ICPPA2015: International Conference on Particle Physics and Astrophysics

Recent Standard Model measurements

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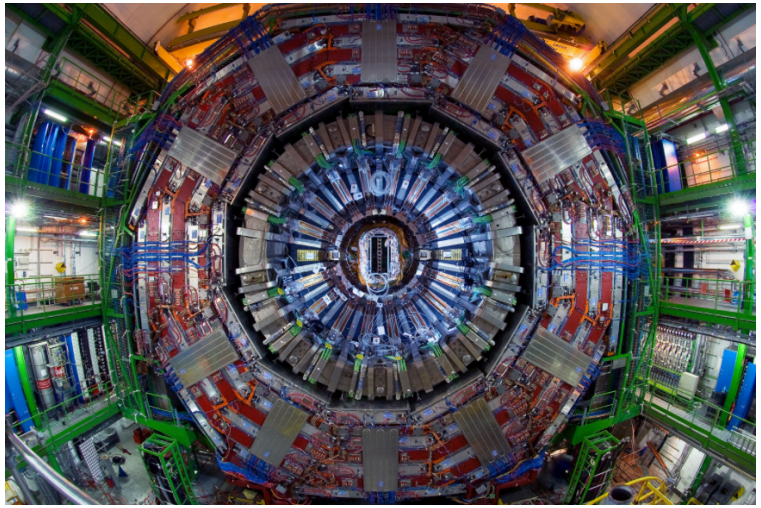
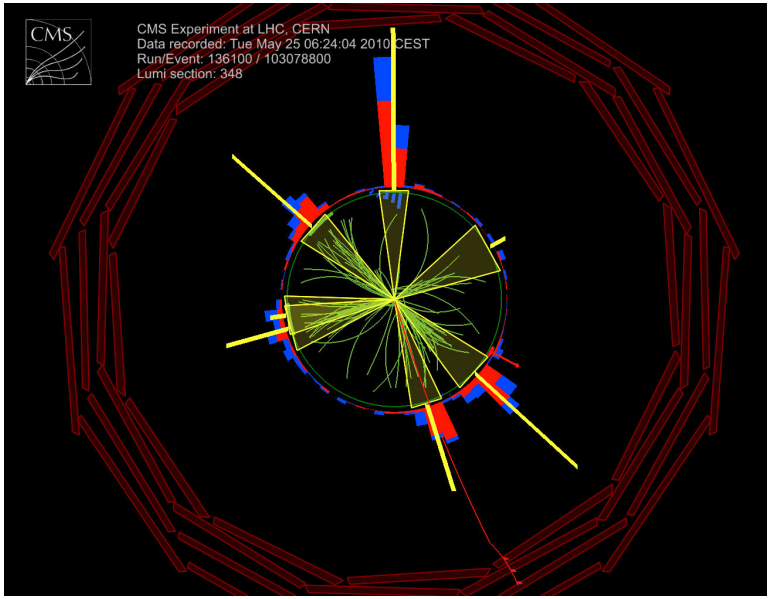
On behalf of the CMS collaboration

5-10 October 2015, Moscow, Russian Federation

Outline

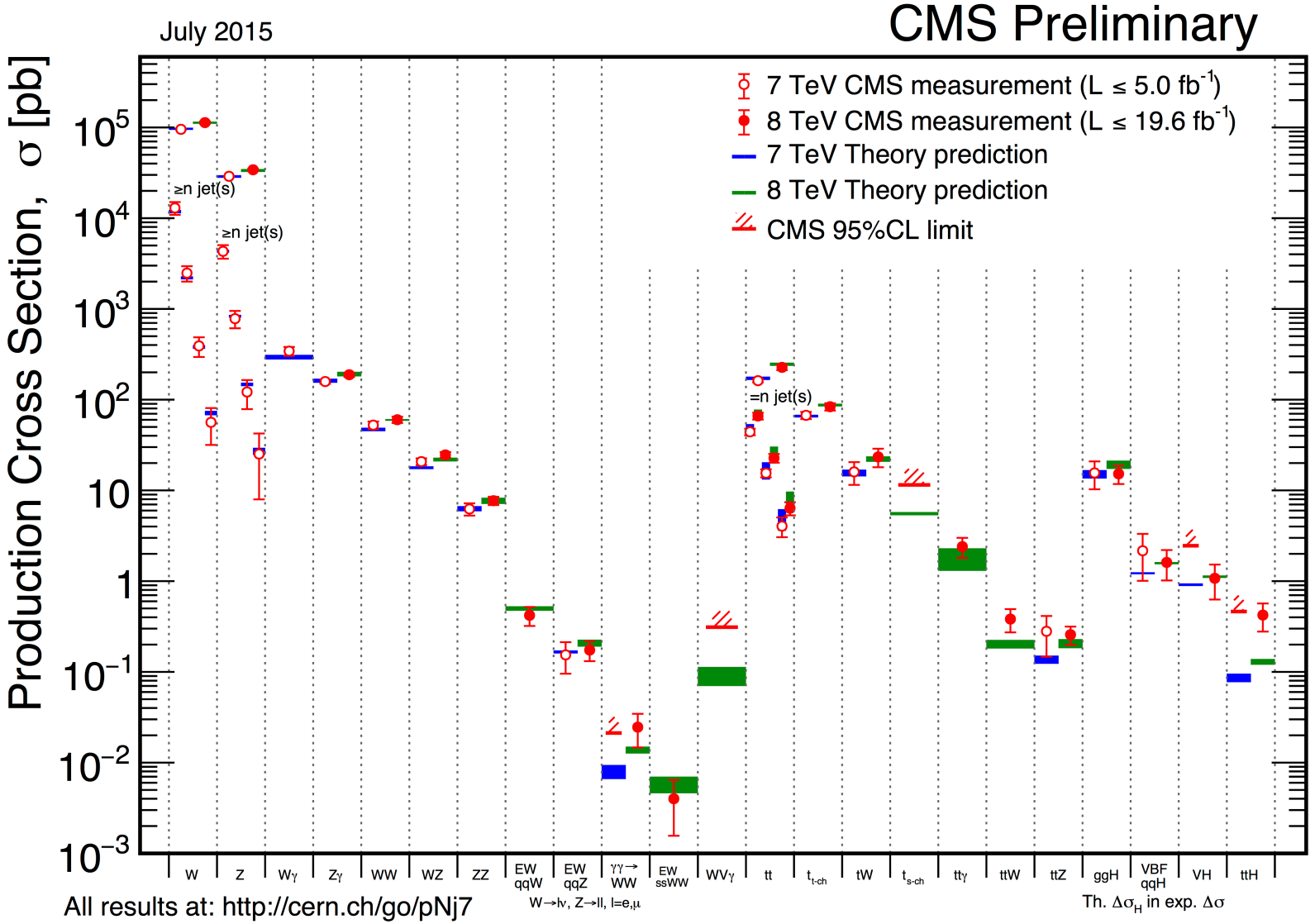
- **Vector Boson Studies**
  - Z boson diff. σ in q_T and |y|
  - Angular coefficients of Z boson
  - DY forward-backward asymmetry
  - FSR Z decay
- **Vector Boson + Jets Studies**
  - σ(Z/γ* + jets) / σ(γ + jets) ratio
  - Production of Z boson with b jets
  - EWK (VBF) W production σ





- **Multiboson Studies**
  - Zγ -> νγ production σ and aTGC
  - EWK Zγ and aTGC search
  - WW production σ and aTGC
  - ZZ->2l2ν and ZZ->4l combined aTGC
- **Jet Physics Studies**
  - Inclusive jets at 2.76 TeV and ratio to 8 TeV
  - Dijet azimuthal decorrelations
- **Forward and small-x QCD Studies**
  - VBF: EWK Z production
  - η distribution of charged hadrons at 13 TeV

Outline


CMS Preliminary
July 2015
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW ssWW
WVγ
tt
t t-ch
tW
t s-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
All results at: http://cern.ch/go/pNj7
W→lν, Z→ll, l=e,μ
Th. Δσ_H in exp. Δσ

Vector Boson Studies

Z boson diff. σ in q_T and |y| at 8 TeV

- Test pQCD, gluon PDFs, important for ttbar, diboson, BSM searches
- The Z boson is reconstructed based on its decay to a pair of muons
- Double diff. σ in 5 bins of |y| and inclusive, agree with FEWZ NNLO

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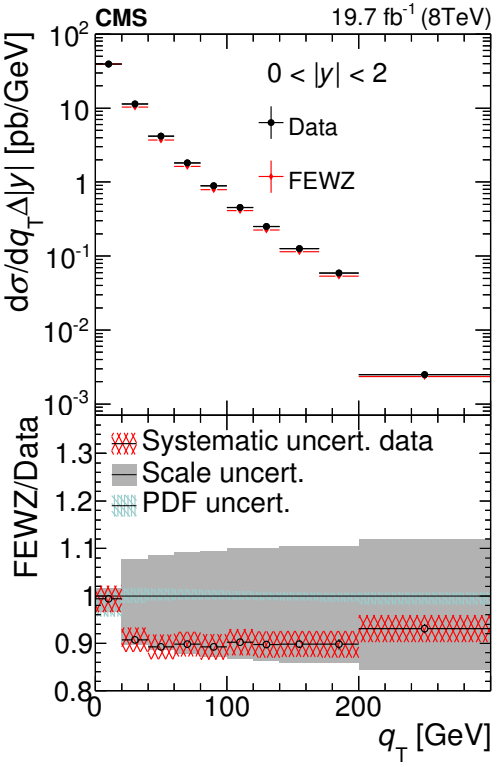

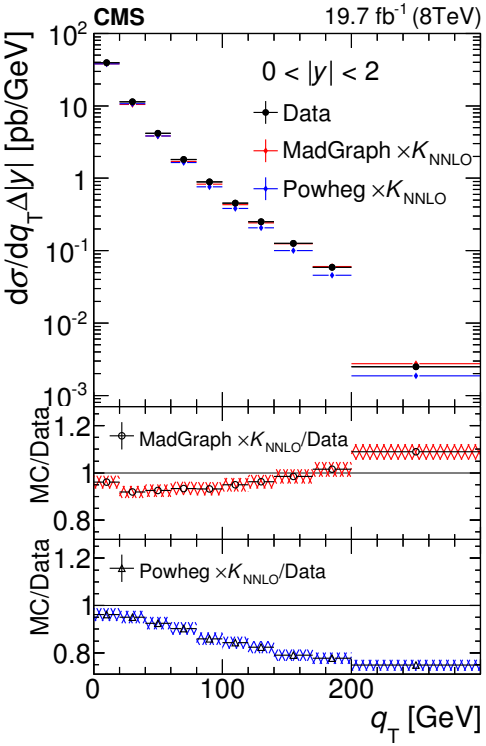

normalised to the inclusive cross section --->

<--- absolute double differential cross section

- Comparison with MadGraph and POWHEG, stat. uncert. very small
- Deviations from data by 20% at the high q_T (from both generators)
- Exp. uncert. much smaller than current theory and PDF uncertainty

Angular coefficients of Z bosons at 8TeV

- First measurement of these coeff. in pp collisions (Z->μμ)
- V-A boson-fermion couplings
- qq prod., but also qg Compton
- The Lam-Tung relation: $A_0 = A_2$
- Measured as func. of q_T and y
- Compared with MadGraph(LO), POWHEG (NLO), FEWZ (NNLO)

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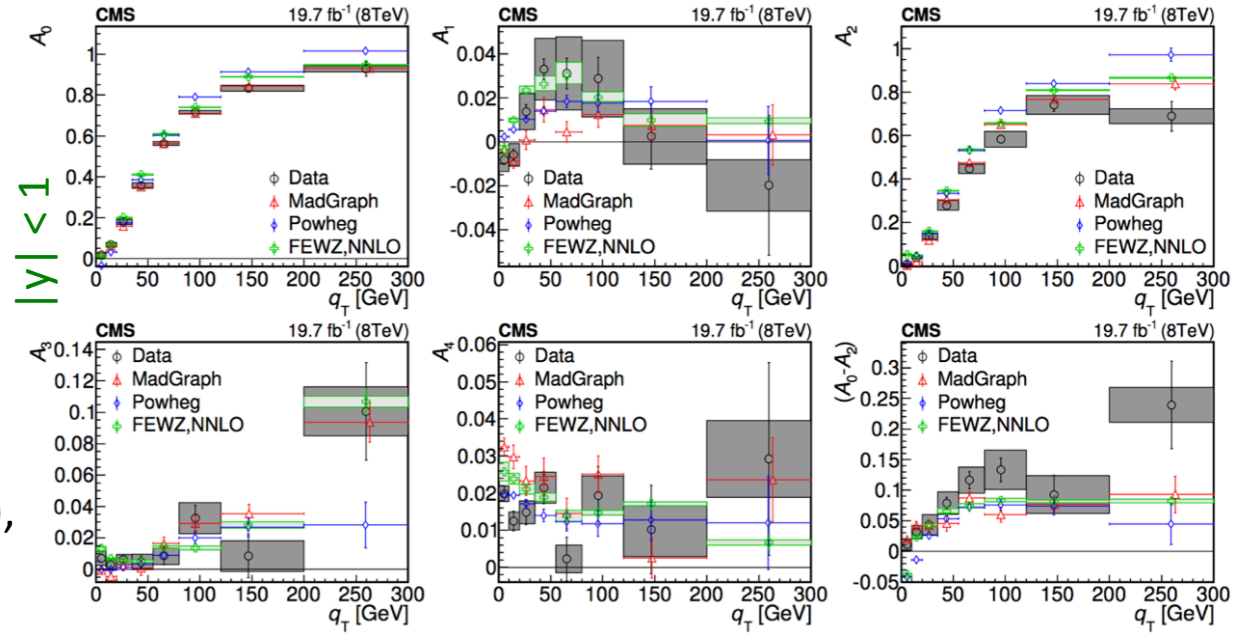
Z boson polarisation

$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \left[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)\right.$$

muons V-A couplings

$$\left. + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\right]$$



- Measured in 8 bins of q_T and 2 rapidity bins ($|y| < 1$ and $1 < |y| < 2.1$) by fitting the $(\cos\theta^*, \phi^*)$
- MadGraph predicts higher A_4 as it calculates Θ_W without considering the radiative corrections
- A_0 and A_2 : Madgraph is better; at $q_T = 0$ the POWHEG is negative -> approx. shower matching
- Violation of the Lam-Tung relation (due to higher order calc.) : $A_0 > A_2$, in particular for high q_T

DY forward-backward asymmetry at 8 TeV

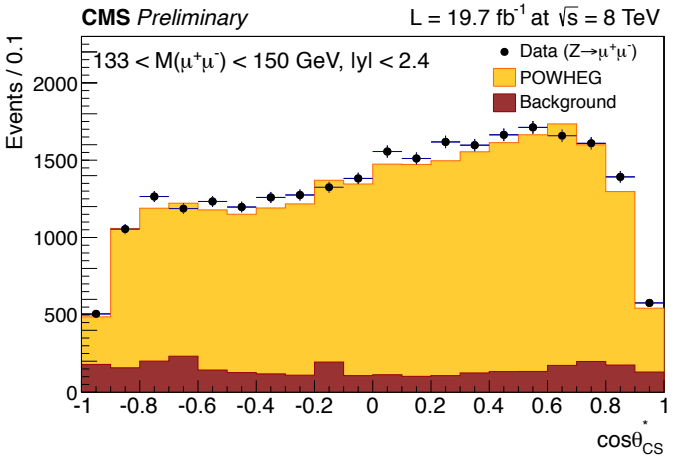
- Vector and axial-vector couplings in (SM) qq->Z/γ*->l+l-

