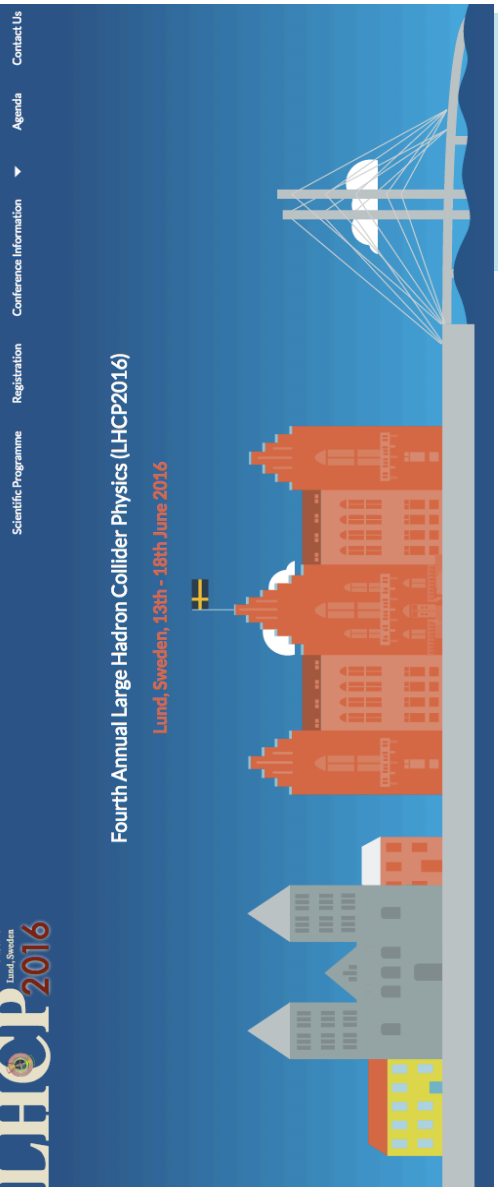


Vector Boson Production in association with Jets and Heavy Flavor Quarks from CMS

Tomislav Seva

Université Libre de Bruxelles

on behalf of CMS collaboration

LHCP2016: Fourth annual Large Hadron Collider Physics,

13-18 Jun 2016, Lund University, Lund (Sweden)

Outline

- Motivations on V+jets physics
- V+jets at Run1 8TeV data 1D&2D results
- V+ heavy quark jets at 8Tev
- Z+jets at 13TeV (muon data only)

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:

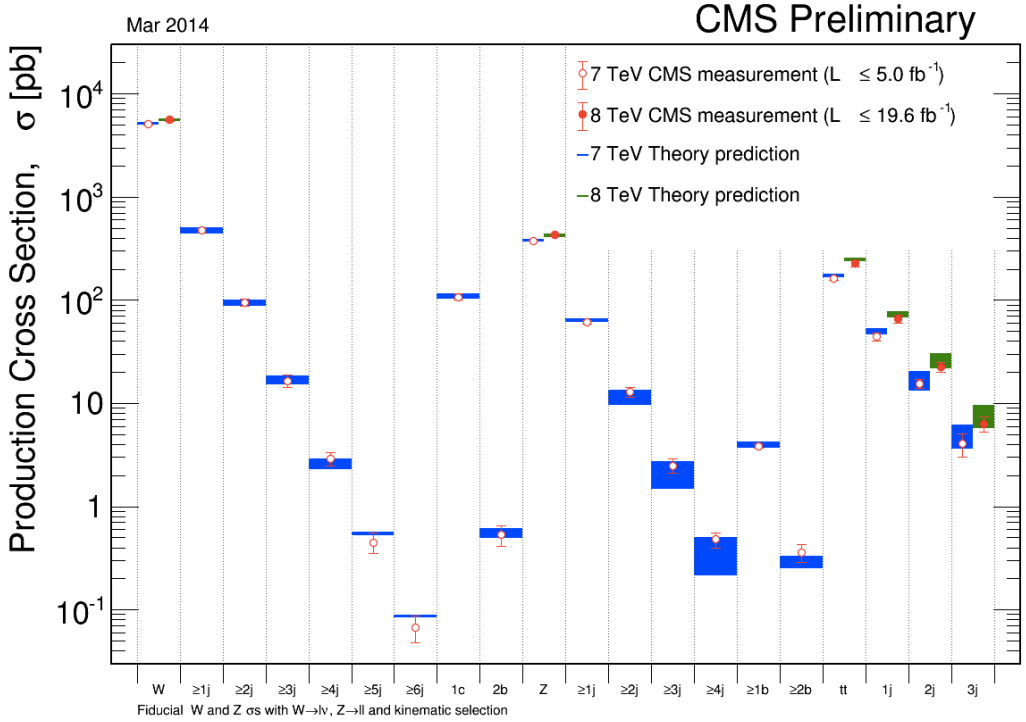
  Top-quark measurements

  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)

Motivations on V+jets physics...2

Physics of V(W,Z, γ+ Jets) is essential part of the CMS research program



powerful tool to deeply test the perturbative QCD predictions:
- PDFs
- new generation MC generators
- NLO effects
- Flavour schemes, b/c mass effects

Higgs and BSM background
- HZZ, HWW, SM backgrounds
- SUSY with hadronic final states
- 4th generations of heavy quarks
- 2HDMs

Latest results not included in this plot

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

Measurement of V + jets cross section at 8 TeV

❑ Data

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

❑ **Phase space selection for Z:**

Lepton selection:

$p_T(l) > 20$ GeV, $|\eta(l)| < 2.4$,

$71 < M(ll) < 111$ GeV

Jet selection:

ak5, $p_T(j) > 30$ GeV, $|\eta(j)| < 2.4$

❑ **Phase space selection for W:**

Muon selection:

$p_T(l) > 30$ GeV, $|\eta(l)| < 2.1$, $M_T > 50$ GeV

Jet selection:

ak5, $p_T(j) > 30$ GeV, $|\eta(j)| < 2.4$

❑ Theory

❑ **Z THEORY COMPARISONS:**

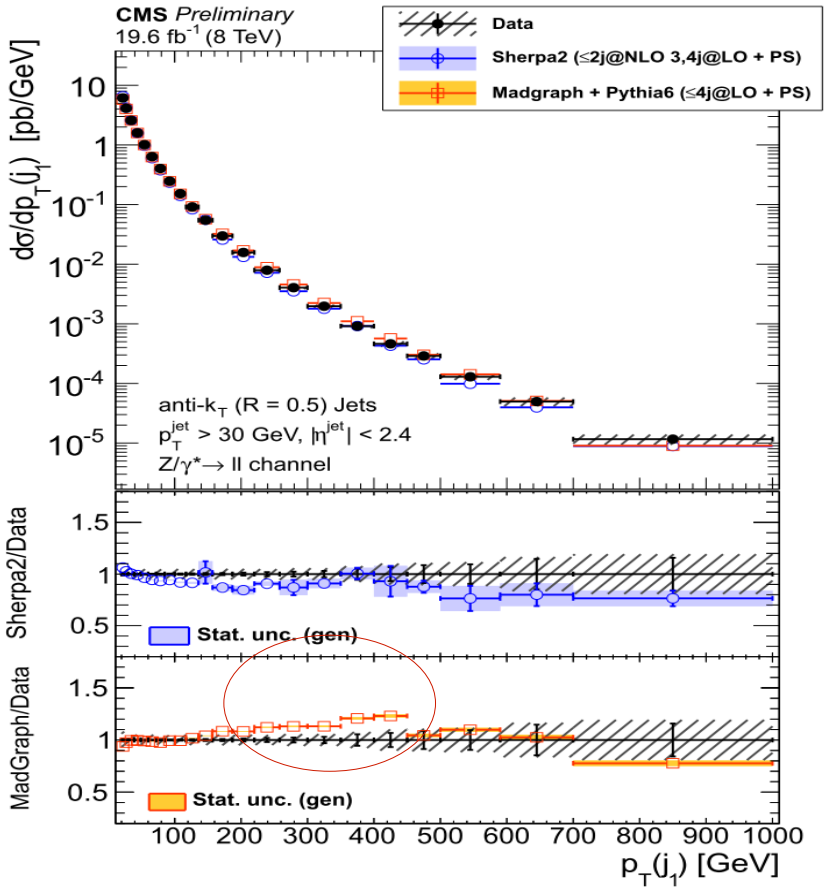
- MadGraph5+Pythia6 kt MLM (LO <=4jets)
- Sherpa+Blackhat(v2) MEPS@NLO
- rescaled to NNLO XSec by FEWZ for both

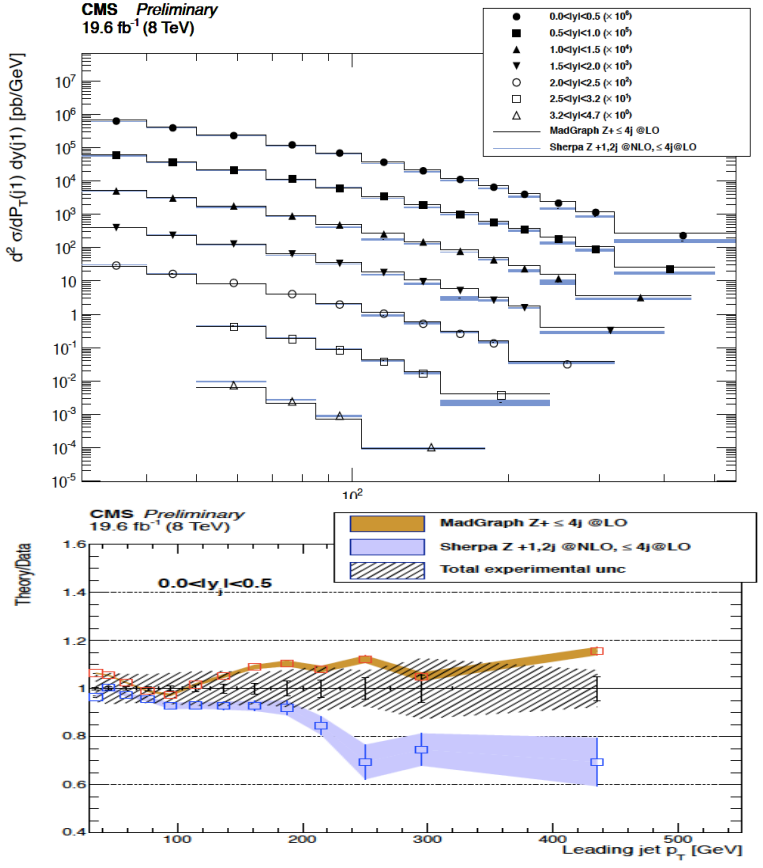
❑ **W THEORY COMPARISONS:**

- MadGraph5_aMC+Pythia6 kt MLM (LO <= 4jets) rescaled to NNLO Xsec by FEWZ
- MadGraph5_aMC+Pythia8 FxFx (NLO <=2jets; 3 LO)
- Sherpa+BlackHat MEPS@NLO (NLO<2jets;3,4LO)
- Sherpa+BlackHat fixed-order NLO
- NNLO1J (fixed-order) (R. Boughezal et al.)
- Non perturbative corrections applied on fixed order predictions

Many measured differential cross sections, few presented in next slides !!!

