

Electroweak physics in the forward direction at the LHC

Pieter David
on behalf of the LHCb collaboration

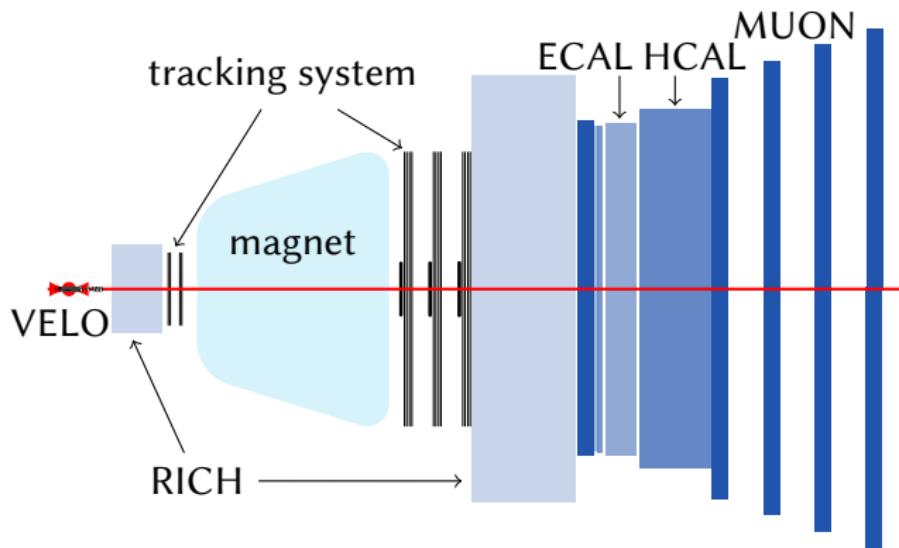
La Thuile 2015



LHCb: a general-purpose detector in the forward direction

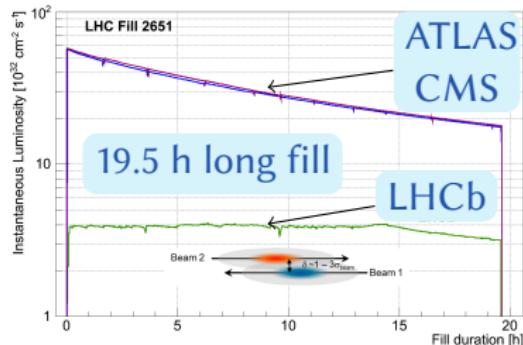
JINST3(2008)S08005;

arXiv:1412.6352 to appear in Int. J. Mod. Phys. A



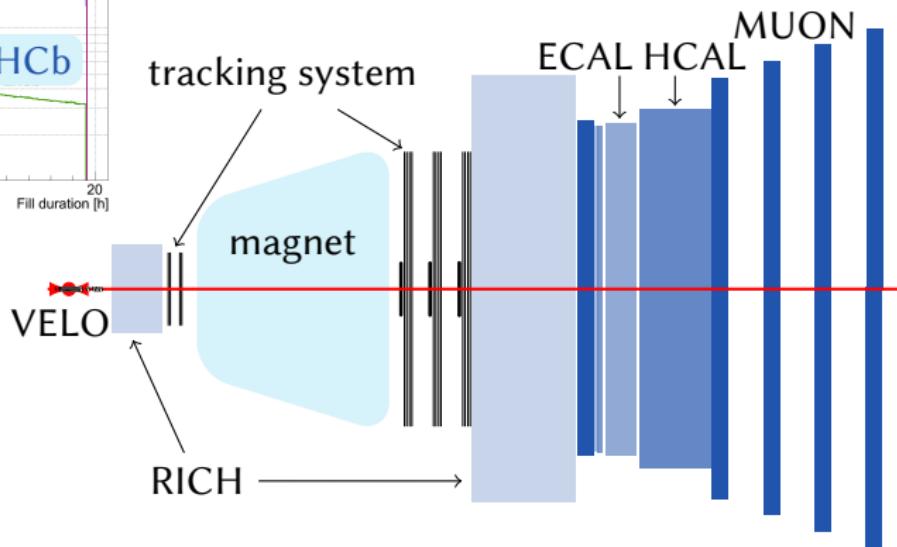
$$2 < \eta < 5$$

LHCb: a general-purpose detector in the forward direction



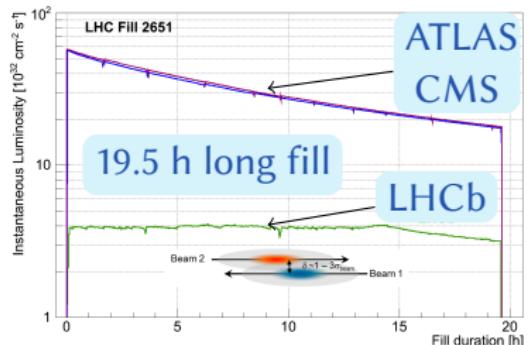
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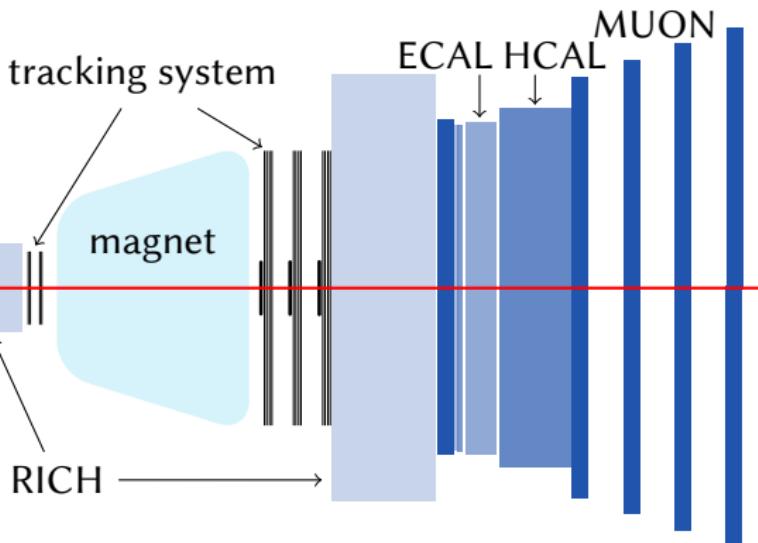
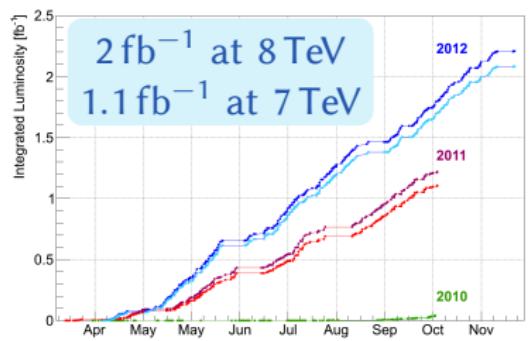


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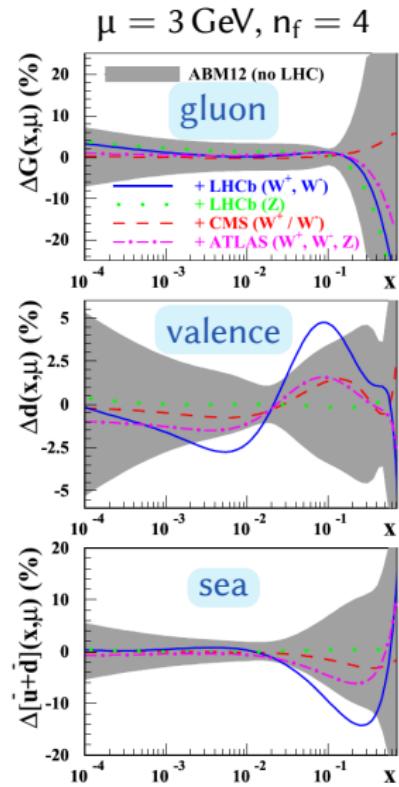
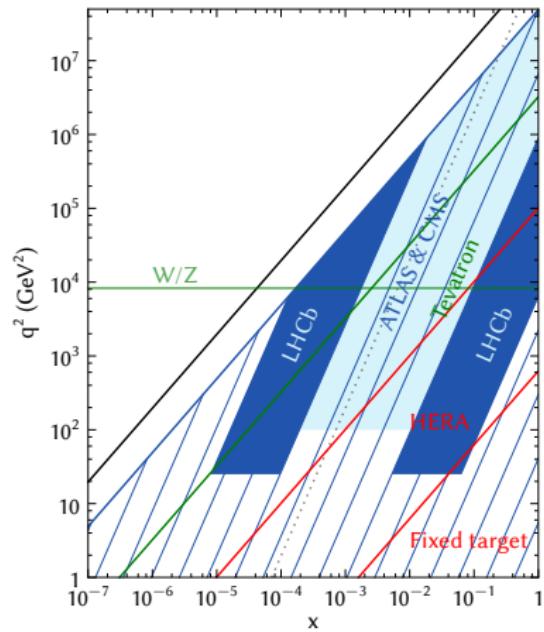
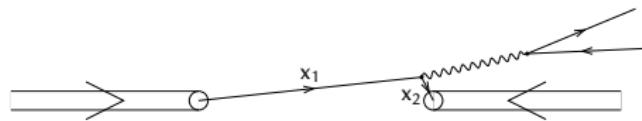
LHCb: a general-purpose detector in the forward direction



