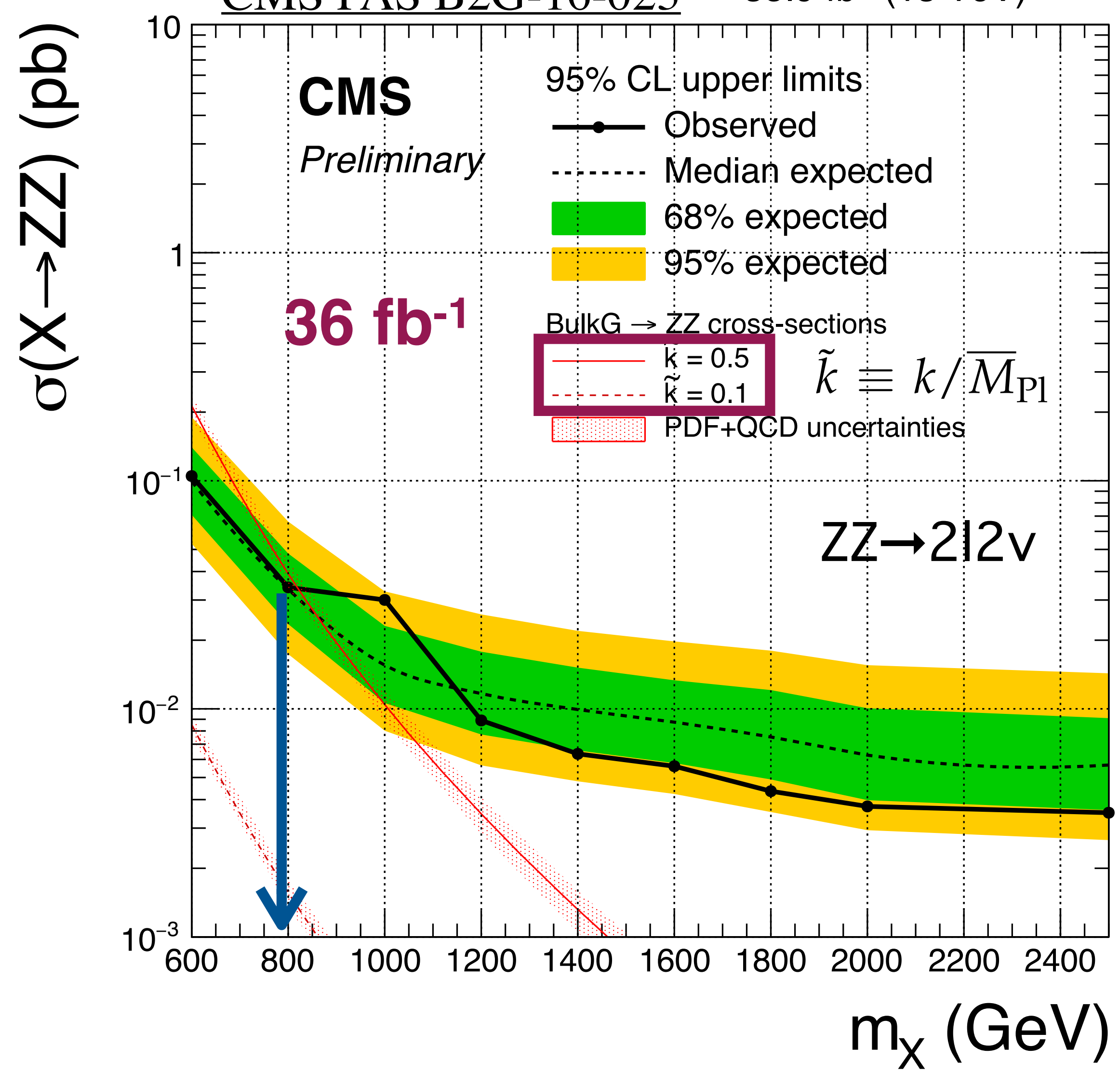
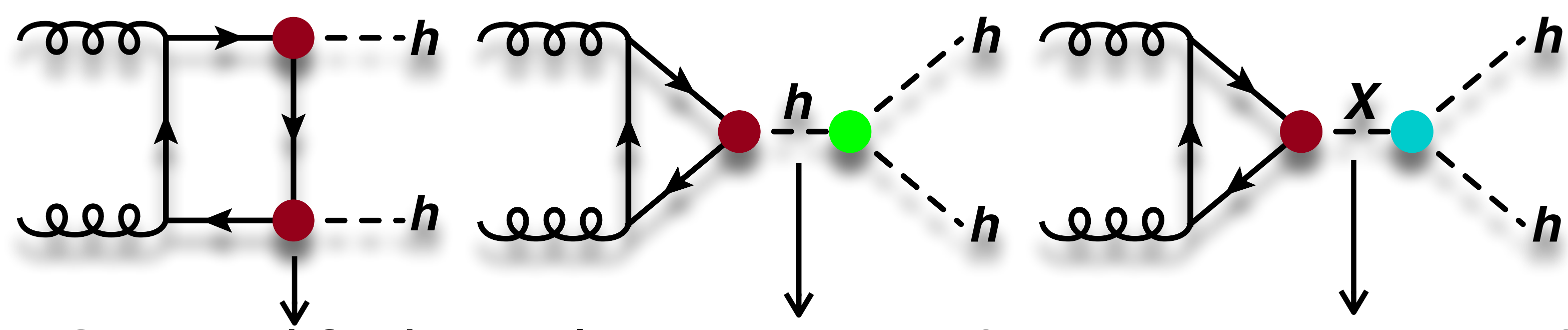
CMS PAS B2G-16-023



Di-Higgs searches

- SM: hh production cross section is several orders of magnitude smaller than the single-Higgs production

SM: destructive interference



BSM: Modified coupling constants? New resonance?

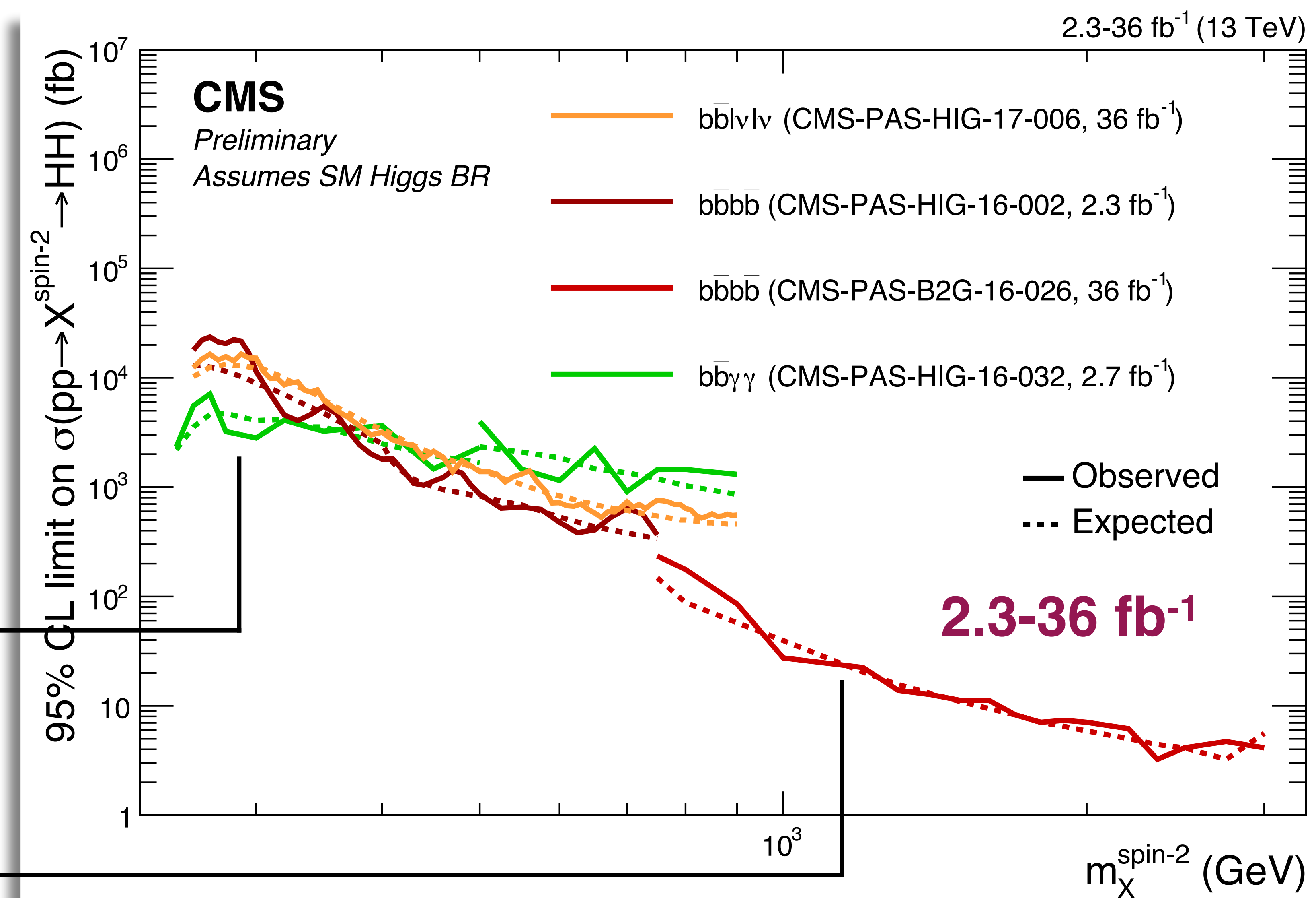
Final states:

Size of Br →

← Clean signature

Low mass:
Clean $\gamma\gamma$ signature
+ excellent $m_{\gamma\gamma}$ resolution

