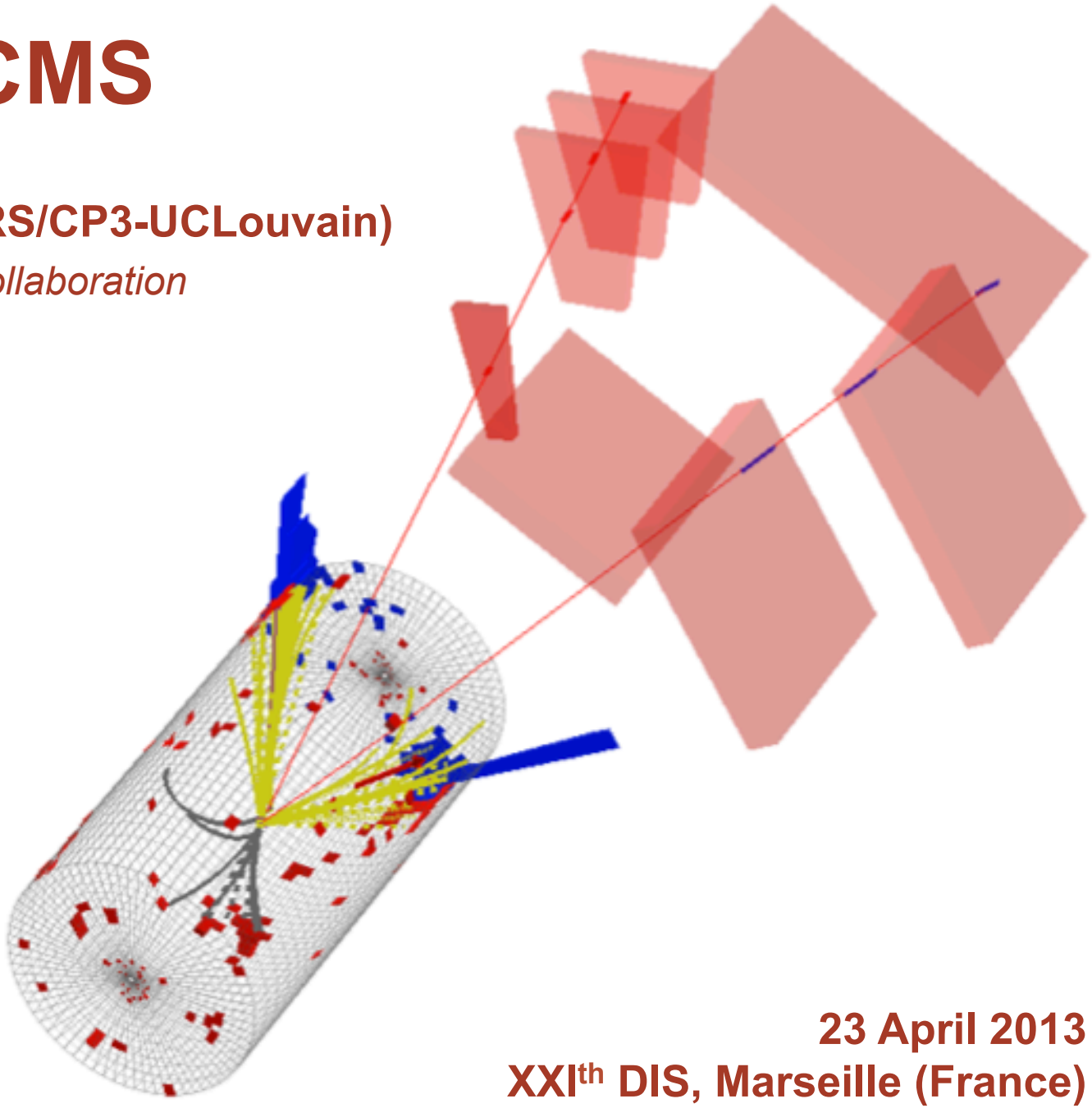
V+jets at CMS

Tristan du Pree (FNRS/CP3-UCLouvain)

on behalf of the CMS Collaboration

V+j
- Z+j
- γ+j
- W+j

V+HF
- Z+b
- W+b
- W+c



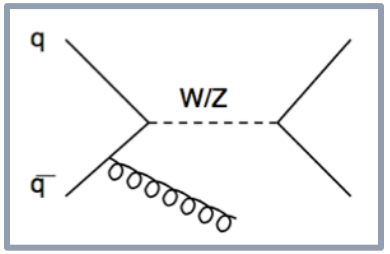
23 April 2013

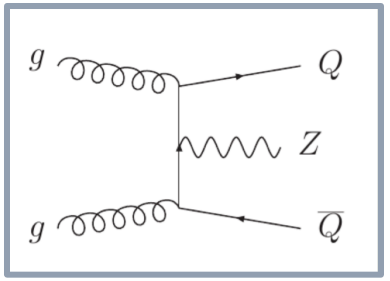
XXIth DIS, Marseille (France)

Introduction

Motivations for V+jets

- **Major backgrounds for many searches**
  - Final states with jets and leptons
  - Higgs, susy, exotica
- **Precision tests of QCD**
  - Including jets from heavy quarks



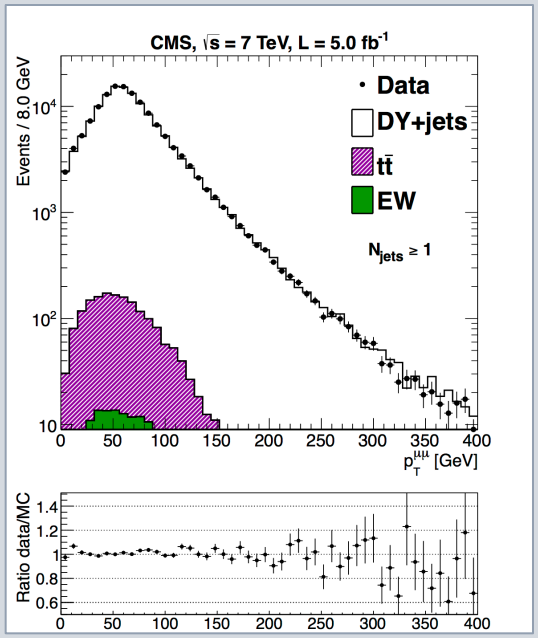


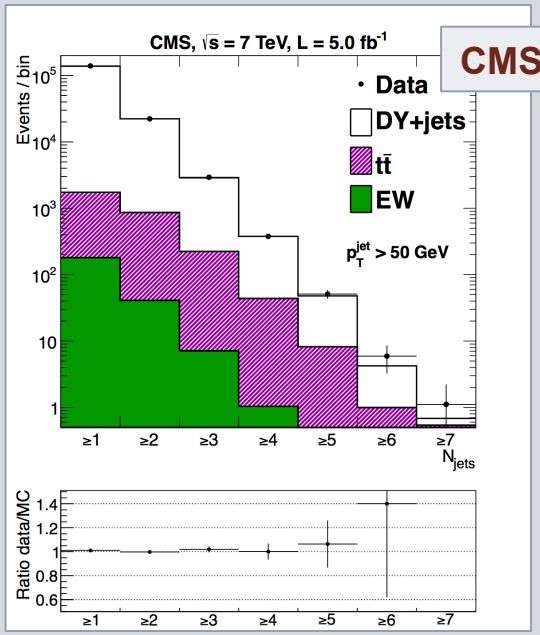
- **V+jets at CMS**
  - Complete overview at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP#Vector_Boson_Jets_Production
- **Coming 15 minutes: most recent CMS V+j results**

Z+jets

$p_T(l) > 20$ GeV
$|\eta(l)| < 2.4$
$|m(ll)-91| < 20$ GeV
$p_T(j) > 50$ GeV
$|\eta(j)| < 2.5$

- **Kinematics after Z+jet selection**
- **Agreement in shape and scale**
  - Applying global NNLO correction ('k factor') on MadGraph+Pythia



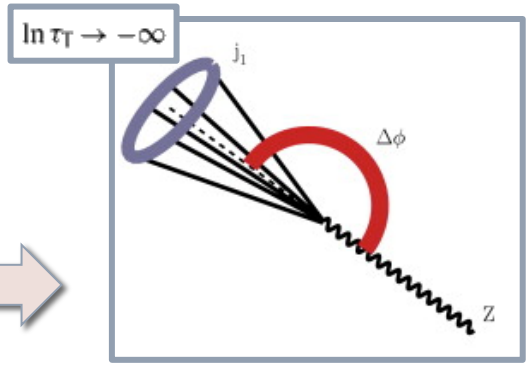


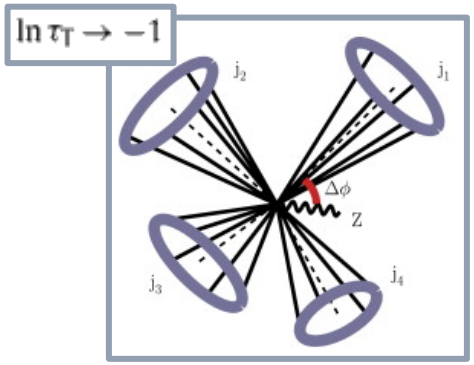
CMS EWK-11-021

- **Study of event shapes**
  - All possible azimuthal correlations in Z+>=3-jets
    ΔΦ(Z,j), ΔΦ(j,j) measured in bins of N_{jet} and $p_T(Z)$ ➔ see backup

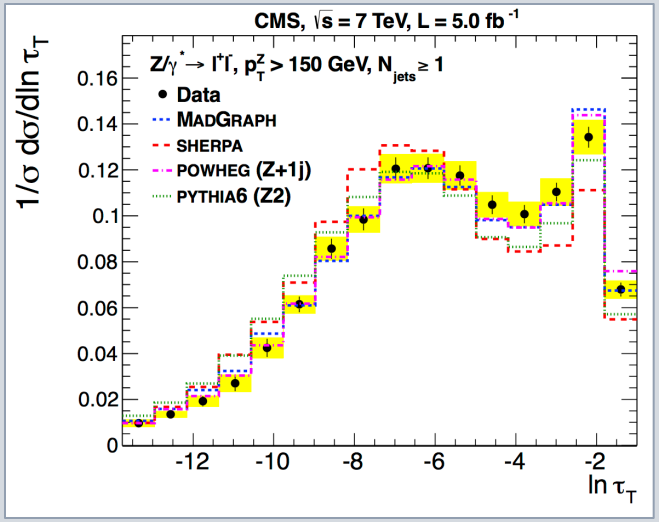
Z+jets

$$\tau_T \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{T,i} \cdot \vec{n}_\tau|}{\sum_i p_{T,i}}$$

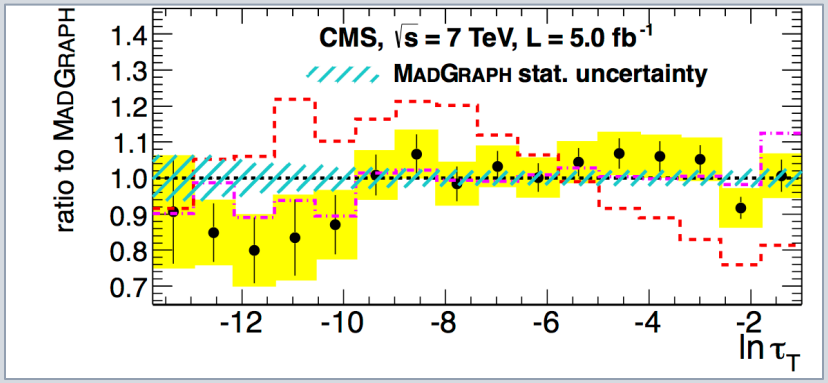




- **Thrust:** test kinematic topology



CMS EWK-11-021



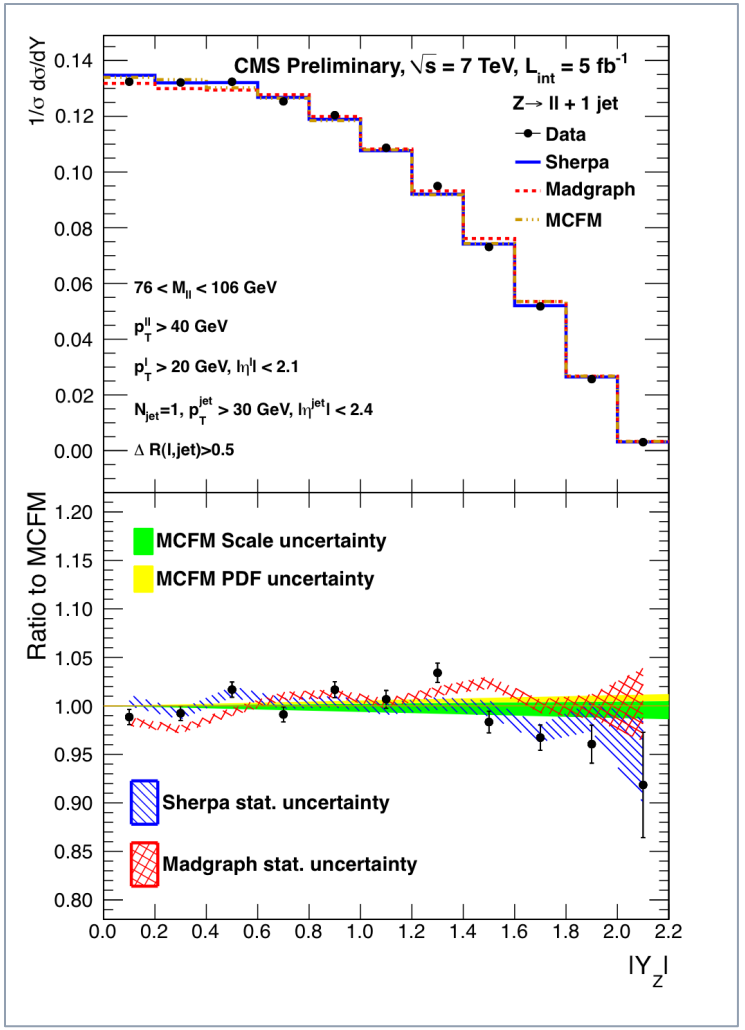
- **Correct description**: MadGraph and Powheg
- **Shifted to lower values**: Pythia6 (PS only) and Sherpa
  - More dijet like

CMS SMP-12-004

Z/γ+1jet

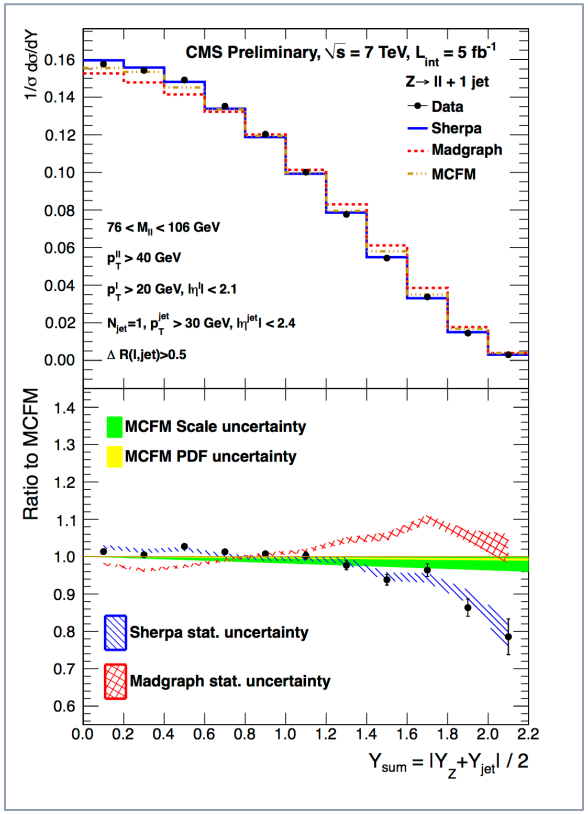
- **Require exactly 1 jet…**
  - $p_T(j)>30$ GeV, $|\eta(j)|<2.4$
- **…and a boson**
  - Photon: $|\eta(\gamma)| < 1.4$
  - Z boson: $76 < m(ll) < 106$ GeV
- **Rapidity distributions agree**
  - At particle level
    - After background & efficiency corrections
    - Y_γ and Y_{jet} in backup

