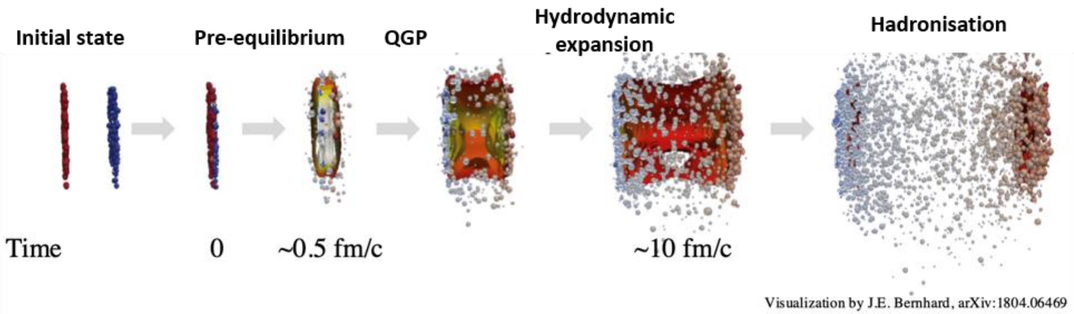
LHCb Upgrade II physics programme with Heavy-Ions

Towards high-precision QCD measurements

Hadronic physics at LHC

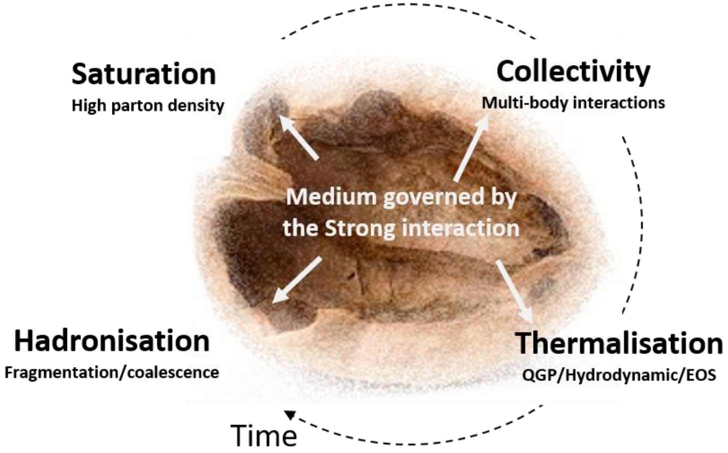
Prospectives nationales IN2P3 – Giens, oct. 2021



- **Studying the strong interaction with hadronic collisions**
  - *pp* collisions → study quark/gluon interactions involving **few partons**
  - *p*A collisions → study quark/gluon interactions involving **many partons**
  - AA collisions → study quark/gluon interactions from **deconfined medium**
    → study deconfined medium properties

- **LHC Run 1 and Run 2 results: *pp*, *p*Pb, PbPb**
  - **confirmed and refined the picture of a nearly-perfect fluid (sQGP)** first observed at RHIC/BNL *(Very dense medium, Azimuthal and long-range correlations, thermalization, recombination,…)*
  - **also lead to striking new results : Collective-like effects** observed **also in** high-multiplicity ***pp*** and ***p*Pb** collisions, **now a major focus of heavy-ion physics**

- **Opened and central long-standing questions**
  - No clear evidence of **saturation** so far
  - **Collectivity (** in **small systems, pre-equilibrium** phase,…)
  - **Equation of State** of QGP phase (hydro describes well mid-rapidity data), color screening,…
  - **Hadronization** behaves differently when comparing e^+e^- and *pp*/*p*Pb/PbPb (strangeness enhancement, baryon/meson ratios,…)



- **LHC Run 3 and Run 4: towards accurate quantitative description (mainly in *pp*, *p*Pb, PbPb)**
  More luminosity (~10x) and improved instrumentations (experimental upgrades)

- **LHC Run 5 and Run 6: towards thorough quantitative description**
  - Challenge theoretical frameworks with new observables, smaller systems, larger rapidity, exotics …
  - For example: *pp* → ***p*O** → ***p*Ar** → ***p*Xe** → *p*Pb → **OO** → **ArAr** → **XeXe** → PbPb → **AB(?)**

Hadronic physics at LHC Previous prospective editions

- **2020 update of the European Strategy for Particle Physics**

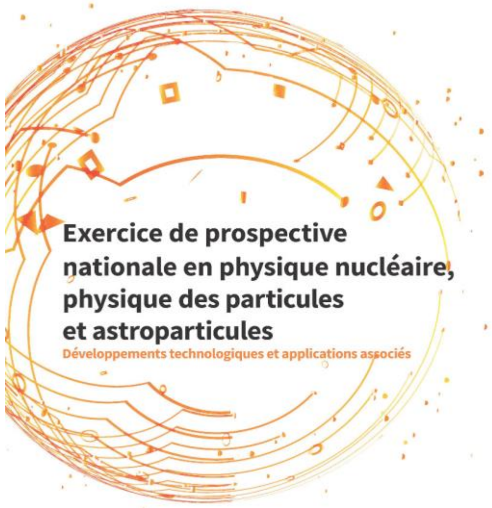
The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

- **Prospectives nationales IN2P3 – Giens, oct. 2021 :**

1. **Fully exploit the physics potential of LHC Run 3 with the upgraded ALICE, CMS and LHCb (+SMOG2)** experiments to pursue the study of matter at high temperature. **The three experiments exhibit very rich and interesting complementarities**, which should be promoted by combining their measurements.

2. **Strengthen efforts involving theorists and experimentalists towards a global interpretation of data** taking advantage of the forthcoming various and precise data from all experiments at different energies and correlating them. **A forum like the GDR QCD should be fully exploited to this end.** Moreover, the establishment of a centralized platform providing various model predictions in a complete manner as already done in particle and cosmic ray physics, would be highly valuable.

3. **Organize the strategic choice to be made for QGP studies after LHC Run 3.** Given the size of the community and the beginning of the EIC program in the US, strategic orientations should be **based on long term perspectives, well-identified French collaborations and comprehensive studies** of the ALICE, CMS and LHCb upgrade-related physics gain.



