20. KONFERENCE ČESKÝCH A SLOVENSKÝCH FYZIKŮ

Novel high-luminosity fixed-target experiment at the LHC

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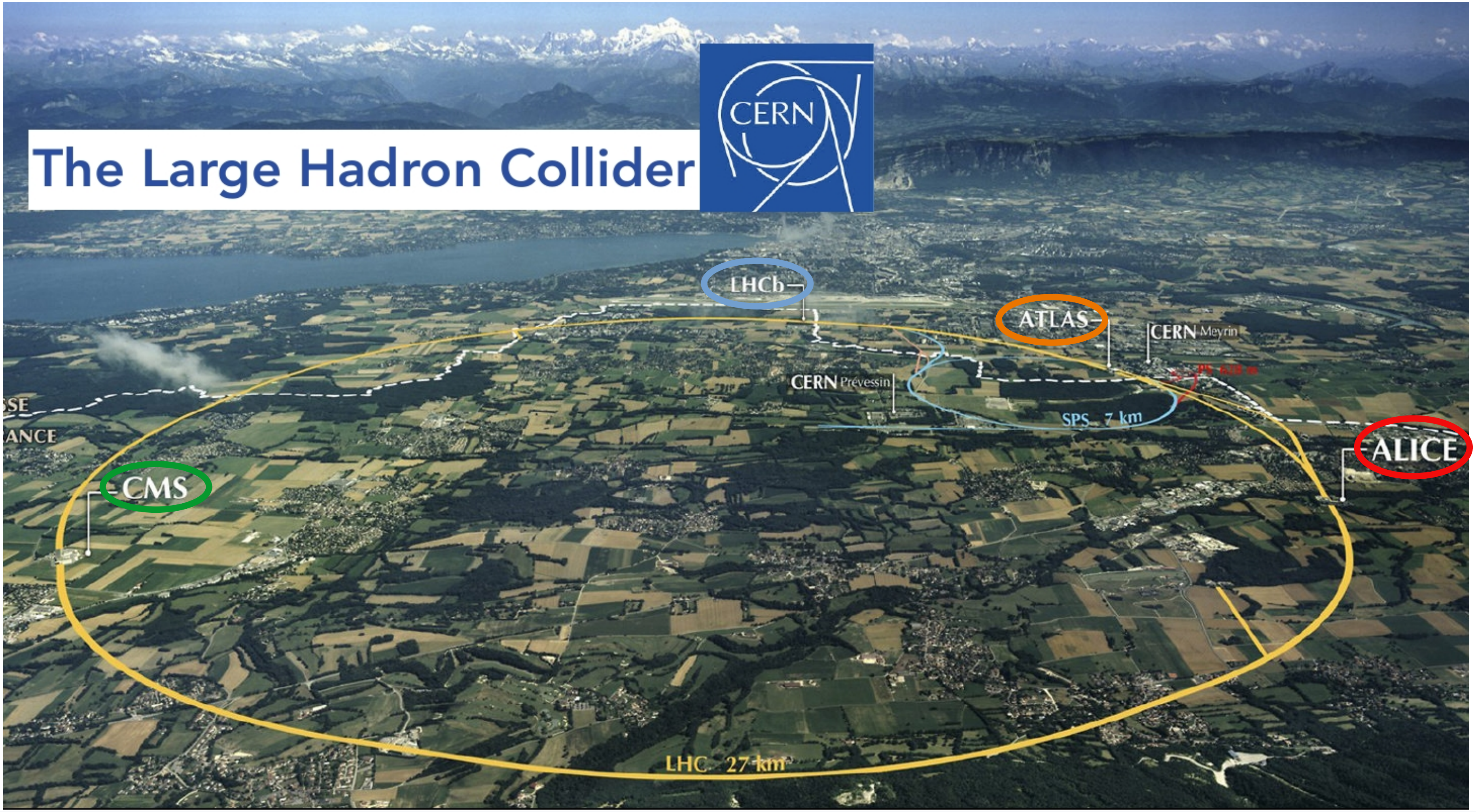
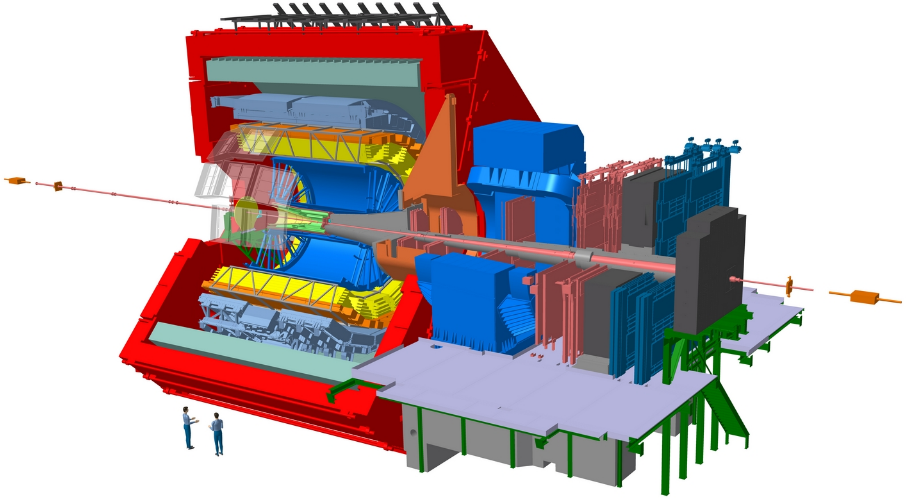
LHC

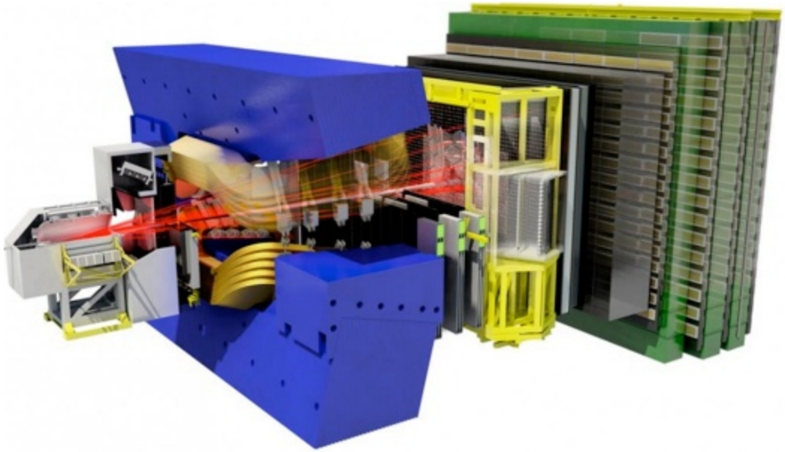

The Large Hadron Collider
CERN
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
LHC 27 km

