Results on Quarkonia

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on behalf of the LHCb Collaboration

8th International Workshop on Heavy Flavor Production
in Nuclear Collisions

July 14, 2022

Brief Introduction

LHCb, Past and Present

- Tens of new hadrons **discovered by LHCb** using data sets from Run 1 (2010–2012) and Run 2 (2015–2018)
- Many are new **charmonium** and **charmonium-like** exotic states
- Also includes pentaquark-like $P_c(4312)^+$, $P_c(4380)^+$, $P_c(4457)^+$
- More than **50 new particles** discovered by LHCb on **New Particles** web page

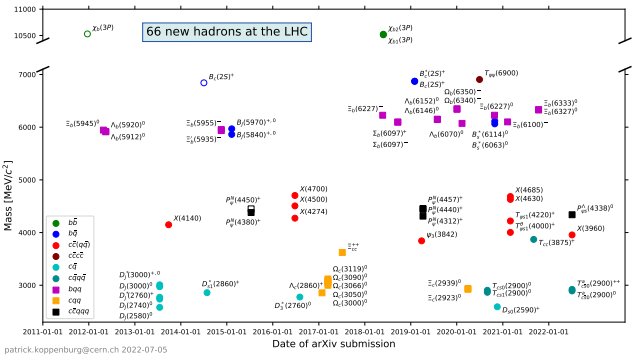
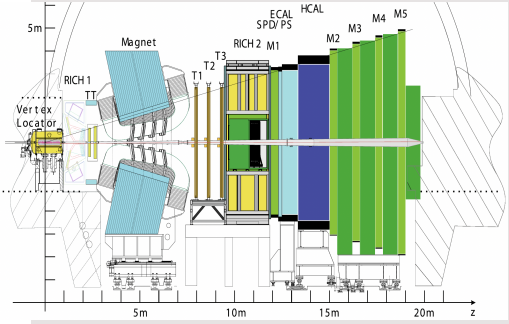


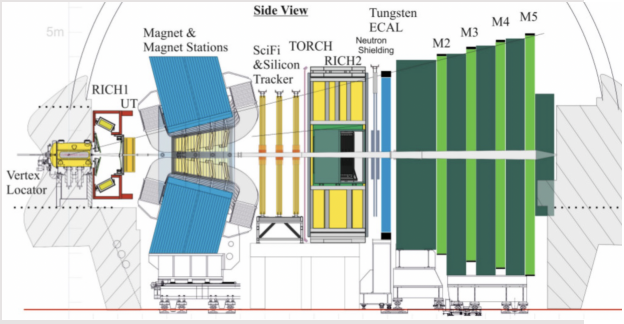
Image Credit: P. Koppenburg (as of July 5, 2022)

LHCb Detector Upgrade

Runs 1 & 2

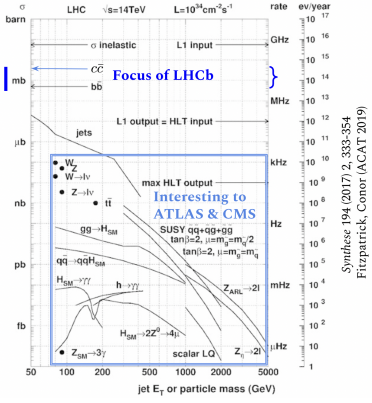


Runs 3–4

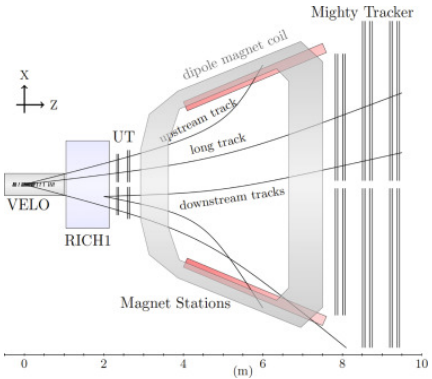


- Designed for searches of new physics in beauty and charm hadron decays
  - Measures particles from $p_T > 0$ at forward pseudorapidity $2 < \eta < 5$
- **LHCb tracking fully upgraded for Run 3 (2022–2026)**

LHCb, Present and Future



Estimated full centrality capabilities by 2030

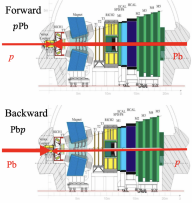


- Run 1/2 trigger limited at L0 (hardware) to 1 MHz → full software trigger running at 40 MHz in now & future **see Patrick Robbe's talk**
- Additional tracking detector inside magnet (Magnet Station) expected ∼2026

