A fixed-target programme at the LHC for heavy-ion, hadron, spin and astroparticle physics

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Outline

A high luminosity Fixed Target ExpeRiment at the LHC

- Kinematic features and advantages
- Physics motivation
- Technical implementations and luminosities with LHC beams
  - ALICE and LHCb
- Selection of physics opportunities and projected performances

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

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AFTER@LHC Study group:
http://after.in2p3.fr/after

Kinematic features

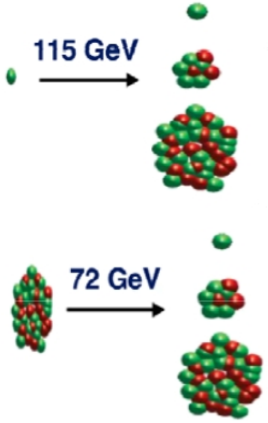
➔ Energy range

7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s} = \sqrt{2 m_N E_p} \approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	

2.76 TeV Pb beam on a fixed target

c.m.s. energy:	$\sqrt{s_{NN}} = \sqrt{2 m_N E_{\mathrm{Pb}}} \approx 72\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	



- √s in-between SPS and top RHIC

Kinematic features

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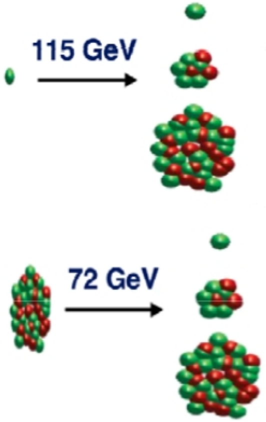
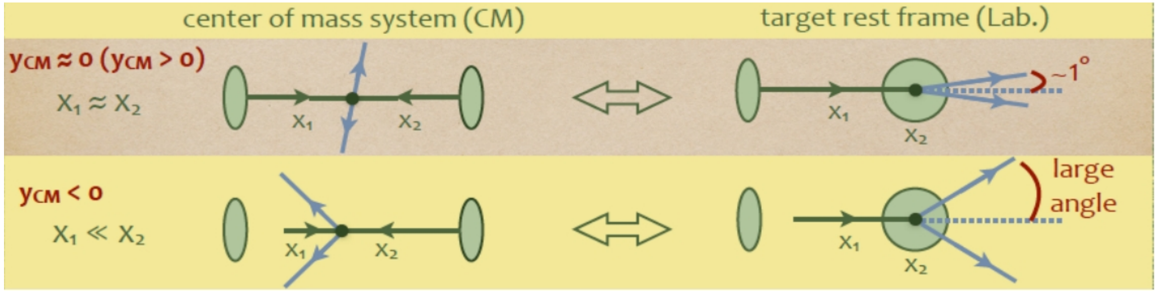


- √s in-between SPS and top RHIC

→ Effect of boost



- Entire forward hemisphere, $y_{cms} > 0$, within 1 degree
- **Easy access to (very) large backward rapidity range, $y_{cms} < 0$**
- **And large parton momentum fraction $x_2 \rightarrow 1$ ($x_F \rightarrow -1$)**

$$[|x_F| \equiv \frac{|p_z|}{p_{z\,\max}} \rightarrow 1]$$

Kinematic features

→ **Energy range**

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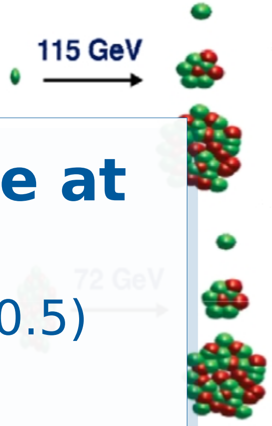
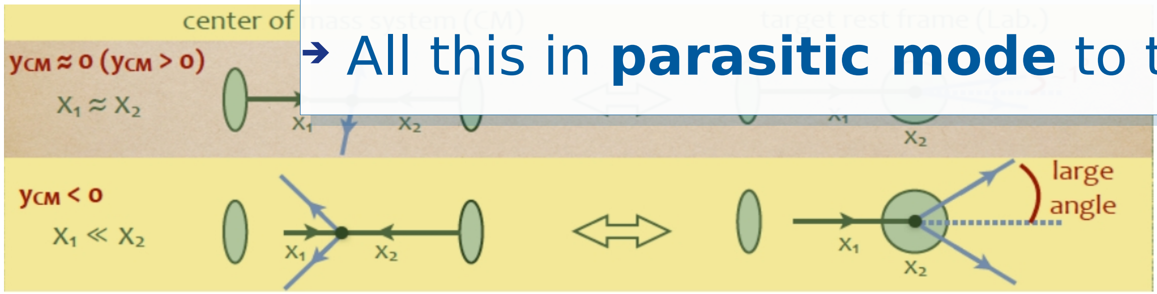


- $\sqrt{s}$ in-between SPS and top RHIC

→ **Effect of boost**



- Entire forward hemisphere, $y_{cms} > 0$, within 1 degree
- **Easy access to (very) large backward rapidity range, $y_{cms} < 0$**
- **And large parton momentum fraction $x_2 \to 1$ ($x_F \to -1$)**

$$[|x_F| \equiv \frac{|p_z|}{p_{z\,max}} \to 1]$$

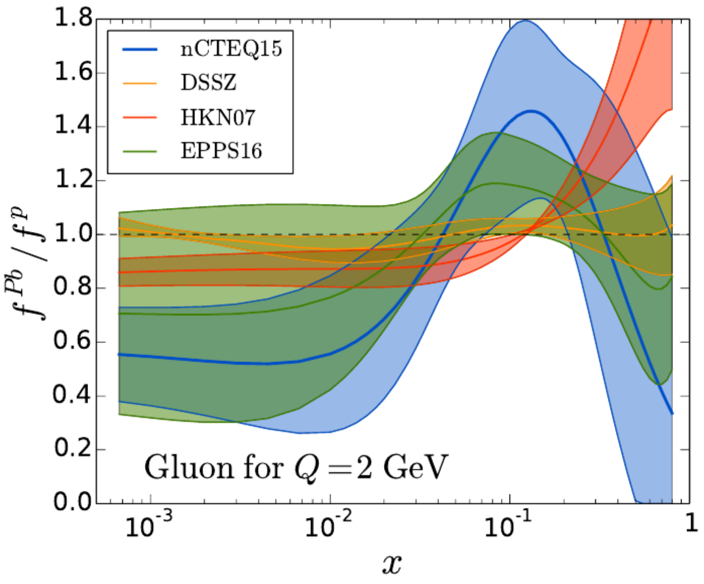
Advantages of a fixed-targed mode at the LHC

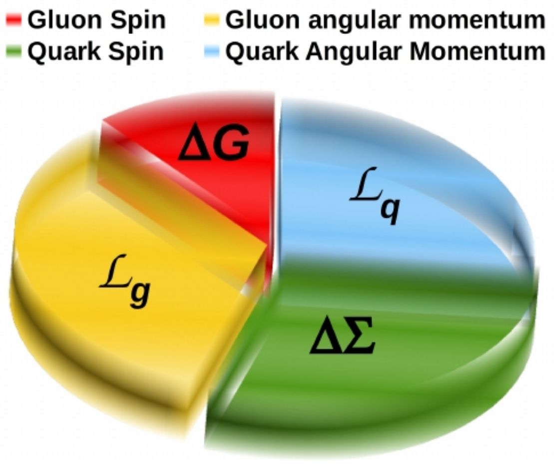
- Accessing **high-x frontier** ($y_{cms} < 0$ and $x > 0.5$)
- Achieving **high luminosities**
- Varying **atomic mass number** of the target
- **Target polarisation**

→ All this in **parasitic mode** to the LHC collider

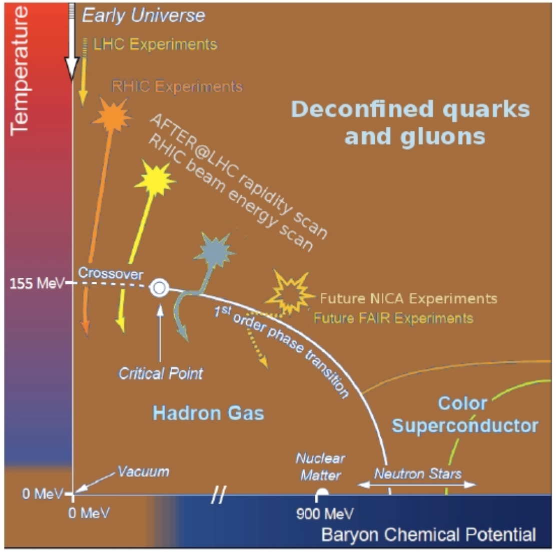
Physics motivations

- Advance our understanding of the **high-x frontier in nucleons and nuclei** (gluon and heavy-quark content) **and its connection to astroparticle physics**
- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
- Studies of the **quark-gluon plasma** in heavy-ion collisions at a new energy domain down to the target-rapidity region





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$

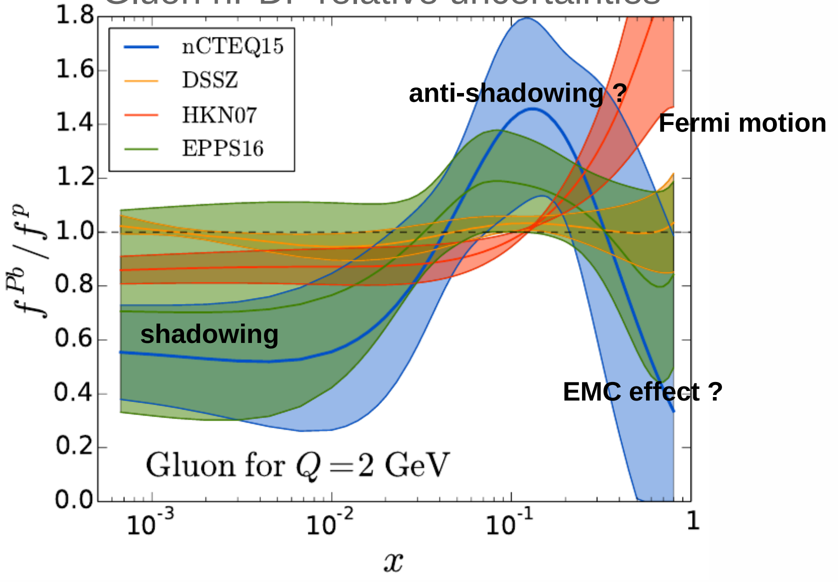


Physics case: high-x

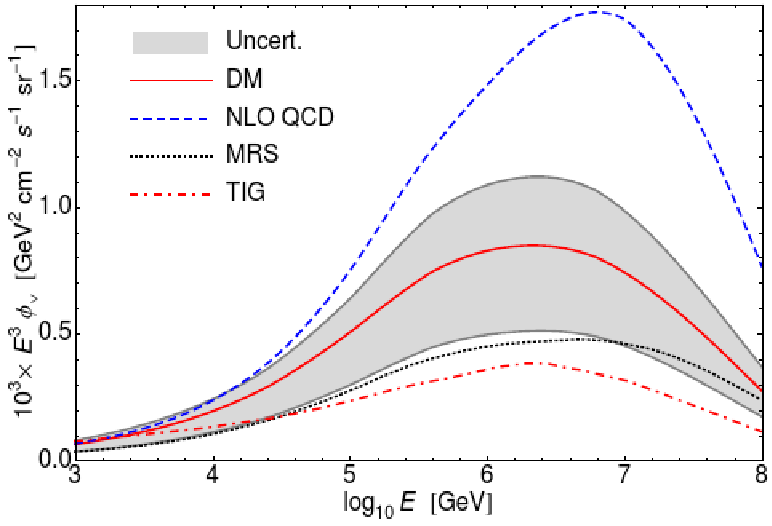
- Advance our understanding of the **high-x frontier in nucleons and nuclei** (gluon and heavy-quark content) **and its connection to astroparticle physics**

- Structure of nucleon and nuclei at high-x is poorly known (x>0.5), both at low and high scales
  - Origin of the nuclear EMC effect in nuclei ?
  - Non-perturbative source of charm or beauty in proton – important for Ultra-High-Energy-Cosmic Rays (UHECR), high-energy neutrino in the PeV range

Gluon nPDF relative uncertainties

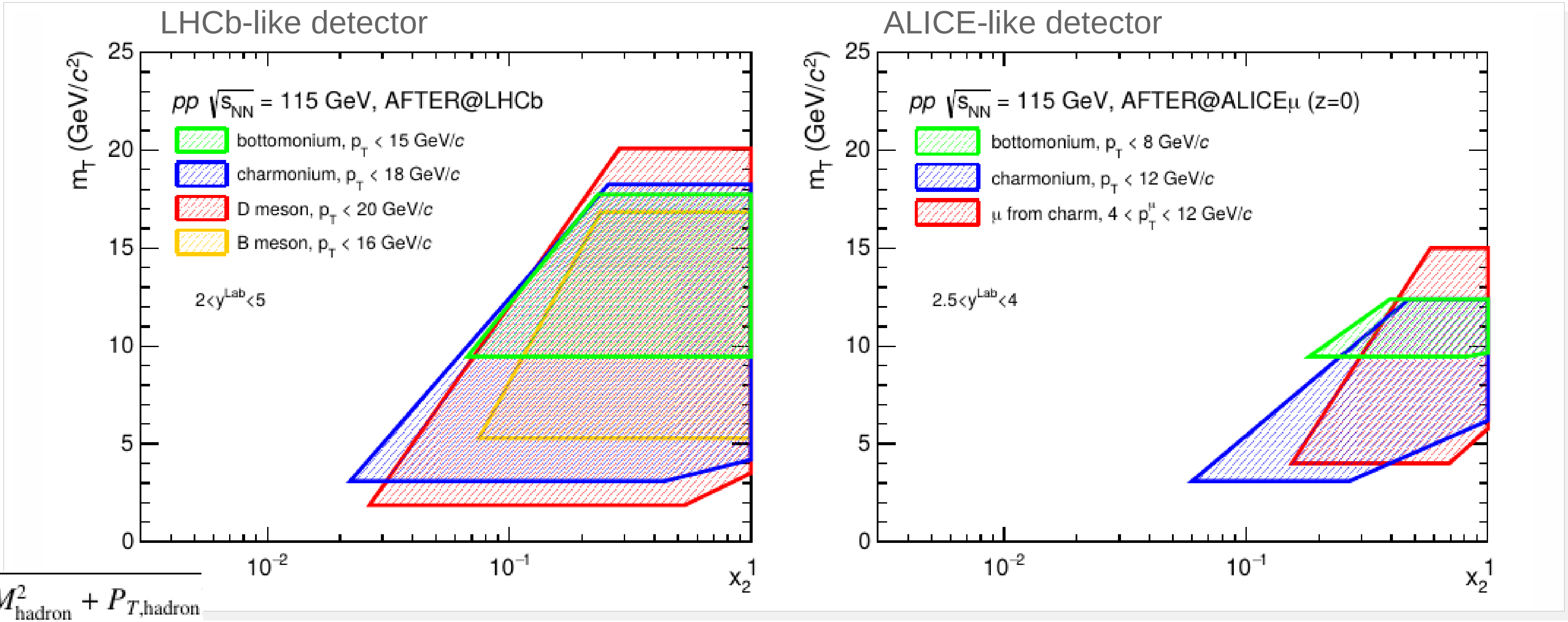


QCD uncertainties on the prompt muon neutrino fluxes



AFTER high-x kinematic reach

- Typical kinematical reach with heavy-hadron production at x_2, proxy to the momentum fraction of the parton in the target, of a fixed-target mode of LHCb- or ALICE-like detectors
  - Gluon-sensitive probes:

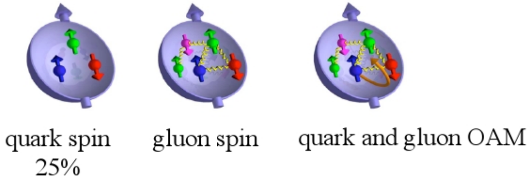


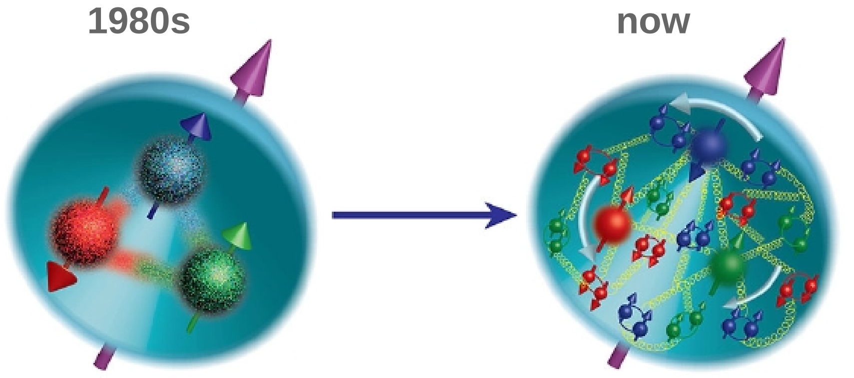
$$m_T = \sqrt{M^2_{\text{hadron}} + P_{T,\text{hadron}}}$$

Physics case: spin

- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
  - 3D mapping of the proton momentum
  - How quarks and gluons bind into a spin-1/2 object

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$



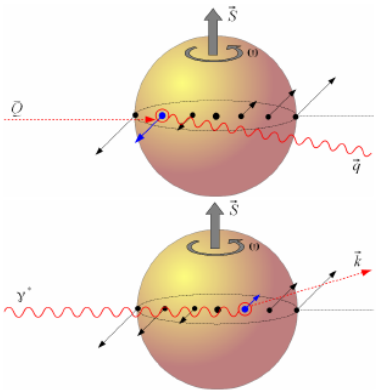


- quark/anti-quark: ~30% of proton longitudinal spin
- gluons: even up to 40%

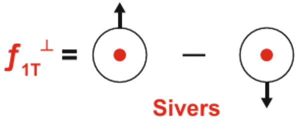
- Missing contribution to the proton spin from the transverse dynamics of quarks and gluons

gluon and quark Orbital Angular Momentum $\mathcal{L}_{g;q}$

- **Single Transverse Spin Asymmetries** (with transversely polarised target) → orbital motion of partons inside hadron: Sivers effect
- **Non-zero quark/gluon Sivers functions → non-zero OAM**



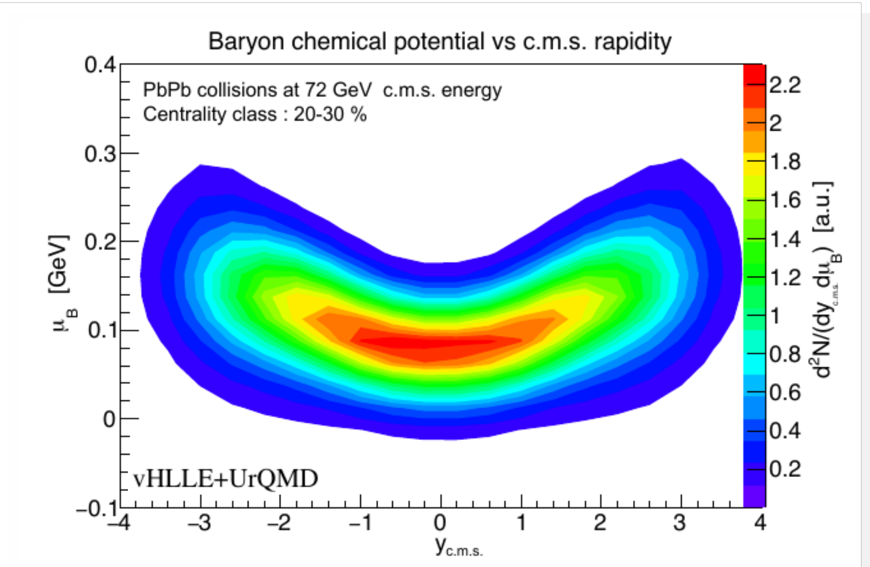
$$A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



