The Future of Ultra-relativistic
Heavy Ion Collisions

22/08/2019

Fixed-target experiment with ALICE at the LHC (run4?)

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Outline

This talk aims to introduce the physics project of fixed-target experiment with ALICE for Run 4.
I personally applied to a Norwegian grant program for investigating the unpolarized gas target solution.

This introductory talk is **based on the work and material** achieved by **Cynthia Hadjidakis** and **Laure Massacrier** (ALICE members from IPNO) within the **AFTER@LHC** study group (link) and the **Physics Beyond Collider** community (link, working group QCD: arXiv:1901.04482).

1. ALICE in fixed-target mode
2. Fixed-target technology and integration
3. Physics opportunities
4. Conclusion and Timeline

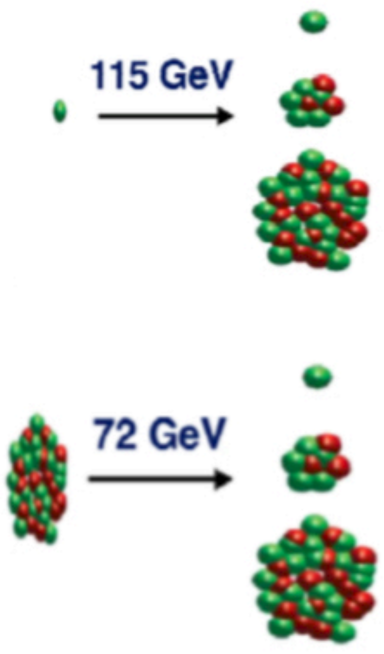
Fixed-target experiment with LHC beams

Main kinematic features:

Energy range

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

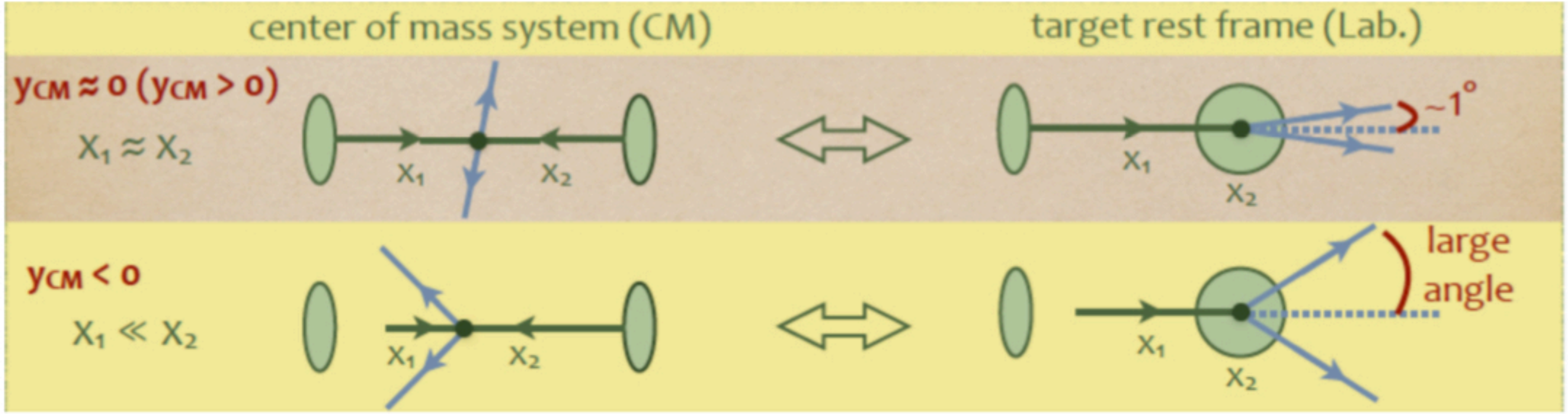
beam type	CM energy $\sqrt{s_{NN}}$	boost $\gamma=\sqrt{s}/2m$	rapidity shift
proton (E = 7 TeV)	115 GeV	61	4.8
lead (E = 2.76 A TeV)	72 GeV	38	4.2



→ 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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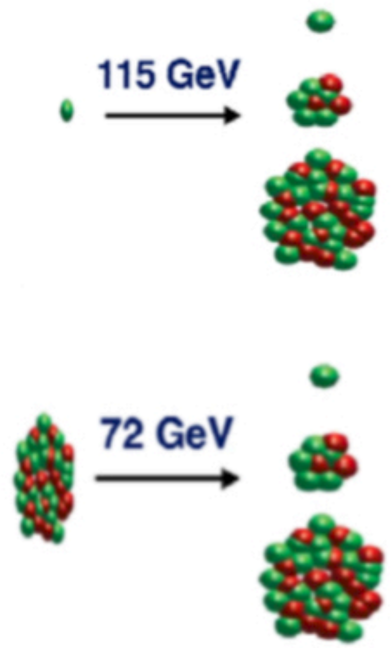

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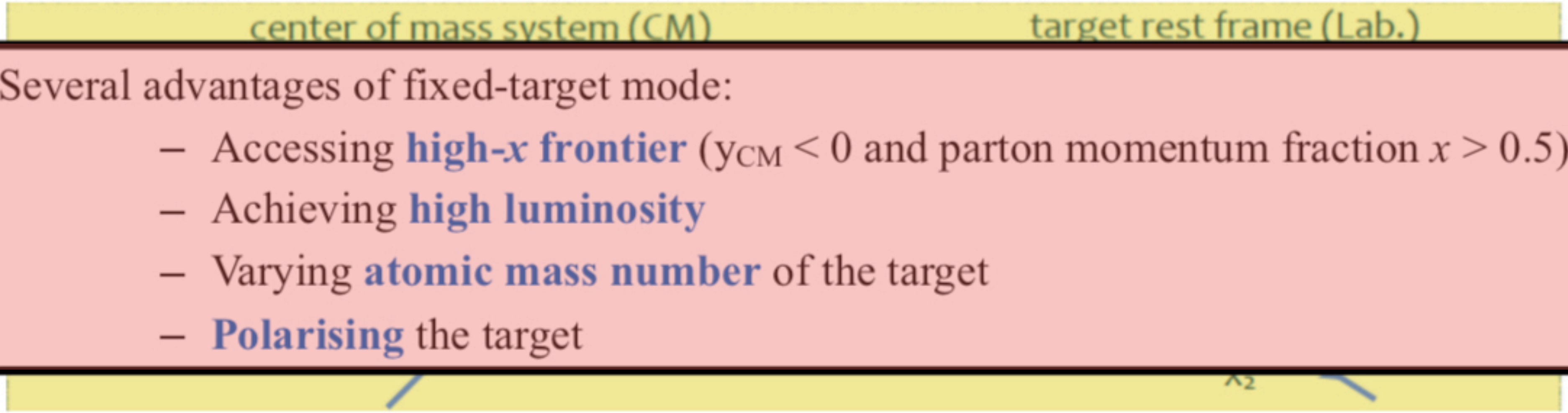
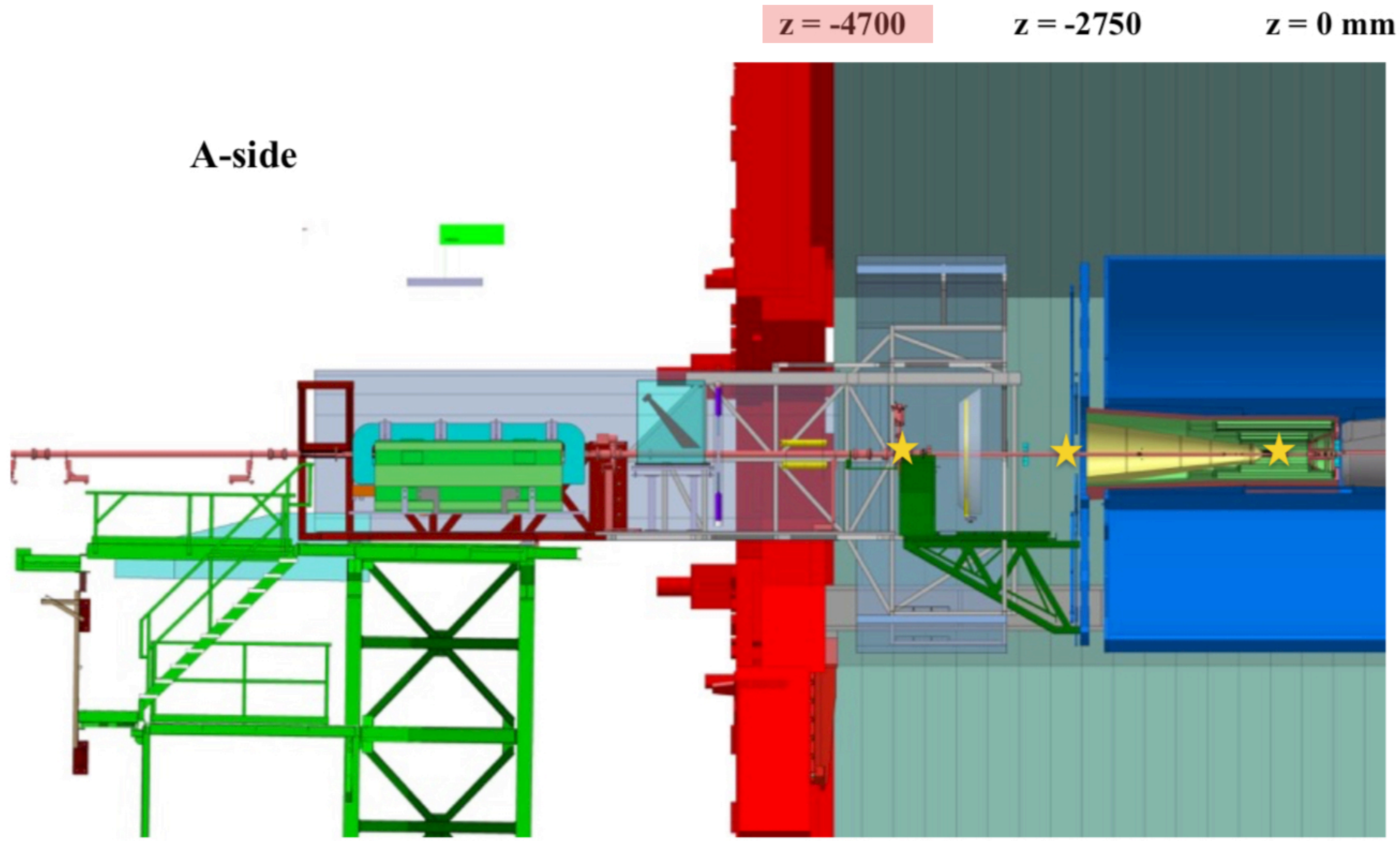


Several advantages of fixed-target mode:

– 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

Target location in ALICE



Running mode:

