Heavy Ion Physics at ATLAS, CMS and LHCb

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– on behalf of the ATLAS EXPERIMENT CMS LHCb collaborations –

Outline

- Introduction
- Quarkonia production
- Correlation studies
- Ultra-peripheral collisions
- Fixed target physics
- Summary

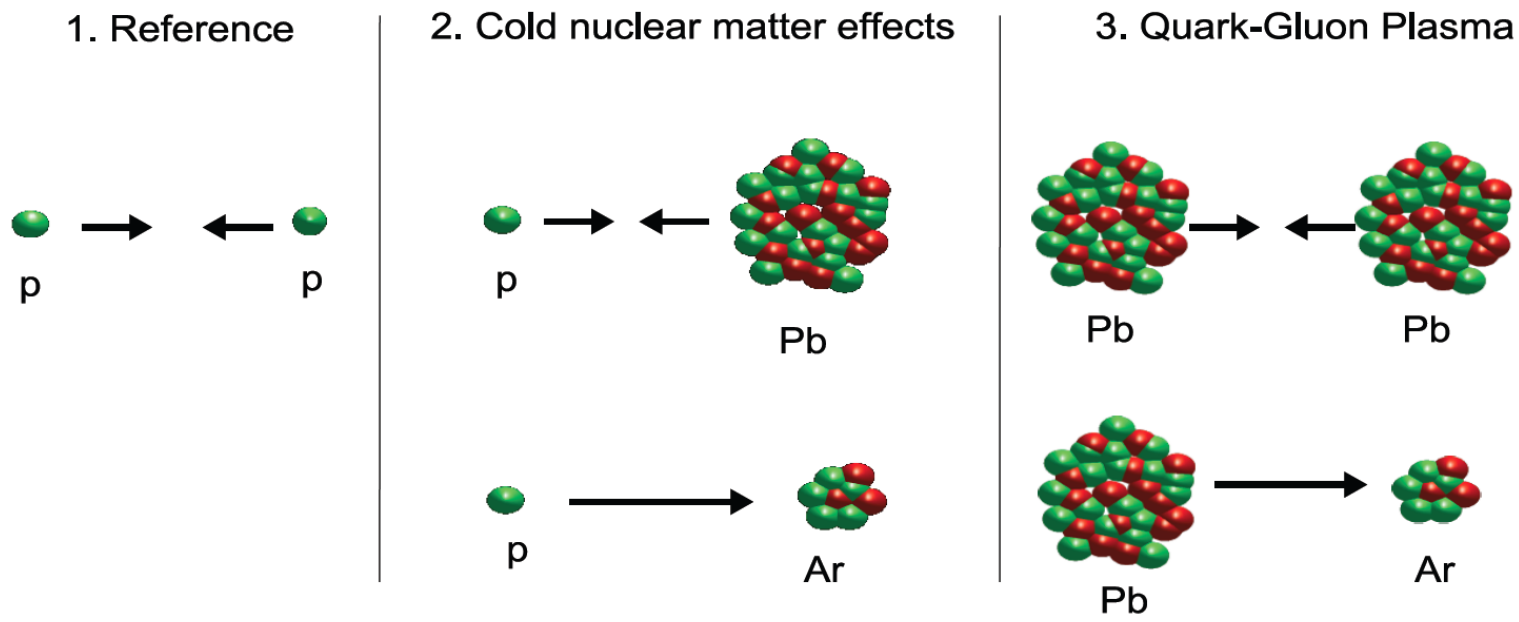
XXXII Les Recontres de Physique de la Vallée d'Aoste

1 Introduction

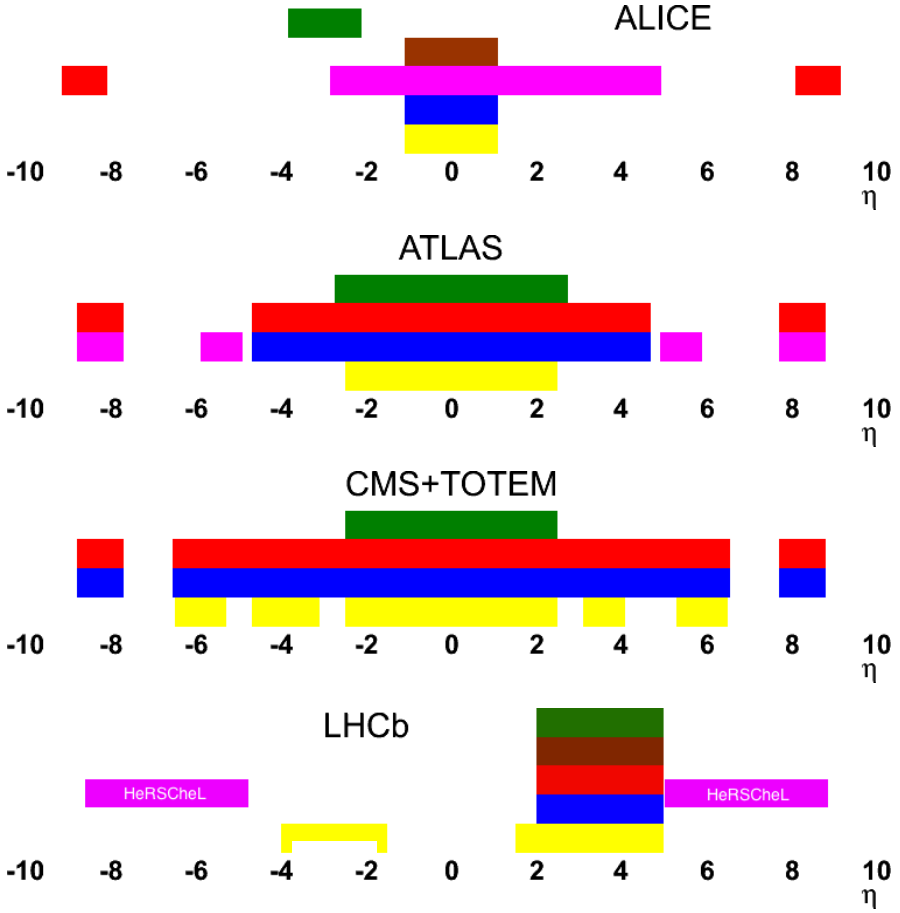
- theoretical understanding of strong interactions:
  - the QCD Lagrangian is well known and tested
    - good agreement between data and theory where perturbative QCD is applicable
  - many open questions in the non-perturbative regime, such as . . .
    - properties of hadronic matter at high densities and temperatures (QGP)
    - bound states, e.g. nucleon structure (vital for BSM searches)
    - nuclear effects in multiparticle production (nuclear PDFs, energy loss)
    - dynamics of soft processes, e.g. diffractive scattering and hadronisation
    - also interesting: QED at extreme field strengths

❖ Experimental approach

- different nucleon-nucleon centre-of-mass energies
- different beam-target combinations
- comparison of different systems ➜ always look at the complete picture



❖ Angular coverage of the LHC experiments



- ALICE
  - central detector
  - forward muon coverage
- ATLAS & CMS
  - central tracking detectors
  - forward calorimeter
- LHCb
  - forward detector
  - tracking, PID and calorimetry in the full acceptance

hadron PID
muon system
lumi counters
HCAL
ECAL
tracking

❖ rich harvest of papers and conference notes

- generic topics addressed in papers:

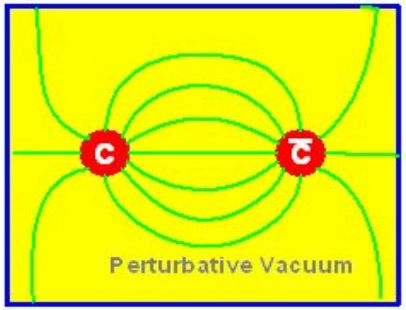
	ATLAS	CMS	LHCb
Flow- and correlation measurements	17	24	1
Jets and QCD	10	19	0
Quarkonia	3	10	4
Particle production	6	15	1
Electroweak gauge bosons	3	5	1
QED	1	1	0
total	40	74	7

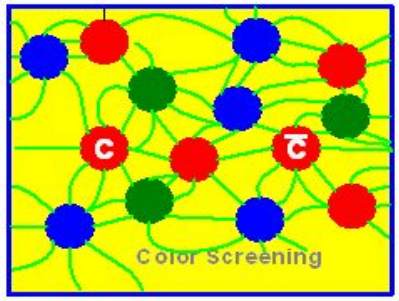
- plus $>$ 200 papers by the ALICE collaboration (➜ next talk)
- many papers touch on more than a single topic

textbook results from the LHC ➜

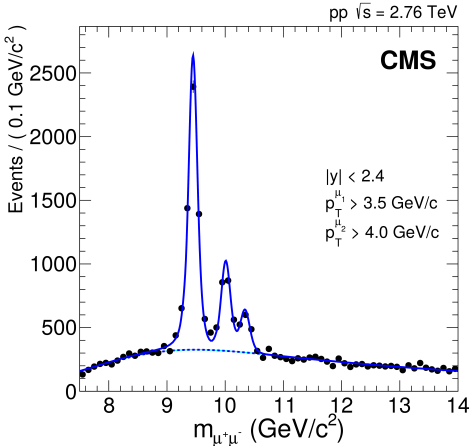
Melting of bound states in QGP

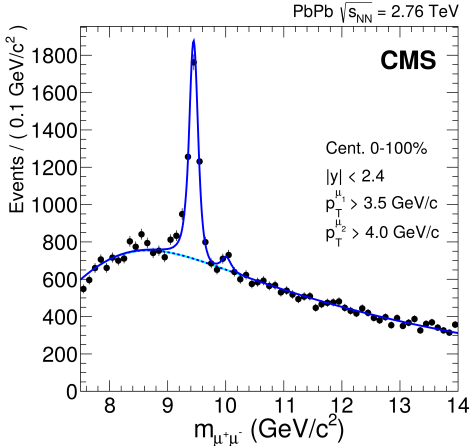
❖ check the Matsui-Satz-idea regarding $b\bar{b}$ and $c\bar{c}$ systems





heavy-quark bound states melt in the hot medium of the deconfined colour charges of a QGP





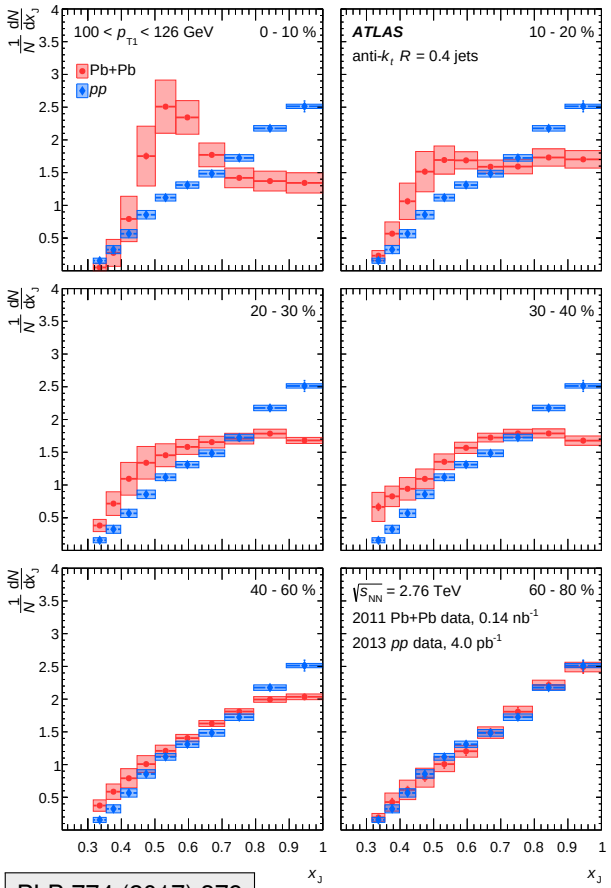
PLB770(2017)357

➜ experiment: Υ production in pp and PbPb collisions

- negligible recombination
- less tightly bound states are strongly suppressed

➜ intriguing QGP signature

Jet quenching



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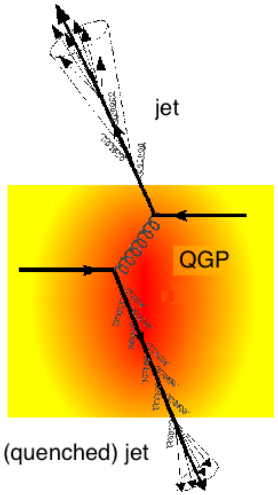
❖ energy loss of hard partons in QGP

- look at the p_T-ratio for jet pairs

$$x_J = \frac{p_{T_2}}{p_{T_1}} \quad \text{with} \quad p_{T_1} > p_{T_2}$$

- preference for balanced jets
- comparison of pp and PbPb
  - fewer high-energy jets in central PbPb collisions
  - same behaviour for pp and peripheral PbPb collisions

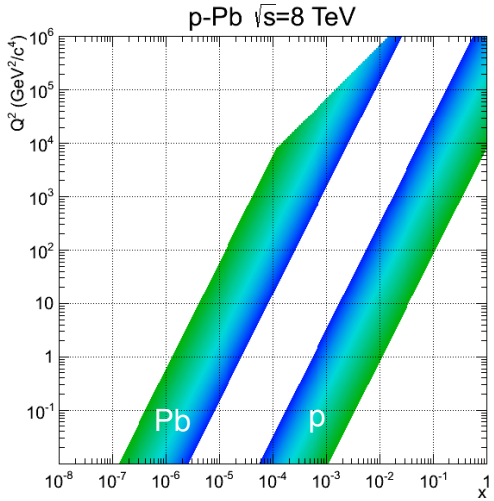


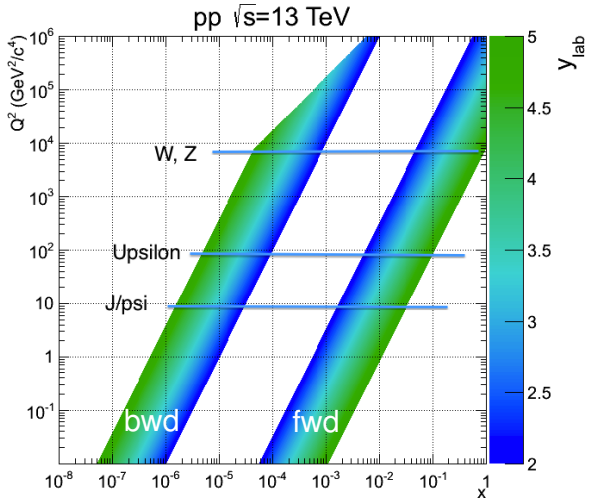
➜ signature of a dense deconfined QCD medium