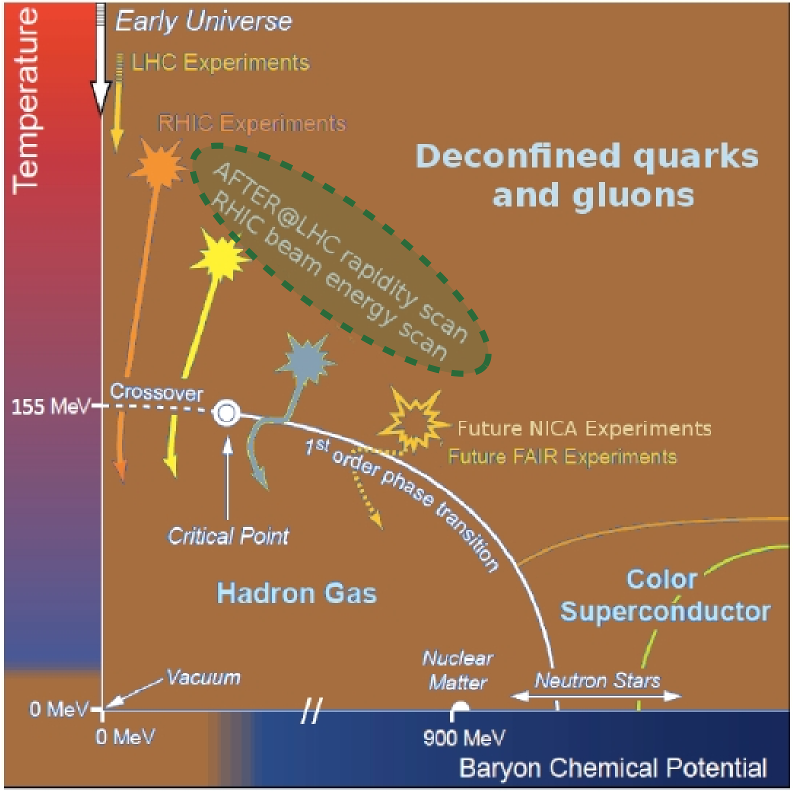
transverse-momentum distribution correlated with the transverse polarization vector of the nucleon

Physics case: QGP

- Study of the **quark-gluon plasma** between SPS and top RHIC energies of $\sqrt{s_{NN}}$ = 72 GeV over broad rapidity range
- Complete studies as a function of rapidity, centrality and system size → **scan in μ_B** complementary to RHIC BES programme

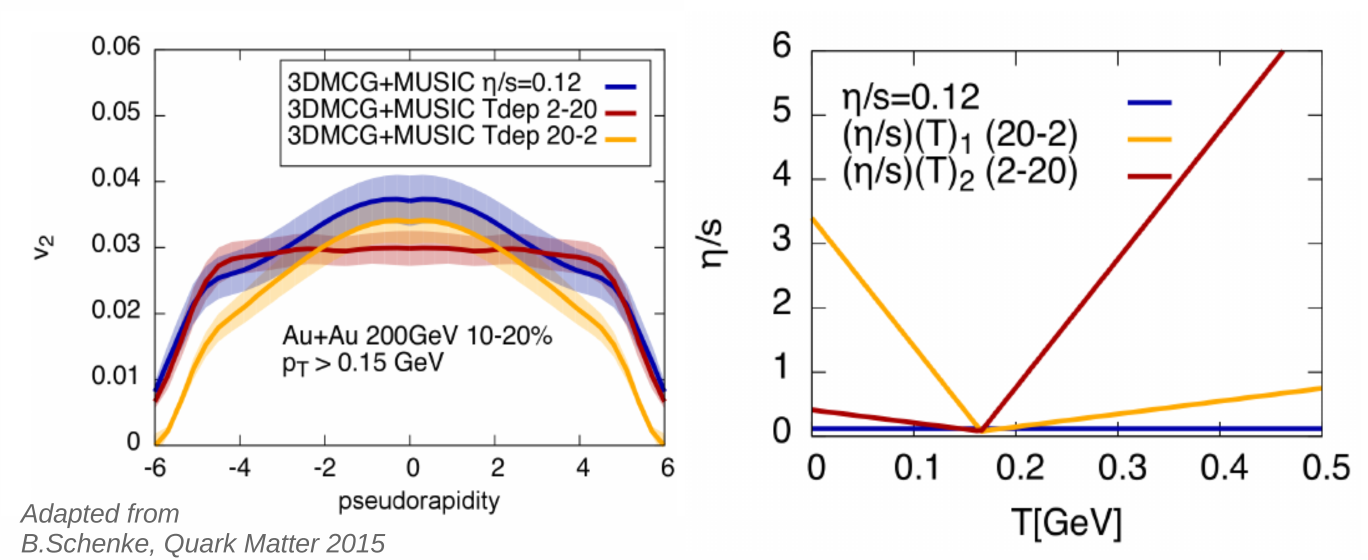


I.Karpenko, Acta Phys. Polon. B50 (2019), 141-148



Physics case: QGP (1)

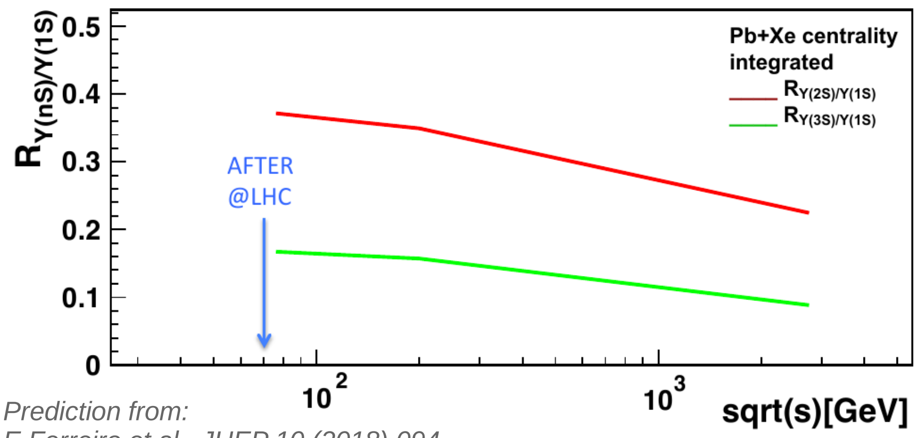
- Study of the **quark-gluon plasma** between SPS and top RHIC energies of $\sqrt{s_{NN}}$ = 72 GeV over broad rapidity range
- Complete studies as a function of rapidity, centrality and system size → **scan in μ_B**
- Explore the longitudinal expansion of the QGP
  - Particle yields and v_n → temperature dependence of the shear viscosity



Adapted from B.Schenke, Quark Matter 2015

Physics case: QGP (2)

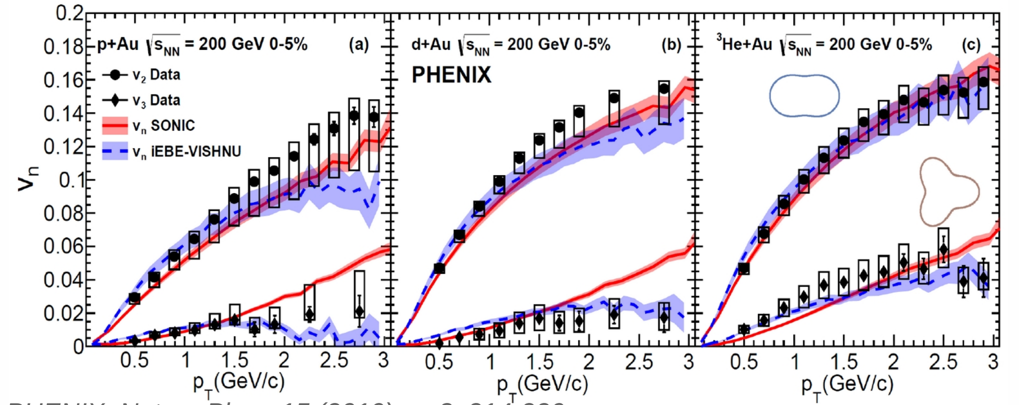
- Study of the **quark-gluon plasma** between SPS and top RHIC energies of $\sqrt{s_{NN}}$ = 72 GeV over broad rapidity range
- Complete studies as a function of rapidity, centrality and system size → **scan in μ_B**
- Explore the longitudinal expansion of the QGP
  - Particle yields and v_n → temperature dependence of the shear viscosity
- Unique access to hard probes at this energy domain
  - Quarkonium suppression in QGP → thermodynamic properties of the QGP
  - D meson R_{AA} and v_2 → heavy-flavour energy loss, transport properties of the QGP



Prediction from:
E.Ferreiro et al., JHEP 10 (2018) 094

Physics case: QGP (3)

- Study of the **quark-gluon plasma** between SPS and top RHIC energies of $\sqrt{s_{NN}}$ = 72 GeV over broad rapidity range
- Complete studies as a function of rapidity, centrality and system size → **scan in μ_B**
- Explore the longitudinal expansion of the QGP
  - Particle yields and v_n → temperature dependence of the shear viscosity
- Unique access to hard probes at this energy domain
  - Quarkonium suppression in QGP → thermodynamic properties of the QGP
  - D meson R_{AA} and v_2 → heavy-flavour energy loss, transport properties of the QGP
- p-A, lighter ions and high-multiplicity pp collisions
  - Test of collectivity in small systems
  - factorization of CNM effects from pA to AB → Drell-Yan (insensitive to QGP formation)



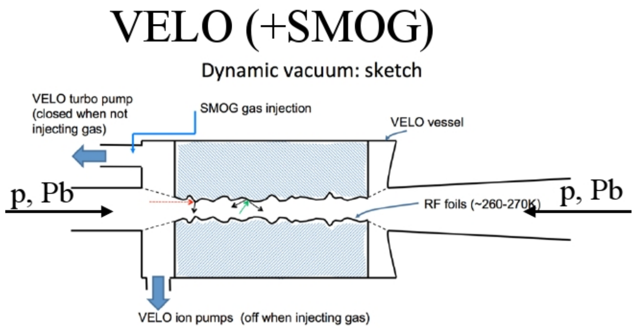
PHENIX, Nature Phys. 15 (2019) no.3, 214-220

Possible implementations

- **Internal gas target**
  - Full LHC beam flux on internal gas target
  - **Use of an existing LHC experiment**
  - Feasibility demonstrated by SMOG at LHCb
  - Storage cell target (HERMES-like) or gas-jet system (RHIC H-jet polarimeter) for (un)polarised gases

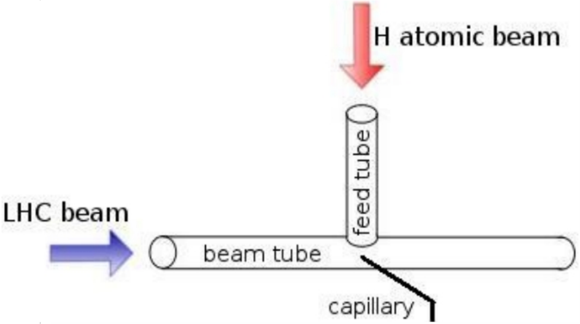
SMOG@LHCb

System for Measuring Overlap with Gas



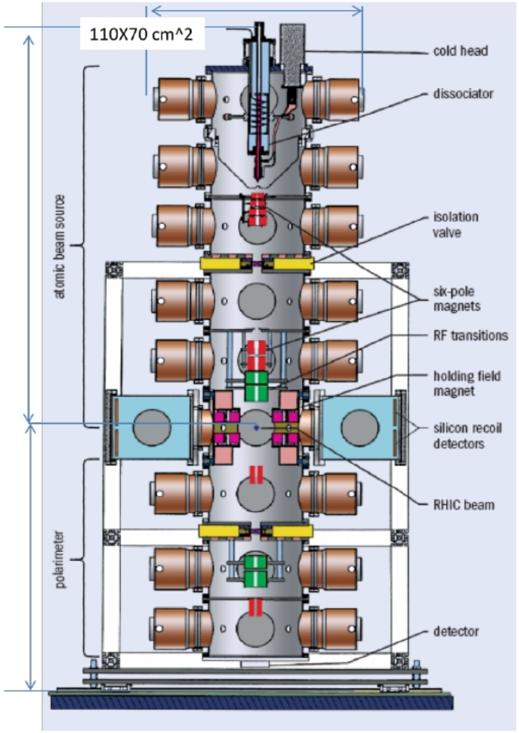
- Unpolarised noble gases
- Gas injected into vertex locator (VELO) vacuum
- Low gas pressure

Target cell for polarised gas HERMES-like



- High pressure
- Polarised H and D (^{3}He)
- Unpolarised Kr, Xe

H-jet system at BNL-RHIC

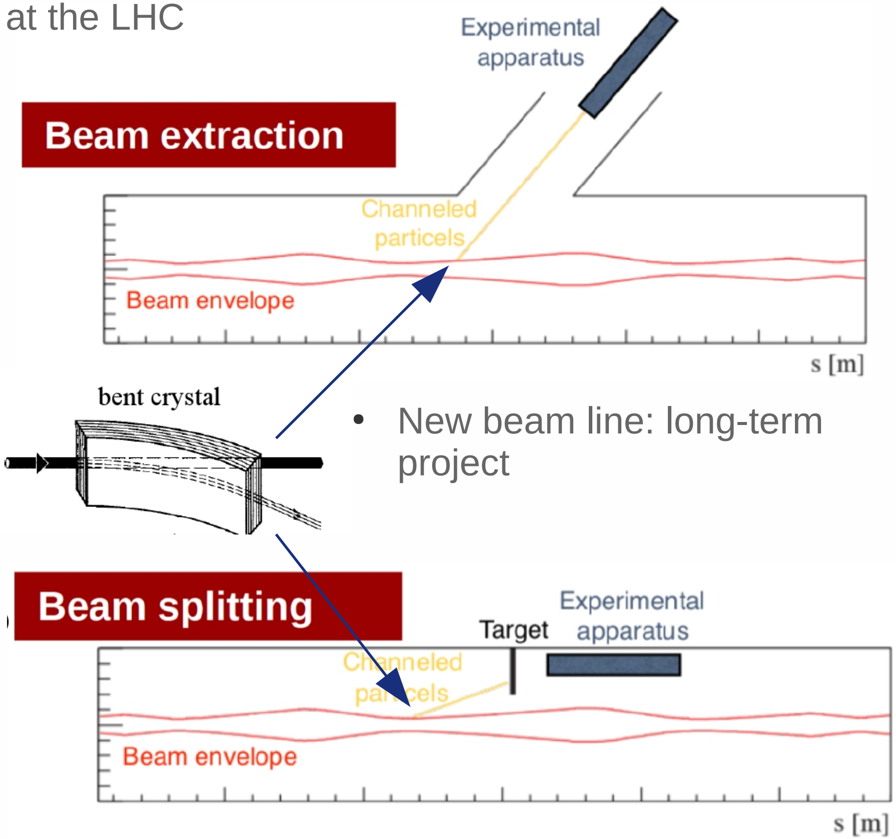


- Measures proton beam polarisation at RHIC
- Polarised gas: H, D and He possible

Possible implementations (2)

- **Internal gas target**
  - Full LHC beam flux on internal gas target
  - **Use of an existing LHC experiment**
  - Feasibility demonstrated by SMOG at LHCb
  - Storage cell target (HERMES-like) or gas-jet system (RHIC H-jet polarimeter) for (un)polarised gases
- **Internal wire/foil target**
  - Beam halo recycled directly on internal solid target
  - As HERA-B and STAR, heavy-nucleus targets
- **Beam line extracted with a bent crystal**
  - Beam halo deflected onto an external target
  - Thick (un)polarised and cryogenic polarised targets
  - Considerable amount of civil engineering
- **Beam "split" by a bent crystal**
  - Beam halo deflected onto an internal solid or gas target
  - **Inside beam pipe of an existing LHC experiment**

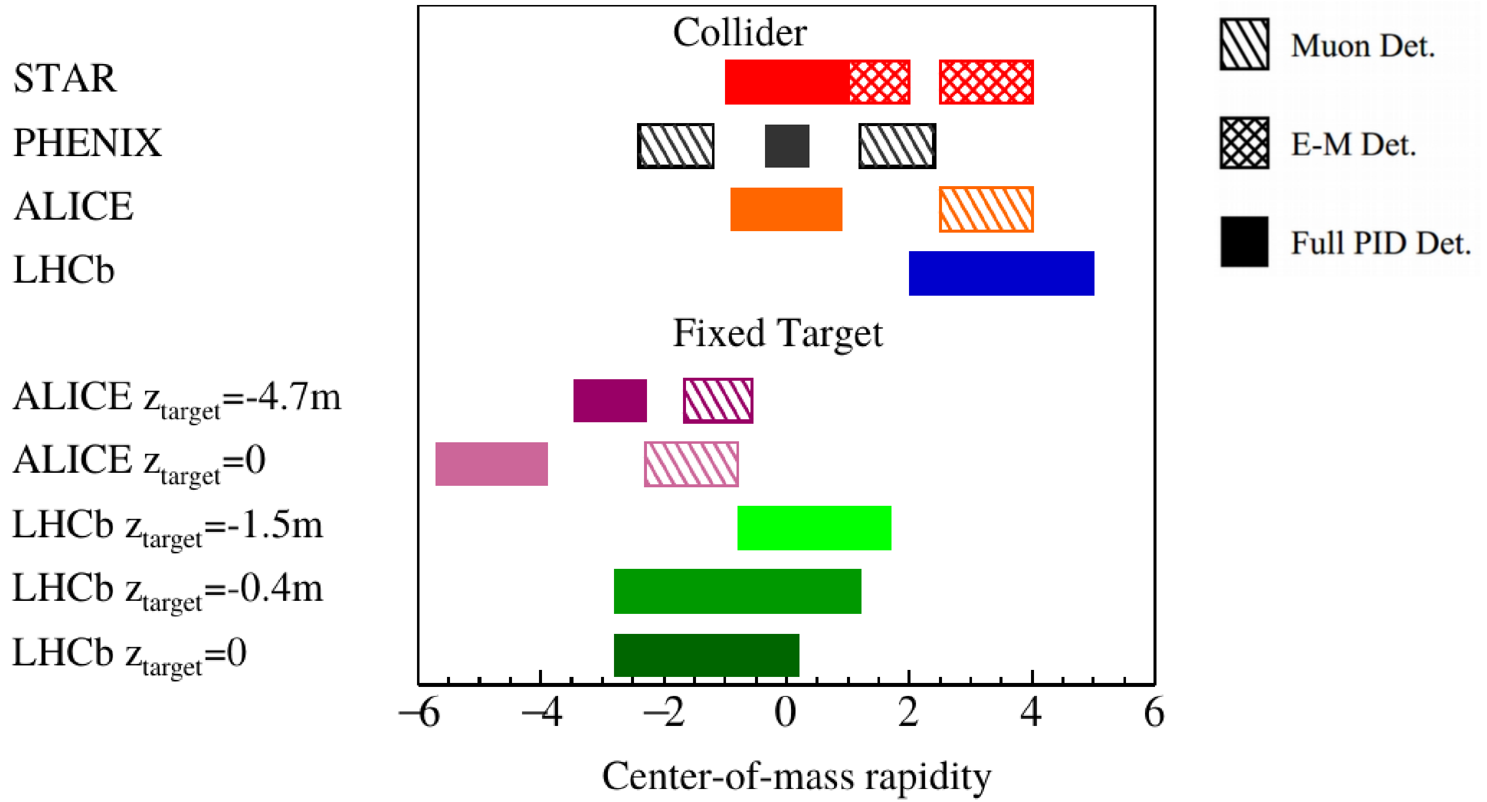
Bent crystal studies by UA9 for collimation purpose at the LHC



