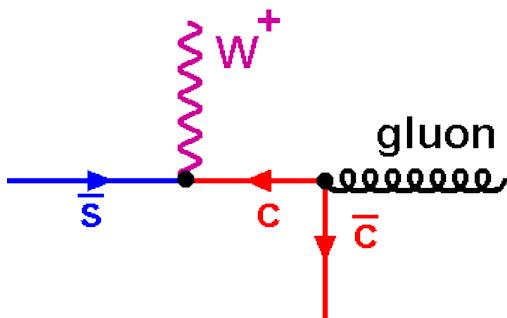
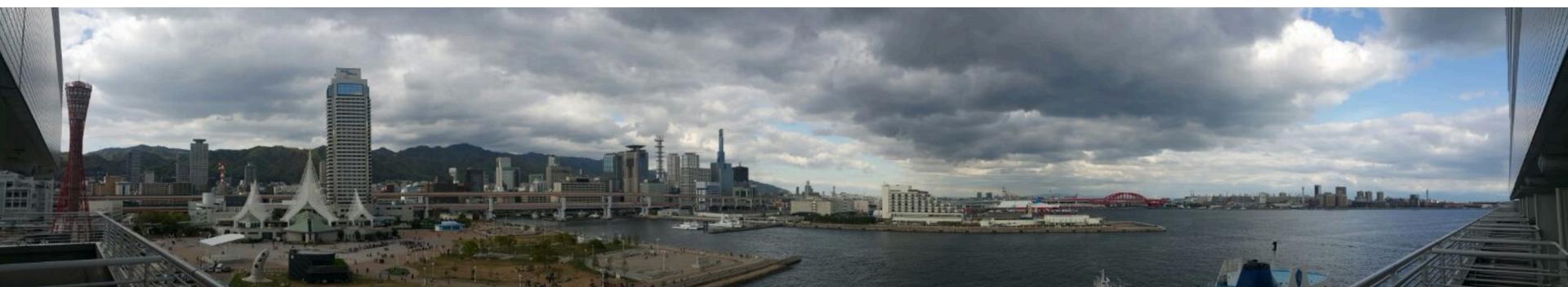
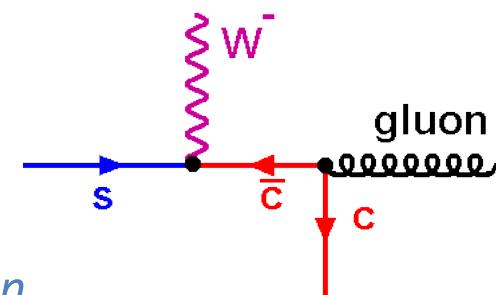




# Vector Boson production with heavy flavor quarks from CMS



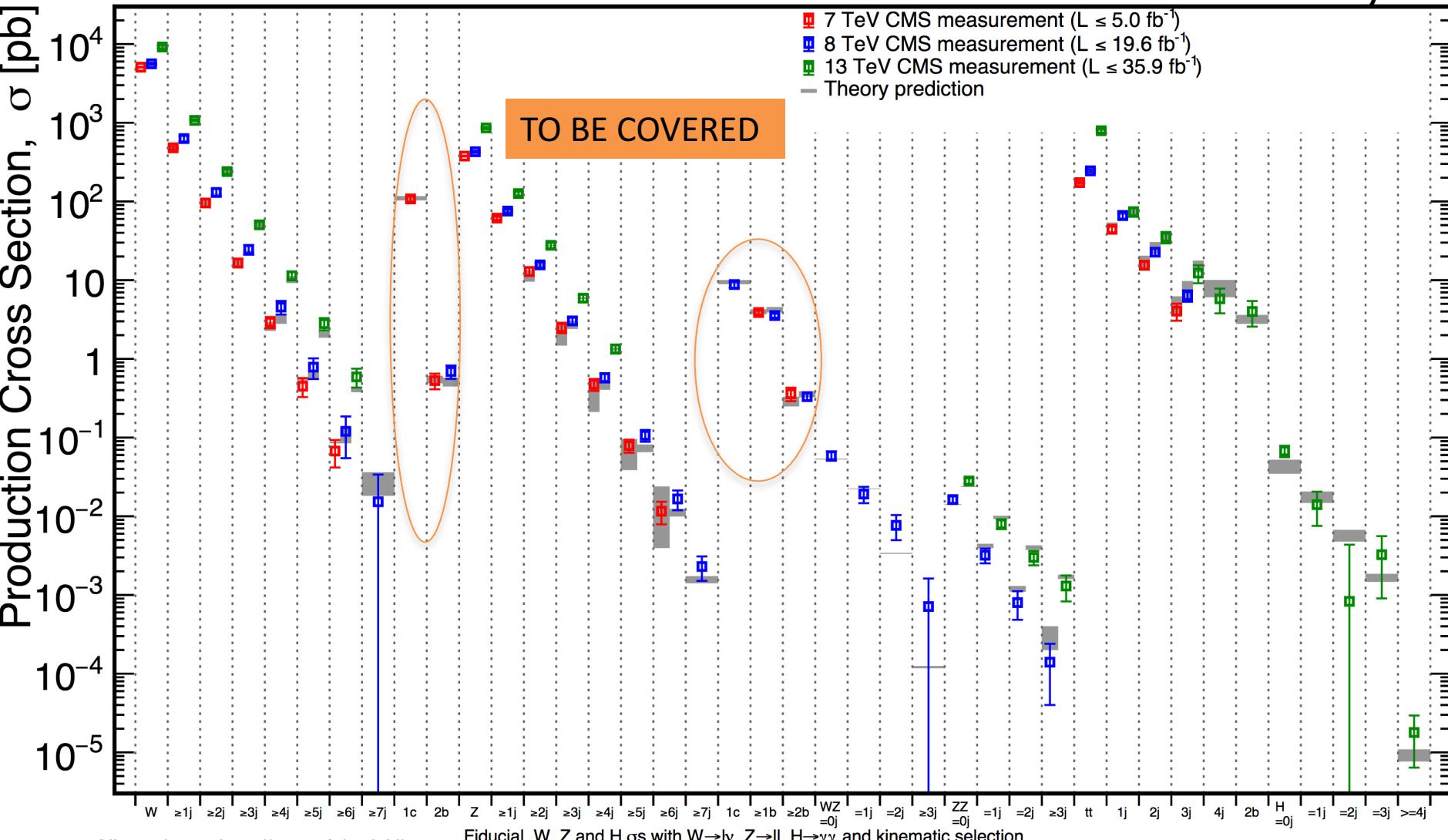
Buğra BİLİN  
IIHE-ULB  
Bruxelles, Belgium  
on behalf of CMS Collaboration  
DIS 2018  
Kobe Japan