Z+jets differential cross section as a function of jet pT at 8 TeV





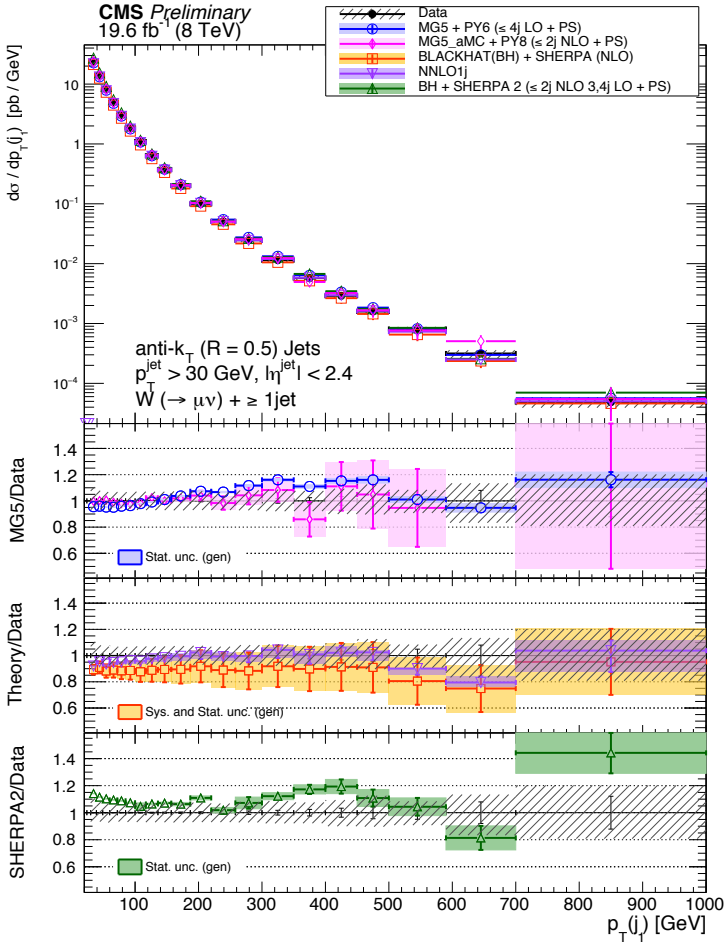
CMS-SMP-13-007

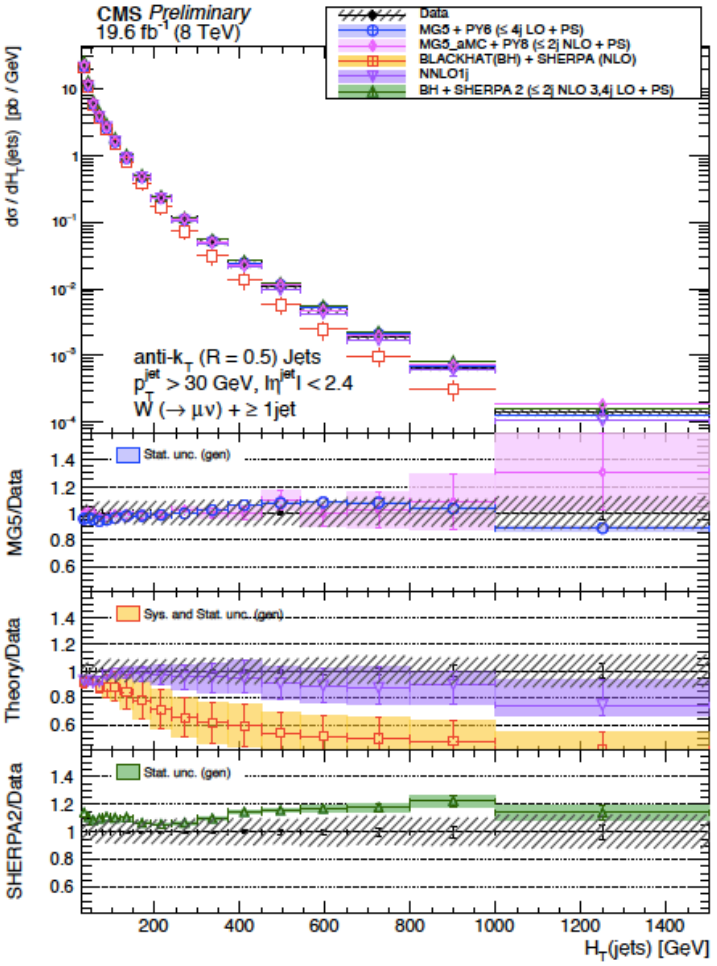
CMS-SMP-14-009

Good agreement with predictions and improved with NLO (SHERPA2)

Measurement of W + jets cross section at 8 TeV

CMS-SMP-14-023



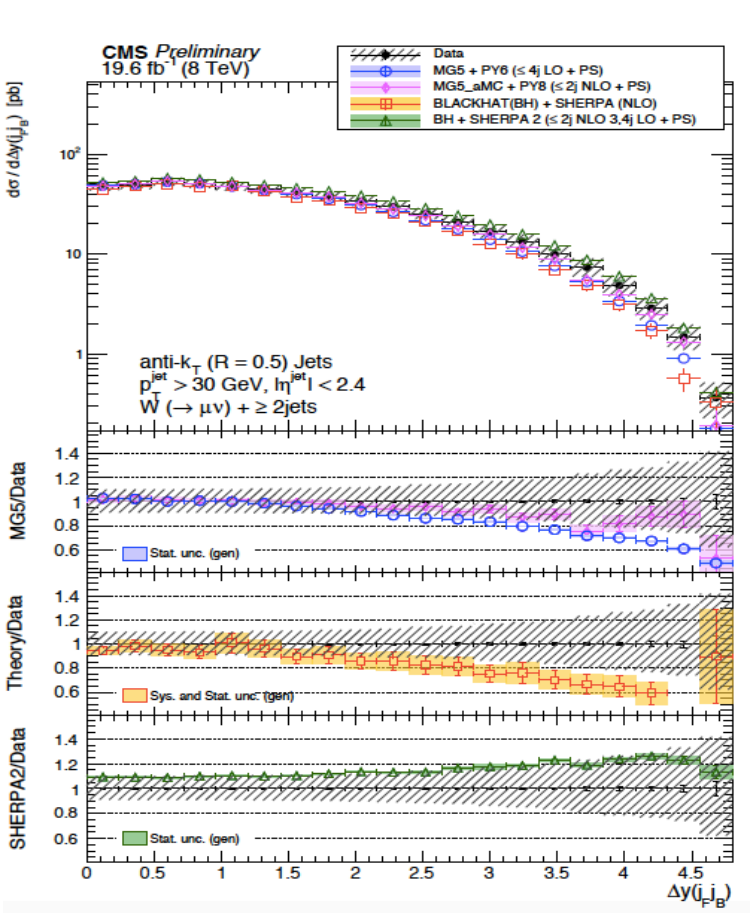


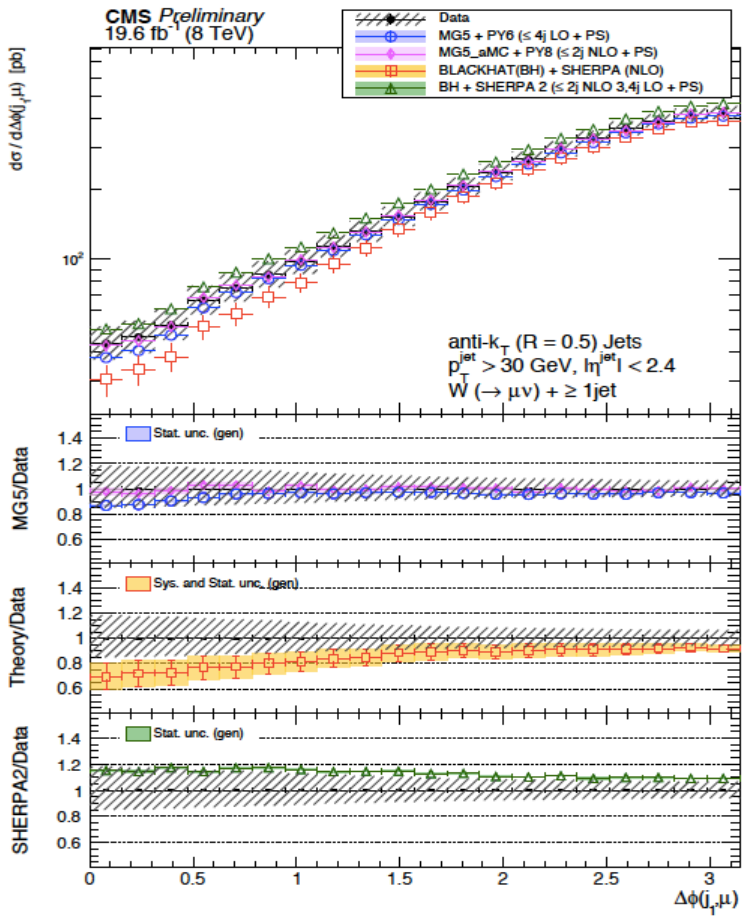
Very good agreement with NLO 0,1,2 jets FxFx and NNLO 1 jet

Measurement of W + jets cross section at 8 TeV

CMS-SMP-14-023

Angular correlations between two jets and muon and a jet





Some discrepancies observed at large $\Delta\eta$ (j_F,j_B) and small $\Delta\Phi$(mu, jet)

