Production of Vector bosons in association with jets at CMS

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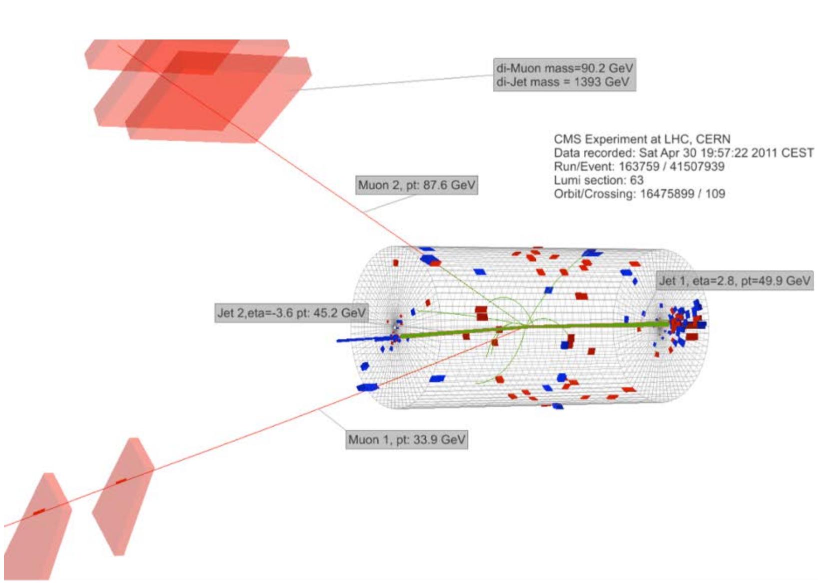
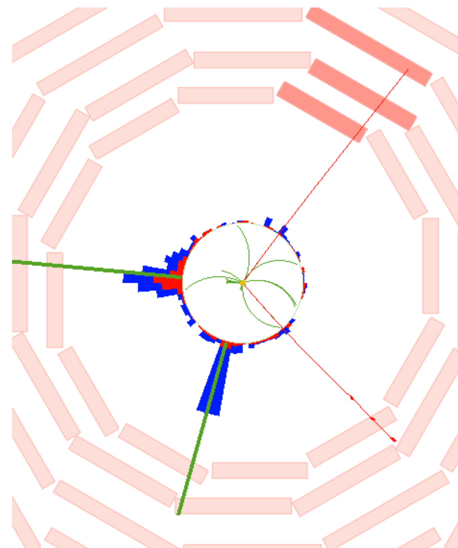
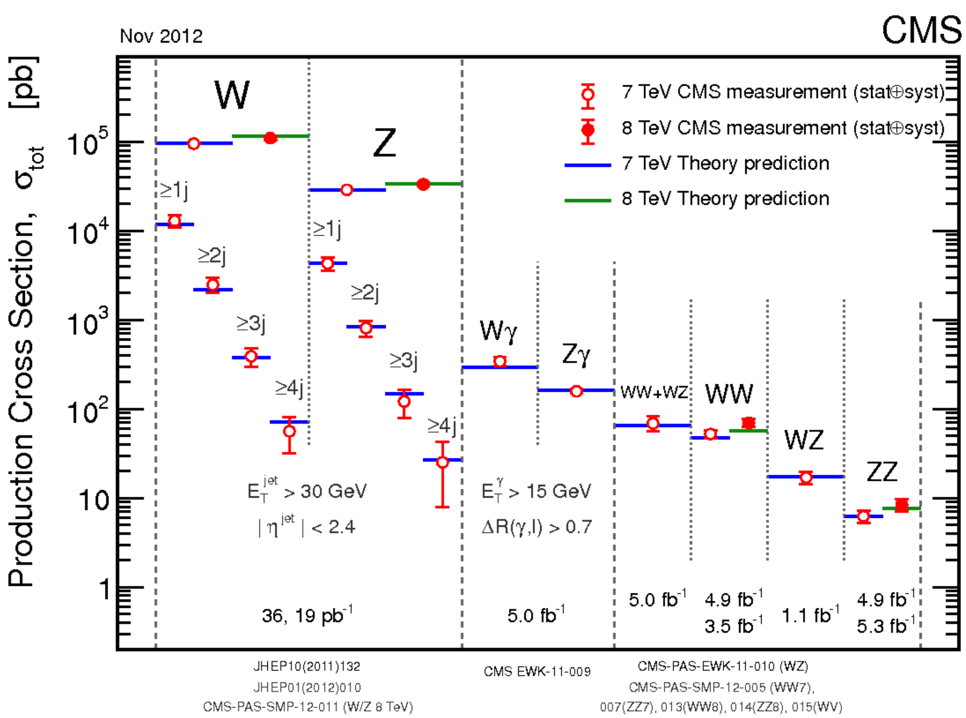




JetLHC2013, Durham UK, 17-19 July 2013

Overview

- Measurements of W/Z + jets production rates and properties in proton-proton collisions at the LHC are important for:
  - ✓ testing pQCD predictions at the highest jet p_T and jet multiplicities
  - ✓ tuning MC generators and theoretical calculations
  - ✓ probing strange, heavy flavour, and gluon content in proton
  - ✓ constraining parton distribution functions
  - ✓ modeling backgrounds to rare SM and beyond SM signatures



V+jets measurements at CMS

- CMS recent results covered in this talk:

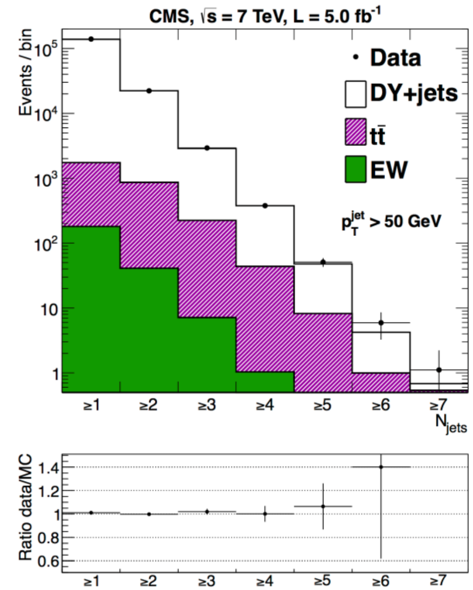
  all measurements at 7 TeV, with 5 fb^{-1} (except for the γ + jets differential cross-section measurement, which uses 2.1 fb^{-1})

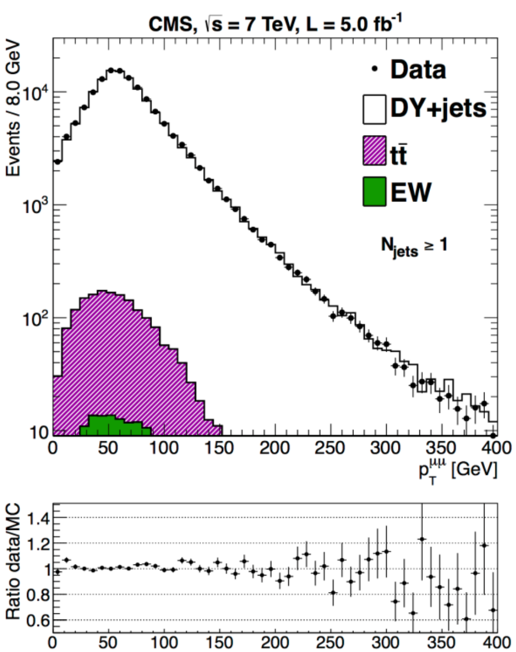
channel	measurement	documentation
Z+jets	azimuthal correlations and event shape	Phys. Lett. B 722 (2013) 238-261
Z/γ + 1 jet	rapidity distributions	CMS-PAS-SMP-12-004
γ + jets	differential cross-section	CMS-PAS-QCD-11-005
Z +2 jets	EW production cross-section	CMS-PAS-FSQ-12-019
W+2 jets	double parton scattering	CMS-PAS-FSQ-12-028
Z+b, bb	cross-section	CMS-PAS-SMP-13-004
Z+bb	angular correlations	CMS-PAS-EWK-11-015
W+bb	cross-section	CMS-PAS-SMP-12-026
W+c	differential cross-section	CMS-PAS-SMP-12-002

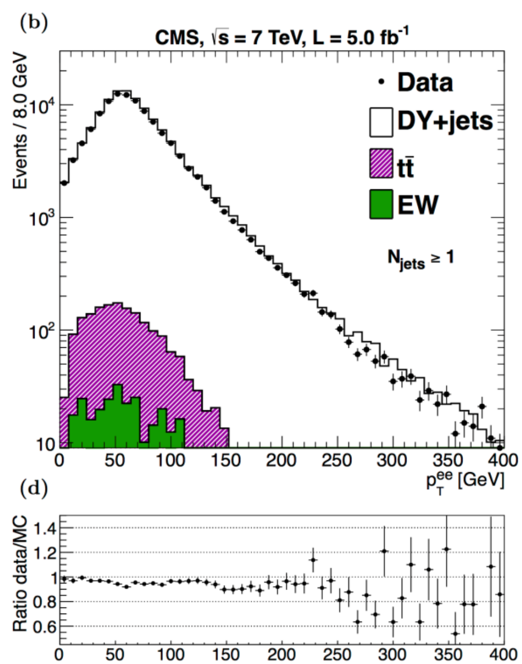
Phys. Lett. B 722 (2013) 238-261

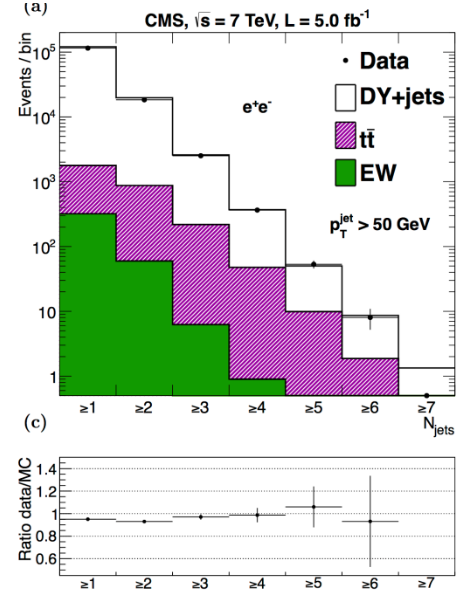
Z+jets event shapes and azimuthal correlations

- Basic Z+jets selection:
  - ✓ two leptons with p_T>20 GeV and $|\eta|$<2.4
  - ✓ at least one jet, p_T>50 GeV and $|\eta|$<2.5
  - ✓ dilepton mass 71 < $M_{\ell\ell}$ < 121 GeV
- Data/MC kinematic comparison:
  - ✓ Madgraph MC using NNLO theory σ's for Drell-Yan and W+jets, NNLL for tt and LO for di-bosons









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

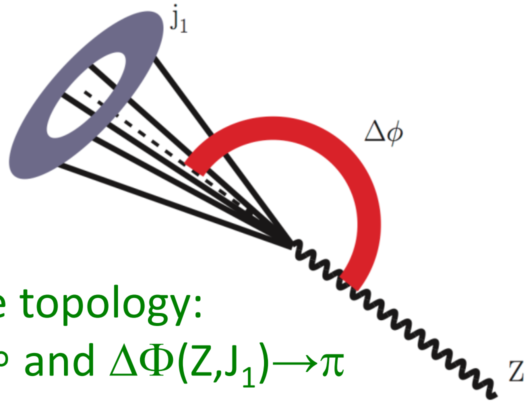
Z+jets event shapes and azimuthal correlations

- Reconstruction of event shapes:
  - ✓ Azimuthal correlations $\Delta\Phi(Z,J_i)$ and $\Delta\Phi(J_i,J_j)$
  - ✓ Transverse thrust τ_T

