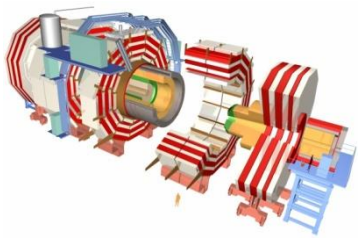


Vector Boson Production in association with Jets and Heavy Flavor Quarks from CMS

Fengwangdong Zhang

on behalf of CMS collaboration

Peking University & Université Libre de Bruxelles

XXIV International Workshop on Deep Inelastic Scattering and Related Subjects

DESY Hamburg

2016/04/11 – 2016/04/15

Outline

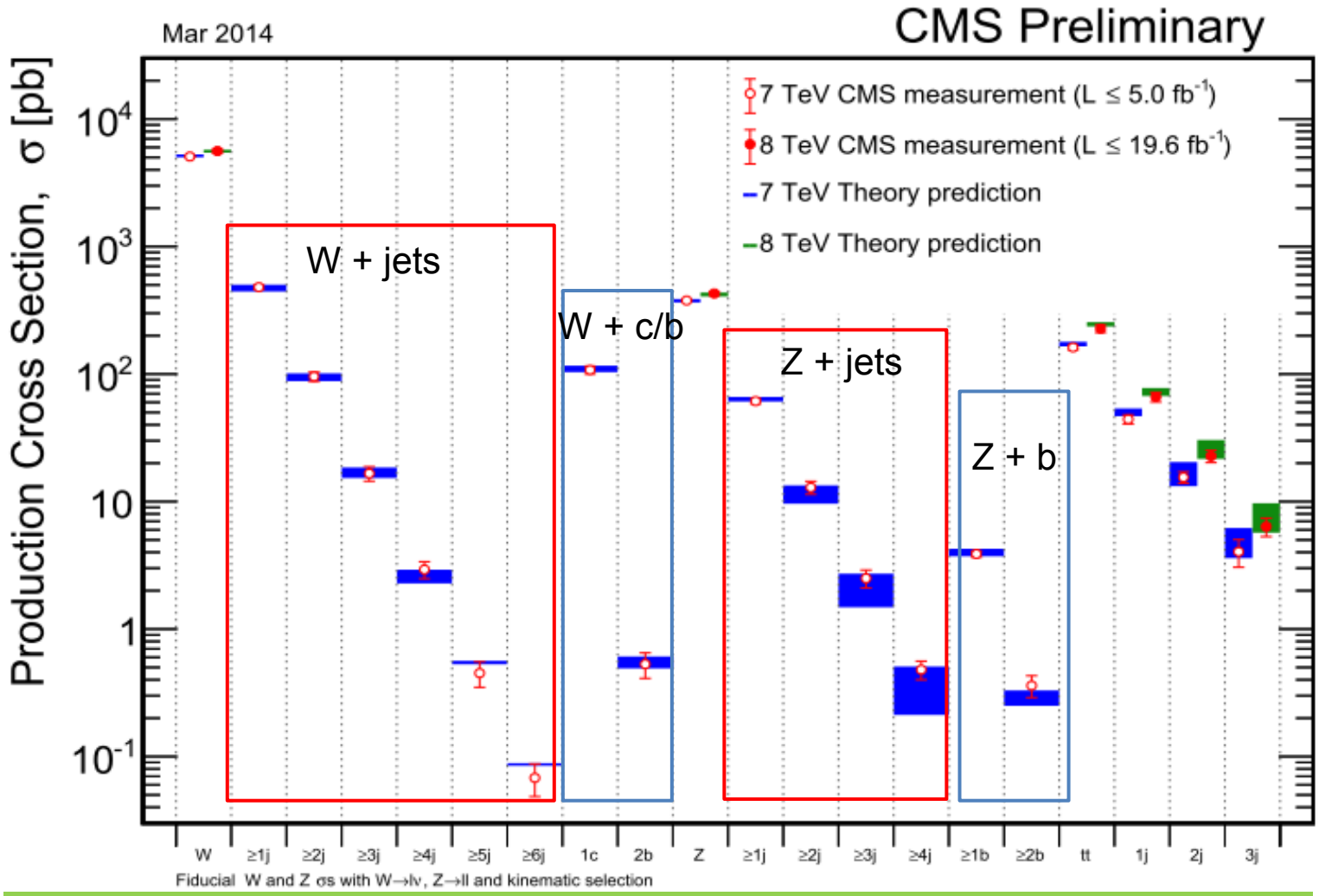
- Standard Model Public Results from CMS
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

- Many experimental results on V+jets subjects, here only focus on：

- 8TeV ($L \leq 19.8\ fb^{-1}$):
  - Z boson + jets
  - Photon (γ) + jets
  - W/Z boson + heavy flavor quark jets
    - W boson + b quark jets
    - Z boson + b quark jets

- 13 TeV ($L = 2.5\ fb^{-1}$):
  - Z boson + jets

7 TeV & 8 TeV of V+jets (RunI)



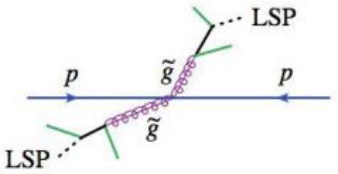
- Good agreement between experimental measurement and theory for RunI
- High precision up to very low cross section (high jet multiplicity)

Motivations on V+jets physics

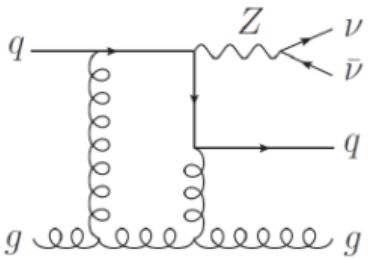
- One can probe different aspects of QCD calculations with V+jets processes
- Actual understanding and modeling of QCD interactions is crucial on the potentials for precision measurements
  - W/Z+jets is a dominant background for:
    - Top-quark measurements
    - Precision measurement of Higgs physics in VH(->bb) channel
  - It is significant for the modeling the production mechanism involved in new physics searches (e.g. Supersymmetry)

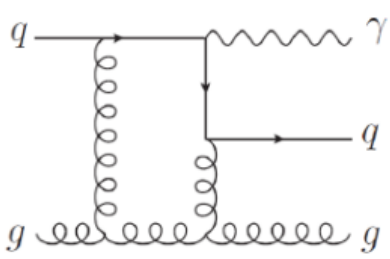
- Z+jets as background to new physics searches:
  - Z(->νν)+jets in SUSY (MET+jets) searches
  - Exploit NLO computations of W+jets/Z(->νν)+jets or γ+jets/Z(->νν)+jets ratios to calculate the transfer functions from W/γ +jets to Z(->νν)+jets
    - ✓ important to constrain theory extrapolation with data

MET+ 4 jets



JHEP 10 (2012) 018
PRD 90, 052008 (2014)
arXiv:1405.7875





$$\sigma(pp \to Z(\to \nu\bar{\nu}) + \text{jets}) = \sigma(pp \to \gamma + \text{jets}) \times R_{Z/\gamma}$$

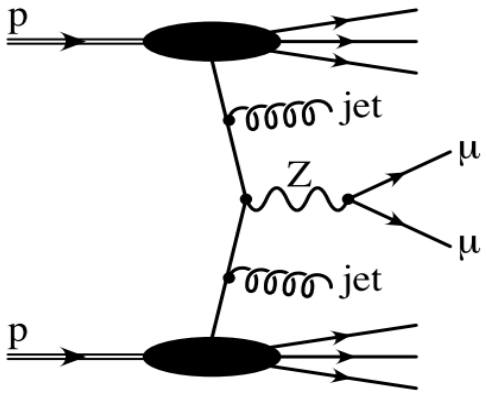
irreducible background — measure this — theory input

Measurement of Z + jets cross section at 8/13 TeV

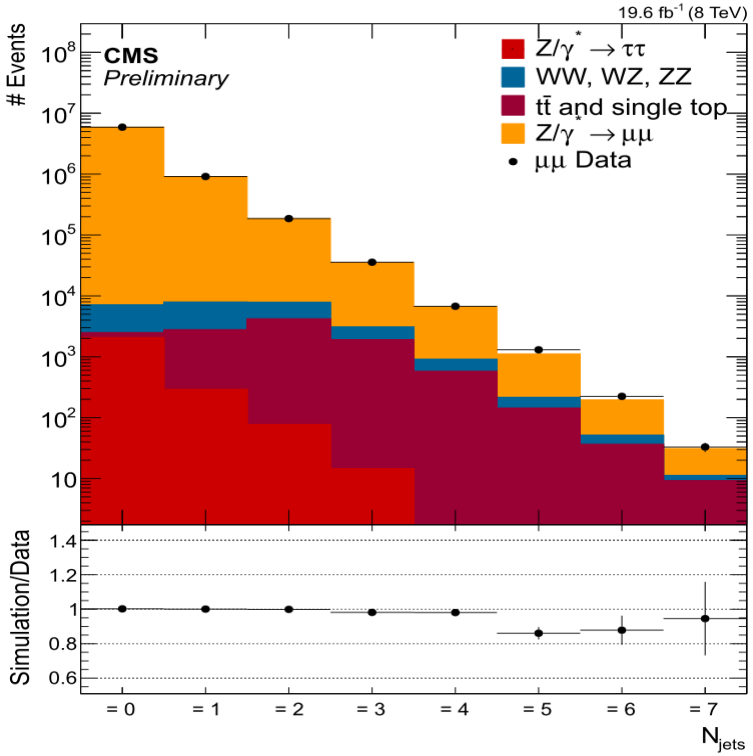
- **Data**
- taken during 2012 (8 TeV) and 2015 (13 TeV)
- Measured differential cross section as a function of several observables

Phase space:

- **Lepton selection:**
  - p_T (l) > 20 GeV
  - |η (l)| < 2.4
  - 71 < M (ll) < 111 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |y (j)| < 2.4