2 Quarkonia production

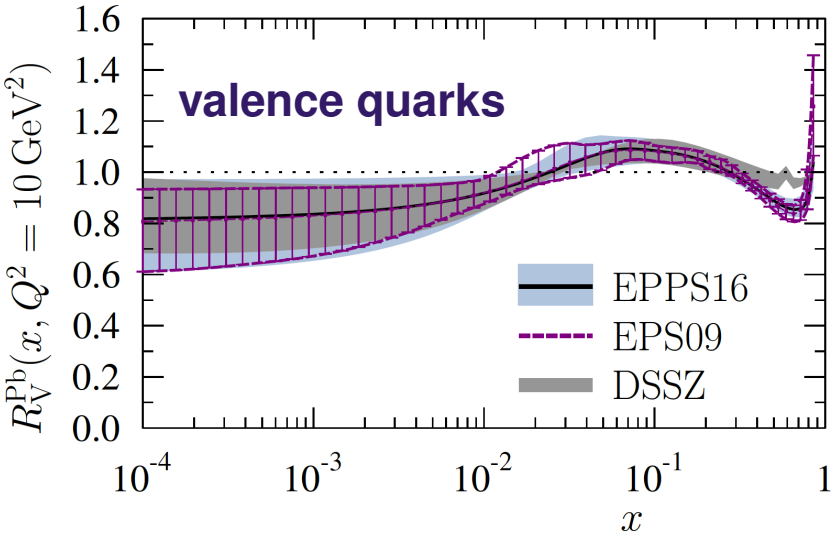
- study p-Pb collisions to probe cold nuclear matter effects
  - effects of energy loss in nuclear matter
  - modification of parton densities of bound nucleons
  - study by inclusive particle production of heavy resonances

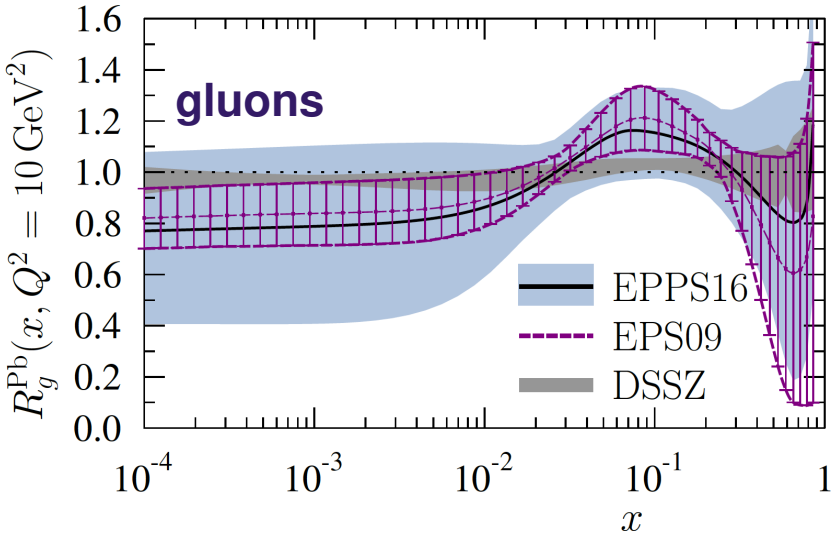
➜ probe two x-values for given rapidity y and mass M: $x_{1,2} \approx e^{\pm y} \frac{M}{\sqrt{s}}$





❖ parametrisation of nuclear PDFs by ratios of nucleon PDFs: $F_N(\mathrm{Pb})/F_N(\mathrm{free})$





arXiv:1704.0436

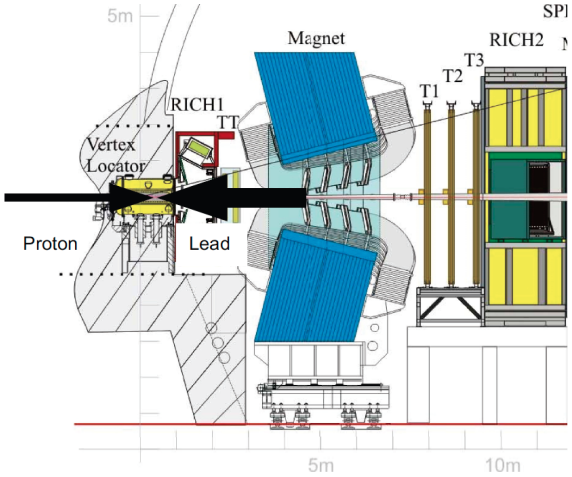
- still large uncertainties - EPPS16 error band for gluons larger than EPS09
- suppression at small x ➜ shadowing
- enhancement at medium x ➜ anti-shadowing
- enhancement at large x ➜ EMC effect

❖ experimental observable sensitive to nuclear effects:

nuclear modification factor: $R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy}$

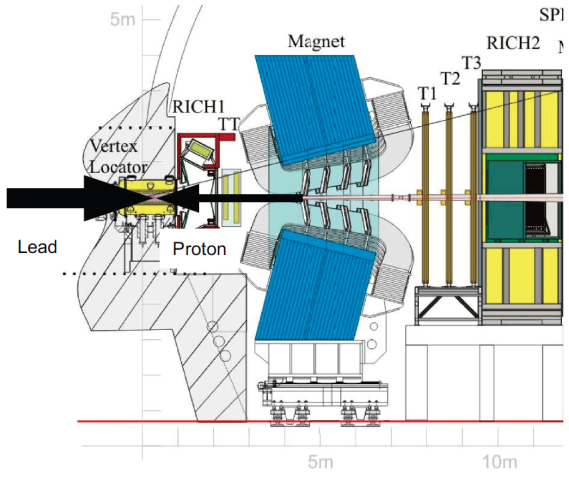
- central detectors: simultaneous measurement of forward and backward production
- forward detectors: flip beam directions to measure both hemispheres

p



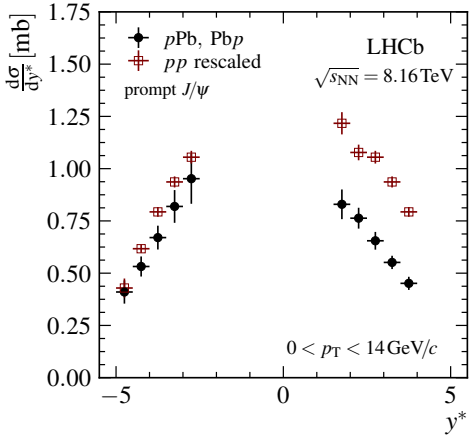
FORWARD (p hemisphere)

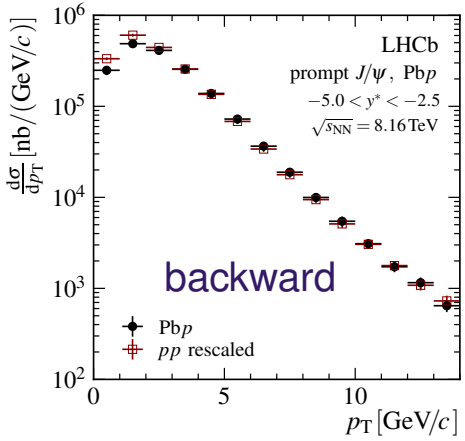
Pb

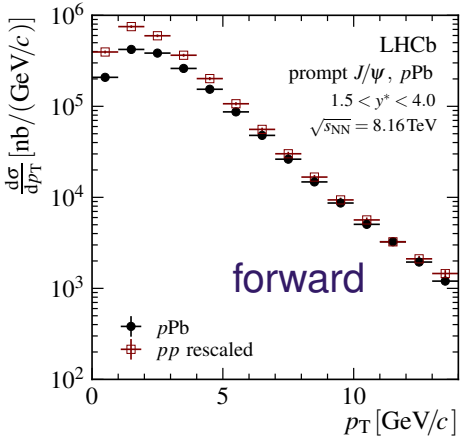


BACKWARD (Pb hemisphere)

