Plans for future fixed target experiments at the LHC

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Town meeting: Relativistic Heavy Ion Physics
CERN
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Outline

- Physics motivations for a high-luminosity fixed-target experiment at the LHC
- Technical implementations with LHC beams and achievable luminosities in ALICE and LHCb
- A selection of physics opportunities and projected performances

Mostly based on the work of the AFTER@LHC Study Group: http://after.in2p3.fr

AFTER@LHC review paper arXiv:1807.00603
Submitted to Physics Report

A Fixed-Target Programme at the LHC:
Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

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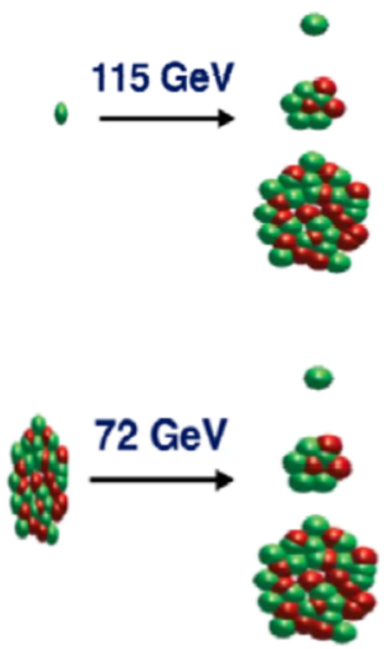
Fixed-target at LHC: kinematic features and advantages

Energy range

- 7 TeV proton / 2.76 Pb beam on a fixed target

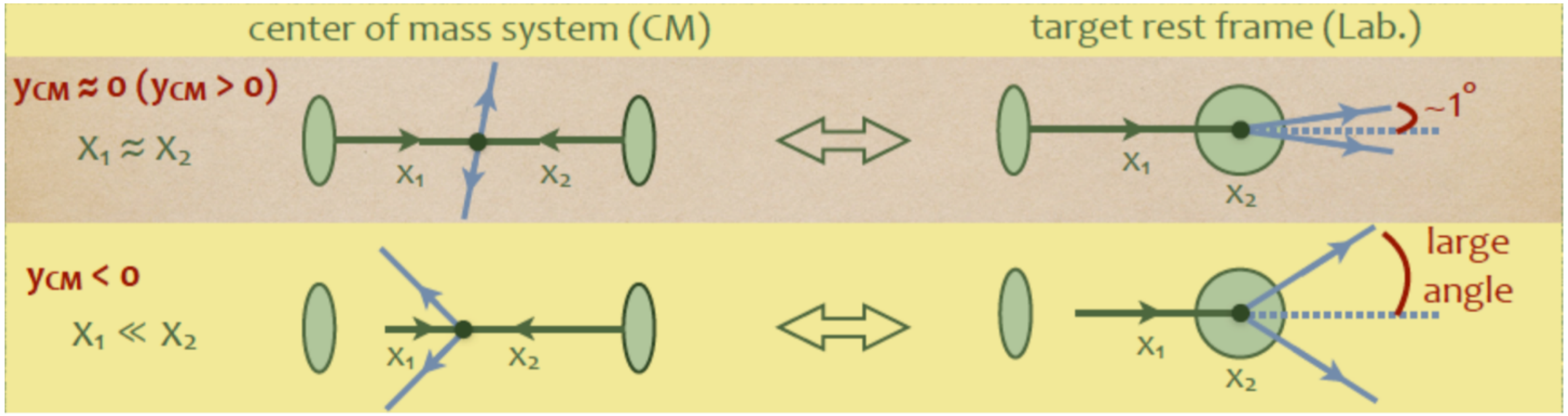


beam type	CM energy $\sqrt{s_{(NN)}}$	boost $\gamma=\sqrt{s}/2m$	rapidity shift
proton (E = 7 TeV)	115 GeV	61	4.8
lead (E = 2.76 TeV)	72 GeV	38	4.2

→ center-of-mass energy in-between SPS at CERN and nominal RHIC

Rapidity range

- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Easy access to (very) large backward rapidity range ($y_{CM} < 0$) and large parton momentum fraction in the target (x_2)



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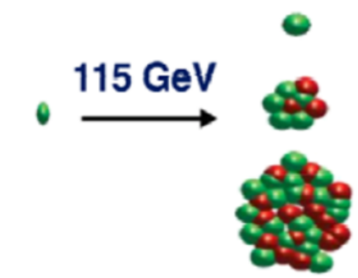

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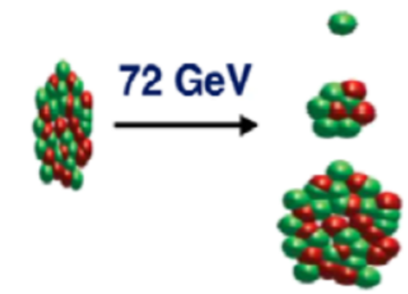

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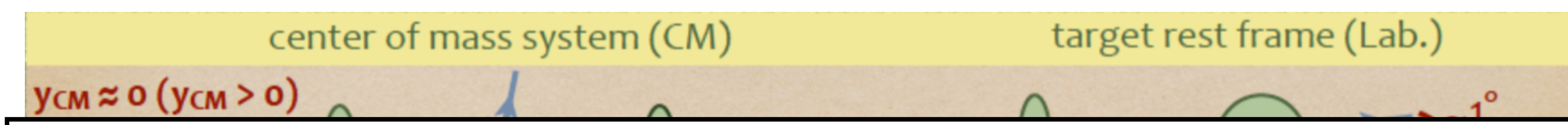
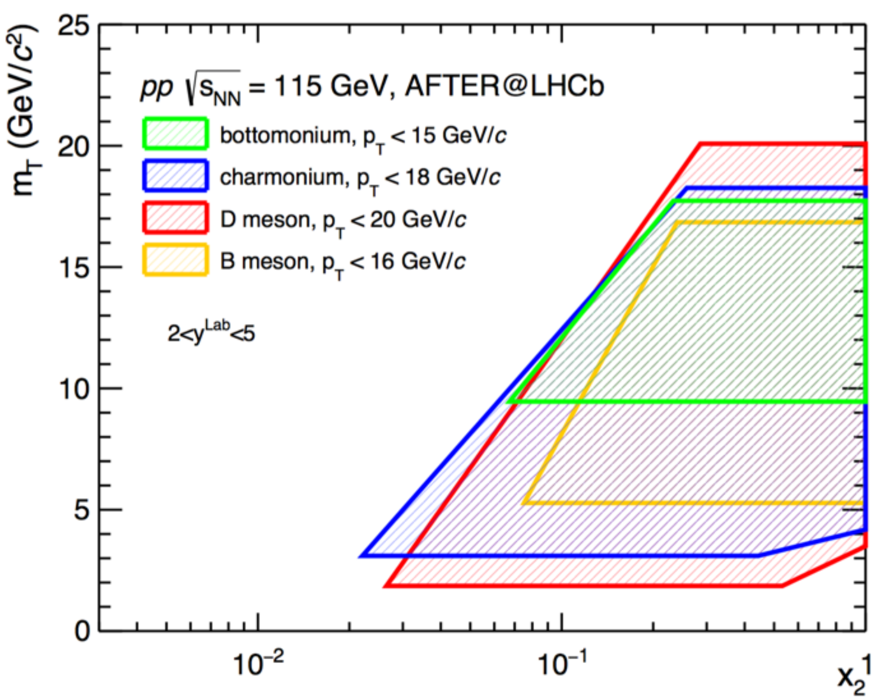
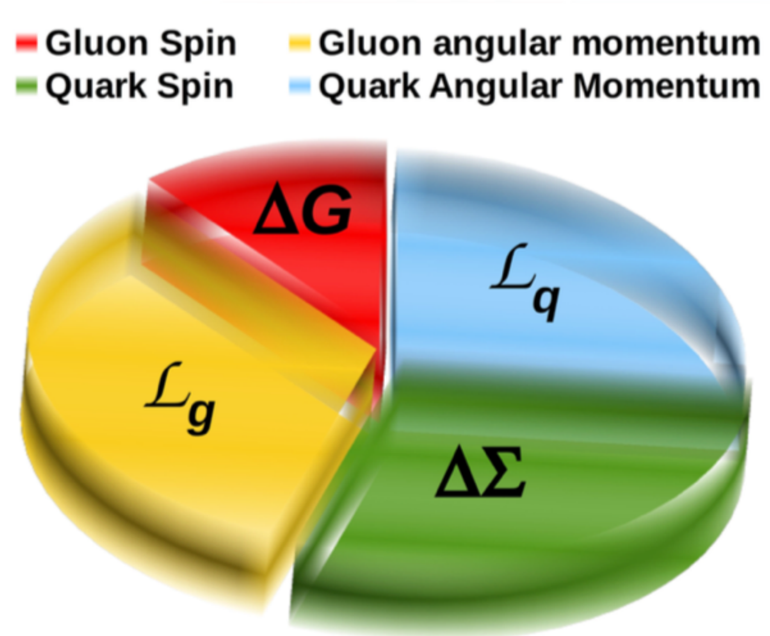


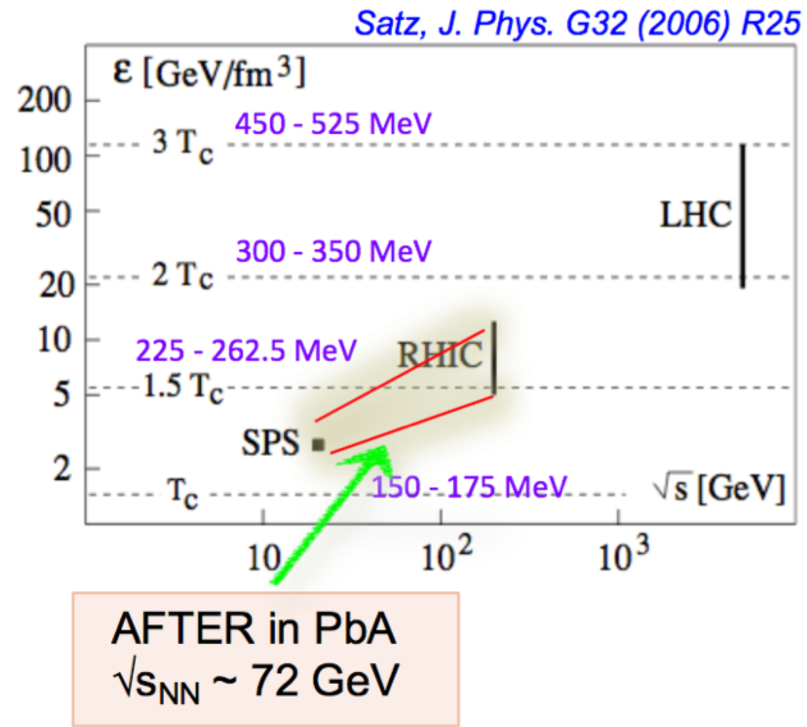
- Several advantages of fixed-target mode:
  - Accessing **high-*x* frontier** ($y_{CM} < 0$ and parton momentum fraction $x > 0.5$)
  - Achieving **high luminosity**
  - Varying **atomic mass number** of the target
  - **Polarising** the target
- This can be realized at LHC in a parasitic mode!

Physics motivations

- Advance our understanding of the **high-*x* gluon, antiquark and heavy-quark content in the nucleon and nucleus and its connection to astroparticles**
- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
- Study the **quark-gluon plasma** between SPS and RHIC energies over a broad rapidity domain







Possible fixed-target implementations

– Internal gas target

- Full LHC proton flux on internal gas target
- Validated by SMOG at LHCb at small gas density
- Storage cell target (HERMES-like) for (un)polarised gases
- Gas-jet target (RHIC polarimeter) for (un)polarised gases

→ high intensity beam on gas target (e.g. $H^{\uparrow}$, $D^{\uparrow}$, $^{3}He^{\uparrow}$, noble gases up to Xe)

– Internal wire/foil target as in HERA-B, STAR

- Beam halo is recycled directly on internal solid targets

– Beam line extracted with a bent crystal

- Beam halo is deflected by a bent crystal
- Bent crystal successfully tested with proton and lead beam at LHC by UA9
- Provides a new facility but civil engineering required

– Beam "split" by a bent crystal

- Beam halo is deflected on a solid target internal to the LHC beam pipe
- Similar fluxes as for beam extraction

→ beam halo on dense target (e.g. Be, Cu, W)

Internal gas and solid target can be coupled with an existing LHC detector

Technical implementations currently discussed within the CERN Physics Beyond Collider working group (http://pbc.web.cern.ch/) with the fixed-target working group evaluating the effect on the LHC beams

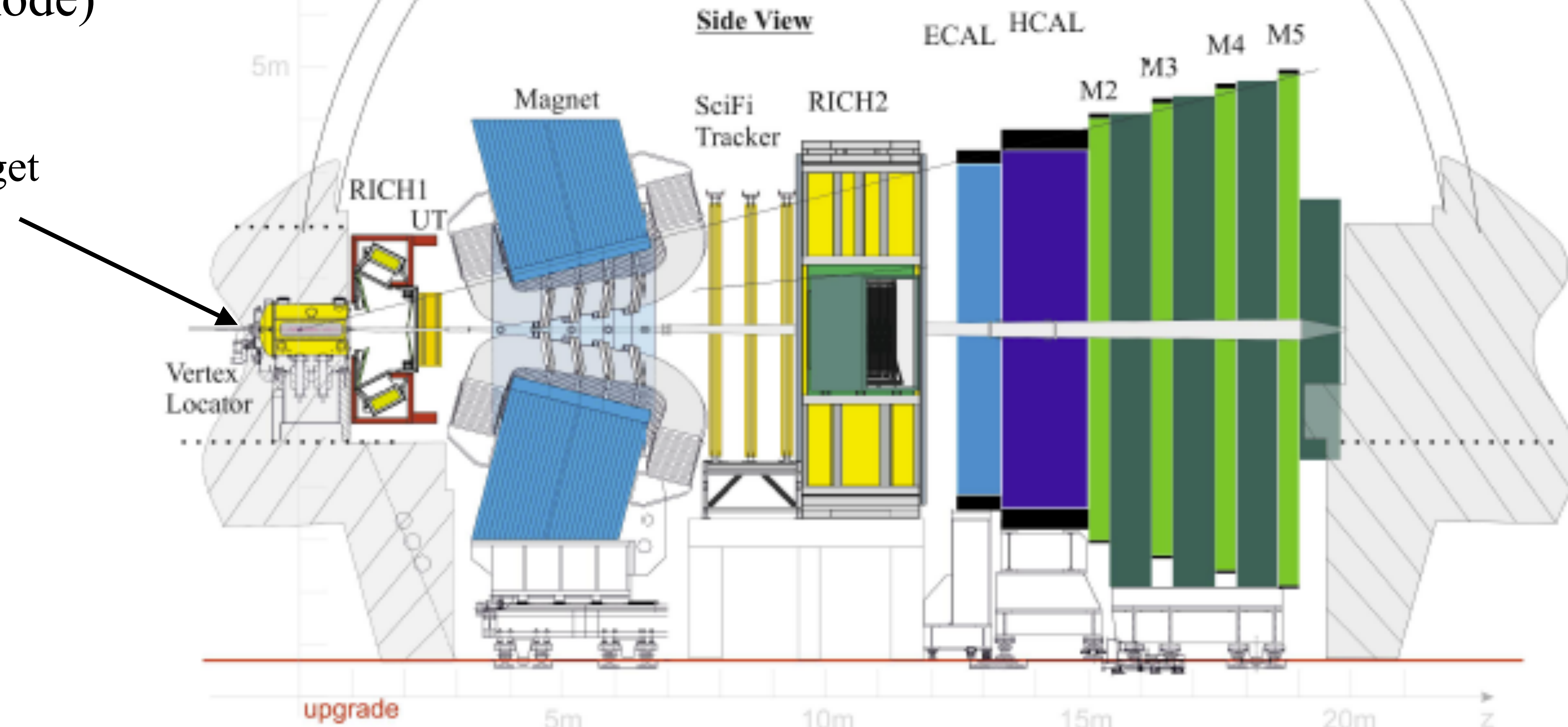
S.Redaelli et al. Proceedings of IPAC2018

Physics Beyond Collider Working Group meeting June 2018: https://indico.cern.ch/event/706741/

