Probing QCD Dynamics in Small and Large Systems at LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

UFRJ
UNIVERSIDADE FEDERAL
DO RIO DE JANEIRO

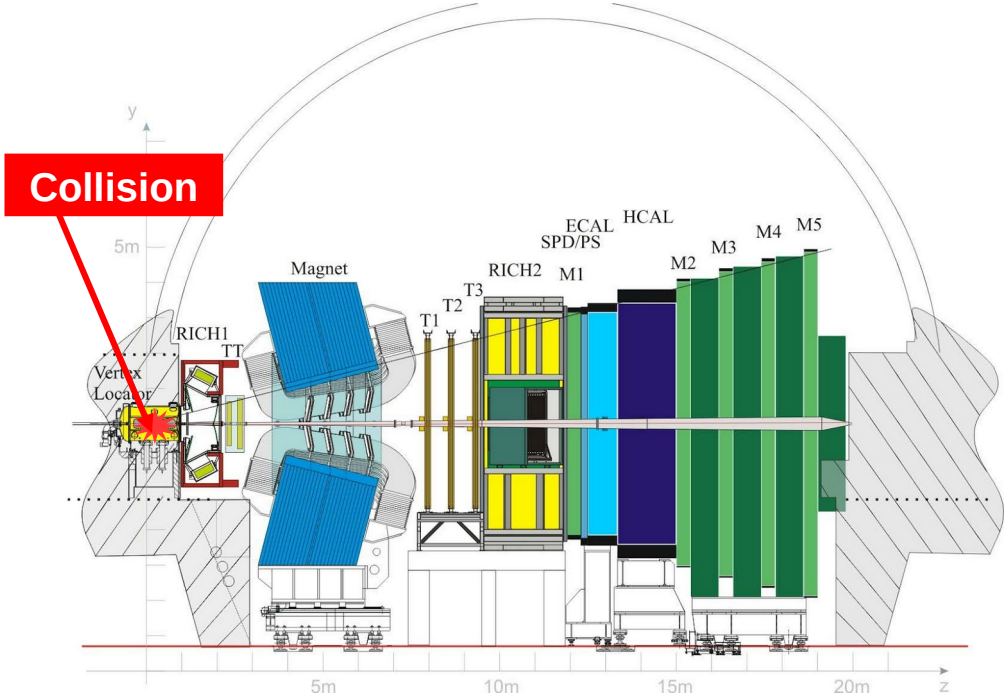
EMMI Workshop: Mining for gluon saturation at the LHC and the future EIC

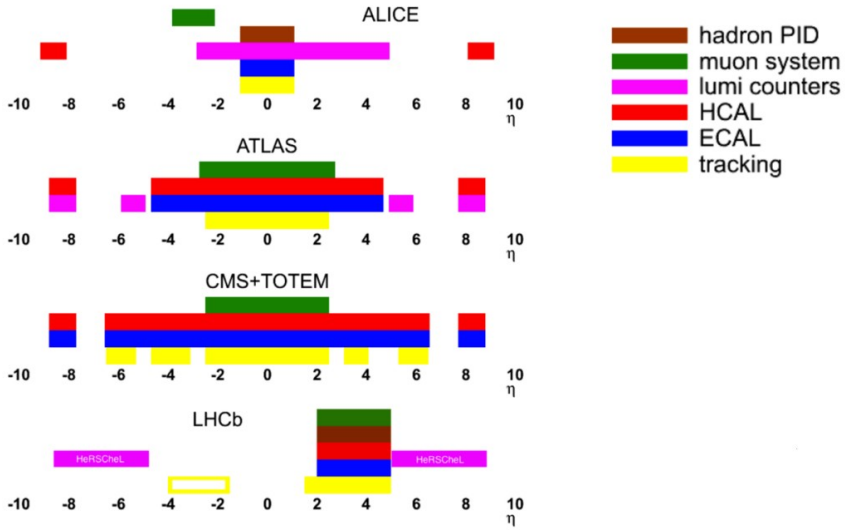
LHCb experiment overview (Run 1/2 detector)

Single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)

Designed for heavy flavour physics and also exploited for general purpose physics

[Int. J. Mod. Phys. A 30, 1530022 (2015)]





LHCb experiment overview (Run 3 detector)

[JINST 19 (2024) P05065]

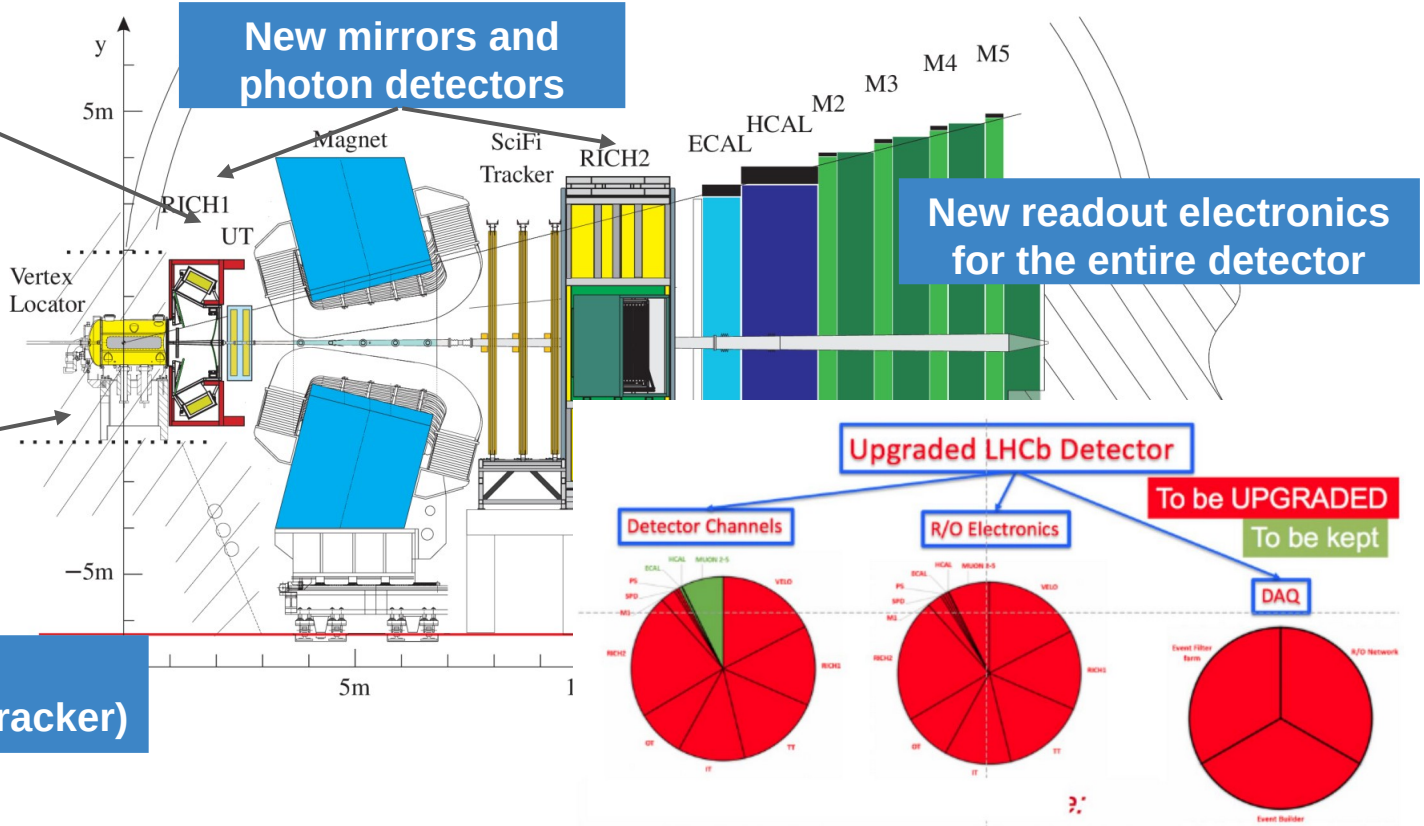
UT
(new silicon tracker)

New mirrors and photon detectors

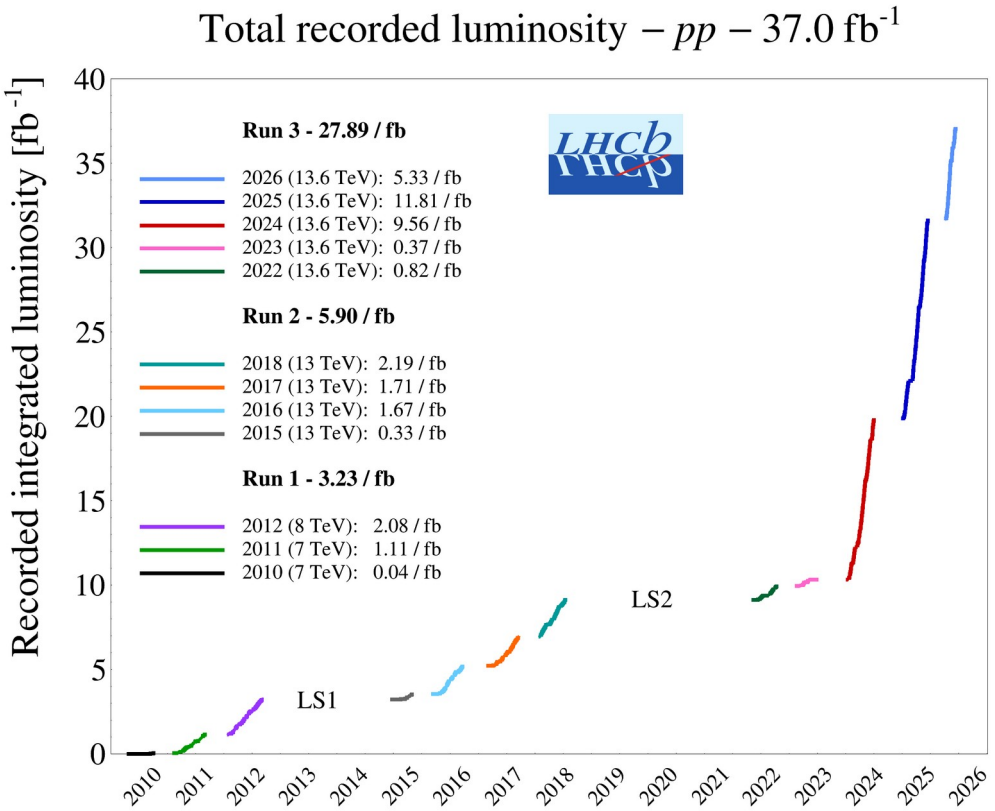
New readout electronics for the entire detector

New VELO
(Pixel Detector)

