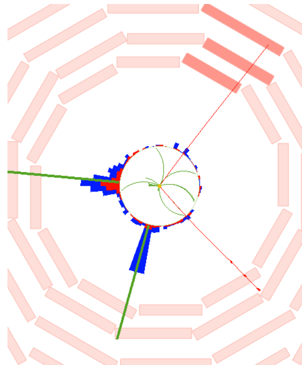
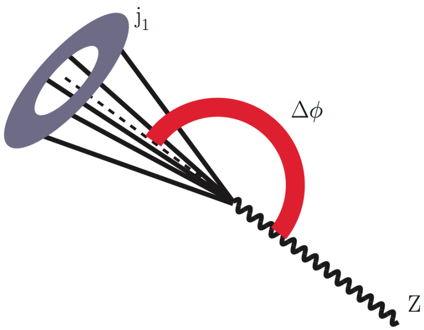
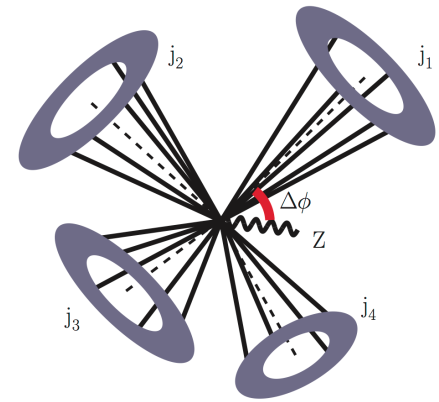


V+jets production at the CMS





Buğra BİLİN

METU Ankara, Turkey

on behalf of CMS Collaboration

Jet vetoes and multiplicity observables

2016, IPPP Durham, United Kingdom

MOTIVATION

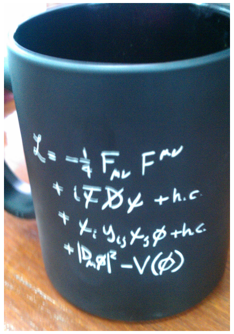
→Processes involving W & Z boson production are of the best understood processes at hadron colliders

→W->lν , Z->ll, (l=e,μ) are among the cleanest final states experimentally

→Test of perturbative QCD

→Precision measurements are sensitive to BSM effects.

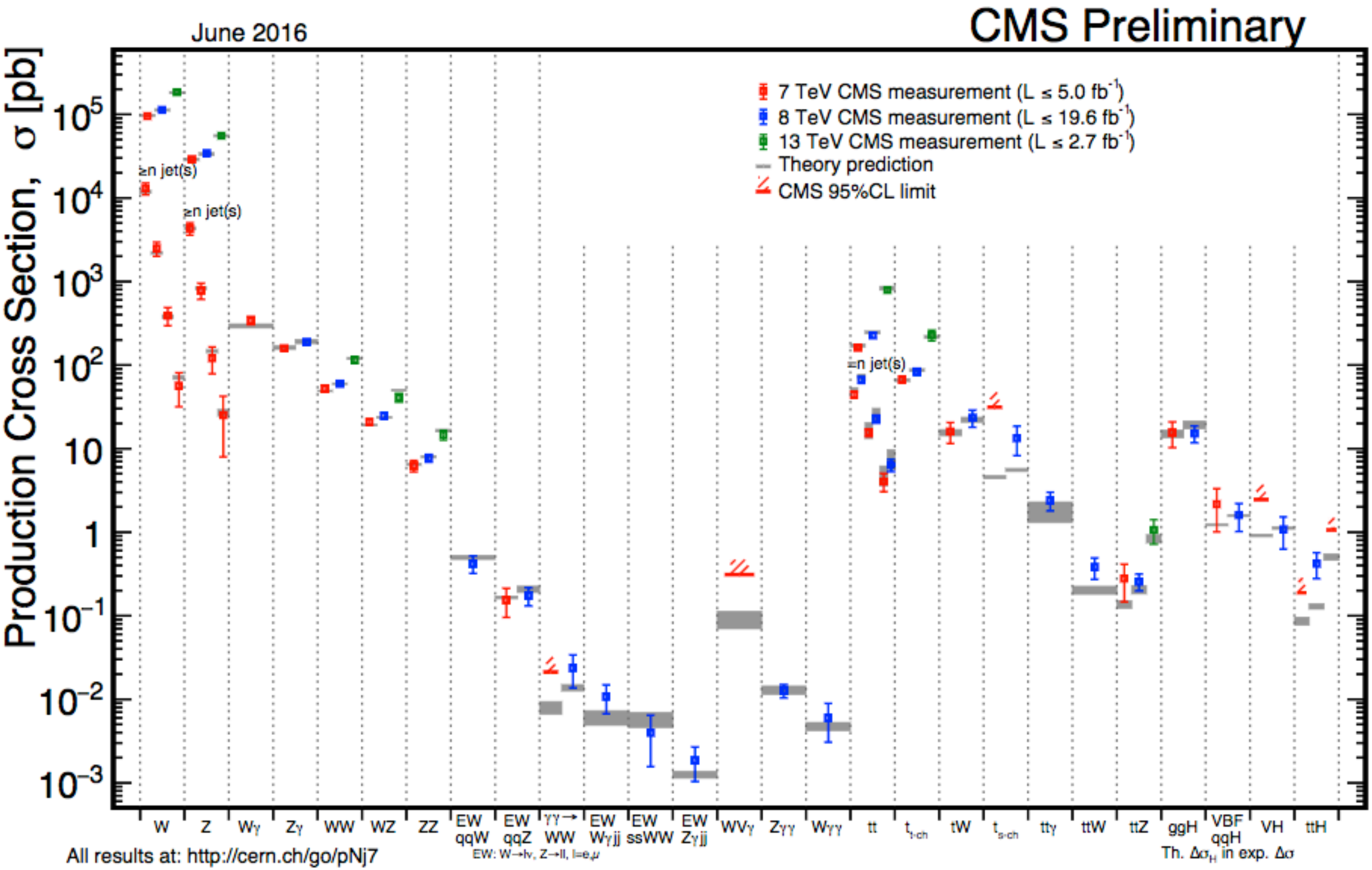
→Provide constraints to PDFs



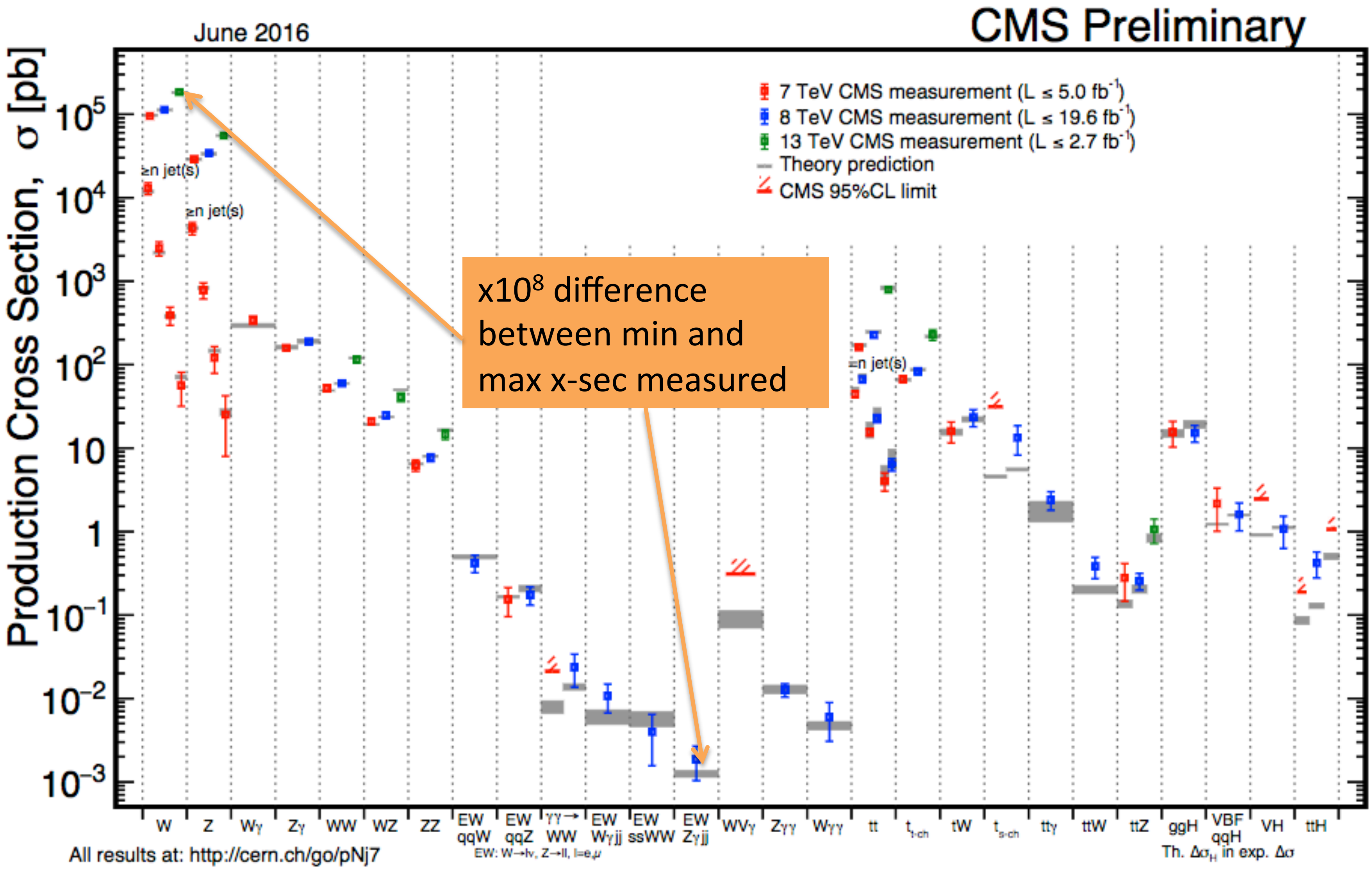
→Improve MC generators

→Backgrounds to New Physics & Higgs Searches

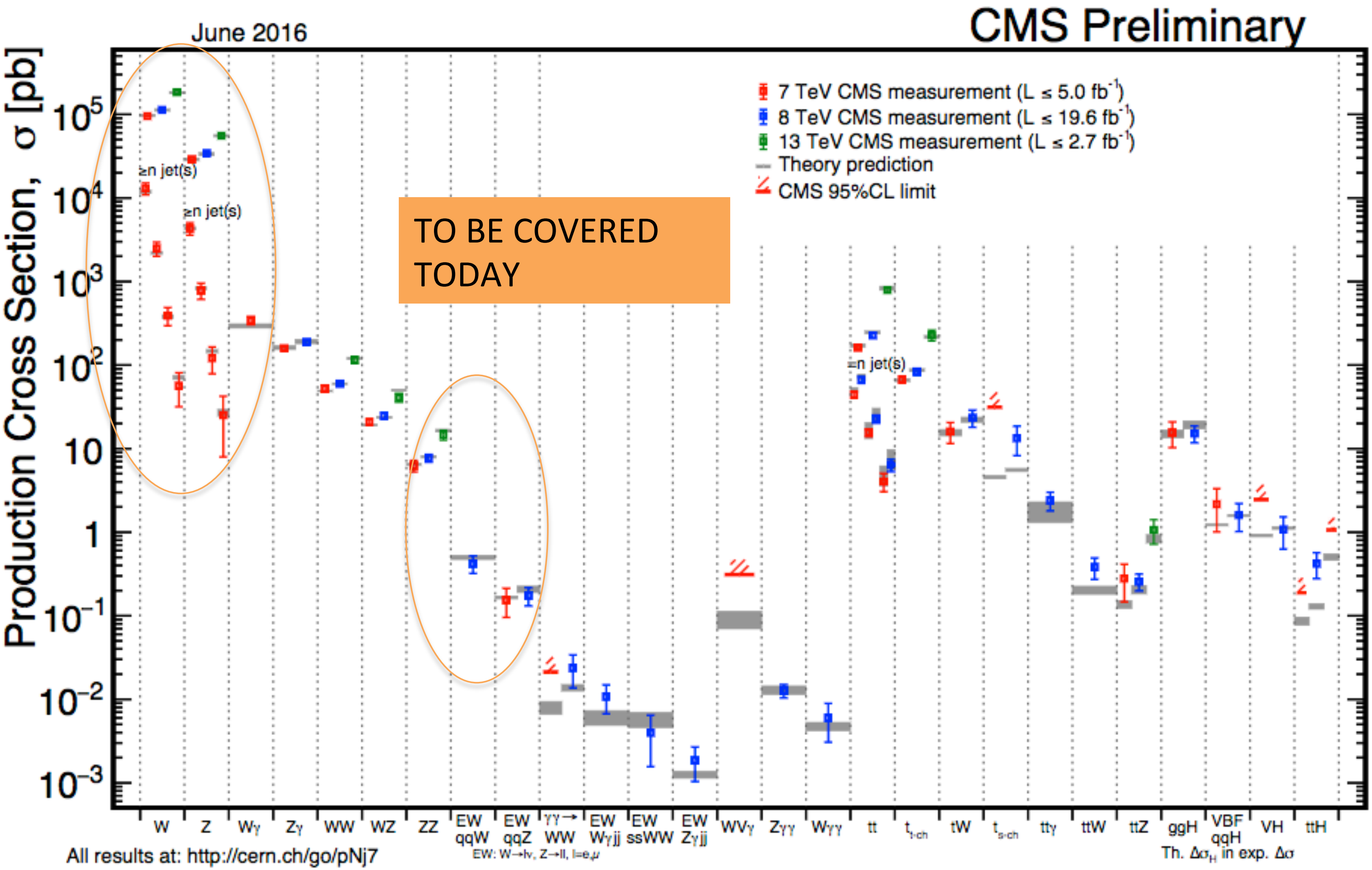
Status by June 2016



Status by June 2016



Status by June 2016



CONTENT

- →Z+jets differential x-sec measurement at 7 TeV(PRD 91 (2015) 052008)
- →Z+jets differential x-sec measurement at 8 TeV (PAS-13-007,14-009)
- →Z+jets differential x-sec measurement at 13 TeV(PAS-15-010)
- →W+jets differential x-sec measurement at 7 TeV(PLB 741 (2015) 12)
- →W+jets differential x-sec measurement at 8 TeV (PAS-14-023)
- →W+jets differential x-sec measurement at 13 TeV(PAS-16-005)
- →ZZ+jets differential x-sec measurement at 8TeV(PAS-15-012)
- →Z+jets, azimuthal correlations and event shape (PLB 722 (2013) 238–261)
- →Electroweak Z + forward-backward jets production at 7 TeV(JHEP 10 (2013) 101)
- →Electroweak Z + forward-backward jets production at 8 TeV(EPJ. C 75 (2015) 66)
- →Electroweak W + forward-backward jets production at 8 TeV(arXiv:1607.06975)
- →Measurement of Z + b jet at 8 TeV (PAS-SMP-14-010)
- →Measurement of Z + c jet at 8 TeV (PAS-SMP-15-009)
- →Measurement of W + bb jet at 8 TeV (PAS-SMP-14-020)
- →Z+ b, bb jet cross sections at 7 TeV (JHEP 06 (2012) 126, JHEP 06 (2014) 120)
- →W+bb cross section at 7 TeV (PLB 735 (2014) 204)
- →W+c differential cross section at 7 TeV (JHEP 02 (2014) 013)
- →Z+bb jets, b hadron angular correlations at 7 TeV (JHEP 12 (2013) 039)
- →Z+1 jet and photon+1 jet rapidity distributions (PRD 88 (2013) 112009)
- →Photon+jets differential cross section (JHEP 06 (2014) 009)
- →Z+jet γ+jet comparison at 8 TeV (JHEP 10 (2015) 128)
- →Double parton scattering in W+jets (JHEP 03 (2014) 032)
- →W+2 jets, dijet mass spectrum (PRL 109 (2012) 251801)

16 publications, 9 preliminary results (Physics Analysis ummaries)

Phys. Rev. D 91 (2015) 052008, Phys. Lett. B 741 (2015) 12, PAS-SMP-13-007, 14-009, 14-023, 15-010, 16-005

p-p √s=7 ,8 &13 TeV
5, 19.8 & 2.5 fb^{-1}

V (W,Z) + jets

→Z boson decaying to pair of leptons is almost background-free.