The collider mode at LHC

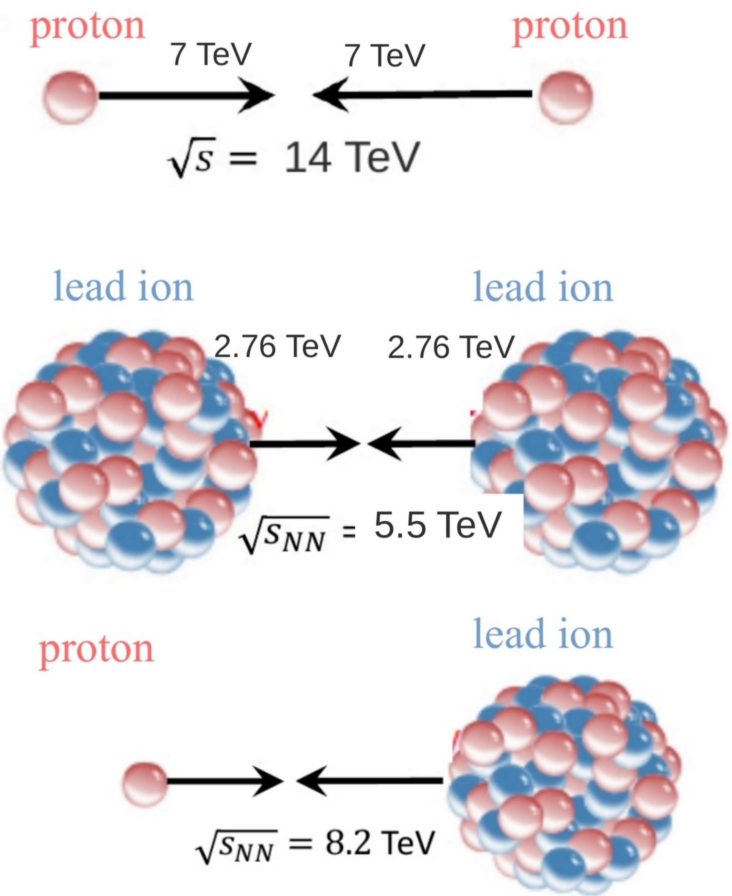
ALICE



LHCb



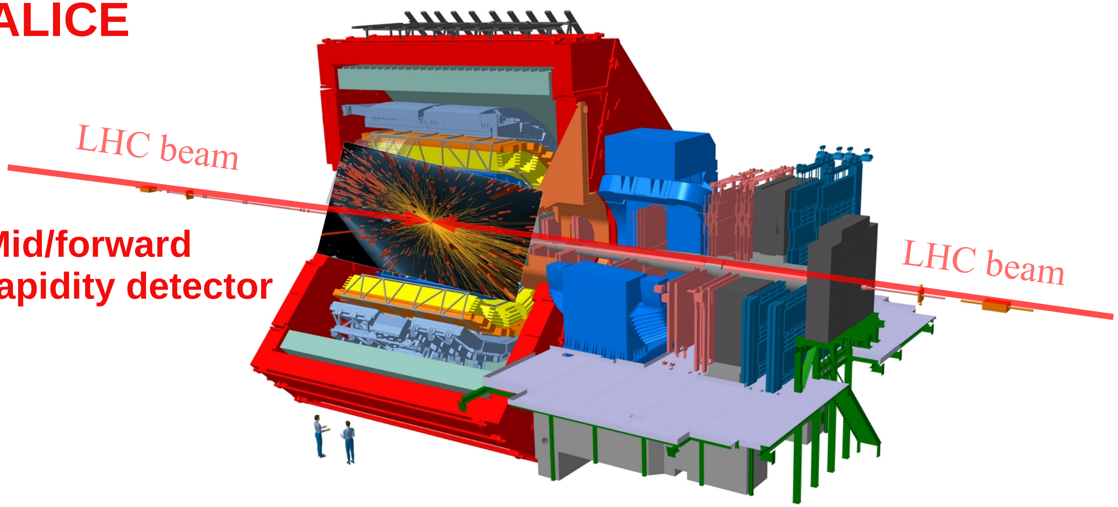
Collider Mode



The collider mode at LHC

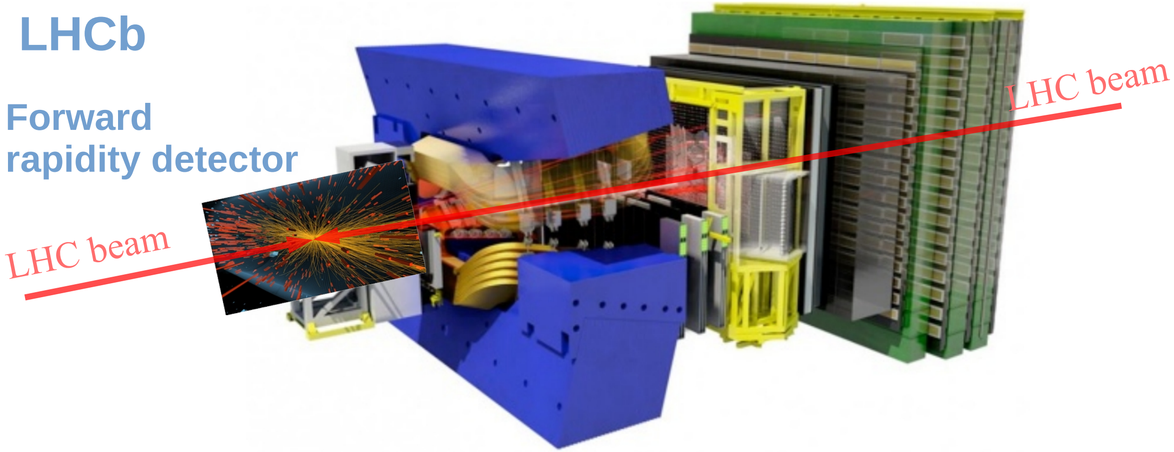
ALICE

Mid/forward rapidity detector



LHCb

Forward rapidity detector



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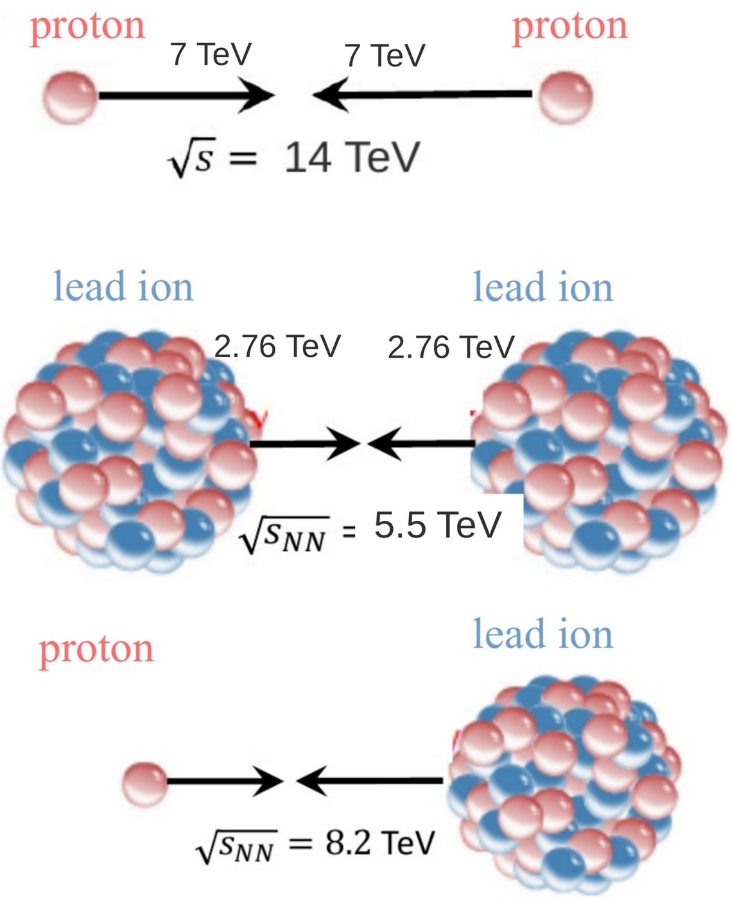
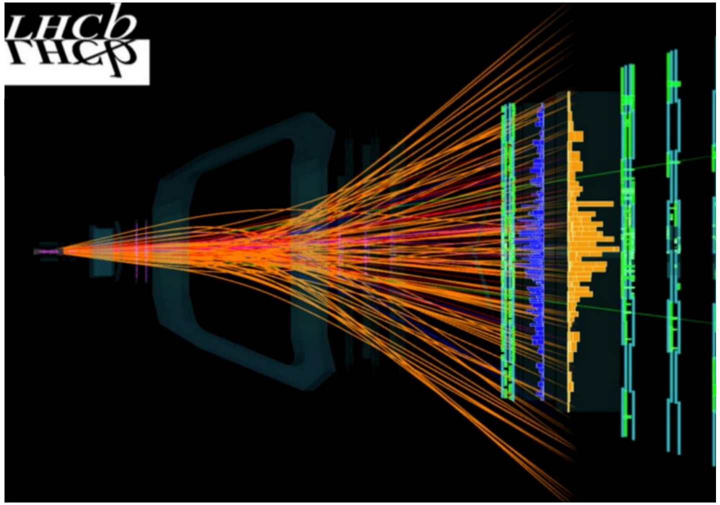
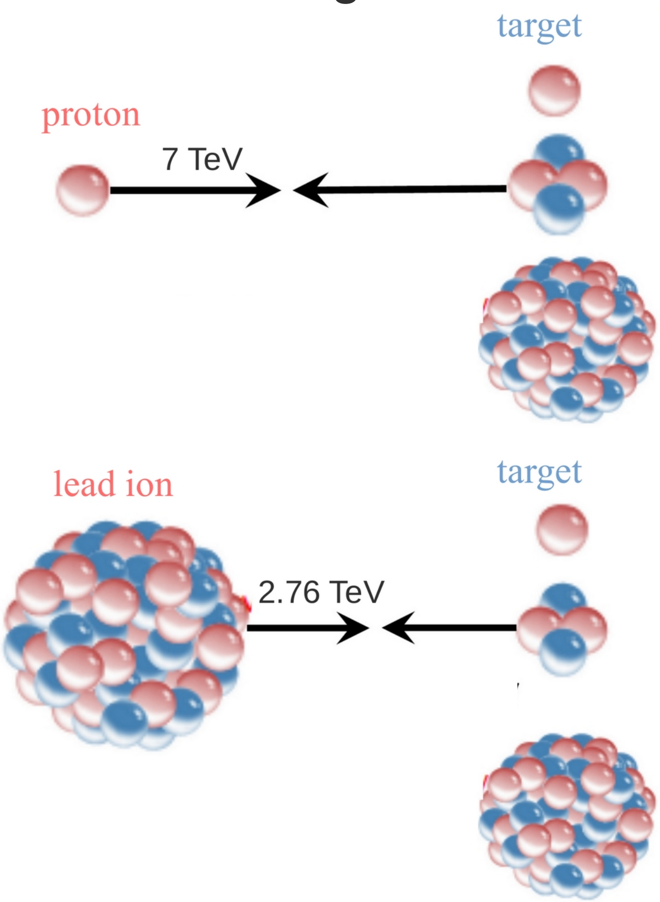