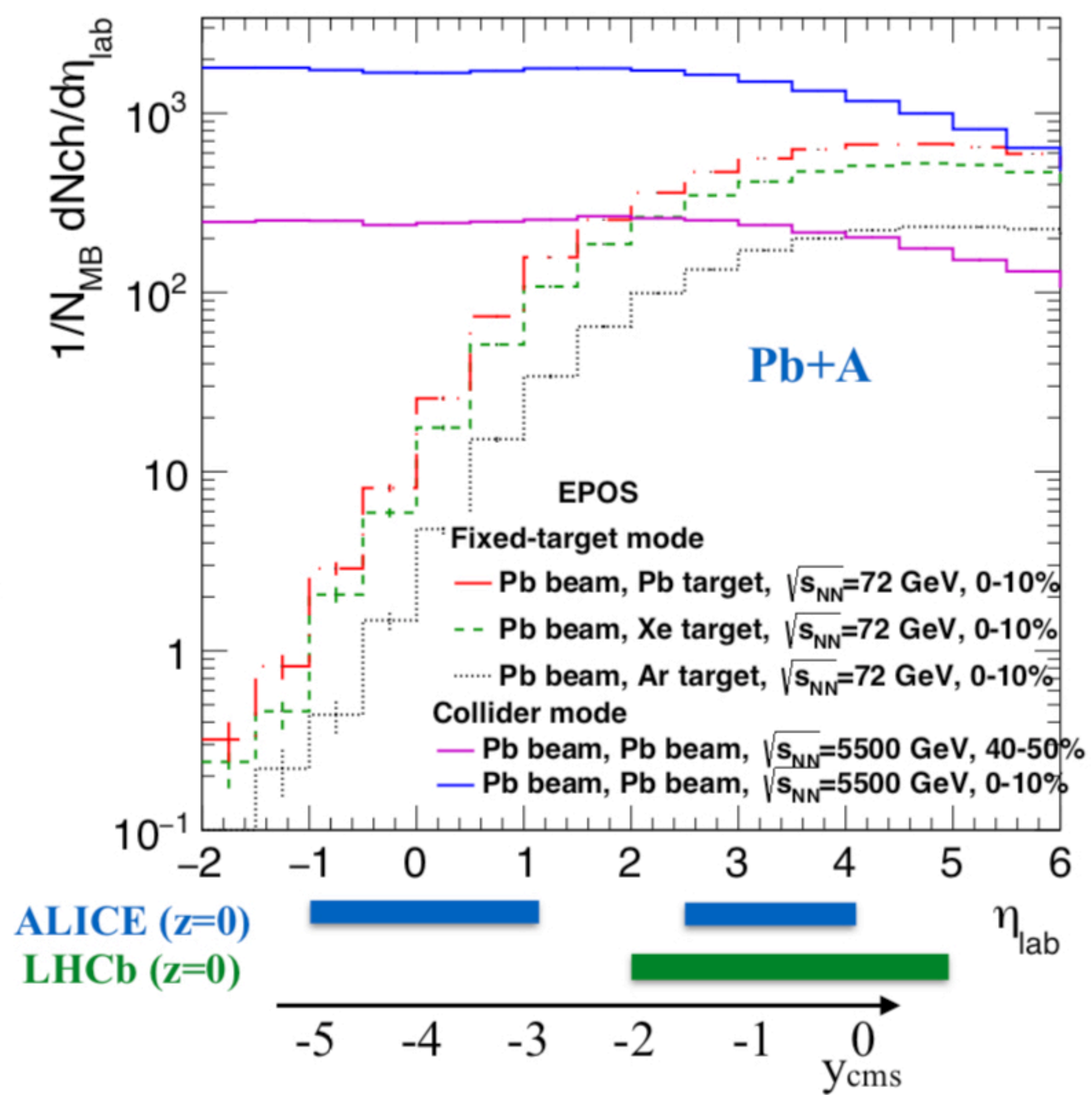
- Parasitic mode: running in parallel with the collider collisions
  —> the collision rate has to be limited not to interfere with other physics programs
- Dedicated runs
  —> run could be shorter, with a higher target density (storage-cell solution).

The ALICE Collaboration could potentially release a significant amount of data taking time for used by a FT program (especially with the proton beam), allowing the collection of large integrated luminosities and the investigation of several target species

ALICE main strengths in fixed-target mode

- **Good performance in high-multiplicity events**
  - Multiplicities always smaller in Pb-A fixed-target modes than in the most central Pb-Pb collisions (0-10%) in collider mode (rapidity shift of Δy=4.8 with 7 TeV proton beam and Δy=4.2 with 2.76 A.TeV lead beam)
  - Access to most central Pb-A collisions in fixed-target mode possible with ALICE detectors (if reasonable interaction rate)
- **Wide rapidity coverage**
  - From target fragmentation region (Central Barrel) up to center-of-mass system (c.m.s) mid-rapidity region (Muon Spectrometer)

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



Fixed-target technology and its integration

- **Internal gas target**
  - [Similar to SMOG at LHCb, inspired by HERMES target and RHIC gas-jet]
  - Full LHC proton flux: 3.4 x 10^{18} p/s and Pb flux: 3.6 x 10^{14} Pb/s on internal gas target
- **Beam "splitting" by a bent crystal**
  - Beam halo is deflected by a bent crystal, upstream of the experiment
  - Solid target located inside the beam pipe close to ALICE detectors
  - Deviated halo proton flux: 5 x 10^8 p/s and Pb flux: 10^5 Pb/s on a solid target
- **Integrated luminosities calculated**
  - Assuming 1 LHC year: t = 10^7s for proton beam and t=10^6s for lead beam
  - Considering ALICE data taking rate capabilities (compatibility with simultaneous collider programme still to be verified)

Beam splitting by bent crystal and internal solid target

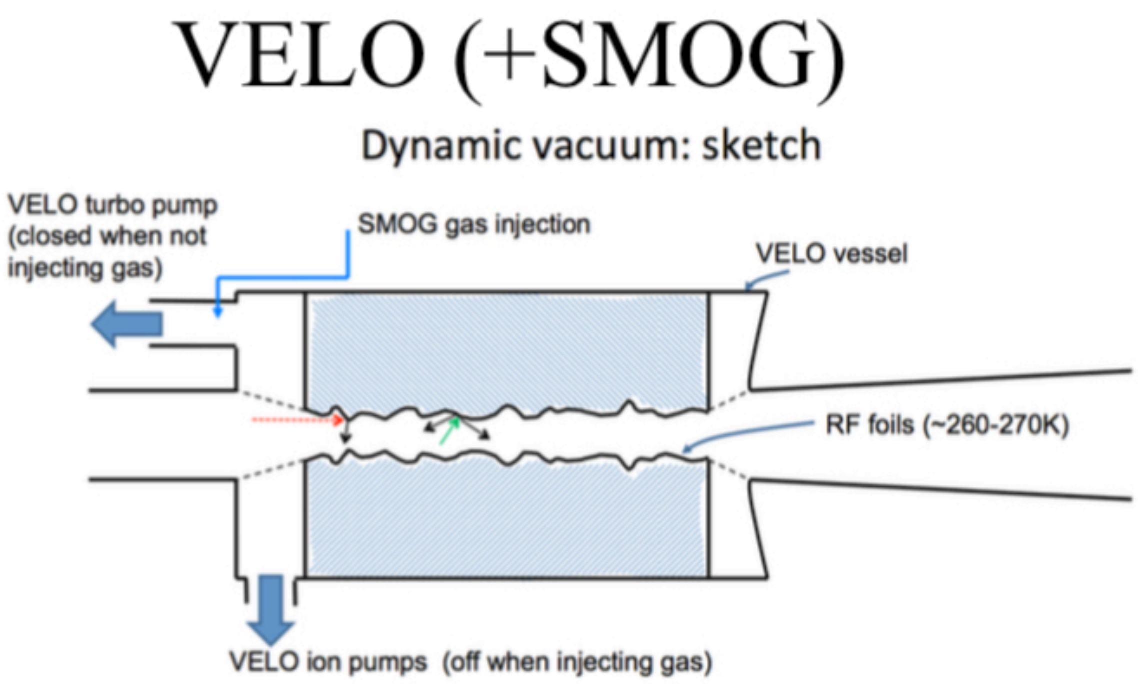
System	Solid target (5 mm thick unless specified)		
	L_{int}	σ_{inel}	Inelastic rate
p+W (37-185 μm)	1.2-5.9 pb^{-1}	~1.7 b	200 kHz-1 MHz
Pb+W	3.2 nb^{-1}	~6.9 b	22kHz

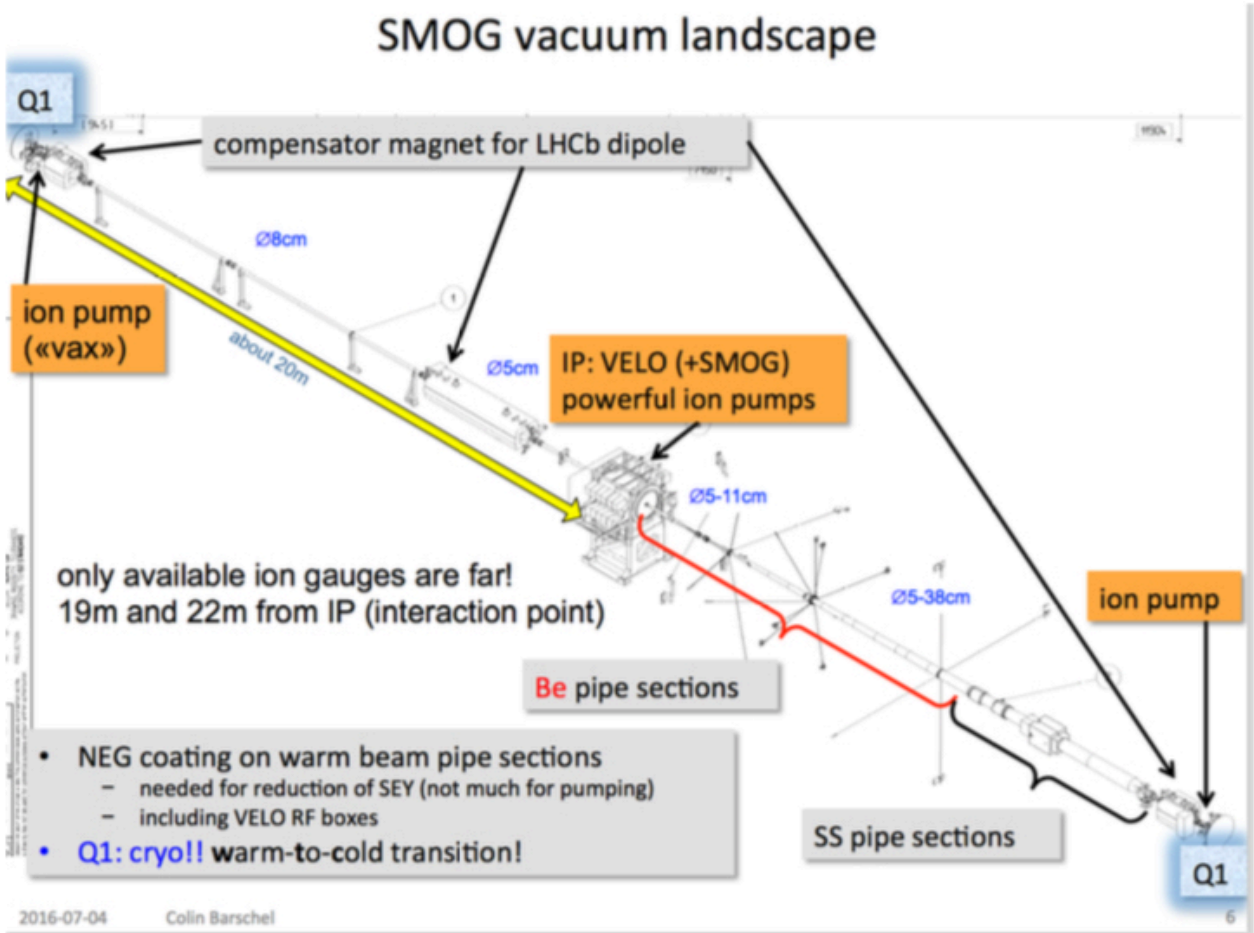
Full beam on internal gas target

System	Gas jet / Storage cell		
	L_{int}	σ_{inel}	Inelastic rate
p+H↑	45 pb^{-1}	~27 mb	100 kHz
p+H_2	90-450 pb^{-1}	~27 mb	200 kHz - 1 MHz
p+Xe	1.5-7.7 pb^{-1}	~1.3 b	200 kHz - 1 MHz
Pb+Xe	8.1 nb^{-1}	~6.2 b	50 kHz

