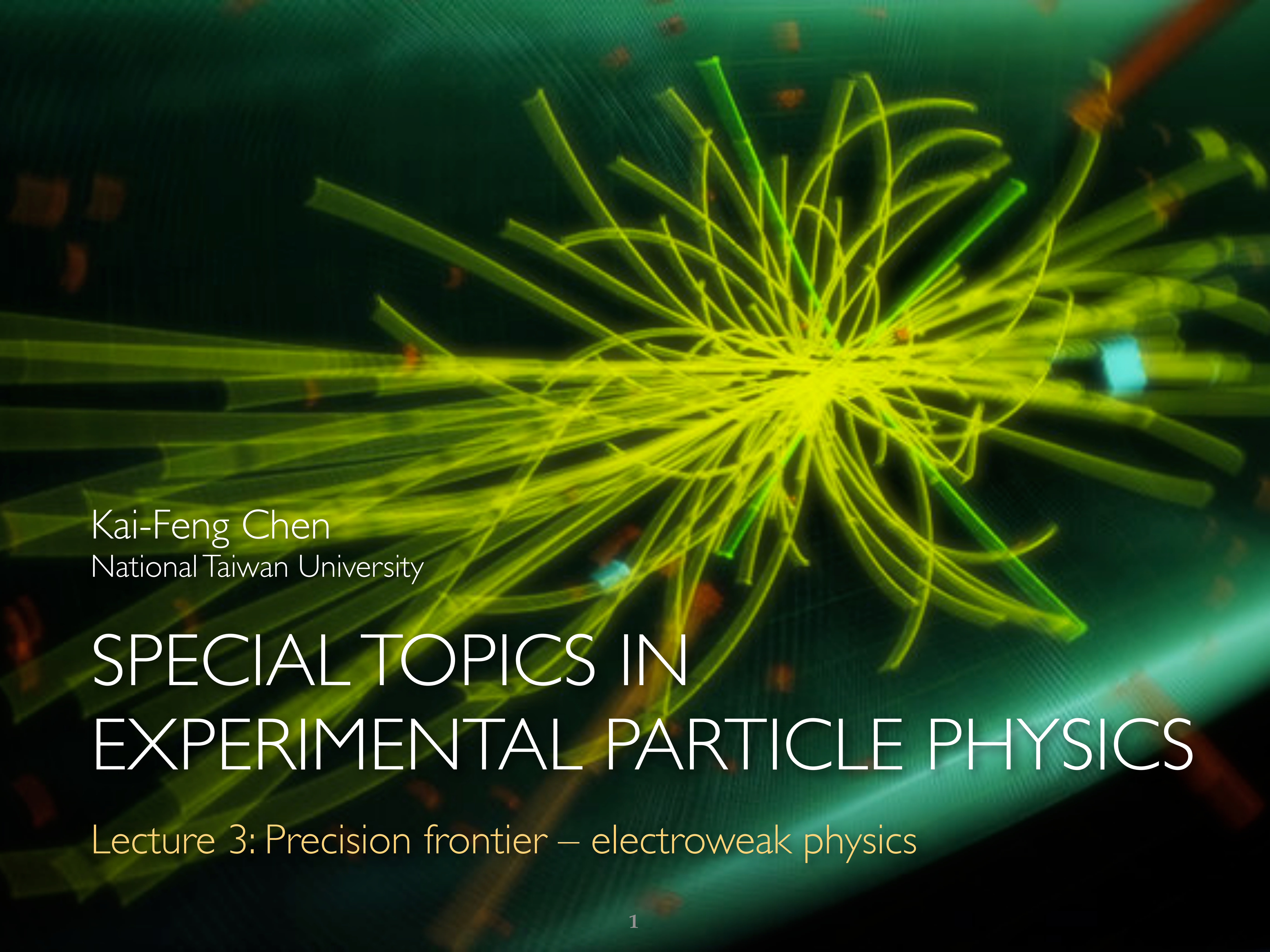


Kai-Feng Chen
National Taiwan University

SPECIAL TOPICS IN EXPERIMENTAL PARTICLE PHYSICS

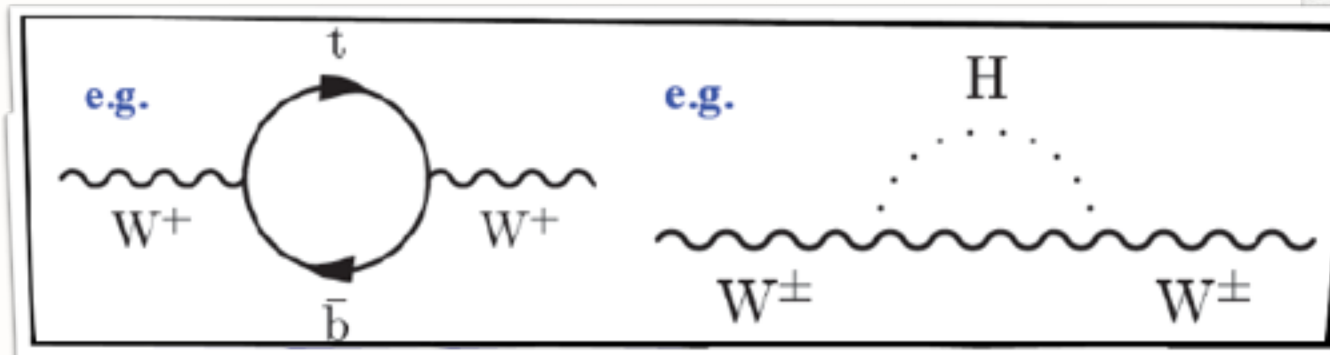
Lecture 3: Precision frontier – electroweak physics

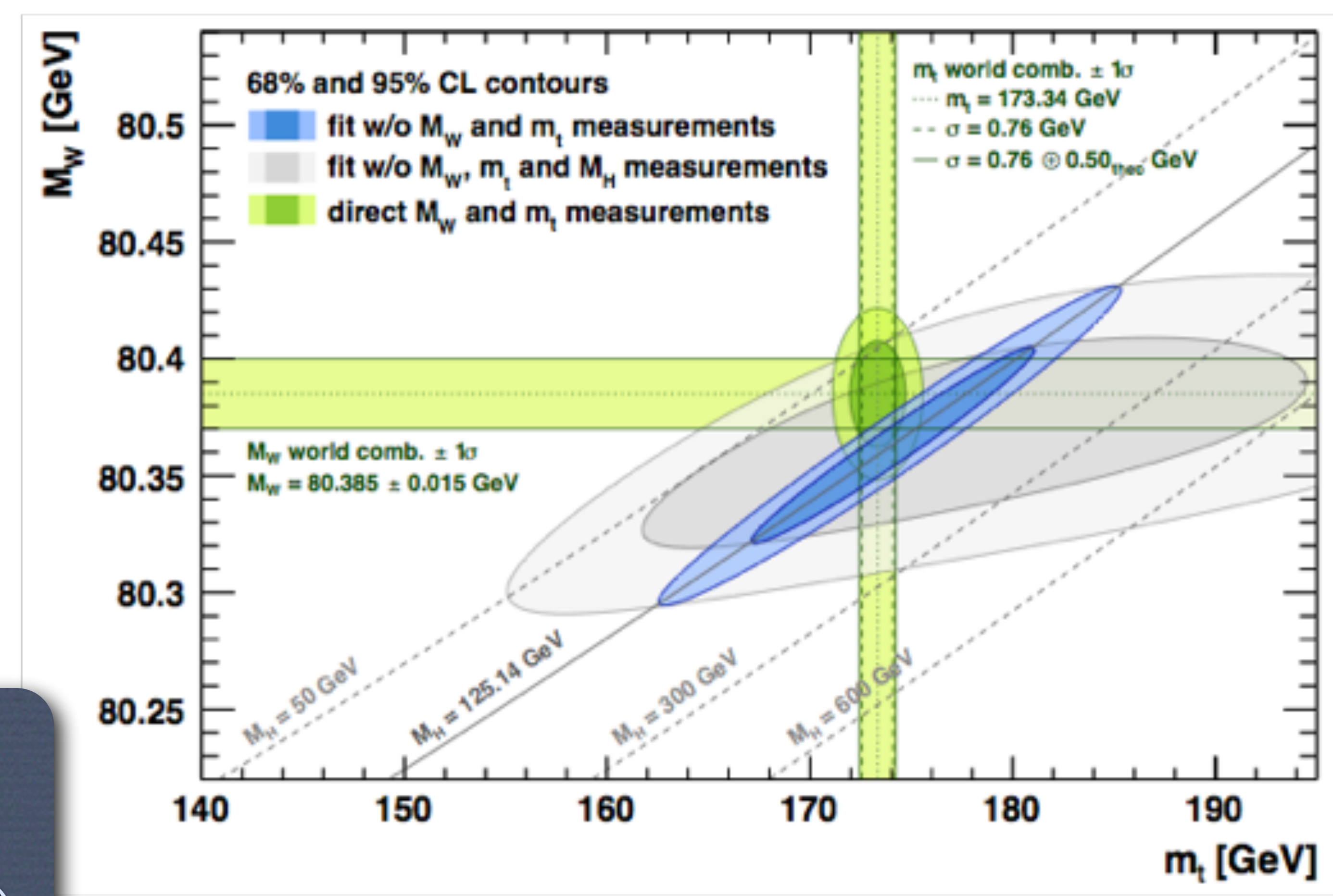
INTRODUCTION

- The standard model in any case is a successful "model". Especially now a SM-like Higgs boson has been discovered.
- However, it is most likely that the standard model is STILL a low-energy approximation to a (close-to) fundamental theory.
- At the LHC, one may be able to discover new particles and interactions of new physics, especially for the upcoming new energy LHC run II.
- Before finding new stuff/based on the history of the particle physics — precision electroweak measurements can provide us indirect access to new physics beyond the SM.

THE PRECISION FRONTIER

- Precision electroweak measurements are sensitive to top quark mass, W boson and the Higgs boson masses via quantum loop corrections.
- As we already introduced at the last lecture, the global EWK fit does give estimates for those masses before the real discoveries.

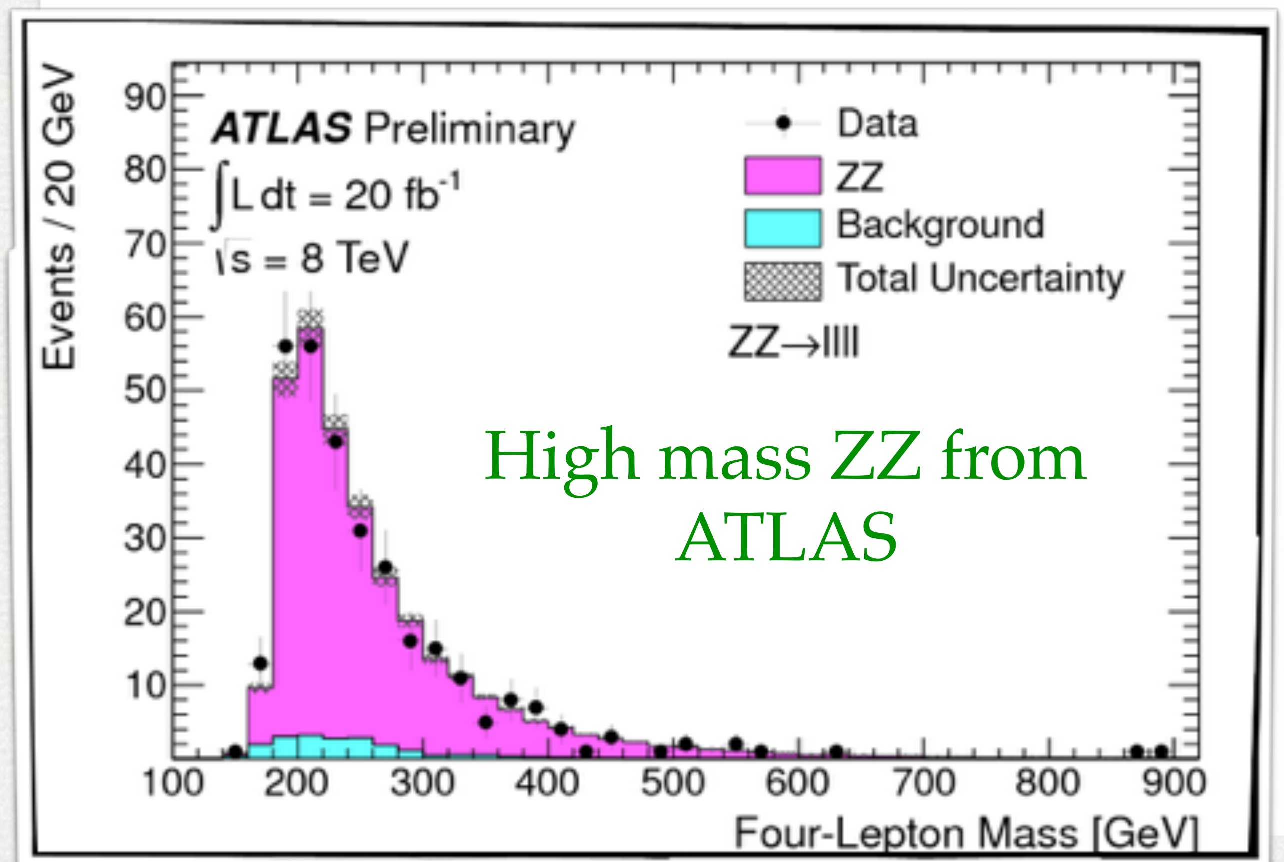


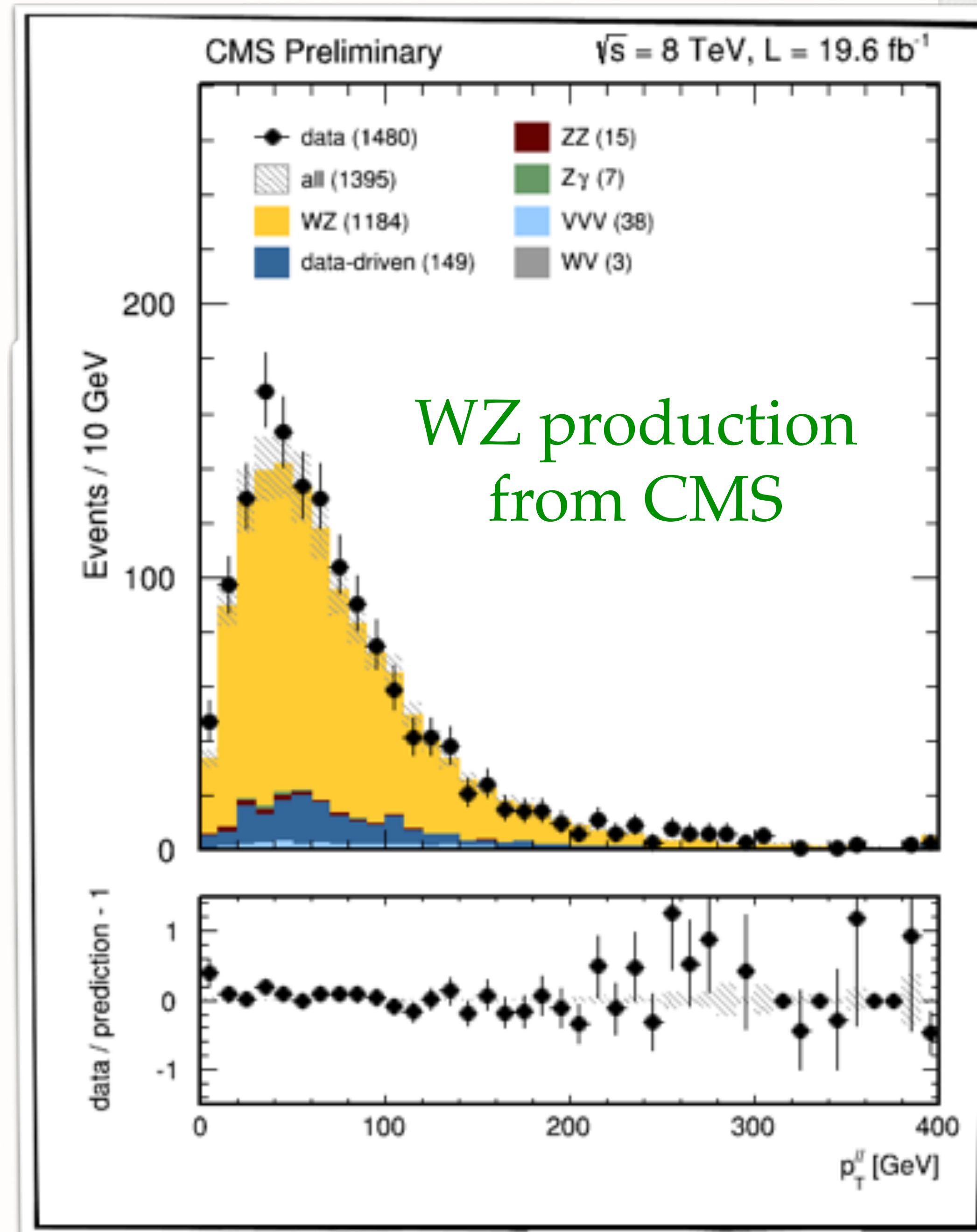


SM-like Higgs discovery at ~126 GeV is compatible with global EWK data at 1.3σ (p-value = 0.18)

THE PRECISION FRONTIER

- The data from the successful LHC Run I provides TeV-scale tests of single and multiple electroweak boson production!
- Several nice examples:

