# ALICE Fixed-Target

## Recent progress and status

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PBC WG meeting, 5-6 November 2019, CERN

# Recent news

- Contribution submitted in Dec. 2018 to European Particle Physics Strategy Update 2018-2020
  CERN-PBC-Notes-2019-004 : http://cds.cern.ch/record/2671944/files/PDF%20document%20submitted%20to%20ESPP%20strategy%20update.pdf?version=1
- Informal meeting in presence of ALICE technical coordination with LHC vacuum and impedance experts (Mar. 2019)
  https://indico.cern.ch/event/801807/
- Project discussed during ALICE technical board (Mar. 2019): https://indico.cern.ch/event/750575/
- Organisation of regular monthly ALICE fixed target meeting since Sept. 2019: https://indico.cern.ch/category/11595/
- Workshop on Fixed-Target Physics at the LHC (7-8th Mov. 2019) / KickOff of the STRONG2020 european joint research activities related to fixed-target projects: https://indico.cern.ch/event/853688/
- Working on the preparation of a calendar for the project

# Physics motivations for a fixed-target setup in ALICE

- Three main physics goals identified (see arXiv:1807.00603):
  - Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon and nucleus
    - ✓ Structure of nucleon and nuclei at large-x poorly known
    - ✓ Study possible gluon EMC effect in nuclei
    - ✓ Existence of possible non-perturbative source of c/b quarks in the proton : useful for HE neutrino and CR physics
  - Advance our understanding of the dynamics and spin of gluons inside polarised nucleons (with a polarised target)
    - ✓ Limited understanding of nucleon spin structure
    - ✓ Test TMD factorization formalism
  - Study heavy-ion collisions between SPS and RHIC energies towards large rapidities
    - ✓ Explore the longitudinal expansion of QGP formation
    - ✓ Study collectivity in small systems with new probes thanks to high luminosity (heavy quarks)
    - ✓ Test factorization of CNM effects with Drell-Yan

# Fixed-Target implementation in ALICE

- **Beam splitted thanks to a bent crystal + a solid target inside ALICE :**
  - Halo particles deflected by a bent crystal (~70m upstream ALICE) sent onto an internal solid target in the ALICE cavern
  - Particles not interacting with the target need to be absorbed

- Possibility to use a (polarised) gas target also considered (Varsaw group, STRONG2020)

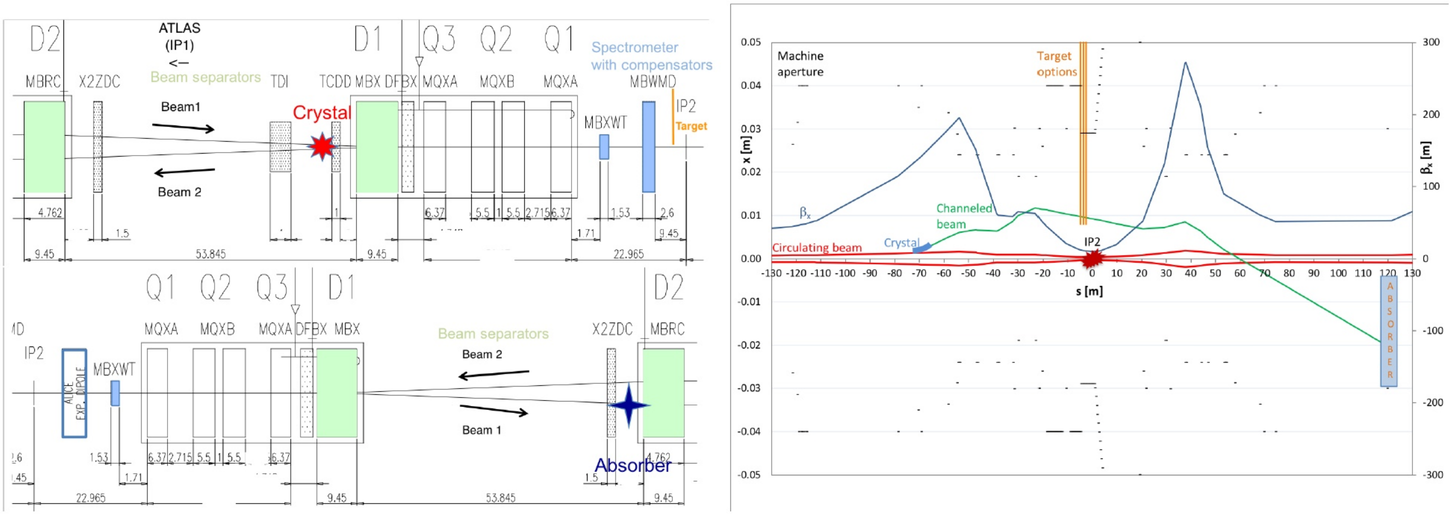



Figure 1: Left: A possible layout for an internal fixed-target experiment at the LHC: a bent crystal is used to deflect the beam halo onto an internal solid target. Right: Particle trajectories for an internal fixed-target experiment: a bent crystal splits and deflects the halo (green) from the circulating beam (red), and sends it on an internal target (orange) placed in front of the ALICE detectors; the non-interacting channeled particles are caught by an absorber downstream; a safe distance is maintained between the channeled beam (green) and the machine aperture (black).

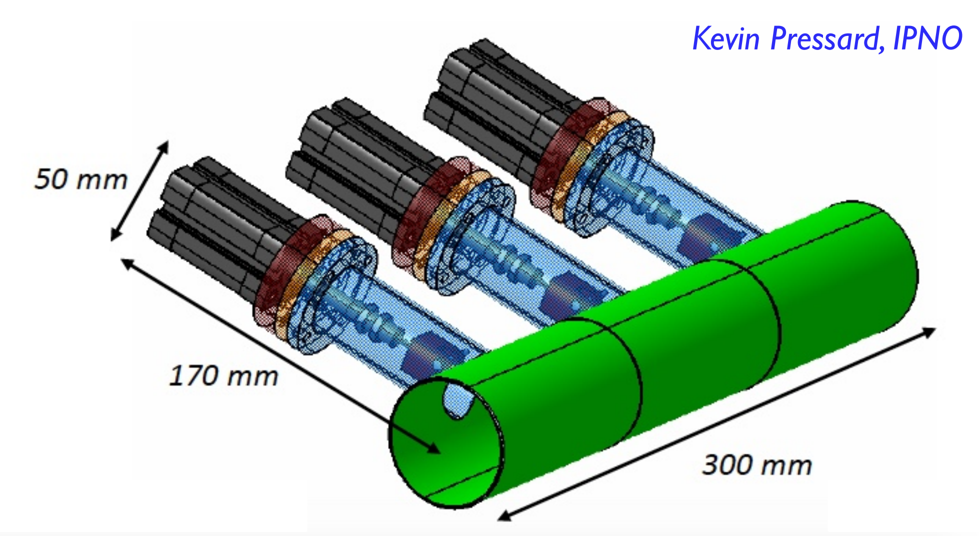
*Simulation of the deflected beam at ALICE IP, F. Galluccio, W. Scandale UA9*

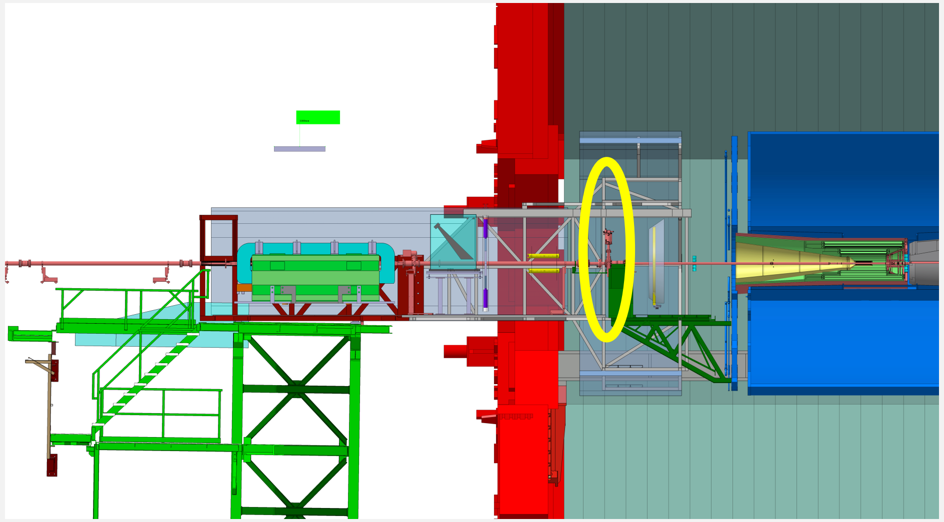
# Target setup and integration constraints

- Target System :
  - Size : 5 mm diameter, 0.2mm to 5mm thickness
  - Target holder : interface between target and motion system (also heat drain)
  - Pneumatic motion system (electromagnetic compatibility)
  - Electro-valve distribution away from setup
- Integration constraints :
  - Need to isolate the pipe region where the target will be located
  - Avoid shadow to existing detector
  - Take into account ITS removal constraints during winter shutdown
  - Need pumping system because of outgassing and bake-out device
  - RF shielding probably needed (need further impedance studies)

➡ Easiest location for installing the target is before the already existing valve at Z ~ - 4.8m on the ALICE A-side

- Output of discussion at the ALICE technical board:
  - Manpower needed for vacuum and impedance work
  - Discussion needed with FOCAL (both projects target LS3 and similar location, solution to be found for the valve)
  - Encourage to pursue the studies on bent crystal (layout, deflected beam intensities) and ALICE TPC tracking performances for displaced verteces