A fixed-target mode at LHC

- **Energy range**



Fixed-target Mode



A fixed-target mode at LHC

➔ Energy range

7 TeV proton beam on a fixed target

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

2.76 TeV Pb beam on a fixed target

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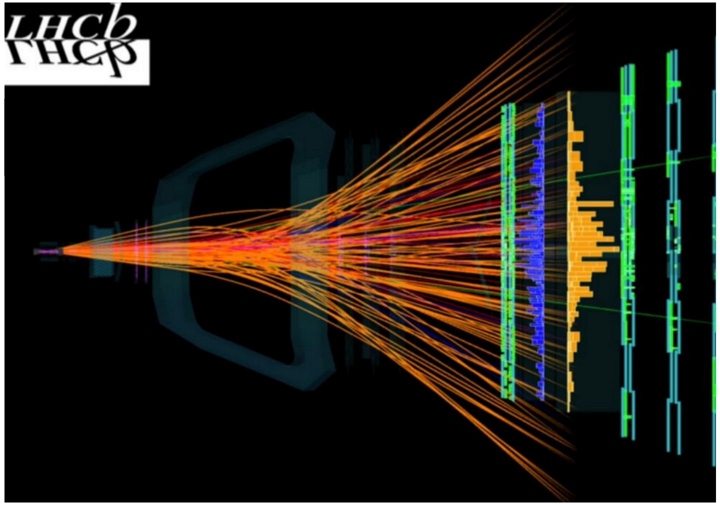
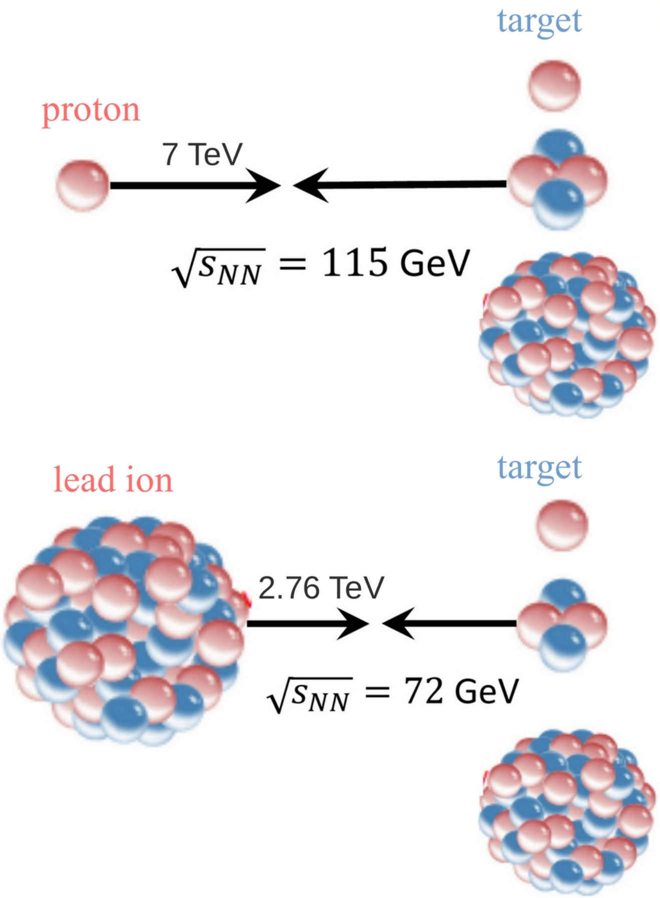


Fixed-target Mode



A fixed-target mode at LHC (2)

Effect of boost

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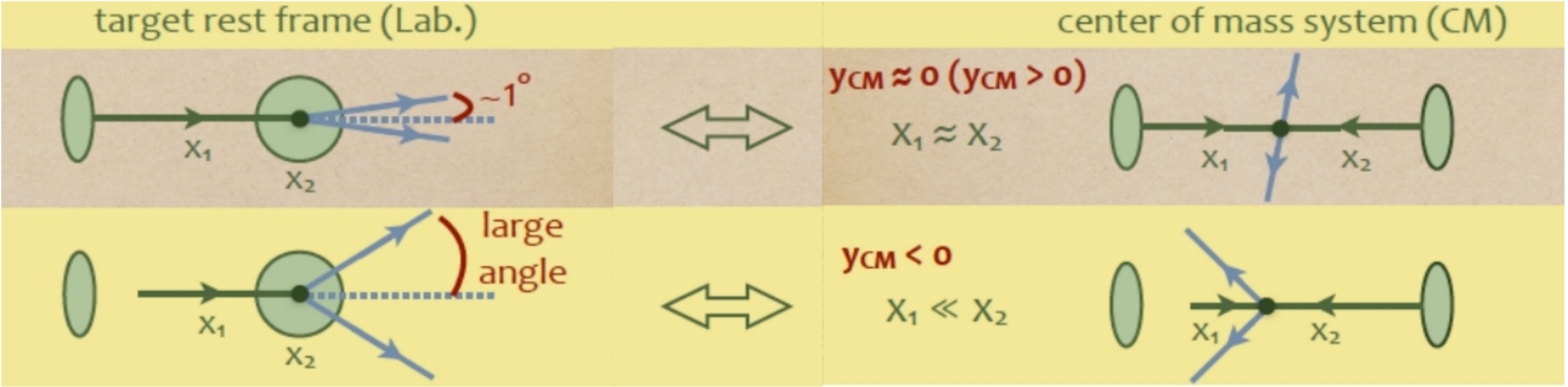