High mass:
High Br to bb

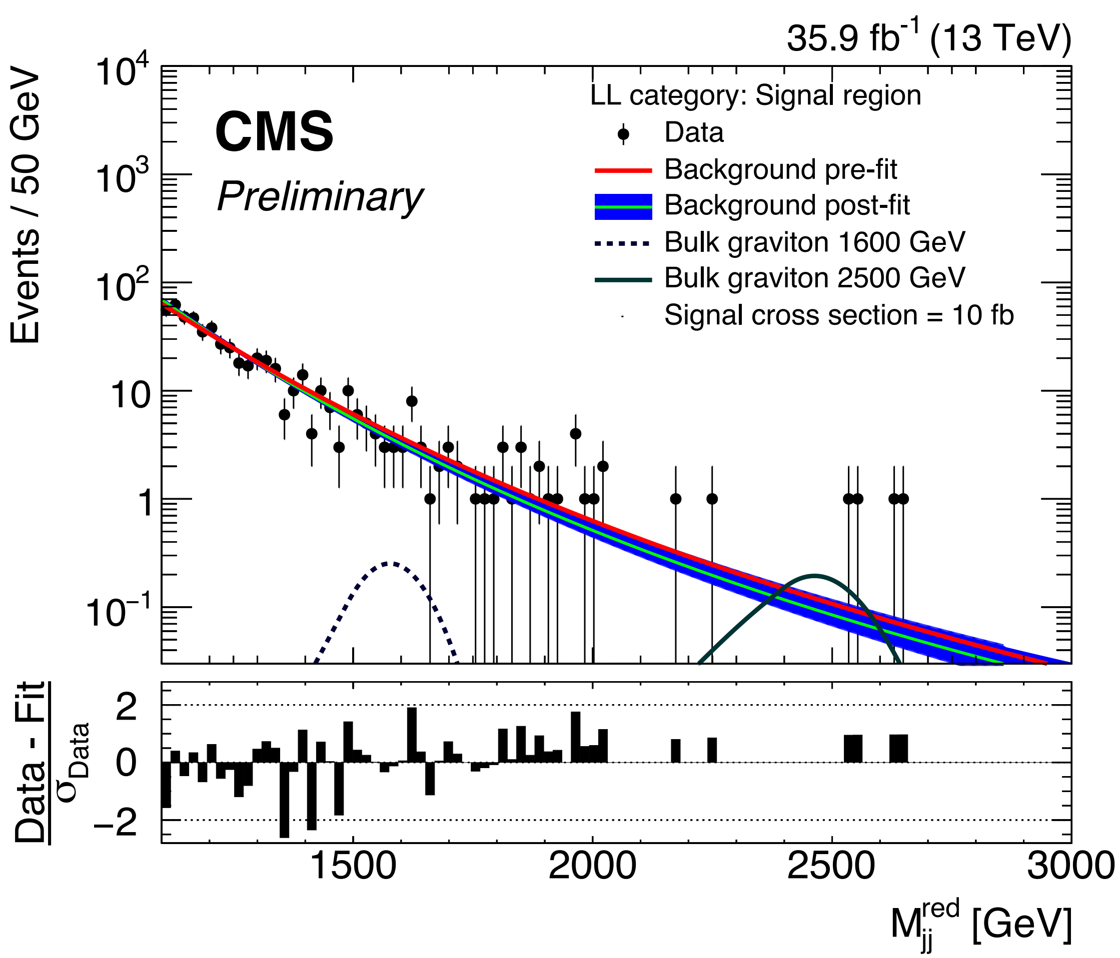


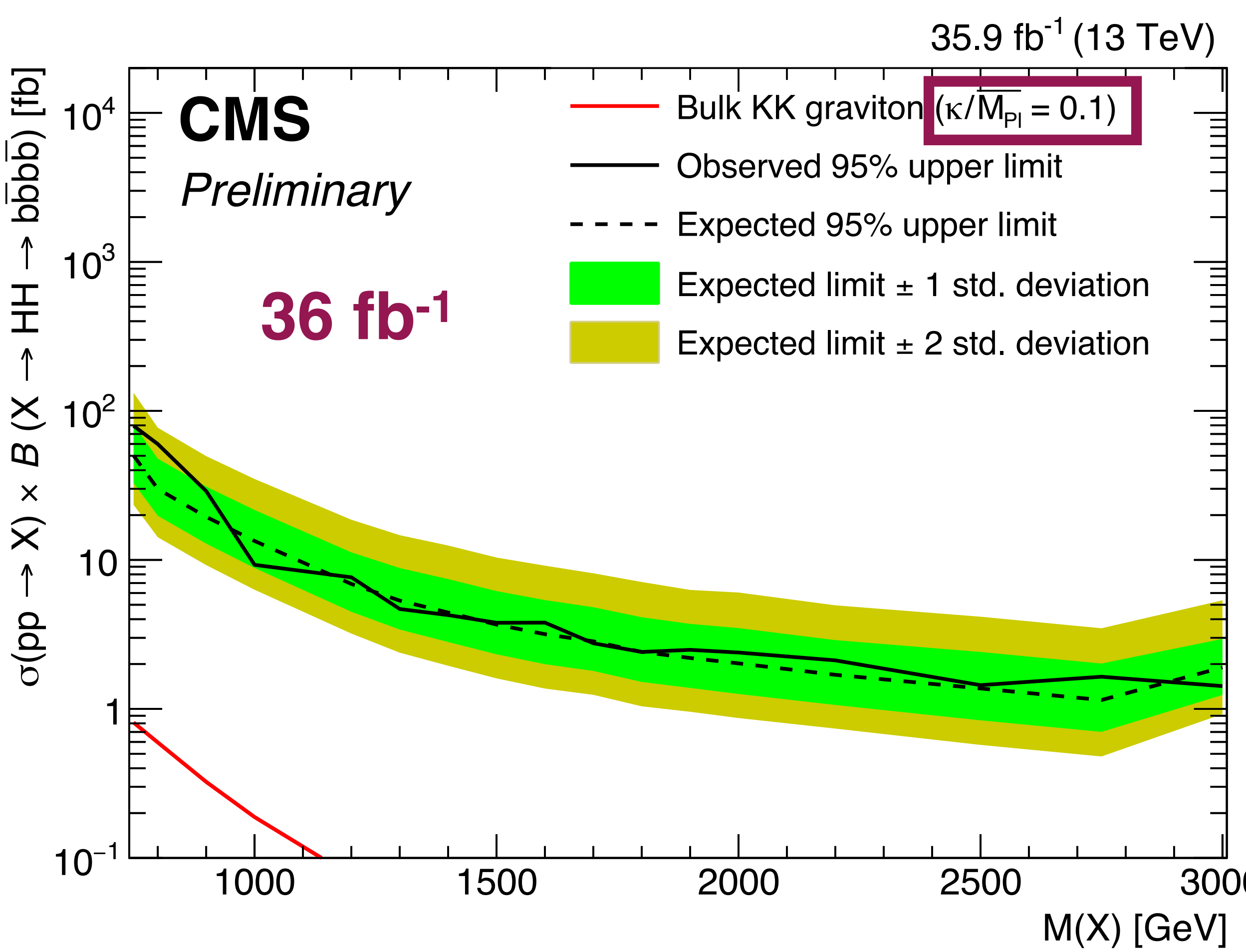
HH→4b

NEW

CMS PAS B2G-16-026

- Two H-tagged fat jets: **M_{jj}>750 GeV**
- **Reduced dijet mass** (to improve dijet resolution): $M_{jj}^{red} = M_{jj} - (M_{j_1} - M_H) - (M_{j_2} - M_H)$
- 2 categories of events depending on the double-b-tag discriminator: **LooseLoose & TightTight**
- **Multijet events** (dominant background)
  - Estimated using data from the “anti-tag” region of the leading jet (inverted b-tag discriminator)
  - Normalisation constrained using the leading jet mass sidebands

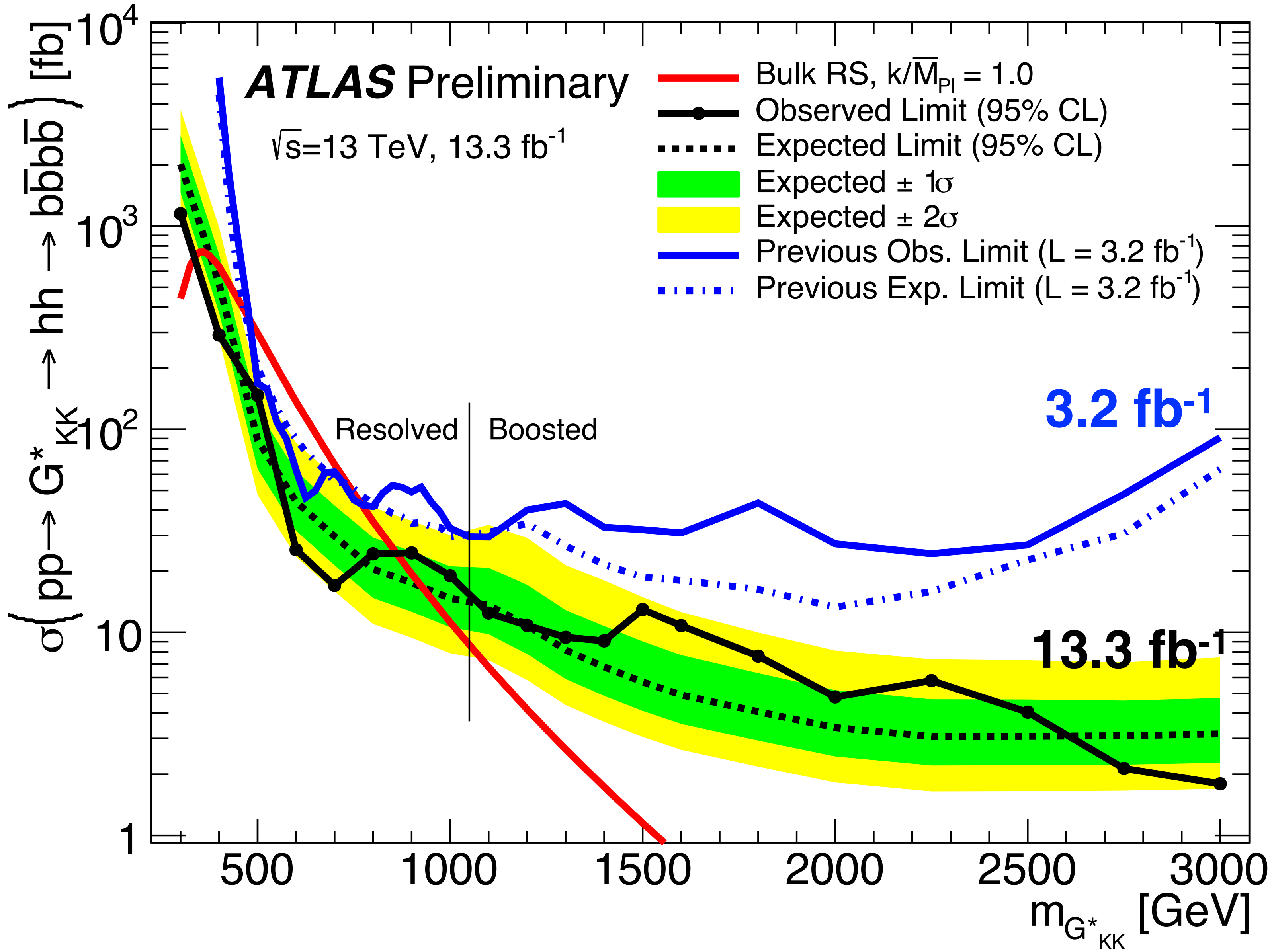




HH→4b

- **Resolved** regime: reconstruct 4 jets R=0.4 (m_{HH}<1000 GeV & non-resonant production)
- **Boosted** regime: reconstruct 2 fat jets R=1.0 (m_{HH}>1000 GeV)

ATLAS-CONF-2016-049



Improvement at high-mass:

Increase signal acceptance by requiring >=1 b-tagged track jet matched to H-jet (instead of >=2 previously)

Improvement at low-mass + non-resonant:

Increase signal acceptance by loosening topological selection requirements

non-resonant prod.	SM expected	95% CL UL expected	95% CL UL observed
$\sigma(pp \to hh \to b\bar{b}b\bar{b})$	$11.3^{+0.9}_{-1.0}$ fb	430 fb	**330 fb**

Conclusion

- Presented several analyses using the 15-36 fb^{-1} of 2015+2016 data
- Many other results with the full 36 fb^{-1} dataset are expected to come out this summer
- New data coming soon!
  - Bringing factor ~5 increase in the luminosity
  - But also challenges in terms of pile-up…
  - ➡ Jet reconstruction, boosted boson tagging techniques, trigger… being continuously refined to cope with this challenge and improve the limits
- Stay tuned!

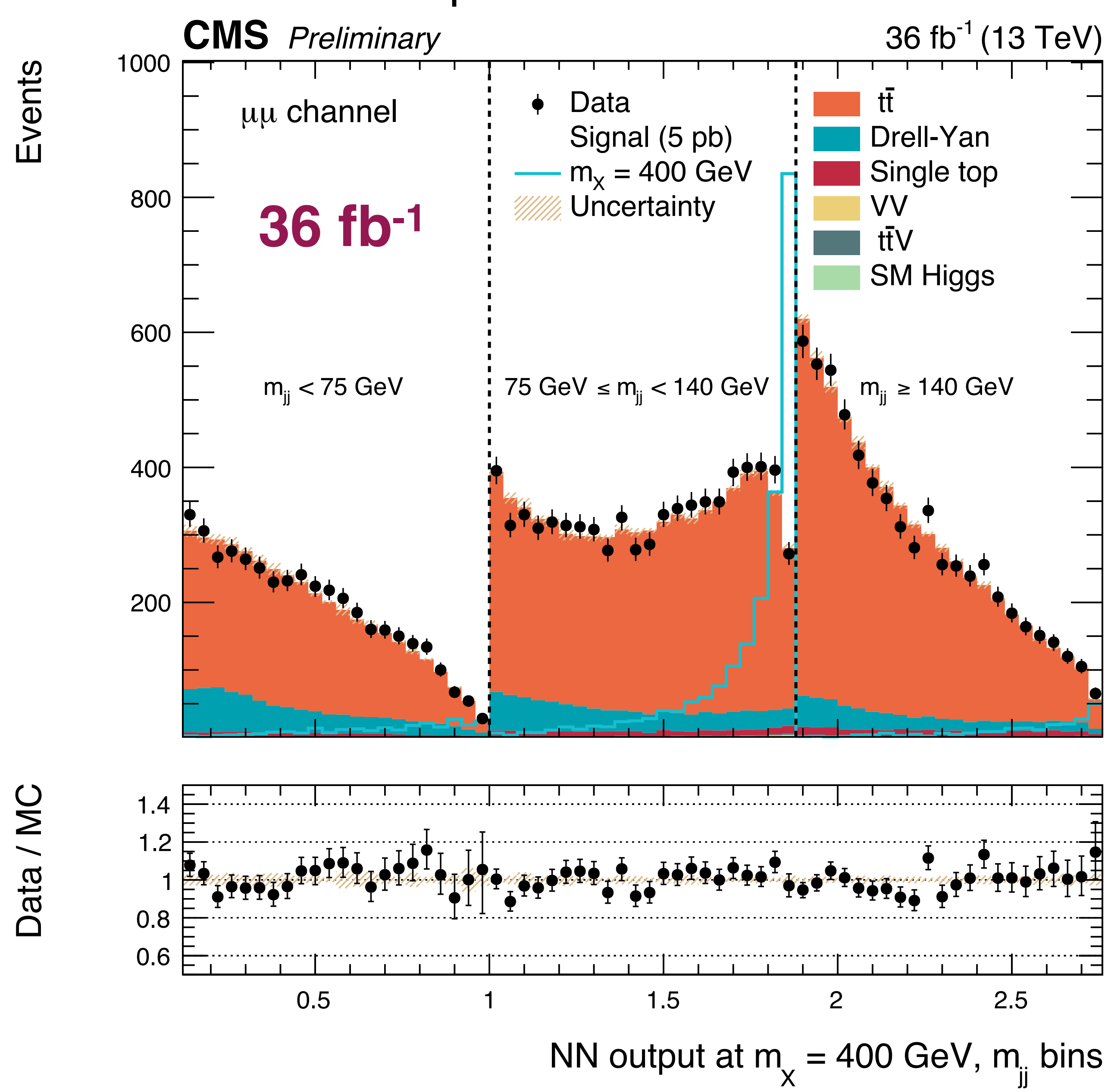
Backup

HH→bblνlν

- Select events with 2 b-tagged jets and 2 leptons of opposite charge
- Search for a resonant-like excess compatible with M_H in M_{bb} distribution
- Use deep neural network (DNN) to improve signal-to-background separation