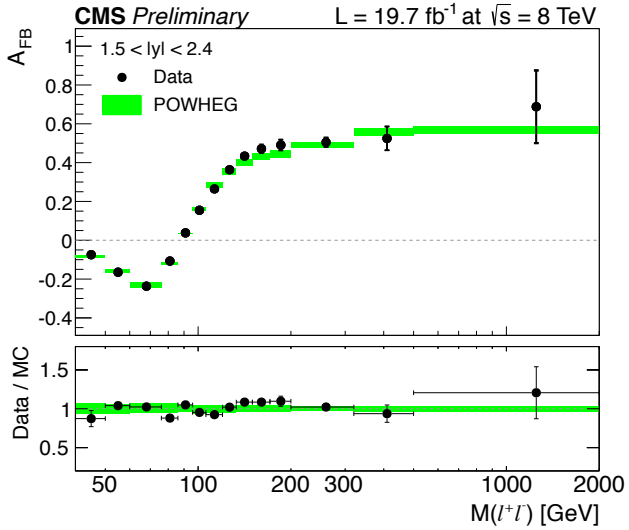
$$\frac{d\sigma}{d(\cos\theta)} = A(1+\cos^2\theta) + B\cos\theta \qquad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\cos\theta^*_{CS} = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{Q^2(Q^2+Q_T^2)}} \qquad \cos\theta^*_{CS} \to \frac{|P_z(\ell^+\ell^-)|}{P_z(\ell^+\ell^-)}\cos\theta^*_{CS}$$

- The A_{FB} measured for 40 GeV < m_{ll} < 2 TeV and |y| < 5
- Backgrounds: Z->ττ and QCDjj (low), ttbar (high mass)

CMS-SMP-14-004



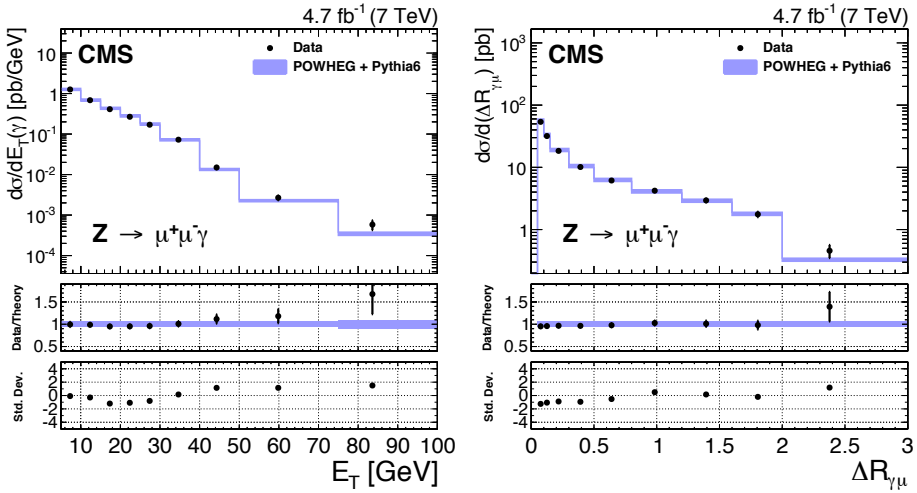


- Corrections for detector resolution, acceptance and FSR
- Good agreement with SM (POWHEG) in all |y| regions

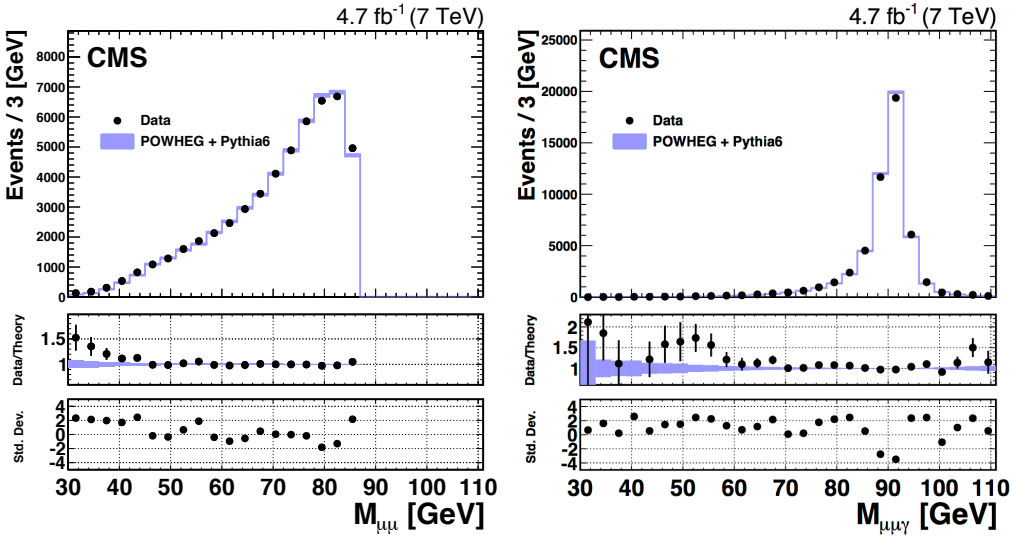
FSR Z decay at 7 TeV

Phys. Rev. D 91 (2015) 092012

- Diff. σ for photons in the Z -> $\mu^+\mu^-\gamma$ decays
- Important for m(W), Z+γ and BSM (with γ)
- Backgrounds: non-prompt γ,DY, tt, diboson



- Good agreement with POWHEG+PYTHIA prediction, discrepancies w.r.p. to data below 5%.



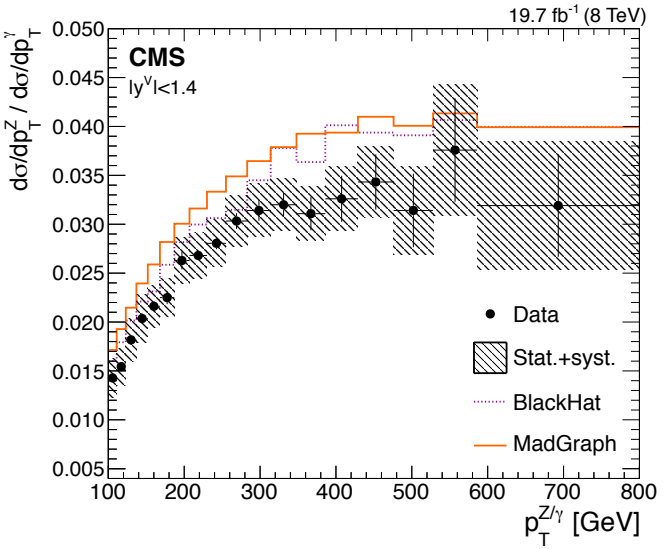
- Small increase in ratio for $M_{\mu\mu} < 40$ GeV
- 3-body mass distrib. is nearly symmetric

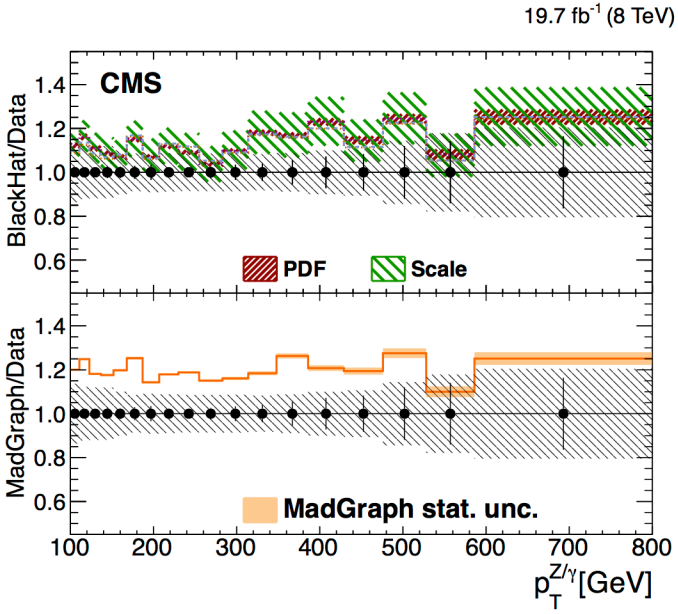
Vector Boson + Jets Studies

σ(Z/γ* + jets) / σ(γ + jets) ratio at 8 TeV

- Important for FS with hard jets and large E_t^{miss} (SUSY M_{T2})
  JHEP10(2012)018
- Z->νν+jets background modeled using measured γ+jets scaled by the ratio of Z->νν+jets to γ+jets (from the MC)
- Measured (Z->ee, μμ) ratio can reduce the uncertainties
- Small m_Z effects for high p_T^V and LO, the is ratio constant

arXiv:1505.06520, Accepted by JHEP



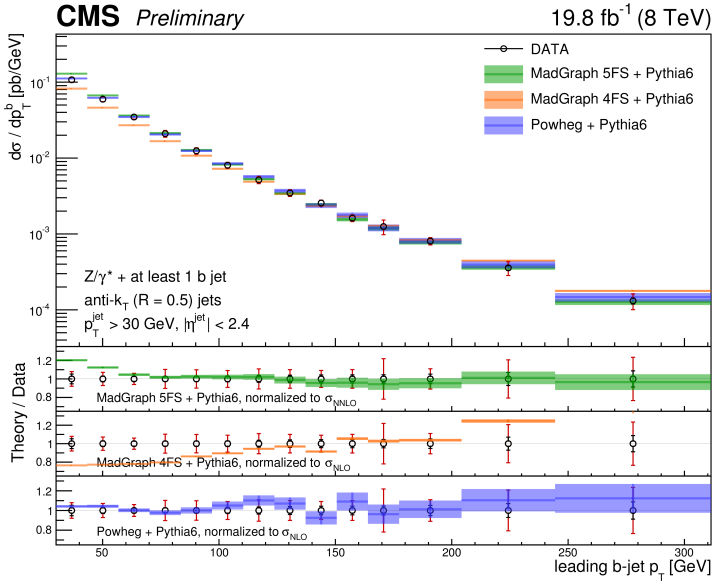


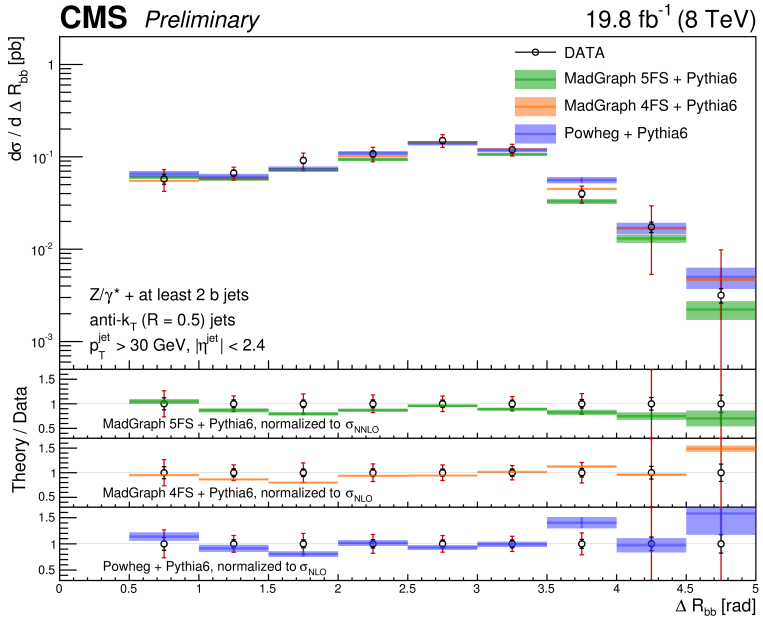
- MadGraph and BlackHat above data by 20% at high p_T
- Simulations reproduce better the shape of the ratio of p_T^Z to p_T^γ than the shapes of the individual distributions

Production of Z boson with b jets at 8 TeV

- Important background for Higgs and BSM searches
- Z(1b) diff. σ in b-jet p_T and $|\eta|$, Z p_T, H_T and $\Delta\phi_{Zb}$
- 4FS: shape better for soft b-jets, scale off by 20%
- Diff. σ ratio between Z+b and Z+jets also measured

CMS-PAS-SMP-14-010





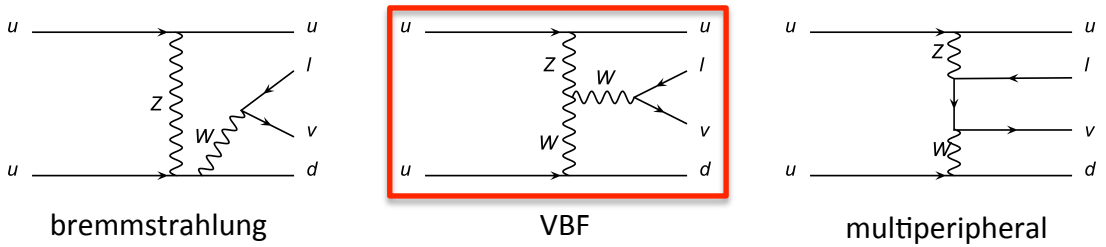
- Z(2b) diff. σ in various kinematic variables: 1st and 2nd b-jet p_T, Z p_T, $\Delta\phi_{bb}$, ΔR_{bb}, ΔR_{Zb}^{min}, A_{zbb}, m_{bb}, m_{Zbb}

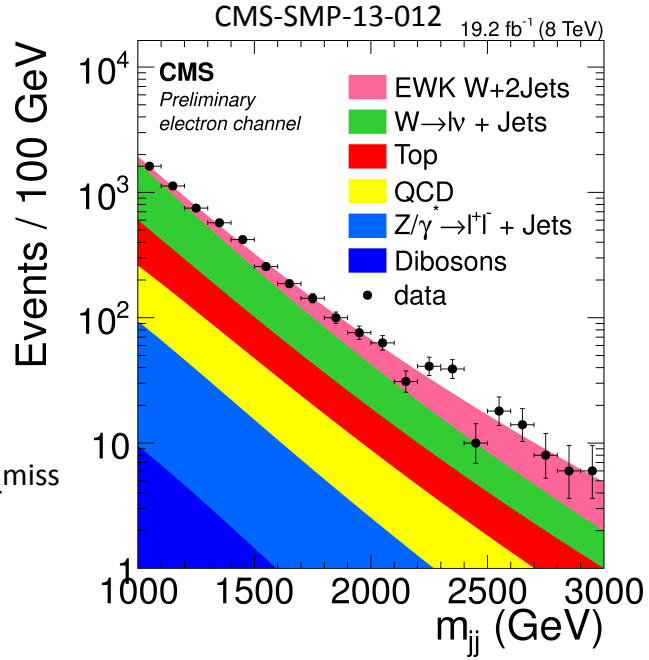
$$A_{Zbb} = \frac{(\Delta R_{Zb}^{max} - \Delta R_{Zb}^{min})}{(\Delta R_{Zb}^{max} + \Delta R_{Zb}^{min})}$$ <--- indirect test of pQCD

