

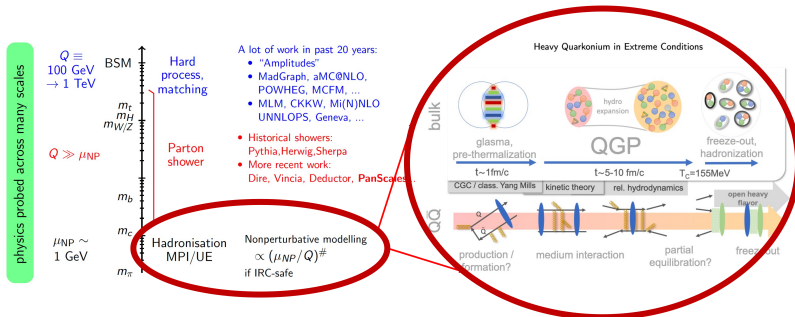
The ion and fixed-target program of LHCb

Michael Winn
Irfu/CEA, university Paris-Saclay

QCD@LHC, Oxford, 02.10.2026



The frontiers in strong interaction physics at colliders today



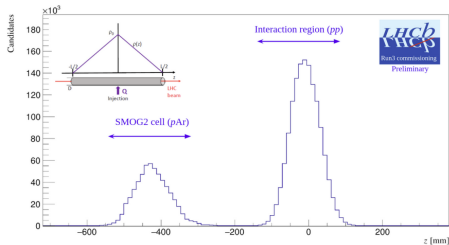
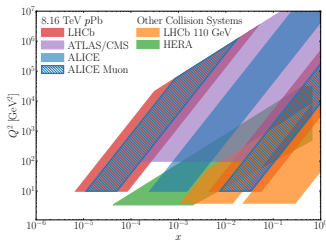
Left: Figure from Grégory Soyez

Right: Figure from Alexander Rothkopf

QCD in the standard model of particle physics with two frontiers at colliders

- Precision: requirement for electroweak precision and searches
→ traditional focus of this conference
- Many-body & non-perturbative: understand emergent phenomena
→ thermal matter, nuclear effects, cosmic ray, ultimate limit for precision
→ **this talk**

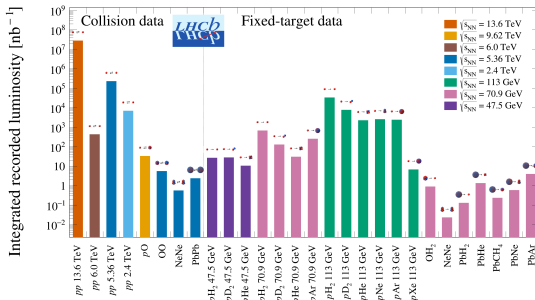
LHCb: two experiments in one



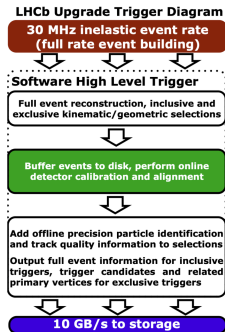
Right: Phys. Rev. Accel. Beams 27, 111001 (2024)

- ▶ simultaneous collider & fixed-target data taking over full Run 3
- ▶ 1 order of magnitude different centre of mass energy