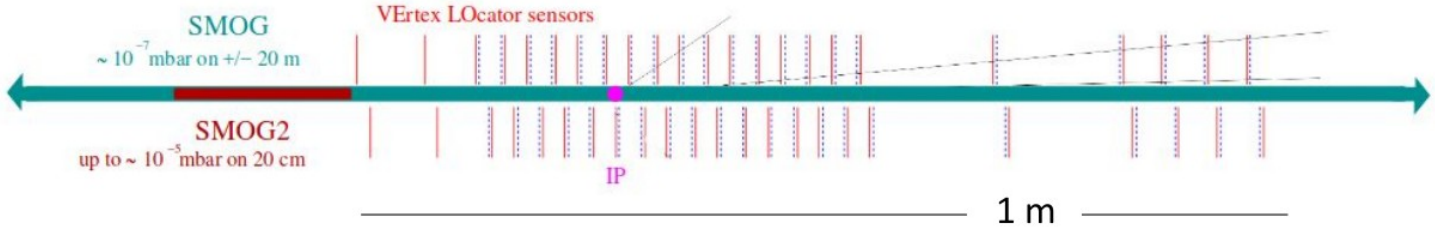
SciFi
(new scintillating fibre tracker)



LHCb pp data


Total recorded luminosity – pp – 37.0 fb-1
Recorded integrated luminosity [fb-1]
Run 3 - 27.89 / fb
2026 (13.6 TeV): 5.33 / fb
2025 (13.6 TeV): 11.81 / fb
2024 (13.6 TeV): 9.56 / fb
2023 (13.6 TeV): 0.37 / fb
2022 (13.6 TeV): 0.82 / fb
Run 2 - 5.90 / fb
2018 (13 TeV): 2.19 / fb
2017 (13 TeV): 1.71 / fb
2016 (13 TeV): 1.67 / fb
2015 (13 TeV): 0.33 / fb
Run 1 - 3.23 / fb
2012 (8 TeV): 2.08 / fb
2011 (7 TeV): 1.11 / fb
2010 (7 TeV): 0.04 / fb
LHCb
LS1
LS2
0
5
10
15
20
25
30
35
40
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

LHCb SMOG2



SMOG / Run 2 (PRL 122, 132002 (2019)):

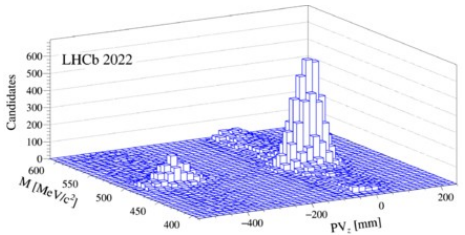
Gas was injected in the VELO vessel

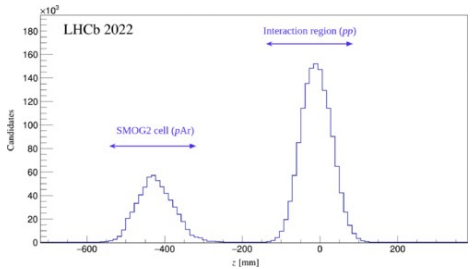
Overlap with the pp

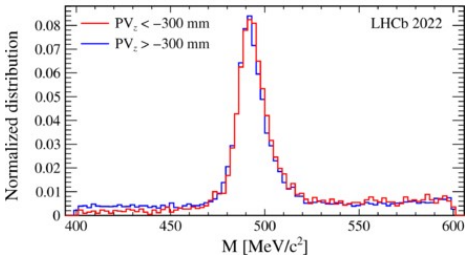
SMOG2 / Run 3 (Phys. Rev. Accel. Beams 27, 111001)

Gas confined in a cell (1 cm diameter) upstream of the LHCb IP

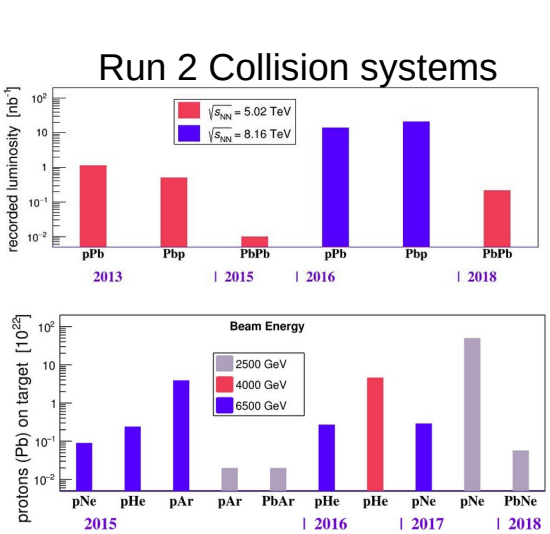
Increase of ~100 times the gas pressure wrt SMOG for the same gas flow