- Generally, good agreement within the uncertainties

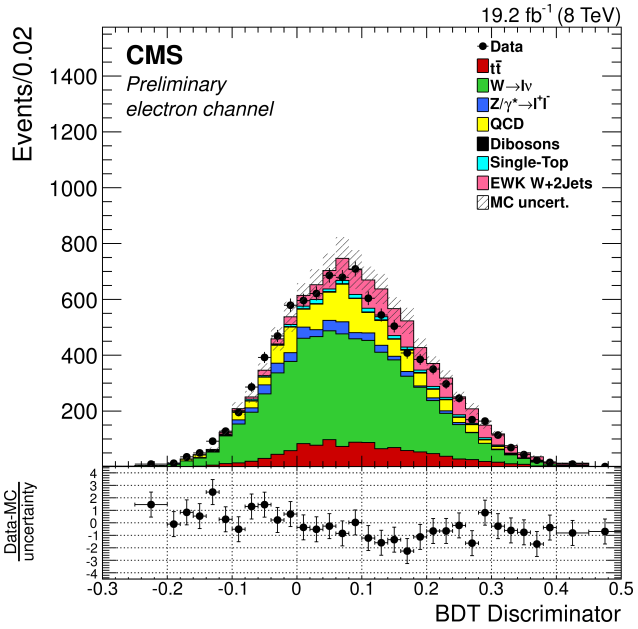
EWK (VBF) W production σ at 8 TeV

- W boson produced centrally with two jets separated in |η|





- Events with isolated electron or muon, two jets and large E_T^{miss}



- BDT to distinguish the signal from background events
- Unbinned max. likelihood fit to the m_{jj} to extract signal

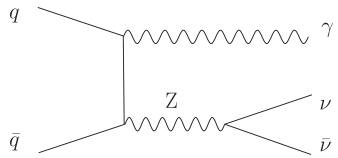
σ_{meas} = 0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb

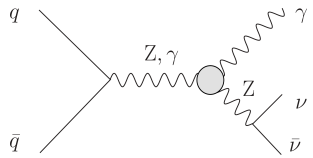
σ_{th} = 0.50 ± 0.02 (scale) ± 0.09 (PDF) pb (MG+PYTHIA6)

Multiboson Studies

Zγ -> νγ production σ and aTGCs

- Important test of EWK sector of SM, sensitive to ZZν and Zνν

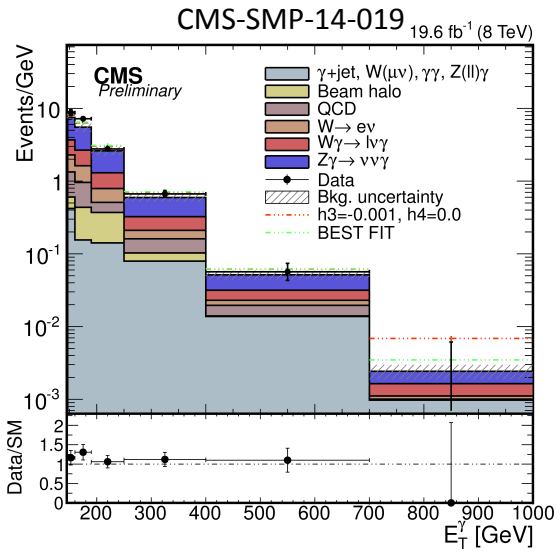


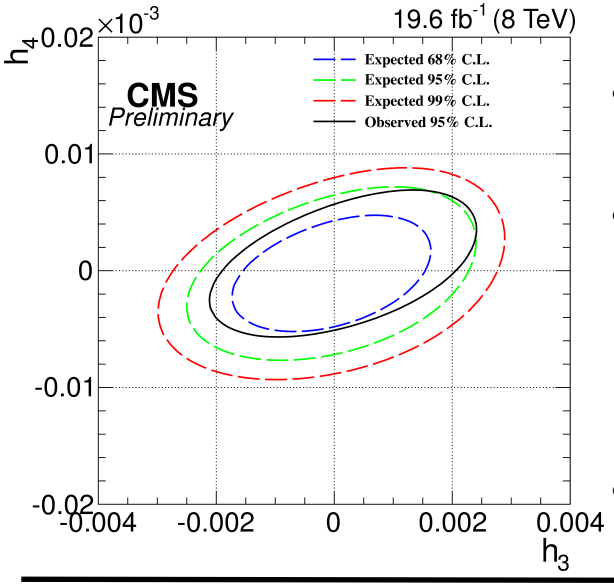


- Six times larger BR for Z to νν than to ll, larger acceptance for ν

- The σ measured in E_T^{miss} > 140 GeV, E_T^{γ} > 145 GeV, $|\eta^{\gamma}| < 1.44$:

σ_{meas} = 52.7 ± 2.1 (stat.) ± 6.4 (syst.) ± 1.4 (lumi.) pb σ_{NNLO} = 50 + 2.4 - 2.2 pb





- Lorentz- and gauge-invariant ZVγ vertex, four parameters h_i^V

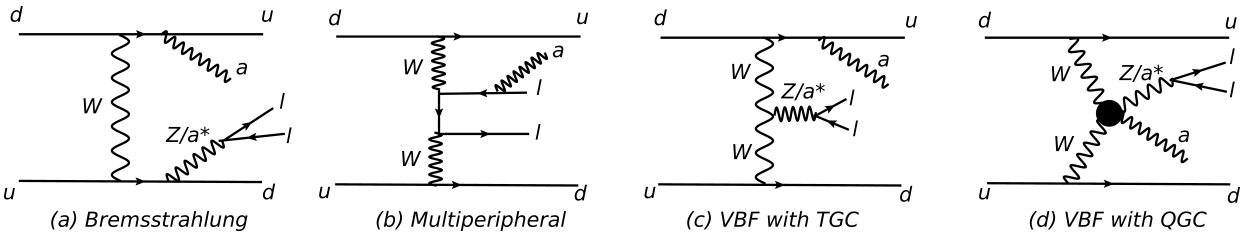
- E_t^{γ} spectrum to set aTGC limits using the likelihood formalism

Coupling	h_3 Lower limit 10^{-3}	h_3 Upper Limit 10^{-3}	h_4 Lower limit 10^{-6}	h_4 Upper Limit 10^{-6}
$Z\gamma\gamma$	-1.12	0.95	-3.80	4.35
$ZZ\gamma$	-1.50	1.64	-3.96	4.59

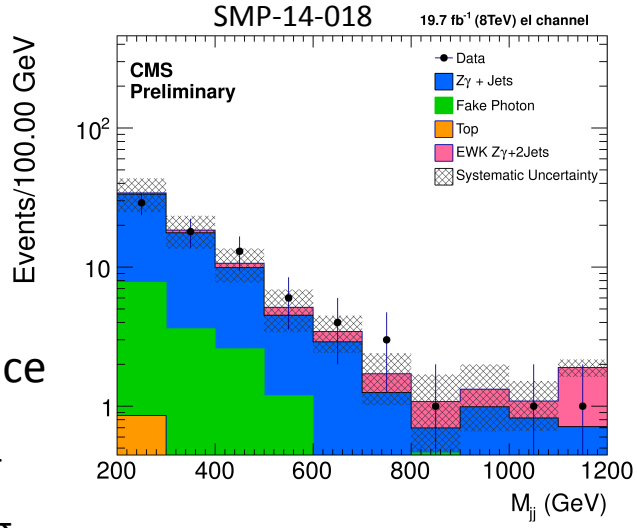
- The most stringent limits on neutral trilinear gauge couplings

Evidence for EWK Zγ and aTGC search at 8 TeV

- Pure EWK (aTGC, VBS, VBF): small σ w.r.p. QCD background



(a) Bremsstrahlung (b) Multiperipheral (c) VBF with TGC (d) VBF with QGC

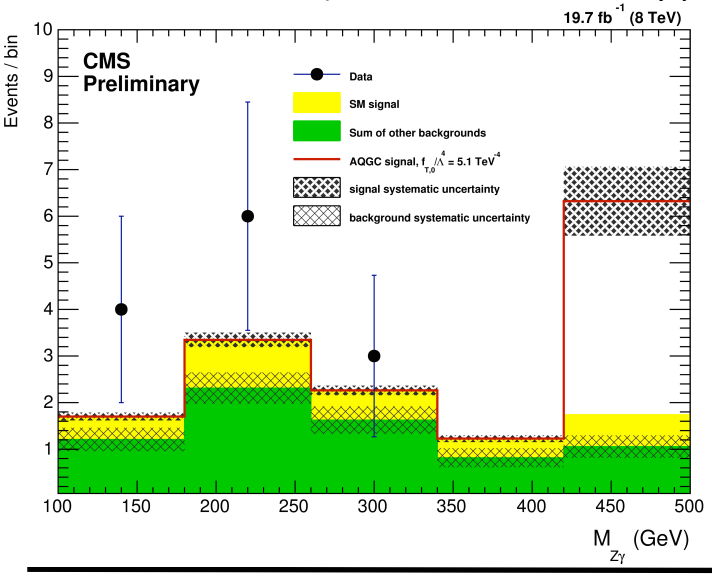


- Difficult to isolate VBS, all processes considered + interference

$\sigma_{EWK} = 1.86^{+0.89}_{-0.75}$ (stat.) $^{+0.41}_{-0.27}$(syst.) ± 0.05 (lumi.) pb — 3.0(2.1)σ

$\sigma_{EWK+QCD} = 1.00 \pm 0.43$ (stat.) ± 0.26 (syst.) ± 0.03 (lumi) pb — 4.3(4.5) σ

(consistent with theory prediction) — obs.(exp.)



- aQGC Lagrangian (Madgraph), $M_{Z\gamma}$ to extract the limits
- dim8 operators, limits on aQGC parameters at 95% CL
- The neutral parametes $f_{T8,9}$ measured for the first time:

$$-2.7\ (\mathrm{TeV}^{-4}) < f_{T8}/\Lambda^4 < 2.7\ (\mathrm{TeV}^{-4})$$
$$-6.0\ (\mathrm{TeV}^{-4}) < f_{T9}/\Lambda^4 < 6.0\ (\mathrm{TeV}^{-4})$$

W^+W^- production σ and aTGC at 8 TeV

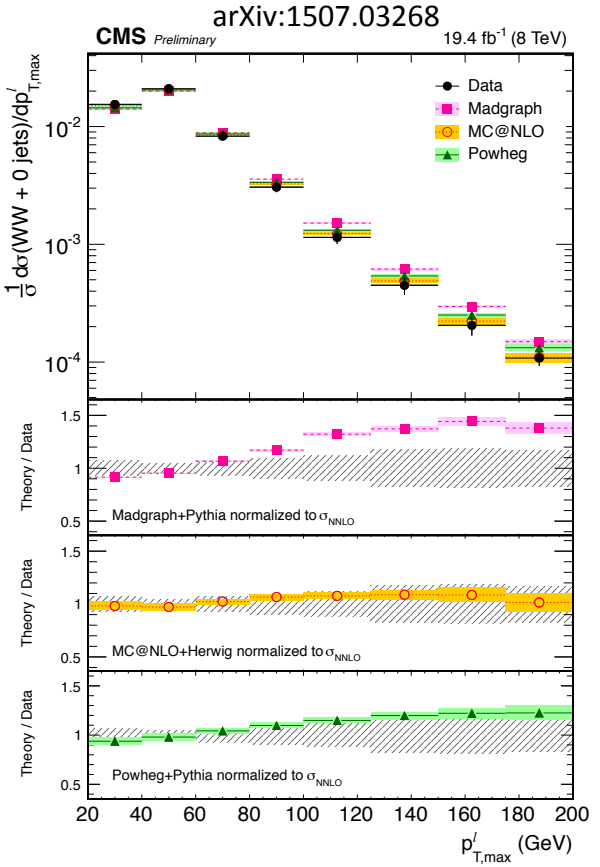
- W^+W^- has the largest cross section of all di-boson processes
- CERN LHC: qq->WW dominant, gg->WW only 3%, (~~H->WW~~)
- Two high p_T leptons, large E_t^{miss} and zero or one high p_T jet

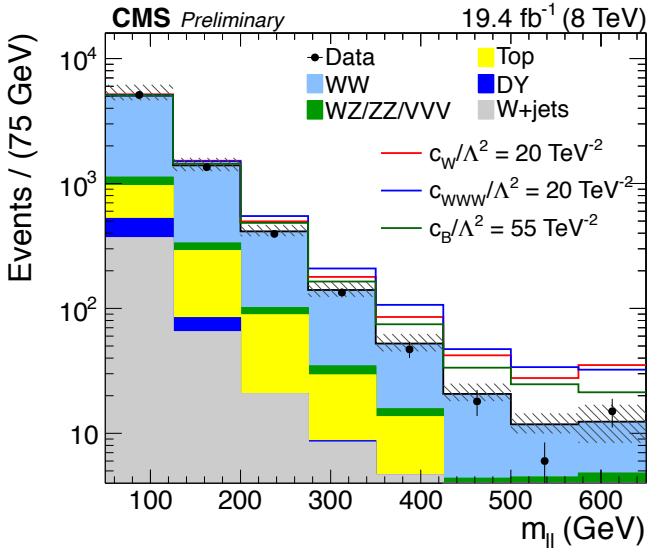
  $\sigma_{meas} = 60.1 \pm 0.9\ (stat) \pm 3.2\ (exp) \pm 3.1\ (lumi.)\ pb$

  $\sigma_{NNLO} = 59.8^{+1.3}_{-1.1}\ pb$

- Normalized diff. σ as a function of various kinematic variables

arXiv:1507.03268





- Dim6 EFT ---> aTGC limits
- WWZ, WWγ -> no evidence
- Improved measurement of the coupling constant c_{WWW}/Λ^2

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)

ZZ -> 2l2ν σ and combined aTGC limits at 8 TeV

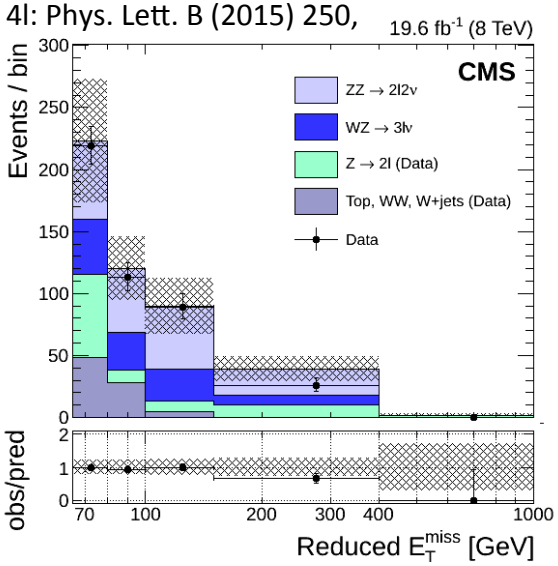
- BR is 6x larger than ZZ->4l, large backgrounds (DY, WW, ttbar)
- MET reconstruction is crucial, distinctive w.r.p. to DY process
- Reduced MET variable, previously used at D0 & OPAL searches

