

Heavy Flavour and vector bosons associated production

Arnaud Pin¹
On behalf of the CMS Collaboration

1 : center for Cosmology, Particle Physics and Phenomenology,
Université Catholique de Louvain, Belgium

arnaud.pin@cern.ch

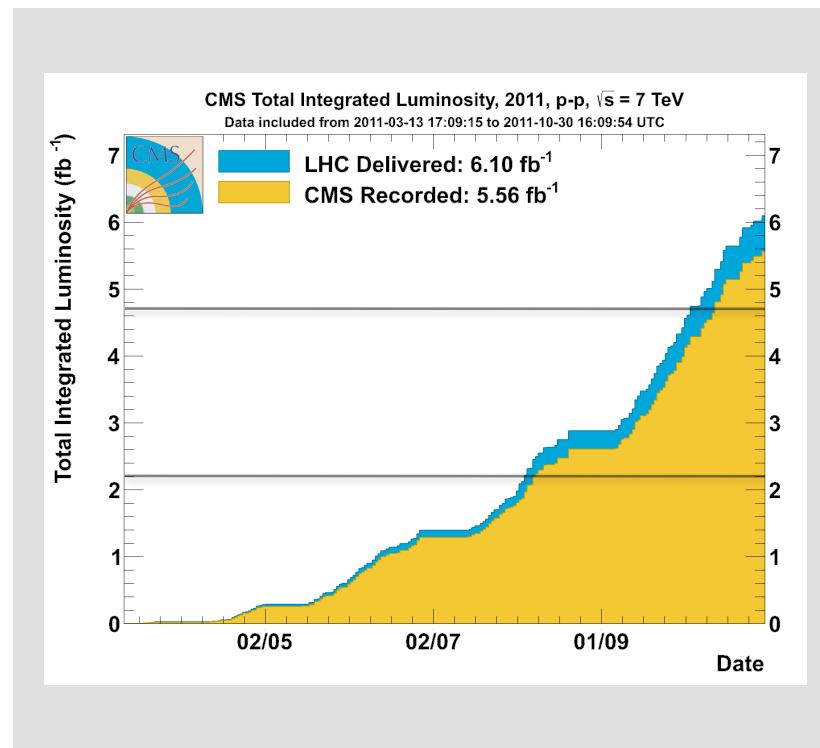


23-28th July – BEACH 2012– Wichita, KS

- Motivation

- Vector boson plus heavy flavour jets:
 - $Z(l\bar{l}) + bb$ cross section (2.1 fb^{-1})
[CMS-PAS-SMP-12-003]
 - $Z(l\bar{l}) + b$ cross section (2.2 fb^{-1})
[arXiv : 1204.1643v1]
 - Angular correlation in $Z+BB$ (4.6 fb^{-1})
[CMS-PAS-EWK-11-015]
 - $W+c$ measurement (36 pb^{-1})
[CMS-PAS-EWK-11-013]

- Summary



Motivations

- Measurement of associated production of Z boson with b quark:
 - Cross section measurement of **Z+1b, 2b**, is important to understand NLO QCD effects.
 - Measurement of Z+BB useful to understand B hadrons production in soft/**colinear region**. From gluon splitting or from a boosted resonance.
- Measurement of Z boson production in association with b-quark:
 - Background for standard model **higgs analysis** : $Z(l\bar{l})H(bb)$.
 - Background for **beyond standard model higgs** : $H \rightarrow Z(l\bar{l})A(bb)$.
- Measurement of associated production of W boson with c quark sets constraints on the **strange and anti-strange quark parton density functions** at electroweak scale.

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

STEEL RETURN YOKE
~13000 tonnes

Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

➤ Analysis performed with C.M.S. pp collisions @ $\sqrt{s} = 7 \text{ TeV}$ data.

SILICON TRACKER
Pixels ($100 \times 150 \mu\text{m}^2$)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals

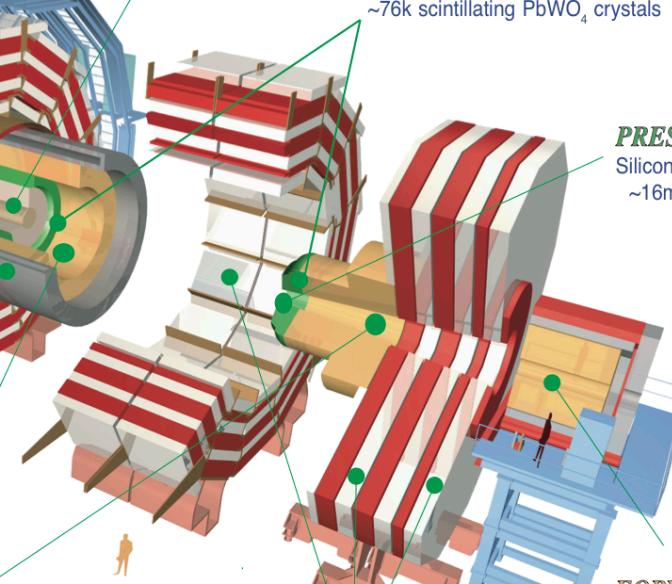
PRESHOWER
Silicon strips
~16m² ~137k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

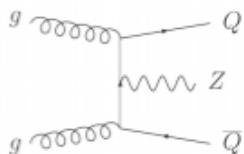
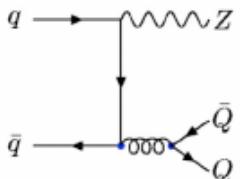
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A



Z/ γ^* (ll) + b(b): introduction

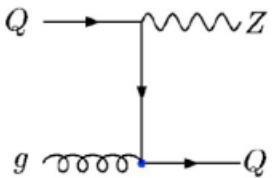
- **Z/ γ^* (ll) + b** measurement : Two theoretical schemes should agree at NLO.