LHCb Results Overview

Six recent LHCb analyses focus on the following collision systems and present the following measurements:

- pp collisions at $\sqrt{s} = 5$, 8, and 13 TeV
- p**Pb** collisions at $\sqrt{s_{NN}} = 8.16$ TeV
- **PbNe** collisions at $\sqrt{s_{NN}} = 68.5$ GeV
- **PbPb** collisions at $\sqrt{s_{NN}} = 5$ TeV

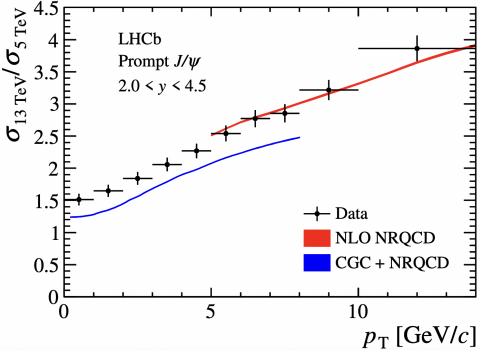


1. J/ψ production in pp collisions
2. Bottomonium nuclear modification in pPb collisions
3. $\chi_{c1}(3872)$ and $\psi(2S)$ production in pPb collisions
4. Fixed target J/ψ and D^0 production
5. J/ψ and $\psi(2S)$ production in UPC collisions

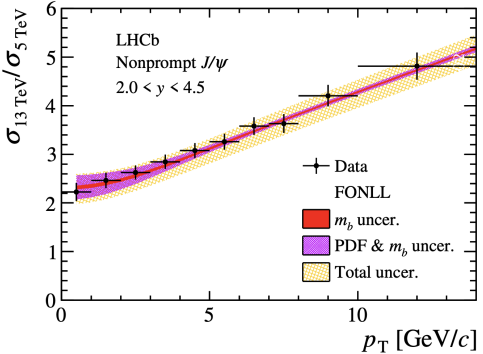
LHCb Quarkonia Results

J/ψ Production in pp Collisions

Prompt



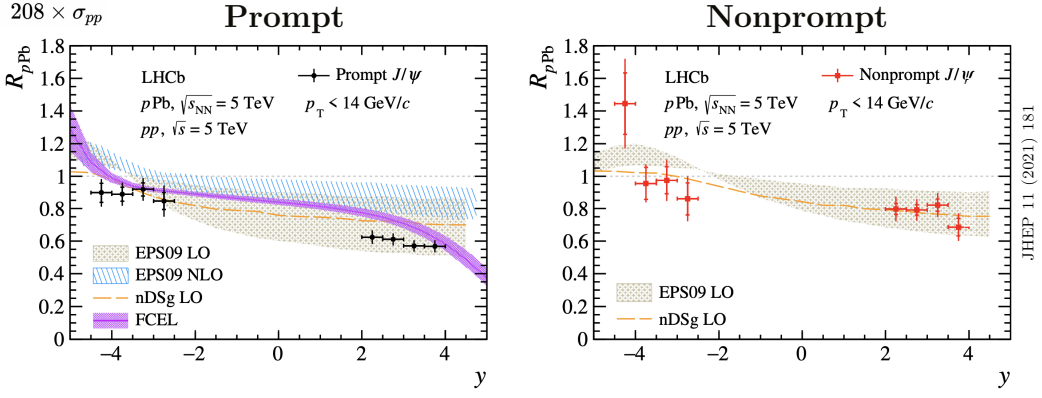
Nonprompt



- Ratio of differential J/ψ cross-section at 13 TeV vs. 5 TeV increases with p_T
  - Discrepancy between prompt J/ψ ratio & CGC+NRQCD[2] (errors mostly cancel)
  - Nonprompt J/ψ data consistent with FONLL[3] predictions as function of p_T