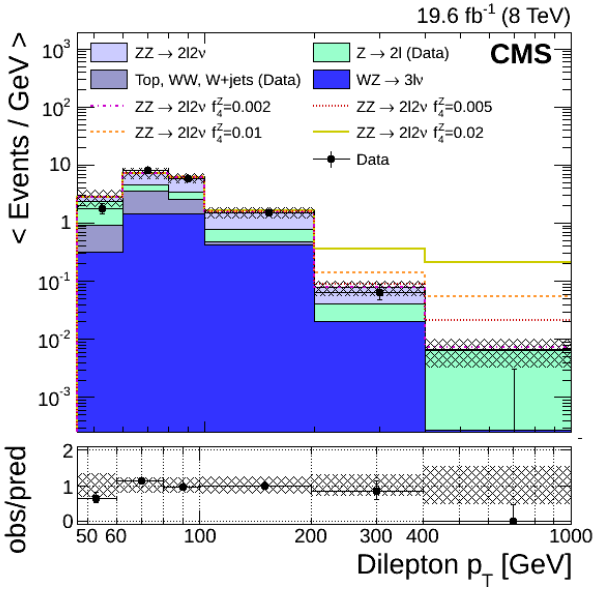
$$\text{reduced-}E_{\mathrm{T}}^{\mathrm{miss}\,i} = -q_{\mathrm{T}}^{i} - R_{c/u}^{i}$$

$$B = E_{\mathrm{T}}^{\mathrm{miss}} / q_{\mathrm{T}}$$

Variable	Value
Dilepton invariant mass	$\lvert m(\ell\ell) - 91\rvert < 7.5$ GeV/c^2
Dilepton p_{T}	$q_{\mathrm{T}} > 45$ GeV/c
b-tag veto	based on vertex info. (for jet with $p_{\mathrm{T}} > 20$ GeV/c)
Jet veto	no jets with $p_{\mathrm{T}} > 30$ GeV/c
Reduced $E_{\mathrm{T}}^{\mathrm{miss}}$	> 65 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$ balance	$0.4 < B < 1.8$
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}$,jet)	> 0.5 rad
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}$,lept.)	> 0.2 rad
Lepton veto	no additional leptons (e/μ) with $p_{\mathrm{T}} > 10/3$ GeV/c

2l2ν: arXiv.1503.05467 Submitted to EPJC
4l: Phys. Lett. B (2015) 250,





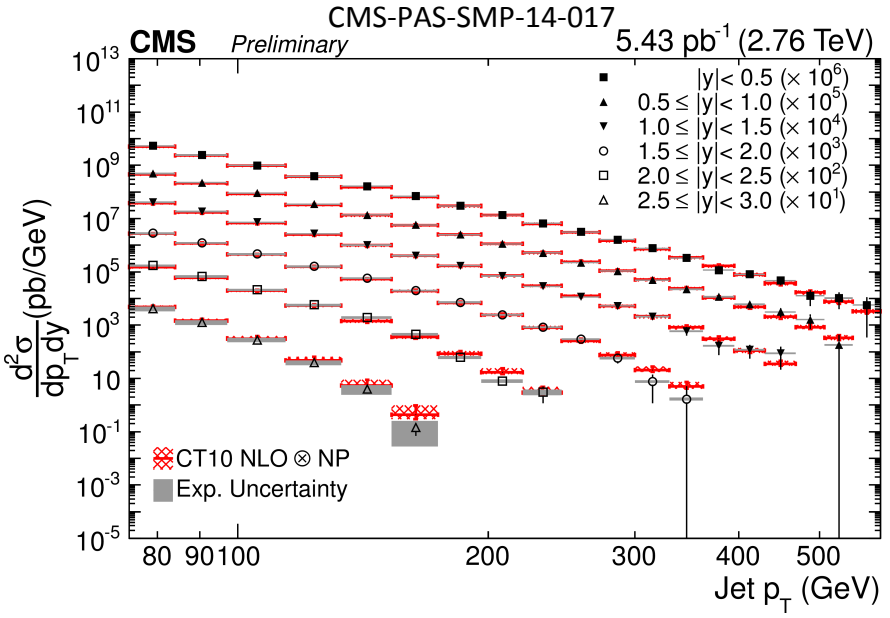
- NLO EW corrections to SM ZZ->4l included, same as in 2l2ν
- Combined results improve sensitivity of individual channels

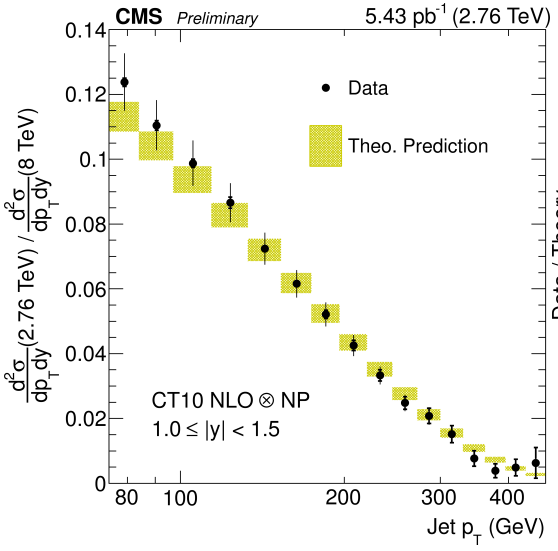
Dataset	f_4^Z	f_4^γ	f_5^Z	f_5^γ
7 TeV, 4ℓ	[-0.010; 0.011]	[-0.012; 0.013]	[-0.011; 0.011]	[-0.013; 0.013]
7 TeV, $2\ell2\nu$	[-0.010; 0.011]	[-0.012; 0.013]	[-0.010; 0.010]	[-0.013; 0.013]
8 TeV, 4ℓ	[-0.0041; 0.0044]	[-0.0052; 0.0048]	[-0.0041; 0.0040]	[-0.0048; 0.0045]
8 TeV, $2\ell2\nu$	[-0.0032; 0.0037]	[-0.0043; 0.0037]	[-0.0032; 0.0034]	[-0.0038; 0.0043]
Combined	[-0.0021; 0.0026]	[-0.0030; 0.0026]	[-0.0022; 0.0023]	[-0.0026; 0.0027]
Expected (4ℓ and $2\ell2\nu$, 7 and 8 TeV)	[-0.0036; 0.0039]	[-0.0045; 0.0041]	[-0.0036; 0.0036]	[-0.0042; 0.0043]

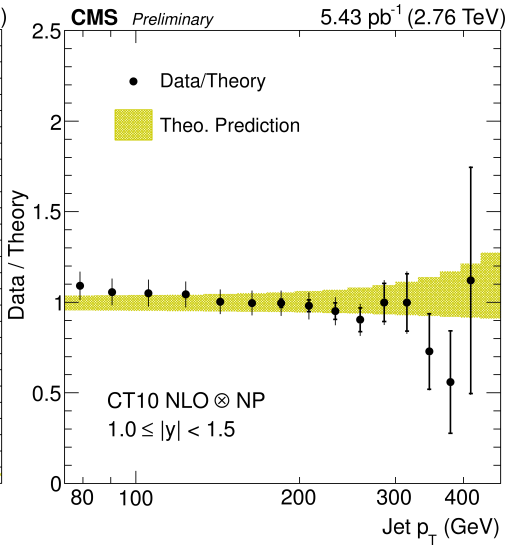
Jet Physics Studies

Inclusive jet production at 2.76 TeV and ratio with 8 TeV

- Jet production rate is sensitive to PDFs and α_S
- Double diff. σ as a function of jet p_T and $|\eta|$
- CT10 and NNPDF3.0 show the best agreement
- HERAPAD1.5, MMHT14, ABM11 not that well







- Ratio of double diff. σ at 2.76 and 8 TeV

$$\rho = \frac{\sigma_{\text{Data}}^{2.76\ \text{TeV}} / \sigma_{\text{Theory}}^{2.76\ \text{TeV}}}{\sigma_{\text{Data}}^{8\ \text{TeV}} / \sigma_{\text{Theory}}^{8\ \text{TeV}}}$$

- Syst. uncert. partially cancel in the ratio
- pQCD tested with improved accuracy

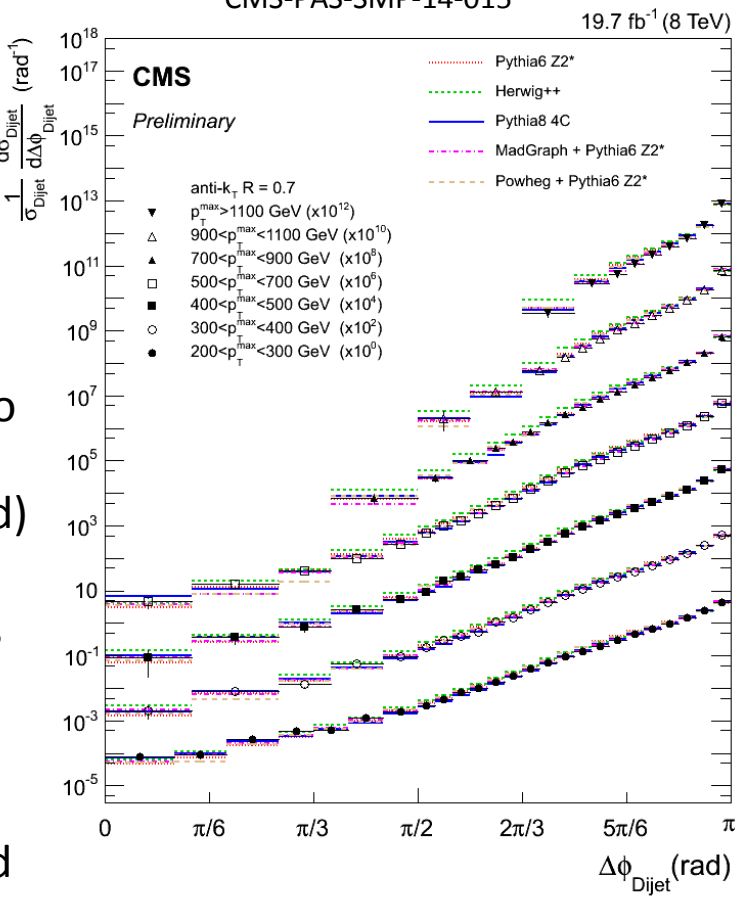
Dijet azimuthal decorrelations at 8 TeV

- pQCD(LO): Two partons balanced in p_T -> back-to back
- NP effects of MPI have only mild perturbation: $\Delta\phi \approx \pi$
- 3rd high p_T jet leads to decorrelation in azimuthal angle
- If more than 3 jets are produced, $\Delta\phi$ can approach zero

$$\frac{1}{\sigma_{\text{Dijet}}}\frac{d\sigma}{d\Delta\phi_{\text{Dijet}}}$$ (many exp. and th. uncert. are reduced)

- Compared to pQCD prediction for 3-jet up to 4 partons
- The NLO for $2/3\pi < \Delta\phi < \pi$ and LO for $\pi/2 < \Delta\phi < 2\pi/3$
- 7 p_T^{max} ranges and 5 different MC generators compared

CMS-PAS-SMP-14-015

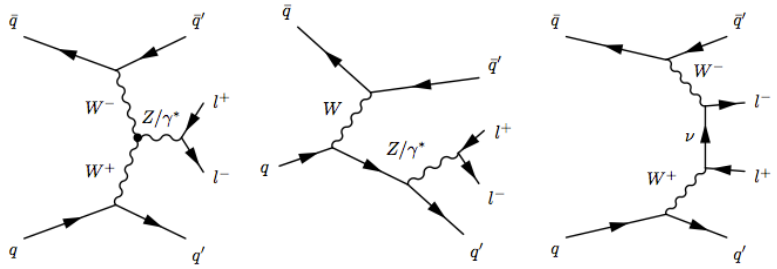


- Overestimate from PYTHIA6, HERWIG++ and POWHEG, better agreement from PYTHIA8
- Overall very good description of data with (multijet improved) MadGraph with PYTHIA6

Forward and small-x QCD Studies

VBF : EWK Z production

- Zjj production is a mixture of EW and strong (ref: DY Zjj)
- EWK Zjj signal characterized by a large $\Delta\eta_{jj}$ and large M_{jj}
- Part of more general studies of VBS and VBF processes
- Two types of jets: “jet-plus-track” and “particle-flow”

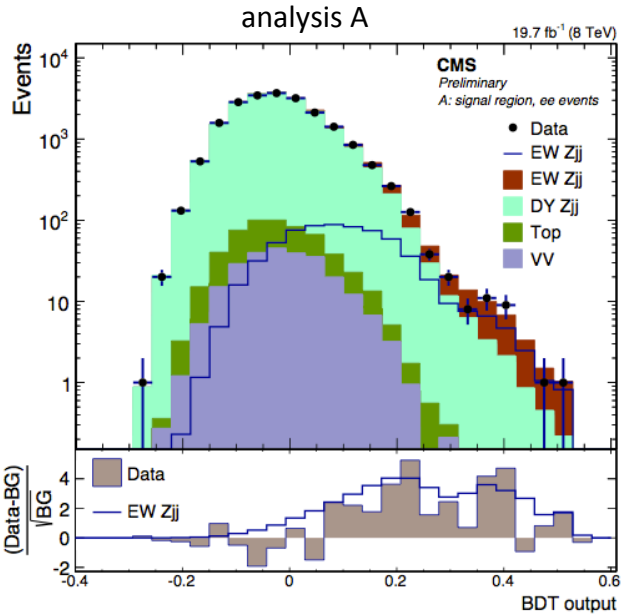


- Multivariate analyses used to provide separation of EW Zjj and DY Zjj from the inclusive lljj spectrum:

A. μμ & ee (PF jets), dijet and Z kinematics as input to the MVA

B. μμ (JPT jets), BDT: full kinematics of tagging jets and Z boson

C. μμ & ee (PF jets), only dijet-related variables as input to MVA

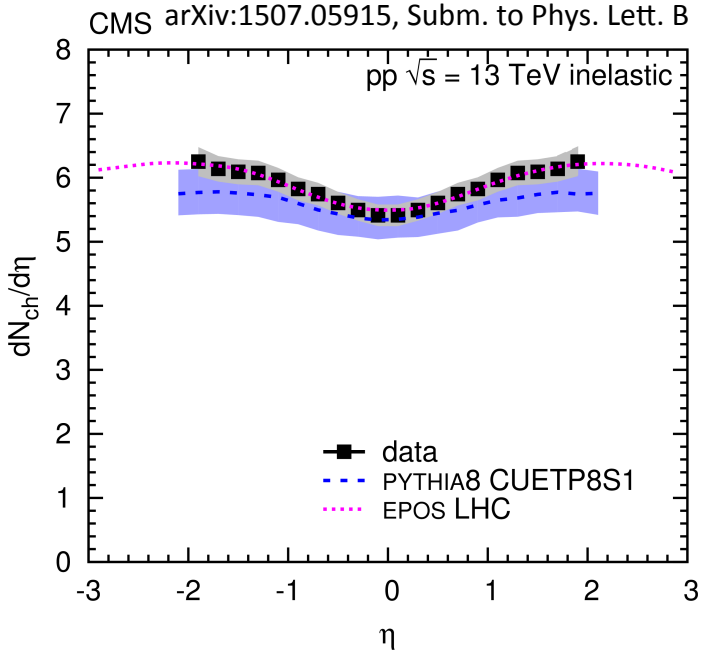


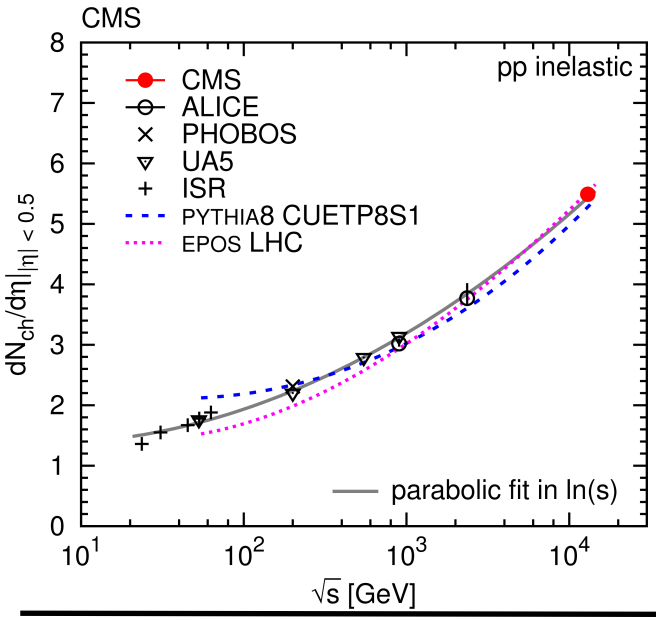
- Measured signal cross section is in a good agreement with the SM prediction at leading order (LO):

$$\sigma(\text{EW}\,\ell\ell\text{jj}) = 174 \pm 15\,(\text{stat}) \pm 40\,(\text{syst})\,\text{fb} = 174 \pm 42\,(\text{total})\,\text{fb} \qquad \sigma_{\text{LO}}(\text{EW}\,\ell\ell\text{jj}) = 208 \pm 18\,\text{fb}$$

η distribution of charged hadrons at 13 TeV

- $dN_{ch}/d\eta$: first publication at 13 TeV, zero magnetic field
- Dependence on √s reflect the roles of soft/hard scatter
- Low-intensity beam, 0.2-5% p-p prob. per bunch cross
- Two reconstruction techniques, based on hits in Pixel :
  - tracklet method (using hit pairs), bkg. data driven
  - track method (using hit triplets), additional hit req.
- Agreement < 2% (central) and < 3% (forward) η region





$dN_{ch}/d\eta_{|\eta<0.5|} = 5.49 \pm 0.01\ (stat) \pm 0.17\ (syst)$

- Comparison in √s with the ISR, UA5, PHOBOS and ALICE
- Central region consistent with PYTHIA8 and EPOS LHC
- Wider η range is better described by EPOS generator

Summary

- Recent Standard Model results from CMS using the LHC Run 1 data have given us possibility to perform extensive tests of the electroweak and strong interactions

- Studies of the vector boson production showed unprecedented precision and enabled testing of the pQCD over large kinematic region that has never been probed before

- Measurements of the vector boson plus jets production were improved, various MC generators have confirmed predictive capabilities of pQCD; new PDF constraints

- The multiboson studies resulted with new aTGC/aQCG limits, many are world-leading

- Jet production measured in the extended phase space, reduced PDF uncertainties

- Interesting times ahead as the LHC Run 2 is ongoing, with the energy of 13 TeV, higher pileup and more challenging trigger conditions, new results there already

Backup

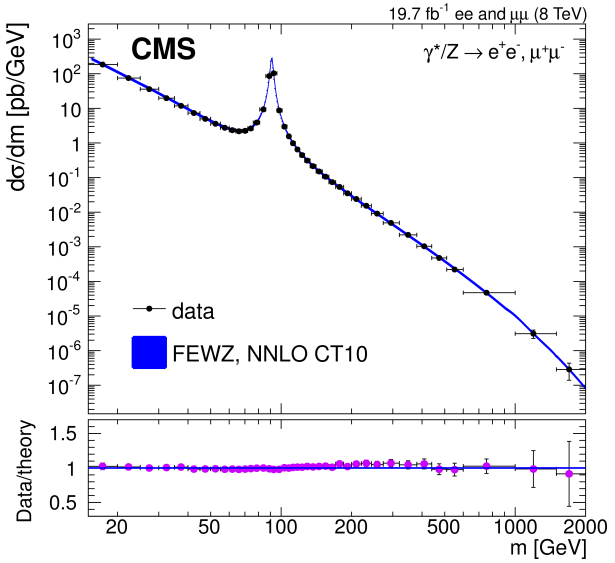
(Double) differential Drell-Yan σ at 8 TeV

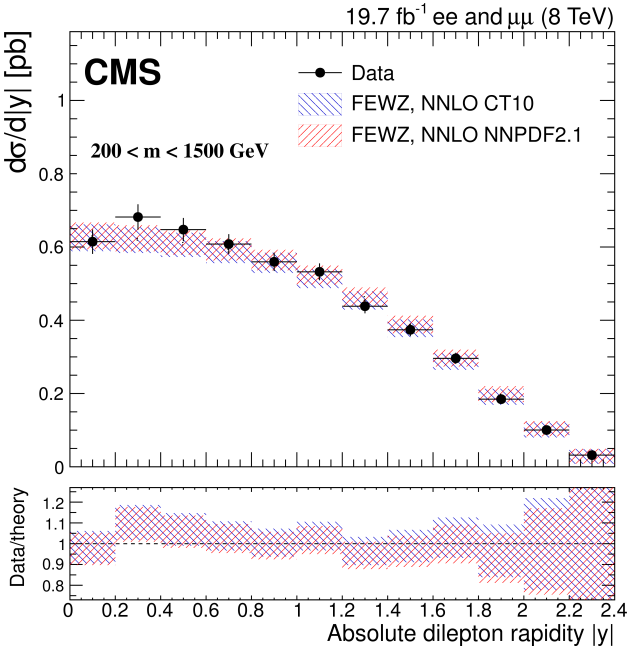
- pQCD, PDFs, background for ttbar, diboson, Higgs, BSM etc.

σ(meas.) = 1138 ± 8(exp.) ± 25(th.) ± 30(lum.) fb
σ(FEWZ, CT10) = 1137 ± 36(scale) fb

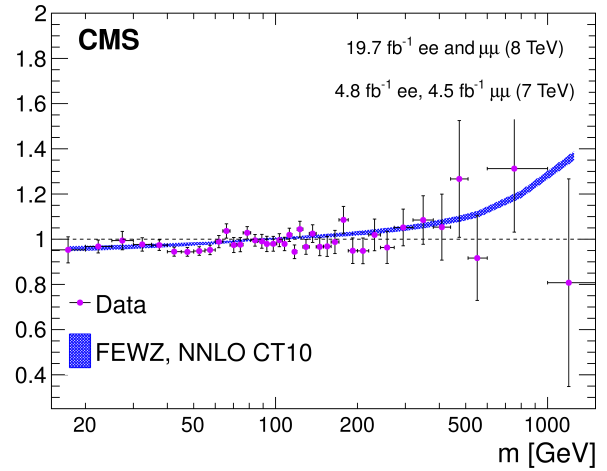
} ee and μμ comb. $60 < m_{ll} < 120$ GeV

Eur. Phys. J. C75 (2015) 147 8 TeV





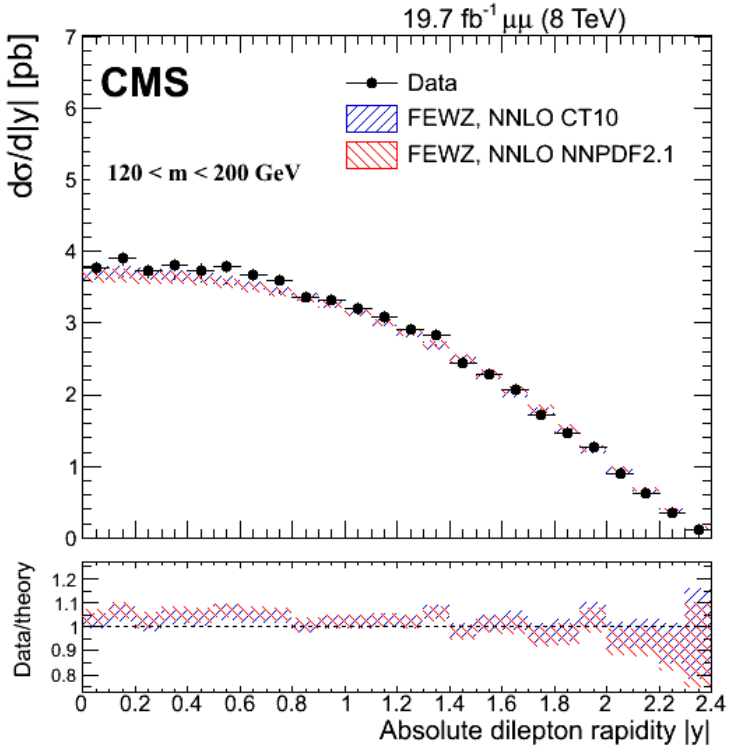
- Diff. dσ/dm, full phase space
- In agreement with the NNLO
- Double diff. $d^2\sigma/dmd|y|$, for six different mass ranges
- Low mass -> NNPDF2.1 NNLO
- Z peak -> both agree well
- High mass -> stat. uncert. at the order of PDF uncertainty

