Overview of LHCb Monte Carlo Simulation Framework

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Outline

- Particle Simulation in High Energy Physics
  The LHCb Detector at the LHC

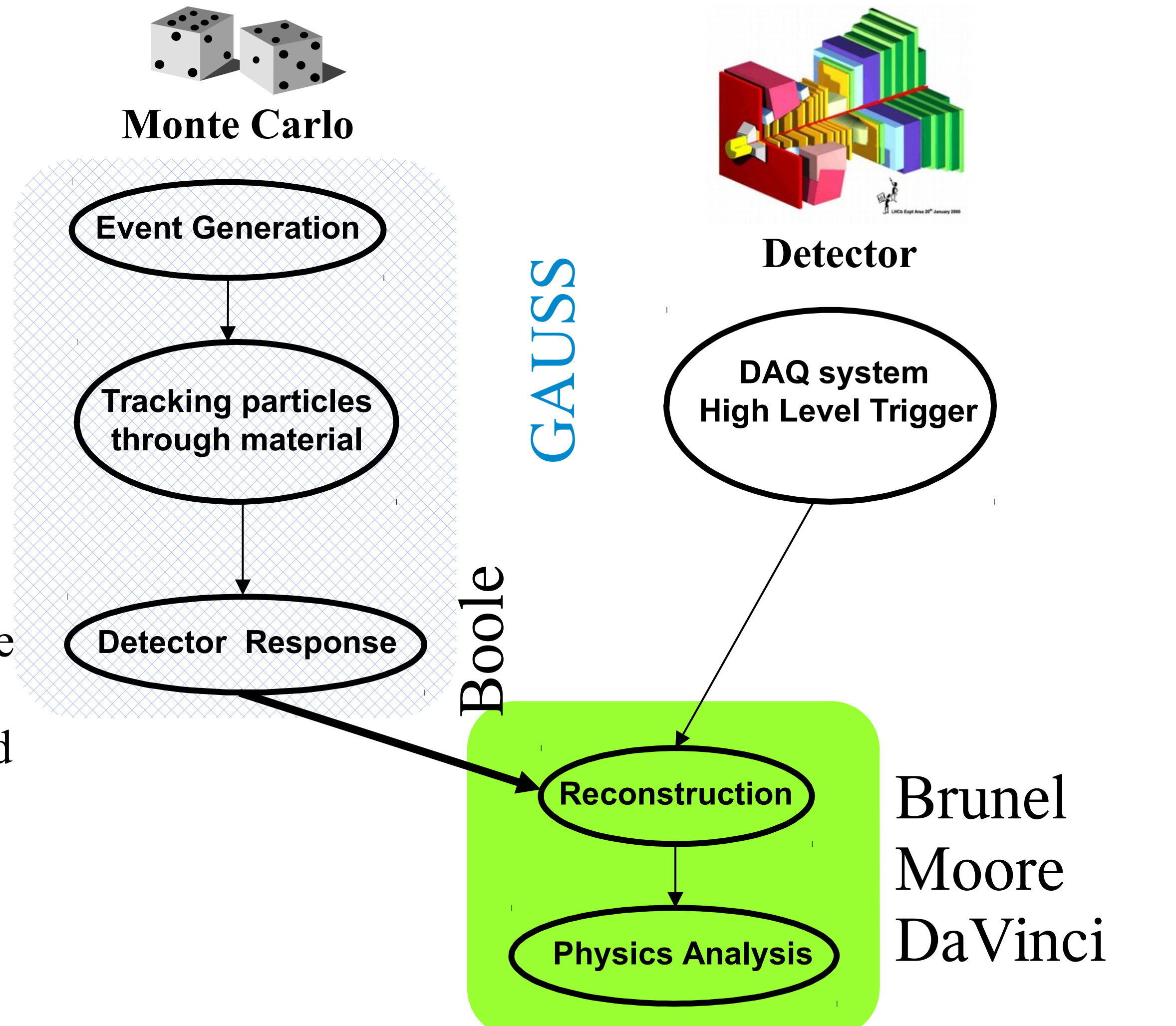
- The LHCb Simulation Software Framework

- Summary & Outlook at LHCb Simulation Upgrades

Particle Simulation in High Energy Physics

- Event Generation. Detector Simulation
  - implement collision model
  - generate (un)stable particles
  - perform unstable particle decay;
    get final state particles (fsp)
  - restrict to detector fiducial phase space
  - propagate fsp through detector material
  - simulate detector response

- Candidate Particle Reconstruction. Physics Analysis
  - reconstruct generated particles using same methods as for recorded (real) data
  - match reconstructed particles to generated particles
  - compare simulation to reality:
    direct interpretation,
    obtain efficiencies to extrapolate measurement to generator level, i.e. eliminate detector effects from measurement on real data



G. Corti, "LHCb Simulation(s)", LHCb UK Students Meeting, 28th April 2014

The LHCb detector at the LHC *

JINST 3 (2008) S080005; IJMP A30 (2015) 1530022

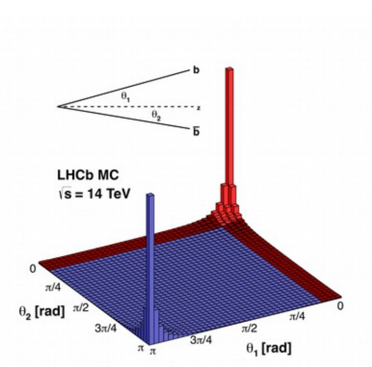
Fully instrumented single-arm spectrometer.

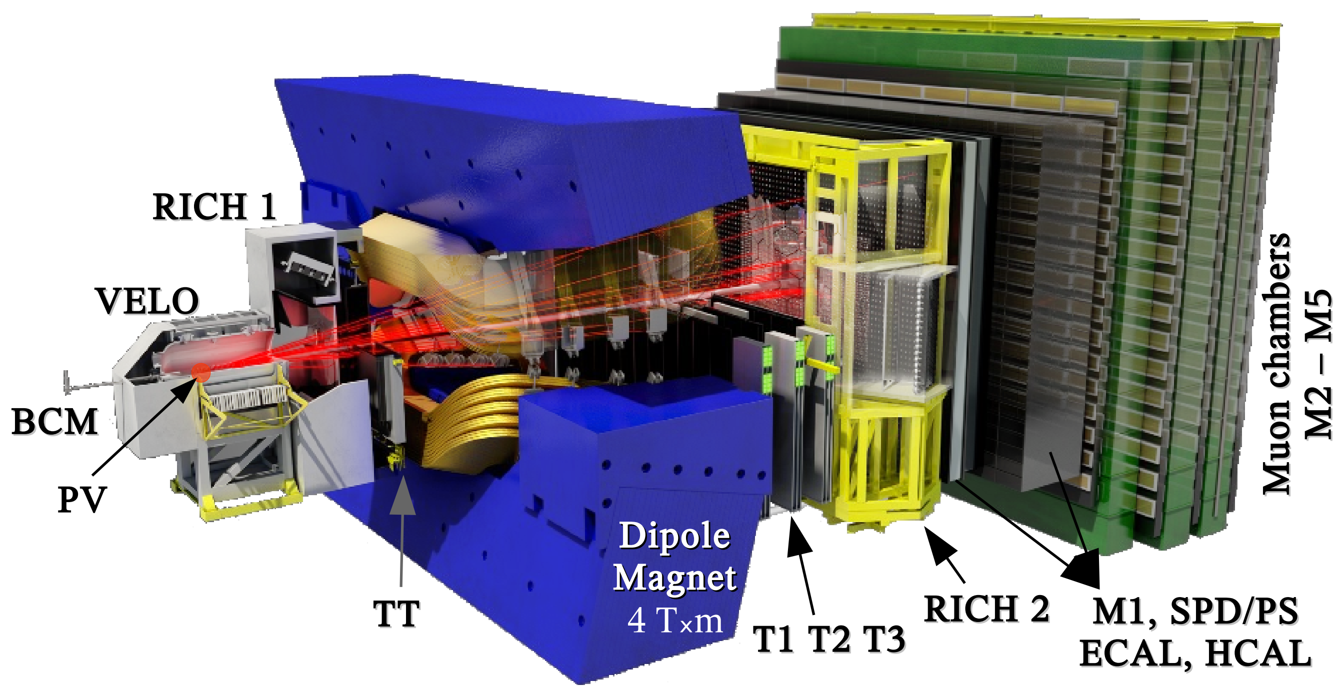
Unique pseudorapidity range:
- forward: $2 < \eta < 5$
- backward: $-3.5 < \eta < -1.5$ (PV in **VE**rtex **Lo**cator; no momentum measurement)

High precision tracking & vertexing: Impact Parameter (IP) resolution ~20 μm at high-p_T

Momentum resolution ($\Delta p / p$): from 0.5 % below 20 GeV/c to 1.0 % @ 200 GeV/c

Good PID efficiency:
– π, p, K: RICH 1,2
– e, γ, μ: CALO/M1-M5



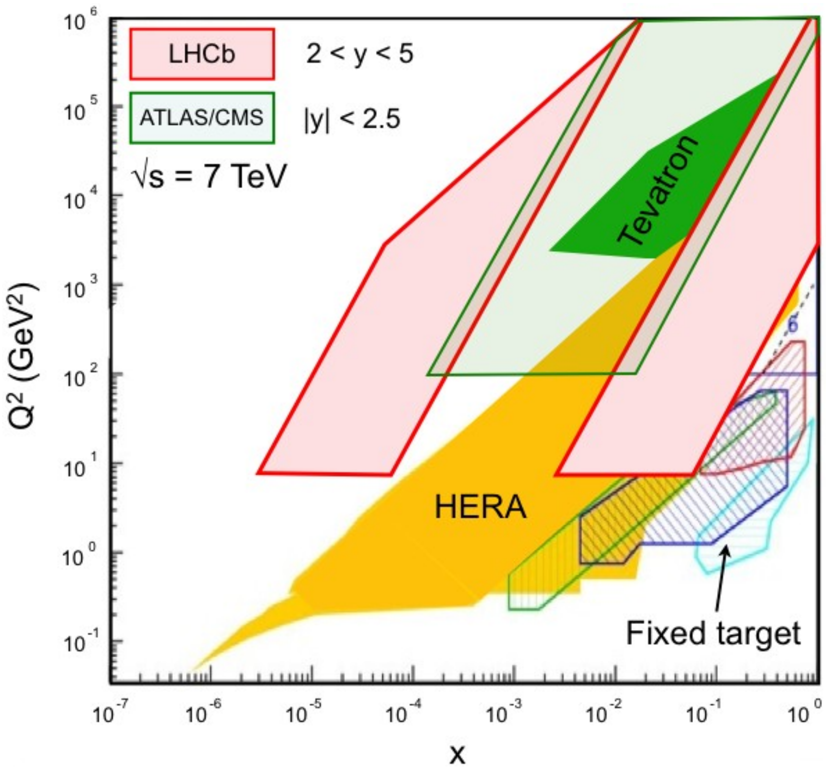


* more details in back-ups

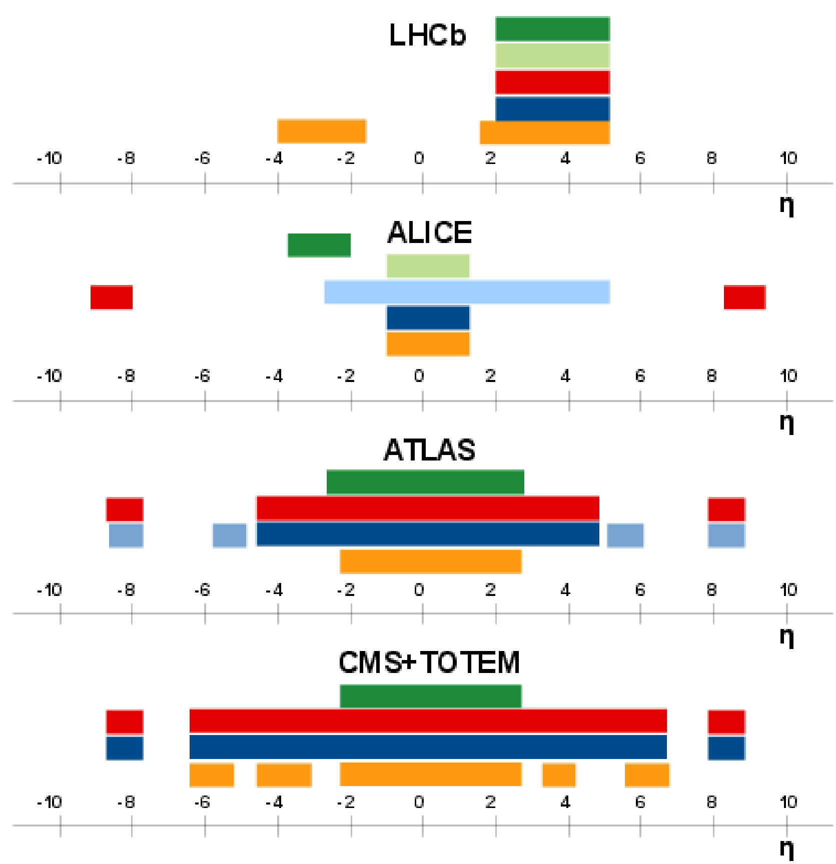
The LHCb detector at the LHC

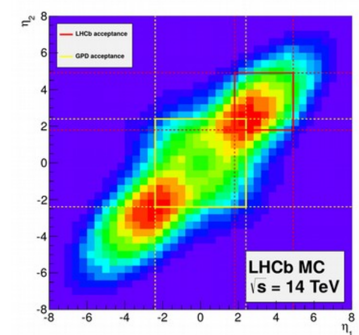
JINST 3 (2008) S080005; IJMP A30 (2015) 1530022

