Jet results in the LHCb experiment

Oscar Augusto on behalf of the LHCb Collaboration

CERN/CNPq attached to Liverpool

Jet Vetoes & Jet Multiplicity 2016

IPPP Durham

19/09/16

Outlook

Introduction

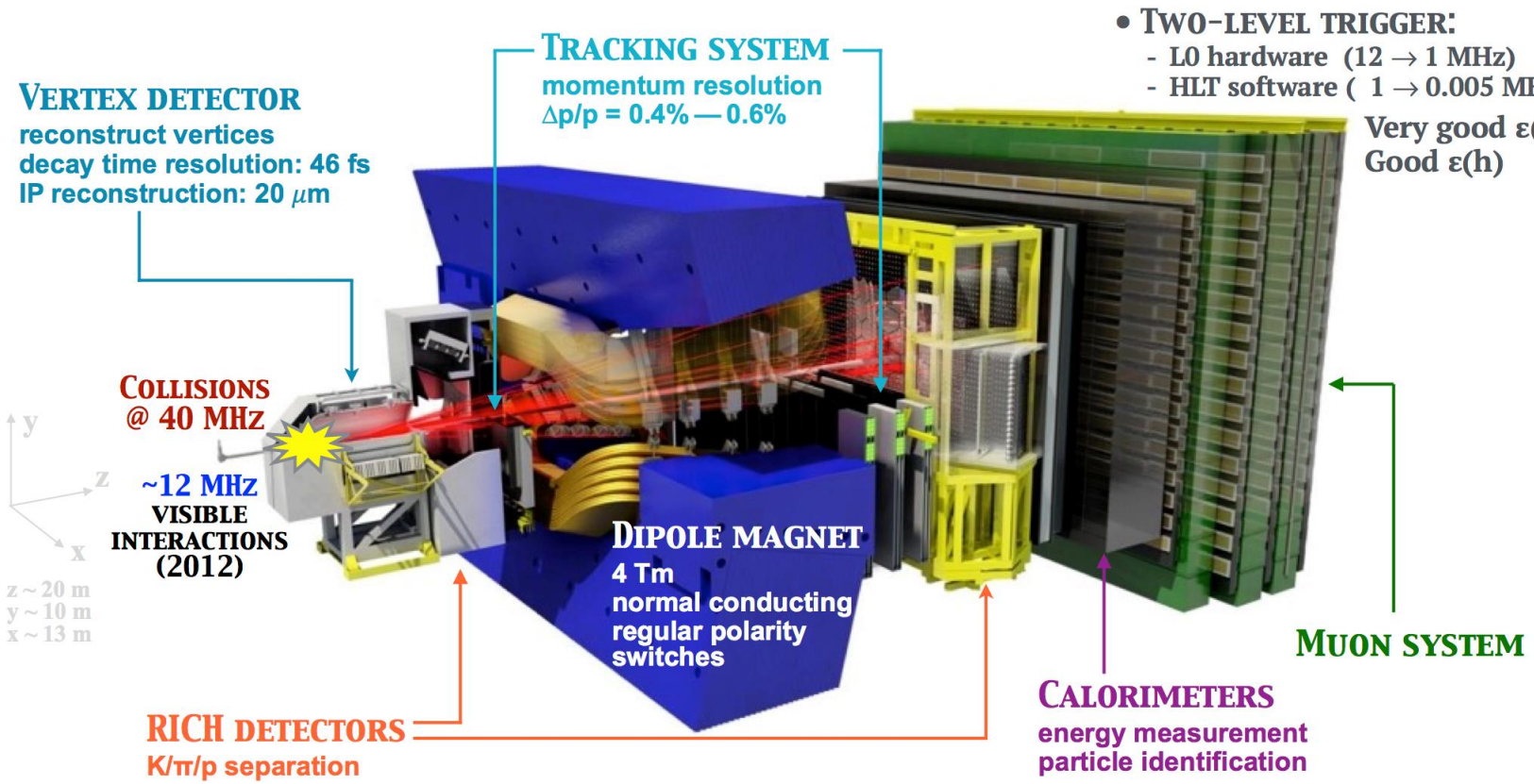
- LHCb experiment
- Jet reconstruction and tagging

This talk will cover

- *J. High Energy Phys.* 05 (2016) 131 - Measurement of forward W and Z production in association with jets
- *Phys. Rev. Lett.* 115 (2015) 112001 – Forward top measurement
- LHCb-PAPER-2016-038 in preparation - Measurement of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production cross-section
- LHCB-CONF-2016-006 in preparation -Search for the SM Higgs boson decaying in $b\bar{b}$ or $c\bar{c}$ in association to W or Z boson

Conclusion

LHCb experiment

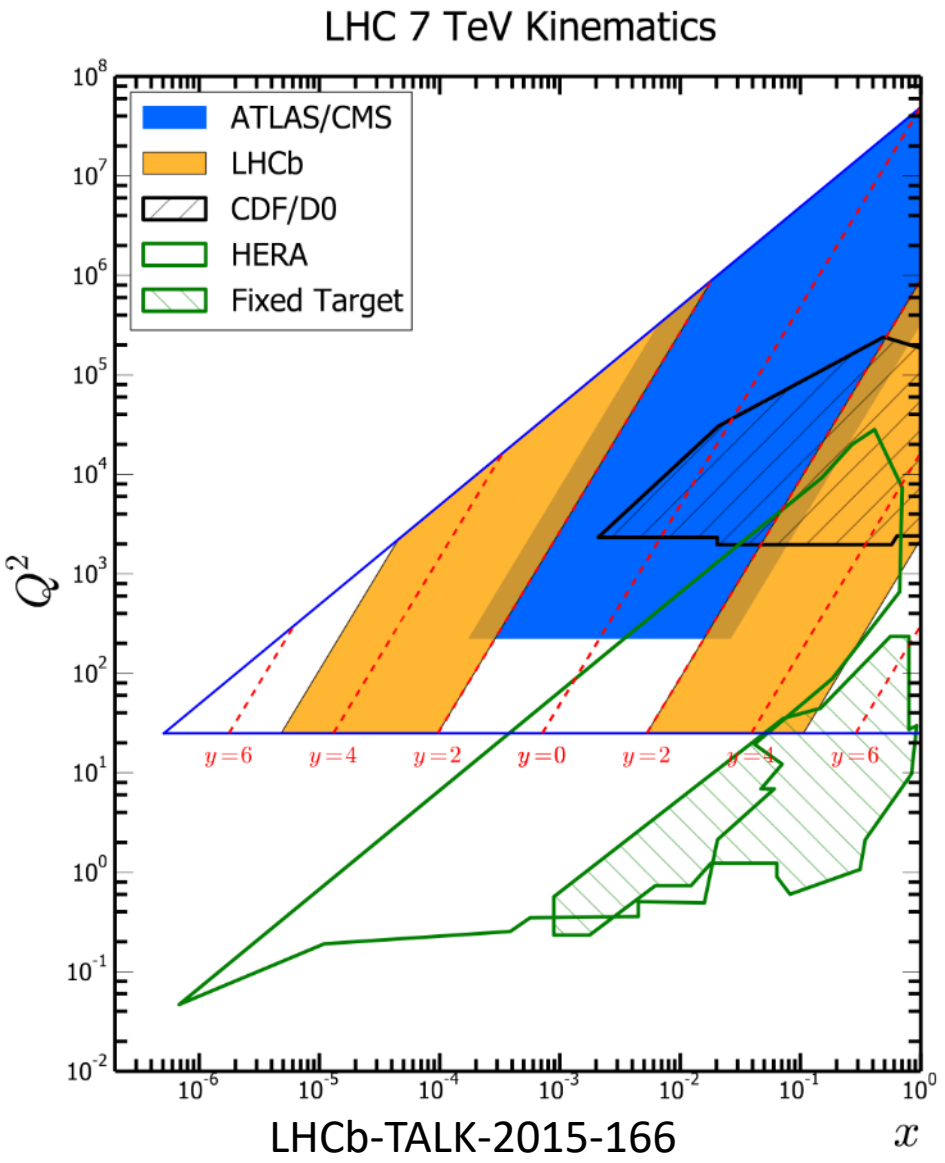


Forward spectrometer $(2 < \eta < 5)$

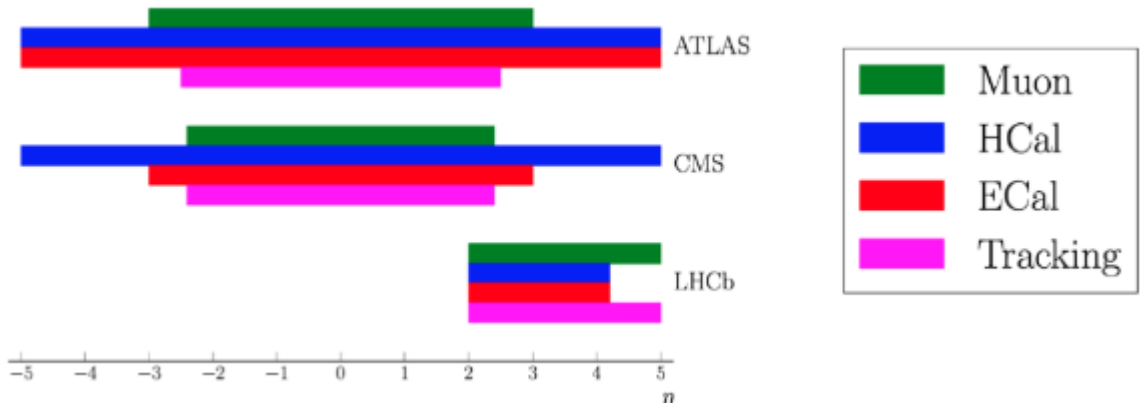
[*Int. J. Mod. Phys. A* 30 (2015) 1530022]

- Designed to measure CP violation, rare decays involving B and D mesons and search for beyond Standard Model physics
- Luminosity collected:
  - $\sim 1\ \mathrm{fb}^{-1}$ in 2011
  - $\sim 2\ \mathrm{fb}^{-1}$ in 2012
- Low number of pp interactions per bunch crossing $\mu \sim 1.7$ (1.5) for 2012 (2011)
- Precise determination of the integrated luminosity
  - ~2% (~1%) for 2011 (2012)
- Excellent vertex reconstruction
  - for a primary vertex (PV) with 25 tracks:
    - $\sigma_{PV_z} = 71\ \mu\mathrm{m}$
    - $\sigma_{PV_T} = 13\ \mu\mathrm{m}$