- New beam line: long-term project
- Beam splitting: crystal located ~100m downstream of the target

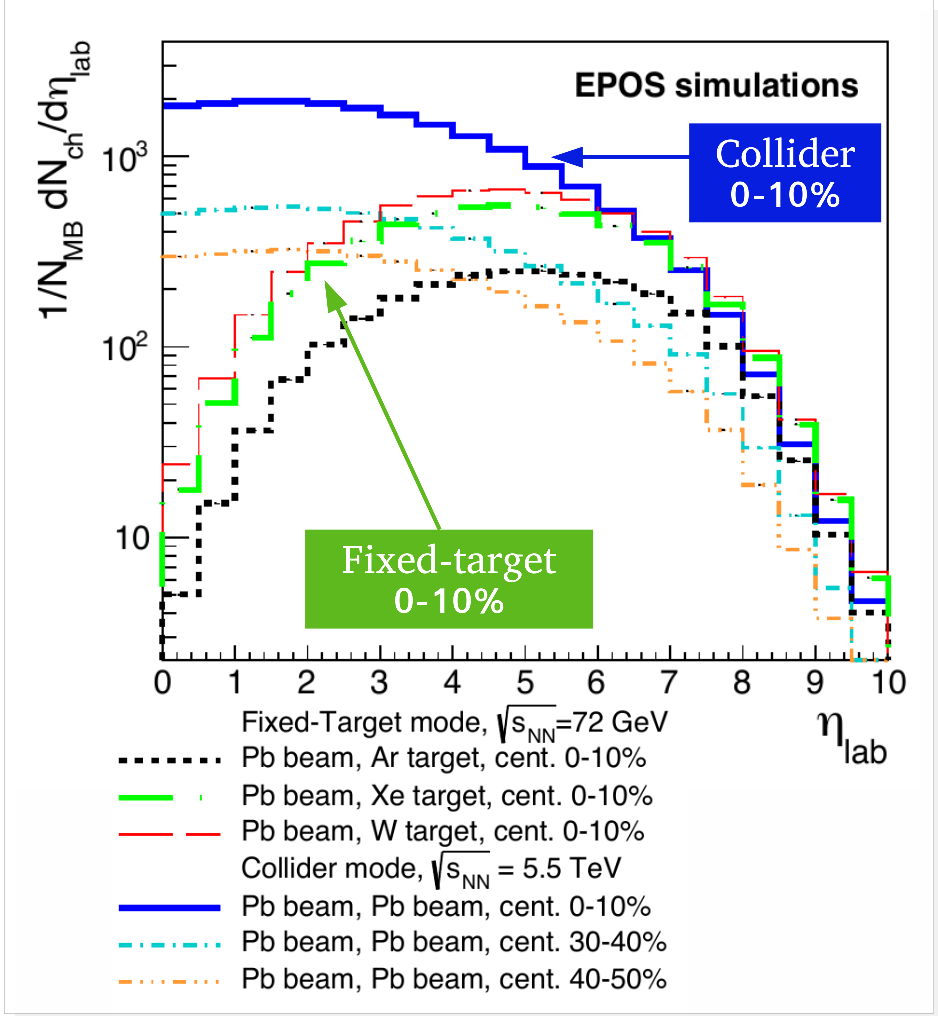
Acceptance in centre-of-mass y

- With7 TeV proton beam
  $\Delta y = 4.8$



- ALICE: central barrel: very backward y ($x_2 \rightarrow 1$), Muon Spectrometer: more central y
- LHCb: central and half of the backward $y_{c.m.s.} < 0$

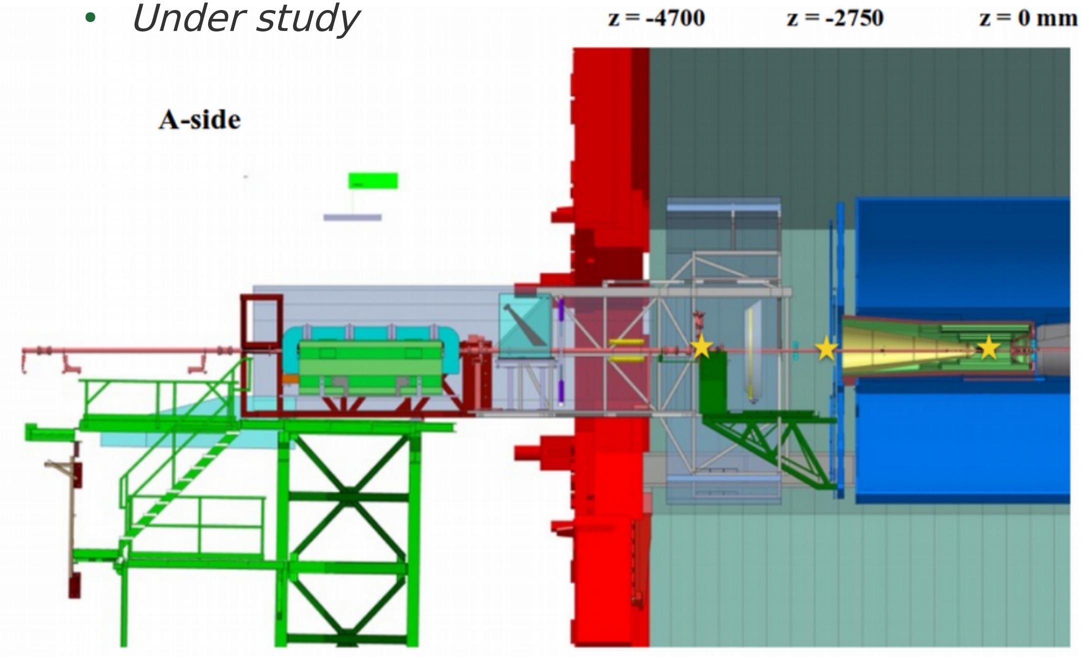
Detector requirements



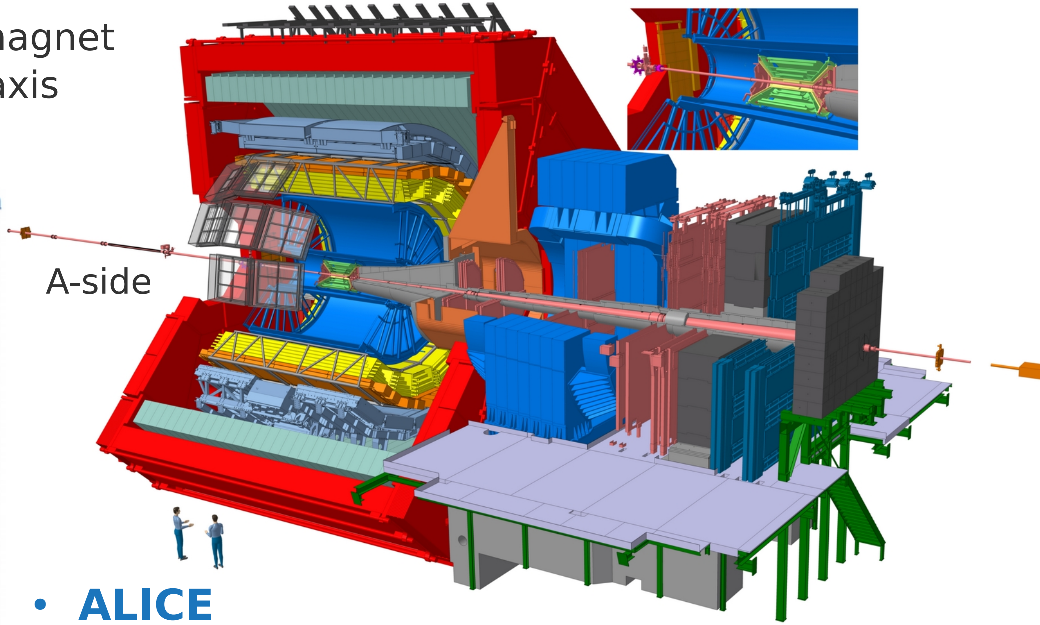
- **Wide rapidity coverage** of backward and mi-rapidity in $y_{c.m.s.}$
  p beam: $y_{lab.}$ range 0 – 4.8
  Pb beam: $y_{lab.}$ range 0 – 4.2
- With (low p_T) **PID and vertexing** capabilities
- Heavy-ion: good performance in **high-multiplicity events**, up to 600 – 700 charged tracks per unit of rapidity at η_{lab}~4.2
- Readout **rate similar to LHC** collider:
  up to 36 MHz in pp,
  300 MHz in pXe,
  190 kHz in PbXe
- Polarised target requires space e.g. for pumping system

Possible implementation: ALICE

- **Beam splitting with bent crystal + internal target**
  - Crystal installed prior of the IP2 (ALICE), at ~70m
  - Deviates the beam halo onto a solid target in L3 magnet
  - Target *z* position< 4.8m, ~1.3 cm from the beam axis
- **Gas storage cell target**
  - *Under study*



ALICE Readout for Run3: 50 kHz in Pb-Pb and 200kHz-1 MHz in p-p/p-A



- **ALICE**
  - wide rapidity coverage
  - excellent PID capabilities in the central barrel
  - experiment designed to cope with high-multiplicity events
  - reconstruction of charged particles down to p_T ~ 0.15 GeV/c at mid-rapidity

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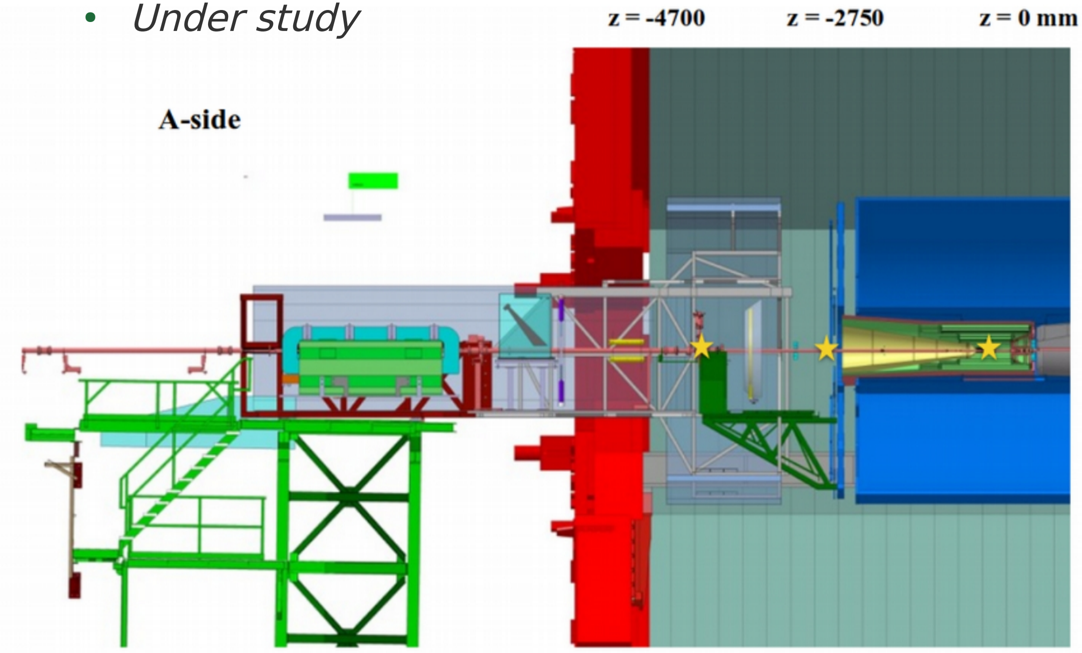
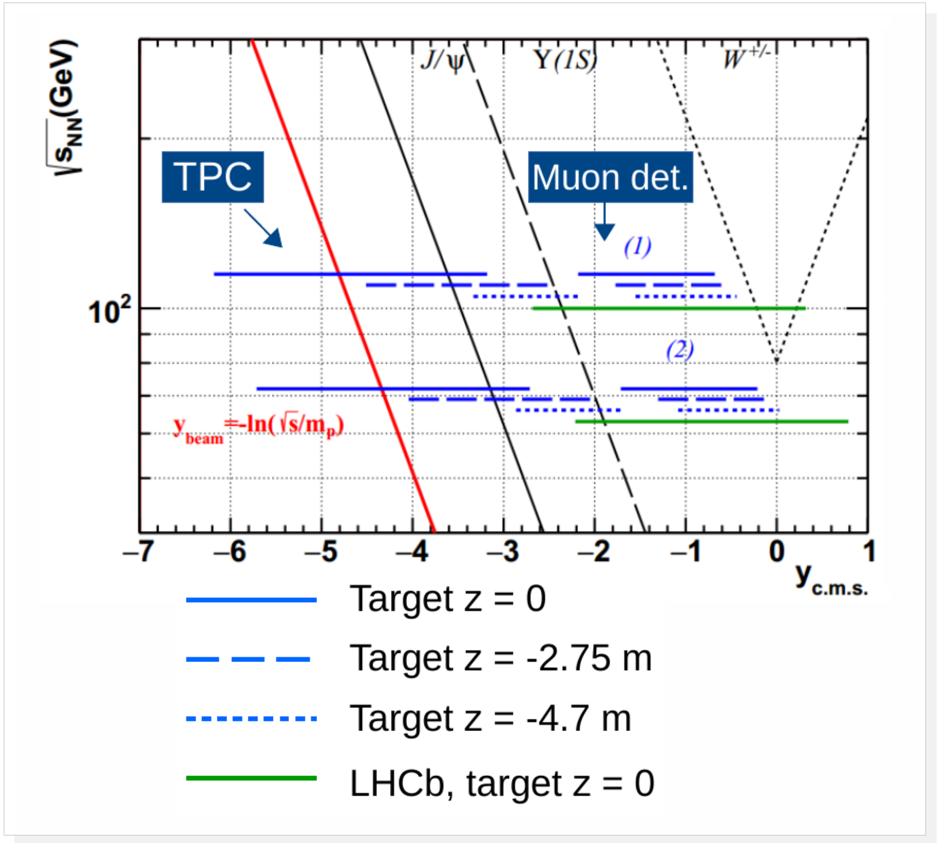
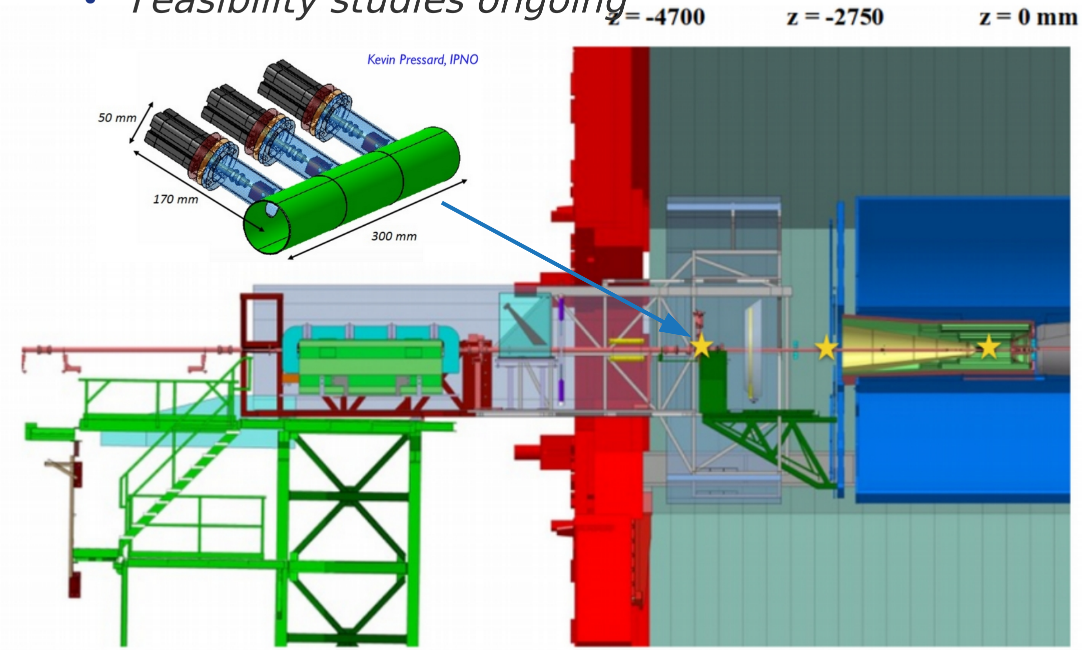




Possible implementation: ALICE (2)

➔ Beam splitting with bent crystal + internal target

- Crystal installed prior of the IP2, deviates the beam halo onto a solid target
- Pneumatic motion system with two position IN and OUT of the beam pipe
- Various target type: Be, Ca, C, Ti, Ni, Cu, Os, Ir, W
- Target length from ~100μm to 5 mm
- *Feasibility studies ongoing*