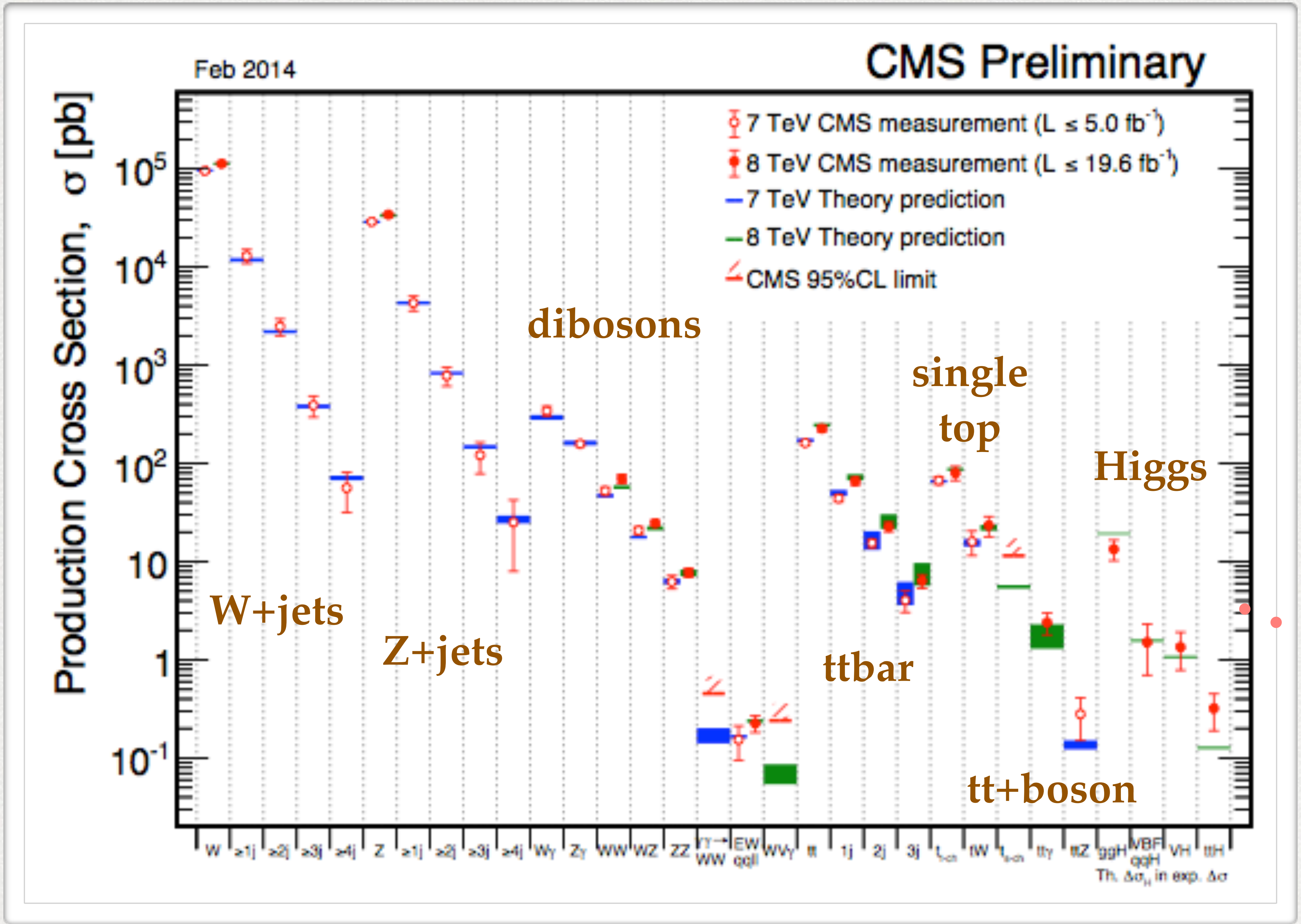




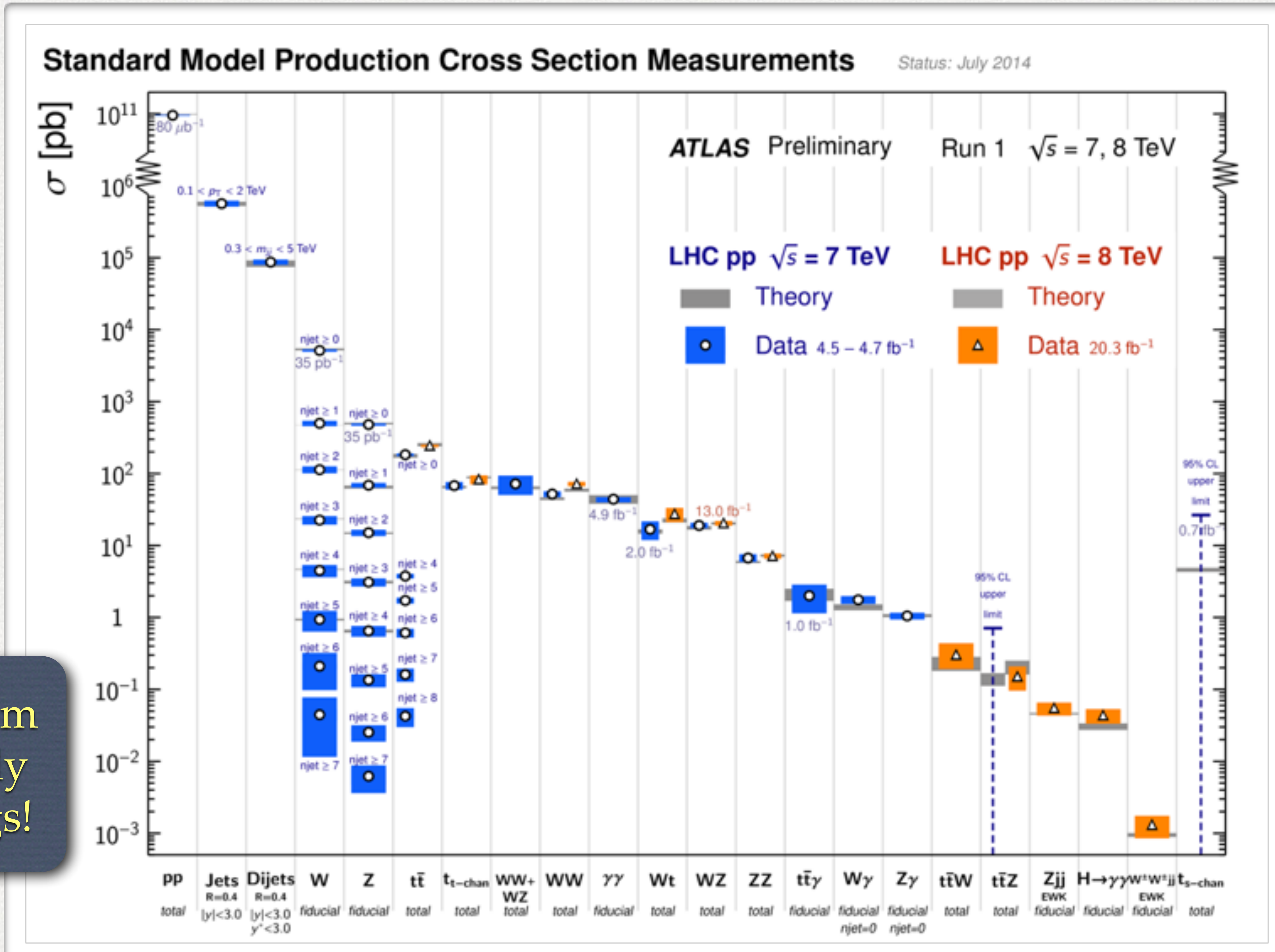
W,Z PRODUCTIONS AND PROPERTIES

- The W boson and Z boson productions are the benchmark processes for the SM physics at the LHC.
- They provide good calibration of the energy scale and the rates. Worked as control samples for many studies.
- Electroweak processes and properties have sensitivity to new physics beyond the SM through radiative corrections.
- Typical W/Z+X events are also the backgrounds for many physics processes of interest. It is necessary to understand these processes in high precision.
- One remark: top-pair events are also very important background sources, in particular for the WW production. However the top events also help to calibrate the jet energy scale.

(PRECISION) MEASUREMENTS



(PRECISION) MEASUREMENTS



The same plot from ATLAS...it already tells a lot of things!

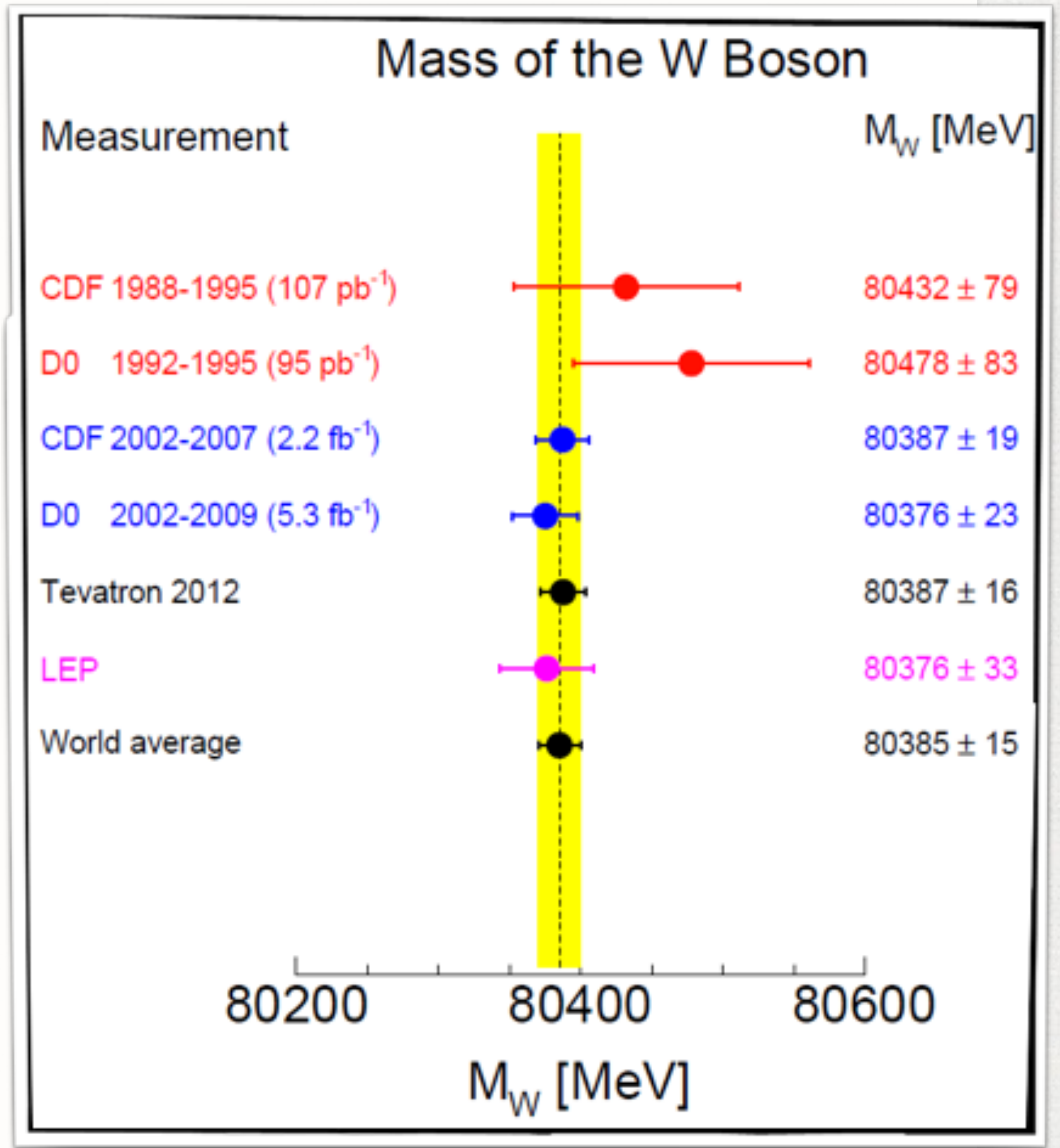
W BOSON: MASS

- The W boson mass is a key parameter in the standard model.
- So far, the measurements of W mass with best precision are from the Tevatron experiments:

CURRENT PRECISIONS

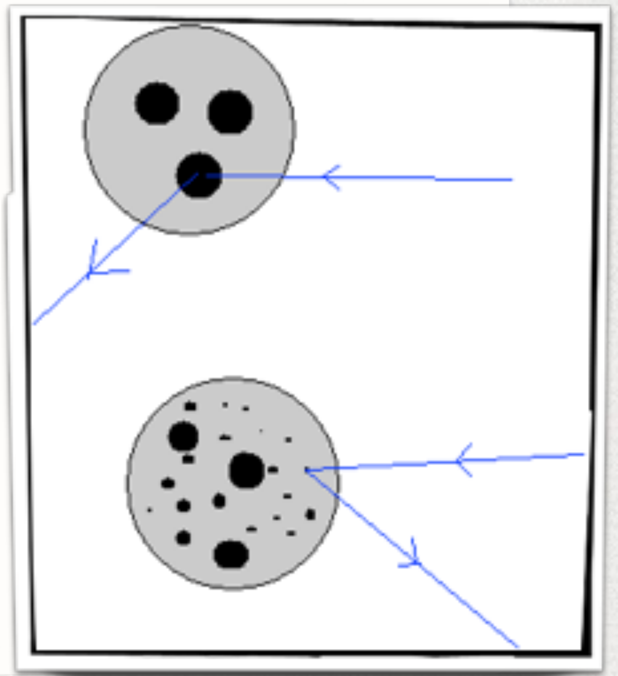
CDF: 19 MeV
D0: 23 MeV
LEP2: 33 MeV
World Average (2012): 15 MeV

Tevatron Combined Projected: 9 MeV



W MASS AT LHC

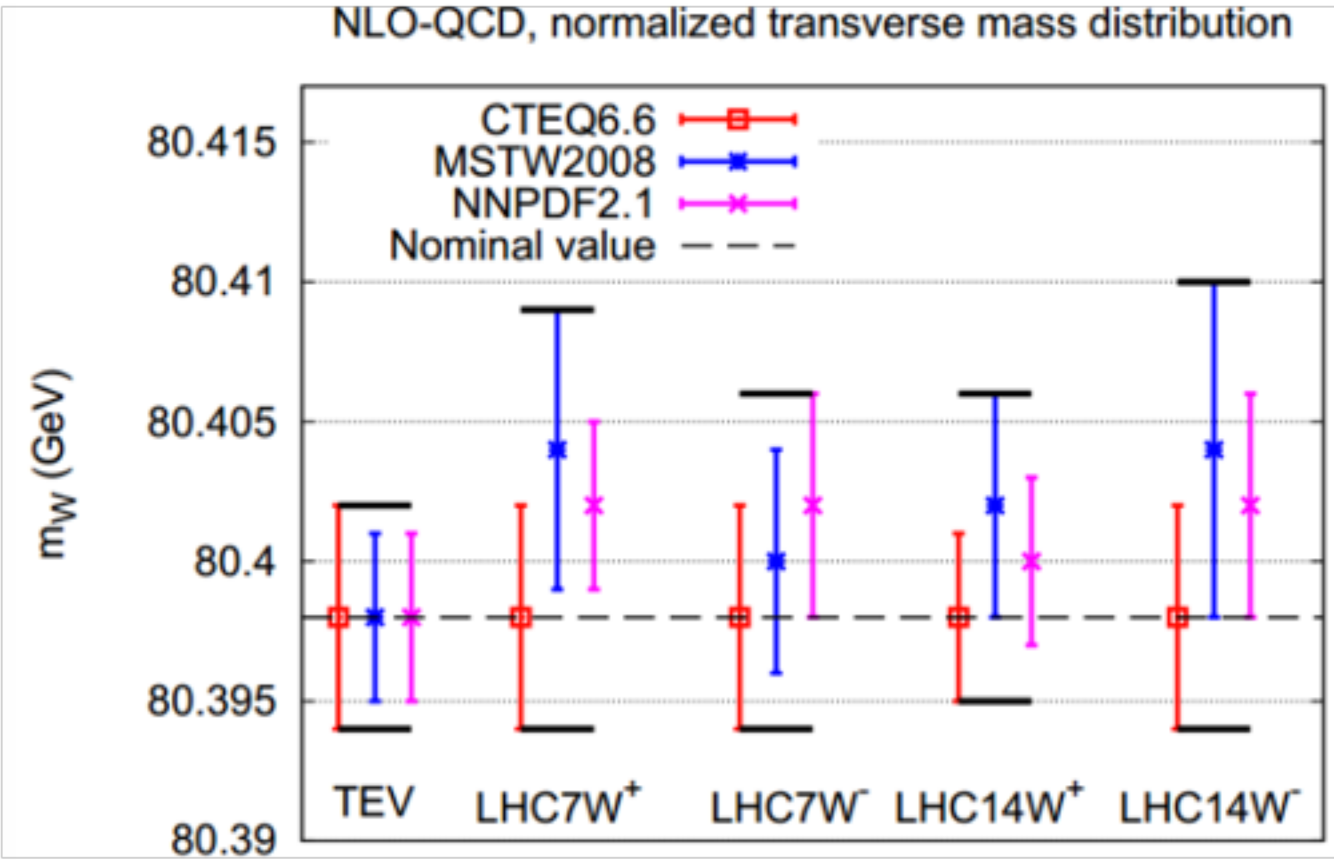
- The LHC experiments have excellent detectors and huge statistics. For example, CMS in full Run I has:
  - ~100 million W(→μν) events
  - ~10 million Z(→μμ) events
- It does have a very good potential for measurements with <10 MeV uncertainty, however:
  - Need significant better **parton distribution functions** (PDFs).
  - The momentum scale of leptons.
  - Precision of hadronic recoil/ missing transverse energy measurement
  - Even the pile-up condition at a higher luminosity.



Statistics is not a problem here!
How to pin down the systematics is critial.

W MASS AT LHC

ref. arXiv:1310.6708



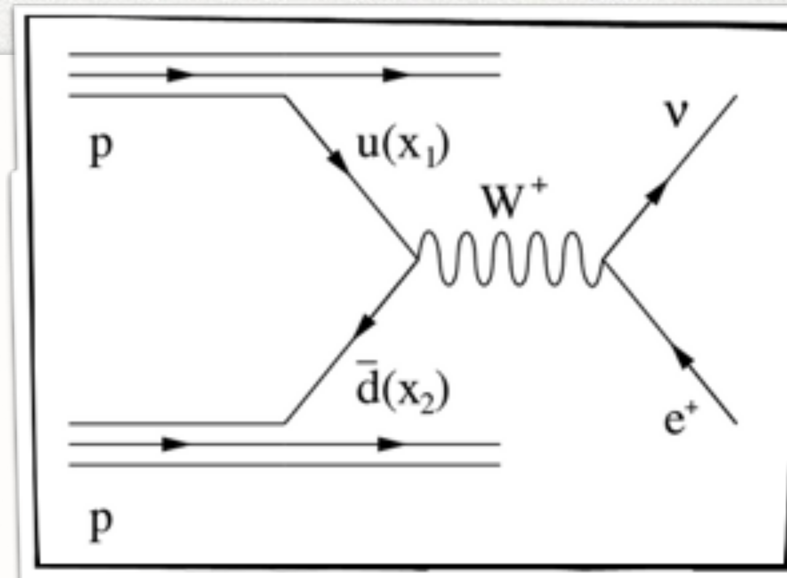
ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

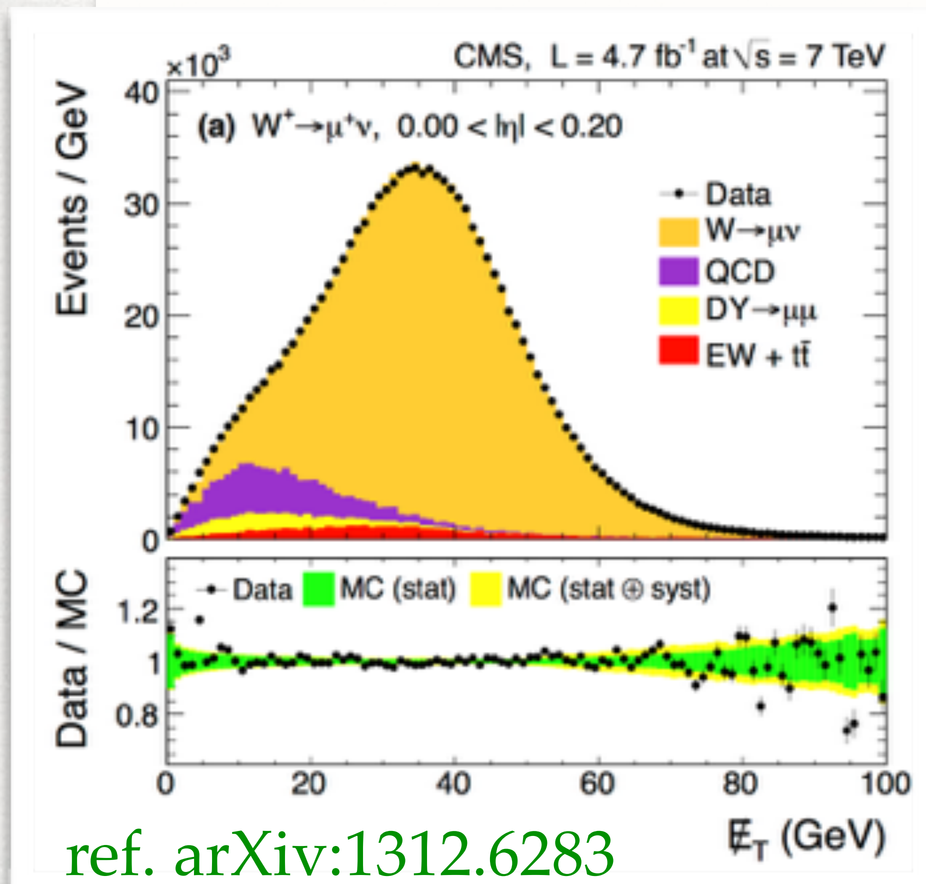
Effects of PDF is crucial here! Different PDF gives different "predictions" of W-mass observable.

