Associated production of heavy flavors and W,Z bosons at CMS

XI INTERNATIONAL CONFERENCE
ON HYPERONS, CHARM AND BEAUTY HADRONS
UNIVERSITY OF BIRMINGHAM, UK, 21-26 JULY 2014

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On the behalf of the CMS Collaboration

- Physics of W/Z + heavy flavors at LHC

W

$W + c$ differential cross section @ 7 TeV

$W + b$ cross section @ 7 TeV

Z

$Z + b$ cross sections @ 7 TeV

$Z + B\overline{B}$ angular correlations @ 7 TeV

- Summary and perspectives

Physics of W/Z + heavy flavors at LHC

perturbative QCD

- *Wc :* access the strange quark content of the proton
- *Zb :* understand the production mechanism
  - tree level vs NLO
  - 4FS ($m_b \neq 0$) vs 5FS ($m_b = 0$)
- PDF studies, NLO effects

Electroweak Measurements

- Higgs background *HZ*, *HW*
- Differential Cross sections
- *Zb* polarization asymmetry $\sin^2\Theta_W^{eff}$, couplings

Beyond the Standard Model

- 4th generation heavy *b',t'* quarks decaying to *Vb*
- Multi Higgs-doublets Models
- supersymmetry with *sbottoms*

$$W + c$$

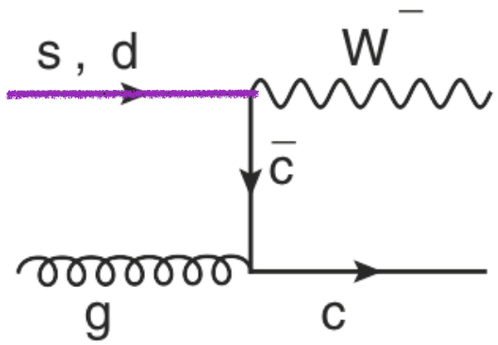
arXiv:1312.6608

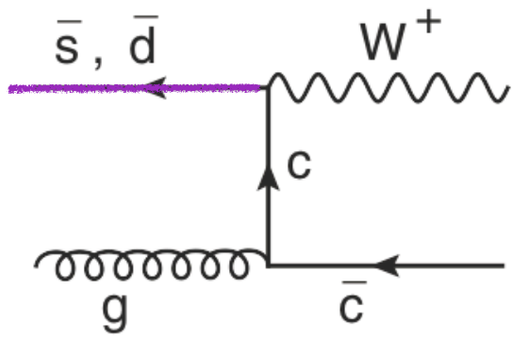
JHEP 02 (2014) 013

$W + c$

$\int Ldt = 5\ \text{fb}^{-1} \quad \sqrt{s} = 7\ \text{TeV}$

direct access to the strange content of the proton





- solve ambiguities in DIS and neutrino data
- very important for future W mass studies @LHC
- s / s̄ asymmetry candidate to explain NuTeV anomaly

Strategy

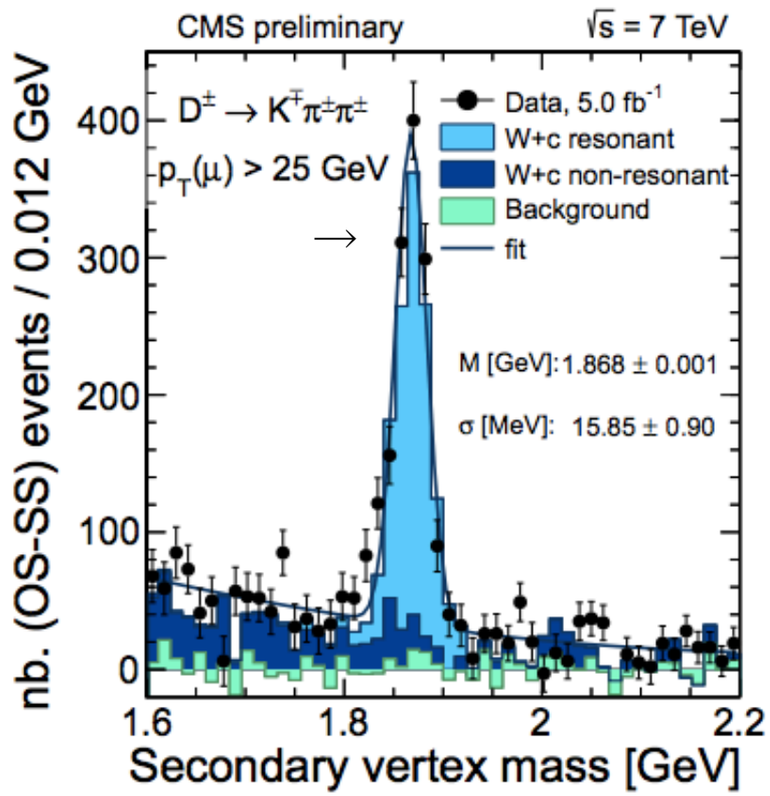
- $W \to \ell\nu$: isolated leptons with high pt

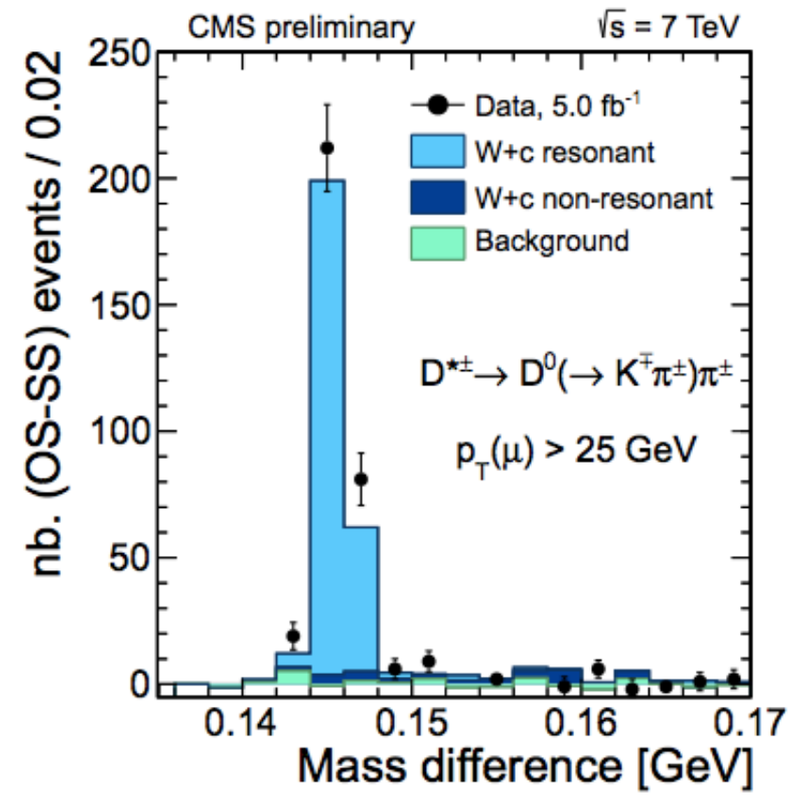
$p_T(e,\mu) > 25\ (35)$ GeV ; $|\eta| < 2.1$