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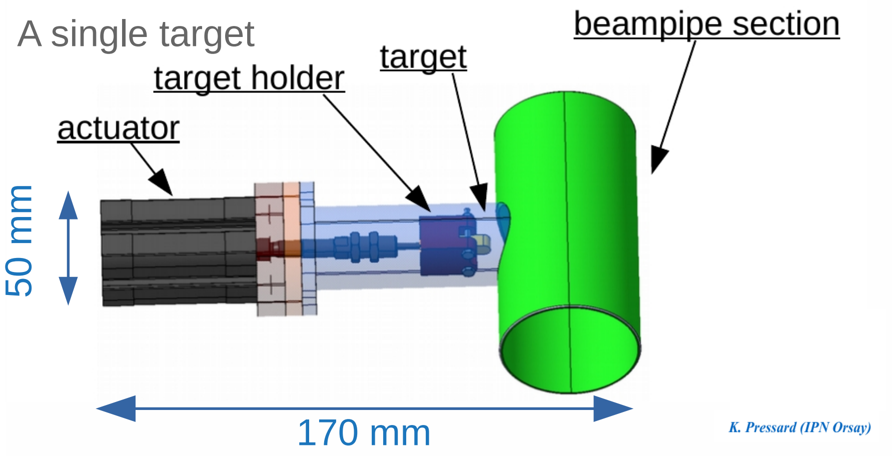
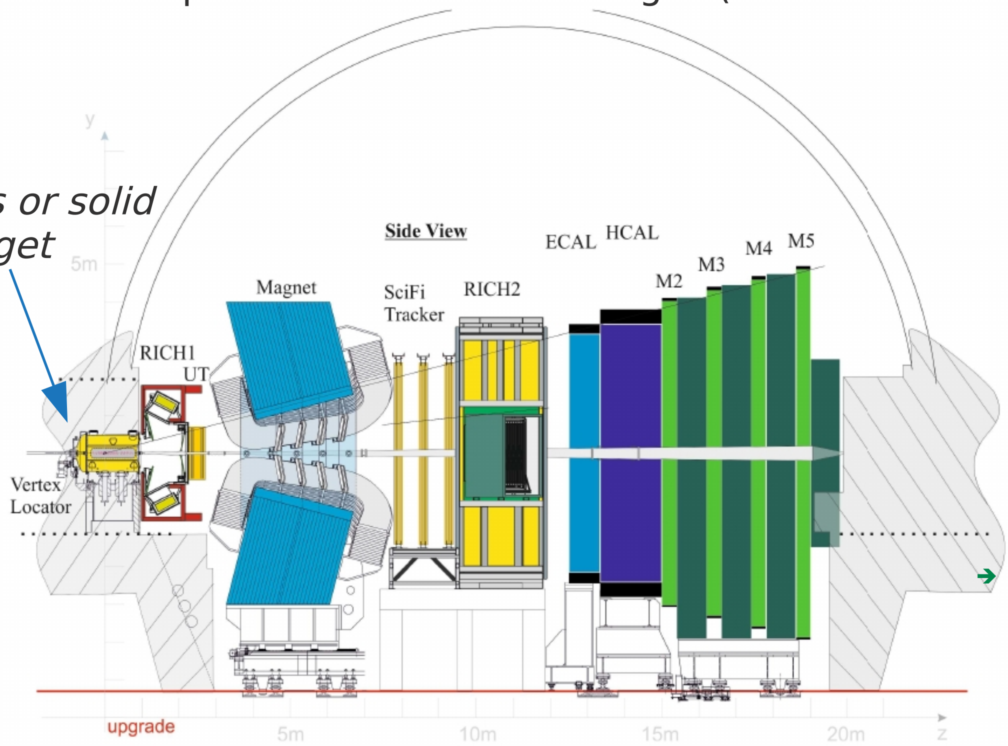
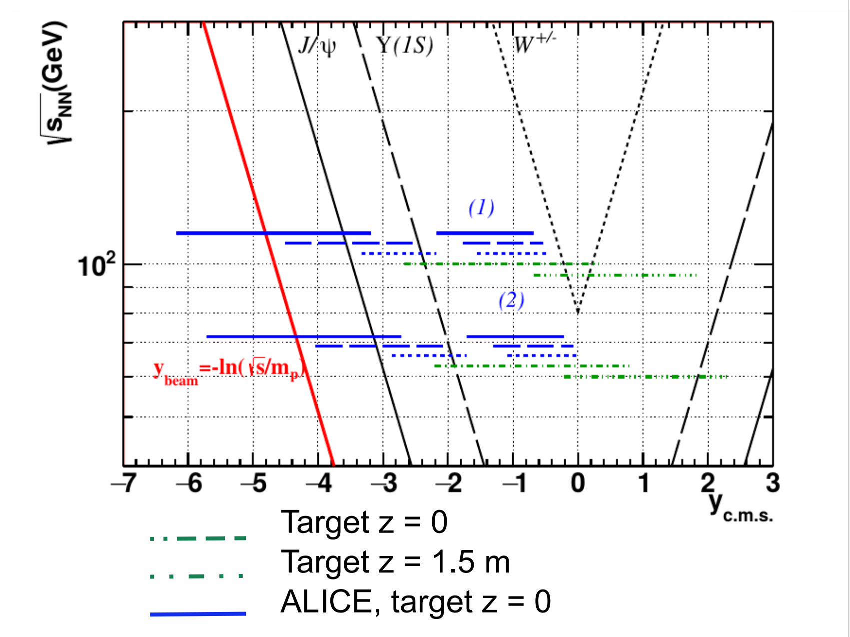


Possible implementation: LHCb

- Several investigations/projects:
  - Unpolarised storage cell gas target: SMOG2
  - Polarized storage cell gas target: LHCSpin, R&D needed with possible installation in LS3
  - Beam split and internal W solid gas (with a second crystal)

gas or solid target

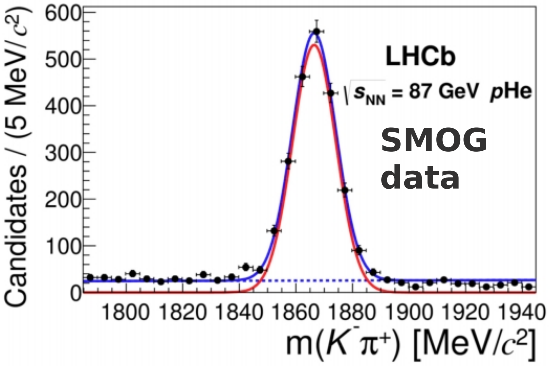


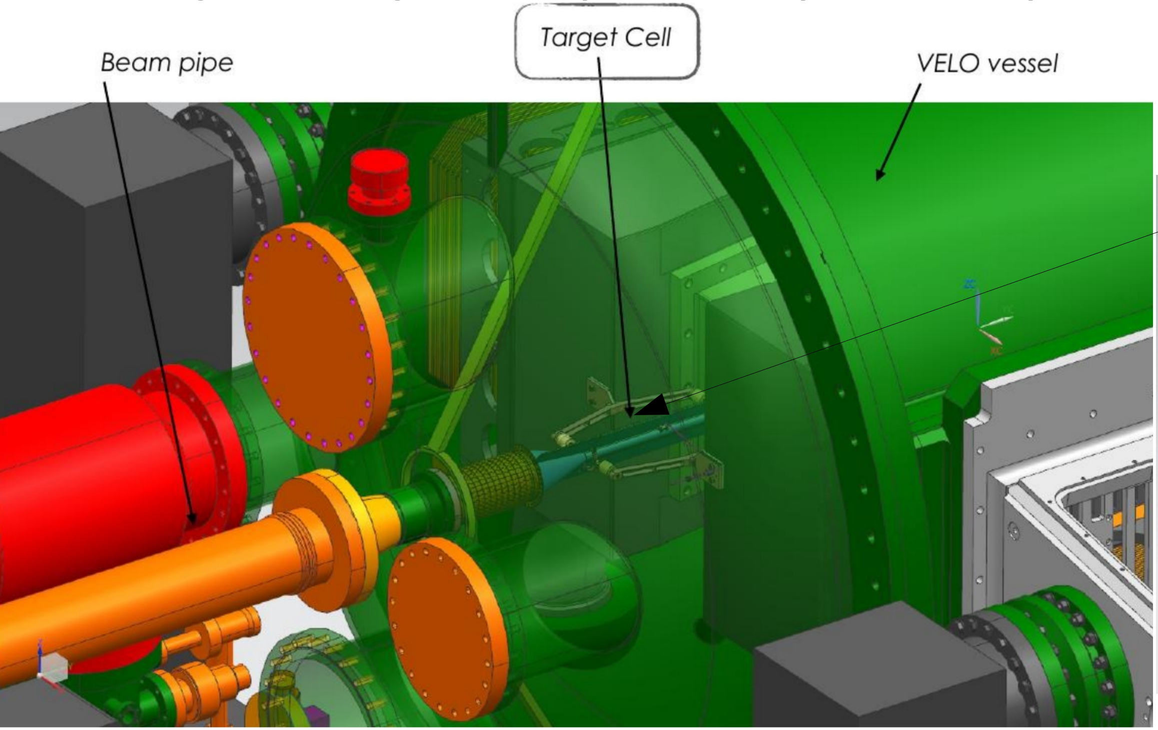


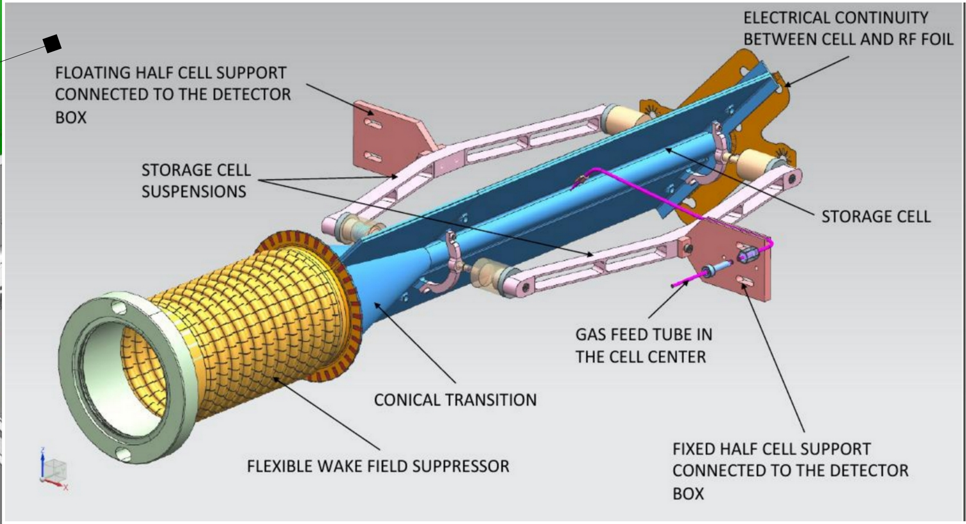
- **LHCb:**
  - Forward detector with full PID, $2 < \eta_{lab} < 5$
  - Precision tracking system, vertex locator
  - Limitation in high-multiplicity event reconstruction
  - New VELO: high readout rate, higher multiplicities

SMOG2 @LHCb

- Unpolarised storage cell gas target: **SMOG2**
  - Installation of an openable storage cell during LS2
  - 20 cm long tube with 1 cm diameter, displaced from IP
  - Higher local gas density, luminosity increase by factor ~100

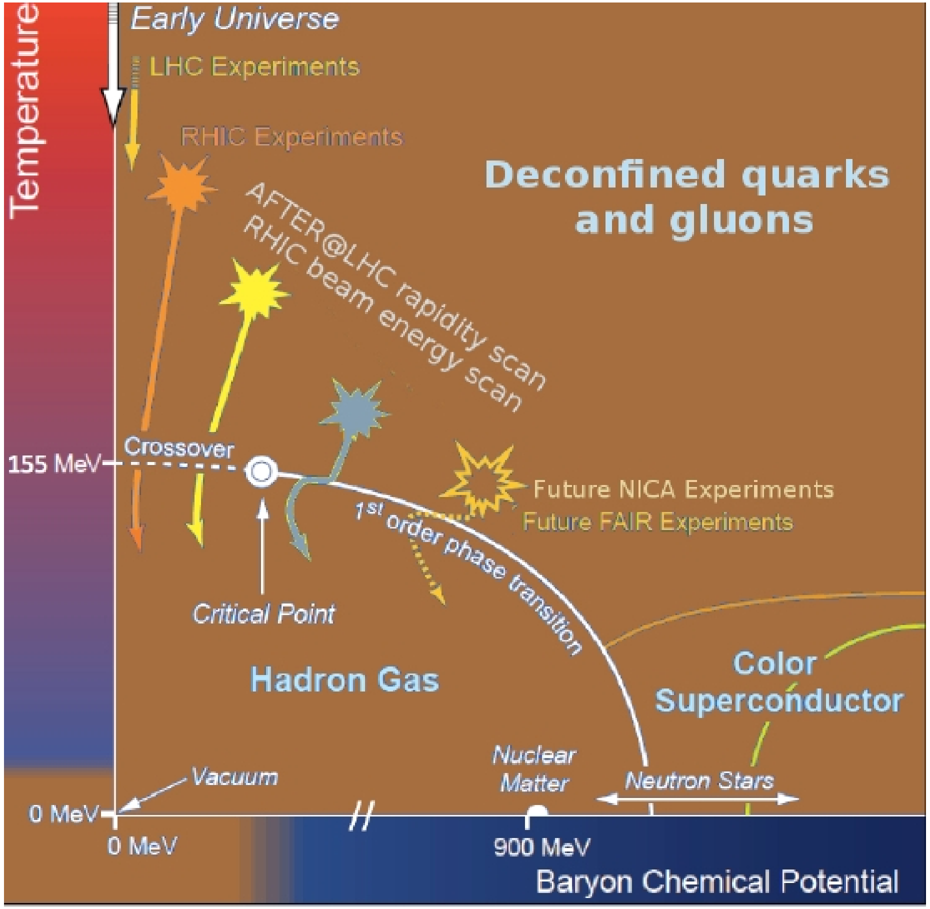




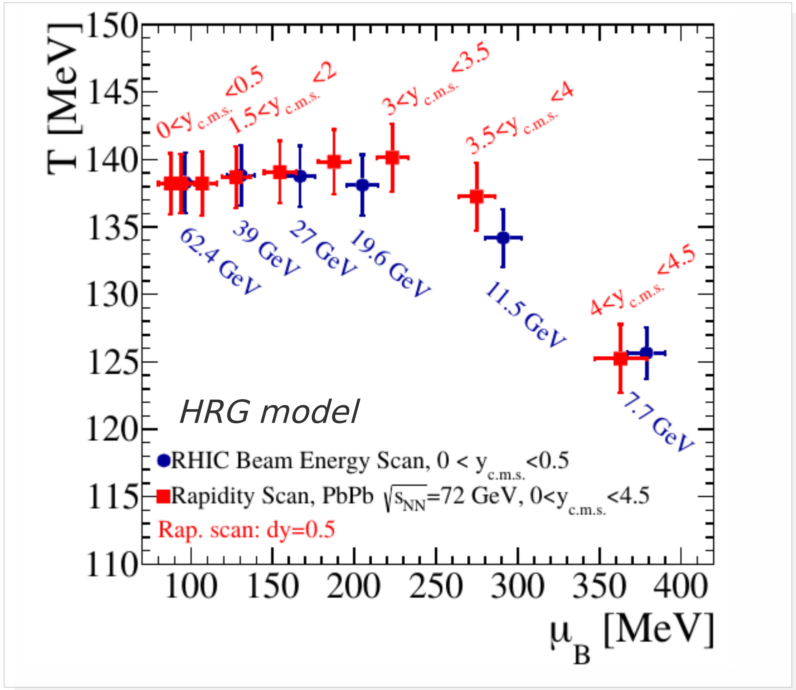


LHCb-PUB-2018-015 & CERN-PBC-Notes-2018-007

Projections:QGP



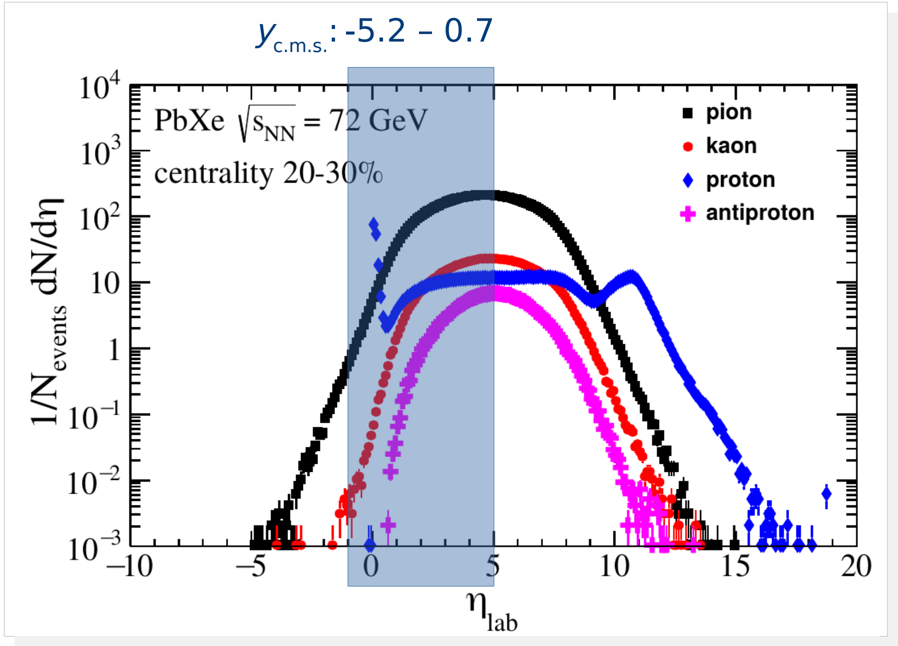
- Rapidity scan of the QGP phase diagram: complementary to RHIC BES

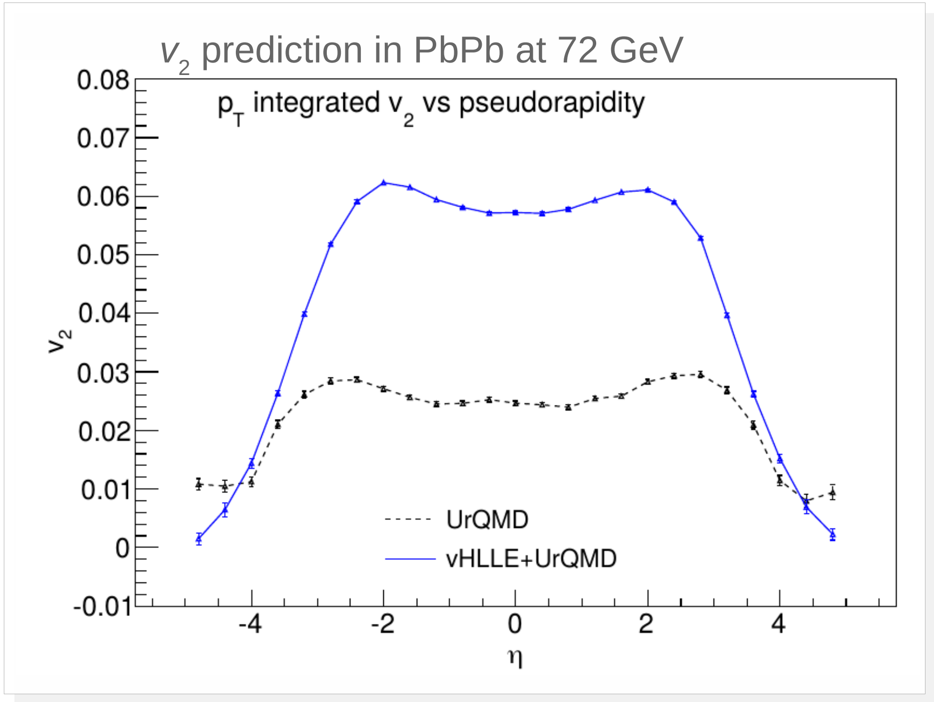


More in arXiv:1807.00603

Soft probes (1)

