QCD results in the forward region (LHCb)

Xabier Cid Vidal (USC)

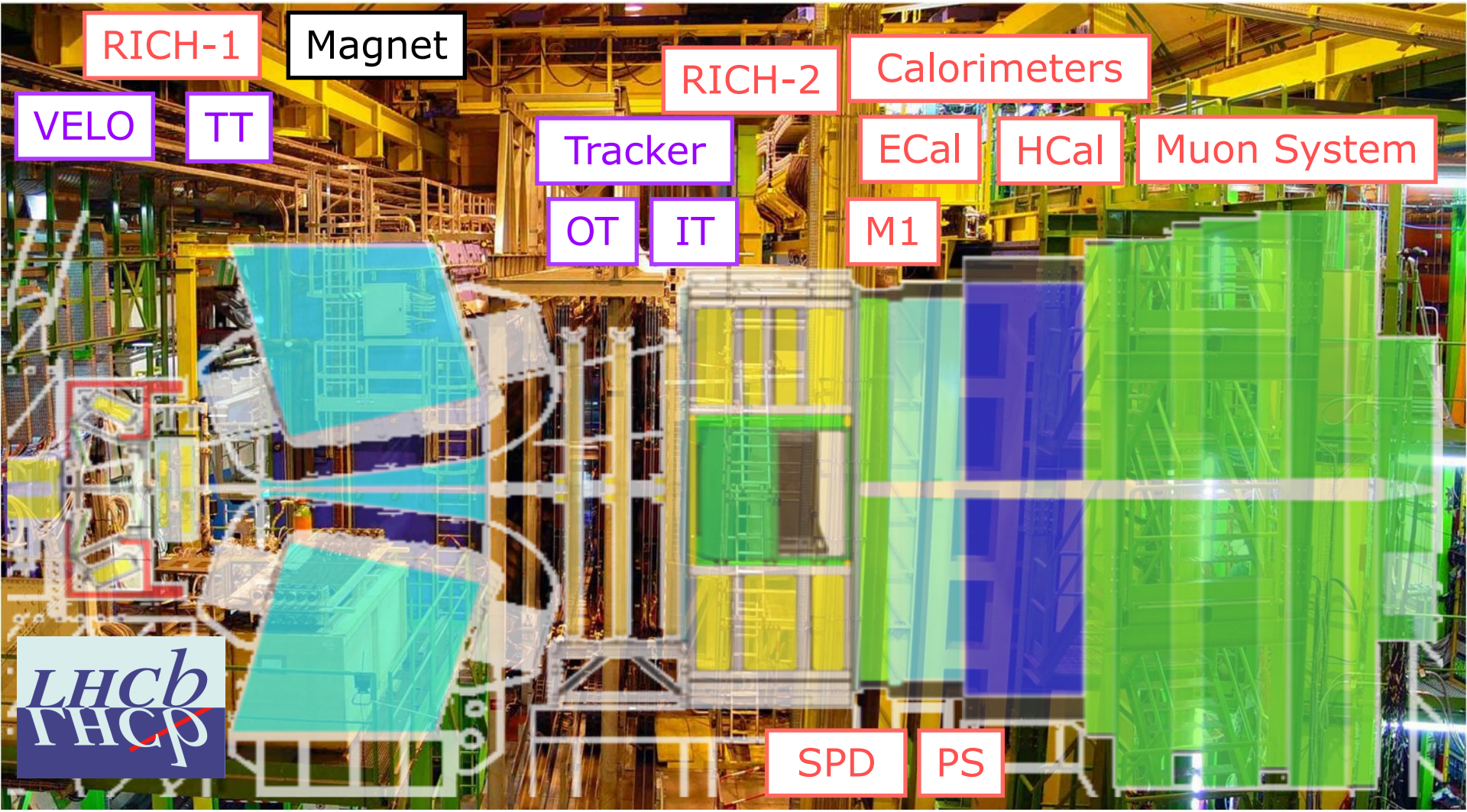
On behalf of the LHCb collaboration

Excited QCD 2016

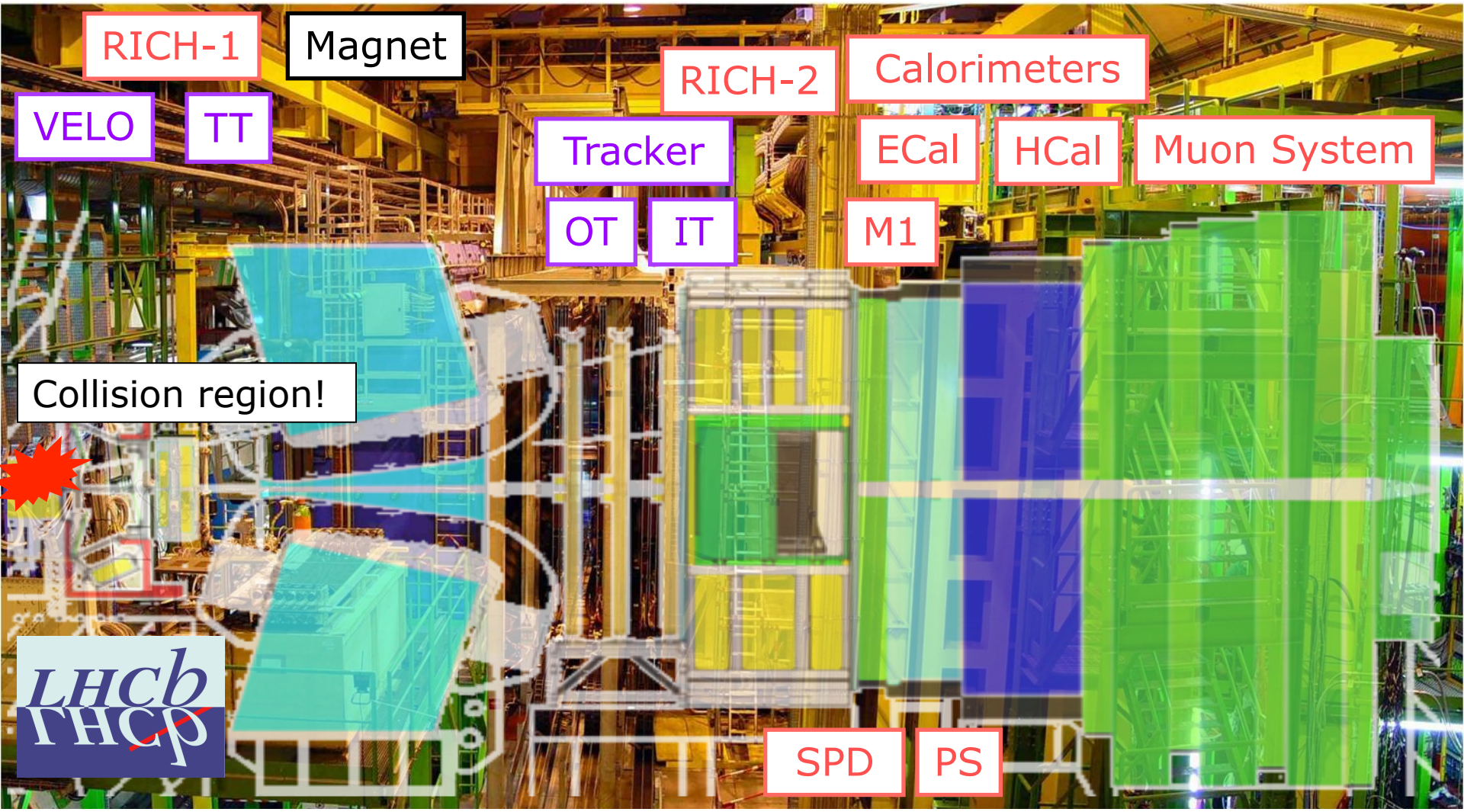
March 8th 2016

LHCb detector

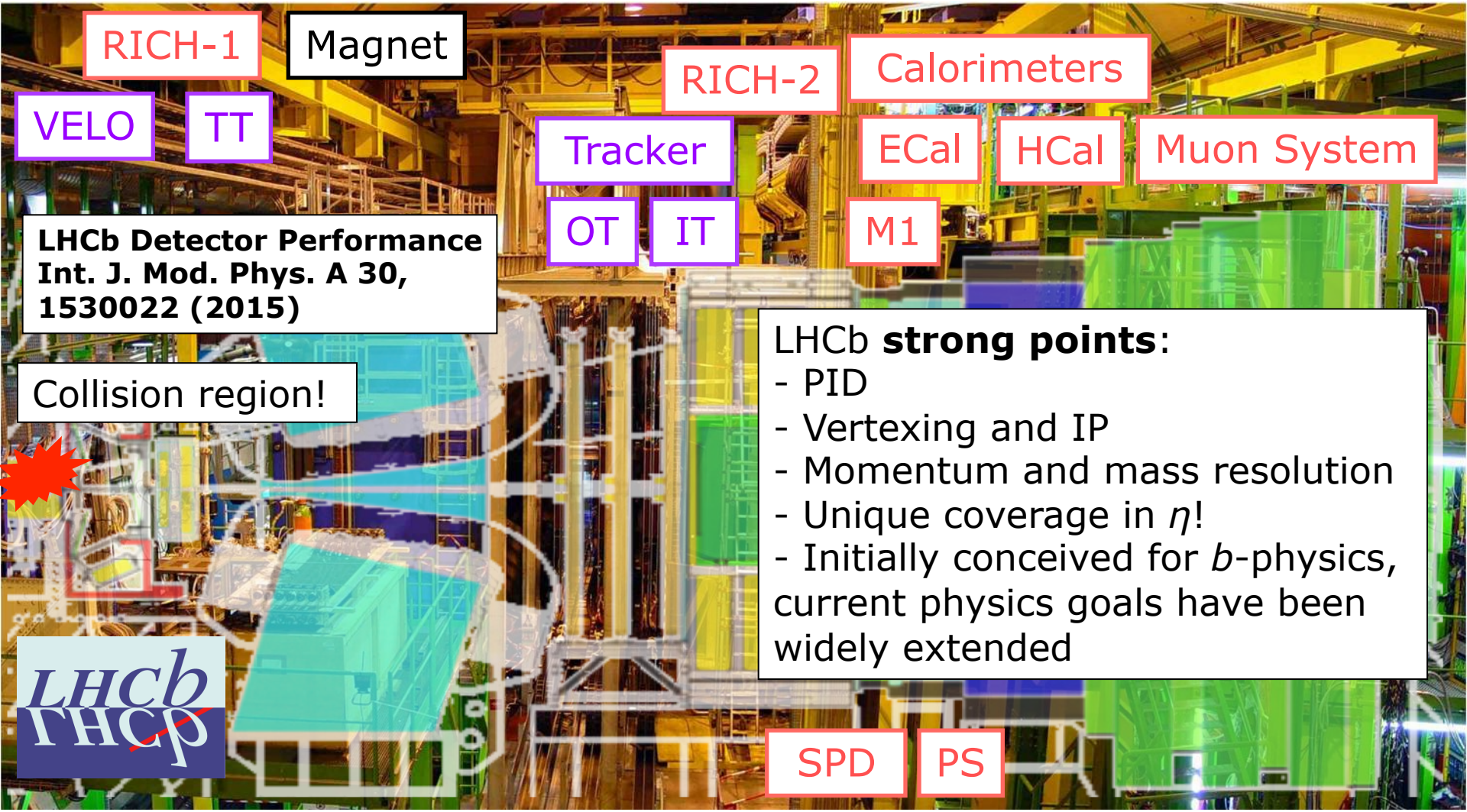
LHCb detector



LHCb detector



LHCb detector

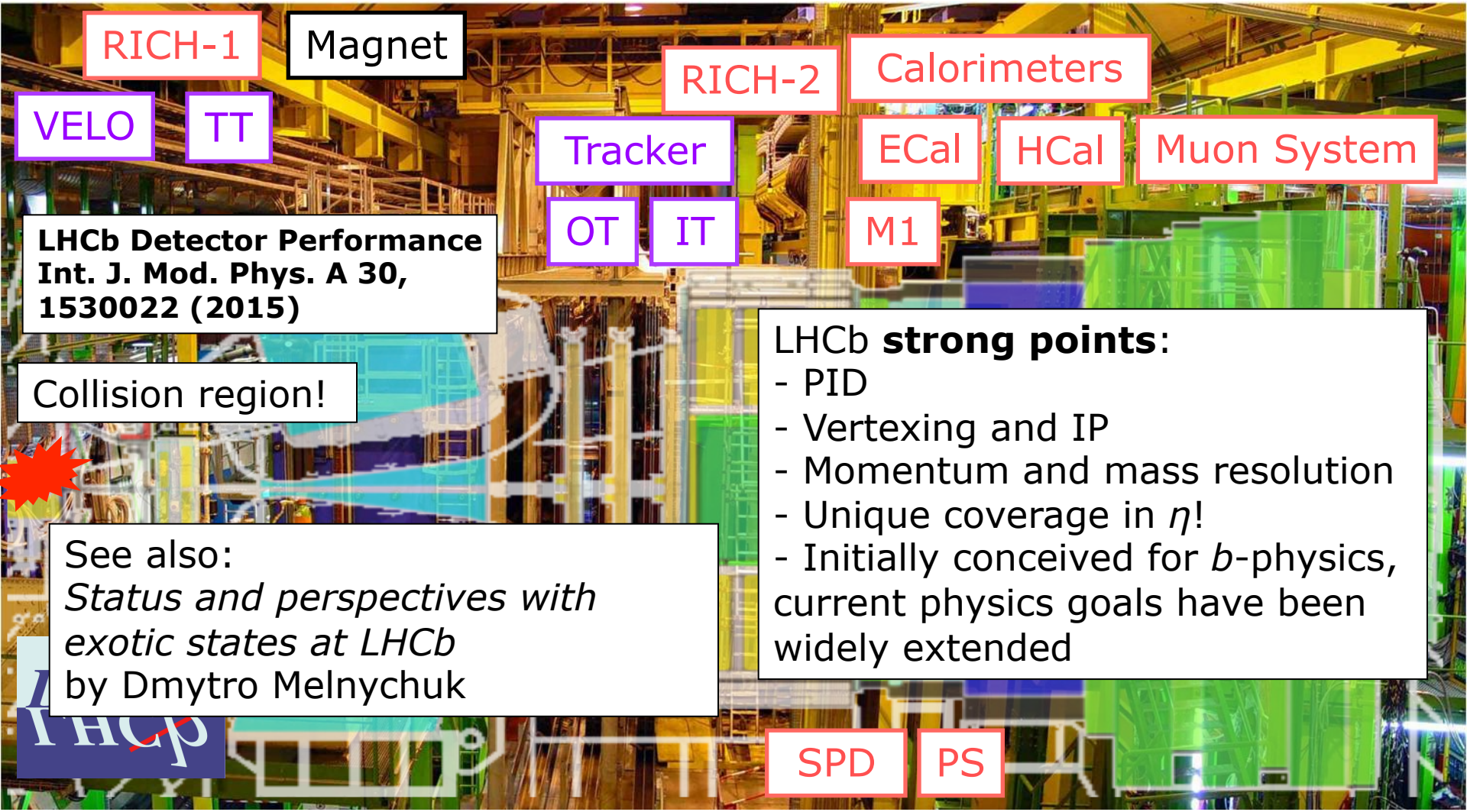


LHCb Detector Performance
Int. J. Mod. Phys. A 30, 1530022 (2015)

Collision region!

LHCb **strong points**:
- PID
- Vertexing and IP
- Momentum and mass resolution
- Unique coverage in η!
- Initially conceived for *b*-physics, current physics goals have been widely extended

LHCb detector



LHCb Detector Performance
Int. J. Mod. Phys. A 30, 1530022 (2015)

Collision region!

LHCb **strong points**:
- PID
- Vertexing and IP
- Momentum and mass resolution
- Unique coverage in η!
- Initially conceived for *b*-physics, current physics goals have been widely extended

See also:
Status and perspectives with exotic states at LHCb
by Dmytro Melnychuk

LHCb datasets

- b physics imposes dealing with lower luminosities with respect to ATLAS or CMS… *pp* data taken

→ 1 fb^{-1} at $\sqrt{s}$=7 TeV

→ 2 fb^{-1} at $\sqrt{s}$=8 TeV

→ 300 pb^{-1} at $\sqrt{s}$=13 TeV

* As a benefit, very stable conditions in terms of trigger/luminosity!