LHCb experiment



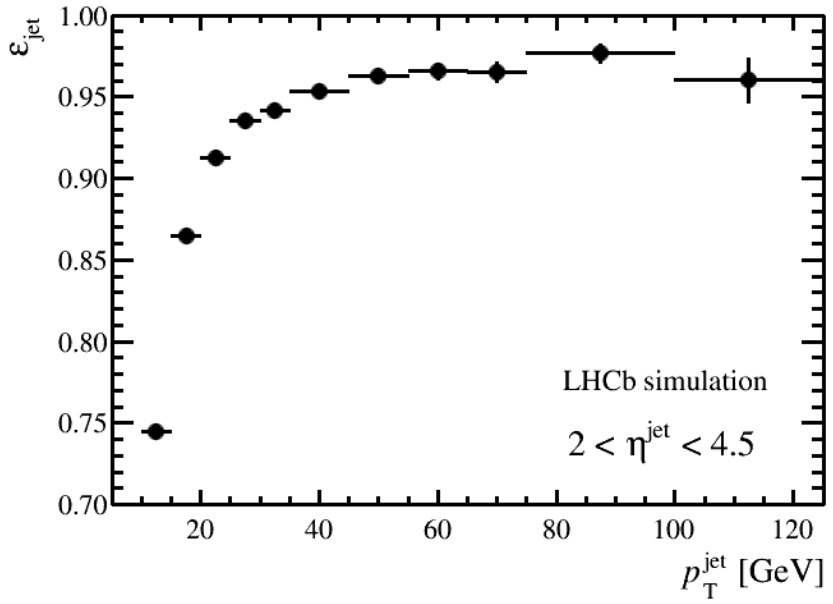
- LHCb offers an unique coverage
  - Complementary to CMS and ATLAS
- Probe Parton Density Function (PDFs) in an previously unexplored region of low x and high Q^2
- Important tests for pQCD
- Understanding of important background for Standard Model and beyond Standard Model searches

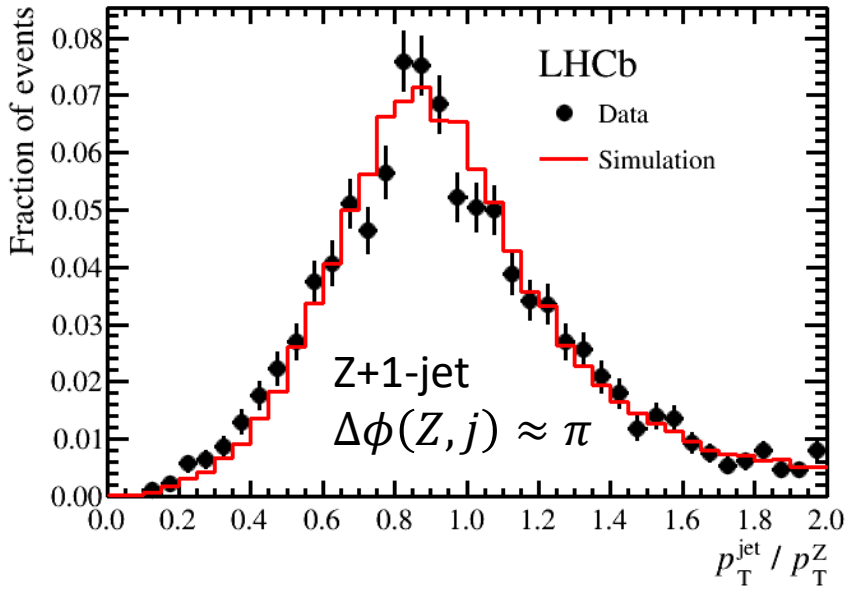


Jet reconstruction

- Particle flow algorithm
- Neutral recovery
  - Excess of energy in the calorimeter nearby a track is treated as an additional neutral particle
- Clustering algorithm: anti-kt with R=0.5
- Jet reconstruction efficiency is ~95% for high p_T jets after the quality criteria (jet identification)
- Jet energy resolution is $\sim 10 - 15\%$ for $10\ \mathrm{GeV} < p_T^j < 100\ \mathrm{GeV}$
- The jet energy is dominated by the tracks (charged particles)

J. High Energy Phys. 01 (2014) 033



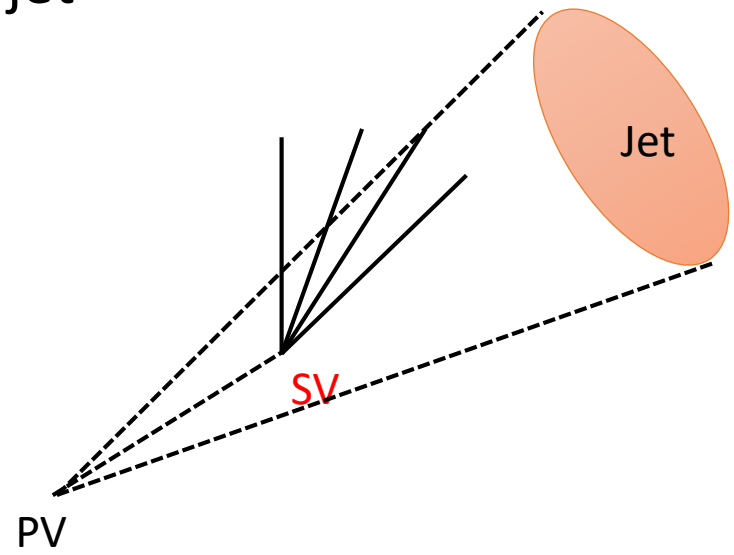


Tagging

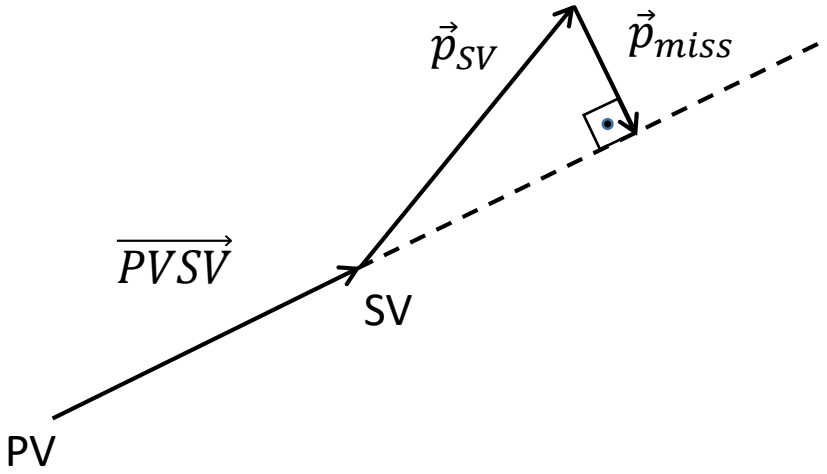
J. Instrum. 10 (2015) P06013

Two BDT responses

- Discrimination between heavy and light jets (BDT(bc|udgs))
- Discrimination between bottom and charm jets (BDT(b|c))
- The secondary vertex (SV) is required to be in the jet



- Several variables are used including:
  - The SV mass M
  - The SV corrected mass (M_{corr})
  - The flight distance χ^2
  - Fraction of jet p_T carried by the SV

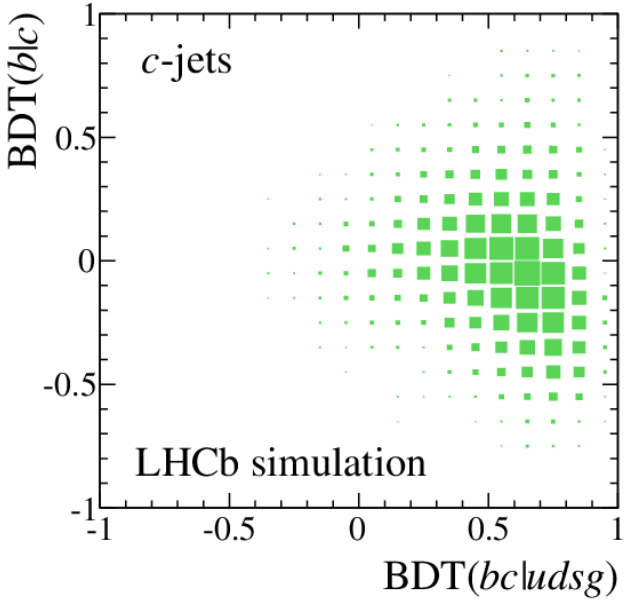


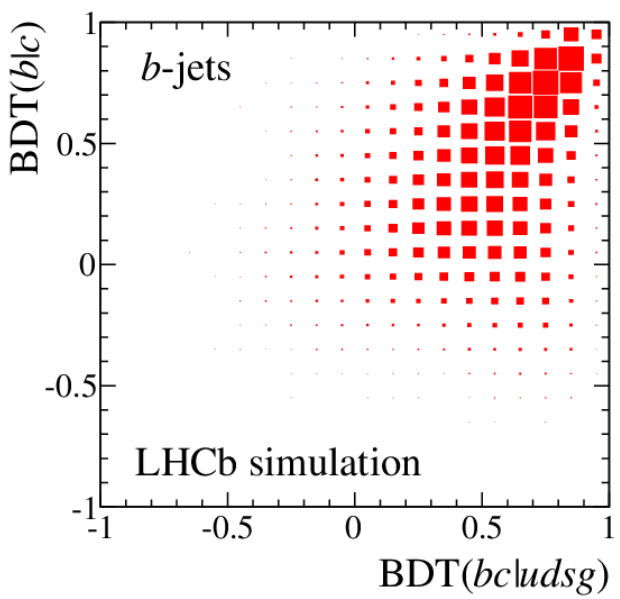
$$M_{corr} = \sqrt{M_{SV}^2 + \vec{p}_{miss}^{\,2}} + \vec{p}_{miss}$$