- Fixed flavor scheme (4F) [[arXiv:hep-ph/1106.6019](https://arxiv.org/abs/hep-ph/1106.6019)]:

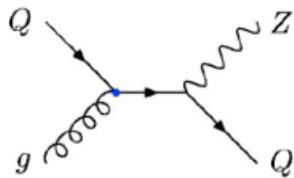


- Massive b-quark ($M_b \gg \Lambda_{\text{QCD}}$).
- aMC@NLO : full event description.

- Variable flavour scheme (5F) [[arXiv:hep-ph/0312024](https://arxiv.org/abs/hep-ph/0312024)] :



+



- Massless b-quark.
- Splitting inside the proton.
- Use to describe our signal.

- Topology characterized by:

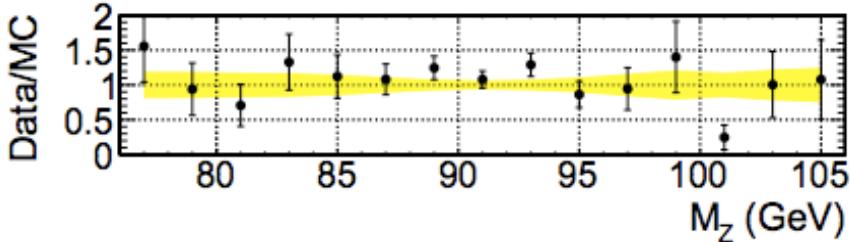
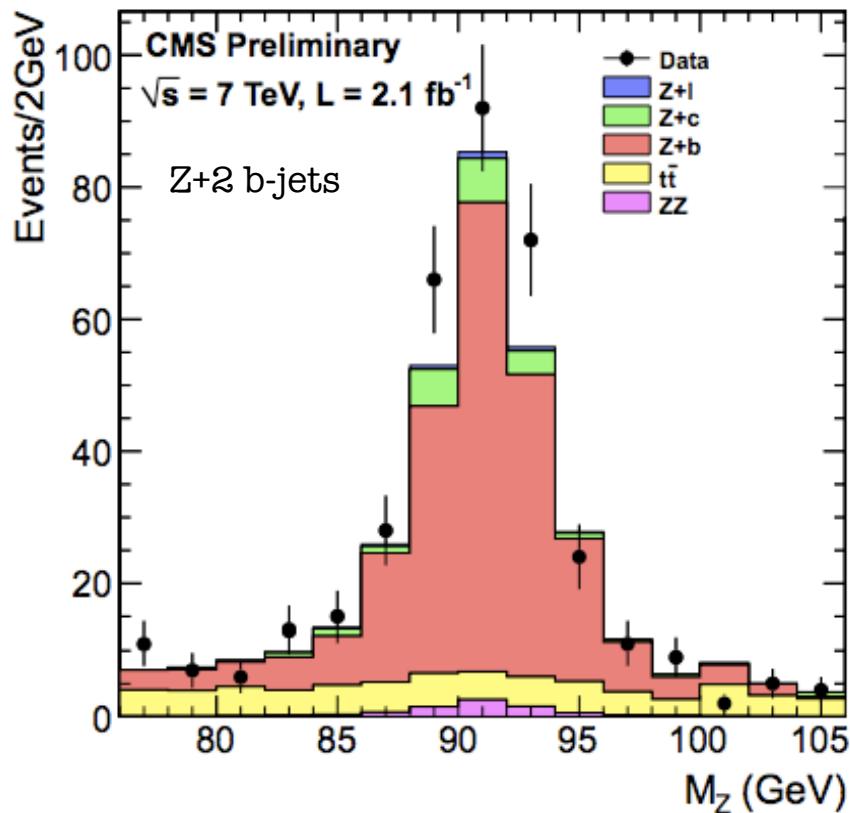
- two leptons.
- one (or two) b-jet(s) that can be soft.
- No transverse missing energy

Lepton Selection:

- Two opposite charge leptons ($ee - \mu\mu$) ,
- Electrons :
 - $P_T > 25 \text{ GeV}$, $|\eta| < 2.5$,
- Muons :
 - $P_T > 20 \text{ GeV}$, $|\eta| < 2.1$,
- $76 < M_{ll} < 106 \text{ GeV}$: select best Z candidate
- $60 < M_{ll} < 120 \text{ GeV}$: [Z+1b \(arXiv : 1204.1643v1\)](#),
[Z+BB](#)

