Standard Model Physics at CMS

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for the CMS collaboration

8 Aprile 2015

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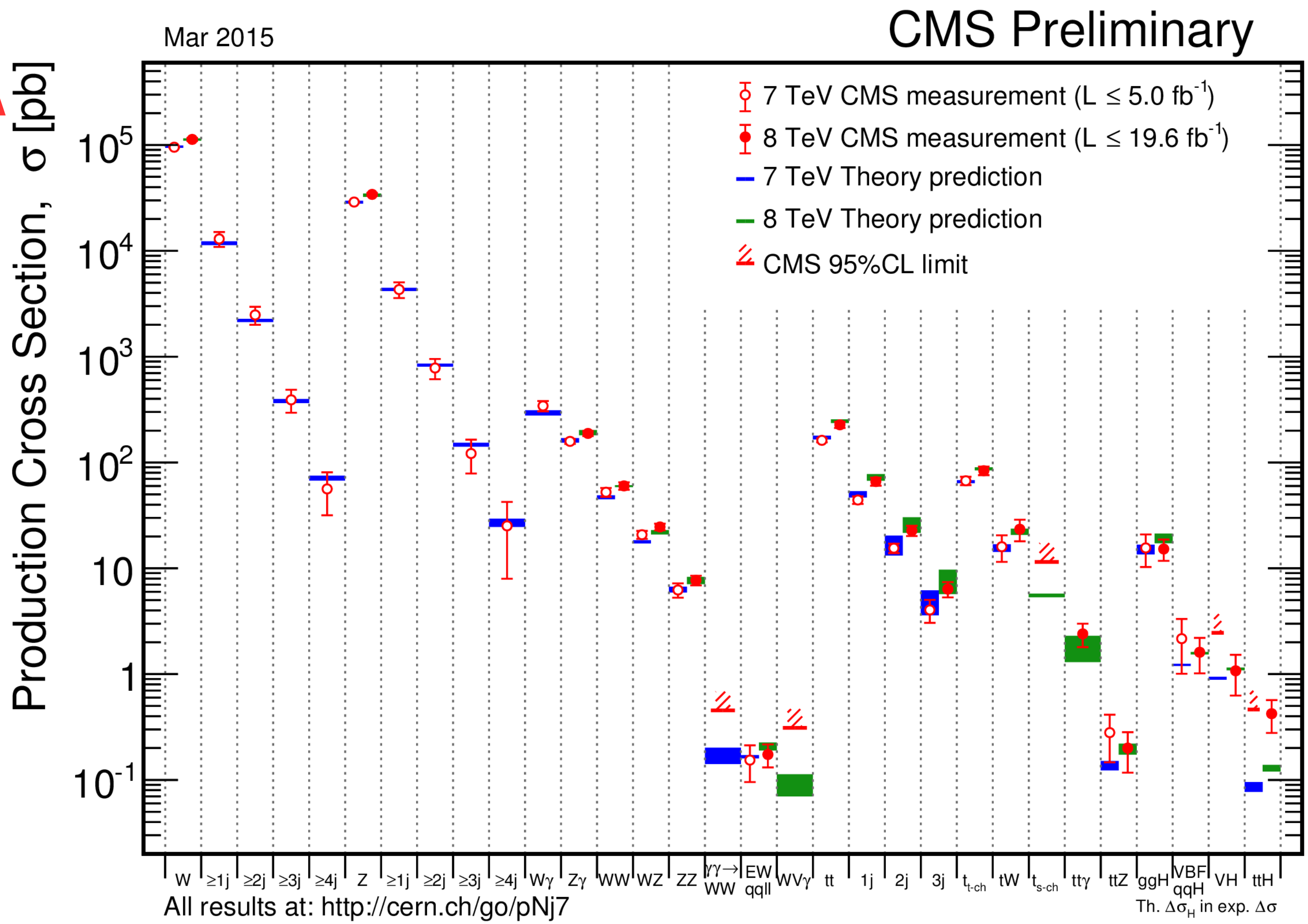
Cross sections for SM processes

6 orders of magnitude

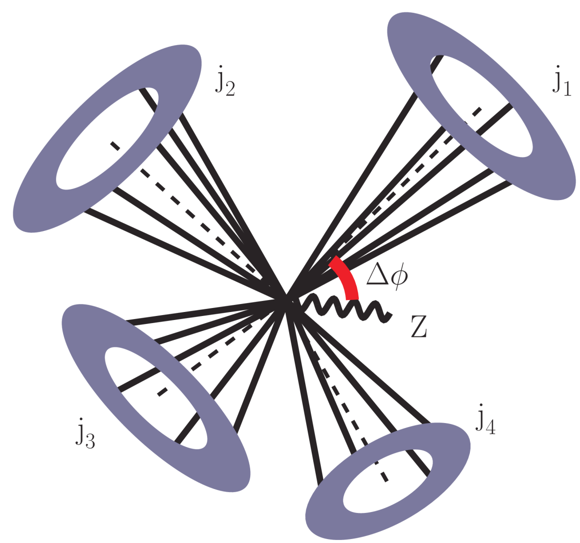
W(lν) ~100M
Z (ll) ~10M
tt (l+X) ~0.4M



- Impressive agreement

QCD at the TeV scale

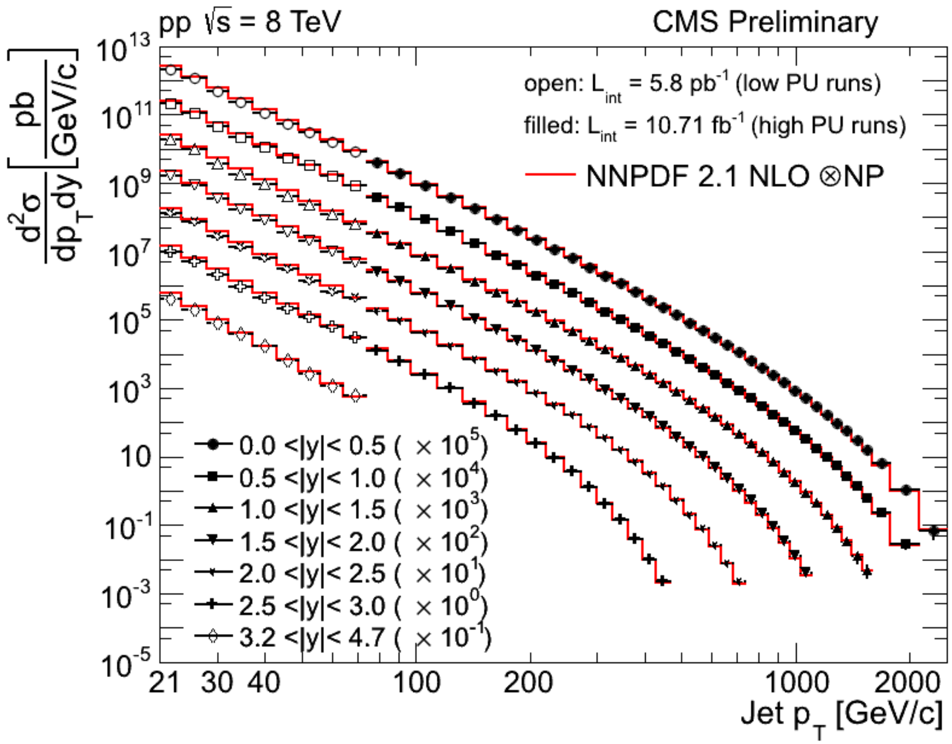
- PDFs and scale uncertainties are among the main systematics for Higgs cross section measurement
- QCD is ubiquitous source of background for any new physics signal
- The LHC has done a great deal of work during Run 1 to understand QCD at the energy frontier
  - Important input for PDF fits
  - Put into light the importance of state of the art theoretical predictions



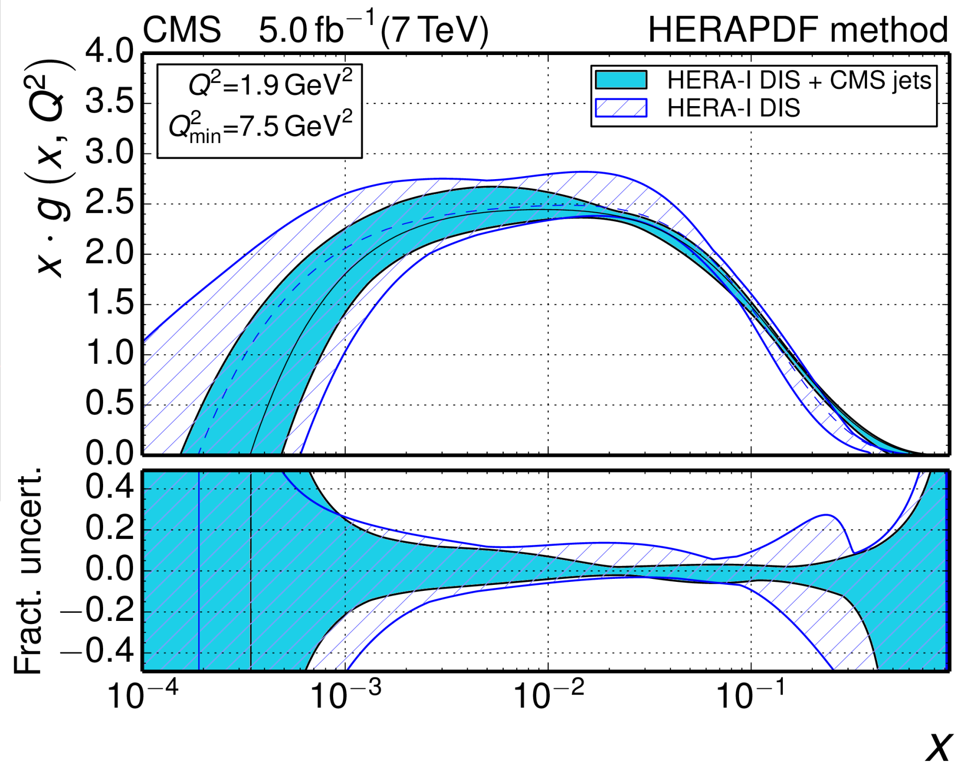
Gluon PDF

Central rapidities are particularly relevant for gluon PDF

Forward rapidities and high pT are expected to have an impact on quark PDFs



Inclusion of jet data predicts a significantly harder gluon



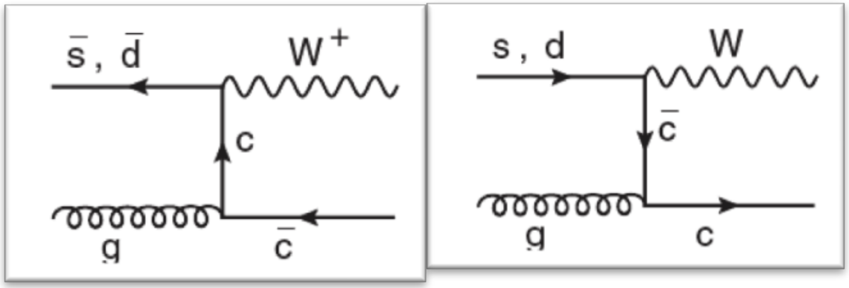
CMS-FSQ-12-031

CMS-SMP-12-012

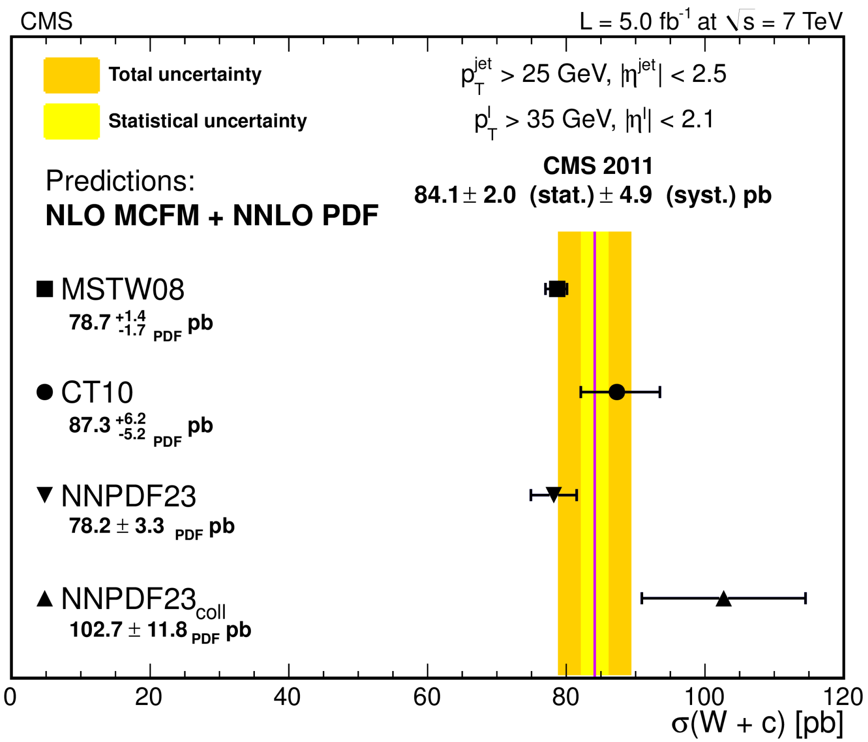
CMS-SMP-12-028

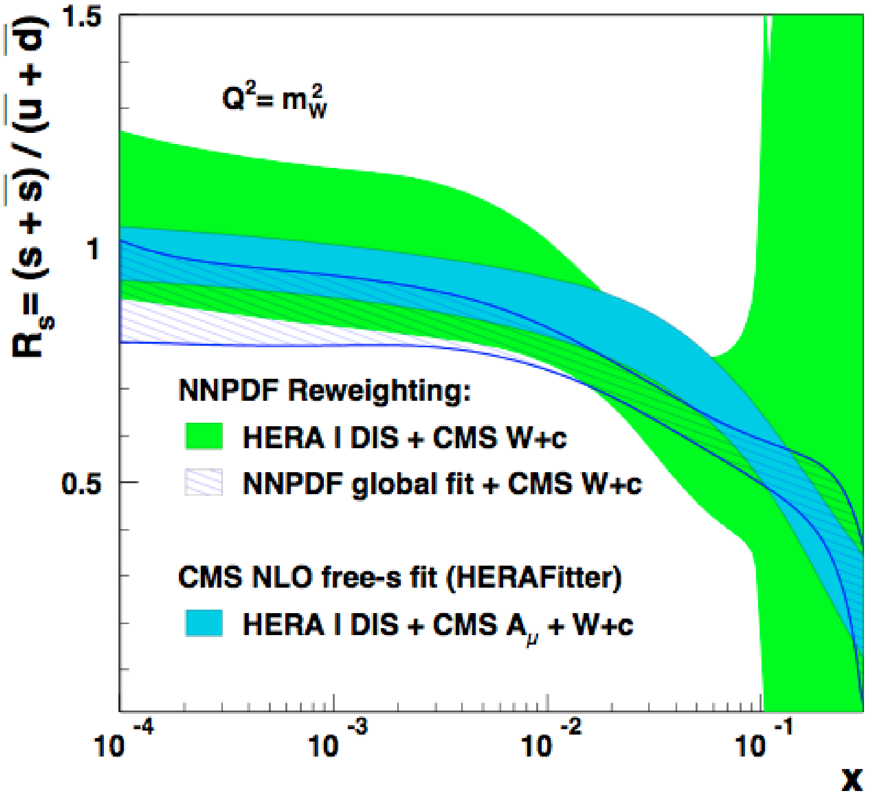
W+charm

- Probes the strange quark pdf
- Different PDFs predict different suppressions of s quark w.r.t. d quark



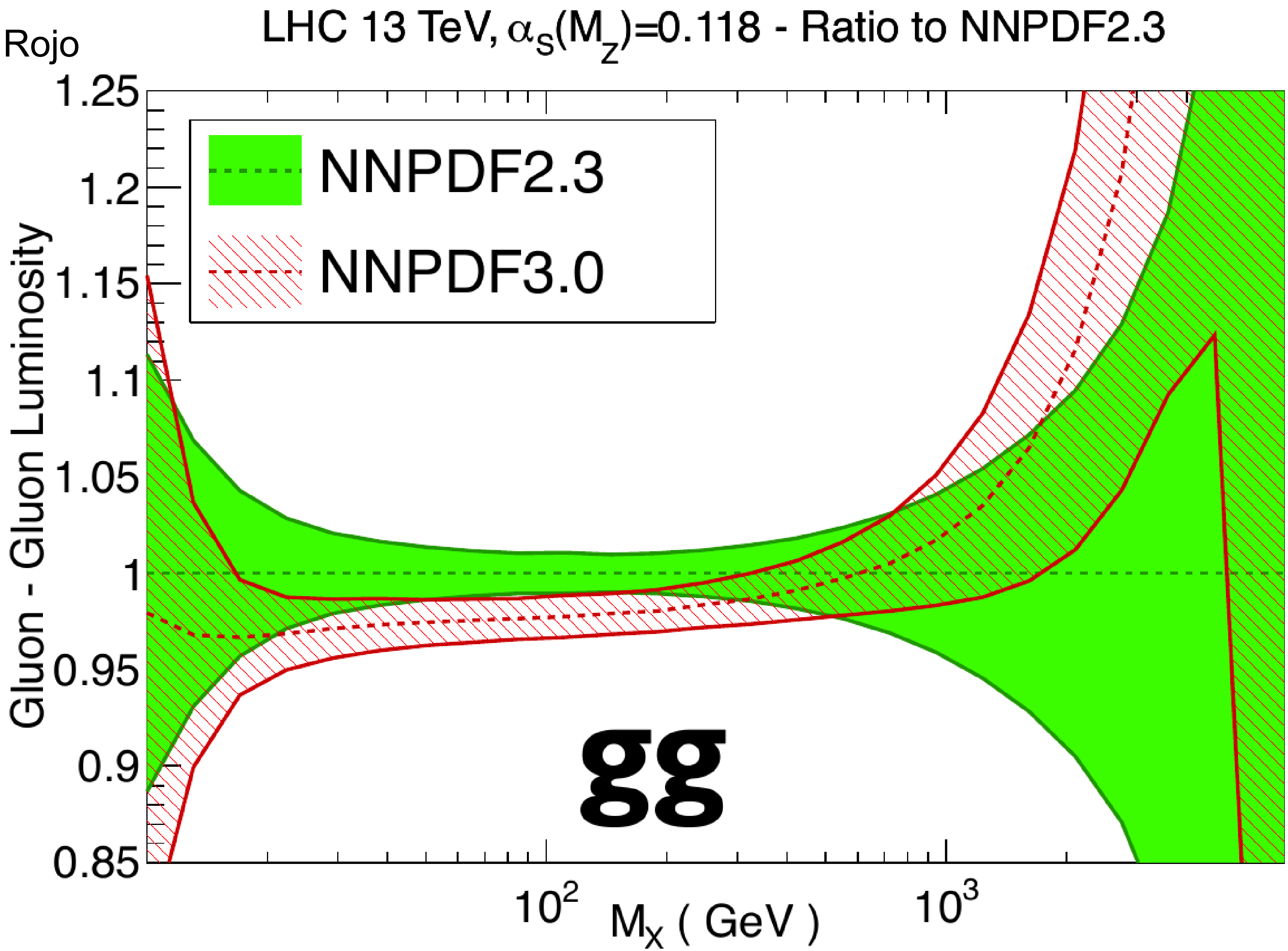
JHEP02(2014)013





Impact of LHC on PDF

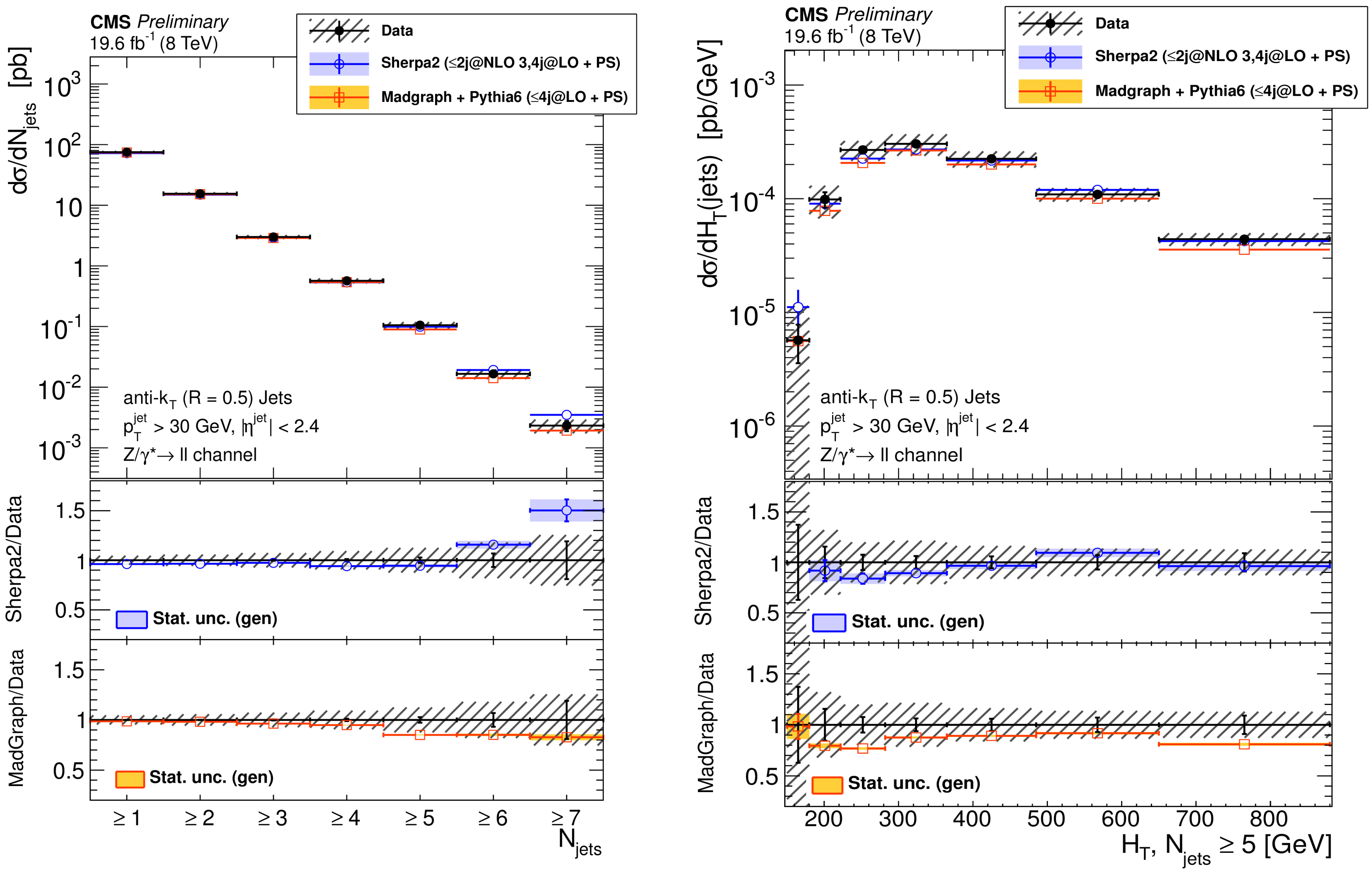
J. Rojo



Hard QCD probes

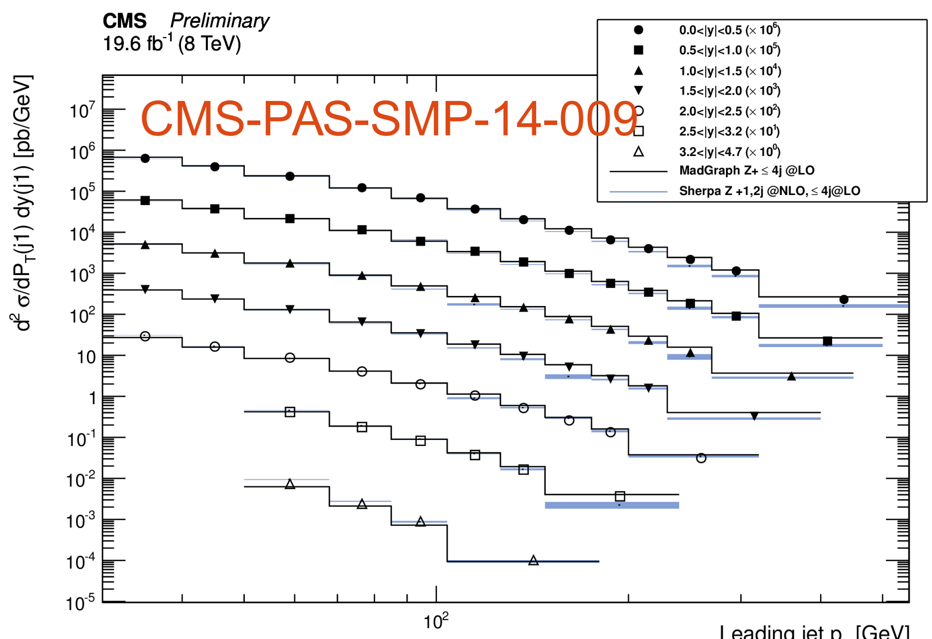
- Associated production of vector bosons plus jets has been extensively used to test the predictions of pQCD
  - Several models compared to data

