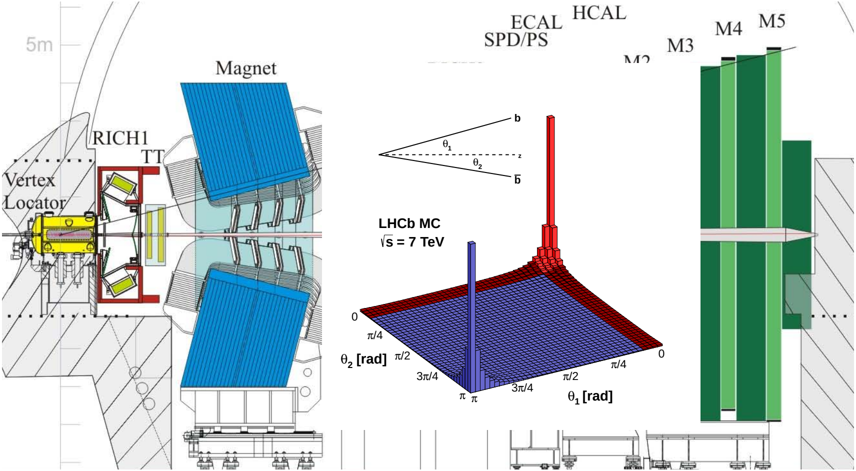
Selected Results of LHCb with Focus on Exotic Hadrons and QCD

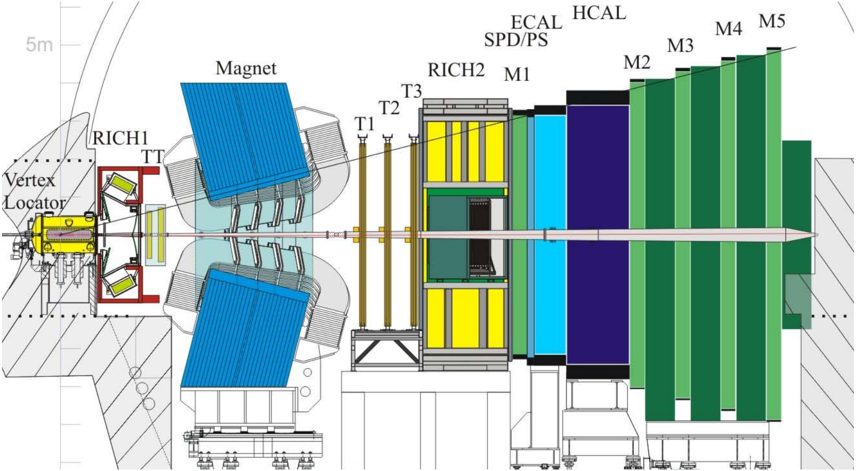
Mexican Workshop of Particles and Fields 2015
Mazatlán (Sinaloa) México

Albert Frithjof Bursche
on behalf of the LHCb collaboration

University of Zurich

6th November 2015


5m
Magnet
RICH1
TT
Vertex
Locator
ECAL
HCAL
SPD/PS
M3
M4
M5
b
θ_1
θ_2
z
$\bar{b}$
LHCb MC
$\sqrt{s}$ = 7 TeV
0
π/4
π/2
3π/4
π
θ_2 [rad]
0
π/4
π/2
3π/4
π
θ_1 [rad]


5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5

What is LHCb?

Compared to Atlas and CMS

- Only forward Acceptance ($2 < \eta < 5$)
- Levelled Luminosity ($4 \cdot 10^{32} \frac{1}{\mathrm{cm}^2\mathrm{s}}$)
- Higher Trigger Rate (Hardware $\approx 950\,\mathrm{kHz}$, Software $5\,\mathrm{kHz} - 15\,\mathrm{kHz}$)
- Particle ID ($e^{\pm}$, γ, $\mu^{\pm}$, $K^{\pm}$, $\pi^{\pm}$, $p\bar{p}$)
- Smaller track momentum $\frac{\sigma_p}{p} \approx 0.4\%$ and vertex resolution ($15\mu\mathrm{m} + \frac{29\mu\mathrm{m}\,\mathrm{GeV}}{p_T}$)

Compared to BaBar and Belle

- Access to many b hadrons ($B^{\pm}$, B^0, B_s^0, $B_c^{\pm}$, Λ_b^0, Σ_b, Ξ_b, Ω_b)
- Focus on fully reconstructed states and on tracks rather than neutrals
- Larger statistics
- pp initial state ($\rightarrow$ no missing energy or momentum)

Flavour Physics Programme

- Constrain CKM triangle from $B^{\pm,0}$ decays
  - γ from $B \to D\ K$, $B \to DK^*$, $B^- \to DK^-\pi^+\pi^-$, $B^- \to D\pi^-\pi^+\pi^-$...
  - ϕ_s from $B_s^0 \to J/\psi\ \phi$
- Flavour Physics with Charm
  - Daliz Plot Analysis of $D^\pm$
  - CP violation in $D^0\overline{D}^0$
- New Physics Searches in rare $B_{(s)}^{\pm,0}$ decays
  - $B^0 \to K^*(892)\mu^+\mu^-$
  - $B_s^0 \to \mu^+\mu^-$
  - $B^0 \to K^*(892)\lambda$
- b decays in heavier hadrons
  - $\Lambda_b^0 \to \Lambda\mu^+\mu^-$
  - $B_s^0 \to J/\psi\ \phi$
  - $B_c^+ \to J/\psi\,\pi^+$, $B_c^+ \to J/\psi\,K^+$, $B_c^+ \to \psi(2S)\pi^+$, $B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi\,D_s^+$, $B_c^+ \to J/\psi\,p\overline{p}$

This is the original programme from the Letter of Intend

But there is more...

- Soft QCD
  - Charged Particle Multiplicity
  - Forward Energy Flow
  - Multi Parton Interactions
  - Hadron Cross Sections $D^{\pm,0}_{(s)}$, $B^{\pm}$, J/ψ ...
  - Hadron Properties $X(3872)$, $Z^{-}(4430)$ ...
  - Diffractive Physics (CEP, Single Diffractive ...)
- Hard QCD
  - Precision Measurements of $W^{\pm}/Z$ boson production
  - $W^{\pm}+c$ Production (s PDF)
  - $c\bar{c}$, $b\bar{b}$, $t\bar{t}$ production
- Electroweak
  - $\sin^2\vartheta_W$ from A_{FB} in $Z\to\mu^+\mu^-$
  - A_{FB} in top quarks (needs more luminosity)
- Exotic Searches
  - Heavy Stable Charged Particles (using the RICH detectors)
- Heavy Ions
  - Particle Production in proton Lead collisions (J/ψ, Z...)
  - Studies in Fixed Target collisions (proton Neon, proton Argon, Lead Neon)

Outline

Rare B Decays

- Angular Analysis of $B^0 \to K^* \mu^+ \mu^-$
- $B_s^0 \to \mu^+ \mu^-$
- Probe Lepton Universality with $B^\pm \to K^\pm \ell^+ \ell^-$
- Lepton Universality in $B^0 \to D^{*+} \tau^- \overline{\nu}$

Exotic Hadrons

- X(3872) Meson
- $Z^-(4430)$ Meson
- Observation of two Pentaquark states $P_c(4380)^+$ and $P_c(4450)^+$

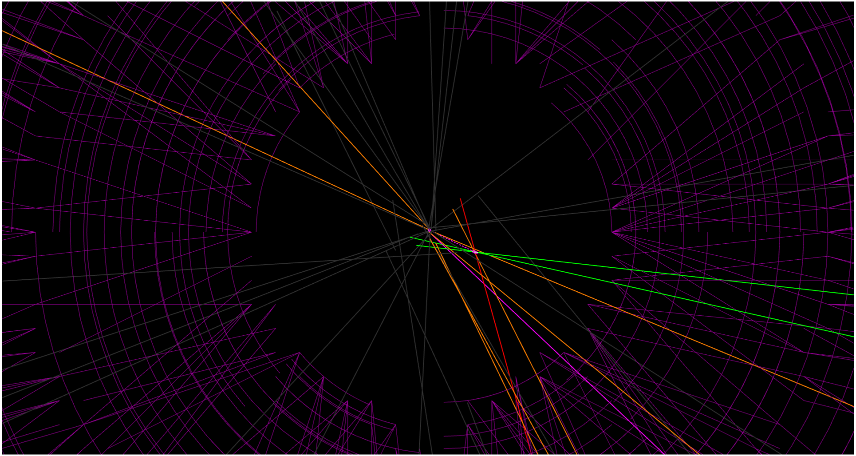
QCD Studies using EW Gauge Bosons

- Inclusive Z Production
- Inclusive $W^\pm$ Boson Production at 7 TeV
- Associated Production of a Z Boson with Jets
- First Observation of Top Quark Production in LHCb

Selected Rare B decays

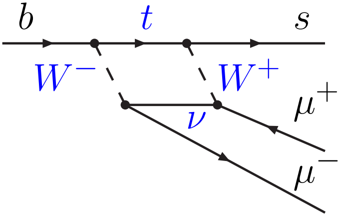
Used to test the Standard Model interactions in the decay and Lepton Universality

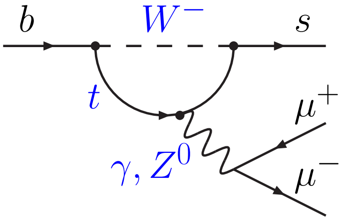
$B^0 \rightarrow K^{*}\mu^{+}\mu^{-}$



Rare Beauty Decays ($B^0 \rightarrow K^* \mu^+ \mu^-$)

$b \rightarrow s$ transitions are highly suppressed in the Standard Model

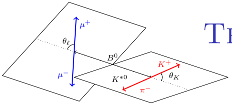




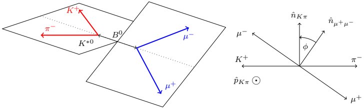
New physics can enter at the same level

Change in Branching Fractions and Angular Observables

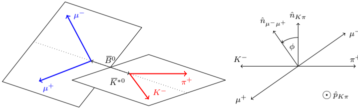
Definition of the Angles



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

Three angles describe the decay

- ϕ Angle between the $\mu^+\mu^-$ and the $K^+\pi^-$ plane in the B^0 rest frame
- θ_ℓ Angle between μ^+ and the flight direction in the $\mu^+\mu^-$ rest frame
- θ_K Angle between K^+ in the K^* rest frame

Measurement in bins of the invariant mass q^2 of the dimuon system
Using about 2300 candidates

Angular Observables

$$\frac{1}{\mathrm{d}\,\Gamma + \bar{\Gamma} / \mathrm{d}\,q^2} \frac{\mathrm{d}^3(\Gamma + \bar{\Gamma})}{\mathrm{d}^3\,\vec{\Omega}} = \frac{9}{32\pi} \Bigg(\frac{3}{4}(1 - F_L)\sin^{\theta}_{K} + F_L \cos^2\theta_K \\
+ \frac{1}{4}(1 - F_L)\sin^2\theta_K \cos 2\theta_\ell \\
- F_L \cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + S_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \\
+ \frac{3}{4} A_{FB} \sin^2\theta_K \cos\theta_\ell + S_7 \sin 2\theta_K \sin\theta_\ell \cos\phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + S_9 \sin^2\theta_K \sin\theta_\ell \sin 2\phi$$

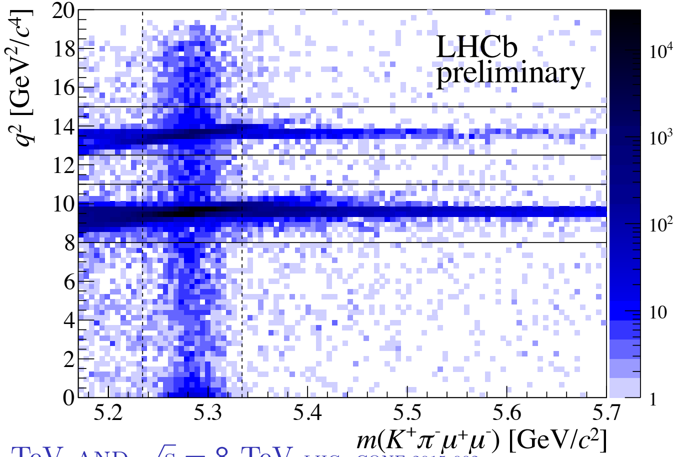
F_L, A_{FB}, S_i depend on the Wilson coefficients $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$ as well as hadronic Form Factors.