LHCb Run 3 harvest

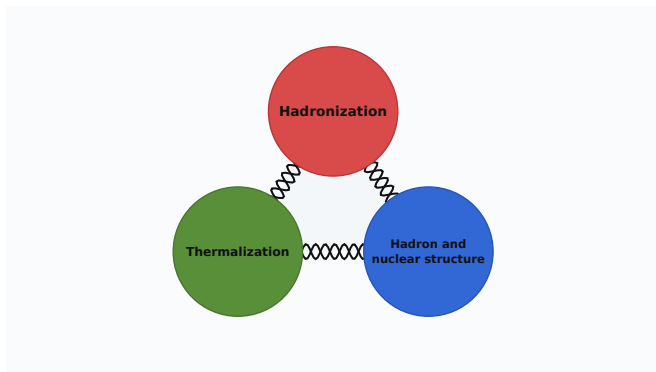


Run 3 Collision system



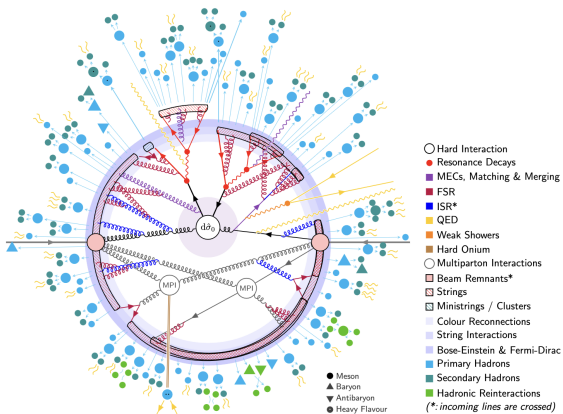
- ▶ software trigger inspecting full luminosity during pp data
- ▶ ion-beam data: trigger 'overdesigned': minimum bias mode for hadronic collisions & open exclusive lines
- ▶ Which physics with this plethora of data and LHCb upgrade 2?
→ Give you a taste today!

LHCb Ion and fixed-target program for QCD



- ▶ relevant for:
Quark-Gluon-Plasma, saturation, parton distributions, cosmic ray,
low-energy nuclear physics
- ▶ in the following: recent show cases

Hadronization



Pythia $t\bar{t}$ event [SciPost Phys.Codeb. 2022 \(2022\) 8](#)

Quarkonium production in proton-nucleus collisions

- ▶ leading twist gluon shadowing

review Klasen, Paukkunen: [ARNPS74\('24\) 1, 49](#)

- ▶ coherent energy loss

Arleo et Peigné: [JHEP 1303 \('13\)](#)

- ▶ higher-twist shadowing, dipole propagation in nucleus

Kopeliovich et al., e.g. [PRC 95 \(2017\) 6, 065203](#)

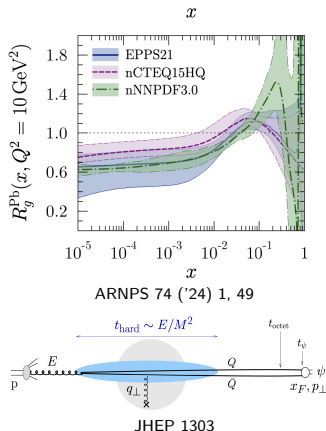
- ▶ 'comover' interactions

Ferrero [PLB 749 \('15\) 98](#)

- ▶ nuclear absorption

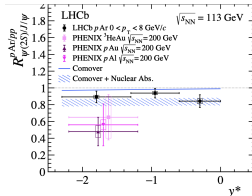
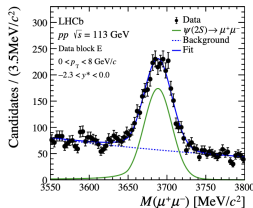
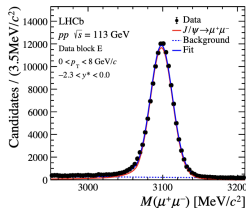
→ e.g. Ferreiro, Fleuret, Maurice [Eur.Phys.J.C](#)

[82 \(2022\) 3, 201](#)



- ▶ rich phenomenology even excluding low- x phenomena not relevant for LHCb fixed-target kinematics
- ▶ important for deconfinement studies in nucleus-nucleus collisions

Quarkonium production in proton-nucleus collisions: precision data from fixed-target Run 3



[arXiv:2608.30534](https://arxiv.org/abs/2608.30534)

- ▶ precision measurement of $\psi(2S)/J/\psi$ from 2024: Hydrogen & Argon gas injections
- ▶ sensitive to comovers and nuclear absorption
- ▶ indication of nuclear effects for $A = 40 \rightarrow 2026$ data: pXe ($A^{average} \approx 130$)
- ▶ baseline for Pb-gas collisions in LHCb to come!

