V+Jets in CMS

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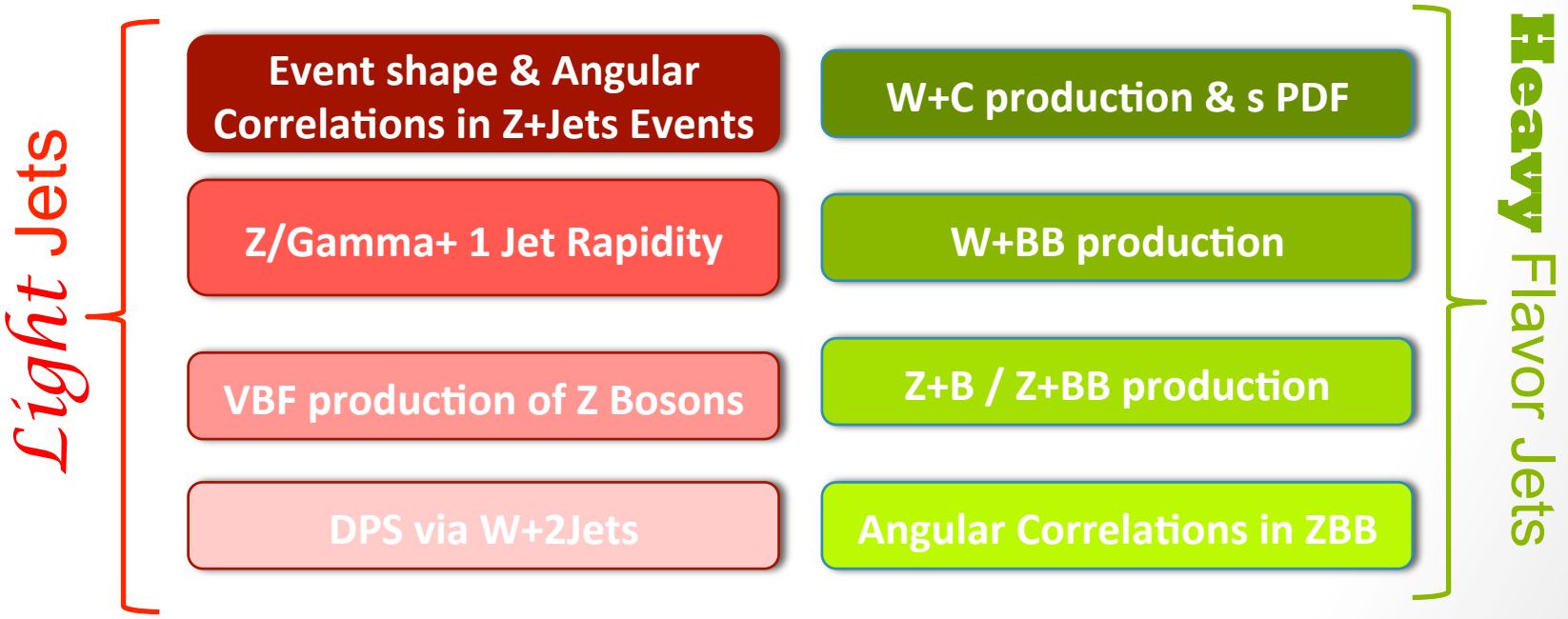
PASCOS 2013: 19th International Symposium on Particles, Strings and Cosmology

Vector Boson + Jets

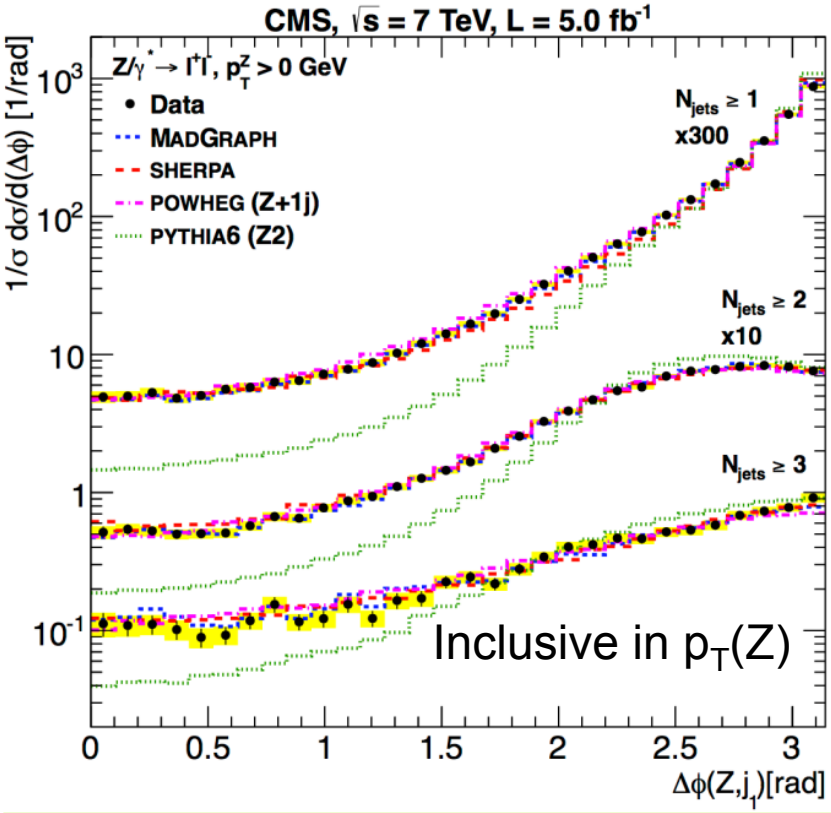
- The study of the production and kinematics of vector bosons associated with light and heavy jets provides an excellent testing ground for perturbative QCD predictions and Monte Carlo techniques
- CMS counts with an extensive program for V+Jets studies, covering from cross section measurements to angular correlation studies → this talk will focus on some of CMS most recent results:

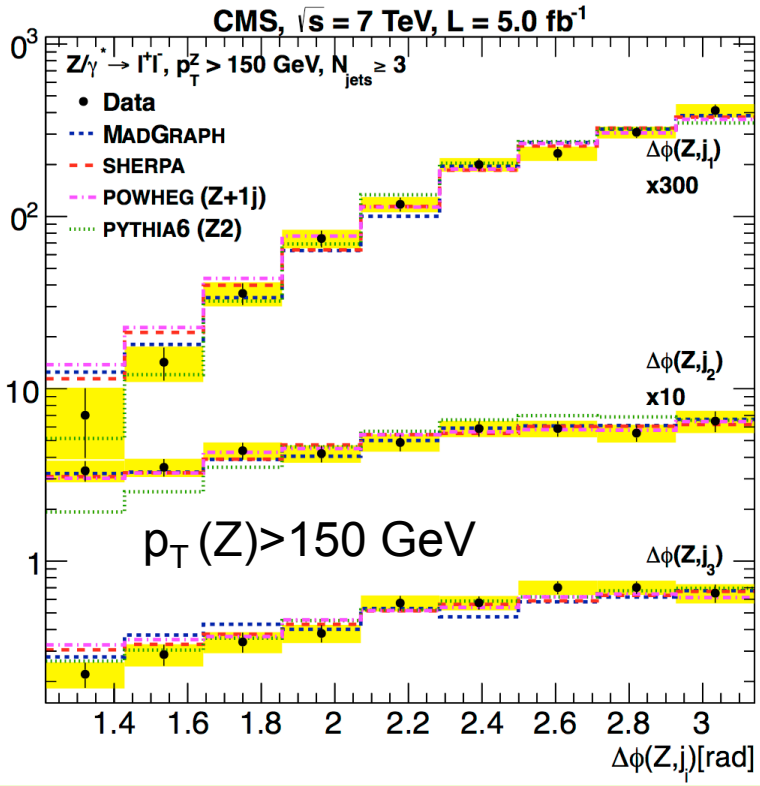


Event Shape & Angular Correlations in Z+Jets (I)

- Topological properties on azimuthal plane, inspired by dijet observables
- Boosted Z (p_T > 150 GeV) explored for the first time → phase space very critical for searches for new phenomena based on large imbalanced system

Measured Δφ correlations between Z and up to the 3rd jet, and between jets:





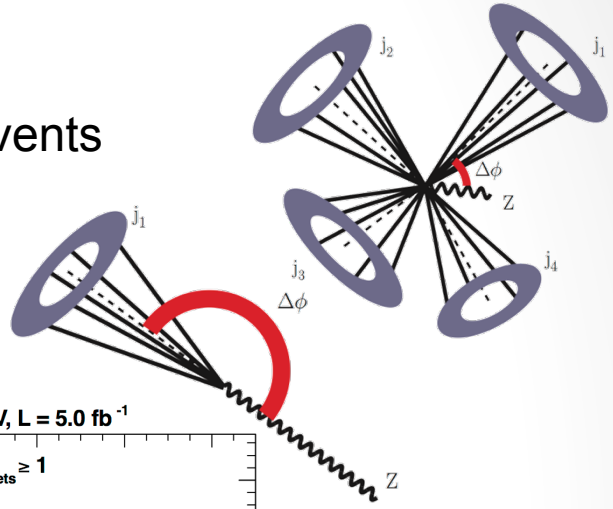
Madgraph, Sherpa, Powheg describe data well at low and high ZP_T for events with 1-3 jets

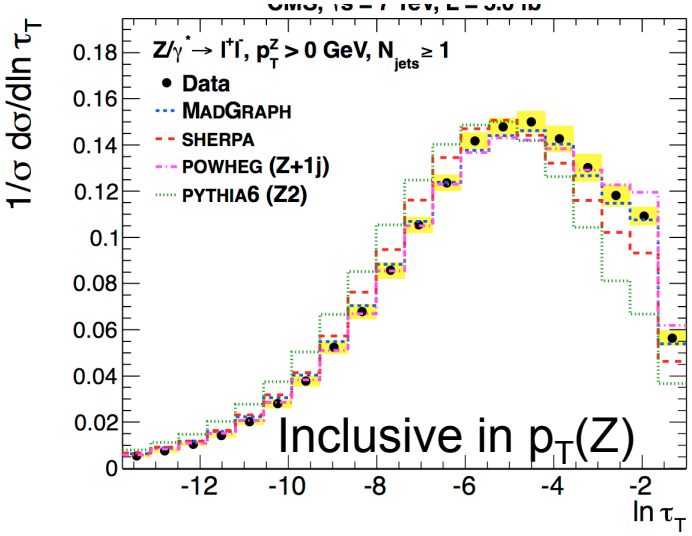
Phys. Lett. B 722 (2013) 238–261
arXiv:1301.1646

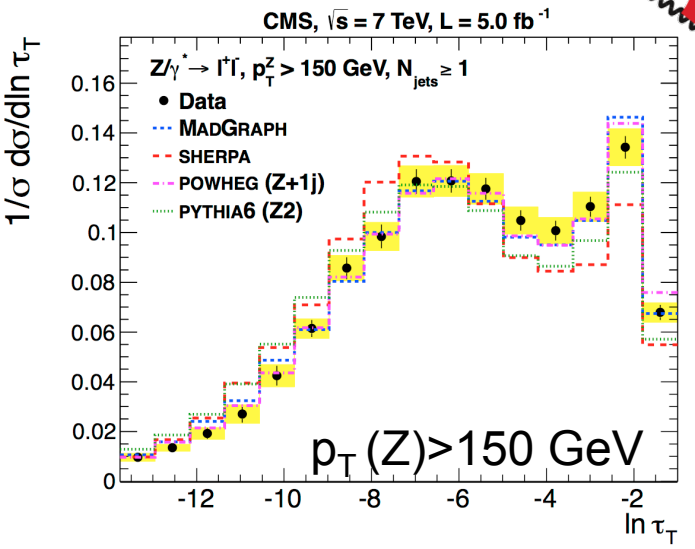
Event Shape & Angular Correlations in Z+Jets (II)

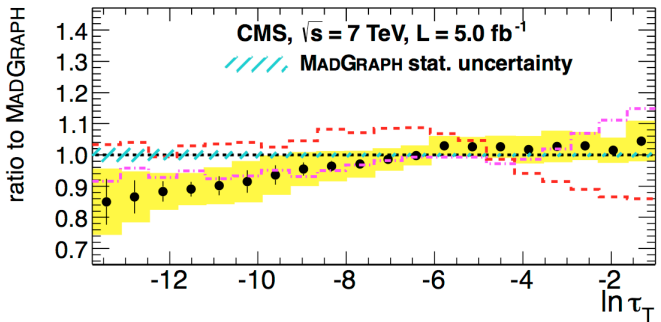
Sensitivity to the modeling of Z+2 jet and Z+3 jet events enhanced through the thrust variable:

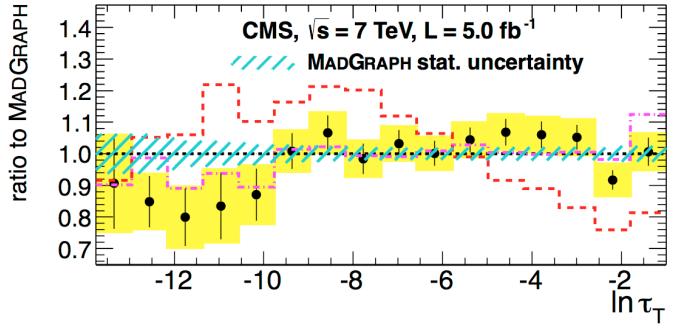
$$\tau_T \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_\tau|}{\sum_i p_{T,i}},$$









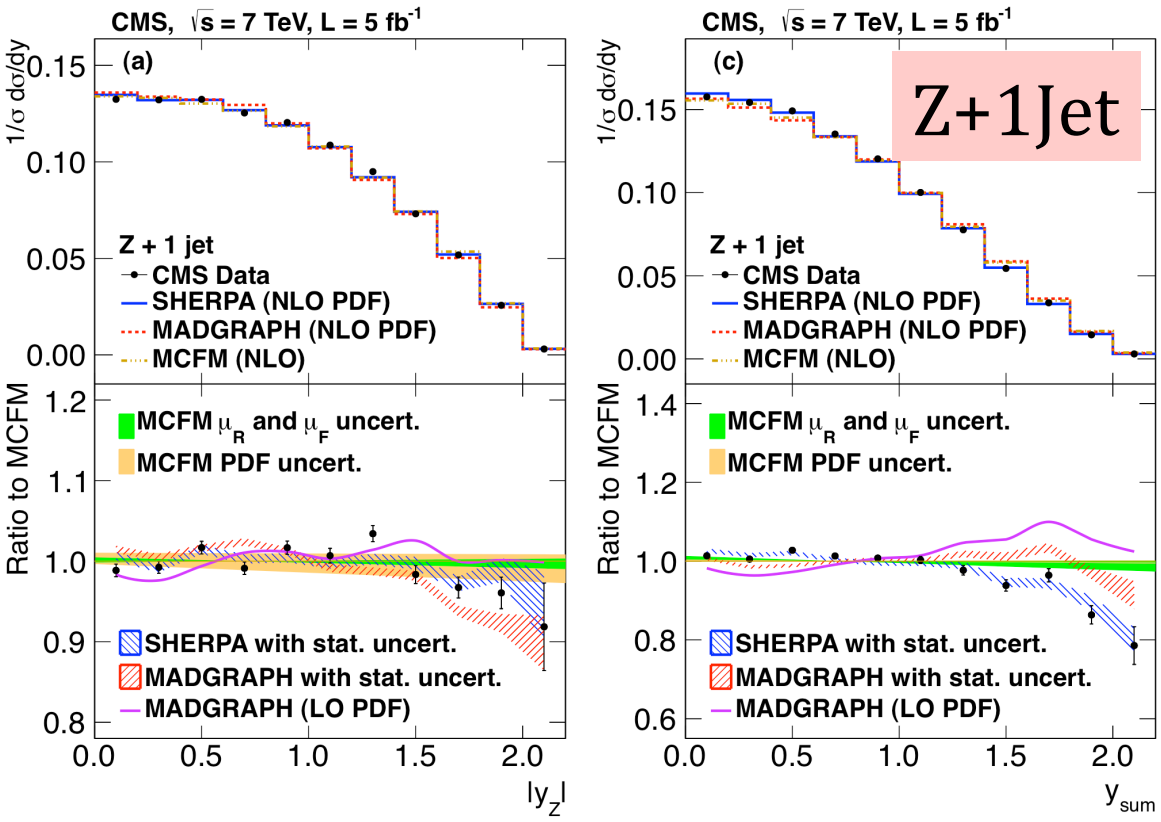


Well described by Madgraph & Powheg – tension with Sherpa

Phys. Lett. B 722 (2013) 238–261
arXiv:1301.1646

Measurement of Z/γ+ jet angular distributions (I)

- Observables based on Y_V, Y_{jet}:
  - $Y_{dif}=(Y_V-Y_{jet})/2$ → closely related to cosθ*
  - $Y_{sum}=(Y_V+Y_{jet})/2$ → boost from the lab frame to the rest frame of the system



Comparison of unfolded rapidity distributions:

- Good agreement (5%) with NLO (MCFM, Owens) for all observables
- Y_V, Y_{jet} → Agreement at the 5% level for MG and Sherpa (LO+PS)
- Y_{dif}, Y_{sum} → Sherpa and MG show different behavior (MS+PS difference). Better description of the data with Sherpa.

Exactly 1 jet (p_T>30 GeV, |η|<2.4); Boson p_T>40 GeV

arXiv:1310.3082 (accepted by PRD)

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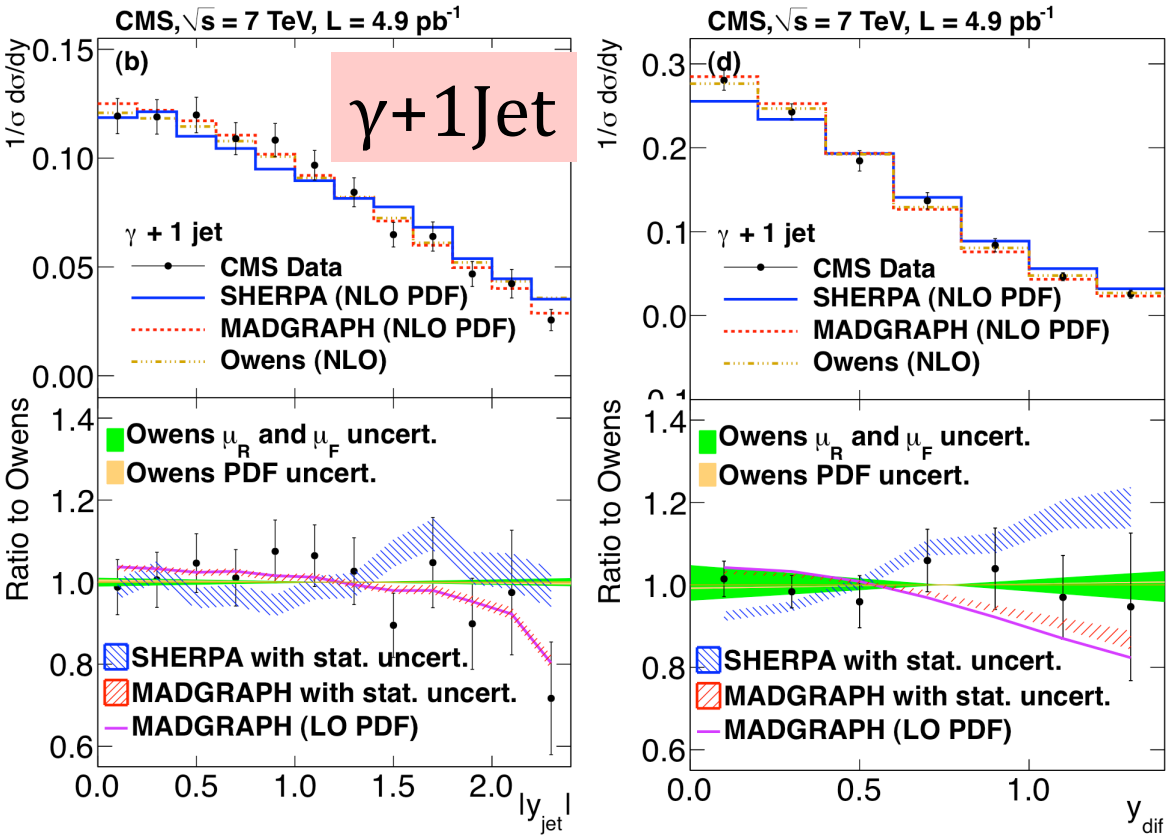

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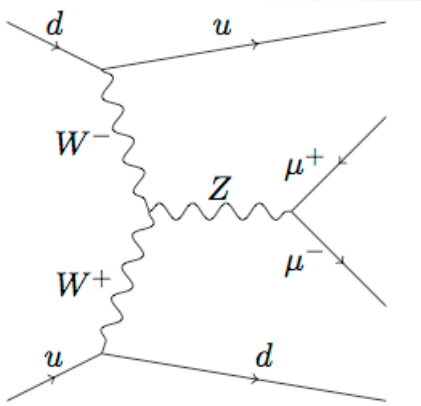
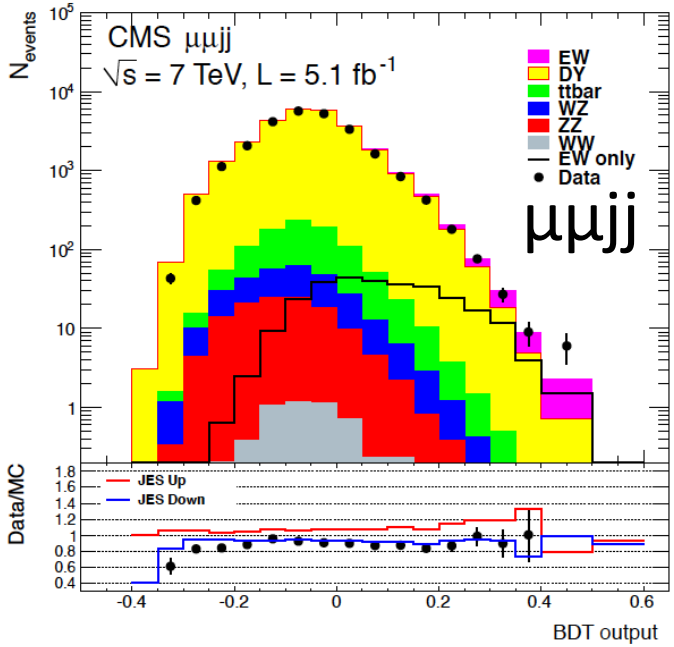
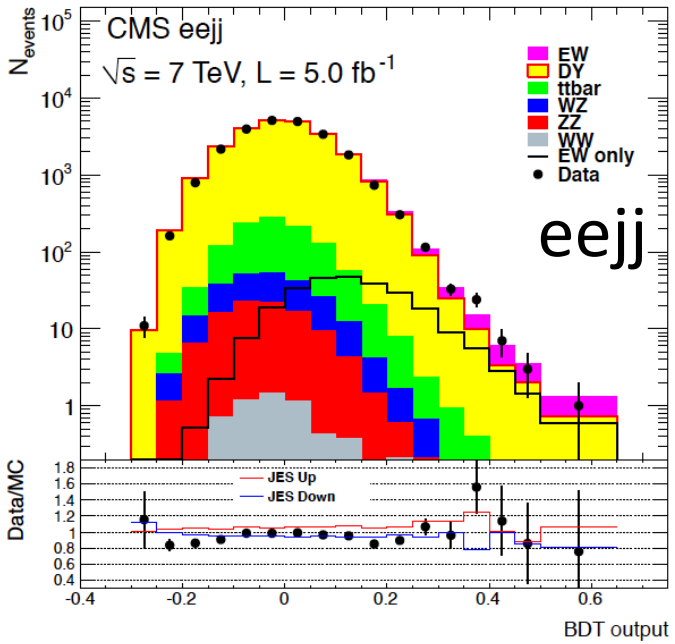
Measurement of VBF Z production at 7 TeV …

- Benchmark for VBF Higgs searches
- Dominant background from standard DY production → BDT discriminant used to extract the signal
- Measurement of the hadronic activity in the rapidity gap between the forward-backward jets



$$\sigma^{EWK}_{\text{meas, }\mu\mu+ee} = 154 \pm 24(\text{stat.}) \pm 46(\text{exp.syst.}) \pm 27(\text{th.syst.}) \pm 3(\text{lumi.})\ \text{fb}$$





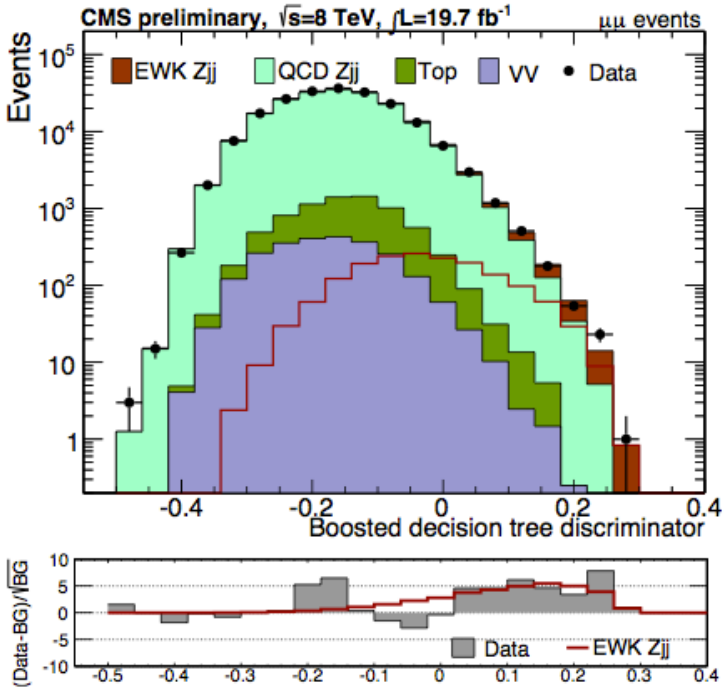
Agreement with NLO prediction (σ_{NLO}(EWK lljj)=166 pb, VBFNLO, CT10)