Few target types indicated in the table: other targets possible
Large luminosities foreseen

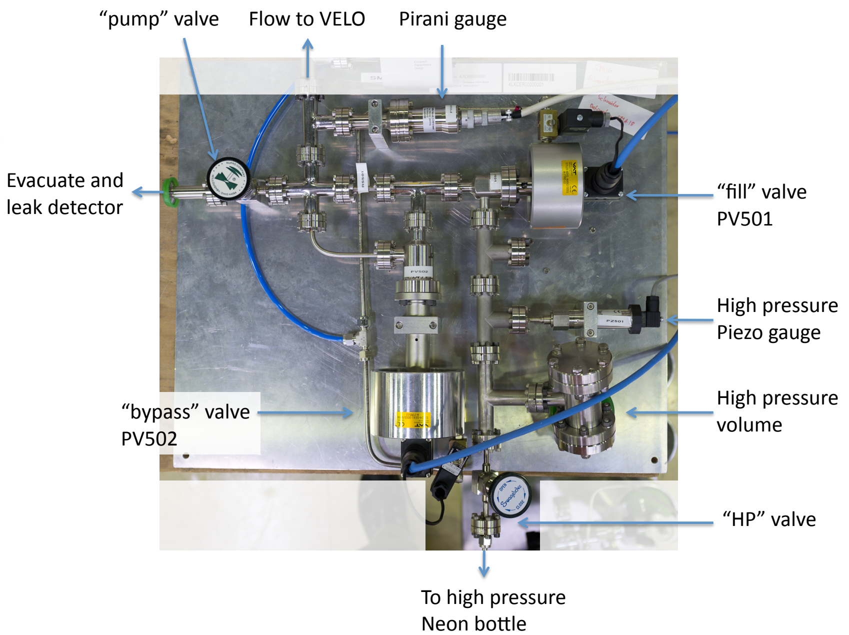
Internal gas target: SMOG in LHCb





SMOG/LHCb (System for Measuring the Overlap with Gas)

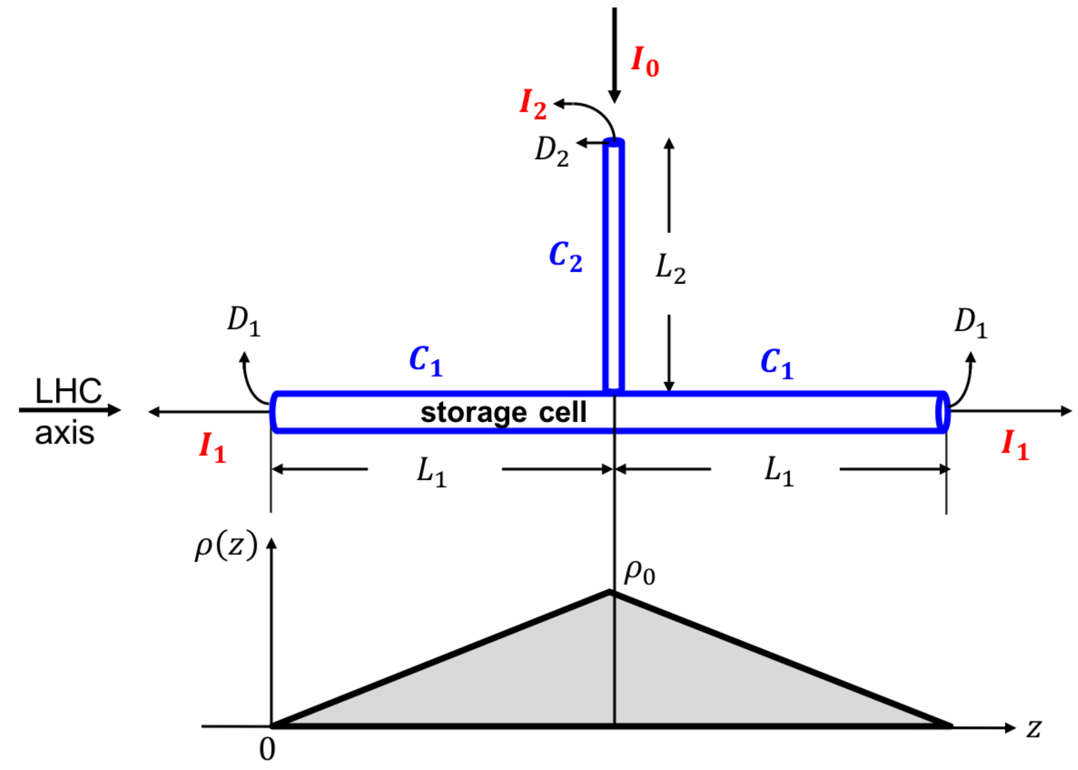
- Gas injecting into Vertex Locator (VELO) vacuum chamber: P ~1.5 10^{-7} mbar
- LHC vacuum ion pump stations located ±20m on both sides
- Noble gas injected so far: He, Ne, Ar
- Limited running time: so far, at most 2 weeks
- Last run: pNe with L_{int} ~ 200/nb
- Proposal for an improved SMOG (SMOG2) with higher gas density in Run3



Internal gas target: storage cell

HERMES/DESY T-shape internal storage cell target:

- Vacuum chamber target ~ 72 cm x 50 cm and pumping system
- Polarised H and D (also $_3He$ gas): atomic beam source
  Holding field in the target chamber
- Diagnostic systems: target gas analyzer and polarimeter
- Unpolarized gas via capillary: H_2 and noble gases
- Proposal for LHC using an openable storage cell of 1m long and 2.8 cm wide: ***C. Barschel et al. Adv.High Energy Phys. 2015 (2015) 463141***



Density

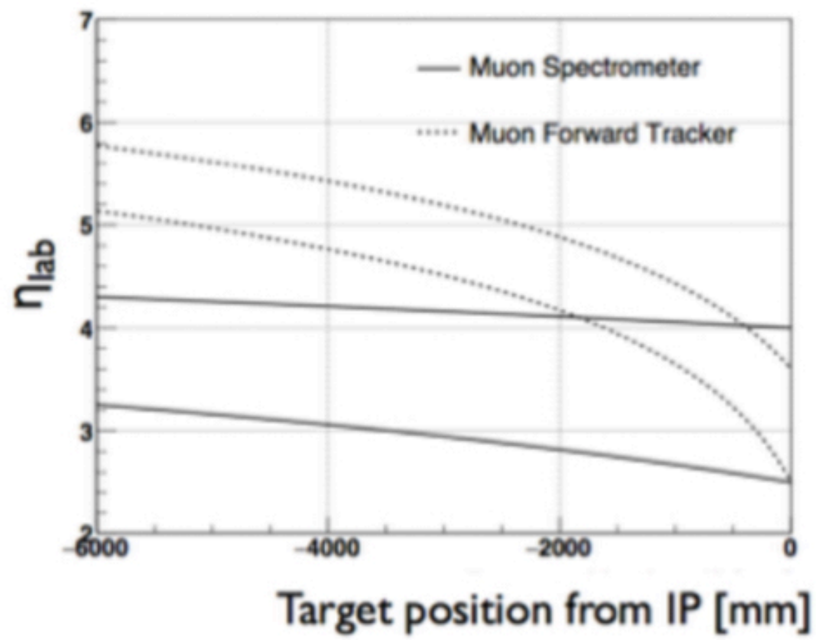
- Polarised inlet $H_\uparrow$ flux: $6.5\ 10^{16}\ H_\uparrow/s$
- Areal density $\vartheta_{H\uparrow} = 2.5\ 10^{14}$ atoms/cm^2 (~100 × gas jet)
- Unpolarised gas pressure limited by beam lifetime

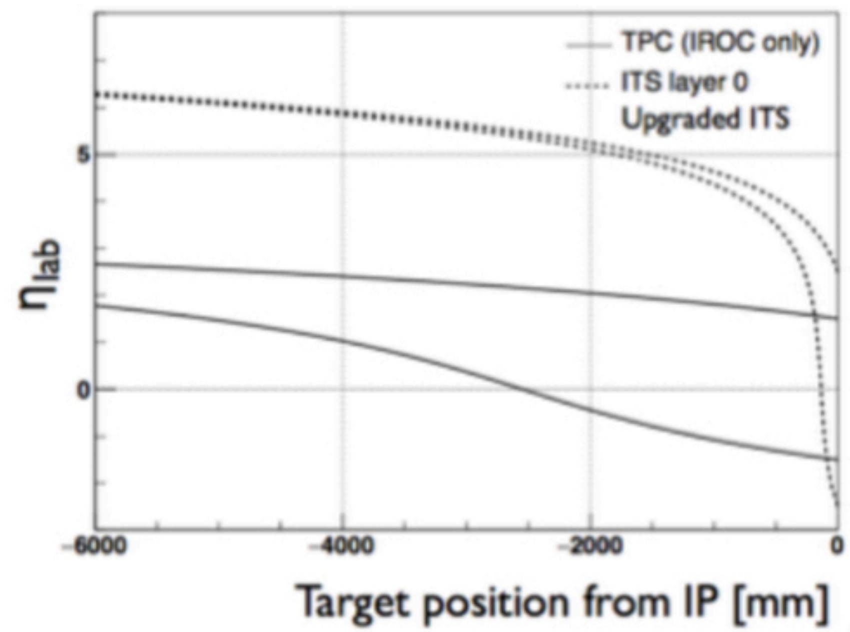
Luminosity

- $\mathscr{L}_{p\text{-}H\uparrow} = 0.9\ 10^{33}\ cm^{-2}s^{-1}$
- $\mathscr{L}_{p\text{-}H2} = 5.8\ 10^{33}\ cm^{-2}s^{-1}$
- $\mathscr{L}_{Pb\text{-}Xe} = 3\ 10^{28}\ cm^{-2}s^{-1}$

