University of Zurich[UZH]

Search for new physics in bosonic final states at the LHC

Andreas Hinzmann
University of Zurich (UZH)

on behalf of the ATLAS, CMS and LHCB collaborations

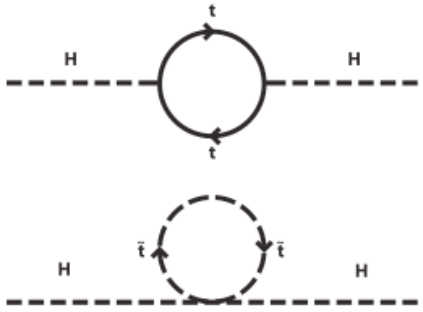
at

LHCP2016: Fourth annual Large Hadron Collider Physics,
13-18 Jun 2016, Lund University

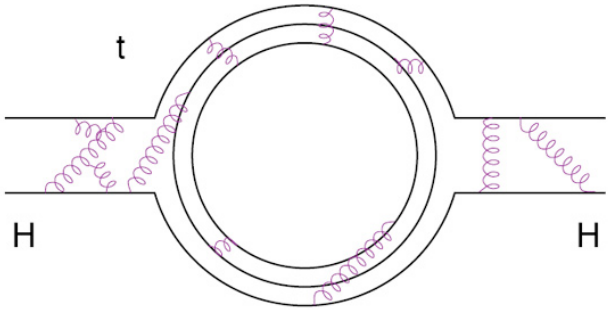
New physics with bosonic final states

- Fundamental questions
  - Hierarchy between the electroweak and Planck scale?
  - Quantum corrections to the Higgs mass?

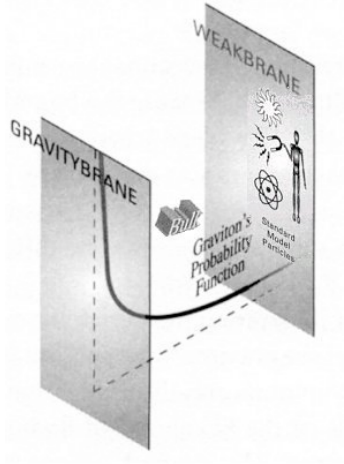
SUSY/
2HDM



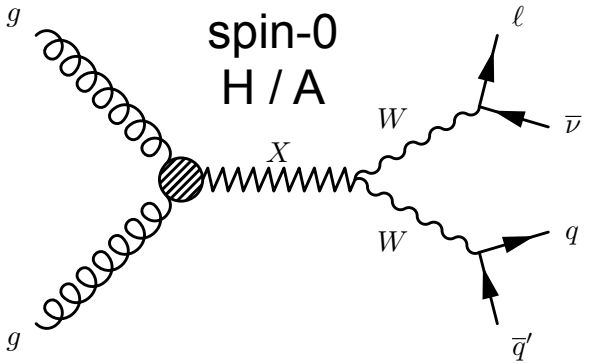
Compositeness

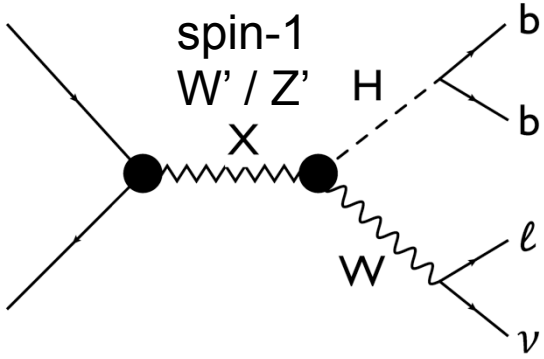


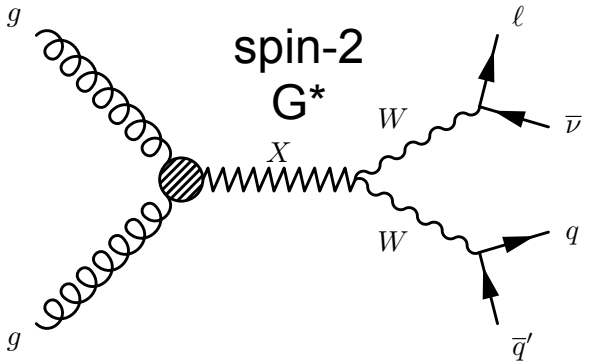
Extra dimensions



- Popular solutions predict signatures with γ, W, Z and H bosons

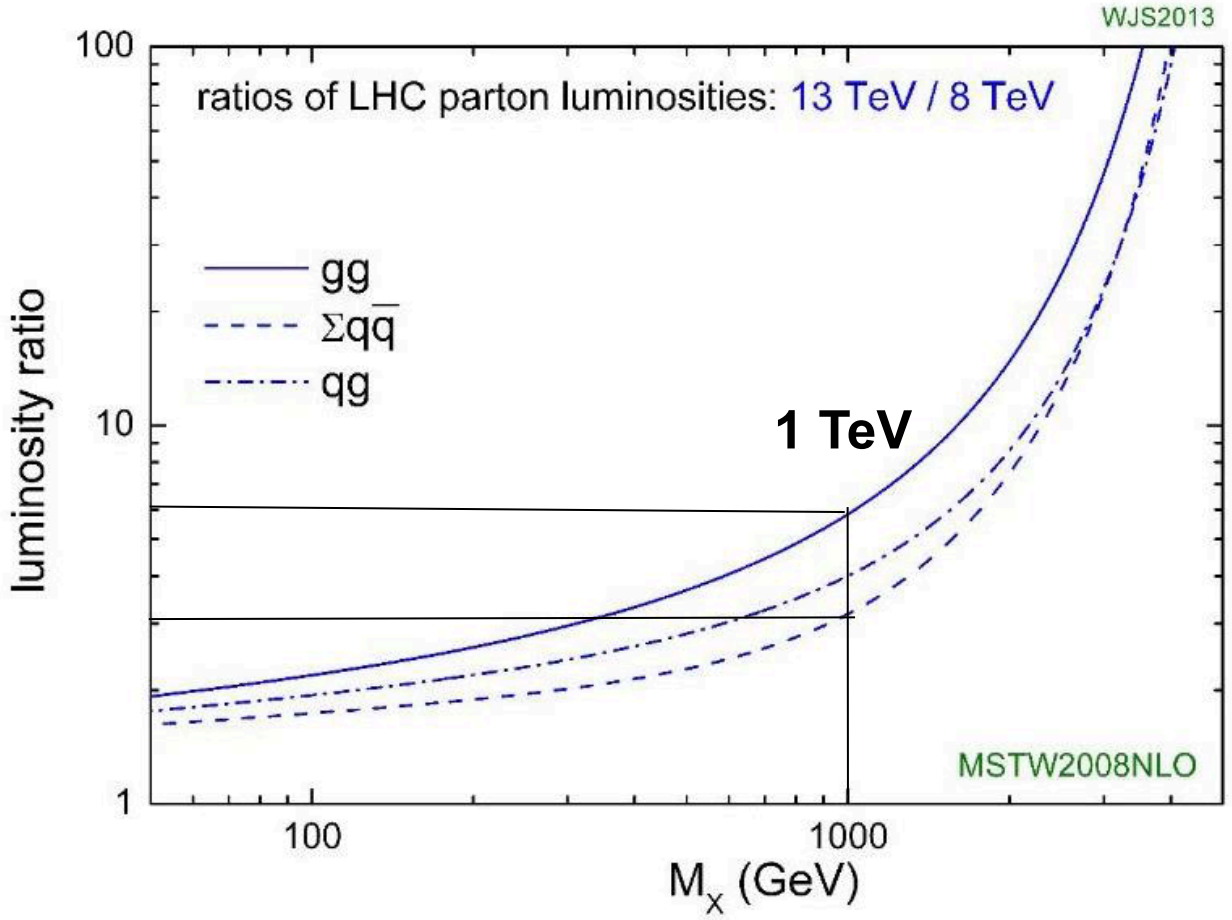






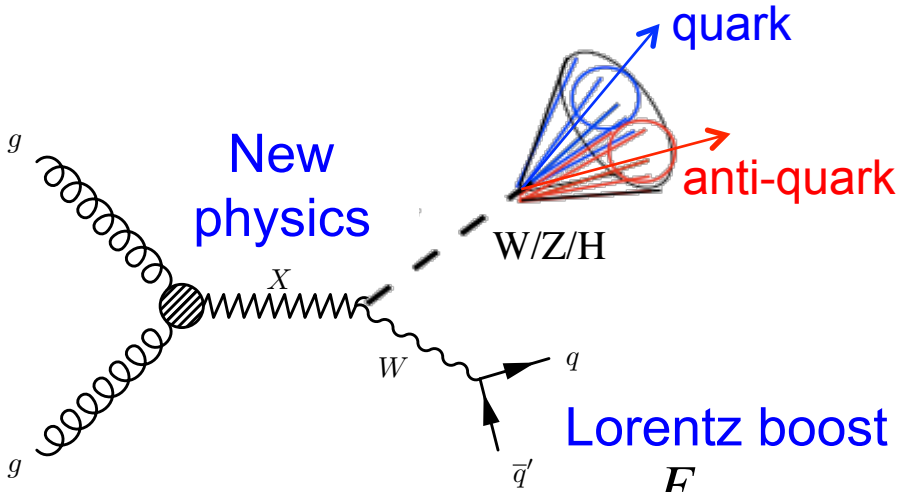
The LHC at 13 TeV

- Data collected by ATLAS/CMS
  - in 2012: 8 TeV, 20/fb
  - in 2015: 13 TeV, 3/fb
- Similar sensitivity >~1 TeV:
  - $\sigma(qq)\times\mathcal{L}$ (2012→2015) = 0.5
  - $\sigma(gg)\times\mathcal{L}$ (2012→2015) = 0.8



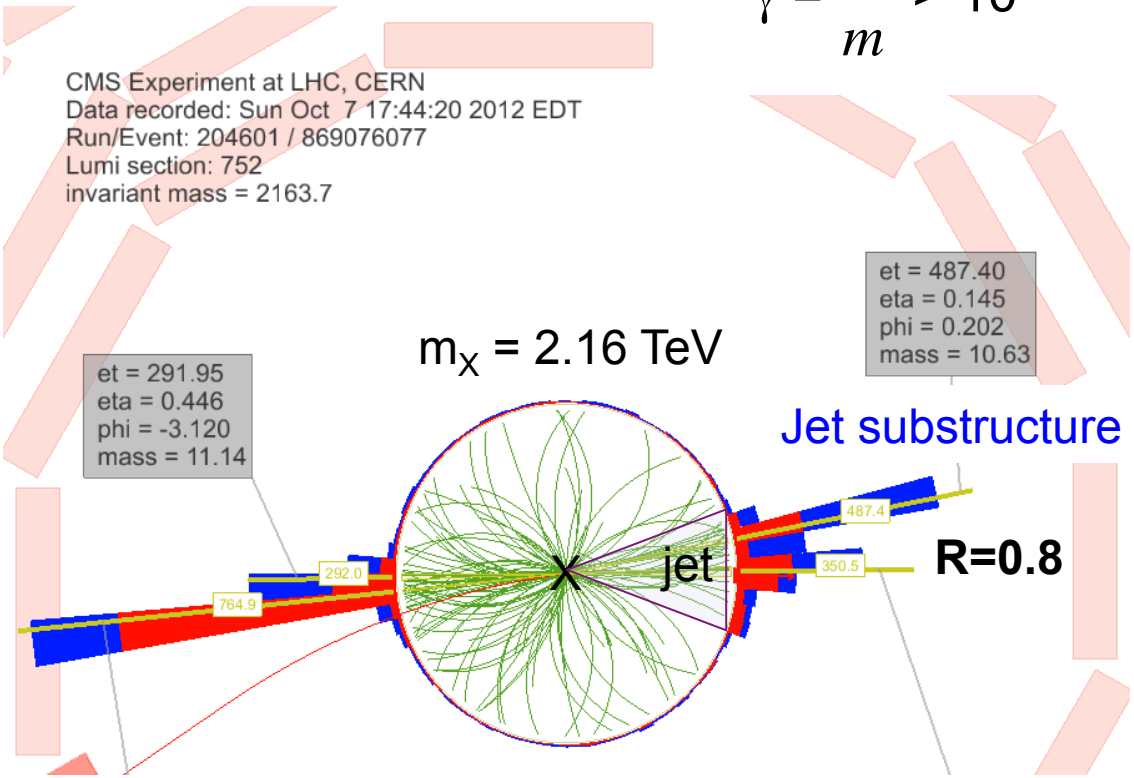
- 2015 LHC data allows discoveries of TeV new physics signatures