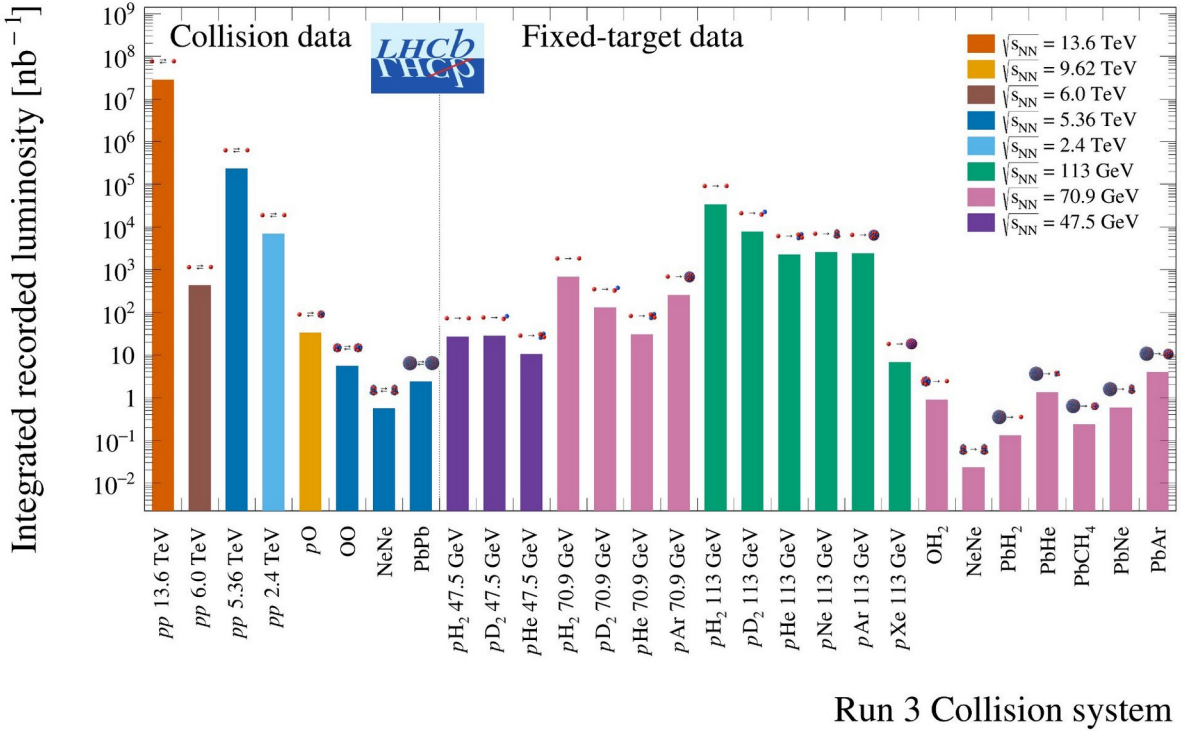






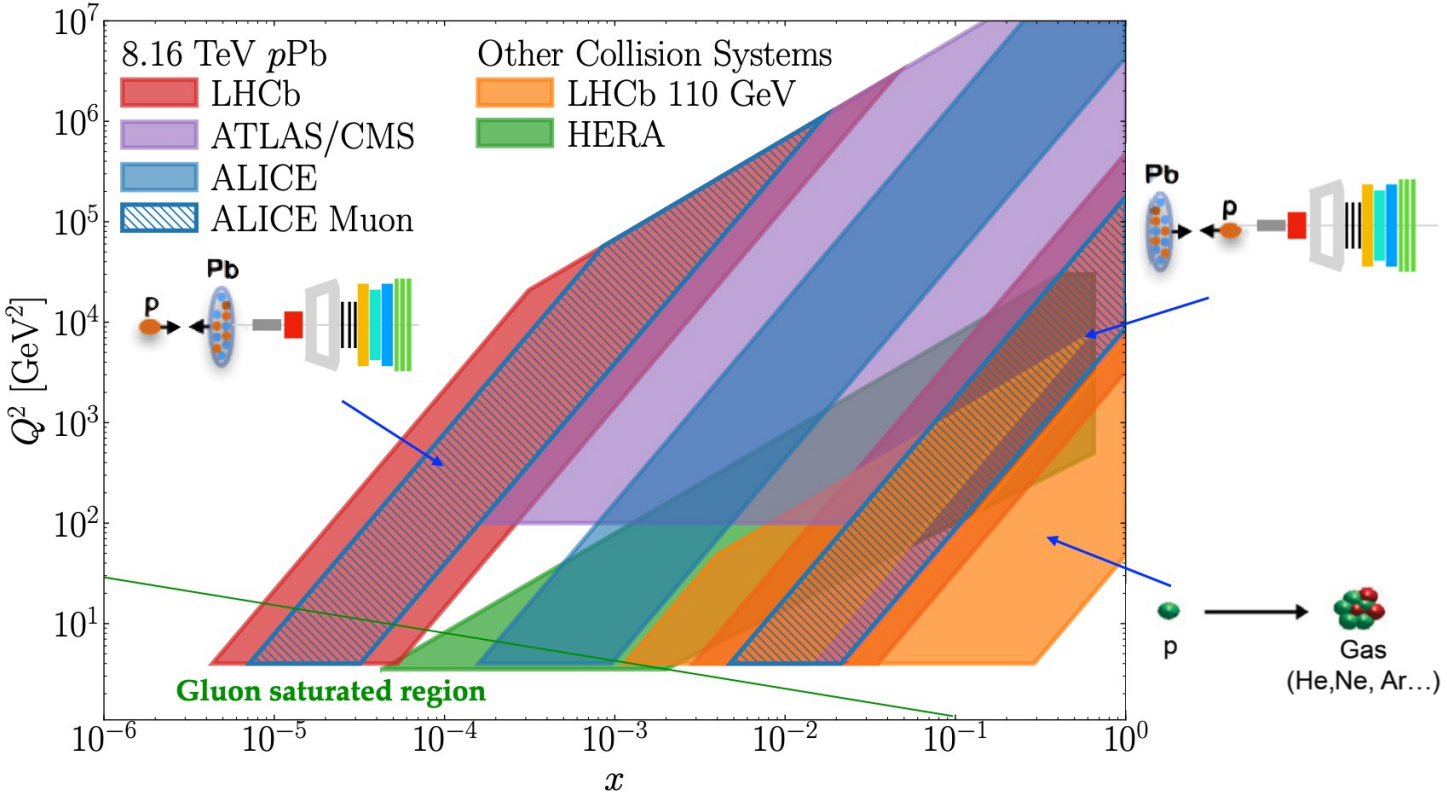
LHCb Heavy-ion and Light-ion data





Run 3 Collision system

LHCb experiment reach

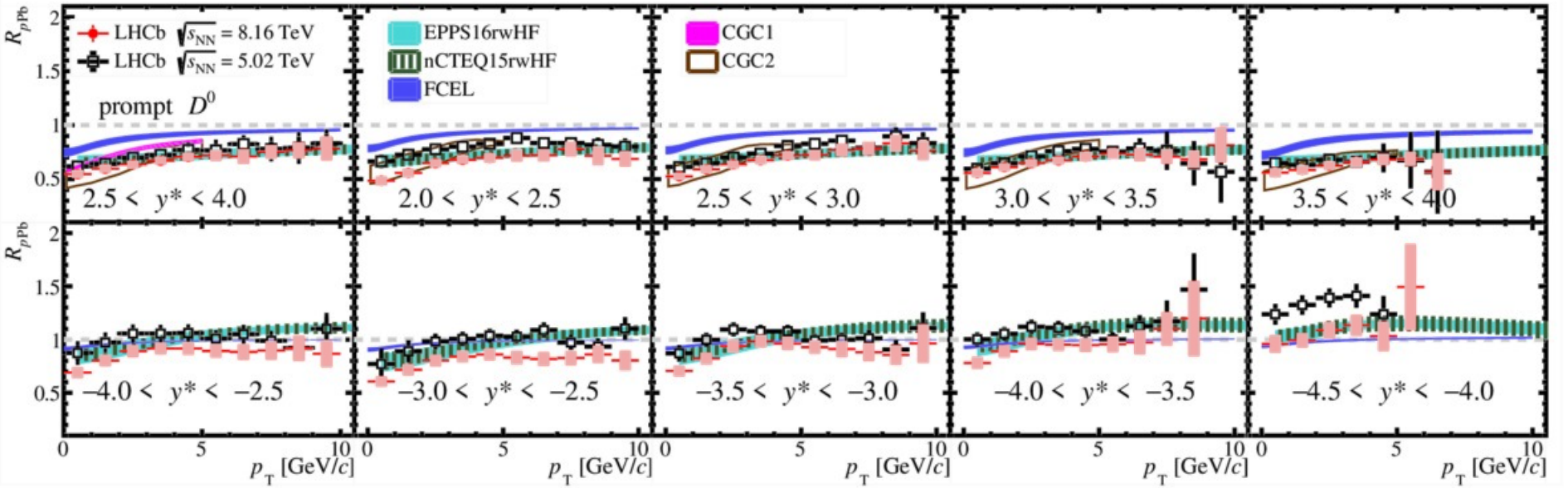


Prompt D^0 production in pPb at 8.16 TeV

Phys. Rev. Lett. 131 (2023) 102301

→ pPb data at 5 TeV → Prompt D^0 decaying into $K^{\pm}\pi^{\mp}$

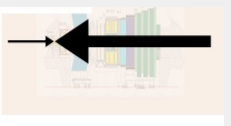
→ Nuclear modification factor in different rapidity bins



++ R_{pPb} in forward regions in general agreement with CGC and nPDF models

++ Stronger suppression for R_{pPb} at lowest p_T in forward rapidity than nPDF prediction

++ More suppressed R_{pPb} at high p_T in backward region than nPDF models

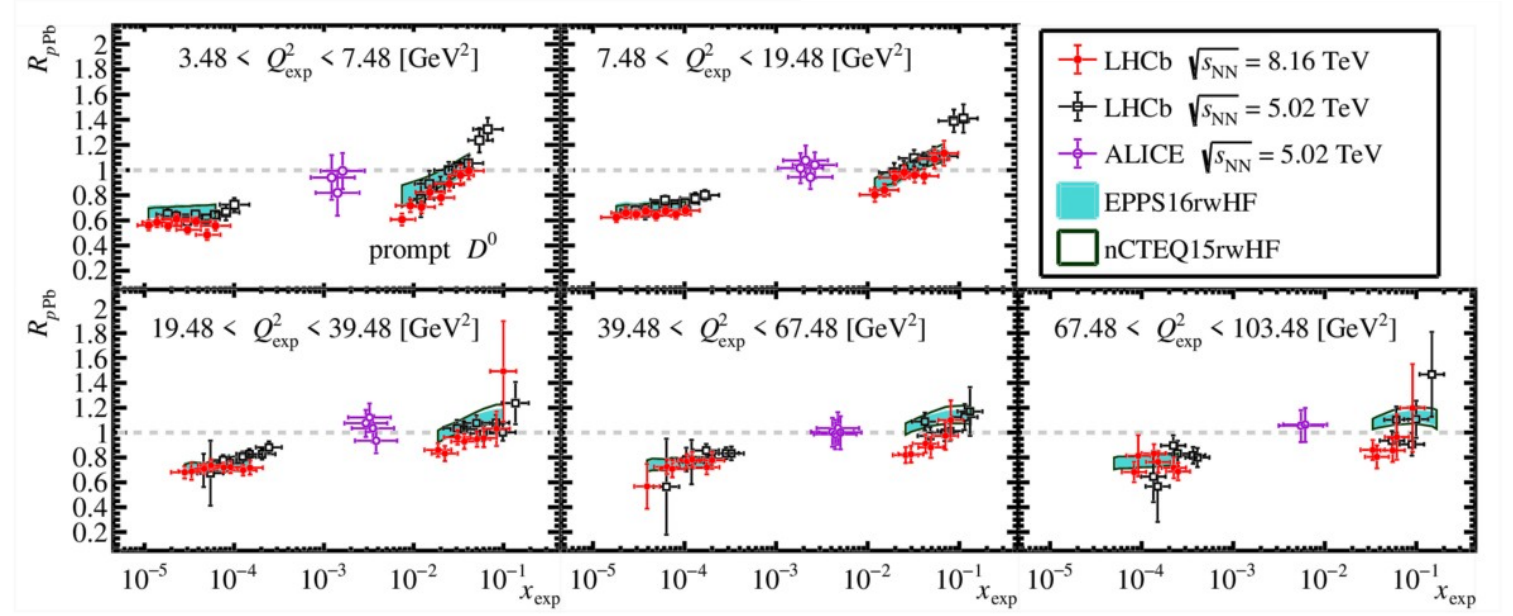


Prompt D^0 production in pPb at 8.16 TeV

Phys. Rev. Lett. 131 (2023) 102301

→ Experimental proxies for comparing results in different energy and kinematic regions

$$x_{\mathrm{exp}} \equiv 2\frac{\sqrt{p_{\mathrm{T}}^2(D^0)+M^2(D^0)}}{\sqrt{s_{\mathrm{NN}}}}e^{-y^*} \text{ and } Q^2_{\mathrm{exp}} \equiv p_{\mathrm{T}}^2(D^0)+M^2(D^0)$$



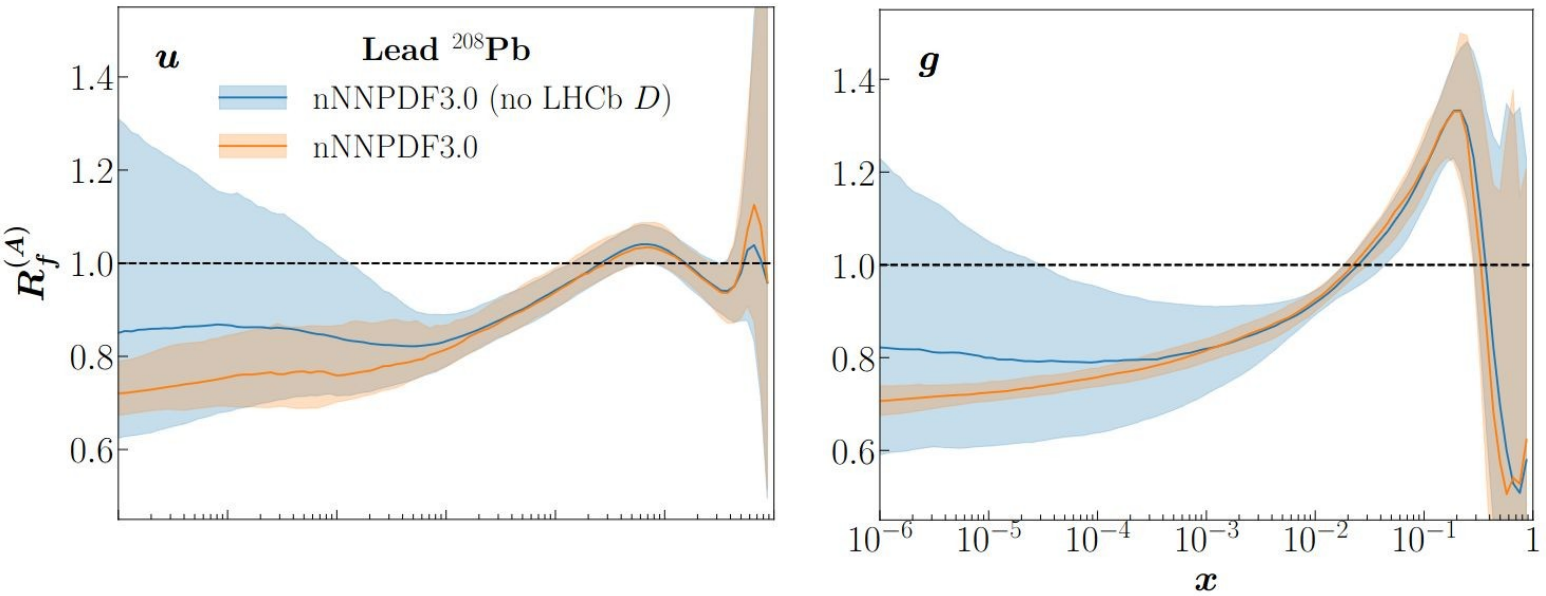
Consistency between LHCb results at 5.02 TeV and 8.16 TeV

Stronger suppression than nPDF calculations in x ~0.01 at larger Q^2

Impact on PDFs (example)

