QCD and Vector Bosons plus Jets with CMS

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On behalf of the ***CMS Collaboration***

Les Rencontres de Physique de La Vallée d'Aoste
La Thuile - 3 March, 2015

QCD & V+Jets

- ➡ Important tests of perturbative QCD
- ➡ Constraint for PDF and α_S determination
- ➡ Characterization of backgrounds for Higgs studies and new physics searches

Vector Bosons plus Jets:

- **Z+jets** @ 7 TeV (SMP-12-017, arXiv:1408.3104, accepted by PRD)
- **Z+jets** @ 8 TeV (CMS-PAS-SMP-13-007, CMS-PAS-SMP-14-009)
- **Z/gamma+jets** (CMS-PAS-SMP-14-005)
- **W+jets** (SMP-12-023, Phys. Lett. B 741 (2015) 12)
- **Z+b, Z+bb** (SMP-13-004, JHEP 1406 (2014) 120)
- **Z+2B Hadrons** (EWK-11-015, J. High Energy Phys. 12 (2013) 39)
- **W+bb** (SMP-12-026, PLB 735 (2014) 204)

QCD:

- **Dijet production @ 8 TeV** (CMS-PAS-SMP-14-002)
- **Hadronic event shapes** (SMP-12-022, JHEP 10 (2014) 087)
- **Inclusive multijet production**
  (QCD-11-006, arXiv.1502.04785, Submitted to EPJC)
- **Inclusive jet AK5/AK7 cross section ratio**
  (SMP-13-002, Phys. Rev. D 90 (2014) 072006)
- **3-jet mass differential cross section and α_S**
  (SMP-12-027, arXiv:1412.1633, Submitted to EPJC)
- **PDF constraints and extraction of α_S from the inclusive jet cross section**
  (SMP-12-028, arXiv:1410.6765, Submitted to EPJC)

Z+jets, 7 and 8 TeV

$Z \rightarrow ll(e,\mu)$ in association with at least 1 jet:

- 2011 data $\sqrt{s}$ = 7 TeV, Int. luminosity: 4.9 fb^{-1}
- 2012 data $\sqrt{s}$ = 8 TeV, Int. luminosity: 19.6 fb^{-1}
- Results unfolded at particle level: jet multiplicity, jet p_T and η ($\leq$ 4 jets), jet H_T

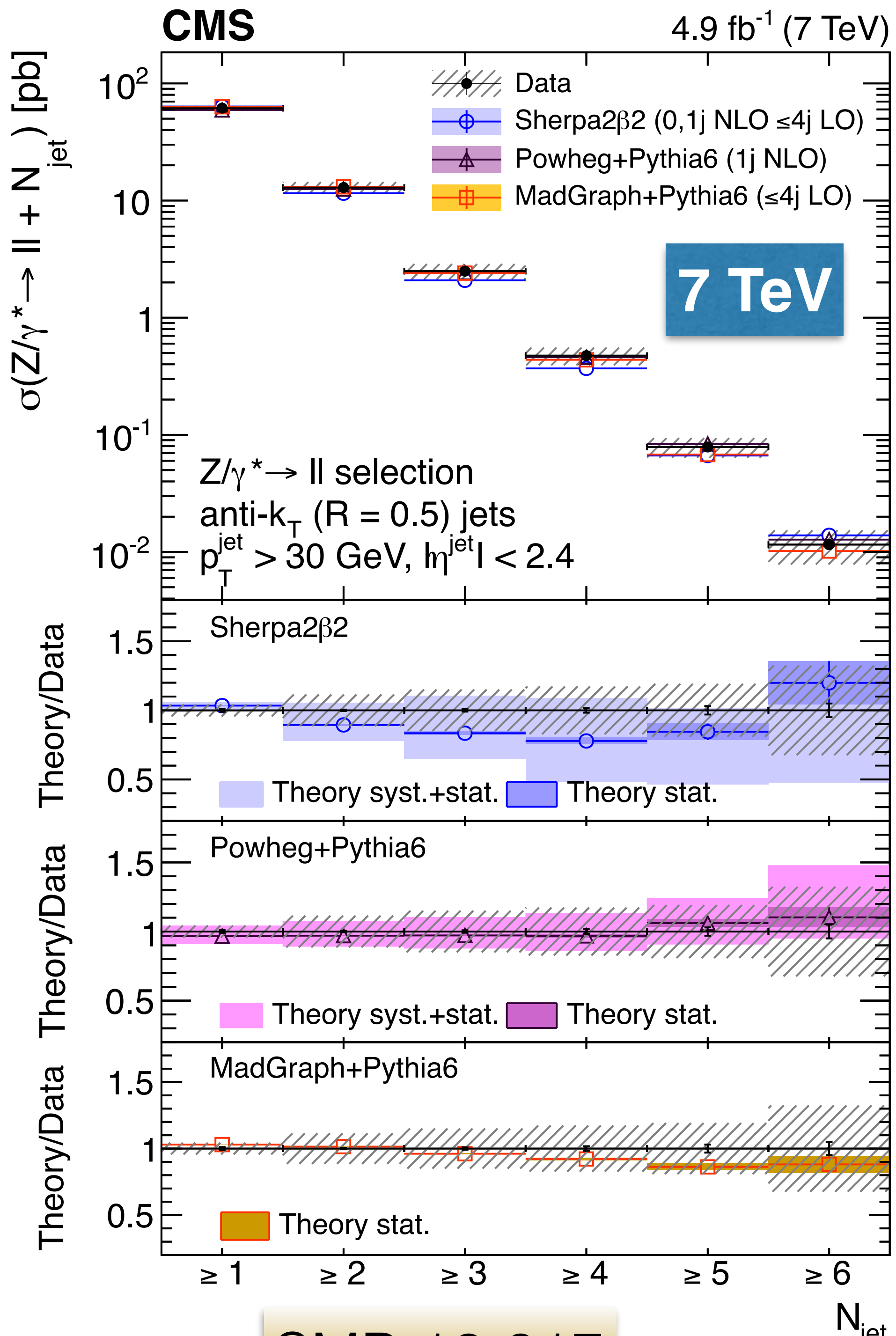
Phase space:

- Electrons, muons: $p_T > 20$ GeV, $|\eta| < 2.4$
- Dilepton invariant mass: $71 < m_{ll} < 111$ GeV
- Jets: anti-k_t (R=0.5), $p_T > 30$ GeV, $|\eta| < 2.5$ and ΔR(jet, lepton) > 0.5

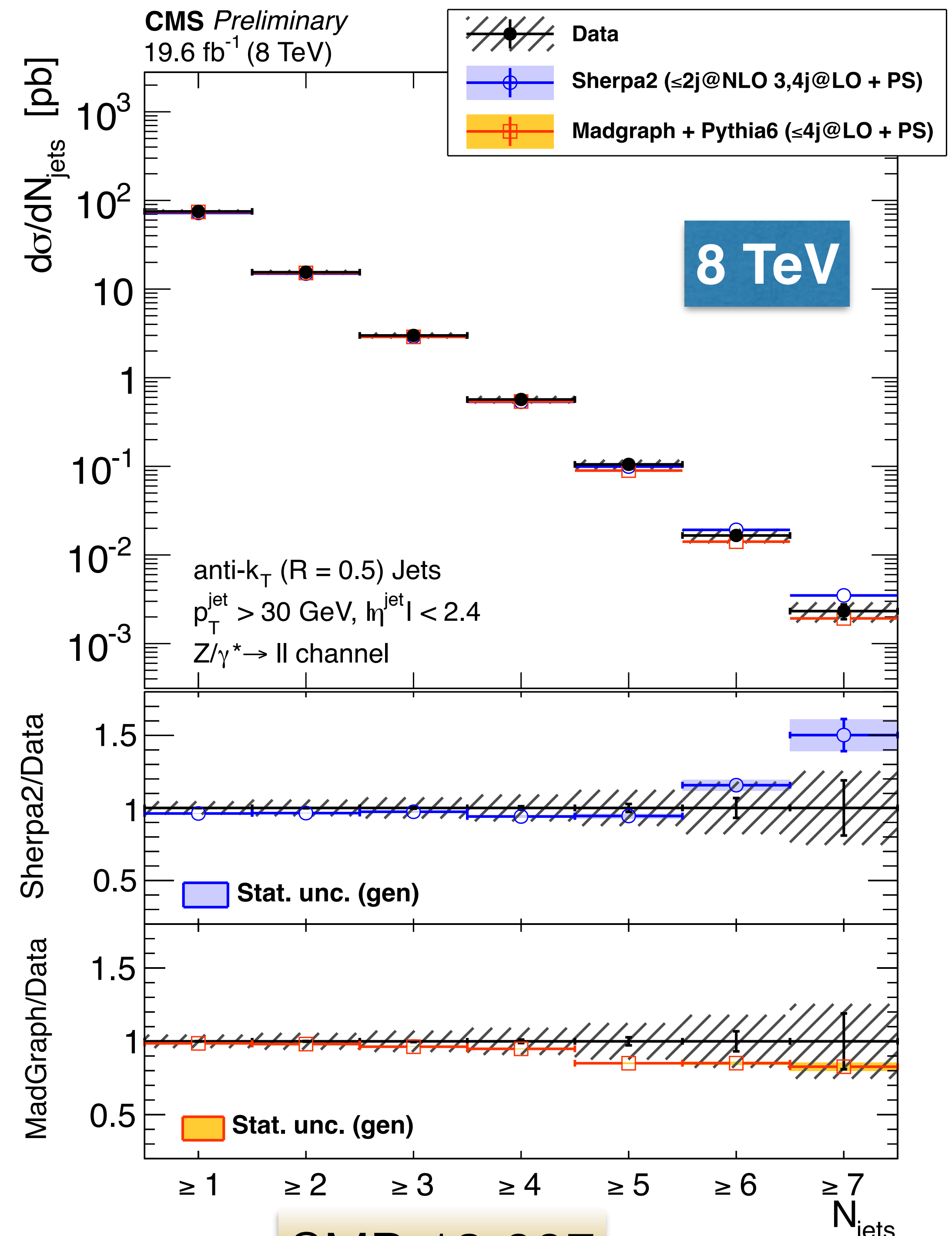
Theory comparisons:

- **7 TeV:**
  - **Sherpa2β2**, NLO ME (Z + 0/1 jets) + LO ME ($\leq$ 4 jets) + PS
  - **Powheg + Pythia6**, NLO ME (Z + 1 jet) + PS
  - **MadGraph + Pythia6**, LO ME (Z + $\leq$ 4 jets) + PS
- **8 TeV:**
  - **Sherpa2**, NLO ME (Z + 0/1/2 jets) + LO ME ($\leq$ 4 jets) + PS
  - **MadGraph + Pythia6**, LO ME (Z + $\leq$ 4 jets) + PS

Z+jets, 7 and 8 TeV - Jet multiplicity



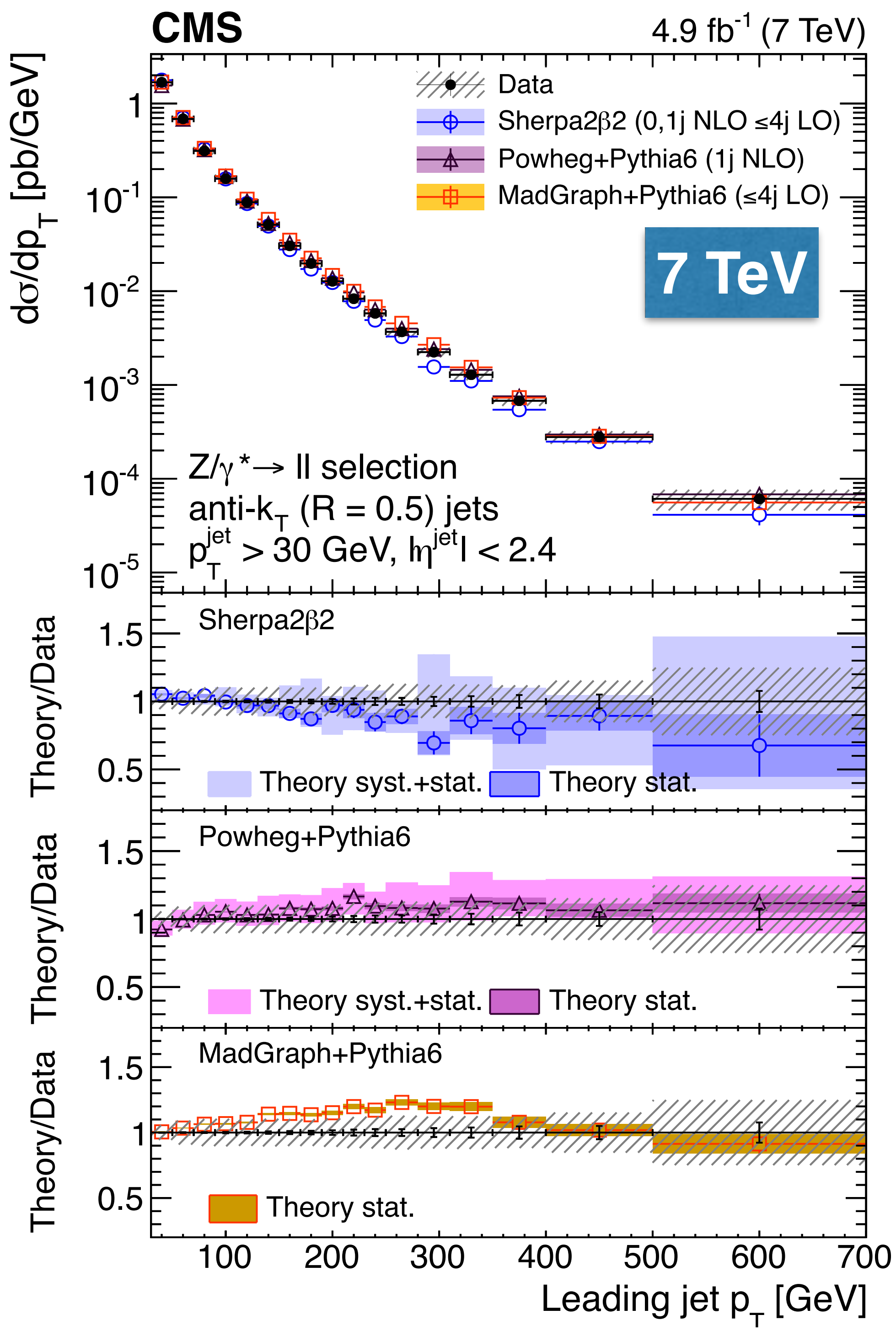
SMP-12-017

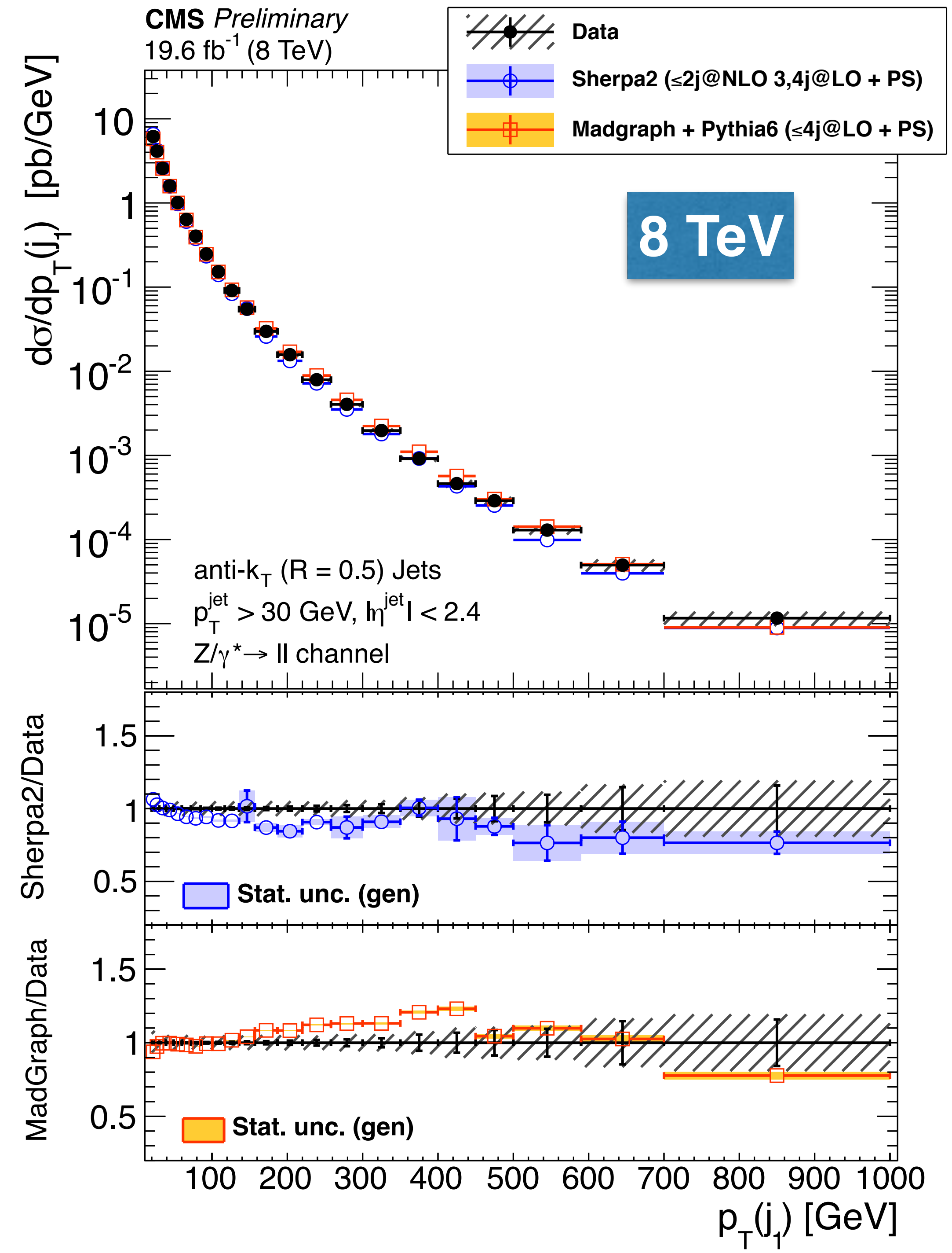


SMP-13-007

The distribution of the jet multiplicity is in good agreement with the predictions.

Z+jets, 7 and 8 TeV - 1st Jet p_T





- Similar results at 7 and 8 TeV: LO + PS overestimates the1st jet p_T above ~100 GeV
- Similar results obtained with different PDF sets (CT10, NNPDF21, MSTW2008)

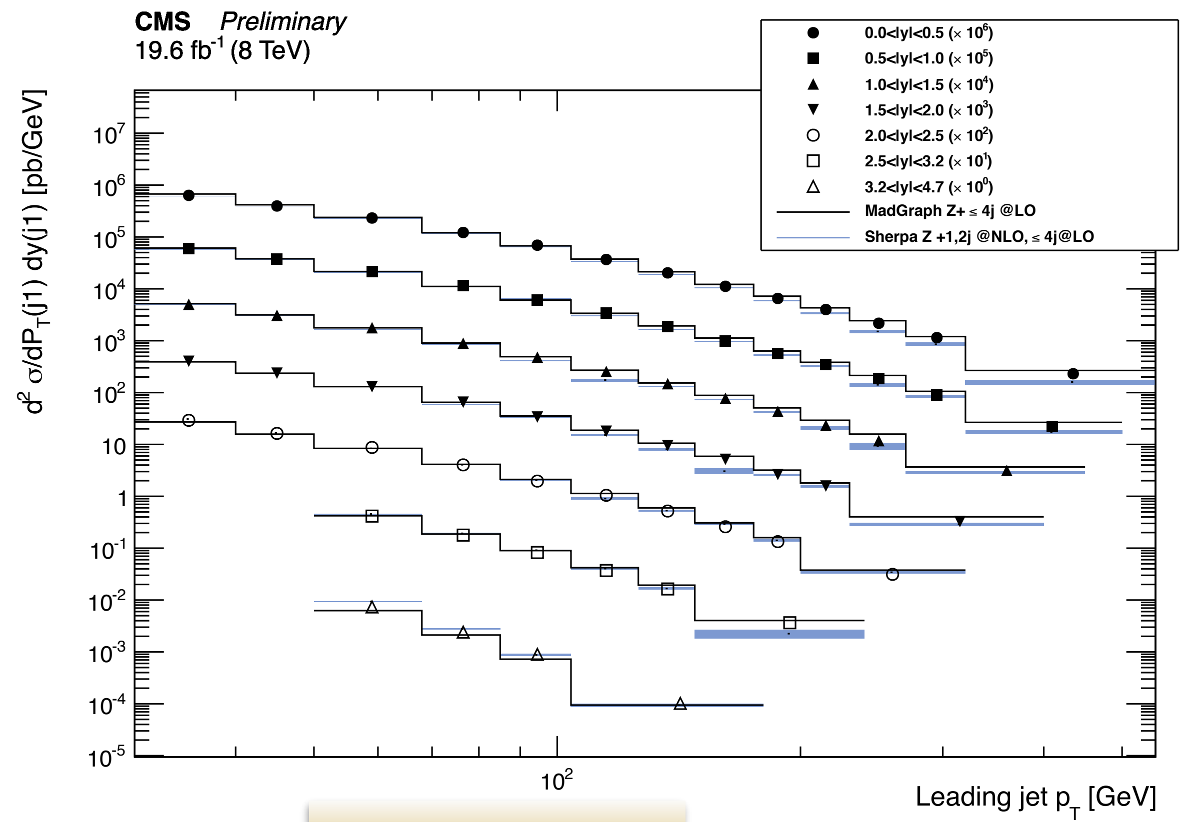
Z+jets, 8 TeV - Leading jet double differential cross section

$$\frac{d^2\sigma}{dp_T^j dy^j} = \frac{1}{\mathcal{L}\times\epsilon}\times\frac{N}{2\times\Delta|y^j|\times\Delta p_T^j}$$