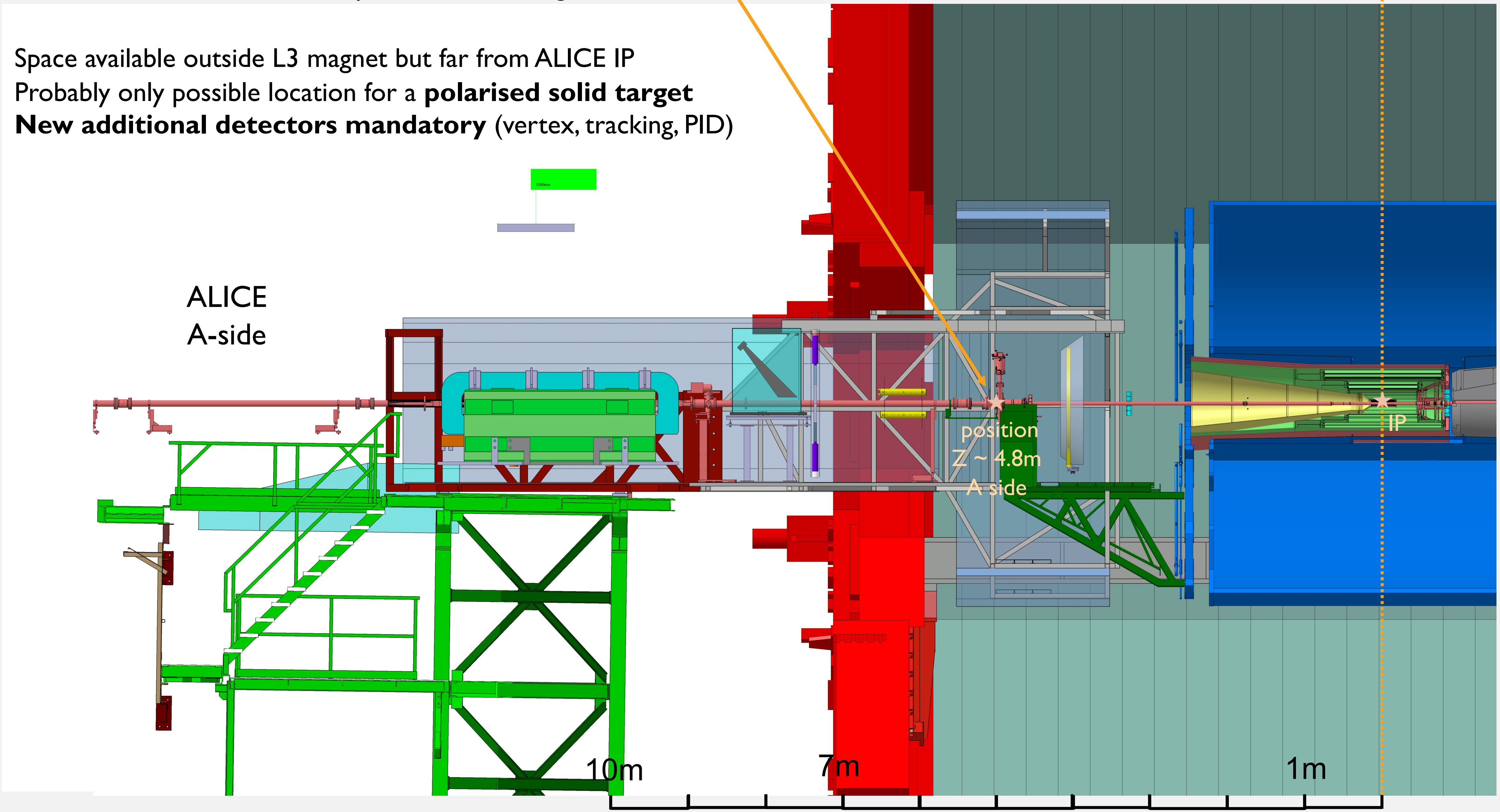


# Possible target location

Favored position from integration studies

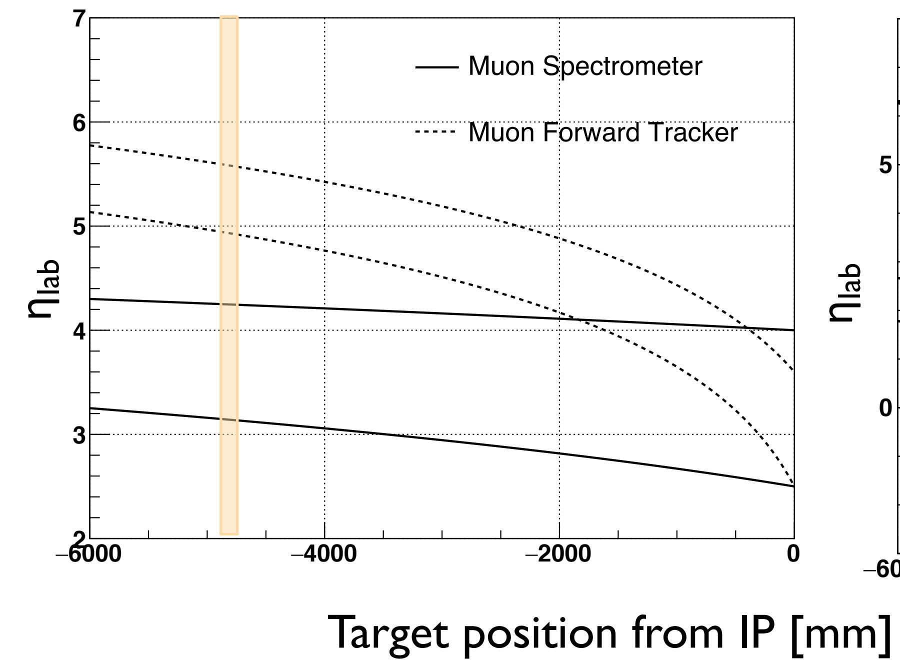
Space available outside L3 magnet but far from ALICE IP
Probably only possible location for a **polarised solid target**
**New additional detectors mandatory** (vertex, tracking, PID)



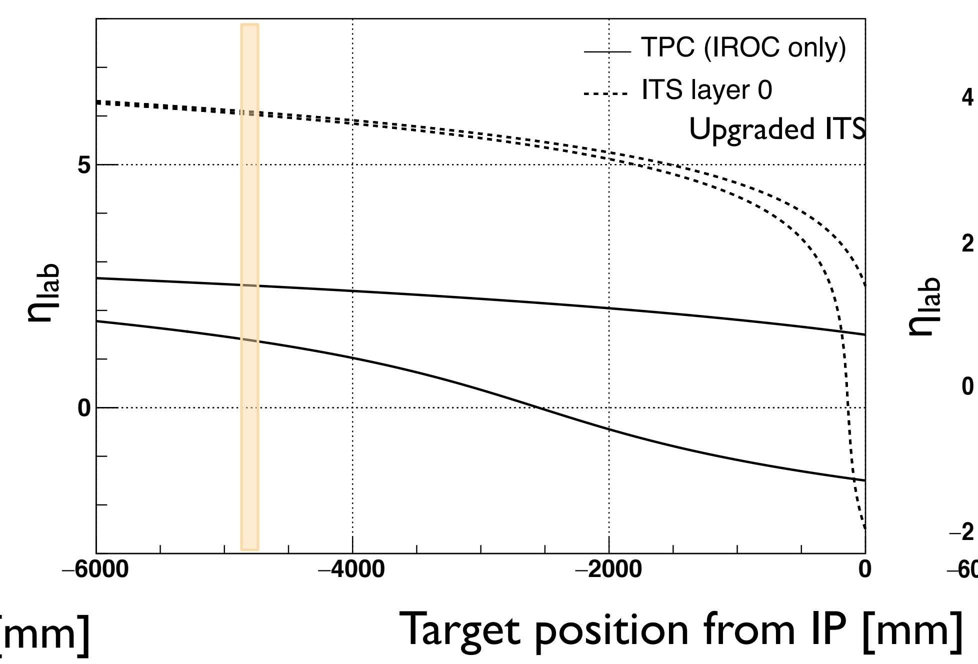
# ALICE detector acceptance vs $z_{target}$

- Considering Z direction negative on A side and forward pseudo-rapidity in the lab defined positively
- Based on simple geometrical considerations

possible target location




possible target location

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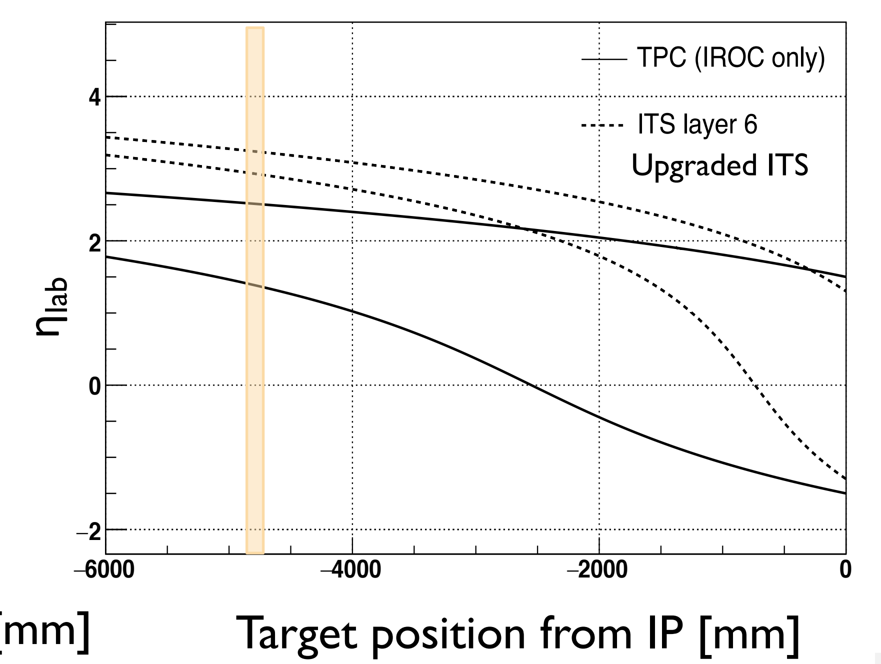



If target at Z << 0, new vertex detector (and probably other detectors) needed

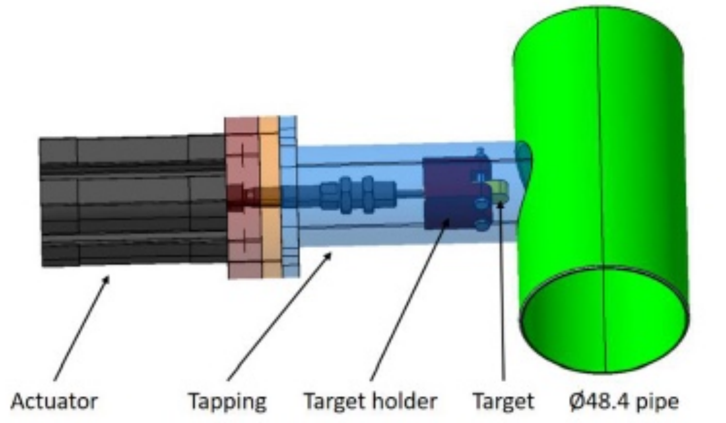
The tracking performances of the TPC and the effect of material budget for large negative Z have still to be studied

At large Z << 0, no acceptance shared anymore between MFT and muon spectrometer

# Target requirements

- Some target requirements to conduct the full heavy-ion programme foreseen:
  - Have a reference system, ie. a target with lowest possible atomic number (ideally pH):
    - ✓ Solid H probably not compatible with LHC vacuum
    - ✓ Lighter target that could be envisonned is probably Beryllium (Z = 4)
  - Have good target versatily : take data with different target species / be able to change frequently the target
  - Have target with large atomic numbers
    - ✓ W might be possible if cooled
    - ✓ Pb probably not usable because of too low melting temperature
  - Other possible target species: Ca, C, Os, Ir, Ti, Ni, Cu
- Target holder and other elements : stainless steel
- Retractable target : active position at 8 mm from the beam axis, parking position out of the beam pipe