Angular Observables

$$\frac{1}{\mathrm{d}\,\Gamma+\bar{\Gamma}/\,\mathrm{d}\,q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}^3\,\vec{\Omega}} = \frac{9}{32\pi}\Big(\frac{3}{4}(1-F_L)\sin^{\theta}_{K} + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$-F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\frac{3}{4}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin\theta_\ell\sin 2\phi$$

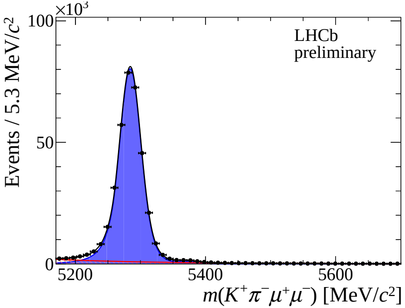
F_L, A_{FB}, S_i depend on the Wilson coefficients $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$ as well as hadronic Form Factors. Different Observables reduce Form Factor dependence. e.g. $P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$

Mass Distribution

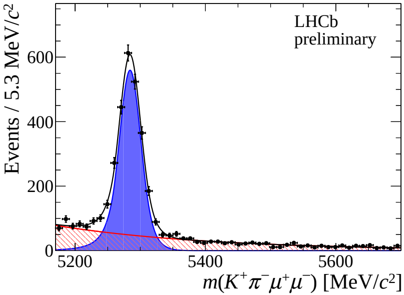


$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV LHCb-CONF-2015-002 preliminary

Mass Distribution II



$B^0 \to J/\psi K^*$ Control Sample

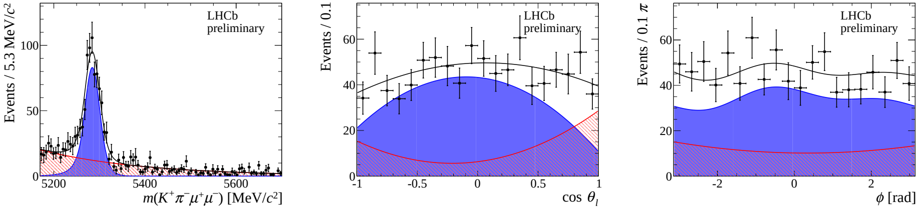


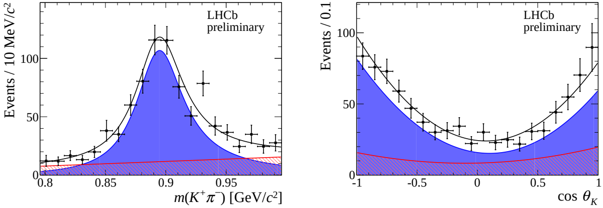
$B^0 \to K^* \mu^+\mu^-$ Signal Sample

Peaking background is controlled by PID and vetos with changed mass hypotheses. Dominant $\Lambda_b^0 \to pK^-\mu^+\mu^-$.

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV LHCb-CONF-2015-002 preliminary

Angular Analysis - One q^2 Bin

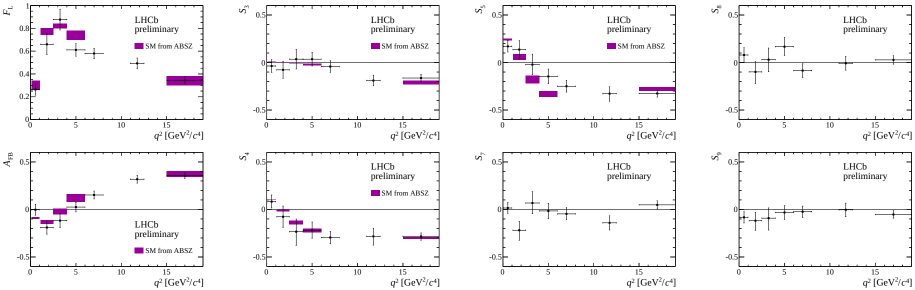




- 5 dimensions for the data
- $9 + 3 \cdot 3$ free parameter
- binned in q^2

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV LHCb-CONF-2015-002 preliminary

Results I

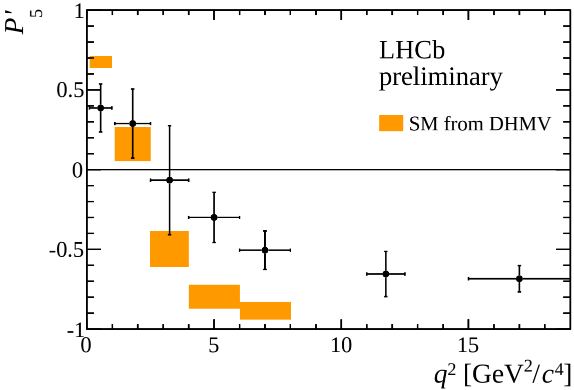


Agreement with Standard Model apart from S_5

The zero crossing point of A_{FB} is measured as $3.7^{+0.8}_{-1.1}\,\mathrm{GeV}^2$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV LHCb-CONF-2015-002 preliminary

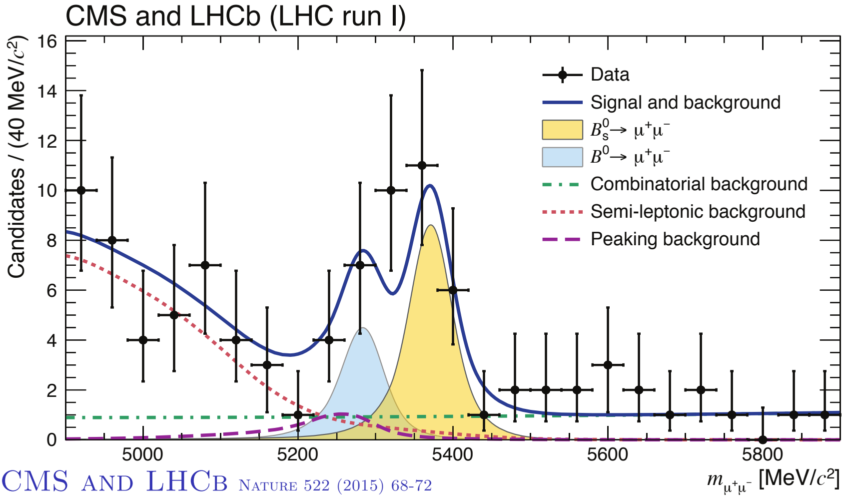
Results II



Deviation to the Standard Model of 3.7σ $(0.1 < q^2 < 8\,\mathrm{GeV}^2)$

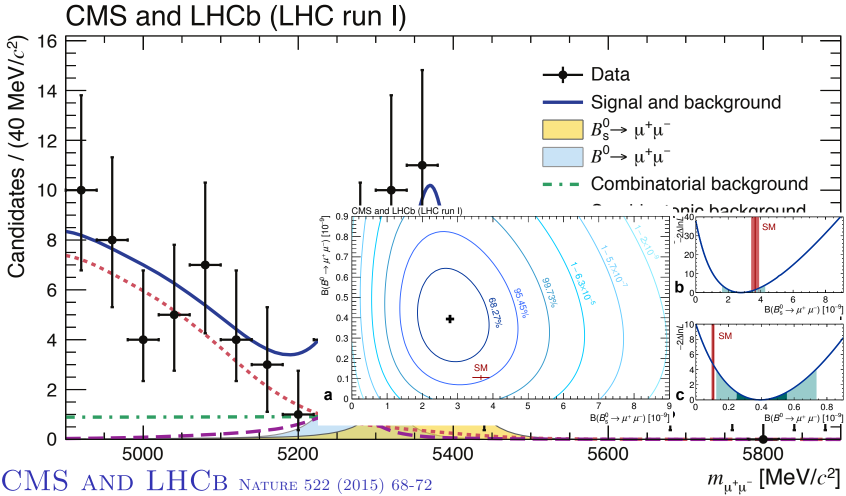
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV LHCb-CONF-2015-002 preliminary

Observation of the rare Decay $B_s^0 \rightarrow \mu^+ \mu^-$



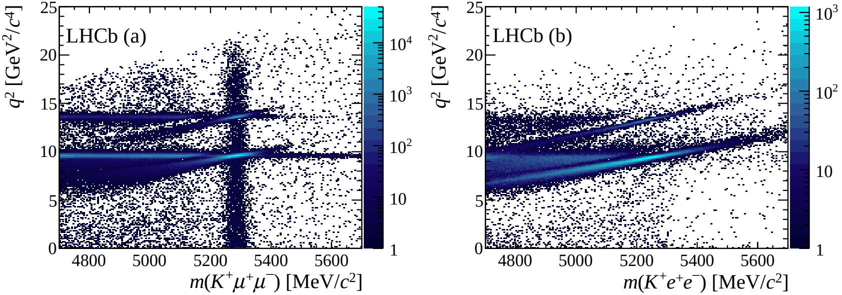
CMS and LHCb Nature 522 (2015) 68-72

Observation of the rare Decay $B_s^0 \to \mu^+\mu^-$



CMS and LHCb Nature 522 (2015) 68-72

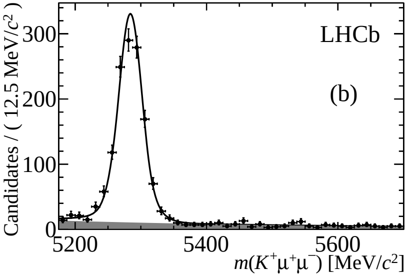
Branching Fraction Ratio $B^{\pm} \rightarrow K^{\pm} e^{+} e^{-}$ to $B^{\pm} \rightarrow K^{\pm} \mu^{+} \mu^{-}$



- Measure the Branching fractions and compare
- Electrons loose energy due to Bremsstrahlung which is incompletely recovered. $\rightarrow$ reduced Resolution

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 113 (2014) 151601

Branching Fraction Ratio $B^{\pm} \rightarrow K^{\pm}e^{+}e^{-}$ to $B^{\pm} \rightarrow K^{\pm}\mu^{+}\mu^{-}$