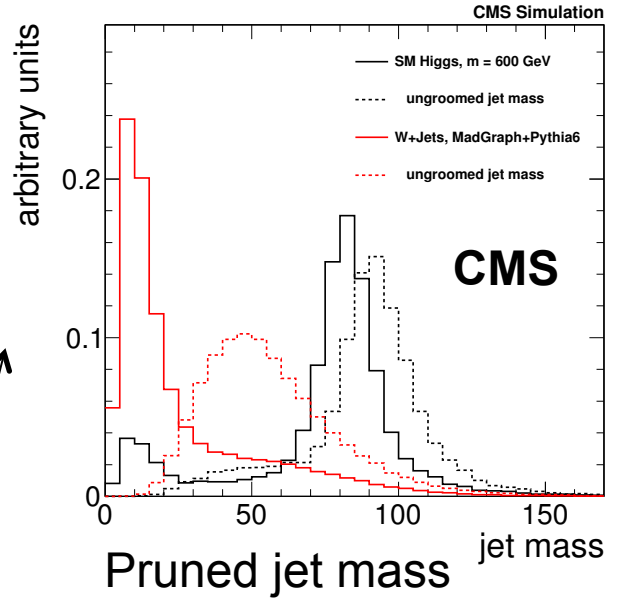
Boosted bosons from TeV new physics

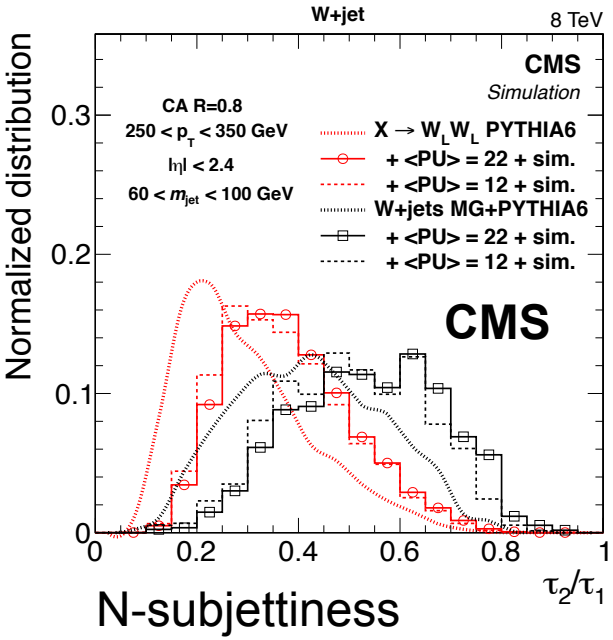


Lorentz boost

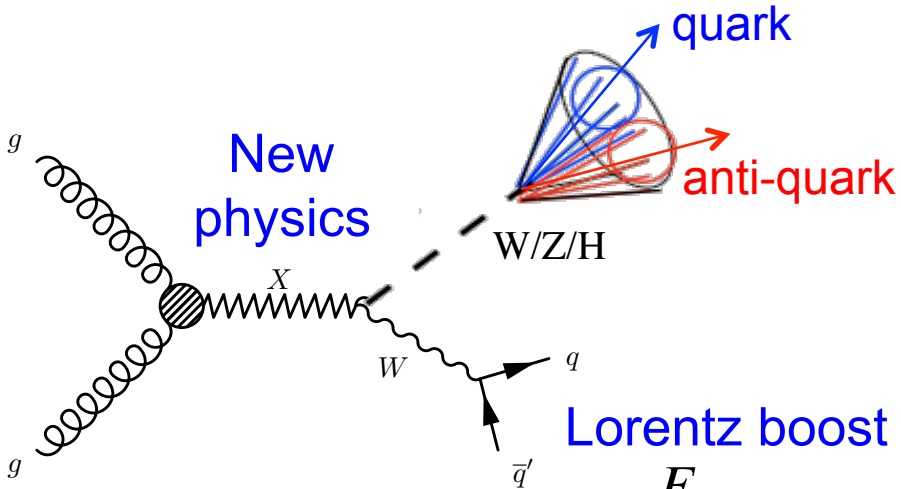
$$\gamma = \frac{E}{m} > 10$$







Boosted bosons from TeV new physics



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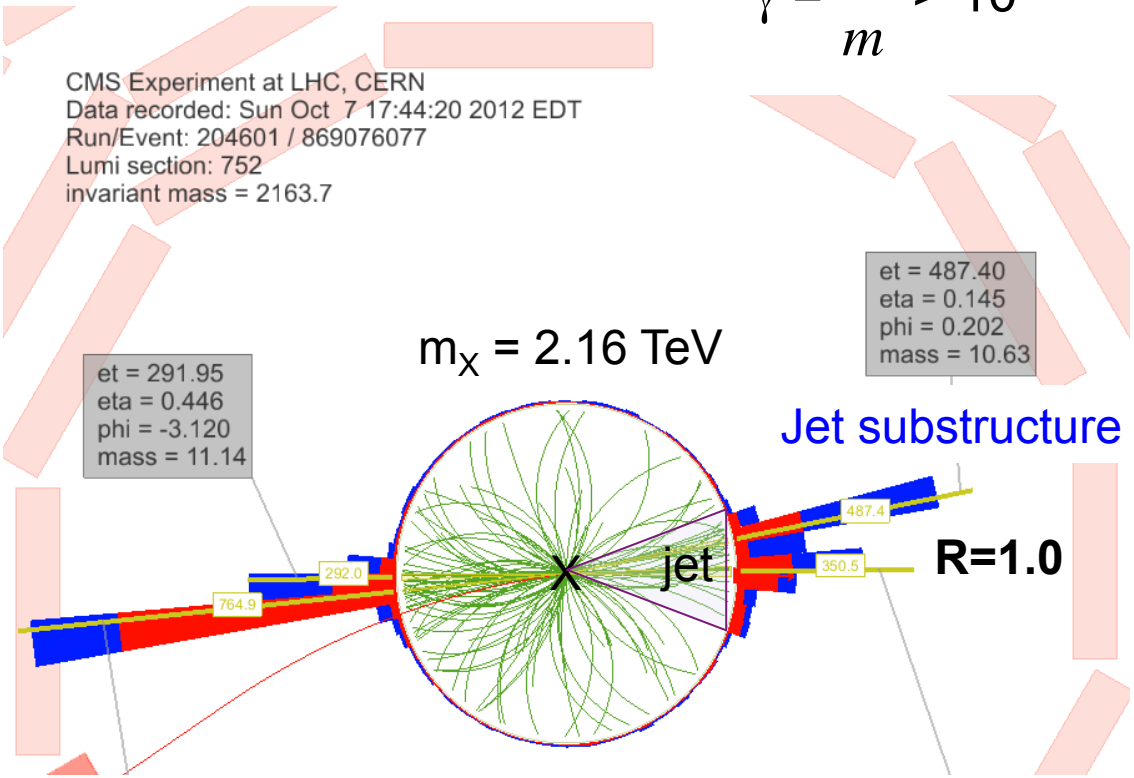
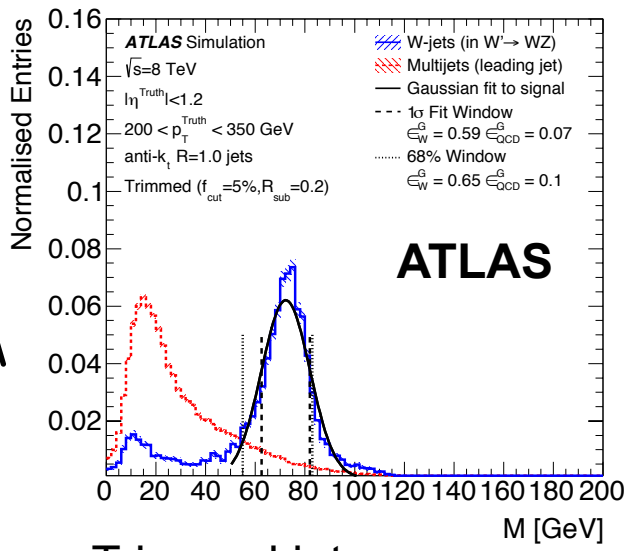
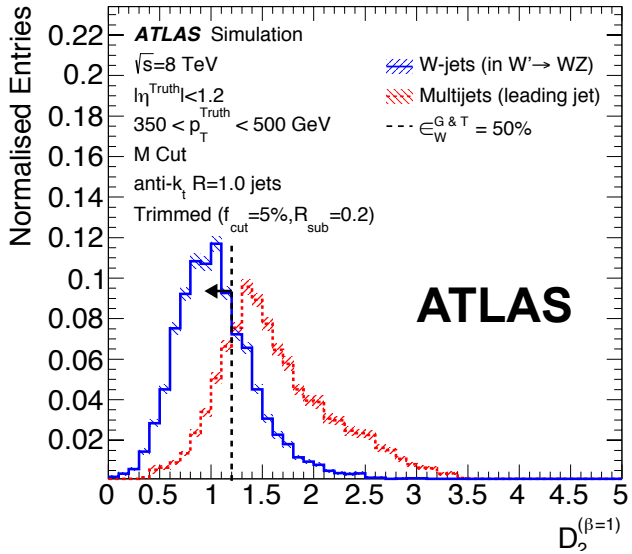


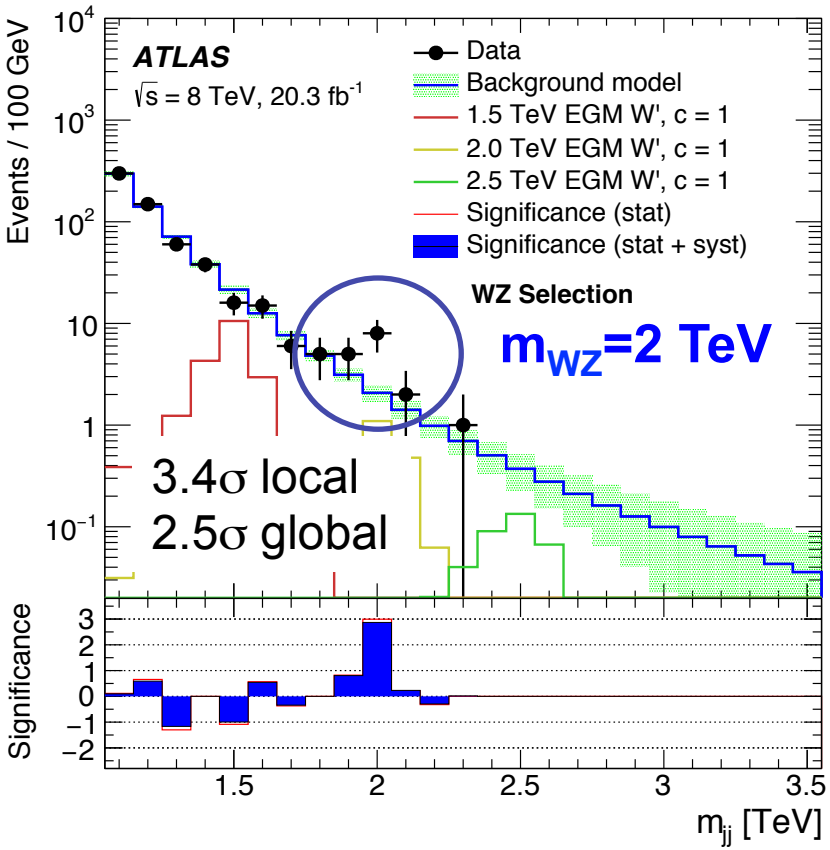


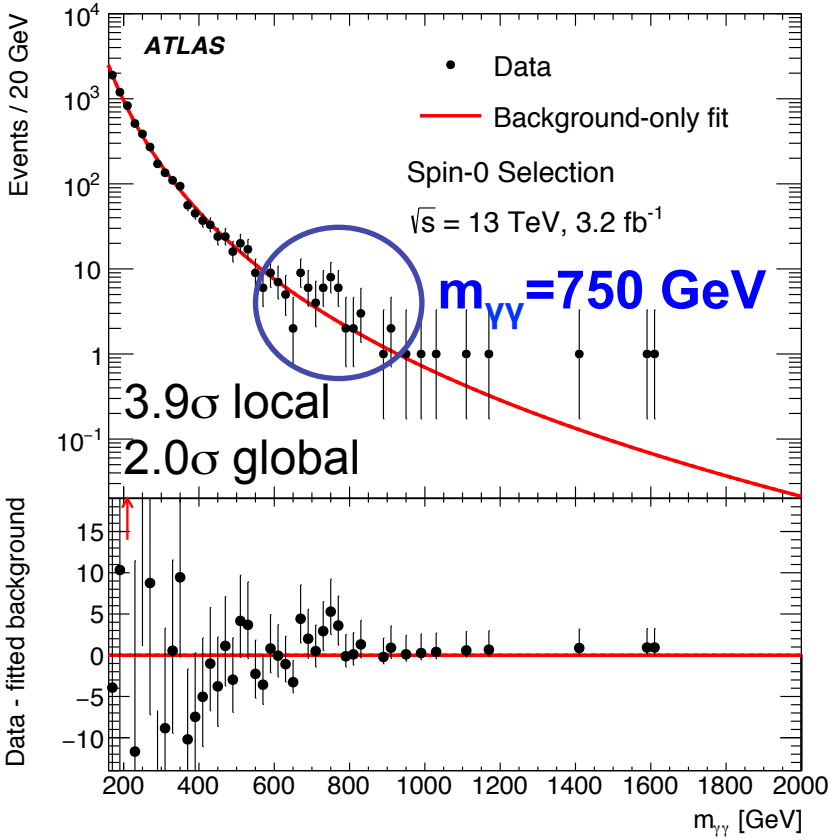
Trimmed jet mass



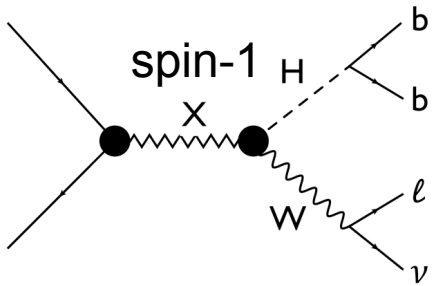
Energy correlation ratio

Recent excitement in di-boson searches

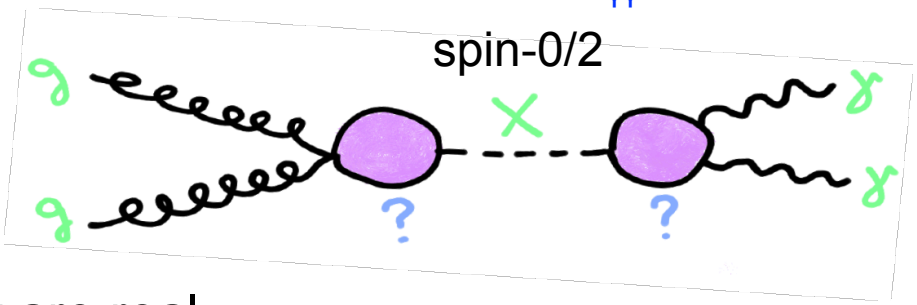




+ 2.2σ local in CMS m_{WH}=1.8 TeV



+ 2.9σ local in CMS $m_{\gamma\gamma}$=760 GeV



- 2015+2016 LHC data can tell if they are real
- If 750 GeV is real, there must me more new physics

Recent results – contents of the talk

Signature	Final state	ATLAS	CMS
γγ	γγ	ATLAS-CONF-2015-081 *10.1103/PhysRevLett.113.171801* *10.1103/PhysRevD.92.032004*	CMS-PAS-EXO-15-004 *CMS-PAS-EXO-12-045* *10.1016/j.physletb.2015.09.062*
	combination	**arXiv:1606.03833**	**arXiv:1606.04093**
γZ	γll	ATLAS-CONF-2016-010 *10.1016/j.physletb.2014.10.002*	CMS-PAS-EXO-16-019 *CMS-PAS-HIG-16-014*
	γqq	ATLAS-CONF-2016-010	**CMS-PAS-EXO-16-020**
	combination		**CMS-PAS-EXO-16-021**
WW/WZ/ZZ	qqqq	**arXiv:1606.04833**	CMS-PAS-EXO-15-002 *10.1007/JHEP08(2014)174*
	qqll	**arXiv:1606.04833**	
	qqlv	**arXiv:1606.04833**	CMS-PAS-EXO-15-002 CMS-PAS-B2G-16-004
	qqvv	**arXiv:1606.04833**	
	combination	**arXiv:1606.04833**	CMS-PAS-EXO-15-002
WH/ZH	bbll	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	bblv	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	bbvv	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
	combination	**ATLAS-CONF-2015-074**	CMS-PAS-B2G-16-003
Combination of VV/VH			**CMS-PAS-B2G-16-007**
HH	bbbb	**arXiv:1606.04782**	*CMS-PAS-EXO-12-053*
$B^0 \to K^{*0}\chi$	K^{*0}ll	**LHCB**: *10.1103/PhysRevLett.115.161802*	

- Listing only latest (**new/submitted**) results covering TeV resonances
- *8 TeV results indicated in italic*
- More di-boson searches in context of SUSY/2HDM covered by Higgs BSM

arXiv:1606.03833
arXiv:1606.04093

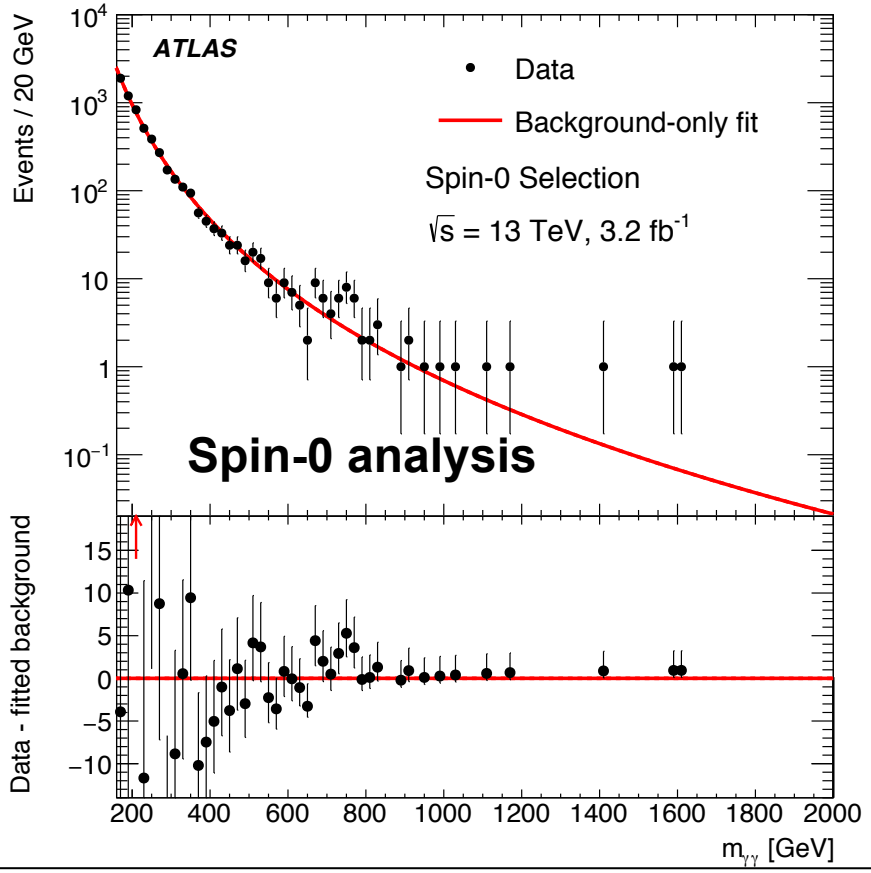
Di-photon (ATLAS)

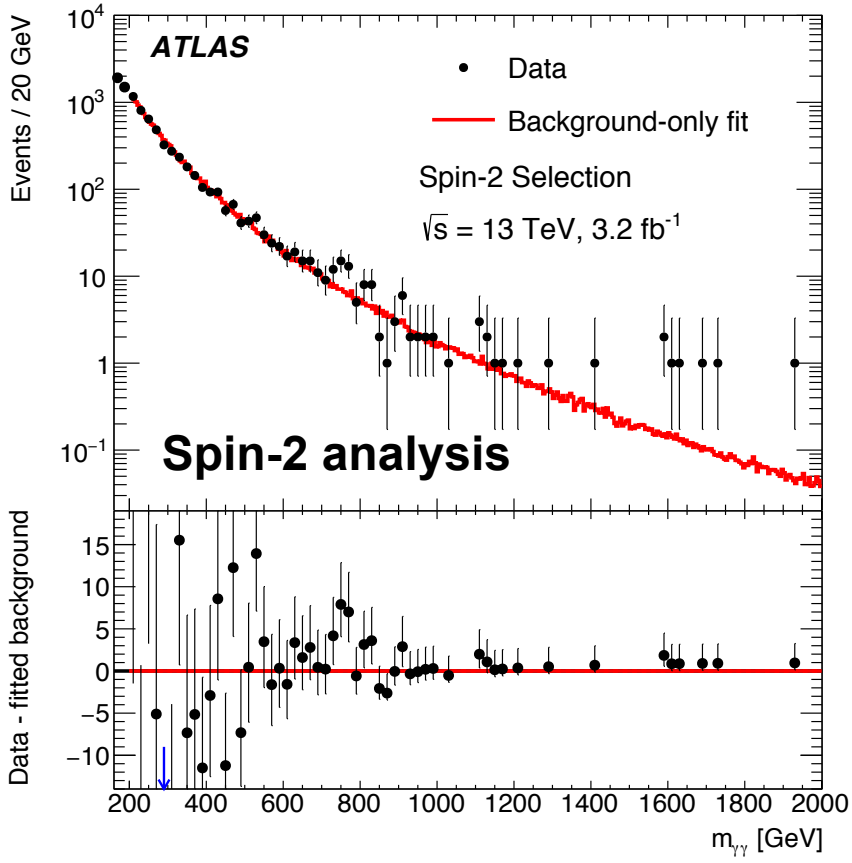
Submitted

- Spin-0 analysis: two photons with E_T>40(30) GeV and E_T>0.4(0.3)$m_{\gamma\gamma}$
  - Background from signal + smooth background fit

$$f_{(k)}(x;b,\{a_k\}) = N(1-x^{1/3})^b x^{\sum_{j=0}^{k} a_j (\log x)^j}, \quad x = \frac{m_{\gamma\gamma}}{\sqrt{s}}, \quad k = 0$$