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Unique sensitivity to parton distribution functions



PhysRevD89(2014)054028

Outline

① Vector boson production

- ▶ $W^\pm \rightarrow \mu^\pm v$ at 7 TeV
- ▶ $Z \rightarrow e^+ e^-$ at 8 TeV
- ▶ $Z + \text{jet}$ at 7 TeV
- ▶ $Z + b\text{-jet}$ at 7 TeV

② Exotic results

- ▶ Search for long-lived particles decaying to jet pairs

③ Exclusive production

- ▶ Exclusive J/ψ and $\psi(2S)$ production at 7 TeV
- ▶ Observation of exclusive charmonium pair production

Measurement of W boson production at 7 TeV

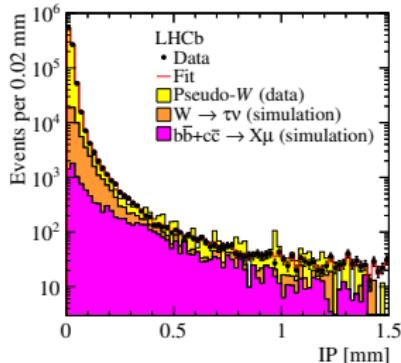
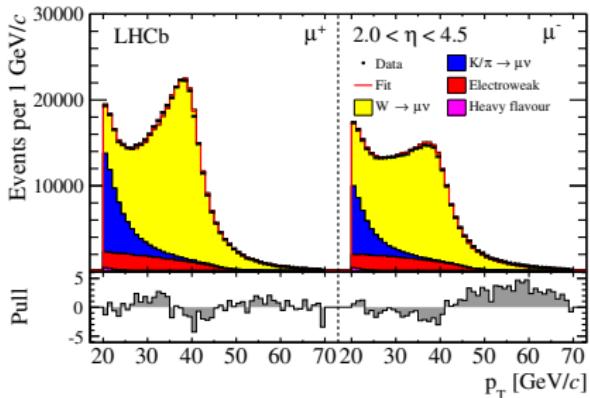
JHEP12(2014)079

$$p_{T,\mu^\pm} > 20 \text{ GeV}/c \quad 2 < \eta_{\mu^\pm} < 4.5$$

Template fit to muon p_T distribution:

- $W \rightarrow \mu\nu$: ResBos-weighted PYTHIA
- **decays in flight**: shape from data
- $Z \rightarrow \mu^+\mu^-$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau^+\tau^-$: MC, yield from $Z \rightarrow \mu^+\mu^-$ data
- **$b\bar{b}$, $c\bar{c}$** : MC, yield from template fit to IP distribution
- K, π punchthrough: negligible after $E_{\text{calo}}/pc < 4\%$

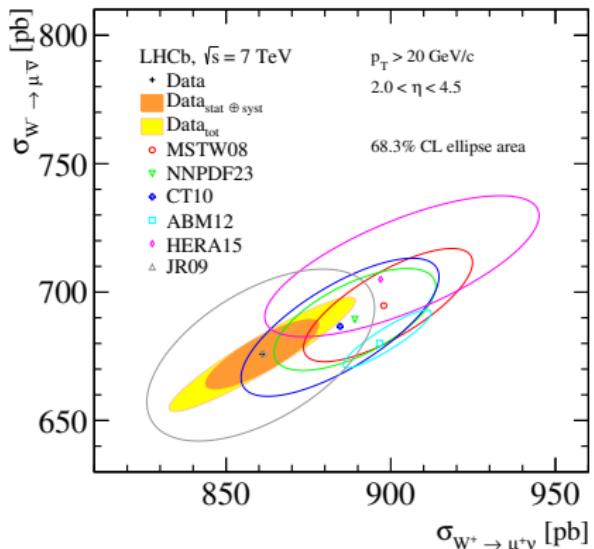
Data-driven efficiencies from
 $Z \rightarrow \mu^+\mu^-$ tag and probe



Measurement of W boson production at 7 TeV

JHEP12(2014)079

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NNLO calculations with FEWZ

MSTW08 EurPhysJC63(2009)189

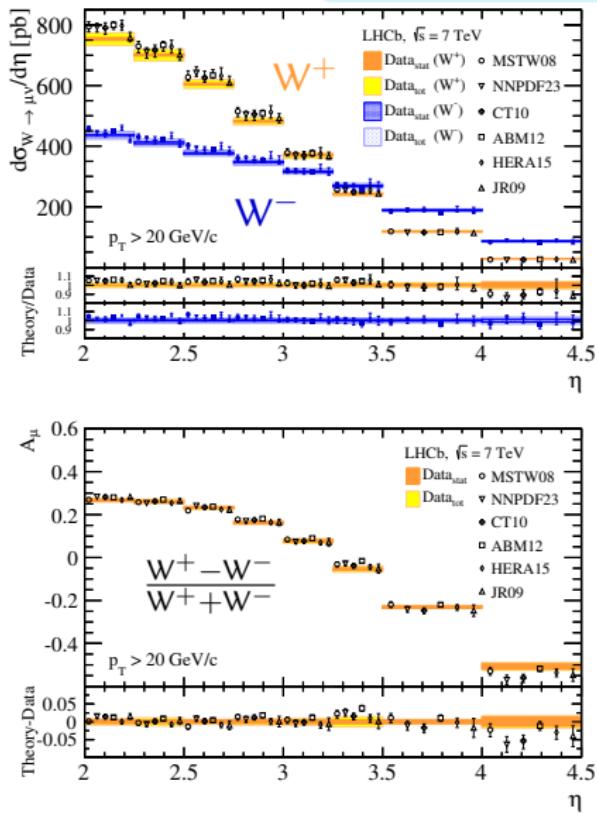
ABM12 PhysRevD89(2014)054028

NNPDF23 NuclPhysB867(2013)244

HERA15 PoSEPS-HEP2011(2011)320

CT10 PhysRevD89(2014)033009

JR09 PhysRevD79(2009)074023



Measurement of $Z \rightarrow e^+e^-$ production at $\sqrt{s} = 8 \text{ TeV}$

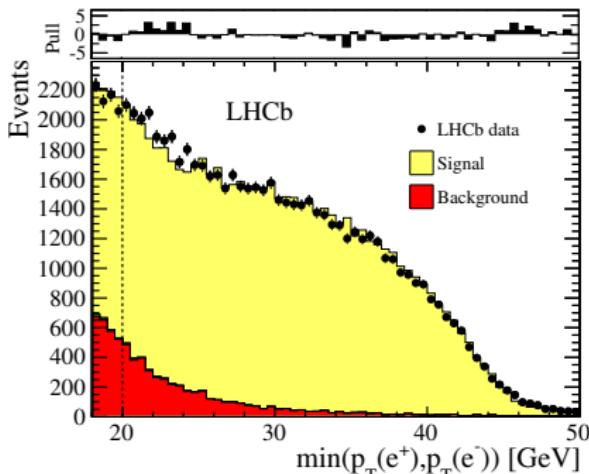
arXiv:1503.00963 submitted to JHEP

$$p_{T,e^\pm} > 20 \text{ GeV}/c \quad 2 < \eta_{e^\pm} < 4.5$$
$$60 < m(e^+e^-) < 120 \text{ GeV}/c^2$$

- Electron energy resolution degraded due to Bremsstrahlung (calorimeter saturation for $E_T \gtrsim 10 \text{ GeV}/\text{channel}$)
- σ measured in bins of rapidity and

$$\phi^* = \frac{\tan((\pi - |\Delta\phi|)/2)}{\cosh(\Delta\eta/2)} \approx \frac{p_T}{M}$$