- Apart from that… bonus data! **pPb**, **PbPb** and **SMOG** data

E_{beam} (p)	p-SMOG	pPb/Pbp	Pb-SMOG	PbPb
2.5 TeV	69 GeV			
3.5 TeV				
4.0 TeV	87 GeV	5 TeV	54 GeV	
6.5 TeV	110 GeV		69 GeV	5 TeV

Center-of-mass energies (per ion)

LHCb datasets

- b physics imposes dealing with lower luminosities with respect to ATLAS or CMS… *pp* data taken

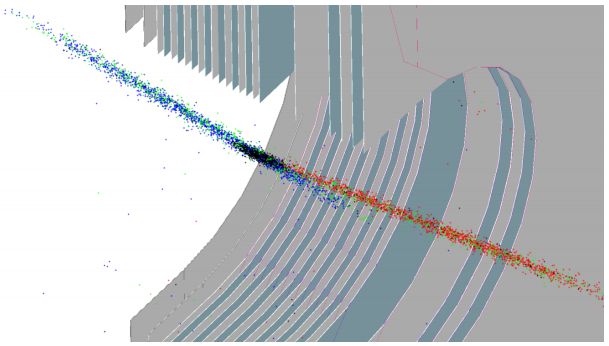
→ 1 fb^{-1} at $\sqrt{s}$=7 TeV

→ 2 fb^{-1} at $\sqrt{s}$=8 TeV

→ 300 pb^{-1} at $\sqrt{s}$=13 TeV

* As a benefit, very stable conditions in terms of trigger/luminosity!

- **SMOG**: System for Measuring the Overlap with Gas
  - Done by injecting noble gas into the interaction region: He, Ne, Ar (maybe Kr & Xe)
  - Fixed target physics in pA and PbA configurations
  - Partial sensitivity to $-3.5 < \eta < -1.5$!
  - Physics: Strangeness production, cosmic rays physics and cosmology,….



LHCb datasets

- b physics imposes dealing with lower luminosities with respect to ATLAS or CMS… *pp* data taken

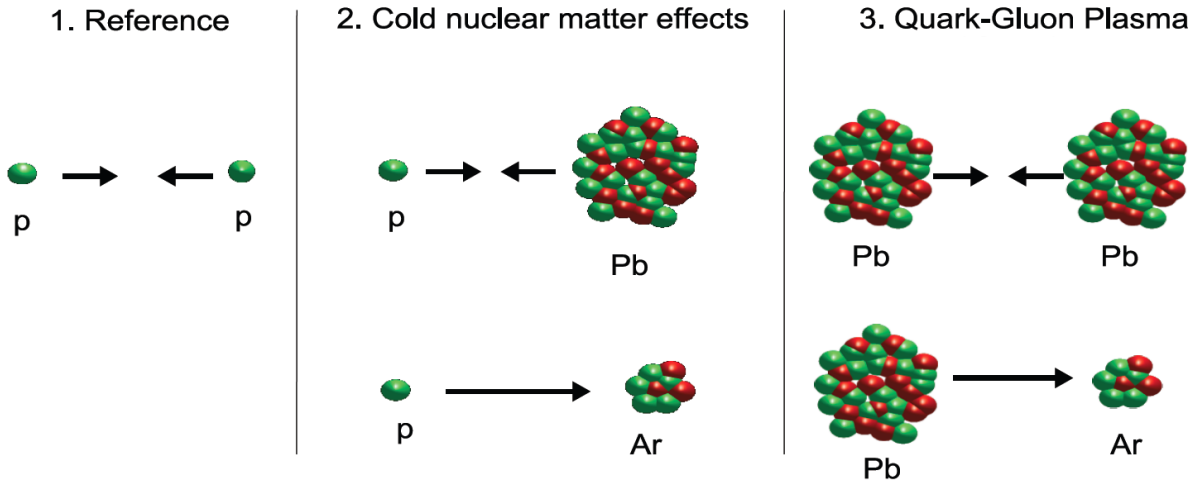
→ 1 fb^{-1} at $\sqrt{s}$=7 TeV

→ 2 fb^{-1} at $\sqrt{s}$=8 TeV

→ 300 pb^{-1} at $\sqrt{s}$=13 TeV

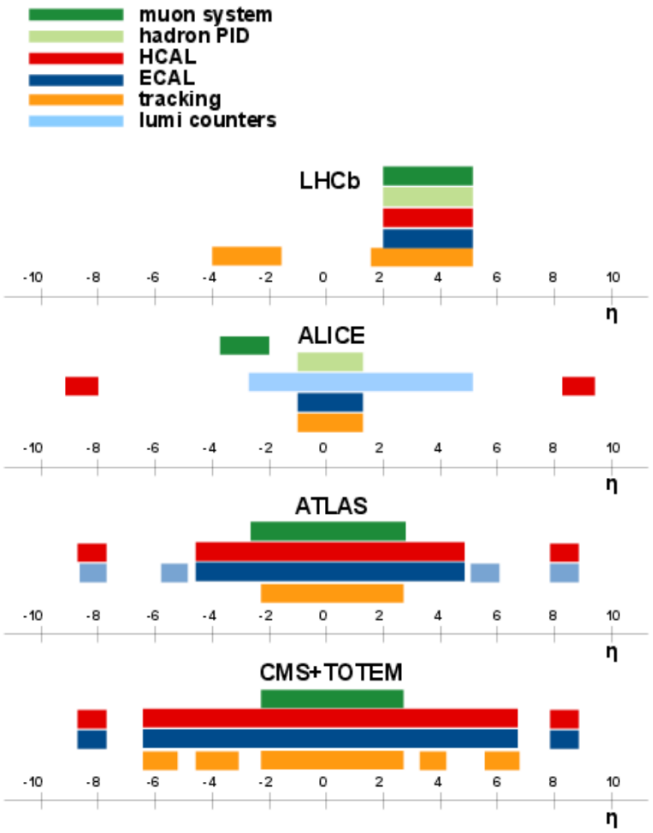
* As a benefit, very stable conditions in terms of trigger/luminosity!