LHCb as a fixed-target detector

- Forward detector ($2 < \eta < 5$) with full PID: ideal detector for fixed-target experiment
- Limitation in high-multiplicity event reconstruction (up to ~50% less central events in Pb-Pb collider mode)

gas or solid target



Achievable yearly luminosities:

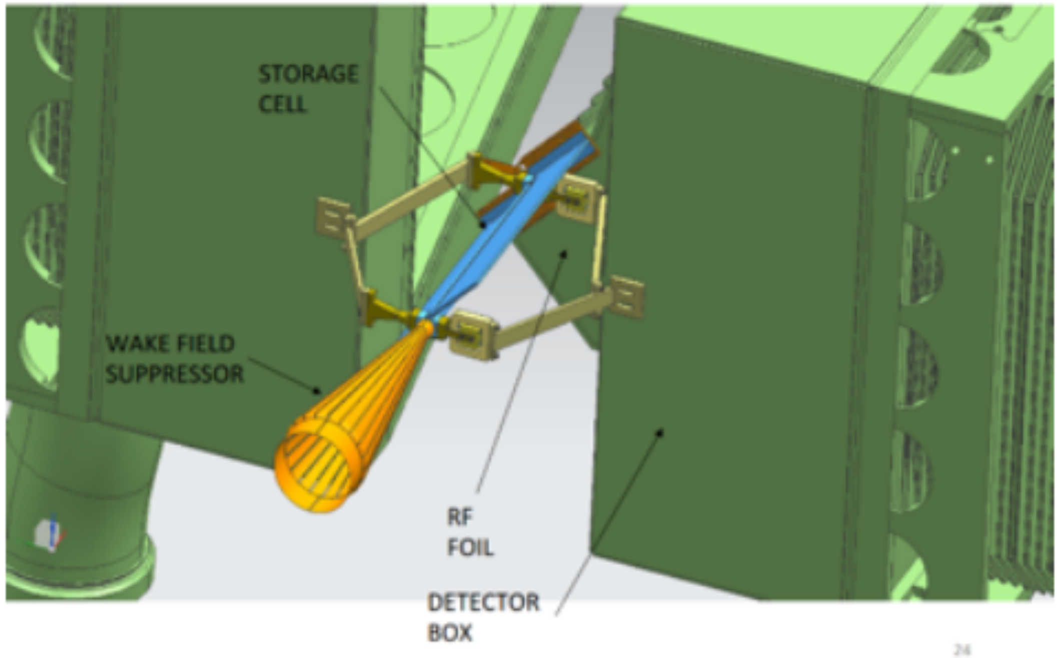
- With gas target (storage cell)
  - $\mathscr{L}_{\text{p-H}\uparrow\text{@115GeV}} = 10/\text{fb}$, $\mathscr{L}_{\text{p-Xe@115GeV}} = 300/\text{pb}$ [$t = 10^7$s]
  - $\mathscr{L}_{\text{Pb-Xe@72GeV}} = 30/\text{nb}$, $\mathscr{L}_{\text{Pb-H}\uparrow\text{@72GeV}} = 100/\text{nb}$ [$t = 10^6$s]
- With beam splitting and 5 mm solid target
  - $\mathscr{L}_{\text{p-W@115GeV}} = 160/\text{pb}$ [$t = 10^7$s]
  - $\mathscr{L}_{\text{Pb-W@72GeV}} = 3/\text{nb}$ [$t = 10^6$s]

Projects under investigation in LHCb

Several investigations/projects:

- Unpolarized storage cell gas target (SMOG2)
- Polarized storage cell gas target
- Beam split and internal W solid target (with a second crystal) for Electromagnetic Dipole Moment of charmed baryons

Unpolarised storage cell: closed position view



SMOG2 internal storage cell target:

- Openable storage cell attached to the VELO for unpolarised gas
- Installation foreseen in LS2

P. DiNezza Annual Workshop PBC, November 2017

Density

- Gas pressure up to 100 × SMOG: P ~ 10^{-5} mbar

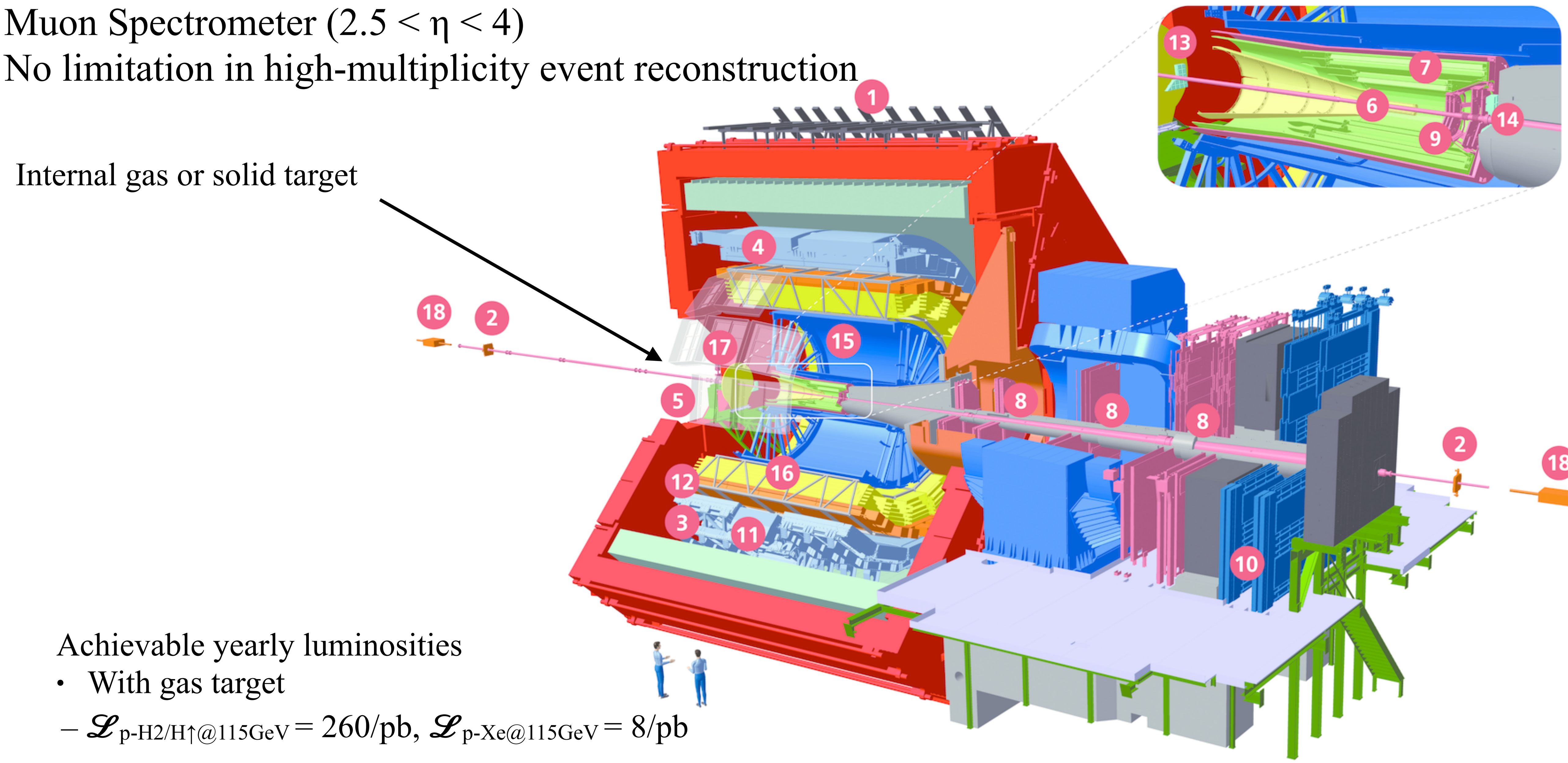
Possible systems and luminosities in Run3

- p-H_2, p-D_2, p-Ar, Pb-Ar, …
- $\mathscr{L}_{\text{p-A@115GeV}} = 30$/pb
- $\mathscr{L}_{\text{Pb-Ar@72GeV}} = 5$/nb (+ $\mathscr{L}_{\text{p-Ar@72GeV}} = 1$/pb)
- Luminosity increase by up to an order of magnitude could be feasible

G.Graziani Annual Workshop PBC, June 2018

ALICE in a fixed-target mode

- Central Barrel (|η|< 0.9) with full PID
- Muon Spectrometer (2.5 < η < 4)
- No limitation in high-multiplicity event reconstruction



Achievable yearly luminosities

- With gas target
  - $\mathscr{L}_{\text{p-H2/H}\uparrow\text{@115GeV}} = 260/\text{pb}$, $\mathscr{L}_{\text{p-Xe@115GeV}} = 8/\text{pb}$
  - $\mathscr{L}_{\text{Pb-Xe@72GeV}} = 8/\text{nb}$
- With beam splitting and at most 5 mm solid target
  - $\mathscr{L}_{\text{p-W@115GeV}} = 6/\text{pb}$
  - $\mathscr{L}_{\text{Pb-W@72GeV}} = 3/\text{nb}$

Fixed-target investigation in ALICE

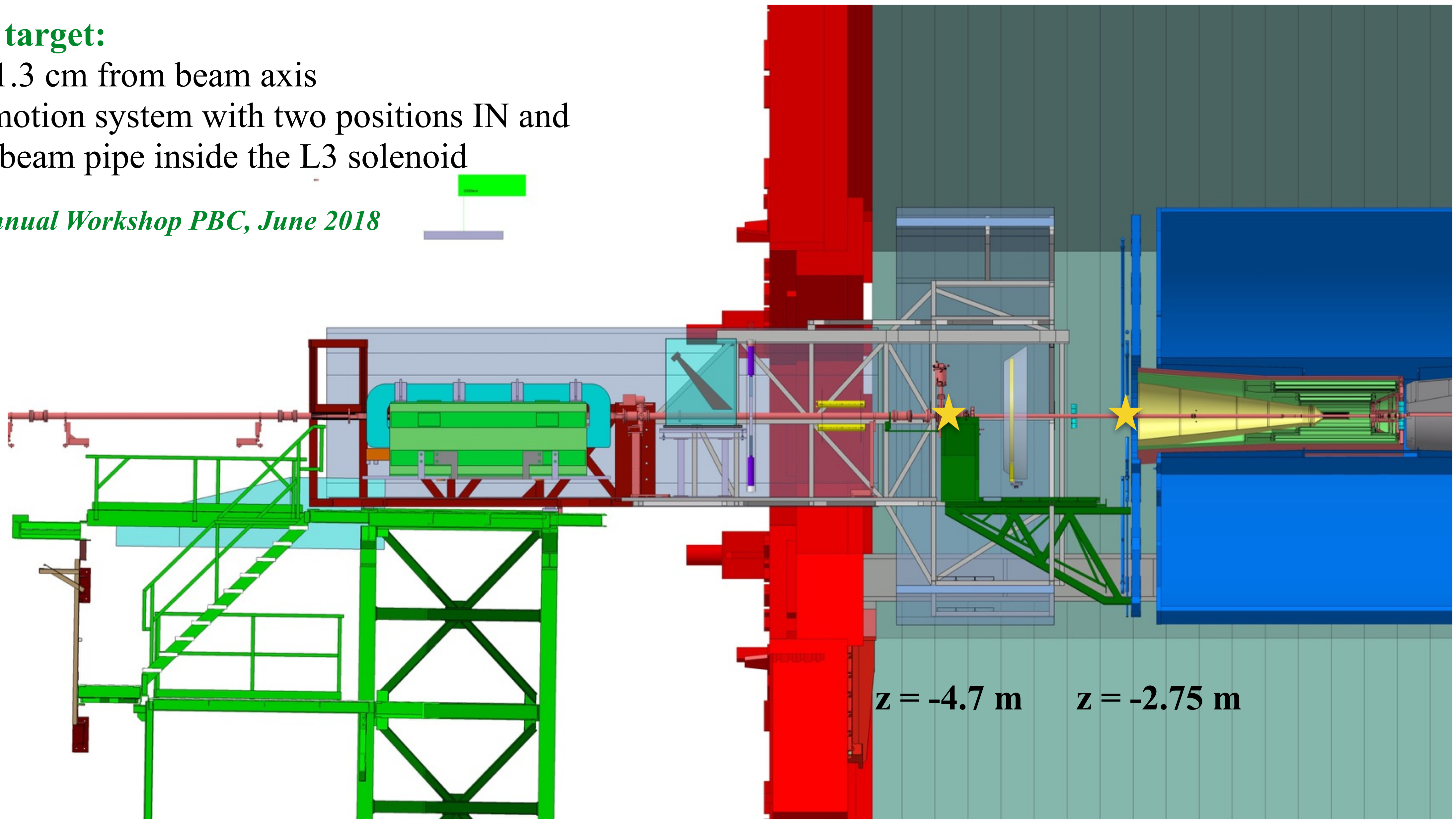
Current investigation:

- Beam split option with crystal and internal solid target

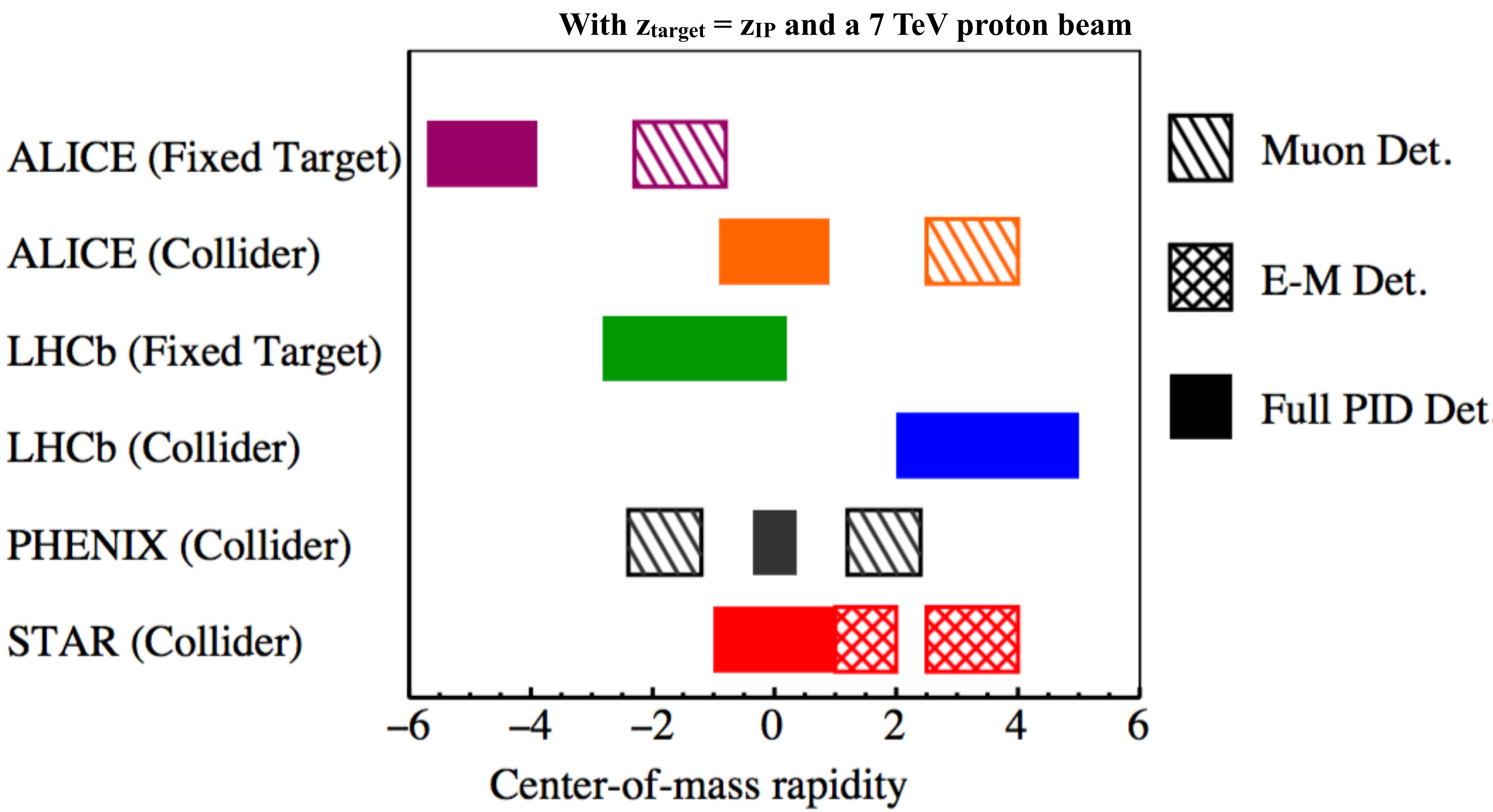
Internal solid target:

- located at ~1.3 cm from beam axis
- Pneumatic motion system with two positions IN and OUT of the beam pipe inside the L3 solenoid

C.H. Annual Workshop PBC, June 2018



Acceptance in center-of-mass rapidity



In a fixed-target mode:

– ALICE Central Barrel covers very backward rapidity and Muon Spectrometer covers rapidity interval towards mid-rapidity

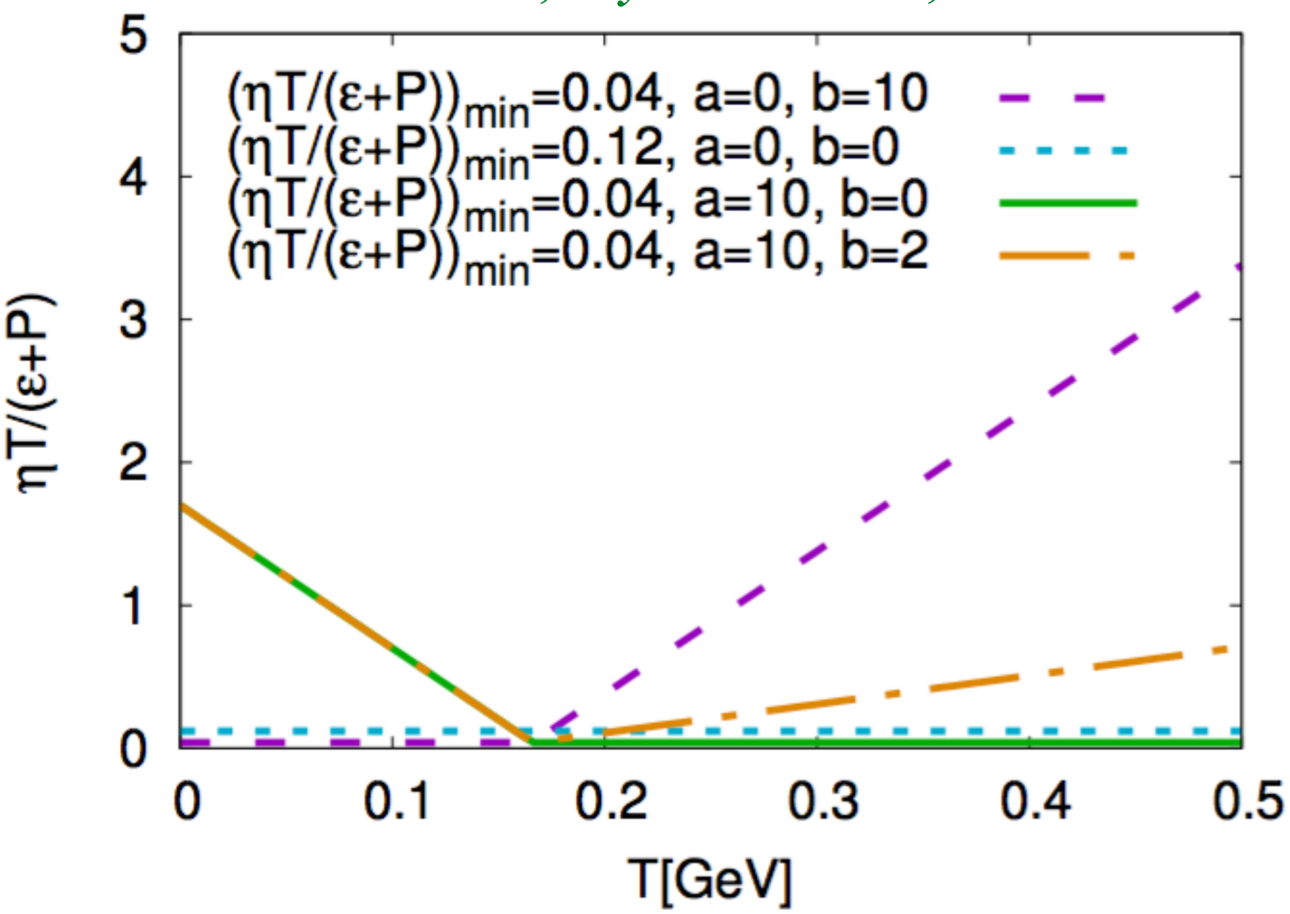
– LHCb: wide rapidity range starting from $y_{cms} \sim 0$

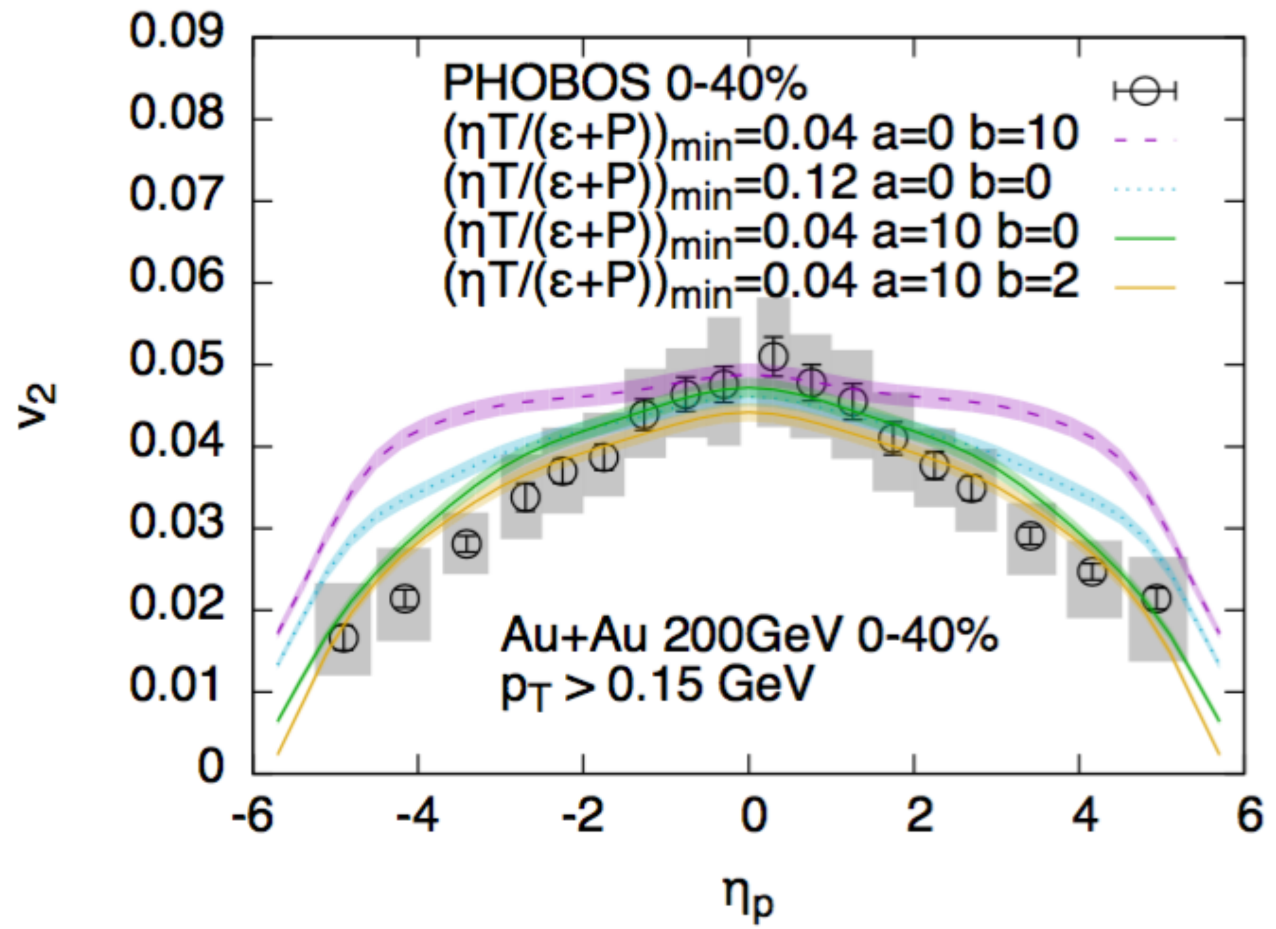
A selection of physics opportunities and projected performances

More in AFTER@LHC review paper arXiv:1807.00603

Identified charged particles towards large rapidity

G. Denicol et al, Phys.Rev.Lett. 116, 212301





– Particle yields and v_n vs rapidity: useful tool to access the temperature dependence of the shear viscosity

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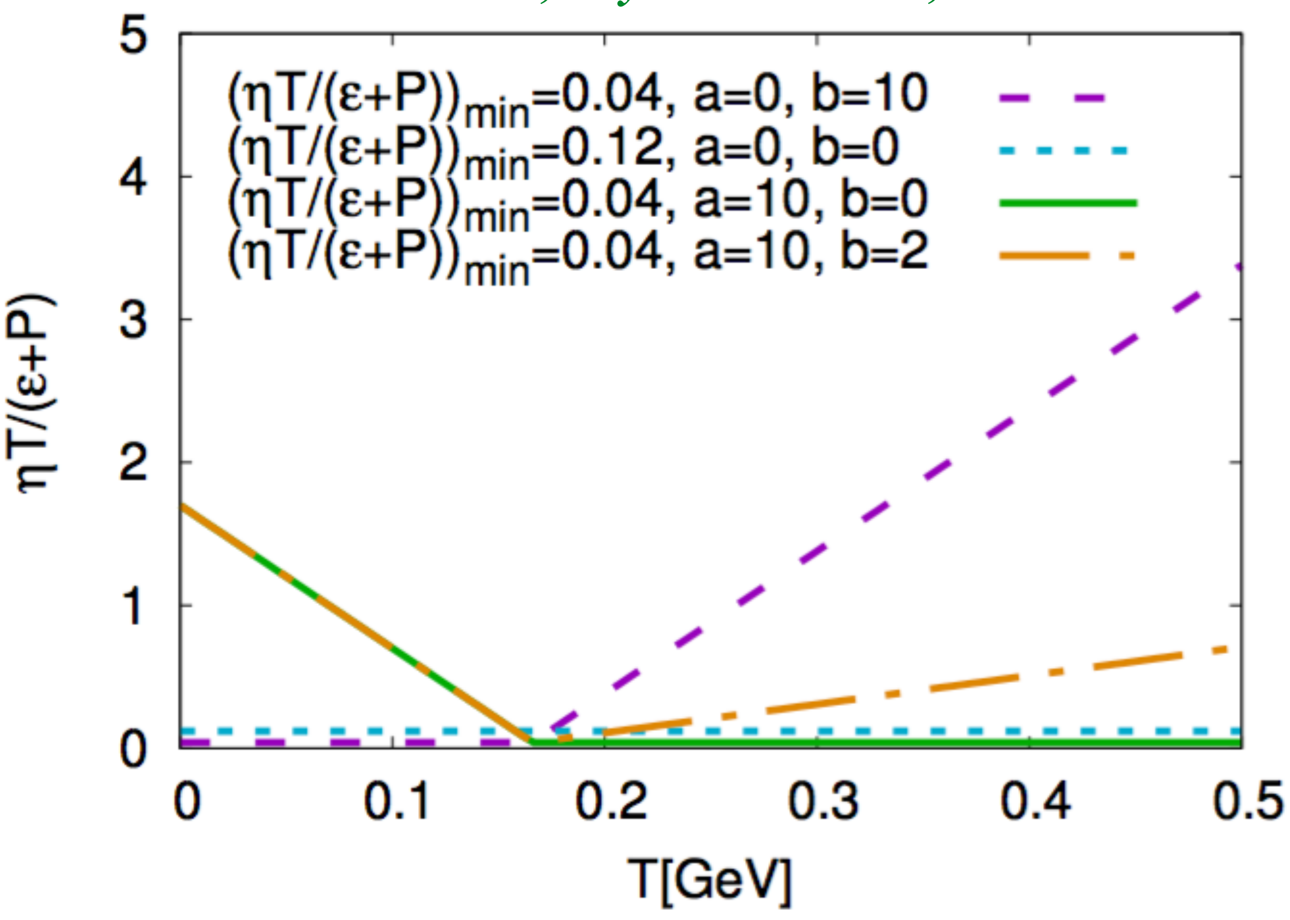
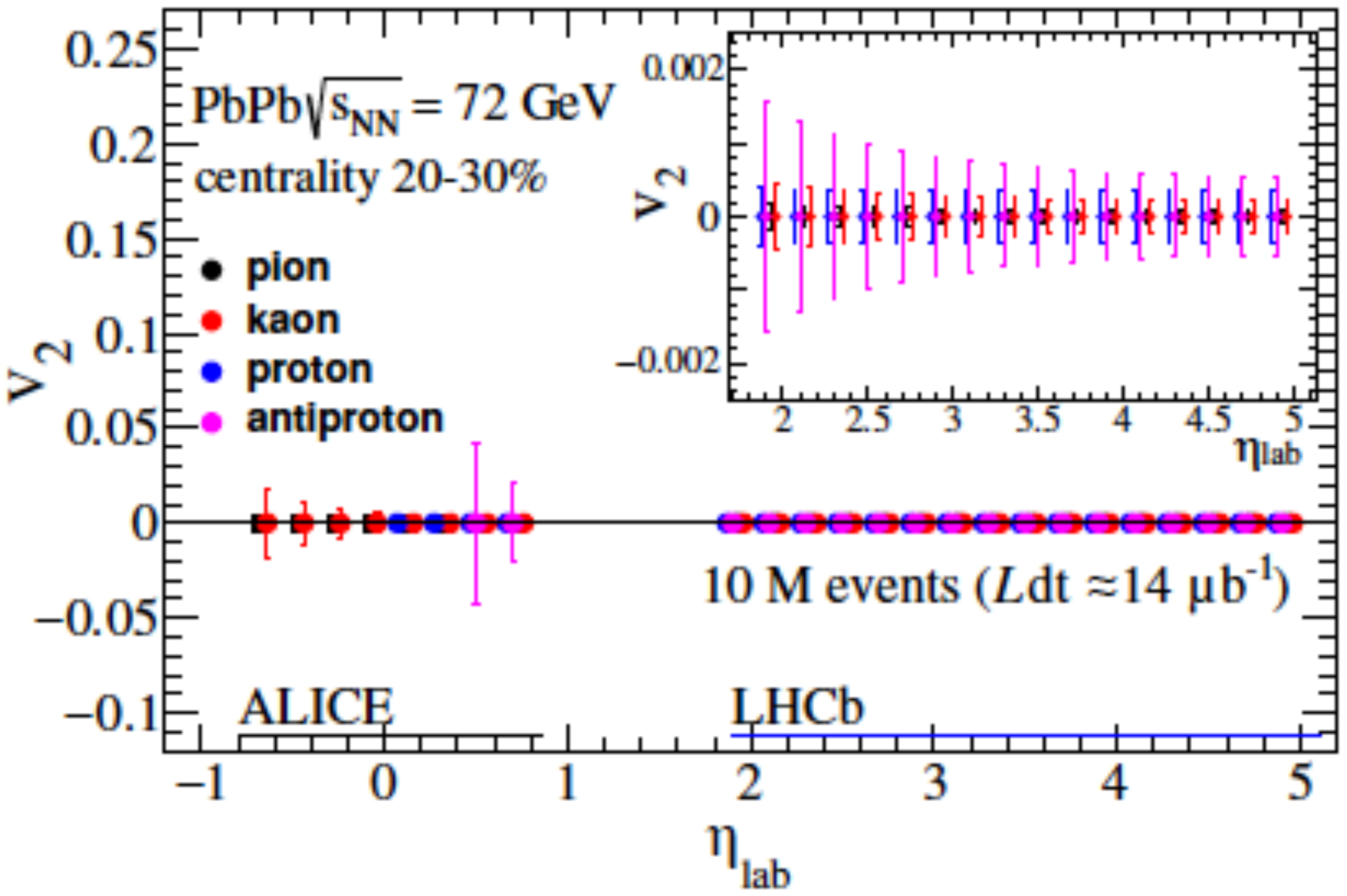