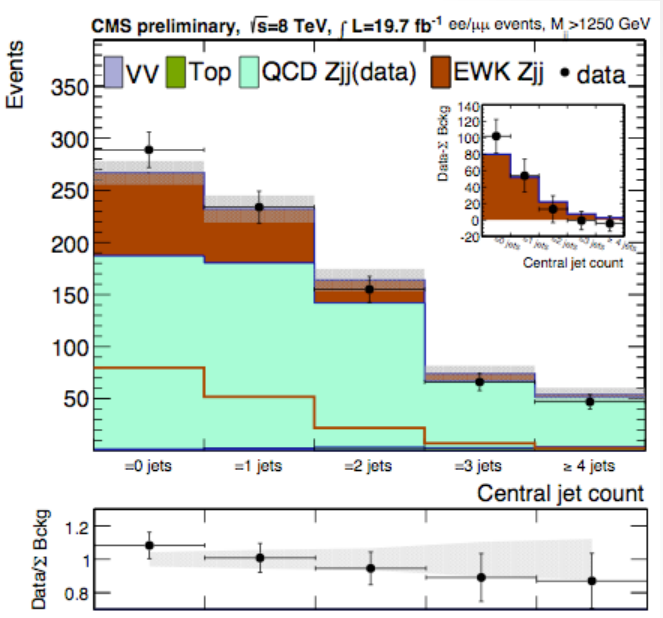
JHEP 10 (2013) 101
arXiv:1305.7389

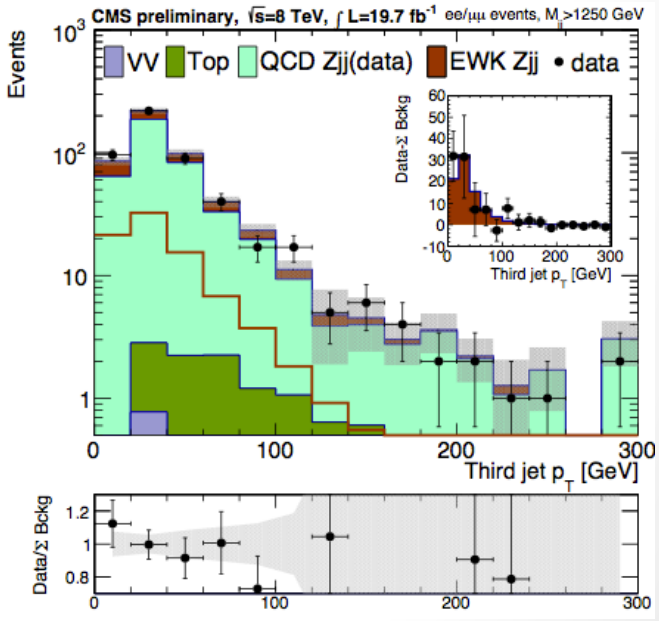
… and 8 TeV

$$\sigma^{EWK}_{\text{meas},\,\mu\mu+ee} = 226 \pm 26(\text{stat.}) \pm 35(syst.)\ \text{fb}$$

(NLO prediction: 239 fb)







Multijet properties explored in EWK-enriched subsample (Mjj > 1250 GeV) → Kinematics of the third jet & central jet multiplicity well described by Madgraph (w. kfactor)

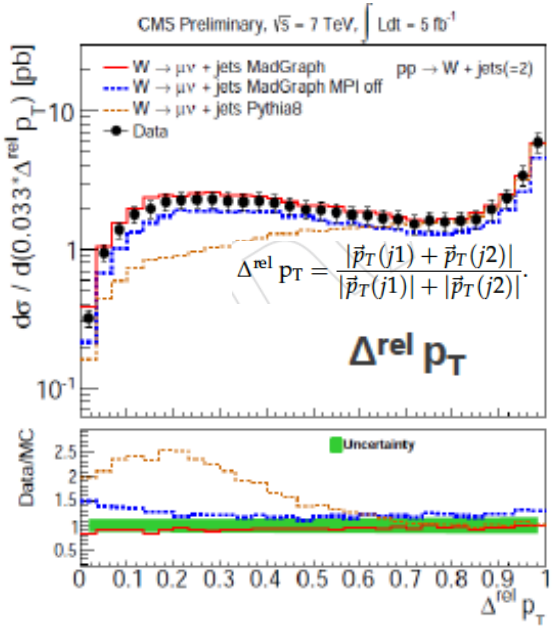
Double Parton Scattering via W+2jets

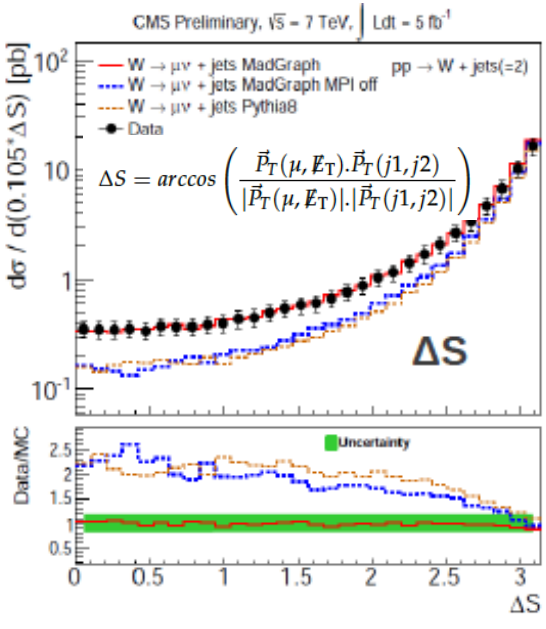
- Study of DPS processes provides information on:
  - Spatial structure of hadrons.
  - Multi-parton correlations in hadronic wave function.
  - Background in new Physics searches at LHC
- Studied in W + 2 jets events

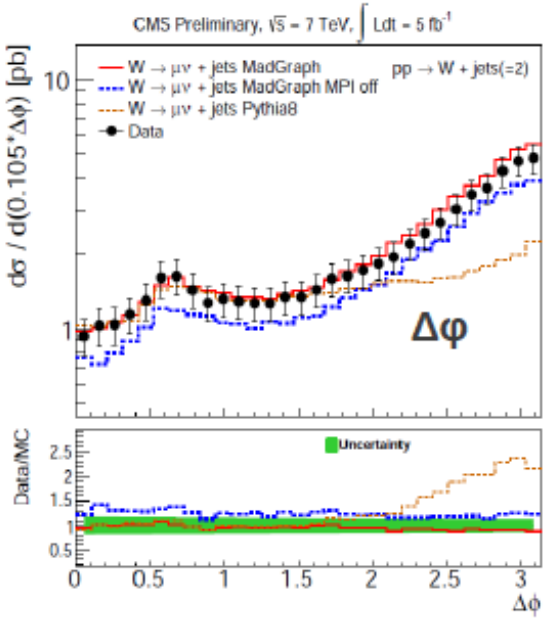
  → Main background, SPS production of W

- Nice agreement of corrected data with MadGraph MPI on.
- MadGraph without MPI underestimates data by 19%.
- Pythia8 underestimates by a factor of 1-2 in DPS sensitive region (missing higher order processes)

- Exclusive (==2 jets) and inclusive (>=2 jets) results
- Observables unfolded and compared to Madgraph+Pythia6 (Z2*, with and without MPI) and Pythia8 (4C tune, MPI on)





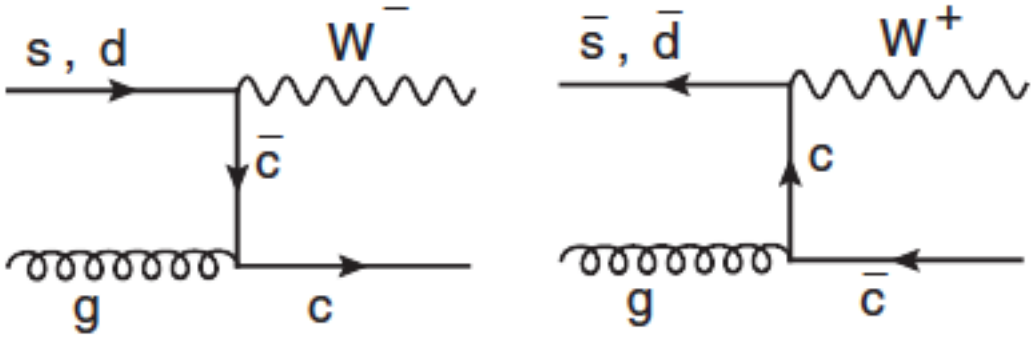


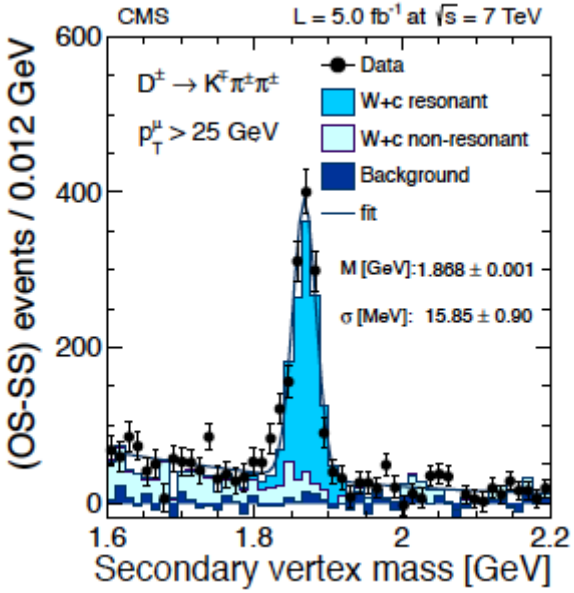
Measurement of associated charm production in W final states

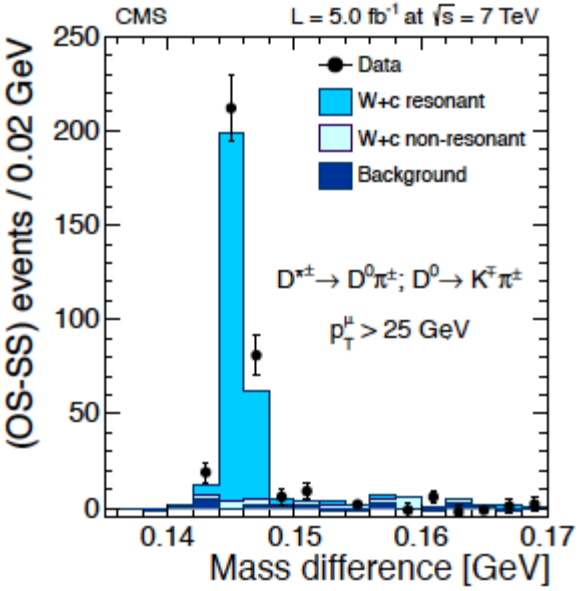
- **$\sigma(W^+ + \bar{c})$ and $\sigma(W^- + c)$**

→ **Direct probe to the strange content of the proton**

→ **Precise input to future PDFs**







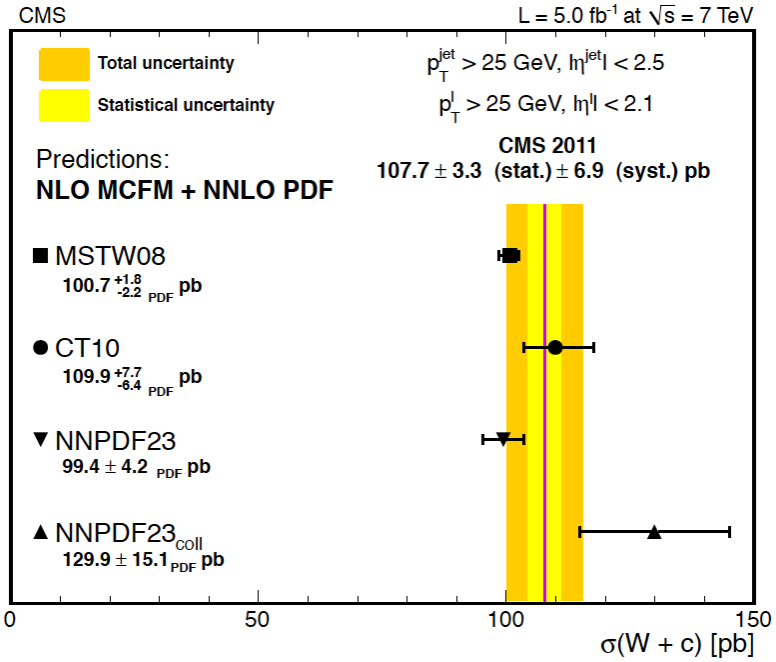
- OS-SS strategy reduces to a minimum background contamination from other Lepton+HeavyJet processes → Counting experiment (essentially background free)
- **c tagging through decay mode identification:**
  - reconstruction of $D^{\pm}$, D* and dilepton decays
  - unambiguous charge identification
- 6 independent measurements (2 lepton flavors (muon, electron) x 3 decay modes)