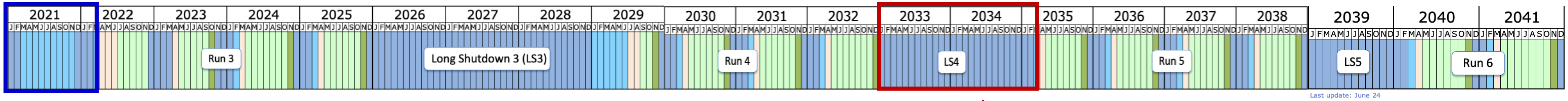
In the following, will focus on LHCb upgrade II (Run 5+Run 6)

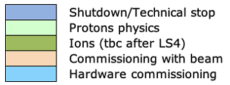
The LHCb experiment – towards Run5 & Run6

Lumi *pp*
Goal: 50 fb^{-1} (Run3 + Run4)

Lumi *pp*
Goal: 300 fb^{-1}(Run5 + Run6)

(Run1 + Run2) 9 fb^{-1}





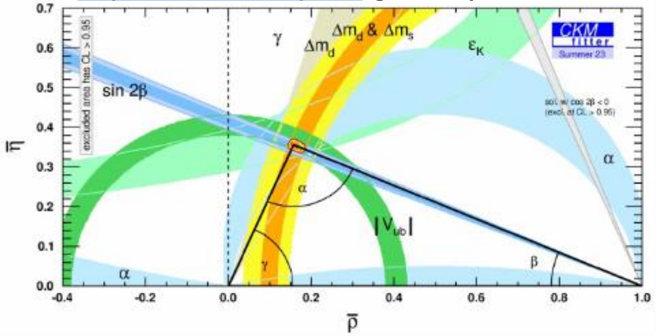
Upgrade I
Major LHCb upgrade

Upgrade II
Major LHCb upgrade

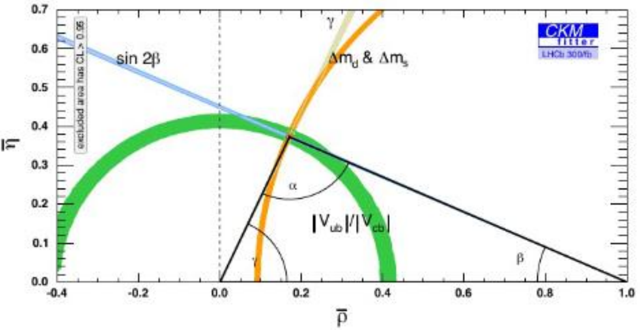
- **From low to large pileup in *pp***
  - LHCb Run 1&2: no pileup (μ~1)
  - LHCb Run 3&4: small pileup (μ~5)
  - **LHCb Run 5&6: large pileup (μ~40)**

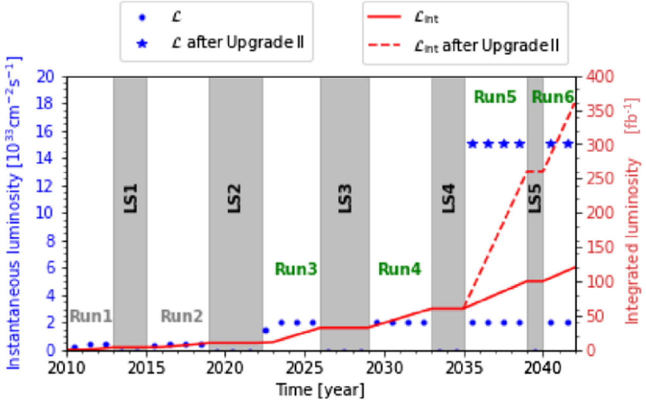
- **Experimental requirements for Run5 and Run6**
  - Keep the same detector performances (wrt Run1-4)
  - Requires **detector upgrades with larger granularity,** tens of picoseconds Time of Flight resolution, improved data acquisition and Real Time Analysis
  - **Heavy Ion physics constraints taken into account** for upgrade II

http://ckmfitter.in2p3.fr/ global inputs as of 2023



LHCb Upgrade II with 300 fb^{-1}





PHYS. REV. ACCEL. BEAMS 27, 061003 (2024)

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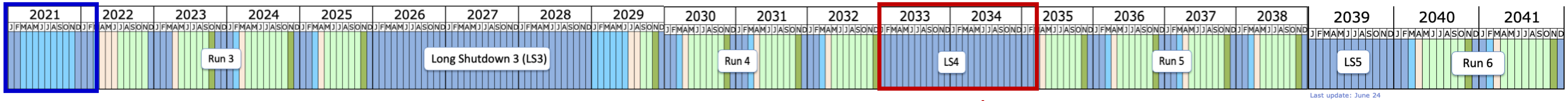

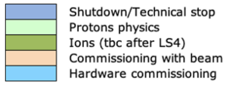

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Major LHCb upgrade

Upgrade II
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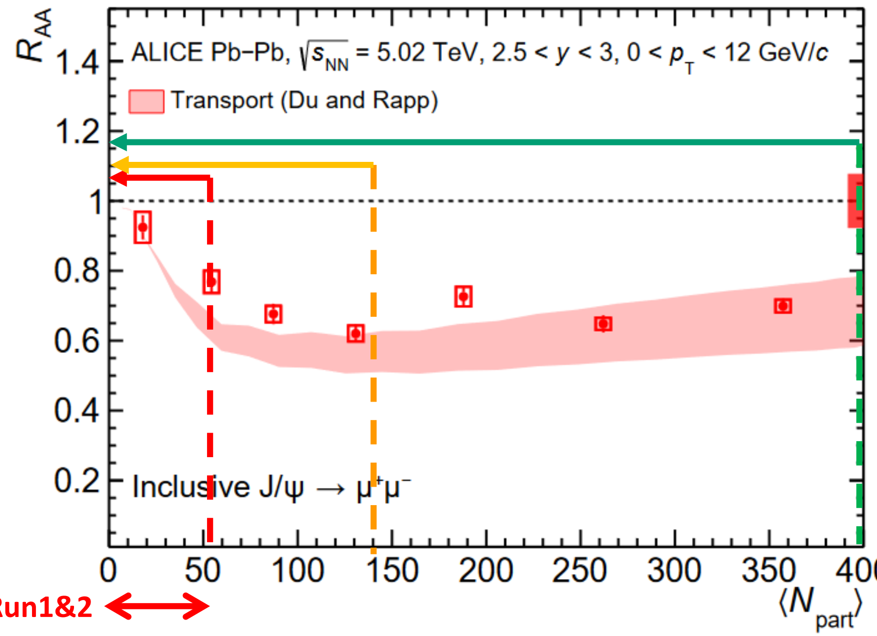
- **Consequences for the Heavy Ion program**
  - Tracking limitation (due to occupancy) in **Run1&2: PbPb 60<centrality<100%**
  - Better tracking performances in **Run3&4: PbPb 30<centrality<100%**
  - **Full tracking performances** for **Run5&6: PbPb 0<centrality<100%**