Also access low x_{Bj} (~ 10^{-6}) and low Q^2 (> 10 GeV^2).



LHCb covered phase-space region complementary to other detectors at LHC

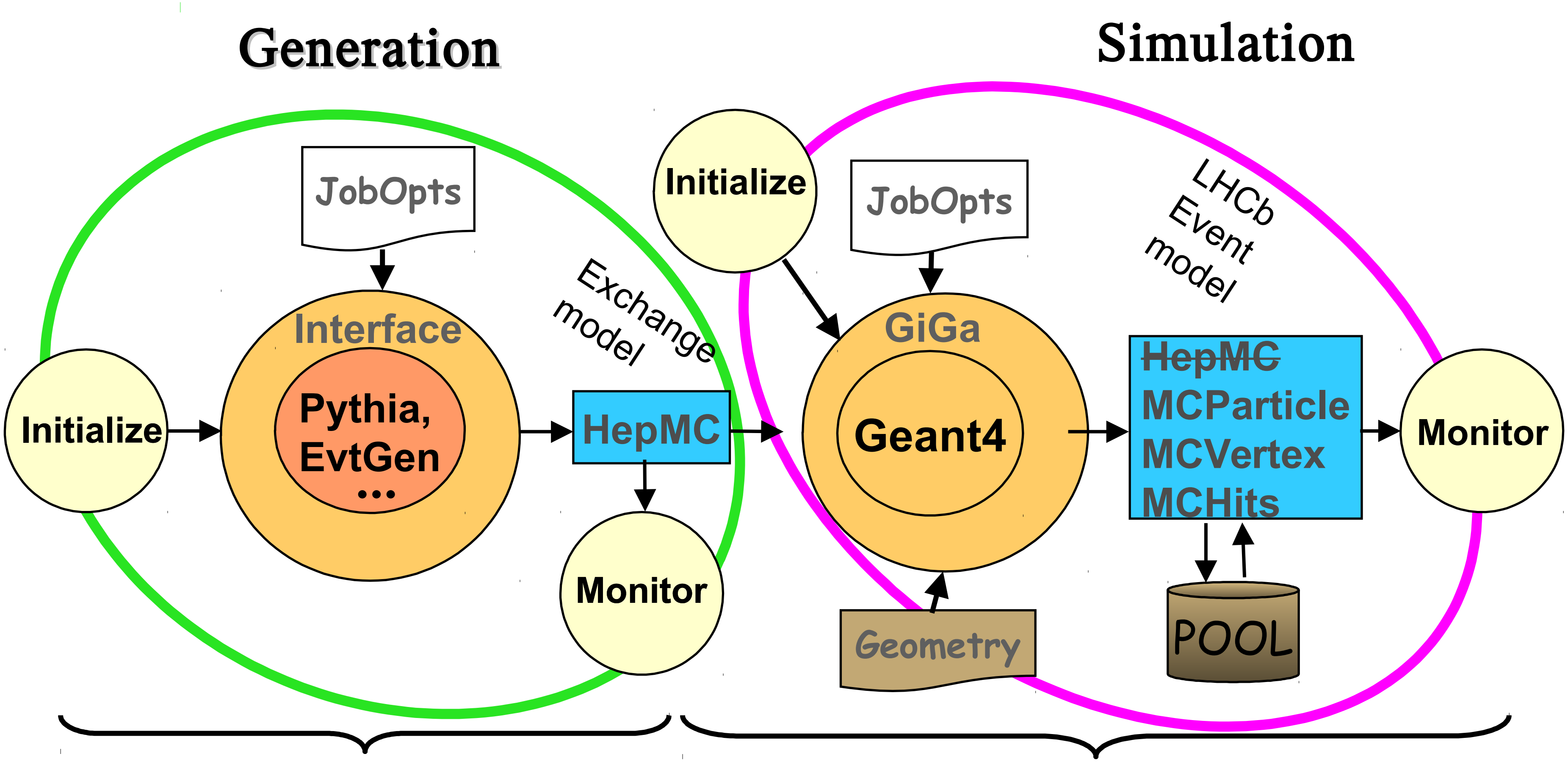




Recorded data sample statistics in back-ups

LHCb Simulation Software Framework - GAUSS

Two separate steerable stages that can be run independently:



Event Generation

primary event generator
specialized decay package
pile-up generation

Detector Simulation

geometry of the detector (LHCb → Geant4)
tracking through materials (Geant4)
hit creation and MC truth information (Geant4 → LHCb)

M.Clemencic, G. Corti et al., “The LHCb Simulation Application, Gauss: Design, Evolution and Experience”, CHEP-2010, Taipei

MC Event Generators in GAUSS

- Virtualizing production theoretical model implementation – GAUDI ProductionTool classes (examples in back-ups) with specific interfaces
- Reproduce specific cocktails of generation-decay model implementations
- General Purpose Event Generators (GPEG) – compromise QCD, global description of whole event
  - ➔ Toolkit for High Energy Physics Event Generation – ThePEG based:
    - **PYTHIA 6.427.2 & PYTHIA 8.186** – successor to JETSET (since 1978)
    - HERWIG – successor to EARWIG (since 1984);
  - ➔ SHERPA – developed since 2000s (different architecture, newly added)
  - ➔ CRMC 1.5.6 – implementing cosmic ray models: EPOS, PHOJET, QSJET, SIBYLL (see A. Ene's talk)

MC Event Generators in GAUSS

- Specialized Generators – provide in detail specific aspects of generated event; (some times) pluggable into GPEGs; for LHCb – Gaudi interfaces spiced for experiment needs
  - ALPGEN – multi-parton processes in hadronic collisions
  - GenXicc, SuperChic, BCVEGPY – modelling production of heavy hadron states containing *b* and *c* quarks
  - Photos++ – generate bremsstrahlung photons in decay of particles and resonances
  - Tauola++ – C++ interface to Tauola to simulate narrow τ lepton decay with spin and electro-weak corrections
  - POWHEGBOX – NLO calculations for showering
  - HIJING 1.383 – particle production in high energy hadronic and nuclear collision focusing on the accompanying jet structures
  - EvtGen – main component to model heavy flavour hadron decays. Steered by so-called dkfiles (more details in Elena's talk)

Simulation in GAUSS

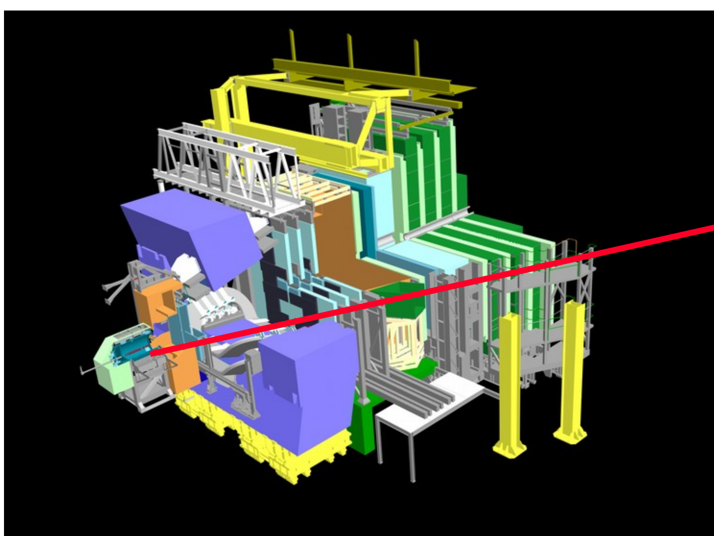
- Detector simulation based on GEANT4

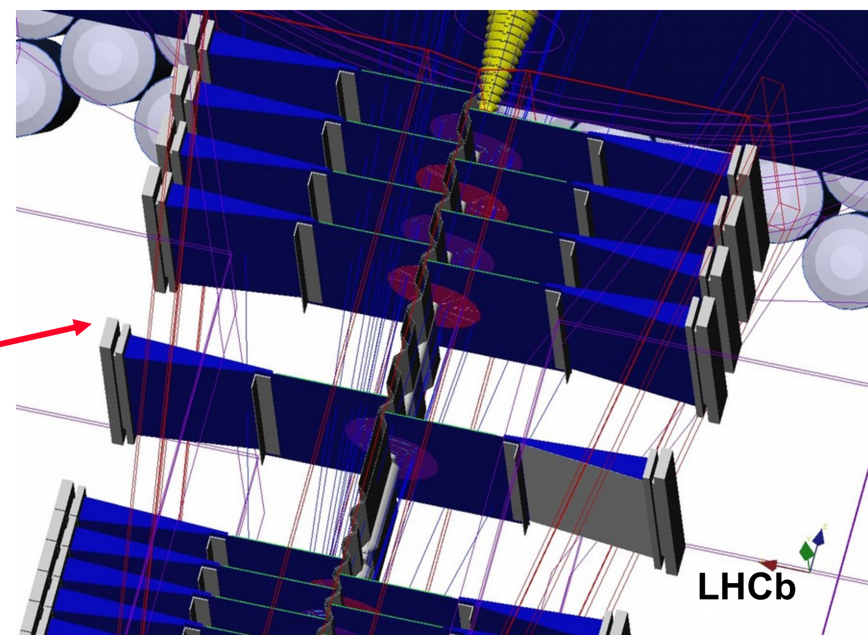
  ➔ Converting (friendly) XML detector description (DDDB) to GEANT4 geometry – allows in/exclusion of individual sub-detectors

  ➔ Status of sub-detector parts controlled from data base of conditions (CondDB; for simulation a.k.a. SimCondDB)

  ➔ Detector material description (accurate, but fast)

G. Corti, “LHCb Simulation(s)”, LHCb UK Students Meeting, 28th April 2014





LHCb VErtex LOcator

Simulation in GAUSS

- GEANT4 simulates a great variety of physics processes combined in Physics Lists (PL):
  - Mixture of theory/parametrization-based and empirical formulae
  - Library of physics process simulation implementation:
    Standard and Low energy EM processes, Hadronic and nuclear processes, Optical photon processes, Decay processes, etc.
  - Extend/tweak PL – implement processes in GAUSS:
    e.g. for RICH: photoelectric process (creation of photoelectrons in HPDs), energy loss in the silicon of HPDs
- Provide collections of hits, secondary and surviving primary particles
- Digitize detector response in Boole
- Reconstruct primary particles in Brunel
- Emulate hardware and software trigger response in Moore
- Further selection for physics analysis in DaVinci
- In simulation one *always* knows the truth – final state particles related to initial state ones

Summary & Outlook at Simulation Upgrade

➢ Unique fiducial volume at LHC experiments

➢ GAUSS – the Gaudi-based LHCb Simulation Software.
Evolving into experiment independent framework Gaussino – w/ help from ATLAS, ILC; under FCC supervision.