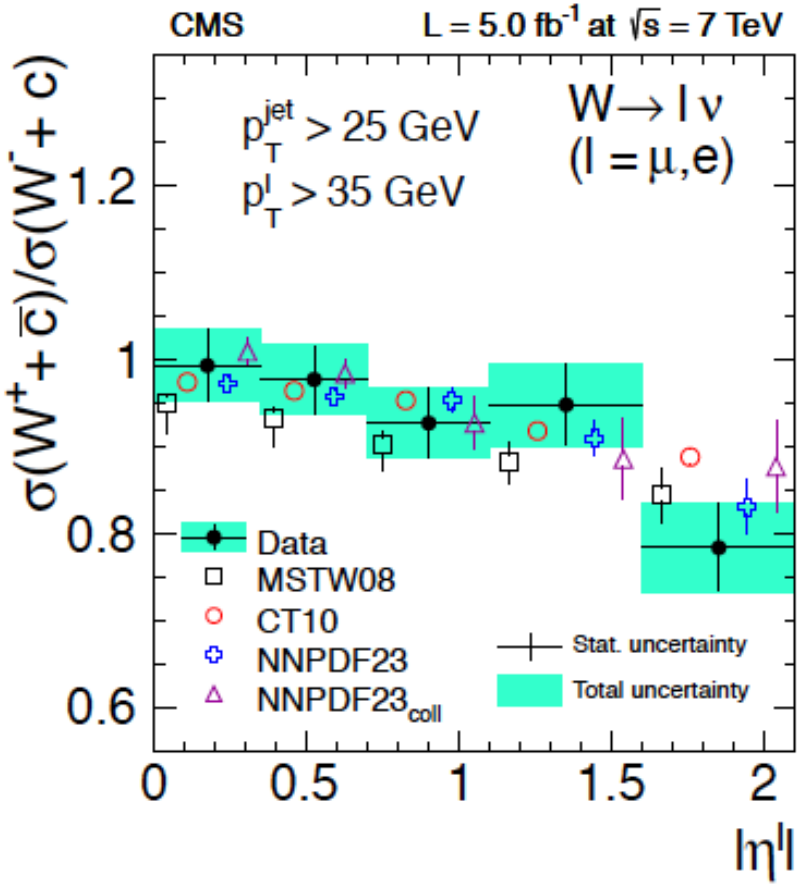
Cross Section & Charge Ratio

$$\sigma(W+c) = \frac{N_{sel} - N_{bkg}}{\mathcal{L}_{int}\,\mathcal{B}\,\mathcal{A}\,\epsilon}$$

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

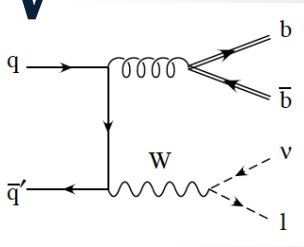
- **MCFM 6.1 at NLO:** CT10, MSTW08, NNPDF2.3 (also coll. only), ABM11 JR09 and HERAPDF1.5
- 5 bins of muon and electron pseudorapidity





Good agreement with theoretical predictions at NNLO

W+$b\bar{b}$ cross section at 7 TeV

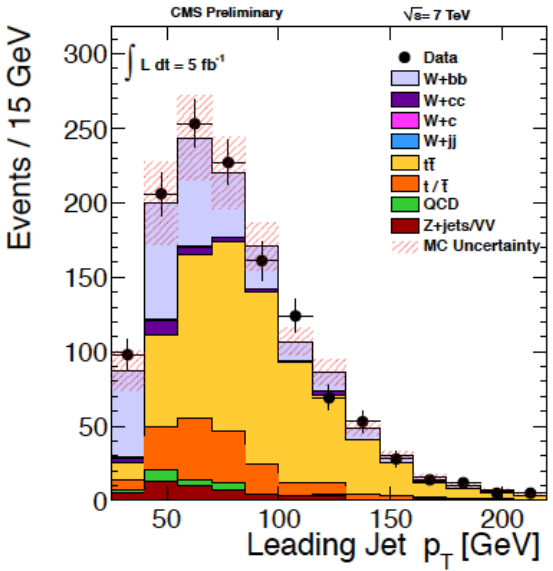


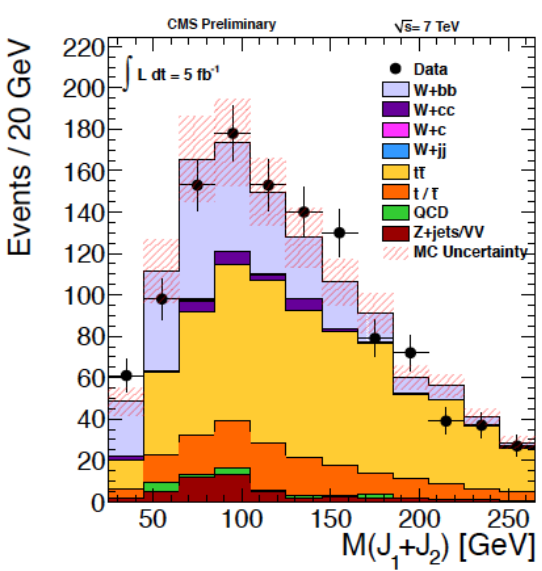
- Production of W + central b jets
  - Historical disagreement between experiment and data
  - Critical background for searches (Hbb, BSM)
- Phase-Space of the measurement: **Wμν + 2 well identified, separated b jets, veto on extra jets**

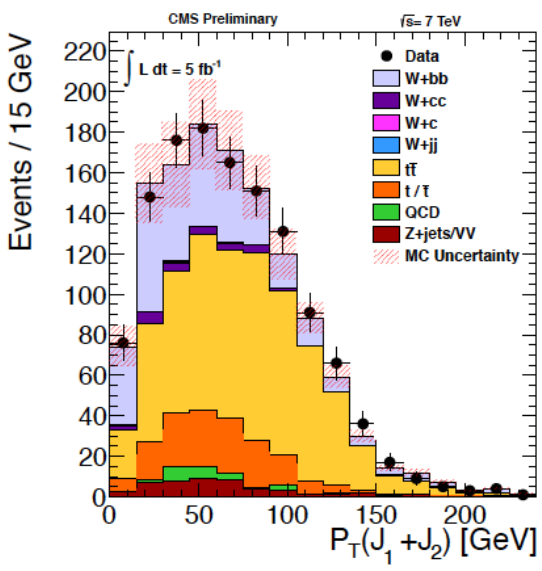
  → **First measurement performed in this phase-space!**
- Signal extraction via a binned maximum-likelihood fit (leading jet pt, ttbar CR)
- Agreement at the 1 sigma level with the prediction (MCFM@NLO, 0.52+-0.03 pb)

$$\sigma(pp \to \mathrm{W} + \mathrm{b\bar{b}}, p_T^{\mathrm{b}} > 25\ \mathrm{GeV}, |\eta^{\mathrm{b}}| < 2.4) \times \mathcal{B}(\mathrm{W} \to \mu\nu, p_T^{\mu} > 25\ \mathrm{GeV}, |\eta^{\mu}| < 2.1) = \\ = 0.53 \pm 0.05\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{theo.}) \pm 0.01\,(\mathrm{lum.})\ \mathrm{pb}.$$

- Event kinematics well described by MadGraph :

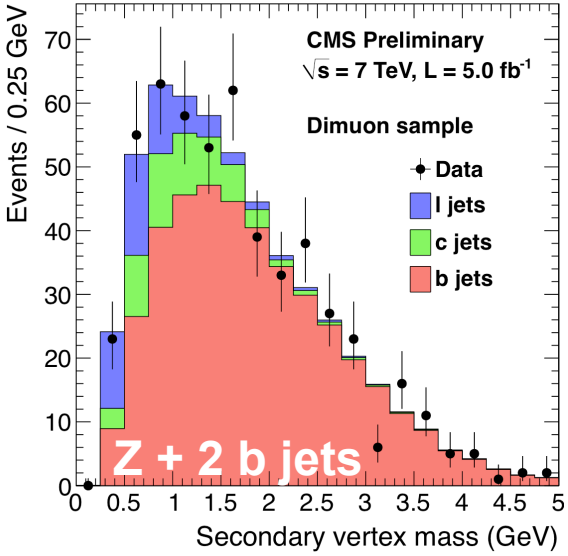


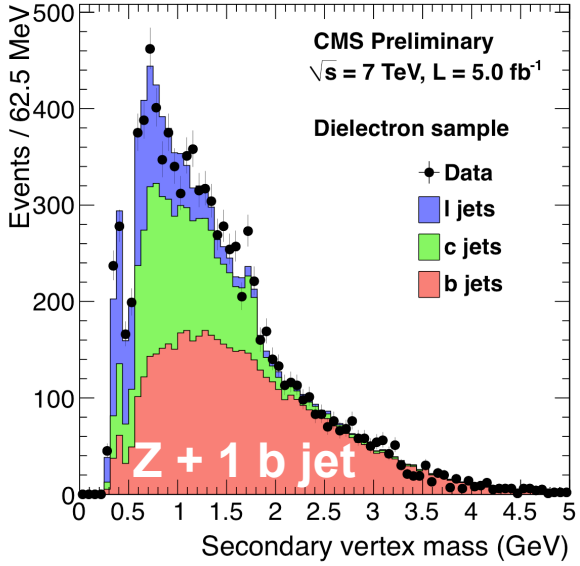


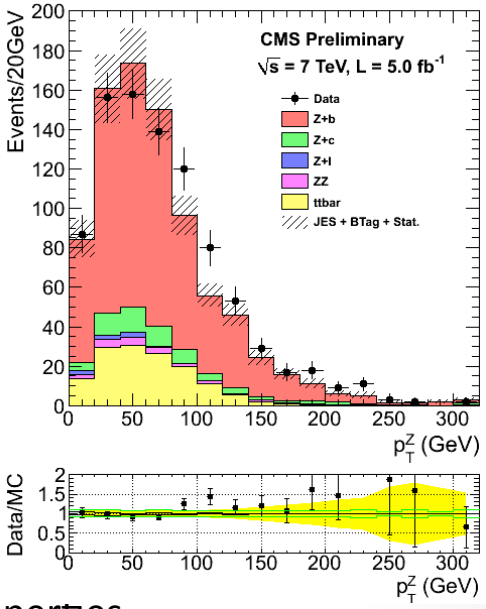


Z+b / Z+bb

- Based on the identification of b-quark jets based on reconstruction of b decay vertex







- Overall good agreement in the data/MC comparison of kinematic properties

→ some tension in Z P_T

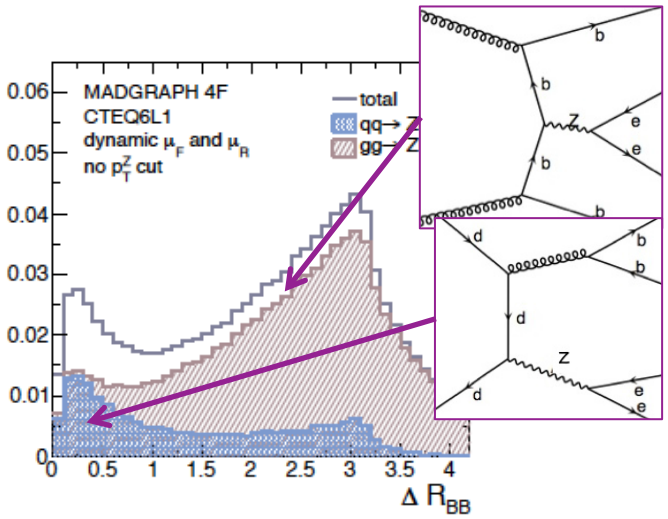
Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)+b)$ (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03

(MadGraph predictions scaled up to NNLO using a global k factor)

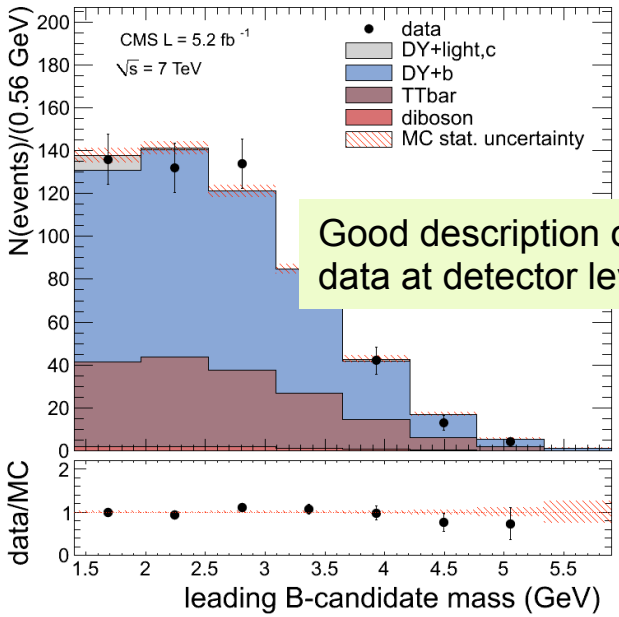
Extension of the previously published result (J. High Energy Phys. 06 (2012) 126 arXiv:1204.1643)