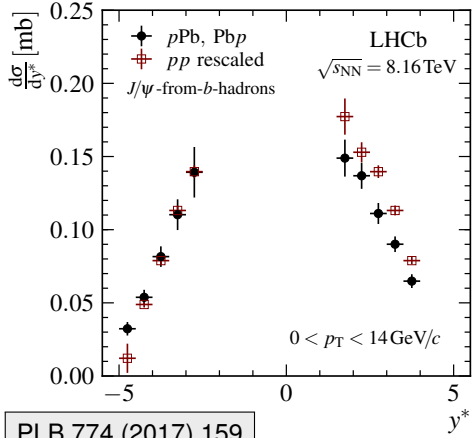
Results from prompt J/ψ and J/ψ from b-decays

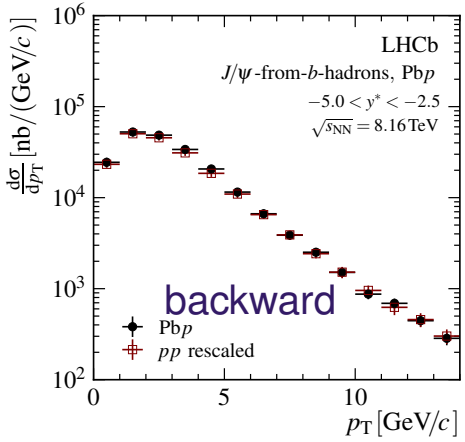


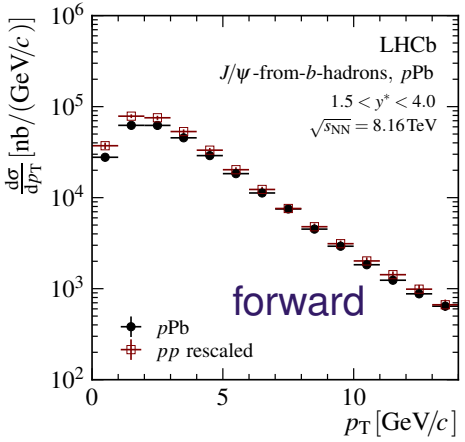




prompt J/ψ compared to $208 \times \sigma_{pp}$ (red)







delayed J/ψ compared to $208 \times \sigma_{pp}$ (red)

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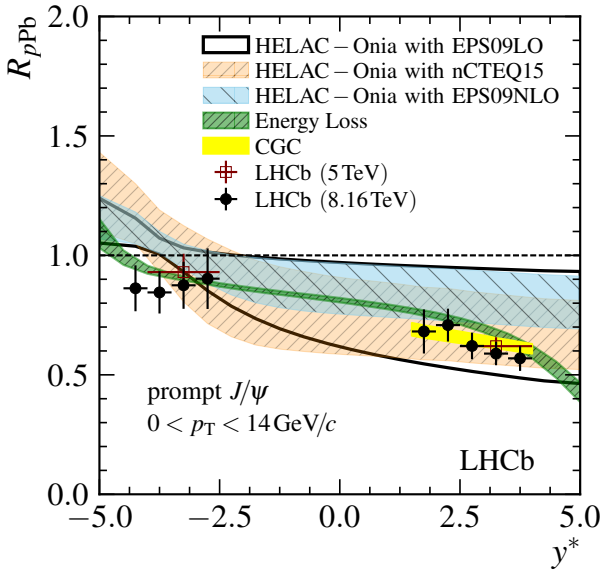
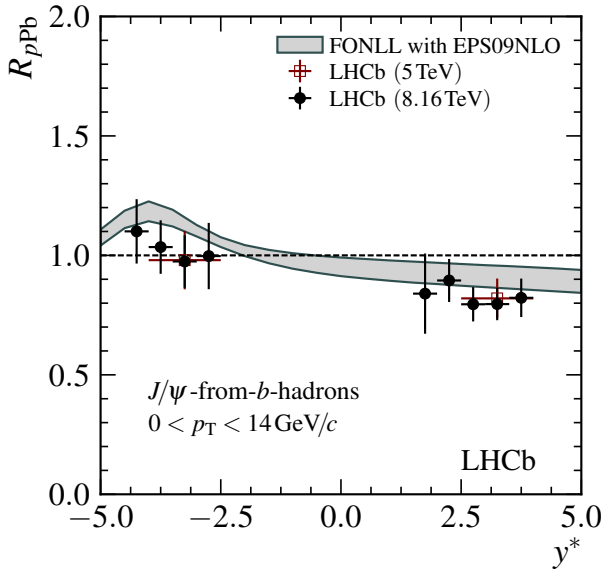
❖ nuclear modification factors in the forward/backward region





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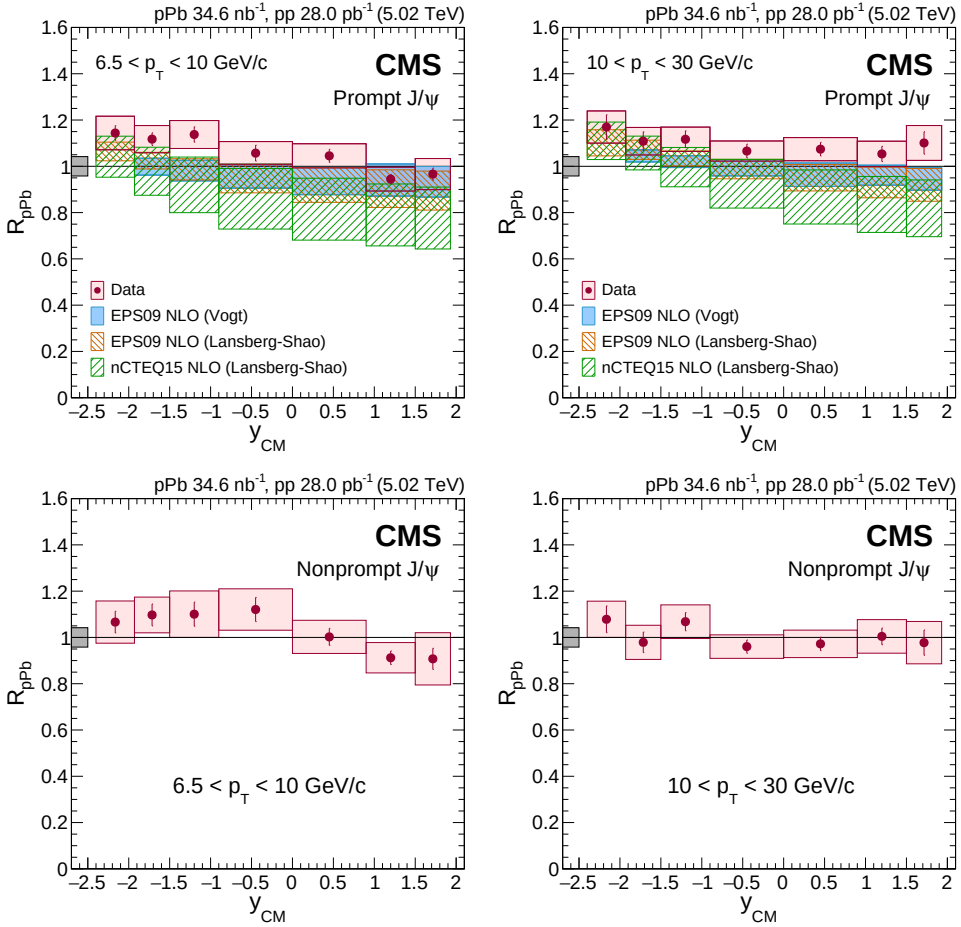
- consistent results for data with $\sqrt{s_{NN}}$ =5 and 8.16 TeV
- nuclear effects clearly visible in the forward region
- stronger effects for prompt J/ψ production than for J/ψ from b-meson decays
- J/ψ from b-meson decays described by effects of NLO nPDFs
- prompt J/ψ described by NLO nPDFs plus energy loss effects