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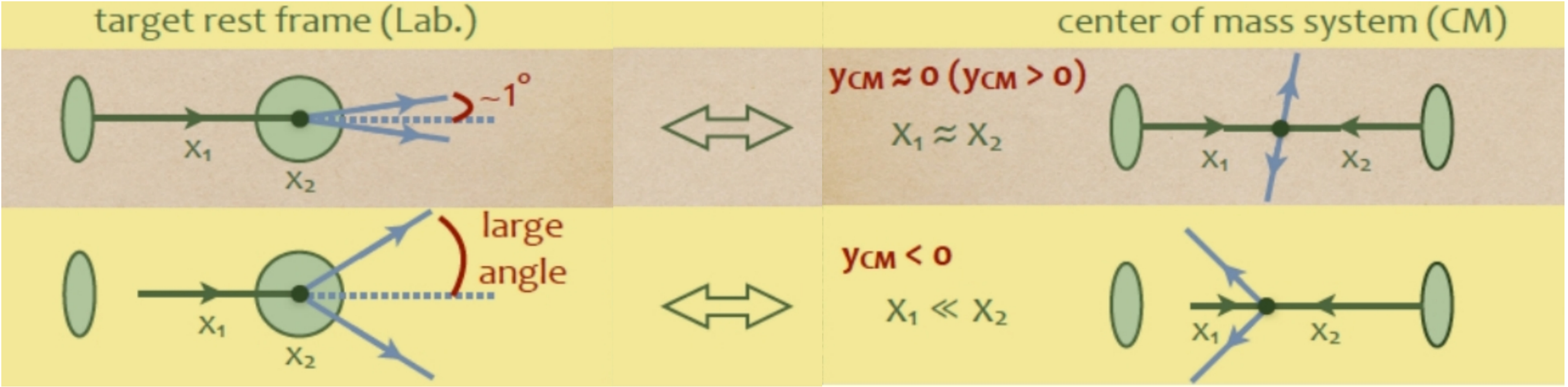
  Entire forward hemisphere within 1°



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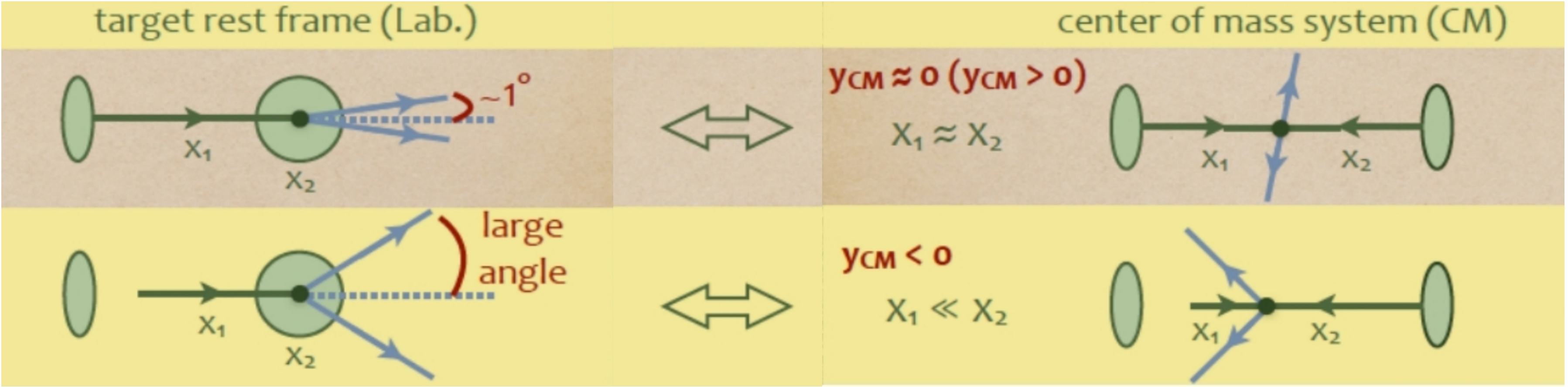
- $\mathbf{y_{cms} < 0}$

  Easy access to (very) large CM backward rapidity range,

  And large parton momentum fraction $x_2 \rightarrow 1$ ($x_F \rightarrow -1$)

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



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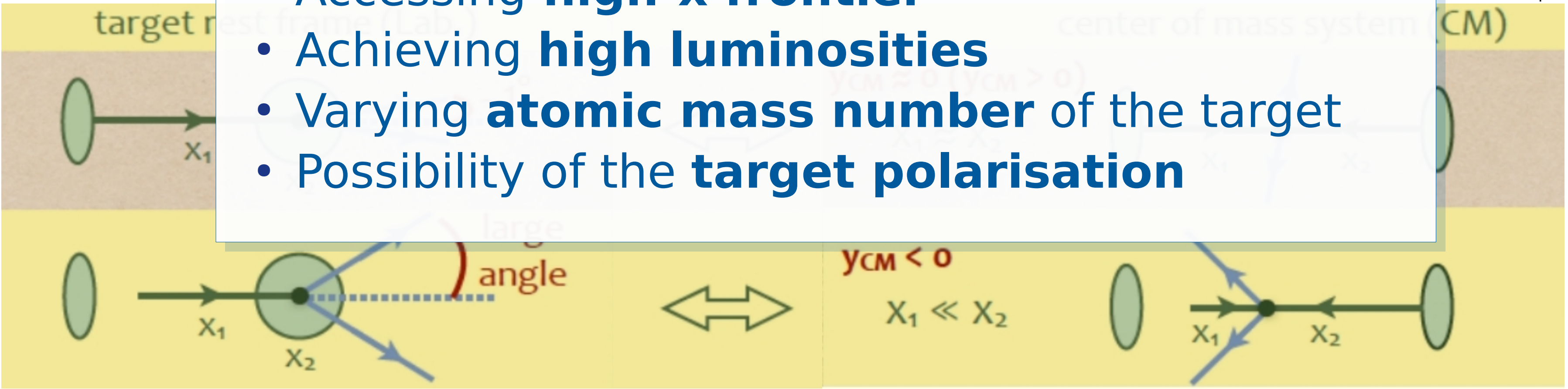
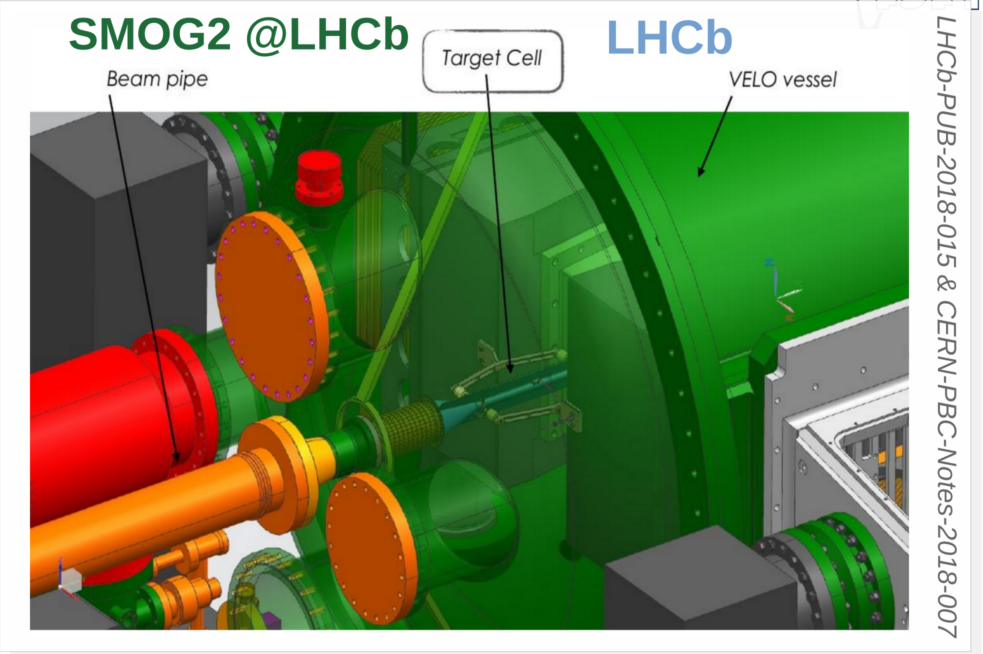