Important impact of pPb LHCb open charm measurements → reducing uncertainties

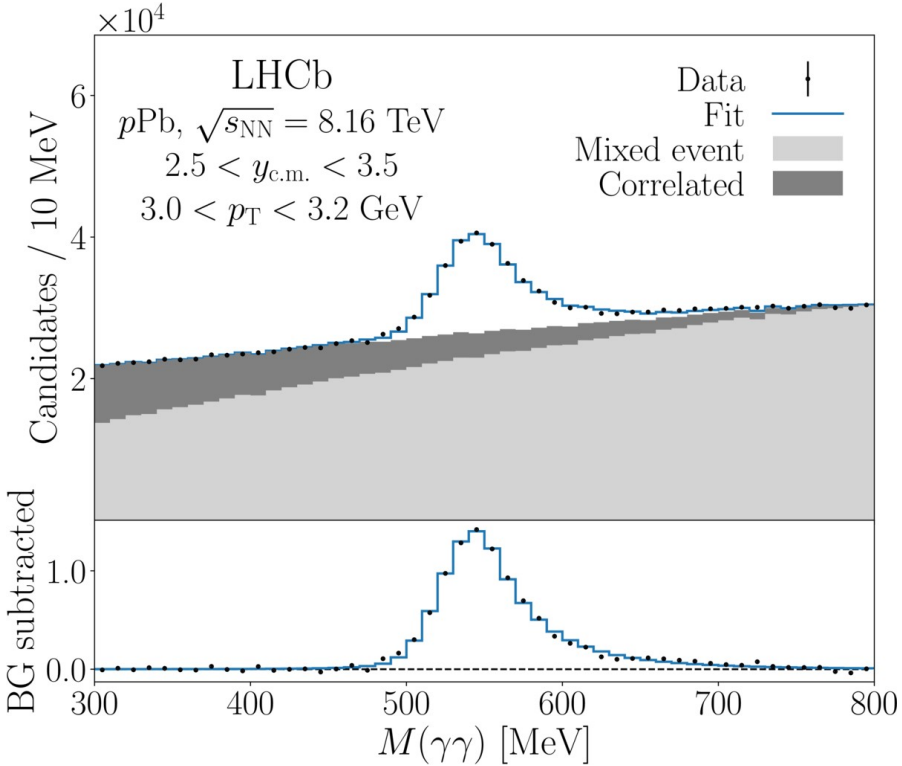
EPJ C82 (2022) 6, 50

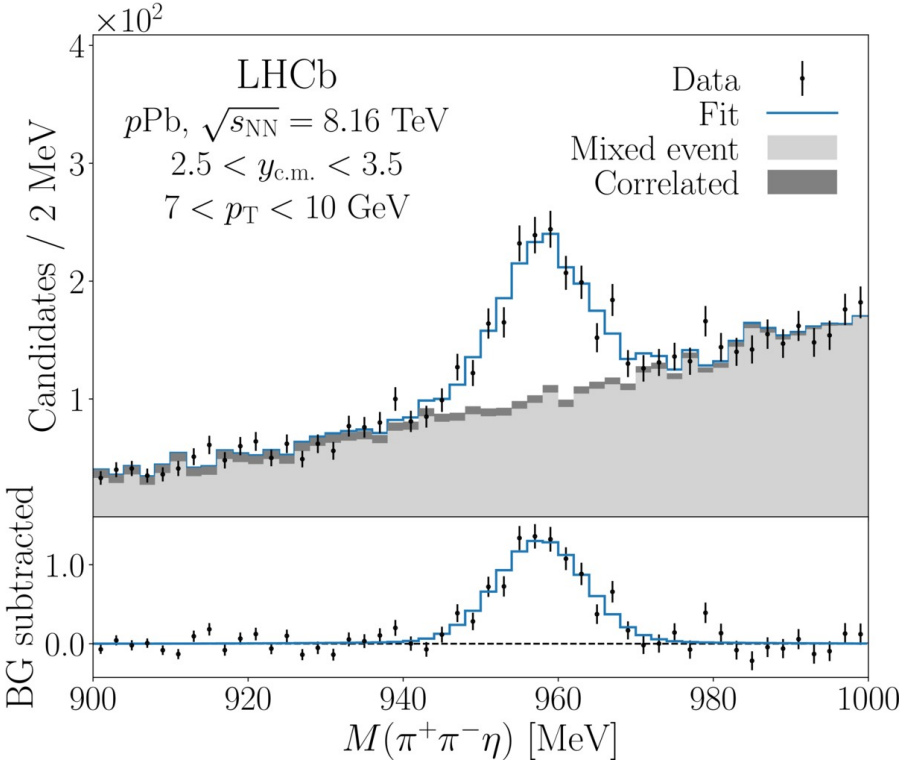


η and η′ production in pp and pPb collisions

Phys. Rev. C109 (2024) 024907

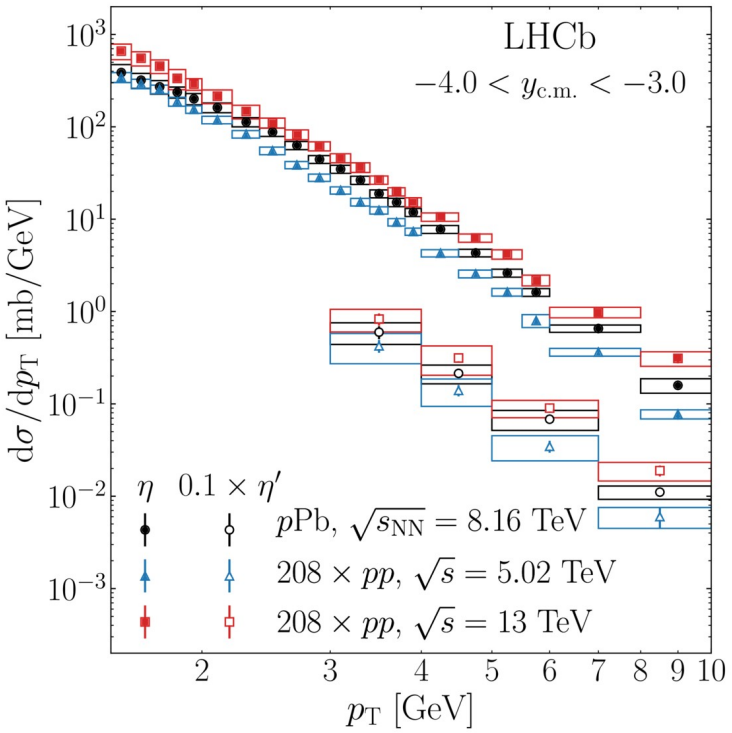
$y_{CM} = y_{lab} - 0.465$

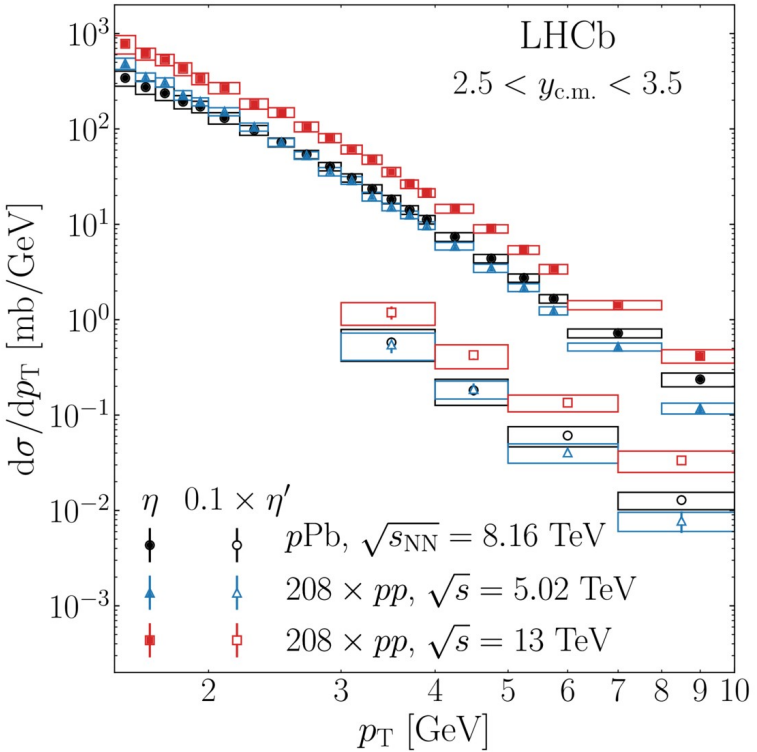




η and η′ production in pp and pPb collisions

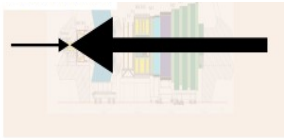
Phys. Rev. C109 (2024) 024907

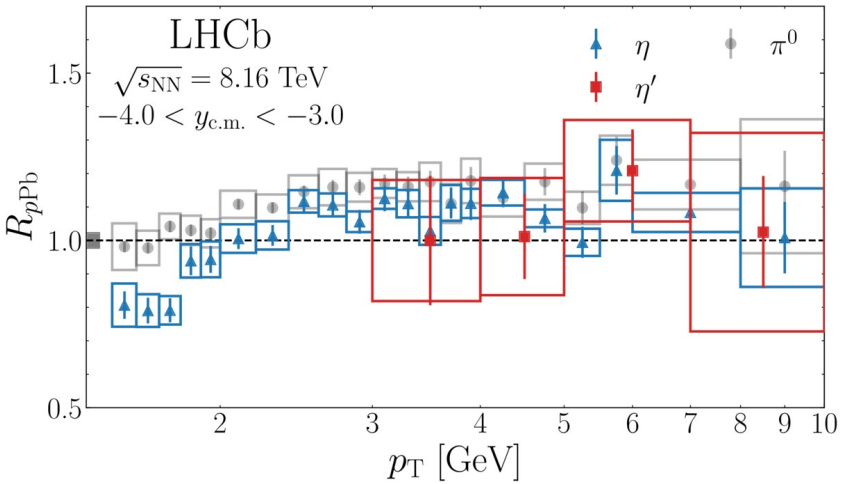


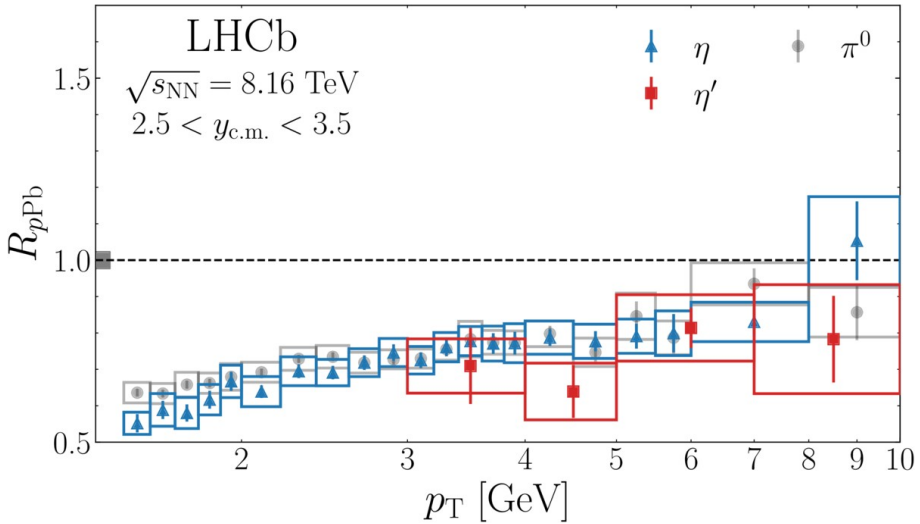


η and η′ production in pp and pPb collisions

Phys. Rev. C109 (2024) 024907



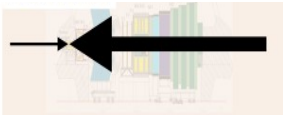


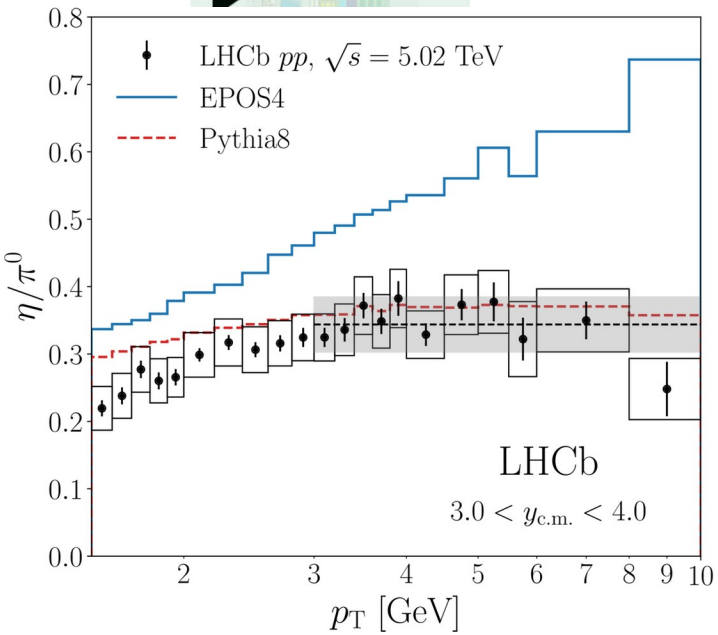


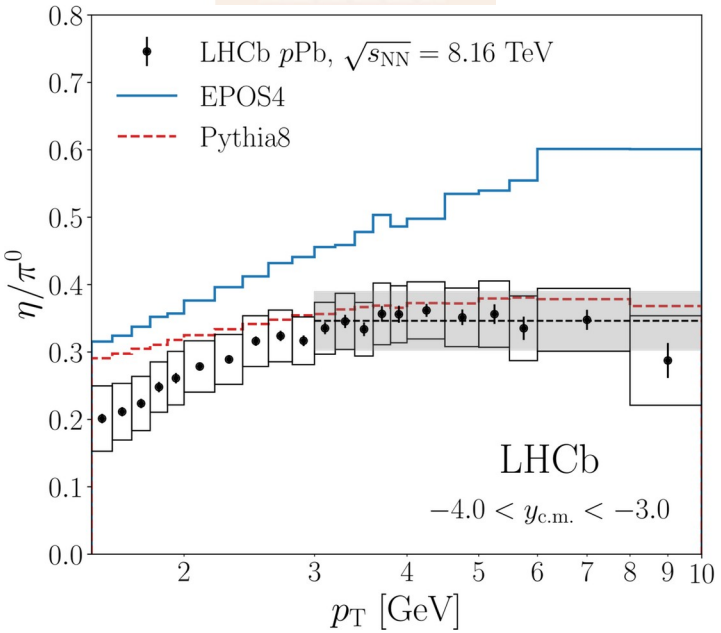
-- Observed suppression consistent with the effects of nuclear shadowing