→Important to study V+jets production:

- →Backgrounds for many SM processes and BSM signals.
- → To test beyond LO theory predictions and new parton shower algorithms.

→Various kinematic properties of jets produced with W and Z boson production are studied.

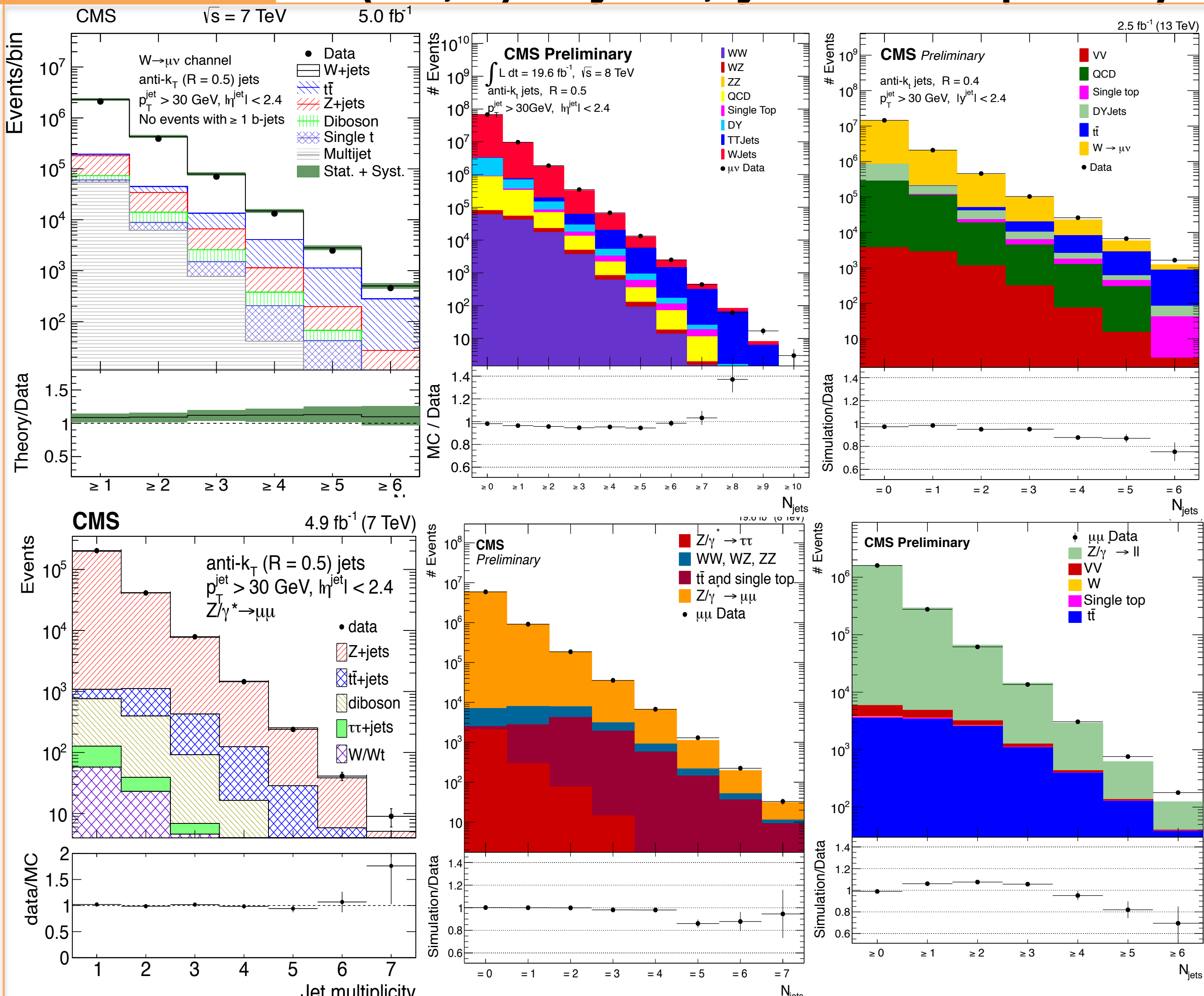
- →N_{jets}, p_T, y (or η), H_T,Δy, ΔR, $\Delta\varphi$,$M(jj)$...

Phys. Rev. D 91 (2015) 052008, Phys. Lett. B 741 (2015) 12,
PAS-SMP-13-007, 14-009, 14-023, 15-010, 16-005

p-p √s=7 ,8 &13 TeV
5, 19.8 & 2.5 fb^{-1}

Detector level

V (W,Z) + jets, jet multiplicity



→ Jet multiplicity well described by the MC generators,
~ in all cases
→ Up to the level of ME calculations

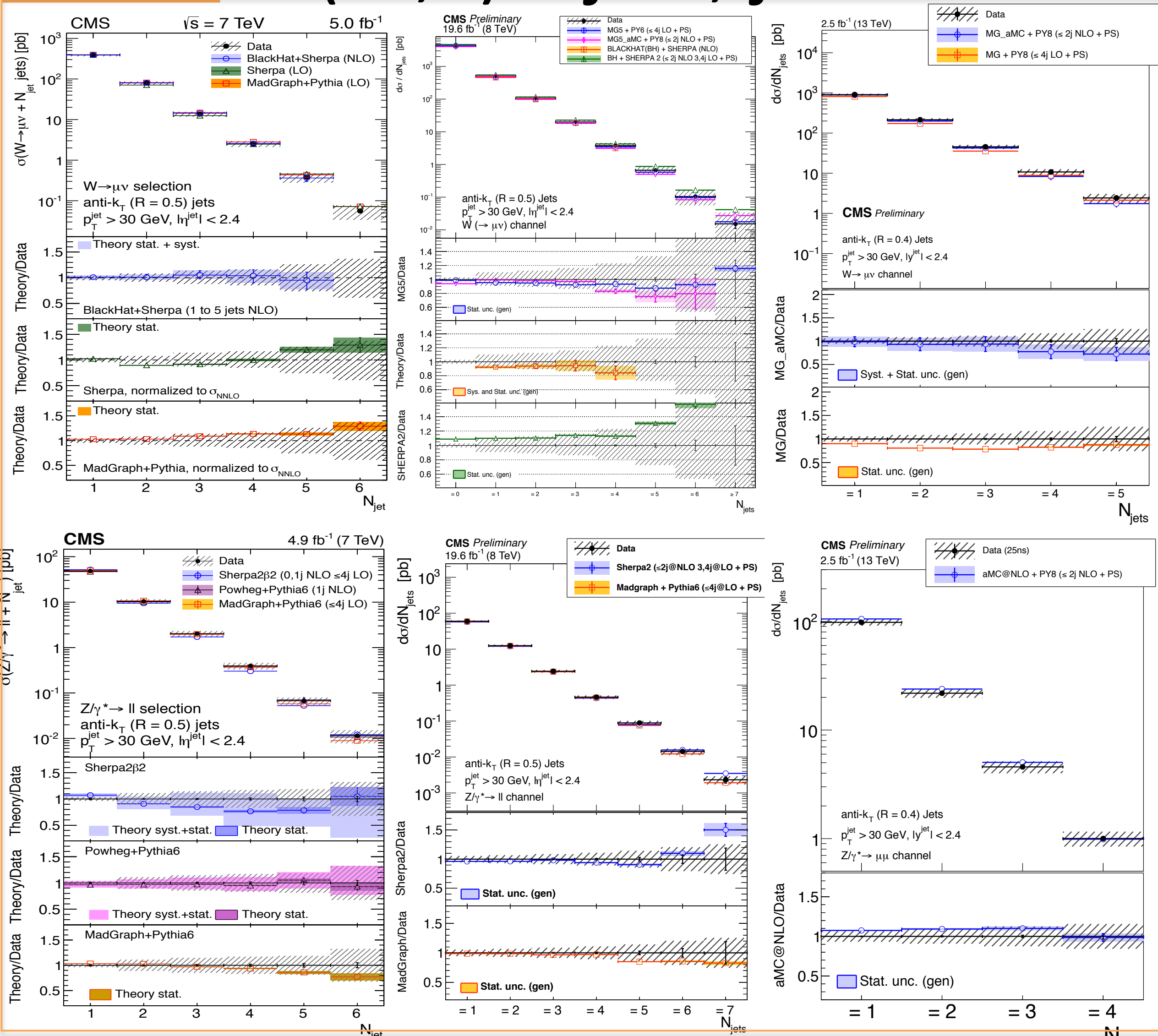
→ Wjet measurements are carried out with vetoing events with b-jets
→ Surpress tt bkg.

Phys. Rev. D 91 (2015) 052008, Phys. Lett. B 741 (2015) 12, PAS-SMP-13-007, 14-009, 14-023, 15-010, 16-005

p-p √s=7 ,8 &13 TeV
5, 19.8 & 2.5 fb^{-1}

Unfolded

V (W,Z) + jets, jet multiplicity



→ Corrected to particle level for detector efficiencies and smearing effects

→ Jet multiplicity well described by the MC generators, ~ in all cases

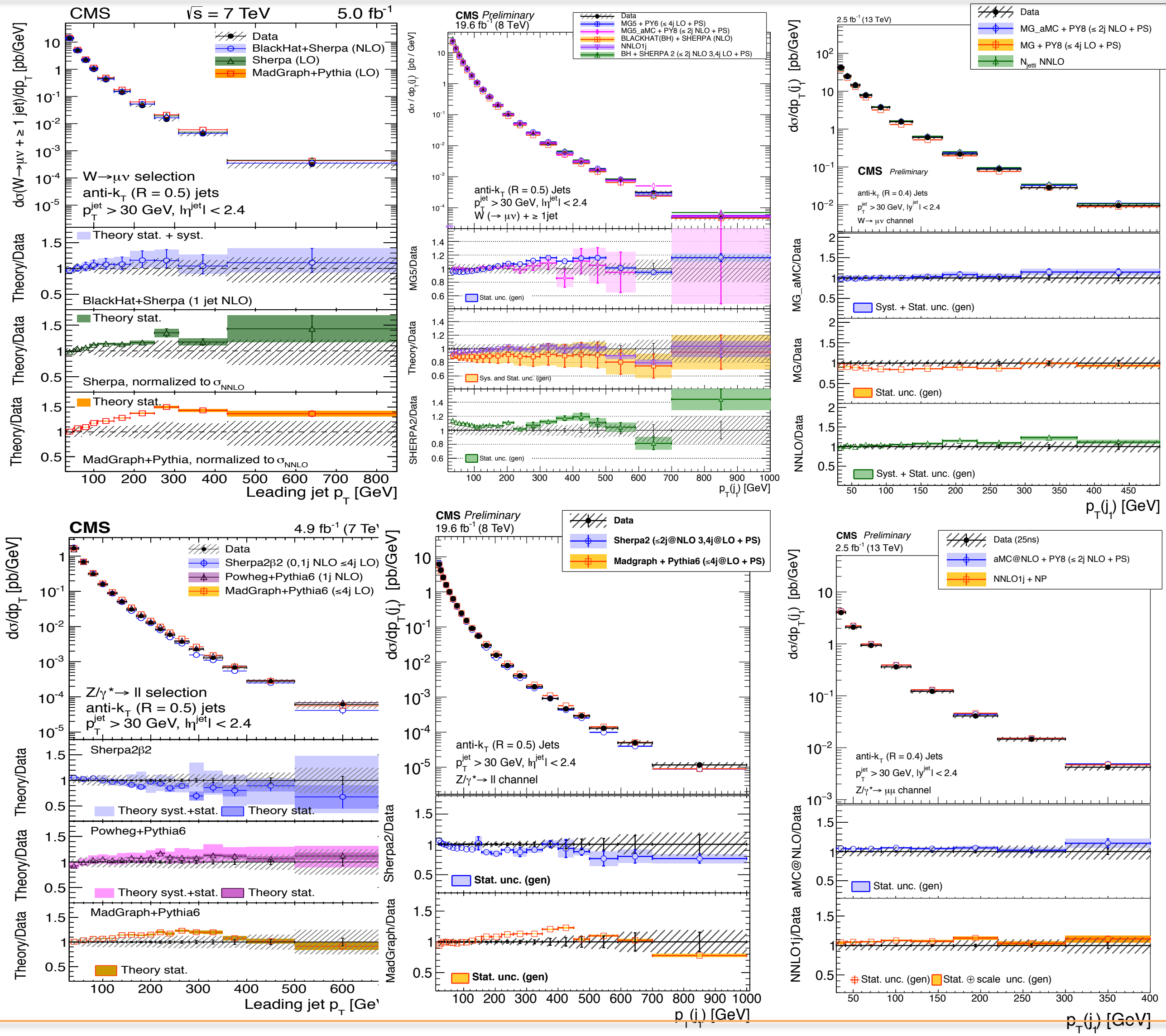
→ Up to the level of ME calculations

Phys. Rev. D 91 (2015) 052008, Phys. Lett. B 741 (2015) 12, PAS-SMP-13-007, 14-009, 14-023, 15-010, 16-005