Good agreement with both MG5F and MG4F

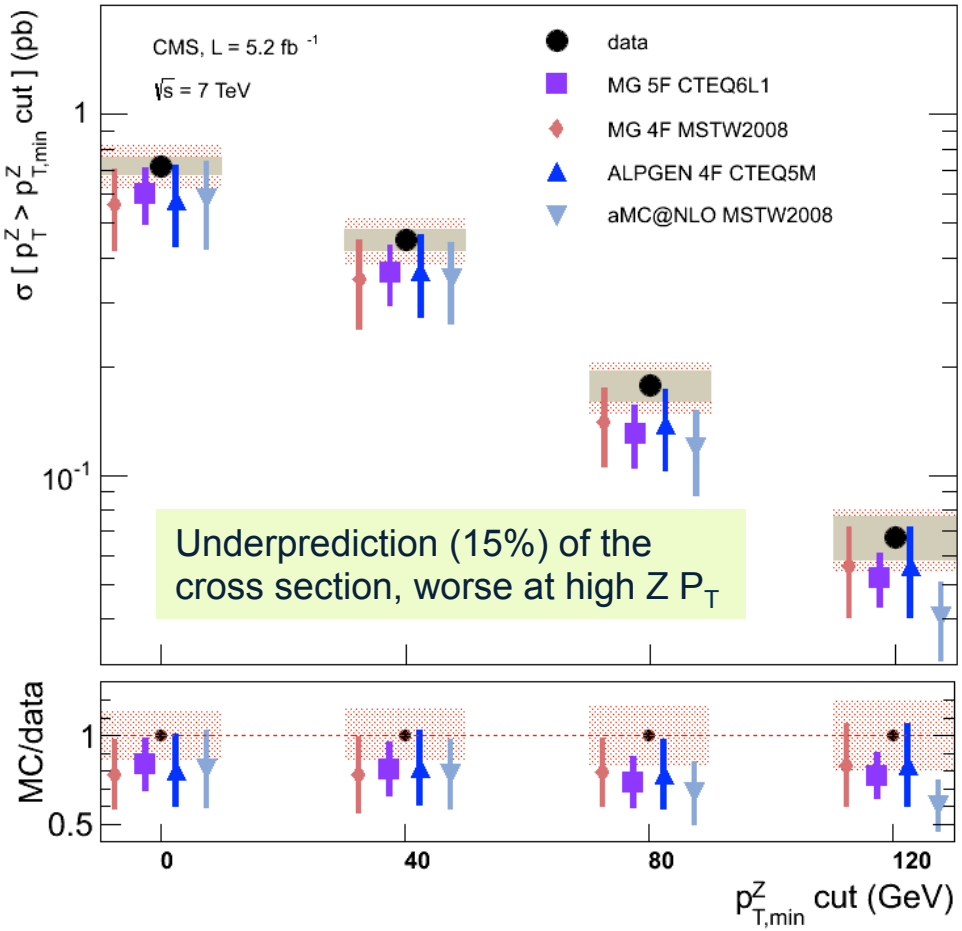
Angular Correlations in Z+BB



- Zoom in the collinear BB production using a track-based b hadron identification technique reliant on displaced decay vertices (no jets!)
- Excellent angular resolution δΔR~0.02



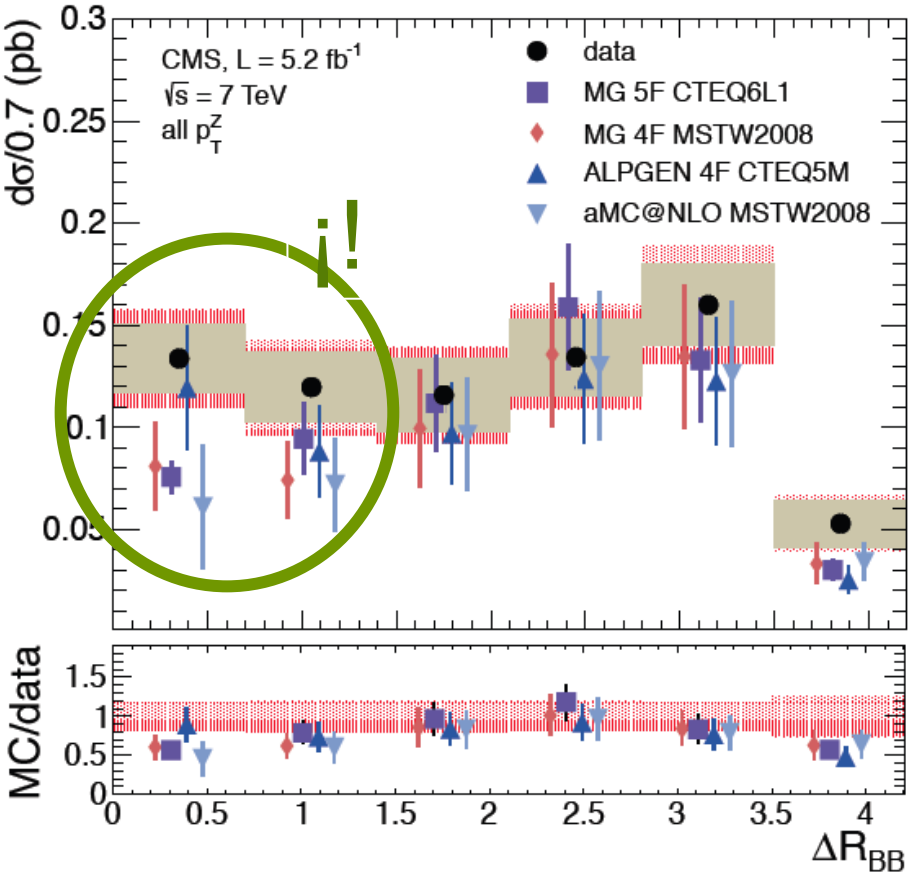
Good description of the data at detector level

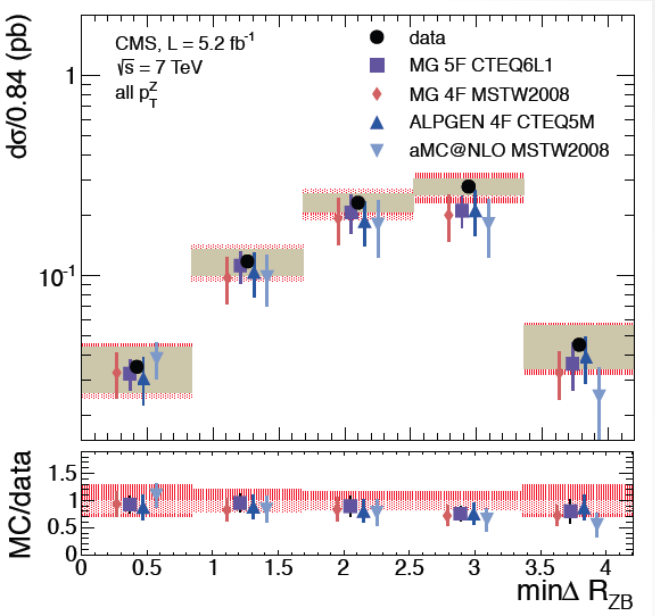


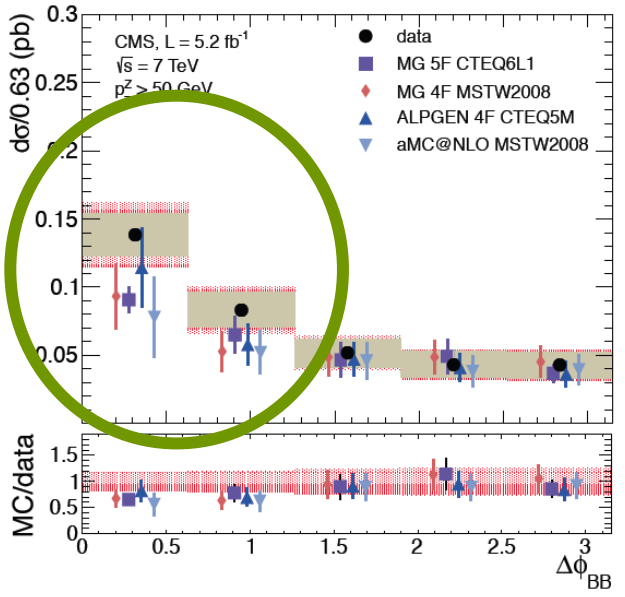
Underprediction (15%) of the cross section, worse at high Z P_T

Unfolded ΔR

- Bad description of the B-hadron correlation. Specially evident in the collinear region
- Good description of the Z to BB system correlation
- Two Z p_T regimes studied: inclusive and boosted (p_T(Z)>50 GeV)







arXiv:1310.1349

Summary

- CMS has explored the associated production of Vector Bosons and Jets in most relevant areas with the 5 fb^{-1} 7 TeV dataset

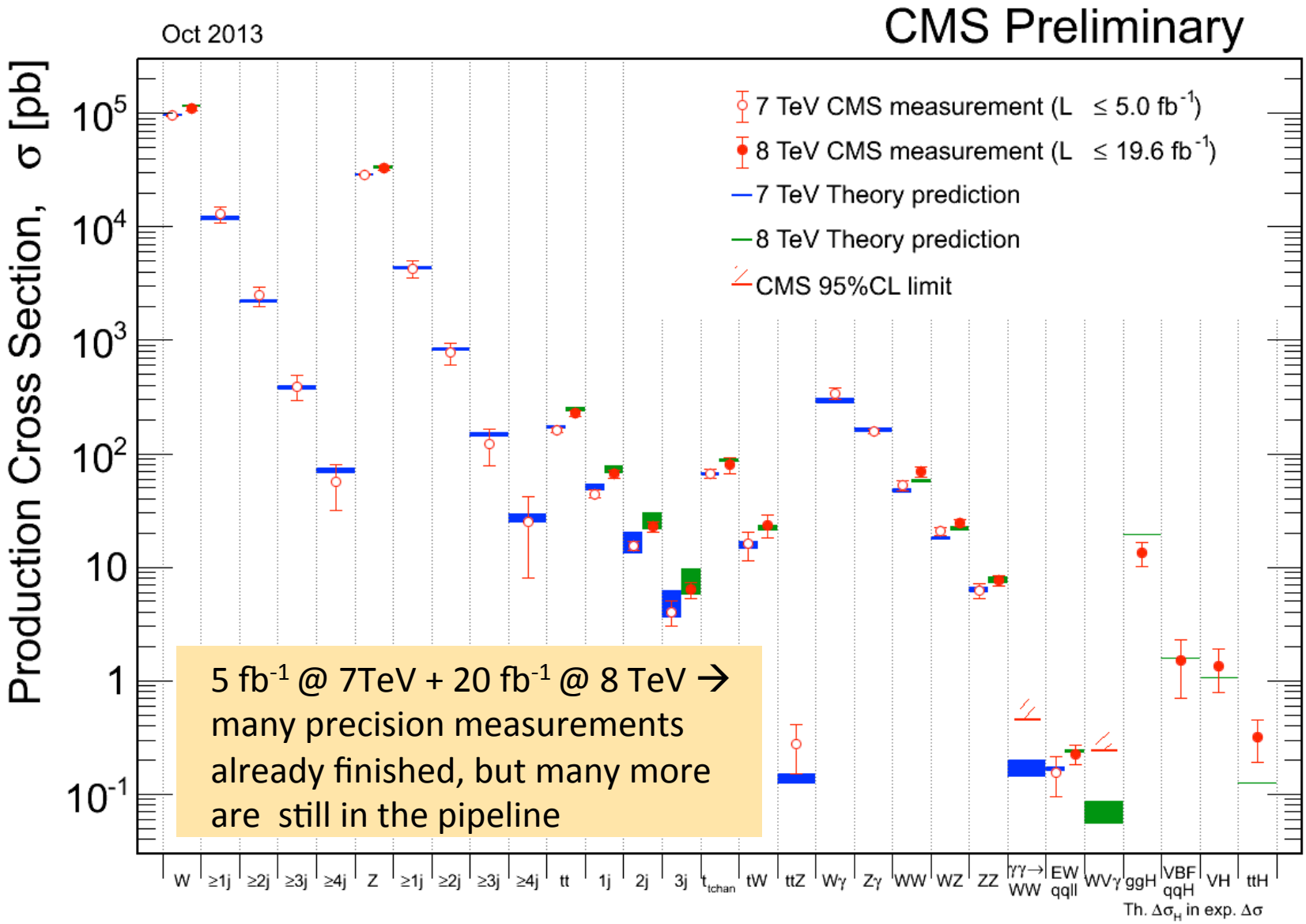
- Overall, we observe good agreement with theoretical predictions (NLO/NNLO)
  - → Specific observables show some tension with the predictions
  - → Sensitivity to precise tunings / models