*Kevin Pressard, IPNO*



# Achievable luminosities considering ALICE detector rate limitations

| Target | | | ALICE proton beam ($\sqrt{s_{NN}} = 115$ GeV) $\mathcal{L}$ [cm$^{-2}$ s$^{-1}$] | $\sigma_{inel}$ | Inel rate [kHz] | $\int \mathcal{L}$ | Pb beam ($\sqrt{s_{NN}} = 72$ GeV) $\mathcal{L}$ [cm$^{-2}$ s$^{-1}$] | $\sigma_{inel}$ | Inel rate [kHz] | $\int \mathcal{L}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Internal gas target | Gas-Jet | $H^{\uparrow}$ | $4.3 \times 10^{30}$ | 39 mb | 168 | 43 pb$^{-1}$ | $5.6 \times 10^{26}$ | 1.8 b | 1 | 0.56 nb$^{-1}$ |
| | | $H_2$ | $2.6 \times 10^{31}$ | 39 mb | 1000 | 0.26 fb$^{-1}$ | $2.8 \times 10^{28}$ | 1.8 b | 50 | 28 nb$^{-1}$ |
| | | $D^{\uparrow}$ | $4.3 \times 10^{30}$ | 72 mb | 309 | 43 pb$^{-1}$ | $5.6 \times 10^{26}$ | 2.2 b | 1.2 | 0.56 nb$^{-1}$ |
| | | $^{3}He^{\uparrow}$ | $8.5 \times 10^{30}$ | 117 mb | 1000 | 85 pb$^{-1}$ | $2.0 \times 10^{28}$ | 2.5 b | 50 | 20 nb$^{-1}$ |
| | | Xe | $7.7 \times 10^{29}$ | 1.3 b | 1000 | 7.7 pb$^{-1}$ | $8.1 \times 10^{27}$ | 6.2 b | 50 | 8.1 nb$^{-1}$ |
| Beam splitting | Unpol-arised solid target | C (658 $\mu$m) | $3.7 \times 10^{30}$ | 271 mb | 1000 | 37 pb$^{-1}$ | – | – | – | – |
| | | C (5 mm) | – | – | – | – | $5.6 \times 10^{27}$ | 3.3 b | 18 | 5.6 nb$^{-1}$ |
| | | Ti (515 $\mu$m) | $1.4 \times 10^{30}$ | 694 mb | 1000 | 14 pb$^{-1}$ | – | – | – | – |
| | | Ti (5 mm) | – | – | – | – | $2.8 \times 10^{27}$ | 4.7 b | 13 | 2.8 nb$^{-1}$ |
| | | W (184 $\mu$m) | $5.9 \times 10^{29}$ | 1.7b | 1000 | 5.9 pb$^{-1}$ | – | – | - | – |
| | | W (5 mm) | – | – | – | – | $3.1 \times 10^{27}$ | 6.9 b | 21 | 3.1 nb$^{-1}$ |

Assumptions:

| | proton beam | lead beam |
|---|---|---|
| Number of bunches in the LHC | 2808 | 592 |
| Number of particles per bunch | $1.15 \times 10^{11}$ | $7 \times 10^{7}$ |
| LHC Revolution frequency [Hz] | | 11245 |
| Particle flux in the LHC [s$^{-1}$] | $3.63 \times 10^{18}$ | $4.66 \times 10^{14}$ |
| LHC yearly running time [s] | $10^{7}$ | $10^{6}$ |
| Nominal energy of the beam [TeV] | 7 | 2.76 |
| Fill duration considered [h] | 10 | 5 |
| Usable particle flux in the halo (when relevant) [s$^{-1}$] | $5 \times 10^{8}$ | $10^{5}$ |

- ❑ ALICE runs the full year in fixed target mode
- ❑ Maximum readout rate considered 1MHz in pp/pA collisions and 50kHz in PbA
- → higher rate could be envisoned in fixed-target mode depending on detector occupancy (factor ~2 Pb/Xe, factor ~10 pH)

Proton flux to be (re)considered from recent studies: $10^6$ p/s (could potentially be increased to $10^7$ p/s) CERN-PBC-REPORT-2019-001

Decrease of the flux can be compensated by increasing the target thickness

eg: pC ($\Phi = 10^6$ p/s, length = 1cm, $L_{int} = 1.1$pb$^{-1}$)

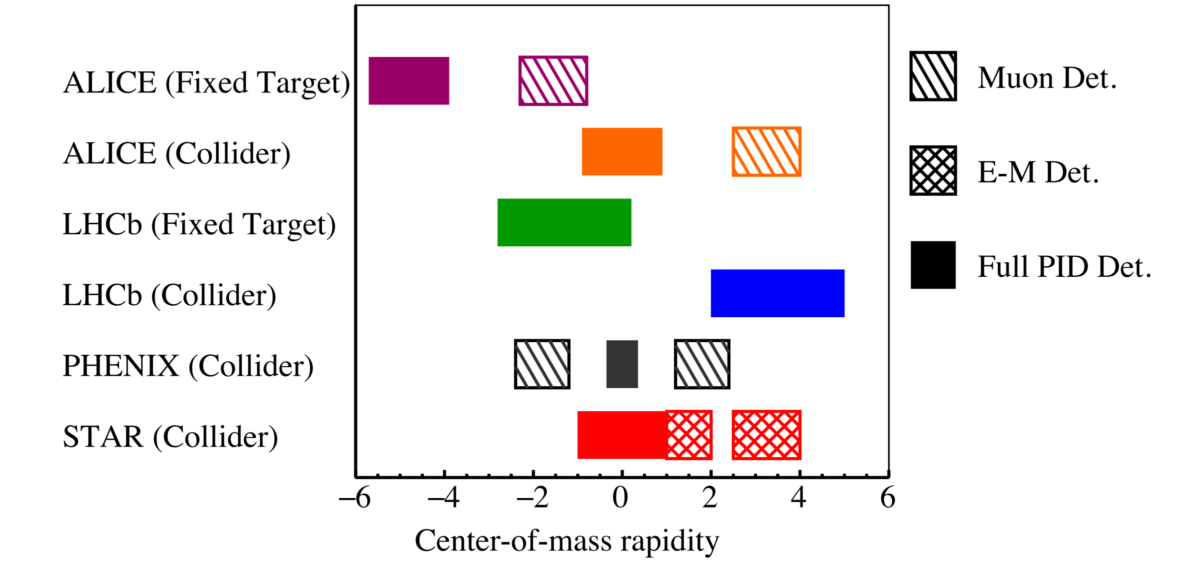
Extraction of Pb beam with bent crystal needs further studies (crystal location (primary/secondary/tertiary halo), composition in terms of species of the channelled ion beam…)

Phys. Lett. B703 (2011) 547–551 (UA9 studies with Pb beam)

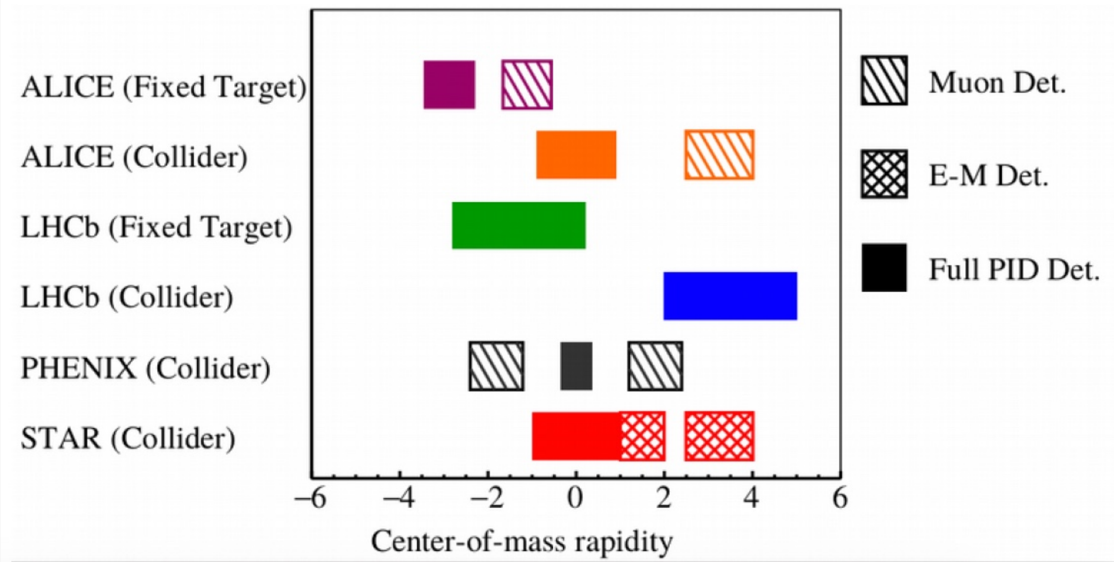
# Main strengths of the ALICE detector in fixed-target mode

- Large rapidity coverage
  - ALICE muon arm (+ future MFT) access the mid- to backward- rapidity region ($y_{c.m.s}$<0)
    - ✓ Quarkonium detection down to zero $p_T$
    - ✓ Rejection of background from π and K decays thanks to the absorber : asset for Drell-Yan studies at low energy
  - ALICE central barrel probes very backward region (unique wrt to LHCb)
    - ✓ Excellent PID capabilities, particle detection and identification down to low $p_T$
    - ✓ Caveat: For $Z_{target}$ << 0, ALICE central barrel coverage shifts toward mid-rapidity