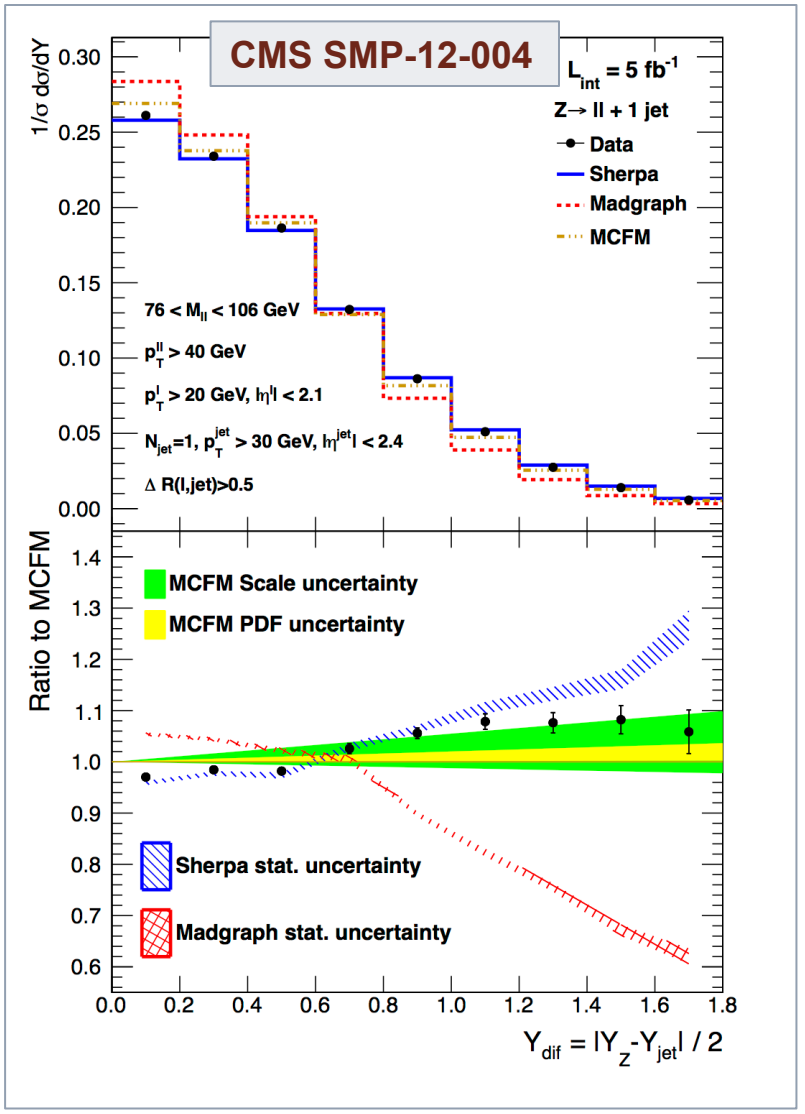
- Rapidity sum & Rapidity difference in V+J center-of-momentum ('COM')
  - $\mathbf{Y_{dif}} = |Y_V - Y_{jet}|/2$
    - Related to polar angle cosθ* in V+j COM
  - $\mathbf{Y_{sum}} = |Y_V + Y_{jet}|/2$
    - Boost from lab to V+j COM



Z/γ+1jet

- **Agreement with NLO predictions at particle level**
  - MCFM (Z+jet) and Owens (γ+jet)





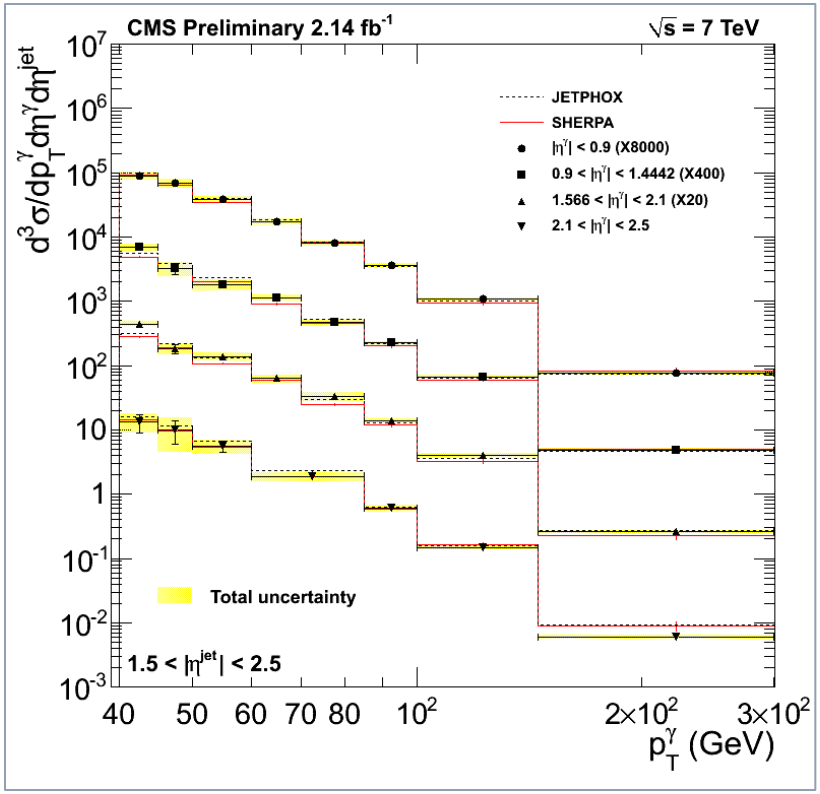
- **Sherpa** reproduces data better than **MadGraph**
  - Differences attributed to **matching procedure**

CMS QCD-11-005

γ+jets

- **Photon+jet**
  - $p_T(\gamma) > 40$ GeV
  - $p_T(j) > 30$ GeV
  - $|\eta| < 2.5$
- **Triple differential cross section**
  1. $p_T(\gamma)$
  2. $\eta(\gamma)$
  3. $\eta(j)$

➢ Comparison with Sherpa (tree-level) and Jetphox (NLO) after correcting for backgrounds and efficiencies

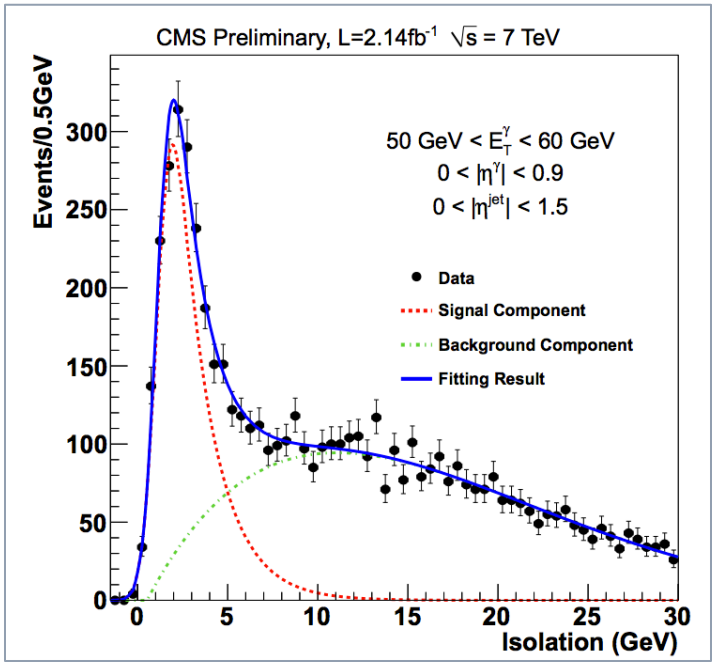


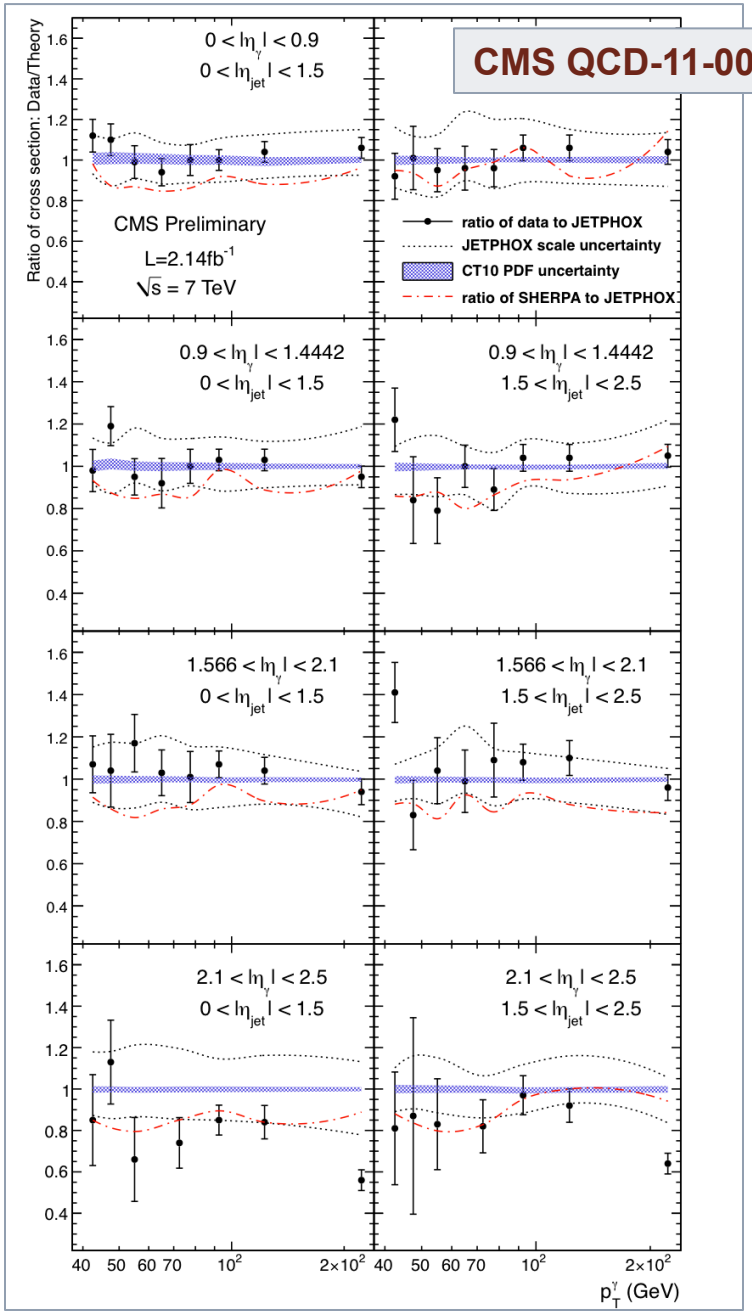
➢ **Study of orientations between photon and jet**

➢ Eight differential measurements in different η bins

γ+jets

- **Compare predictions with data**
  - Main systematic uncertainty: **photon signal purity**
- **Jetphox** agrees well
- **Sherpa** underestimates



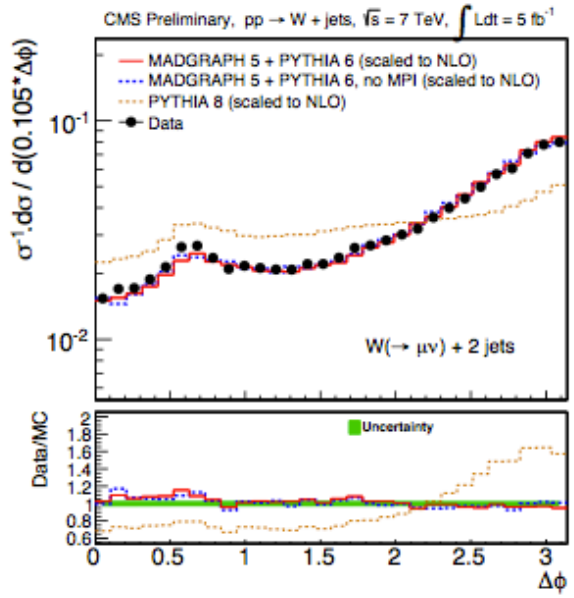


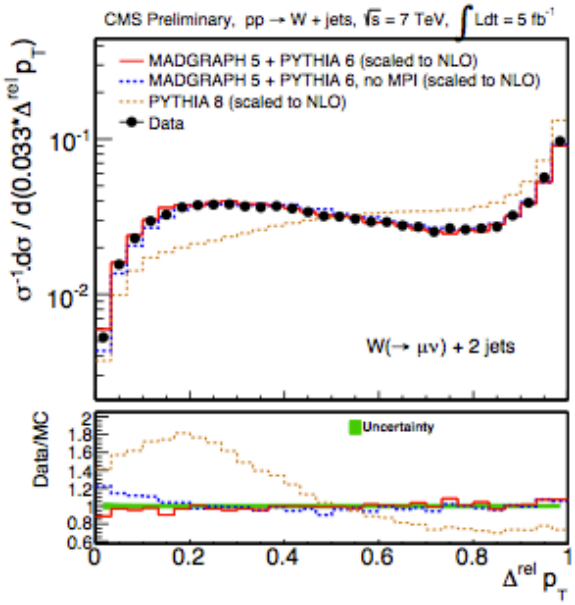
W+2-jets: DPS

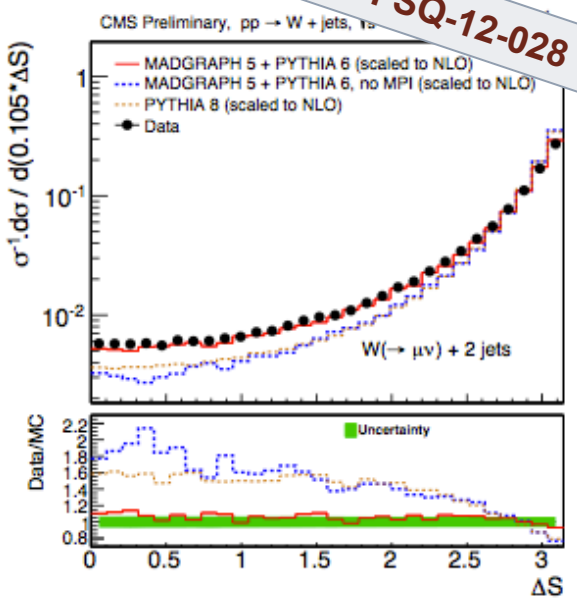
$p_T(l) > 35$ GeV
$|\eta(l)| < 2.1$
$M_T > 50$ GeV
$p_T(j) > 20$ GeV
$|\eta(j)| < 2.0$