-- Small deviations at low $p_T < 3$ GeV.
-- No significant evidence for mass dependence of the nuclear modification factor of light neutral mesons.

η and η′ production in pp and pPb collisions

Phys. Rev. C109 (2024) 024907







Pythia8 generally describes the data well
EPOS4 generally overestimates the η/π^0 ratio, especially at high p_T .

Particle flow in pPb collisions

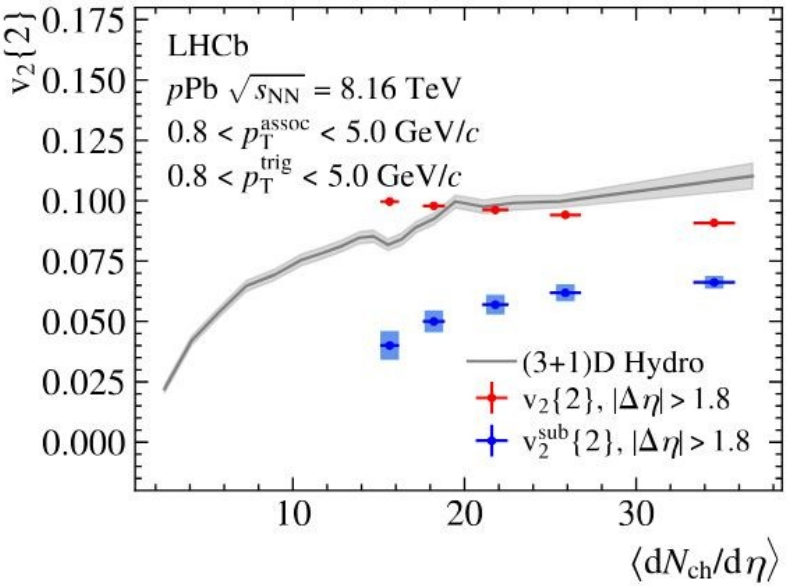
JHEP 10 (2025) 124

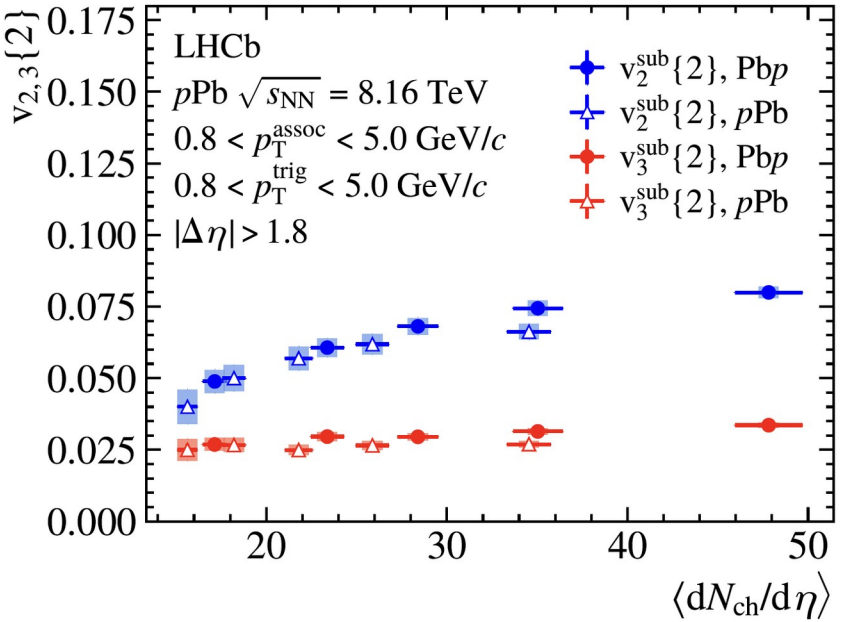
Two-particle correlation

→ observed smaller ellipticity wrt mid-rapidity experiments

→ Hydrodynamic models unable to reproduce flow coefficients at forward rapidities

→ Forward region (pPb) sensitive to gluon saturation

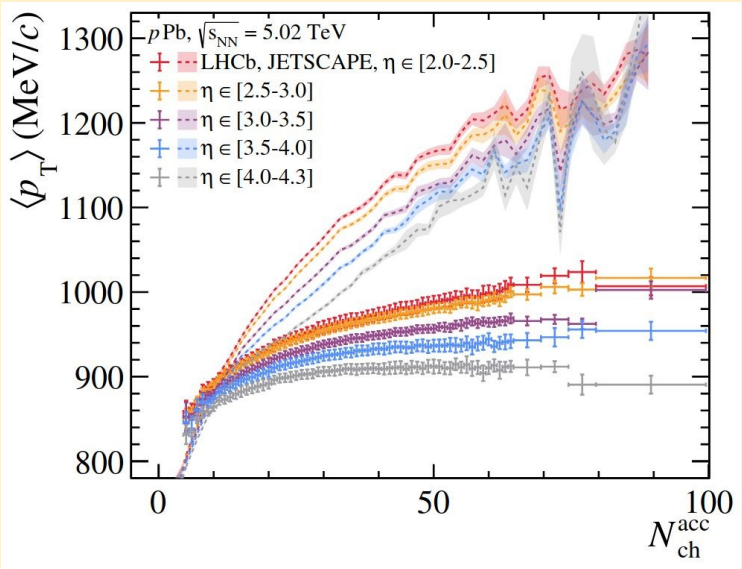


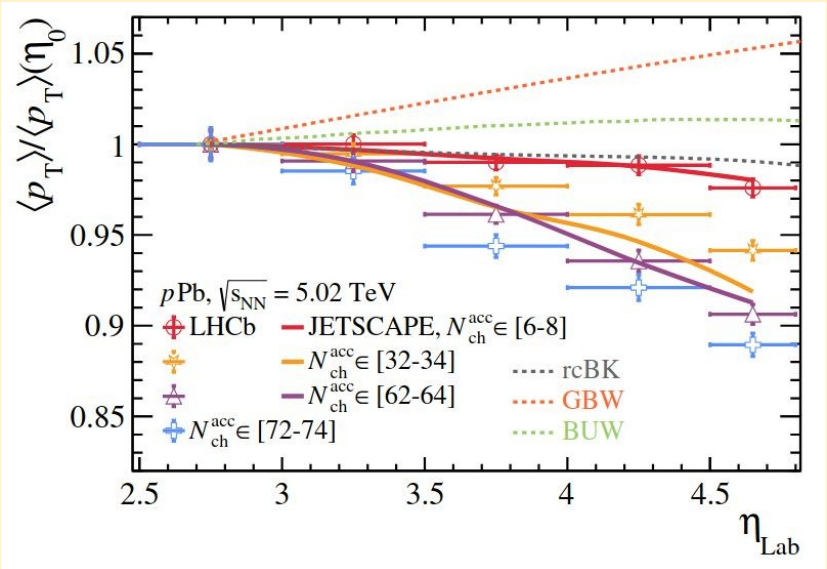


Average transverse momentum in pp and pPb

LHCb-PAPER-2026-012 (to be submitted)