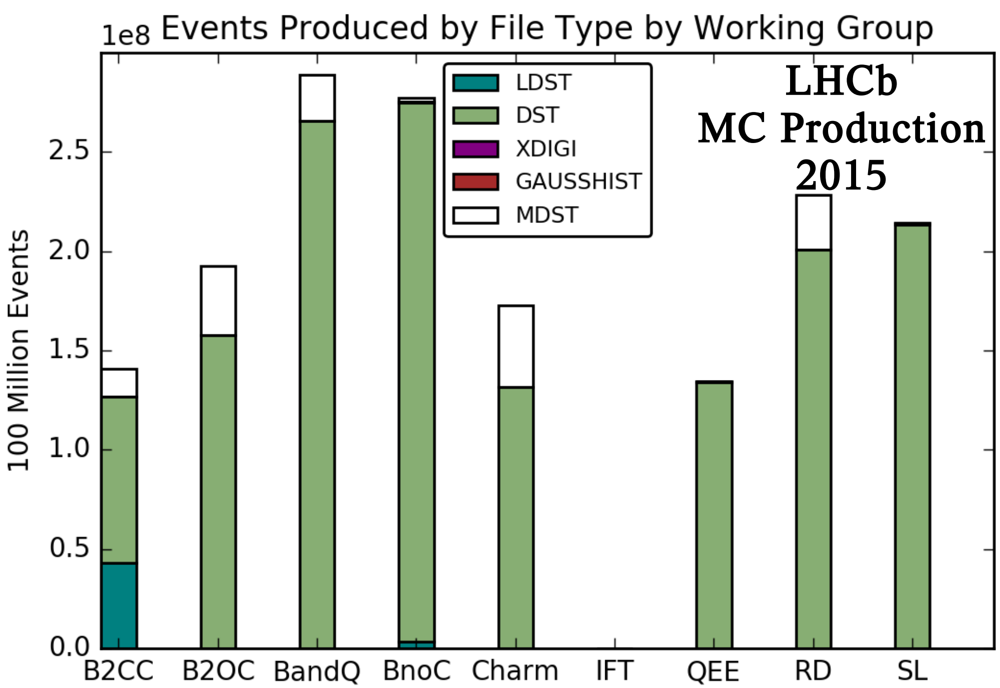
➢ MC Generator Tuning: individually running in GAUSS or specific GAUSS flavour "cocktail" (specialized generator + GPEGs) – improvement of data description.
Plethora of measurements to be used as reference in event generator tuning

→ back-ups!

➢ Simulation phase. Detailed description of (sub)detector. Yet, keep it fast !
FLUKA

➢ Keep up with (sub)detector upgrades.
Optimize material knowledge.

➢ Go to GEANT4.10 MT on GRID.



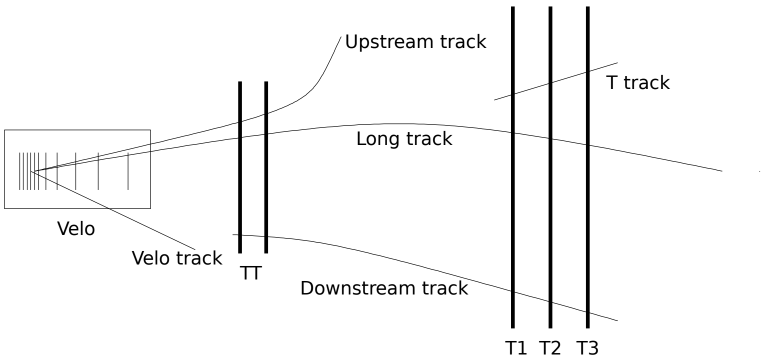
Thank you!

BACKUPS

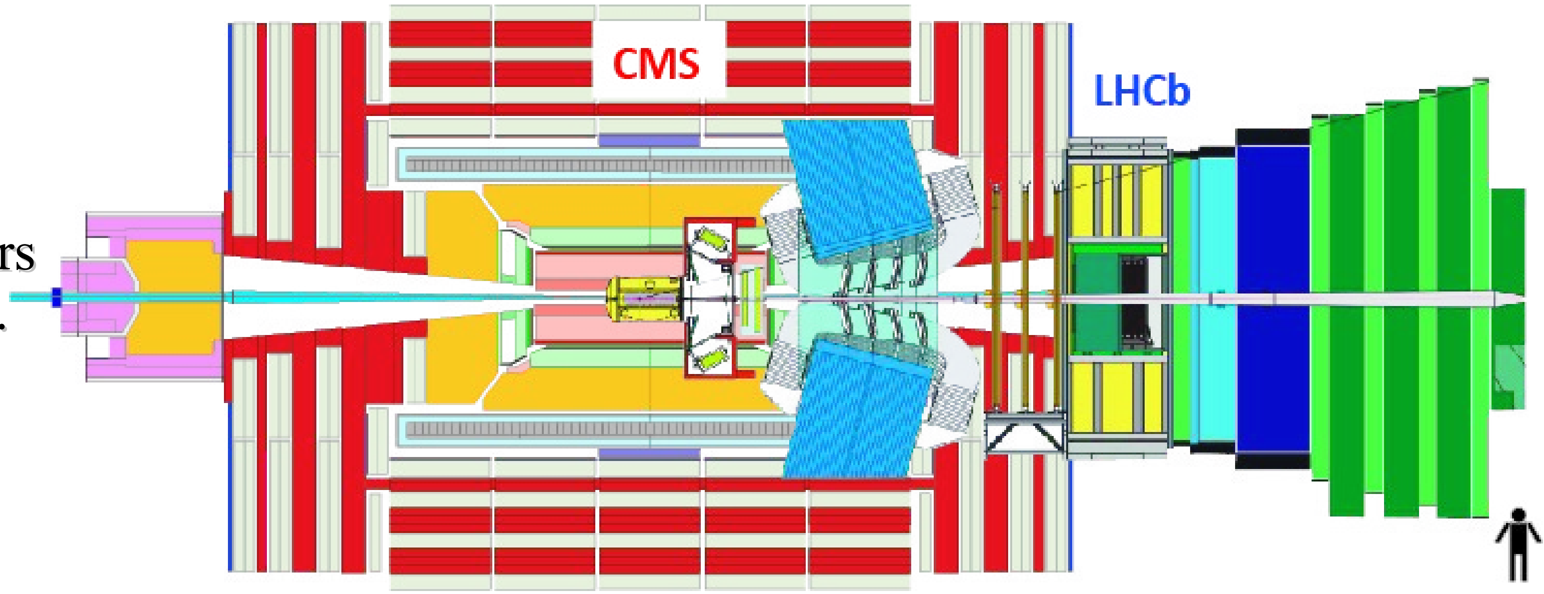
The LHCb Detector Performance

IJMP A30 (2015) 1530022

- **Impact Parameter (IP) resolution:** $(15 + 29/p_T[\mathrm{GeV/c}])$ μm, i.e., ~ 20 μm at high p_T
- **Momentum resolution:** $\Delta p/p \sim 0.5$ % ($p < 20$ GeV/c) → 1.0 % ($p \sim 200$ GeV/c)
- **ECAL resolution (nominal):** 1 % + 10 %/ $\sqrt{(E[\mathrm{GeV}])}$
- **Invariant mass resolution:**
  - ~8 MeV/c^2 for B → J/ψ X decays with constraint on J/ψ mass
  - ~22 MeV/c^2 for two-body B decays
  - ~100 MeV/c^2 for Bs → φ γ, dominated by photon contribution
- **Trigger efficiencies:**
  - ~90 % for dimuon channels
  - ~30 % for multi-body hadronic final states
- **Track reconstruction efficiency:** ~ 96% for Long Tracks
- **Particle ID efficiency:**
  - Electron ID ~ 90 % for ~ 5 % e→h mis-id probability
  - Kaon ID ~ 95 % for ~ 5 % π→K mis-id probability
  - Muon ID ~ 97 % for 1-3 % π→μ mis-id probability
- **Integrated luminosity for datasets:**
  - 7 TeV (2011): 1.0/fb ± 1.7%
  - 8 TeV (2012): 2.0/fb ± 1.2%
  - 13 TeV (2015): 0.3/fb ± 3.9% (to improve in 2016)
- **Data taking efficiency:** 90% (99% good for physics analyses)



The LHCb Detector & Data Samples



Extends central detectors phase coverage at LHC.

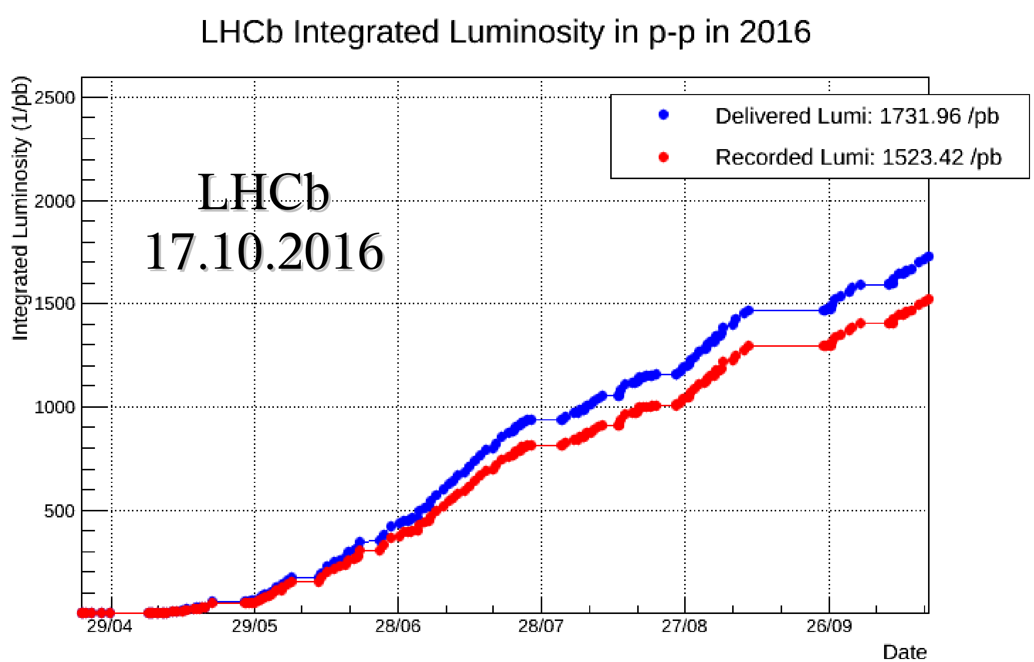
Integrated luminosity

LHC Run I

2010: 37 pb^{-1} 2011: 1.0 fb^{-1} 2012: 2 fb^{-1}

LHC Run II

2015: 1.0 fb^{-1} 2016: >1.5 fb^{-1}



Event Generator Tunes & Theoretical Models

- PYTHIA 6.4 — T. Sjöstrand, S. Mrenna, P. Skands, JHEP **05** (2006) 026

LHCb MC tune (GAUSS: PYTHIA6.4+EVTGEN+PHOTOS)
I. Belyaev *et al.*, Nuclear Science Symposium Conference Record (NSS/MIC) (IEEE, New York 2010), p. 1155

Perugia0, PerugiaNOCR, Perugia 2010 tunes — P. Z. Skands, Phys. Rev. D **82** (Oct, 2010) 074018

- PYTHIA 8.1 — T. Sjöstrand, S. Mrenna, P. Skands, Comput. Phys. Commun. **178** (2008) 850