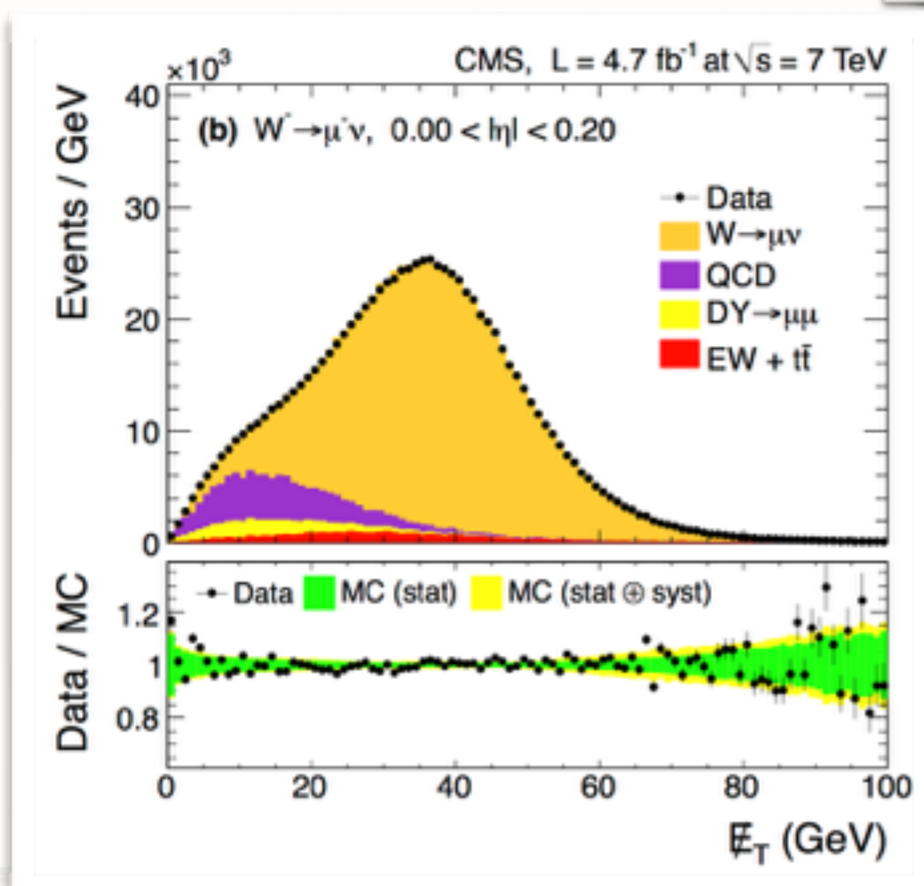
Current precision and projected precision for future LHC

W CHARGE ASYMMETRY

- In proton-proton collisions, more W^+ are produced than the W^- since u dominates over d.
- One can measure the W charge asymmetry, which probes u/d ratios from the proton.







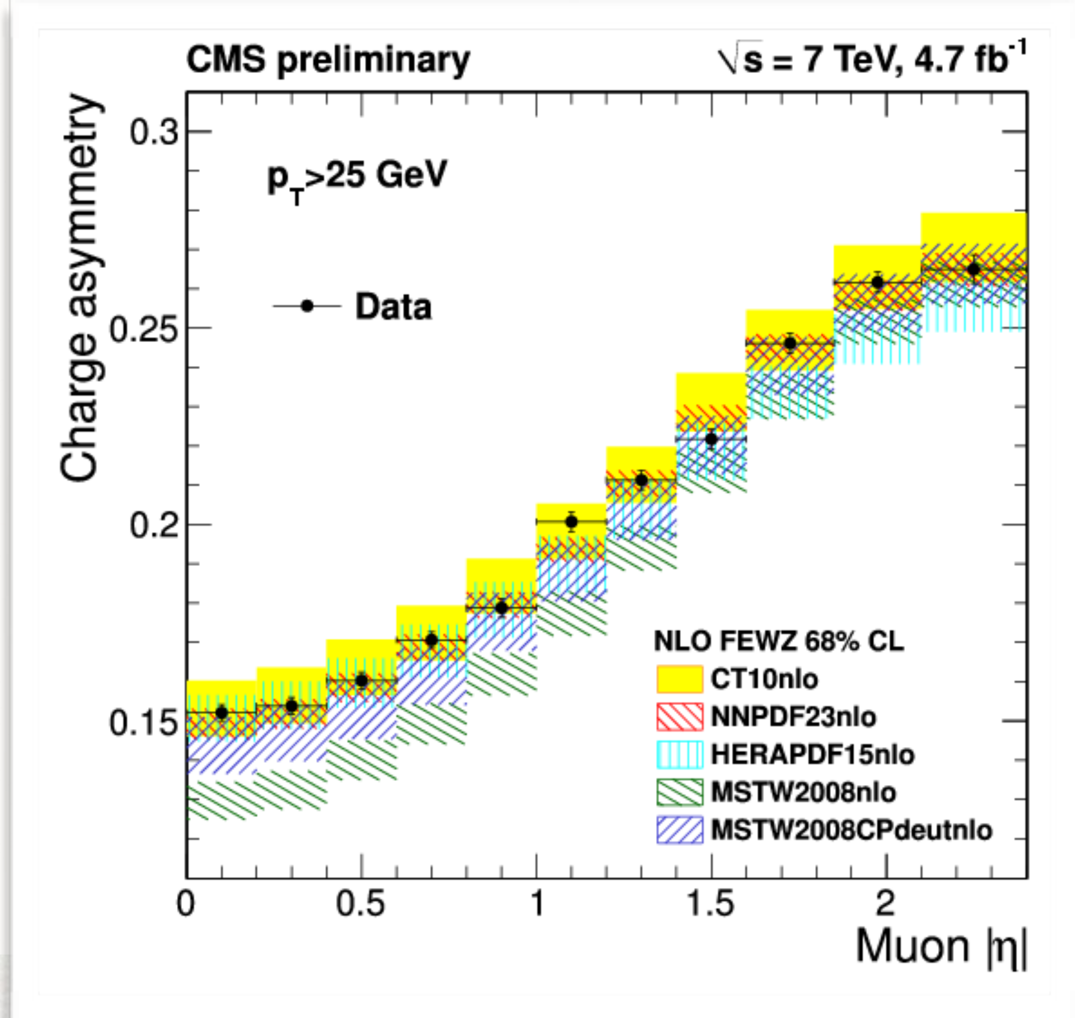
⇐ missing energy from the neutrino

ref. arXiv:1312.6283

W CHARGE ASYMMETRY

- Asymmetry more pronounced at larger rapidities; differential asymmetry measurements provide more information.
- A CMS new measurement with > 20 M W events:
  - Measured in 11 rapidity bins and with two p_T thresholds
  - Experimental uncertainty per bin 0.2~0.4% — very powerful for distinguishing/constraining different PDFs.

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

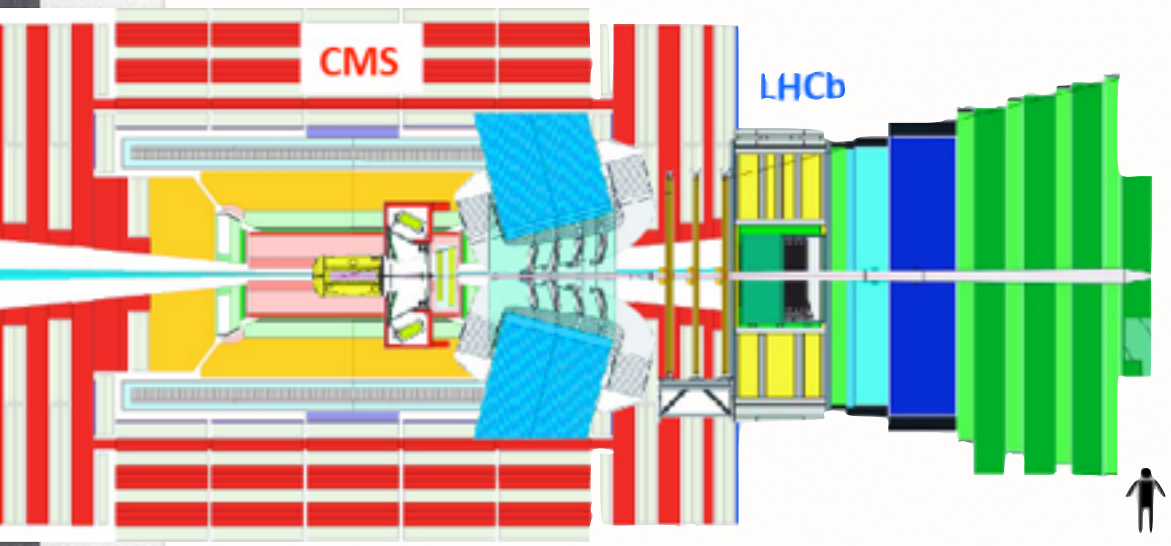


ref. arXiv:1312.6283

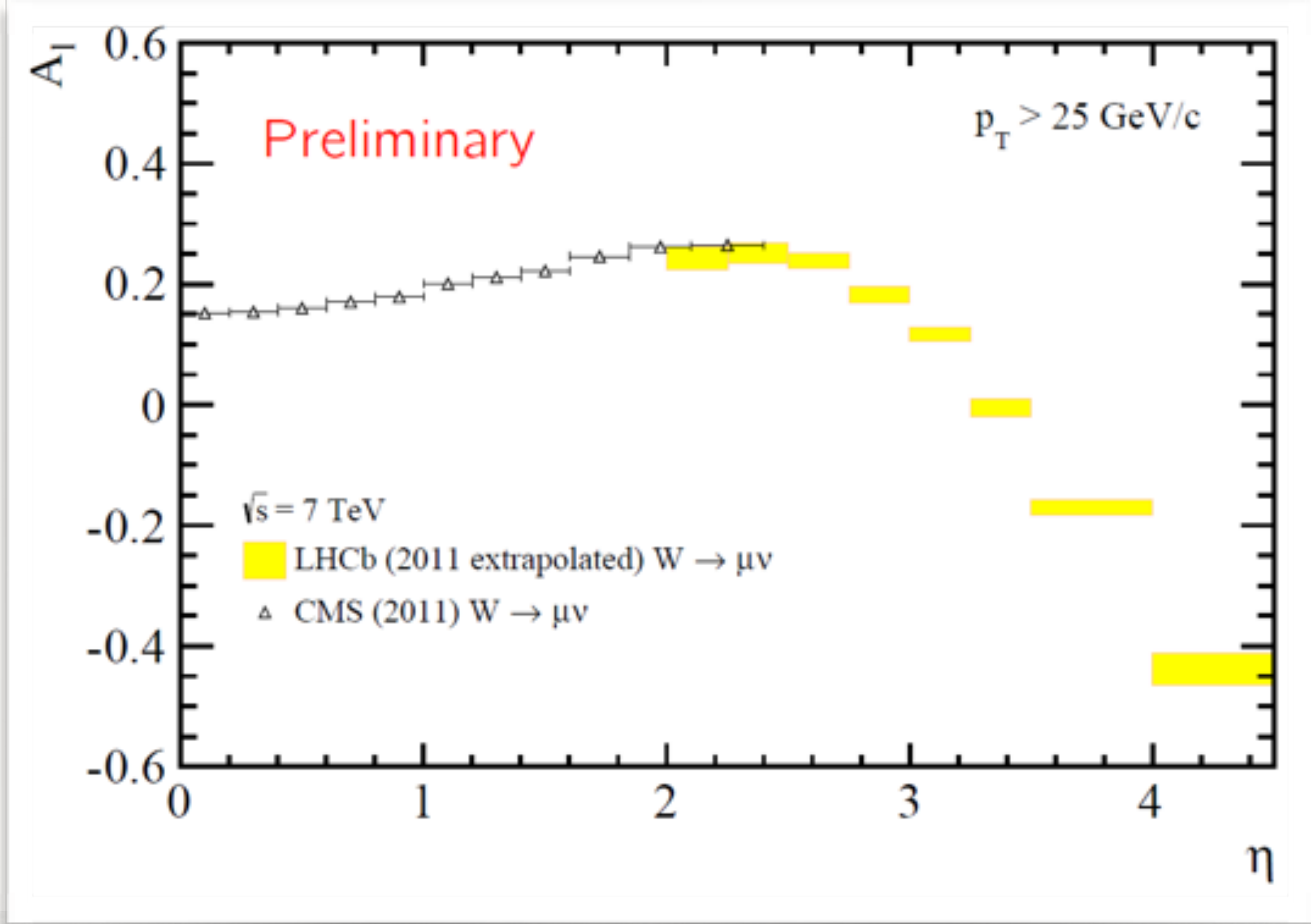
W CHARGE ASYMMETRY

- Actually the LHCb experiment has an unique access to high rapidity leptons (2<|η|<4.5).
- New measurements are in agreement with CMS in the overlap region.

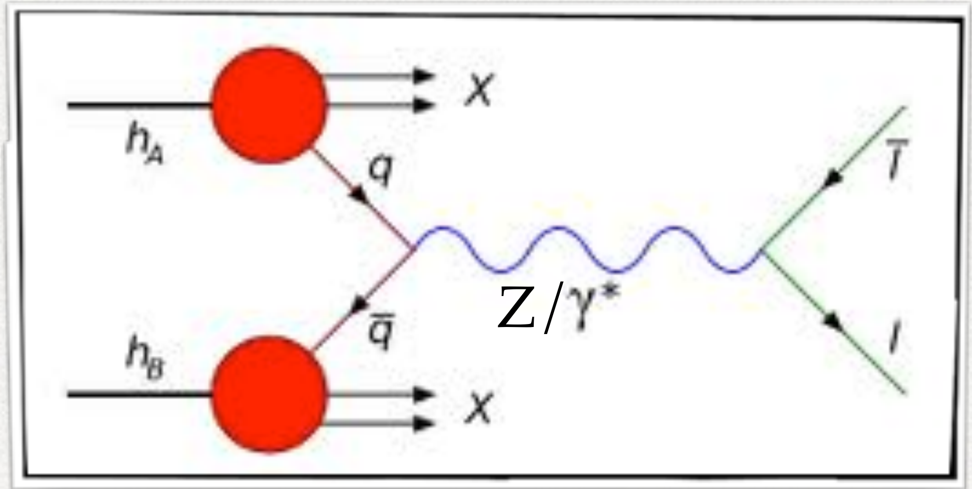
CMS/ATLAS only in barrel (up to 2.x in η)



