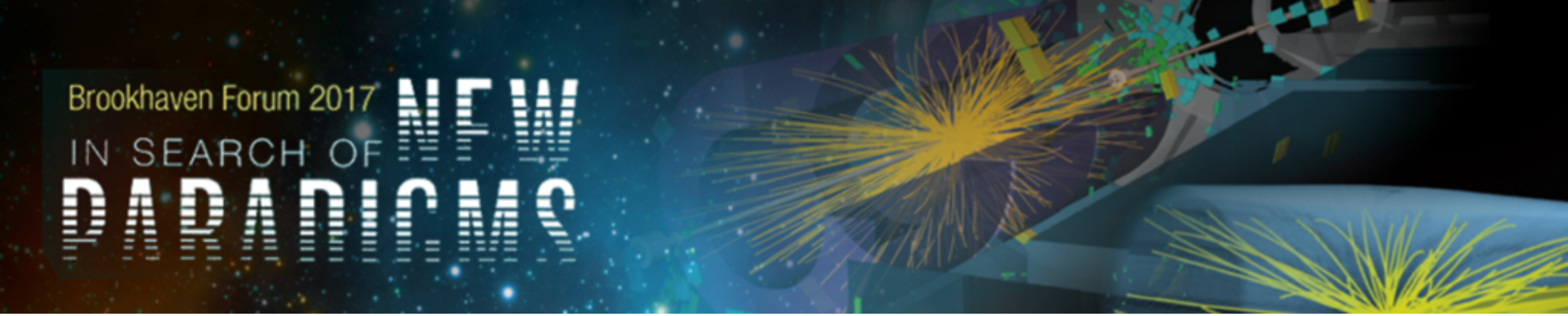


Electroweak Summary for ATLAS and CMS

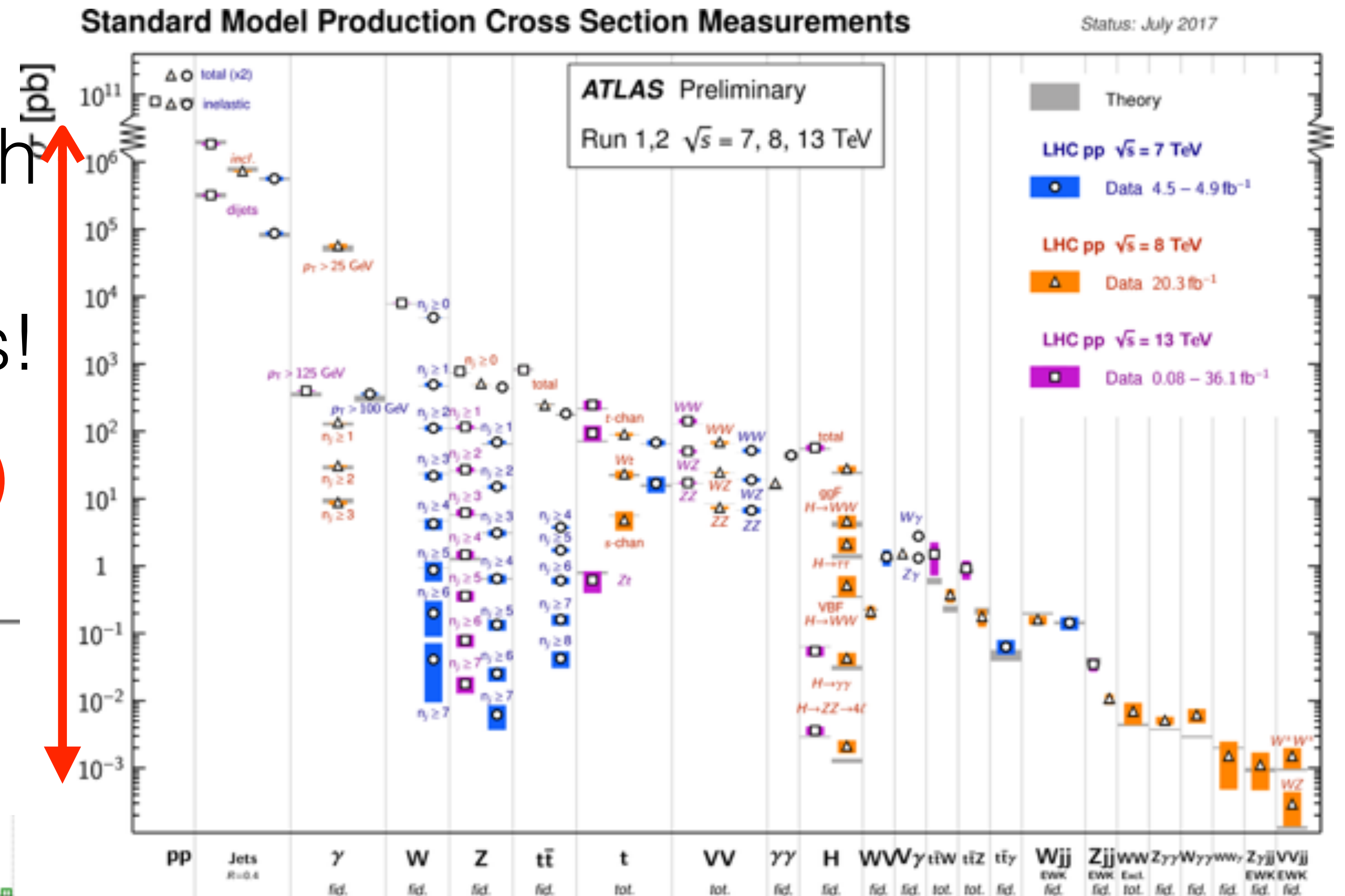
Shih-Chieh Hsu
University of Washington
October 11 2017

Motivation for Electroweak measurements

- Confront the Standard Model in regions of complex calculations
  - Higher order corrections
  - Electroweak correction with (Next) Next Leading Order QCD
  - Resummation techniques
  - Merging of perturbative QCD and parton showers
- Constrain (or observe) new physics contributions via virtual corrections or modified gauge couplings
  - Precision measurements of W mass, $\sin^2\theta_{eff}^{lep}$
  - Anomalous Triple and Quartic gauge interactions
- Provide accurate and precise predictions of background rates for BSM searches and for Higgs measurements
  - Vector Boson +jets or multi bosons often most important backgrounds
  - tails of distributions and production with additional objects

Standard Model cross-section measurements

Thanks for spectacular performance of LHC which enables rare SM production measurements!



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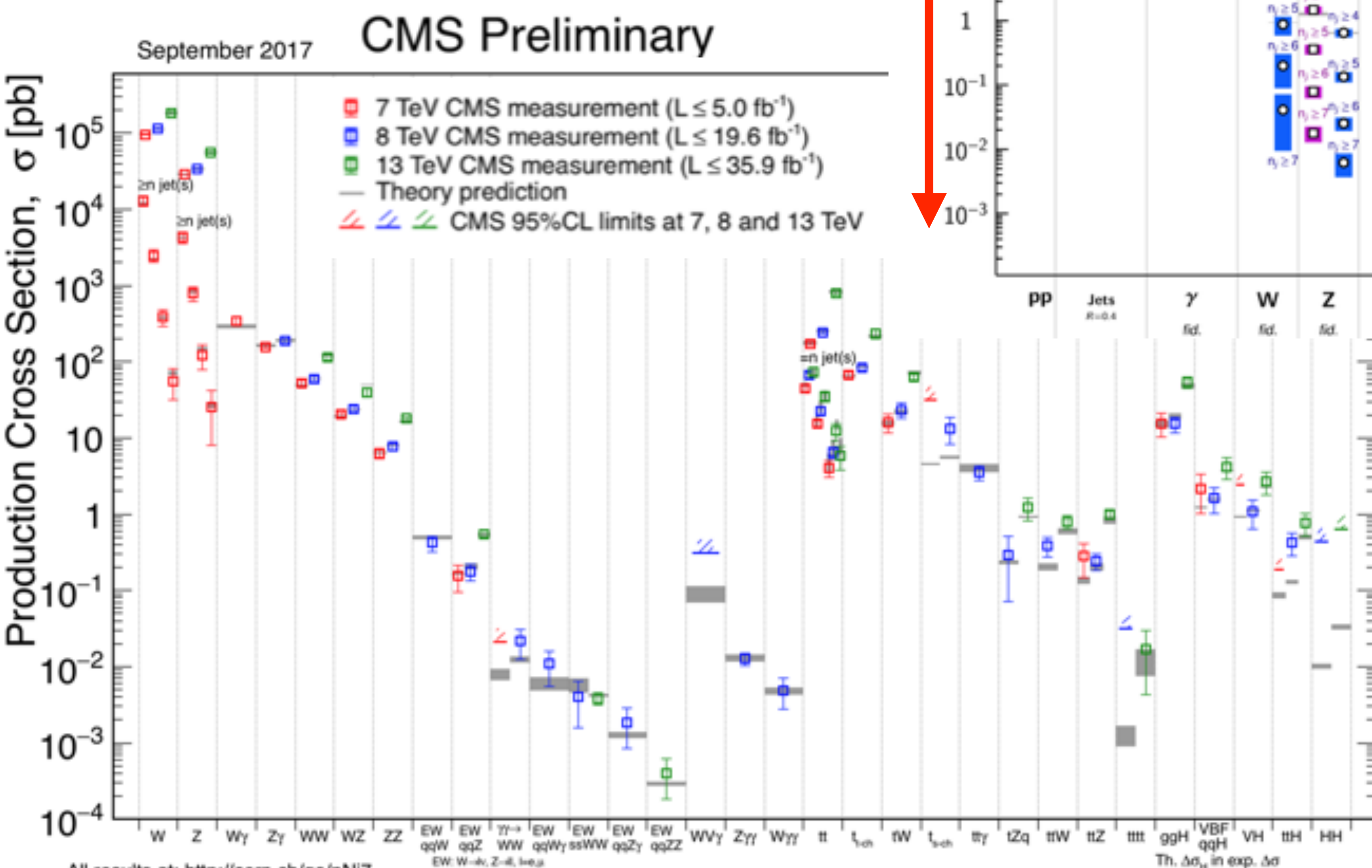
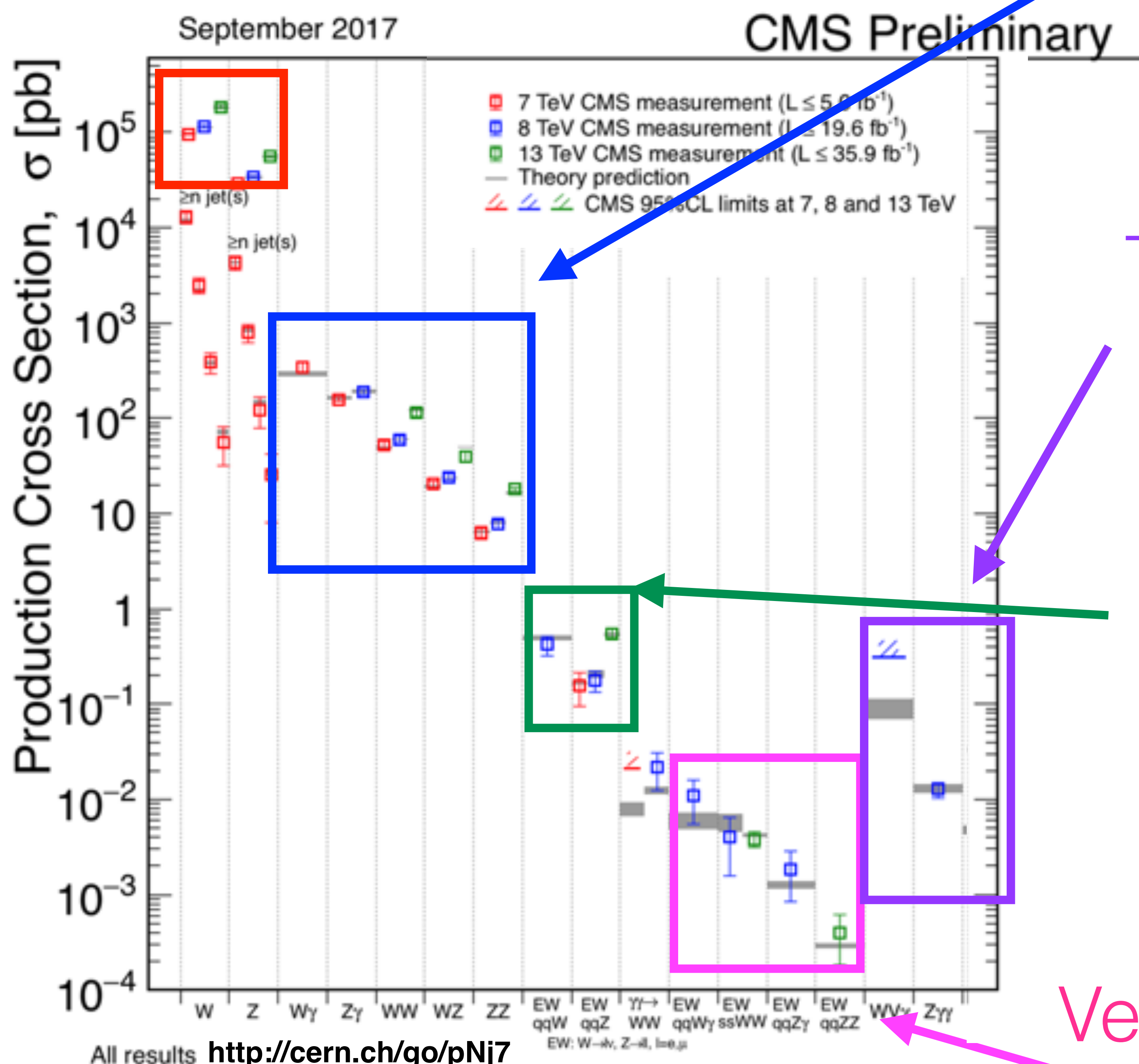


Overall good agreement with theory.
Prefers **NNLO** to NLO.