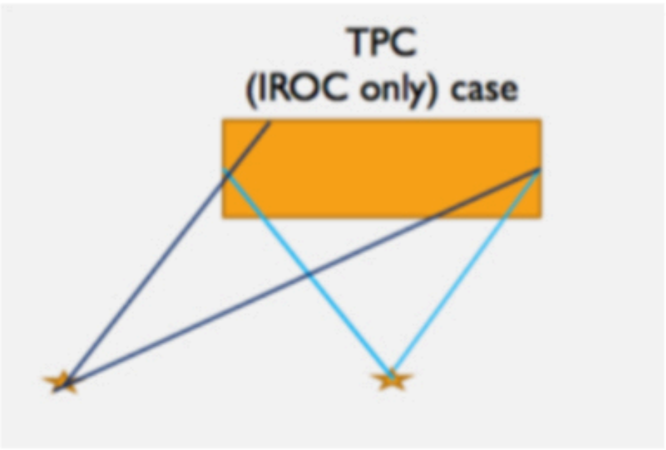
Detector acceptance vs z_{target}

Convention: z-direction positive on C-side

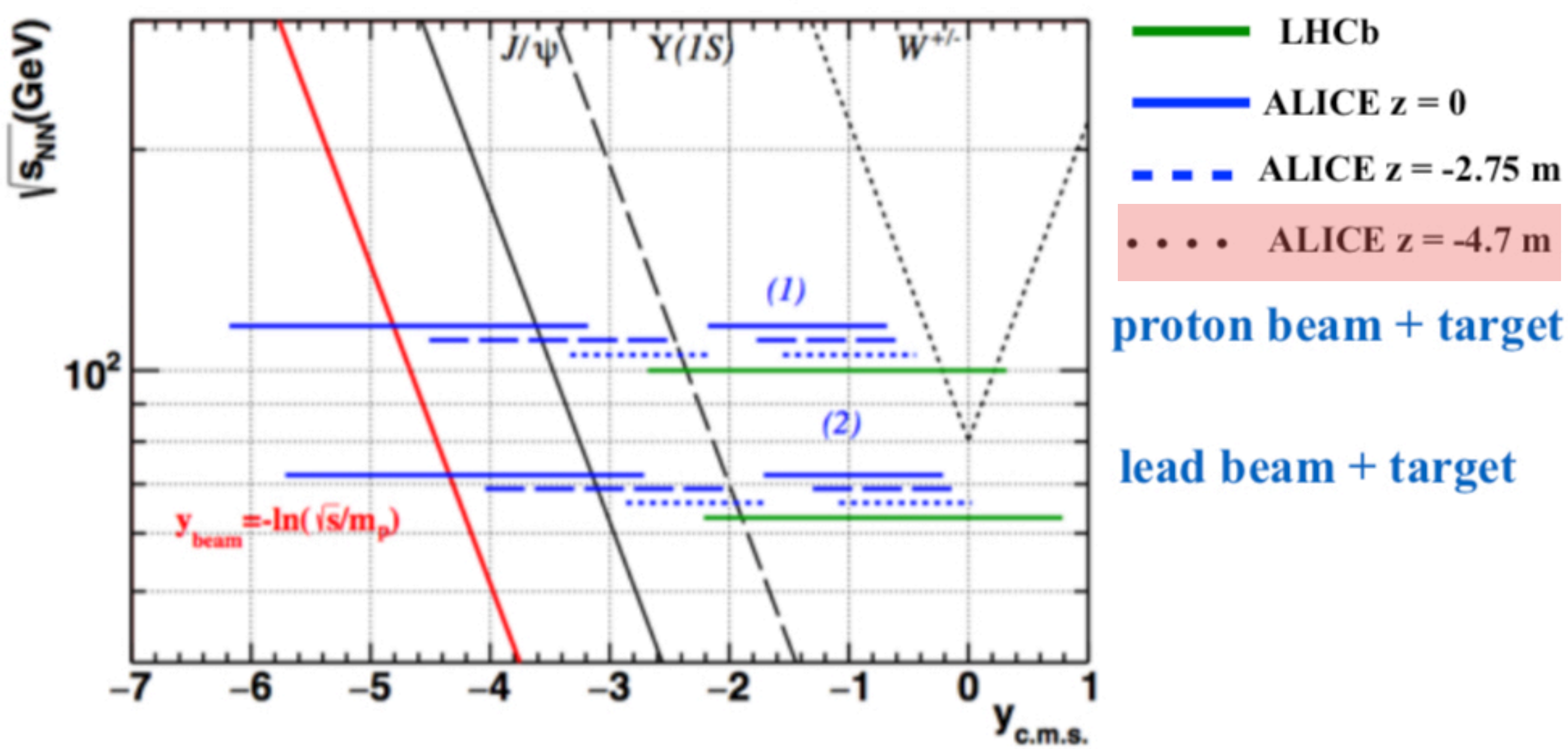




Caveat: simple geometry considerations using reduced track length in TPC



- With a vertex located few meters upstream of the I.P., the rapidity coverage is shifted towards mid-rapidity in the c.m.s
- If target at z <<0, a new vertex detector is needed
- Tracking performances of the TPC and effect of material budget for target position at large negative z have to be studied



Three main physics cases:

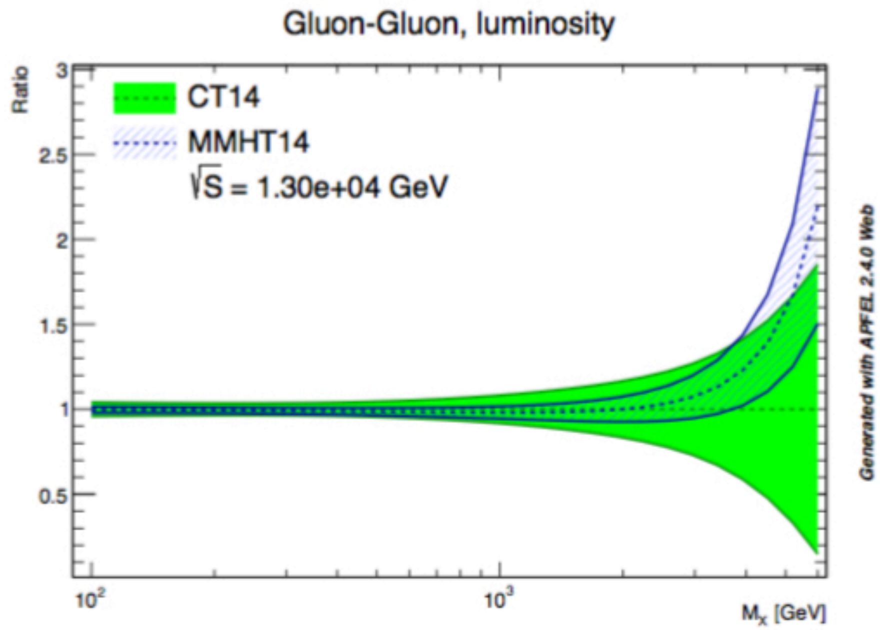
- **High-*x* gluon and heavy-quark content in the nucleon and nucleus** and input to astroparticle:
  - Quarkonium production in the Muon Spectrometer in pp and pA
  - Open charm production in the Central Barrel in pp and pA
  - J/ψ photo-production in the Central Barrel and Muon Spectrometer in pp and $pp^{\uparrow}$
  - Antiproton measurements in pp and pA as input to astroparticle
- **The spin of the nucleon**
  - Strangeness production in the Central Barrel in $pp^{\uparrow}$
- **Quark Gluon Plasma at $\sqrt{s_{NN}} \sim 72$ GeV**
  - Quarkonium production in the Muon Spectrometer in PbA
  - Open charm production in the Central Barrel in PbW
  - Longitudinal expansion of the QGP formation: with v_2 and yield measurements of identified light particles in Central Barrel
  - Limiting fragmentation with identified light particles (no performance plot)

Other physics opportunities unique to ALICE:

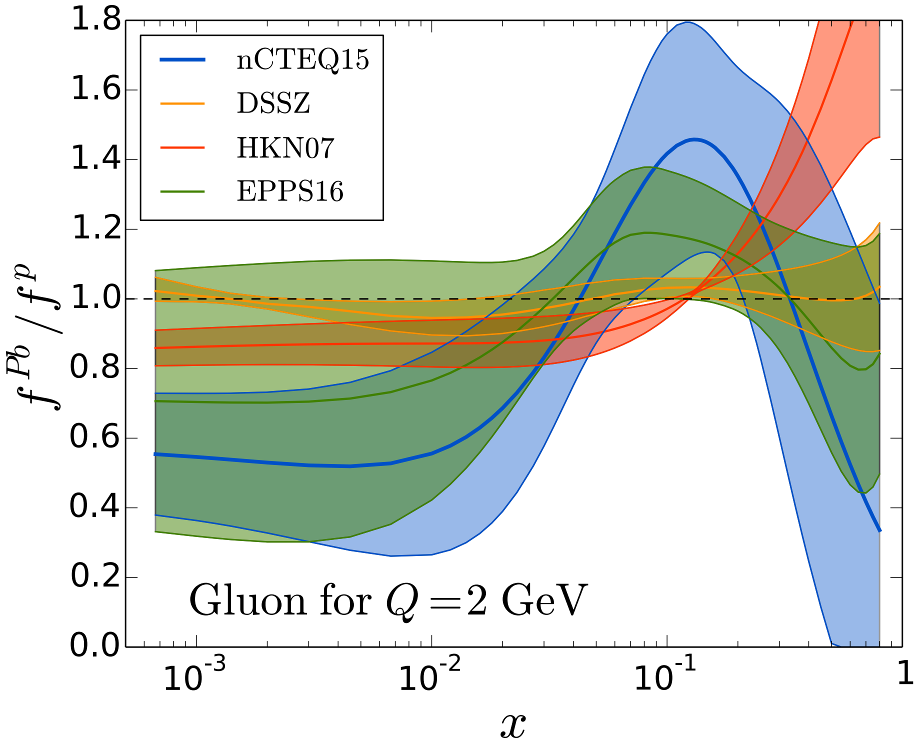
- Mid-backward rapidity correlations (muon-hadron correlations)
- Drell-Yan measurements (factorization of CNM effects in heavy-ion) with the Muon Spectrometer

Nucleon and nuclear structure at high-x

- Advance our understanding of the high-x gluon, antiquark and heavy-quark content in the nucleon and nucleus
  - Structure of nucleon and nuclei at high-x are poorly known ($x > 0.5$)
  - Some longstanding puzzles:
    - Proton charm content (also important for high-energy neutrino and cosmic-ray physics)
    - Origin of nuclear EMC effect: studying a possible gluon EMC effect
  - Search and study rare proton fluctuation where one gluon carries most of the proton momentum: test QCD in a new limit never explored