# Status by Nov 2017

November 2017

CMS Preliminary



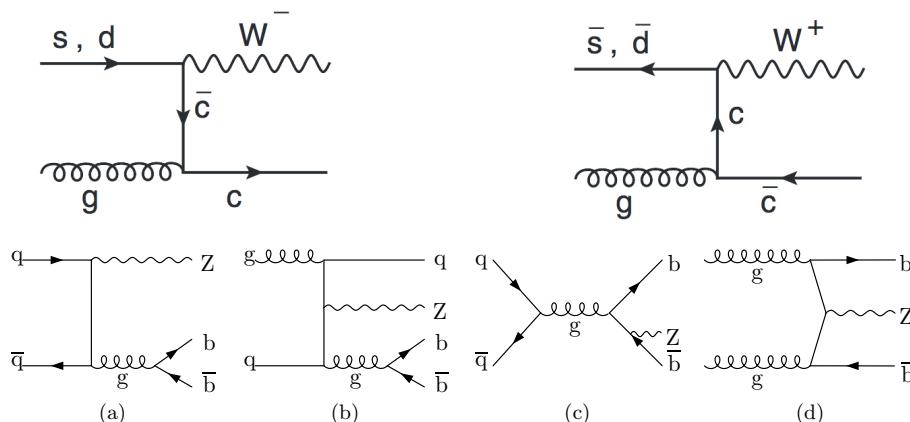
All results at: <http://cern.ch/go/pNj7>

Fiducial W, Z and H  $\sigma$ s with  $W \rightarrow l\nu$ ,  $Z \rightarrow ll$ ,  $H \rightarrow \gamma\gamma$  and kinematic selection

# MOTIVATION

- Processes involving W & Z boson production are one of the better understood processes at hadron colliders
  - $W \rightarrow l\nu, Z \rightarrow ll$ , ( $l = e, \mu$ ) are among the cleanest final states experimentally
- Important to study V+ HF production at the LHC
  - To test pQCD and validate MC
  - Probe HF PDFs
  - Collinear production of b quarks (gluon splitting)
- They are backgrounds to other measurements and BSM searches

See also S. Pflitsch's talk



Example Feynman  
diagrams for  $W+c$  and  $Z + bb$  productions

- Measurements carried out in fiducial phase space
  - corrected for detector effects

# CONTENT

- Measurement of Z + b jet at 8 TeV (Eur. Phys. J. C (2017) 77: 751)
- Measurement of Z + c jet at 8 TeV (Eur. Phys. J. C (2018) 78: 287)
- W+c differential cross section at 13 TeV (CMS-PAS-SMP-17-014)
- Measurement of W + bb jet at 8 TeV (Eur. Phys. J. C (2017) 77: 92)
- Z+ b, bb jet cross sections at 7 TeV (JHEP 06 (2012) 126, JHEP 06 (2014) 120)
- W+bb cross section at 7 TeV (PLB 735 (2014) 204)
- W+c differential cross section at 7 TeV (JHEP 02 (2014) 013)
- Z+bb jets, b hadron angular correlations at 7 TeV (JHEP 12 (2013) 039)



8 publications  
2 new after DIS2017  
1 new prelim. result

DIS 2018

# $V(Z,W) +>=1 b$

p-p  $\sqrt{s}=7,8$  TeV  
5, 19.8  $\text{fb}^{-1}$

$Z + >=1 b$

$p_T^{\prime\prime} > 20 \text{ GeV}, |\eta'| < 2.4$

$76 < M_{ll} < 106 \text{ GeV}$

$71 < M_{ll} < 111 \text{ GeV}$

$p_T^j > 25 \text{ GeV}, |\eta^j| < 2.1$

$p_T^j > 30 \text{ GeV}, |\eta^j| < 2.4$

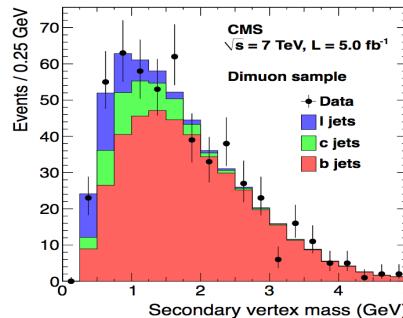
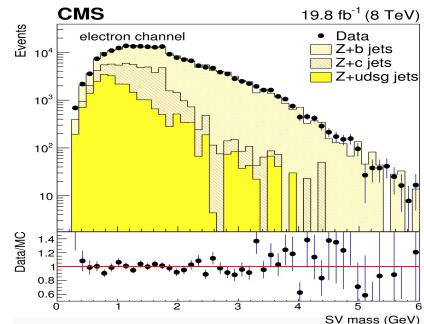
$W + bb$