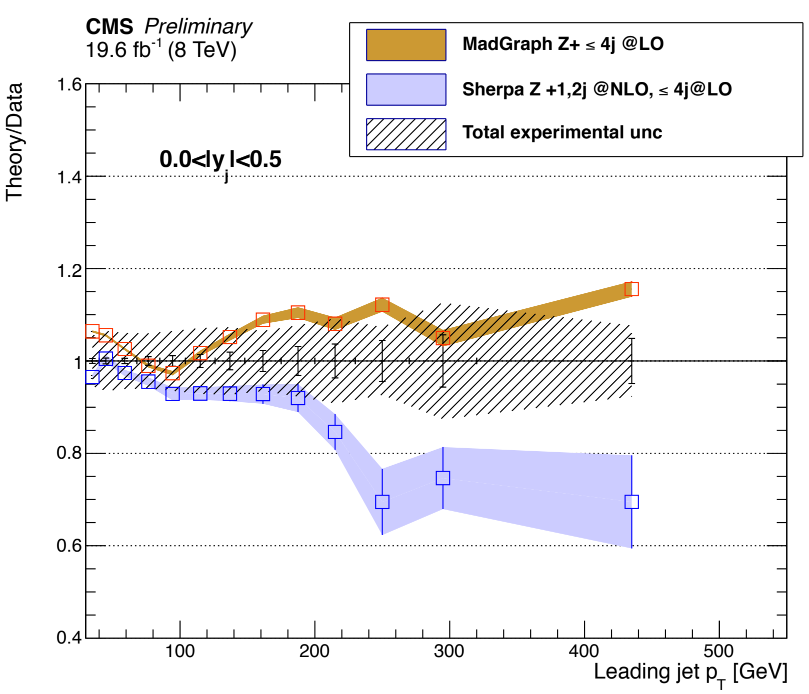
Phase space:

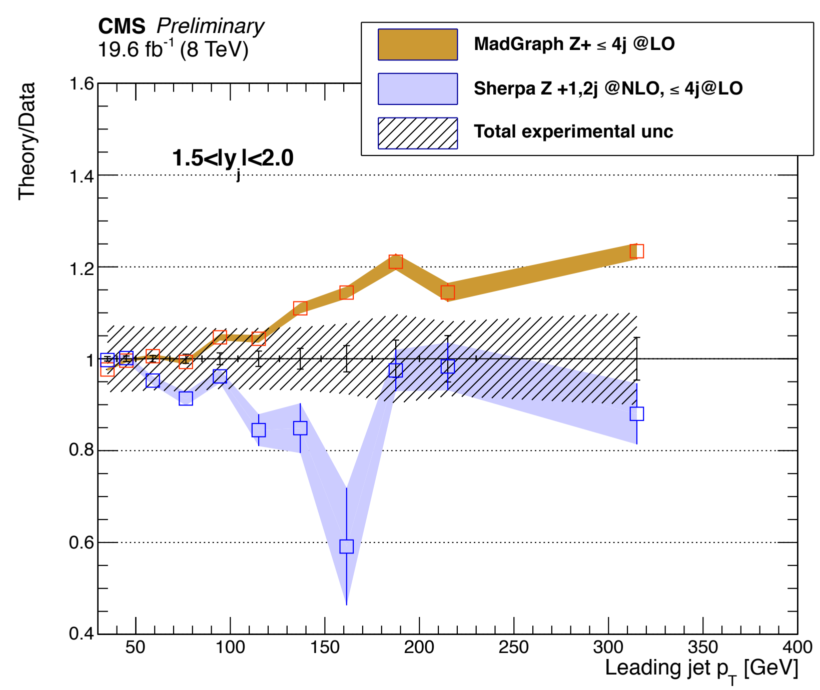
- Muons: $p_T > 20$ GeV, $|\eta| < 2.4$
- Dilepton inv. mass: $71 < m_{ll} < 111$ GeV
- Jets:
  - anti-k_t (R=0.5), $p_T > 30$ GeV, $|\eta| < 2.5$ and $\Delta R(\text{jet},\mu) > 0.5$.
  - $p_T > 50$ GeV, **$2.5 < |\eta| < 4.7$**

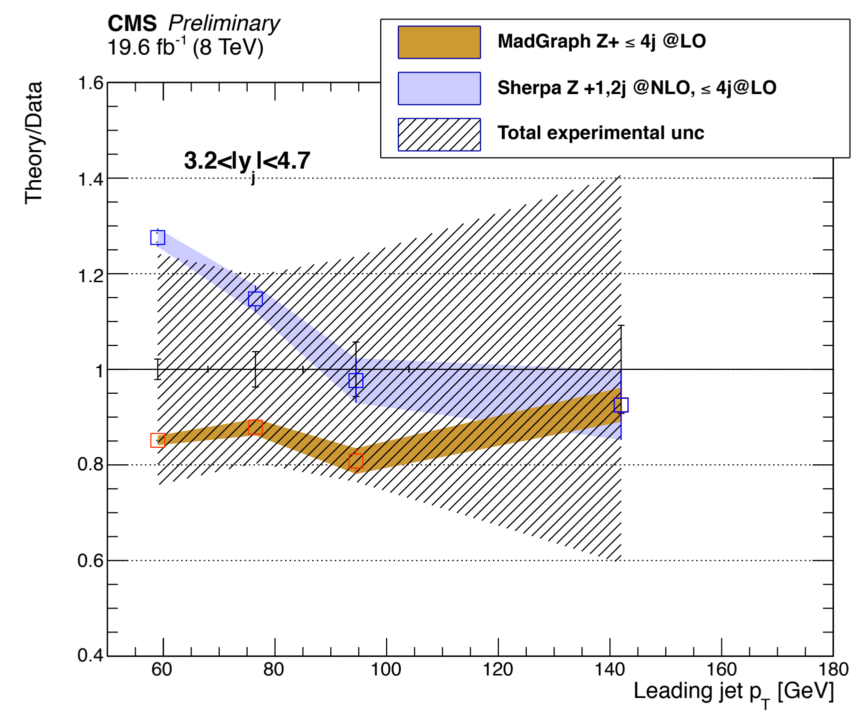
- Similar selection to Z+jets @ 8 TeV (SMP-13-007)
- Only muon channel ($Z\to\mu\mu$ + jets) probed
- **Extendend η range**



SMP-14-009



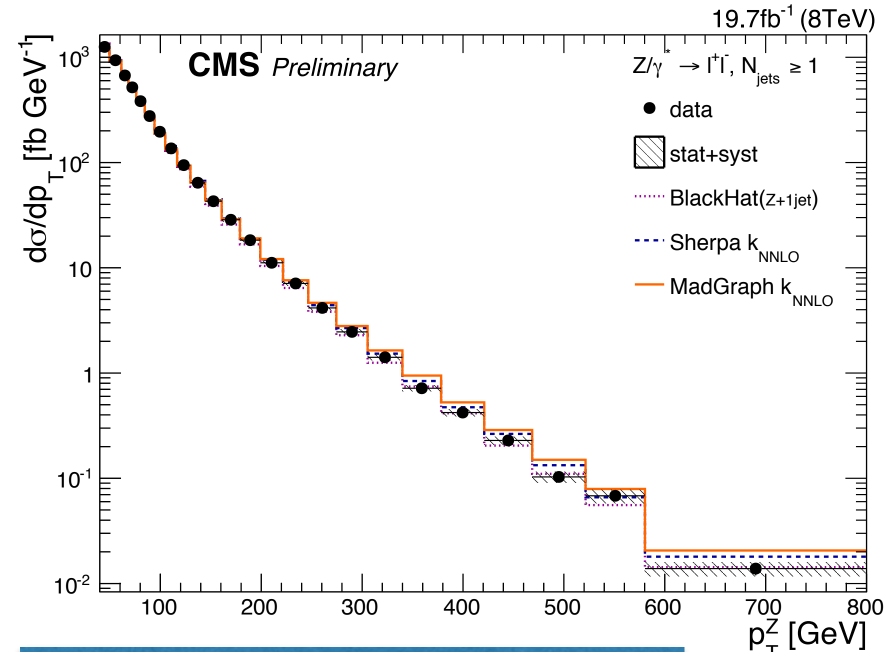




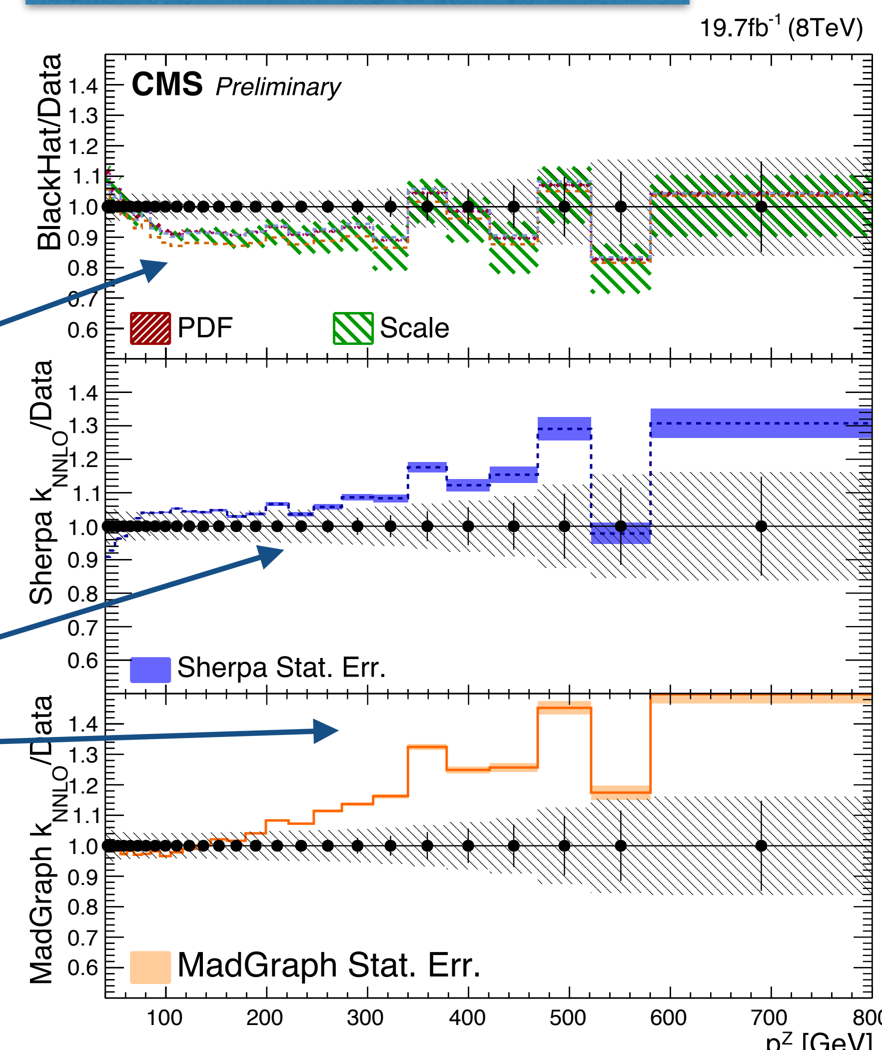
MadGraph overestimates the 1st jet p_T spectrum for $p_T \gtrsim 100$ GeV

Z + jets, 8 TeV: Z boson p_T

- Analysis performed in the same phase space as Z+jets @ 8 TeV (SMP-13-007):
  - Events selected with Z p_T > 100 GeV
  - $N_{jets} \geq 1,2,3$
  - Jet H_T > 300 GeV
- Several ratios: Z p_T over jet multiplicity, jet p_T, jet H_T.
- Comparison with γ+jets spectrum: high statistic probe for Z→νν in searches with missing E_T (<u>see next slide</u>).
- Theory predictions:
  - **Blackhat + Sherpa**, NLO ME (Z + 0/1/2/3 jets)
  - **MadGraph and Sherpa-1.4**, LO ME (Z + ≤ 4 jets)



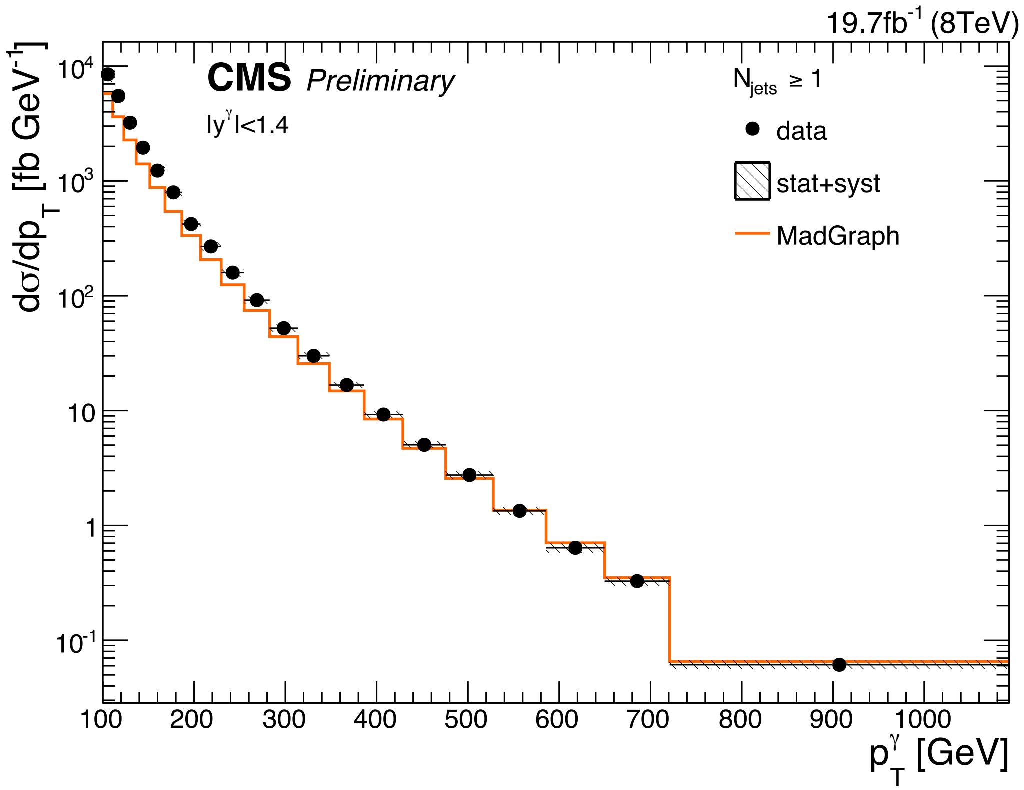
dσ/dp_T(Z) ($N_{jets} \geq 1$)

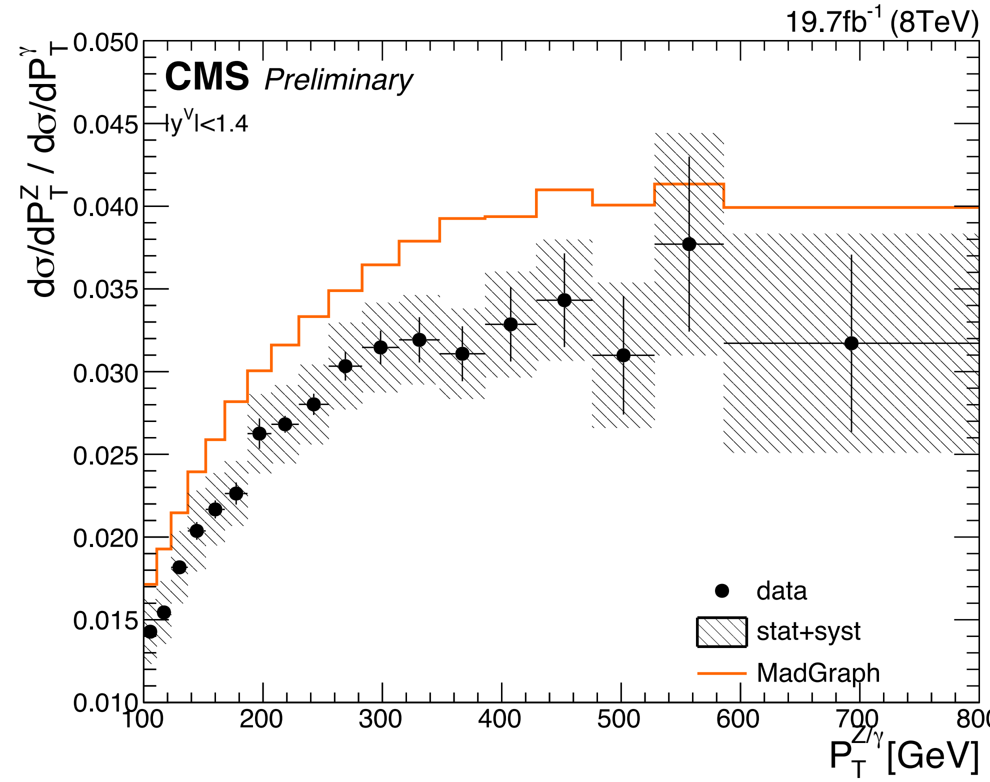


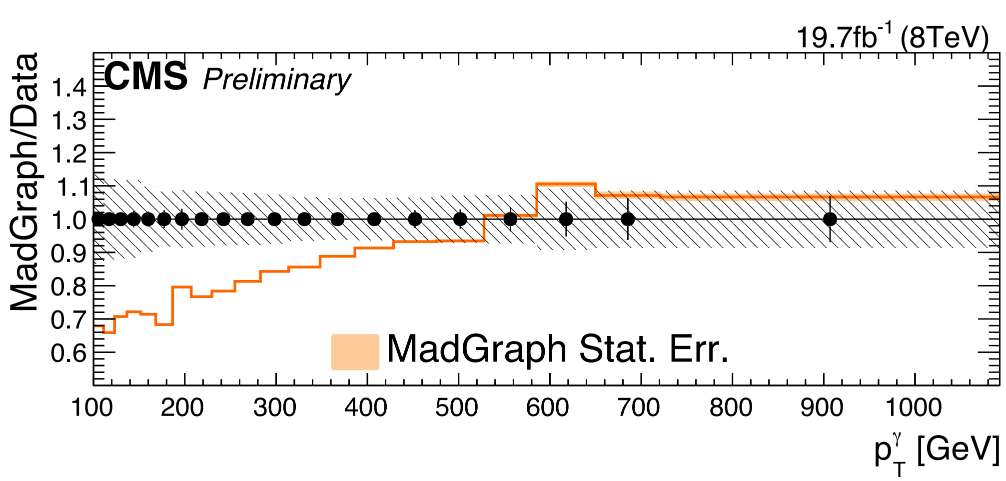
➡ 10 % disagreement in Z p_T (N_{jets}>1 sample) prediction at NLO

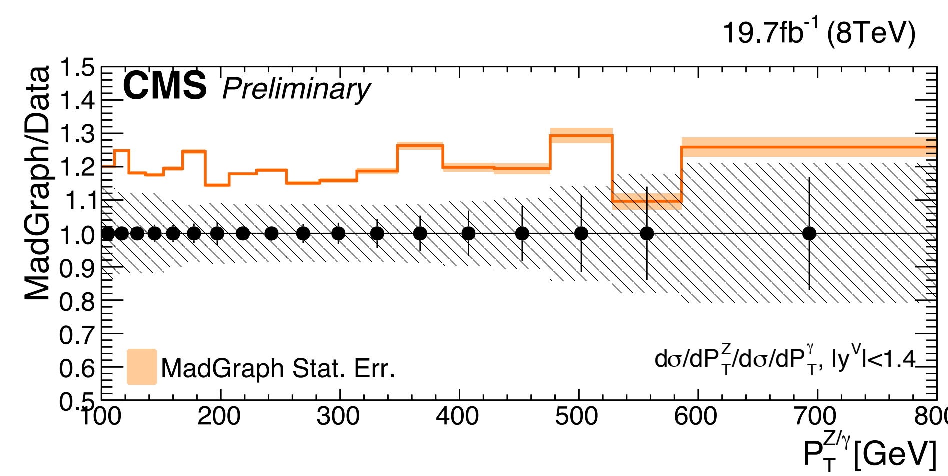
➡ LO ME calculations overestimate the high Z p_T tails

SMP-14-005









$d\sigma/dp_T(\gamma)$ (Njets ≥ 1)

SMP-14-005

$\frac{d\sigma/dp_T(Z)}{d\sigma/dp_T(\gamma)}$ (Njets ≥ 1)

As for the Z p_T, LO ME + PS calculations poorly describe the γ p_T.