p-p √s=7 ,8 &13 TeV
5, 19.8 & 2.5 fb^{-1}

Unfolded

V (W,Z) + jets, jet 1 pT



→ Leading order MG+py6 predictions fail to describe jet pT

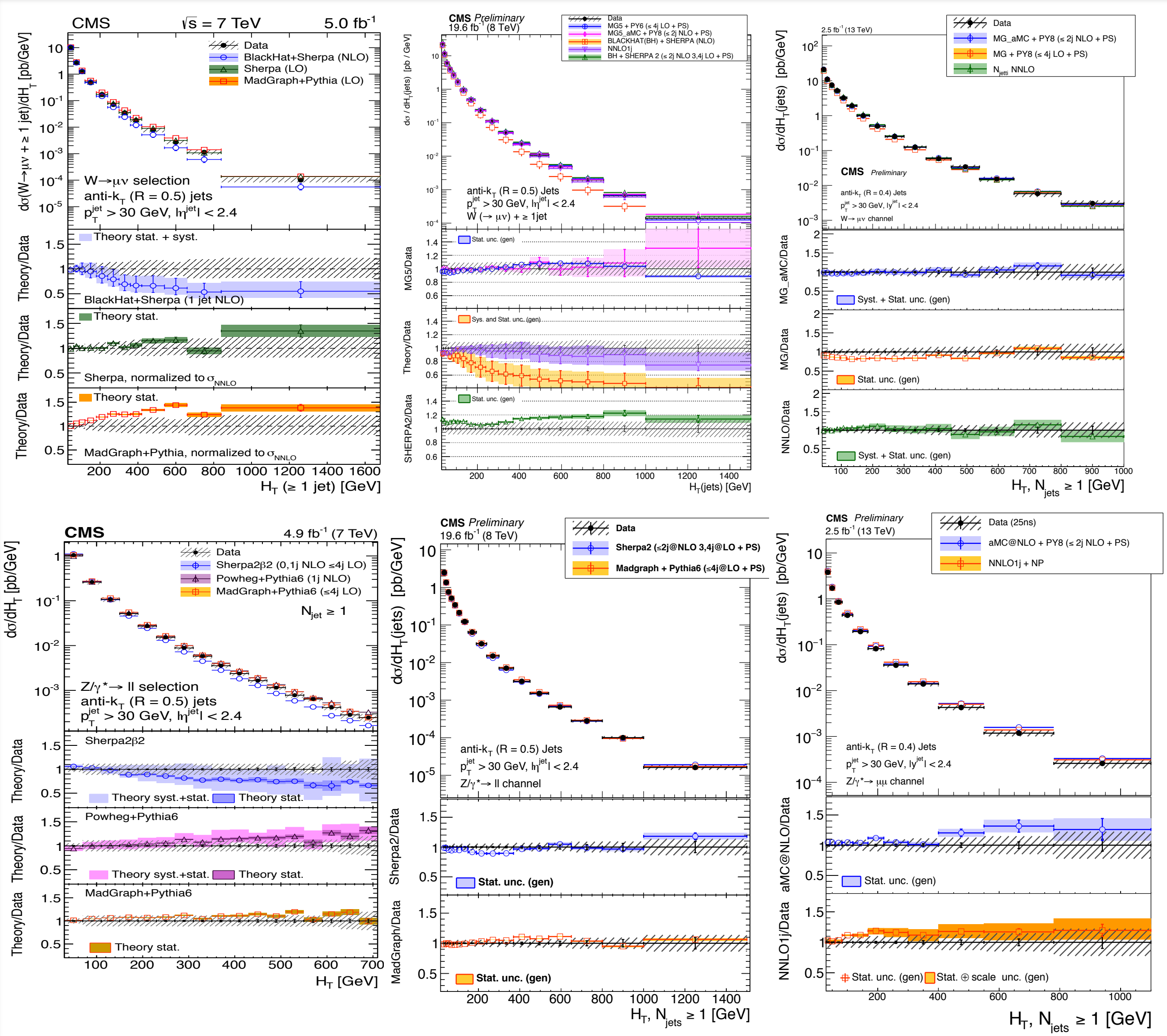
→ Better description with (N)NLO calculations

Phys. Rev. D 91 (2015) 052008, Phys. Lett. B 741 (2015) 12,
PAS-SMP-13-007, 14-009, 14-023, 15-010, 16-005

p-p √s=7 ,8 &13 TeV
5, 19.8 & 2.5 fb^{-1}

Unfolded

V (W,Z) + jets, H_T



→ Leading order MG +py6 predictions fail to describe jet p_T, reflecting also to H_T

→ Better description with (N)NLO calculations

→ BH + Sherpa predicts softer H_T (W+j)

PAS-SMP-14-009

p-p √s=8 TeV
19.8 fb^{-1}

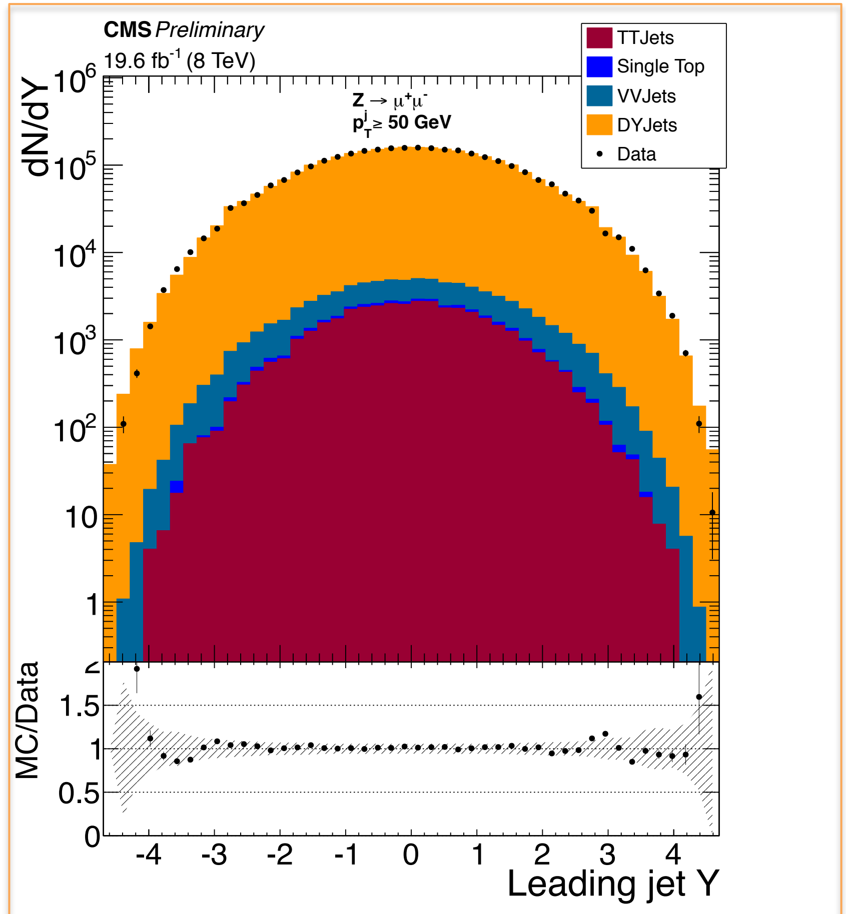
Z + jets, Double differential x-sec

→ Large amount of Z+jet events in data allows for multi differential cross section measurements

→ As an extension to SMP-13-007, double differential Z+jet x-sec is measured

→ $d^2\sigma/dp_T(j)dY(j)$

→ Extending the measurement for forward jets |y|<4.7

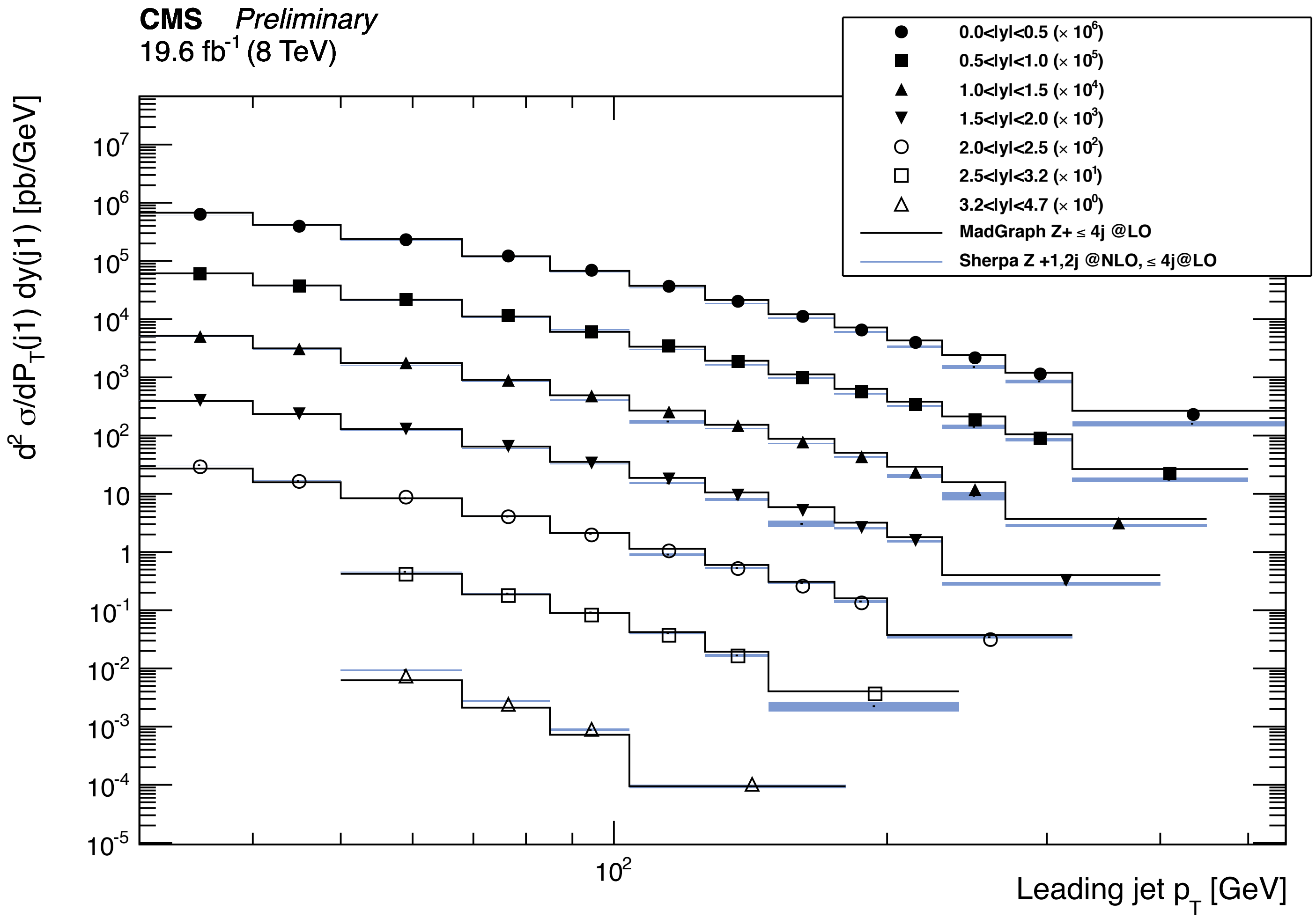


PAS-SMP-14-009

p-p √s=8 TeV
19.8 fb^{-1}

Z + jets, Double differential x-sec

Unfolded

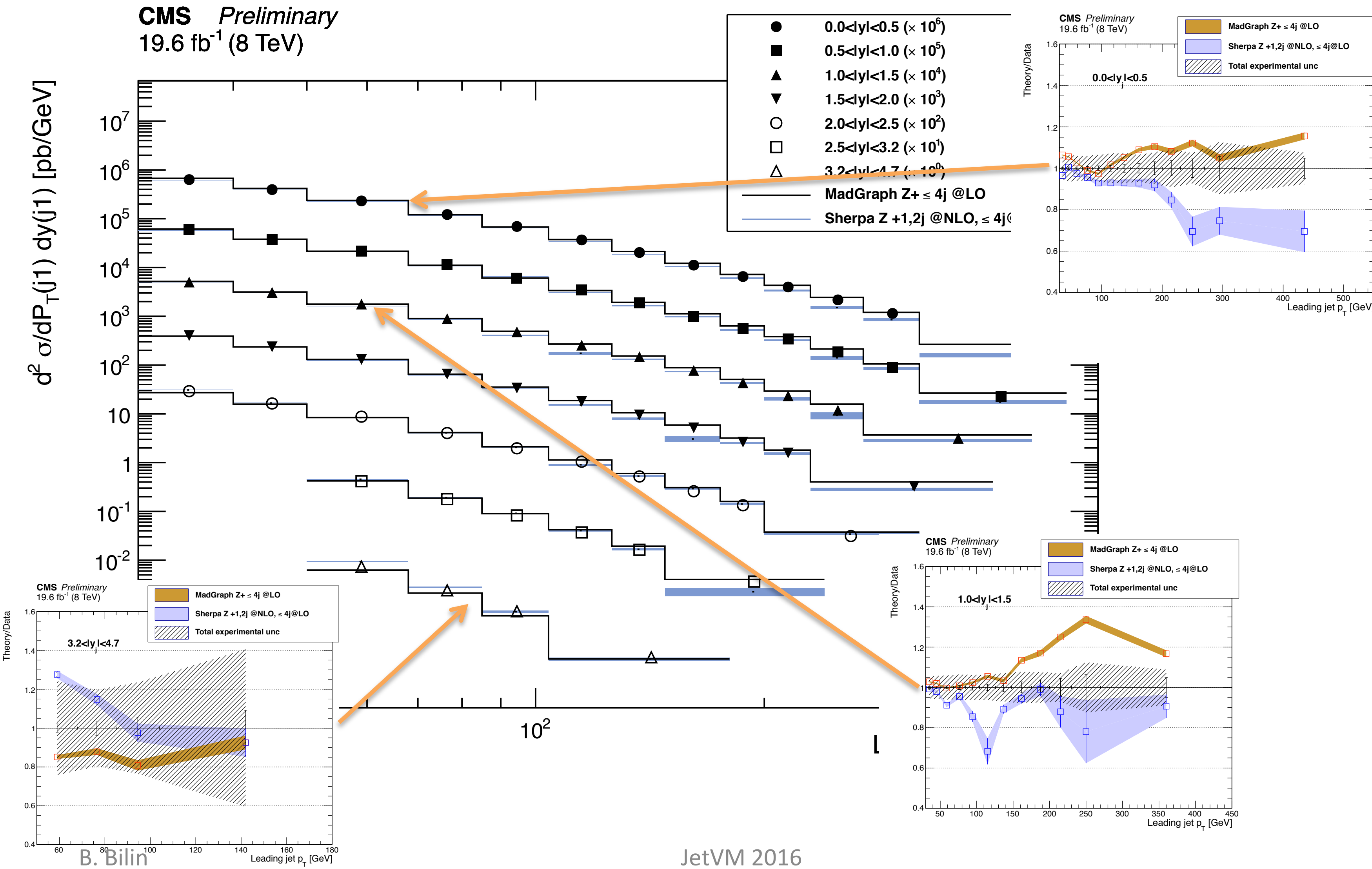


$d^2\sigma/dp_T(j)dY(j)$

Compared with
→ Madgraph+py6
→ Sherpa2.0

p-p √s=8 TeV
19.8 fb^{-1}

Z + jets,
Double differential x-sec



PAS-SMP-15-012

ZZ + jets

p-p $\sqrt{s}$=8 TeV
19.8 fb^{-1}

→Jet properties produced with ZZ pairs decaying into 4l is measured
- →As an extension of aTGC measurement (PLB 740 (2015) 250-272)