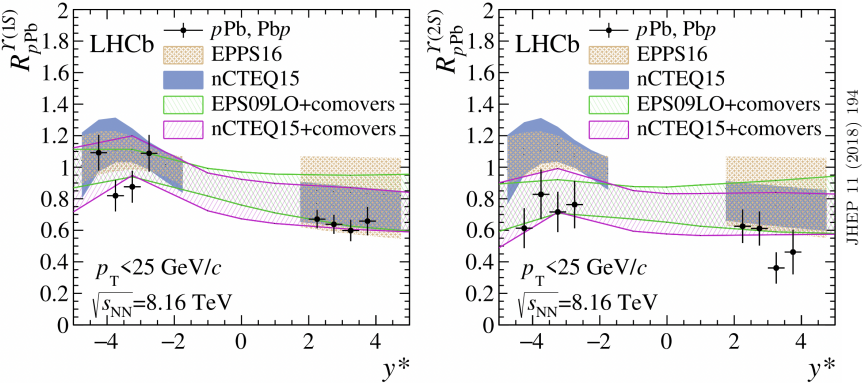
J/ψ Nuclear Modification in pPb Collisions

$$R_{pPb} = \frac{\sigma_{pPb}}{208 \times \sigma_{pp}}$$



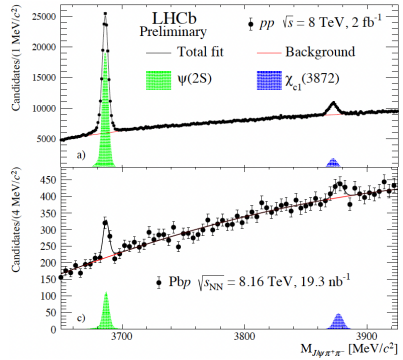
- At forward rapidity, prompt and nonprompt J/ψ nuclear modification consistent with nPDF predictions (EPS09 LO, nDSg LO)[4]
- Prompt J/ψ R_{pPb} more suppressed than EPS09 LO, NLO[5] for $-4.5 < y < -2$

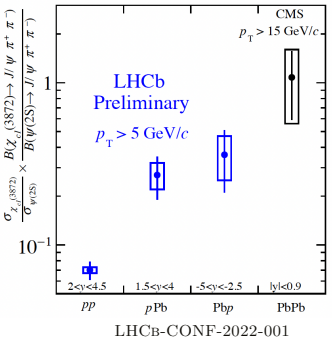
Bottomonium Nuclear Modification in pPb Collisions



- At both forward and backward rapidity, $\Upsilon(2S)$ more suppressed than $\Upsilon(1S)$
- At backward rapidity, nPDFs alone do not fully describe modification of either state
  - nPDF+comovers[6] calculations provide better description of data

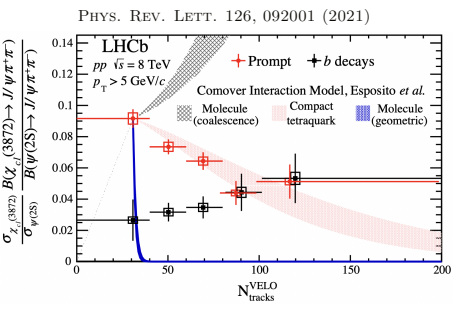
$\chi_{c1}(3872)$ & $\psi(2S)$ Production in pPb Collisions





LHCb-CONF-2022-001

Phys. Rev. Lett. 126, 092001 (2021)

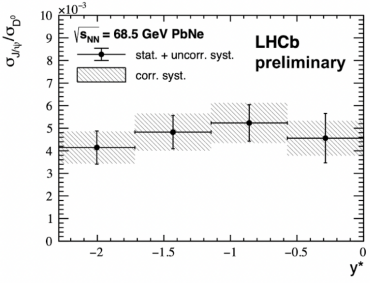


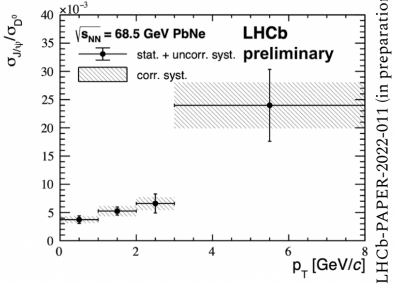
- First measurement of $\chi_{c1}(3872)$ in pPb collisions from LHCb
- Ratio of prompt $\chi_{c1}(3872)$ to $\psi(2S)$ shows increasing trend from small to larger systems
  - Suggests quark coalescence could be affecting $\chi_{c1}(3872)$ production