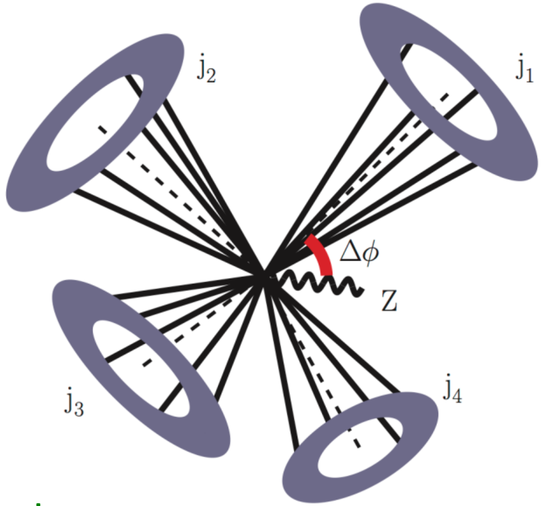
$$\tau_T \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_\tau|}{\sum_i p_{T,i}}$$

thrust axis

sums over Z and jets p_T's



Pencil-like topology:
$\ln(\tau_T)\rightarrow -\infty$ and $\Delta\Phi(Z,J_1)\rightarrow\pi$

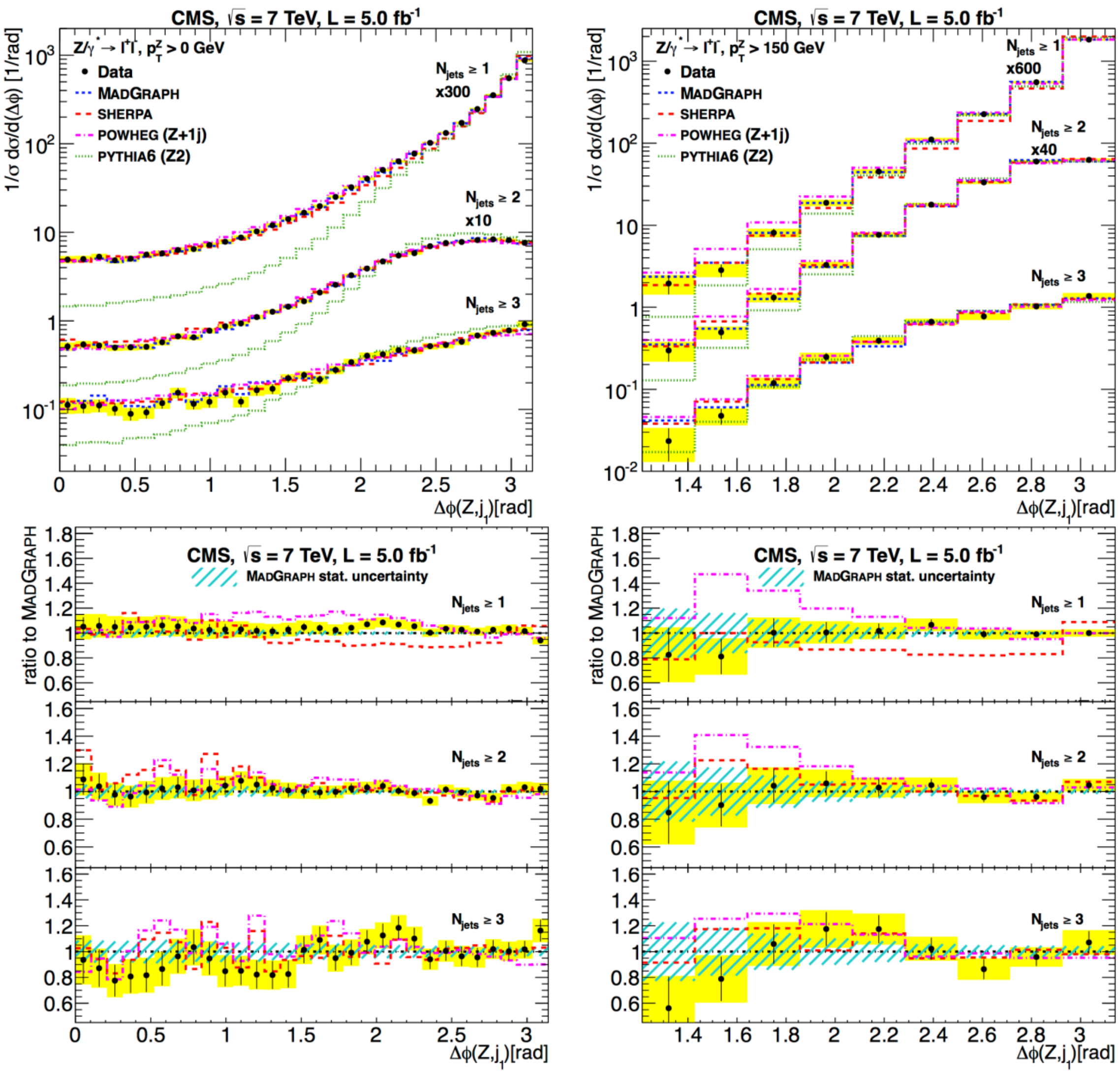


- Data unfolded to correct for detector effects and compared with MC particle-level.
- Measurements in two different regimes:
  - ✓ Inclusive: $p_T(Z) > 0$
  - ✓ Boosted: $p_T(Z) > 150$ GeV. Of particular interest for searches for new physics.

Isotropic topology:
$\ln(\tau_T)\rightarrow -1$ and $\Delta\Phi(Z,J_1) \ll \pi$

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

Z+jets event shapes and azimuthal correlations



Comparison with:

✓MADGRAPH(LO)+PYTHIA

✓SHERPA

✓POWHEG(NLO at 1 jet)+PYTHIA

✓PYTHIA standalone (LO at 1 jet)

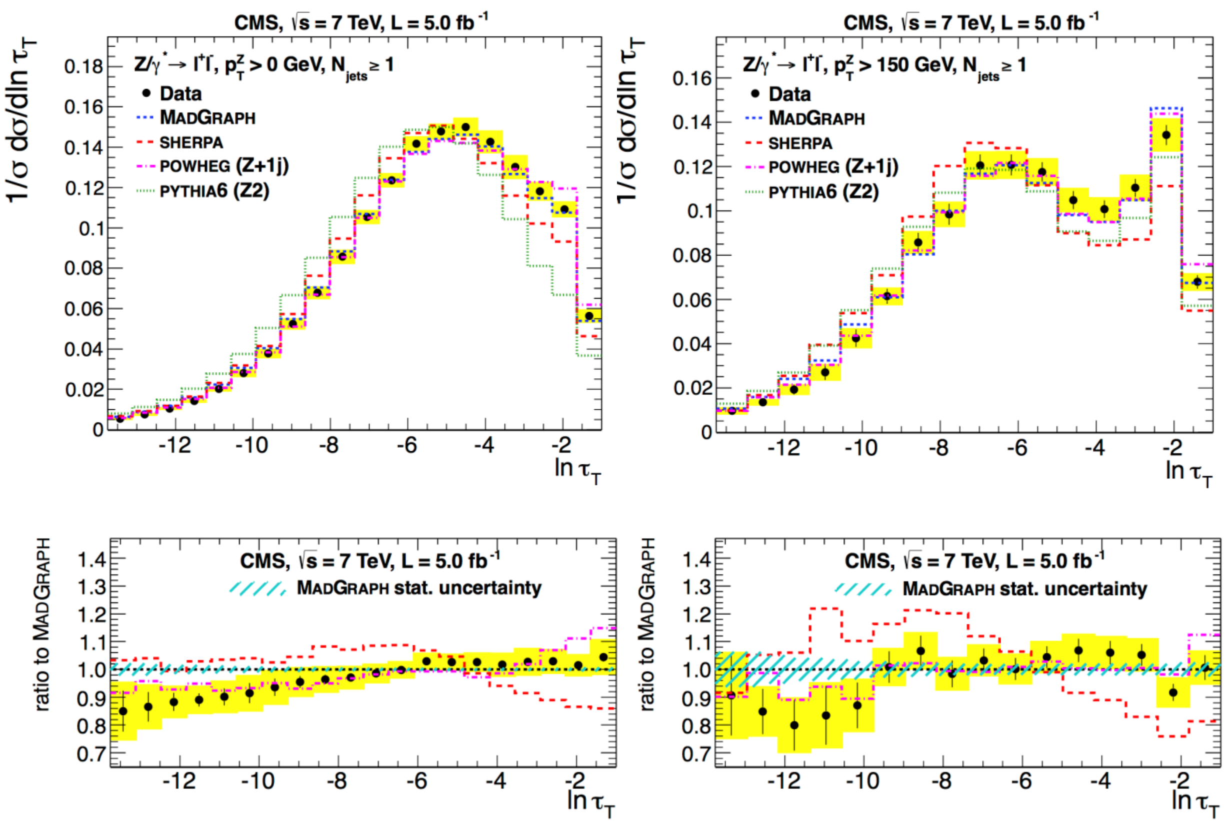
Agreement in $\Delta\Phi(Z,J_1)$

- Good for MADGRAPH
- 10% lower for SHERPA in 1st jet bin (better at high N_{jets}).
- 10% higher for POWHEG in 1st jet bin (better at high N_{jets}).
- Off for PYTHIA standalone, although agreement improves in high Z boost regime.
- Good agreement for other angular correlation variables, with similar observations for PYTHIA standalone.

PYTHIA standalone not included in ratio plots due to large deviations

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

Z+jets event shapes and azimuthal correlations



Comparison with:

- ✓MADGRAPH(LO)+PYTHIA
- ✓SHERPA
- ✓POWHEG(NLO at 1 jet)+PYTHIA
- ✓PYTHIA standalone (LO at 1 jet)

Agreement in ln τ_T

- ➢Good for MADGRAPH and POWHEG (within 10%).
- ➢A shift towards lower ln τ_T observed for SHERPA and PYTHIA standalone
- ➢Overall poor agreement for PYTHIA standalone

PYTHIA standalone not included in ratio plots due to large deviations

Z/γ + 1 jet rapidity distributions

- Z (or γ) + 1 jet selection:
  - ✓ two leptons with p_T>20 GeV and $|\eta|$<2.1
  - ✓ dilepton mass 76 < $M_{\ell\ell}$ < 106 GeV
  - ✓ p_T^{γ}>40 GeV and $|\eta^{\gamma}|$<1.45
  - ✓ one jet with p_T>30 GeV and $|\eta|$<2.4
- Data unfolded and compared with MC particle-level.

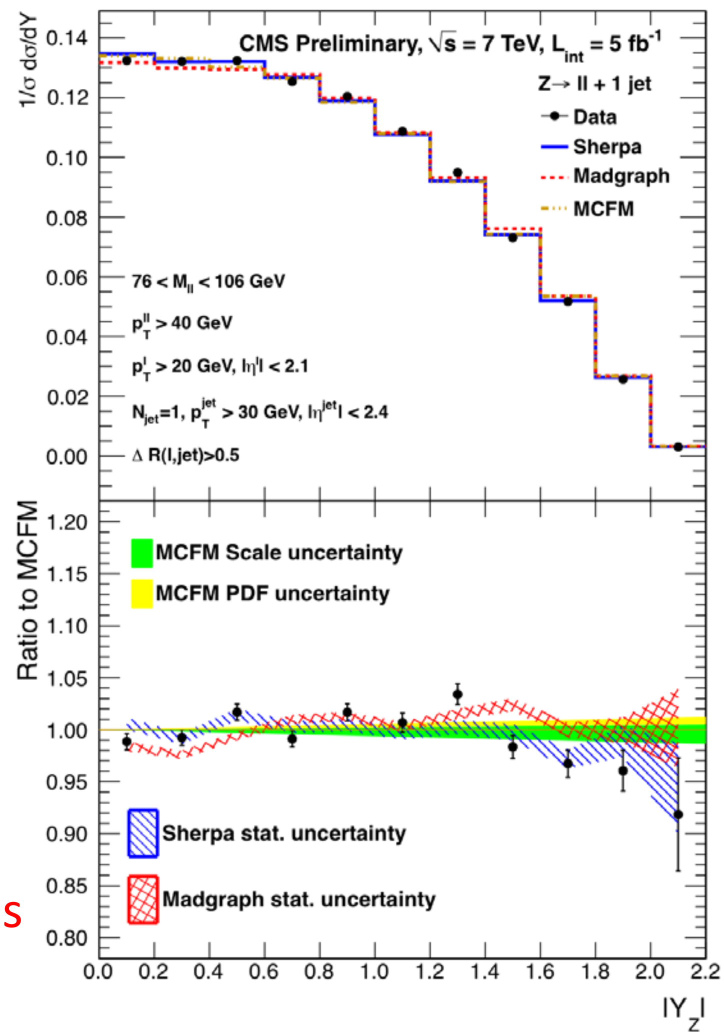
- Comparison with:

✓MADGRAPH(LO)+PYTHIA.
with MLM matching scheme (20/10 GeV matching scale for Z/γ).