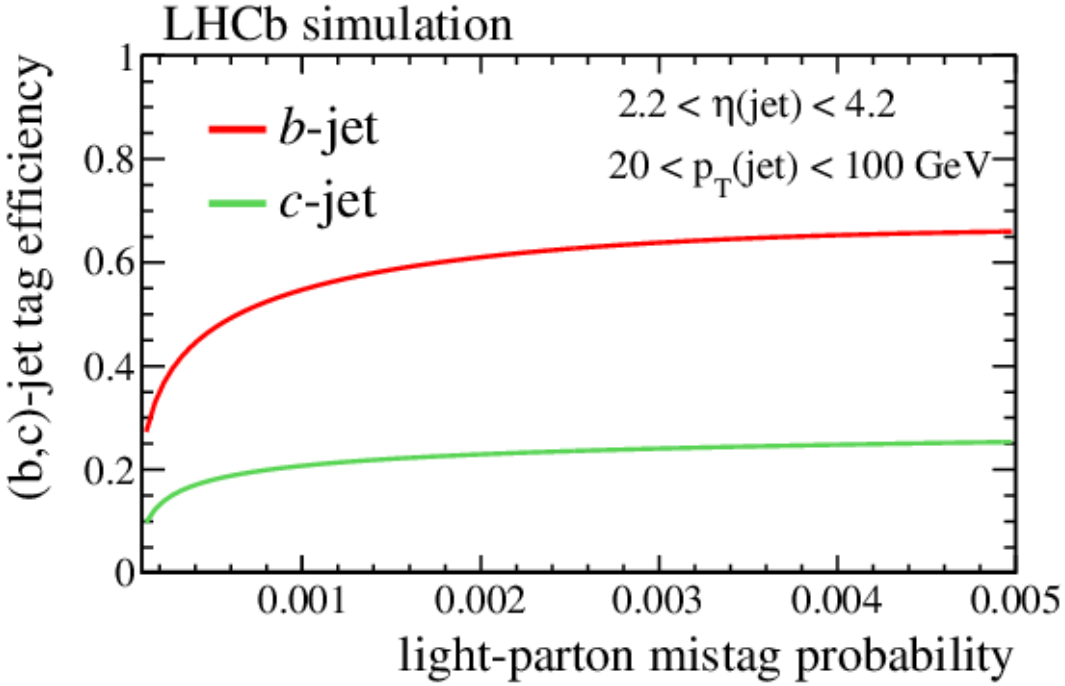
Tagging

J. Instrum. 10 (2015) P06013

- Powerful heavy quark tagging
- For jets with $20\ \text{GeV} < p_T^j < 100\ \text{GeV}$ and $2.2 < \eta^j < 4.2$:
  - Efficiency of b-jet tagging $\sim 65\%$
  - Efficiency of c-jet tagging $\sim 20\%$
  - Misidentification of a light-jet $\sim 0.3\%$







Measurement of forward W and Z boson production in association with jets

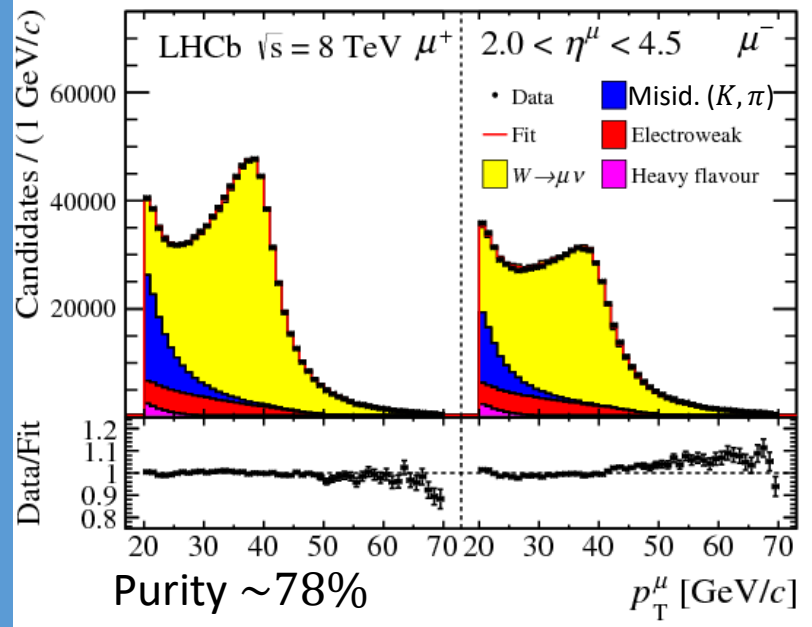
J. High Energy Phys. 01 (2016) 155

Important background for beyond Standard Model searches
Test pQCD
Probe different PDF sets

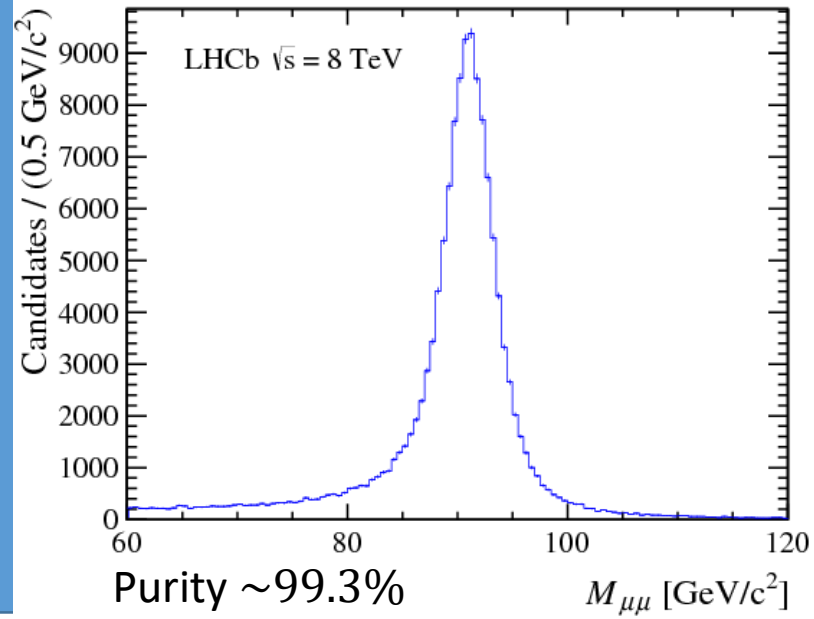
Fiducial selection:

- $2.0 < \eta^{\mu} < 4.5$ and $p_T^{\mu} > 20$ GeV
- 60 GeV $< m_{\mu\mu} < 120$ GeV (For Z boson decays)
- $2.2 < \eta^{j} < 4.2$ and $p_T^{j} > 20$ GeV
- Jets well separated from leptons coming from the boson ($\Delta R(\mu, j) > 0.5$)

$W(\mu\nu)$ inclusive



$Z(\mu\mu)$ inclusive



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Measurement of forward W and Z boson production in association with jets

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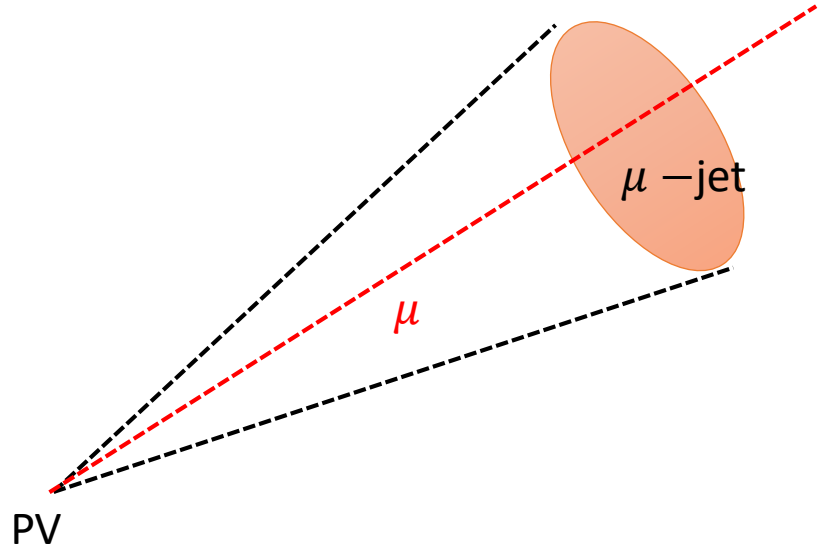
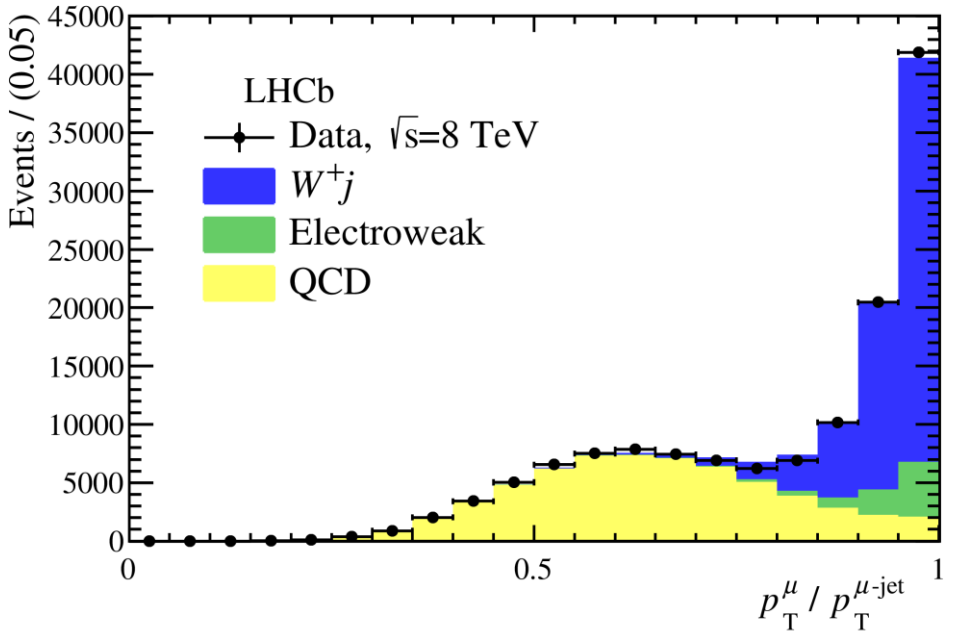
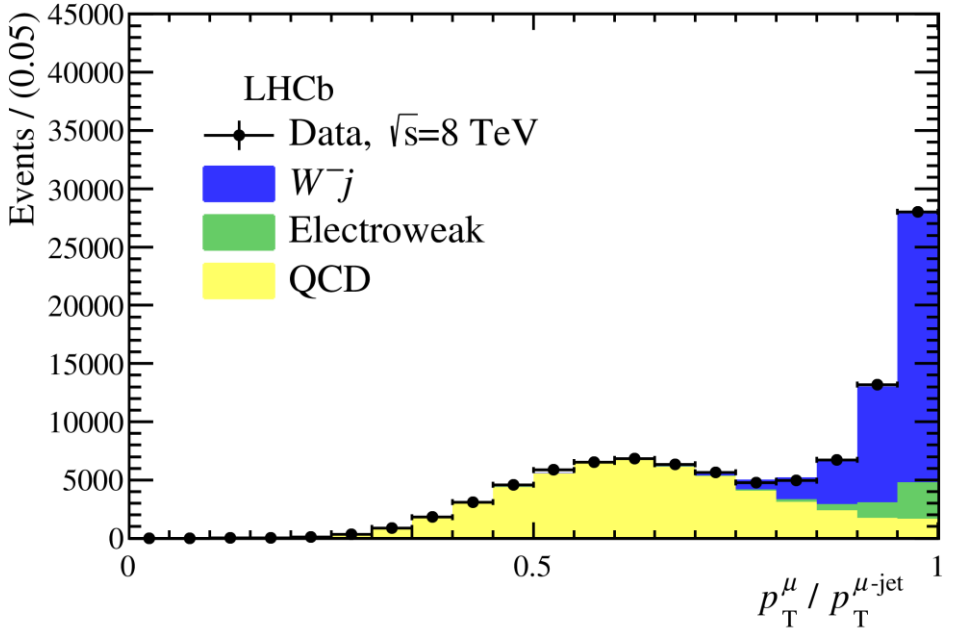
The $\mu - jet$ is defined as the jet that contains a μ that comes from a Z or W candidate.