- **Study of Douple Parton Scattering**
  - Different MPI-sensitive observables

CMS FSQ-12-028





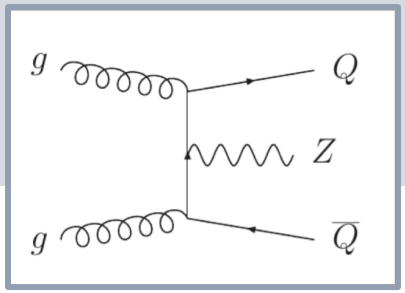


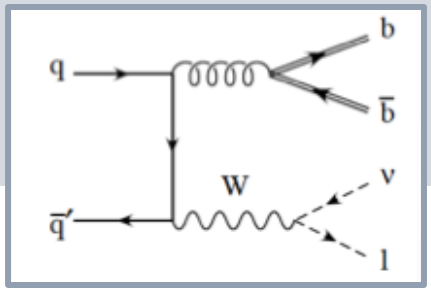
- **MadGraph+Pythia correctly describes observations**
  - More details in presentation of Paolo Bartalini

V+j → V+HF

V+HF

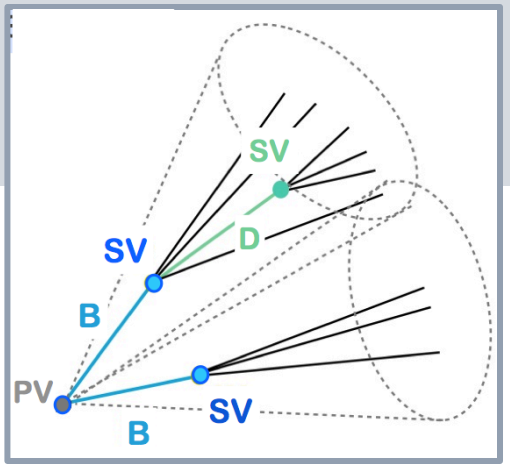
- Heavy flavor quarks





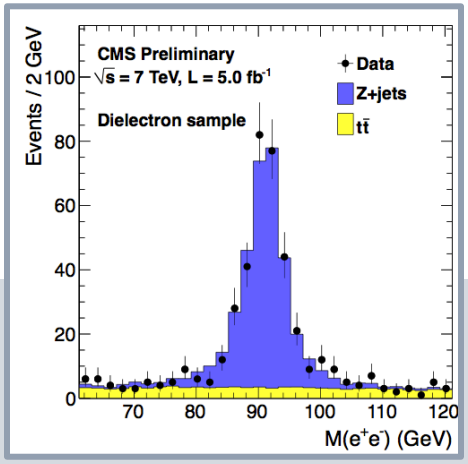
Identify HF jets

- B-tagging



Backgrounds increase

- E.g. ttbar

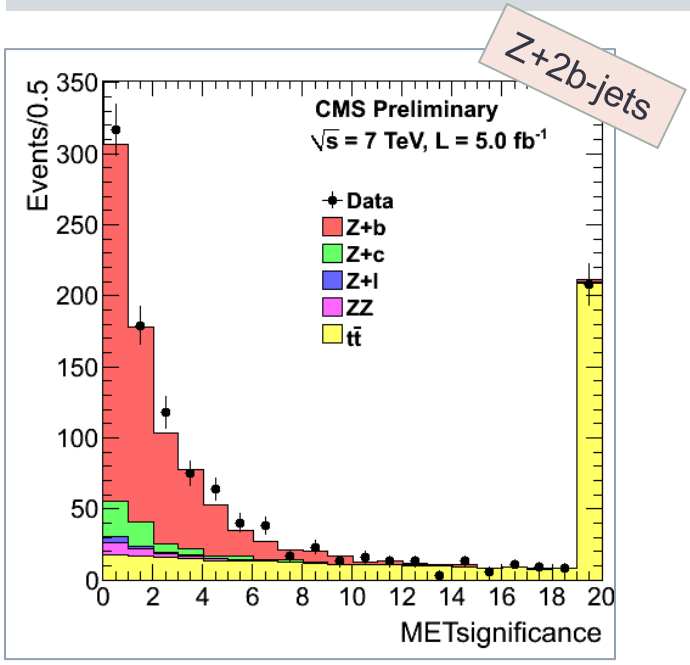


CMS SMP-13-004

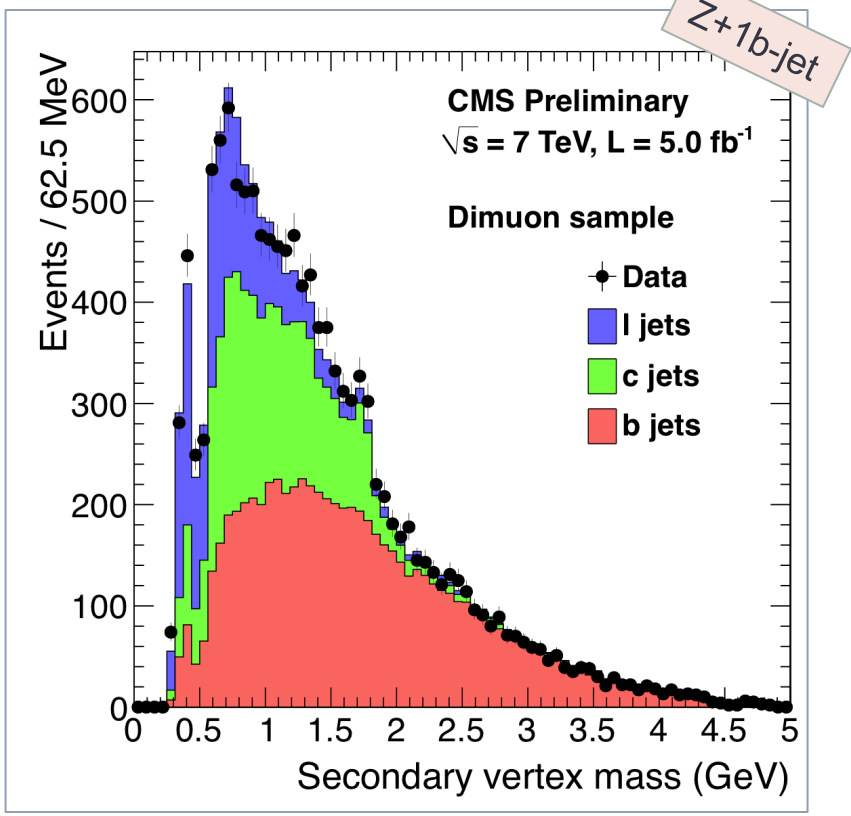
Z+b's

Backgrounds

- **ttbar**
  - Reduce with **MET-significance**
    - Event-by-event MET likelihood
  - Estimate from fit to **dilepton mass**



- **ZZ**: small contribution
  - From MC, normalized with CMS measurement
    - See presentation by Daniele Trocino



- **Light jets**
  - Reduce with **flight distance significance**
  - Estimate from fit to **secondary vertex mass**

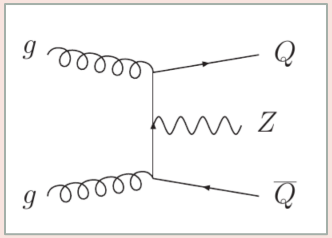
CMS SMP-13-004

Z+b's

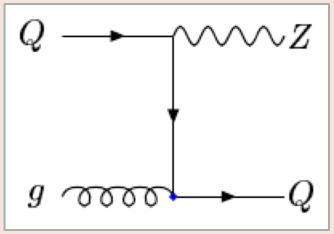
Cross sections

Compare calculation schemes

4 Flavor
(arXiv:hep-ph/1106.6019)
Massive b's
b's in ME



5 Flavor
(arXiv:hep-ph/0312024)
Splitting inside PDF
Massless b



- **Cross sections at particle level**
  - Background subtraction and efficiency correction as function of b-jet multiplicity

Multiplicity bin	measured	MG5F	MG4F
σ(Z($\ell\ell$)+1b) (pb)	$3.52 \pm 0.02(stat.) \pm 0.20(syst.)$	$3.66 \pm 0.02(stat.)$	$3.11 \pm 0.03(stat.)$
σ(Z($\ell\ell$)+2b) (pb)	$0.36 \pm 0.01(stat.) \pm 0.07(syst.)$	$0.37 \pm 0.01(stat.)$	$0.38 \pm 0.01(stat.)$
σ(Z($\ell\ell$)+b) (pb)	$3.88 \pm 0.02(stat.) \pm 0.22(syst.)$	$4.03 \pm 0.02(stat.)$	$3.49 \pm 0.03(stat.)$
σ(Z($\ell\ell$)+b) / σ(Z($\ell\ell$)+j) %	$5.15 \pm 0.03(stat.) \pm 0.25(syst.)$	$5.35 \pm 0.02(stat.)$	$4.60 \pm 0.03(stat.)$

- **Agreement** with MadGraph **in both calculation schemes**
  - Scaling to DY NNLO cross section with k factor

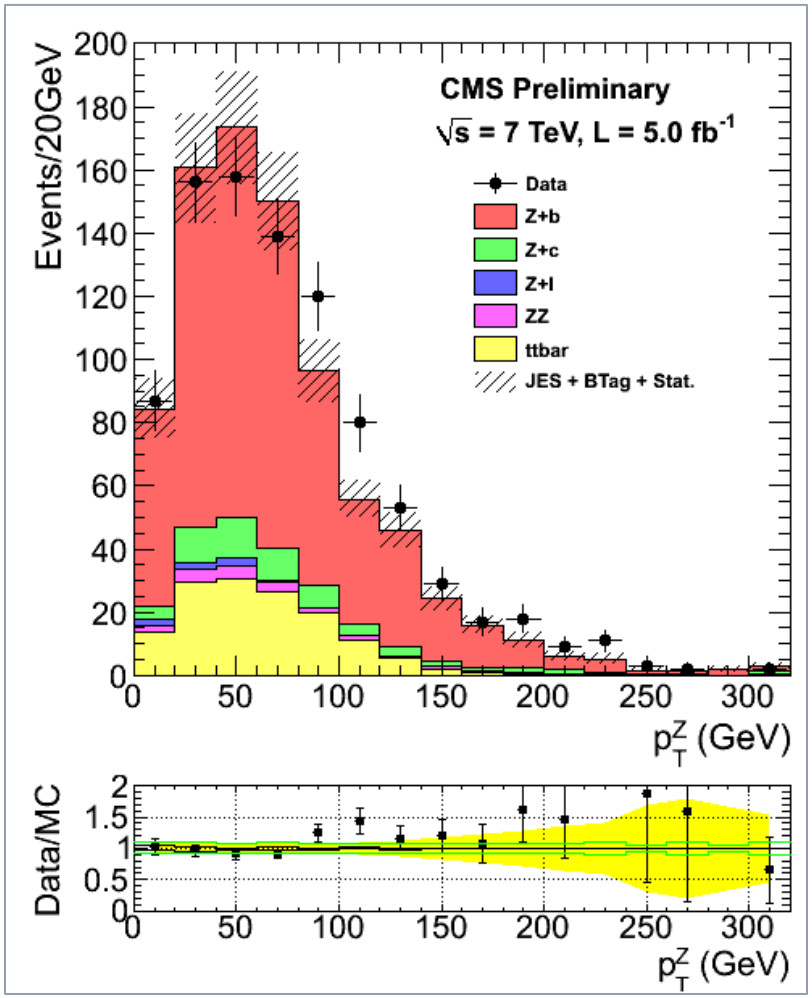
Z+2b
Kinematics

CMS SMP-13-004

- **Observables relevant for searches**
  - Subset of variables well described
    - E.g. M(bb), ΔΦ(Z,bb) (see backup)
- **Tension in $p_T(Z)$**
  - Compared to prediction by MG5F

Also harder $p_T(Z)$ spectrum:
1. **Z+1b-jet**
   http://arxiv.org/abs/1204.1643
2. **NLO with massive b's**
   http://arxic.org/abs/1106.6019v2

- **Investigate generators**
  - 4F **vs** 5F
  - Tree-level with additional light partons **vs** NLO with up to one light parton
  - PDFs, scales, etc...



Z+2b: ΔR(b,b)

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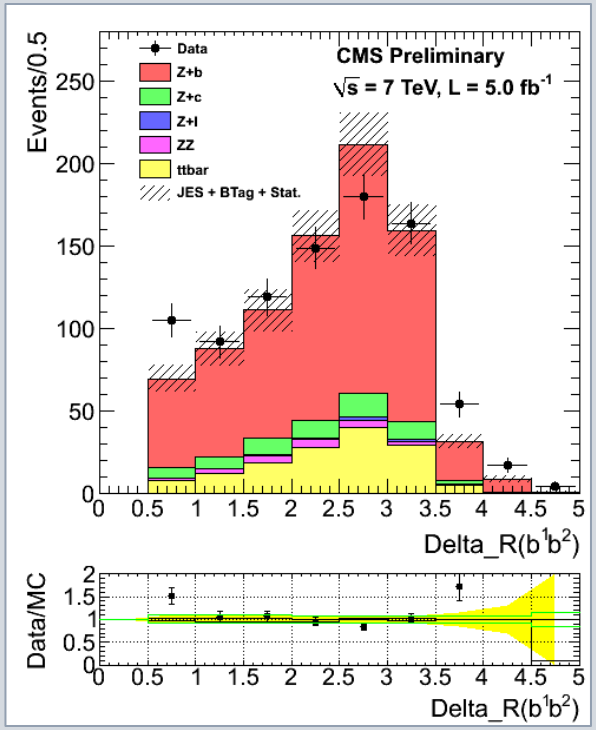
CMS EWK-11-015

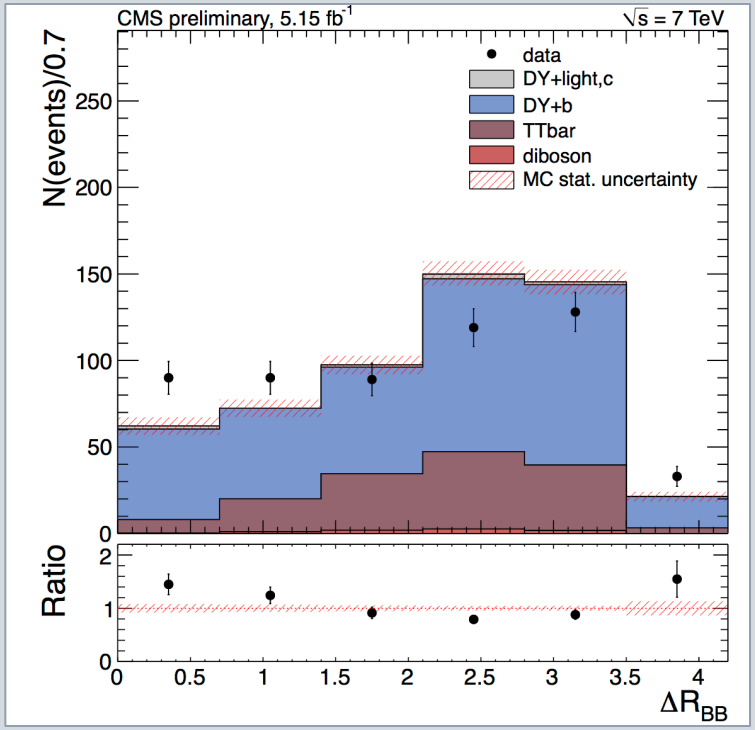
Z+2b-jets

- Jet-based b-tagging



Z+2b-hadrons

- No jets: tag b-hadron SV

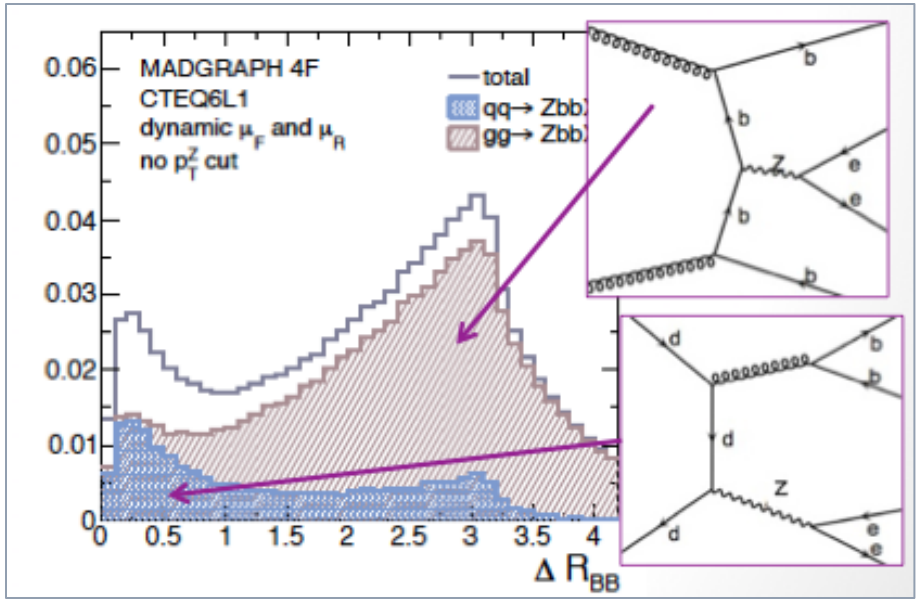


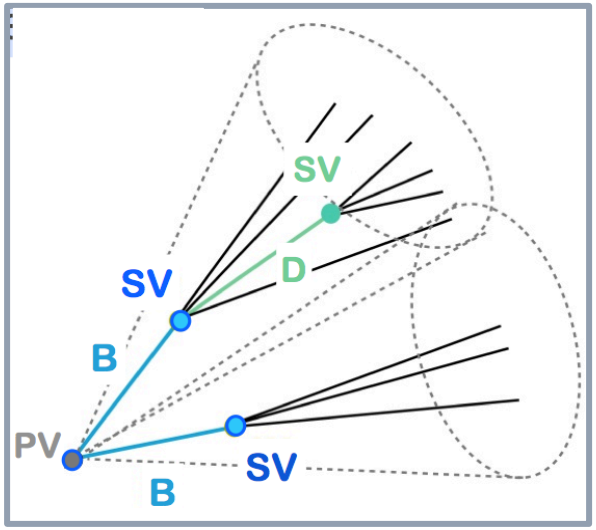
- **Similar tensions** at reconstruction level with different b-tagging approaches