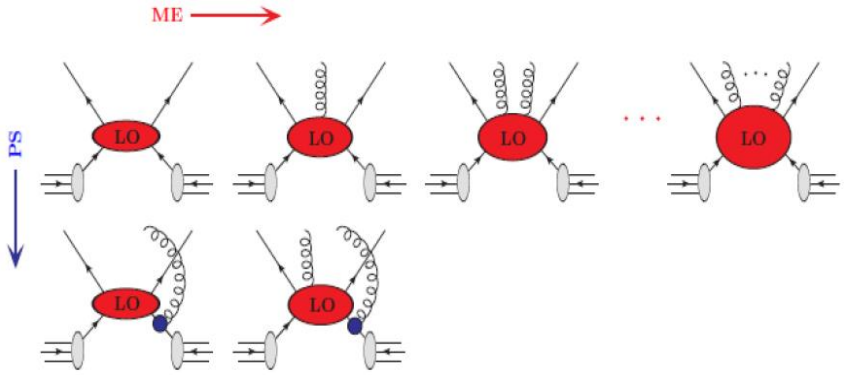
Z+jets at 8 TeV from CMS



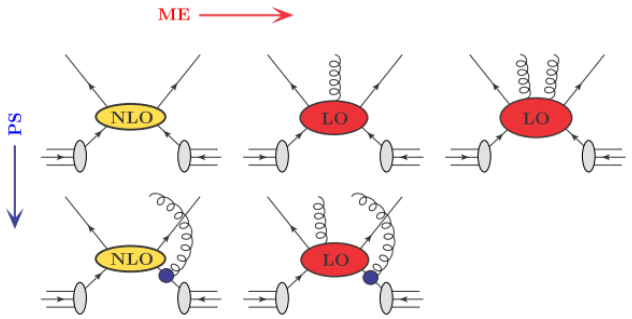
- **Signal process has clean signature with low amount of background contamination**
- **The presence of data goes up to large jet multiplicity region**

Monte Carlo Generator for Z + jets cross section comparison at 8 TeV

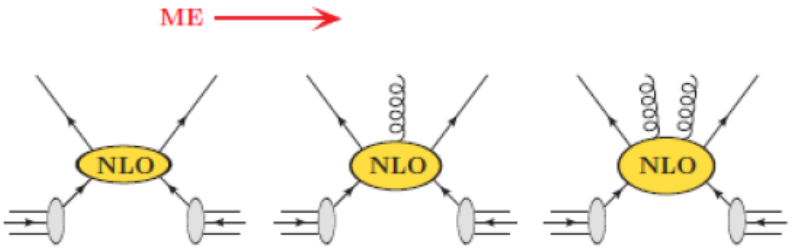
- **Multileg LO with 0~4 final partons in matrix element:**
  - MADGRAPH5 + PYTHIA6: kt-MLM merging, CTEQ6L1 PDF
  - SHERPA1.4: CKKW merging, CT10 PDF
  - Hadronization and mutiple parton interactions are implemented



- **Multileg with 0~2 partons at NLO, 3~4 partons at LO:**
  - SHERPA2 (+ BLACKHAT): MEPS@NLO merging, CT10 PDF
  - Hadronization and mutiple parton interactions are implemented



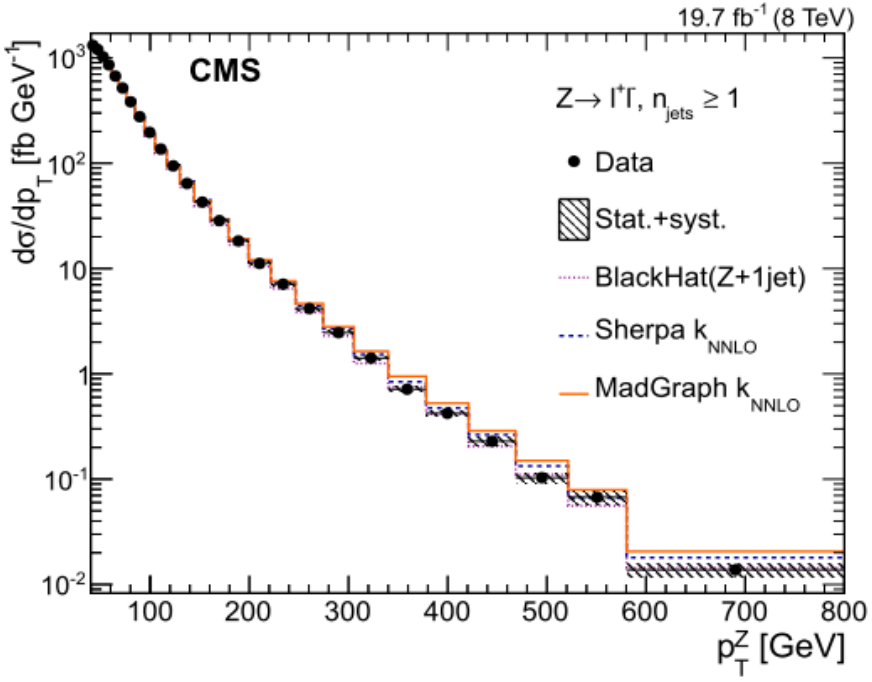
- **Fixed order Z + N jets (NLO):**
  - BLACKHAT (+SHERPA): MSTW2008 NLO PDF
  - Correction for hadronization and multiple parton interactions computed with MG5+PYTHIA6