CMS-PAS-SMP-13-007

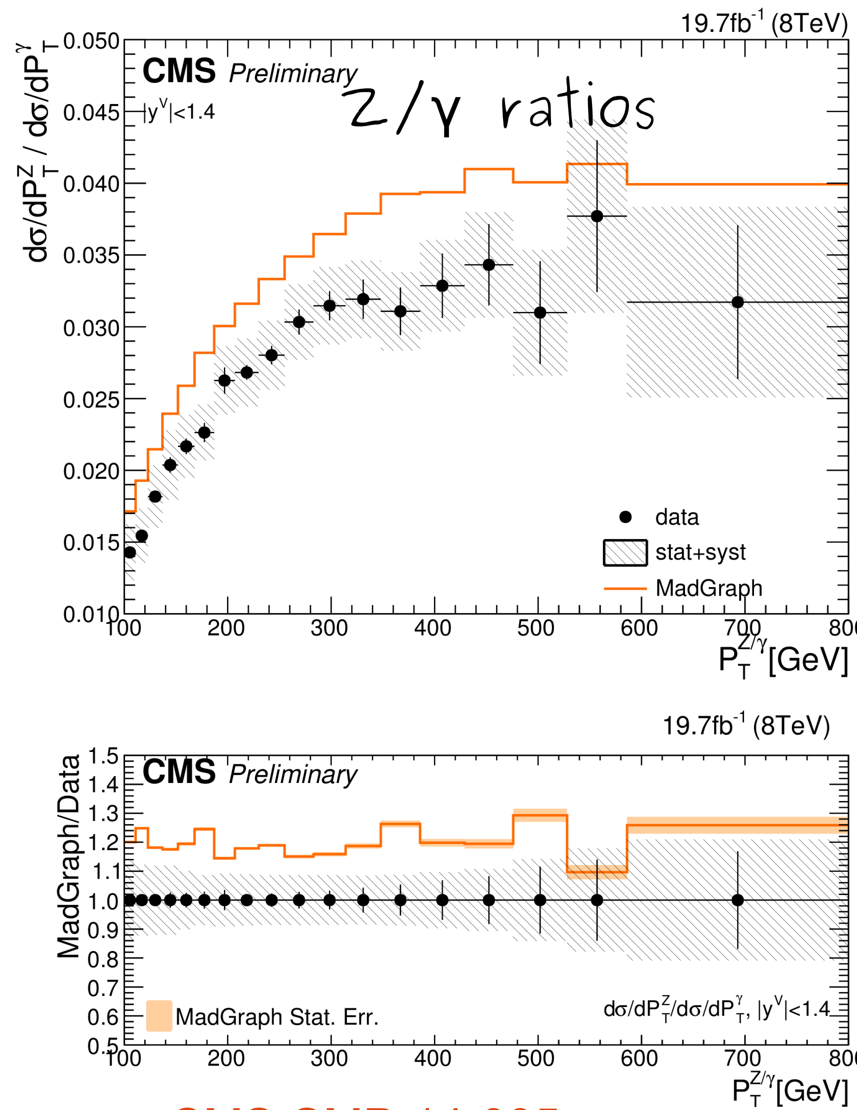


Hard QCD probes

- Complex observables!
- The Run 1 statistics already allows
  exploration of extreme phase space
  corners
  - Relevant for searches



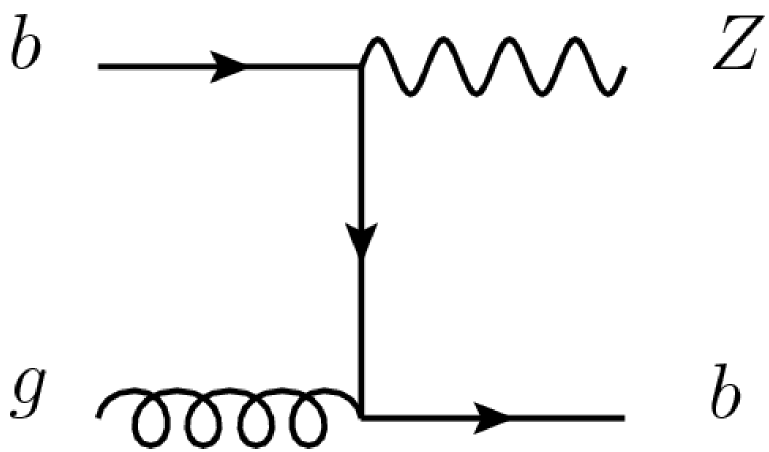
Leading jet pT in bins of Z rapidity



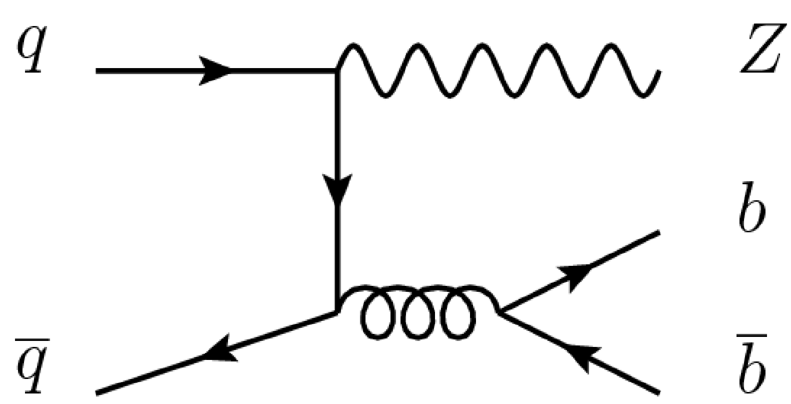
CMS-SMP-14-005

Z+heavy flavor

- Large theoretical uncertainties
- Important for searches
- Two main approaches
  - 4-flavor scheme: use PDFs without a b quark and produce all b quarks via matrix element
  - 5-flavor scheme: b quarks allowed in the initial state

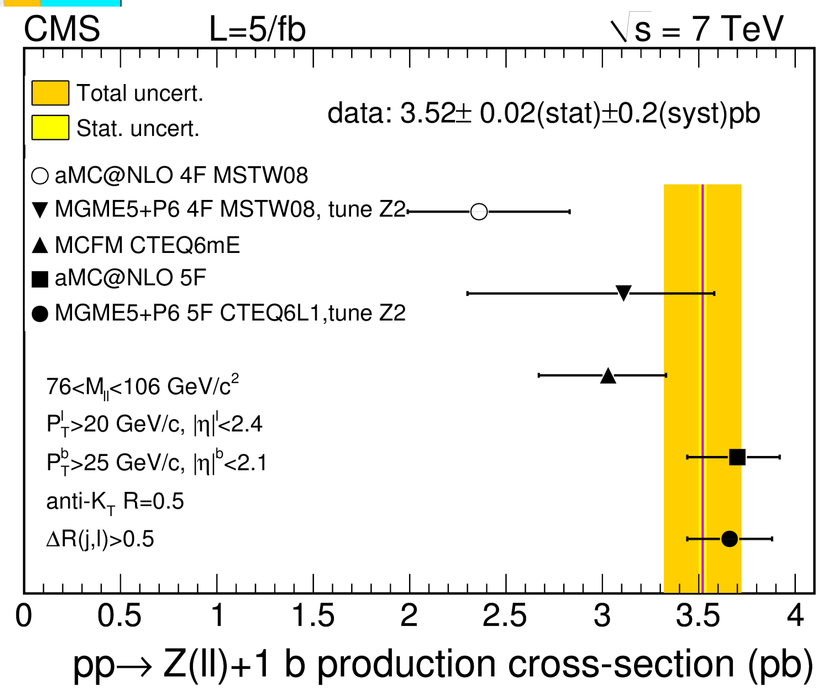


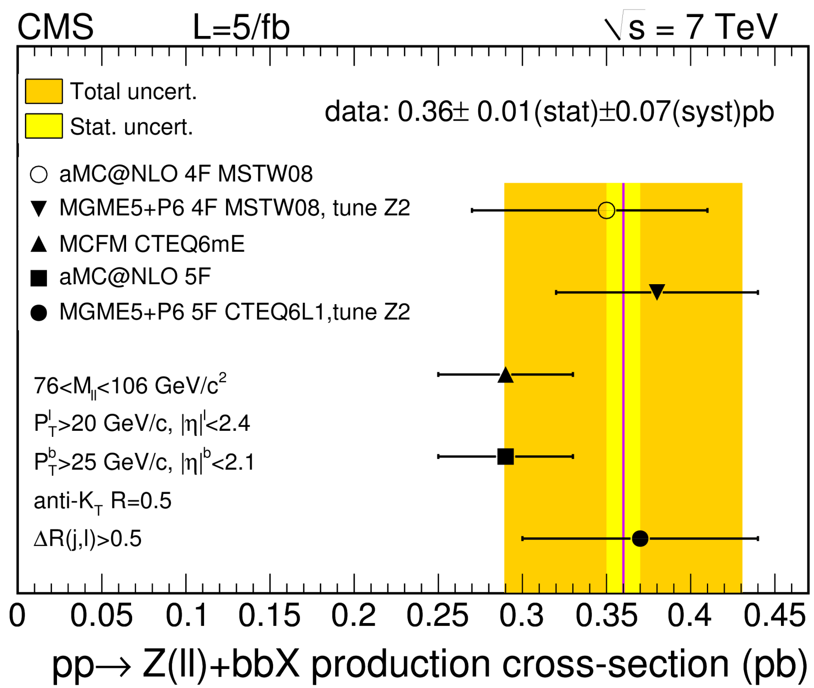
LO for Z+>=1b in 5-f



LO for Z+>=1b in 4-f

Z+heavy flavor

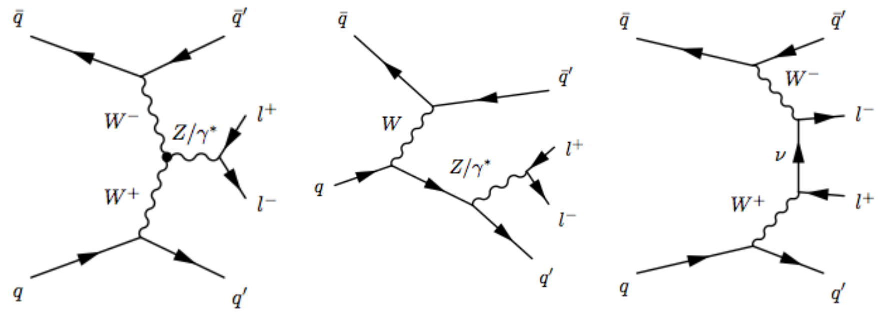




JHEP06(2014)120

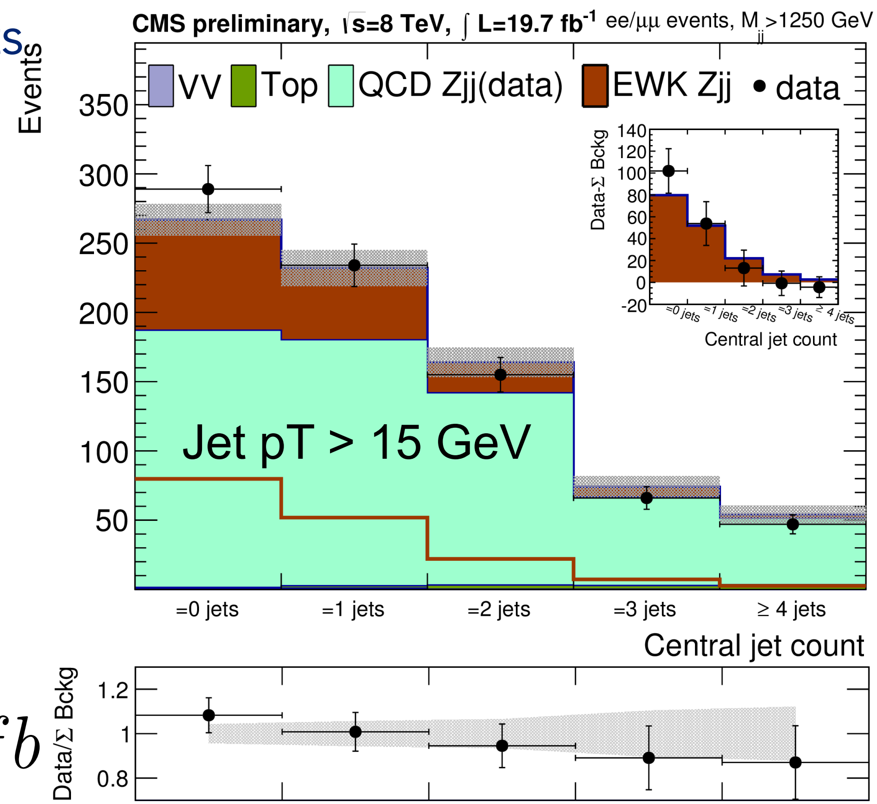
- 5-F scheme gives the best description of Z+>=1b jet
    - Unclear why, for Z+1b both 4F and 5F should correspond to the same order
- 4-F scheme gives good description of Z+>=2b jets

Electroweak Z production



- $O(\alpha^4_{EWK})$ production of di-leptons has been investigated
- Tiny cross section, the VBF like diagram interferes destructively with the others
- Main background is $O(\alpha^2_{EWK}\alpha^2_s)$ Z+2jets
- Analysis is based both on an MVA approach and a data drive approach to estimate Z+2 jet from γ+2jets
- 5 sigma observation of this process!
    - Due to the large VBF destructive interference, this could be regarded as the first observation of VBF in CMS

$$\sigma = 226 \pm 26(stat.) \pm 35(syst.)\ fb$$

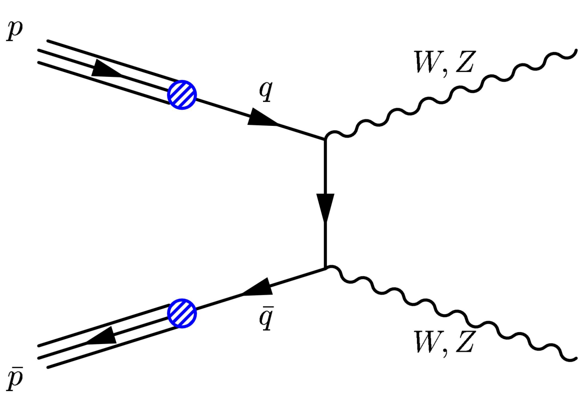


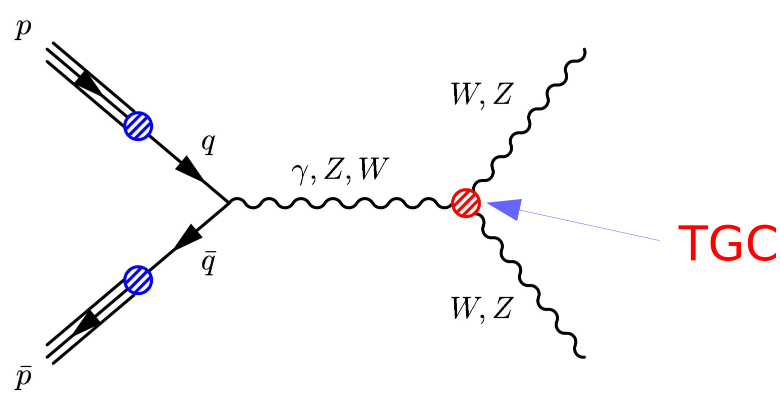
CMS-PAS-FSQ-12-035

Diboson production

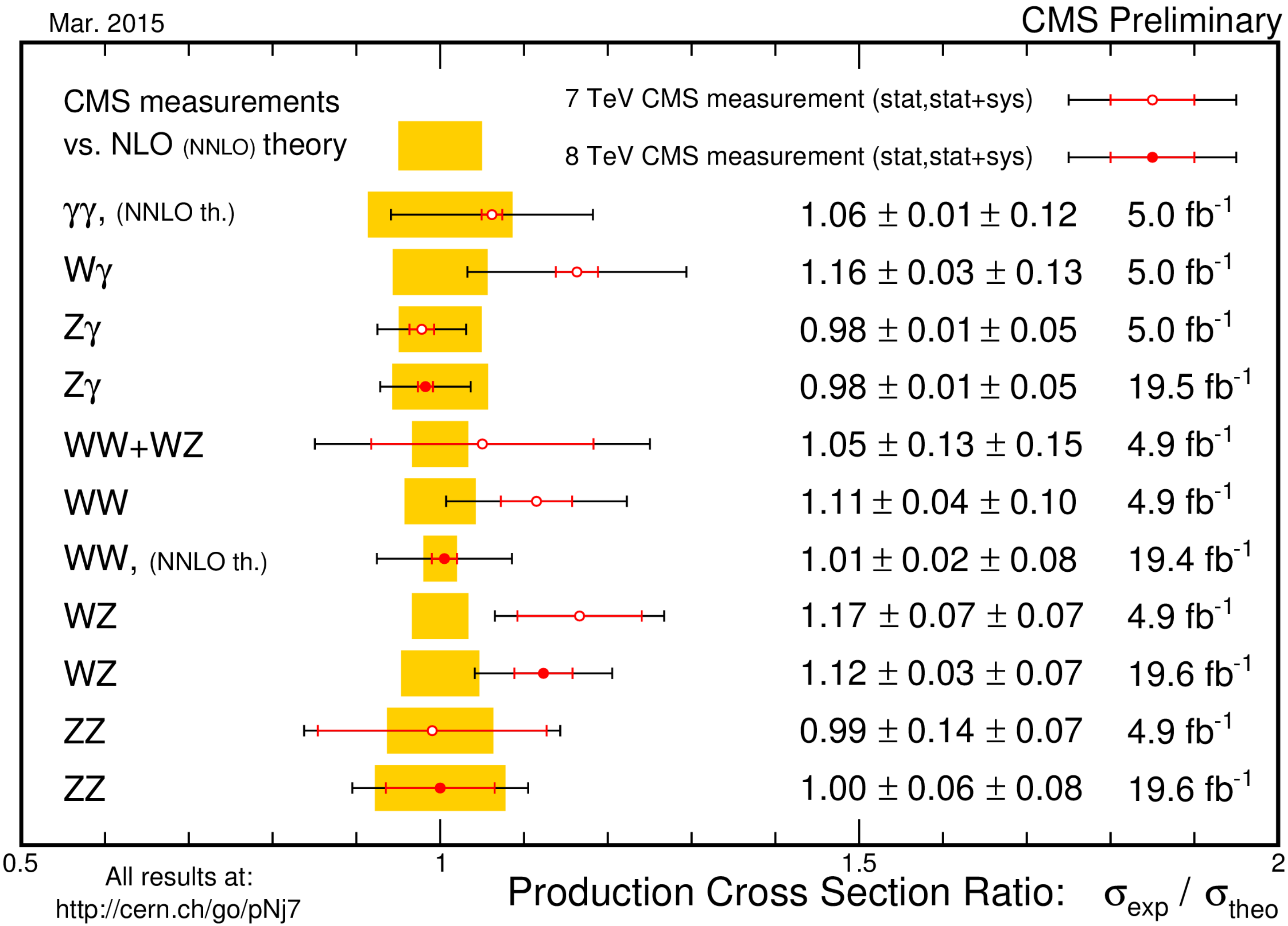
- Important test of the gauge sector of the SM
- Irreducible background for Higgs and searches
- Test of triple gauge couplings
  - Charged TGC (WWZ, WWγ) allowed in SM
  - Neutral TGC (ZZZ, ZZγ) forbidden in SM
- Anomalous couplings generally lead to larger cross sections, especially in the high transverse momentum tails

Coupling	Parameters	Channel
WWγ	λ_γ, $\Delta\kappa_\gamma$	WW,Wγ
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW,WZ
ZZγ	h_3^Z, h_4^Z	Zγ
Zγγ	h_3^γ, h_4^γ	Zγ
ZZZ	f_4^Z, f_5^Z	ZZ
ZγZ	f_4^γ, f_5^γ	ZZ





Diboson production



WW production

- Recently updated with full 8 TeV statistics
- Requiring two charged leptons and MET
- Inclusive cross section

CMS-PAS-SMP-14-016

$$\sigma_{CMS} = 60.1 \pm 0.9(stat.) \pm 3.2(exp.) \pm 3.1(th.) \pm 1.6(lum.)\ \mathrm{pb}$$

In good agreement with SM NNLO predictions $59.8^{+1.3}_{-1.1}$ pb

Gehrmann, Grazzini et al

- Also in a fiducial phase space

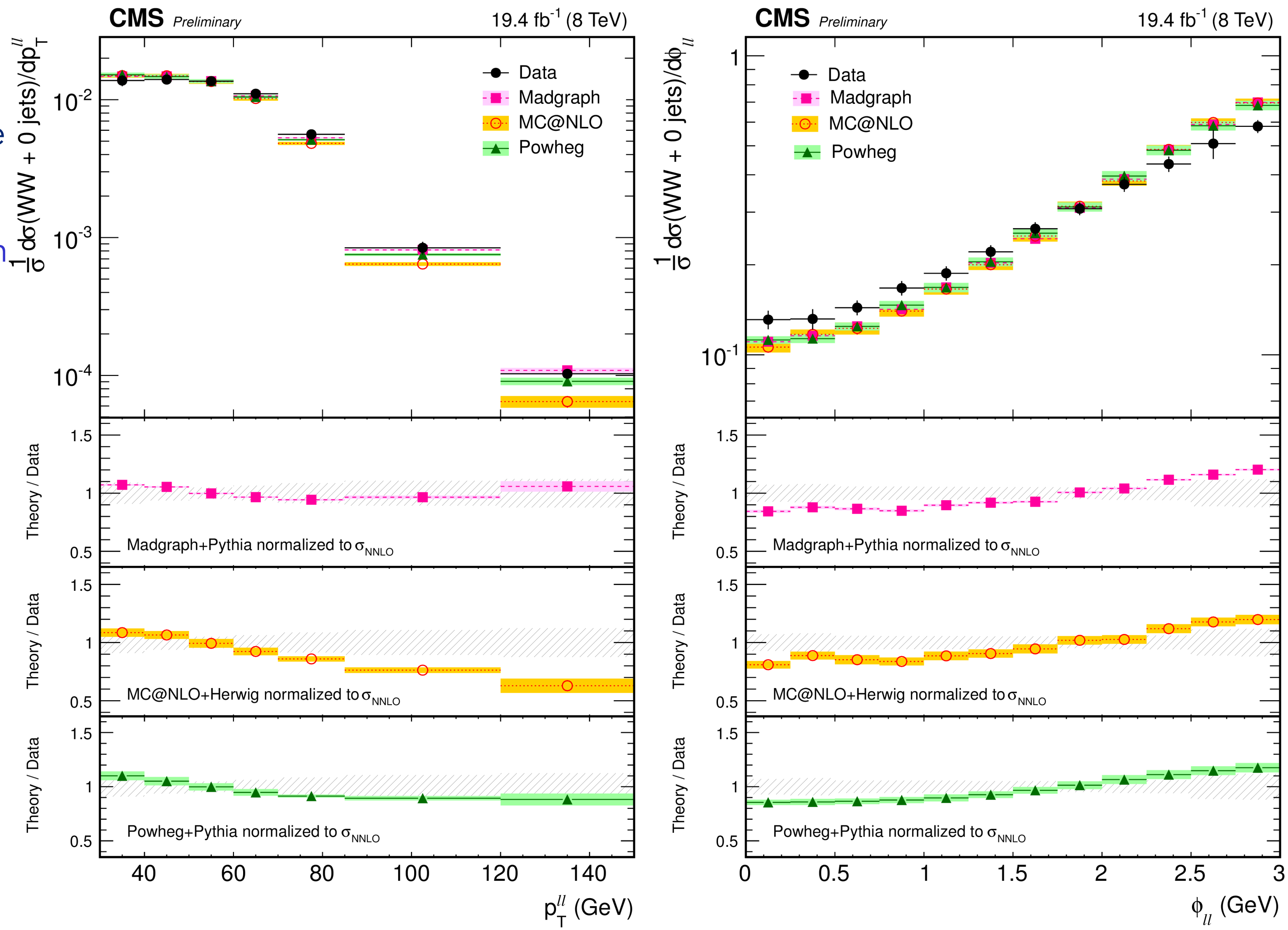
p_T^{jet} threshold (GeV)	σ_{0jet} measured (pb)	σ_{0jet} predicted (pb)
20	36.2 ± 0.6 (stat.) ± 2.1 (exp.) ± 1.1 (th.) ± 0.9 (lum.)	36.7 ± 0.1 (stat.)
25	40.8 ± 0.7 (stat.) ± 2.3 (exp.) ± 1.3 (th.) ± 1.1 (lum.)	40.9 ± 0.1 (stat.)
30	44.0 ± 0.7 (stat.) ± 2.5 (exp.) ± 1.4 (th.) ± 1.1 (lum.)	43.9 ± 0.1 (stat.)

p_T^{jet} threshold (GeV)	$\sigma_{0jet,\mathrm{W}\to\ell\nu}$ measured (pb)	$\sigma_{0jet,\mathrm{W}\to\ell\nu}$ predicted (pb)
20	0.223 ± 0.004 (stat.) ± 0.013 (exp.) ± 0.007 (th.) ± 0.006 (lum.)	0.228 ± 0.001 (stat.)
25	0.253 ± 0.005 (stat.) ± 0.014 (exp.) ± 0.008 (th.) ± 0.007 (lum.)	0.254 ± 0.001 (stat.)
30	0.273 ± 0.005 (stat.) ± 0.015 (exp.) ± 0.009 (th.) ± 0.007 (lum.)	0.274 ± 0.001 (stat.)

