Studies of Forward Particle Production with LHCb

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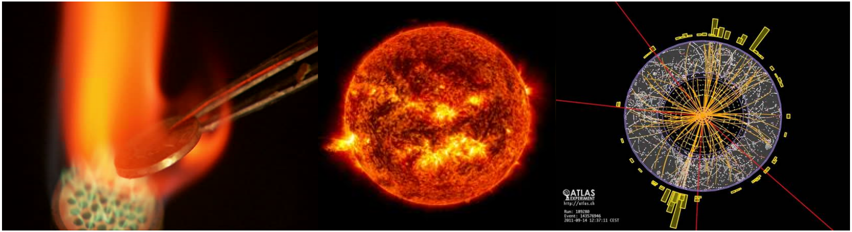
Outline

- *Introduction*
- *The LHCb Detector*
- *Proton-Proton Collisions*
- *Proton-Lead Collisions*
- *Lead-Lead Collisions*
- *Fixed-Target Physics*
- *Summary and Outlook*

→ *LHC and LHCb – setting the stage . . .*



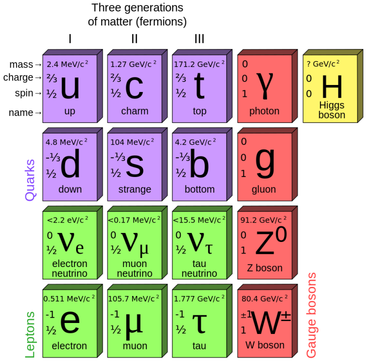
$T \sim 10^3\,\mathrm{K}$	$T \sim 10^7\,\mathrm{K}$	$E \sim 10^{12}\,\mathrm{eV}$
$kT \sim 0.1\,\mathrm{eV}$	$kT \sim 10^3\,\mathrm{eV}$	$T \sim 10^{16}\,\mathrm{K}$
$N \sim 10^{23}$ particles	$N \sim 10^{57}$	$N \sim 10^2 \ldots 10^{16}$

- physics at the “Tera-scale” $\equiv$ “extreme chemistry”
- probe extreme conditions and search for new heavy particles

close connection to fundamental questions →

The Standard Model of particle physics

➜ *moderately small number of fundamental fields and interactions*



particles and antiparticles
mesons: quark-antiquark
(anti)baryons: 3 (anti)quarks

➜ *. . . why . . . ?*

- 1 fundamental scalar
- 2 types of fermions
- 3 generations
- 4 fermions/generation
- 3 gauge interactions
- 4 gauge bosons

➜ *open questions . . .*

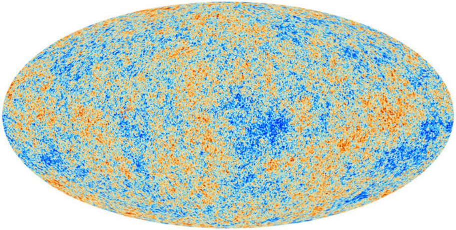
What is the origin of mass?

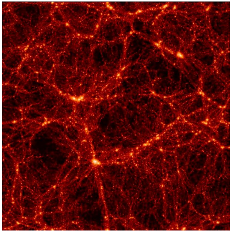
- *how do fundamental particles acquire mass?*
  - Standard Model: Higgs mechanism
    - space is filled with a Higgs background field
    - mass arises from coupling to this field
    - if the model is correct, then a Higgs particle must exists as an excitation of this background field
      - the LHC experiments found a Higgs-particle

- *what determines the mass values?*
  - the Higgs mechanism does not predict mass values
  - understanding mass hierarchy requires New Physics
    - new (heavy) particles and fields
    - rich new phenomenology

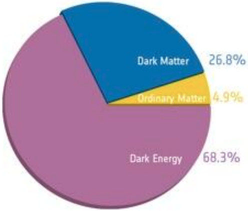
What is Dark Matter made of?

➜ *cosmic microwave background & structure formation:*





- the universe is "flat" (euclidean)
- its energy content is:
  - ➜ 4.9% ordinary matter
  - ➜ 26.8% dark matter – heavy particles (?)
  - ➜ 68.3% dark energy (??)



(Planck)

Where is the Antimatter?

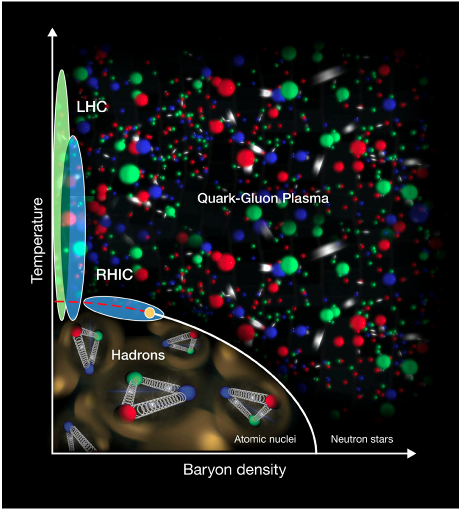
➜ *the puzzle*

- antimatter (in small quantities) is observed in lab-experiments
- always same amounts of matter and antimatter created
- the same processes occured in the early universe
- no evidence for sizeable amounts of antimatter in the universe

(HST)

- no evidence for anti-matter annihilation radiation
- no evidence for anti-nuclei in cosmic rays

Properties of matter at extreme conditions?