CMS PAS HIG-17-006

DNN output is the final discriminant



HH→bblvlv

- Select events with 2 b-tagged jets and 2 leptons of opposite charge

CMS PAS HIG-17-006

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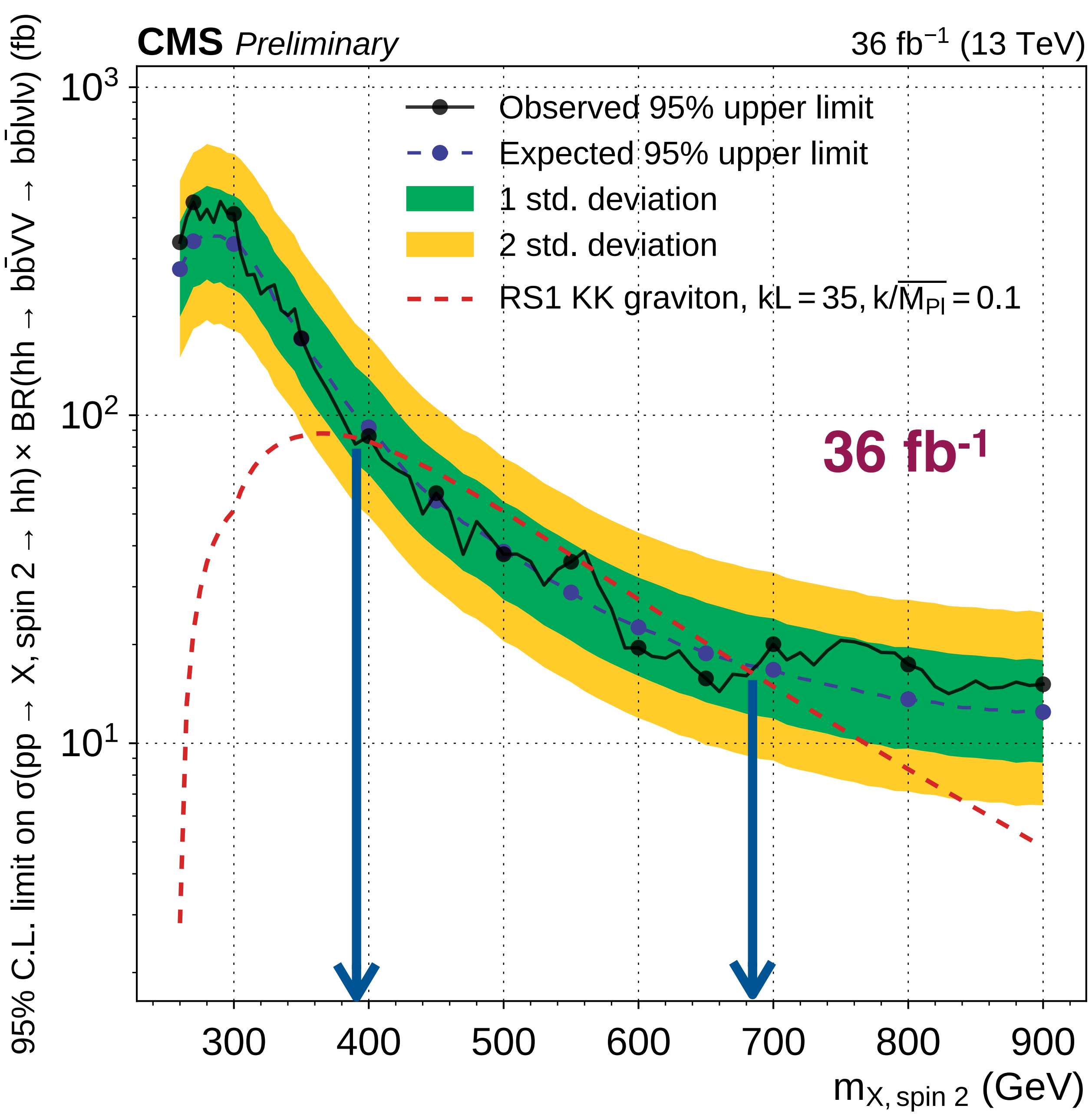
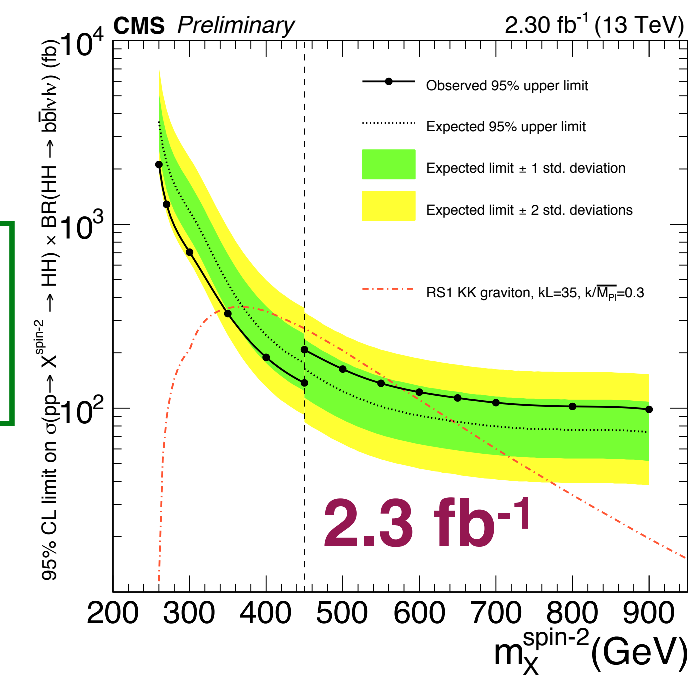


Limit improved in the whole range



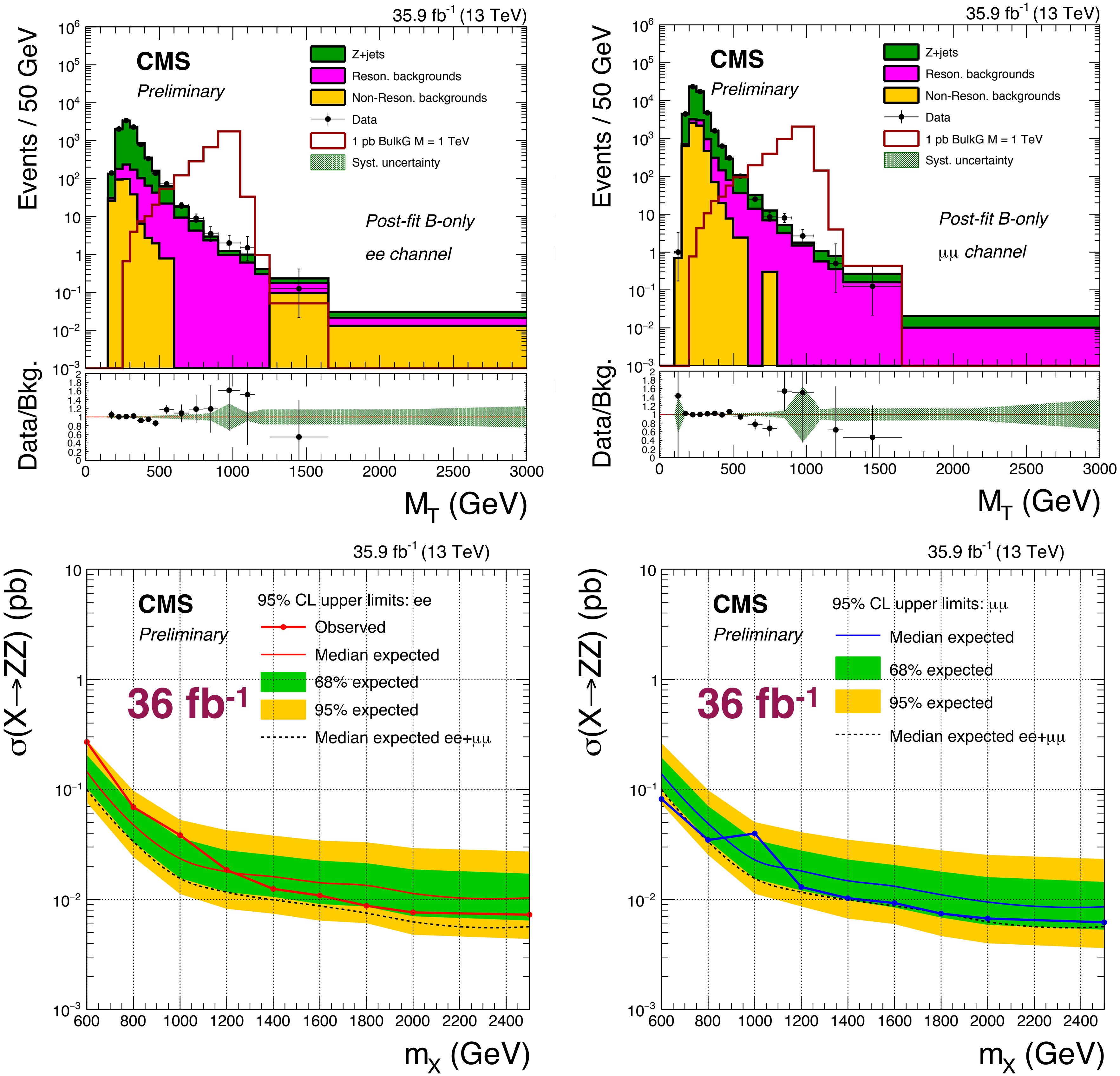
non-resonant prod.	$\sigma(pp \to hh \to b\bar{b}l\nu l\nu)$
95% CL UL expected	81^{+42}_{-25} fb
95% CL UL observed	**72 fb**

↓

amounts to 79 x the SM prediction

NEW ZZ→2l2ν

CMS PAS B2G-16-023



NEW

ZZ→2l2ν

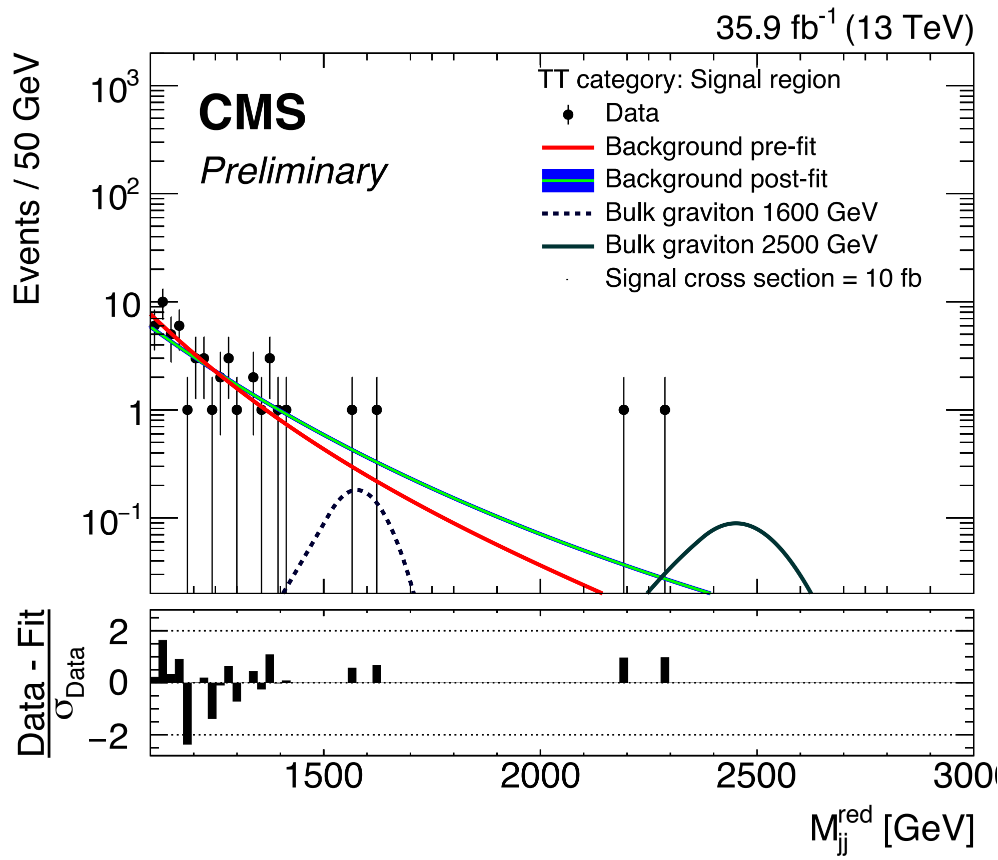
CMS PAS B2G-16-023

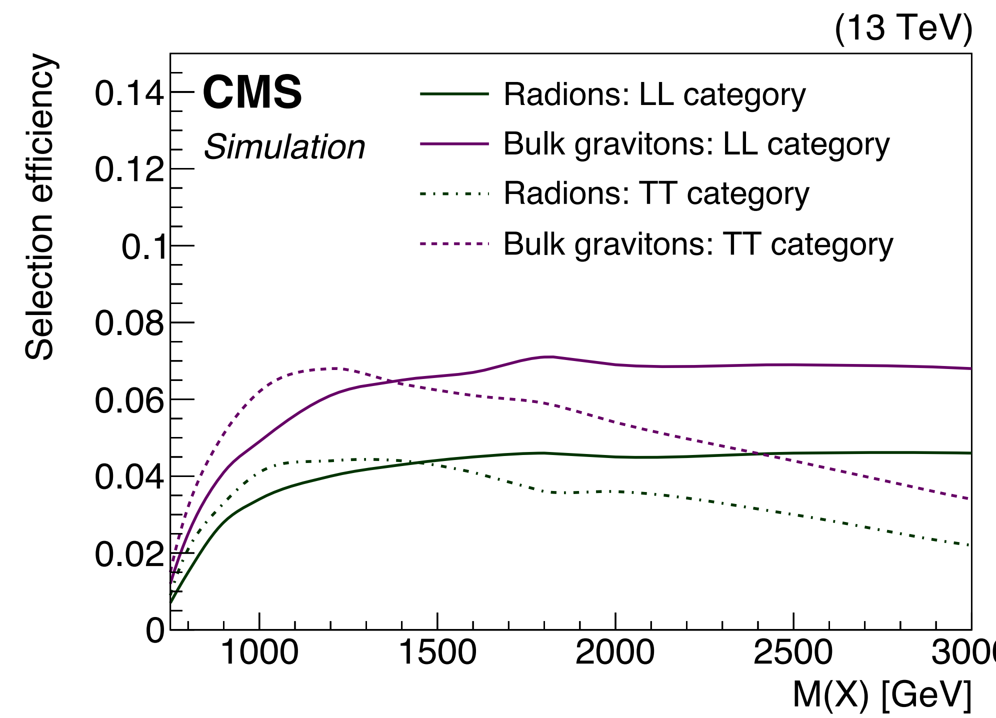
	Source	Signal	Z+jets	Reson.	Non-Reso
	Luminosity	2.5%	2.5%	2.5%	2.5%
	PDF on cross-section	-	1.7%	1.7%	-
	QCD on cross-section	-	2.3%	3.0%	-
	EW NLO correction	-		3.0%	-
Electron channel	PDF on acceptance	1.0%	3.4%	1.0%	-
	QCD on acceptance	(-)	22.7%	2.9%	-
	Trigger eff.	0.1%	-	(-)	-
	Lepton ID eff.	0.5%	-	(-)	-
	Z p_T reweighting	-	2.1%	-	-
	Non-reson. scale fact.	-	-	-	10.0%
E_T^{miss} modeling uncertainties	Muon scale	0.1%	-	10.1%	-
	Elec. scale	1.8%	-	0.4%	-
	Photon scale	2.9%	-	0.5%	-
	Jet energy scale	1.5%	-	0.4%	-
	Jet energy resolution	1.5%	-	0.5%	-
	Unclustered E	2.3%	-	0.5%	-
	Hadronic recoil	-	0.1%	-	-
Muon channel	PDF on acceptance	1.0%	3.4%	1.0%	-
	QCD on acceptance	(-)	13.1%	2.9%	-
	Trigger eff.	0.2%	-	(-)	-
	Lepton ID eff.	0.9%	-	(-)	-
	Tracking eff.	1.0%	1.0%	1.0%	1.0%
	Z p_T reweighting	-	0.5%	-	-
	Non-reson. scale fact.	-	-	-	2.4%
E_T^{miss} modeling uncertainties	Muon scale	10.9%	-	1.8%	-
	Elec. scale	(-)	-	(-)	-
	Photon scale	0.1%	-	(-)	-
	Jet energy scale	1.2%	-	0.1%	-
	Jet energy resolution	1.9%	-	0.2%	-
	Unclustered E	1.8%	-	0.3%	-
	Hadronic recoil	-	0.1%	-	-