Z + b jets differential cross sections at 8TeV

CMS-SMP-14-010

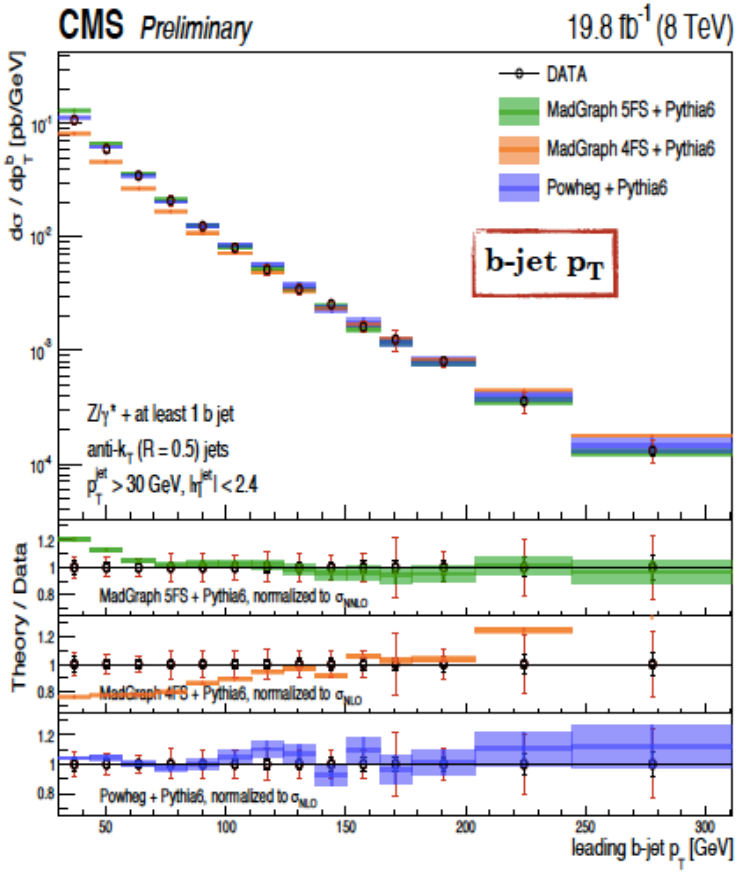
SELECTION
- => 1 antiKT05 jet with pt>30 GeV,|eta|<2.4
- b-tagging: exploiting SV mass discriminator
- ≥1/2 b-tagged jet with pT > 30 GeV, |η|<2.4

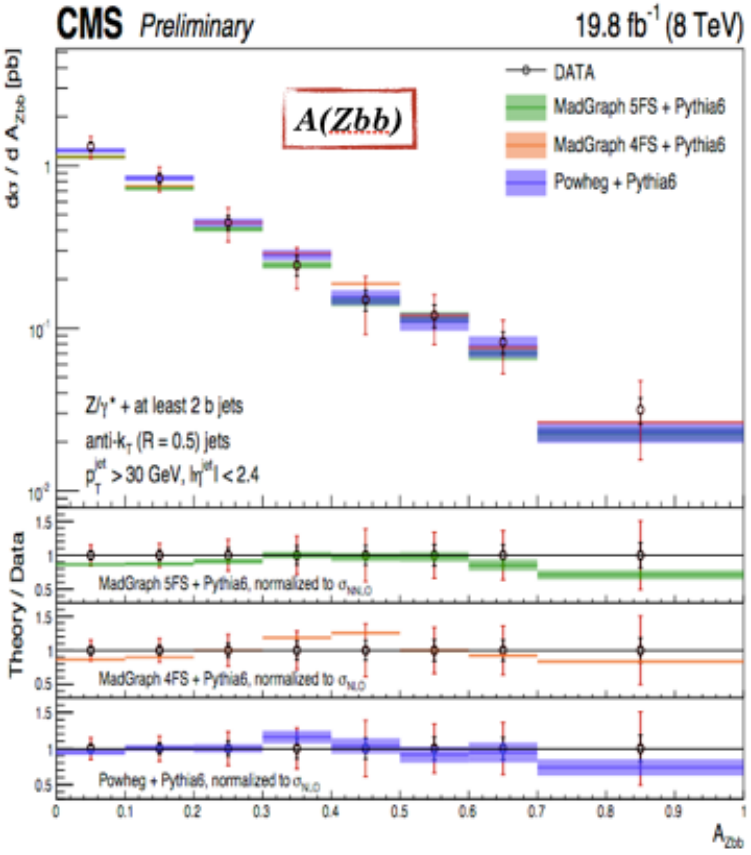
- important test of pQCD with heavy flavors: 4 flavor scheme (b massive) and 5 flavor schemes (b massless)

•Important background for new physics and Higgs:HZZ, SUSY, 4th generation...

$$A_{Zbb} = \frac{(\Delta R_{Zb}^{max} - \Delta R_{Zb}^{min})}{(\Delta R_{Zb}^{max} + \Delta R_{Zb}^{min})}.$$

(Z + at least 2 b jet selection)





W+bb jets differential cross sections at 8TeV

CMS-SMP-14-020

❑ **Phase space selection:**

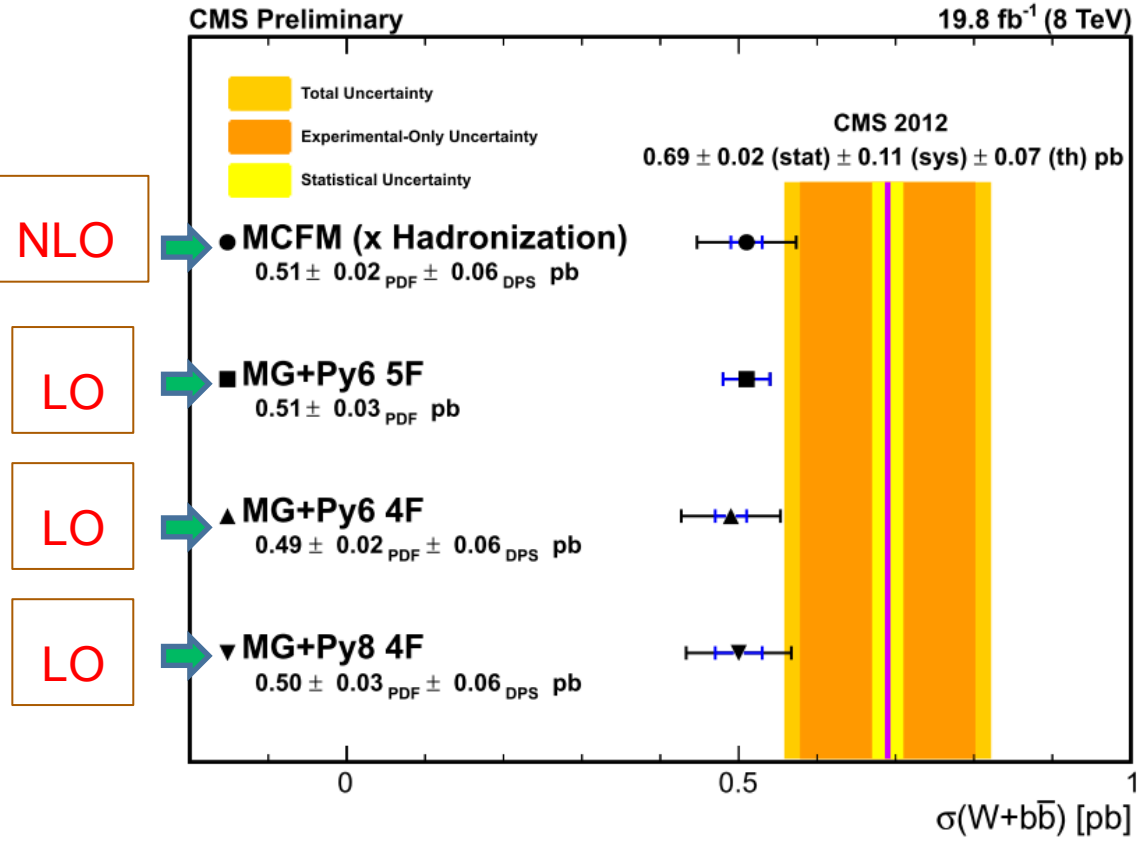
Muon selection:

$p_T(l) > 30$ GeV, $|\eta(l)| < 2.1$,
$71 < M(ll) < 111$ GeVV

B-tagged Jet selection:

ak5, $p_T(j) > 25$ GeV, $|\eta(j)| < 2.4$

The MCFM and MG+Py with 4 flavour scheme do not account for the bb system coming from multiple parton interaction. DPS corrections derived from MG+Py 5F.

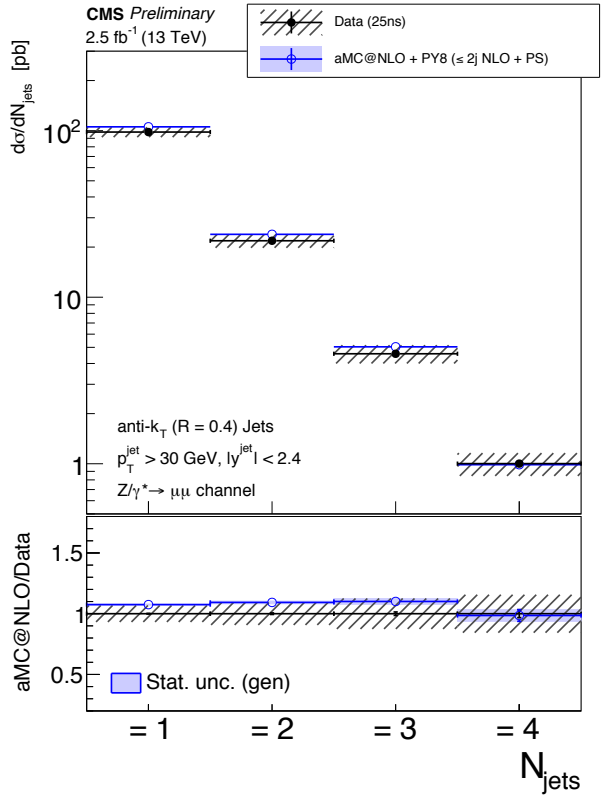


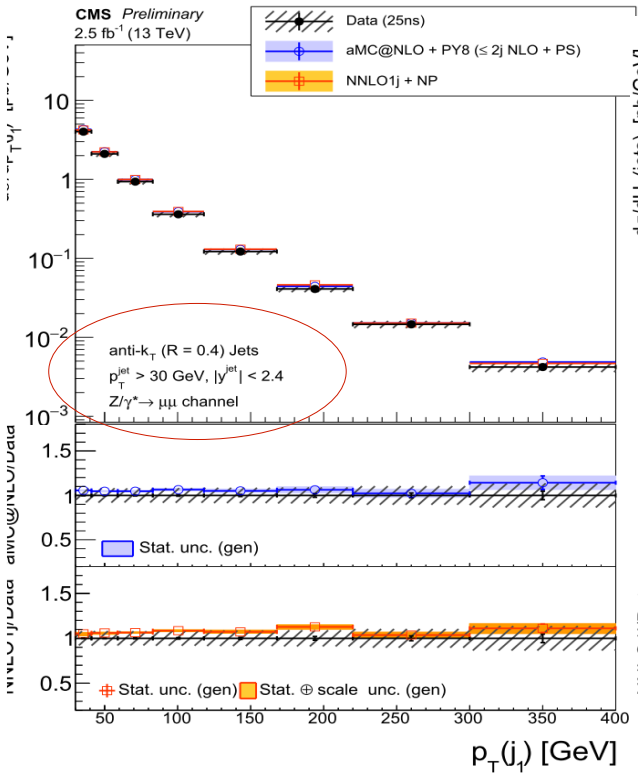
All the predictions agree with measured cross section within one standard deviation