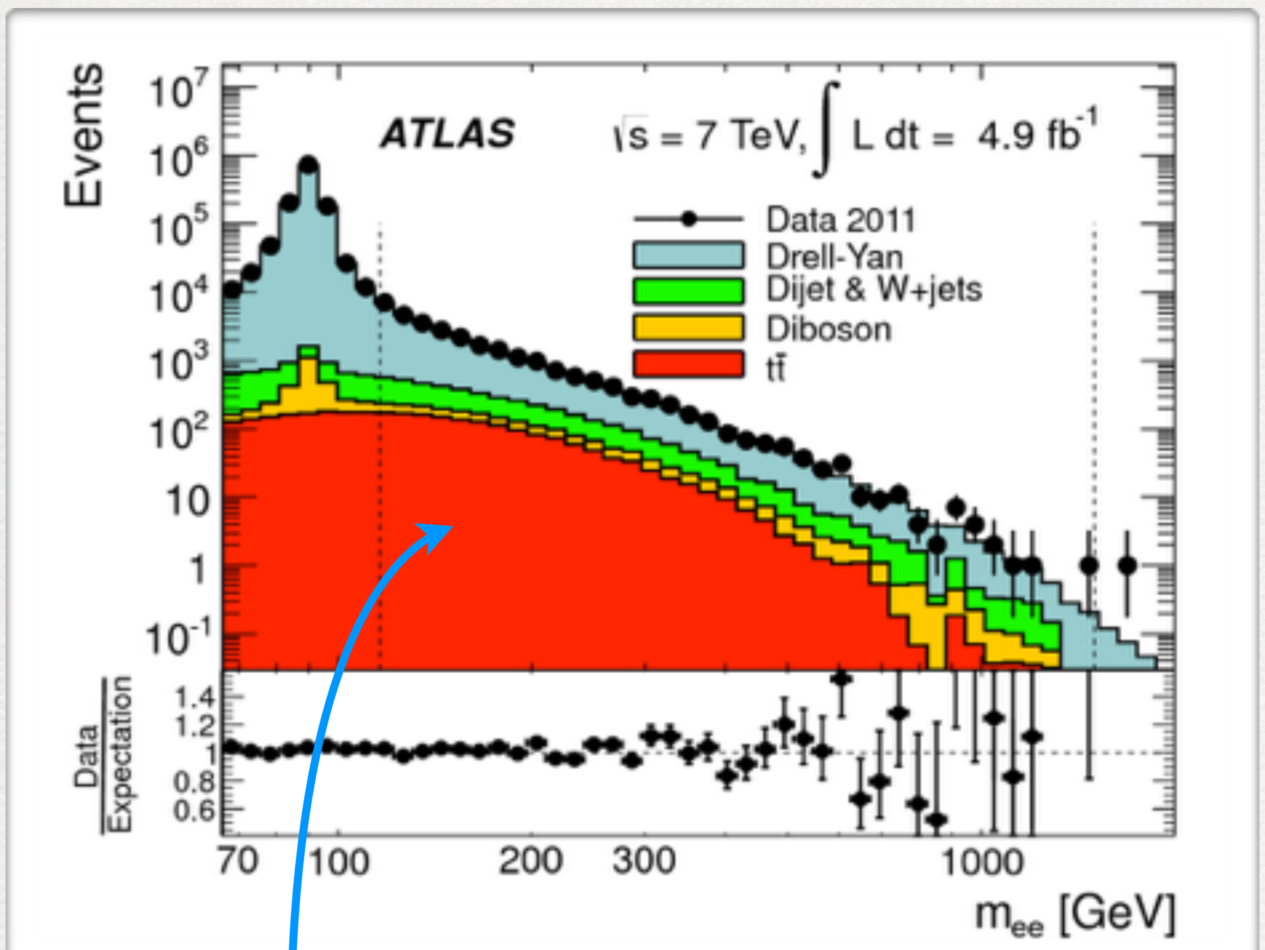
LHCb covers to η~4.5

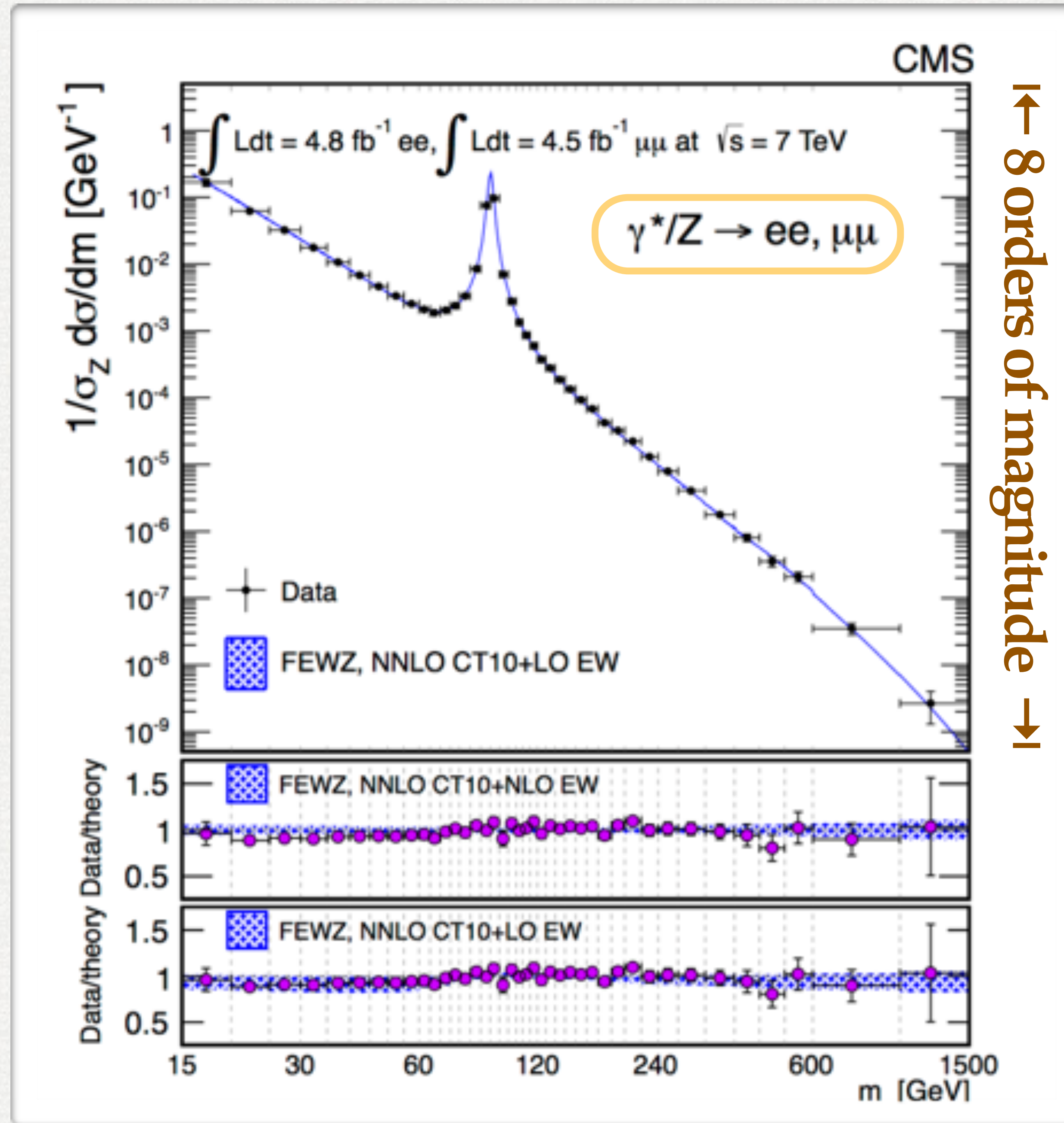


Z/DRELL-YAN PROCESS



⇤ 2 orders of magnitude ⇥

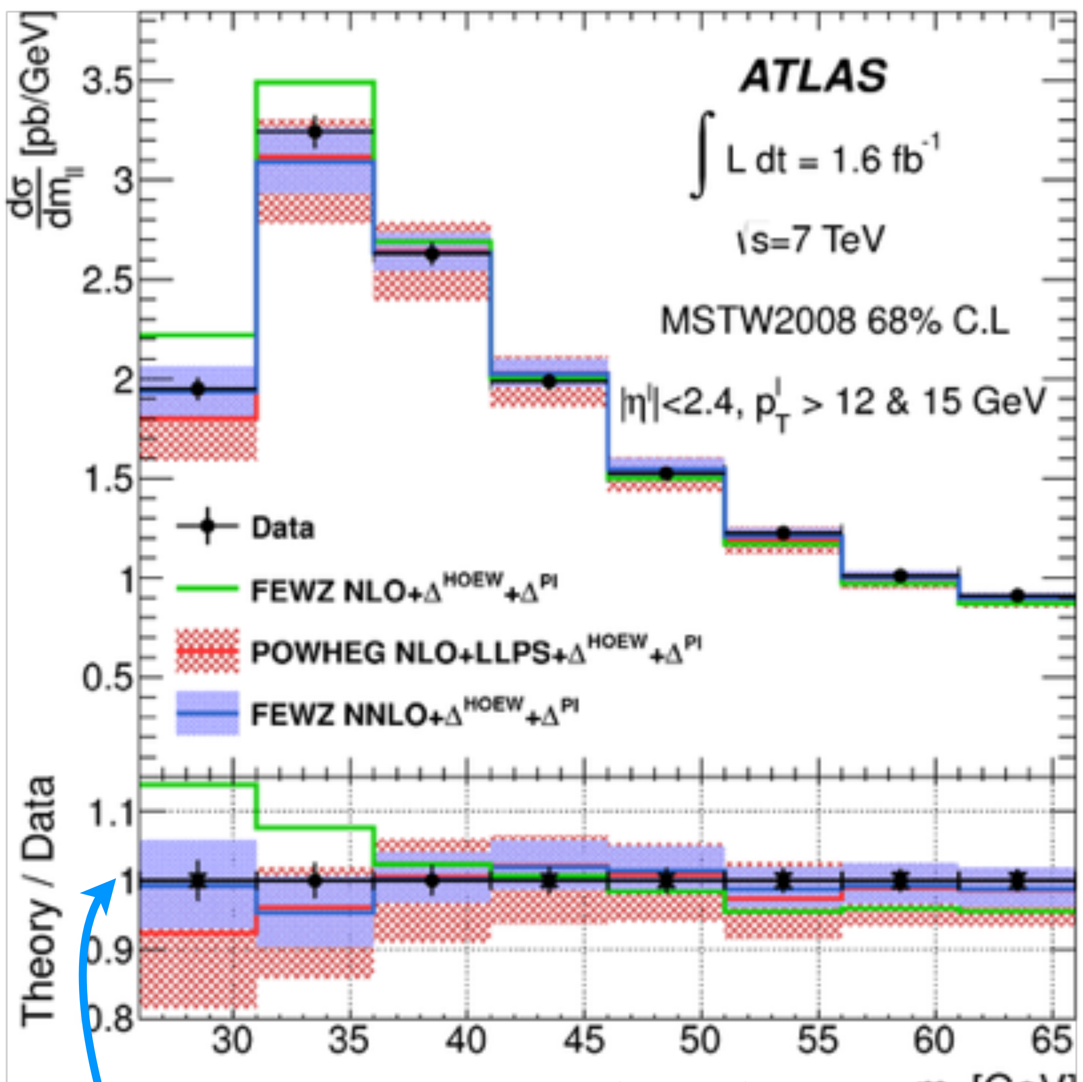




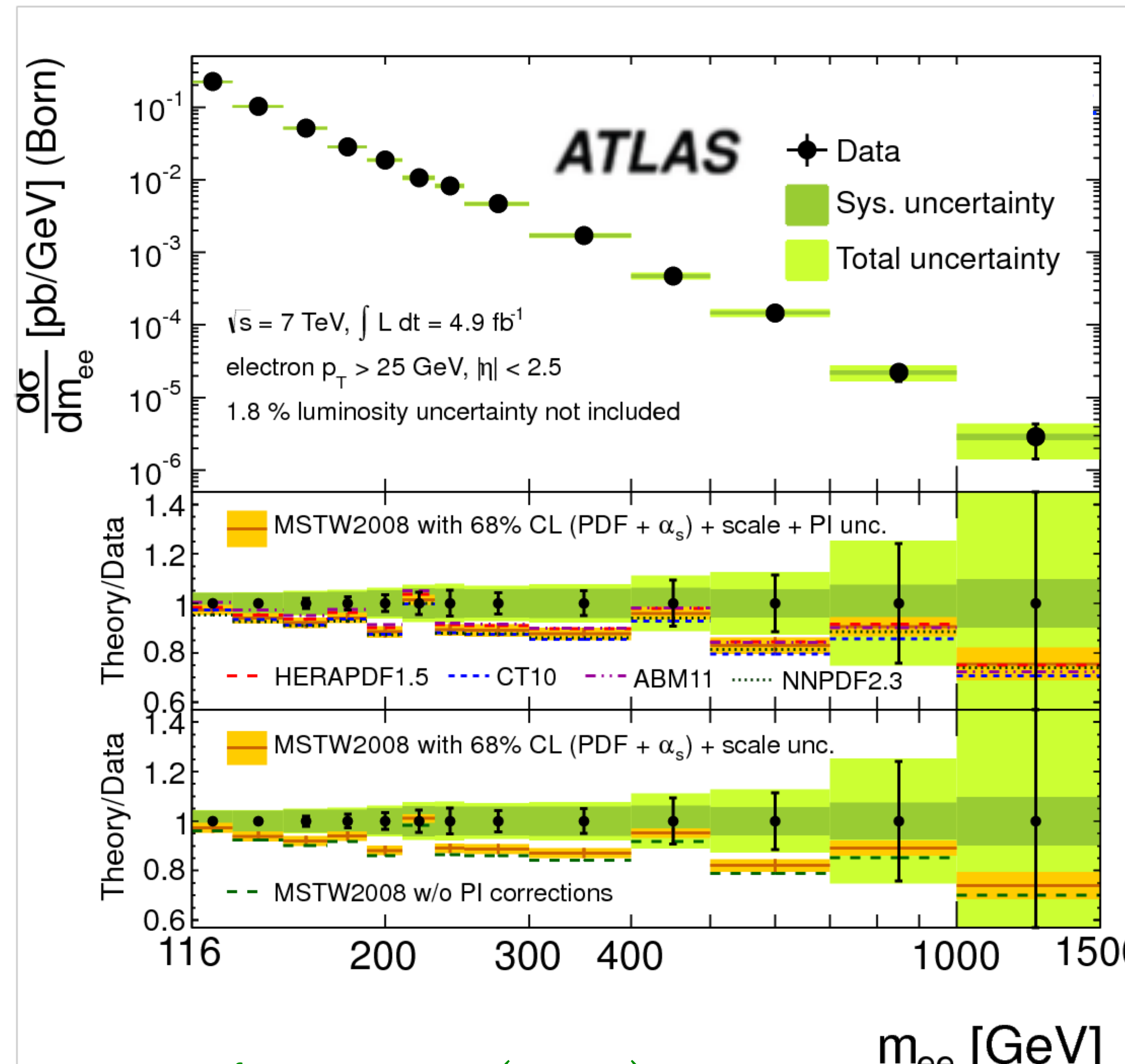
⇤ 8 orders of magnitude ⇥

Very low background!

DIFFERENTIAL MEASUREMENTS



ref. JHEP 06 (2014) 112

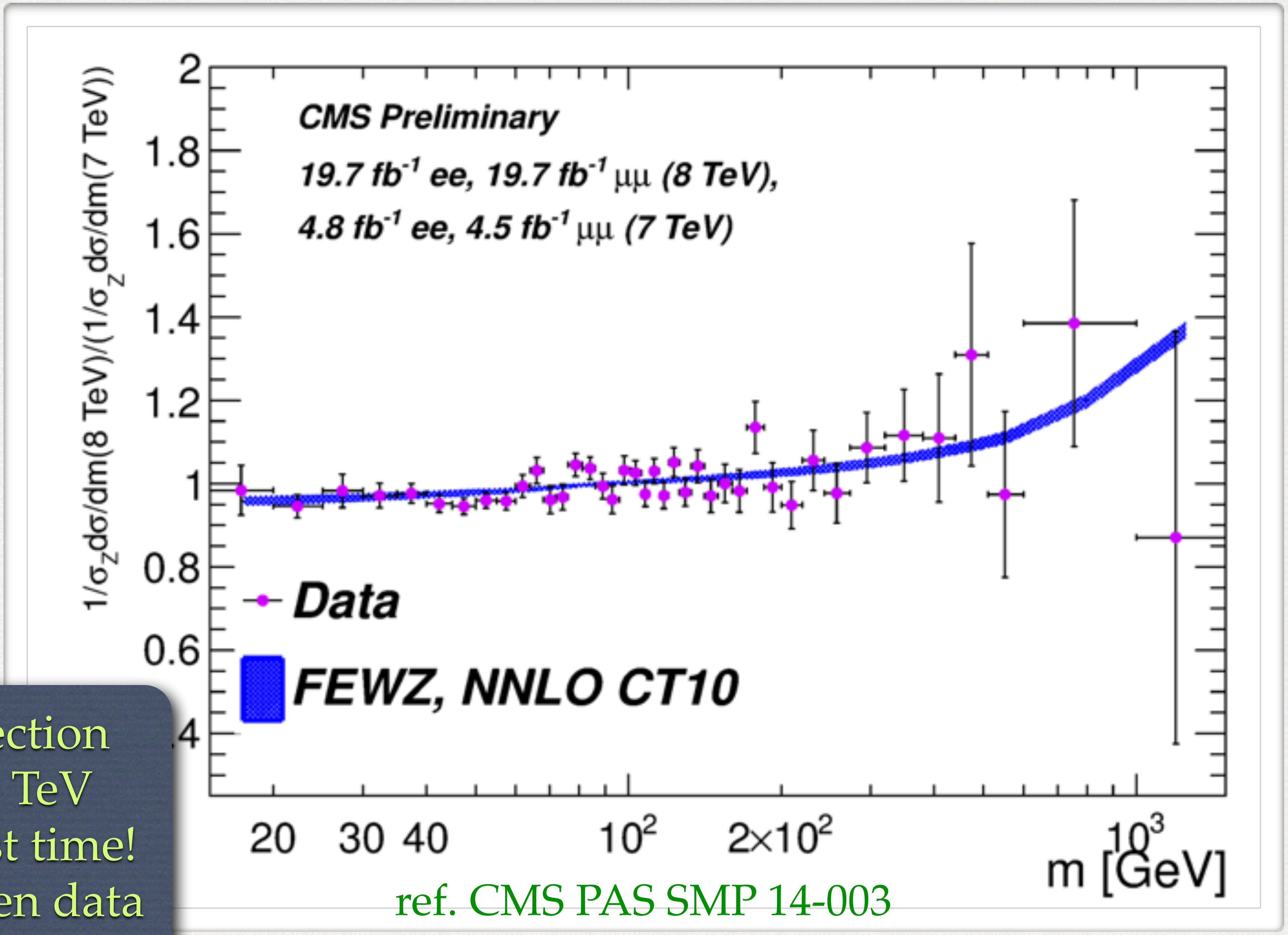


ref. PLB 725 (2013) 223

Next-to-Next-to-Leading Order (NNLO) corrections seem to be important at low mass.

Data seems above the predictions slightly for m ~120-400 GeV.