$p_T^{\prime\prime} > 25 \text{ GeV}, |\eta'| < 2.1$

$p_T^{\prime\prime} > 30 \text{ GeV}, |\eta'| < 2.1$

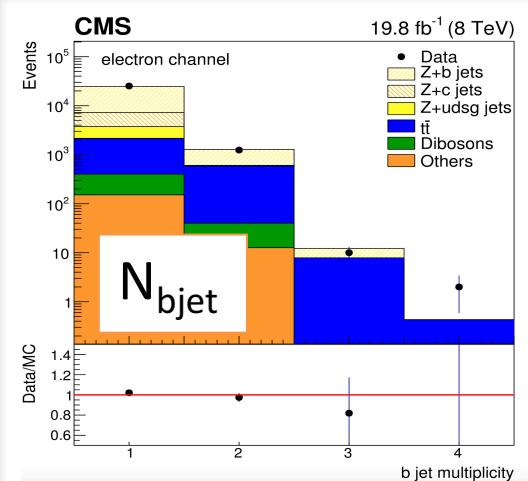
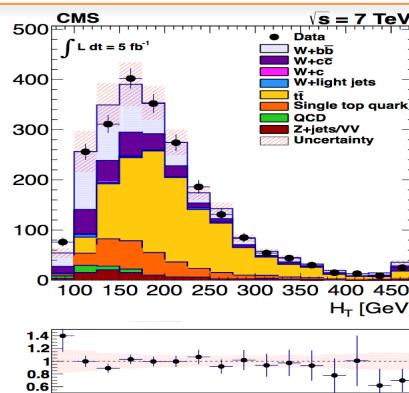
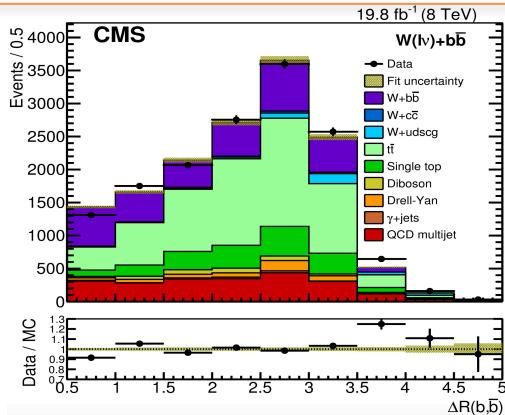
two b-jets  $p_T^j > 25 \text{ GeV}, |\eta^j| < 2.4$

&& no other jets with  $p_T^j > 25 \text{ GeV}, |\eta^j| < 4.7$



→ SSV (CSV) algorithms to tag jets originating from b.  
→ Chosen WP gives ~50% b- efficiency and ~1% of mistag rate

SV mass, input for b-tag algorithms



Studies of various variables are carried out

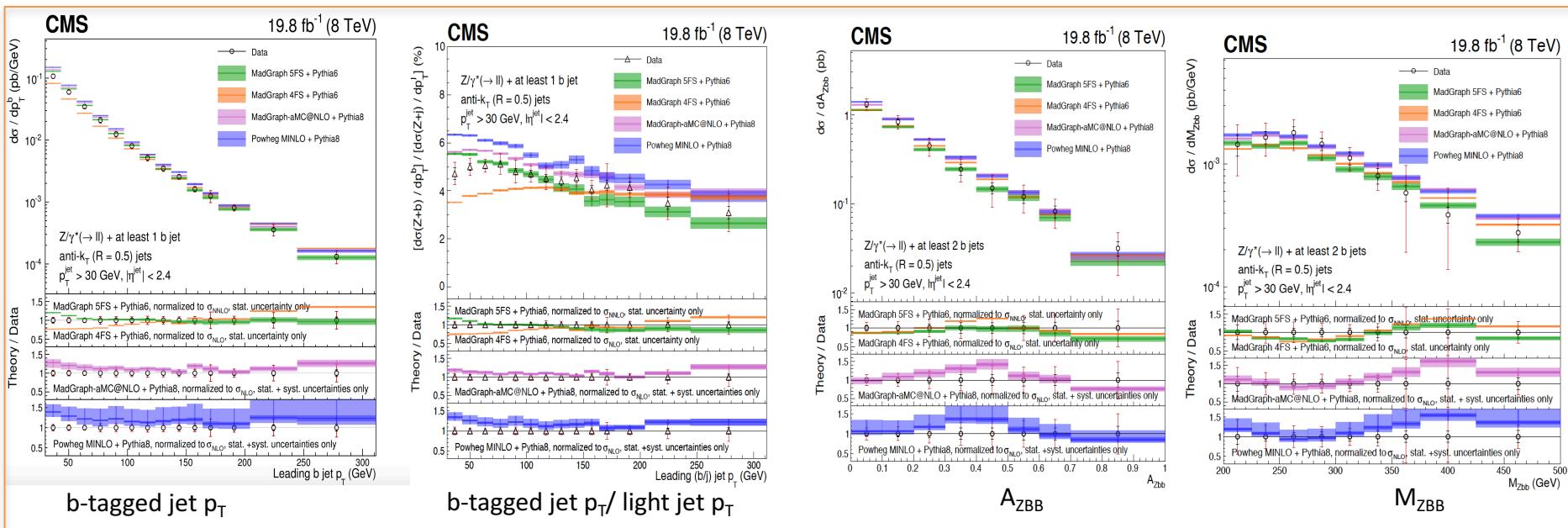
Z+b:  $p_T^b$ ,  $\eta^b$ ,  $p_T^Z$ ,  $H_T$ ,  $\Delta\phi(Z,b)$

Z+bb:  $p_T^{b1}$ ,  $p_T^{b2}$ ,  $p_T^Z$ ,  $M^{bb}$ ,  $M^{Zbb}$ ,  $p_T^{bb}$ ,  $\Delta\phi(bb)$ ,  $\Delta\phi(bb,Z)$ ,  $\Delta R(bb)$ ...