- Cosmic-ray models:
  - **EPOS**: T. Pierog and K. Werner, Nucl. Phys. Proc. Suppl. **196** (2009) 102
  - **QGSJET**: S. Ostapchenko, Status of QGSJET, AIP Conf. Proc. **928** (2007) 118
  - **SYBILL**: E.-J. Ahn *et al.*, Phys. Rev. D **80** (2009) 094003

- Other Monte Carlo Event Generators and Theoretical Models:
  - **PHOJET**: R. Engel, Z. Phys. C **66** (1995) 203; doi
  - **HERWIG++**: M. Bahr et al., Eur. Phys. J. C **58** (2008) 639-707; doi
  - **SUPERCHIC**: L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur. Phys. J. C 65 (2010) 433
  - **STARLIGHT**: S.R. Klein, J. Nystrand, Phys. Rev. Lett. **92** (2004) 142003

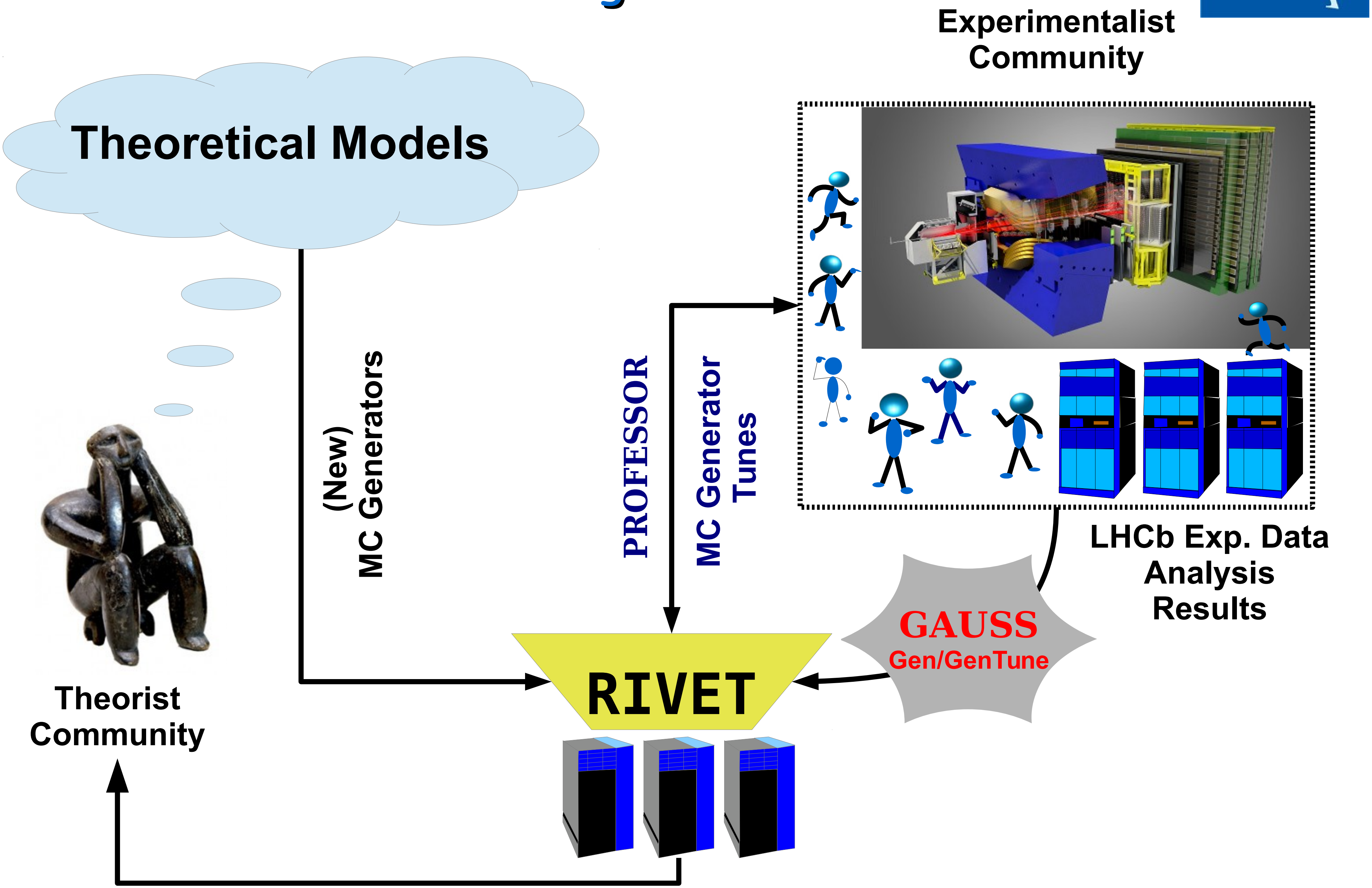
G&M model: V.P. Gonçalves and M.V.T. Machado, Phys. Rev. C **84** (2011) 011902; arXiv:1106.3036
Sch&S model: W. Schäfer and A. Szczurek, Phys. Rev. D **76** (2007) 094014; arXiv:0705:2887
JMRT model: Jones S., Martin A., Ryskin M. and Teubner T., JHEP **11** (2013) 085

- PythiaProduction: (being retired) interface to Pythia6
  Complete FORTRAN generator which contains a lot of different physics processes.
- Pythia8Production: (the new default) C++ Pythia version Pythia8 with the most recent developments
- HerwiggppProduction: General purpose with different production mechanism than Pythia
- HijingProduction: For ions interactions
- AlpGenProduction: NLO Hard Processes , in LHCb as s input to Pythia6 for now
- PowhegProduction: NLO Hard Processes , in LHCb as input to Pythia6 for now
- BcVegPyProduction: LHCb in house generator for B_c production, as input to Pythia6 (and 8 soon)
- GenXiccProduction: LHCb in house generator for Xi_{bc} and Xi_{cc} production, as input to Pythia6 (and 8 soon)
- SherpaProduction: General purpose, with proof of principle in LHCb, also for decays

What and How to Tune

- **Matrix Elements** – NO, but precise measurements may provide new/better values.
- **Hadronisation** – many parameters for flavour selection including *b* and *c* fragmentation functions, some for kinematics
- **Showers** – very sensitive in some generators. Optimize cut-off scale and coupling constant(s).
- **M**ultiple **P**arton **I**nteractions (MPI) – last before completing a tune to give as strict boundaries as possible
- **LHCb Approach to Tuning**
  - Limited by available measurements: use as many compatible sets as possible from different experiments at multiple energies; weight to favour data to describe
  - Start from existing (global) tunes
  - Keep in mind tunes in central region may not be best for forward region and vice versa
  - Preliminary re-tune of light flavour production – better match underlying event (UE)
  - Tune hadronisation of heavy flavour
  - Re-tune non-perturbative QCD sector
  - Hope for a quick convergence if not repeat
- **Method/Tools**
  - Parametrisation – Hamacher & Weierstall (1995) quadratic interpolation; re-implemented as Professor & RIVET (arXiv:hep-ph/1003.0694; EPJ C65 (2010) 331)

Professor/RIVET Integration in LHCb Software



LHCb Experimental Input to Generator Tuning

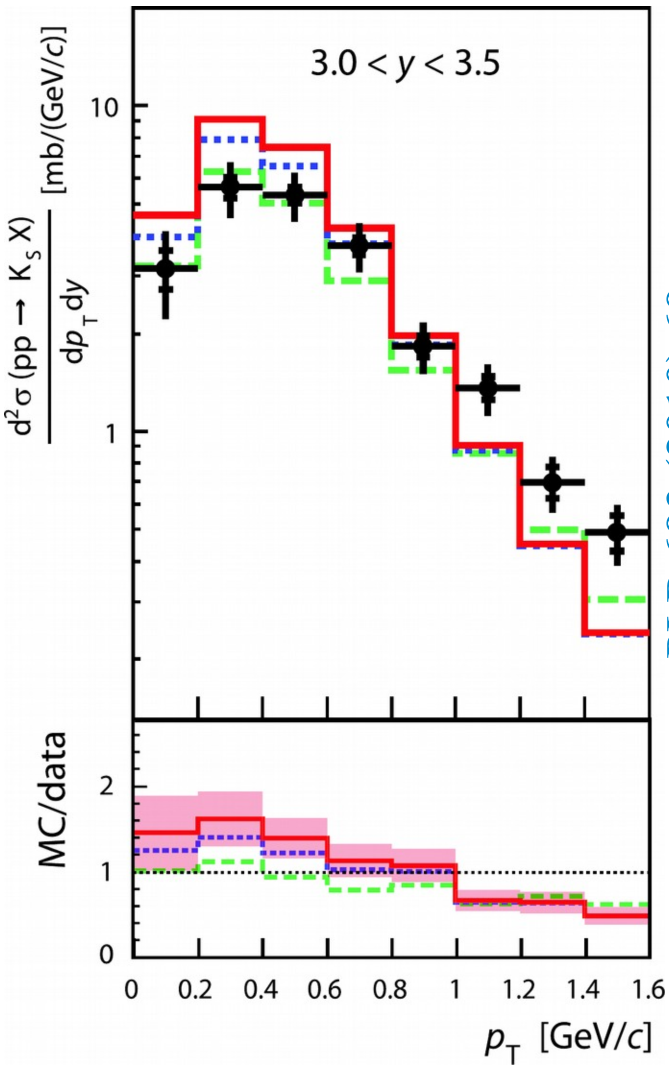
Light Flavour Production*

- K_S production:
  - 0.9 [PLB 693 (2010) 69]
  - 7 & 8 (limited by data sample)
  - 13 (on-going)

- V^0 ratios:
  - 0.9 & 7** [JHEP 08 (2011) 034]
  - 2.76, 13 (on-going)

- Φ production:
  - 7** [PLB 703 (2011) 267]
  - 13 (planned)

- Prompt light hadron:
  - 0.9 & 7** [EPJ C72 (2012) 2168]
  - 2.76, 13 (planned)



PLB 693 (2010) 69

* numbers represent √s in TeV for pp collisions
** used in first PYTHIA8 tuning in the forward region

- Many more measurements on-going; different √s; comparison to newer tunes from LHC data

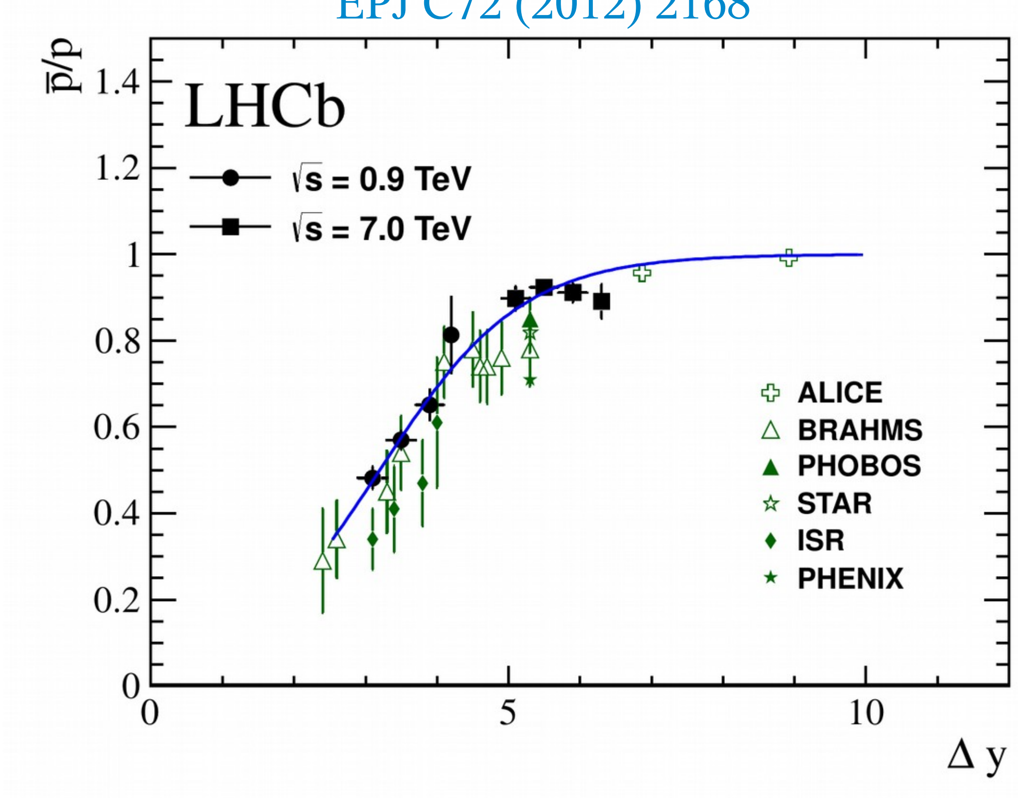
LHCb Experimental Input to Generator Tuning