DIFFERENTIAL MEASUREMENTS



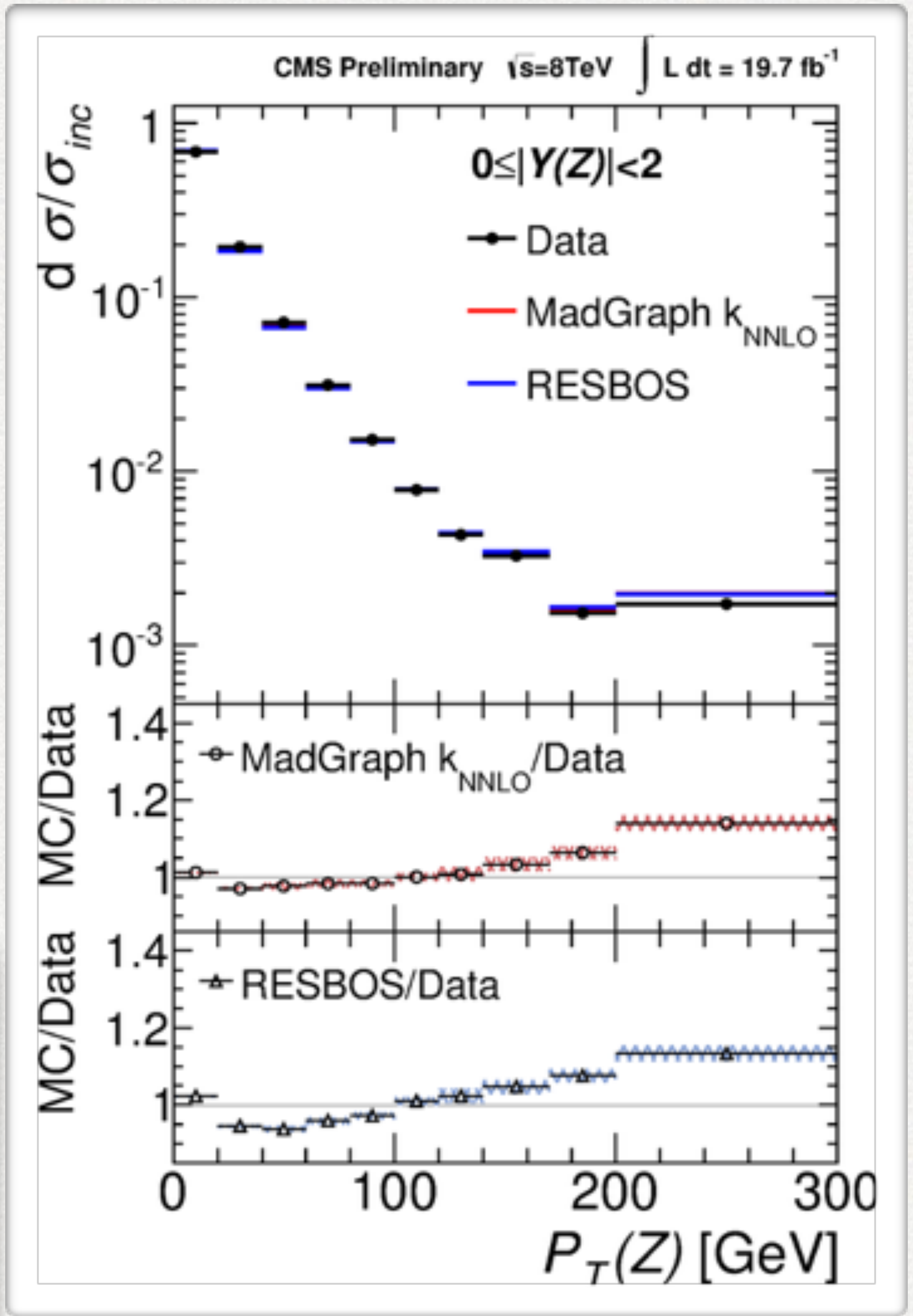
ref. CMS PAS SMP 14-003

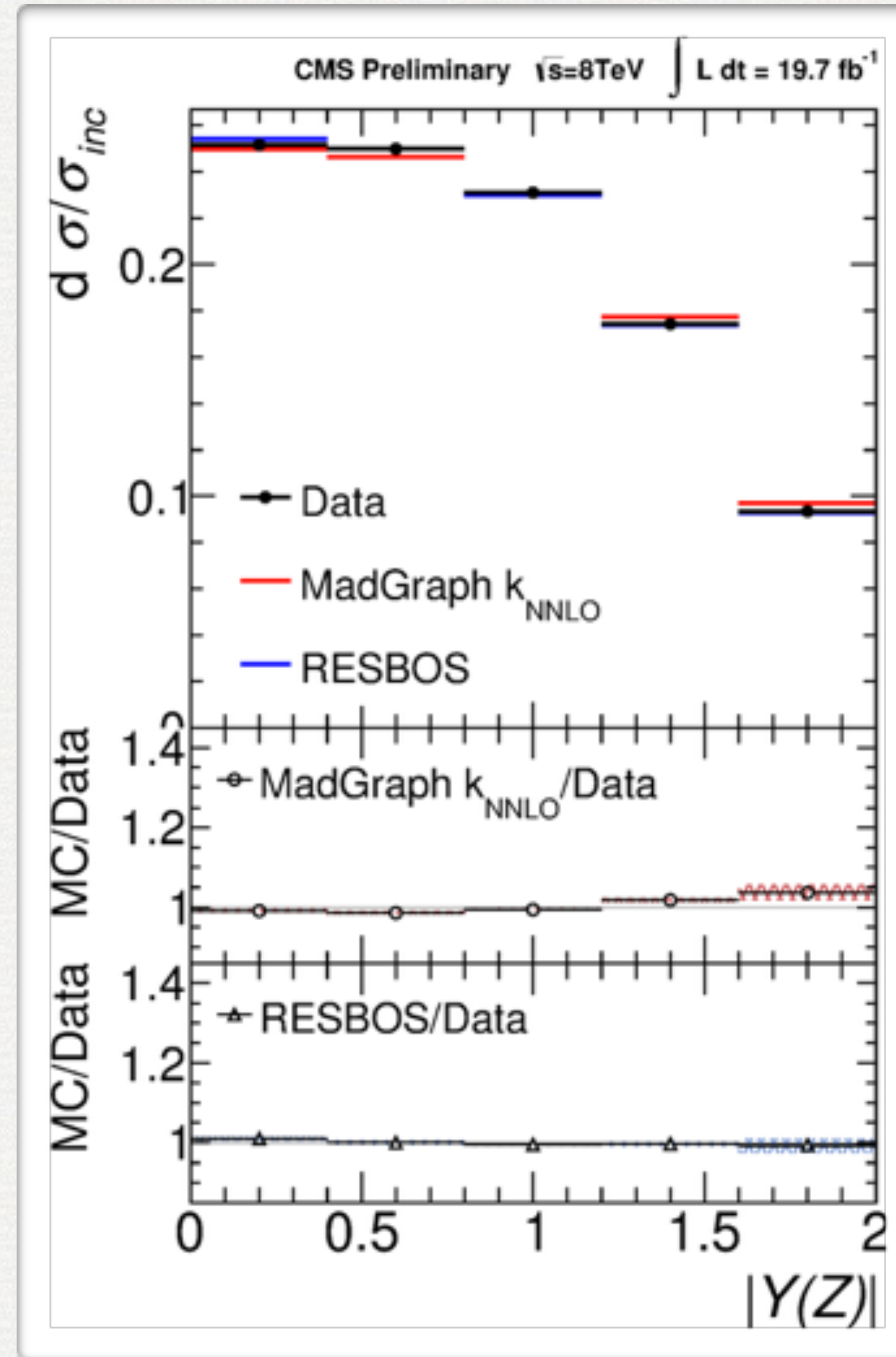
Differential cross section ratios for the 7 & 8 TeV measured for the first time! Nicely agreed between data and prediction!

DIFFERENTIAL MEASUREMENTS

ref. CMS PAS SMP 13-003

Disagreement with predictions
at low and high pT

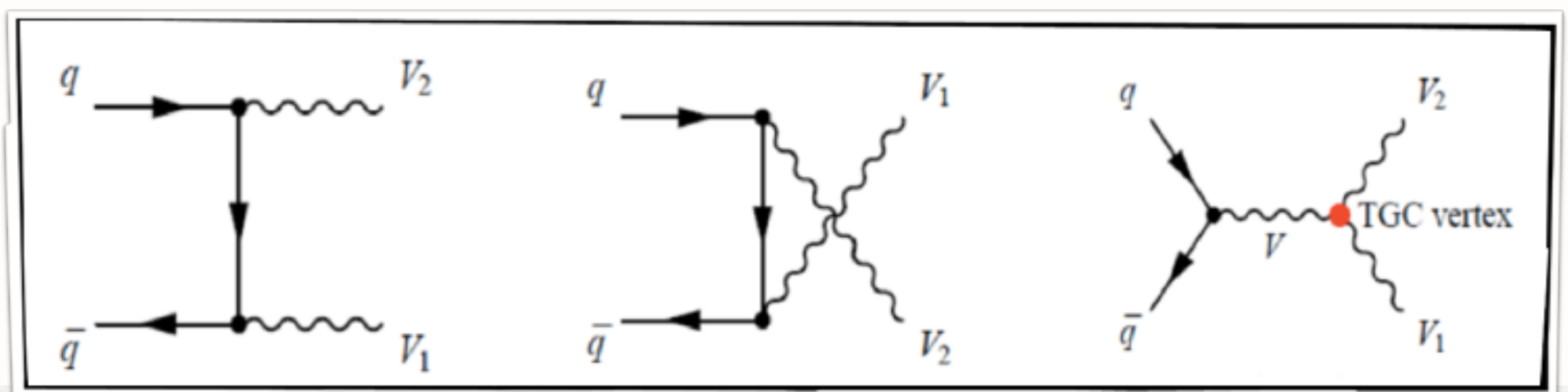




Z boson p_T and rapidity are measured and compared with the predictions.

DIBOSON PRODUCTIONS

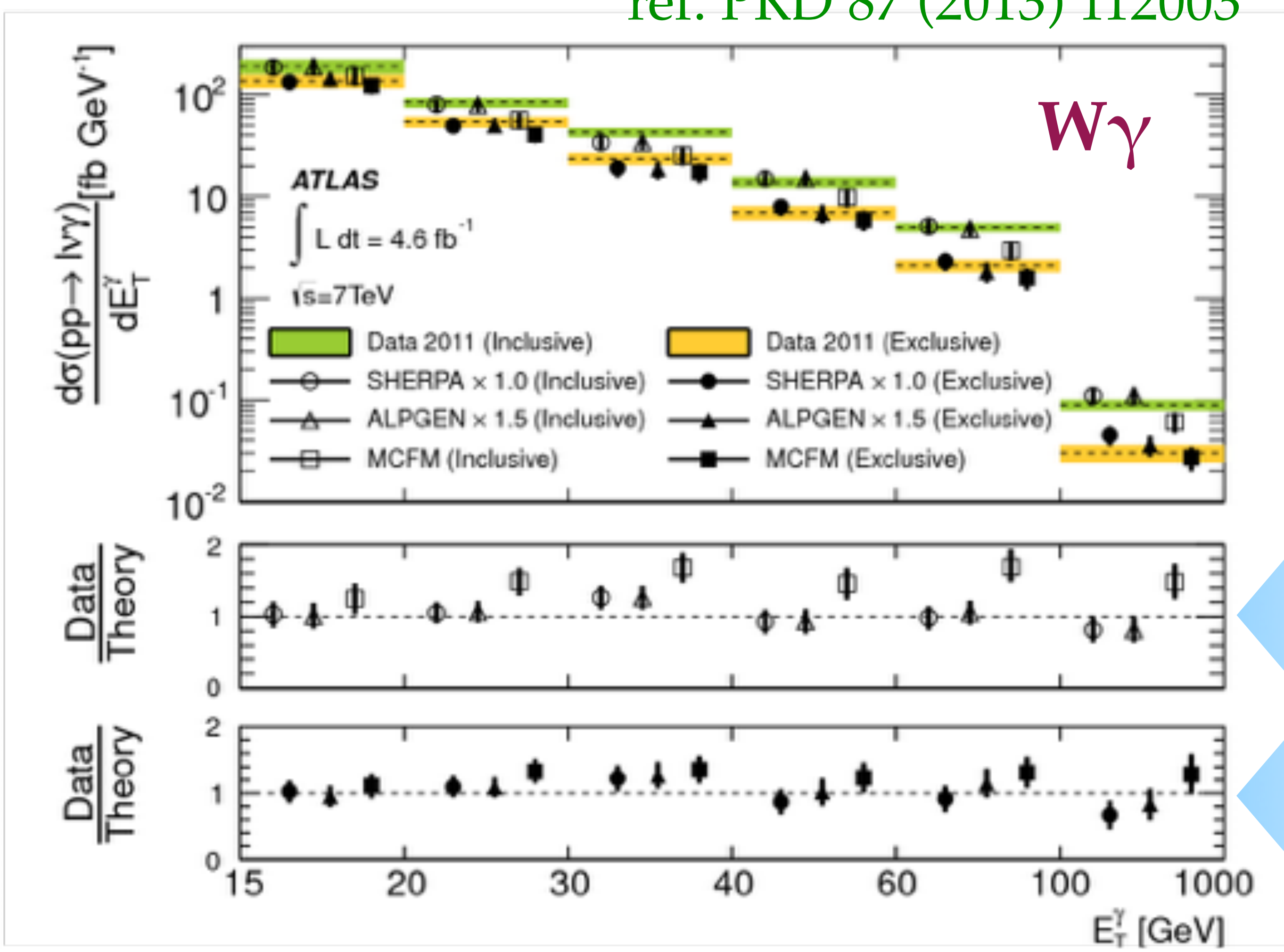
- Measurements of diboson production (Wγ, Zγ, WW, WZ, ZZ) are good tests of the Standard Model:
  - Vector boson self-couplings are fundamental predictions.
  - Any deviations from SM i.e., anomalous triple gauge couplings (aTGC) would indicate new physics.
  - Sensitive to new particles decaying into boson pairs.
  - Non-resonant diboson production is an irreducible background to Higgs production processes — critical for understanding of the properties of the Higgs boson.

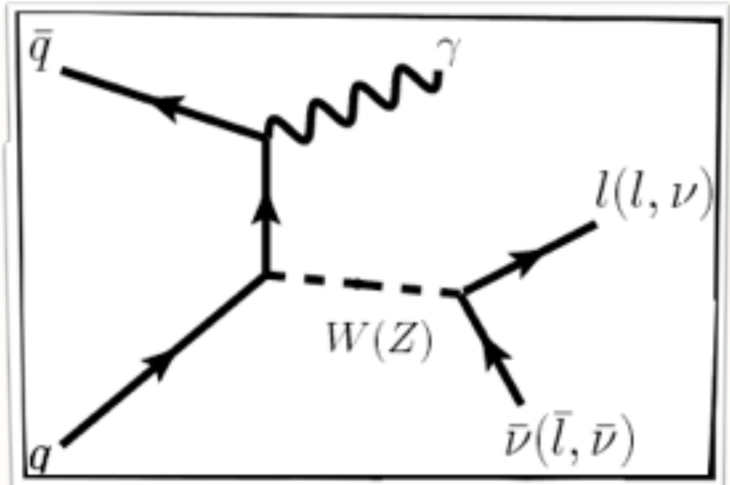


Wγ/Zγ PRODUCTIONS

- Clean and large signal!
- Major background are from fake photons and fake leptons
- No evidence of new physics in high p_T tails (so far).