- Sensitive to b-quark PDF and initial-state gluon splitting
- Differences between Flavor Schemes.
- Sensitive to presence of heavy intermediate particles

$$A_{Zbb} = \frac{\Delta R_{Zb}^{\max} - \Delta R_{Zb}^{\min}}{\Delta R_{Zb}^{\max} + \Delta R_{Zb}^{\min}}.$$

$$R(x) = \frac{d\sigma(Z+(\geq 1b))/dx}{d\sigma(Z+jets)/dx},$$



# $V(W,Z) +>=1 b$

p-p  $\sqrt{s}=7,8$  TeV  
5, 19.8 fb $^{-1}$

## Z+b results at 7 TeV

Cross section	Measured
$\sigma_{Z+1b}$ (pb)	$3.52 \pm 0.02 \pm 0.20$
$\sigma_{Z+2b}$ (pb)	$0.36 \pm 0.01 \pm 0.07$
$\sigma_{Z+b}$ (pb)	$3.88 \pm 0.02 \pm 0.22$
$\sigma_{Z+b}/Z+j$ (%)	$5.15 \pm 0.03 \pm 0.25$

## Z+b results at 8 TeV

Cross section	Measured
$\sigma_{Z+1b}$ (pb)	$3.55 \pm 0.12 \pm 0.2$
$\sigma_{Z+2b}$ (pb)	$0.331 \pm 0.011 \pm 0.035$
$\sigma_{Z+b}$ (pb)	---
$\sigma_{Z+b}/Z+j$ (%)	$9.3 \pm 0.4 \pm 0.7$

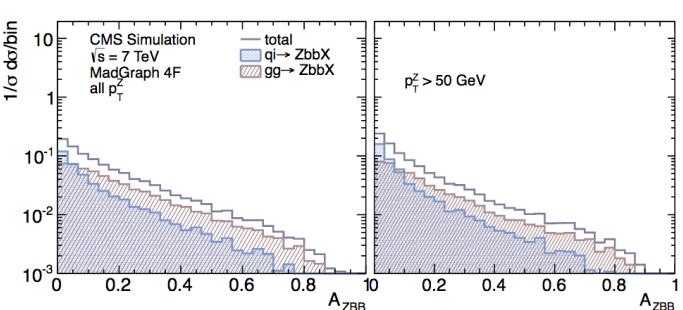
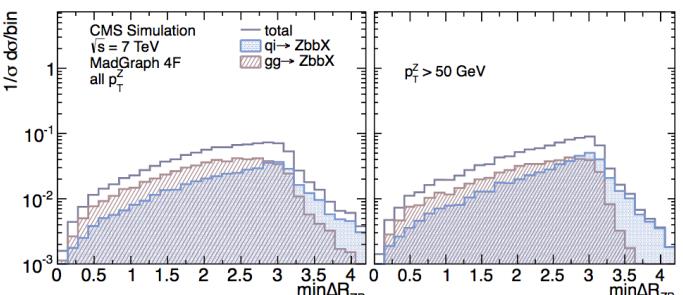
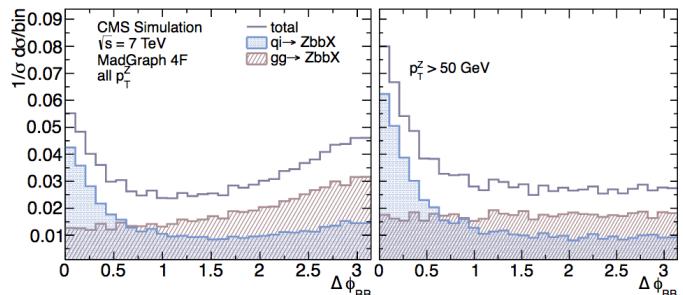
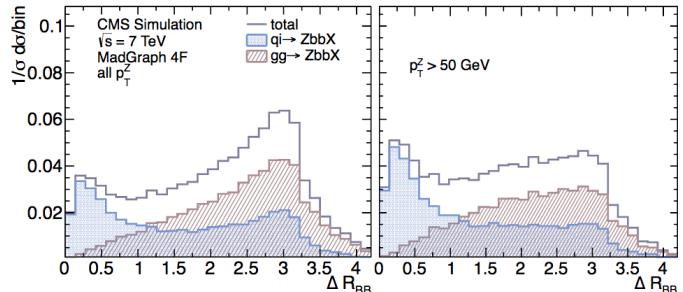
$W(-\!>\!l\nu) + 2b$  cross section at 7 TeV  
 $0.53 \pm 0.05$  (stat)  $\pm 0.09$  (syst)  $\pm 0.06$   
 (theo.)  $\pm 0.01$  (lumi) pb

$W(-\!>\!l\nu) + 2b$  cross section at 8 TeV  
 $0.64 \pm 0.03$  (stat)  $\pm 0.10$  (syst)  $\pm 0.06$   
 (theo.)  $\pm 0.02$  (lumi) pb

