Probe SM and BSM via Multi-Boson signatures with ATLAS detector

李数

李政道研究所/上海交通大学

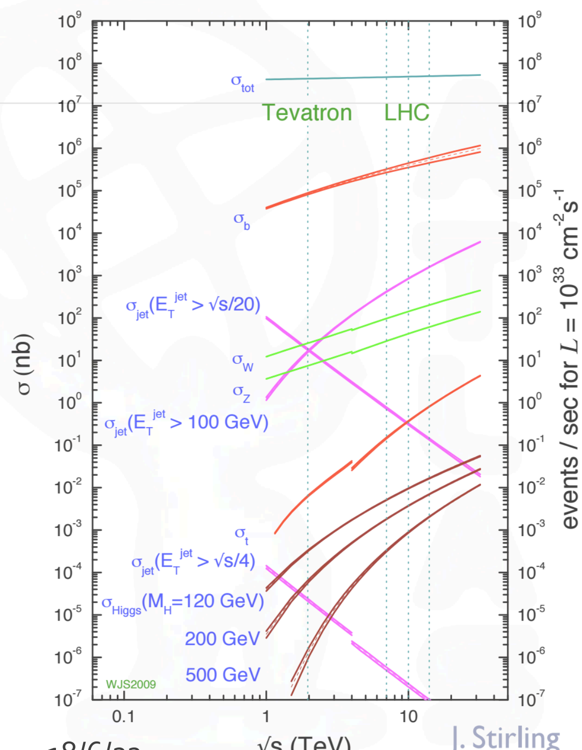
On behalf of ATLAS collaboration

Standard Model Shortly

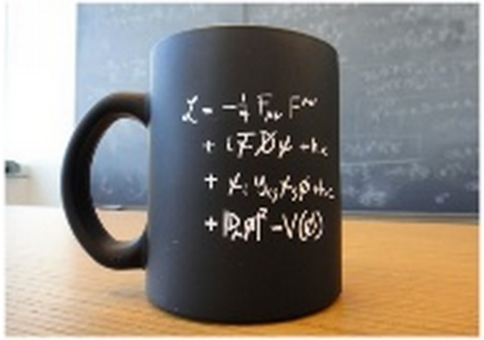
Applausive arguments:

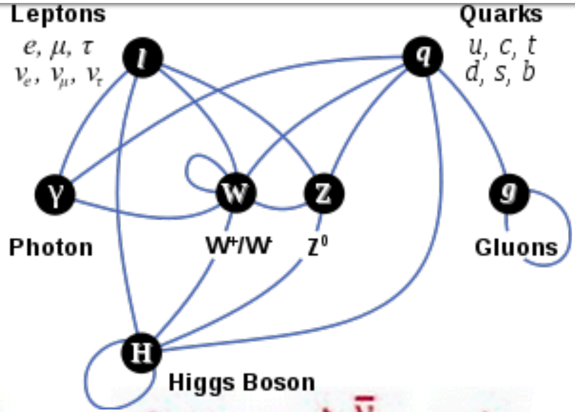
SM widely succeeded in describing fundamental particles and Interactions with very few ingredient over reasonably broad range of energies

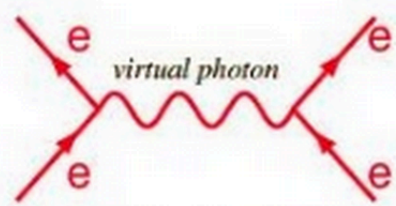
proton - (anti)proton cross sections



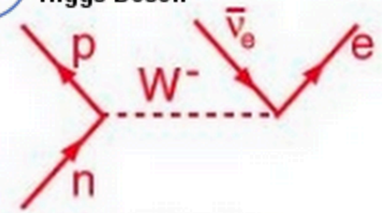
J. Stirling



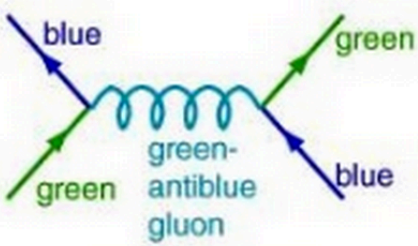




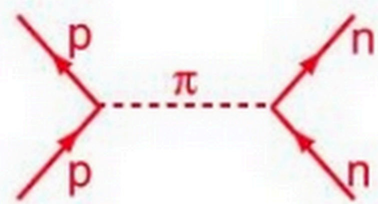
Electromagnetic Interaction



Weak Interaction



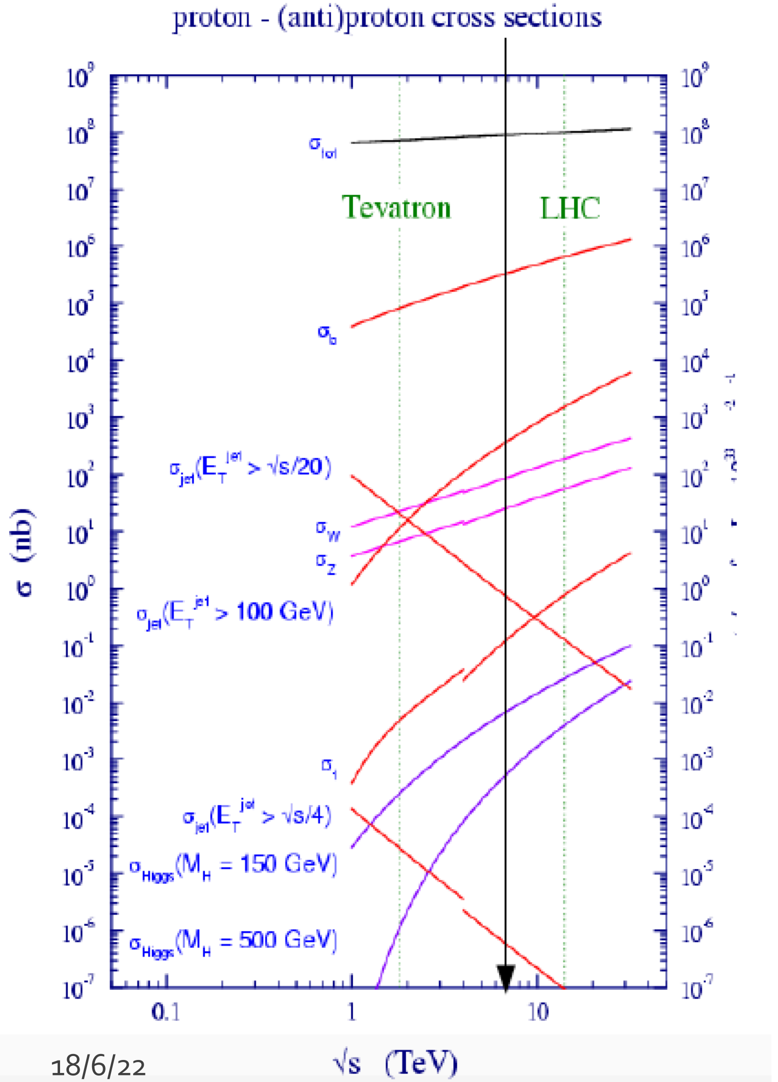
between quarks

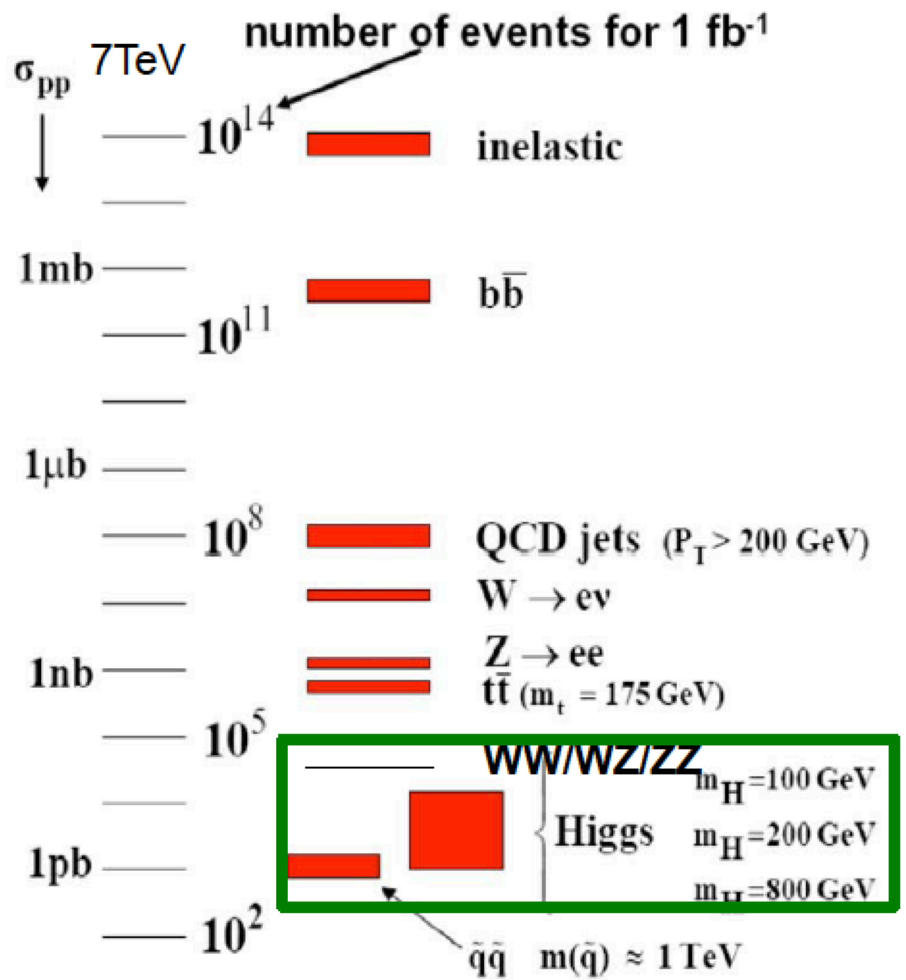


between nucleons

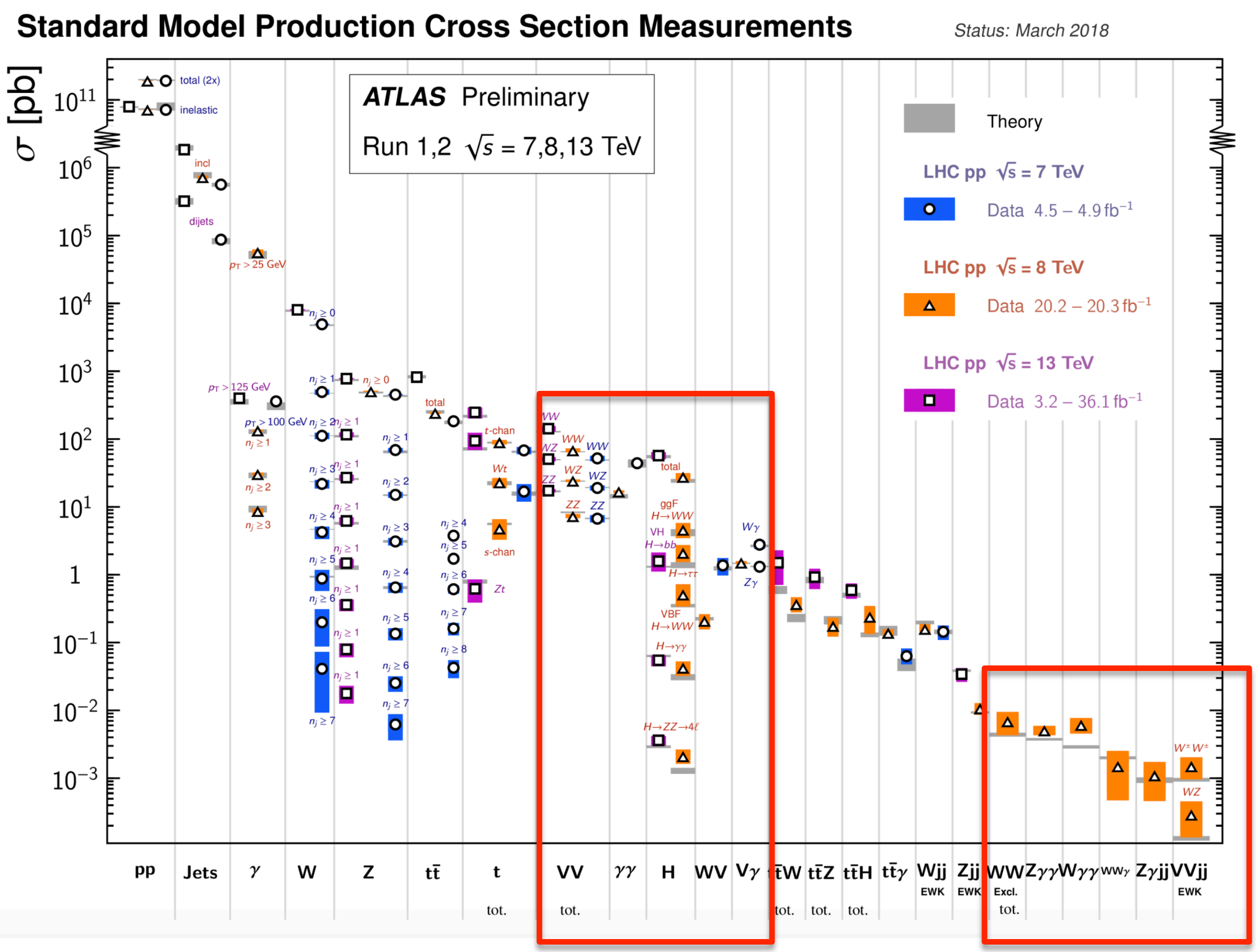
Strong Interaction

Diboson among the rare processes to be worked out in ATLAS



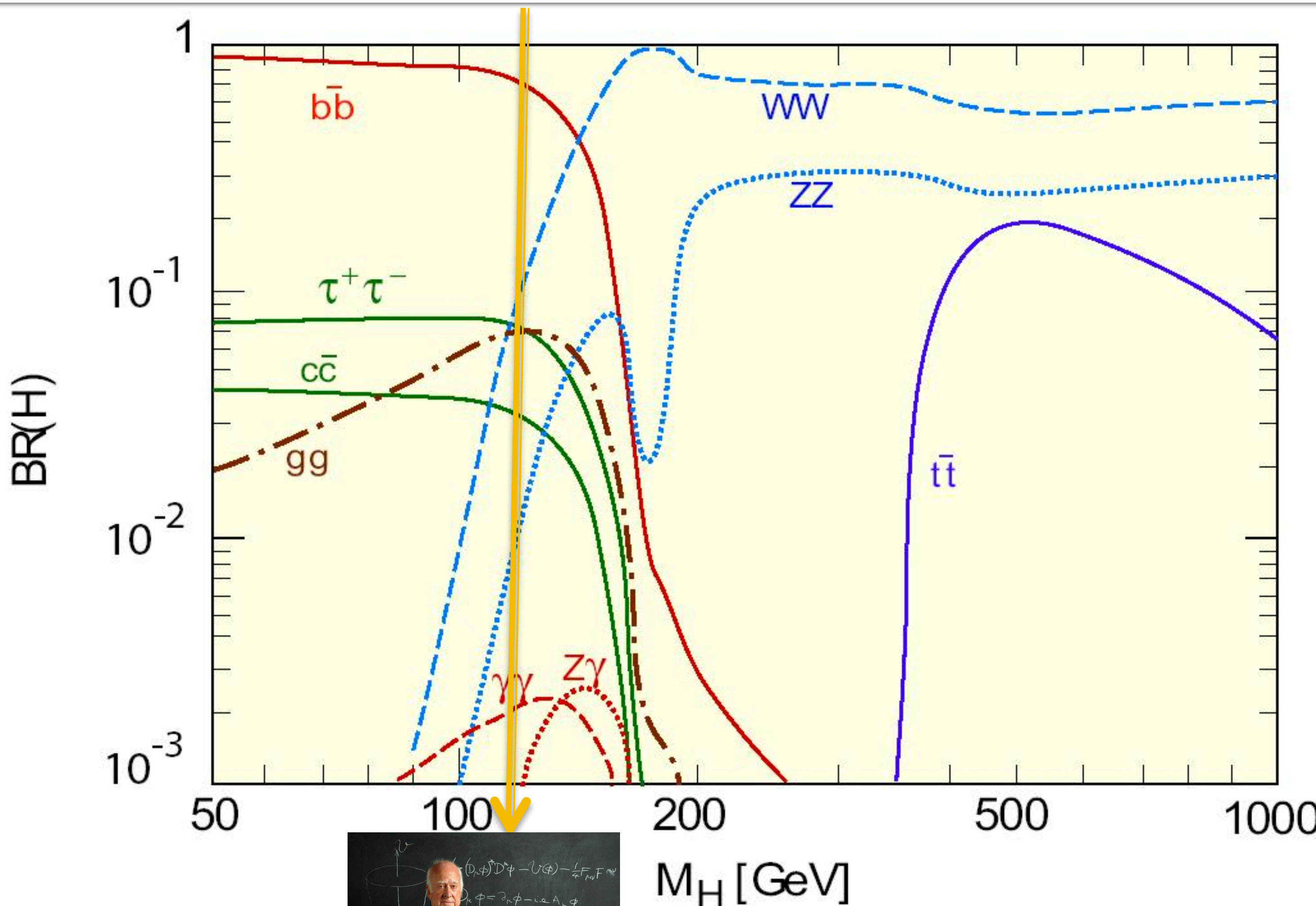


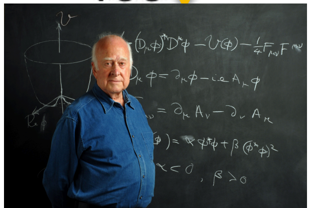
Summary of SM measured total cross-section and comparisons with theory predictions from ATLAS Run-I/Run-II