  ➔ **Full tracking performances for lighter systems**



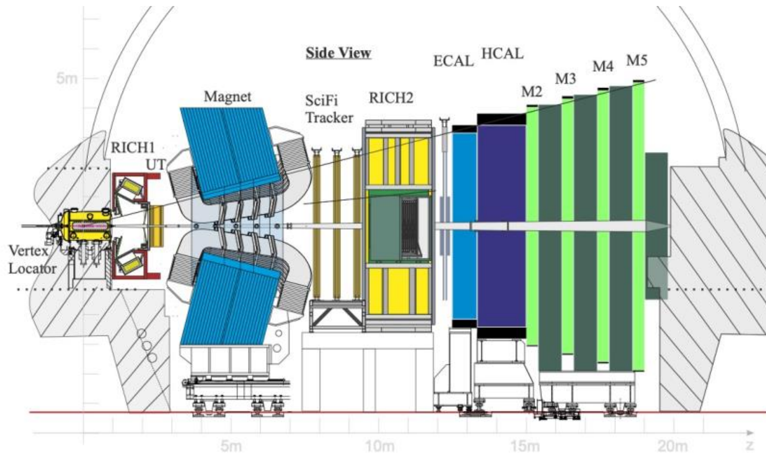
LHCb Run1&2 ↔

LHCb Run3&4 ↔

LHCb Run5&6 ↔

The LHCb experiment – main features

- **Designed for heavy flavour physics**
- **Single arm spectrometer, fully instrumented in $2 < \eta < 5$**



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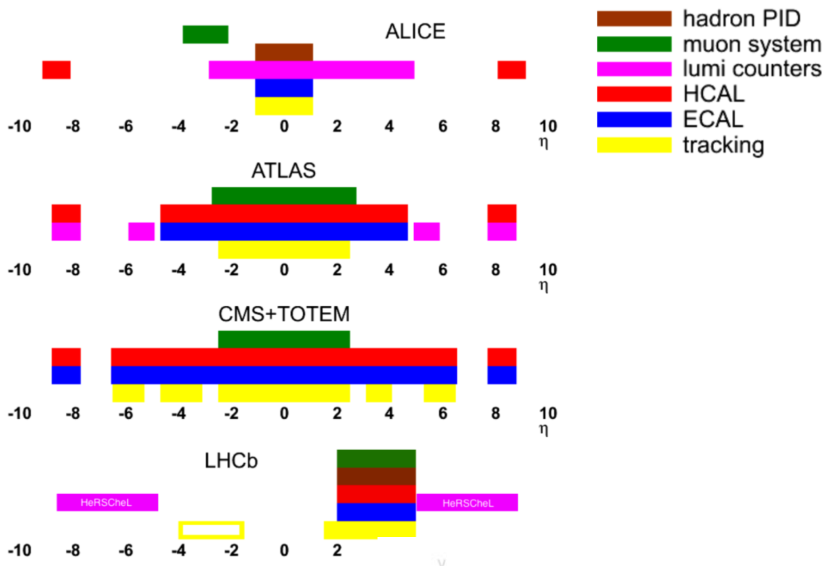


Excellent vertex, IP and decay time resolution

$\sigma(IP) \approx 20\mu m$

Very good momentum resolution

$\delta p/p \approx 0.5-1\%$ for $0<p<200$ GeV/c

Particle identification

$\varepsilon_{K\to K} \approx 95\%$ for $\varepsilon_{\pi\to K} \approx 5\%$ up to 100 GeV/c

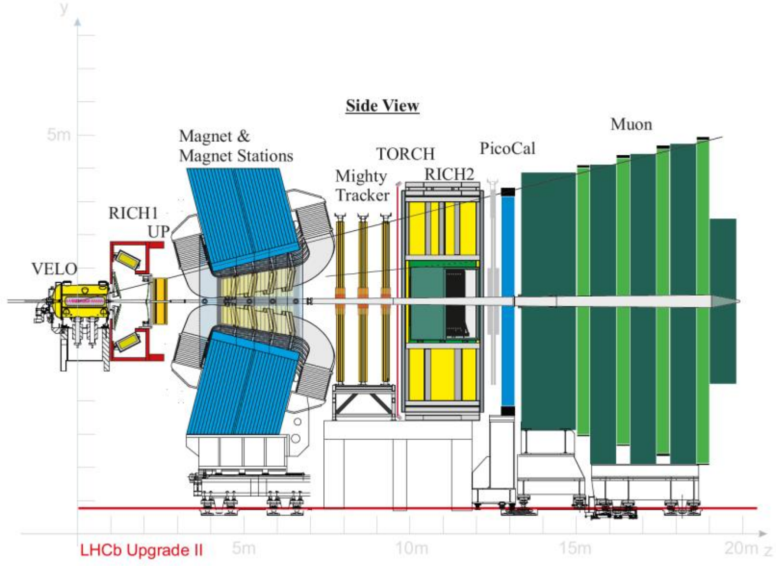
$\varepsilon_{\mu\to\mu} \approx 97\%$ for $\varepsilon_{\pi\to\mu} \approx 1-3\%$

Fixed target setup

$\sqrt{s_{NN}} \sim 70 - 110$ GeV

$-2.5 \lesssim y^* \lesssim 0.5$

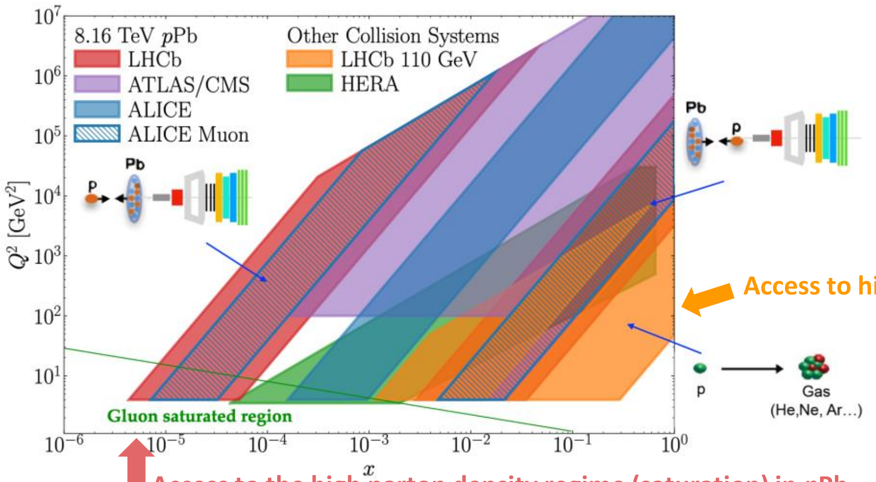
- **LHCb Upgrade II**
  - Improve detector performances to cope with **pileup ~40 in *pp*** and **full PbPb centrality reach**
  - **Tracking will benefit from ongoing R&D on CMOS silicon sensors**