ref. PRD 87 (2013) 112003



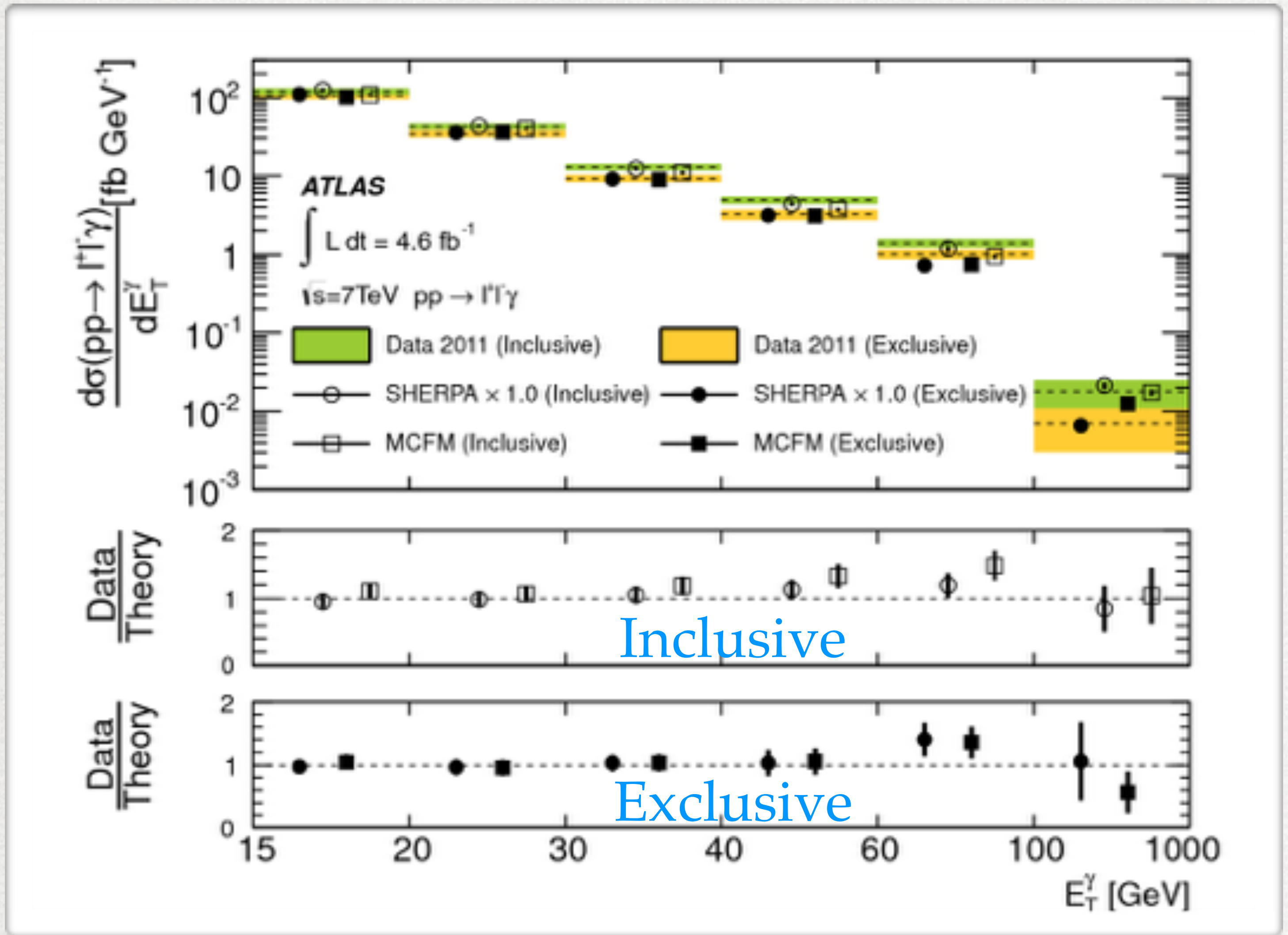


Inclusive = W+γ+X

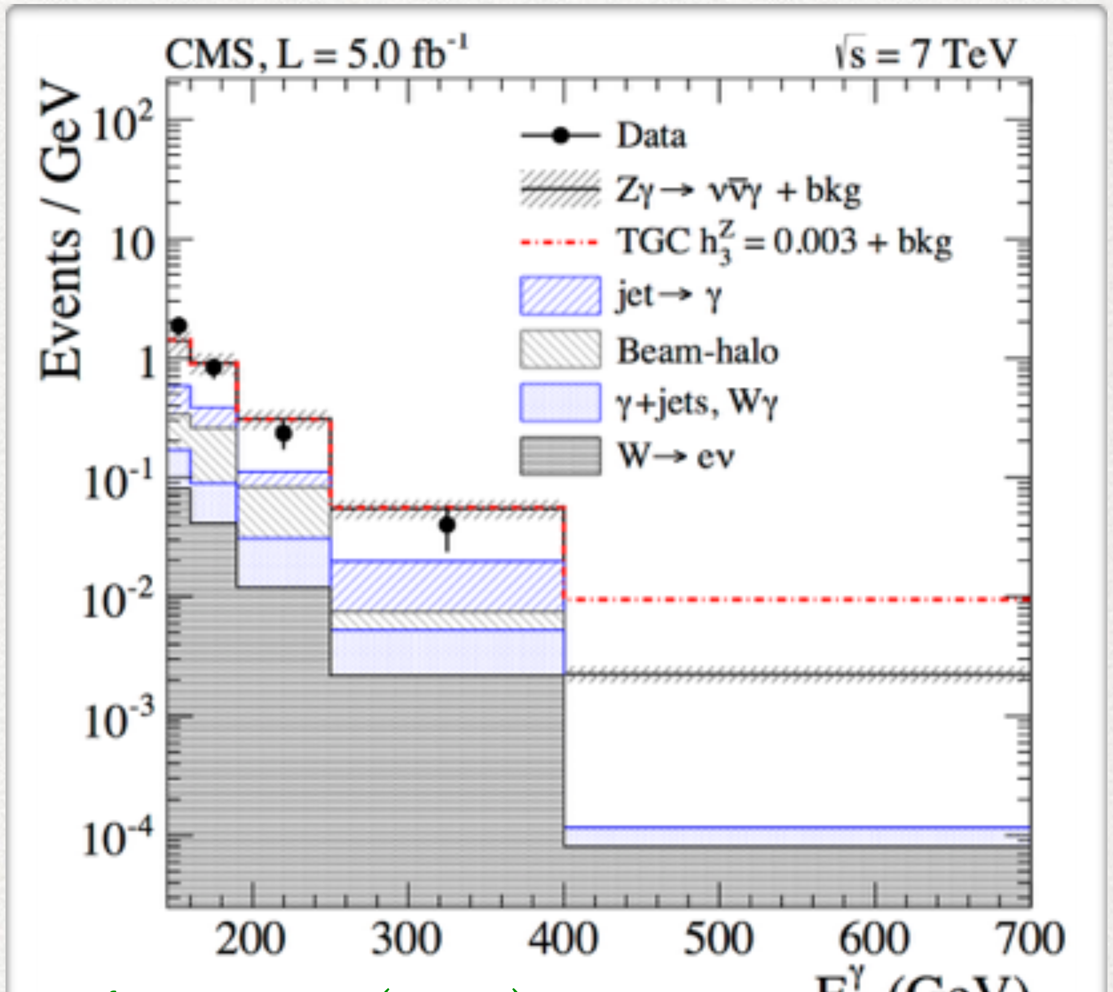
Exclusive = W+γ+0 jet

Wγ/Zγ PRODUCTIONS

Z(→ll)γ



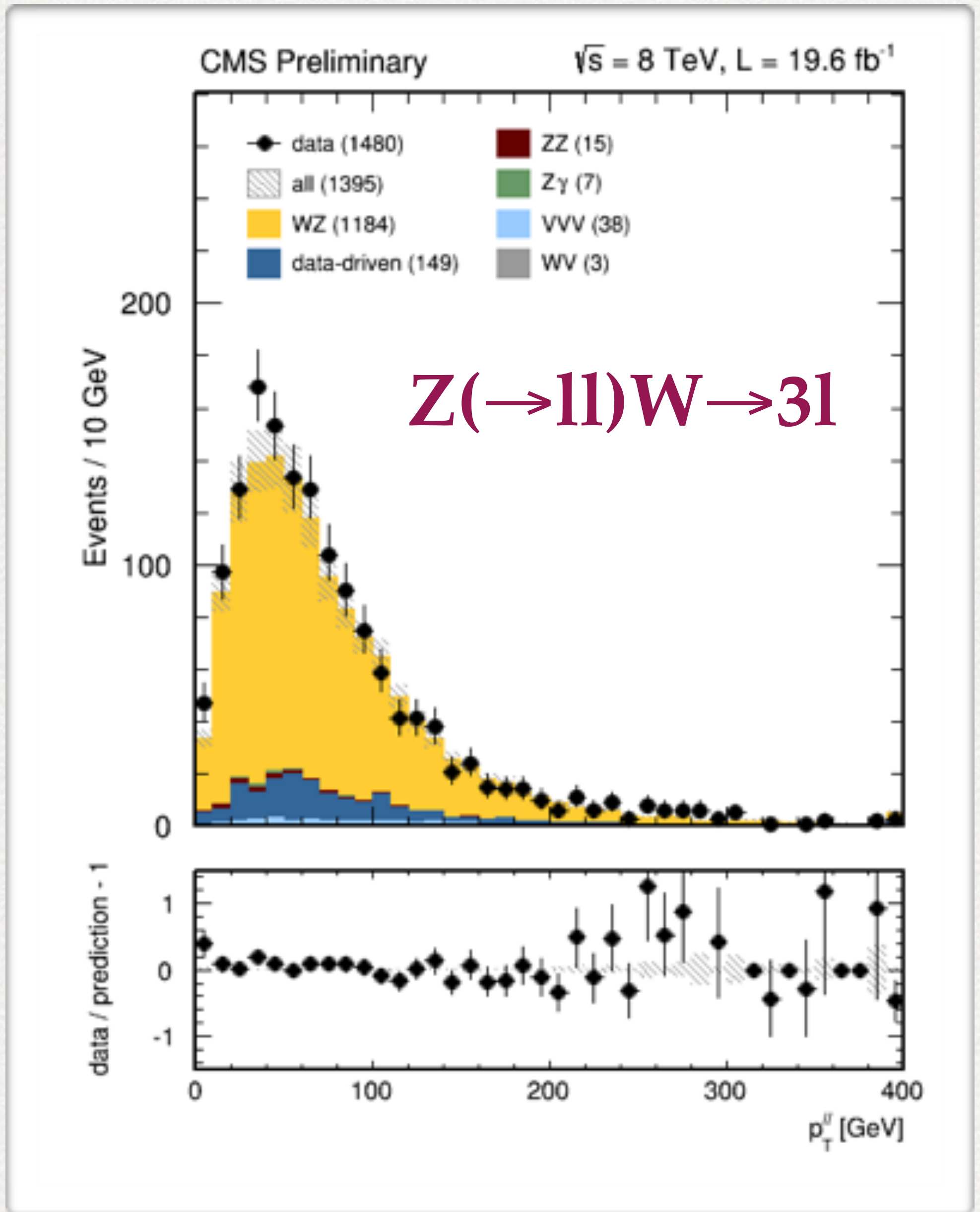
Z(→νν)γ



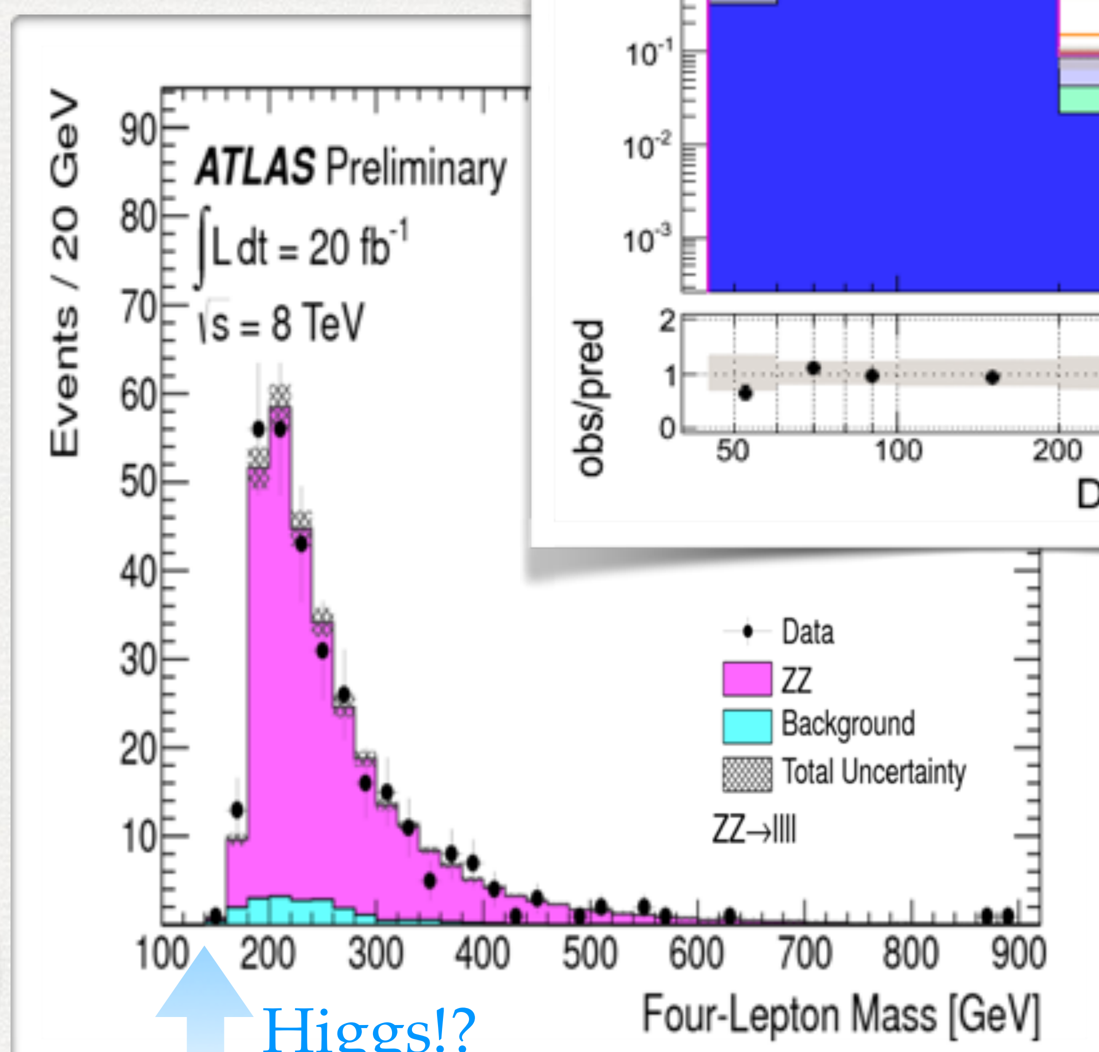
ref. JHEP 10 (2013) 164

Requiring missing energy + 1 isolated (high p_T) photon. Background is low if p_T is high.

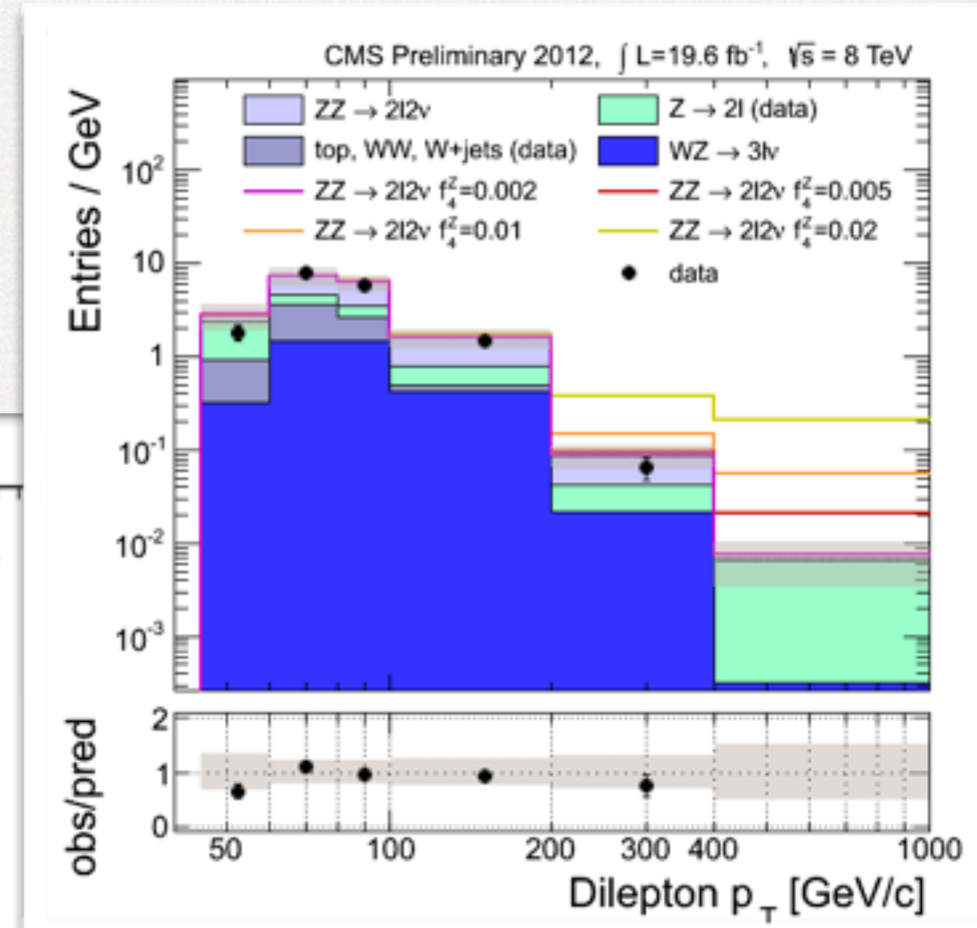
ZZ/WZ PRODUCTIONS



ZZ→4l



ZZ→2ν2l

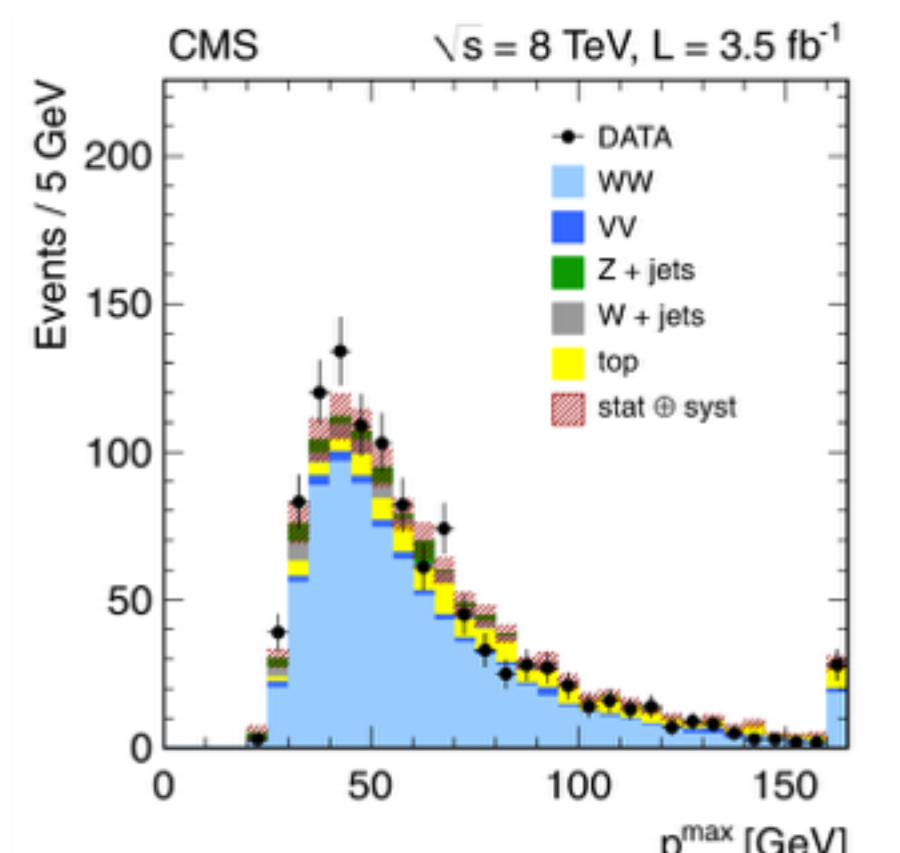


All with large and clean signal!

WW PRODUCTIONS

- Kinematic shapes agree with prediction but the cross section is higher by ~20% (similar situation in both CMS and ATLAS).