Charm baryon polarization: motivation

Baryon	System	Beam energy [GeV]	Result	p_T range [GeV/c]
1976 Λ^0	$p\text{Be}$	300	18%	1.5
	$p\text{Be}$	400	24%	2.1
	$p\text{C}$ and $p\text{W}$	920	~ 0	~ 0.8
	$p\text{N}$	450	up to 0.29%	0.86
1978 $\bar{\Lambda}^0$	$p\text{Be}$	400	0	up to 1.2
	$p\text{-X}$	400	0	up to 2.4
	$p\text{Be}$	800	~ 0	[0.5, 1.3]
1993 Σ^+	$p\text{Cu}$	800	16%	1.0
	Ξ^0 $p\text{Cu}$ and $p\text{Be}$	400	$\sim 20\%$	1.6
	Ξ^+ $p\text{Be}$	800	up to 0.09%	0.76
1990 Ξ^-	$p\text{Be}$	400	up to 10%	1.21
	$p\text{Cu}$	400	up to 0.07%	0.63
	$p\text{Be}$	800	up to 0.1%	>0.8



Features that seem to emerge:

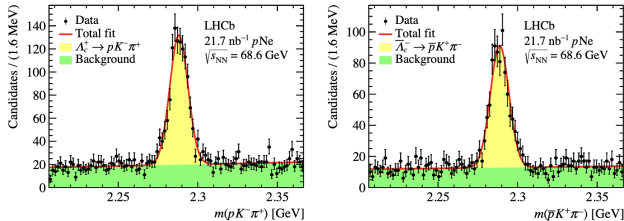
- Increasing polarization with p_T
- A (not well-defined) target dependence
- Different polarization between hyperon and anti-hyperon.

taken from E. Niel.

- ▶ polarization observed for hyperon hadroproduction with unpolarized beams
→ origin not understood
- ▶ charm baryon polarization:
requisite to access magnetic dipole moment of charm quarks via charm baryon measurements and spin processing

see [EPJC 80 \(2020\)](#)

Polarization of Λ_c^+ and $\bar{\Lambda}_c^-$ in fixed-target collisions@LHC



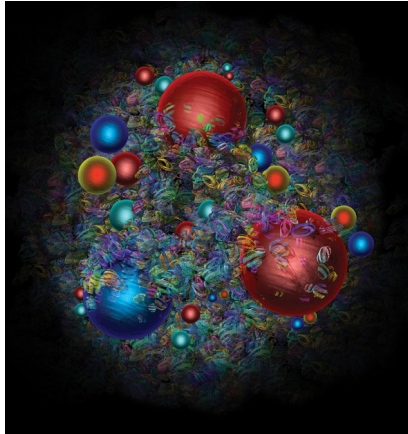
$$P_{\Lambda_c^+} = (24.4 \pm 9.5 (\text{stat}) \pm 2.2 (\text{syst})) \%,$$

$$P_{\bar{\Lambda}_c^-} = (-8 \pm 12 (\text{stat}) \pm 3 (\text{syst})) \%.$$

PRL 137 (2026) 091901

- ▶ indication of Λ_c^+ polarisation with 2.4σ , $\bar{\Lambda}_c^-$ consistent with no pol.
- ▶ Run 2 result
→ Run 3 with more than 2 orders of magnitude larger luminosity
- ▶ see also transverse hyperon polarization measurement in pPb collider collisions consistent with zero PRD 112 (2025) 112022

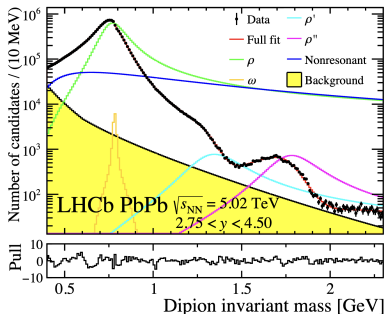
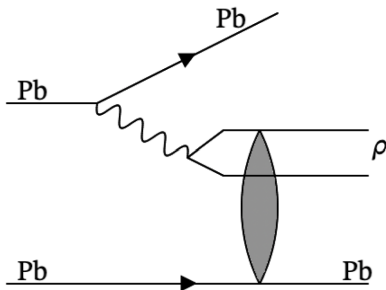
Hadron and nuclear structure