→ All measurements consistent with SM predictions  
 and among each other

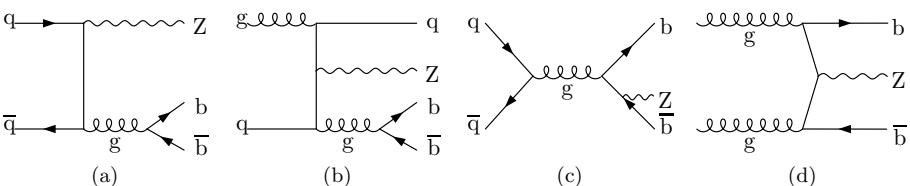
# Z+ b hadrons

$p_T' > 20$  GeV,  $|\eta'| < 2.4$        $81 < M_{ll} < 101$  GeV  
 $p_T^b > 15$  GeV,  $|\eta^b| < 2$

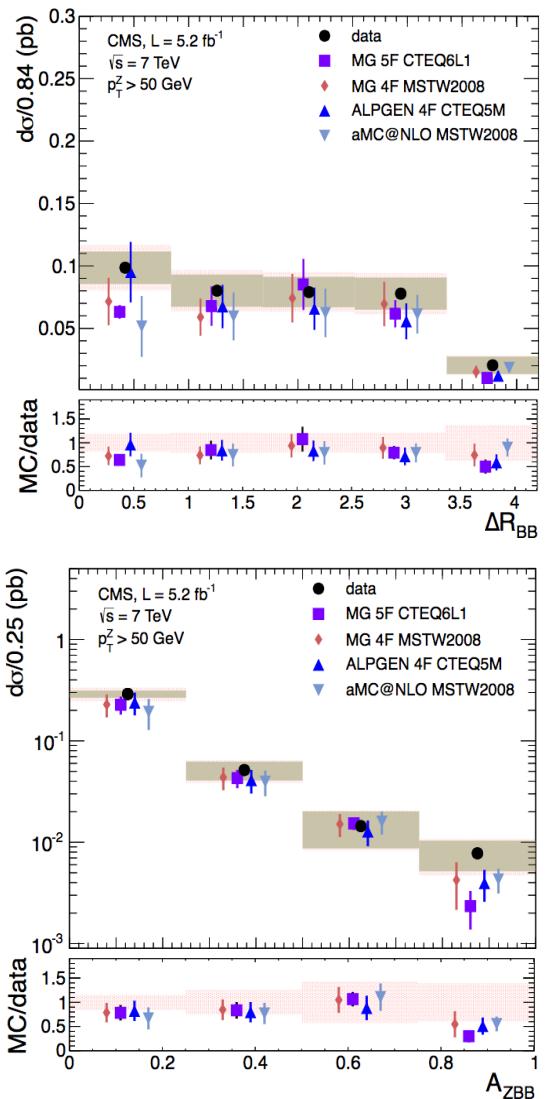
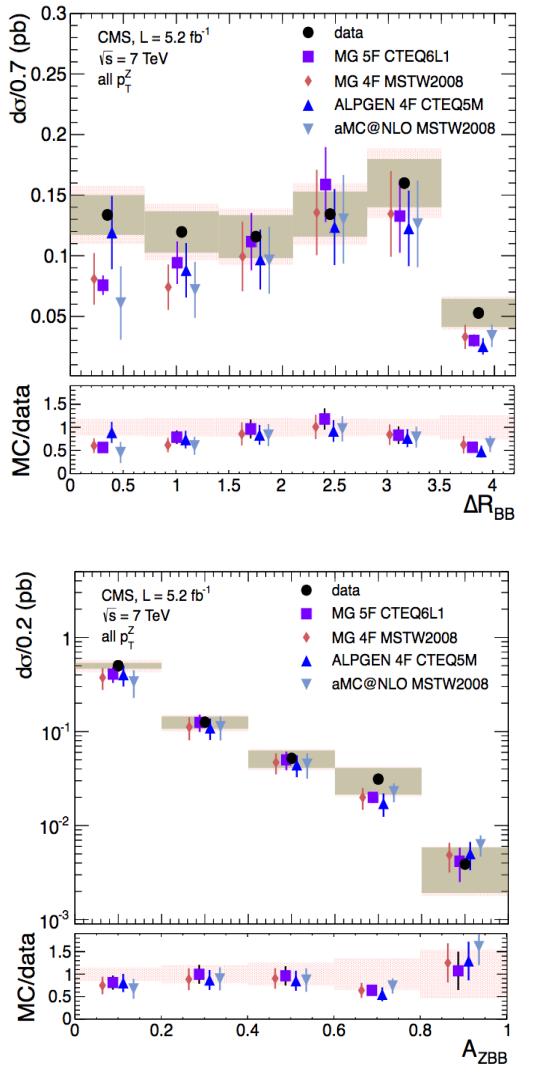


- Study production of b hadrons associated with Z
- B hadrons identified using displaced secondary vertices
- No jet reconstruction, measurement not restricted to jet cone

$$A_{Zbb} = \frac{\Delta R_{Zb}^{\max} - \Delta R_{Zb}^{\min}}{\Delta R_{Zb}^{\max} + \Delta R_{Zb}^{\min}}.$$



# Z+ b hadrons



→ Study production of b hadrons associated with Z  
 → No unfolding  
 → Corrected for efficiency and acceptance  
 → Bin to bin migrations are accounted for as a source of systematic uncertainty