The purity of the samples are 46.7% (36.7%) for W^+j (W^-j).
The purity for the Zj sample is 97.8%.





Measurement of forward W and Z boson production in association with jets

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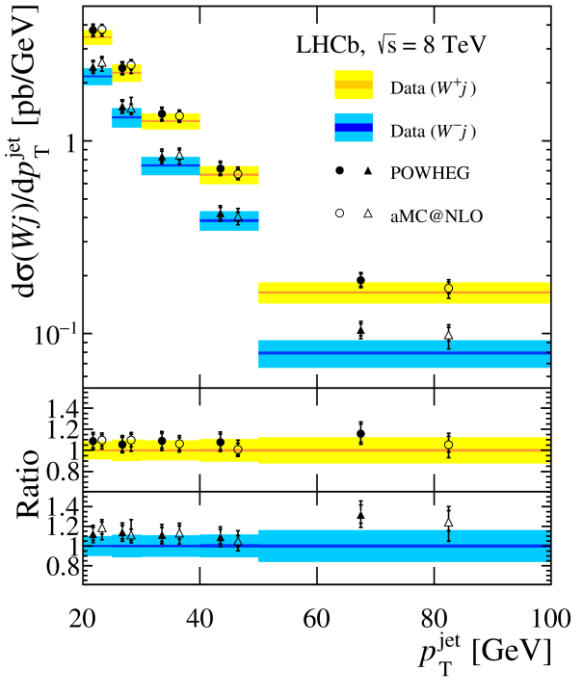
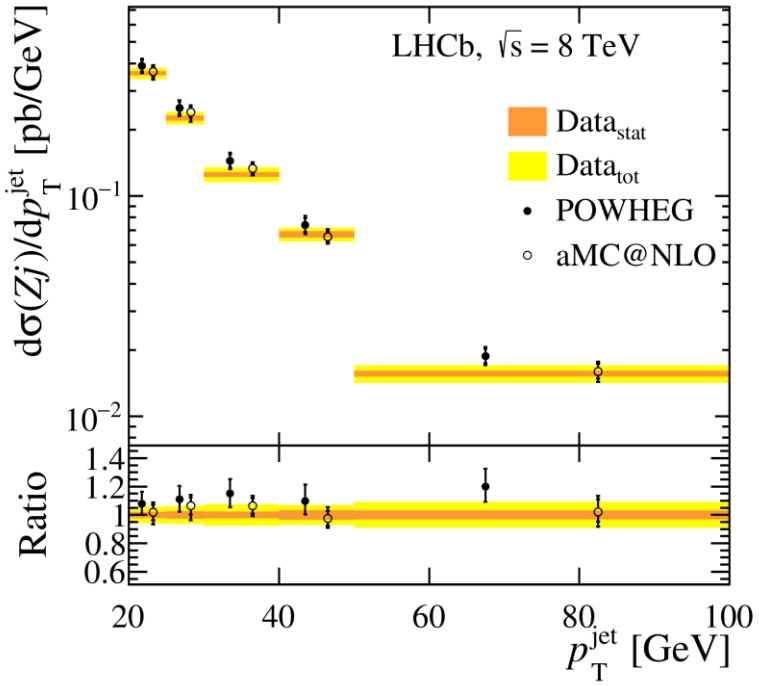
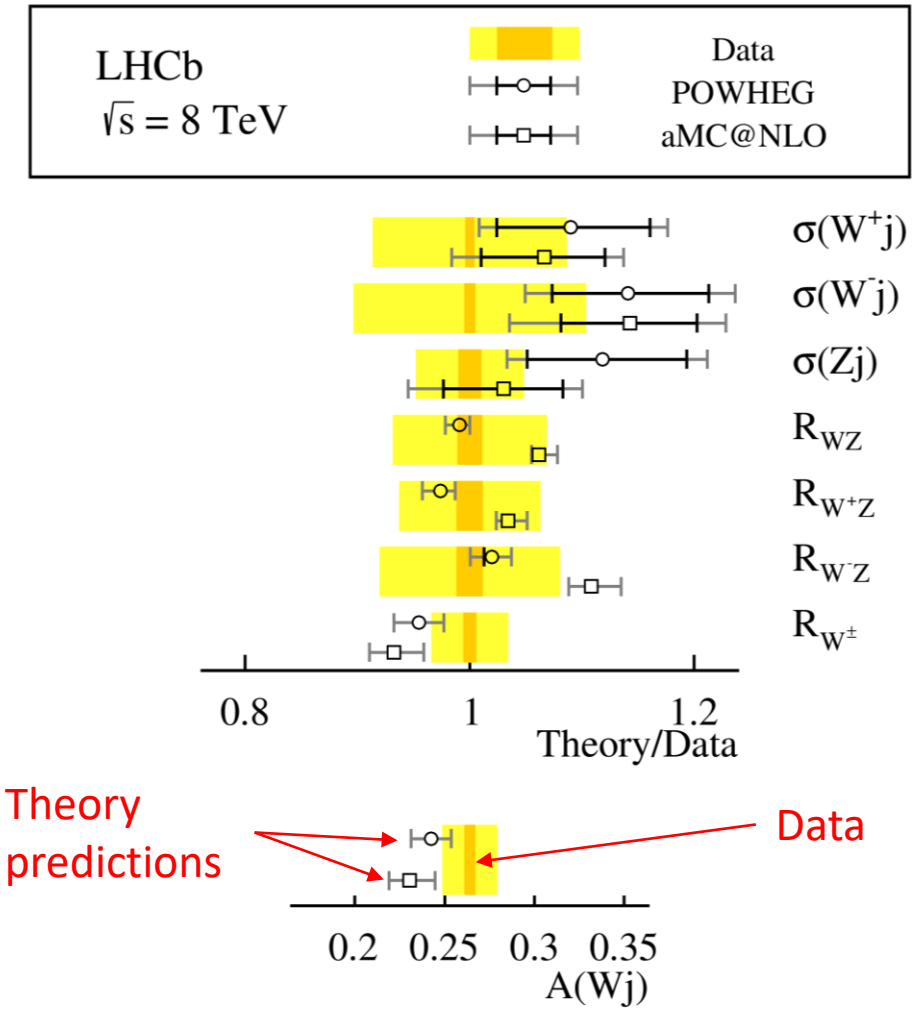
- Unfolding is used to correct for bin migrations in η^j and p_T^j
- The asymmetry of W charge production (A) and ratios of W and Z (R) were measured
- NNPDF3.0 PDF set is used for the theoretical predictions
- More plots can be found in the paper!