Advantages of a fixed-targed mode at the LHC

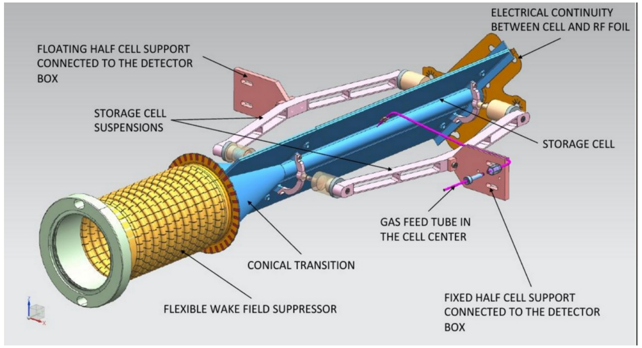
- Accessing **high-x frontier**
- Achieving **high luminosities**
- Varying **atomic mass number** of the target
- Possibility of the **target polarisation**

Possible implementations

- **Internal gas target**
  - Full LHC beam flux on internal gas target
  - Feasibility demonstrated by SMOG at LHCb
  - Storage cell target (HERMES-like) or gas-jet system (RHIC H-jet polarimeter) for (un)polarised gases
  - **Can be coupled with an existing experiment**
- **Internal wire/foil target**
  - Beam halo recycled directly on internal solid target
  - As HERA-B and STAR, heavy-nucleus targets



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



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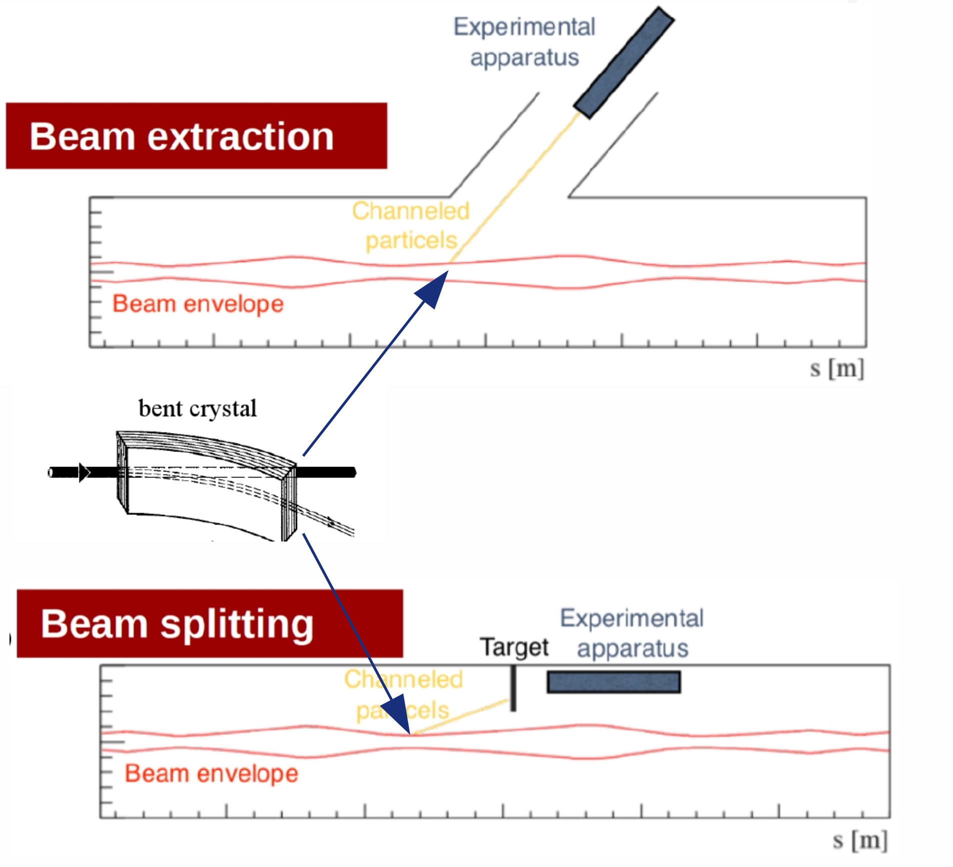
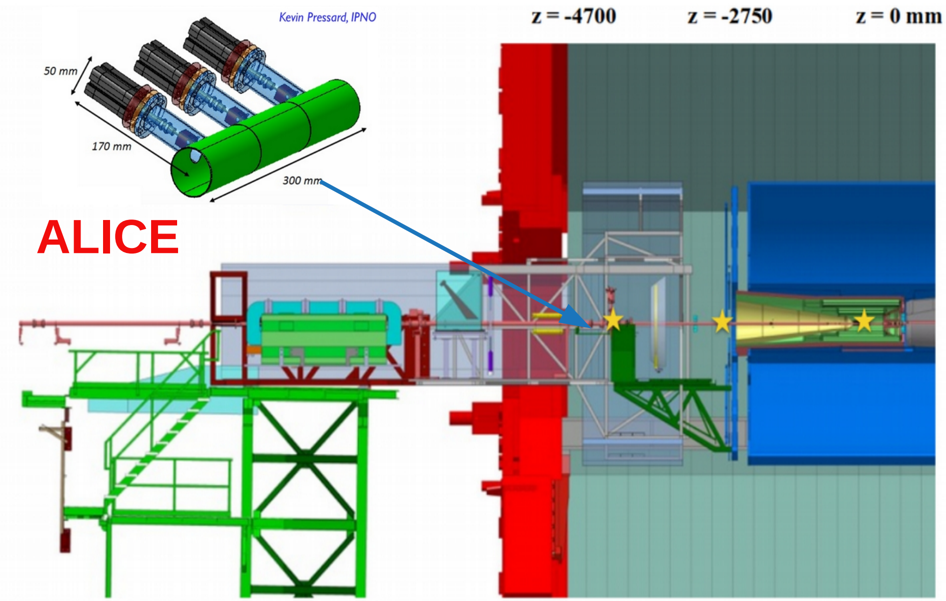
- **Beam line extracted with a bent crystal**
  - Beam halo deflected onto an external target
  - Thick (un)polarised and cryogenic polarised targets
  - Considerable amount of civil engineering
- **Beam "split" by a bent crystal**
  - Beam halo deflected onto an internal solid or gas target
  - **Inside beam pipe of an existing LHC experiment**



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

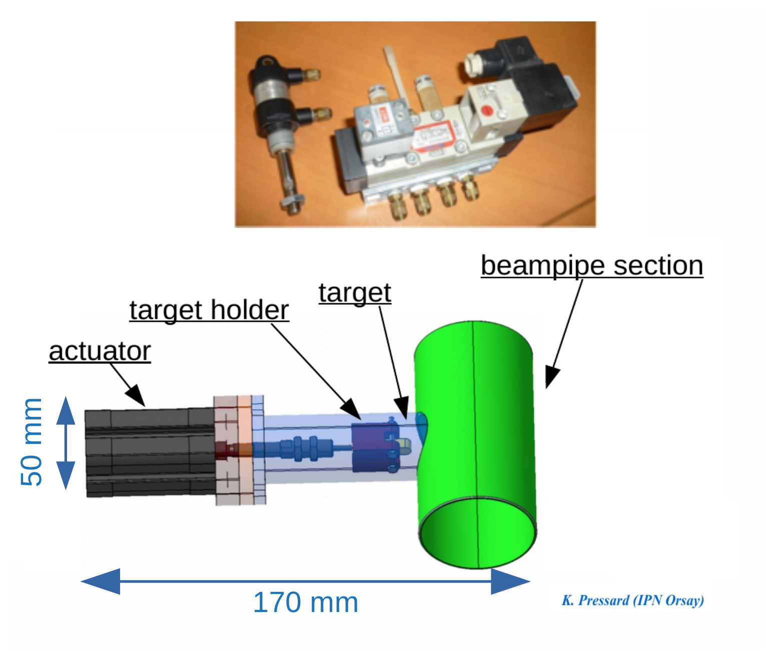
Possible implementations: ALICE

- **Beam splitting with bent crystal + internal target**
  - Crystal installed prior of the IP2, deviates the beam halo onto a target
  - Pneumatic motion system with two position, IN and OUT of the beam pipe
  - Various target type: from Be to W
  - Target length from ~100μm to 1 cm
  - ***Feasibility studies ongoing***