W+jets, 7 TeV

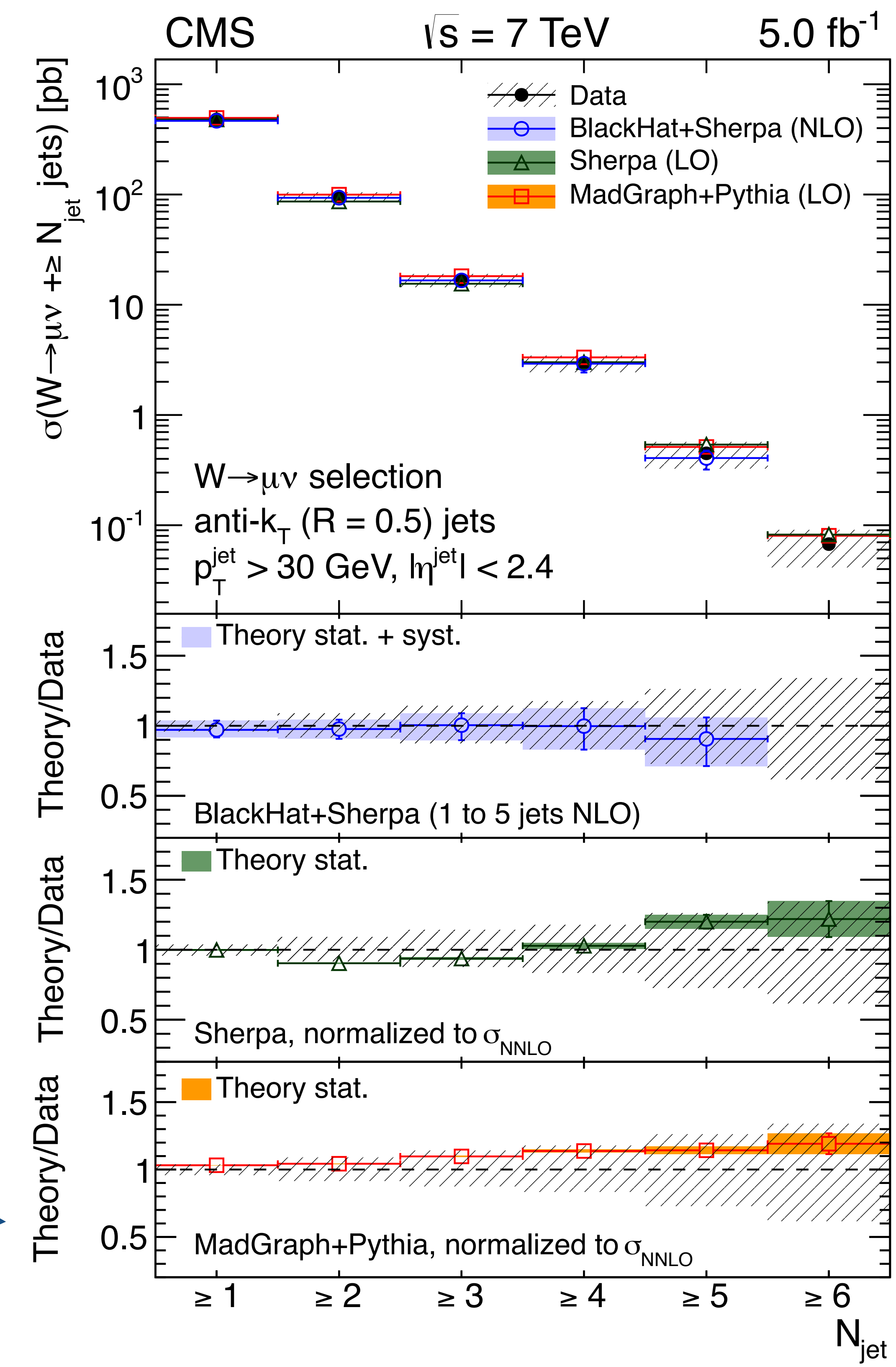
SMP-12-023

$W \rightarrow \mu\nu$ in association with at least 1 jet:

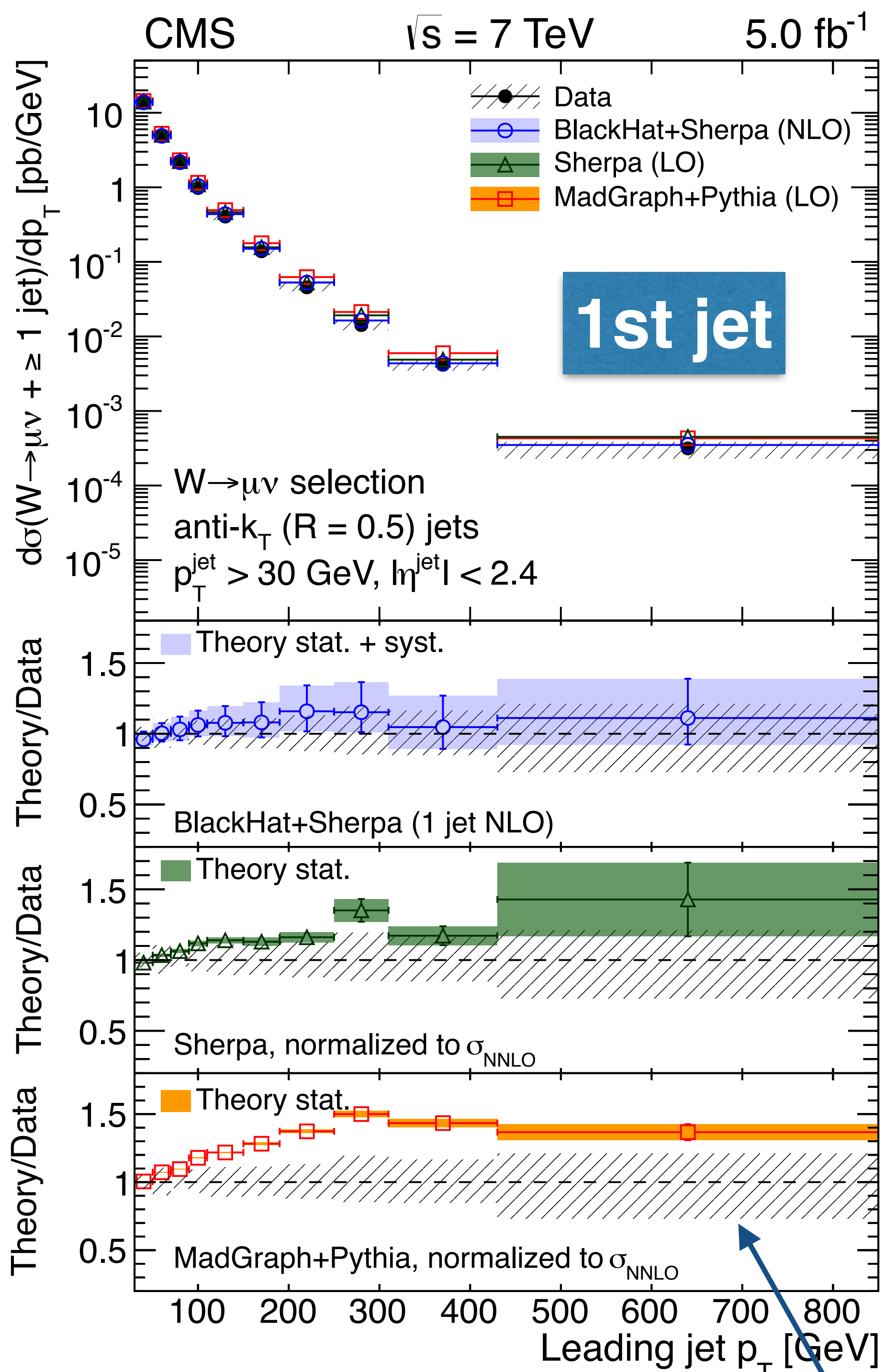
- 2011 data $\sqrt{s}$ = 7 TeV, Int. luminosity: 5.0 fb^{-1}
- muons: $p_T > 25$ GeV, $|\eta| < 2.1$
- $M_T(\mu$, missing $E_T) > 50$ GeV
- Jets: anti-k_t (R=0.5), $p_T > 30$ GeV, $|\eta| < 2.5$ and ΔR(jet, lepton) > 0.5
- Results unfolded at particle level: jet multiplicity, jet p_T and η ($\leq$ 4 jets), jet H_T

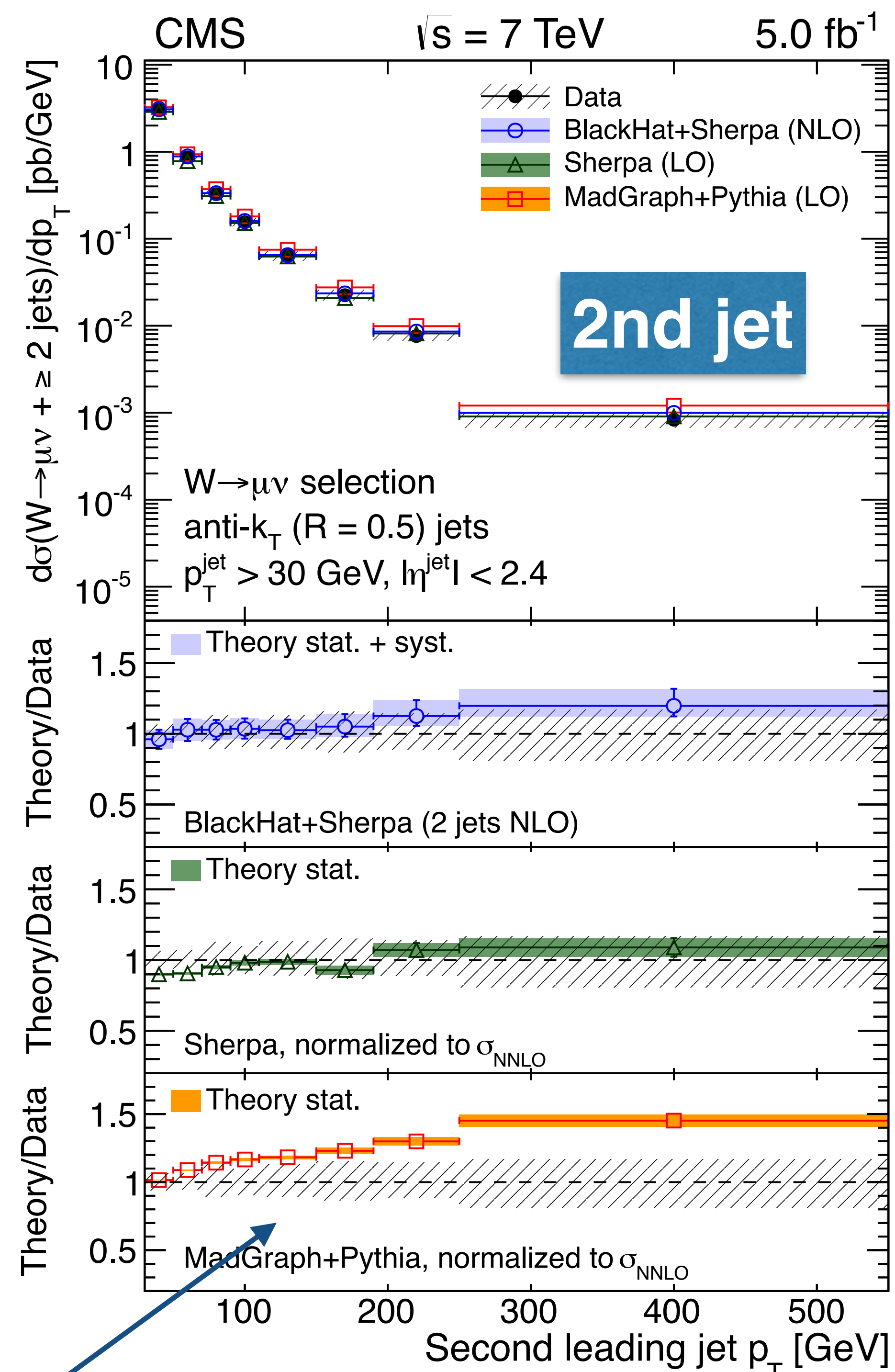
Theory comparisons:

- **7 TeV:**
  - **Blackhat+Sherpa**, fixed NLO (W + 0/1/2/3/4 jets) + PS
  - **Sherpa-1.4 and MadGraph+Pythia6,** LO ME (W + ≤ 4 jets) + PS



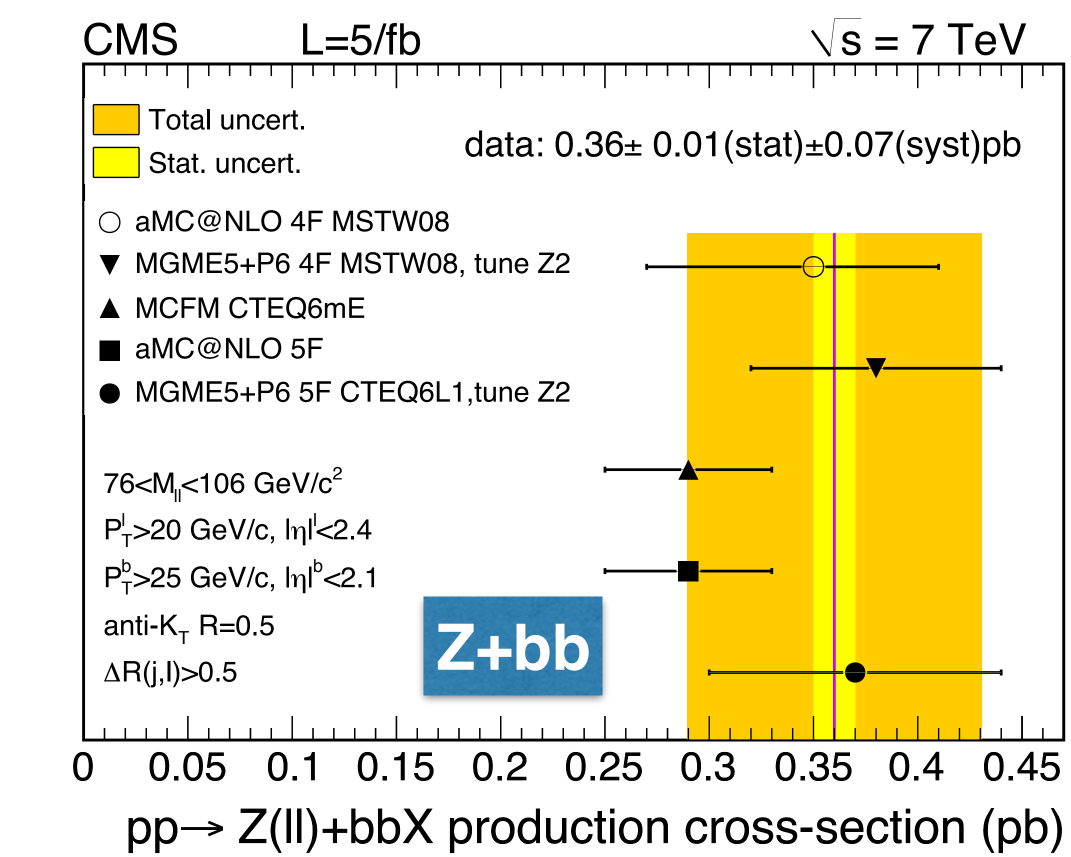
W+jets, 7 TeV - Jet p_T



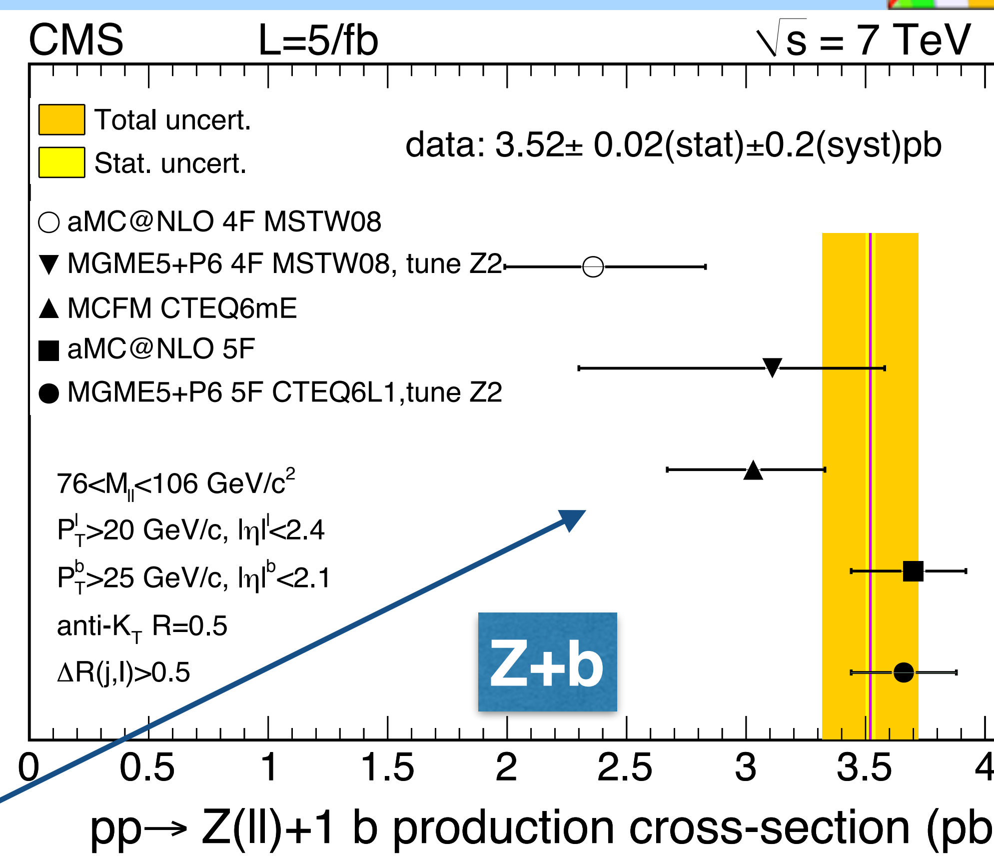


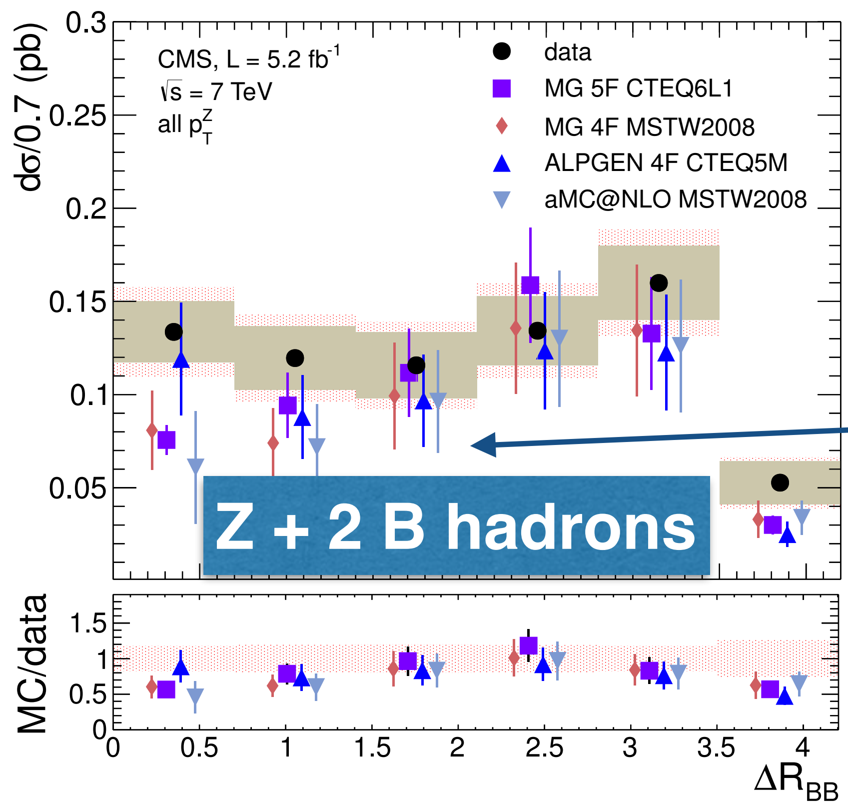
LO ME + PS calculations overestimate the p_T jet spectrum at high values.

W,Z + b jets, 7 TeV



SMP-13-004

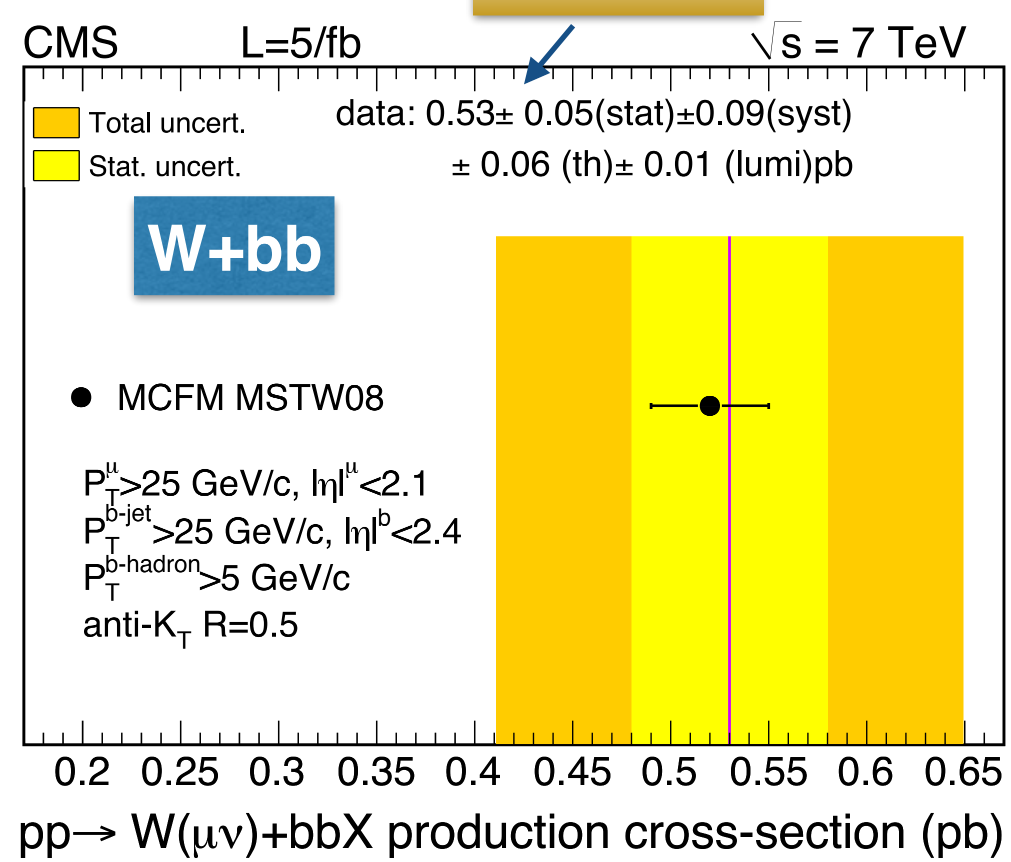




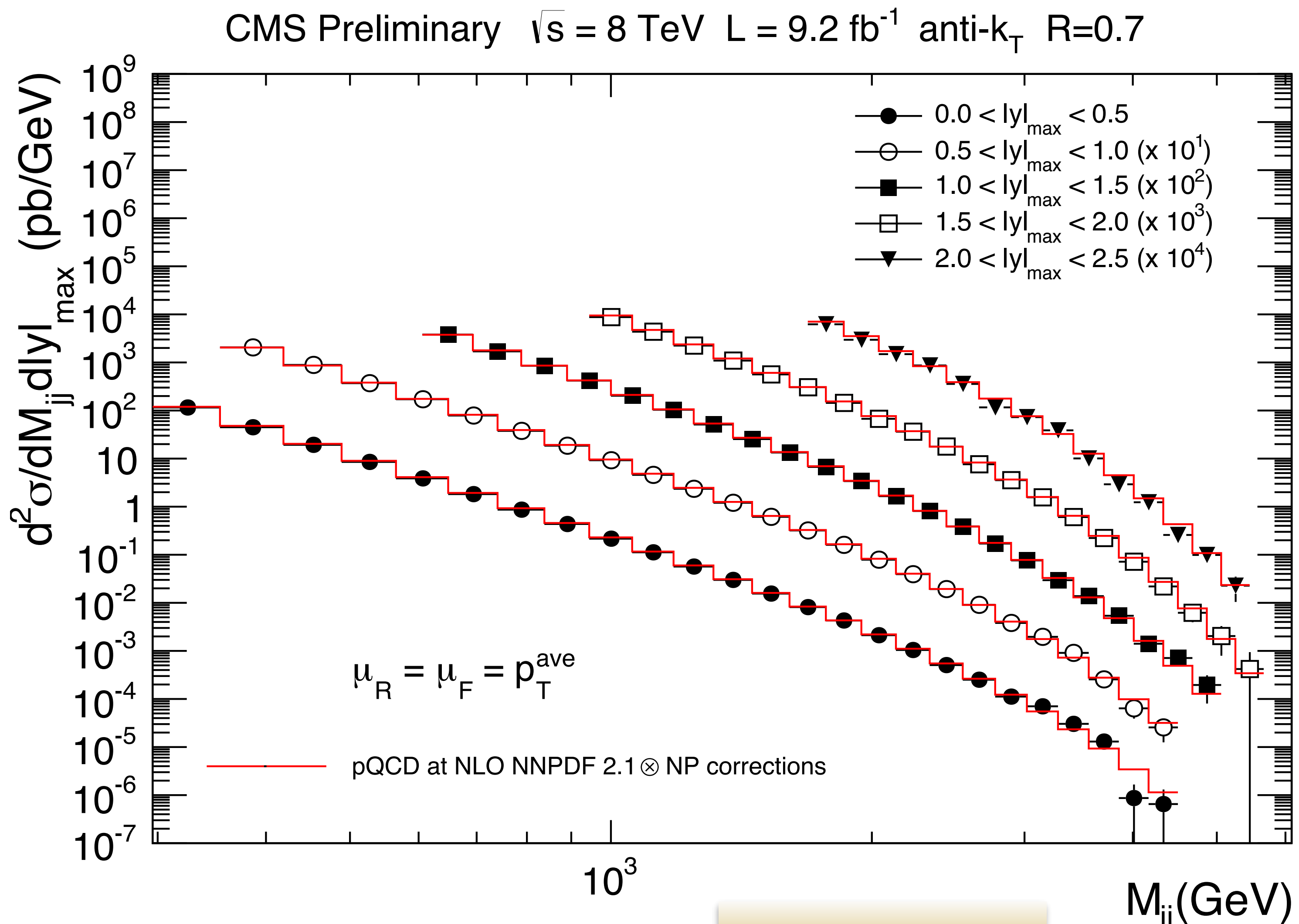
- Agreement dependent on flavour scheme.
- b jets collinear region not very well described.