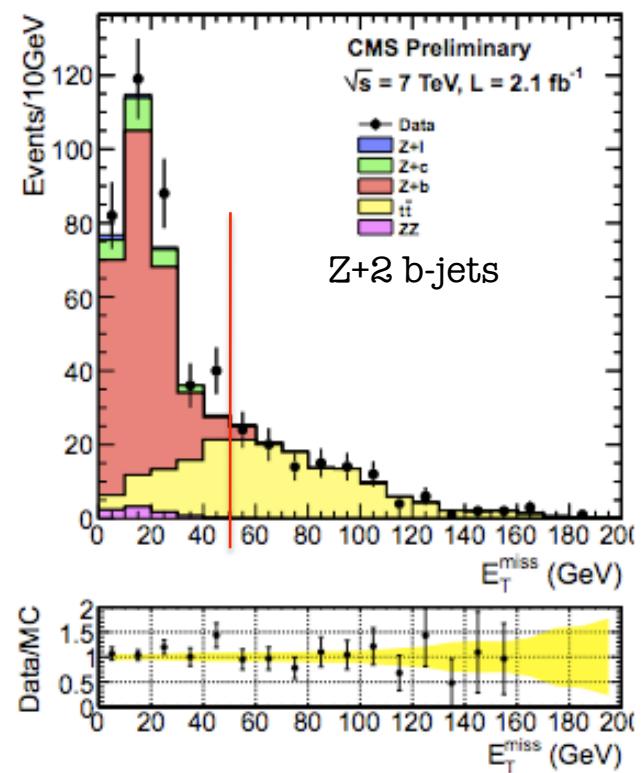
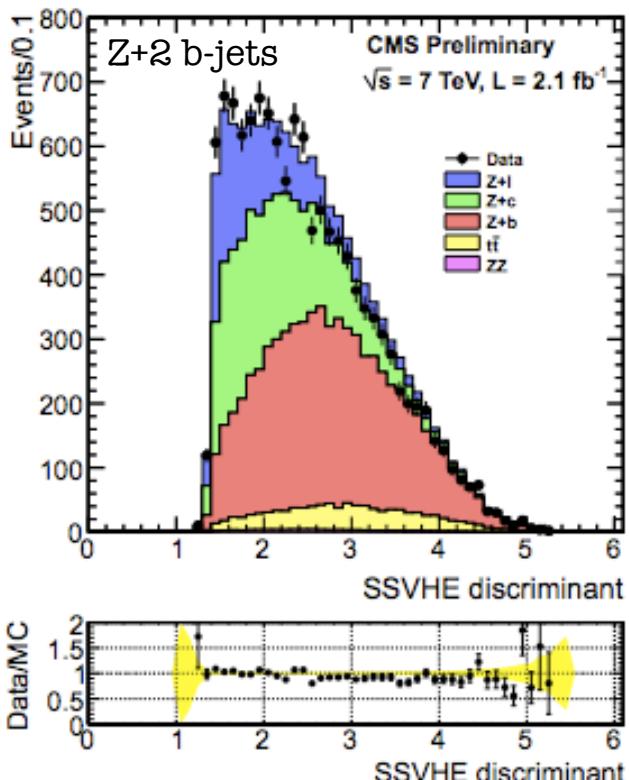
b-jets and MeT selection:

- Jets : $P_T > 25 \text{ GeV}$, $|\eta| < 2.1$, $\Delta R(\ell, jet) > 0.5$
- B-tagging
- $\text{MeT} < 50 \text{ GeV}$ required to reduce $t\bar{t}$ background (**Z+2 b-jets only**).



$Z/\gamma^*(l\bar{l}) + b(\bar{b})$: selection

- B-tagging: secondary vertex higher efficiency ($\text{eff} \approx 55\%$; mistag $\approx 1\%$) : $Z+>2$ b-jets
higher purity ($\text{eff} \approx 35\%$; mistag $\approx 0.1\%$) : $Z+>1$ b-jet
- $\text{MeT} < 50 \text{ GeV}$ required to reduce $t\bar{t}$ background ($Z+2$ b-jets only).



Z/ $\gamma^*(ll) + b(b)$: background estimation

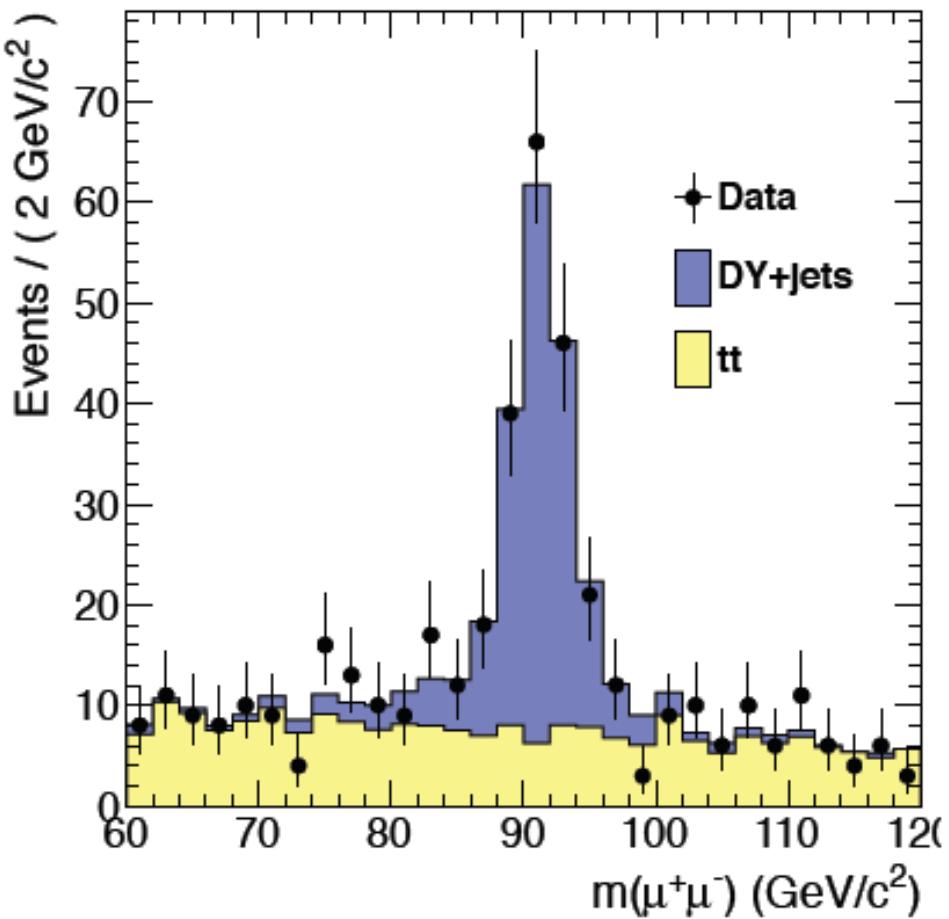
$t\bar{t}$ background estimation :

- Estimation from extrapolation of upper sideband under signal region of the M_{ll} distribution.

