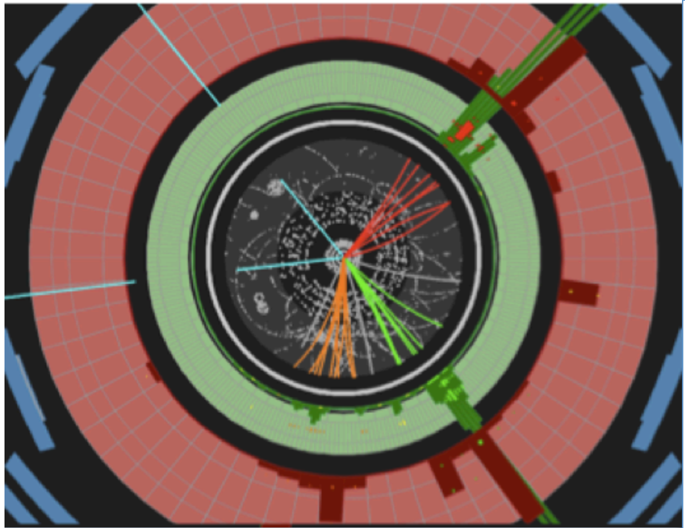

# Recent results at the LHC and Tevatron on W & Z Bosons + (HF) jet production


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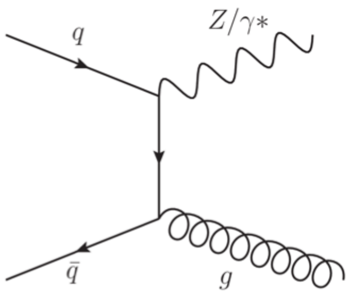
*On behalf of the ATLAS & CDF & CMS & D0 Collaborations*

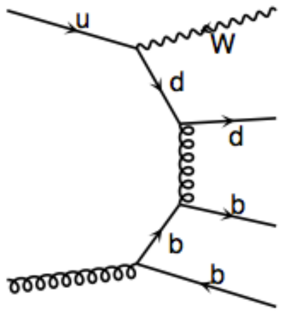

Large Hadron Collider Physics Conference – LHCP 2013

Barcelona, Spain, May 13-18th, 2013

# Outline




- Introduction
- Analysis procedure
- Theory predictions
- Main experimental aspects of the analyses
- Latest Z/W+ light jets @ Tevatron and LHC
- Latest Z/W+ c/b jets @ Tevatron and LHC
- Conclusions



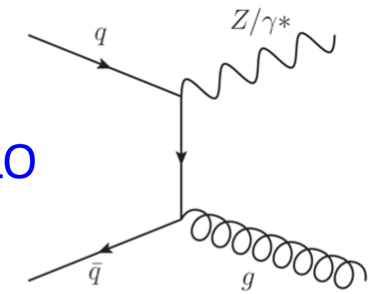

**Not a complete summary, only few most recent results are presented.**

**For more details, look @ related talks by ATLAS and CMS members Lea Michaela Caminada and Marco Musich**

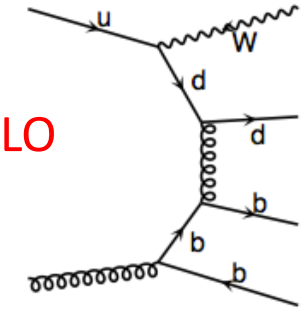
# Main Motivations

- **Test of perturbative QCD**
  - *** improve calculations & generators**

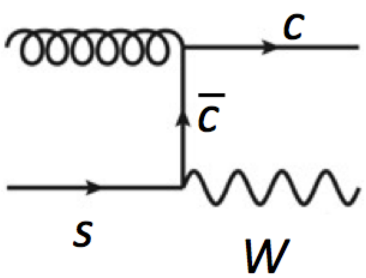
LO



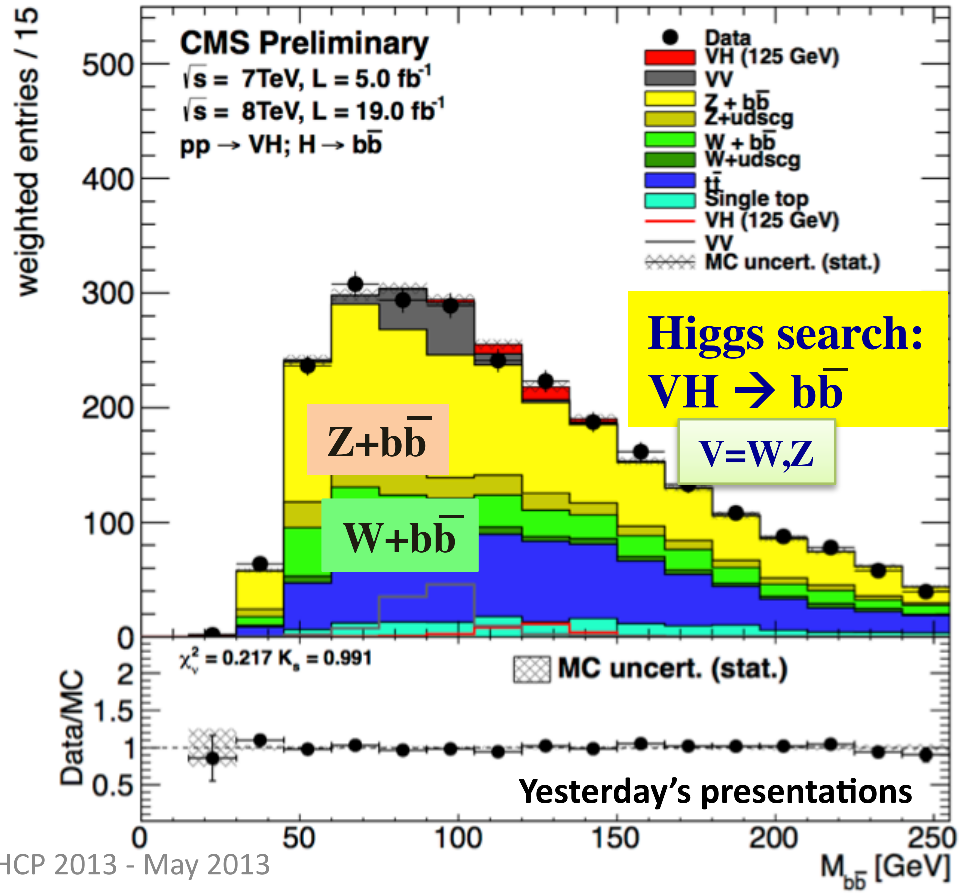

NLO




- **Probe the strange and heavy flavour content in proton (various Flavor Number Schemes, FNS)**




- **Background for rare SM processes (top, dibosons, Higgs) and for New Physics searches**



# Data samples

## Tevatron – Run II

**$p\bar{p}$ @ $\sqrt{s}$ = 1.96 TeV**

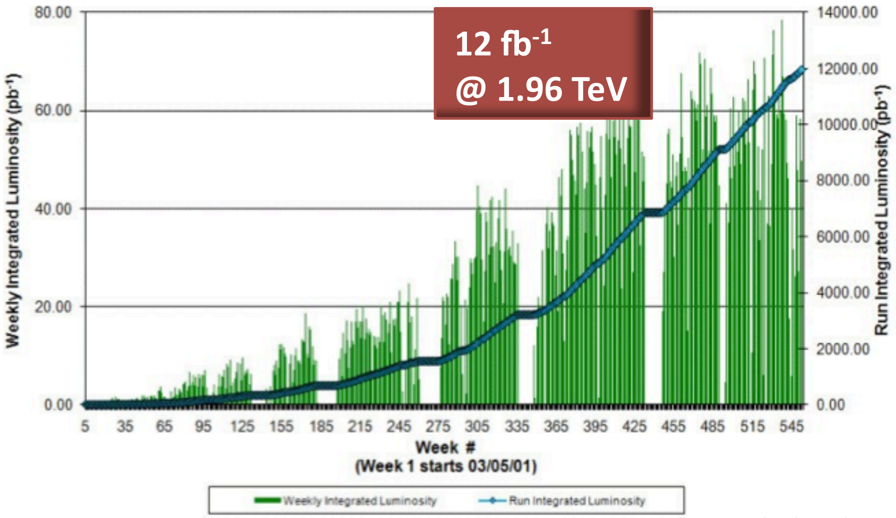
**~ 10 years of data acquisition, end of operation in September 2011**

**Results shown here from: CDF & D0**

**Data set/experiment: 12 $fb^{-1}$delivered ~ 10 $fb^{-1}$ for analysis**

**Z(ee)+ ≥ 1 jet ~ 13K events**

**Run II - Integrated Luminosity**




## LHC

**pp @ $\sqrt{s}$ = 7 and 8 TeV (*)**

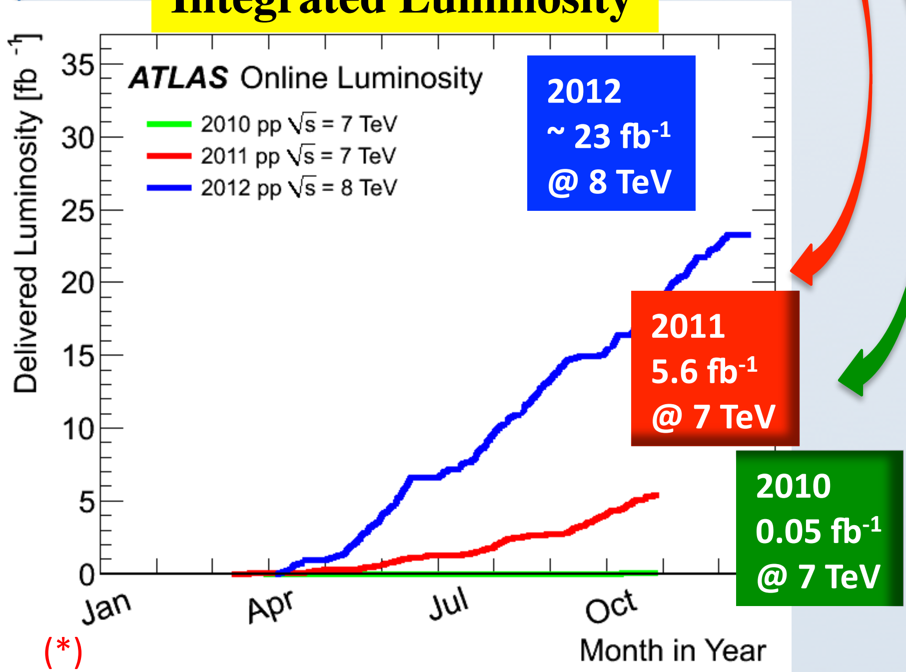
**~ 3 years of data acquisition, end of Run I in February 2013**

**Results shown here from: ATLAS & CMS**

**( public results from 7 TeV Run)**

**Z(ee)+ ≥ 1 jet ~ 190 K events**

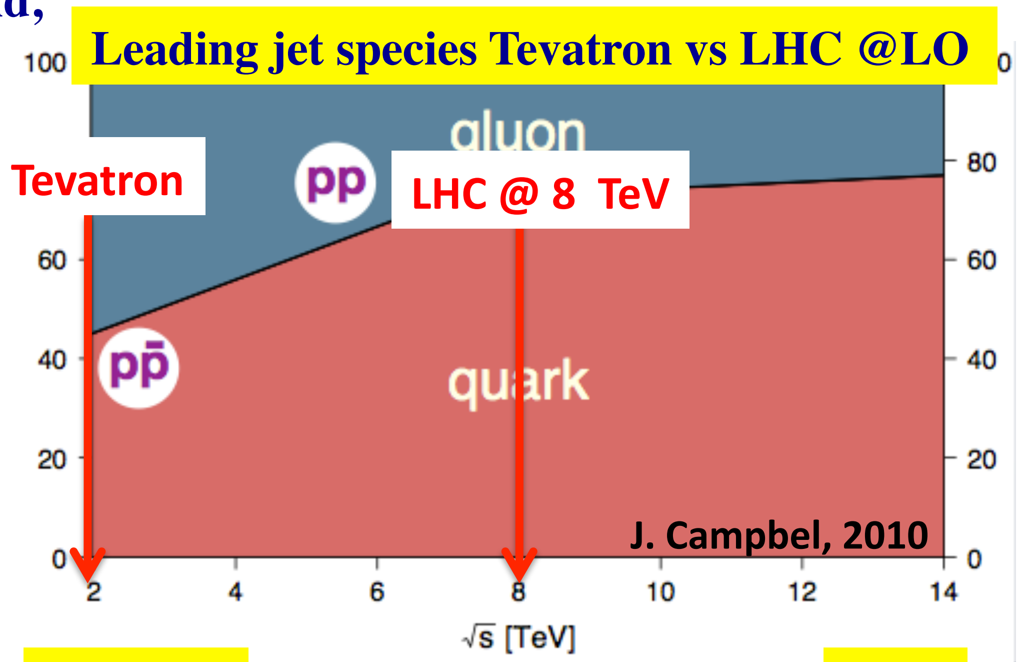
**Integrated Luminosity**




(*) **also Pb-Pb and p-Pb data, not discussed here**

# Tevatron and LHC

**Tevatron** has been a pioneer in the field, still very important to extend W,Z+ (HF) jets studies @ LHC

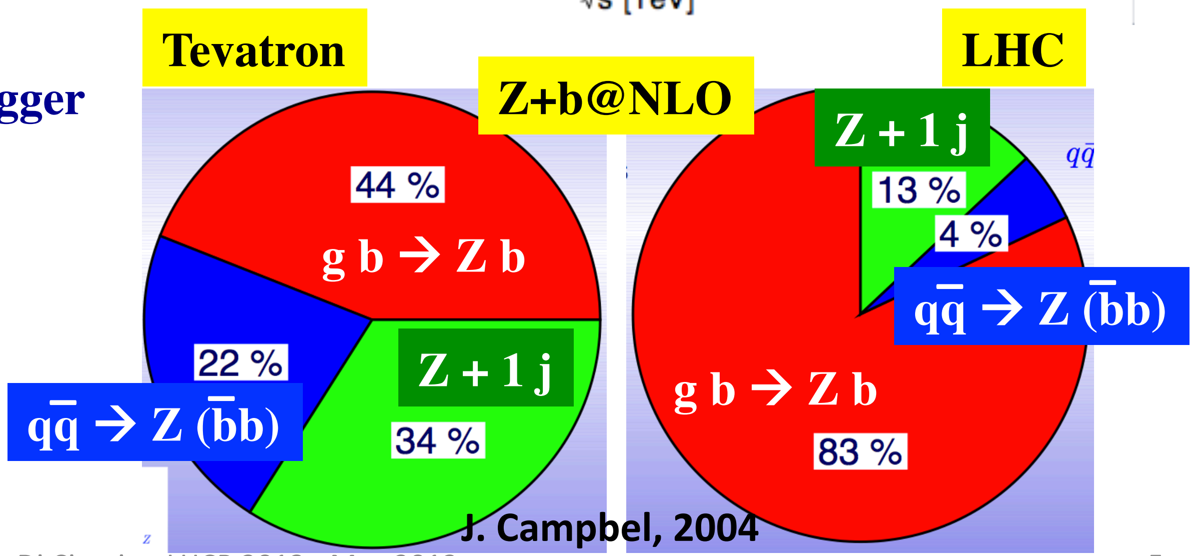



**@ Tevatron and LHC**

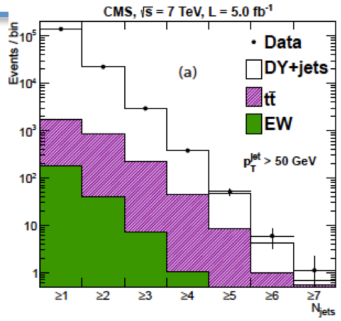
different mixture of quarks and gluons jets in the final state: for the leading jet ~ equal mix at Tevatron, mostly quark jets at LHC

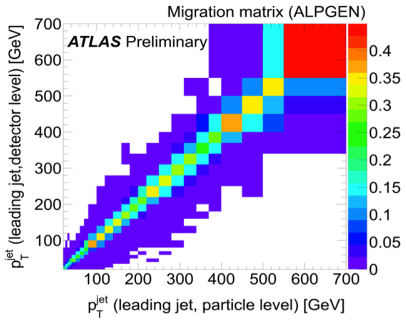
**@ Tevatron** $q\bar{q}$ contribution is bigger than @ LHC

**@ LHC** bigger contribution from processes with heavy flavor in **the initial state**, also higher jet $P_T$, multiplicity, different PDF regime, etc ..