AFTER@LHC study group
B.Trzeciak et al.Few-Body Syst (2017) 58:148

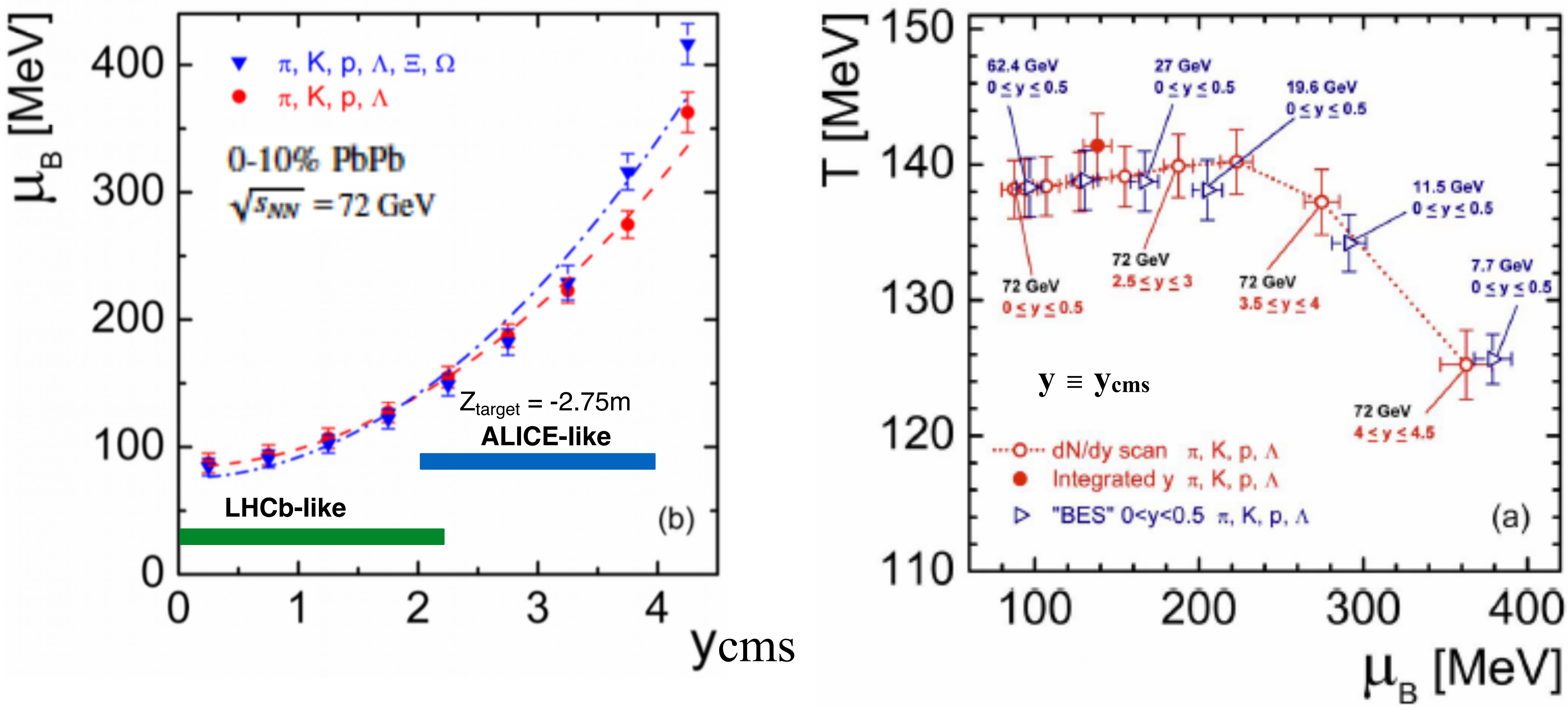


– Particle yields and v_n vs rapidity: useful tool to access the temperature dependence of the shear viscosity

– Broad rapidity coverage of identified particles if both LHCb and ALICE Central Barrel are combined

Rapidity scan of the QGP phase diagram

V.Begun et al. Phys.Rev.C 98, 034905 (2018) (see also *I.Karpenko arXiv:1805.11998* based on vHLLE+UrQMD)



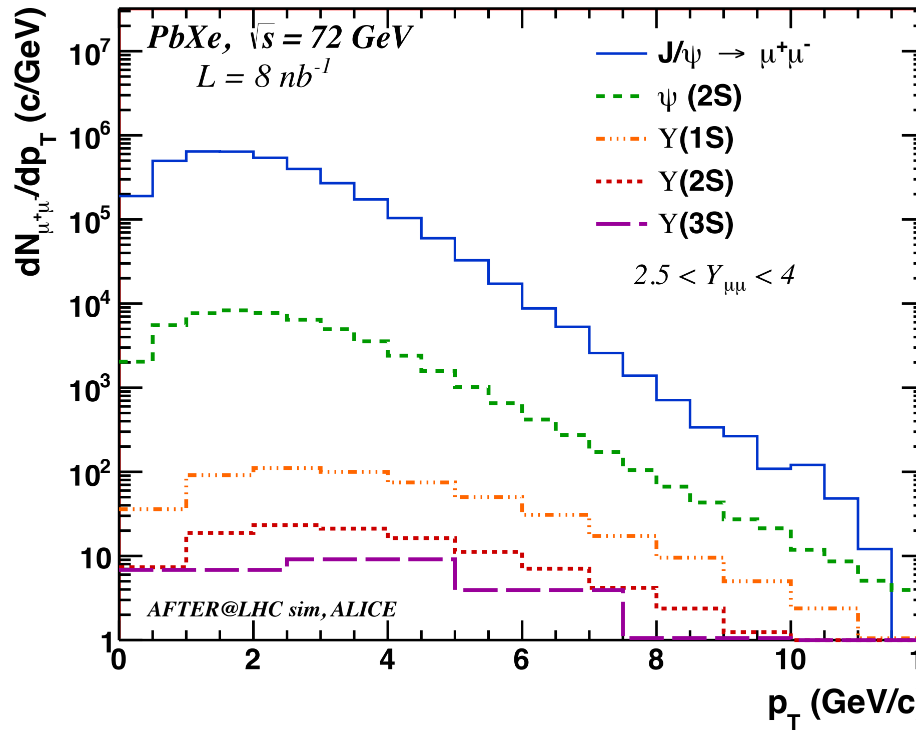
– System temperature at freeze-out and baryonic chemical potential (μ_B) extracted from a fit of identified hadrons dN/dy by hadron resonance gas (HRG) model

– Measurements over a broad rapidity range provides a scan of μ_B at fixed collision energy (similar to the μ_B scan performed at RHIC with different beam energy)

Probing QGP with quarkonia

- Thermodynamic properties of the QGP with quarkonium family in PbA
- Less combinatorial background at low energy: probably easier to access χ_c and η_c
- Very good precision expected on open heavy-flavor to complement the quarkonium measurements
- Cold nuclear matter effects to be studied in pA

ALICE-like



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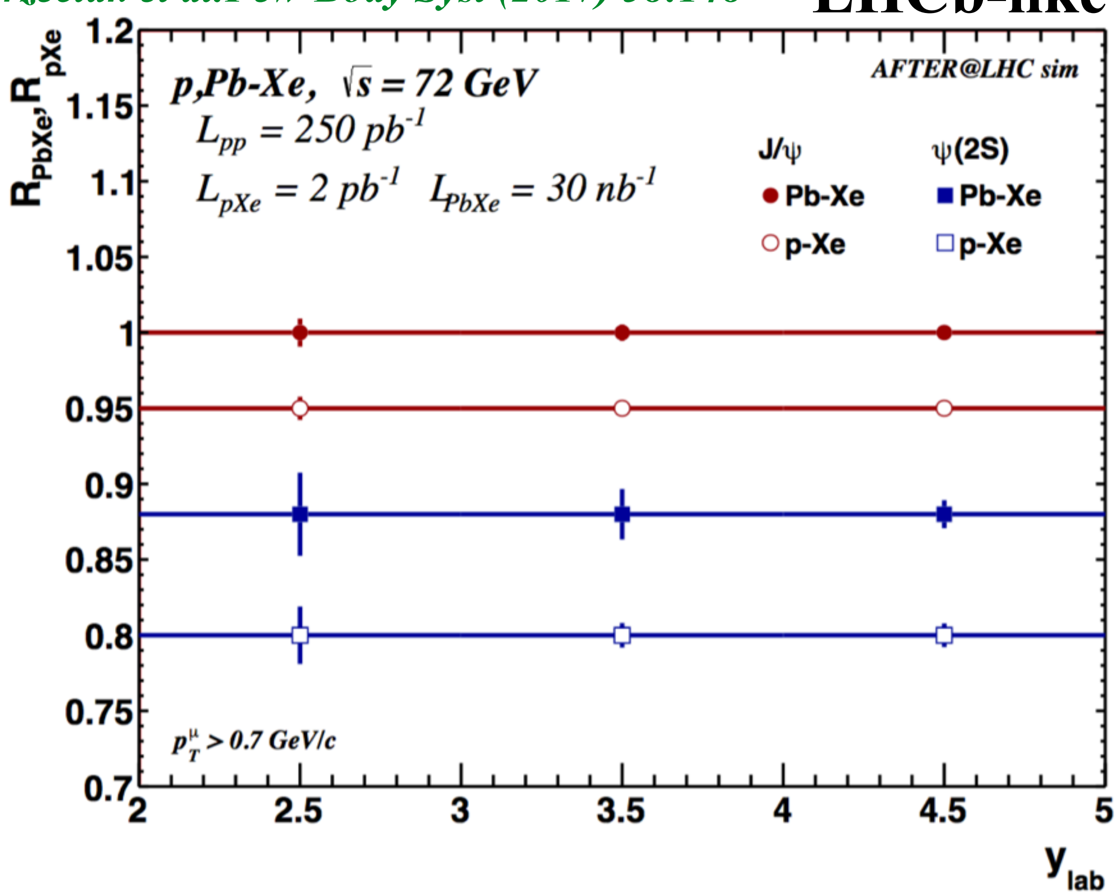
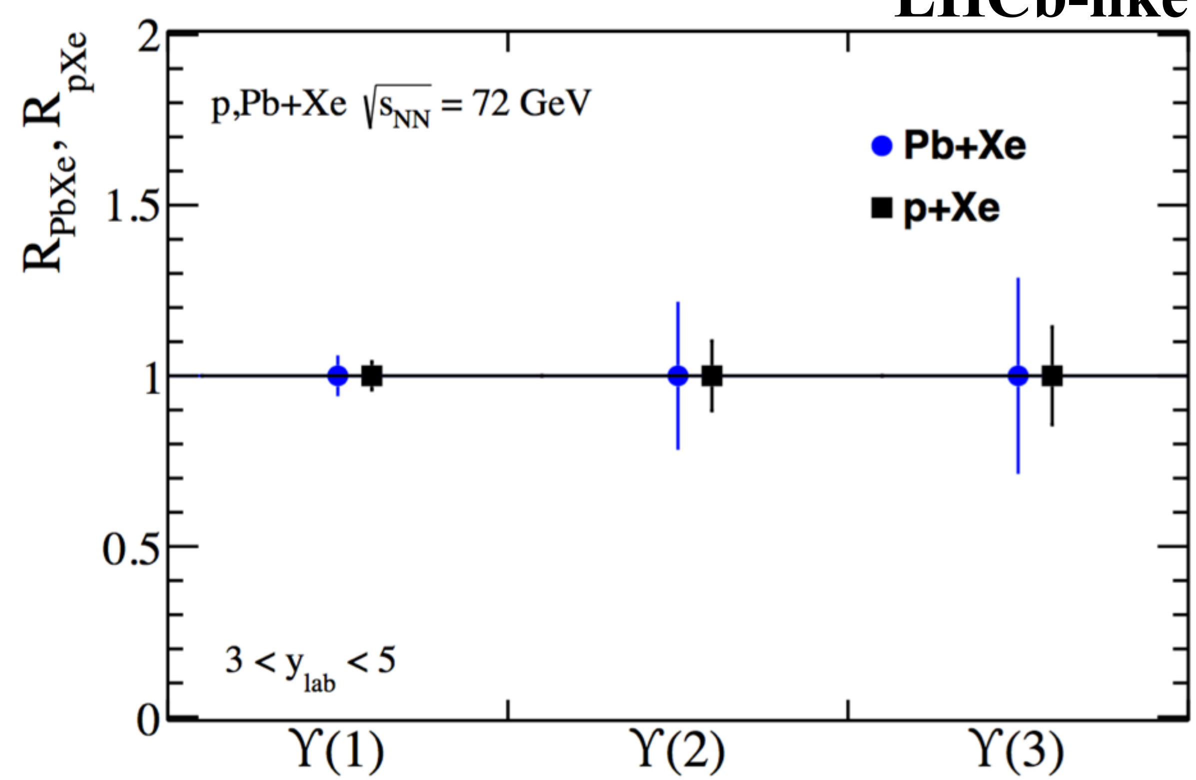
LHCb-like



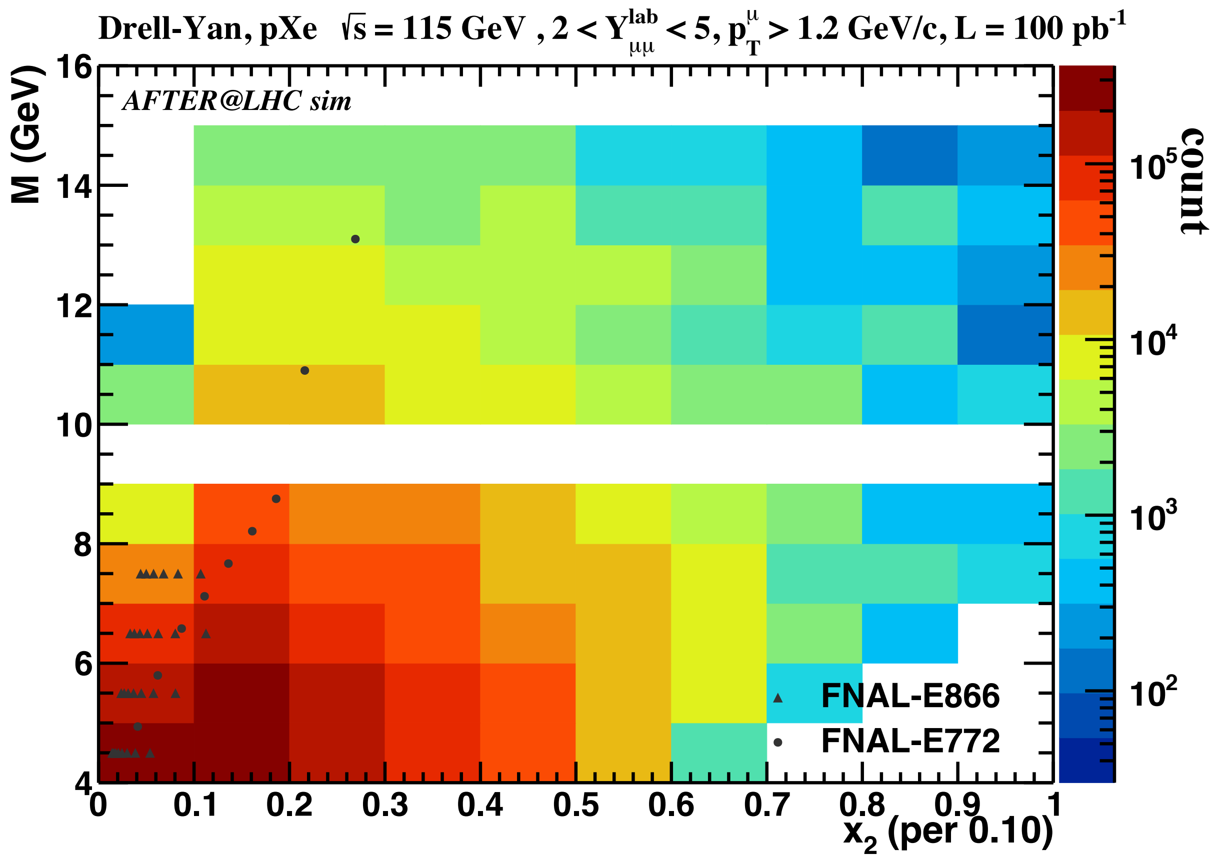
LHCb-like



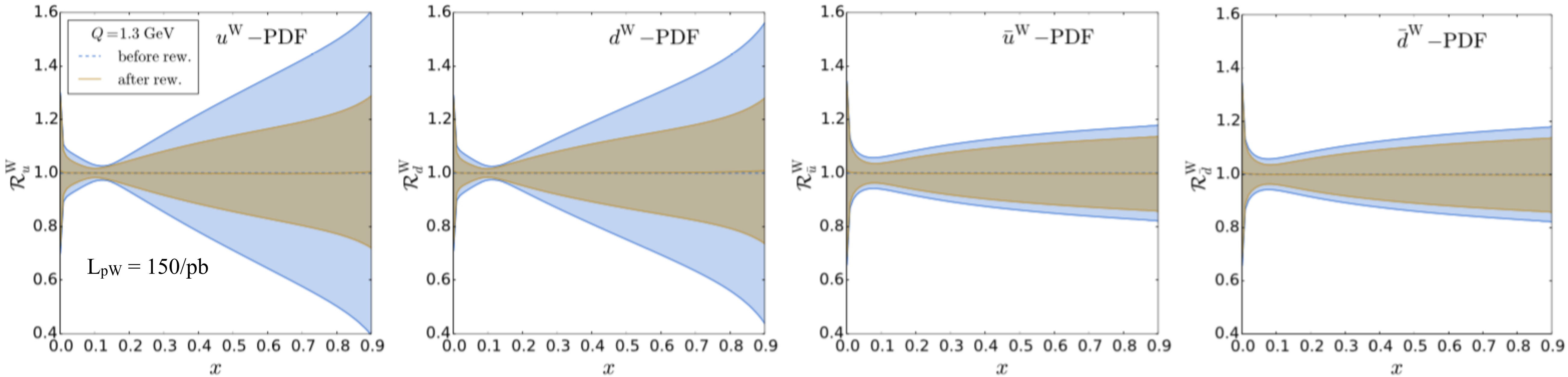
Nuclear structure with Drell-Yan

- Much larger kinematical coverage in pA@115 GeV than Drell-Yan Fermilab measurements used for nPDF fit
- Access to large quark x-value $\rightarrow$ 1 at low mass scales
- Impact of Drell-Yan measurements on nPDF evaluated by using pseudo data on nuclear ratio R_{pA} (example with L=150/pb for pW@115 GeV and L=10/fb for pp): significant decrease of the uncertainties for u and d quark nPDF at large x
- Gluon content of nucleus can be probed as well with D and B mesons and Quarkonia