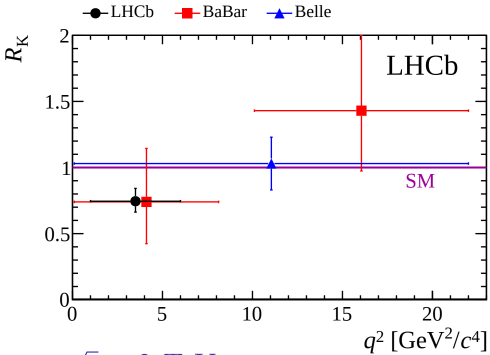
- Measure the Branching fractions and compare
- Electrons loose energy due to Bremsstrahlung which is incompletely recovered. $\rightarrow$ reduced Resolution

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 113 (2014) 151601

Result

1226 ± 41 signal decays in the $\mu^+\mu^-$ channel (≈ 200 for e^+e^-)

$$R_K(1 < q^2 < 6\,\mathrm{GeV}) = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{sys})$$



$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 113 (2014) 151601 2.6σ

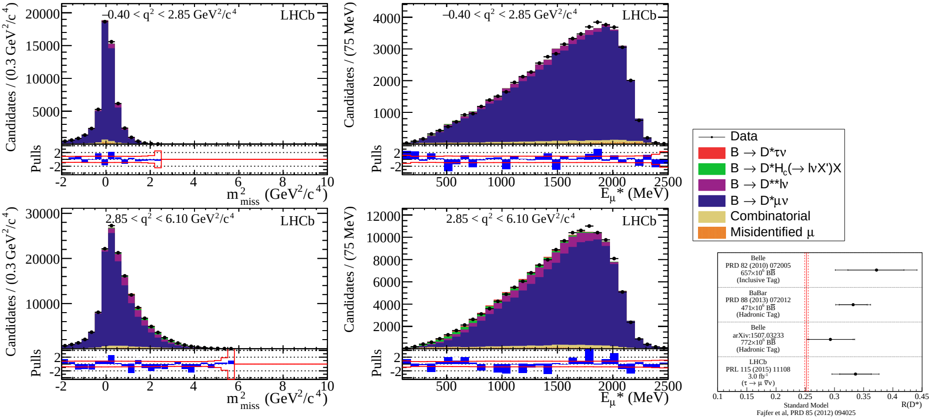
Analysis Strategy

Similar Measurement as before now with $R_{D^{*+}} = \frac{\mathcal{B}(D^{*}\tau^{-}\overline{\nu})}{\mathcal{B}(D^{*+}\mu\overline{\nu})}$.

- Select $D^{*+} \rightarrow D^{0}\pi^{+}$ with $D^{0} \rightarrow K^{-}\pi^{+}$
- Not fully reconstructed decay (neutrinos)
- Compare $B^{0} \rightarrow D^{*+}(\tau^{-} \rightarrow \mu^{-}\overline{\nu}_{\mu}\nu_{\tau})\overline{\nu}_{\tau}$ to the direct decay to a muon $B^{0} \rightarrow D^{*+}\mu^{-}\overline{\nu}_{\mu}$
- $p_{zB^{0}} = (p_{D^{*+}} + p_{\mu^{-}})_{z}$
- Transverse p Components from p_{z} and flight direction
- p_{e} from $\|\vec{p}\|$ and PDG mass.
- $m^{2}_{\text{miss}} = (p_{B^{0}} - p_{D^{*+}} + p_{\mu^{-}})^{2}$
- 3D fit in m^{2}_{miss}, E^{*}_{μ} binned in q^{2} of the lepton system

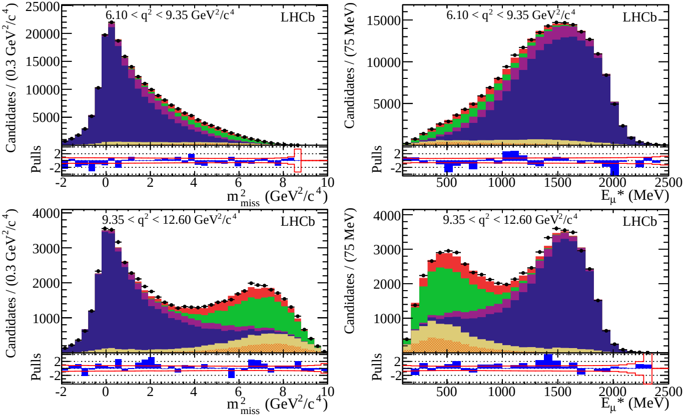
$\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 111803

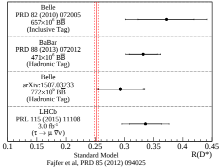
Fit



- At low q^2 the τ channel is not open
- $R_{D*+} 0.336 \pm 0.027(stat) \pm 0.030(syst)$
  $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 111803

Fit





- At low q^2 the τ channel is not open
- $R_{D^{*+}} 0.336 \pm 0.027(stat) \pm 0.030(syst)$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 111803

Exotic Hadrons

What kind of bound states exist in in QCD?

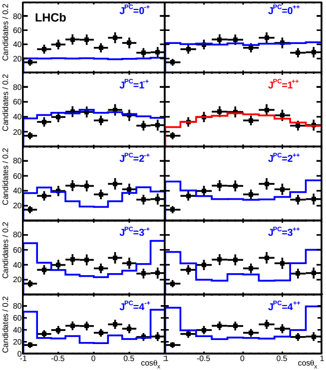
The X(3872) Meson

- In $B^{\pm} \rightarrow K^{\pm} J/\psi \pi^{+}\pi^{-}$ decays Belle discovered a
- narrow resonance close to $D^0 \overline{D}^0$ mass in the $J/\psi \pi^{+}\pi^{-}$ mass
- Charmonium?, $D^0 \overline{D}^{0*}$?, strong tetraquark?
- J^{PC} remained undetermined
- CDF Narrowed it down to either $J^{PC} = 1^{++}$ or 2^{-+}

Belle 2003 ,PRL 91, 262001

Analysis

- Select $B^{\pm} \to K^{\pm} X(3872)$ candidates with $X(3872) \to \rho^0 J/\psi$
- 5 dimensional fit to helicity angles $(\theta_X, \theta_{\rho^0}, \theta_{J/\psi})$ and $\Delta\phi_{X,\rho^0}$, $\Delta\phi_{X,J/\psi}$
- Improve mass resolution with mass constraint on $B^{\pm}$ and by requiring the momentum to point to a PV in full kinematic fit.

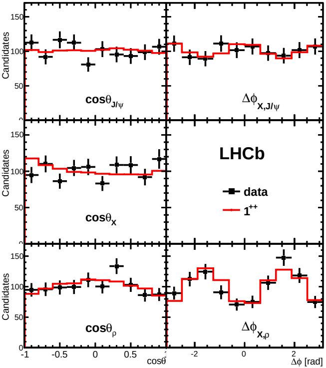


X(3872) is a $J^{PC} = 1^{++}$ state. All other states are excluded.

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV PR D 92, 011102 (2015)

Analysis

- Select $B^{\pm} \to K^{\pm}X(3872)$ candidates with $X(3872) \to \rho^0 J/\psi$
- 5 dimensional fit to helicity angles $(\theta_X, \theta_{\rho^0}, \theta_{J/\psi})$ and $\Delta\phi_{X,\rho^0}$, $\Delta\phi_{X,J/\psi}$
- Improve mass resolution with mass constraint on $B^{\pm}$ and by requiring the momentum to point to a PV in full kinematic fit.



X(3872) is a $J^{PC} = 1^{++}$ state. All other states are excluded.

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV PR D 92, 011102 (2015)

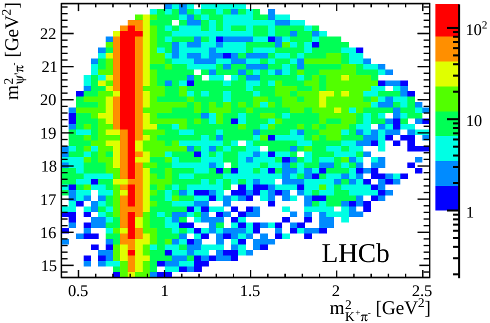
The $Z^{-}(4430)$ Meson

- In $B^0 \to K^{\pm} J/\psi \pi^{+}$ decays Belle discovered a
- brought resonance in the $J/\psi \pi^{+}$ mass.
- minimal quark content $c\bar{c}d\bar{u}$
- $J^P = 1^+$ favoured
- BaBar: Compatible with K^* reflections

Belle 2008: PRL100 (2008)142001

LHCb Measurement

- $B^0 \rightarrow \psi(2S) K^- \pi^+$
- Background Substraction with *sPlot*
- 4D amplitude fit in $m^2_{K^-\pi^+}$, $m^2_{\psi(2S),\pi^-}$, $\cos\theta_{\psi(2S)}$ and ϕ)
- Include all known K^* resonances in the fit: $K^*(800)$, $K^*(1430)$, $K^*(892)$, $K^*(1410)$, $K^*(1680)$, $K^*{}_2(1430)$, $K^*{}_3(1780)$

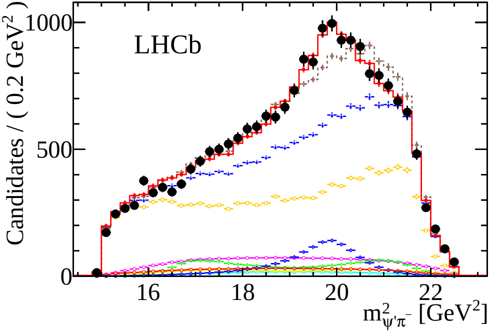


$K^*(892)$, $K^*(1430)$ and $Z(4430)^-$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 112 (2014) 222002

Fit

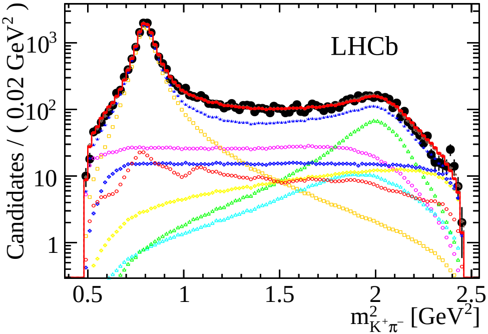
- Z_1^-
- full model with Z_1^-
- full model without Z_1^-
- $K^*(892)$, $S-$wave, $K^*(1410)$, $K^*(1680)$, $K^*(1430)$ and combinatorial background



$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 112 (2014) 222002

Fit

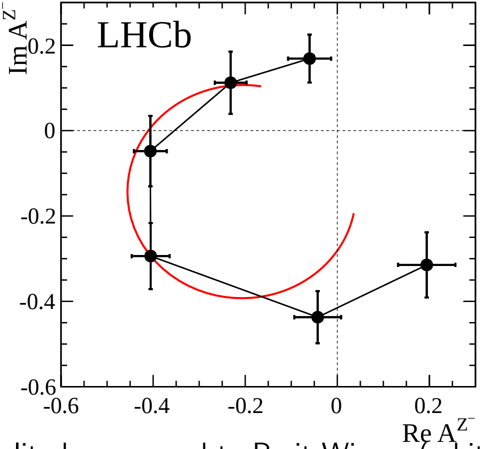
- Z_1^-
- full model with Z_1^-
- full model without Z_1^-
- $K^*(892)$, $S-$wave, $K^*(1410)$, $K^*(1680)$, $K^*(1430)$ and combinatorial background