See Elena's talk today for the WZ channel interesting results

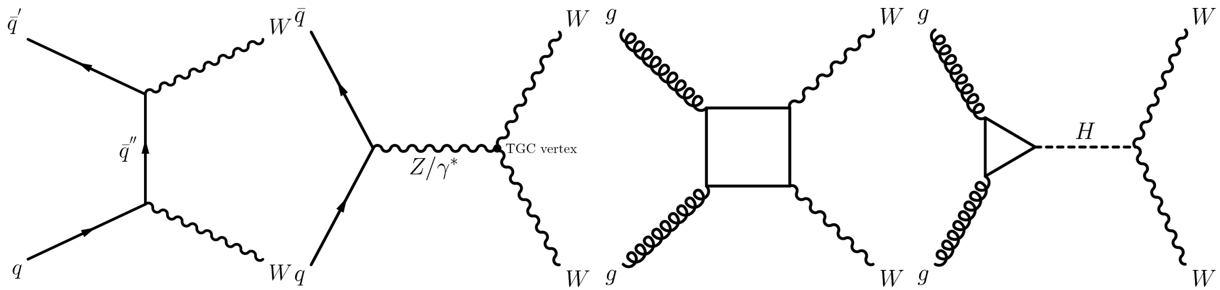
Why do multi-boson: signature matters essentially at ATLAS for new physics

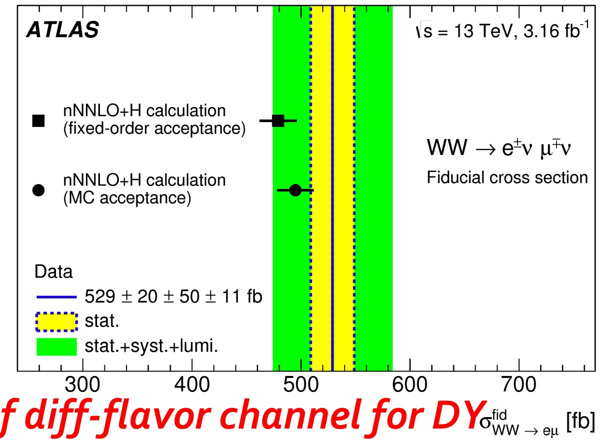




Measurement of the WW production cross section in full leptonic final state

WW production via quark-antiquark annihilation(dominant) and gg-fusion



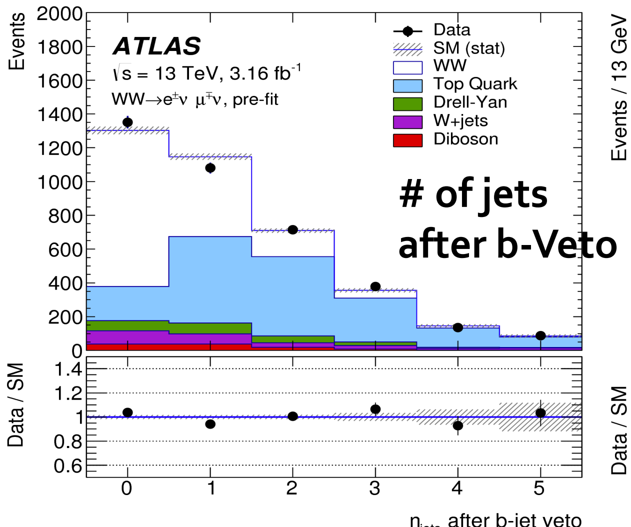


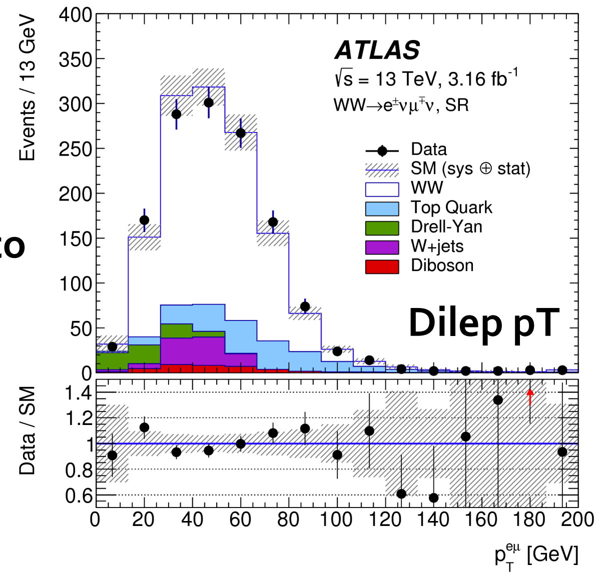
Bgd challenges: mainly Data-Driven (DD)

ttbar(DD: high #jet), DY(DD: low Et^{miss}, low dilep pT)

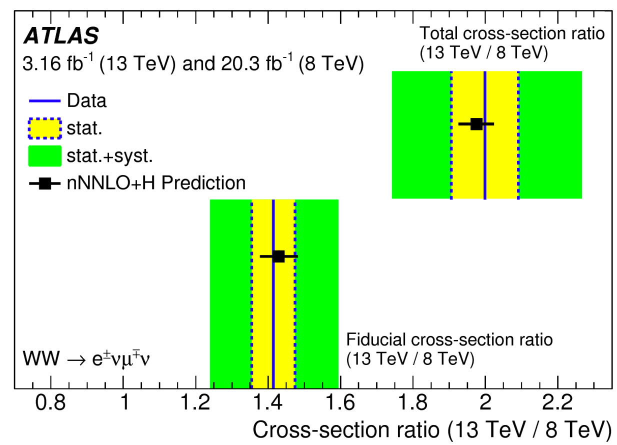
W+X(DD: lepton fake), other diboson (MC)

Use of diff-flavor channel for DY suppression





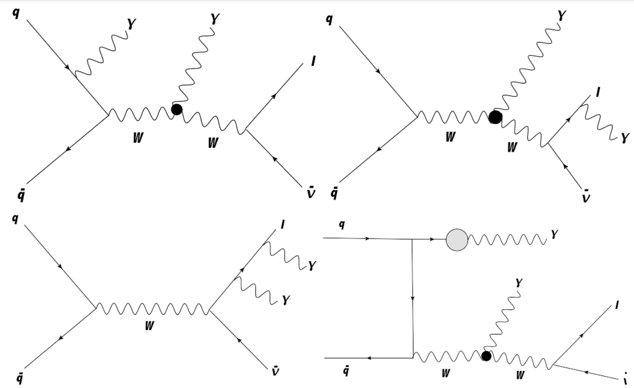
Phys. Lett. B 773 (2017) 354



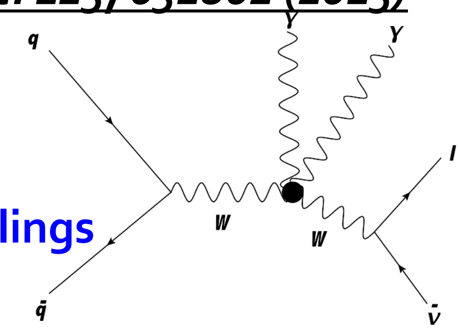
First evidence of tri-boson production in Wγγ final state at 8TeV

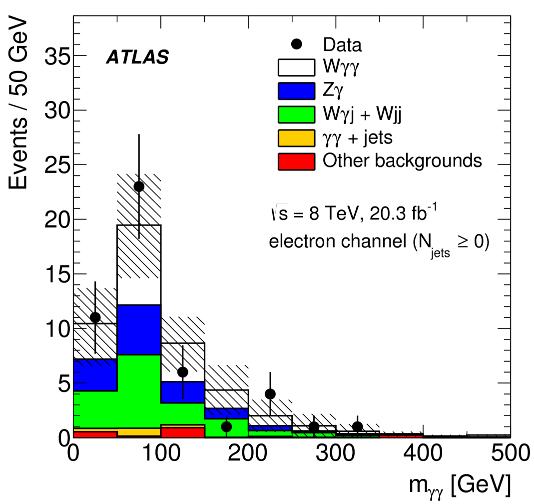
Phys. Rev. Lett. 115, 031802 (2015)

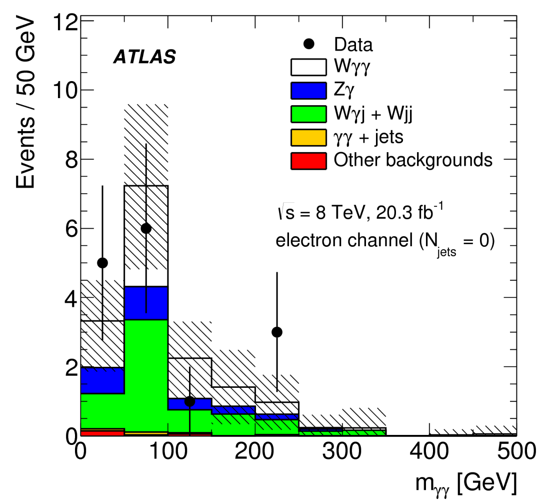
Wγγ topologies

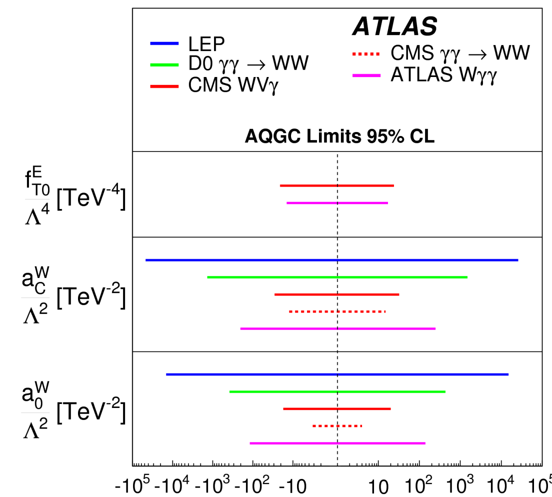


Anomalous Quartic Couplings





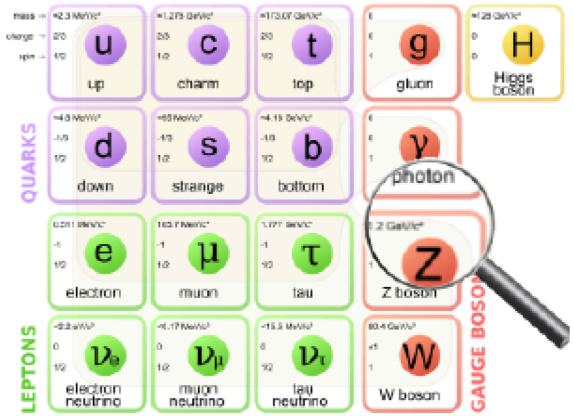




Cross section measured in fully leptonic (e/μ) channels
For inclusive(#jet>=0) and exclusive(#jet==0) regions

First triboson aQGC limits of high dimension operators f_{T0} a_0^W and a_C^W, determined in jet-exclusive region with Mγγ>300GeV, dipole-FF unitarized

Zγ(γ) topologies in short

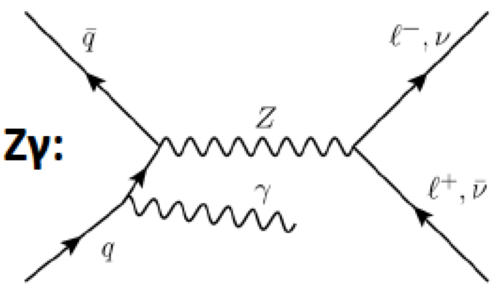


Measured processes

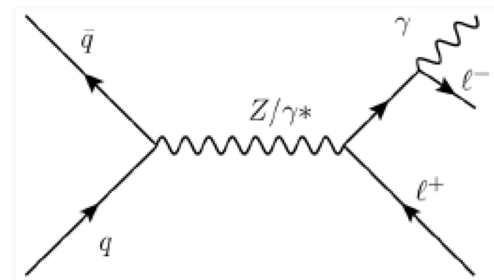
Study of Zγ and Zγγ production probes EW sector via interactions between two types of neutral bosons.

SM diagrams

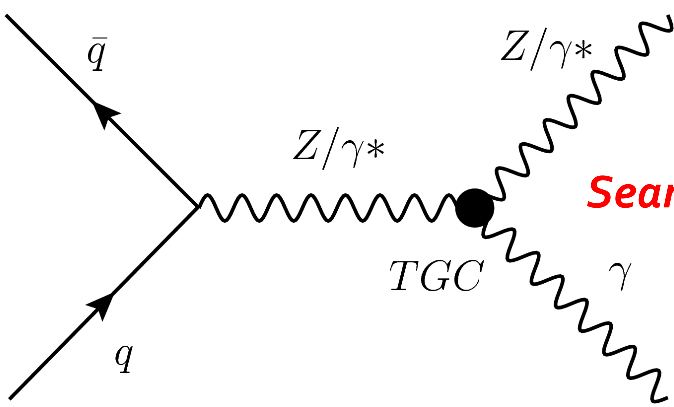
Zγ:



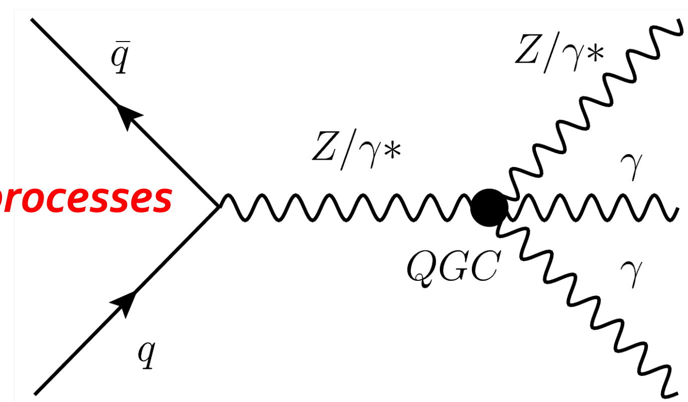
Initial state radiation (ISR)



Final state radiation (FSR)