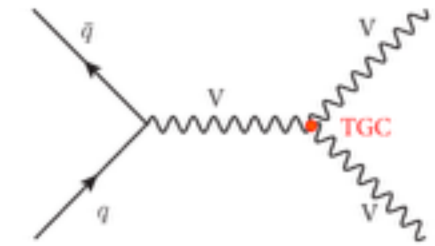
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Electroweak measurements

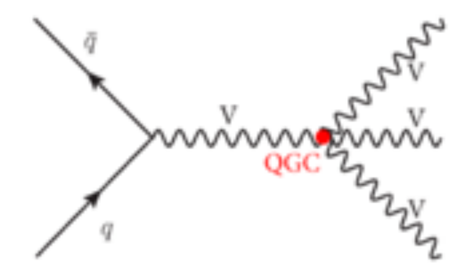
W, Z properties



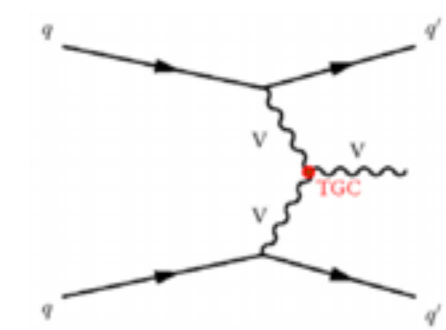
Diboson



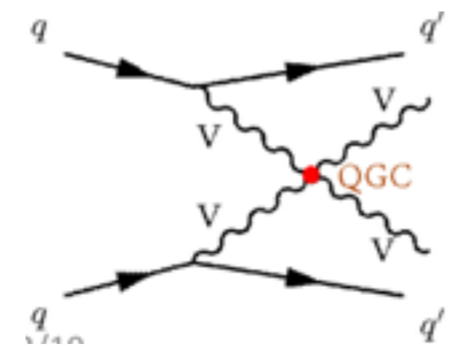
Triboson



Vector Boson Fusion



Vector Boson Scattering



In this talk, I'll highlight selected results from recent measurements.

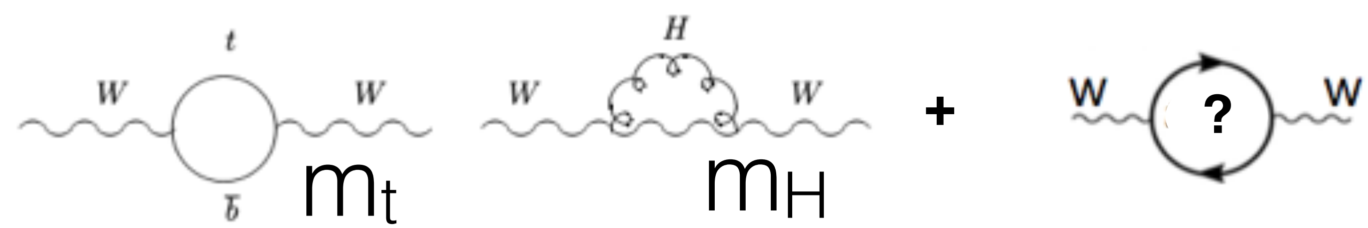
Gauge Sector of the Standard Model

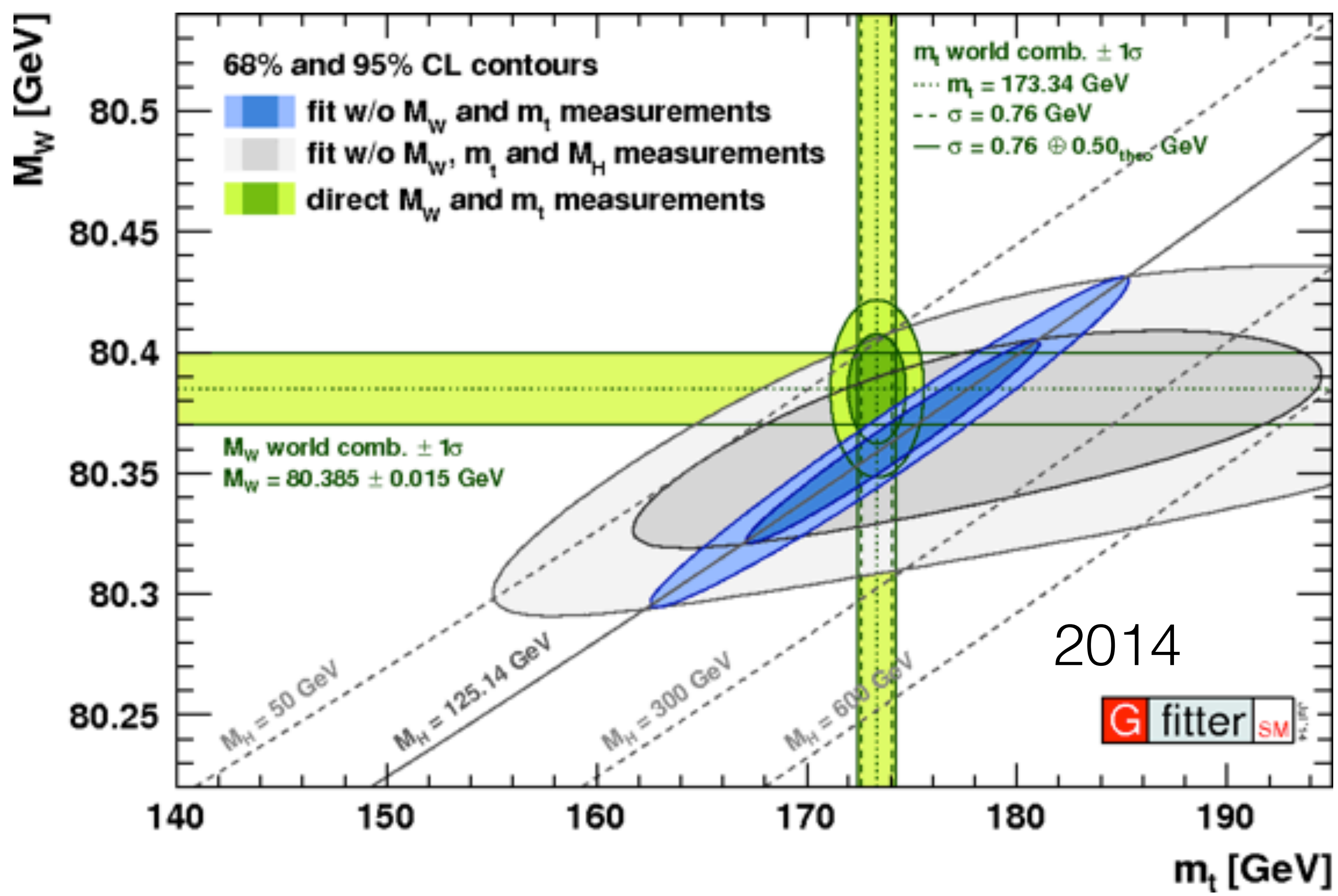
- The mass of the W boson at leading order:

$$m_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F} \qquad \sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

- Higher order correction Δr from virtual loop :

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$





Inputs

$$\alpha = 1/137.035999139(31)$$
$$G_F = 1.16637(1)\times 10^{-5}\ \text{GeV}^{-2}$$
$$m_Z = 91.1876(21)\ \text{GeV}$$

W mass:
theory prediction is more precise than experimental measurement!

W mass measurement

arXiv:1701.07240

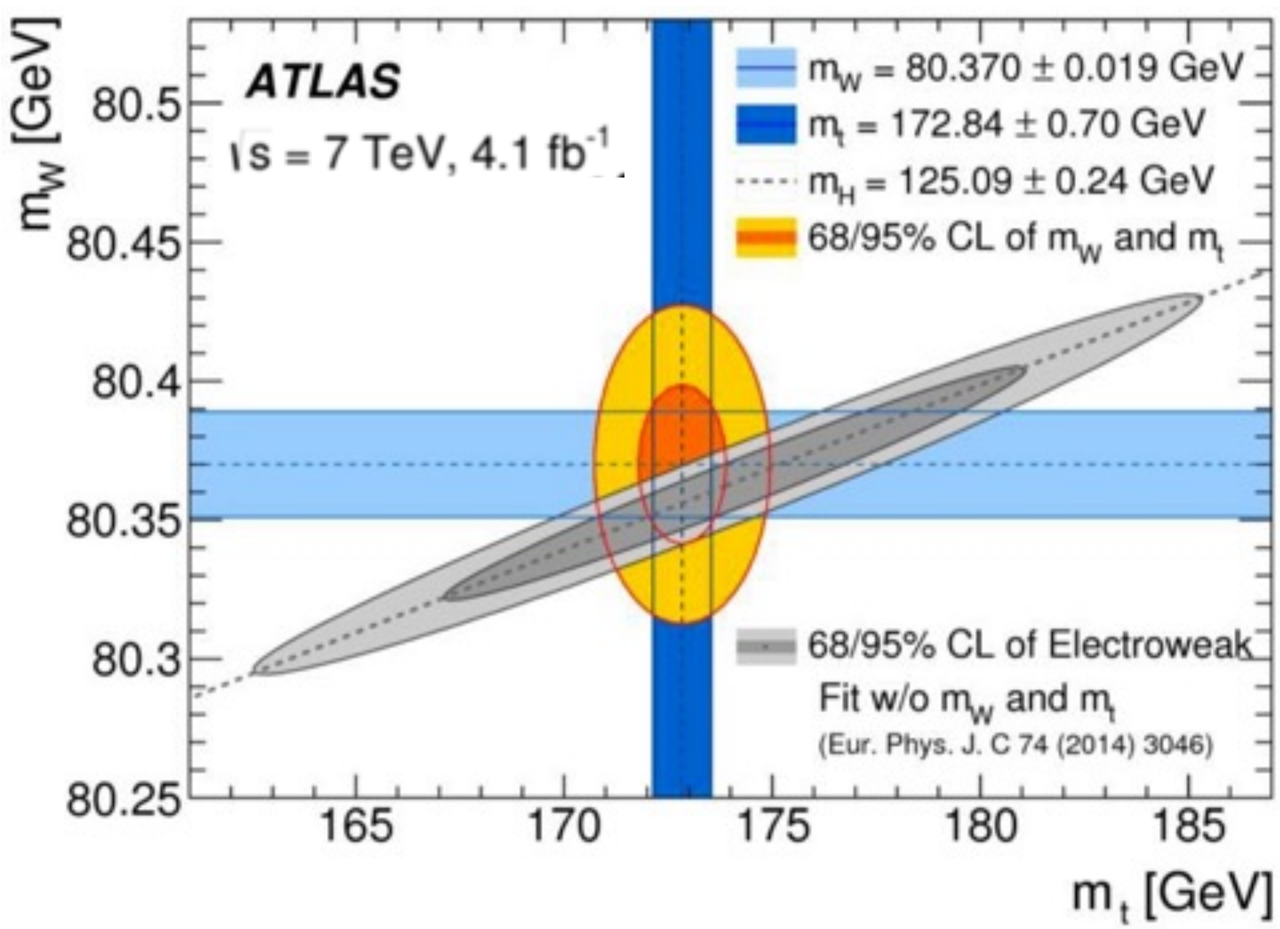
- Mass is determined by fitting lepton (7.8M e and 5.9M μ) p_T and transverse mass m_T with 7 TeV collisions. Huge efforts to understand detector response and modeling

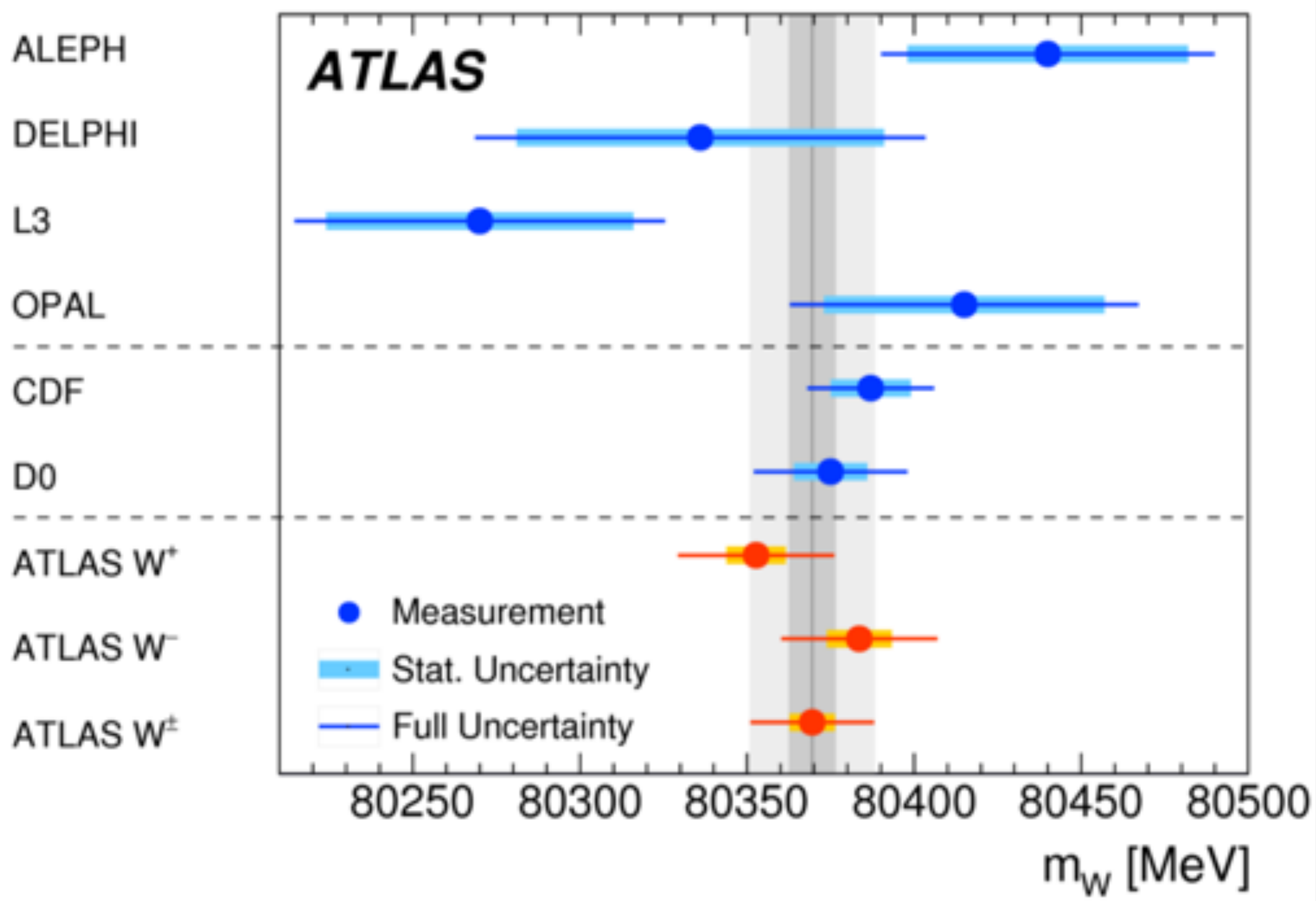
$$m_W = 80370 \pm 19 \text{MeV} \quad = 80370 \pm 7(\text{stat}) \pm 11(\text{syst}) \pm 14(\text{modelling}) \text{ MeV}$$