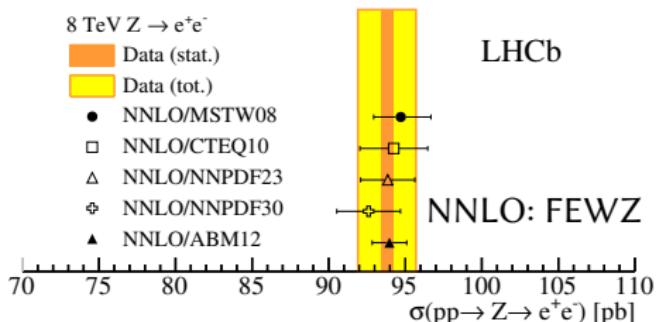
- background from mis-identified hadrons removed using same-sign data



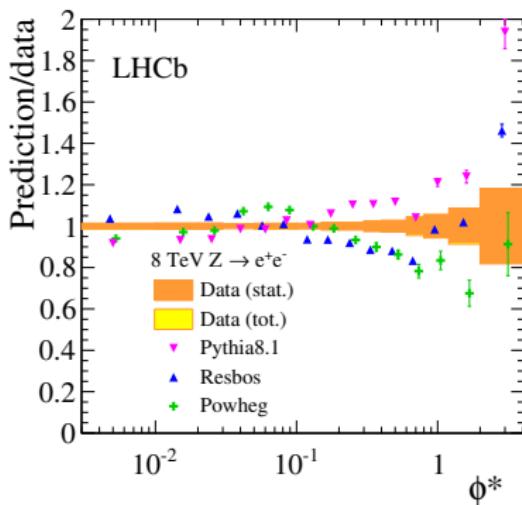
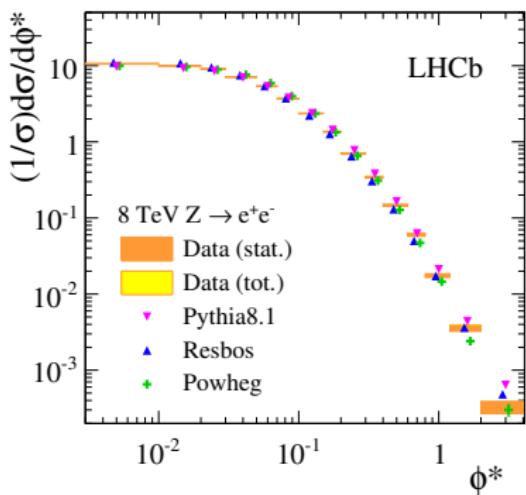
- $Z \rightarrow \tau^+\tau^-$ background from simulation
- negligible contribution from heavy flavour, EW and $t\bar{t}$

Measurement of $Z \rightarrow e^+e^-$ production at $\sqrt{s} = 8$ TeV

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Production measurements with $\mathcal{O}(1\%)$ precision

$Z \rightarrow e^+e^-$ [arXiv:1503.00963 submitted to JHEP]

	Average value	Fractional uncertainty	
		Uncorrelated	Correlated
ϵ_{track}	0.912	0.001	0.010
ϵ_{kin}	0.507	0.002	0.006
ϵ_{PID}	0.838	0.001	0.007
ϵ_{GEC}	0.916	—	0.006
ϵ_{trig}	0.892	0.001	—
ϵ	0.319	0.002	0.016
f_{MZ}	0.969	0.001	—
Background estimation	—	—	0.004
$\int \mathcal{L} dt (\text{pb}^{-1})$	1976	—	0.0122

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[JINST9(2014)P12005], see talk by Rosen Matev later today

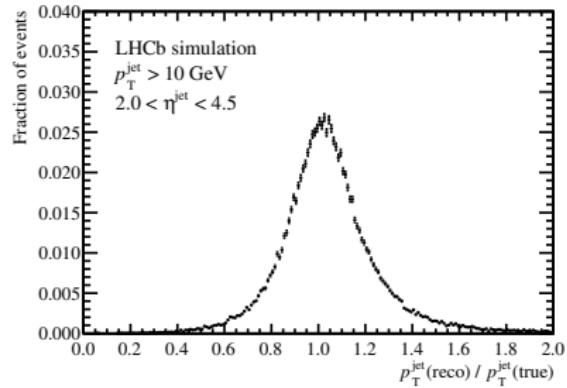
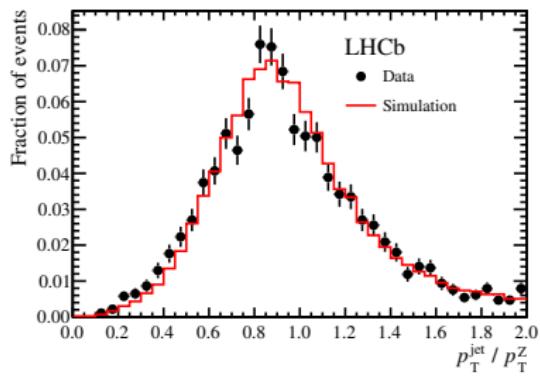
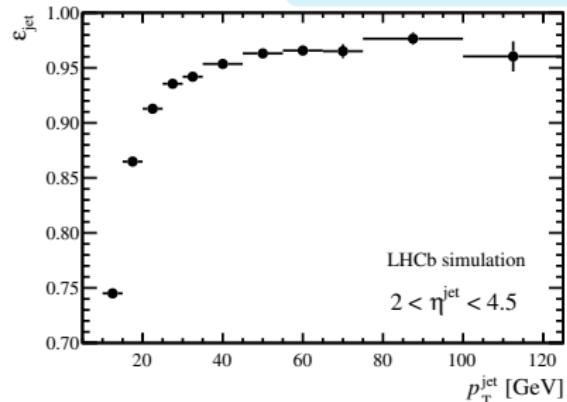
Measurement of Z + jet production at 7 TeV

$R = 0.5$ anti- k_T jets $\Delta R(\mu, \text{jet}) > 0.4$

$p_{T,\text{jet}} > 10; 20 \text{ GeV}/c$ $2 < \eta_{\text{jet}} < 4.5$

JHEP01(2014)033

- Particle Flow jet reconstruction
 - tracking for charged particles
 - calorimetry for neutral particles
 - charged energy subtracted from calorimeter deposits

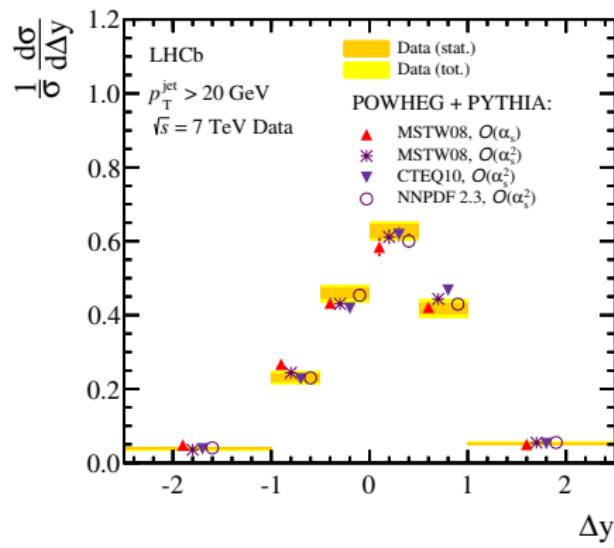
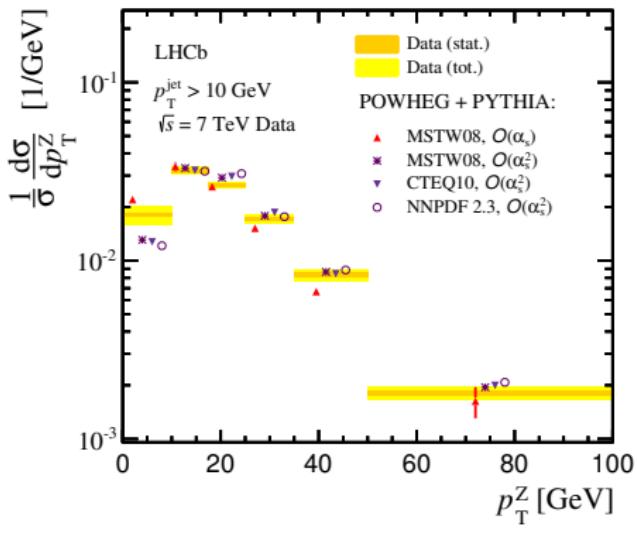