✓SHERPA+APACIC++(PS)+PYTHIA(fragmentation)
with CKKM matching scheme (20/10 GeV matching scale for Z/γ).

✓ MCFM and Owens NLO calculation.

Good agreement of the rapidity distributions Y_Z (Y_γ) and Y_{jet} in the lab frame.



Z/γ + 1 jet rapidity distributions

- From Y_V (V=Z or γ) and Y_{jet} build the sum and the difference of rapidities:

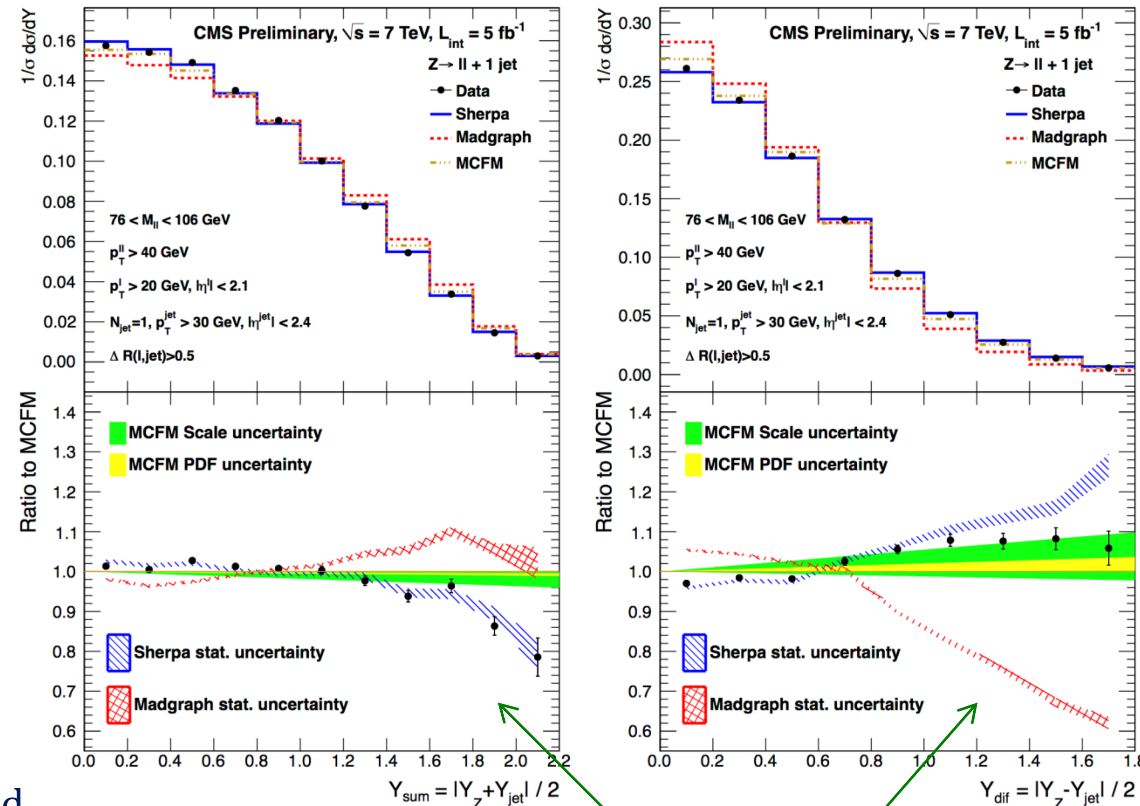
$$Y_{sum} = \frac{|Y_V + Y_{jet}|}{2}$$

Y_{sum} is the rapidity boost from the lab to the CM frame of the V and jet

$$Y_{diff} = \frac{|Y_V - Y_{jet}|}{2}$$

the cross-section at LO depends on Y_{diff} through θ^*, the polar angle in the V and jet CM frame.

Y_{sum} and Y_{diff} are approximately uncorrelated.



Ratios to MCFM predictions

- Comparison of Z + 1 jet with MC predictions:

✓ Y_{sum} data best described by SHERPA (and next by MCFM)

✓ Y_{diff} data best described by MCFM (and next by SHERPA)

✓ Differences between SHERPA and MADGRAPH in Y_{diff} ascribed to the different ME+PS matching procedures

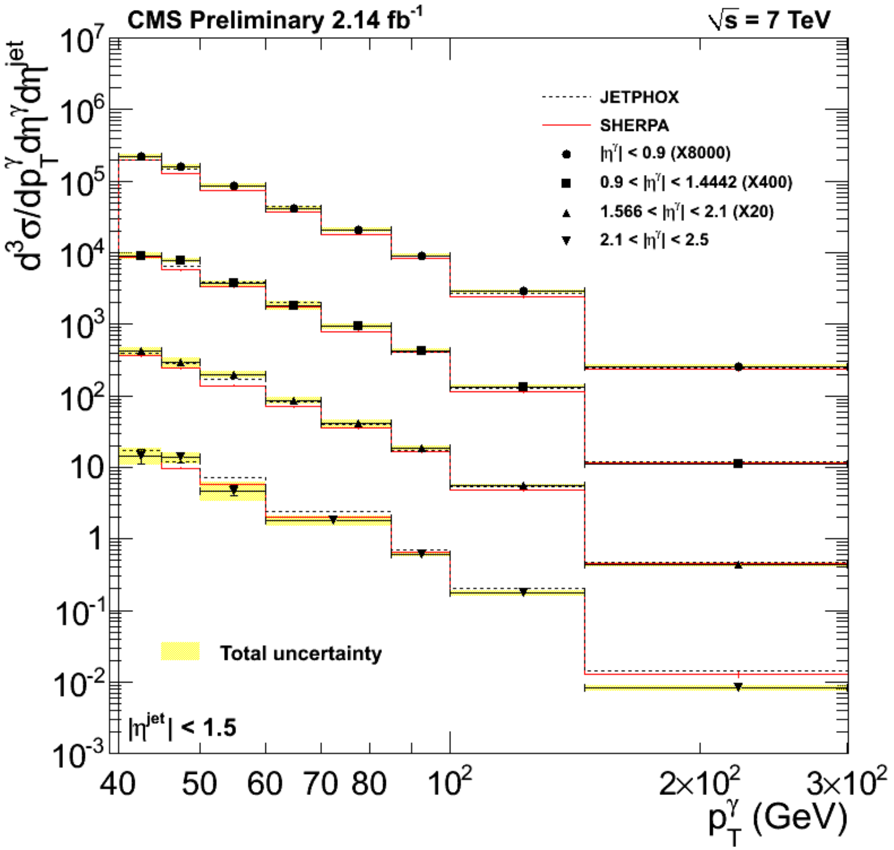
✓ Compatible findings in γ + 1 jet, but with lower statistics

γ + jets differential cross-section

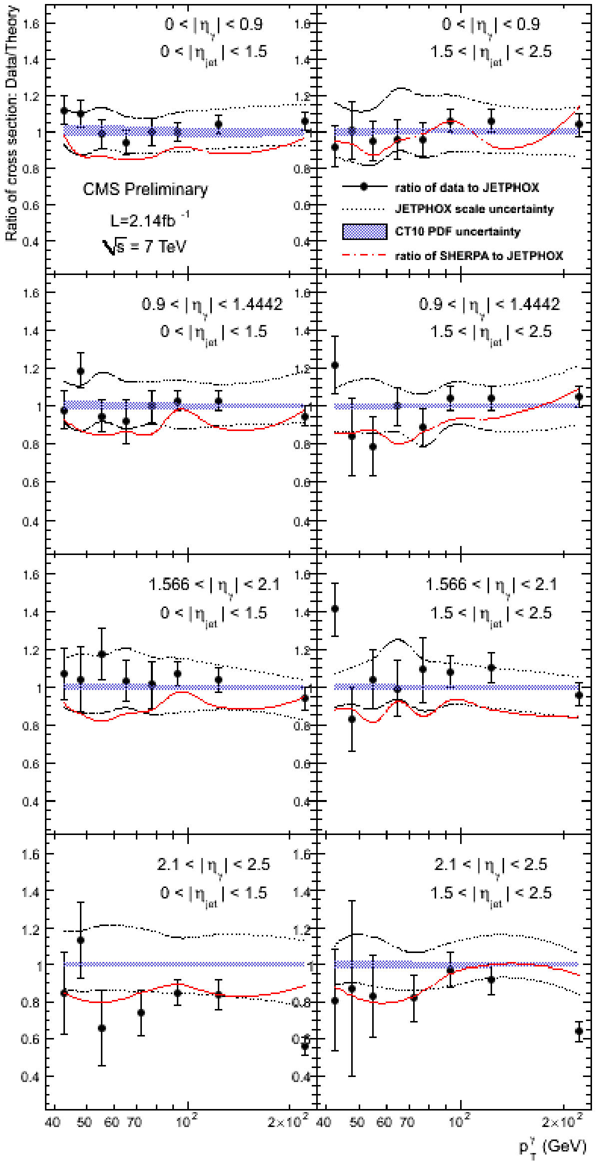
- γ + jets selection:
  - ✓ $40 < p_T^{\gamma} < 300$ GeV and $|\eta^{\gamma}|<2.5$
  - ✓ one or more jet with $p_T>30$ GeV and $|\eta|<2.5$
- Data unfolded to particle-level after background subtraction and efficiency corrections.
- Triple differential cross-section:

$$\frac{d^3\sigma}{dp_T^{\gamma}d\eta^{\gamma}d\eta^{jet}}$$

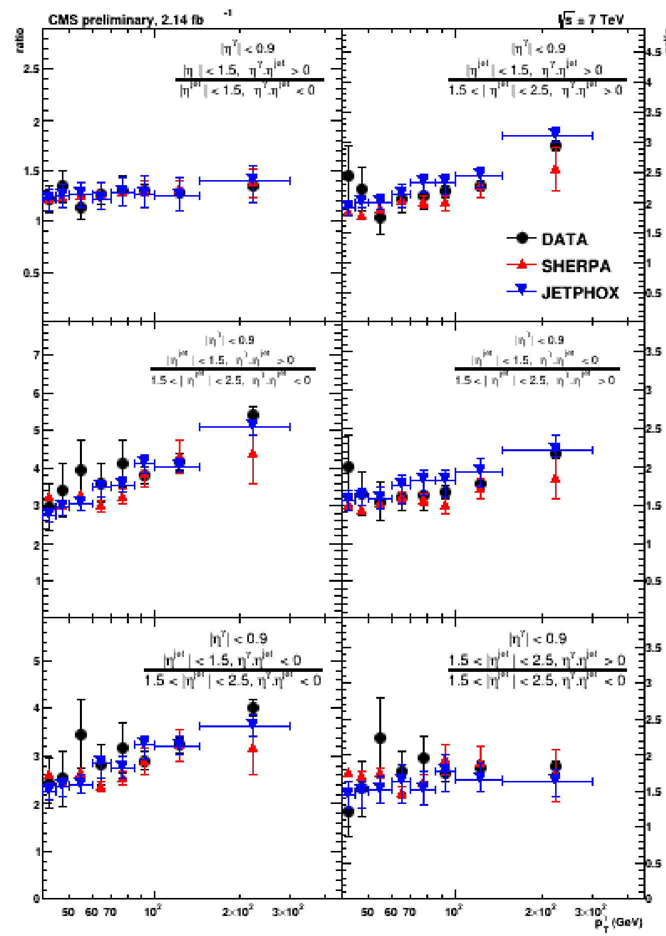
- Comparison with the predictions of:
  - ✓ SHERPA MC
  - ✓ JETPHOX NLO calculation



γ + jets differential cross-section



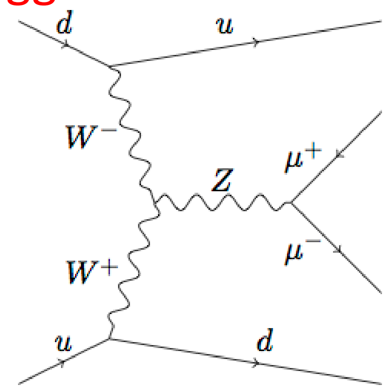
- Ratios of measured triple differential cross-sections to JETPHOX predictions:
  - ✓ in agreement with JETPHOX predictions.
  - ✓ SHERPA underestimates.