NEW

# $V(W,Z) + c$

p-p  $\sqrt{s}=7,8,13 \text{ TeV}$   
5, 19.8, 35.7  $\text{fb}^{-1}$

$p_T^j > 21 \text{ GeV}, |\eta^j| < 2.1, 71 < M_{jj} < 111 \text{ GeV}$

$p_T^j > 25 \text{ GeV}, |\eta^j| < 2.1$

$p_T^j > 25 \text{ GeV}, |\eta^j| < 2.4$

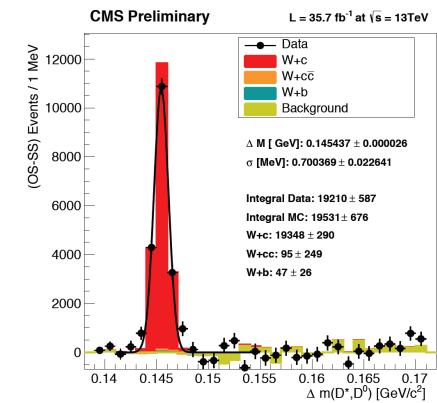
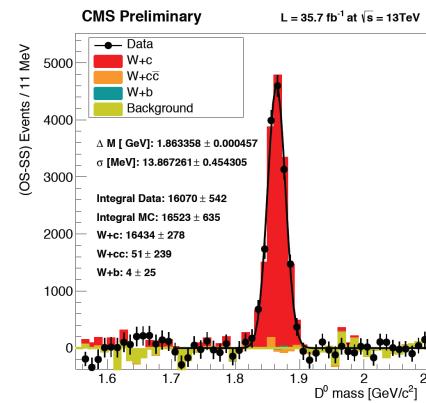
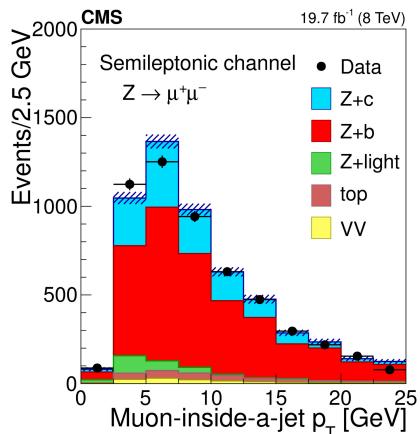
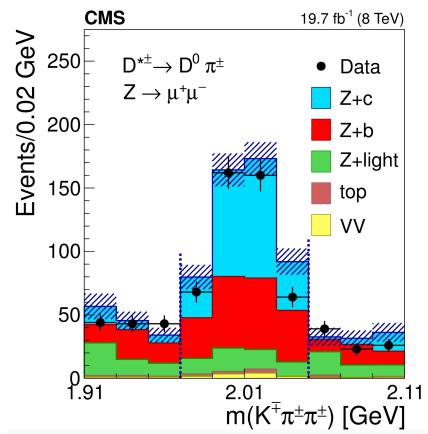
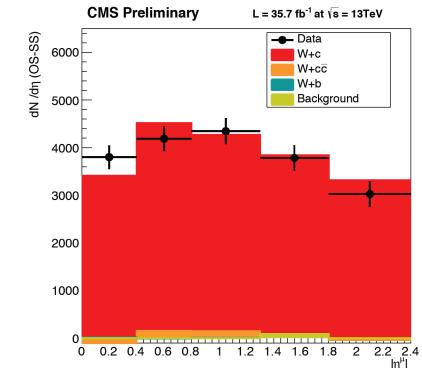
$p_T^\mu > 26 \text{ GeV}, |\eta^\mu| < 2.4$

- V + c measurements provide constraints to strange and charm PDF's
- They provide BG's for searches

- Tagging of heavy flavor jets carried out in 3 signatures (only 3<sup>rd</sup> for 13 TeV results)

- Semileptonic decay of hadron leading to a muon from a displaced vertex
- A displaced SV with 3 tracks consistent with  $D^\pm$  decay
- A displaced secondary vertex with two tracks consistent with  $D^0$  decay and associated to a previous  $D^{*+}(2010)$  decay

- W+c: OS- SS method to subtract BG
- BG contributions from the gluon splitting.

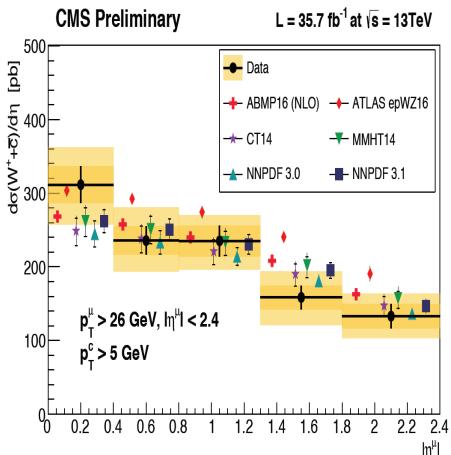
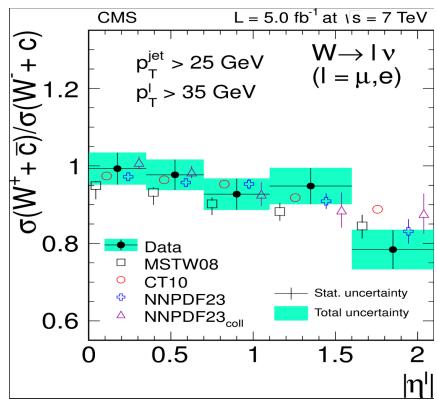
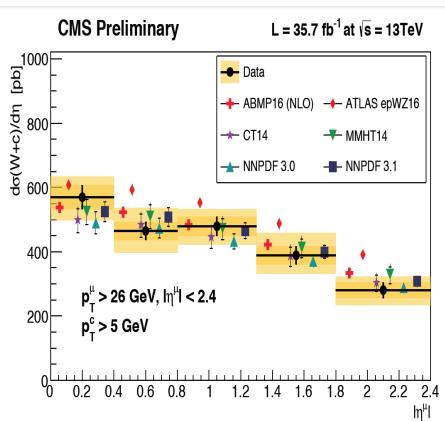
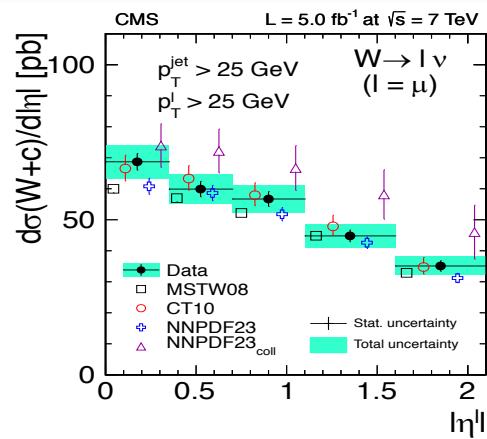