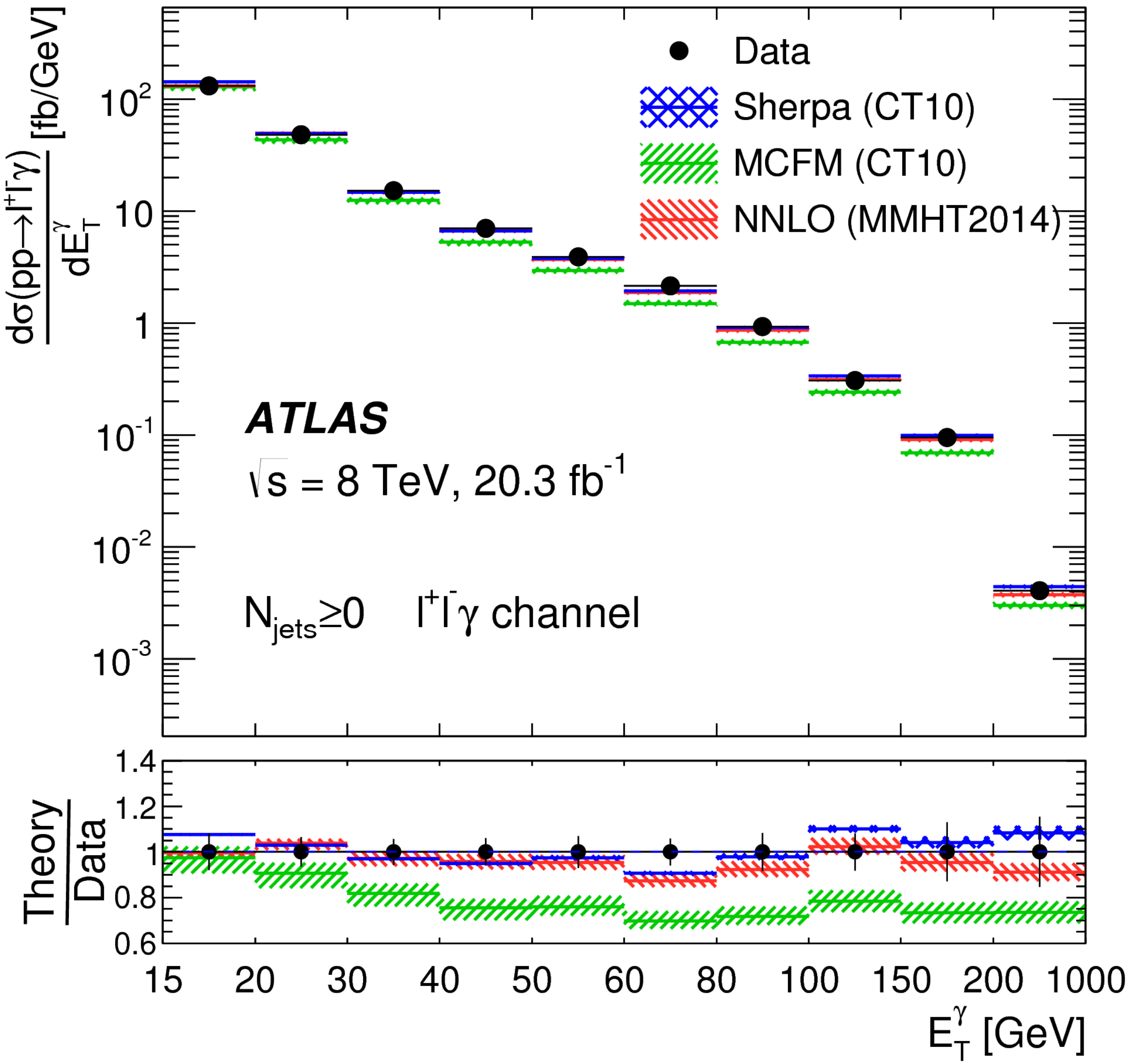


Searched processes

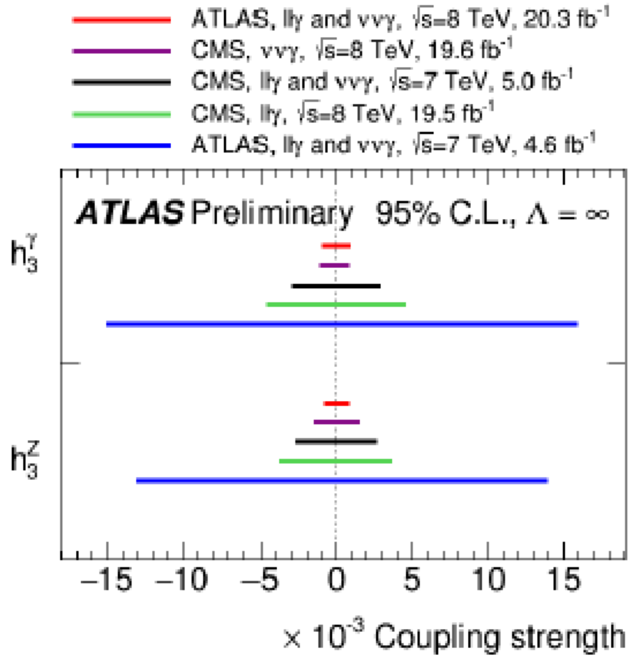


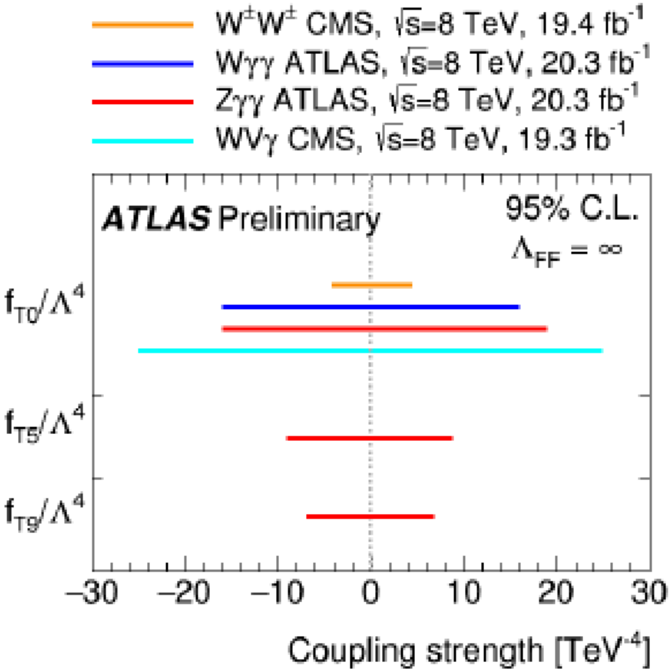
Zγ: SM Measurements vs SM Theory prediction (w/ high order corrections)

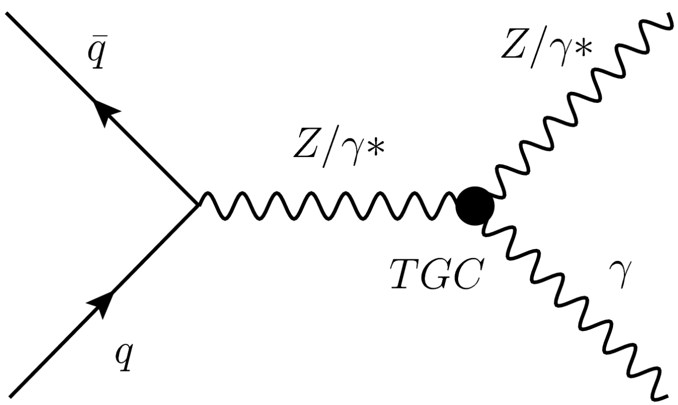
Measured Cross section Can only agree with theory prediction when NNLO correction is adopted

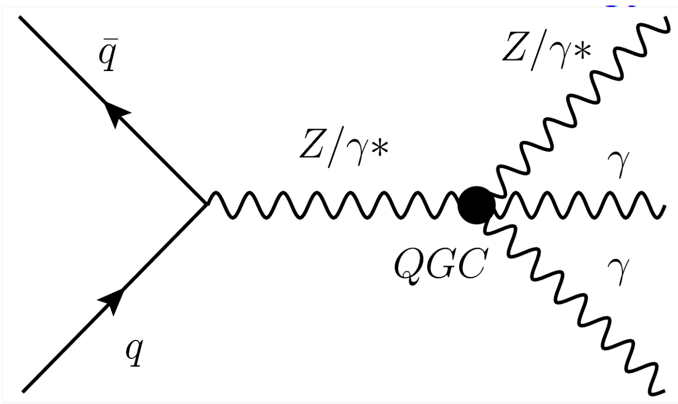


Anomalous coupling summary and comparisons







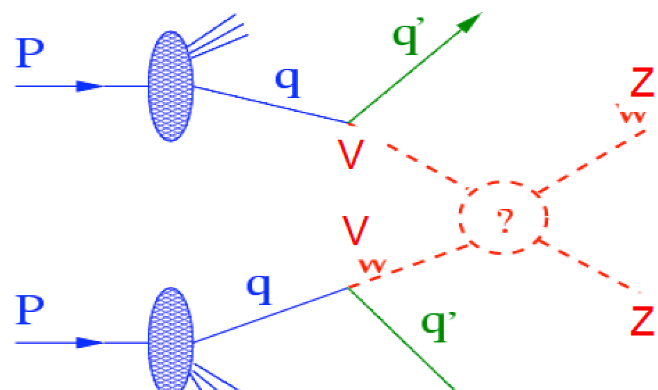


Diboson→VBS: SM, precision, unitarization and new physics

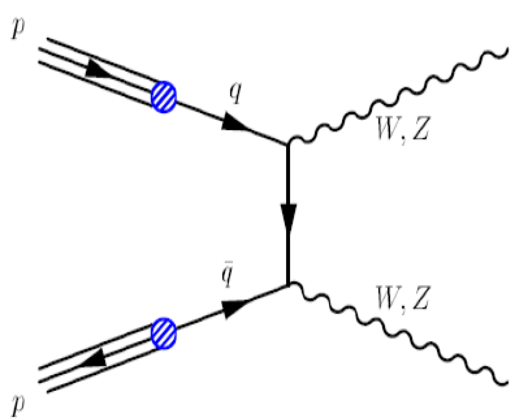
Unitarity violation of Vector Boson Scattering

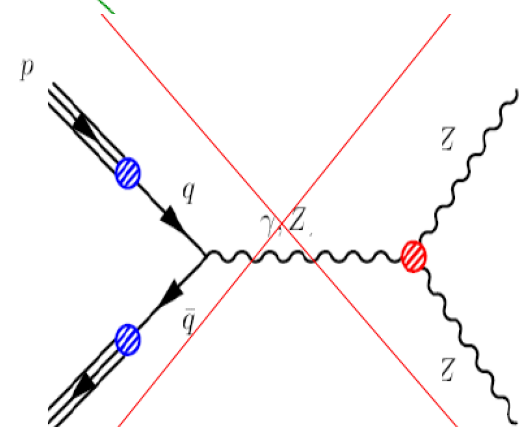
$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$

"bulk" production mode incorporating SM processes and probing high precision QCD/EWK high order calculation via measuring the decay products of bosons



New physics show up via SM boson self-interactions, parameterized by effective lagrangians and effective field theories





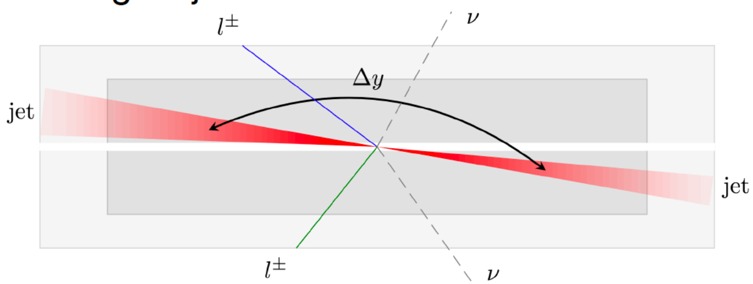
SM tree-level forbidden

First Measurement of W±W±jj Electroweak production with evidence in ATLAS

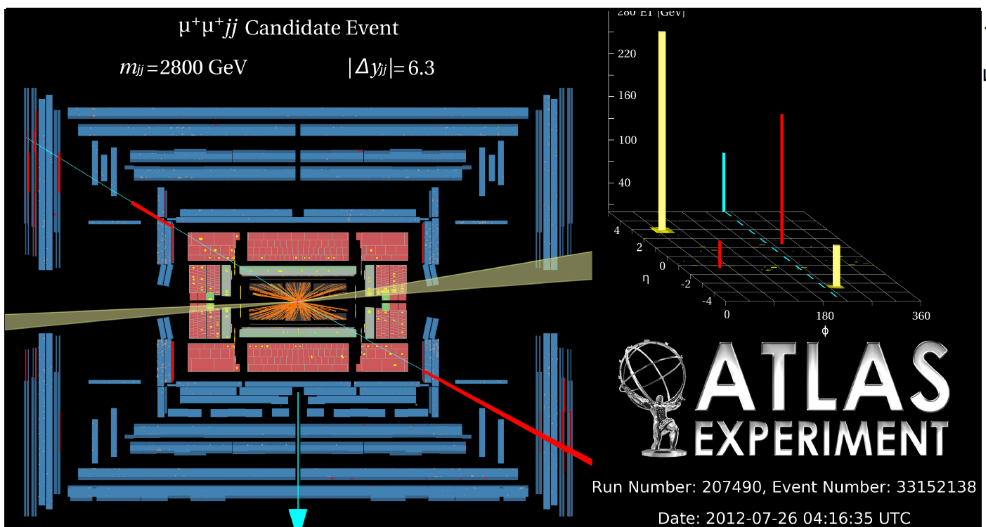
Phys. Rev. Lett. 113, 141803

$$W^\pm W^\pm jj \to \ell^\pm \nu \, \ell^\pm \nu$$

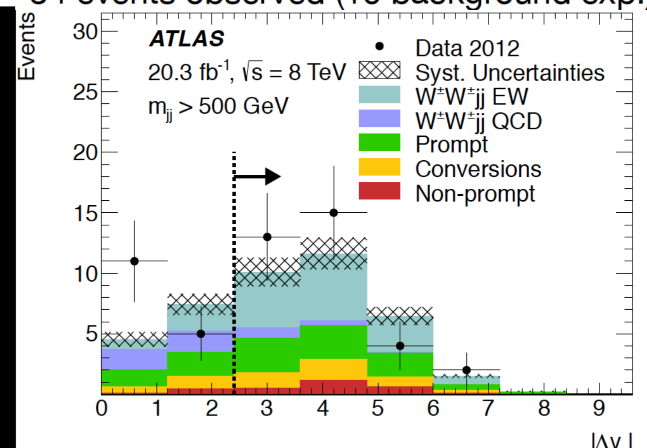
- Presence of two jets in forward regions
- Large dijet invariant mass



Exactly two tight same-electric-charge leptons with $p_T > 25$ GeV
At least two jets with $p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$
$m_{\ell\ell} > 20$ GeV
$E_T^{miss} > 40$ GeV
$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV (only for the $e^\pm e^\pm$ channel)
No third veto-lepton
No identified b-jets with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.5$
$m_{jj} > 500$ GeV
$\lvert\Delta y_{jj}\rvert > 2.4$



34 events observed (16 background exp.)

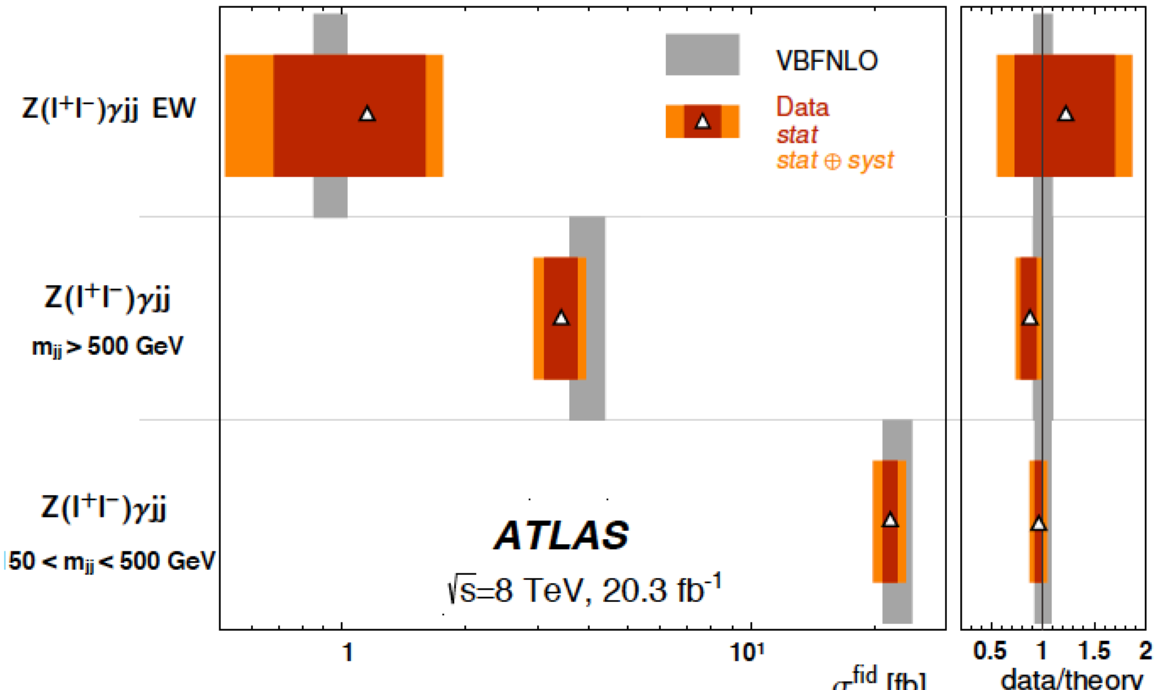


$$\sigma^{fid}_{EW\ W^\pm W^\pm jj} = 1.5 \pm 0.5(stat) \pm 0.2(syst)\ \text{fb}$$

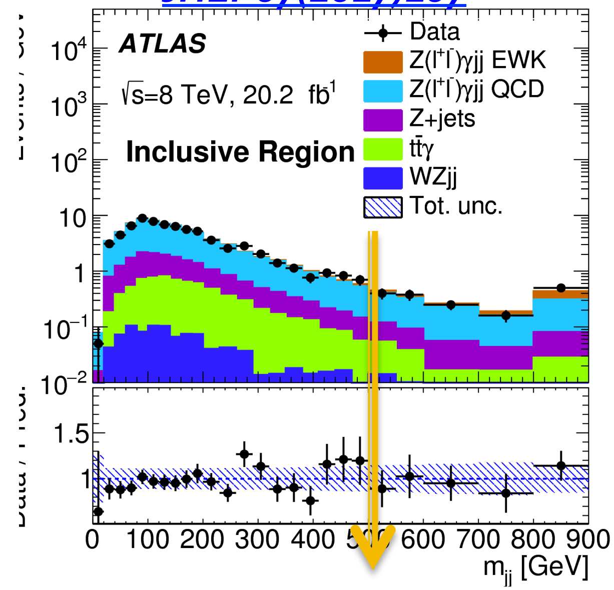
0.95 ± 0.06 fb expected

See 1st 5-sigma observation paper (PRL 120 (2018) 081801) by CMS, ATLAS is coming soon

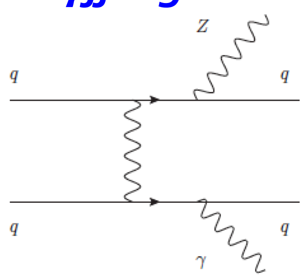
First ever Measurement of Zγ+jj Electroweak production in ATLAS



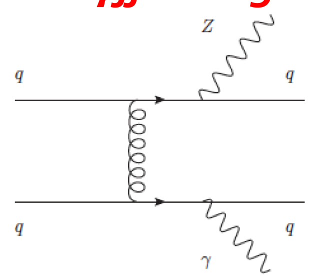
[Zhijun Liang, Shu Li, et al. JHEP07(2017)107]()