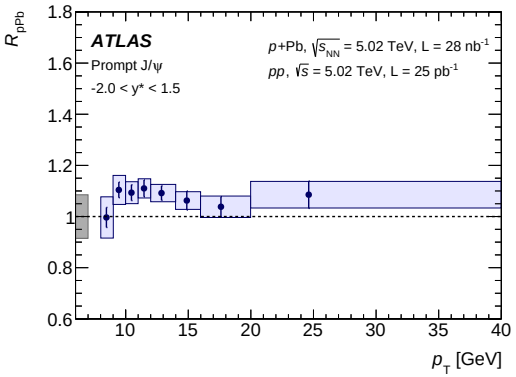
❖ nuclear modification factors in the central region

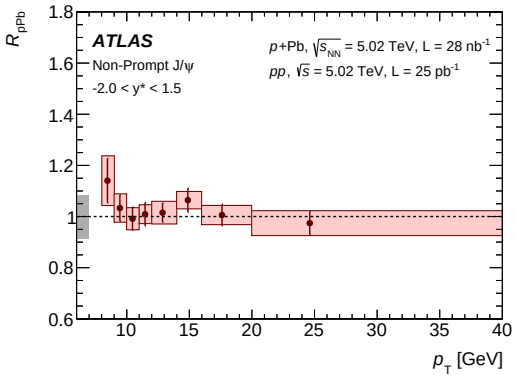


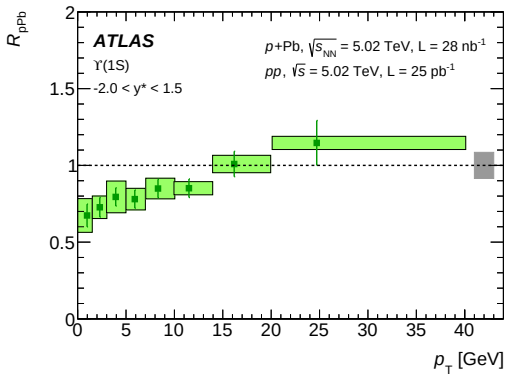
EPJC77(2017)269

- nuclear modification factors close to unity
- theory lower, though consistent, with the data
- similar behaviour for prompt and non-prompt J/ψ mesons
- indication for a slight enhancement for lower p_T

❖ closer look at p_T dependence







arXiv:1709.03089

- small nuclear effects for centrally produced J/ψ mesons
- indication for slight enhancement of prompt production
- no significant p_T dependence for prompt and non-prompt J/ψ production
- indication of p_T dependence for Υ production
  - open and hidden heavy flavour seem to be affected differently
  - maybe related to breakup of bound states in nuclear matter, which for J/ψ from b is compensated by recombination and/or anti-shadowing?

3 Correlation studies

❖ distribution of phase space distance between particle pairs

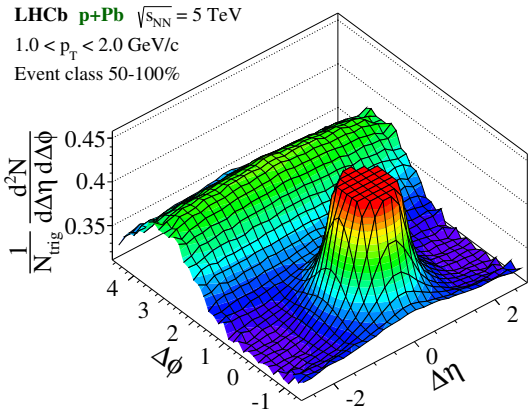
- probing the underlying dynamics, e.g.
  - dimensions of the particle emitting regions – Bose-Einstein correlations, HBT
  - particle production in jets – fragmentation dynamics
  - flow effects due to properties of QCD medium
- example: per trigger-particle associated yield vs angular distances $\Delta\eta$ and $\Delta\phi$

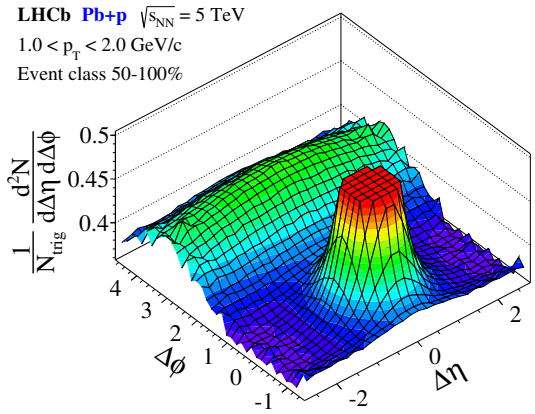
$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta\, d\Delta\phi} = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)} \times B(0,0)$$

  - 2-dim correlation functions of prompt particles in $(\Delta\eta, \Delta\phi)$
  - select particles in fixed p_T-range as “trigger”and study all pairs with the trigger
  - compare associated yields per trigger, within an event ($S(\Delta\eta, \Delta\phi)$) and with random combinations ($B(\Delta\eta, \Delta\phi)$) from mixed events

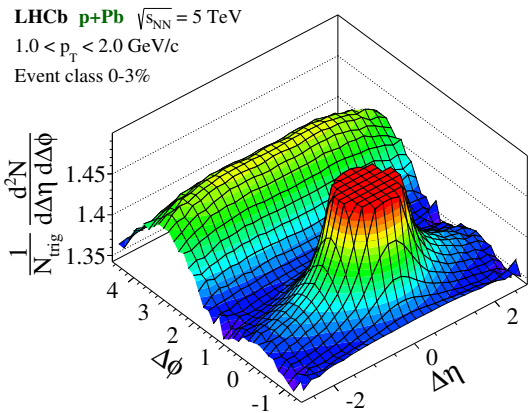
❖ example: two-particle correlations in p-Pb collisions

