W/Z+jets (including heavy flavor) measurements at the LHC

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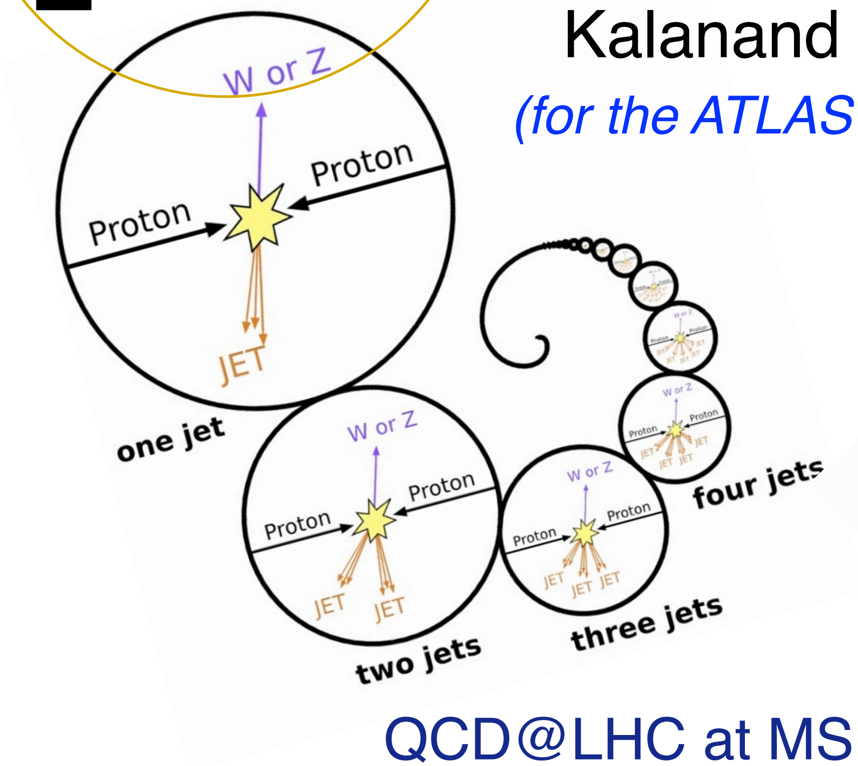
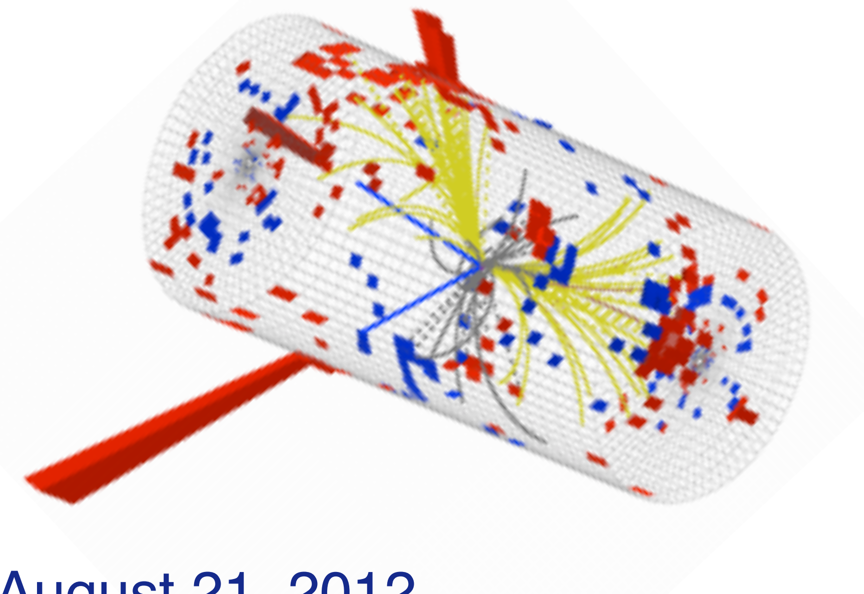
(for the ATLAS & CMS Collaborations)





QCD@LHC at MSU, August 21, 2012

Outline

- Introduction
  - -production rate, topology, predictions
  - -experimental issues, comparison with theory

- Measurements of W/Z+jets
  - -cross sections and observables as a function of N_{jets}
  - -angular correlations and event shapes

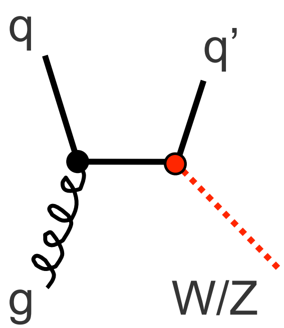
- Measurements involving heavy flavors
  - -W/Z+b-jets (important bkg for H→bb measurement)
  - -W+charm (useful for constraining s-quark pdf)

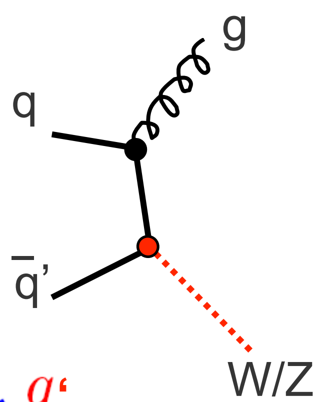
- Summary

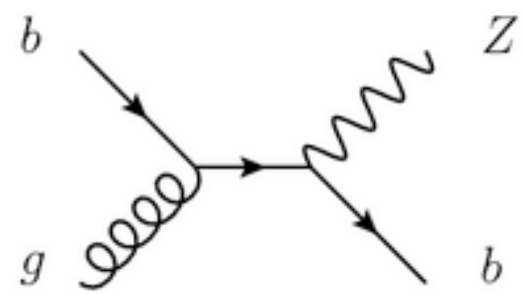
Why we care about W/Z+jets at LHC

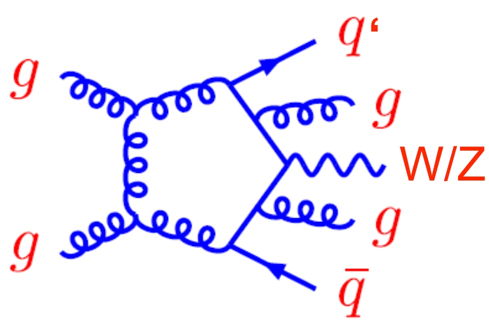
Important for two broad classes of reasons

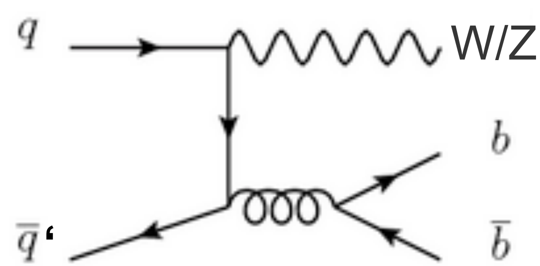
- a ubiquitous source of background for virtually any signal (both SM and searches) at the LHC
- a tool to test the predictions of perturbative QCD





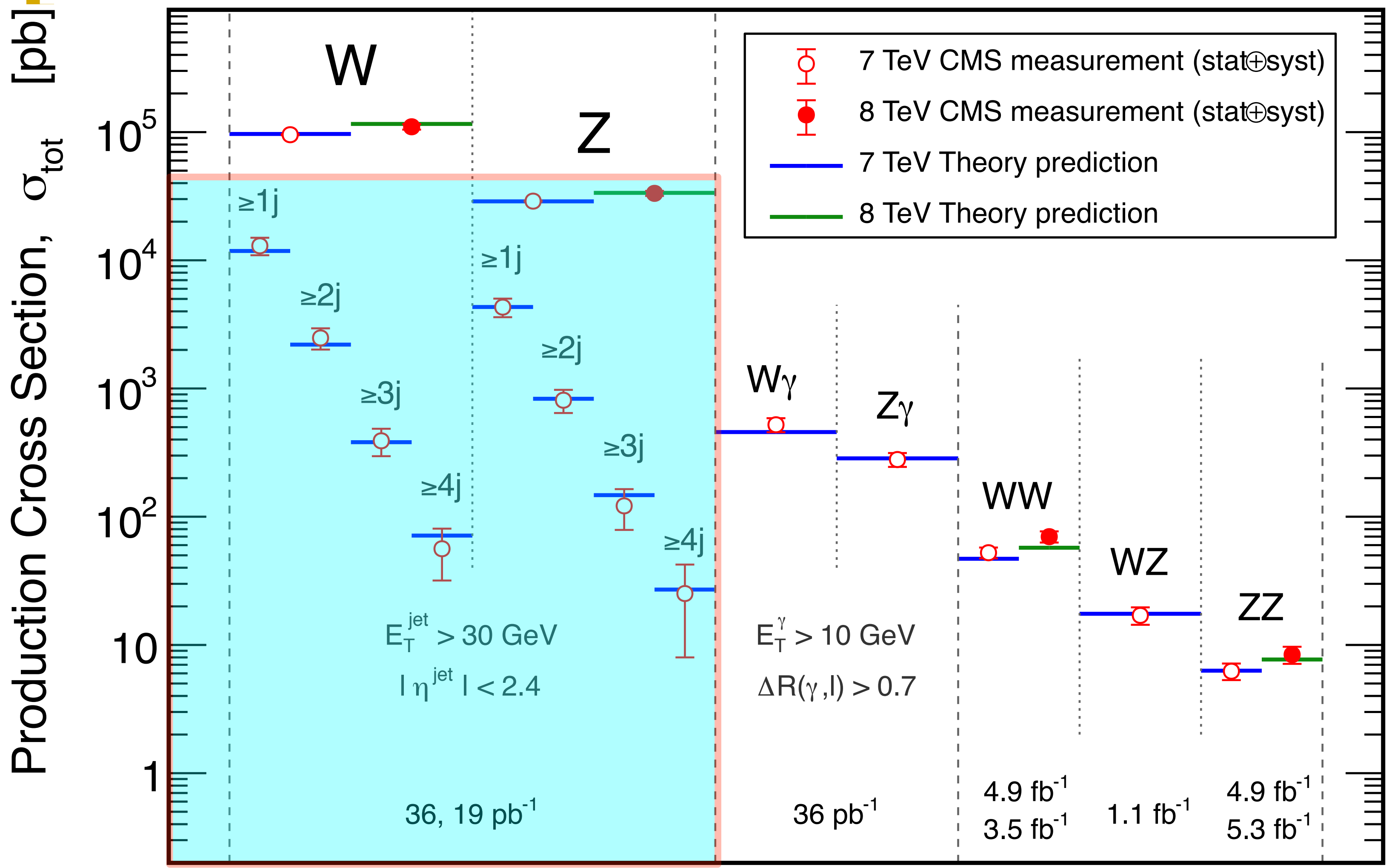






Availability of large datasets & well-understood LHC detectors allow for precision QCD measurements.

Production rate is huge: 10's of nanobarn



JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

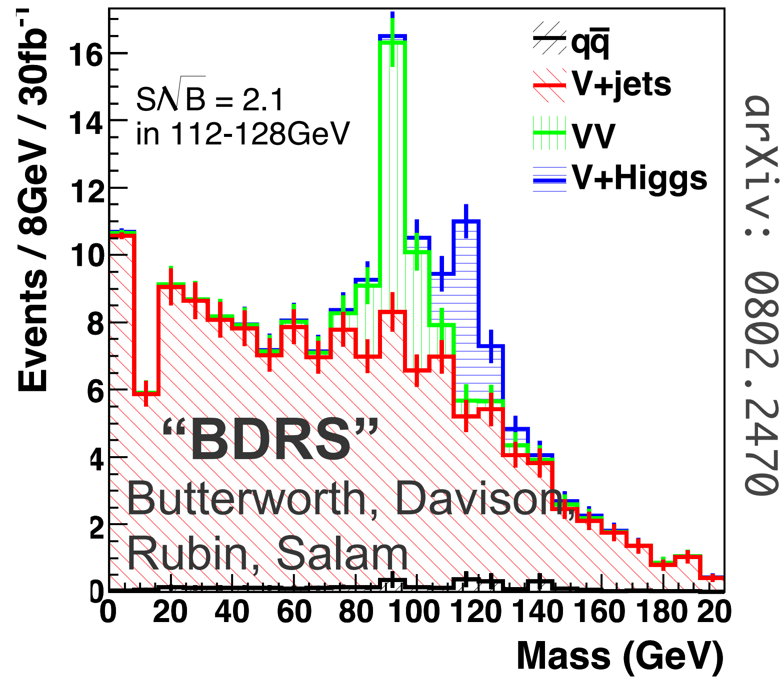
PLB701(2011)535

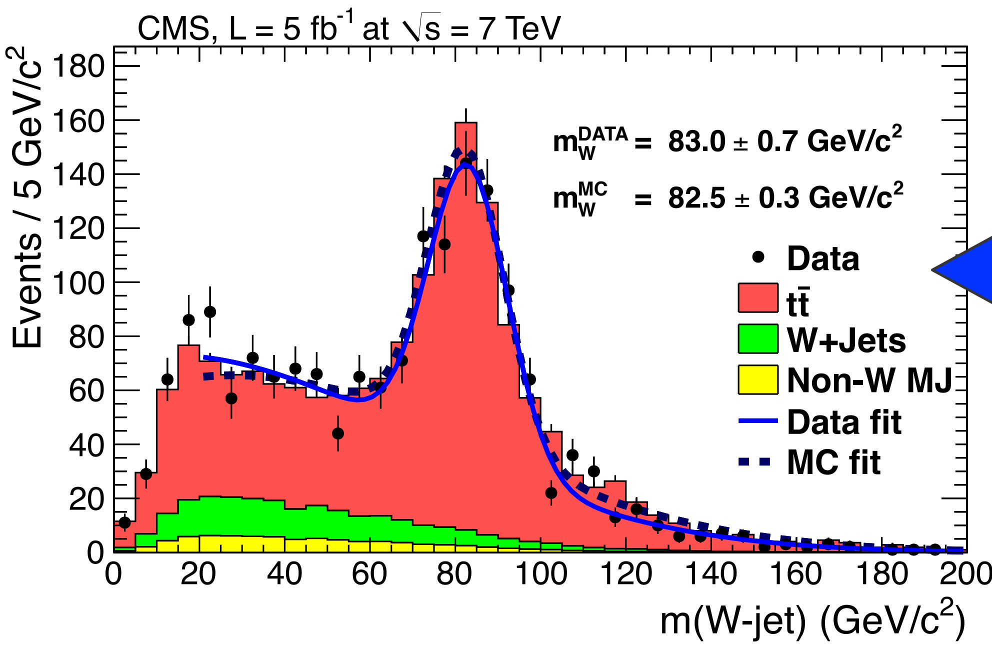
CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

Often need to estimate rate in specific phase space

Need to understand well the W/Z +jets bkg to improve sensitivity of hadronic decays of boosted heavy particles such as Higgs, W/Z, top

This is what we aim to do



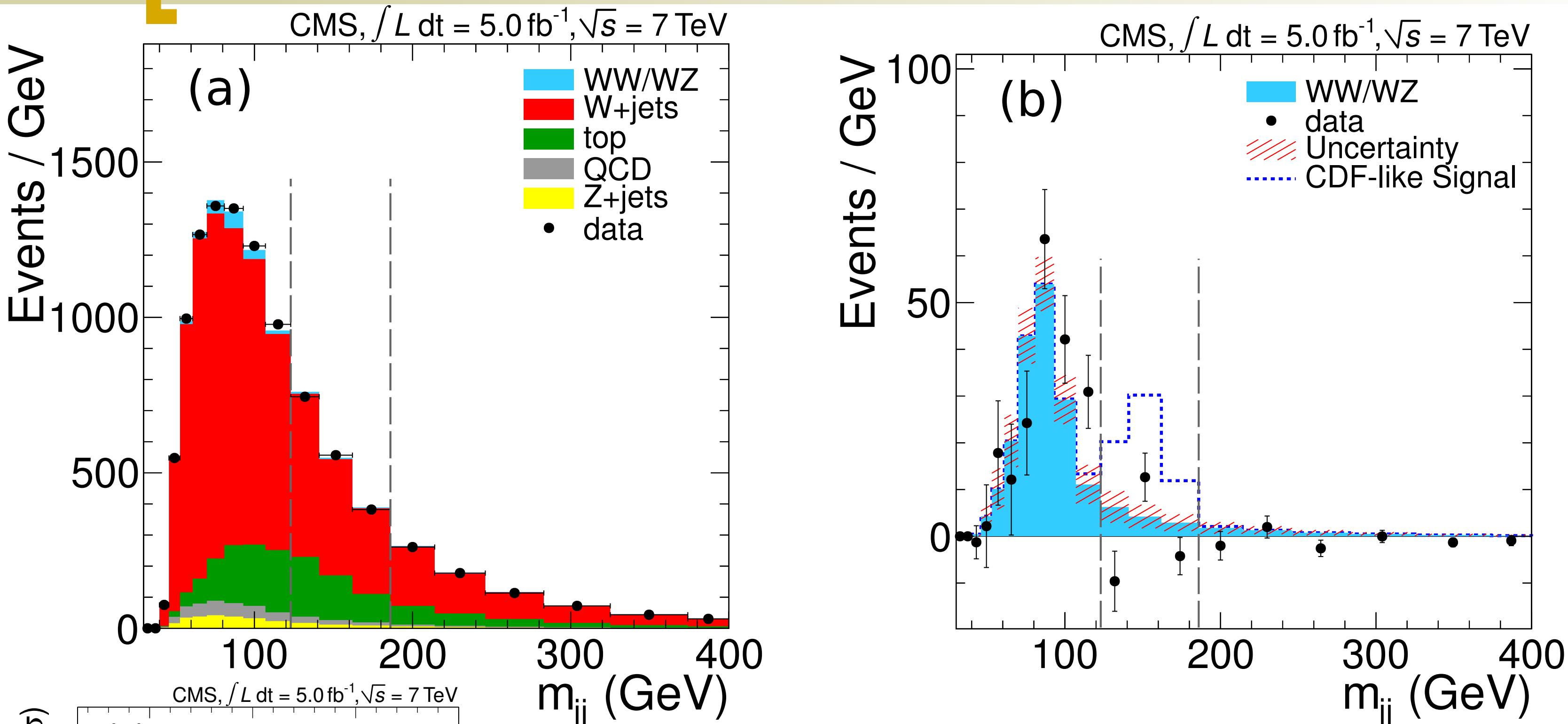


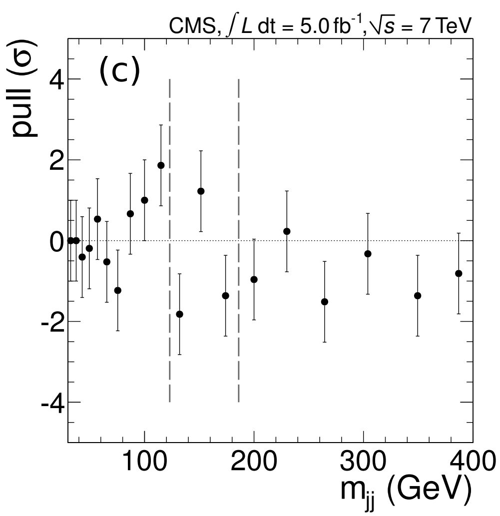
Started with hadronic W in boosted top events

http://cdsweb.cern.ch/record/1370237

See talks by D. Miller and D. Lopes-Pegna (Mon) for jet substructure analyses/tools.