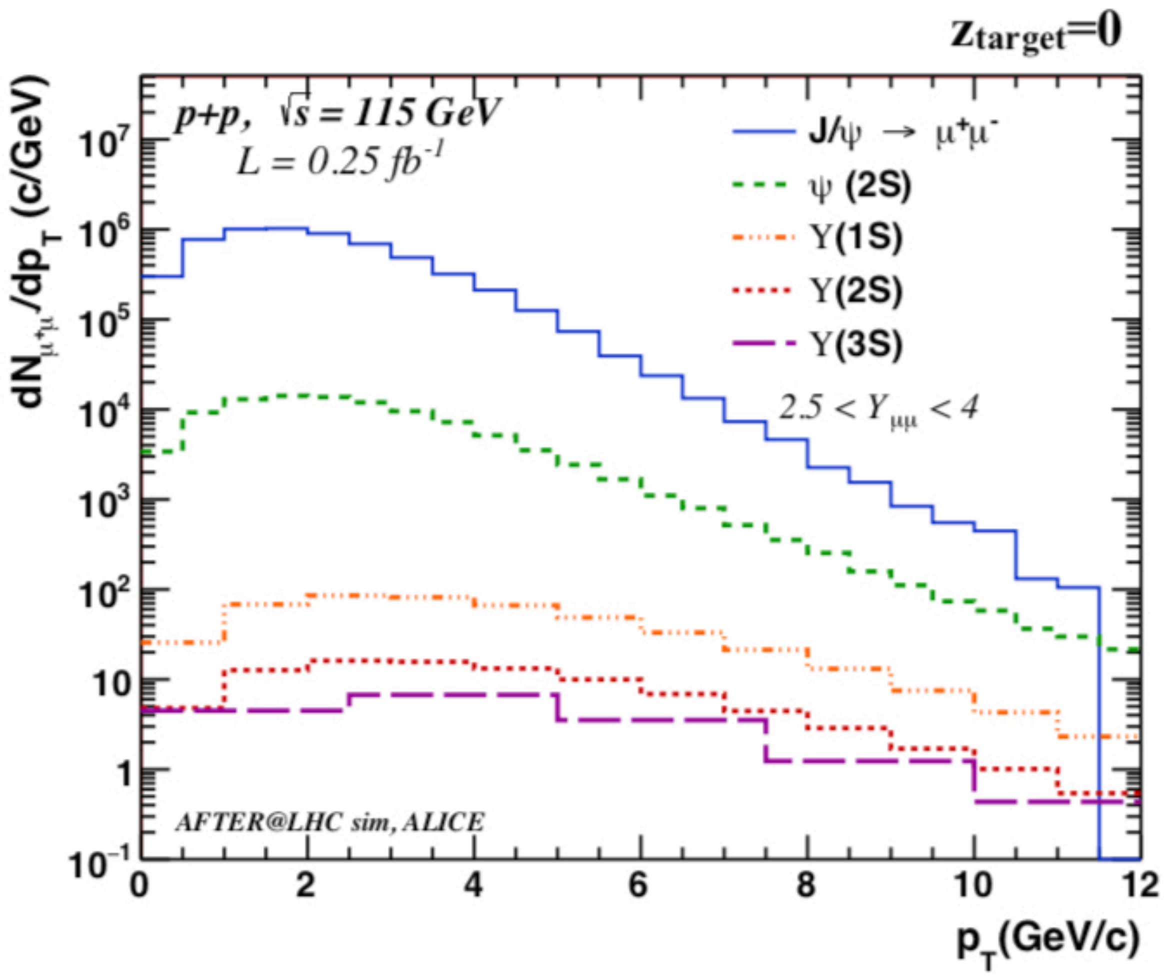


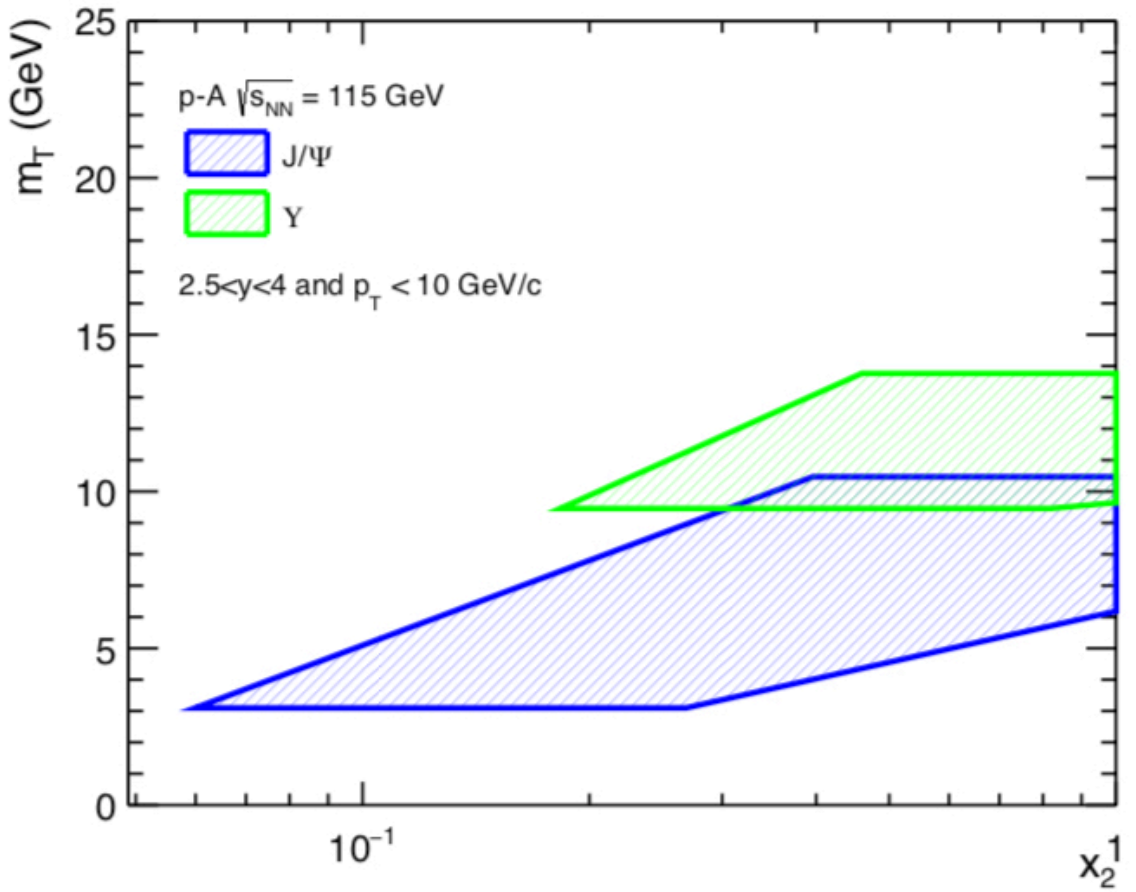
Uncertainty on the gluon-gluon luminosity



Gluon density in Pb nuclei

Quarkonium production in pp and pA



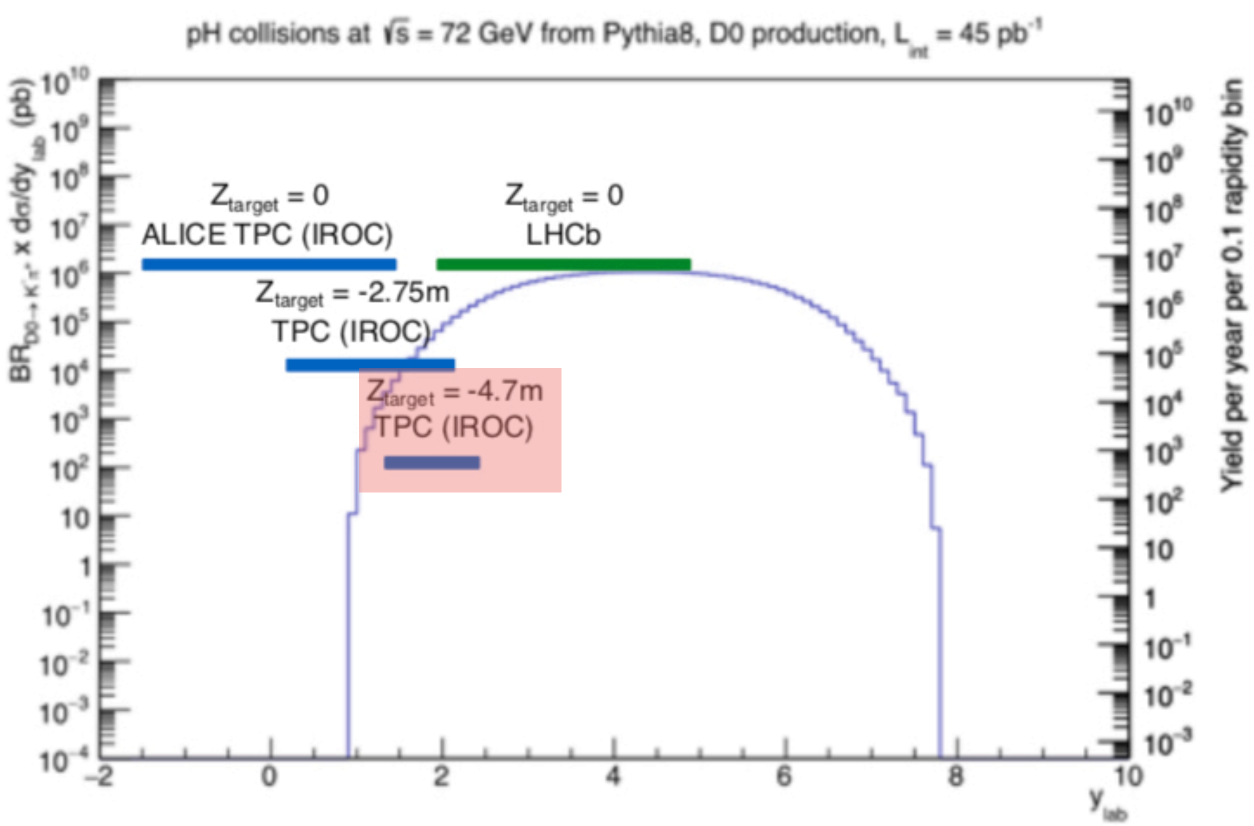


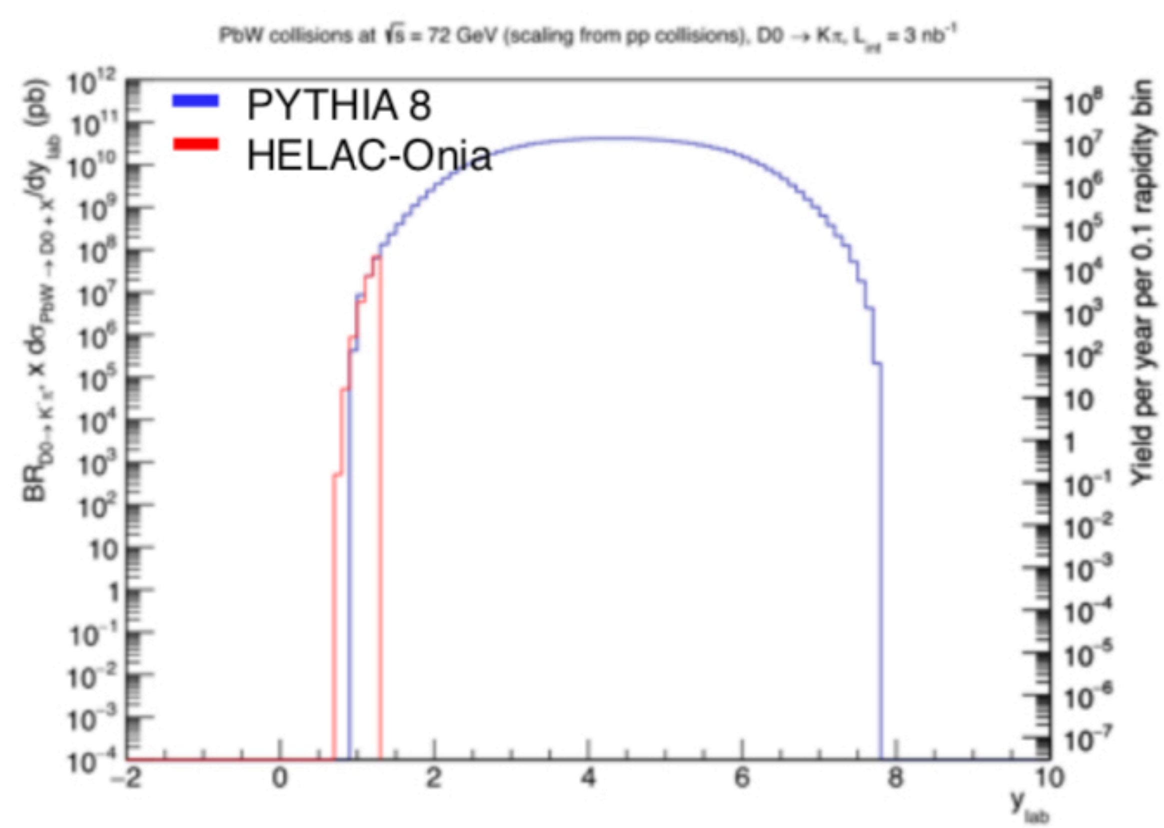
- Quarkonia in ALICE muon spectrometer
- Simulation inputs from HELAC-Onia ***Laure Massacrier et al. Adv.High Energy Phys. 2015 (2015) 986348.***
- Luminosities corresponding to 1/2 year of p-H_2 of data-taking
- Rapidity cuts on dimuon but AccxEff not accounted for
- Large yields expected for charmonia, statistics of the same order in p-W
- Probe high-x gluon in the target in p-p and p-A in particular with Υ(1S) within the Muon Spectrometer acceptance

In pp collisions: study of the intrinsic charm (IC) component in the proton at large-x

- $D^0 \rightarrow K\pi$ PYTHIA simulation (rapidity dependence at end of phase space compared with HELAC-Onia)
- σ(cc) = 0.143 mb assumed (but large theoretical uncertainties)
- About 1/10th of a pH_2 LHC year and 1 LHC year of PbW collisions
- Efficiency and PID not accounted for
- Kinematic limits of D^0 meson at $y_{D\,lab} \sim 0.6$ (from $x_{target} = M_D/\sqrt{s}\, e^{-y_{cms}} = 1$)

- At $y_{lab} \sim 1$, about 500 D^0 produced per 0.1 rapidity unit in one year in pp and about 100 D^0 in PbW collisions (large theoretical uncertainties: IC can boost the D^0 yield)
- Measurements at 0.5 < ylab < 1.5 suitable to probe D meson at the end of the phase space