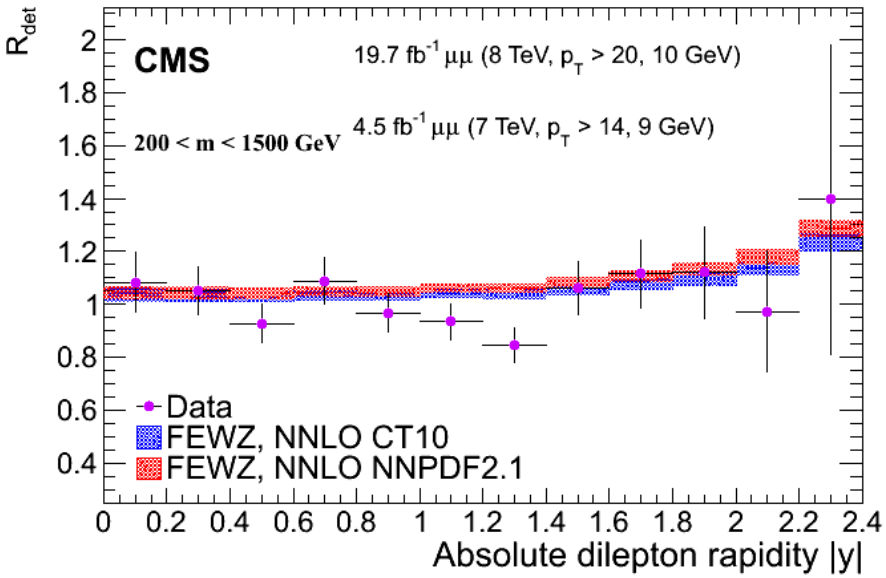


- Ratio of (double) diff. σ at 7 and 8 TeV -> NNLO QCD, PDFs

(Double) differential Drell-Yan σ at 8 TeV

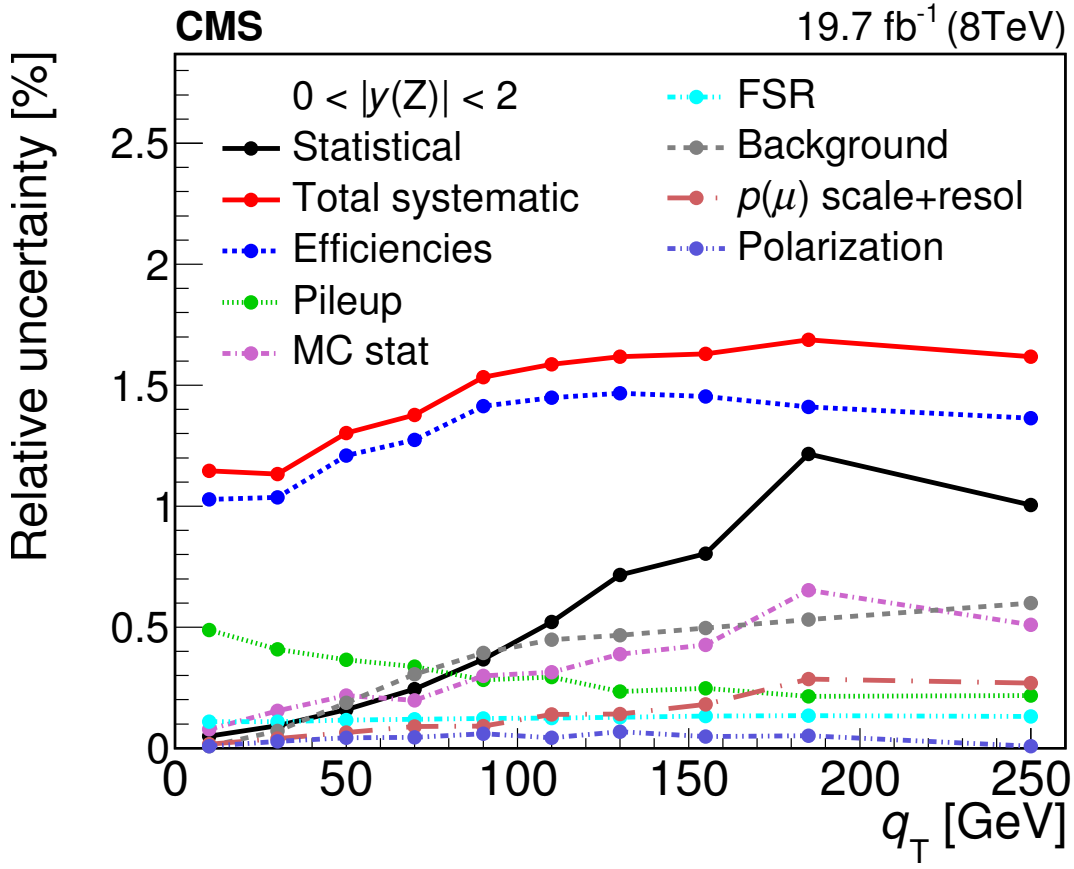
Eur. Phys. J. C75 (2015) 147 8 TeV





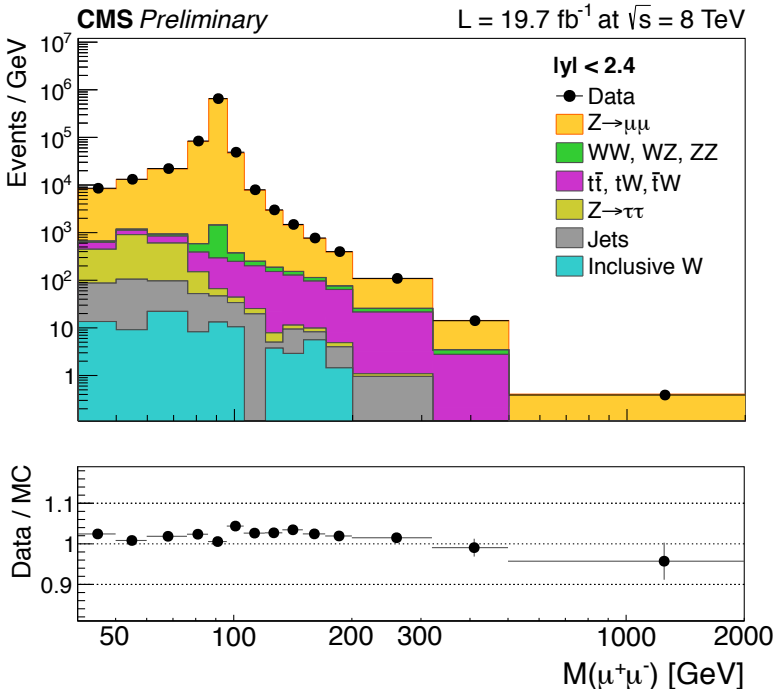
Z boson diff. σ in q_T and |y| at 8 TeV

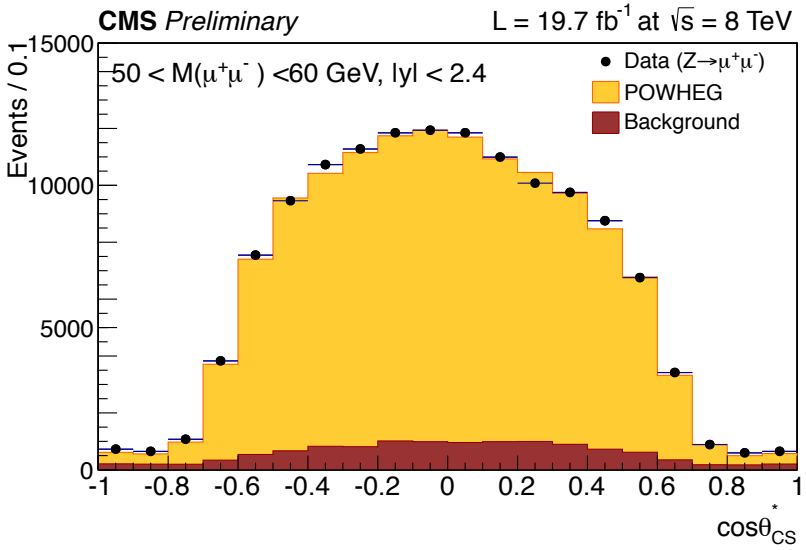
Phys. Lett. B 749 (2015) 187



DY forward-backward asymmetry at 8 TeV

CMS-SMP-14-004

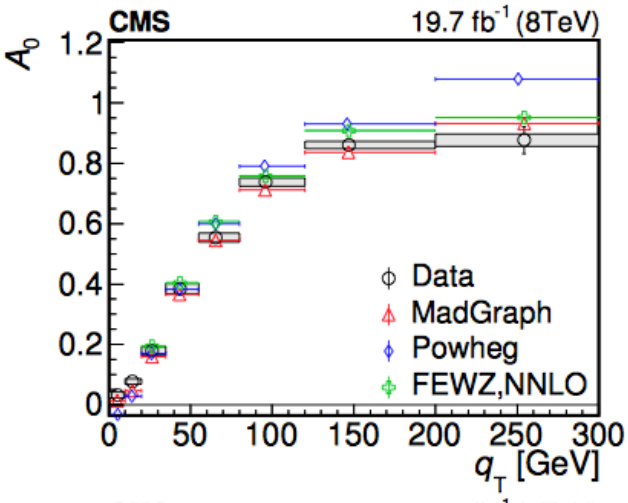


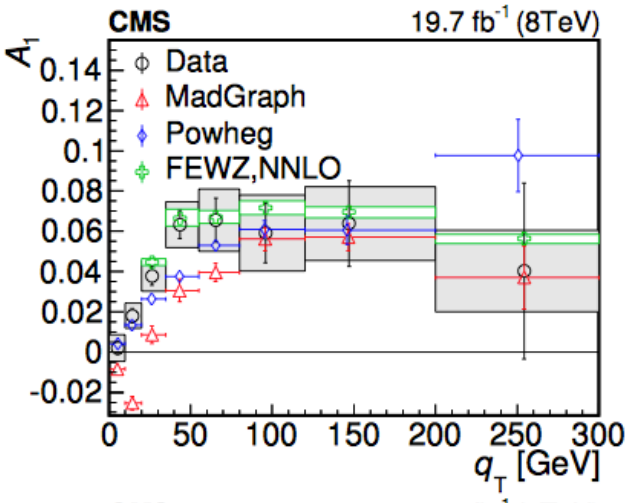


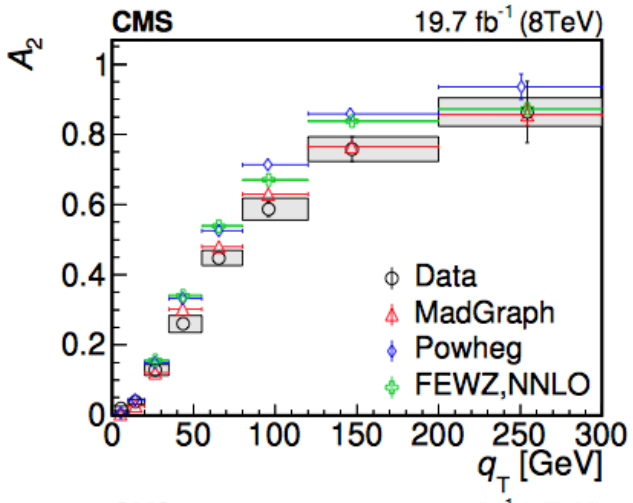
V boson: Z angular vars/coeff

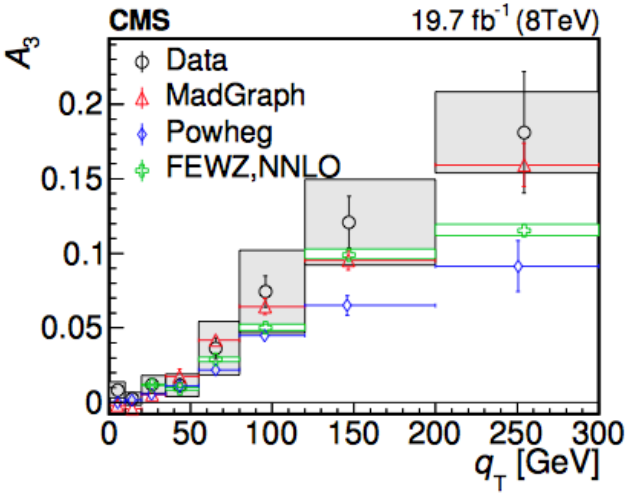
arXiv.1504.03512 Submitted to PLB

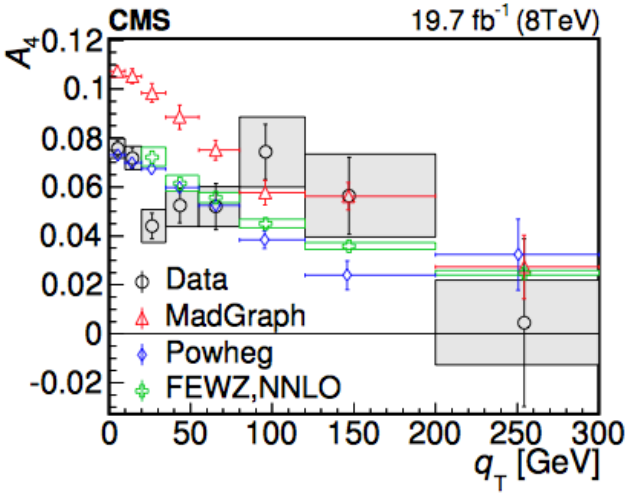
$1 < |y| < 2.1$

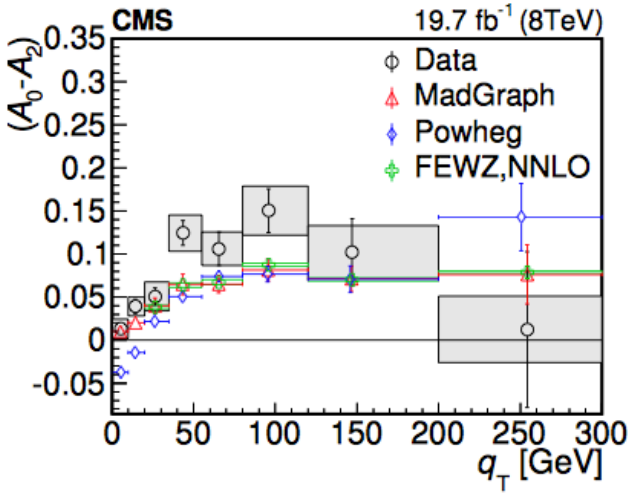






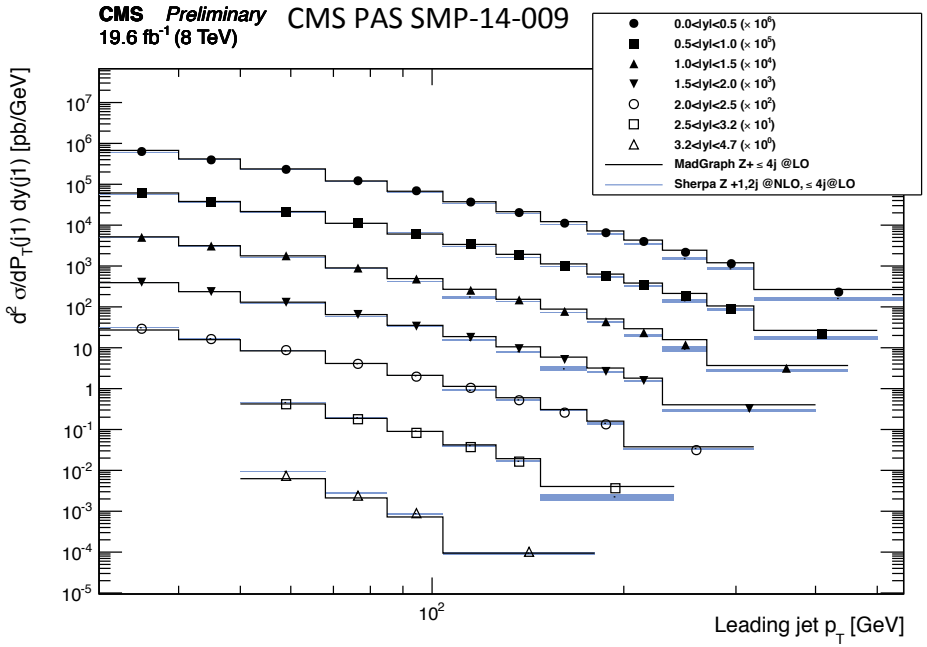






(Double) diff. Z+jets σ at 8 TeV

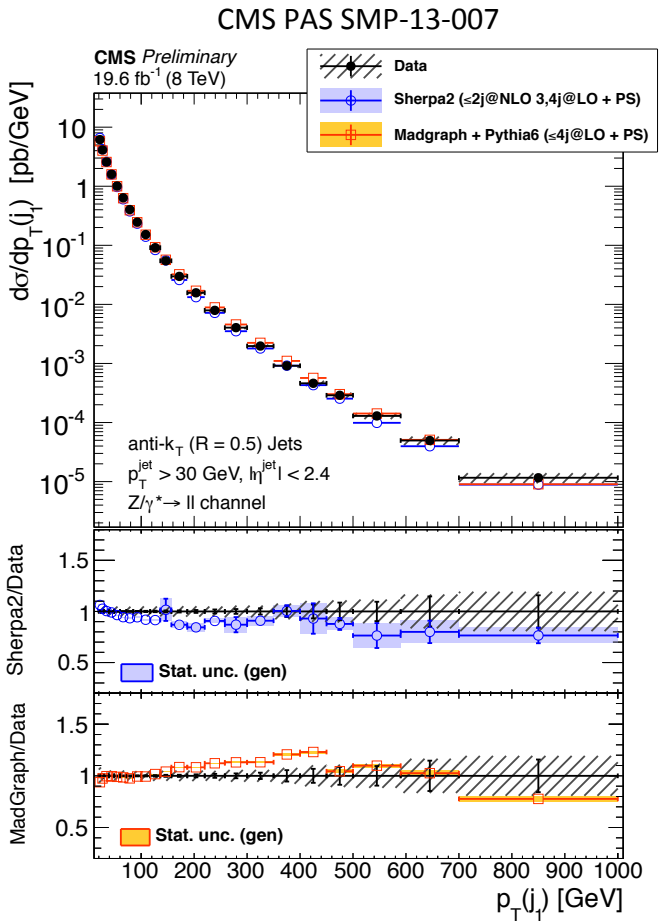
- Test pQCD, background for ttbar, VBF, WW, Higgs, SUSY
- Diff. σ measured as function of N_{jet}(exc./inc.), p_T, H_T, $|\eta|$
- MadGraph: $p_{T,jet\ 1}$ excess in 150-450 GeV, as was in 7 TeV
- SHERPA 2: slightly harder spect., diff. prediction at low p_T