J/ψ & D^0 Production in PbNe Collisions

Fixed Target

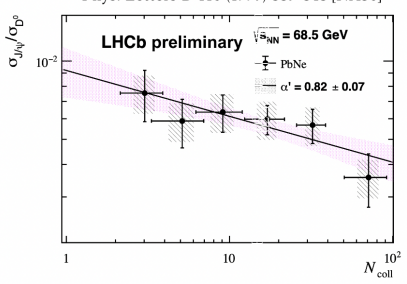
$$\frac{\sigma_{J/\psi}}{\sigma_{D^0}} = \frac{\sigma^{pp}_{J/\psi}}{\sigma^{pp}_{D^0}} \times \langle N^{\alpha'-1}_{coll} \rangle = C' \times \langle N^{\alpha'-1}_{coll} \rangle$$





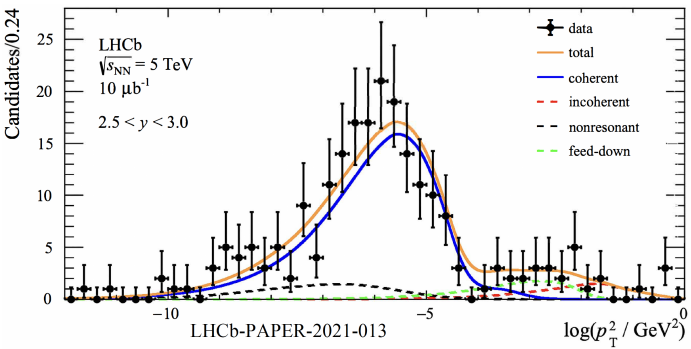
LHCb-PAPER-2022-011 (in preparation)

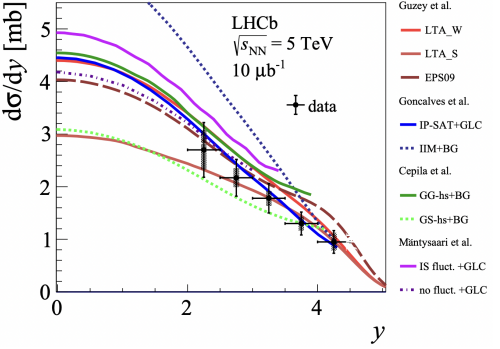
Phys. Letters B 410 (1997) 337-343 [NA50]



- Fixed target configuration with p or Pb projectiles at GeV COM energies (see P. Robbe talk)
  - Noble gases injected into VELO using SMOG (System for Measuring Overlap with Gas)
- Fit to ratio of J/ψ to D^0 vs. N_{coll} consistent with NA50 results in p+A collisions
  - α' indicates no anomalous J/ψ suppression as seen in NA50 PbPb results

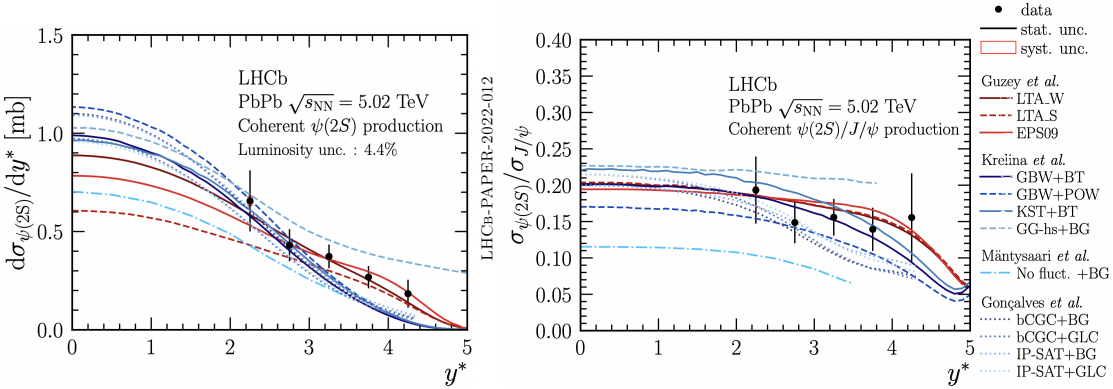
Coherent J/ψ Production in PbPb UPC





- Fit to the log of p_T^2 distribution performed to isolate coherent from incoherent production
- Differential cross-section for coherent J/ψ production decreases as function of y
  - Several of the CGC-based predictions (blue dotted, solid magenta & solid green curves) overestimate the J/ψ production

Coherent $\psi(2S)$ Production in PbPb UPC



- First measurement at LHC for coherent $\psi(2S)$ production at forward rapidity
  - pQCD calculations (red curves) by Guzey *et al.* describe data well at large y
- Ratio of $\psi(2S)$ to J/ψ not as well described by CGC predictions (blue curves)