Another example: need to model bkg in W+jj events





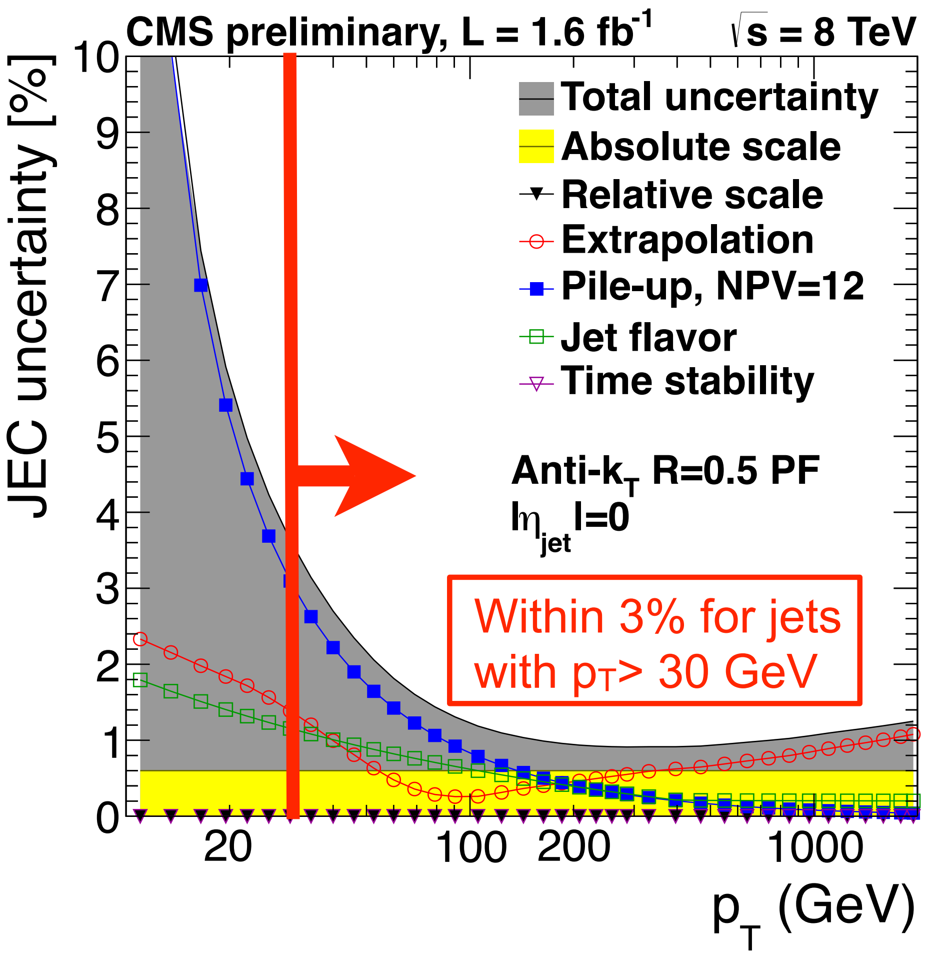
We had to float fact/renorm scale & ME-PS matching threshold within uncertainties to get good modeling of data

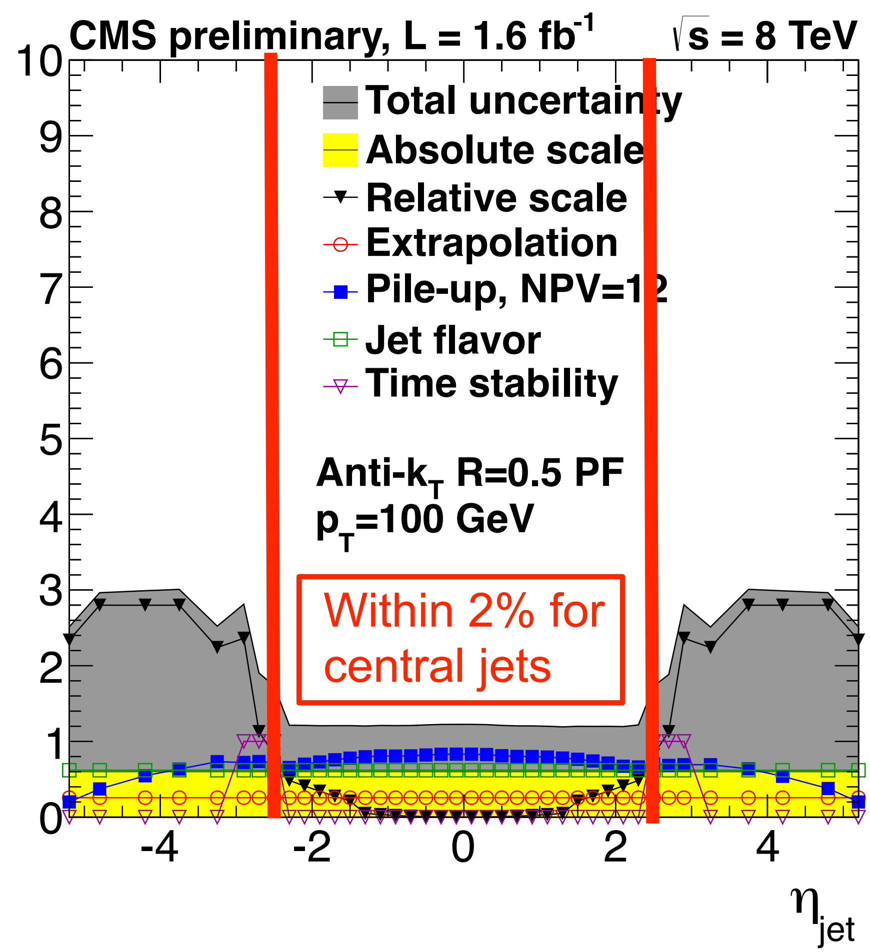
$$\mathcal{F}_{\mathrm{W+jets}} = \alpha \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1-\alpha-\beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2),$$

Consistent values of α, β in electron and muon channels.

Good understanding of jet energy scale

- Uncertainties in 2012 data comparable to 2010, 2011.
  - Pileup uncertainties increasing due to higher average pileup.



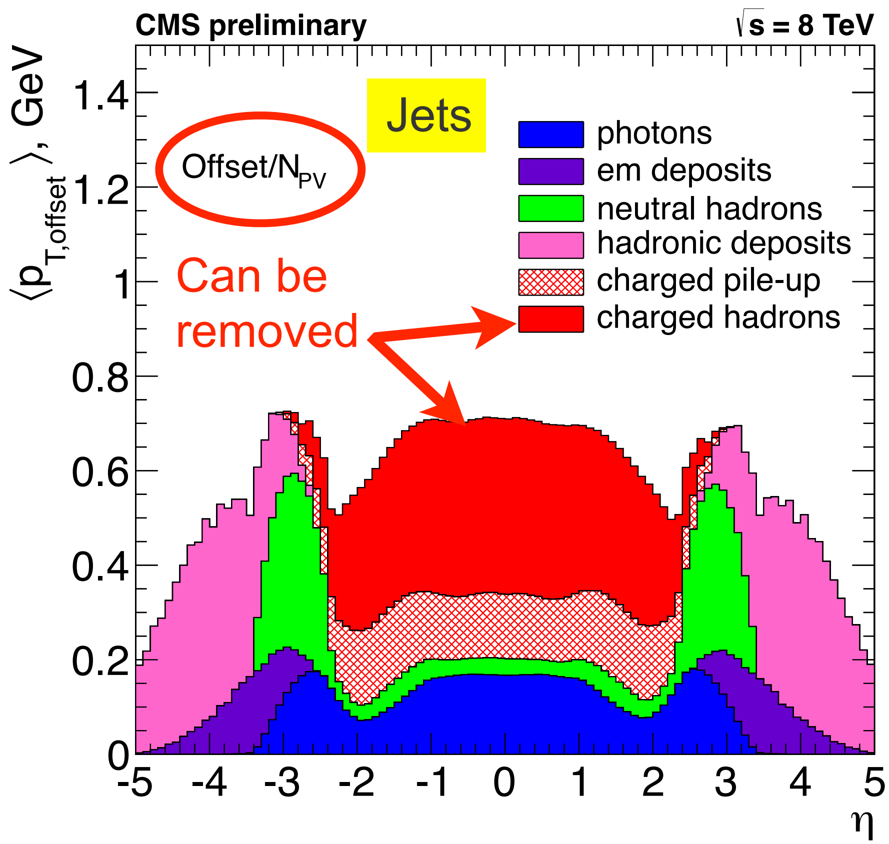


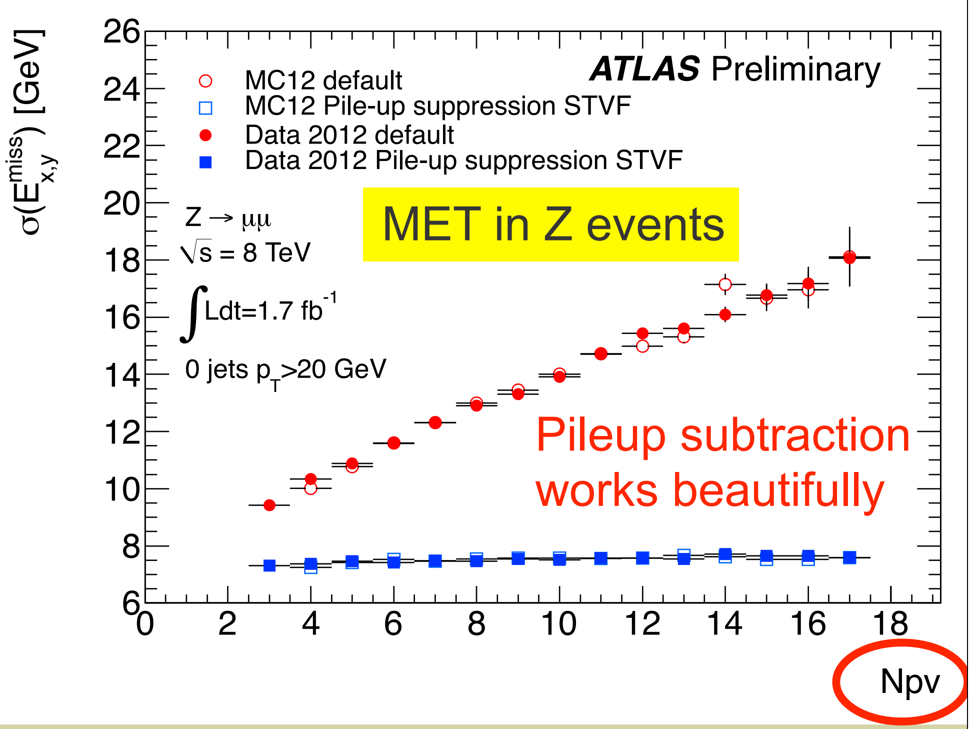
Dealing with pileup: subtract its cont^n to jet energy

✦Pileup measured with Zero Bias data and MC

- Most charged hadrons can be associated to pileup vertices & removed
- Residual contribution removed using FastJet area subtraction

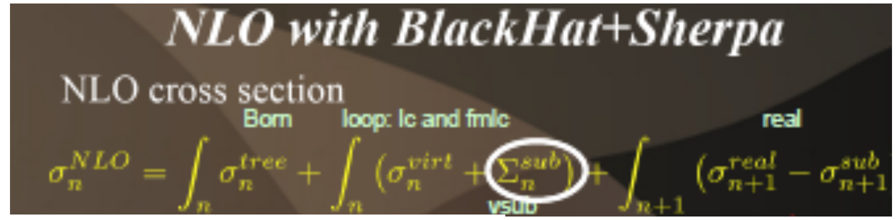
See talk by M. Voutilainen (Mon) for details on JES/pileup subtraction.

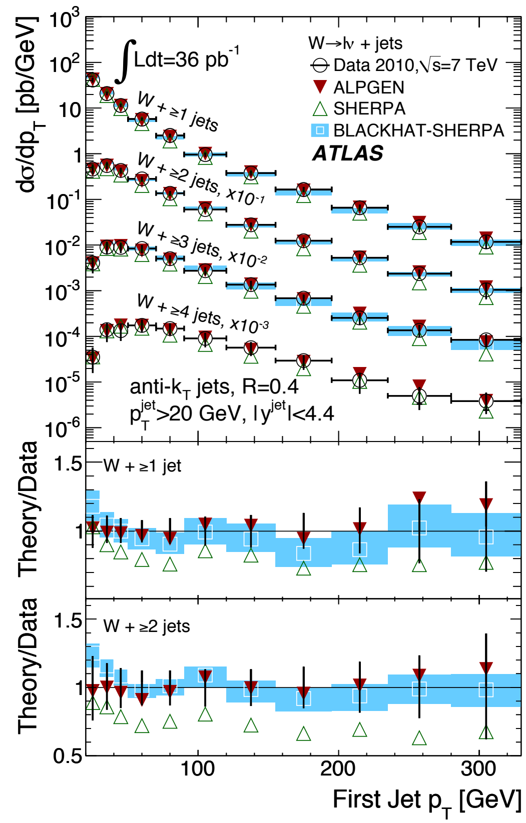




Available theoretical predictions

- Accurate predictions for W/Z+jets production at the LHC are available
  - Monte Carlo event generators
    - NLO + parton shower (MC@NLO, POWHEG...)
    - LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)
  - Parton level codes for distributions at NLO
    - BlackHat, Rocket...
- Modern parton distribution functions
  - LHC data start to contribute to PDF fits





A comprehensive summary in J. Huston's talk at Cambridge, March 6, 2012. www.talks.cam.ac.uk/talk/index/32618

Breaking news: W+5 jets at NLO

W/Z+jets measurements

Default MC versions used for W/Z+jets

	ATLAS	CMS
ME	ALPGEN 2.13	Madgraph-5 1.3.30
PS	Pythia 6.4.21	Pythia 6.4.22
Matching threshold	20 GeV (MLM)	20 GeV (MLM)
UE tune	AUET1/2	Z2
Default PDF	CTEQ6L1	CTEQ6L1
Fact./Renorm. scale	$m_V^2 + \sum_{\text{partons}} (p_T^2)$	$\sqrt{[m_V^2+p_{T,V}^2]}$ dynamic