ALICE $Z_{target}$ = 0 cm




ALICE $Z_{target}$ = -4.7 m



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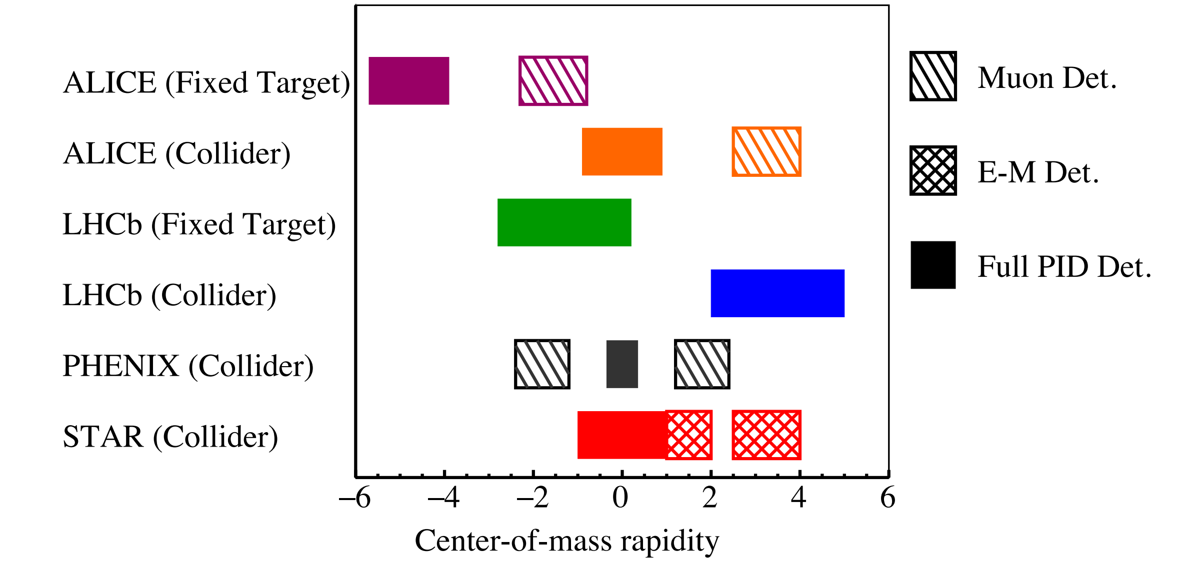
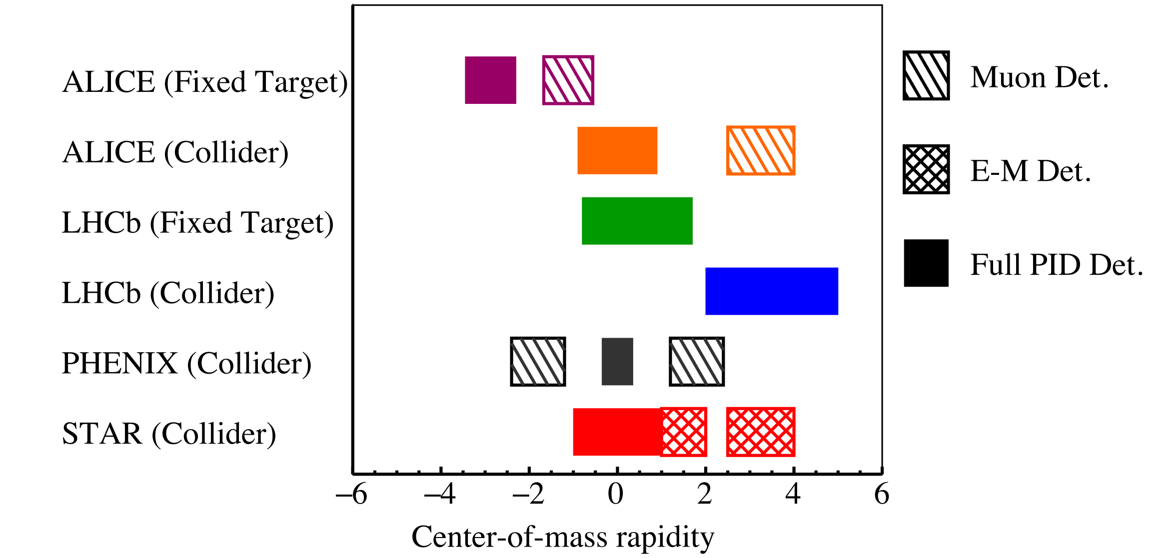



ALICE $Z_{target}$ = -4.7 m, LHCb $Z_{target}$ = -1.5m



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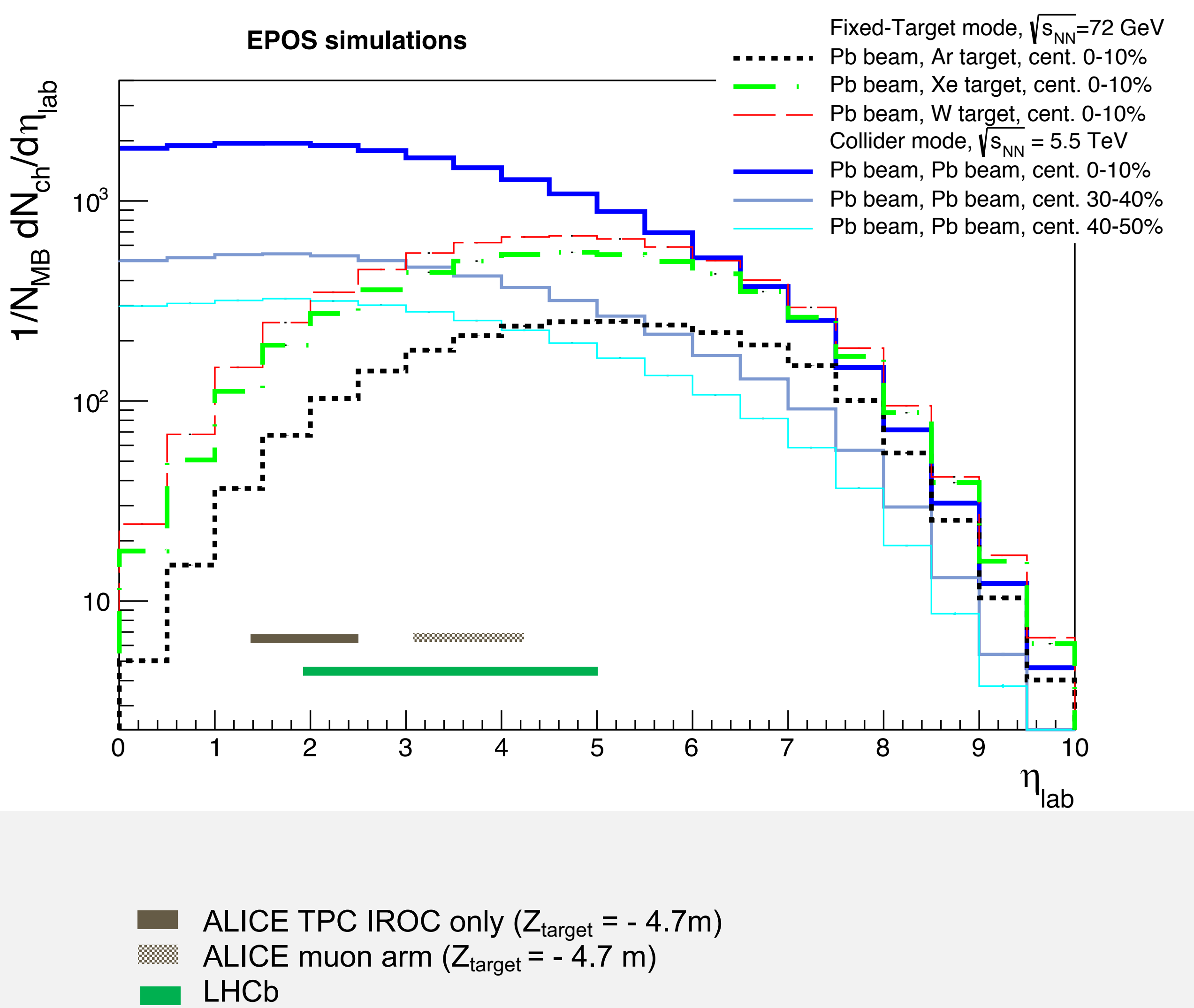



- ALICE can operate with good performance in a high multiplicity environment
- Multiplicities in AA collisions in fixed target mode always smaller than the multiplicity in Pb-Pb collisions (centrality 0-10%) in collider mode at $\sqrt{s_{NN}}$ ~ 5.5 TeV, in the ALICE acceptance
- Multiplicities in most central fixed target Pb-Xe / Pb-W collisions above multiplicity in Pb-Pb collider events for y > 2 (centrality 40-50%) , y > 3.5 (centrality 30-40%)
- Access to most central fixed target AA collisions should be possible with ALICE (if reasonable interaction rate)
- ALICE could potentially devote significant time to a fixed-target programme
  - → Collection of large integrated luminosities
  - → Investigation of several target types

# A selection of physics projections for ALICE Fixed-Target

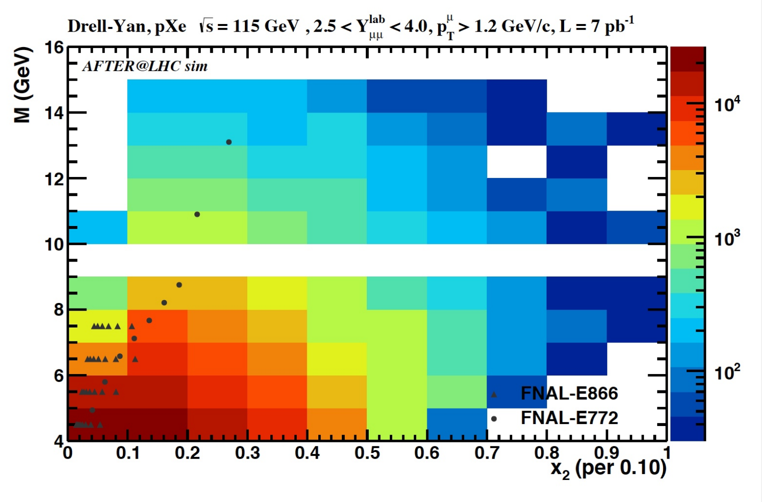
- Updates with reduced luminosity
- Updates for $Z_{target}$ = - 4.7 m
- Simulations for PbW/PbXe instead of PbPb

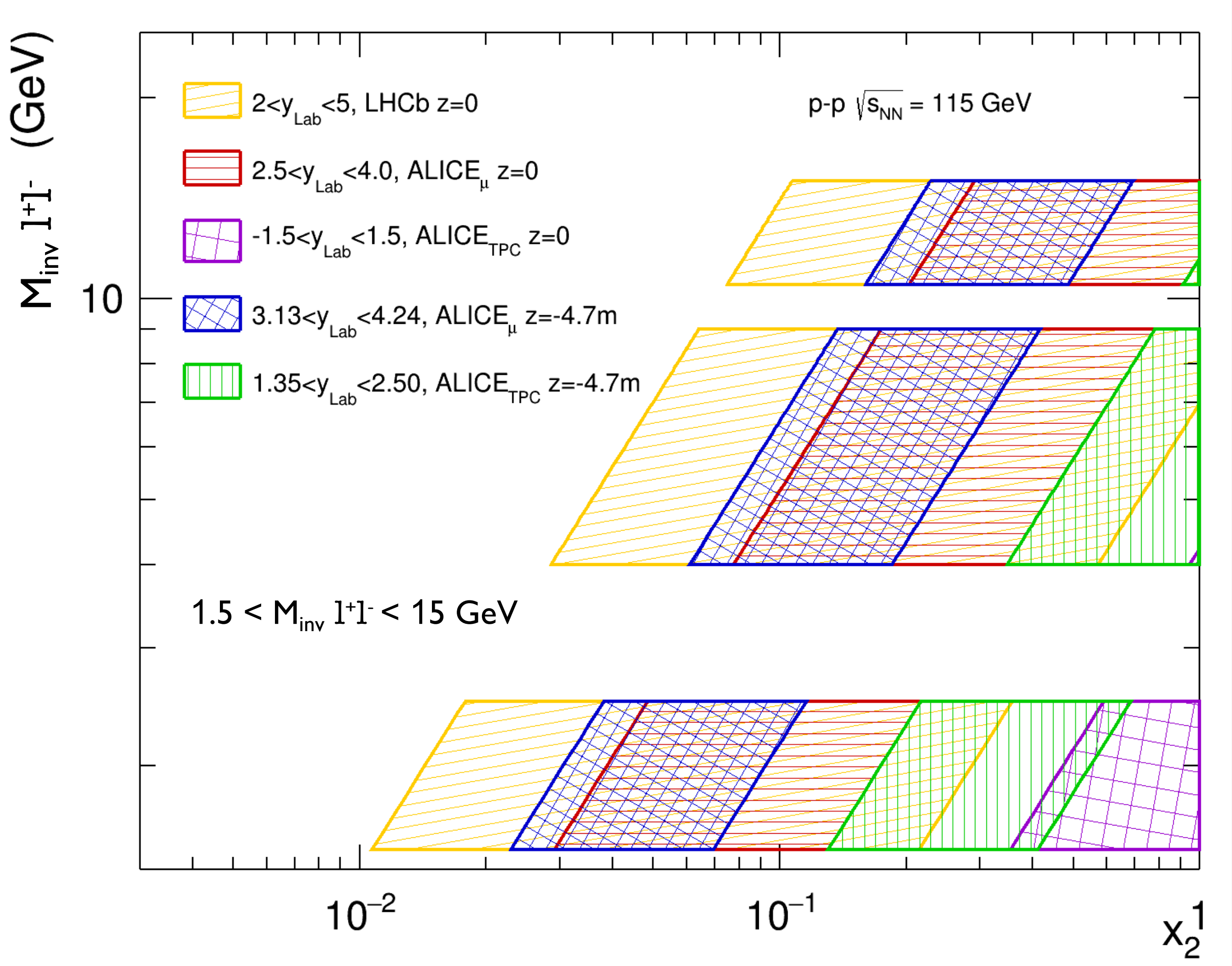
# High-x physics: Drell-Yan to probe the nucleon structure