- Precise tool to study the bulk properties of the nuclear matter

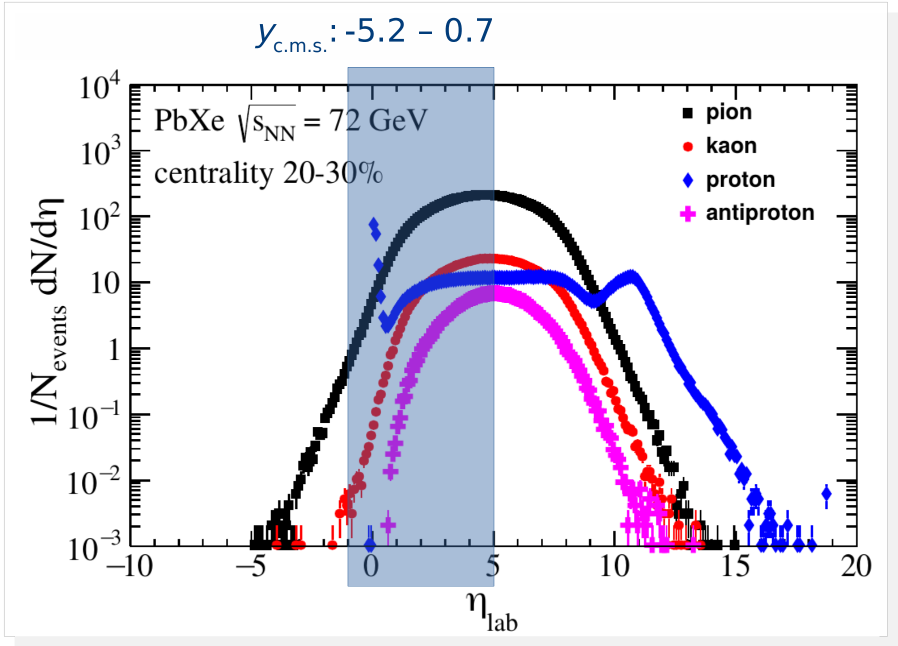


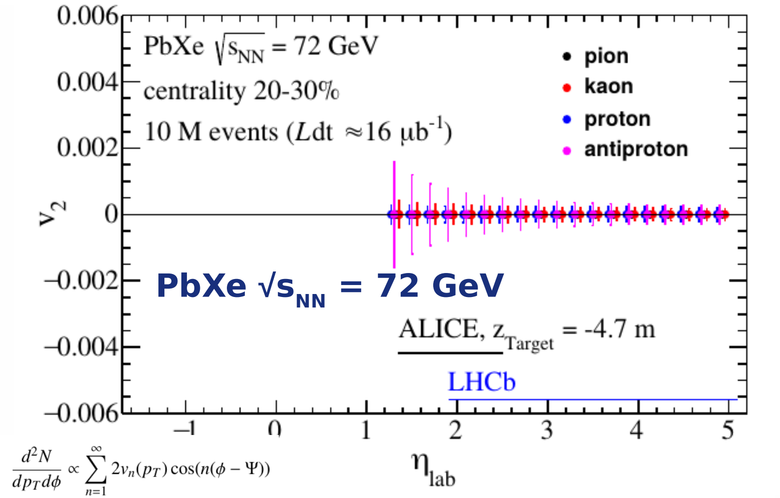


- Particle yields and v_n over very broad rapidity range
- Studies of the longitudinal expansion of the matter

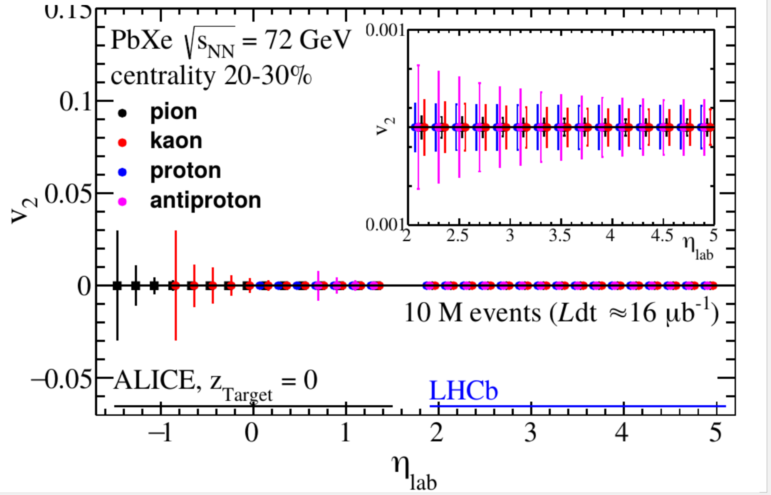
Soft probes (2)

➔ Precise tool to study the bulk properties of the nuclear matter





$$\frac{d^2N}{dp_T d\phi} \propto \sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\phi - \Psi))$$



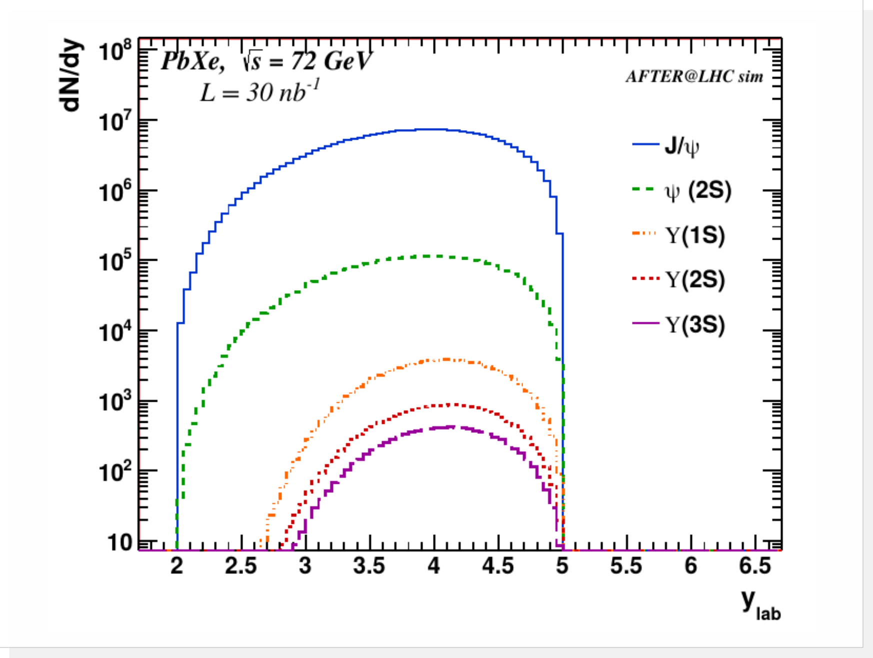
- Particle yields and v_n over very broad rapidity range
- Studies of the longitudinal expansion of the matter

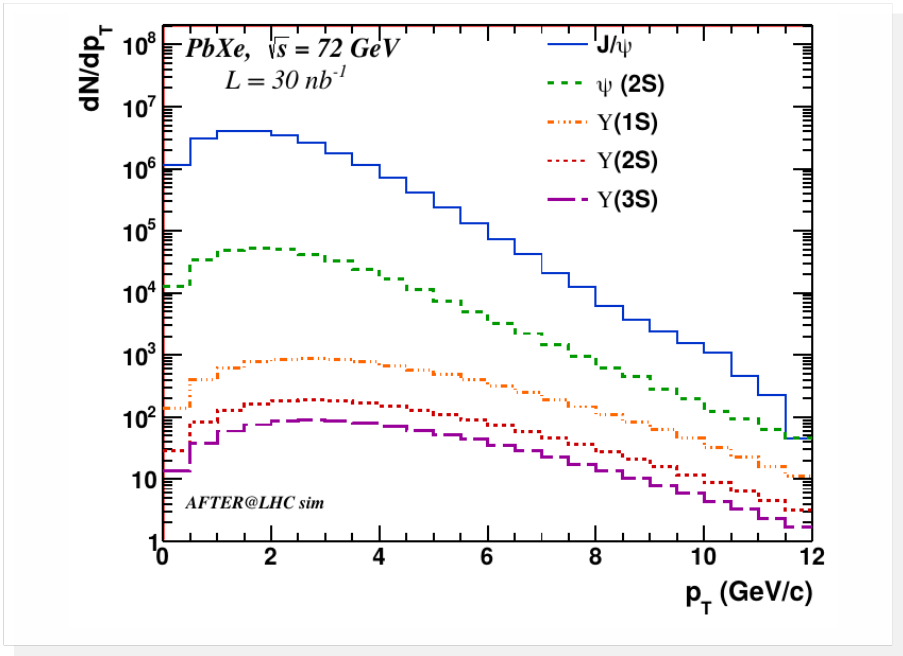
Quarkonia (1)

➔ Determination of the QGP thermodynamic properties

- Precise measurements of ψ and **ϒ(nS)** states down to 0 p_T, in pp, pA and PbA
- Negligible contribution from recombination

LHCb-like



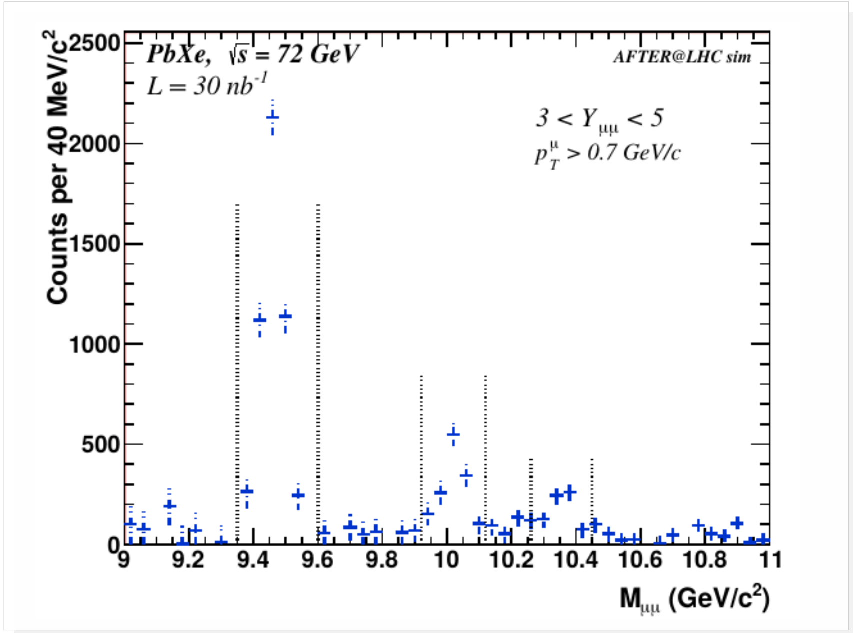


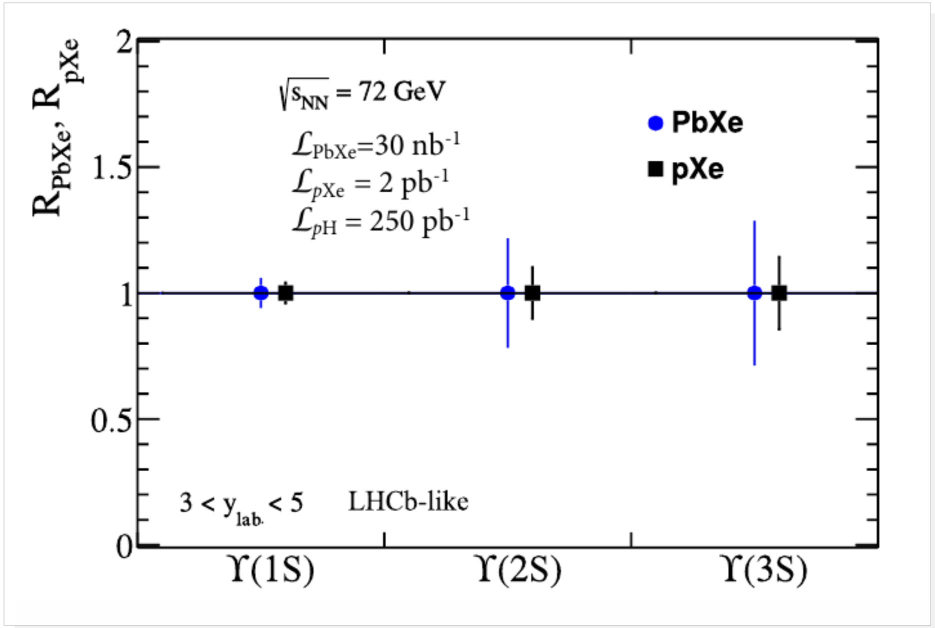
Quarkonia (2)

➔ Determination of the QGP thermodynamic properties

- Precise measurements of ψ and **Υ(nS)** states down to 0 p_T, in pp, pA and PbA
- Negligible contribution from recombination

LHCb-like





- Possibility to access χ_C and η_C, J/ψ – J/ψ and J/ψ – D correlations
- Very good precision expected for open heavy-flavour as well

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

AFTER@LHC Study group:
http://after.in2p3.fr/after

Backup

Physics case: high-x (2)

➔ Advance our understanding of the **high-x frontier in nucleons and nuclei** (gluon and heavy-quark content) **and its connection to astroparticle physics**

- Structure of nucleon and nuclei at high-x are poorly known (x>0.5)
- Long-standing puzzles:
  - Origin of nuclear EMC effect – studying a possible gluon EMC
  - Charm content in the proton, existence of possible non-perturbative source of c/b quarks in the proton – important for high-energy neutrino and comic-ray physics
- Search and study rare proton fluctuations where one gluon carries most of the proton momentum: test QCD in a new limit never explored
- nPDFs – initial state for HI collisions

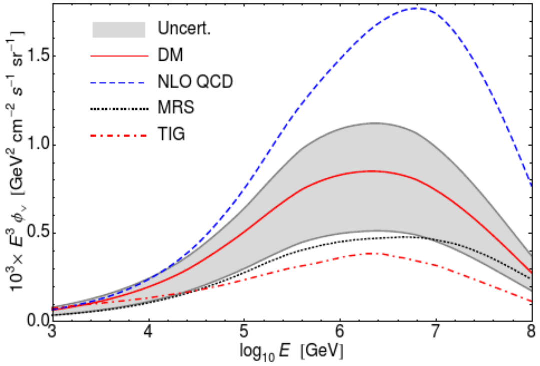
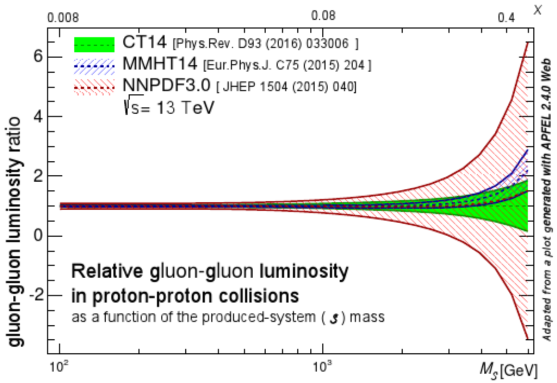
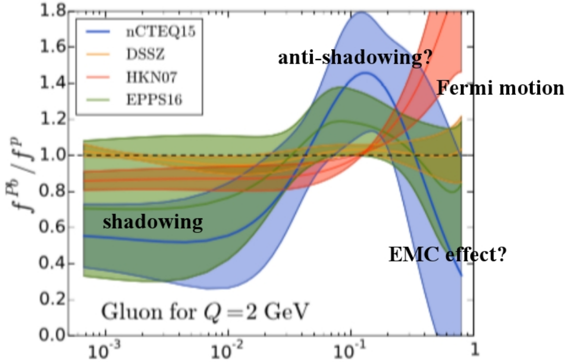


Illustration of the QCD uncertainties (QCD corrections, PDF uncertainties,…) on the prompt muon neutrino fluxes



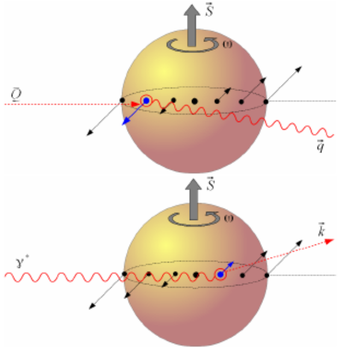


Physics case: spin (2)

- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
- 3D mapping of the proton momentum
- Missing contribution to the proton spin: gluon and quark Orbital Angular momentum $\mathcal{L}_{g;q}$
- With a transversally polarised target:
  - Single Transverse Spin Asymmetries (STSA) in hard-scattering processes, with a transversal polarised hadron: indirect access to the orbital motion of partons
    - Access information of the orbital motion of partons bound inside hadrons – Sivers effect
    - Non-zero quark/gluon Sivers function → non-zero quark/gluon OAM
    - Test TMD (Transverse Momentum Dependent functions) factorisation formalism: sign change of A_N between semi-inclusive DIS and Drell-Yan

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$

$$A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



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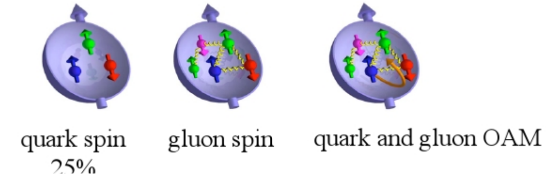

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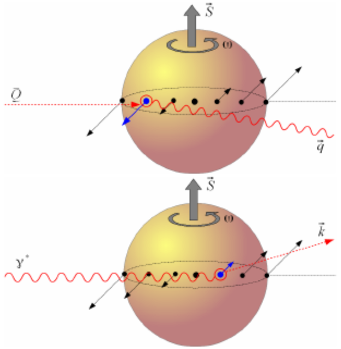
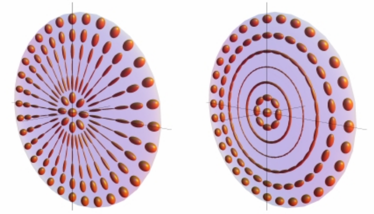
    - Test TMD (Transverse Momentum Dependent functions) factorisation formalism: sign change of A_N between semi-inclusive DIS and Drell-Yan
  - Determination of linearly polarised gluons in an unpolarised proton – Boer-Mulders effect