Measurement of $Z + \text{jet}$ production at 7 TeV

JHEP01(2014)033

$$R = 0.5 \text{ anti-}k_T \text{ jets} \quad \Delta R(\mu, \text{jet}) > 0.4$$

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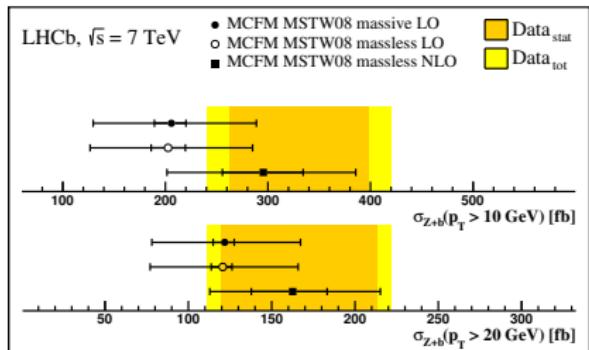
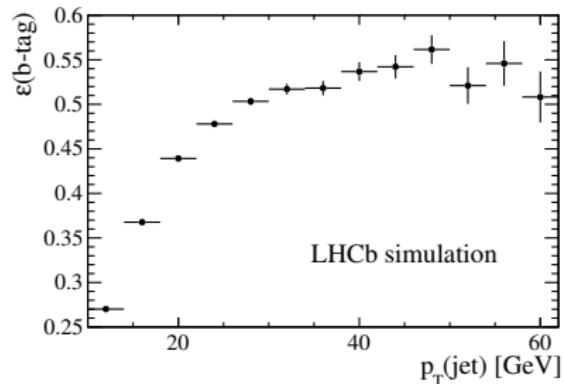
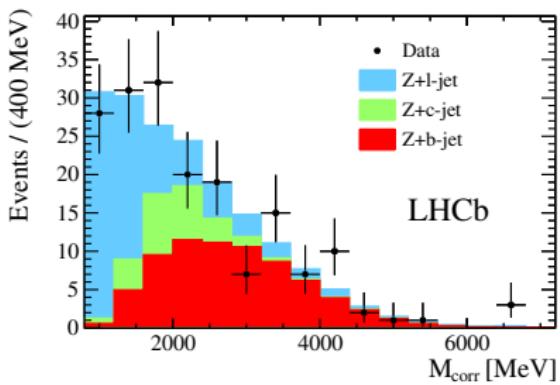
Measurement of Z + b-jet production at 7 TeV

JHEP01(2015)064

- b-tagging based on 2,3,4-track seed

$$M_{\text{corr}} = \sqrt{M^2 + p^2 \sin^2 \theta + p \sin \theta}$$

- templates from MC, cross-checked using tag and probe with $B^\pm \rightarrow J/\psi K^\pm$ and $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$

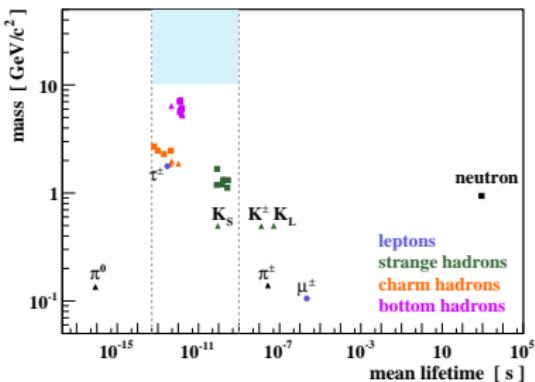


fragmentation and hadronisation correction: PYTHIA8 with MSTW08

Search for long-lived particles decaying to jet pairs

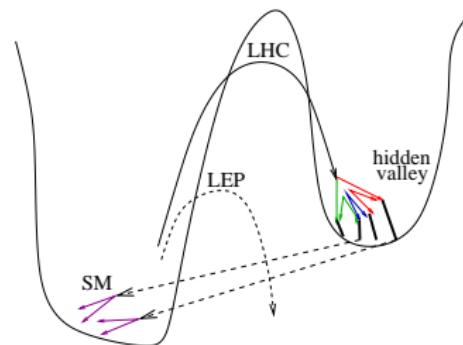
arXiv:1412.3021 to appear in Eur. Phys. J. C

- exotic long-lived particles with mass 25–50 GeV/c², lifetime 1–100 ps ($\gamma\beta c\tau \lesssim 20$ cm)
- predicted by Hidden Valley models, GMSB PhysLettB**661**(2008)263; PhysRevLett**103**(2009)241803
- benchmark signal: $H \rightarrow \pi_v \pi_v$, $\pi_v \rightarrow b\bar{b}$
- 0.62 fb⁻¹ of 7 TeV data



Analysis strategy:

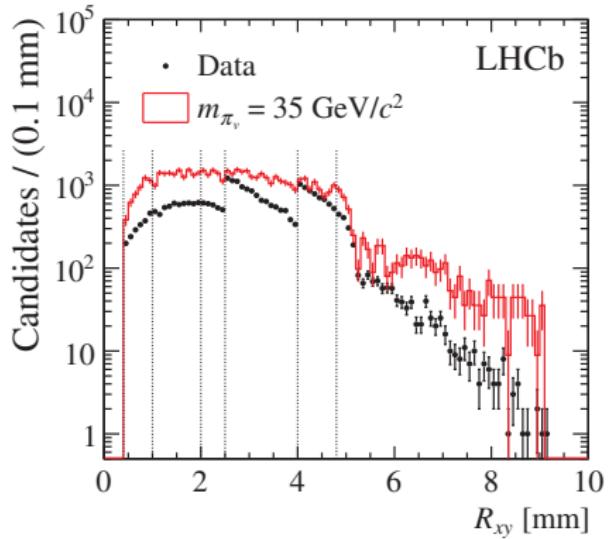
- ① Vertex finding in software trigger
- ② Particle Flow jets for mass reconstruction
- ③ Invariant mass fit in bins of transverse displacement R_{xy}



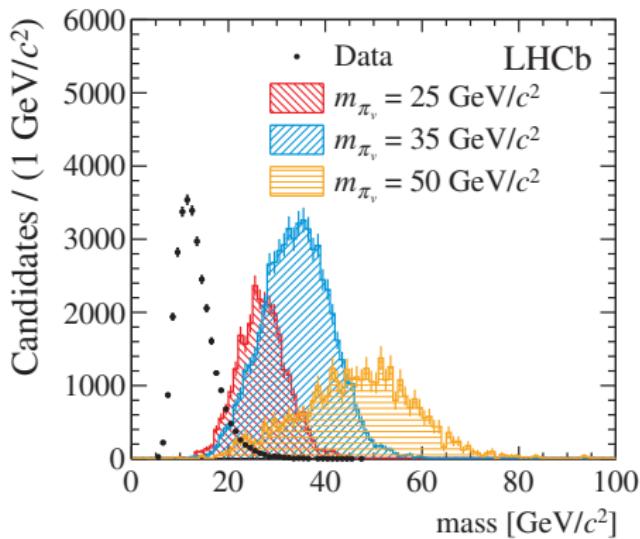
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Vertex reconstruction

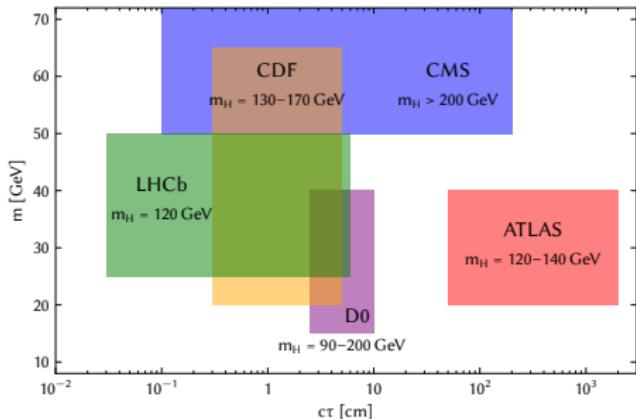
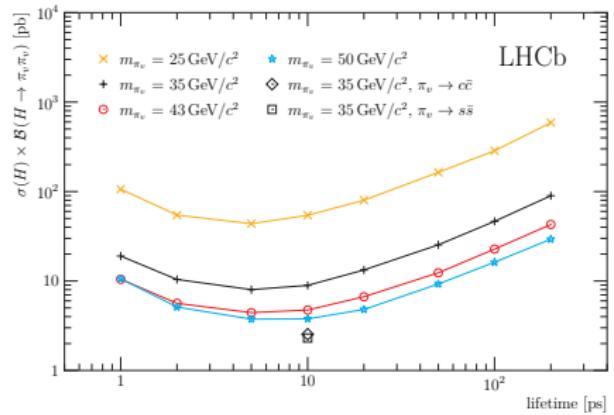