# Analysis Procedure




Experiment (detector level)

Pythia
Alpgen, Sherpa
MadGraph
PowHeg
aMC@NLO
….

Subtract background
Correct & unfold data
for efficiencies, resolution,
bin migration

Comparison

Particle level
(in fiducial region)

Theory predictions
@ particle level
(in fiducial region)

Correct for non perturbative
effects (Underlying Event,
fragmentation)

Theory predictions
@ parton level

MCFM
Black-Hat + Sherpa
….

Compare many, many, many
differential cross-sections
(often normalised to inclusive)

# (Many) Theory Predictions

**Very active field. Predictions of pQCD @ NLO: W/Z + 1, 2, 3, 4, 5 jets[(*)]**

[(*)] L.Dixon. CERN Academic Training 2013

see also:
Matteo Cacciari,
Stefano A. Pozzorini,
Leif Lonnblad

## Theory predictions @ PARTON level

- **MCFM : (LO) NLO fixed order pQCD (up to 2p)**
- **BLACKHAT+SHERPA : (LO) NLO fixed order pQCD (up to 4p)**

## Theory predictions @ PARTICLE level

- **PYTHIA, HERWIG: LO ME+PS**
- **ALPGEN, SHERPA: LO ME+PS tree level multipartons (mp) up to 5p**
- **SHERPA: ME NLO+PS**
- **MADGRAPH+PYTHIA: LO ME+PS tree level multipartons (mp) up to 5p**
- **(a)MC@NLO+HERWIG: NLO + PS**
- **POWHEG+PYTHIA : NLO + PS**

## … and also @ PARTON level:

**HEJ : Wide angle resummation**
**LOOPSIM+MCFM: Approximate nNLO**
**NLO QCD x NLO EW : Factorized NLO QCD and EW**

# Signatures and Jet Reconstruction

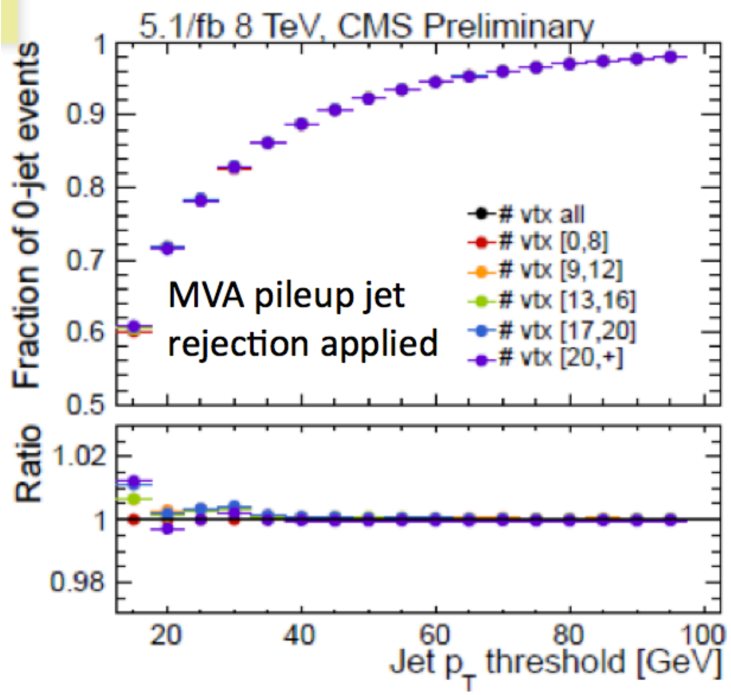
**Signatures:**

- **Z+jets:** 2 high $P_T$ and isolated μ or e + jets
- **W+jets :** 1 high $P_T$ and isolated μ or e + $E_{Tmis}$ + jets

} analyses need ~ all reco objects

**@ LHC: high(er) Pile UP. It affects in particular:**
- **Lepton isolation**
- **$E_{Tmis}$ and Jet reconstruction**

**→ Robust algorithms & PU corrections**




**@ Tevatron :Midpoint cone algorithm**

**CDF:** R = 0.7 (R=0.4, 0.7 heavy flavor jets)
(typically $P_T^{jet}$ > 20-30 GeV, $|Y^{jet}|$ < ~2)

**D0 :** R = 0.5
(typically $P_T^{jet}$ > 20 GeV, $|Y^{jet}|$ < 2.5-3.2)

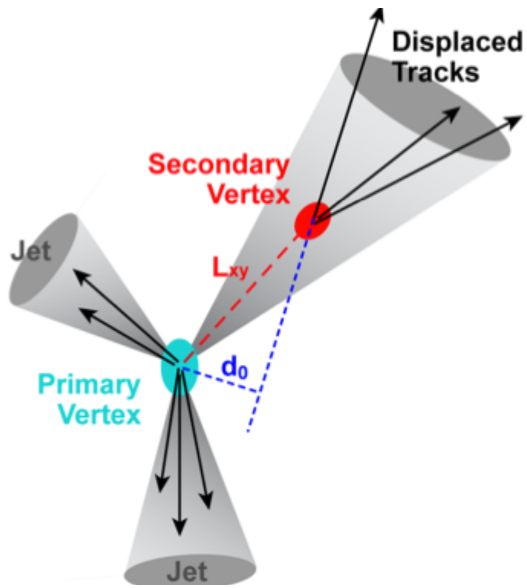
**@ LHC : anti-$K_T$ algorithm**

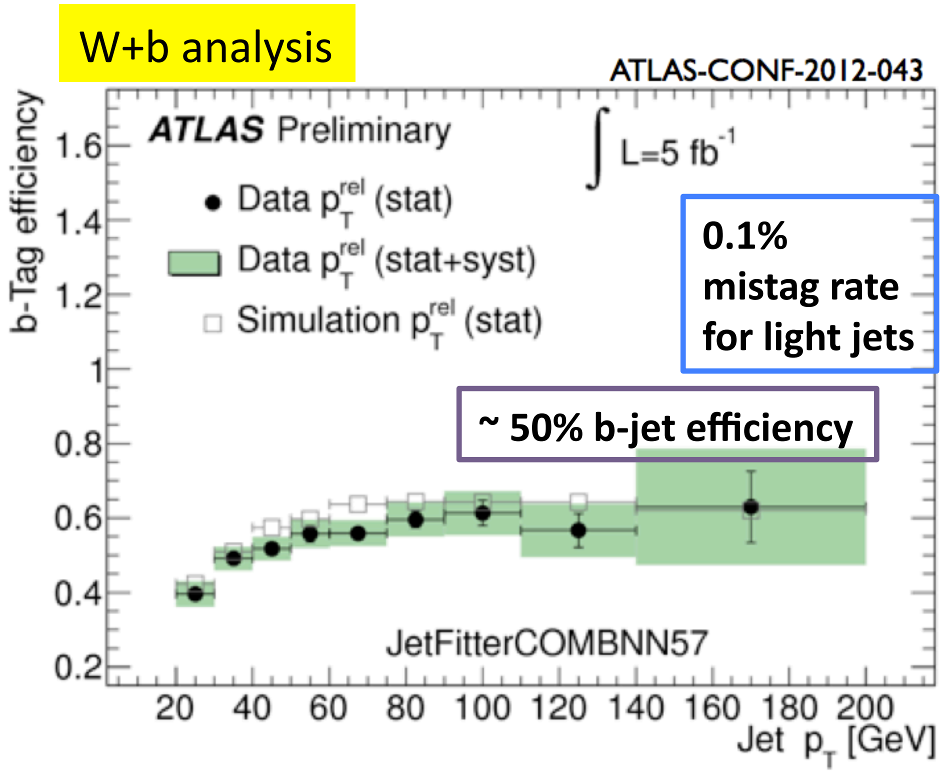
**ATLAS :** R=0.4, Calo Topo clusters, PU corrected,
(typically $P_T^{jet}$>25-30 GeV, $|y^{jet}|$ < 4.4, $|y^{jet}|$ < 2.1 for HF-jets)

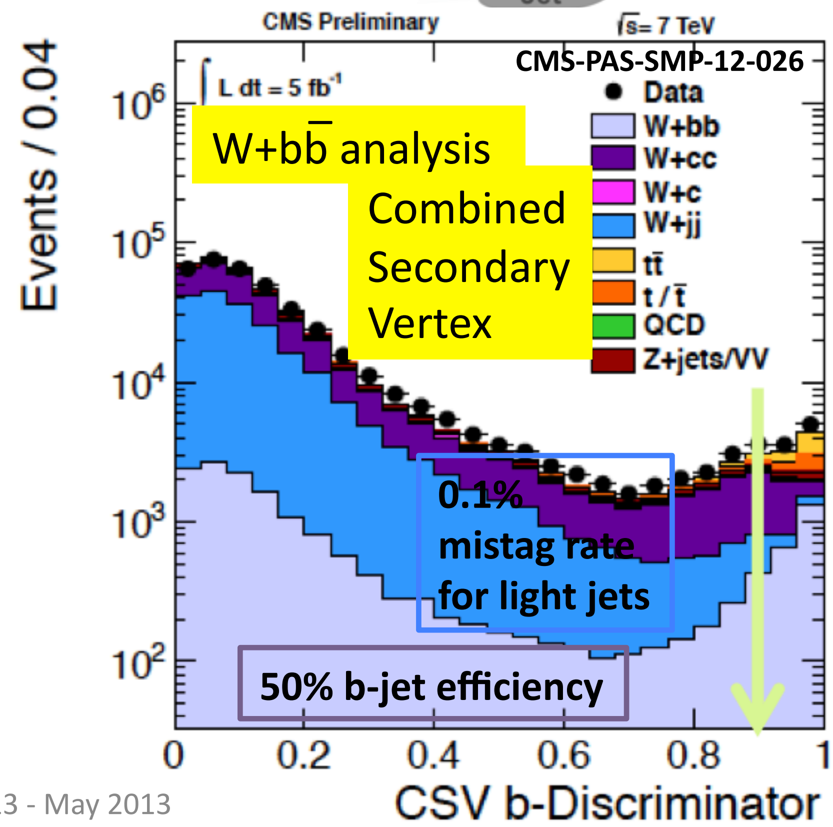
**CMS :** R=0.5, Particle Flow objects, PU corrected, (typically $P_T^{jet}$> 25-30 GeV, $|\eta^{jet}|$ < 2.5 )

# b and c-jet tagging

- W,Z+HF jets challenging: small cross sections, large bkg
- b and c-jets identifyed by exploiting lifetime, D mesons reconstruction (W+c analysis), semileptonic decays and by using statistical discriminants
- Challenging to distinguish b from c-jets



# Main systematic uncertainties and backgrounds

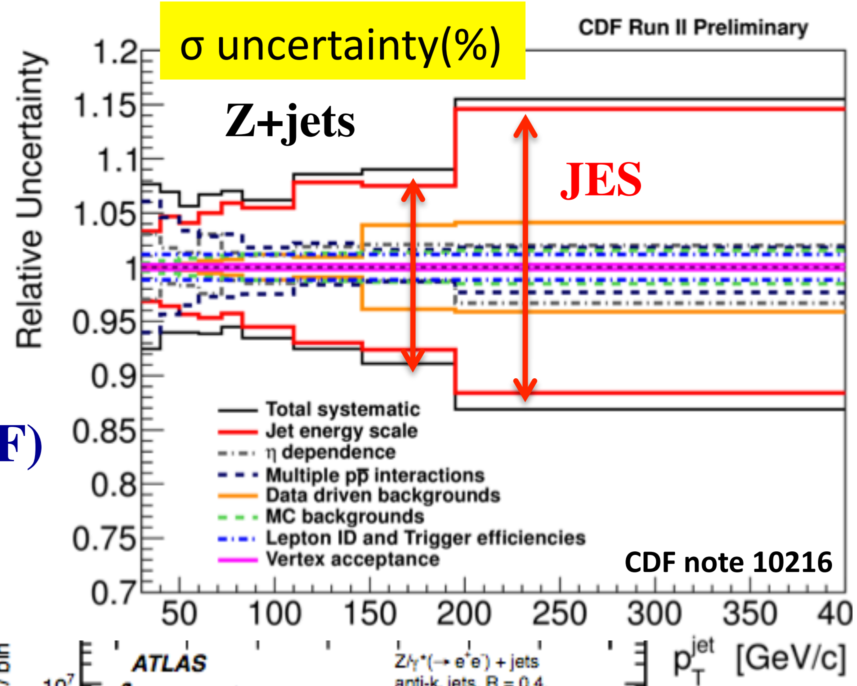
- **Main systematic uncertainties:**
  - **Jet Energy Scale (JES)**
    **determined using simulation & in situ measurements**
  - **Jet energy resolution**
  - **B-tagging efficiency and purity (W,Z+HF)**

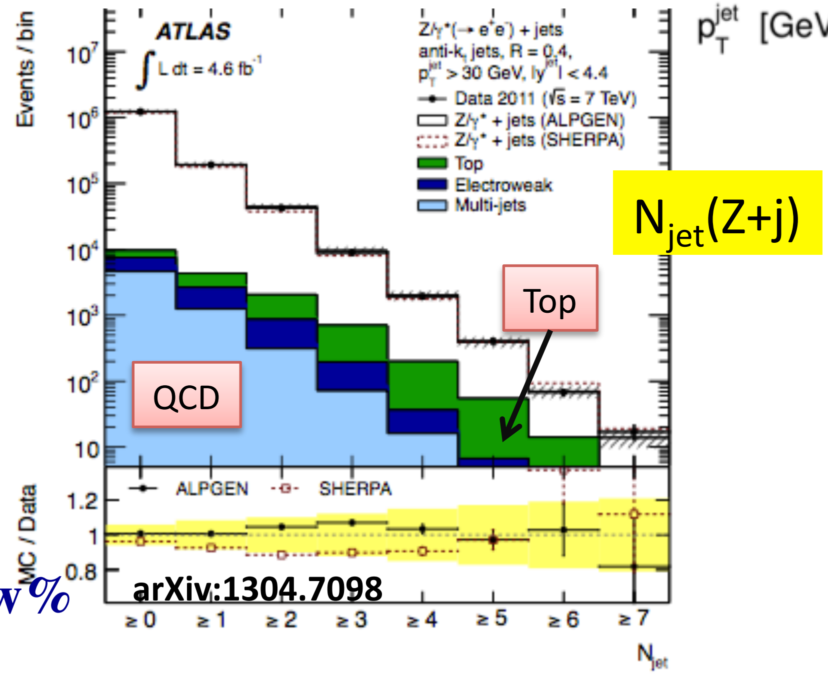
**Ratios (i.e. Z+jets /W+jets) allow reduced JES uncertainty, then one the main systematic uncertainties is from background evaluation**

- **Main backgrounds**
  **(often estimated from data):**
  - **top (higher @ high jet multiplicity)**
  - **'QCD' (multijets)**