LHCb striking features – Rapidity Coverage

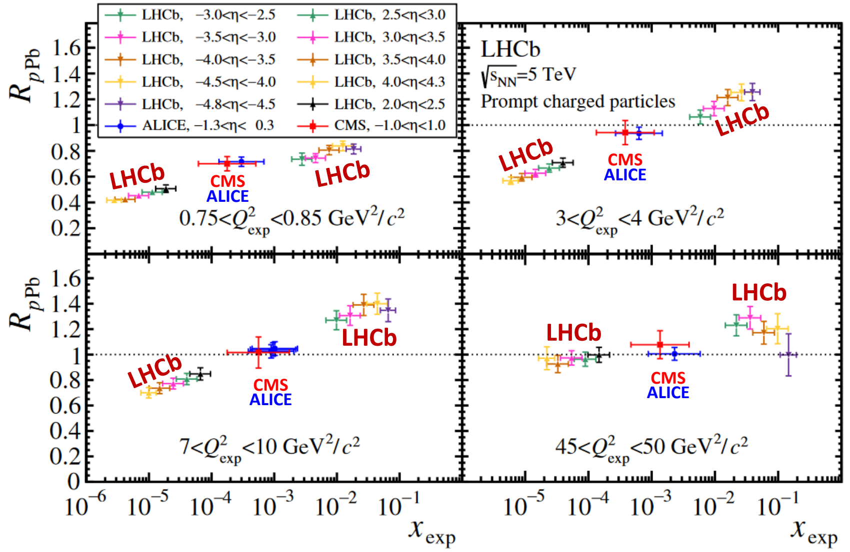
- **Pseudo-rapidity coverage**
  - LHCb acceptance : $2 < \eta < 5$
  - Sole experiment providing full detection capabilities in this range
  - Well placed to access the high parton density regime (saturation)

- **Bjorken-x coverage**
  - $x_{1,2} \sim \frac{Q}{\sqrt{s_{NN}}} e^{\pm\eta} \; with \; Q^2 \sim m^2 + p_T^2$
  - LHCb in *collider mode* :
    - pPb: $10^{-6} < x < 10^{-4}$
    - Pbp: $10^{-3} < x < 10^{-1}$
  - LHCb in Fixed-Target mode (pA)
    - $10^{-3} < x < 0.5$



Access to high Bjorken-x in Fixed Target

Access to the high parton density regime (saturation) in pPb



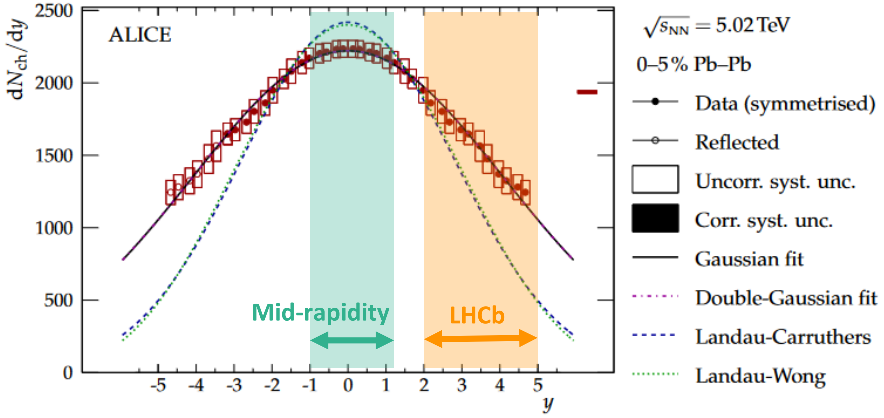
PRL 128, 142004 (2022)

Prompt charged particle production in pPb

LHCb striking features – Rapidity Coverage

J.-Y. Ollitrault, LHCb IFT Workhop Santiago de Compostela, 1-3 July 2024

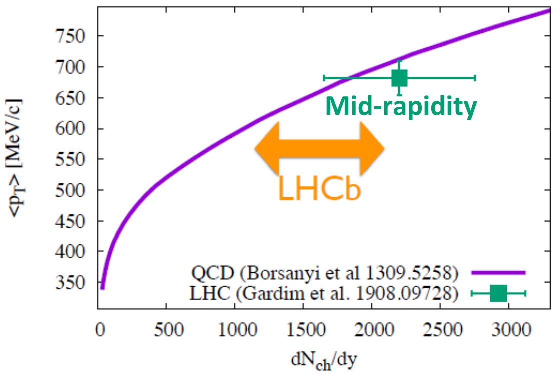
- **Multiplicity smaller at large rapidity (within the same transverse area) ➔ initial temperature smaller at large rapidity**



Phys.Lett. B 772 (2017) 567-577

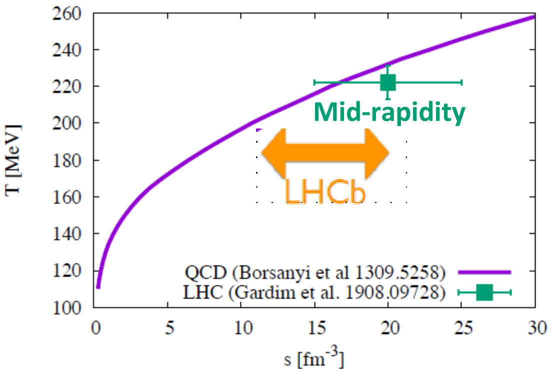
- **LHCb acceptance : 2<η<5**

Ollitrault et al, Nature Physics 16, 615-619 (2020)



$s(T_{eff}) \propto \frac{dN_{ch}}{dy}$

$T_{eff} \propto \langle p_T \rangle$



LHCb allows a precise scan of the equation of state in the range 190 < T < 220 MeV

LHCb striking features – Heavy Flavour

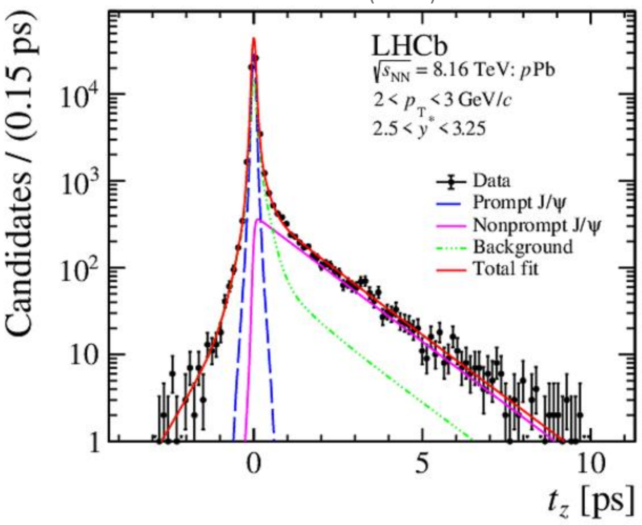
- **LHCb is dedicated to heavy flavour measurement**
  (best way to explore deconfinement)

  - Precise vertexing
    - separation of prompt production from *B* decay products (IP resolut°: 20μm)

