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

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# Outline

- Physics of $W/Z$ + heavy flavors at LHC

  $W$
  - *charm* + $W$ differential cross section @ 7 TeV [ arXiv:1312.6608 JHEP 02 (2014) 013]
  - *beauty* + $W$ cross section @ 7 TeV [ arXiv:1312.6608 submitted to PLB ]

  $Z$
  - *beauty* + $Z$ cross sections @ 7 TeV [ arXiv:1402.1521 submitted to JHEP ]
  - *beauty* + $Z$ differential cross sections @ 8 TeV [endorsed as a PhD Thesis]

- 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

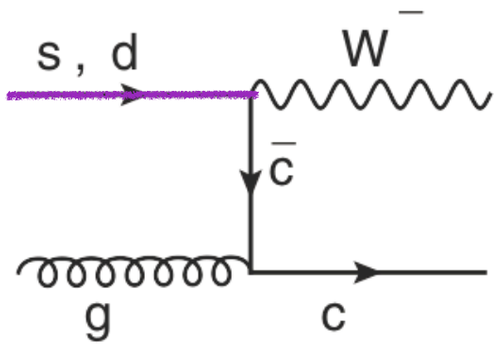
Beyond the Standard Model

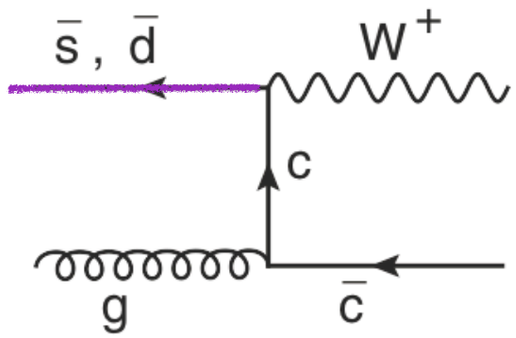
- 4th generation heavy *b',t'* quarks decaying to *Vb*
- supersymmetry with *sbottoms*
- Multi Higgs-doublets Models
- potential new physics with $A^{pol}(Zb)$

# *charm + W*

$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 5/fb

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

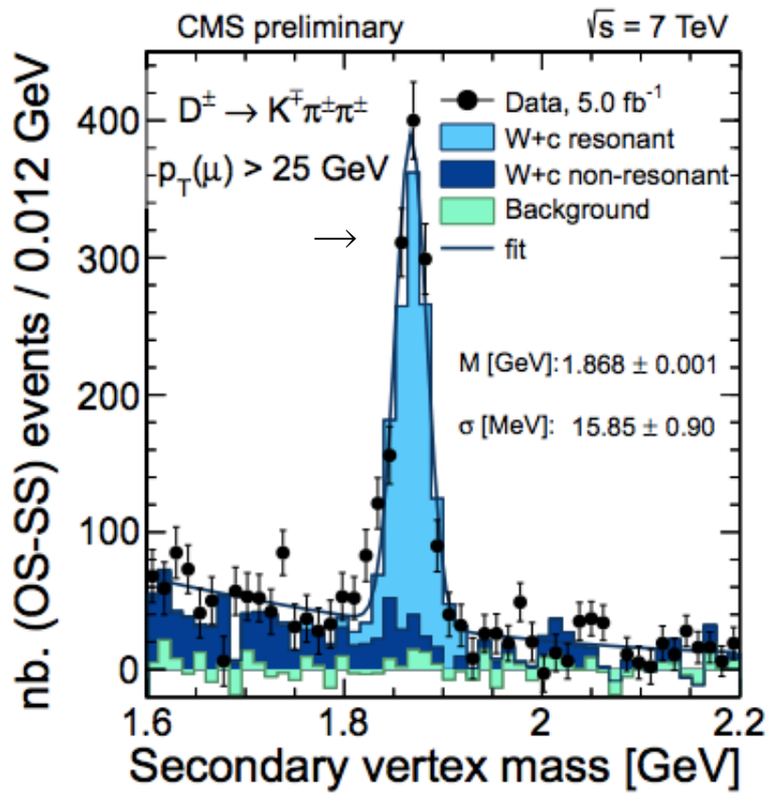
- $W \to \ell\nu$ : isolated leptons with high pt

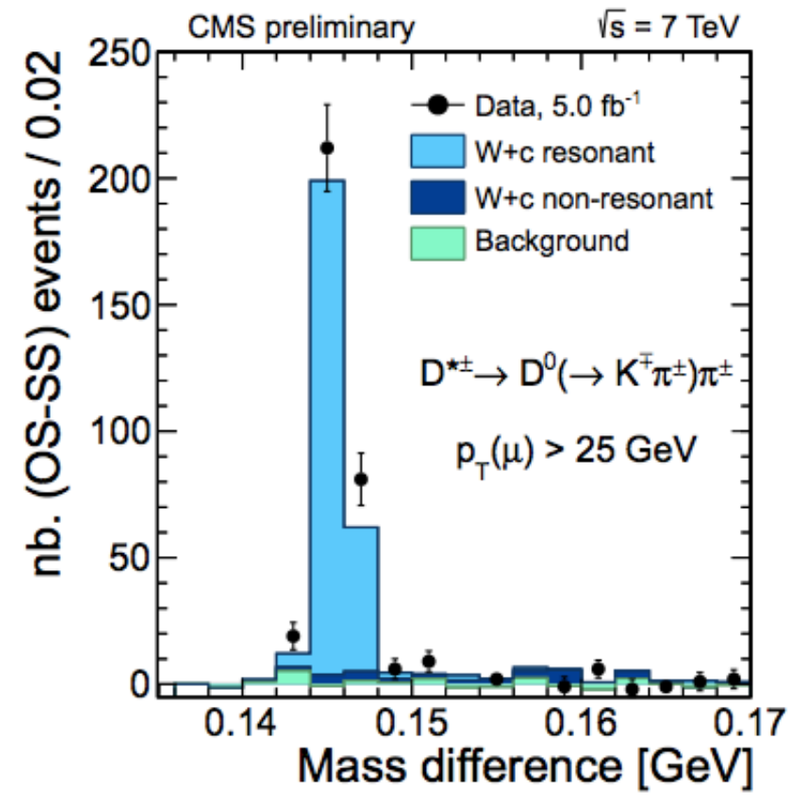
$p_T(\ell) > 25\ (35)$ GeV ; $|\eta| < 2.1$

