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First Measurement of Electroweak Vector Boson Scattering and Potential for New Physics Discovery at ATLAS

Jessica Metcalfe

VBS

First Evidence for Electroweak Vector Boson Scattering!

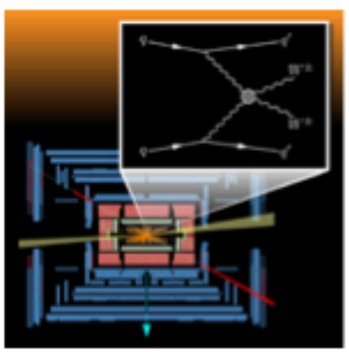
→Same (electric charge) sign WW (ssWW) scattering: **pp -> $W^{\pm}W^{\pm}$jj -> $l^{\pm}\nu l^{\pm}\nu$jj**

Editors' Suggestion

Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad et al. (ATLAS Collaboration)

Phys. Rev. Lett. **113**, 141803 (2014) – Published 3 October 2014



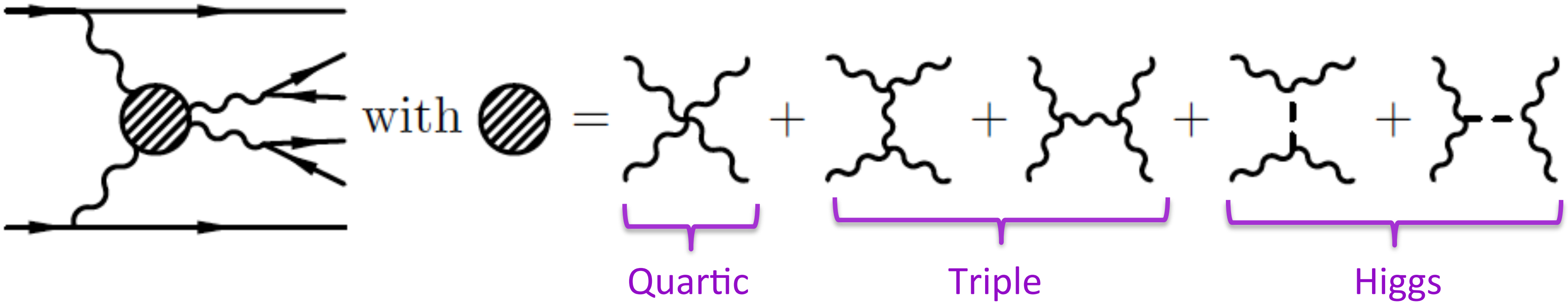
The ATLAS experiment at the LHC has found evidence for the scattering of two massive vector bosons, a previously unseen process predicted by the Standard Model.

Show Abstract +

✧ Future prospects for new physics

What are the possible VV interactions?

Vector Boson Scattering:



Electroweak VBS Scattering:

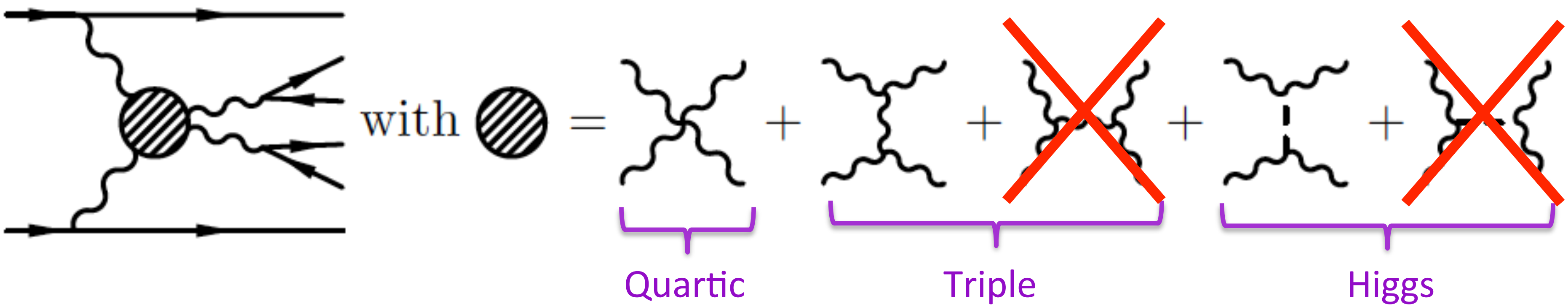
- Vector boson self-interactions (Quartic never observed before!)
  - Sensitive to new physics via anomalous triple and quartic gauge couplings: aTGC's and aQGC's
- Vector boson-Higgs interactions
- Sensitive to Electroweak Symmetry Breaking

VBS

What are the possible VV interactions?

Vector Boson Scattering:

Don't Exist for ssWW



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- Vector boson self-interactions (Quartic never observed before!)
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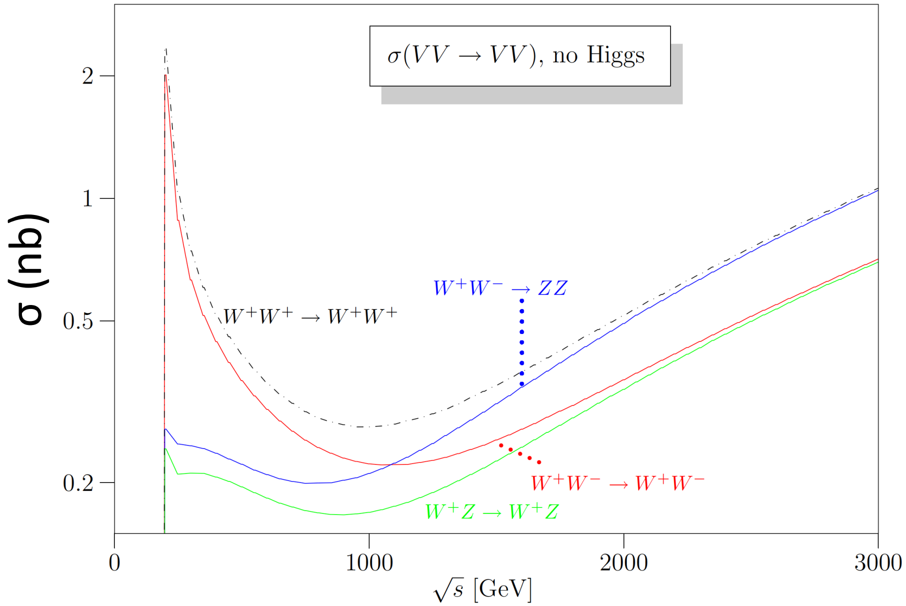
- Sensitive to Electroweak Symmetry Breaking (EWSB)