We confirm the $Z(4430)^-$ with $J^C = 1^+$ at 18.7σ.
Other configurations are ruled out with at least 9.7σ,
S-wave decays only (D wave $< 4\%$)

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 112 (2014) 222002

Resonant Behaviour



Decay amplitude compared to Breit Wigner (arbitrary units)

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 112 (2014) 222002

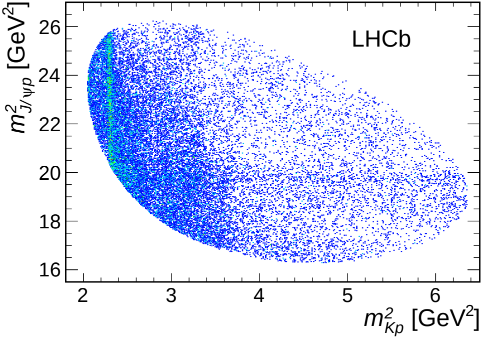
$\Lambda_b^0 \to J/\psi\, pK^-$

$\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV PHYS. REV. LETT. 115 (2015) 072001

$\Lambda_b^0 \to J/\psi\, pK^-$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

Daliz Plot



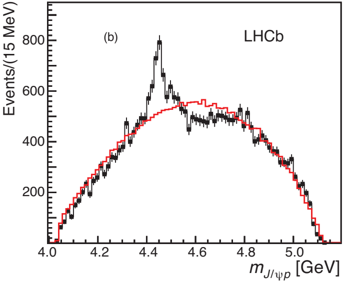
- Λ_b^0 Selection using BDTG
- Structure in the pK^- mass
- Structure in the pJ/ψ mass
- No structure in the $K^- J/\psi$ mass

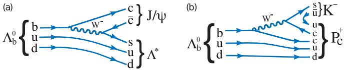
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

What is that?

There is a bump in the $J/\psi\, p$ invariant mass in $\Lambda_b^0 \to J/\psi\, pK^-$ decays.

- What is it?
- If it is a resonance it is a pentaquark because it decays strongly to $(uud)(c\bar{c})$.
- Is is just a reflection of a Λ^*?
- Full amplitude analysis to answer this.
- Using 26k $\Lambda_b^0 \to J/\psi\, K^- p$ decays.

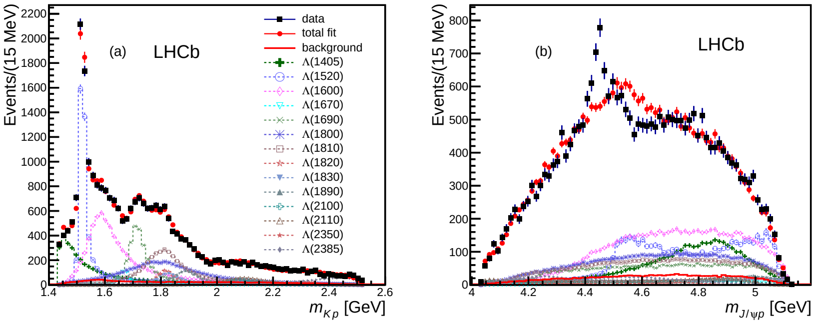




$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

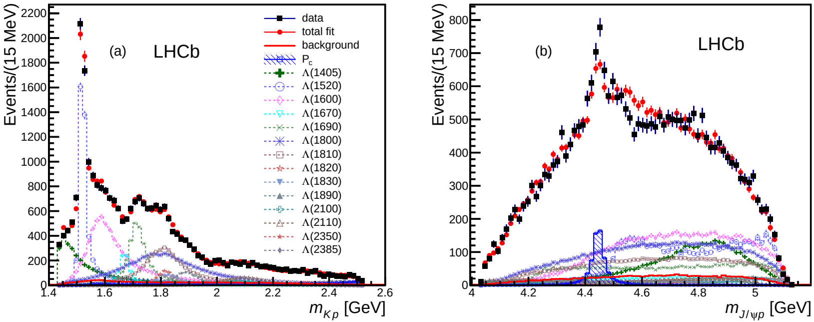
Background Only Hypothesis

Amplitude Analysis using 16 Λ^* resonances with experimental evidence leading to a model with 146 free parameters "extended model".



$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

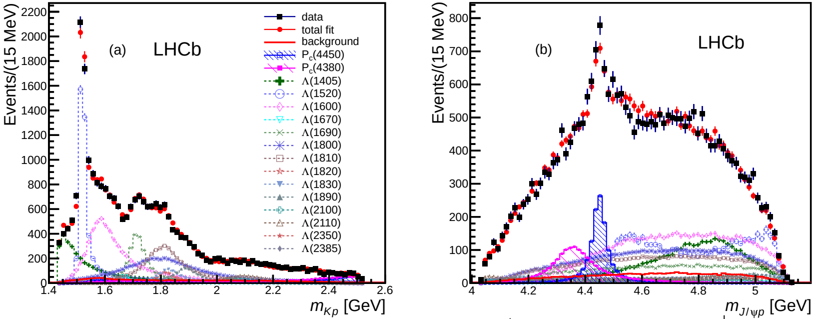
Best Fit Result - Only one P_c^+



- Some of the Λ^* states or poor experimental data
- Reduced model without unlikely Λ^* and high $L^{\Lambda^*}_{\Lambda_b^0}$ amplitudes (64 p.)
- One P_c^+ state with different J^P still not Ok ($\Delta \ln \mathcal{L} = 14.7$)

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

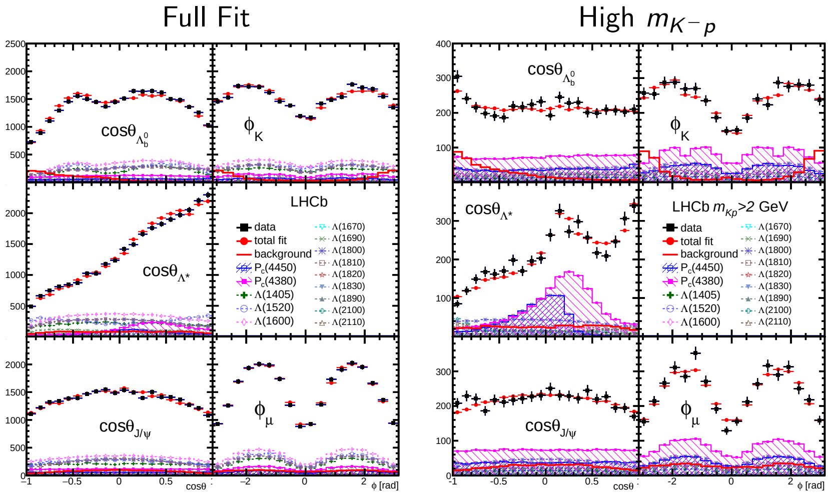
Best Fit Result - Both P_c^+



- Acceptable fit quality only with two P_c^+ states with $5/2^+$ and $3/2^-$ ($\Delta \ln \mathcal{L} = 18.7$)
- The extended model is always used for cross checks and never gives a acceptable description without the two P_c^+ states.

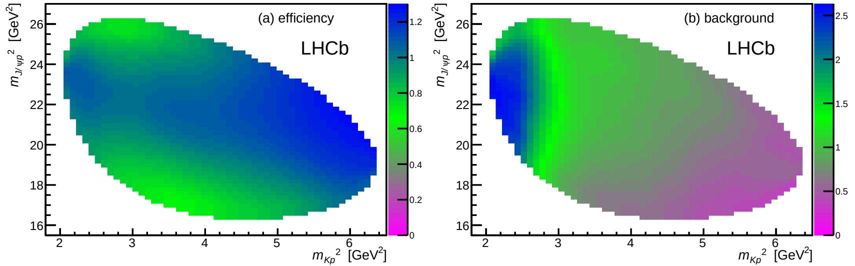
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

Full Fit



$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

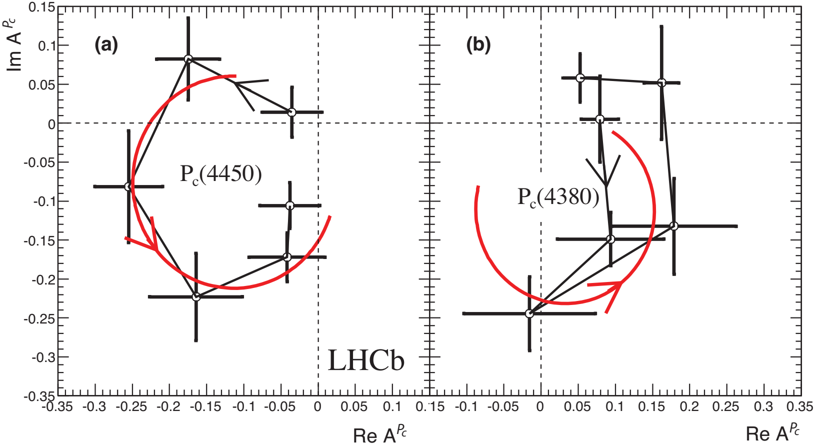
Is it an Artefact of the Reconstruction?



Relative efficiency and background density are smooth. This doesn't generate fake peaks.

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

Complex Decay Amplitudes



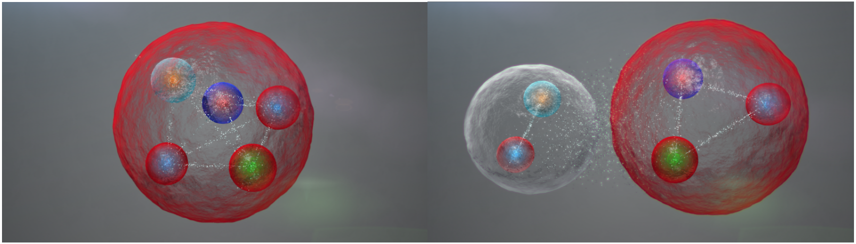
The decay amplitudes are well described by a Breit Wigner

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

Result

- LHCb observed two states strongly decaying to $J/\psi\, p$ with quark content $(uudc\bar{c})$.

	mass				width	
$P_c(4380)^+$	4380	$\pm$ 8	$\pm$ 29	MeV	$205 \pm 18 \pm 86$ MeV	$3/2^-$
$P_c(4450)^+$	4449.8	$\pm$ 1.7	$\pm$ 2.5	MeV	$39 \pm 5 \pm 19$ MeV	$5/2^+$



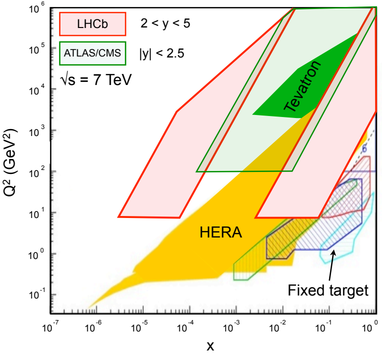
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 072001

QCD Studies with Electroweak Gauge Bosons

Use $W^{\pm}$ and Z to probe quarks and gluons in the proton and QCD calculations.