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

- Exploit decays of charmed mesons

Measure the displaced secondary vertex



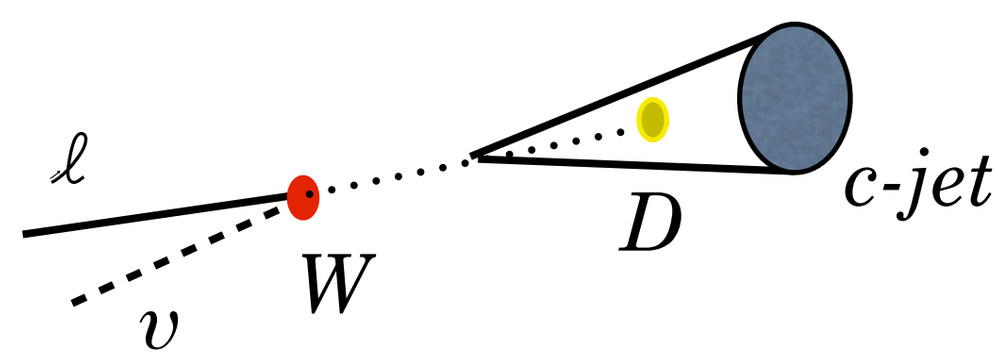




charge of the charm
unequivocally determined
in the three decay chains

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

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

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

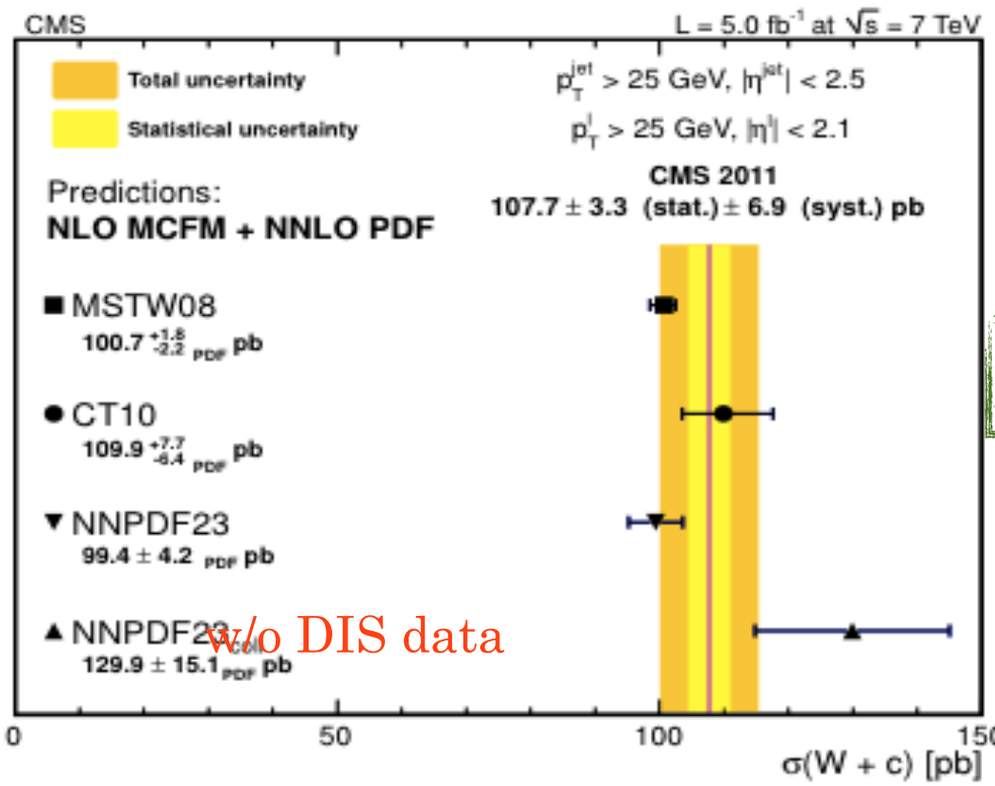



$p_T(c) > 25$ GeV ; $|\eta| > 2.5$

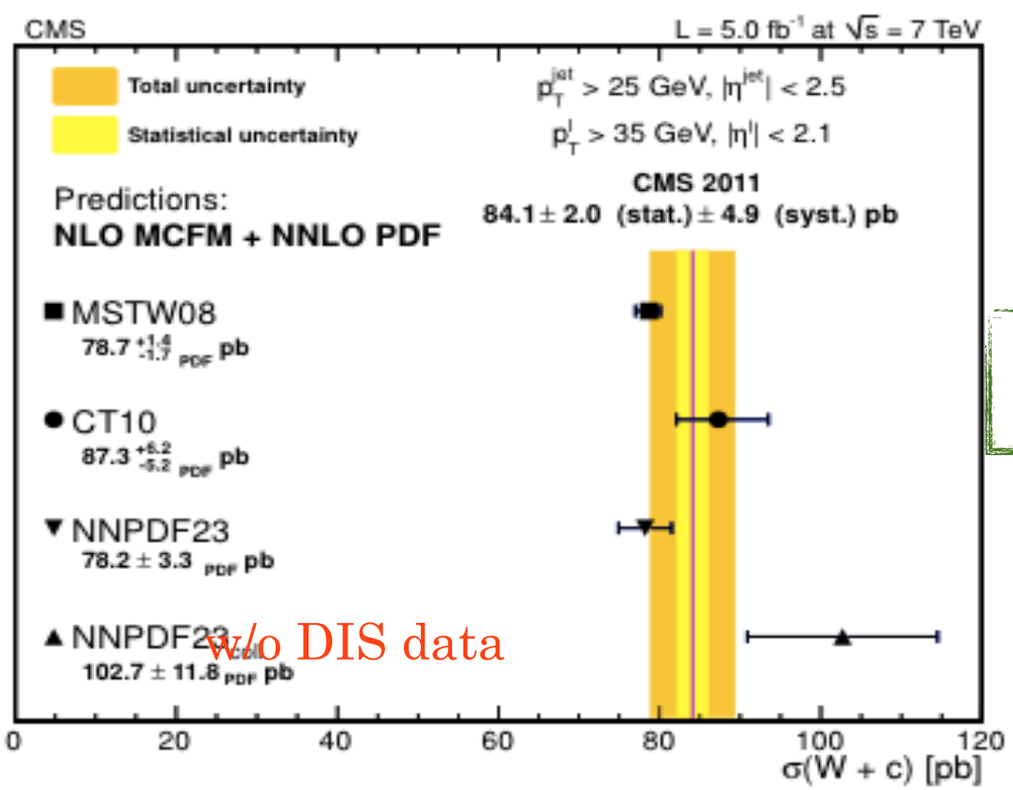
# *charm* + *W* cross section

$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 5/fb

MCFM @ NLO v.6.1




$W \to e\nu$




$W \to \mu\nu$

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

**systematic uncertainties**

Jet Energy Scale 3%

branching ratios 3%

PDFs :