Particle Flow jets

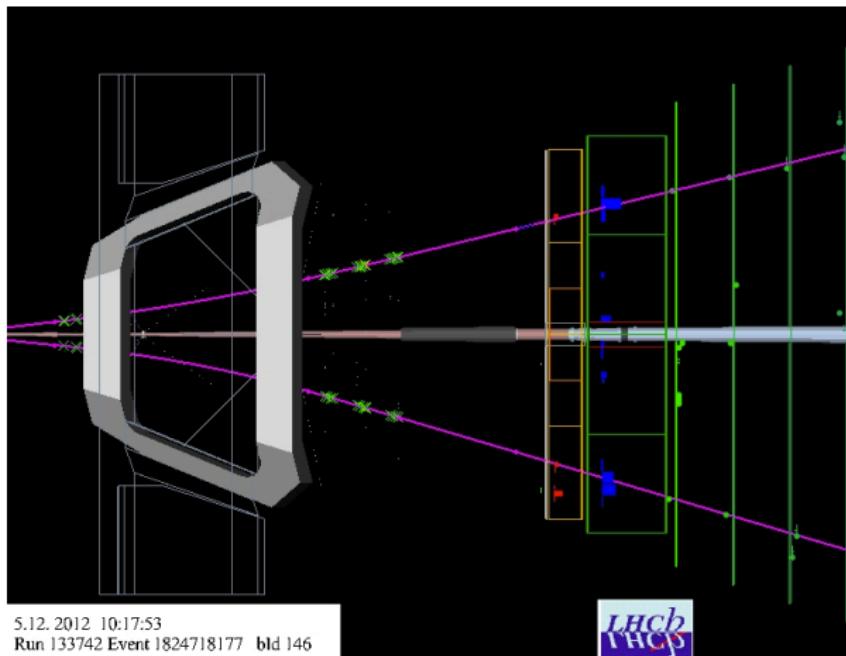
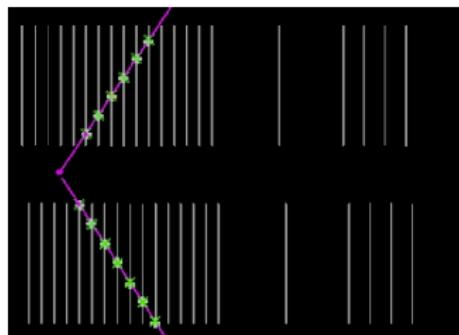
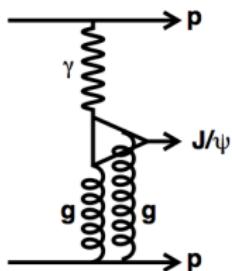


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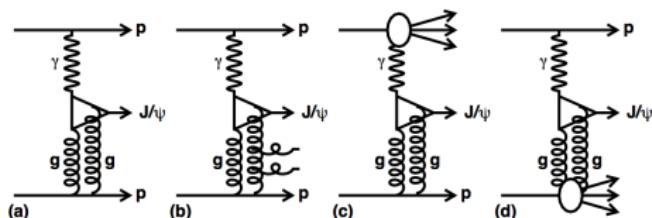


Exclusive production



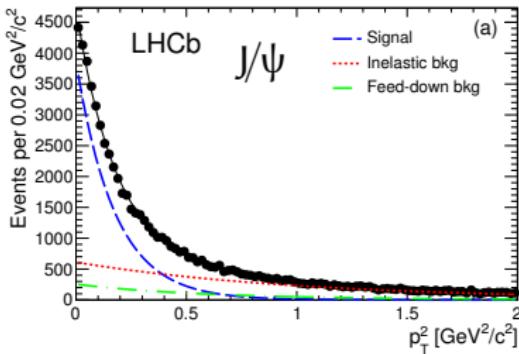
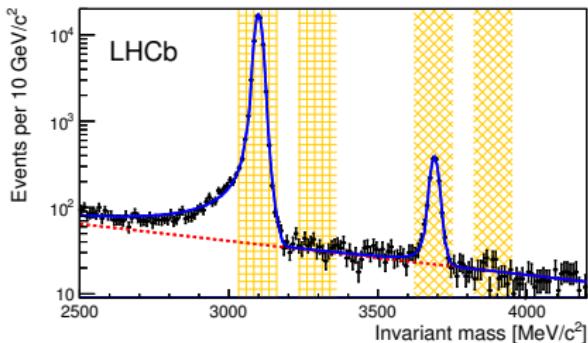
Exclusive J/ψ and $\psi(2S)$ production at 7 TeV

JPhysG41(2014)055002



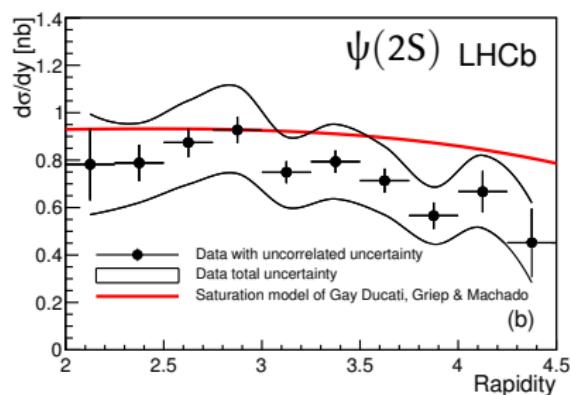
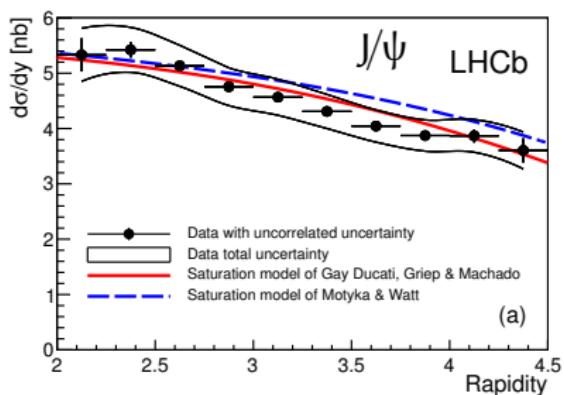
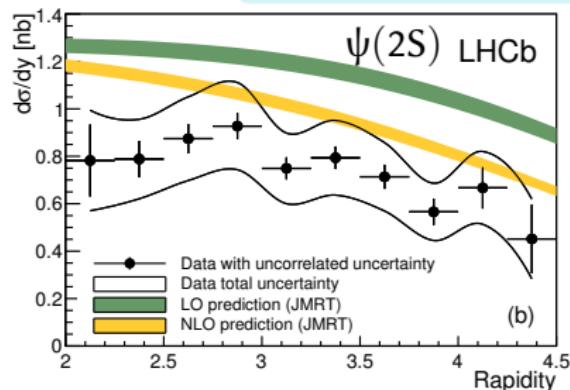
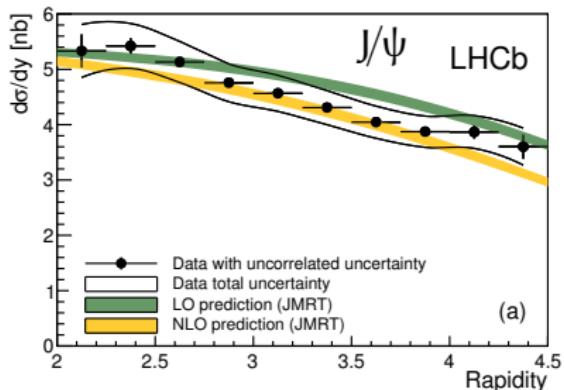
$$2.0 < \eta_{\mu^\pm} < 4.5$$

- 1/4 of events have only one primary interaction
- forward (3.5 units) and backward (1.7 ± 0.5 units) rapidity gap
- inelastic and feed-down background removed using p_T^2 fit: templates from previous measurements and Regge theory, feed-down normalised with data



Exclusive J/ψ and $\psi(2S)$ production at 7 TeV

JPhysG41(2014)055002

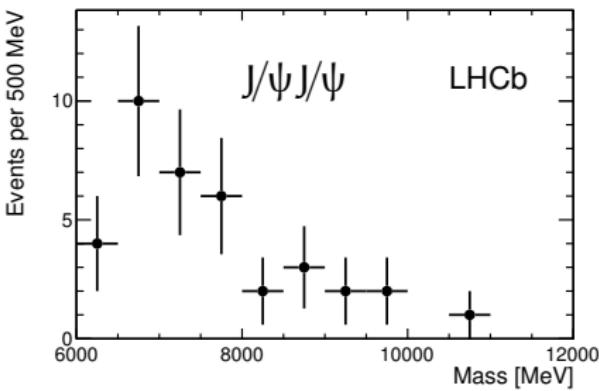
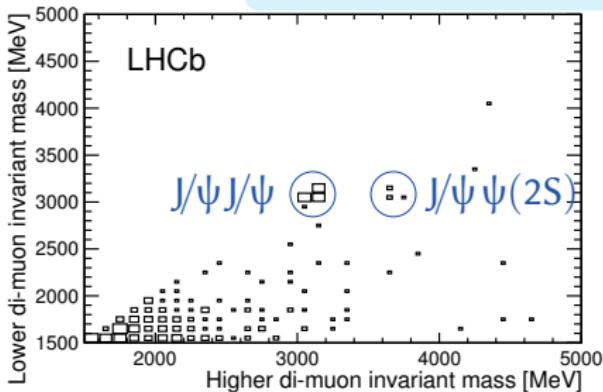
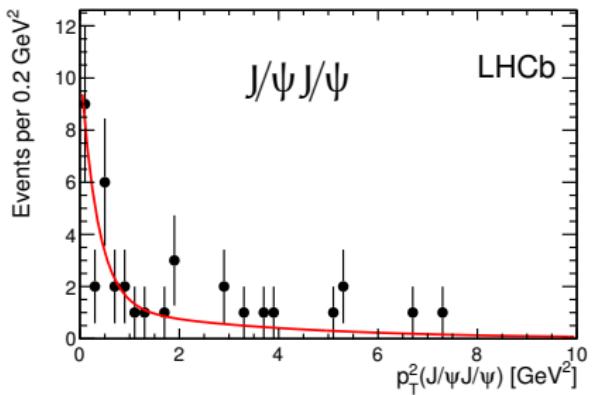