Antiproton measurements as input to astroparticles in p+H and p+A (A=He,C,N,O) collisions

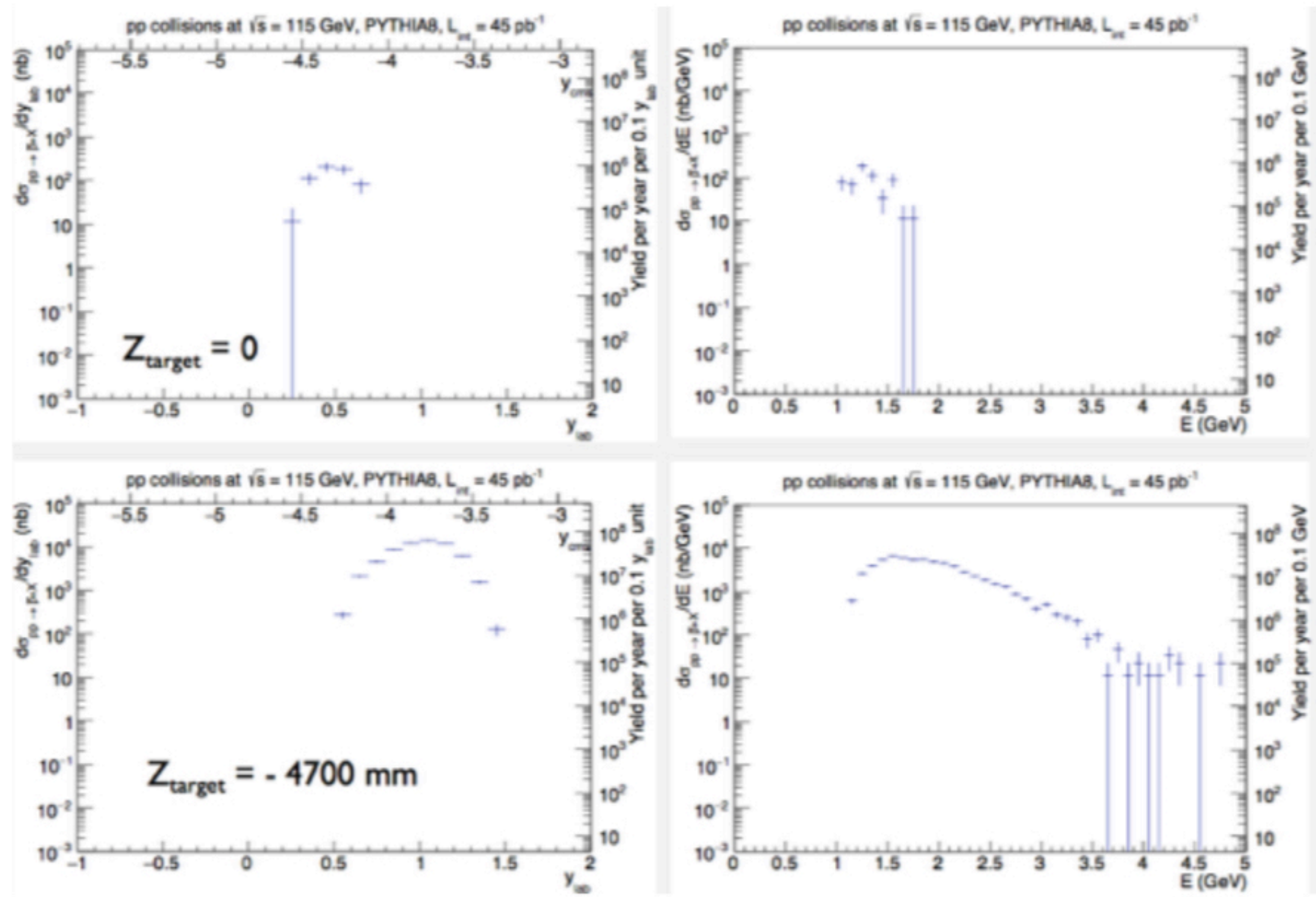
Cosmic antiproton production

p/^{4}He/^{12}C/^{14}N/^{16}O/… (cosmic ray)+ H (at rest)
→ antiproton of large E

Equivalent to:

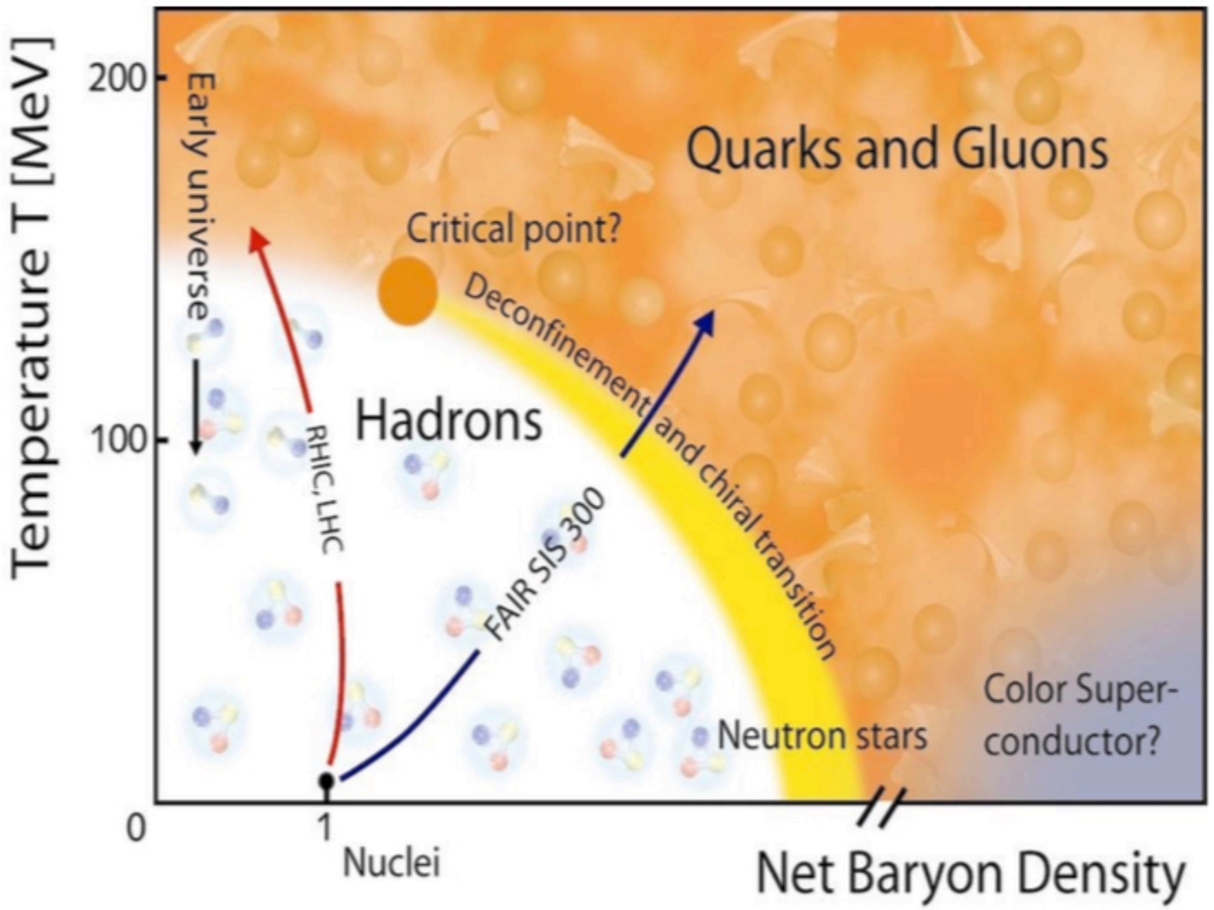
p (7 TeV beam) + p/^{4}He/^{12}C/^{14}N/^{16}O/… (at rest)
→ antiproton of small E

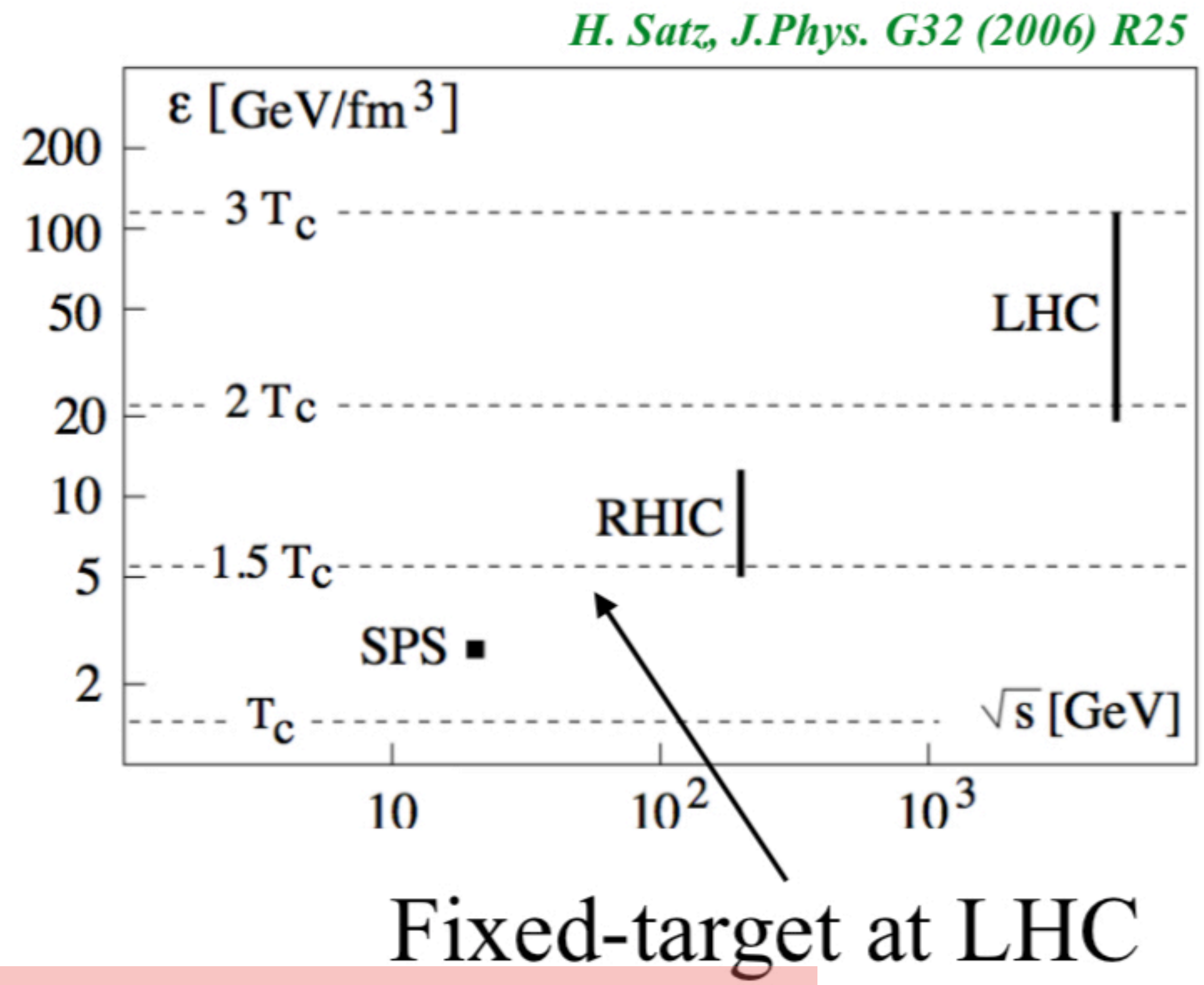
Inverse kinematics and detection of small energy anti-protons possible with the ALICE Central Barrel