LHCb-like

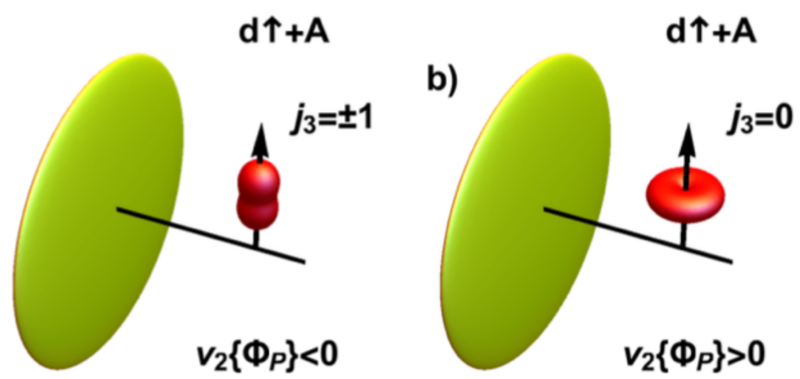


AFTER@LHC study group arXiv:1807.00603



Other opportunities: collective-like effects in Pb-D↑

- Intrinsic deformation of polarized (transversally) deuteron → non-zero v_2 in case of collective dynamics (hydro, transport models) wrt transverse target polarisation axis in Pb+D↑ for charged particles
- No azimuthal asymmetries expected from the correlation from gluon dynamics (CGC model): powerful probe to discriminate among models



P. Bozek and W. Broniowski. arXiv:1808.09840

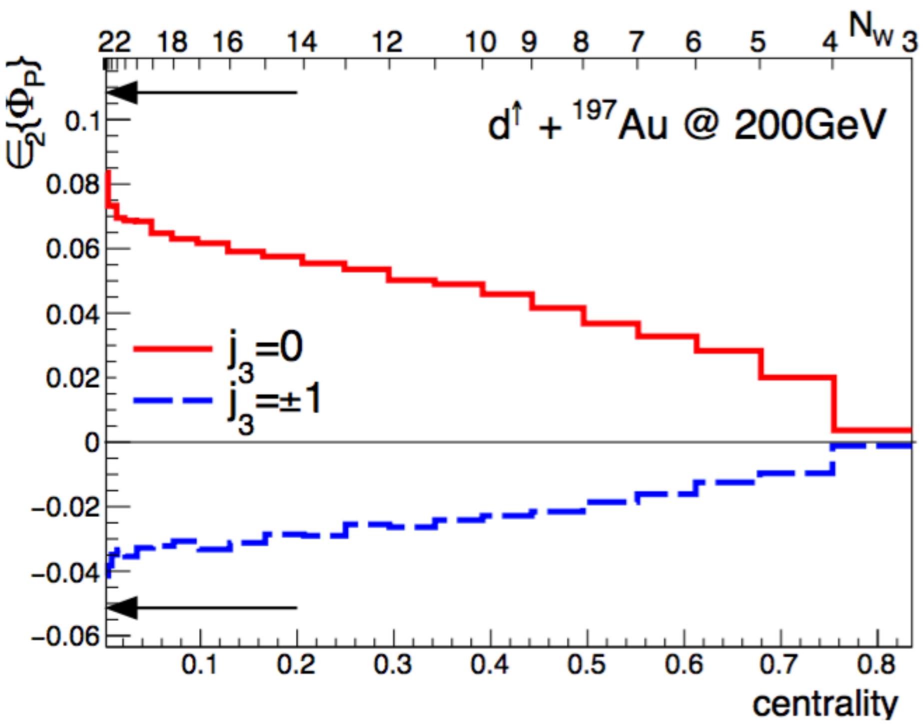


FIG. 3. Ellipticities of the fireball formed in polarized d+Au collisions at the energy of $\sqrt{s_{NN}} = 200$ GeV. The lower coordinate axis shows the centrality as defined via the produced entropy S. The top coordinate axis shows the corresponding number of the wounded nucleons. The arrows indicate the ellipticities of the modulus squared of the deuteron wave function of Eq. (8).

Summary

- Three main physics motivations for a high-luminosity fixed-target program at the LHC:
  - **High-*x* frontier**: nucleon and nuclear structure and connections with astroparticles
  - **Nucleon spin** and the transverse dynamics of partons
  - **Quark Gluon Plasma** over a broad rapidity domain

- Two promising technical implementations with large luminosities:
  - **internal gas-target (gas-jet or storage cell)**
  - beam halo extraction with **a bent crystal on an internal solid target**

- Based on fast simulations, the AFTER@LHC study group has made Figure of Merits for ALICE and LHCb in a fixed-target mode, see ***arXiv:1807.00603***: these studies support a full physics program

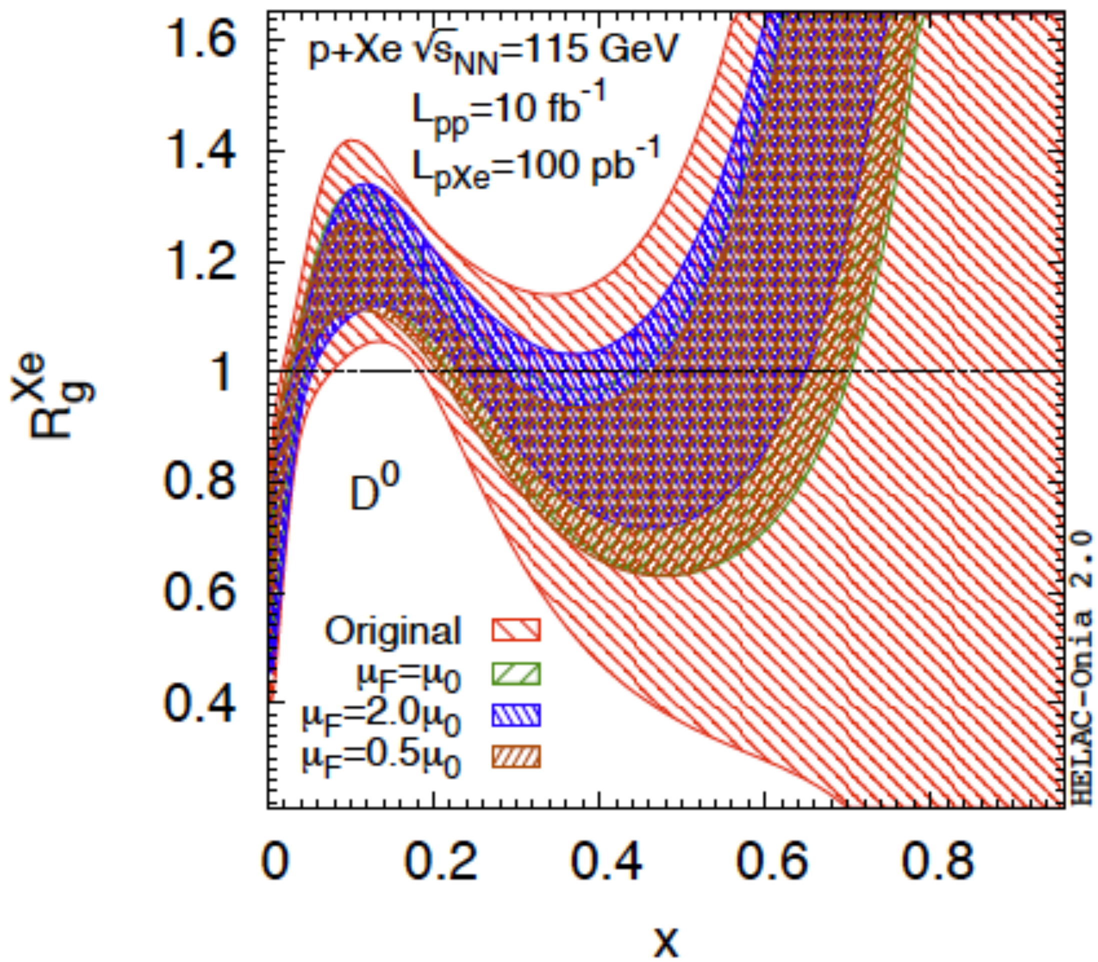
- Investigations/projects in **ALICE** and **LHCb** ongoing for the implementation of fixed-target setup within the CERN Physics Beyond Collider working group

- European Hadron Physics proposal STRONG-2020 funded. One work package on fixed-target experiments at LHC [FTE@LHC Spokespersons: Pasquale Di Nezza, C.H] with studies/R&D of fixed-target implementation in ALICE and LHCb and phenomenological/theoretical studies.

backup slides

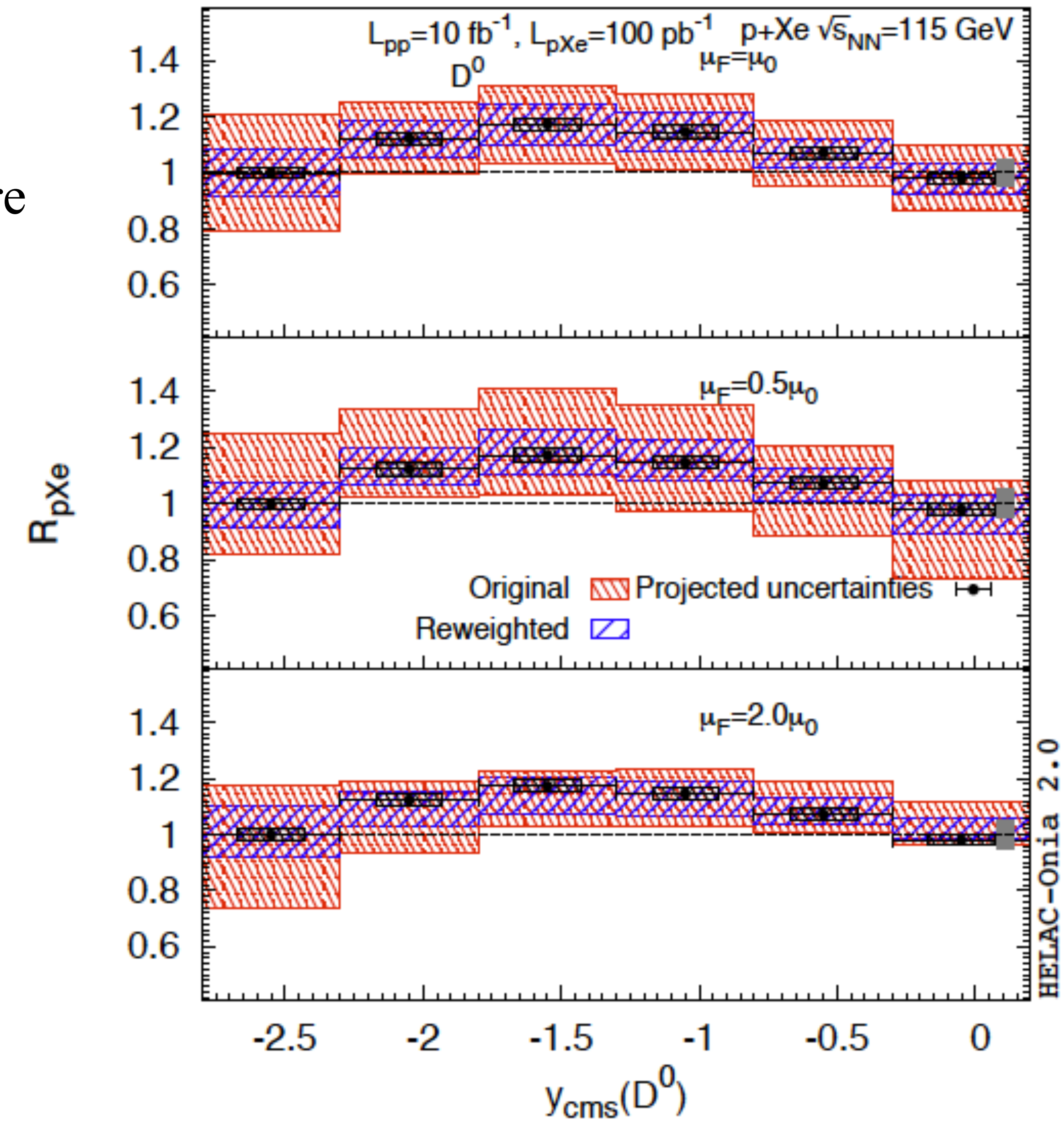
Probing high-x gluons on nucleus

- Gluon nuclear pdf almost unknown at large $x > 0.1$: anti-shadowing, EMC effect?
- Impact of D (also B, J/ψ and ϒ) measurements on nPDF evaluated by using pseudo-data on R_{pA}. Projections done assuming other nuclear effects are under control.
- Large reduction of the gluon nPDF uncertainty: unique constraints at large x and low scales