Notes

1. Also use alternative choices for data/MC comparison; list them when relevant

2. Normalize to NLO cross section

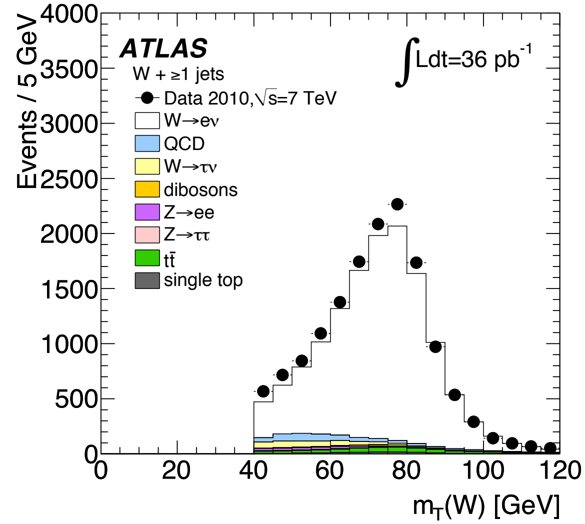
3. Data results at particle level

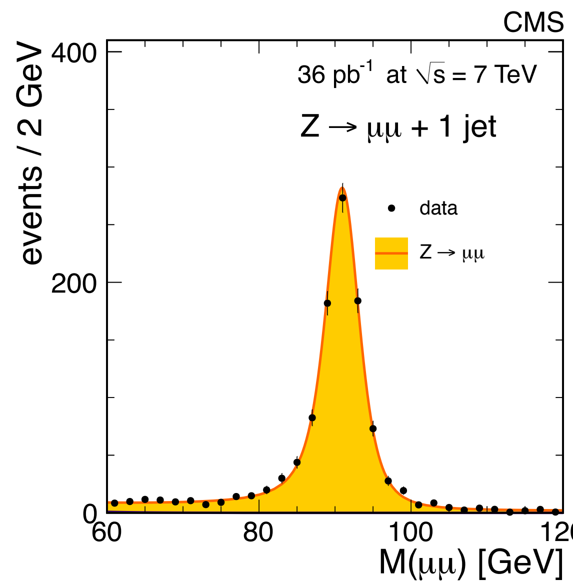
W/Z+jets production rate & observables vs N_{jets}

ATLAS arXiv:1108.4908, PLB 708 (2012), 221 (W/Z ratio)
arXiv:1201.1276, PRD 85 (2012), 092002 (W+jets)
arXiv:1111.2690, PRD 85 (2012), 032009 (Z+jets)
CMS arXiv:1110.3226, JHEP 01 (2012), 010

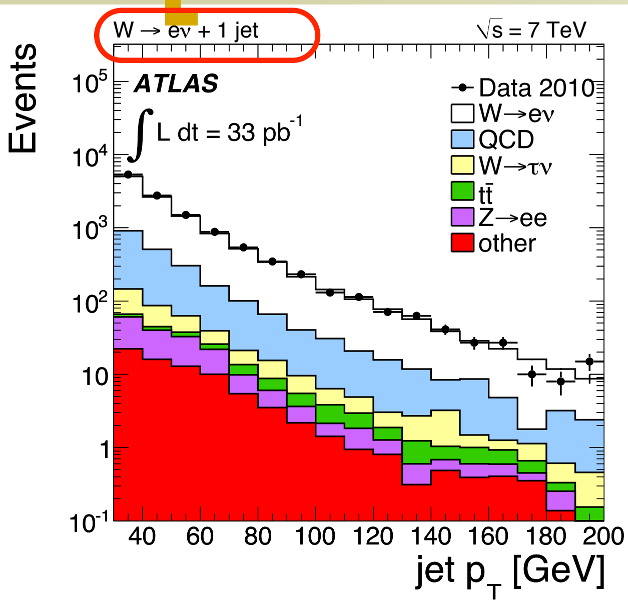
- Using 36 pb^{-1} data samples (2010)
  - -Normalized to inclusive cross section
  - -Ratios of events with n/n-1 jets
  - -Ratios of W/Z vs N_{jets}
  - -W charge asymmetry vs N_{jets}
- Ratios allow cancellation of systematics
  - -Luminosity, Jet energy scale, efficiency,...
- Results quoted in kinematic acceptance
  - -But detector effects have been unfolded

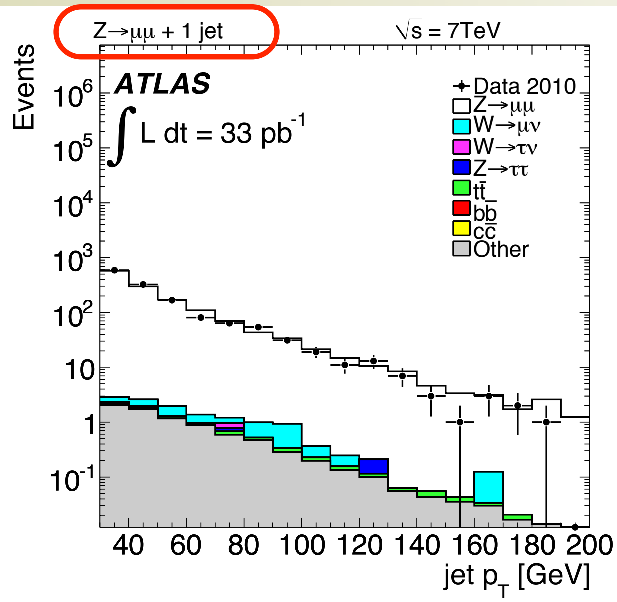
Lepton selection same as in the inclusive W/Z analysis.
See talks by J. Da Costa & J. Berryhill (Mon) for details.

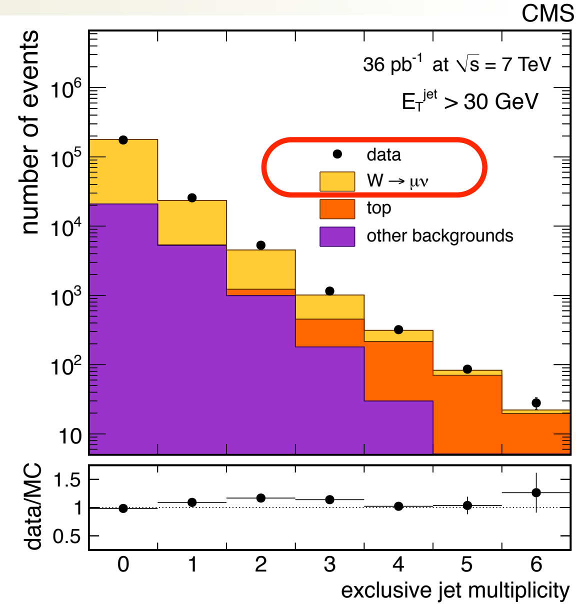


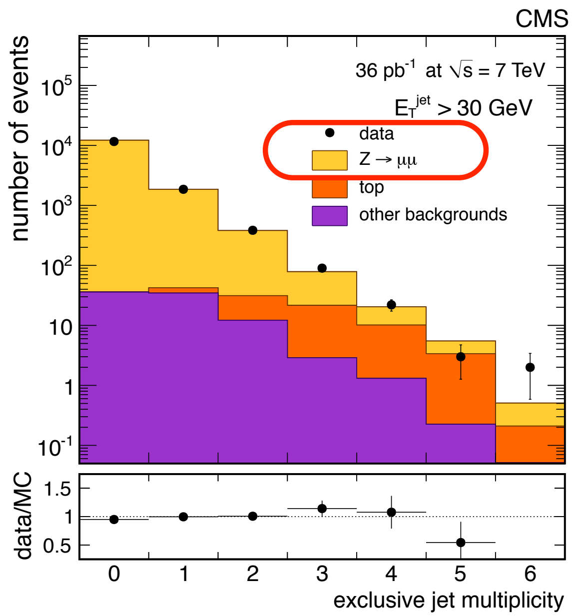


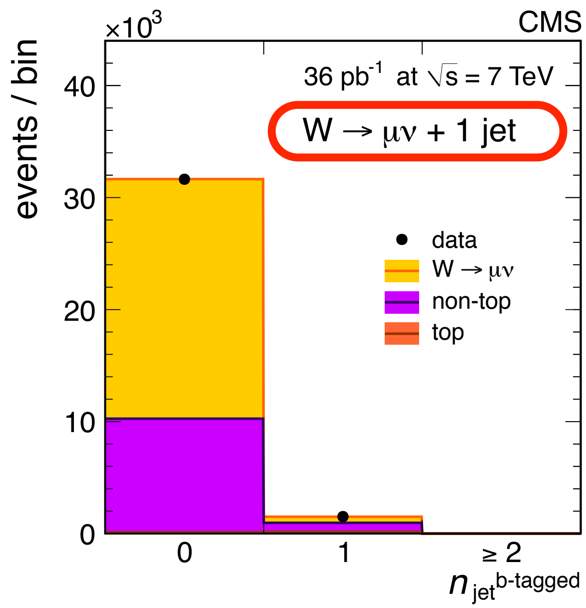
Some raw kinematic distributions (I)

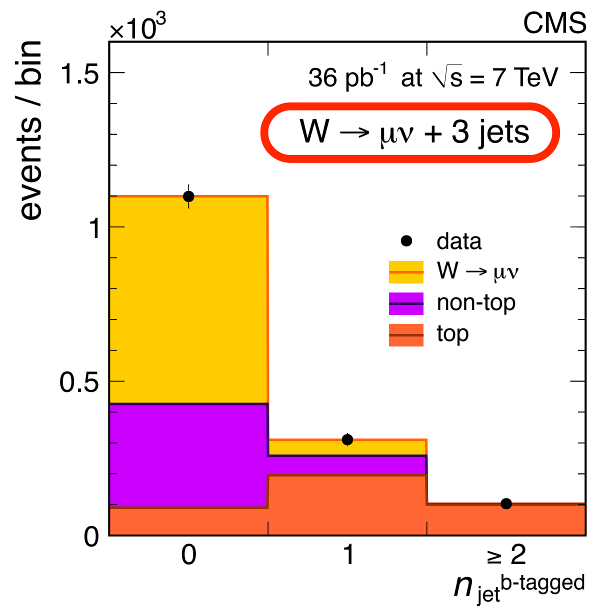






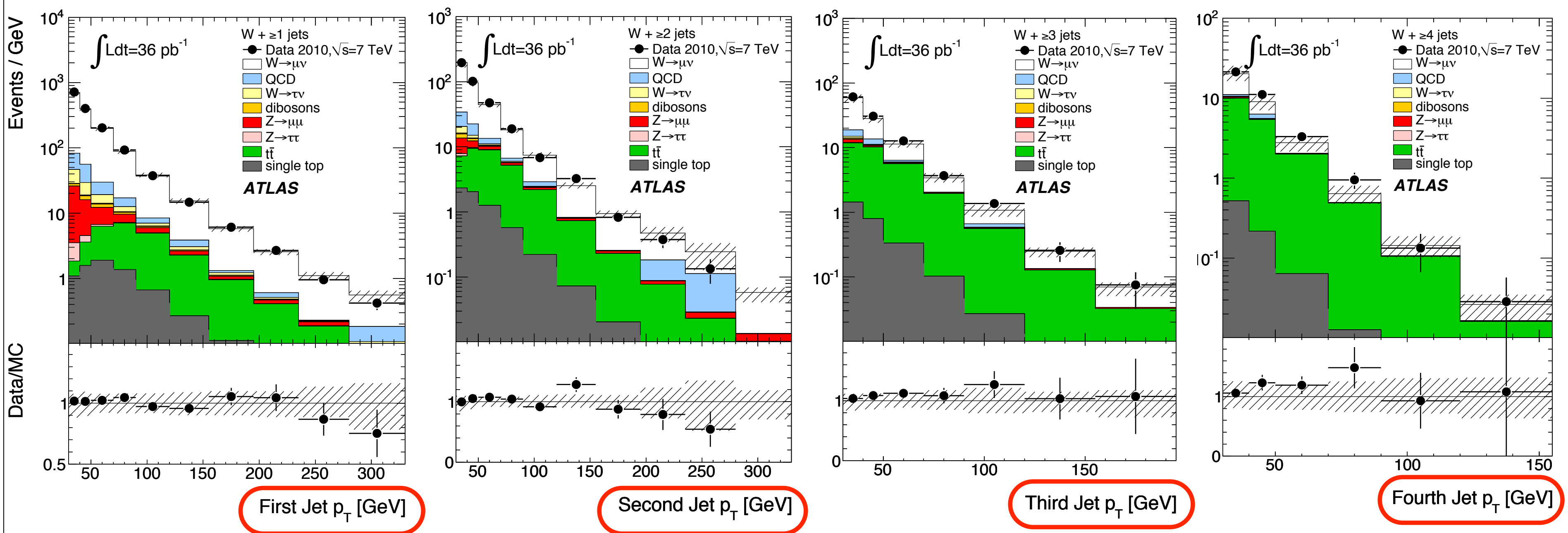






Some raw kinematic distributions (II)

Plot the p_T distributions of the first four leading jets in W+jets events

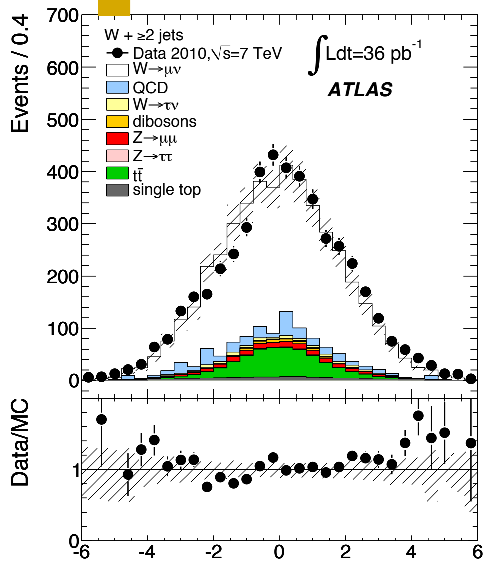


- $p_T^{\mathrm{lepton}} > 20$ GeV ,
- $|\eta^{\mathrm{lepton}}| < 2.4$,
- $E_T^{\mathrm{miss}} > 25$ GeV ,
- $m_{T,W} > 40$ GeV ,
- $p_T^{\mathrm{jet}} > 30$ GeV ,
- $|y^{\mathrm{jet}}| < 4.4$,
- $\Delta R^{\mathrm{lepton-jet}} > 0.5$.

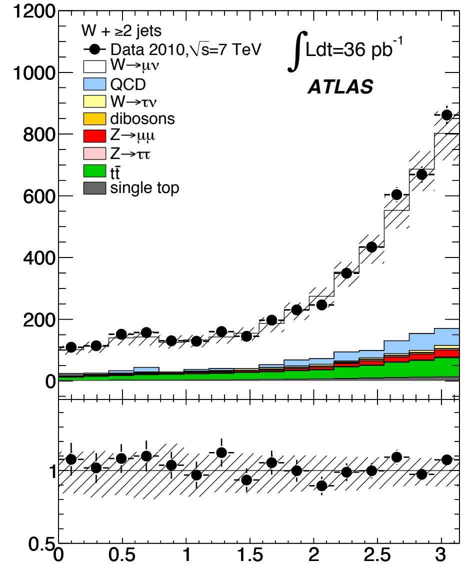
ATLAS event selection. CMS has similar selection and plots.

These distributions are very useful in comparing with the predictions of pQCD. E.g., We already see small discrepancies in the tails.