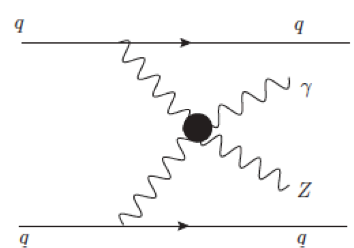
EW Zγjj Signal



QCD Zγjj Background

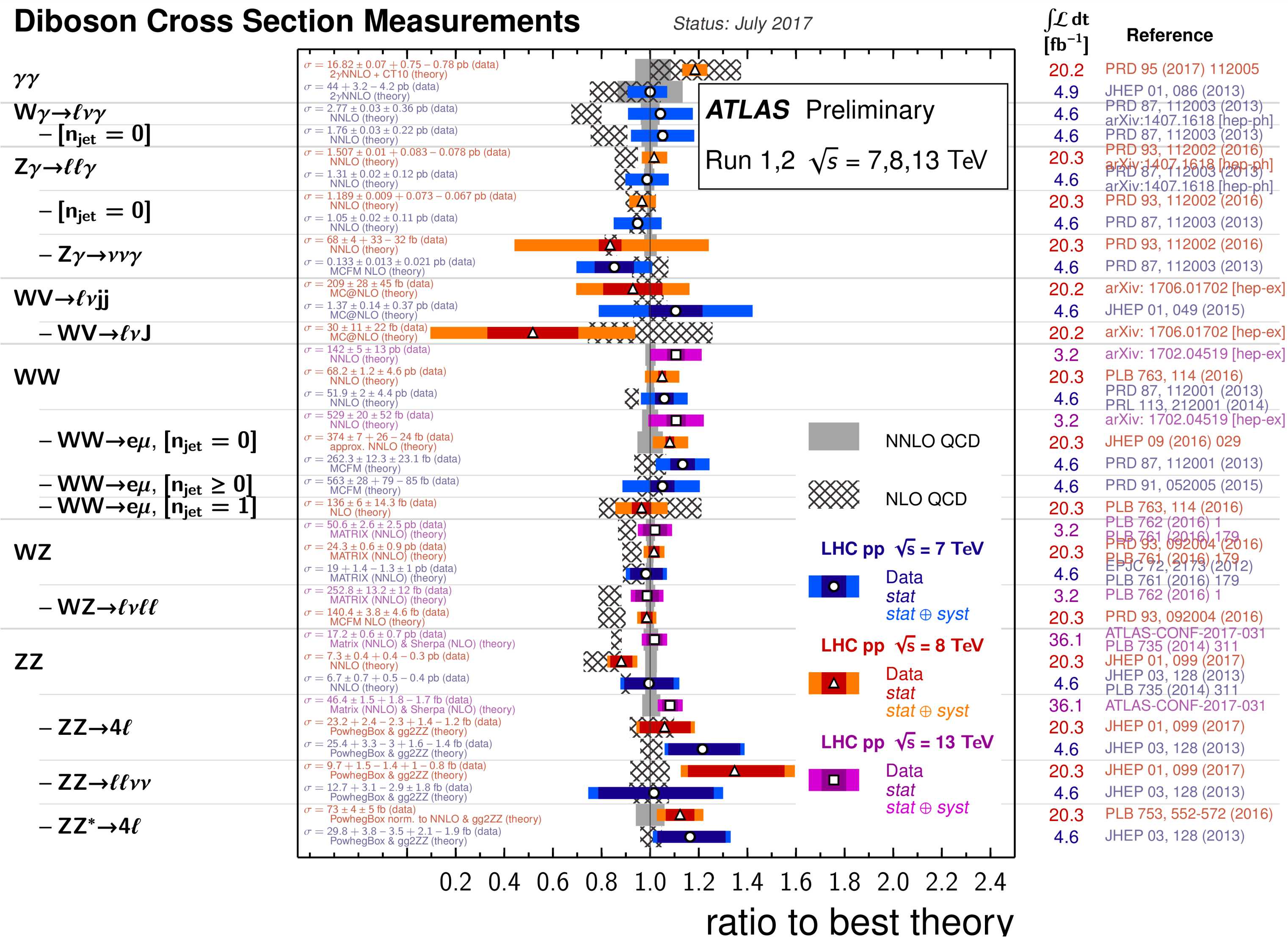


New Physics Vertex (BSM signal)



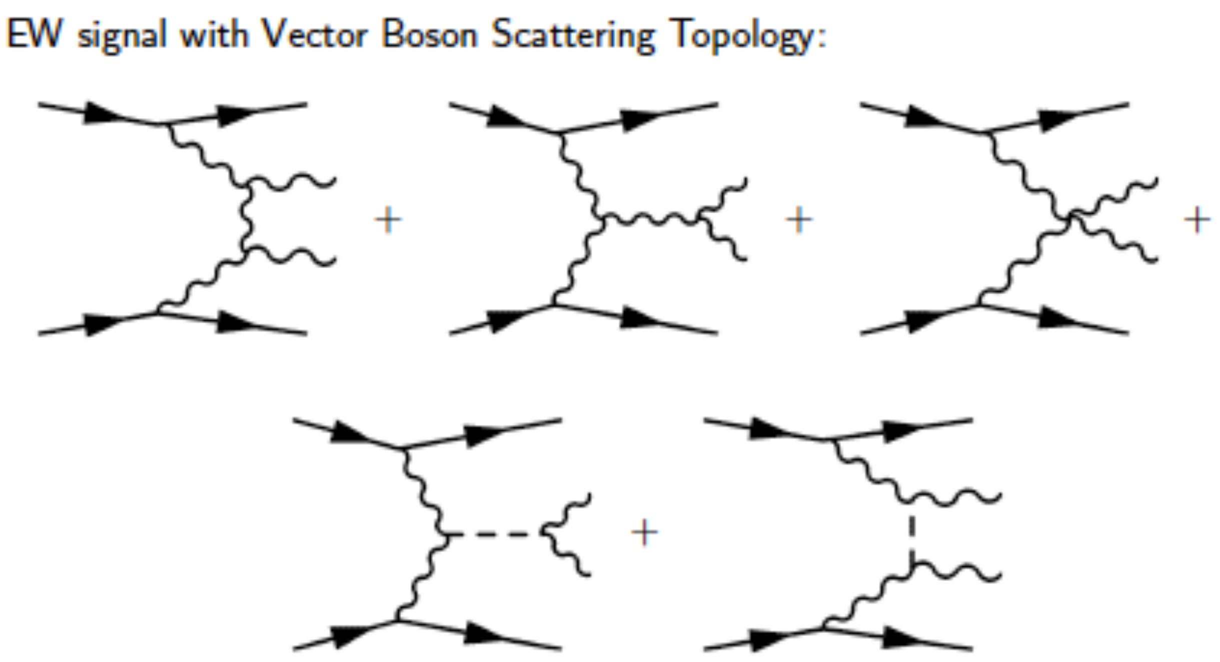
CMS cross-reference: PLB 770 (2017) 380

Summary of Diboson measurements



EFT with dim8 operators I

- Assuming Higgs boson belongs to a $SU(2)_L$ doublet
- dimension 8: the lowest dimension operators exhibiting quartic couplings in VBS but NOT in two or three gauge boson vertices



EFT with dim8 operators II

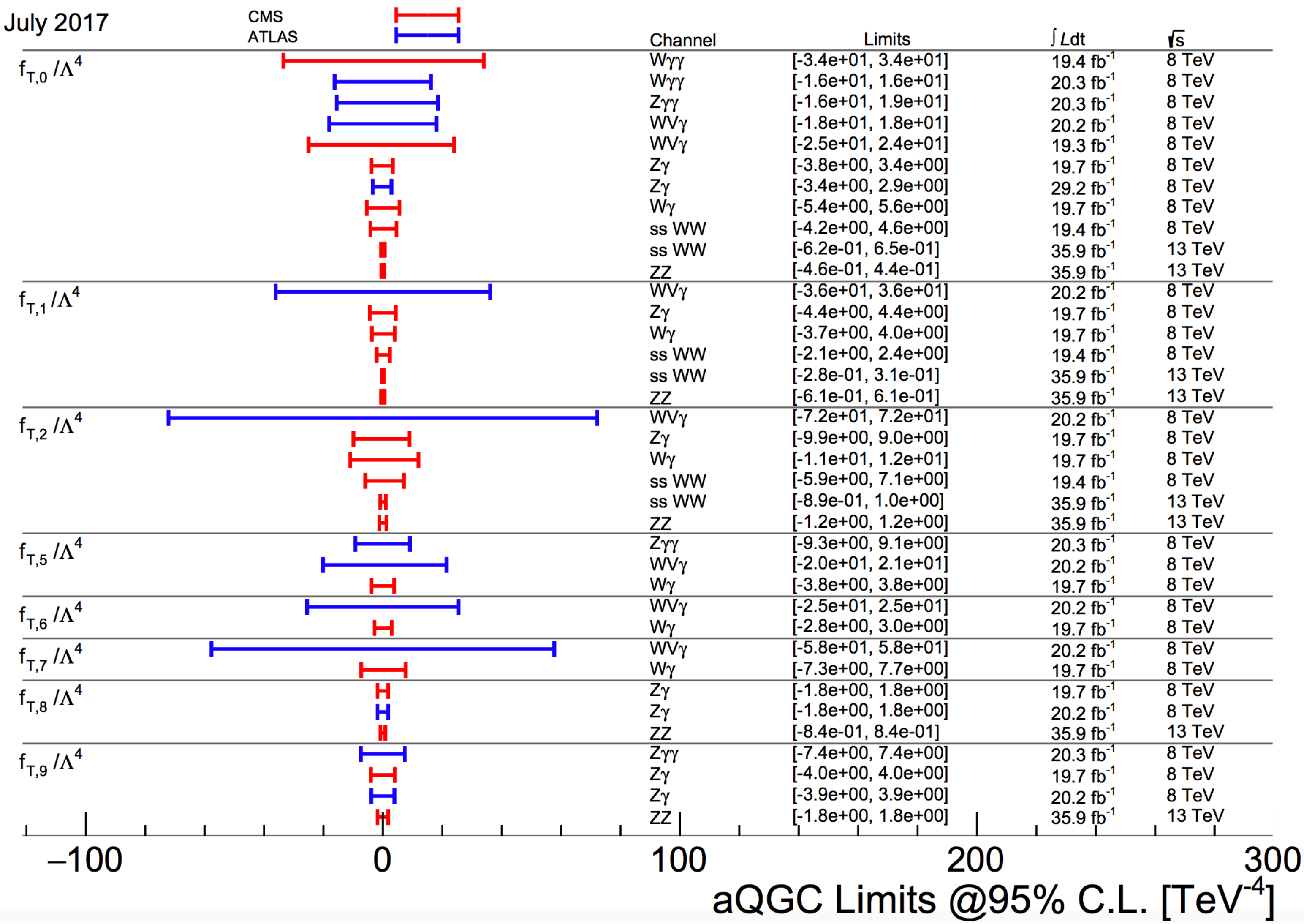
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \qquad \mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\begin{aligned}
\mathcal{L}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{L}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{L}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \\
\mathcal{L}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \\
\mathcal{L}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{L}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{T,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \\
\mathcal{L}_{T,1} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \\
\mathcal{L}_{T,2} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \\
\mathcal{L}_{T,5} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,6} &= \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \\
\mathcal{L}_{T,7} &= \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \\
\mathcal{L}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{L}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}
\end{aligned}$$

- Currently available dim8 operators in MadGraph
  - LS0,LS1: wwjj, wzjj, zzjj
  - LM0,LM1: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz,zzz
  - LM2,LM3: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz, zzz
  - LT012: wwjj, wzjj, zzjj, wajj, zajj, waa, wwa, zaa, zza, www, wwz, zzz
  - LT8,LT9: zzjj, zajj, zaa, zza, zzz

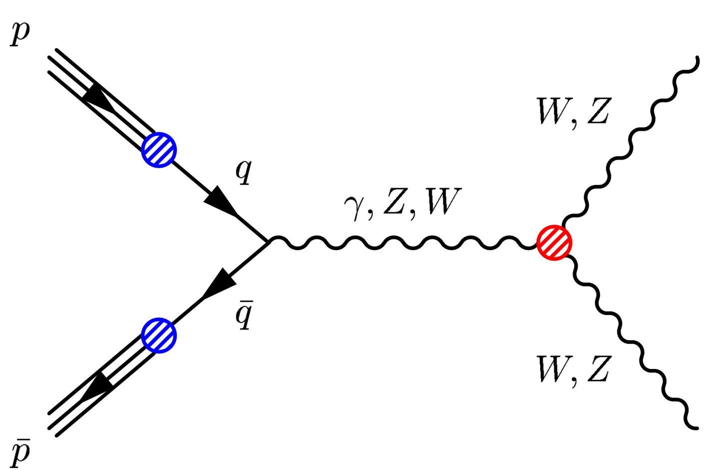
Current limits on the aQGCs

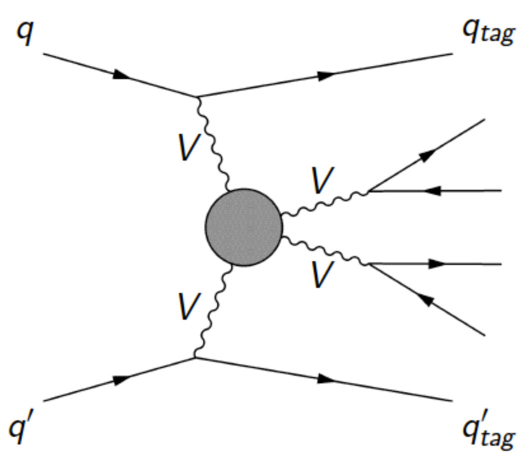


BSM physics methodology

Two general ways:

- ***Direct search of new particles***
- ***New interactions of known particles of SM***
  - Traditional anomalous coupling framework
  - Effective field theory approach



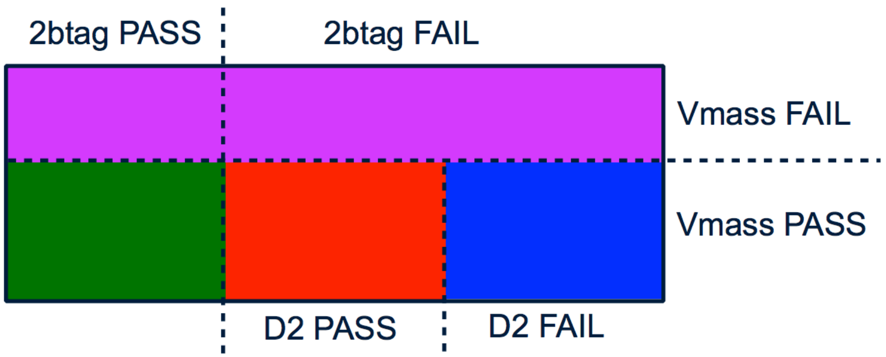


Di-boson resonance search

- Vast range of decay channels and various experimental signature categories to explore
  - WW: lvlv, lvqq, qqqq
  - WZ: lvll, lvqq, llqq, qqqq
  - ZZ: llll, llvv, llqq, qqqq, vvqq
  - VH: see Jun Guo's talk previously
  - Vγ/Hγ: see following slides
  - Experimental signature of the "merged" outgoing jets from boson decays: large-R jets (boosted jets)
  - Spin property, polarization effect
- Many inspiring models and effective theory interpretations: HVT, RS graviton, 2HDM, etc.
- Largely overlap the Higgs searches and SM measurements with similar final states

2015+2016 Event selection and categorization

- Baseline selection
  - high p_T photon trigger: HLT_g140_loose
  - Preselection: GRL + LooseBadJet cut on Resolved jets
  - At least one photon in barrel calorimeter ($|\eta|<1.37$)
  - 1 Tight Photon in the barrel & 1 Fat Jet (anti-kt R=1.0)
  - Jet and photon OR: $\Delta R(\text{jet}, \gamma) > 1.0$



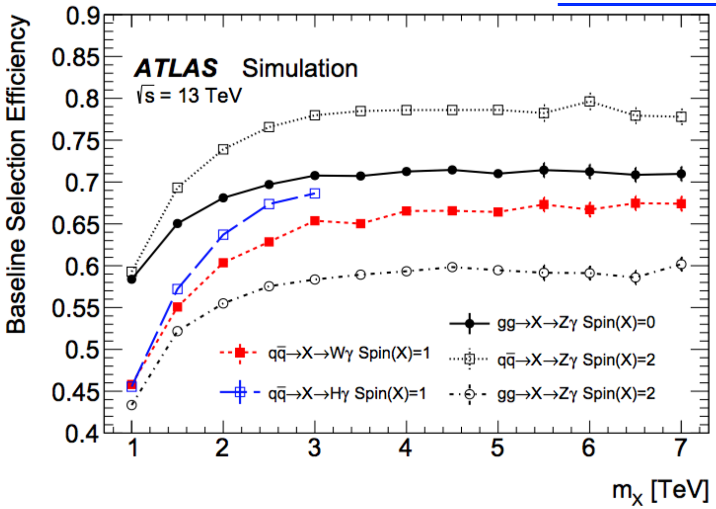
- Categorization:
  - Zγ: btagged, D2, Vmass, else
  - Wγ: D2, Vmass, else
  - Hγ: btagged
  - Note: "Else" recover high mass eff.
  - Note: only H→bb is considered

[Bo Liu, Zhijun Liang, Shu Li, et al arXiv:1805.01908]