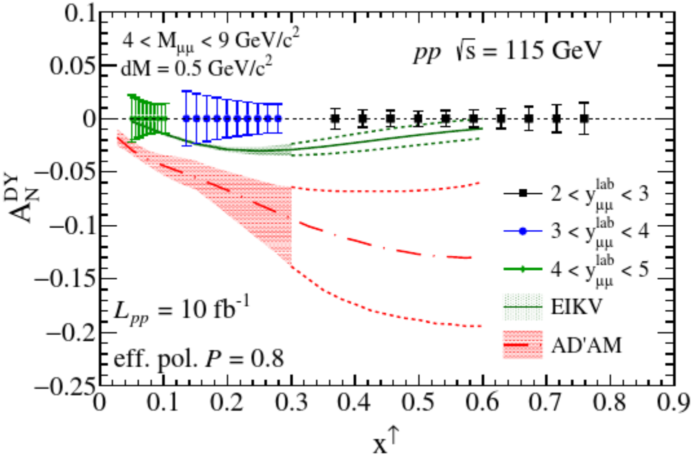


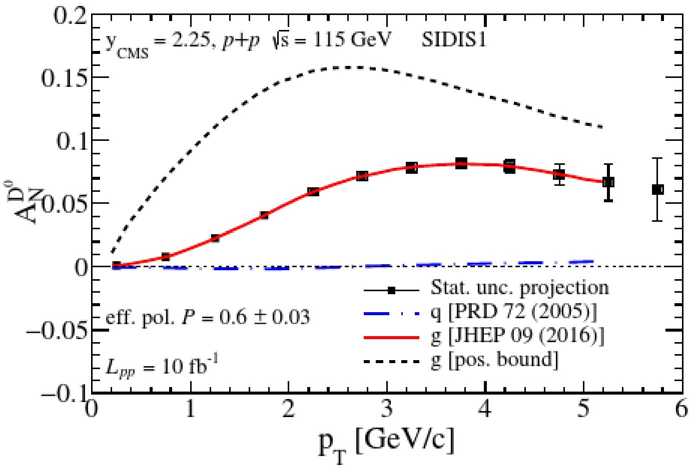


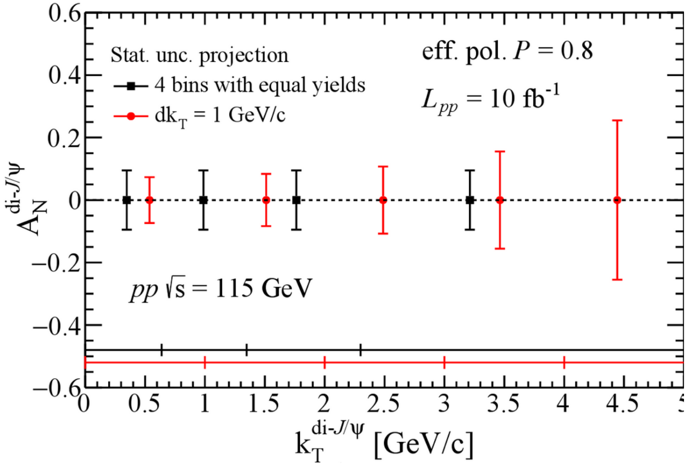
Spin projections

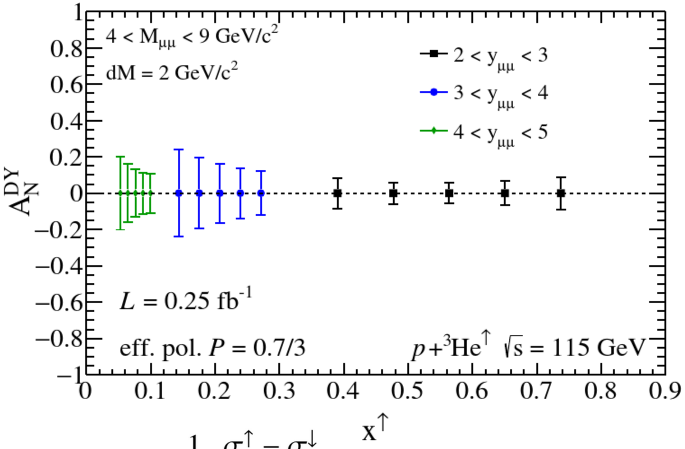
pp, √s = 115 GeV

- Transversely polarised target
  - Quark Sivers effect – check the sign change in A_N DY vs SIDIS
  - ^{3}He target → Sivers effect in the neutron via DY: unique
  - Gluon Sivers effect:
    - With D^0 – difference in A_N of D^0 vs D^0 gives A_N of D^0 vs D^0 access to C-odd correlators (PHENIX: 1703.09333)
    - Quarkonia (Υ never measured) and di-J/ψ – access to k_T dependence of the gluon Sivers function for the first time









$$A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

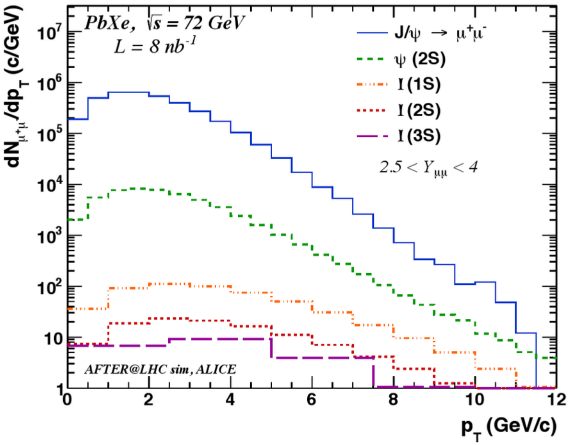
LHCb-like

QGP: Charmonia

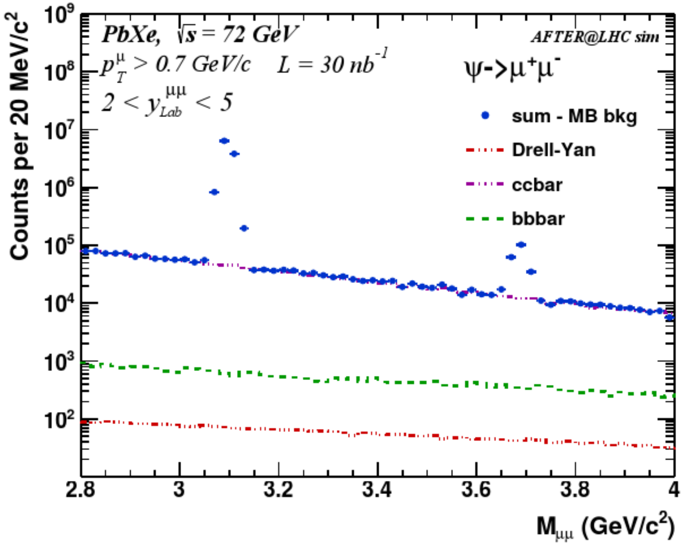
Pb-A , $\sqrt{s_{NN}}$ = 72 GeV

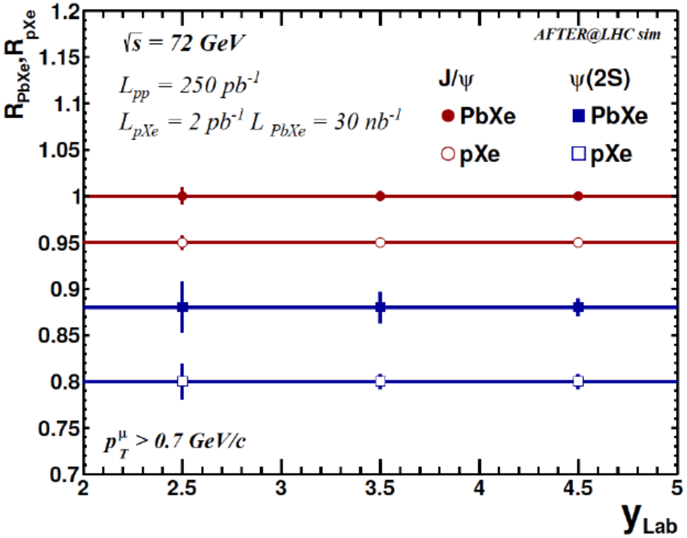
- Determination of QGP thermodynamic properties
- Negligible recombination
- p-A: Cold Nuclear Matter effects
- Precise measurements of J/ψ and ψ(2S) in Pb-A and p-A
- Wide p_T coverage down to 0 p_T

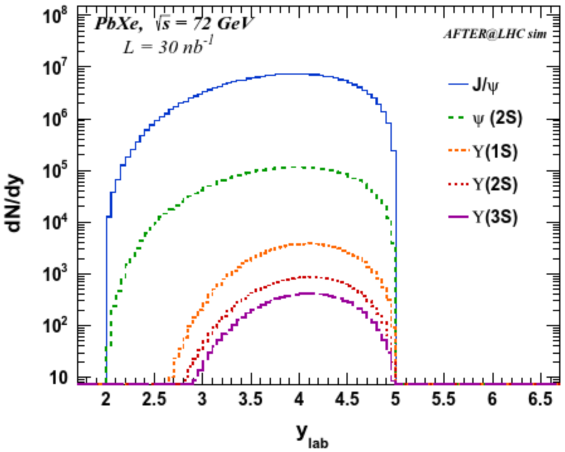
ALICE-like



LHCb-like

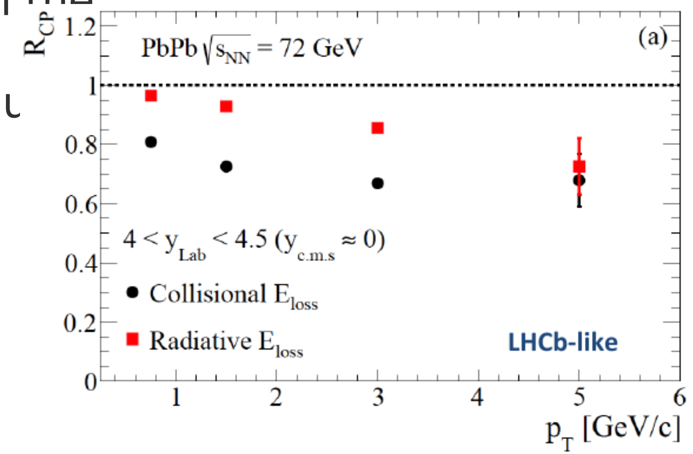


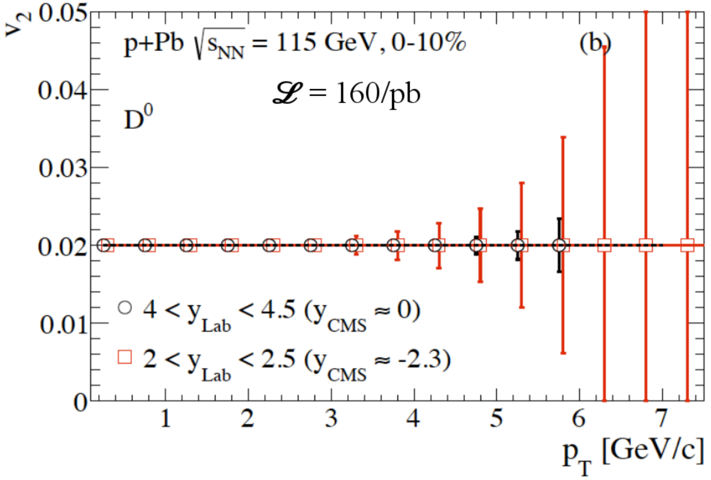




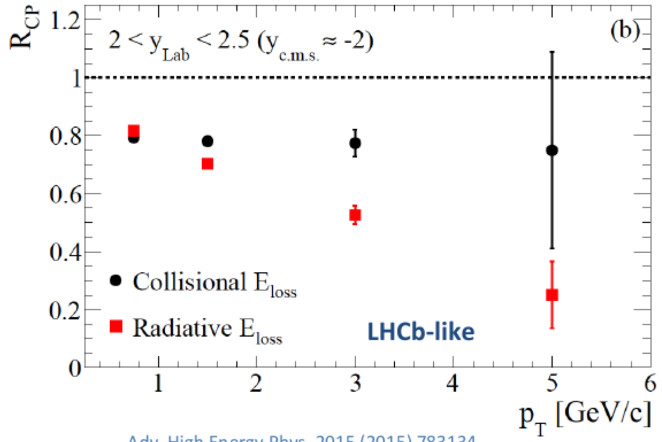
QGP: Open Heavy-Flavour

- Open heavy-flavour in A-A → heavy-quark energy loss in the medium
- Precise suppression measurements of charm and beauty vs rapidity and p_T → medium transport coefficient
- Useful reference for charmonium studies
- p-A: study collective-like effects in small systems
- Precise D meson v_2 measurement
  - Studies vs y and different target type





LHCb-like



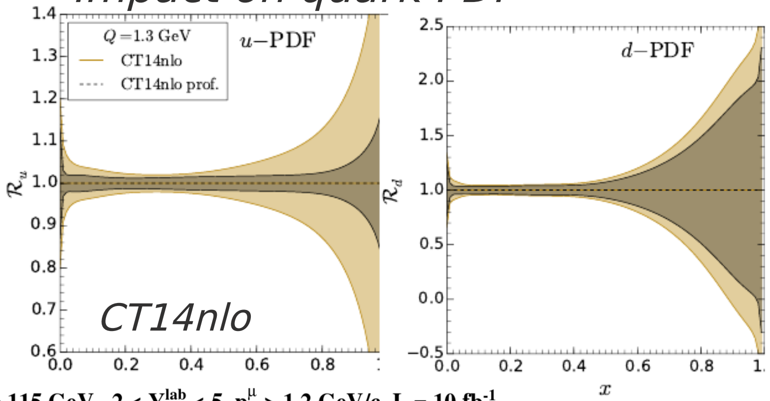
Adv. High Energy Phys. 2015 (2015) 783134.

quark PDF with Drell-Yan

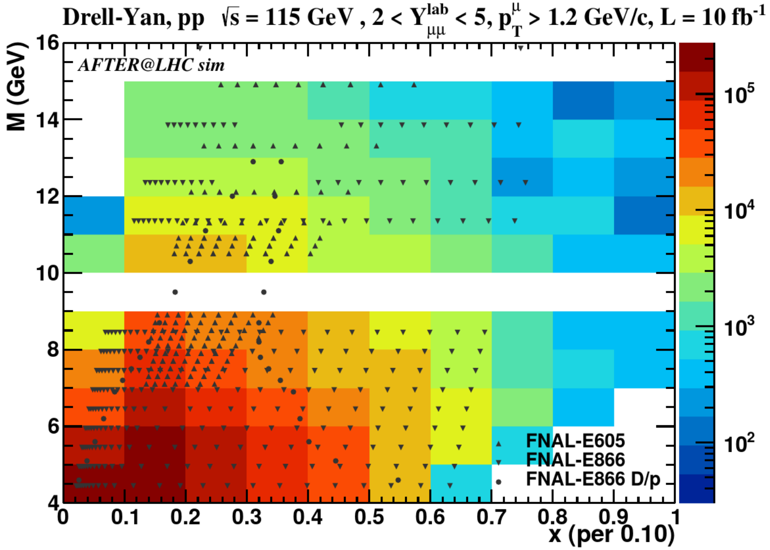
pp, $\sqrt{s}$ = 115 GeV

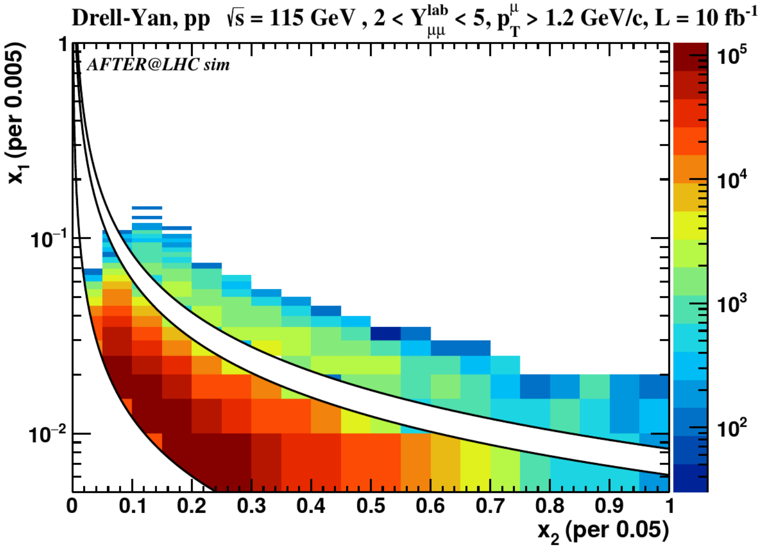
- Constraining quark PDF with Drell-Yan measurement
  - Profiling analysis and generating psedo-data
- Extension of the coverage of the existing Fermilab Drell-Yan data; NuSea data statistically limited
- Knowledge of valence quark distribution considerably improved for x > 0.4 (more pronounced effect for u quark)

Impact on quark PDF



LHCb-like



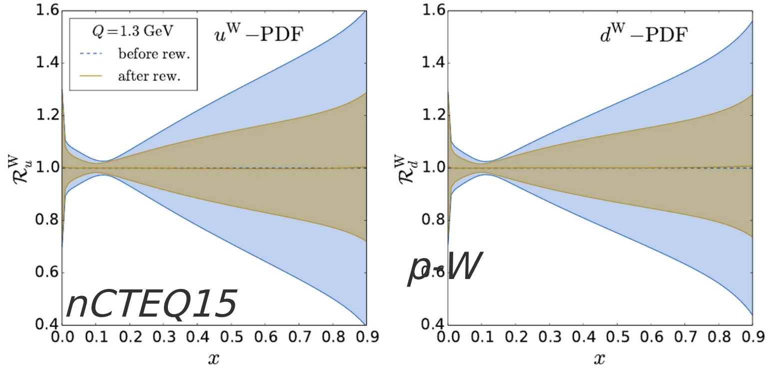


quark nPDF with Drell-Yan

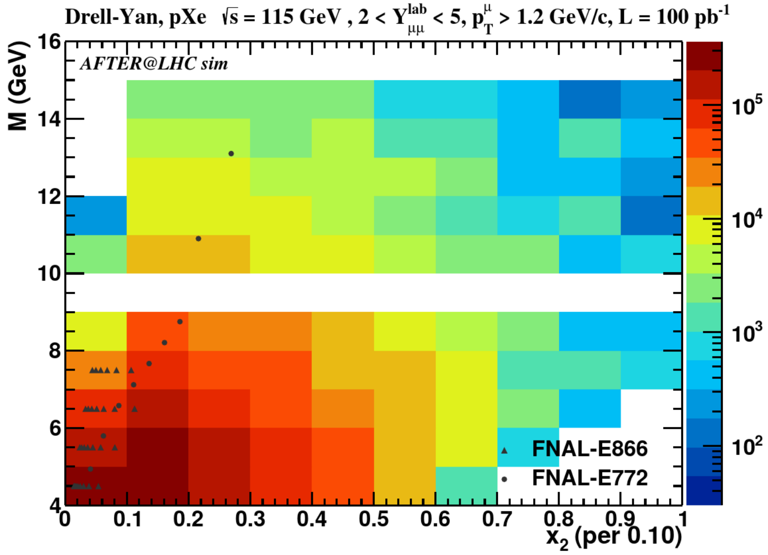
pA, $\sqrt{s}$ = 115 GeV

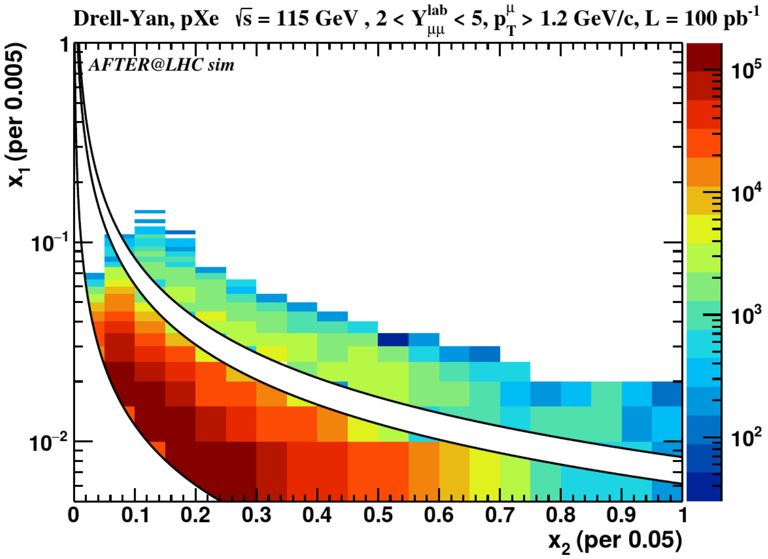
- Constraining quark nPDF with Drell-Yan measurement
  - Reweigting analysis with pseudo data on R_{pW},R_{pXe}
- Unique acceptance compare to existing DY data
- Extremely large yields up to $x_2 \rightarrow 1$
- Significant decrease of error for u/d quark distributions