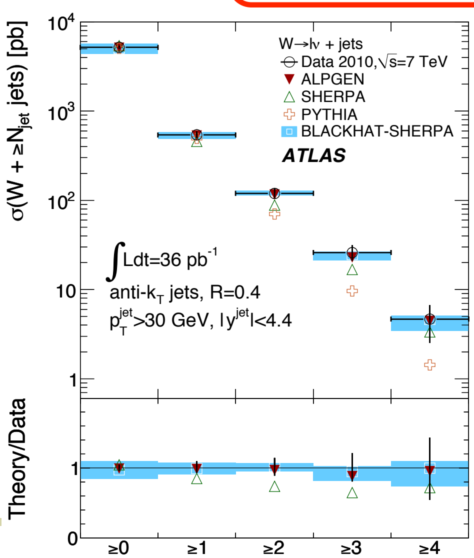
Differential distributions



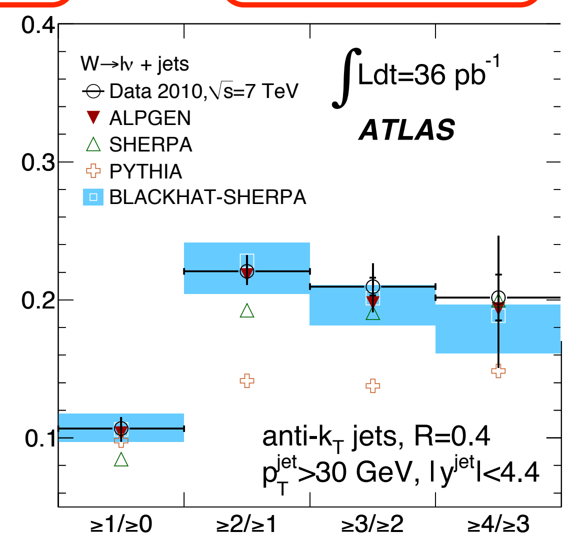
y(First Jet) - y(Second Jet)



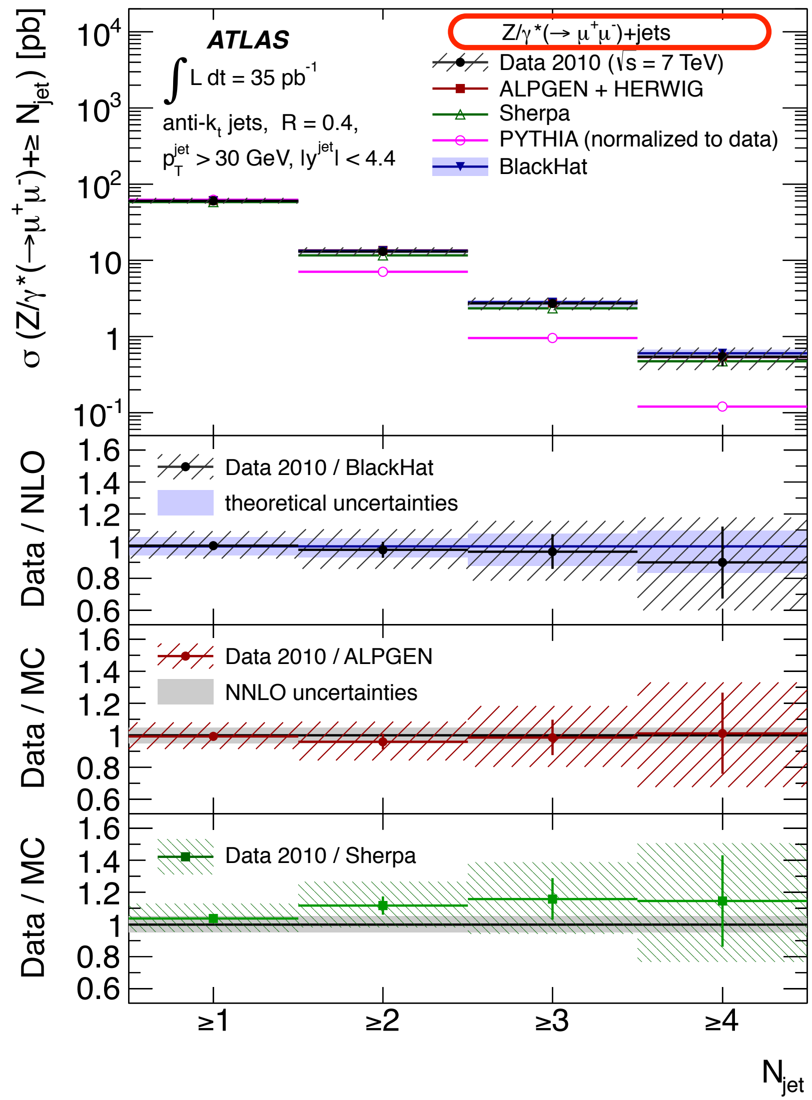
Δφ(First Jet, Second Jet)



Inclusive Jet Multiplicity, N_{jet}



Inclusive Jet Multiplicity Ratio

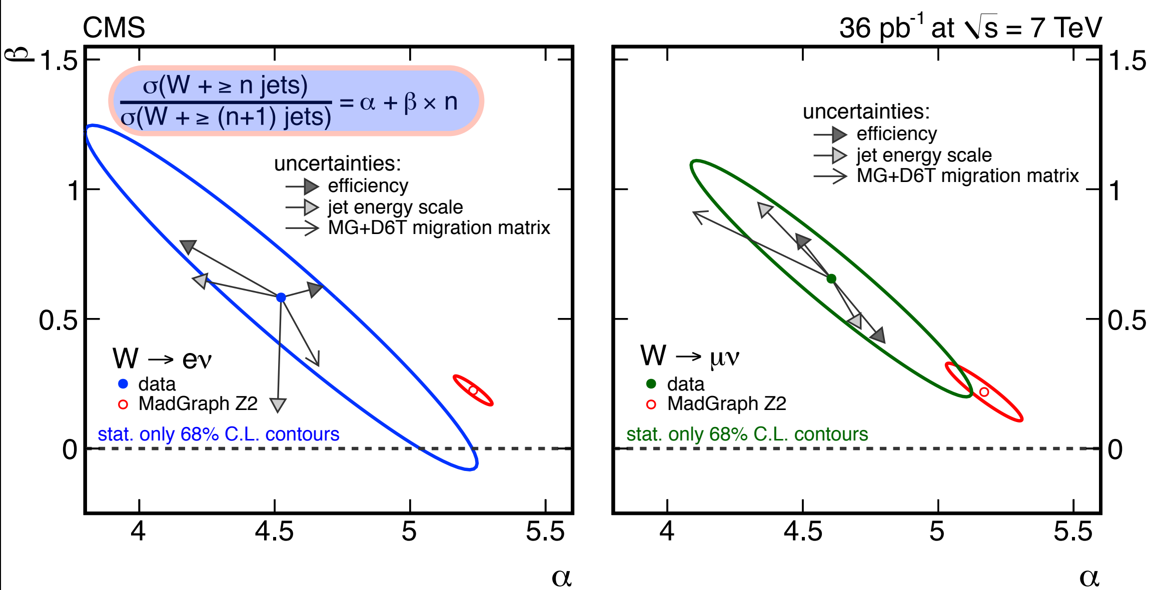


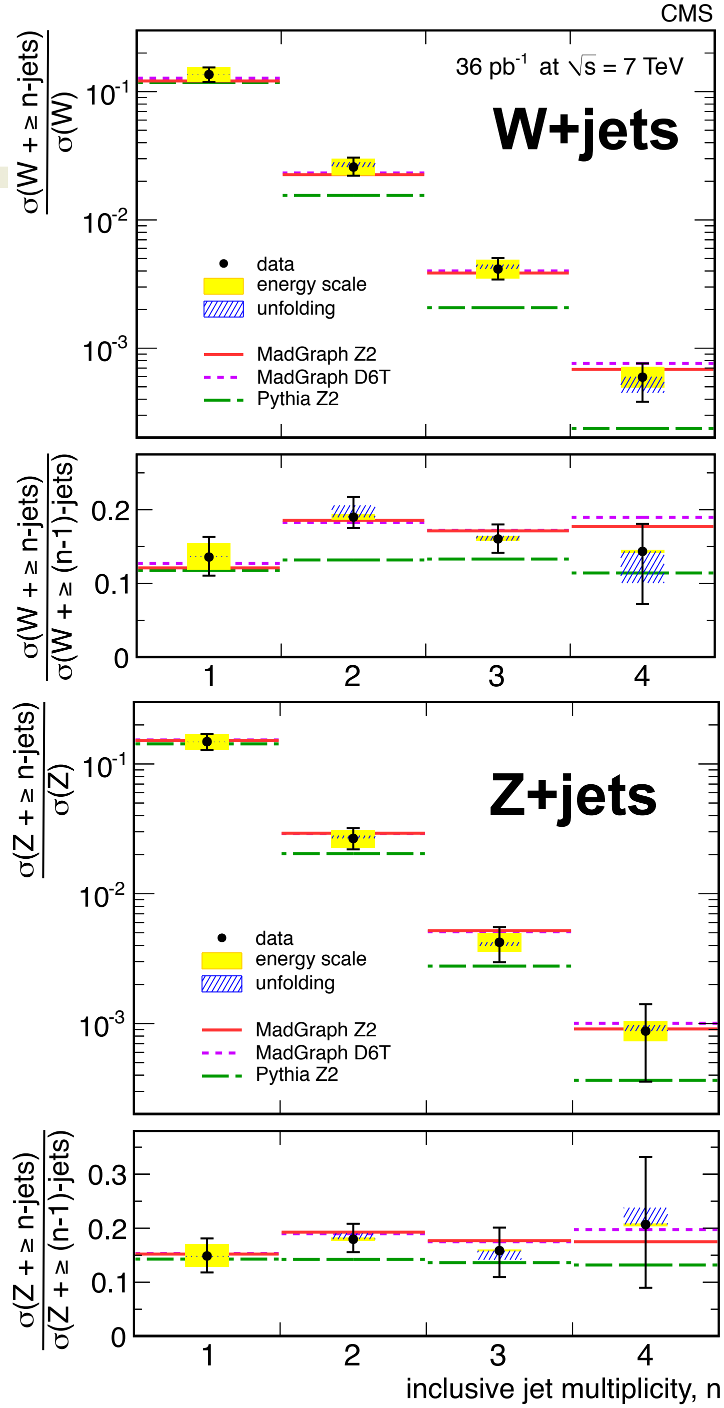
*ATLAS uses R=0.4 (topo-cluster), CMS R=0.5 (pFlow)

Cross section, N_{jets} scaling

- Normalize to inclusive W/Z cross section
  - -plot n/(n-1) jets
- Good agreement with predictions of matrix element+ parton shower (Madgraph)
  - -Pure parton shower (Pythia) fails

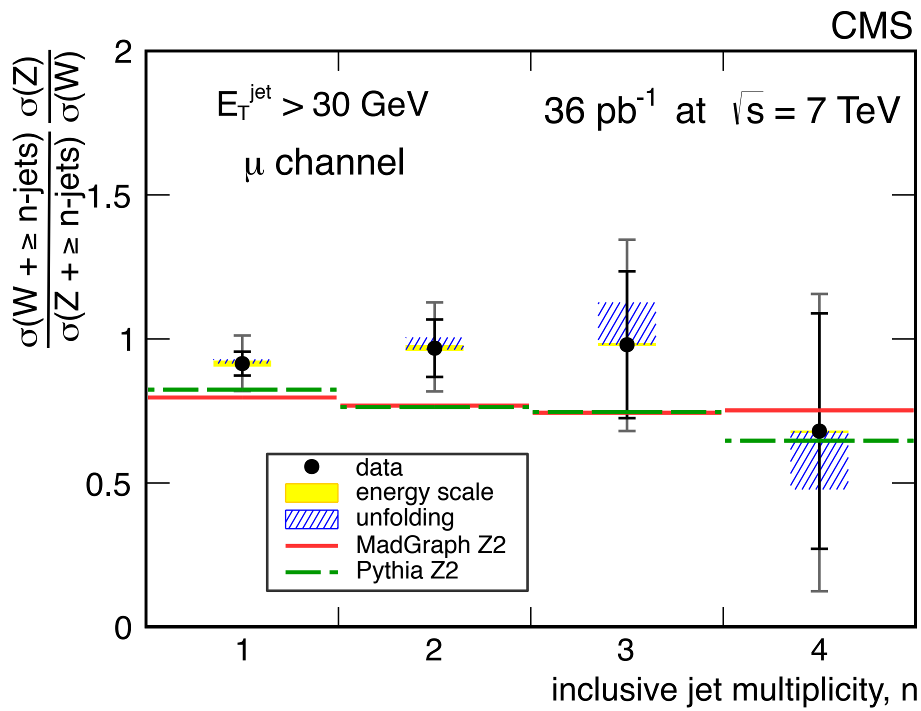
Berends-Giele scaling states that ratio of n jets to n+1 jets is approx constant for n≥1

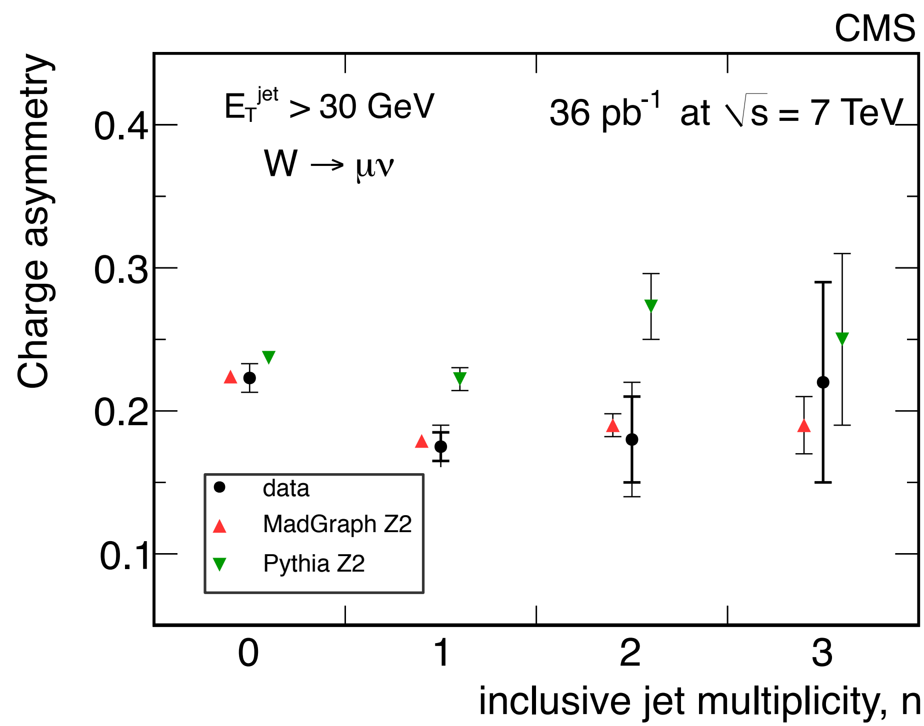




W/Z ratio and W charge asymmetry vs N_{jets}

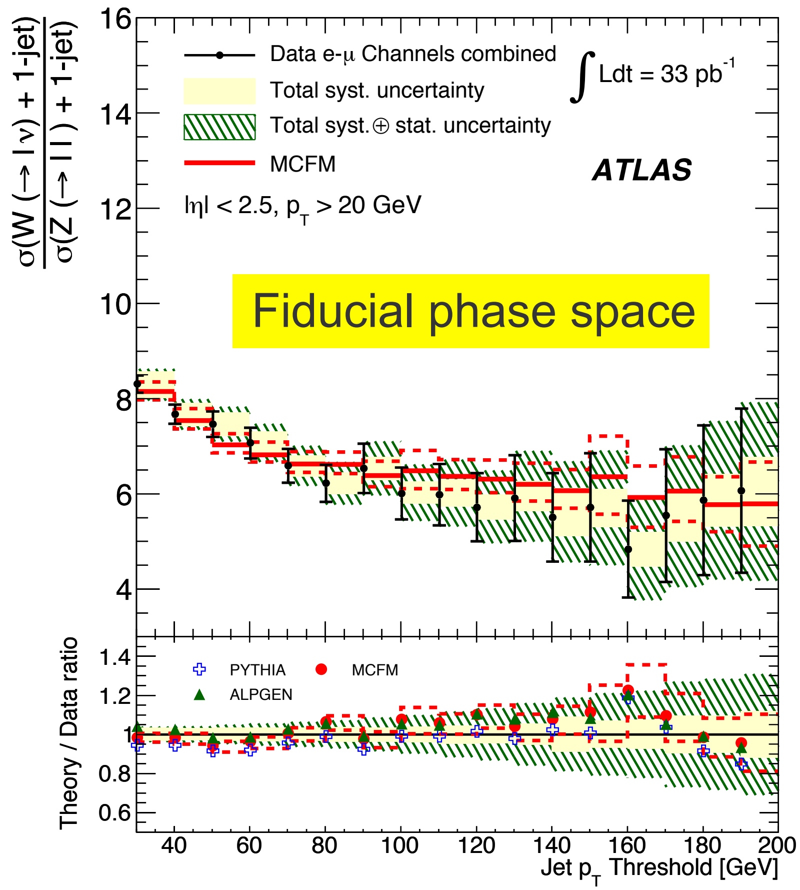
- W/Z Ratio: [σ(W+jet)/σ(W)] / [σ(Z+jet)/σ(Z)]
  - An observable with small systematic uncertainty
  - Jet energy scale systematic cancels almost completely
- Charge asymmetry: [$\sigma(W^+)-\sigma(W^-)$]/ [$\sigma(W^+)+\sigma(W^-)$]
  - Depends on the fraction of valence/sea quarks in qq→W

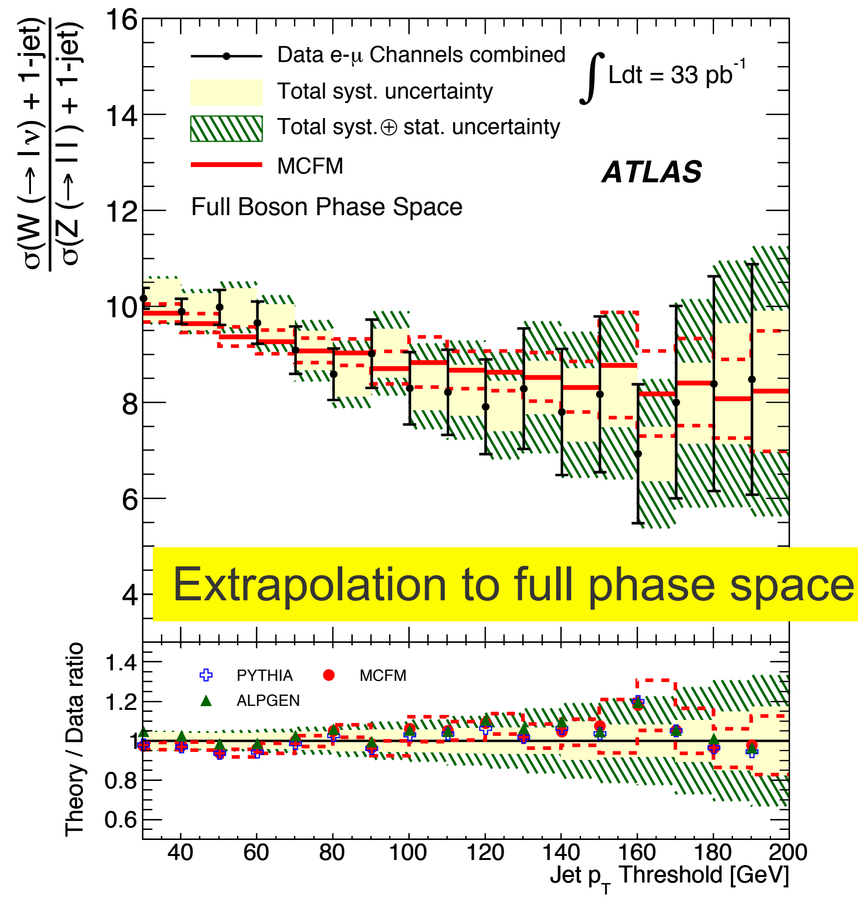




W/Z ratio vs p_T for N_{jets} = 1

- Similar performance of W+jets and Z+jets is confirmed by precise measurement of the W/Z ratio
  - -Differential measurement done in 1 exclusive jet bin