WW production

CMS-PAS-SMP-14-016

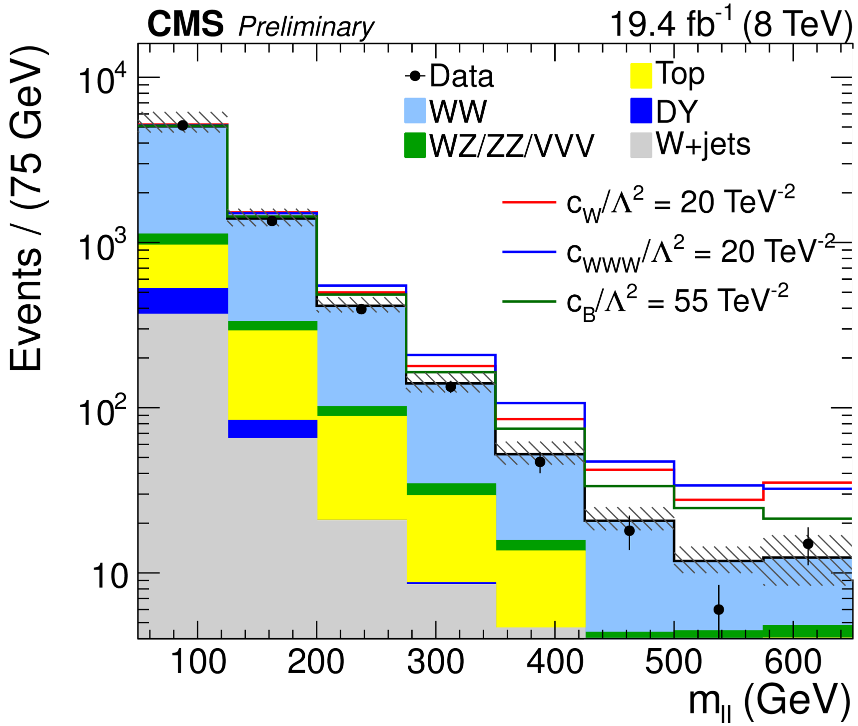
- Differential measurements unfolded to particle level
  - Good agreement with matched LO+PS predictions at high transverse momentum
  - Angular distributions show some degree of disagreement with all predictions

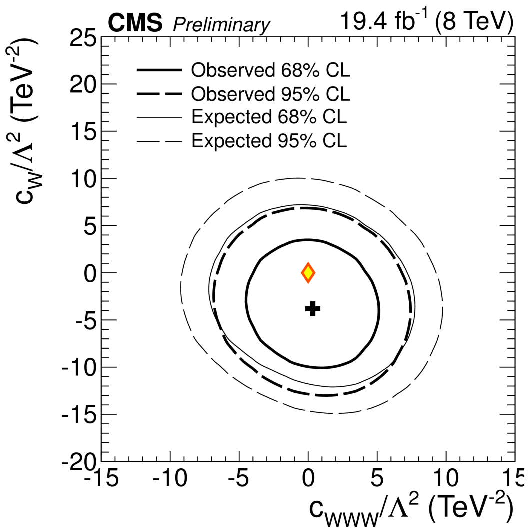


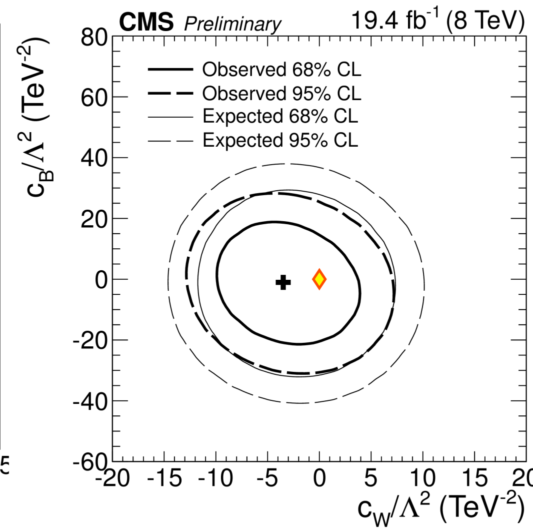
WW production

CMS-PAS-SMP-14-016

- This measurement is sensitive to aTGC for WWZ and WWγ
  - No deviations from SM have been observed and limits have been set





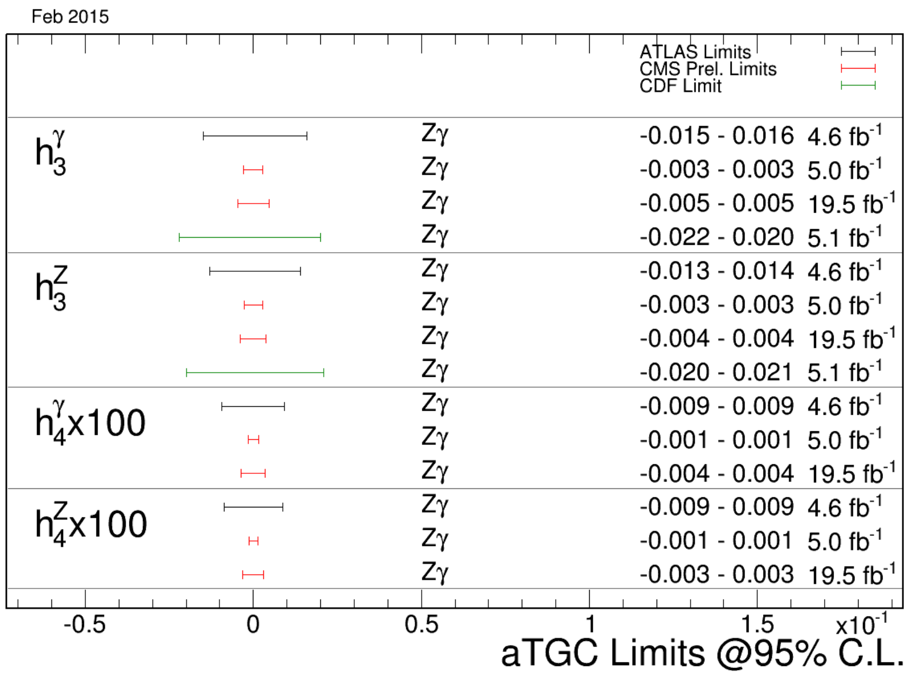


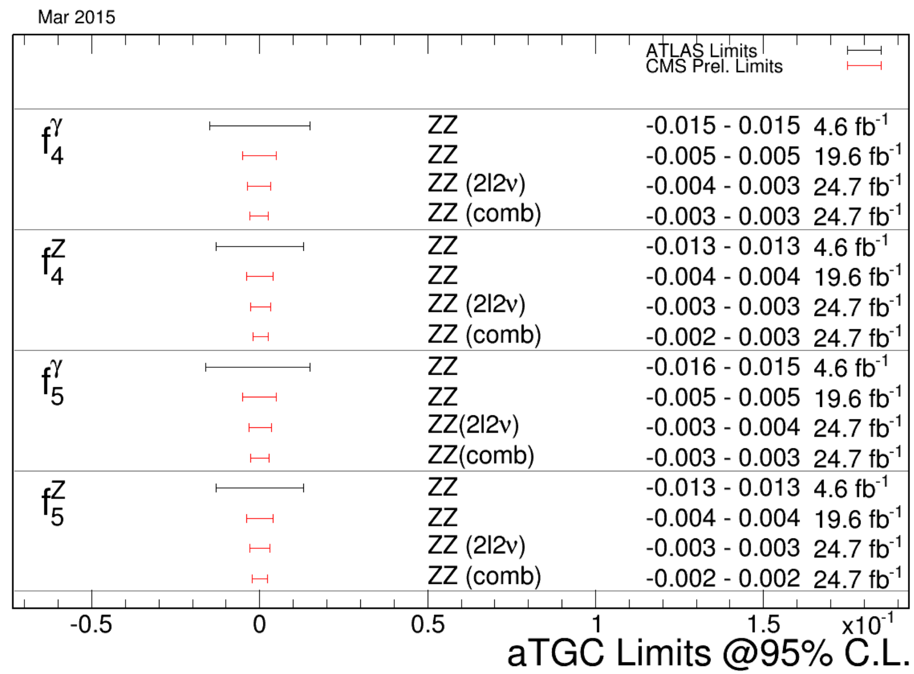
A single measurement competitive with LEP combination

Coupling constant	This result (TeV^{-2})	This result 95% interval (TeV^{-2})	World average (TeV^{-2})
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8 (from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$ (from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$ (from κ_γ and g_1^Z)

Neutral aTGC

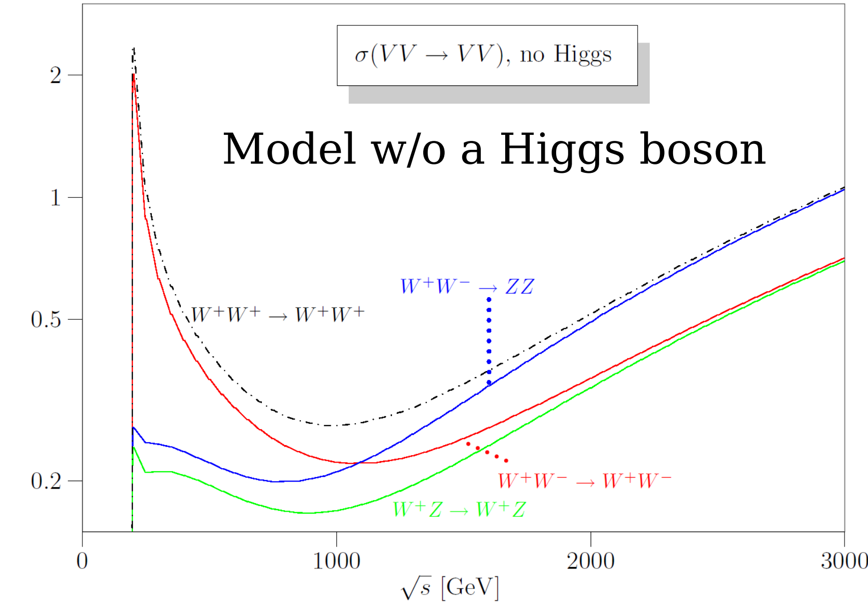
No deviation from SM observed so far...



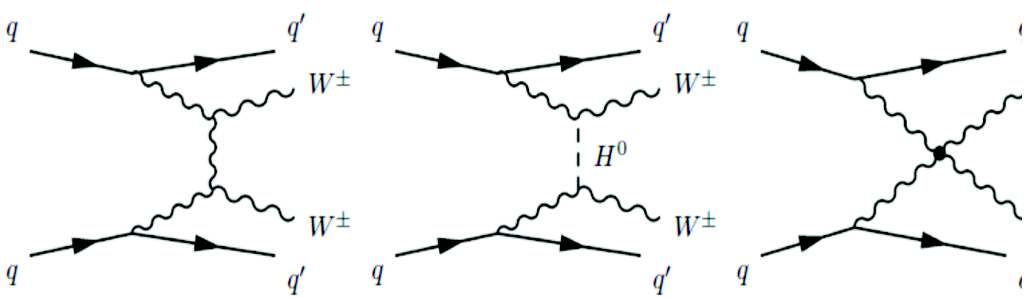


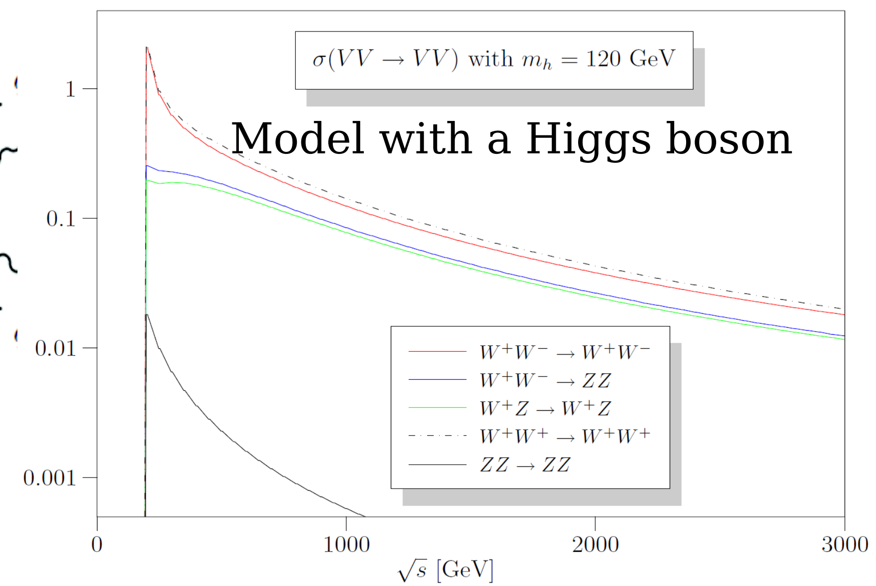
Vector boson scattering

- Important process to probe EWSB
- The role of the Higgs in EWSB is essential to preserve unitarity of VBS cross section
- Same sign WW scattering provides the best S/B



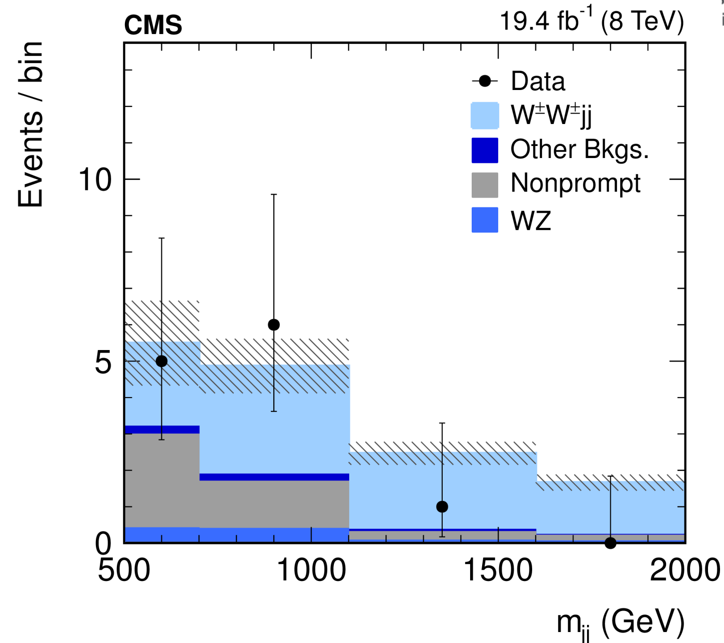
arXiv:0806.4145





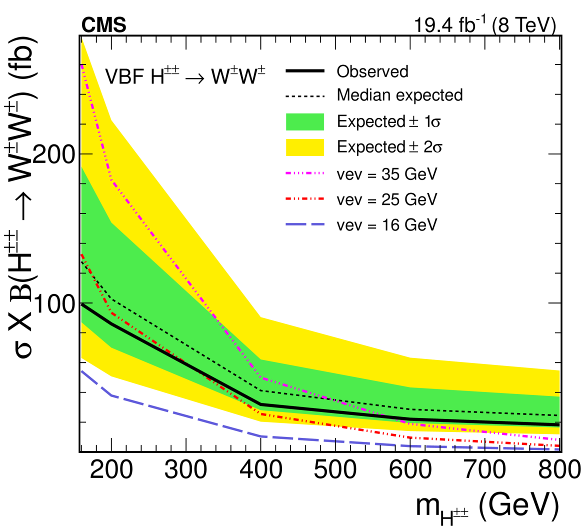
VBS in WWjj same sign

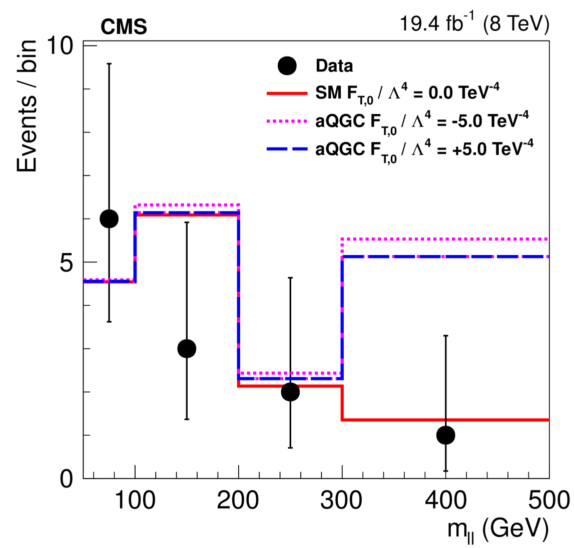
- Analysis strategy
  - Look into the high di-jet mass tail of events with two same sign leptons
- Backgrounds
  - Non-prompt leptons (75%)
  - WZ
  - Wong sign, DPS, VVV
- Result in agreement with SM
  - **2σ observed**, 3.1σ expected
- Limits put on alternative models, such as H^{++} and aQGC



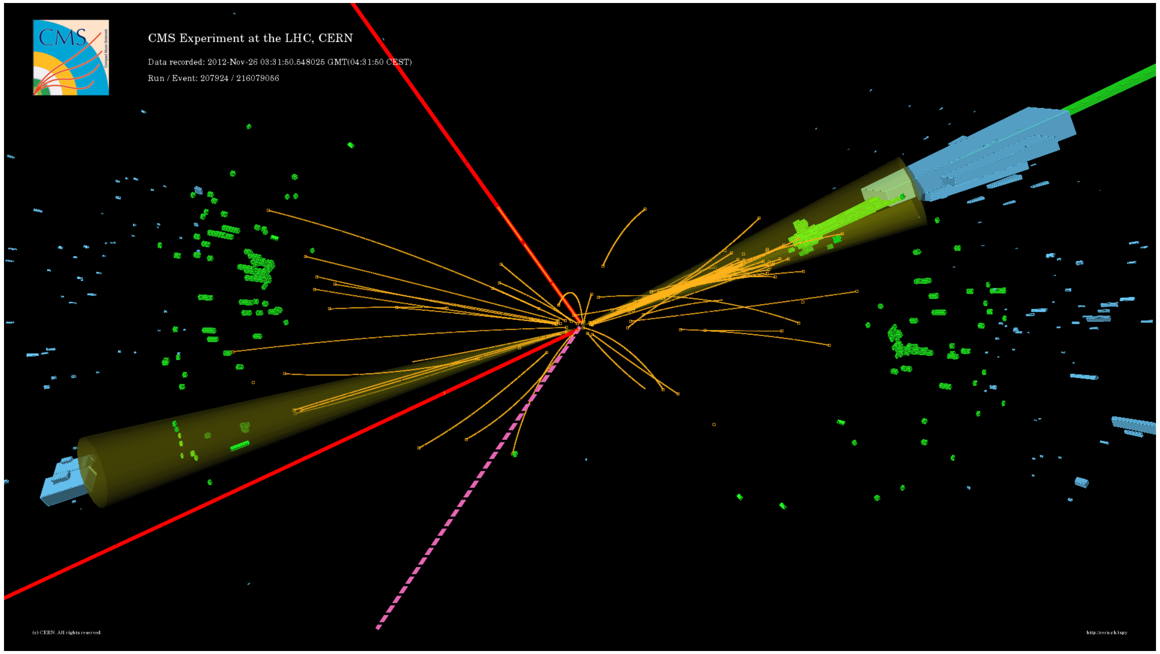
$$\sigma_{fid}(W^{\pm}W^{\pm}jj) = 4.0^{+2.4}_{-2.0}(stat)^{+1.1}_{-1.0}(syst)\, fb$$

PhysRevLett.114.051801





Conclusion



Candidate VBS event in the di-muon channel

- An impressive amount of SM measurement has been carried out by CMS on LHC Run 1 data
- Next main goals for precision measurement will be
  - W mass, triple and quartic gauge couplings, VBS
  - And an ever improving precision on QCD measurements
- ...hoping to find hints of new physics

Backup

Jet reconstruction (CMS)

- Jets are reconstructed with the anti-kt algorithm, with radius of 0.5 or 0.7
- 3 available algorithms for jet reconstruction
  - Calo-Jets: use only the calorimeter towers
  - Jet-Plus-Track Jets: improve the calorimeter jets using the tracks in the jet cone
  - Particle-Flow jets: uses particle flow candidates as input to the clustering algorithm
    - Particle flow reconstruction:
      - global event reconstruction
      - Identifies muons, electrons, taus, photons, charged hadron, neutral hadrons
      - Combines the information from all detectors

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Jet energy scale (CMS)

We use a multi-step procedure to correct the energy of our jets

($p_{\mu}^{cor} = \mathcal{C} \cdot p_{\mu}^{raw}$ ·nts f $\mathcal{C} = C_{\mathrm{offset}}(p_T^{raw}) \cdot C_{\mathrm{MC}}(p'_T, \eta) \cdot C_{\mathrm{rel}}(\eta) \cdot C_{\mathrm{abs}}(p''_T)$
Offset

The method uses correction factors extracted from the full simulation of CMS, C_{MC}

Residual differences with respect to data are accounted for as further scaling factors

- C_{rel} accounts for non-uniformity in eta. It is obtained applying on data and MC the di-jet balance method
- C_{abs} accounts for residual absolute scale differences between data and MC. It is obtained applying on data and MC the γ+jet and Z +jet pT balancing

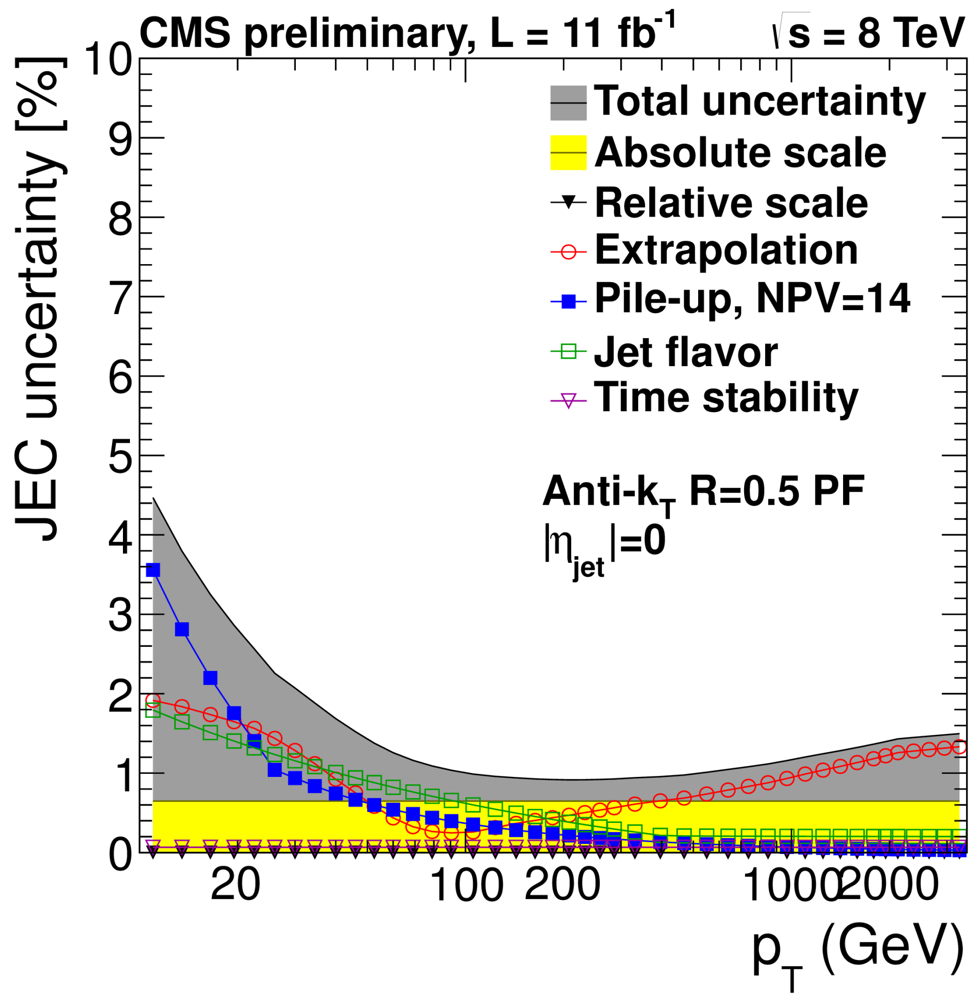
In this MC + residual method effects like the presence of additional radiation spoiling dijet or γ+jet and Z +jet balancing enter only at second order

Jet energy scale (CMS)

Total systematic uncertainty on the energy scale for particle-flow jets

The main sources of uncertainty are:

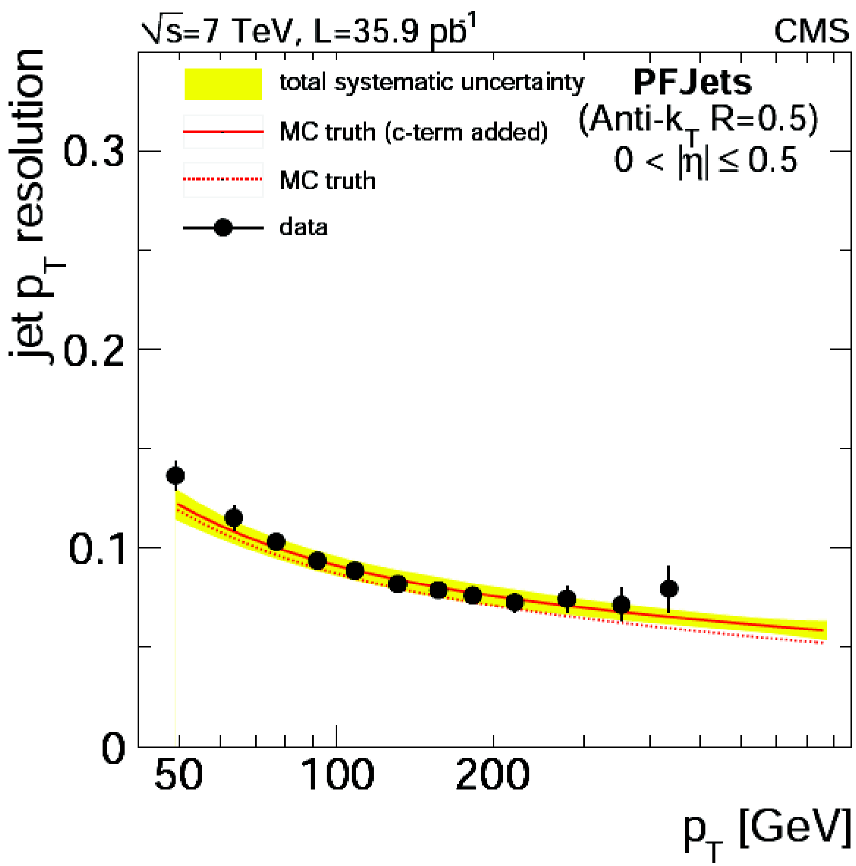
- The photon energy scale, known at 1%
- The relative response acros detector regions
- Pile-up effects
- Extrapolations down to 0 fc the additional activity in the balance methods
- Dependency on jet flavor ir the MC used

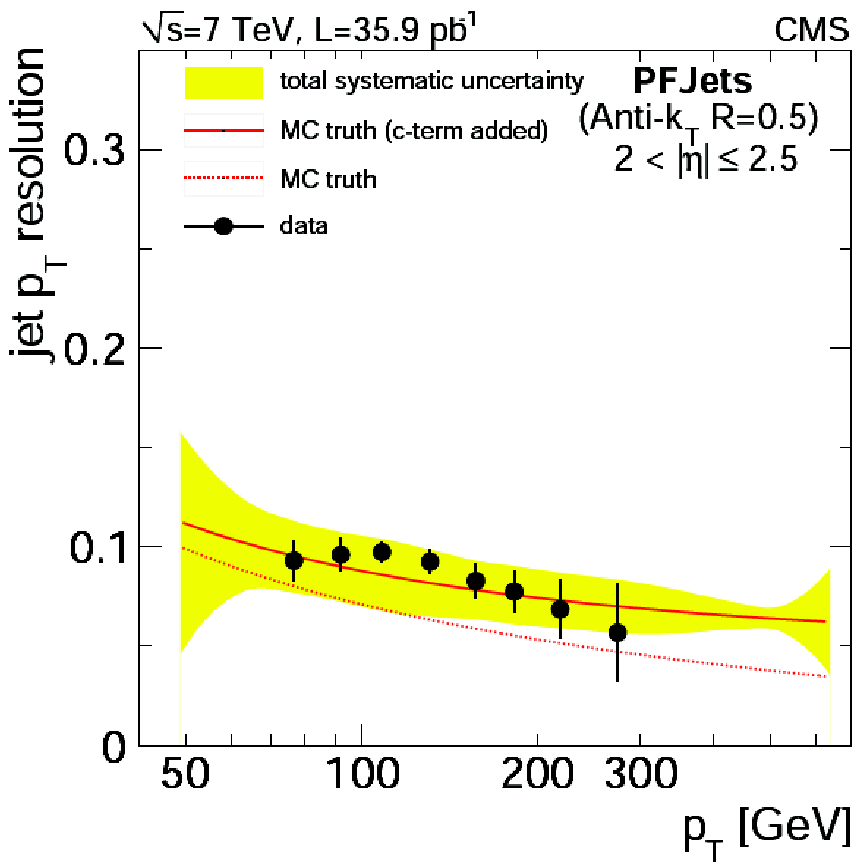


Jet energy resolution (CMS)