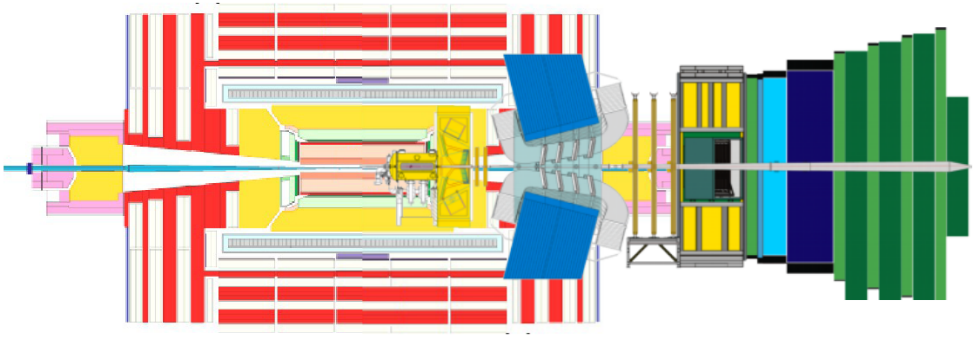
- **Heavy ions physics!**

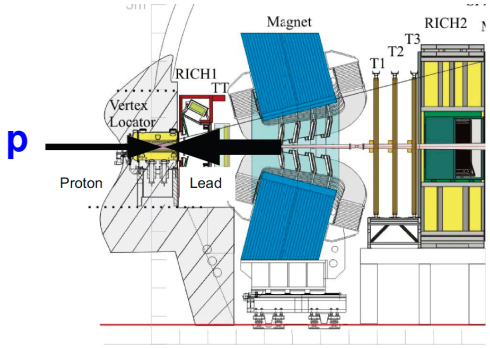


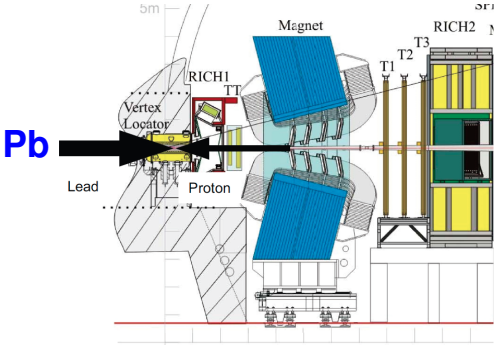
Detector complementarity

- LHCb can offer unique coverage at the LHC





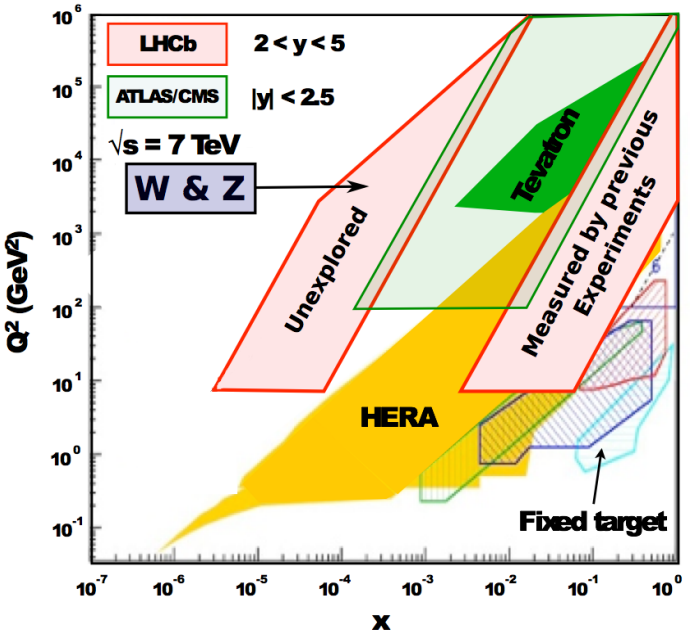




QCD physics at LHCb (I)

- LHCb **EW production measurements** probe two Bjorken x – Q^2 regions
  - Low x, high Q^2 previously unexplored
  - LHCb produces W/Z by collisions between low-x and high-x partons
  - Overlap region allows direct ATLAS/CMS comparison

arxiv:1602.09006

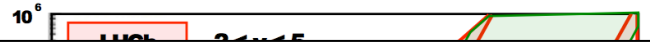


where
x parton longitudinal momentum fraction
Q² momentum transfer

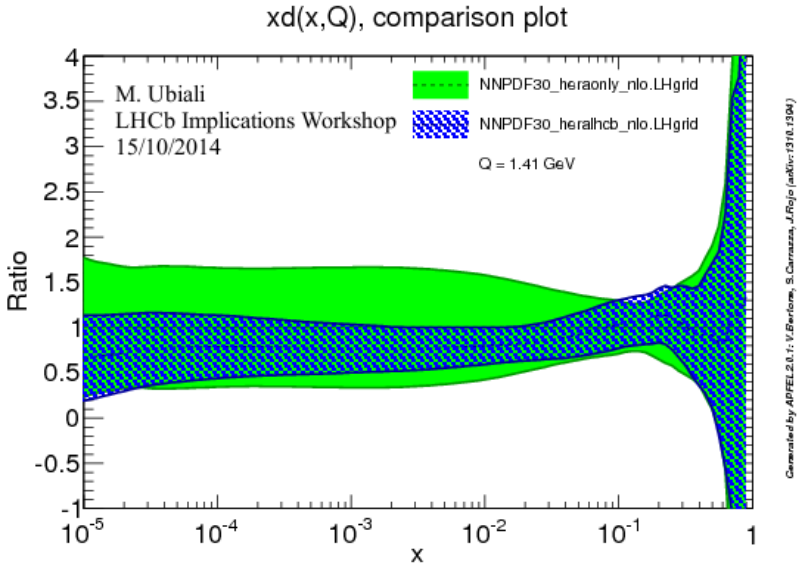
QCD physics at LHCb (I)

- LHCb **EW production**

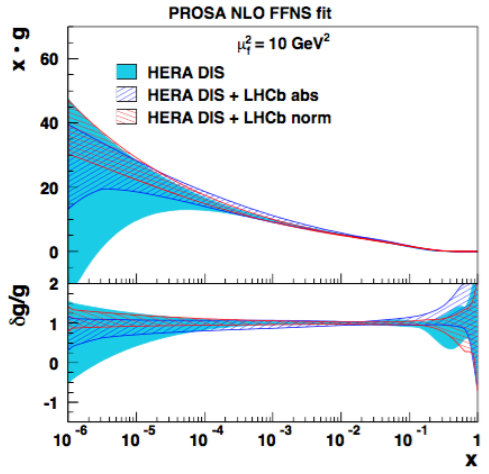
arxiv:1602.09006



- NNPDF down quark PDF and uncertainties (normalized so central value pre-LHC is unity):
  - Green: PDF fit using HERA data
  - Blue: PDF fit using HERA data and 7 TeV LHCb data



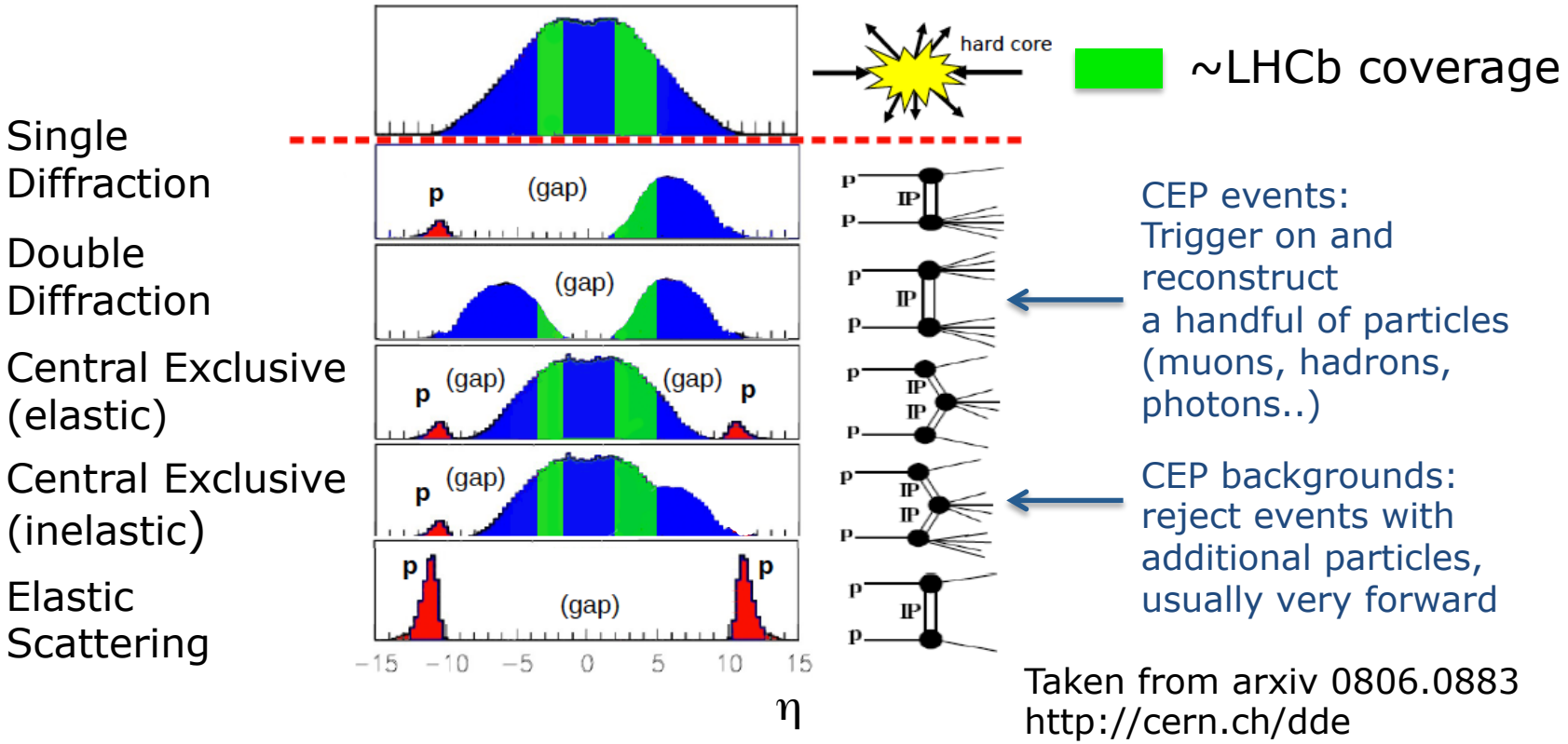
- Similar impact from LHCb **b** and **c** production papers
  - Measurement of B meson production cross-sections at √s = 7 TeV; *JHEP 1308 (2013) 117*
  - Prompt charm production in pp collisions at √s=7; TeV *Nucl.Phys. B871 (2013) 1-20*



PROSA Collaboration Eur. Phys. J. C75 (2015), no. 8 396

QCD physics at LHCb (II)

- **Central exclusive production** (CEP)
  - Experimentally, very empty low p_T events!
  - Rich physics case: Photon-Pomeron, Double-Pomeron, Photoproduction, Glueballs, Exotica,…

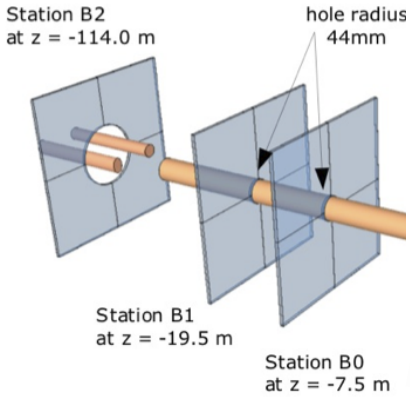


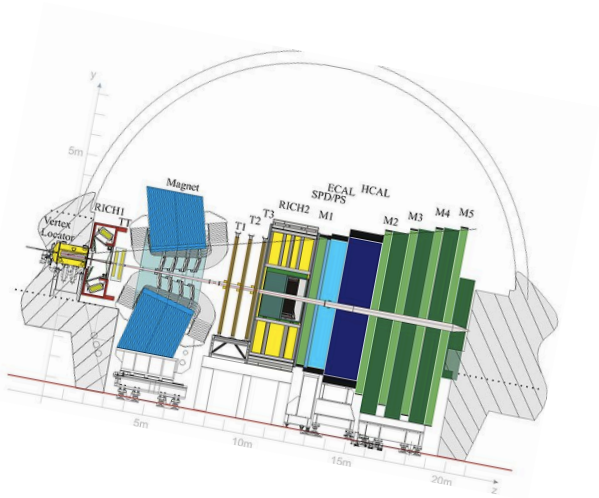
Taken from arxiv 0806.0883
http://cern.ch/dde

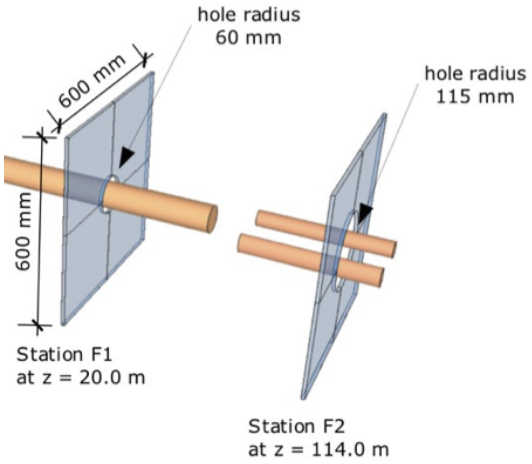
QCD physics at LHCb (II)

- **Central exclusive production** (CEP)

- **HeRSCheL**: High Rapidity Shower Counters for LHCb
  - Forward scintillators for selecting rapidity gaps
  - Up to ±114 m from IP: Full gap size **2 < η < 8**
  - Fully operative from 2015!