Impact on nPDFs



LHCb-like



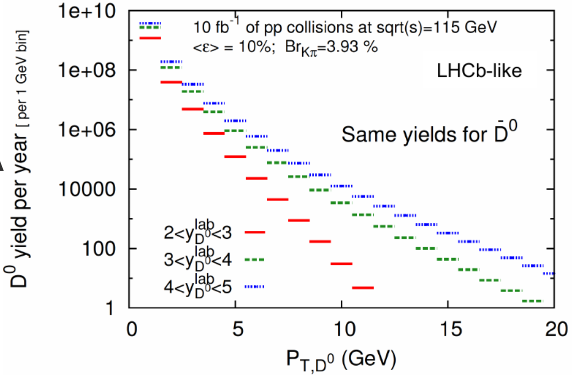


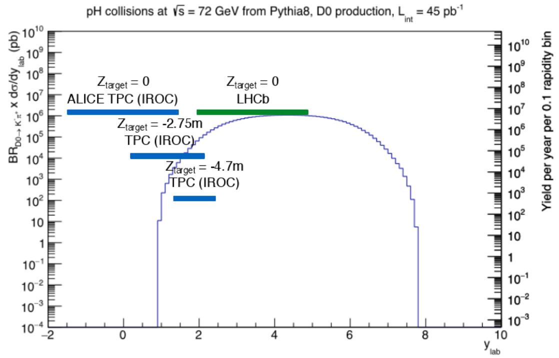
charm PDF (IC) with D

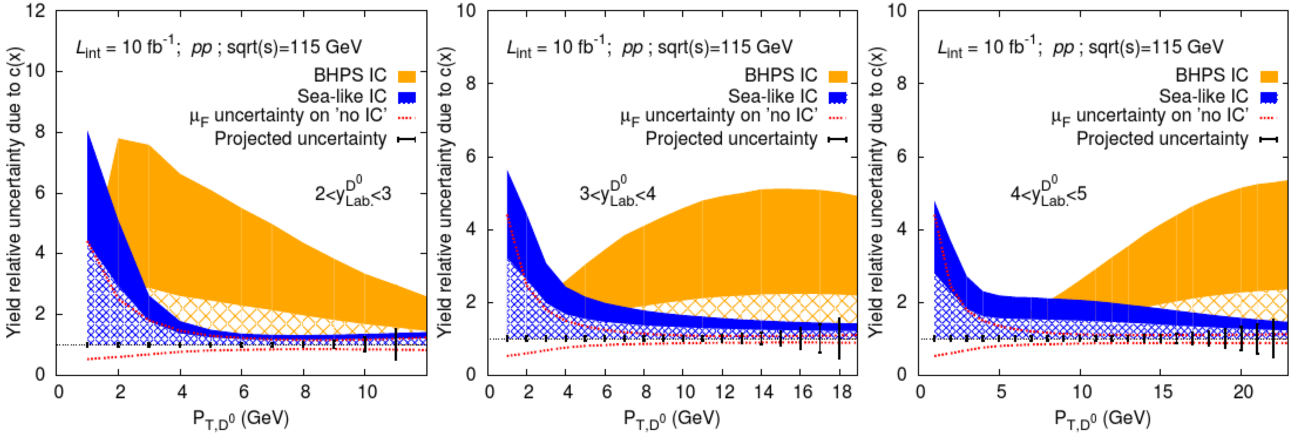
pp, $\sqrt{s}$ = 115 GeV

- Extremely good prospects for charm
  - Down to 0 p_T → total charm x-section
  - Wide rapidity coverage, x_F → -1
  - High statistical precision in pp, p-A, A-A
  - With LHCb background well under control
- Intrinsic charm modifies significantly D meson yields at large p_T or forward rapidity
- Large-x → large charm PDF uncertainty
  - Perturbative via gluon splitting vs non-perturbative from intrinsic charm
- Impact on neutrino flux and cosmic-ray physics

$D^0 \rightarrow K^- \pi^-$





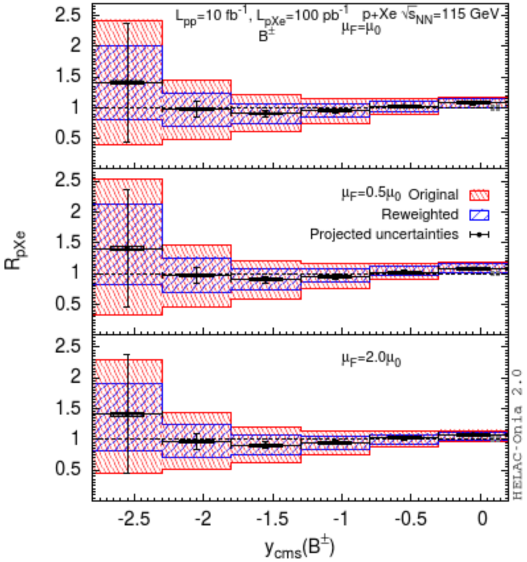


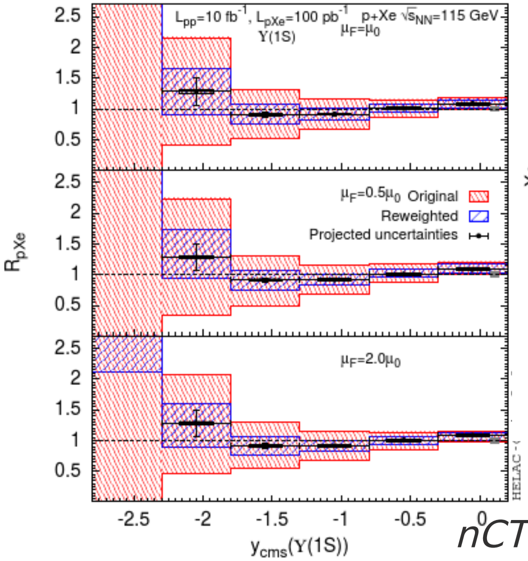
(a) $2 < y_{Lab} < 3$ (b) $3 < y_{Lab} < 4$ (c) $4 < y_{Lab} < 5$

gluon nPDF with heavy-flavour

pA, $\sqrt{s}$ = 115 GeV

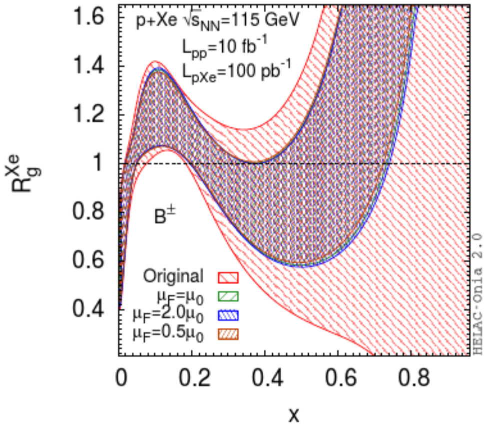
- Constraining gluon nPDF with D, B and quarkonium measurements
- Almost unknown for x > 0.1; anti-shadowing, EMC effect ?
  - Reweigting analysis with pseudo data on R_{pA}
- Large reduction on the gluon nPDF uncertainty: unique constraints at large x and low scales
- Other nuclear effects in play: nuclear absorption, …

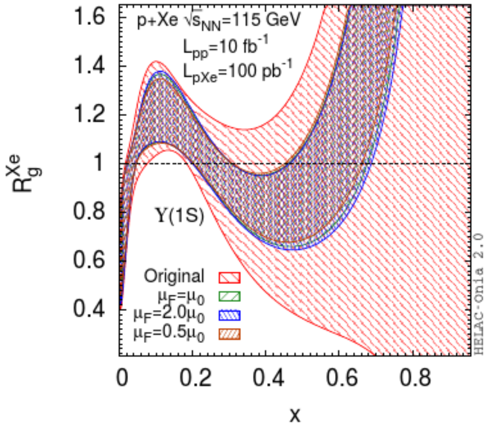




LHCb-like

nCTEQ15



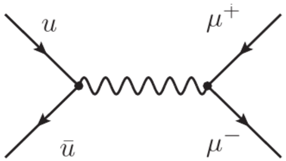


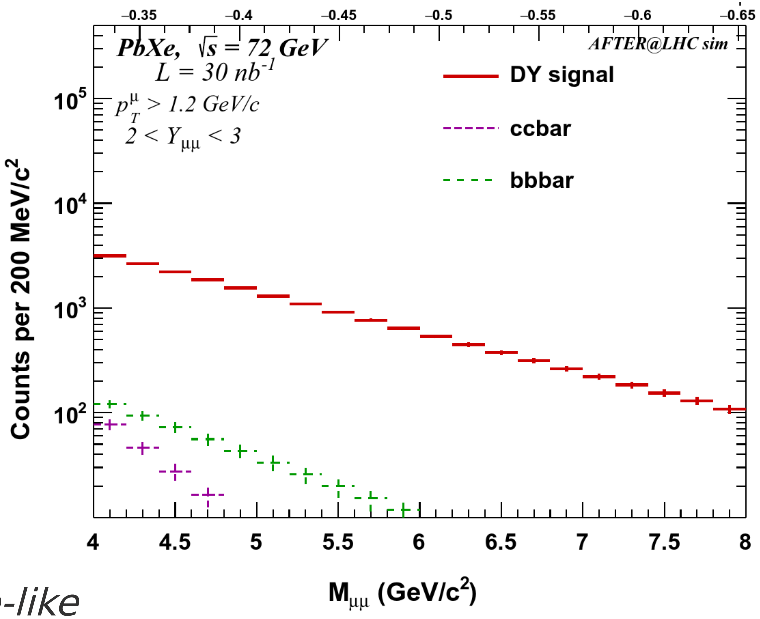
Impact on gluon nPDFs

Initial state effects with Drell-Yan

Pb-A ,
$\sqrt{s_{NN}}$ = 72 GeV

- Test of factorisation of the initial state effect in AA collisions
- Drell-Yan produced from initial state partons and do not interact with nuclear matter
- Ideal to test the factorisation of initial state effects from pA to AA
- Low correlated background, decreasing with y_{lab}





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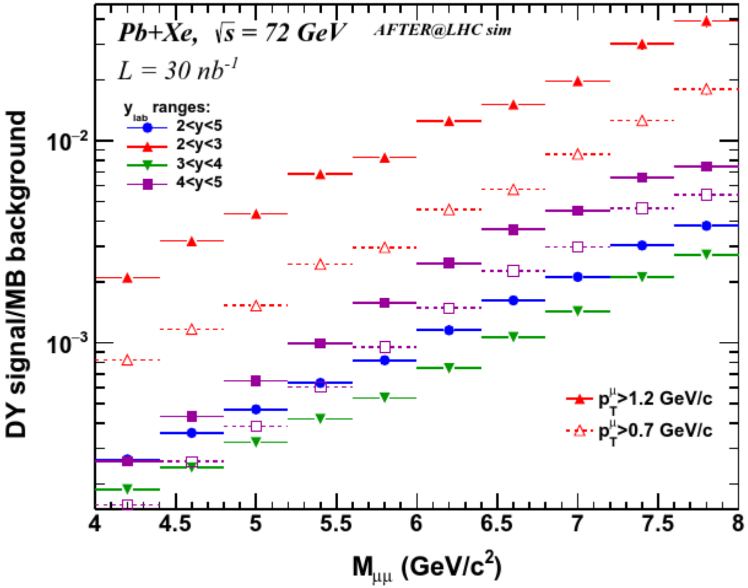


Possible implementations

– **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 existing LHC detector

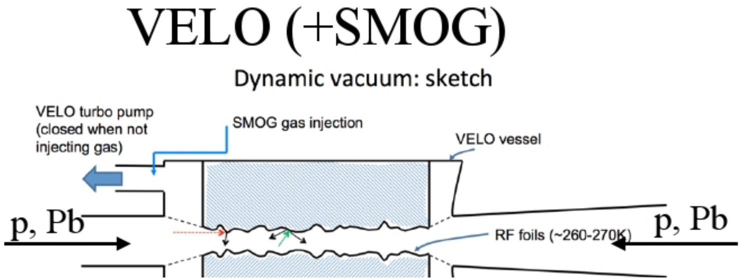
Technical implementation currently discussed within the CERN Physics Beyond Collider working group

C. Hadjidakis et al. Proceedings of IPAC2018

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

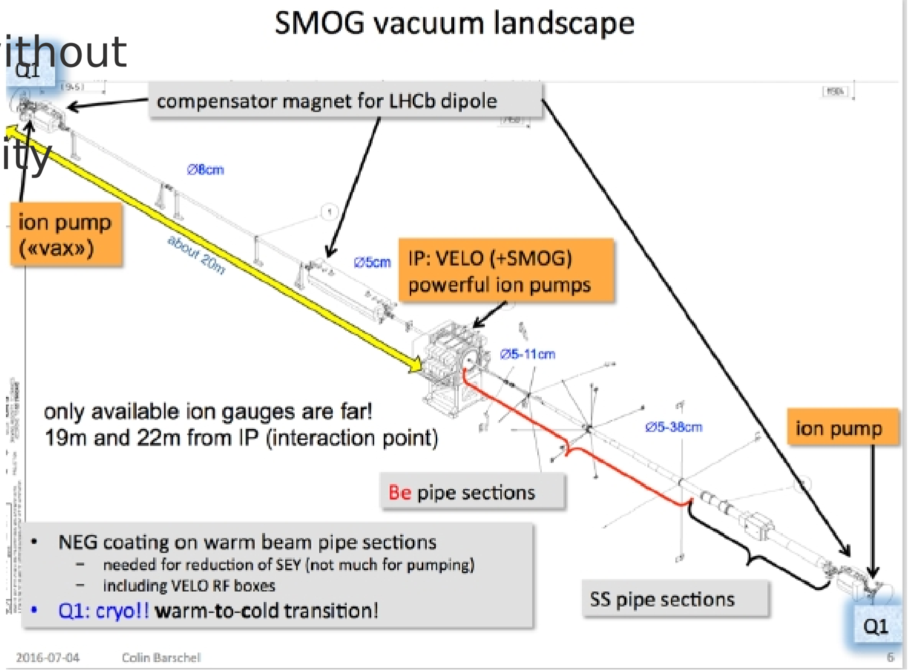
SMOG@LHC: gas target

- SMOG@LHCb (System for Measuring Overlap with Gas)
  - Demonstrator with unpolarized noble gases, so far: He, Ne, Ar
  - Gas injected into Vertex Locator (VELO) vacuum
  - LHC vacuum ion pump stations located +/- 20m on both sides
  - Full intensity of the LHC proton and lead beams without decrease of the beam lifetime
  - Low pressure, P~1.5 10^{-7} mbar → limited luminosity
    - No p-H beseline, no heavy nuclei



Luminosity

- Maximum obtained luminosity so far: $\mathscr{L}_{\text{p-Ne@68GeV}} = 100/\text{nb}$



Internal gas target: gas-jet

- Polarised H-jet polarimeter at RHIC-BNL
  - Measure proton beam polarisation at RHIC
  - 9 vacuum chambers: 9 stages of different pumping
  - Polarised gas: H, D and He possible
  - Holding field in the vacuum chamber
  - Diagnostic system: Breit-Rabi polarimeter

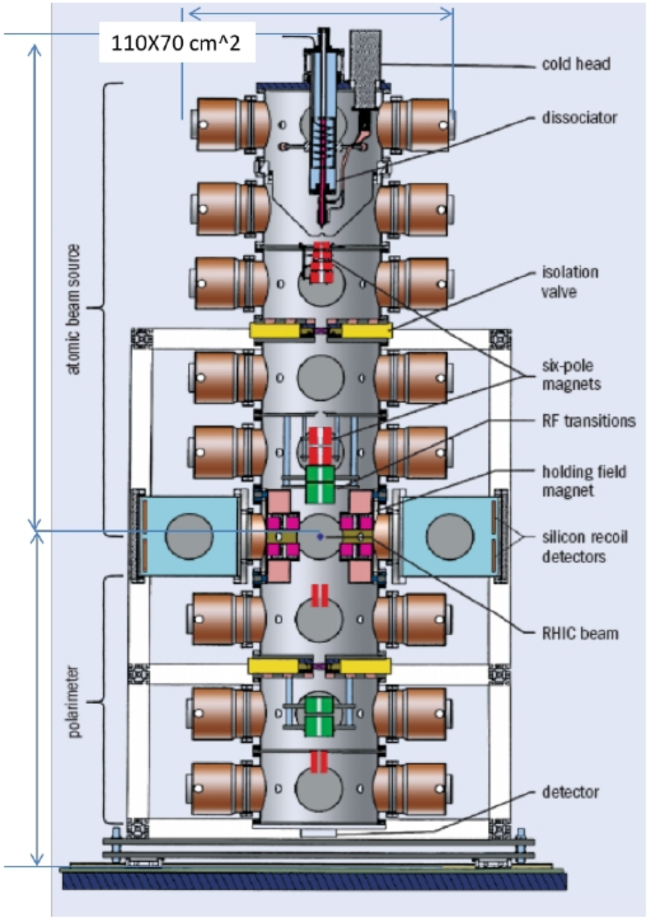
Density

- Polarised inlet $H_{\uparrow}$ flux: $1.3\ 10^{17}$ H/s
- Areal density $\vartheta_{H\uparrow} = 1.2\ 10^{12}$ atoms/cm^2 (7-15 × SMOG)
- Higher flux can be obtained for $^3He_{\uparrow}$ (x100) and H_2 (x1000)
- Gas target profile at interaction point: gaussian with a full width of ~6 mm

Typical luminosity

- Using nominal LHC bunch number [2808 bunches for proton and 592 for lead] and for 1 LHC year [10^7s proton beam and 10^6s lead beam]
- $\mathscr{L}_{p\text{-}H\uparrow} = 4.5\ 10^{30}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H\uparrow}$ = 45/pb]
- $\mathscr{L}_{p\text{-}H2} = 10^{33}\text{-}10^{34}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H2}$ = 10-100/fb]

Zelenski et al. NIM A 536 (2005) 248



Internal gas target: storage cell

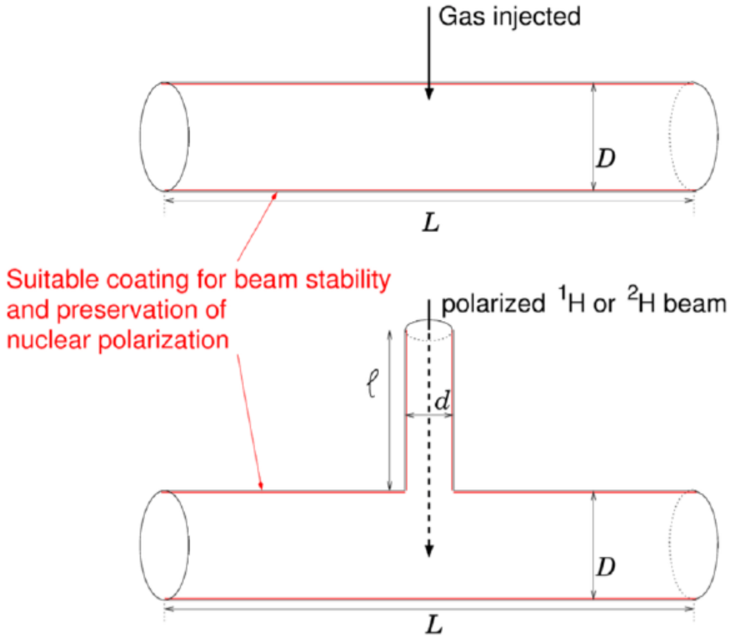
- HERMES/DESY T-shape internal storage cell target
  - Vacuum chamber target ~ 72 cm x 50 cm and pumping system
  - Polarised gas: atomic beam source
  - Holding field in the target chamber
  - Diagnostic system: target gas analyzer and polarimeter
  - Unpolarised gas via capillary
  - Proposal for LHC:

Density

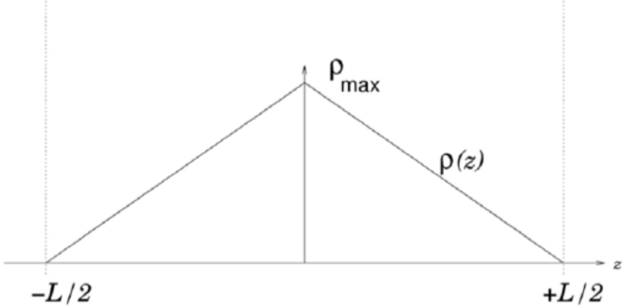
- Polarised inlet $H_{\uparrow}$ flux: 6.5 10^{16} $H_{\uparrow}$/s
- Areal density $\vartheta_{H\uparrow} = 2.5\ 10^{14}$ atoms/cm^2 (~100 × gas jet)
- Unpolarised gas pressure limited by beam lifetime

Typical luminosity

- $\mathscr{L}_{p\text{-}H\uparrow} = 0.9\ 10^{33}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H\uparrow}$ = 9/fb]
- $\mathscr{L}_{Pb\text{-}H\uparrow} = 1.2\ 10^{29}$ cm^{-2}s^{-1} [t = 10^6s: $\mathscr{L}_{Pb\text{-}H\uparrow}$ = 100/nb]
- $\mathscr{L}_{p\text{-}H2} = 5.8\ 10^{33}$ cm^{-2}s^{-1} [t = 10^7s: $\mathscr{L}_{p\text{-}H2}$ = 58/fb]
- $\mathscr{L}_{Pb\text{-}Xe} = 3\ 10^{28}$ cm^{-2}s^{-1} [t = 10^6s: $\mathscr{L}_{Pb\text{-}Xe}$ = 30/nb]



C. Barschel et al. Adv.High Energy Phys. 2015 (2015) 463141



Slow beam extraction: bent crystal

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

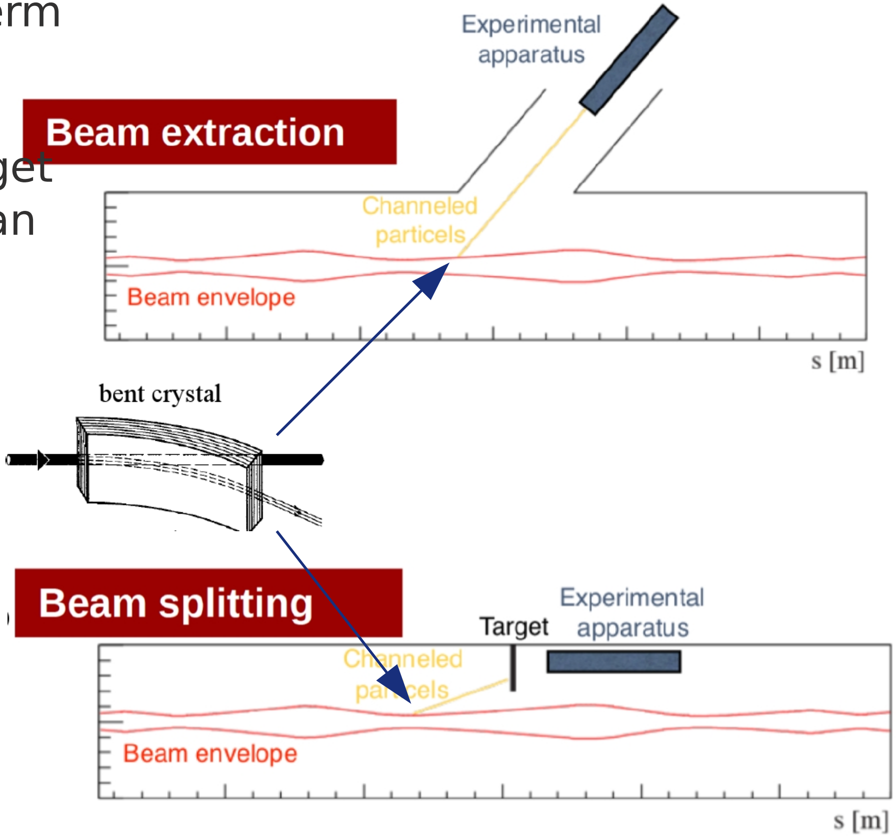
- Bent crystal studies by UA9
  - For collimation purpose at the LHC
  - Beam extraction: new beam line possible (long-term project)
  - Beam splitting:
    - Crystal located ~100 m downstream of the target
    - Solid target internal to the beam pipe close to an existing experimental apparatus
    - Absorber ~100 m upstream the detector

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

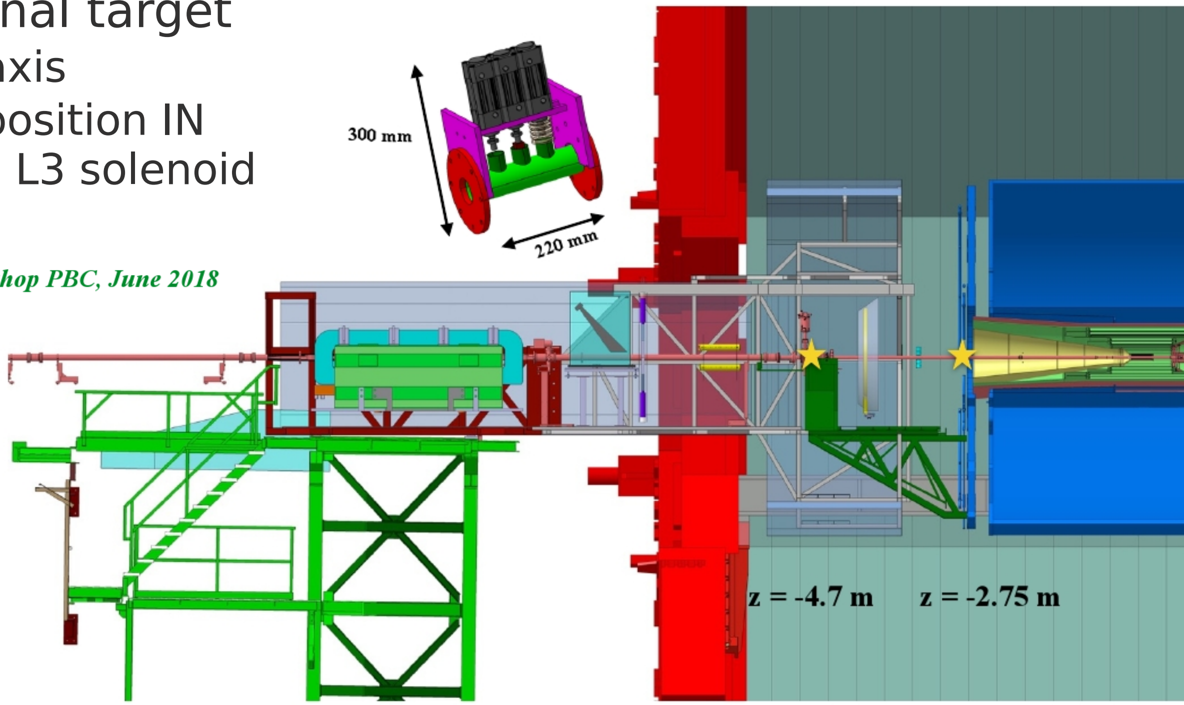
- Assuming 5 mm target length
- $\mathscr{L}_{p\text{-}W} = 1.6\ 10^{31}\ cm^{-2}s^{-1}$ [$t = 10^7 s$: $\mathscr{L}_{p\text{-}W} = 160$/pb]
- $\mathscr{L}_{Pb\text{-}W} = 3\ 10^{27}\ cm^{-2}s^{-1}$ [$t = 10^6 s$: $\mathscr{L}_{Pb\text{-}W} = 3$/nb]



Possible implementation: ALICE

- Beam splitting with crystal + internal target
  - Located at ~1.3 cm from the beam axis
  - Pneumatic motion system with two position IN and OUT of the beam pipe inside the L3 solenoid
  - Target type: Be, C, Ti, W
  - Discussion ongoing

Annual Workshop PBC, June 2018



- Achievable yearly luminosities:
  - With gas target (storage cell)
    - $\mathcal{L}_{\text{p-H2/H}\uparrow\text{@115GeV}} = 260/\text{pb}$, $\mathcal{L}_{\text{p-Xe@115GeV}} = 8/\text{pb}$
    - $\mathcal{L}_{\text{Pb-Xe@72GeV}} = 8/\text{nb}$
  - With beam splitting and at most 5 mm solid target
    - $\mathcal{L}_{\text{p-W@115GeV}} = 6/\text{pb}$
    - $\mathcal{L}_{\text{Pb-W@72GeV}} = 3/\text{nb}$

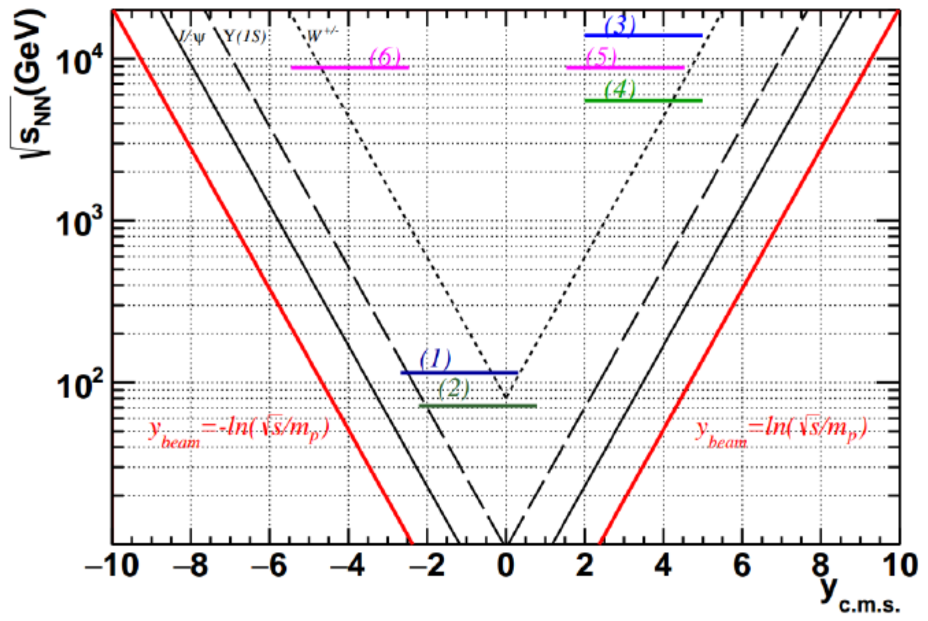
ALICE Readout for Run3: 50 kHz in Pb-Pb and 200kHz-1 MHz in p-p/p-A

Integrated luminosities: ALICE

Target		ALICE: proton beam ($\sqrt{s_{NN}}$= 115 GeV) $\mathcal{L}$ [$cm^{-2}\ s^{-1}$]	Inel. rate [kHz]	$\int \mathcal{L}$	ALICE: Pb beam ($\sqrt{s_{NN}}$= 72 GeV) $\mathcal{L}$ [$cm^{-2}\ s^{-1}$]	Inel. rate [kHz]	$\int \mathcal{L}$
Internal gas target (gas-jet option)	$H^{\uparrow}$	4.3×10^{30}	168	43 pb^{-1}	5.6×10^{26}	1	0.56 nb^{-1}
	H_2	2.6×10^{31}	1000	0.26 fb^{-1}	2.8×10^{28}	50	28 nb^{-1}
	$D^{\uparrow}$	4.3×10^{30}	309	43 pb^{-1}	5.6×10^{26}	1.2	0.56 nb^{-1}
	$^3He^{\uparrow}$	8.5×10^{30}	1000	85 pb^{-1}	2.0×10^{28}	50	20 nb^{-1}
	Xe	7.7×10^{29}	1000	7.7 pb^{-1}	8.1×10^{27}	50	8.1 nb^{-1}
Beam splitting	C	3.7×10^{30}	1000	37 pb^{-1}	5.6×10^{27}	18	5.6 nb^{-1}
	Ti	1.4×10^{30}	1000	14 pb^{-1}	2.8×10^{27}	13	2.8 nb^{-1}
	W	5.9×10^{29}	1000	5.9 pb^{-1}	3.1×10^{27}	21	3.1 nb^{-1}

Interaction rate limited to 1 MHz by the expected detector data taking rate capabilities

Kinematic coverage: LHCb



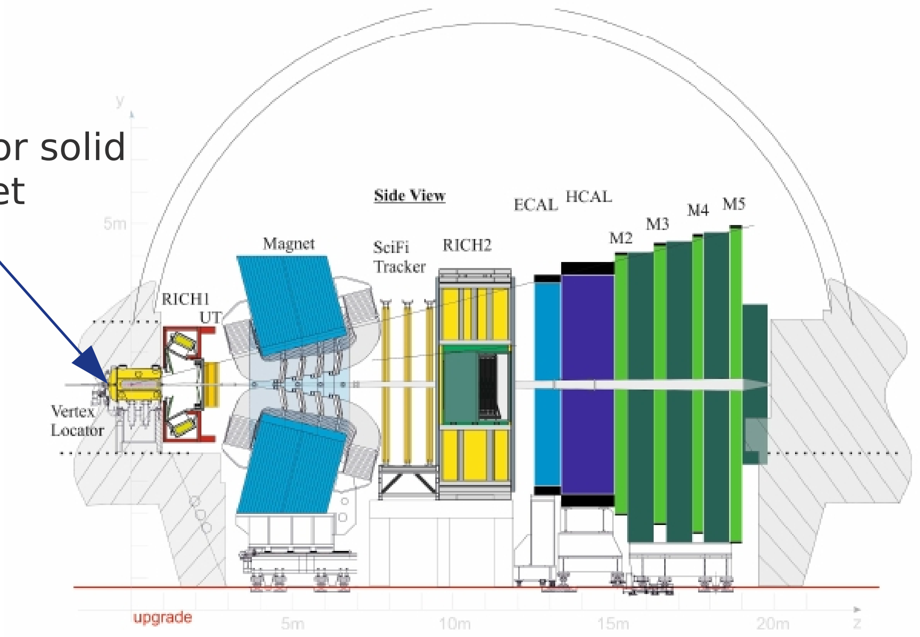
LHCb: $2 < \eta^{lab} < 5$

(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV; (2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV; (3) collider mode, $\sqrt{s}$ = 14 TeV; (4) collider mode, $\sqrt{s_{NN}}$ = 5.5 TeV,

(5),(6) $\sqrt{s_{NN}}$ = 8.8 TeV

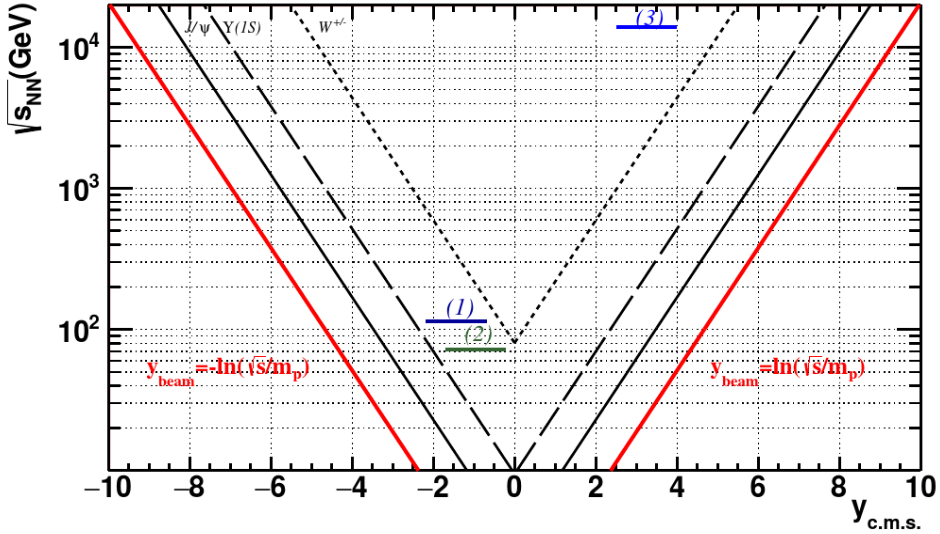
- Forward detector with full PID
- Limitation in high-multiplicity event reconstruction

gas or solid target



Kinematic coverage: ALICE

for $Z_{target} \sim 0$



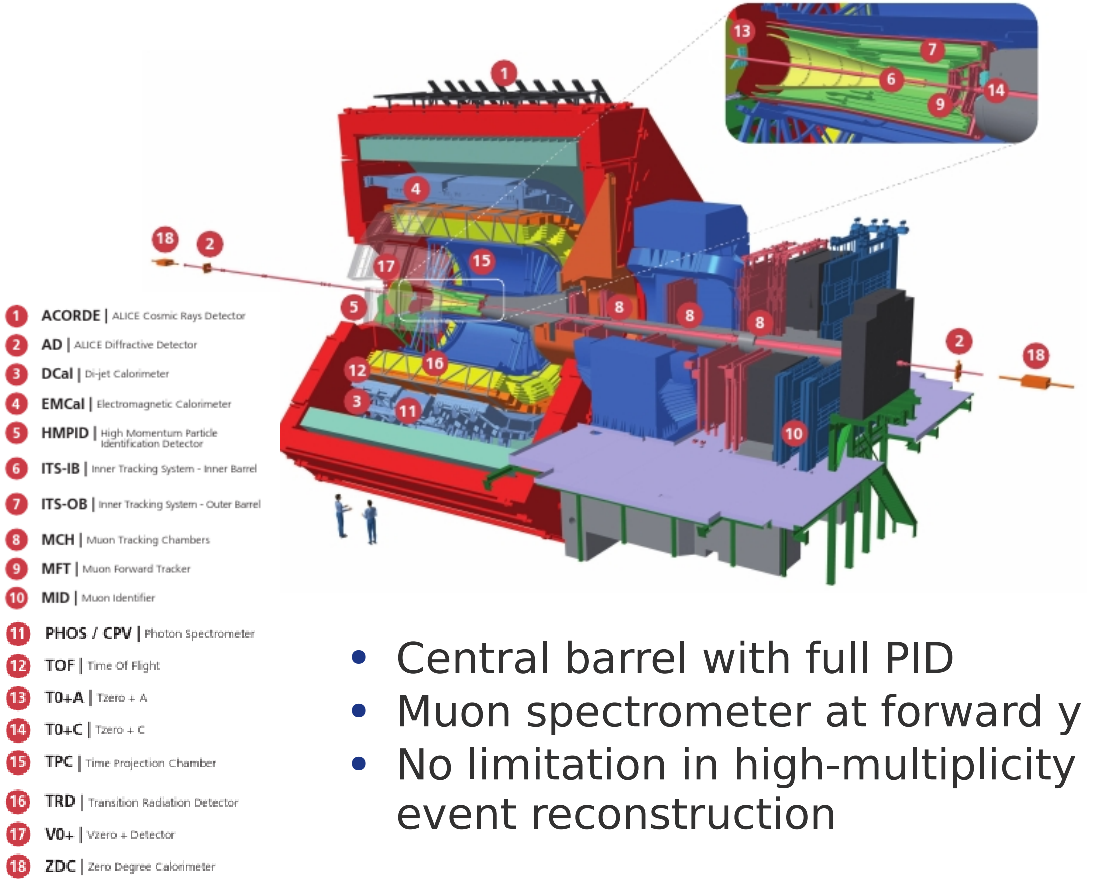
ALICE: Muon Det.: $2.5 < \eta^{lab} < 4$,

TPC: $|\eta^{lab}| < 0.9$

(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV;

(2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV;

(3) collider mode, $\sqrt{s}$ = 14 TeV;



- Central barrel with full PID
- Muon spectrometer at forward y
- No limitation in high-multiplicity event reconstruction