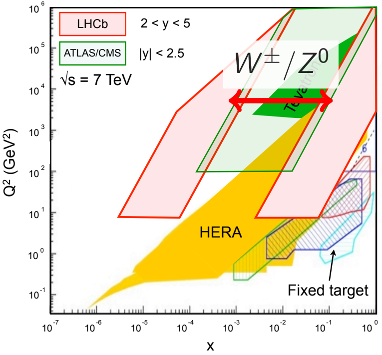
LHCb Sensitivity to Parton Distribution Functions

- unique kinematic acceptance
- $Q^2 = M^2$, $x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$
- combination of KNOWN high-x with UNEXPLORED low-x partons

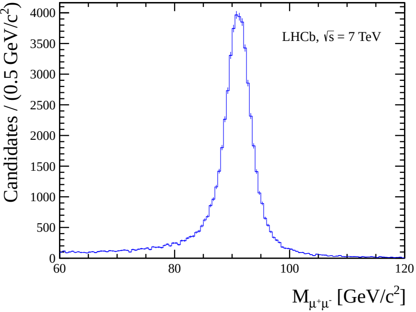


LHCb Sensitivity to Parton Distribution Functions

- unique kinematic acceptance
- $Q^2 = M^2$, $x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$
- combination of KNOWN high-x with UNEXPLORED low-x partons
- For Z^0, $W^\pm$
  - $Q^2 \approx 10000$ GeV^2
  - x_2 down to $1.7 \cdot 10^{-4}$.



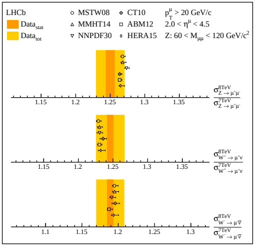
Inclusive Z Production at Run I



- Down to $x \approx 1.7 \cdot 10^{-4}$
- $2 < \eta_\mu < 4.5$
- $p_{T,\mu} > 20\,\mathrm{GeV}$
- $60 < m_{\mu\mu} < 120\,\mathrm{GeV}$
- Large statistics available

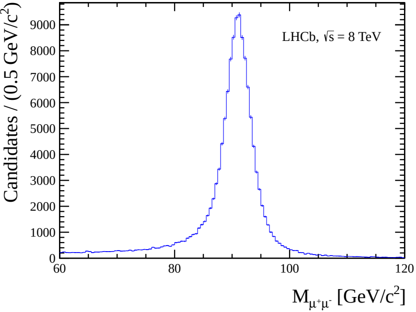
$$\sigma^{7\,\mathrm{TeV}}_{Z\to\mu\mu} = 76.0 \pm \underset{stat}{0.3} \pm \underset{sys}{0.5} \pm \underset{beam\ energy}{1.0} \pm \underset{lumi}{1.3}\,\mathrm{pb}$$

$$\sigma^{8\,\mathrm{TeV}}_{Z\to\mu\mu} = 95.0 \pm \underset{stat}{0.3} \pm \underset{sys}{0.7} \pm \underset{beam\ energy}{1.1} \pm \underset{lumi}{1.1}\,\mathrm{pb}$$



$\sqrt{s} = 7$ TeV and 8 TeV JHEP 08 (2015) 039 and LHCb-PAPER-2015-049 (preliminary)

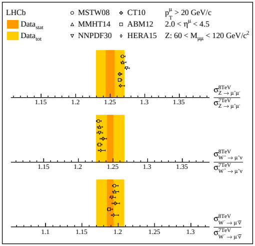
Inclusive Z Production at Run I



- Down to $x \approx 1.7 \cdot 10^{-4}$
- $2 < \eta_\mu < 4.5$
- $p_{T,\mu} > 20\,\mathrm{GeV}$
- $60 < m_{\mu\mu} < 120\,\mathrm{GeV}$
- Large statistics available

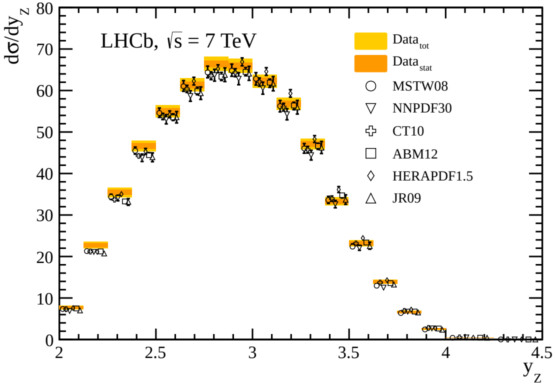
$$\sigma^{7\,\mathrm{TeV}}_{Z\to\mu\mu} = 76.0 \pm \underset{stat}{0.3} \pm \underset{sys}{0.5} \pm \underset{\text{beam energy}}{1.0} \pm \underset{lumi}{1.3}\,\mathrm{pb}$$

$$\sigma^{8\,\mathrm{TeV}}_{Z\to\mu\mu} = 95.0 \pm \underset{stat}{0.3} \pm \underset{sys}{0.7} \pm \underset{\text{beam energy}}{1.1} \pm \underset{lumi}{1.1}\,\mathrm{pb}$$



$\sqrt{s} = 7$ TeV and 8 TeV JHEP 08 (2015) 039 and LHCb-PAPER-2015-049 (preliminary)

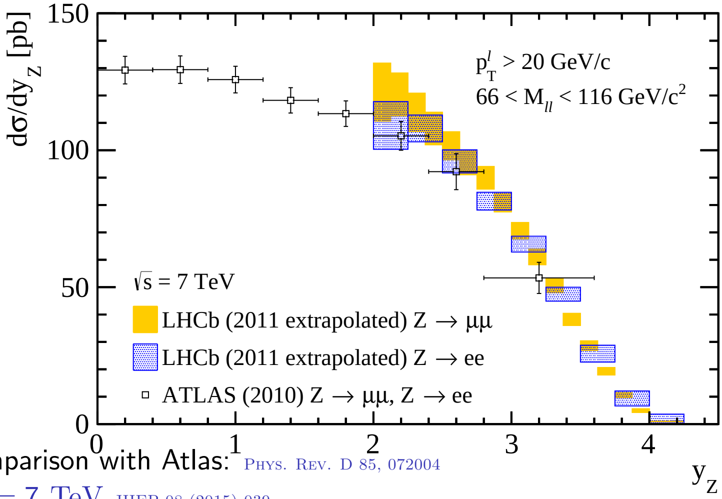
Z: Probe PDFs $x_{1,2} = \frac{me^{\pm y}}{\sqrt{s}}$



Predictions: FEWZ at NNLO Y. Li and F. Petriello, PRD 86 (2012) 094034

$\sqrt{s} = 7$ TeV JHEP 08 (2015) 039

Z: Comparison to Atlas

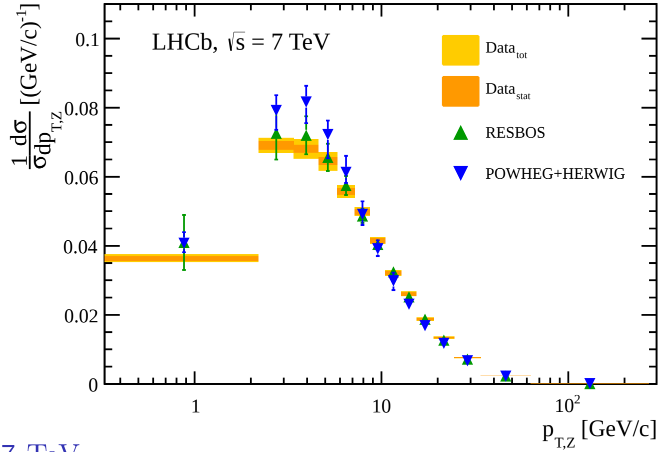


Comparison with Atlas: Phys. Rev. D 85, 072004

$\sqrt{s} = 7$ TeV JHEP 08 (2015) 039

Z: Probe pQCD with Z p_T

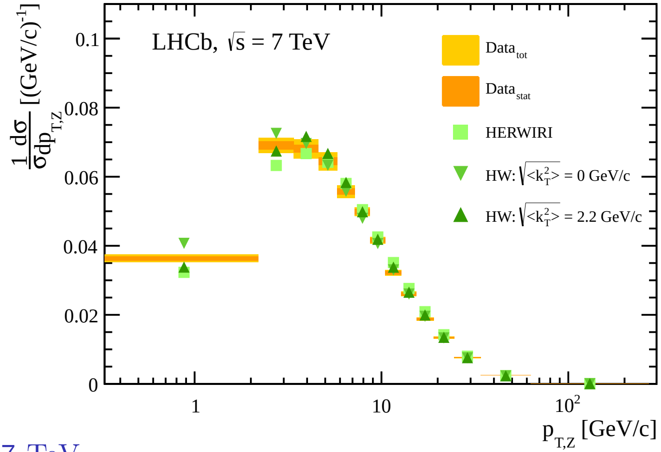
ResBos G. A. Ladinsky and C.P. Yuan PRD 50 (1994) 4239
PowHEG P. Nason, JHEP 11 (2004) 040
Herwig G. Corcella et al. JHEP 01 (2001) 010
HERWIRI S. Joseph, S. Majhi, B.F.L. Ward and S.A. Yost, PRD D 81 (2010) 076008



$\sqrt{s} = 7$ TeV JHEP 08 (2015) 039

Z: Probe pQCD with Z p_T

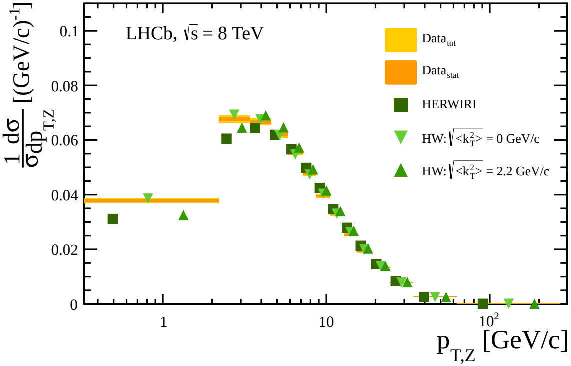
ResBos	G. A. Ladinsky and C.P. Yuan PRD 50 (1994) 4239
PowHEG	P. Nason, JHEP 11 (2004) 040
Herwig	G. Corcella et al. JHEP 01 (2001) 010
HERWIRI	S. Joseph, S. Majhi, B.F.L. Ward and S.A. Yost, PRD D 81 (2010) 076008



$\sqrt{s} = 7$ TeV JHEP 08 (2015) 039

Z: Probe pQCD with Z p_T (Preliminary)

ResBos	G. A. Ladinsky and C.P. Yuan PRD 50 (1994) 4239
PowHEG	P. Nason, JHEP 11 (2004) 040
Herwig	G. Corcella et al. JHEP 01 (2001) 010
HERWIRI	S. Joseph, S. Majhi, B.F.L. Ward and S.A. Yost, PRD D 81 (2010) 076008