Observation of exclusive charmonium pair production

JPhysG41(2014)115002

$$2.0 < \gamma_{J/\psi J/\psi, J/\psi\psi(2S)} < 4.5$$

- Full 3 fb^{-1} Run I data set
- First observation of exclusive $J/\psi J/\psi$ and $J/\psi\psi(2S)$ production
- Elastic contribution to $J/\psi J/\psi$: $(42 \pm 13)\%$



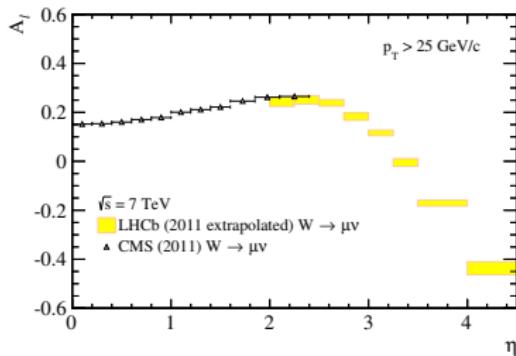
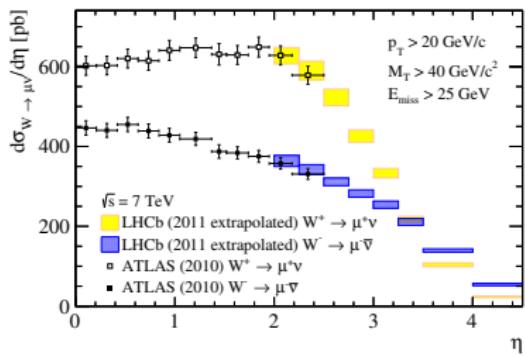
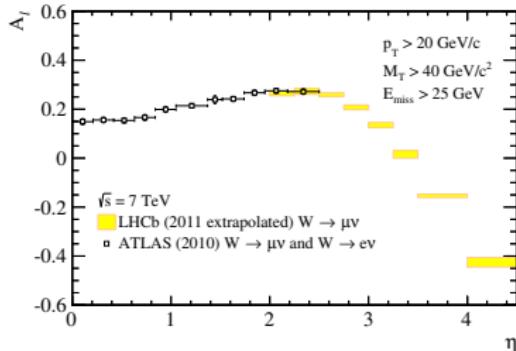
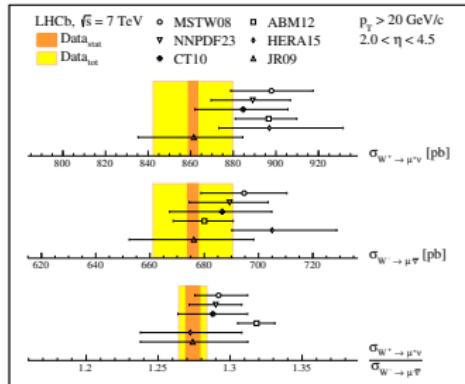
Conclusions

- LHCb covers a kinematic region complementary to central detectors
- Vector boson production measurements with $\mathcal{O}(1\%)$ precision, comparable to theory uncertainties
- Most precise luminosity measurement at the LHC
- New $Z \rightarrow e^+e^-$ results at 8 TeV
- More 7–8 TeV results coming in the next few months and then 13–14 TeV
- Forward acceptance also interesting for exotics searches
- Unique capability to study exclusive production