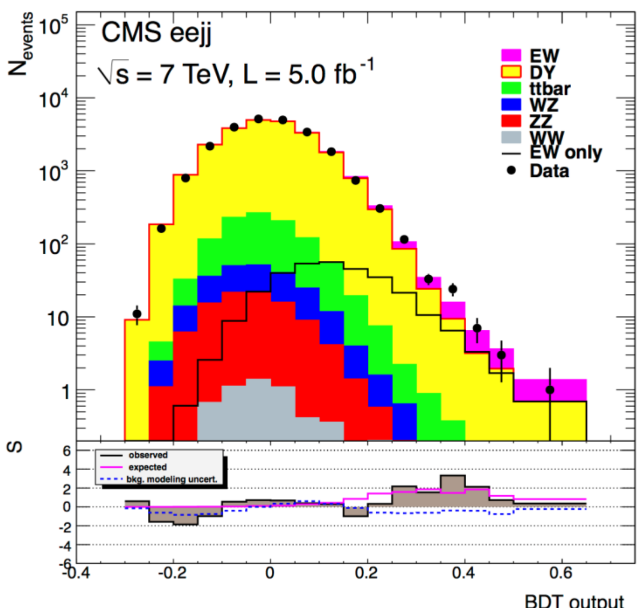


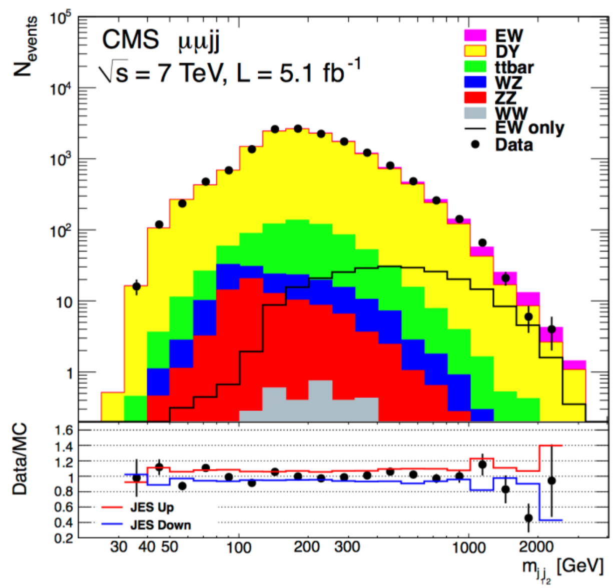
- Ratios of measured cross-sections for various jet orientations w.r.t. the photon .
  - ✓ Systematic uncertainties largely canceled.
  - ✓ JETPHOX and SHERPA reproduce ratios fairly well.

EW production of Z+2 jets

- Probes Triple Gauge Couplings and background to VBF Higgs searches
- Forward-backward jets (plus Z) topology:
  - ✓ $j_1(j_2)$ p_T > 65(40) GeV, $|\eta_j|$<3.6 , $M(j_1j_2)$ > 600 GeV
  - ✓ Z rapidity in rest frame of jets $|y^*|$<1.2
  - ✓ 2 ℓ's, p_T>20 GeV, $|\eta|$<2.4 in M_Z window
- Small signal (backgrounds: DY ℓℓjj, ttbar, VV)
  - ✓ Signal extracted via fits to: MVA output or $M(j_1j_2)$







- Measured cross section in agreement with NLO (VBFNLO σ=166fb)

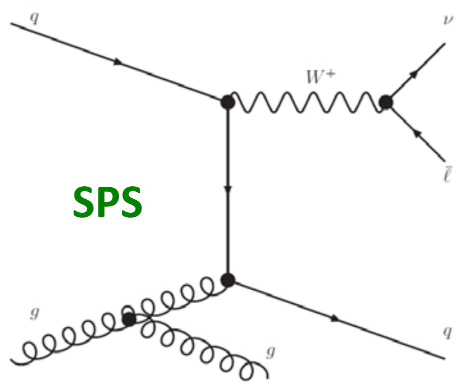
  $\sigma_{\ell\ell}^{EW}$ = 154±24(stat.) ± 46(exp sys.) ± 27(theo.) ± 3(lumi) fb

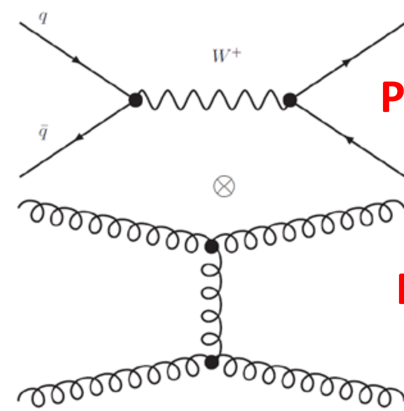
Double Parton Scattering in W+2 jets

- Study of various observables sensitive to DPS (kinematics of DPS is different from SPS)

$$\sigma^{tot}_{A+B} = \sigma^{SPS}_{A+B} + \sigma^{DPS}_{A+B}$$

SPS





Process A

Process B

DPS

- Basic W+≥2 jets selection:
  - ✓ one muon with p_T>35 GeV and $|\eta|$<2.1
  - ✓ E_T^{miss}>30 GeV and $M_T(\mu, E_T^{miss})$>50 GeV
  - ✓ leading 2 jets with p_T>20 GeV and $|\eta|$<2.1
- Variables studied for inclusive and exclusive W+2 jets events are:

$$\Delta\phi_{jets}$$

Jets are back-to-back in DPS (A and B are independent)

$$\Delta^{rel} p_T = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}$$

Small in DPS (jets balance each other)

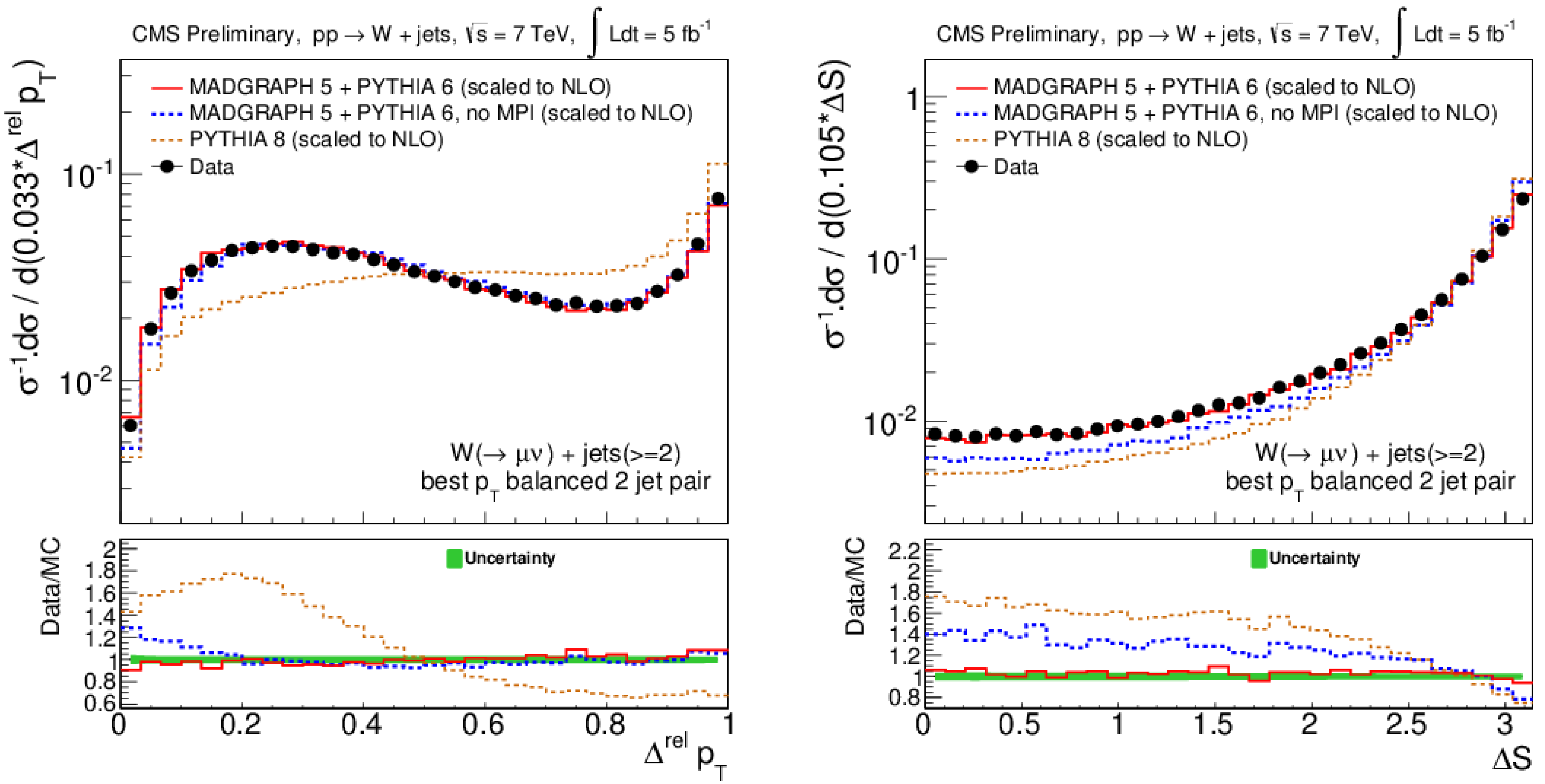
ΔS Azimuthal angle between W and dijet system

W and dijet random in DPS (back-to-back in SPS)

- Distributions unfolded to particle-level are compared with MC predictions can be used to measure the fraction of DPS fraction, test the modeling of double parton scattering, etc. DPS is also a background to new physics searches.

Double Parton Scattering in W+2 jets

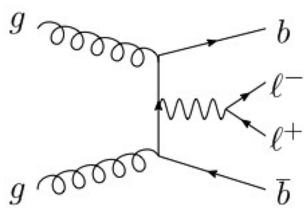
- ❑ Particle-level unfolded distributions are compared with:
  - ✓MADGRAPH(LO)+PYTHIA6 with and w/o MPI, and with PYTHIA8

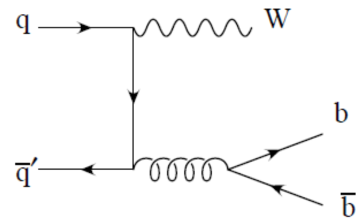


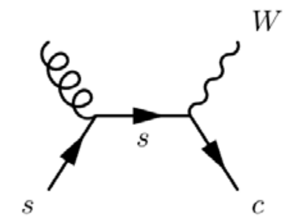
- ❑ Good agreement with standard MADGRAPH(LO)+PYTHIA6
  - ✓ MC without MPI does not describe the distributions nor the integrated cross-section
  - ✓ PYHTIA8 largely underestimates the distributions not due to DPS, but to missing hard processes