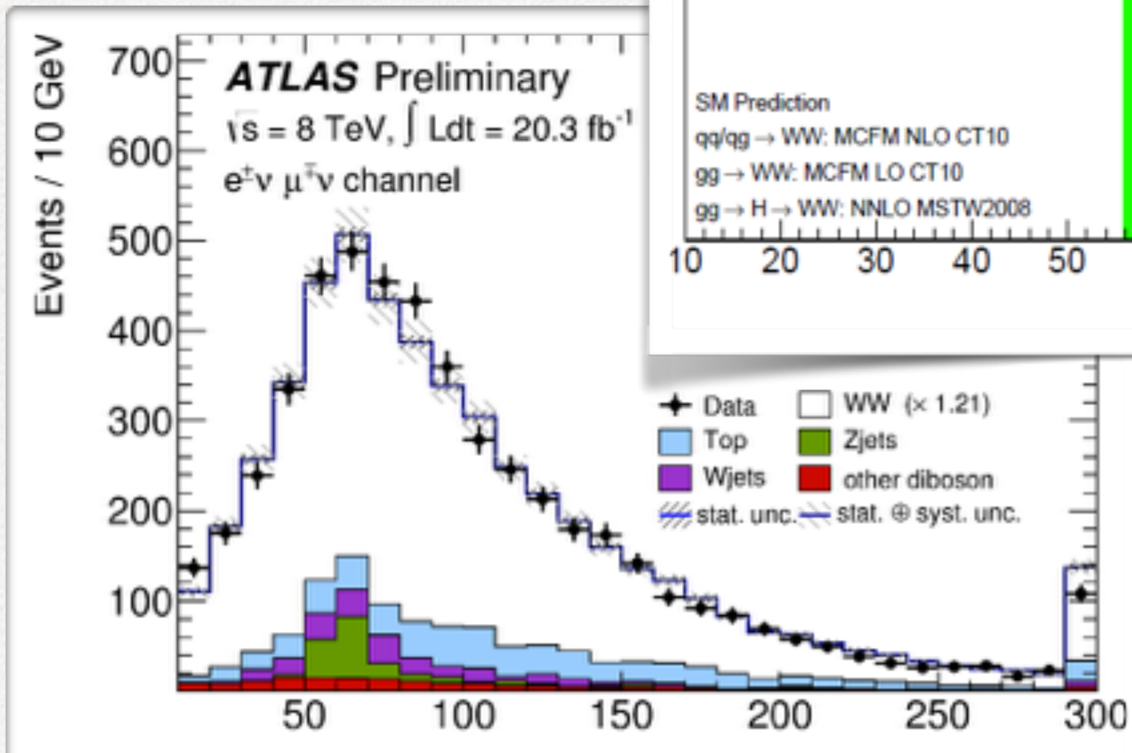
TH: 58.7±30 pb



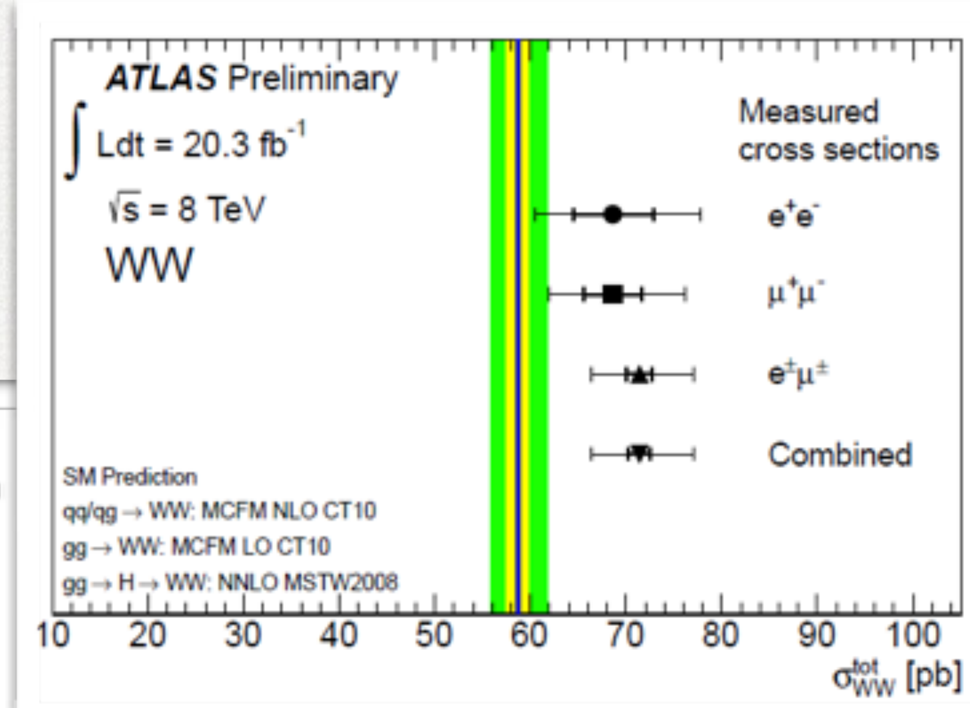
ref. PLB 721 (2013) 190

CMS
69.9 ±2.8±5.6±3.1 pb

ATLAS
71.4 ±1.2±5.0±2.2 pb

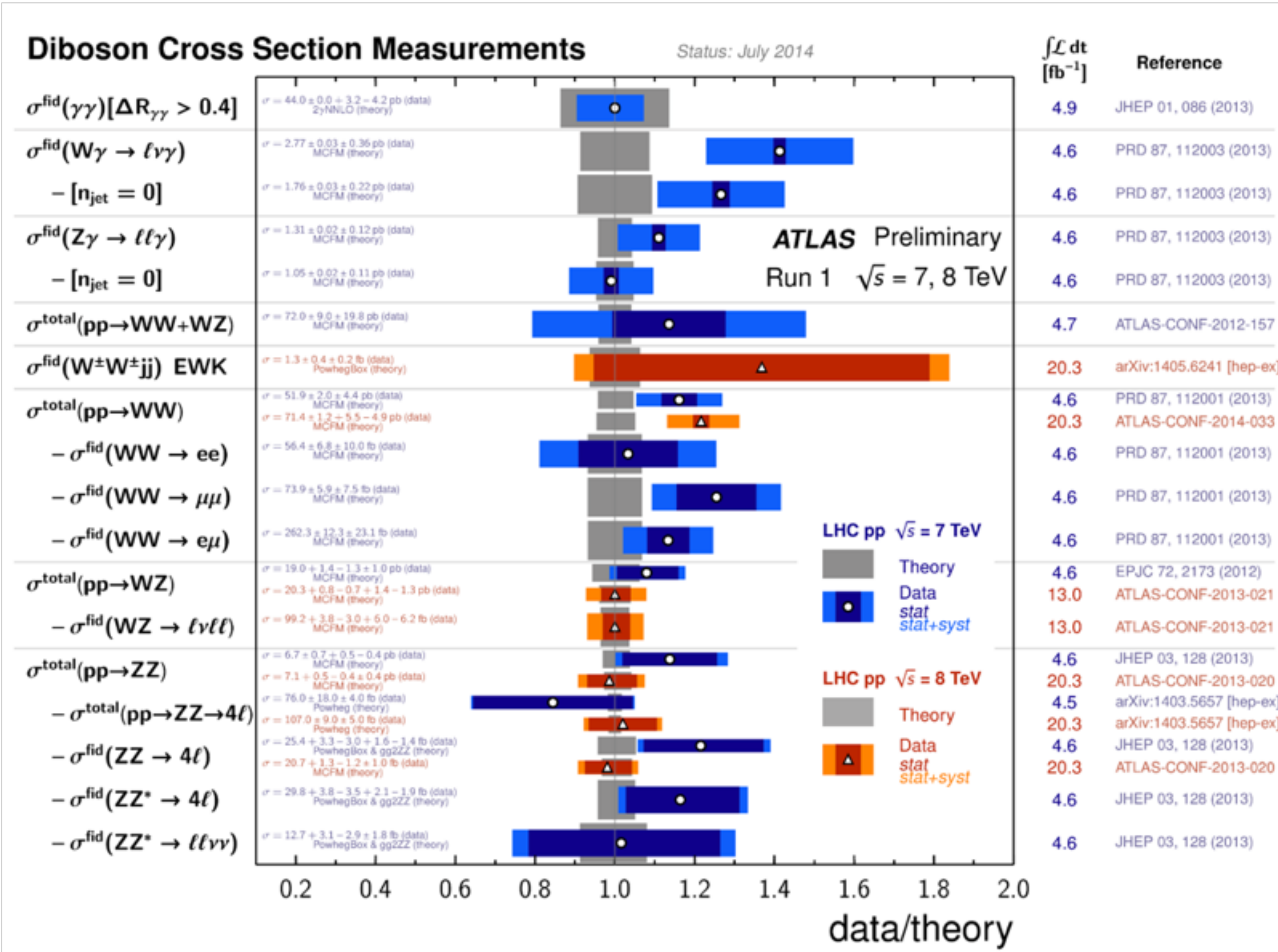


ref. ATLAS-CONF-2014-033

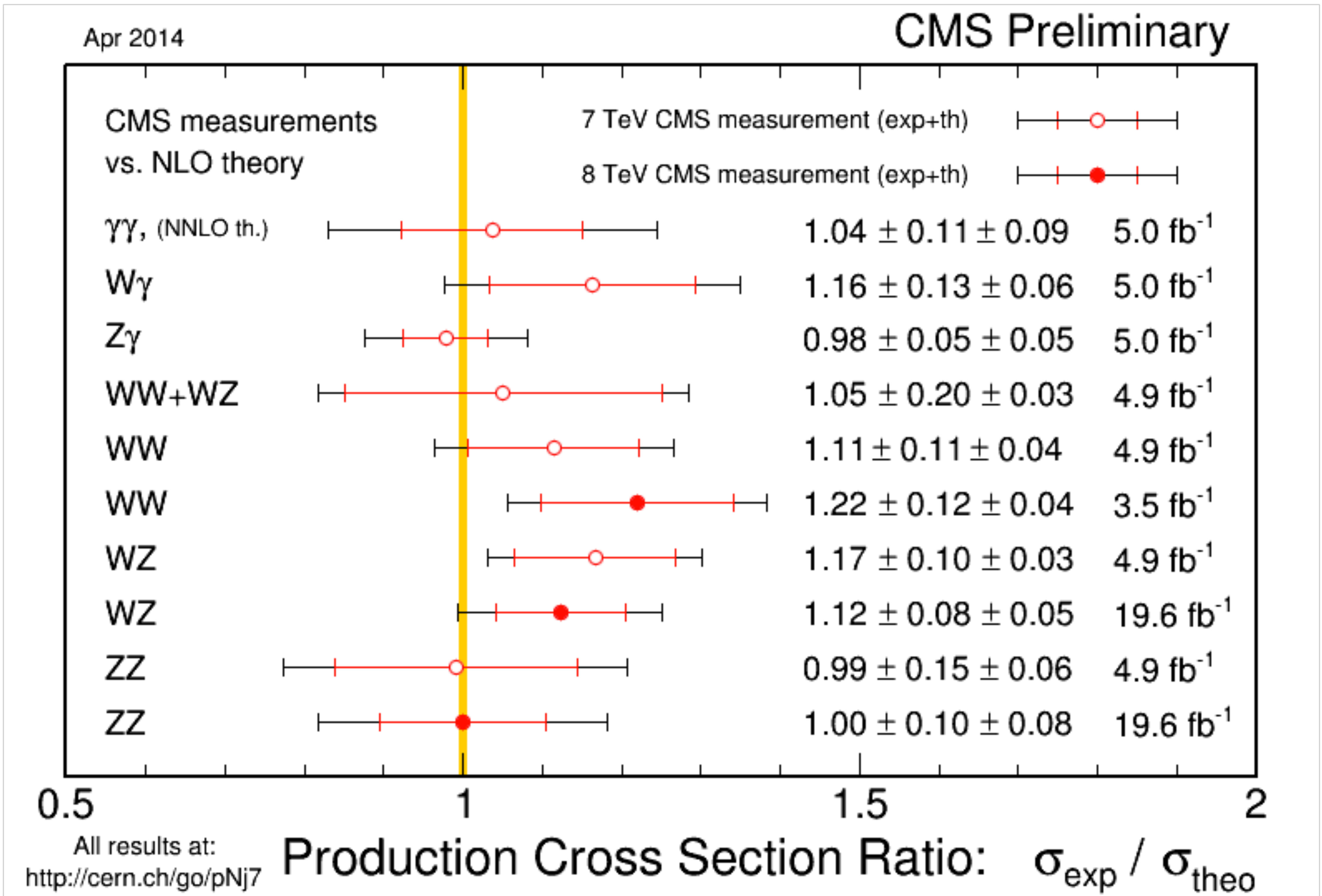


Need higher order corrections!?

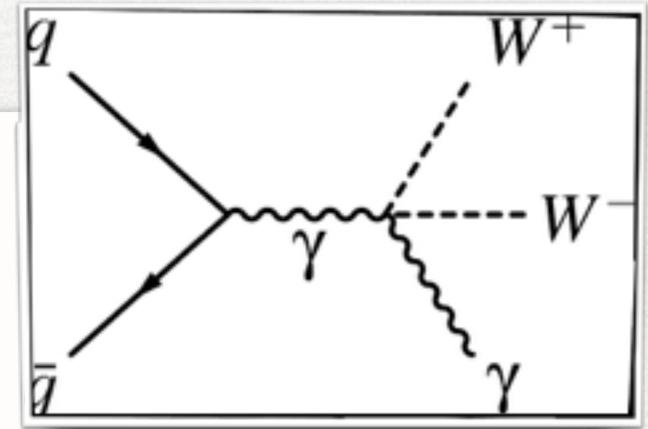
ATLAS SUMMARY



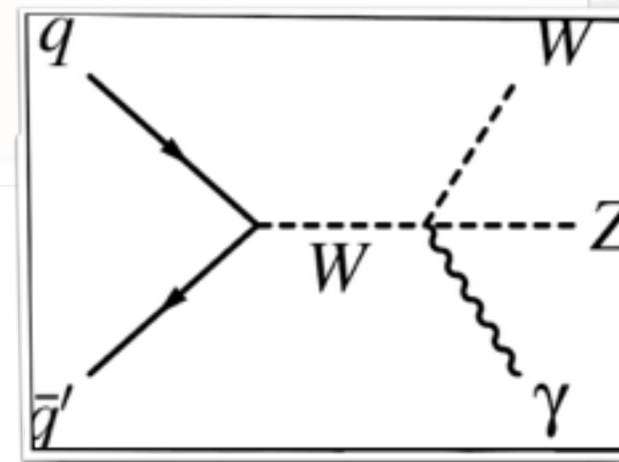
CMS SUMMARY


Apr 2014
CMS Preliminary
CMS measurements
vs. NLO theory
7 TeV CMS measurement (exp+th)
8 TeV CMS measurement (exp+th)
γγ, (NNLO th.)
1.04 ± 0.11 ± 0.09
5.0 fb-1
Wγ
1.16 ± 0.13 ± 0.06
5.0 fb-1
Zγ
0.98 ± 0.05 ± 0.05
5.0 fb-1
WW+WZ
1.05 ± 0.20 ± 0.03
4.9 fb-1
WW
1.11 ± 0.11 ± 0.04
4.9 fb-1
WW
1.22 ± 0.12 ± 0.04
3.5 fb-1
WZ
1.17 ± 0.10 ± 0.03
4.9 fb-1
WZ
1.12 ± 0.08 ± 0.05
19.6 fb-1
ZZ
0.99 ± 0.15 ± 0.06
4.9 fb-1
ZZ
1.00 ± 0.10 ± 0.08
19.6 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo

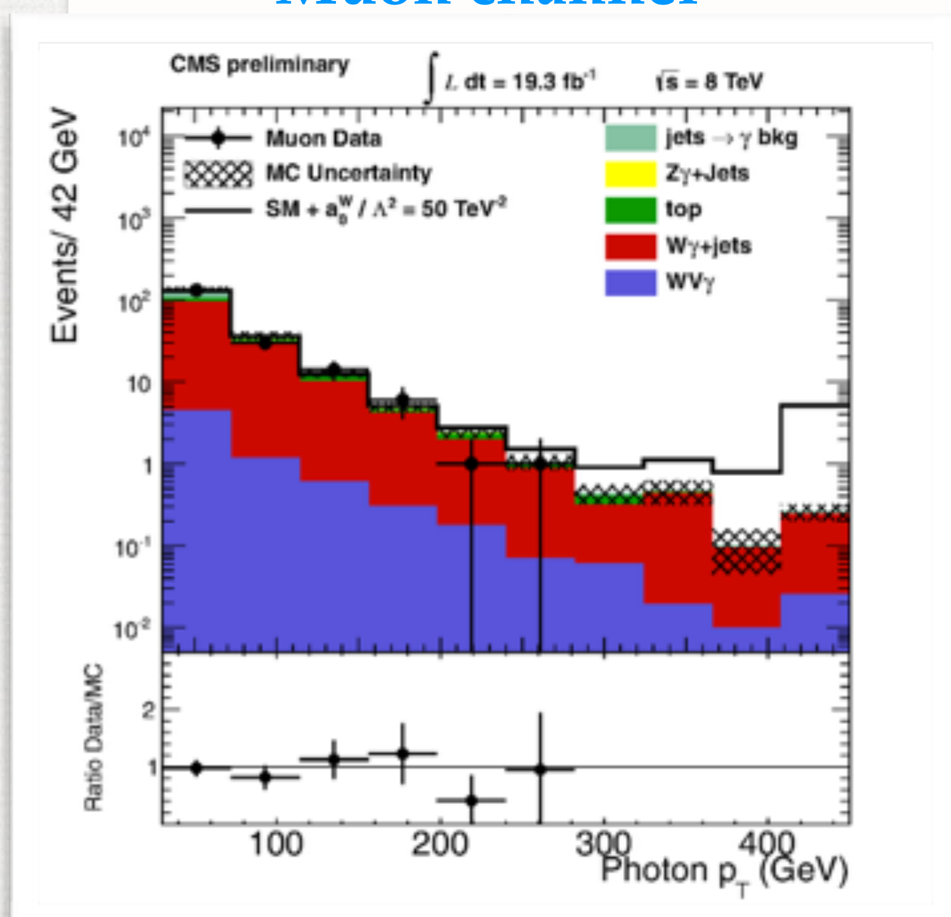
IF "2" IS NOT ENOUGH...



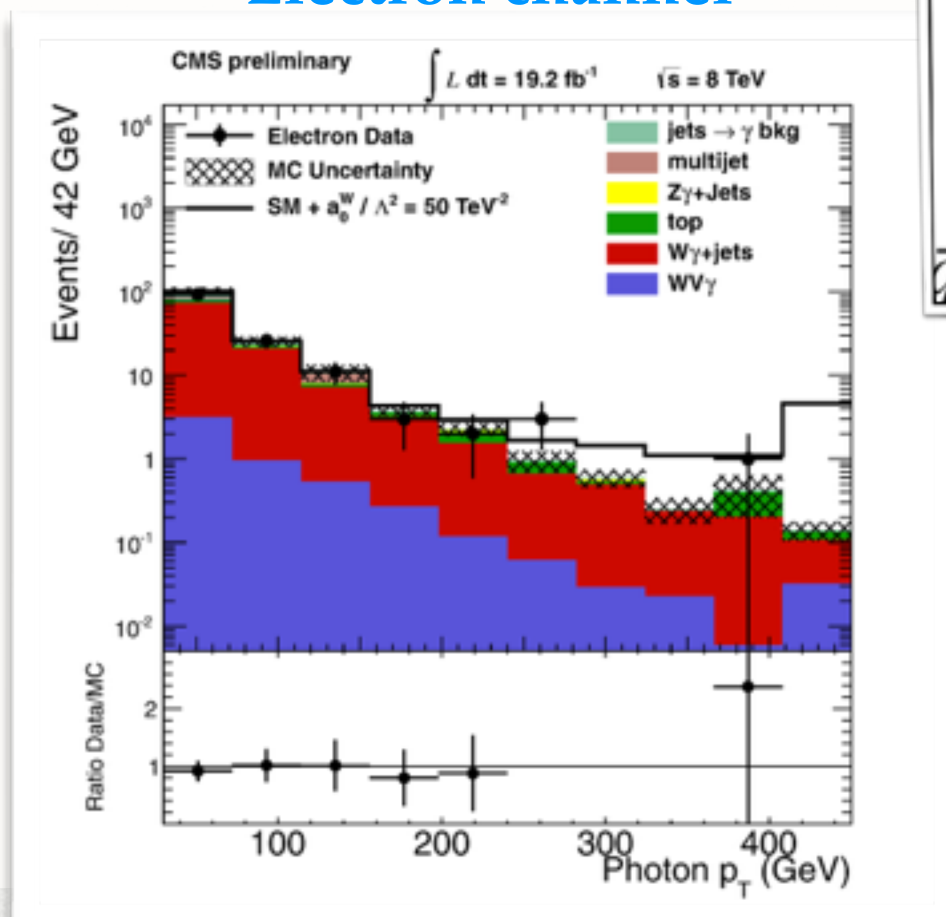
- Studied in lν+jj+γ final state; no anomalous coupling at photon high p_T tail.
- Cross section upper limit is set (~3.4 x SM predicted value).