Credit: D. Dominguez/CERN

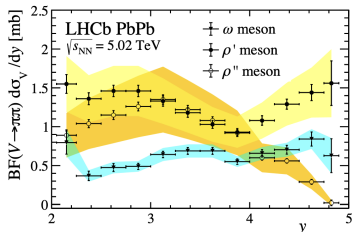
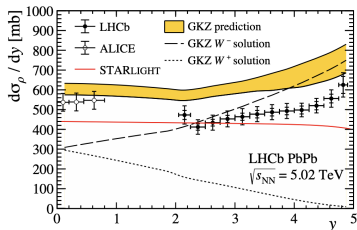
Coherent photoproduction in PbPb

- ▶ ultra-peripheral collisions: large impact parameter $|b| > 2R_A$
- ▶ Photoproduction of vector mesons
 - sensitive to nuclear shadowing and saturation
 - ρ_0 : Bjorken- $x \approx 10^{-6}$ probed
- ▶ HeRSChel detector $5 < \eta < 10$ is used for UPC selection [JINST 13 P04017, 2018](#)



[JHEP 11 \(2025\) 103](#): ρ (+interference with non-resonant component) and ω mesons, ρ' and ρ'' needed

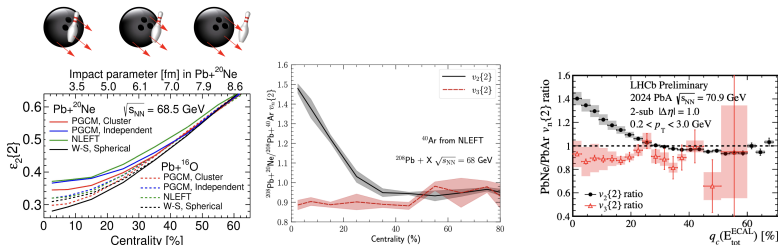
Coherent photoproduction in PbPb



JHEP 11 (2025) 103

- ▶ the cross-sections are measured differentially
- ▶ Excited states are consistent with from PDG
- ▶ error bars are the statistical uncertainty while band corresponds to the total one
- ▶ cross-section:
 - rapidity dependency not reproduced by STARLIGHT
 - overestimated by Guzey, Kryshen and Zhalov (GKZ)

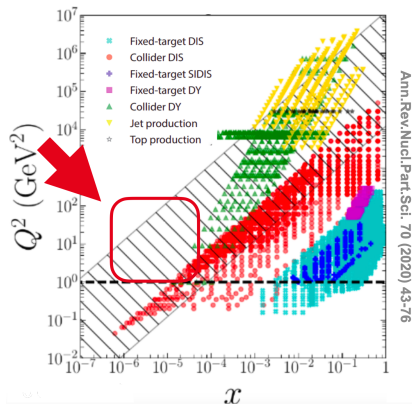
Azimuthal correlations in nuclear collisions as probe of nuclear structure



Left: [Phys.Rev.Lett. 134 \(2025\) 8, 082301](#), middle/right: [LHCb-CONF-2025-001](#).

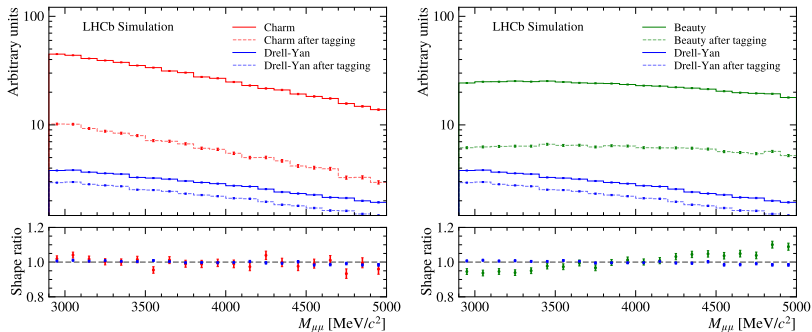
- hydrodynamic response to initial state eccentricity:
experimental confirmation of the distinctive bowling-pin shape of the ground-state $N = 20$
- Proof-of concept:
fixed-target provides a larger pool of nuclei to study
→ e.g. C^{12} shape through CH_4 collisions taken in 2026