➜ *open questions*

- behaviour of hadronic matter
  - ➜ at extreme densities
  - ➜ at extreme temperatures
- equation of state?
- phase transitions?
- critical point?

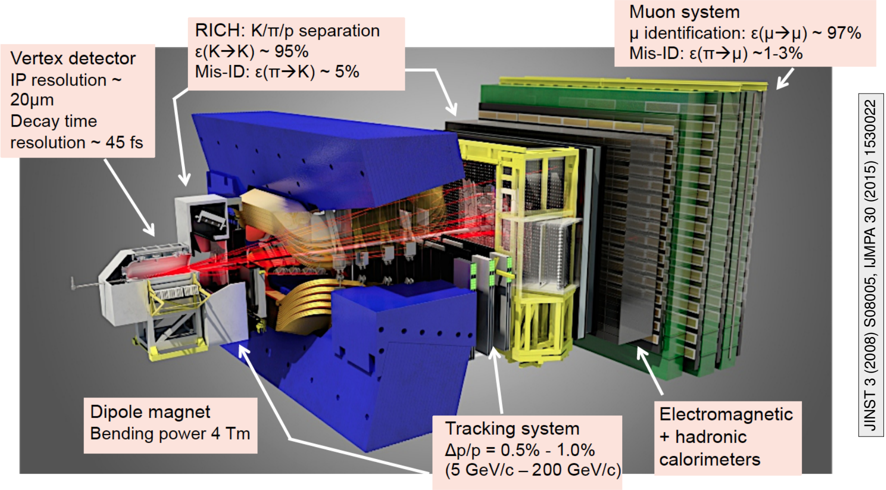
❖ ultimate goal:

understanding of our universe from the big bang until today

LHC
LHCb
SPS
CERN Meyrin - PS

Schematic view of LHCb

Vertexing, tracking, particle-ID and calorimetry in the forward region down to low p_T



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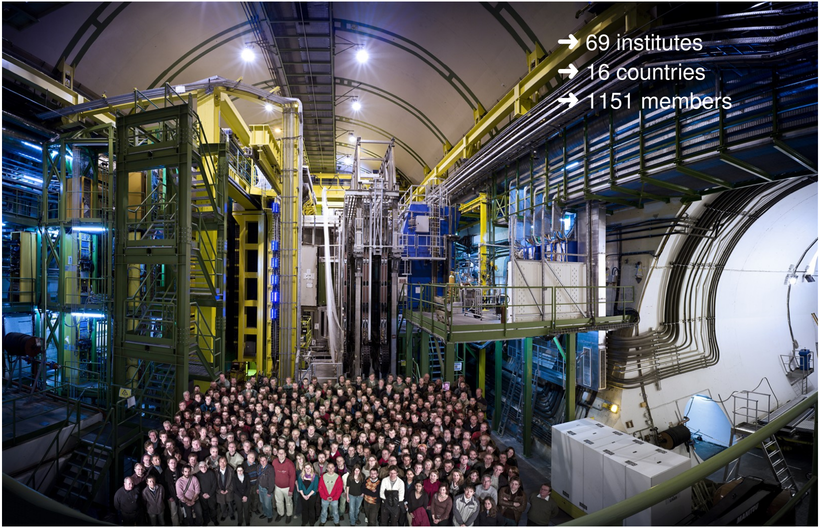
Installation in the cavern

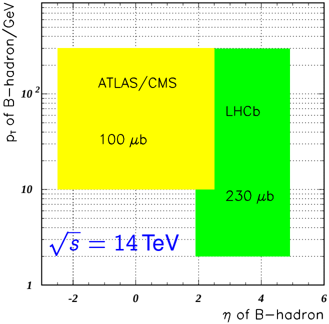


Inside the spectrometer magnet

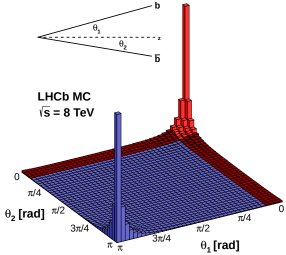
Design aspects of LHCb

→ *designed for B physics . . . but able to do much more*

- exploit forward angular coverage → large boosts: B decay lengths O(1 cm)
- focus on vertex reconstruction and particle identification
- phase space coverage down to low p_T, small x and small polar angles θ

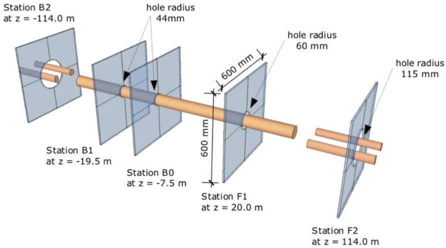


$$\eta \sim -\ln \theta/2$$



Forward extension of the detector

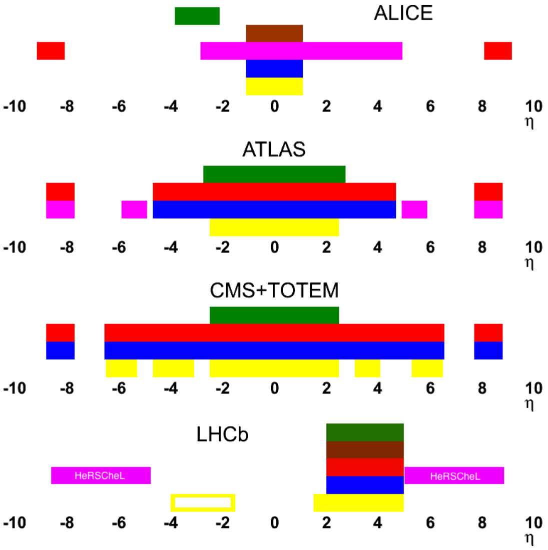
➜ HeRSCheL: High Rapidity Shower Counters for LHCb