MSTW08 (+DIS data)

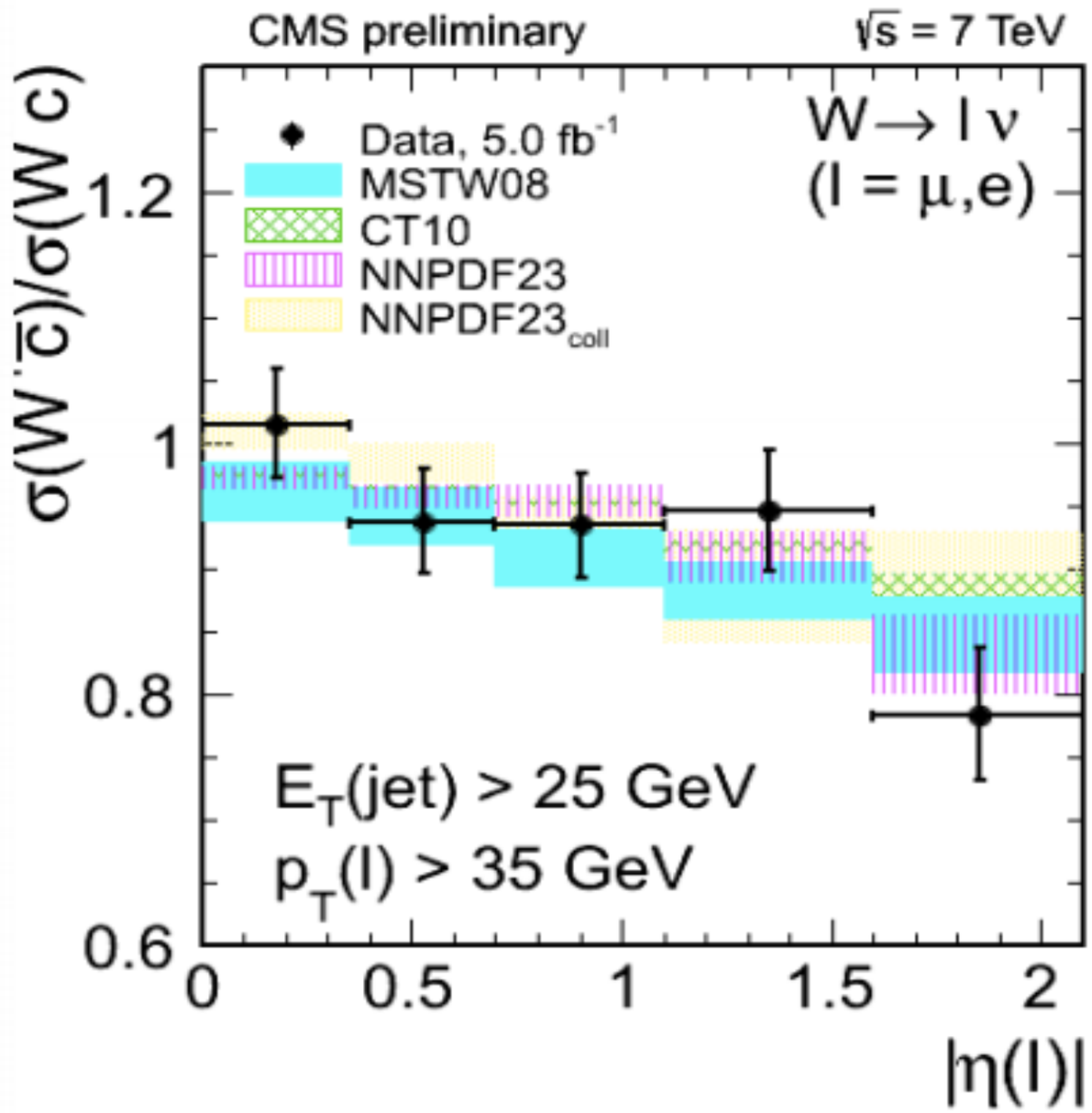
CT10 (+DIS data)

NNPDF23 (+DIS data)

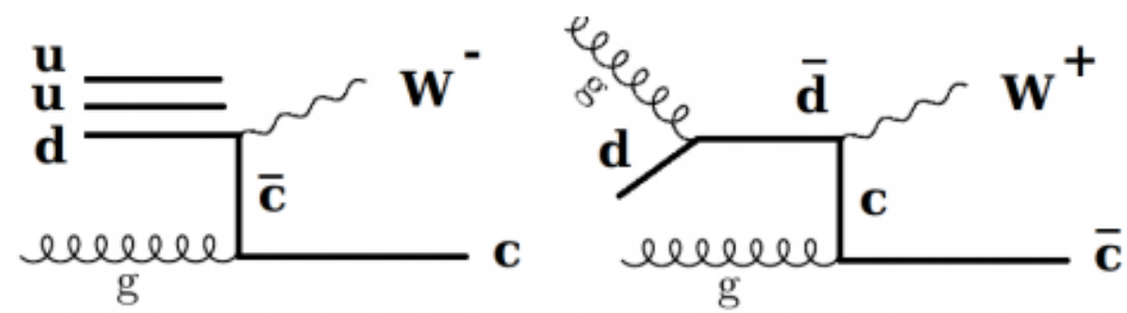
# *charm* + *W* cross section ratio

$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 5/fb

Differential Cross section Ratio vs. lepton pseudorapidity




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




Good agreement with MCFM @ NLO

PDFs :

MSTW08 (+DIS data)

CT10 (+DIS data)

NNPDF23 (+DIS data)

**no asymmetry is observed !**

# *beauty* + *W*

$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 5/fb

## $pp \rightarrow W(\rightarrow \mu\nu) + bb$

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

## *b*-tagging

- use discriminating variables b with displaced vertex measurement → high rejection of light and charm quarks

- Main backgroun 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)