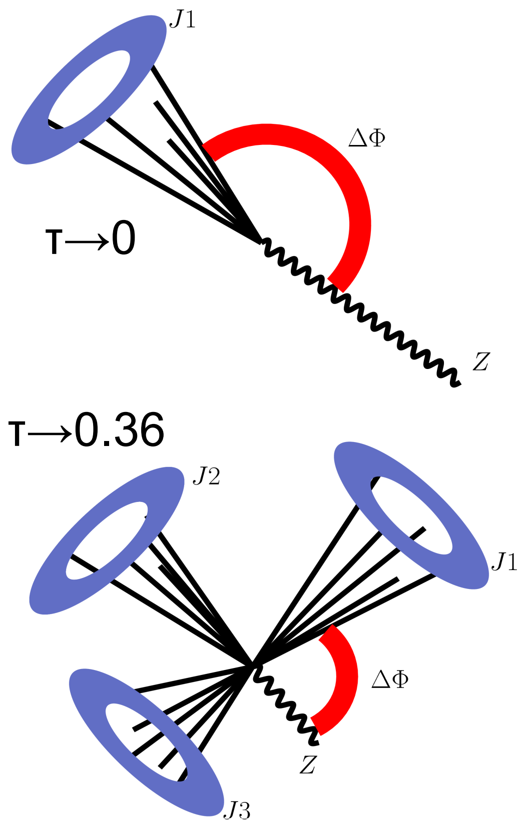




Azimuthal correlation & event shape in Z+jets

Transverse thrust:

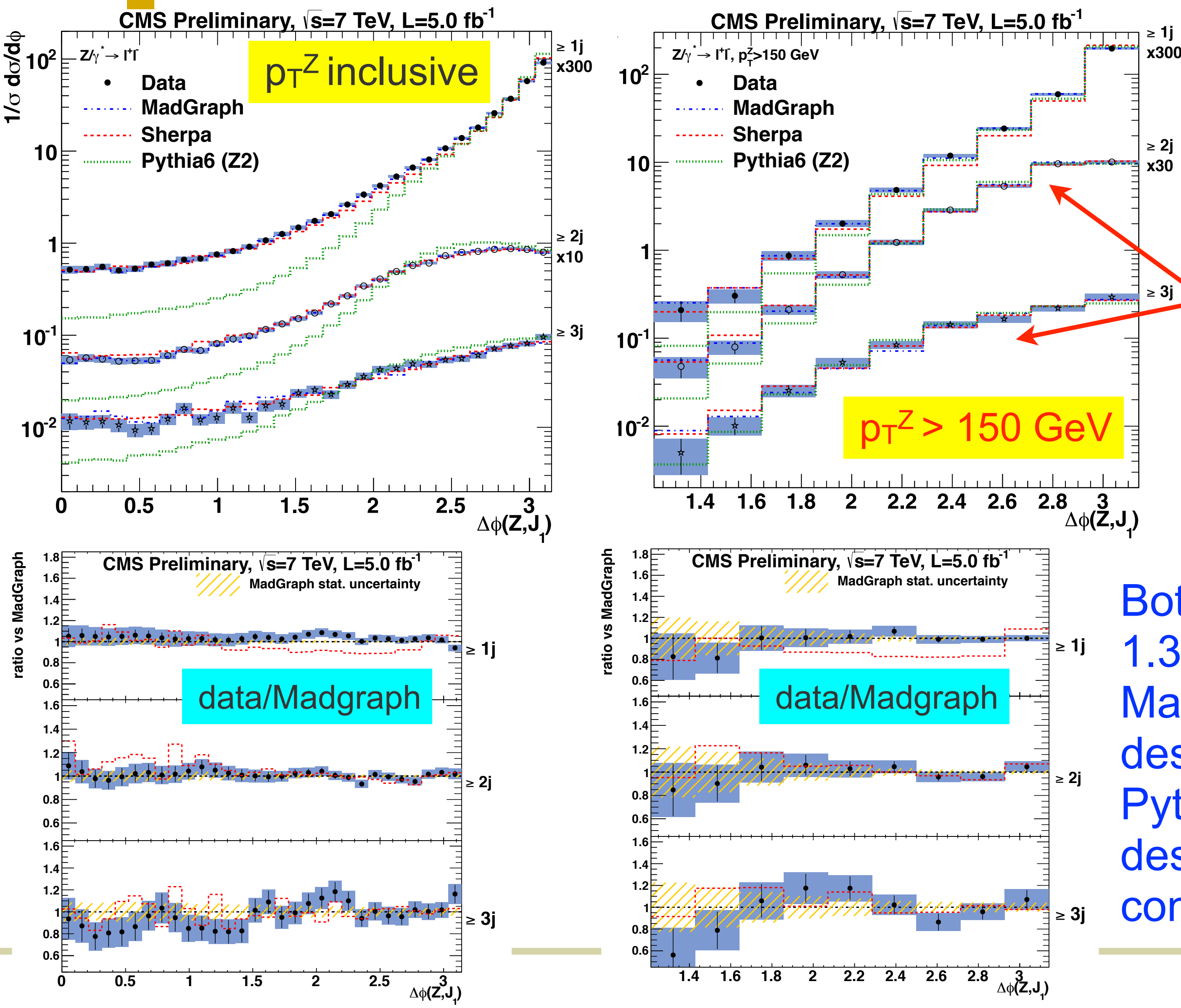
$$\tau_\perp \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11021

- In depth characterization of the topology of Z+jets (2011 data, 5 fb^{-1})
  - -ΔΦ(Z, lead jet), ΔΦ(j,j), and thrust
  - -inclusively and in boosted regime $p_T(Z)>150$ GeV
- Event selection:
  - ≥1 jet with $p_T>50$ GeV, $|\eta|<2.5$
  - 71 GeV < $m_{\ell\ell}$ < 111 GeV
- Results unfolded at particle level

Δϕ(Z, leading jet)

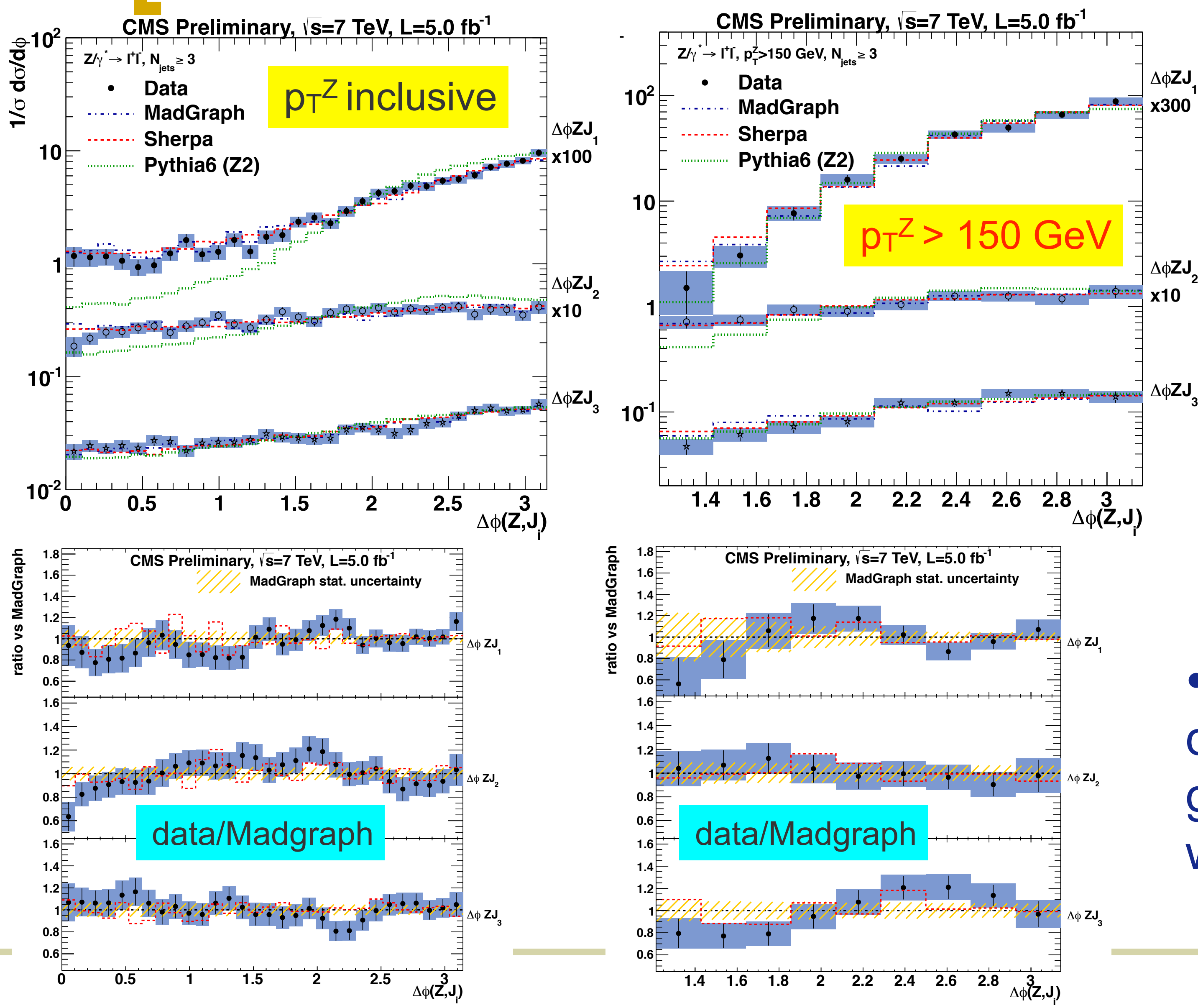


Error bars: data stat
Shaded: data syst
Hatched: MC stat

Distribution gets flatter with increase in N_{jets}, i.e., the correlation b/w Z & J1 gets weaker.

Both Sherpa (version 1.3.1, default tune) and Madgraph give a good description of data. Pythia is unable to describe multi-jet configurations.

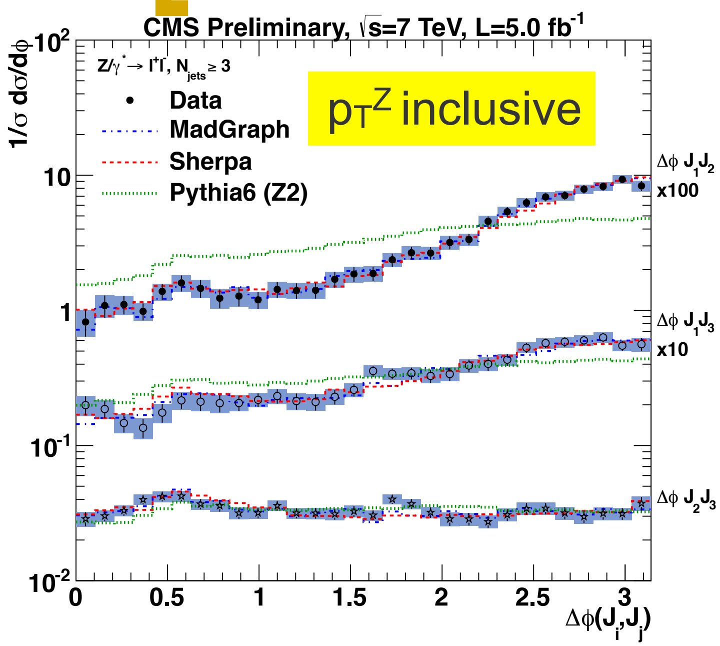
$\Delta\phi(Z, J_i)$ in events with high hadronic activity

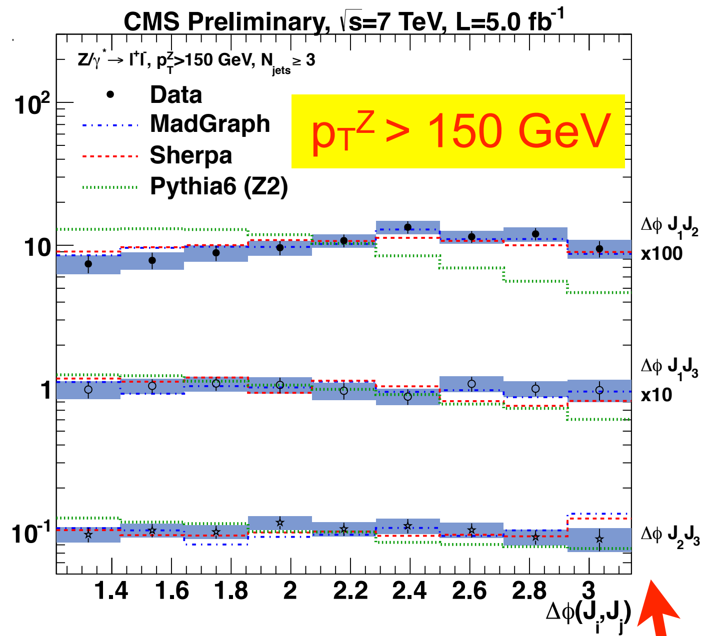


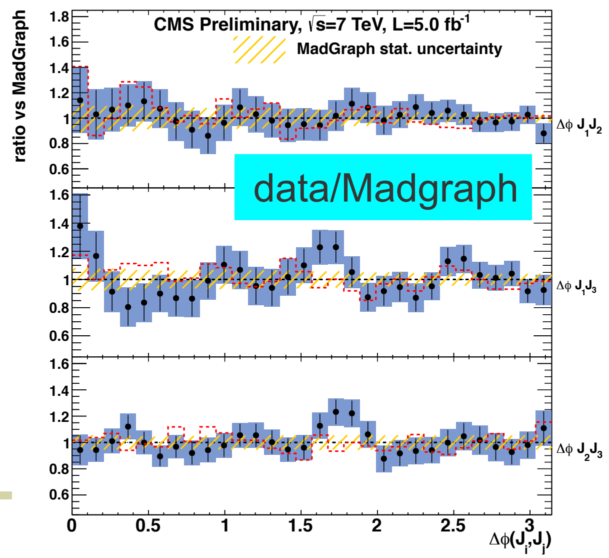
- ≥3 jets. Typically Z & a sub-leading jet balance the leading jet.

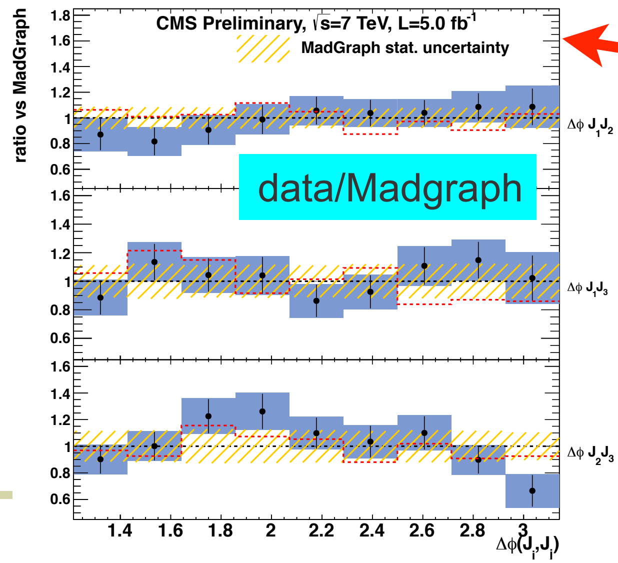
- The ME+PS descriptions in good agreement with data.