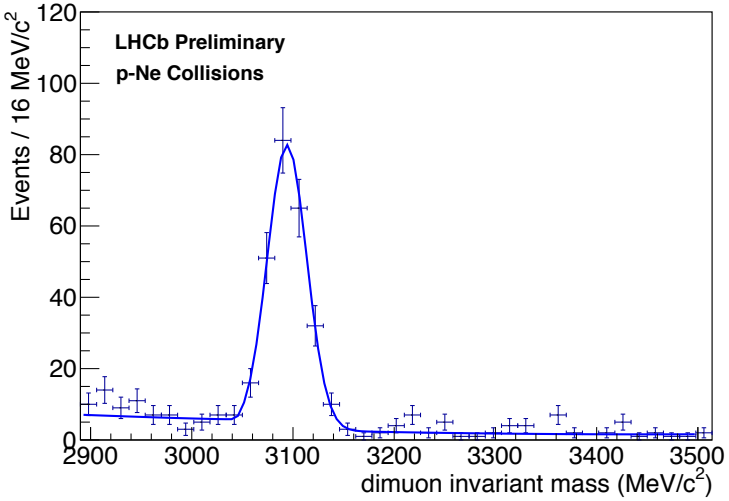


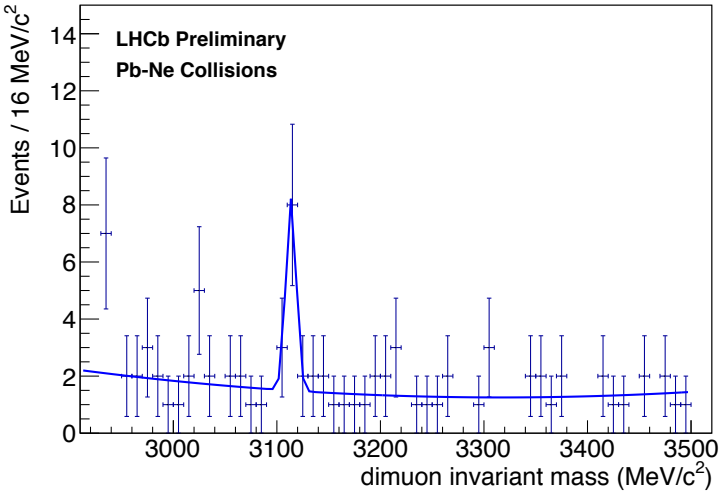




QCD physics at LHCb (III)

- Study of **hadronic collisions**



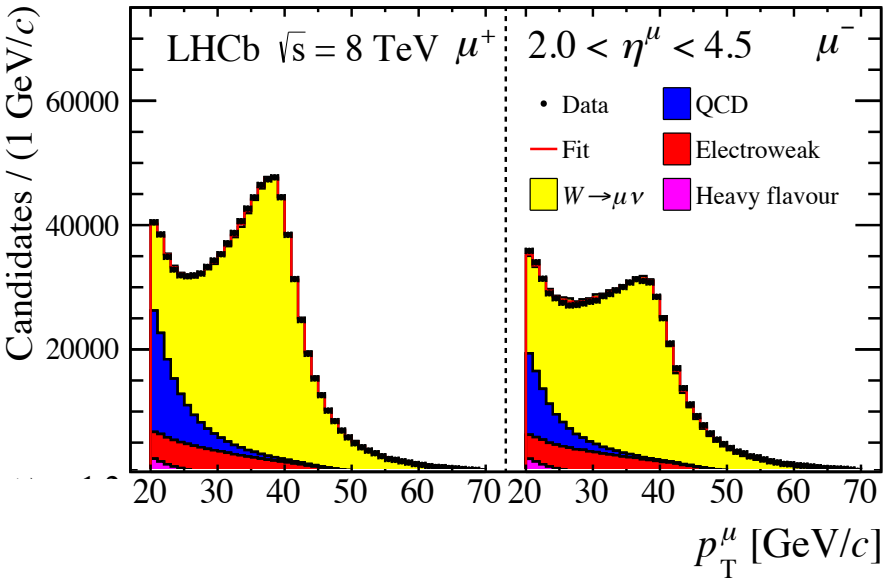


- Other interesting physics…: Test of MC models, Double Parton Scattering…

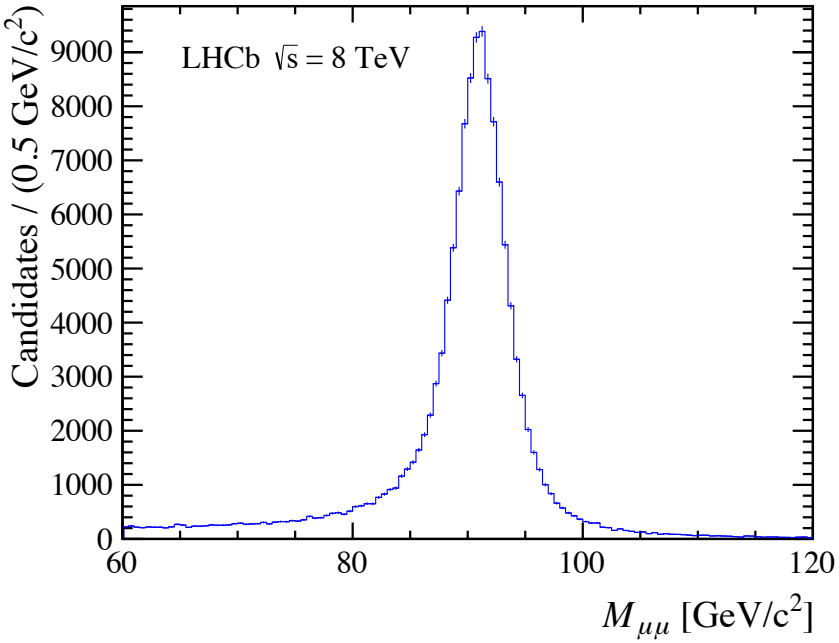
- Will show a selection of results (personal bias, most recent results…). For a complete list see
  https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbQEEPublicResults

W and Z at √s = 8 TeV (I)

- Measurement in muon final states
  - No missing E_T at LHCb…!



~79% purity



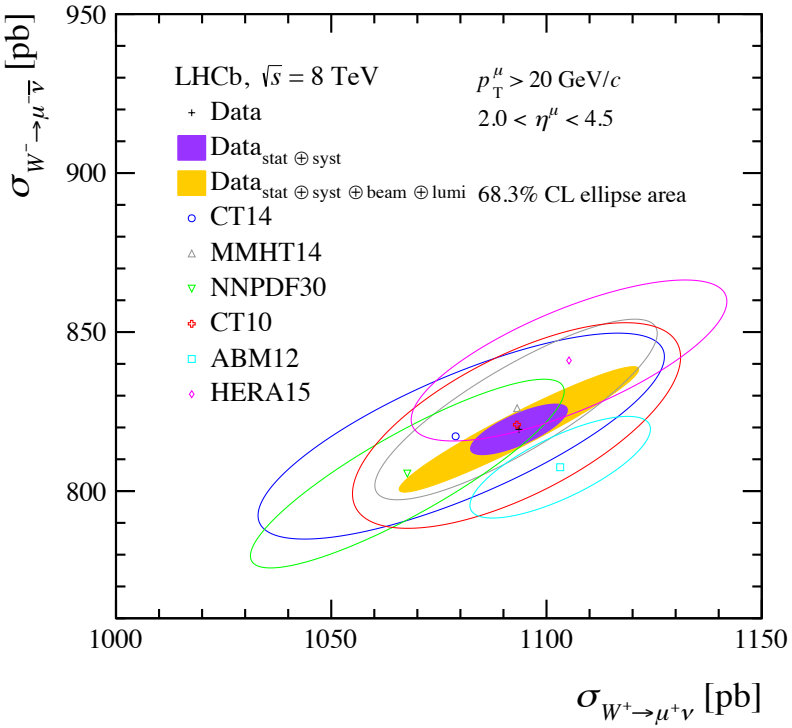
>99% purity

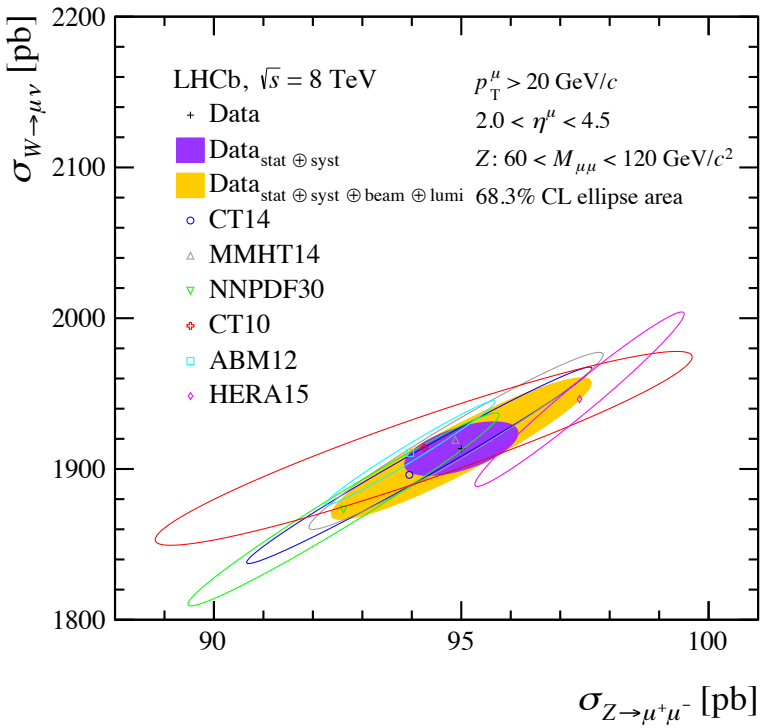
JHEP 01 (2016) 155

W and Z at √s = 8 TeV (II)

- Measurement of cross sections, data driven efficiencies

JHEP 01 (2016) 155



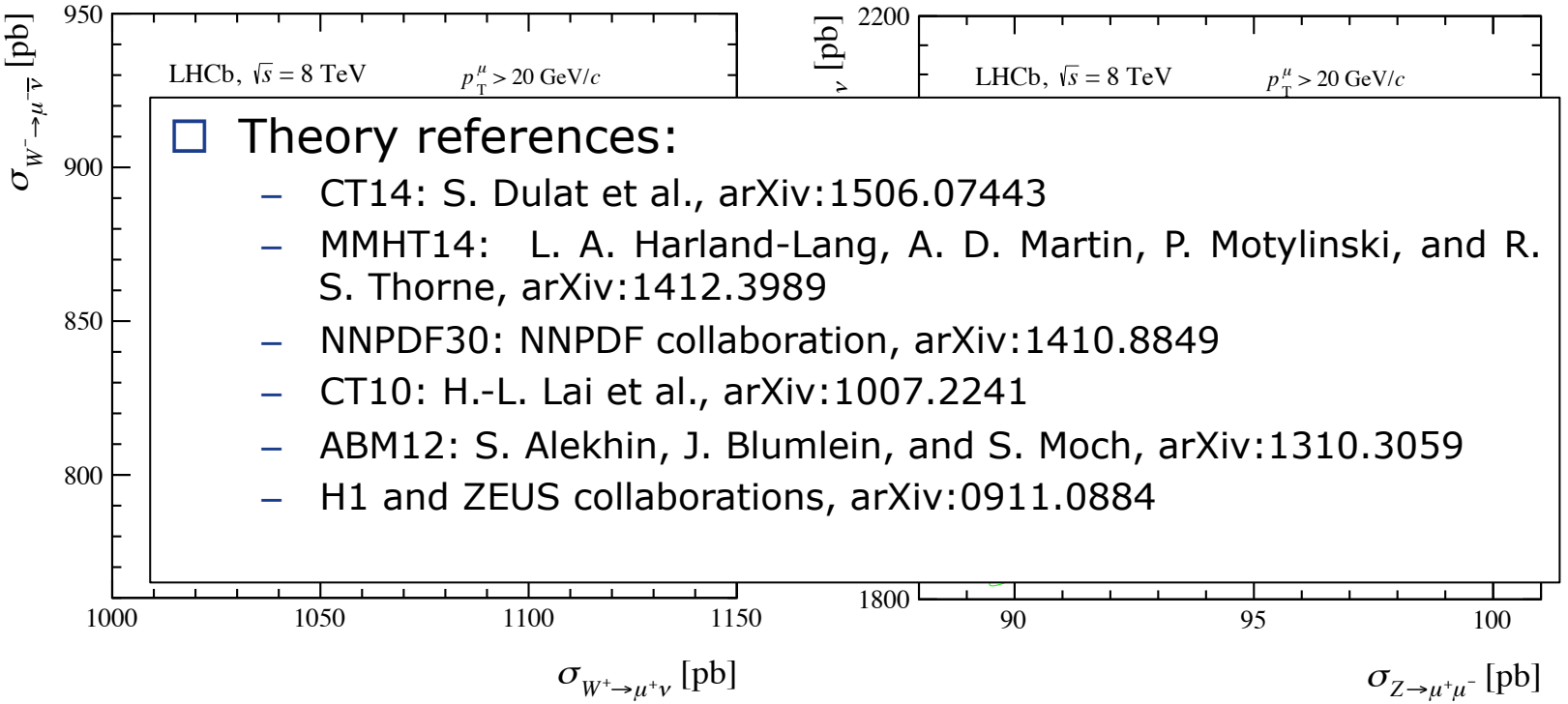


- Small (~1%) luminosity uncertainty!
- Consistent results with data
- Differential measurements also available in the paper