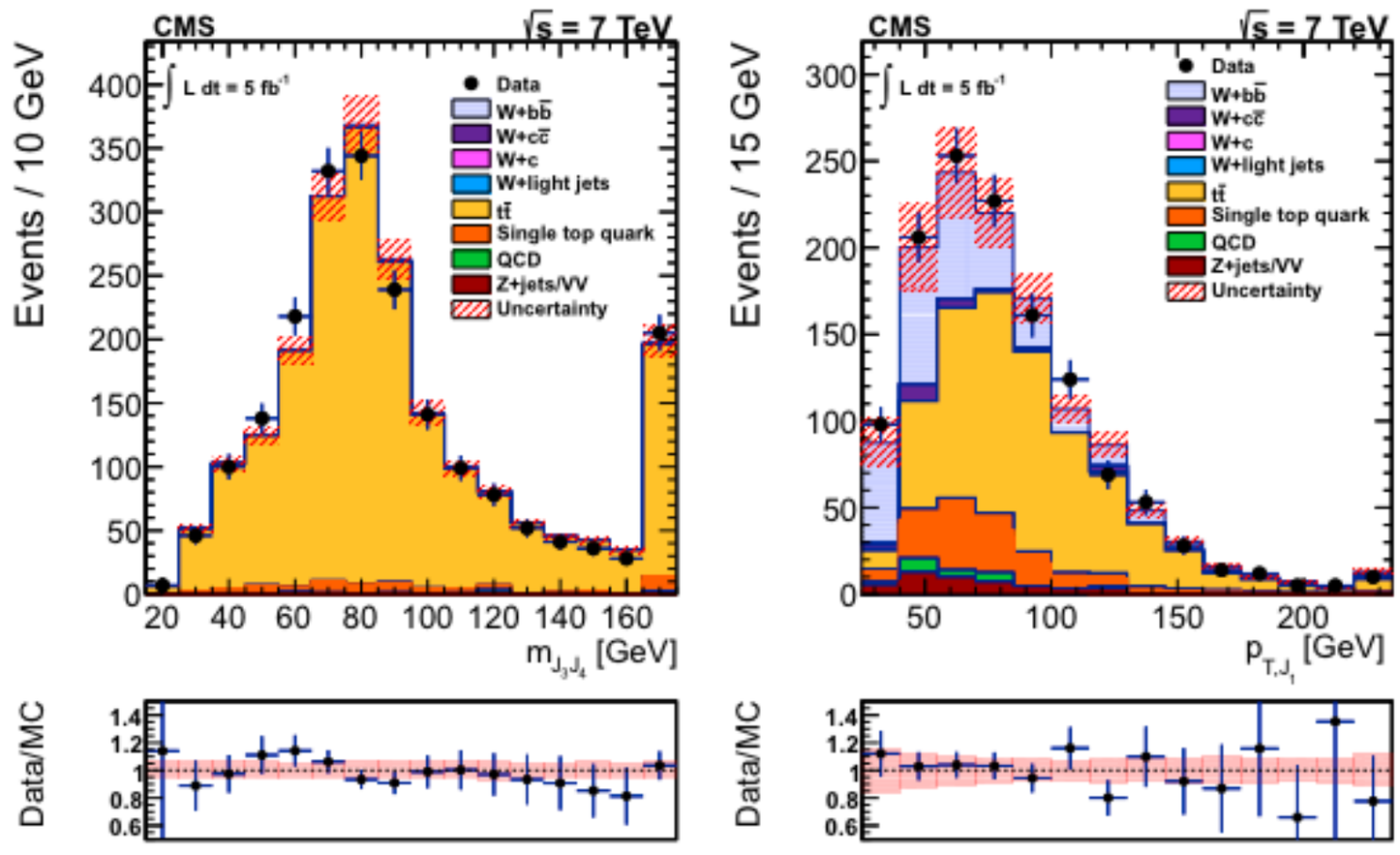
- good agreement with MadGraph+Pythia

## *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)



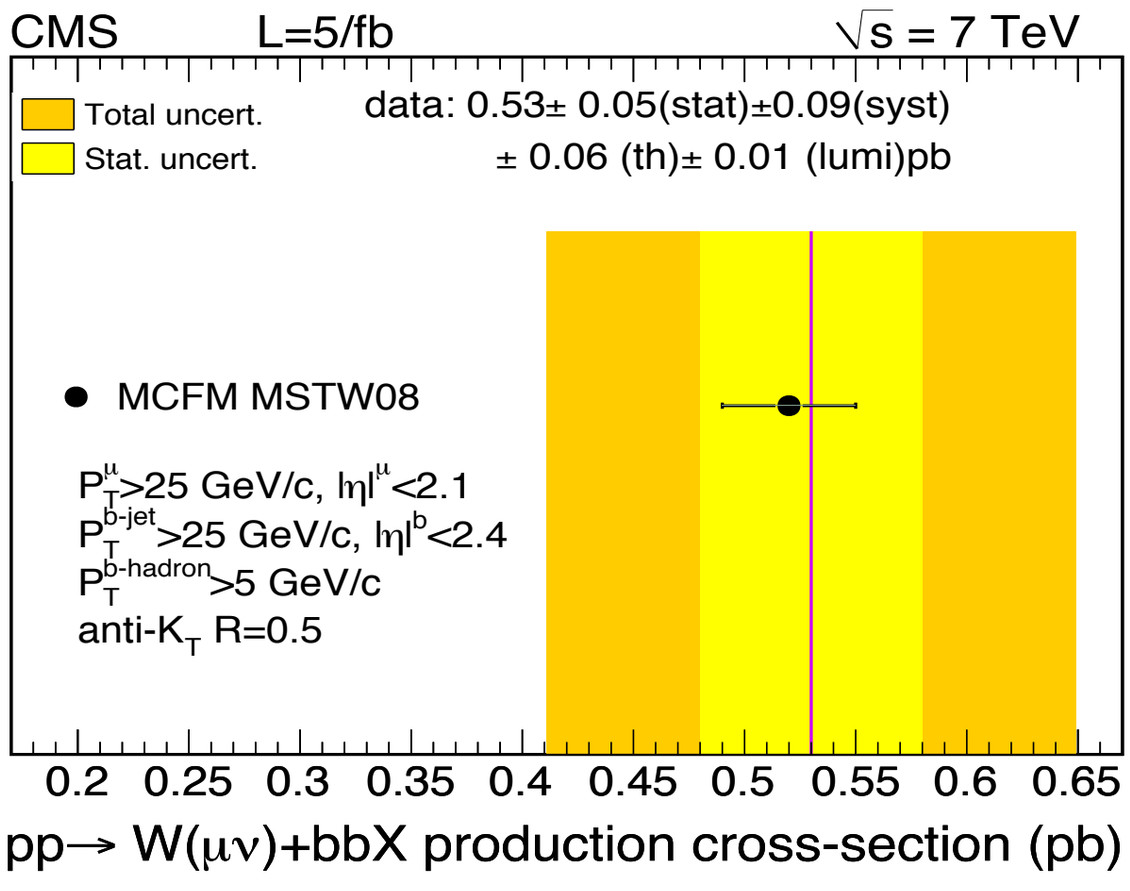
# *beauty* + *W* cross section

$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 5/fb

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

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

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

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

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

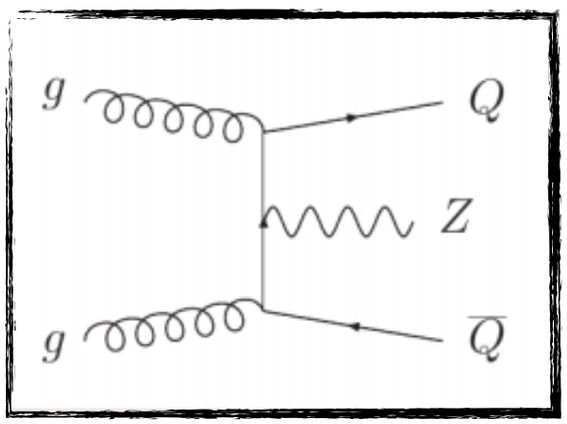
$$\sigma(pp \to W + b\bar{b}) \times \mathcal{B}(W \to \mu\nu) = 0.53 \pm 0.05\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.06\,(\text{th.}) \pm 0.01\,(\text{lum.})\,\text{pb}.$$