Determined with di-jet and γ+jet pT balance

- Plots show two example regions in η
- Resolution is of the order of 10% around 50 GeV

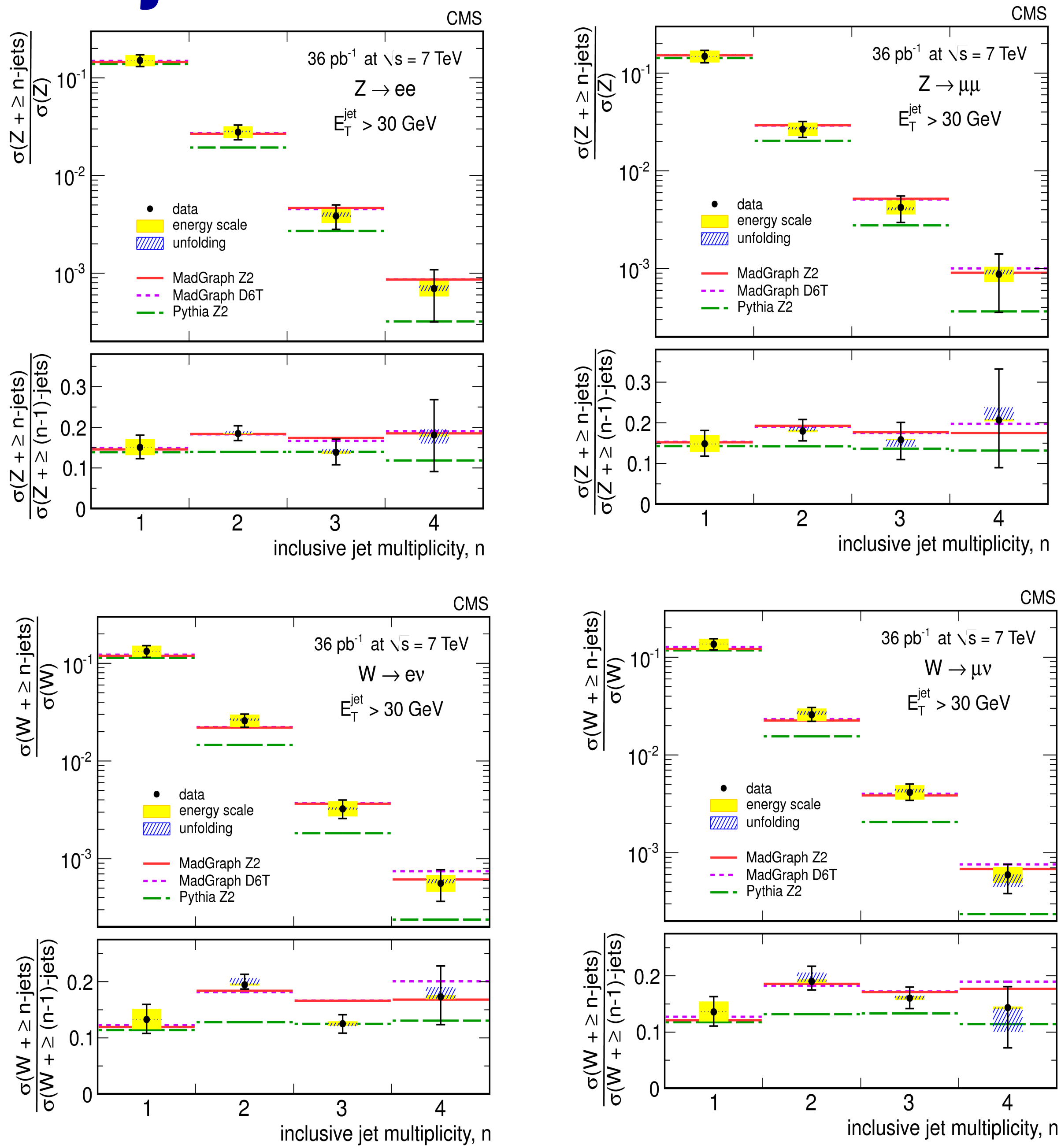




W/Z+jets: rates

JHEP01(2012)010

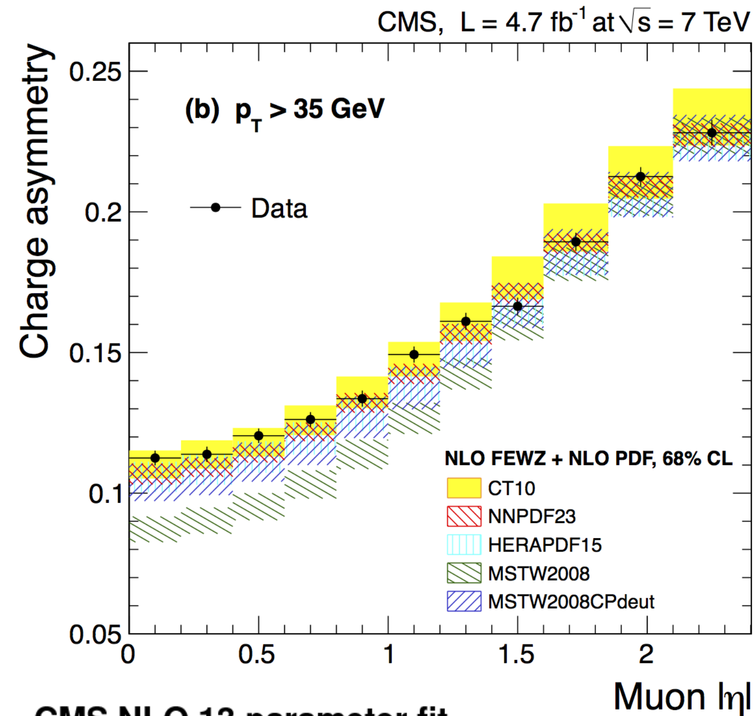
- Jet rates
  - Normalized to the inclusive cross section
  - n/(n-1) jets
- The comparison to the predictions of multi-leg matrix element + parton shower (Madgraph) shows good agreement
  - Pure parton shower (pythia) fails to predict multi-jet final states
- Given the pT threshold the sensitivity to underlying event is negligible

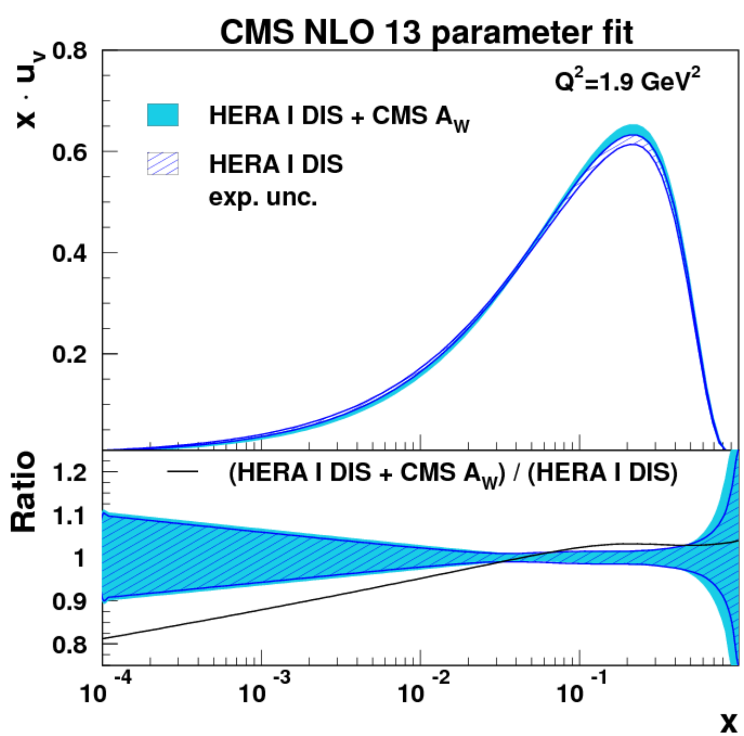


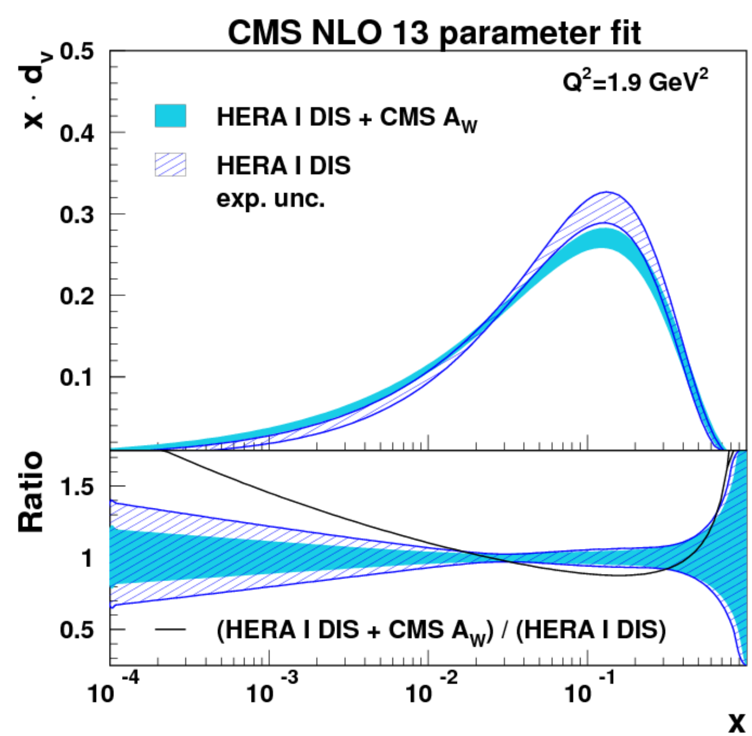
W charge asymmetry

- Probe of valence quarks
- Including CMS data predicts slightly more u and less d

PRD 90 (2014) 032004





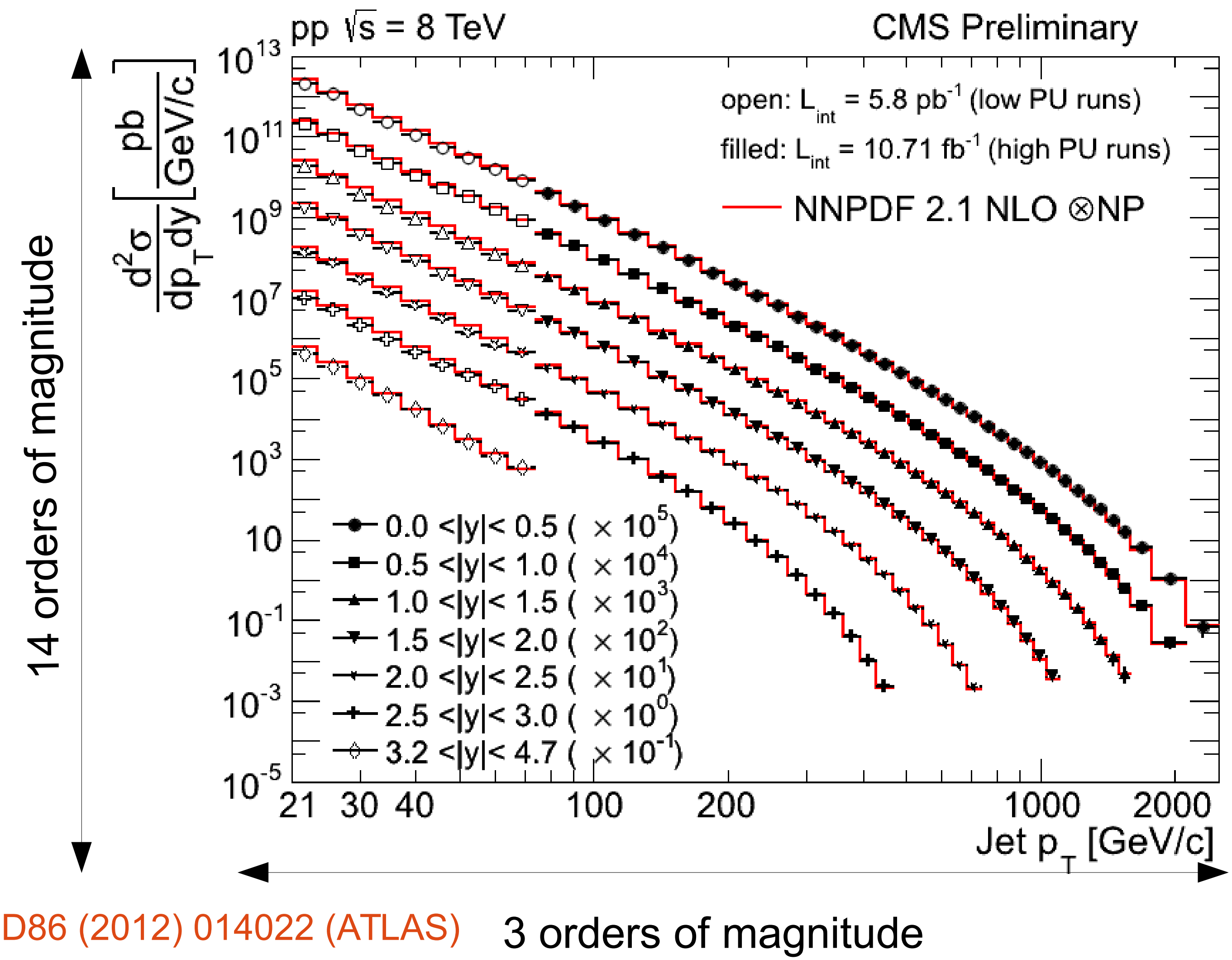


Inclusive jets

CMS-SMP-12-012

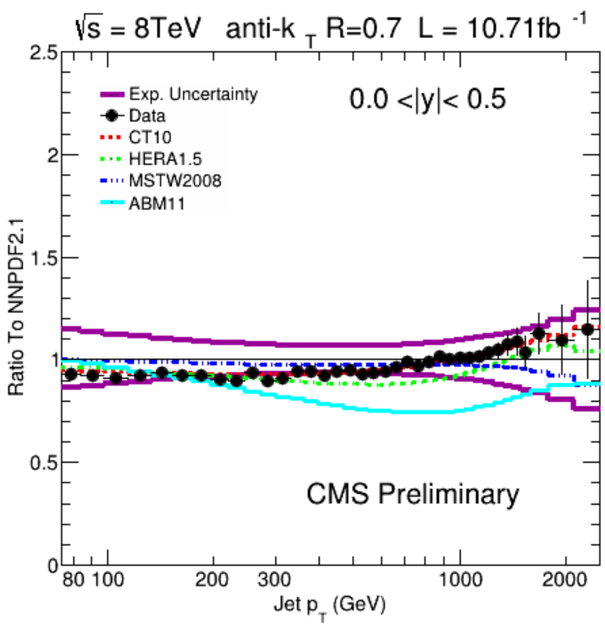
CMS-FSQ-12-031

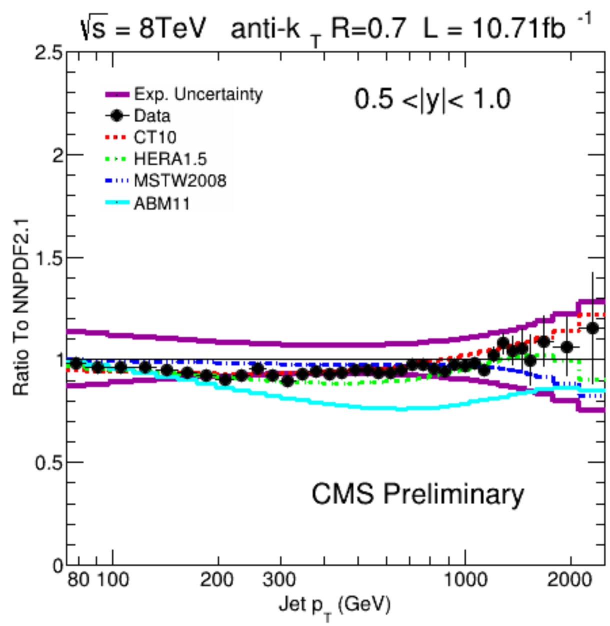
- Measurement of inclusive jets at 8 TeV
- Data are compared with the predictions at NLO (NLOJet++), including non-perturbative (NP) corrections obtained with a shower MC

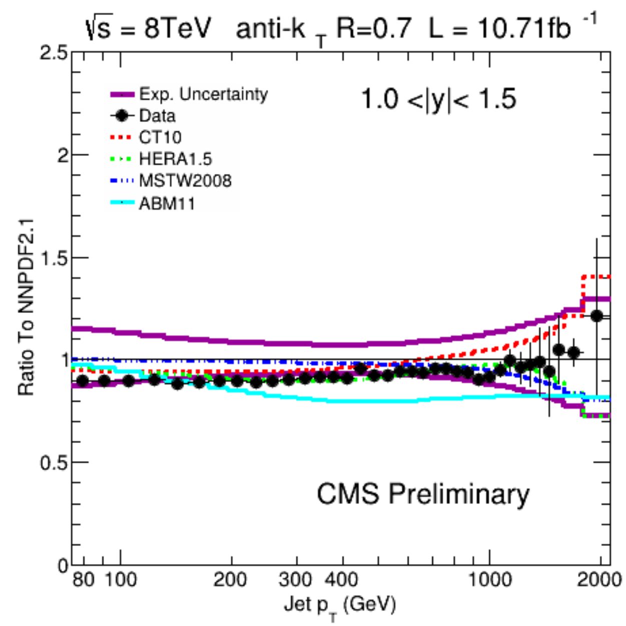


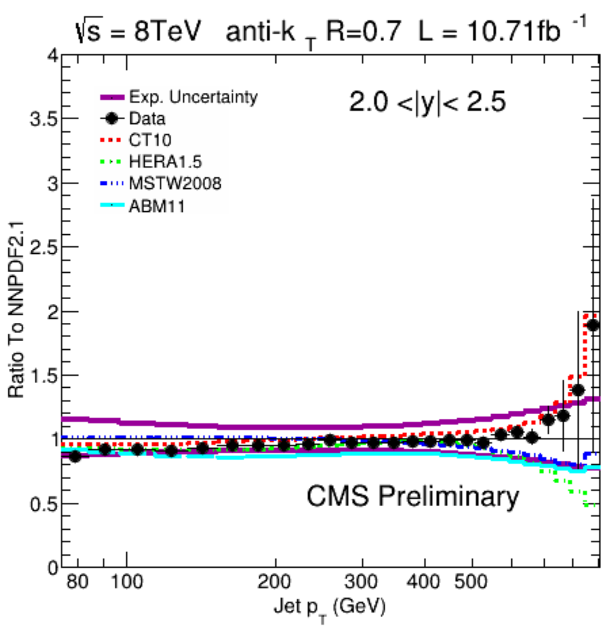
Phys.Rev. D86 (2012) 014022 (ATLAS)

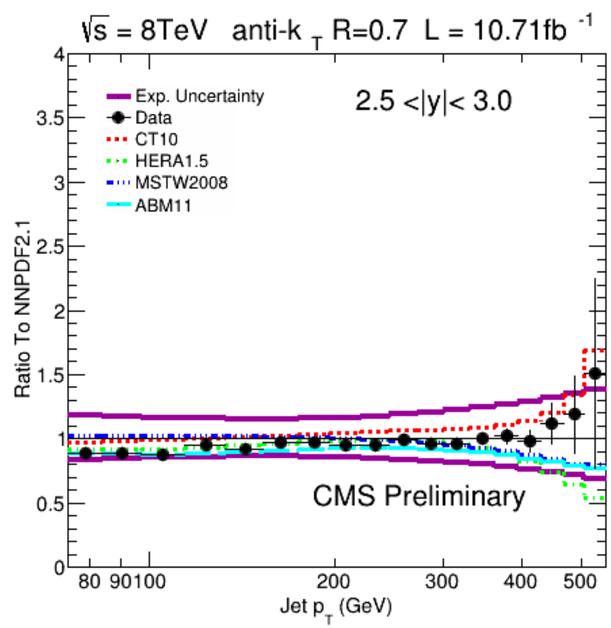
Inclusive jets







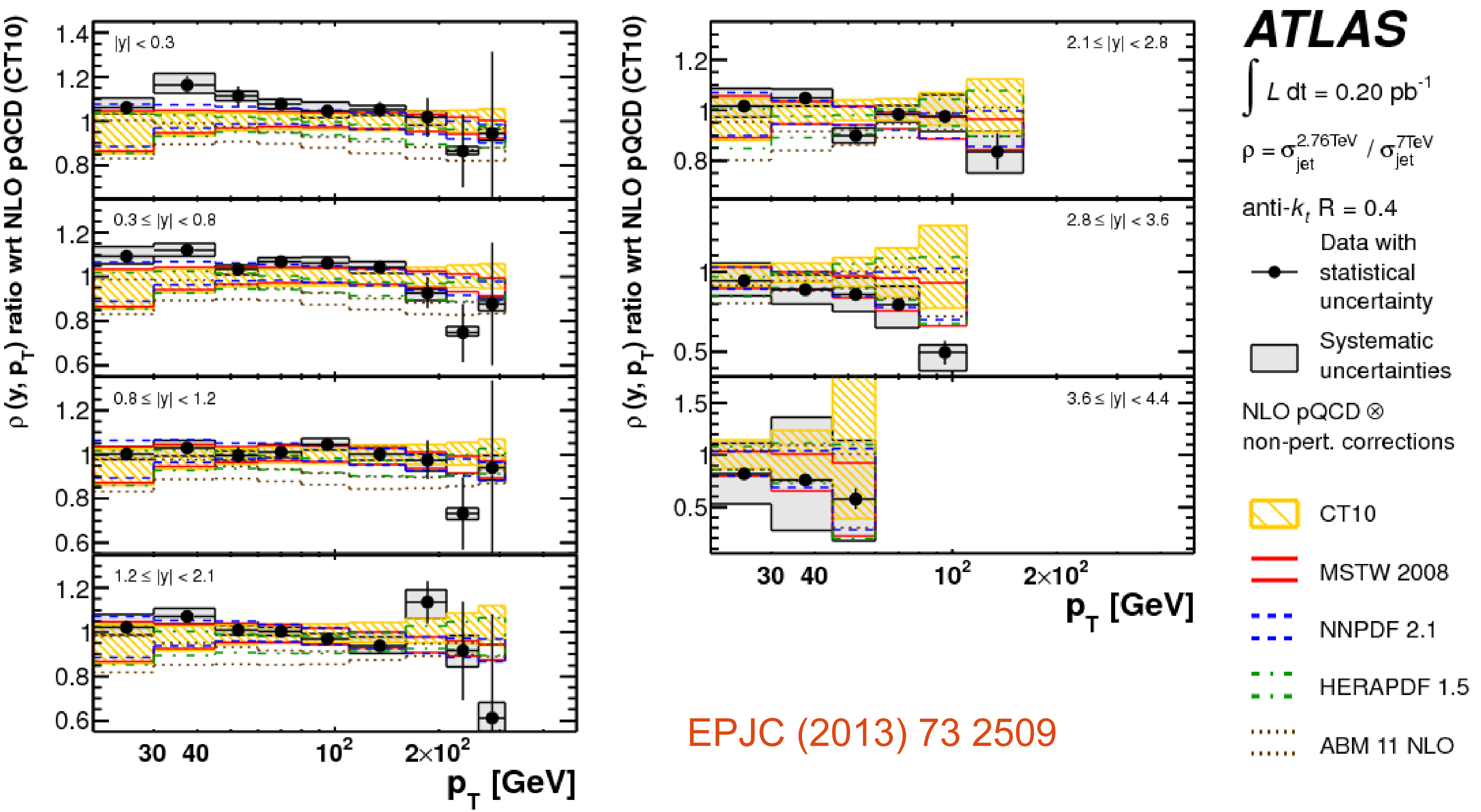




- Sensitive to PDFs
- Good agreement with several PDF sets
- Predictions disagree mainly at very high pT

Inclusive jets

- Very interesting comparison between 7 TeV and 2.76 TeV
- Has power to constrain PDFs in the central region

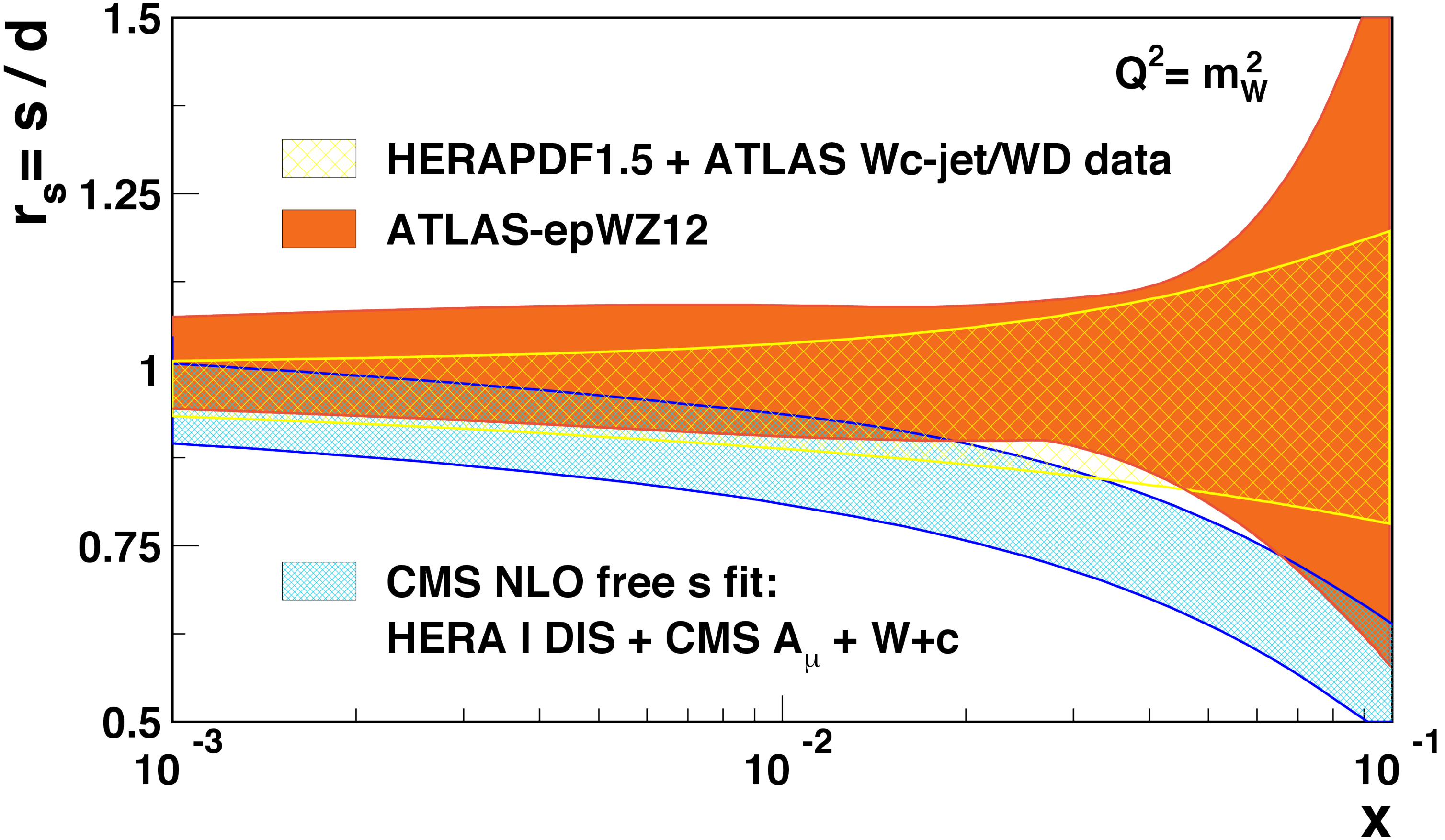


EPJC (2013) 73 2509

W+charm

- CMS tends to favor s suppression
  - Some tension between CMS and ATLAS on this measurement