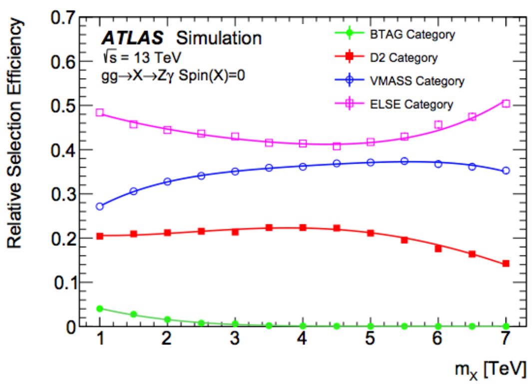
2015+2016 signal efficiency review

Baseline selection efficiency

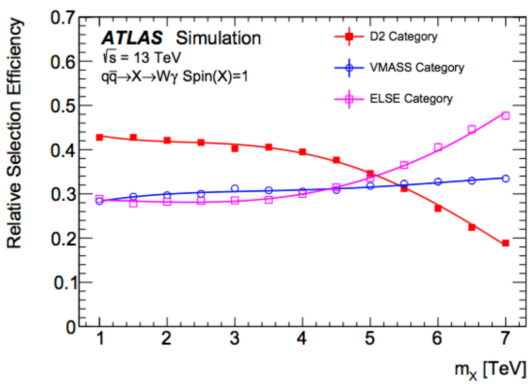
[Bo Liu, Zhijun Liang, Shu Li, et al. arXiv:1805.01908]



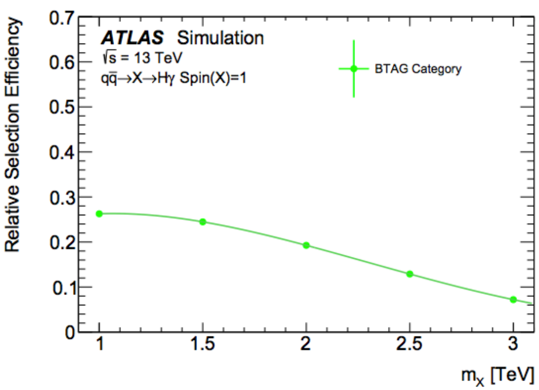
Zγ spin-2



Wγ spin-1

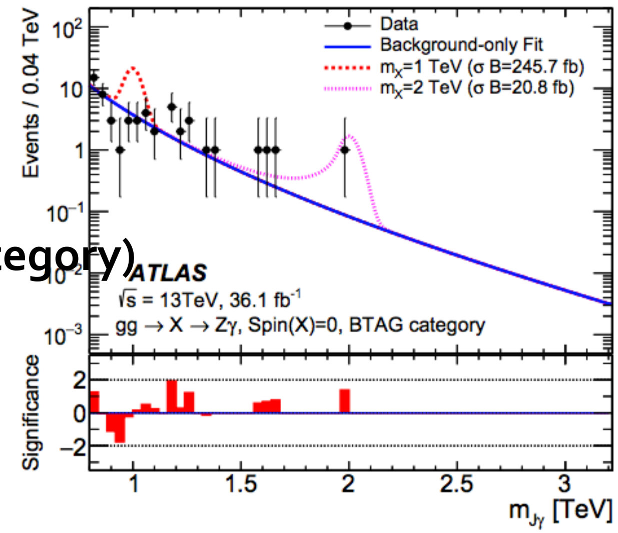


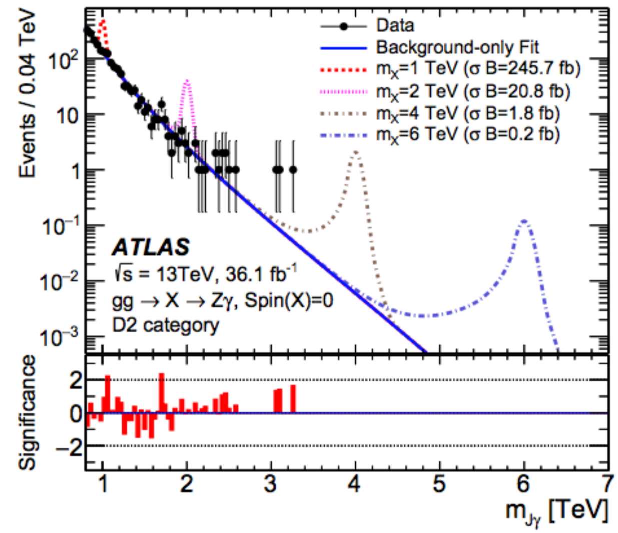
Hγ spin-1



2015+2016 Zγ mass spectra (spin-0)

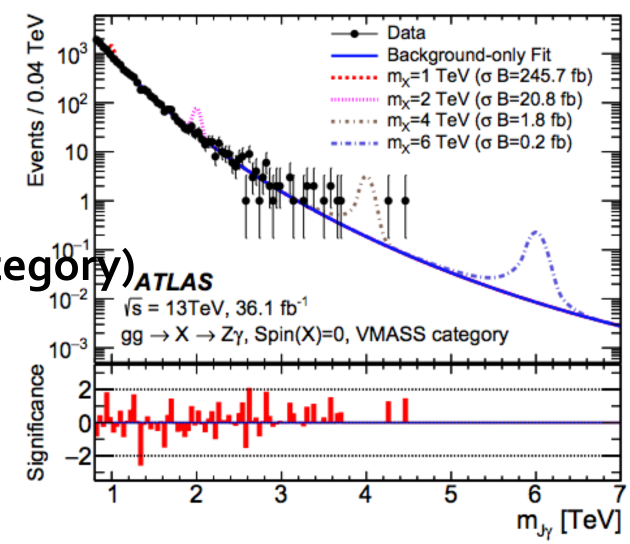
Zγ
(btagged category)

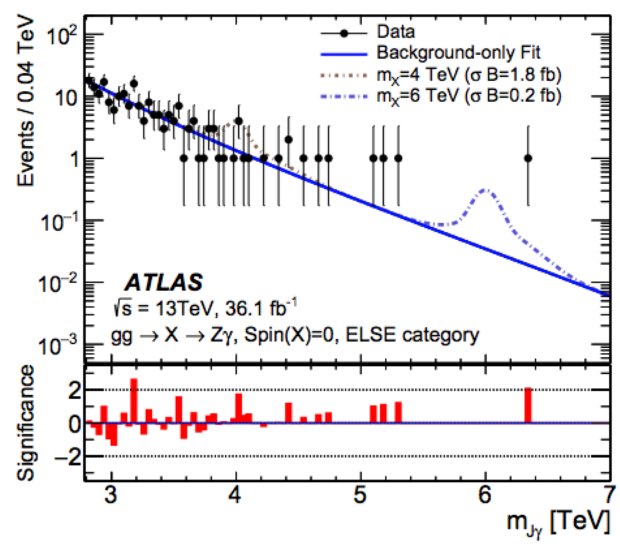




Zγ
(D2 category)

Zγ
(Vmass category)

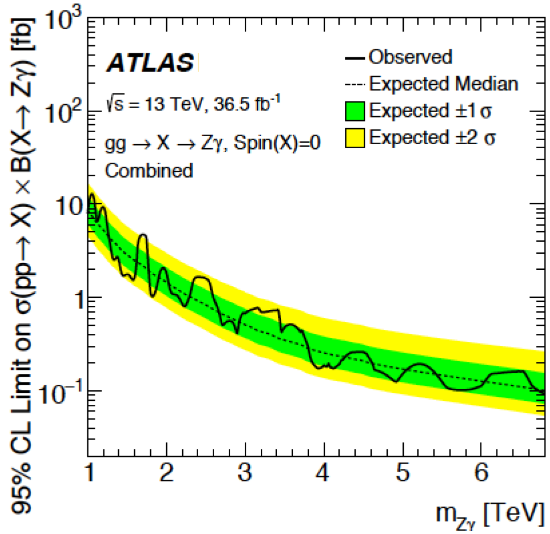


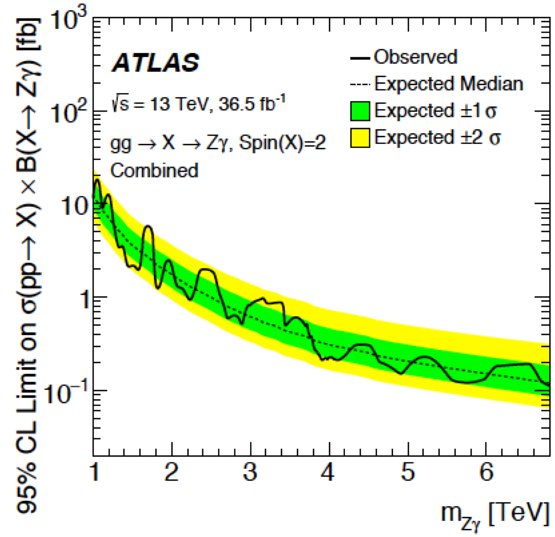


Zγ
(else category)

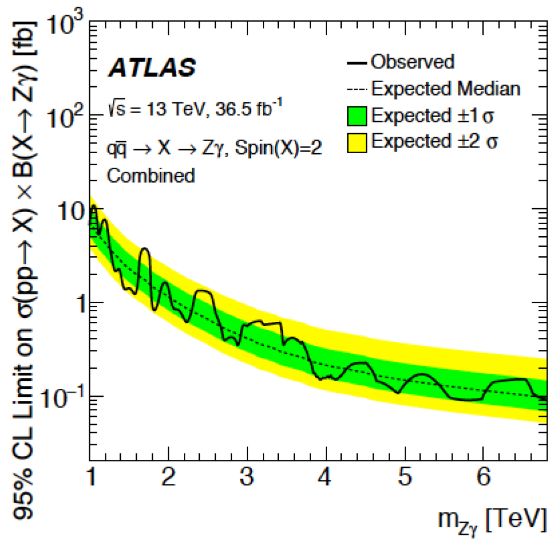
2015+2016 Zγ limits

gg→Zγ
spin-0





gg→Zγ
spin-2

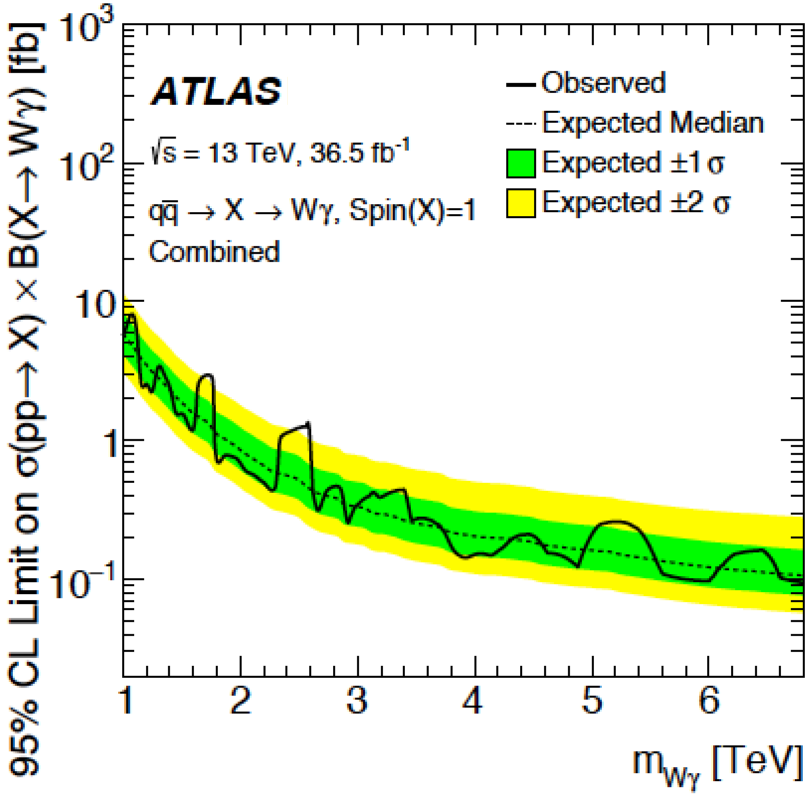


qq→Zγ
spin-2

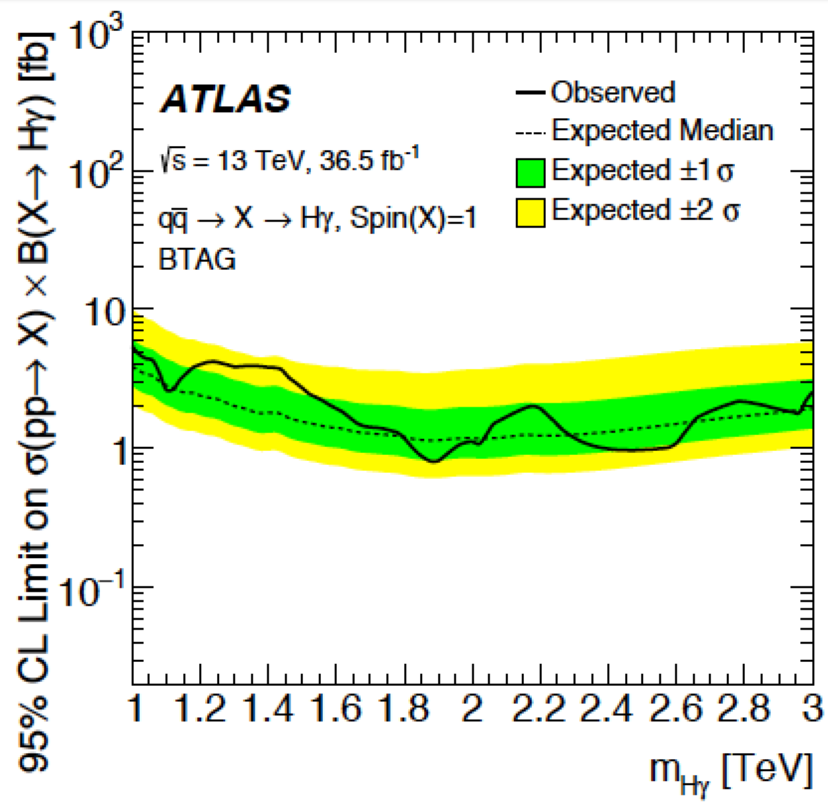
arXiv:1805.01908
ATLAS Physics Briefing [link]

2015+2016 Wγ and Hγ limits

Wγ (combined limits)



Hγ (combined limits)



arXiv:1805.01908

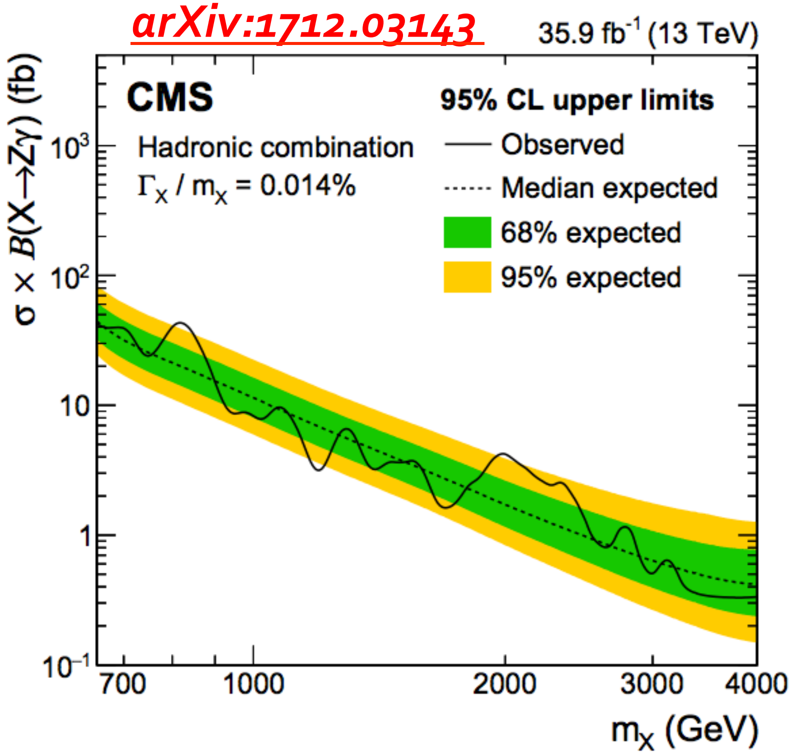
ATLAS Physics Briefing [link]

1st ever Hγ resonance search limits at LHC

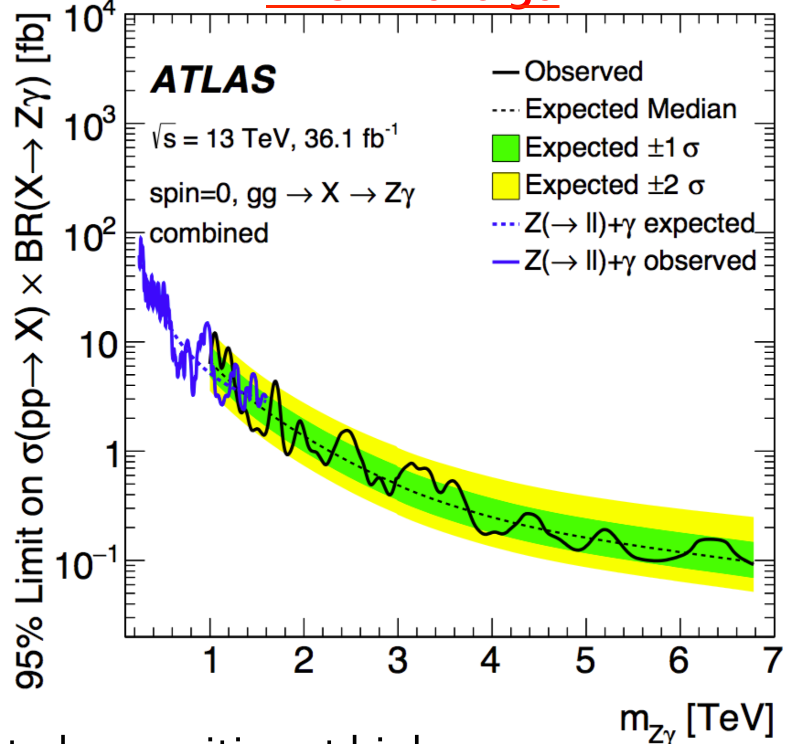
CERN 2018 Physics Briefing highlight

Reminder: High mass resonance search in X->Zγ final states, leptonic vs hadronic

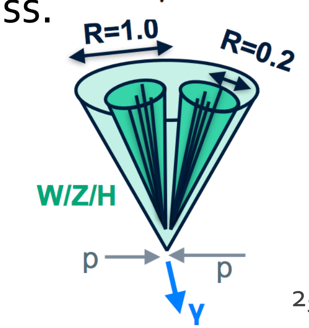
arXiv:1712.03143



EXOT-2016-30

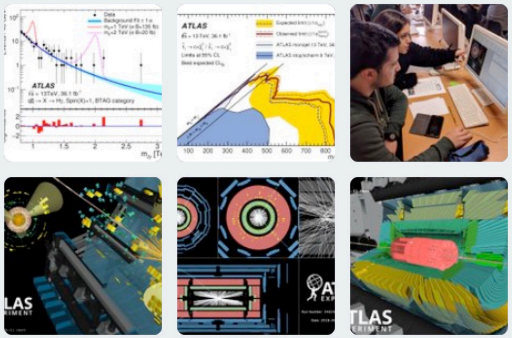


- The hadronic V/H+γ search analysis is designed to be sensitive at high mass.
    - Cross point of leptonic vs hadronic Zγ: m(X)~1.5TeV.
- The 2016 analysis of hadronic channel makes use of categorization in combination of btagged category to enhance the low mass sensitivity
    - W/H+γ channels are done for the 1st time!