VBS

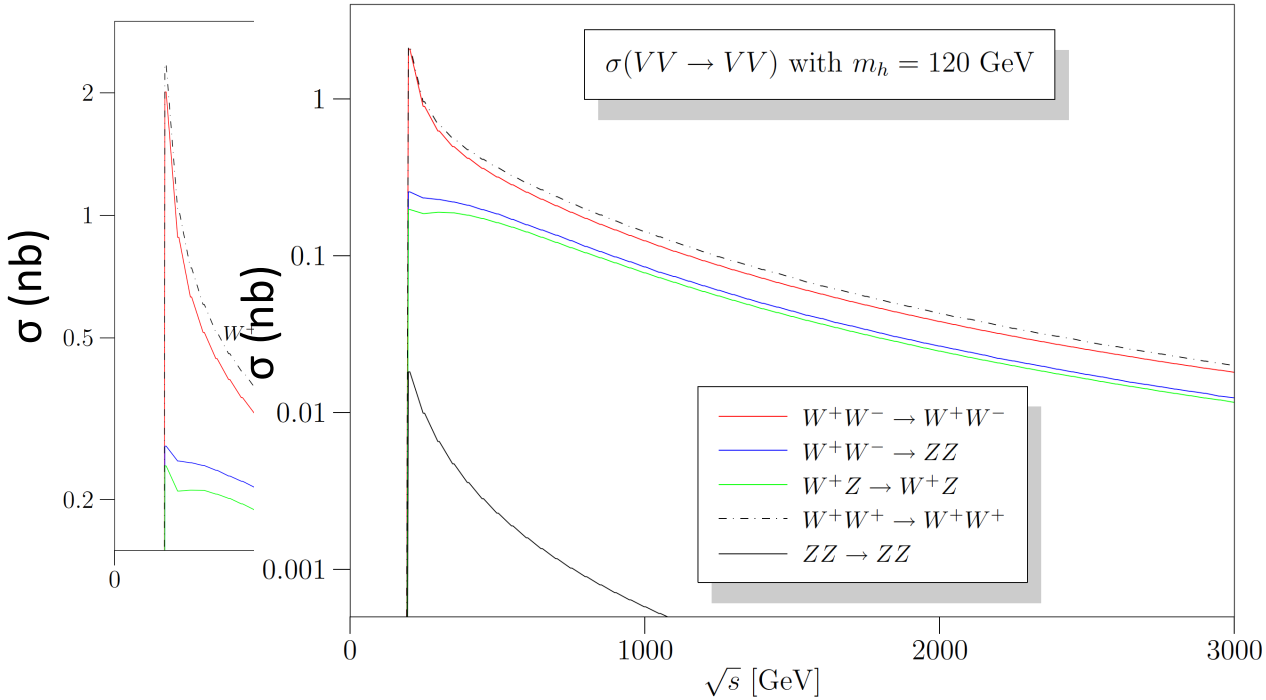


A. Alboteanu, et. al, arXiv:0806.4145v1

Why is VBS interesting? EWSB

- Without a Higgs the VV scattering amplitude increases with center-of-mass energy and violates unitarity at scales ~ 1TeV

VBS



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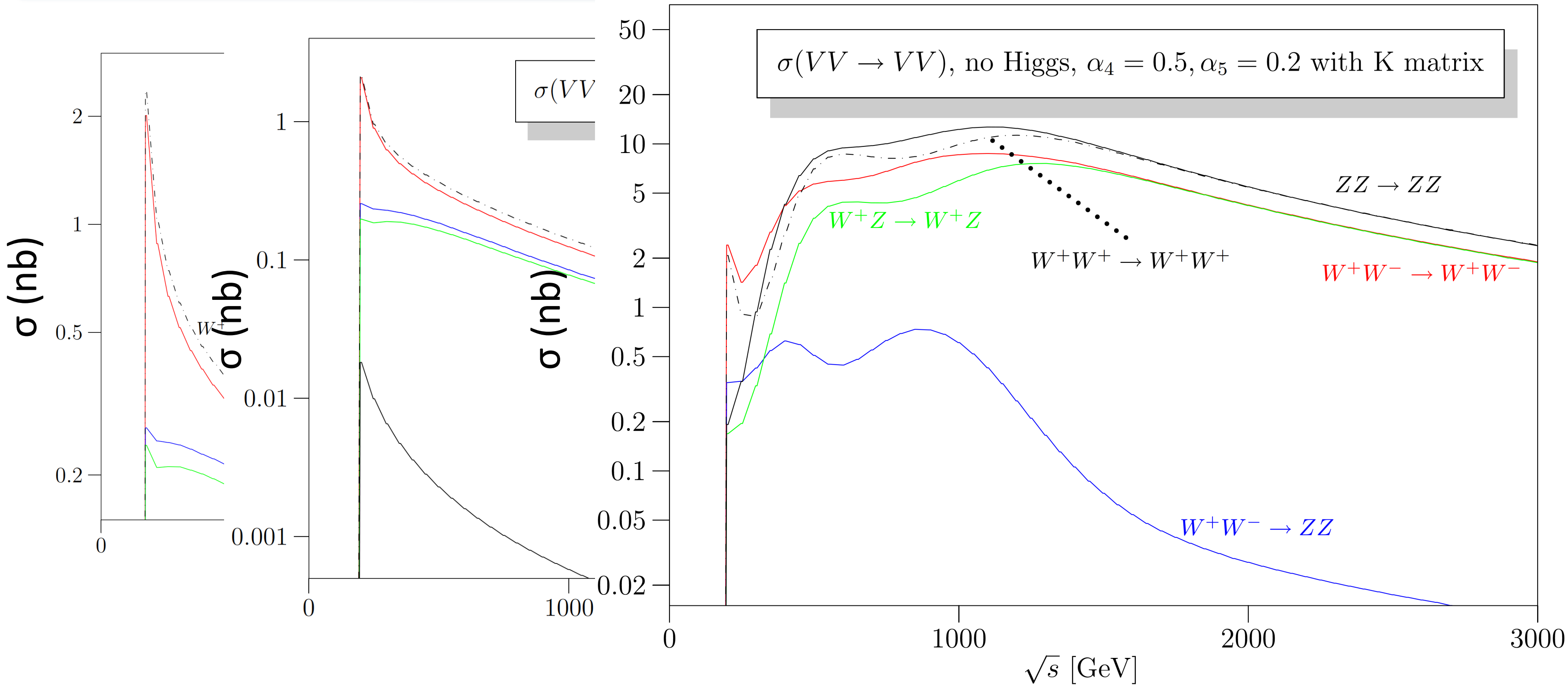
VBS



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- Without a Higgs the VV scattering amplitude increases with center-of-mass energy and violates unitarity at scales ~ 1TeV
- The 125 GeV SM-like Higgs provides a method to bring back unitarity, but may not be the whole story
- There can be other new physics that can preserve unitarity—in this example, the α_4 and α_5 variables from an Effective Field Theory

➔ **VV scattering is a good method to probe EWSB**

Same-sign $W^{\pm}W^{\pm}$ (ssWW)

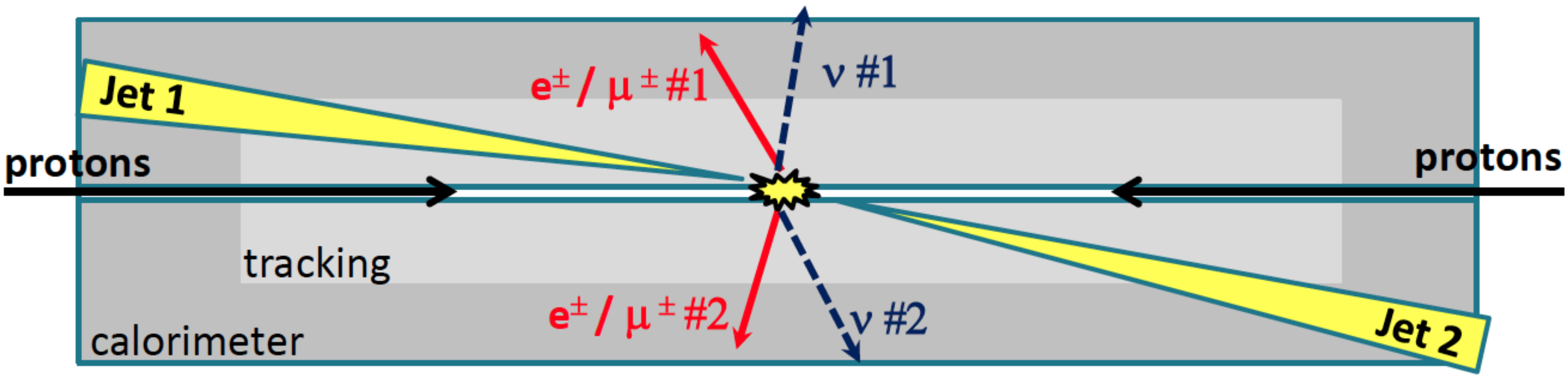
final state	process	$VVjj$−Ewk [fb]	$VVjj$−Strong [fb]	Ewk/Strong
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign)	$W^{\pm}W^{\pm}$	19.5	18.8	1.04
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3	3030	0.030
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2	687	0.043
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5	106	0.014
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4	162	0.015

- ssWW has the highest ratio of EW compared to QCD production
  - Almost 1:1
- Fewer backgrounds to deal with since there is no gluon-gluon production