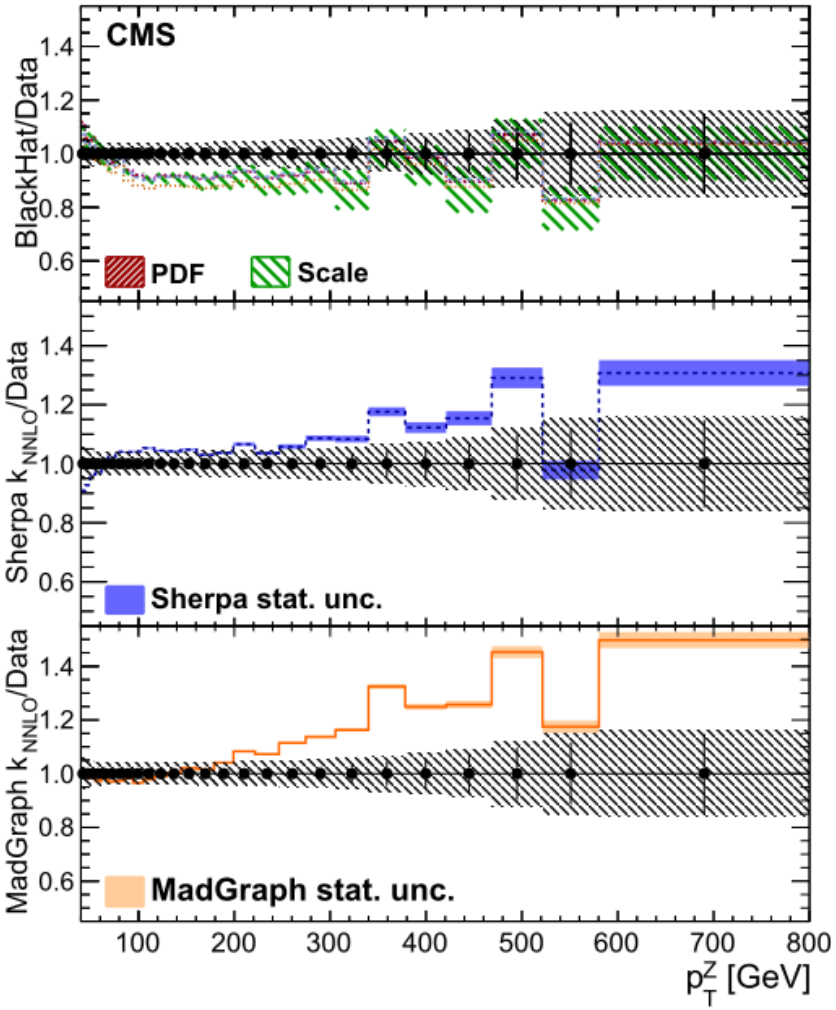


Z + ≥ 1 jet cross section as function of Z p_T

JHEP10(2015)128

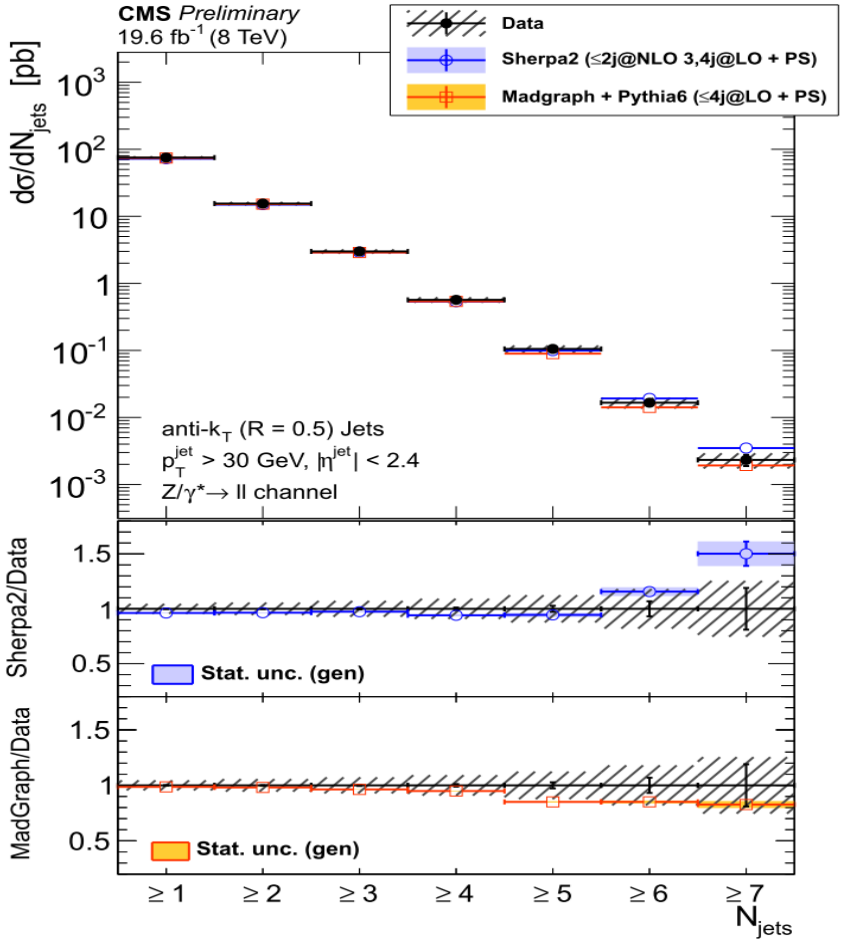
Published recently

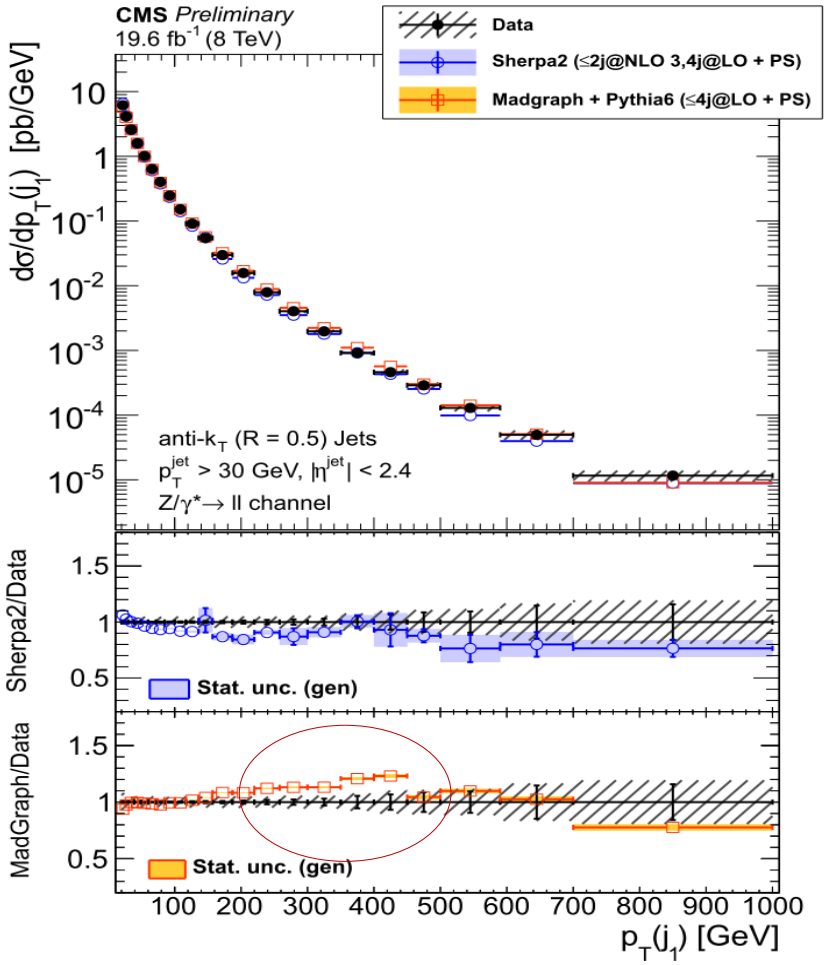




- K_{NNLO}: Z+>=0 jet cross section rescaled to NNLO value from FEWZ
- MG5+Pythia6 comparison is flat until around 200 GeV and up to about 30% discrepancy, which is same for Z+ ≥ 2 jets case
- BLACKHAT reproduces the shape of data in the same region

Z + jets differential cross section as function of jet p_T





PAS: SMP-13-007

- Good agreement with SHERPA2 (NLO)
- Discrepancy with LO computation has disappeared with NLO accuracy

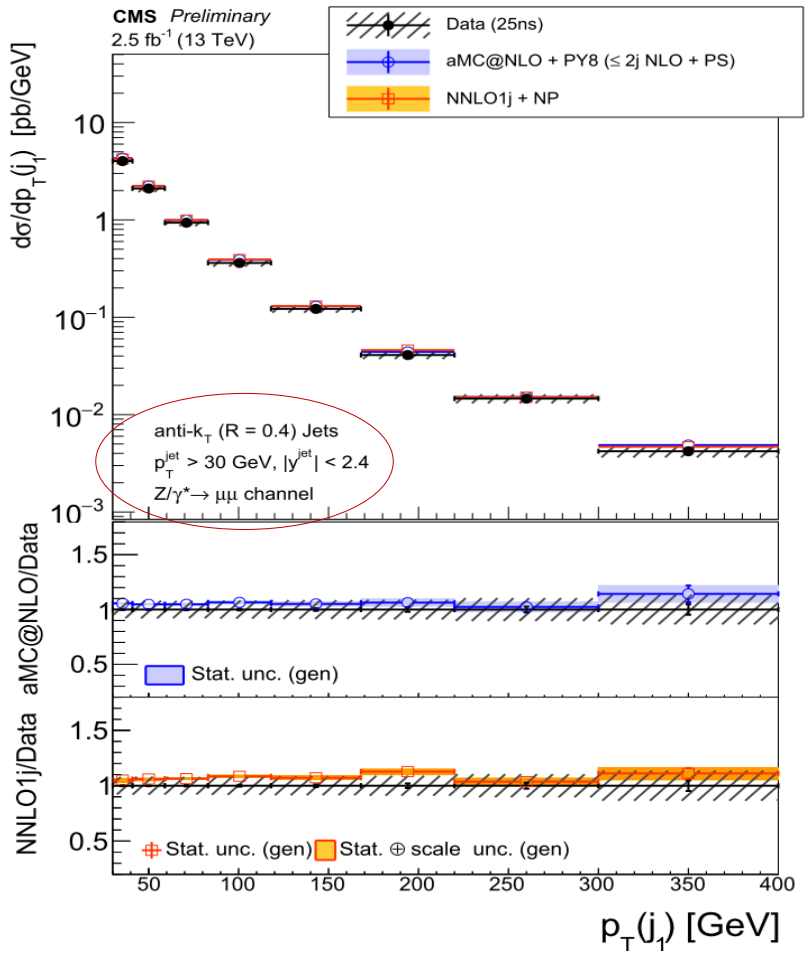
Monte Carlo Generator for Z + jets cross section comparison at 13 TeV

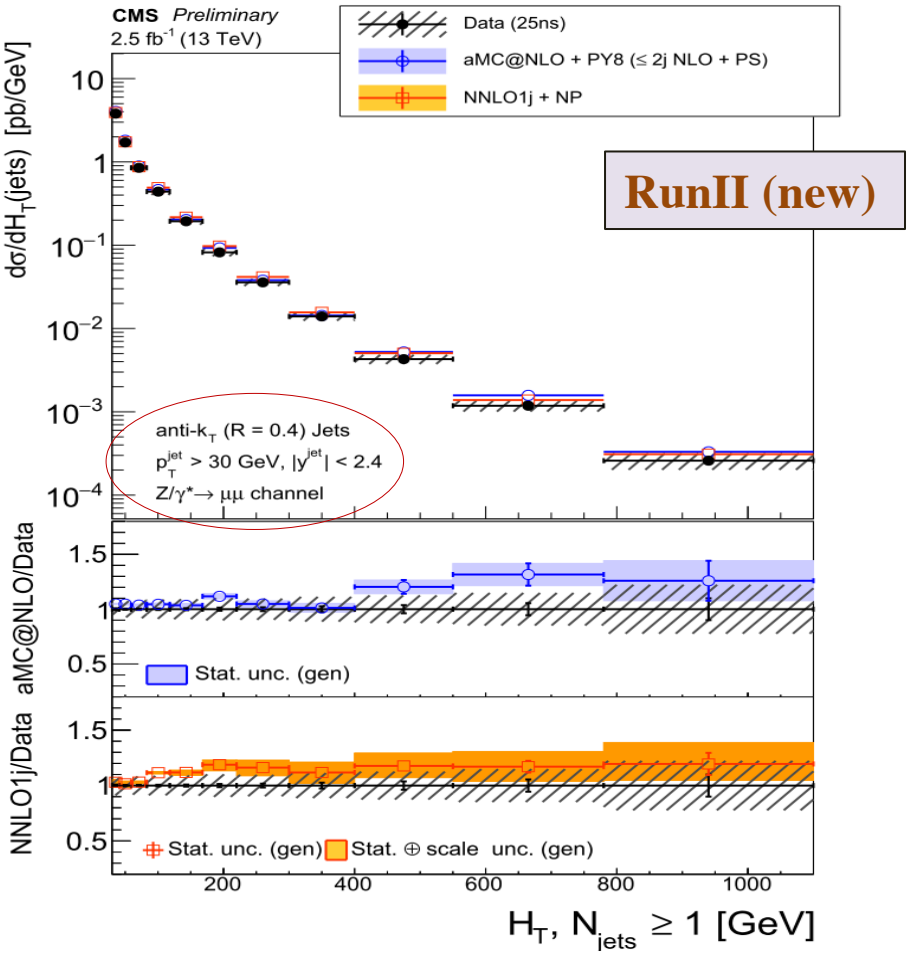
- MADGRAPH5_AMC@NLO + PYTHIA8
  - Next leading order multileg matrix element up to two partons in final state, LO accuracy for 3~4 partons
  - FxFx jet merging scheme
  - NNPDF3.0 NLO PDF set used in the generator
  - CUETP8M1 PYTHIA8 tune

RunII (new)

- NNLO
  - NNLO Z+1jet with fixed order
  - Correction for hadronization and multiple parton interaction computed with MADGRAPH5_AMC@NLO + PYTHIA8
  - CT14 PDF set
  - References:
    - arXiv:1602.08140
    - arXiv:1512.01291
    - Phys. Rev. Lett. 115, no.6, 062002 (2015)

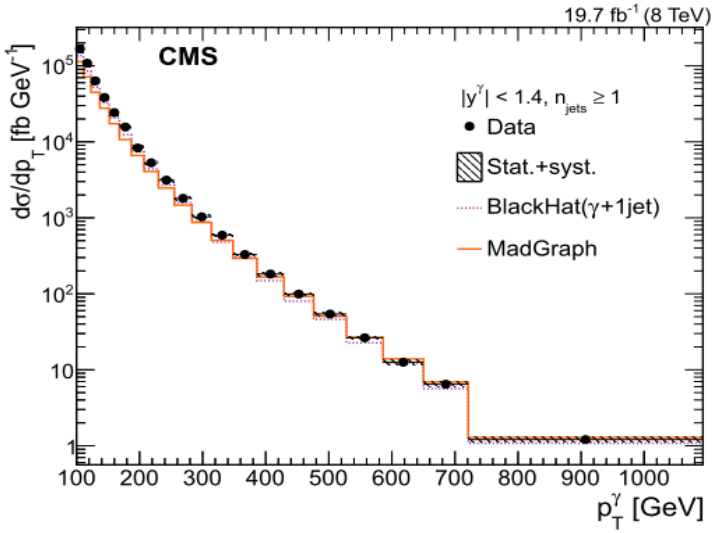
Z + jets differential cross section at 13 TeV