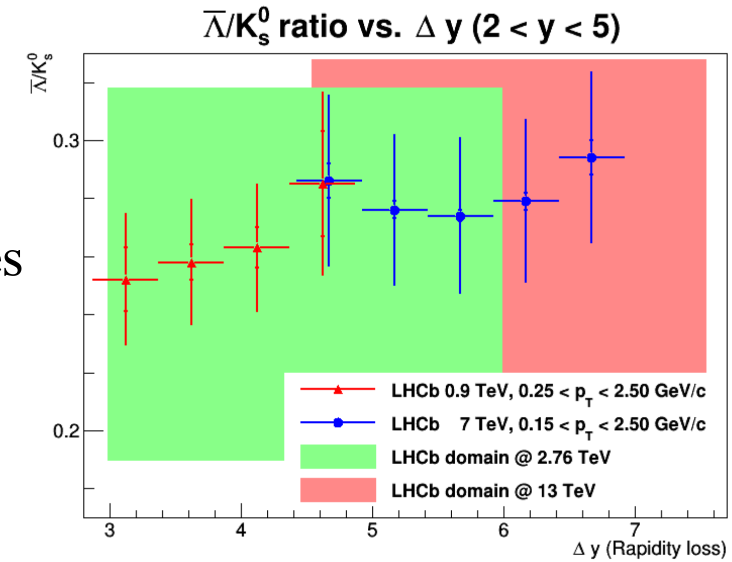
Light Flavour Production

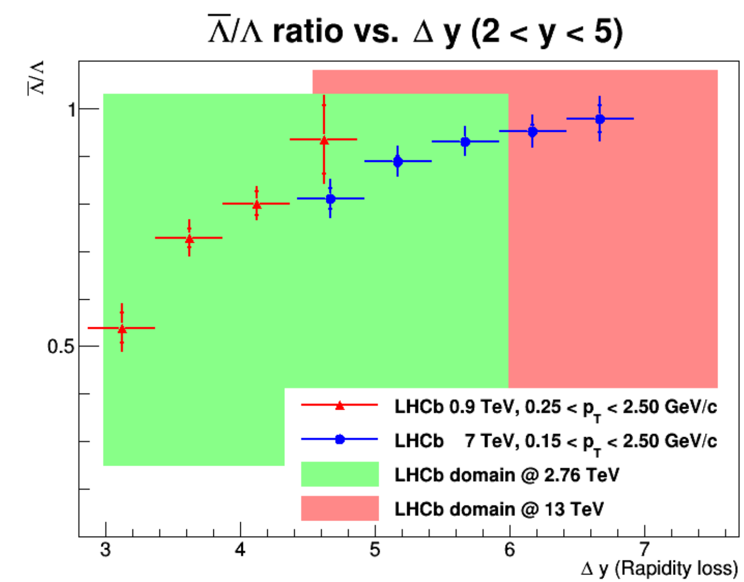
- (LHCb) **prompt light particles** include products of heavy hadron decays.

- Optimize baryon number transport ($\bar{p}/p$, $\bar{\Lambda}/\Lambda$), baryon supression ($\bar{\Lambda}/K_s$, $(\bar{p}+p)/(\pi^+ + \pi^-)$,…), strangeness production
- Further constraints from charged particle multiplicities

EPJ C72 (2012) 2168







JHEP 08 (2011) 034

LHCb Experimental Input to Generator Tuning

Global Event Characteristics

Charged particle multiplicities in pp collisions at 7 TeV

EPJ C72 (2012) 1947

Selection: at least 1 trk in $2 < \eta < 5$

Kinematic range: $-2.5 < \eta < -2.0$, $2.0 < \eta < 4.5$ (minbias);

$p_T > 1$ GeV/c, $2.5 < \eta < 4.5$ (hard QCD)

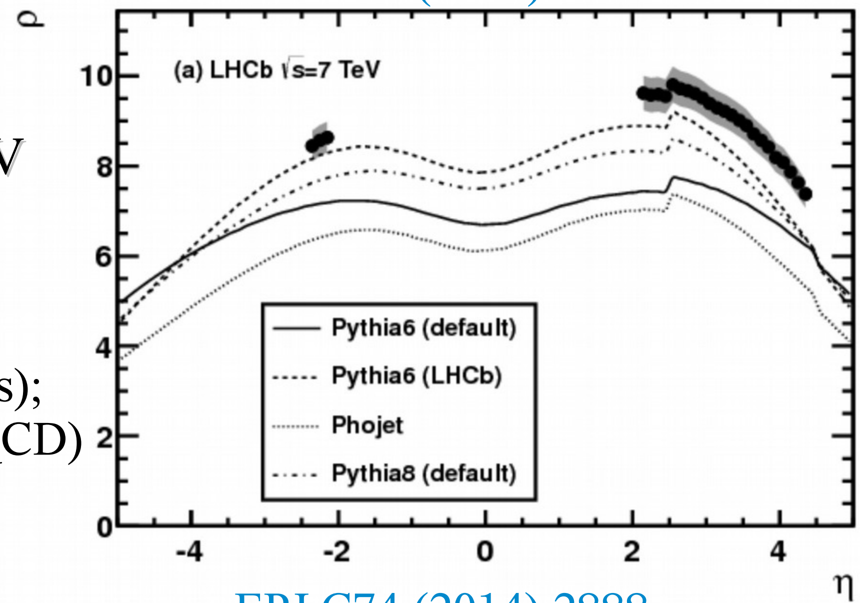
EPJ C74 (2014) 2888

Selection: $p_T > 0.2$ GeV/c, $p > 2$ GeV/c, $2.0 < \eta < 4.8$

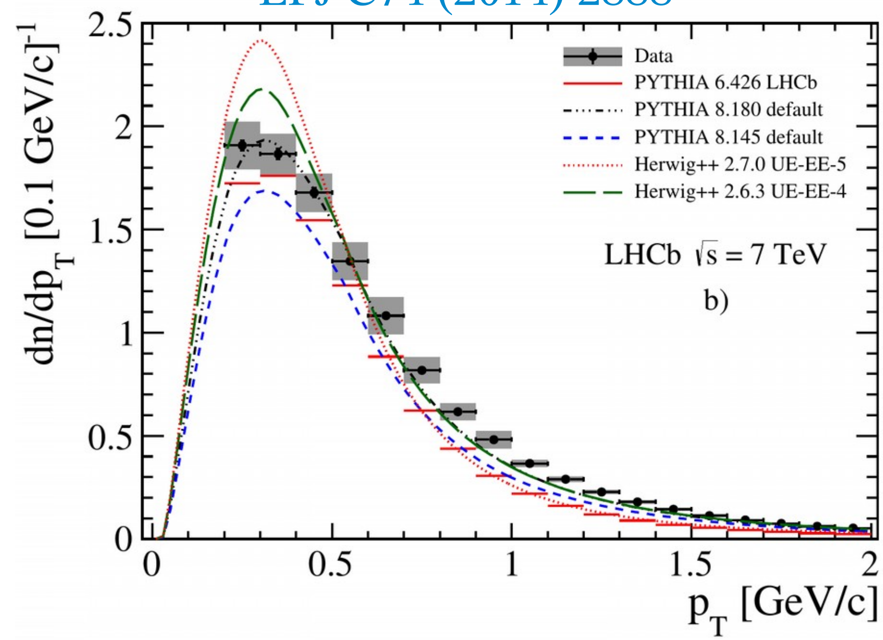
Kinematic range: $0.2 < p_T < 2.0$ GeV/c; $2.0 < \eta < 4.5$

13 TeV measurement on-going

EPJ C72 (2012) 1947



EPJ C74 (2014) 2888



LHCb Experimental Input to Generator Tuning

Global Event Characteristics

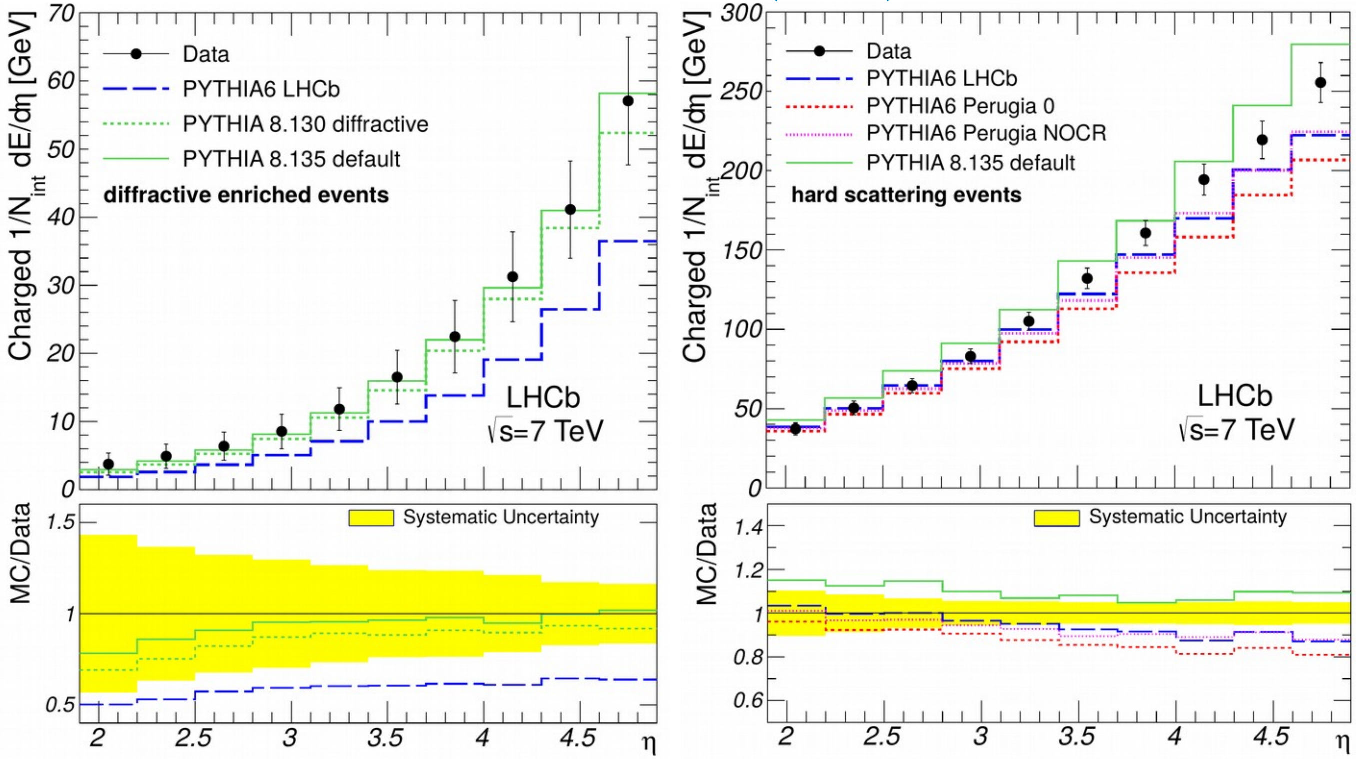
EPJ C73 (2013) 2421

Energy Flow at 7 TeV

Selection: at least 1 trk from PV

Event classes:

- minbias $1.9 < \eta < 4.9$, $2 < p < 10^3$ GeV/c
- hard scattering $p_T > 3$ GeV/c
- diffractive enriched no trk. in $-3.5 < \eta < -1.5$
- non-diffractive enriched at least 1 trk. $-3.5 < \eta < -1.5$



→ Largest divergence between models in forward region where LHCb data has smallest uncertainties. Reference for tuning both MC and cosmic ray generators.