Z+2b

CMS EWK-11-015

Low ΔR(b,b): of interest for
- **Searches**
- **Gluon splitting**





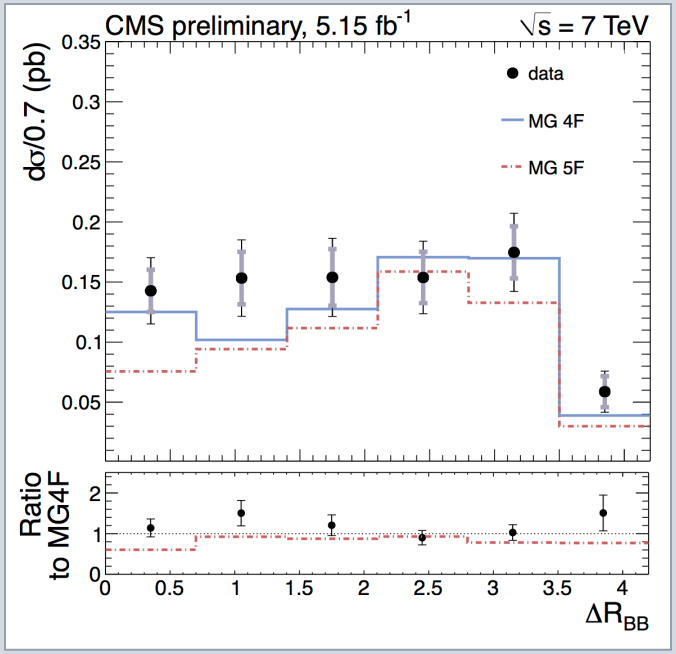
Inclusive Vertex Finder
- No jets, no angular limitation ➔ down to ΔR<0.5
- Exploit CMS tracking
- Excellent angular resolution: σ(ΔR)~0.02

- **Probe collinear region**

Z+2b

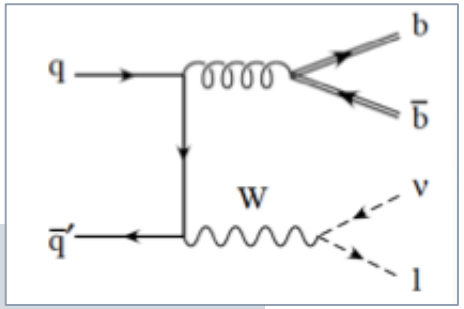
CMS EWK-11-015

- **Signal extraction**
  - After correcting for acceptance, efficiency, and background



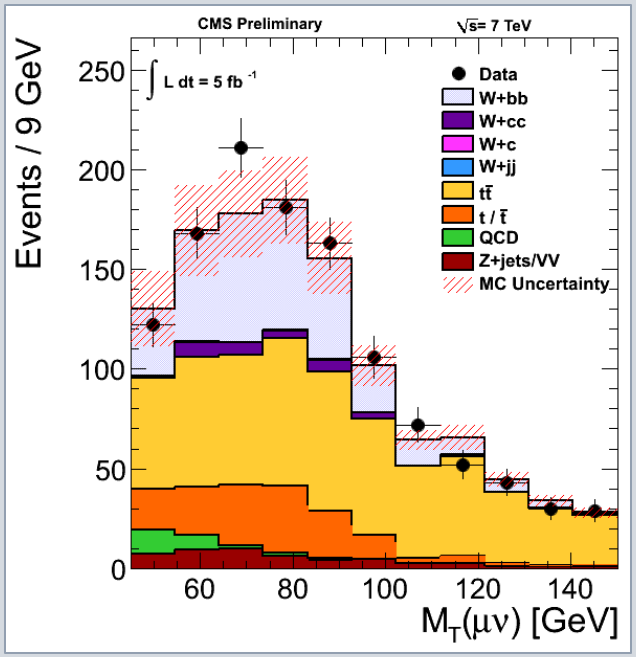
- **Better description by MadGraph 4F**
  - **MadGraph 5F** underestimates collinear region

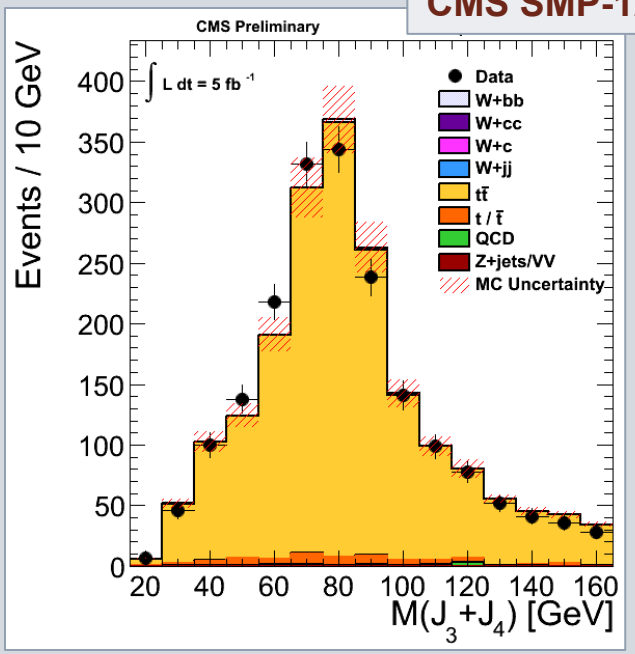
W+2b



- **W+2b-jets: dominated by ttbar background**
  - Two b-tagged jets, one lepton, M_T > 45 GeV

CMS SMP-12-026





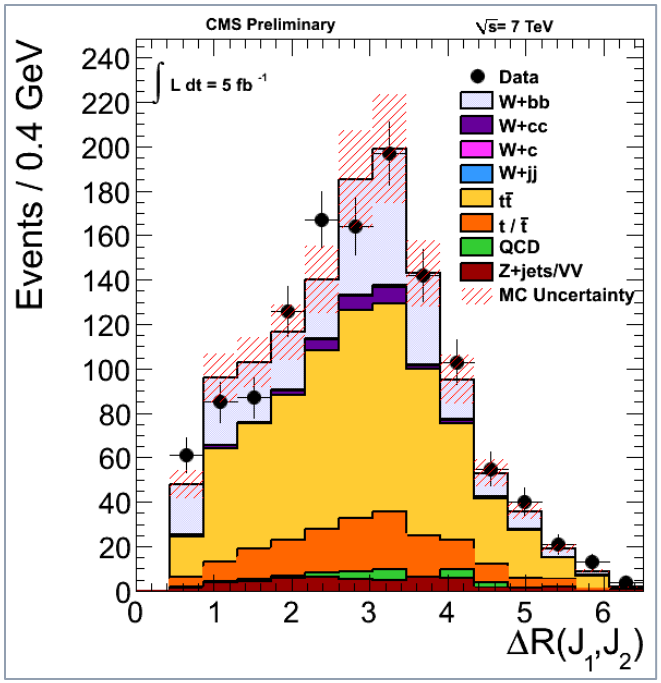
- **Yields estimated from fit**
  - Signal region: two b-tagged jets
  - Ttbar control region: 4 jets (two b-tagged)

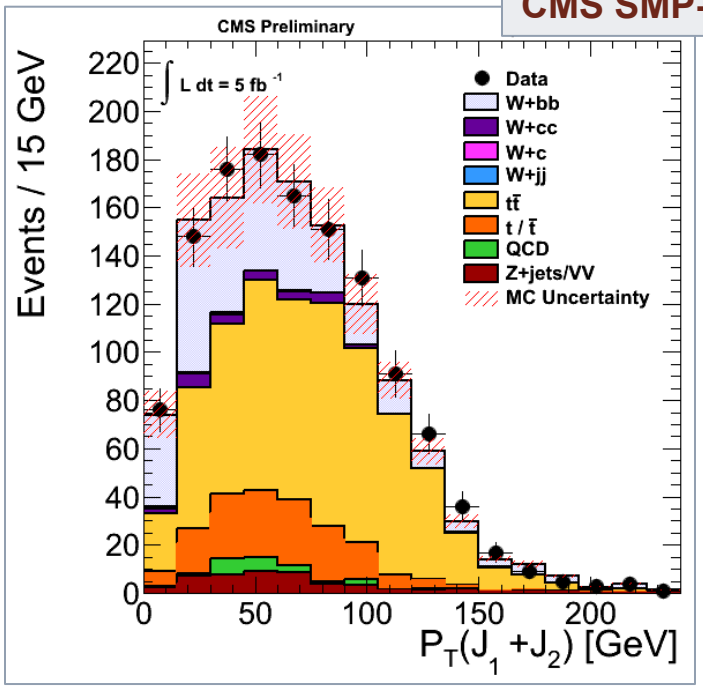
W+2b

$p_T(\mu) > 25$ GeV
$|\eta(\mu)| < 2.1$
$M_T(\mu\nu) > 45$ GeV
$p_T(b) > 25$ GeV
$|\eta(b)| < 2.4$

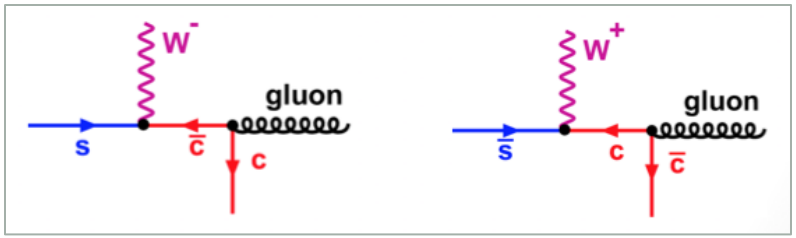
- **Cross section** at particle level
  - $\sigma(W(\mu\nu)+bb) = \mathbf{0.53} \pm 0.05\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.06\,(\text{theo.}) \pm 0.01\,(\text{lum.})$ **pb**
    - Uncertainties dominated by b-tag&JES systematics
- **In agreement with MG+Pythia scaled to NNLO**
  - Kinematics well described by MadGraph 5F + Pythia6

CMS SMP-12-026

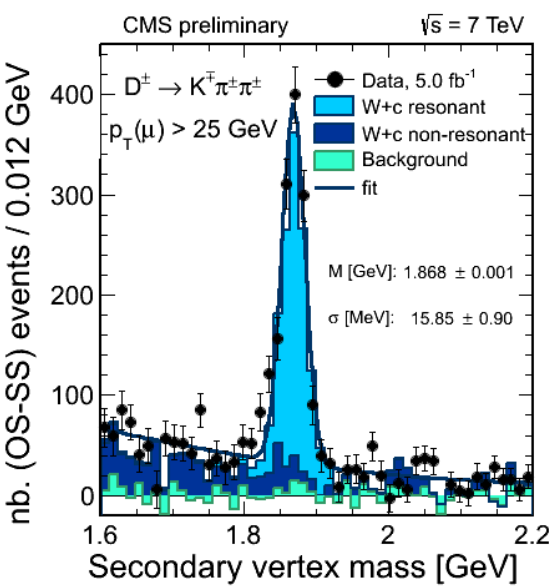


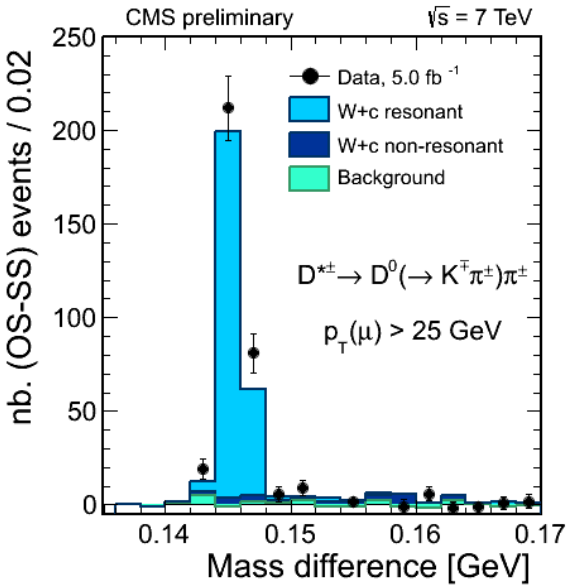


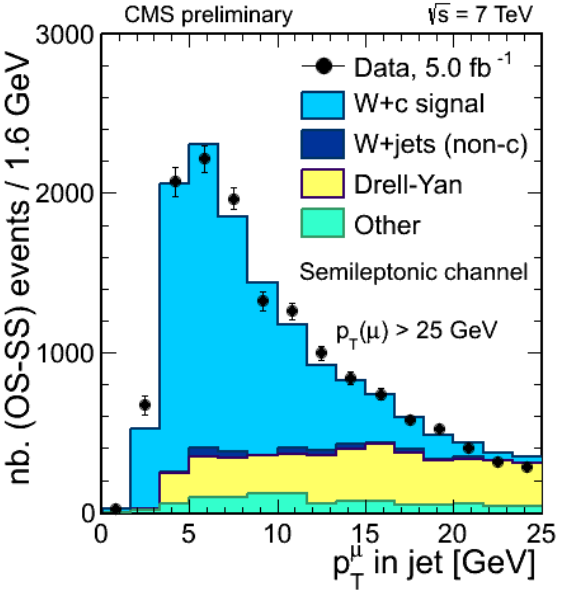
W+c



- **Motivation:** access **strange quark content** of proton
- **Strategy:** exploit **OS nature** of W+c production: use charged D-meson decays
  - $c^{\pm} \rightarrow D^{\pm}$ / $c^{\pm} \rightarrow D^{*\pm} \rightarrow D^0\pi^{\pm}$ / $c^{\pm} \rightarrow l^{\pm}$
    - Exclusive track/vertex reconstruction of D meson decays
  - Correct the predicted branching ratio
  - Use SS tags for background estimate in signal region