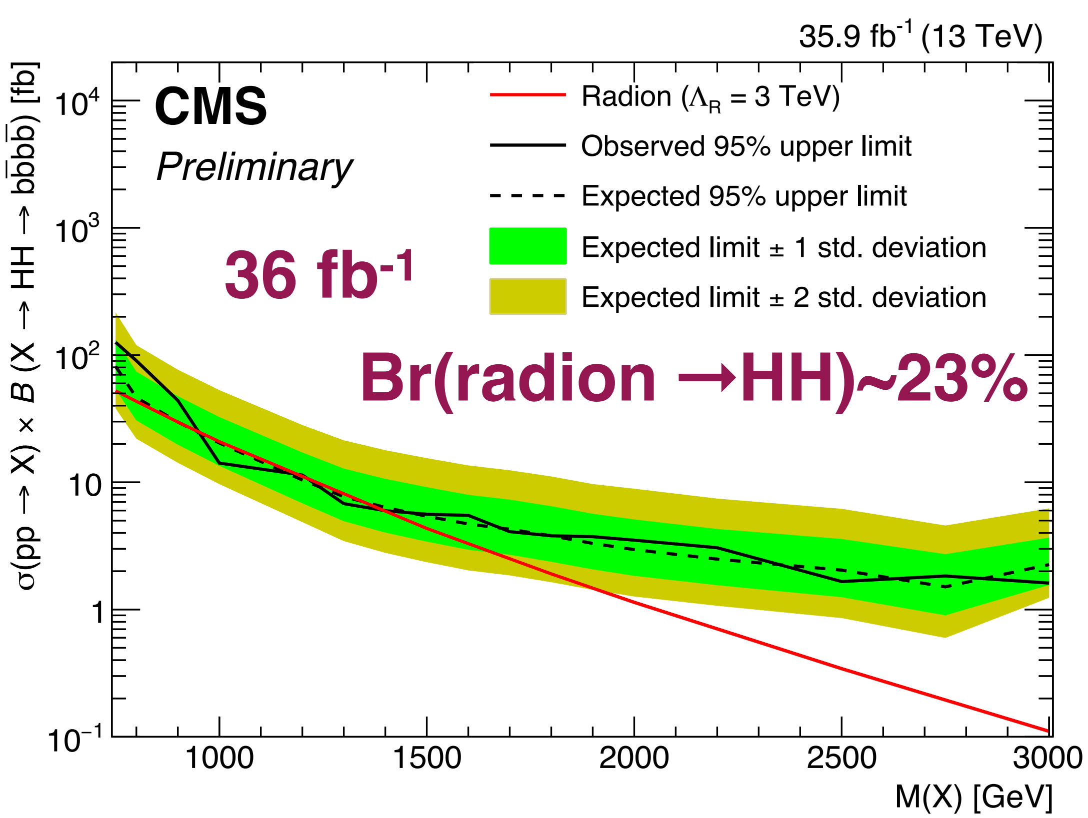
HH→4b

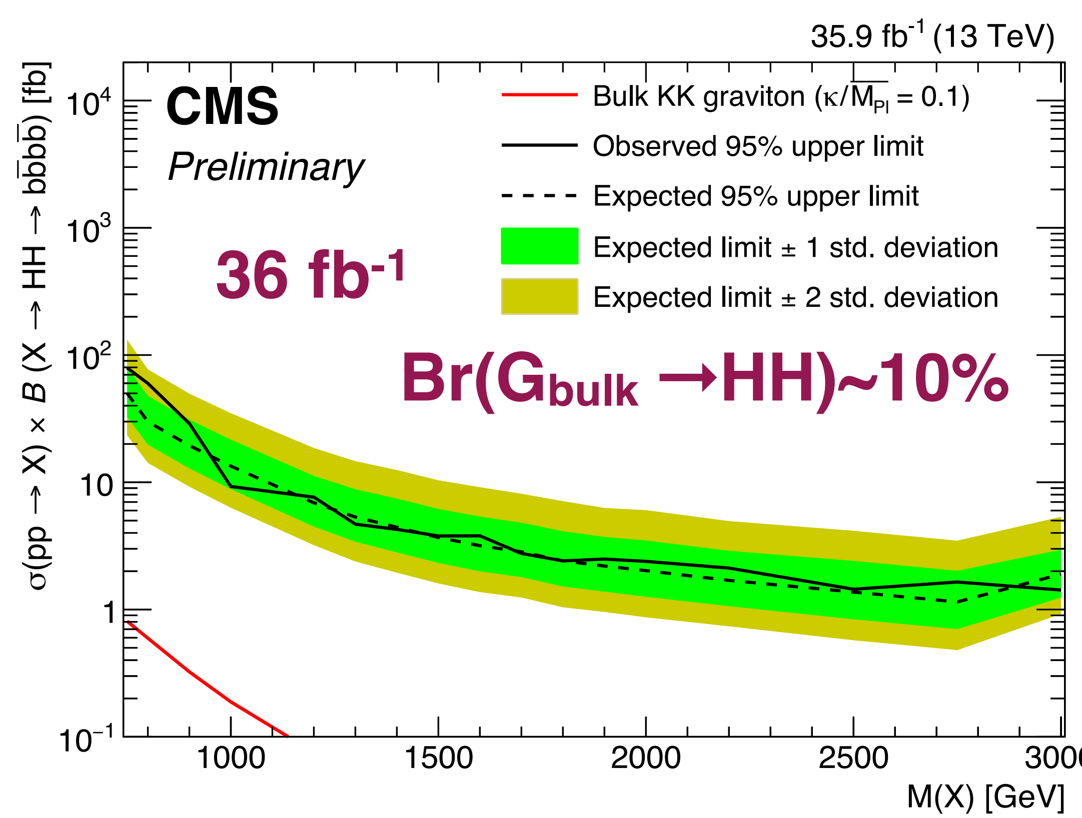
NEW

CMS PAS B2G-16-026







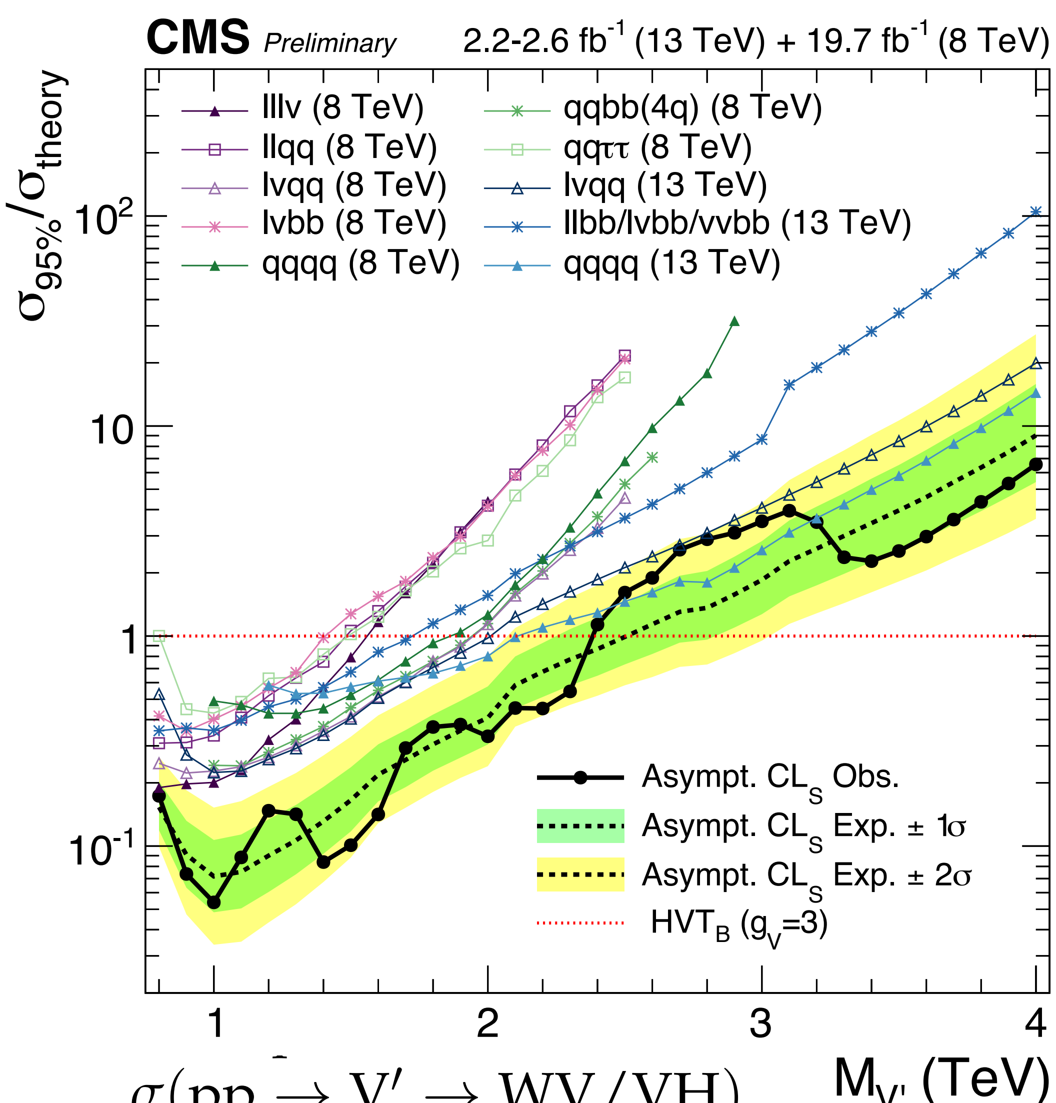


CMS - combinations

- Combination with this lumi not sensitive enough to exclude G_{bulk} with $\tilde{k}$=0.5
- 36 fb^{-1} searches @ 13 TeV more sensitive than the combination

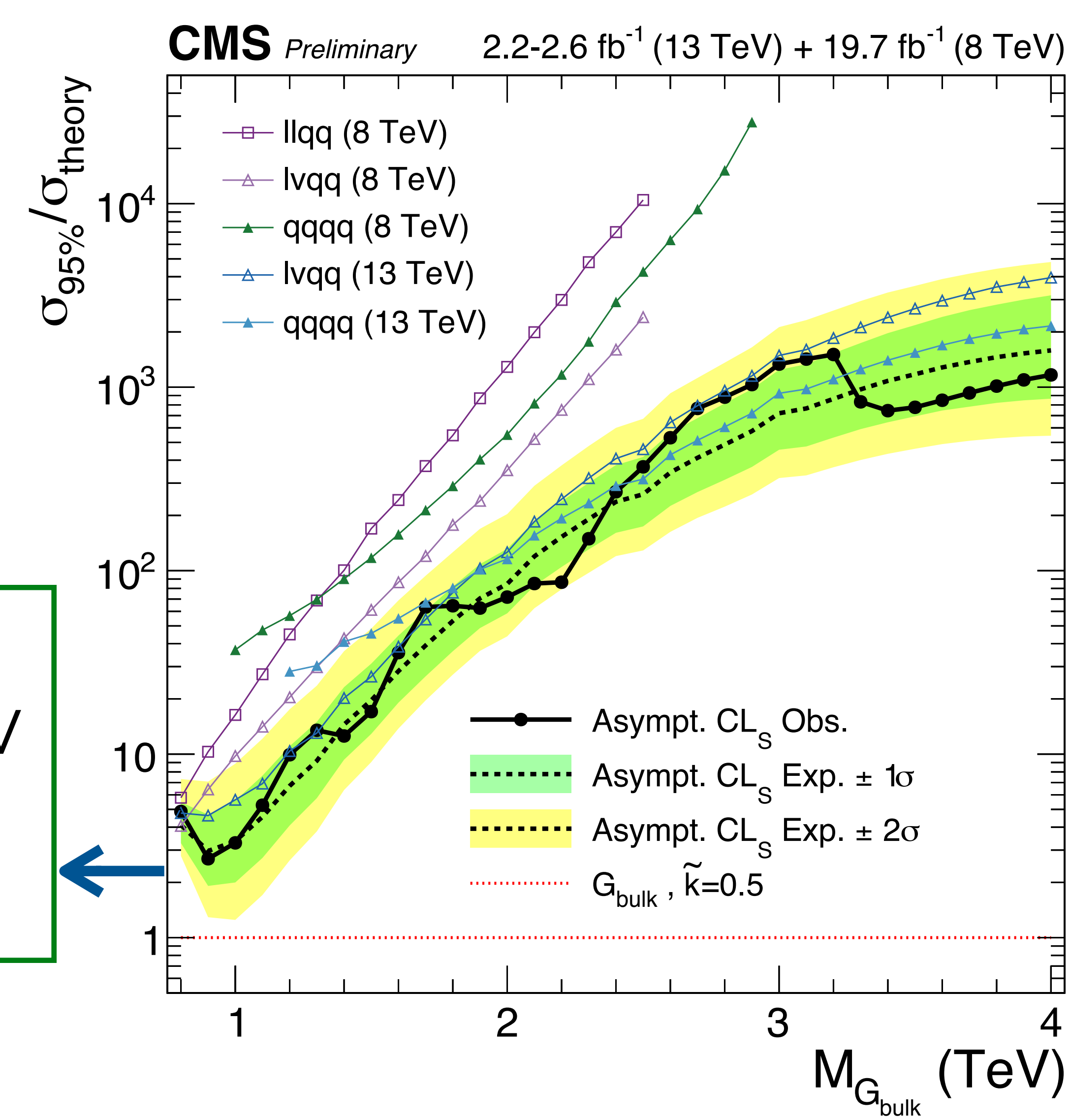
~2.5 fb^{-1} (13 TeV) + 19.7 fb^{-1} (8TeV)