- DY measurement can constraint the valence and light sea quark PDFs at large-x

- Measurement of DY pairs in the ALICE central barrel would allow measurement up to $x_2 \rightarrow 1$ for intermediate mass Drell-Yan pairs

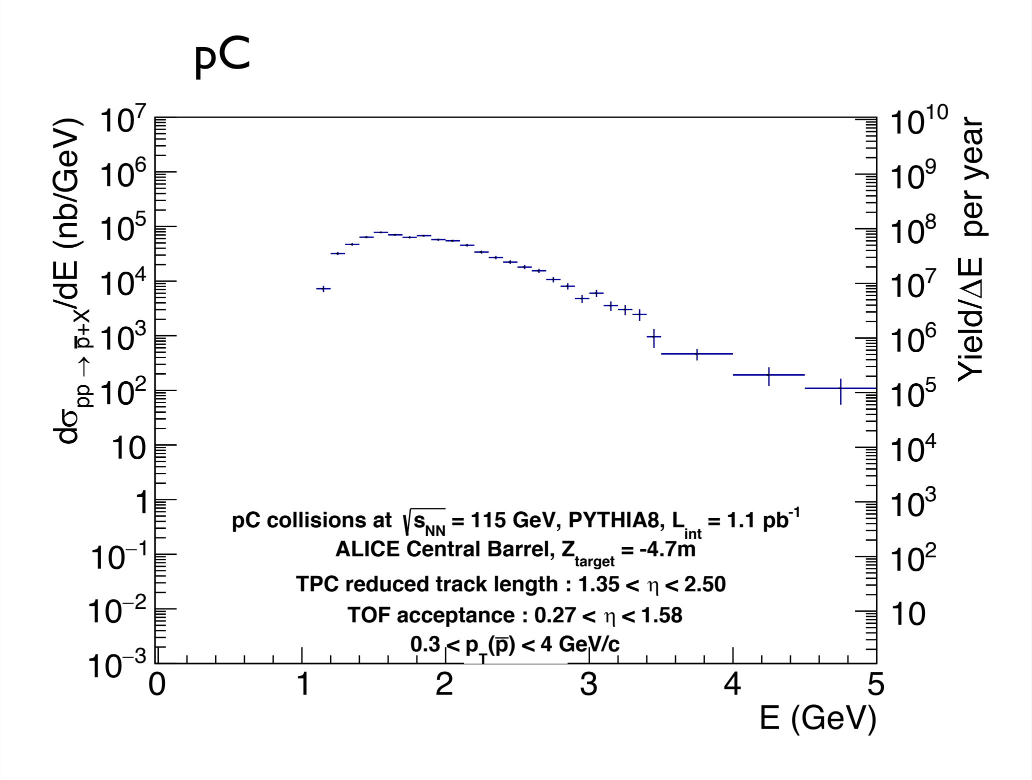
pXe, $Z_{target}$ = 0 (not updated)



# Antiproton production for CR physics

- Antiproton production in pH, pA collisions : important input for astrophysics (Dark Matter searches)
- Constrain models for secondary antiproton production in interstellar medium and be able to confirm excess in data (AMS)
  - **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**
  - Complementary measurement with respect to LHCb

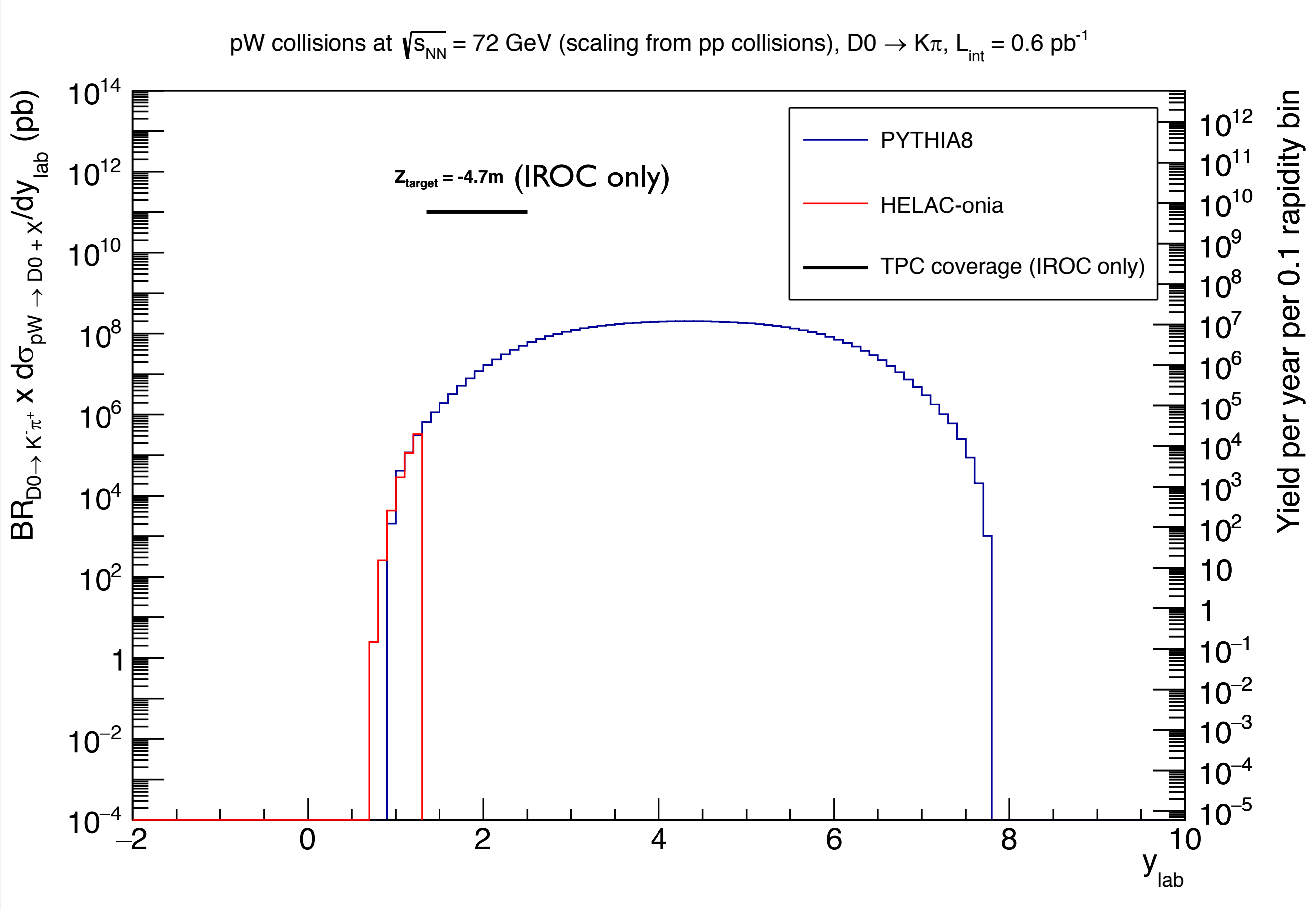



- Minimum bias pp collisions scaled to pC
- "ALICE-like" detector performances (central barrel)
- $Z_{target}$ = - 4.7m
- Reduced yearly luminosity ($L_{int}$ = 1.1pb$^{-1}$) :
  - proton flux deflected by bent crystal : **10$^6$ p/s**
  - Target length : 1 cm

➡ ALICE CB is accessing the very low energy domain for antiproton production
Large yearly yields expected

# High-x and HI physics : Open heavy flavours

- Study large-x gluon nPDFs [assuming modification of nPDF is the dominant Cold Nuclear Matter effect, also need pH reference]
  Phys.Rev.Lett. 121 (2018) no.5, 052004
- Search for collective dynamics of partons in small systems at low energy with heavy flavour ($v_2$ of D mesons)



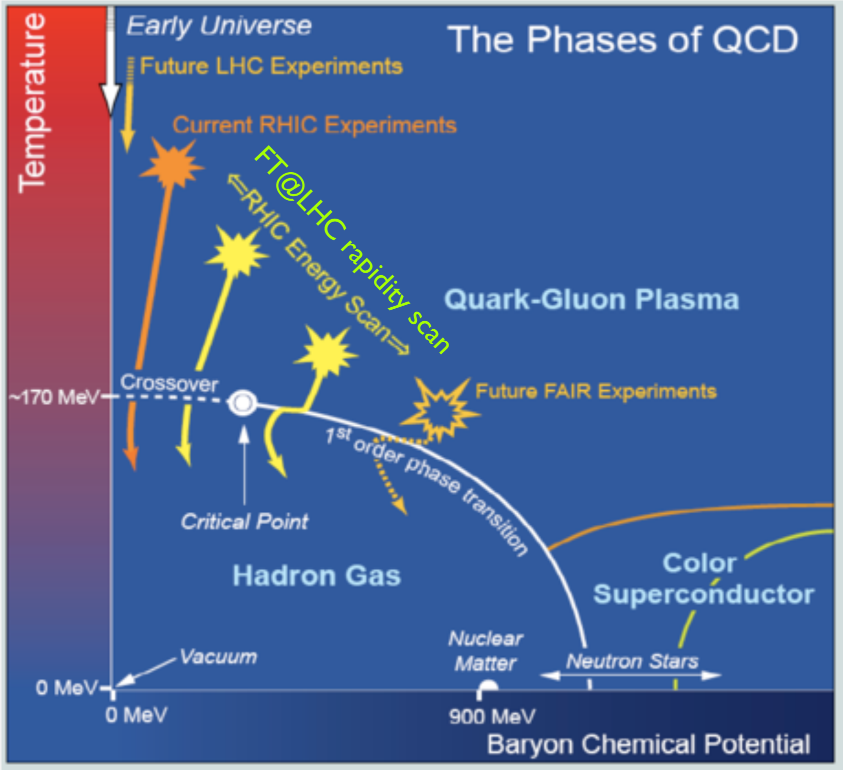

- Hard $c\bar{c}$ pair production in pp collisions scaled to pW
- "ALICE-like" detector performances (central barrel)
- $Z_{target}$ = - 4.7m coverage in black
- Reduced yearly luminosity ($L_{int}$ = 0.6 $pb^{-1}$) :
  - proton flux deflected by bent crystal : **$10^6$ p/s**
  - Target length : 1 cm