→First measurement of ZZ cross section in exclusive jet multiplicity

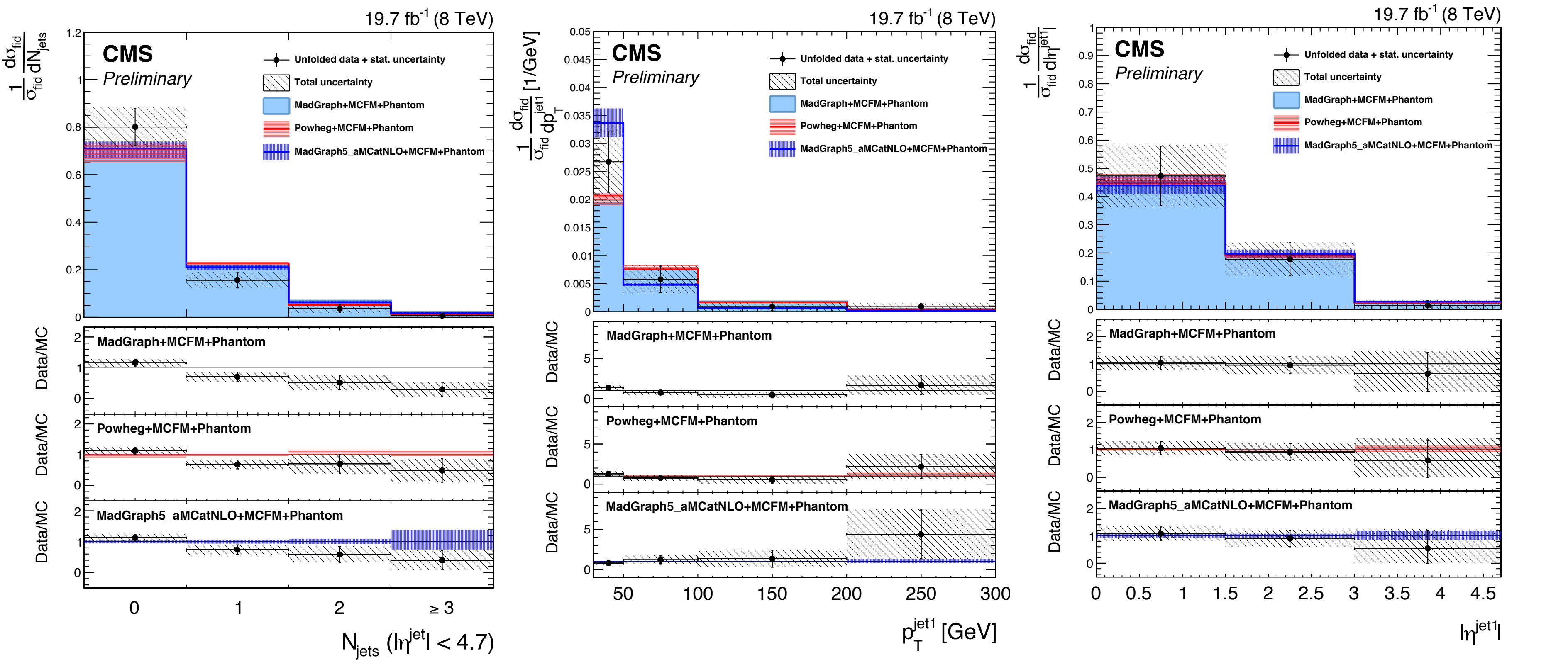
→Extending jet acceptance to forward region $|\eta|<4.7$

→Measurement carried out differentially wrt
- →N_{jet}, $m(j,j)$, $\Delta\eta(j,j)$, p_T^j and η^j

PAS-SMP-15-012

ZZ + jets

p-p $\sqrt{s}$=8 TeV
19.8 fb^{-1}



→Jets have softer pT spectrum in data

→ This reflects to the multiplicity plot

→ jets in data less likely to pass 30 GeV threshold

→ Possible explanations are; higher order corrections to ZZ production not taken into account; and parton shower effects

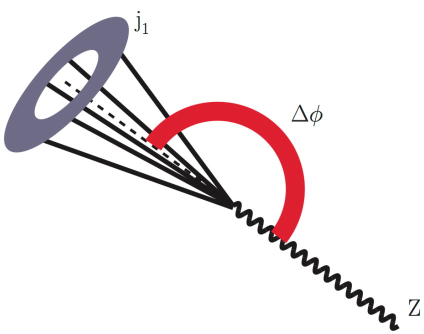
Phys. Lett. B 722 (2013) 238–261

p-p √s=7 TeV
5 fb^{-1}

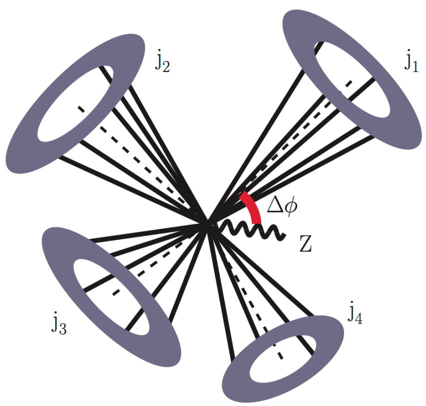
Z + Jets: Angular Correlations

Measurements in two different regimes
$P_T(Z)>0$ GeV (Inclusive) & $P_T(Z)>150$ GeV (Boosted regime)

→Boosted regime is of particular interest: critical in BSM searches
→Uncertainity of BG contribution is limited by the accuracy of MC models
→Accuracy of current MC models can be improved by studying correlations of Z & Jets



$\Delta\phi(Z,j_1)=\pi$
$\ln \tau_T \to -\infty$



$\Delta\phi(Z,j_1)\ll\pi$
$\ln \tau_T \to 1$

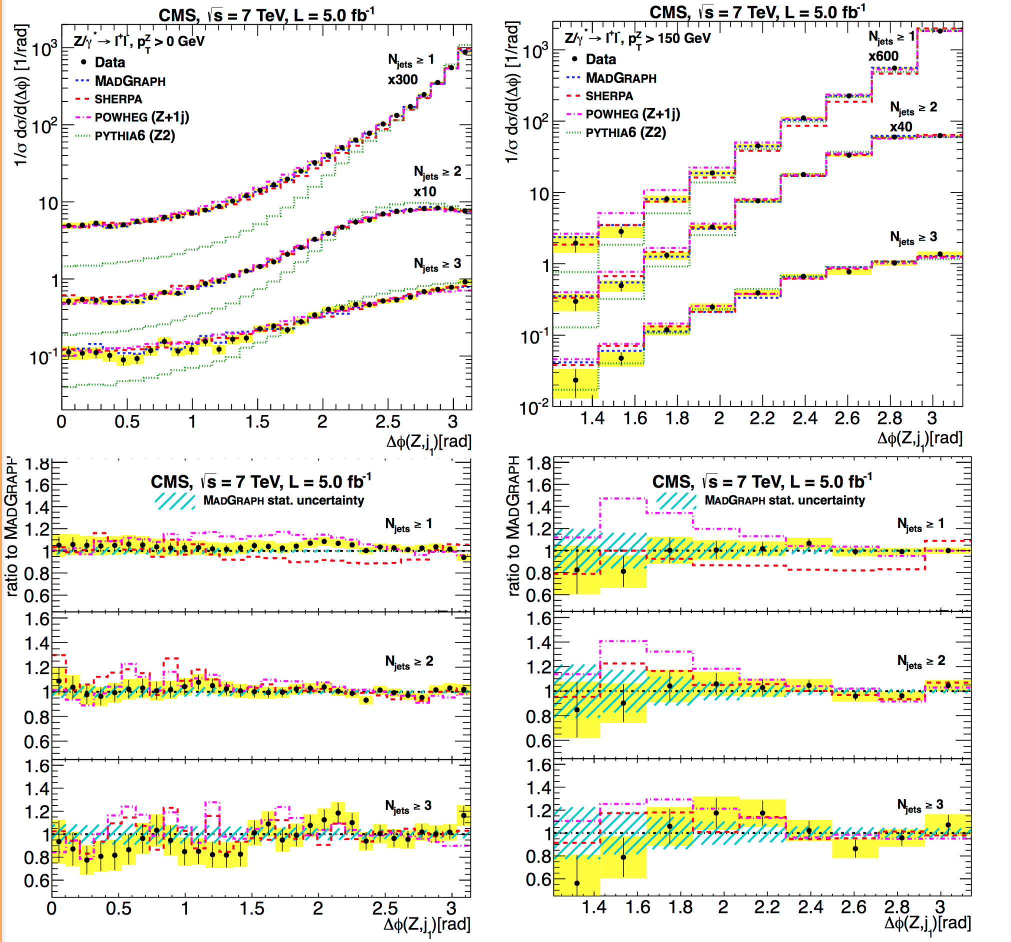
Transverse Trust:kinematic topology

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

Phys. Lett. B 722 (2013) 238–261

p-p √s=7 TeV
5 fb^{-1}

Z + Jets: Angular Correlations



$\Delta\phi(Z,j_1)$

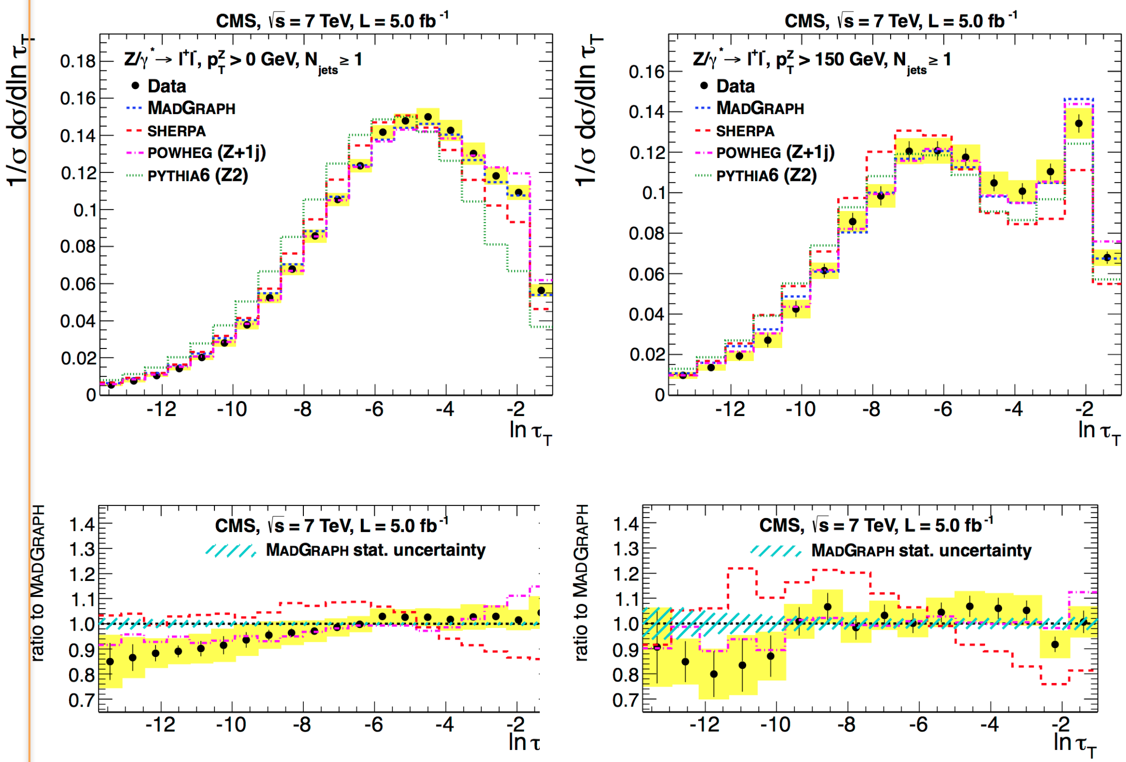
→Unfolding to correct for detector effects
→Direct comparison with theory
→MC simulations from Sherpa, Pythia6, Powheg and MadGraph.

Phys. Lett. B 722 (2013) 238–261

p-p √s=7 TeV
5 fb^{-1}

Z + Jets: Angular Correlations

Inclusive | Boosted Regime



ln τ_T

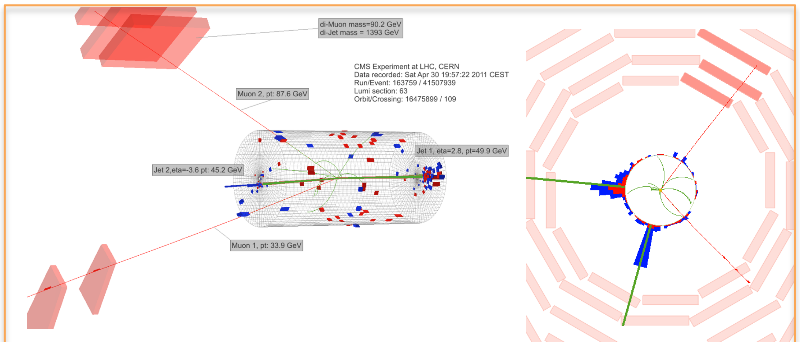
→MadGraph and Powheg reproduces data well
→Pythia6 (PS only) and Sherpa underestimate data

JHEP 10 (2013) 101, Eur. Phys. J. C 75 (2015) 66, arXiv:1607.06975

p-p √s=7 &8 TeV
5 &19.8 fb^{-1}

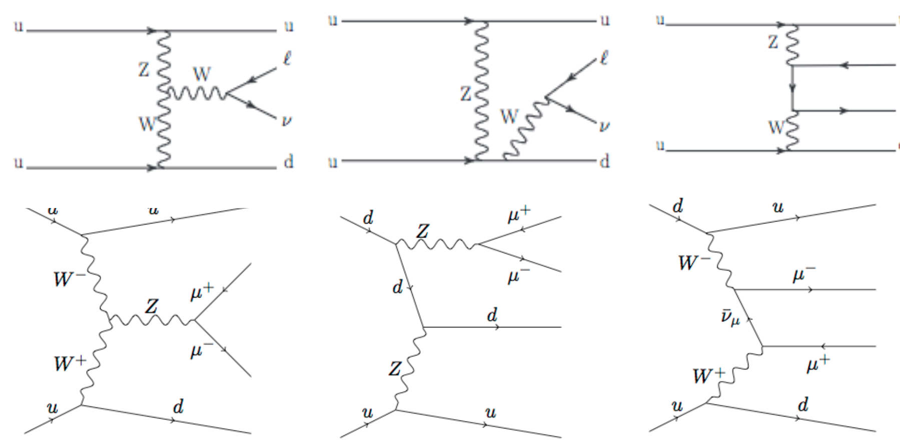
Electroweak V (W,Z) + forward-backward jets production

→EW production of W,Z + 2 well separated jets is quite sizeable @LHC
→Study of these processes are important for
- →VBF studies
- →Higgs boson searches
- →Measurements of EWK gauge couplings & Vector Boson scattering



Recorded data
M(μμ)=90.2 GeV
M(jj)=1.4 TeV.