Low-mass Drell-Yan measurements



- ▶ Run 3 trigger: dimuons with $p_{T,\mu} > 1 \text{ GeV}/c$ down to J/ψ mass
- ▶ enable Drell-Yan at low mass, low- x & low p_T :
PDFs, transverse momentum dependent distributions + saturation
- ▶ low S/B: up to 100 larger B: semileptonic decays of charm & beauty
→ new tools required

New tools for low-mass Drell-Yan measurements



J. Phys. G: Nucl. Part. Phys. 53 095002

- ▶ SemiCharmTag: tag semileptonic decays of charm and beauty hadrons with reconstruction of hadron+ pairs
- ▶ double tag: increase S/B by a factor 4 at an efficiency of 80%
- ▶ single tag: calibrate discriminative variables for charm & beauty via tag-and-probe
- ▶ pp starting point for measurements in fixed-target and ion data

'The single most important question in the physics of heavy ion collisions is

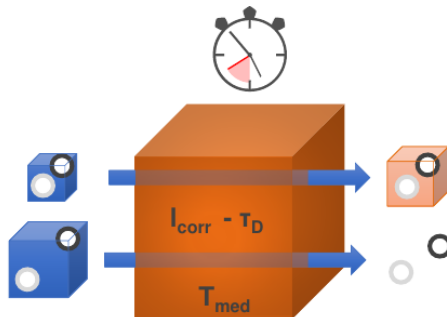
Thermalization.'

'Bottom up' thermalization in heavy ion collisions,

R. Baier (Bielefeld), A. H. Mueller (Columbia), D. Schiff (Orsay) , D.T. Son (Columbia U. & RIKEN BNL), 2000

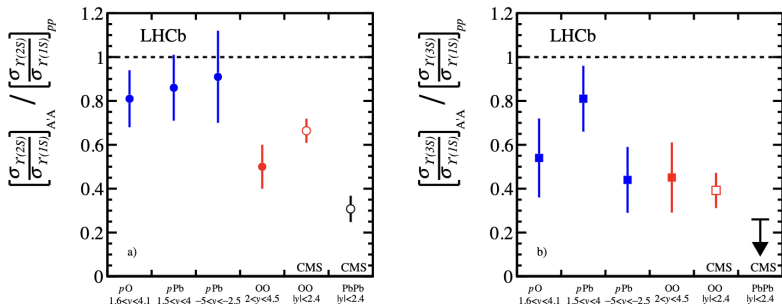
Bottomonium suppression: signature of deconfinement

- ▶ bottom heavier than charm:
thermalisation more difficult to achieve
- ▶ less abundant production
- ▶ theoretical description:
QGP as a sieve for traversing quantum state
→ 'sequential suppression'



A. Rothkopf [Phys.Rept. 858 \(2020\) 1](#)

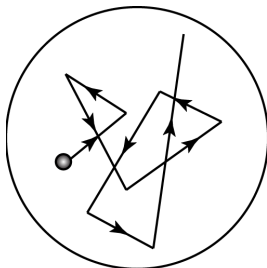
Precision bottomonium results by LHCb



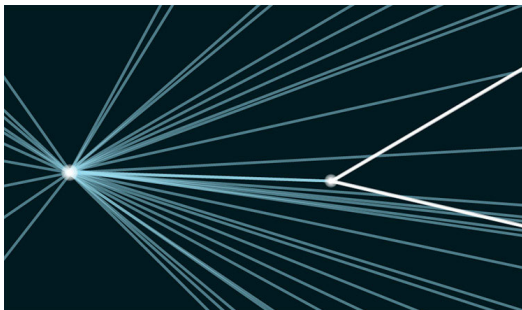
arXiv:2608.00182

- ▶ Sequential bottomonium suppression observed in Oxygen-Oxygen
- ▶ precise data from pp to pO and OO
 - OO more suppressed than pO data
 - data described by model calculations invoking deconfined medium
 - understand deconfinement in small collision systems and confounding effects → consistent findings by CMS [arXiv:2607.13758](https://arxiv.org/abs/2607.13758)