Additional material

Measurement of W boson production at 7 TeV

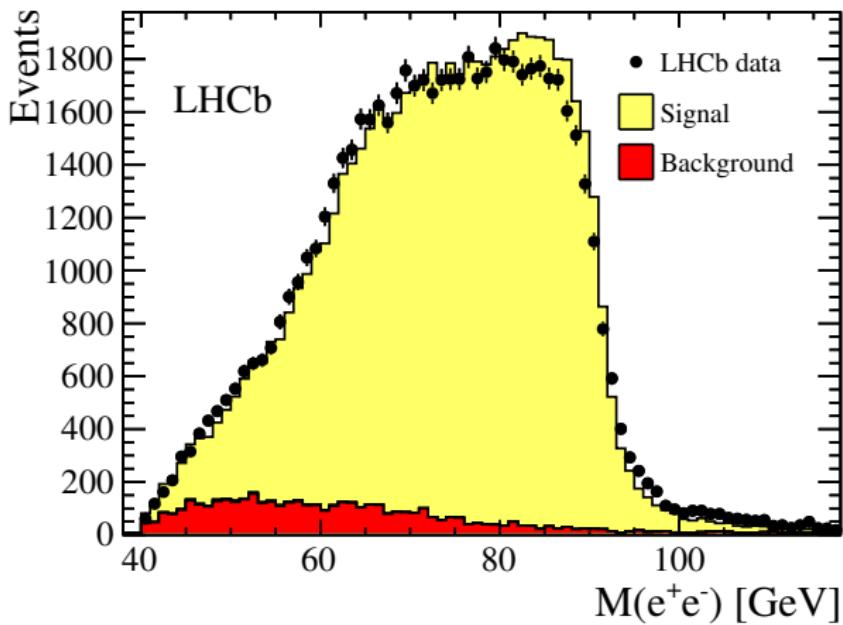
JHEP12(2014)079



ATLAS: PhysRevD85(2012)072004; CMS: PhysRevD90(2014)032004

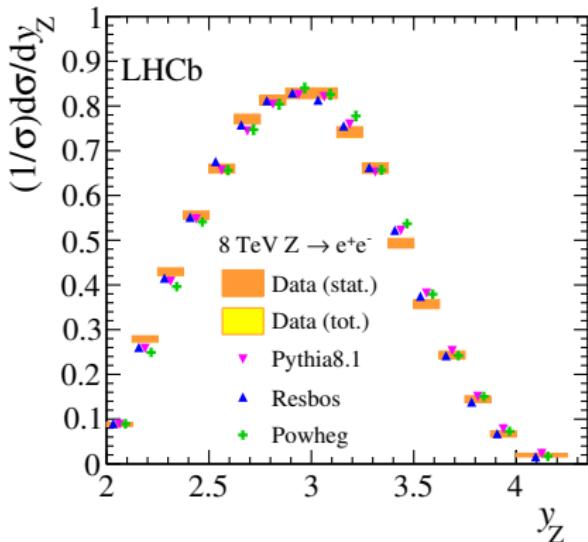
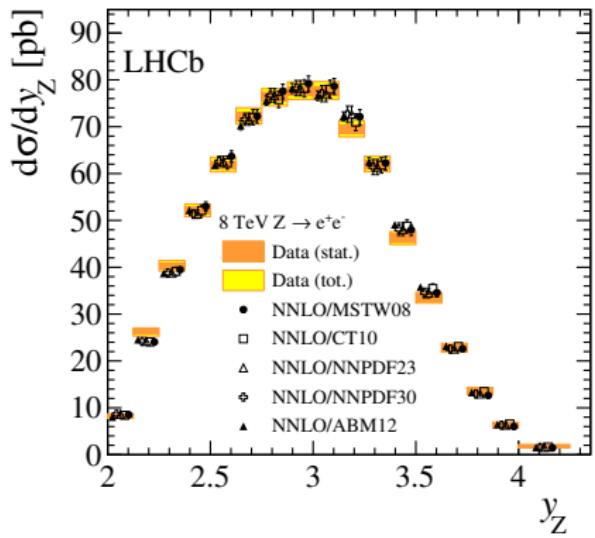
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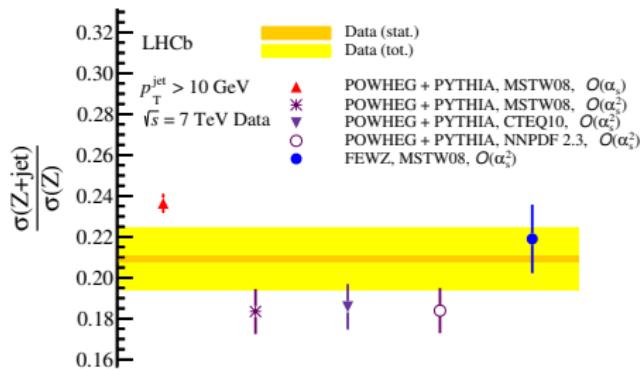
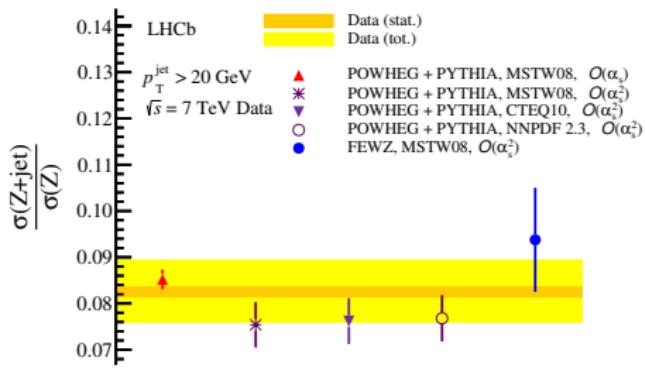
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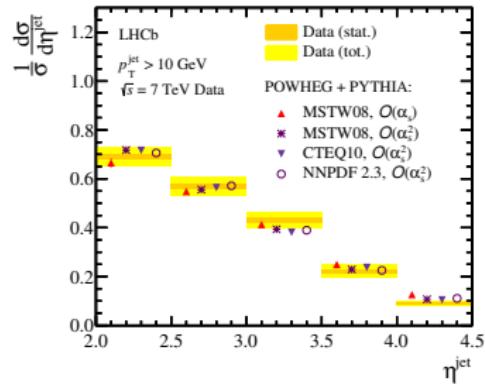
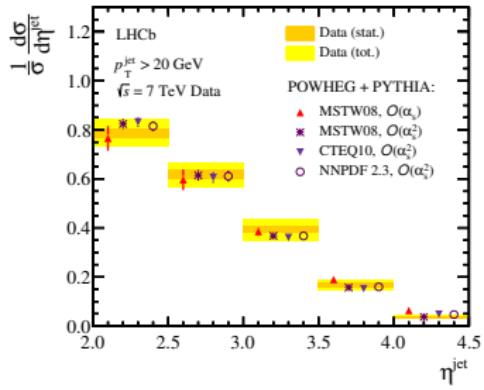
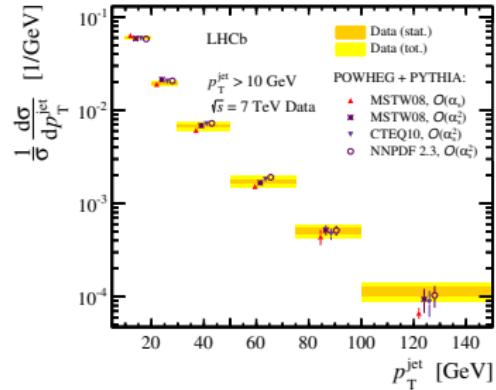
Measurement of Z + jet production at 7 TeV

JHEP01(2014)033



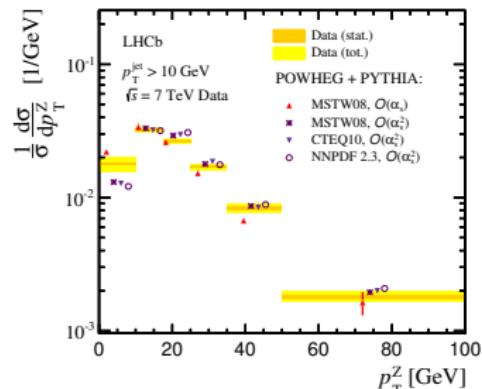
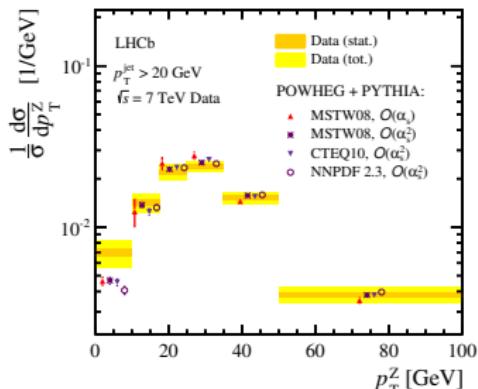
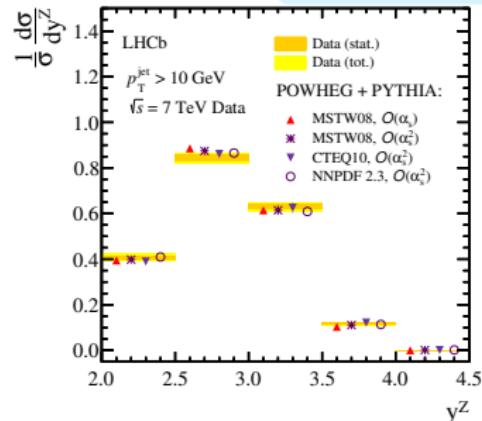
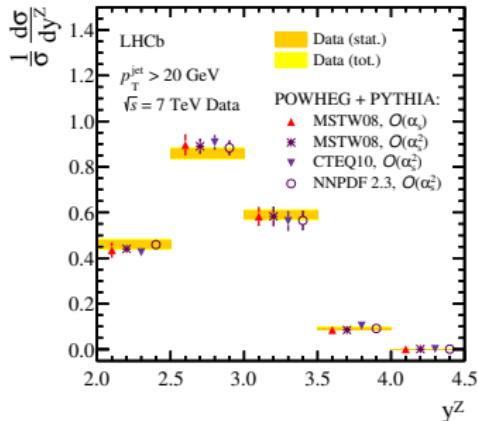
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JHEP01(2014)033



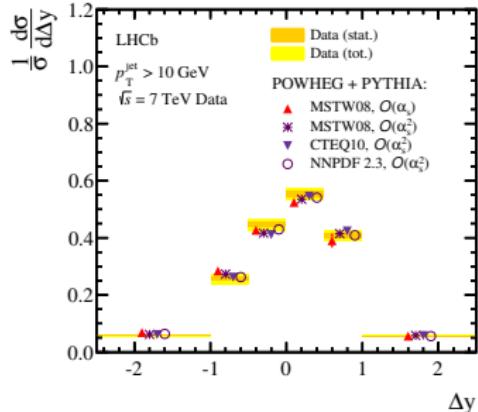
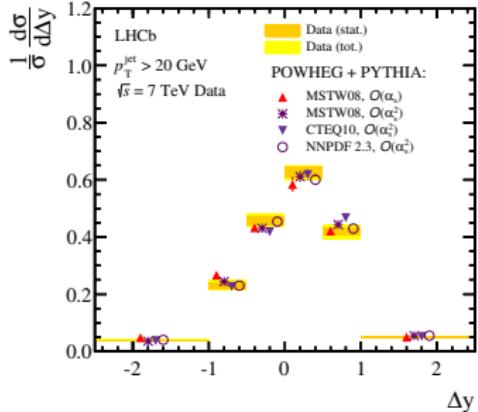
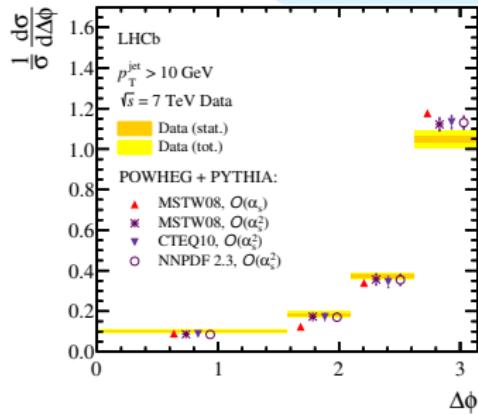
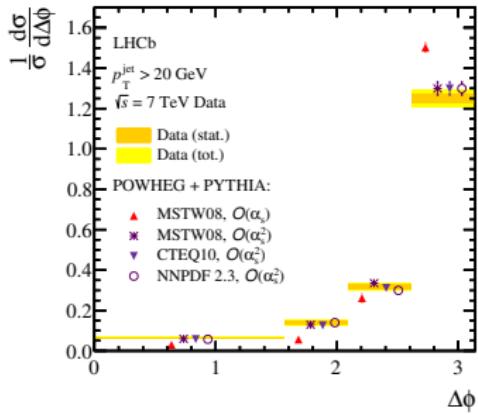
Measurement of $Z + \text{jet}$ production at 7 TeV