- Spin-2 analysis: two photons with E_T>55 GeV
  - γγ background from NLO prediction, γ+jets, dijets from isolation sidebands
- Scan over resonance mass and width Γ/M≤10%





arXiv:1606.03833
arXiv:1606.04093

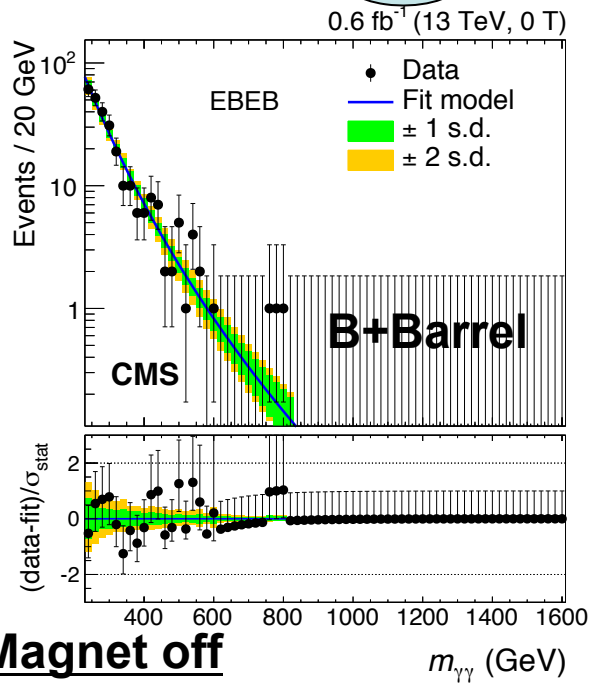
Di-photon (CMS)

Submitted

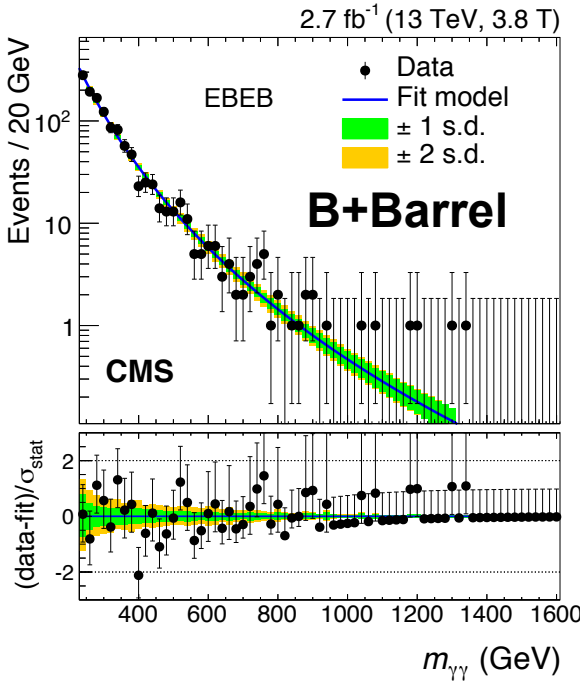
- Common spin-0 and spin-2 analysis
  - Two photons with E_T>75 GeV
  - At least one in ECAL barrel, two event categories according to second photon in barrel or endcap
  - Data with magnet on (2.7/fb) and off (0.6/fb)
  - Background from signal + smooth background fit

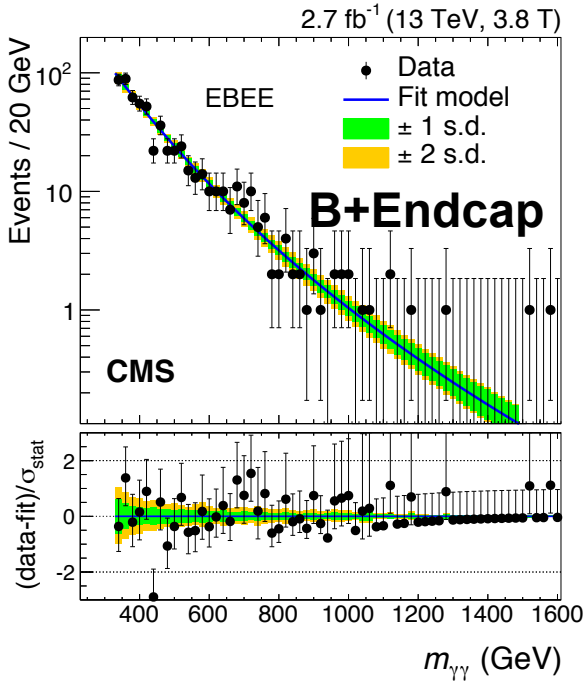
$$f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\cdot\log(m_{\gamma\gamma})}$$

- Scan over resonance mass and width Γ/M≤5.6%

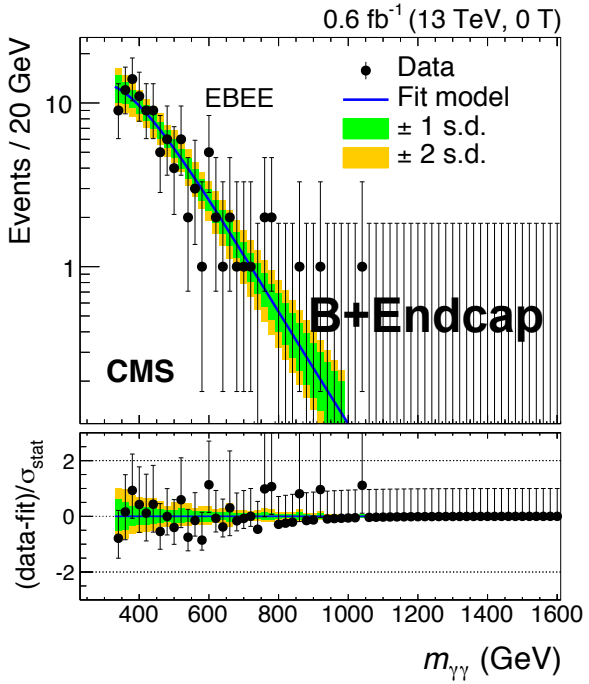


Magnet on





Magnet off



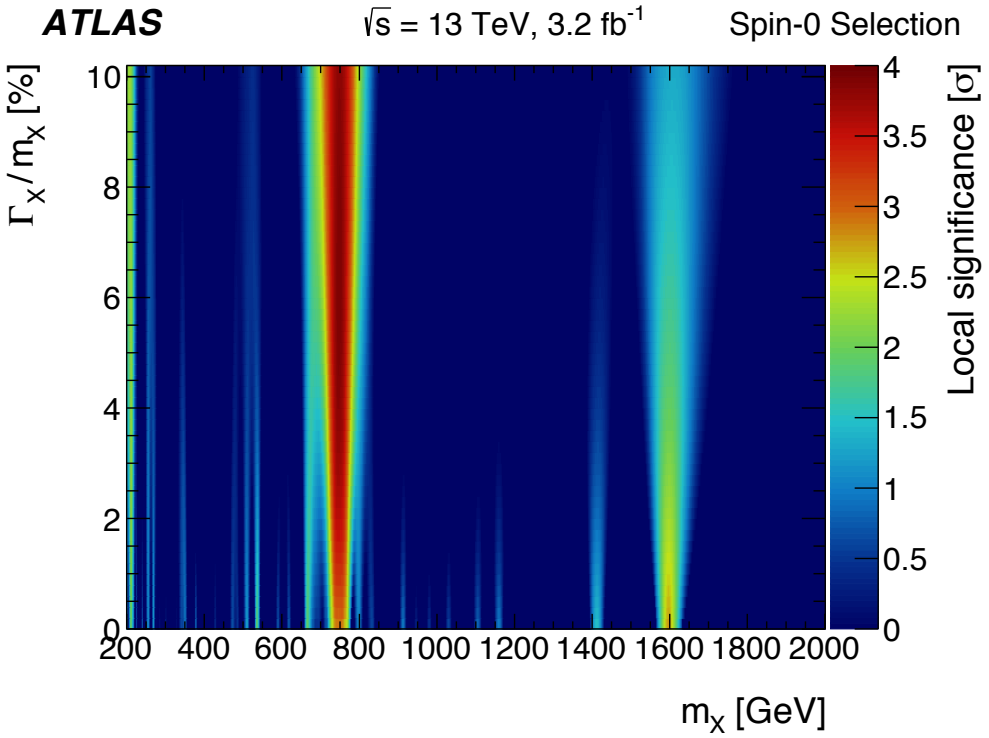
arXiv:1606.03833
arXiv:1606.04093

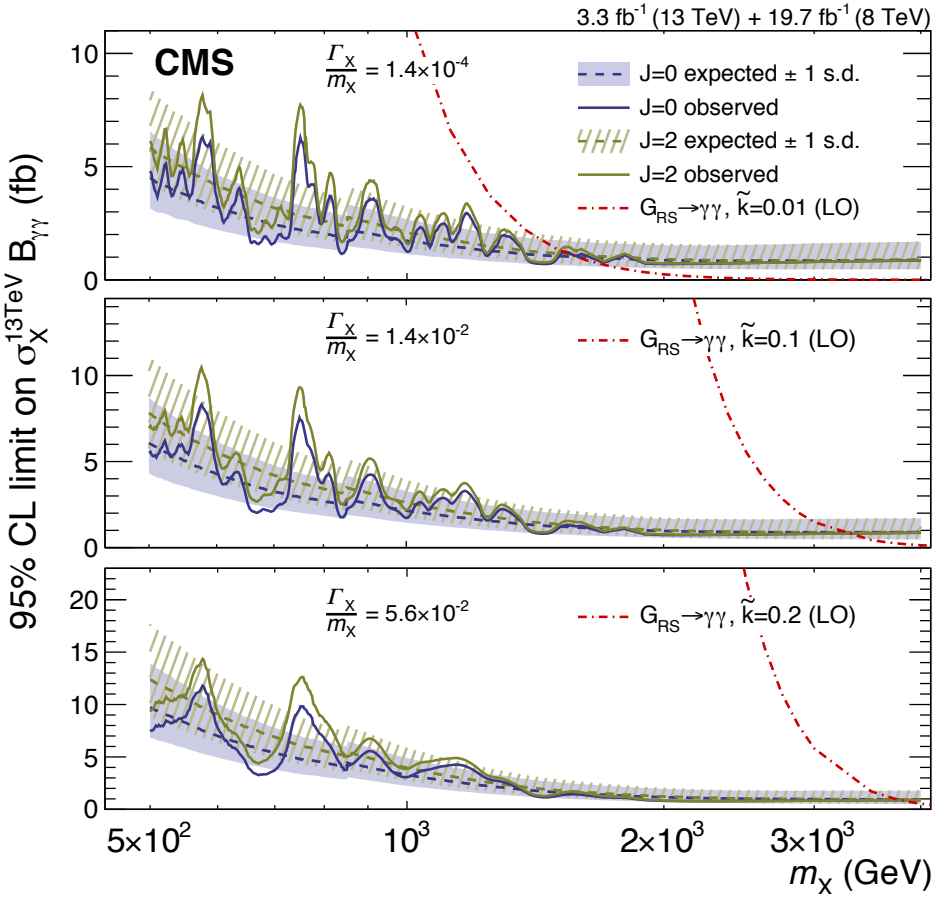
Di-photon 13 TeV results

Submitted

- ATLAS: 3.9σ(2.1σ) local (global) at 750 GeV 6% width spin-0
- CMS: 2.9σ(<1σ) local (global) at 760 GeV 1.4% width spin-0

- Similar significances under spin-2 hypothesis



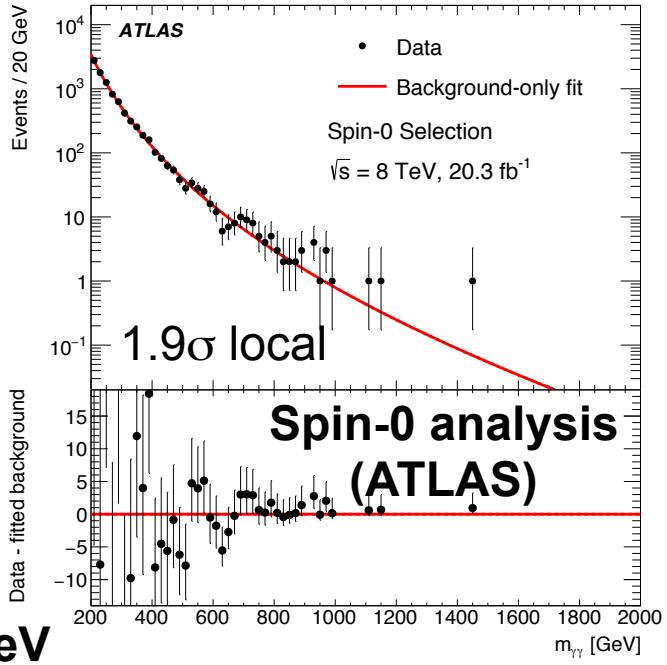


arXiv:1606.03833
arXiv:1606.04093

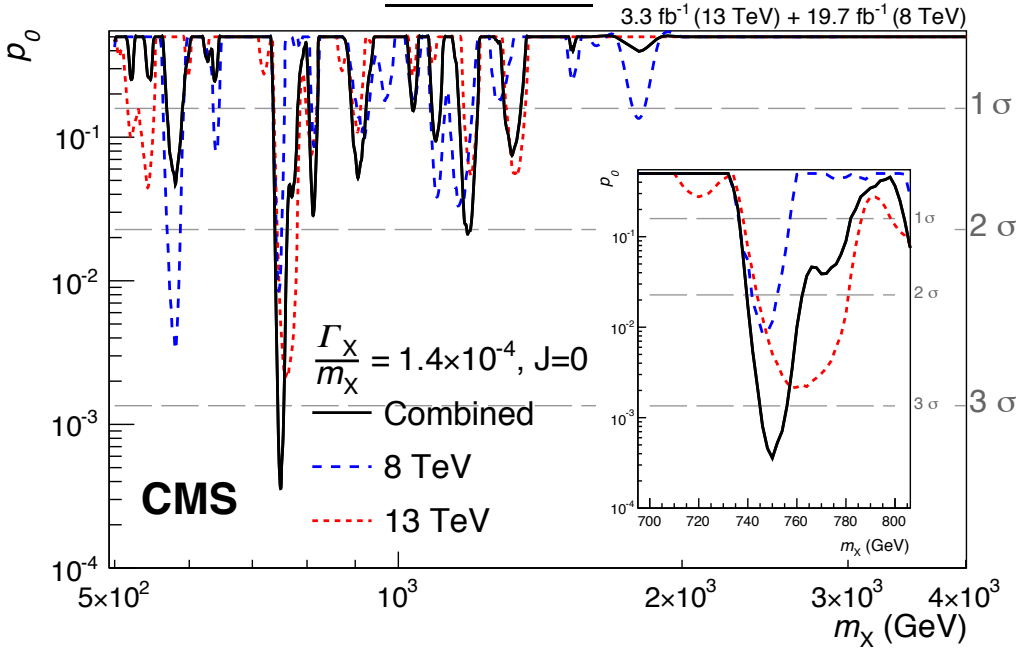
Di-photon 8+13 TeV results

Submitted

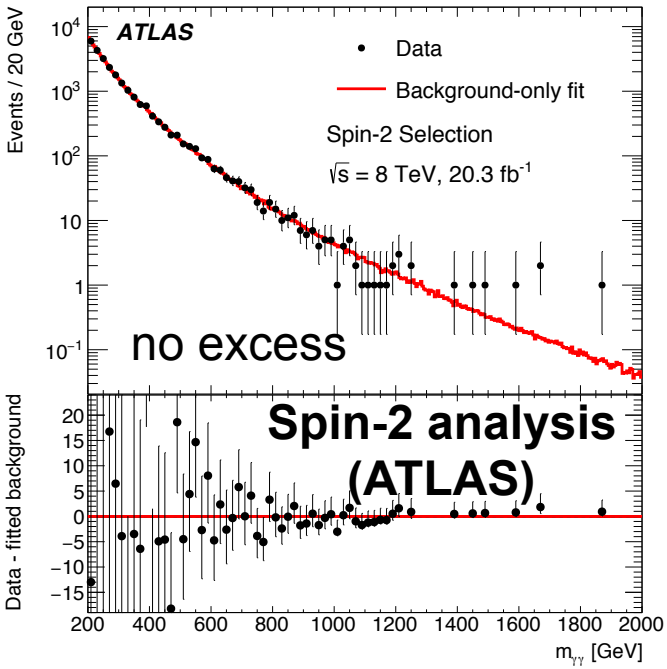
- ATLAS: 8 and 13 TeV data consistency
  - 1.2σ for gluon-fusion spin-0 at 750 GeV
  - 3.3σ for qq-annihilation spin-2 at 750 GeV
- CMS: 8 and 13 TeV data analyses combination
  - 3.4σ (1.6σ) local (global) for spin-2 RSG (mix of qq-annihilation and gluon-fusion) at 750 GeV