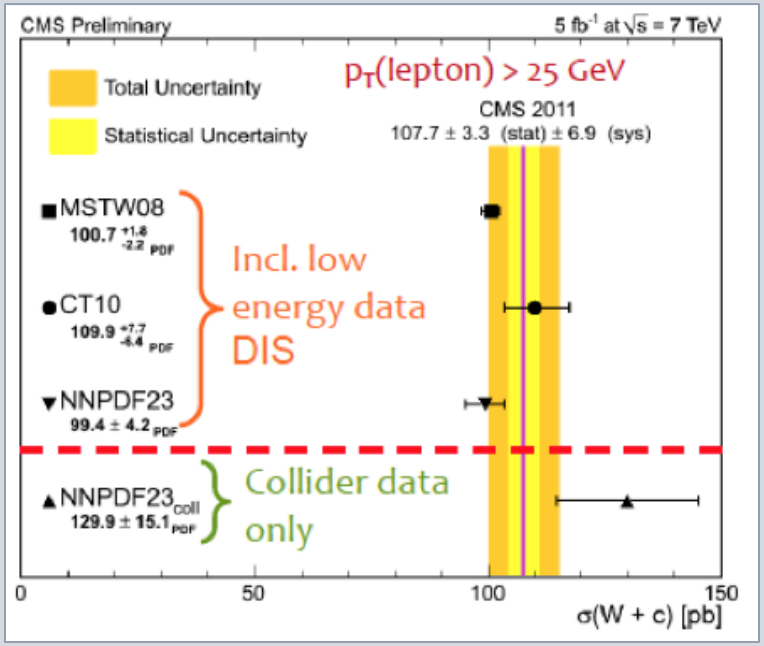


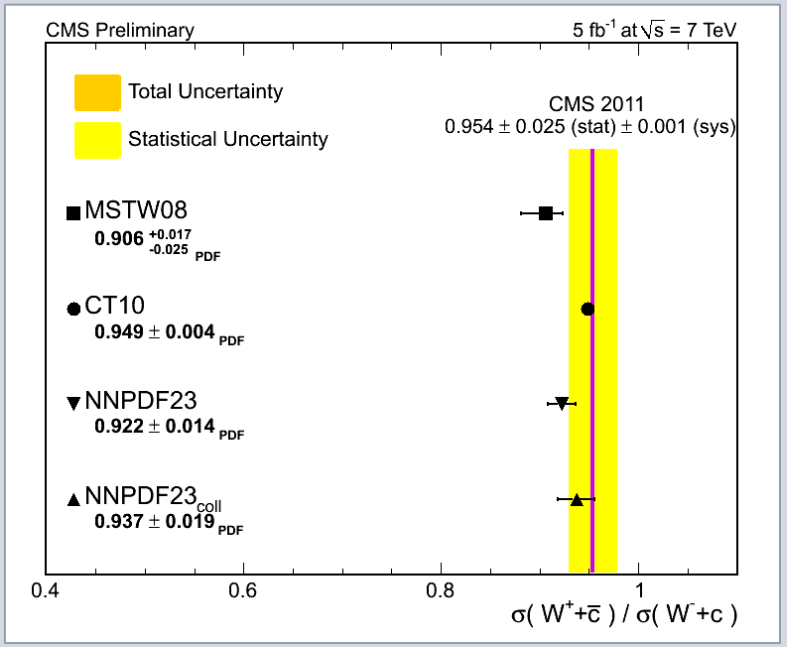


W+c

$p_T(\mu) > 25$ GeV
$|\eta(\mu)| < 2.1$
$M_T(\mu\nu) > 40$ GeV
$p_T(j) > 25$ GeV
$|\eta(j)| < 2.5$

- Inclusive cross section: **W+c** and **Ratio(W^+c^-/W^-c^+)**

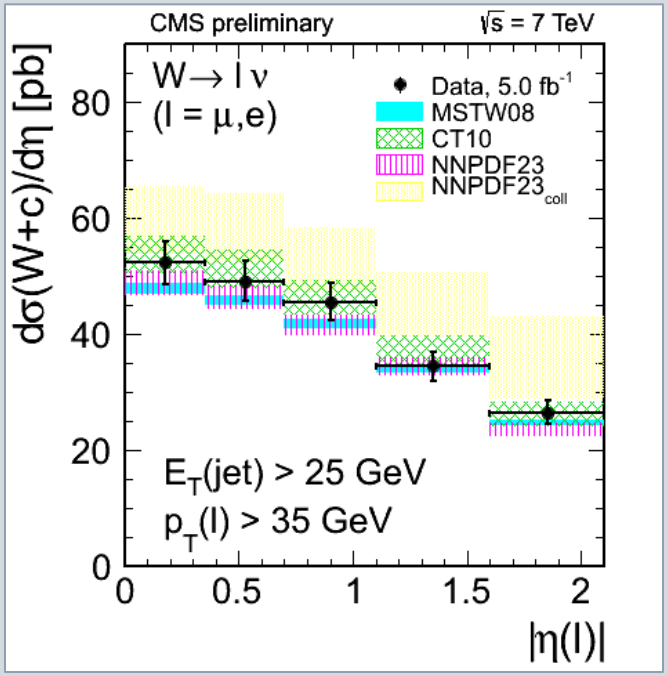


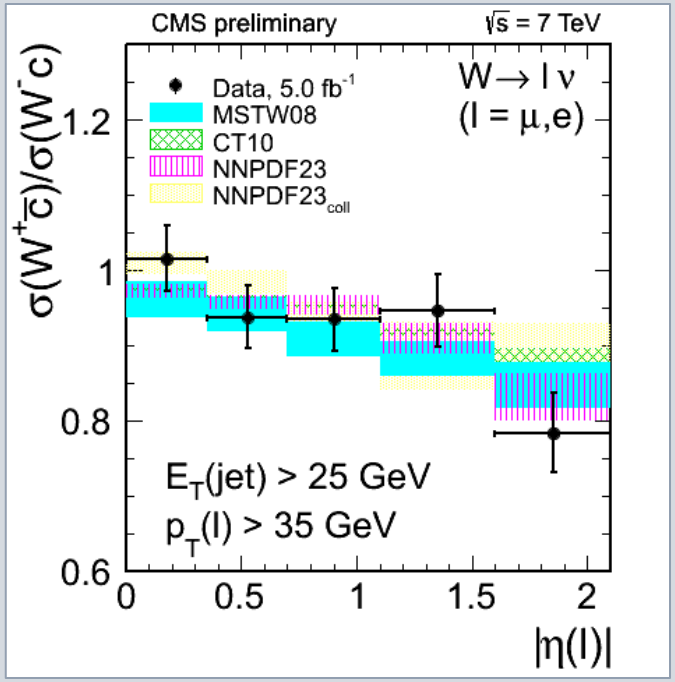


- **In agreement with predictions**

W+c

- **Differential cross sections**

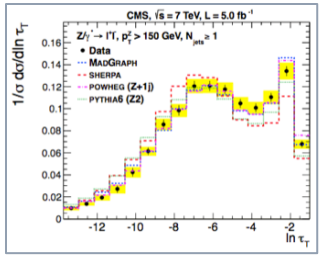


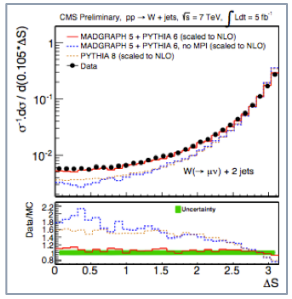


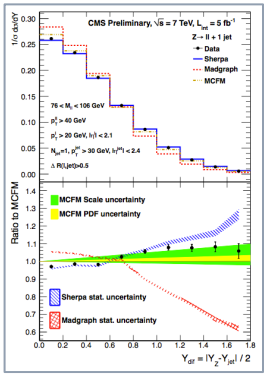
- **Discriminate between different PDFs**
  - Use to constrain PDFs

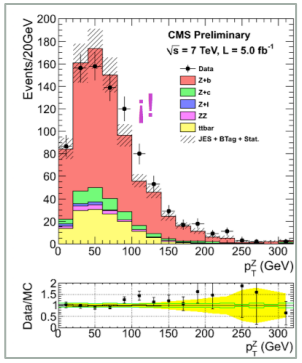
Conclusions

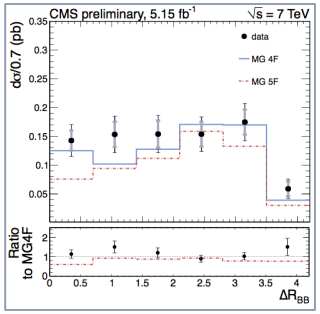
- **V+J**
  - Studies of W/Z/γ+jets
    - **Z/γ+jets**: kinematics
      - Discrepancies observed in **event topologies**
        - Thrust, angular observables, rapidity sum/difference
    - **W+jets**: multiple parton interactions
      - DPS-sensitive variables agree with predictions
- **V+HF**
  - Results for **Z+b, W+b, W+c**
    - For different HF-jet multiplicities
      - Cross sections overall in agreement
    - Tensions in comparisons of kinematics
      - Z+b: **p_T(Z)** and **ΔR(b,b)**









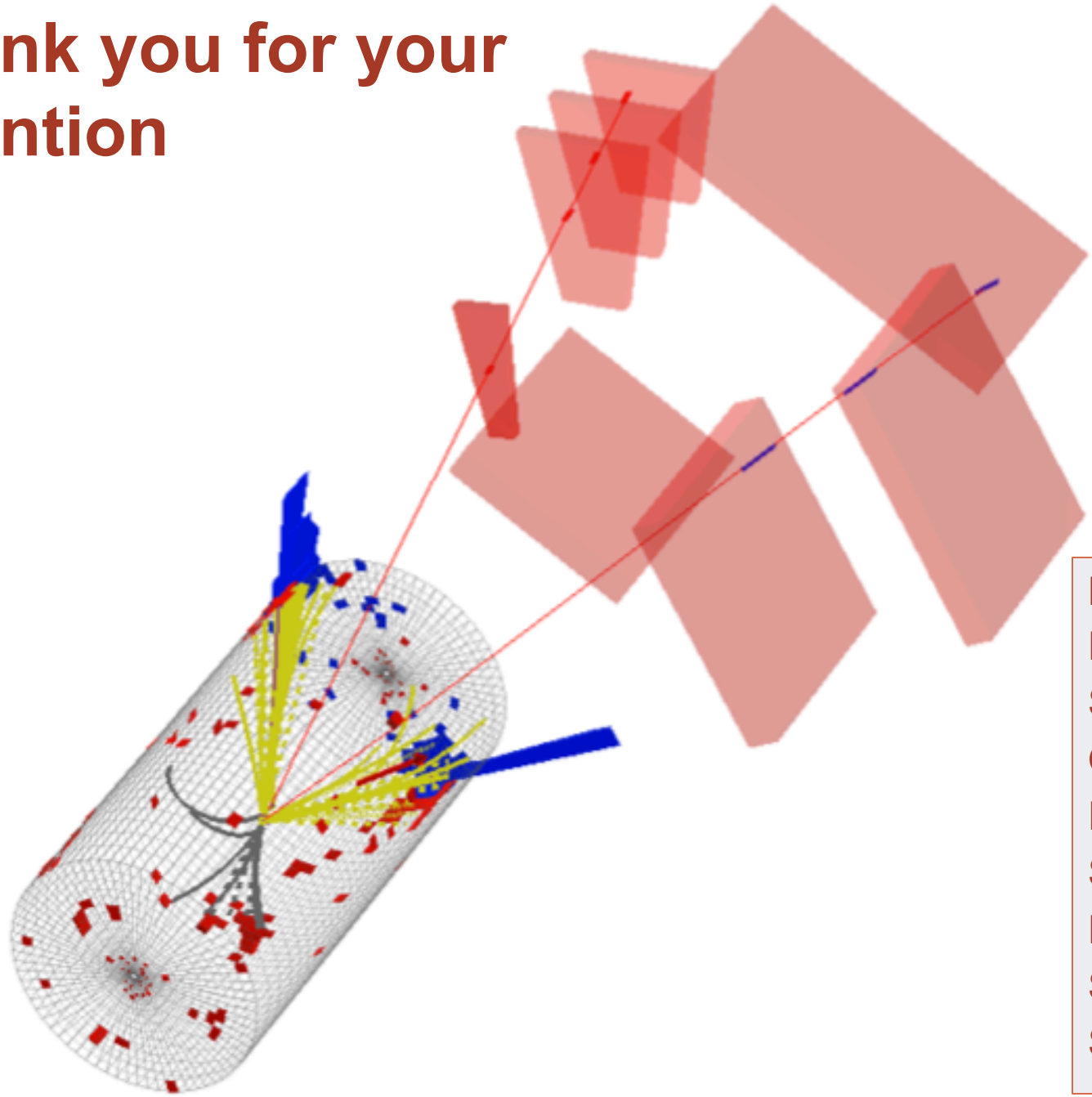


Conclusions

- **V+J**
  - Studies of W/Z/γ+jets
    - **Z/γ+jets**: kinematics
      - Discrepancies observed in **event topologies**
        - Thrust, angular observables, rapidity sum/difference
    - **W+jets**: multiple parton interactions
      - DPS-sensitive variables agree with predictions
- **V+HF**
  - Results for **Z+b, W+b, W+c**
    - For different HF-jet multiplicities
      - Cross sections overall in agreement
    - Tensions in comparisons of kinematics
      - Z+b: **p_T(Z)** and **ΔR(b,b)**

- **Understand the tensions**
  - Important for searches
  - Understanding of QCD

Thank you for your attention



References

EWK-11-021

SMP-12-004

QCD-11-005

FSQ-12-019

SMP-13-004

EWK-11-015

SMP-12-026

SMP-12-002

BACKUP

References

Links:
CMS results
CMS SMP-VJ results

V+j

- **Z+j (thrust): CMS EWK-11-021**
  - arXiv:1301.1646
- **Z+j (rapidity): CMS SMP-12-004**
- **Y+jet (triple diff.): CMS QCD-11-005**
- **W+jet (DPS): CMS FSQ-12-019**

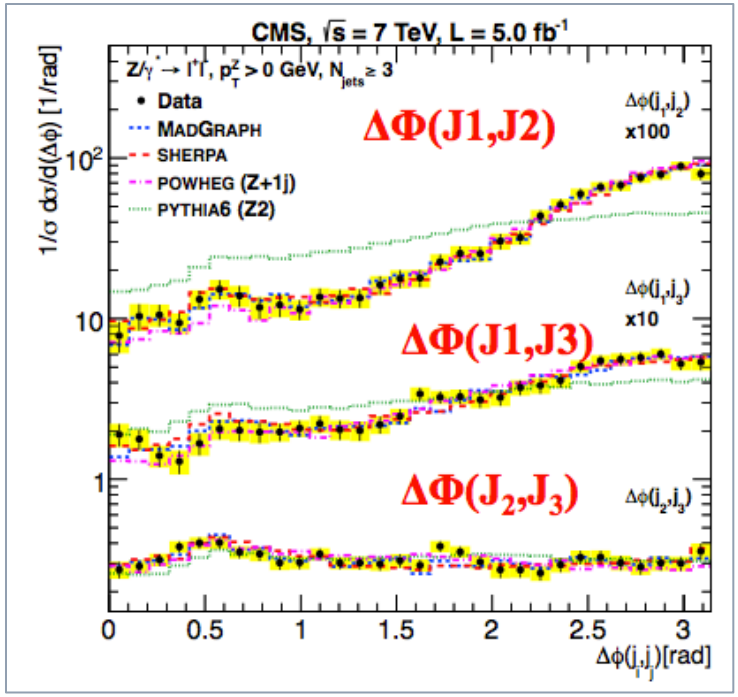
V+HF

- **Z+b (jets): CMS SMP-13-004**
- **Z+b (hadrons): CMS EWK-11-015**
- **W+b: CMS SMP-12-026**
- **W+c: CMS SMP-12-002**