- charm: not possible to directly tag c's
  b- contamination, large systematics

- Exploit decays of charmed mesons

Secondary Vertex + c decay reconstruction





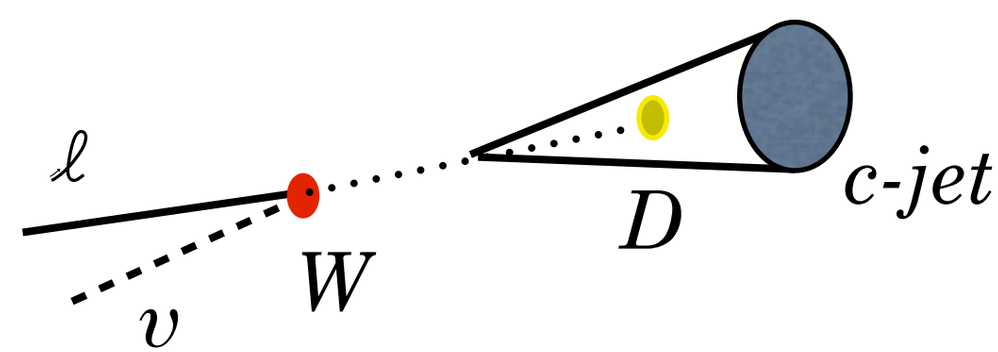
charge of the charm
unequivocally determined
in the three decay chains

$c^\pm \to D^\pm$ 3 tracks

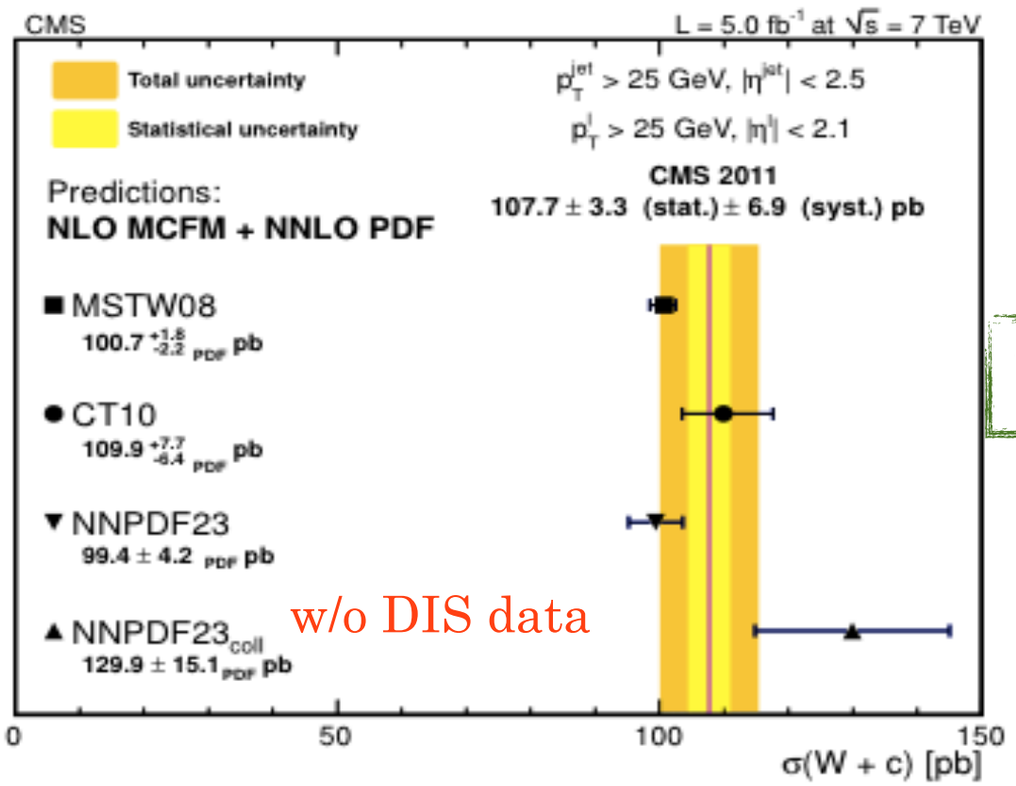
$c^\pm \to D^{*\pm} \to D^0\pi^+$ 2 tracks

$c^\pm \to \ell^\pm$ identify the muon

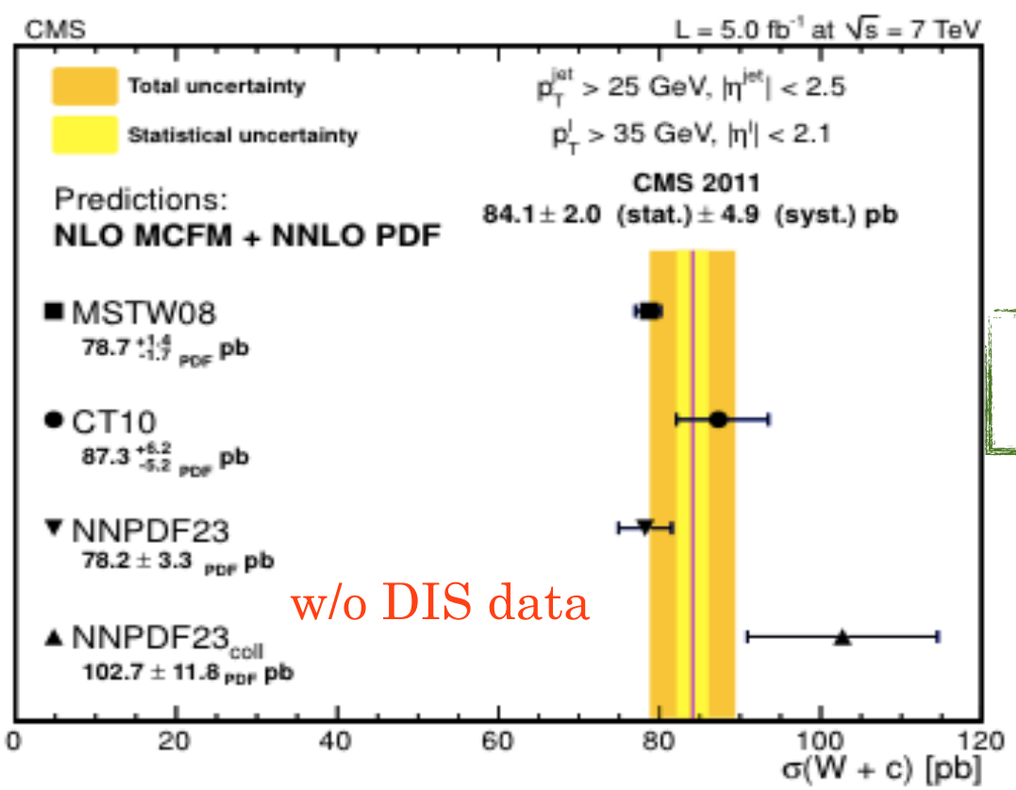
$p_T(c) > 25$ GeV ; $|\eta| < 2.5$



$W + c$ cross section



$W \to e\nu$



$W \to \mu\nu$

NLO MCFM v.6.1

$$\sigma(W + c) = \frac{N_{sel} - N_{bkg}}{\mathcal{L}_{\rm int}\, \mathcal{B}\, \mathcal{A}\, \epsilon}$$

systematic uncertainties

Jet Energy Scale 3%

branching ratios 3%

PDFs :