PDG average $m_W = 80385 \pm 15$ MeV (mainly CDF and D0)

SM prediction $m_W = 80356 \pm 8$ MeV (arXiv:1407.3792 with updated m_t and m_H)

- ATLAS reaches precision equal to the best previous single measurement from CDF
- Further progress requires improving modeling (theory and W kinematics)

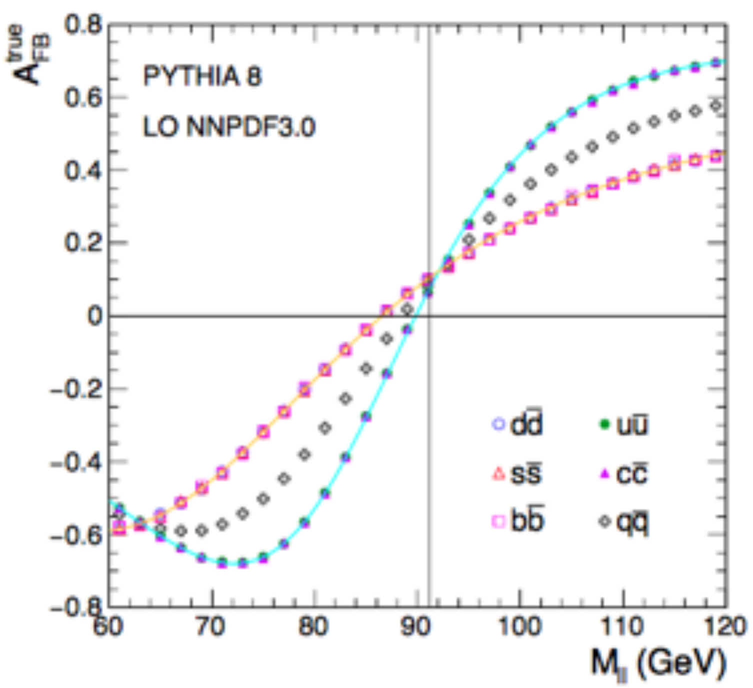




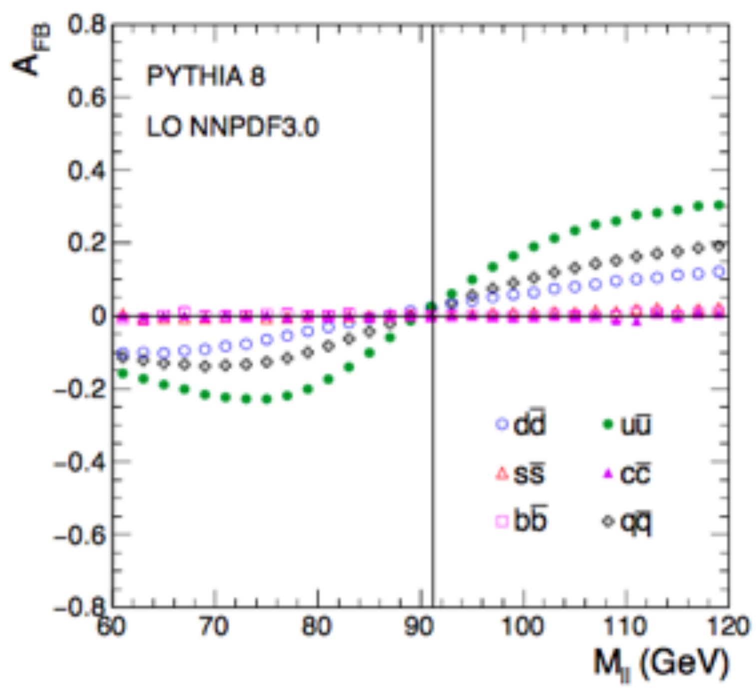
Z forward backward asymmetry

EPJC C76 (2016) 325 | CMS-PAS-SMP-16-007

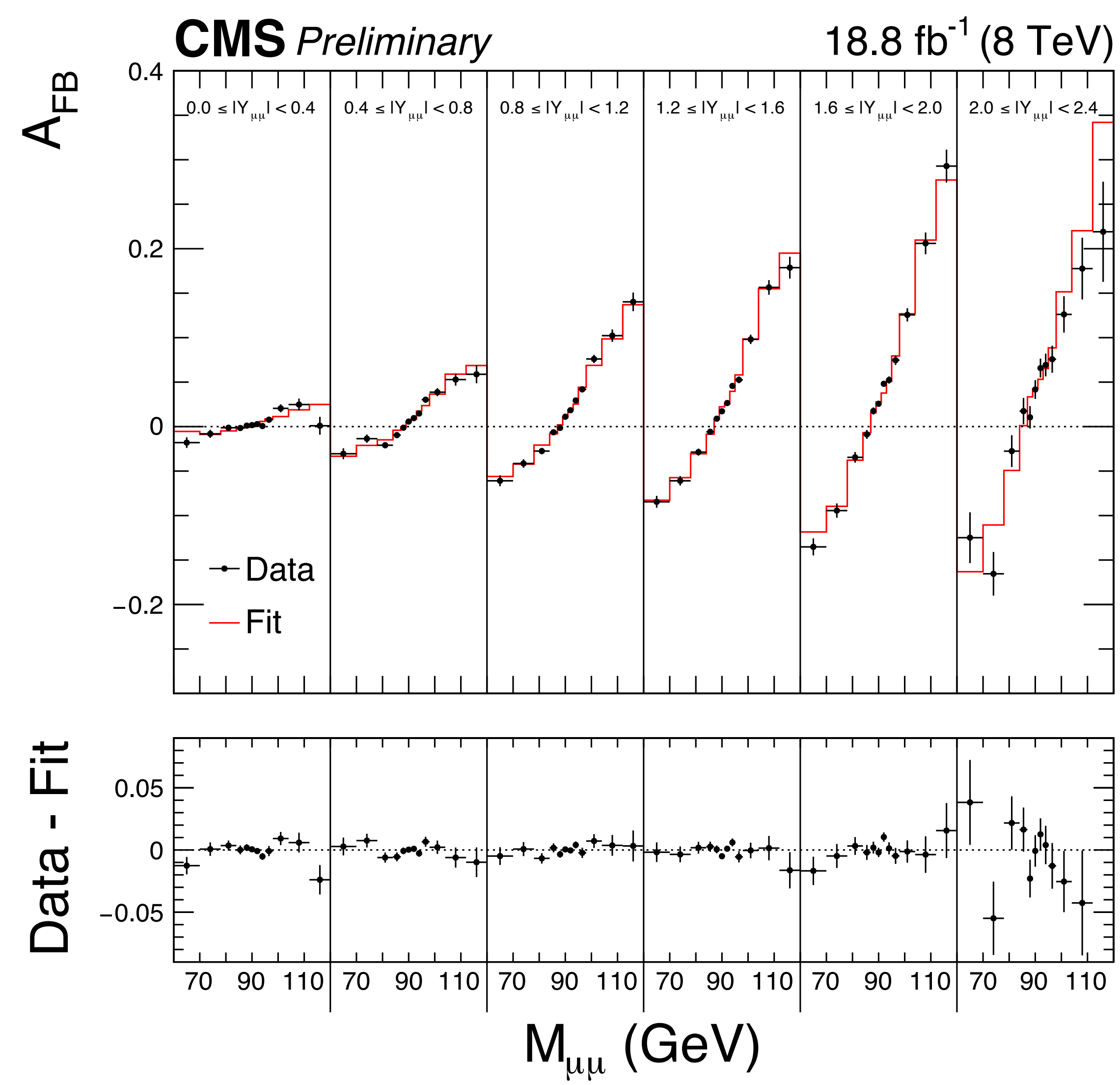
- Weak mixing angle measured in forward-backward asymmetry (A_{FB}) of DY (e^+e^-, $\mu^+\mu^-$) events in 8 TeV collisions
  - Z boost preferentially selects direction of valence quark
  - Ambiguity of quark direction is more significant in low |Y|
- $\sin^2\theta_{eff}$ extracted by performing a fit to the m_{ll} and Y dependence of A_{FB}
- pdf uncertainties also get constrained in the fit



Truth



Measured



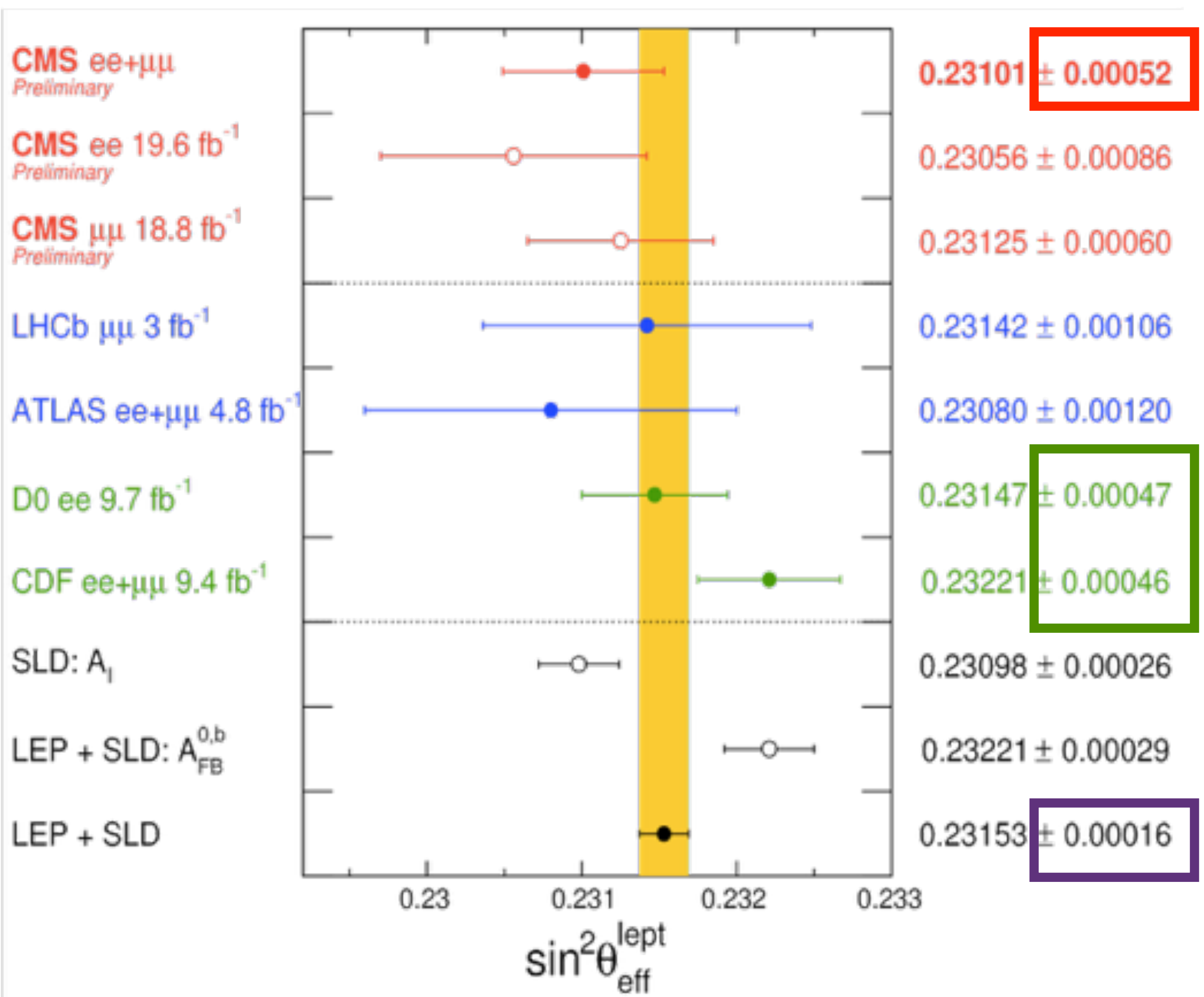
The Best $\sin^2\theta^{lep}_{eff}$ results at the LHC