Heavy-quarks: Brownian motion within produced matter

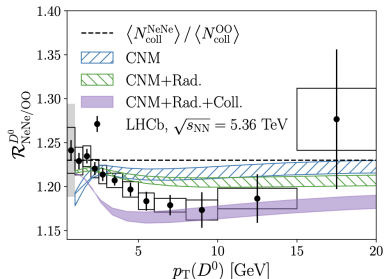
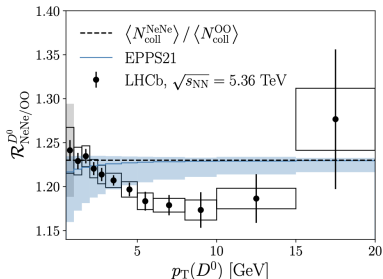


Brownian Movement



- ▶ open heavy-flavour hadrons at low p_T :
 - $M_{quark} \approx M_{hadron}$: hadron kinematics close to quark kinematics
 - heavy quark diffusion coefficient & degree of thermalisation
- ▶ LHCb originally built for this event topology:
 - profiting from longitudinal boost
- ▶ what happens in light-ion collisions?

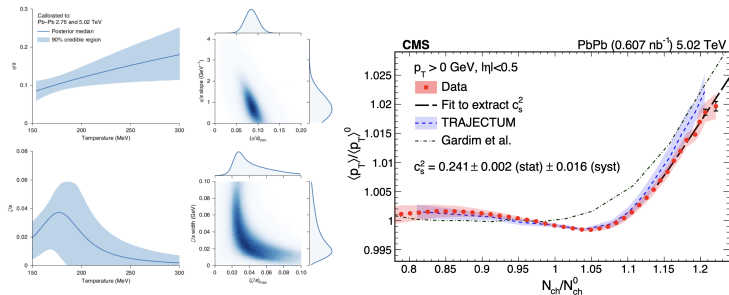
Precise open charm in Oxygen-Oxygen and Neon-Neon



[arXiv:2605.27273](https://arxiv.org/abs/2605.27273)

- ▶ comparison of nuclear modification in Oxygen-Oxygen ($A = 16$) and Neon-Neon ($A = 20$)
- ▶ precision measurement with modest luminosity for charm
- ▶ evidence of variation as a function of p_T : inconsistent with nuclear modification of nucleon structure alone
- ▶ consistent with the onset of QGP with increasing nuclear size

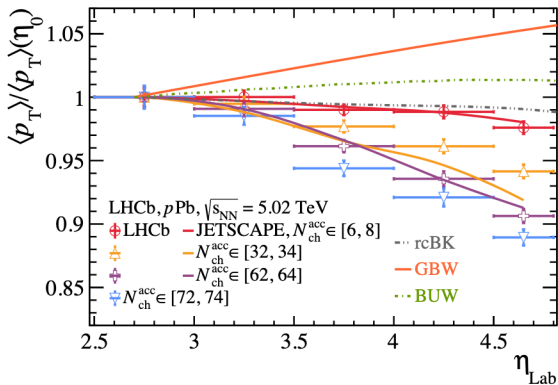
Soft particle production: the hydrodynamic paradigm



left: [Bernhard, Moreland, Bass, Nature Phys. 15, 1113–1117 \(2019\)](#), Right: [Rep. Prog. Phys. 87 \(2024\) 077801](#)
see for recent developments of Bayesian fits [G. Nii@Light ions 26](#)

- ▶ in heavy-ion collisions: momentum distributions & azimuthal correlations with hydrodynamic modelization
→ infer transport properties, the speed of sound and nuclear structure
- ▶ in small collision system:
initial state or hydrodynamics everywhere?