EWK-11-015

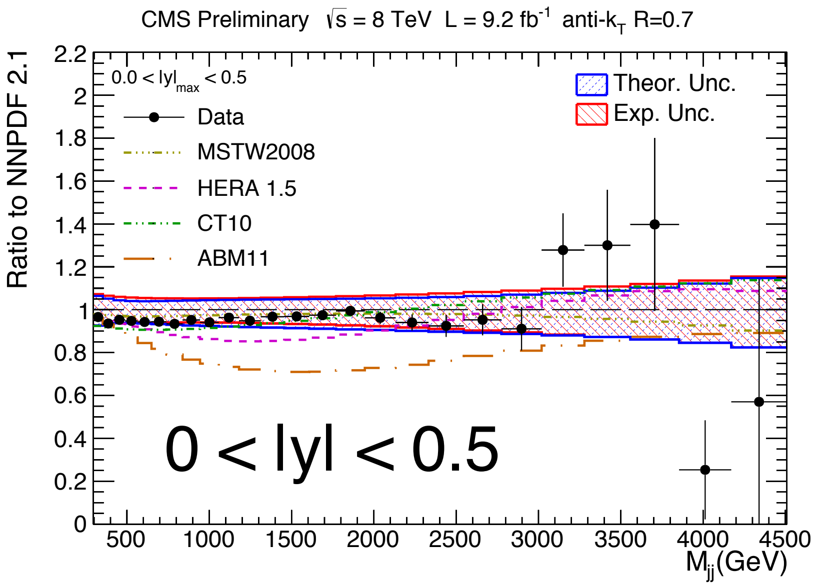
SMP-12-026

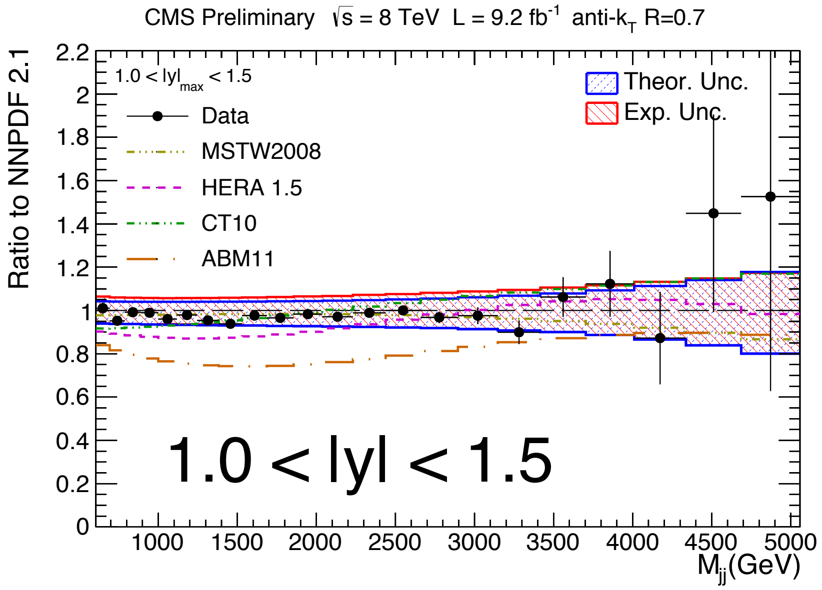


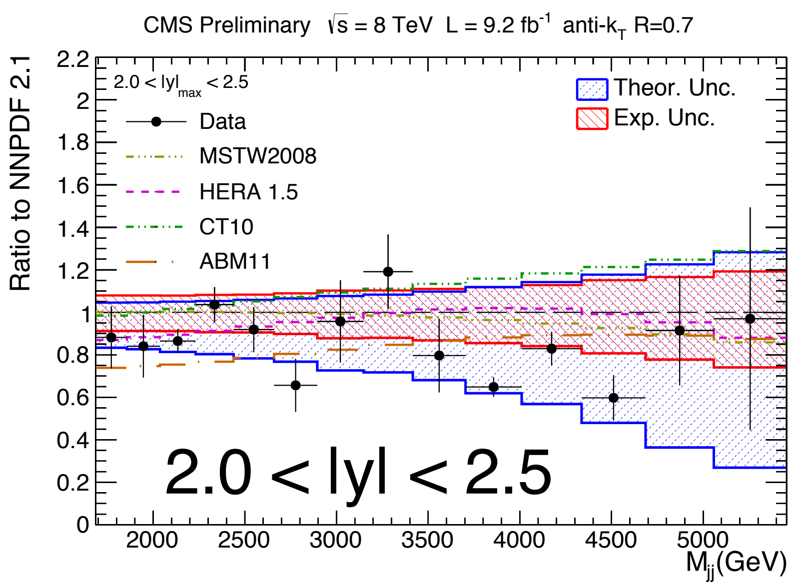
Dijet production at 8 TeV



SMP-14-002





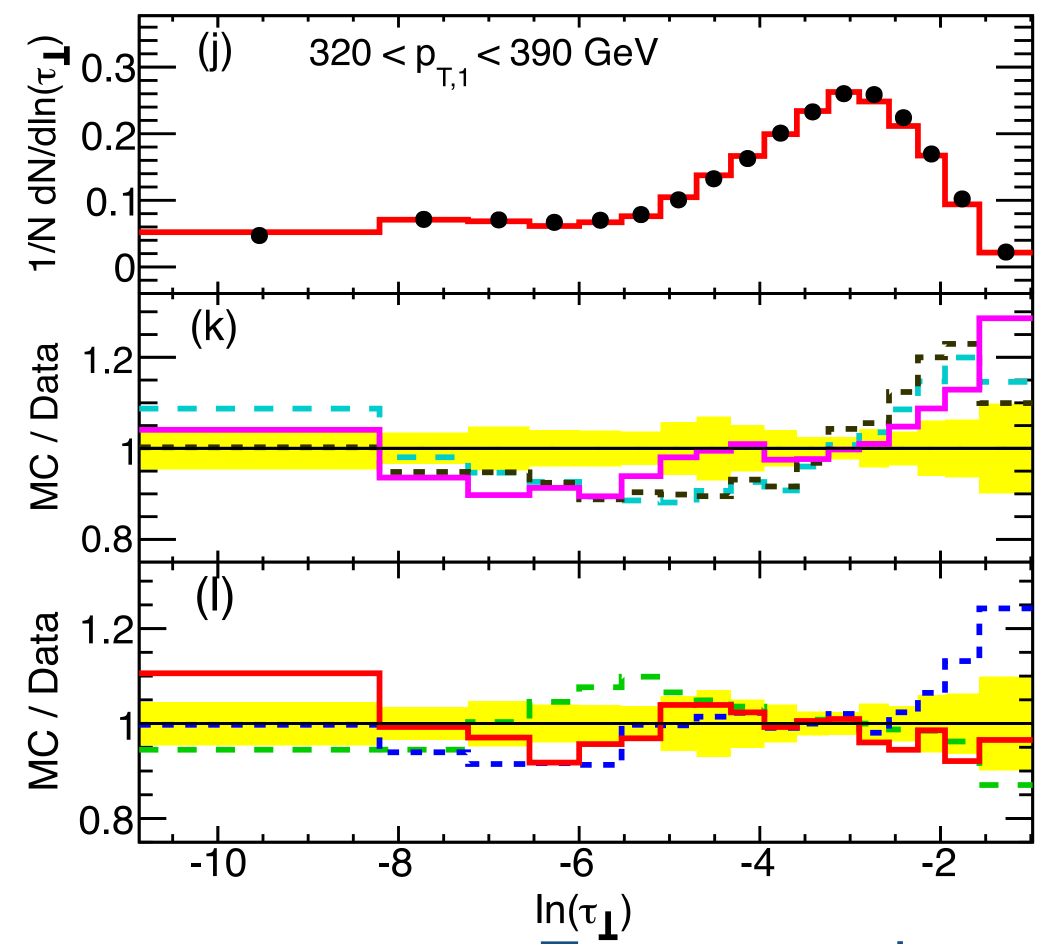


- Measurement of dijet differential cross section as a function of dijet mass and rapidity is a stringent test to pQCD calculations and may constrain the proton PDF.
- Events with $N_{jets} \geq 2$ jets: $p_T(1st) > 60$ GeV, $p_T(2nd) > 30$ GeV and $|y| < 2.5$.

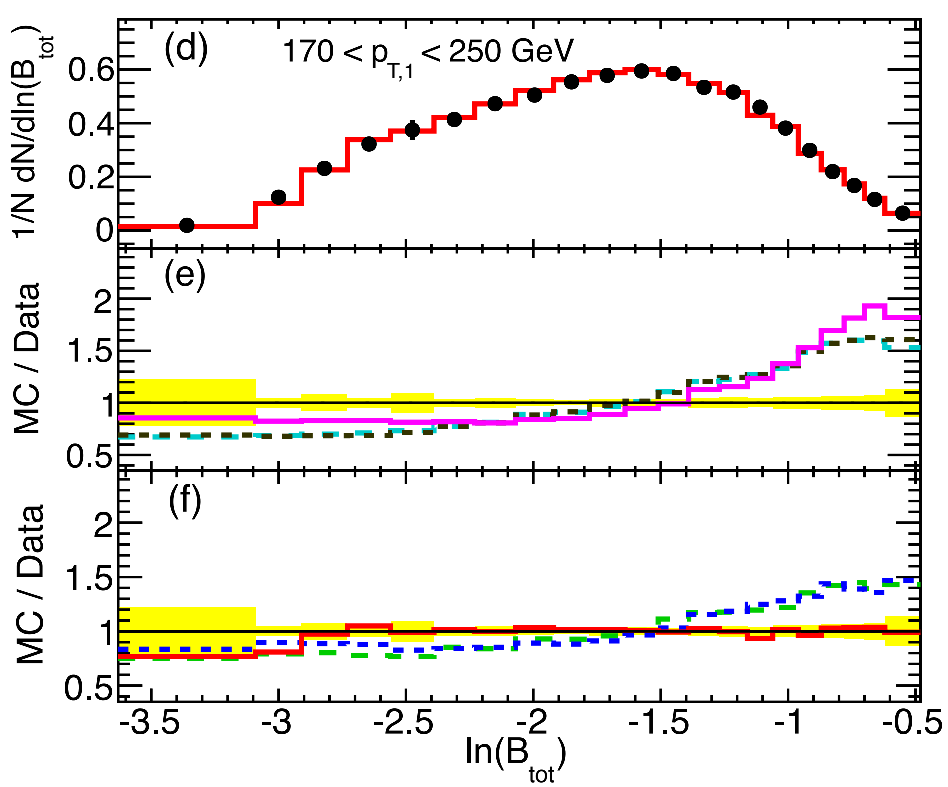
Event shapes, 7 TeV

- **Multijet final states** allow to test both perturbative and non-perturbative QCD effects.
- Several topological variables (infrared and collinear safe) sensitive to higher order approximate effects.
- Comparison with:
  - **MadGraph+Pythia6** (LO ME + PS)
  - **Pythia6, Pythia8 and Herwig++** (PS).

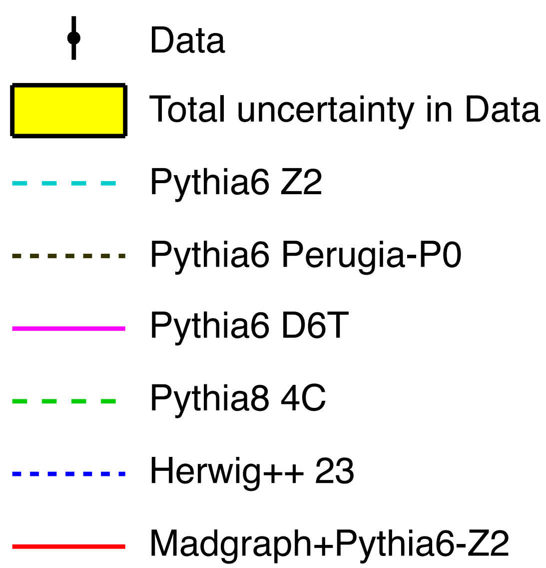
➡ MagGraph generally provides best results (ME with multiparton final states)



Transverse thrust



Jet broadening

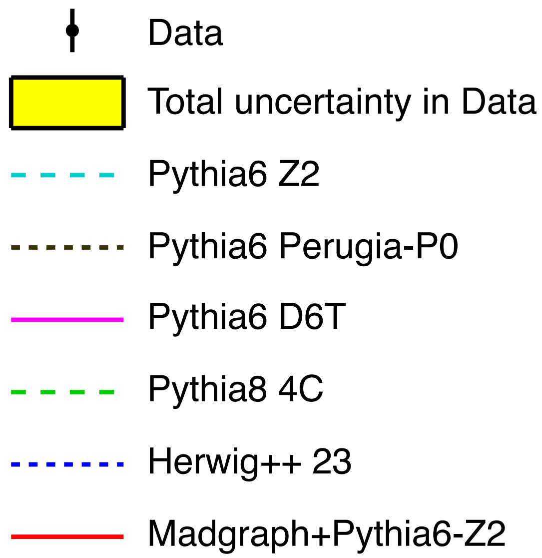


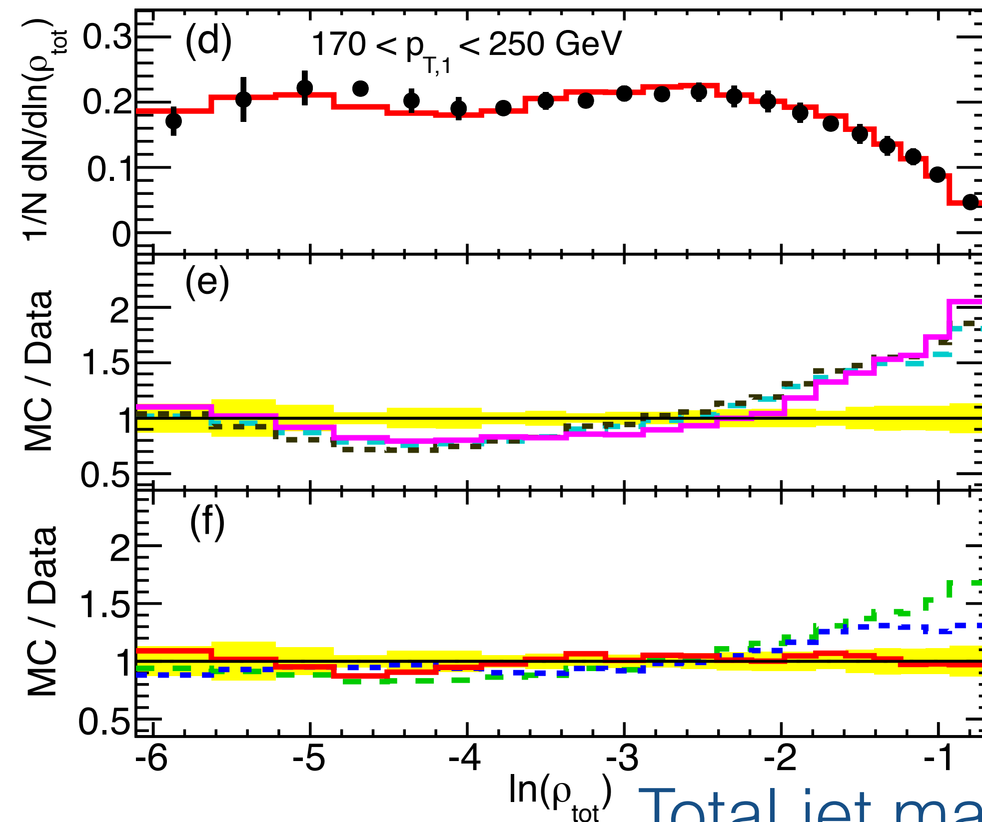
➡ Transverse thrust and jet broadening: sensitive to hard parton emissions and hadronization process.

SMP-12-022

Event shapes, 7 TeV

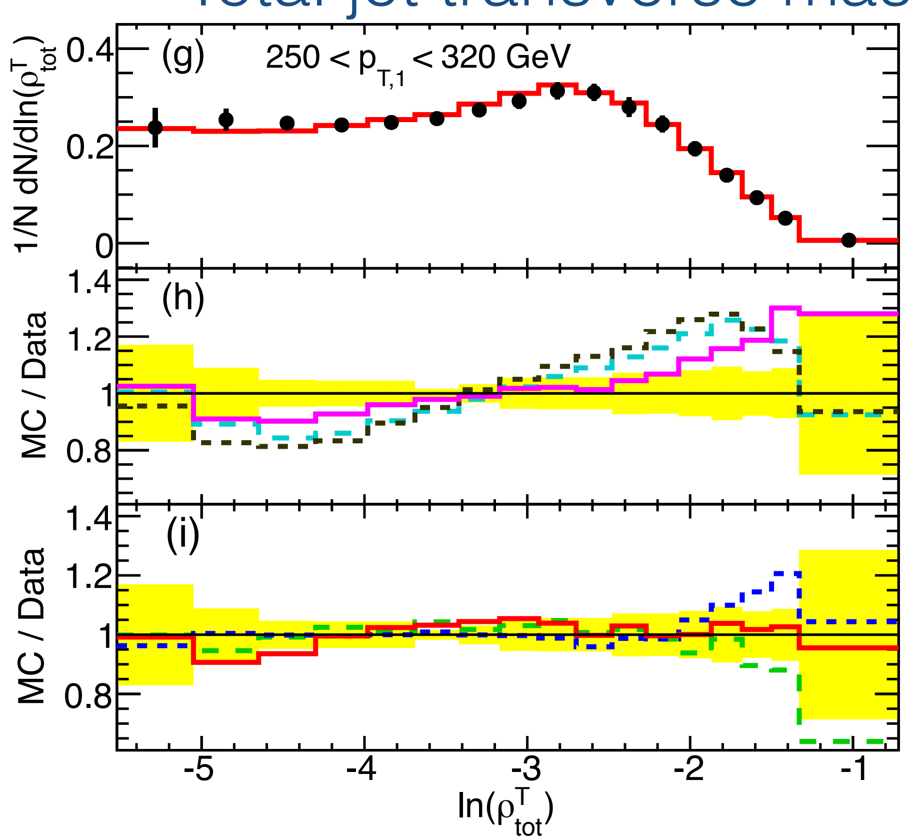
- At least one jet: $p_T > 110$ GeV, $|\eta| < 2.4$
- Several bins of p_T of the leading jet.