- PYTHIA simulation, pp collisions, PID and tracking efficiency not accounted for
- Pseudo-rapidity of antiproton within TPC (IROC only) and TOF and $0.5 < p_T < 4$ GeV/c
- Luminosities corresponding to 1/10 year of p-H_2 of data-taking
- Very large yield produced in the central barrel acceptance

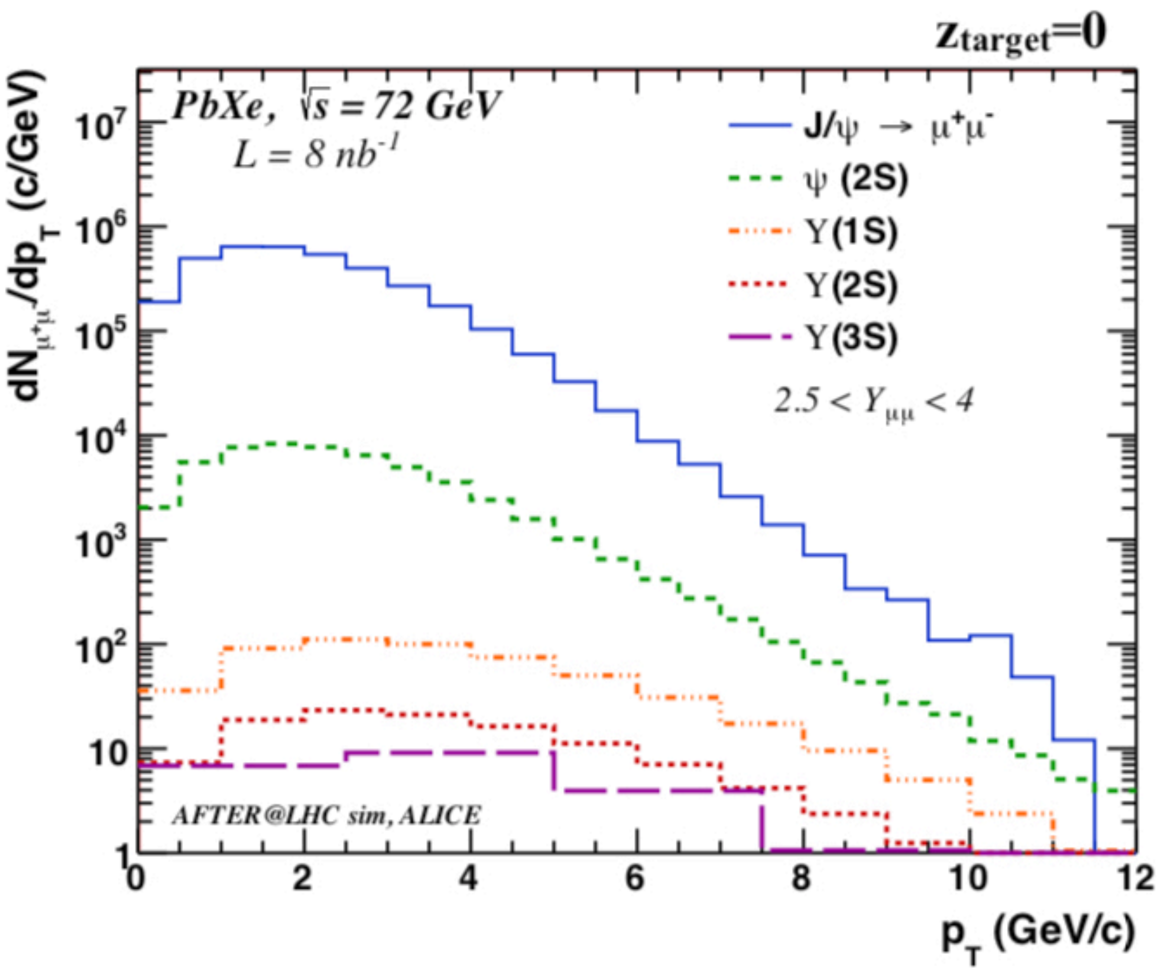
- QGP studies between SPS and RHIC energies at $\sqrt{s_{NN}} \sim 72$ GeV with a nuclear target





- Varying the target type:
  - Study small system p+A (Cold Nuclear Matter, collective effects)
  - Test the factorisation of CNM effects using Drell-Yan measurements in p+A, p+B and A+B

Quarkonium production in Pb-A



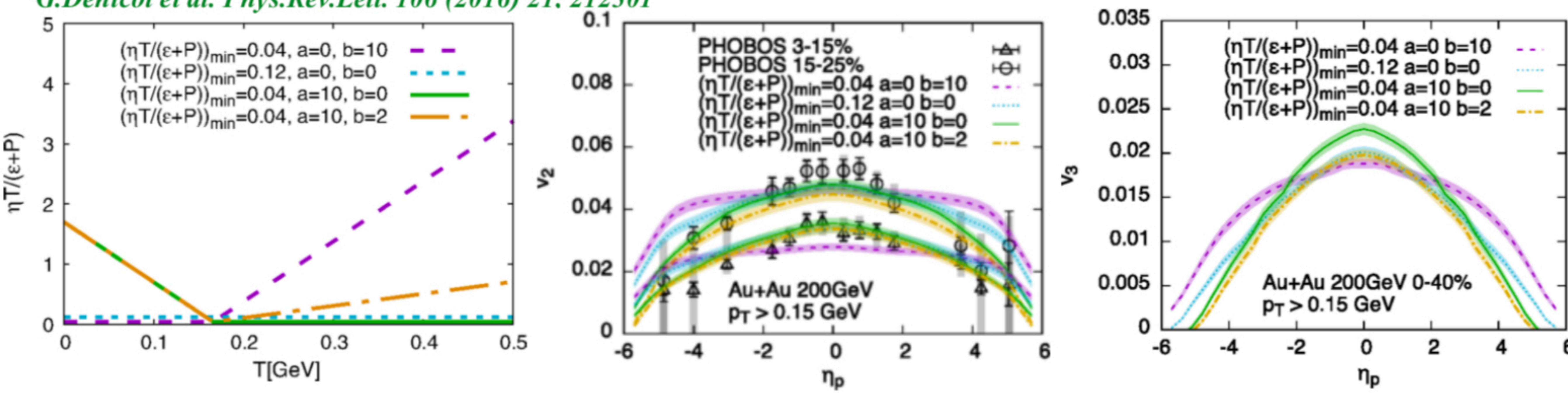
- Simulation inputs from HELAC-Onia ***L. Massacrier et al. Adv.High Energy Phys. 2015 (2015) 986348.***
- Luminosities corresponding to 1 year of Pb-Xe data-taking
- Rapidity cuts on dimuon but tracking and trigger efficiency not accounted for
- Large yields expected for charmonia
- Υ(1S) at reach, excited Υ states statistically limited

QGP towards large (backward) rapidities

- From mid- to large backward rapidities: explore the longitudinal expansion of QGP formation
- Particle yields and flow coefficients measured at large rapidities to constrain the medium shear viscosity and temperature
- High precision studies complementary to the ones performed at RHIC