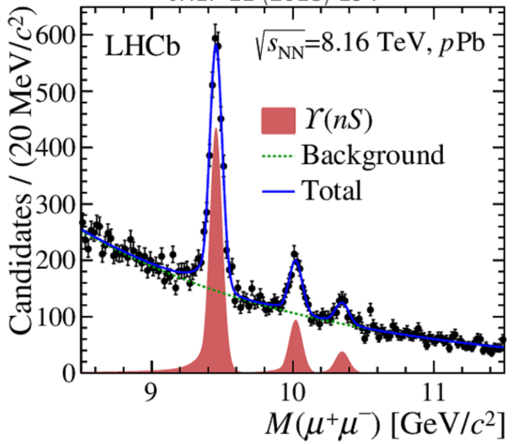
  - Precise tracking
    - reconstruction down to p_T=0

  - Precise particle identification
    - full reconstruction of hadronic decays of charm or beauty, such as $D^0 \rightarrow K\pi$

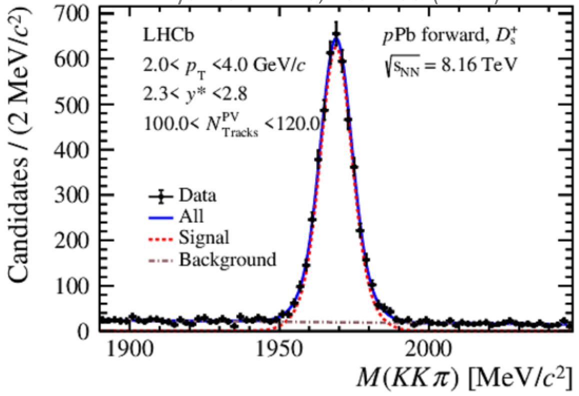
JHEP 04 (2024) 111



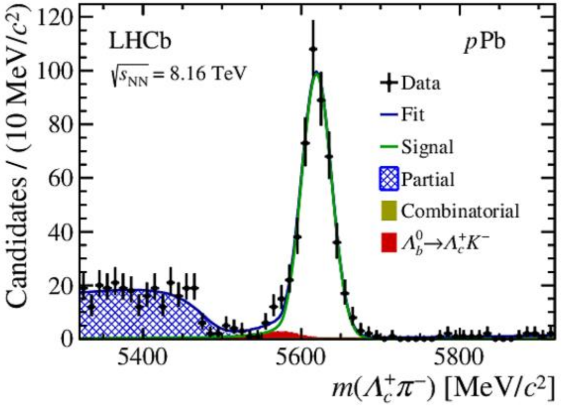
JHEP 11 (2018) 194



Phys. Rev. D110, L031105 (2024)

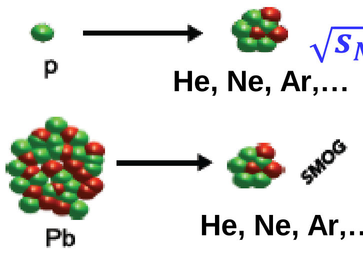


Phys. Rev. D99 052011 (2019)



LHCb striking features – Fixed-target

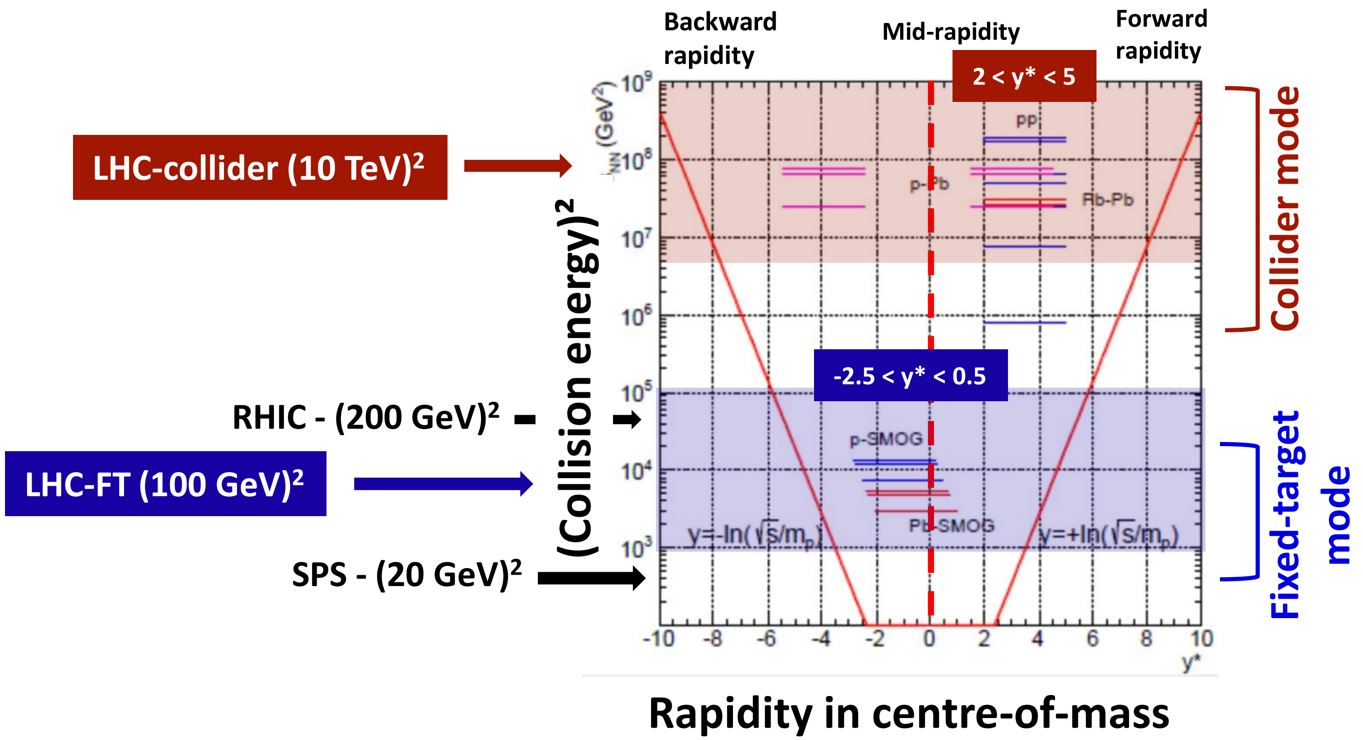
- **UNIQUE feature at LHC**
- **Specificities**



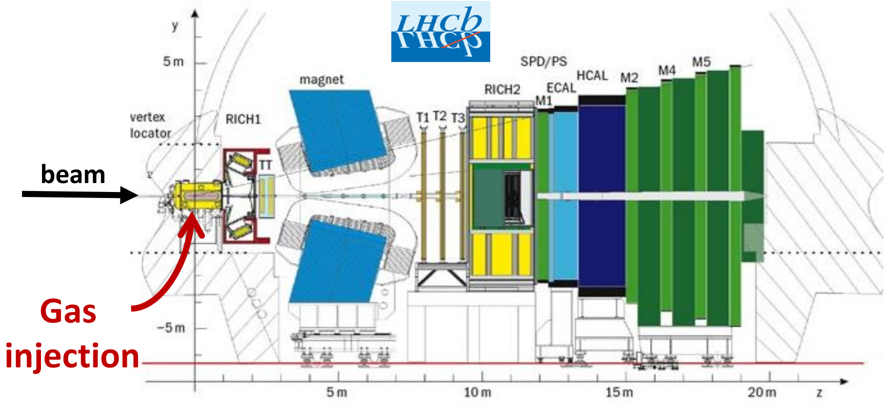
$\sqrt{s_{NN}}$ =70 to 110 GeV

$\sqrt{s_{NN}}$ =70 GeV

At $\sqrt{s_{NN}} = 110$ GeV, $y_{centre\text{-}of\text{-}mass} = y_{lab} - 4.77$