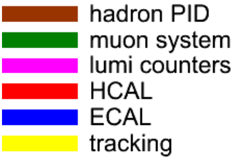
- scintillators at large rapidities
- up to ± 114 m from IP
- central region not covered
- coverage $5 < |\eta| < 9$
- sensitive to activity (no tracking)

❖ huge gain for diffractive physics and central exclusive production

Angular coverage of the LHC experiments

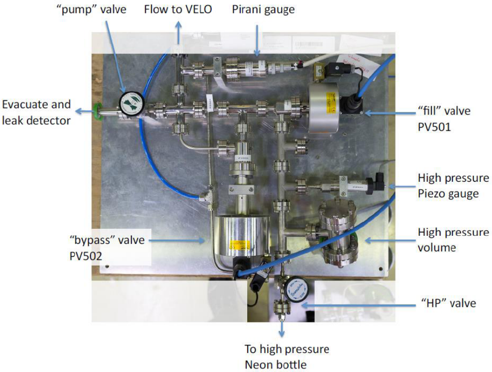


- ALICE
  - ➜ central
  - ➜ forward muon coverage
- ATLAS & CMS
  - ➜ central detectors
- LHCb
  - ➜ forward detector
  - ➜ tracking, particle-ID and calorimetry in full acceptance

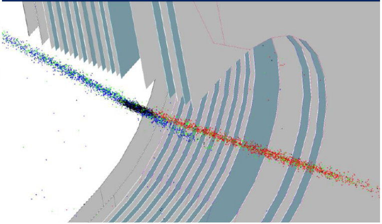


Fixed-target physics with LHCb

➜ SMOG: System for Measuring Overlap with Gas



- injection of gas into interaction region
- very simple robust system
- used for a precise luminosity determination

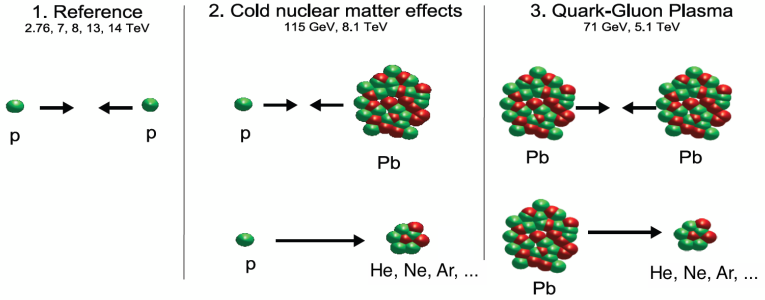


- possibility to inject (noble) gases: He, Ne, Ar (maybe Kr)
- fixed-target physics in pA and PbA configuration

LHCb beam configurations

➜ *possibility to study hadronic collisions. . .*

- as a function of the centre-of-mass energy
- for different beam-target combinations



➜ symmetric configurations: pp and PbPb

➜ asymmetric configurations: pPb and fixed target

LHCb running modes

→ *available/upcoming LHCb running modes and* $\sqrt{s_{NN}}$

E_{beam}(p)	pp	p-Gas	p-Pb/Pb-p	Pb-Gas	Pb-Pb
450 GeV	0.90 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV$^{(1)}$			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV$^{(2)}$	5 TeV	54 GeV$^{(3)}$	
6.5 TeV	13 TeV	110 GeV$^{(4)}$	8.2 TeV	69 GeV$^{(5)}$	∼5 TeV

(1) SMOG with ^{40}Ar few h (2015)

(2) SMOG with ^{20}Ne 2.5 h (2012)

(3) SMOG with ^{20}Ne 30 min (2013)

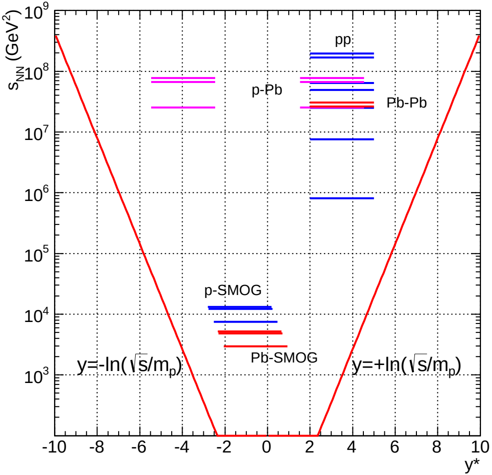
(4) SMOG with ^{4}He 8 h (2015) + 2 d (2016), ^{20}Ne 12 h (2015), ^{40}Ar 3 d (2015)

(5) SMOG with ^{40}Ar 1.5 weeks (2015)