Summary

LHCb Quarkonia Summary

① J/ψ **Production in** pp **and** p**Pb Collisions**
- **Discrepancy between prompt** J/ψ **data and CGC+NRQCD at low** p_T
- **Prompt** J/ψ R_{pPb} **more suppressed than EPS09 NLO for** $-4.5 < y < -2$

② **Bottomonium Nuclear Modification in** p**Pb Collisions**
- $\Upsilon(2S)$ **more suppressed than** $\Upsilon(1S)$ **at both rapidities**
- **At backward rapidity, nPDFs alone do not fully describe modification**

③ **Exotic Meson Production in** p**Pb Collisions**
- **First measurement of** χ_{c1}**(3872) in** p**Pb collisions**
- **Ratio of** χ_{c1}**(3872) to** ψ**(2S) increases from small to large systems**

④ J/ψ **and** D^0 **Production in Fixed Target PbNe Collisions**
- **Ratio of** J/ψ **to** D^0 **vs.** N_{coll} **shows no anomalous QGP suppression**

⑤ **Charmonium Production in Ultra-Peripheral PbPb Collisions**
- **First measurement of coherent** ψ**(2S) production at forward rapidity**
- **Ratio of coherent** ψ**(2S) to** J/ψ **consistent with pQCD predictions**

LHCb

Theoretical References

[1] Ma, Yan-Qin and Wang, Kai and Chao, Kuang-Ta
$J/\psi(\psi')$ production at the Tevatron and LHC at $\mathcal{O}(\alpha_s^4 v^4)$ in nonrelativistic QCD
Phys. Rev. Lett. 106 (2011) 042002

[2] Ma, Yan-Qin and Venugopalan, Raju
Comprehensive Description of J/ψ Production in Proton-Proton Collisions at Collider Energies
Phys. Rev. Lett. 113 (2014) 192301

[3] Cacciari, M. and Mangana, Michelangelo and Nason, Paolo
Gluon PDF constraints from the ratio of forward heavy-quark production at the LHC at $\sqrt{s} = 7$ and 13 TeV
Eur. Phys. J. C75 (2015) 610

[4] Ferreiro, E.G. and Fleuret, F. and Lansberg, J.P.
Impact of the Nuclear Modification of the Gluon Densities on J/ψ production in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV
Phys. Rev. C 88 (2013) 4, 047901

[5] Albacete, J.L. and Armesto, N. and Baier, R. et al.
Predictions for p+Pb Collisions at $\sqrt{s_{NN}} = 5$ TeV
Int. J. Mod. Phys. E 22 (2013) 1330007

[6] Ferreiro, Elena and Lansberg, Jean-Philippe
Is bottomonium suppression in proton-nucleus and nucleus-nucleus collisions at LHC energies due to the same effects?
J. High Energy Phys. 10 (2018) 094

[7] Arelo, Francois and Peigne, Stephane
J/ψ suppression in p-A collisions from parton energy loss in cold QCD matter
Phys. Rev. Lett. 109 (2012) 122301

LHCb

Back-Up

Selected LHCb Quarkonia Talks Since 7th HF-WINC

DIS 2019, QM 2019, QM 2022, DIS 2022, LHCP 2022, and SQM 2022 (all talks hyperlinked)

Quarkonia Production in Ultraperipheral PbPb collisions at LHCb

New Measurements in Fixed-Target Collisions at LHCb

Open and Hidden Beauty Production in pPb Collisions at LHCb

Heavy Flavor and Exotic Production at LHCb

Charmonium Production in PbPb Ultraperipheral Collisions (UPC) and Z Production in pPb at LHCb

SMOG: Experimental Results

Quarkonia Production in (Ultra)peripheral PbPb Collisions at LHCb

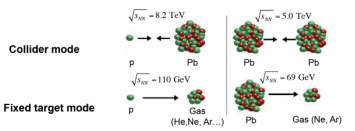
New Measurements in Fixed Target Collisions at LHCb

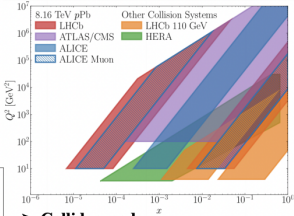
Heavy Flavor Hadron Production at LHCb

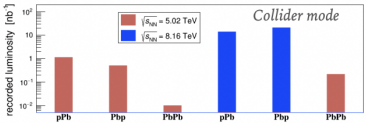
Production of Exotic Hadrons in High Multiplicity pp and pPb Collisions at LHCb