$$R_{t\bar{t}}^{MC} = R_{t\bar{t}}^{MC}(sig)/R_{t\bar{t}}^{MC}(side)$$

Diboson (ZZ) background :

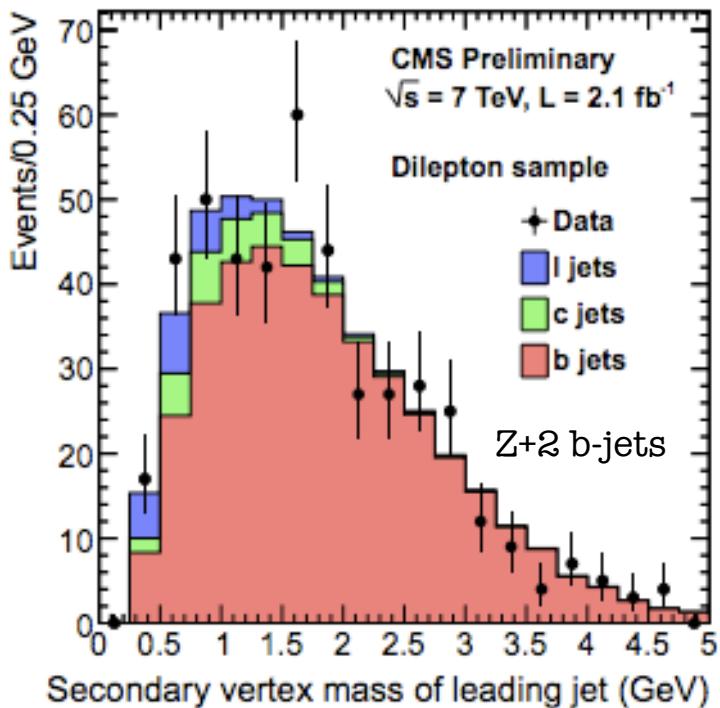
- Yields from Monte-Carlo prediction using cross section and uncertainty from CMS.
- Negligible in $Z+1b$ (arXiv : 1204.1643v1)



b-purity estimation :

- › Data driven technique.
- › b-purity estimated from Secondary vertex mass distribution **fitted to the Data**: for leading and subleading* b-jet (* for $Z+2b$).
- › $Z + \ell\ell$ negligible

$$f_{bb} = 1 - f_{cc} - f_{lb} - f_{bl} = 83 \pm 6 \%$$



Z+2 b-jets analysis

	$Z(ee) + b\bar{b}$	$Z(\mu\mu) + b\bar{b}$
yields	148	219
b-purity	$(83 \pm 6) \%$	$(83 \pm 6) \%$
ftt	$(17 \pm 5) \%$	$(20 \pm 5) \%$
N_{zz}	3.0 ± 0.2	5.2 ± 0.2

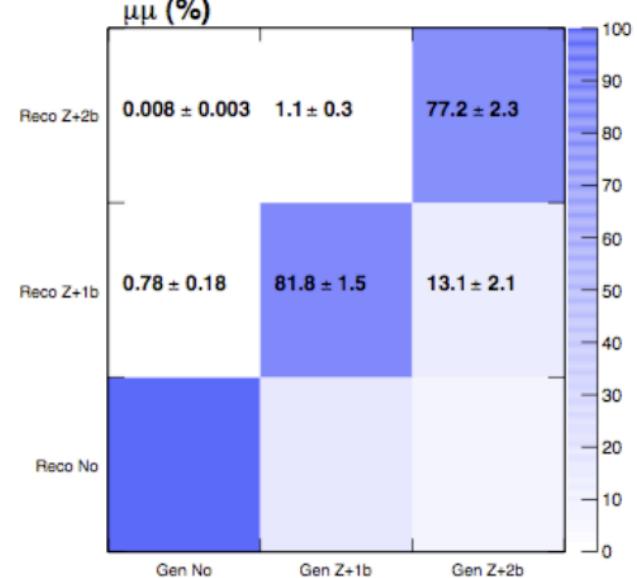
$Z/\gamma^*(l l) + b(b)$: Cross section

$$\sigma_{Z+1(2)b} = \frac{N_{Z+1(2)b}^{gen}}{L}$$

➤ $Z+b$ and $Z+bb$ yields at hadron level obtained by unfolding :

Hadron level	\mathbf{A}_I	$\boldsymbol{\epsilon}_r$	$\boldsymbol{\epsilon}_l$	$\boldsymbol{\epsilon}_b$	Reco level
	$\begin{pmatrix} \frac{1}{A_I^1} & 0 \\ 0 & \frac{1}{A_I^2} \end{pmatrix}$	$\begin{pmatrix} \epsilon_r^{11} + R\epsilon_r^{01} & \epsilon_r^{21} + R\epsilon_r^{01} \\ \epsilon_r^{12} + R\epsilon_r^{02} & \epsilon_r^{22} + R\epsilon_r^{02} \end{pmatrix}^{-1}$	$\begin{pmatrix} \frac{1}{\epsilon_I^1} & 0 \\ 0 & \frac{1}{\epsilon_I^2} \end{pmatrix}$	$\begin{pmatrix} \frac{1}{\epsilon_b^{11}} & -\frac{\epsilon_b^{21}}{\epsilon_b^{22}\epsilon_b^{11}} \\ 0 & \frac{1}{\epsilon_b^{22}} \end{pmatrix}$	$\begin{pmatrix} N_{Z+1b}^{tag} \\ N_{Z+2b}^{tag} \end{pmatrix}$

- b-tagging efficiency: ϵ_b
Scale MC to data expectation (per jet)
- lepton efficiency: ϵ_l
Scale MC to data expectation (per lepton)
Z Tag and Probe
- detector resolution: ϵ_r
Correct yields to generator level acceptance
- Acceptance: A_I