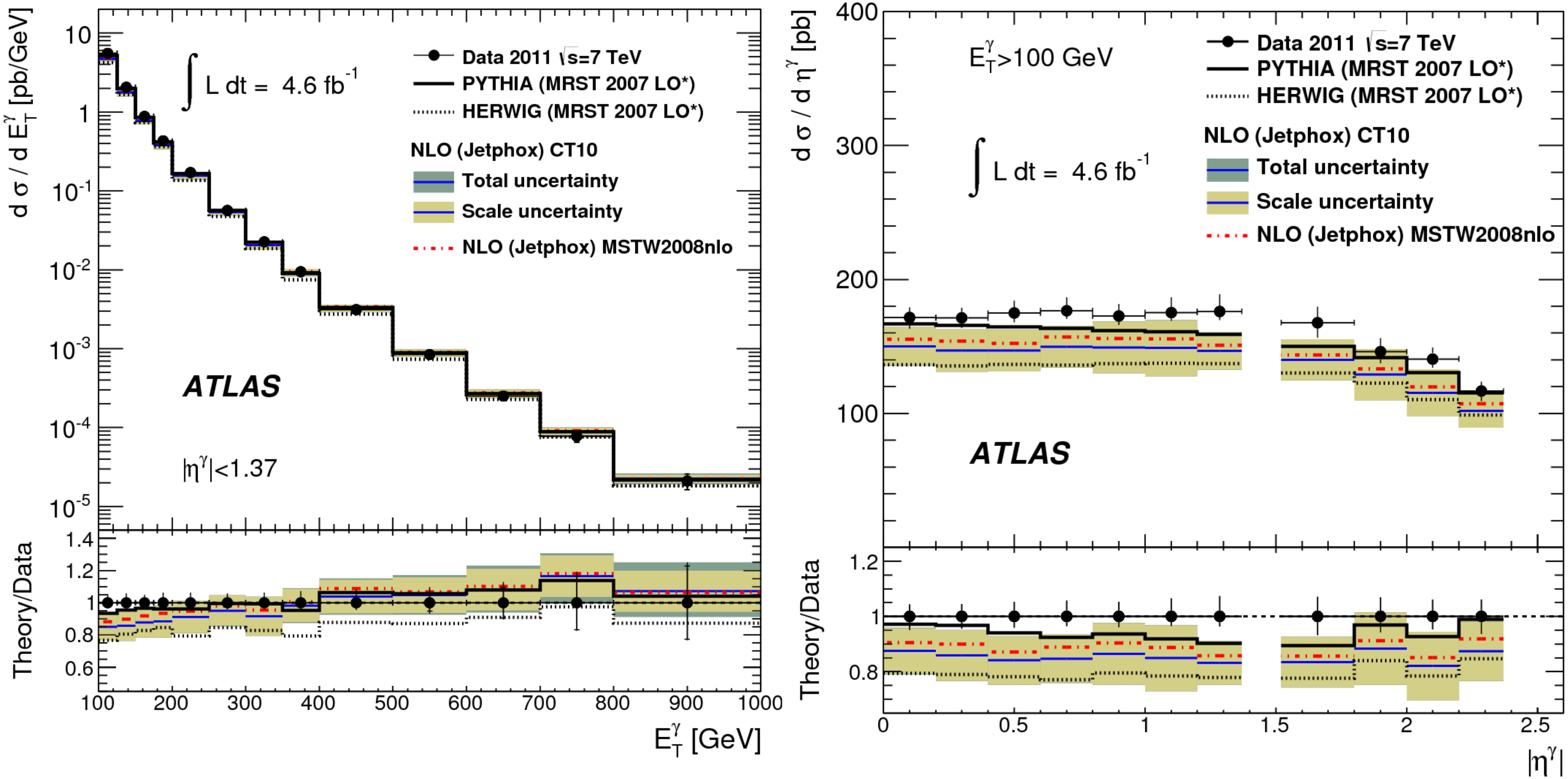
Alekhin et al



Isolated Photons

Useful for gluon constraint

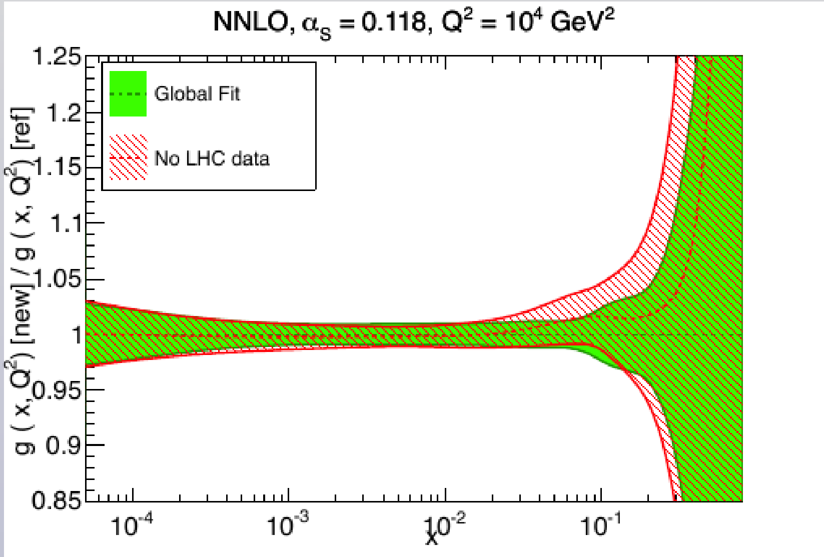
Phys. Rev. D 89, 052004 (2014)



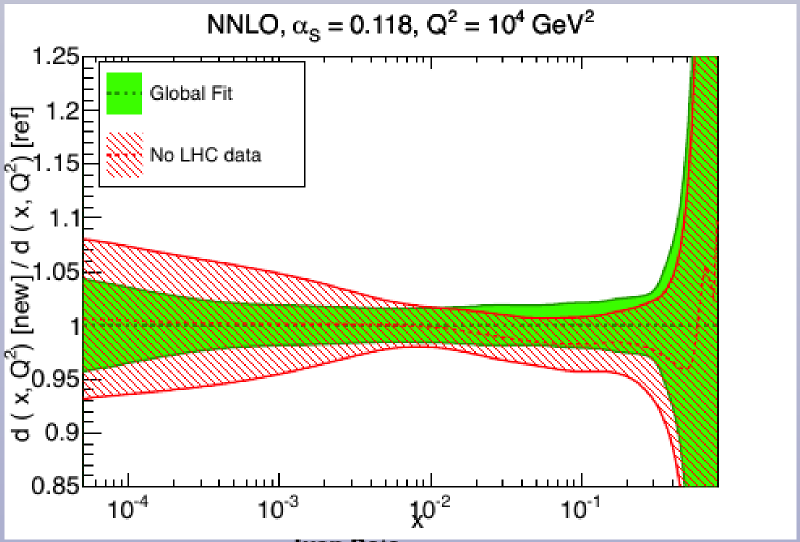
Impact of LHC on PDF

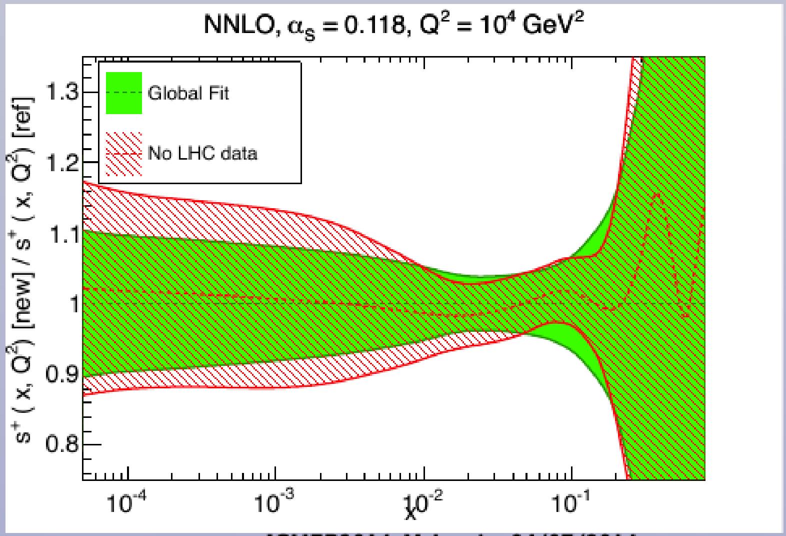
Impact of LHC data

J. Rojo



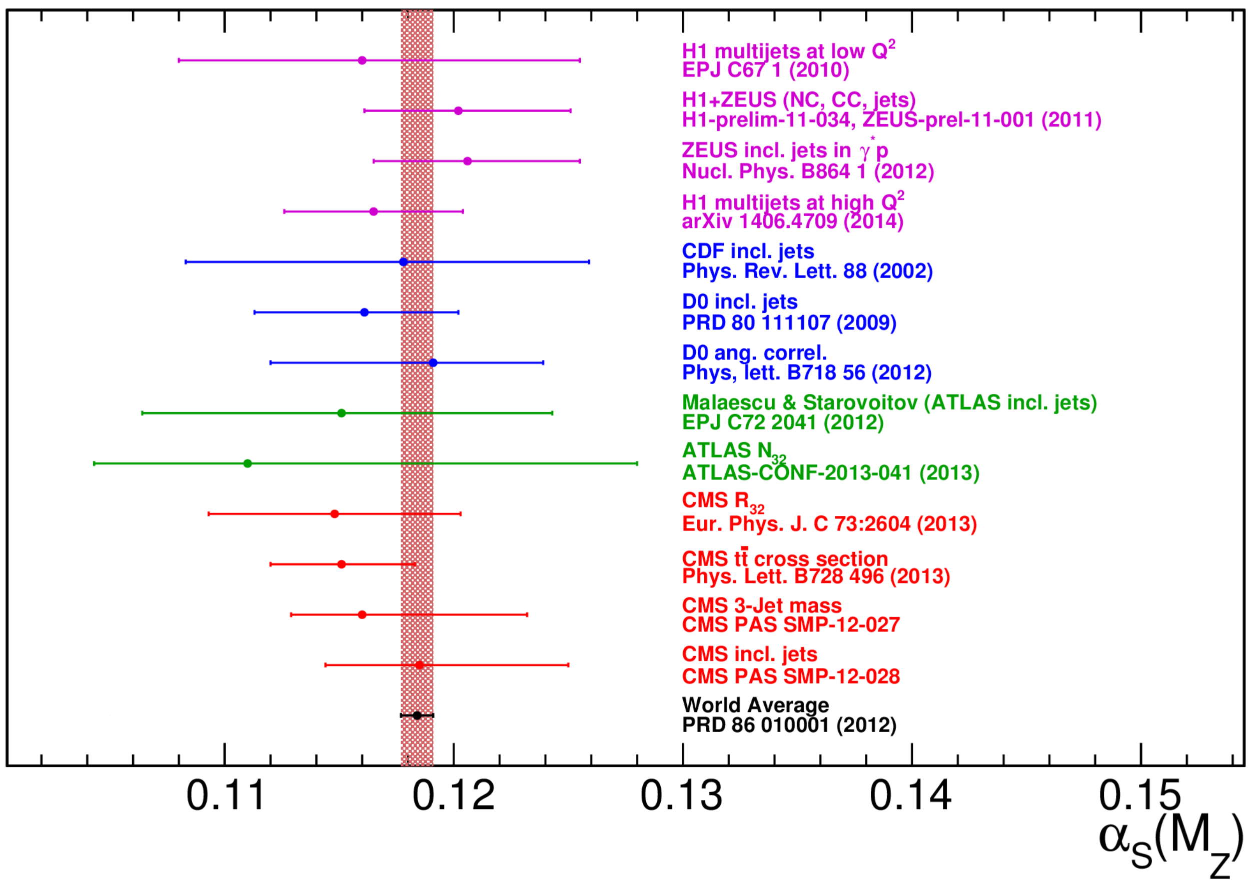
- Compare global NNPDF3.0 fit with a fit **without LHC data**
- PDF uncertainties on **large-x gluon** reduced due to **top quark and jet data**
- PDF uncertainties on **light quarks** reduced from the **Drell-Yan** and **W+charm data**
- The **description of all new LHC data**, already good in NNPDF2.3, is further improved in NNPDF3.0





α_s determination

- Several measurements using different observables
  - Inclusive jets, R32, 3-jet mass $t\bar{t}$ cross section
  - Running probed up to the TeV scale



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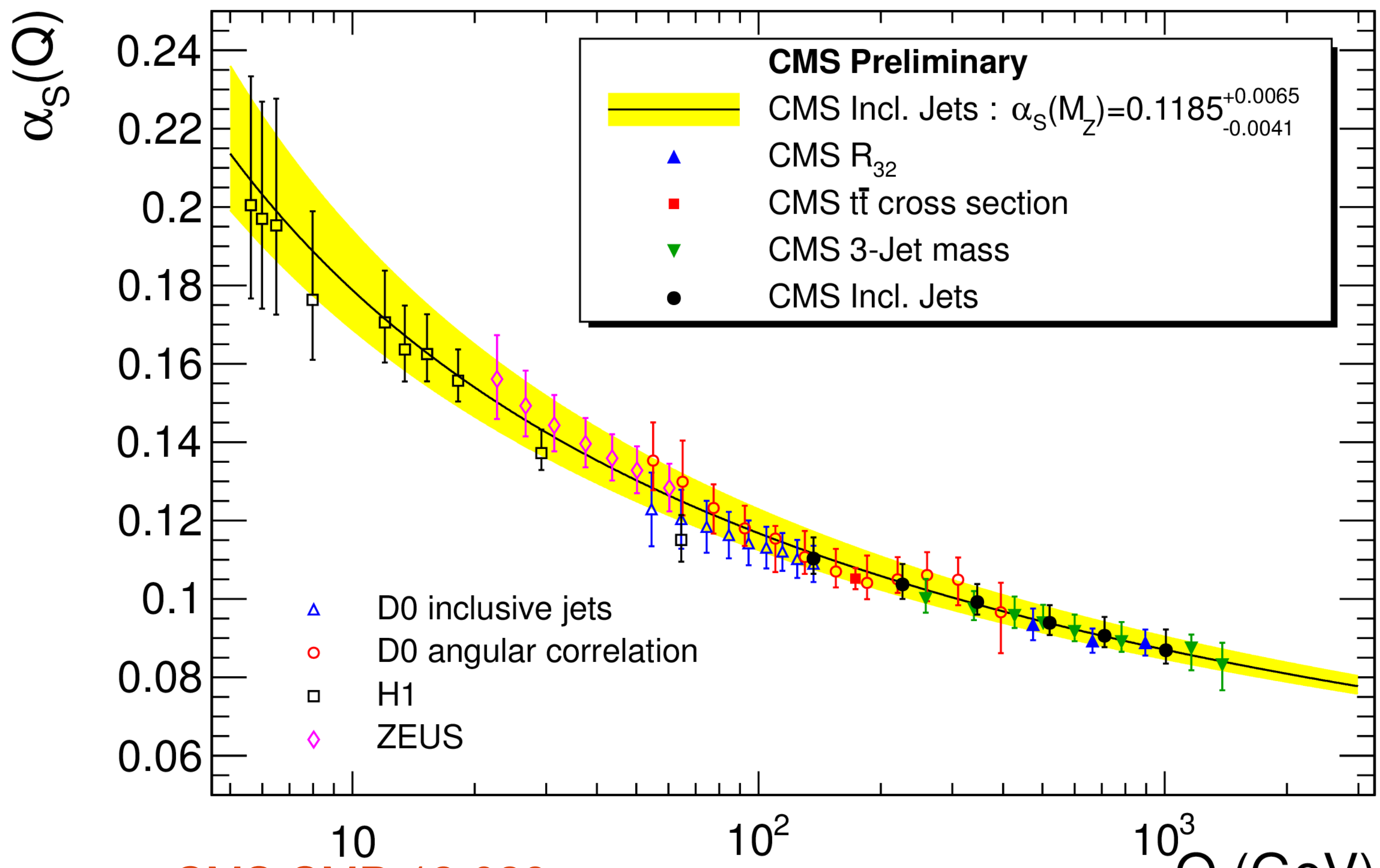
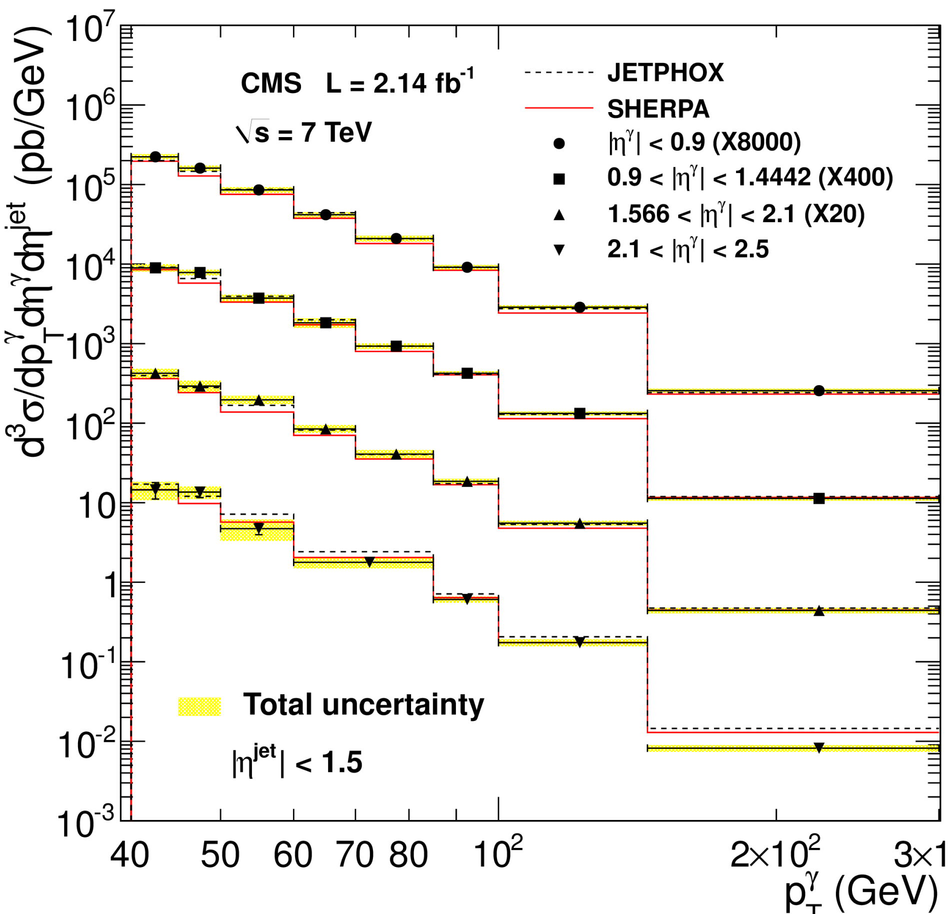
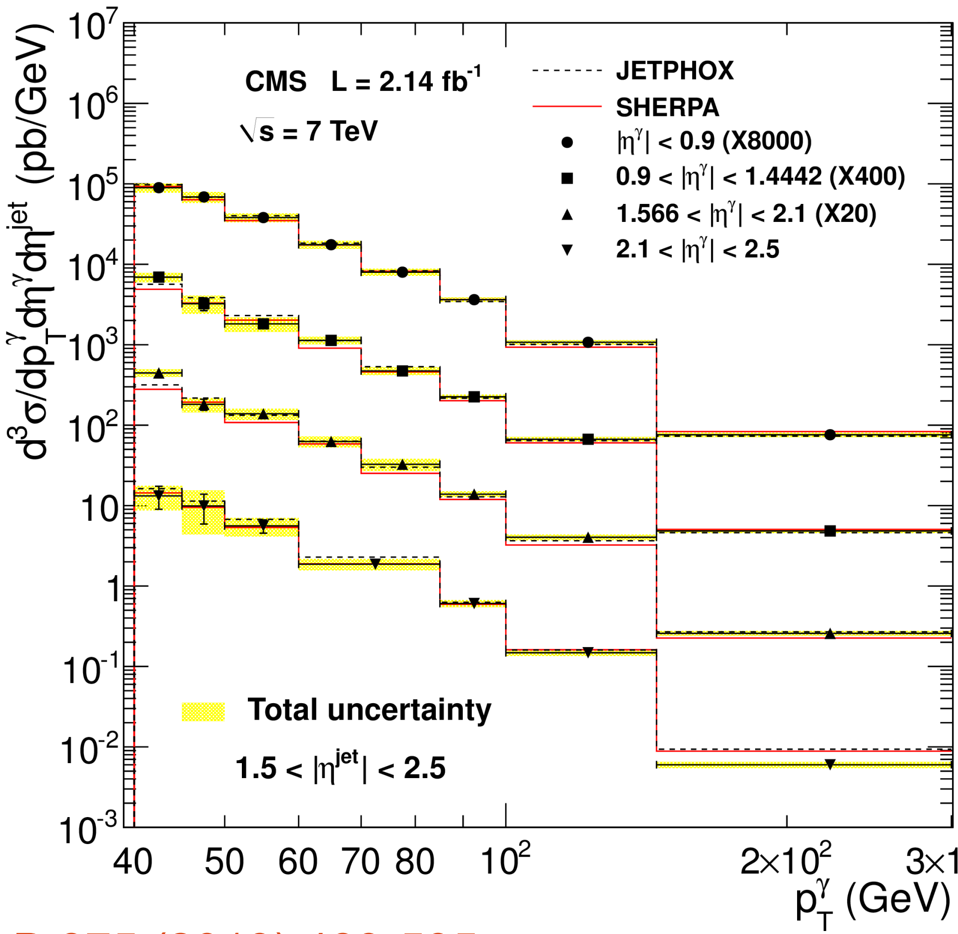


CMS-SMP-12-028

Photon + jets

- Jet pt > 30 GeV, |η|<2.4
- Good agreement with NLO QCD
- Also good agreement with Sherpa
  - Including extended matrix element + parton shower approach to photons





JHEP06(2014)009

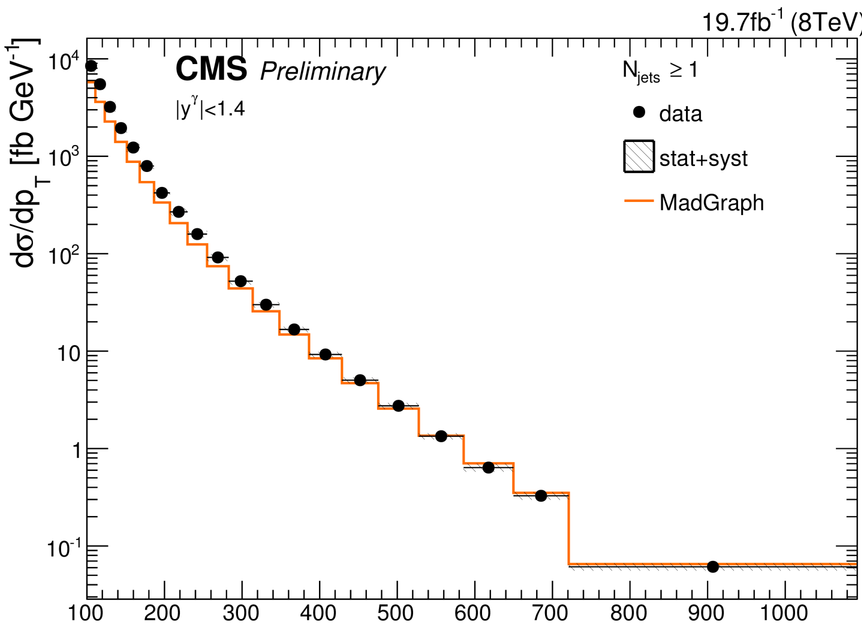
Nucl. Phys, B 875 (2013) 483-535

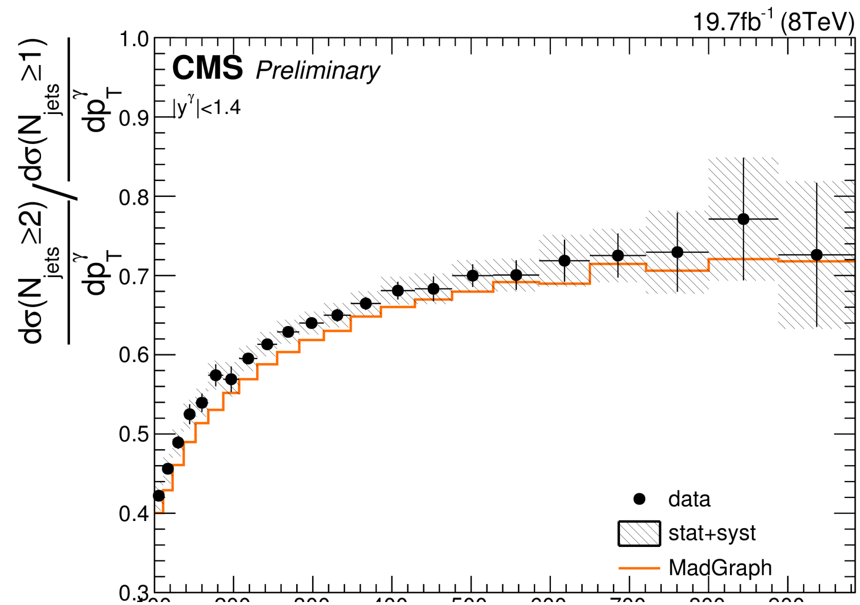
Photon+jets

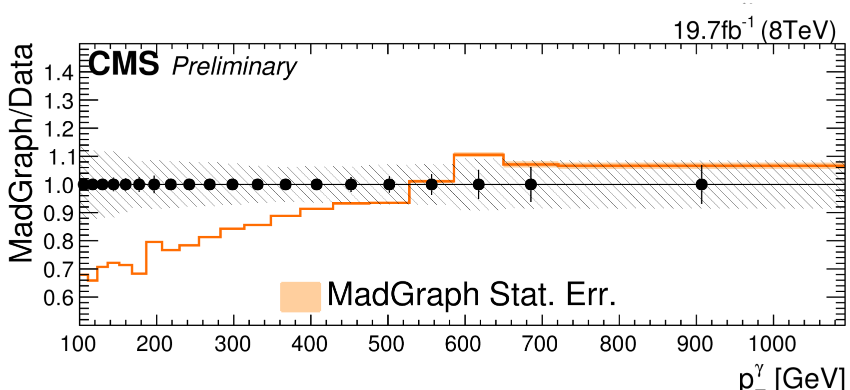
- Differential in jet multiplicity and HT
- Interesting test for ME+PS
- Studied ratios also, reduced experimental (and theoretical) systematics