# *beauty* + $Z$

## $Z + b$ 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**)

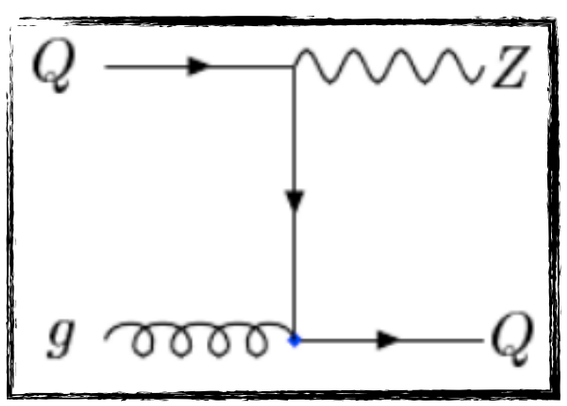



4FS ⟶ $m_b \neq 0$

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 ⟶ $m_b = 0$

prediction: MadGraph 5FS (tree level)

NLO prediction: MCFM, Powheg

# *beauty + Z*

$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 5/fb

## $Z + b$ @ 7 TeV

- dielectron and dimuon trigger:
  two high $p_T$ - opposite charge isolated $e,\mu$.

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

backgrounds
from ***top-antitop***, 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± 6 %

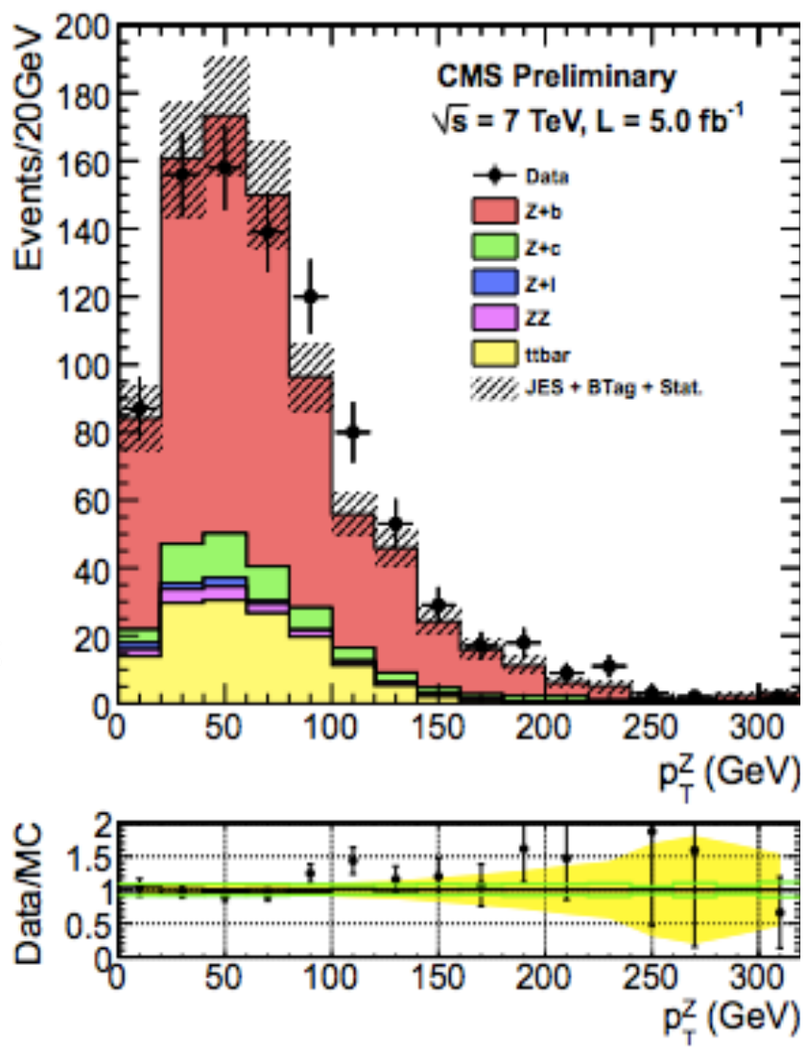
Corrected for detector-level
effects: acceptance, efficiencies:
detector level → particle level