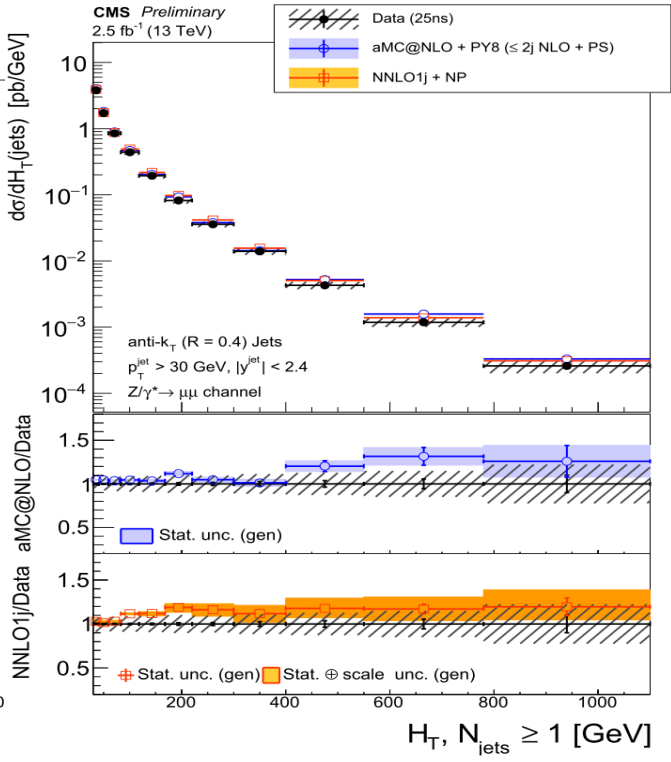
Hadronization and DPS corrections derived from MG+Py 5F for MCFM and MG 4

Z + jets differential cross section at 13 TeV

CMS-SMP-15-010







- Good agreement with multileg NLO and NNLO calculations
- The pT,rapidity, HT (scalar sum of jet pt) of jet for inclusive jet multiplicities up to 3 jets have also been measured

Conclusions

- 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

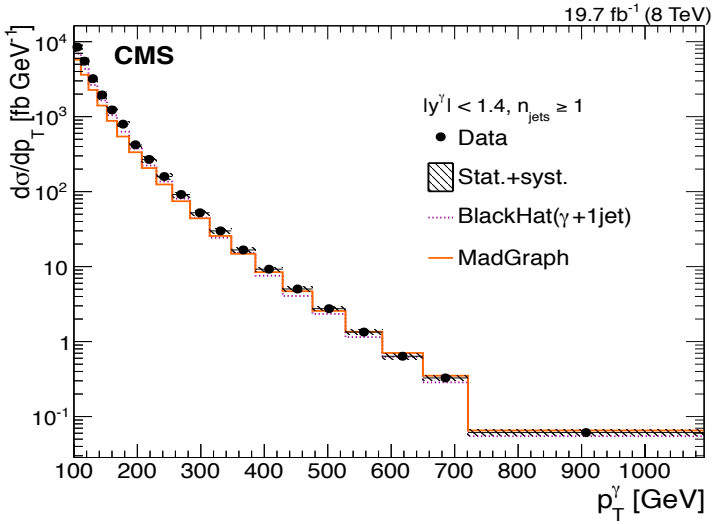
- There have been significant improvements on theoretical predictions and experimental measurements:
  - Reach high precision of measurement
  - Better agreement with higher order (NLO) calculation than LO in general
  - Remained discrepancy and large uncertainty motivate the ongoing work to improve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

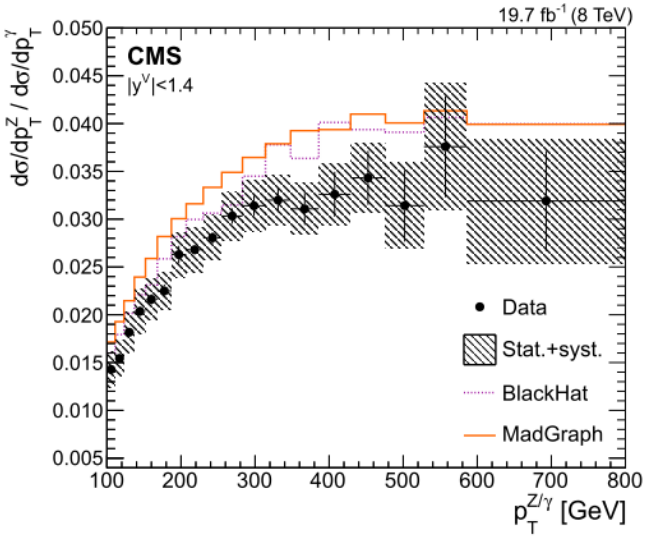
- More results at 8TeV / 13TeV will come out soon!

Backup

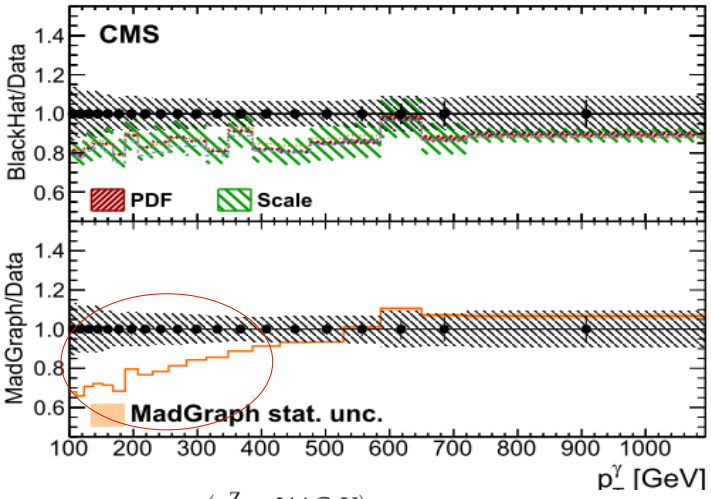
Photon (γ) + jets cross section at 8 TeV

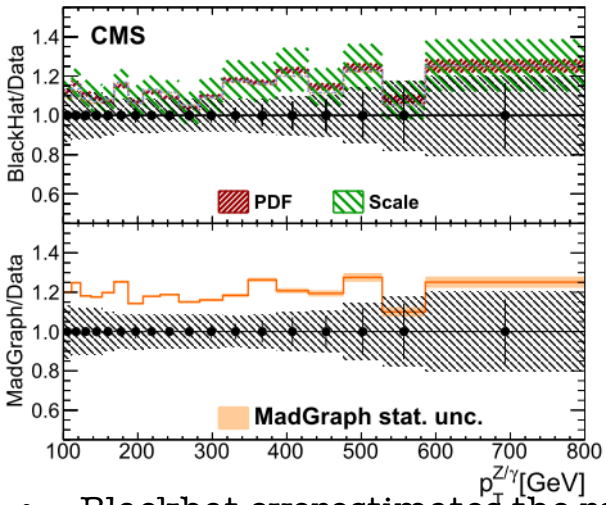
See G. Flouris' talk





Selection:
Lepton :
$P_T(l)>20GeV, |eta|<2.4$
Photon:
$P_T(l)>20GeV$
Jets:
$P_T(j)>20GeV, |eta|<2.4$





JHEP10(2015)128

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

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

Z+b jets differential cross sections at 8TeV

CMS-SMP-14-010

SELECTION
- => 1 antiKT05 jet with pt>30 GeV,|eta|<2.4
- b-tagging: exploiting SV mass discriminator
- ≥1/2 b-tagged jet with pT > 30 GeV, |η|<2.4

- important test of pQCD with heavy flavors: 4 flavor scheme (b massive) and 5 flavor schemes (b massless)

•Important background for new physics and Higgs:HZZ, SUSY, 4th generation...