- **From SMOG to SMOG2**
  - ***SMOG: During Run 2*** injecting gas directly in the VELO tank
    - **Limited to noble gas** (He, Ne, Ar,…)
    - **Limited in target density** (pressure ~10^{-7} mbar)
    - Share **same IP region with collider** mode
    - Limited to **Ne in PbA** (because of occupancy limitations)
  - ***SMOG2: Starting Run 3*** injecting gas in a storage cell 30 cm upstream of the VELO
    - **Not limited to noble gas** (can inject in addition H_2, D_2, O_2)
    - Up to **100 x more stat** than SMOG (10^5 to 10^6 J/ψ in *p*A)
    - **SMOG2 IP displaced** wrt to collider IP → operating in parallel with collider mode
    - Limited to **Ar in PbA** (because of occupancy limitations)



Heavy Ion physics with LHCb Upgrade II

- **Workshop dedicated to LHCb HI@Run5 and beyond**
  (LHCb public note to be released soon)
  - *Define priorities and flagship measurements*
  - *Identify complementarities with other LHC experiments*

- **Topics *(theoricist, experimentalist)***
  - **Bulk properties** *(Jean-Yves Ollitrault, Imanol Corredoira)*
  - **Electromagnetic probes** *(Jacopo Ghiglieri, C. Da Silva)*
  - **Heavy Flavor** *(Zhao Jiaxing, Benjamin Audurier)*
  - **Quarkonia** *(Jean-Philippe Lansberg, Oscar Boente Garcia)*
  - **Jets** *(Bin Wu, Kara Mattioli)*
  - **Exotica** *(Laura Tolos, John Matthew Durham)*
  - **UPC** *(Kate Lynch, Charlotte Van Hulse)*
  - **Fixed-target physics at LHCb** *(Andrea Signori, Saverio Mariani)*

LHCb IFT Workshop Santiago de Compostela

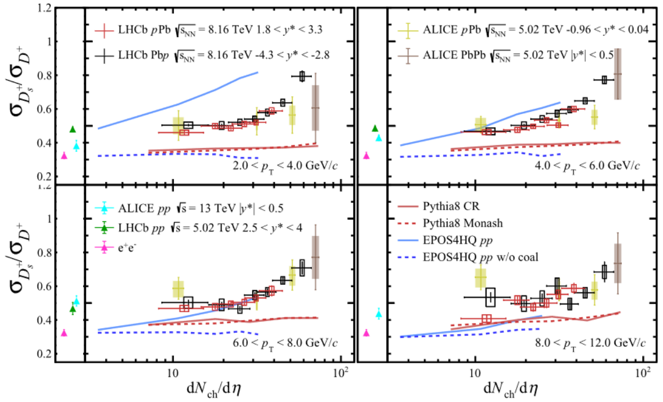
Heavy Flavour with LHCb

- **Classic heavy ion physics**
  - Testing nPDFs, saturation, hadronization, coalescence, medium properties…
- **Now reaching a point where we need to further explore**
  - **Open heavy flavour** production
  - **Quarkonium** feed-downs
- **High luminosity samples needed**
  - Up to most central (0%) PbPb events

  (Santiago workshop expectations performed with $\mathcal{L}_{PbPb} = 10\ \text{nb}^{-1}$)
  - With lighter systems (O, Ar, Xe,…)

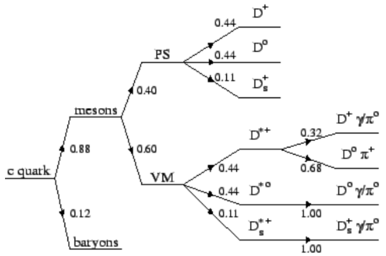
Strangeness enhancement with charmed mesons in 8.16 TeV pPb (~30 nb^{-1})

PRD 110, L031105 (2024)



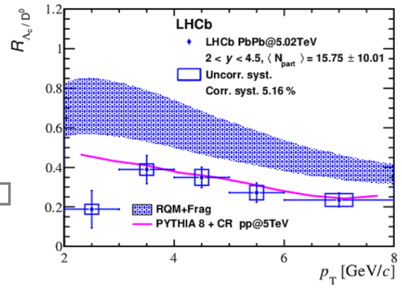
Fragmentation functions in e^+e^-

(*Eur.Phys.J.C* 76 (2016) 7, 397)

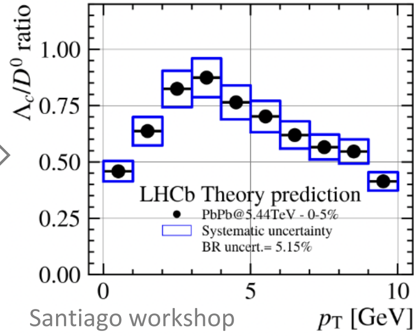


Λ_c^+ to D^0 ratio in peripheral (90−65%) 5.02 TeV PbPb (0.2 nb^{-1})

JHEP06(2023)132



LHCb Upgrade II



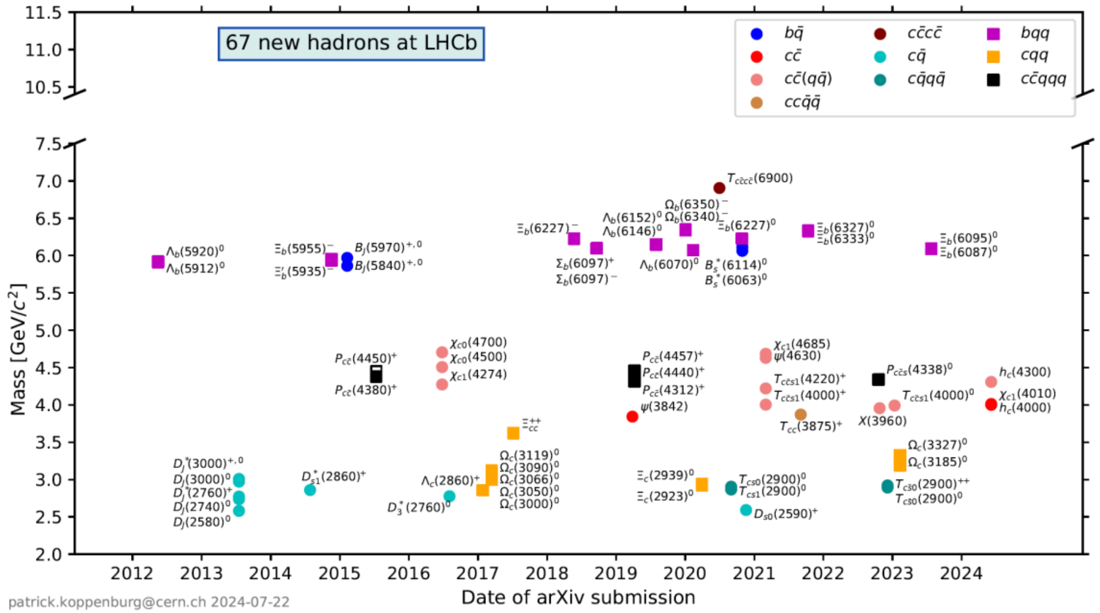
Santiago workshop
$\mathcal{L}_{PbPb} = 10\ nb^{-1}$