**W+jets: ≈ 10-30% top, QCD ≈ 2 -30%**

**Z+jets : ≈ 0.5-30% top, QCD ≈ 0.5 – few%**



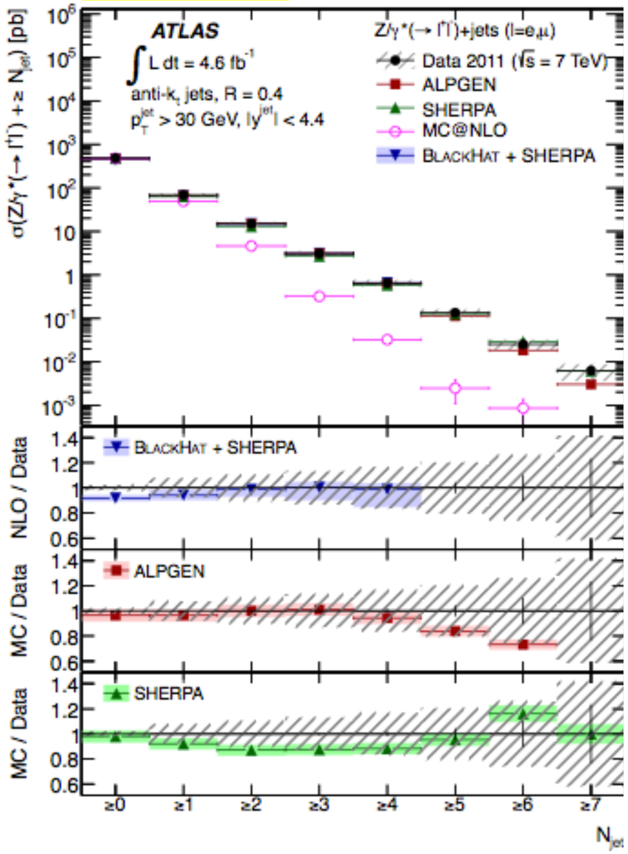



# Jet Multiplicity and Jet $P_T$ in Z+jets @LHC

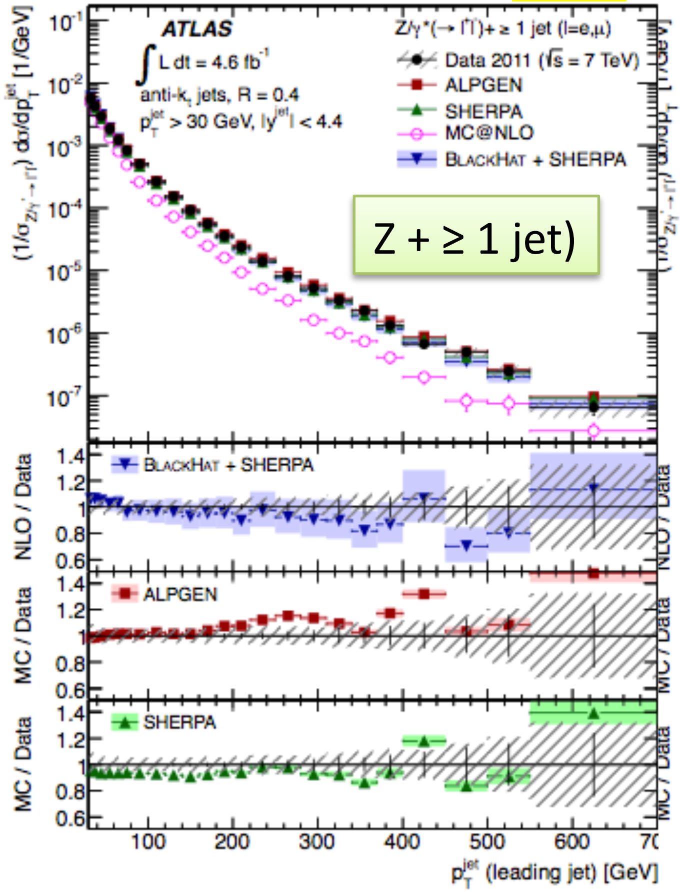
arXiv:1304.7098

## Measurement up to $Z + \geq 7$ jets → limits of ME(LO)+PS generators reached (Alpgen & Sherpa use PS for multiplicities beyond 5)

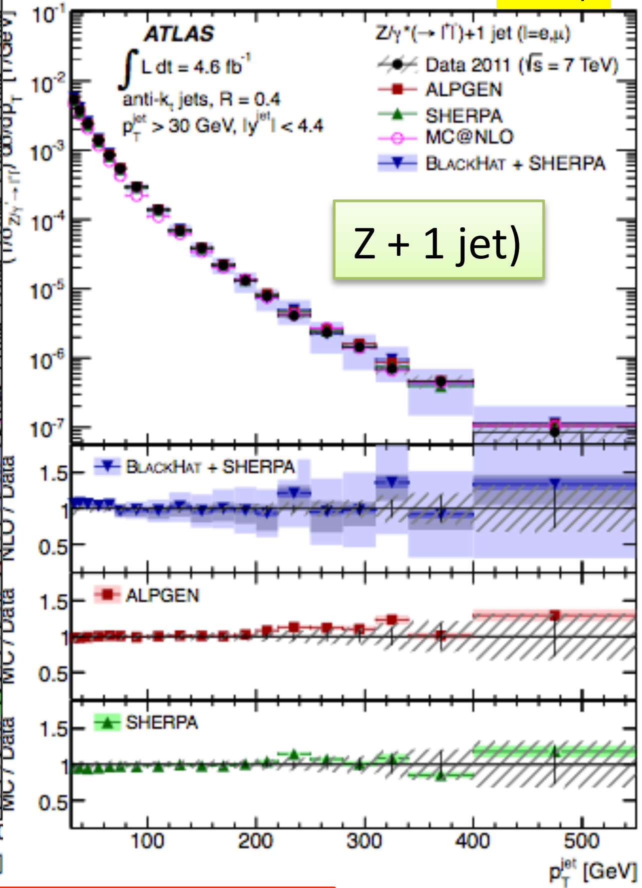
$\sigma (\geq N_{jet})$




$P^{jet}_T$




$P^{jet}_T$

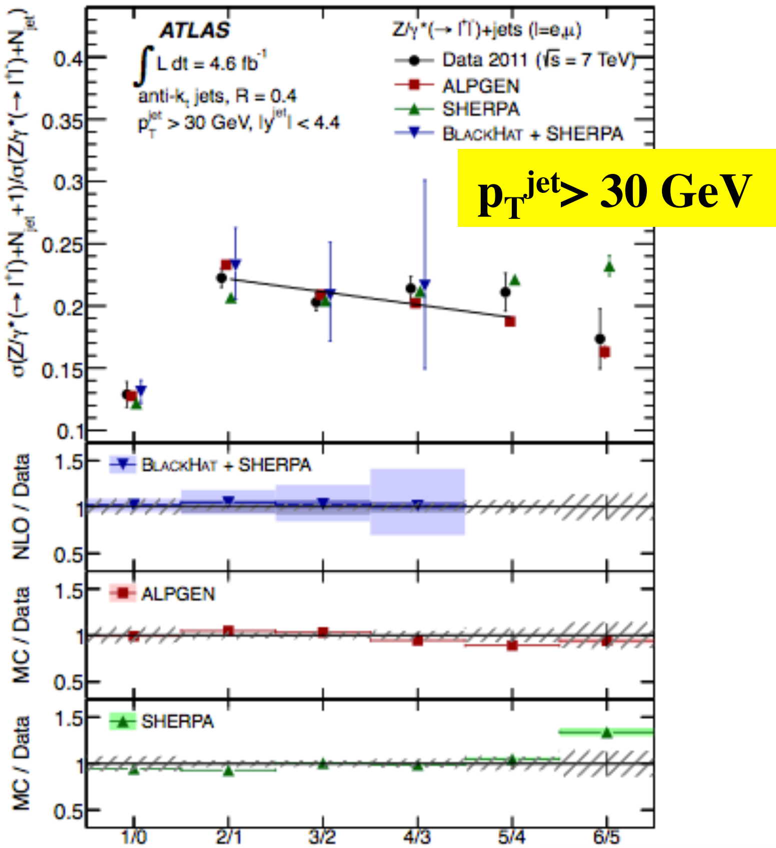



- NLO pQCD, mp ME(LO)+PS : describe reasonably data
- @ Large jet $P_T$, QCD and/or EWK missing high orders

# Exclusive jet multiplicity scaling in Z+jets @LHC

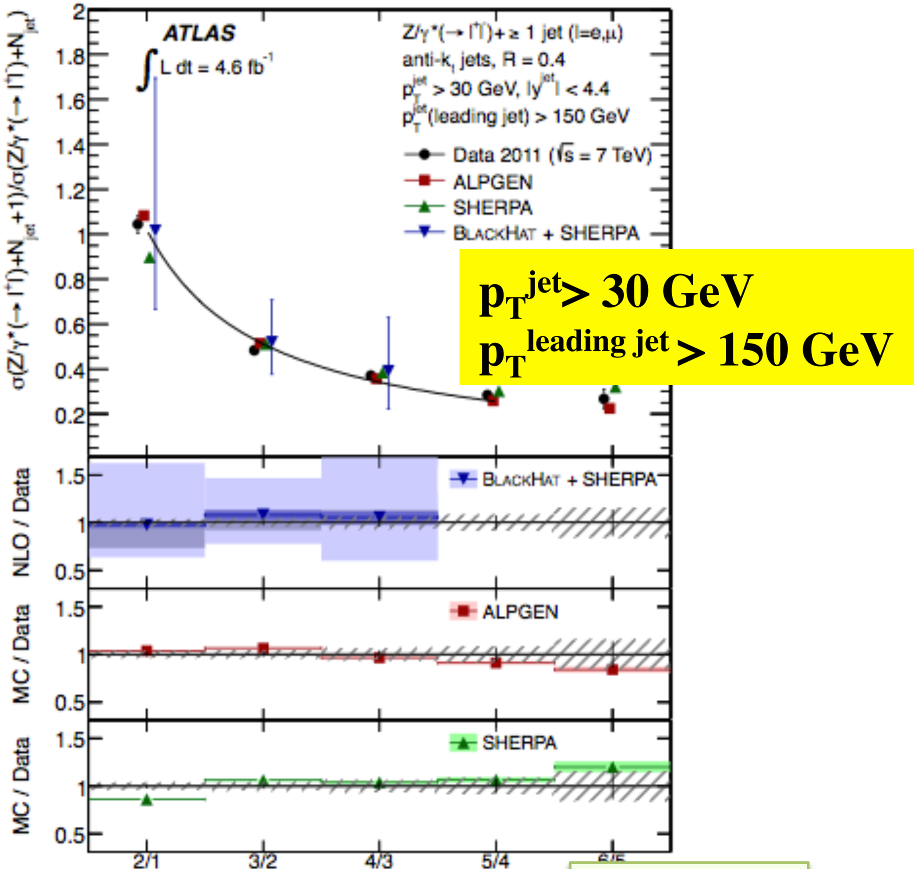
arXiv:1304.7098

- **Exclusive jet multiplicity ratio probed at different scales:**
  - **democratic jet selection: non-abelian type FSR** $R_{n+1}/R_n \sim const$ **(Staircase scaling)**
  - **large scale separation : abelian type FSR, limit of QCD** $R_{n+1}/R_n = \langle n \rangle / n$ **(Poisson scaling)**




**Staircase scaling**

$N_{jet}+1/N_{jet}$




**Poisson scaling**

$N_{jet}+1/N_{jet}$

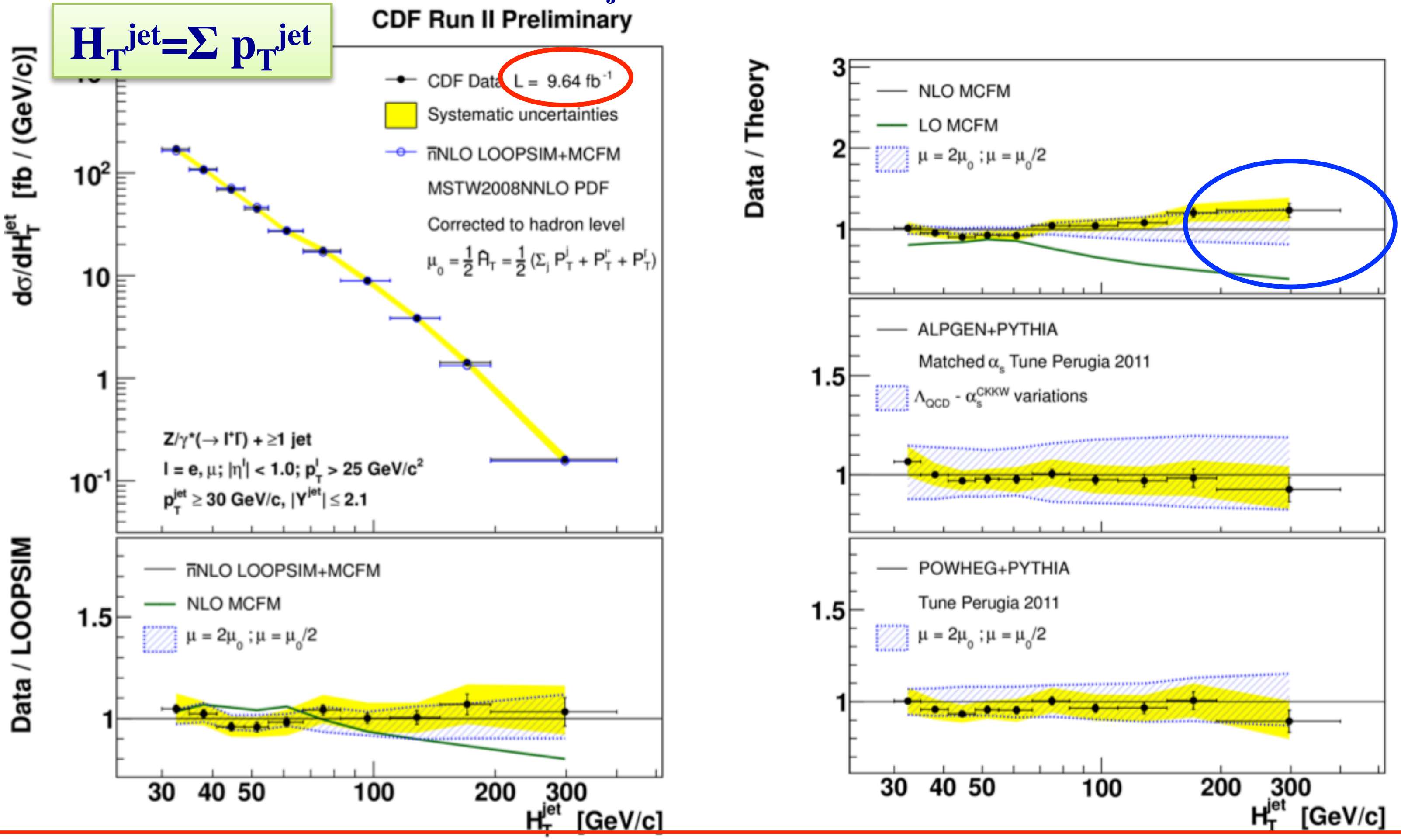
- **Change of scaling pattern generally well modeled by NLO pQCD and mp ME(LO)+PS**

# Z+jets @ Tevatron

FERMILAB-THESIS-2012-12

- **Many differential cross sections: $N_{jet}$, $p_T^{jet}$, |y|, $H_T^{jet}$, di-jet mass, $\Delta\phi$, $\Delta R$**