➔ Want to measure the Electroweak production of ssWW

ssWW Signature

pp -> $W^{\pm}W^{\pm}jj$ -> $l^{\pm}\nu l^{\pm}\nu jj$

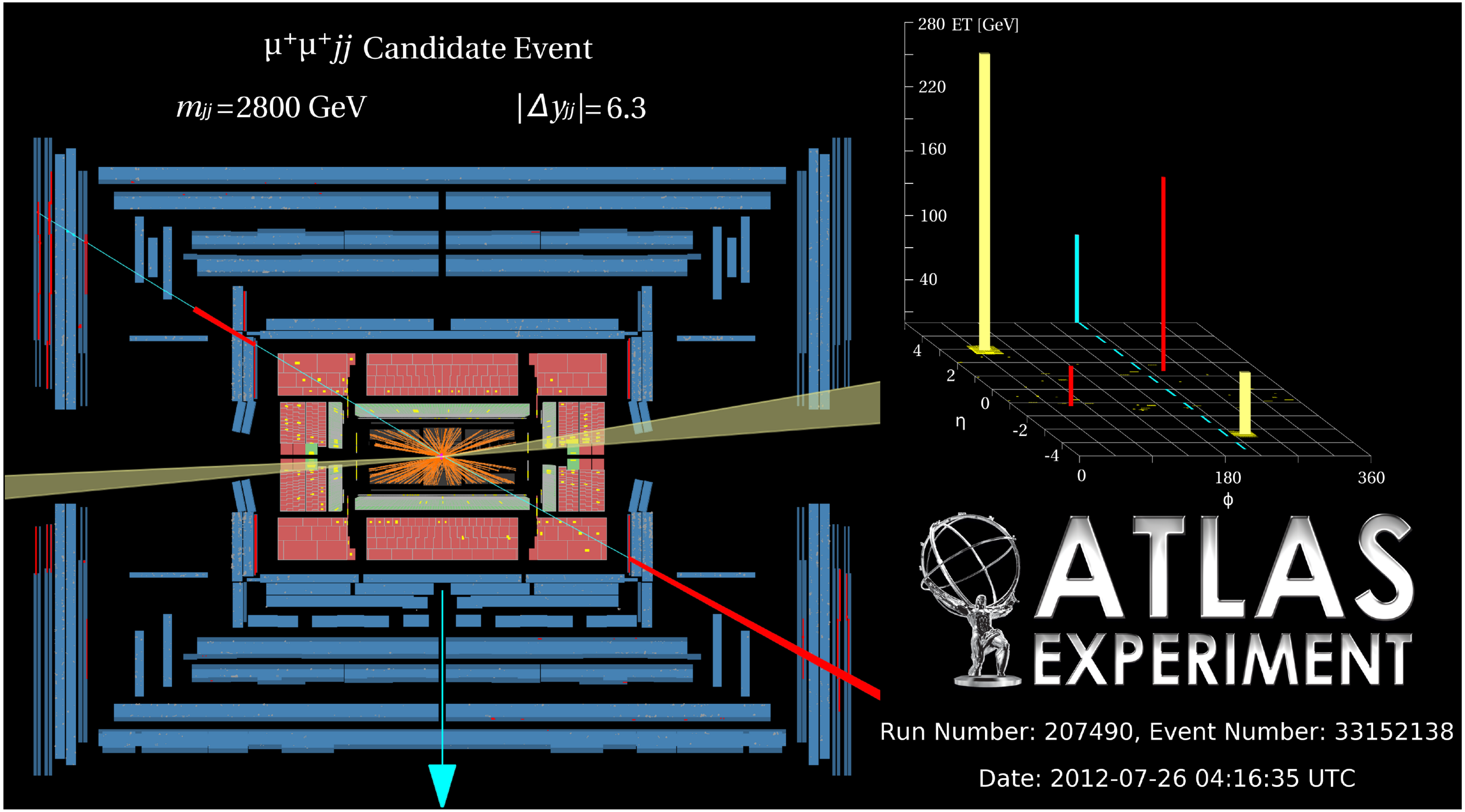


- Measure the ssWW final state where W's decay into lepton neutrino pair
- Leptons tend to be more central from the recoil of the W emmission
- Jets tend to be more forward due to small angle recoil of the initial quarks
- Large missing E_T associated with leptons

ssWW Signature

pp -> $W^{\pm}W^{\pm}jj$ -> $l^{\pm}\nu l^{\pm}\nu jj$

ATLAS-STDM-2013-06



VBS

Event Selection for the 8 TeV analysis:

- Data quality/Event cleaning
- Trigger: single lepton trigger
- Exactly 2 same-sign leptons
- Lepton $p_T > 25$ GeV
- Veto 3rd leptons using looser criteria
- $\Delta R(\mu,jet)_{min} > 0.3$
- $|m_{ee} - m_Z| > 10$ GeV
- $E_T^{Miss} > 40$ GeV
- ≥ 2 jets with $p_T > 30$ GeV
- B-jet veto

- $M_{jj} > 500$ GeV *Inclusive Signal Region* EW+Interference + QCD

- **$|\Delta y(j,j)| > 2.4$** ***VBS Signal Region*** EW+Interference

Backgrounds

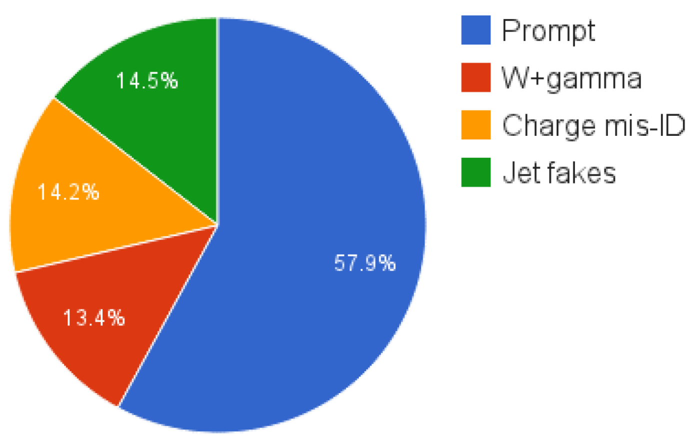
Backgrounds:

- Prompt Backgrounds
  - WZ + jets: Sherpa
  - ZZ + jets: Sherpa
  - $t\bar{t}$ + V: MadGraph + Pythia
- Photon Conversions:
  - $W\gamma$ + jets: AlpgenJimmy
  - Z+jets and $t\bar{t}$ events with electron charge mis-ID
- Other Non-Prompt:
  - Leptons originating from hadronic jets