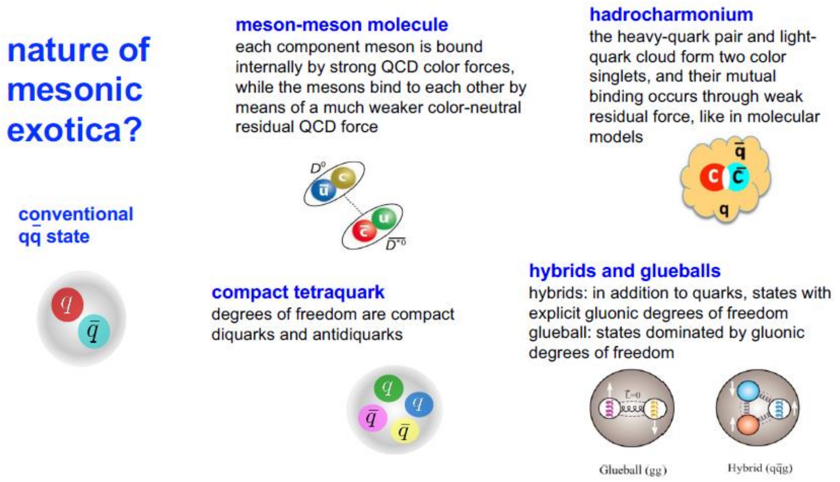
Centrality [%]	$\langle N_{coll}\rangle$	$\langle N_{part}\rangle$	J/ψ	$\psi(2S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
10-0	1570.3	357.2	16700000	223000	35500	3010	690
			$\chi_c(1P)$	$\chi_b(1P)$	$\chi_b(2P)$	$\chi_b(3P)$	
			502000	1060	266	106	
			$\chi_{c0}(1P)$	$\chi_{c1}(1P)$	$\chi_{c2}(1P)$	$\chi_{b0}(1P)$	$\chi_{b0}(1P)$
			160	3900	2220	17	8

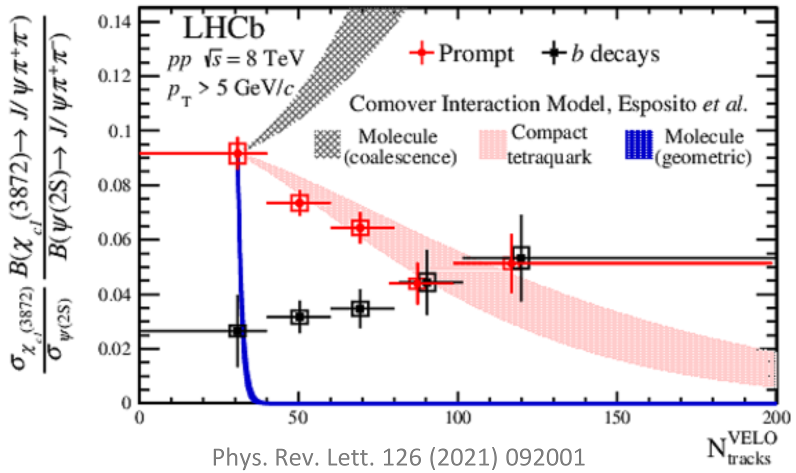
Santiago workshop
$\mathcal{L}_{PbPb} = 10\ nb^{-1}$

Heavy Flavor with LHCb

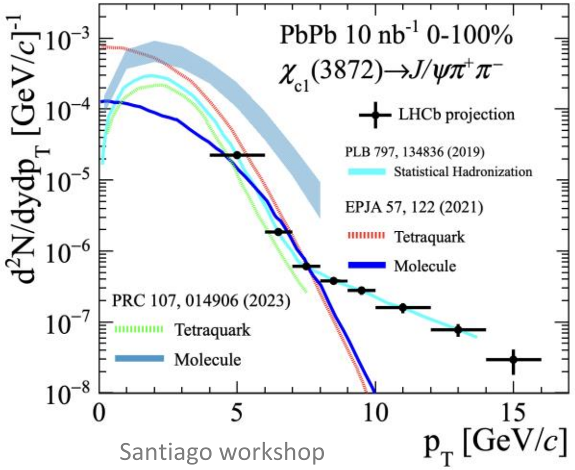
- **Classic heavy ion physics**
  - Testing nPDFs, saturation, hadronization, coalescence, hydrodynamics, pre-equilibrium…
  - **Exotica**
    - *pp* to discover new hadrons
      - 67 new hadrons discovered by LHCb so far
    - High mult *pp*, *p*A and AA to study their nature