**$H_T^{jet} = \Sigma\, p_T^{jet}$**

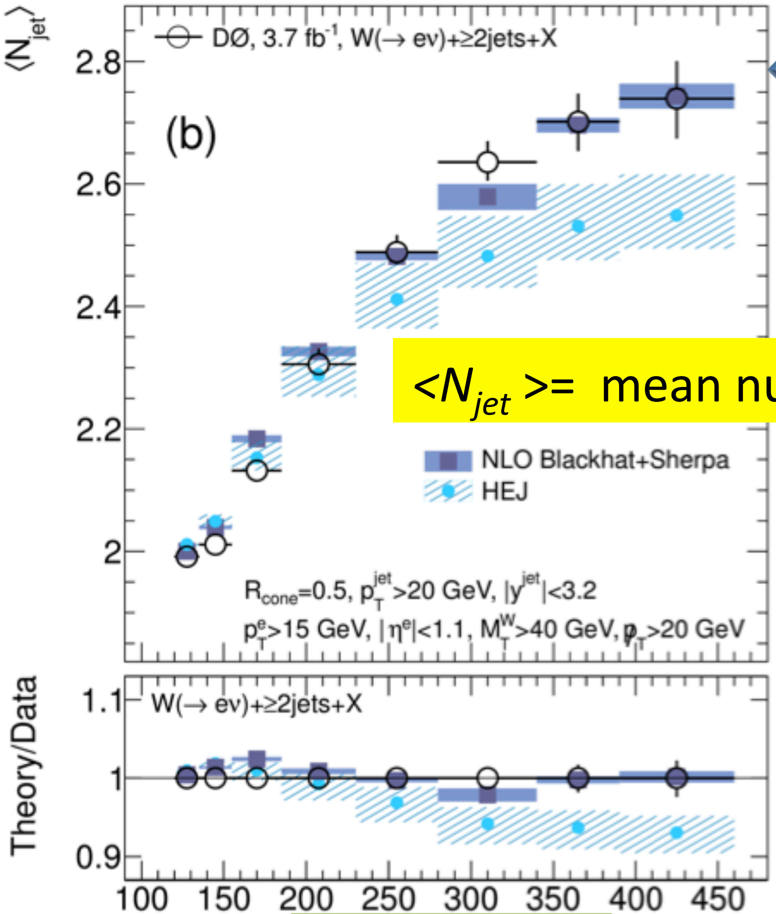


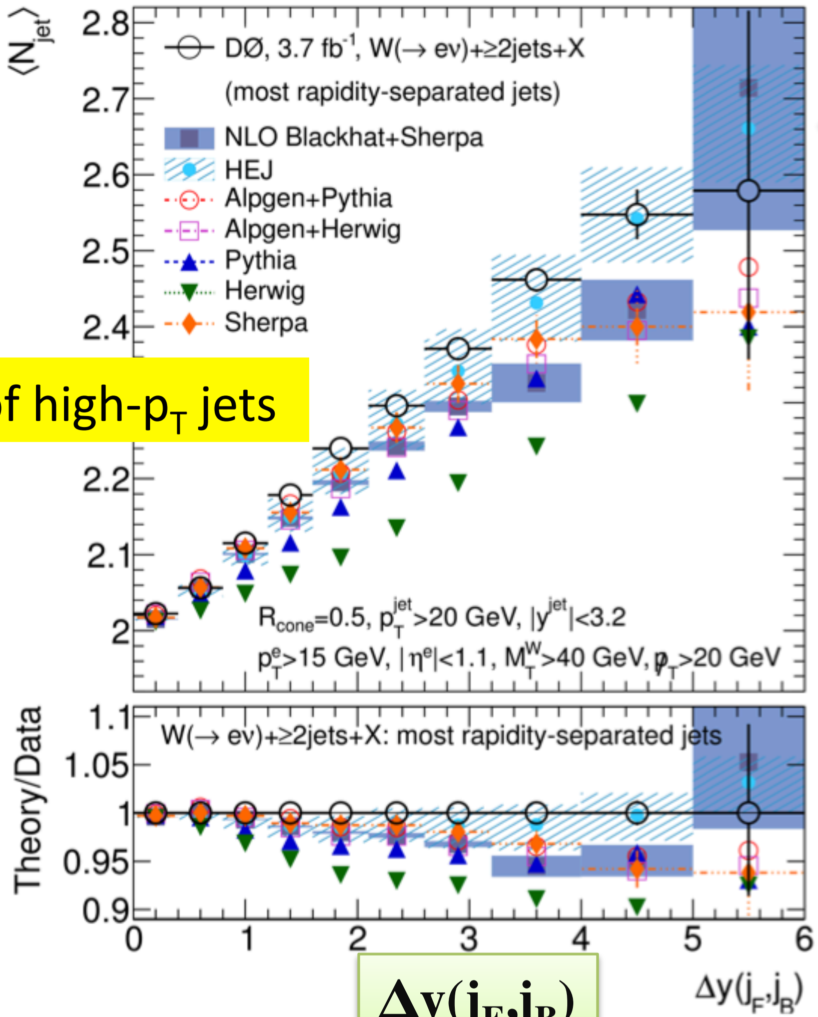

- **nNLO (LOOPSIM+MCFM), NLO+PS (POWHEG+PYTHIA), mp ME(LO)+PS (ALPGEN) properly model data (LOOPSIM has reduced scale uncertainty)**
- **Large NLO/LO K factor at high $H_t^{jet}$**

# W+jets @ Tevatron

arXiv:1302.6508

- **40 differential cross sections measured**




$<N_{jet}>$ = mean number of high-$p_T$ jets

$H_T^{jet}=\Sigma\, p_T^{jet}$

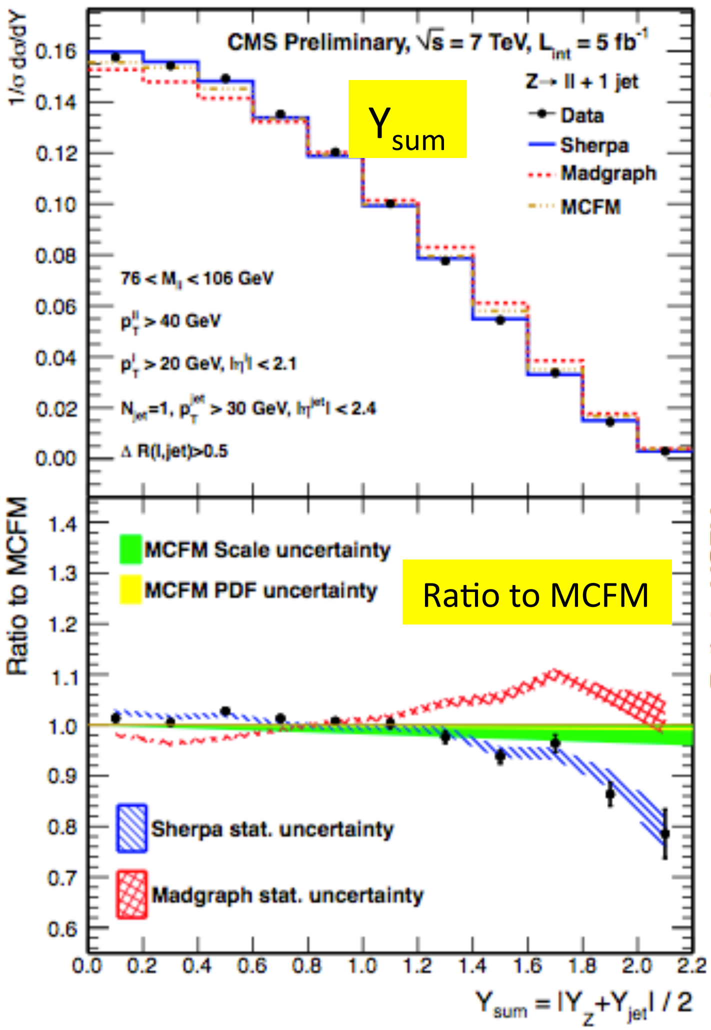
$\Delta y(j_F, j_B)$

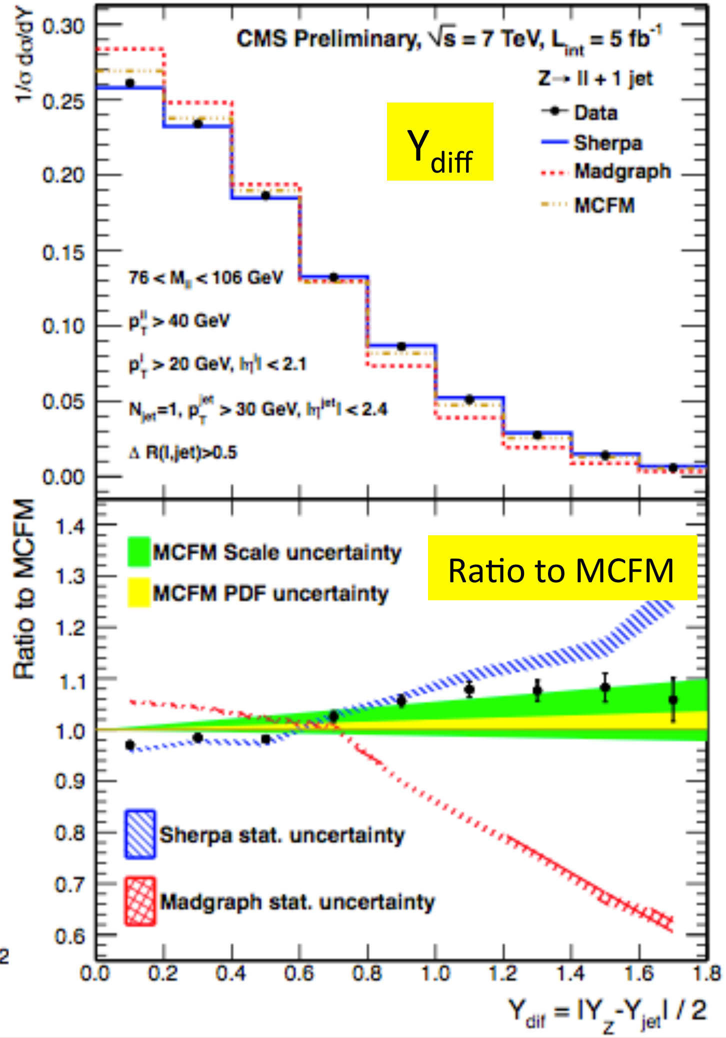
- **NLO pQCD (Blackhat+Sherpa) describe data**
- **HEJ large-angle resummation provides a better description at wide di-jet angle**

# Rapidity distributions in Z+1 jet @LHC

CMS-PAS-SMP-12-004

$Y_{jet}$ and $Y_Z$ described reasonably by NLO pQCD and ME(LO)+PS (forward regions a bit more difficult, see presentation of Marco Musich)




$Y_{sum} = |Y_Z + Y_{jet}|/2$

$Y_{diff} = |Y_Z - Y_{jet}|/2$

$Y_{sum}$ are $Y_{dif}$ approximately uncorrelated quantities

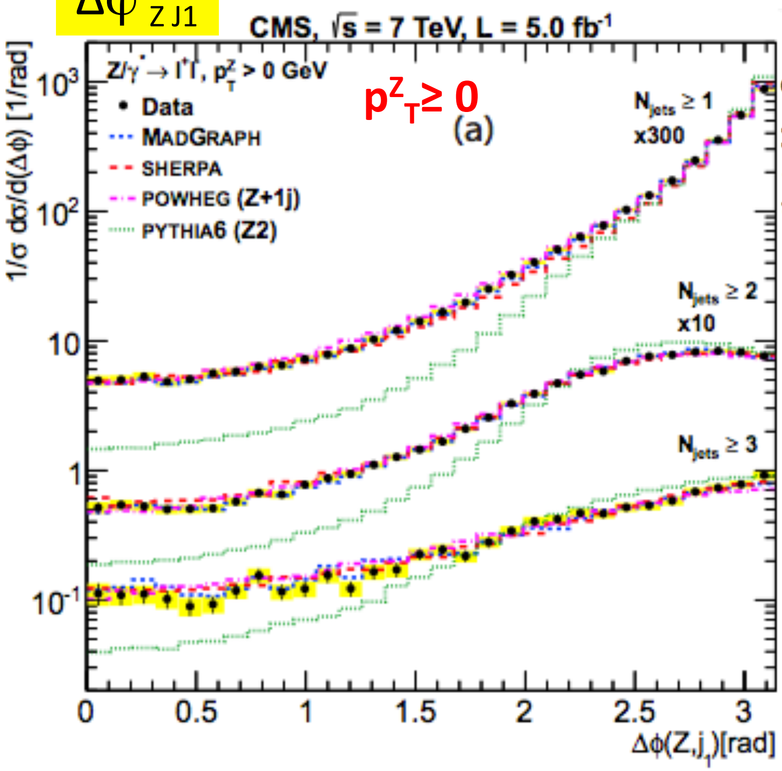
- Sherpa (mp ME(LO)+PS) describes well $Y_{sum}$: difference with Madgraph (mp ME(LO)+PS ) could be attributed to the matching scheme (CKKW vs MLM)

# Azimuthal correlations in Z+jet

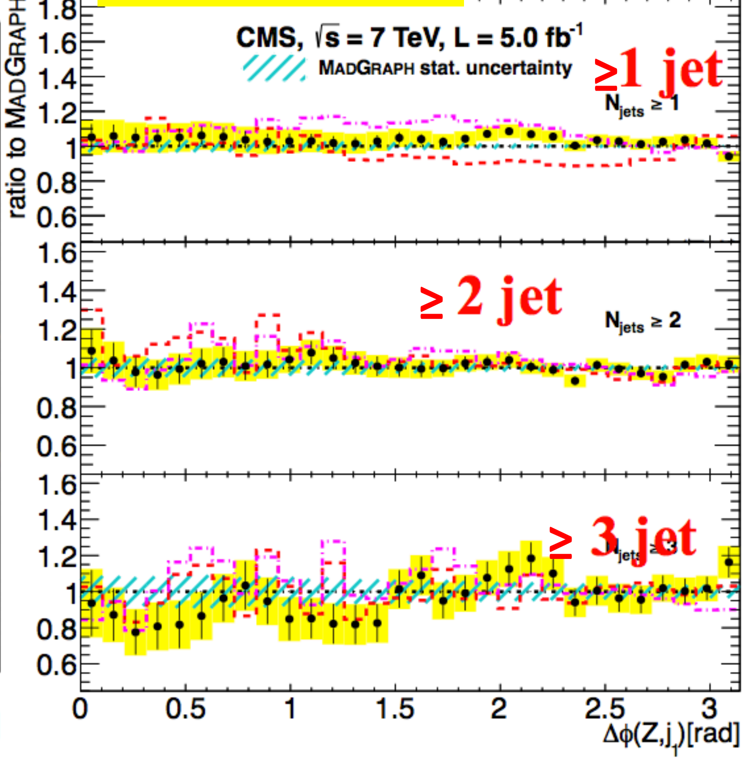
Phys. Lett. B722(2013) 238

## Interesting for New Physics studies ($Z \rightarrow \nu\bar{\nu}+j$)

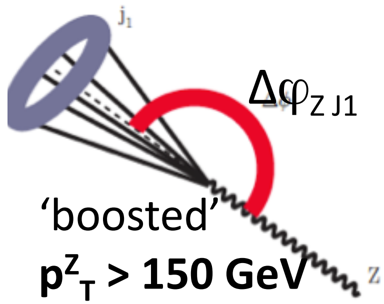
$\Delta\varphi_{Z J1}$

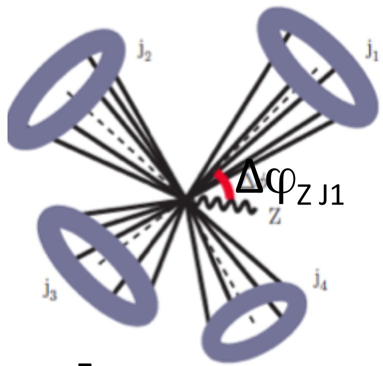



Ratio to Madgraph




Study different regimes:



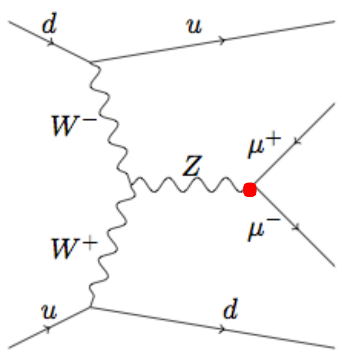




$p^Z_T \geq 0$

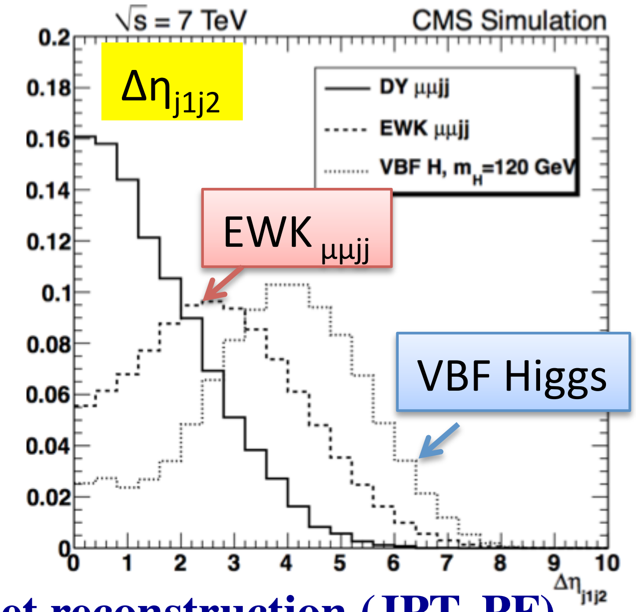
- NLO+PS (POWHEG) and mp ME(LO)+PS (MADGRAPH, SHERPA) describe the data
- 1 jet bin the most difficult
- Also true for other shape variables ( like the transverse thrust )

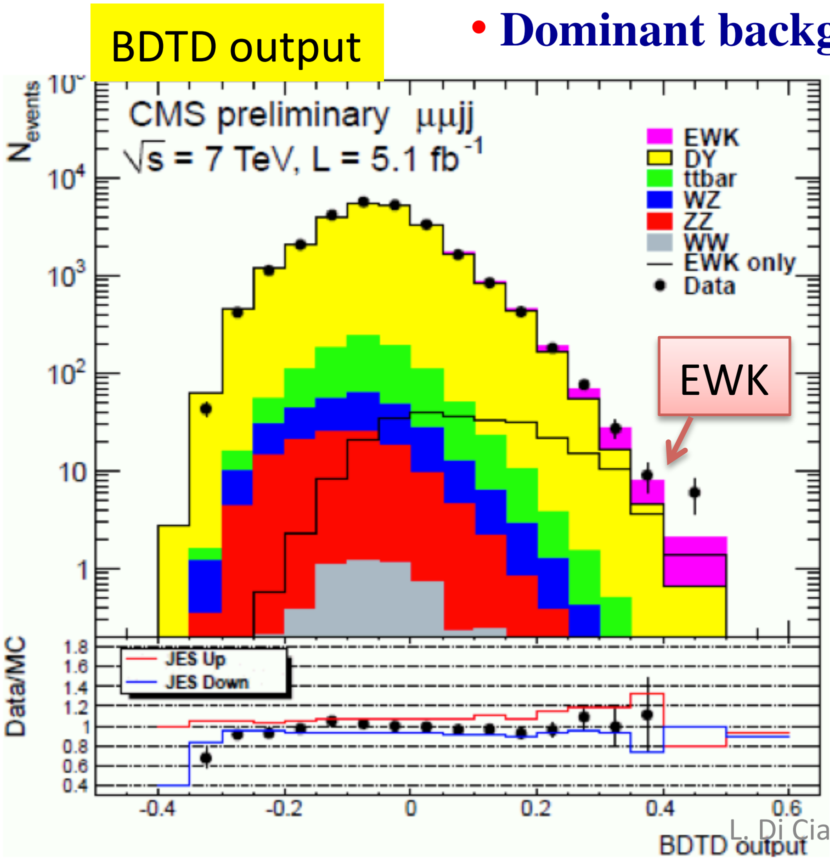
# EW production of Z with two forward jets

CMS-PAS-FSQ-12-019




- **Probe for anomalous Triple Gauge boson Couplings**
- **Background to VBF Higgs signal**
- **Very small signal**
- **Dominant background: Z+jet**




- **Two methods of jet reconstruction (JPT, PF)**
- **Quark-gluon likelihood discriminator**
- **To extract signal cross section:**
  1) fit Boosted Decision Tree output
  2) cross-checked with dijet mass fit
- **Main systematic uncertainty: JES+JER**

**Measured cross section in agreement with NLO prediction (VBFNLO= 166 fb)**

**$154 \pm 24_{(stat)} \pm 46_{(exp.syst)} \pm 27_{(th.syst)} \pm 3(\text{lumi})$ fb**

# W/Z+ HF jets @ Tevatron

**W+ c : CDF, L = 4 fb$^{-1}$, Phys.Rev.Lett. 110 (2013) 071801:**

$\sigma_{W+c} \times Br(W \to l\nu)$ = 13.6±2.2(*stat*)−1.9(*syst*)±1.1(*lumi*) pb

$\sigma_{W+c} \times Br(W \to l\nu)$ = 11.4±1.3 *pb* MCFM NLO prediction

**OK**

**W+ b : 2.8 σ excess wrt NLO predictions reported by CDF with 1.9 fb$^{-1}$**

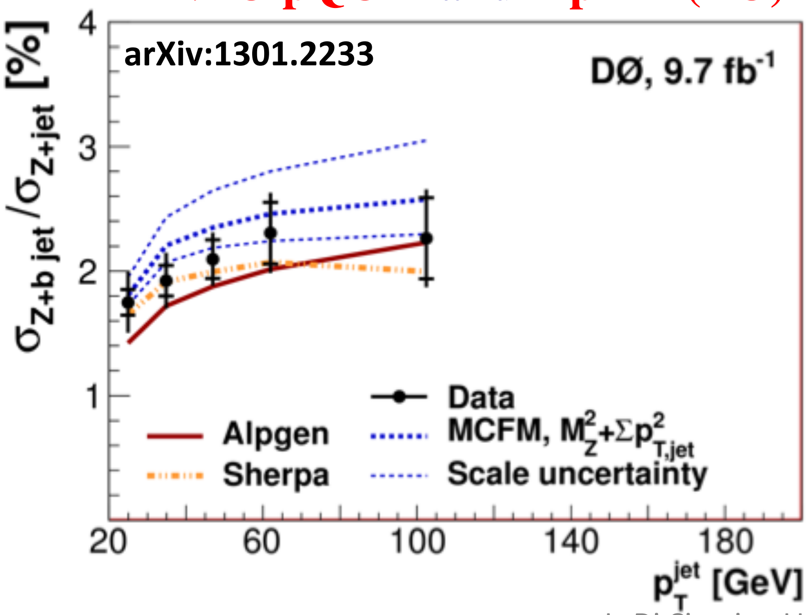
**New D0 measurement, L = 6.1 fb$^{-1}$, Phys.Lett. B718 (2013) 1314-1320**

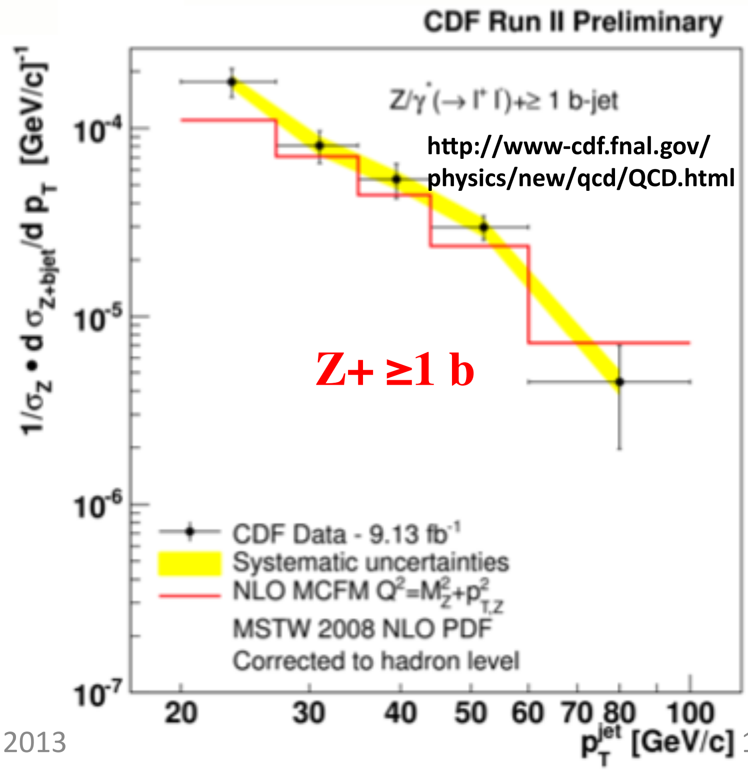
$\sigma_{W+b} \times Br(W \to l\nu)$ =1.05±0.03 (*stat*)±0.12(*syst*) pb

$\sigma_{W+b} \times Br(W \to l\nu)$ =1.34+0.41 *pb* MCFM NLO prediction

**Deviation of new D0 result from theory : - 0.8 σ OK?**

**Z + b : CDF & D0 Reasonable agreement with NLO pQCD and mp ME(LO)+PS**



Phys. Lett. B706 (2012) 295

# Z+ b @ LHC

SMP-13-004
CMS-PAS-EWK-11-015

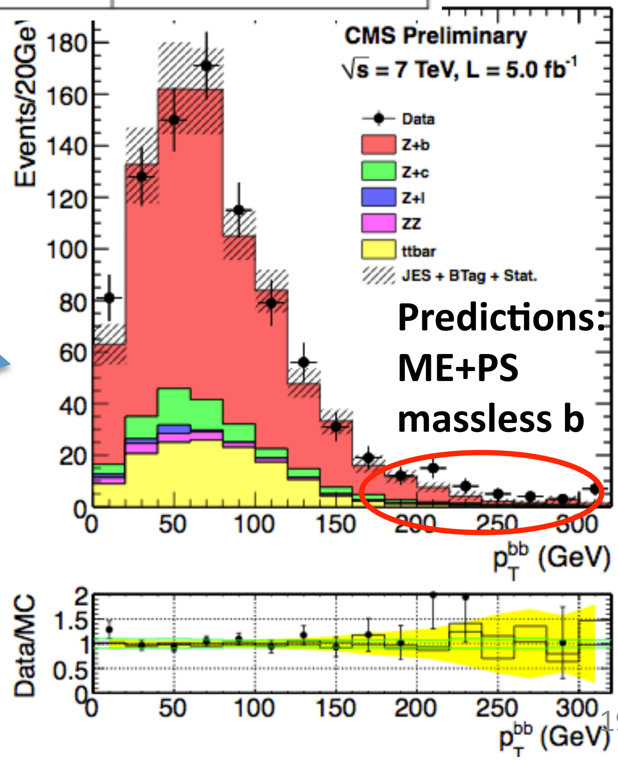
## Important for Z H($b\bar{b}$) search !

**ATLAS : good agreement with NLO MCFM and SHERPA, ~ 1.2 deviation wrt ALPGEN. It favors 4 FNS(*). It doesn't favor massless over massive scheme**

**CMS: fiducial cross sections:**

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

- **Cross sections in good agreement with MadGraph (MG) scaled to NNLO**
- **Good description of kinematics, but harder $P_T^{b\bar{b}}$ spectrum than expected**
- **Angular separation ΔR(BB-hadrons): reasonable agreement with MG4F, MG5F seems to undershoot the data in the collinear region (small ΔR, see presentation of Marco Musich)**

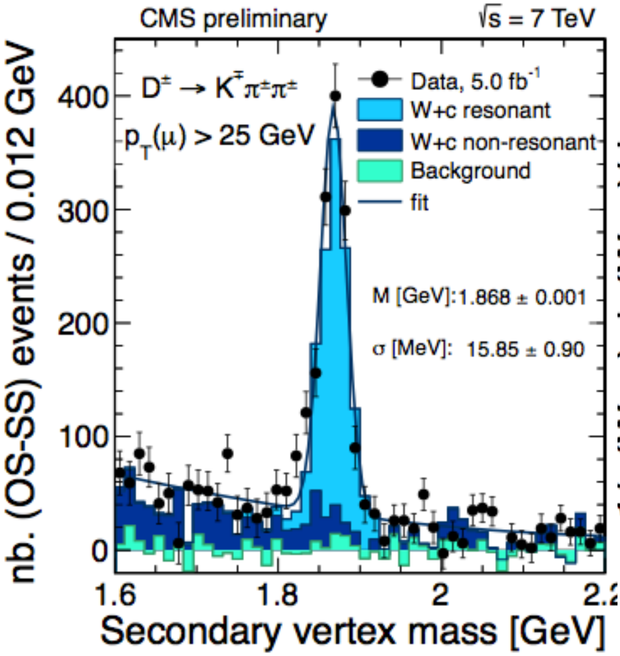



**(*) FNS = Flavour Number Scheme**

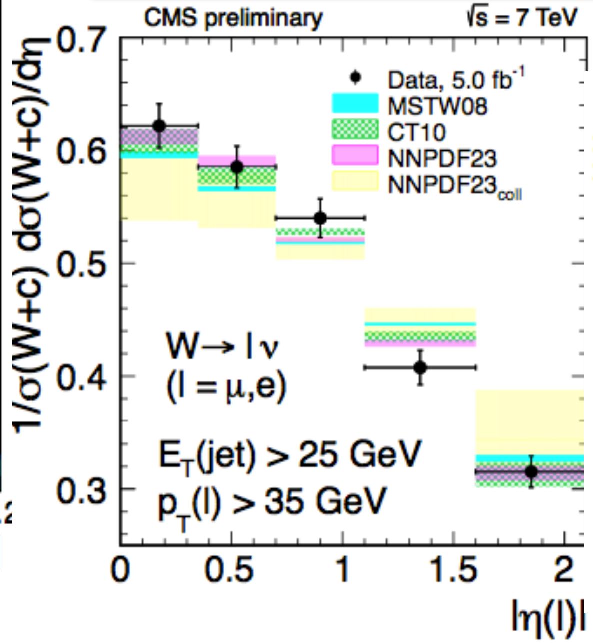
# W+ c @ LHC



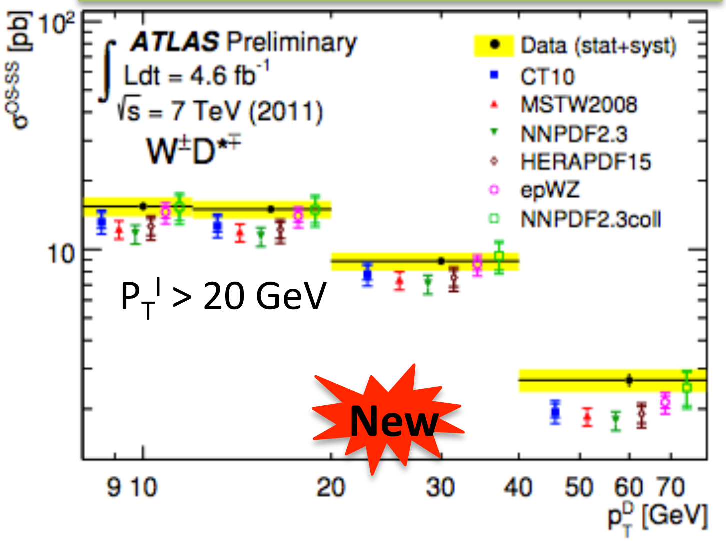
- **CMS: W (lν)+ a leading jet with charm content, identified using a displaced vertex consistent with a $D^{\pm}$, $D^{0}$, $c \rightarrow X\,l\nu$**
- **ATLAS: W (lν)+ a charm hadron ($D^{\pm}$, $D^{*\pm}$)** **New** **see presentation of Lea M. Caminada**
- **Counting measurement after OS – SS Subtraction (sign of "c-charge" wrt W lepton)**