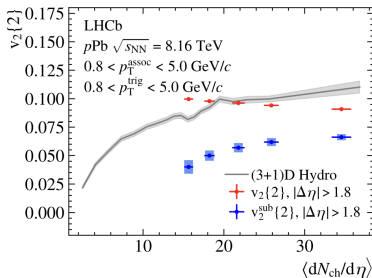
$\langle p_T \rangle$ in pp & in pPb forward/backward: saturation vs. hydro



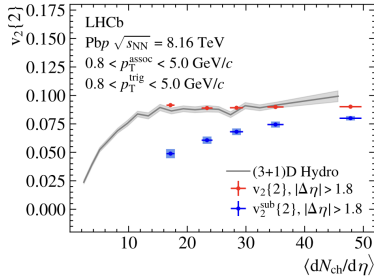
pPb (forward) results: [arXiv:2607.26783](https://arxiv.org/abs/2607.26783)

- rapidity differential result by LHCb
 - inconsistent with available saturation-based models
 - well described by generic dependence expected with hydrodynamics

Azimuthal correlations in pPb forward/backward: no effects from Bjorken-x

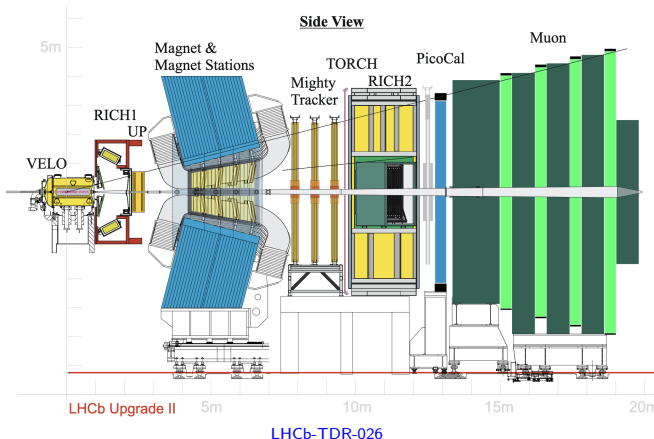


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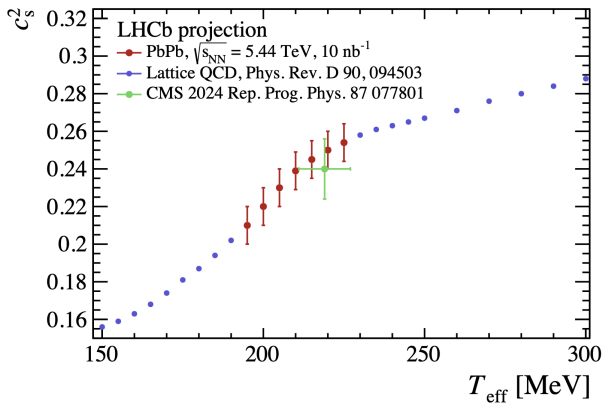
- ▶ elliptic flow (v_2) and triangular flow (v_3) of soft particle production
- ▶ very similar results forward and backward
- ▶ consistent with hydrodynamic simulation expectation

LHCb U2 in view of ion and fixed-target program



- a multipurpose forward detector
 - for pile-up 40 in pp collisions
 - full centrality reach in heavy-ion collisions
 - polarized target in fixed target mode for unique hadron structure data

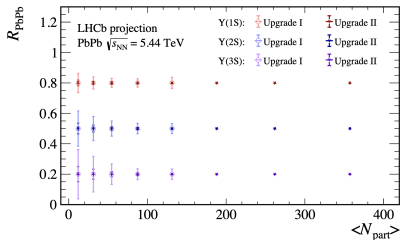
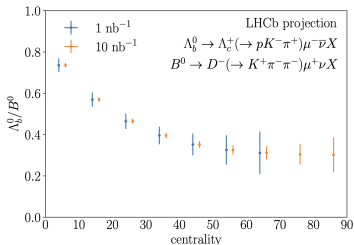
LHCb U2: equation of state