- In combination with the analysis of the 8 TeV dataset, CMS V+Jets program will be able to provide a excellent benchmark to tune the predictions and prepare for the next LHC run

- Much more to come in the near future

THANKS! ☺

Measuring the SM



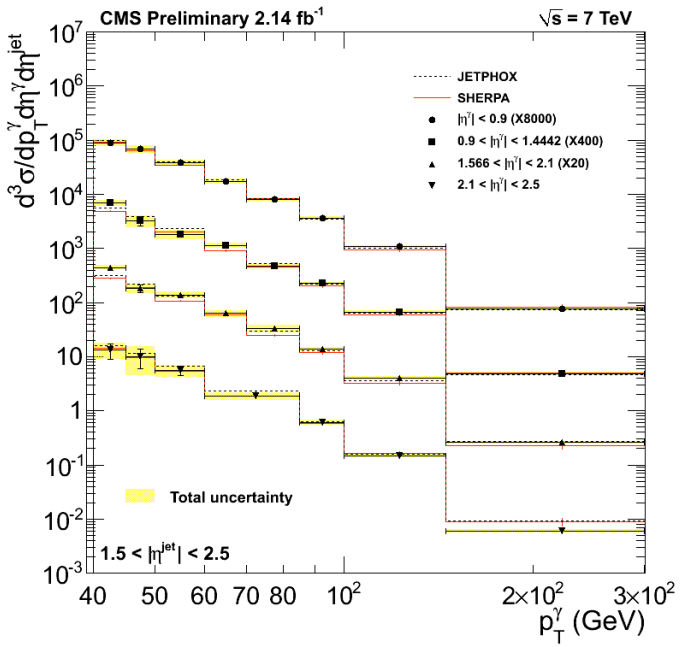
5 fb^{-1} @ 7TeV + 20 fb^{-1} @ 8 TeV → many precision measurements already finished, but many more are still in the pipeline

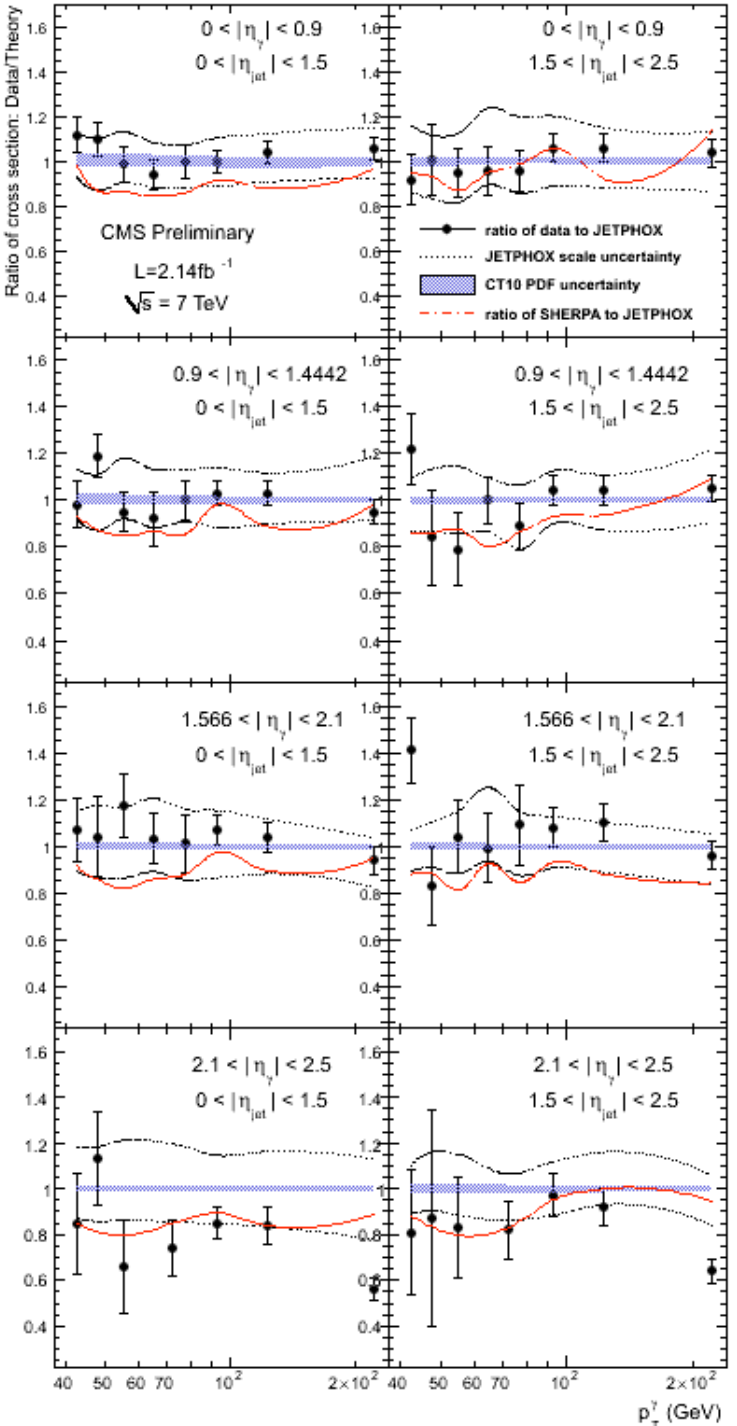
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Measurement of triple-differential cross section of γ+jet production

- Events with γ+N jet in the final state are important background to new physics searches, and are a useful probe of the gluon PDF and of higher-order pQCD calculations
- Comparison with JETPHOX and SHERPA

$$\frac{d^3\sigma_{\gamma+jet}}{dE_T^{\gamma}d\eta^{\gamma}d\eta^{Jet}} = \frac{1}{\Delta E_T^{\gamma}\Delta\eta^{\gamma}\Delta\eta^{Jet}} U \frac{N_{Yield}^{\gamma}}{L\cdot\varepsilon}$$

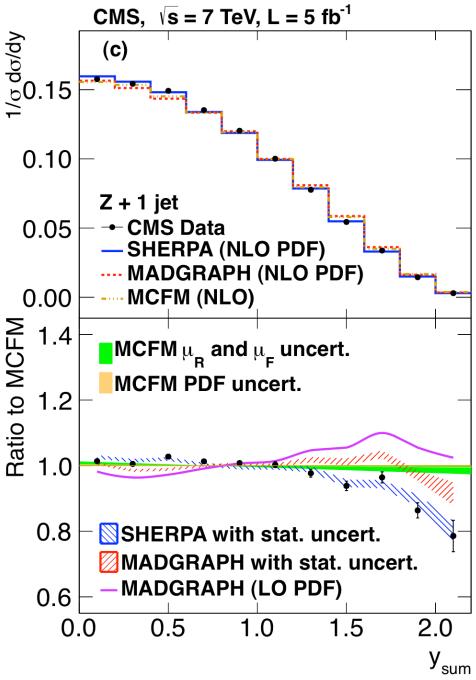


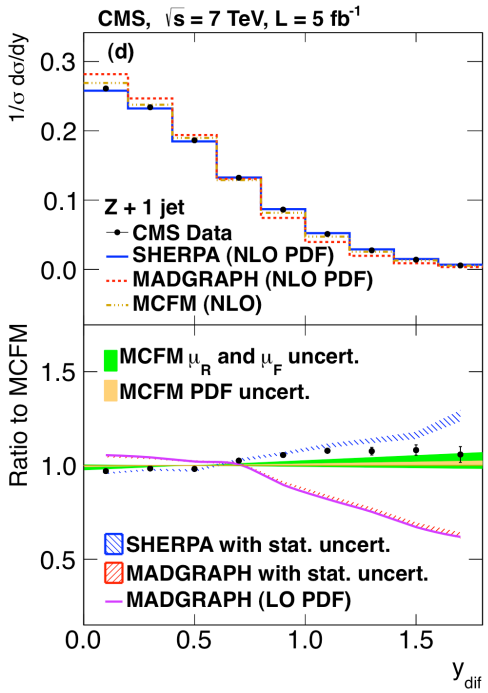


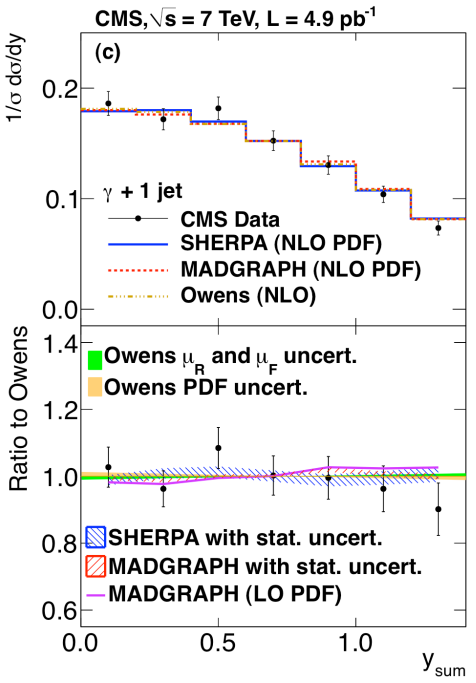
arxiv:1307.6795

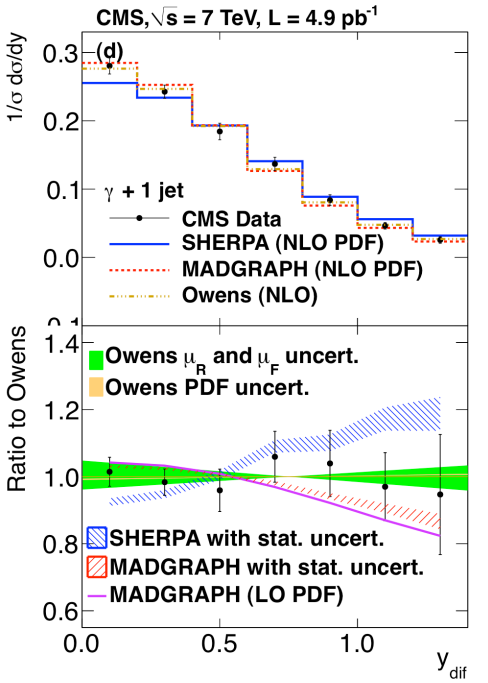
Measurement of Z/γ+ jet angular distributions

- Comparison of Z & γ observables







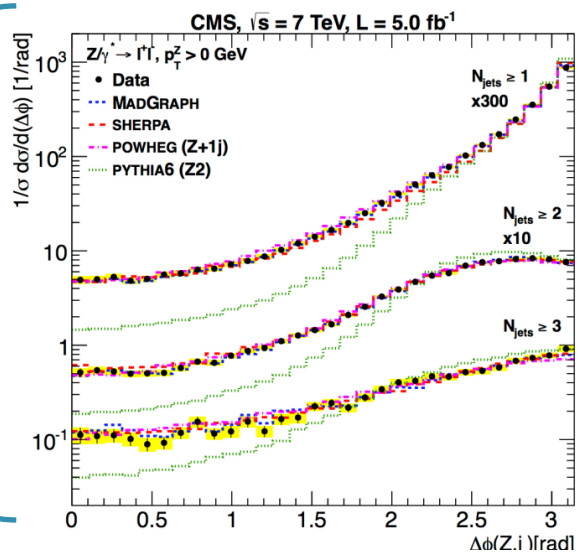


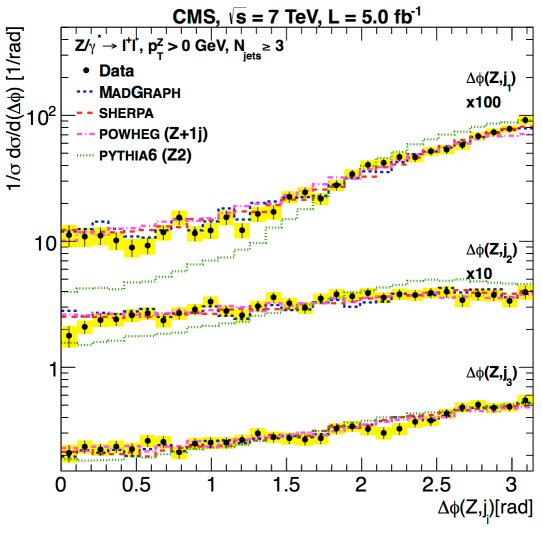
arXiv:1310.3082 (accepted by PRD)

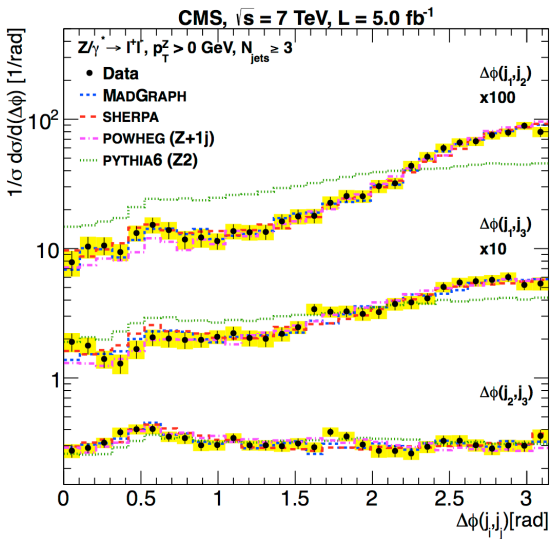
Event Shape & Angular Correlations in Z+Jets