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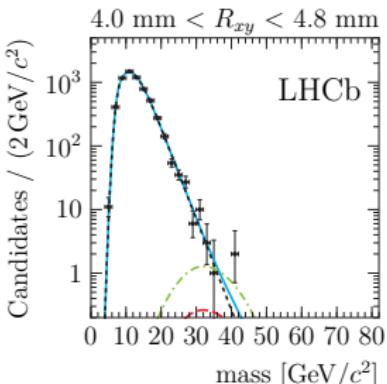
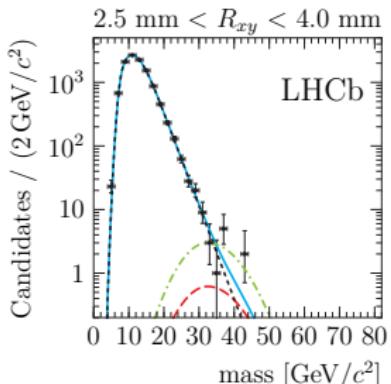
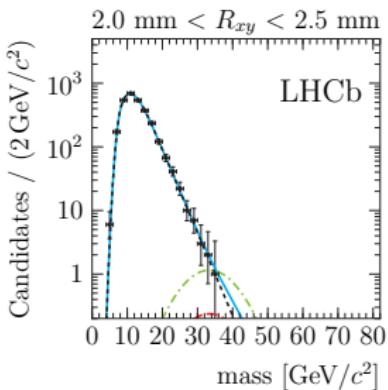
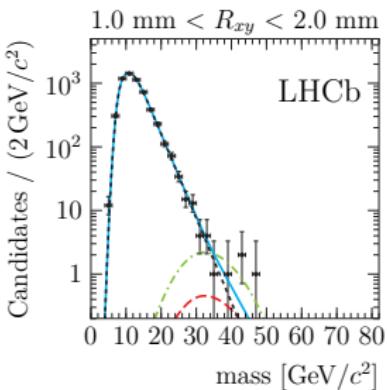
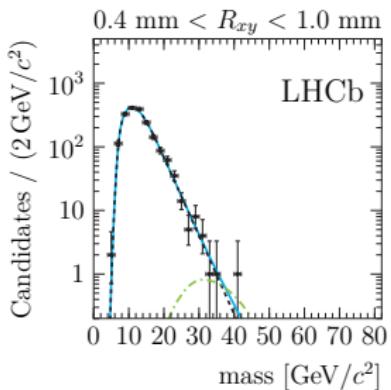
Measurement of $Z + \text{jet}$ production at 7 TeV

JHEP01(2014)033



Search for long-lived particles decaying to jet pairs

arXiv:1412.3021 to appear in Eur. Phys. J. C



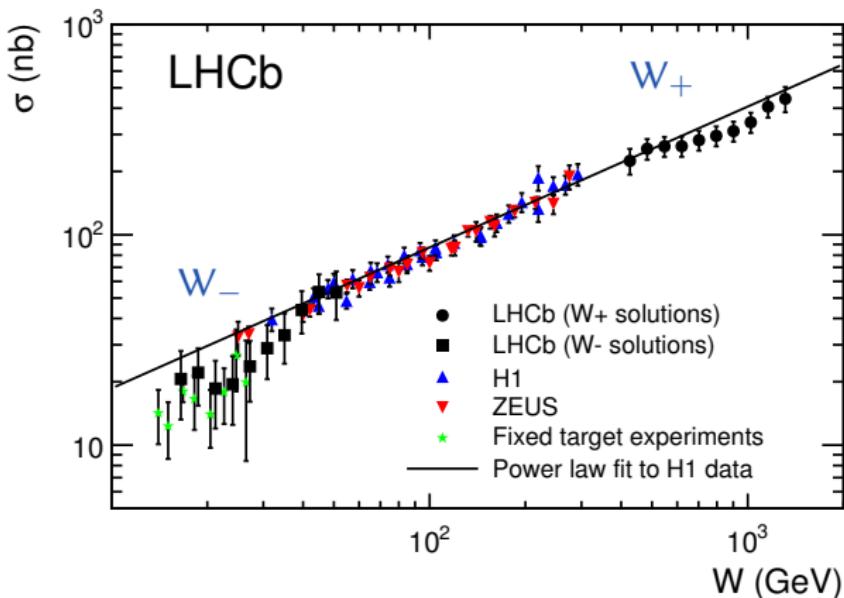
Red long-dashed: best fit signal
Green dash-dotted: signal for SM Higgs cross-section, 100 % BR

Exclusive J/ ψ and $\psi(2S)$ production at 7 TeV

JPhysG41(2014)055002

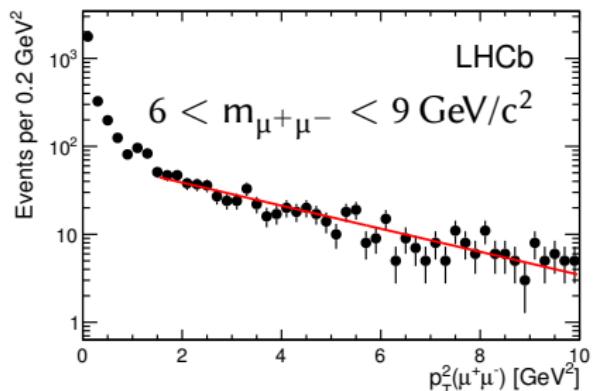
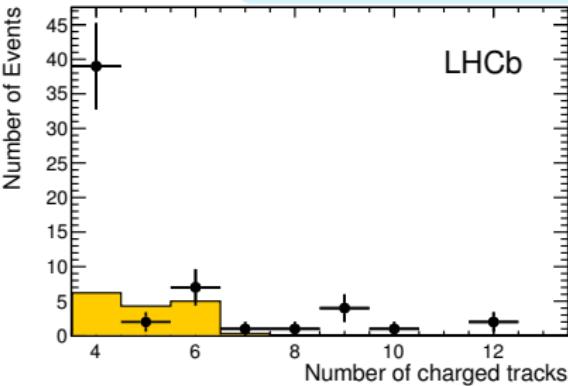
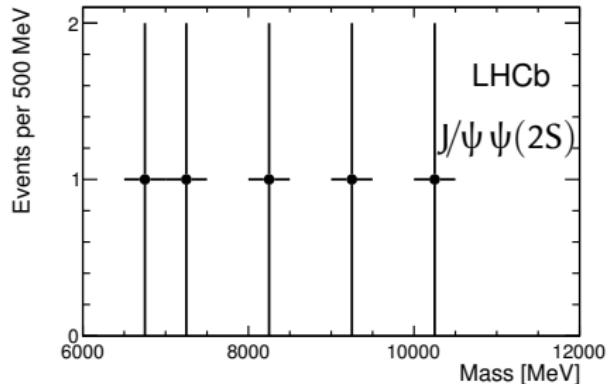
Exclusive J/ ψ production in pp collisions is related to photoproduction:

$$\frac{d\sigma}{dy_{pp \rightarrow pJ/\psi p}} = r_+ k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow J/\psi p}(W_-)$$



Observation of exclusive charmonium pair production

JPhysG41(2014)115002



$$\begin{aligned}\sigma^{J/\psi J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst}) \text{ pb} \\ \sigma^{J/\psi \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst}) \text{ pb} \\ \sigma^{\psi(2S)\psi(2S)} &< 237 \text{ pb} \\ \sigma^{\chi_{c0}\chi_{c0}} &< 69 \text{ nb} \\ \sigma^{\chi_{c1}\chi_{c1}} &< 45 \text{ pb} \\ \sigma^{\chi_{c2}\chi_{c2}} &< 141 \text{ pb}\end{aligned}$$

Results

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- ▶ LHCb collaboration, Measurement of the Z+b-jet cross-section in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the forward region, [JHEP 01 \(2015\) 064](#), [arXiv:1411.1264](#).
- ▶ LHCb collaboration, Search for long-lived particles decaying to jet pairs, [arXiv:1412.3021](#), to appear in [Eur. Phys. J. C](#).
- ▶ LHCb collaboration, Updated measurements of exclusive J/ψ and $\psi(2S)$ production cross-sections in pp collisions at $\sqrt{s} = 7 \text{ TeV}$, [J. Phys. G41 \(2014\) 055002](#), [arXiv:1401.3288](#).
- ▶ LHCb collaboration, Observation of charmonium pairs produced exclusively in pp collisions, [J. Phys. G41 \(2014\) 115002](#), [arXiv:1407.5973](#).

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