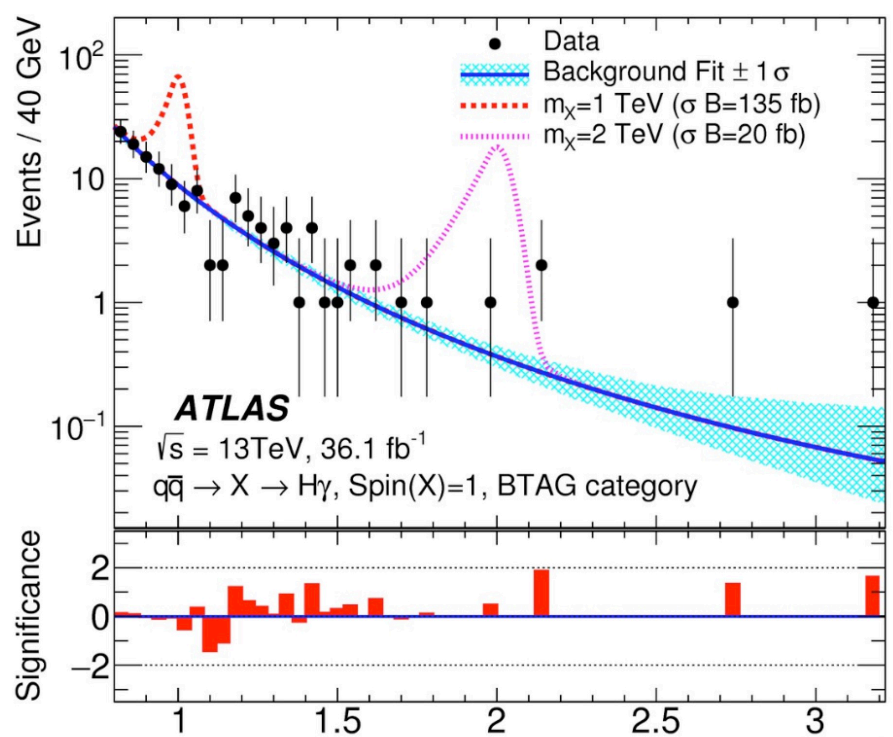
Physics Briefing highlight

882 Photos and videos



ATLAS Experiment @ATLASexperiment · 53m

[Physics Briefing] Searching for forces beyond the Standard Model: a new ATLAS measurement extends searches for new bosons up to masses about 70 times the mass of the Z boson. Find out more: cern.ch/go/p9Zj



arXiv:1805.01908

ATLAS Physics Briefing [link]

ATLAS Official twitter highlight [link]

Summary

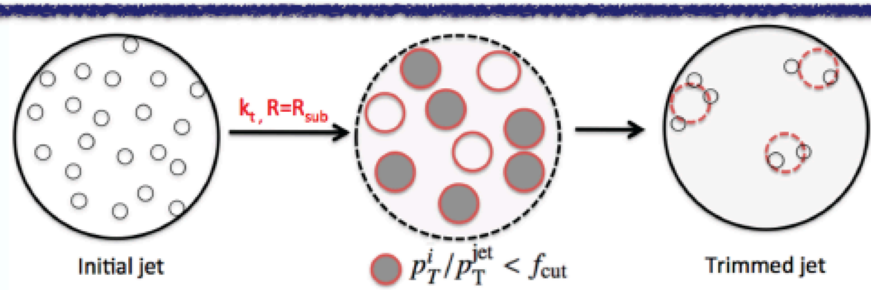
- Multi-boson interactions are one of the most sharpened signatures to measure and explore because of so much topical items break into the particle physics foundations
  - Solid validation of SM predictions and high precision/high order calculations of the SM boson coupling and interactions
  - Substantiate the findings of new physics signatures which decay into SM bosons: irreducible backgrounds
  - Effective theory parameterization platform incorporating new physics inducing SM anomalous interactions

- Many Fruitful Run-I/II achievements in SM multi-boson production measurements and searches. Surely will be a continuous hotspot to explore further in a new Center-of-Mass energy era at ATLAS/LHC

Spare

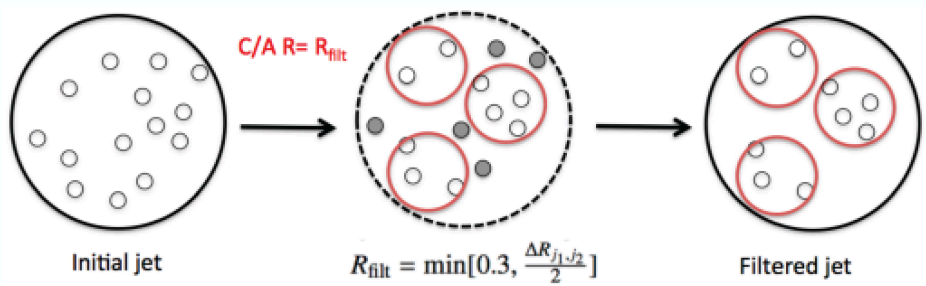
- Energy depositions in calorimeter are grouped into topological clusters, which are used to form large-R jet (R=1.0, anti-kt) JHEP09 (2013) 076

Trimming



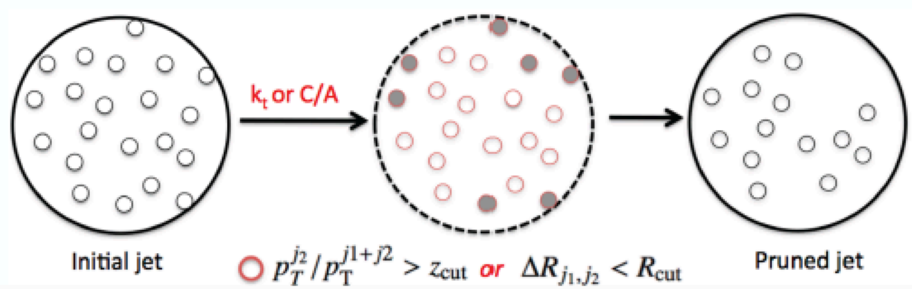
Compares pT(constituents) with pT(jet) – removes soft components which are primarily from UI & PU

Filtering



Remove constituents that are outside of subjets

Pruning



Similar to trimming but occurs during jet reconstruction ⇒

does not require subjet reconstruction

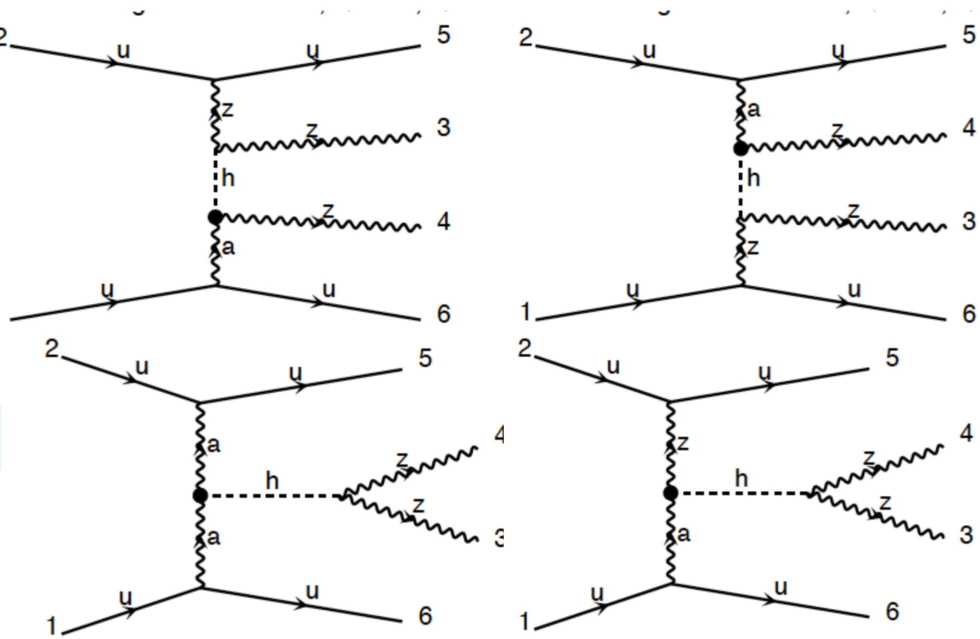
EFT with Dim6 operators II

- We choose to test dim6 operators unique to VBS
- Not constrained by inclusive diboson
- Fully gauge invariant

$$\mathcal{O}_{\phi d} = \partial_{\mu}\left(\phi^{\dagger}\phi\right)\partial^{\mu}\left(\phi^{\dagger}\phi\right)$$

$$\mathcal{O}_{\phi W} = \left(\phi^{\dagger}\phi\right)\mathrm{Tr}[W^{\mu\nu}W_{\mu\nu}]$$

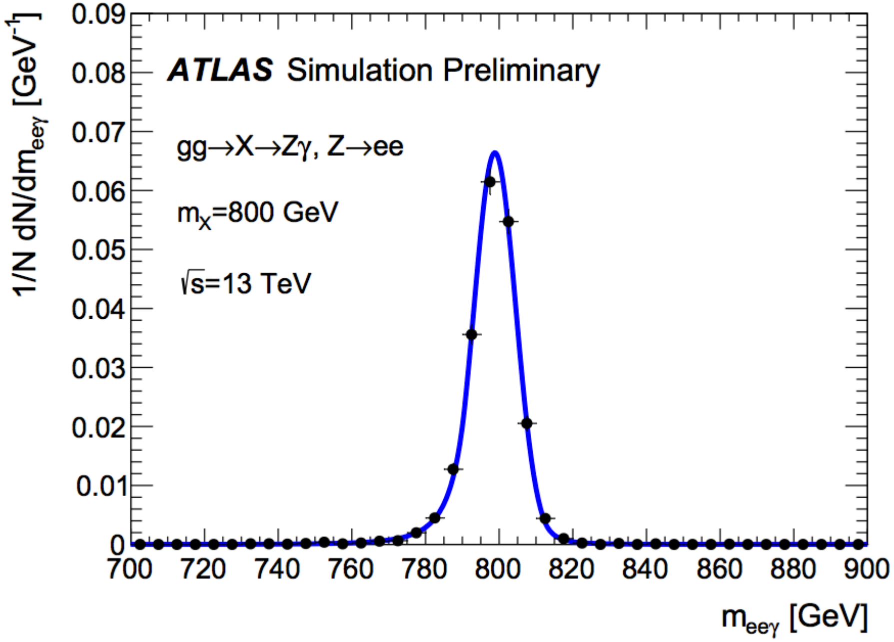
$$\mathcal{O}_{\phi B} = \left(\phi^{\dagger}\phi\right)B^{\mu\nu}B_{\mu\nu}$$

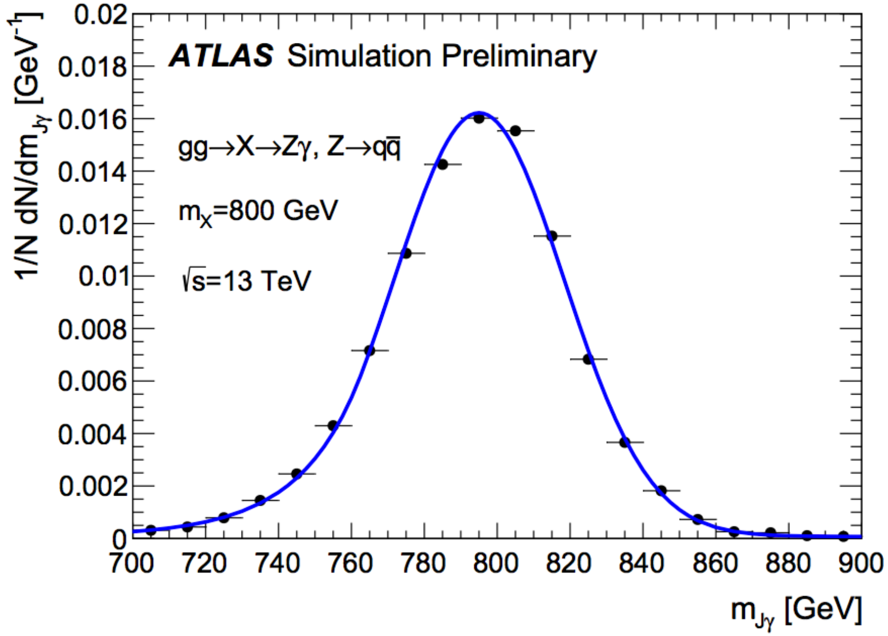


New physics (NP) on TGC vertices

Signal modeling

ATLAS-COM-CONF-2016-008

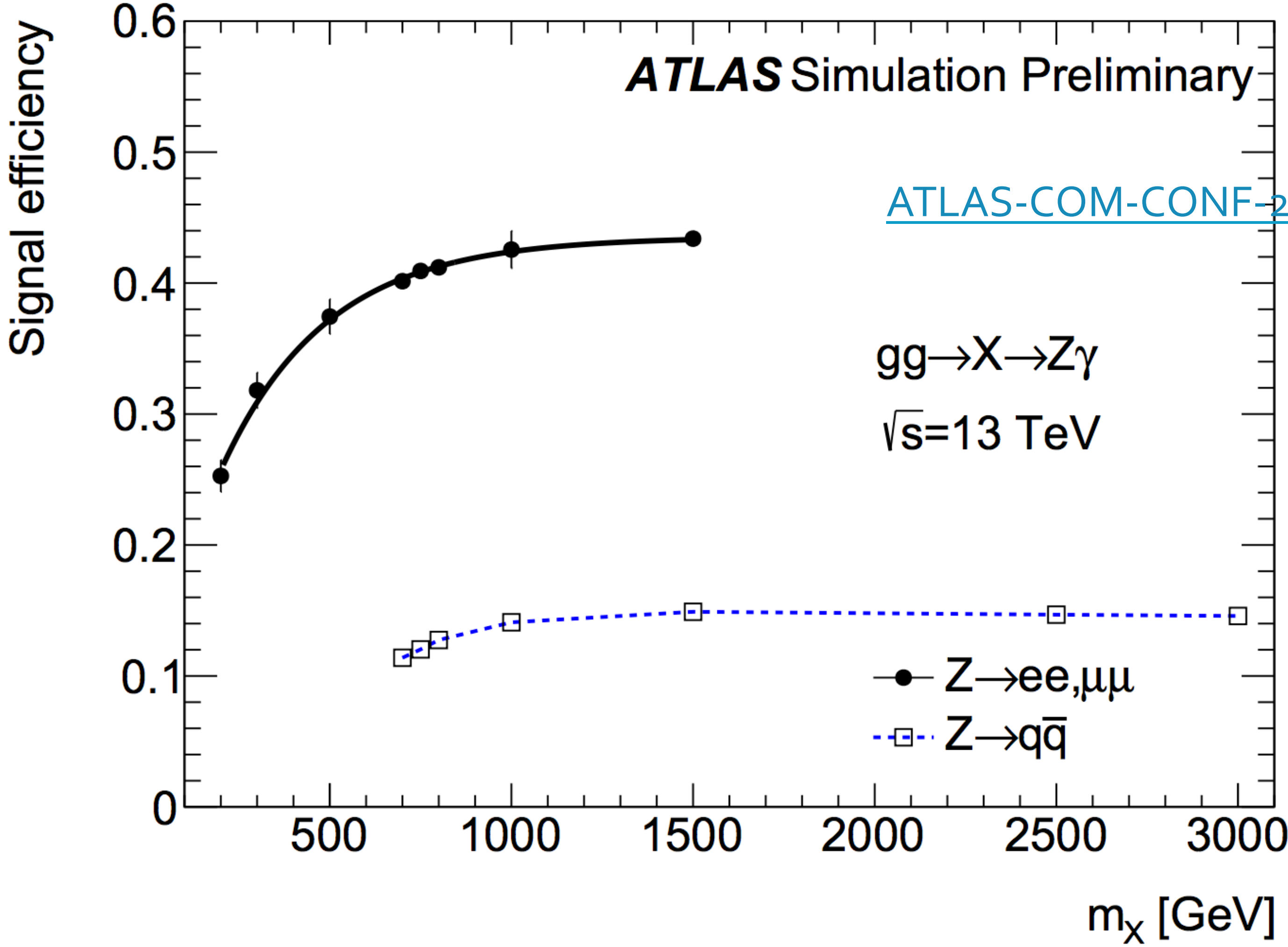




Signal invariant mass distribution of Z→ll and Z→J
Parametrised with analytical function: double-sided CB for leptonic channel and Crystal Ball (CB)+Gaussian for hadronic channel