Muon channel



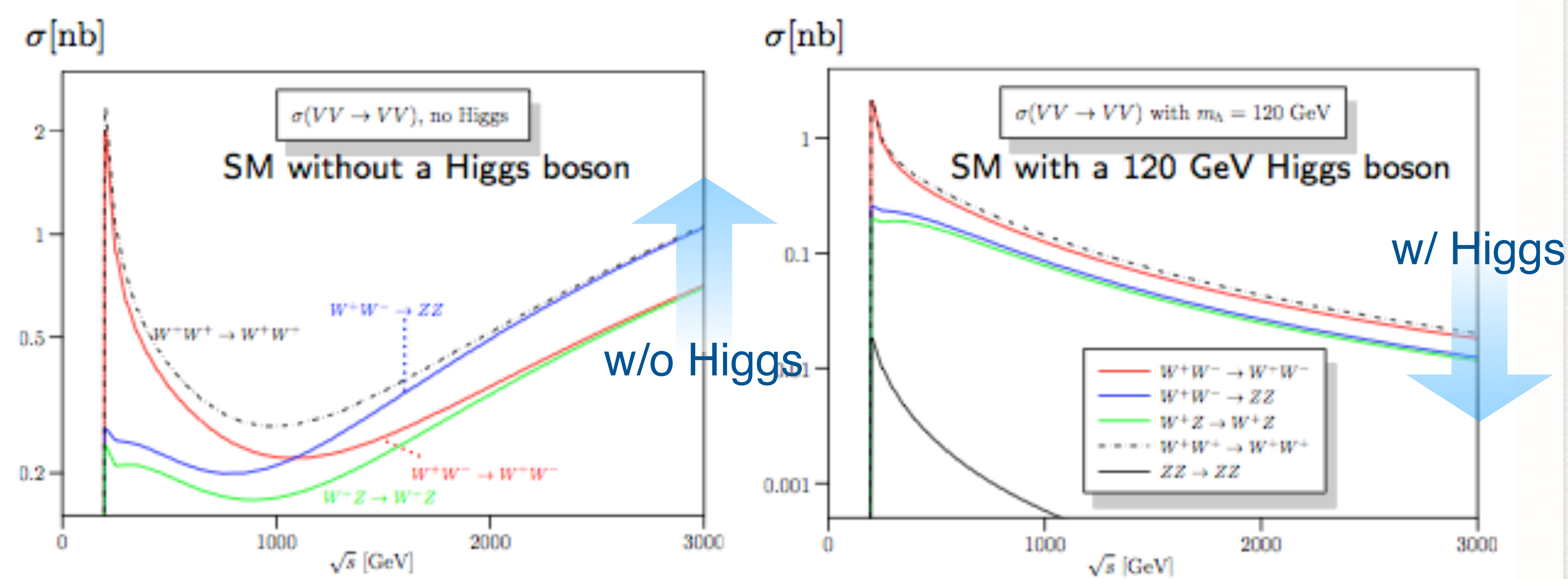
Electron channel



ref.
PRD 90, 032008 (2014)

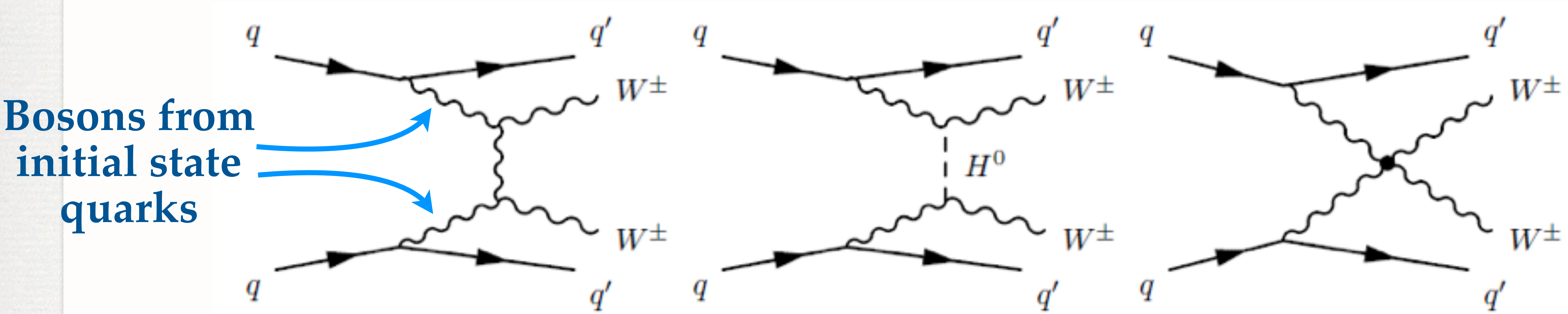
VECTOR BOSON SCATTERING

- Vector Boson scattering is an important process for probing the nature of electroweak symmetry breaking.
- In the standard model, the Higgs boson is essential to preserve the VV scattering cross section at high energy:

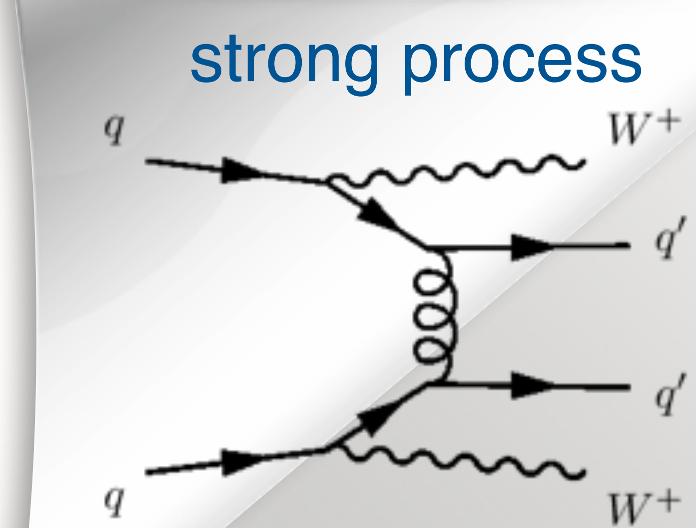


VECTOR BOSON SCATTERING

- The vector boson scattering process produces two vector bosons (VV) and two jets (jj) in the final state:

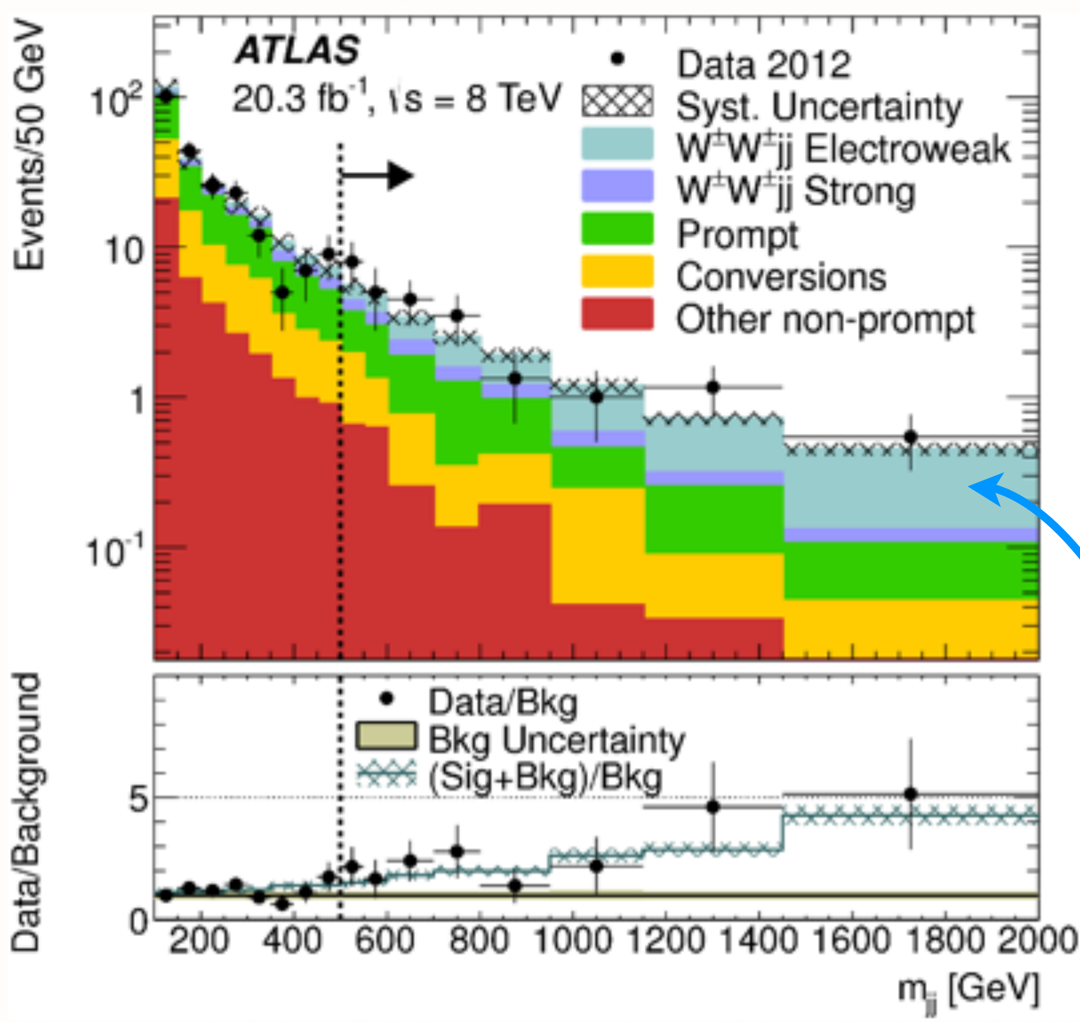


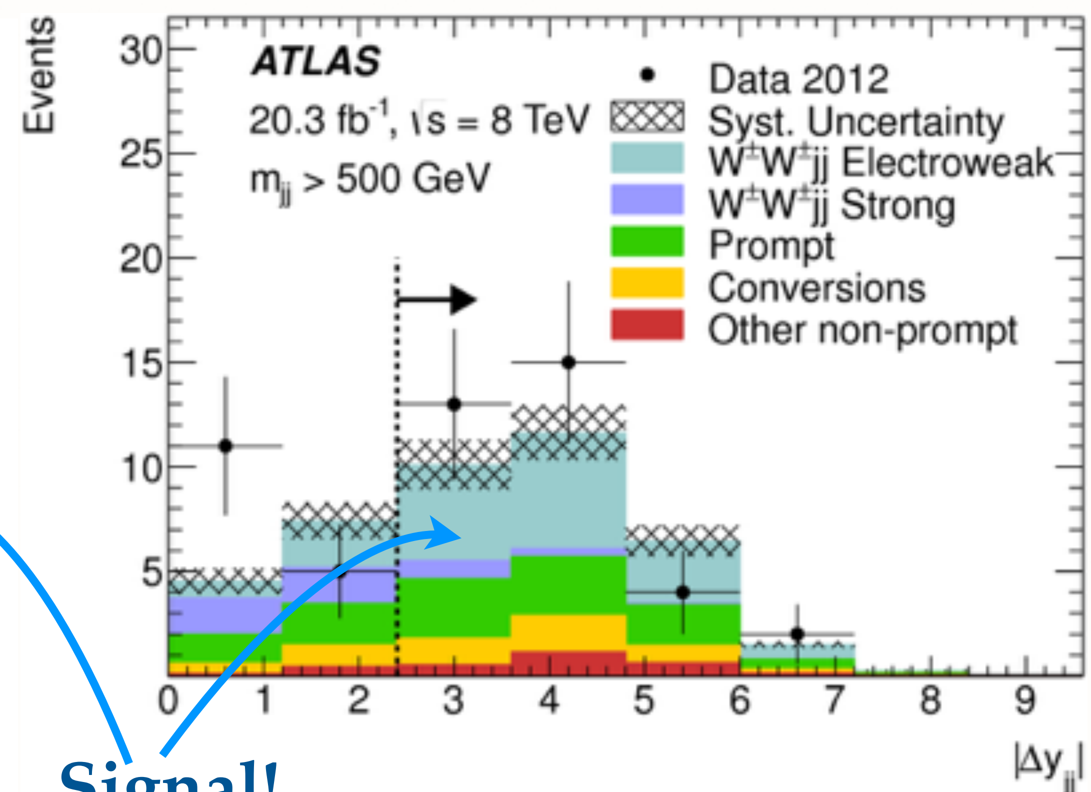
- The VVjj final state can have contributions from strong production processes as well.
- However if one select “same-sign” $W^{\pm}W^{\pm}$ plus jets, the strong interaction background is small and makes this study feasible!



$W^{\pm}W^{\pm}$+2J PRODUCTION

- Experiments have searched for the same-sign WW+2 jets events.
- Signature: large dijet mass, large dijet rapidity gap:



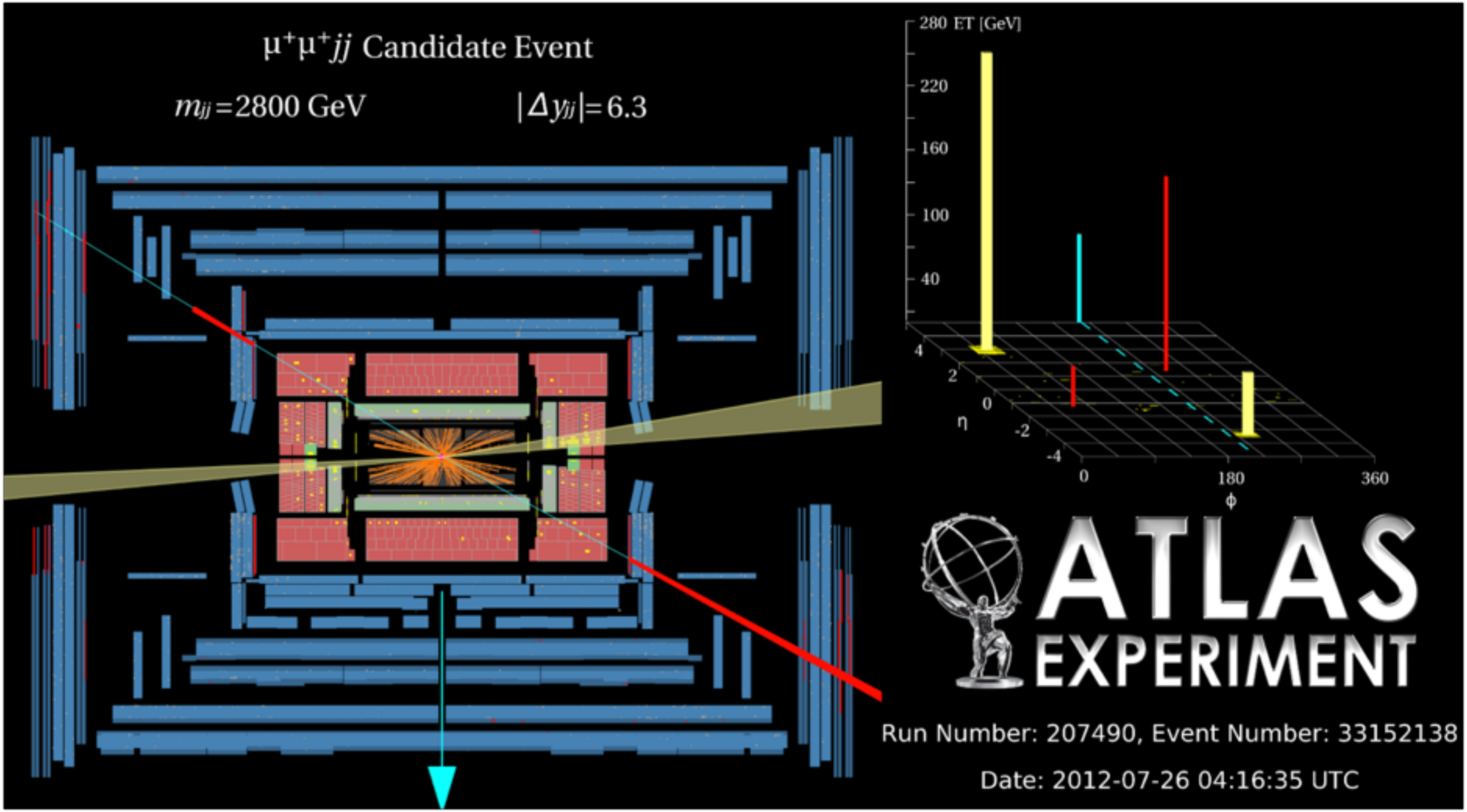


Signal!

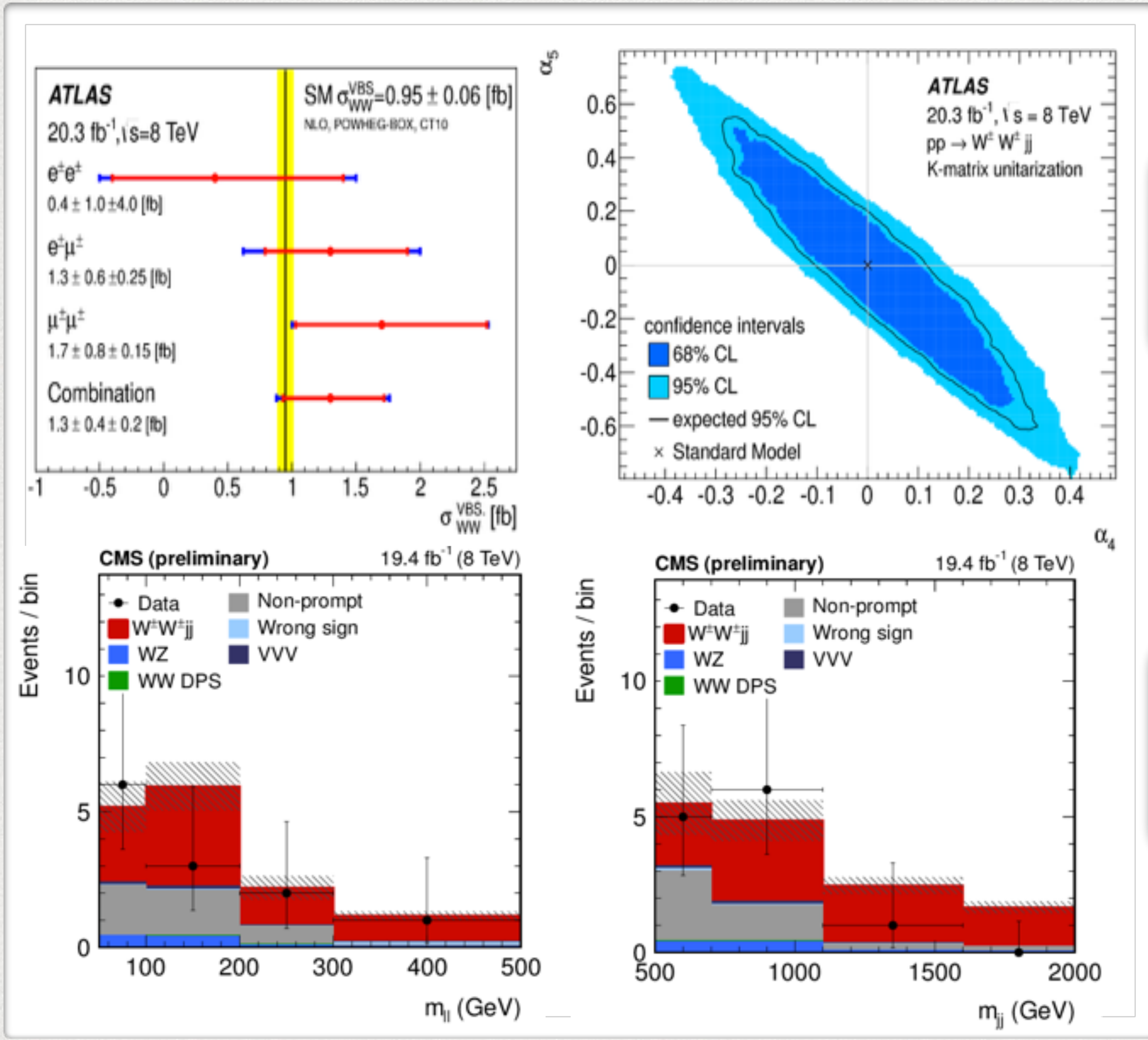
ref. arXiv:1405.6241

Good agreement with SM.
Background mainly from real multi-lepton processes (e.g. diboson, top)

A $W^{\pm}W^{\pm}$+2J CANDIDATE



$W^{\pm}W^{\pm}$+2J RESULTS



ref. arXiv:1405.6241

ATLAS $Z_{obs} = 3.6\ \sigma$

$\sigma = 1.3 \pm 0.4 \pm 0.2$ fb

$\sigma_{TH} = 0.95 \pm 0.06$ fb

ref. CMS-PAS-SMP-13-015

CMS $Z_{obs} = 2.0\ \sigma$

$\sigma = 4.0^{+2.4\ +1.1}_{-2.0\ -1.0}$ fb

$\sigma_{TH} = 5.8 \pm 1.2$ fb

Note the “cross sections” are defined in different regions.

SUMMARY

- Precision electroweak measurements at the LHC can provide indirect access to new physics beyond the SM.
- As you can see there are many impressive results from ATLAS and CMS experiments.
- First evidence for EWK vector boson scattering seen in the same-sign WWjj production.
- Topics which are not covered:
  - Many details. :-)
  - Weak mixing angle ($\sin^2\theta_{eff}$) measurements.
  - Constraints on anomalous triple gauge couplings.

BACKUP SLIDES