Measurement of forward W and Z boson production in association with jets

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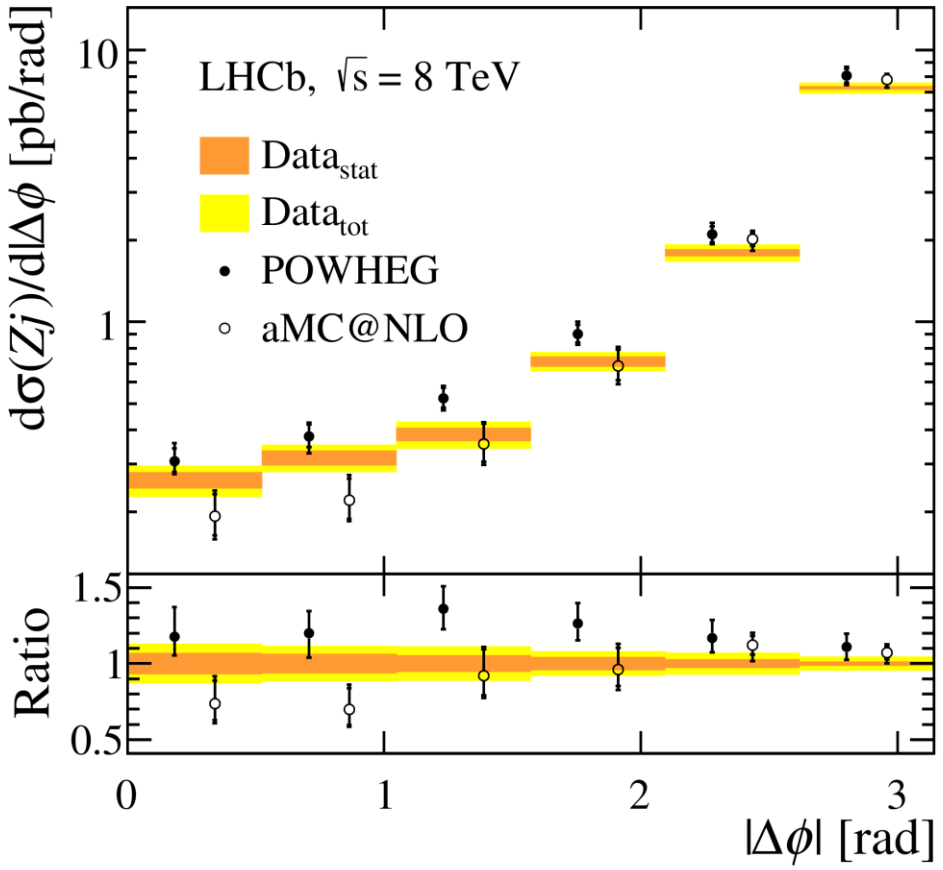
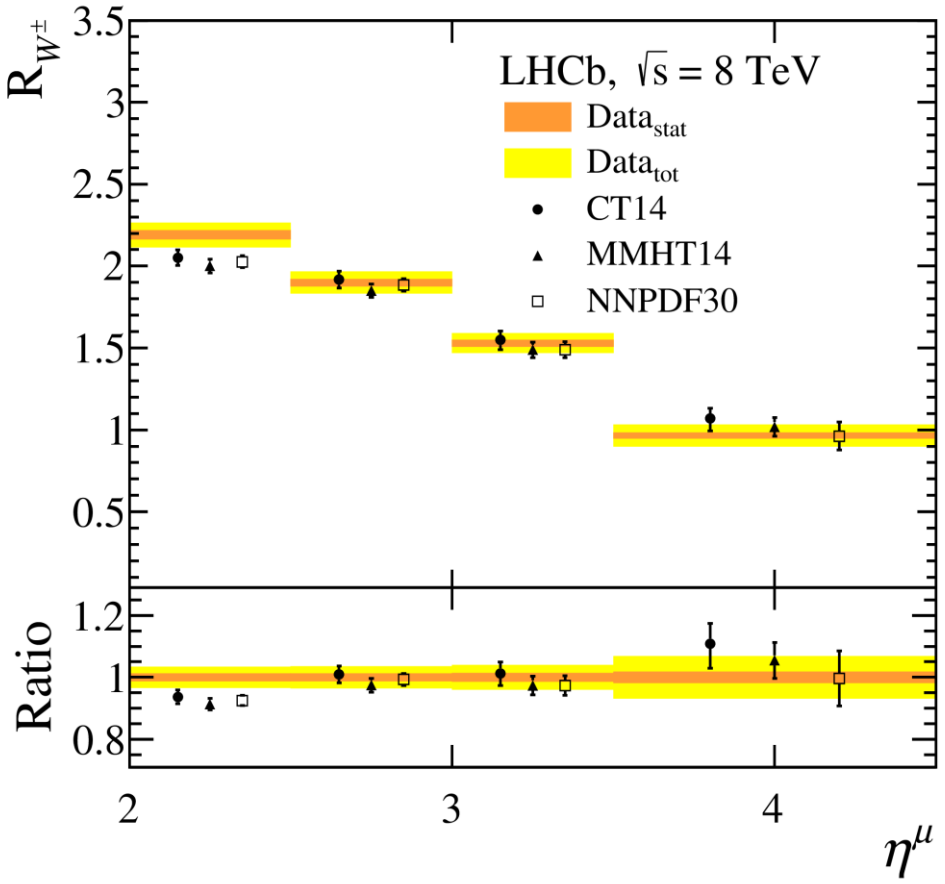
Theoretical prediction performed with NNPDF3.0 PDF set



Theoretical prediction performed with FEWZ



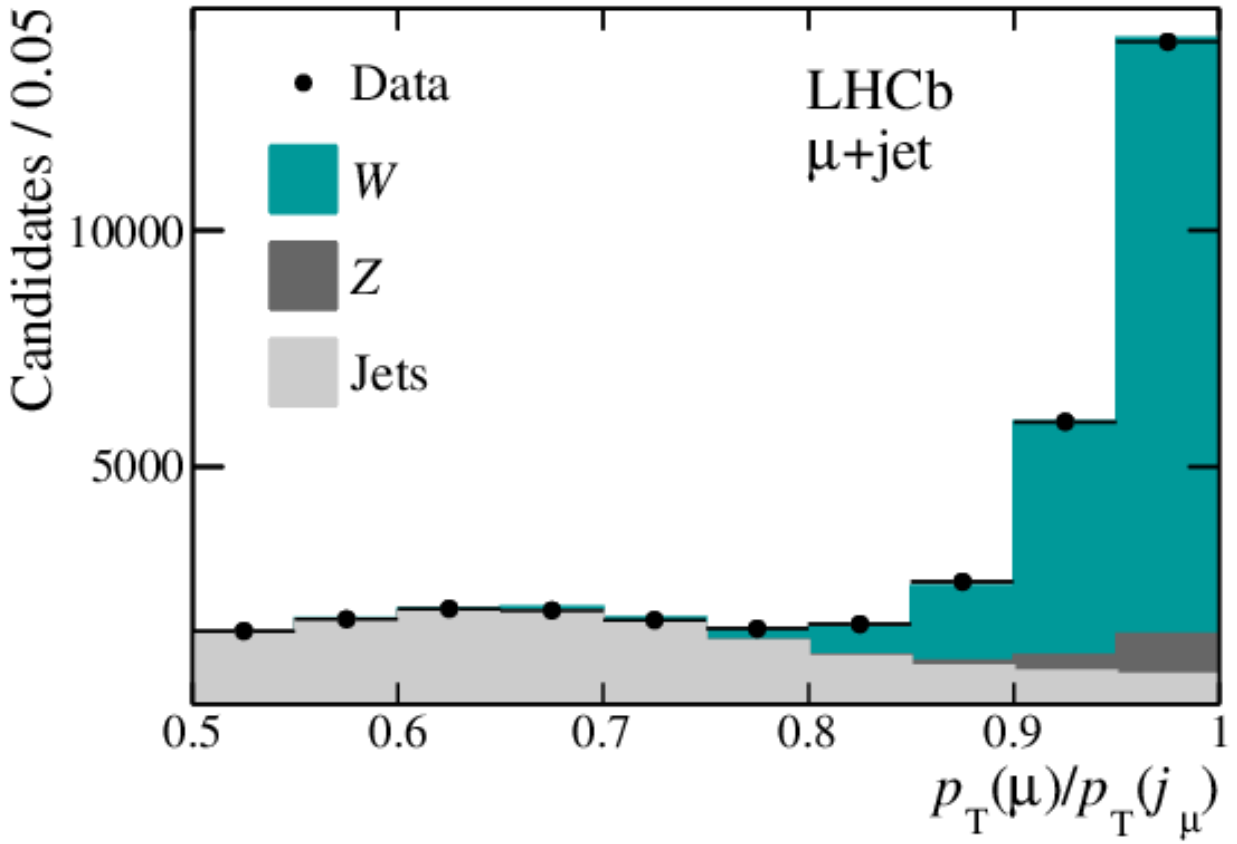
Forward Top measurement

Phys. Rev. Lett. 115 (2015) 112001

- First measurement of the top production in the forward region
- 75% comes from $t\bar{t}$ production
- Sample is enriched by $q\bar{q}$ and qg scattering (reduced gg contribution)
- $W(\mu\nu) + b - jet$

Fiducial selection:

- $2.0 < \eta^{\mu} < 4.5$ and $\boldsymbol{p_T^{\mu} > 25\ \text{GeV}}$
- $2.2 < \eta^{j} < 4.2$ and $\boldsymbol{50\ \text{GeV} < p_T^{b-jet} < 100\ \text{GeV}}$
- $\boldsymbol{p_t^{\mu+b-jet} > 20\ \text{GeV}}$
- $\Delta R(\mu, j) > 0.5$



Forward Top measurement

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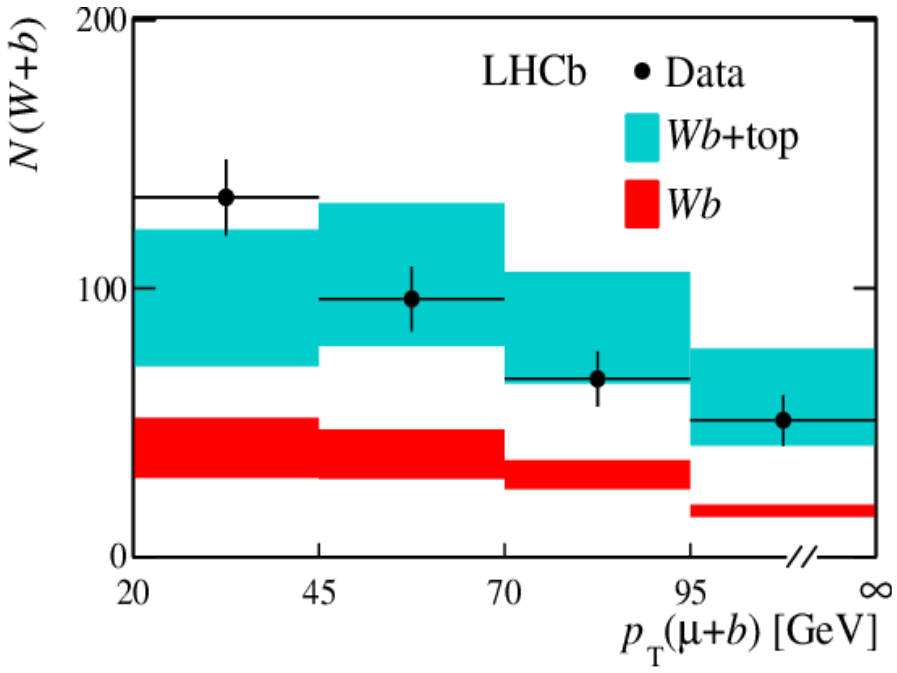
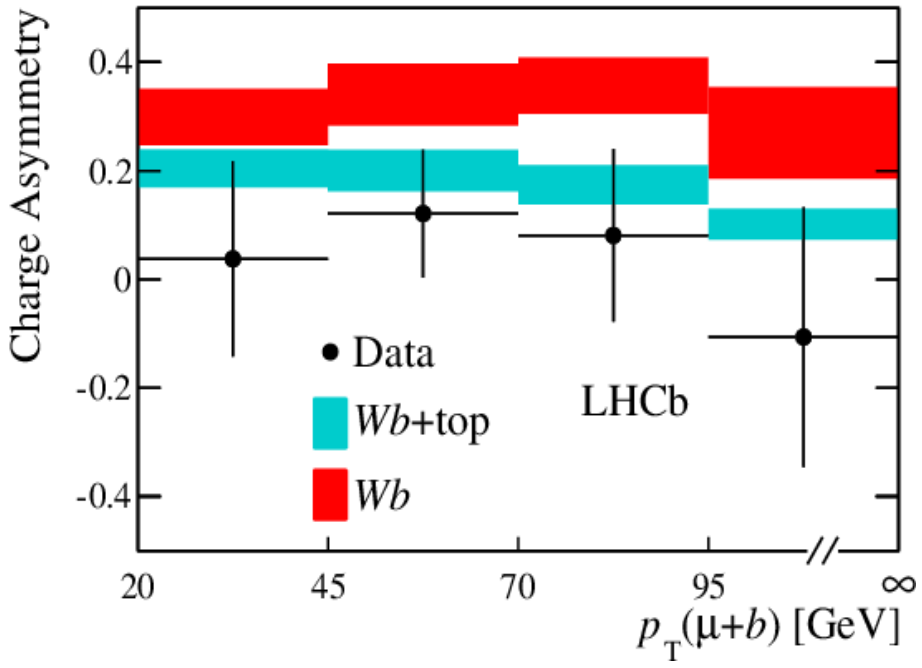