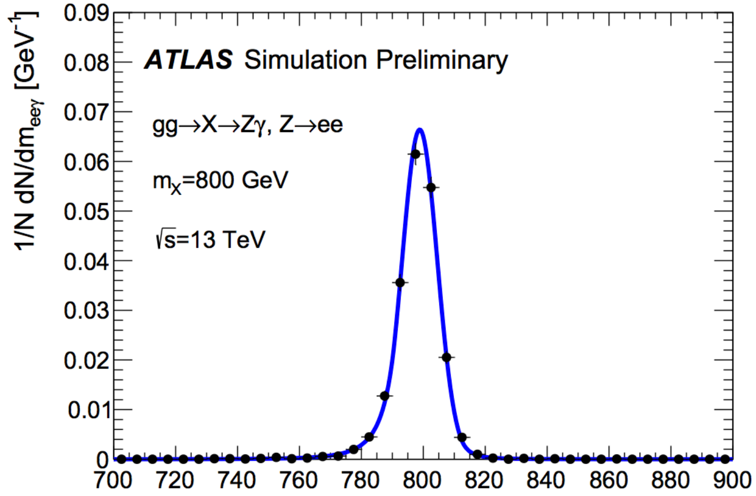
$m_{ll\gamma}$ resolution ~1%; $m_{J\gamma}$ resolution between 3% GeV for m_X = 750GeV and 1.7% for m_X = 3 TeV

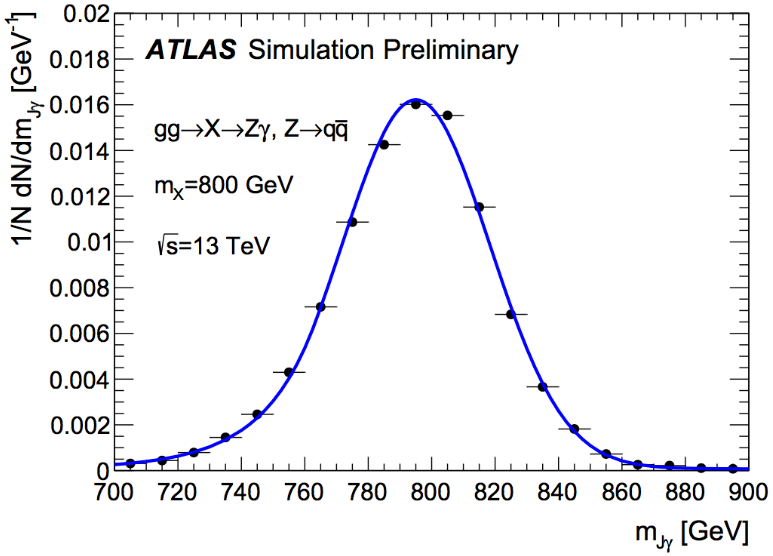
Signal efficiency comparison between two channels



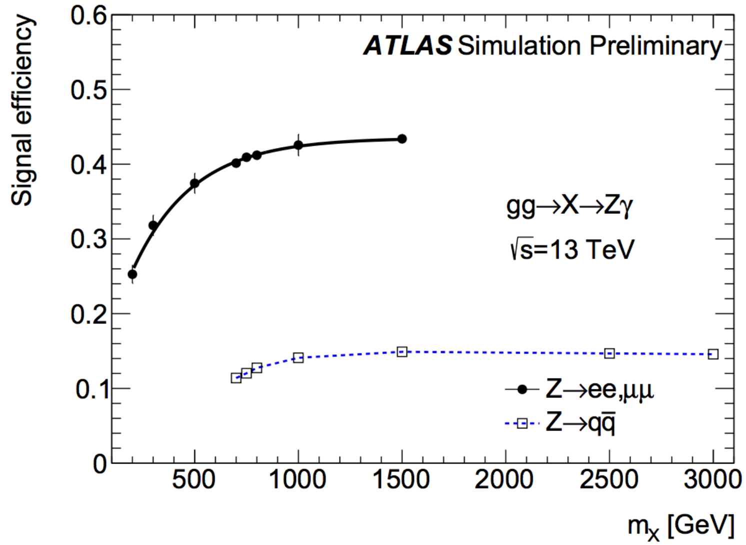
ATLAS-COM-CONF-2016-008

Signal modeling and acceptance difference





Boosted Hadronic channel relies on Jet Substructure cuts and can afford lower effciencies as motivated by higher signal production rate and worse background contaminations as well as worse detector resolutions



Background fit

Background is measured through a max-L fit of data with a suitable parametric form on M(Jg)

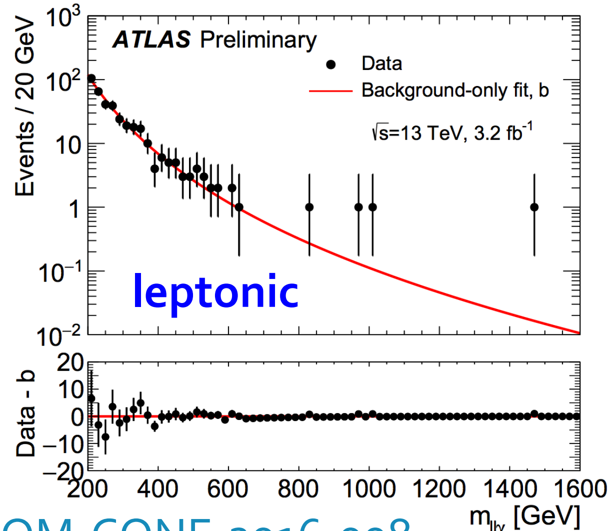
Hadronic $p_1(1-x)^{p_2+\xi p_3} x^{p_3}$

Leptonic $(1-x^{1/3})^b x^{a_0}$

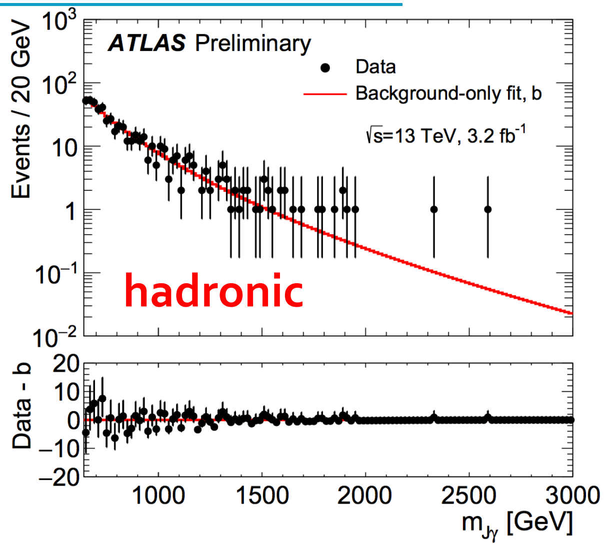
Hadronic:
Tested with high stat. γ+jets MC events. (other bgd verified by MC to be negligible: j->γ, ttγ+X, SM Vγ)

Leptonic:
High statistic SM Zγ and Zjets

Fit range:
Hadronic: [640, 3000]GeV, 20GeV-binned
Leptonic: [200, 1600]GeV, 20GeV-binned

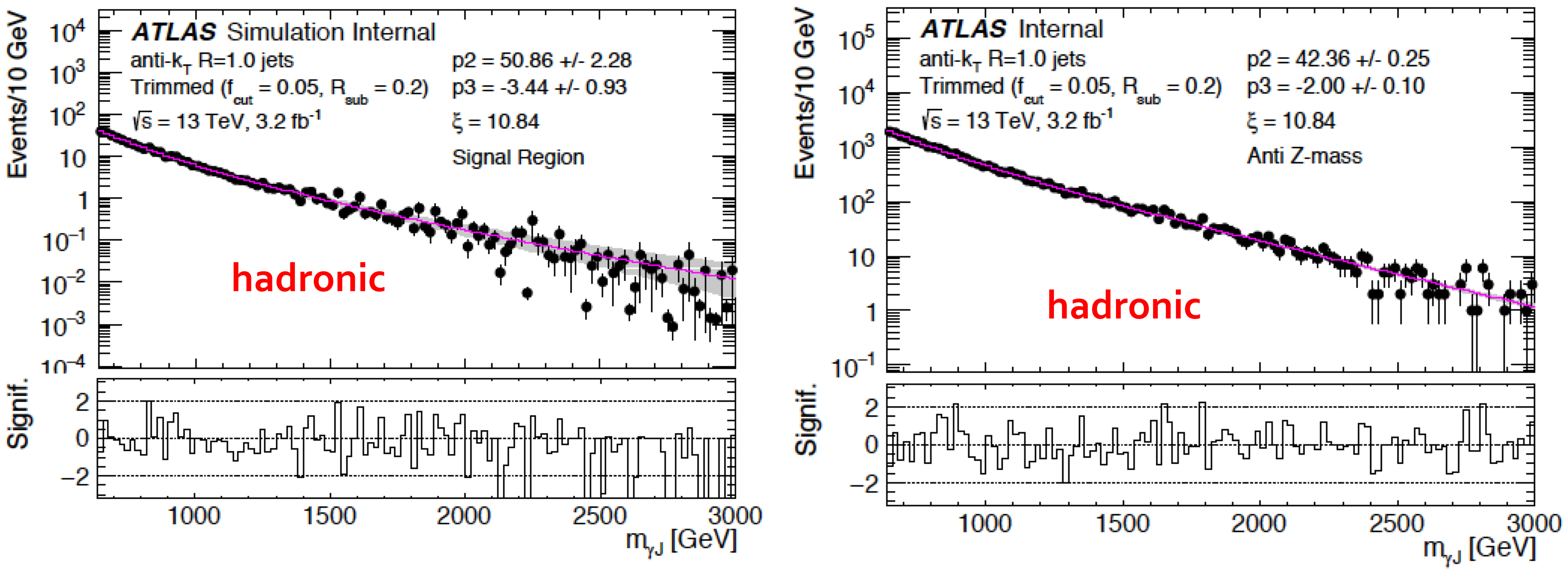


ATLAS-COM-CONF-2016-008



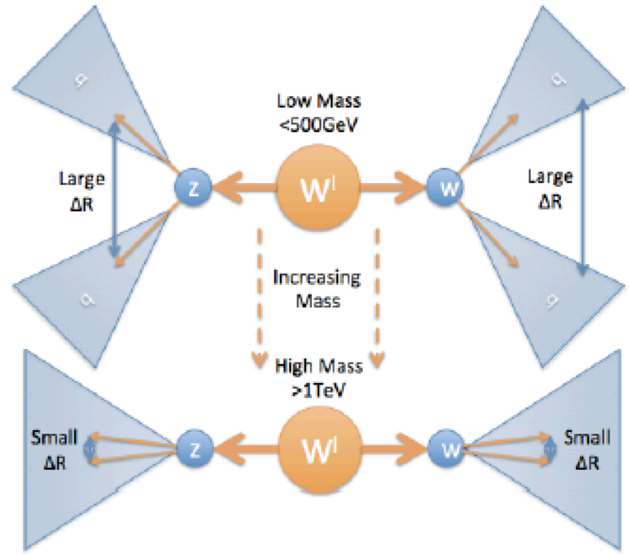
Background fit: validation in CR

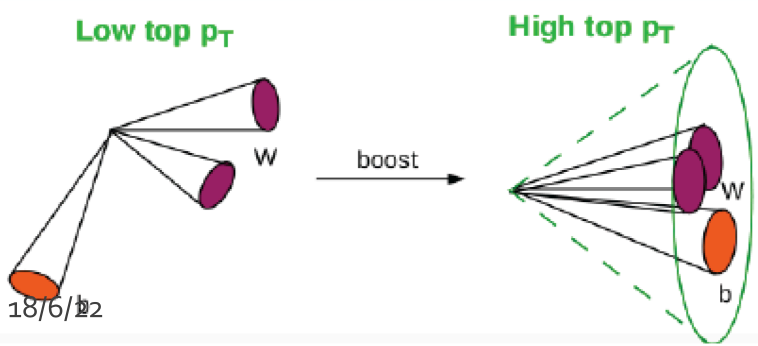
The background model is tested against a data $m_{\gamma J}$ distribution for events in a validation region
(i.e. Using the signal region requirements except the Z jet mass window cut being vetoed.)



Boosted topology and experimental signature

- "Natural" angular separation $\Delta R \sim 2m/p_T$
- Resolved regime: the boson has relative low momentum in the lab frame so we are able to reconstruct one jet for each quark
- Boosted Regime: the boson has high momentum in the lab frame - the outgoing quarks are very close so the jets begin to merge

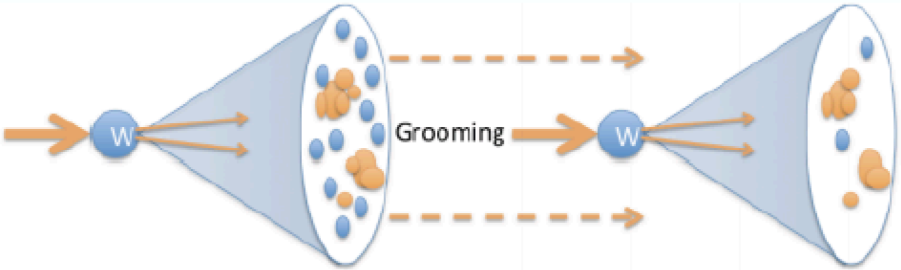




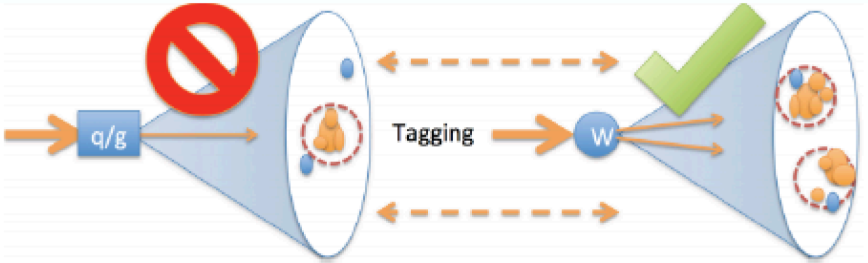
Traditional reconstruction techniques relying on one-to-one jet-to-parton assignment are inadequate

Boosted tagging techniques

1. Large-R jet: large distance parameter to pick up all the radiation from the original decay
2. Grooming (different techniques available):
   - Signal: take out jet constituents that don't belong to the signal decay
   - Background: preserve background characteristics in the jet