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

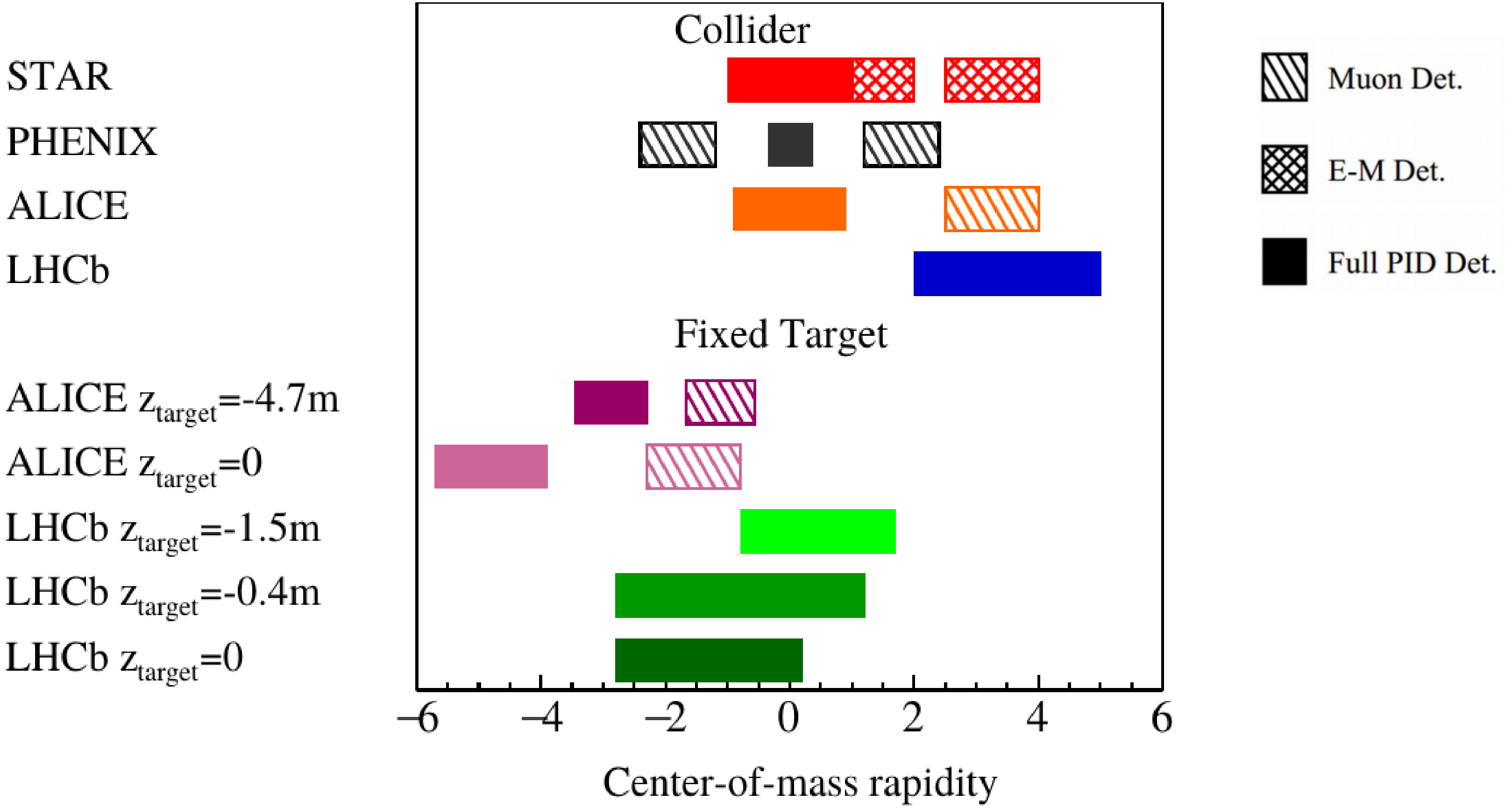
CERN-PBC-Note-2019-004
https://cds.cern.ch/record/2671944



- **Gas storage cell target**
  - *Under study*

Acceptance in centre-of-mass y

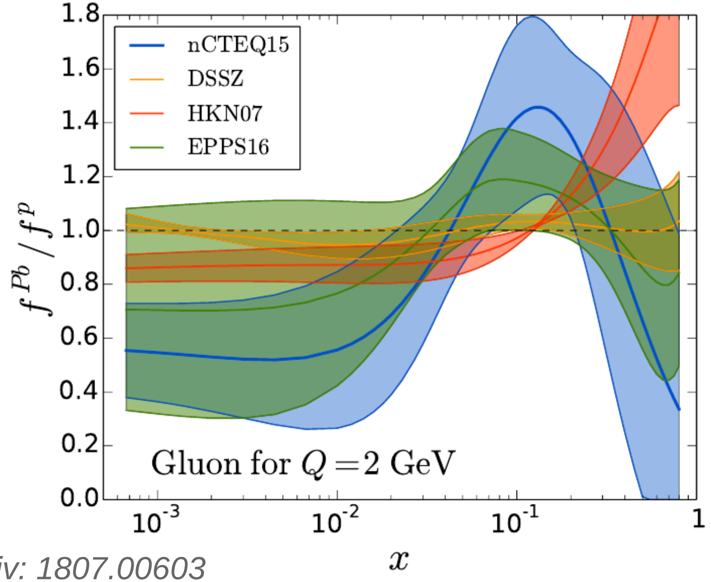
- With7 TeV proton beam
  $\Delta y = 4.8$



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**

Gluon nuclear PDF uncertainties in lead nuclei



arXiv: 1807.00603

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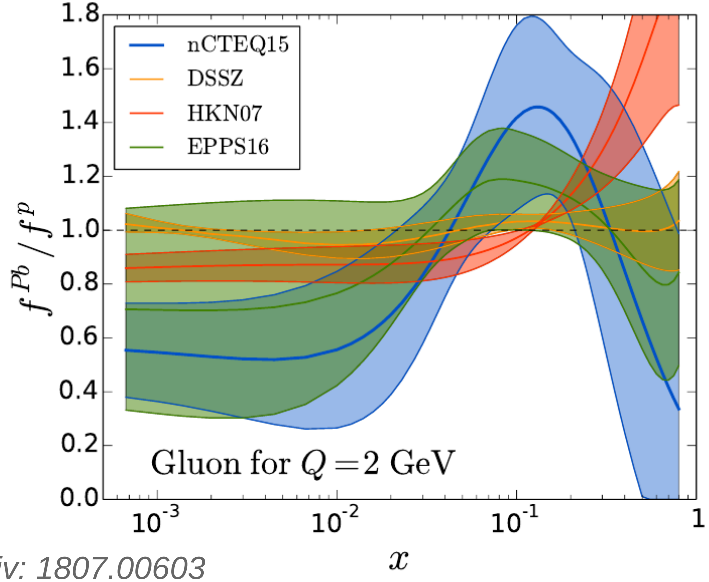