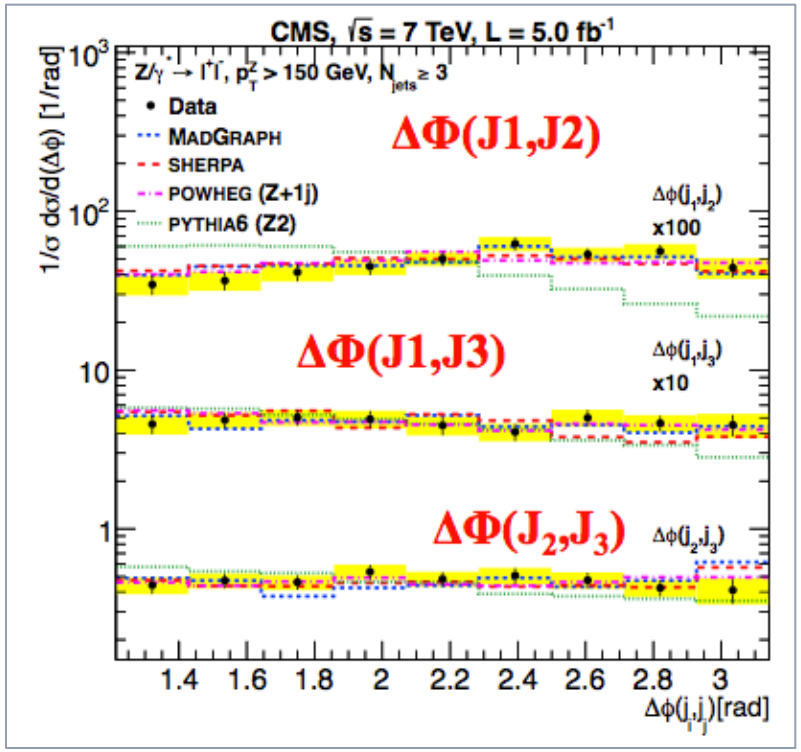
Z+3-jets

CMS EWK-11-021

- **DeltaPhi(j,j) in agreement with MadGraph/Powheg/Sherpa**
  - Pythia6 agrees for DeltaPhi(j2,j3)

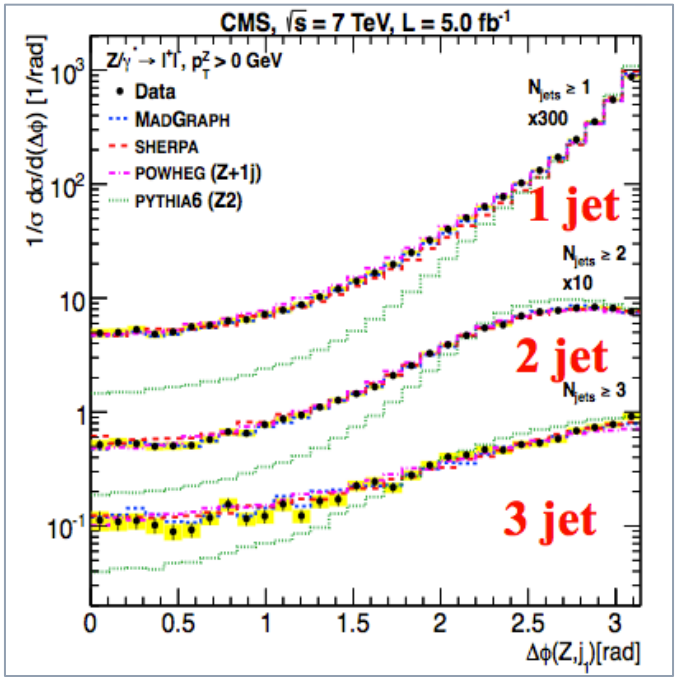


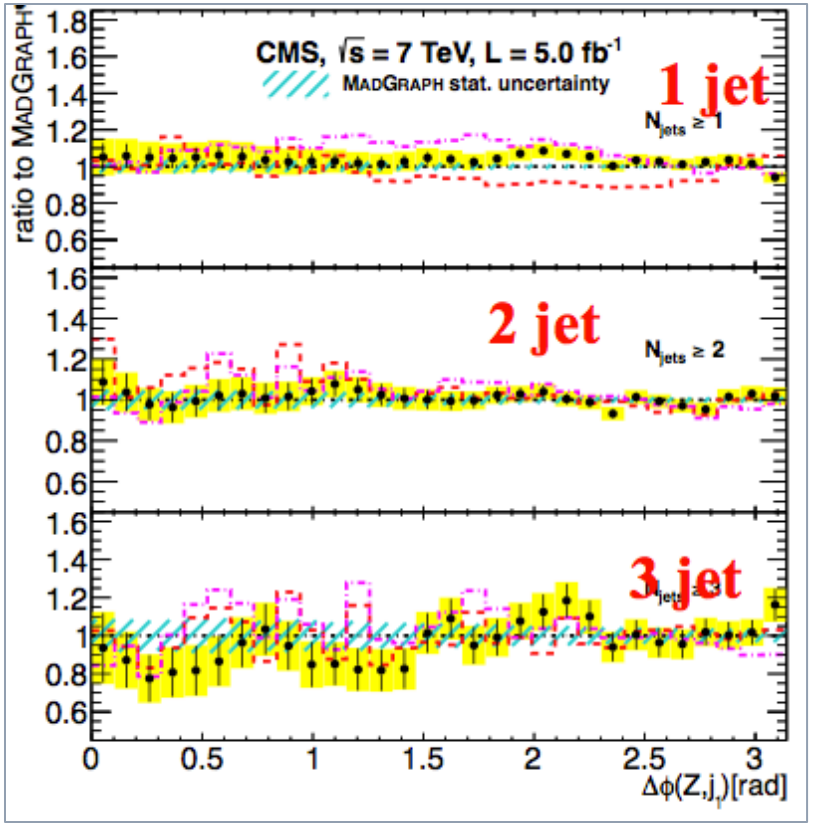
- **Boosted Z**
  - pT(Z)>150 GeV
- **DeltaPhi(j,j) agreement with MadGraph/Powheg/Sherpa**
  - Pythia agrees for DeltaPhi(j2,j3)



Z+jets

CMS EWK-11-021





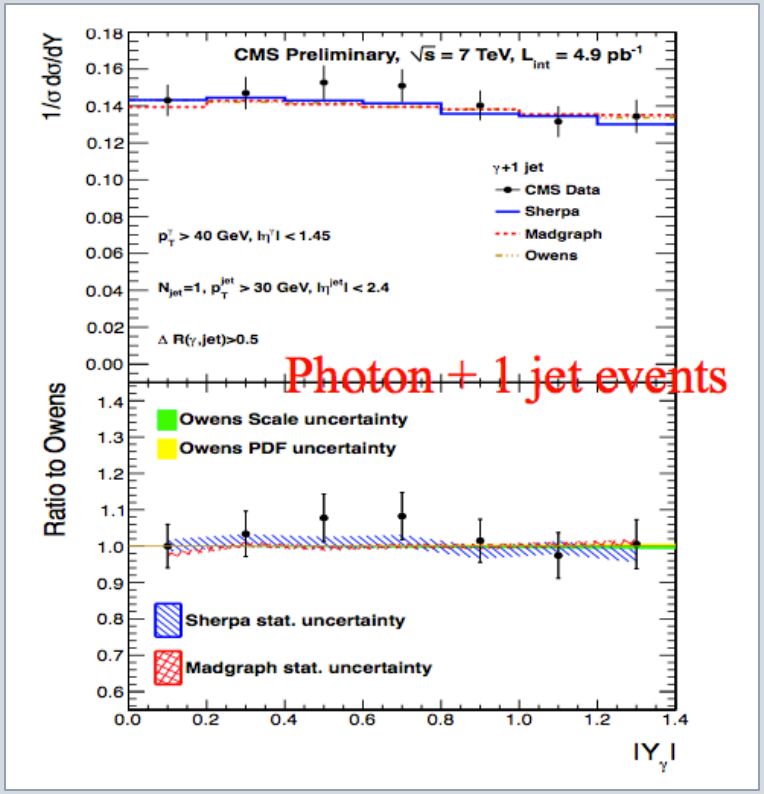
- **ΔΦ(Z,j) in multiplicity bins**
  - **MadGraph** and **Powheg** in agreement with measurement
  - **Sherpa** off by 10% in Z+1-jet bin
  - **Pythia** shifted to lower value

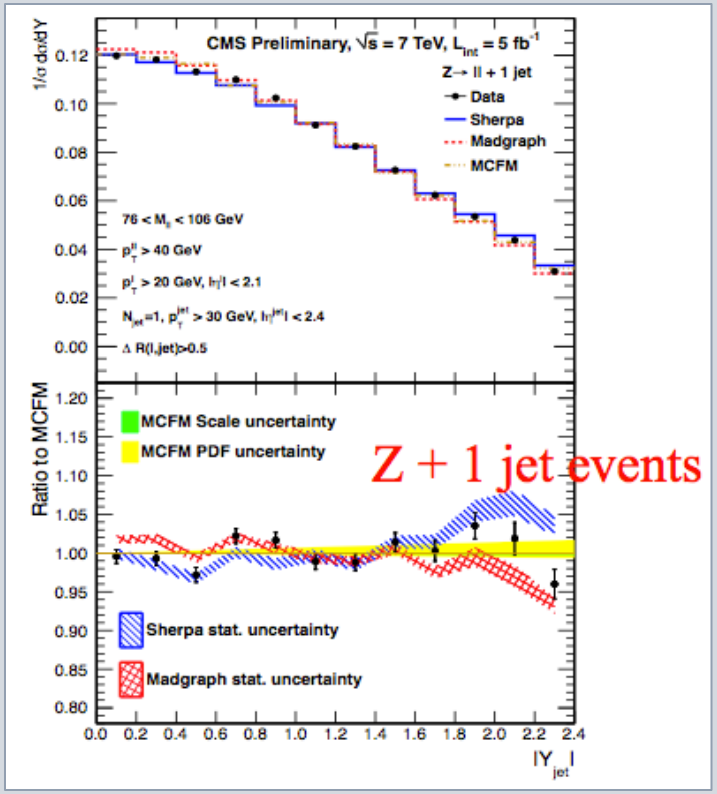
- **MadGraph/Powheg/Sherpa describe well ΔΦ(j,j)**
  - Also in boosted regime ($p_T Z > 150$ GeV)
  - See backup