Migration effect between multiplicity bin (1b-jet/2b-jets) are quantified

$Z/\gamma^*(ll) + b(b)$: Cross section results

For the $Z+2$ b-jets selection

Multiplicity bin	$\sigma \pm \delta_{\sigma}^{stat} \pm \delta_{\sigma}^{syst} \pm \delta_{\sigma}^{theo}$ (pb)
$\sigma_{hadr}(Z(ll) + 1b)$	$3.41 \pm 0.05 \pm 0.27 \pm 0.06$
$\sigma_{hadr}(Z(ll) + 2b)$	$0.37 \pm 0.02 \pm 0.07 \pm 0.02$
$\sigma_{hadr}(Z(ll) + b)$	$3.78 \pm 0.05 \pm 0.31 \pm 0.08$

MadGraph expectation (DY+jet) NLO:

$$\sigma_{Z(ll)bb} = 0.33 \pm 0.01_{(stat)} \text{ pb}^{-1}$$

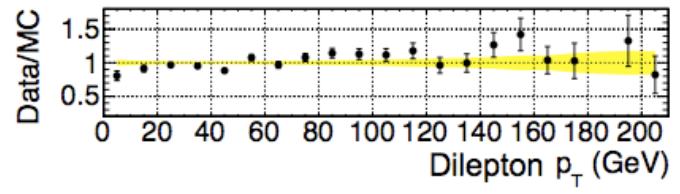
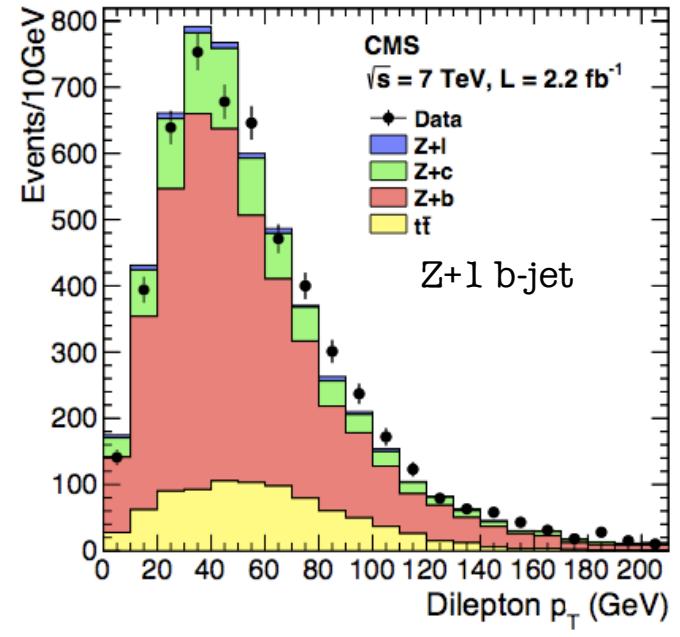
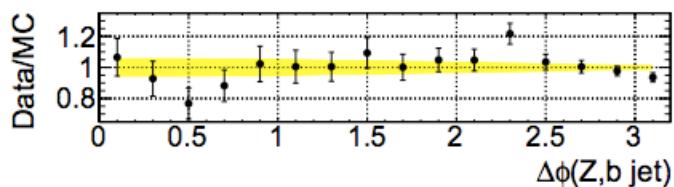
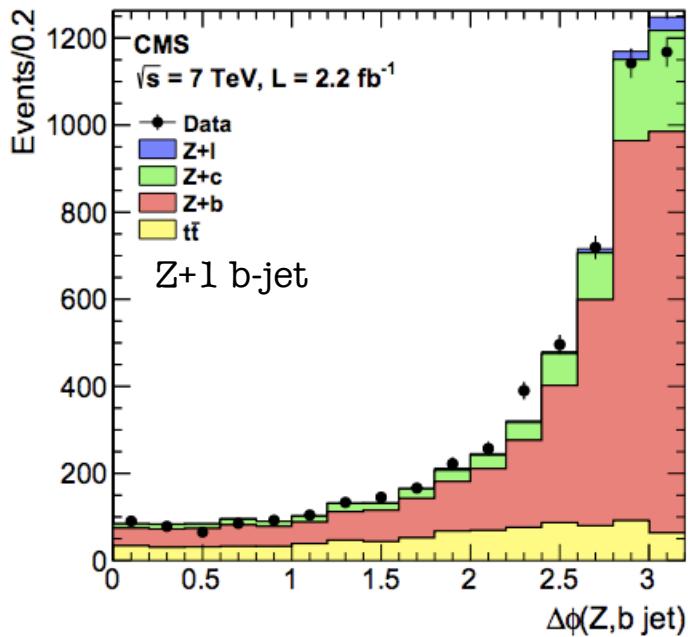
MCFM prediction at NLO:

$$\sigma_{Z(ll)+b} = 3.97 \pm 0.47 \text{ pb}^{-1}$$

	ee(%)	$\mu\mu$ (%)		
Correlated sources	Z+1b	Z+2b	Z+1b	
b-jet purity	3.5	10.3	2.5	11.0
t <bar>t</bar>				
b-tagging efficiency	4.0	7.4	3.9	7.5
Jet energy scale	3.9	6.9	3.8	6.4
Luminosity	4.5	4.5	4.5	4.5
MET selection	0.3	2.4	0.3	2.4
Pileup	1.7	1.8	0.3	0.3
ZZ contribution	0.1	0.5	0.1	0.7
Jet energy resolution	0.1	0.2	0.1	0.1
Mistagging rate	0.02	0.08	0.02	0.07
Theory (via \mathcal{A}_I)	1.8	5.9	3.0	6.4
Uncorrelated sources	Z+1b	Z+2b	Z+1b	
MC sample stat.	1.2	5.1	0.9	4.2
Dilepton selection	4.0	4.0	1.9	1.9
Statistical	2.4	10.0	1.8	8.2
Experimental systematic	9.1	18.9	7.7	18.8
Theoretical systematic	1.8	5.9	3.0	6.4