W/Z + heavy flavour (HF) jets

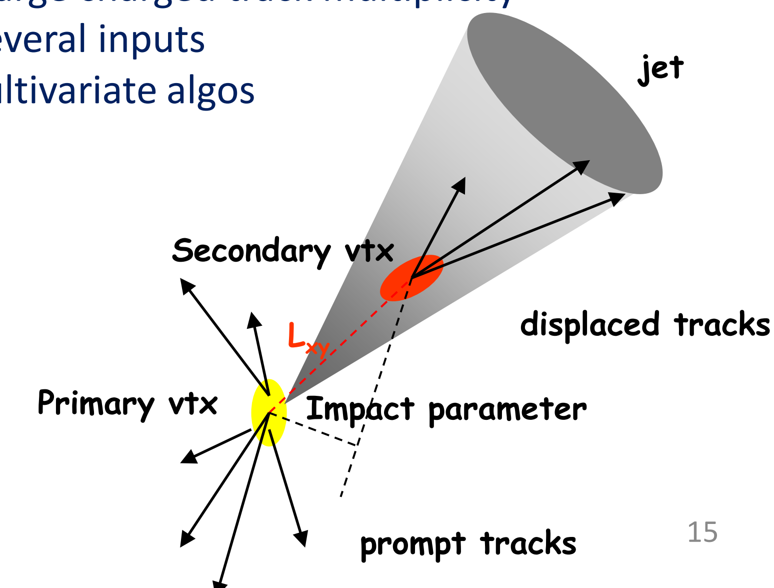
- Measurements of the Z+b(b), W+bb, W+c processes are crucial for the understanding of SM Higgs VH production, H→bb decays, single top, and searches for new physics







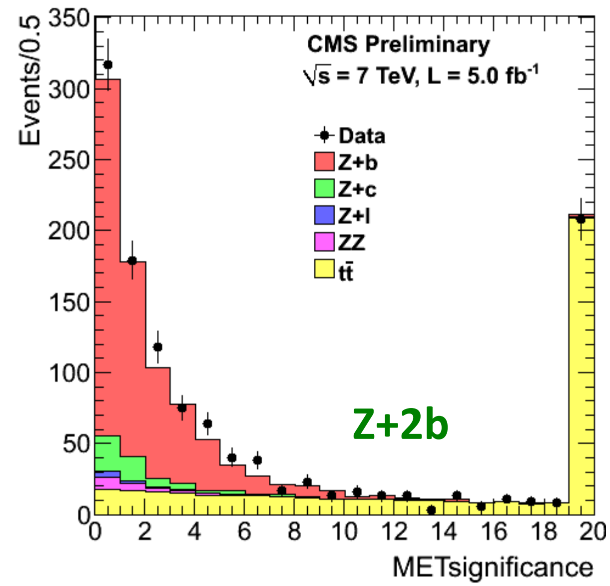
- Rely on displaced vertex reconstruction (HF jet tagging) and bottom/charm separation:
  - Signature of a B hadrons decay is a displaced vertex:
  - ✓ Long lifetime of B hadrons (cτ~450µm)+boost
  - ✓ B hadrons travel L_{xy} ~ 3mm before decaying with large charged track multiplicity
  - ✓ improved tagging performance from combining several inputs (displaced vertex, lifetime, jet kinematics) with multivariate algos
  - c-jets and b-jets separation achieved by explicit reconstruction of D mesons or statistical discriminants.
- Background levels are higher than for V+light jets channels.
- Added model uncertainties include flavour scheme (FS) choices, quark masses, etc.



Z+b(b) cross-section

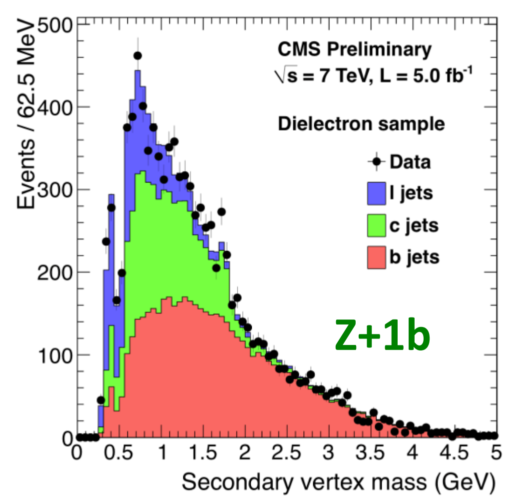
❑ Z+ HF jets selection:

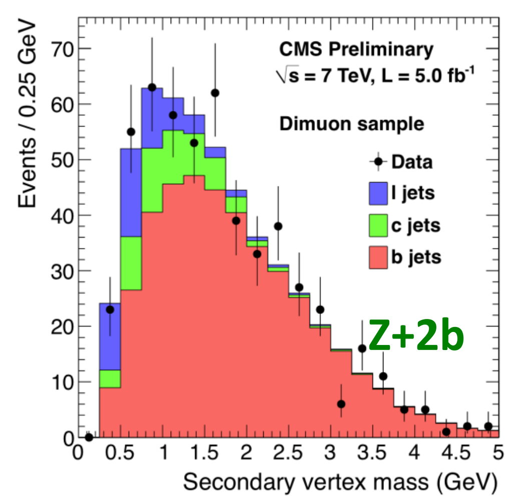
- ✓ two leptons with p_T>20 GeV and $|\eta|$<2.4
- ✓ 1 or 2 b-jets (SSV secondary vertex tagger).
- ✓ jet p_T>25 GeV, $|\eta|$<2.1, and $\Delta R(\ell,\mathrm{jet})$>0.5
- ✓ dilepton mass 76 <$M_{\ell\ell}$ < 106 GeV



❑ Background estimates:

- ✓ ttbar in Z+2b reduced by requiring MET significance <10. Top and Z+jets yields determined from fits to $M_{\ell\ell}$ templates.
- ✓ Z + light jets estimated from fits to secondary vertex mass templates.
- ✓ ZZ from MC simulation, normalized to CMS measurement of σ_{ZZ}.



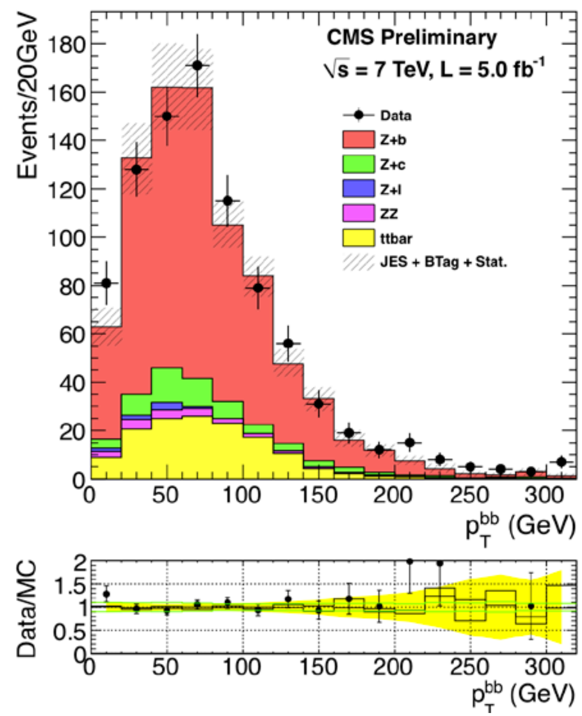


Z+b(b) cross-section

- Measured cross-section is compared to Madgraph (4FS and 5FS) predictions with NNLO scaling: good agreement in both schemes

Multiplicity bin	measured	Madgraph 5 FS	Madgraph 4 FS
σ(Z +1b) (pb)	$3.52 \pm 0.02(stat.) \pm 0.20(syst.)$	$3.66 \pm 0.02(stat.)$	$3.11 \pm 0.03(stat.)$
σ(Z+2b) (pb)	$0.36 \pm 0.01(stat.) \pm 0.07(syst.)$	$0.37 \pm 0.01(stat.)$	$0.38 \pm 0.01(stat.)$
σ(Z+b) (pb)	$3.88 \pm 0.02(stat.) \pm 0.22(syst.)$	$4.03 \pm 0.02(stat.)$	$3.49 \pm 0.03(stat.)$
σ(Z+b) /σ(Z+j) %	$5.15 \pm 0.03(stat.) \pm 0.25(syst.)$	$5.35 \pm 0.02(stat.)$	$4.60 \pm 0.03(stat.)$

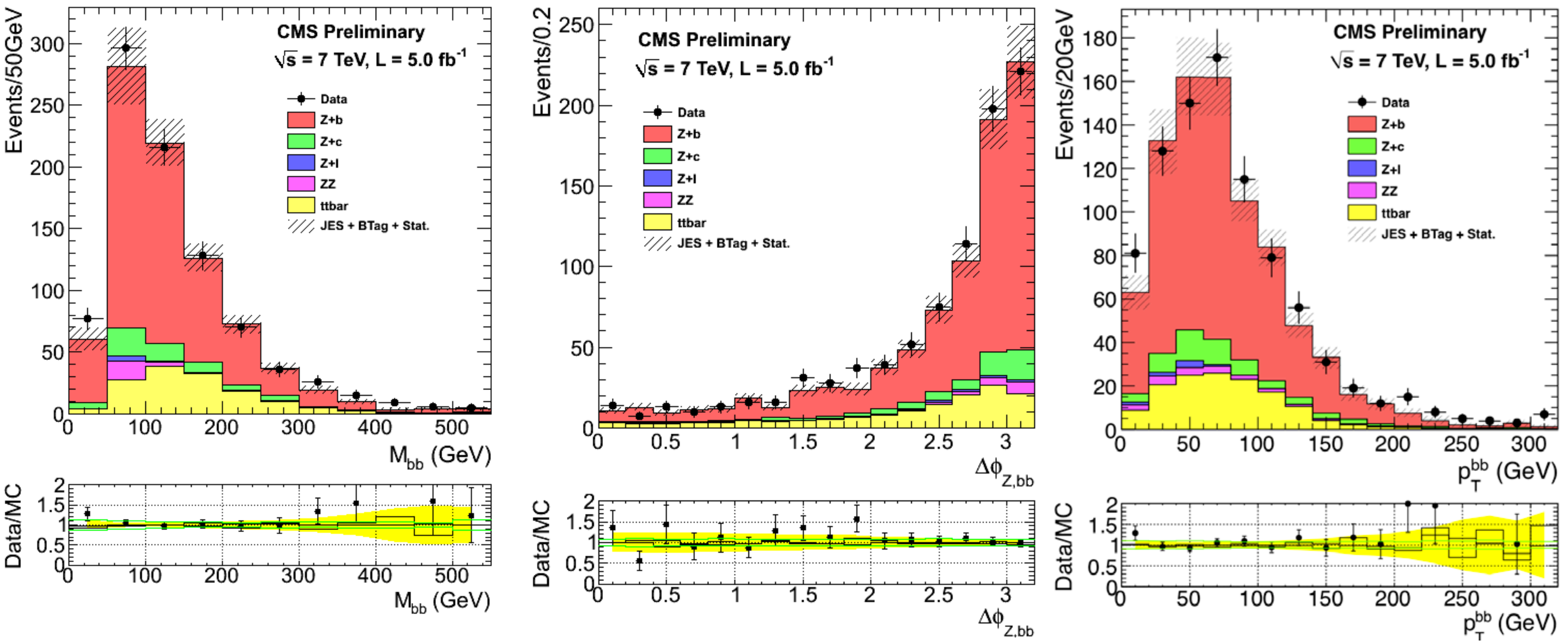
- Kinematic distributions:
  - ✓ Several distributions are in good agreement, M_{bb}, $\Delta\phi(Z,b)$, $\Delta\phi(Z,bb)$
  - ✓ p_T spectra, both $p_T(Z)$ and $p_T(bb)$ are harder than MC prediction. Potential limitations coming from simulation employing ME+PS at LO and massless b-quarks.