W and Z at √s = 8 TeV (II)

- Measurement of cross sections, data driven efficiencies

JHEP 01 (2016) 155



- Theory references:
  - CT14: S. Dulat et al., arXiv:1506.07443
  - MMHT14: L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, arXiv:1412.3989
  - NNPDF30: NNPDF collaboration, arXiv:1410.8849
  - CT10: H.-L. Lai et al., arXiv:1007.2241
  - ABM12: S. Alekhin, J. Blumlein, and S. Moch, arXiv:1310.3059
  - H1 and ZEUS collaborations, arXiv:0911.0884

- Small (~1%) luminosity uncertainty!
- Consistent results with data
- Differential measurements also available in the paper

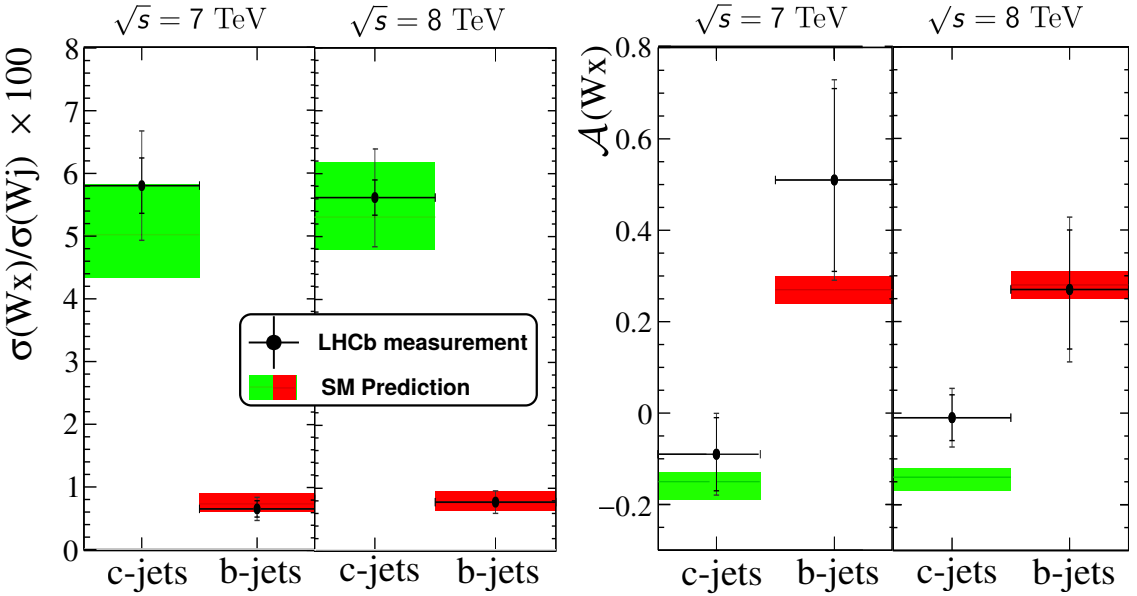
W+b/c jets with Run I data

- Jets reconstructed with anti-k_T, Particle Flow approach
  - Have developed powerful b/c jet tagging

JINST 10 (2015) P06013

  - Measurement at $\sqrt{s}$ = 7 and 8 TeV

$$\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}.$$



Phys. Rev. D 92, 052001 (2015)

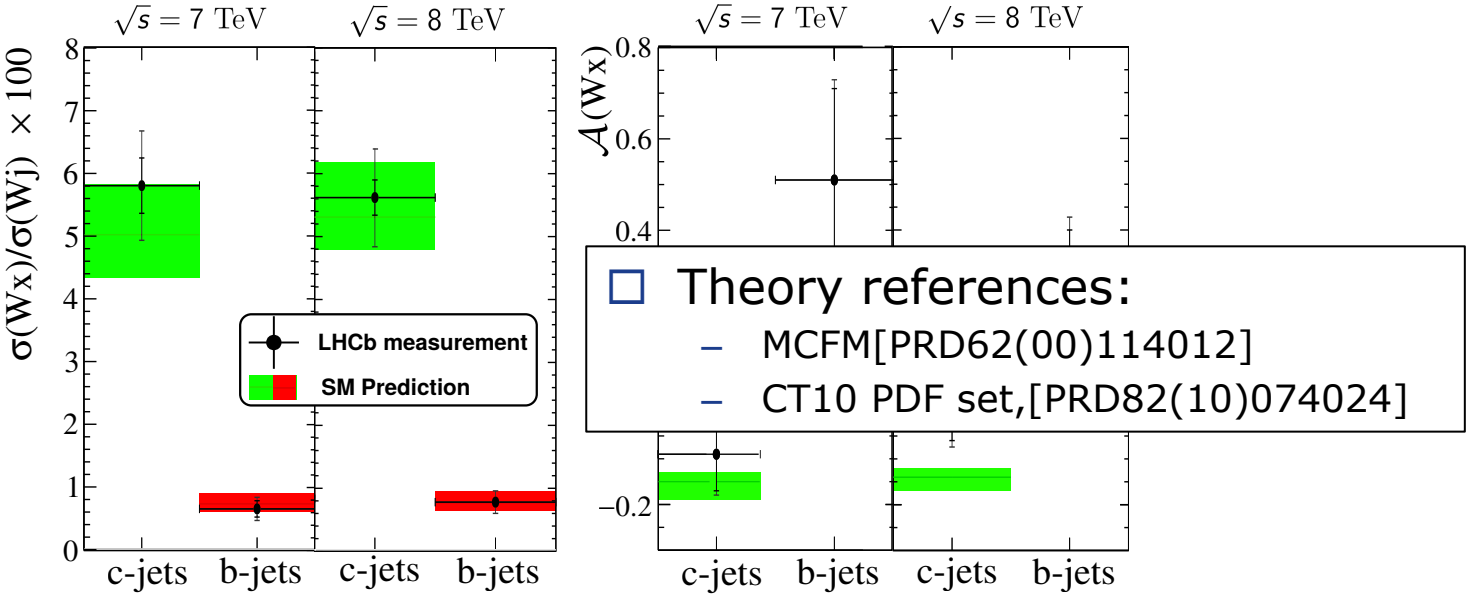
W+b/c jets with Run I data

- Jets reconstructed with anti-k_T, Particle Flow approach
  - Have developed powerful b/c jet tagging

JINST 10 (2015) P06013

  - Measurement at $\sqrt{s}$ = 7 and 8 TeV

$$\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}.$$



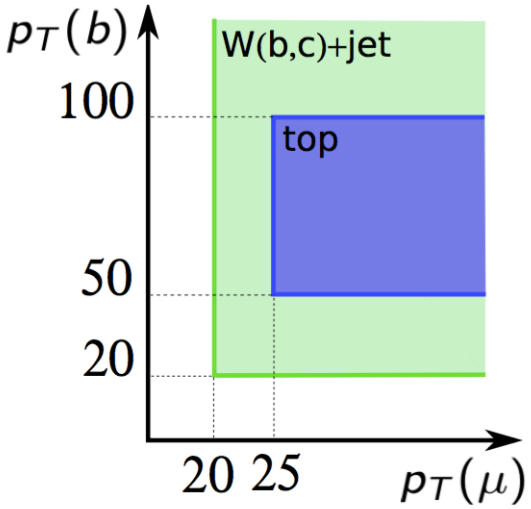
- Theory references:
  - MCFM[PRD62(00)114012]
  - CT10 PDF set,[PRD82(10)074024]

Phys. Rev. D 92, 052001 (2015)

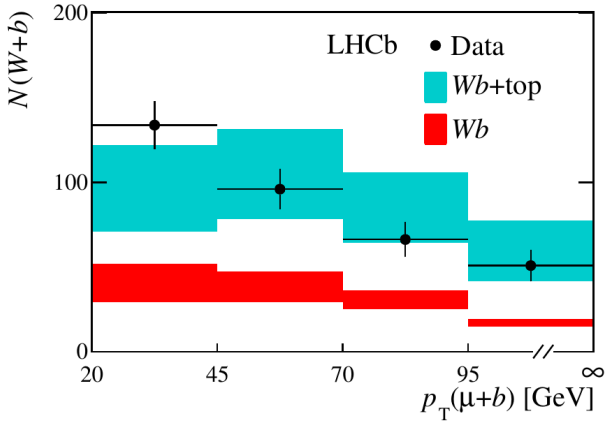
Top in the forward direction

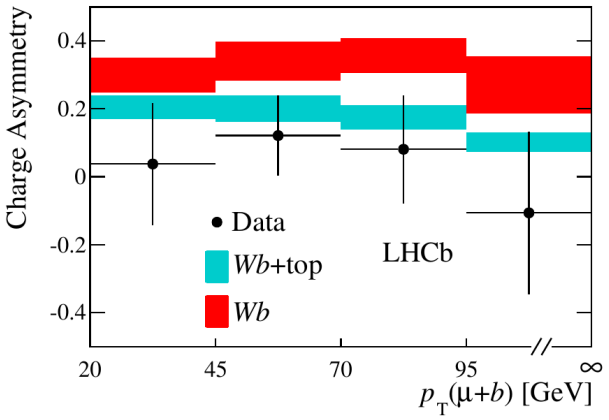
PRL 115 (2015) 112001

- Tightening the same selection allowed the discovery of the top quark at LHCb!
  - p_T (μ + b) provides discrimination between top and W + b-jets.
  - *A*(W+b) ~1/3 while *A*(top) ~0.1, mainly from single-t
  - Look for an excess of μ + b events and deviation of *A* as function of pT (μ + b).



5.4σ observation!