Δφ(Ji, Jj) in events with high hadronic activity



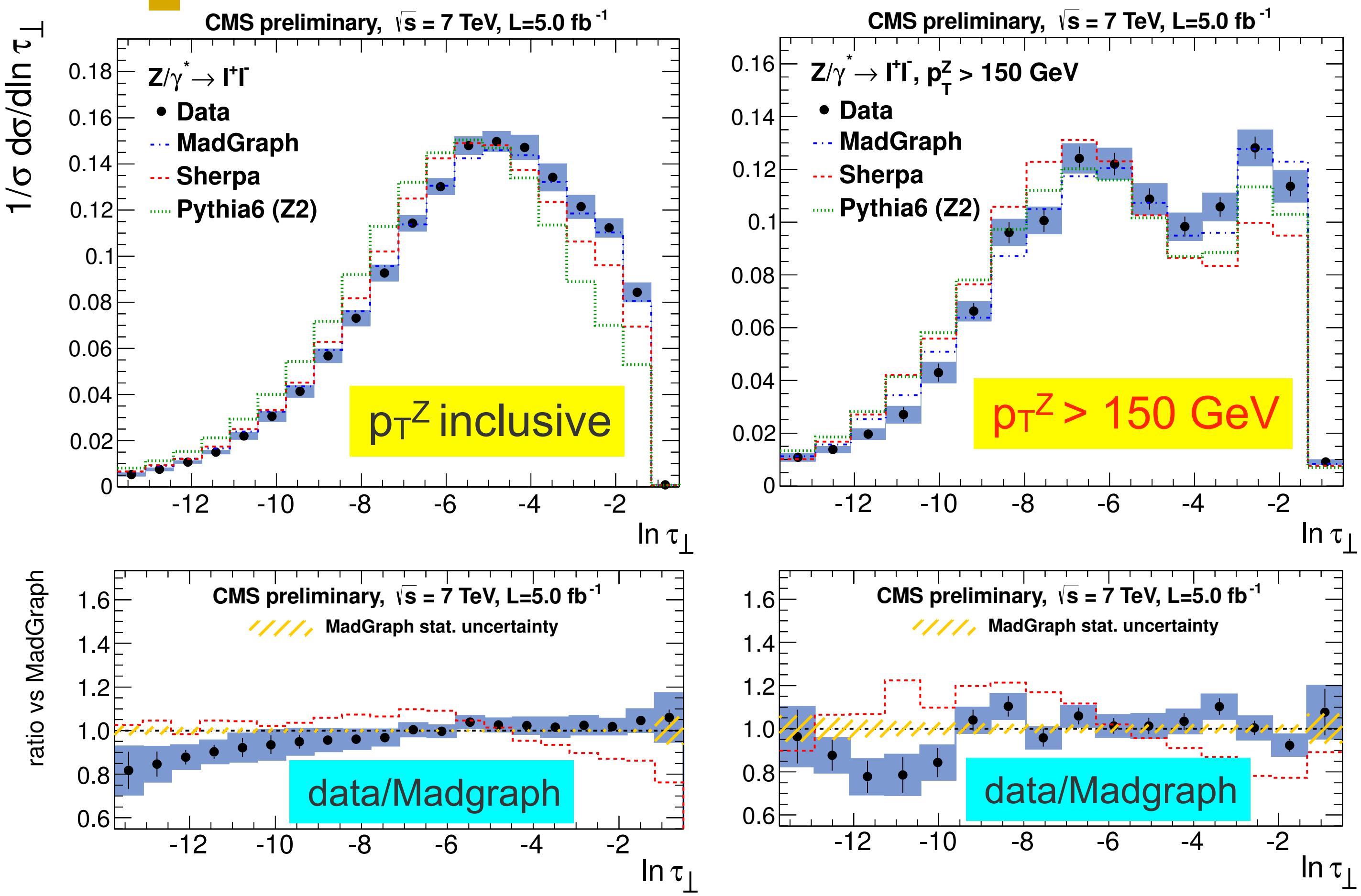






In this extreme kinematic regime (≥3 jets & a boosted Z), the correlation between the jets becomes flat.

Event shape



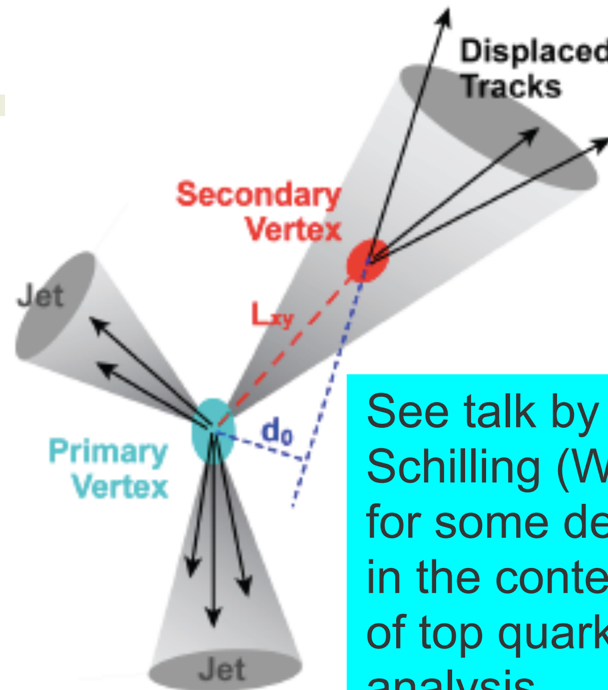
- Madgraph shows nice agreement with data
- Sherpa is shifted left
  - Consistent with the pattern observed in ΔΦ distributions
  - Fewer events with high N_{jets}

- The requirement on p_T^Z shifts the distribution towards lower values
- The selection enhances Z+1 jet topologies

W/Z production with heavy flavor jets

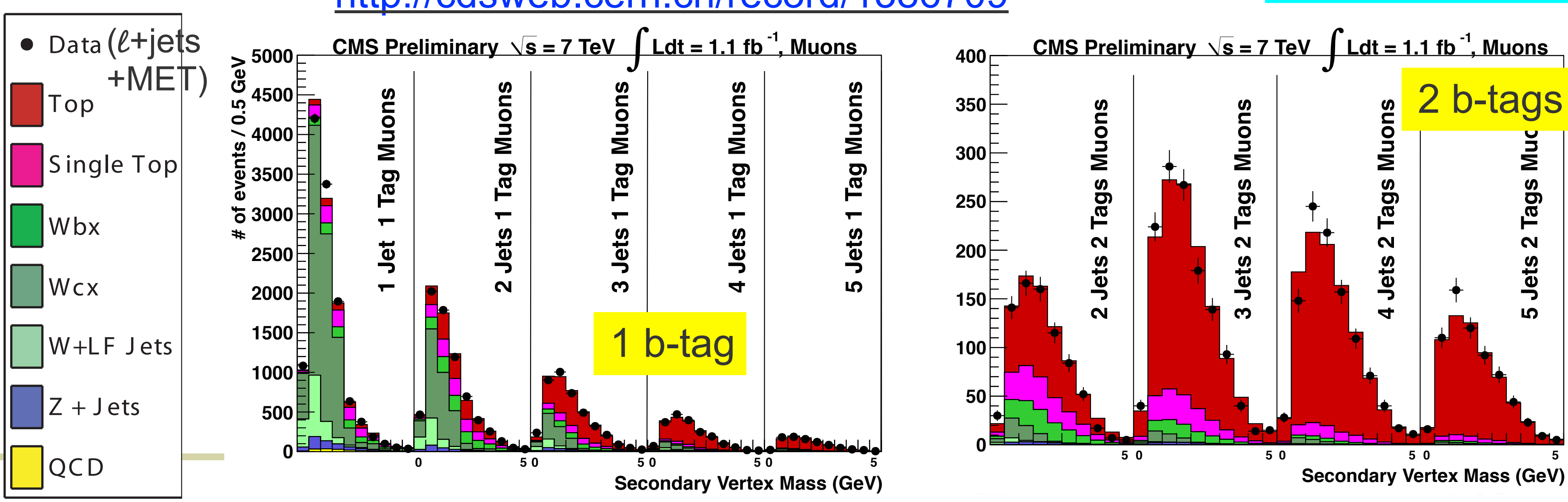
W/Z+ heavy flavor

- b-jets are identified by exploiting the long lifetime and large mass of B-hadrons
  - -b-tagging requires a displaced secondary vertex in a jet
  - -b-tagging affects sample composition
- Fraction of W/Z+b/c/l jets can be extracted from a fit to the secondary vertex mass or lifetime/decay-length distribution



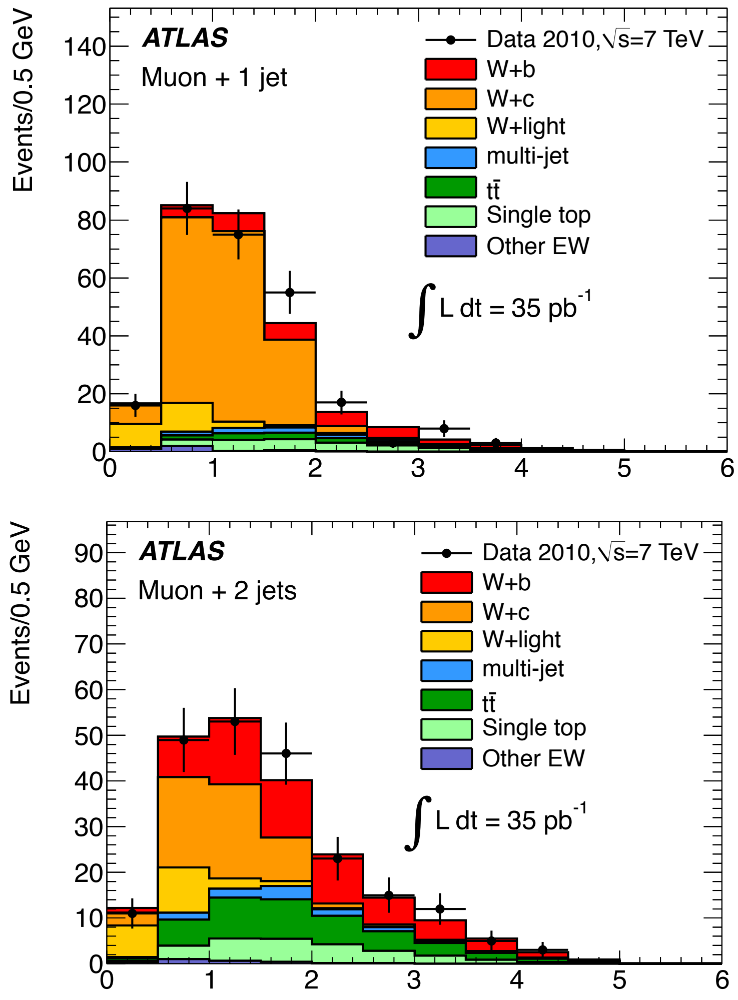
See talk by F. Schilling (Wed) for some detail in the context of top quark analysis.

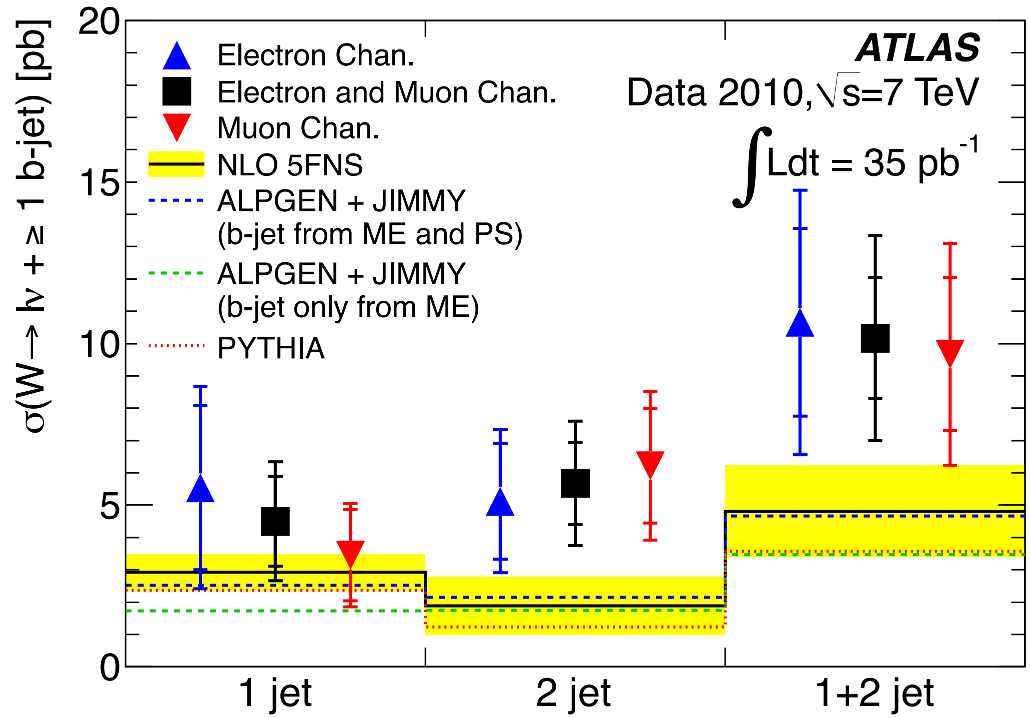
http://cdsweb.cern.ch/record/1386709



W+b-jets cross section (with jet p_T > 25 GeV, y<2.1)

arXiv:1109.1470, Phys. Lett. B707 (2012) 418



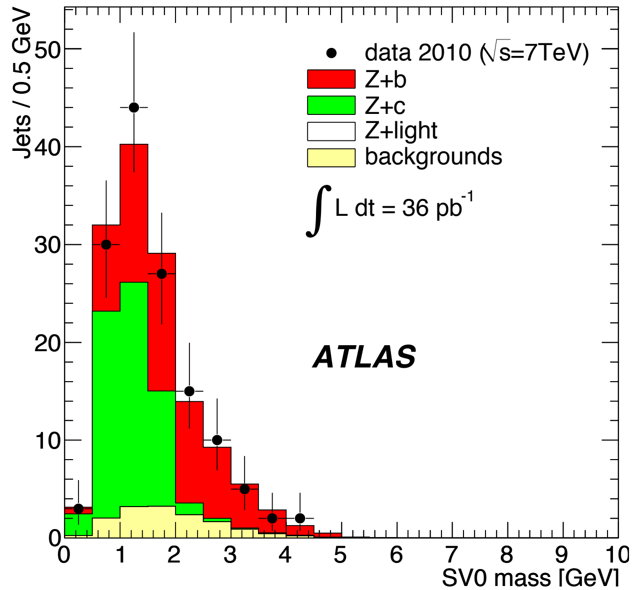


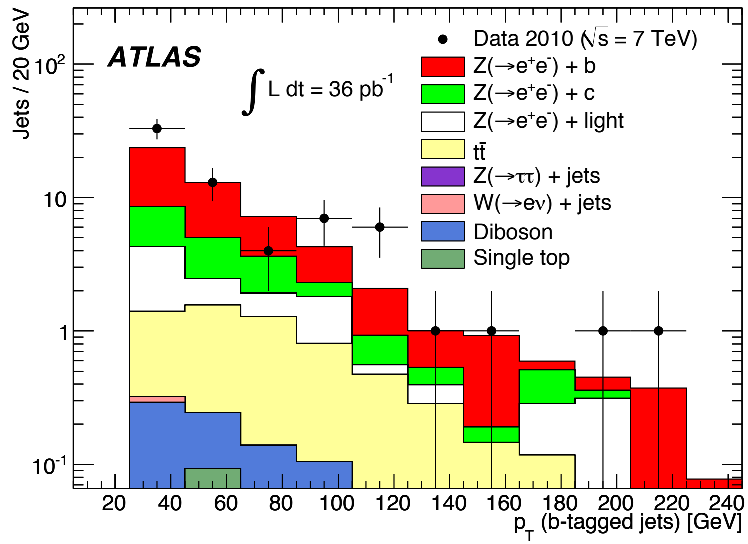
Some tension between theory & measurement, but need more data to conclude

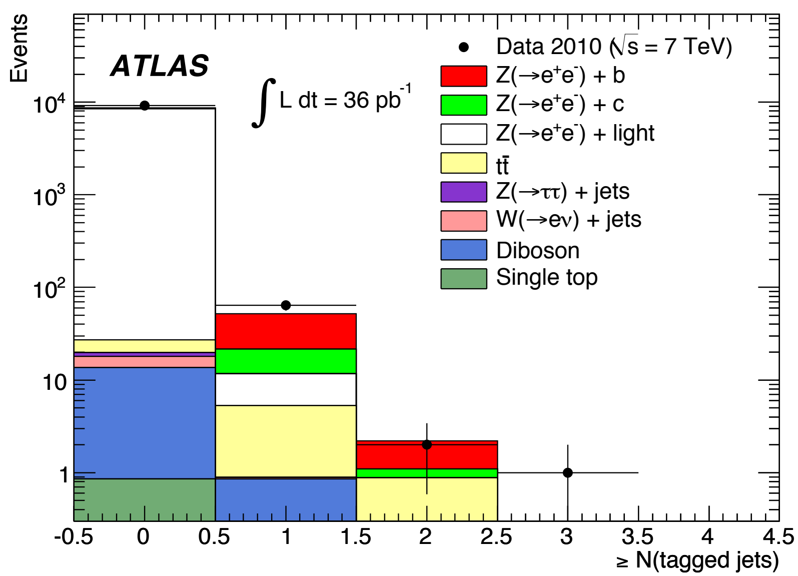
Main systematic uncertainties: b-tag efficiency & purity, theory uncertainty (via acceptance), ttbar contribution, JES.