BACKGROUND

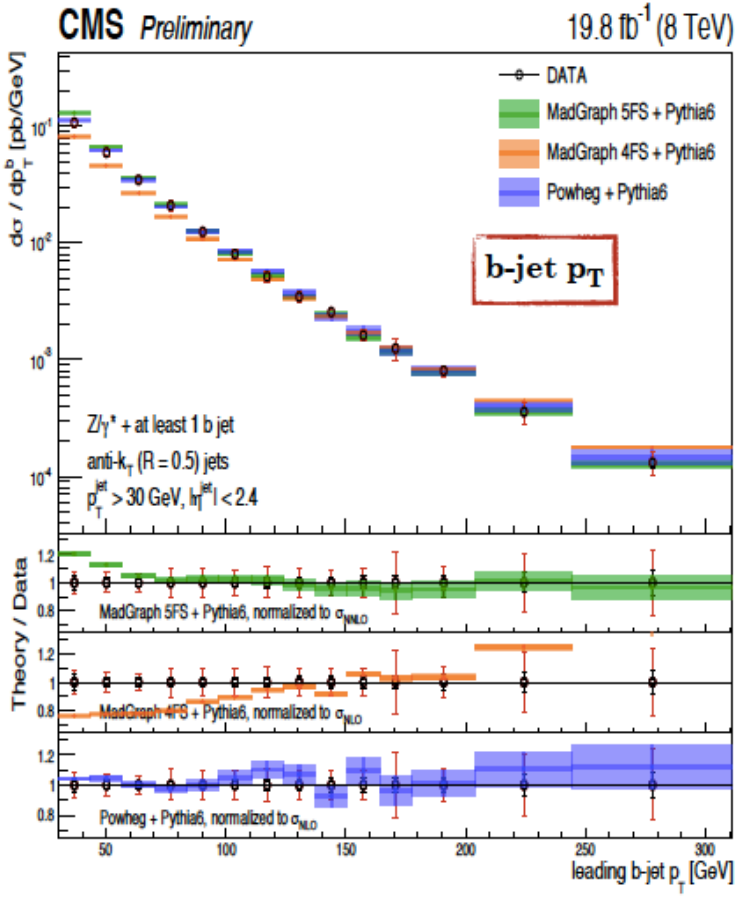
ttbar: data-driven estimation in an eμ+jets control sample:
Extract both shape and normalization
- Z+c, Z+light- flavor MC templates extracted from SV mass fit and subtracted
- dibosons taken from MC

CROSS SECTIONS

unfolded (SVD) data compared

SYSTEMATICS

Jet energy corrections
Unfolding



Motivations on V+jets physics

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- Actual understanding and modeling of QCD interactions is crucial on the potentials for precision measurements

  W/Z+jets is a dominant background for:

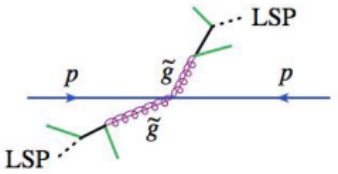
  Top-quark measurements

  Precision measurement of Higgs physics in VH(->bb) channel

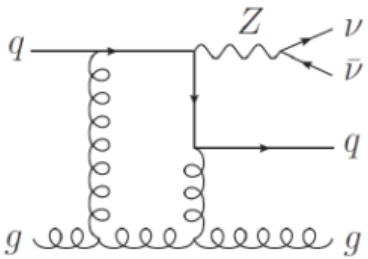
  - It is significant for the modeling the production mechanism involved in new physics searches (e.g. Supersymmetry)

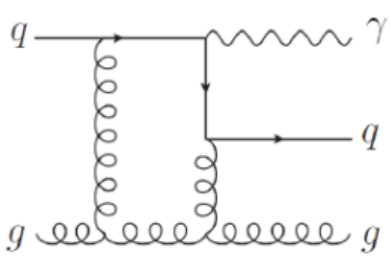
- Z+jets as background to new physics searches:
  - Z(->νν)+jets in SUSY (MET+jets) searches
  - Exploit NLO computations of W+jets/Z(->νν)+jets or γ+jets/Z(->νν)+jets ratios to calculate the transfer functions from W/γ +jets to Z(->νν)+jets
    - ✓ important to constrain theory extrapolation with data

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

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

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)

[CMS-PAS-SMP-14-010]

Z+b, Z+bb jets differential cross sections at 8TeV

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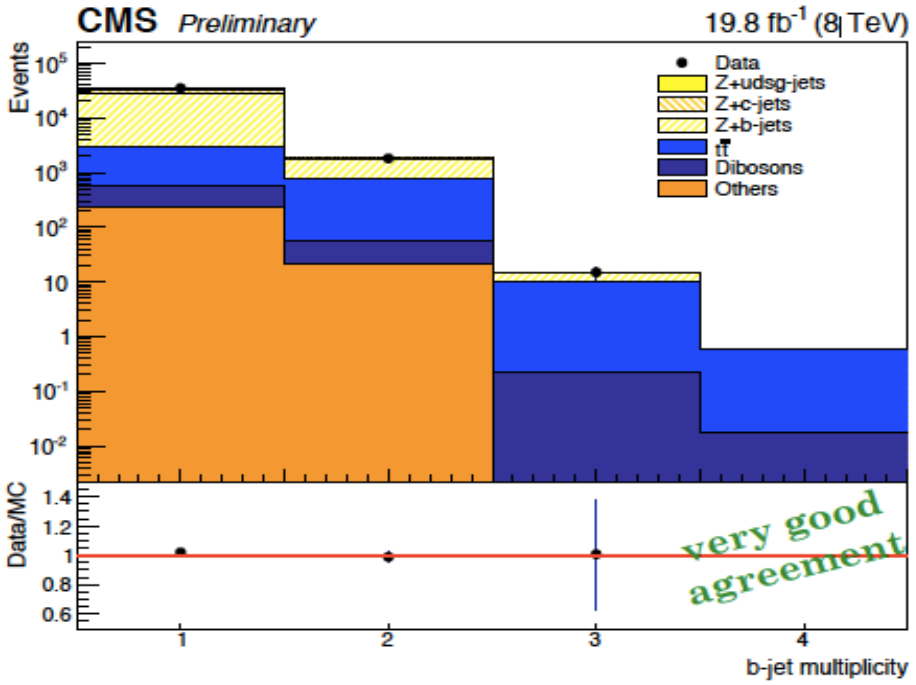
CROSS SECTIONS

unfolded (SVD) data compared

SYSTEMATICS

Jet energy corrections
Unfolding

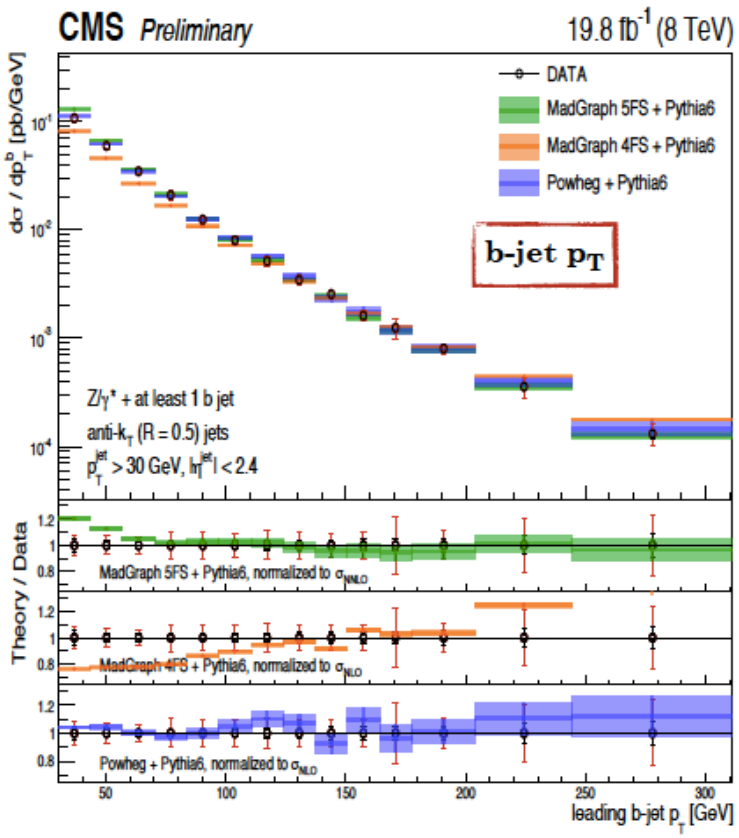


[CMS-PAS-SMP-14-010]

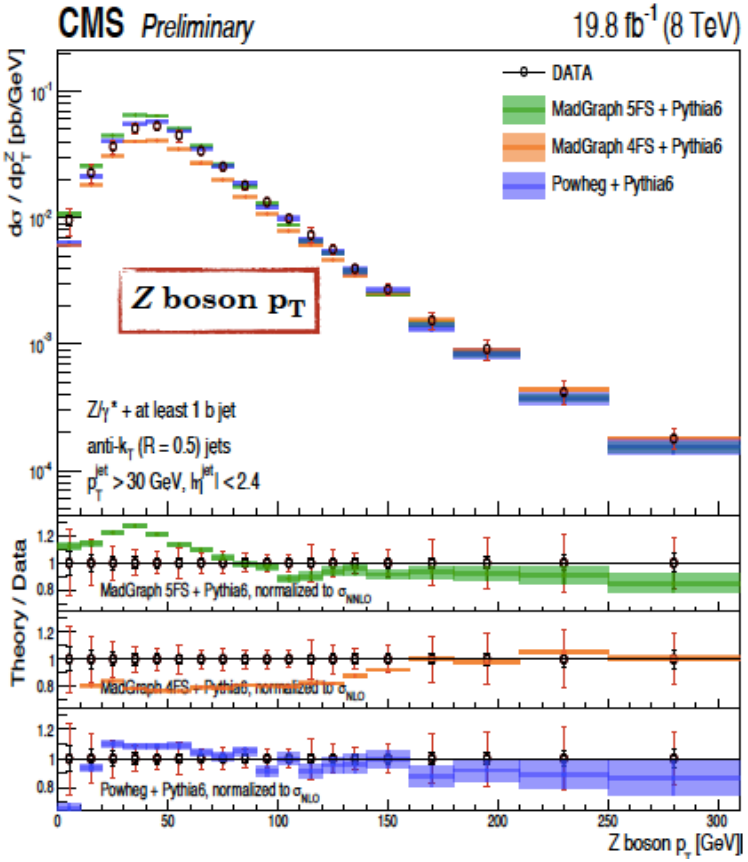
Z+b, Z+bb jets differential cross sections at 8TeV

Z + at least 1 b jet selection:

unfolded leading b-jet pT cross section



unfolded Z boson pT cross section



Simulation samples (background)

- TTbar background and single top are generated by POWHEG, interfaced with PYTHIA 8
- Double vector boson BKG:
  - WW: generated by POWHEG
  - WZ: generated by aMC@NLO, interfaced with PYTHIA8
  - ZZ: generated by PYTHIA 8
- Wjets sample is generated by aMC@NLO, interfaced with PYTHIA 8

Background	Events	Xsec (pb)
TT_TuneCUETP8M1_13TeV-powheg-pythia8	3.32461e+07	831.76
ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	995600	35.6
ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	988500	35.6
ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.3187e+06	10.32
WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	3.73654e+12	61526.7
WWTo2L2Nu_13TeV-powheg	1.9652e+06	12.21