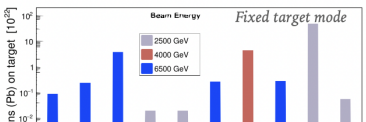
Quarkonia Production in Ultraperipheral PbPb Collisions at LHCb

LHCb heavy ion collision modes and datasets









➤ Collider mode

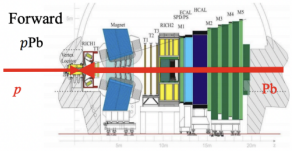
- pPb/Pbp:
  - 5.02 TeV and 8.16TeV
  - Probes saturation region and small Bjorken-x physics
- PbPb: centrality-limited to 60%

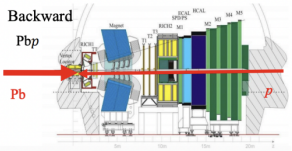
➤ Fixed-target mode (SMOG)

- pNe, pHe, pAr: $\sqrt{s_{NN}}$~ 100 GeV
- PbNe: $\sqrt{s_{NN}}$ ~ 68.6 GeV
- Covers mid to backward rapidity: anti-shadowing region

➤ pPb/Pbp rapidity coverage

- y^*: rapidity in nucleon-nucleon cms
- $y^* = y \pm 0.465$
- Forward: $1.5 < y^* < 4.0$
- Backward: $-5.0 < y^* < -2.5$
- Common region: $2.5 < |y^*| < 4.0$



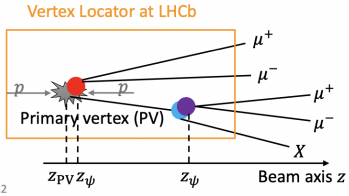


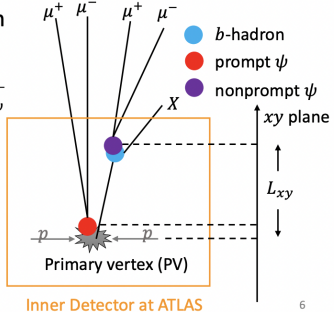
Credit: Jiayin Sun, Quark Matter 2022

Quarkonium in pp collisions

- Charmonium (J/ψ, $\psi(2S)$) in pp collisions:
  - Prompt: originate from the primary pp collision vertex
  - Nonprompt: originate from b-decay vertex
- Bottomonium (Υ) in pp collisions: only prompt
- To separate prompt and nonprompt charmonium
  - Pseudo decay time

forward$-y$: $t_z = \dfrac{z_\psi - z_{\mathrm{PV}}}{p_z/m_\psi}$ mid$-y$: $\tau = \dfrac{L_{xy}}{p_{\mathrm{T}}/m_\psi}$



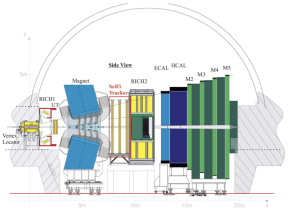


Credit: Li Xu, Quarkonium as Tools 2022

A large Scintillating Fibre Tracker for LHCb

Daniel Berninghoff, Physikalisches Institut, Heidelberg University
on behalf of the LHCb Scintillating Fibre Tracker Collaboration

The LHCb Detector



The upgraded LHCb detector.

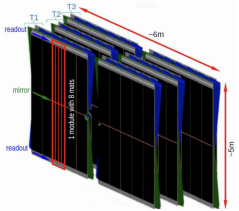
Single-arm forward spectrometer with a pseudorapidity acceptance between 2 and 5 that is specialised in the search of new physics in beauty and charm hadron decays

LHCb Upgrade: 2019-2022

Upgrade of the LHCb detector to increase the precision on key observables and extend its physics reach by obtaining 5 to 10 times higher signal yields.

- ⇒ 5 times higher instantaneous luminosity
- ⇒ Triggerless 40 MHz readout
- ⇒ New front- and back-end electronics
- ⇒ **Replacement of complete tracking system**

The Scintillating Fibre (SciFi) Tracker



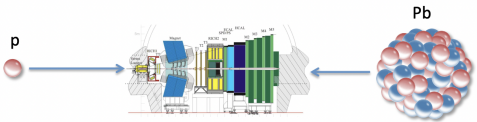
Large and high granular scintillating fibre tracker that is readout by arrays of silicon photomultipliers (SiPMs).