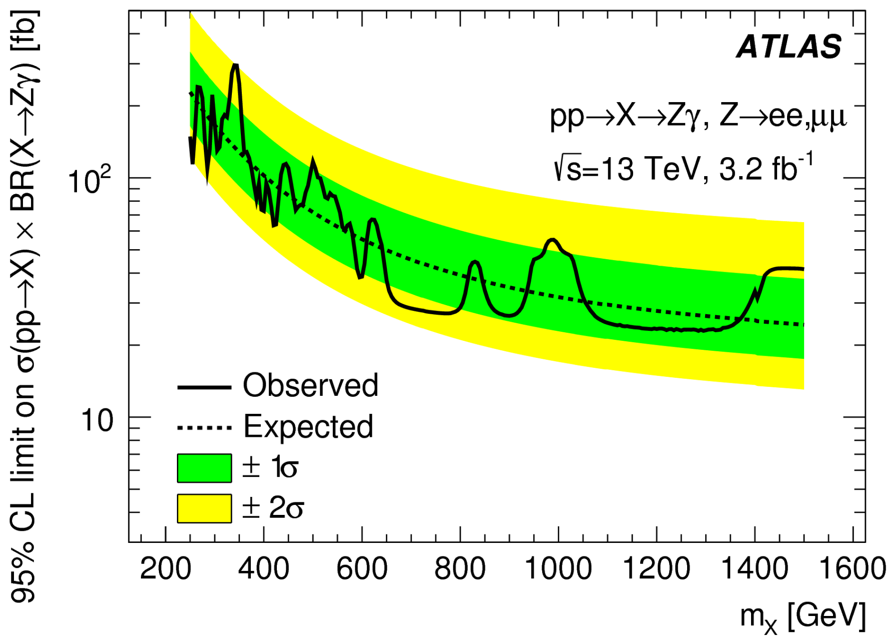


3. Tagging:
   - Use differences in signal and background jet characteristics to reject background jets

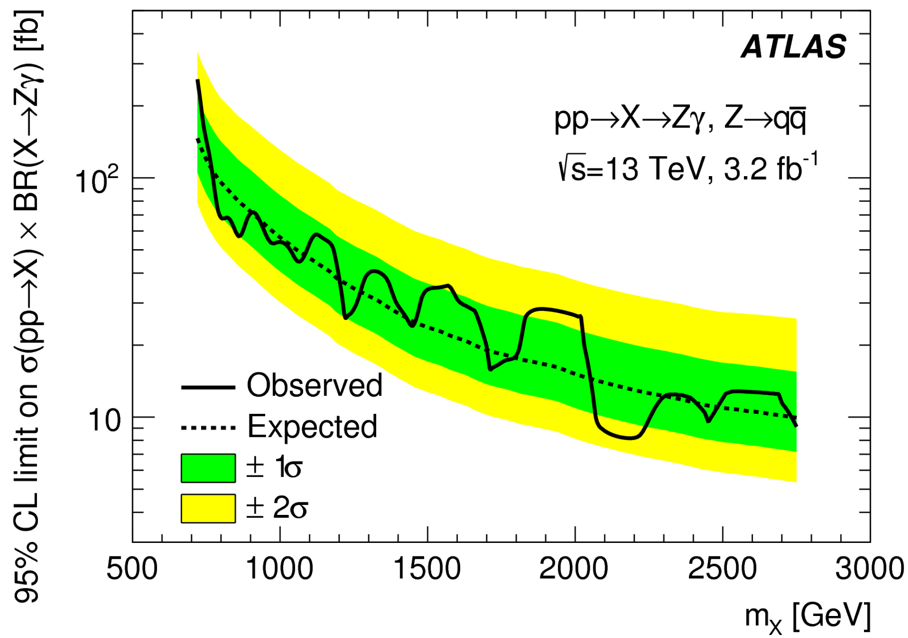


2015 limits on σ(X→Zγ)

leptonic analysis



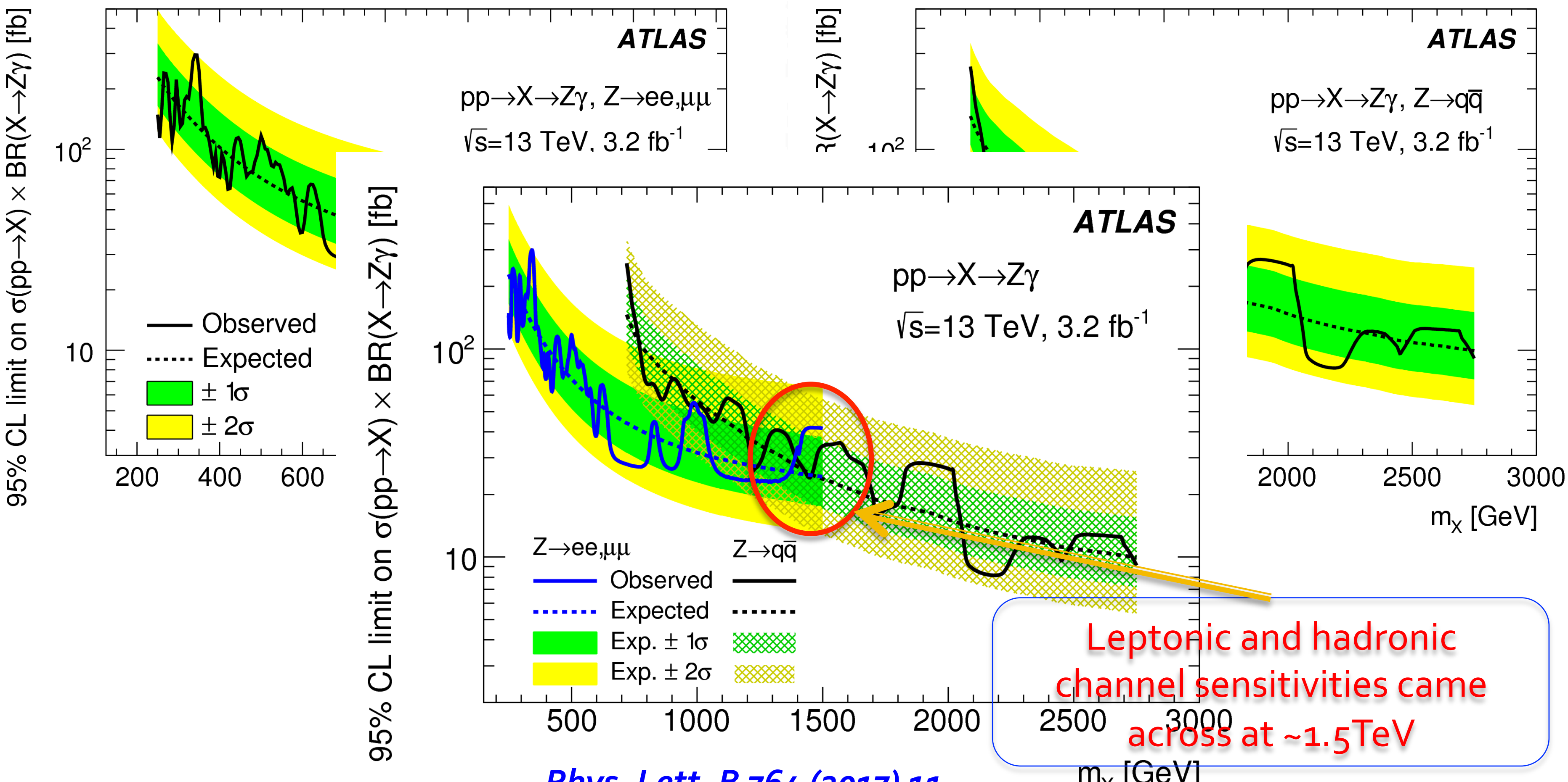
hadronic analysis



Expected limits [230, 10] fb from m_X =250 GeV to m_X =2.75 TeV
Observed limits [295, 8.2] fb from m_X = 340 GeV to m_X = 2.15 TeV
@750GeV: expecting cross section limit ~42 (130) fb and observing ~27 (200) fb for leptonic (hadronic)

2015 limits on σ(X→Zγ): cross point

leptonic analysis hadronic analysis

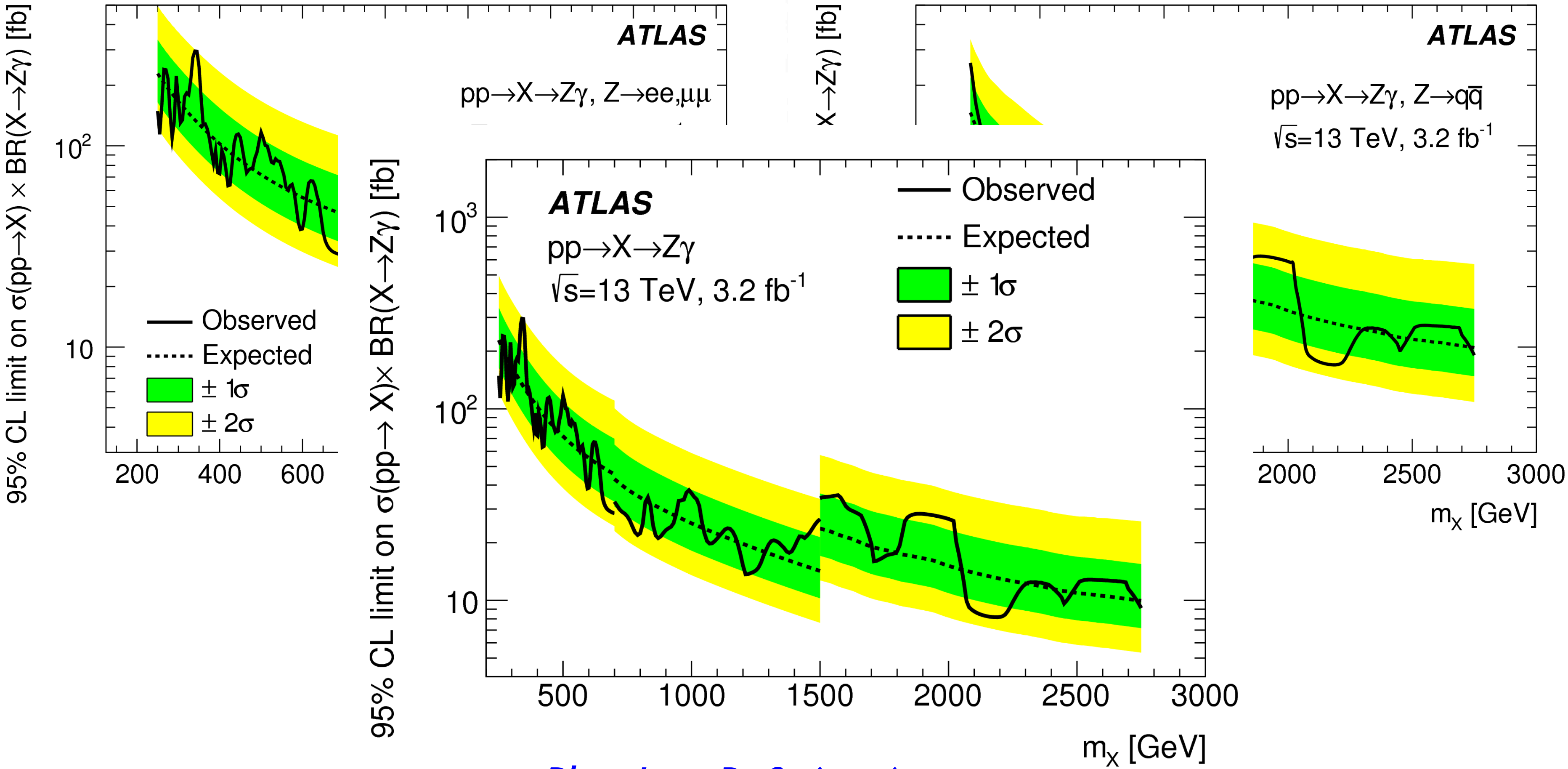


Leptonic and hadronic channel sensitivities came across at ~1.5TeV

[Phys. Lett. B 764 (2017) 11](#)

2015 Combination of limits

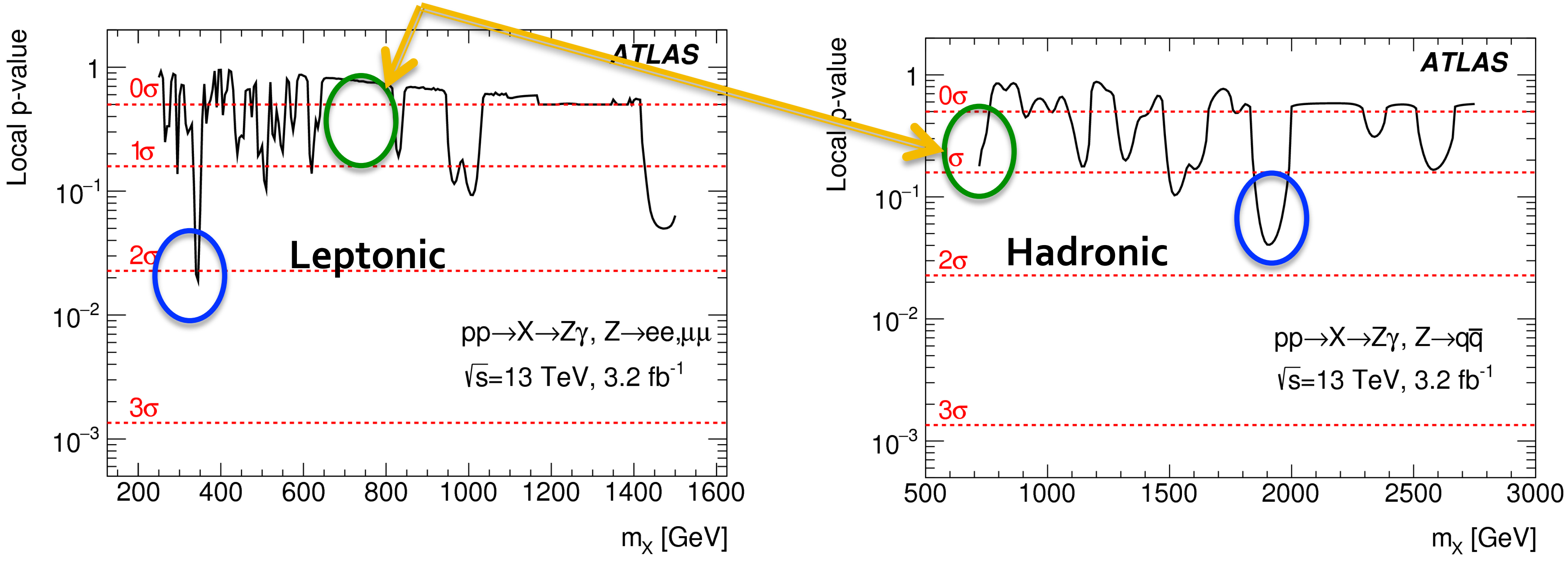
leptonic analysis hadronic analysis



[Phys. Lett. B 764 (2017) 11]

2015 P-values

- Uncapped p-values for the full mass range [250, 2750] GeV
- Maximum local significance within 2σ
  - Largest significance ~2σ at 350GeV and 1.9TeV
  - *No 750 bonus ☺ by now*



[Phys. Lett. B 764 (2017) 11](#)

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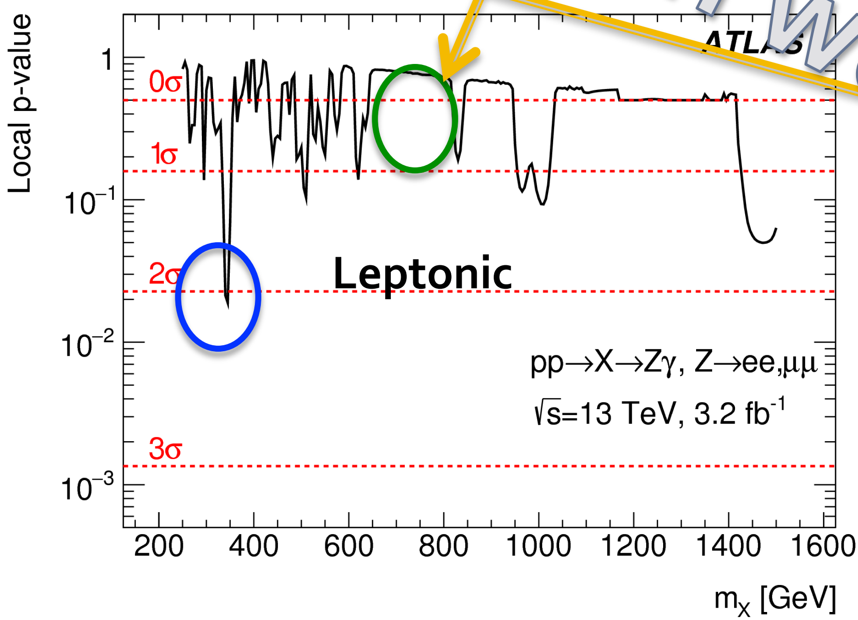
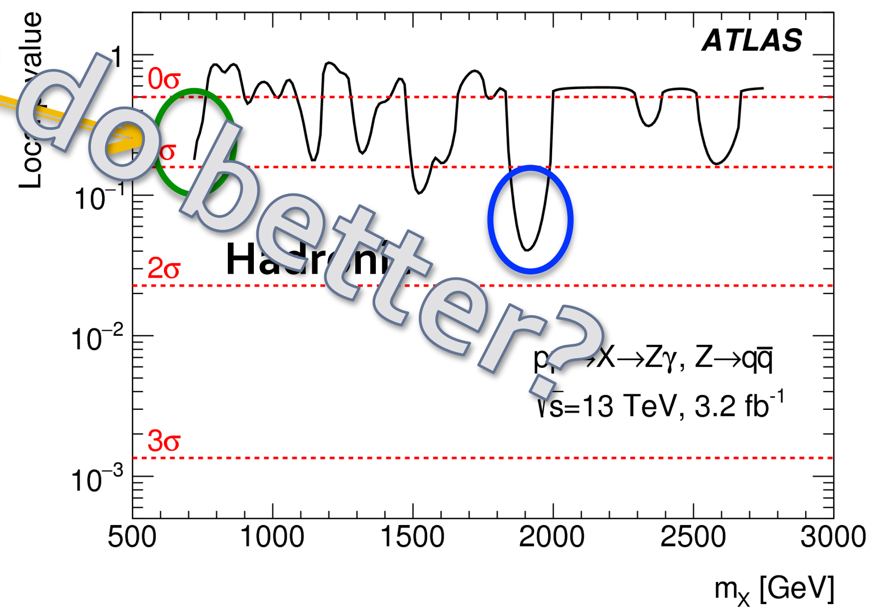
How can we do better?





[Phys. Lett. B 764 (2017) 11]

2015+2016 new BSM interpretations

Signal configuration and modeling

Channel	Generator	Spin	Production	V Polarization
$Z\gamma$	Powheg+Pythia8	0	$gg\rightarrow X$	Transvers
$Z\gamma$	MadGraph+Pythia8	2	$gg\rightarrow X$	Transvers
$Z\gamma$	MadGraph+Pythia8	2	$qq\rightarrow X$	Transvers
$W\gamma$	MadGraph+Pythia8	1	$qq\rightarrow X$	Longitudinal
$H\gamma$	MadGraph+Pythia8	1	$qq\rightarrow X$	-

Main backgrounds

Channel	Generator
γ+jets ***dominant***	Sherpa
SM W+γ	Sherpa
SM Z+γ	Sherpa
tt+γ(all hadronic and no all hadronic)	MadGraph + Pythia8