NEW

# W + c

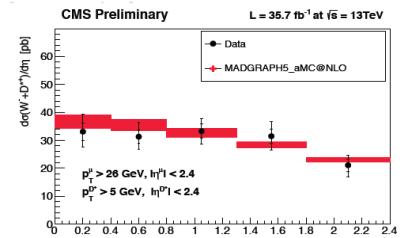
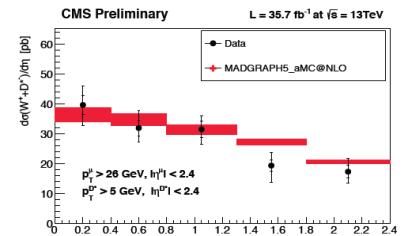
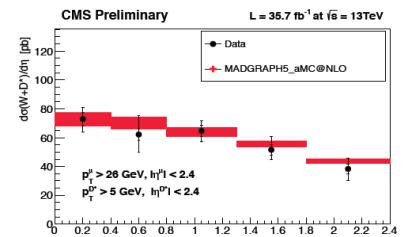
p-p  $\sqrt{s}=7,13$  TeV  
5,35.7  $\text{fb}^{-1}$

- Measured W + c cross section as well as W<sup>+</sup>+c/W<sup>+</sup>+b ratio
- inclusively
- differentially wrt lepton  $\eta$



→ Differential W + c and W<sup>+</sup>+c/W<sup>+</sup>+c cross section results

- 13TeV: extrapolation to the unmeasured phase space
- As cross check: W + D\* x-sec is measured in fiducial range

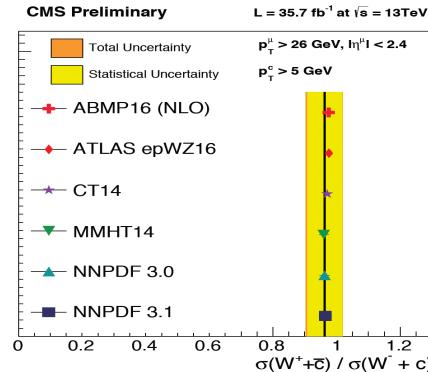
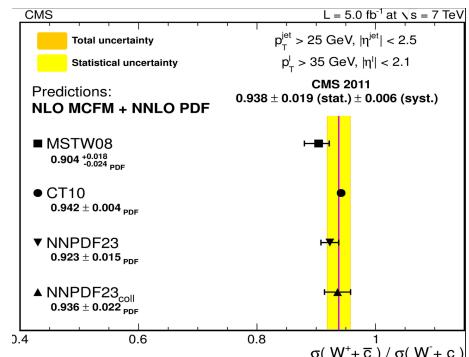
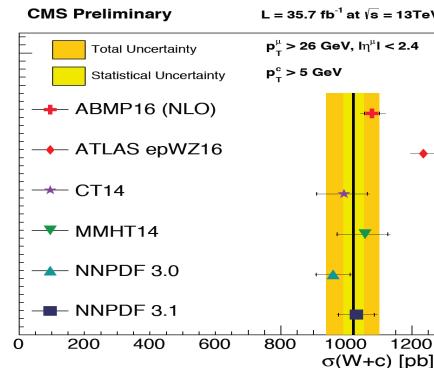
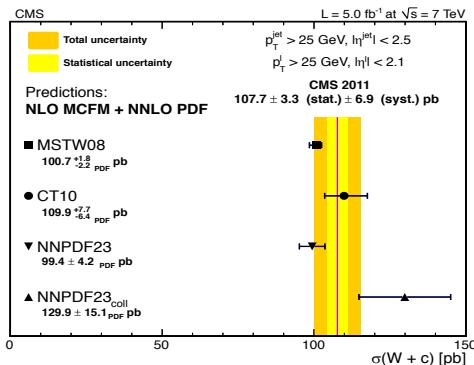


NEW

## W + c

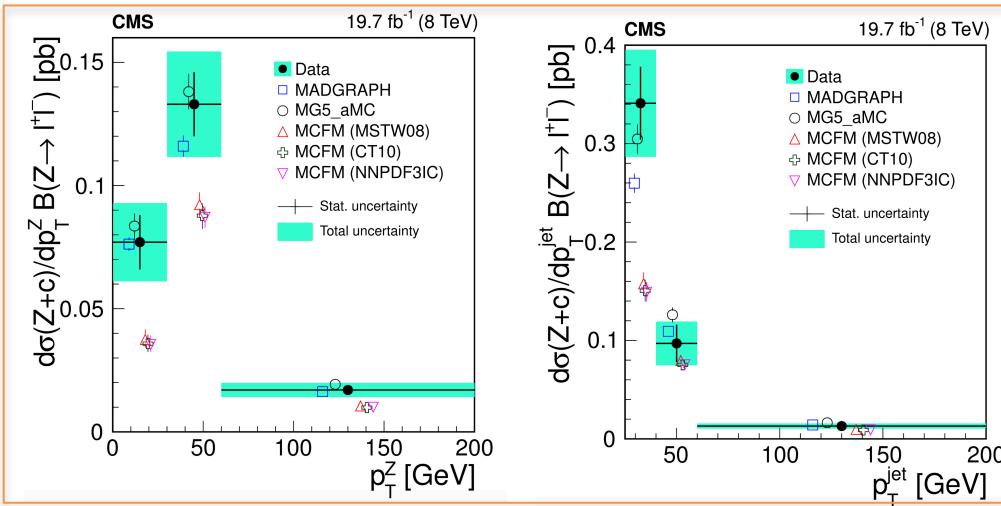
p-p  $\sqrt{s}=7,13$  TeV  
 $5,35.7 \text{ fb}^{-1}$