CMS PAS B2G-16-007



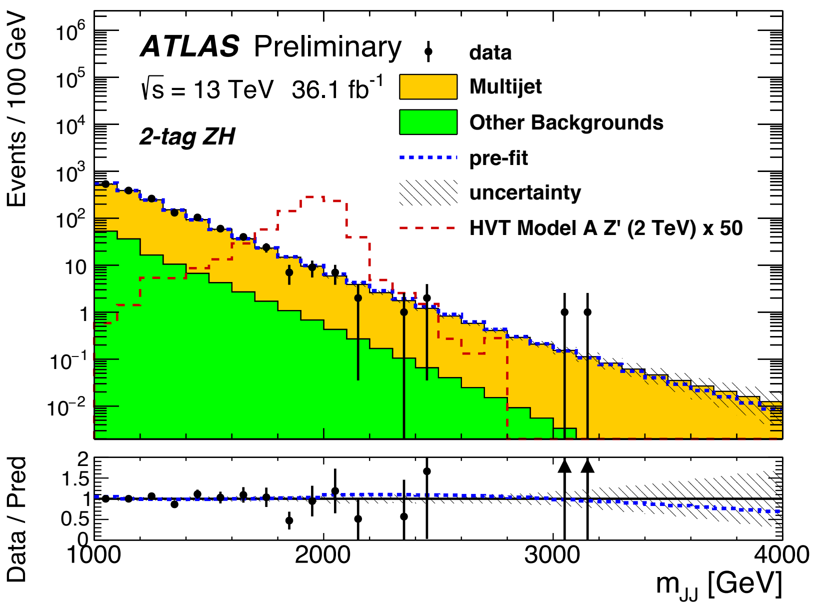
$\sigma(pp \to V' \to WV/VH)$

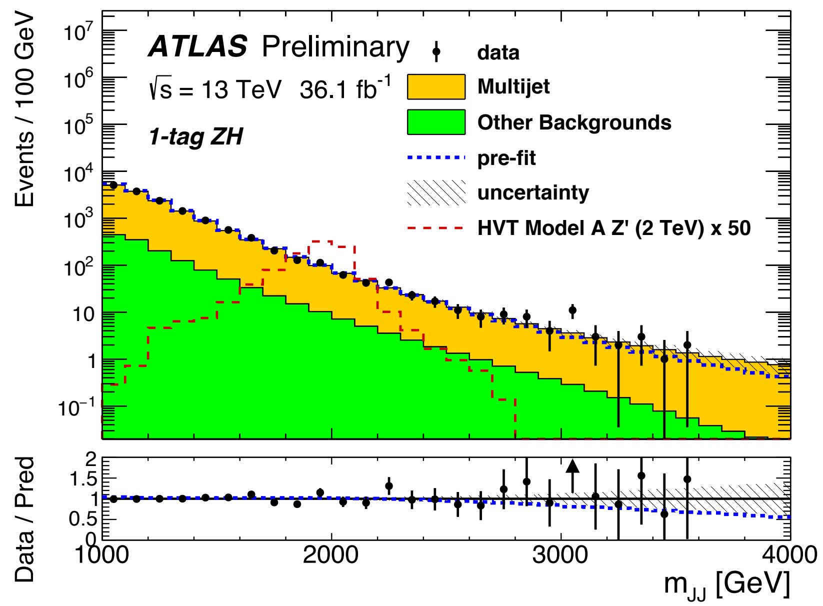
Gbulk excluded below 800 GeV for $\tilde{k}$=0.5 with 36 fb^{-1} 2l2v

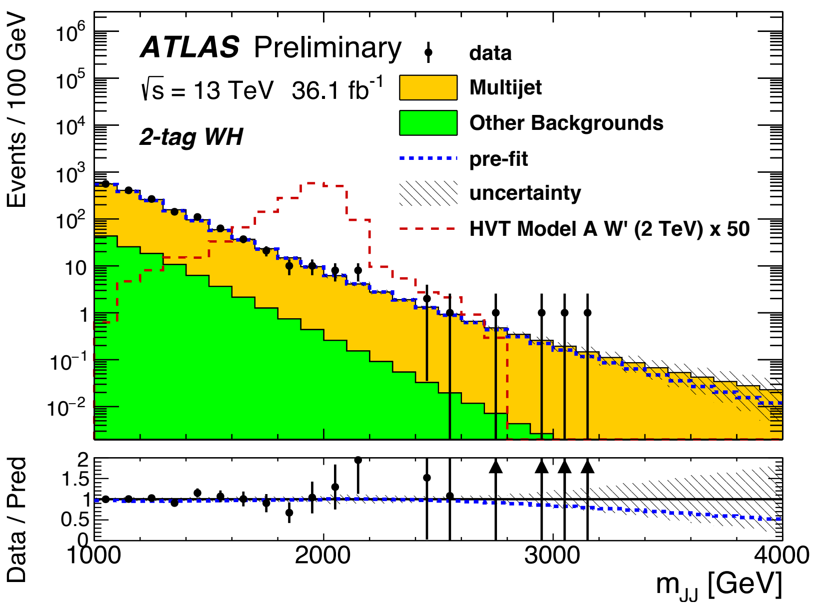


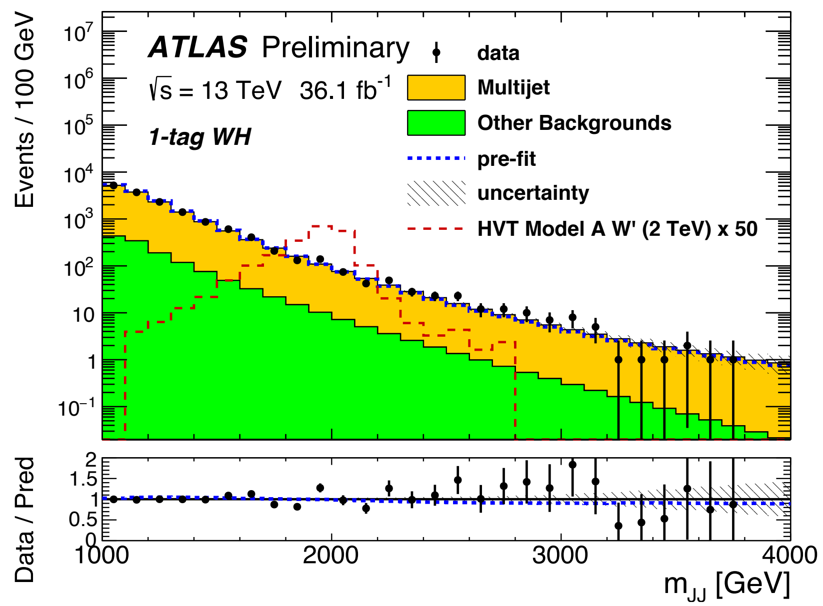
WH/ZH→qqbb

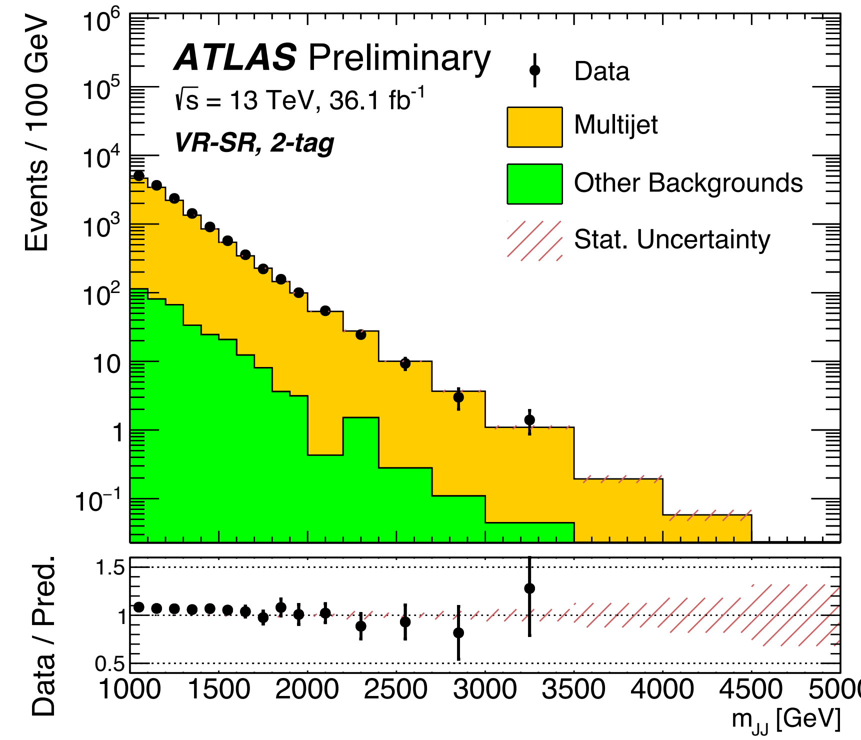
ATLAS-CONF-2017-018

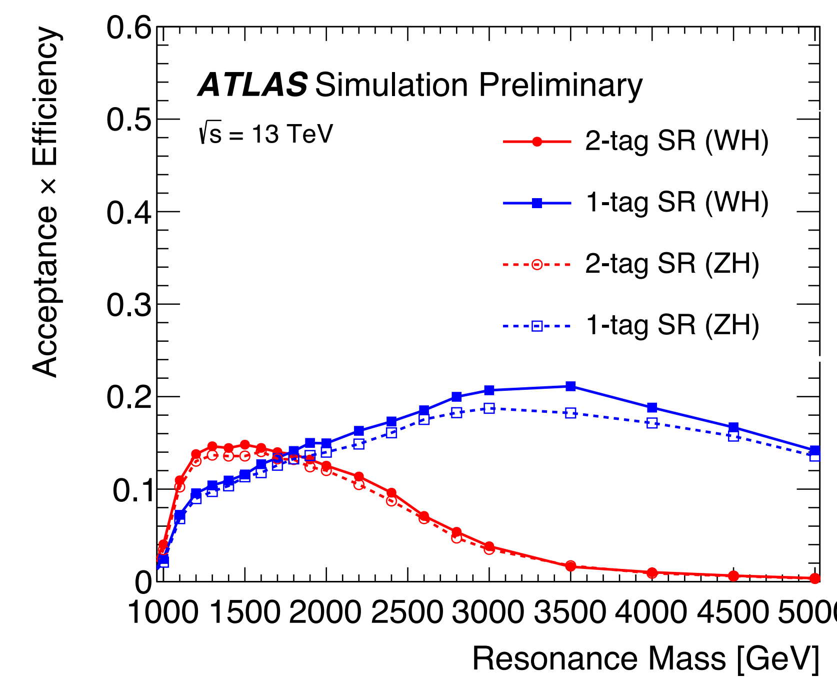










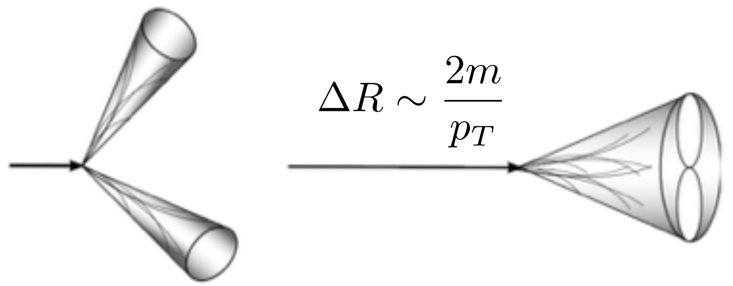


Source	*WH* 2 tag yield variation [%] Background	*WH* 2 tag yield variation [%] HVT *Model B W′* (2 TeV)	*WH* 1 tag yield variation [%] Background	*WH* 1 tag yield variation [%] HVT *Model B W′* (2 TeV)
Luminosity	0.2	3.2	0.3	3.2
Jet energy scale	2.4	5.7	0.8	5.6
Jet mass resolution	1.2	11	0.3	10.4
b-tagging	1.6	10.6	0.4	15.2
$t\bar{t}$ Normalization	1.9	-	2.5	-
Multijet Normalization	4.3	-	2.8	-

ATLAS: Combined jet mass

- For a high Lorentz boost ΔR comparable with the calorimeter granularity
- Use track-assisted mass (TA) to maintain performance:

$$m^{\mathrm{TA}} = \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}} \times m^{\mathrm{track}}$$