❖ *bridge the gap from SPS to LHC in a single experiment*

Phase space coverage of LHCb

➜ *kinematic acceptance for E_{beam}(p) between 450 GeV and 7 TeV*



y^*: rapidity in nucleon-nucleon centre-of-mass system, with forward direction (+ values) in direction of the proton/beam

some results ➜

➜ *Energy Flow (EF): average energy per event in a given η-interval*

$$EF: \qquad \frac{1}{N_{int}} \frac{dE}{d\eta} = \frac{1}{\Delta\eta} \left(\frac{1}{N_{int}} \sum_{i=1}^{N_{part,\eta}} E_{i,\eta} \right)$$

- ➜ part of underlying event
- ➜ sensitive to multi-parton interactions & parton radiation
- ➜ comparison to PYTHIA 6, PYTHIA 8 and cosmic ray models (generators used to model cosmic ray induced air showers)

❖ analysis for different event classes:

- inclusive minimum bias: ≥ 1 tracks with $\eta \in [1.9, 4.9]$ and $p > 2\,\mathrm{GeV}/c$
- hard scattering: inclusive && ≥ 1 tracks with $p_T > 3\,\mathrm{GeV}/c$
- diffractive enriched: inclusive && 0 tracks with $\eta \in [-3.5, -1.5]$
- non-diffractive enriched: inclusive && ≥ 1 tracks with $\eta \in [-3.5, -1.5]$

Energy Flow: data vs PYTHIA

➜ *results:*

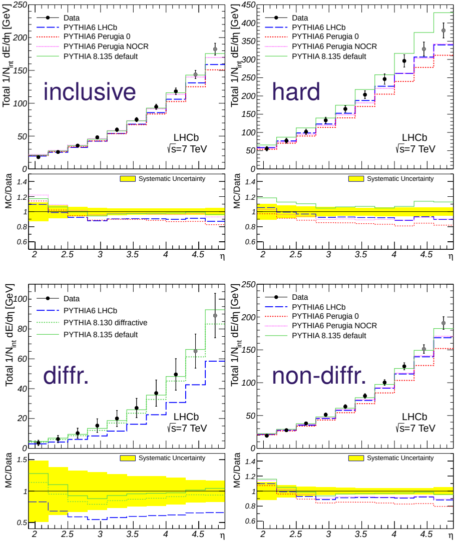
- Energy Flow increases with momentum transfer

$$EF_{diff} < EF_{incl} < EF_{ndiff} < EF_{hard}$$

- highest sensitivity at large η
- largest uncertainties at small η

PYTHIA 6: Energy Flow is
- ➢ overestimated at small η
- ➢ underestimated at large η

PYTHIA 8.135 default:
- ➢ except for hard scattering the Energy Flow is well described for all samples



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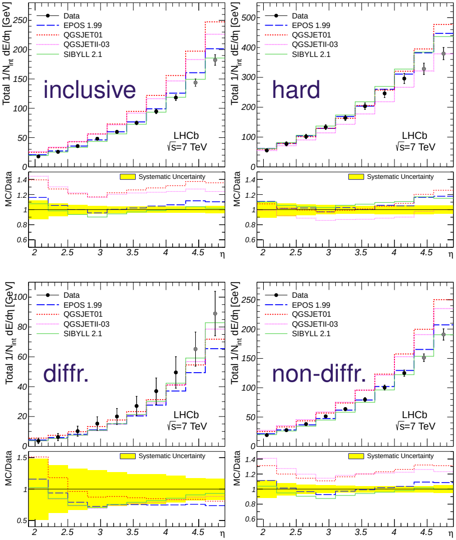
Energy Flow: data vs cosmic ray models

➜ *models not tuned to LHC(b)*

- EPOS & SIBYLL: good description of EF for inclusive and non-diffractive events
- QGSJET models: overestimated EF for inclusive and non-diffractive events; good description of hard scattering
- best description by SIBYLL
- all models underestimate the EF of diffractive events



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Identified light particles

→ *particle production ratios as a function of y and p_T*

- antiparticle/particle ratios and ratios of different particle species

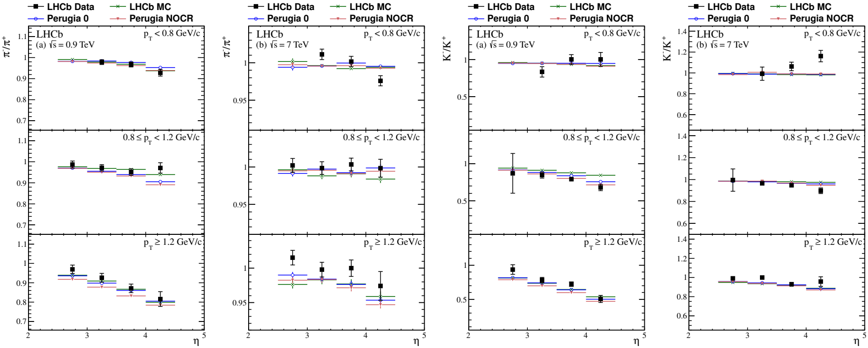
$$\frac{\pi^-}{\pi^+},\ \frac{K^-}{K^+},\ \frac{\bar{p}}{p},\ \frac{\bar{\Lambda}}{\Lambda}\quad \text{and} \quad \frac{K^+ + K^-}{\pi^+ + \pi^-},\ \frac{p+\bar{p}}{\pi^+ + \pi^-},\ \frac{p+\bar{p}}{K^+ + K^-},\ \frac{\bar{\Lambda}}{K^0_S}$$