- Competitive with Tevatron results, despite quark direction dilution

$$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = 0.23101 \pm 0.00036(\mathrm{stat}) \pm 0.00018(\mathrm{syst}) \pm 0.00016(\mathrm{theory}) \pm 0.00030(\mathrm{pdf})$$

$$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = 0.23101 \pm 0.00052.$$

- Best measurements remain LEP+SLD: ±0.00016



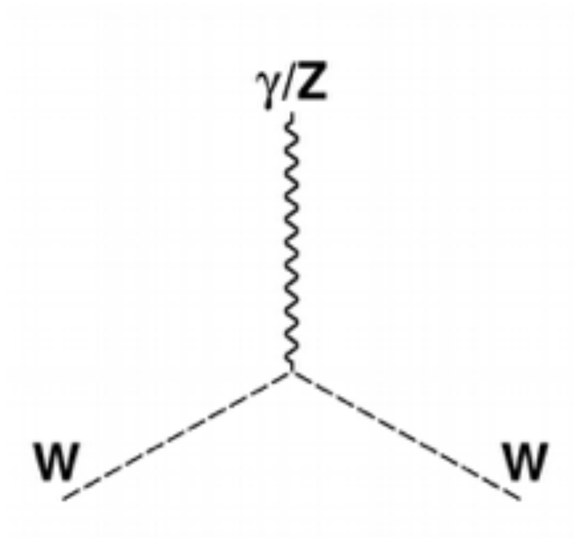
Hadron Collider measurements

Error (10^{-3})	Stat	Syst	PDF
CMS 8 TeV	0.36	0.24	0.30
ATLAS 7 TeV	0.5	0.6	0.9
LHCb ($\mu\mu$)	0.73	0.52	<0.56
D0 (ee only)	0.43	0.08	0.17
CDF	0.43	0.07	0.16

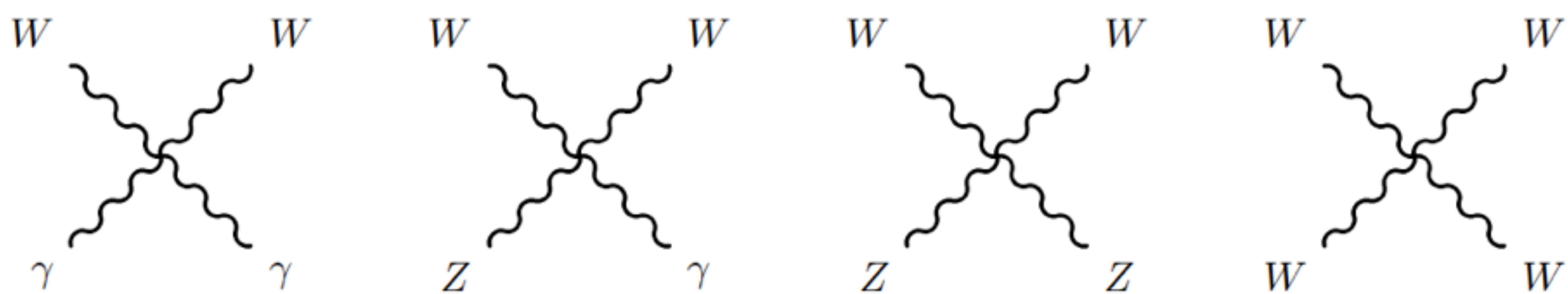
- Uncertainties for LHC measurements will decrease as luminosity increases
- LHCb measures very forward rapidity (upto 4) - potentially measure high precision results.

Electroweak boson couplings

Triple Gauge Coupling (TGC)



Quartic Gague Coupling (QGC)



- $SU_L(2)XU(1)_Y$ Gauge theory defines uniquely Gauge Boson Couplings
  - No other couplings allowed, e.g. no neutral TGC such as ZZZ
- Precise measurements in multi boson final states test the EW theory!
  - NLO EW correction and NNLO QCD correction calculated

Total Xsec $\sigma_{\text{meas}} = \frac{N_{\text{meas}}}{AC\mathcal{L}_{int}}$ where $N_{\text{meas}} = N_{\text{obs}} - N_{\text{bkg}}$, $\mathcal{L}_{int}$ = integrated luminosit

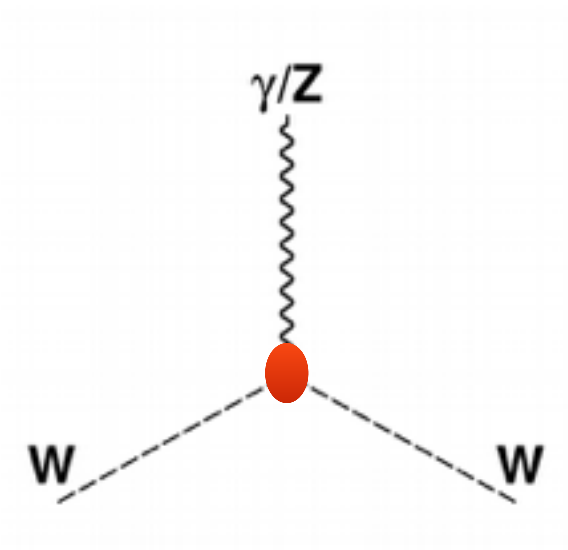
$A = \frac{N^{\text{gen.}}_{\text{total}}}{N^{\text{gen.}}_{\text{fiducial}}}$ theoretical only uncertainty

Fid Xsec $\sigma_{\text{fid}} = \frac{N_{\text{meas}}}{C\mathcal{L}_{int}}$

$C = \frac{N^{\text{gen}}_{\text{fiducial}}}{N^{\text{reco}}_{\text{fiducial}}} \frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}}$ the. + exp. uncertainty

Unfolded differential Xsec: detailed test of the SM gauge structure!

Anomalous TGC and QGC



Add terms to the SM Lagrangian with minimal constraint

$$ig_1^V\left(W_{\mu\nu}^{+}W^{-\mu} - W_{\mu\nu}^{-}W^{+\mu}\right)V^{\nu} + i\kappa_V W_{\mu}^{+}W_{\nu}^{-}V^{\mu\nu} + i\frac{\lambda_V}{M_W^2}V^{\mu\nu}W_{\nu}^{+\rho}W_{\rho\mu}^{-}$$ (V= γ or Z)

K. Hagiwara et al. PhysRevD.48.2182

Preserve unitarity using Form factor $\zeta(\hat{s}) = \frac{\zeta_0}{(1+\hat{s}/\Lambda_{FF}^2)^n}$

Moving to EFT: discussed under LHCEW WG

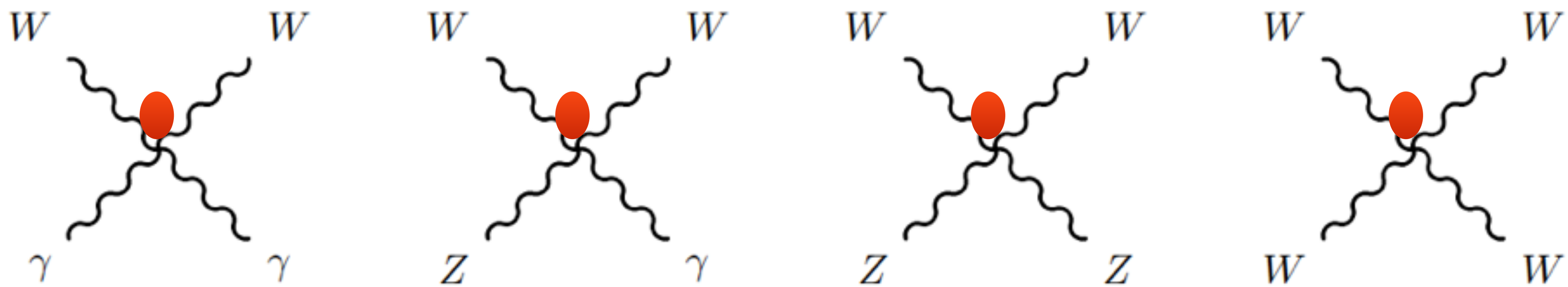
$$L_{EFT} = L_{SM} + \sum_i \frac{C_i^d}{\Lambda^{d-4}} O_i^d$$

Unitarization Form factor $\frac{1}{(1+\hat{s}/\Lambda_{FF}^2)^2}$ or energy cut-off

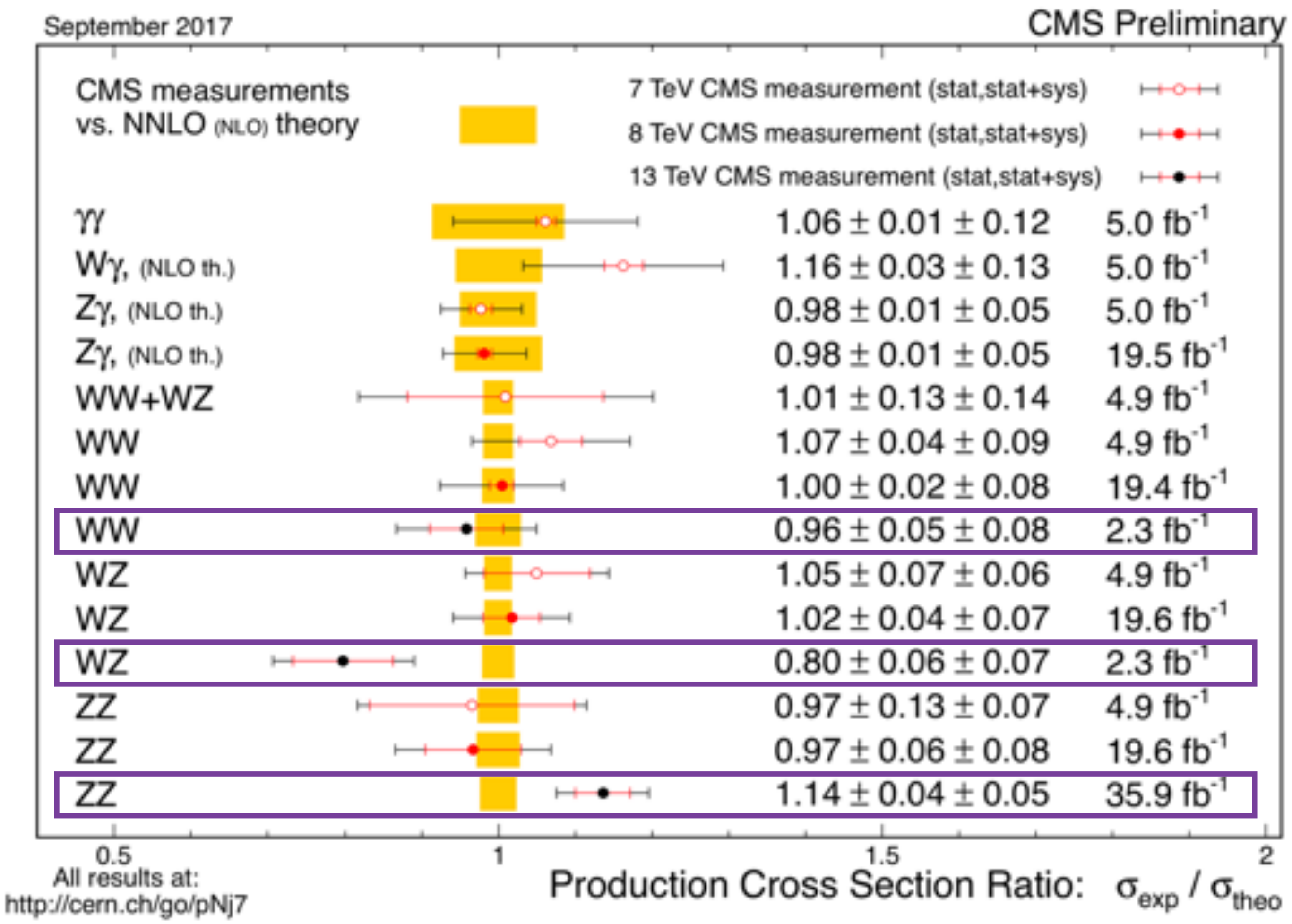
- The adapted model assumes Dime8 operators only impact QGC with no effect on TGC