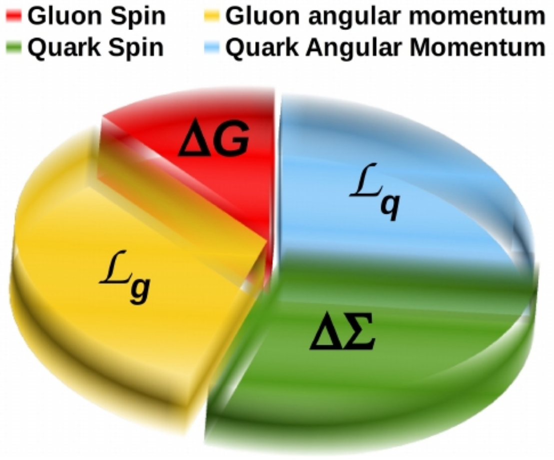

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$

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- Studies of the **quark-gluon plasma** in heavy-ion collisions at a new energy domain down to the target-rapidity region

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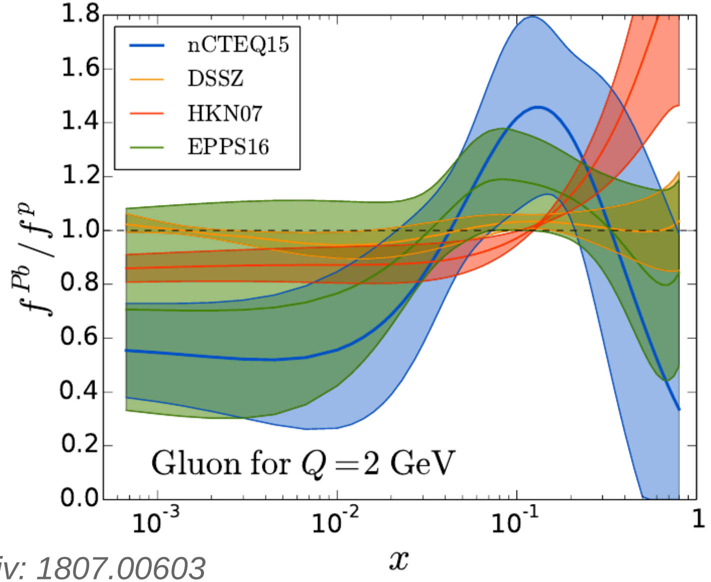

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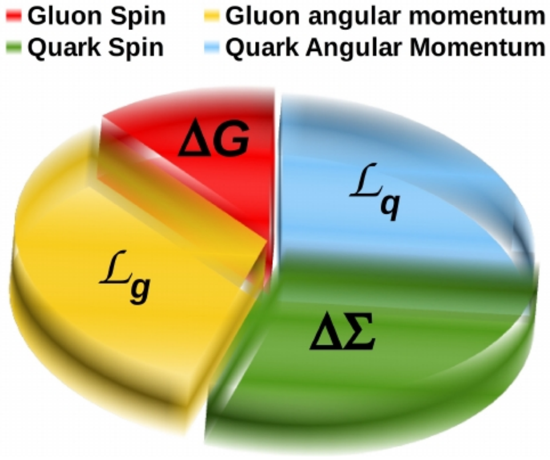

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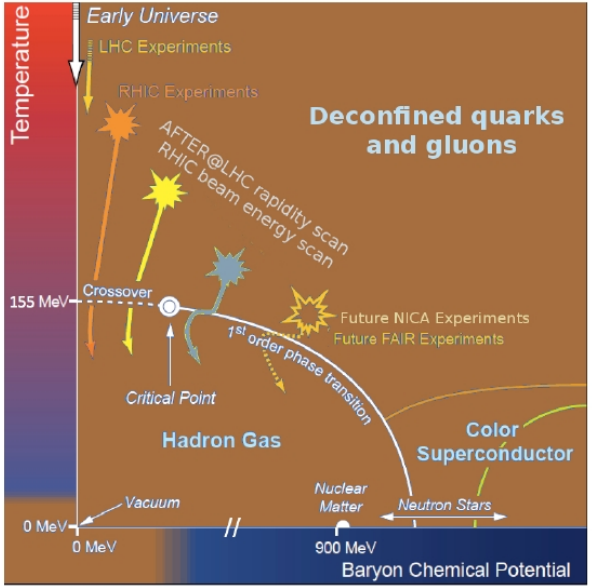
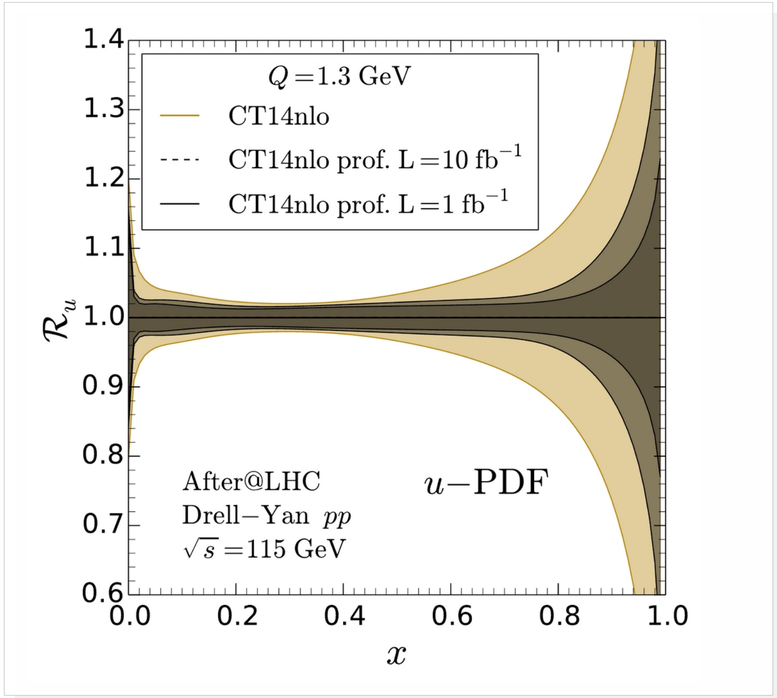


High-x PDF and nPDF

- Structure of nucleon and nuclei at high-x (>0.5) is poorly known, both at low and high scales
- Intrinsic (non-perturbative) charm (beauty) content of proton ?
  Important for reducing uncertainties of the neutrino flux

u quark PDF uncertainties



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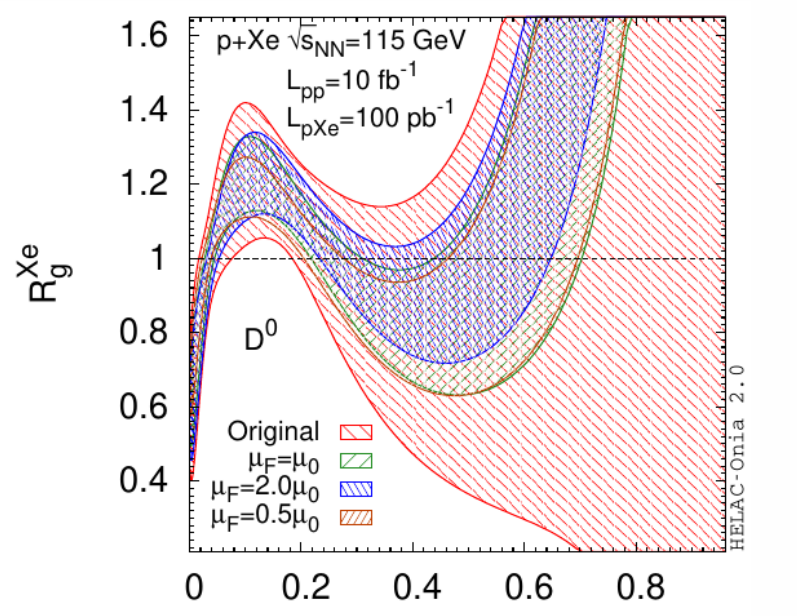

nCTEQ15/ CT14, Q=2GeV

arXiv: 1807.00603

Spin of nucleon

- 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

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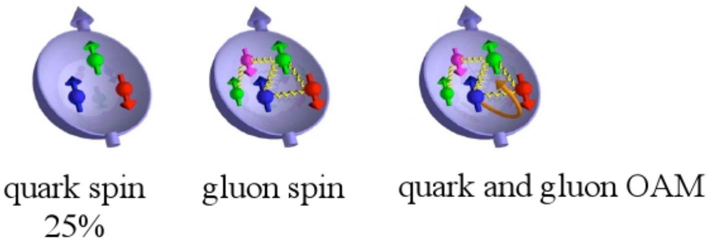