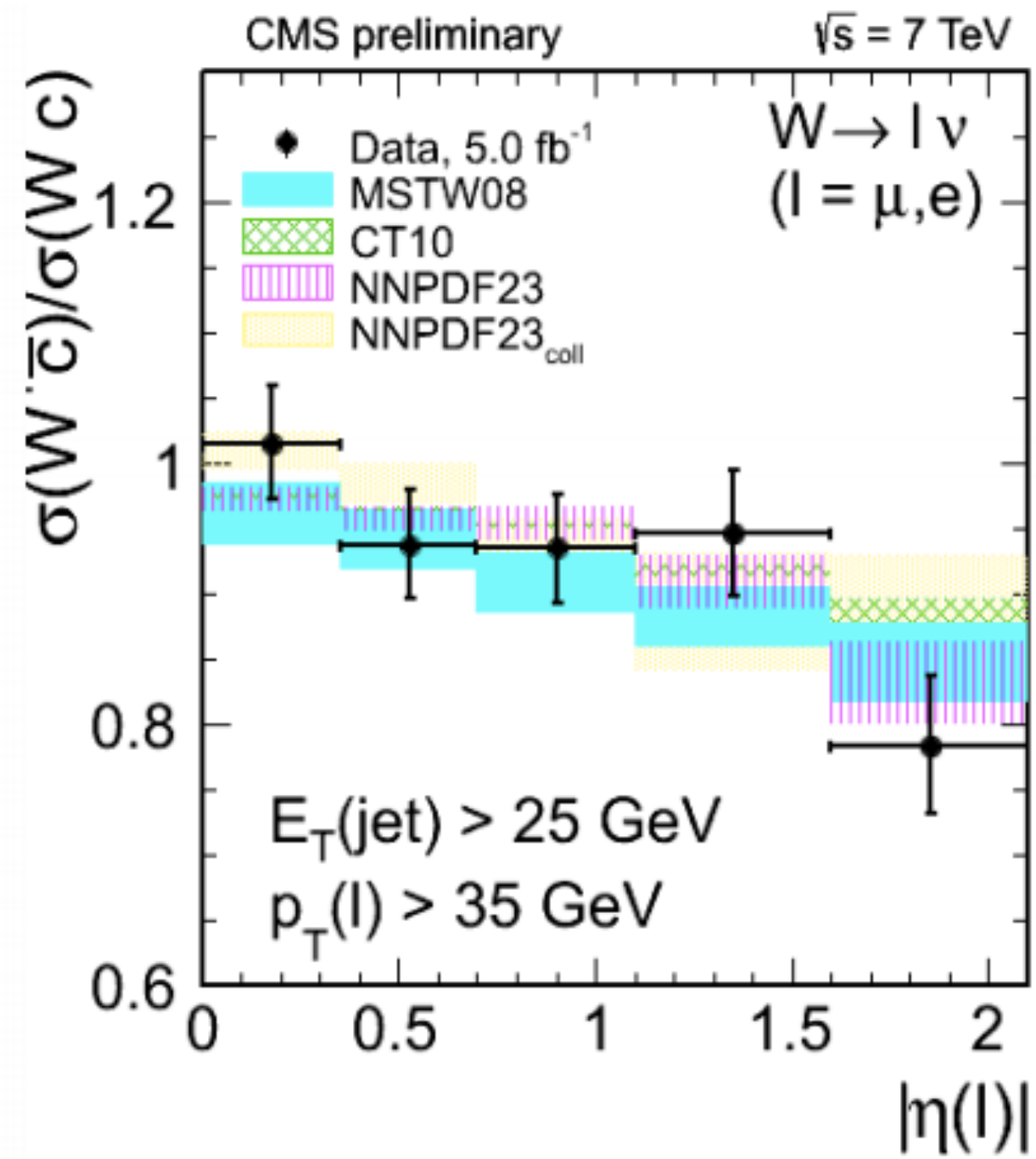
MSTW08 (+DIS data)

CT10 (+DIS data)

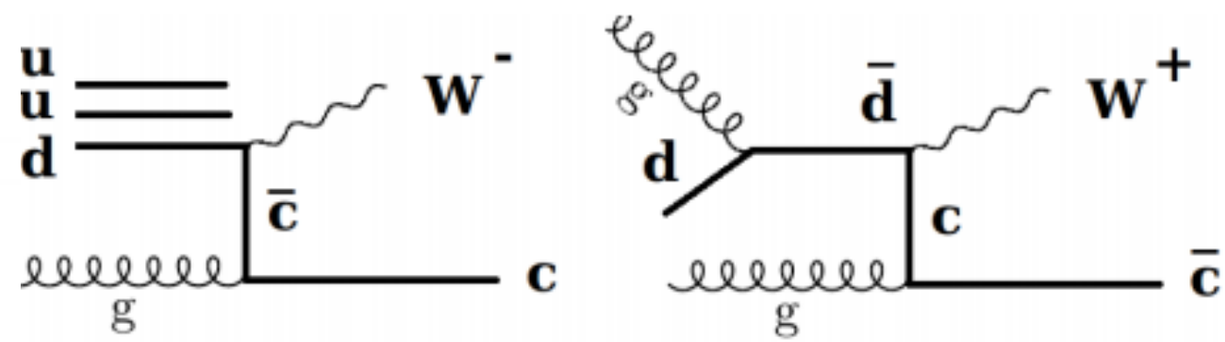
NNPDF23 (+DIS data)

$W + c$ cross section ratio

Differential Cross section Ratio vs. lepton pseudorapidity



$$R_c^{\pm} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} = \frac{(N^+{}_{OS} - N^+{}_{SS})}{(N^-{}_{OS} - N^-{}_{SS})}$$



PDFs :

MSTW08 (+DIS data)

CT10 (+DIS data)

NNPDF23 (+DIS data)

Good agreement with NLO MCFM

$$W + b$$

arXiv:1312.6608

accepted by PLB

$W + b$

$\int Ldt = 5\ \text{fb}^{-1} \quad \sqrt{s} = 7\ \text{TeV}$

$pp \to W(\to \mu\nu) + bb$

- main background in the *HW* production with *bb* final state
- impact on signature for BSM processes

b-tagging

- use discriminating variables based on displaced vertex measurement → high rejection of light and charm quarks

- Main background from $t\bar{t}$:

  use a control region requiring an additional lepton and two additional light jets

- simultaneous binned likelihood fit to the

  - leading jet p_T (signal region)

  - J1J2 invariant mass (*top* control region)