$\sqrt{s} = 8$ TeV LHCb-PAPER-2015-049 (preliminary) to be submitted to JHEP

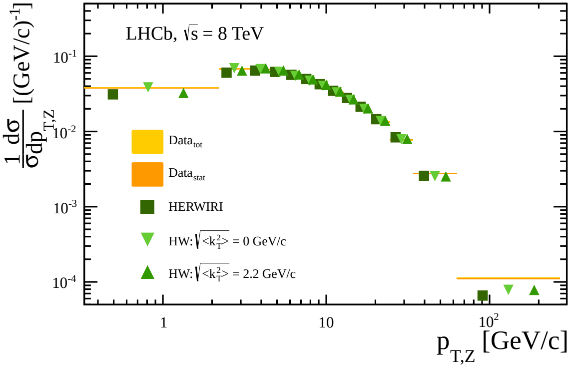
Z: Probe pQCD with Z p_T (Preliminary)

ResBos G. A. Ladinsky and C.P. Yuan PRD 50 (1994) 4239

PowHEG P. Nason, JHEP 11 (2004) 040

Herwig G. Corcella et al. JHEP 01 (2001) 010

HERWIRI S. Joseph, S. Majhi, B.F.L. Ward and S.A. Yost, PRD D 81 (2010) 076008

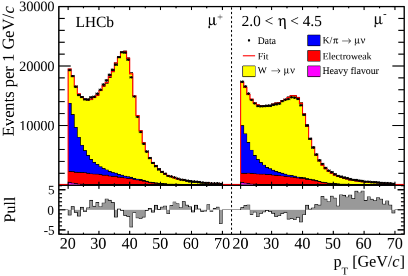


$\sqrt{s} = 8$ TeV LHCb-PAPER-2015-049 (preliminary) to be submitted to JHEP

$W^{\pm} \rightarrow \mu^{\pm}\nu$–Selection

- 2011 dataset, $975 \pm 17\ \mathrm{pb}^{-1}$ at 7 TeV
- Isolated muons prompt muons
- $20 < p_T^{\mu} < 70$ GeV
- Veto second muon in the event ($p_T > 2\,\mathrm{GeV}$)
- Impact Parameter less than 40 μm
- This leads to a purity of 77%
- Purity from fit to $p_{T,\mu^{\pm}}$

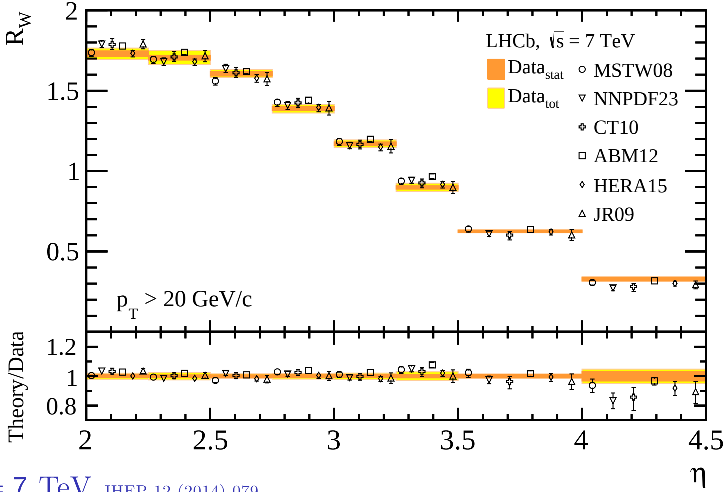
8 TeV result soon to be published



- Signal Template from Simulation (Pythia corrected to ResBos).
- $W^{\pm} \rightarrow \tau\nu$ from Pythia, normalised to W cross section.
- $Z \rightarrow \tau\ \tau$ from Pythia, normalised to Z cross section.
- $Z \rightarrow \mu^{+}\mu^{-}$ from Pythia corrected to ResBos and normalised to Z.
- $K^{\pm}, \pi^{\pm}$ decay in flight shape from data and normalisation from fit.

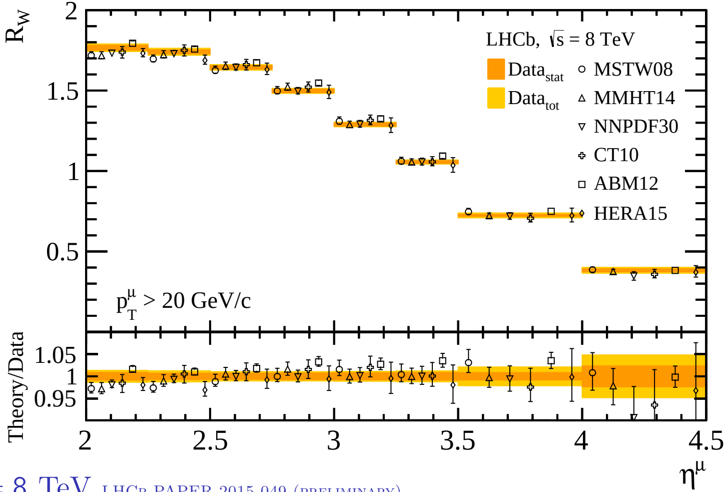
$\sqrt{s} = 7$ TeV JHEP 12 (2014) 079

Differential Cross Section Ratio



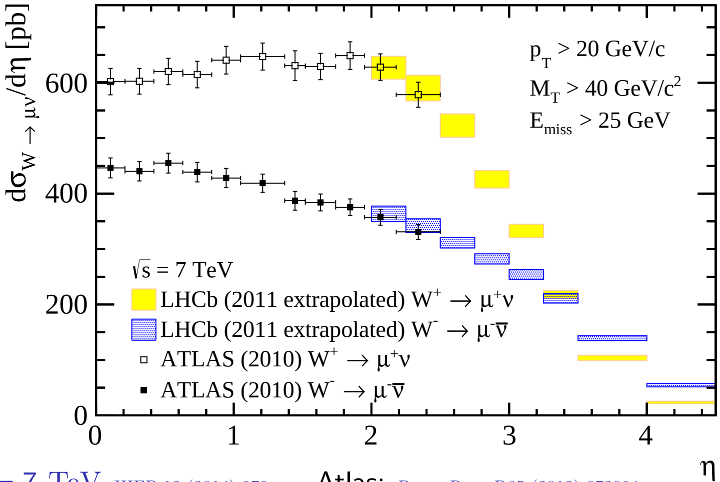
$\sqrt{s} = 7$ TeV JHEP 12 (2014) 079

Differential Cross Section Ratio



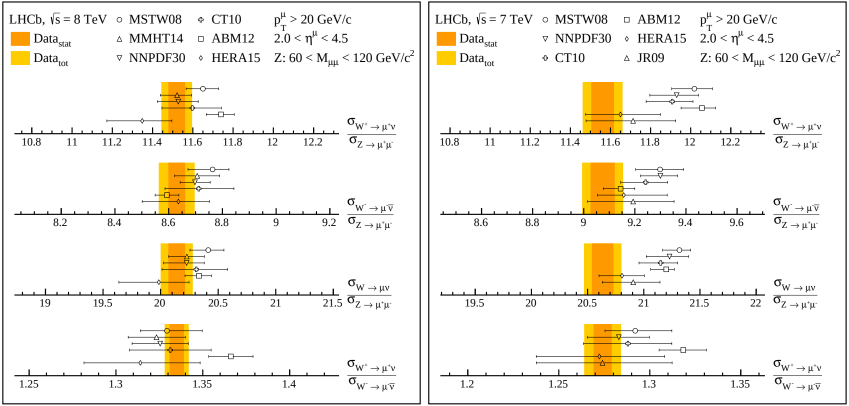
$\sqrt{s} = 8$ TeV LHCb-PAPER-2015-049 (preliminary)

Comparison to Atlas



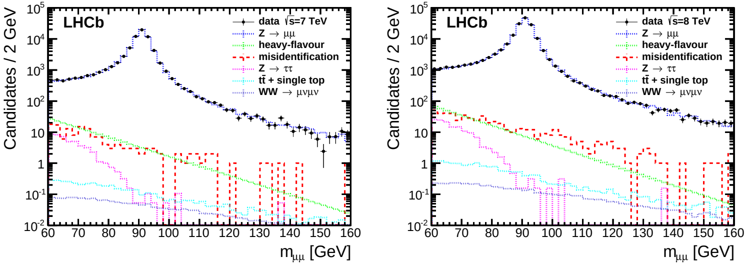
$\sqrt{s} = 7$ TeV JHEP 12 (2014) 079 Atlas: Phys. Rev. D85 (2012) 072004

$W^{\pm}Z$ Cross Section and Ratios



$\sqrt{s} = 7, 8$ TeV JHEP 12 (2014) 079 JHEP 08 (2015) 039 and LHCb-PAPER-2015-049 (preliminary)

$\sin^2\theta_W$ from A_{FB} in $Z \to \mu^+\mu^-$ Events

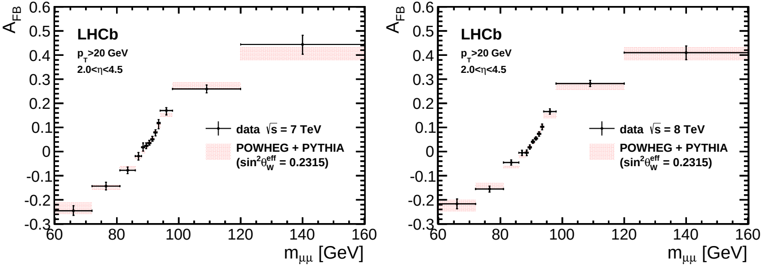


$$\frac{d\,\sigma}{d\cos\theta^*} = A(1 + cos^2\theta^*) + B\cos\theta^*$$

$\cos\theta^*$ is the polar angle of the μ^+ in the Collins Soper frame

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV arχiv:1509.07645 Submitted to JHEP

$\sin^2\theta_W$ from A_{FB} in $Z \to \mu^+\mu^-$ Events

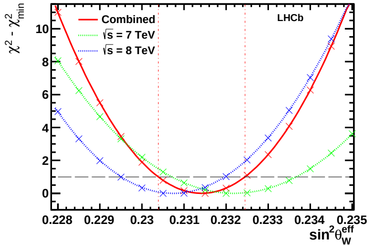


B depends on the forward backward asymmetry A_{FB}

$$A_{FB} = \frac{N_{\text{forward}} - N_{\text{backward}}}{N_{\text{forward}} - N_{\text{backward}}}$$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV arχiv:1509.07645 Submitted to JHEP

$\sin^2\theta_W$ FROM A_{FB} IN $Z \to \mu^+\mu^-$ EVENTS

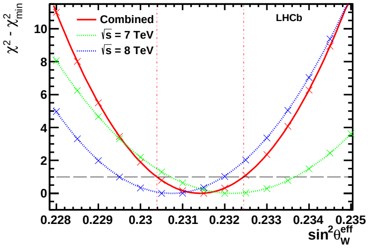


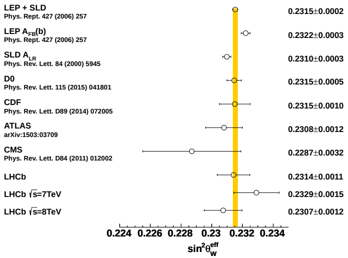
Do a χ^2 test on a scan of possible values for $\sin^2\theta_W$

$$\sin^2_{\text{eff}} = 0.23142 \underset{stat}{\pm} 0.00073 \underset{systematic}{\pm} 0.00052 \underset{theory}{\pm} 0.00056$$