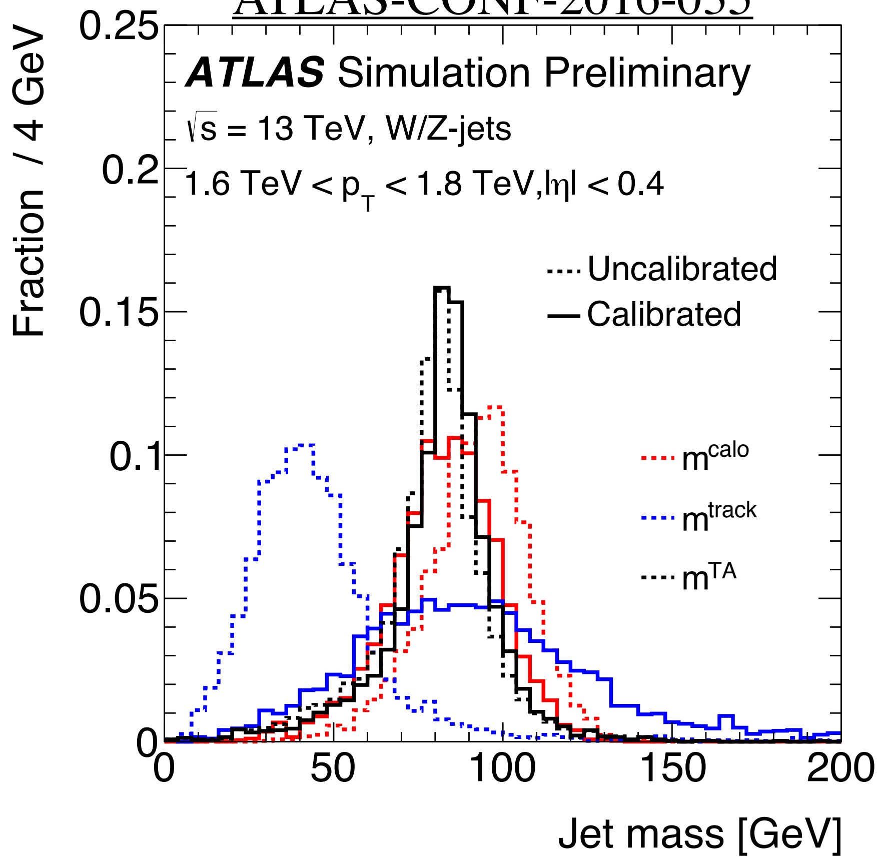
- Combined jet mass:

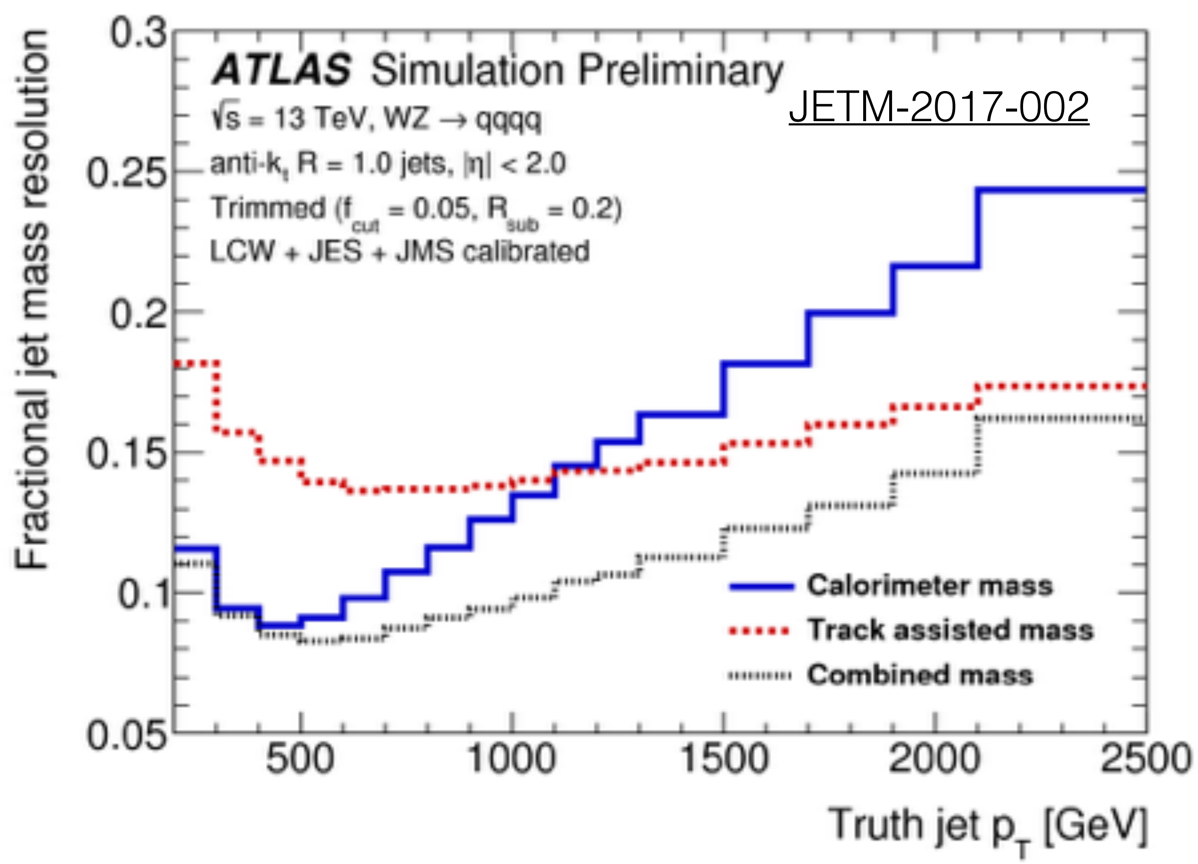
$$m_J \equiv w_{\mathrm{calo}} \times m_{\mathrm{J}}^{\mathrm{calo}} + w_{\mathrm{track}} \times \left(m_{\mathrm{J}}^{\mathrm{track}} \frac{p_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{\mathrm{track}}} \right)$$

[ATLAS-CONF-2017-018]

  - w_{calo} and w_{track} are p_T-dependent functions of the calorimeter and track-based jet mass resolutions used to optimize the combined mass resolution

ATLAS-CONF-2016-035





VV→lvqq

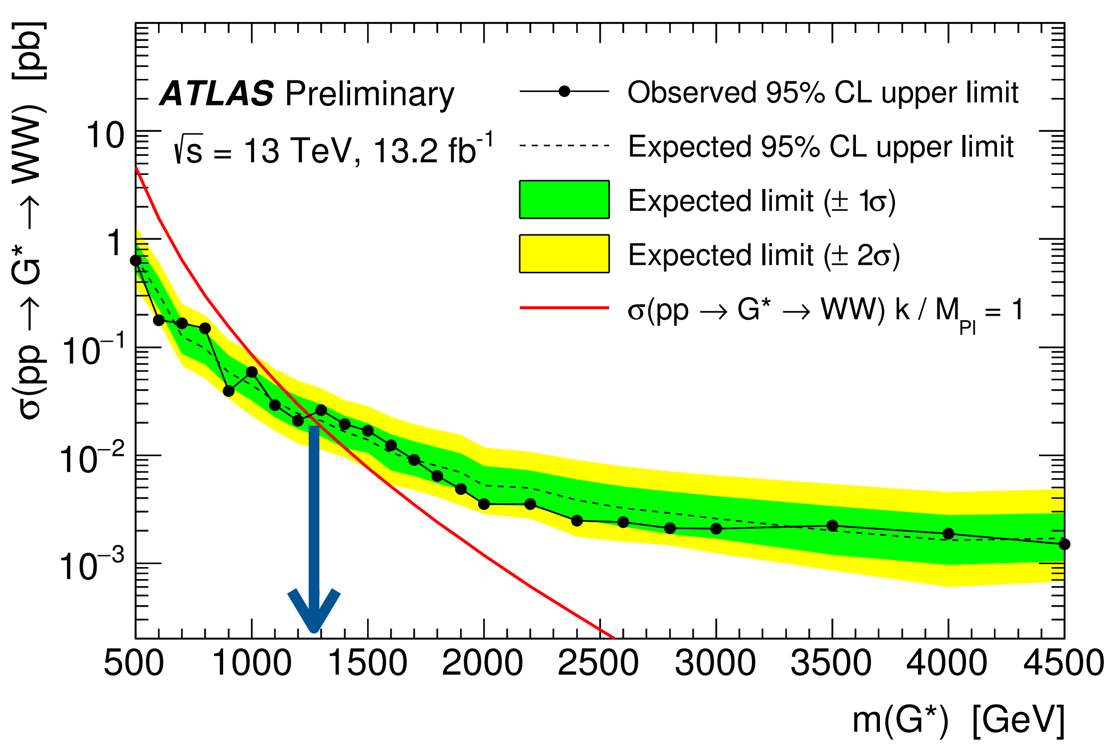
ATLAS-CONF-2016-062
CMS PAS B2G-16-020

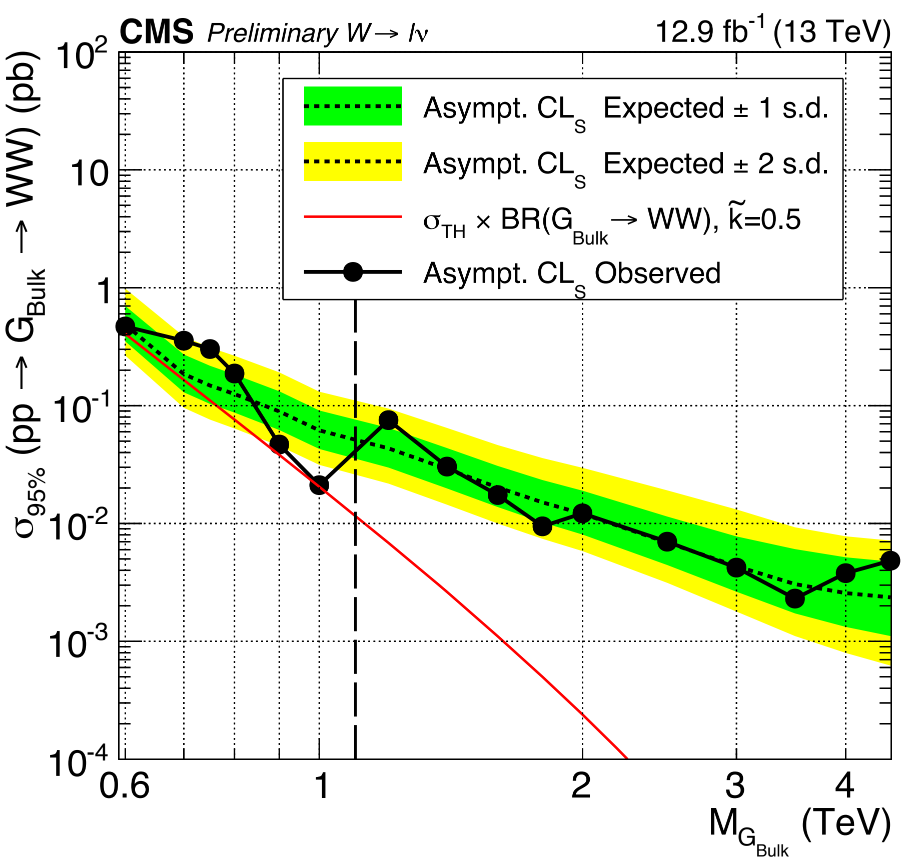
Limits with a narrow width assumption:

- natural width of the resonance much smaller than the experimental resolution (~8% of the $M_{resonance}$)

→ detector effects on the signal shape independent of the signal model used

→ the observed limit is a limit on the on-shell cross section only and does not include contributions from interference or PDF effects