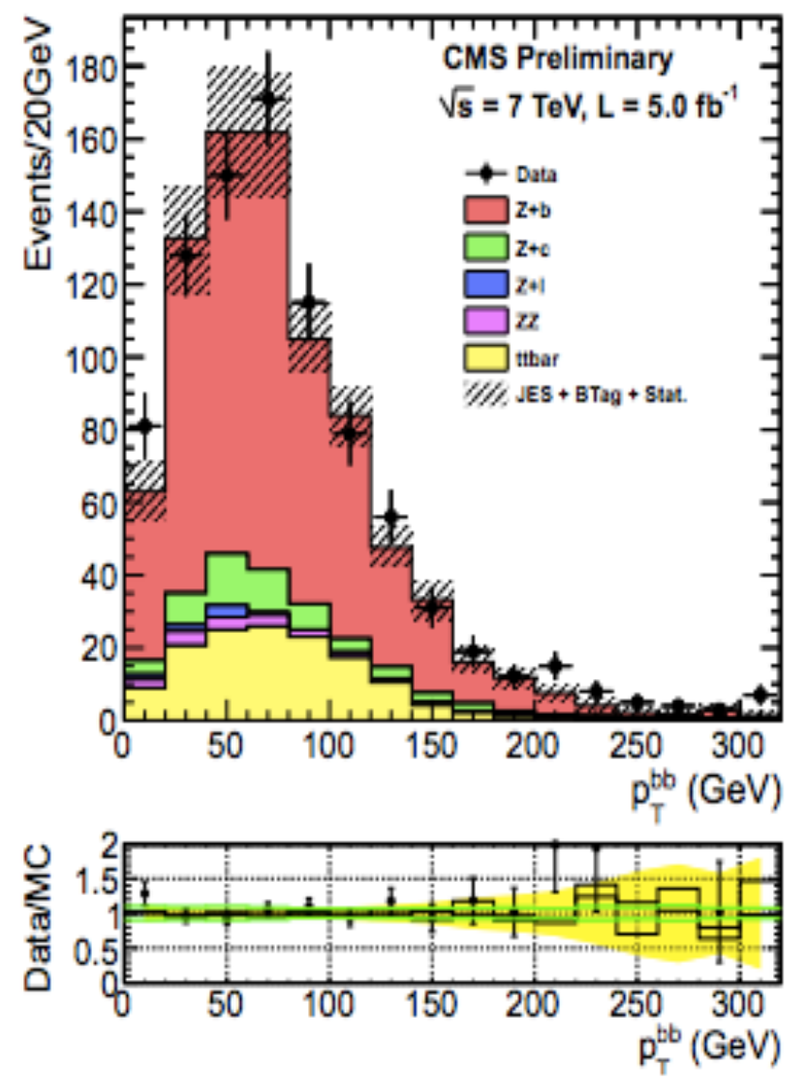
### $Z$ selection

$p_T(\mu, e) > 25,20$ 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
- $\Delta R(\mu,j) > 0.5$



# *beauty* + *Z* cross section

$\sqrt{s}$ = 7 TeV
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## $Z + b$ @ 7 TeV

Systematics Uncertainties