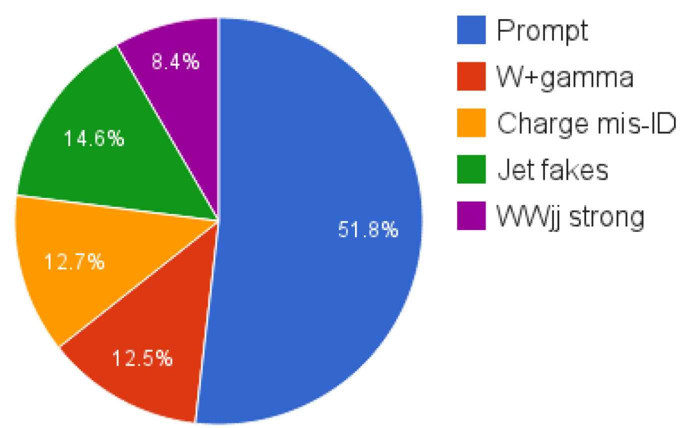
MC

Data-driven

Inclusive Analysis Region

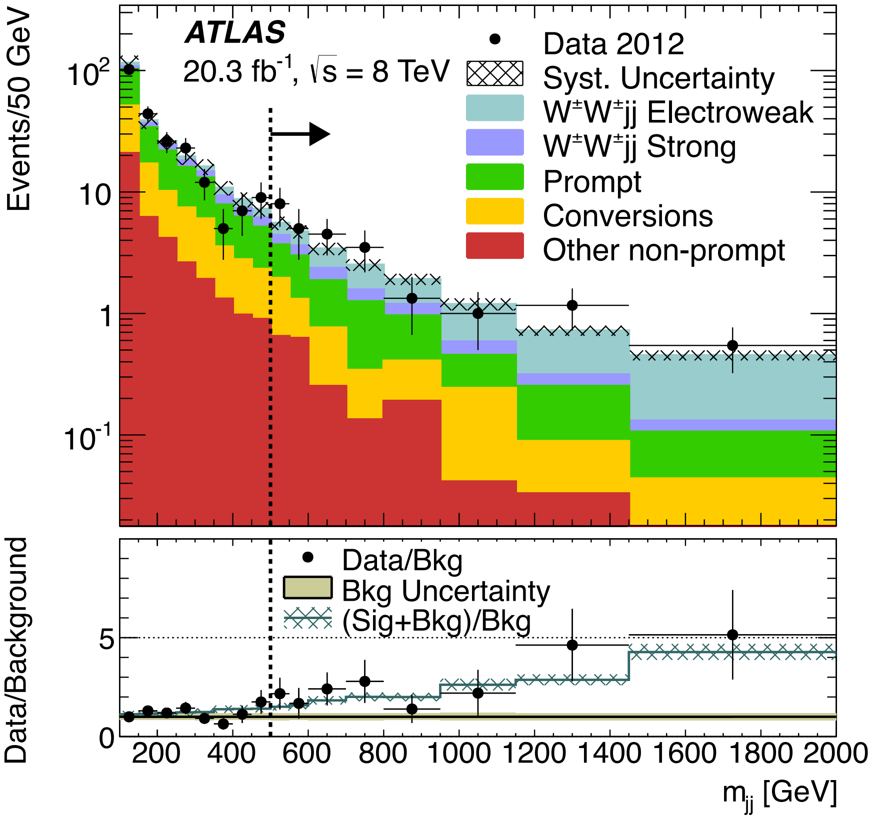


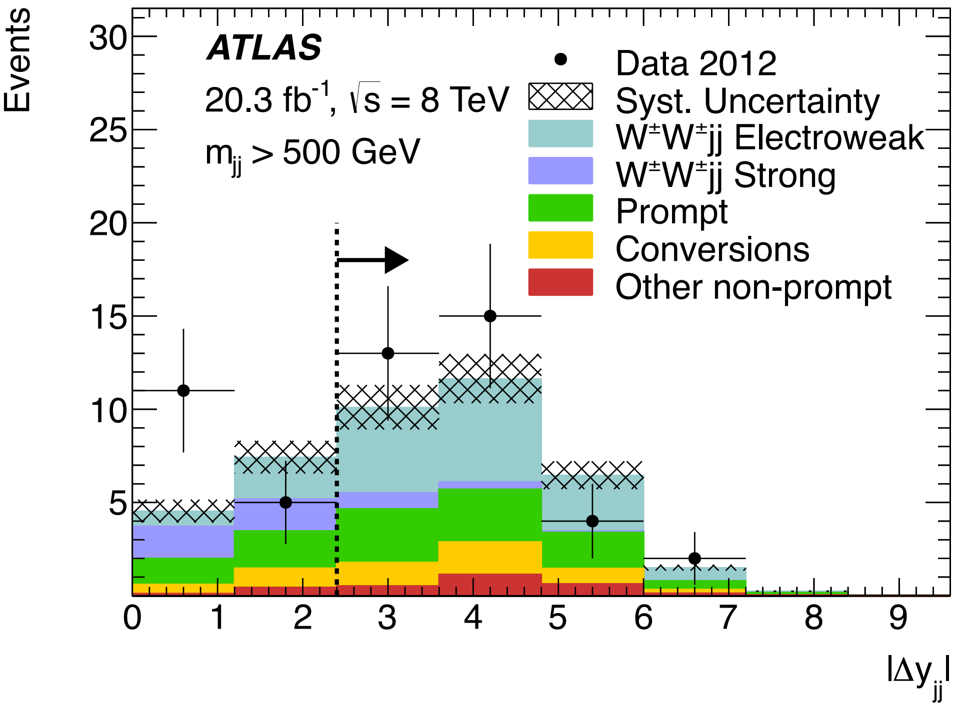
VBS Analysis Region



VBS

Inclusive signal region without m_{jj} cut

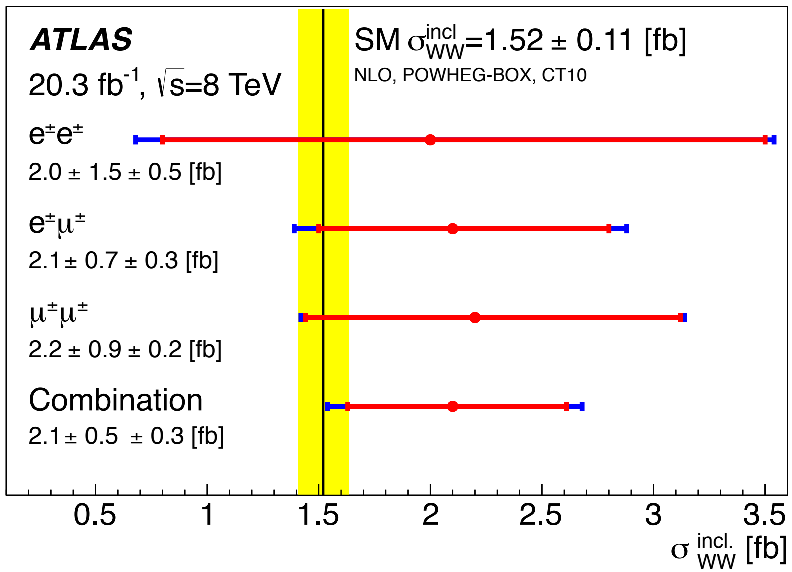




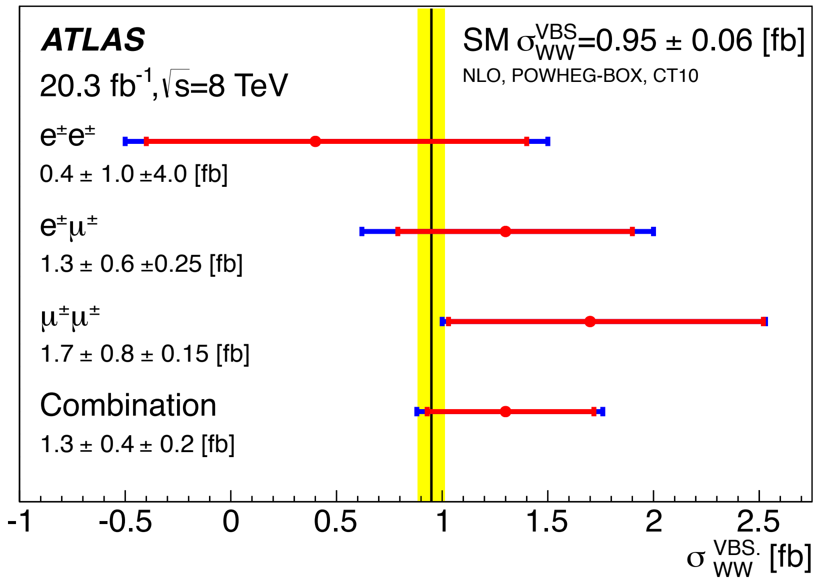
Inclusive Signal Region:	50 events measured (41.7 predicted)
VBS (EW) Signal Region:	34 events measured (29.8 predicted)

Cross-sections

Inclusive



VBS



Inclusive Signal Region
Combined Significance:
4.5σ

VBS (EW) Signal Region
Combined Significance:
3.6σ

- Statistically dominated uncertainties
- Overall agreement with SM predictions within uncertainties
- **First Evidence for ssWW production!!**