- Measured W + c cross section as well as W<sup>+</sup>+c/W<sup>-</sup>+b ratio
  - inclusively
  - differentially wrt lepton  $\eta$

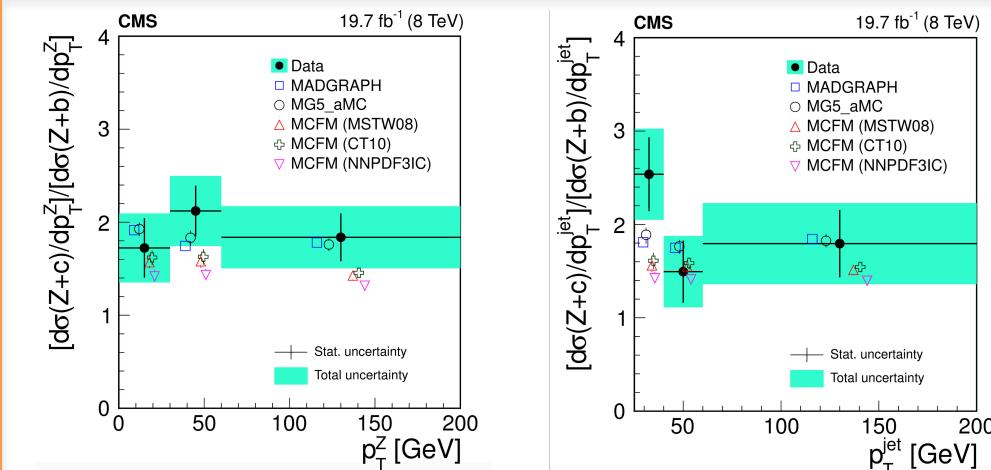


→ Comparison of  
W+c result to  
several sets of  
PDFs

- Measured Z + c cross section as well as Z+c/Z+b ratio
- inclusively
- differentially wrt Z  $p_T$  and jet  $p_T$



→ Differential  
Z+ c cross  
section results



→ Differential  
Z+ c/ Z+b  
cross section  
results

# V (W,Z) + c inclusive results

p-p  $\sqrt{s}=7,8,13$  TeV  
5, 19.8, 35.7  $\text{fb}^{-1}$

$$\sigma(\text{pp} \rightarrow W + c + X) \times \mathcal{B}(W \rightarrow \mu\nu)(p_T^\mu > 25 \text{ GeV}) = 107.7 \pm 3.3 \text{ (stat.)} \pm 6.9 \text{ (syst.) pb},$$

$$\sigma(\text{pp} \rightarrow W + c + X) \times \mathcal{B}(W \rightarrow \ell\nu)(p_T^\ell > 35 \text{ GeV}) = 84.1 \pm 2.0 \text{ (stat.)} \pm 4.9 \text{ (syst.) pb.}$$

7 TeV

$$\frac{\sigma(\text{pp} \rightarrow W^+ + \bar{c} + X)}{\sigma(\text{pp} \rightarrow W^- + c + X)}(p_T^\mu > 25 \text{ GeV}) = 0.954 \pm 0.025 \text{ (stat.)} \pm 0.004 \text{ (syst.)},$$

$$\frac{\sigma(\text{pp} \rightarrow W^+ + \bar{c} + X)}{\sigma(\text{pp} \rightarrow W^- + c + X)}(p_T^\ell > 35 \text{ GeV}) = 0.938 \pm 0.019 \text{ (stat.)} \pm 0.006 \text{ (syst.)}.$$

$$\begin{aligned} \sigma(W + c) &= 1026 \pm 31 \text{ (stat)} {}^{+76}_{-72} \text{ (syst) pb,} \\ \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} &= 0.968 \pm 0.055 \text{ (stat)} {}^{+0.015}_{-0.028} \text{ (syst).} \end{aligned}$$

13 TeV

NEW

$$\sigma(\text{pp} \rightarrow Z + c + X) \mathcal{B}(Z \rightarrow \ell^+ \ell^-) = 8.8 \pm 0.5 \text{ (stat)} \pm 0.6 \text{ (syst) pb.}$$

$$\sigma(\text{pp} \rightarrow Z + c + X) / \sigma(\text{pp} \rightarrow Z + b + X) = 2.0 \pm 0.2 \text{ (stat)} \pm 0.2 \text{ (syst).}$$

→ All measurements consistent with SM predictions



## SUMMARY

- The measurements provide a detailed description of V+HF production topological structure
    - Testing the validity of QCD
    - Providing confidence in existing MC models for;
      - Describing SM
      - Determining BG in BSM searches
  - Overall scale good agreement between Data and SM Monte Carlo predictions
  - All CMS SMP public results can be found under the following link:  
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP>
- More to come; stay tuned!



THANK YOU!  
どうもありがとうございます