- measurements at $\sqrt{s} = 0.9$ and 7 TeV
- use decay modes $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$
- in the ratios many systematic uncertainties cancel
- mainly information about the hadronization process:
  - → baryon number transport from $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$
  - → baryon suppression from baryon/meson ratios
  - → strangeness suppression from kaon/pion ratios

data compared to PYTHIA 6 →

Antiparticle/particle ratios

π^-/π^+		K^-/K^+	
$\sqrt{s} = 0.9$ TeV	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 0.9$ TeV	$\sqrt{s} = 7$ TeV



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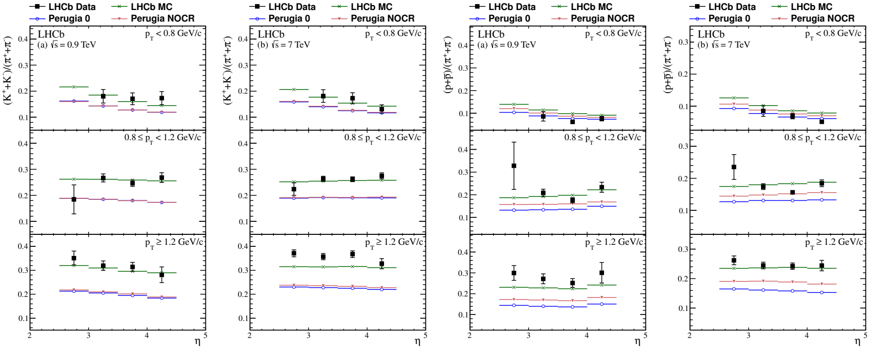
- ➜ charge ratio drops towards larger rapidities (proton beam)
- ➜ effect more pronounced at higher p_T
- ➜ general behavior reproduced by all PYTHIA 6 tunes

Strangeness and baryon suppression

$$(K^+ + K^-)/(\pi^+ + \pi^-) \qquad (\bar{p} + p)/(\pi^+ + \pi^-)$$

$\sqrt{s} = 0.9$ TeV $\quad \sqrt{s} = 7$ TeV $\quad \sqrt{s} = 0.9$ TeV $\quad \sqrt{s} = 7$ TeV



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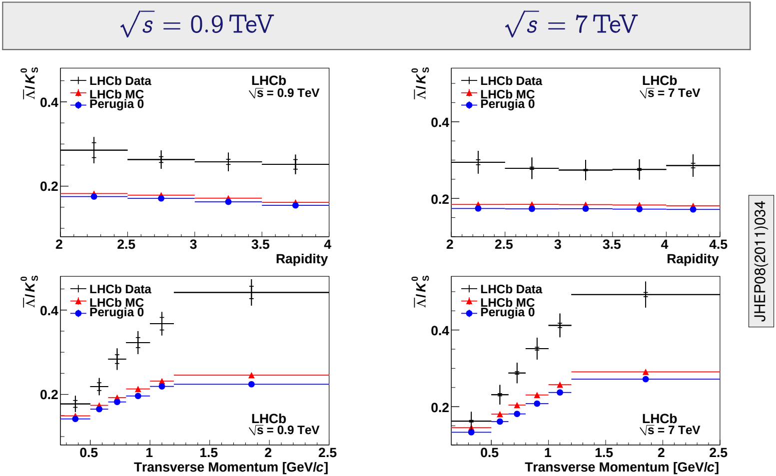
- ➜ strangeness suppression very similar to baryon suppression
- ➜ less suppression at larger p_T
- ➜ reasonable description only by LHCb-tune of PYTHIA 6

Strange-baryon suppression

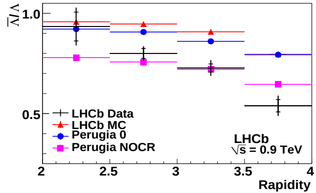


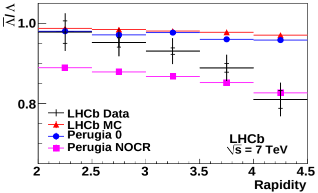
➜ significantly reduced baryon suppression at large p_T

➜ all considered PYTHIA 6 tunes fail to describe the strangeness-data

Baryon number transport

$\sqrt{s} = 0.9\,\mathrm{TeV}$	$\sqrt{s} = 7\,\mathrm{TeV}$





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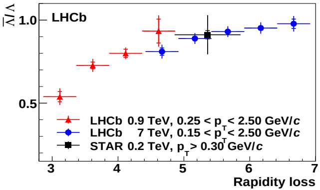
- all considered PYTHIA 6 tunes fail to describe observed y-dependence
- behavior as a function of Δy is independent of $\sqrt{s}$ for $\bar{\Lambda}/\Lambda$ and $\bar{p}/p$



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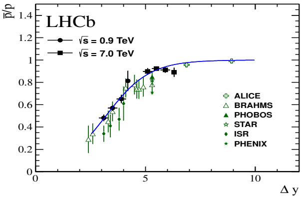