Δφ correlations between Z and the leading jet, for events with 1, 2 and 3 jets:

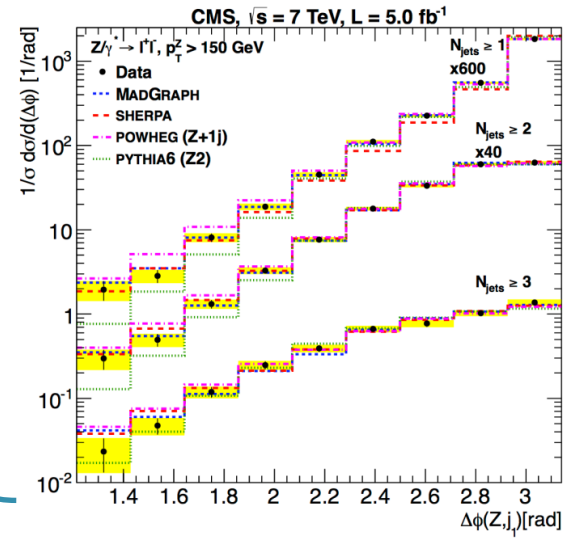
Inclusive in $p_T(Z)$

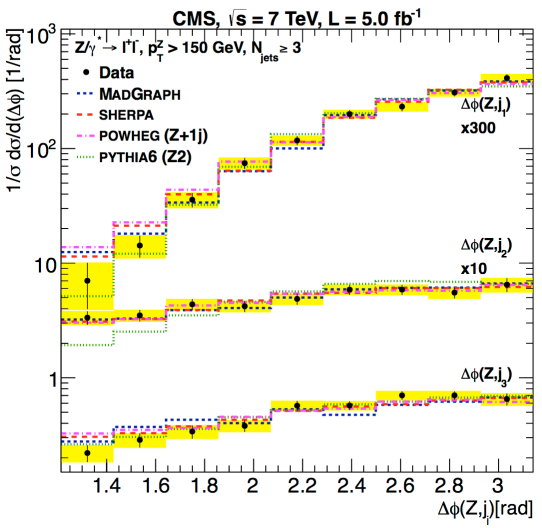


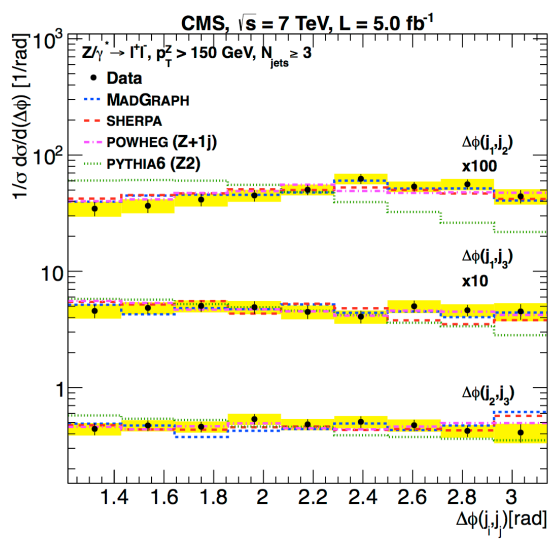




$p_T(Z)$>150 GeV



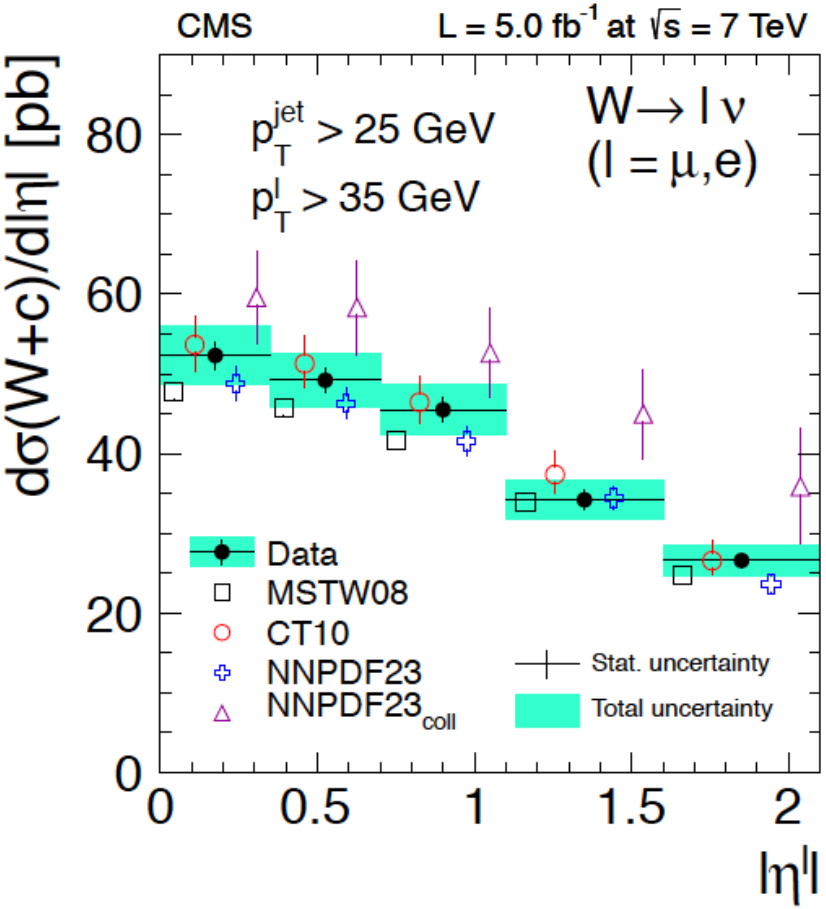


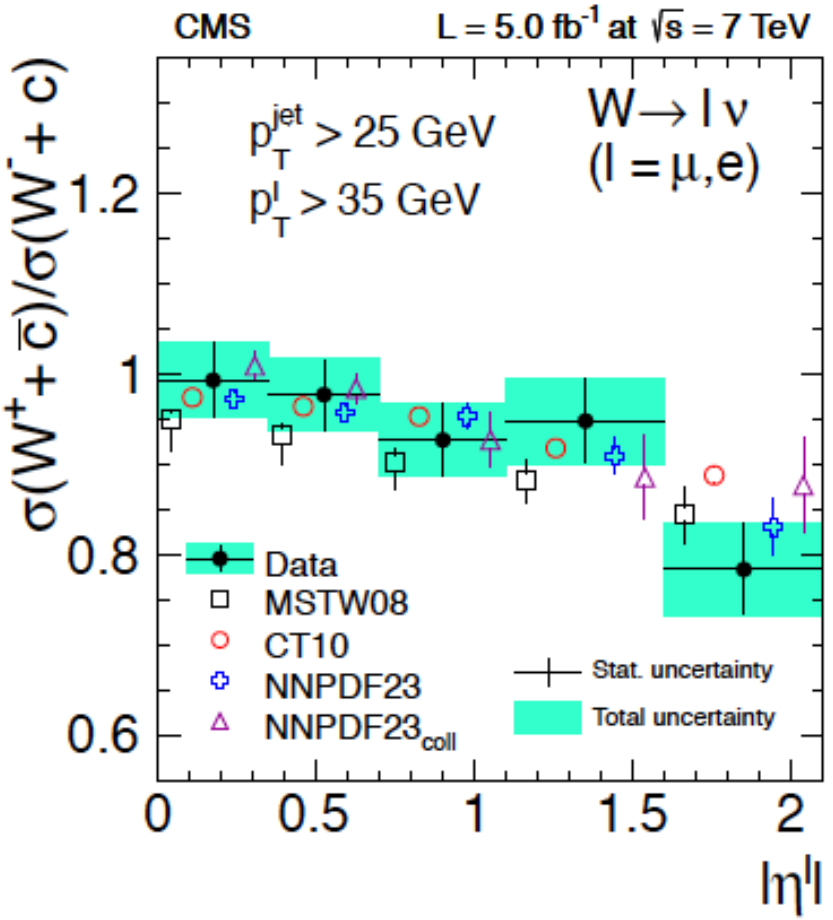


Phys. Lett. B 722 (2013) 238–261
arXiv:1301.1646

W+C: Differential Cross Section

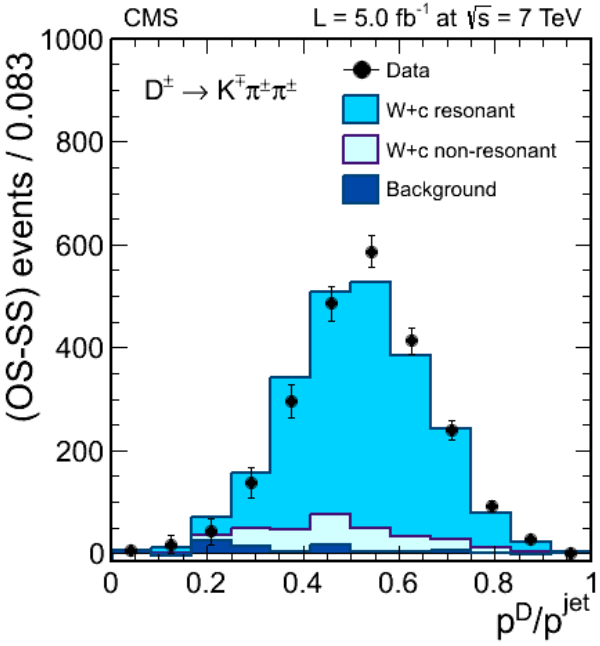
- 5 bins of μ, e pseudorapidity
- Theoretical predictions (MSTW, CT10, NNPDF23) reproduce rather well the exp. Measurement