EW production diagrams: VBF (left), bremsstrahlung (middle), and multiperipheral (right).

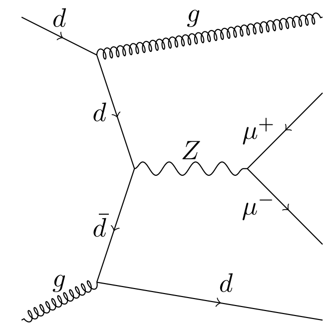


JHEP 10 (2013) 101, Eur. Phys. J. C 75 (2015) 66

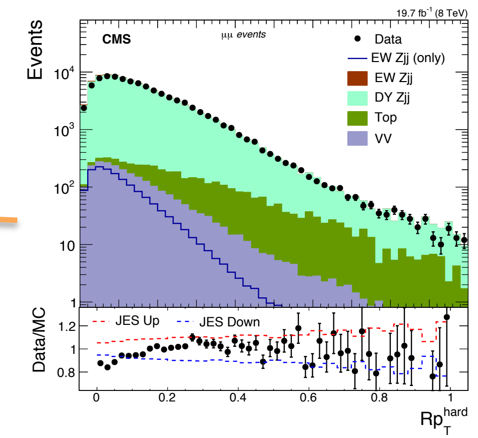
p-p $\sqrt{s}$=7 &8 TeV
5 &19.8 fb^{-1}

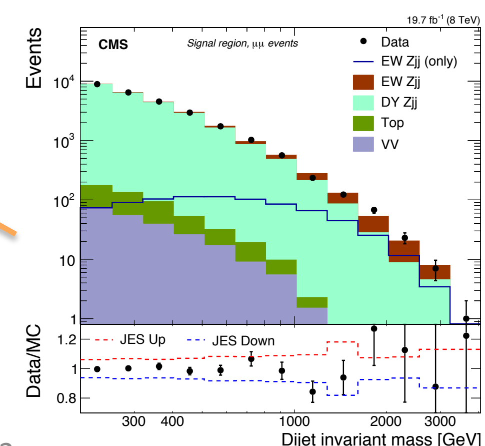
Electroweak Z + forward-backward jets production

→The EW process is burried in huge DY background
→ BDT deployed to extract the signal



	Analysis A	Analysis B	Analysis C
Channels	ee, $\mu\mu$	$\mu\mu$	ee, $\mu\mu$ binned in M_{jj}
Selection	$p_{Tj1,j2} > 50, 30$ GeV; $Rp_T^{hard} < 0.14$; $\lvert y^* \rvert < 1.2$; $M_{jj} > 200$ GeV	$p_{Tj1,j2} > 50, 30$ GeV; $Rp_T^{hard} < 0.14$; $\lvert y^* \rvert < 1.2$; $M_{jj} > 200$ GeV	$p_{Tj1,j2} > 50, 30$ GeV; $p_{TZ} > 50$ GeV; $\lvert yZ \rvert < 1.4442$; $M_{jj} > 450$ GeV
Jets	PF	JPT	PF
Variables used			
M_{jj}	•	•	•
p_{Tj_1}, p_{Tj_2}		•	•
η_{j_1}, η_{j_2}			•
$\Delta_{rel}(jj) = \frac{\lvert \vec{p}_{Tj_1} + \vec{p}_{Tj_2} \rvert}{p_{Tj_1} + p_{Tj_2}}$			•
$\Delta\eta_{jj}$		•	
$\lvert\eta_{j_1}\rvert + \lvert\eta_{j_2}\rvert$	•	•	•
$\Delta\phi_{jj}$		•	•
$\Delta\phi_{Z,j_1}$		•	
yZ	•	•	
z^*Z	•		
$p_T Z$	•	•	
Rp_T^{hard}		•	
q/g discriminator	•		•
DY Zjj model	MC-based	MC-based	From data





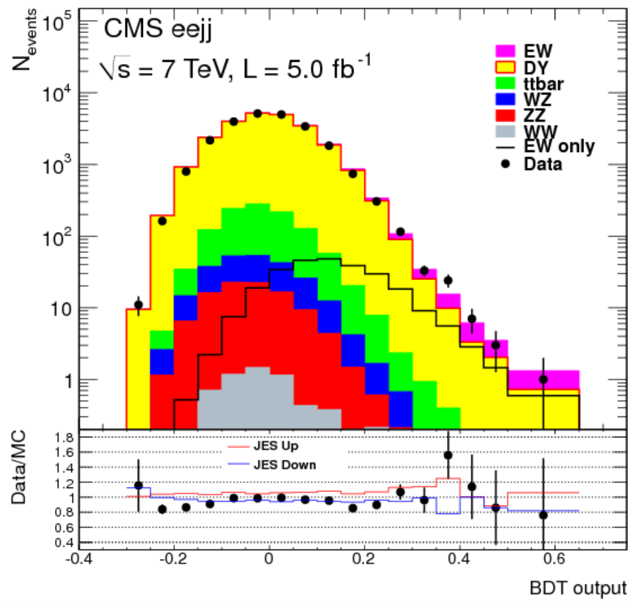
JHEP 10 (2013) 101, Eur. Phys. J. C 75 (2015) 66

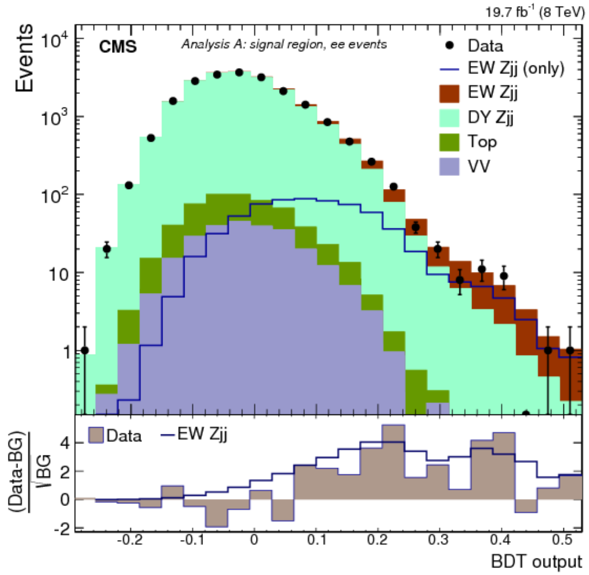
p-p √s=7 &8 TeV
5 &19.8 fb^{-1}

Electroweak Z + forward-backward jets production

→Corrected to parton level selections: mℓℓ>50 GeV, ptj>25 GeV, |ηj|<4.0 (5.0), mjj>120 GeV

BDT outputs used to discriminate EW signal





σ_{meas}=154±24(stat)±46(exp.syst) ±27(th.syst)±3(lumi) fb

7 TeV

σ_{meas}=174±15(stat)±40(syst) fb

8 TeV

arXiv:1607.06975

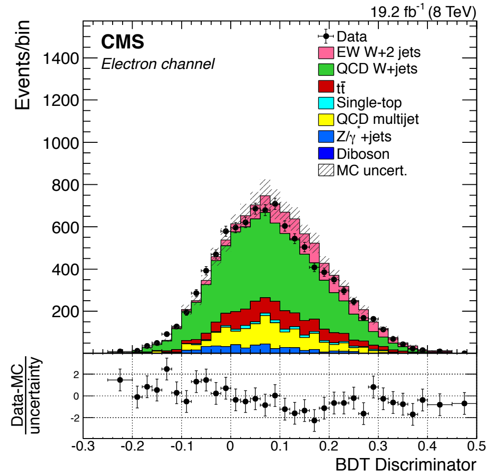
p-p √s=8 TeV
19.8 fb^{-1}

Electroweak W + forward-backward jets production

→Corrected to parton level selections: ptj1>60 GeV, ptj2>25 GeV, |ηj|<4.7 , mjj>1000 GeV

$W \to \ell\nu$ Lepton requirements	Jet requirements
Single lepton trigger	$p_T^{j1} > 60$ GeV, $p_T^{j2} > 50$ GeV
High-quality lepton ID and isolation	$\lvert y_W - (y_{j1} + y_{j2})/2 \rvert < 1.2$
Electron (muon) $p_T > 30$ (25) GeV	$m_{jj} > 1000$ GeV
$E_T^{miss} > 30$ (25) GeV for electron (muon) channels	
W transverse mass > 30 GeV	
Veto second lepton	

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



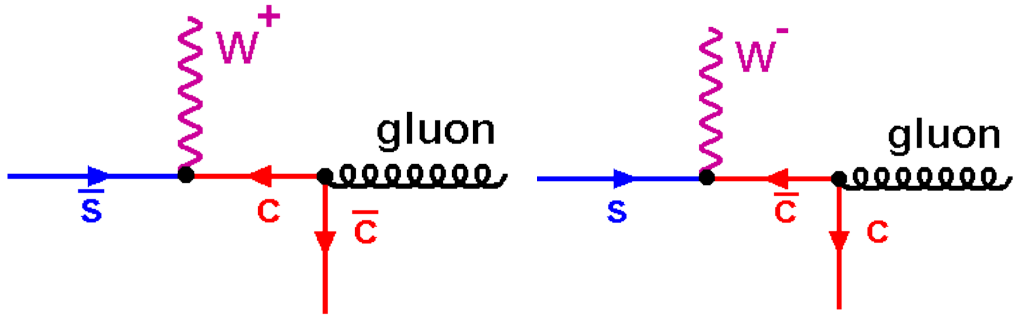
BDT outputs used to discriminate EW signal

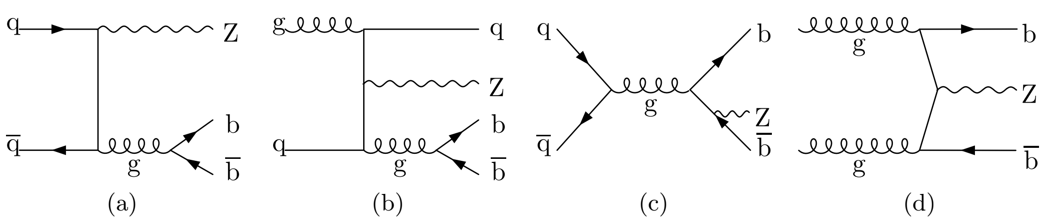
JHEP 12 (2013) 039, JHEP 02 (2014) 013, PLB 735 (2014) 204, JHEP 06 (2012) 126, JHEP 06 (2014) 120, PAS-SMP-14-020, PAS-SMP-15-009, PAS-SMP-14-010

V + HF

p-p √s=7,8 TeV
5, 19.8 fb-1

→Important to study V+ HF production at the LHC
  →To test pQCD and validate MC; for HF PDFs
  →They are backgrounds to other measurements and BSM searches



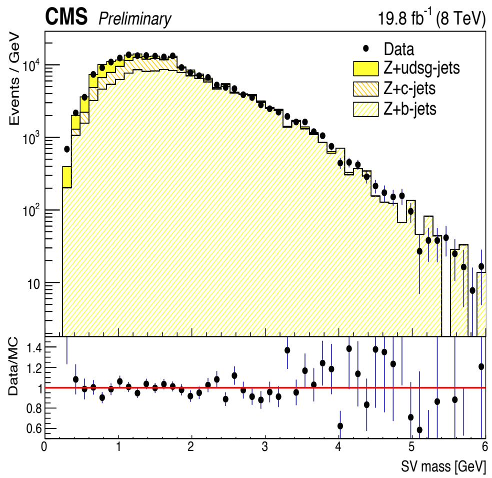


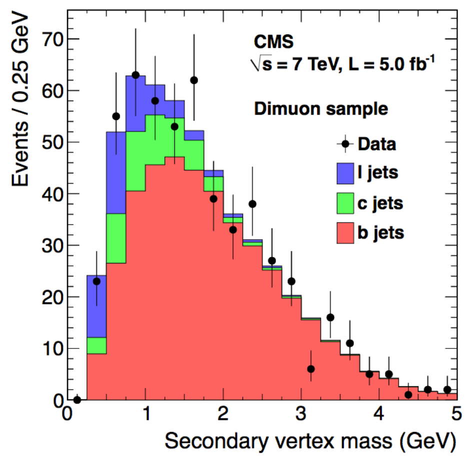
Example feynman diagrams for W+c and Z + bb productions

V(W,Z) +>=1 b

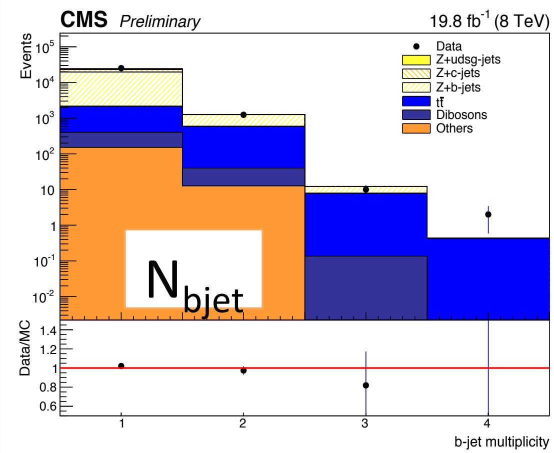
p-p √s=7,8 TeV
5, 19.8 fb^{-1}

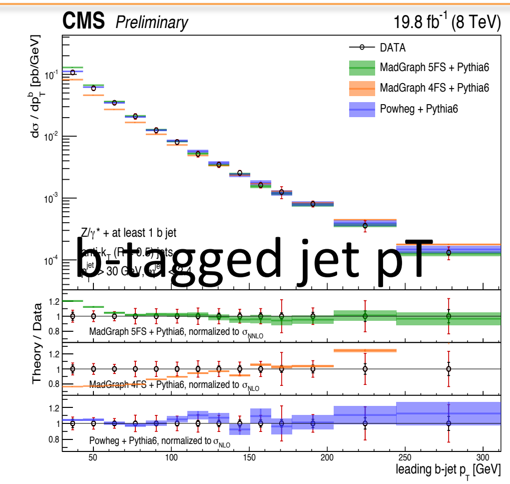
→SSV (CSV) algorithms to tag jets originating from b.
→ Chosen WP gives ~50% b- efficiency and ~1% of mistag rate