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Charm production

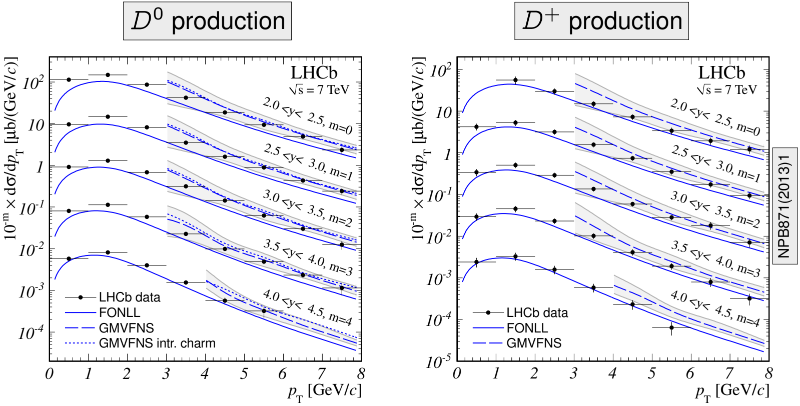
➜ *prompt charm production in 7 TeV pp collisions, using:*

$$
\begin{aligned}
D^0 &\to K^- \pi^+ \\
D^+ &\to K^- \pi^+ \pi^+ \\
D^{*+} &\to D^0(K^- \pi^+)\, \pi^+ \\
D_s^+ &\to \phi(K^+ K^-)\, \pi^+ \\
\Lambda_c^+ &\to p\, K^- \pi^+
\end{aligned}
$$

- charge conjugate modes are summed
- kinematic range: $0 < p_T < 8\,\mathrm{GeV}/c$ and $2.0 < y < 4.5$
- exploit RICH detectors for kaon identification
- separate prompt and secondary charm from b decays by impact parameter

efficiency and branching -fraction corrected cross-sections ➜

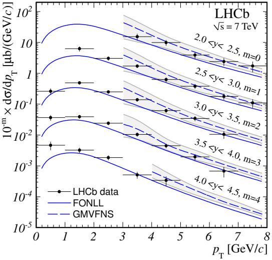
Prompt charm cross-sections



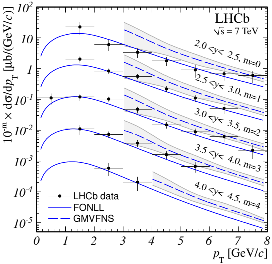
- qualitative behaviour described by theory
- large theoretical (scale) uncertainties
- little sensitivity to intrinsic charm in LHCb acceptance
  - ➜ expected to be important at large y and large p_T

Prompt charm cross-sections

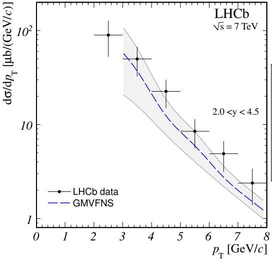
D^{*+} production



D_s^+ production



Λ_c^+ production



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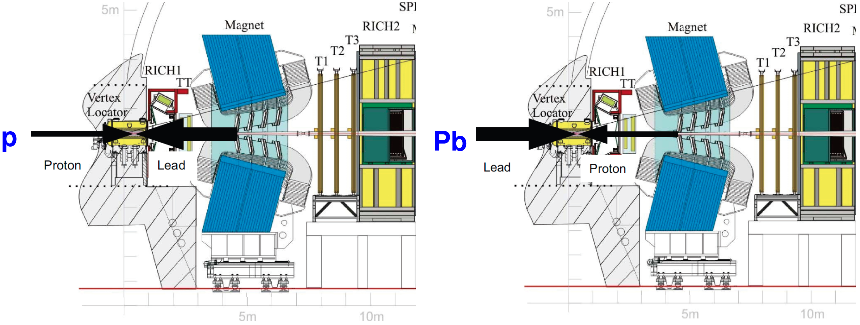
➜ *cross-section* $\sigma(c\bar{c}) \rightarrow \text{hadron}(p_T < 8\,\text{GeV}/c, 2.0 < y < 4.5)$

- use fragmentation fractions $f(c \rightarrow h)$ from e^+e^- measurements
- combined result from all 5 measurements

$$\sigma(c\bar{c})_{p_T<8\,\text{GeV}/c, 2.0<y<4.5} = 1419 \pm 12_{\text{(stat)}} \pm 116_{\text{(syst)}} \pm 65_{\text{(frag)}}\ \mu\text{b}$$

➜ 2.5% of inelastic pp cross-section, 20 times larger than $\sigma(pp \rightarrow b\bar{b})$

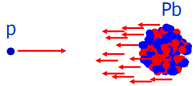
➜ *experimental configurations:*



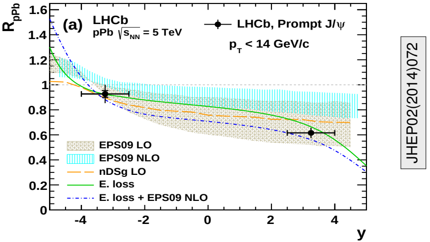
- asymmetric colliding beam mode: 4 TeV p on 1.58 TeV/nucleon Pb
- swap beam directions to measure both hemispheres
  - ➜ "forward" $\equiv$ proton direction
  - ➜ "backward" $\equiv$ lead direction