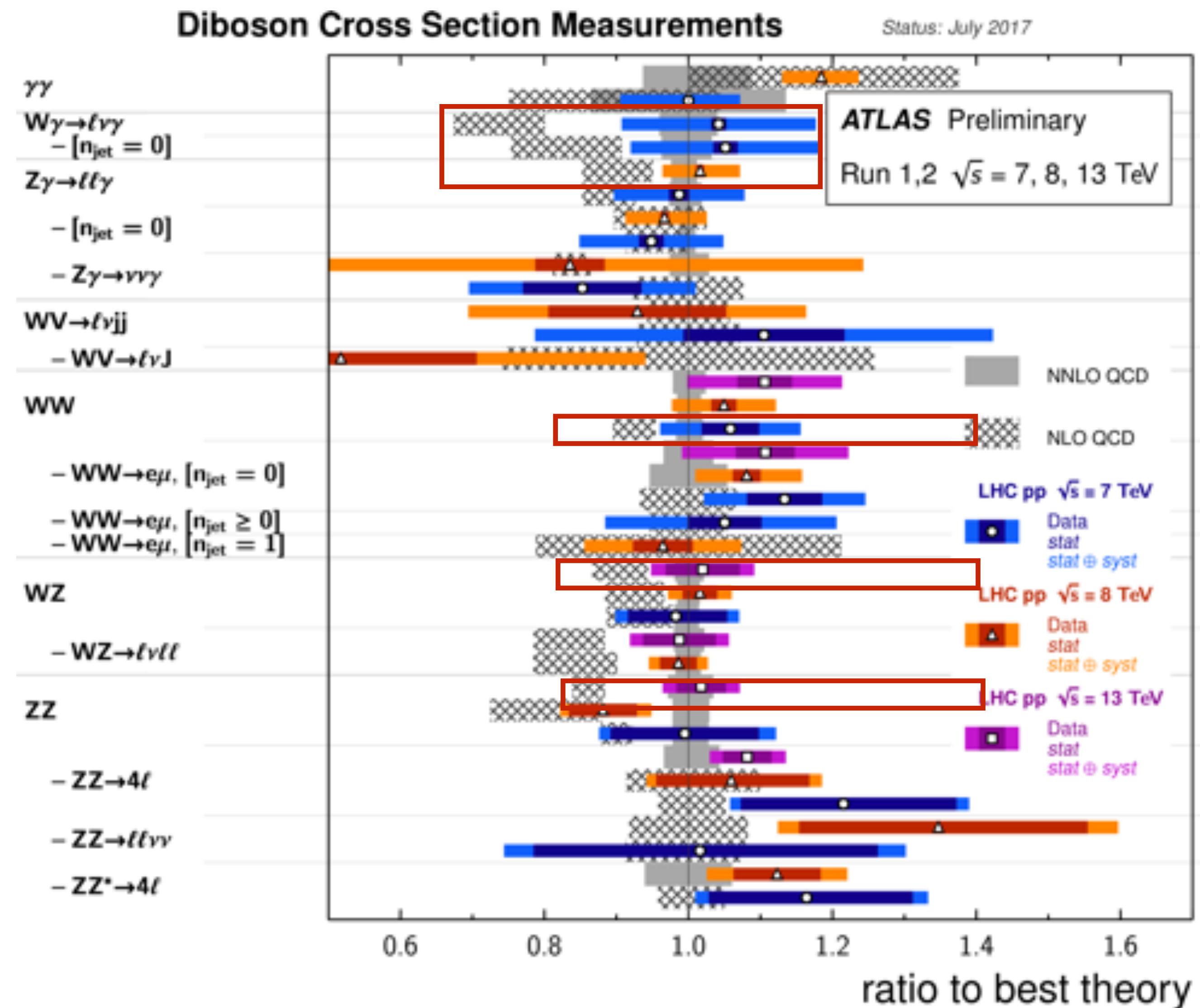
example of Dim8 $\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$

- Constrain from multi-channels including VBS diboson production



Diboson cross section

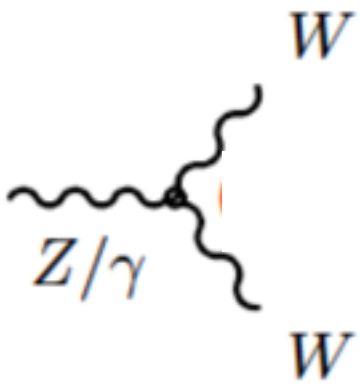




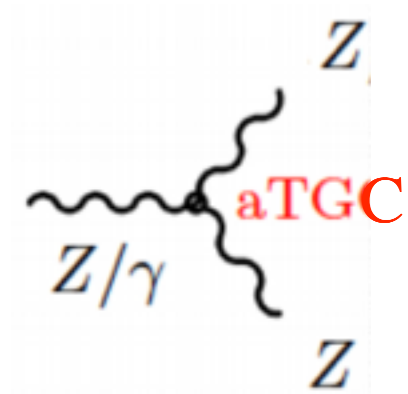
- Overall good agreement with the Standard Model
  - NNLO improves agreement substantially
  - NNLO reduces uncertainty to 10~20% from NLO at 60% (arXiv: 1604.08576))
- Almost all recent measurements are limited by systematics uncertainties

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

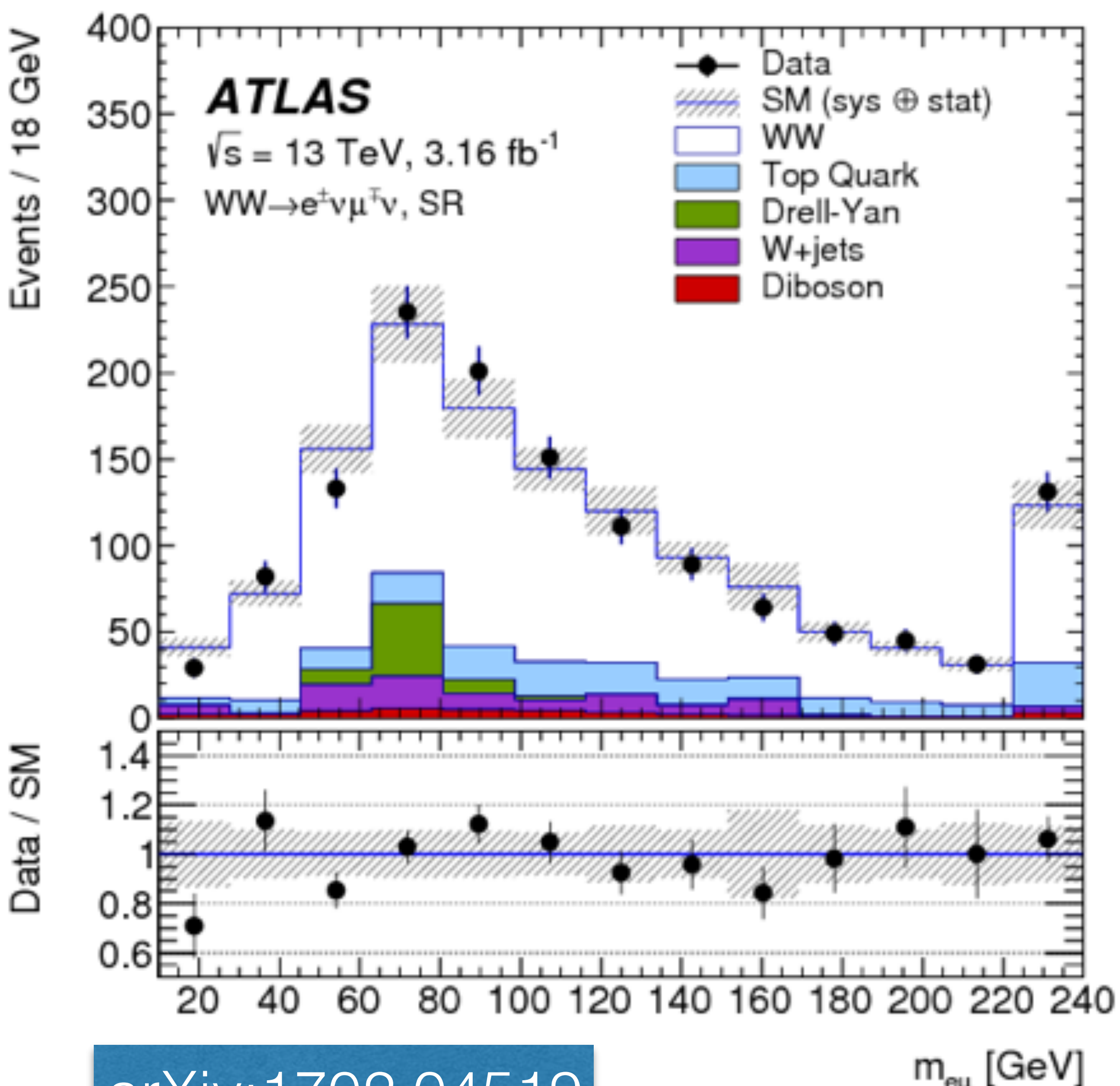
Disobey differential cross section



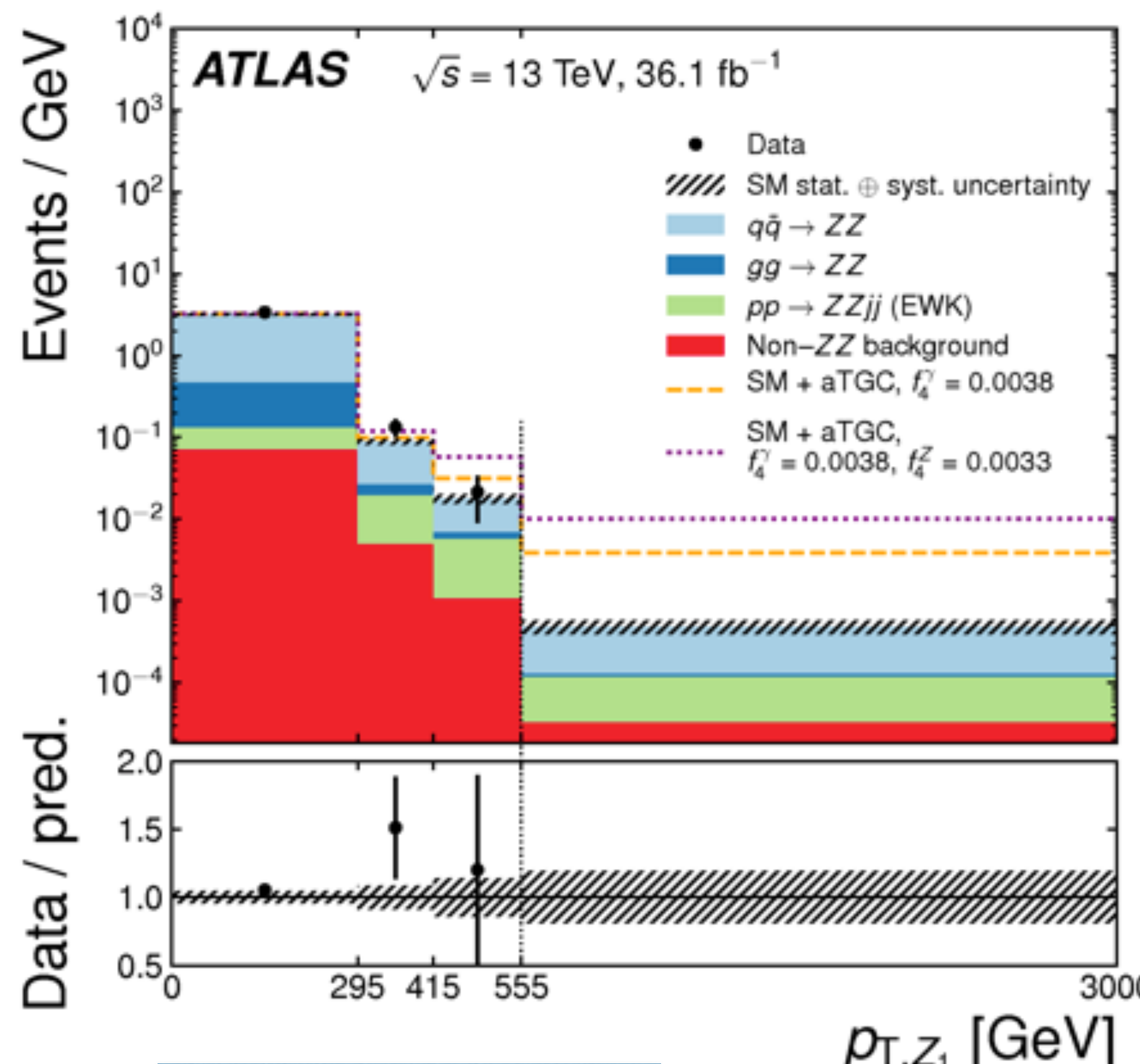
- 0 or 1 jet analysis. Signal MC normalized to NNLO Xsec
- Systematic dominant analysis
- ~10% uncertainty dominated by jet systematics



- Statistics and systematic getting comparable at 5%.
- Dominant systematics is lepton efficiency