- Findings consistent with $2.2 fb^{-1}$ Z+1 b-jet CMS published result: JHEP 06 (2012) 126

Z+b(b) cross-section

- More kinematic distributions:

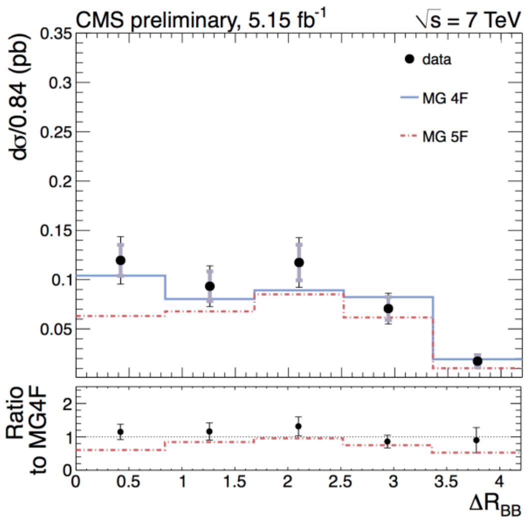


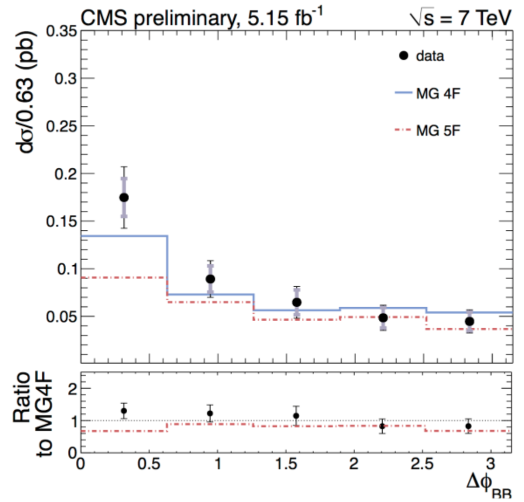
Z+B hadrons cross-section and angular correlations

- Z+ B hadrons selection:
  - ✓ two leptons with p_T>20 GeV and $|\eta|$<2.4
  - ✓ two B hadrons with p_T>15 GeV, $|\eta|$<2.05
  - ✓ dilepton mass 81 <$M_{\ell\ell}$ < 101 GeV
- B hadrons reconstruction: (inclusive vertex tagger)
  - ✓ no jets requirement, makes optimal use of tracking information.
  - ✓ B hadrons are identified as secondary vertices.
  - ✓ Optimal tool for studying production of B hadrons at small angular separations
- Data unfolded to particle-level after background subtraction and efficiency corrections.
- Comparison of total and differential cross-sections with MC predictions:

✓ Reasonable agreement with Madgraph 4F

✓ Madgraph 5F underestimates data in the collinear region

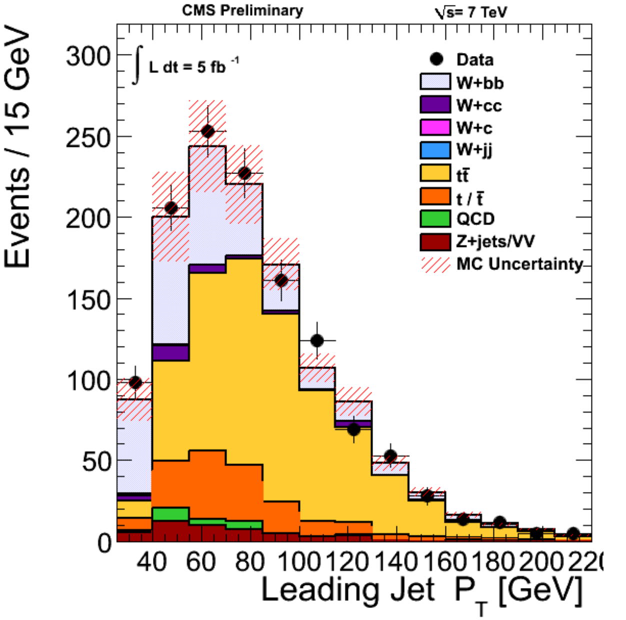


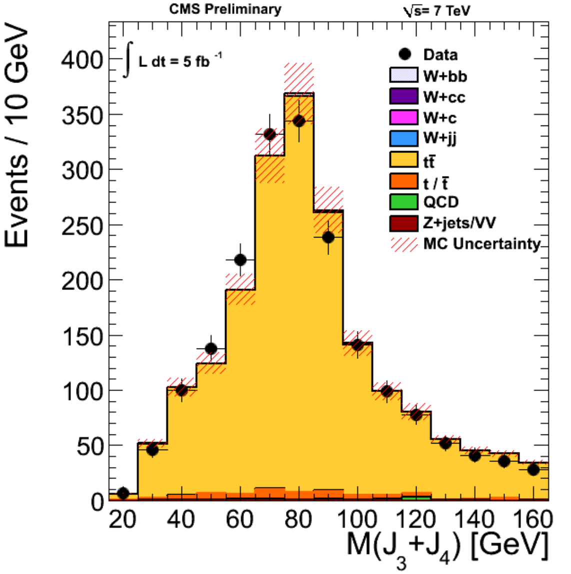


$p_T(Z)$>50 GeV

W+bb cross-section

- **W(→μν)+ HF jets selection:**
  - ✓ one muon with p_T>25 GeV and |η|<2.1
  - ✓ 2 b-jets (CSV combined secondary vertex tagger) with p_T>25 GeV, |η|<2.4.
  - ✓ M_T (μ, E_T^{miss}) > 45 GeV
- **Background estimates:**
  - ✓ Normalizations determined in control regions for Z+jets, ttbar, single top.
  - ✓ The high CSV discriminant value efficiently reduces W+jets (u,d,c,s,g)
  - ✓ Final yields determined from likelihood fit to:
    - Leading jet p_T spectrum in signal region
    - Invariant mass of the two highest p_T light jets in the ttbar control region (4 jets, 2 b-tagged).
- **Background-subtracted data is corrected to the level of final state particles.**





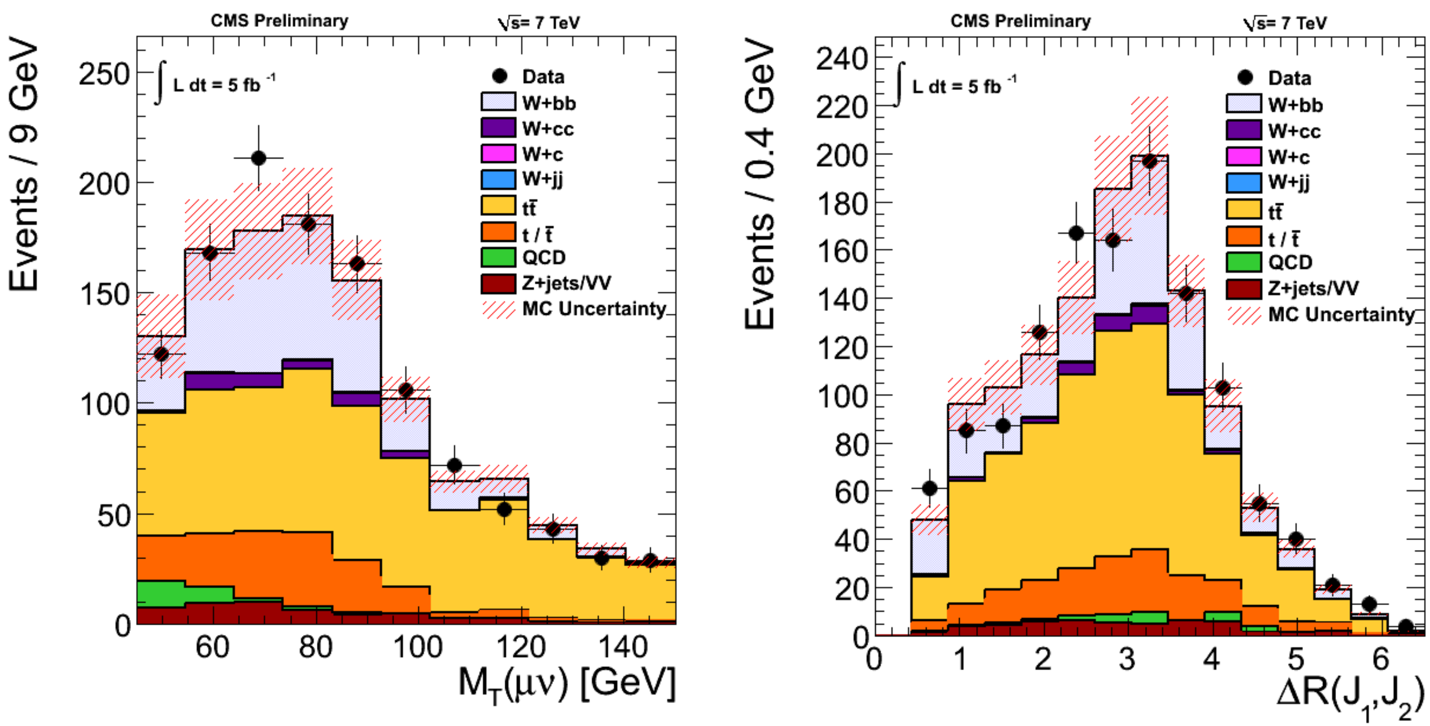
W+bb cross-section

- The fiducial Wbb cross-section is measured to be:

$$\sigma(pp\rightarrow W(\mu\nu)bb) = 0.53\pm0.05(\text{stat.}) \pm 0.09(\text{sys.}) \pm 0.06(\text{theory}) \pm 0.01(\text{lumi})\ \text{pb}$$

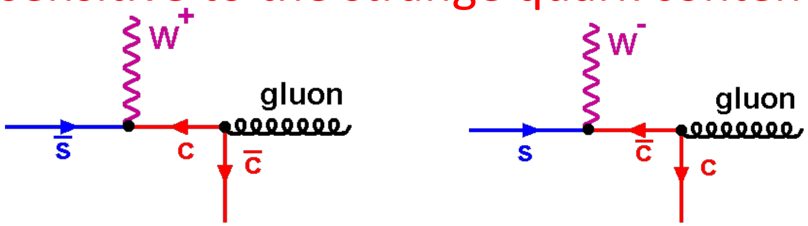
well in agreement with the MCFM NLO prediction of 0.52±0.03 pb

- Kinematics in general well described by MC simulation (Madgraph+Pythia scaled to NNLO):



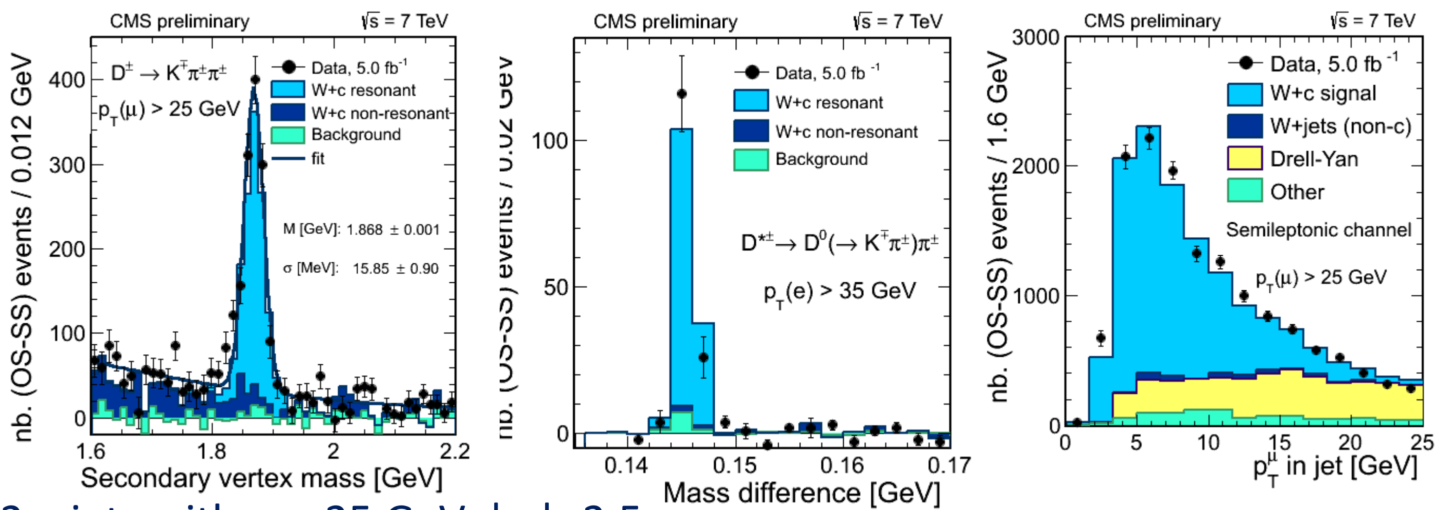
W+c cross-section

- Measurement sensitive to the strange quark content of the proton:



Signature: a W boson and a c-quark of opposite charge in the final state.