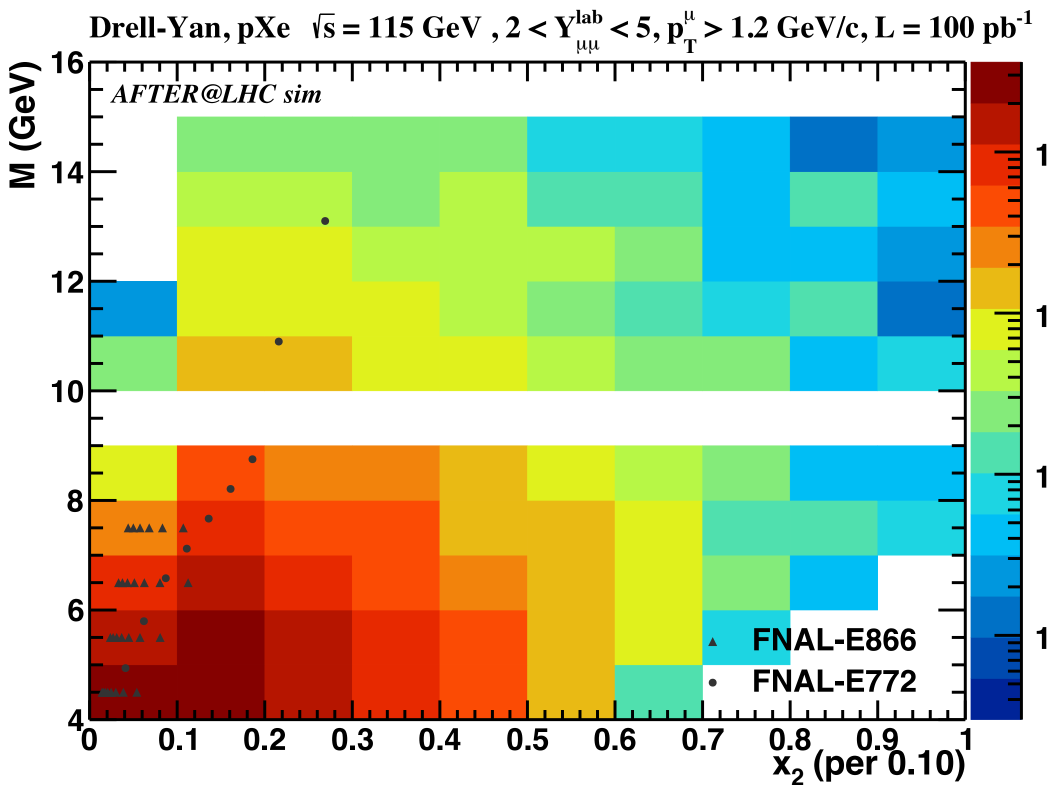


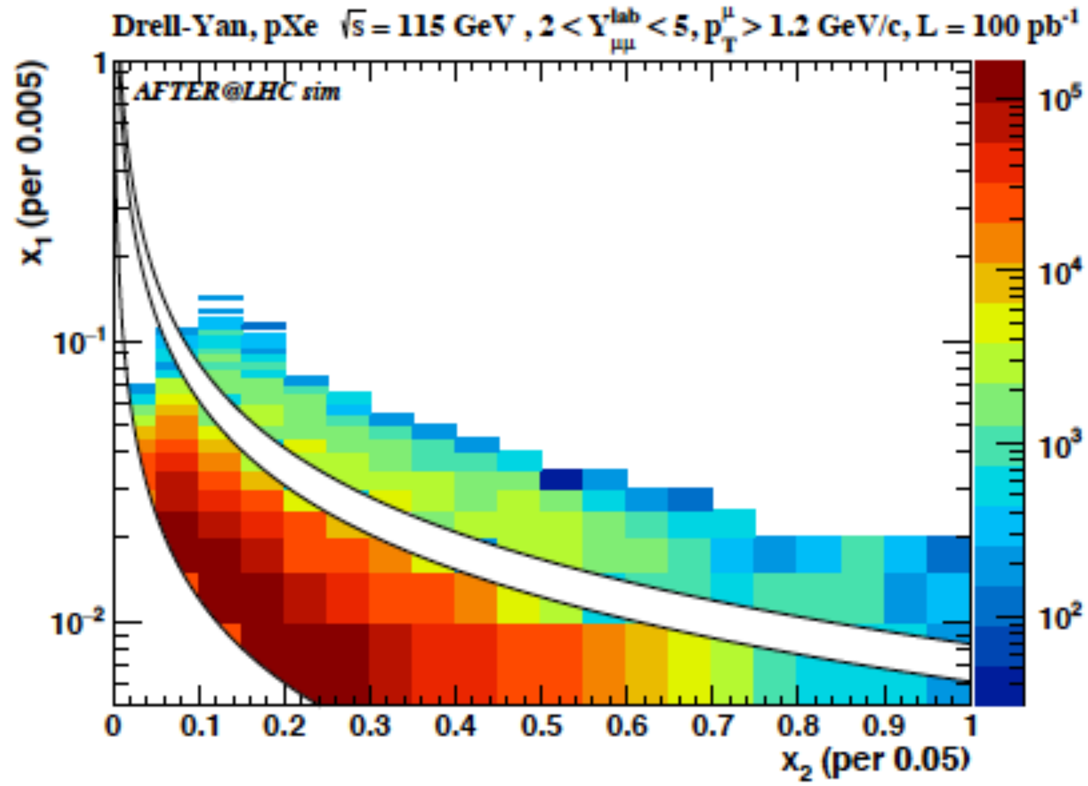
LHCb-like

AFTER@LHC study group arXiv:1807.00603

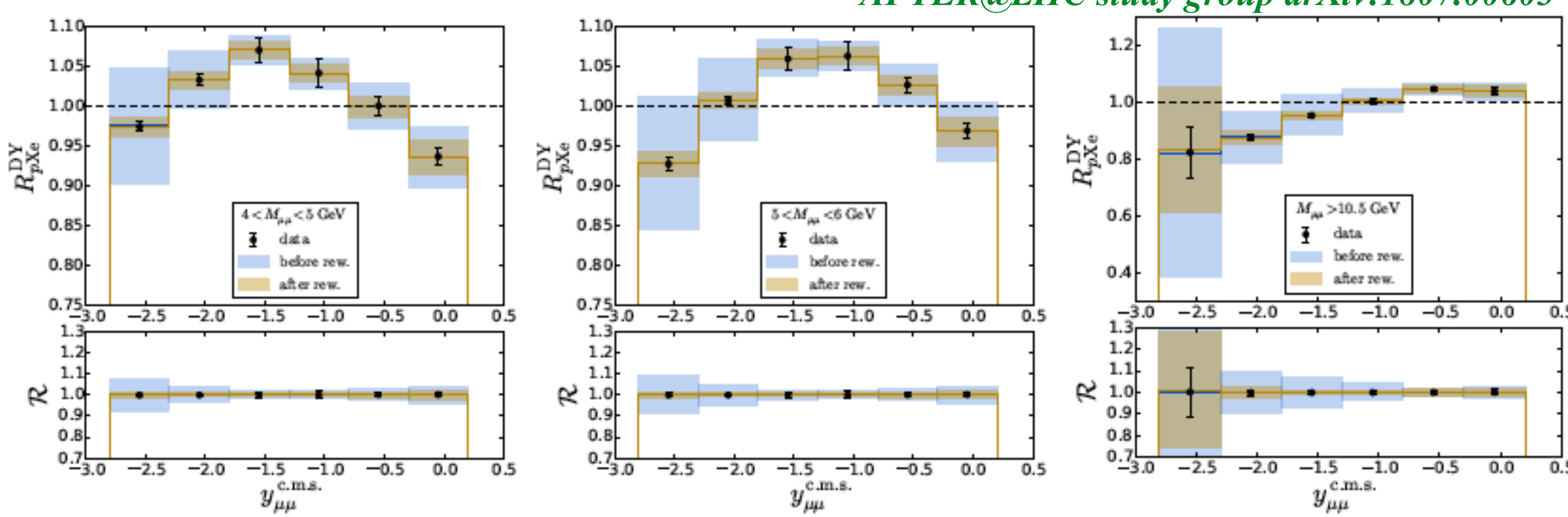


Drell-Yan measurements in pA





AFTER@LHC study group arXiv:1807.00603

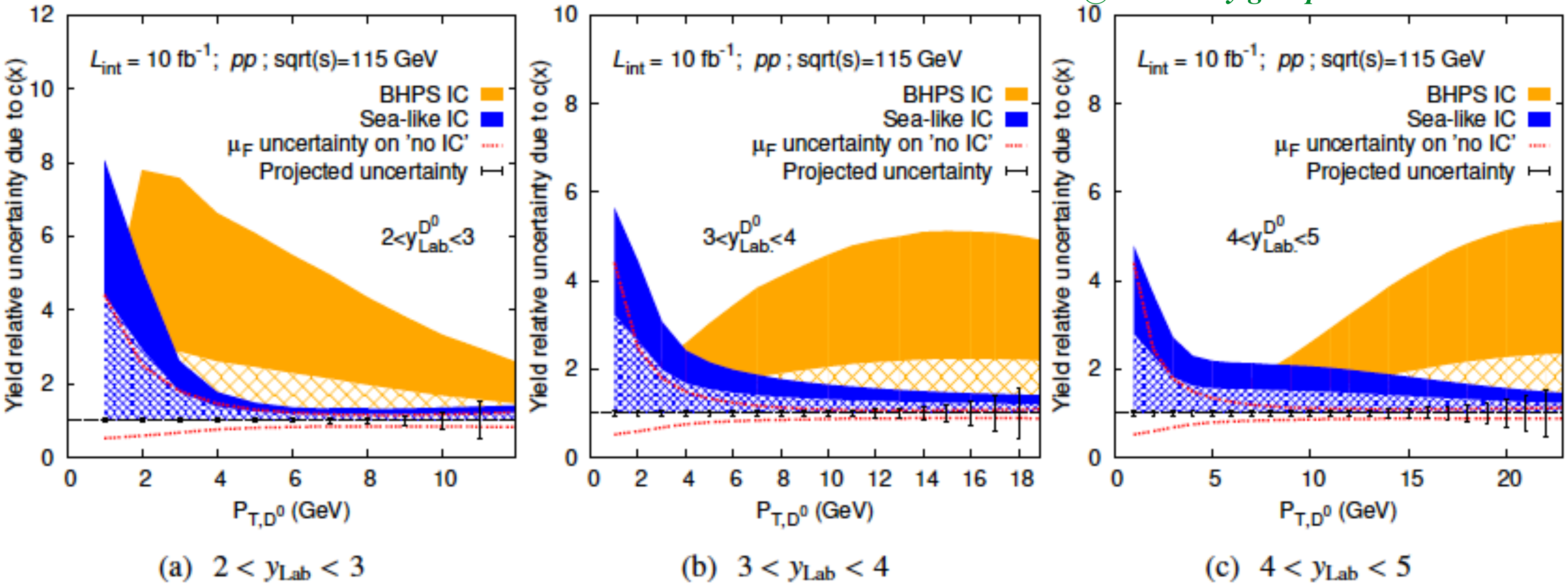


(a) $4 < M_{\mu\mu} < 5$ GeV (b) $5 < M_{\mu\mu} < 6$ GeV (c) $10.5 < M_{\mu\mu}$ GeV

Figure 20: Projection of the statistical uncertainties on the R_{pA} for Drell-Yan pair production in pXe collisions in different mass ranges compared to the uncertainties encoded in nCTEQ15 nPDFs (in blue 'before rew.'), which are representative of typical nPDF uncertainties. The projected statistical uncertainties arise from the subtraction of the uncorrelated MB background (based on the like-sign technique) and assuming the yearly integrated luminosities of $\mathcal{L}_{pp} = 10$ fb^{-1} and $\mathcal{L}_{pXe} = 100$ pb^{-1}. The brown band ('after rew.') correspond to the uncertainty of the R_{pA} after a Bayesian reweighting of the nPDF using the corresponding pseudo-data.

Open charm measurements in pp

AFTER@LHC study group arXiv:1807.00603



(a) $2 < y_{Lab} < 3$ (b) $3 < y_{Lab} < 4$ (c) $4 < y_{Lab} < 5$

Figure 18: Impact of the uncertainty on the charm content of the proton on the D^0 yield as function of p_T compared to projected uncertainties from the measurement of the D^0 yield in pp collisions at $\sqrt{s}$ = 115 GeV in the LHCb acceptance. The orange (resp. blue) zones correspond to yields computed with charm PDFs including BHPS-like (resp. sea-like) IC [193, 194]. The filled areas correspond to yields computed with up to $\langle x_{c\bar{c}} \rangle = 2\%$ (resp. 2.4%) and the hashed areas up to $\langle x_{c+\bar{c}} \rangle = 0.57\%$ (resp. 1.1%). The dashed red curves indicate the factorisation scale (μ_F) uncertainty on the 'no-IC' yield obtained by varing μ_F between $m_T/2$ and $m_T/2$ with $m_T^2 = m_c^2 + p_T^2$. Systematic uncertainties of 5% are included and the statistical uncertainty for the background subtraction is assumed to be negligible which is reasonable assuming LHCb-like performances, see [101]. The rates were computed by assuming an average efficiency of $\langle \varepsilon \rangle = 10\%$ and $\mathcal{B}(D^0 \to K\pi) = 3.93\%$.

Testing factorization of initial state effects with Drell-Yan

- Drell-Yan lepton pairs do not interact with the formed medium: **ideal probe of the initial state effects in AA**
- Background contributions to lepton pairs at low mass:
  - combinatorial background challenging but decrease with energy
  - open heavy flavour contribution is low specially at backward rapidity ($2 < y_{lab} < 3$)
- Drell-Yan at **low mass scale** seems accessible in AA and other systems
- Allow to test the **factorization of initial effects from pA to AA**