arXiv:1702.04519

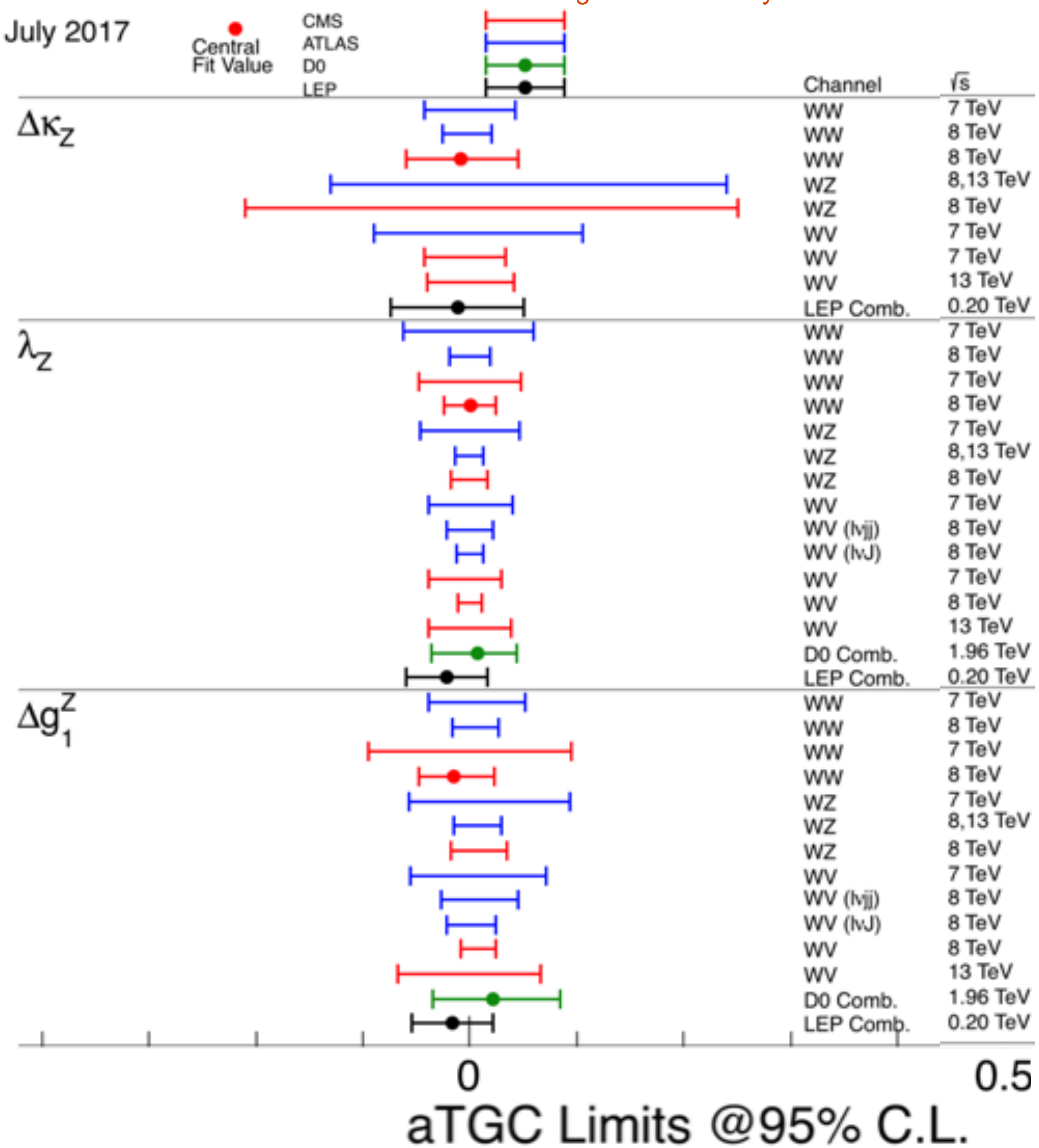


arXiv:1709.07703

aTGC limits

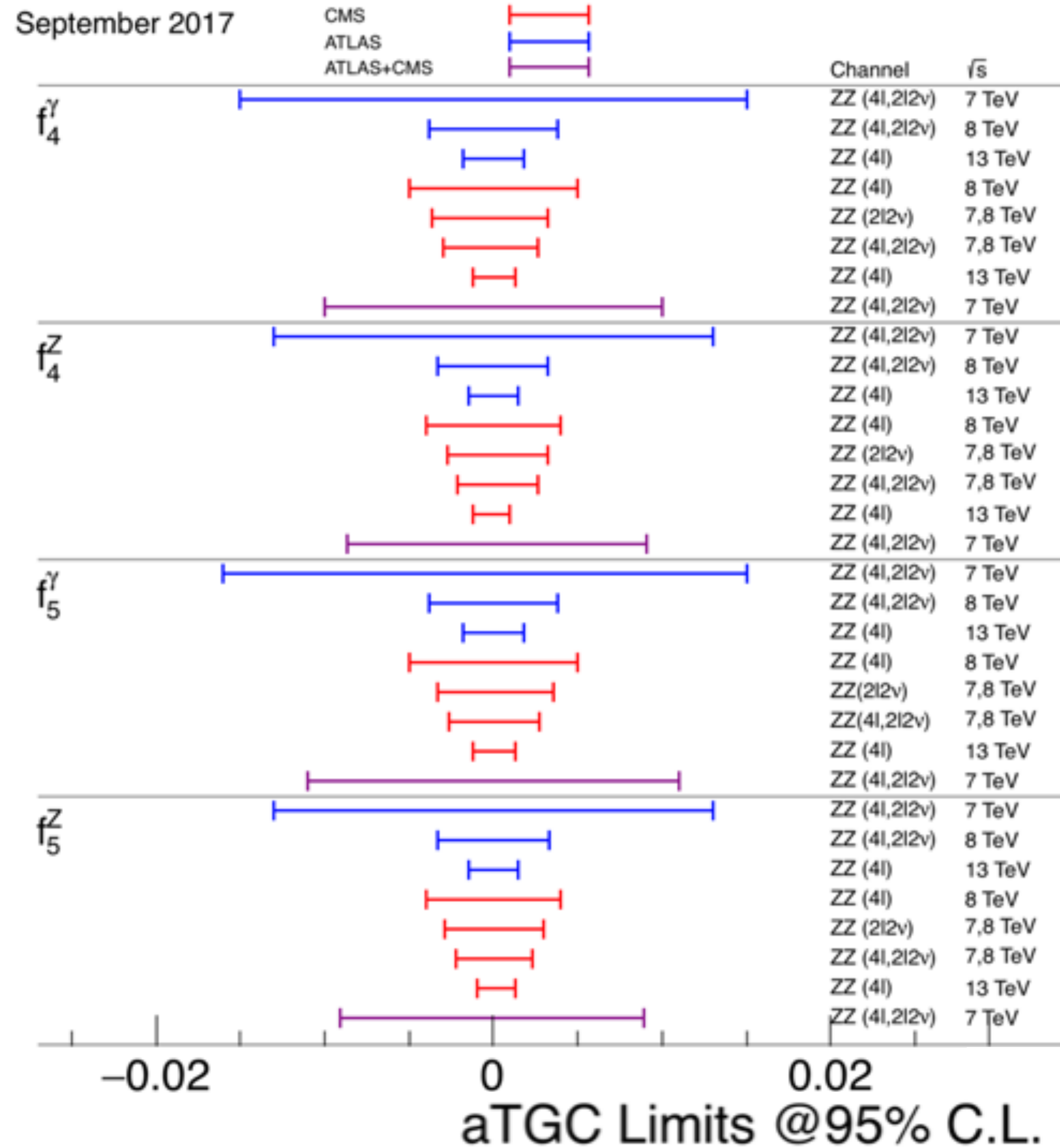
charged dim-6

K. Hagiwara et al. PhysRevD.48.2182



neutral dim-8

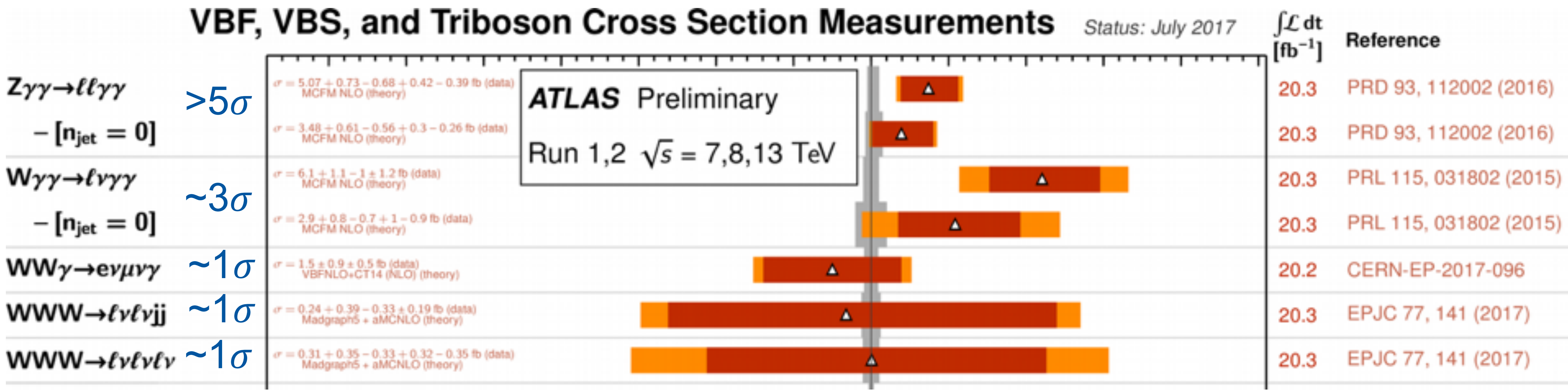
G. J. Gounaris et al. PRD 61, 073013

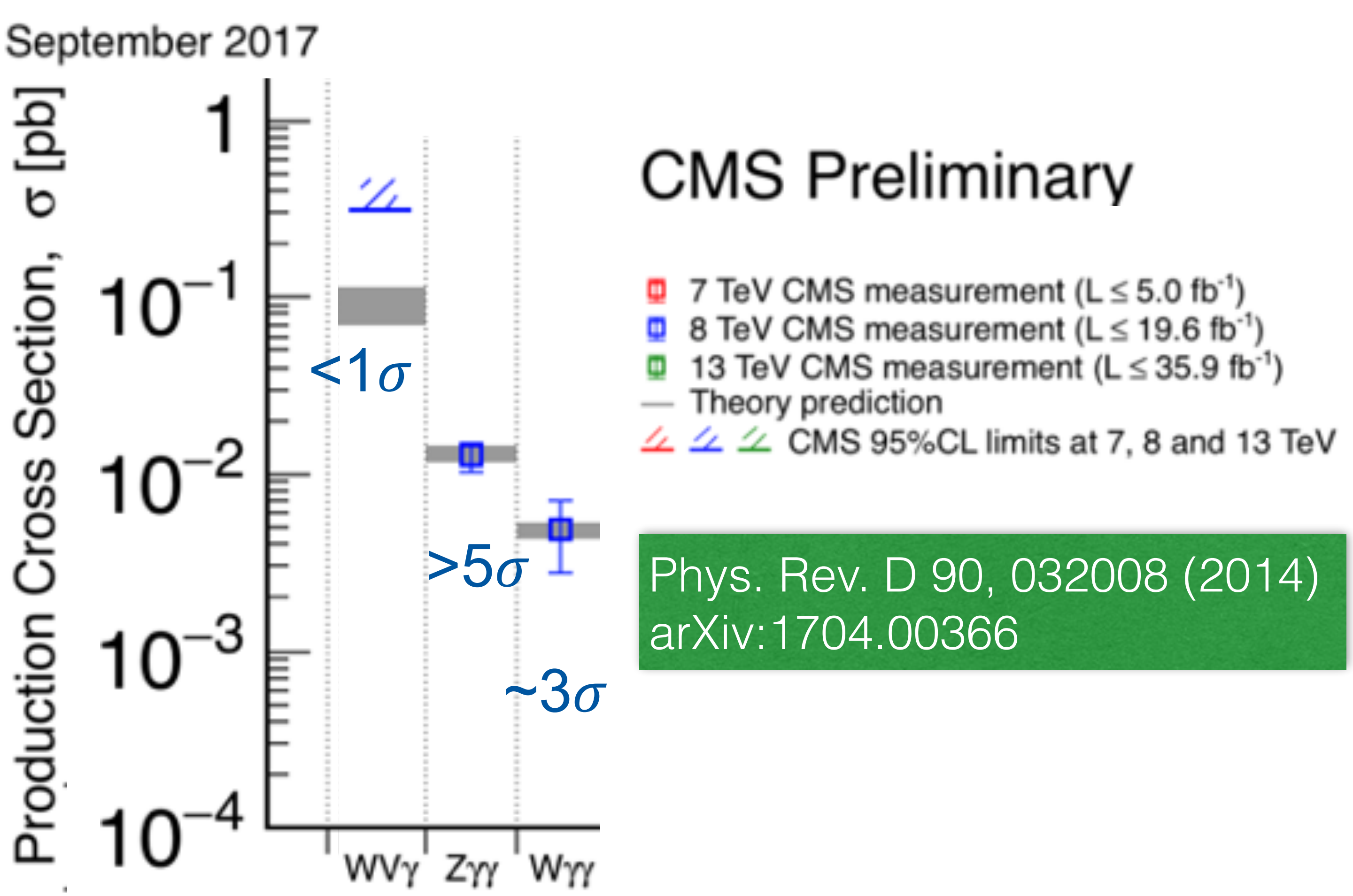


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCEW

Triboson Summary

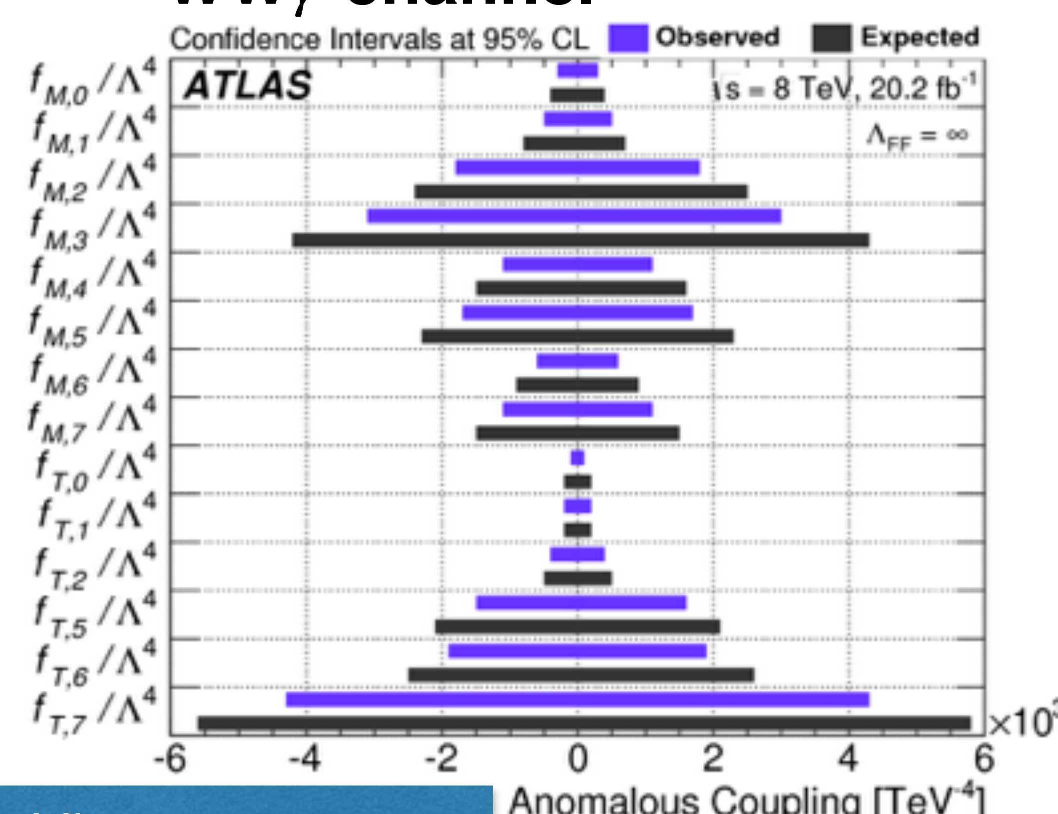
Mostly statistics uncertainty dominated.
Largest systematic in all cases is on fake background model.