SV mass, input for b-tag algorithms





V(W,Z) +>=1 b

p-p √s=7,8 TeV
5, 19.8 fb^{-1}

Z+b results at 7 TeV		Z+b results at 8 TeV	
Cross section	Measured	Cross section	Measured
σ_{Z+1b} (pb)	$3.52 \pm 0.02 \pm 0.20$	σ_{Z+1b} (pb)	3.55 +-0.12 +-0.2
σ_{Z+2b} (pb)	$0.36 \pm 0.01 \pm 0.07$	σ_{Z+2b} (pb)	0.331+-0.011+0.035
σ_{Z+b} (pb)	$3.88 \pm 0.02 \pm 0.22$	σ_{Z+b} (pb)	---
$\sigma_{Z+b/Z+j}$ (%)	$5.15 \pm 0.03 \pm 0.25$	$\sigma_{Z+b/Z+j}$ (%)	9.3 +- 0.4 +- 0.7

W(->lv) + 2b cross section at 7 TeV
0.53 +- 0.05 (stat) +-0.09 (syst)+-0.06 (theo.) +- 0.01 (lumi) pb

W(->lv) + 2b cross section at 8 TeV
0.64 +- 0.03 (stat) +-0.10 (syst)+-0.06 (theo.) +- 0.02 (lumi) pb

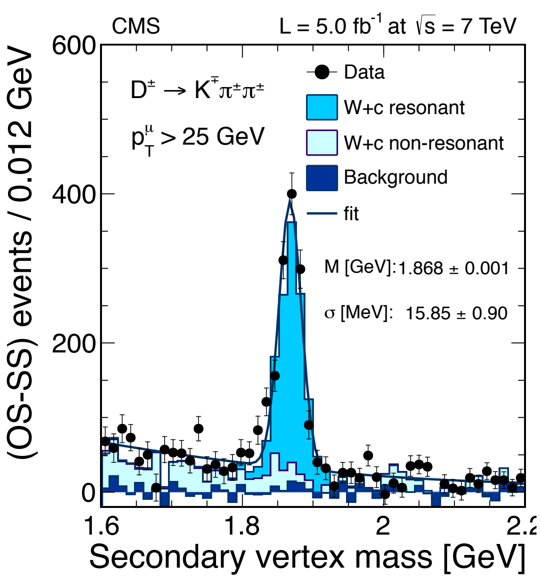
→ All measurements consistent with SM predictions and among each other

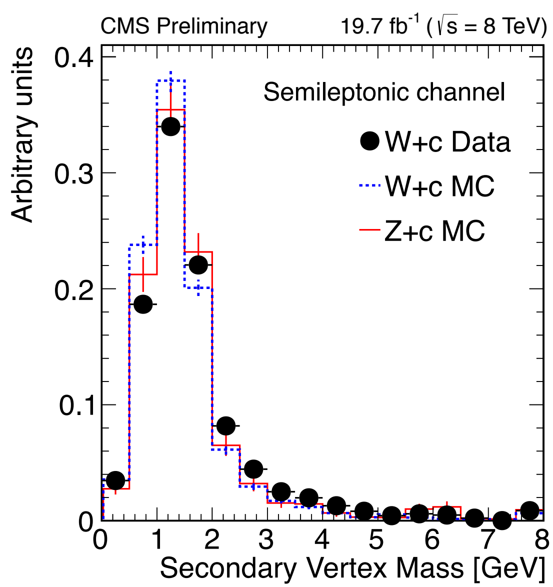
V(W,Z) + c

p-p √s=7,8 TeV
5, 19.8 fb^{-1}

→ V + c measurements provide constraints to strange and charm PDF's
→ They provide BG's for searches

→ Tagging of heavy flavor jets carried out in 3 signatures
- → Semileptonic decay of hadron leading to a muon from a displaced vertex
- → A displaced SV with 3 tracks consistent with $D^{\pm}$ decay
- → A displaced secondary vertex with two tracks consistent with D^0 decayand associated to a previous $D^{*+}(2010)$ decay



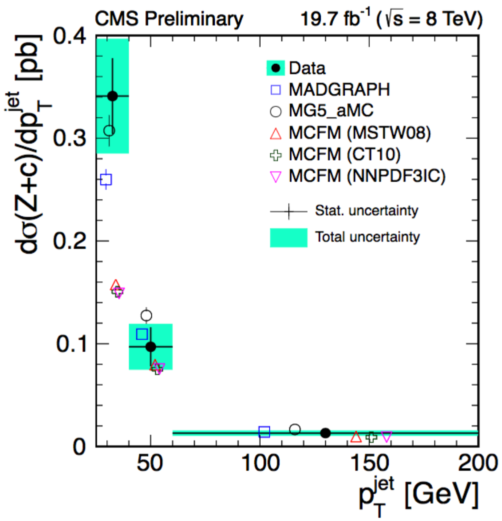


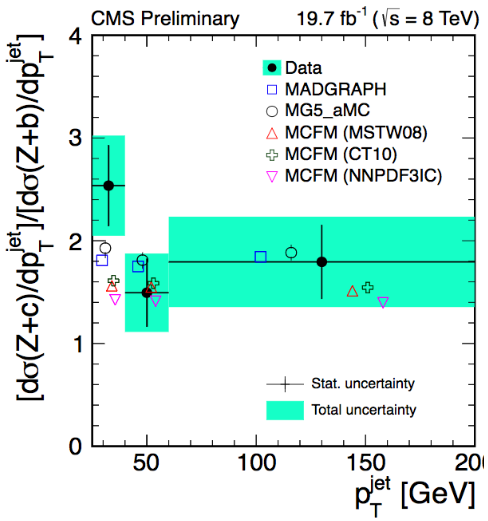
→ Measured V + c cross section inclusively as well as differentially.

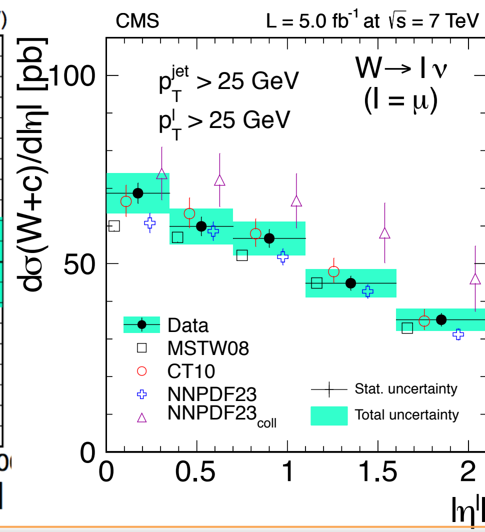
V(W,Z) + c

p-p √s=7,8 TeV
5, 19.8 fb^{-1}

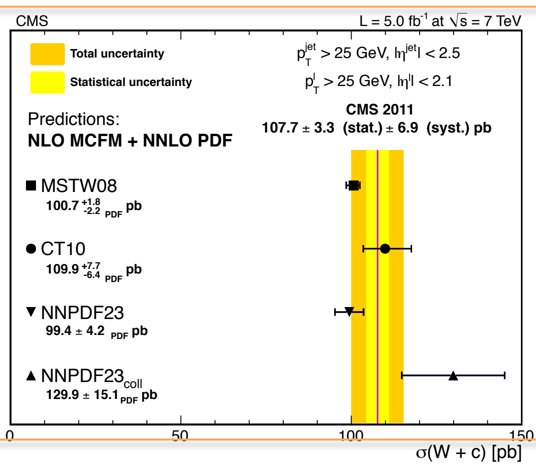
→ Measured V + c cross section as well as V+c/V+b ratio
- → inclusively
- → differentially wrt Z pT and jet pT (lepton η for W+c)







→ Differential V+ c cross section results



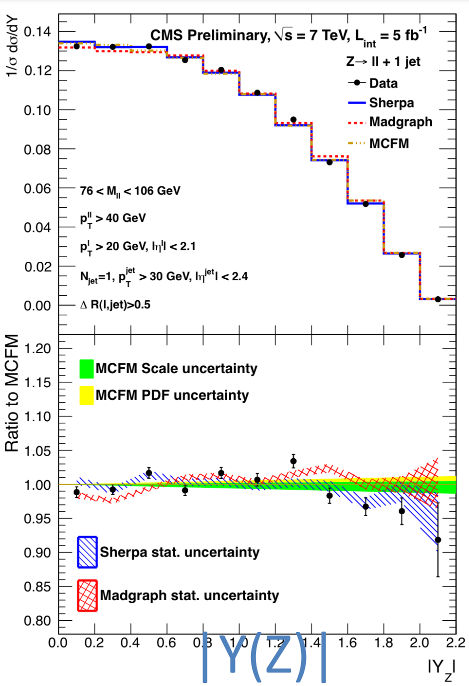
→ Comparison of W+c result to several sets of PDFs

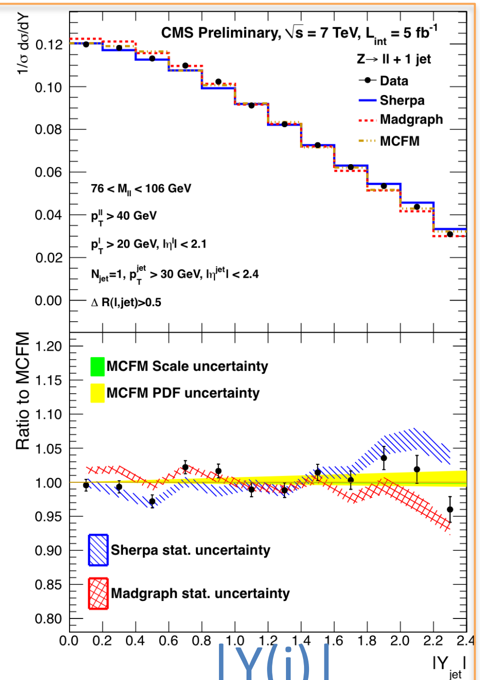
PRD 88 (2013) 112009

Z+1 jet rapidity distributions

p-p $\sqrt{s}$=7 TeV
5 fb^{-1}

→Angular distributions is crucial in understanding structure & interactions of matter since Rutherford
→Measurement of Y in Z+jet events provides modeling of H properties in theory calc.
→Presence of EWK vertex makes the perturbative calc. more stable
→NLO pQCD calc. exist for Z+ up to 4 jets & γ+jet





→The rapidity distributions for events with a Z boson + one jet

→$Z \to l^+l^-$ + 1 j, l= e,μ
→P_T (l)>20. GeV
→|η(l)|<2.1
→76 GeV<MZ<106 GeV
→ P_T(ll)>40 GeV
→P_T (j)>30. GeV
→|η(j)|<2.4