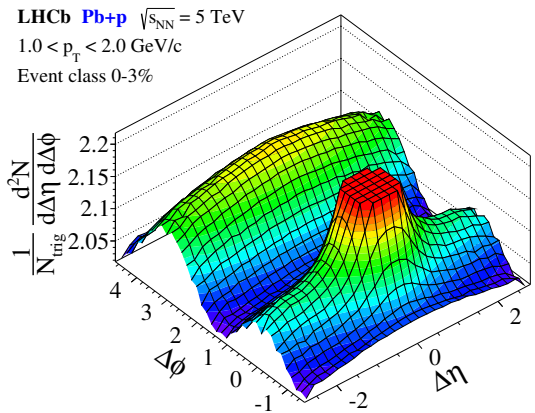
forward (p-Pb, p direction) backward (Pb-p, Pb direction)





low activity





high activity

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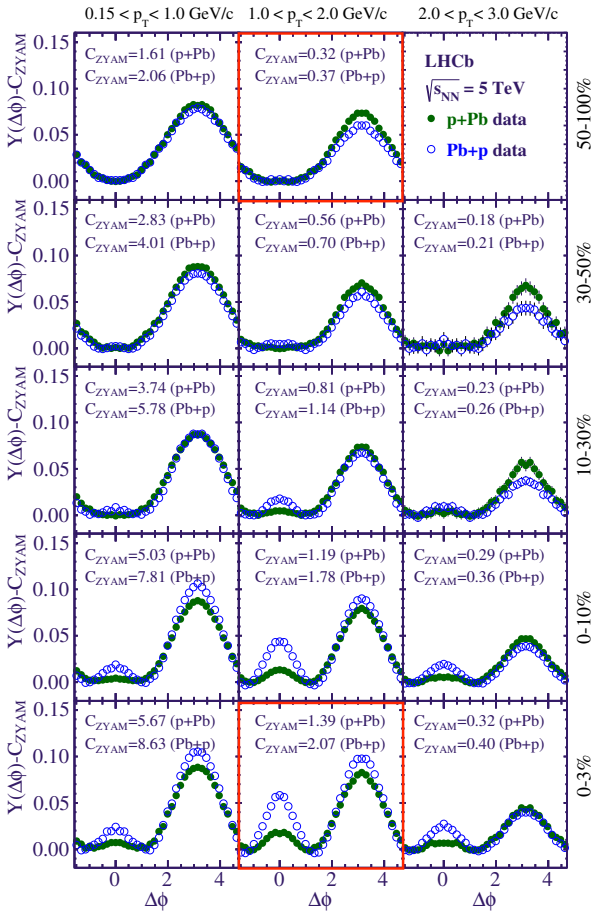
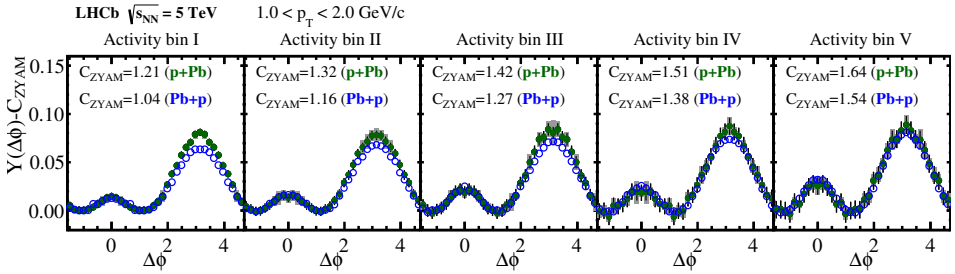
❖ $\Delta\eta$-integrated yields in p-Pb/Pb-p outside of the jet peak vs $\Delta\phi$



after offset subtraction (Zero-Yield-At-Minimum):

- near-side ridge largest at $1 < p_T < 2\,\text{GeV}/c$
- fixed relative activity (left):
  ridge of the 3% most active Pb-p events stronger than the ridge of the 3% most active p-Pb events
- fixed absolute activity in the LHCb acceptance:
  similar ridges in p-Pb and Pb-p events



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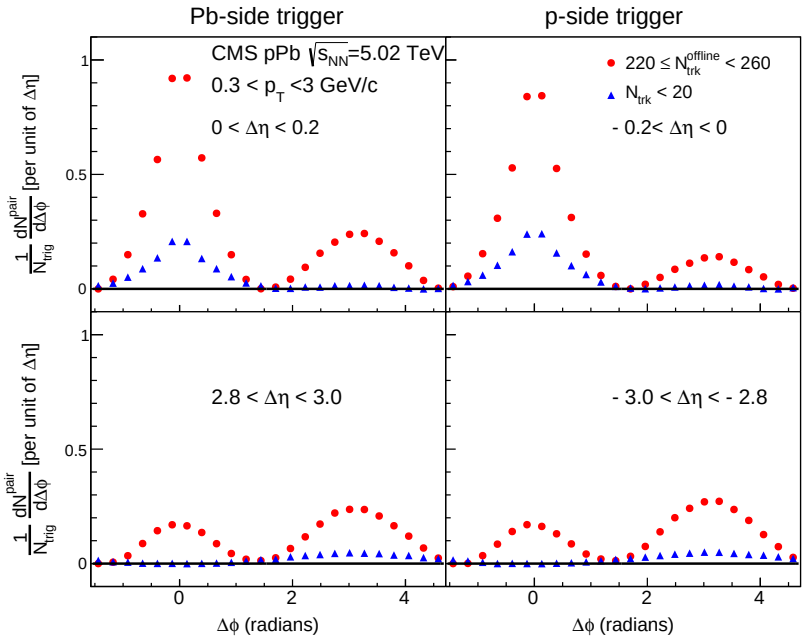
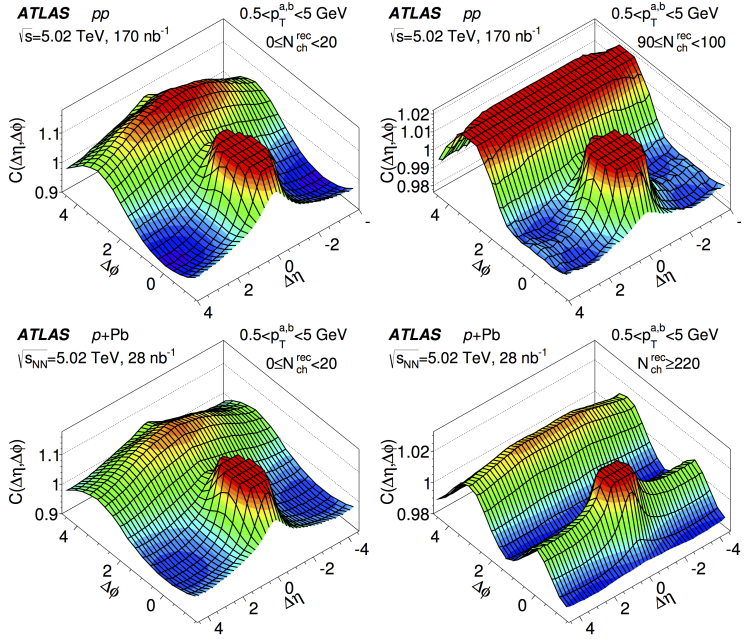
❖ results from central measurements



PRC96 (2017) 014915

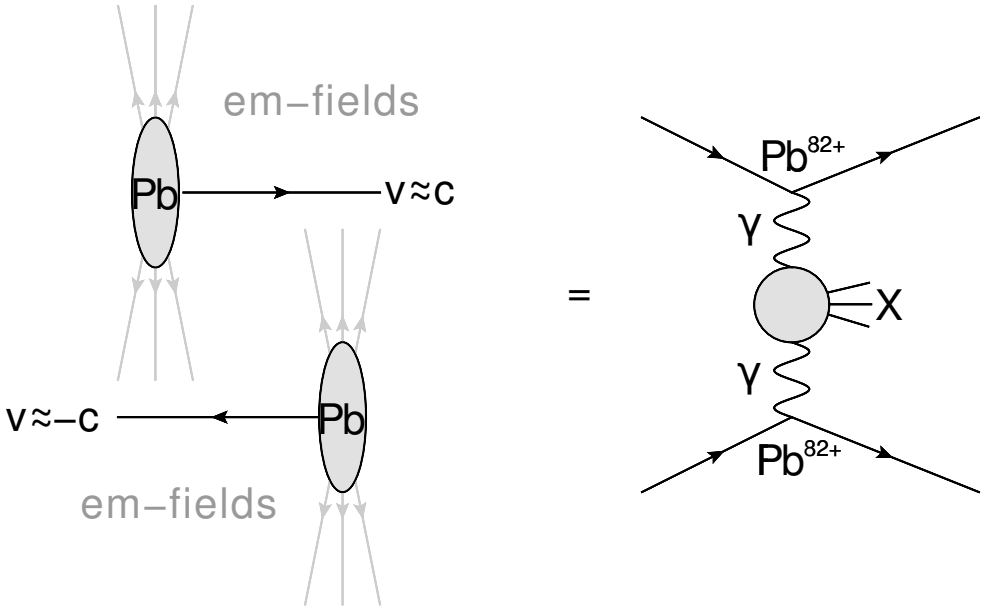


PRC96 (2017) 024908

- outside the jet peak (bottom) the ridge appears in high-multiplicity events (red)
- similar strengths for p-side and Pb-side
- ridge also in high multiplicity pp events
- universal feature when many QCD degrees of freedom are present?