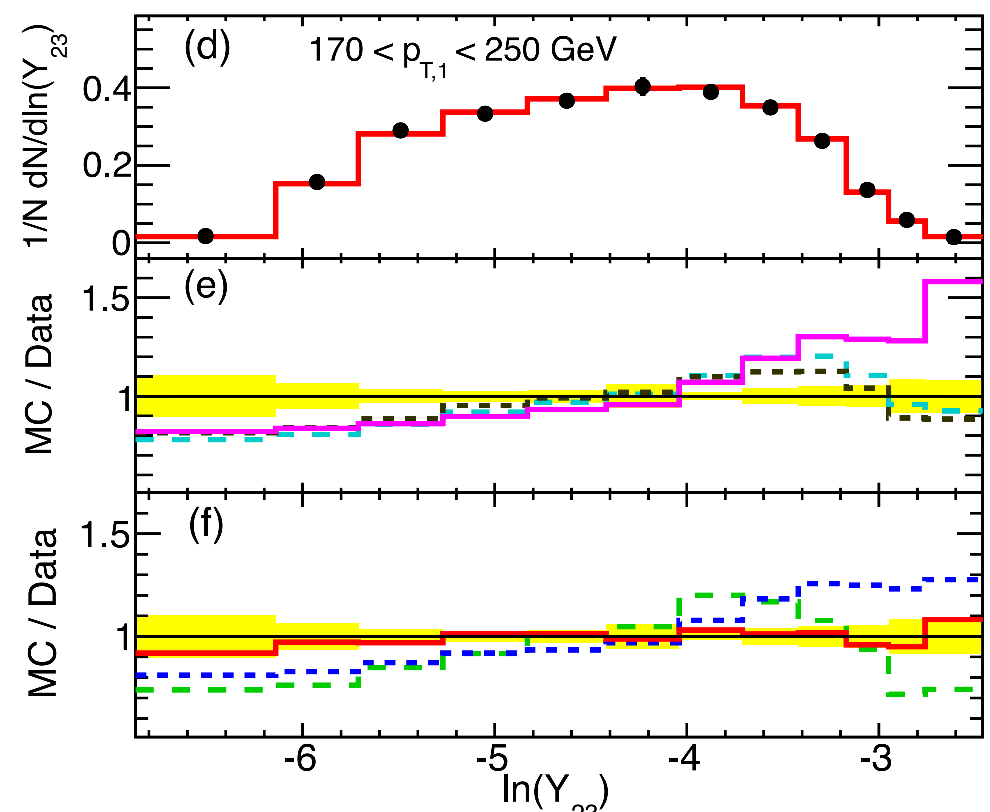




Total jet mass

Total jet transverse mass





Third jet resolution parameter

Inclusive multijet production, 7 TeV

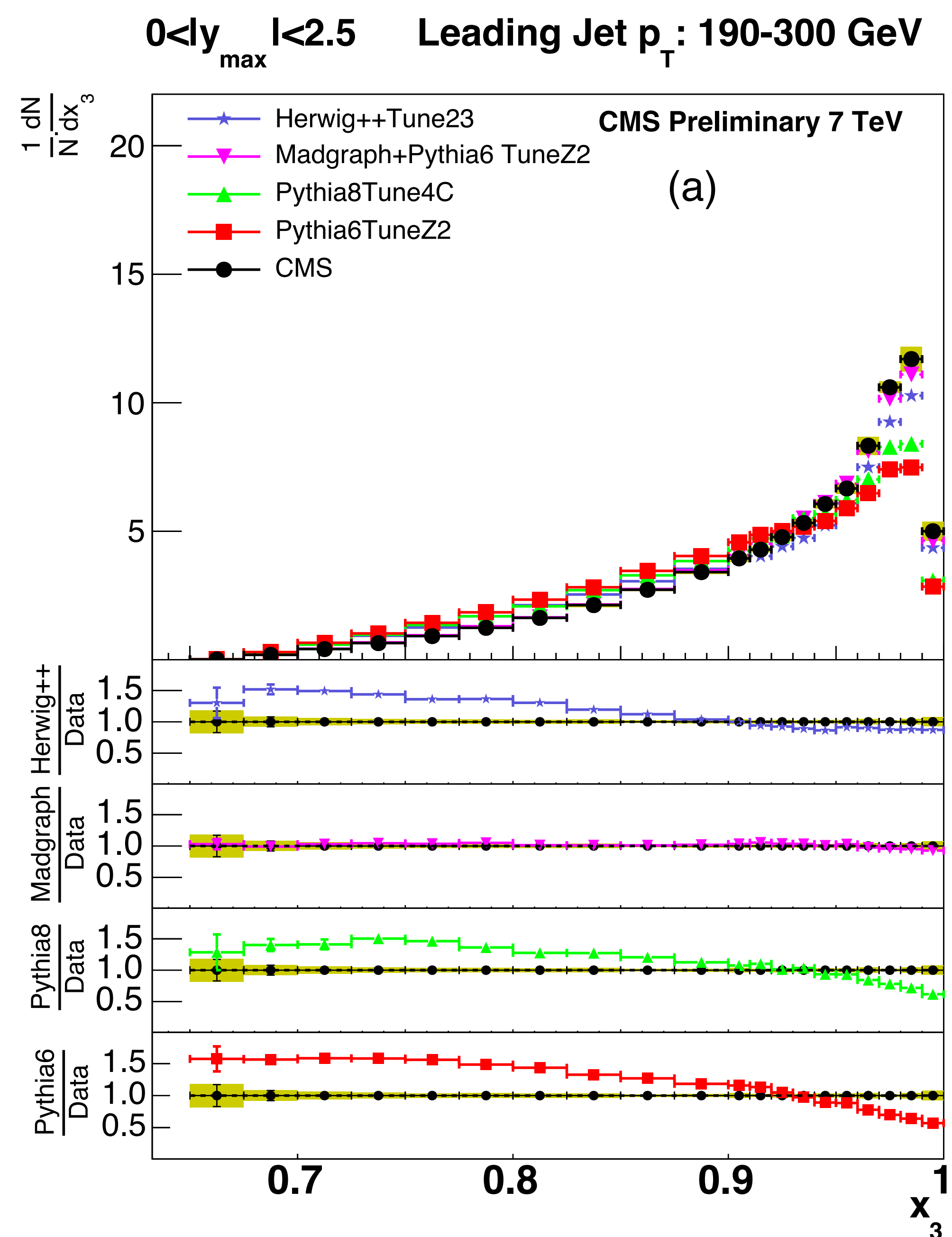
- At least **three** jets: $p_T > 50$ GeV, $|\eta| < 2.5$
- Measurement performed in two bins of p_T of the leading jet: 190-300 GeV and > 500 GeV.
- Definition of three- and four-jet variables sensitive to approximations of higher order implemented within PS, ME+PS event generators:
  - three-jet mass
  - four-jet mass
  - $x3 = p_T(1st)/\sqrt{s}$
  - $x4 = p_T(2nd)/\sqrt{s}$
  - Bengtsson-Zerwas angle:

$$\cos\chi_{BZ} = \frac{(\vec{p}_3 \wedge \vec{p}_4) \cdot (\vec{p}_5 \wedge \vec{p}_6)}{|\vec{p}_3 \wedge \vec{p}_4||\vec{p}_5 \wedge \vec{p}_6|}$$

  - Nachtman-Reiter angle:

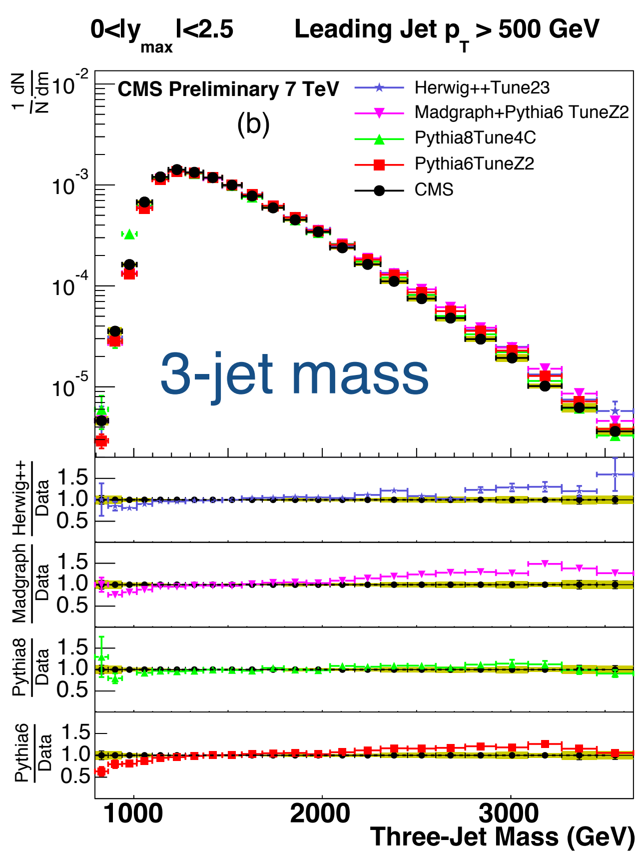
$$\cos\theta_{NR} = \frac{(\vec{p}_3 - \vec{p}_4) \cdot (\vec{p}_5 - \vec{p}_6)}{|\vec{p}_3 - \vec{p}_4||\vec{p}_5 - \vec{p}_6|}$$

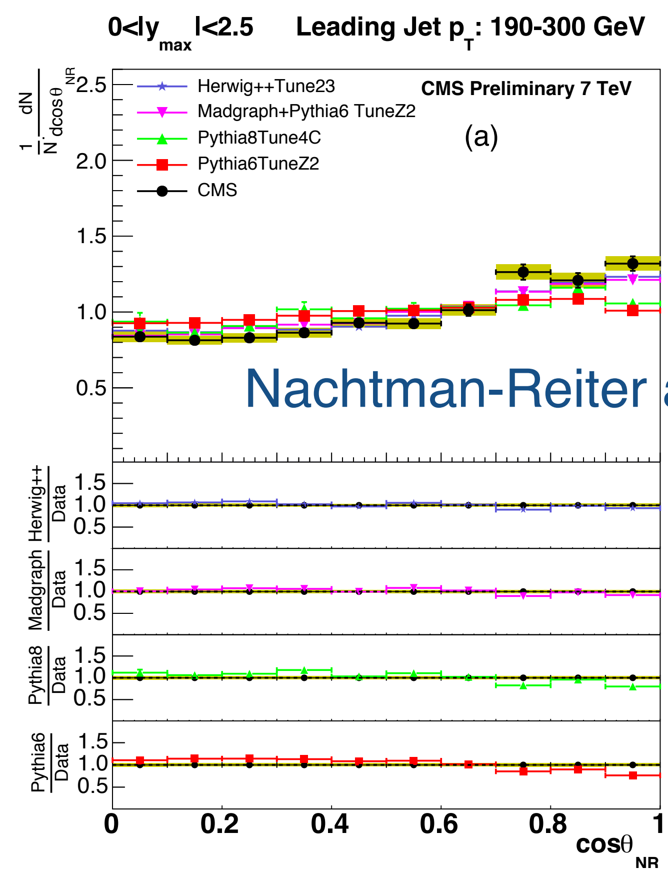
QCD-11-006

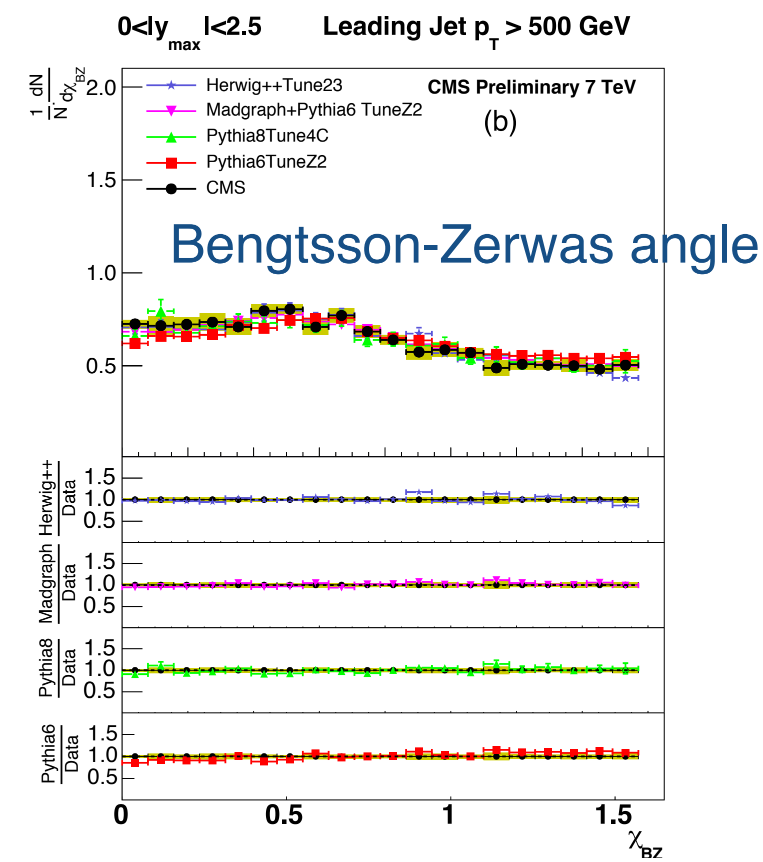


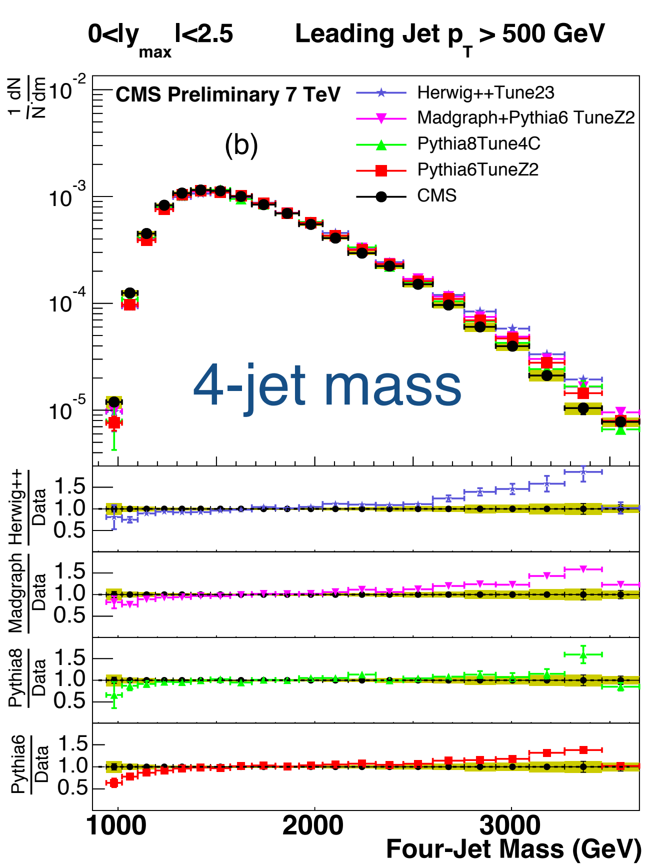
➡ x_3: PS fails to describe the pT of the leading jet scaled by $\sqrt{s}$

Inclusive multijet production, 7 TeV

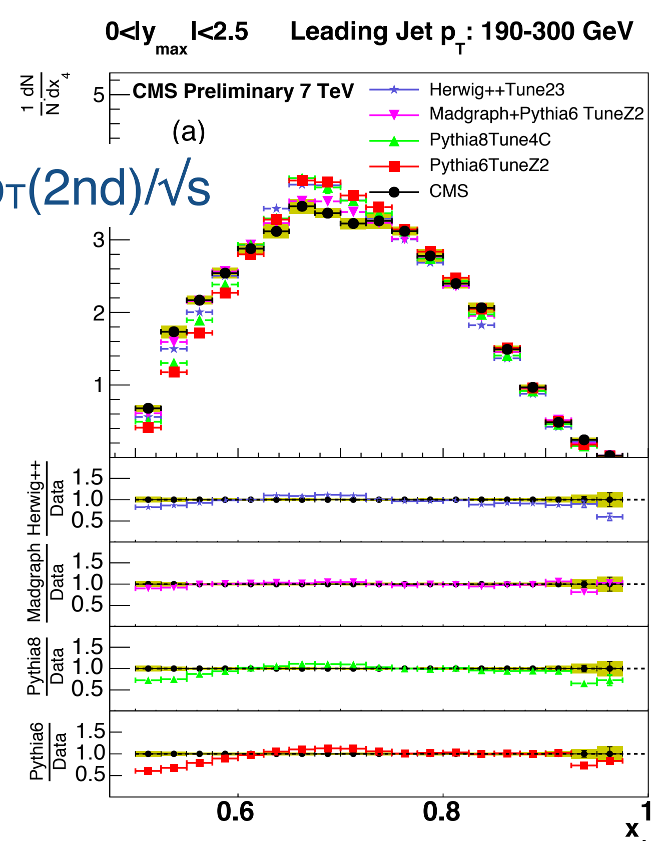








$x4 = p_T(2nd)/\sqrt{s}$



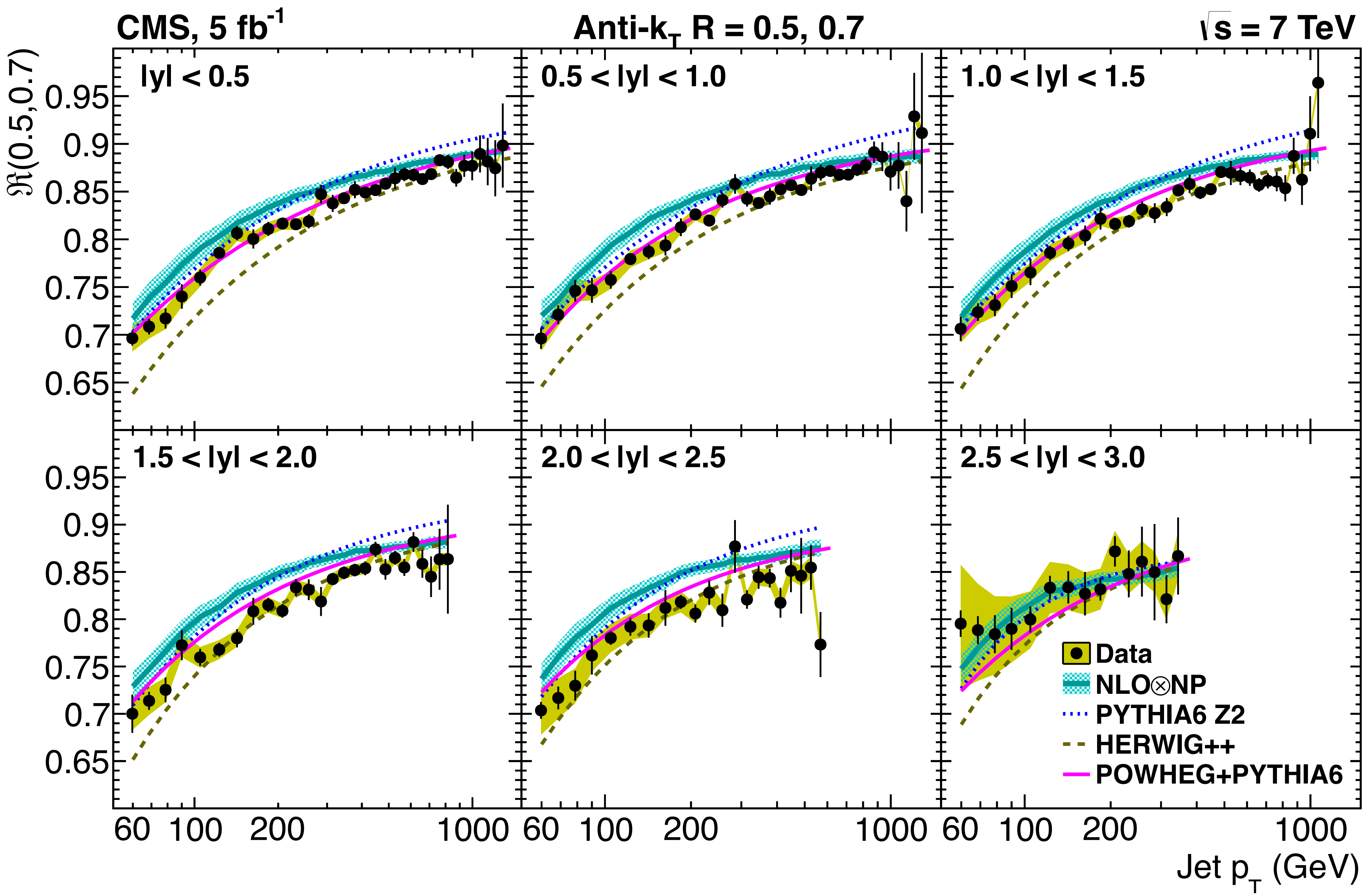
The PS describes well the angular quantities, but fails to describe the pT in 3-jet and 4-jet final states.

Best results are achieved with LO ME + PS (MadGraph+Pythia6)

Jet size

- Ratio of **anti-k$_T$** jets with **R=0.7** and **R=0.5**: sensitive to the emission of collinear partons.
- The choice of R is a matter of compromise:
  - collinear emission losses and non-perturbative effects;
  - pileup and underlying event contamination.