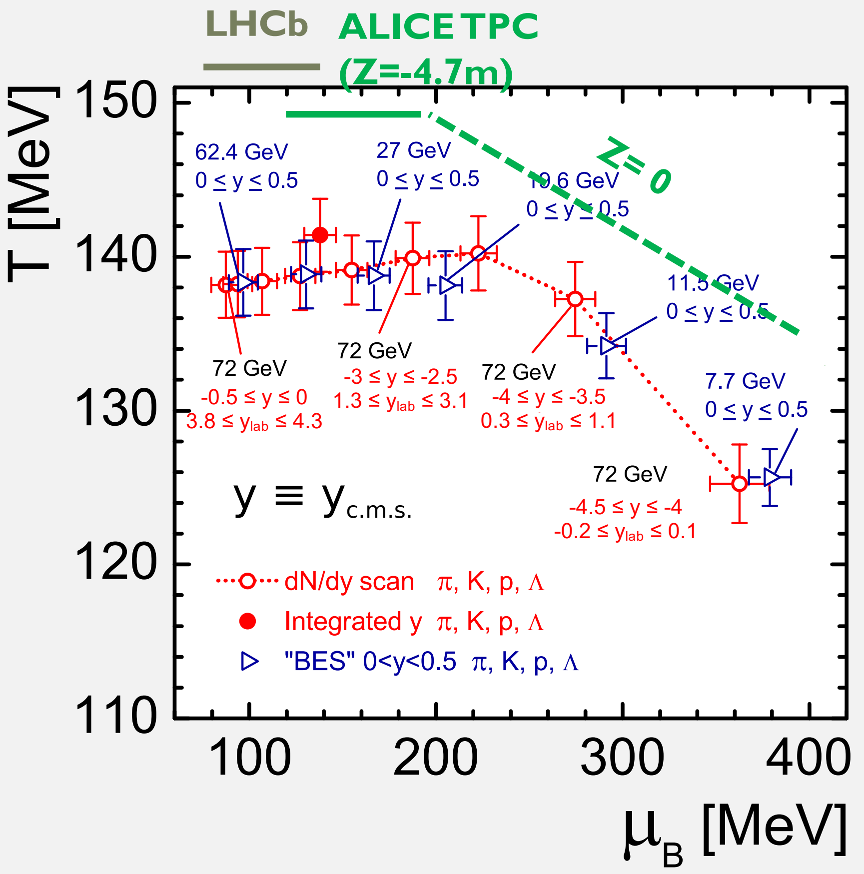
ALICE CB is accessing the very backward domain for D meson production → sensitivity to large-x gluon nPDFs
Large yields for $Z_{target}$ = -4.7 m to allow for $v_2$ measurements

# HI physics : rapidity scan to search for the QCD critical point

- **Advance the understanding of hadronic matter properties under extreme conditions (QGP) and explore the phase diagramme of nuclear matter thanks to a rapidity scan down to the target rapidity**

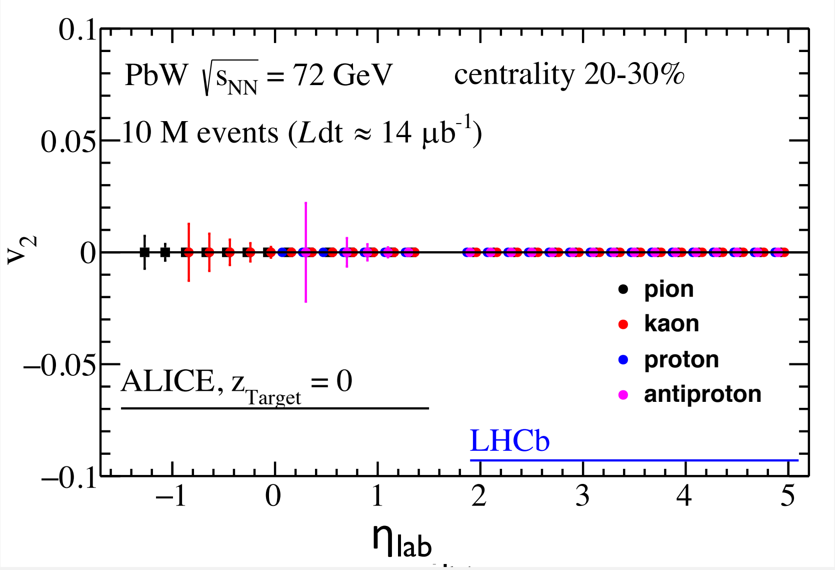
- Systematic studies of the medium properties with three experimental degrees of freedom : rapidity scan, different colliding systems, centrality dependence
- Rapidity scan at 72 GeV with FT@LHC can complement the RHIC beam energy scan from 62.4 GeV down to 7.7 GeV (at $y_{cms}$ ~ 0)
- A novel way to search for the QCD critical point and probe the nature of the phase transition to confined partons

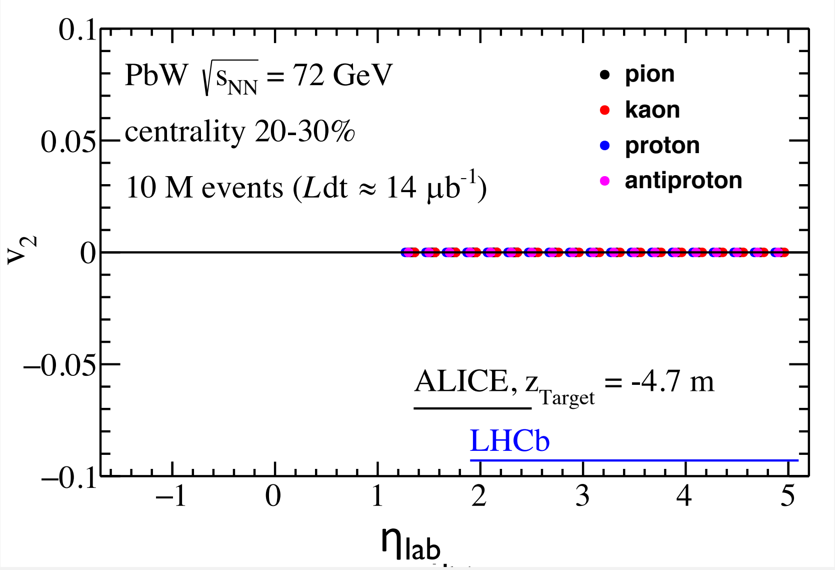



*V. Begun, D. Kikola, V. Vovchenko, D. Wielanek, PRC 98 (2018) 034905*

# HI physics : particle flow coefficient to constrain T dependence of η/s




- **Advance our understanding of QGP macroscopic properties by probing the temperature dependence of the shear viscosity to entropy density ratio (η/s) of the created matter**
  - Thanks to particle yields and flow ($v_N$) coefficients
  - Compare to hydrodanymic models which include the medium longitudinal expansion (ie. not only the transverse dynamics of the QGP at mid-y)
  - Clarification of collective effects between SPS and LHC energies

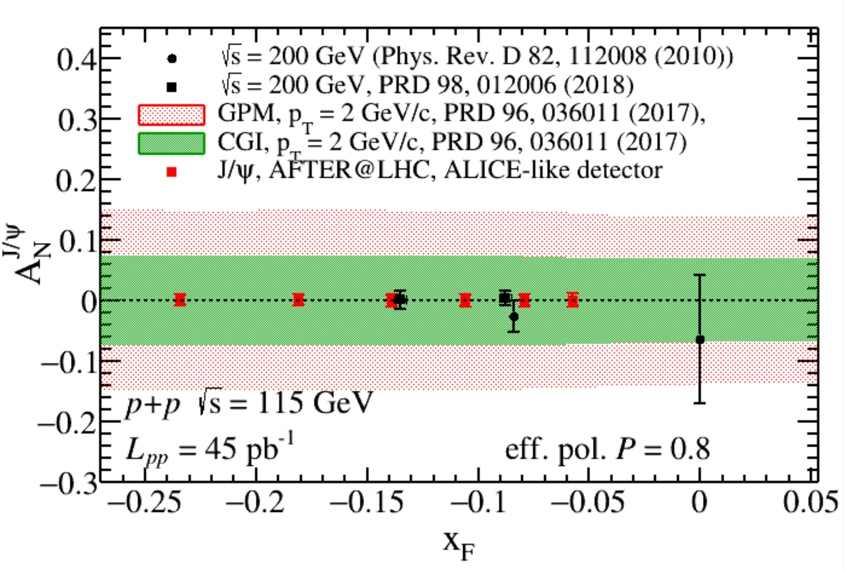
- Pb-W collisions (centrality 20-30%)
- « ALICE-like » and « LHCB-like » detectors
- Update with $Z_{target}$ = -4.7m for ALICE
- 100M MB events (few hours of data-taking)
- Percent level statistical accuracy for the $v_2$ measurement

➡ Study of identified particles in wide rapidity range
Complementary coverage between ALICE and LHCb