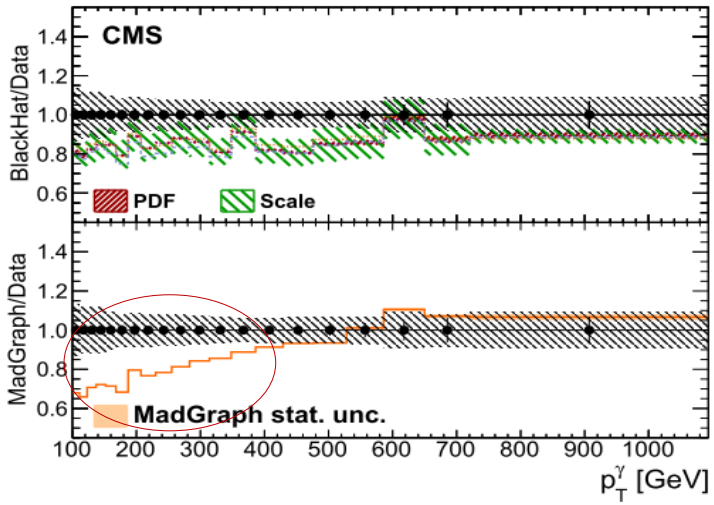




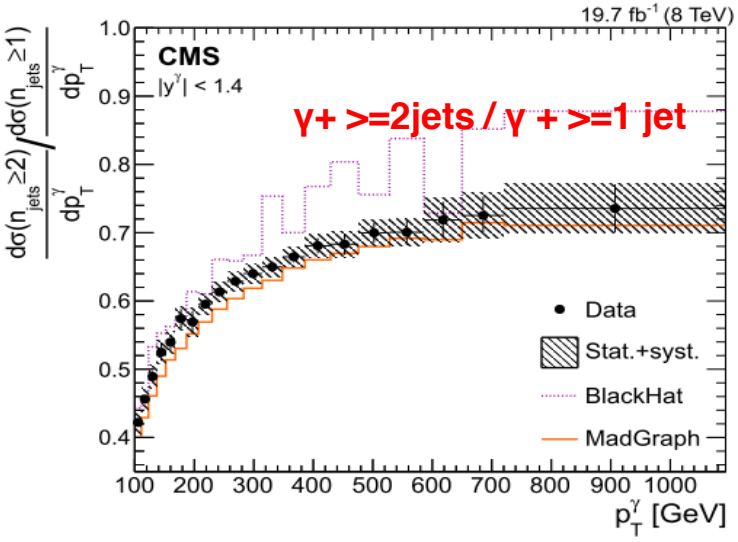
- Good agreement with multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

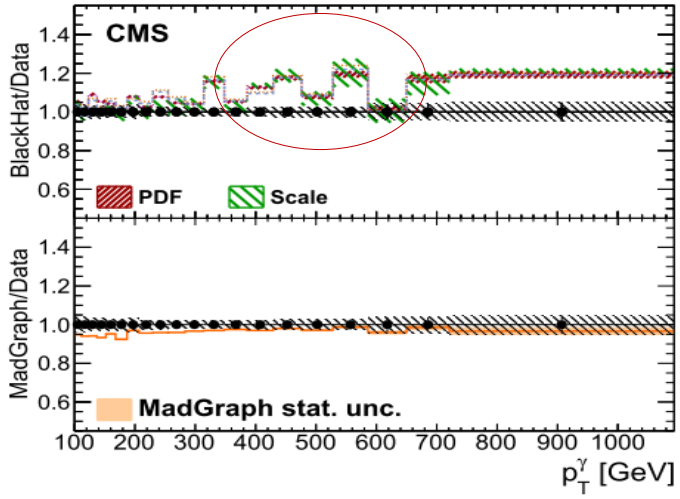
Photon (γ) + jets cross section at 8 TeV





- BLACKHAT reproduces the shape of data better than MADGRAPH





- BLACKHAT overestimates the ratio by 10% for p_T (γ) > 100 GeV
- LO prediction describes the data shape very well

- **Lepton selection:**
  - p_T (l) > 20 GeV
  - |η (l)| < 2.4
- **Photon selection:**
  - p_T (γ) > 20 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |η (j)| < 2.4

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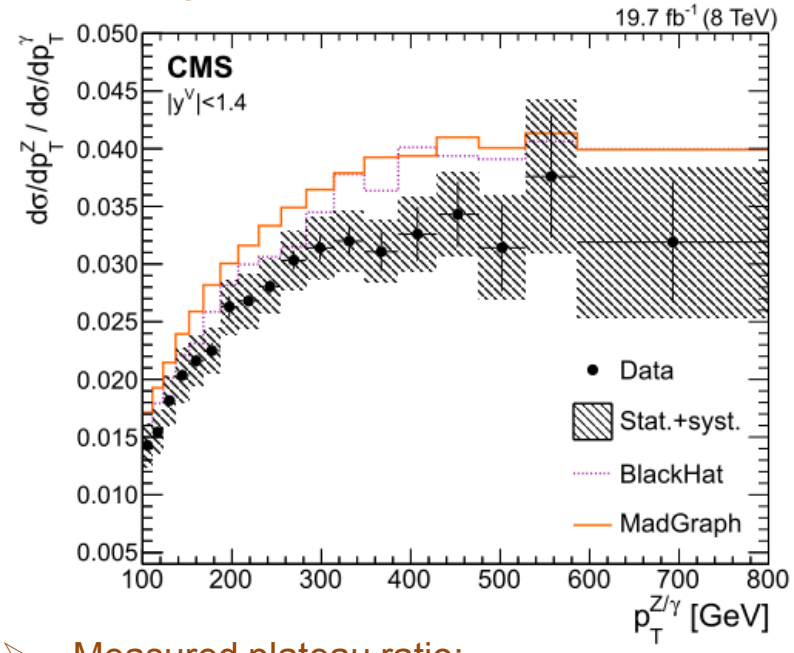
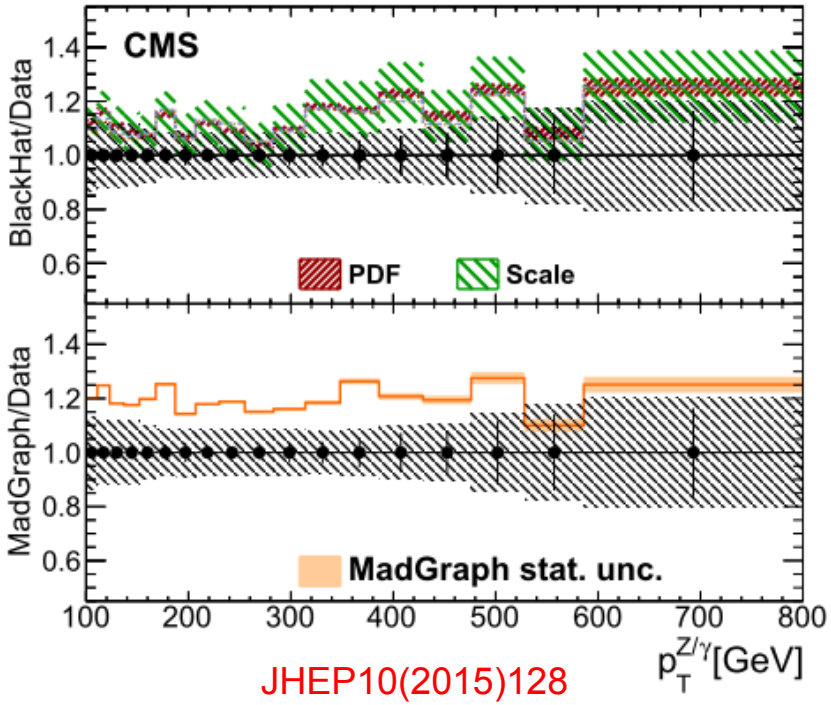
Z + jets & γ +jets cross section ratio at 8 TeV

- Precise measurement of this ratio provides important information about the higher order effects of logarithmic corrections at higher transverse momentum
- It helps to reduce the systematical uncertainties corresponding to the Z(->νν)+jets background estimation in SUSY searches





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- Measured plateau ratio:

$$R_{\text{dilep}} = \frac{\sigma_{Z\to\ell^+\ell^-}(p_T^Z > 314\,\text{GeV})}{\sigma_\gamma(p_T^\gamma > 314\,\text{GeV})} = 0.0322 \pm 0.0008\,(\text{stat}) \pm 0.0020\,(\text{syst})$$

- The observed ratio increases gradually and saturates around 300~350 GeV of p_T:
  - The main distinctions between two processes are mass difference and different coupling
- Madgraph (Tree level) has already reproduced the shape of data well

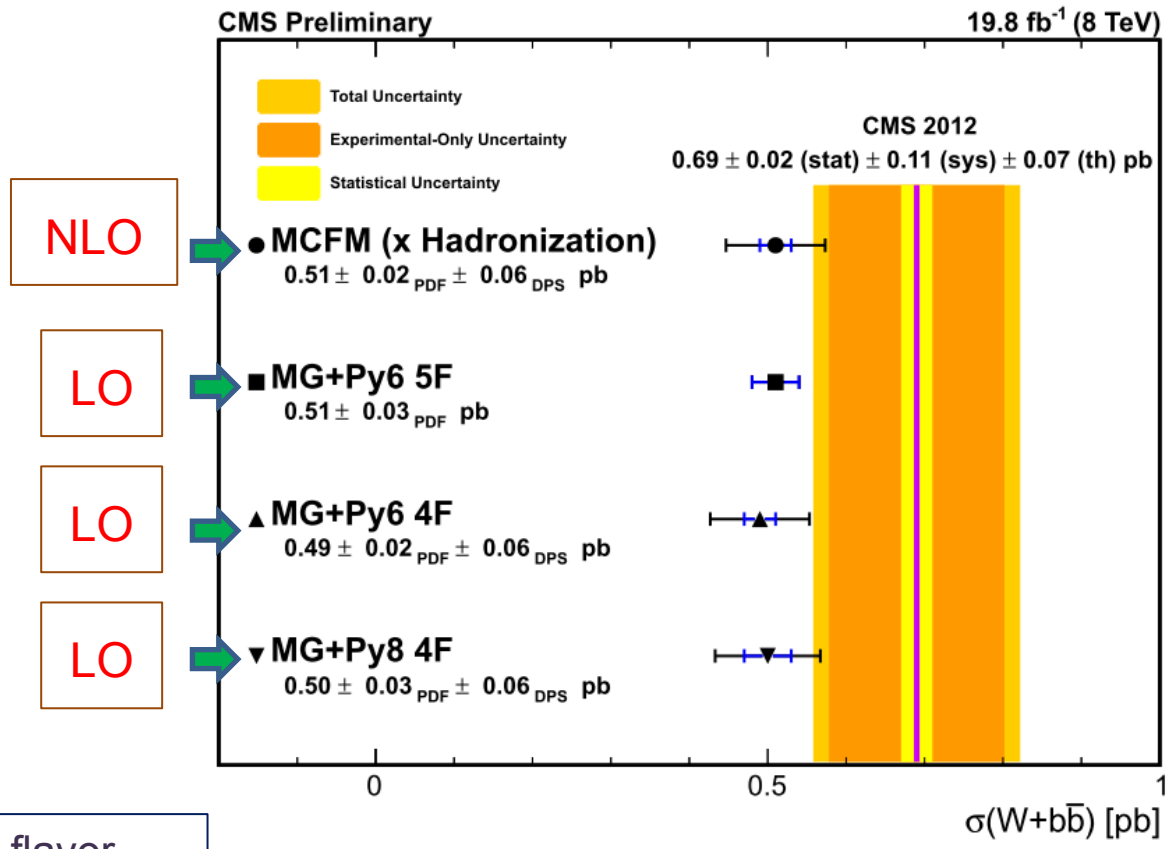
W/Z + heavy flavor jets ($b/\bar{b}$) measurement at 8 TeV