$Z/\gamma^*(ll) + b$: Kinematics

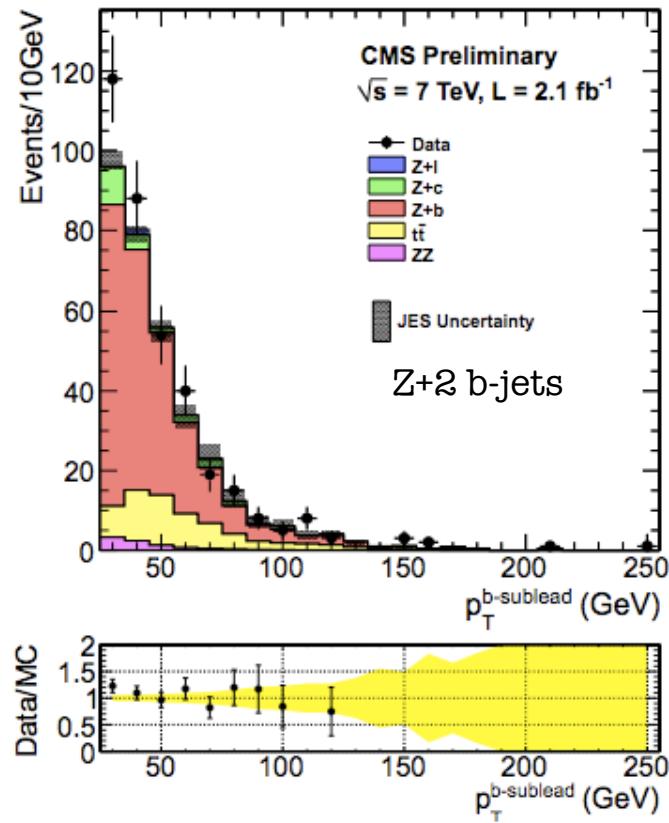
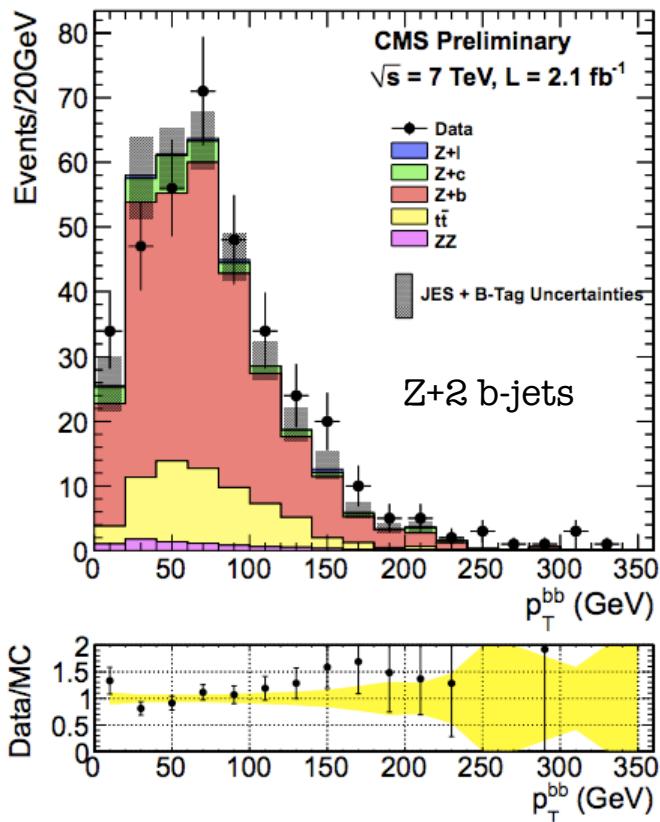
- $Z+1b$ inclusive analysis : $P_T Z$ and $\Delta\Phi(Z,b)$
- Monte Carlo : MadGraph 5F + Pythia



- $\Delta\Phi(Z, b\text{jet})$: sensitivity to hard radiation
- $P_T Z$: 4-5 flavour approach

Z/ γ^* (ll) + bb : Kinematics

- P_T bb harder in data than in MC (MadGraph 5-flavour + Pythia)

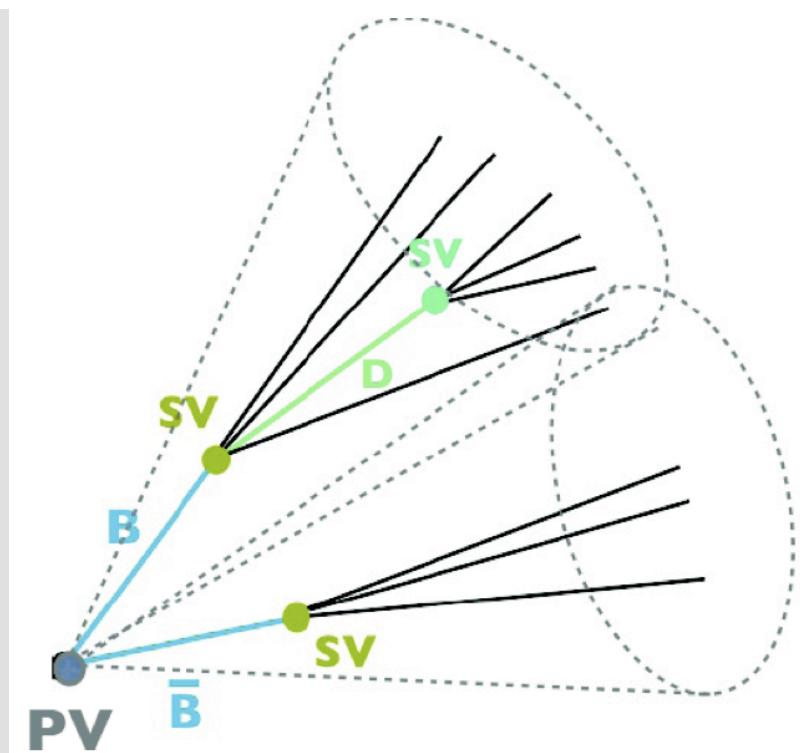


- Grey band: systematic uncertainty due to jet energy and b-tagging uncertainty.
- Tension in comparison of kinematic properties between Data and MC.