$\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV ARχIV:1509.07645 SUBMITTED TO JHEP

$\sin^2\theta_W$ from A_{FB} in $Z \to \mu^+\mu^-$ Events





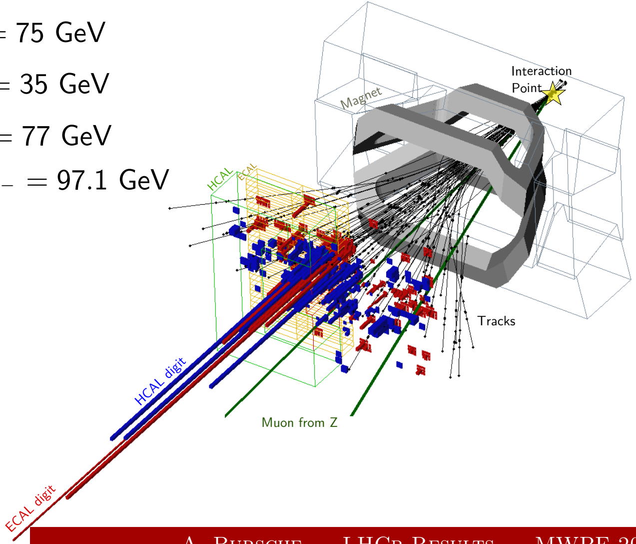
Do a χ^2 test on a scan of possible values for $\sin^2\theta_W$

$$\sin^2_{\text{eff}} = 0.23142 \underset{stat}{\pm} 0.00073 \underset{systematic}{\pm} 0.00052 \underset{theory}{\pm} 0.00056$$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV arXiv:1509.07645 Submitted to JHEP

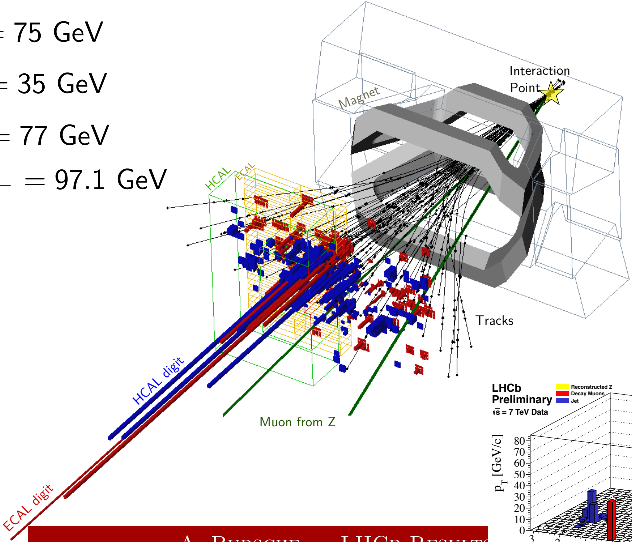
$Z^0 \to \mu\mu$ plus Jet Event

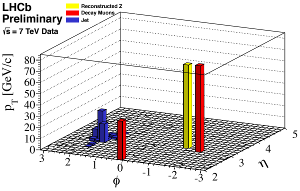
- $p_T^{\text{jet}} = 75$ GeV
- $p_T^{\mu^+} = 35$ GeV
- $p_T^{\mu^-} = 77$ GeV
- $m_{\mu^+\mu^-} = 97.1$ GeV



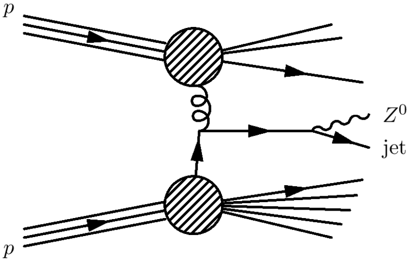
$Z^0 \to \mu\mu$ plus Jet Event

- $p_T^{\text{jet}} = 75$ GeV
- $p_T^{\mu^+} = 35$ GeV
- $p_T^{\mu^-} = 77$ GeV
- $m_{\mu^+\mu^-} = 97.1$ GeV





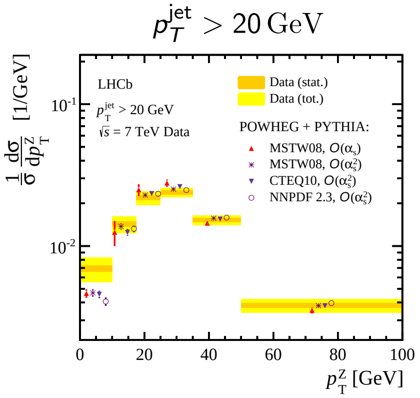
Z plus Jets at $\sqrt{s} = 7$ TeV

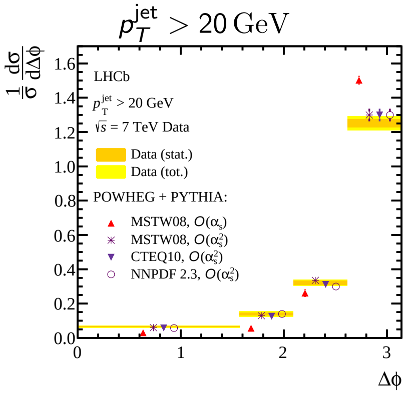


- Measurements only in $Z \to \mu\mu$ final state
- Anti–k_T jets with R=0.5 from tracks and neutral clusters
- Two momentum thresholds considered ($p_t > 10\,\mathrm{GeV}, 20\,\mathrm{GeV}$)
- $2 < \eta^{\mathrm{Jet}} < 4.5$
- $\Delta R_{\mathrm{jet},\mu} > 0.4$
- Largest uncertainty from JES

$\sqrt{s} = 7$ TeV JHEP 01 (2014) 033

Z +JETS: Z p_T AND $\Delta\Phi$

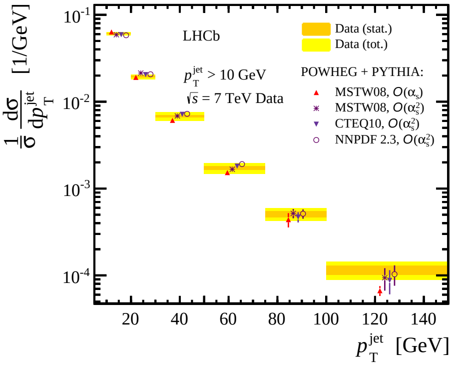




This is also measured for the $p_T > 10$ GeV threshold.

$\sqrt{s} = 7$ TeV JHEP 01 (2014) 033

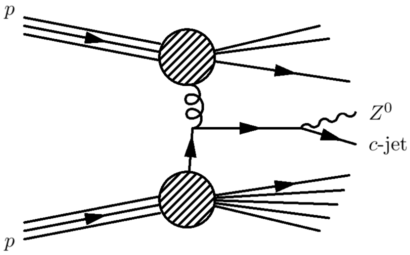
Z +JETS: JET p_T



- Compared to POWHEG
- Parton Shower with PYTHIA

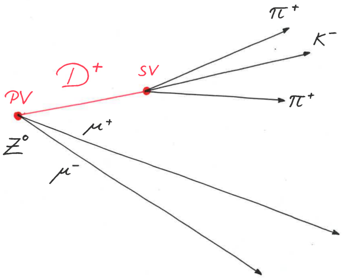
$\sqrt{s} = 7$ TeV JHEP 01 (2014) 033

Z plus D



$\sqrt{s} = 7$ TeV JHEP 04 (2014) 091

Z plus D



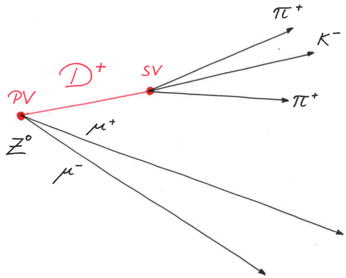
- Z from PV with zero lifetime
- D from secondary vertex but associated to the same PV as the Z

Overview

- $Z \to \mu^+\mu^-$ as before
- $2 < p_{T,D} < 12\,\mathrm{GeV}$
- $D^0 \to K^-\pi^+$ $(3.89 \pm 0.05\%)$
- $D^+ \to K^-\pi^+\pi^+$ $(9.22 \pm 0.21\%)$

$\sqrt{s} = 7$ TeV JHEP 04 (2014) 091

Z plus D



- Z from PV with zero lifetime
- D from secondary vertex but associated to the same PV as the Z

Overview

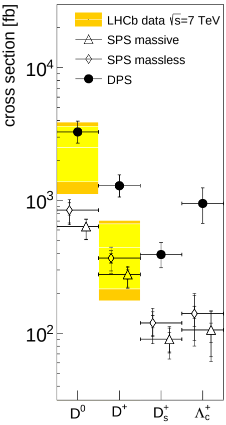
- $Z \to \mu^+\mu^-$ as before
- $2 < p_{T,D} < 12\,\mathrm{GeV}$
- $D^0 \to K^-\pi^+$ $(3.89 \pm 0.05\%)$
- $D^+ \to K^-\pi^+\pi^+$ $(9.22 \pm 0.21\%)$

Background

- Feed Down, Pile Up, Combinatorial
- Purity 95%

$\sqrt{s} = 7$ TeV JHEP 04 (2014) 091

Results

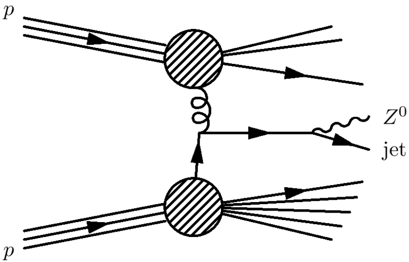


- $\sigma_{Z\to\mu^+\mu^-,D^0}\mathcal{B}_{Z\to\mu^+\mu^-} = 2.50 \pm 1.12 \pm 0.22\,\mathrm{pb}$
- $\sigma_{Z\to\mu^+\mu^-,D^+}\mathcal{B}_{Z\to\mu^+\mu^-} = 0.44 \pm 0.23 \pm 0.03\,\mathrm{pb}$
- Comparison to SPS and DPS predictions
- The measured cross-section is expected to be composed of both DPS and SPS

LHCb has measured associated production of D^0 with D^0, $D^\pm$, J/ψ and Υ with more conclusive results on DPS.