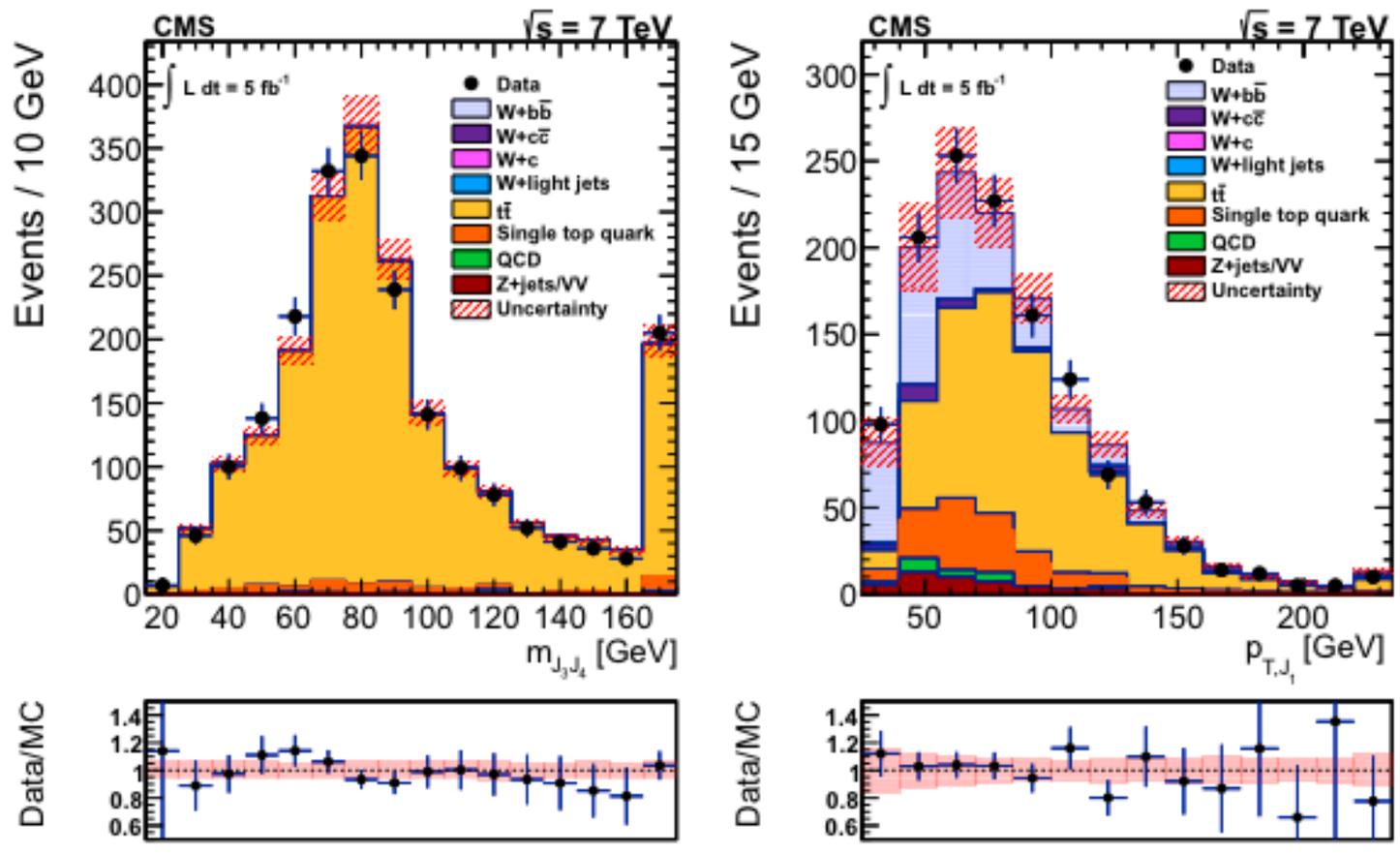
- good agreement with MadGraph+Pythia6

W selection

$p_T(\mu) > 25$ GeV
$|\eta(\mu)| < 2.1$
$m_T(W) > 45$ GeV

bb selection

- exactly 2 b-tagged jets
- anti kt 05
- p_T (b-jet) > 25 GeV
- $\Delta R(\mu, j) < 0.5$ (reject tops)

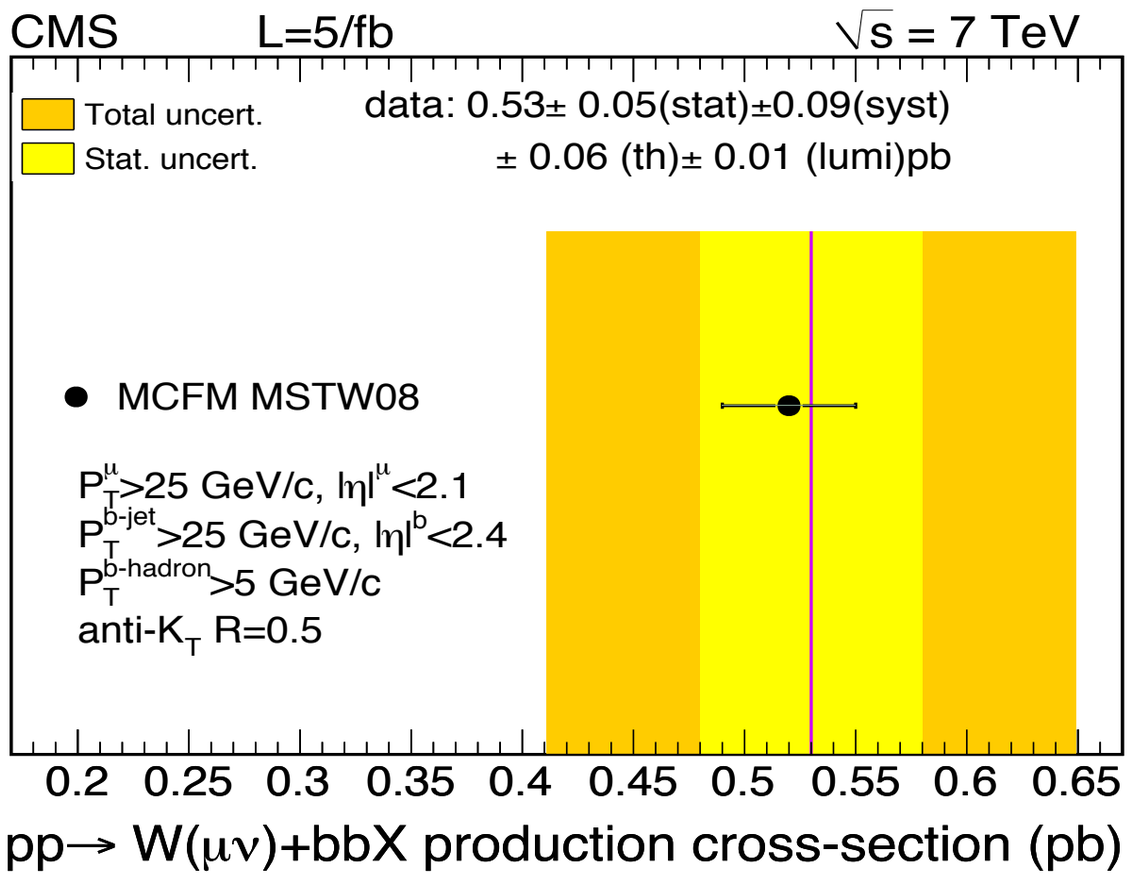


$W + b$

$pp \to W(\to \mu\nu) + bb$

- main background in the *HW* production with *bb* final state
- impact on signature for processes BSM

$$\sigma(\mathrm{pp} \to \mathrm{W} + \mathrm{b\bar{b}}) \times \mathcal{B}(\mathrm{W} \to \mu\nu) = \frac{N_S}{\int \mathrm{L}\,\mathrm{d}t\ \epsilon_{\mathrm{sel}}},$$



W selection

$p_T(\mu) > 25$ GeV
$|\eta(\mu)| < 2.1$
$m_T(W) > 45$ GeV

bb selection

- exactly 2 b-tagged jets
- anti kt 05
- p_T (b-jet) > 25 GeV
- $\Delta R(\mu, j) < 0.5$ (reject tops)

- measurement dominated by systematics
  JES and b-tagging ~6%
- hadronization correction (from MC)
  $C(b \to B) = 0.92 \pm 0.01$
- MCFM NLO prediction
  (MSTW2008NNLO PDF):