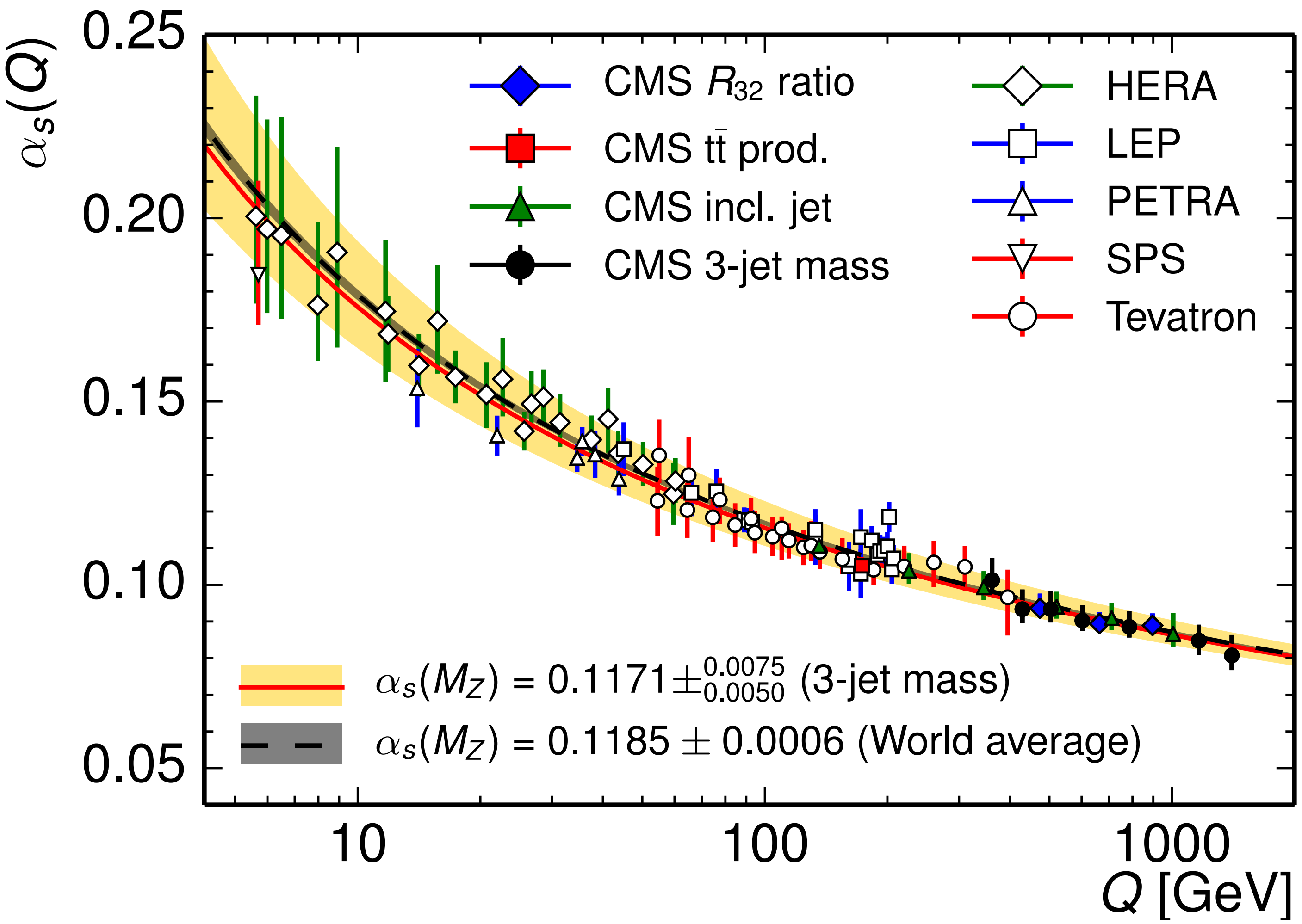
SMP-13-002

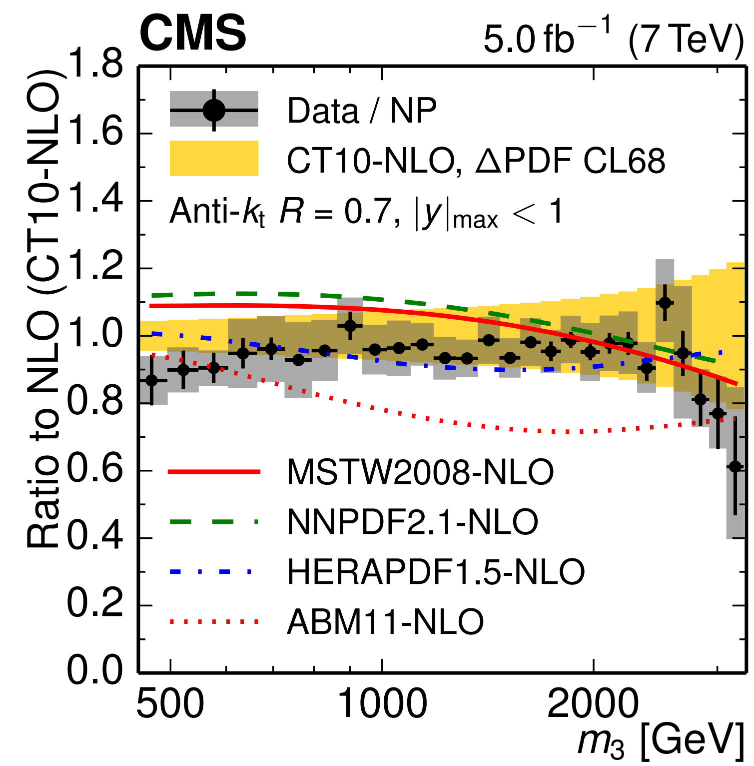


- Comparison with:
  - Fixed order **NLO** prediction (with NP corrections)
  - **Pythia6** and **Herwig++**: $N_{jets} > 2$ modeled with PS
  - **Powheg+Pythia6**: NLO merged with PS
- Herwig++ and Pythia6 alone fail to describe well some kinematical regions, best results achieved through NLO + PS merging.

α_S measurements, 7 TeV

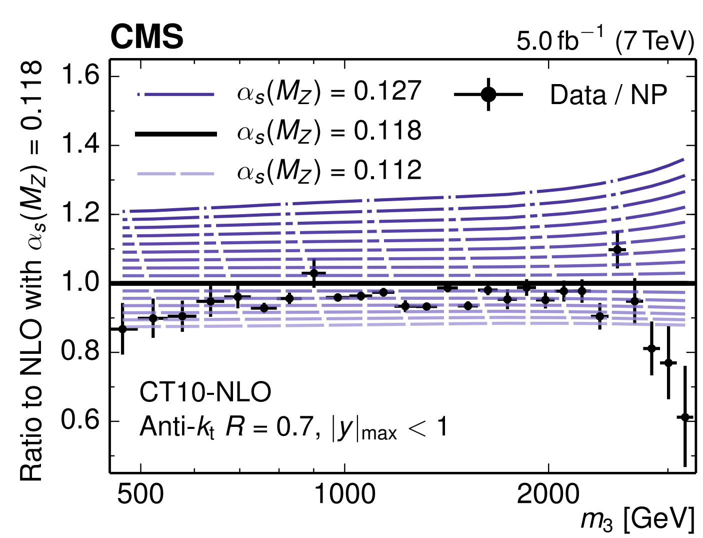
$$\alpha_S(M_Z) = 0.1171 \pm 0.0013\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})\,^{+0.0069}_{-0.0040}\,(\mathrm{scale})$$

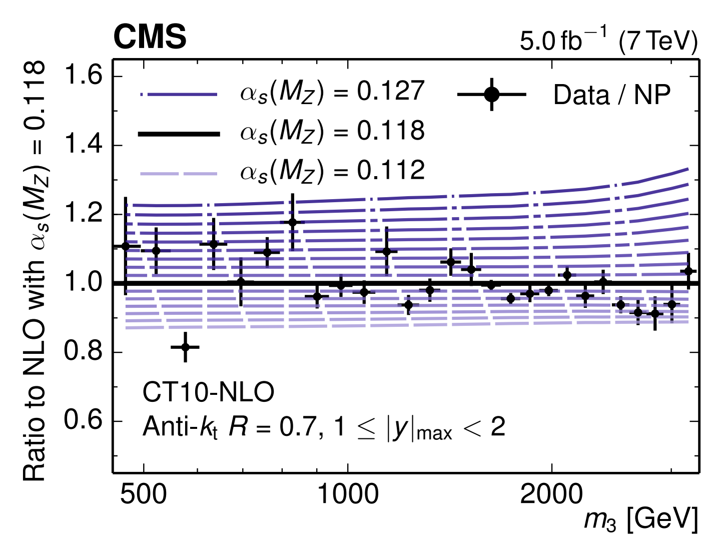




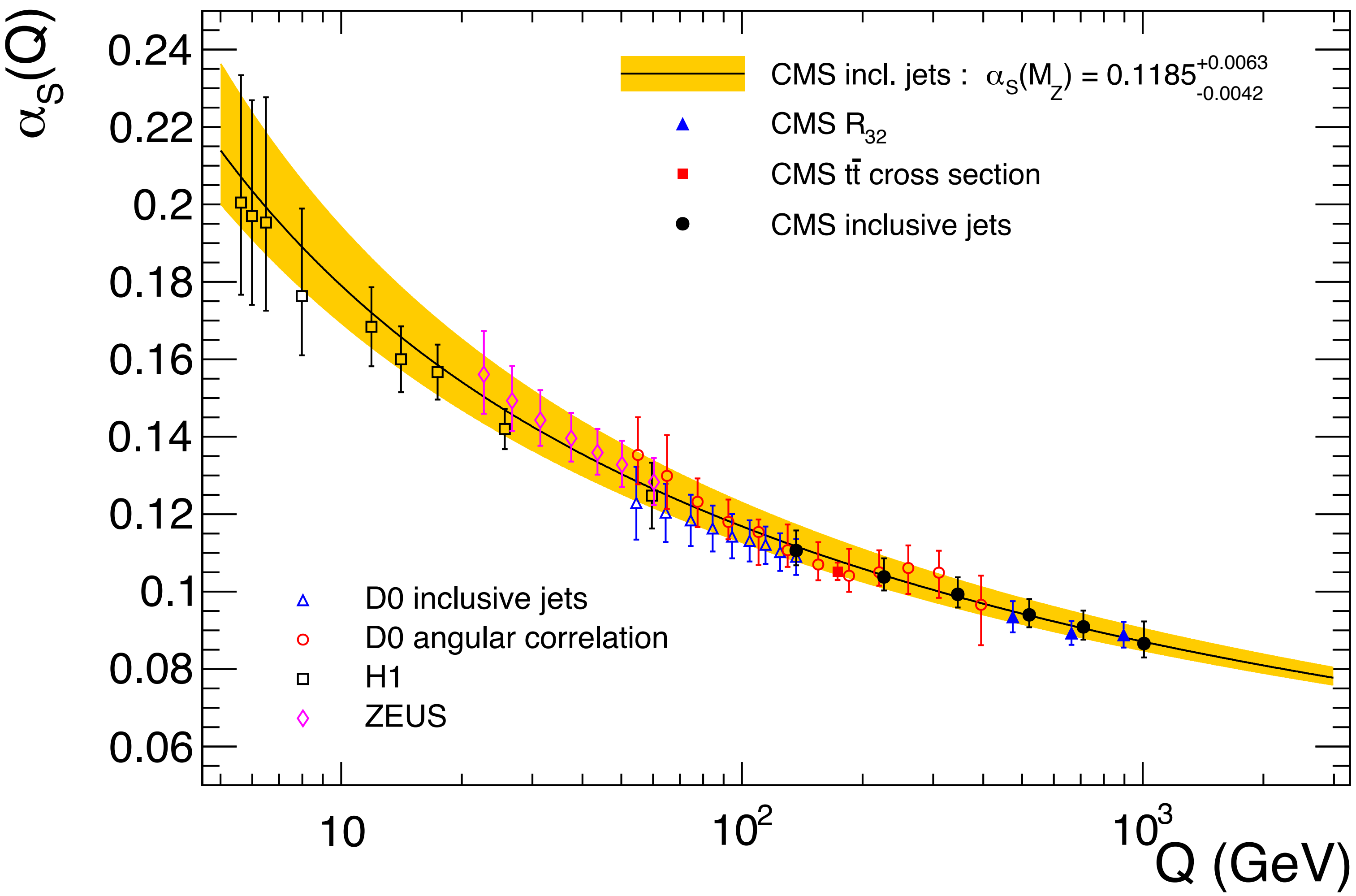
SMP-12-027

- α_S is constrained in **<u>3-jet</u>** differential cross section as a function of 3-jet mass and rapidity up to the TeV.
- Results are in good agreement with world average.
- Q^2 scale nicely follows RGE evolution.

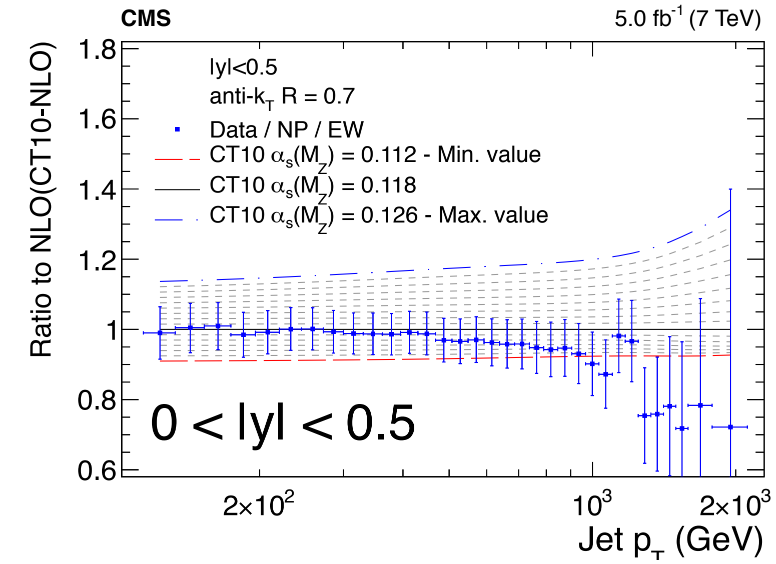


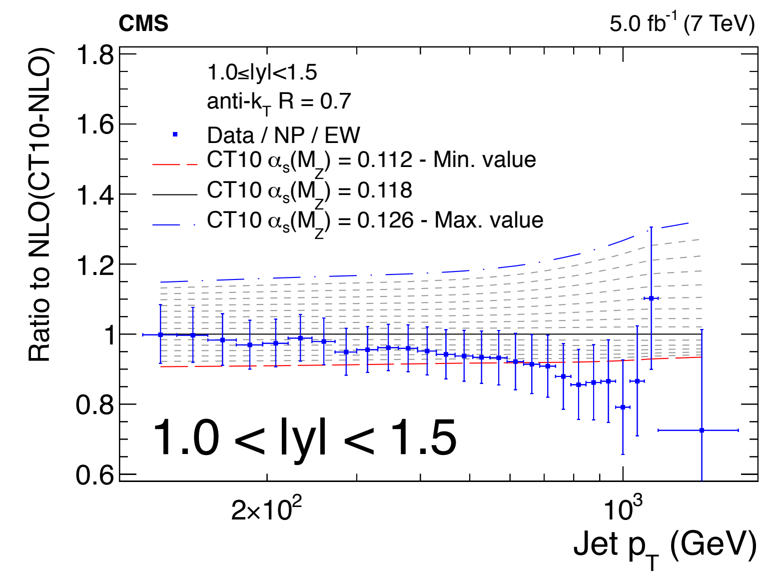


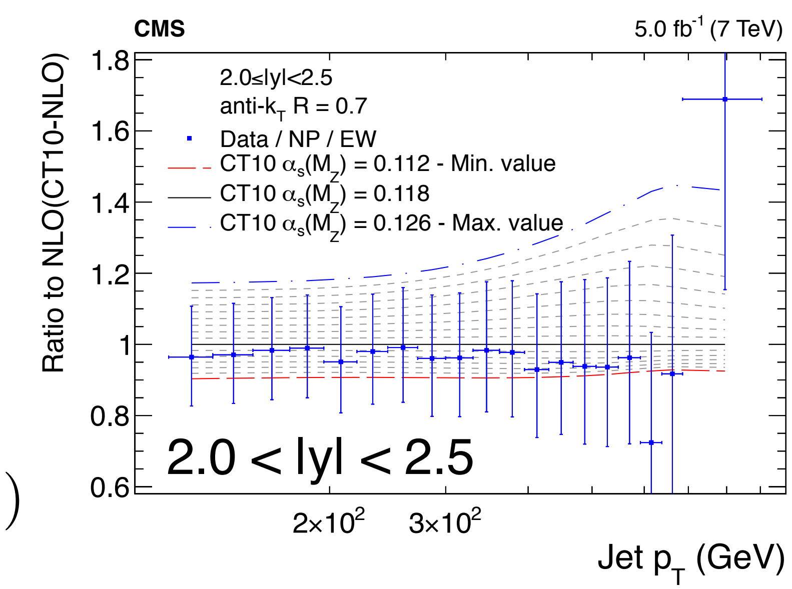
α_S measurements, 7 TeV



SMP-12-028



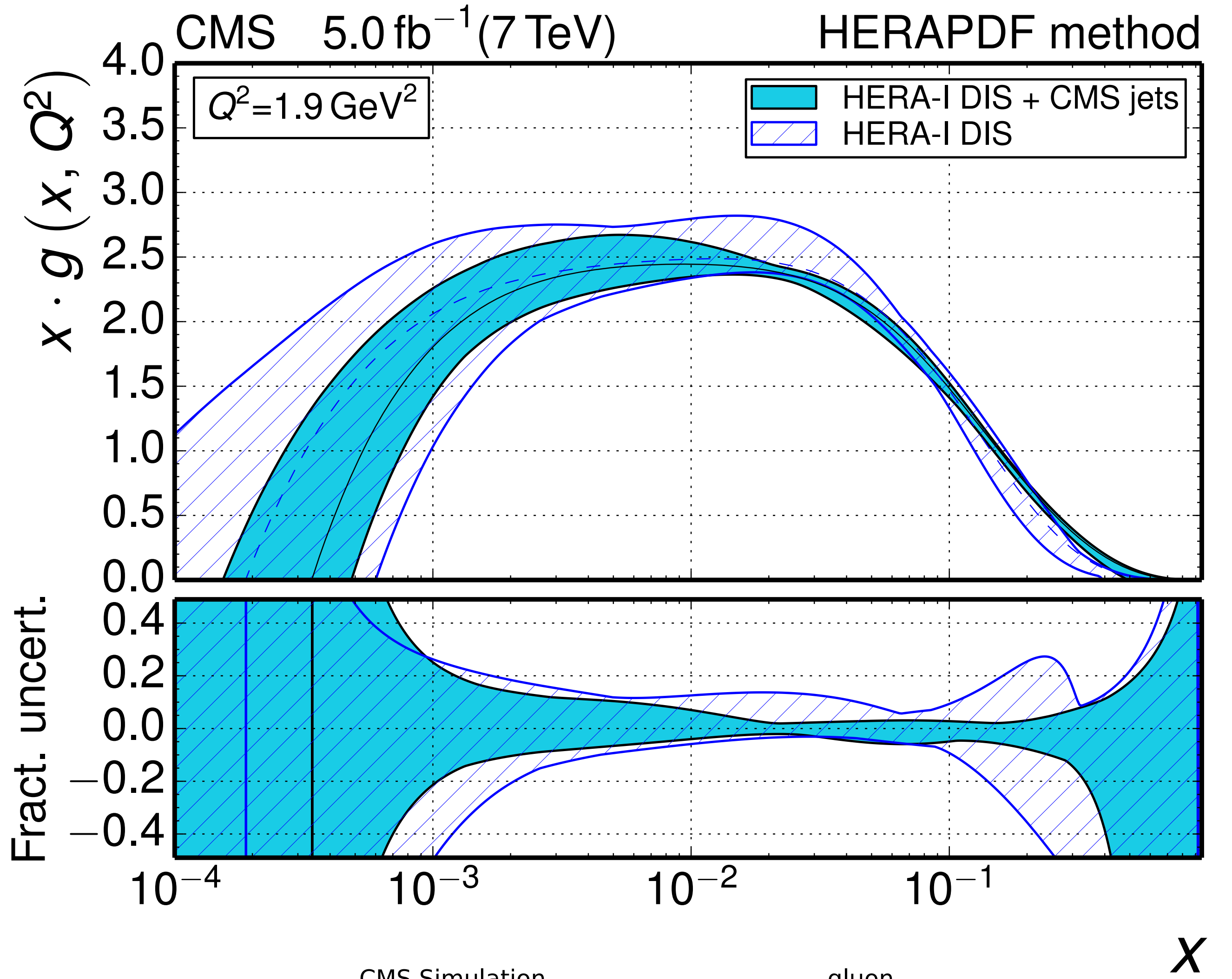


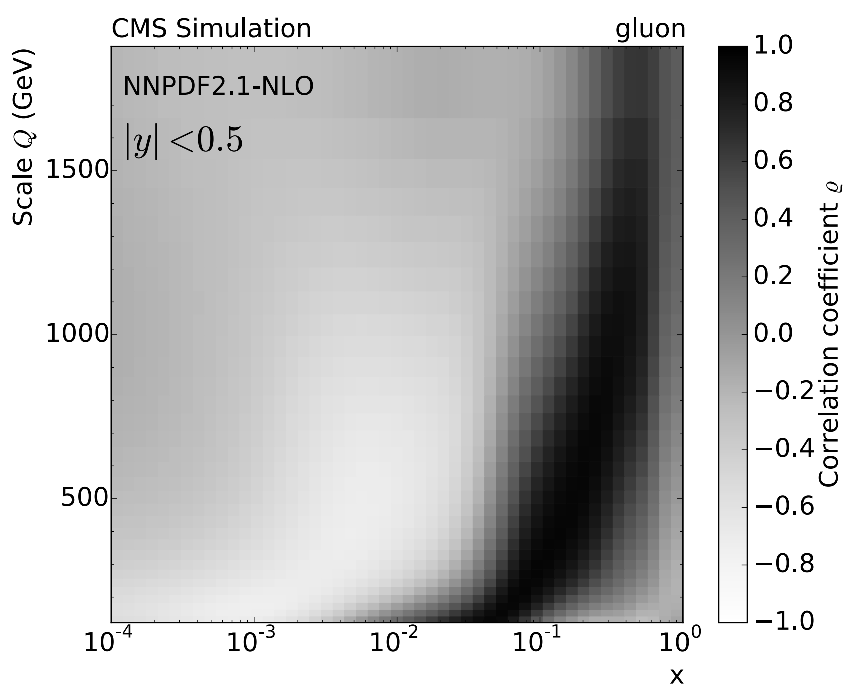


- α_S is constrained in **<u>inclusive jet</u>** differential cross section as a function of p_T and η up to the TeV.
- Results are in good agreement with world average.
- Q2 scale nicely follows RGE evolution.