Phys. Rev. D 90, 032008 (2014)
arXiv:1704.00366

WWγ channel

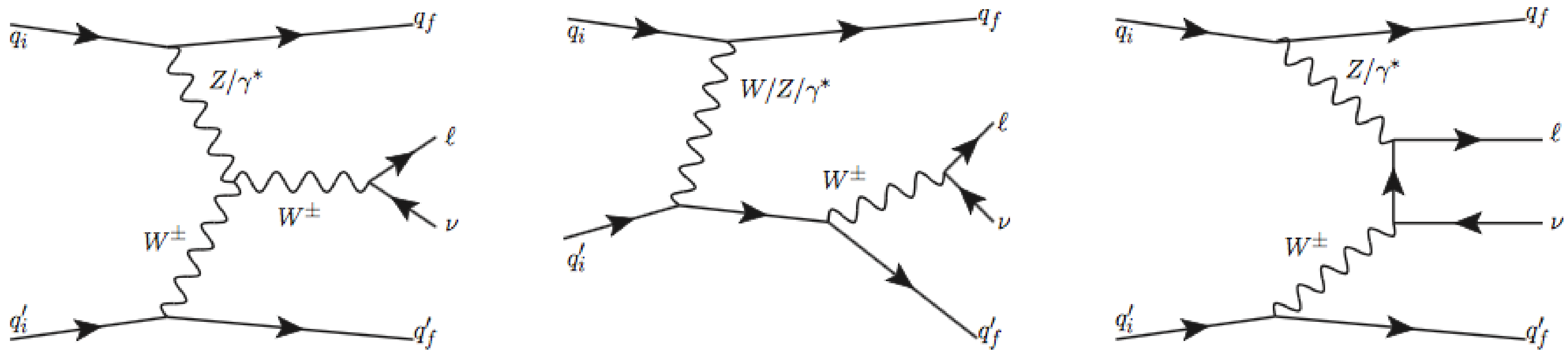


arXiv:1707.05597

Vector Boson Fusion Vjj

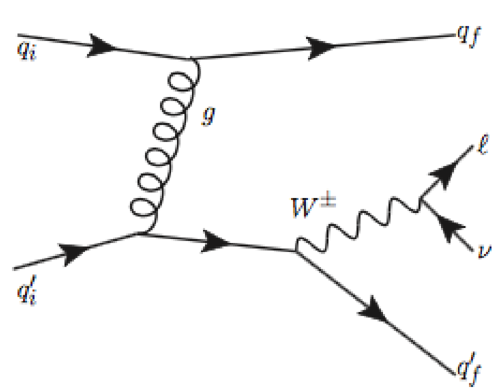
VBF W bremsstrahlung non-resonant

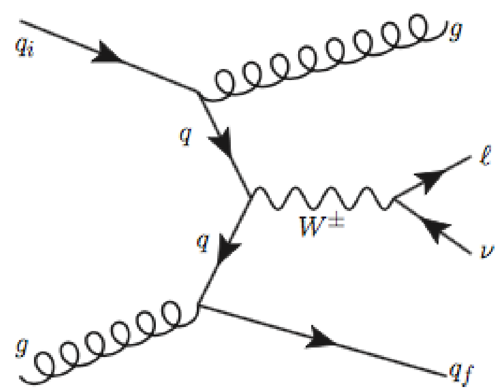
Signal



(a) Vector boson fusion (b) W bremsstrahlung (c) Non-resonant

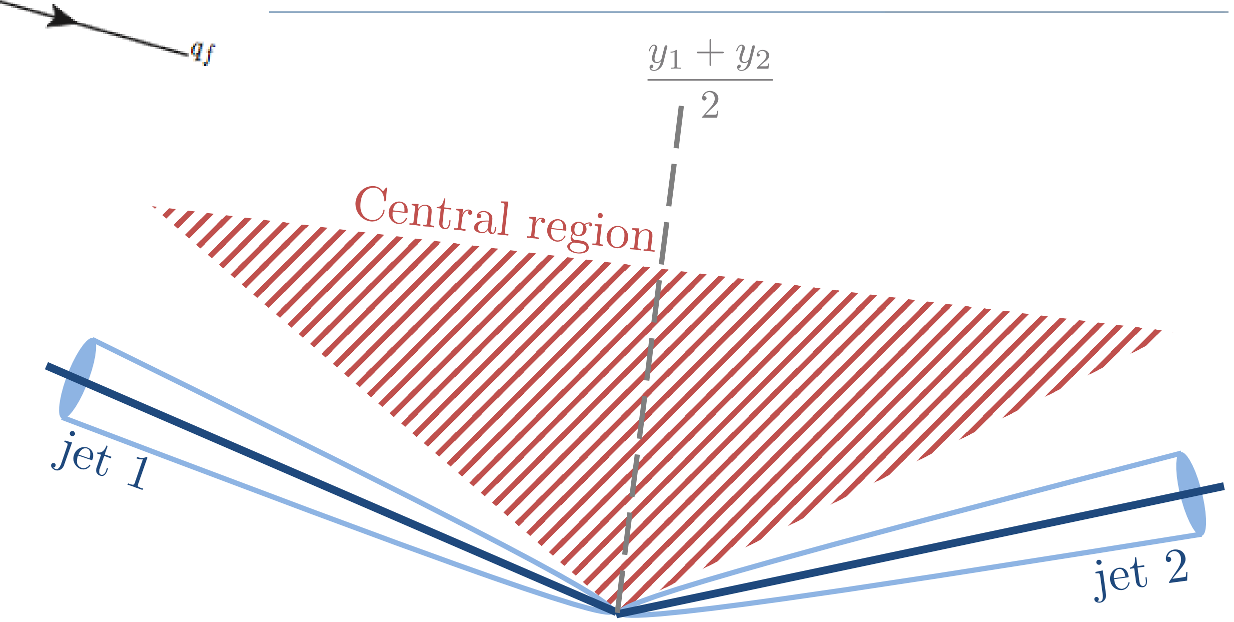
Background (x10 Signal)



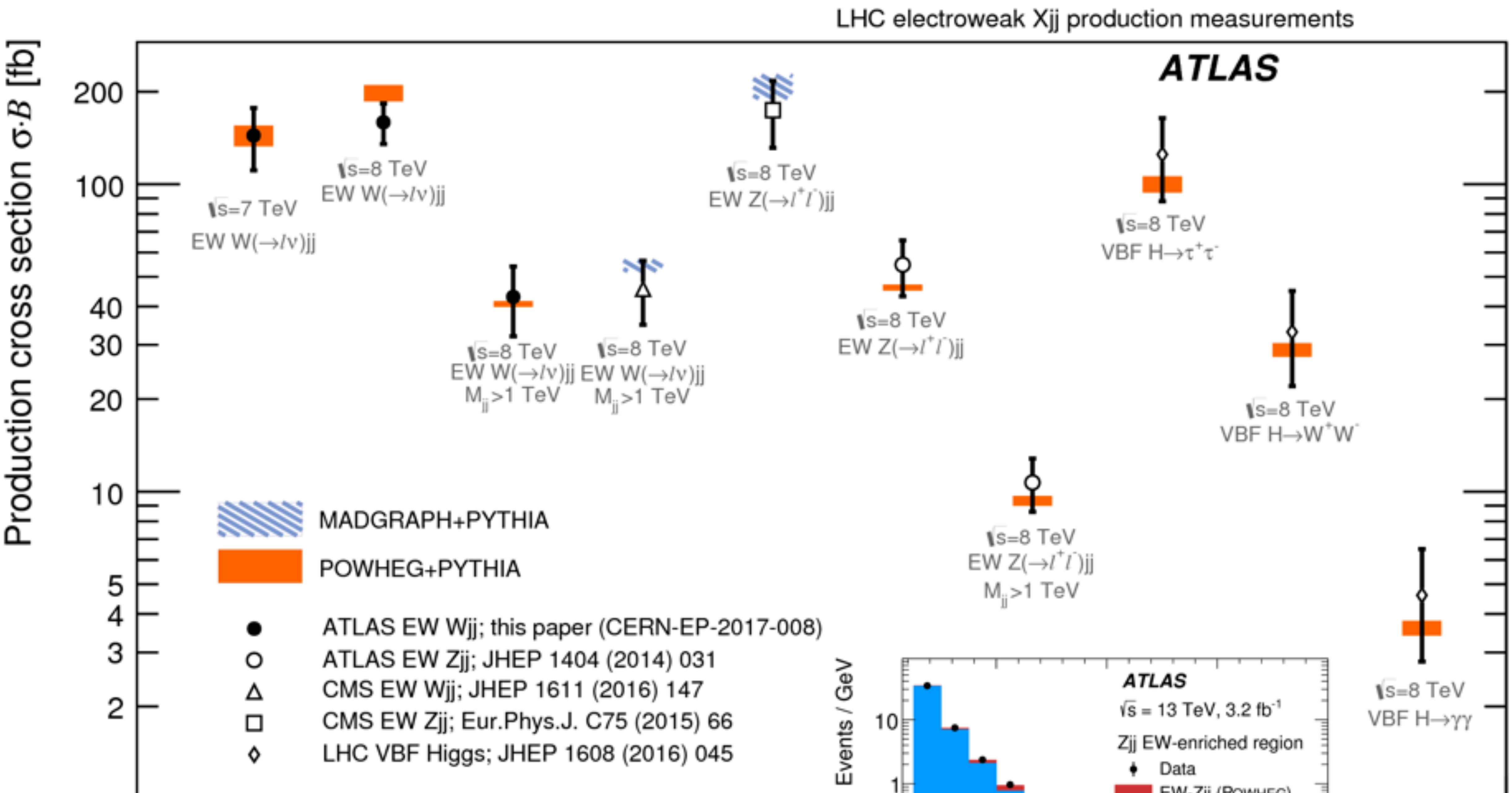


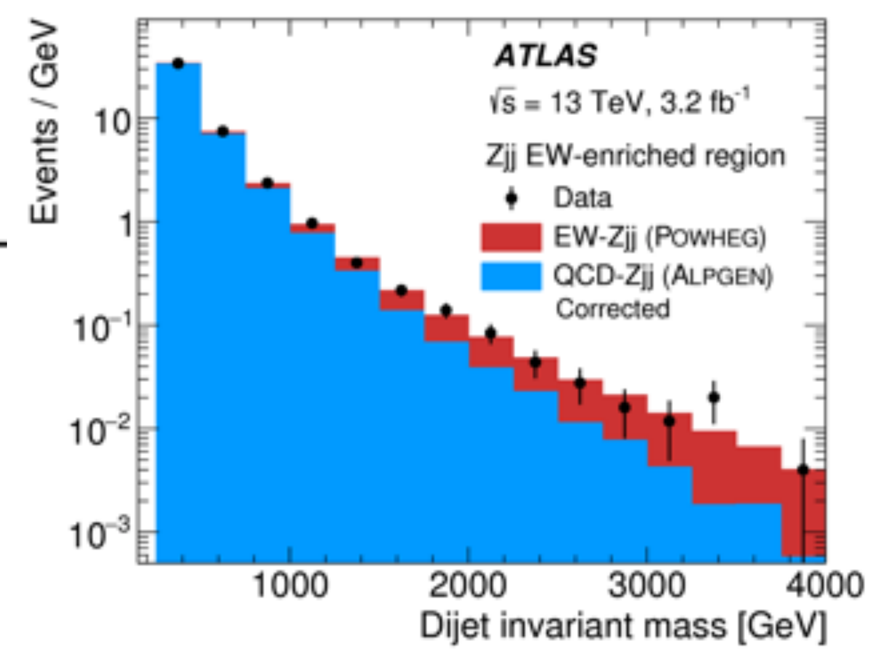
Topology to enhance EW:

- central W/Z+2 forward jets with large m_{jj}
- Only charged lepton accounted in this talk.



VBF Vjj Summary



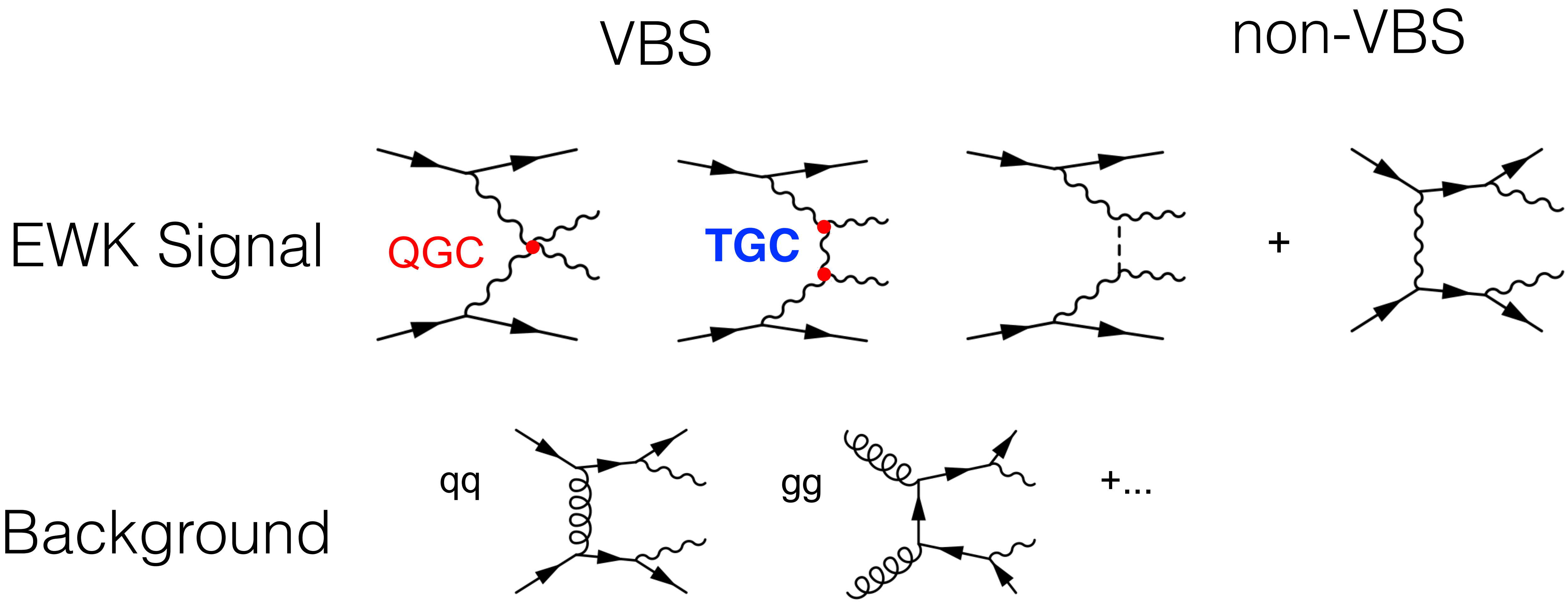


Dominant uncertainties:
Jet energy scale and the statistical uncertainty of the correction from the control region.

arXiv:1709.10264

Vector Boson Scattering: VVjj

- Measurements of the VBS process indirectly reflect/prove **the SM Higgs mechanism** and help searches for new physics in TeV scale.