$\sigma(W+bb)=0.52\pm0.03$ pb

$$\sigma(\mathrm{pp} \to \mathrm{W} + \mathrm{b\bar{b}}) \times \mathcal{B}(\mathrm{W} \to \mu\nu) = 0.53 \pm 0.05\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{th.}) \pm 0.01\,(\mathrm{lum.})\,\mathrm{pb}.$$

$$Z + b$$

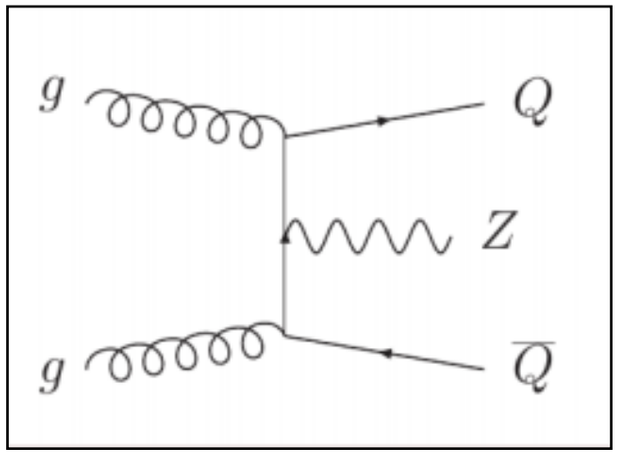
arXiv:1402.1521

accepted by JHEP

$Z + b$

$Z + b$ production at LHC

Two different models in perturbative QCD

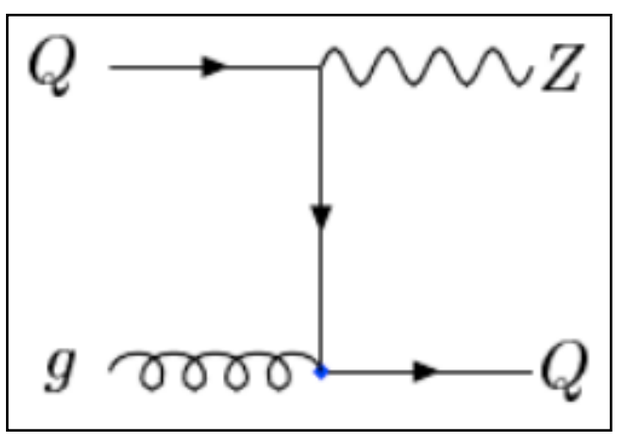


The b quark is produced in the *gluon splitting* and the b PDF is set to zero: only 4 flavours inside the proton (**4-Flavours Scheme 4FS**)

4FS $\longrightarrow$ $m_b \neq 0$

prediction: MadGraph 4FS (tree level)

NLO prediction: aMC@NLO



The *gluon splitting* is included in the b quark PDF, 5 flavours inside the proton (**5-Flavours Scheme 5FS**)

5FS $\longrightarrow$ $m_b = 0$

prediction: MadGraph 5FS (tree level)

NLO prediction: MCFM, Powheg

$Z + b$

$\int Ldt = 5\ \text{fb}^{-1} \quad \sqrt{s} = 7\ \text{TeV}$

$Z + b$ @ 7 TeV

- dielectron and dimuon trigger:
  two high p_T - opposite charge isolated e,μ.

b-tagging
based on displaced
secondary vertices discriminator (CSV).

backgrounds
from $t\bar{t}$, estimated with
template fit to the dilepton
invariant mass in the wide range
60-120 GeV + MET < 50 GeV

purity
light and charm jets
estimated with template from
the secondary vertex mass fitted to data;

$f_b = 83 \pm 6\ \%$

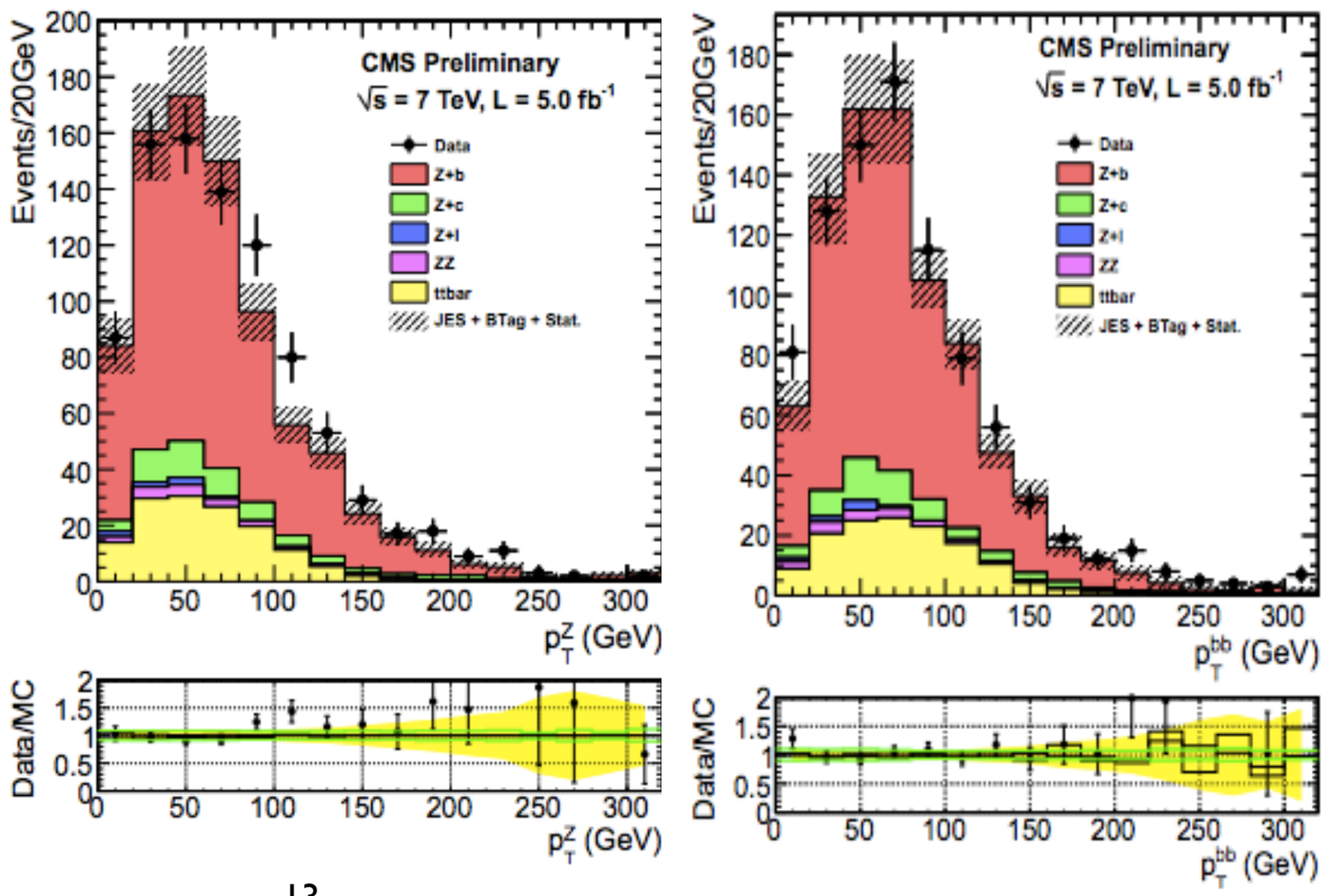
Corrected for detector-level
effects: acceptance, efficiencies:
detector level $\longrightarrow$ particle level

Z selection

$p_T(\mu, e) > 25{,}20$ GeV
$|\eta(\mu, e)| < 2.1$
$76 < m(ll) < 106$ GeV

b selection

- at least 1 b-tagged jet
- anti kt 05
- p_T (b-jet) > 25 GeV
- $\Delta R(\mu, j) > 0.5$