- Theoretical uncertainties on W/Z + heavy flavor jets larger than for light jets case
  - Heavy quark content in the proton
  - Modeling of gluon splitting (initial state or final state)
  - Massive or massless b quark in computations
- Test of QCD predictions with various implementations (LO + Multipartons + parton shower, NLO, NLO+PS)
- Important process for backgrounds of Higgs measurements
- Descriptions of "b-quark initiated processes:"
  - 4 flavors number scheme (4FS): b quark generated with gluon splitting
  - 5 flavors number scheme (5FS): b quark (massless) generated in the initial state

W+b$\bar{b}$ cross section at 8 TeV

- Lepton selection:
  - P_T > 30 GeV
  - |η| < 2.1
- B-tagged jet selection:
  - P_T > 25 GeV
  - |η| < 2.4

PAS: SMP-14-020

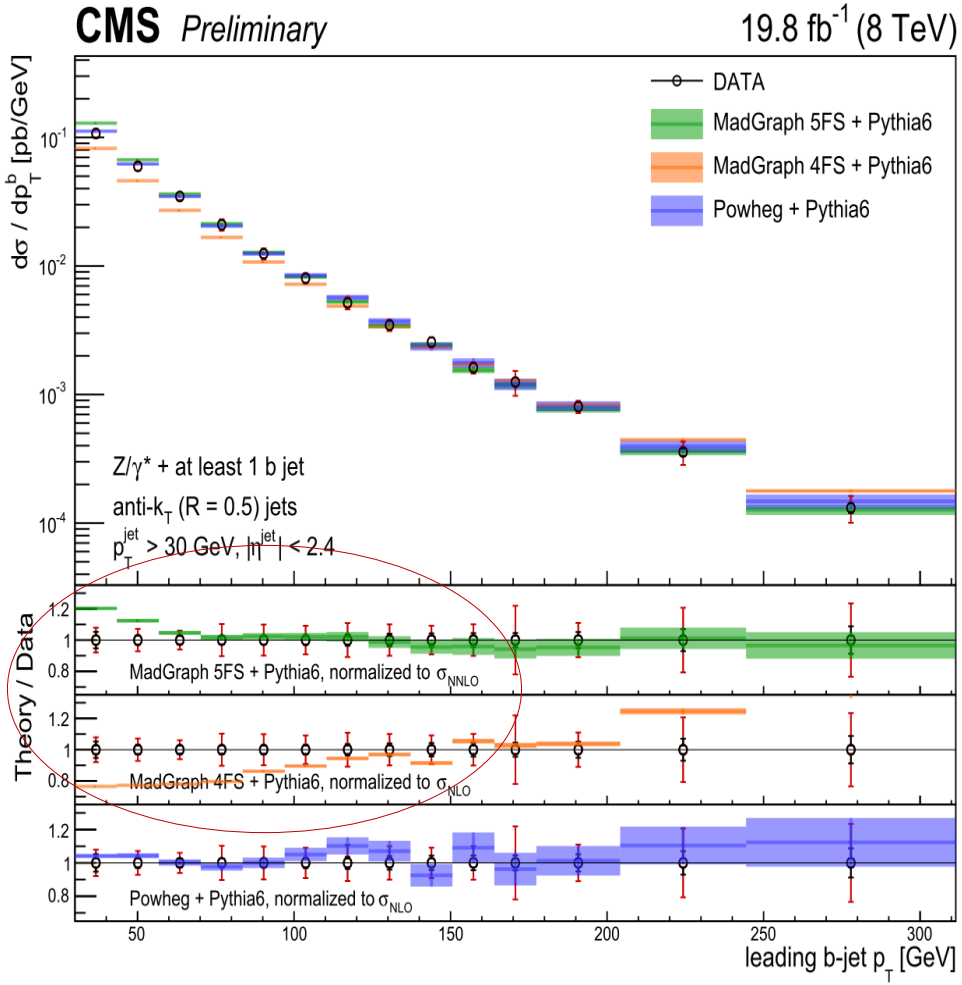


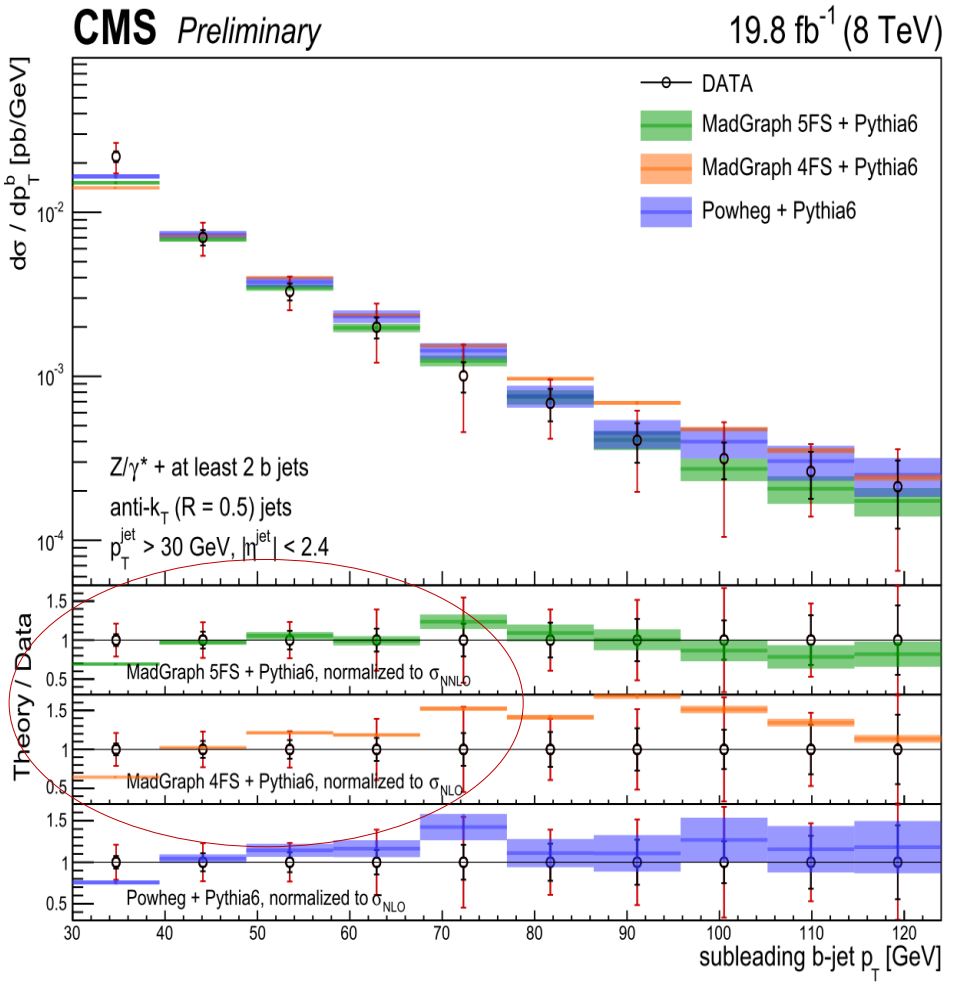
- The MCFM and MG+Py* with 4 flavor scheme do not account for the $b\bar{b}$ system coming from multiple parton interaction

- All the predictions agree with measured cross section within one standard deviation
- Differential cross section will be measured soon

Z+b jets cross section at 8 TeV

PAS: SMP-14-010





- **Discrepancy of about 20% observed for 4FNS-based LO prediction for Z+ b jet case**
- **Overall agreement is observed between measurement and NLO prediction, while the 5FNS-based prediction with slightly overshooting at the small transverse momentum region of b jet (Z + b jet)**
  - **For Z+ 2b jets case, we will benefit from higher statistics of new data**

Conclusion

- The measurement on vector boson plus jets processes is quite important:
  - It deepens our understanding on QCD dynamics
  - It improves the modeling of background for Higgs measurement and new physics searches

- There have been significant improvement on theoretical predictions and experimental measurements:
  - Reach high precision of measurement
  - Better agreement with higher order (NLO) calculation than LO in general
  - Remained discrepancy and large uncertainty motivate the ongoing work to improve modeling and precision

- First results of Z+jets differential cross section measurements at 13 TeV have shown good agreement with predictions

- More results at 8TeV / 13TeV will come out soon!