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

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### *b* selection

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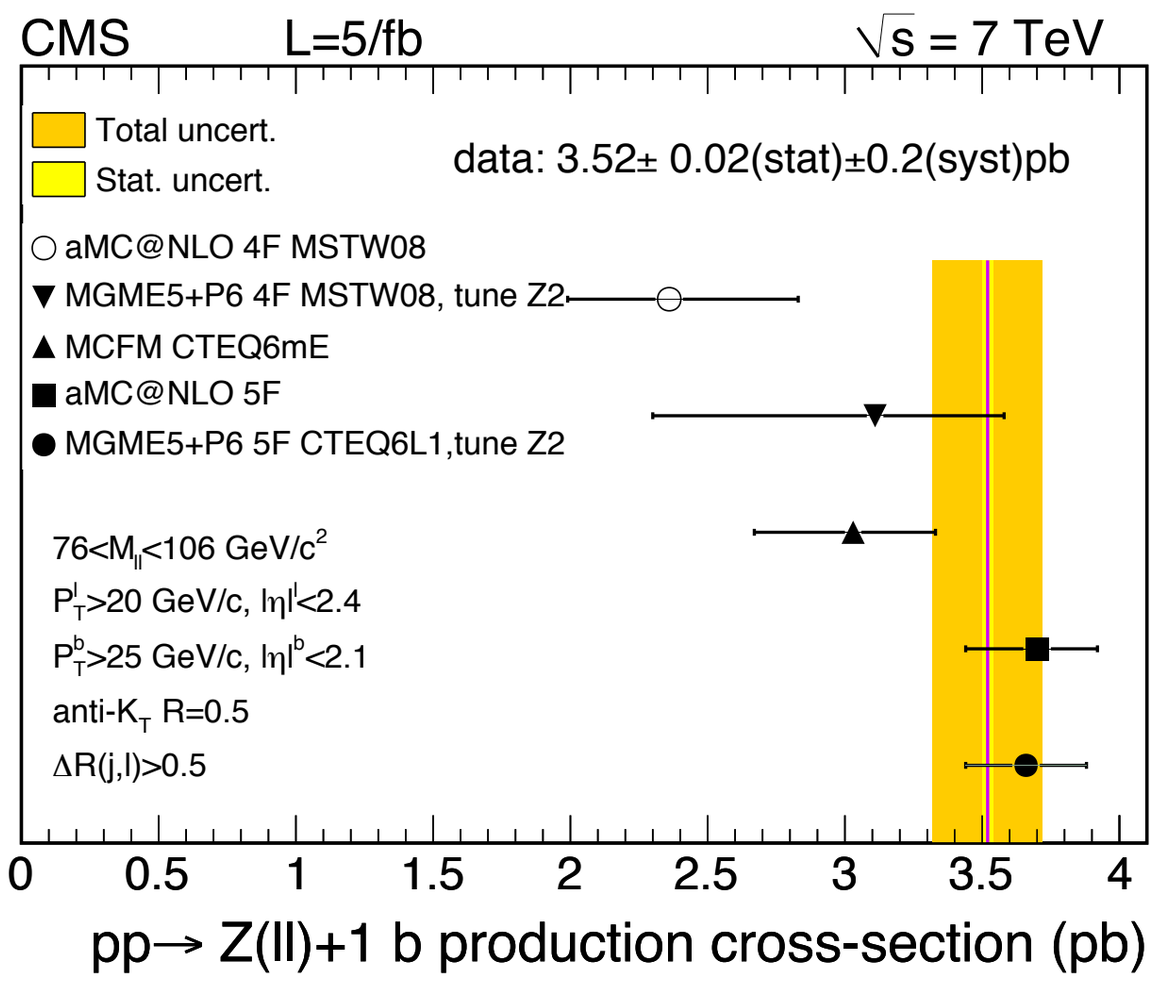
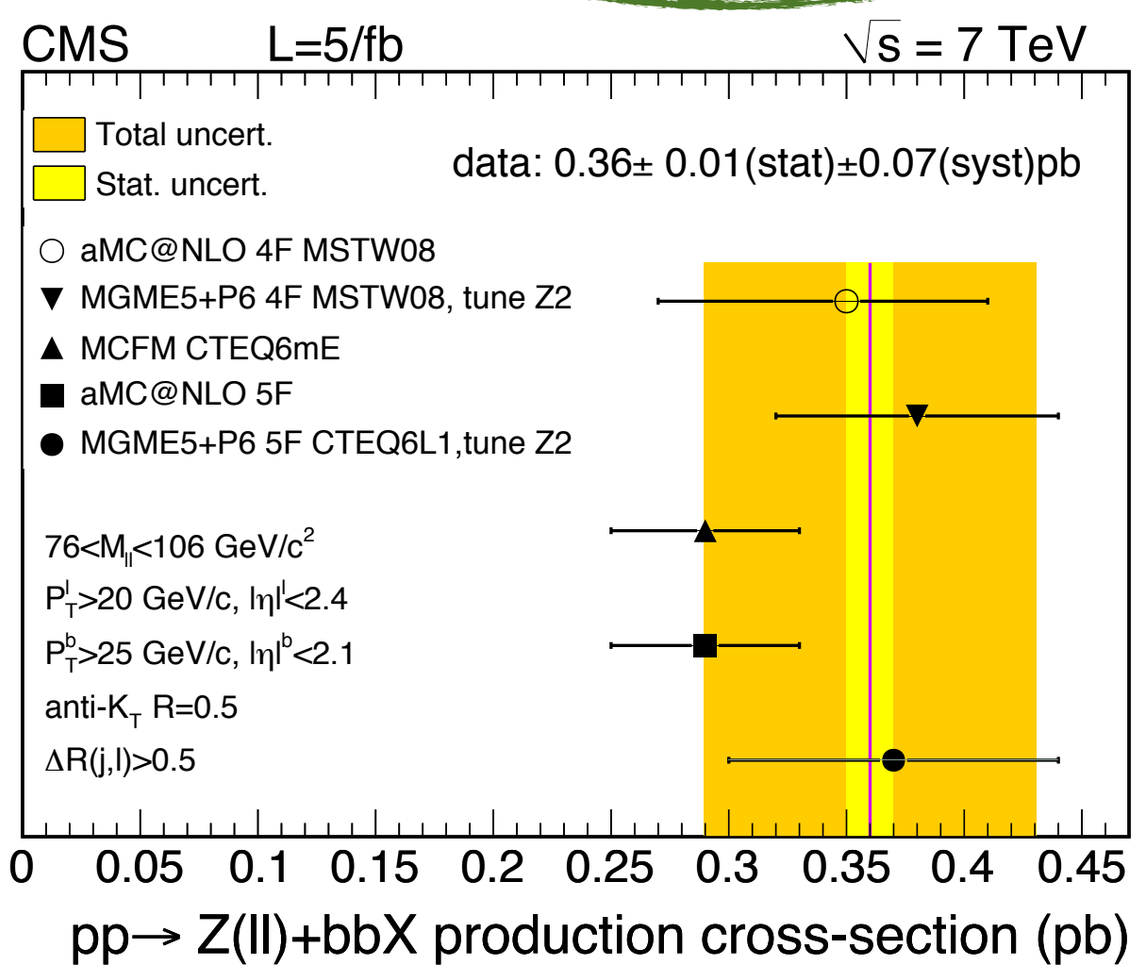
Good agreement between data and theoretical predictions!