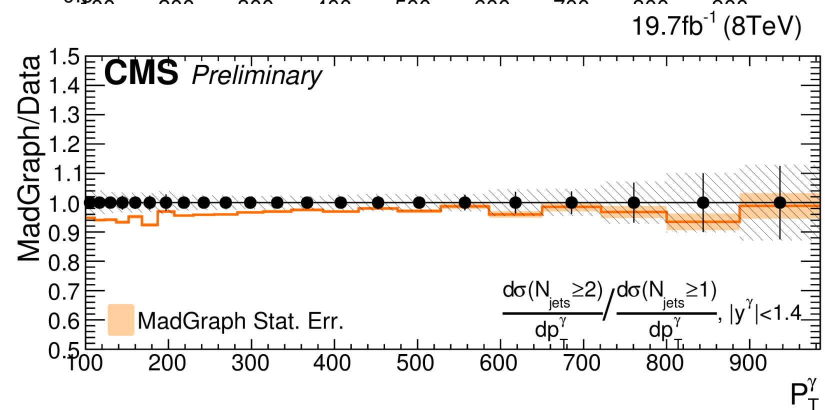
- ~30% discrepancy, not flat in photon pT
    - Better description of the 2j over 1 jet ratio

CMS-SMP-14-005





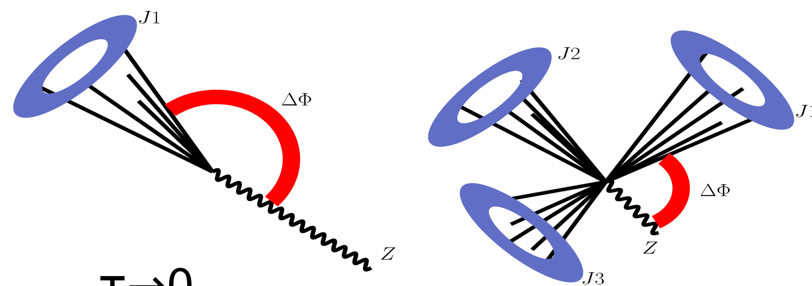




Event shapes in V+jets

Phys. Lett. B 722 (2013) 238-261

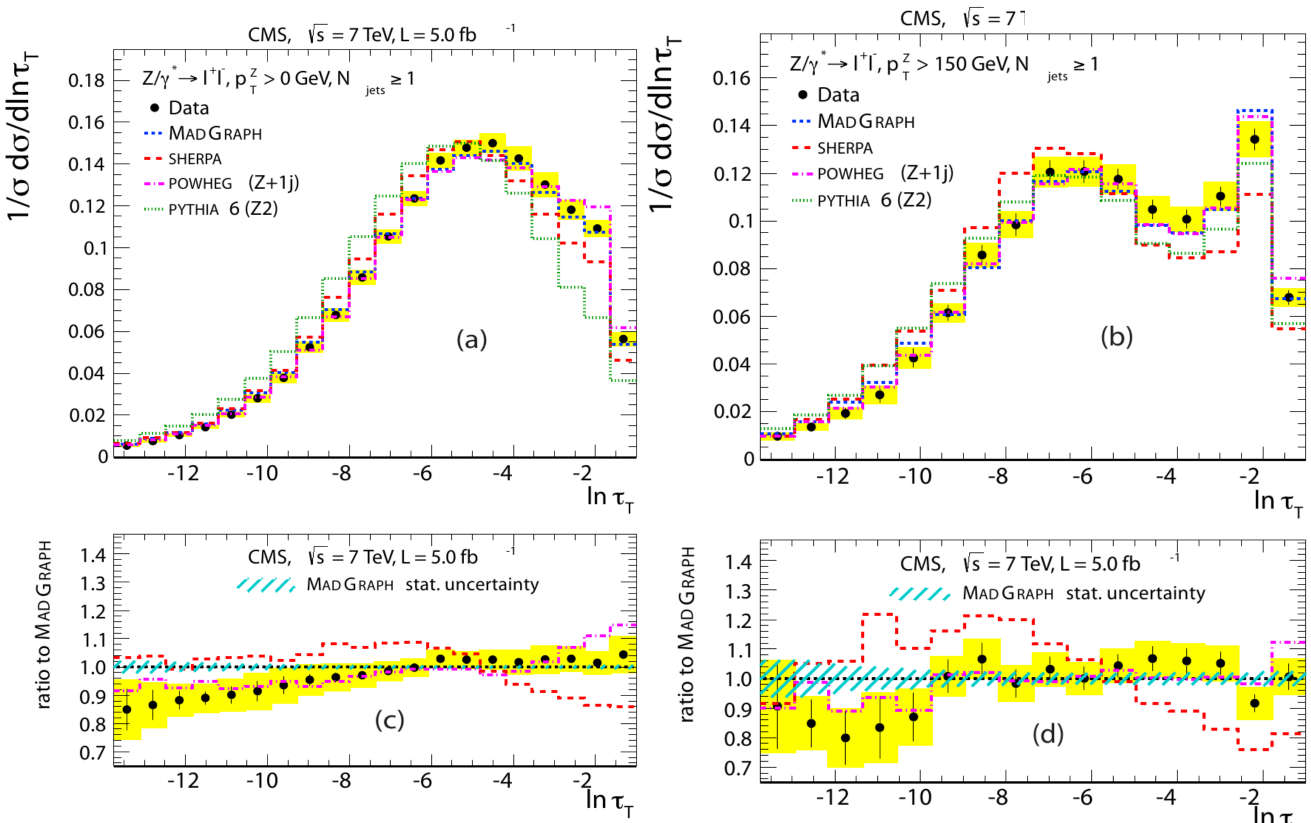
- Central transverse thrust in Z+jets
- Built out of the Z and the jets with pT >50 GeV, |η|<2.4
- Both inclusively, and in a boosted topology where pt(Z)>150 GeV



τ→0

τ→0.36

$$\tau_{\perp} \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$



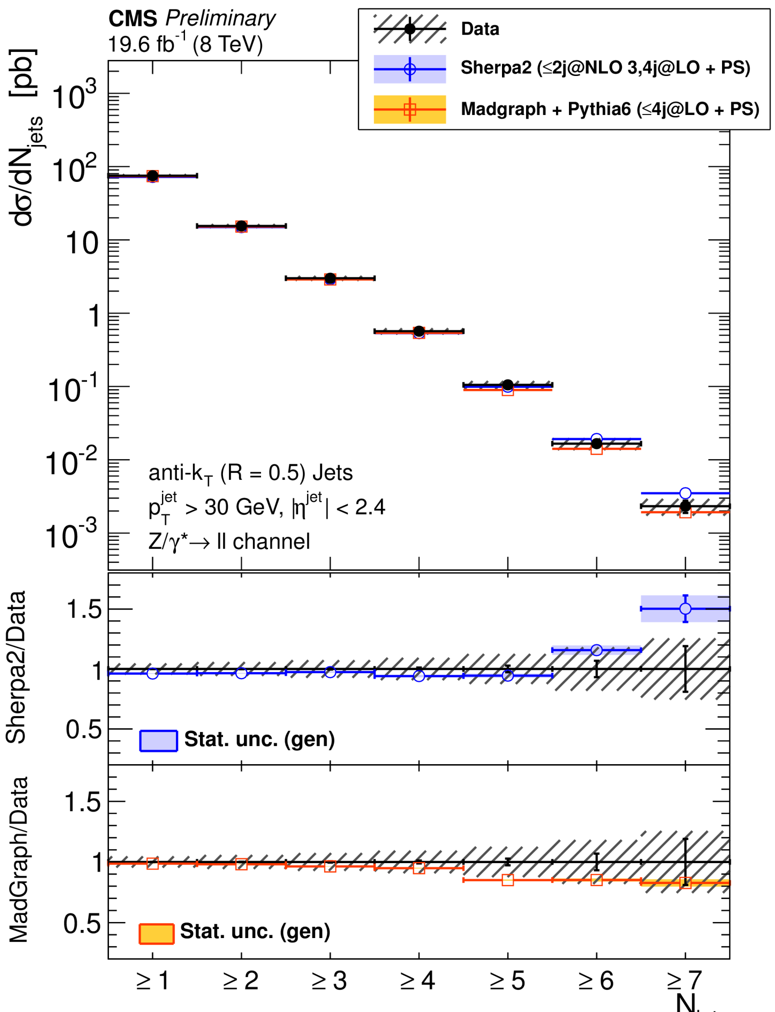
The region dominated by multijet topologies shows agreement with LO+PS (Madgraph)

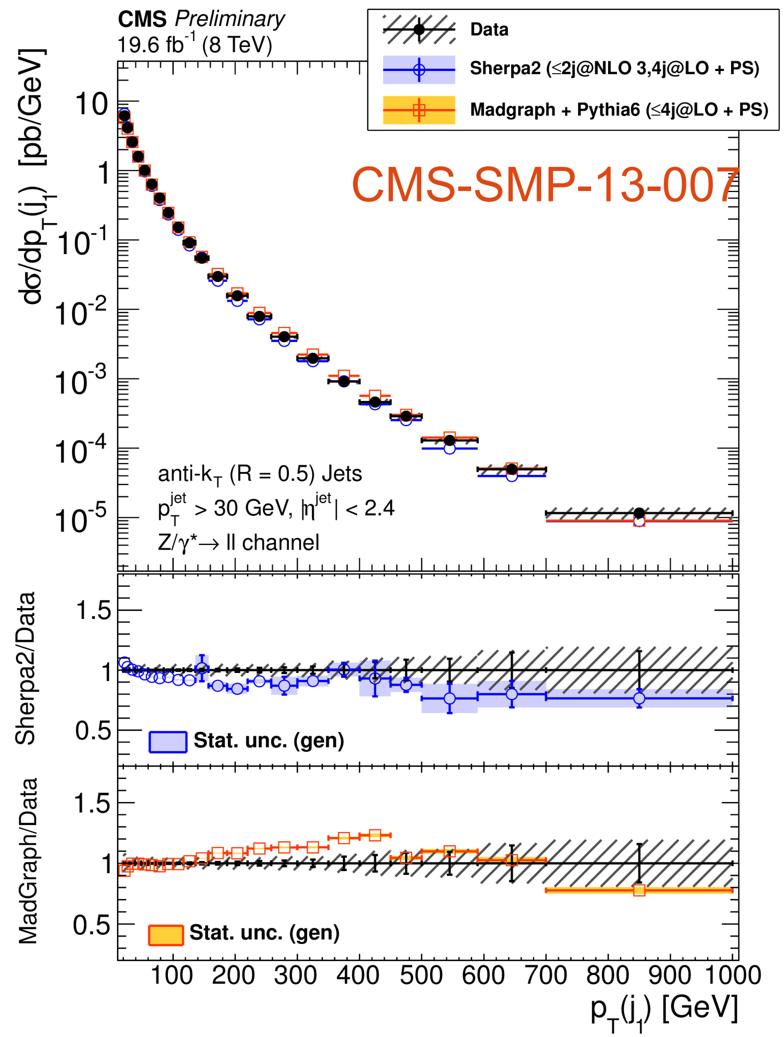
NLO +PS is also good, with a slight tendency to overshoot

Instead, in pencil-like topologies powheg shows best agreement

Z+jets

- Several measurements, differential, up to 7-8 jets with full Run1 stat!
  - Comparison with LO ME+PS and multi leg NLO +PS
  - Nice agreement with ME+PS for multiplicity
  - Some discrepancies in jet pT spectra below 300-400 GeV

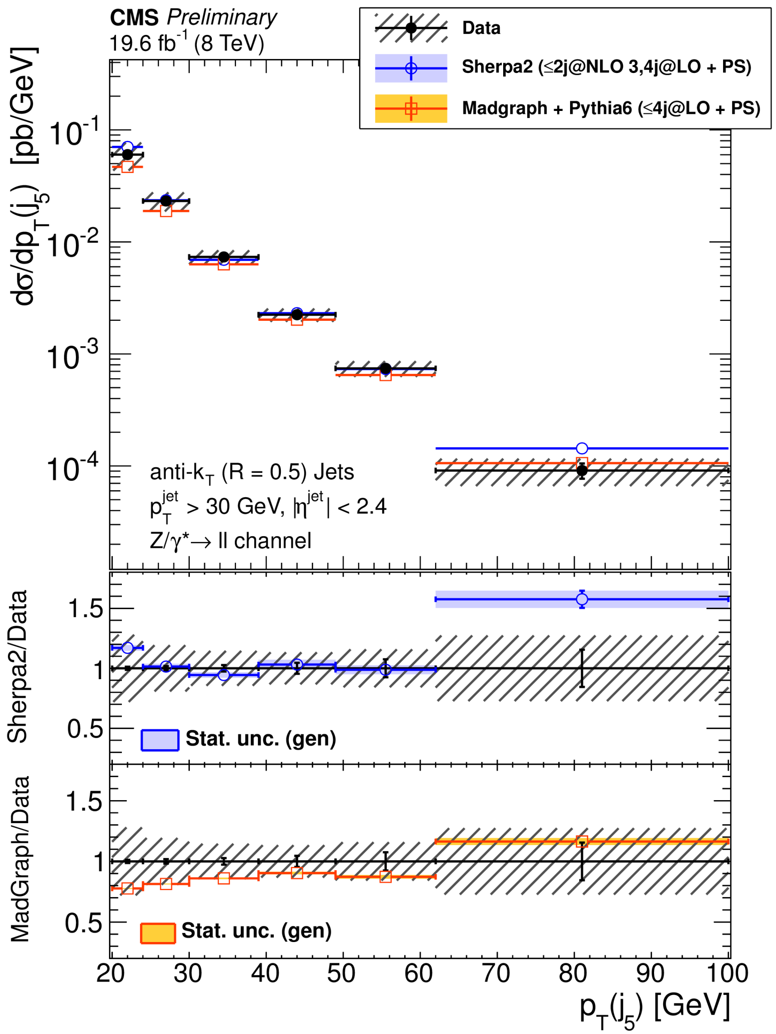


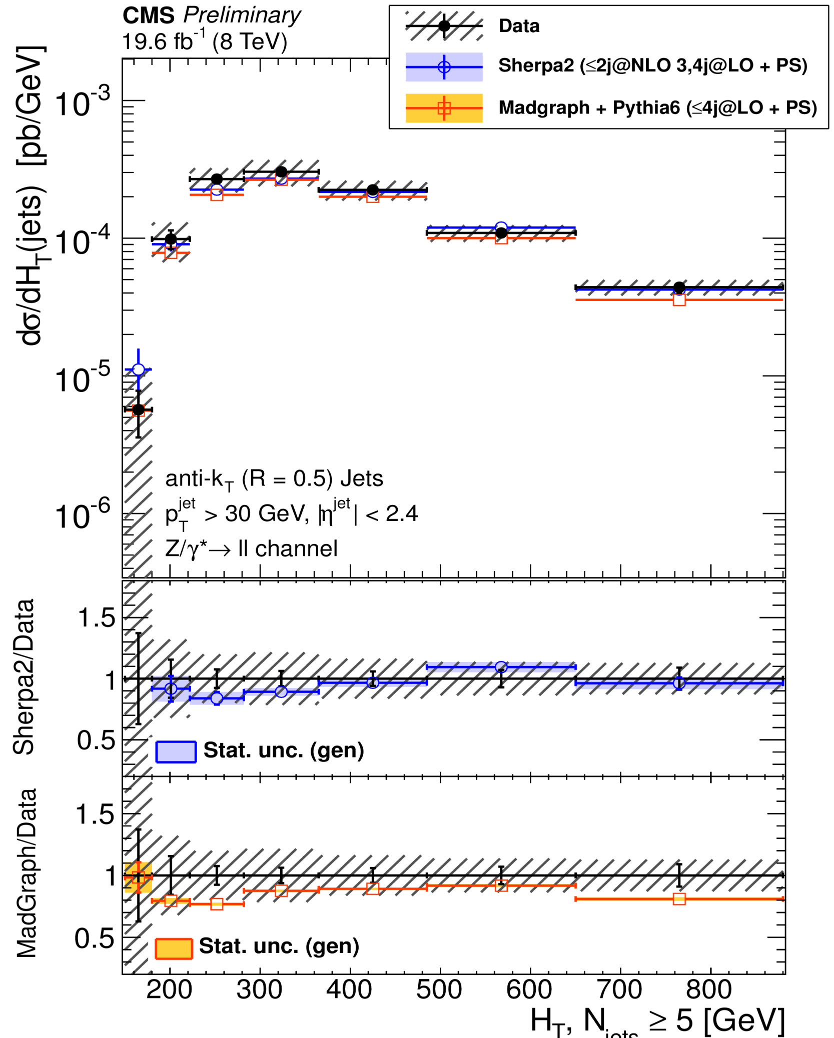


Z+jets

CMS-SMP-13-007

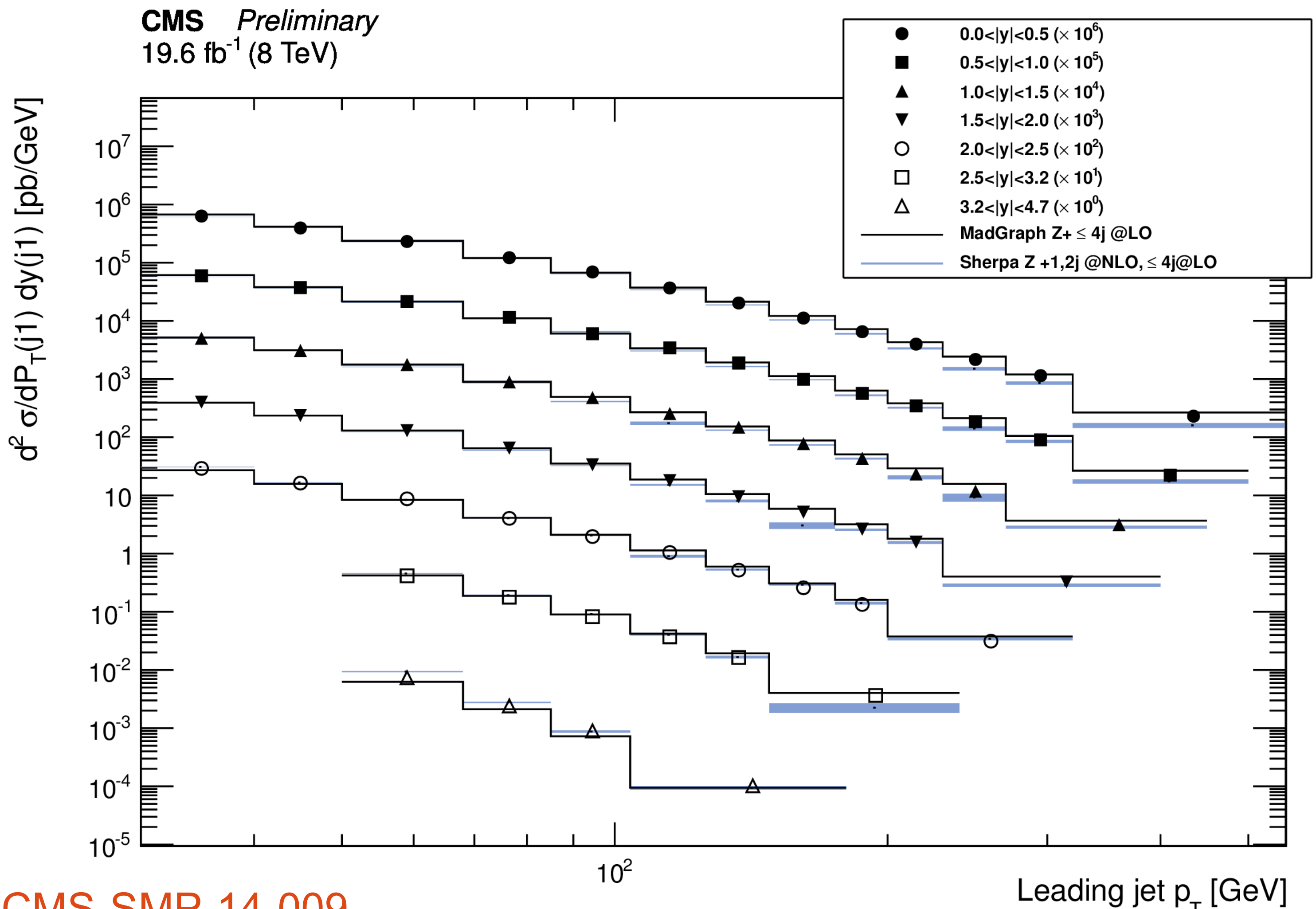
- Remarkable agreement also at very high multiplicity
  - Data/Theory rather flat





Z+jets

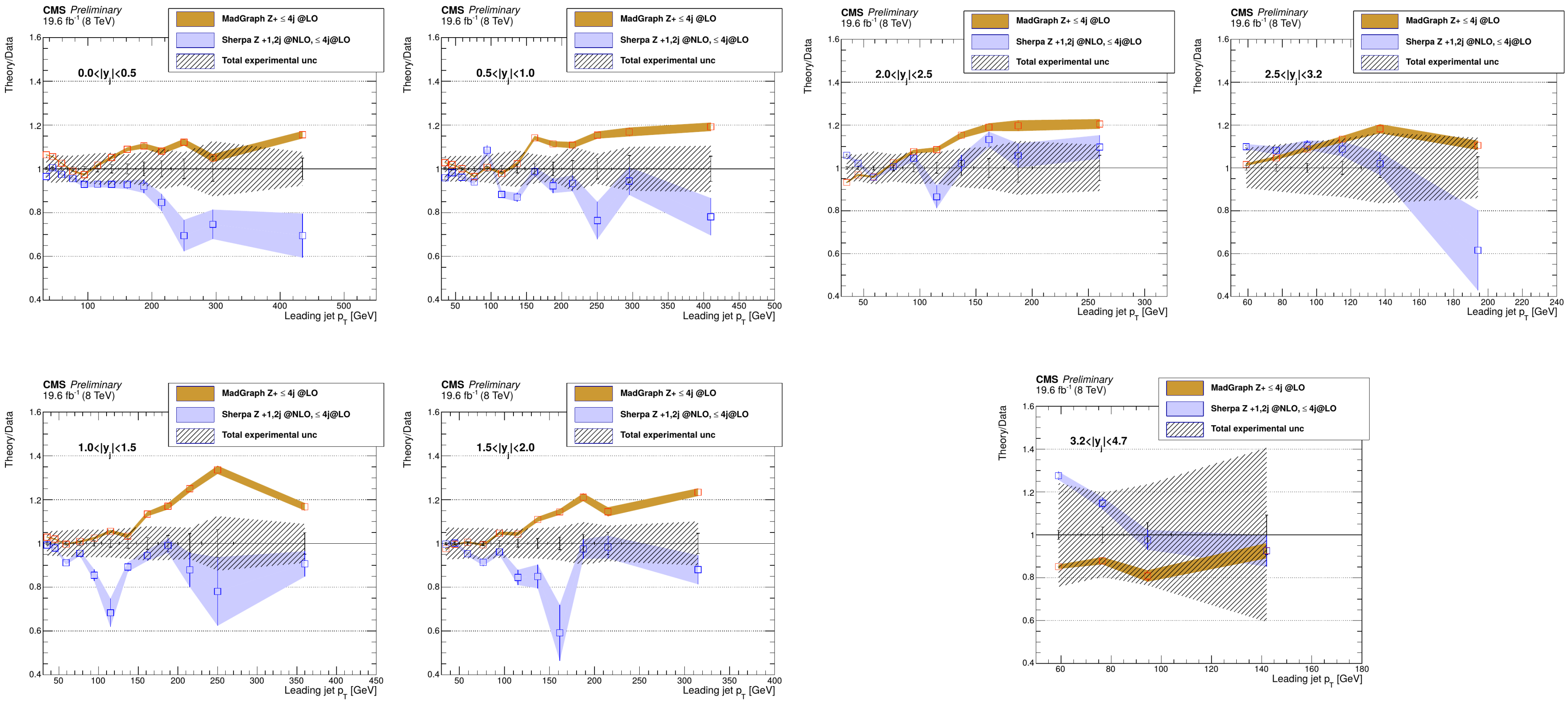
- Leading jet pT in Z+jets
  - Differential in jet rapidity: some discrepancies begin to arise



CMS-SMP-14-009

Z+jets

- Madgraph+Pythia tends to predict harder spectra above ~100GeV
- Sherpa (NLO up to the second jet) shows a few single bin discrepancies