$Z + b$ cross section

$Z + b$ @ 7 TeV

Systematics Uncertainties

- main contributions by
  - b-purity (3%) and
  - b-tagging efficiency (3.6%)

Z selection

$p_T(\mu, e) > 25{,}20$ GeV
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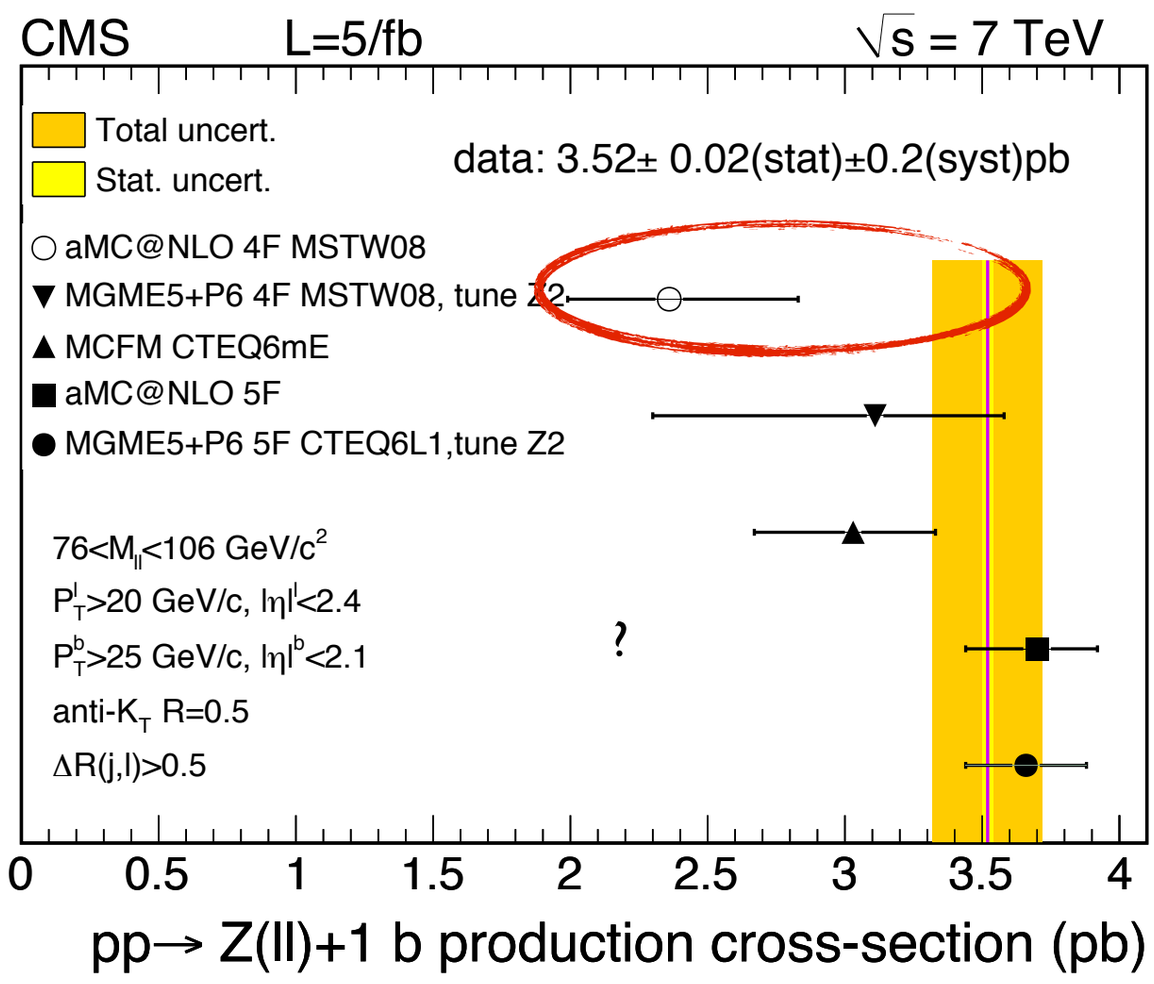
$76 < m(ll) < 106$ GeV

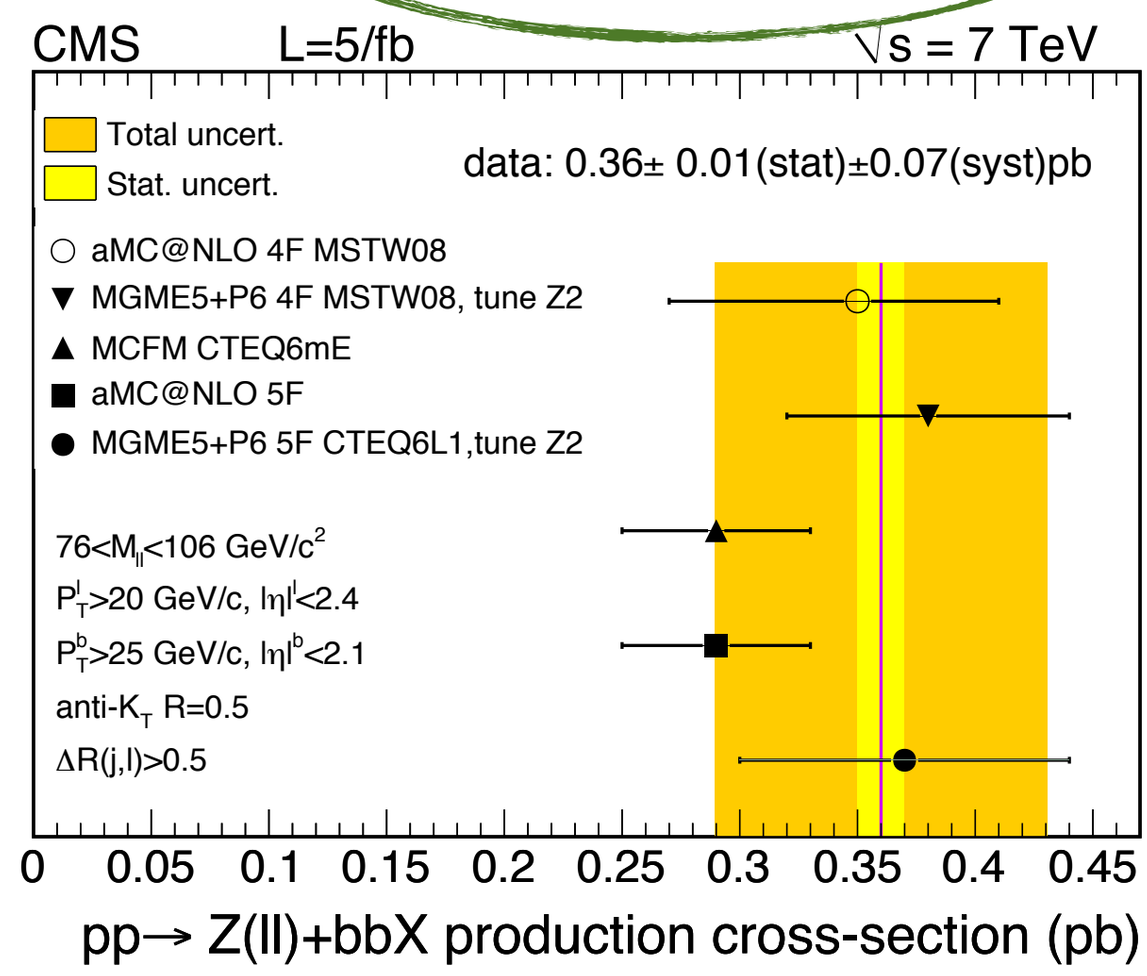
b selection

- at least 1 b-tagged jet
- anti kt 05
- p_T (b-jet) > 25 GeV
- $\Delta R(\mu, j) > 0.5$