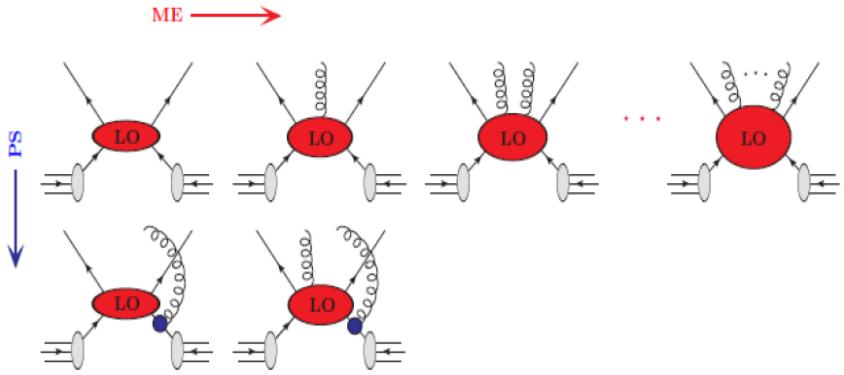
W/Z + heavy flavor jets (b/b) measurement at 8 TeV

W/Z + heavy flavour jets (b/b)

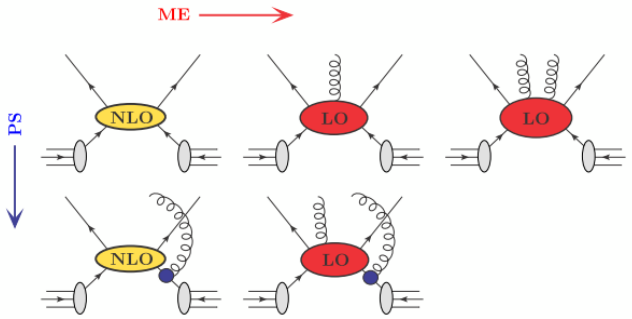
- Theoretical uncertainties on W/Z + heavy flavor jets larger than for light jets case
  - Heavy quark content in the proton
  - Modeling of gluon splitting (initial state or final state)
  - Massive or massless b quark in computations
- Test of QCD predictions with various implementations (LO + Multipartons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

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

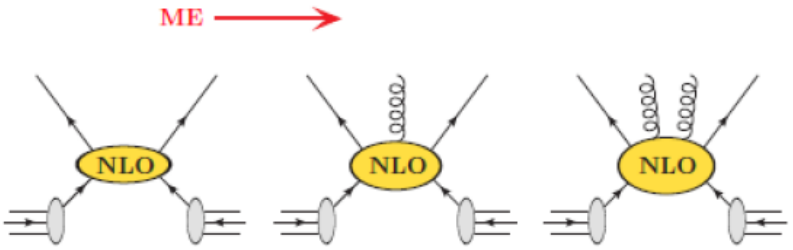
- **Multileg LO with 0~4 final partons in matrix element:**
  - MADGRAPH5 + PYTHIA6: kt-MLM merging, CTEQ6L1 PDF
  - SHERPA1.4: CKKW merging, CT10 PDF
  - Hadronization and mutiple parton interactions are implemented



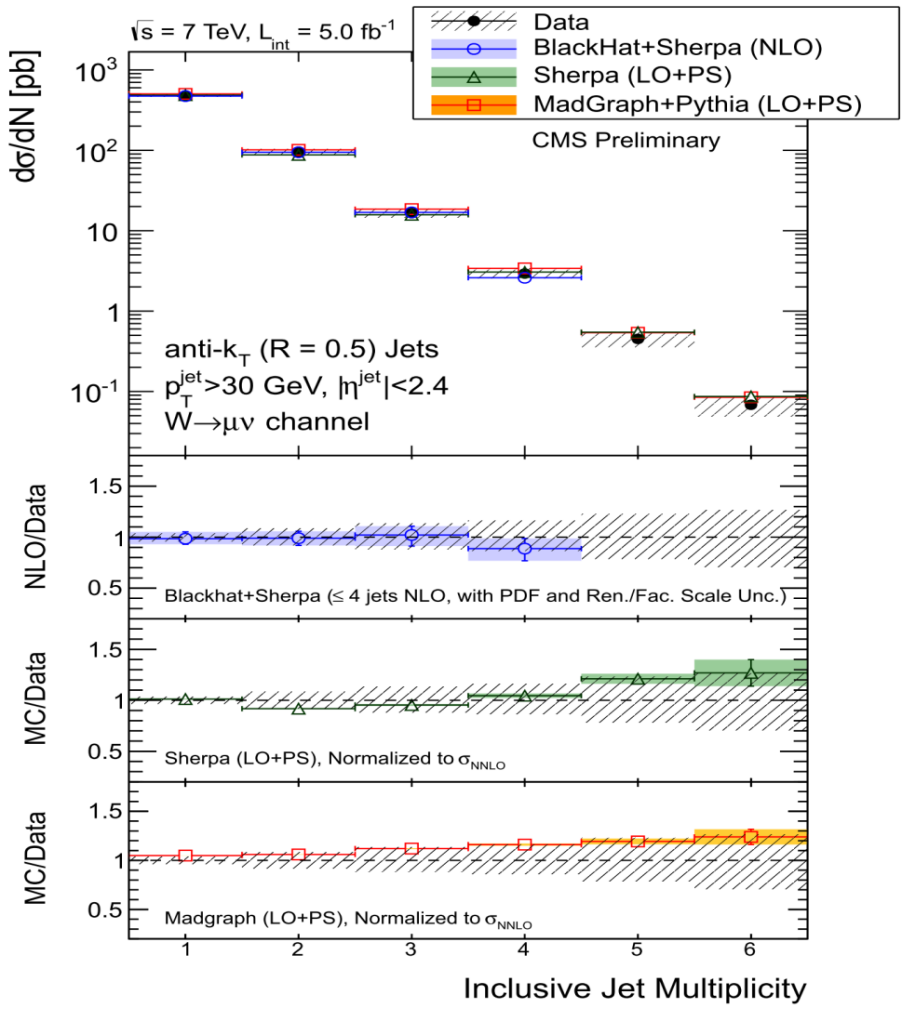
- **Multileg with 0~2 partons at NLO, 3~4 partons at LO:**
  - SHERPA2 (+ BLACKHAT): MEPS@NLO merging, CT10 PDF
  - Hadronization and mutiple parton interactions are implemented

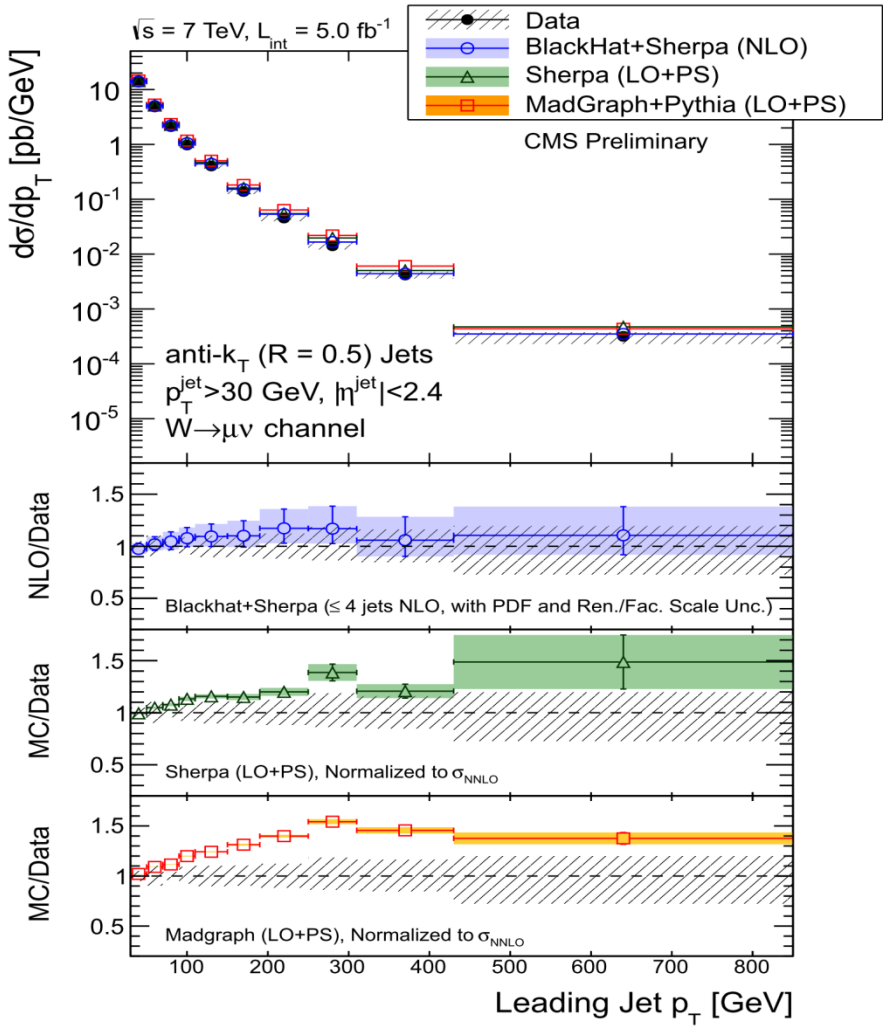


- **Fixed order Z + N jets (NLO):**
  - BLACKHAT (+SHERPA): MSTW2008 NLO PDF
  - Correction for hadronization and multiple parton interactions computed with MG5+PYTHIA6