CMS SMP-12-004

Z+j: rapidities

- **Rapidities**



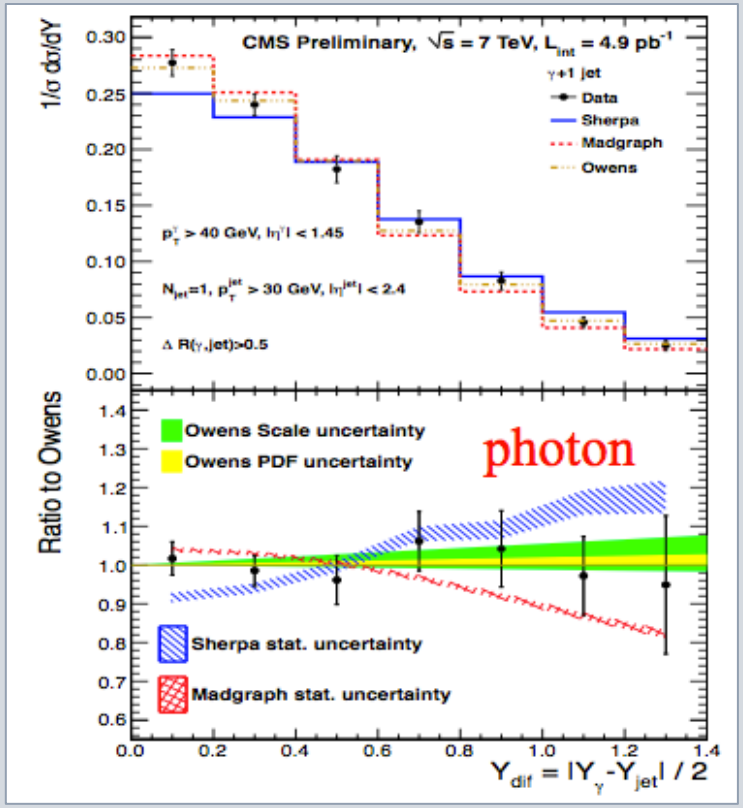


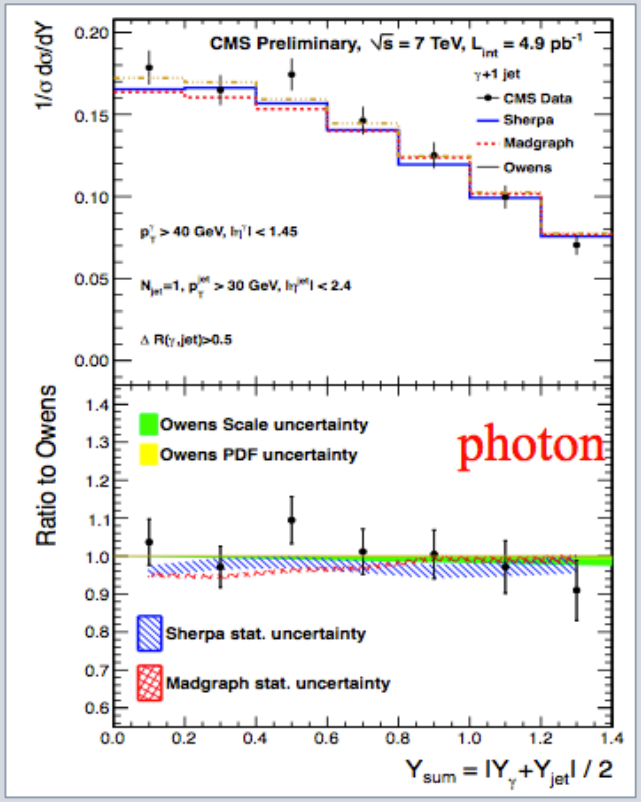
- **Predictions agree within 5%**

CMS SMP-12-004

photon+1j

- **Rapidity difference/sum**





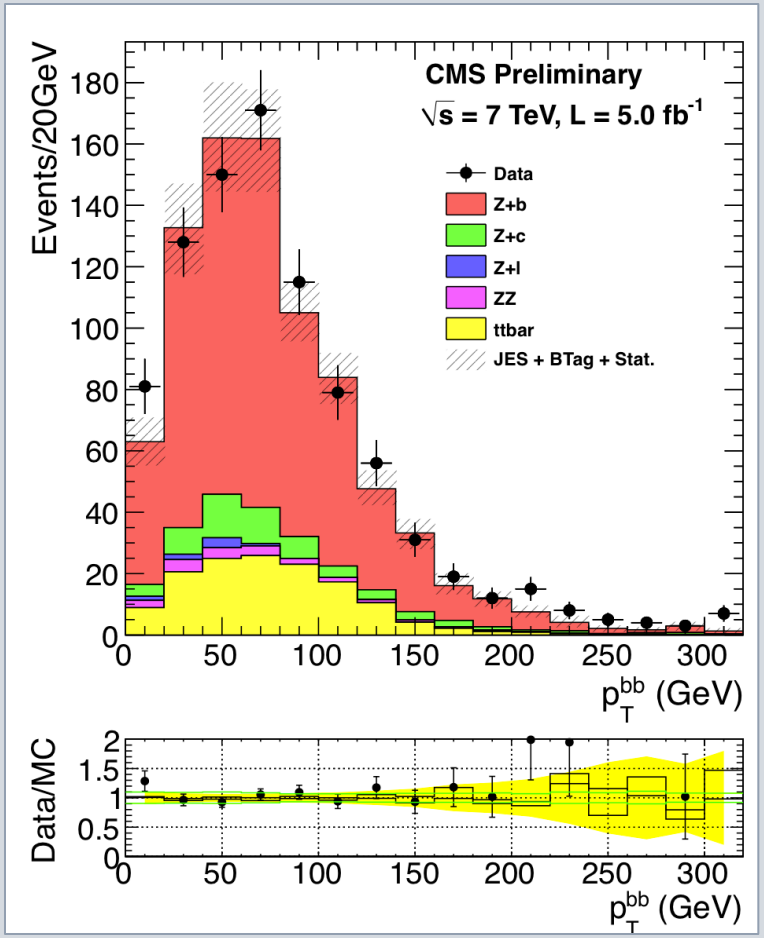
- **Prediction same as for Z+1j**

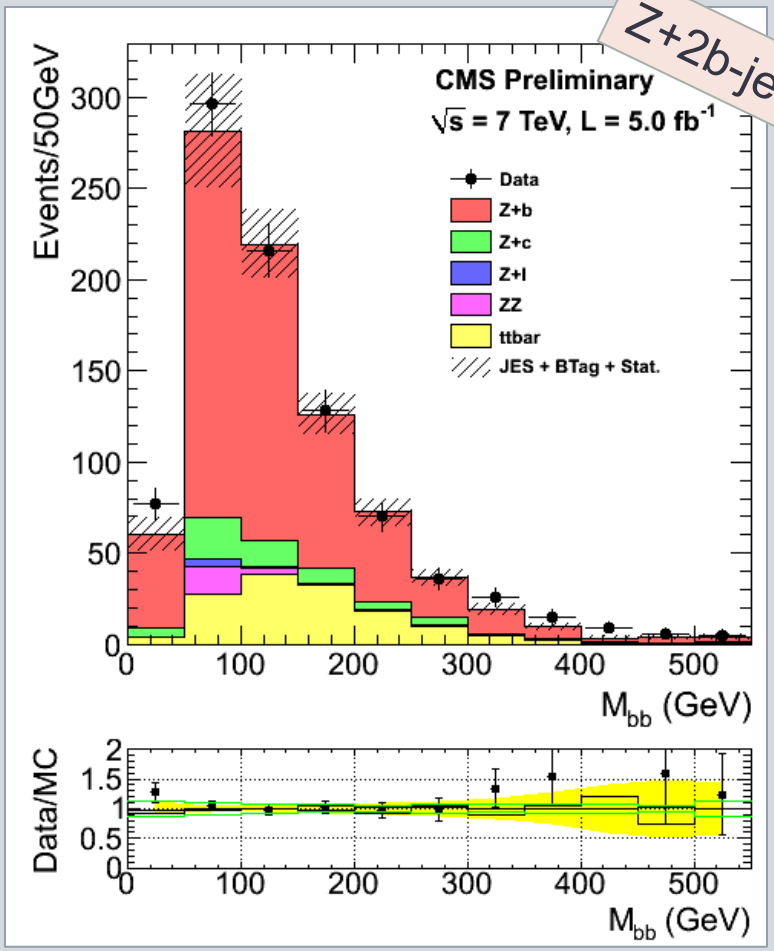
Z+2b

Kinematics

CMS SMP-13-004

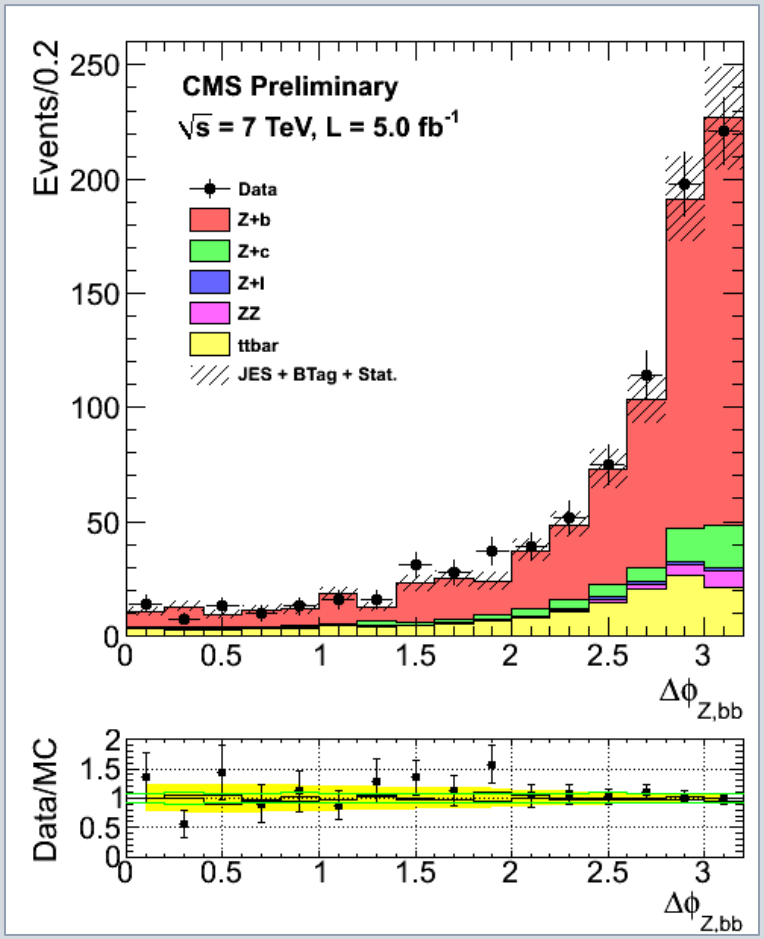
- p_T(bb) & M(bb)

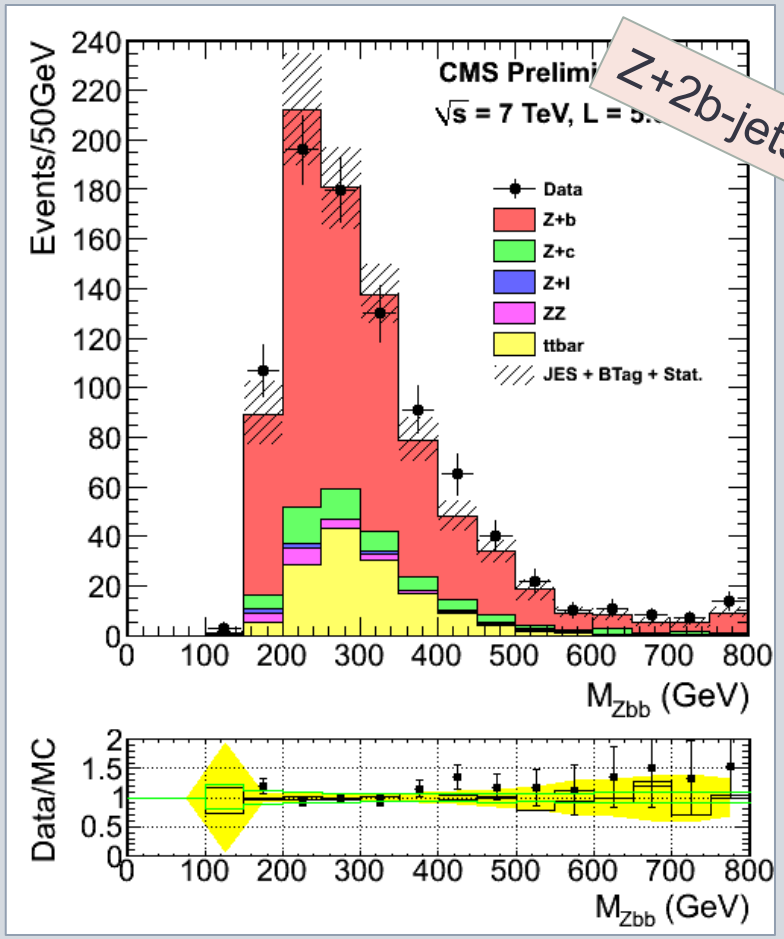




ΔΦ(Z,bb) & M(Zbb)

CMS SMP-13-004

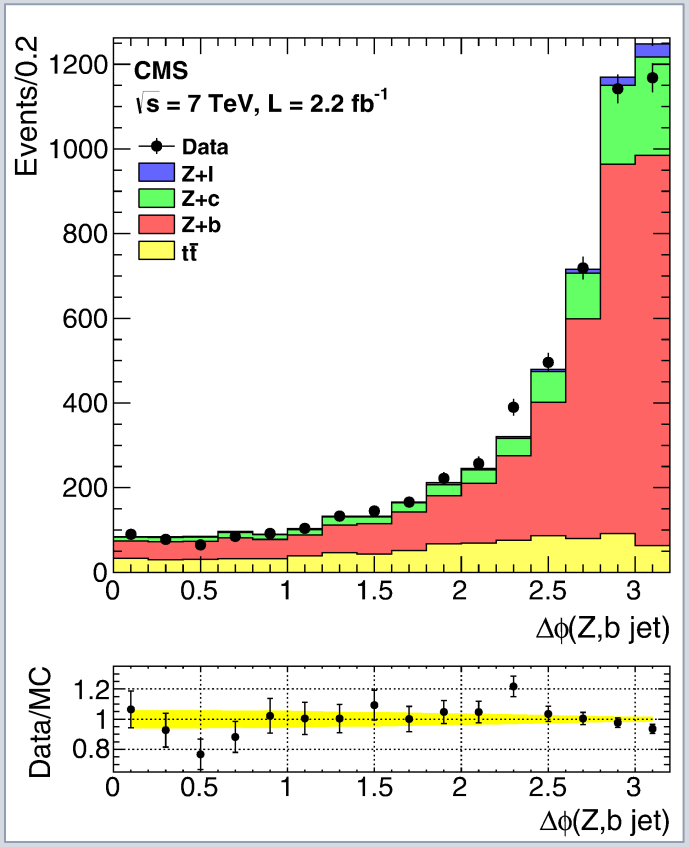


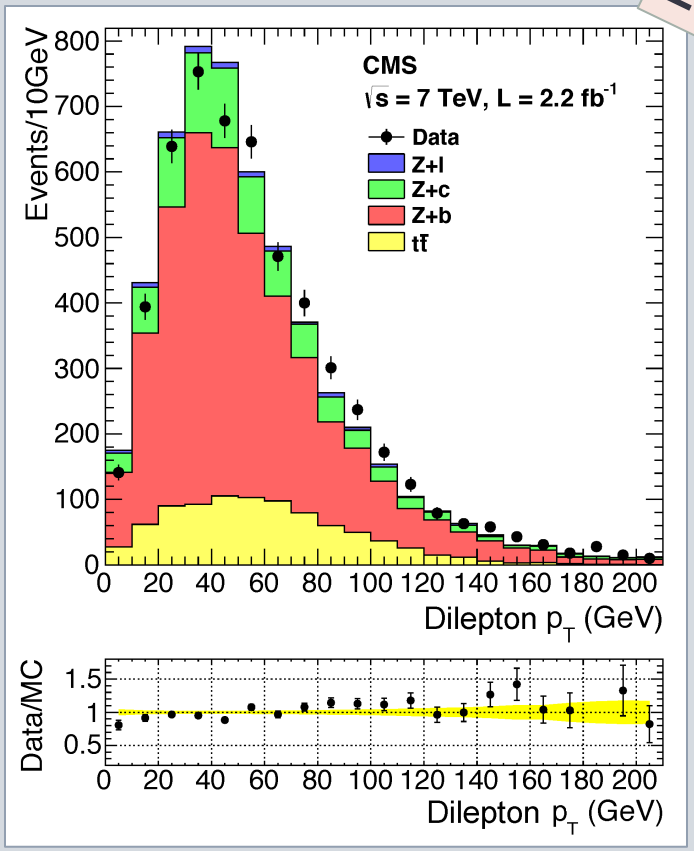


CMS EWK-11-012

Z+1b

- $\Delta\Phi(Z,b)$ & $p_T(Z)$





aMC@NLO

- **Z+2b-jets: $p_T(Z)$ spectrum**
  - Prediction at NLO with massive b's

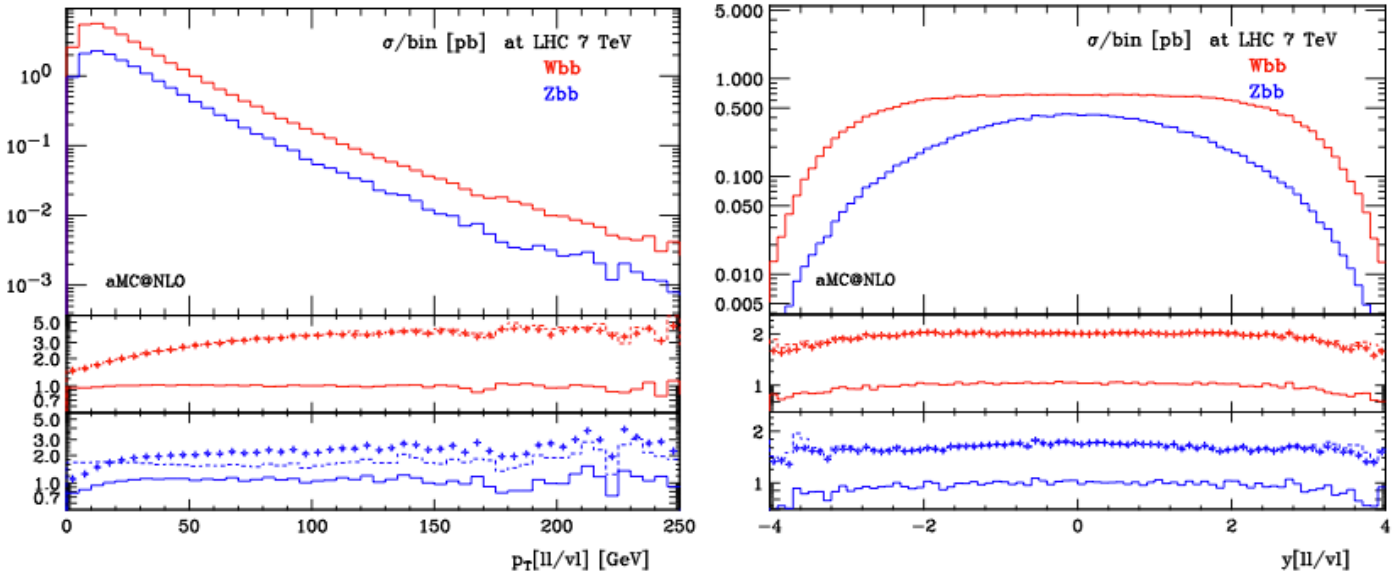


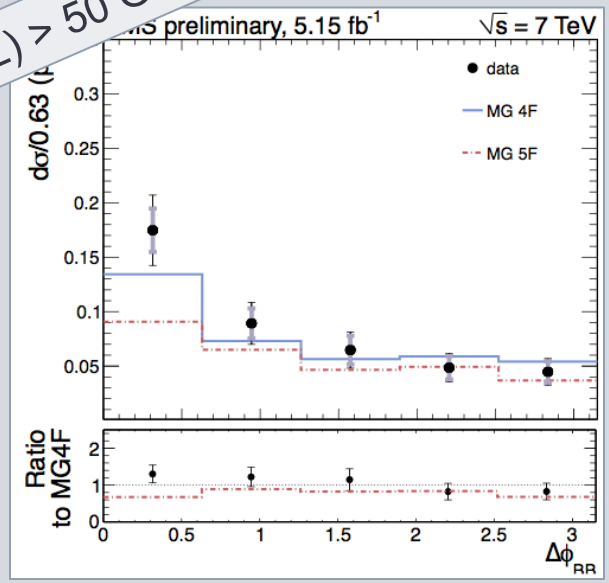
Figure 6: Transverse momentum (left panel) and rapidity (right panel) of the $\ell\nu$ and $\ell^+\ell^-$ pairs (i.e. of the virtual W and Z bosons respectively) in $\ell\nu b\bar{b}$ and $\ell^+\ell^- b\bar{b}$ production. The insets follow the same patterns as those in fig. 2.