- 3 stations (T1, T2, T3) with 4 layers each
- Covering a total area of 340 m^2
- 1 % X_0 per layer
- Spatial resolution < 100 µm
- Single hit efficiency ~99 %
- 524 288 channels in total
- 250 µm fibre diameter and channel width
- 40 MHz readout
- ~20 Tb/s data rate

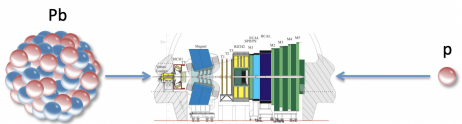
Credit: Daniel Berninghoff, CERN-Poster-2021-1047

Nuclear effects & asymmetric acceptance

"forward"
Measured particles at $\eta > 0$
Probes low x in nuclear PDF



"backward"
Measured particles at $\eta < 0$
Probes high x in nuclear PDF



Nuclear modification factor

$$R_{pPb} = \frac{\text{cross-section for pPb}}{A_{Pb} \times \text{cross-section for pp}}$$

No nuclear effects: $R_{pPb} = 1$

Forward-Backward (FB) ratio

$$R_{FB} = \frac{\text{cross-section for pPb } +|y|}{\text{cross-section for pPb } -|y|}$$

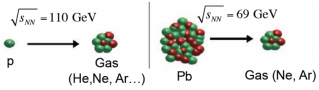
Hans Dembinski | MPIK Heidelberg 8

Credit: Hans Dembinski, Deep Inelastic Scattering 2019

SMOG: fixed-target program

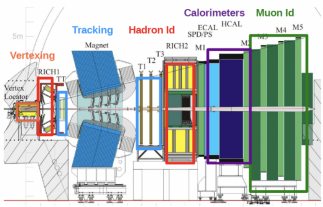
SMOG: System for Measuring Overlap with Gas.

Noble gases at a pressure of O(10^{-7}) mbar are injected into the VELO.



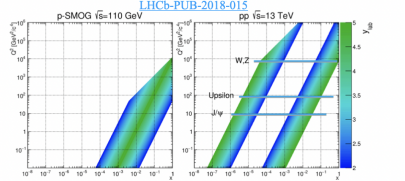
$$y = y^* + ln(\frac{\sqrt{s_{NN}}}{m_p})$$

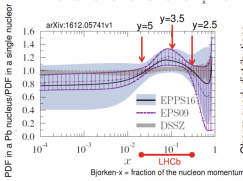
$$x_F \simeq \frac{2}{\sqrt{s_{NN}}}\sqrt{M^2 + p_T^2}\ \ sinh(y^*)$$

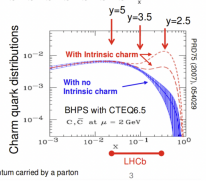


JINST 3 (2008)S08005

LHCb-PUB-2018-015







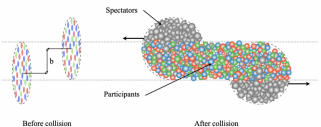
- $-3.0 < y^* < 0$
- Probe intrinsic charm content in the nucleon.
- Access nPDF anti-shadowing region.

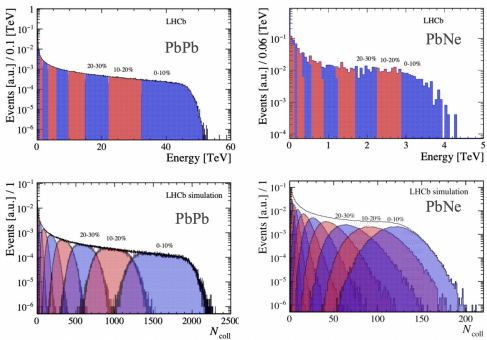
Credit: Sara Sellam, Strangeness in Quark Matter 2022

Centrality determination in PbNe

16

- The centrality of a nucleus-nucleus → overlap region between the nuclei where the nucleons are colliding.
- MC Glauber model used to to isolate the hadronic part and subsequently define the centrality classes
- Proxy: energy deposit in the ECAL (VELO clusters saturates)





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https://arxiv.org/pdf/2111.01607.pdf

Elisabeth Niel - LHCP 2022

Credit: Elisabeth Maria Niel, Large Hadron Collider Physics 2022