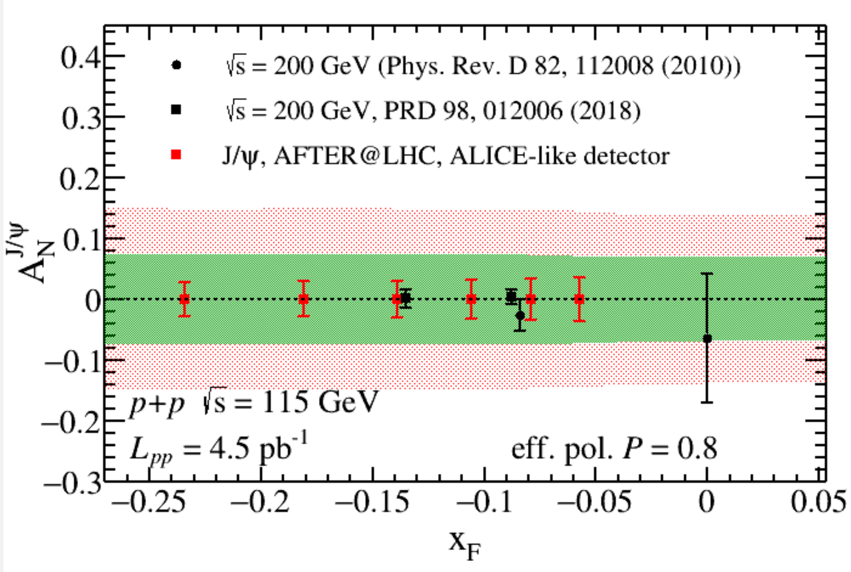
# Spin physics : J/ψ $A_N$ with **polarised target**

- **Probe the gluon Sievers effect over a broad Feynman-x range with gluon sensitive probe (charmonia)**

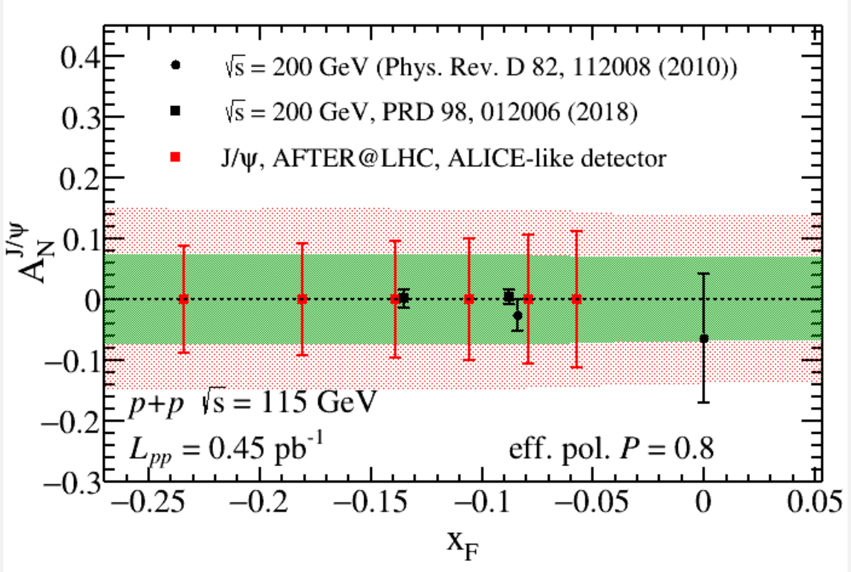
Full luminosity




Reduced luminosity factor 10




Reduced luminosity factor 100

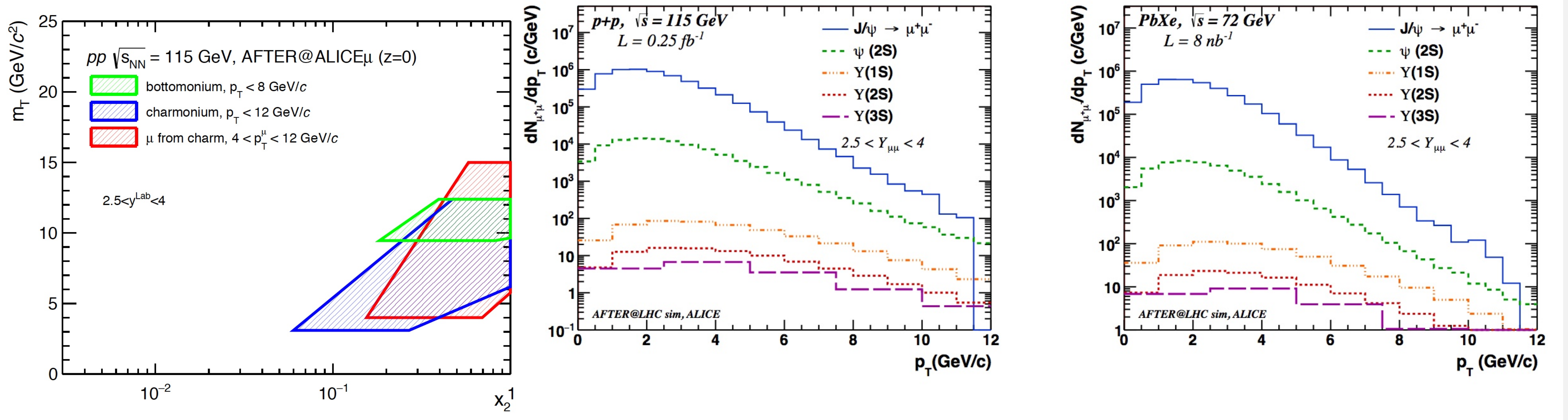



- pH collisions (target polarization P = 0.8)
- "ALICE-like" detector performances (muon arm)
- $Z_{target}$ = 0 (caveat not updated to Z < -4.8m)
- Reduced yearly luminosity by factor 10 and 100

# Other physics projections (not updated)

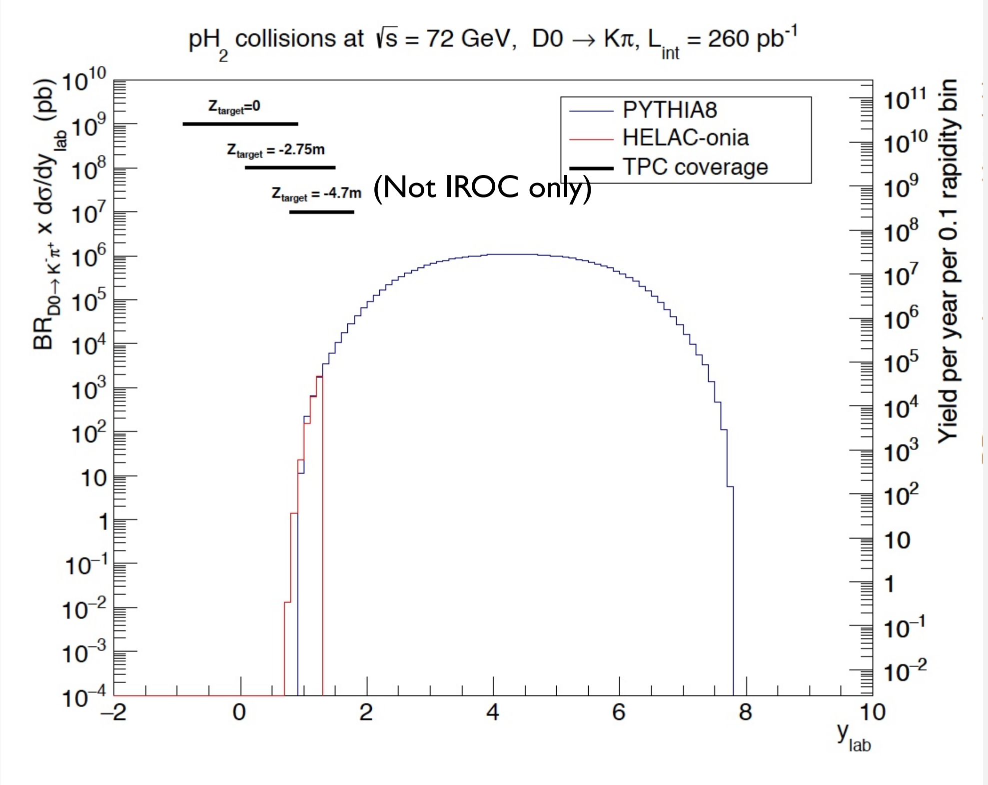
# Quarkonia production in the muon spectrometer

- Sequential quarkonium melting provides insight into thermodynamic properties of deconfined matter
- Abundand production covering an important region in the ($x_2$,$m_T$) plane
- Helac-ONIA simulation inputs (only rapidity cuts on dimuon, tracking/trigger inefficiencies not accounted for), $Z_{target}$ = 0
  - About a «LHC year» of $pH_2$ collisions and a LHC year of PbXe collisions (rate compatible with ALICE detector)
  - Large yelds for charmonia ~ $10^6$ for J/ψ, Υ(1S) at reach, first look at Υ(2S, 3S) already possible both in $pH_2$ and PbXe
  - Quarkonium measurement in central AA collisions unique to ALICE w.r.t LHCb

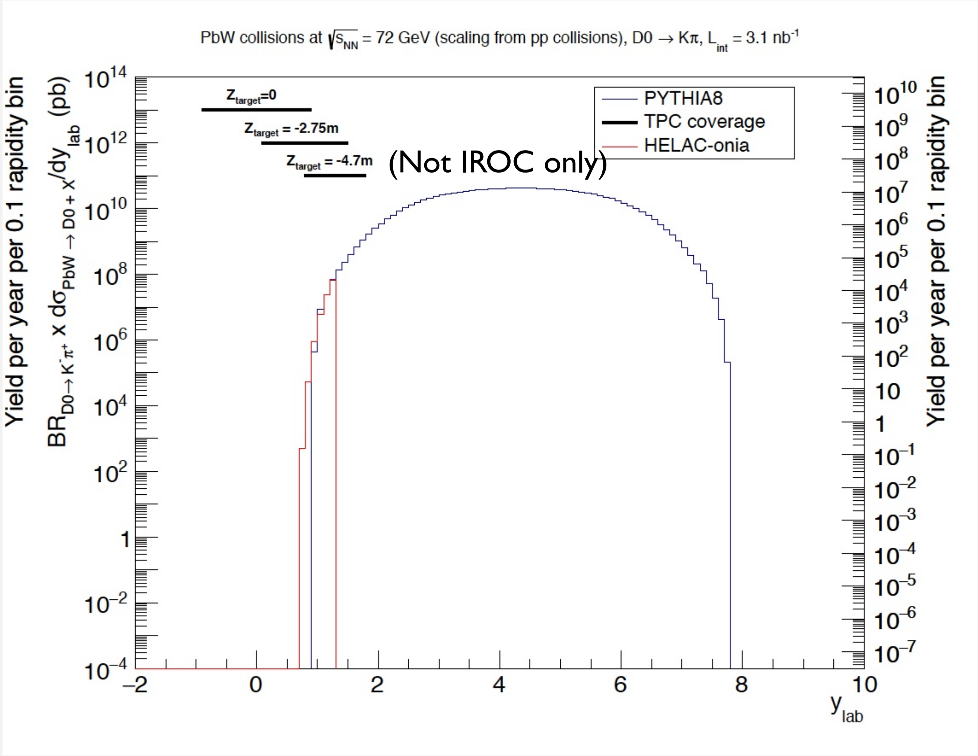


# High-x and HI physics : Open heavy flavour

- ❑ Non-perturbative intrinsic charm component in the proton can modify the D meson yield, especially at backward rapidity
  - ➢ Connexion with high energy cosmic ray physics (prompt atmospheric neutrino flux)