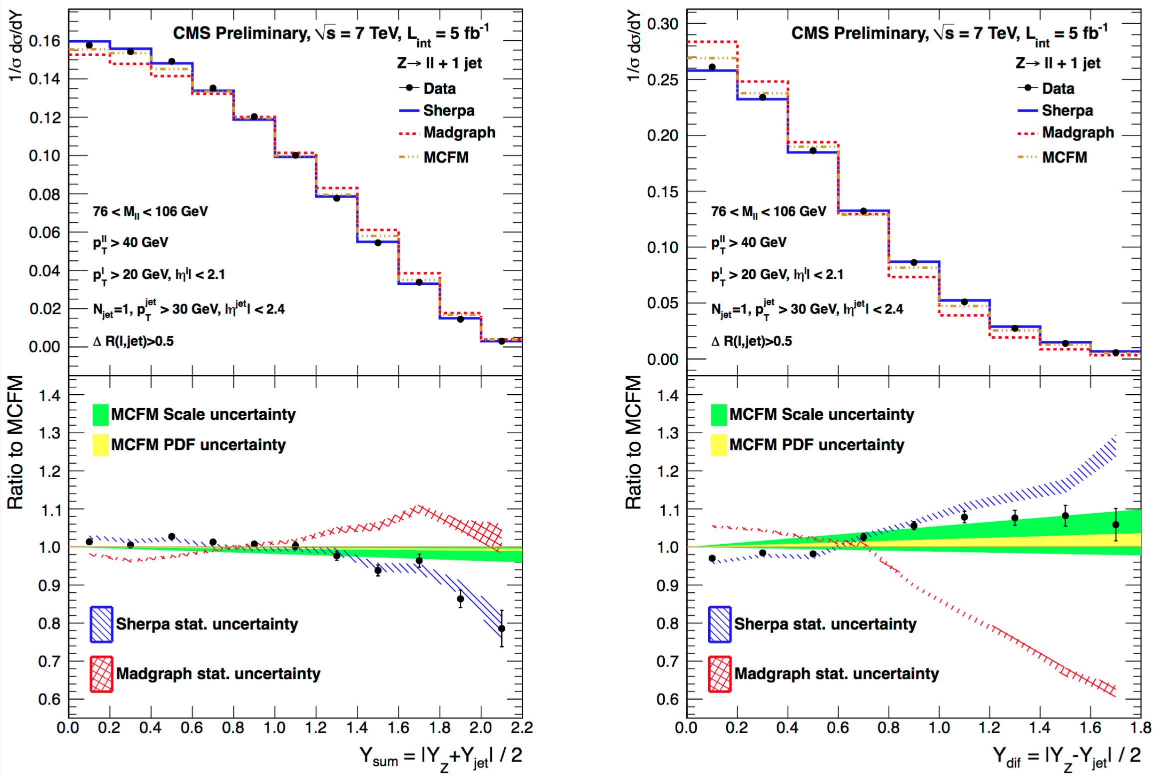
GKB

PRD 88 (2013) 112009

Z+1 jet rapidity distributions

p-p √s=7 TeV
5 fb^{-1}

→The rapidity distributions for events with a Z boson + one jet



Ysum= (|Y(Z) + Y(j)|)/2 Ydiff= (|Y(Z) - Y(j)|)/2

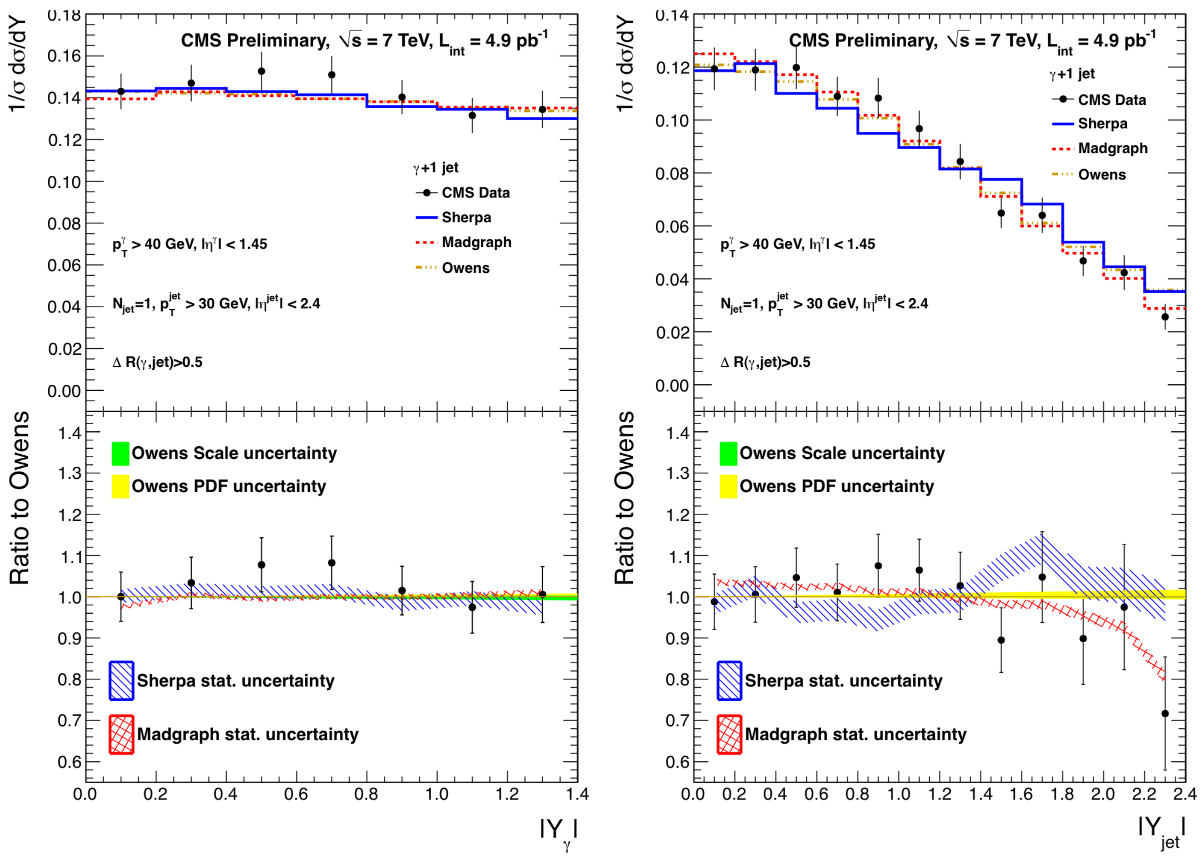
→Comparison with Sherpa, Madgraph MCFM.
→Sherpa aggrees better.

PRD 88 (2013) 112009

photon+1 jet rapidity distributions

p-p √s=7 TeV
5 fb^{-1}

→The rapidity distributions for events with a real photon + one jet



|Y(γ)| |Y(j)|

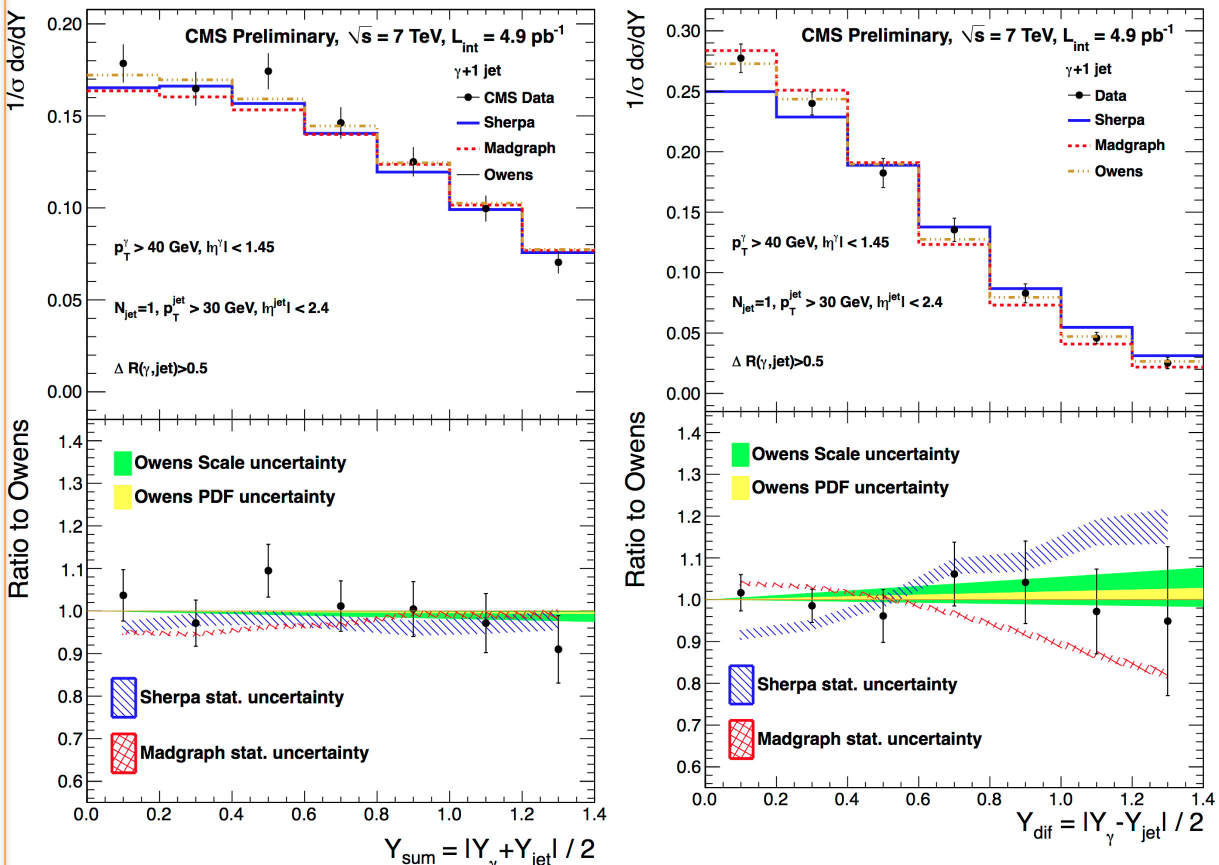
→$p_T(\gamma)$ >30 GeV
→|η(γ)|<1.4
→P_T (j)> 30 GeV
→|η(j)|<2.4

PRD 88 (2013) 112009

photon+1 jet rapidity distributions

p-p √s=7 TeV
5 fb^{-1}

→The rapidity distributions for events with a real photon + one jet



Ysum= (|Y(γ) + Y(j)|)/2 Ydiff= (|Y(γ) - Y(j)|)/2

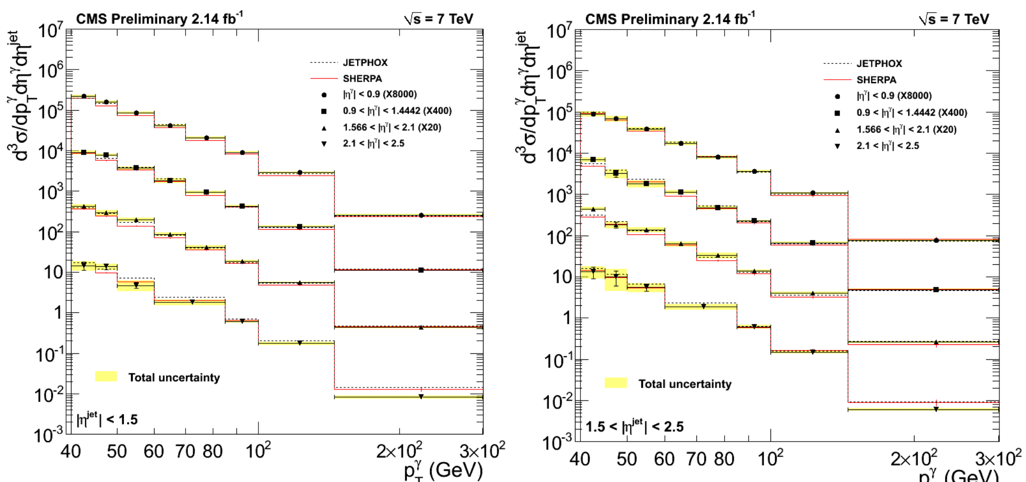
→Comparison with Owens, Sherpa & Madgraph

JHEP 06 (2014) 009

p-p √s=7 TeV
5 fb^{-1}

photon+jets differential cross section

- →Production of γ +jets directly sensitive to gluon PDF in proton
- →BG for many processses, H->γγ, BSM searches
- →Can be used for calibrating jet energies
- →Photons and jets are reconstructed within |η|<2.5
- →P^{j}_{T}>30 GeV 40 <P^{γ}_{T} < 300 GeV



$d^{3}\sigma/dP_{T}^{\gamma}d\eta^{\gamma}d\eta^{j}$

- →Error bars are statistical uncertainties
- →Yellow bands are the total uncertainties obtained by adding in quadrature statistical and systematic uncertainties.

→Comparison with :

- →SHERPA tree-level Monte Carlo generator
- →NLO perturbative QCD calculation from JETPHOX

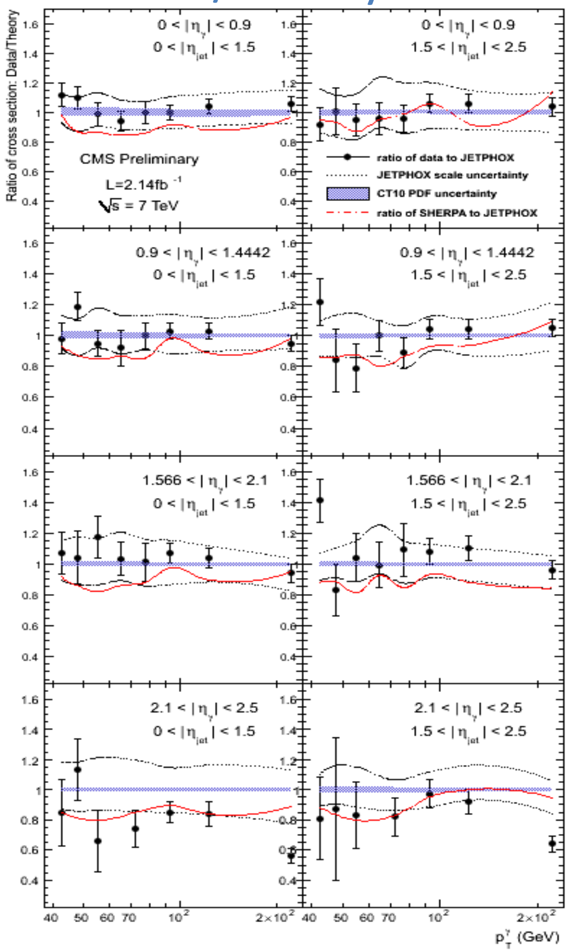
CMS-PAS-QCD-11-005

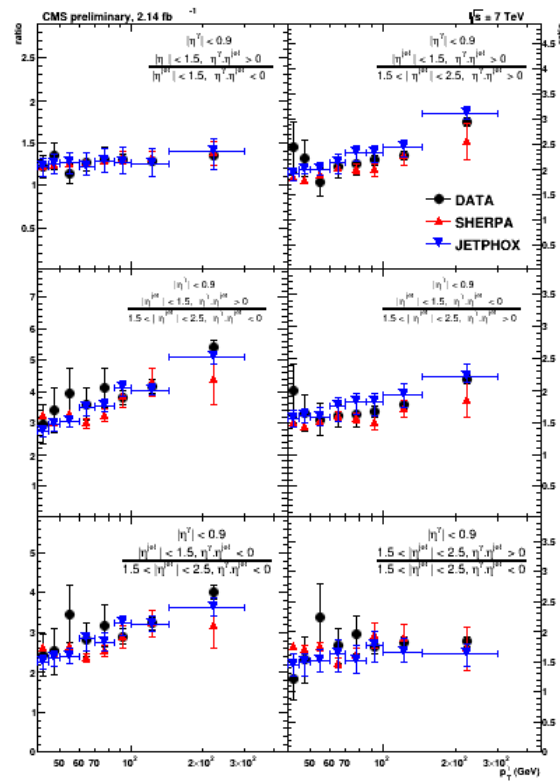
JHEP 06 (2014) 009

p-p √s=7 TeV
5 fb^{-1}

photon+jets differential cross section

Data/Theory





Ratios of cross section for various jet orientations wrt photon

→JETPHOX generally agrees with the data well

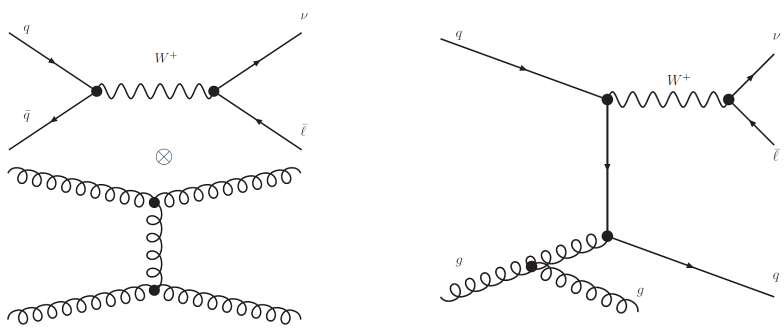
→SHERPA systematically underestimate the data

JHEP 03 (2014) 032

p-p √s=7 TeV
5 fb^{-1}

Double parton scattering in W+jets

→p-p collisions @LHC energies probe small x values carried by partons
 →The large parton densities at small x increase probability of 2 parton-parton scattering producing 2 identifiable hard scattering in p-p interaction
→DPS studies provide info on spatial structure of hadrons
→Constitute as BG to new physics searches @LHC



Feynman Diagrams for W+ 2j production from DPS (left) right and single parton scattering (right).