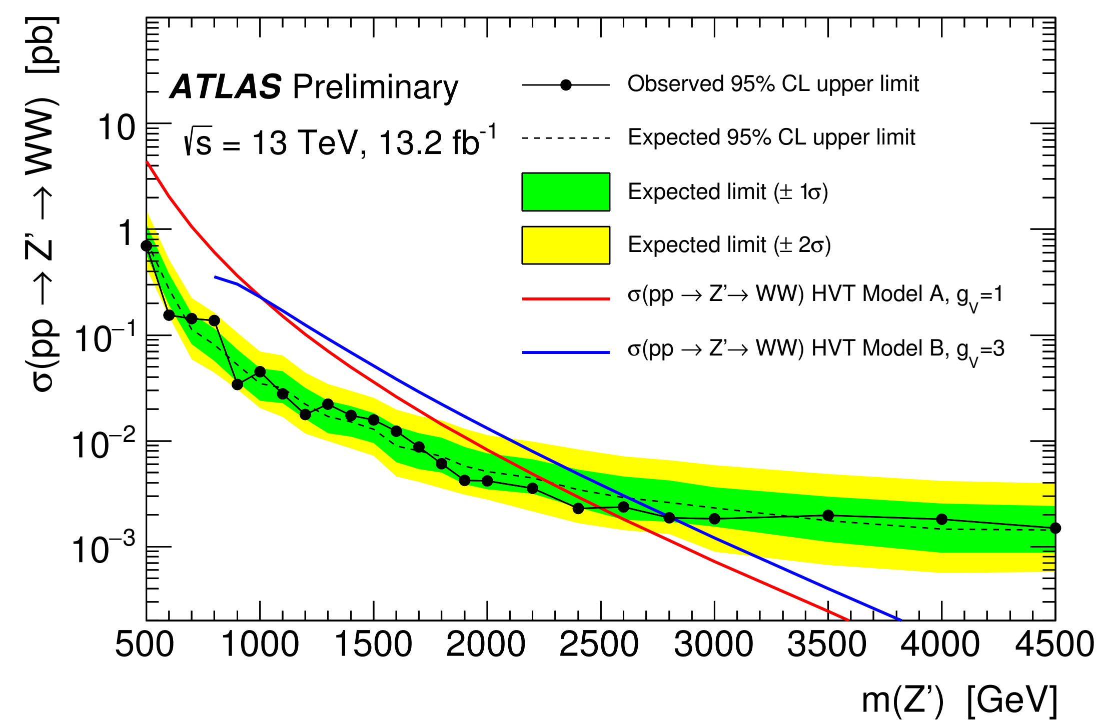


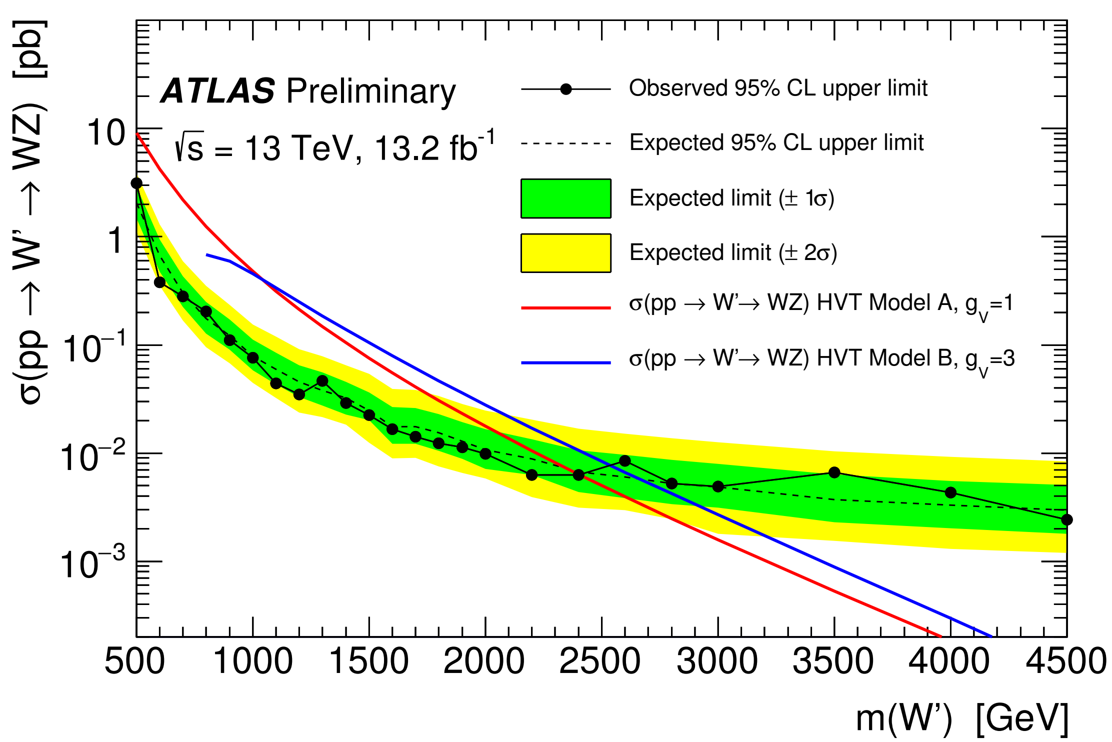


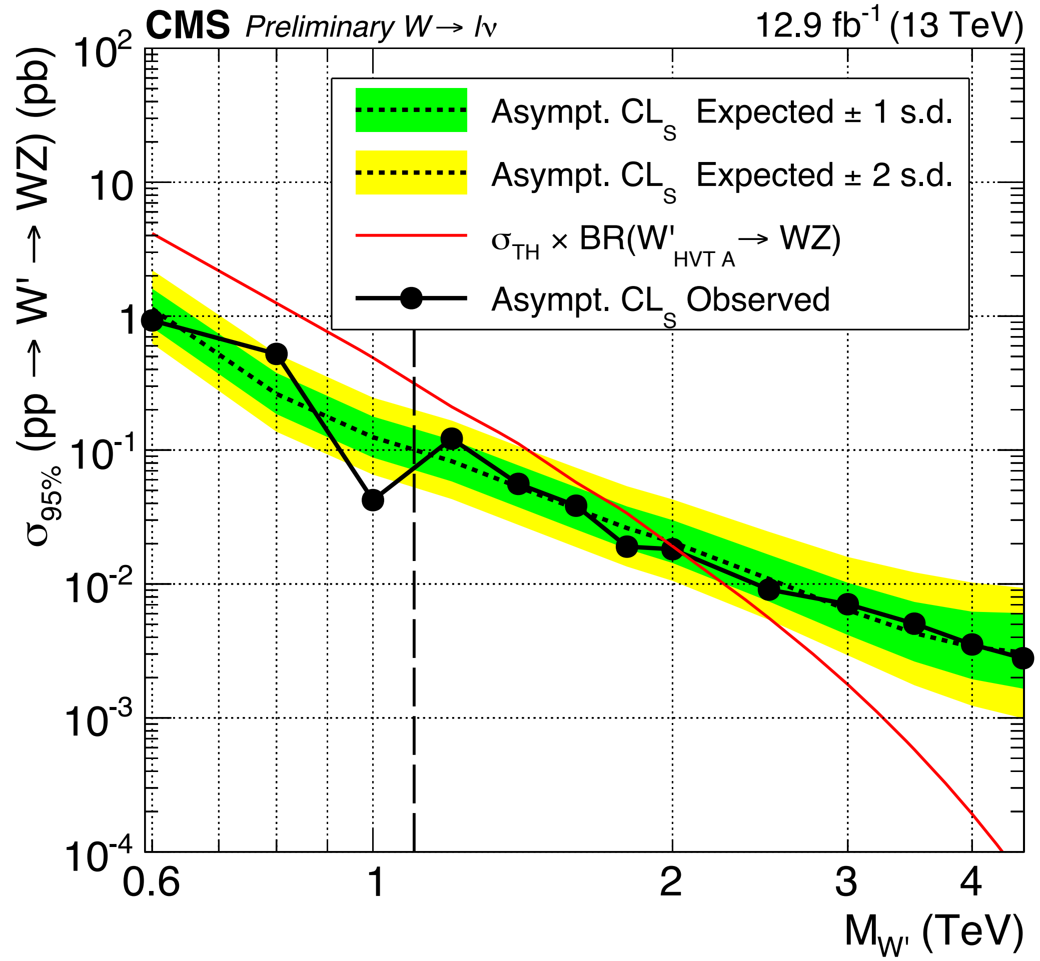
VV→lvqq

ATLAS-CONF-2016-062

CMS PAS B2G-16-020



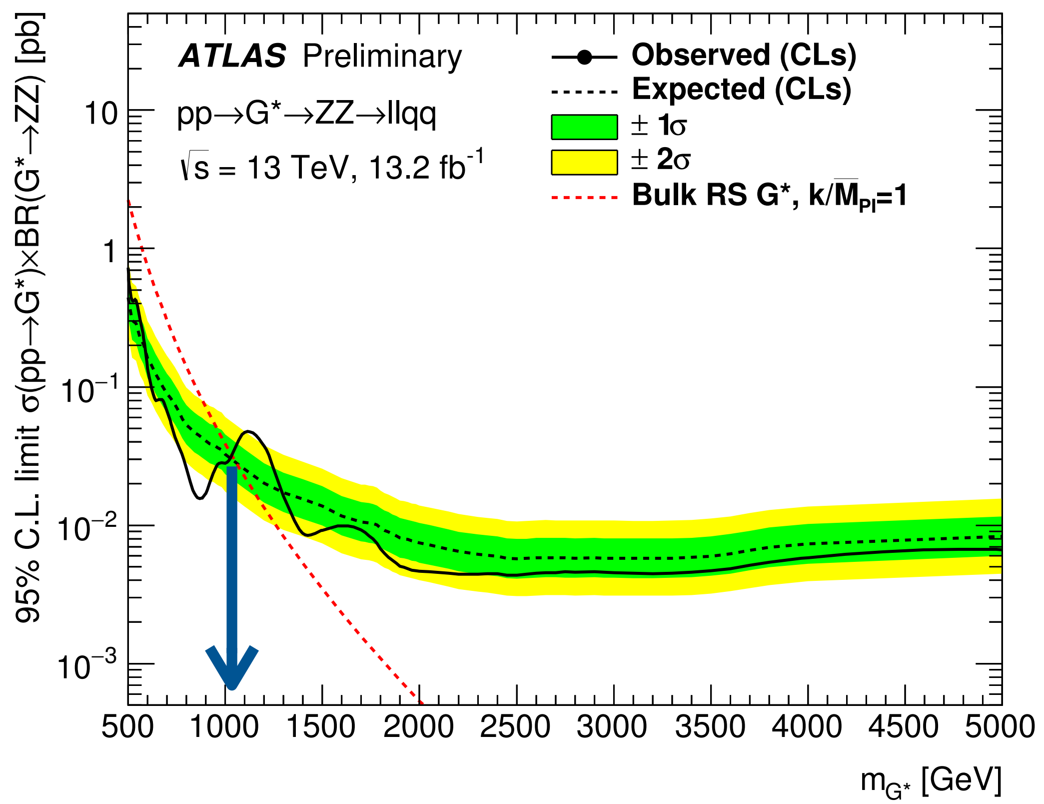


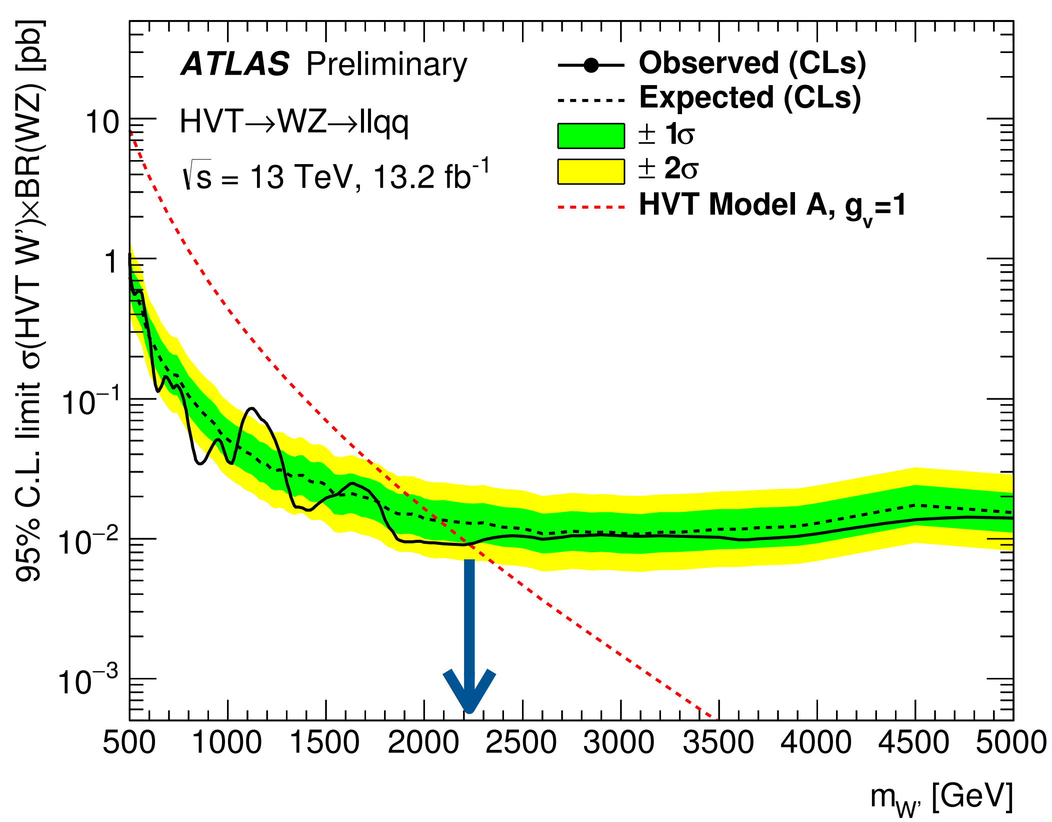


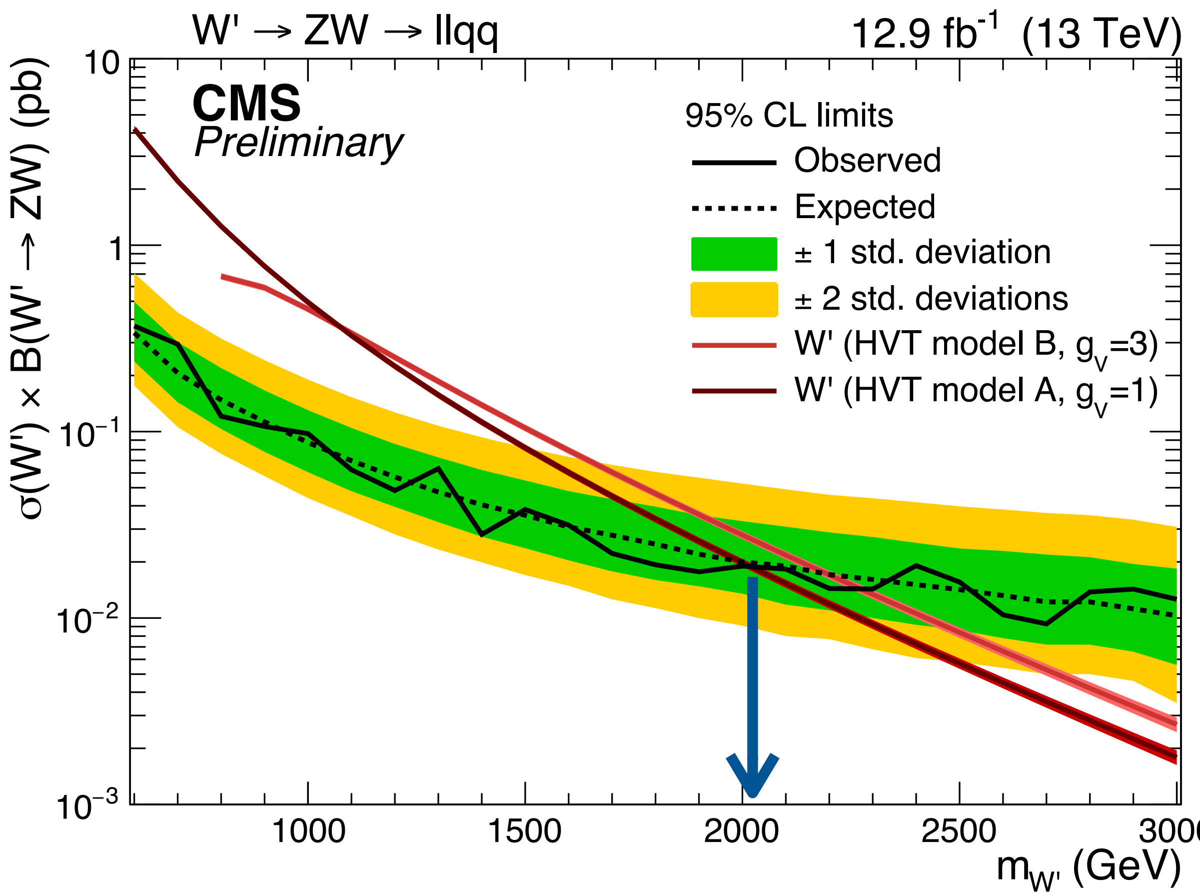
VV→llqq

ATLAS-CONF-2016-082

CMS PAS B2G-16-022

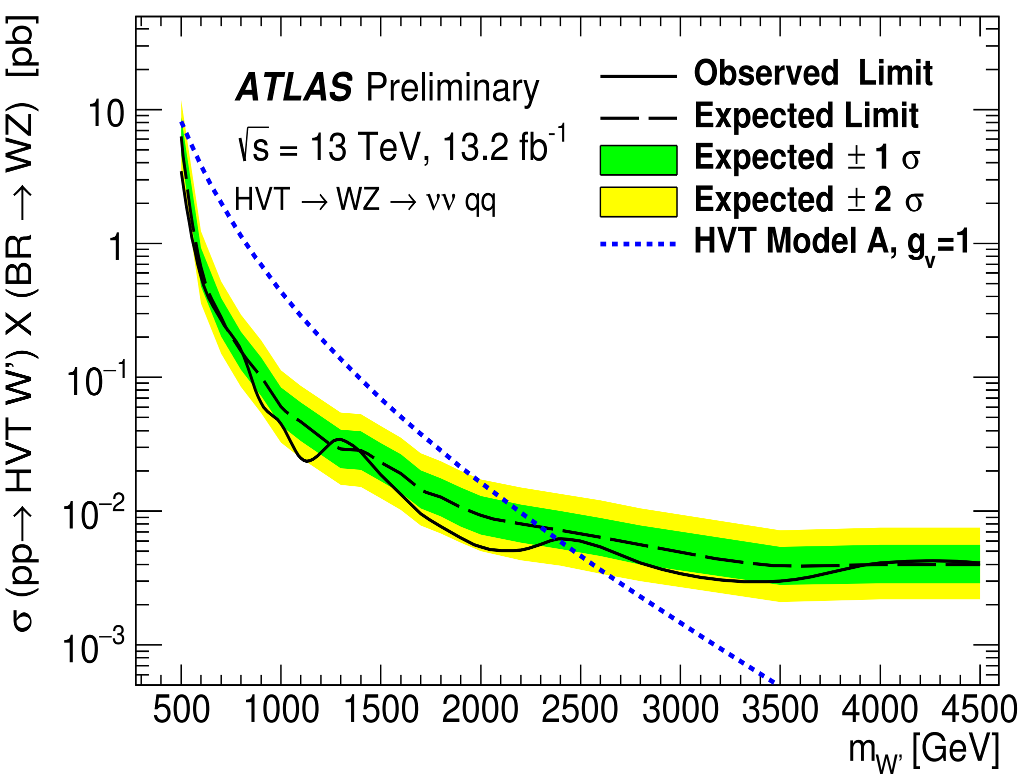


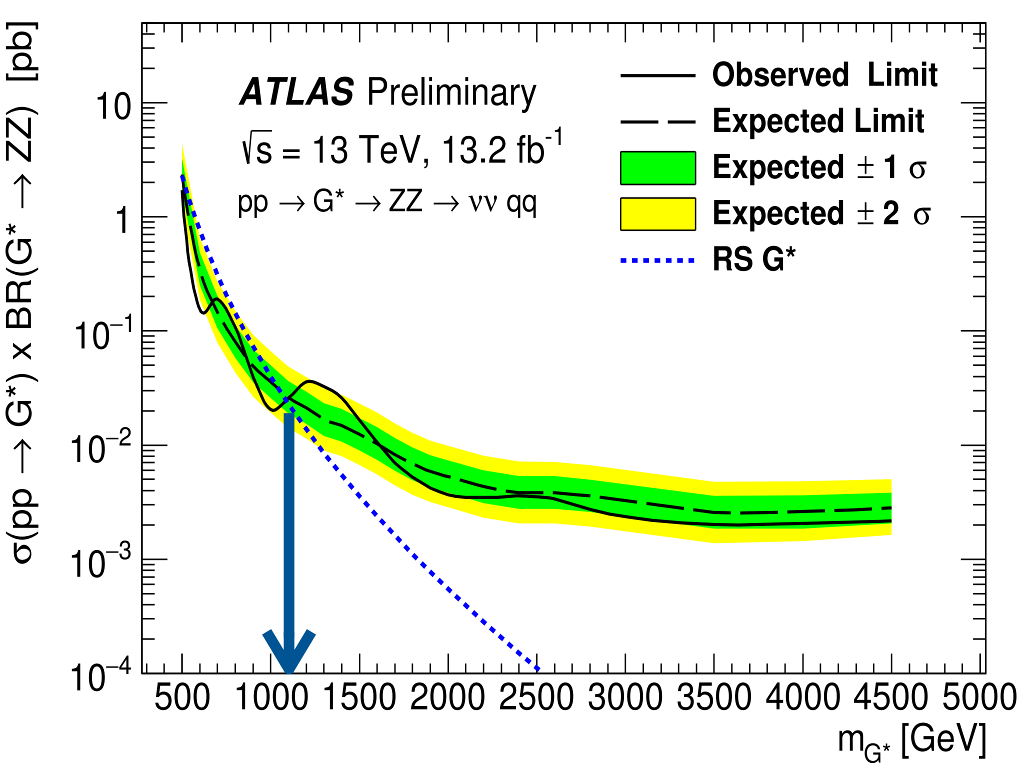




VV→ννqq

ATLAS-CONF-2016-082



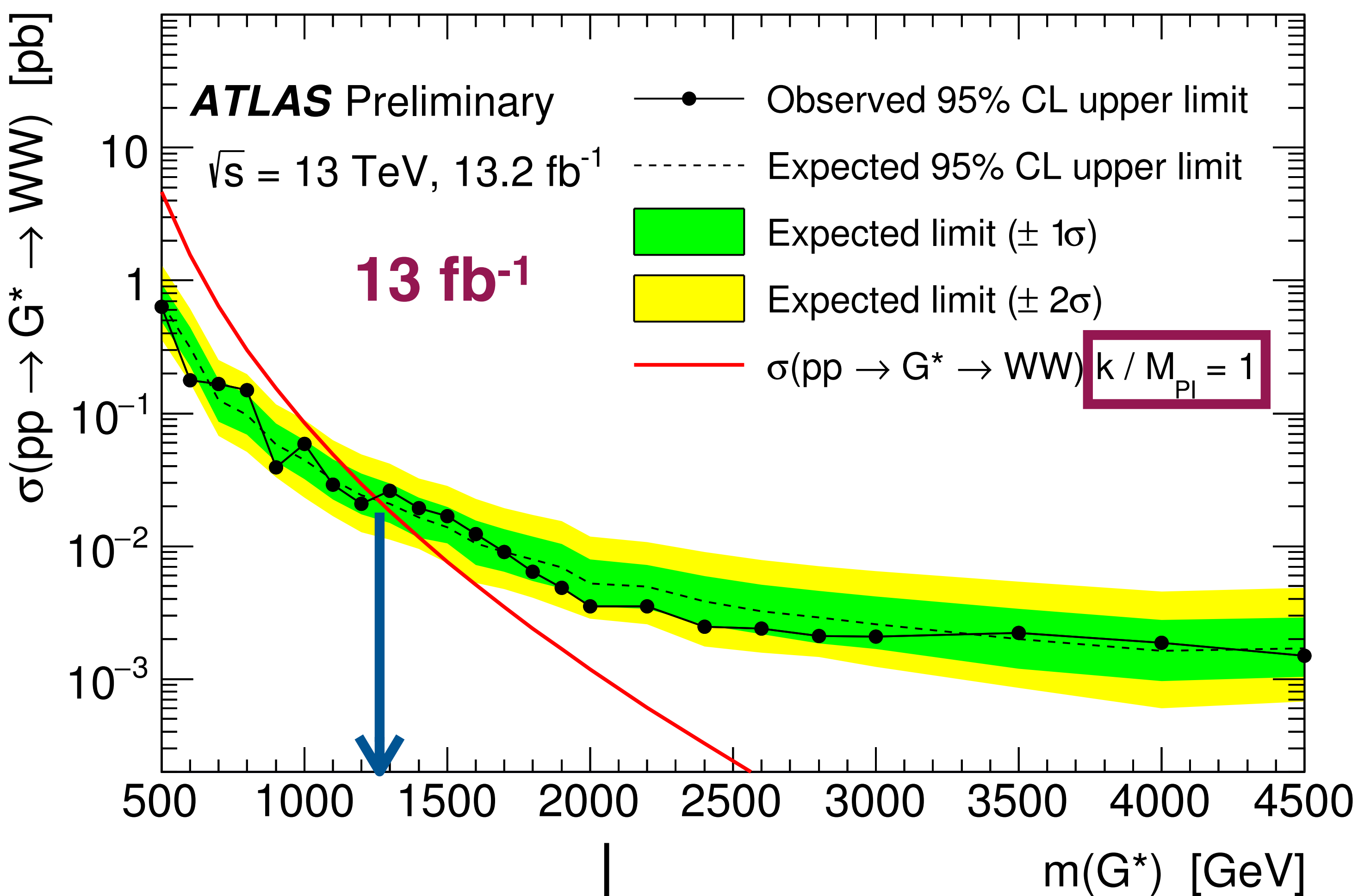