8+13 TeV



8 TeV

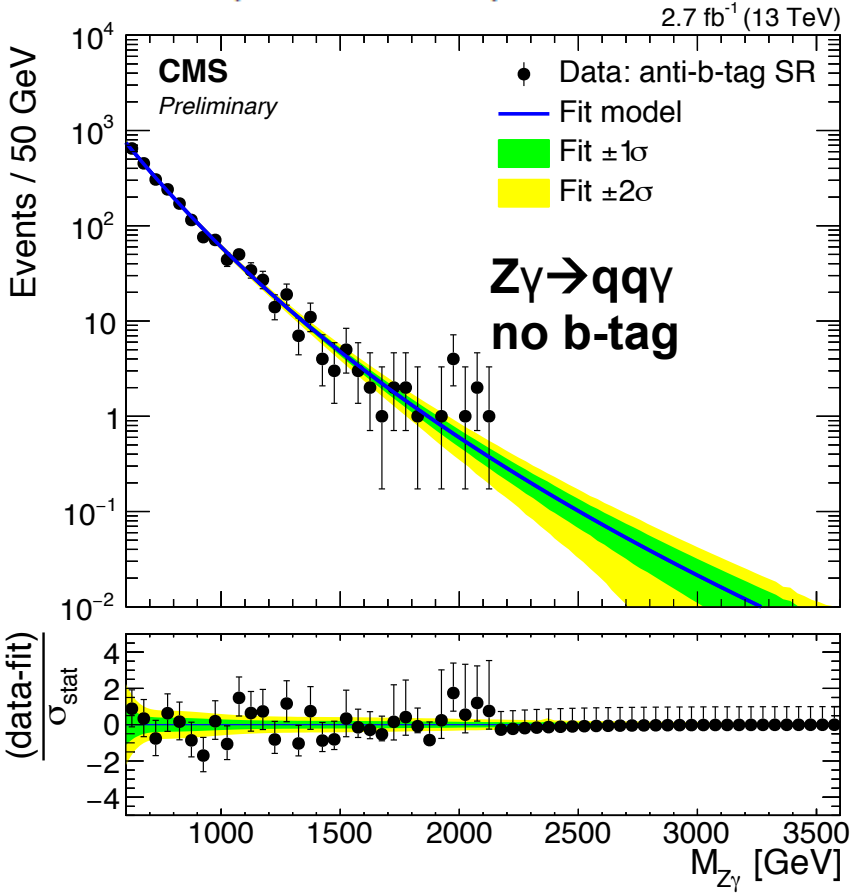


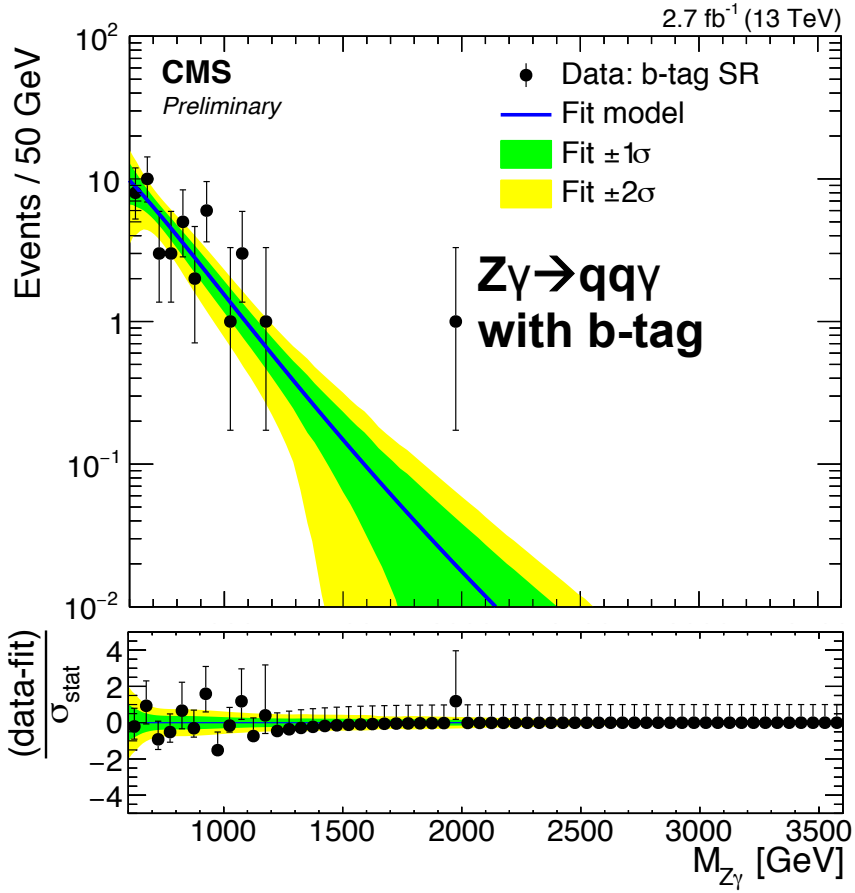
Z+photon → qqγ

New

- Spin-0→Zγ→qqγ
- γ p_T>180 GeV and p_T>0.34 $M_{Z\gamma}$
- Z identification: R=0.8 jet p_T>200 GeV, 75<m_{pruned}<105, subjet b-tag (L/M)
- Background estimated from smooth fit:

$$\frac{dN}{dM_{Z\gamma}} = P_0 \times \left(\frac{M_{Z\gamma}}{\sqrt{s}}\right)^{P_1 + P_2 \times \log\left(\frac{M_{Z\gamma}}{\sqrt{s}}\right)}$$



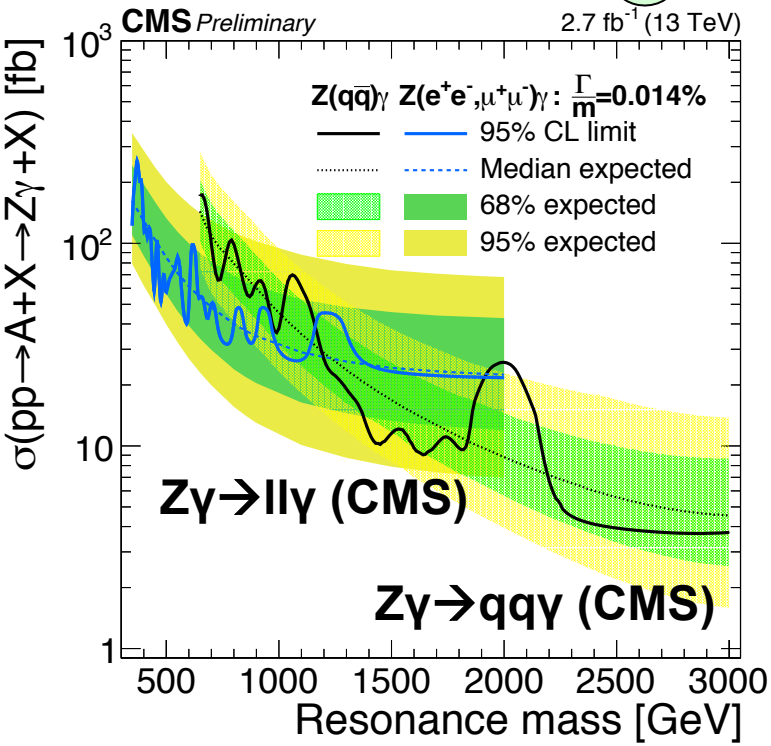


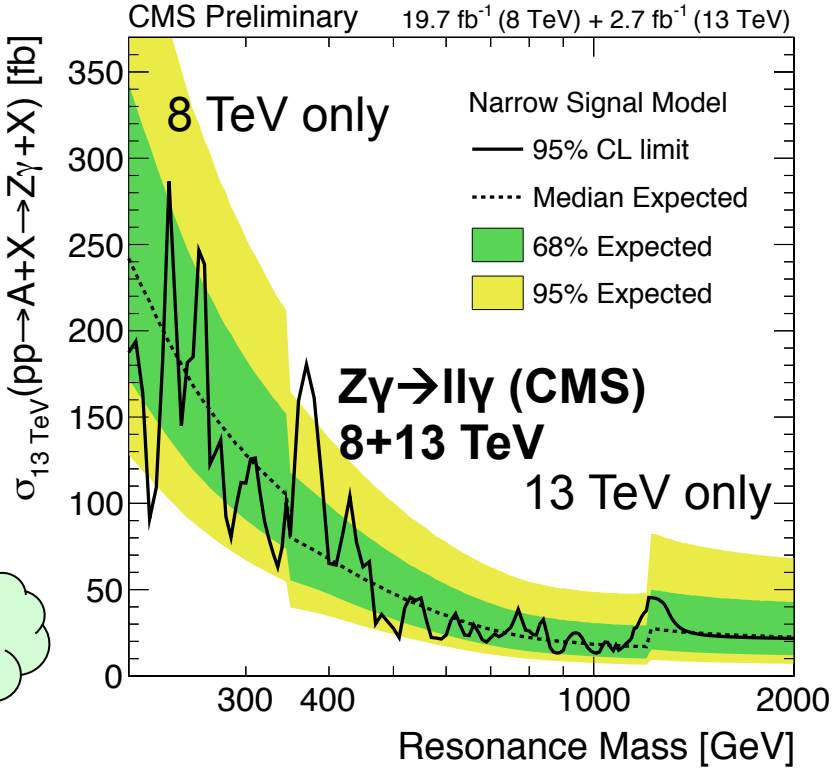
ATLAS-CONF-2016-010
CMS-PAS-EXO-16-019
CMS-PAS-HIG-16-014
CMS-PAS-EXO-16-020
CMS-PAS-EXO-16-021

Z+photon 8+13 TeV results

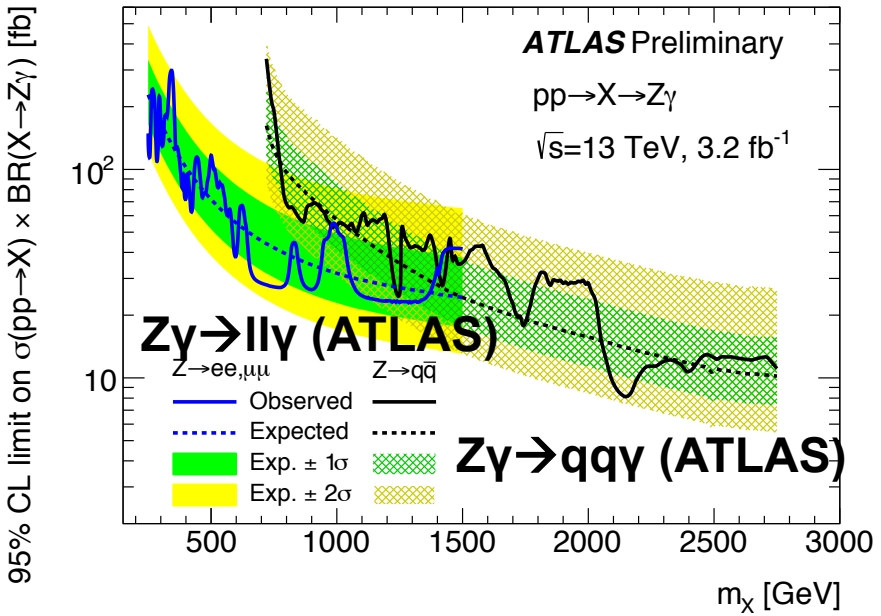
New

- Spin-0→Zγ→qqγ: higher acceptance → best at high mass
- Spin-0→Zγ→llγ: lower trigger threshold, less background → best at low mass
- No significant excess observed
  - Set 95% CL limits for two resonance widths scenario (Γ/m=0.014%, 5.6%)
- Significant gain from 8+13 TeV combination





New

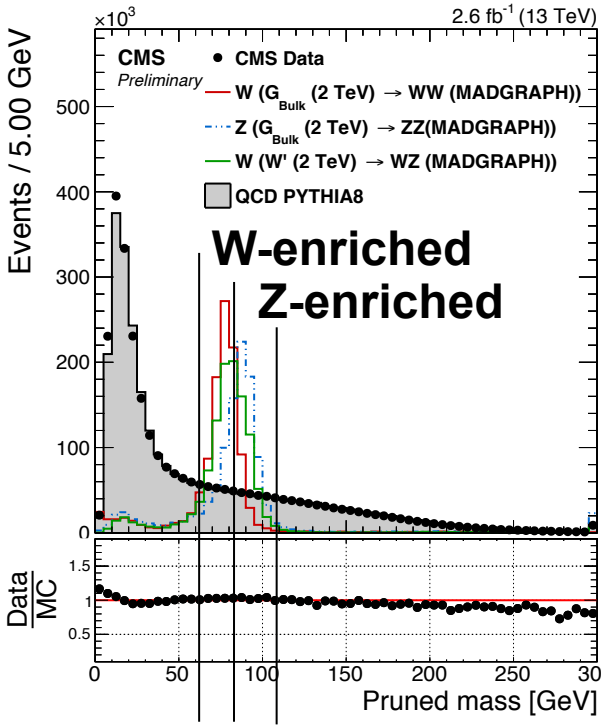


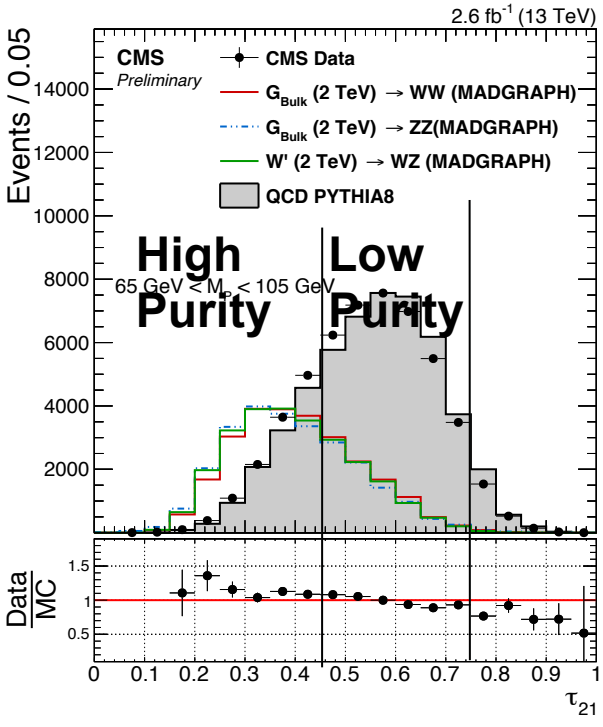
arXiv:1606.04833
CMS-PAS-EXO-15-002

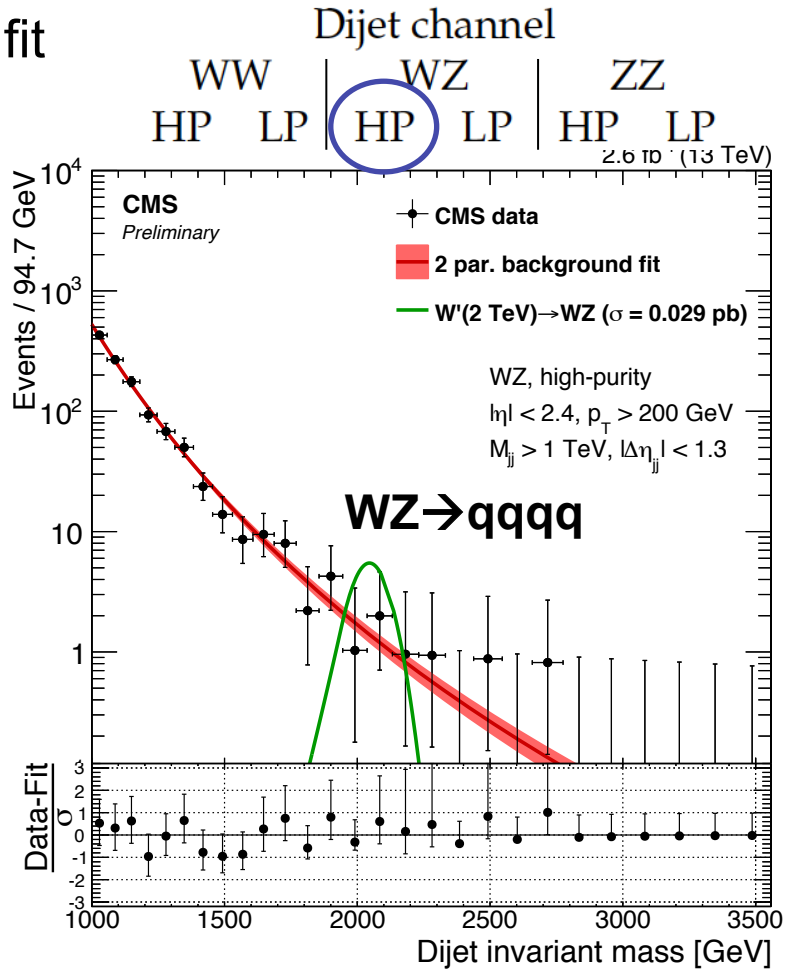
VV → qqqq

- W/Z-jet identification: R=0.8, jet 65<m_{pruned}<105 GeV
  - 3 categories according to m_{J1} and m_{J2}
    → optimal sensitivity to WW, ZZ and WZ (30% improvement)
  - 2 categories in τ_2/τ_1 → high purity at low m_{JJ}, high efficiency at high m_{JJ}
- $|\eta_{J1}-\eta_{J2}|$<1.3 to supress QCD background
- Background from signal + smooth background fit

$$\frac{dN}{dm_{jj}} = \frac{P_0(1-m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}$$





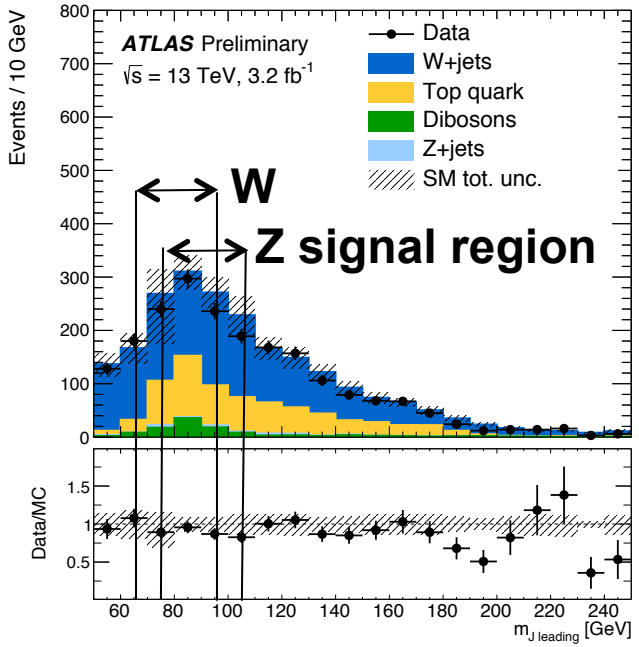


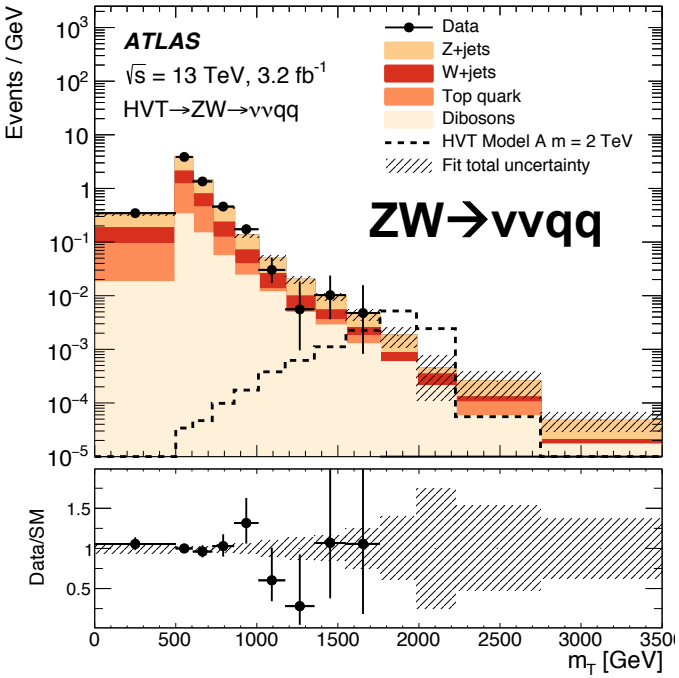
arXiv:1606.04833
CMS-EXO-PAS-15-002
CMS-PAS-B2G-16-004