**MCFM + different PDF sets**




**aMC@NLO + different PDF sets**



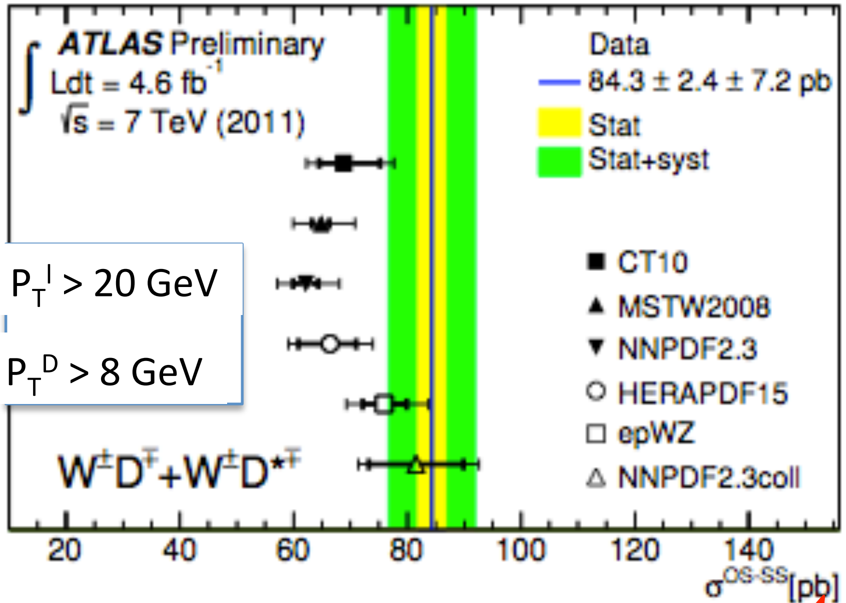

**CMS: NLO theory predictions describe reasonably the shape of the η distribution.**

**ATLAS: the shapes of the $p_T^D$ distributions for the different PDF sets are similar, but the predicted cross sections differ by as much as 25%.**

# W+ c @ LHC

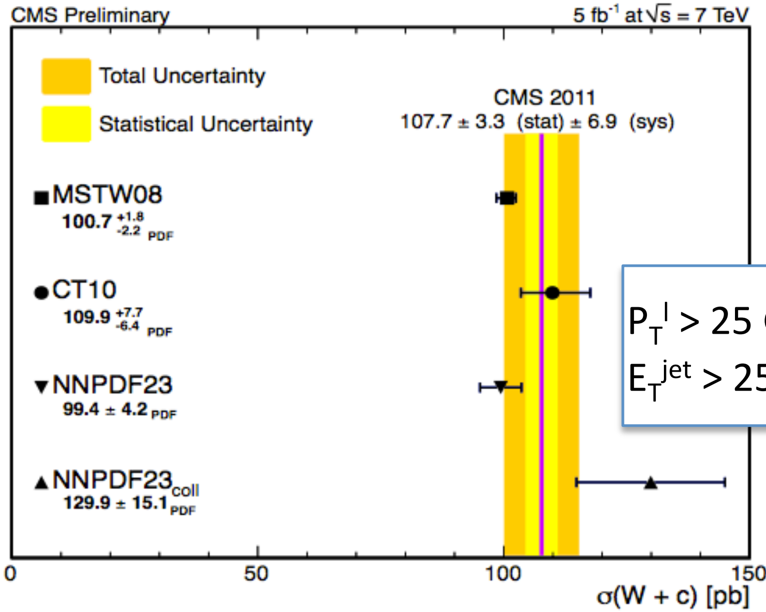


**Predictions: aMC@NLO (ATLAS) & MCFM (CMS) + NLO and NNLO PDF sets differing in the *s*-quark content**




$P_T^l > 20$ GeV

$P_T^D > 8$ GeV




$P_T^l > 25$ GeV

$E_T^{jet} > 25$ GeV

**ATLAS:** New

**PDFs where the *s*-quark and *d*-quark sea contributions are comparable at *x* ~ 0.01 are favored (NNPDF2.3coll)**

**CMS:**

**Cross sections consistent with theory within uncertainties. A symmetric strange sea, as implemented in NNPDF2.3coll seems disfavored**

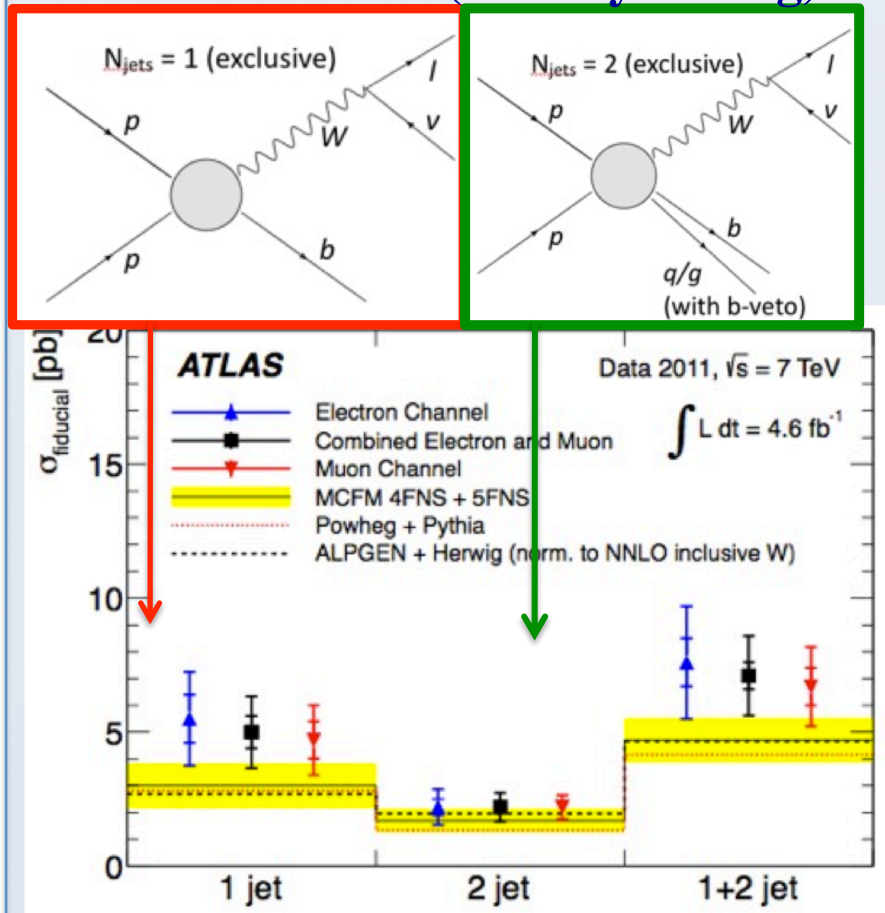
**Need more data to get a clear picture**

# W+ b jets @ LHC

arXiv:1302.2929

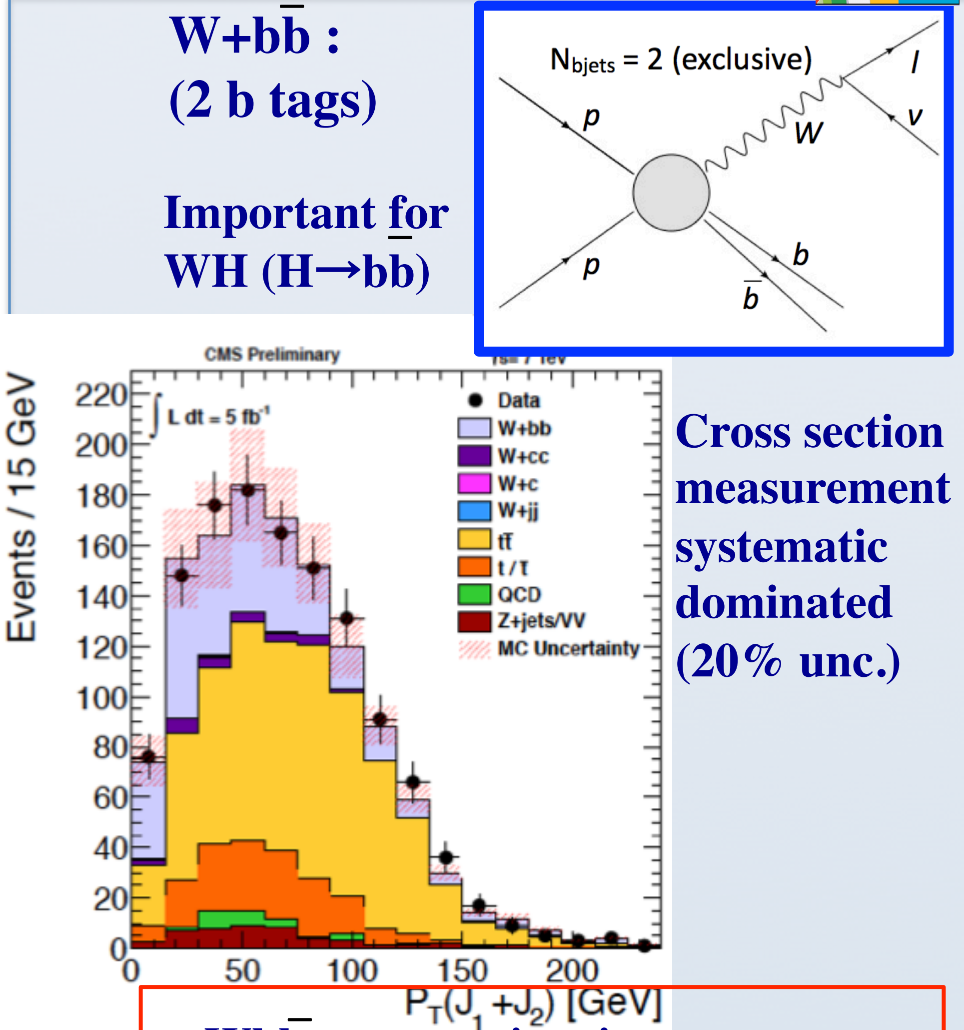
CMS-PAS-SMP-12-026

## W + b ( exactly 1 b tag)




## W+b$\bar{b}$ : (2 b tags)

Important for WH (H→b$\bar{b}$)




Cross section measurement systematic dominated (20% unc.)

- Predictions describe reasonably data.
- 1 jet data ~1σ above NLO calculation (systematically increasing with $P_T^{\,jet}$)
- Including single top (delicate bkg) the differential b-jet $p_T$ measurements show an increased some tension

- W$b\bar{b}$ cross section in agreement with NLO (MCFM) and kinematics also well described by mp ME(LO)+PS (Madgraph + Pythia)

# Conclusions

- Very active field: many analyses have been performed. They:
  - extend the previously probed phase space
  - test and challenge the (many) predictions based on very recent calculations

- The Tevatron measurements have pioneered the study of W,Z +jets, the higher statistic at LHC allows more precise measurements in particular of W,Z + HF jets

- General good agreement with NLO predictions: data/MC tension observed in some distributions attributed to missing higher order or matching schemes needs to be understood (effort started to discuss among experiments and with theorists)

- Understanding the W,Z+ (HF) jet production is a key for finding New Physics

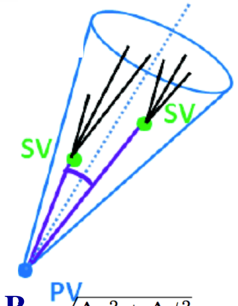
- The LHC data recorded in 2012 have still to be analysed: reduction in the statistical uncertainty (in high multiplicity, high pt bins, and in heavy flavor channels) are expected (as well as of some systematic uncertainties)

Backup

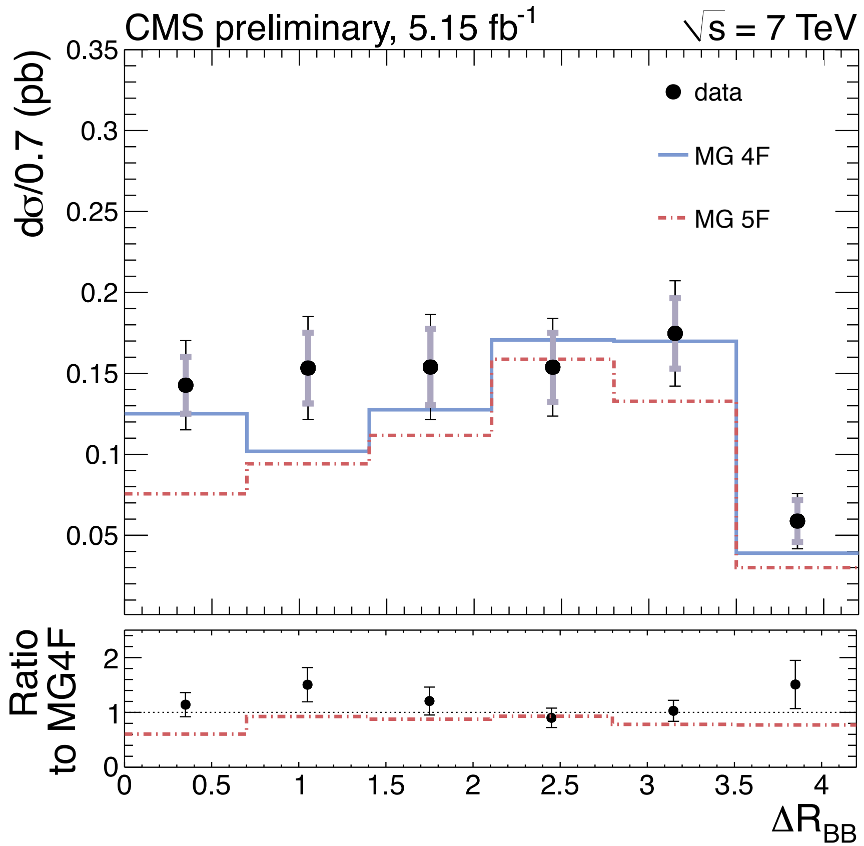
# Z+ b @ LHC

CMS-PAS-EWK-11-015

Study of the **angular separation between B hadrons**.
B hadrons are identified as displaced secondary vertices without use of jets, (Iterative Vertex Finding)
This allows to study B-hadron pair production at **small angular separation**




$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

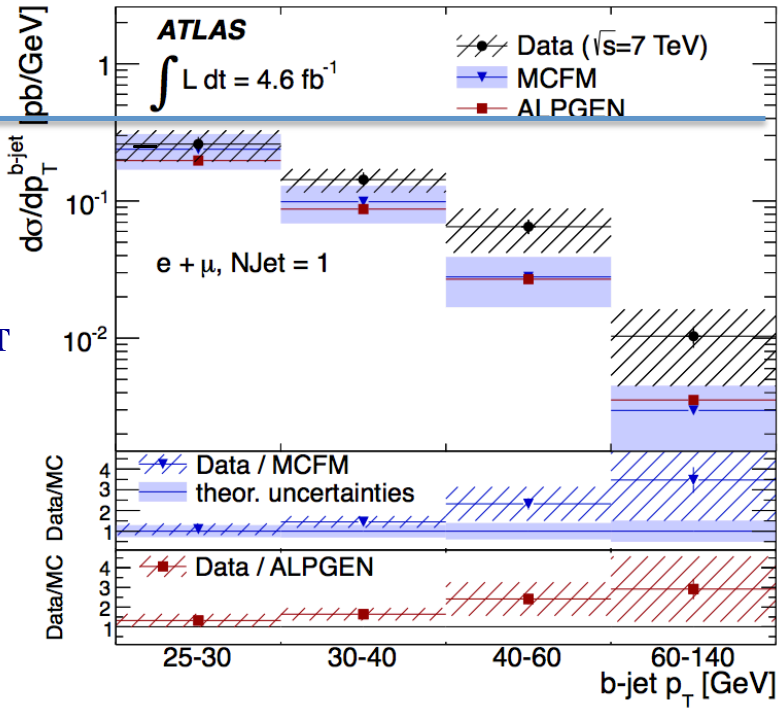



- **ΔR(BB-hadrons):** reasonable agreement with **MG4F**, **MG5F** seems to undershoot the data in the collinear region.