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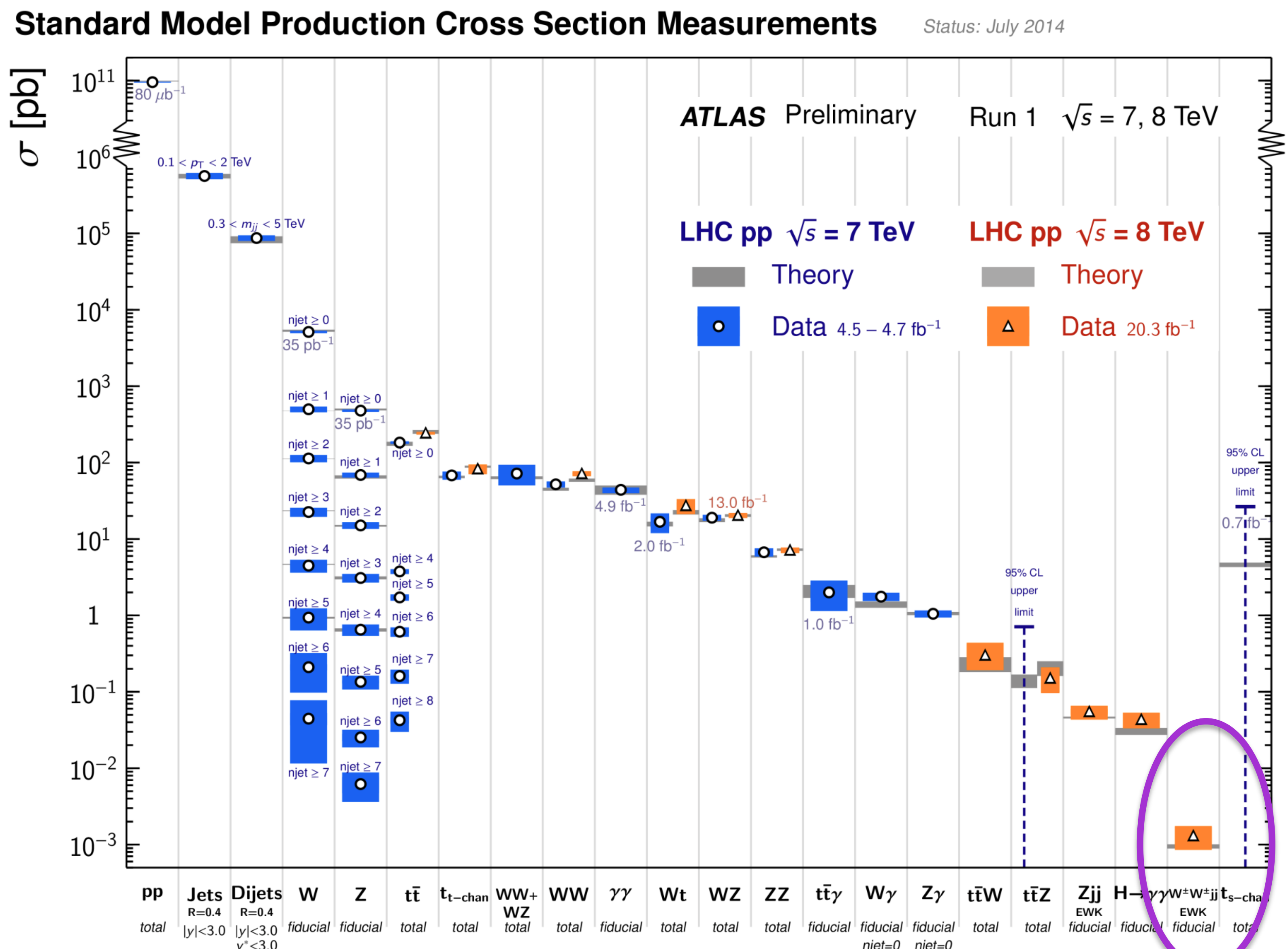
VBS


Standard Model Production Cross Section Measurements
Status: July 2014
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
Data 4.5 – 4.7 fb⁻¹
LHC pp √s = 8 TeV
Theory
Data 20.3 fb⁻¹
σ [pb]
95% CL upper limit
pp
Jets
Dijets
W
Z
tt̄
t_{t-chan}
WW+WZ
WW
γγ
Wt
WZ
ZZ
tt̄γ
Wγ
Zγ
tt̄W
tt̄Z
Zjj EWK
H→γγ
W±W±jj EWK
t_{s-chan}

New Physics

EFT

[1] Snowmass EWK arXiv:1310.6708

Use Effective Field Theory to look for aQGC's and aTGC's:

- Generic, model independent framework

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \underbrace{\sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i}_{\text{Dimension-6}} + \underbrace{\sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}}_{\text{Dimension-8}}$$

- Dimension-6 operators affect triple and quartic gauge vertices
- Dimension-8 operators affect only quartic vertices

Dimension-8 can be written as Chiral lagrangian:

$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(V_\mu V_\nu\right)\right]^2$$

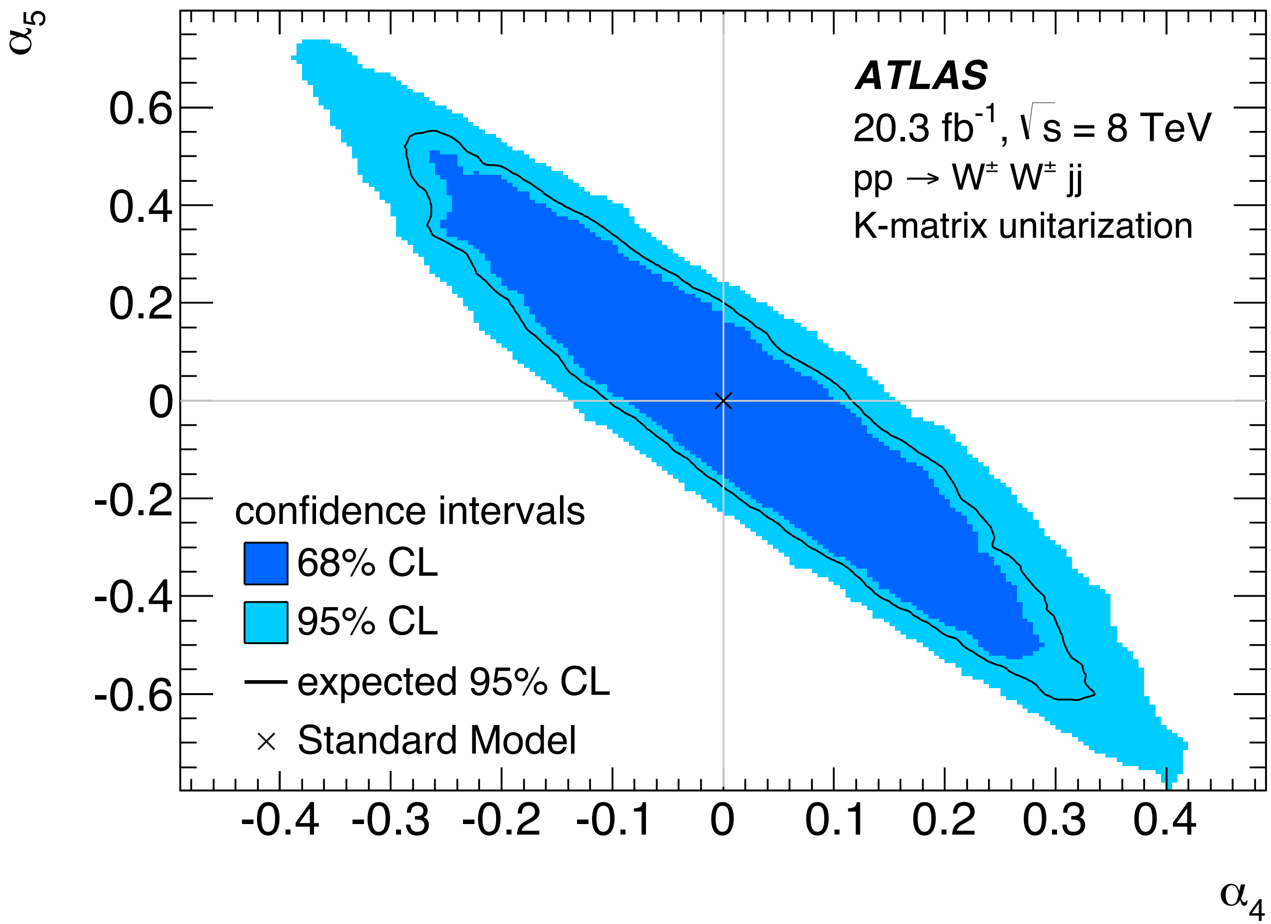
$$\mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(V_\mu V^\mu\right)\right]^2$$

WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

VBS



Set limits on new physics coupling parameters α_4 and α_5:

$-0.14 < \alpha_4 < 0.16$ and $-0.23 < \alpha_5 < 0.24$ observed

$-0.10 < \alpha_4 < 0.12$ and $-0.18 < \alpha_5 < 0.20$ expected

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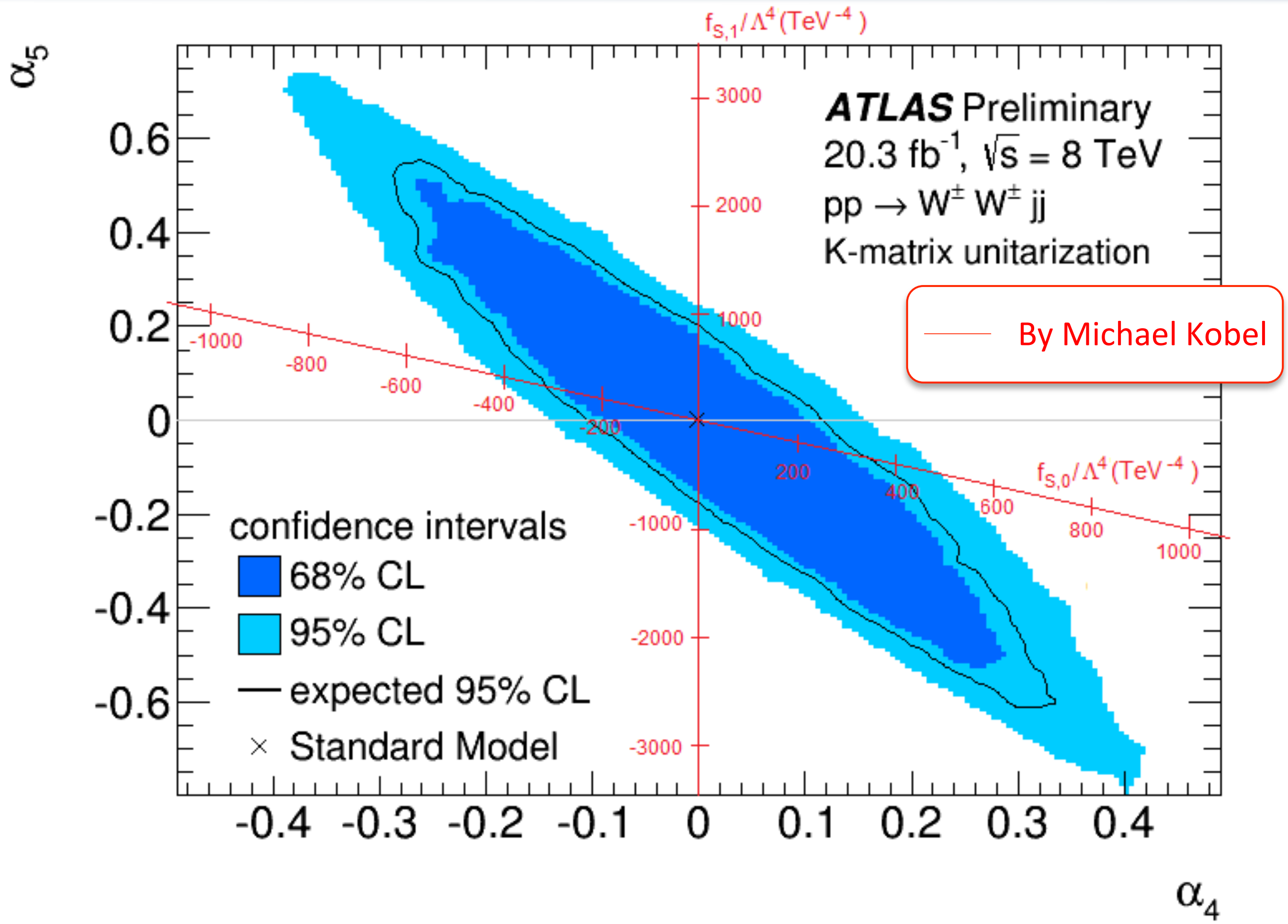

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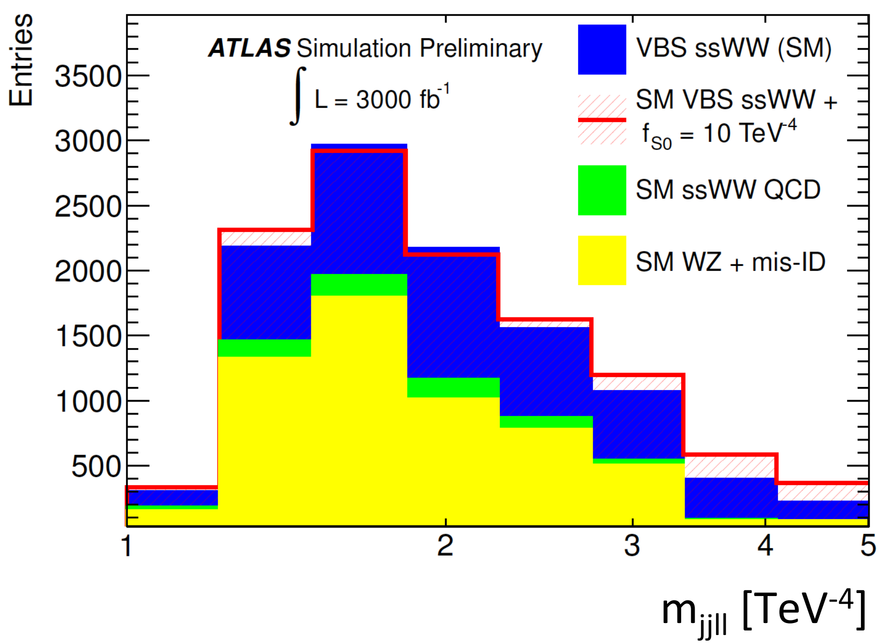
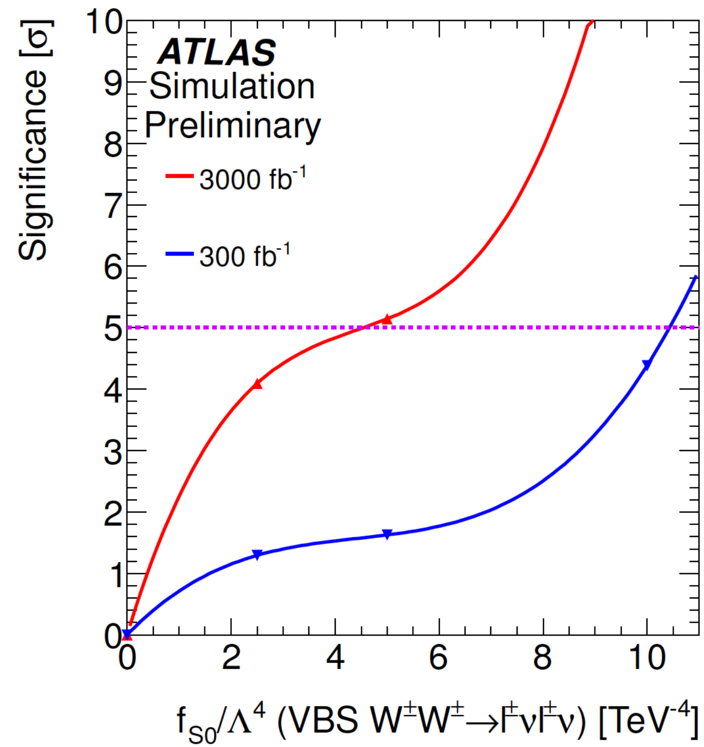
$-400 < f_{S0} < 500$ and $-1000 < f_{S1} < 1000$ observed (approximately)