- Important input to constrain MPI in the light flavour sector
- 13 TeV measurement on-going

LHCb Experimental Input to Generator Tuning

JHEP 02 (2015) 129

Global Event – Total Cross-sections

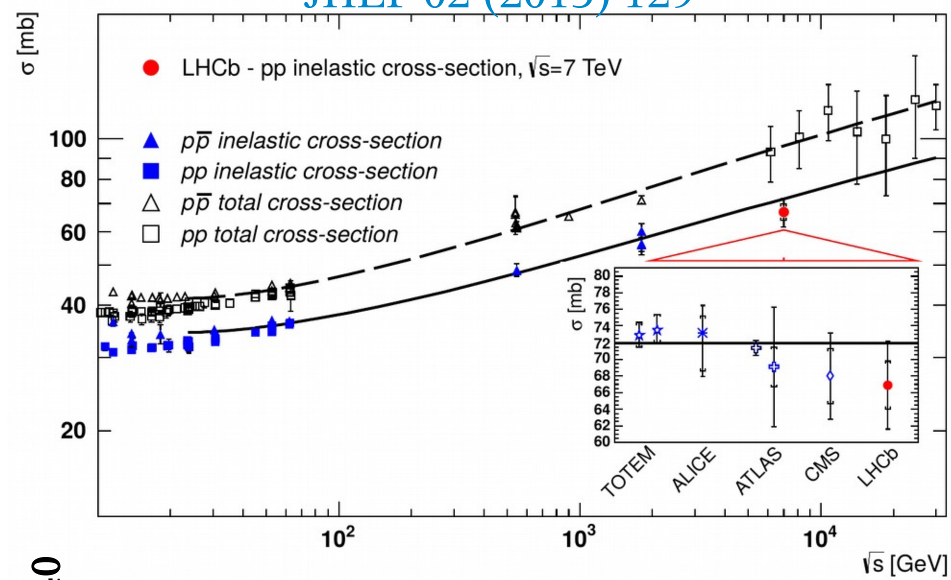
Inelastic pp cross-section @ 7 TeV

$$\sigma_{\rm inel}^{\rm acc} = 55.0 \pm 2.4 \text{ mb}$$

– prompt charged parts., $p_T > 0.2$ GeV/c, $2.0 < \eta < 4.5$

– main uncertainty from luminosity

– 13 TeV measurement is on-going



➔ Preliminary tune of total cross-sections separately from rest of steering parameters; rely on other LHC measurements:

- ATLAS

Nature Com. 2 (2011) 463, EJP C72 (2012) 1926;

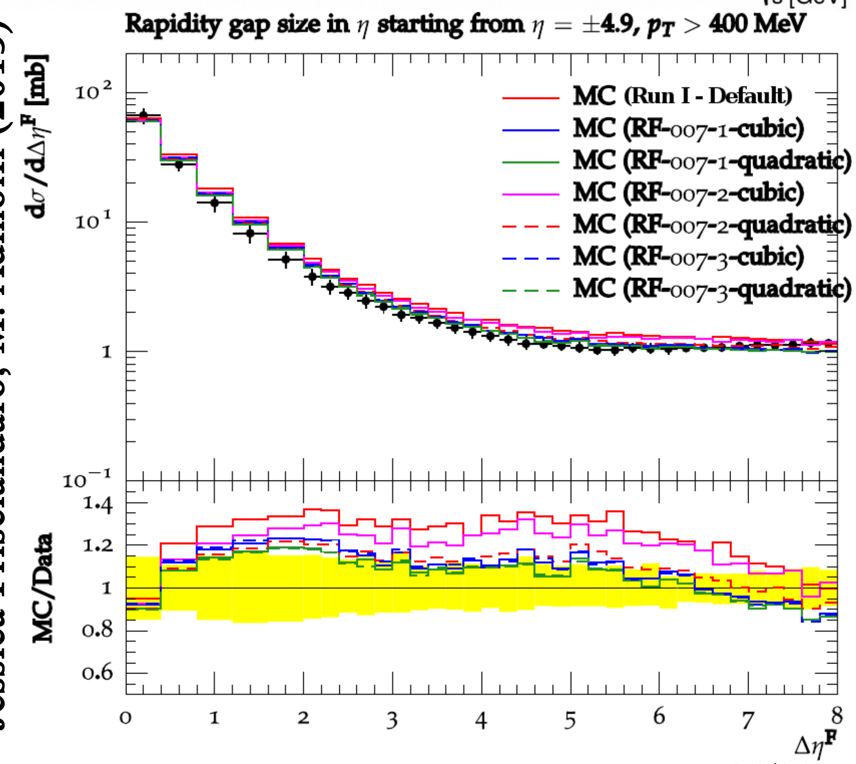
- CMS

PLB 722 (2013) 5, PRD 92 (2015) 012003 [new!];

- TOTEM

EPL 101 (2013) 21002

Preliminary Tune: ATLAS-2012-I1084540
Jessica Prisciandaro, M. Adinolfi (2015)

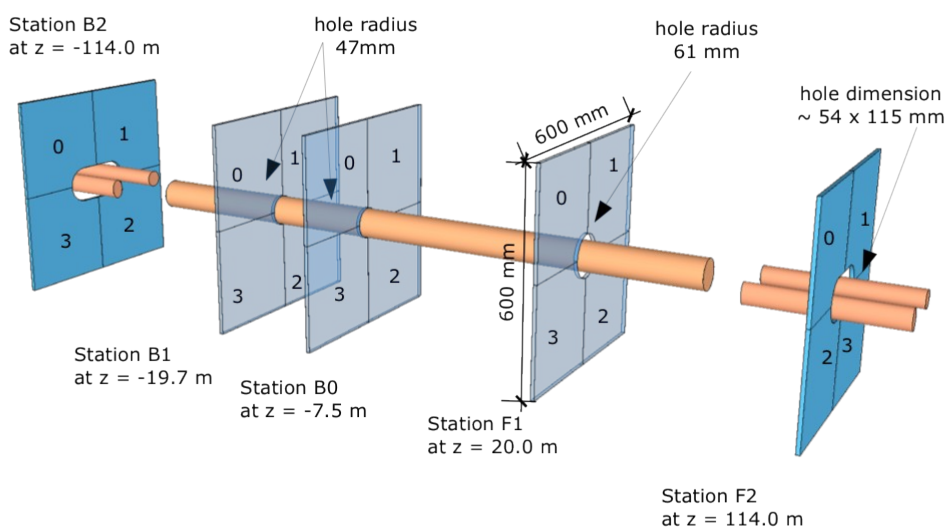


Global Event – Total Cross-sections

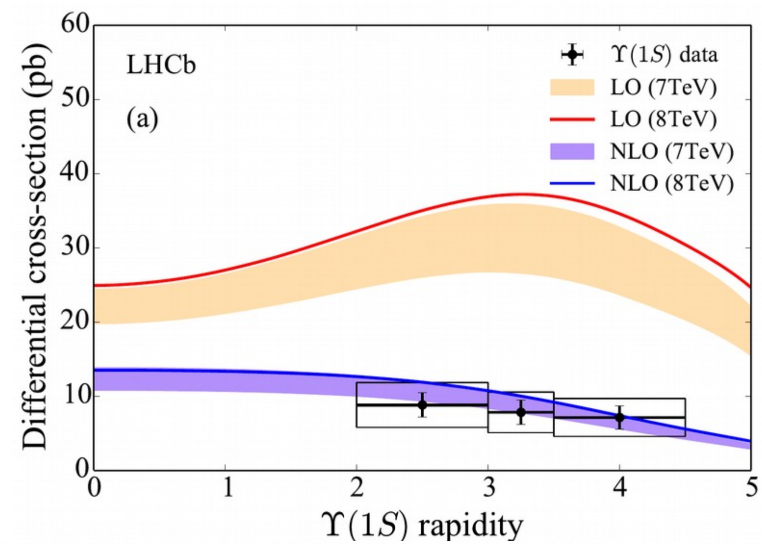
Central diffraction not covered by tune.

Possible input in high mass domain (pomeron PDFs) from central exclusive production measurements:
JPG 40 (2013) 045001, JPG 41 (2014) 055002,
JHEP 09 (2015) 084

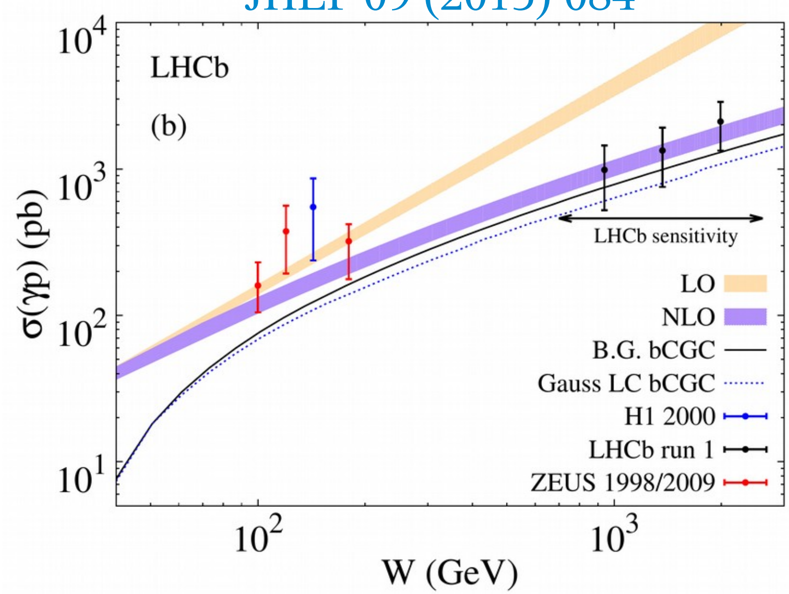
Dedicated sub-system in Run II
HeRSChel – High Rapidity Shower Counters for LHCb



reduce background from non-elastic events outside LHCb acceptance.



JHEP 09 (2015) 084



LHCb Experimental Input to Generator Tuning

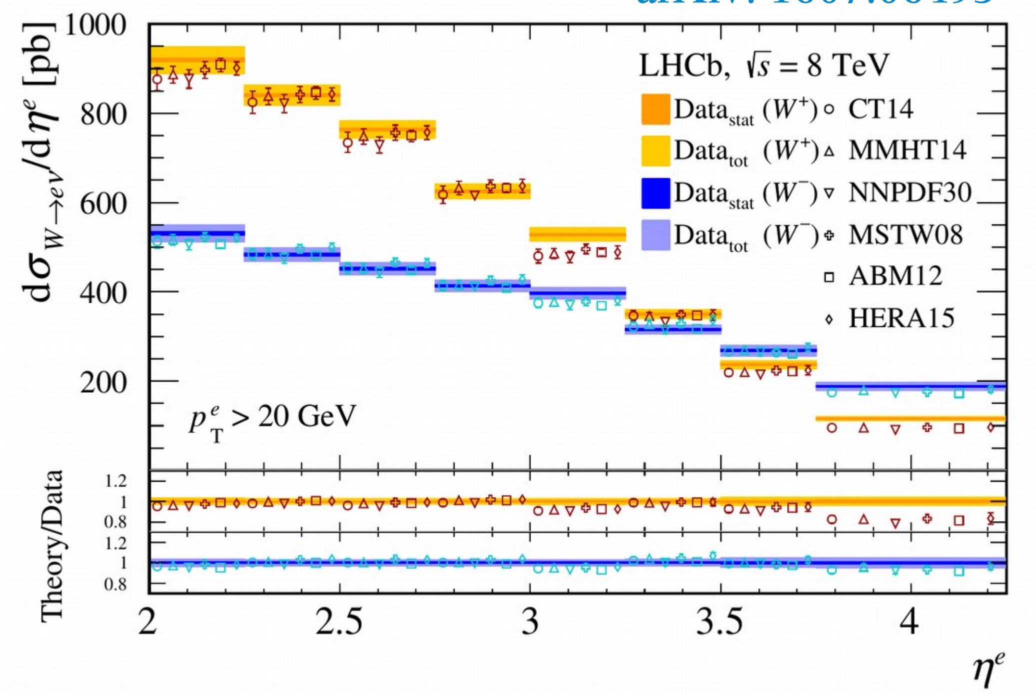
Input to PDF Tuning*

- EW boson production cross-sections and ratios**
  - $Z \rightarrow \ell\ell$ @ 7, 8, 13 TeV + $W \rightarrow \mu\nu$ @ 7, 8 TeV (on-going $W \rightarrow e\nu$)