MadGraph 5F and aMC@NLO 5F
good agreement
aMC@NLO 4F and MCFM
~2σ away

Results





$$Z + B\bar{B}$$

arXiv:1310.1349

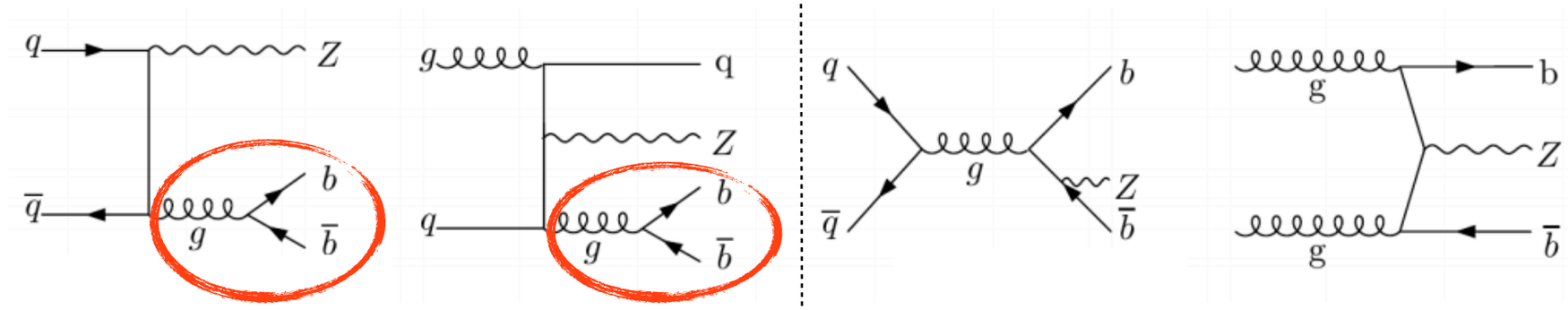
J. High Energy Phys. 12 (2013) 39

$Z + B\bar{B}$

$\int Ldt = 5\ \text{fb}^{-1} \quad \sqrt{s} = 7\ \text{TeV}$

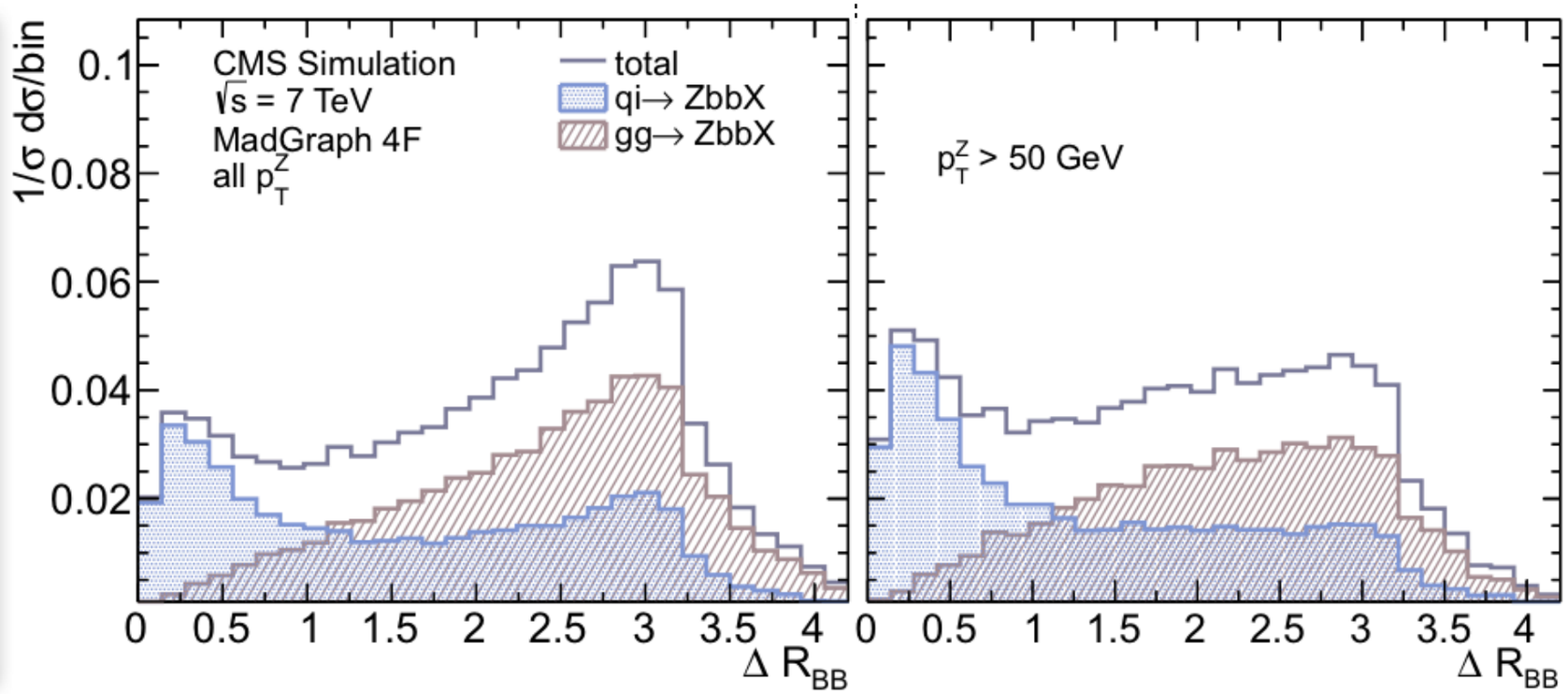
<u>B Hadrons</u>

insight on the collinear region between b's



B Hadrons: Inclusive Vertex Finder (IVF)

reconstructing B hadrons from tracks
allow to access to the collinear region,
small ΔR separation between two B's (~0.05)
independent from jet reconstruction



$qq \rightarrow ZbbX$ $\quad qg \rightarrow ZbbX$ $\quad gg \rightarrow ZbbX$

small ΔR(bb) region $\quad$ higher ΔR(bb) region

backgrounds
top-antitop, estimated by fitting the dilepton mass
c decays estimated from MC

Correct for detector level effects acceptance and efficiencies

Selection: Exactly 2 B hadrons with $p_T > 15$ GeV and $\eta < 2$;
lepton $p_T > 20$ GeV and $\eta < 2.4$; dilepton mass 81-101 GeV