BB angular correlation with Z/ γ^* + secondary vertices

- Original analysis performed with 4.6fb^{-1} .
- Key : identification of displaced vertices **without** reconstructing b-jets.

- Goal : study BB production at **small angular separation**: colinear BB production.
- B hadron candidates reconstructed using the *Inclusive Vertex Finder* (IVF).
 - Based on large impact parameter tracks seed + other track clustered.
 - Vertices from charm decay are merged to B decays.
- Two B-hadrons, $P_T > 15$ and $|\eta| < 2.0$.
- Good angular resolution in B hadron flight direction ($\Delta R \approx 0.02$).

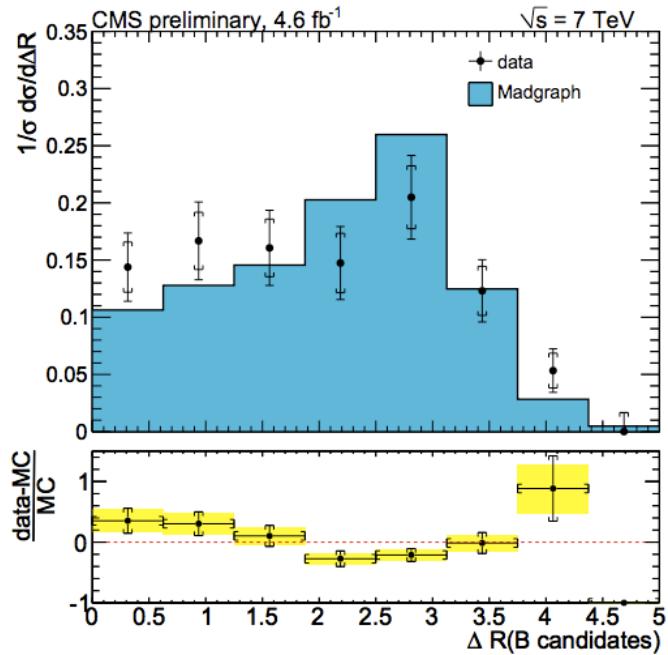


BB angular correlation with Z/γ^* + secondary vertices

$\Delta R(BB)$ shape estimation :

$$\frac{1}{\sigma} \frac{d\sigma}{\Delta R(BB)} = \frac{1}{\sigma_{vis}} \frac{N_i^{data,fit}.P_i}{\epsilon_i^{2SV}.\epsilon_i^l.A^l} \quad i = \text{bin}$$

- $N^{data,fit}$ extracted from M_{ll} fit.
- $N^{data,fit}$ corrected for IVF purity and efficiency, dilepton acceptance/efficiency.
- Normalisation to the visible cross-section



- **Discrepancies** in the comparison with MadGraph (5-flavour) and aMC@NLO.
- Data suggest flatter slope in the small angular separation region.

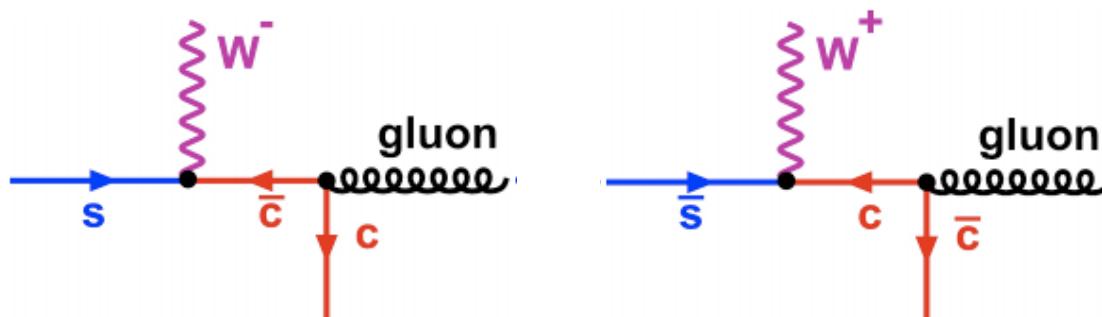
W+c: Motivation

Why W+c measurement are interesting ?

- PP to $W + c + X$ is sensitive to the proton strange quark content.
- Study charm lifetime and tagging efficiency, W+c clean sample with charm jets.