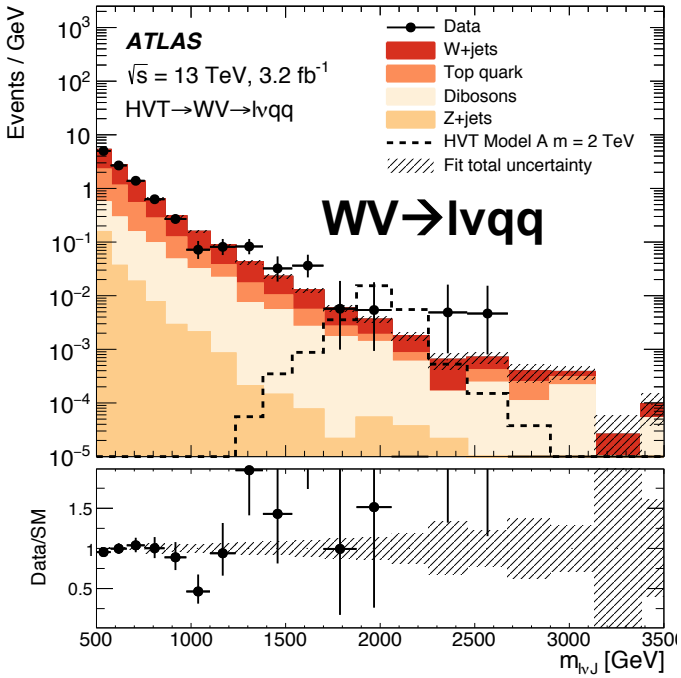
VV → vvqq/lvqq/llqq

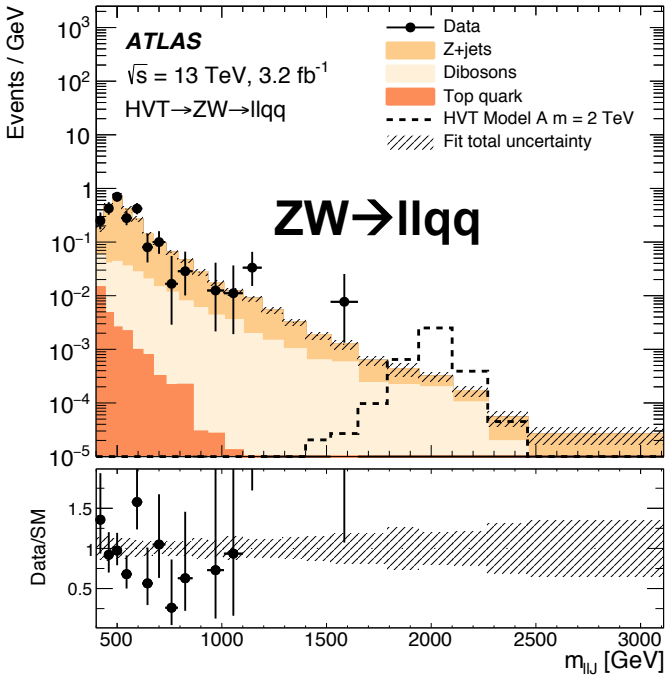
Submitted

- Z/W-jet ID: R=1.0 jet p_T^J>200 GeV, $D_2^{\beta=1}$ (50% eff)
  - 2 separate analyses in $m_{W/Z}$±13-15 GeV
- Z→νν analysis: E_T^{miss}>250 GeV, Δφ(E_T^{miss},jets)>0.6, p_T^{miss}>30 GeV
- W→μν/eν analysis: $p_T^{\mu/e}$>25 GeV, E_T^{miss}>100 GeV, p_T^W>200 GeV and >0.4m_{lvJ}, b-tag-veto
- Z→μμ/ee analysis: $p_T^{\mu/e}$>25 GeV, 84<m_{ee}<99 (66<$m_{\mu\mu}$<116), p_T^Z>0.4m_{llj}
- Backgrounds from V+jets (ttbar) estimated from data in m_J (b-tag) sidebands (and N_μ for νν)









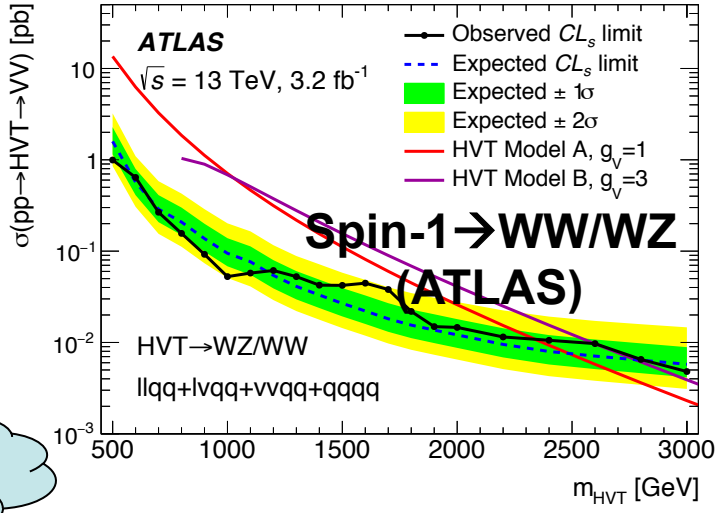
arXiv:1606.04833
CMS-EXO-PAS-15-002
CMS-PAS-B2G-16-004

Spin-1 VV 13 TeV results

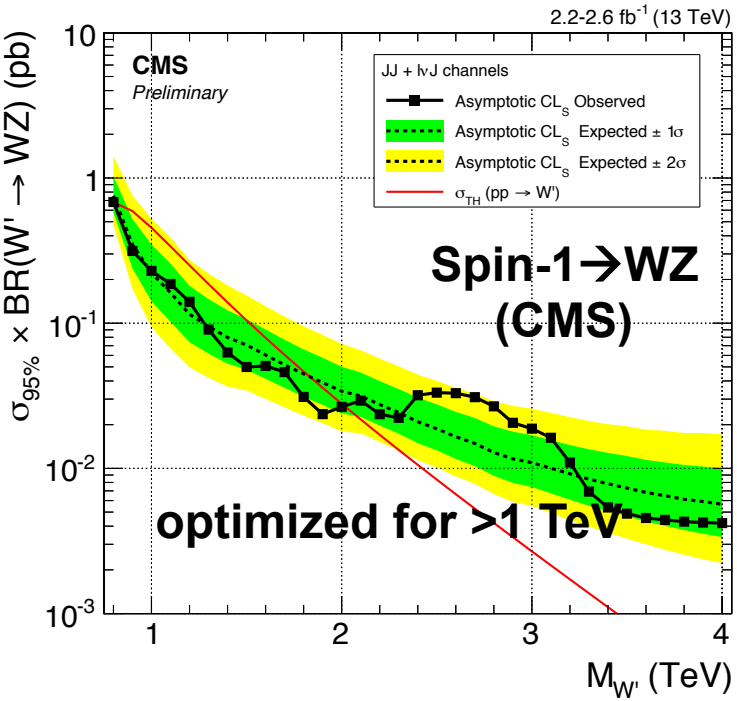
- No excesses observed by CMS and ATLAS
- Better limits than in Run 1
  - $m_{W' \to WZ} > 2.3$ TeV (HVT model B)

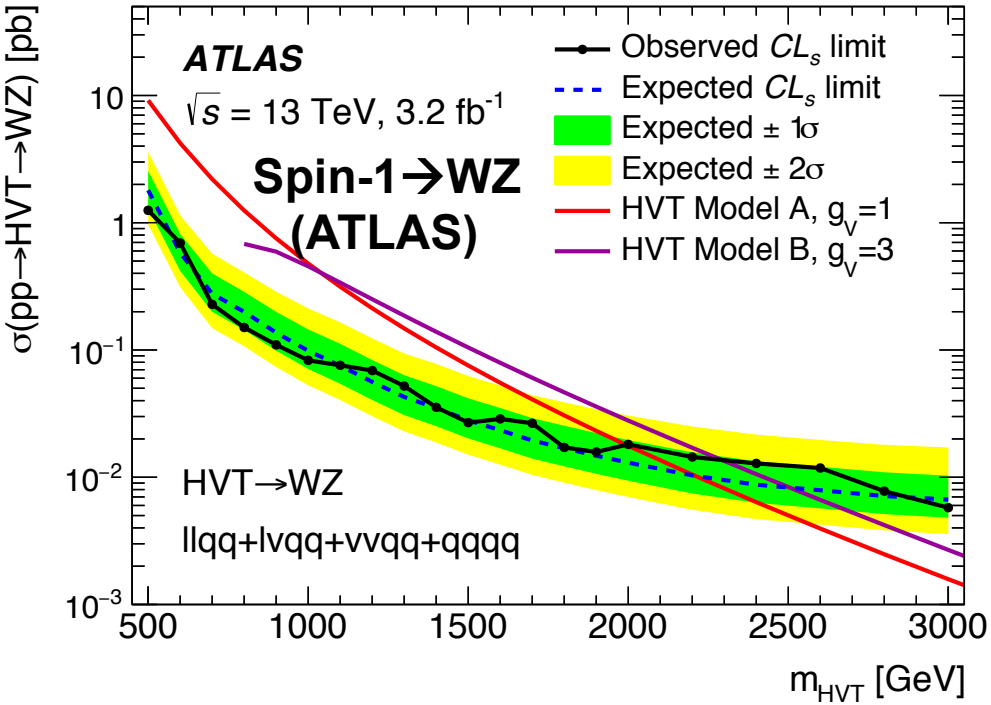
Heavy Vector Triplet B (composite Higgs like)
spin-1 W'± and Z' (like $\rho^{\pm}$, ρ^{0} in nuclear physics)

  - $m_{W'/Z' \to WZ/WW} > 2.6$ TeV (HVT model B)



Submitted

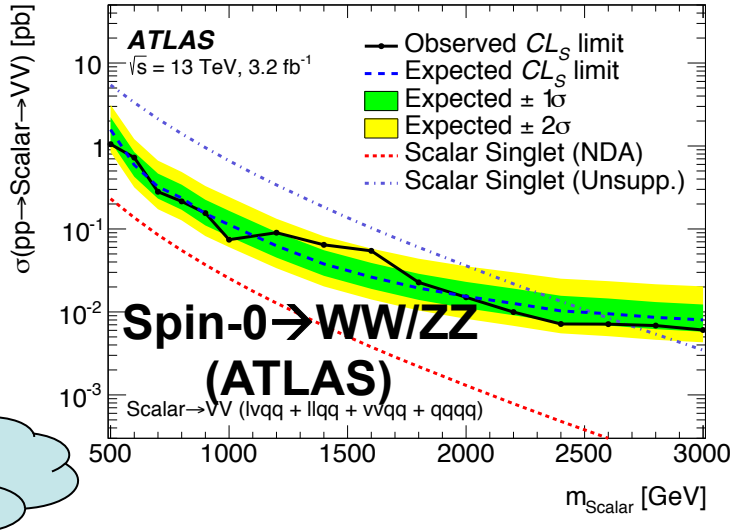




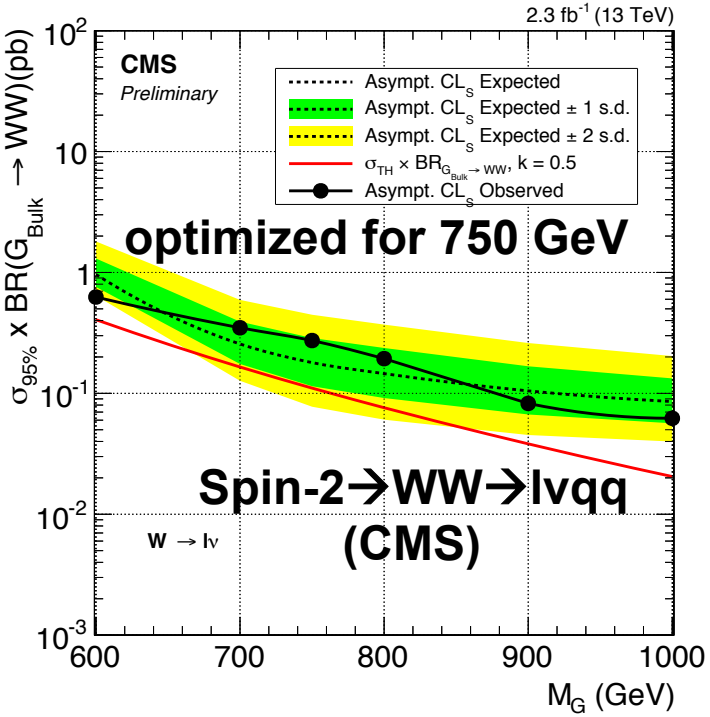
arXiv:1606.04833
CMS-EXO-PAS-15-002
CMS-PAS-B2G-16-004

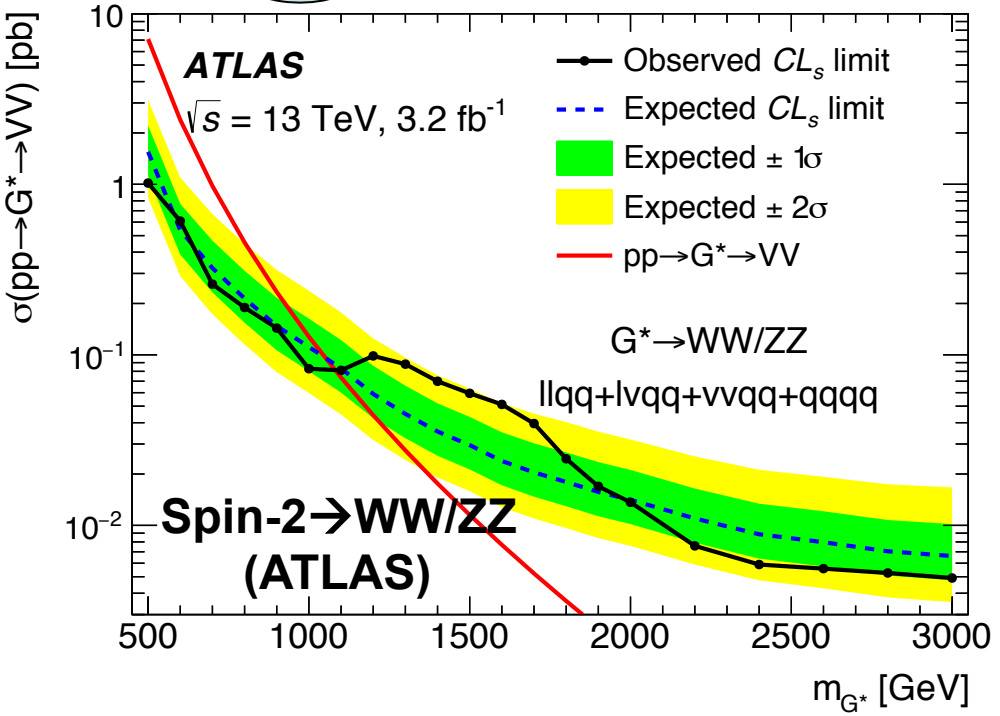
Spin-0/2 VV 13 TeV results

- No excesses observed by CMS and ATLAS
- Better limits than in Run 1
  - $m_{G^*} > 1.06$ TeV ($k/M_{PL}=1.0$)
  - $m_S > 2.65$ TeV (unsuppressed scenario)