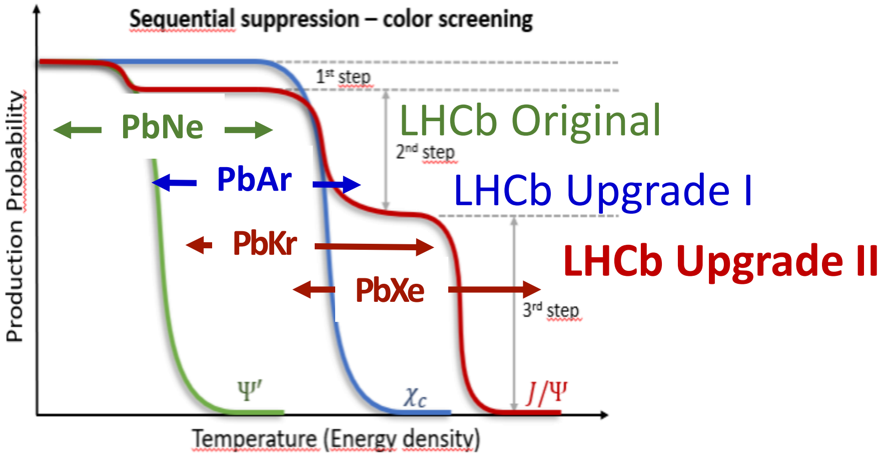
Phys. Rev. Lett. 126 (2021) 092001



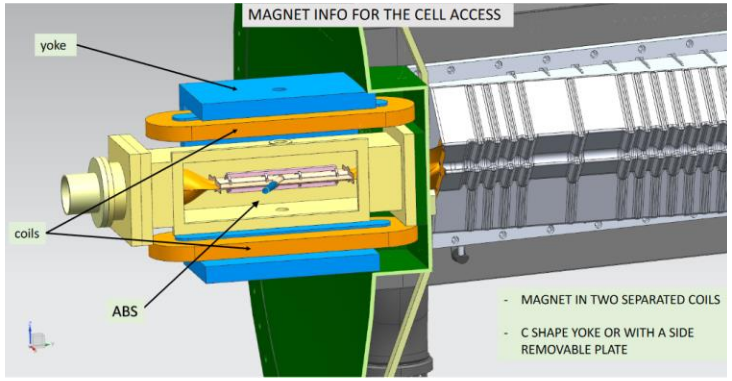
Santiago workshop
$\mathcal{L}_{PbPb} = 10\ nb^{-1}$

Fixed target with LHCb Upgrade II

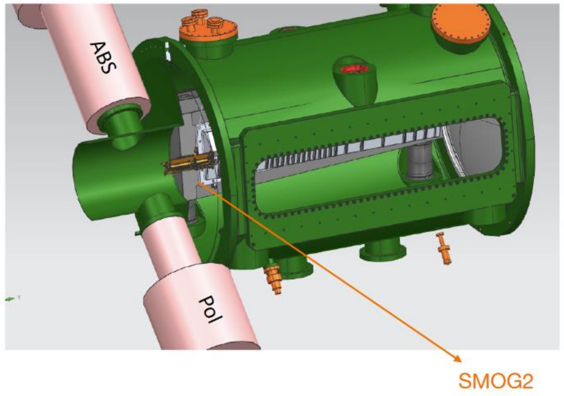
- **Non-polarized target (SMOG2)**
  - In Run 3 and Run 4
    - High *pA* statistics will be recorded
    - In PbA, limited to Ar (A=40)
  - In Run 5 and Run 6
    - No limitation for PbA
    - Explore QGP at high energy density
      - Example with quarkonium sequential suppression



- **Polarized target (LHCspin)**
  - Extending the fixed-target physics program in Run 4+
  - Will allow injection of unpolarised gases



    - Compact dipole magnet (300 mT) → static transverse field
    - Possibility to switch to a solenoid and provide longitudinal polarisation
  - Alternative setup (jet target) being investigated in parallel



Current french contribution to LHCb HI

- **The LHCb Ion and Fixed Target (IFT) physics Working Group**
  - **Created in July 2015** : *proposal for LHCb participation to the Heavy Ion Runs* (LHCb-INT-2015-019)
  - *From 10 people at the beginning to 40 – 50 people nowadays*: **China, France, Germany**, **Italy**, **Spain**, **Ukraine**, **USA**
  - Former IFT Convenors from France: *L. Massacrier*/IJClab (2015-2016), *F. Bossu*/IJClab (2016-2018), *F. Fleuret*/LLR (2018-2020), *M. Winn*/IJClab (2018-2019), *Y. Zhang*/IJClab (2019-2021), *B. Audurier*/LLR (2019-2021)

- **French involvement Timescale (in short)**
  - July 2015 → Contribution to *proposal for LHCb participation to the HI Runs* (P. Robbe/IJClab + F. Fleuret/LLR, IJClab associate)

  → **ESPPU 2018**
  - Sep. 2020 → LLR becomes full member (3 FTE perm.)
  - June 2021 → Irfu becomes technical associate w/ LLR
  - June 2024 → Irfu becomes full member (3 FTE perm.)
  - June 2024 → Subatech becomes technical associate (3.4 FTE perm.) w/ IJClab

  → **ESPPU 2024**

Irfu and Subatech (+LLR interest) have strong expertise on tracking fitting well LHCb needs for Upgrade II

France (IN2P3+Irfu) is very well placed to play a leading role in HI Run5 and Run6

IN2P3

45 / 639	PhD équiv.
7 %	M&O cat. A

LAPP	*Annecy*
LPCA	*Clermont*
CPPM	*Marseille*
IJCLAB	*Orsay*
LLR	*Palaiseau*
LPNHE	*Paris*
+ DPhN/Irfu	*Saclay*
+ Subatech	*Nantes*

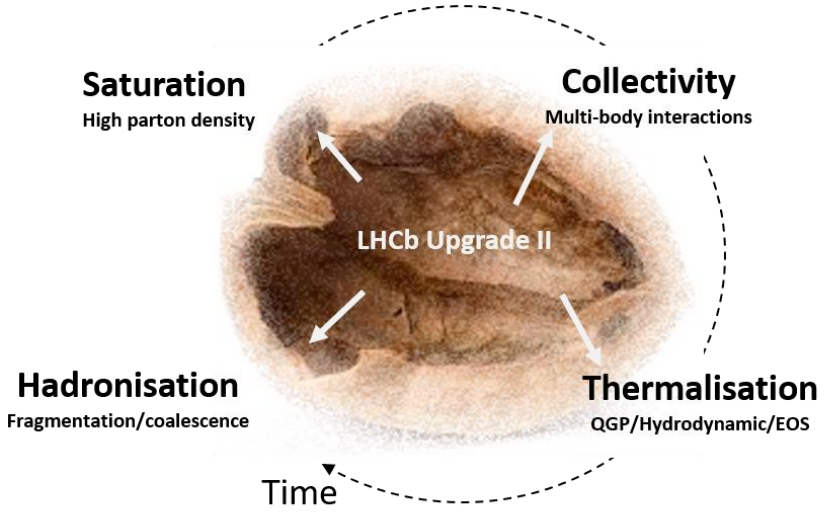
Summary – HI physics at Run 5 and 6 with LHCb

- **Still central question to be addressed regarding our understanding of the strong interaction after Run 4**
  - Need large statistics → **Run 5 and Run 6**
  - Need to explore other systems than pPb and PbPb → **Run 5 and Run 6**

- **LHCb offers striking/unique features**
  - Fully instrumented in $2 < \eta < 5$
  - Designed for Heavy Flavour measurement
  - Operates fixed-target setup, unique at LHC

- **Upgrade II will overcome centrality limitation due to tracking**
  - **Full centrality coverage in PbPb**
  - New tracking systems: VELO, UT, magnet stations, Mighty Tracker

- **French Heavy Ion community (IN2P3+Irfu) is very well placed to play a leading role**
  - **Strong expertise in heavy flavour physics**
  - **Strong connection to French theory community (CPhT, IJClab, IPhT, Subatech)**
  - **Strong expertise in tracking** → UT/Mighty Tracker R&D and design



Expected tracking efficiency with Upgrade II