LHCb-PUB-2024-007

- forward rapidity
→ lever arm to probe different temperature ranges

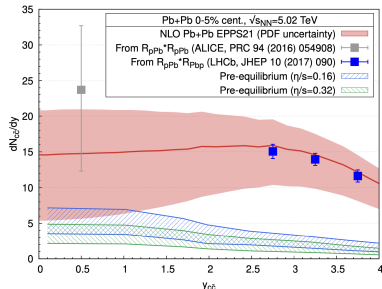
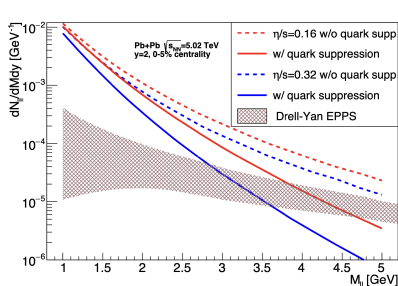
LHCb U2: Heavy-flavour for deconfinement, heavy-quark diffusion



LHCb-PUB-2024-007

- high precision open beauty and quarkonium:
 - constrain hadronisation
 - probe deconfinement transition properties

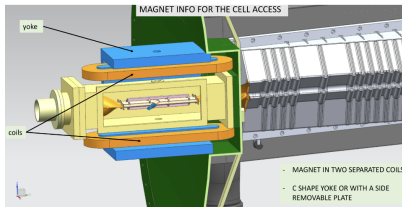
Dileptons and charm production for thermalization



Left: PLB 821 (2021) 136626, right: PLB, 881 (2026) 140931

- ▶ prompt dilepton measurements $m \in [2, 5]$ GeV/ c^2 & precision charm
- ▶ open direct window to thermalization
 - How fast hydrodynamics apply?
 - When do quarks appear?
- ▶ LHCb U2: unique opportunity

LHCSpin: a polarized gas target for the LHC



Channel	Events / week	Total yield
$J/\psi \rightarrow \mu^+ \mu^-$	2.6×10^7	3.1×10^9
$D^0 \rightarrow K^- \pi^+$	1.3×10^8	1.6×10^{10}
$\psi(2S) \rightarrow \mu^+ \mu^-$	4.6×10^5	5.5×10^7
$J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ (DPS)	1.7×10^1	2.1×10^3
$J/\psi J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ (SPS)	5.1×10^1	6.1×10^3
Drell Yan ($5 < M_{\mu\mu} < 9$ GeV)	1.5×10^4	1.8×10^6
$\Upsilon \rightarrow \mu^+ \mu^-$	1.1×10^4	1.3×10^6
$\Lambda_c^+ \rightarrow p K^- \pi^+$	2.6×10^6	3.1×10^8

Table 1: Estimated weekly reconstructed and selected event rates at LHCspin and the total yield over a Run (120 weeks) for various channels.

[arXiv:2504.16034](https://arxiv.org/abs/2504.16034)

- spin physics with polarized target:
 - unique and complementary observables with respect to electron-ion collider
 - Access to transverse momentum dependent distributions, including the gluon sector
 - unique opportunities for generalized parton distribution functions via ultra-peripheral collisions and azimuthal anisotropies

Synthesis LHCb ion and fixed-target program

- ▶ most diverse QCD program at colliders
forward, high luminosity, full instrumentation, software trigger
in collider+ fixed-target
→ a gold mine for QCD in Run 3 & Run 4
- ▶ Upgrade 2:
a multi-purpose forward detector with unique charm/beauty
performances up to central heavy-ion collisions
→ precision thermodynamics, thermalization & hadron
structure with novel observables

Conclusion

- ▶ T. Plehn's lectures on LHC physics (preHiggs): thanks a lot!
Quote: "QCD: the theory of evil"

→ No!

- ▶ half best friend + half stranger
→ we still don't know its most interesting sides.

Thank you for listening and
stay tuned for results to come!