- W+c selection:
  - ✓ one lepton with p_T>25 GeV and $|\eta|$<2.1
  - ✓ c-tagging according to one of three algorithms:
    1. A secondary vertex associated with the reconstruction of a $D^{\pm}$ decay
    2. A secondary vertex associated with the reconstruction of a $D^{*\pm}$ from D^0 decay
    3. A semileptonic decay muon



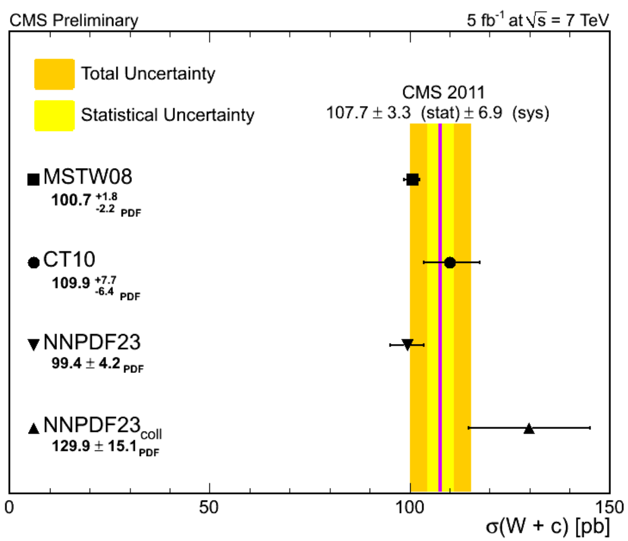
  - ✓ 2 c-jets with p_T>25 GeV, $|\eta|$<2.5.
  - ✓ M_T (ℓ, E_T^{miss}) > 20 GeV

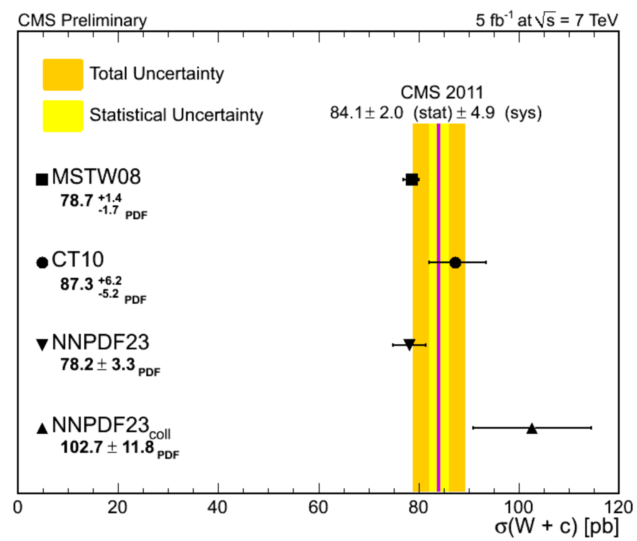
W+c cross-section

- Background estimates:
  - ✓ W and c charge asymmetry used to reduce bkg by using (OS-SS) distributions.
  - ✓ Exclusive reconstruction of $D^{\pm}$ and $D^{*\pm}$ reduces lower track multiplicity bkg.
  - ✓ Non-resonant W+c dominates bkg. Determination from side-bands.
- Measurement of the fiducial W+c cross-section:

  $\sigma(pp\to W+c+X) \times BR(W\to \ell\nu) = 107.7 \pm 3.3(stat.) \pm 6.9(sys.)$ for $p_T^{\ell} > 25$ GeV

  $\sigma(pp\to W+c+X) \times BR(W\to \ell\nu) = 84.1 \pm 2.0(stat.) \pm 4.9(sys.)$ for $p_T^{\ell} > 35$ GeV
- Comparison with MC predictions:
  - ✓ MCFM with different NNLO PDF sets. Set with symmetric light/strange seas ($NNPDF2.3_{coll}$) disfavored though still statistically compatible.



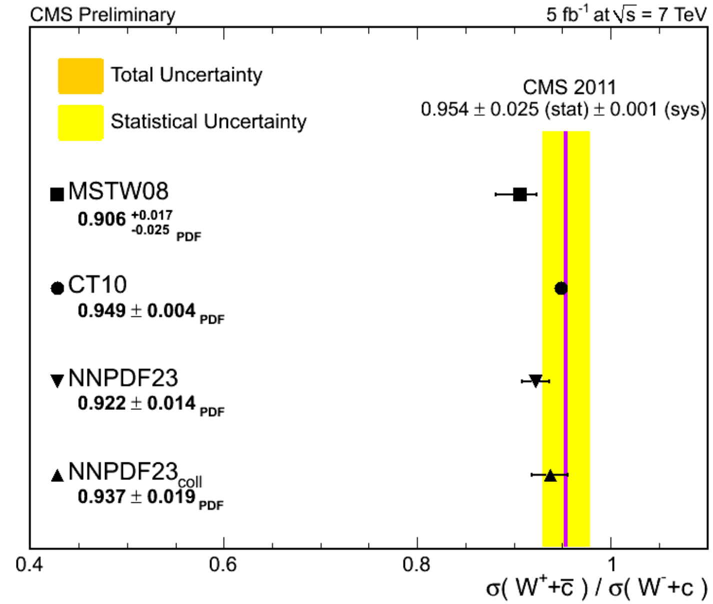


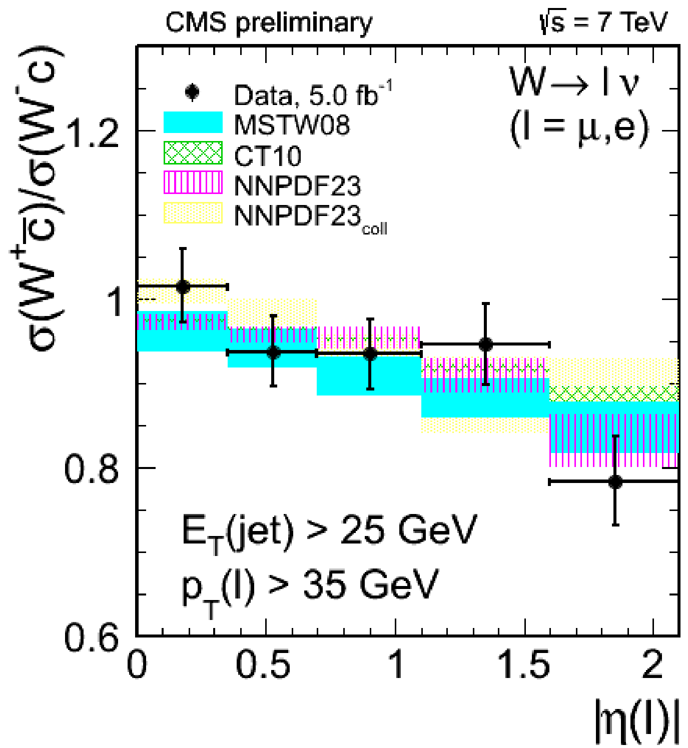
W+c cross-section

- Measurement of the cross-section ratio:

$$R_c^{\pm} = \frac{\sigma(W^+ + c)}{\sigma(W^- + \bar{c})}$$

- ✓ Inclusive and differential in lepton η
- ✓ Sensitive to asymmetry in both the strange and the light quark content of the proton

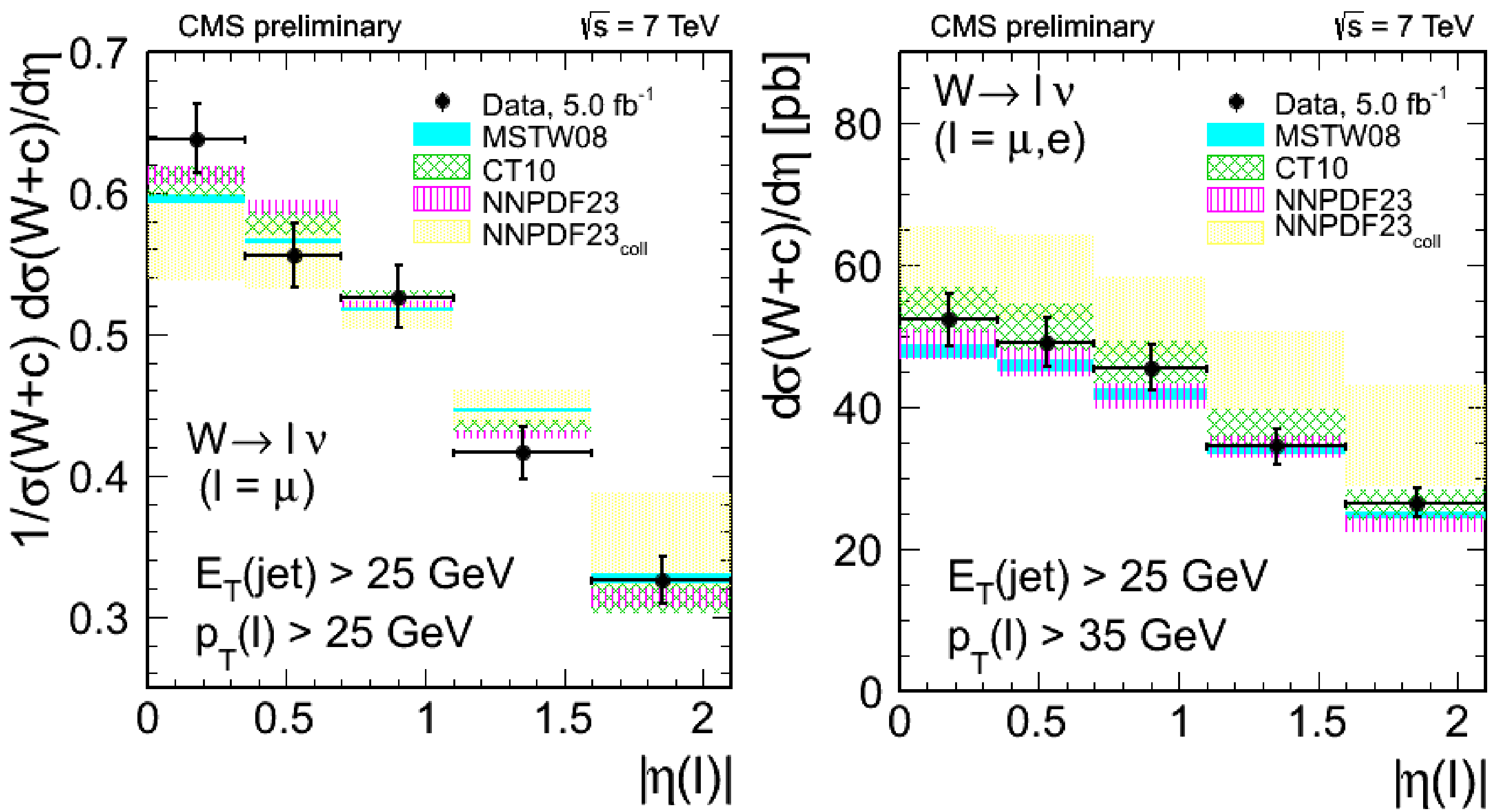




- Comparison with MC predictions:
  - ✓ MCFM with different NNLO PDF sets.
  - ✓ Overall good agreement.
  - ✓ Large variations in values and uncertainties due to different assumptions on the strange anti-strange content of the proton and to different experimental inputs.

W+c differential cross-sections

- Measurement of (normalized) differential cross-section in lepton η:
  - ✓ Useful inputs for constraining PDFs



- Comparison with MC predictions (MCFM with different NNLO PDF sets):
  - ✓ Overall good agreement. As with $R^{\pm}_{c}$, variations in PDF predictions are expected.