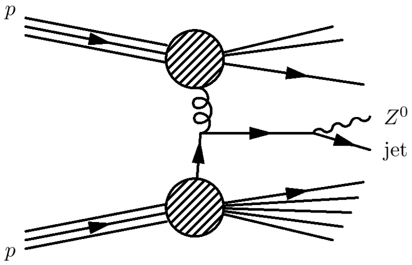
$\sqrt{s} = 7$ TeV JHEP 04 (2014) 091

Z PLUS b-JETS



$\sqrt{s} = 7$ TeV

Z PLUS b-JETS

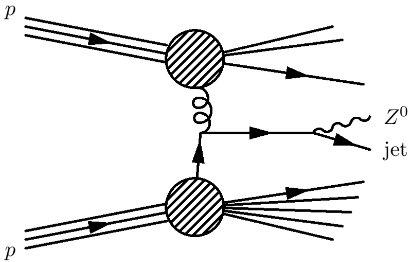


Overview

- $Z \rightarrow \mu^+\mu^-$ as before
- jets as before
- again with two p_T thresholds
- add b-tag from secondary vertex to leading jet

$\sqrt{s} = 7$ TeV

Z PLUS b-JETS



Overview

- $Z \to \mu^+\mu^-$ as before
- jets as before
- again with two p_T thresholds
- add b-tag from secondary vertex to leading jet

BACKGROUND

- light jets
- charm jets

$\sqrt{s} = 7$ TeV

Tagging b-jets

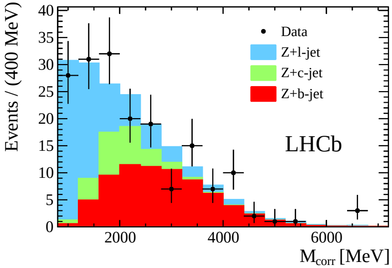
- Form secondary vertices from two, three, and four particles
- Look at corrected mass

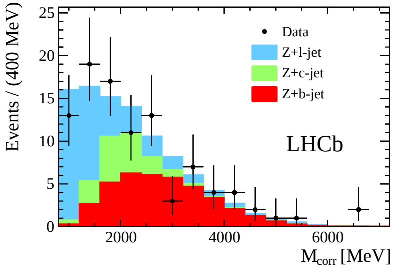
$$m_{\text{corr}} = \sqrt{m^2 + p_\perp^2} + p_\perp$$

where $p_\perp$ it measured with respect to the geometrical flight direction of the secondary vertex.

Purity Determination

Use templates from simulation for light, beauty and charm jets.

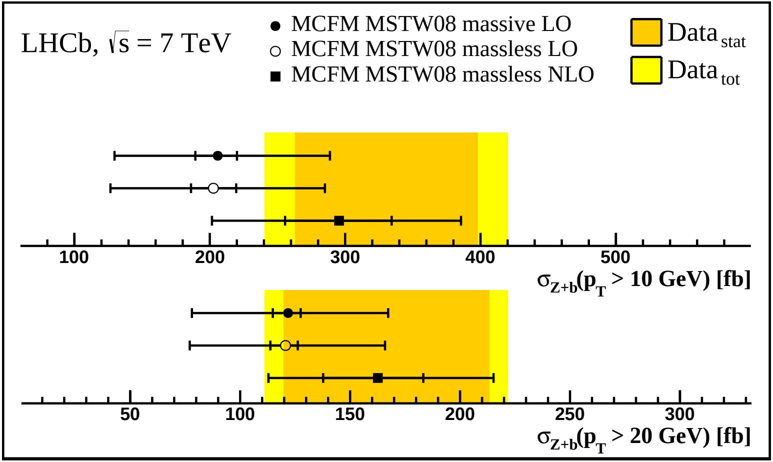




Jets thresholds of $p_T > 10$ GeV and 20 GeV.

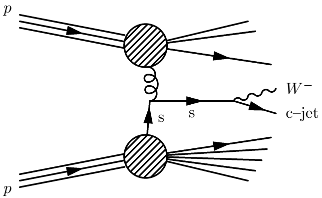
$\sqrt{s} = 7$ TeV J. High Energy Phys. 01 (2015) 064

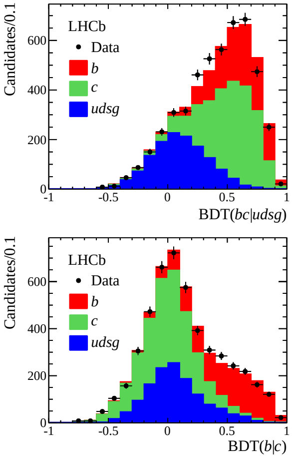
$Z + b$-jet Cross Section



$\sqrt{s} = 7$ TeV J. High Energy Phys. 01 (2015) 064

$W^\pm$ AND CHARMING BEAUTY





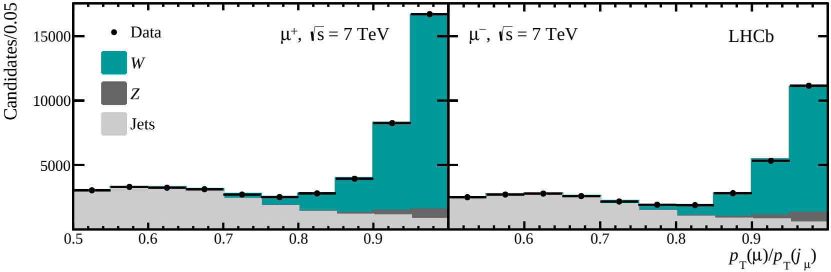
JINST 10 (2015) P06013

- Sensitive to strange PDF
- Anti-k_T jets with $R = 0.5$
- $p_{T\mu} > 20\,\text{GeV}$ $p_{T,\text{jet}} > 20\,\text{GeV}$
- Properties of SV used in two BDTs for light/heavy and beauty/charm separation

$\sqrt{s} = 7$ TeV AND $\sqrt{s} = 8$ TeV PHYS. REV. D 92 (2015) 052001

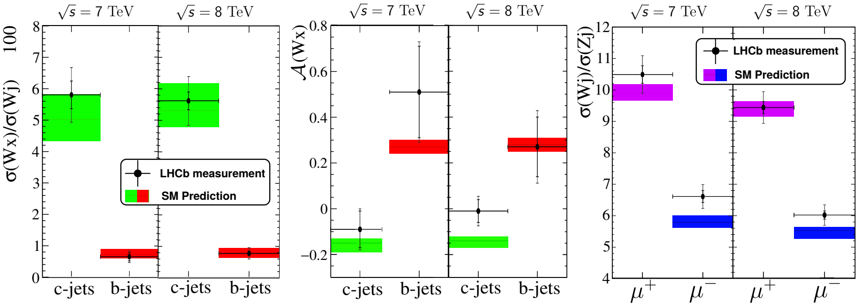
$W^{\pm}$ Purity

- These are $W^{\pm}$ + jets events so muon p_T distribution is not known
- Instead of p_{T_μ} fit obtain purity from muon isolation
- Use the muon in anti-k_T and select the jet containing the muon j_μ
- Study $\frac{p_{T,\mu}}{p_{T,j_\mu}}$
- Obtain templates from $Z \to \mu^+\mu^-$ +jets



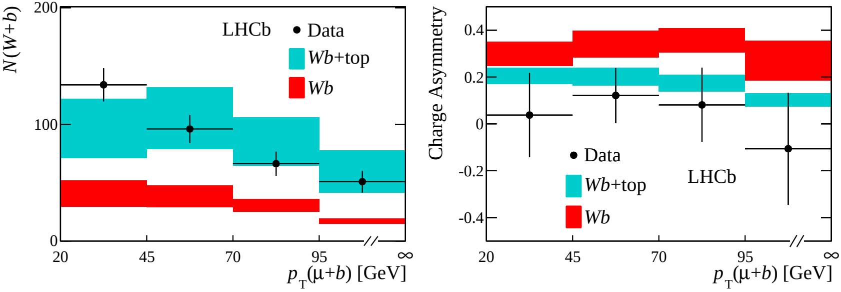
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. D 92 (2015) 052001

Result



$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. D 92 (2015) 052001

Top Quark



$$\sigma_t^{7\,\text{TeV}} = 239 \underset{stat}{\pm} 53 \underset{syst}{\pm} 33 \underset{theory}{\pm} 24\,\text{fb}$$

$$\sigma_t^{8\,\text{TeV}} = 289 \underset{stat}{\pm} 43 \underset{syst}{\pm} 40 \underset{theory}{\pm} 29\,\text{fb}$$

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV Phys. Rev. Lett. 115 (2015) 112001

Conclusion

- Some tantalising Hints in Rare Decays
- $B_s^0 \rightarrow \mu^+ \mu^-$ in agreement with Standard Model
- Tetraquark and Pentaquark States observed and measured
- Excellent Precision Measurement on Gauge Boson Production
- First Signal of Top Quarks

Conclusion

- Some tantalising Hints in Rare Decays
- $B_s^0 \to \mu^+ \mu^-$ in agreement with Standard Model
- Tetraquark and Pentaquark States observed and measured
- Excellent Precision Measurement on Gauge Boson Production
- First Signal of Top Quarks

LHCb has become a Forward Multi Purpose Detector!

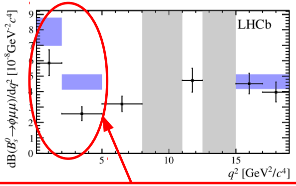
Backup

Backup - $B_s^0 \rightarrow J/\psi\ \phi$

$B_s \rightarrow \varphi\mu^+\mu^-$

JHEP 09 (2015) 179

- Full angular analysis performed
- Not self-tagging → complementarity to $K^{*0}\mu^+\mu^-$
  - Measure also differential branching fraction



SM predictions from arXiv:1411.3161, arXiv:1503.05534

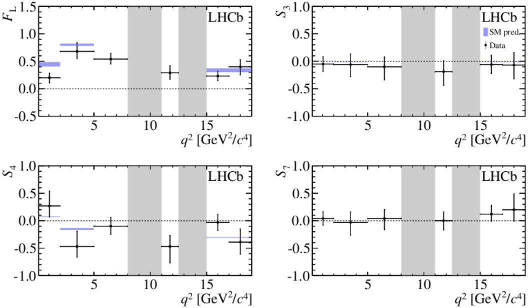
3.3σ tension with SM prediction – consistent picture in $b \rightarrow sl^+l^-$ branching fractions

Backup - $B_s^0 \to J/\psi\ \phi$

SM predictions from arXiv:1411.3161, arXiv:1503.05534

$B_s \to \varphi\mu^+\mu^-$

JHEP 09 (2015) 179



All angular observables consistent with SM

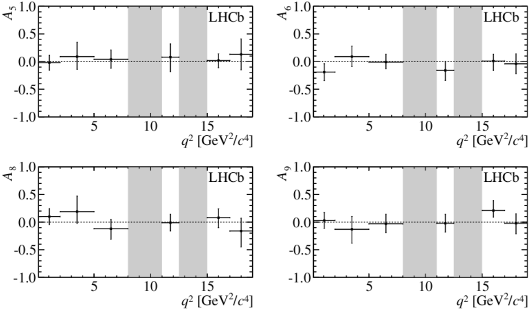
Tim Gershon
Highlights and prospects

25

Backup - $B_s^0 \to J/\psi\ \phi$

$B_s \to \phi\mu^+\mu^-$

JHEP 09 (2015) 179



All angular asymmetries consistent with SM

Tim Gershon
Highlights and prospects

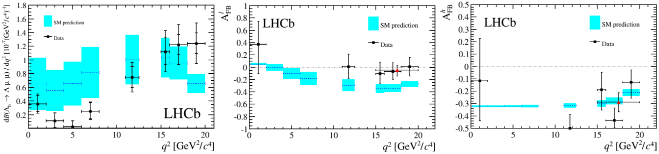
26

Backup - $\Lambda_b^0 \to \Lambda \mu^+ \mu^-$

$\Lambda_b \to \Lambda \mu^+ \mu^-$

SM predictions from
arXiv:1212.4827

JHEP 06 (2015) 115



Similar tension with SM prediction for branching fraction at low q^2
Statistics still low for angular analysis
Baryonic system provides sensitivity to additional observables