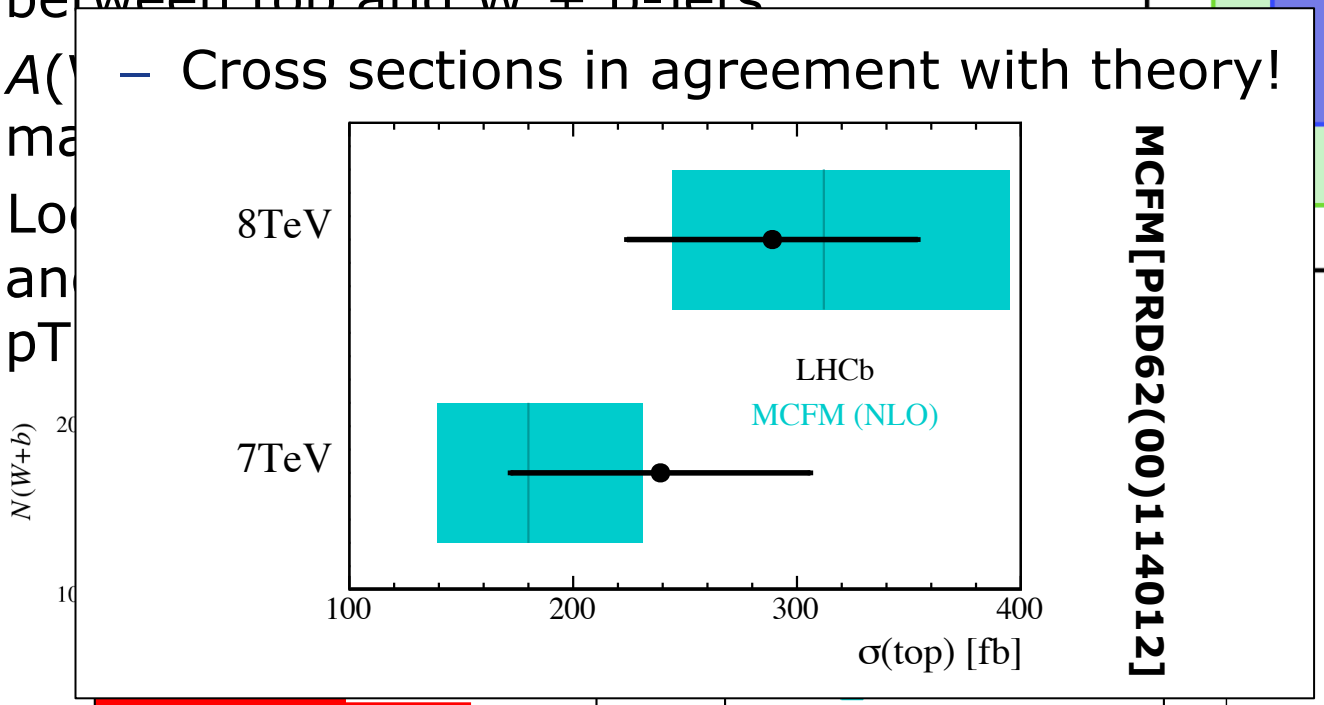


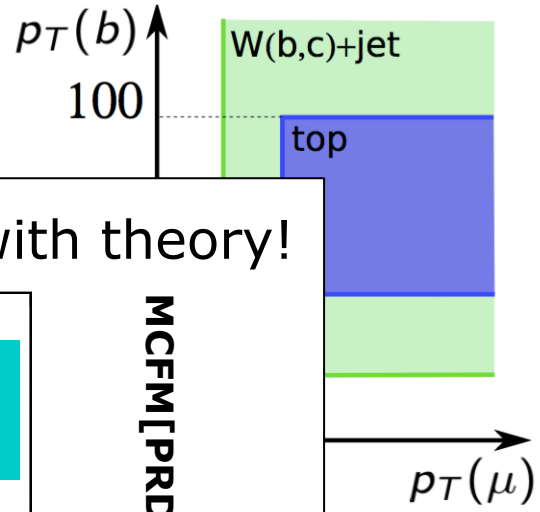


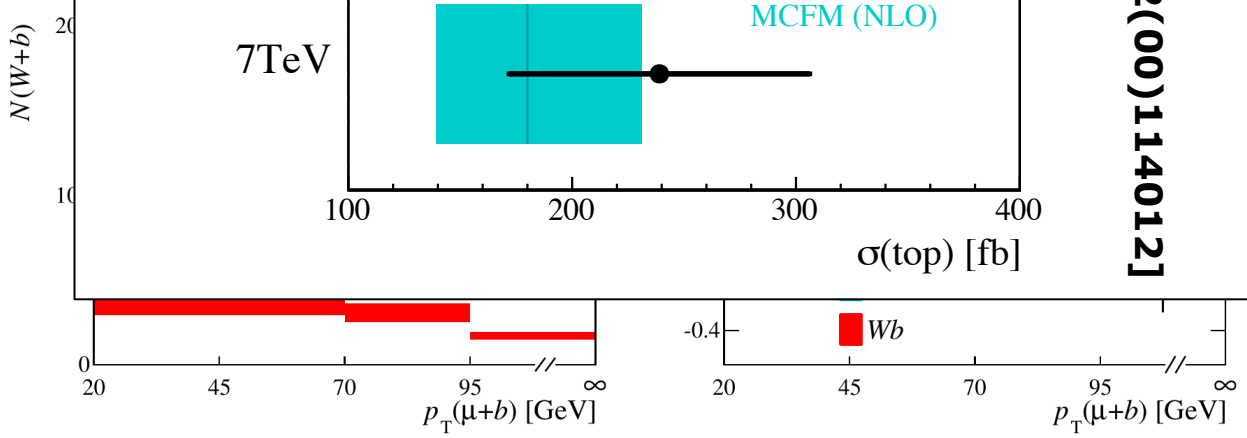
Top in the forward direction

PRL 115 (2015) 112001

- Tightening the same selection allowed the discovery of the top quark at LHCb!
  - p_T (μ + b) provides discrimination between top and W + b-jets
  - *A*(ma
  - Lo an pT
  - Cross sections in agreement with theory!

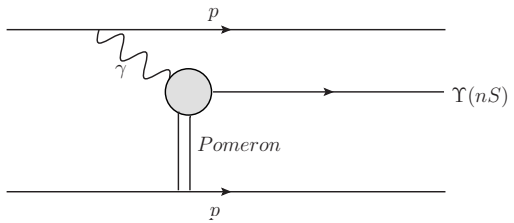


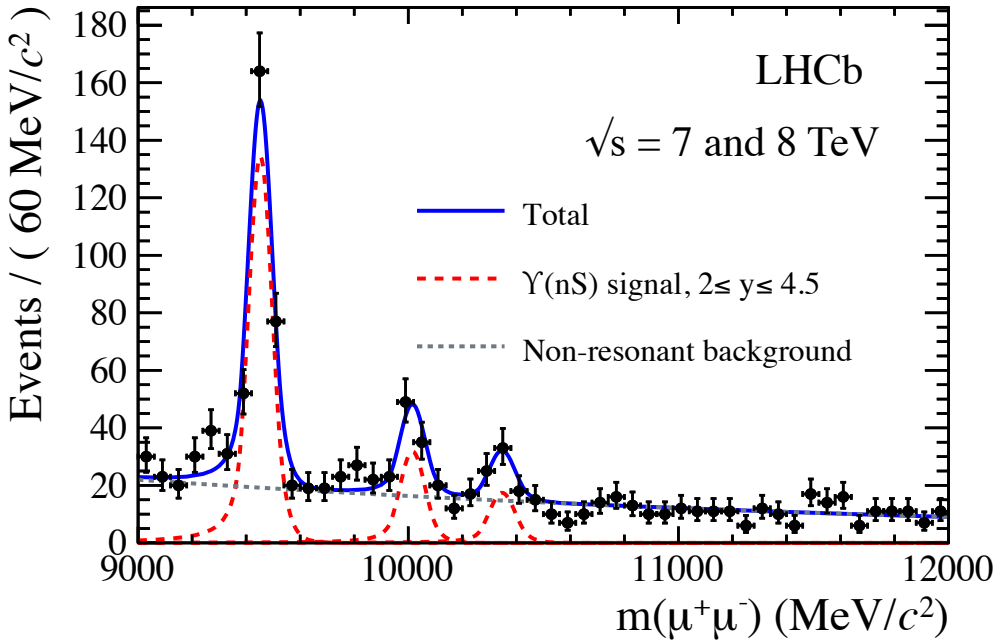




Exclusive Y production (I)

- Measurement performed with $\sqrt{s}$ = 7 and 8 TeV LHCb datasets
  - Y produced by photoproduction!
  - Relatively clean sample in μμ final state!

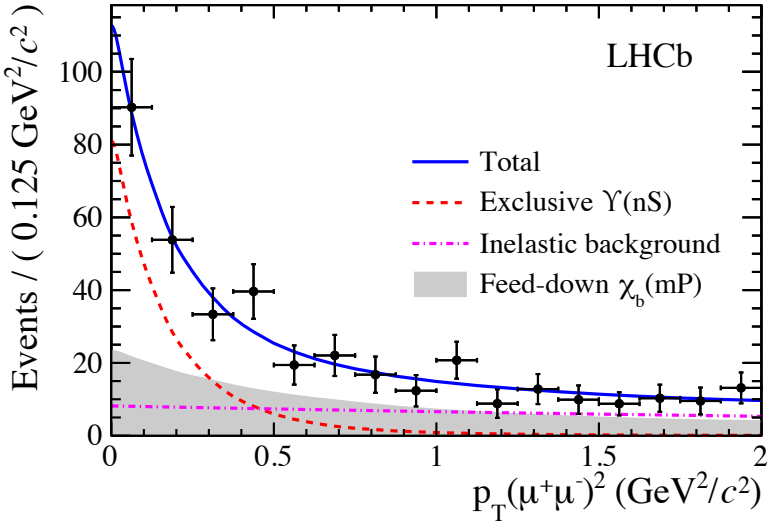




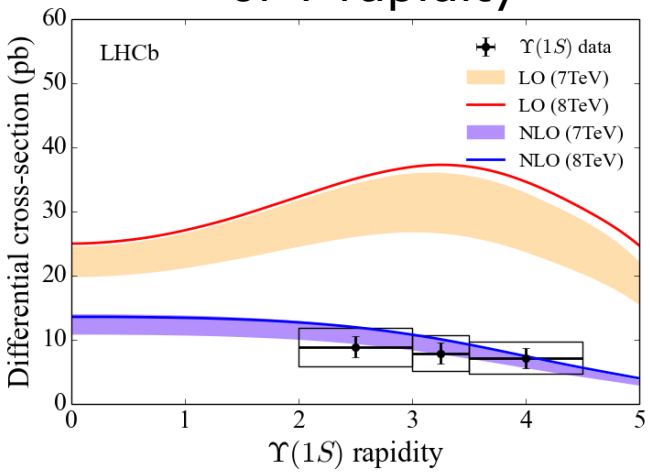
JHEP 1509 (2015) 084

Exclusive Y production (II)

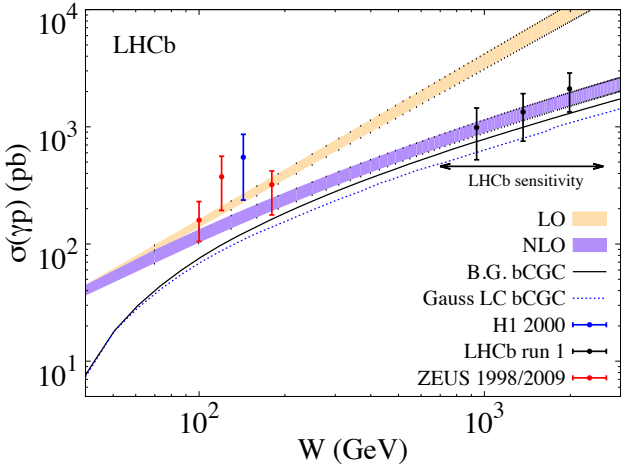
- Exclusive component subtracted with fit to p_T^2 distribution! (dominant syst. uncertainty)
- Y and photo production differential cross section measurements performed