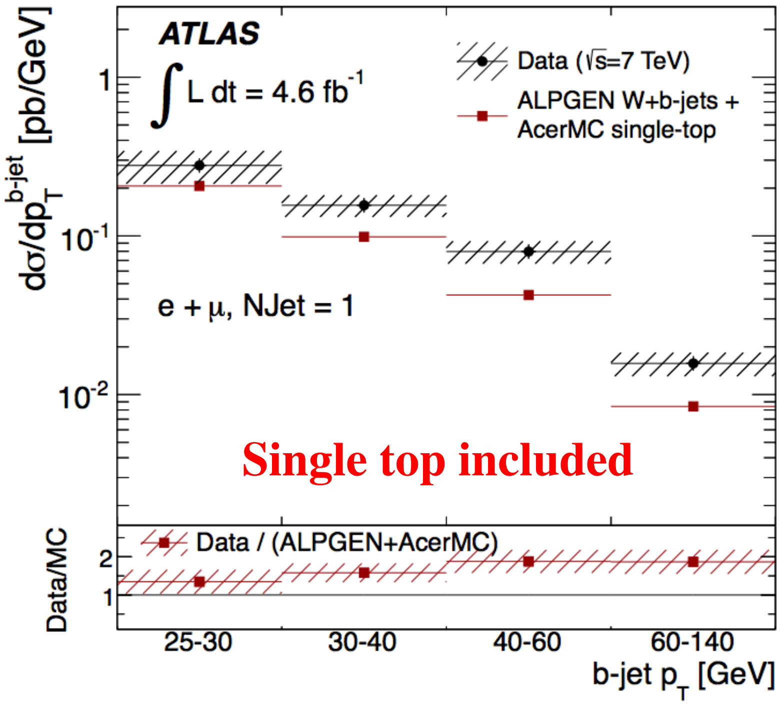
arXiv:1302.2929

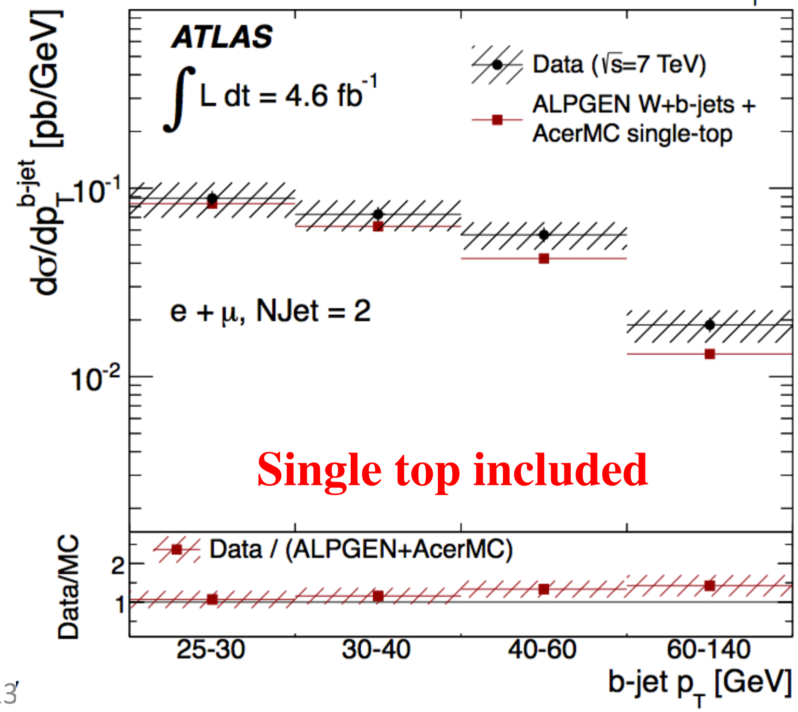
# W+ b jets

- Data/MC systematically increase with $P_T^{\ jet}$
- Top and single-top impact at high $p_T$
- Double-parton-interactions impact at low $p_T$

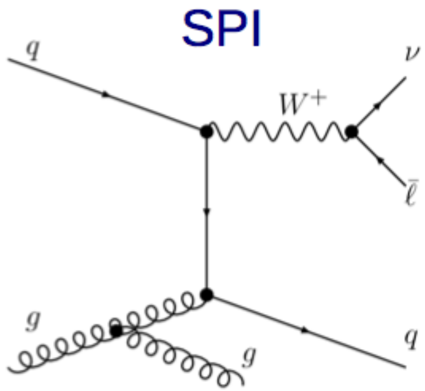


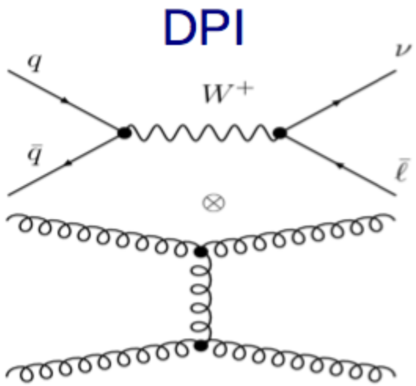

- Single-top is a delicate background
- Significantly reduce total uncertainties by including it in the estimate



# DPI in W + 2 jets




$$\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z} = \frac{\hat{\sigma}_Y \cdot \hat{\sigma}_Z}{\sigma_{\mathrm{eff}}}$$

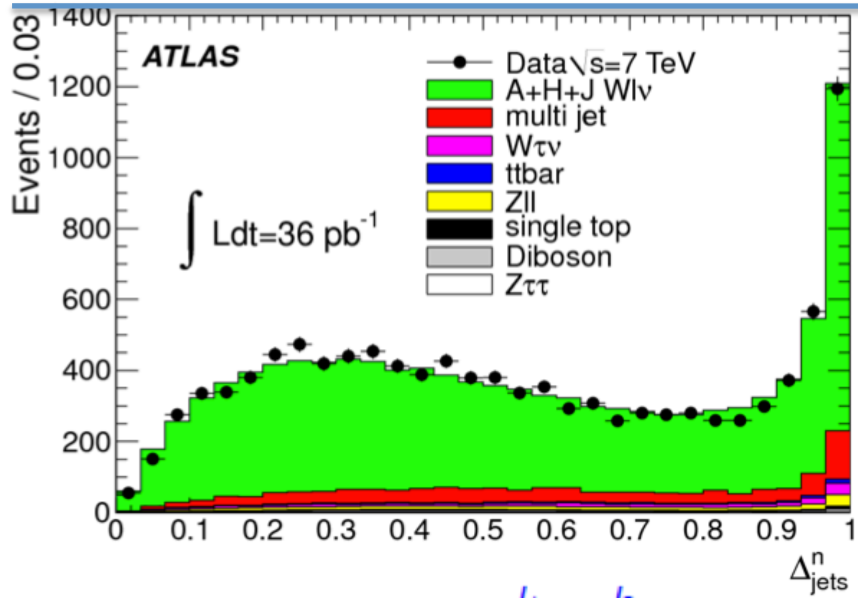
$$\hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s) = \hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s) + \hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s) = \hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s) + \frac{\hat{\sigma}_Y(s) \cdot \hat{\sigma}_Z(s)}{\sigma_{\mathrm{eff}}(s)}$$

$$\sigma_{\mathrm{eff}}(s) = \frac{\hat{\sigma}_Y(s) \cdot \hat{\sigma}_Z(s)}{\hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s) - \hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s)} = \frac{\hat{\sigma}_Y(s) \cdot \hat{\sigma}_Z(s)}{f^{(\mathrm{D})}_{\mathrm{DP}} \cdot \hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s)}$$

$$\sigma_{\mathrm{eff}} = \frac{\sigma_{W_{0j}} \cdot \sigma_{2j}}{\sigma_{W_{0j}+2j_{\mathrm{DPI}}}} = \frac{\sigma_{W_{0j}} \cdot \sigma_{2j}}{f^{(\mathrm{D})}_{\mathrm{DP}} \; \sigma_{W+2j}} = \frac{1}{f^{(\mathrm{D})}_{\mathrm{DP}}} \cdot \frac{N_{W_{0j}}}{N_{W+2j}} \cdot \frac{N_{2j}}{\mathcal{L}_{2j}}$$

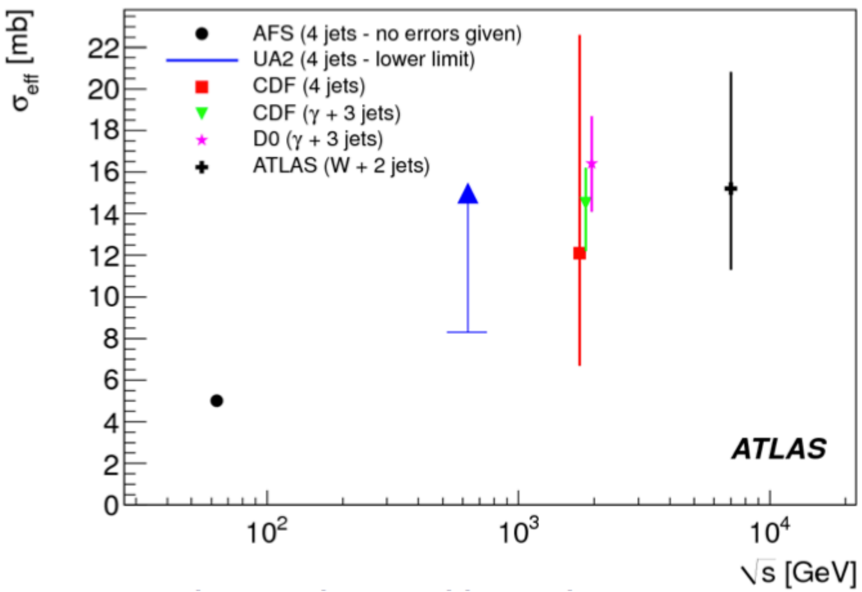
Fraction of DPI-produced in W+2j events at detector level

# DPI in W + 2 jets




**Fraction of DPI events in W+2jets data extracted from a template fit to normalized transverse momentum balance**

$$\Delta^{n}_{\text{jets}} = \frac{|\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}|}{|\vec{p}_T^{\,J_1}| + |\vec{p}_T^{\,J_2}|}$$




**Results consistent with previous measurements at lower energies**

$$f_{\text{DP}}^{(\text{D})} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{sys.})$$

$$\rightarrow \sigma_{\text{eff}}(7\ \text{TeV}) = 15 \pm 3\ (\text{stat.})\ ^{+5}_{-3}\ (\text{sys.})\ \text{mb}$$

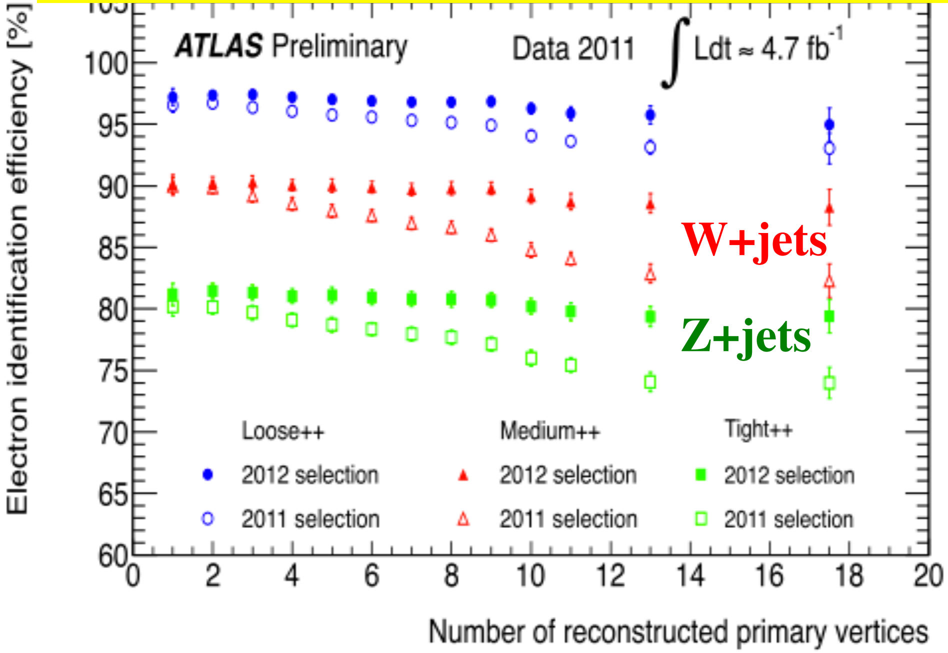
# Pile UP @ LHC

**@ LHC : Pile UP. It affects in particular:**

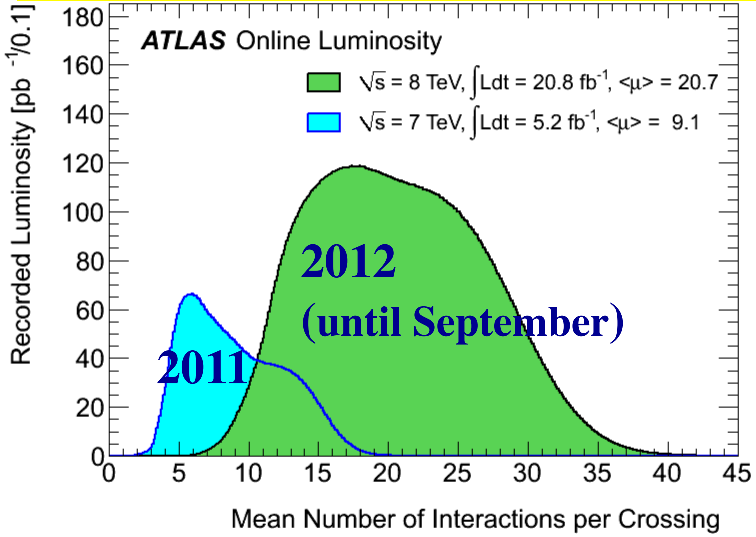
- $E_{Tmis}$ and Jet reconstruction
- Lepton isolation

→ robust algorithms & PU corrections

Electron identification efficiency with 2011 data

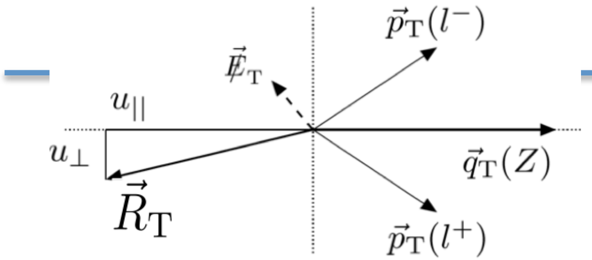


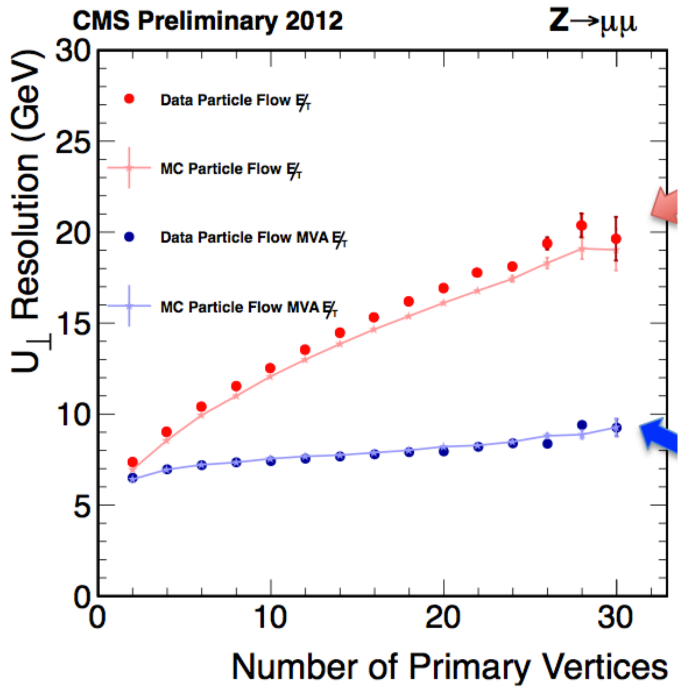

Mean number of interactions/crossing




- ◆ **N.B. : most of the recent results on V+jets are with 2011 data (lower PU)**
- ◆ **For leptons, mainly use : optimized cut based identification & isolation criteria (MultiVariateAlgorithms exist)**