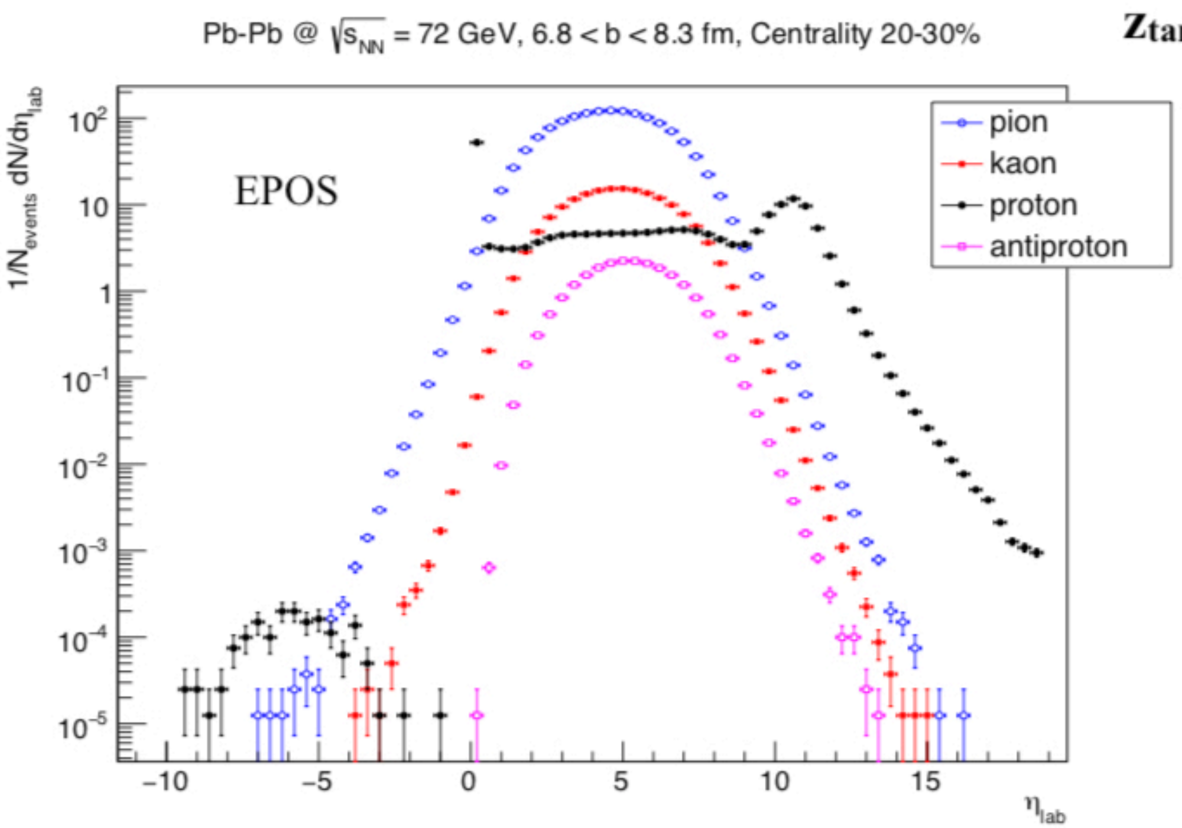
3D +1 viscous hydrodynamic calculations

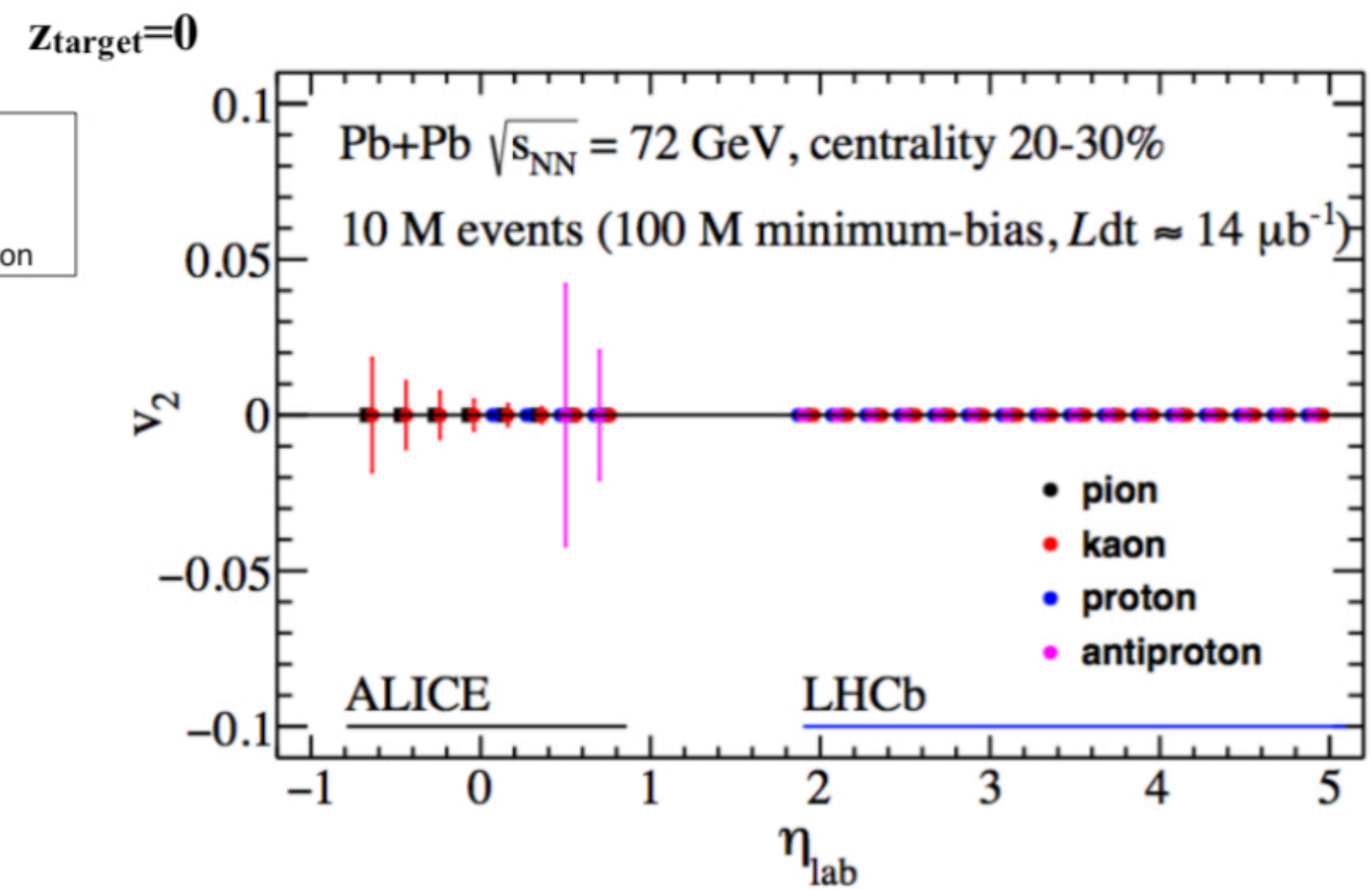
G.Denicol et al. Phys.Rev.Lett. 106 (2016) 21, 212301



- Study limiting fragmentation with identified particles as done at RHIC by PHOBOS (only charged particles) and BRAHMS: identified particles up to y ~ 3

Soft probes towards large (backward) rapidities

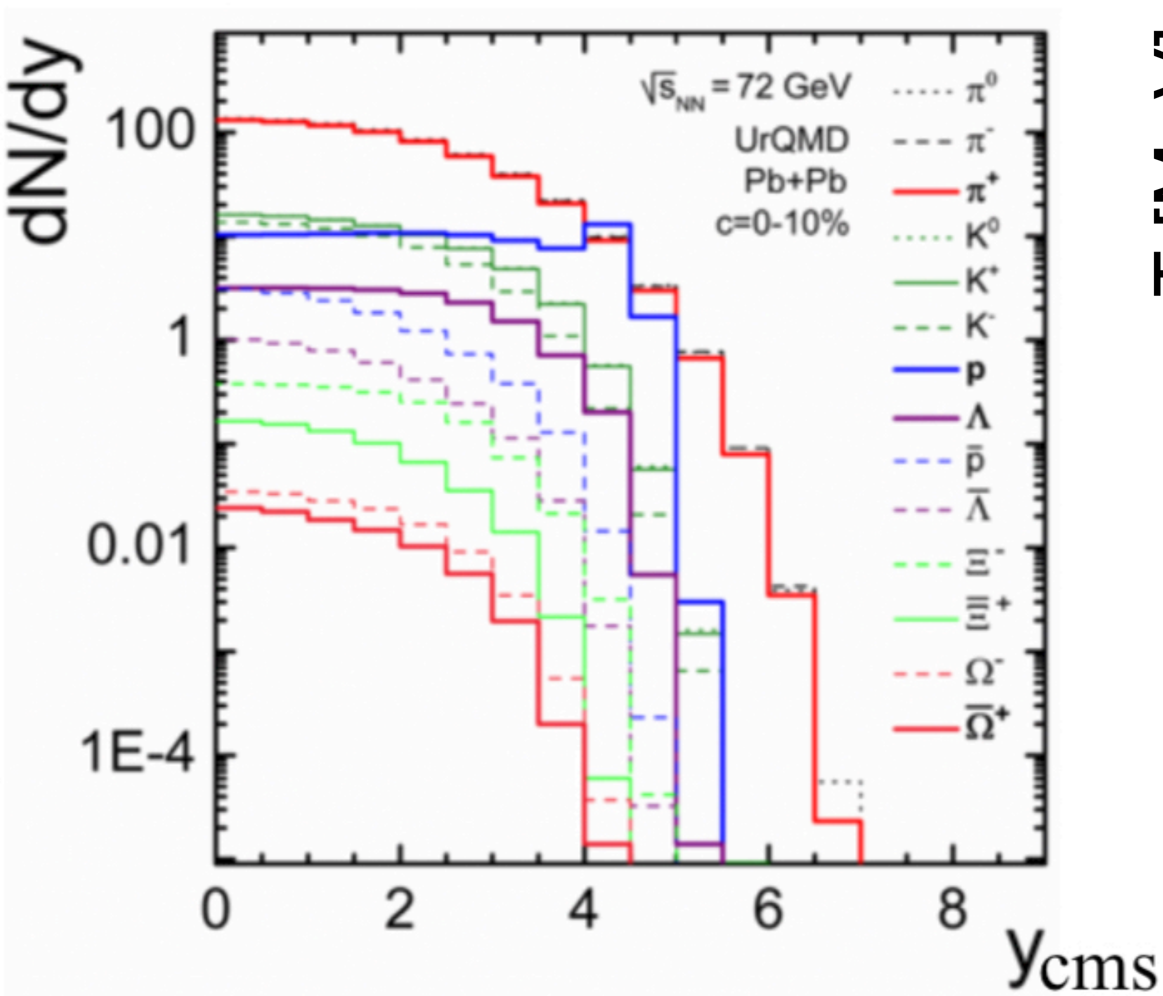


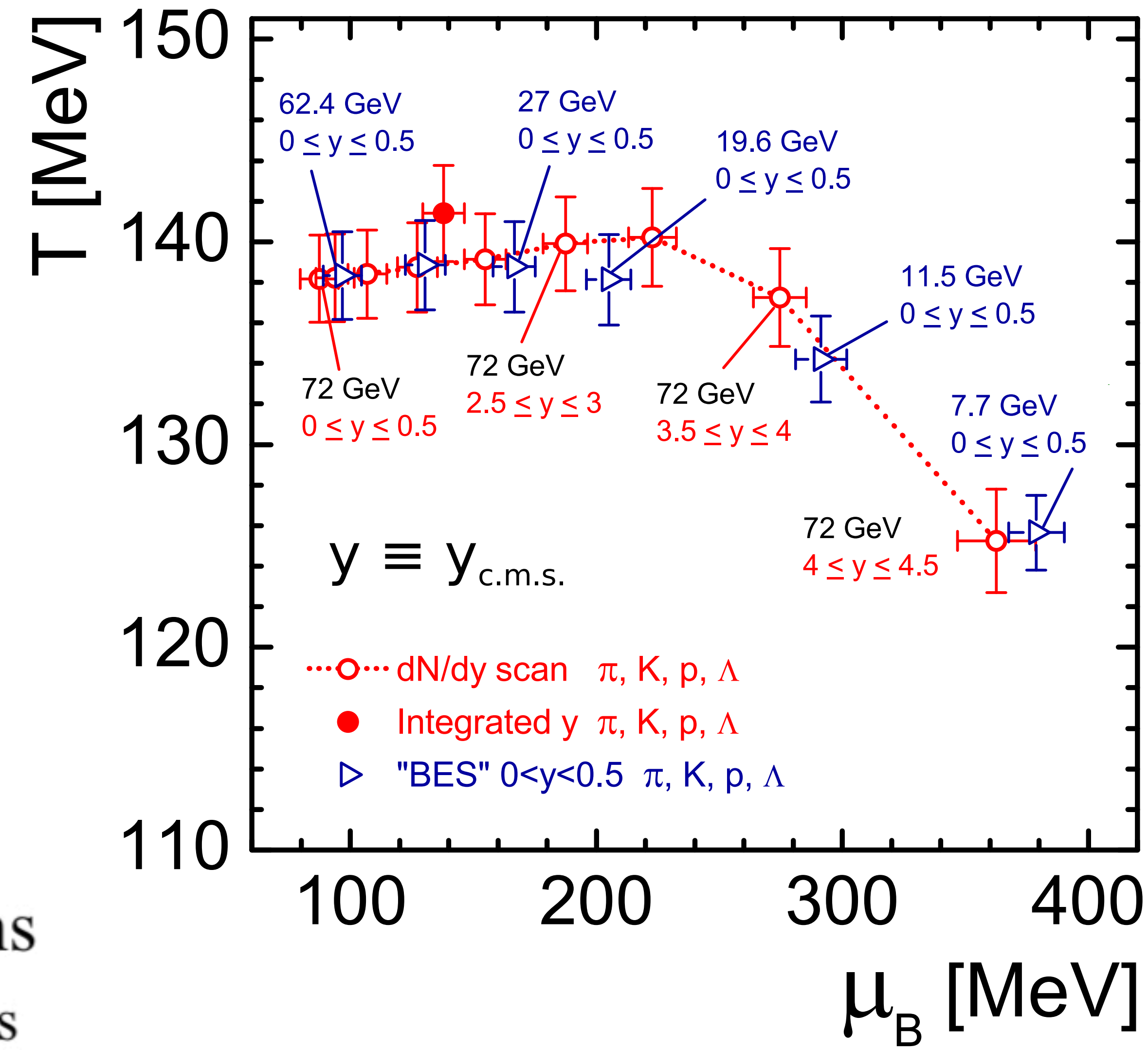


- EPOS simulation inputs in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 72 GeV
- 100 M min. bias events collected in few hours of PbA data taking with a wire target
- Identified soft particles in ALICE central barrel: access to the target rapidity region in a complementary region to LHCb
- PID and tracking efficiency not accounted for
- Statistical projection in ALICE central barrel with $z_{target} = 0$: larger yield if $z_{target} << 0$
- Absolute statistical accuracy better than 0.01 for π and protons, 0.02 for K, 0.05 for antiprotons in 20-30% centrality range

QGP: Identified charged particles in Pb-A

V.Begun et al. arXiv:1806.01303 (see also *I.Karpenko arXiv:1805.11998* based on vHLLE+UrQMD)





- dN/dy from UrQMD model for light hadrons
- Fitted by hadron resonance gas (HRG) model
- System temperature at freeze-out (T) and baryonic chemical potential (μ_B) extracted from the fit
- Rapidity scan from c.m.s mid- to target rapidity provide a scan of μ_B (and of the QCD phase diagram) at fixed collision energy, according to this model. Complementary to the Beam Energy Scan at RHIC

Conclusion

- Physics opportunities by using ALICE in a fixed-target mode with the proton and lead LHC beams are being explored within the ALICE Collaboration (very low man-power nevertheless!)
- The **wide rapidity coverage**, from the target fragmentation region to the center-of-mass mid-rapidity, and the reconstruction of events in **high-multiplicity Pb-A events** are the main strengths of the ALICE detectors
- **First performance studies** for a selection of probes from p-p to heavy-ion collisions have been initiated for three physics motivations: **nucleon and nuclear structure at high-*x* and astroparticle, spin and QGP physics.**
- The fixed-target system **technology** as well as the target location and its integration is under investigation

Thanks