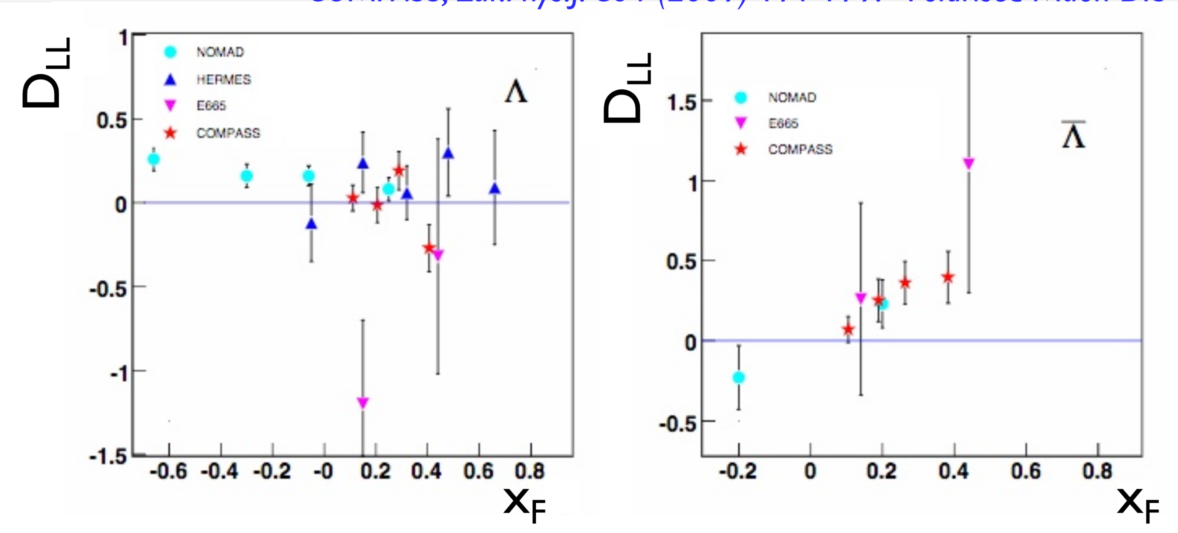



- ❑ Open HF sensitive to the dynamics of the formed medium and could be used to determine fundamental properties of the QGP : charm quark diffusion coefficients
- ❑ Measurements at large rapidities and $p_T$ can help to discriminate between models of heavy quark interactions with the QGP : radiative versus collisional energy loss



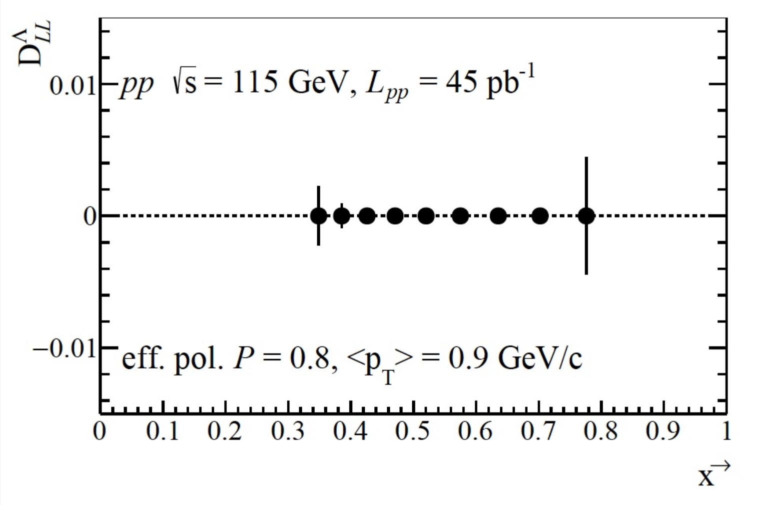
# Spin-physics : strangeness in the central barrel

COMPASS, Eur.Phys.J. C64 (2009) 171-179. Polarised Muon DIS



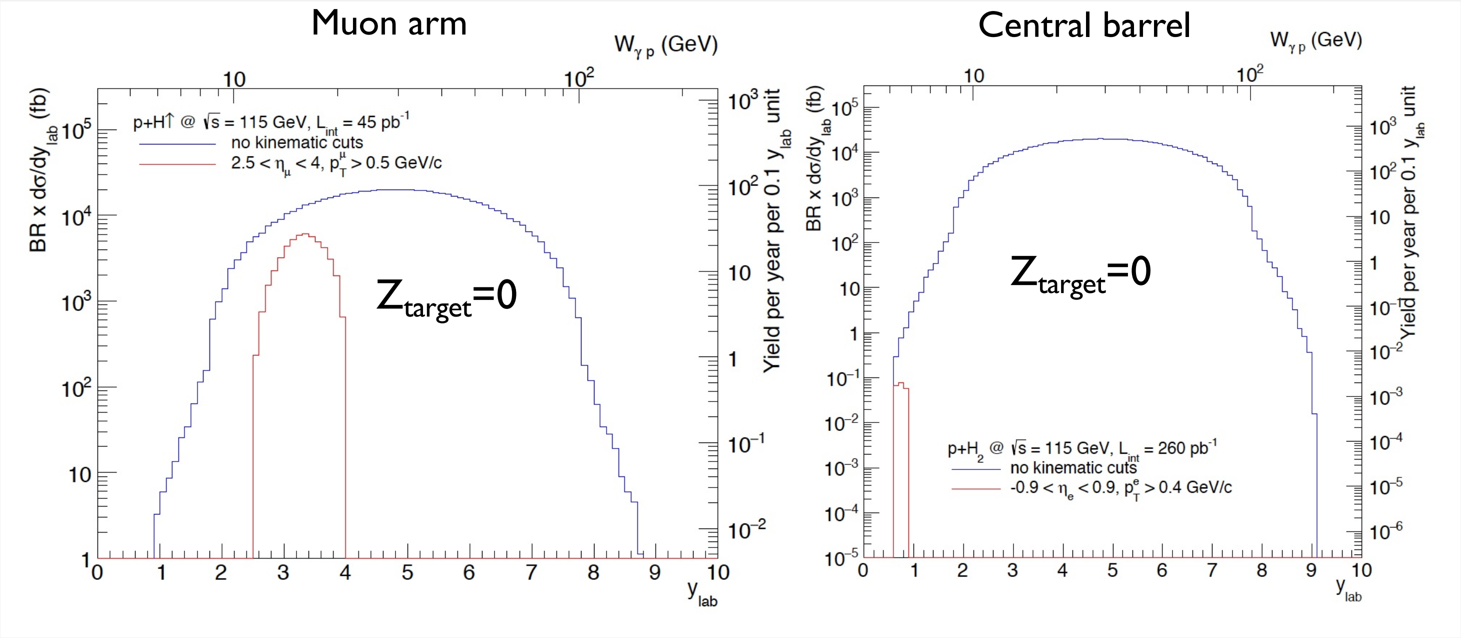

- Understanding of polarised strangeness and anti-strangeness PDFs and their possible asymmetries is an open question
  - Longitudinal spin transfer $D_{LL}$ of $\Lambda$ hyperons permit to access the spin-dependent strange quark (antiquark) density $\Delta s$ and $\Delta \bar{s}$
  - At large negative $x_F$ very little data exists

- Pythia8 minbias simulation, pH↑ collisions, $\sqrt{s}$ = 115 GeV
  - $Z_{target}$ = -4.7 m
  - $L_{int}$ = 45 $pb^{-1}$ one « LHC year » of polarised H↑
  - PID & tracking inefficiencies + decay product geometrical acceptance not accounted for
  - Pseudo-rapidity of the $\Lambda$ within TPC (IROC only) + TOF coverage
  - $p_T(\Lambda)$ > 0.5 GeV/c
  - $10^8$ $\Lambda$ produced per 0.1 rapidity unit, per year at $y_{lab}$~1
  - Sub-percent precision on the $\Lambda$ $D_{LL}$ measurement in the range 0.35 < $x_{target}$ < 0.7



# J/ψ photoproduction in the central barrel and muon arm

- Single transverse spin asymmetry measurement $A_N$ ($\gamma p^{\uparrow} \rightarrow J/\psi p$) gives access to Generalised Parton Distribution (GPD) Eg and to the gluon Orbital angular momentum
- At very backward rapidity access to pentaquark might be possible (don't require polarised target)
  - STARLIGHT simulations of $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ in pp collisions at $\sqrt{s}$ = 115 GeV (both protons are $\gamma$ emitters)
  - One year of data taking with polarised H ($L_{int}$ = 45 $pb^{-1}$) or unpolarised $H_2$ ($L_{int}$ = 450 $pb^{-1}$), $Z_{target}$=0




About 200 $J/\psi \rightarrow \mu^+\mu^-$ produced in the ALICE acceptance in one pH↑ year

Could expect to produce between 2 to 20 pentaquarks per year per 0.1 ylab unit at very backward rapidity in the ALICE acceptance

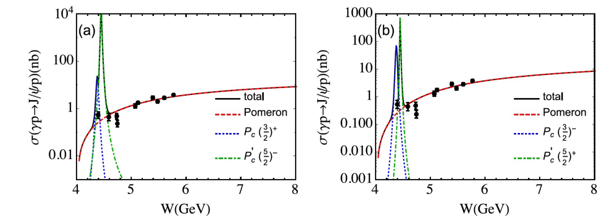



FIG. 3 (color online). The total cross section of $\gamma p \rightarrow J/\psi p$ in terms of the c.m. energy. The red dashed, blue dotted, green dot-dashed and black solid curves are the contributions from Pomeron, $P_c$ with spin 3/2, $P_c$ with spin 5/2 and the coherent sum of all. (a) shows $(3/2^+, 5/2^-)$ combination. (b) shows $(3/2^-, 5/2^+)$ combination. The coupling constants [Eq. (21)] between $J/\psi p$ and the two $P_c$ states are extracted by assuming $J/\psi p$ saturates all their total widths. The experimental data are from Refs. [24–26].

Photoproduction of hidden charm pentaquark states Pc+ (4380) and Pc+ (4450), *Phys. Rev. D 92, 034022 (2015)*
S/B ratios ~ $10^3$ – $10^4$ depending on the state and coupling

# Conclusion

- **Three main physics goals identified to motivate a fixed-target programme at the LHC**
  - High momentum fraction x frontier in nucleon and nuclei
  - Spin and 3D nucleon structure
  - Heavy ion collisions at large rapidities

- **Integration studies of a target setup pursued in ALICE**
  - Technology currently studied : a slow extraction with a bent crystal coupled to a solid target
  - Possible target location identified

- **Fast simulation work has been performed to provide figures of merit for ALICE for a selection of observables (Drell-Yan, Open-HF, quarkonia,  antiproton, identified particles)**

- **Next steps**
  - Impedance and vacuum studies in collaboration with LHC experts
  - Test of the crystal + target system at SPS in Collaboration with UA9
  - Simulation of the TPC performances for displaced verteces