➜ *probe effects of nuclear environment*

- understanding needed to disentangle nuclear effects from quark gluon plasma signatures in PbPb collisions
- use $J/\psi \to \mu^+\mu^-$ decays
- compare pp and pPb cross-sections



$$R_{pPb}(y) = \frac{1}{A_{Pb}} \cdot \frac{\sigma_{pPb}(y)}{\sigma_{pp}(y)}$$

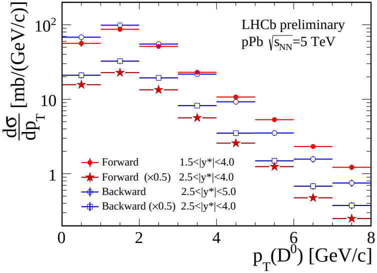


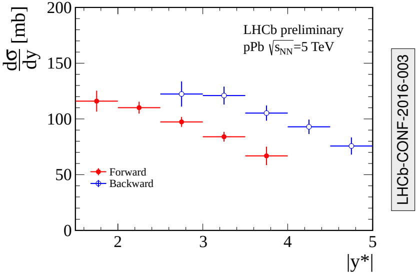
➜ $R_{pPb} \neq 1$: the nucleus is not a loose collection of independent nucleons

➜ theory with known effects reproduces the measurements, although . . .

➜ large theoretical uncertainties – data provide important constraints

→ *differential cross-sections*

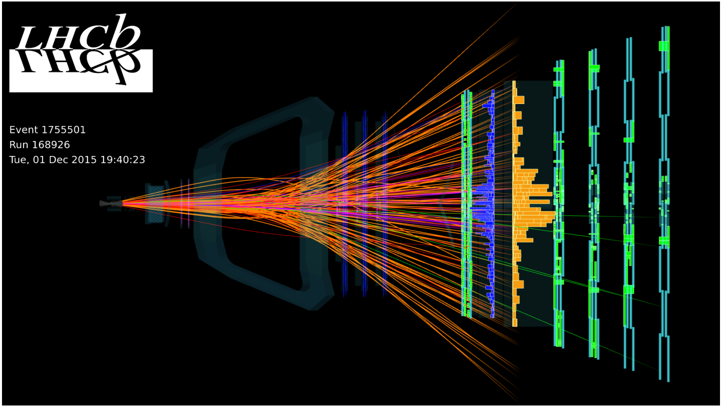




- kinematic range: $p_T < 8\,\text{GeV}/c$, $-5.0 < y < -2.5$ and $1.5 < y < 4.0$
- extraction of prompt yields down to $p_T \to 0$
- similar p_T slopes in beam and target hemispheres
- more forward production in target hemisphere

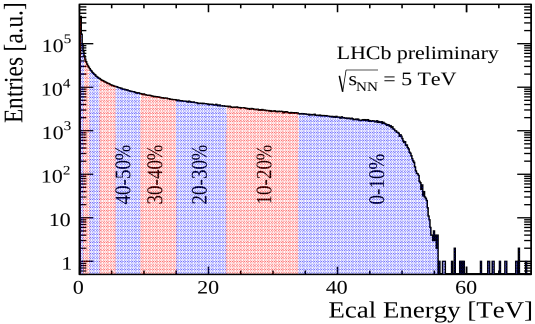
5. Lead-Lead Collisions

➜ *first participation in PbPb running by LHCb in December 2015*
- ➜ 10^9 collisions recorded
- ➜ example: PbPb collision with 1130 reconstructed tracks



Event activity

→ *energy deposit in the electromagnetic calorimeter*



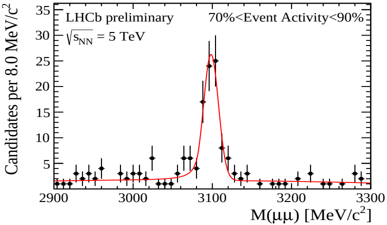
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

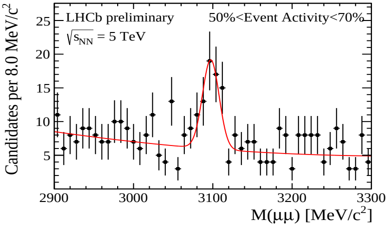
- up to 60 TeV per event
- related to overlap of colliding nuclei
- track based analysis possible for peripheral to semi-central collisions (activity range 100% - 50%)

first signals →

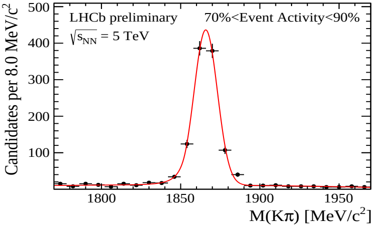
J/ψ and open charm in PbPb collisions

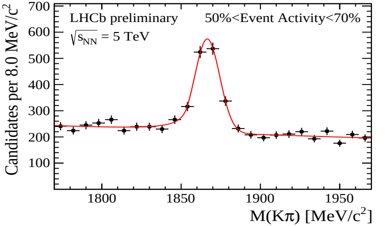
➜ $J/\psi \to \mu^+\mu^-$ decays





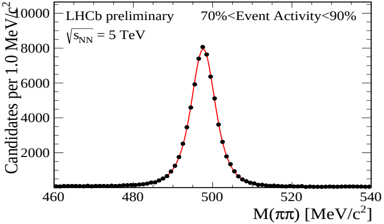
➜ $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$ decays