➤ Production dominated by :

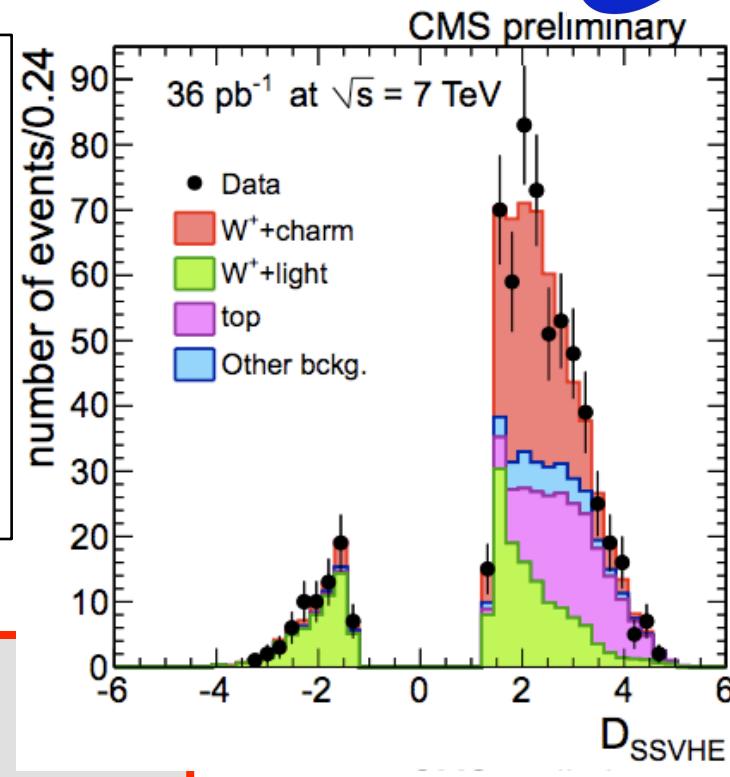
- $\bar{s}g \rightarrow W^+ \bar{c}$,
- $s g \rightarrow W^- c$,
- $d g$ production disfavoured by Cabibbo ($|V_{cd}|^2/|V_{cs}|^2 \sim 0.05$). But d is a valence quark → contribution ~5%



- $W+b$ strongly suppressed (1-2% contribution).

W+c relative cross section

- Measurement using the $W^{+/-} \rightarrow \mu^{+/-} \nu_\mu (\bar{\nu}_\mu)$ channel.
- Main background : $t\bar{t}$, single top
- Event content :
 - muon: $P_T > 25$ GeV, $|\eta| < 2.1$.
 - jet: $P_T > 20$ GeV, $|\eta| < 2.1$, < 3 jets with $P_T > 40$ GeV.
 - $M_T > 50$ GeV.
- **b-discriminant of the most energetic jet.**
 - maximum likelihood fit of $W + c$, $W + \ell$ and $t\bar{t}$.



$$R_c^\pm = \frac{N_{W^{++c}}}{N_{W^{-+c}}} = 0.92 \pm 0.19(\text{stat.}) \pm 0.04(\text{syst.})$$

$$R_c = \frac{N_{W^{++c}} + N_{W^{-+c}}}{\epsilon_c N_{W+jets}} = 0.143 \pm 0.015(\text{stat.}) \pm 0.024(\text{syst.})$$

Result in **agreement** with theoretical prediction at NLO.

Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
R_c^\pm	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005

Summary



- CMS Collaboration has already provided and continue to perform measurement of Heavy flavour + vector boson production:
 - Cross section has been measured for inclusive $Z+b(b)$ and exclusive $Z+b$.
 - Some tensions are observed in the shape of kinematic variables between data and MadGraph (LO) + pythia.
 - $Z+ BB$ angular correlation measured in data show discrepancies with MadGraph and aMC@NLO predictions.
 - $W+c$ studies provides estimation of $W+c$ production rate and charge independance. In agreement with the standard model prediction.
 - It is the first step towards a precise understanding of $s\bar{s}$ p.d.f. of the proton.

Thank you for your attention

Backup

Z/ γ^* (ll) + b inclusive : cross section

$$\sigma_{\text{hadron}}(Z/\gamma^* + b, Z/\gamma^* \rightarrow ll) = \frac{N(ll+b) \times (\mathcal{P} - f_{t\bar{t}})}{\mathcal{A}_\ell \times \mathcal{C}_{\text{hadron}} \times \varepsilon_\ell \times \varepsilon_b \times \mathcal{L}}$$

- Nll+b : number of selected Z+b events
- P is the b-jet purity, ftt fraction of ttbar events
- el eb : respectively the lepton and b-tag efficiency
- Al : lepton acceptance
- Chadron : Correction factor for detector and reconstruction effects
- L : Luminosity

Cross section estimated separately for ee/mumu channel then combined :

	Cross section (pb)
$\sigma_{\text{hadron}}(Z(ll)+b)$	$5.84 \pm 0.08 \text{ (stat)} \pm 0.72 \text{ (syst)} +0.25-0.55 \text{ (theory)}$

Prediction at hadron level corrected to NLO $\sigma_{\text{hadron}} = 3.97 \pm 0.47 \text{ pb}^2$

Measured cross section larger than the NLO prediction.

W+c motivation : W mass precision

	ΔM_W	$\Delta[(M_{W^+} - M_{W^-})]$
$c^{\text{bias}} = 0.9 c$	+148 MeV/ c^2	+17 MeV/ c^2
$s^{\text{bias}} = s + 0.1 c$		
$c^{\text{bias}} = 1.1 c$	-111 MeV/ c^2	-11 MeV/ c^2
$s^{\text{bias}} = s - 0.1 c$		

Table 3: Biases from uncertainties in the 2nd quark family.

**(from M.W. Krasny et al,
arXiv:1004.2597)**

W+c prediction Theory

Theoretical prediction :

Ratio	MCFM (CT10)	MCFM (MSTW08)	MCFM (NNPDF21)
R_c^\pm	$0.915^{+0.006}_{-0.006}$	$0.881^{+0.022}_{-0.032}$	0.902 ± 0.008
R_c	$0.125^{+0.013}_{-0.007}$	$0.118^{+0.002}_{-0.002}$	0.103 ± 0.005

Measurement :

$$R_c^\pm = 0.92 \pm 0.19 \text{ (stat.)} \pm 0.04 \text{ (syst.)}$$

$$R_c = 0.143 \pm 0.015 \text{ (stat.)} \pm 0.024 \text{ (syst.)}$$