W + jets measurement at 7 TeV

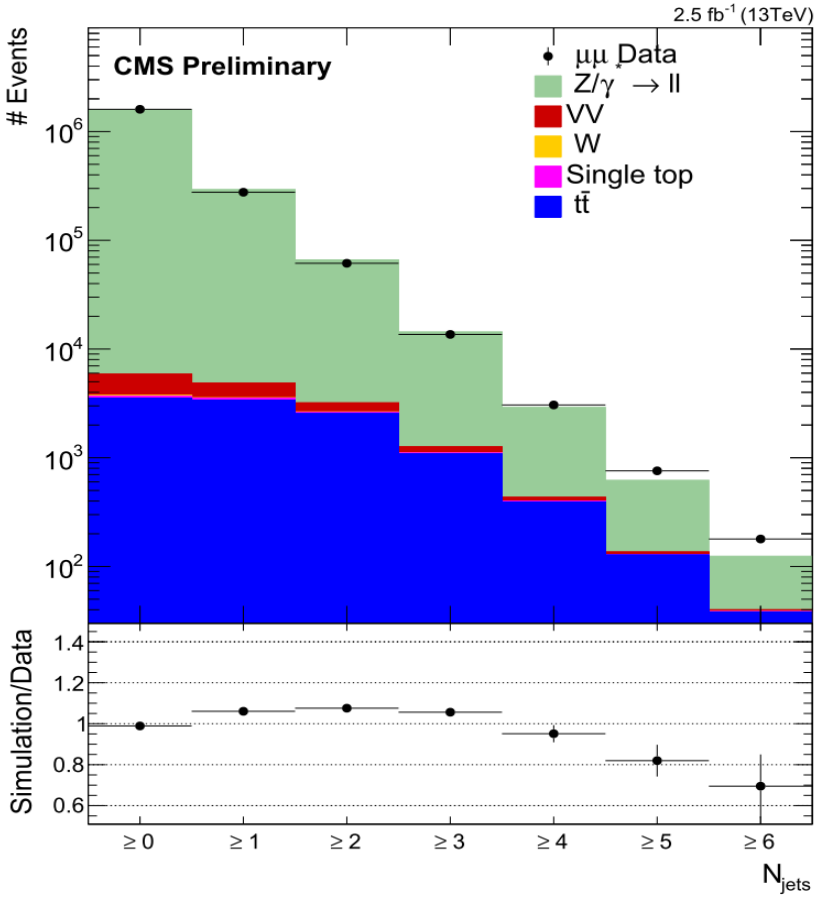


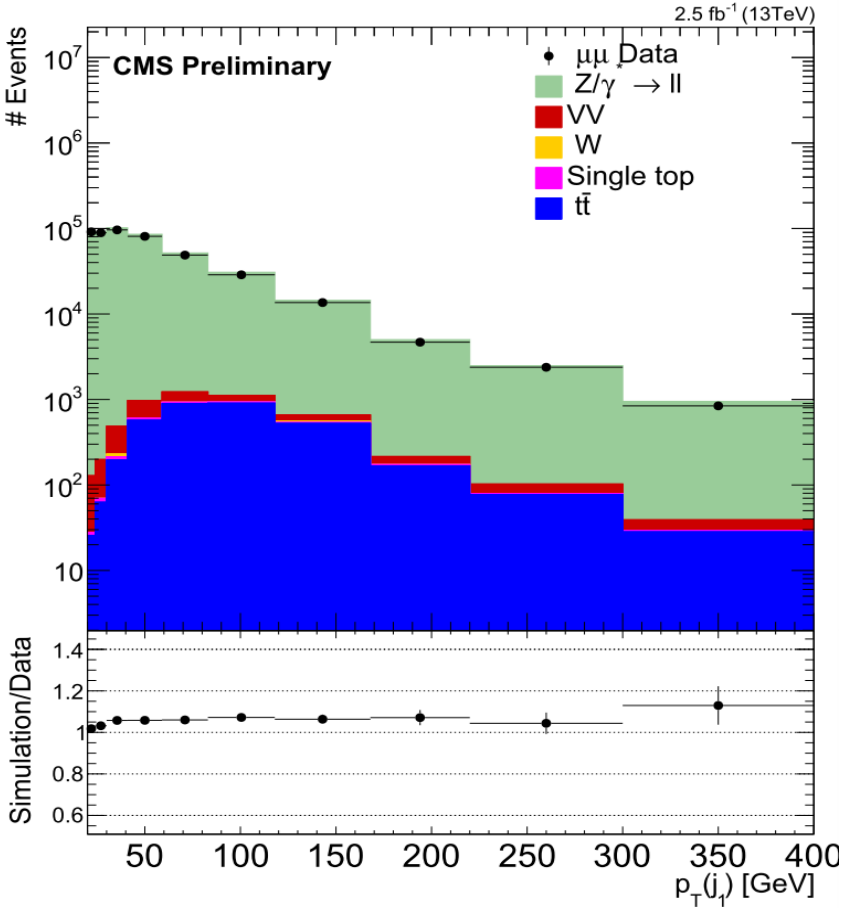


- Good agreement between data and NLO/LO calculation for jet multiplicity
- Discrepancy in LO computation has been compensated by NLO accuracy

Z + jets measurement at 13 TeV

PAS: SMP-15-010

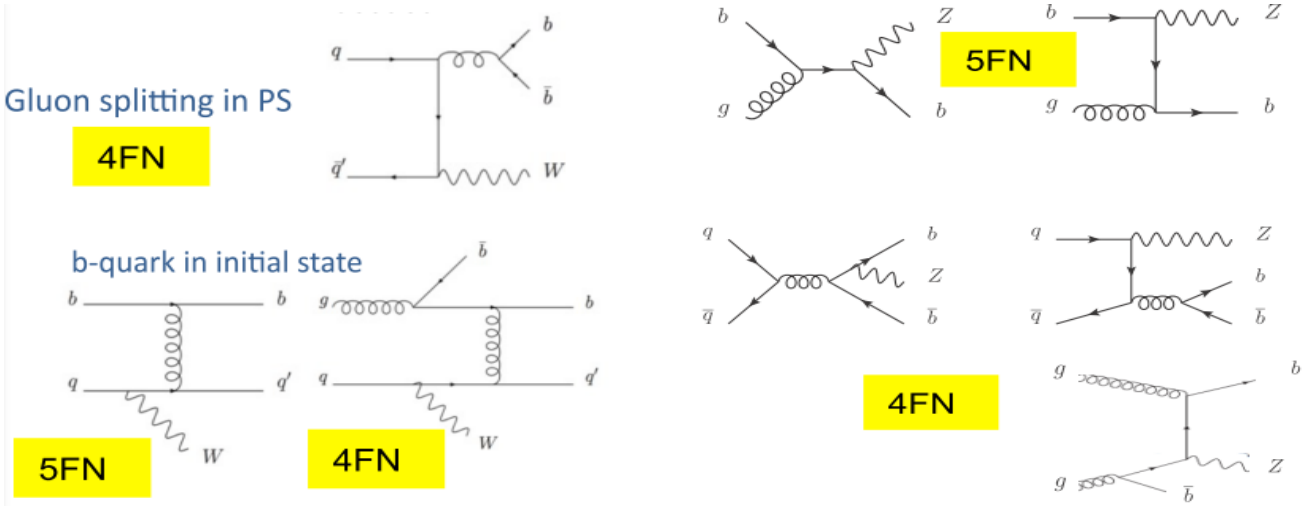




- Siginificant ttbar contribution for N_jets >= 4

W/Z + heavy flavor jets (b/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

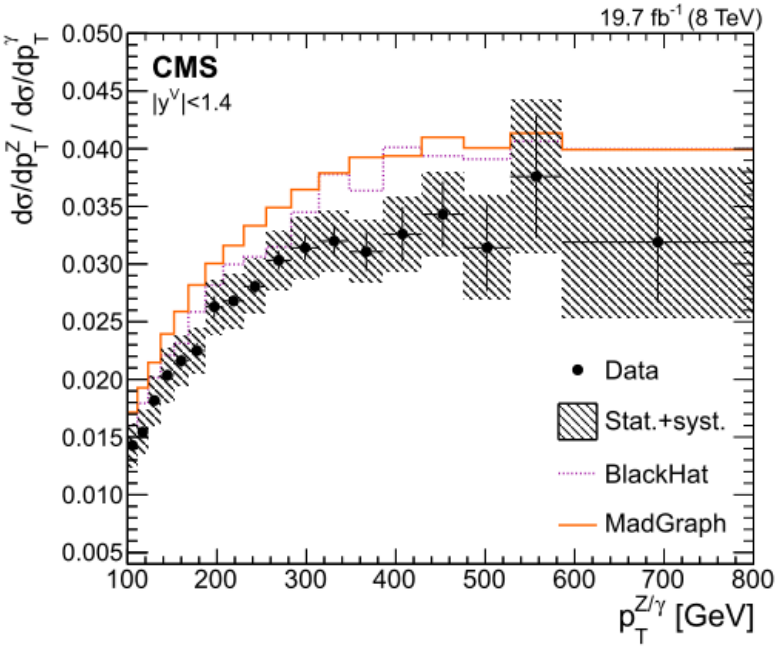


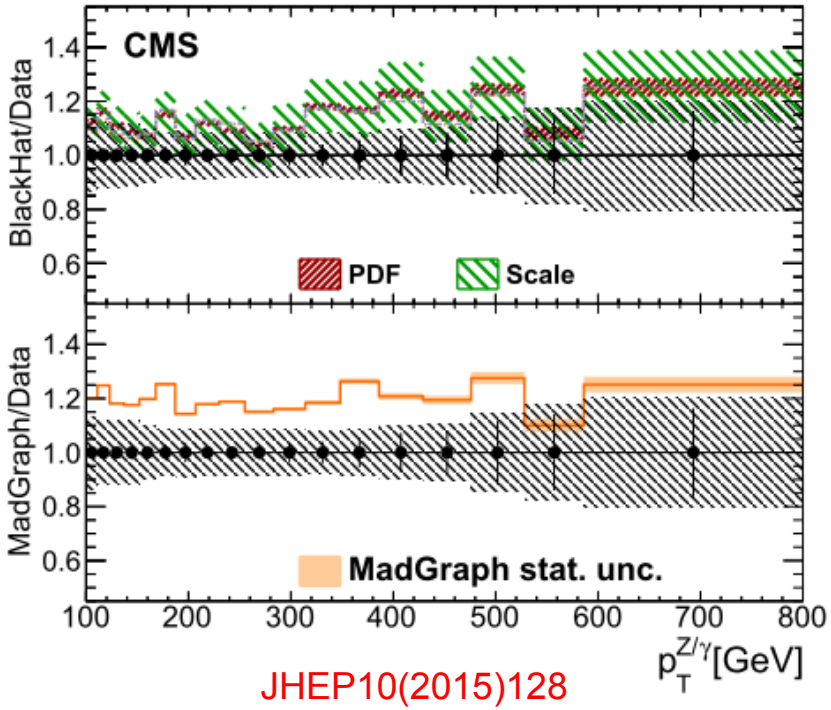
- Descriptions of "b-quark initiated processes:"
- 4 flavors number scheme (4FN): b quark generated with gluon splitting
- 5 flavors number scheme (5FN): b quark (massless) generated in the initial state