The Wb production is not enough to explain the data. The top production is needed.

Observation of the top production in the forward region with 5.4σ!

Energy	$\sigma(top)$[fb]	Stat. [fb]	Syst. [fb]	Theory [fb]	SM prediction [fb]
7 TeV	239	± 53	± 33	± 24	180^{+51}_{-41}
8 TeV	289	± 43	± 40	± 29	312^{+83}_{-68}

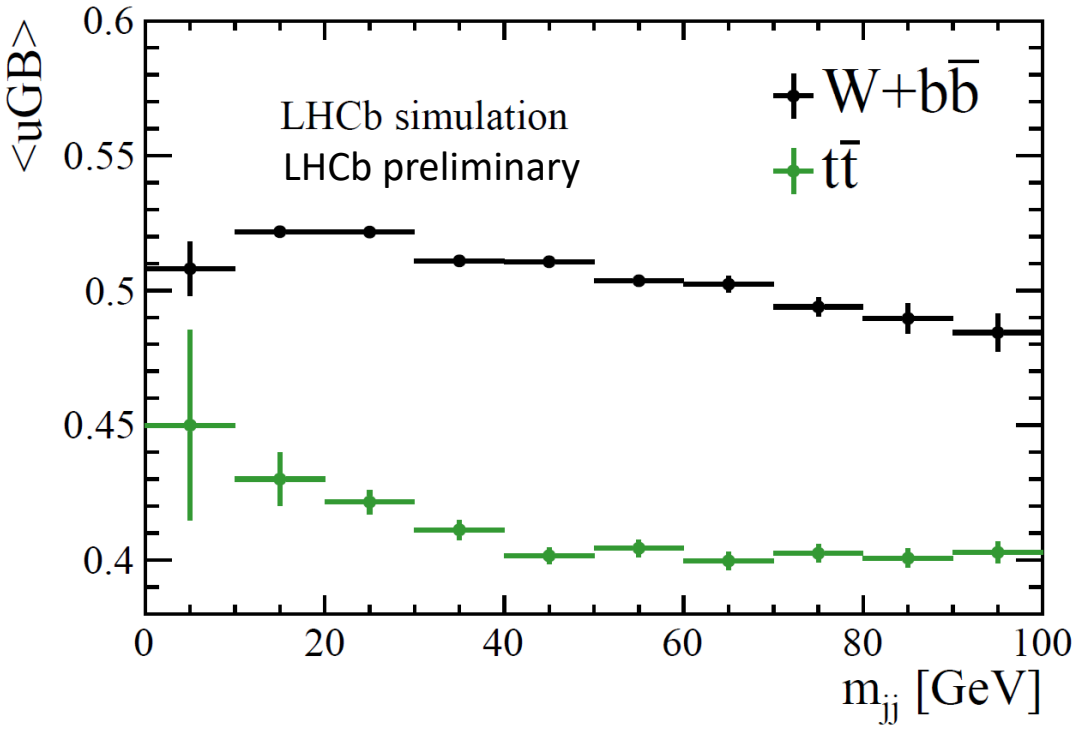
The Standard model prediction was obtained using MCFM with CT10 PDF set at NLO

Measurement of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production cross-section

LHCB-PAPER-2016-038
in preparation

- Novel measurement of the $W + c\bar{c}$ production
- Selection:
  - $W(\mu\nu_\mu)$ or $W(e\nu_e)$
  - $p_T^l > 20$ GeV
  - **$12.5\ \text{GeV} < p_T^j < 100\ \text{GeV}$**
  - $2.2 < \eta^j < 4.2$
  - $2.0 < \eta^\mu < 4.5$ (**$2.0 < \eta^e < 4.25$**)
  - Isolated leptons and jets ($\Delta R > 0.5$)
- Backgrounds: Z+b/c, single top, QCD, ...

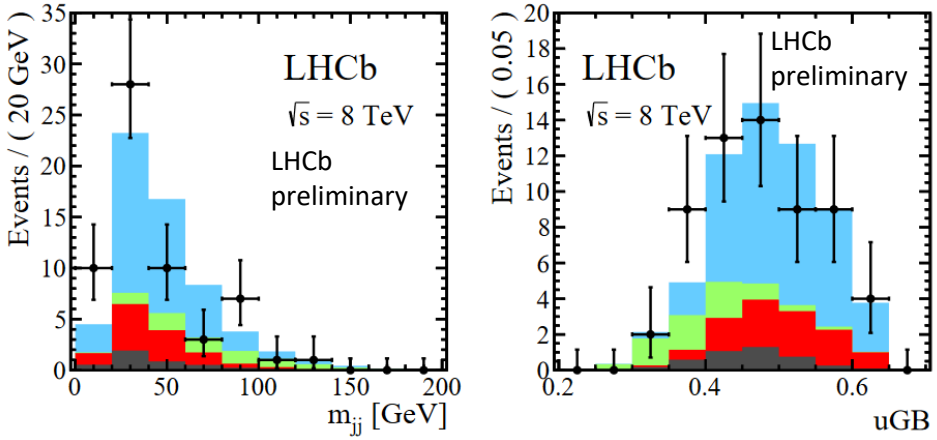
- 4D simultaneous fit for μ^+, μ^-, e^+ and e^- using:
  - $BDT_{b|c}$ for both jets
  - Dijet mass (m_{jj})
  - Uniform Gradient boosting BDT (uGB) to separate $t\bar{t}$ and $W + b\bar{b}$
    J. Instrum. 10 (2015) T03002

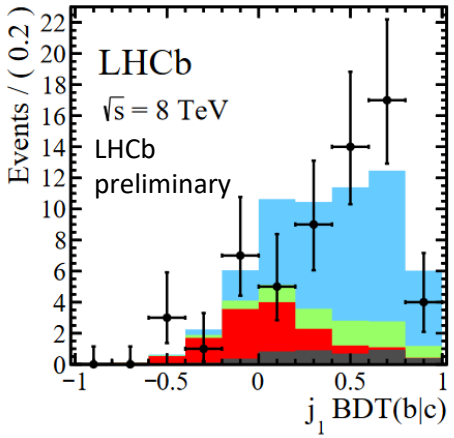


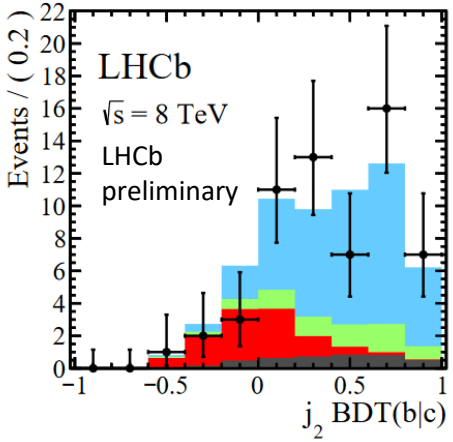
Measurement of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production cross-section