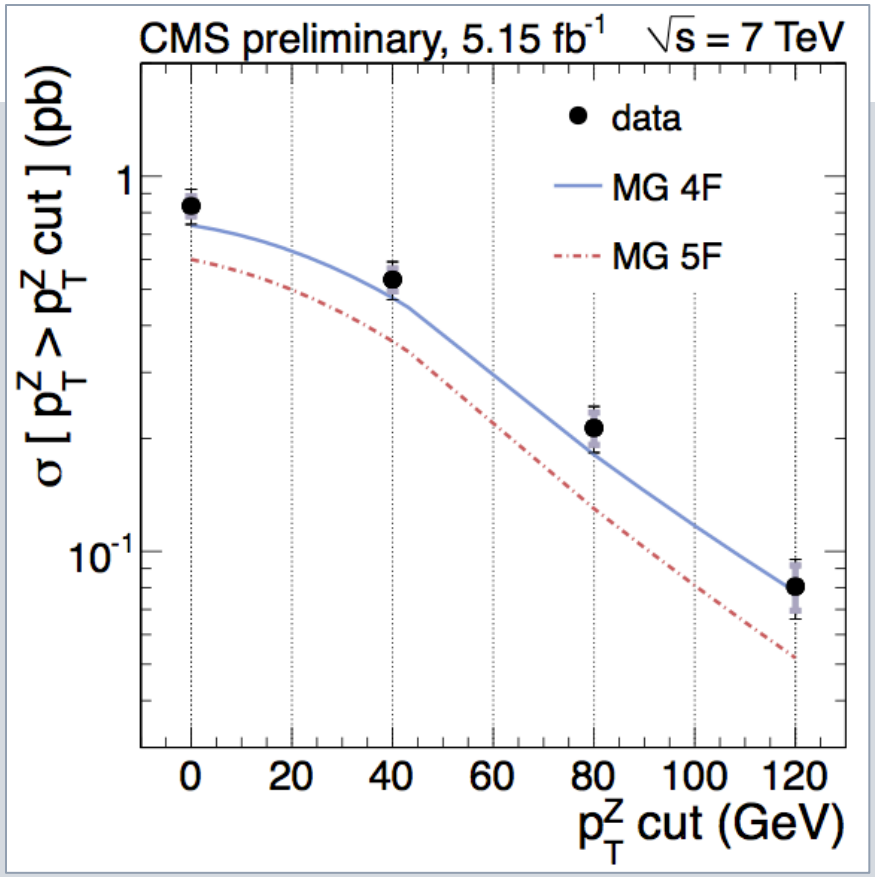
CMS EWK-11-015

Z+2b

- **ΔR(b,b) vs $p_T(Z)$**

$p_T(Z) > 50$ GeV

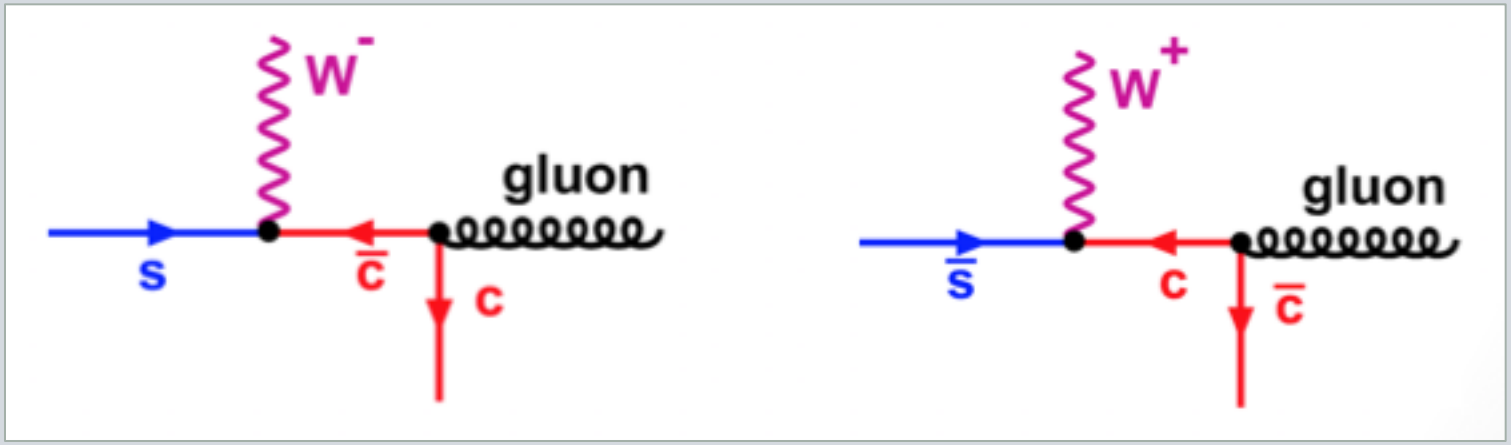




- **MadGraph 5F** underestimates collinear region
- **MadGraph 4F** reproduces data better

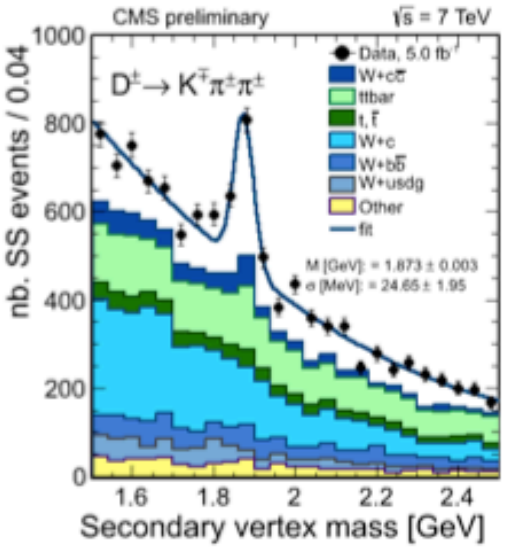
W+c motivation

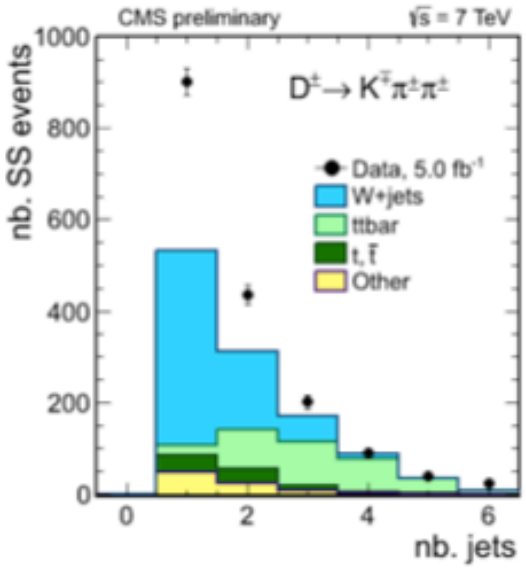
- **Access strange quark content of proton**

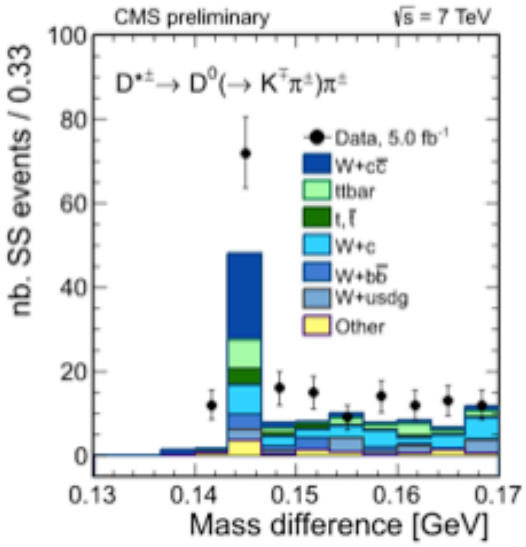


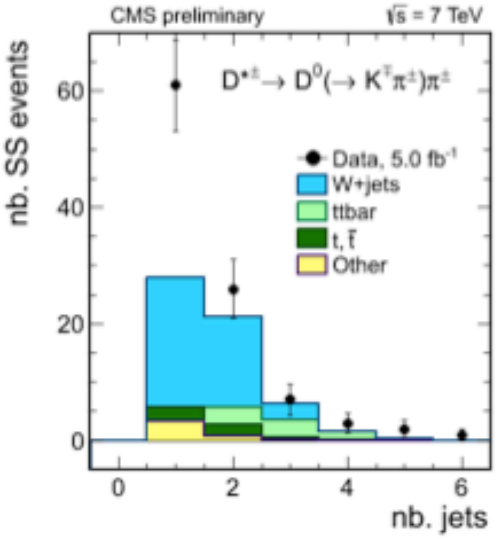
- **Reduce uncertainties on strange-content of PDF**
  - Help resolving existing ambiguities and limitations of low-energy neutrino DIS data

Brief comment on W + 1 SV





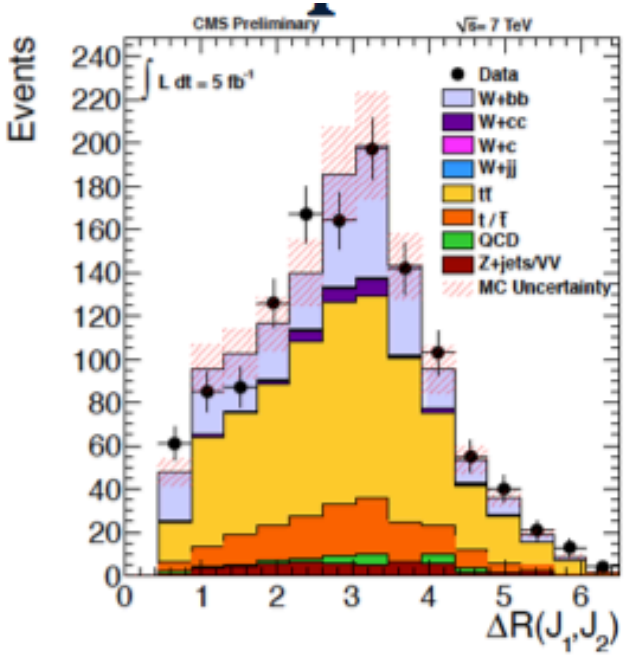


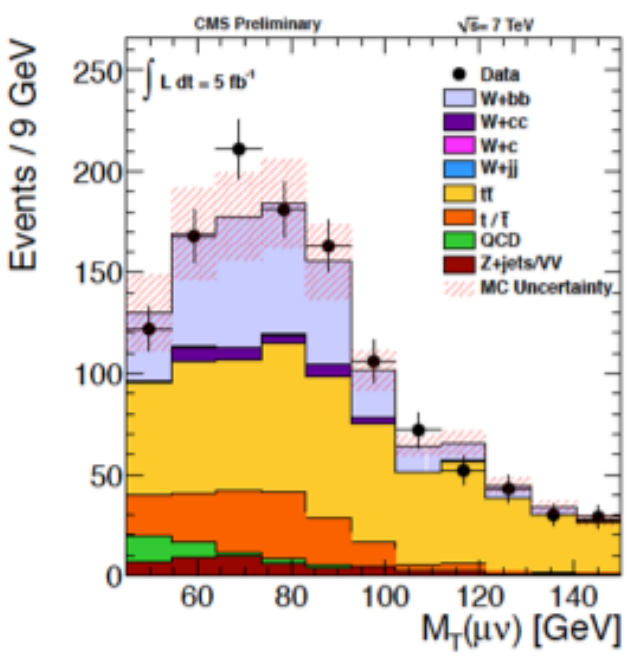


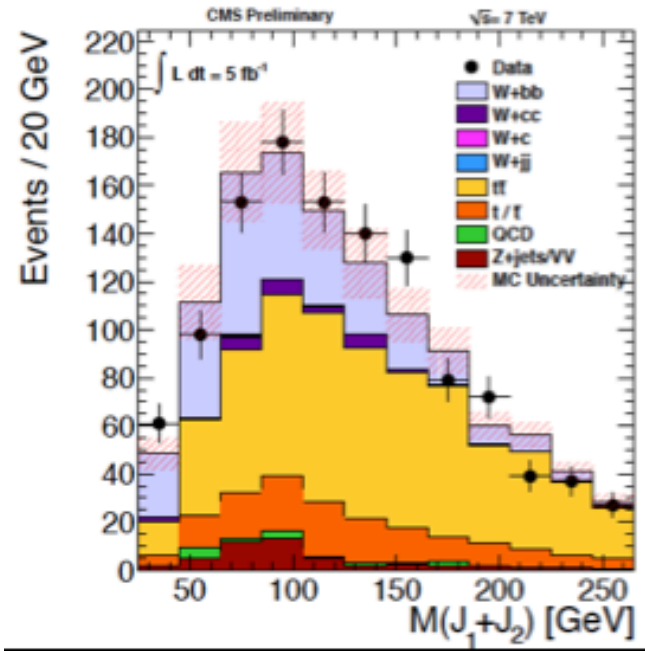
- Sample enriched in ccbar / bbbar events (gluon splitting)
- Comparison with the reference Madgraph+Pythia Monte Carlo
- Significant deficit observed in MC
- Hypothesis: collinear production mismodeling in MG +Pythia?

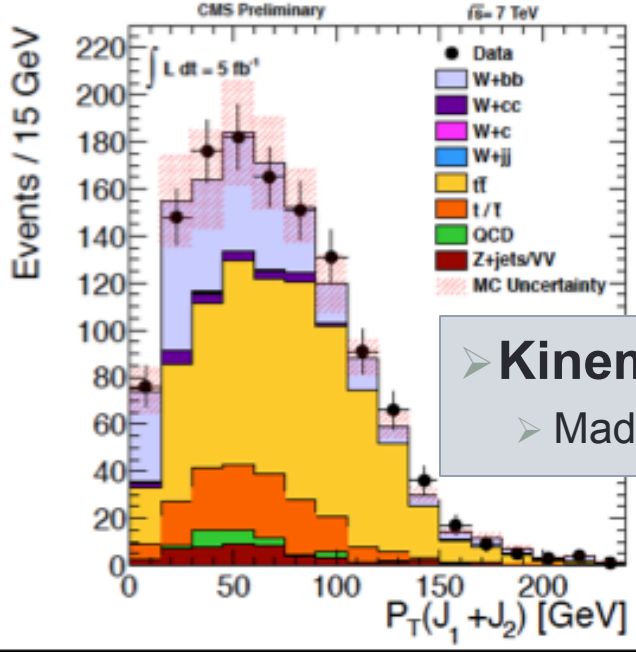
- Taken from V+HF in LHC EWWG

W+b kinematics









- **Kinematics well described**
  - MadGraph 5F + Pythia6