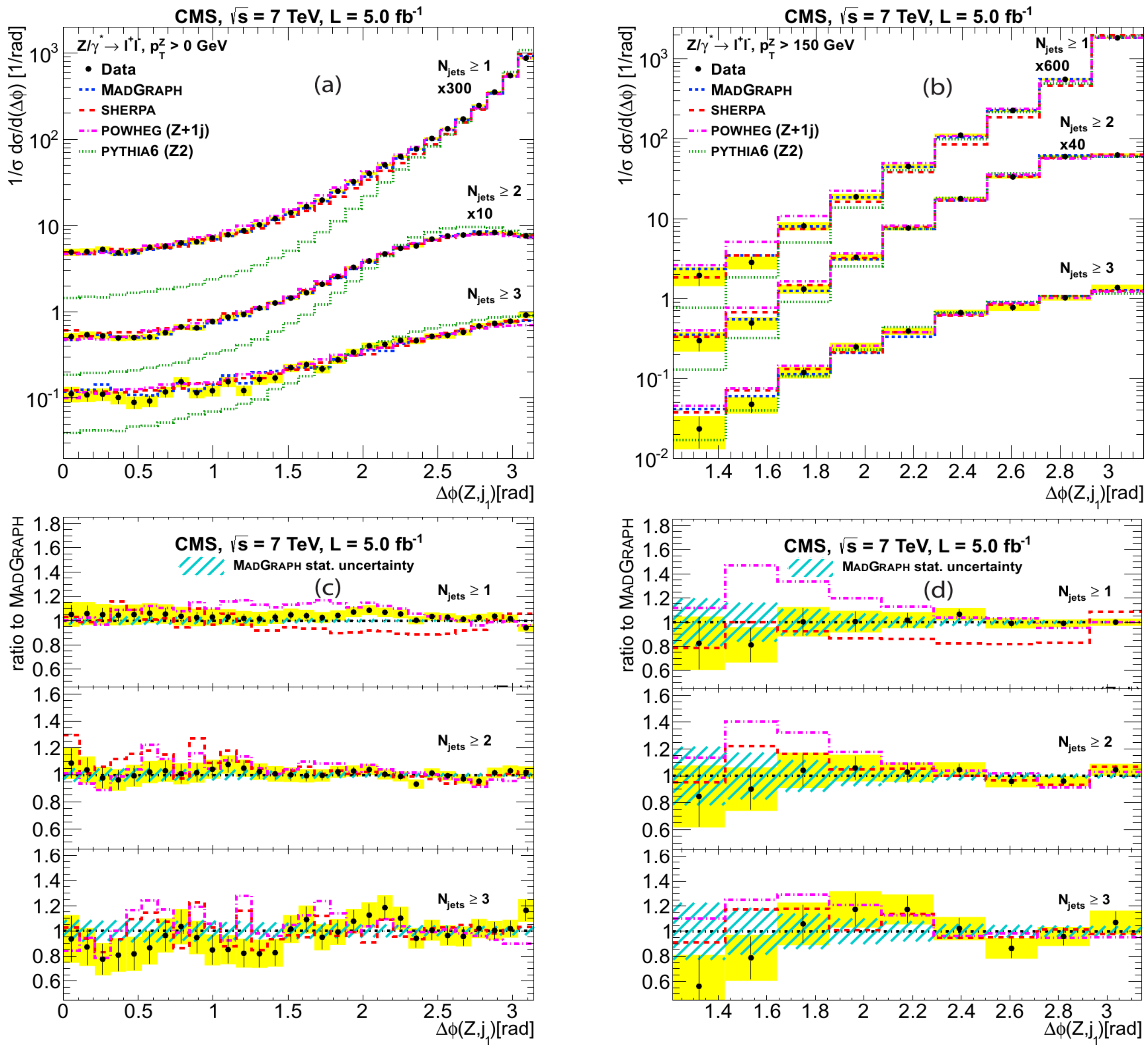


CMS-SMP-14-009

Z+jets

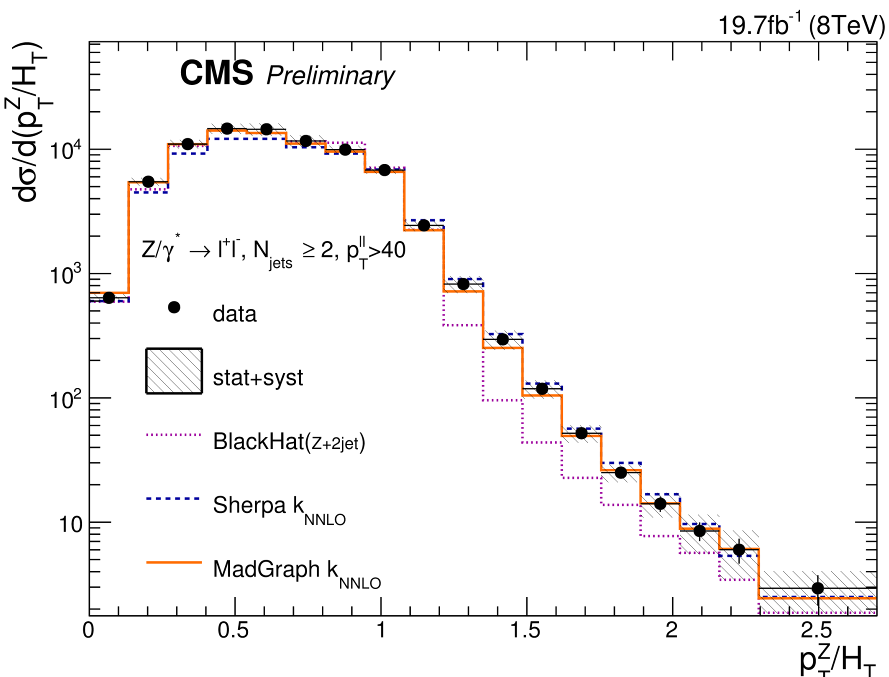
Phys. Lett. B 722 (2013) 238-261

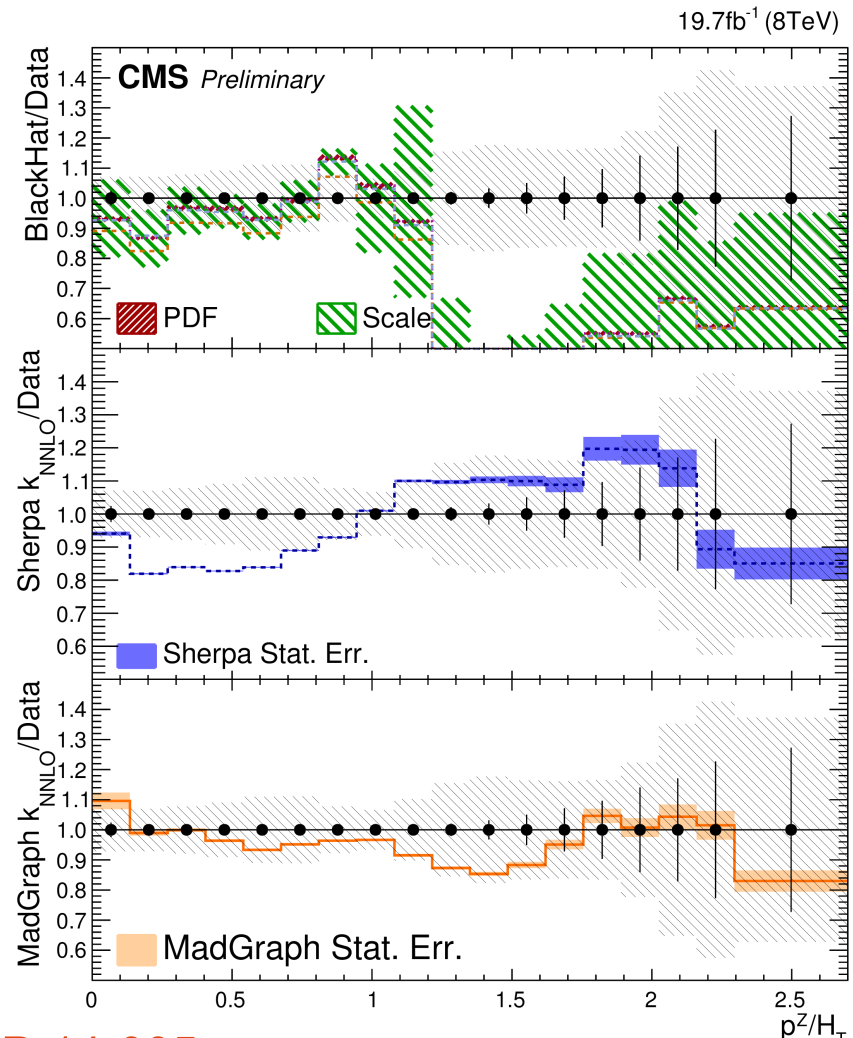
- ΔΦ between the Z and the leading jet
- Jet reconstruction: jet pT > 50 GeV, |η|<2.4
- Good agreement with LO+PS
- Also very nice agreement with NLO+PS



Z+jets

- Ratios pt(Z)/HT or pt(Z)/pt(j) are important for searches and are challenging to predict
  - Large logarithms, missing higher orders





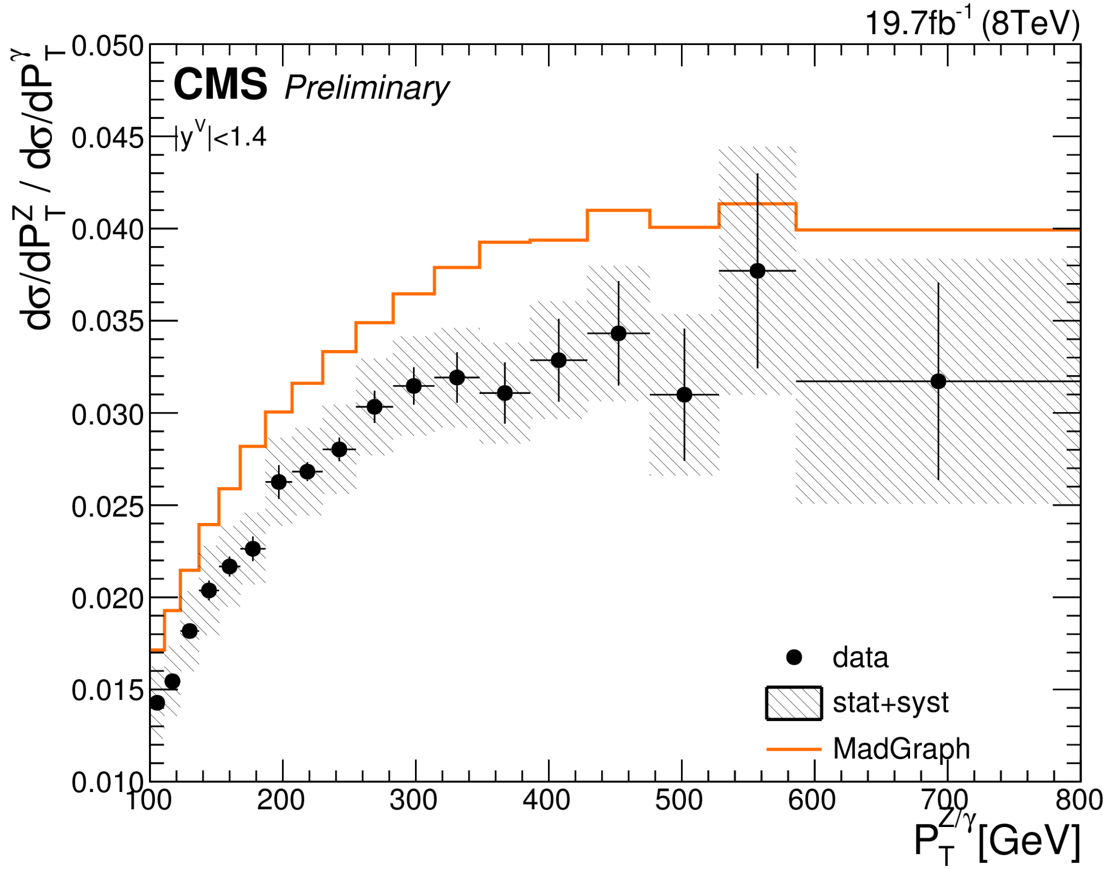
- Fixed order fails in the high pt(Z)/HT region
  - Possibly due to more jets with pT < than the analysis cut

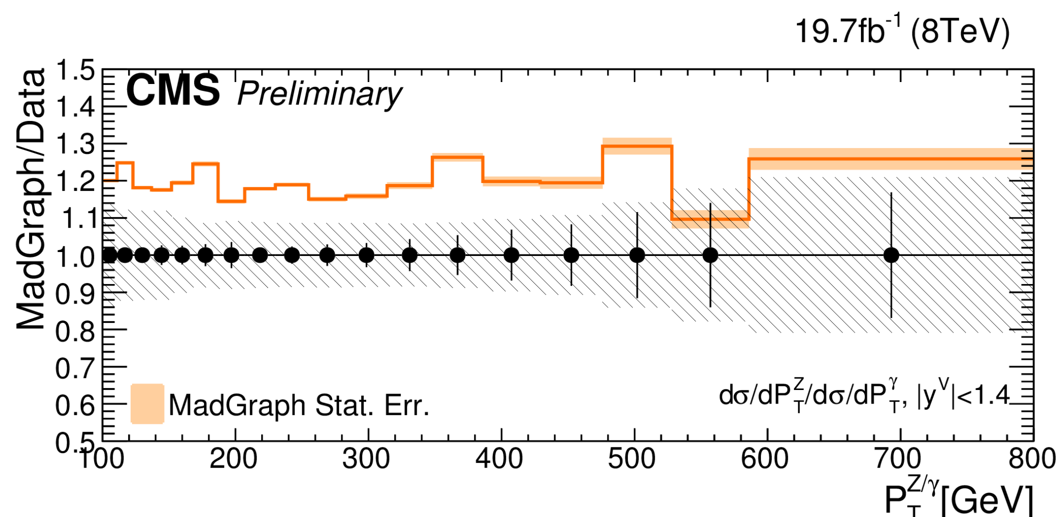
CMS-SMP-14-005

Z+jets over γ+jets

- Important for searches
- At large momenta effects due to the Z mass can be neglected and ratios should flatten
- Measurement in 4 bins
  - >1,2,3 jets and HT>300 GeV
- Comparison with ME+PS is rather flat
  - ~20% off
  - It will be interesting to see how NLO+PS does

CMS-SMP-14-005





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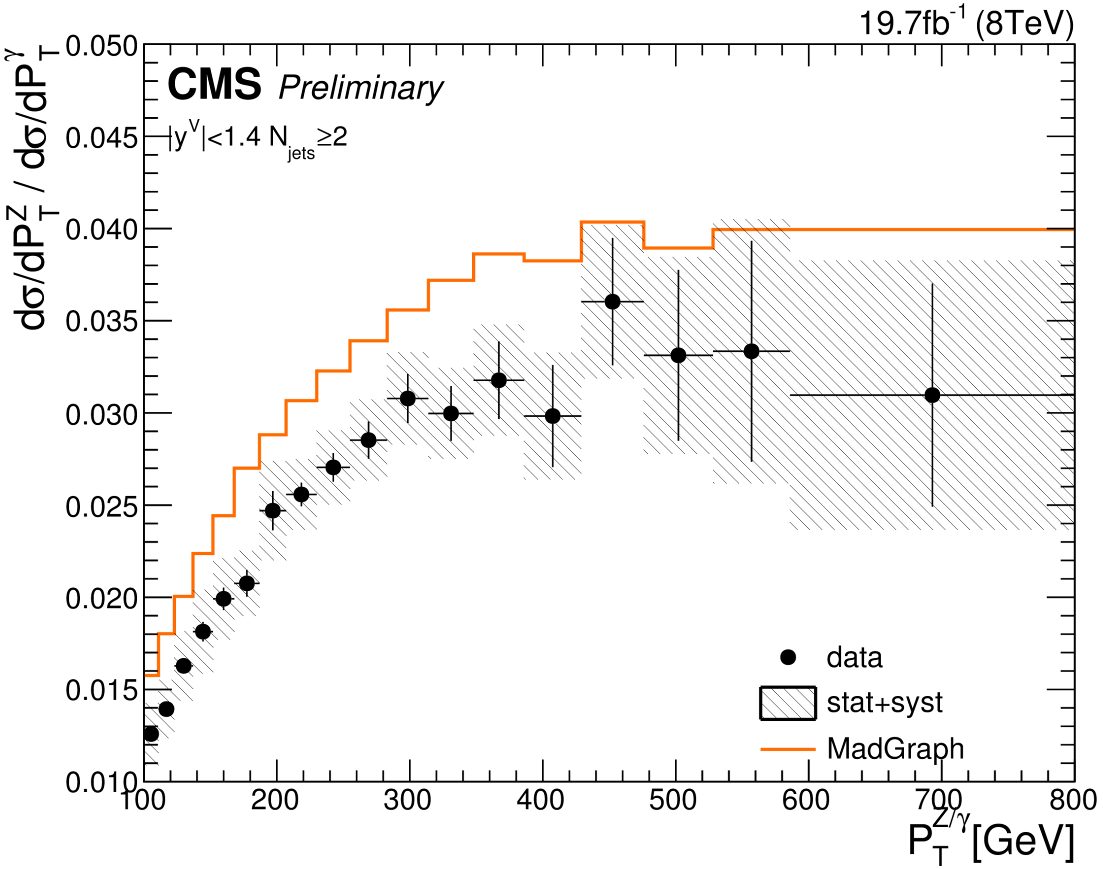

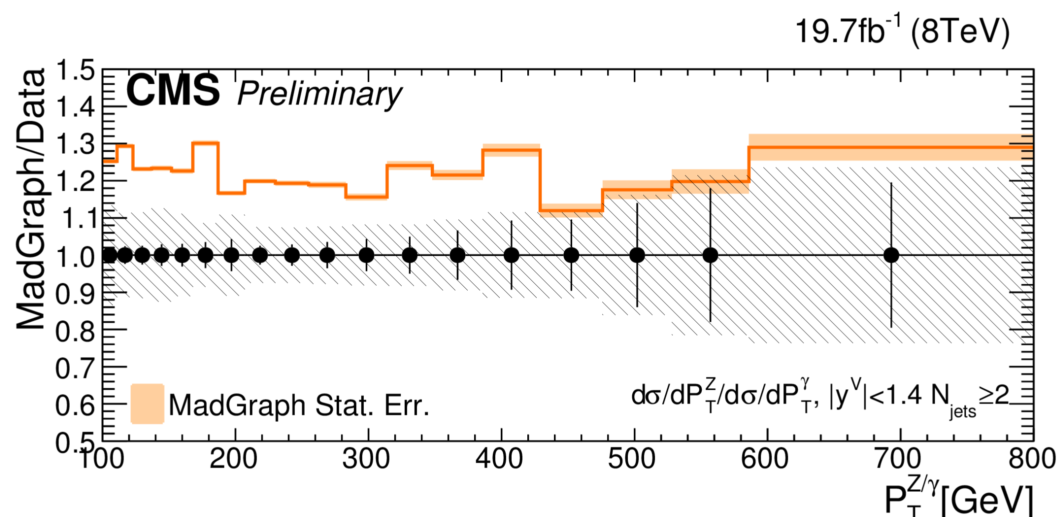

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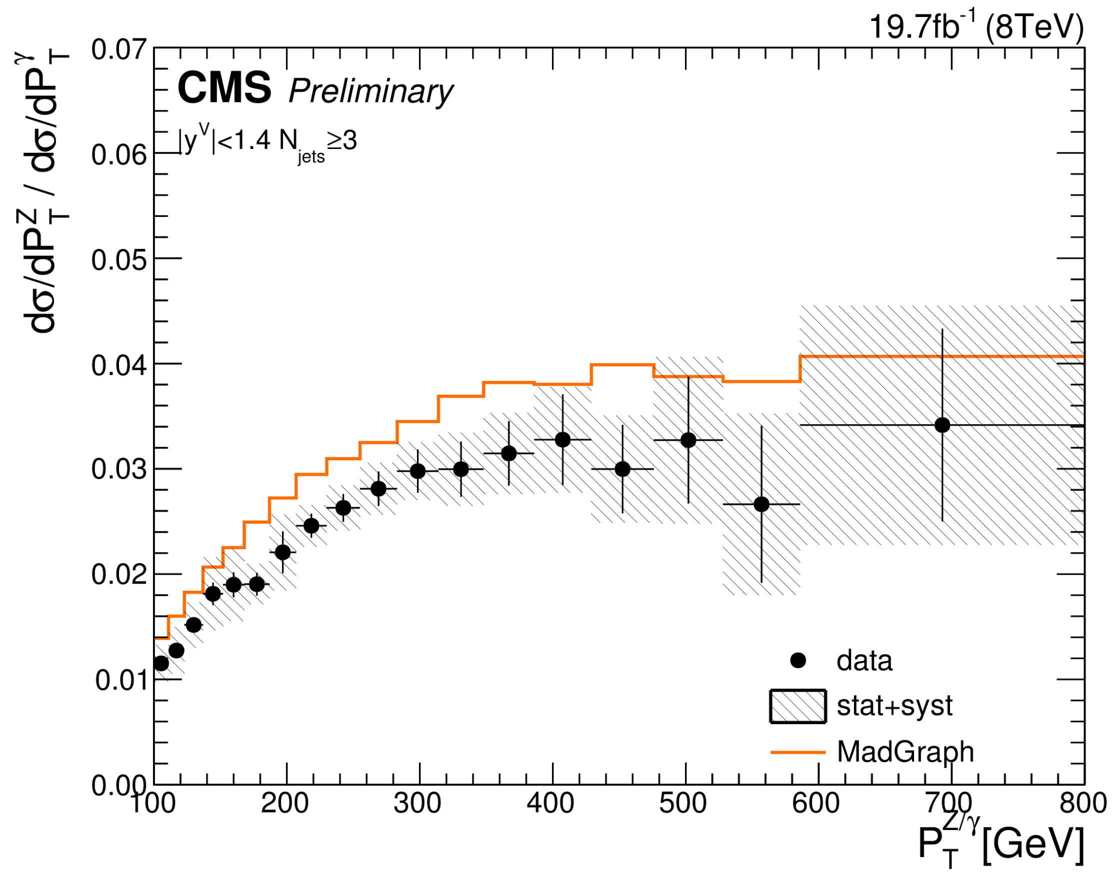
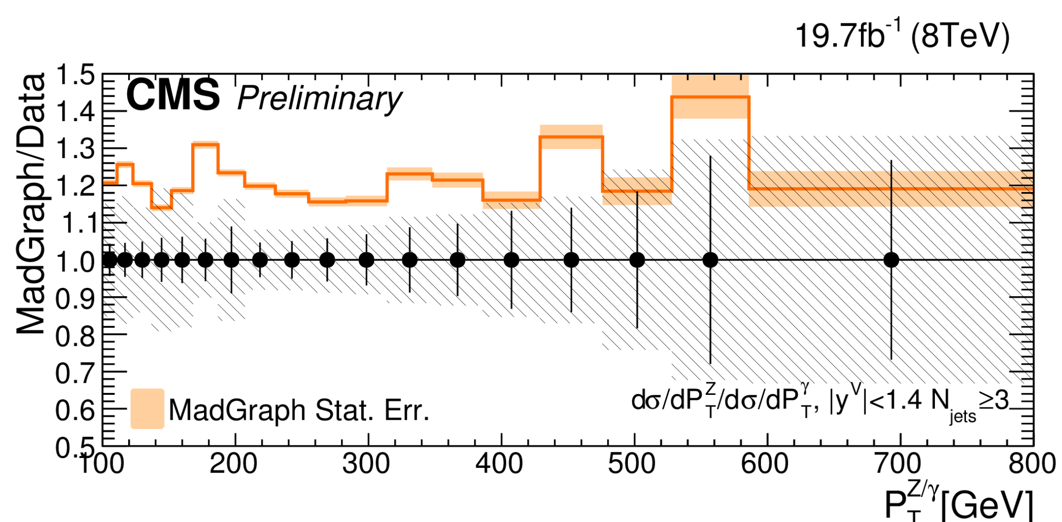
CMS-SMP-14-005





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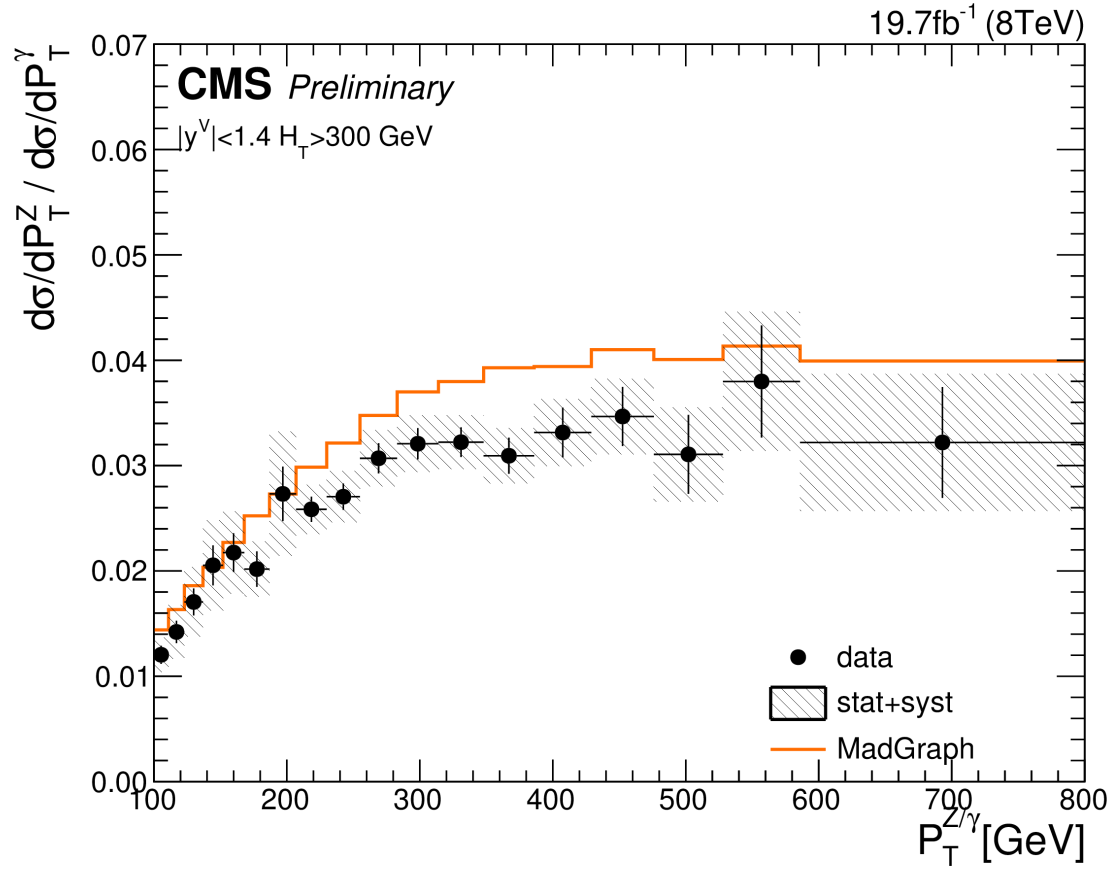
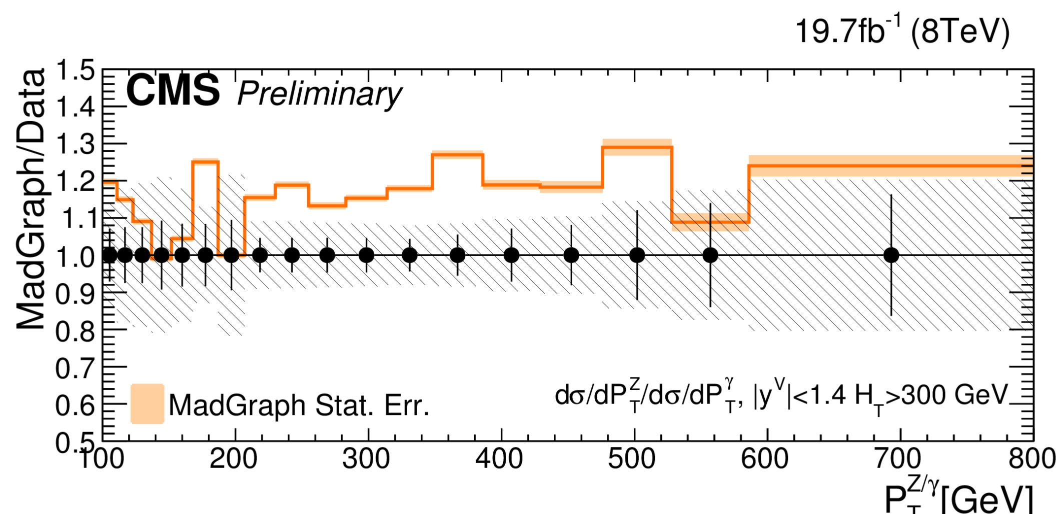
CMS-SMP-14-005





$ZZ \rightarrow lll'l'$ at 8 TeV

CMS-PAS-SMP-13-005
Phys. Lett. B 740 (2015) 250

Signature

- Two lepton pairs peaking at M_Z.
- l=e,μ l'=e,μ,τ

Selections

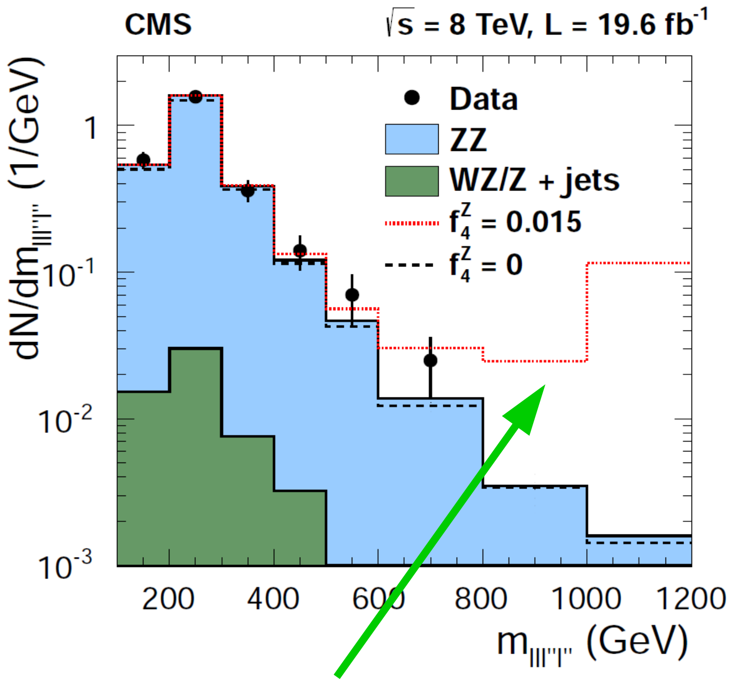
- Two same-flavor and opposite-sign isolated leptons from each Z.
- Lepton pair retained if $60<M_{ll}<120$ GeV.
- At least one lepton with $p_T>20$ GeV and one with $p_T>10$ GeV.