Z+b-jets cross section: ATLAS (with jet p_T > 25 GeV, y<2.1)

arXiv:1109.1403, Phys. Lett. B706 (2012) 295





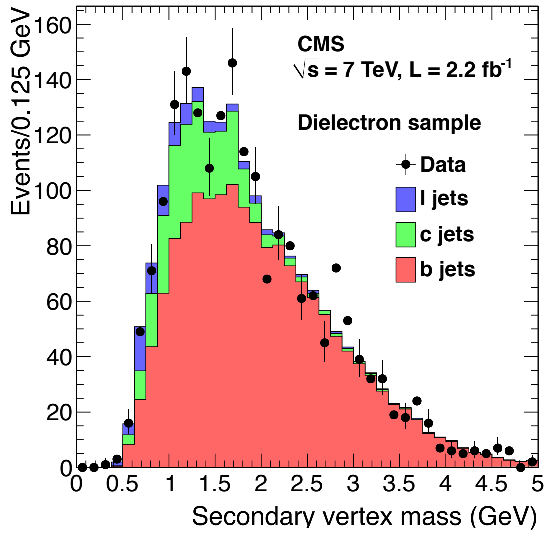


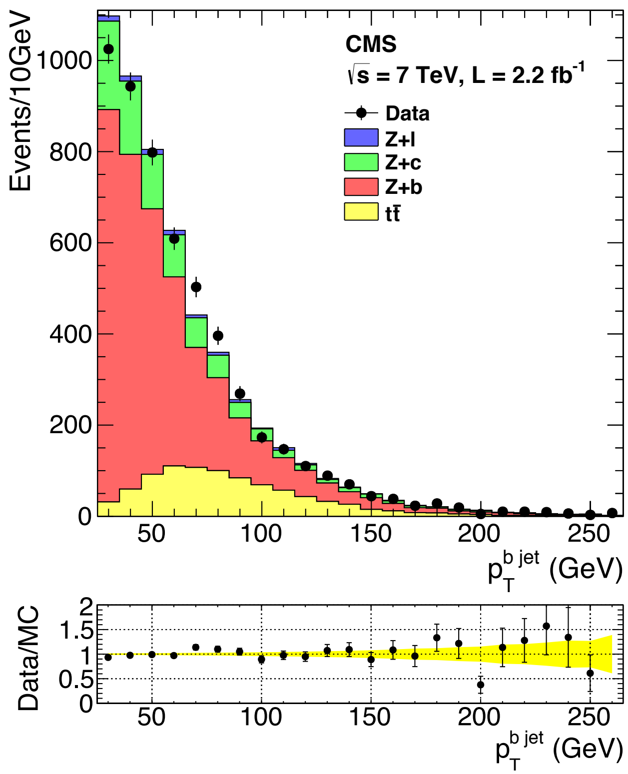
Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

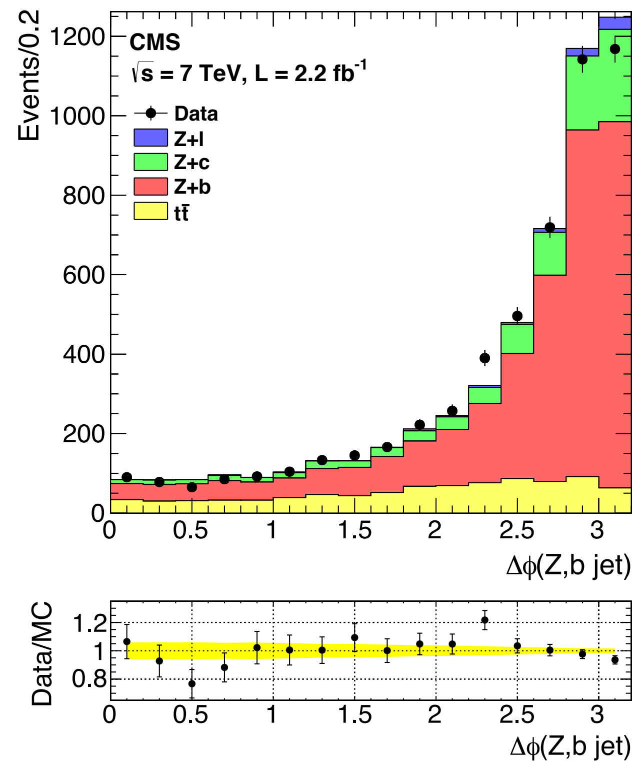
Good agreement with MCFM and Sherpa.

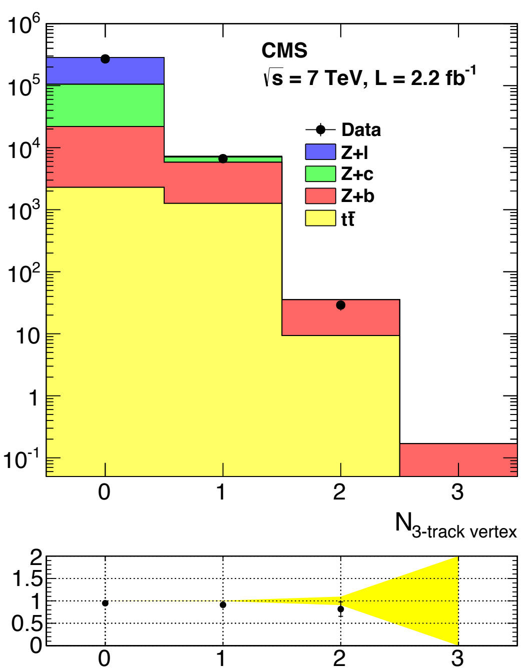
Z+b-jets cross section: CMS (with jet p_T > 25 GeV, y<2.1)

https://cdsweb.cern.ch/record/1428117, arXiv:1204.1643







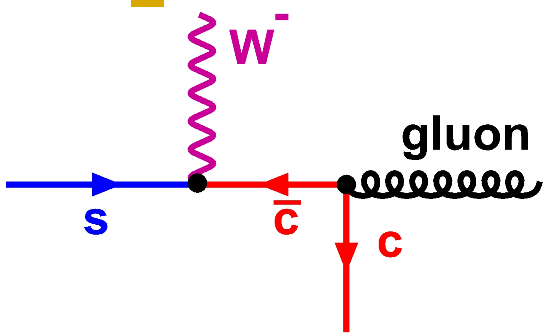


Multiplicity bin	electron + muon channel combined
σ_{hadron}(Z+1b,Z$\rightarrow \ell\ell$)(pb)	$3.41 \pm 0.05(stat.) \pm 0.27(syst.) \pm 0.09(theory)$
σ_{hadron}(Z+2b,Z$\rightarrow \ell\ell$)(pb)	$0.37 \pm 0.02(stat.) \pm 0.07(syst.) \pm 0.02(theory)$

Theory: Z+1b+X (MCFM) = 3.97 ± 0.47 pb Good agreement

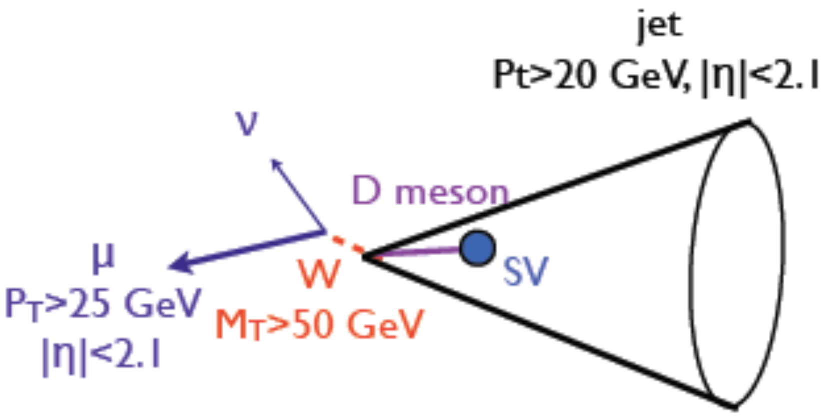
W+c cross section: probe the s-quark pdf

https://cdsweb.cern.ch/record/1369558

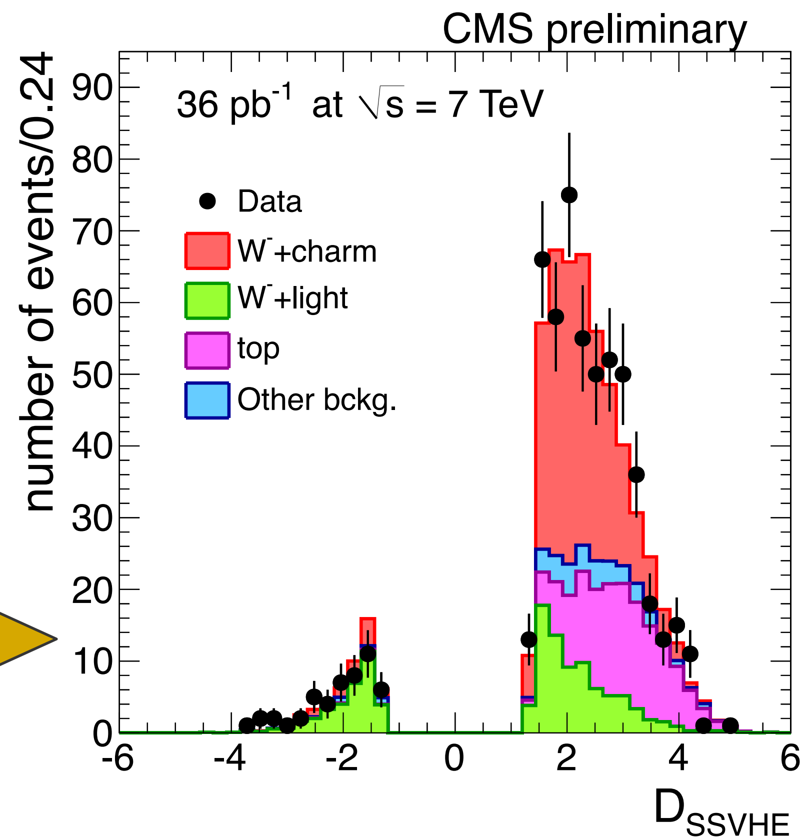


Aim: to check theory prediction regarding

- Is the s-quark PDF antisymmetric under charge conjugaison
- Proportion of Wc into W+jets? $R_c \sim \frac{s+\bar{s}}{\Sigma(q+\bar{q})}$



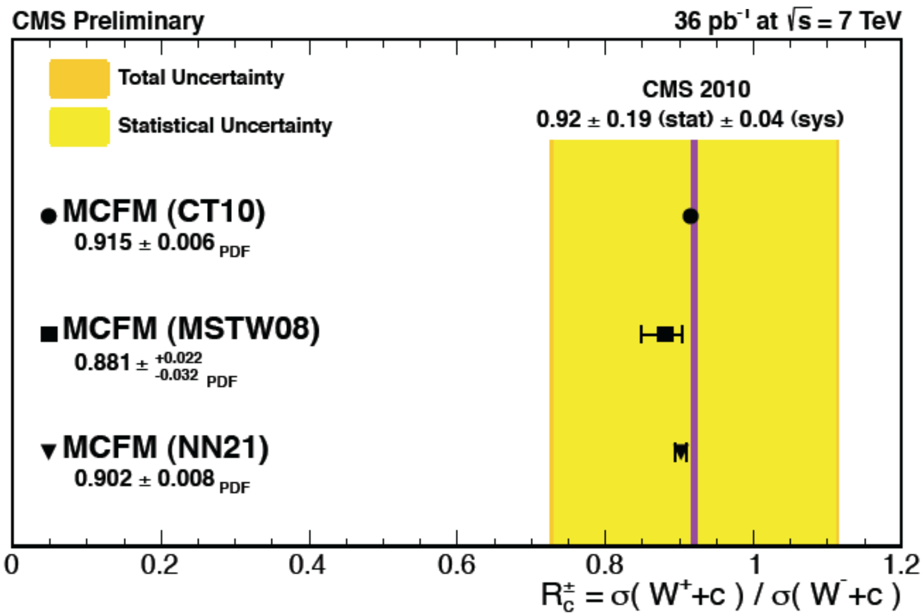
Fit the secondary vertex discriminator to extract W+c content. Only events with flight distance < 0.15 cm are kept.

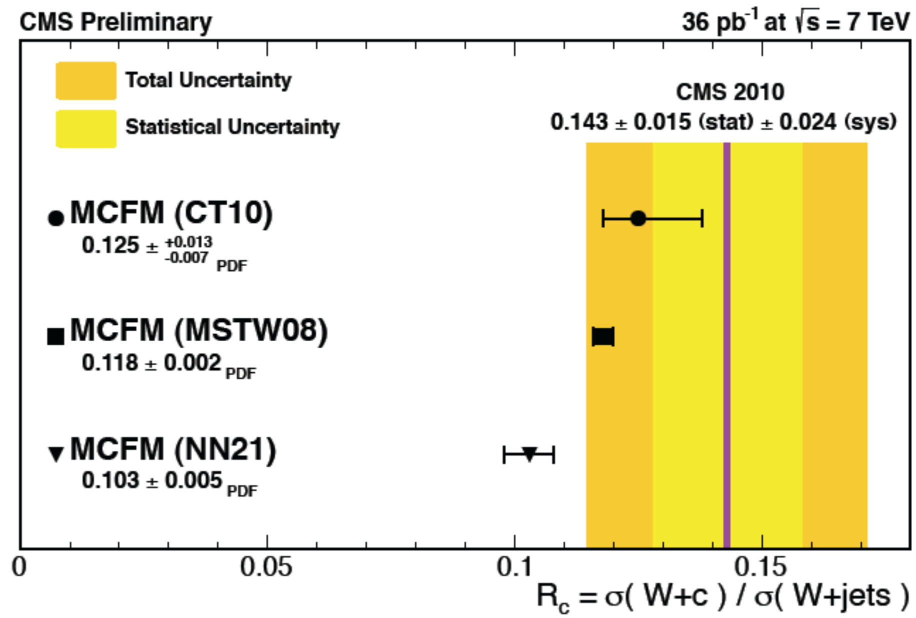


W+c results

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

$$\sigma(W+c)/\sigma(W+jets)$$





$R^{\pm}_c \neq 1$ because of d/dbar PDF difference,
result compatible with s=sbar PDF
see hep-ph/1203.6781

Overall good agreement b/w data & MC. PDF dependence is visible.

Summary

- Probe pQCD in W/Z+jets events in an unprecedented energy regime
  - Jet rates, azimuthal correlations, event shapes, and related observables
  - Good agreement with predictions from matched Matrix Element + Parton Shower

- Have made significant headway on W/Z+HF
  - W/Z+b-jets in bins of N_{tag} and differentially in p_T, η
  - W+charm can significantly constrain s-quark pdf

- Understanding W/Z+jets (including HF) in various corners of kinematic phase space is an important benchmark for searches for new physics