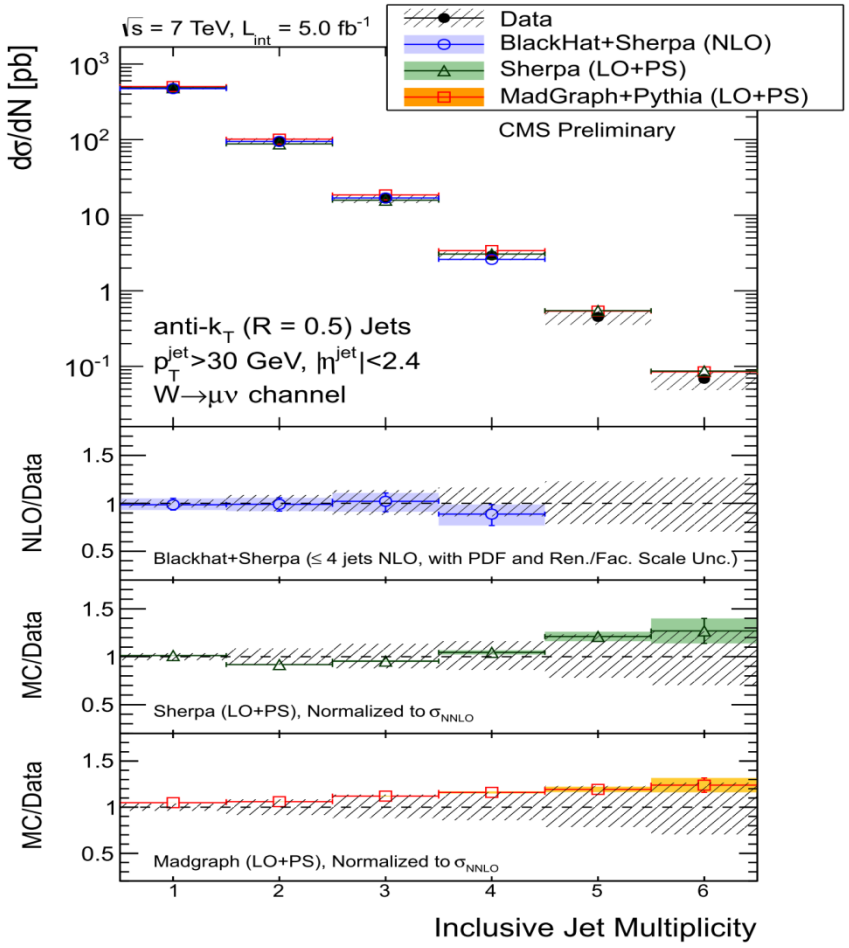
Backup

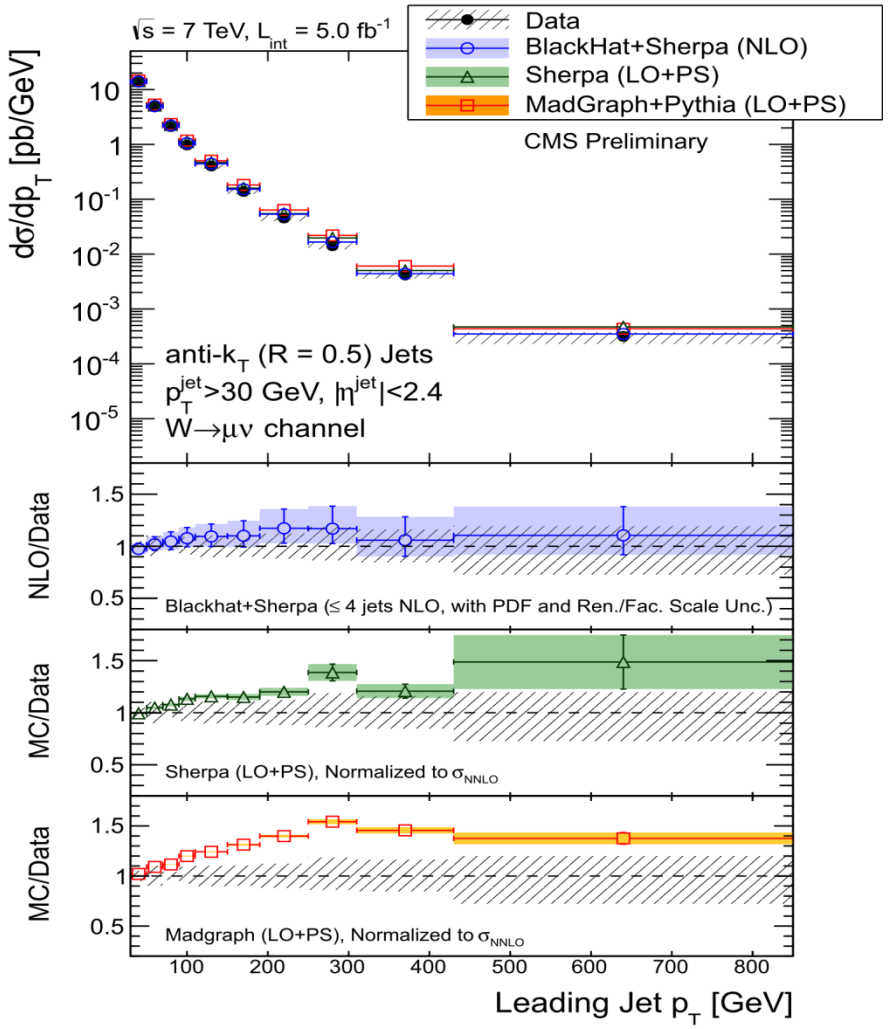
V+jets predictions on Monte Carlo evolution

- There are still theoretical uncertainties related to various sources which can be constrained by data:
  - Higher order QCD corrections (NNLO)
  - Electroweak corrections
  - Parton shower and its matched matrix element
  - Parton density functions
  - Underlying event modeling (multiple parton interactions)

W + jets measurement at 7 TeV

10.1016/j.physletb.2014.12.003

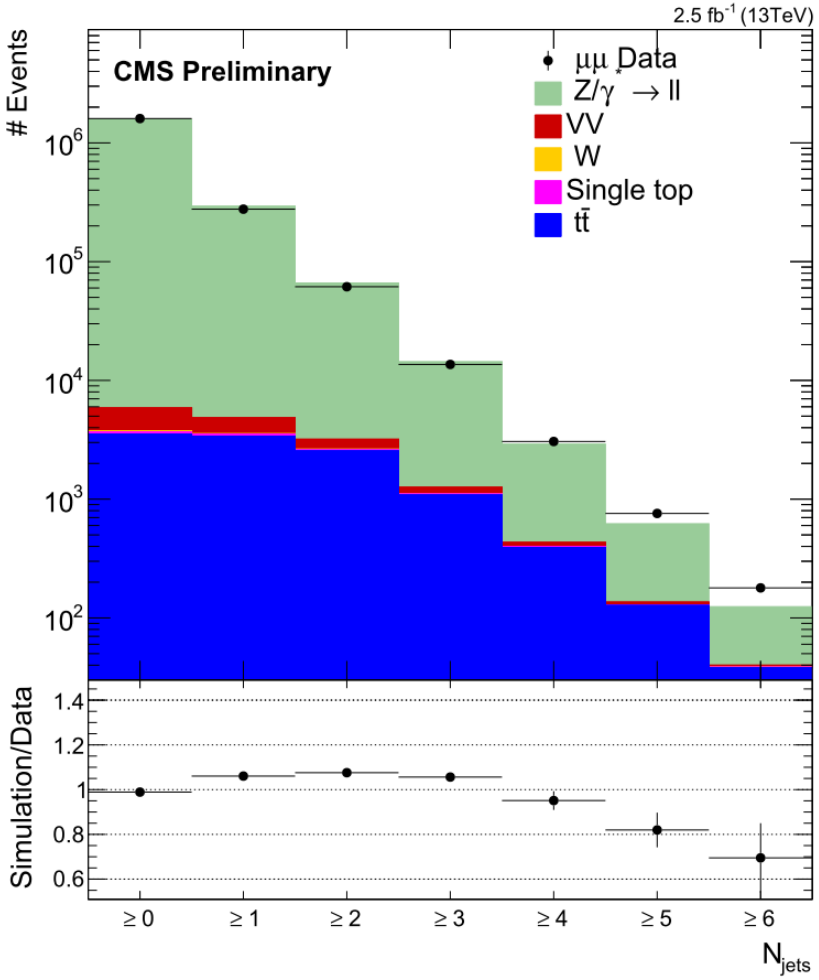


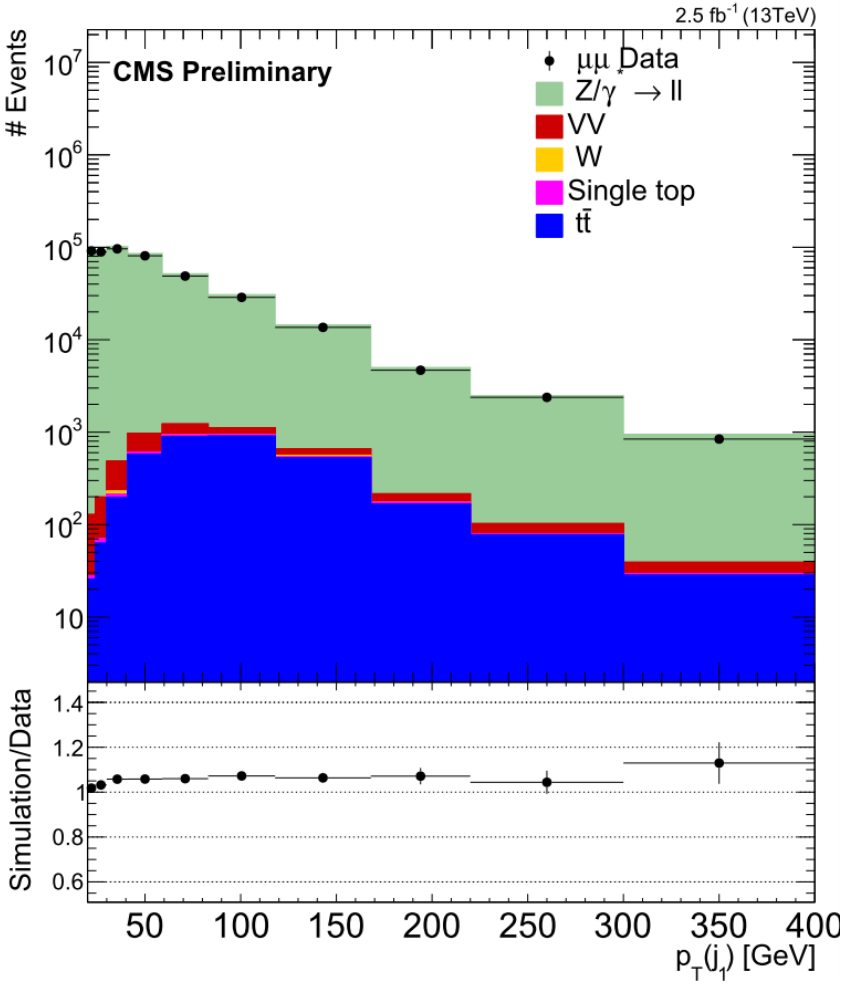


- Good agreement between data and NLO/LO calculation for jet multiplicity
- Discrepancy in LO computation has been compensated by NLO accuracy