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

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

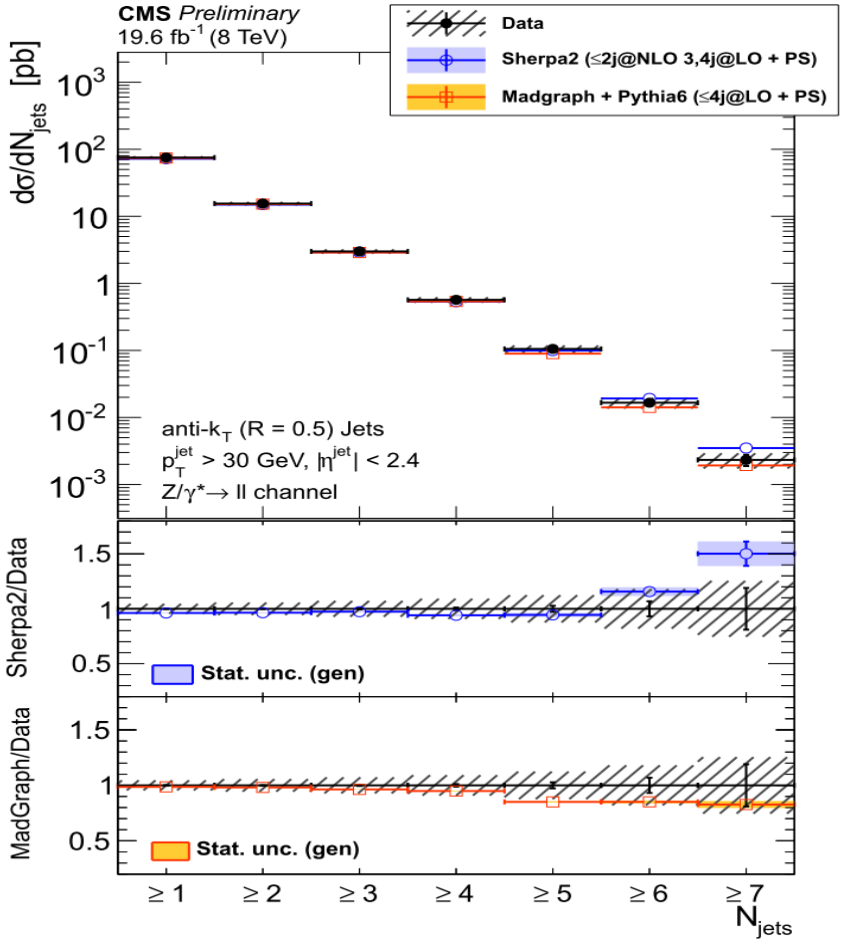
- Z/γ + jets cross section and ratio at 8 TeV (JHEP10(2015)128)

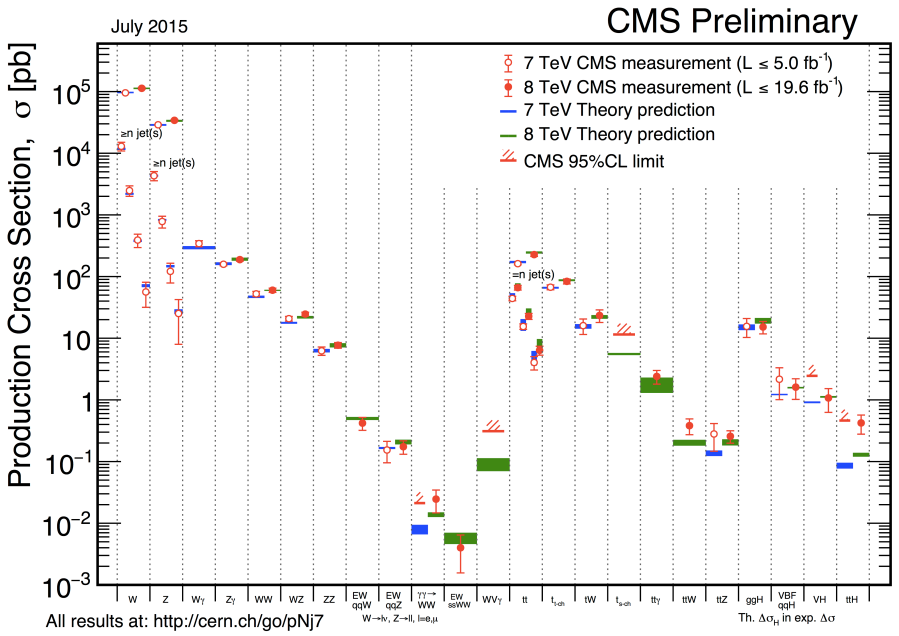
- Z/γ* + jets cross section at 8 TeV (PAS: SMP-13-007)

- Z/γ* + jets cross section at 13 TeV (PAS: SMP-15-010)

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

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


CMS Preliminary
19.6 fb-1 (8 TeV)
Data
Sherpa2 (≤2j@NLO 3,4j@LO + PS)
Madgraph + Pythia6 (≤4j@LO + PS)
dσ/dNjets [pb]
anti-kT (R = 0.5) Jets
pTjet > 30 GeV, |ηjet| < 2.4
Z/γ*→ ll channel
Sherpa2/Data
MadGraph/Data
Stat. unc. (gen)
Stat. unc. (gen)
≥ 1
≥ 2
≥ 3
≥ 4
≥ 5
≥ 6
≥ 7
Njets


July 2015
CMS Preliminary
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
Production Cross Section, σ [pb]
≥n jet(s)
≥n jet(s)
≥n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW ssWW
WVγ
tt
tt-ch
tW
t-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
W→lν, Z→ll, l=e,μ
Th. Δσ in exp. Δσ
All results at: http://cern.ch/go/pNj7

Z + >= 1 jet cross section as a function of ZPt

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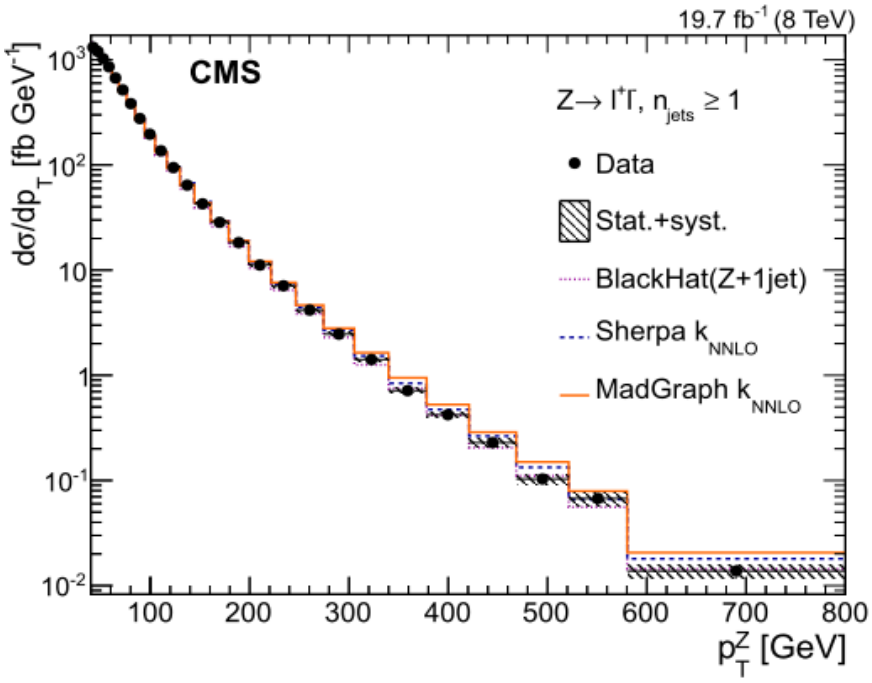

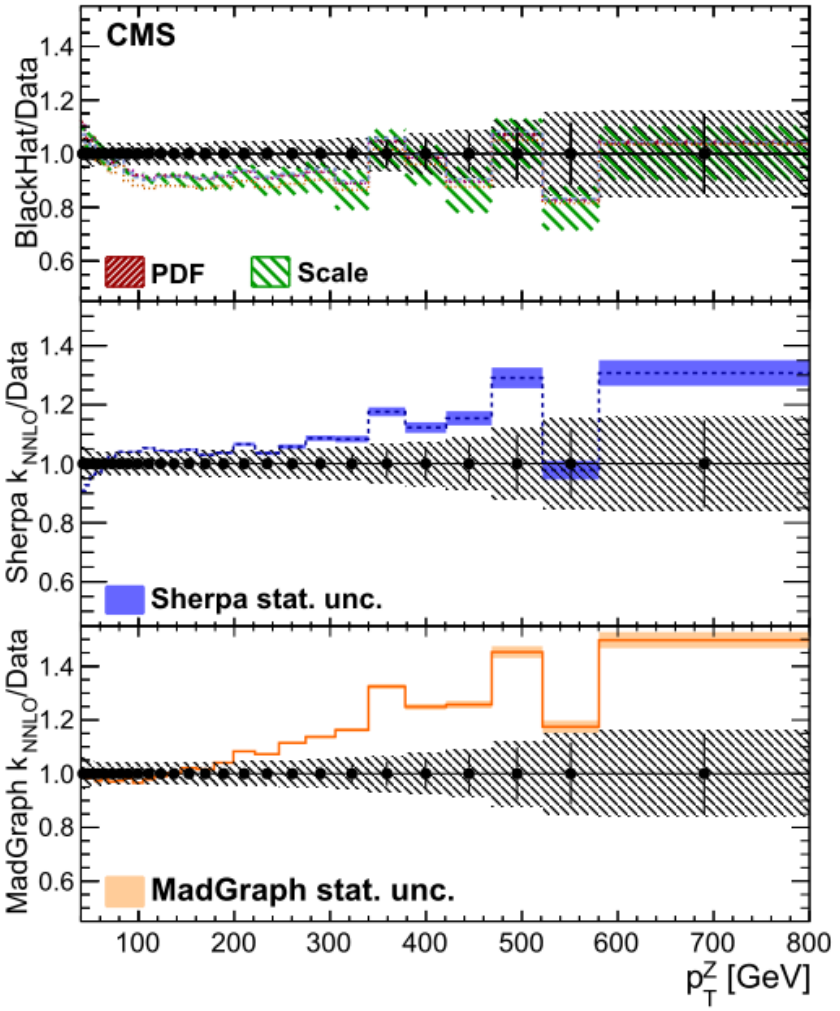

- MG5+Pythia6 comparison is flat until around 200 GeV and up to about 30% discrepancy, which is same for Z+ ≥ 2 jets case
- BLACKHAT reproduces shape of data