→ Sensitive to saturation and hydrodynamics



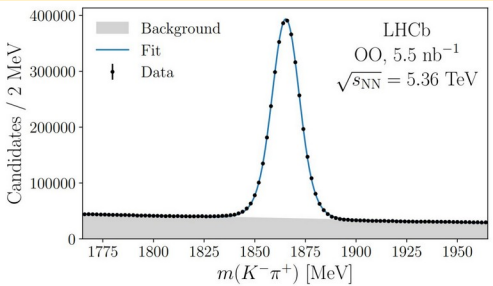


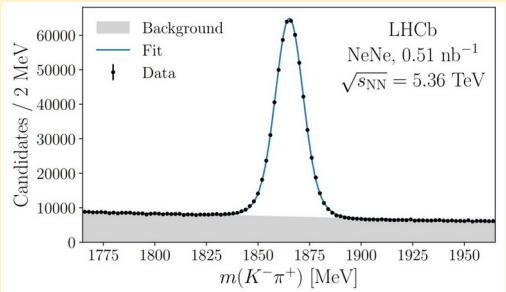
→ Pseudorapidity trend visible at high multiplicities
- compatible with matter collective behaviour
- Color Glass Condensate models fail to the data,
- JETSCAPE in better agreement for the $\langle p_T \rangle$ ratio

Modification of charm production in OO/NeNe

LHCb-PAPER-2026-008 (submitted to PRL)

→ Clean samples and good statistics to study p_T shape



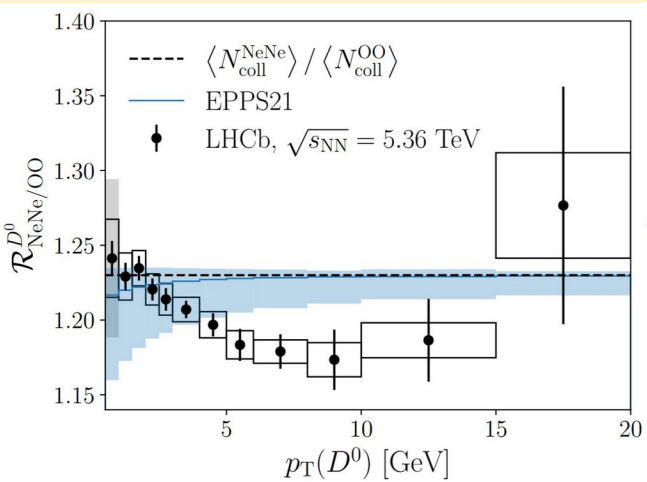


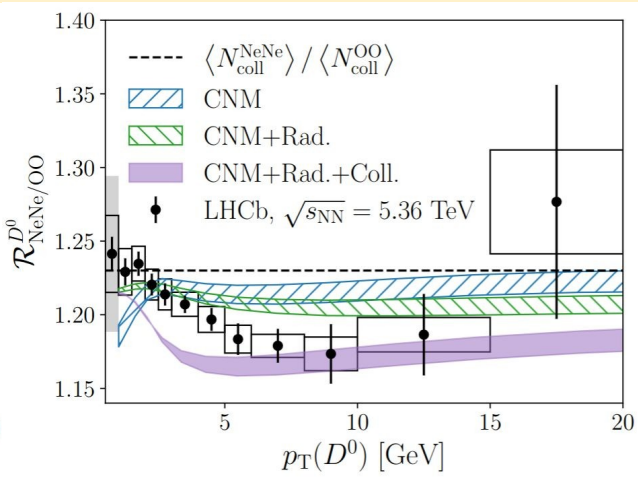
$$\mathcal{R}^{D^0}_{\mathrm{NeNe/OO}} \equiv \frac{\mathrm{d}N^{\mathrm{NeNe}}_{D^0}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N^{\mathrm{OO}}_{D^0}/\mathrm{d}p_{\mathrm{T}}} \frac{N^{\mathrm{OO}}_{\mathrm{inel}}}{N^{\mathrm{NeNe}}_{\mathrm{inel}}}$$

→ Stronger modification in NeNe w.r.t. OO

→ Nuclear PDFs are unable to describe

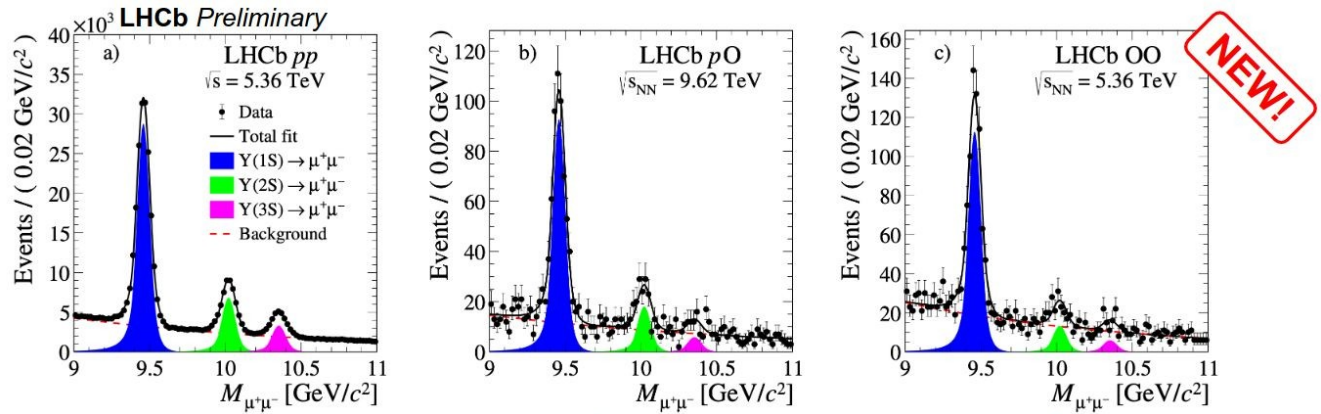
→ CNM effects improve description

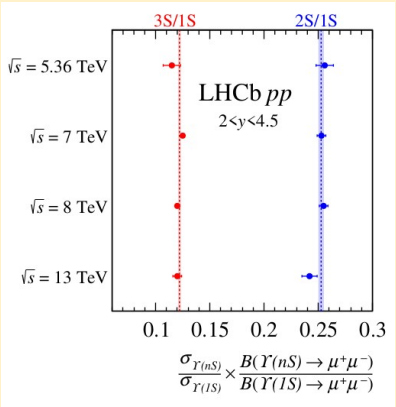




Bottomonia suppression in pO and OO

LHCb-PAPER-2026-027, in preparation



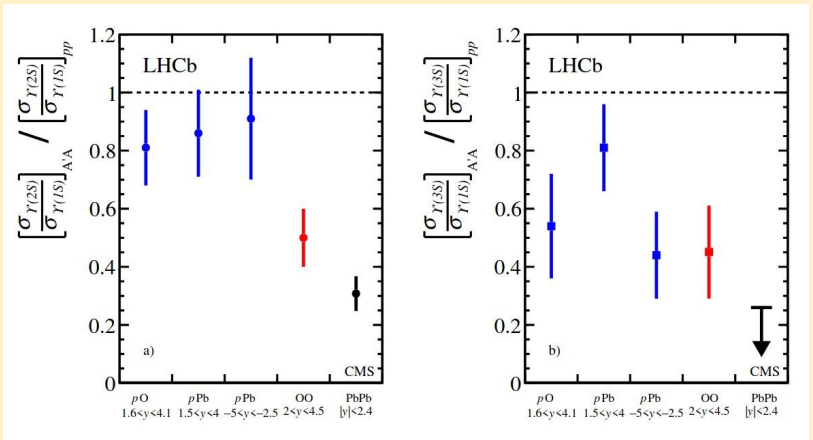


- Moderate 2S-to-1S suppression in pO

- Limited statistics for 3S, but similar trend

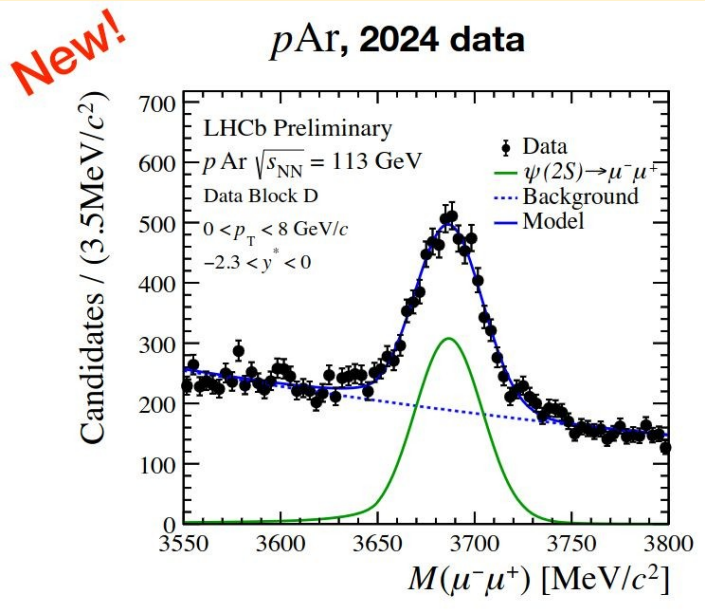
- Double ratio cancels initial-state effects,
  confirms 4.8σ 2S suppression in OO wrt pp