4 Ultra-peripheral collisions

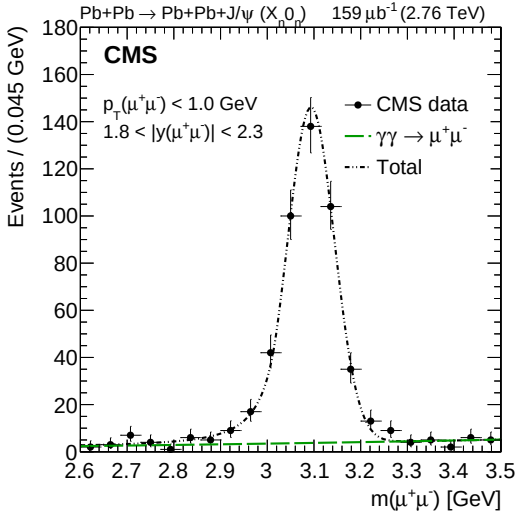
❖ exploit the high-intensity photon flux from relativistic Pb nuclei

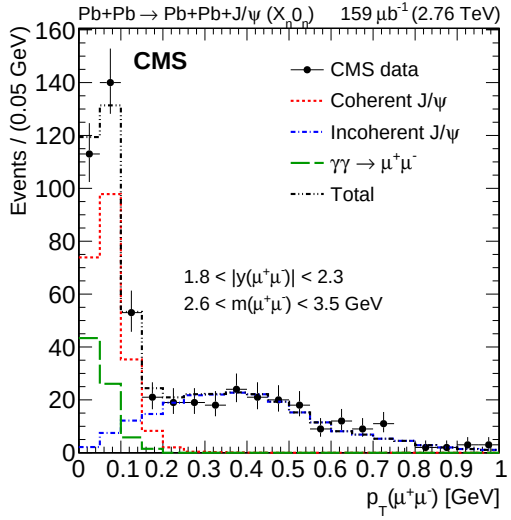


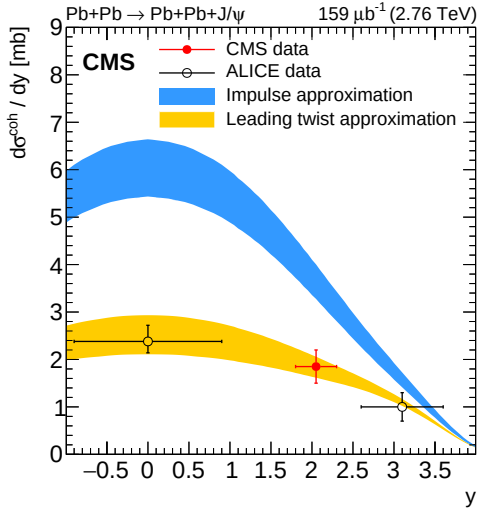
- field strength amplified by γ
- em-coupling amplified by Z^2
- strong coupling regime of QED

- distinguish two photon-processes (depicted above) and photoproduction (not shown)
- common characteristic: low transverse momentum of the final state system
- existing/upcoming results also from LHCb

Coherent production of J/ψ mesons in PbPb collisions



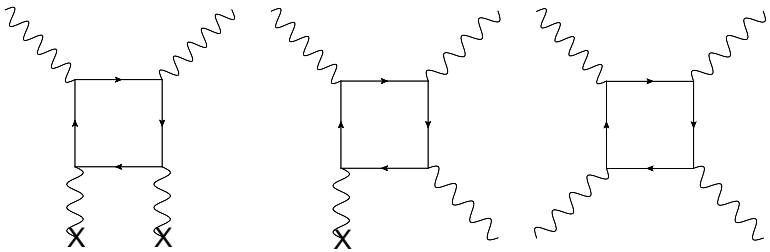


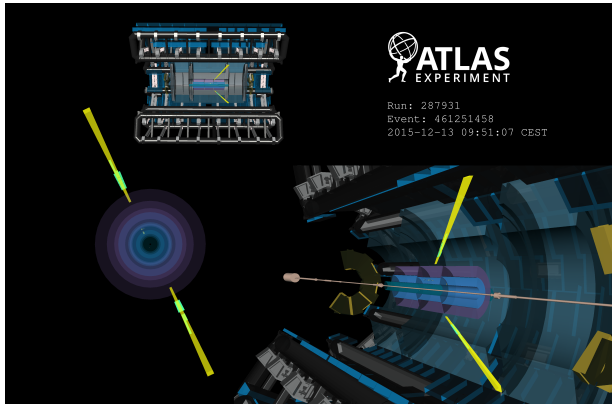


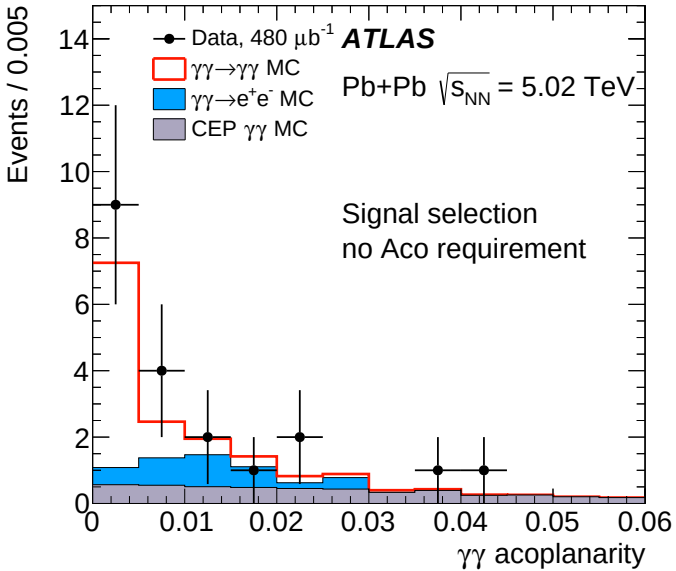
PLB772(2017)489

- experimental selections with a breakup neutron accepts coherent (on the entire nucleus) and incoherent (on a single nucleon) production
- clean signal on top of a small and well understood background
- measurement of the photoproduction cross-section probes the gluon density
- cross-section consistent with nuclear effects as expected from gluon shadowing