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0053}_{-0.0024}\,(\text{scale})$$

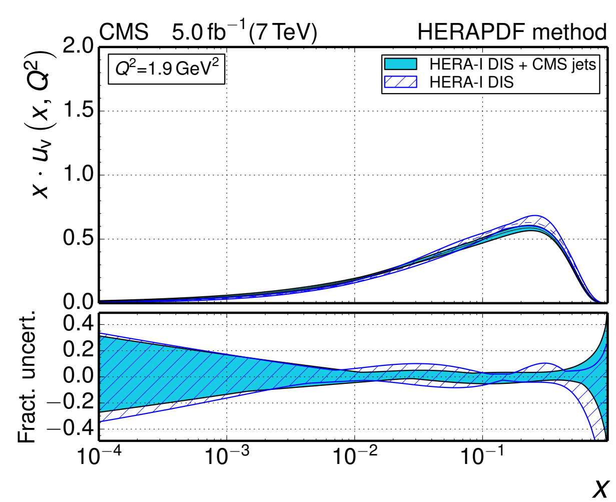
PDF constraints

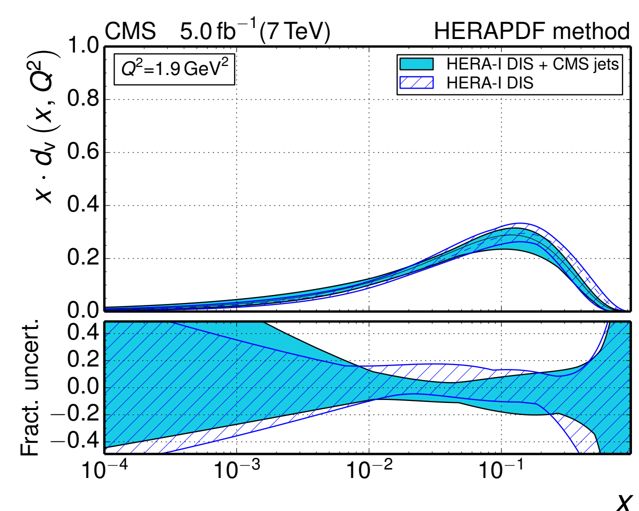




SMP-12-028

- The **inclusive jet cross section** is very sensitive to the gluon PDF at high x (x ≳ 0.01).
- Improvement of PDF constraints obtained through the **HERAFITTER** framework.
- Moderate improvement also on the constraints to valence quark PDFs.





Conclusions

- Several results have been produced by CMS on the V+jets and inclusive jet processes by exploiting the p-p datasets at 7 TeV (2011) and 8 TeV (2012).

- Good understanding of perturbative QCD calculations and proton PDFs is the key to success in physics analyses at $\sqrt{s}$ = 13 TeV.

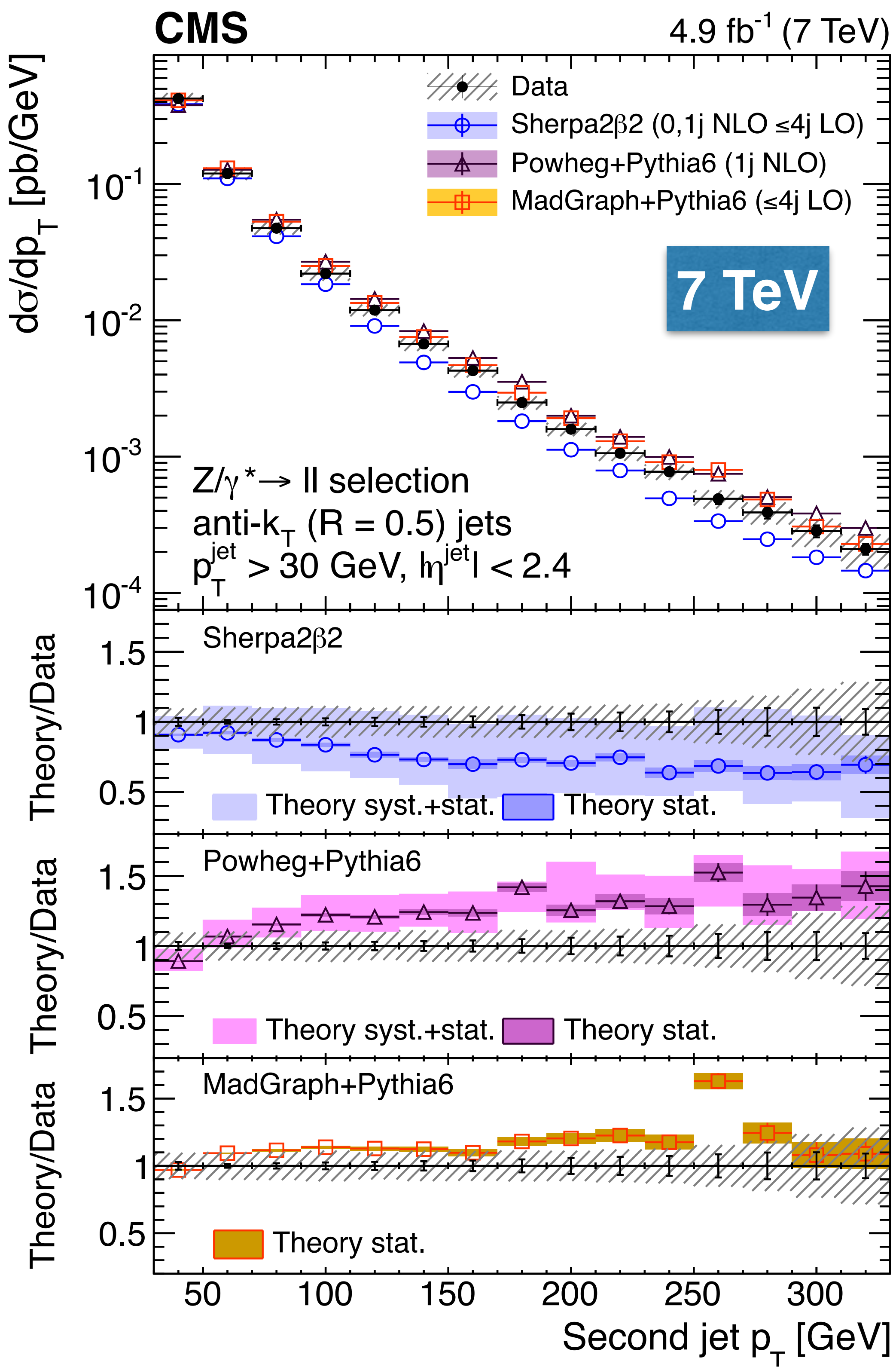
- Valuable input to α_S and PDF fits.

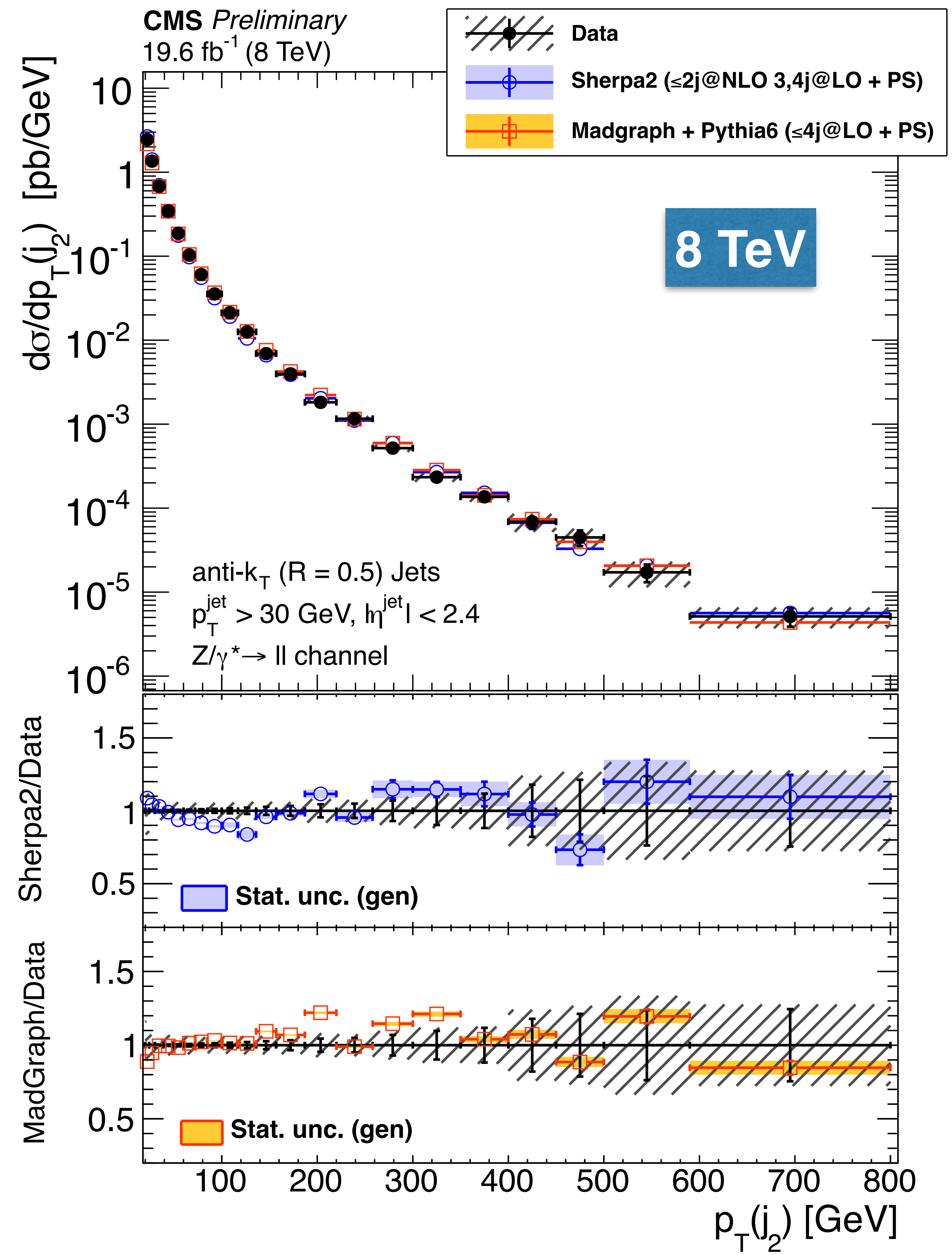
- The NLO calculations merged with PS yield the best description of data and are becoming a standard.

- Some known issues in the theoretical description:
  - pT distribution of jets associated to W,Z in LO ME + PS calculations (MadGraph+Pythia6);
  - b quarks collinear production;
  - NLO fixed order calculations unable to describe some kinematical features.
  - PS alone fails to describe several kinematical distributions, best results achieved through NLO+PS merging.

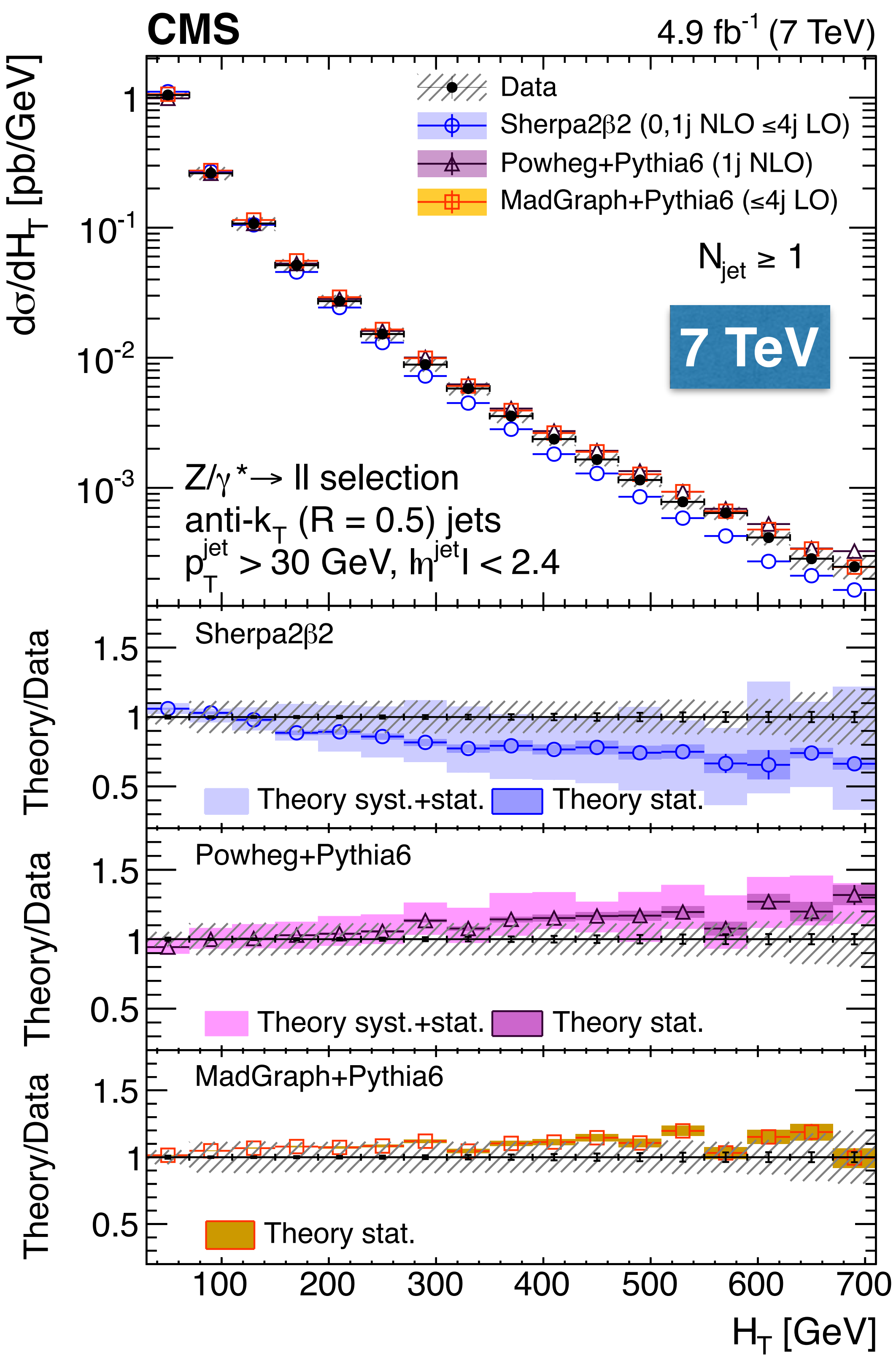
Backup slides

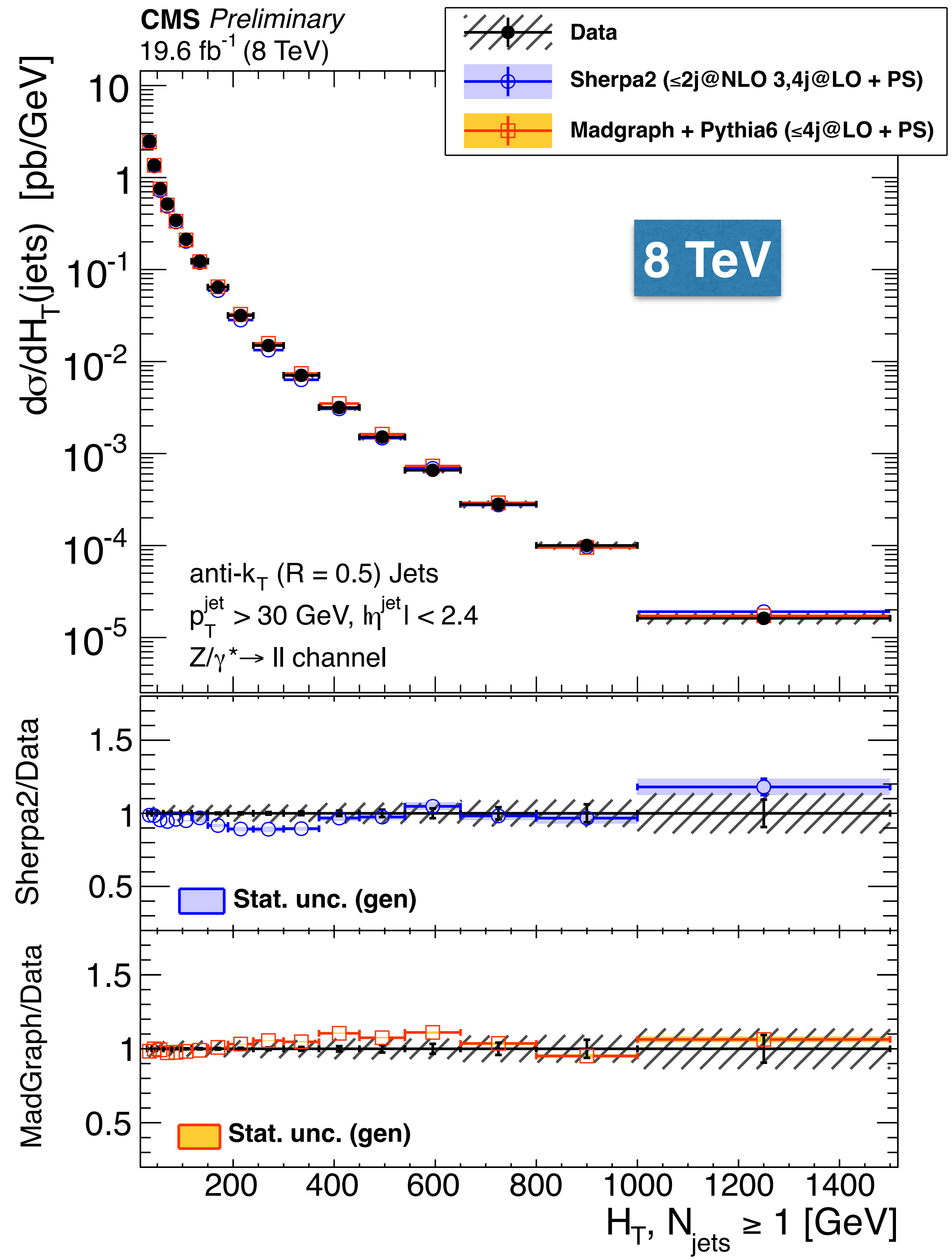
Z+jets, 7 and 8 TeV - 2nd Jet p_T





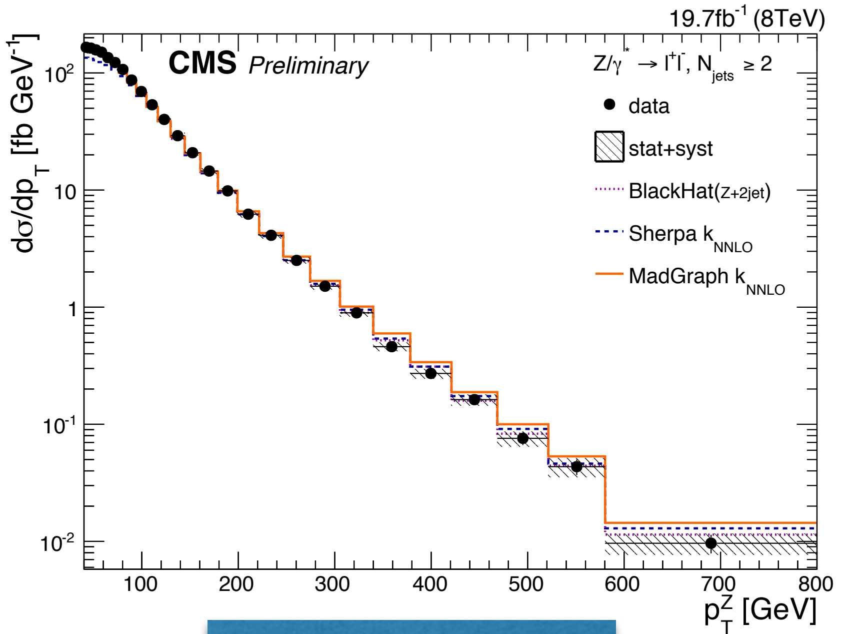
Z+jets, 7 and 8 TeV - Jet H_T ($N_{jets} \geq 1$)