Double diff. in p_T and $|\eta|$

Z-> μμ

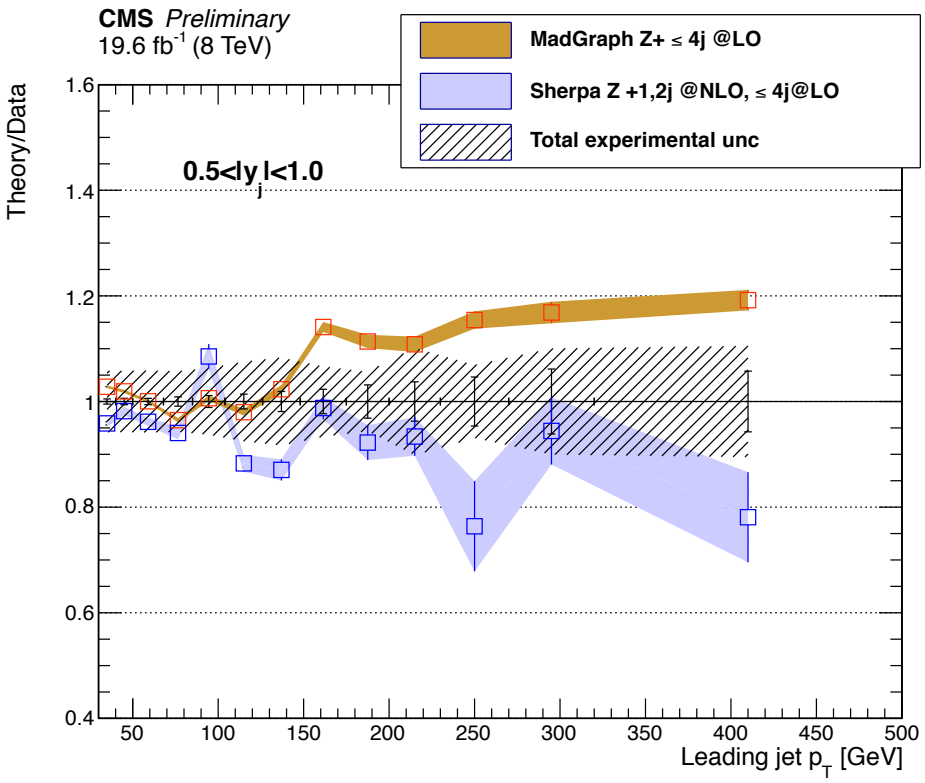
$|\eta| < 4.7$



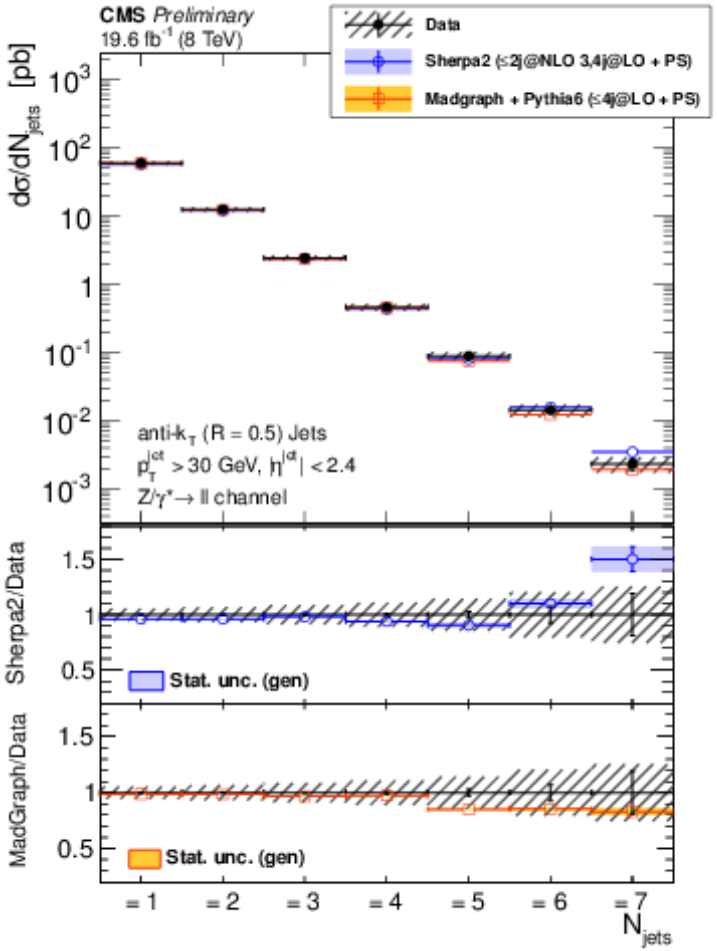
- MadGraph: 10% disagr. for $p_{T,jet\ 1} < 100$ GeV
- SHERPA 2: good agr., disrc. in few $p_{T,jet\ 1}$ bins