## Results



# *beauty + Z*

$\sqrt{s}$ = 8 TeV
$\int L\,dt$ = 20/fb

## $Z + b$ @ 8 TeV

- dielectron and dimuon trigger:
  two high $p_T$ - opposite charged isolated $e,\mu$.

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

backgrounds
***top-antitop*** from data-driven
method with a e+μ sample using
the invariant mass sidebands

***diboson*** from MC

purity
template fits to the MC shape
of the light and charm fraction
using track-based discriminator

$f_b$ = 60 ± 6 %

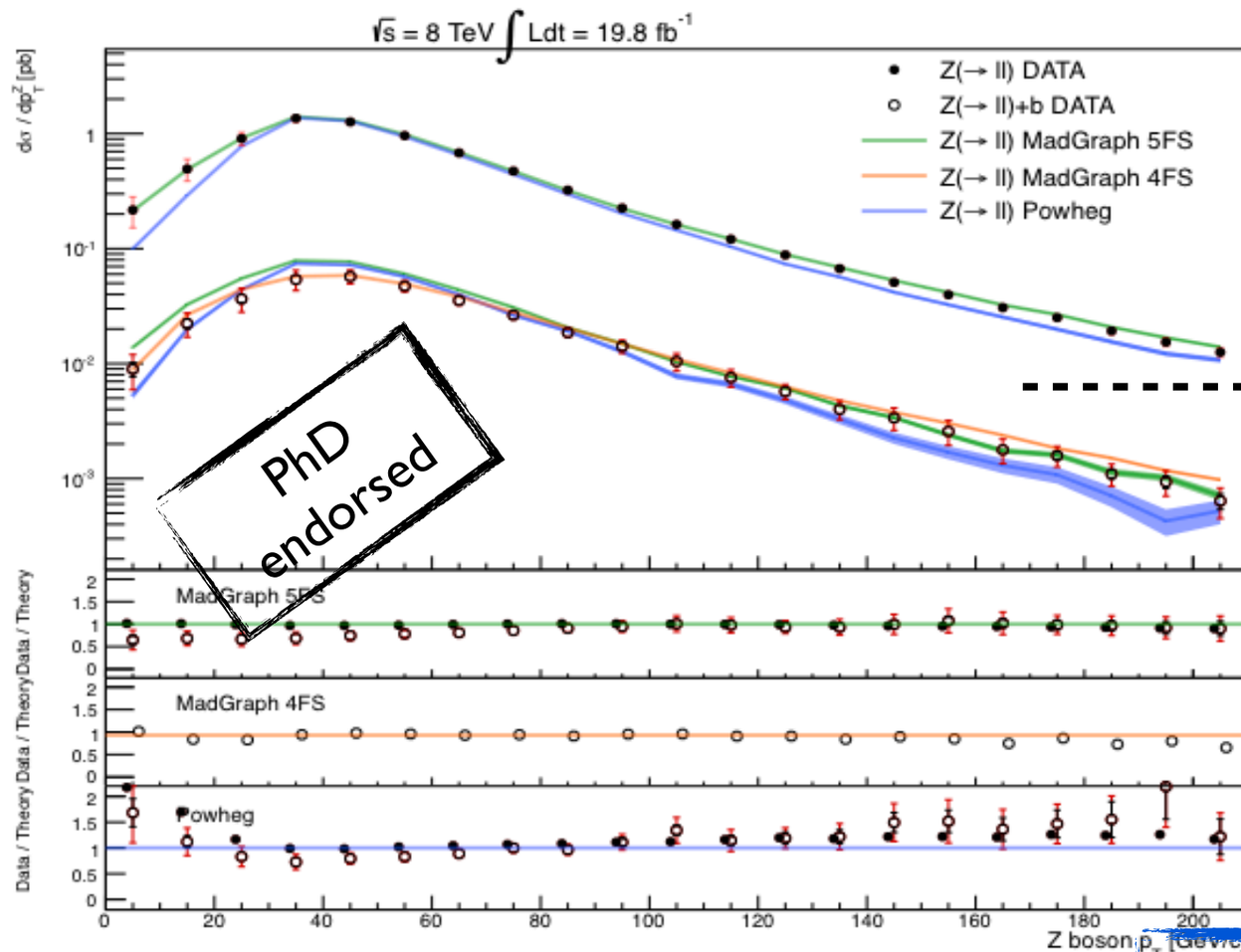
Unfolded with the SVD algorithm

### *Z* selection

$p_T(\mu, e) > 25$ GeV
$|\eta(\mu, e)| < 2.4$
$71 < m(ll) < 111$ GeV

### *b* selection

- at least 1 b-tagged jet
- anti kt 05
- $p_T$ (b-jet) > 30 GeV
- $\Delta R(\mu,j) > 0.5$




unfolded σ(Z+jets)

unfolded σ(Z+b)

Differential unfolded cross sections **σ**(Z+b) vs. ***Z* boson $p_T$**

Compare with the prediction of MadGraph 4FS /5FS @LO and Powheg @LO
+Pythia6 +Pythia6

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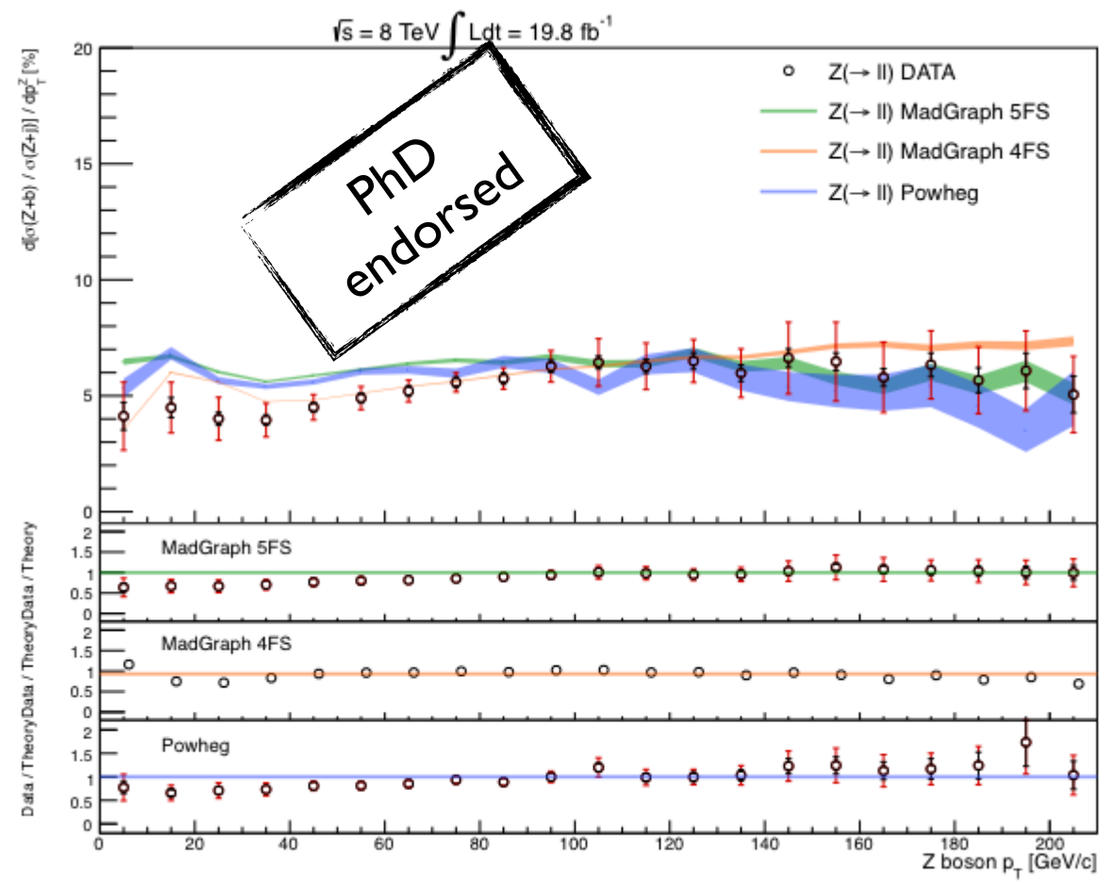
$p_T$ ($\mu$, $e$) > 25 GeV
$|\eta$ ($\mu$, $e$)$|$ < 2.4
71 < m ($ll$) < 111 GeV

### *b* selection

- at least 1 b-tagged jet
- anti kt 05
- $p_T$ (b-jet) > 30 GeV
- ΔR (μ,j) > 0.5

R = **σ**(Z+b) / **σ**(Z+jets) [%] vs. ***Z* boson $p_T$**

differential
cros section
ratios




Compare with the prediction of MadGraph 4FS /5FS @LO and Powheg @LO
+Pythia6 +Pythia6

# 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$^{-1}$**
  - $Z$+$b$ @ 8 TeV differential cross section compared MadGraph 4FS/5FS, Powheg **20 fb$^{-1}$**

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

  *W/Z + 1,2 b-jets/hadrons*, *W*+*c*, *Z*+*c*, PDFs, MPI ...

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

*stay tuned!!!*