W $\rightarrow \mu\nu$ selection	Jet selection
Single muon trigger	anti-kT PF jet with R = 0.5
Muon ID and isolation	$p_T > 20\,\mathrm{GeV}/c$, $\lvert\eta\rvert < 2.0$
Exactly one muon $p_T > 35\,\mathrm{GeV}/c$, $\lvert\eta\rvert < 2.1$	$\beta > 0.4$
$\not{E}_T > 30\,\mathrm{GeV}/c$	$\Delta R(jet - \mu) > 0.5$
W transverse mass $> 50\,\mathrm{GeV}/c^2$	

→Double parton scattering (DPS) is investigated in W->μν + 2j final states

→Exclusive W+2 jets events
→Inclusive W+2 jets events

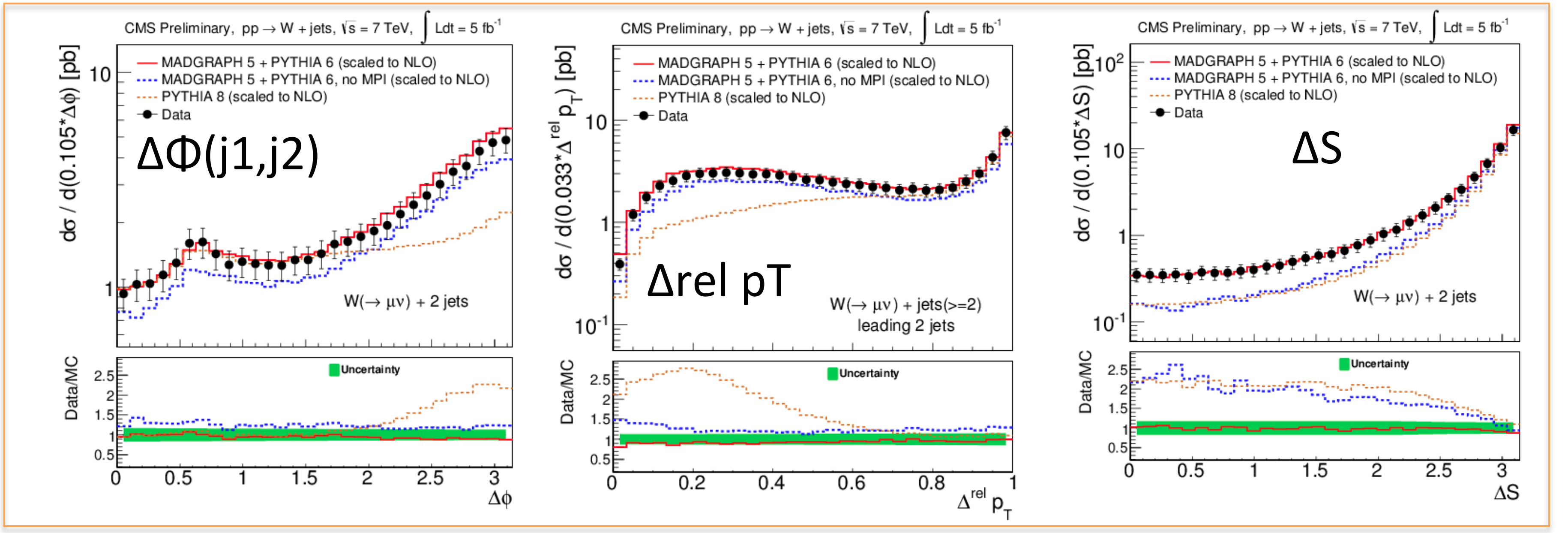
JHEP 03 (2014) 032

Double parton scattering in W+jets

p-p √s=7 TeV
5 fb^{-1}

→Unfolded ΔΦ(j1,j2), Δrel pT, and ΔS distributions for W+2j exclusive sample
→MC predictions of MADGRAPH nicely describe the measurements
→The MC prediction without MPI & Pythia fails to describe the differential x-sec as well as the shape

$$\Delta S = arccos\left(\frac{\vec{P}_T(\mu, \not{E}_T).\vec{P}_T(j1,j2)}{|\vec{P}_T(\mu, \not{E}_T)|.|\vec{P}_T(j1,j2)|}\right) \qquad \Delta^{\mathrm{rel}}\, p_T = \frac{|\vec{p}_T(j1) + \vec{p}_T(j2)|}{|\vec{p}_T(j1)| + |\vec{p}_T(j2)|}$$



p-p $\sqrt{s}$=7 TeV
5 fb^{-1}

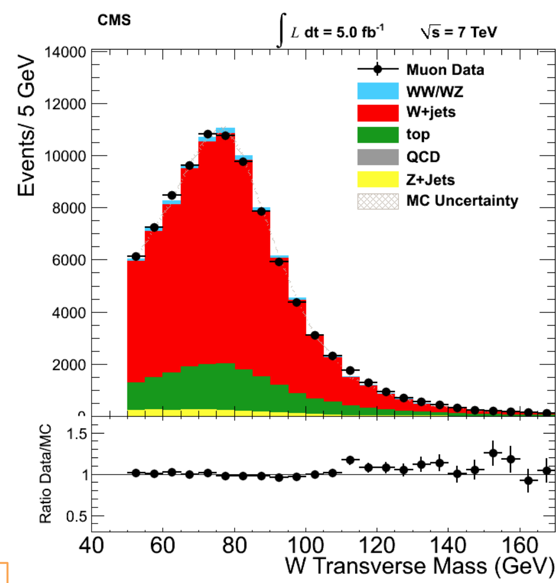
W+2 jets, dijet mass spectrum

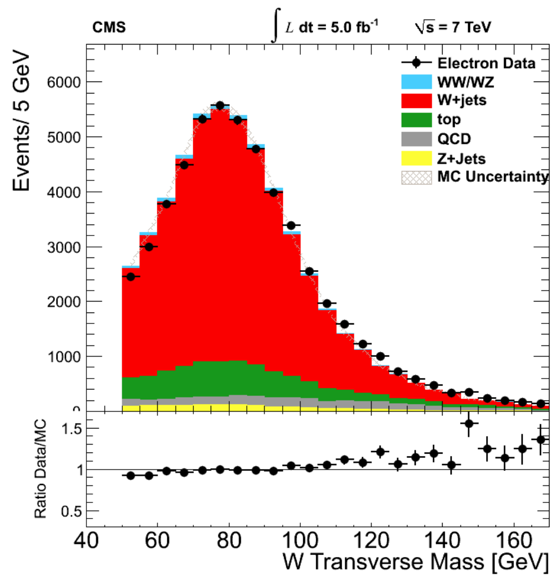
→Search for a former "CDF bump"* in invariant mass spectrum of the two jets with highest transverse momentum in pp→ W+2-jet and W+3-jet events

→pp→W(→lν)+jj final states

$W \to \ell\nu$ selection	Jet selection
Single-lepton trigger	$p_T^{j1} > 40\,\text{GeV}$
Lepton identification and isolation	$p_T^{j2}, p_T^{j3} > 30\,\text{GeV}$
$p_T^{\mu(e)} > 25\ (35)\,\text{GeV}$	$\|\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2}\| > 45\,\text{GeV}$
$\not{E}_T^{\mu(e)} > 25\ (30)\,\text{GeV}$	$\|\Delta\eta(j1, j2)\| < 1.2$
$M_T > 50\,\text{GeV}$	$\Delta\phi(\not{E}_T, \text{j1}) > 0.4$
Exclude events with > 1 lepton	$0.3 < p_T^{j2}/m_{jj} < 0.7$

Control plot:W transverse mass (MT) →

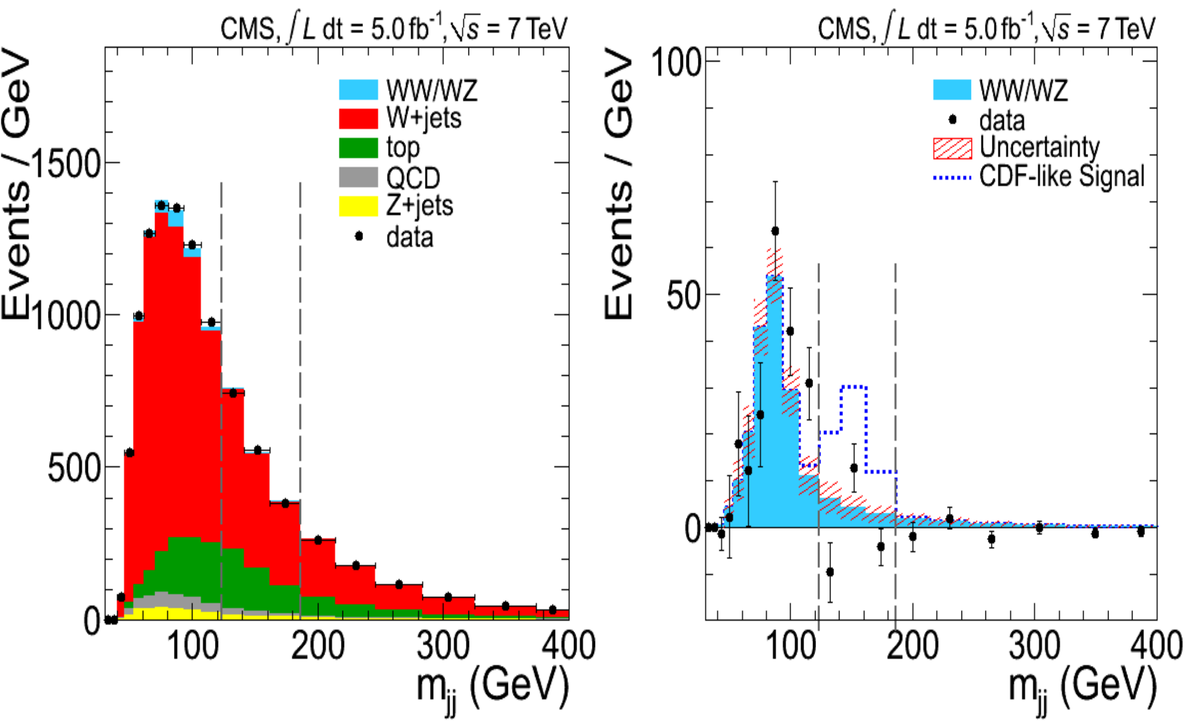




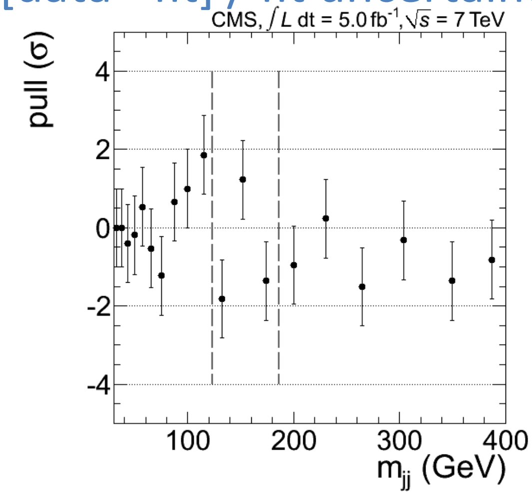
*:Phys. Rev. Lett.106, 171801(2011).

W+2 jets, dijet mass spectrum

M(j1j2) data (μ+ 2 j, μ+ 3 j, e+2 j, and e+ 3 j comdined) before BG subtraction (left) and after BG subtraction except WW/WZ (right)



Pull distribution
[data - fit] / fit uncertainty



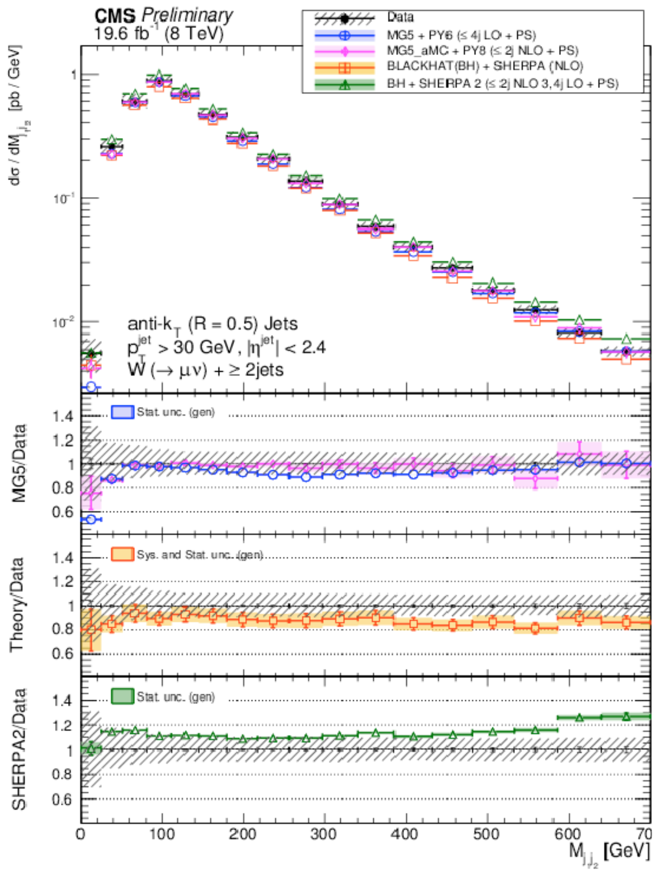
→No excess is observed
→An upper limit of 5.0 pb @ 95 % confidence level on the production cross section for a generic Gaussian signal with mass near 150 GeV.

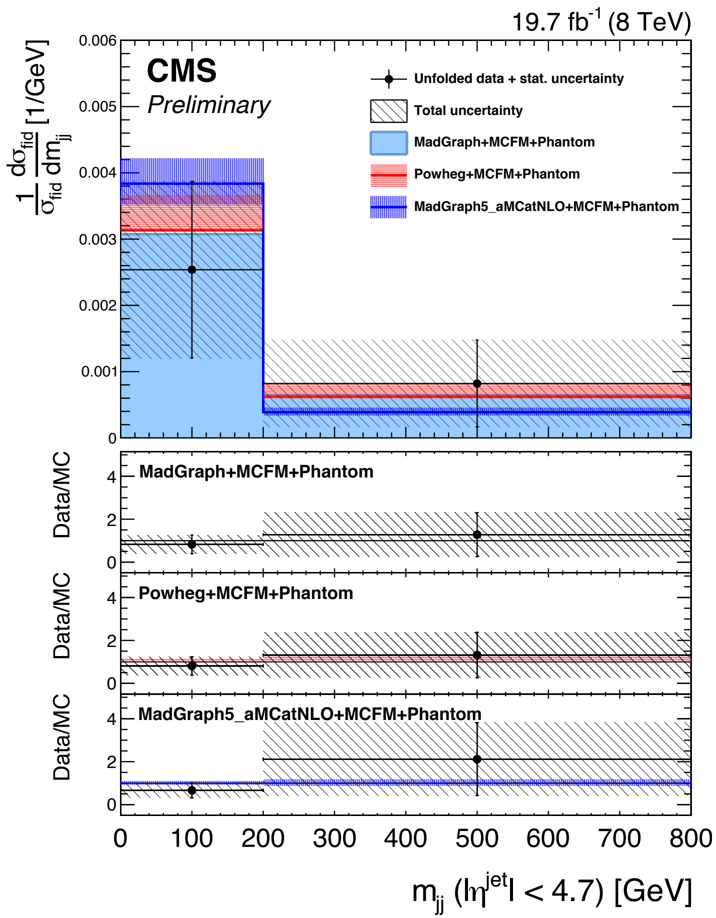
PAS-SMP-14-023,15-012

p-p √s=8 TeV
19.8 fb^{-1}

W (ZZ) + jets, Djet mass

Unfolded





→differential Dijet mass cross section is measured @8 TeV

→(W+jet) Best description of data is given by MadGrapgh5_amc@NLO + Pythia 8 sample

SUMMARY

→The measurements provide a detailed description of V+jets production topological structure

→Testing the validity of QCD

→Providing confidence in existing MC models for;

→Describing SM

→Determining BG in BSM searches

→Overall scale good agreement between Data and SM Monte Carlo predictions

→ Better description of data with beyond LO generators

→ All CMS SMP public results can be found under the following link:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

THANK YOU!