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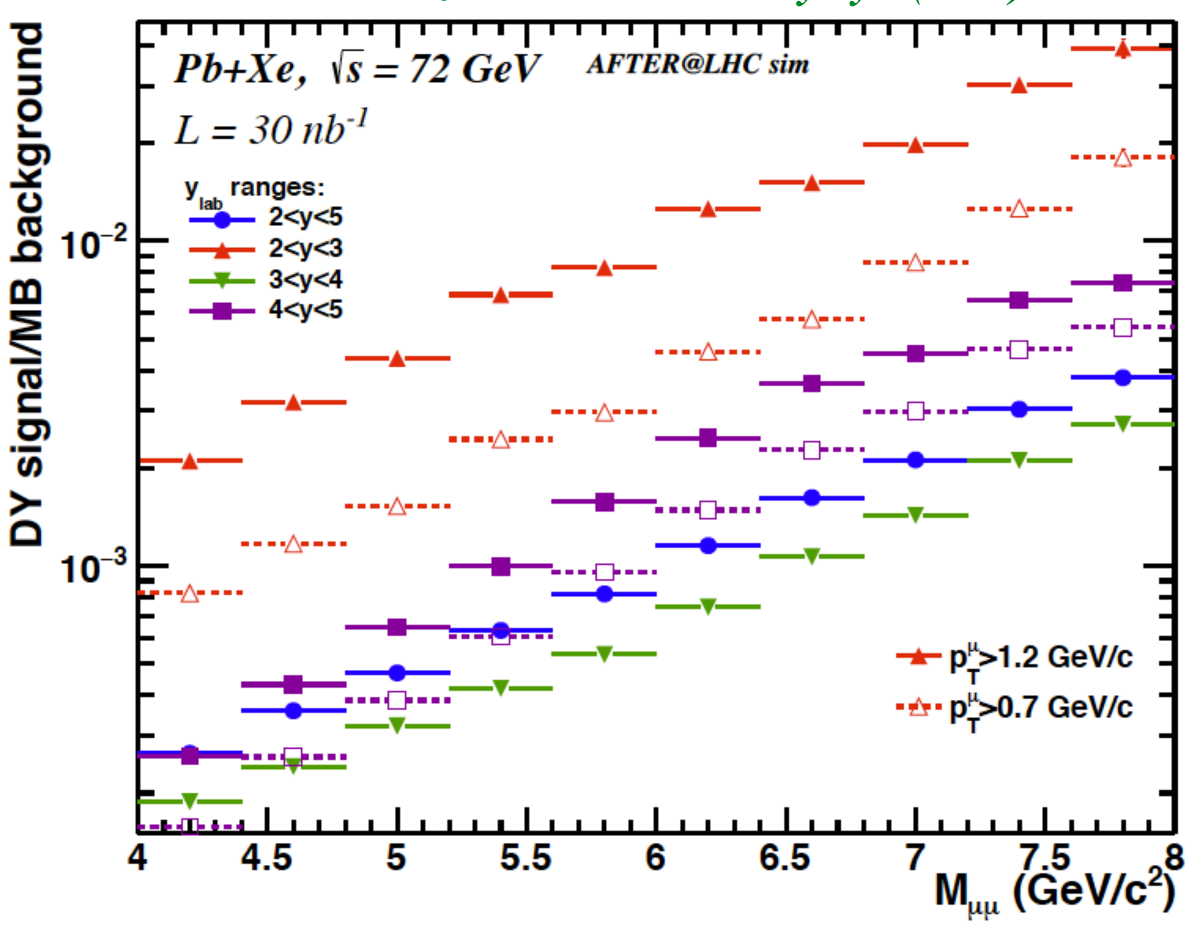
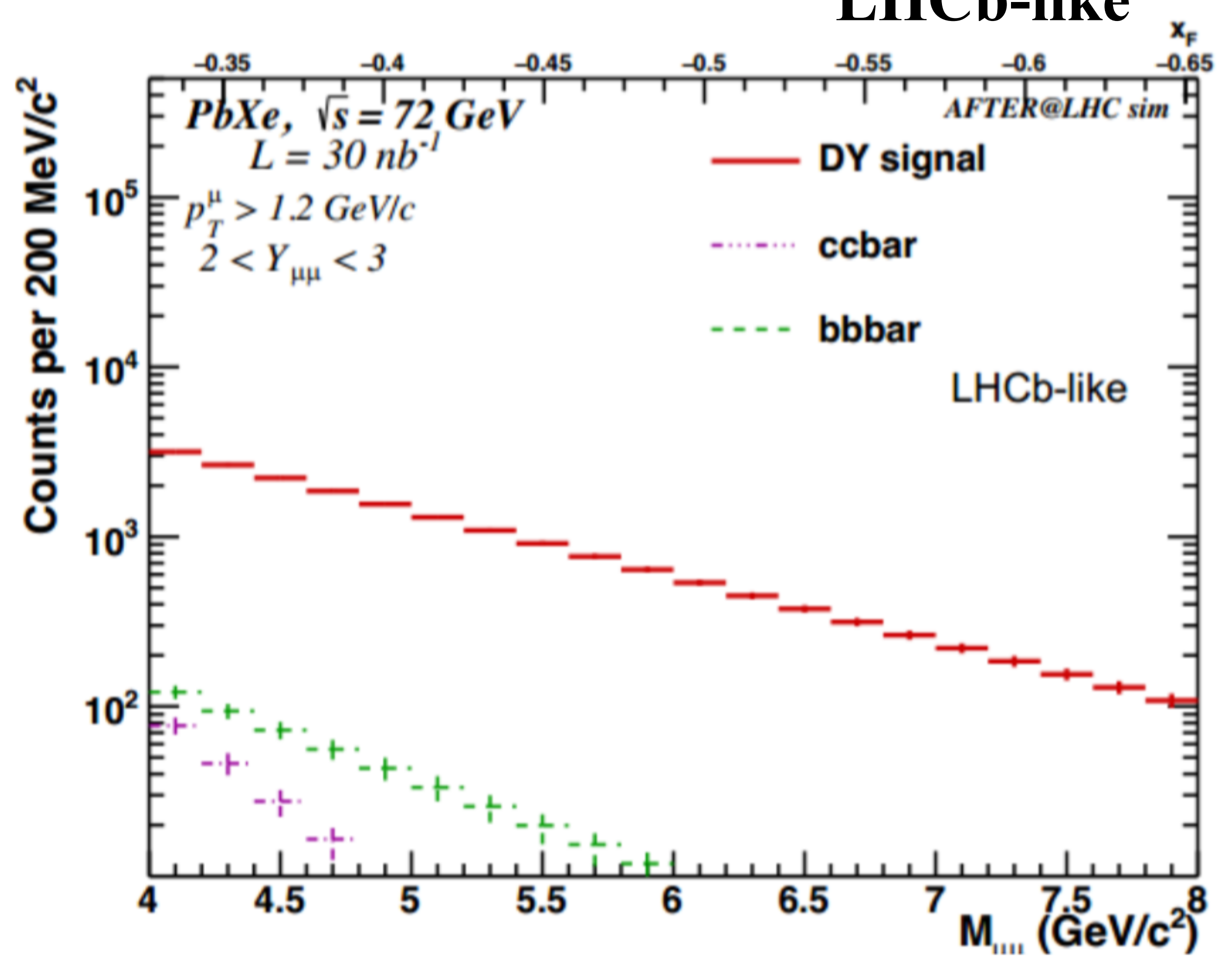
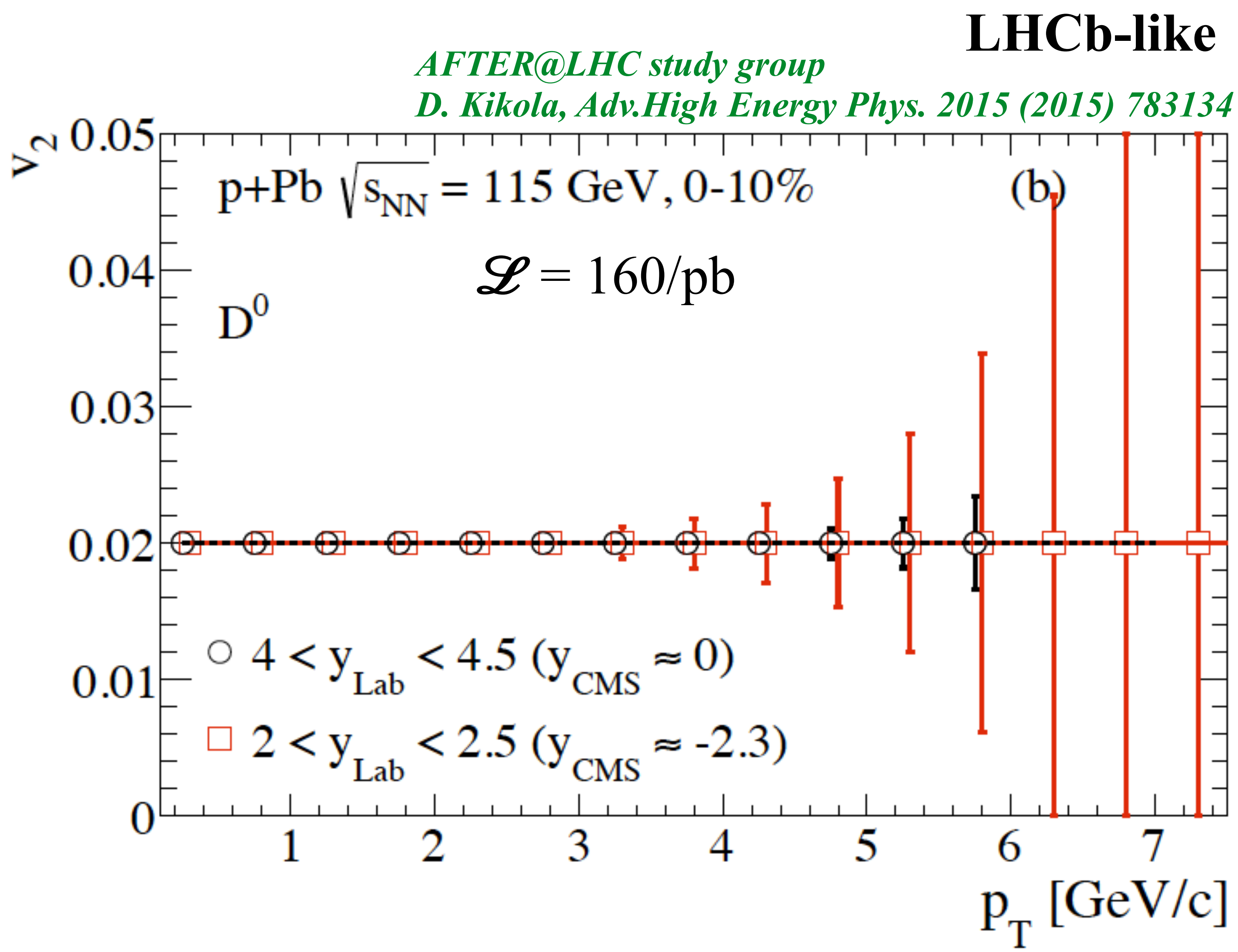
B.Trzeciak et al.Few-Body Syst (2017) 58:148



LHCb-like

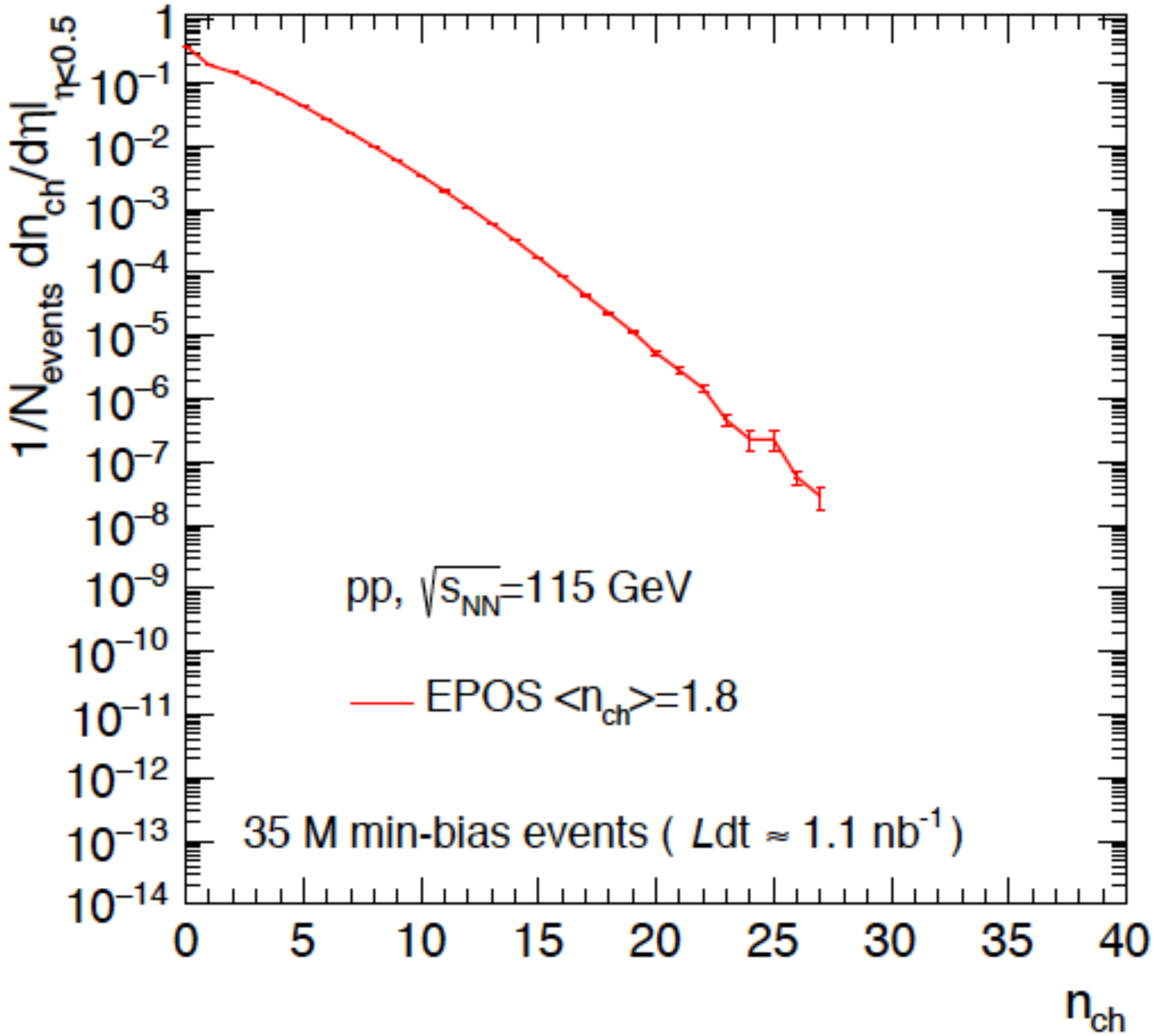


Collective-like effects in small systems



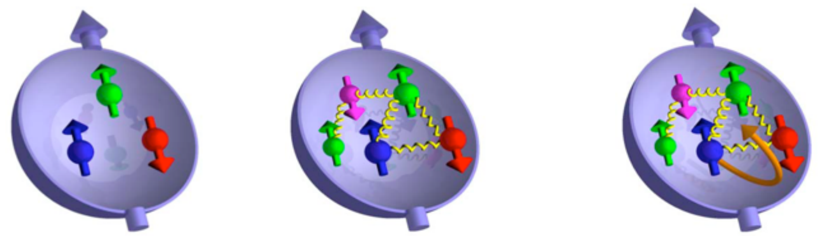
– e.g. accurate precision of D meson elliptic flow
– Different target types and broad rapidity range useful to pin down the mechanisms of these effects

High-multiplicity pp



J/ψ photo-production in p(Pb)+H↑

Proton spin contributions:



quark spin 25%

gluon spin

quark and **gluon Orbital Angular Momentum**

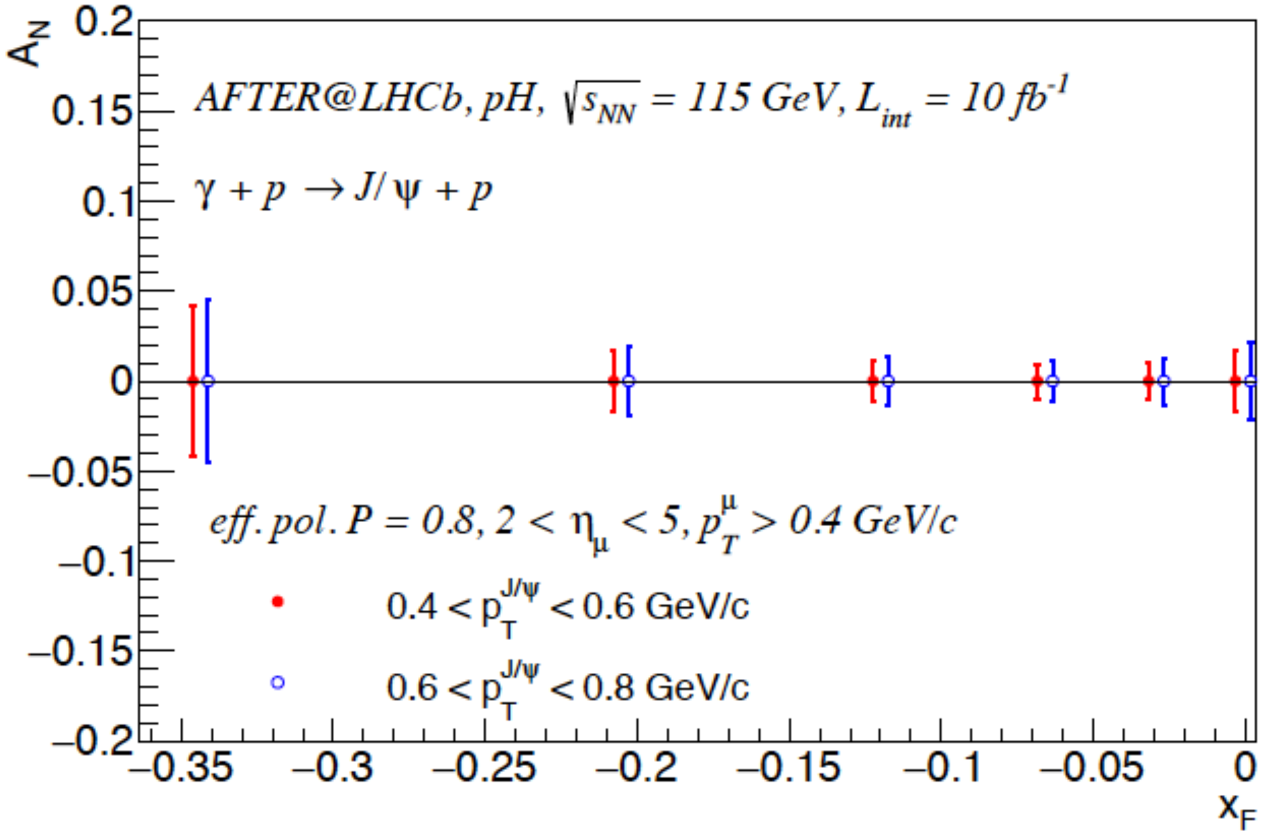
– Transverse spin asymmetry defined as:

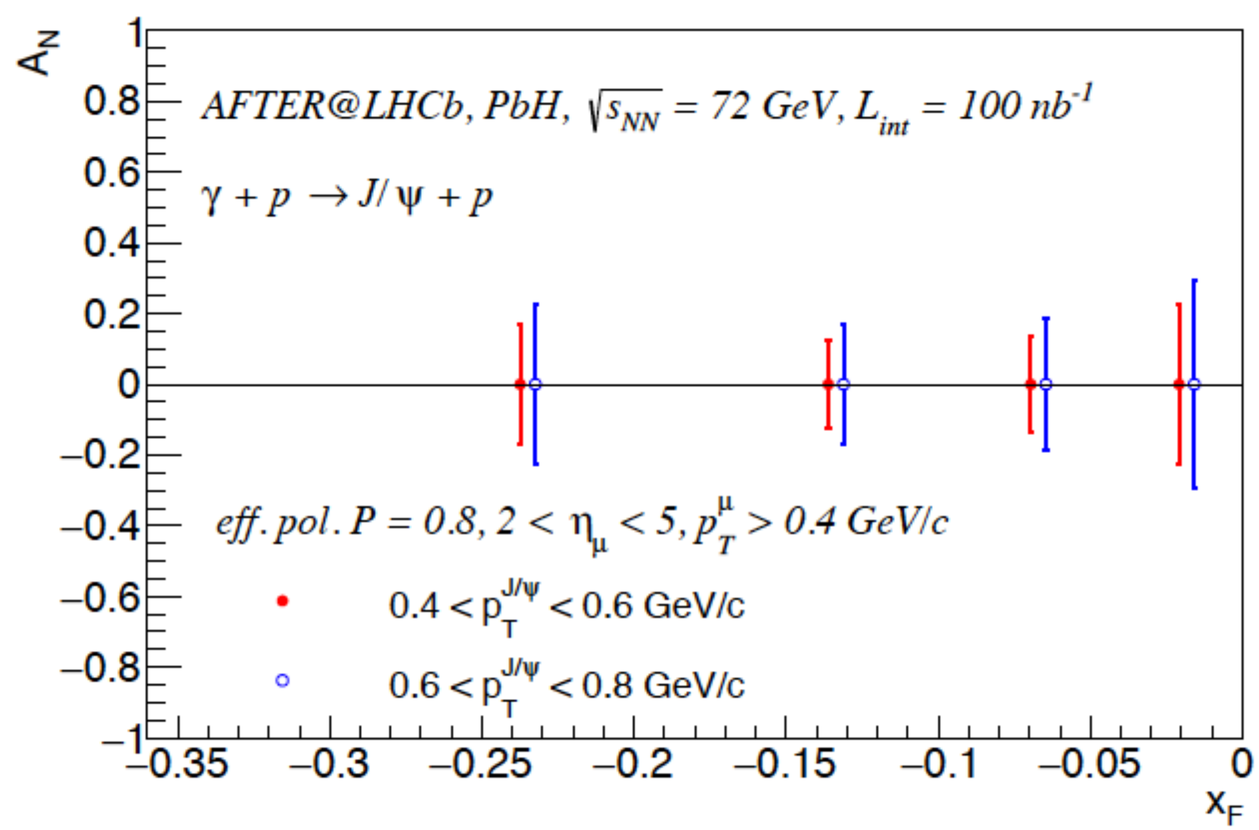
$$A_N = \frac{1}{P}\frac{N^{\uparrow}-N^{\downarrow}}{N^{\uparrow}+N^{\downarrow}}$$

– Photo-produced J/ψ give access to Generalized Parton Distribution E_g and gluon OAM

LHCb-like

L. Massacrier et al. arXiv:1709.09044 & in progress

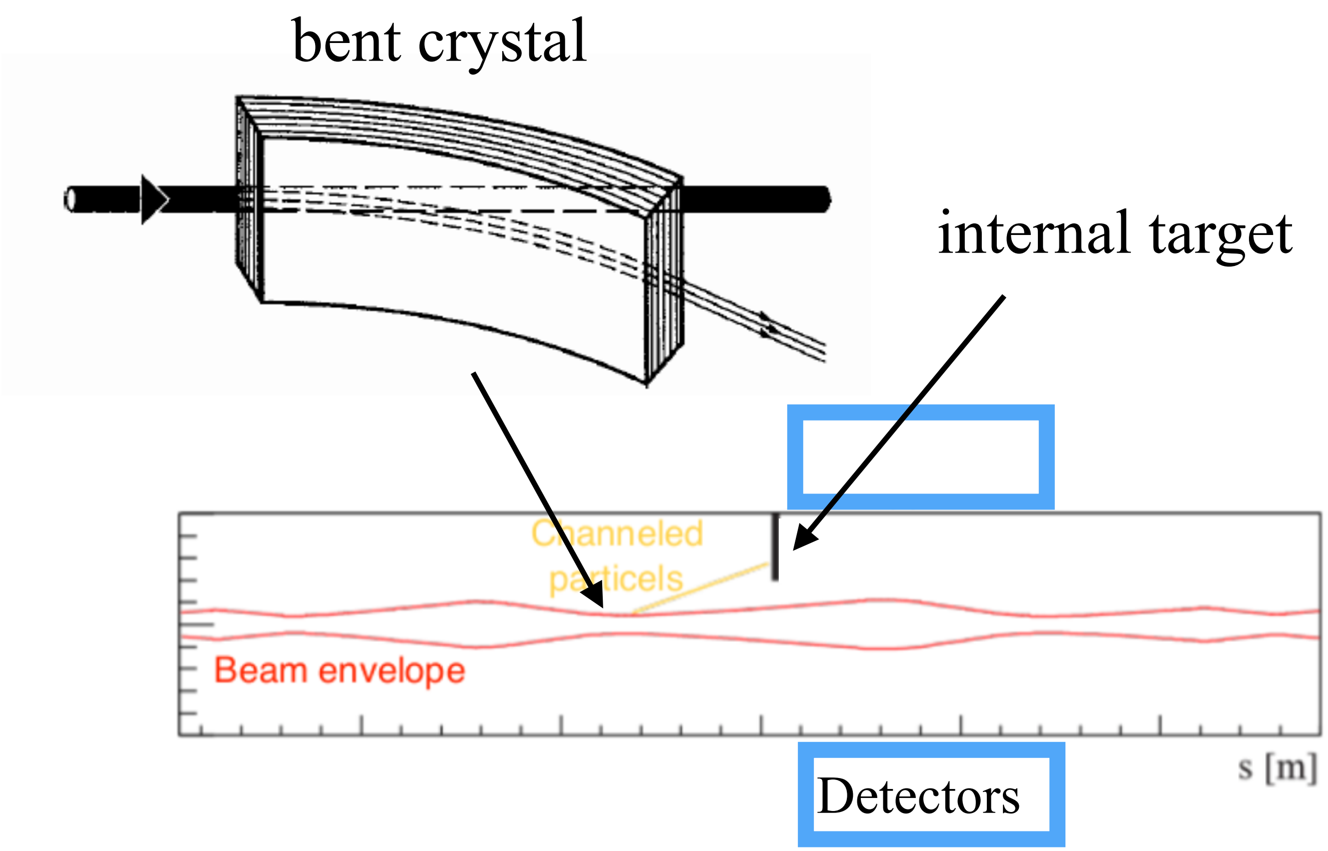




Beam split by using a bent crystal

Bent crystals
- Studied by UA9 for collimation purpose at the LHC
- Channelled particles of the beam halo are deflected
- Beam split by a bent crystal:
    - Crystal located ~100 m upstream the target
    - Solid target internal to the beam pipe close to an existing experimental apparatus
    - Absorber ~100 m downstream the target

S.Redaelli, Physics Beyond Collider Kickoff workshop, CERN, 2016



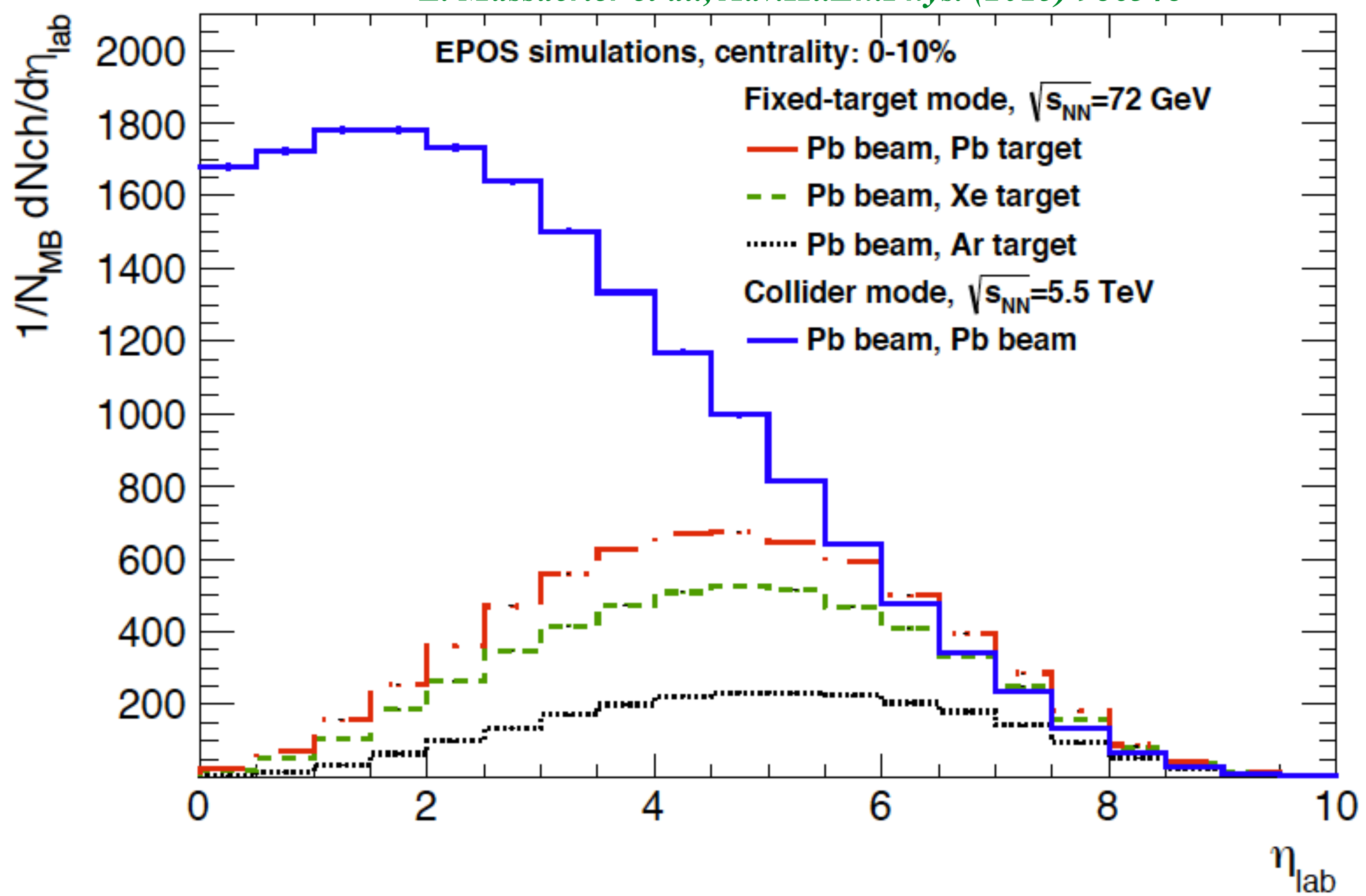
Extracted proton and lead flux
- Proton flux ~5 x 10^8 p/s (LHC beam loss: ~10^9 p/s)
- Lead flux ~2 x 10^5 Pb/s

Typical luminosity
- Assuming 5 mm target length
- $\mathscr{L}_{p\text{-}W} = 1.6\ 10^{31}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}W} = 160/pb$]
- $\mathscr{L}_{Pb\text{-}W} = 3\ 10^{27}\ cm^{-2}s^{-1}$ [$t = 10^6 s$: $\mathscr{L}_{Pb\text{-}W} = 3/nb$]
- Target type: Be, C, W, …

Detector requirements for a LHC fixed-target programme

- **Wide rapidity coverage** (rapidity shift: $\Delta y = 4.8$ with proton beam and 4.2 with lead beam) with PID and vertexing capabilities
- Readout **rate similar as LHC** collider: up to 40 MHz in pp, 300 MHz in pA and 200 kHz in PbA
- Heavy-ion: good detector performance in **high-multiplicity events**, up to 600 charged tracks per unit of rapidity at $\eta_{lab} \sim 4$

L. Massacrier et al., Adv.Hi.En.Phys. (2015) 986348



ALICE and LHCb acceptance in a fixed-target mode

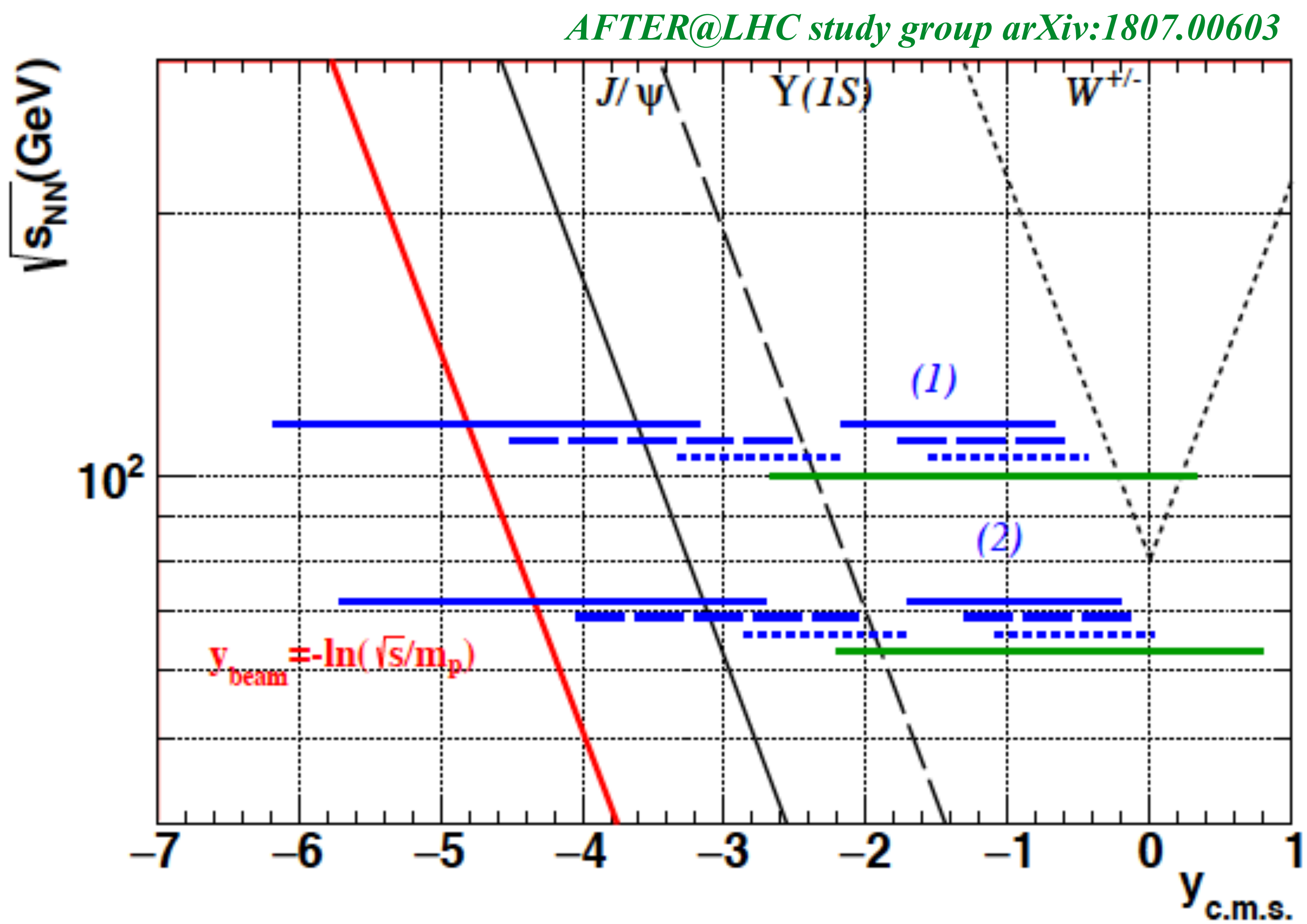


Figure 12: Center-of-mass-rapidity ($y_{c.m.s.}$) coverage as a function of the colliding energies per nucleon pair ($\sqrt{s_{NN}}$) as in Fig. 9. The blue lines represent the acceptance of the TPC and MS of ALICE. The full, long-dashed and short-dashed lines correspond to targets located at the IP, upstream of the IP by z_{target} = 2.75 and 4.7 m, respectively. The green lines represent the acceptance of the LHCb detector with a target at the IP. The long-dashed and short-dashed blue lines as well as the green lines are shifted in energy for a better visibility.