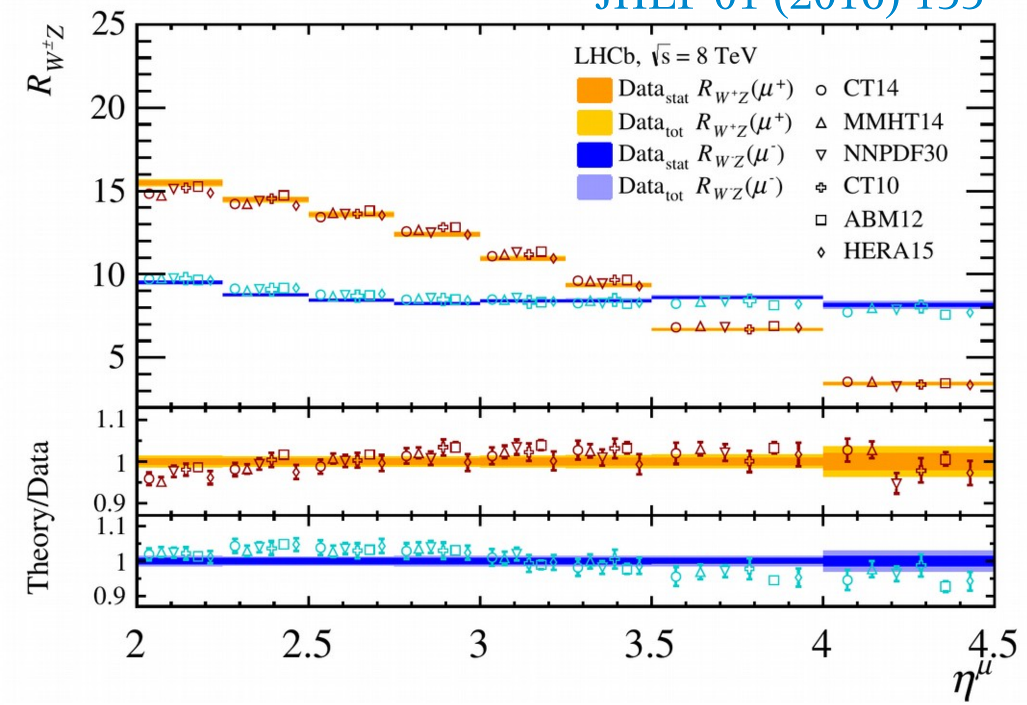
JHEP 08 (2015) 039, JHEP 01 (2016) 155, arXiv: 1607.06495, JHEP 02 (2013) 106, JHEP 05 (2015) 109

  - Good agreement with NNLO predictions; Ratios and double ratios limit PDFs' uncertainties at high lepton pseudorapidity

arXiv: 1607.06495



JHEP 01 (2016) 155



LHCb Experimental Input to Generator Tuning

Measuring SM Free Parameters

- Most precise measurement of the effective weak mixing (Weinberg) angle at hadron colliders.

JHEP 11 (2015) 190

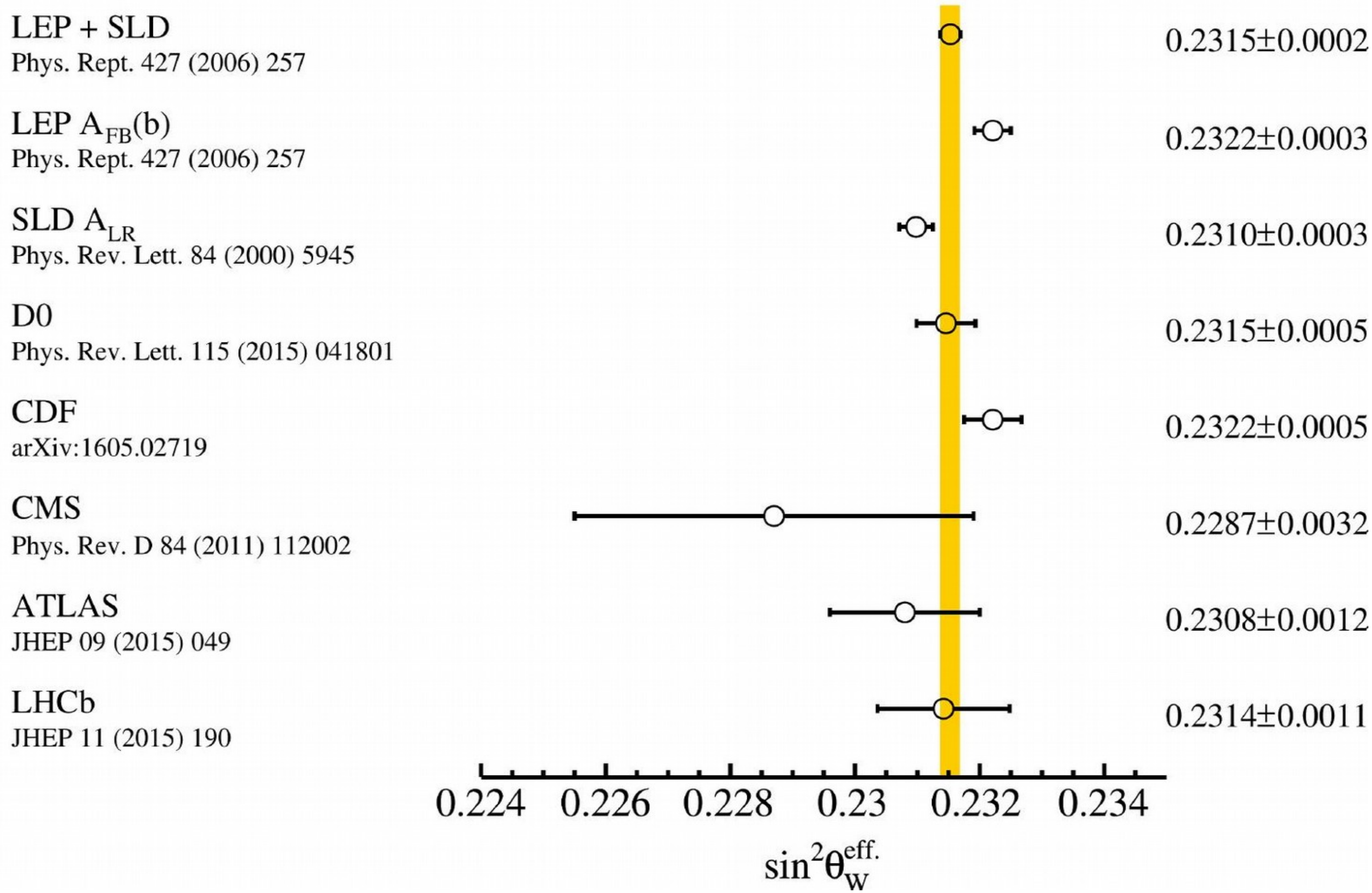


Fig. 4 – Update by Will Barter

LHCb Experimental Input to Generator Tuning

Input to PDF Tuning

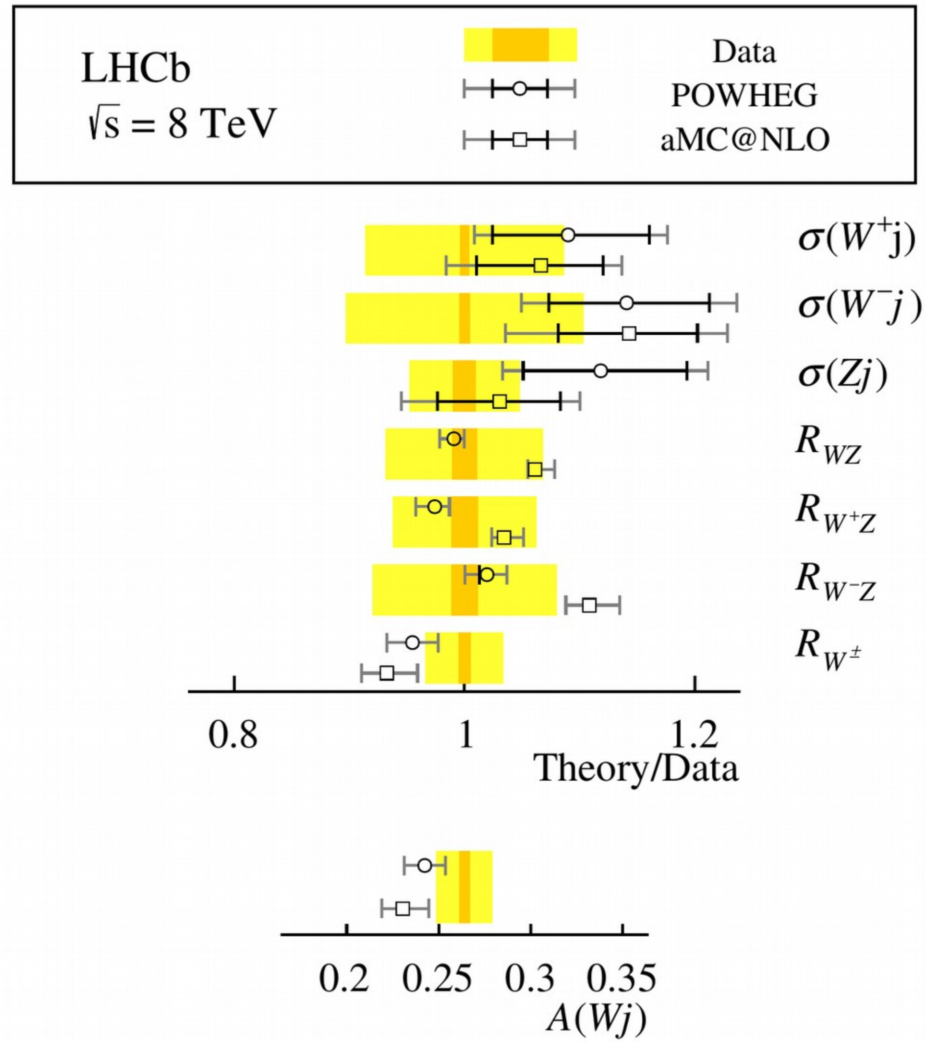
- Probing flavour PDFs in proton – measurements of EW boson + flavour quark jet.