New Physics @ HL-LHC

FS0 @ √s = 14 TeV

ATLAS-PHYS-PUB-2013-006





5σ discovery potential:

model	300 fb^{-1}	3 ab^{-1}
f_{S0}/Λ^4	10 TeV^{-4}	4.5 TeV^{-4}

FS0 @ √s = 8 TeV
-400 < f_{S0} < 500 [TeV^{-4}]
20.3 fb^{-1}

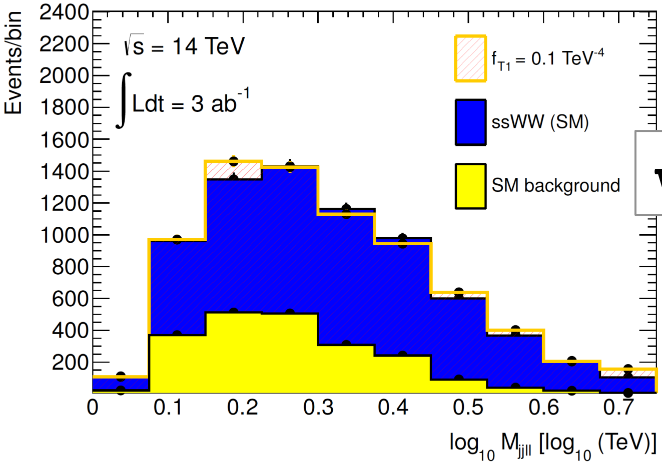
ssWW

FT1

$W^{\pm}W^{\pm} \rightarrow l\nu l\nu$

$FT1/\Lambda^4 = 0.1$ [TeV^{-4}]

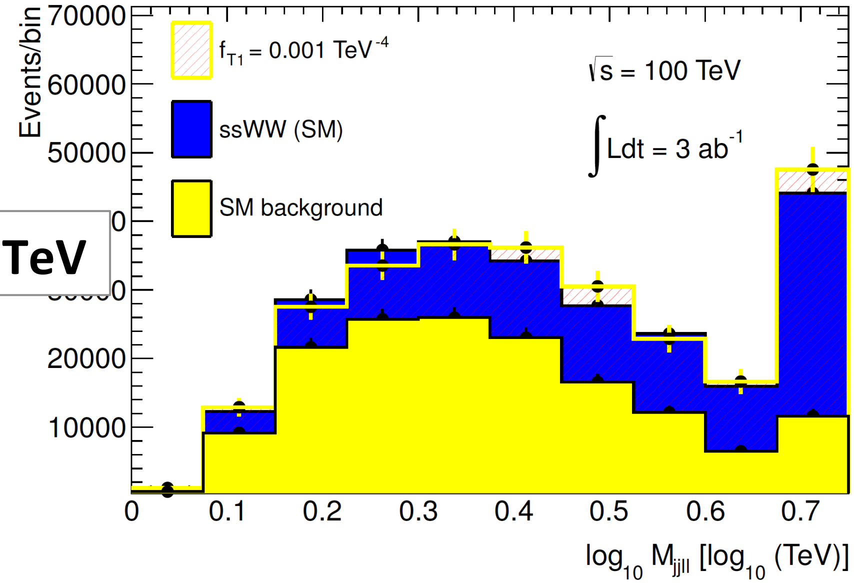
140 PU



√s: 14 -> 100 TeV

$FT1/\Lambda^4 = 0.001$ [TeV^{-4}]

263 PU



Significance = 4.2σ

Significance = 4.0σ

- Higher pp center-of-mass energy enhances high m_{jjll} spectrum in SM and new physics
- Significance remains about the same ~4σ (no UV cutoff applied)
  - Different pileup scenarios
  - No selection optimization

arXiv:1309.7452v1

Summary:

- First evidence of VVVV vertex in the ssWW channel at $\sqrt{s}$ = 8 TeV at ATLAS
  - Inclusive signal region: $\sigma = 2.1\ {+0.58}\ {-0.56}$ fb ➔ 4.5σ significance
  - VBS signal region: $\sigma = 1.3\ {+0.46}\ {-0.42}$ fb ➔ 3.6σ significance

- Placed limits on new physics at $\sqrt{s}$ = 8 TeV for aQGC's
  - $-0.14 < \alpha_4 < 0.16$ and $-0.23 < \alpha_5 < 0.24$
  - Or $-400 < f_{S0} < 500$ and $-1000 < f_{S1} < 1000$ [TeV^{-4}]

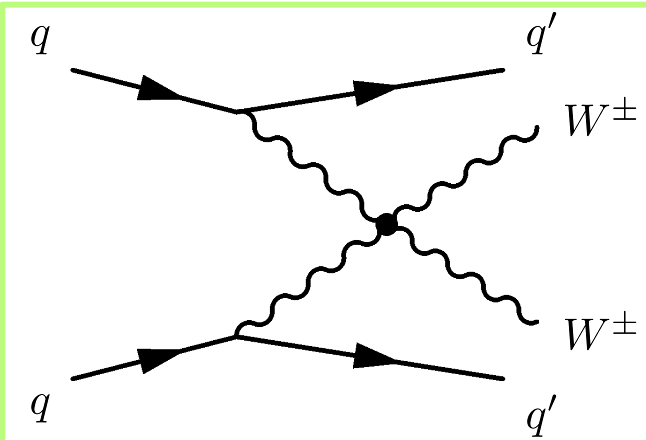
- Expect to be able to push limit by x100 for the full $\sqrt{s}$ = 14 TeV data set for FS0
- Expect to improve a limit on FT1 by x100 from $\sqrt{s}$ = 14 TeV to $\sqrt{s}$ = 100 TeV

- Lots of exciting things to look for at the LHC!

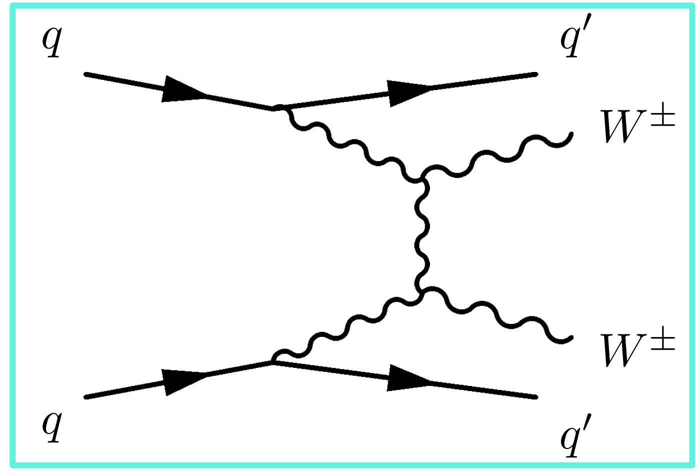
Backup

VBS

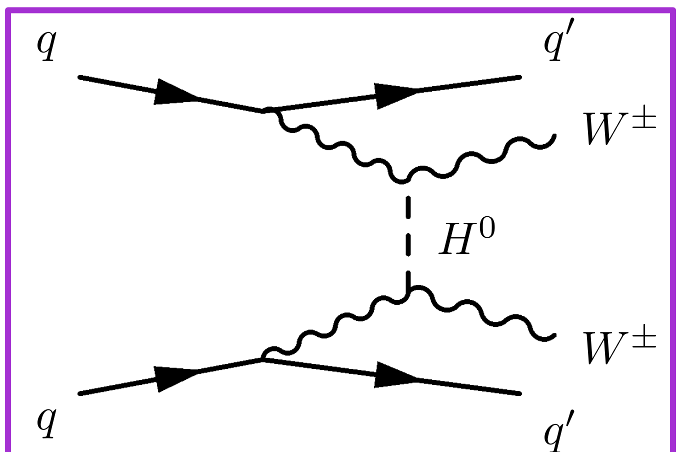
ssWW VBS EW signal diagrams:



quartic scattering vertex



t-channel V exchange

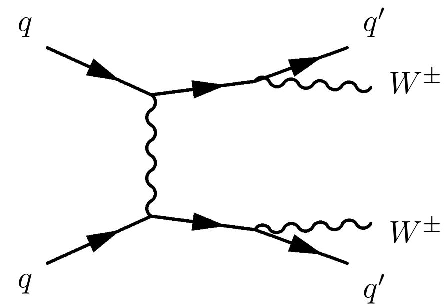


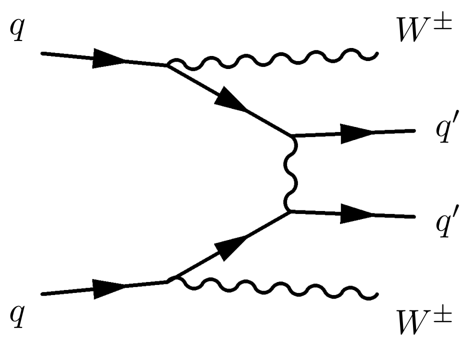
t-channel Higgs

VBS

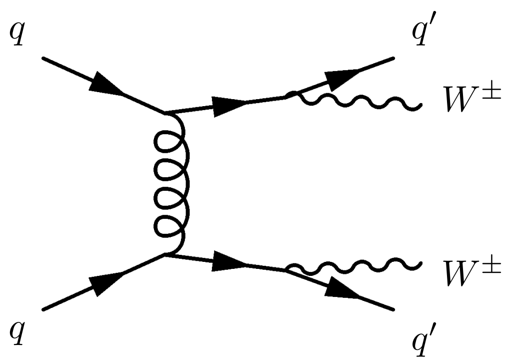
Additional diagrams for the ***Inclusive*** ssWW measurement

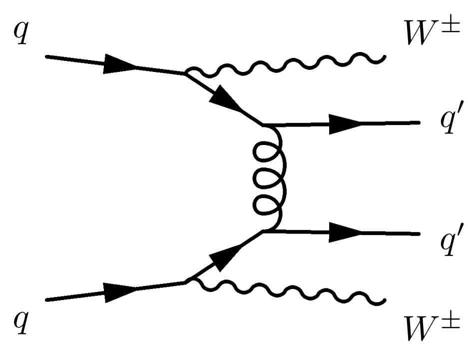
ssWW non-VBS EW diagrams:

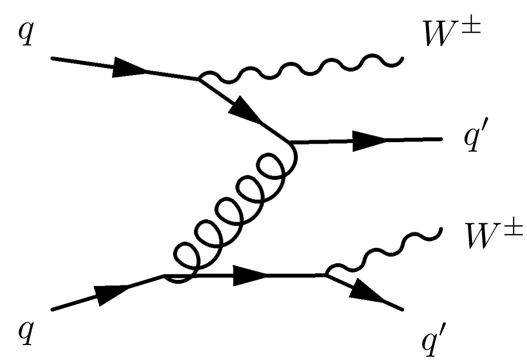




ssWW QCD diagrams:





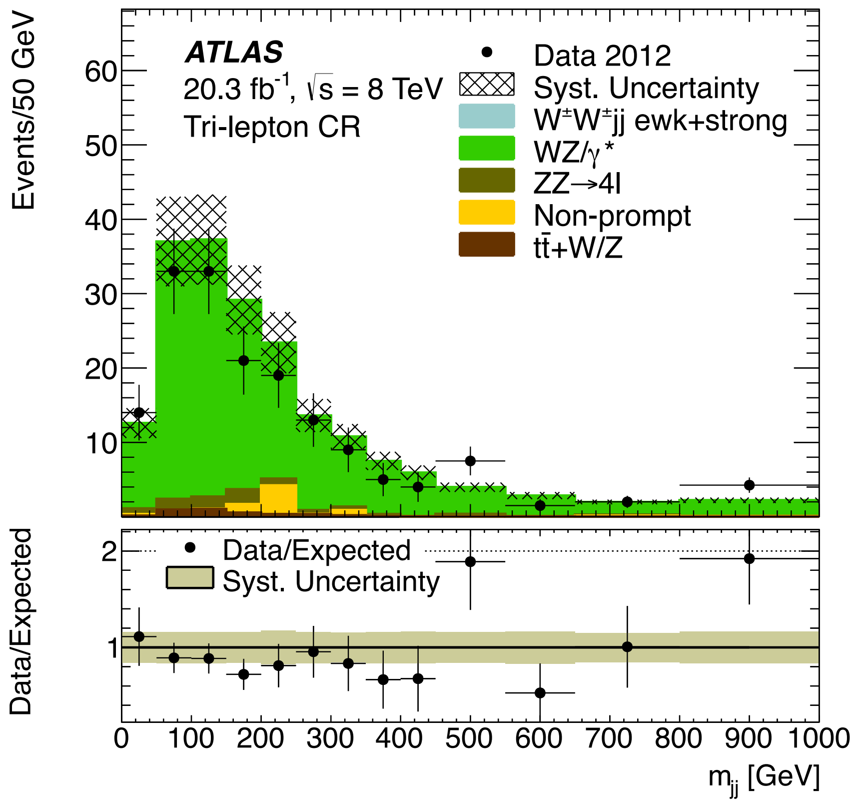


- ssWW production diagrams mediated by the strong force via gluon exchange
- Considered a background to the EW production and signal in the inclusive ssWW production

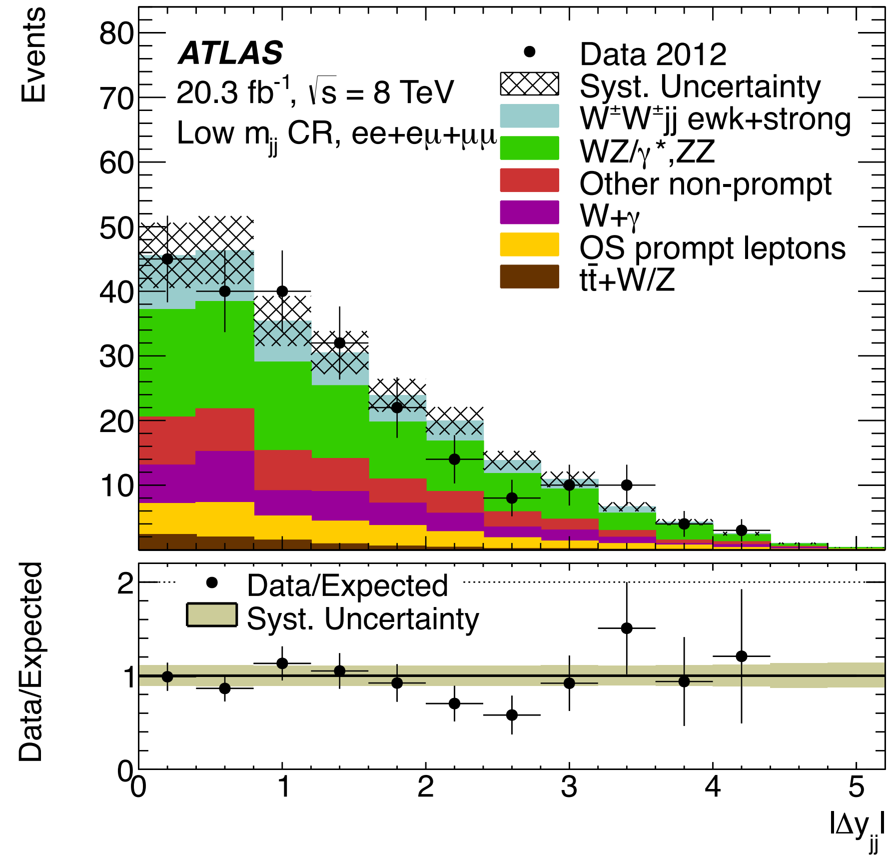
ssWW: Backgrounds

ATLAS-STDM-2013-06

Control Region: Tri-lepton for WZ + jets



Control Region: Low m_{jj}



- Largest background
- Check tri-lepton control region in MC (Sherpa)
  - Require a third lepton that passes the veto criteria (looser selection)
  - m_{jj} and Δy_{jj} cuts are not applied

- Same as the signal region except in the low m_{jj} region: m_{jj} < 500 GeV
- Good overall agreement in background modeling