Evidence for light-by-light scattering







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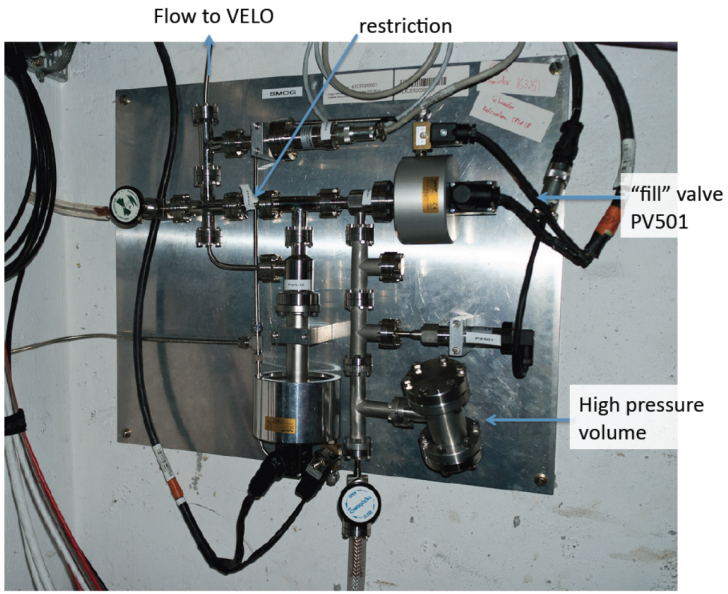
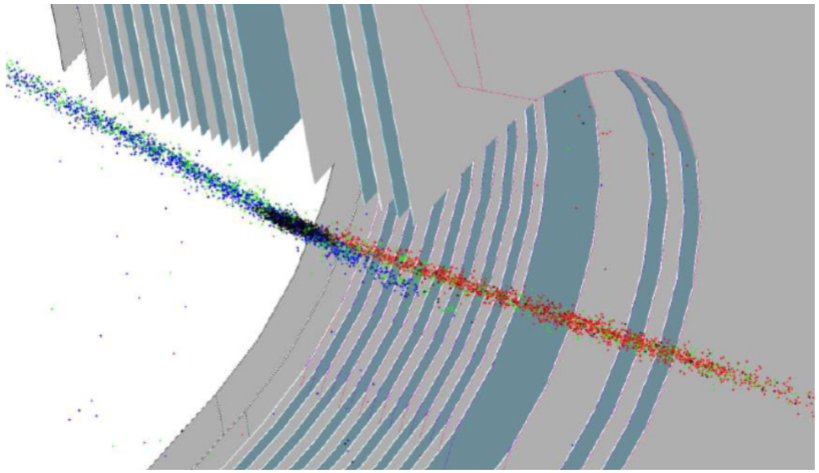
- back-to-back photons transverse to the beam
- 13 candidates in $480 \mu b^{-1}$
- expected background 2.6 ± 0.7 events
- cross-section consistent with SM

5 Fixed target physics

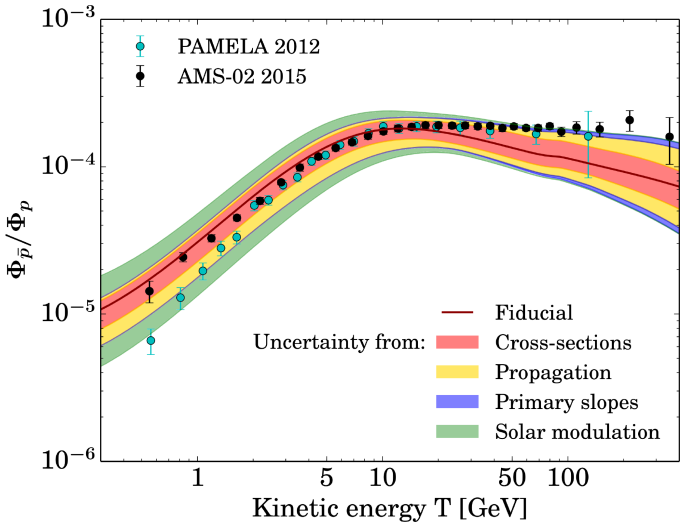
❖ exploit the LHCb SMOG “System for Measuring Overlap with Gas”





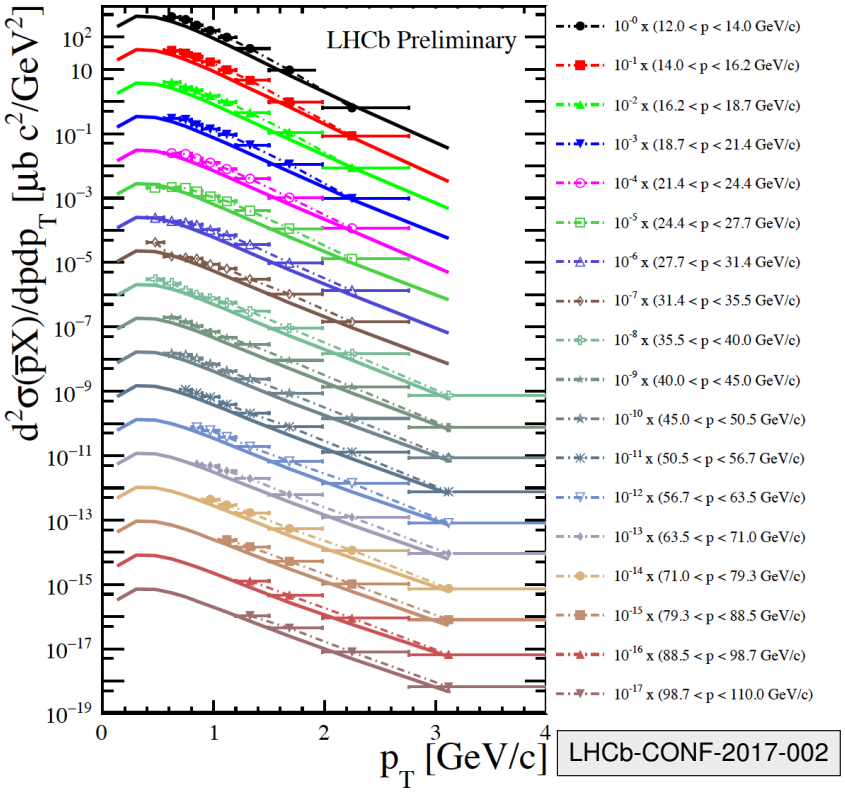
- inject noble gases (10^{-7} mbar) into the interaction region: He, Ne, Ar
- motivation: beam-profile measurements with beam-gas interactions
- plus: full charm and (soft) QCD fixed-target physics program with p and Pb beams

❖ links to cosmic ray and astroparticle physics: antiproton/proton ratio



JCAP 09 (2015) 023

- indication of antiproton excess
- dark-matter annihilation?
- large cross-section uncertainties for pH→ $\bar{p}$X
- predictions vary within a factor 2



LHCb-CONF-2017-002

➜ LHCb: measure pHe→ $\bar{p}$X at $\sqrt{s_{NN}}$ =110 GeV

- 7% uncertainty
- data compared to EPOS-LHC

6 Summary

- extremely rich (heavy) ions physics portfolio and results at the LHC
  - simultaneous views are the key to the understanding of non-perturbative QCD
    - study of the same observables in pp, p-Pb and Pb-Pb collisions
    - central and forward measurements
  - understanding QGP signatures requires understanding of nuclear effects
  - heavy flavour measurements probe nuclear PDFs and properties of the medium
  - correlation measurements probe collective effects in the final state
    - hints of universality when sufficiently many degrees of freedom are excited
  - fixed target physics radiates also into neighbouring fields
  - ultra-peripheral collisions test soft QCD and QED under extreme conditions

Stay tuned for more from the ATLAS EXPERIMENT, CMS, LHCb and ALICE collaborations!