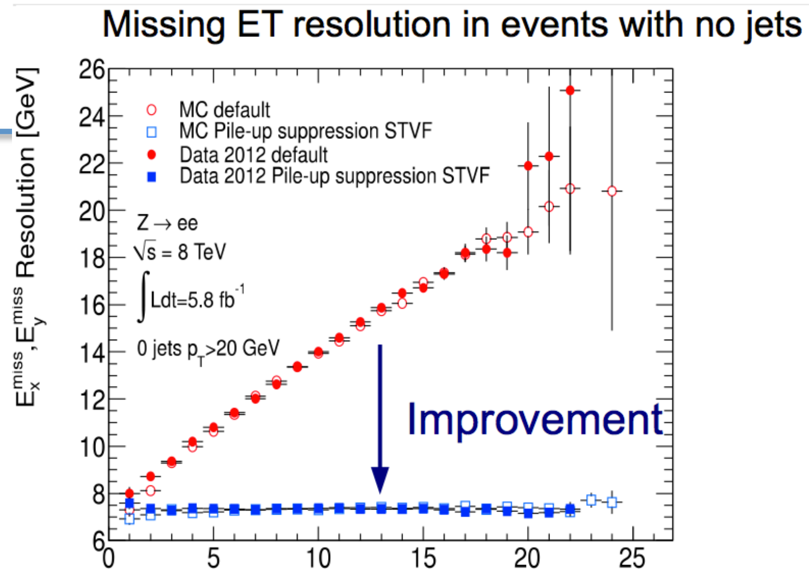
# Et miss

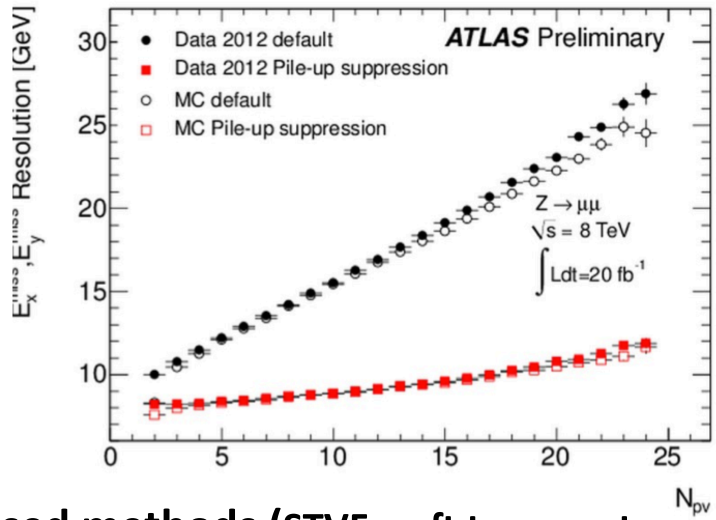



All Particle

MVA



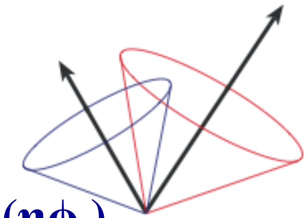



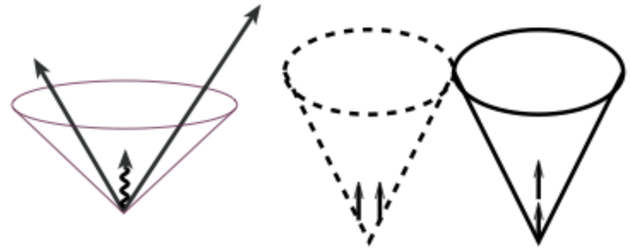

MET from all particles,
MET from PU particles, MET from primary vertex particles …
→ Multivariate MET estimation

**Track-based methods (STVF=soft term vertex Fraction) and Jet area method**

Scales $E_{miss},^{SoftTerm}$ the fraction of tracks (STVF) matched to the $Emiss,_{SoftTerm}$ associated with the hard scattering vertex.

# Jet Algorithms





**Two main categories of jet algorithms based on:**

*** Cone**

**Cluster based on their proximity in (ηϕ )**

**Simple but IR unsafe**

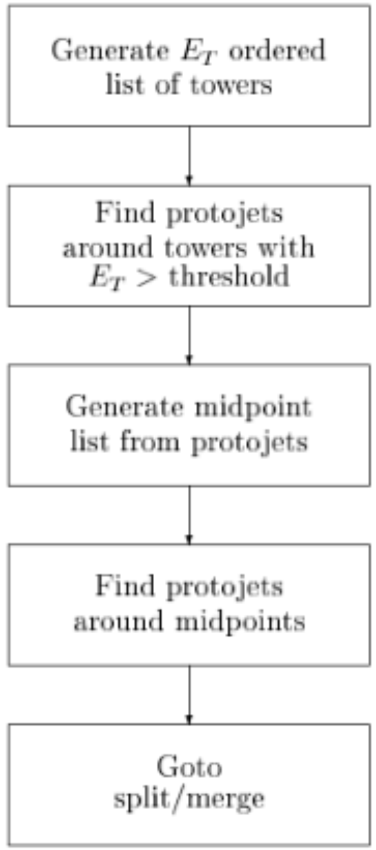
*** Successive Combination**

**Infrared safe**

**Jet geometry can be complicate**

**Mid-cone: approximates a seedless algorithm.**

**It is a seed-based algorithm but with the addition of 'midpoints' in the list of starting seeds.**
**By adding a starting point for clustering at the positions given by $p_i + p_j$ , $p_i + p_j + p_k$ etc.,**
**the sensitivity of the algorithm to soft radiation is essentially removed.**




**Method for addition of midpoints**

# Anti-$k_T$ Algorithm (Cacciari, Salam, Soyez, 2008)

- **Metric:** $d_i = p_{T,i}^{2p}$ and $d_{ij}$

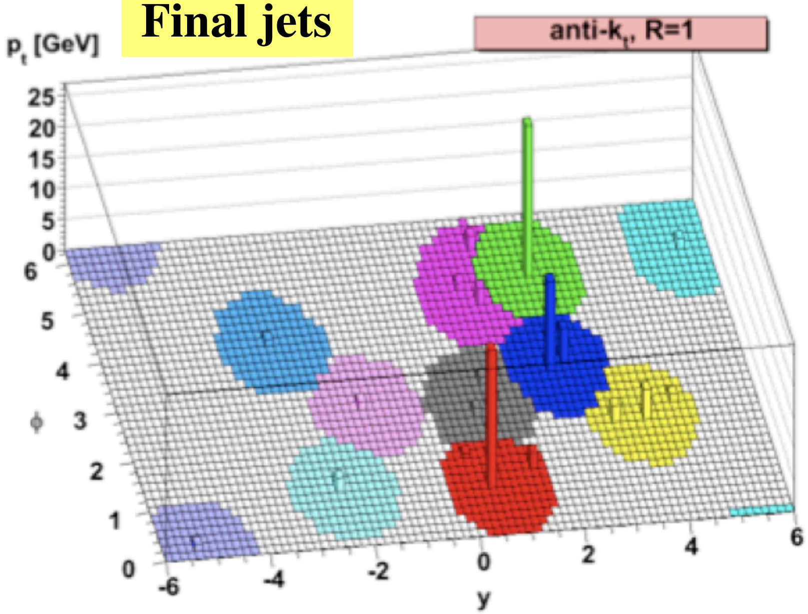
| | |
|---|---|
| p = -1 | Anti-$k_T$ Algorithm |
| p = 0 | Cambridge/Aachen algorithm |
| p = 1 | $k_T$ Algorithm |

- **Resolution parameter:** R [R=0.4, 0.5, 0.6, ..,1]
- **Recombination procedure:**
  - compare all $d_i$ and $d_{ij}$
  - find $d_{min}$
  - if $d_{min}$ is a $d_i$ add particle i to the list of jets,
  - if not replace i and j with the jet ij

$[d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p})\, \Delta R_{ij}^2/R^2]$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

Final jets




http://arxiv.org/abs/0802.1189

**Anti-$k_T$ is the standard jet finding @ LHC:**

★ $d_{min}$ determined mainly by hardest particles →soft particles cluster earlier with hard particles then among themselves
→ Soft particles do not modify shape of jets

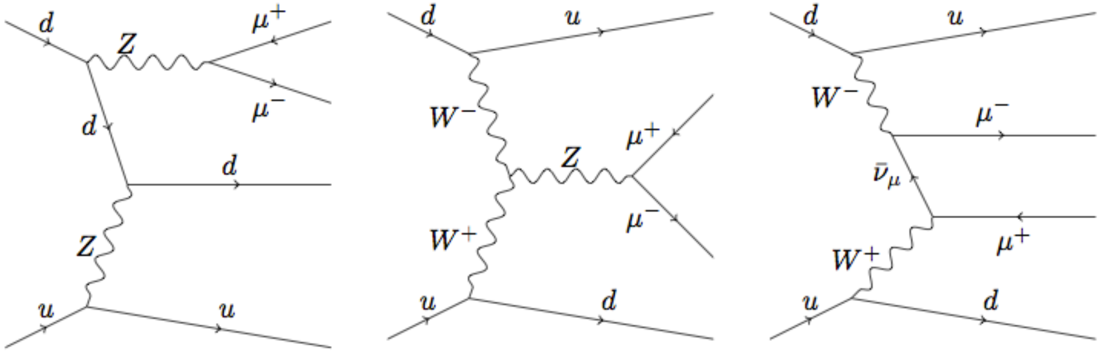
★ If a hard particle has no other hard neighbors it forms a round jet

★ Jets with ~ circular in space good for experimental corrections

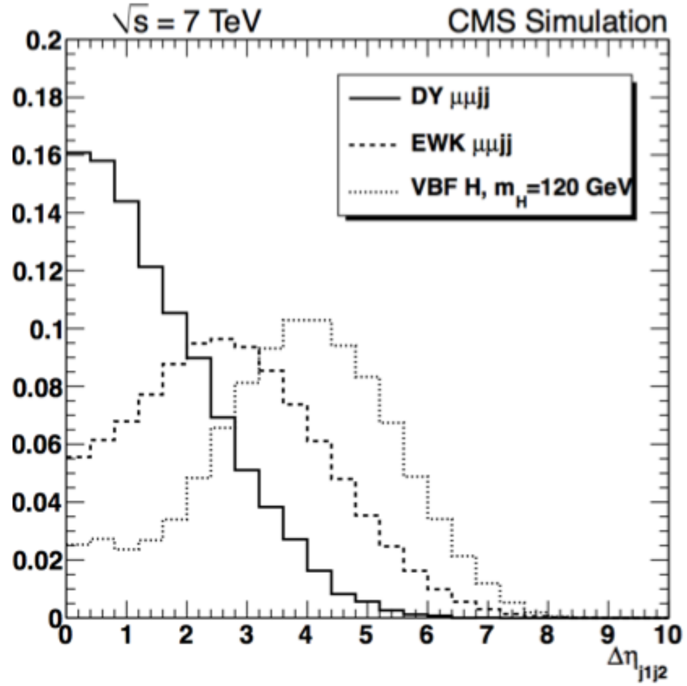
# Theory uncertainties on NLO pQCD – Z+jets

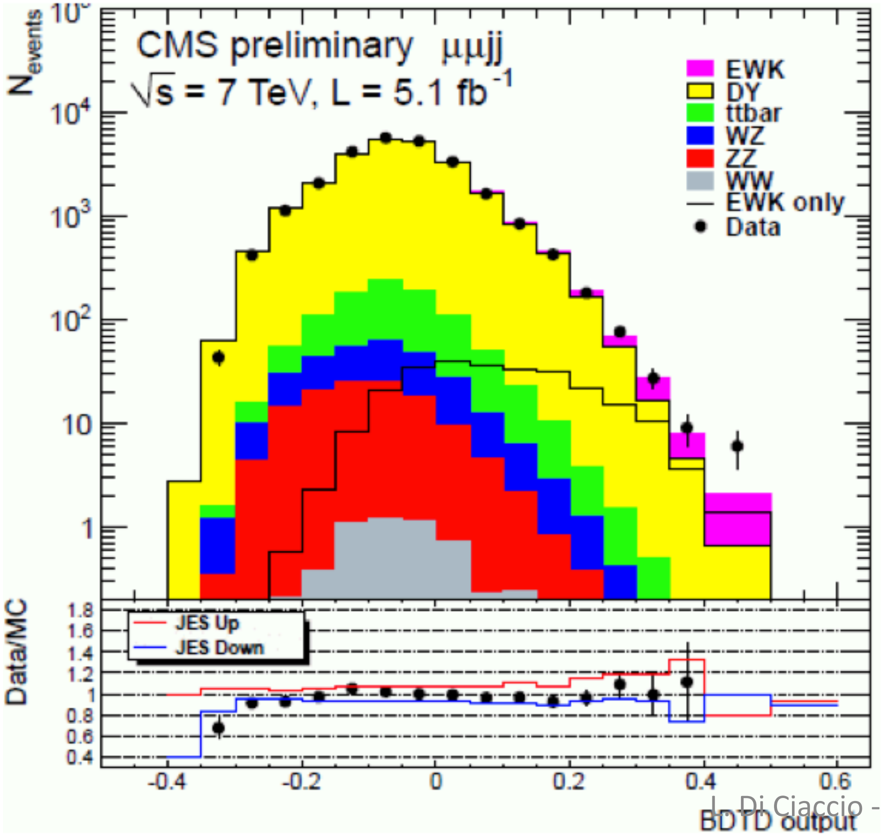
- Scale:
  - Nominal hadronization and factorization scale: $H_T/2$
  - Systematics: varying both scales simultaniously by factor of 2
    → 4% - 13% for $N_{jet} \geq$ 1-4, dominant uncertainty
  - Exclusive distributions: I.W.Stewart, F.J. Tackmann, Phys.Rev. D 85 (2012) 034011
- PDF:
  - CT10
  - Systematics: complete PDF CTEQ10 error set, 68%CL (1% - 3% for $N_{jet} \geq$ 1-4)
- $\alpha_s$ uncertainty:
  - varying the input $\alpha_s$ at the Z scale by +/- 0.0012 (1% - 3% for $N_{jet} \geq$ 1-4)
- Theoretical prediction are corrected for
  - QED radiation effects:
    - Nominal correction: ALPGEN+HERWIG+PHOTOS (~2%)
    - Systematics: Sherpa 1.4 +YFS
  - non-perturbative contributions (UE, fragmentation):
    - Nominal correction: ALPGEN+HERWIG AUET2 tune (~3%-4%)
    - Systematics: ALPGEN+Pythia6 Perugia2011 tune

# EW production of Z with two forward jets




Bremsstrahlung VBF multiperipheral




$m_{ll}$ > 50 GeV,
$p^{j}_{T}$ > 25GeV,
$|\eta j|$ < 4.0,
$m_{jj}$ >120 GeV.

Interference between the EWK and DY lljj production processes found negligible