LHCB-PAPER-2016-038
in preparation

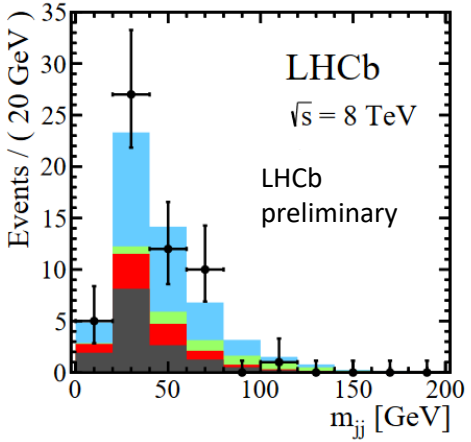
μ^+ sample

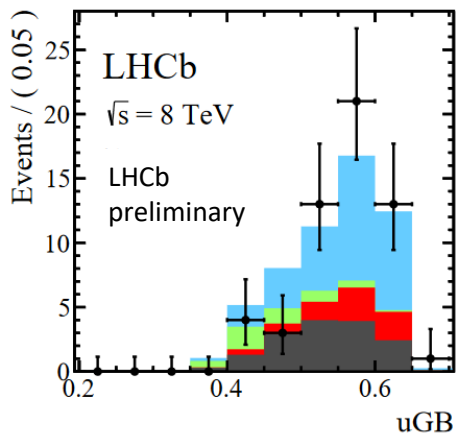


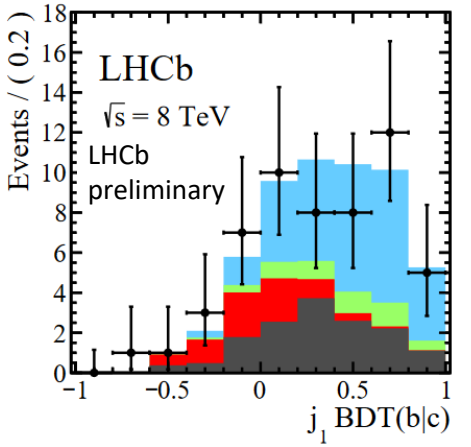


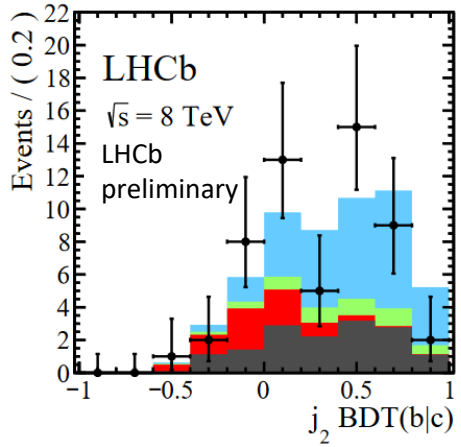


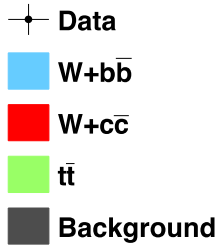
e^+ sample





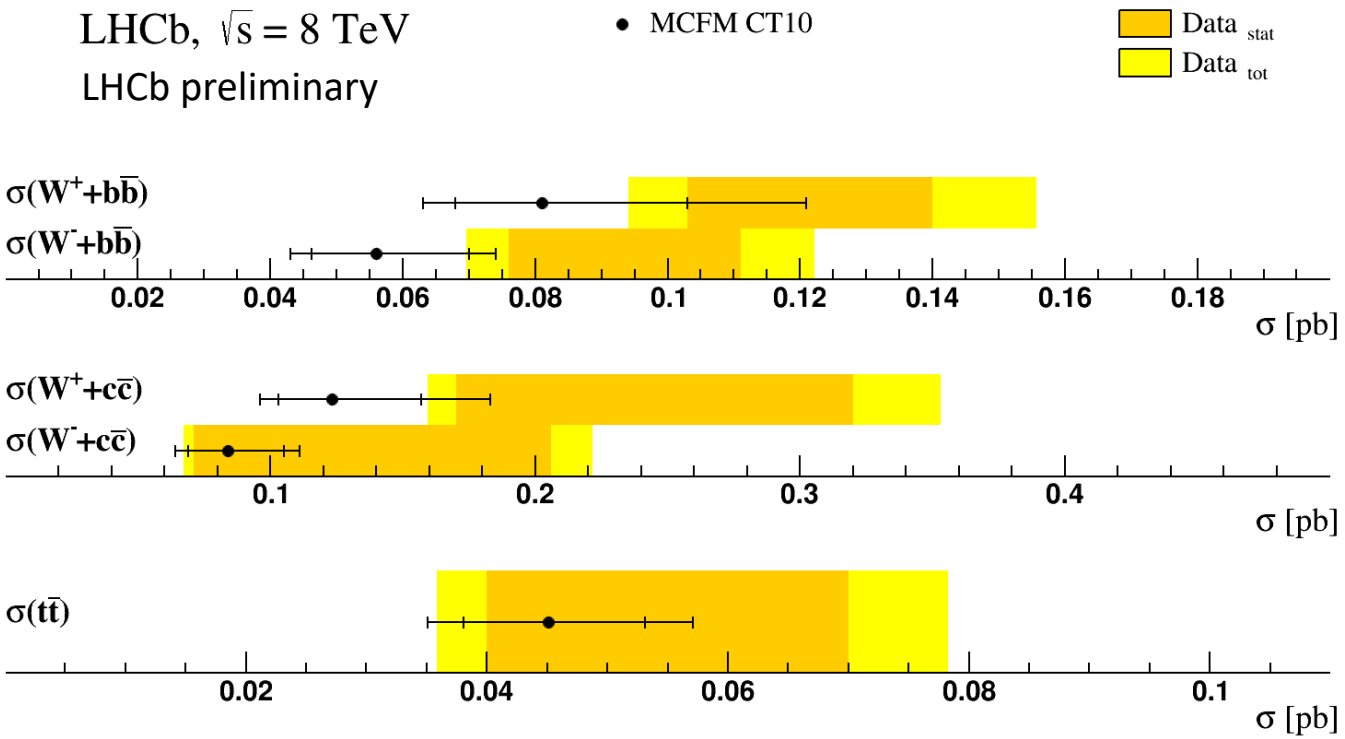






Measurement of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production cross-section

LHCB-PAPER-2016-038
in preparation



Sample	Significance
$t\bar{t}$	4.9σ
$W^+ + b\bar{b}$	7.1σ
$W^- + b\bar{b}$	5.6σ
$W^+ + c\bar{c}$	4.7σ
$W^- + c\bar{c}$	2.5σ

MCFM NLO prediction with PDF set CT10
Showering and hadronization using Pythia 8

Search for the SM Higgs boson decaying in $b\bar{b}$ or $c\bar{c}$ in association with W or Z boson

LHCB-CONF-2016-006
in preparation

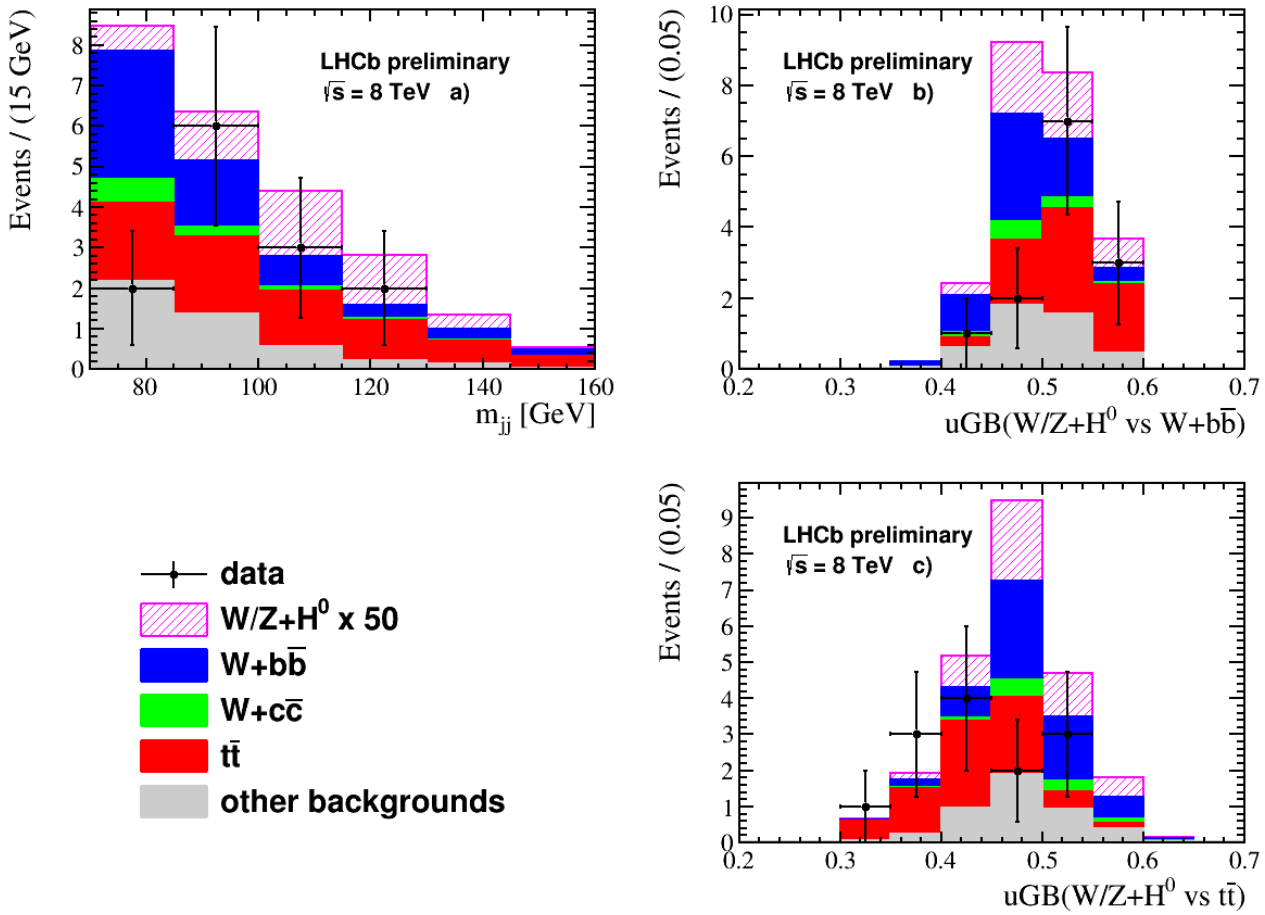
- Selection:
  - Z/W decays into muons or electrons
  - $p_T^l > 20$ GeV
  - **$20\ \text{GeV} < p_T^j < 100\ \text{GeV}$**
  - $2.2 < \eta^j < 4.2$
  - $2.0 < \eta^\mu < 4.5$ (**$2.0 < \eta^e < 4.25$**)
  - Isolated leptons and jets ($\Delta R > 0.5$)
- For the Z/W+H($c\bar{c}$), an additional requirement is applied to the BDT(b|c)
  - ~90% of Z/W+H(bb) is removed
  - ~60% of Z/W+H(cc) efficiency

- No significant excess was found with respect to the backgrounds
- The limits were set:

$\sigma[WZ + H^0(c\bar{c})] < 9.4\ pb\ at\ 95\ \%\ CL\ (6200 \times SM)$

$\sigma[WZ + H^0(b\bar{b})] < 1.6\ pb\ at\ 95\ \%\ CL \quad (50 \times \text{SM})$

Z/W+H($b\bar{b}$) distributions with μ in the final state



Conclusion

LHCb is a general purpose detector in the forward region

- Efficient heavy quark tagging with low light-jet misidentification
- The results reported have a good agreement with the SM predictions
- First measurement of the $W + c\bar{c}$ production
- First observation of the top production in the forward region

More data to come

- $\sim 5\ \mathrm{fb}^{-1}$ in Run II
- $50\ \mathrm{fb}^{-1}$ in Run III (will start in 2021 after the LHCb Upgrade)
- Factor > 10 increase for top production in the Run II
  - More channels will be accessible
  - Differential cross section
  - Separation between $t\bar{t}$ and single-t

Thank you!!!