Y as a function of Y rapidity



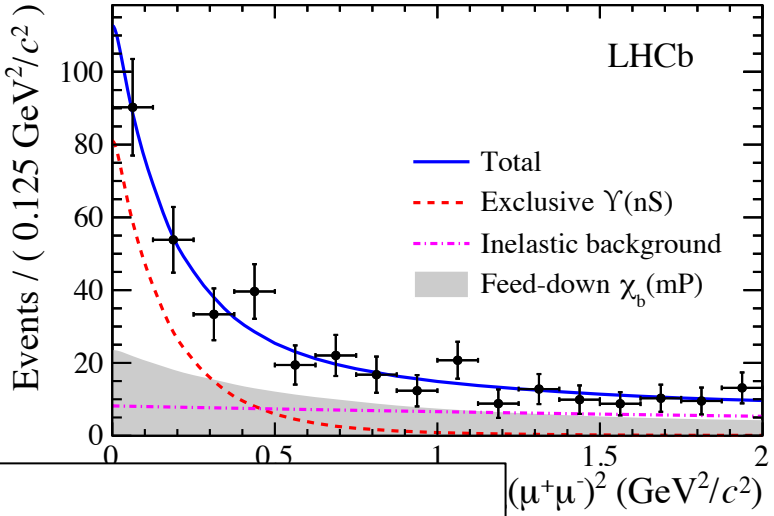
Photoprod. as a function of γp center of mass (W)



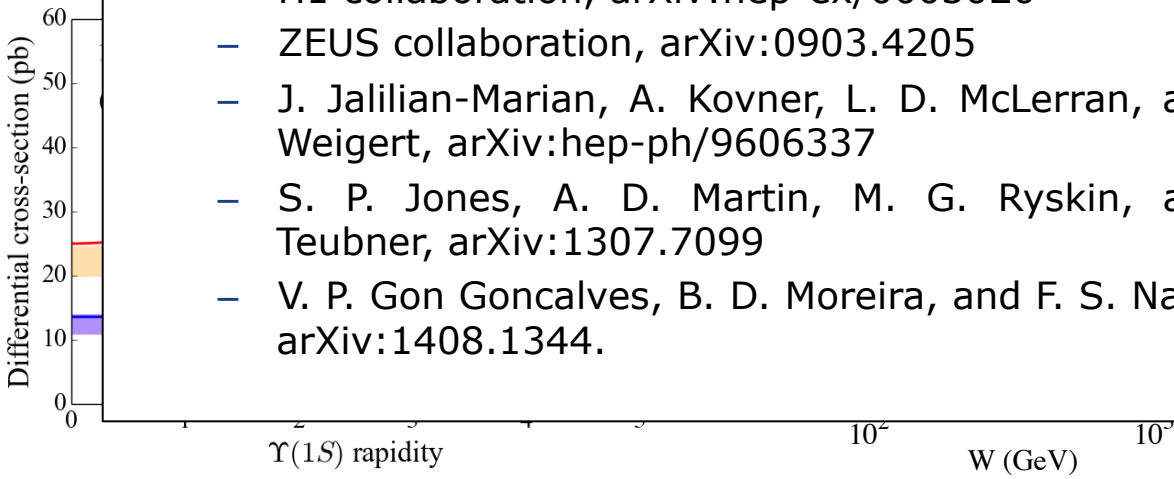
JHEP 1509 (2015) 084

Exclusive Y production (II)

- Exclusive component subtracted with fit to p_T^2 distribution! (dominant syst. uncertainty)
- Y and photo production differential cross section measurements performed



- References:
  - ZEUS collaboration, arXiv:hep-ex/9807020
  - H1 collaboration, arXiv:hep-ex/0003020
  - ZEUS collaboration, arXiv:0903.4205
  - J. Jalilian-Marian, A. Kovner, L. D. McLerran, and H. Weigert, arXiv:hep-ph/9606337
  - S. P. Jones, A. D. Martin, M. G. Ryskin, and T. Teubner, arXiv:1307.7099
  - V. P. Gon Goncalves, B. D. Moreira, and F. S. Navarra, arXiv:1408.1344.

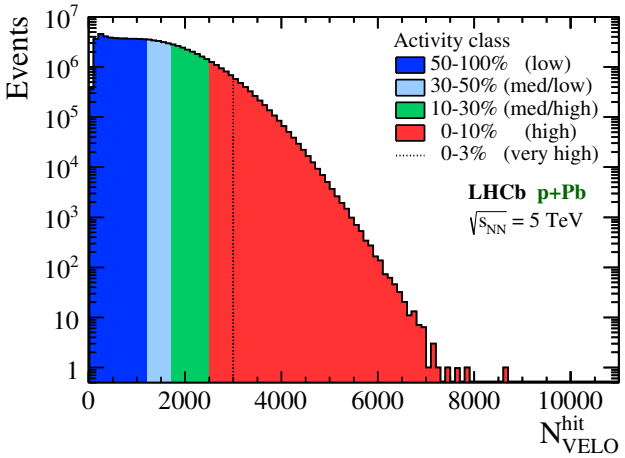


JHEP 1509 (2015) 084

Ridge effect in pA collisions (I)

- Measurement of two-particle angular correlations performed using: **arXiv:1512.00439**
  - L = 0.46 nb^{-1} [p+Pb] ; L = 0.30 nb^{-1} [Pb+p]

- Classify events according to event activity class, scale to allow direct comparison.



  - Total function defined as

$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2 N_{\text{pair}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi} = \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)} \times B(0,0),$$

Where N trig is the amount of particles per bin and

Same event

$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2 N_{\text{same}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi}.$$

Mixed events

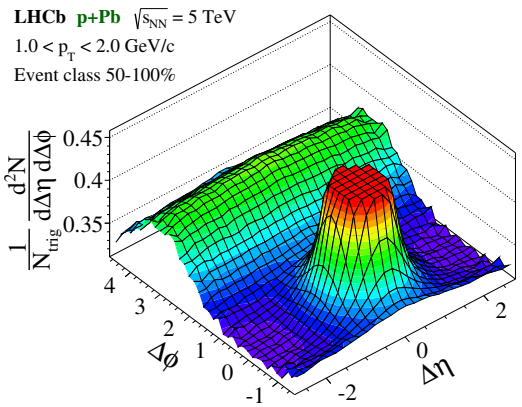
$$B(\Delta\eta,\Delta\phi) = \frac{\mathrm{d}^2 N_{\text{mix}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi}$$

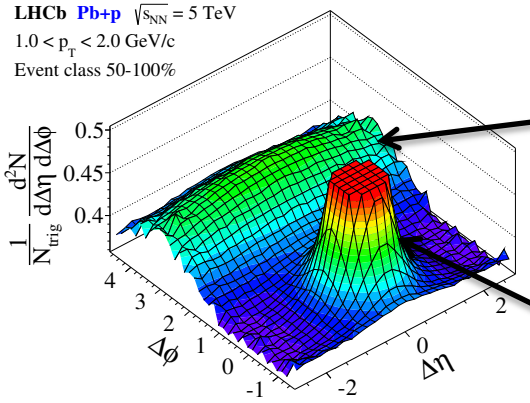
Ridge effect in pA collisions (II)

- Confirm ridge in high multiplicity events seen by other experiments!

arXiv:1512.00439

Low activity

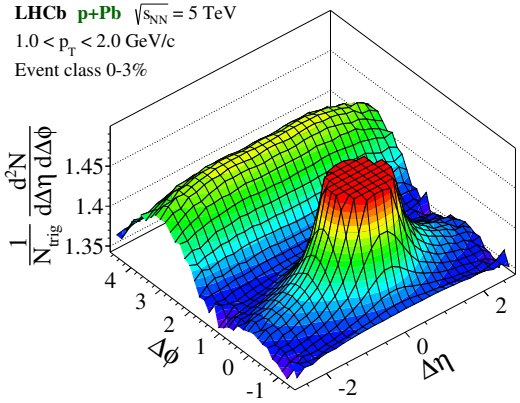


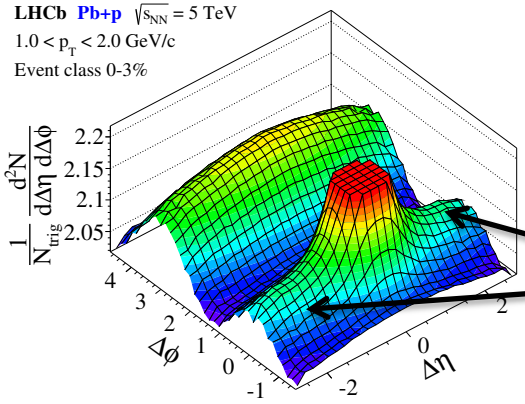


Away side structure: Momentum conservation

Near side + short range structure: Jets

High activity





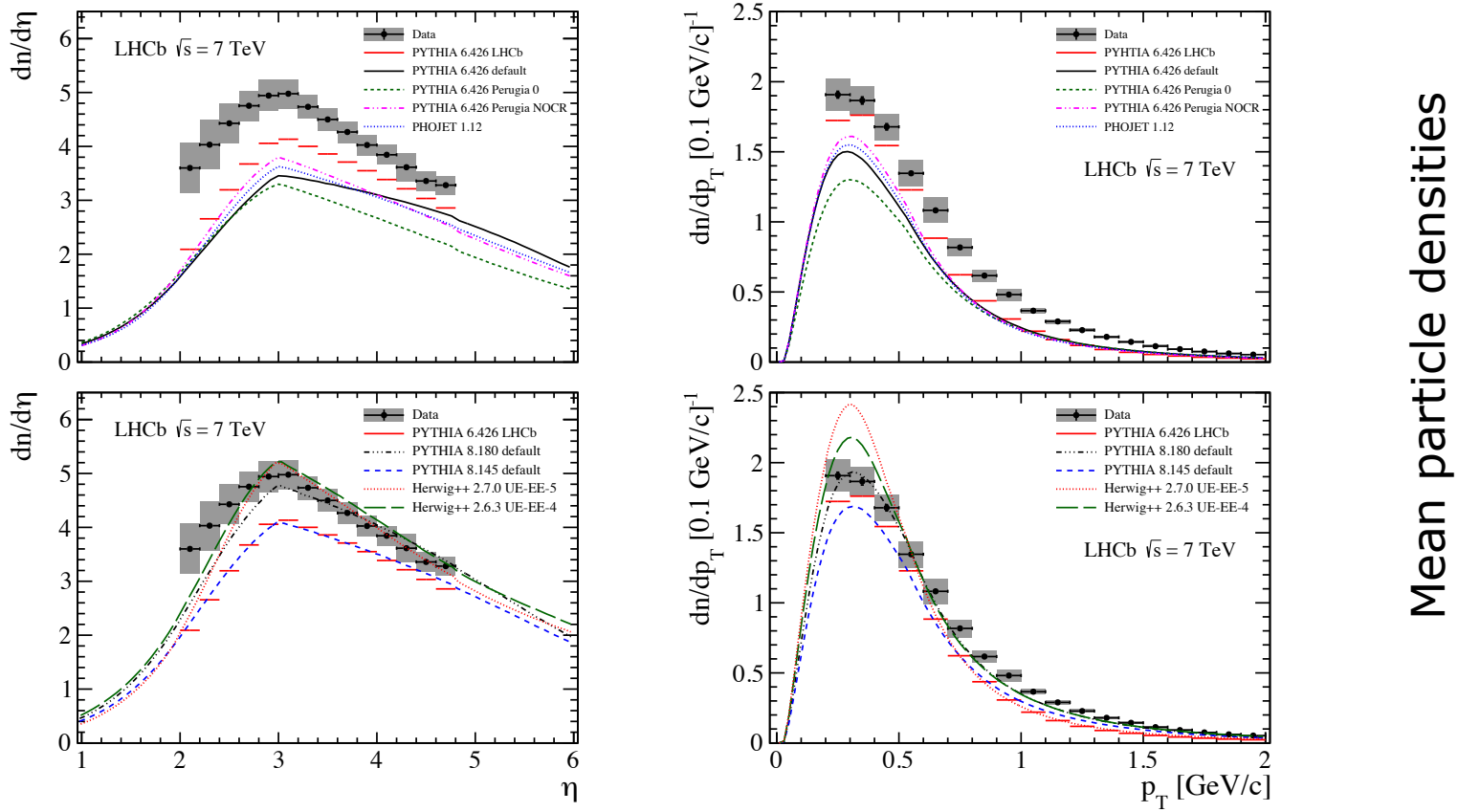
Near side long range structure: **Ridge**!

p+Pb Pb+p

Particle multiplicities

Eur. Phys. J. C (2014) 74:2888

- Minimum bias measurement with $\sqrt{s}$ = 7 TeV
  - $2 < \eta < 4.8$, $p > 2$ GeV/c, $p_T > 0.2$ GeV/c
  - Allows comparison with different MC generators!