Conclusions

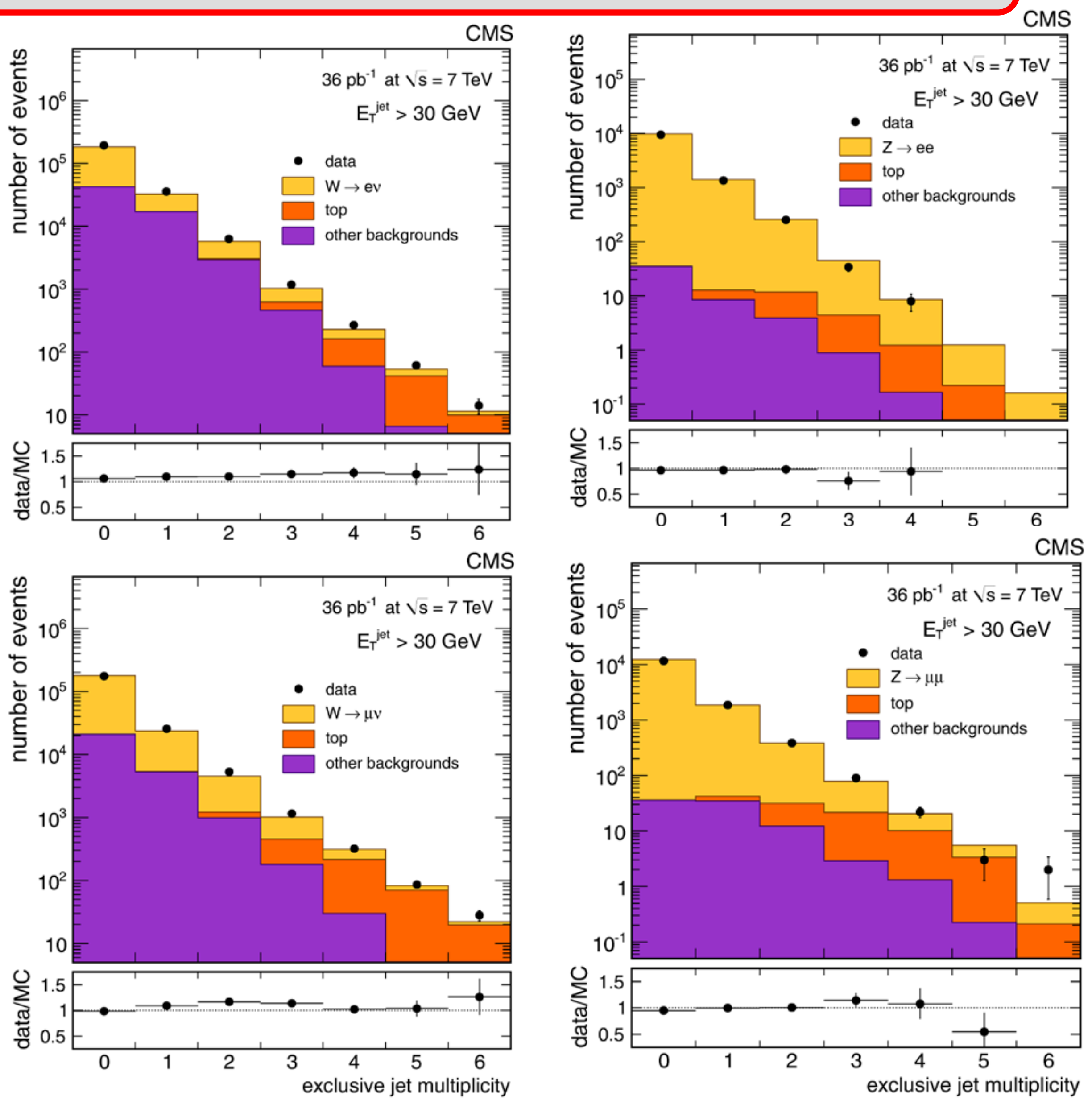
- High statistics allows for a wide variety of measurements in V+jets, detailed determination of kinematic variables and differential cross-sections, HF jets measurements (very crucial for Higgs studies and new physics searches), and studies of DPS.
- Mostly, measurements agree with NNLO predictions and approaching NNLO uncertainties, although discrepancies are observed in several places, pointing to the necessity of a more detailed understanding of the differences between generator implementations, matching schemes, flavor schemes etc.
- Measurements are providing important inputs to the PDF global fits.
- Increased measurement precision and reach to come with the analysis of the 2012 data.

Backup

JHEP 01 (2012) 010

W and Z + jets differential cross-sections

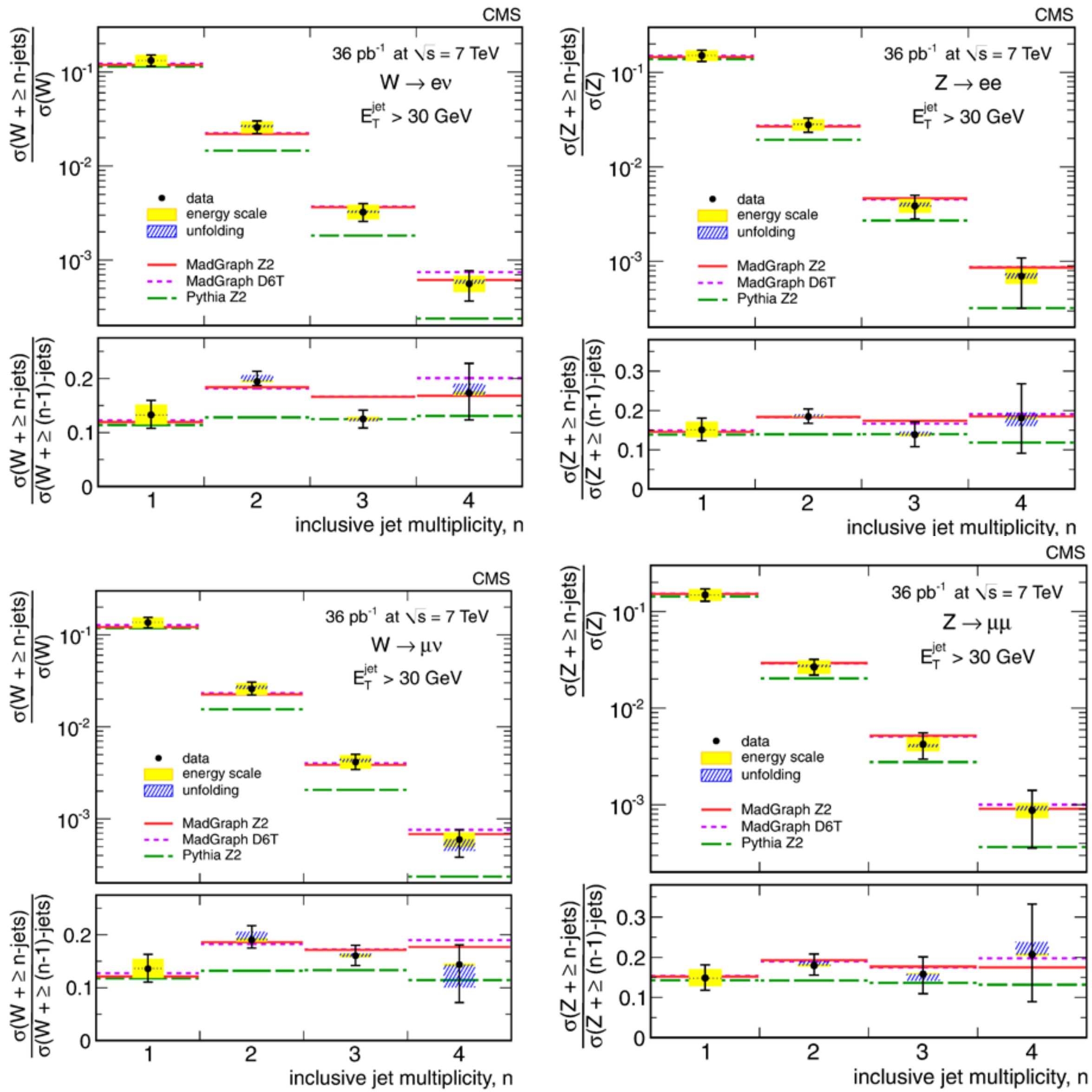
- Early 7 TeV measurement ($36\ pb^{-1}$)



JHEP 01 (2012) 010

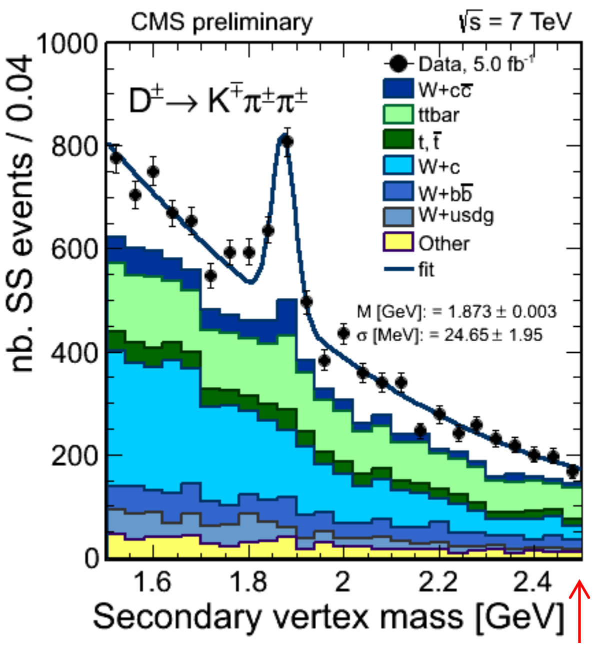
W and Z + jets differential cross-sections

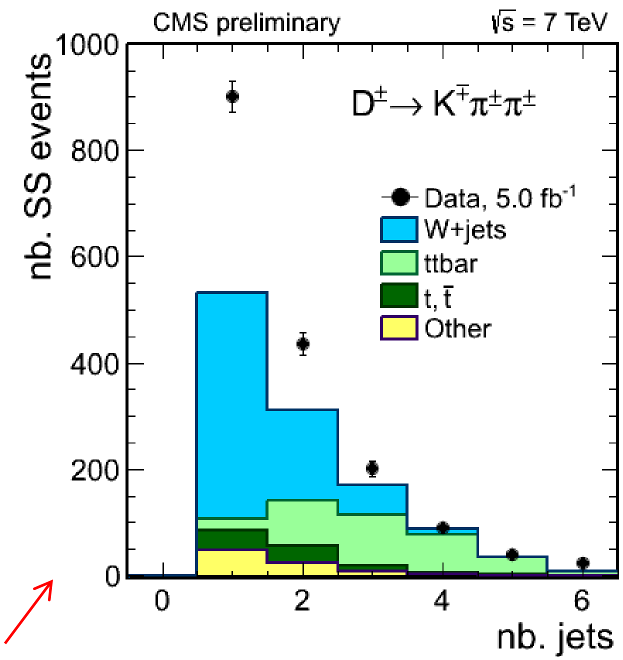
- Unfolded jet multiplicity ratios



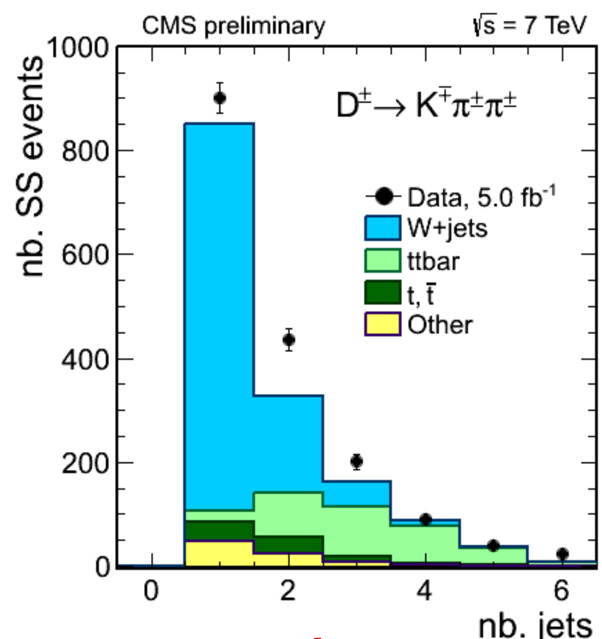
Wbb and Wcc backgrounds (W+c analysis)

- While the measured W+c cross sections are in general consistent with theoretical predictions (within 10%) , data distributions sensitive to Wbb, Wcc backgrounds (Same Sign charm meson and W) show larger differences between MC generators.





Madgraph+Pythia



Sherpa

Dependency of the signal peak region on jet multiplicity

- Differences possibly due to the PS description of the kinematic region dominated by hard-collinear gluon-splitting into heavy quarks.