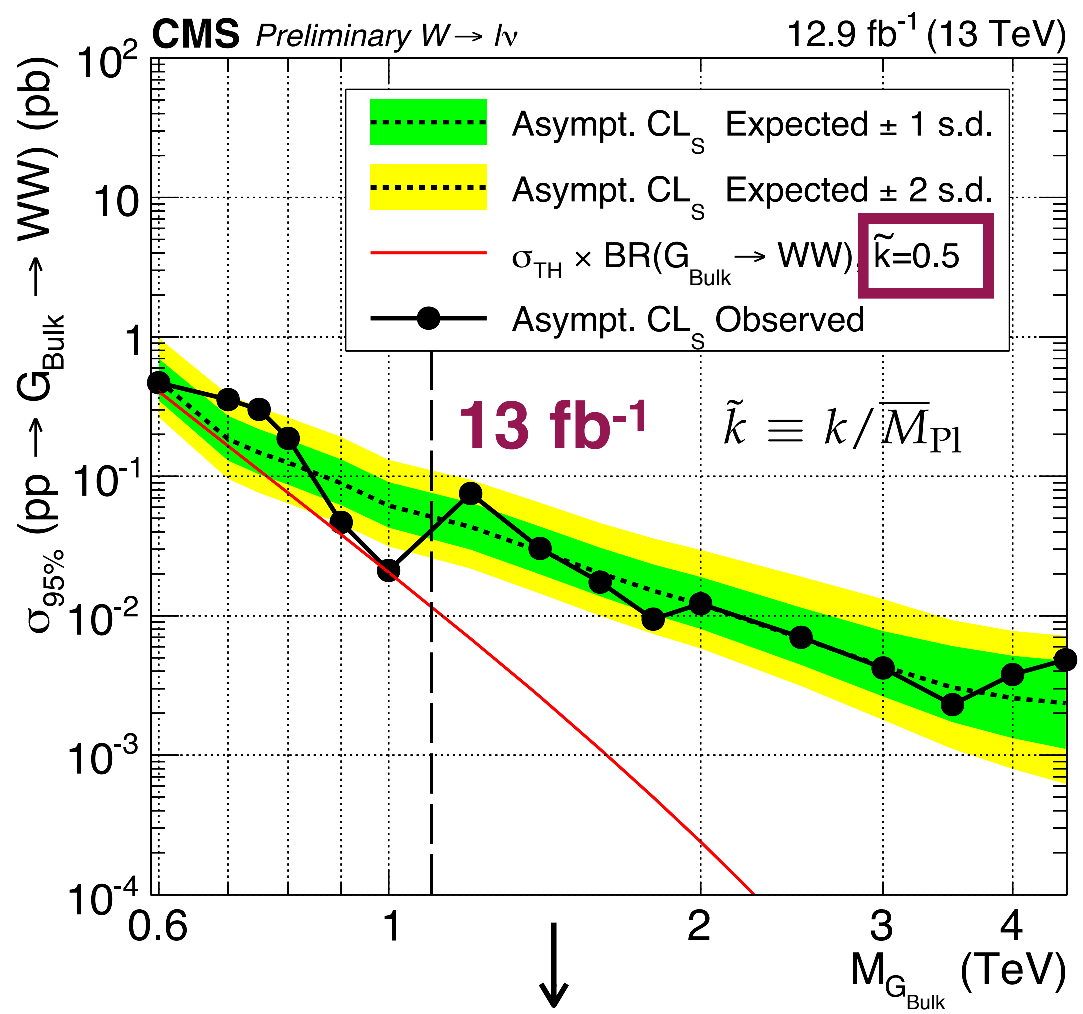
RS graviton - limits

- Currently the best limit on the bulk RS graviton coming from WW→lvqq channel

ATLAS-CONF-2016-062

CMS PAS B2G-16-020





Gbulk excluded below 1.2 TeV for $\tilde{k} = 1$

No limits with 13 fb-1 on Gbulk
for $\tilde{k}$=0.5 (smaller cross section)
➡ but see new 36 fb-1 result in llνν channel!

HVT to leptons

CMS-PAS-EXO-15-006

CMS-PAS-EXO-15-005

- Limits on HVT "model A" in fermionic final states:
  - m(W')<4.4 TeV
  - m(Z')<3.15 TeV
  - More stringent than the limits on "model B"