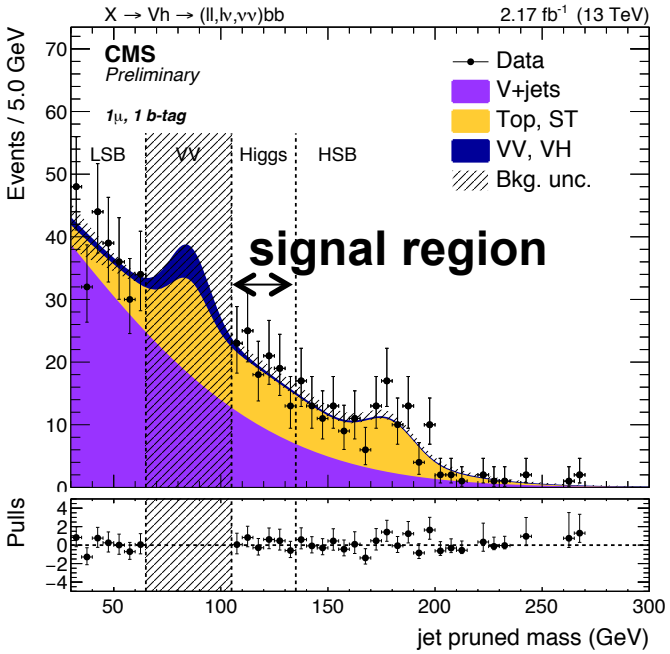
Submitted

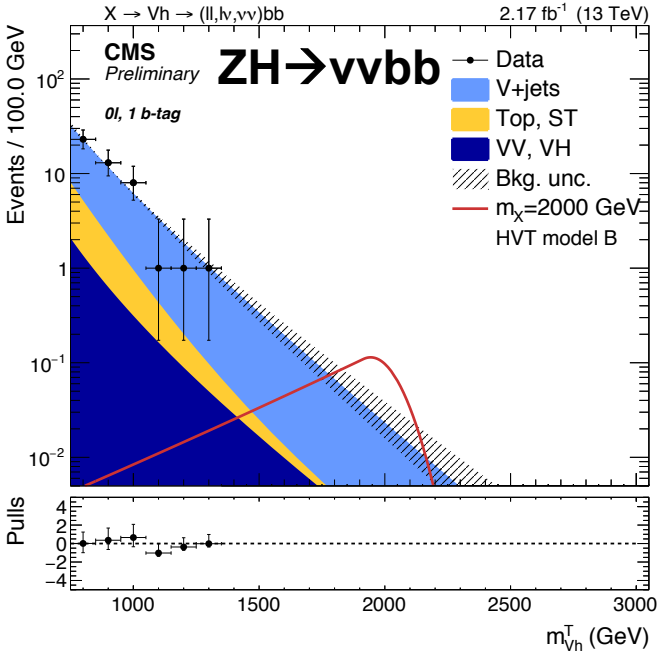


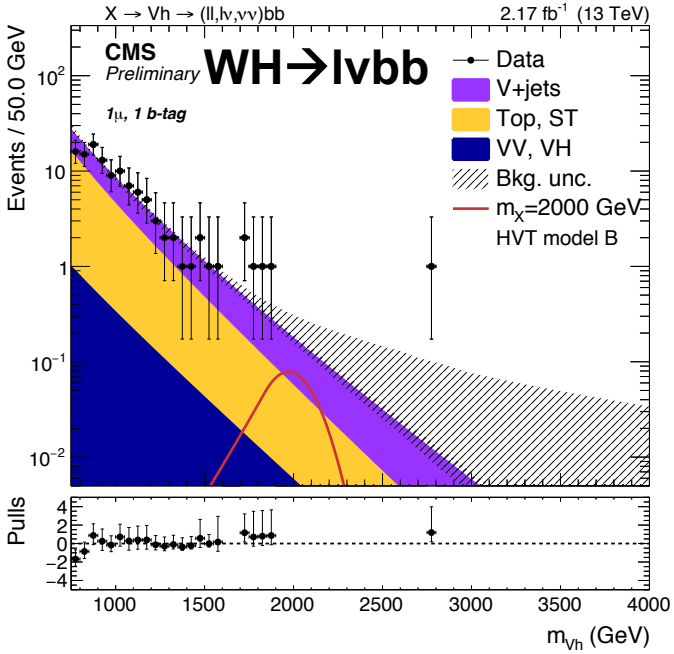


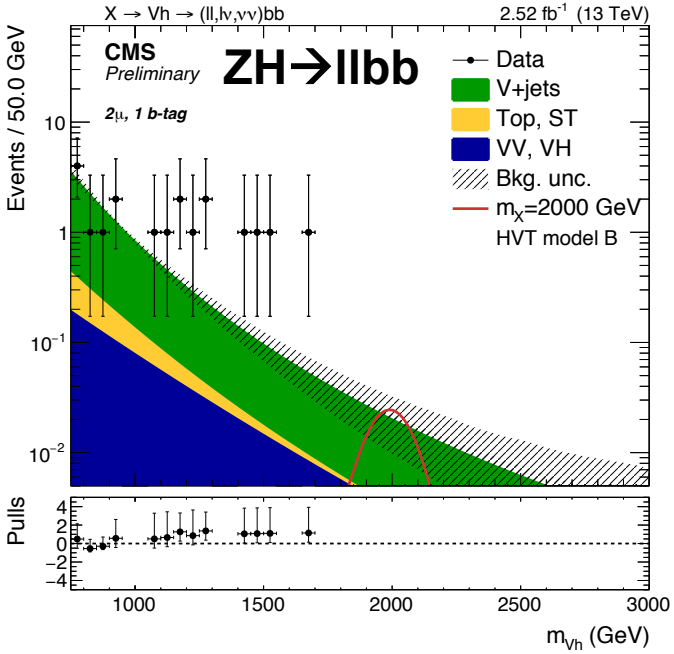
WH / ZH → vvbb/lvbb/llbb

- Higgs identification: p_T^J>200 GeV, 105<m_J<135
  - 1 and 2 subjet b-tag categories
- vv analysis: E_T^{miss}>200 GeV, Δϕ(E_T^{miss},J)>2, b-tag-veto
- μv/ev analysis: p_T^{μ}>55 GeV (p_T^e>135, E_T^{miss}>80 GeV), p_T^W>200 GeV, b-tag-veto
- μμ/ee analysis: p_T^{μ}>55 (p_T^e>135) GeV, 70<m_{ll}<110, p_T^Z>200 GeV, Δϕ(ll,J)>2.5
- Main backgrounds from V+jets (ttbar) estimated from data in m_J (b-tag-veto) sidebands



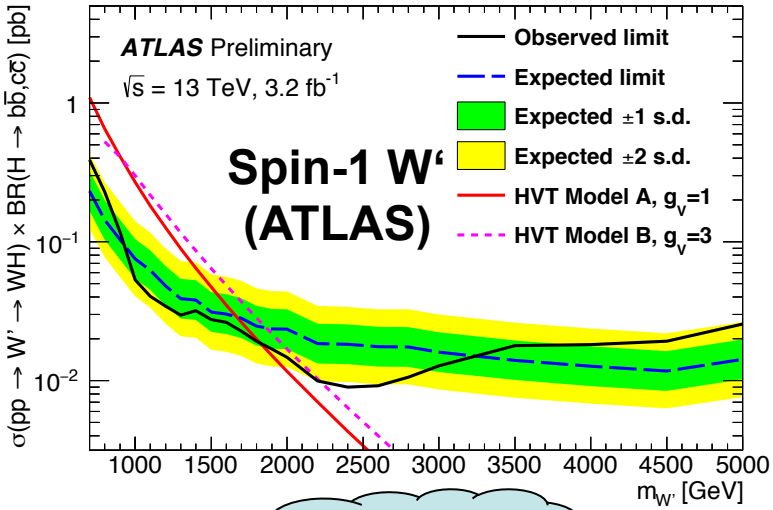


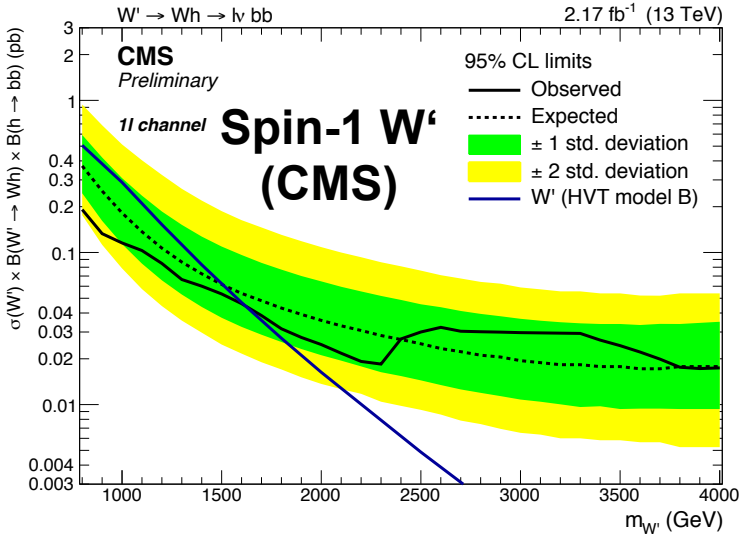




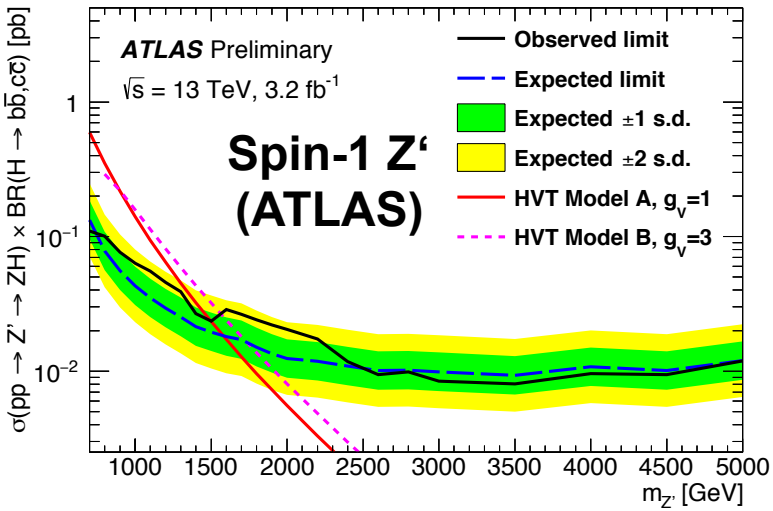
WH / ZH 13 TeV results

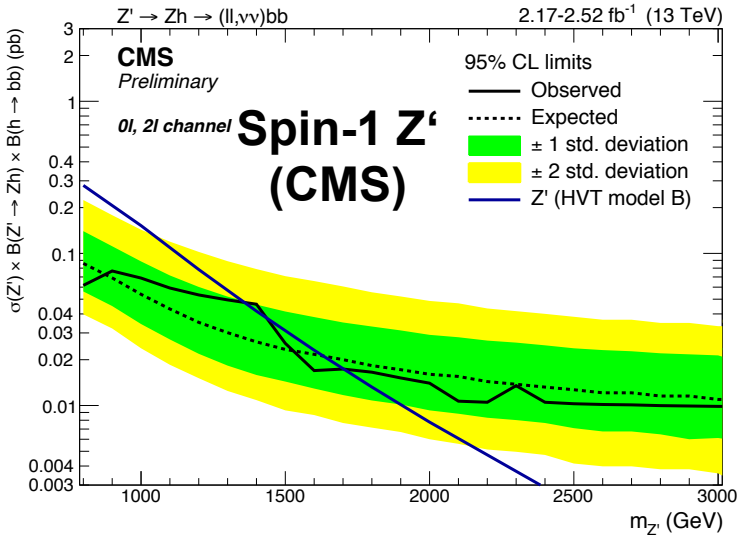
- No significant excess observed over background
- Exclude spin-1 $m_{W'}$<2.2 TeV and $m_{Z'}$<1.7 TeV in HVT model B





Updated

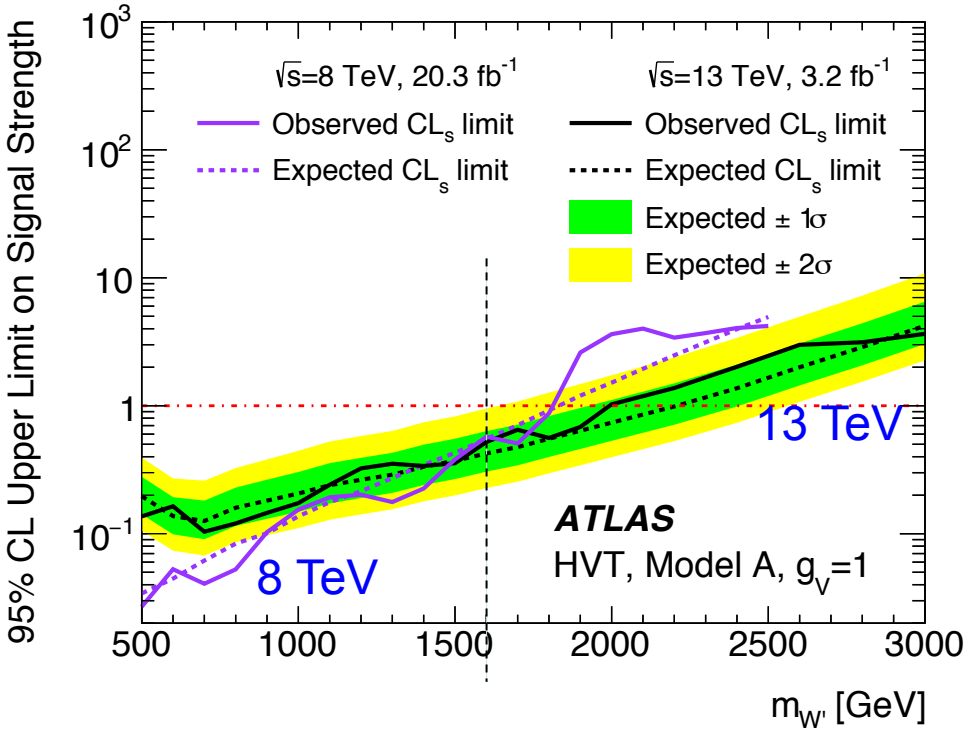


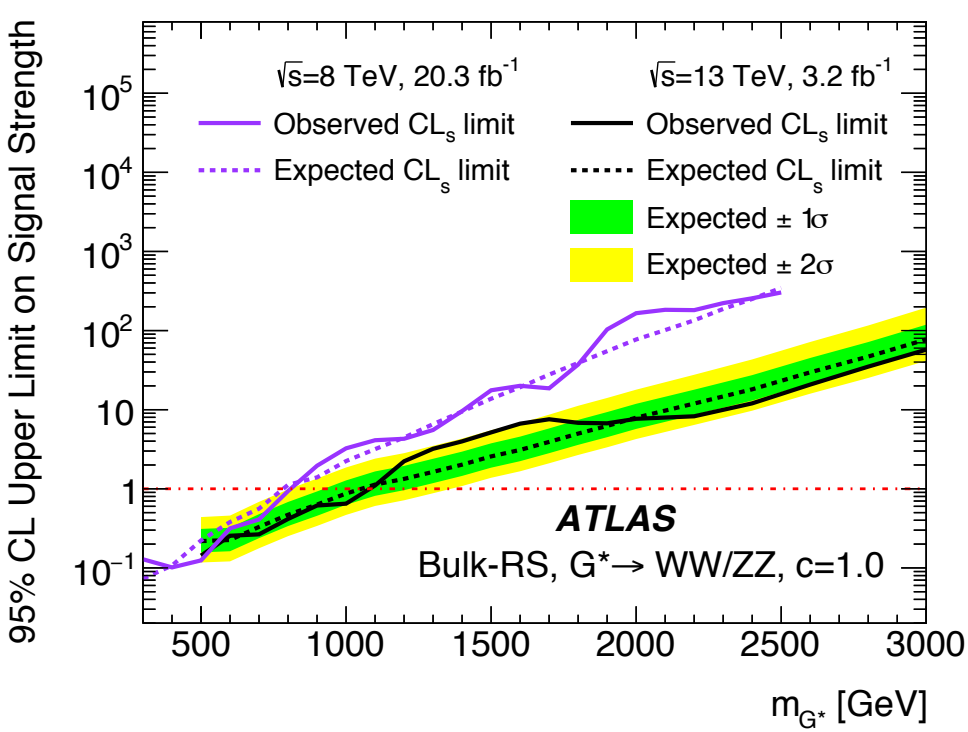


8 vs. 13 TeV sensitivity

Submitted

- Data collected by ATLAS/CMS
  - in 2012: 8 TeV, 20/fb
  - in 2015: 13 TeV, 3/fb