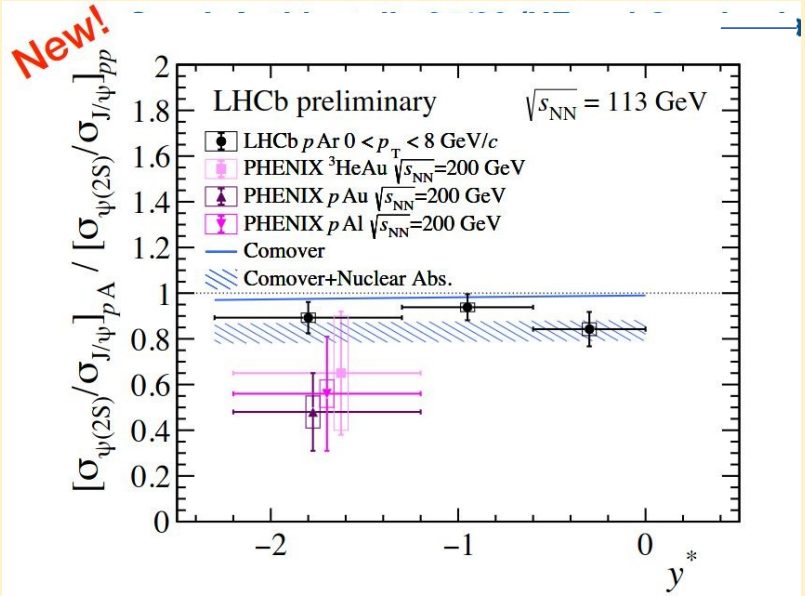
- 3S also suppressed in pA systems



Charmonia production and suppression in SMOG2

LHCb-PAPER-2026-026, in preparation

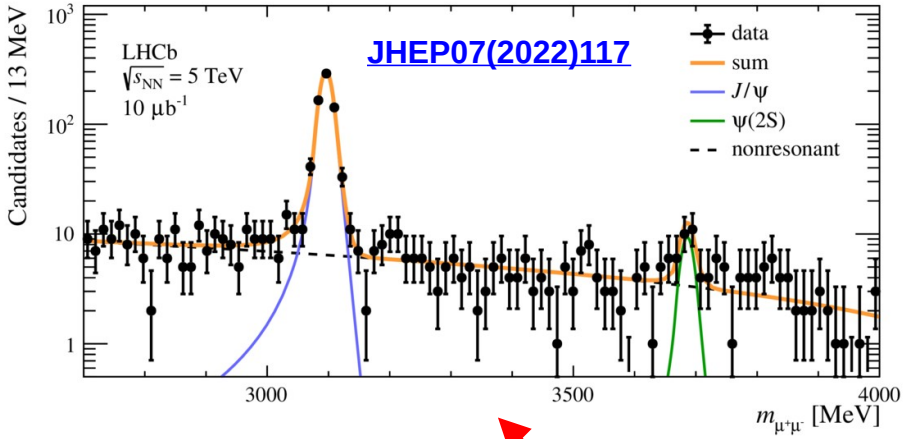


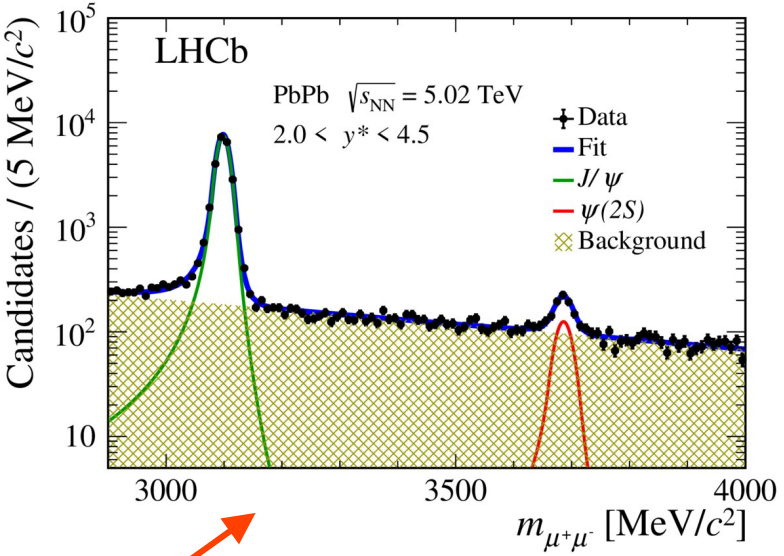


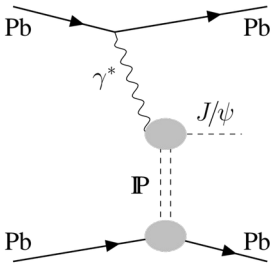
- Initial-state effects are cancelled in the double ratio:
  CNM effects (comover + nuclear absorption) can explain LHCb data

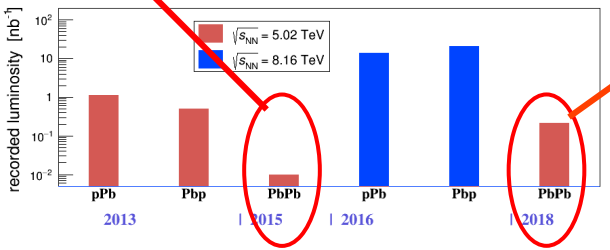
Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

[JHEP 06 (2023) 146]



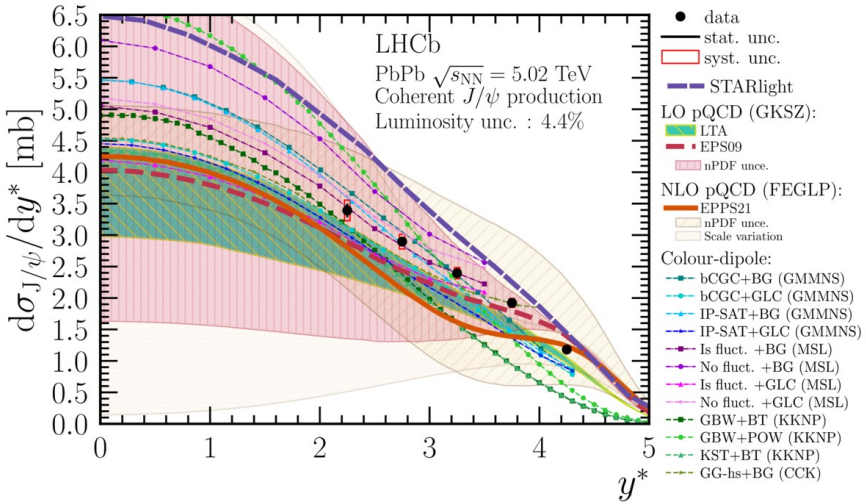


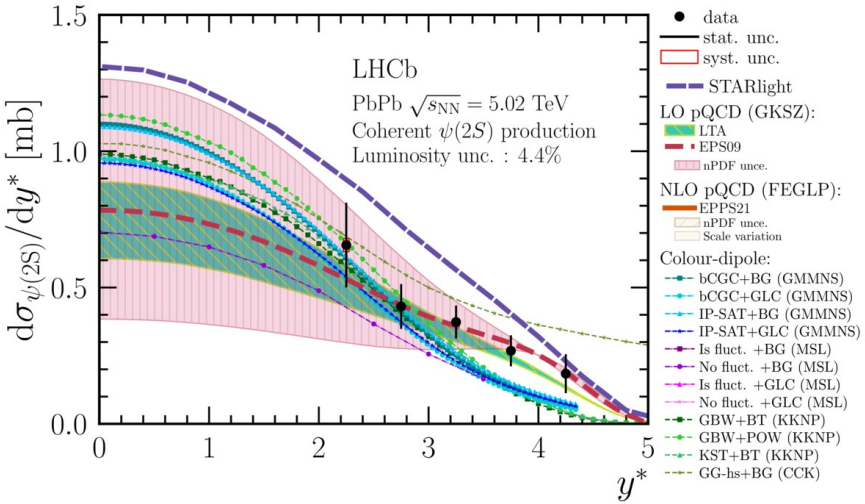




Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

[JHEP 06 (2023) 146]



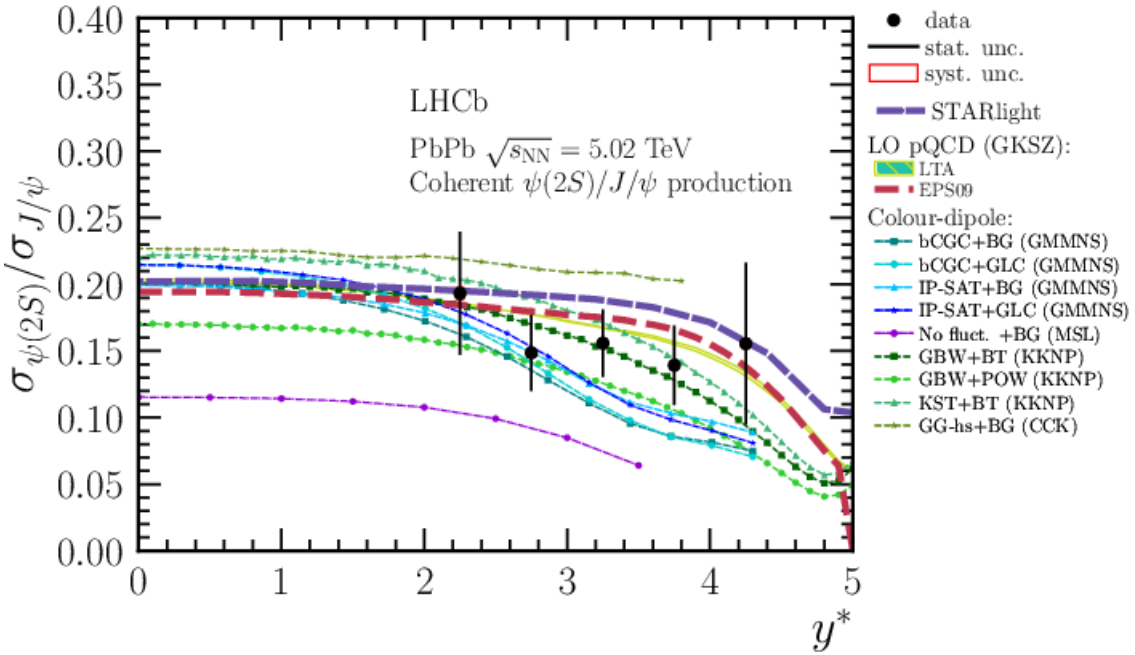


Differential cross-section as a function of rapidity results compared with
- color-dipole model (blue lines)
- pQCD model (red lines) theory predictions

The first coherent ψ(2S) measurement in forward rapidity region at the LHC

Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

[JHEP 06 (2023) 146]