  Z + b-jet @ 7 TeV JHEP 01 (2015) 064

  W + b/c @ 8 TeV PRD 92 (2015) 052001

  W/Z + jets @ 8 TeV JHEP 05 (2016) 131

- Limits on u/d PDFs at high x-Björken



JHEP 05 (2016) 131

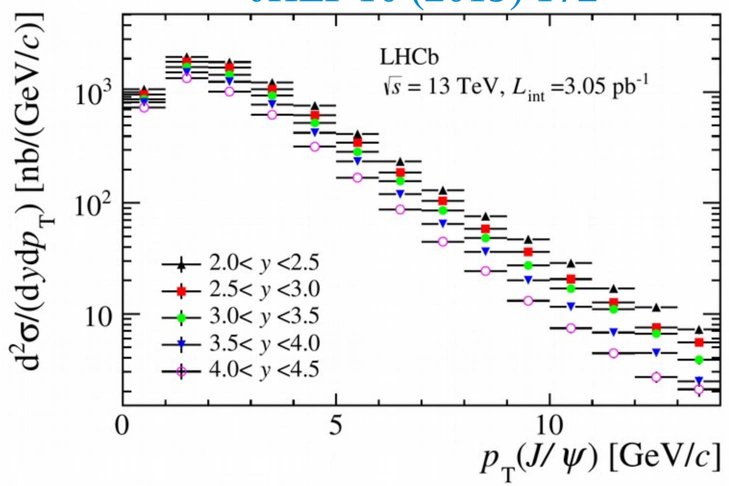
LHCb Experimental Input to Generator Tuning

Heavy Flavour* Production

- Charmonium
  J/ψ @ 2.76, 7, 8, 13 TeV
  $\psi(2S)$ @ 7 TeV
  $\sigma(\chi_{c2})/\sigma(\chi_{c1})$, χ_c:J/ψ, $\eta_c(1S)$:J/ψ,
  χ_{c0}:χ_{c1}:χ_{c2}
  –
  J/ψ, $\psi(2S)$ polarisations @ 7 TeV, but not supported by current colour-octet models

EPJ C74 (2014) 2835
EJP C71 (2011) 1645
JHEP 06 (2013) 064
JHEP 10 (2015) 172
PLB 714 (2012) 215
PLB 718 (2012) 431
EPJ C75 (2015) 311
JHEP 10 (2013) 115
–
EPJ C73 (2013) 2631
EPJ C74 (2014) 2872

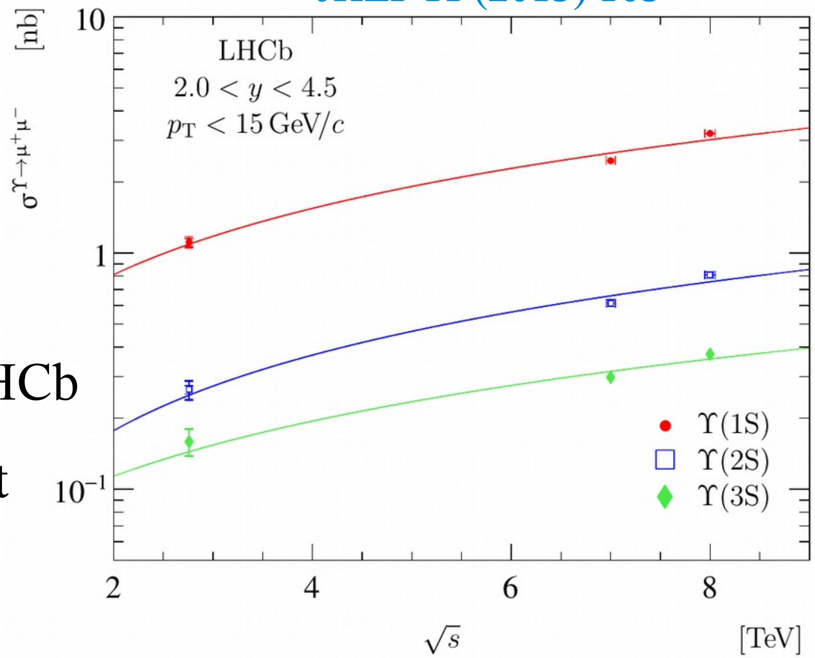
JHEP 10 (2015) 172



- Bottomonium
  $\Upsilon(n\,S)$ @ 2.76, 7, 8 TeV;
  $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ @ 7 TeV

EPJ C74 (2014) 2835
EPJ C72 (2012) 2025
JHEP 11 (2015) 103
JHEP 10 (2014) 088

JHEP 11 (2015) 103



→ Problems describing full phase-space, especially in forward/central regions → input from LHCb

→ Optimize quarkonia NRQCD matrix elements in event generators (altering inclusion in MPI framework, e.g. PYTHIA 8).

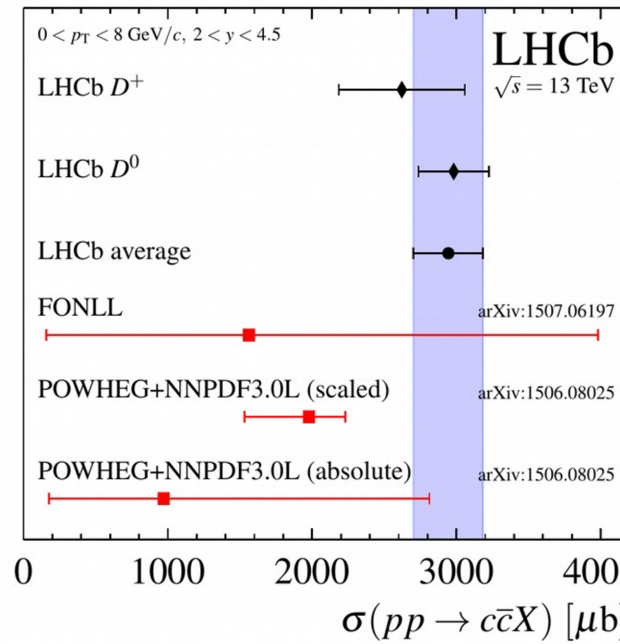
*To be presented in detail in “Heavy quarks” dedicated session in the following days.

LHCb Experimental Input to Generator Tuning

Heavy Flavour Production

- Prompt c – hadrons (D^0, D^+, D_s^+, D^{*+}, Λ_c) @ 7, 13 TeV

NPB 871 (2013) 1-20
JHEP 03 (2016) 159



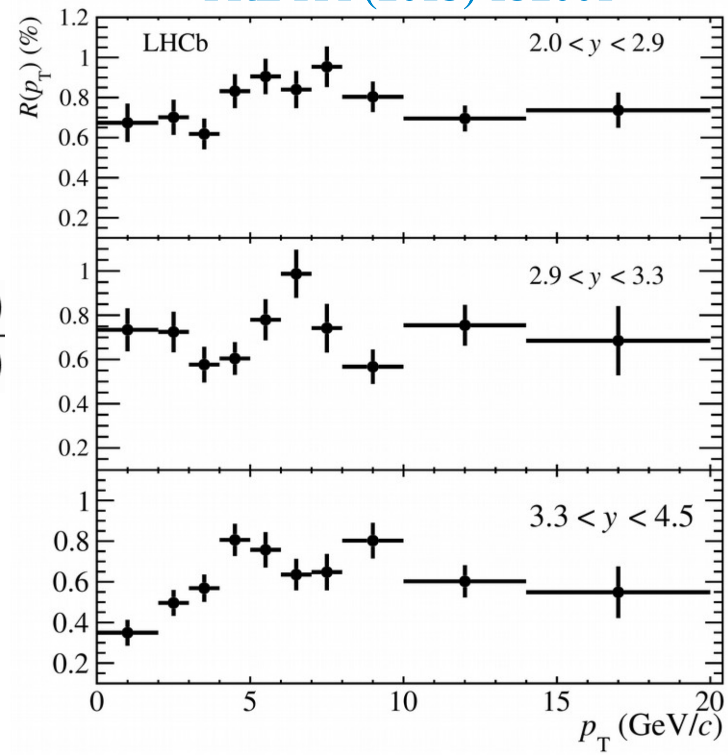
- b – hadrons
  - $B^{\pm}$, B^0, B_s^0 @ 7 TeV
  - B_c^+:B^+ @ 8 TeV

JHEP 04 (2012) 093
JHEP 08 (2013) 117
PRL 114 (2015) 132001

- Constrain parameters of b and c fragmentation functions

PRL 114 (2015) 132001

$$R(p_T, y) = \frac{N_{B_c^+}(p_T, y)}{N_{B^+}(p_T, y)} \frac{\epsilon_{B^+}(p_T, y)}{\epsilon_{B_c^+}(p_T, y)}$$



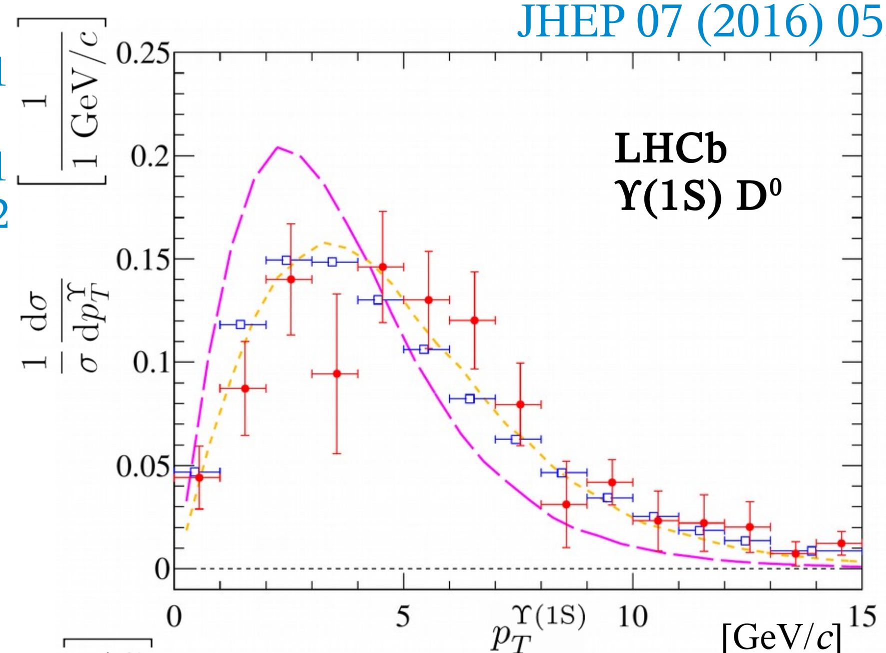
LHCb Experimental Input to Generator Tuning

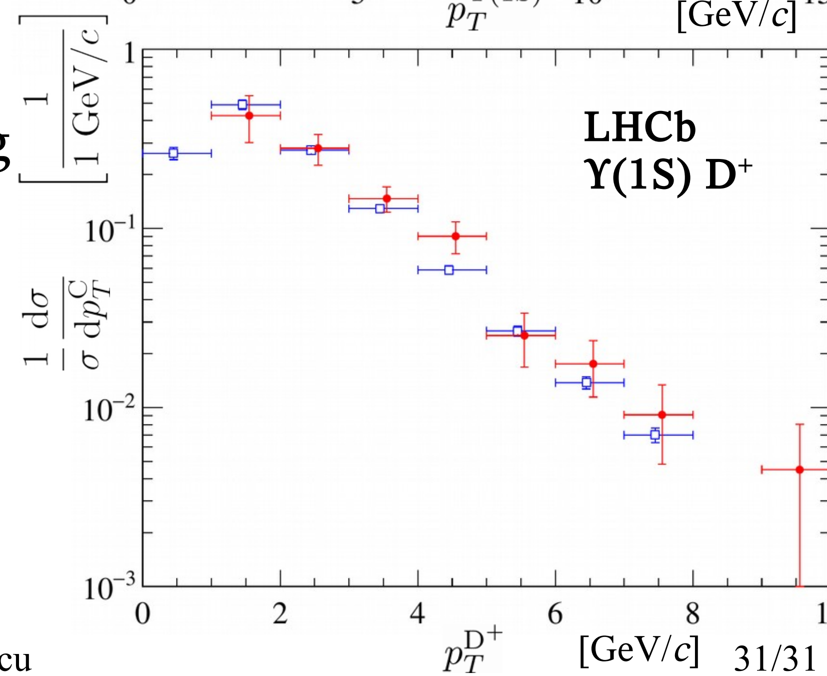
Heavy Flavour – Associated Production

JHEP 04 (2014) 091
PLB 707 (2012) 52
JHEP 06 (2012) 141
JHEP 07 (2016) 052

- Z boson + D meson @ 7 TeV
- J/ψ pair @ 7 TeV
- Charmonium + open charm hadron @ 7 TeV
- ϒ + open charm hadron @ 7 & 8 TeV

JHEP 07 (2016) 052





- Measurements support double parton scattering (DPS) production mechanisms over traditional single parton scattering (SPS) ones. Reference for validating implementation of DPS production mechanisms.

[blue dots – DPS, curves – SPS predictions]