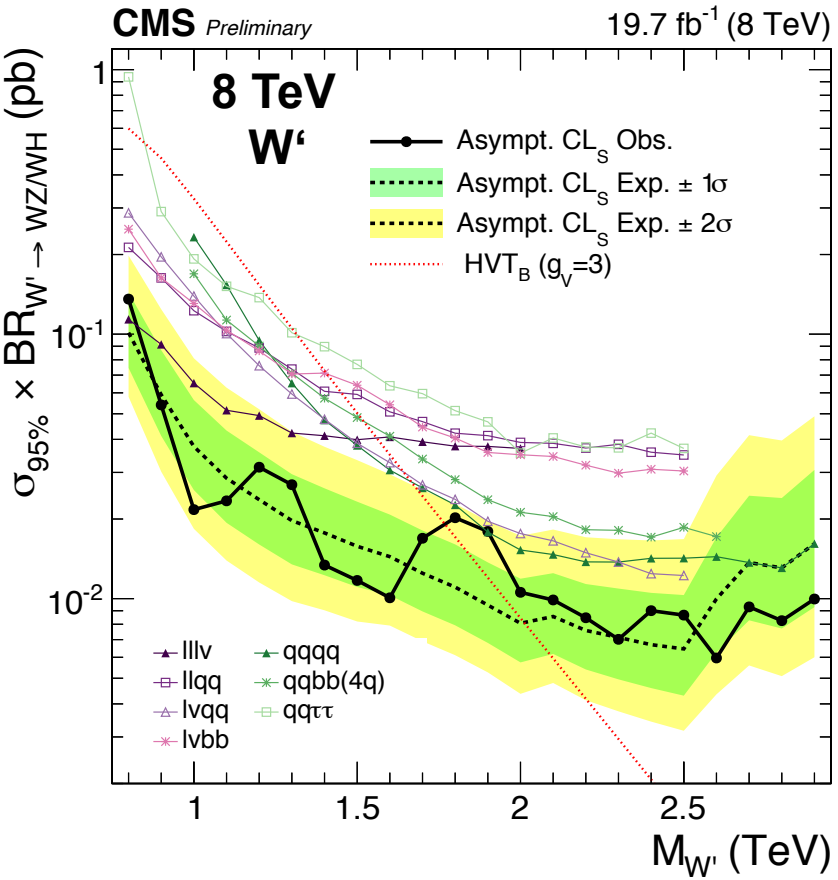


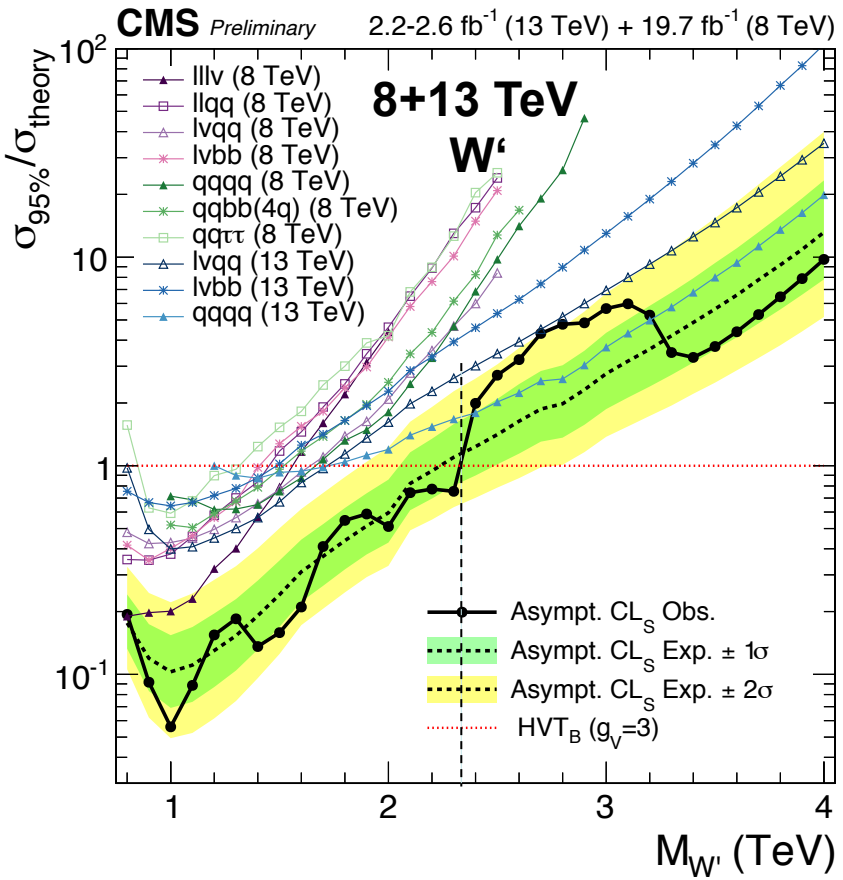


- qq-annihilation production: Run 2 better than Run 1 above ~1.5 TeV
- gg-fusion production: Run 2 better than Run 1 above ~0.5 TeV

VV+VH 8+13 TeV combination

New





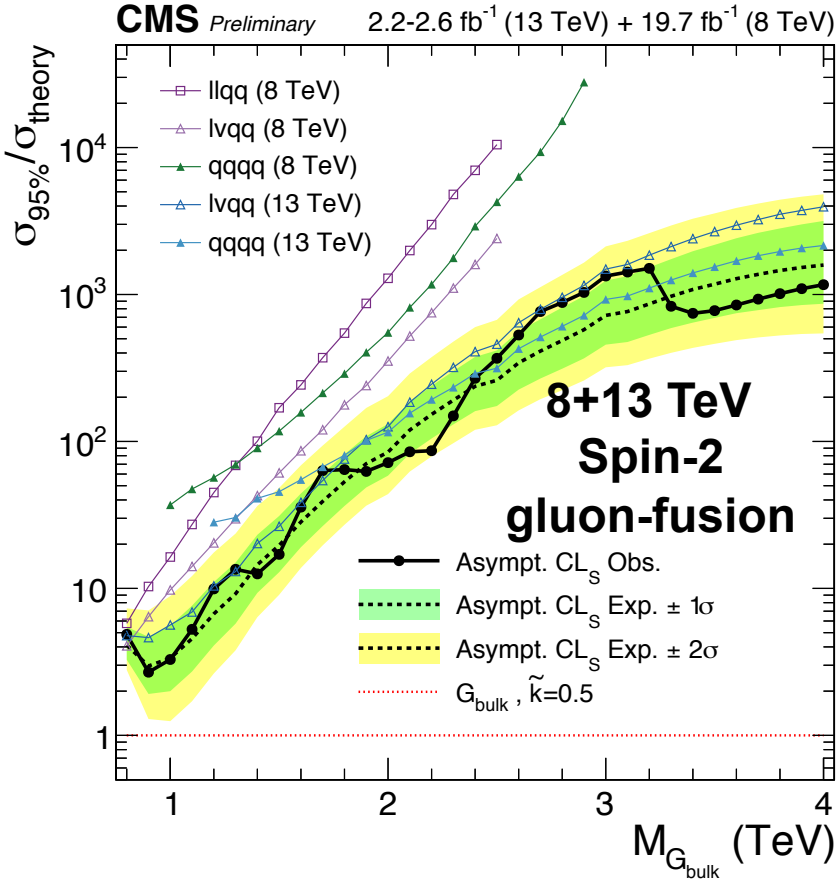
- Most significant excess from Run 1 in CMS: 2.2σ local for W'→WH@ 1.8 TeV
- Combining all 8 TeV VV+VH searches: remains 2.2σ in W' hypothesis
- Combining all 8+13 TeV VV+VH searches: reduced to 0.9σ in W' hypothesis

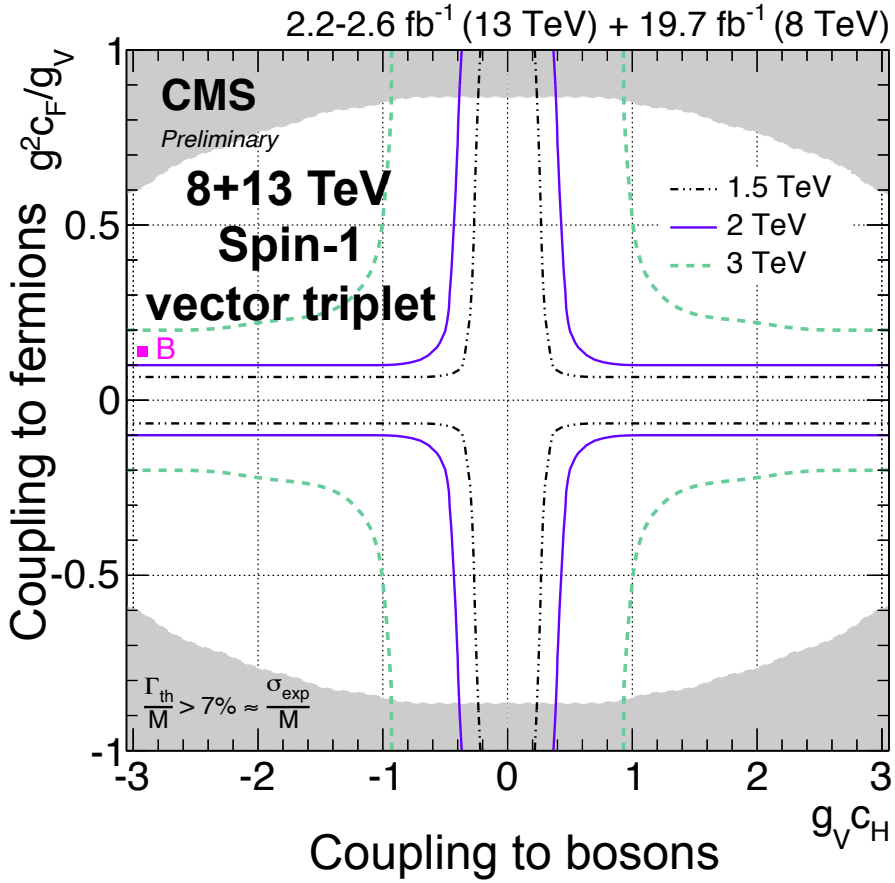
VV+VH 8+13 TeV combination

New

- W', Z', Heavy Vector Triple (W'+Z') and Bulk Graviton interpretations

particle	spin	charge	decay	production	W/Z polarization
W′	1	charged	mainly WZ, WH	mainly $q\bar{q}^{(\prime)}$	mostly longitudinal
Z′	1	neutral	mainly WW, ZH	mainly $q\bar{q}$	mostly longitudinal
G_{bulk}	2	neutral	mainly WW, ZZ	mainly gg	mostly longitudinal



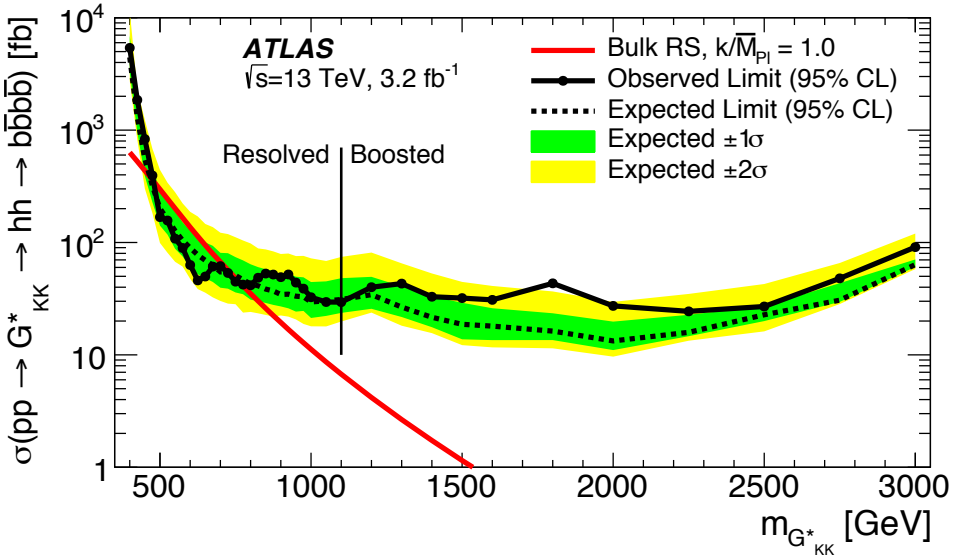


arXiv:1606.04782

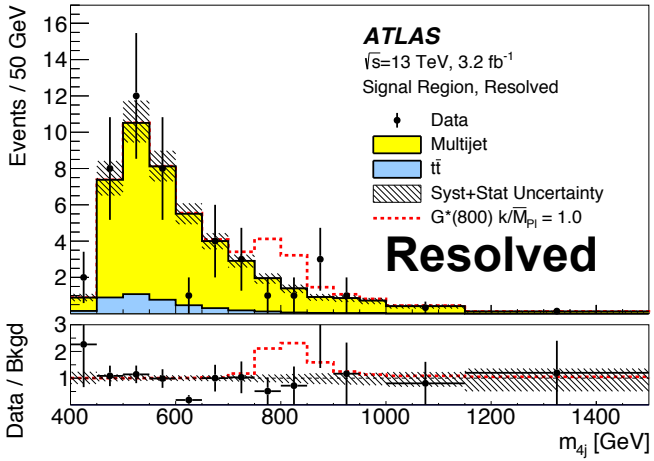
HH → bbbb

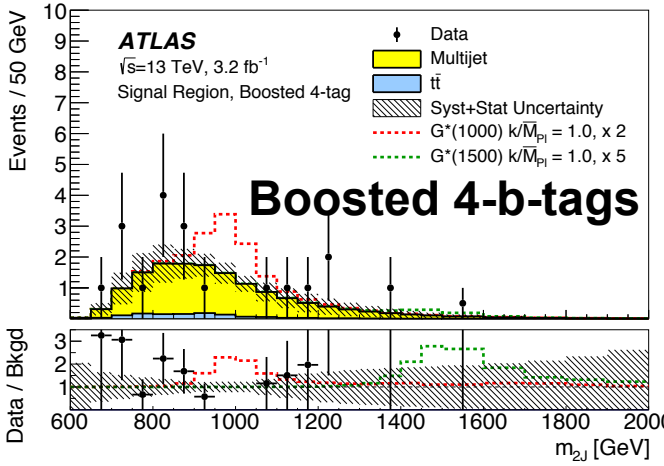
Submitted

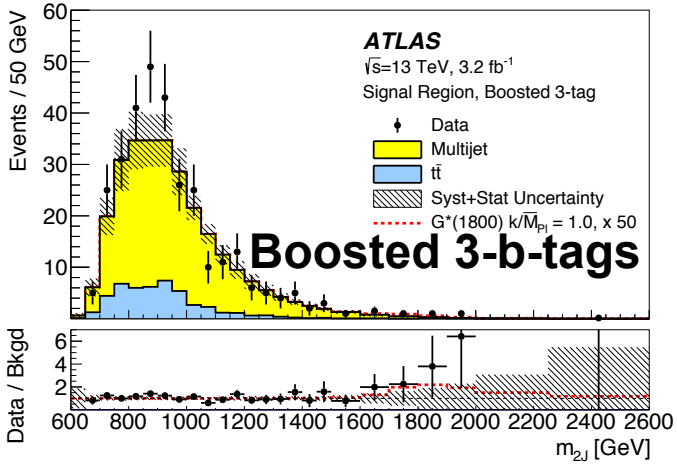
- Spin 0/2→HH→bbbb
- Resolved analysis:
  - 4 b-tag jets, $m_{jj} \sim m_H$
- Boosted analysis:
  - Two R=1.0 jets, $m_J \sim m_H$
  - 3-4 b-tagged matched trackjets
- Main backgrounds from multijets and ttbar estimated from data $N_{b\text{-tags}}$ and m_{jj} sidebands
- Limit on non-resonant HH production



$$\sigma(pp \to hh \to b\bar{b}b\bar{b}) < 1.22 \text{ pb} \qquad (\text{SM: } \sigma(pp \to hh \to b\bar{b}b\bar{b}) = 12.9^{+1.5}_{-1.6} \text{ fb})$$





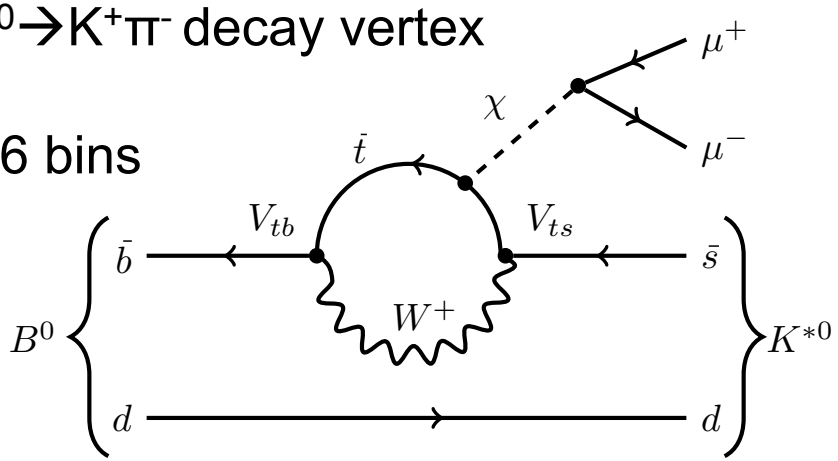


10.1103/PhysRevLett.115.161802

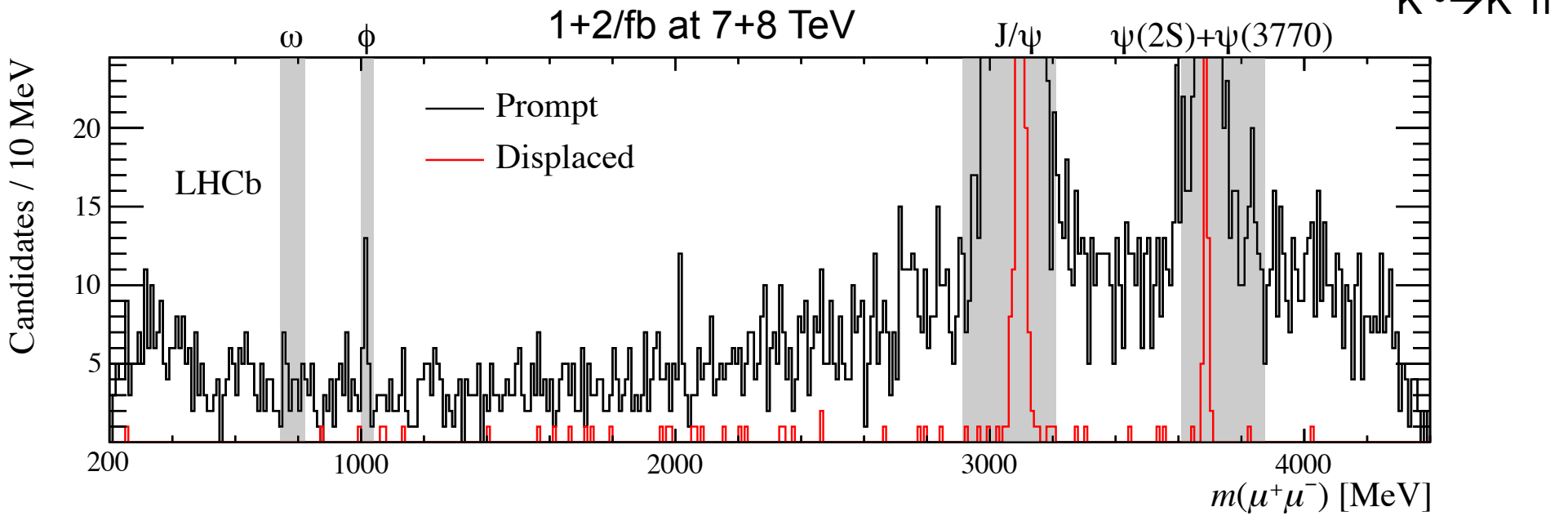
New low mass bosons

- Search for low mass boson $\chi \rightarrow \mu\mu$ with coupling to top quark
- Sensitive to χ decay time reconstructing $K^{*0} \rightarrow K^+\pi^-$ decay vertex
- Background rejection with MVA selection
- Background estimated from neighboring 4-6 bins

- Most stringent constraints to date covering masses 200-4400 MeV



$K^{*0} \rightarrow K^+\pi^-$



Conclusions

- Combining 8 and 13 TeV data, conclude a solid “maybe” on 750 GeV
  - LHC already delivered another 4/fb of data in 2016
    → better understanding soon!