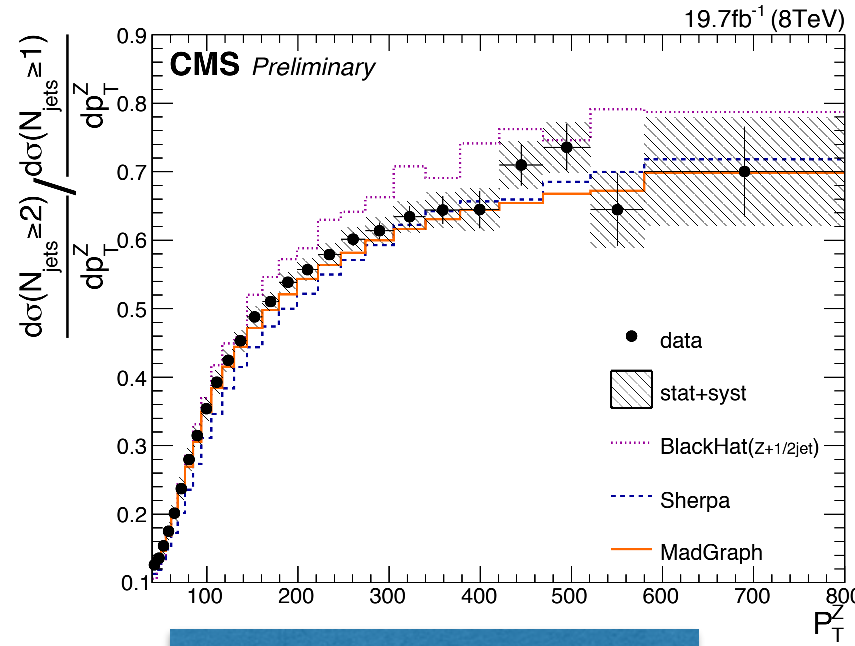


H_T is the scalar sum of the p_T of all the jets in the event

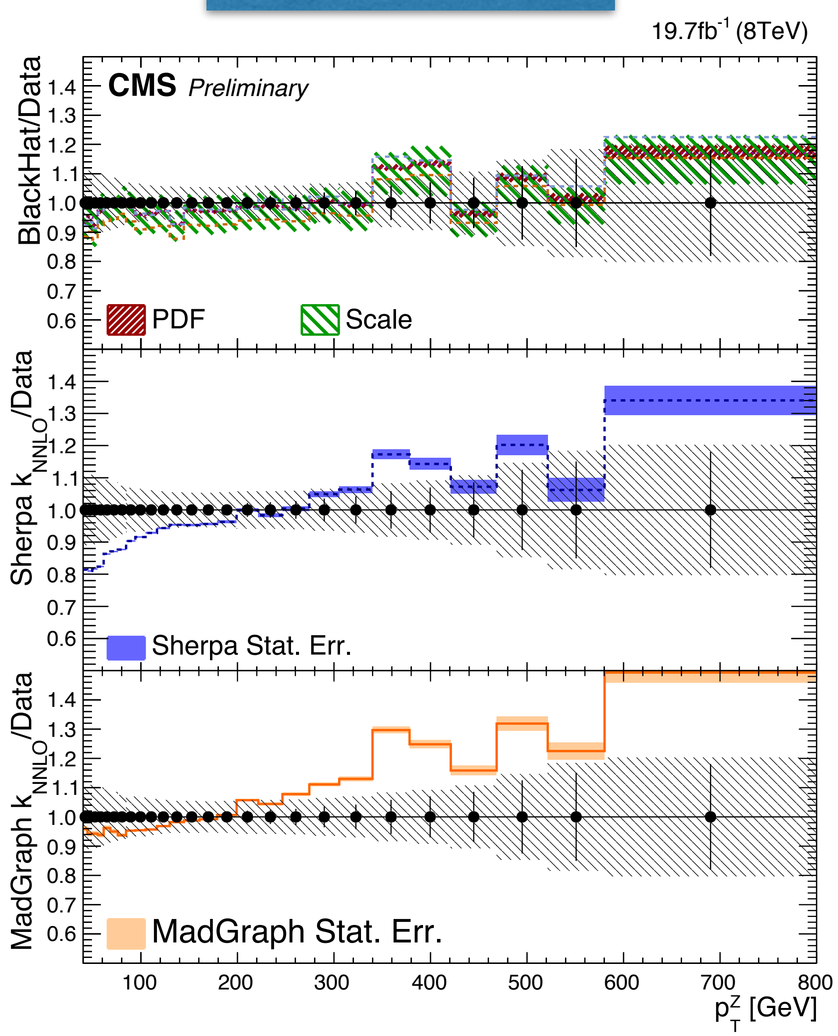
Z + jets, 8 TeV: Z boson p_T

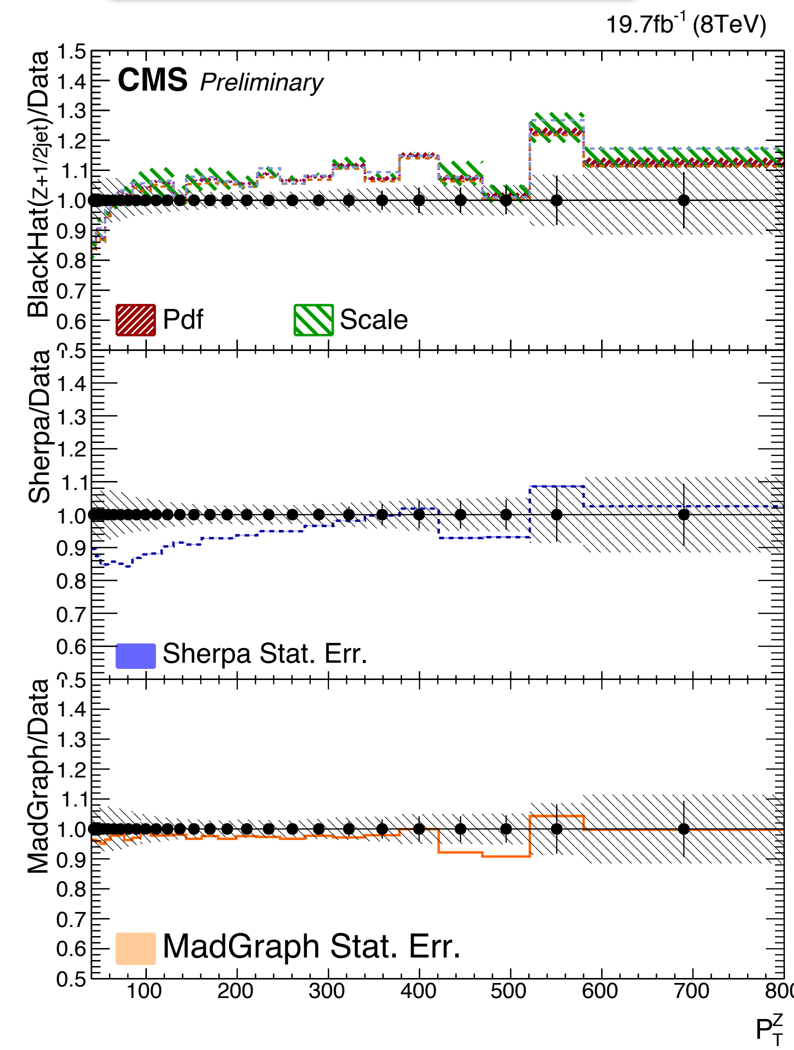


Z p_T, $N_{jets} \geq 2$



$N_{jets} \geq 2$ / $N_{jets} \geq 1$





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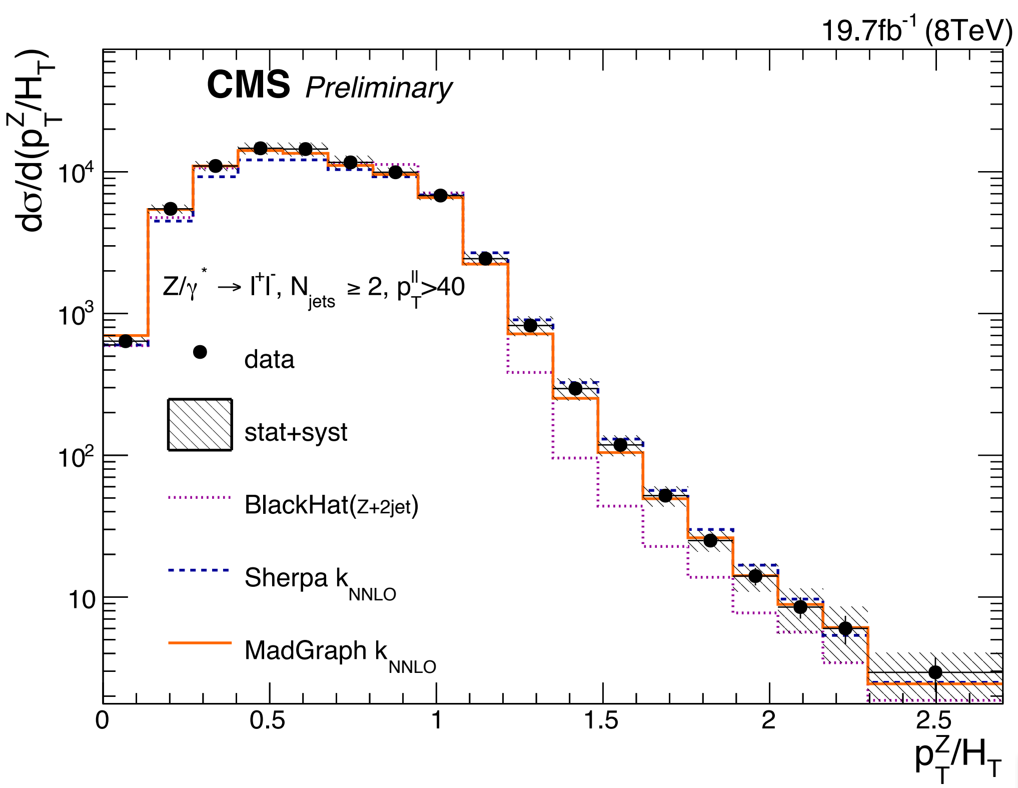
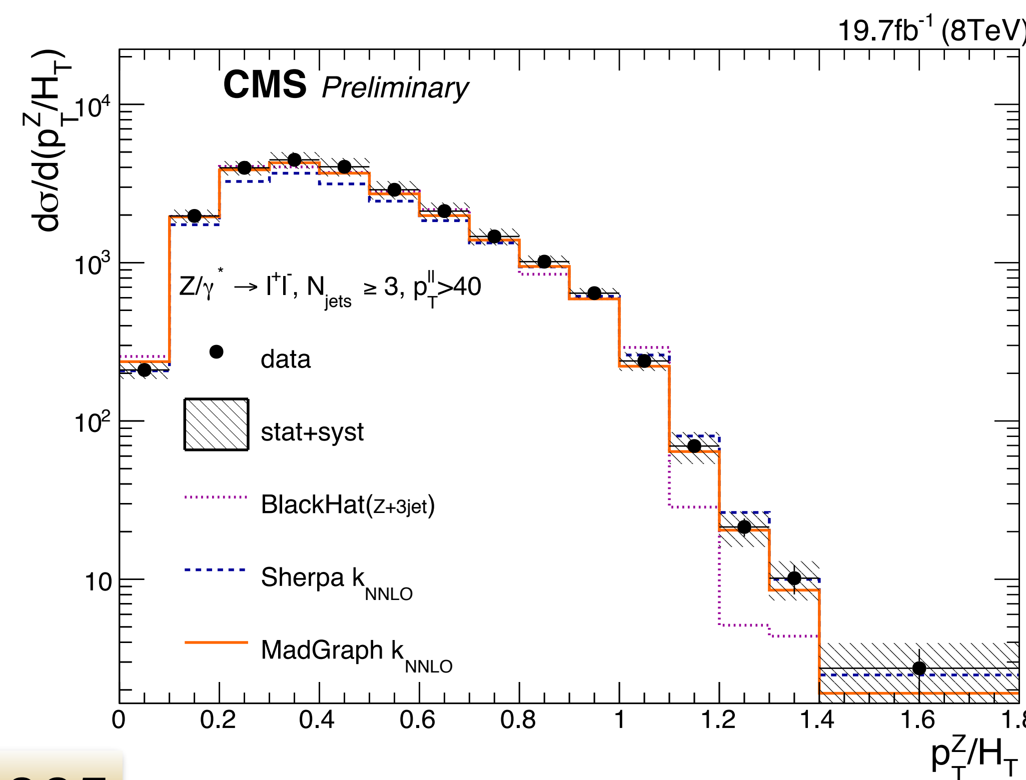
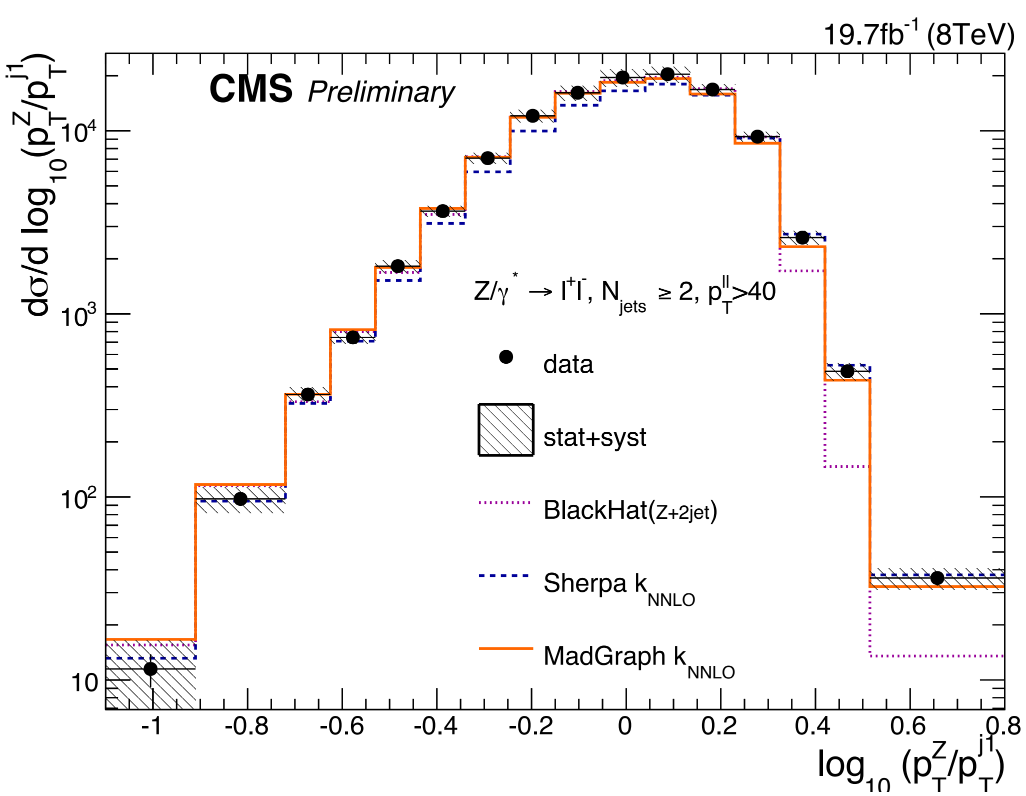
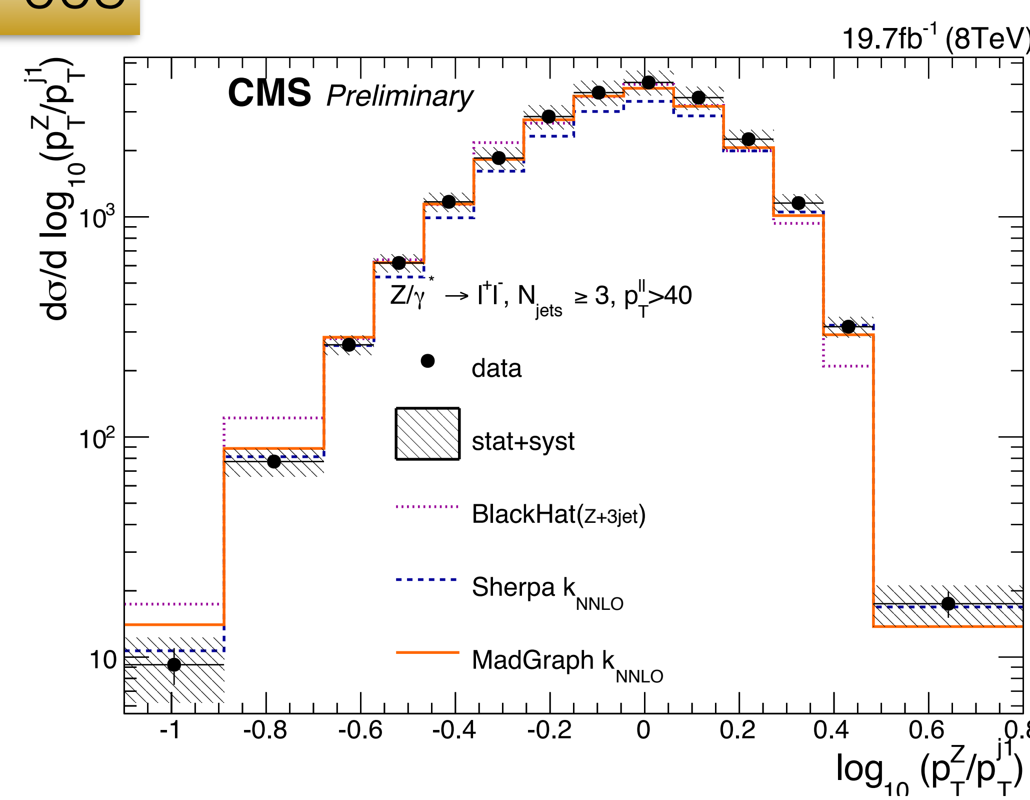
Z + jets, 8 TeV: Z boson p_T





SMP-14-005





Limit of NLO calculation when $p_T(Z) > H_T$ and $p_T(Z) > p_T(J_1)$

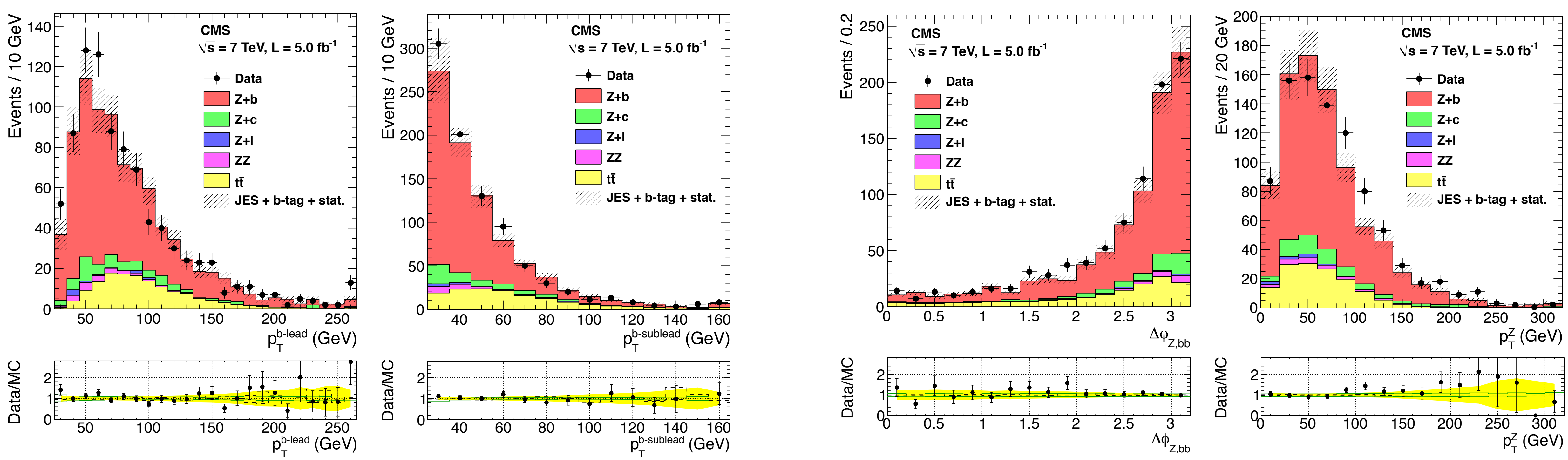
Z +b/bb, 7 TeV

Z → ll (l = e,mu):

- 2011 data $\sqrt{s}$ = 7 TeV, Int. luminosity: 5.2 fb^{-1};
- electrons, muons: $p_T > 20$ GeV, $|\eta| < 2.4$;
- $76 < m_{ll} < 106$ GeV;
- Exactly 1 or at least 2 b-jets: anti-k_t(R=.5), $p_T > 25$ GeV, $|\eta| < 2.1$, ΔR(jet,lepton) > 0.5.
- CSV b-tagging criteria applied.

SMP-13-004

Kinematical distributions:



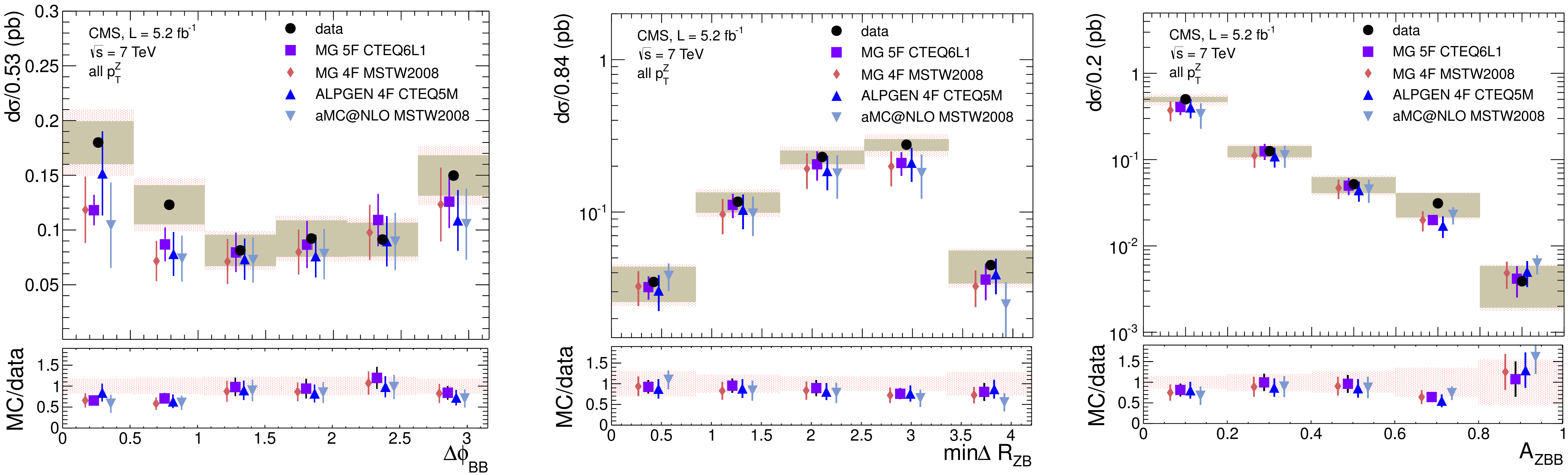
Z + 2B Hadrons, 7 TeV

Z → ll (l = e,mu):

- 2011 data √s = 7 TeV, Int. luminosity: 5.2 fb^{-1};
- electrons, muons: p_T > 20 GeV, Iηl < 2.4;
- 81< m_{ll} < 101 GeV;
- Exactly 2 B hadrons: p_T > 15 GeV, Iηl < 2.

EWK-11-015

Angular distributions:



Event shapes

SMP-12-022

Jet transverse thrust

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

Jet broadening

$$B_{\mathrm{X}} \equiv \frac{1}{2\,P_{\mathrm{T}}} \sum_{i \in \mathcal{C}_{\mathrm{X}}} p_{\mathrm{T},i} \sqrt{(\eta_i - \eta_{\mathrm{X}})^2 + (\phi_i - \phi_{\mathrm{X}})^2},$$

Total jet mass

$$\rho_{\mathrm{tot}} \equiv \rho_{\mathrm{U}} + \rho_{\mathrm{L}}. \qquad \rho_{\mathrm{X}} \equiv \frac{M_{\mathrm{X}}^2}{P^2},$$

Third jet resolution parameter

$$Y_{23} \equiv \frac{\min(p_{\mathrm{T},3}^2, [\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})^2 \times (\Delta R_{ij})^2 / R^2])}{P_{12}^2},$$

with $\hat{n}_{\mathrm{T}}$ the unit vector that maximizes the sum of pT's and X refers to lower and upper side of the event.