LHCb-PUB-2013-009

Backup slides

Measurement of forward W and Z boson production in association with jets

J. High Energy Phys. 05 (2016) 131

Uncertainties in percentage of the final result					
Source	σ_{W^+j}	σ_{W^-j}	σ_{Zj}	R_{WZ}	$R_{W^\pm}$
Statistical	0.4	0.5	1.1	1.2	0.7
Muon Reconstruction	1.3	1.3	0.6	0.9	0.0
Jet Reconstruction	1.9	1.9	1.9	0.0	0.0
Selection	1.0	1.0	0.0	1.0	0.0
GEC	0.5	0.5	0.4	0.2	0.1
Purity	5.5	7.0	0.4	6.0	2.5
Acceptance	0.6	0.6	0.0	0.6	0.0
Unfolding	0.8	0.8	0.8	0.0	0.2
Jet energy	6.5	7.7	4.3	3.4	1.2
Total systematic	8.9	10.7	4.8	7.0	3.3
Luminosity	1.2	1.2	1.2	-	-

The main uncertainty for the σ_{Wj} and σ_{Zj} is the systematic uncertainty related to the **Jet energy**

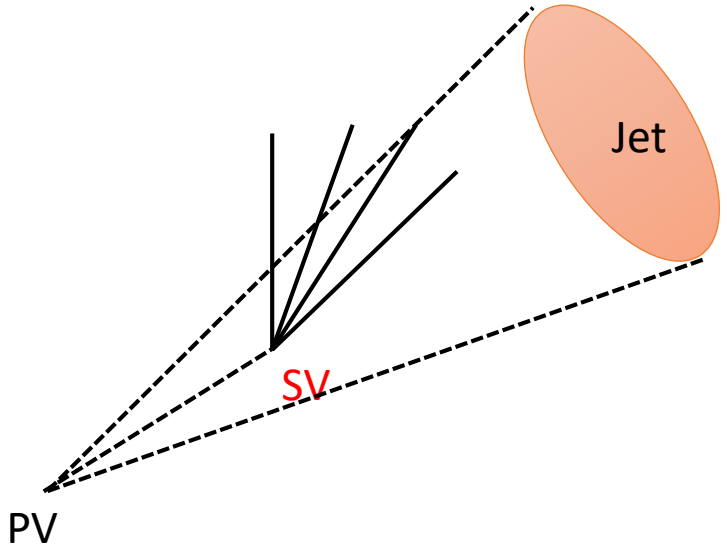
The main uncertainty for the R_{WZ} and $R_{W^\pm}$ is the systematic uncertainty related to the **Purity**

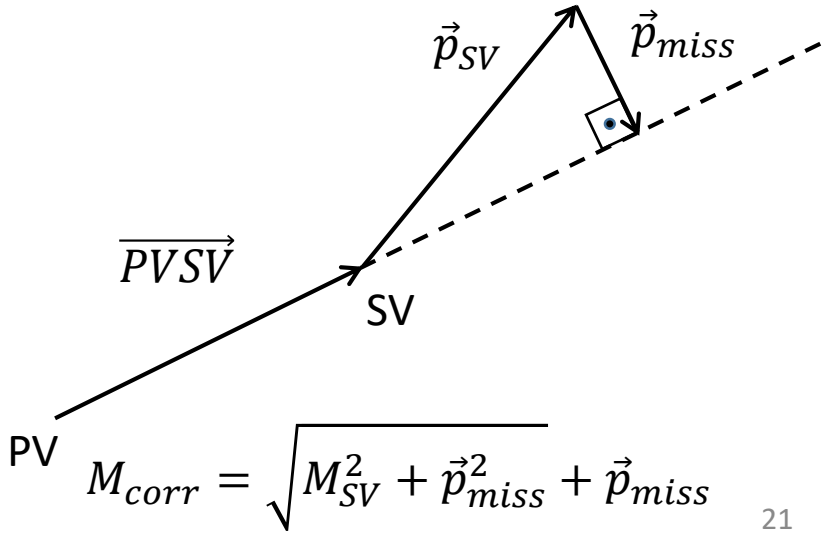
Identification of beauty and charm quark jets at LHCb

J. Instrum. 10 (2015) P06013

Variables used for the BDT(bc|udgs) and BDT(b|c):

- the SV mass M
- the SV corrected mass (M_{corr})
- the transverse flight distance of the two-track SV closest to the PV
- the fraction of the jet p_T carried by the SV
- ΔR between the SV and the jet
- the number of tracks in the SV
- The number of tracks in the jet ($\Delta R < 0.5$)
- the net charge of the tracks that form the SV
- The flight distance χ^2
- The sum of all SV track $\chi^2(IP)$





Expected yields for $t\bar{t}$ measurement in Run II

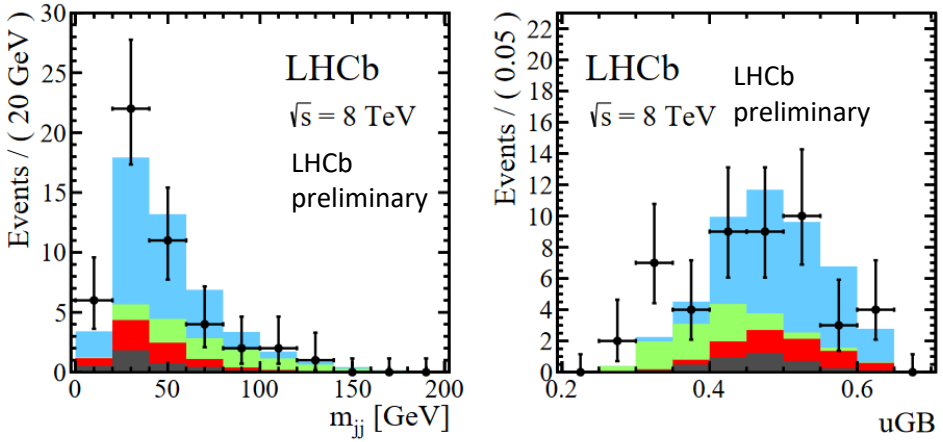
LHCb-PUB-2013-009

$d\sigma$(fb)	7 TeV			8 TeV			14 TeV		
lb	285	$\pm$	52	504	$\pm$	94	4366	$\pm$	663
lbj	97	$\pm$	21	198	$\pm$	35	2335	$\pm$	323
lbb	32	$\pm$	6	65	$\pm$	12	870	$\pm$	116
$lbbj$	10	$\pm$	2	26	$\pm$	4	487	$\pm$	76
l^+l^-	44	$\pm$	9	79	$\pm$	15	635	$\pm$	109
l^+l^-b	19	$\pm$	4	39	$\pm$	8	417	$\pm$	79

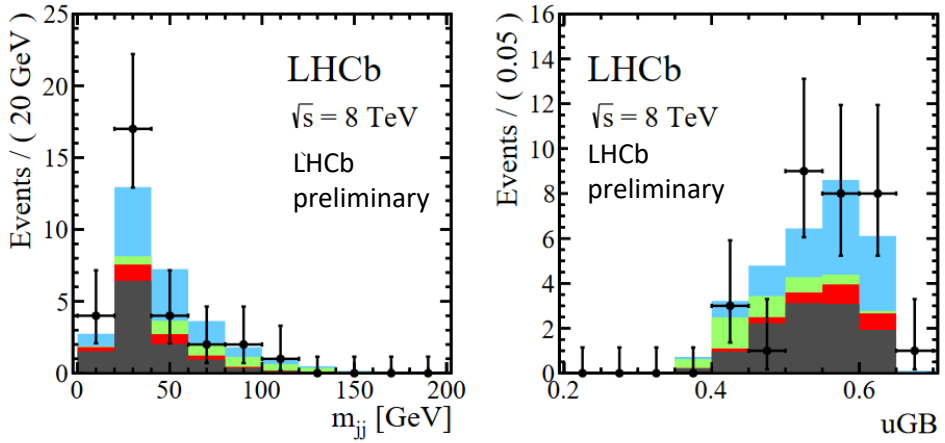
Measurement of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production cross-section

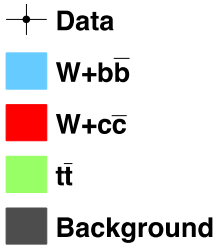
LHCB-PAPER-2016-038
in preparation

μ^- sample



e^- sample

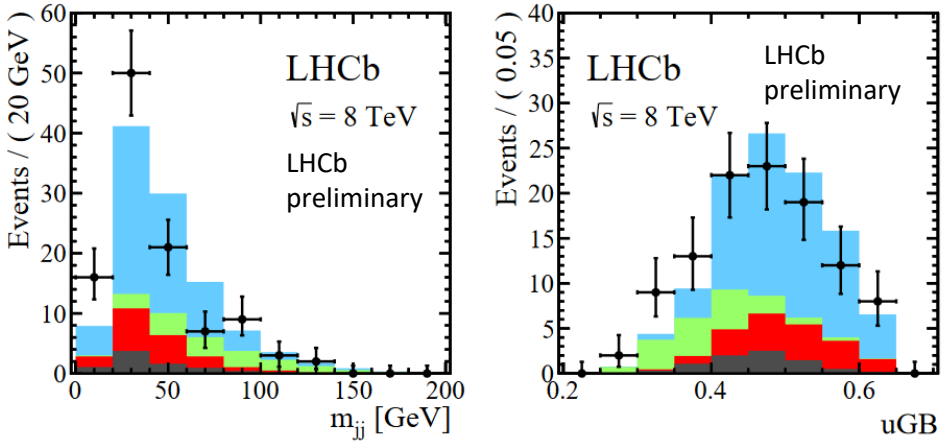




Measurement of the $t\bar{t}$, $W + b\bar{b}$ and $W + c\bar{c}$ production cross-section

LHCB-PAPER-2016-038
in preparation

μ sample merged



e sample merged