(Double) diff. Z+jets σ at 8 TeV

CMS PAS SMP-14-009

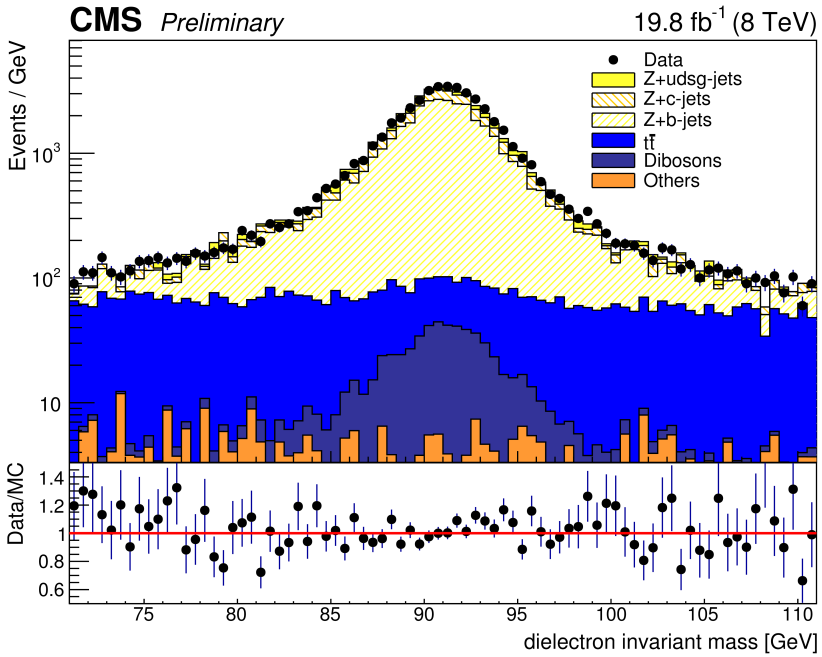


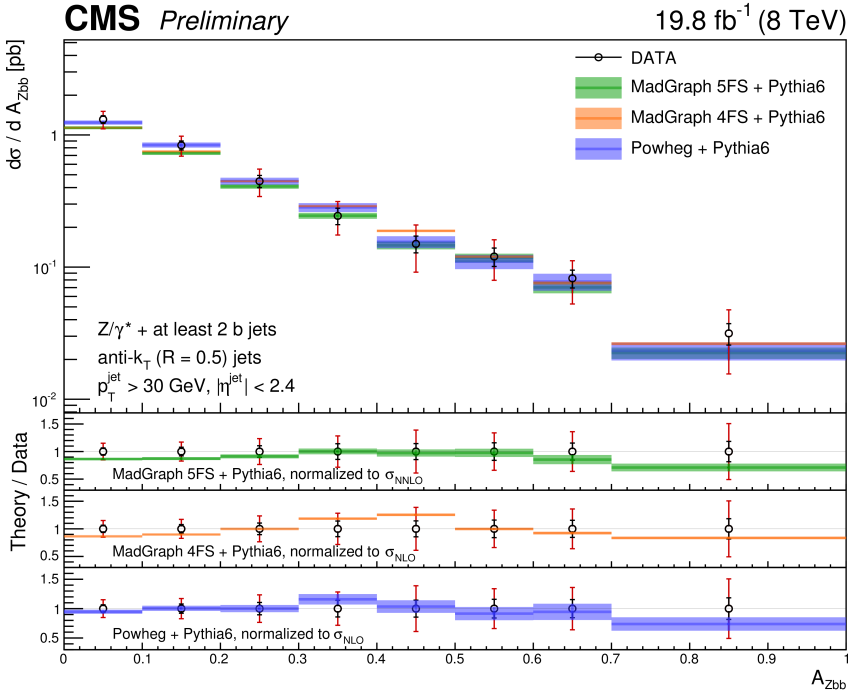
CMS PAS SMP-13-007



Production of Z boson with b jets at 8 TeV

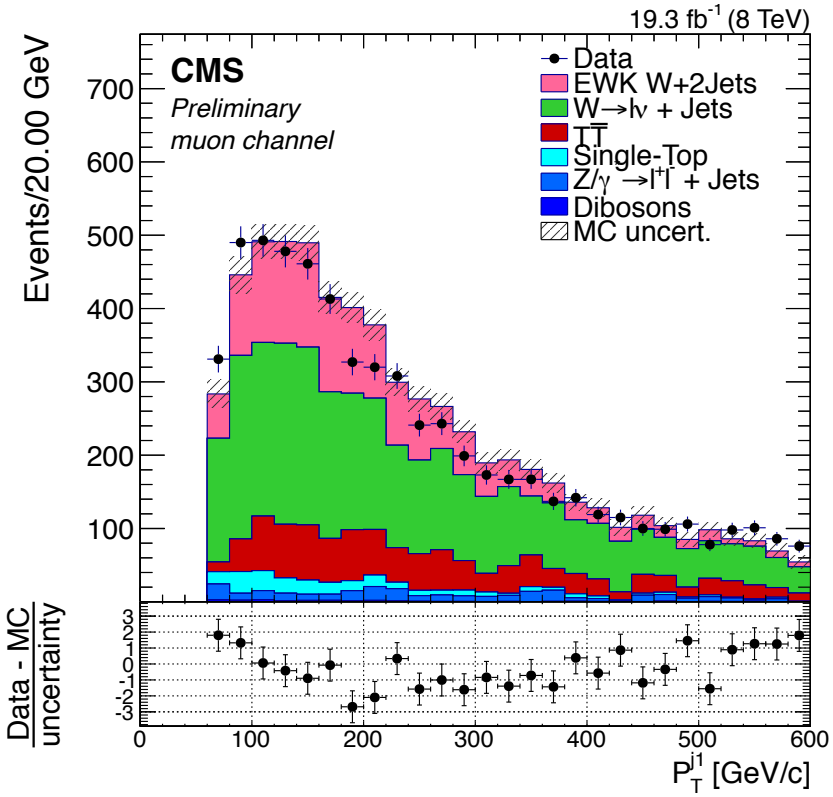
CMS-PAS-SMP-14-010

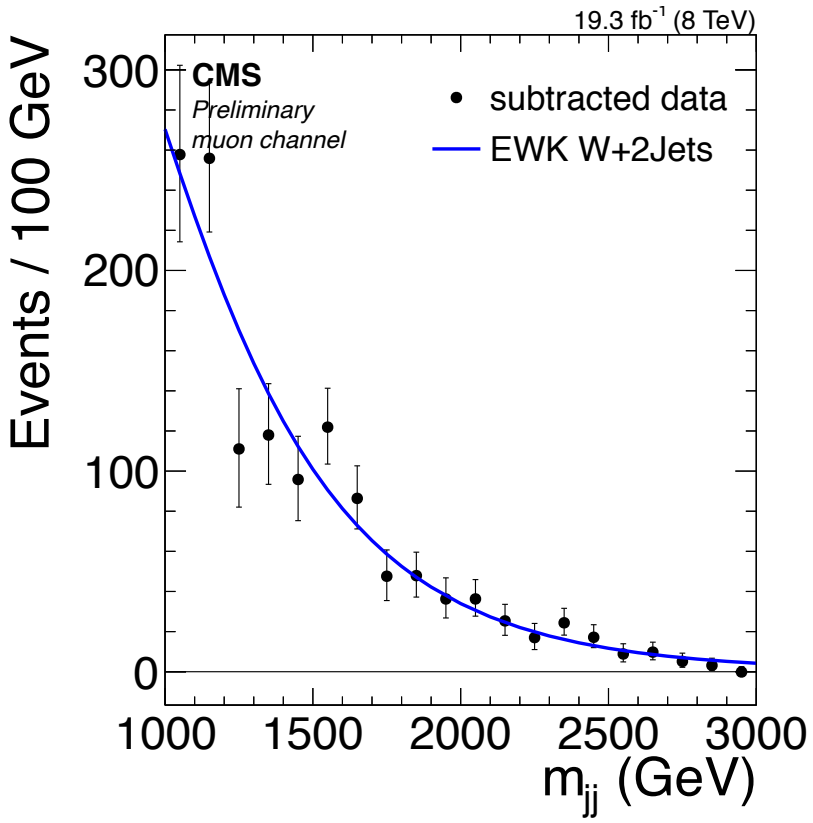




EWK (VBF) W production σ at 8 TeV

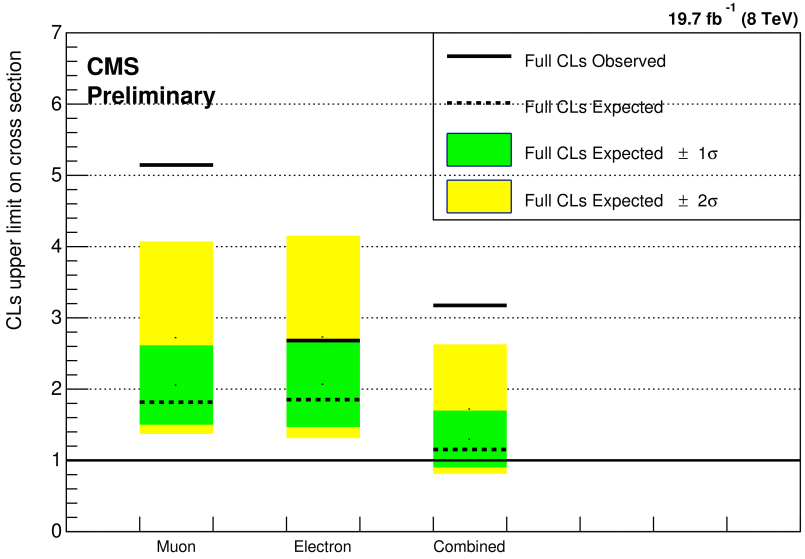
CMS-SMP-13-012

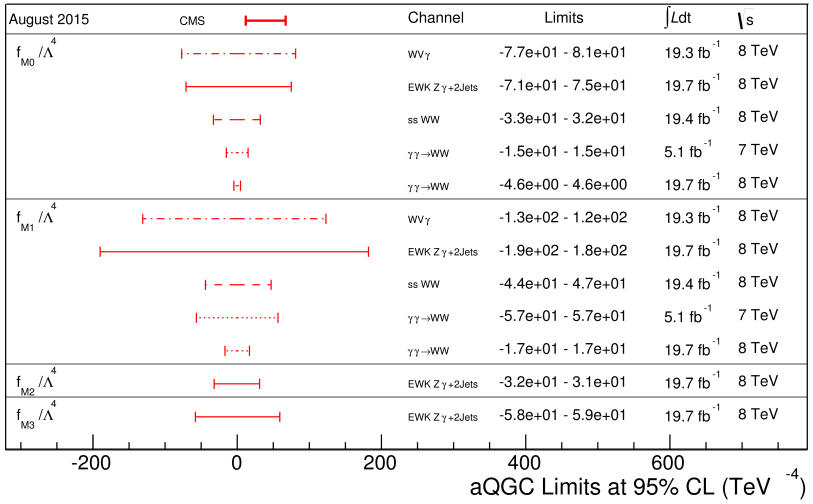


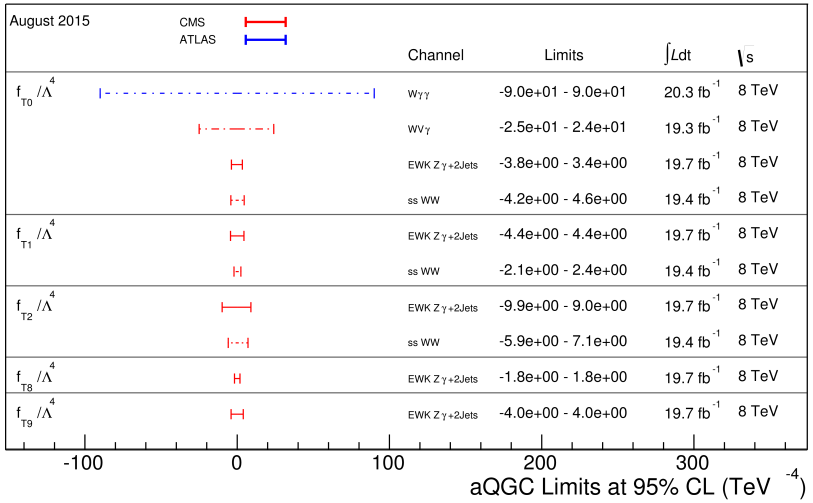


Evidence for EWK Zγ and aTGC search at 8 TeV

SMP-14-018

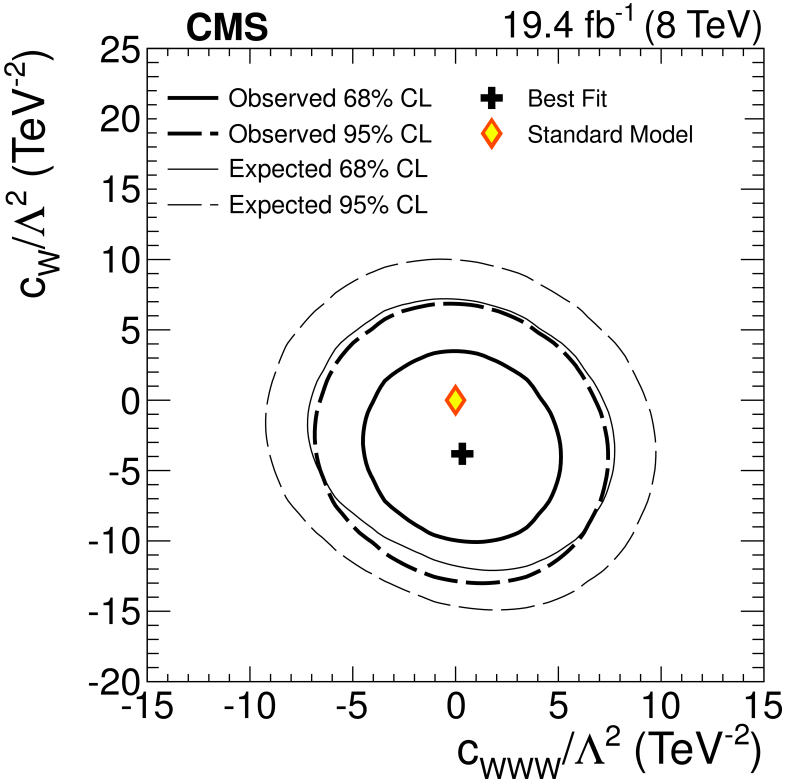


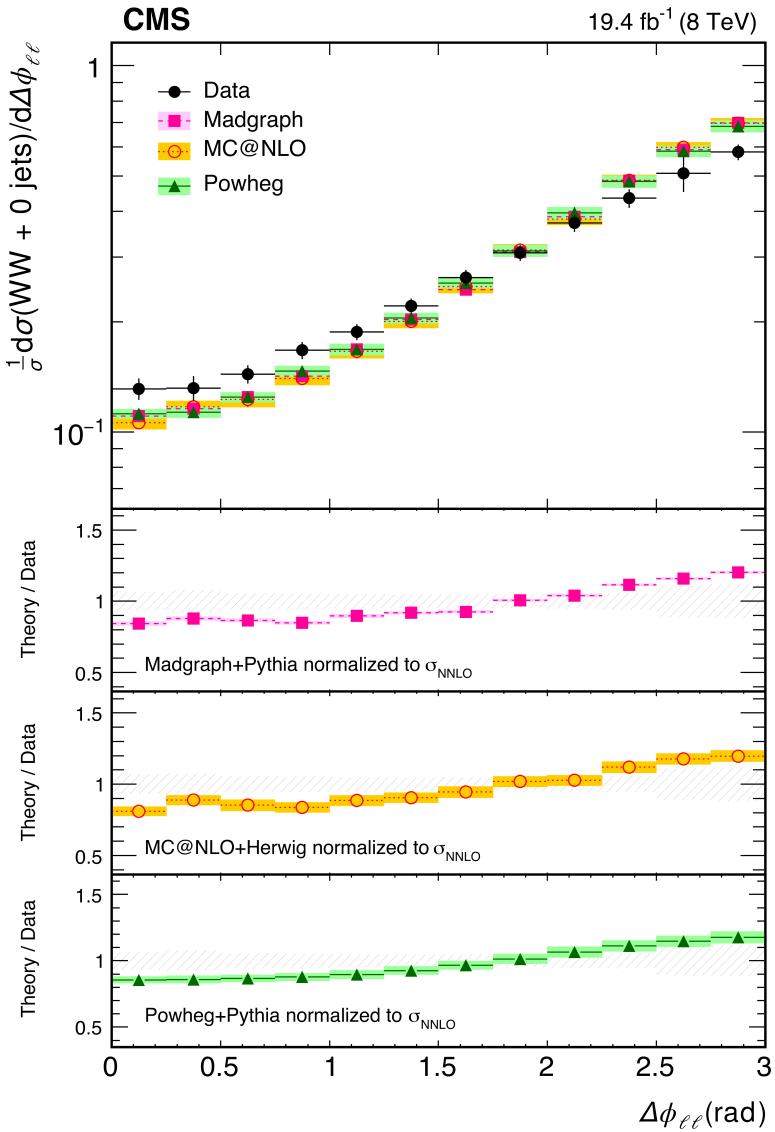




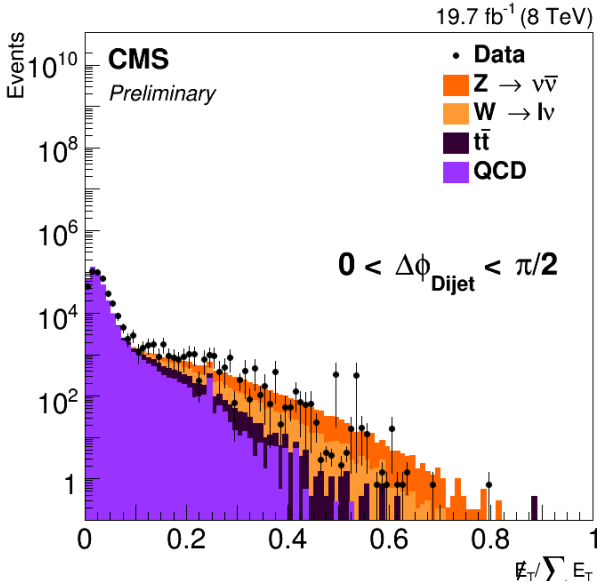
W^+W^- production σ and aTGC at 8 TeV

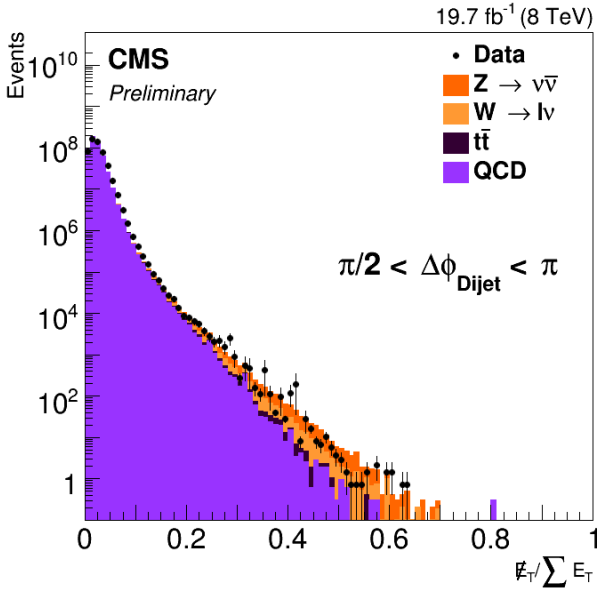
arXiv:1507.03268



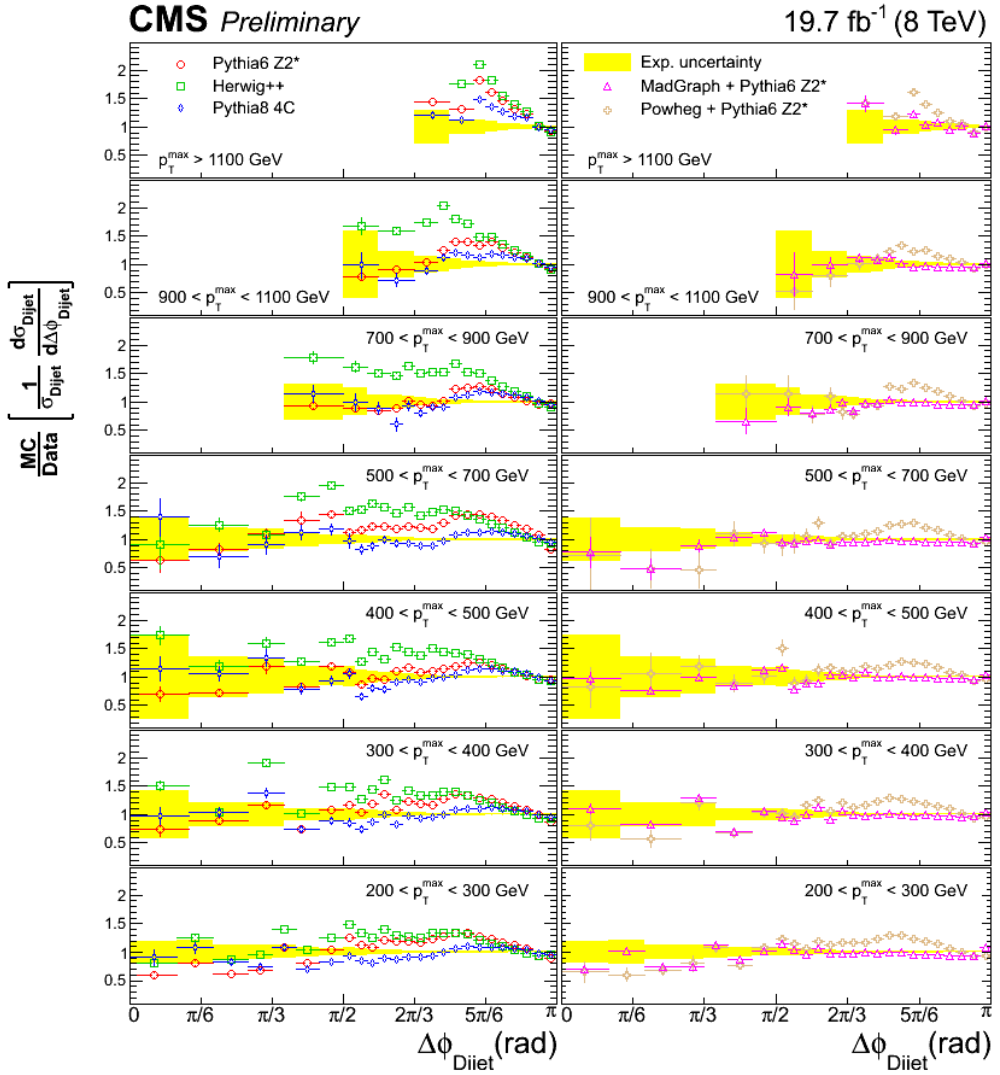


Dijet azimuthal decorrelations at 8 TeV



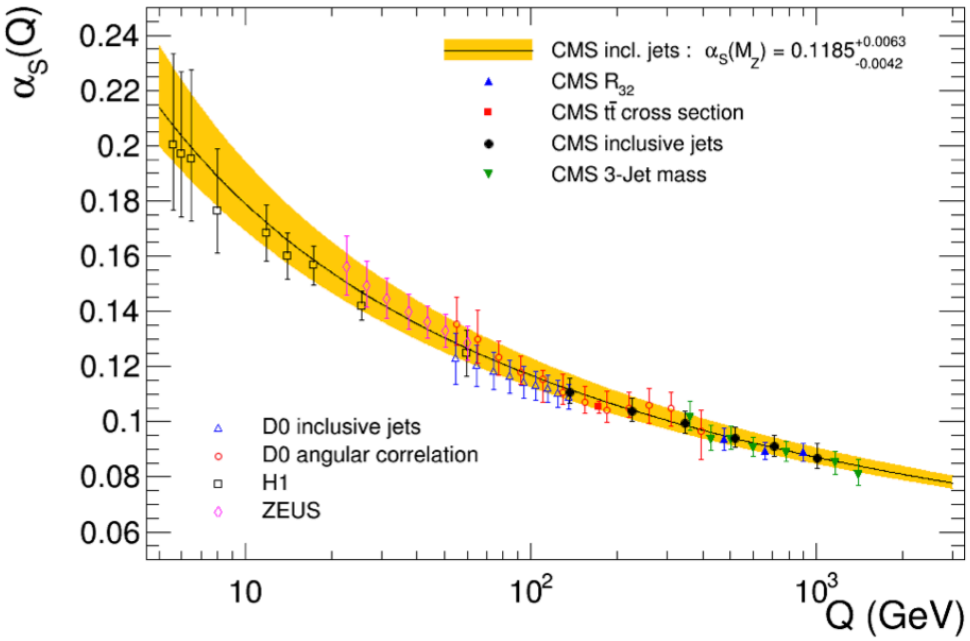


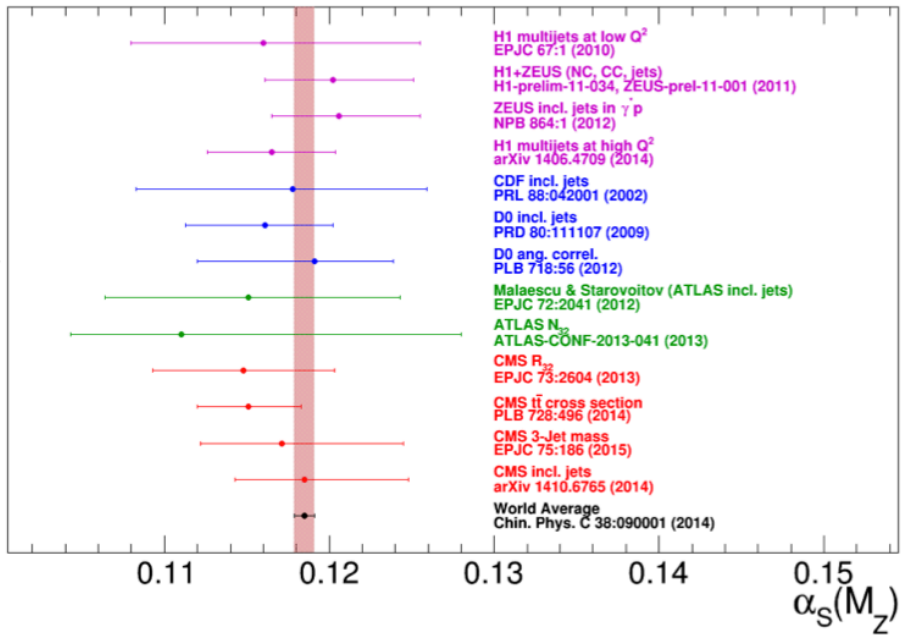
CMS-PAS-SMP-14-015



Jets: Running α_S summary

Eur. Phys. J. C 75 (2015) 288





η distribution of charged hadrons at 13 TeV

arXiv:1507.05915, Subm. to Phys. Lett. B