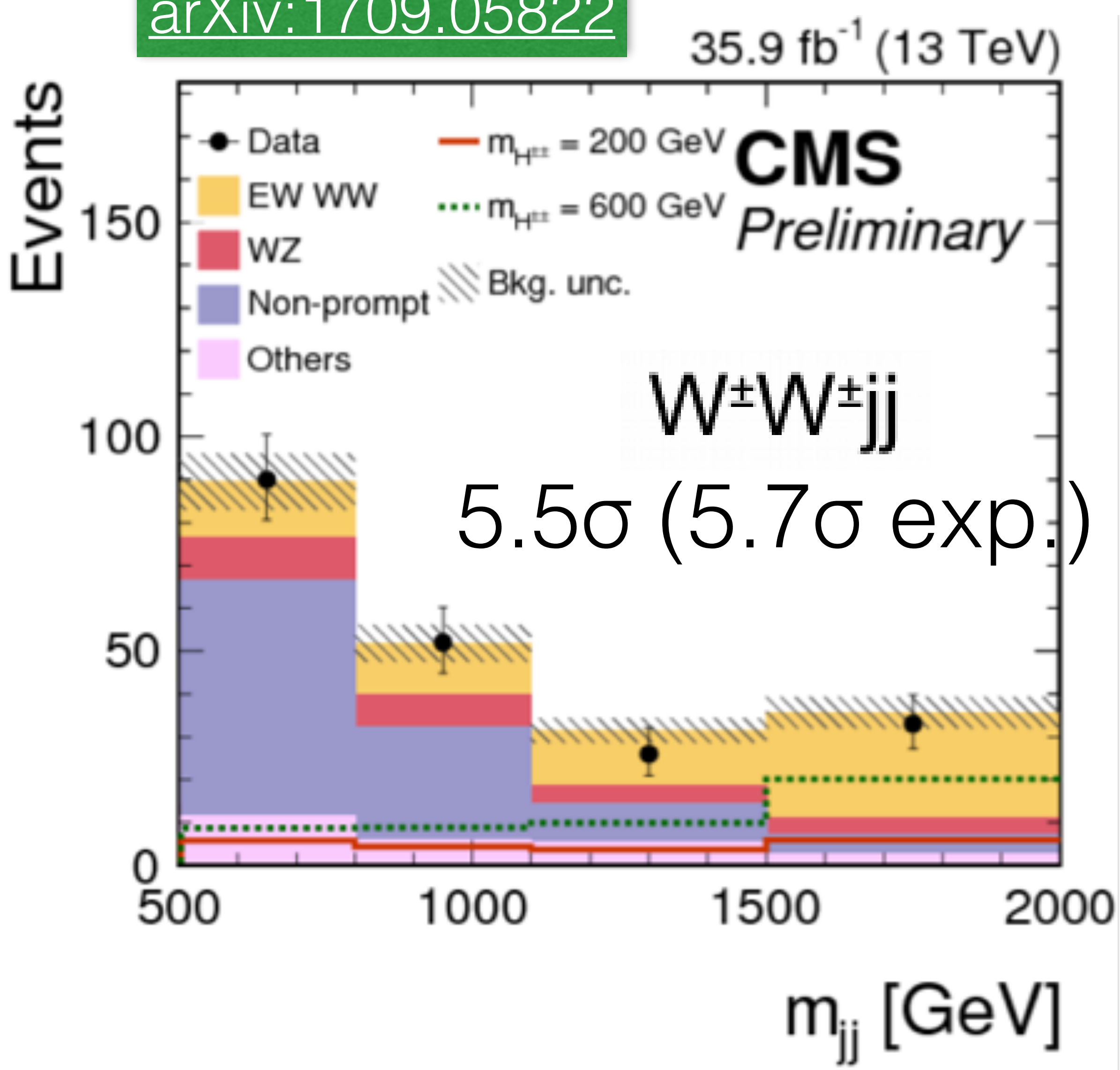


Topology: VV + 2 tagging high p_T jets in the forward-backward regions with large m_{jj}, large rapidity gap and low hadronic activity in between.

Observation of VBS

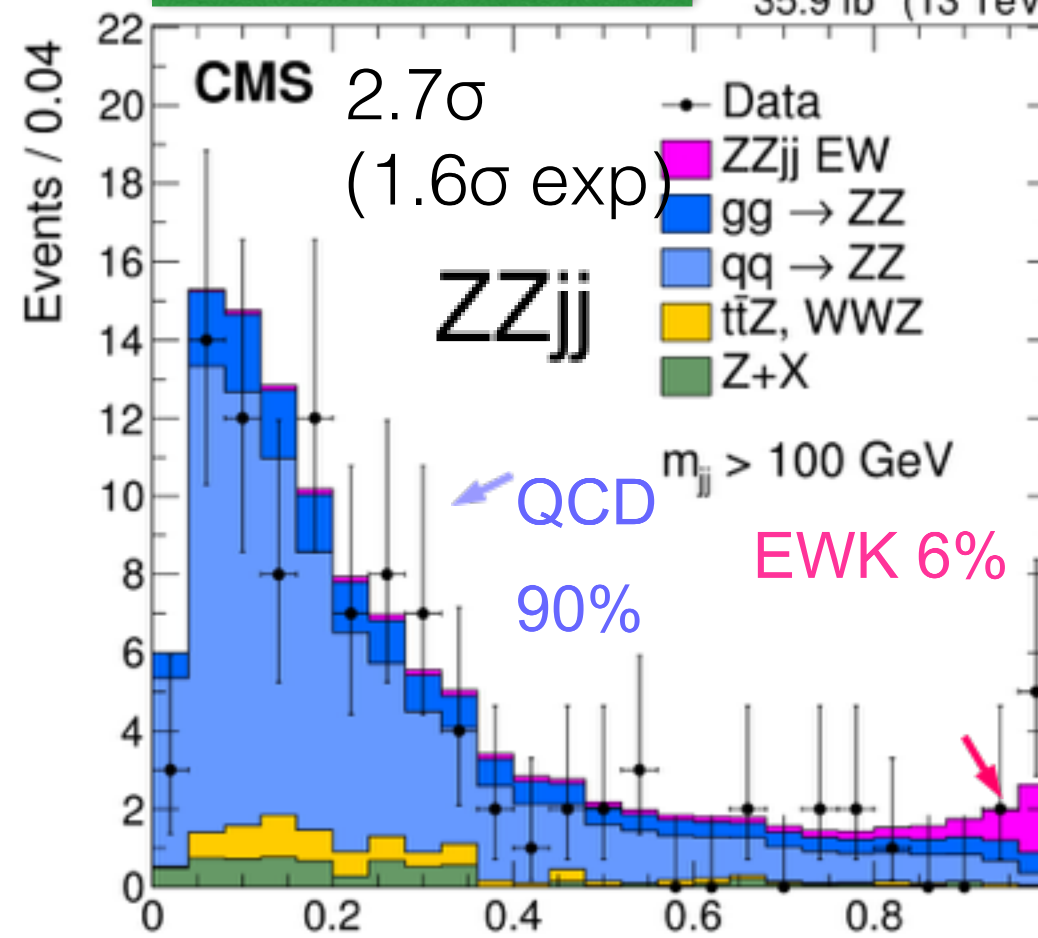
- First **observation** of VBS same-sign WW: a milestone study!
- First study of VBF ZZ: BDT discrimination of large QCD production

arXiv:1709.05822



Yield ratio (LO) = 0.90 ± 0.22

arXiv:1708.02812

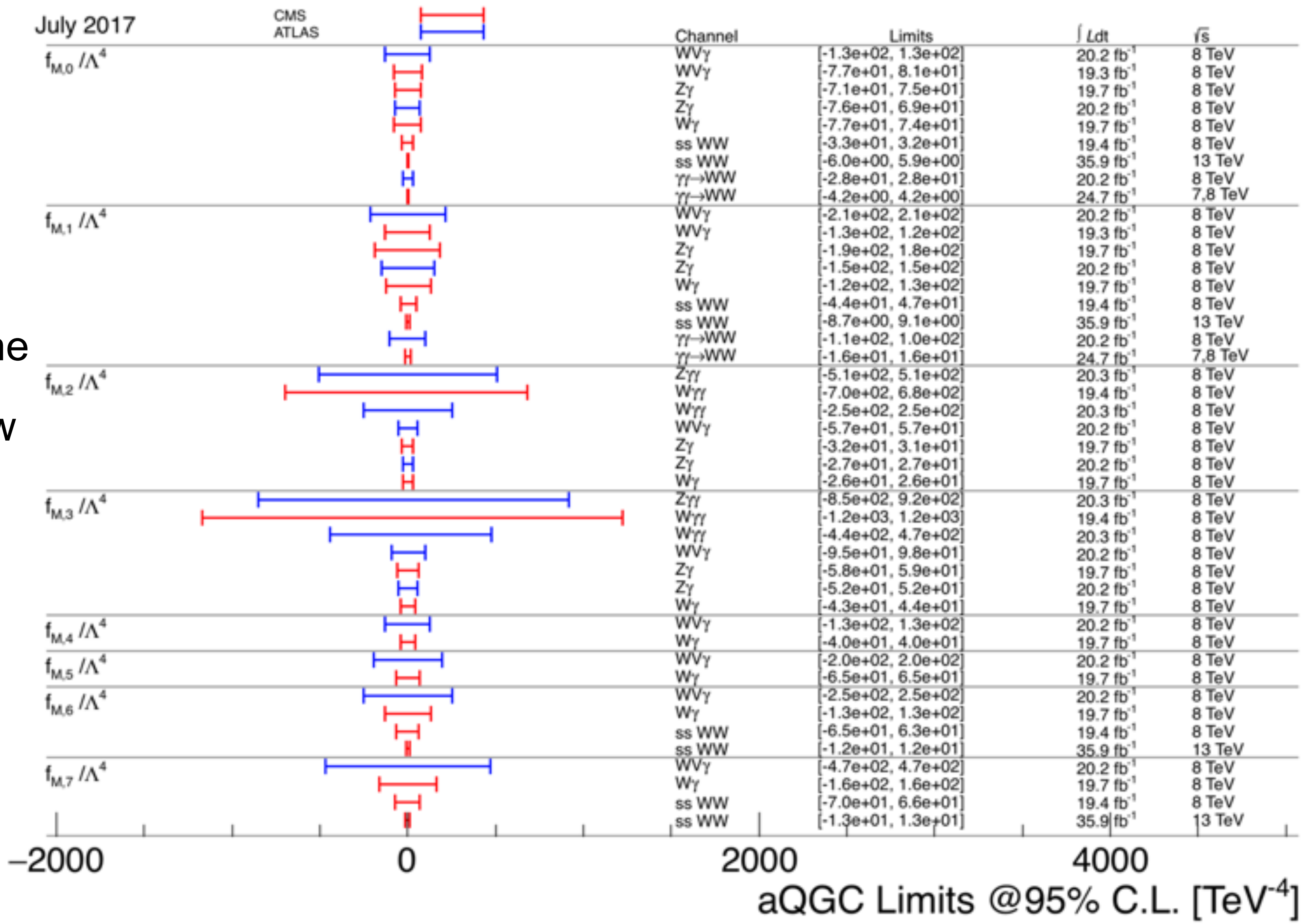


$$\sigma_{\text{fid.}}(\text{EW pp} \to ZZjj \to \ell\ell\ell'\ell' jj) = 0.40^{+0.21}_{-0.16}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})\text{ fb}$$

aQGC Limits results

Some of the limits on the parameters f/Λ^4 are now <1 TeV^{-4}

If one takes f~1 then Λ>1TeV !



Summary

- Thanks for outstanding performance of LHC and experiments
  - Rich program of precision measurements on differential distributions anticipated with larger datasets available, e.g. WW, ZZ, …, etc.
- Precision measurements to constrain virtual corrections
  - Competitive W mass measurements at the LHC
  - Process on measurement of weak mixing angle
- Observation of exciting low cross section processes
  - Measurements of many triboson and VBF channels
  - >5σ observation of VBS process ($W^{\pm}W^{\pm}jj$)
- Multi-bosons analyses are precision tests of the state of the art of the theory :
  - Cross-sections sensitive to NNLO QCD and NLO EWK
  - Probe the EWK gauge structure of the SM : anomalous TGC and QGC