Z + jets measurement at 13 TeV

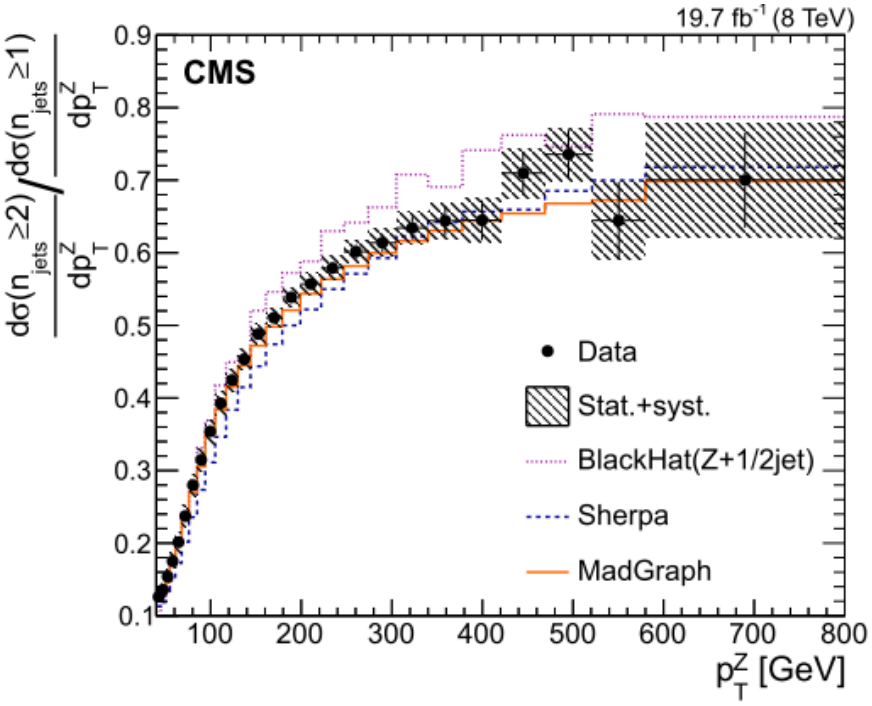
PAS: SMP-15-010





- Not quite good agreement generally between data and simulation in reconstruction level
- Siginificant ttbar contribution for N_jets >= 4

Z+≥1 jet & Z+≥2 jets cross section ratio as function of Z p_T



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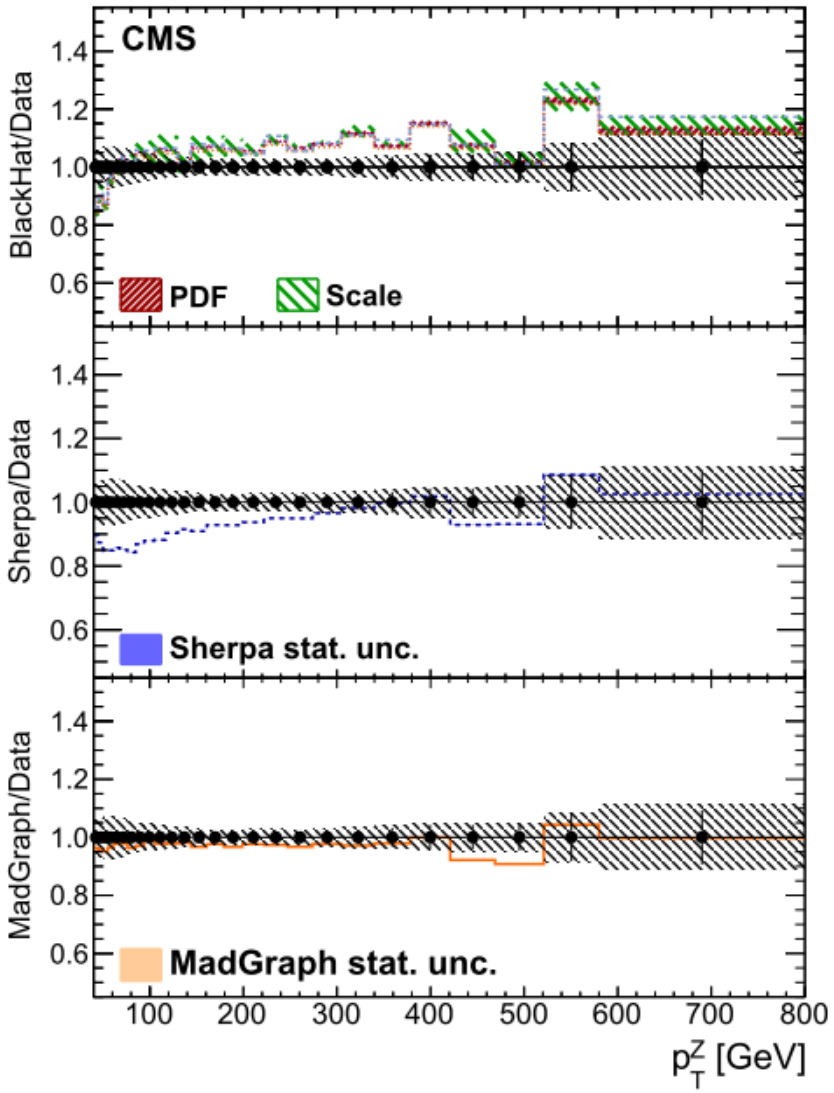

- The ratio increases until reaching around 350 GeV before a plateau
- SHERPA underestimates the relative rate of inclusive 2 jets case
- BLACKHAT overestimates the ratio after around 100 GeV

Z + ≥ 3 jets cross section ratio as function of Z p_T/ HT

- This observable allows to test validity of NLO estimation, which might reach computational limit due to large logarithms or missing higher order effects may play a larger role
- Events in the high-end tail contribute to signatures with a high E_T/HT ratio for hadronic new physics searches

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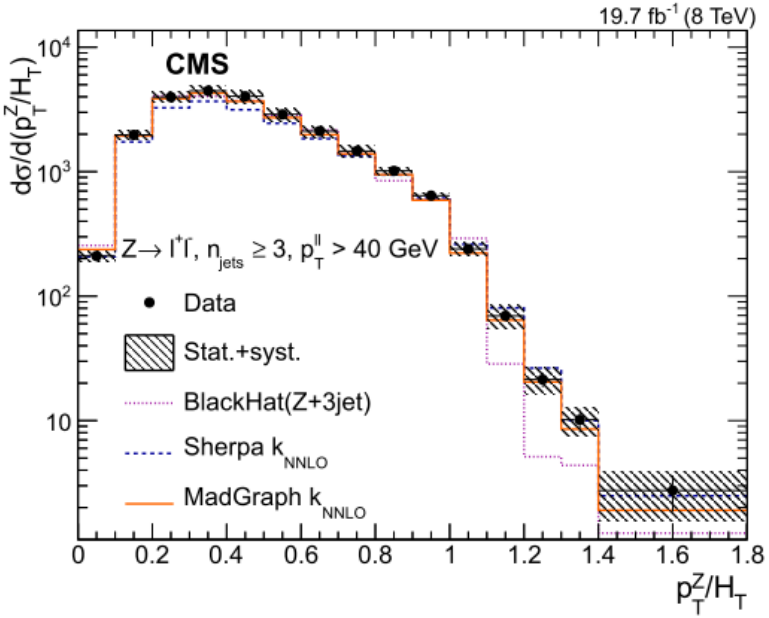
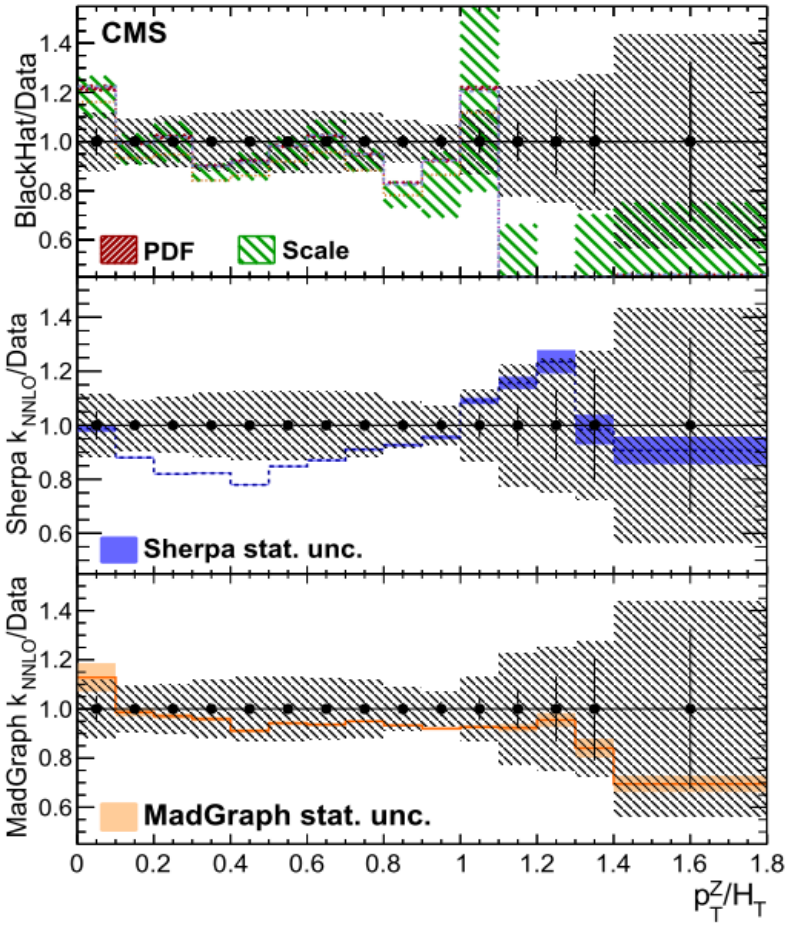
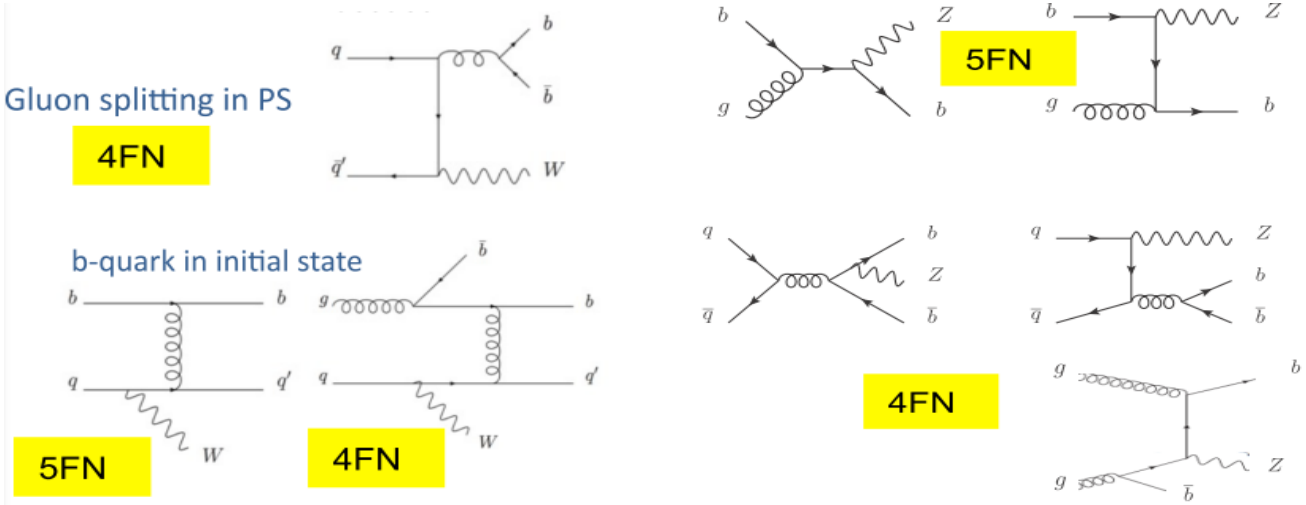