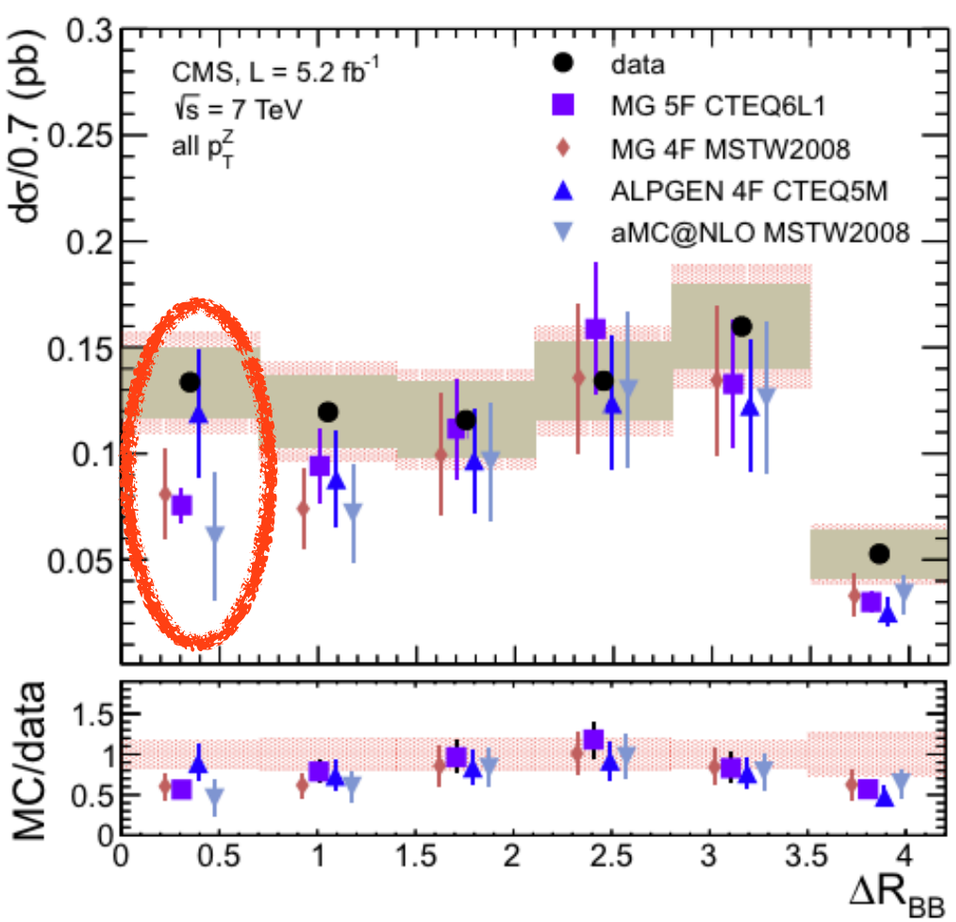
$Z + B\bar{B}$

Differental cross sections

Compare with the prediction of

- MadGraph **4FS / 5FS** @LO /
- Alpgen 4FS @LO
- aMC@NLO

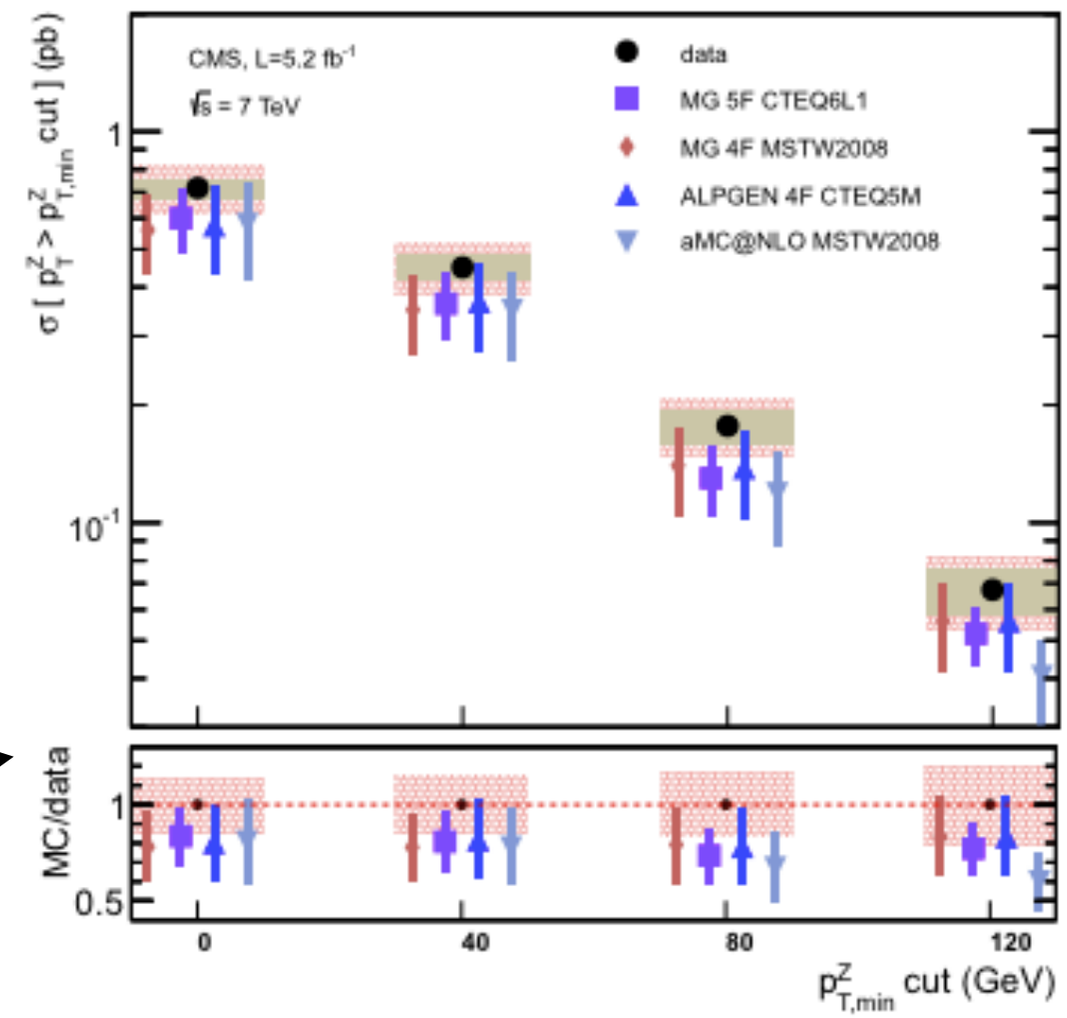
cross section VS ΔR (BB)



Good agreement with both 5FS - 4FS schemes

Collinear region **Only Alpgen 4FS** reproduces data

total cross section as a function of the Z p_T



Systematics

Source	Uncertainty (%)
Dilepton channel combination	2
IVF efficiency scale factors	12
B purity	2.1
Bin-to-bin migrations (ΔR_{BB}, minΔR_{ZB})	1–2
Bin-to-bin migrations ($\Delta\phi_{BB}$, A_{ZBB})	3–4
MC statistics — Differential	2.0–3.7
MC statistics — Total	1.0–3.5
Integrated luminosity	2.2

Summary and perspectives

The $W/Z + HF$ is an important and wide part of the SM physics program of CMS

- W+c @ 7 TeV allowed to test the strange quark PDF of the proton **5 fb^{-1}**
- W+b @ 7 TeV cross section measurement compared to NLO prediction **5 fb^{-1}**
- Z+b @ 7 TeV inclusive cross section compared with MCFM, aMC@NLO, MadGraph **5 fb^{-1}**
- Z+$B\overline{B}$ @ 7 TeV B handrons angular correlation and small ΔR_{BB} regime **5 fb^{-1}**

Many $W/Z + HF$ analyses at 8 TeV with full 20/fb data before LHC run II !

$W/Z + bb$, W+c, Z+c, PDFs, MPI ...

- Testing new experimental techniques: improved b-tagging, c-tagging, jet substructure..