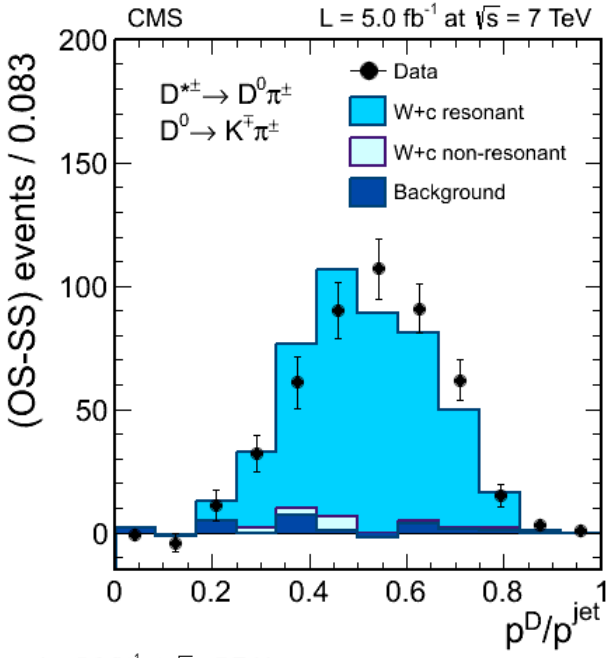


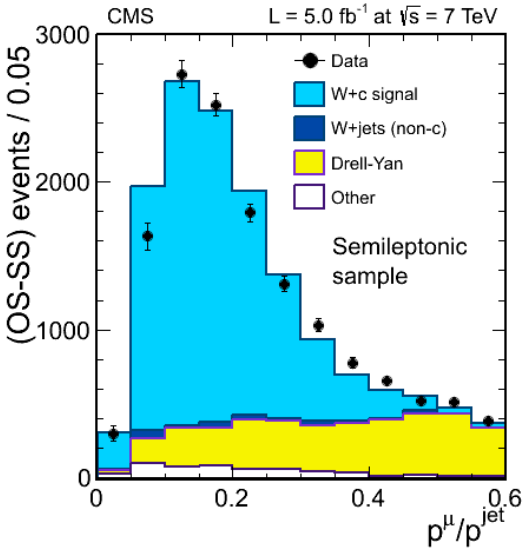


arXiv:1310.1138

W+C: Fragmentation

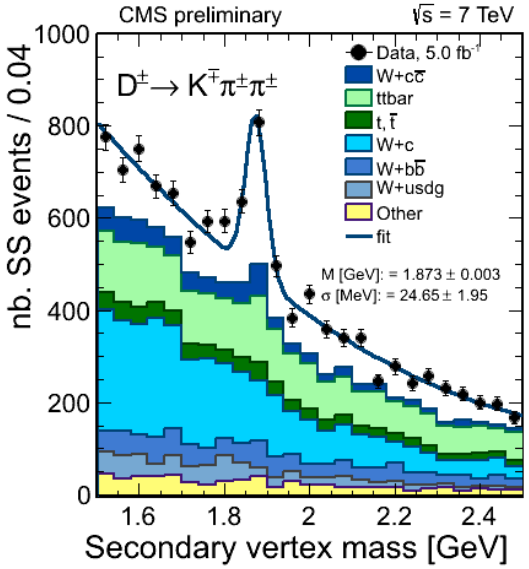


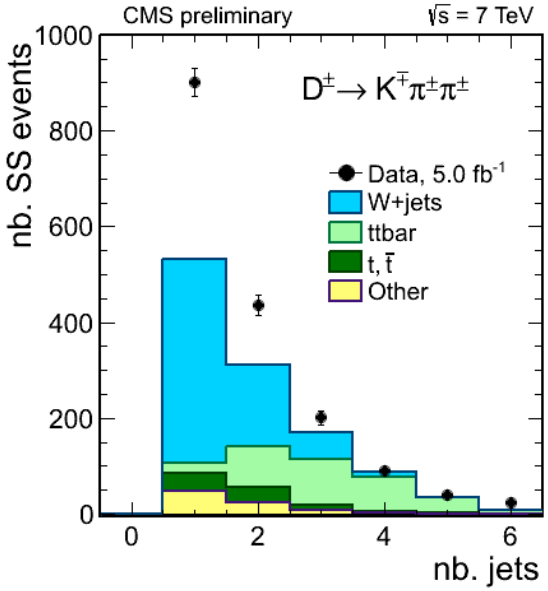


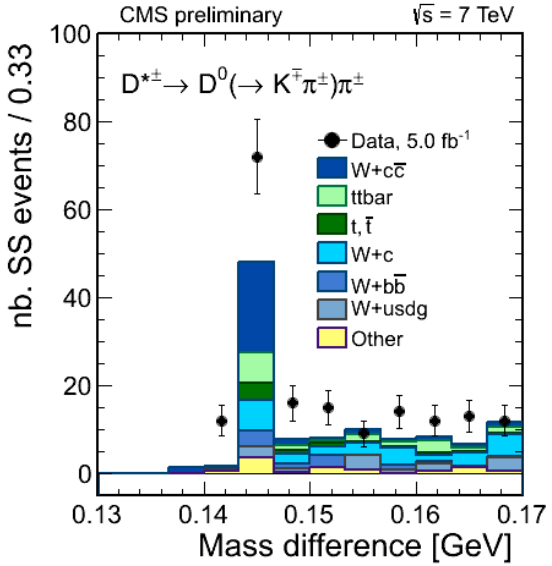


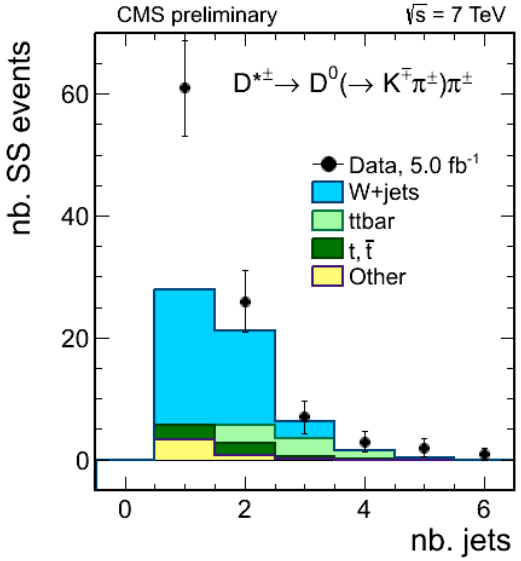
- Distributions normalized to the CMS measurement of the cross section
- Slightly harder fragmentation than what is predicted by Madgraph

Brief comment on W + 1 SV



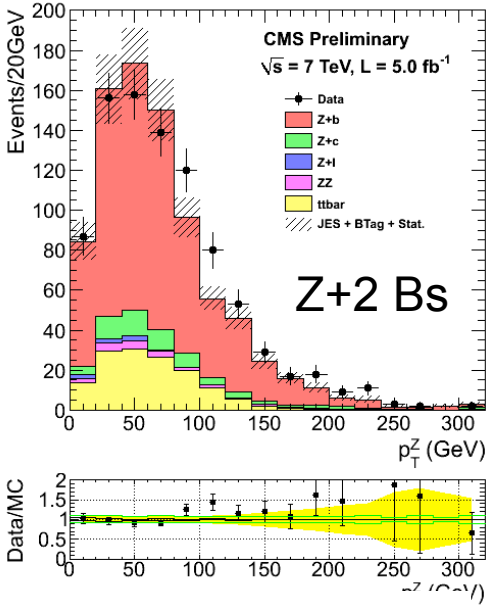


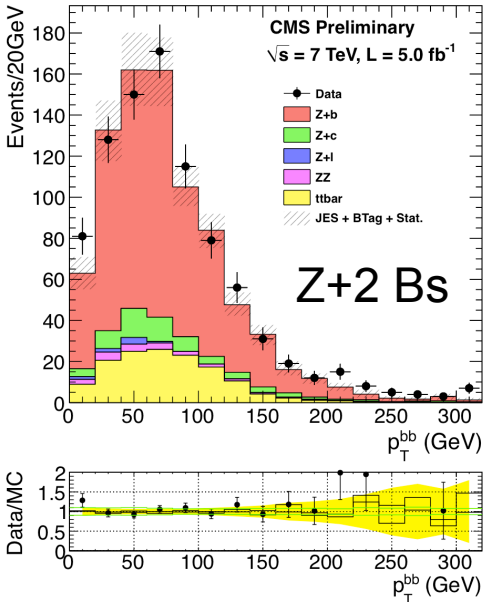


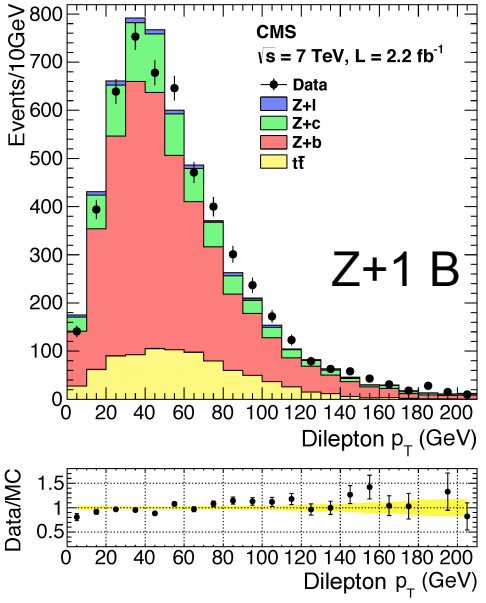


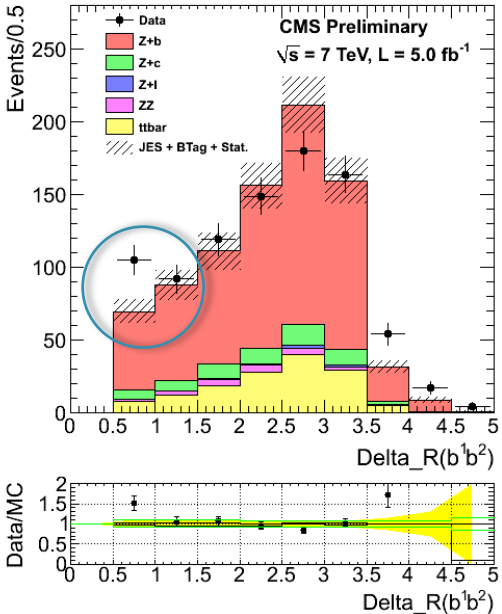
- Sample enriched in ccbar / bbbar events (gluon splitting)
- Comparison with the reference Madgraph+Pythia Monte Carlo
- Significant deficit observed in MC
- Hypothesis: collinear production mismodeling in MG +Pythia?

Z+BB: Kinematic Variables









- Overall good agreement with MG5F prediction

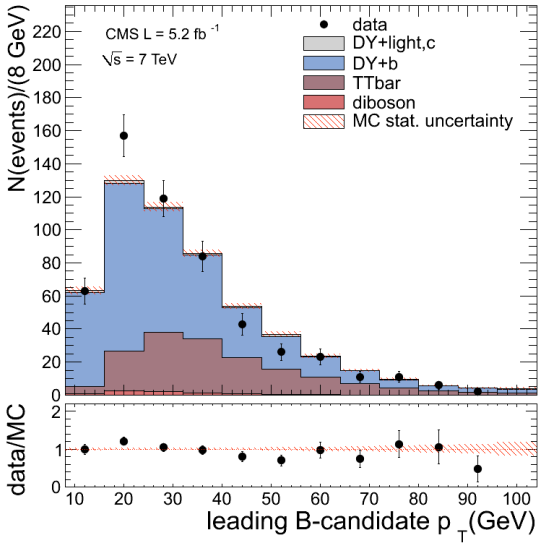
P_T spectrum:

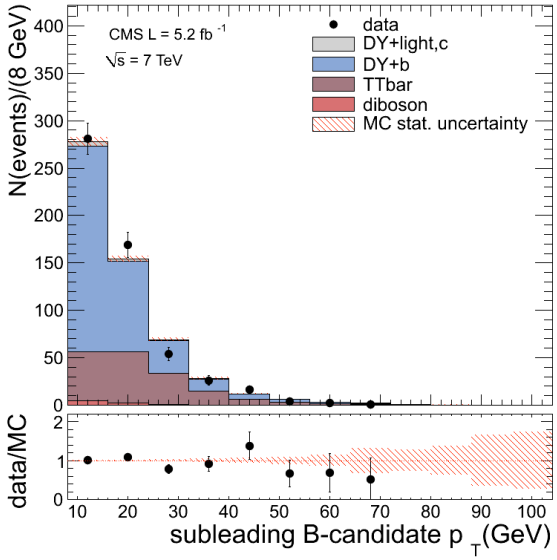
- Some tension with MG5F on Z P_T (not on P_T(bb)!) (A harder p_T(Z) spectrum is expected in 4F or at NLO)
- Also observed in Z+1 B

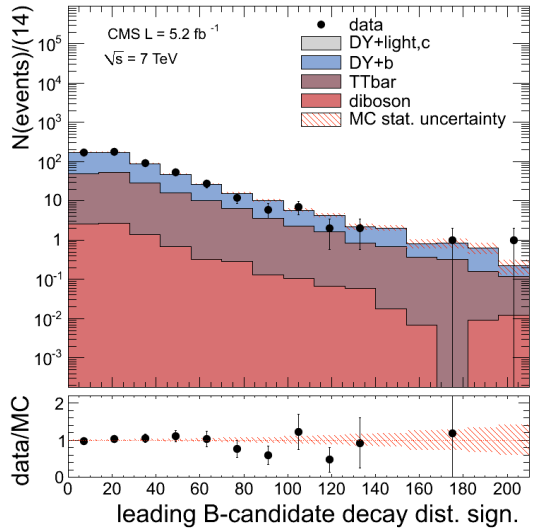
Angular correlation: observed discrepancy at low angle
→ Linked to ZBB Angular correlation study

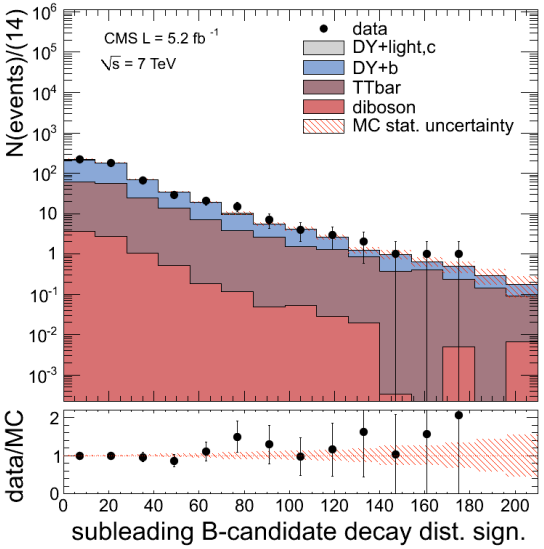
J. High Energy Phys. 06 (2012) 126
arXiv:1204.1643
+
CMS-PAS-12-002

B Hadron Kinematics

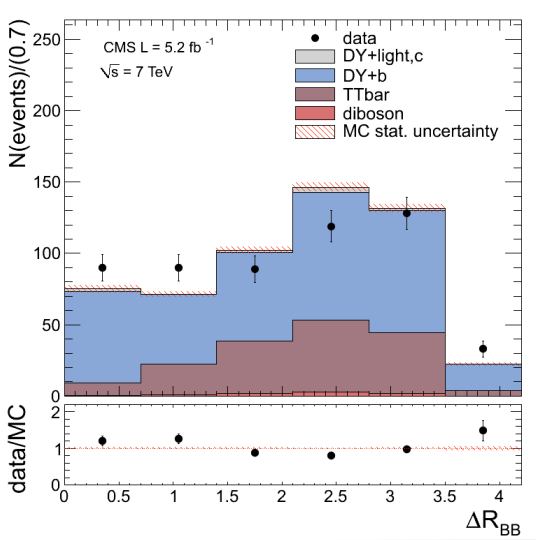








- IVF control plots for different b hadron properties
- Good description of the data at detector level
- Observed discrepancy in angular correlation of BB



arXiv:1310.1349