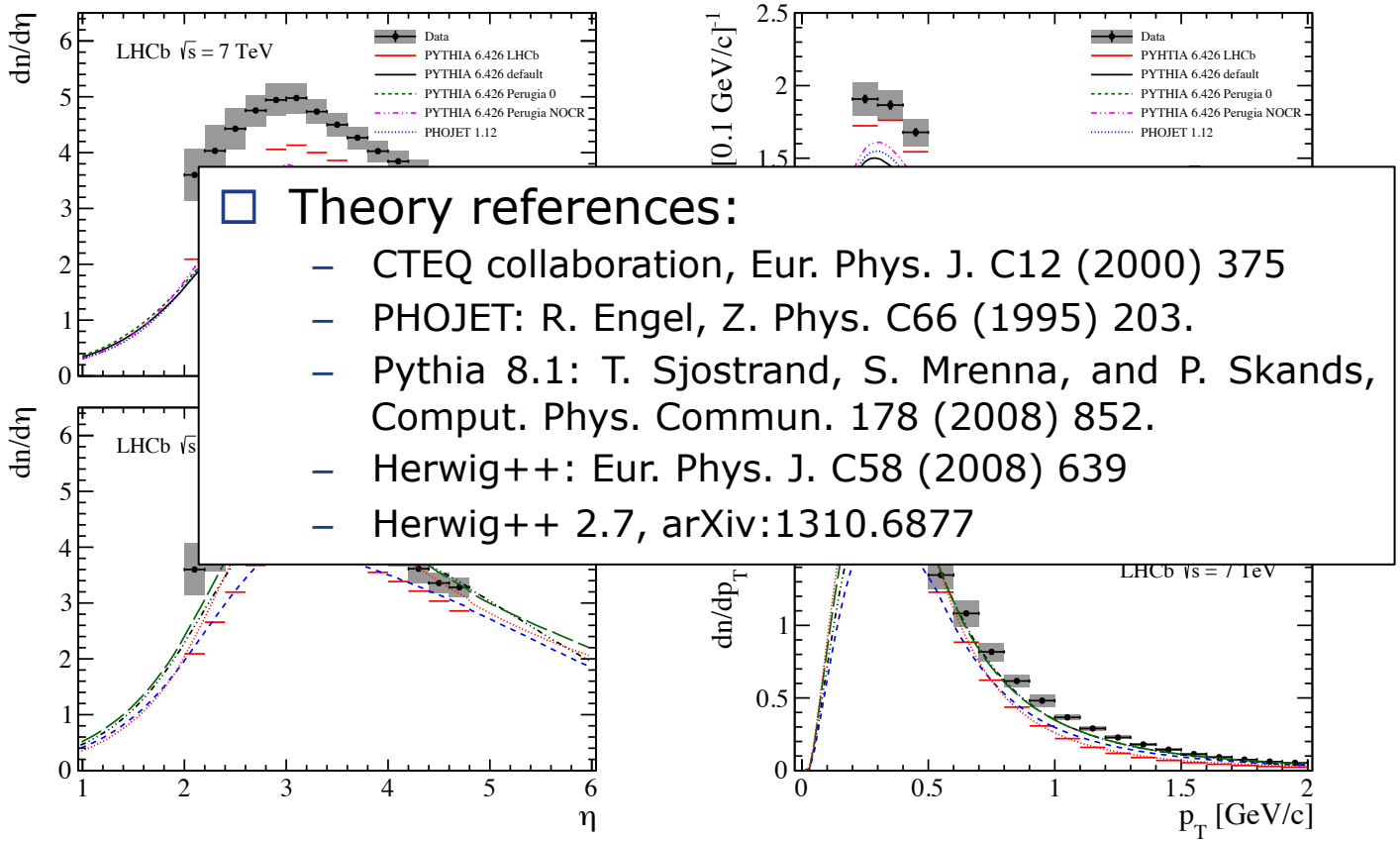


Mean particle densities

Particle multiplicities

Eur. Phys. J. C (2014) 74:2888

- Minimum bias measurement with $\sqrt{s}$ = 7 TeV
  - $2 < \eta < 4.8$, $p > 2$ GeV/c, $p_T > 0.2$ GeV/c
  - Allows comparison with different MC generators!



- Theory references:
  - CTEQ collaboration, Eur. Phys. J. C12 (2000) 375
  - PHOJET: R. Engel, Z. Phys. C66 (1995) 203.
  - Pythia 8.1: T. Sjostrand, S. Mrenna, and P. Skands, Comput. Phys. Commun. 178 (2008) 852.
  - Herwig++: Eur. Phys. J. C58 (2008) 639
  - Herwig++ 2.7, arXiv:1310.6877

Inelastic pp cross-section

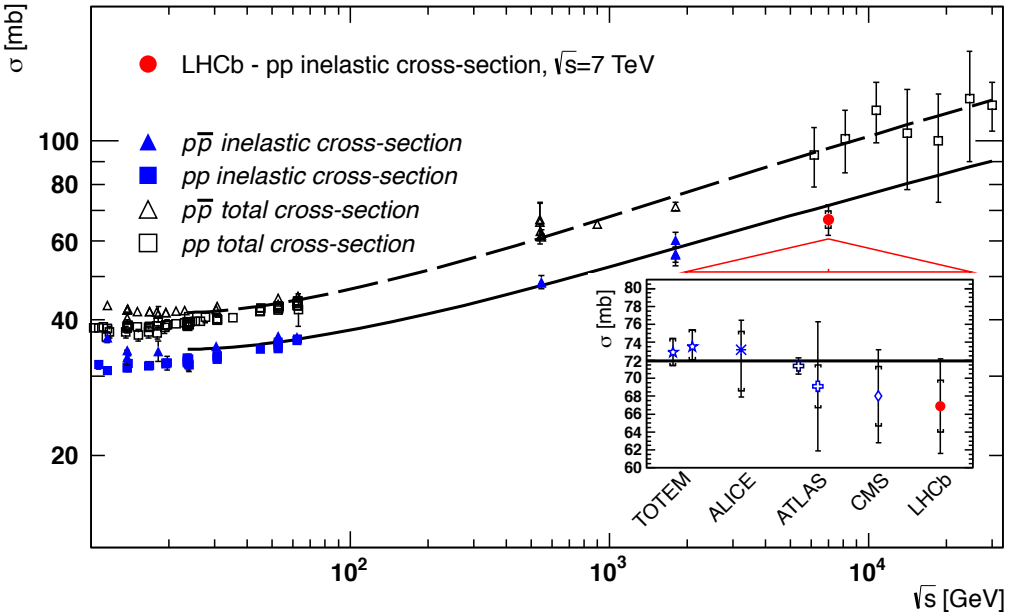
JHEP 1502 (2015) 129

- Measured inelastic proton-proton collisions, with at least one particle with p_T>0.2 GeV/c ; 2.0<η<4.5
  - Measurement done at √s = 7 TeV
  - Uncertainty dominated by systematics (luminosity)

$$\sigma_{\text{inel}}^{\text{acc}}(p_{\text{T}} > 0.2\ \text{GeV}/c,\ 2.0 < \eta < 4.5) = 55.0 \pm 2.4\ \text{mb}$$

Fully systematic uncertainty, statistical tiny in comparison!

  - Extrapolation to full acceptance with Pythia



Inelastic pp cross-section

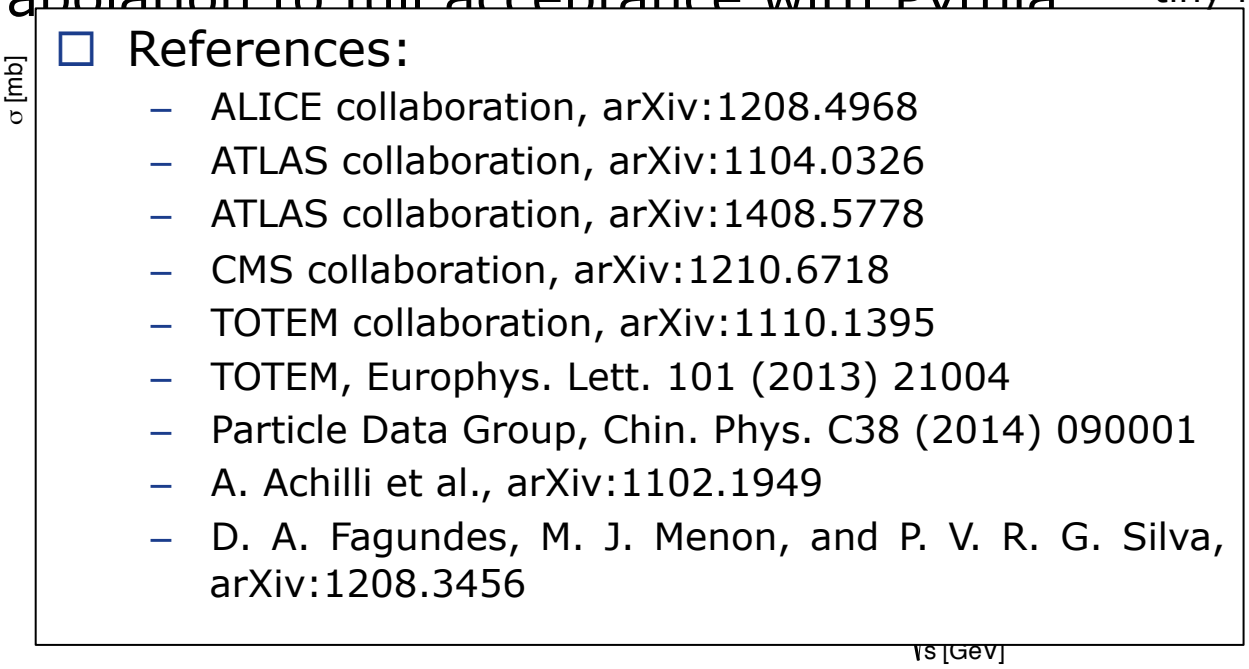
JHEP 1502 (2015) 129

- Measured inelastic proton-proton collisions, with at least one particle with p_T>0.2 GeV/c ; 2.0<η<4.5
  - Measurement done at √s = 7 TeV
  - Uncertainty dominated by systematics (luminosity)

$$\sigma_{\text{inel}}^{\text{acc}}(p_{\text{T}} > 0.2\ \text{GeV}/c,\ 2.0 < \eta < 4.5) = 55.0 \pm 2.4\ \text{mb}$$

Fully systematic uncertainty, statistical tiny in comparison!

  - Extrapolation to full acceptance with Pythia



- References:
  - ALICE collaboration, arXiv:1208.4968
  - ATLAS collaboration, arXiv:1104.0326
  - ATLAS collaboration, arXiv:1408.5778
  - CMS collaboration, arXiv:1210.6718
  - TOTEM collaboration, arXiv:1110.1395
  - TOTEM, Europhys. Lett. 101 (2013) 21004
  - Particle Data Group, Chin. Phys. C38 (2014) 090001
  - A. Achilli et al., arXiv:1102.1949
  - D. A. Fagundes, M. J. Menon, and P. V. R. G. Silva, arXiv:1208.3456

Conclusions

- Wide program on QCD physics at LHCb!
- Exploit our unique geometry to complement other experiments
- Presented results related to
  - EW bosons
  - Central Exclusive Production
  - Heavy ion physics
- Many data yet to be analyzed and to be taken (Herschel, 2015 data…), stay tuned!

Backup

b/c jet tagging at LHCb

JINST 10 P06013

- ParticleFlow jets with anti-k_T (R=0.5)
  - Inclusive 2-body vertexing merged in n-body vertices (SV)
  - light jet mistag rate < 1%, ε_b ~ 65%, ε_c ~ 25%
  - SV properties (displacement, kinematics, multiplicity,...) and jet properties combined in two BDTs.
  - $BDT_{bc|udsg}$ optimised for heavy flavour versus light discrimination.
  - $BDT_{b|c}$ optimised for b versus c discrimination.