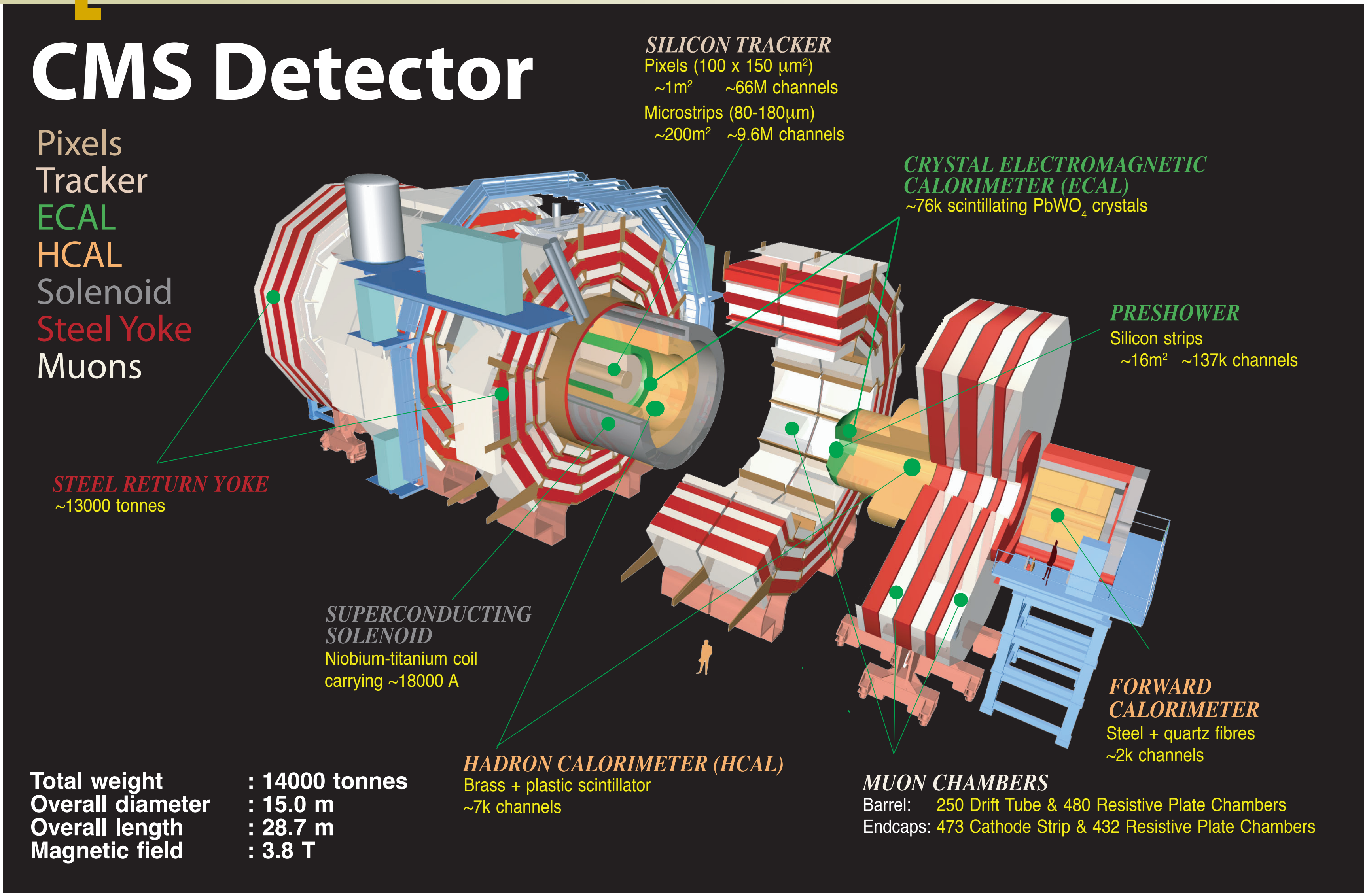
BACKUP SLIDES

Other measurements I didn't have time to cover

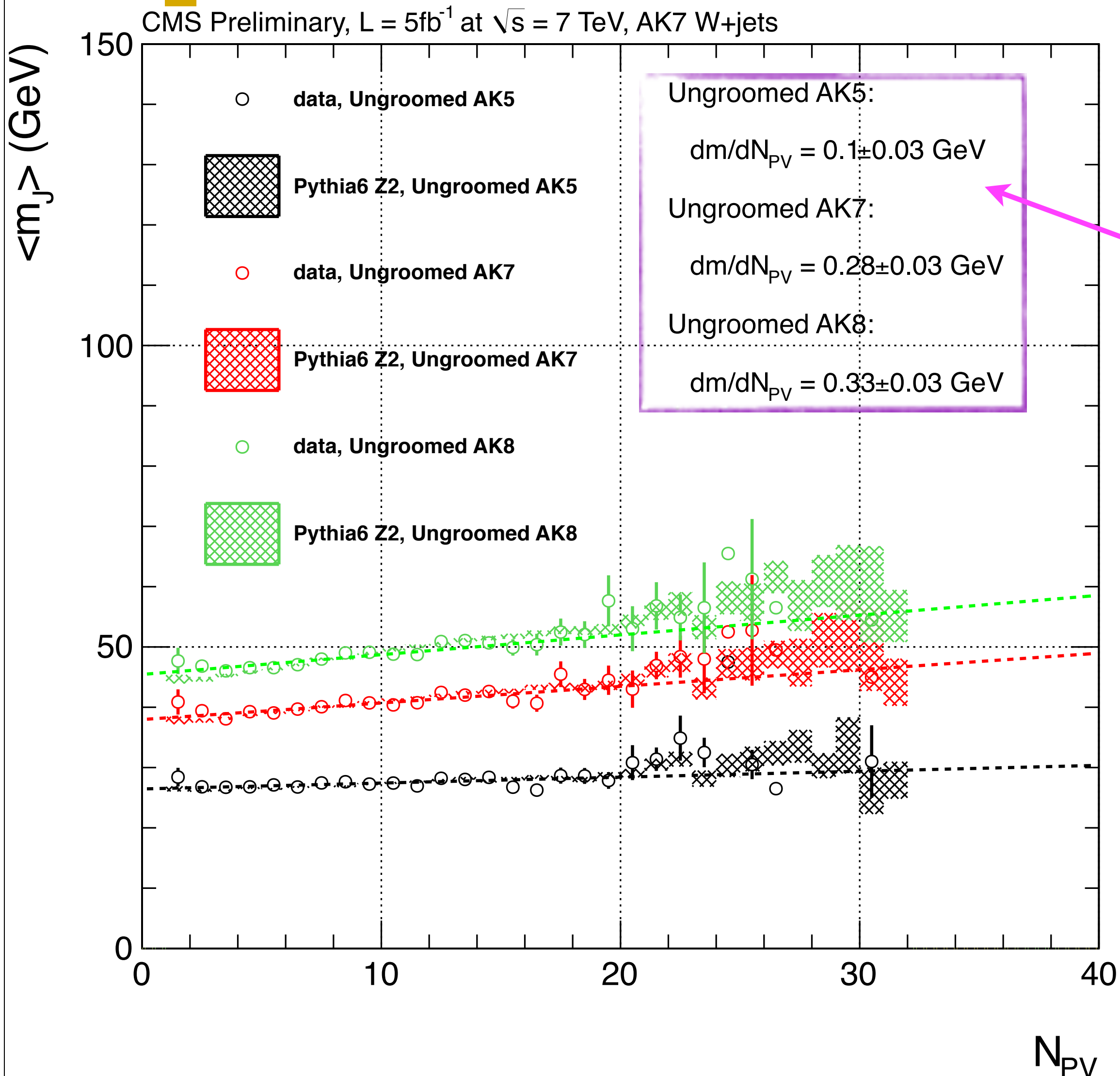
•Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC (CMS, 36/pb)
http://cdsweb.cern.ch/record/1345777 Phys. Rev. Lett. 107 (2011) 021802

•Angular correlation between B hadrons produced in association with a Z boson in pp collisions at $\sqrt{s}$ = 7 TeV (CMS, 5/fb)
https://cdsweb.cern.ch/record/1430694

Understanding CMS detector

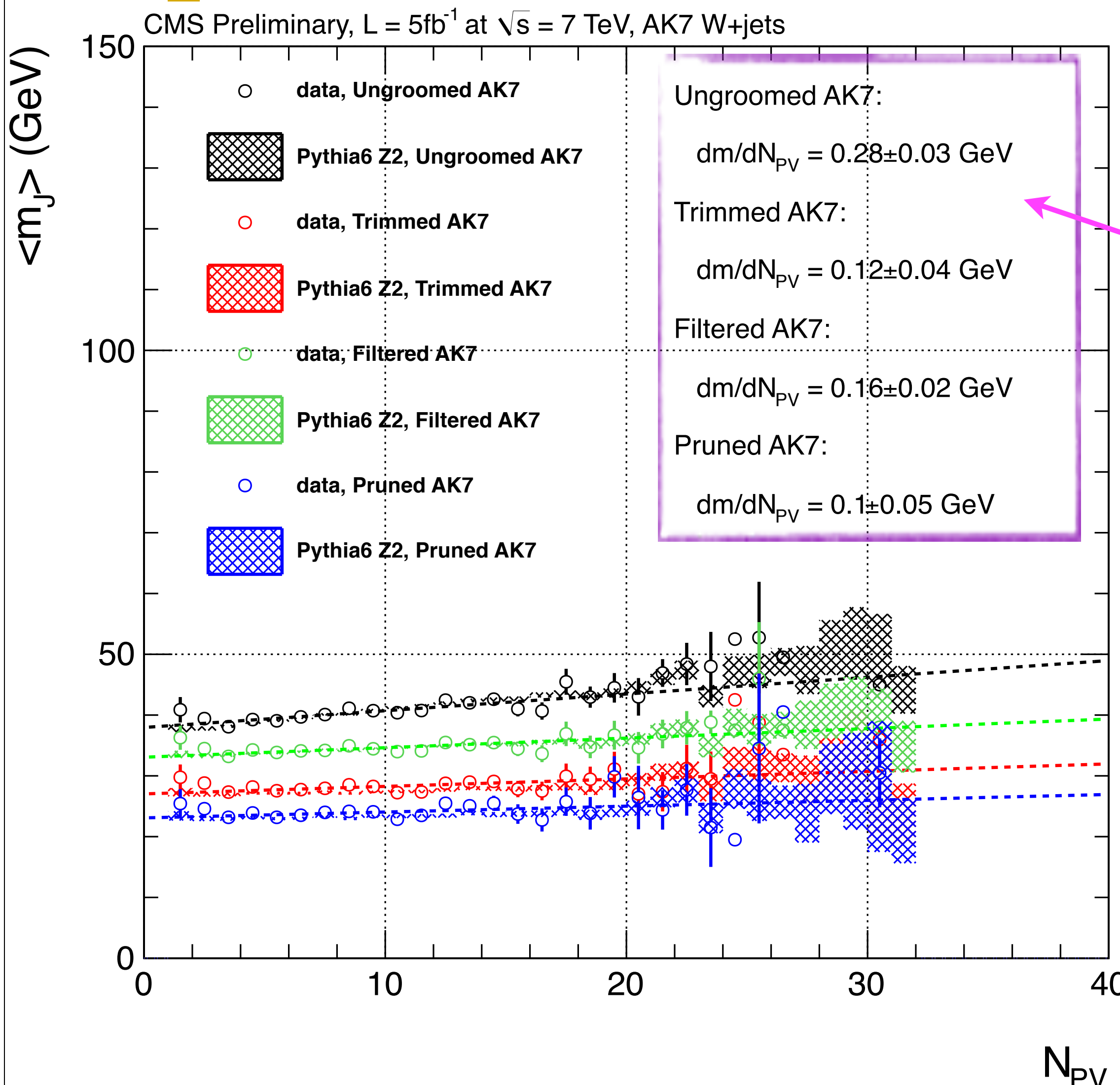


Performance versus pileup by jet size



- ✦Ungroomed jet mass is very sensitive to PU
  - •<mJ> increases linearly as a function of the number of primary vertices
- ✦Effect becomes more pronounced as the jet size increases
  - •AK8 shows much worse effect than AK5

Performance versus pileup for groomed jets



- ✦Grooming techniques are less sensitive to PU
  - •$\langle m_J \rangle$ vs NPV slope becomes flatter
  - •~ perfectly flat for pruned jets

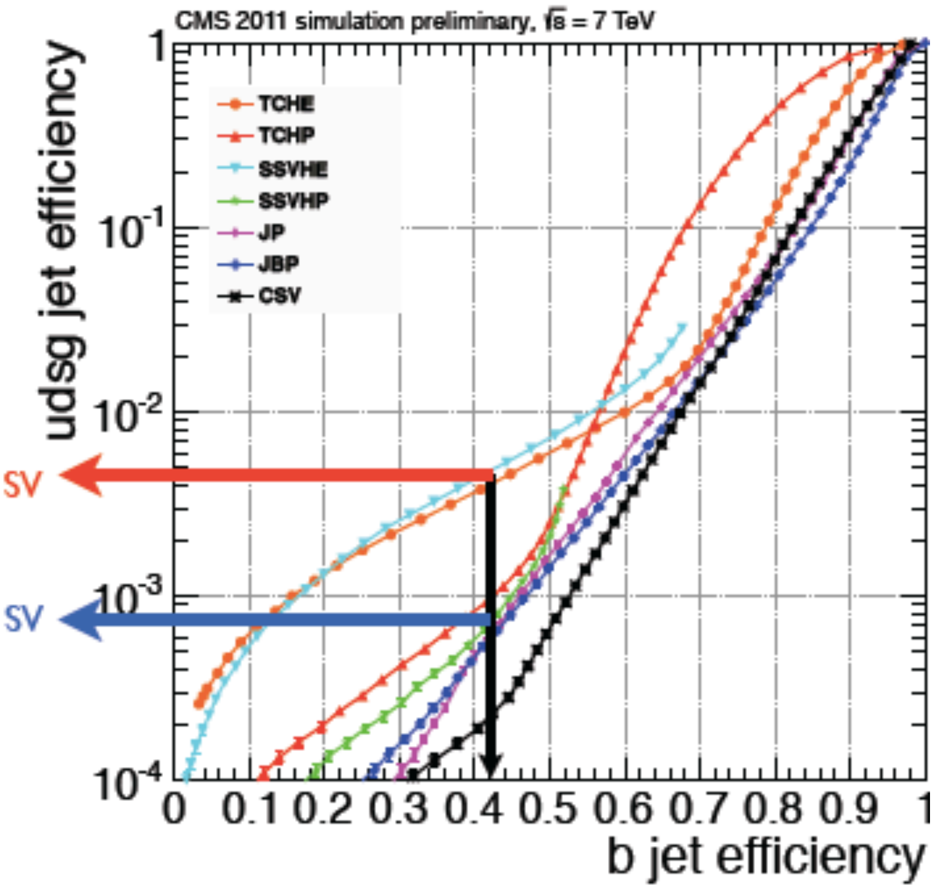
- ✦Observe the expected behavior that $\langle m_J \rangle$ typically scales as R^3

$$s_{0.7}/s_{0.5} = 2.7 \pm 0.9 \qquad ((0.7/0.5)^3 = 2.74),$$
$$s_{0.8}/s_{0.5} = 3.3 \pm 1.0 \qquad ((0.8/0.5)^3 = 4.10),$$
$$s_{0.8}/s_{0.7} = 1.2 \pm 0.2 \qquad ((0.8/0.7)^3 = 1.49)$$

B-tag efficiency and mis-tag rates (I)

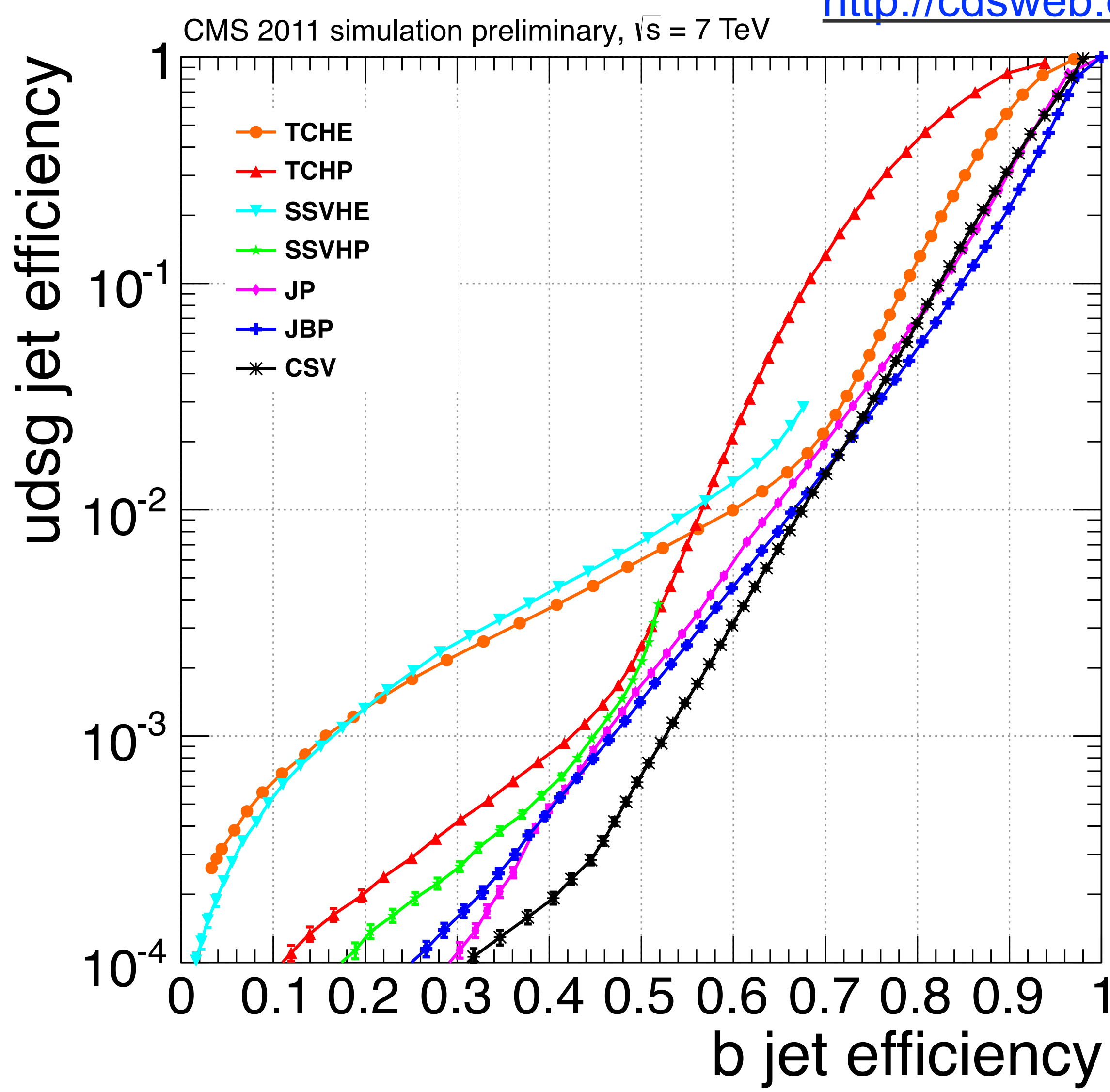
http://cdsweb.cern.ch/record/1427247

- Simple Secondary Vertex (SSV) tagger.
  - Detect the presence of a displaced secondary vertex (SV) inside a jet
  - Use the SV flight distance significance as discriminator $D_{SSV} = sign(S)log(1+|s|), S = \frac{L_{3D}(PV-SV)}{\sigma_{3D}(PV-SV)}$
  - Cut on discriminator defines the b-tagging efficiency
  - Two versions
    - High efficiency (HE): >=2 tracks attached to the SV
    - High purity (HP): >=3 tracks attached to the SV



B-tag efficiency and mis-tag rates (II)

http://cdsweb.cern.ch/record/1427247



B-tag efficiency and mis-tag rates (III)

http://cdsweb.cern.ch/record/1427247