- Di-boson resonance masses >TeV explored in all important final states
  - Interpretations in spin-0, spin-1 (HVT), spin-2 (RSG) scenarios

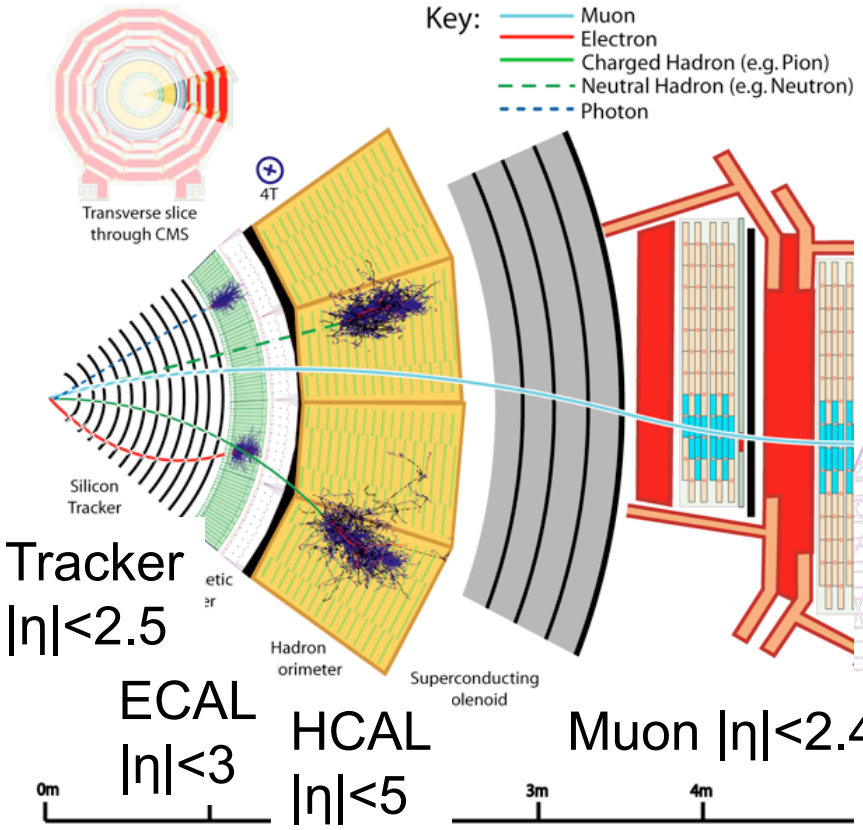
- Analyses with 13 TeV data supersede 8 TeV searches at >TeV masses
  - Most stringent mass limits on W’/Z’/G^* resonances

- Combination of 8+13 TeV VV+VH searches disfavors bump at 2 TeV
  - Final confirmation with 2016 data

Backup

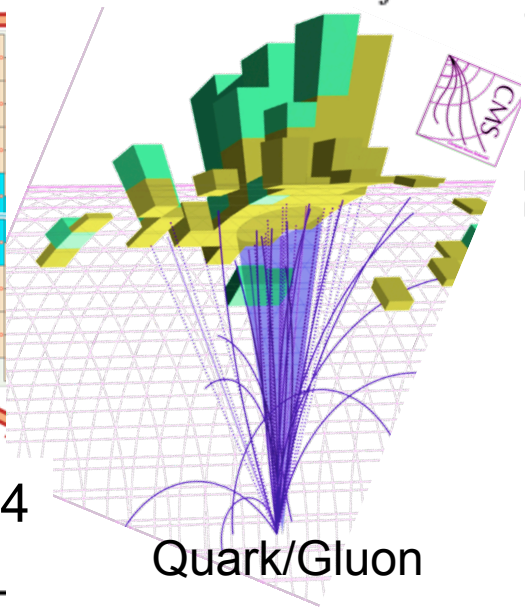
Jet reconstruction in CMS

Particle flow reconstruction

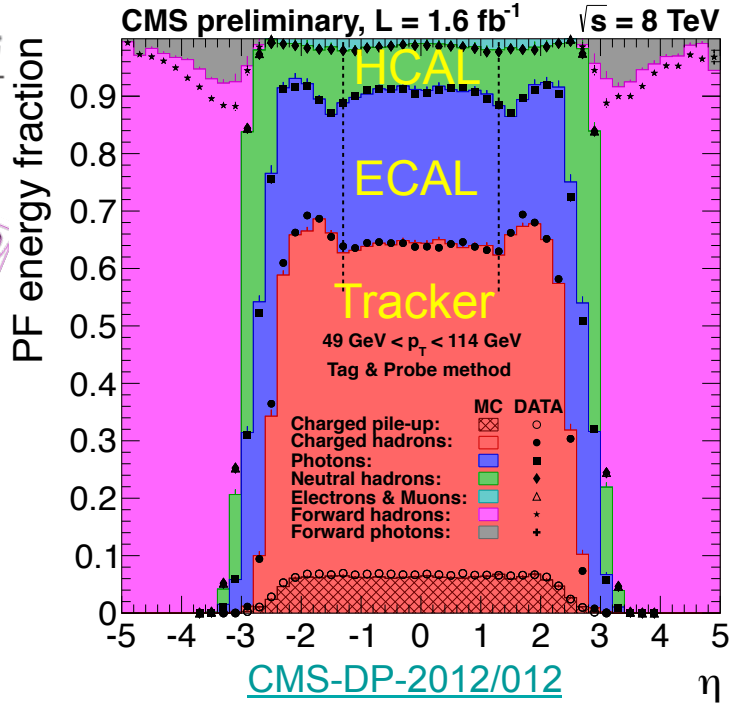


Jet clustering (anti-k_T or CA) R=0.4/0.5/0.8

$$d_{ij} = \frac{1}{\max(k_{Ti}^2, k_{Tj}^2)} \frac{\Delta R_{ij}^2}{R^2}$$



Jet energy reconstruction



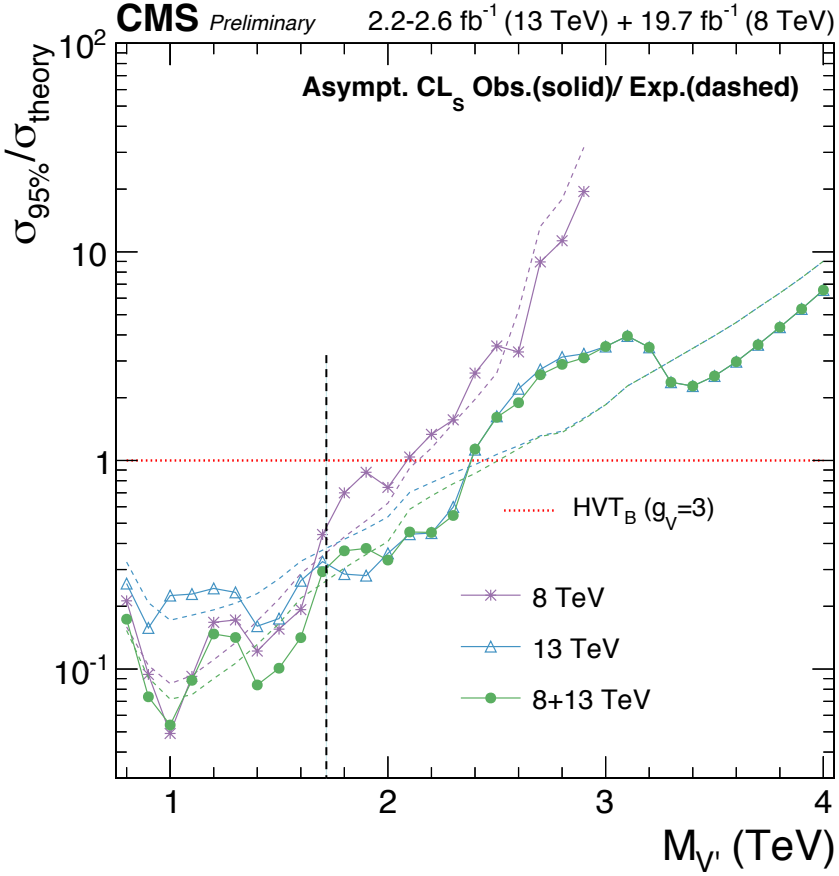
CMS-DP-2012/012

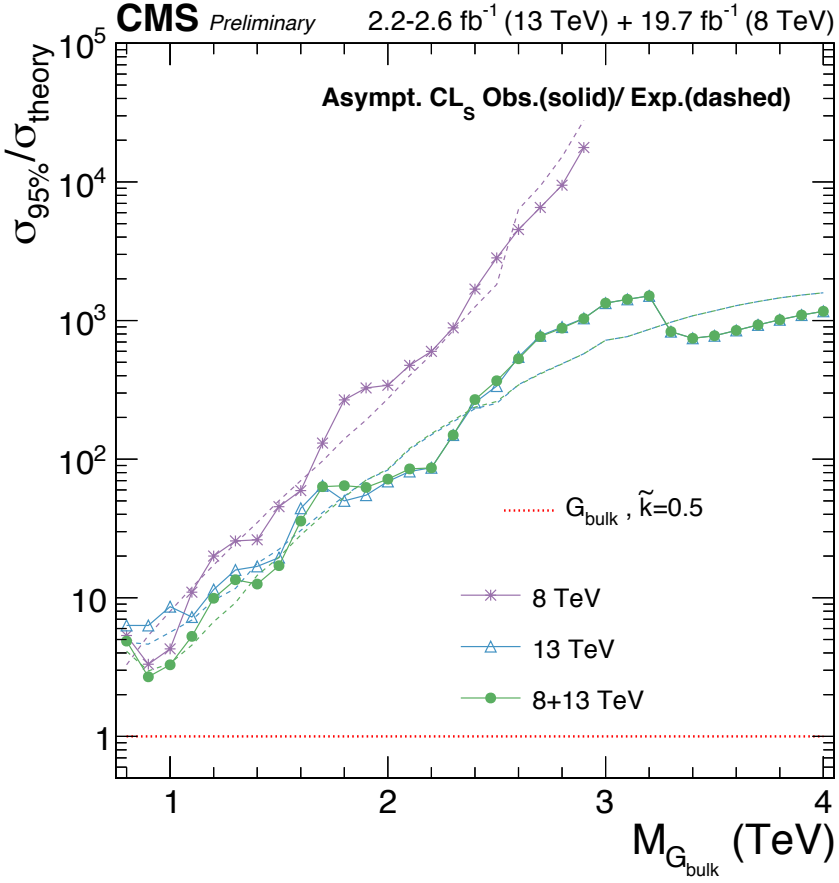
Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

8 vs. 13 TeV comparison

New at LHCP

- Data collected by ATLAS/CMS
  - in 2012: 8 TeV, 20/fb



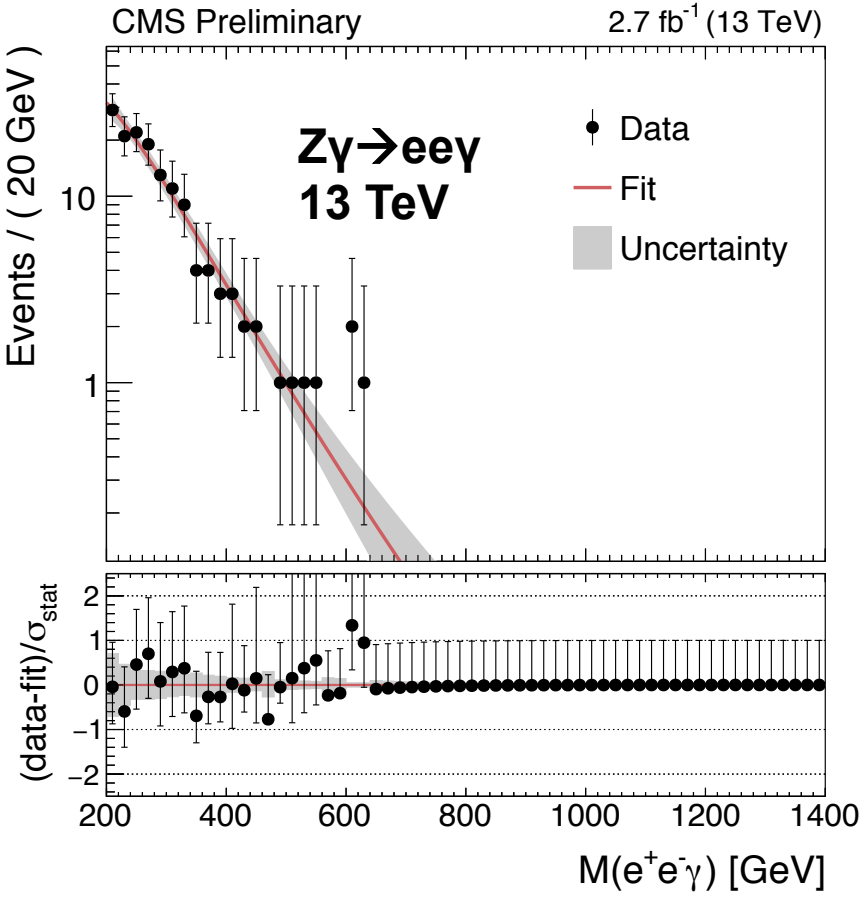


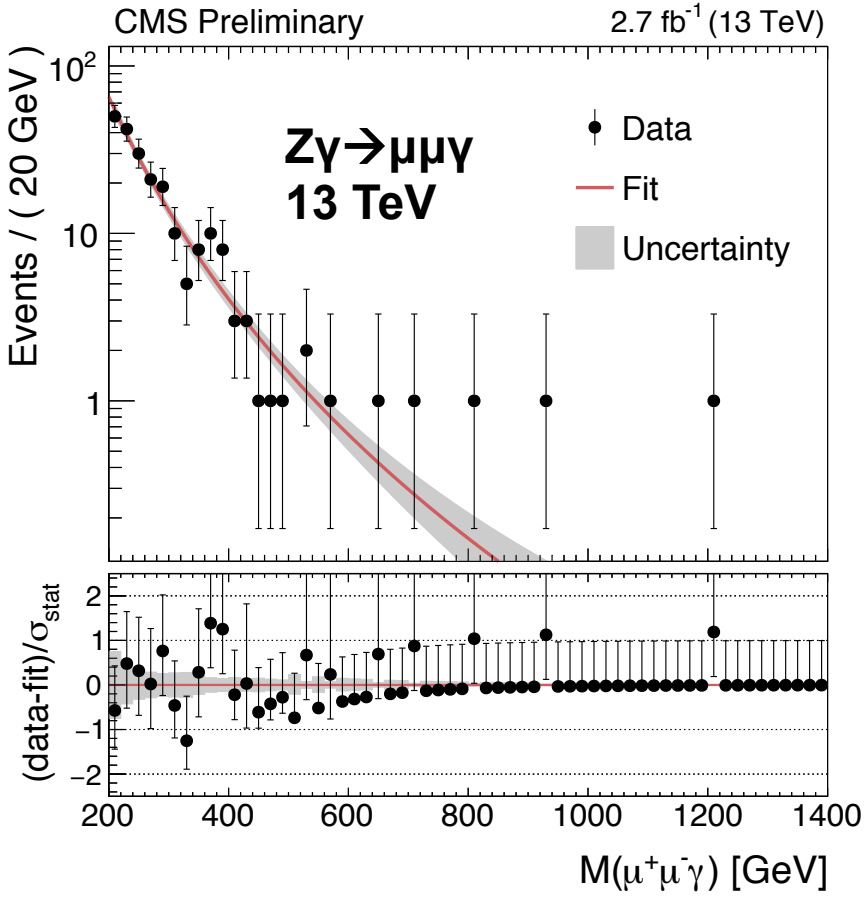
- qq-annihilation production: Run 2 better than Run 1 above ~1.5 TeV
- gg-fusion production: Run 2 better than Run 1 above ~0.5 TeV

Z+photon → llγ

- Spin-0→Zγ→llγ
- lepton $p_T^{e/\mu}$>25(20) GeV, shrinking isolation cone, 50<m_{ll}<130 GeV
- γ p_T>40 GeV and p_T>0.27 $M_{Z\gamma}$, ΔR(γ,l)>0.4
- Background estimated from smooth fit:

$$f(m_{Z\gamma}) = m_{Z\gamma}^{a+b\log m_{Z\gamma}}$$





ATLAS-CONF-2016-010
CMS-PAS-EXO-16-019
CMS-PAS-HIG-16-014
CMS-PAS-EXO-16-020
CMS-PAS-EXO-16-021

Z+photon → llγ

- Spin-0→Zγ→llγ
- lepton $p_T^{e/\mu}$>25(20) GeV, shrinking isolation cone, 50<m_{ll}<130 GeV
- γ p_T>40 GeV and > 0.27 $M_{Z\gamma}$, ΔR(γ,l)>0.4
- Background estimated from smooth fit:

$$f(m_{Z\gamma}) = m_{Z\gamma}^{a+b\log m_{Z\gamma}}$$