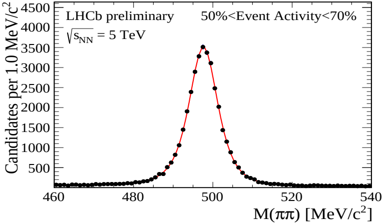




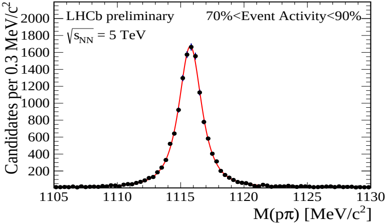
https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

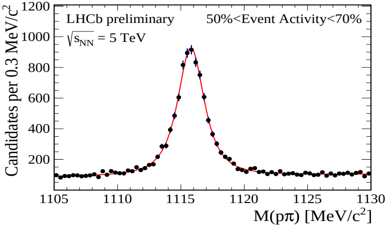
➜ $K_S^0 \rightarrow \pi^+\pi^-$ decays





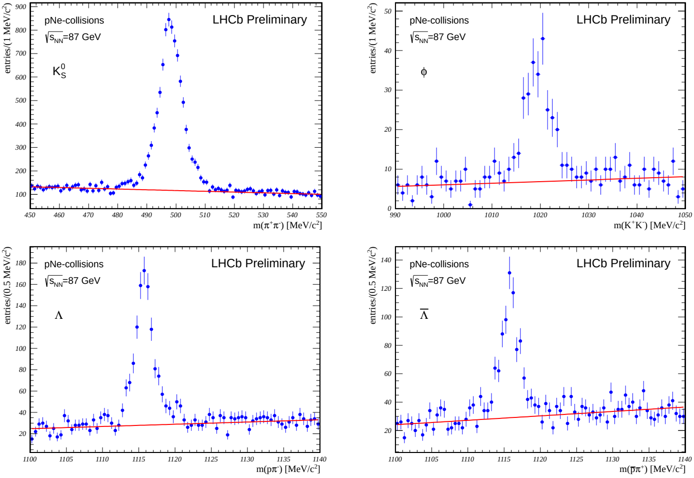
➜ $\Lambda \rightarrow p\pi^-$ + CC decays





https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

➜ *strangeness production in pNe collisions (2012) at $\sqrt{s_{NN}} = 87$ GeV*



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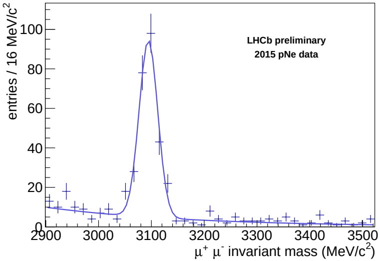
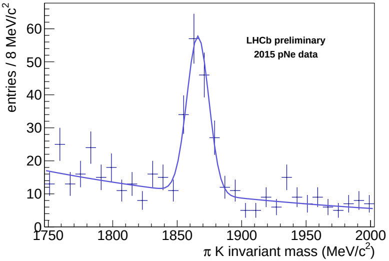
J/ψ and open charm production

→ *charm production in pNe collisions (2015) at* $\sqrt{s_{NN}} = 110\,GeV$





https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

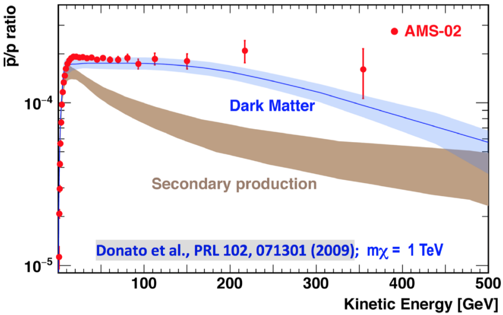
- clean signals
- next: luminosity determination based on elastic pe^- scattering
- goal: cross-section measurements for He, Ne and Ar targets

Links to other communities

➜ *cosmic ray physics and cosmology*

- understanding of extensive air showers ➜ MC tuning
- understanding the AMS antiproton/proton ratio

AMS $\bar{p}/p$ results and modeling



❖ use fixed-target measurements to clarify: QCD or Dark Matter annihilation

7. Summary and Outlook

➜ *a few selected results on forward particle production:*

- proton-proton interactions:
  - ➜ energy flow surprisingly well described by cosmic ray models
  - ➜ difficulties to describe particle composition in Pythia-based models
- proton-lead interactions:
  - ➜ charm production to probe cold nuclear matter effects
  - ➜ needed to disentangle QGP effects in heavy ion collisions
- lead-lead collisions:
  - ➜ measurements possible for peripheral to semi-central collisions
  - ➜ expect sensitivity to QGP signatures
- fixed-target physics with (so far) {p,Pb} on {He,Ne,Ar}:
  - ➜ upcoming strangeness and charm production measurements
  - ➜ links to cosmic ray physics and cosmology

❖ LHCb is more “general purpose” than the GPDs . . .