- MG5 generally predicts best on the shape
- SHERPA shows discrepancy on shape and rate
- BLACKHAT performs well on the bulk of distribution while failing to reproduce the tails

W/Z + heavy flavor jets (b/$\bar{b}$) measurement at 8 TeV

- Theoretical uncertainties on W/Z + heavy flavor jets larger than for light jets case
  - Heavy quark content in the proton
  - Modeling of gluon splitting (initial state or final state)
  - Massive or massless b quark in computations
- Test of QCD predictions with various implementations (LO+Multipartons + parton shower, NLO, NLO+PS)
- Important process for backgrounds of Higgs searches

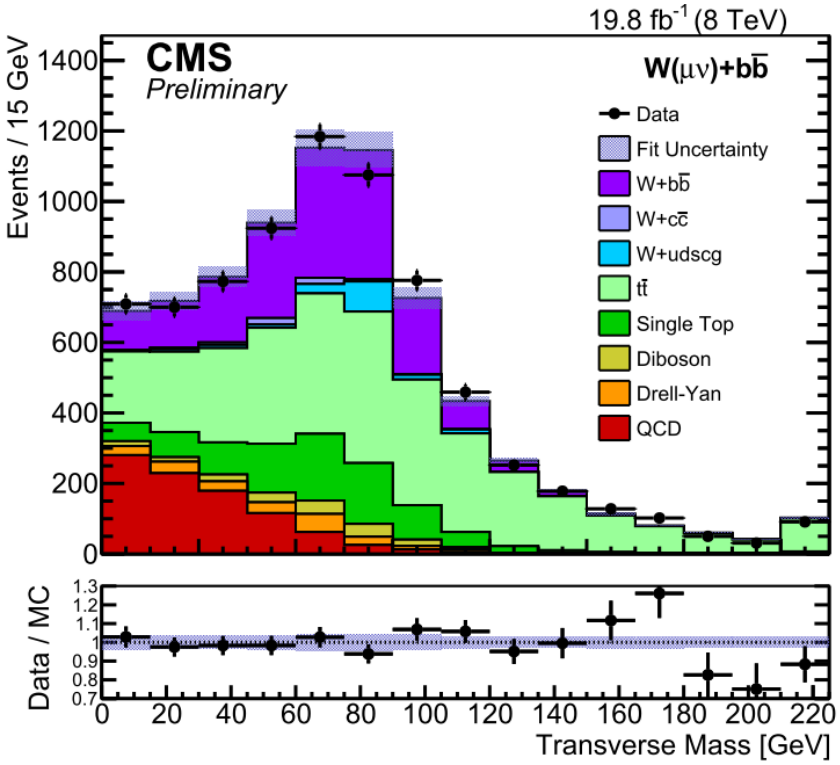


- Descriptions of “b-quark initiated processes:”
- 4 flavors number scheme (4FN): b quark generated with gluon splitting
- 5 flavors number scheme (5FN): b quark (massless) generated in the initial state

W+b$\bar{b}$ measurement at 8 TeV

PAS: SMP-14-020

- Lepton selection:
  - P_T > 30 GeV
  - |η| < 2.1
- B-tagged jet selection:
  - P_T > 25 GeV
  - |η| < 2.4

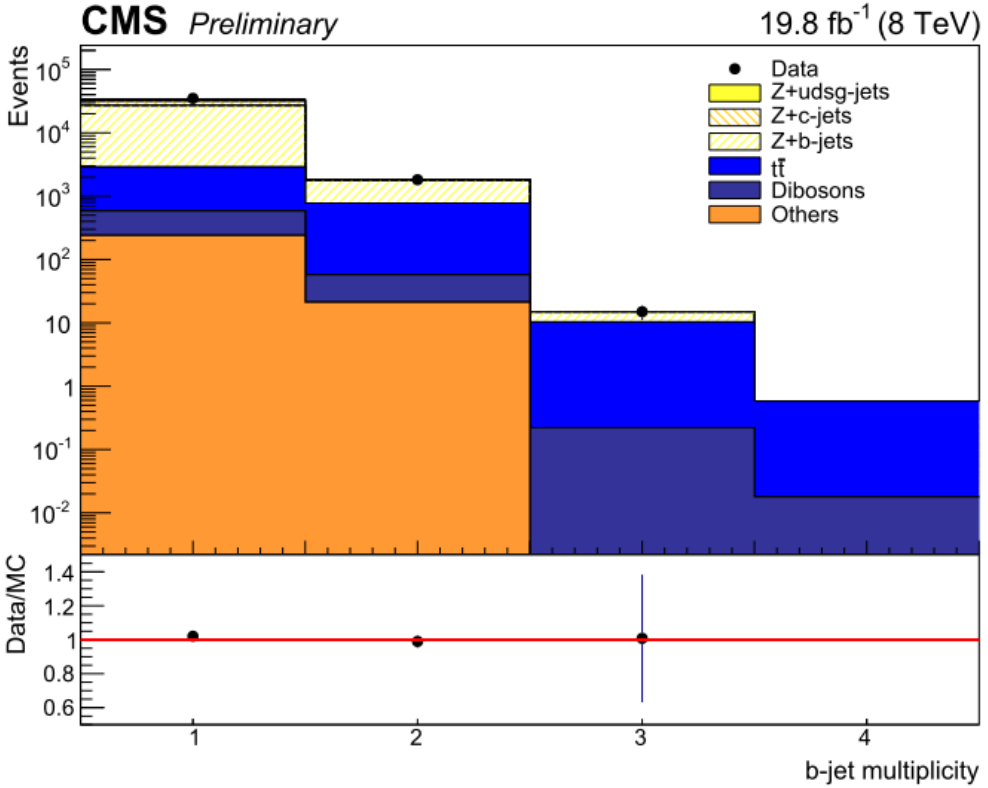


- The signal sample is generated at tree-level by MADGRAPH5 interfaced with PYTHIA6
- The $t\bar{t}$ is the dominant background, which is reweighted by data in the signal free region, in order to predict the transverse mass distribution in the signal region

Z+b jets measurement at 8 TeV

PAS: SMP-14-010

- Lepton selection:
  - P_T > 20 GeV
  - |η| < 2.4
  - 71 < Mll < 111 GeV
- B-tagged jet selection:
  - P_T > 30 GeV
  - |η| < 2.4



- The signal sample is generated with MADGRAPH5 implementing a matrix element up to 4 partons in the final state, interfaced with PYTHIA6
- The $t\bar{t}$ is the dominant background, which is also generated with MG5 implementing a matrix element up to 3 partons in the final state

Predictions summary for comparisons

- Z/γ+jets differential cross section and ratio measurements (8TeV)
  - MADGRAPH 5.1.3.30 + PYTHIA 6.4.26 (LO + PS)
  - SHERPA 1.4.2 (LO) (only for Z+jets)
  - BLACKHAT (NLO)

- Z/γ*+jets differential cross section measurements (13TeV)
  - MADGRAPH5_AMC@NLO + PYTHIA 8 (NLO + PS)

- W+bb jets cross section measurements (8TeV)
  - MCFM with MSTW2008 NLO PDF (correction for hadronization)
  - MADGRAPH5 interfaced with PYTHIA6 in four flavor scheme (NNLO PDF)
  - MADGRAPH5 interfaced with PYTHIA6 in five flavor scheme (CTEQ6L PDF)
  - MADGRAPH5 interfaced with PYTHIA8 in four flavor scheme (NNLO PDF)

- Z+b(b) jets differential cross section measurements (8TeV)
  - MADGRAPH5 interfaced with PYTHIA6 in five flavor scheme (CTEQ6L1 PDF) (>= 4 partons)
  - MGDGRAPH5 interfaced with PYTHIA6 in four flavor scheme (MSTW2008 PDF) (>= 4 partons)
  - NLO POWHEG interfaced with PYTHIA6 in five flavor scheme (CT10 PDF)

References

- Standard Model Public Results from CMS
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

- Z/γ + jets cross section and ratio at 8 TeV (JHEP10(2015)128)

- Z/γ* + jets cross section at 8 TeV (PAS: SMP-13-007)

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- W+bb cross section at 8 TeV (PAS: SMP-14-020)

- Z+b(b) cross section at 8 TeV (PAS: SMP-14-010)

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