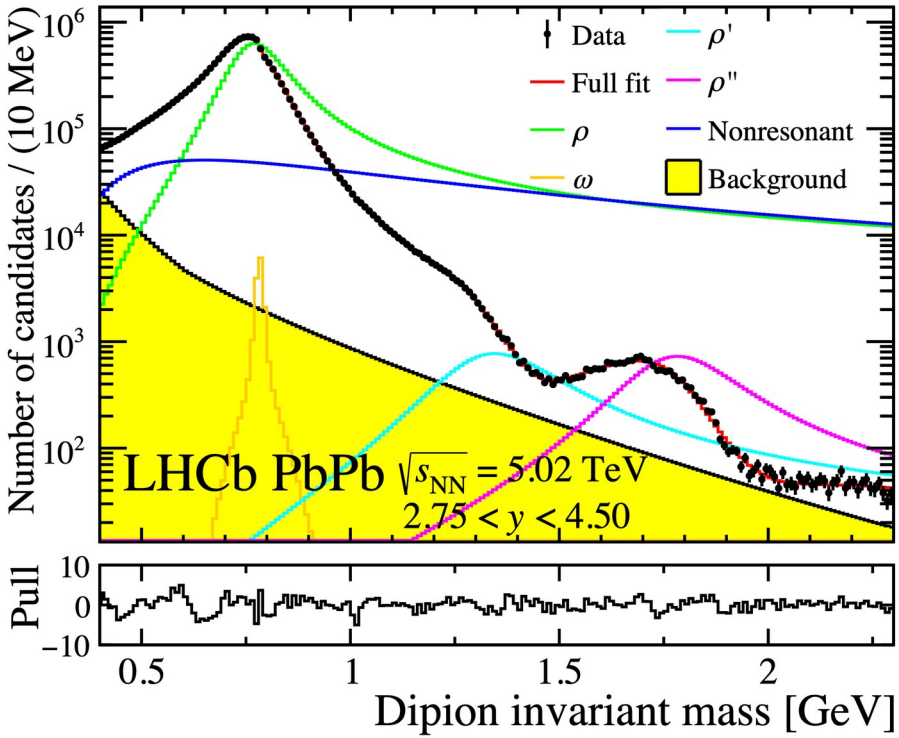
→ theoretical uncertainties cancel in cross-section ratios

→ data is compatible with different models

DiPion Production in UPC

JHEP 11 (2025) 103

Adding ω with additional ρ data can be fitted with the Söding model

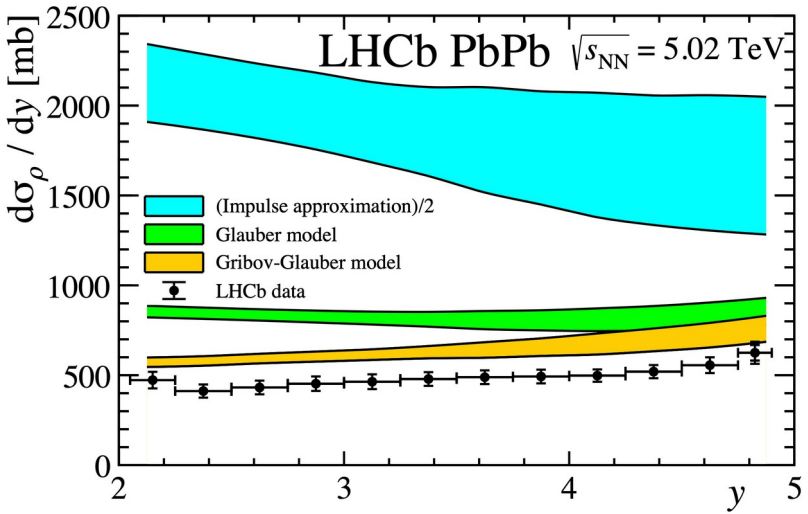


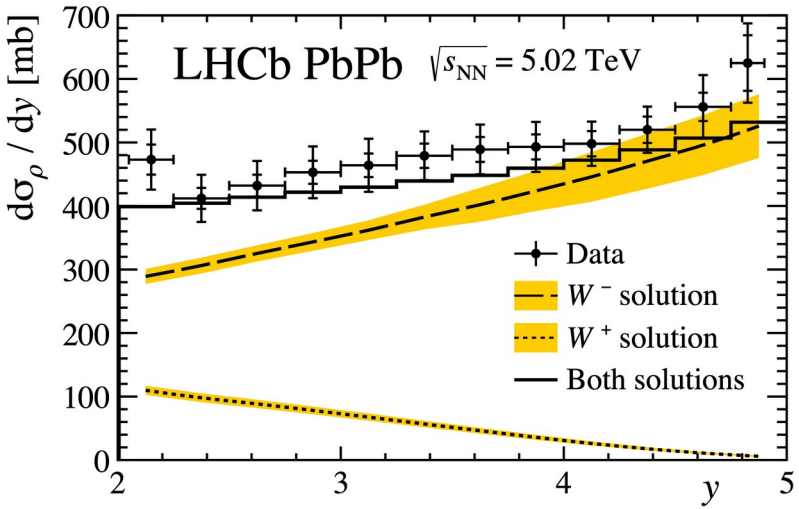
Parameter (Eq. 7)	Result
m_ρ [MeV]	774 ± 3
Γ_ρ [MeV]	148 ± 7
$\lvert f_{\rm nr}/f_\rho \rvert$	0.18 ± 0.03
$\phi_{\rm nr}$	-0.1 ± 0.1
Λ [MeV]	420 ± 150
δ	1.2 ± 0.1
$\lvert f_\omega/f_\rho \rvert$	0.14 ± 0.02
ϕ_ω [rad]	-0.20 ± 0.06
$\lvert f_{\rho'}/f_\rho \rvert$	0.013 ± 0.008
$m_{\rho'}$ [MeV]	1350 ± 20
$\Gamma_{\rho'}$ [MeV]	320 ± 40
$\phi_{\rho'}$	2.4 ± 0.3
$\lvert f_{\rho''}/f_\rho \rvert$	0.006 ± 0.002
$m_{\rho''}$ [MeV]	1790 ± 20
$\Gamma_{\rho''}$ [MeV]	290 ± 40
$\phi_{\rho''}$	1.2 ± 0.7

DiPion Production in UPC

JHEP 11 (2025) 103

Number of ρ mesons in different rapidity regions is used to calculate cross-section





Cross-section shows a slow rise with rapidity

Suppression factors of

0.84 ± 0.04 for x ~ 5 × 10−3

0.83 ± 0.06 for x ~ 5 × 10−6

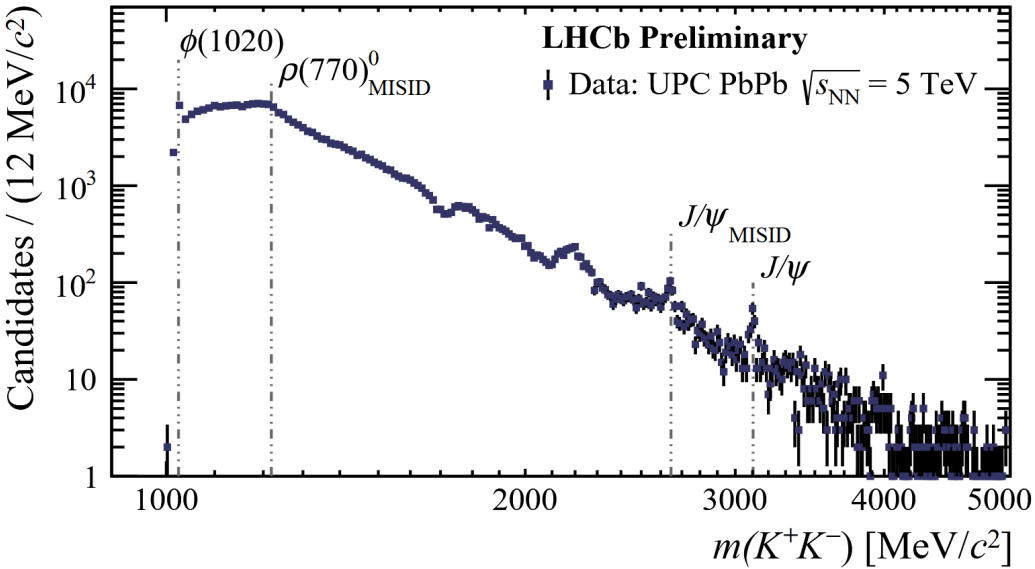
$$\frac{d\sigma_{PbPb\to Pb\rho Pb}}{dy} = (S^+_{model})^2 \left(k\frac{dN_\gamma}{dk}\right)^+ \sigma^{model}_{\gamma Pb\to\rho Pb}(W^+) + (S^-_{model})^2 \left(k\frac{dN_\gamma}{dk}\right)^- \sigma^{model}_{\gamma Pb\to\rho Pb}(W^-)$$

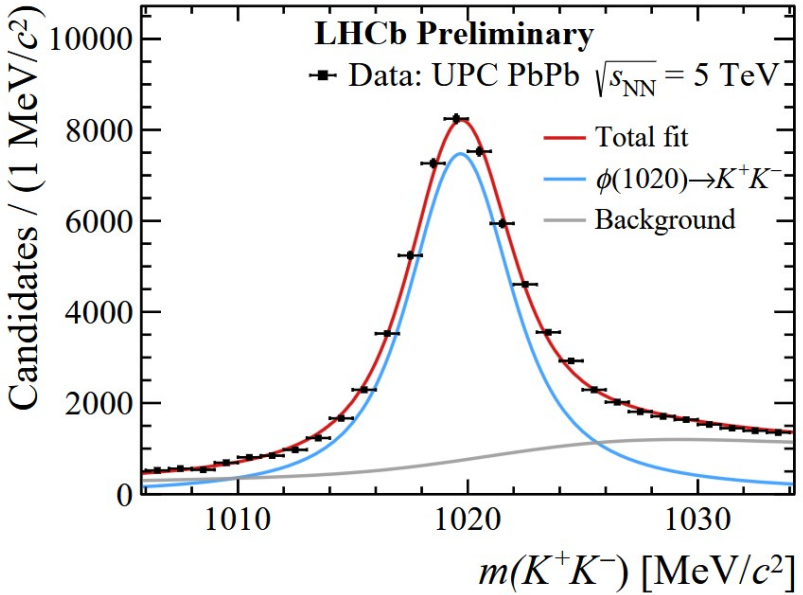
K^+K^- mass spectrum in UPC

LHCb-CONF-2024-006

Study of coherent ϕ production - perturbative and non-perturbative regime - saturation effects studies

→ Challenging analysis due to background





Dikaon invariant-mass spectrum has a rich structure

vector, scalar, and tensor mesons?

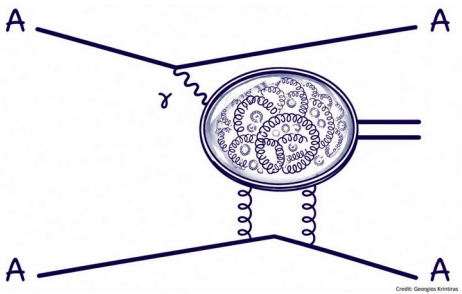
Summary

--- Rapidly growing LHCb heavy-ion and fixed-target physics programs.

--- Successful Run 3 data-taking: strong pipeline of upcoming results, boosted by upgraded trigger lines.

--- Delivering unique constraints on several models framework for both light- and heavy-ion systems.

--- Many other measurements not shown can be found https://lbfence.cern.ch/alcm/public/analysis




7015 km Saturation
Hadronization 57 km
HIT
194 km
Shadowing
656 km Energy Loss
Energy Loss 455 km
CERN
9312 km
Absorption
6722 km CGC
nPDF 9388 km
iThemba LABS

THANK YOU