Backgrounds

- Mostly rejected by isolation and identification criteria.
- The remnants are Z/WZ+jets.

$$\sigma = 7.7 \pm 0.5(stat)^{+0.5}_{-0.4}(syst) \pm 0.4(theo) \pm 0.2(lumi)\, pb$$

Cross section in agreement with MCFM NLO expectation.



Anomalous couplings effects simulated with SHERPA and used to set limits on ZZZ and ZZγ couplings.

$W^+W^- \to 2l2\nu$ at 8 TeV

Phys. Lett. B 721 (2013) 190–211

Signature

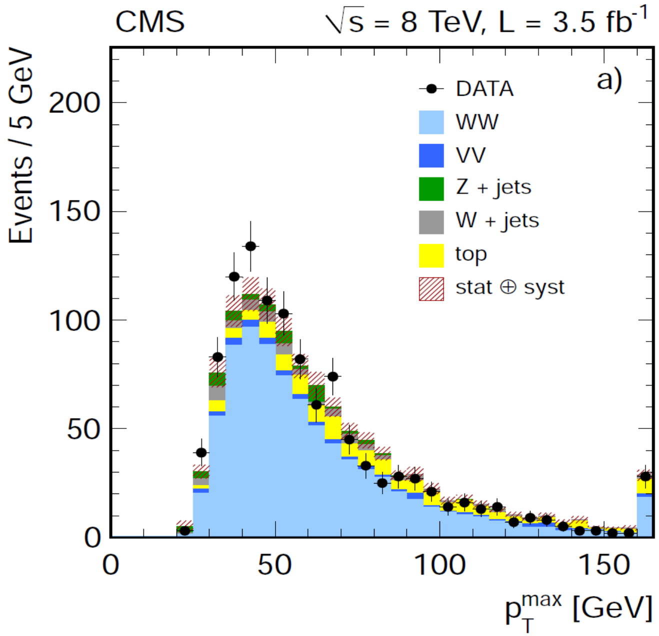
- Two oppositely charged electrons or muons with p_T>20 GeV plus MET.

Selections

- Jet veto and anti top-tagging to suppress top background.
- E_T^{miss}>45 GeV in same flavor final state to suppress DY.
- E_T^{miss}>20 GeV in opposite flavor.
- Extra lepton veto.

Backgrounds

- $t\bar{t}$ and tW
- VV
- Z/W + jets



$$\sigma = 69.9 \pm 2.8 (stat) \pm 5.6 (syst) \pm 3.1 (lumi)\ pb$$

Inclusive cross section slightly higher than the SM NLO expectation of $57.3^{+2.3}_{-1.6}$ pb.

ATLAS result

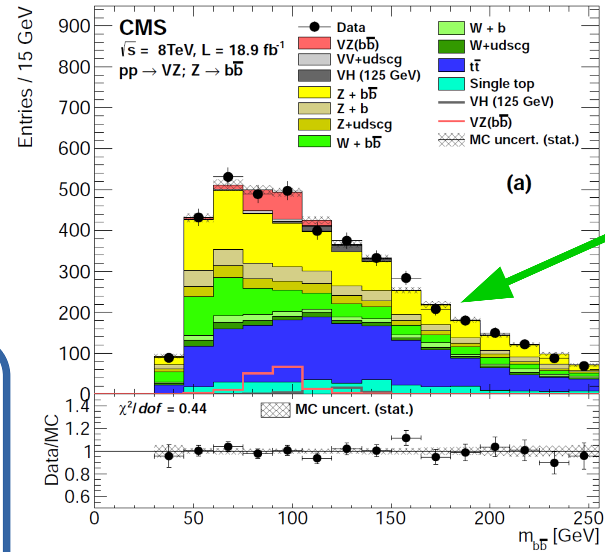
$$\sigma = 71.4 \pm 1.2 (stat) \pm 5.0 (syst) \pm 2.2 (lumi)\ pb$$

$VZ \rightarrow V$+2 b-jets

CMS-PAS-SMP-13-011
EPJC 74 (2014) 2973

Signature

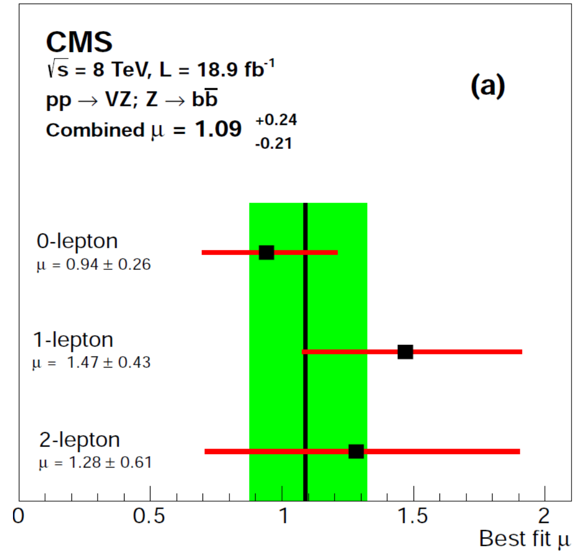
- Very similar to VH analysis with $H \rightarrow b\bar{b}$.
- Two b-tagged jets from Z decay.
- V detected through leptonic decay.



Main backgrounds are $t\bar{t}$ and V+jets

Selections

- Analysis divided into three lepton categories.
- *$Z \rightarrow ll$* : isolated and oppositely charged leptons with $60<M_{ll}<120$ GeV.
- *$W \rightarrow l\upsilon$* : single isolated lepton + $E_T^{miss}>45$ GeV
- *$Z \rightarrow \upsilon\upsilon$* : $E_T^{miss}>100$ GeV.
- $p_T^V>100$ GeV in each channel.

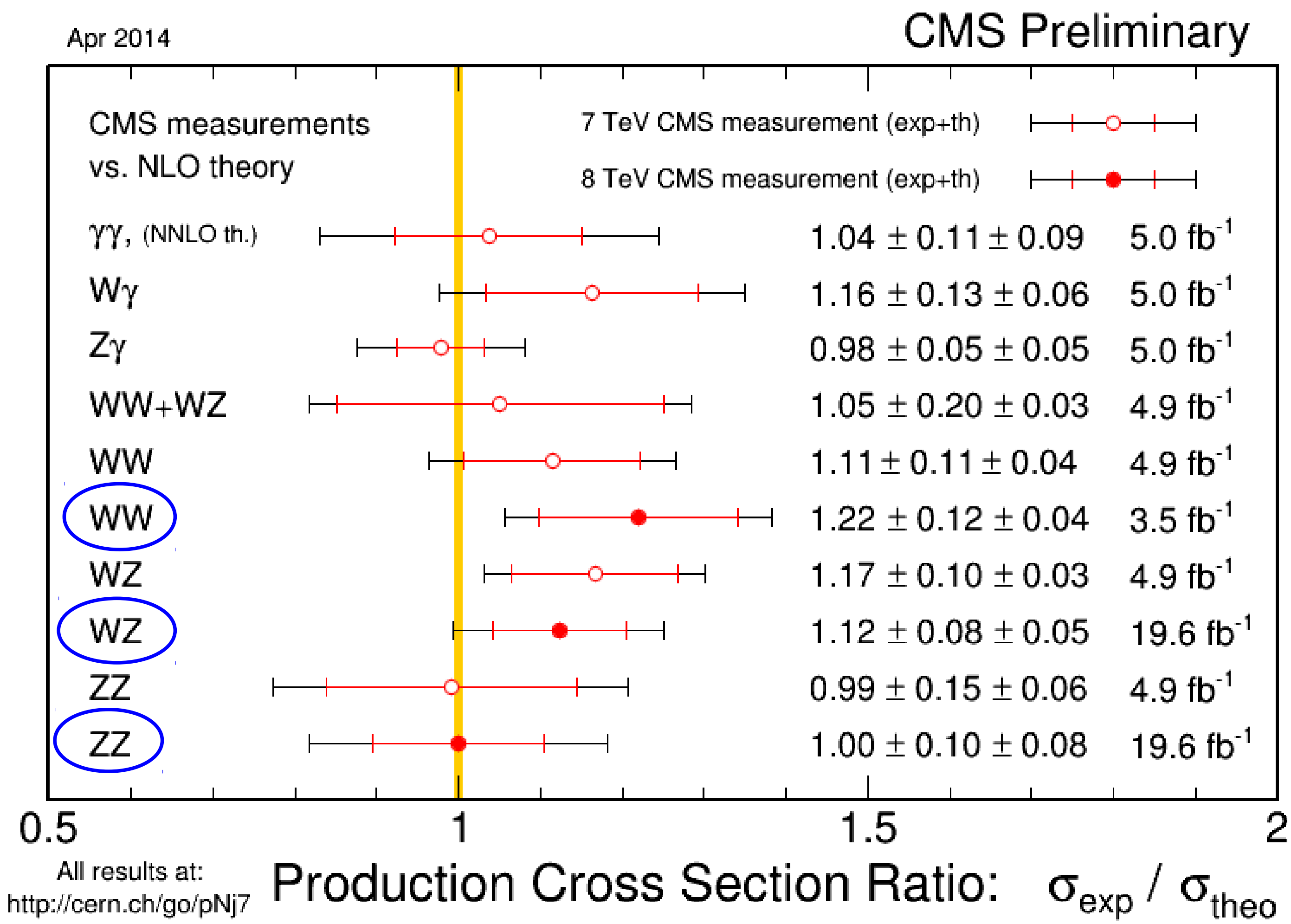


MCFM NLO cross section = 22.3 ± 1.1 pb

In agreement also with *$WZ \rightarrow 3l\upsilon$* channel

$$\sigma(WZ)=30.7\pm9.3(stat)\pm7.1(syst)\pm4.1(theo)\pm1.0(lumi)\,pb$$

Diboson cross sections results

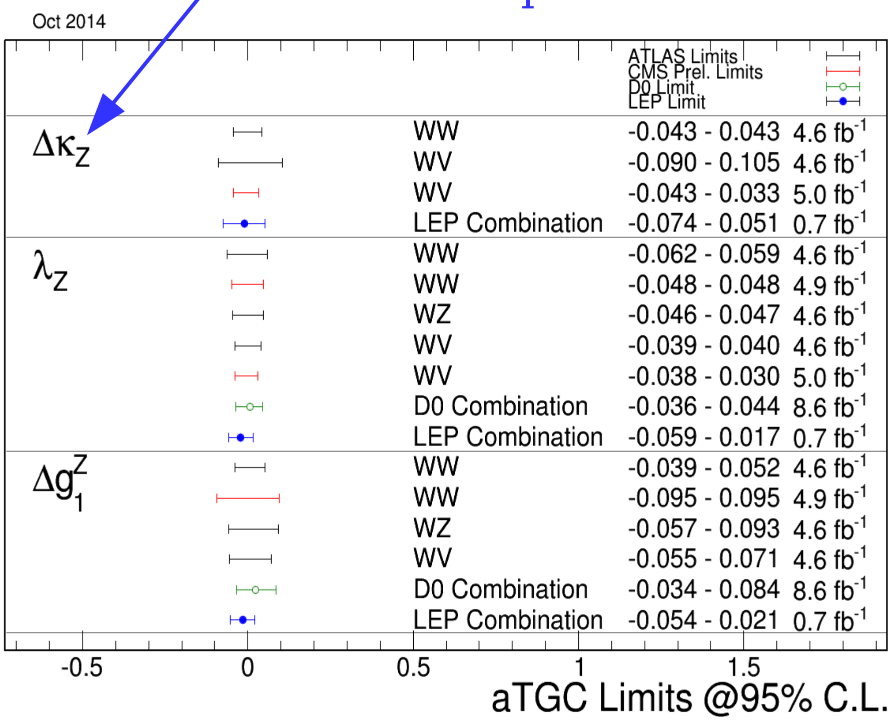


aTGCs results

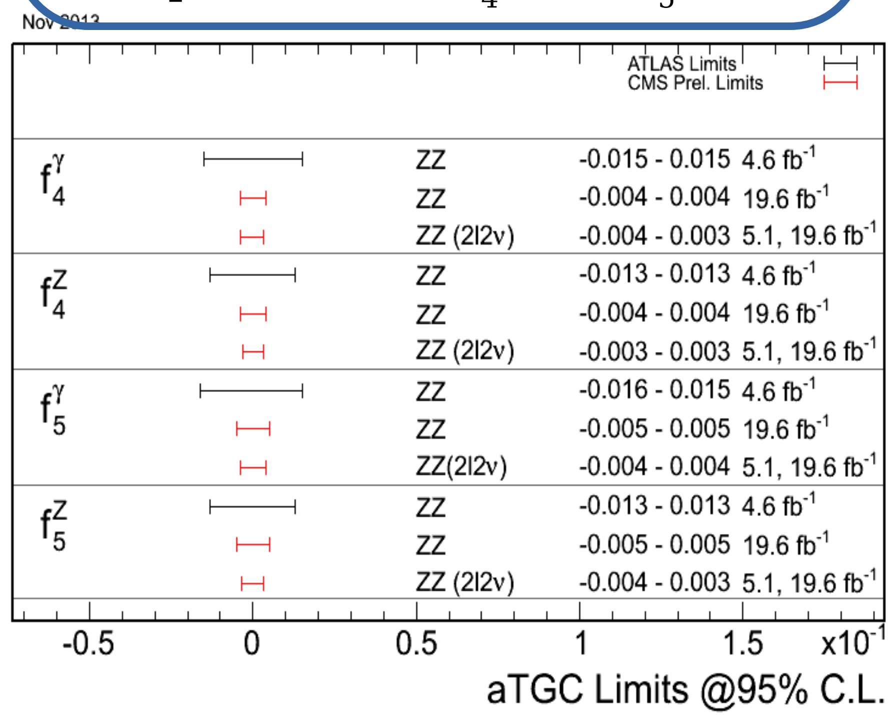
Charged aTGCs described using the LEP parameterization.

arXiv:hep-ph/9601233

WWZ vertex parameters



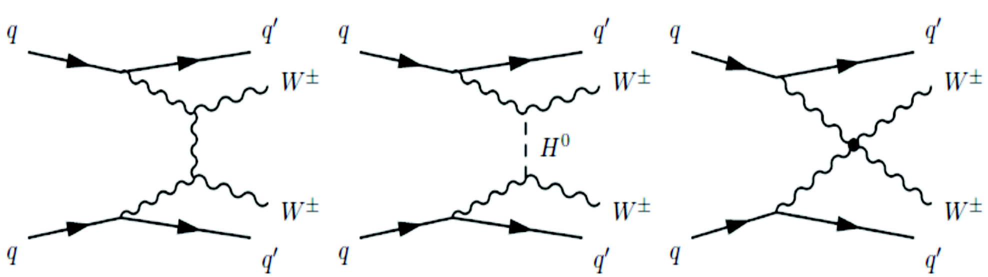
In SM all neutral TGCs are zero at tree level.
Limits are set on ZZZ and ZZγ couplings using anomalous parameters f_4^V and f_5^V.

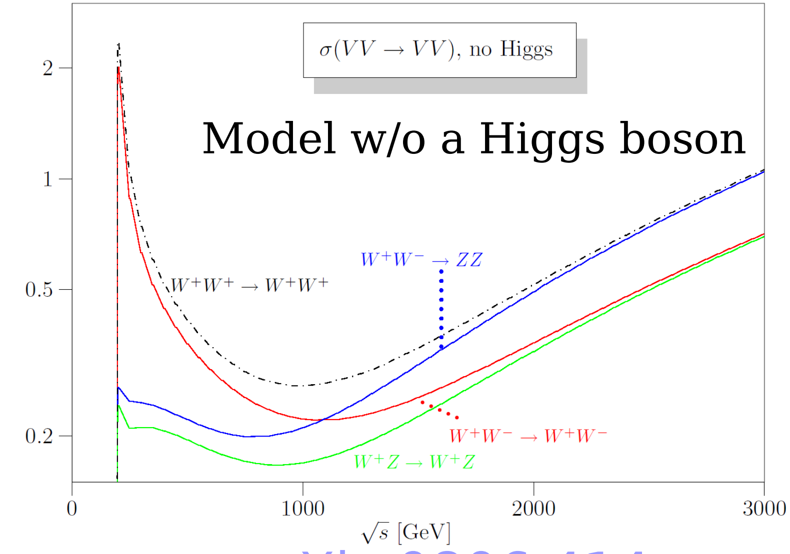


No evidence of anomalous triple gauge couplings is observed

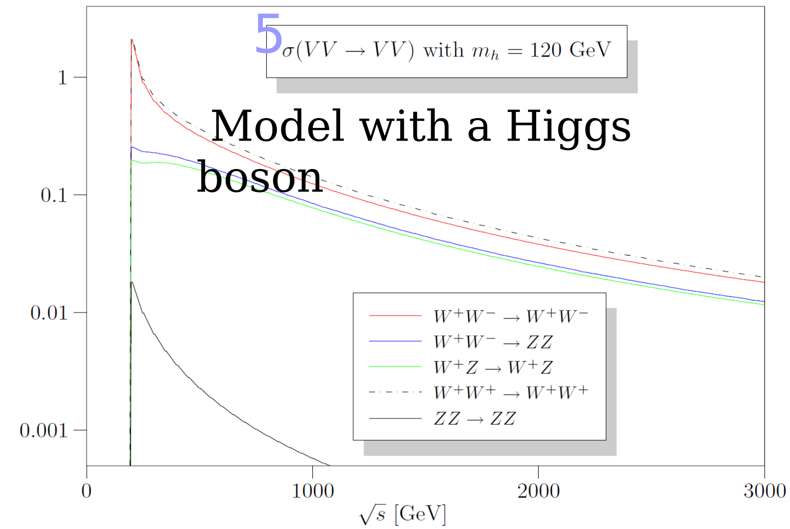
Vector Boson Scattering (VBS)

- Important process to probe the EWSB mechanism.
- The role of the Higgs boson in EWSB is essential to preserve the unitarity of VBS cross section.
- Same sign VBS provides the best S/B.





arXiv:0806.4145



VBS in $W^{\pm}W^{\pm}jj$

CMS-PAS-SMP-13-015

Signature & selections

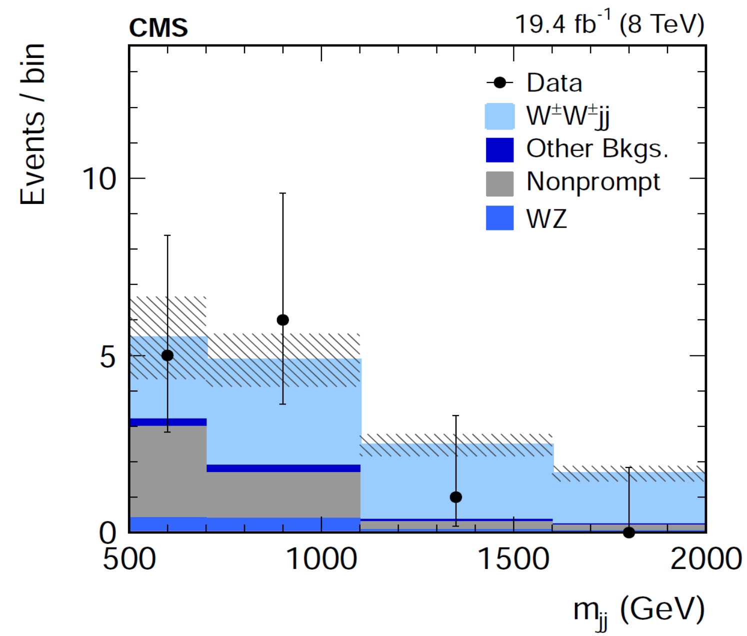
- Similar to $H \rightarrow WW$ analysis in VBF channel.
- Two leptons with same charge.
- Two forward jets with M_{jj}>500 GeV and $|\Delta\eta_{jj}|$>2.5.
- M_{ll}>50 GeV to reduce W+jets and top backgrounds.
- E_T^{miss} > 40 GeV.
- Z/top veto.

Backgrounds

- Nonprompt leptons (75%).
- $WZ \rightarrow 3l\upsilon$ (15%).
- Wrong-sign, DPS and VVV (10%).

$$\sigma_{fid}(W^{\pm}W^{\pm}jj) = 4.0^{+2.4}_{-2.0}(stat)^{+1.1}_{-1.0}(syst)\,fb$$

MadGraph+VBFNLO correction: 5.8 ± 1.2 fb



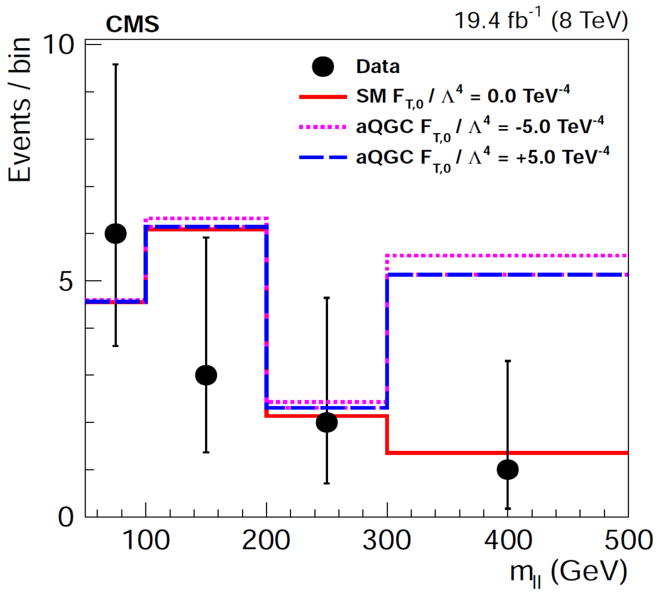
Results

- Results in agreement with SM with an observed (expected) significance of the $W^{\pm}W^{\pm}jj$ process of **2.0σ** (3.1σ).

VBS in $W^{\pm}W^{\pm}jj$

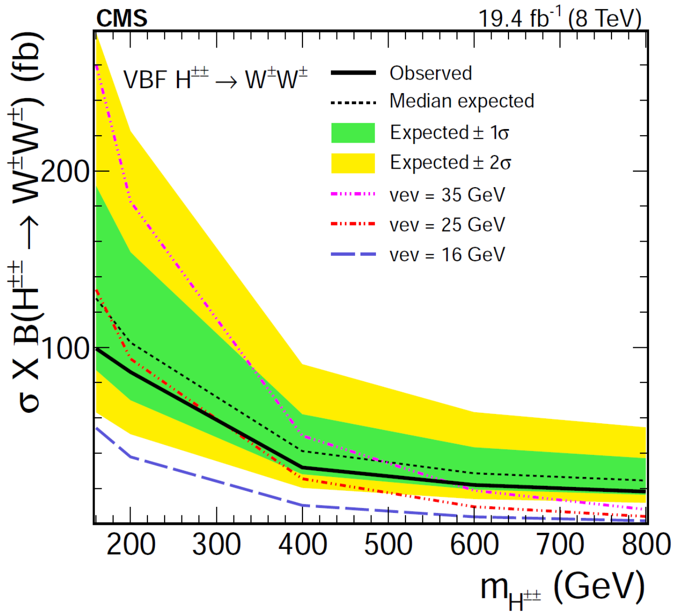
Limits on alternative models

- An excess of events could be also interpreted in terms of aQGCs or models with doubly-charged Higgs boson.



M_{ll} distribution most sensitive to aQGCs.

No evidence of aQGCs is observed



Upper limit on doubly-charged Higgs cross section

VBS in $W^{\pm}W^{\pm}jj$

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\ \mu}],$$
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}W_{\mu\nu}(D^{\nu}\Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}B_{\mu\nu}(D^{\nu}\Phi).$$