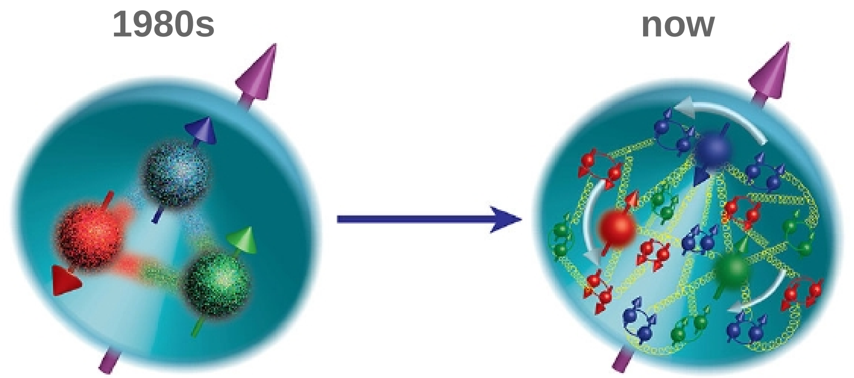

  - quark/anti-quark: ~30% of proton longitudinal spin
  - gluons: even up to 40%

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

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

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quark spin 25% | gluon spin | quark and gluon OAM

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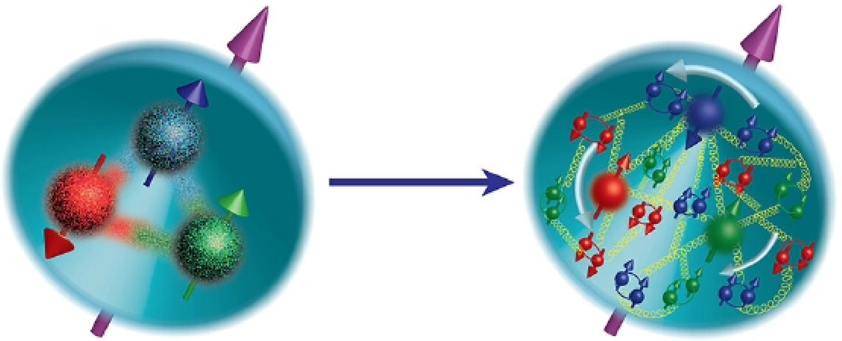


- **Single Transverse Spin Asymmetries** (with transversely polarised target) → orbital motion of partons inside hadron: Sivers effect
- **Non-zero quark/gluon Sivers functions → non-zero OAM**

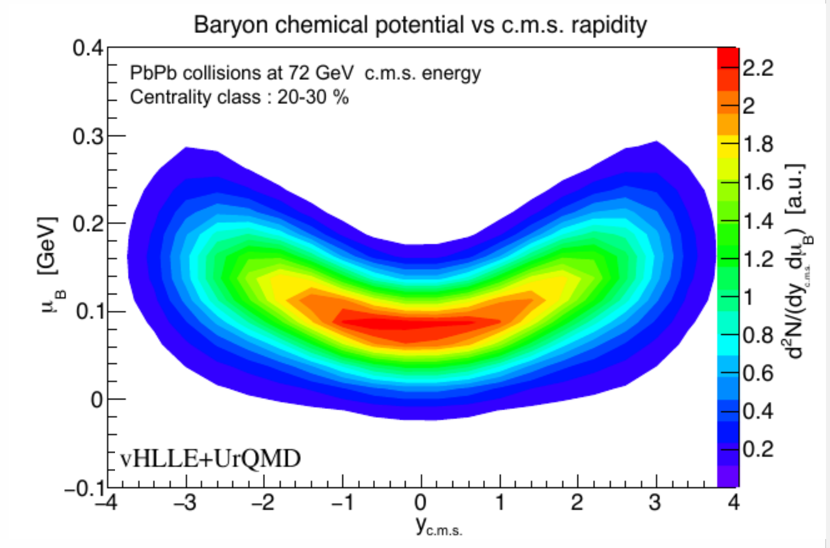
$f_{1T}^{\perp}$ =

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

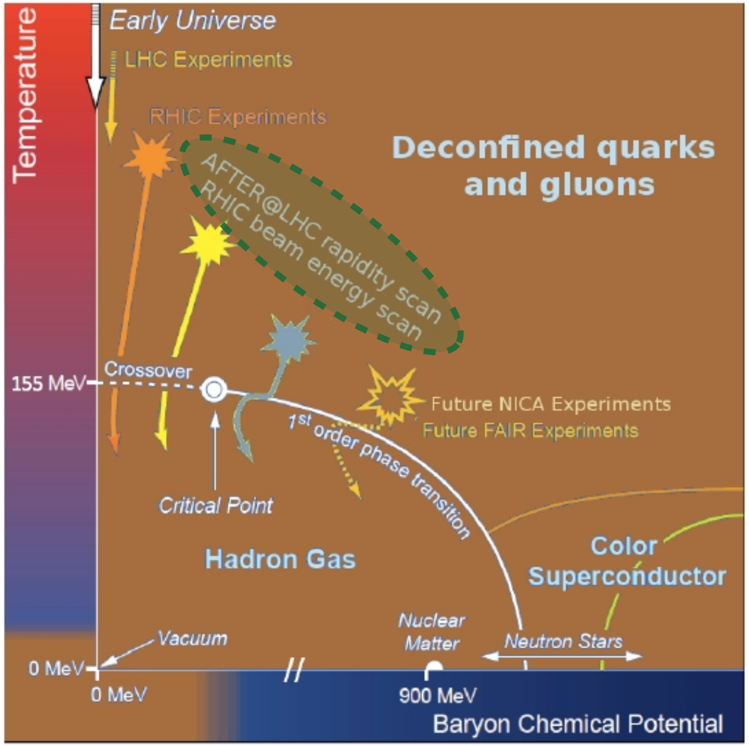
arXiv: 1807.00603

Quark-Gluon Plasma

- 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



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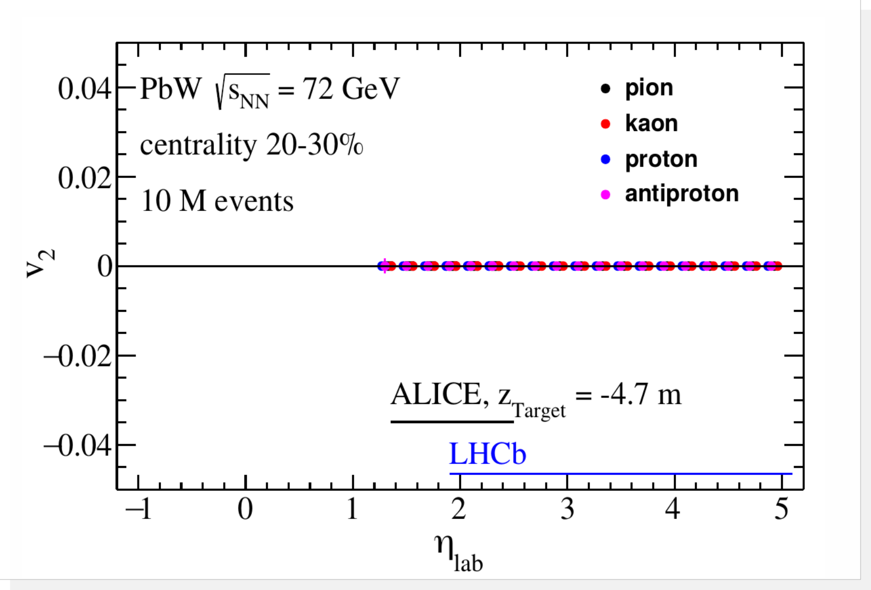
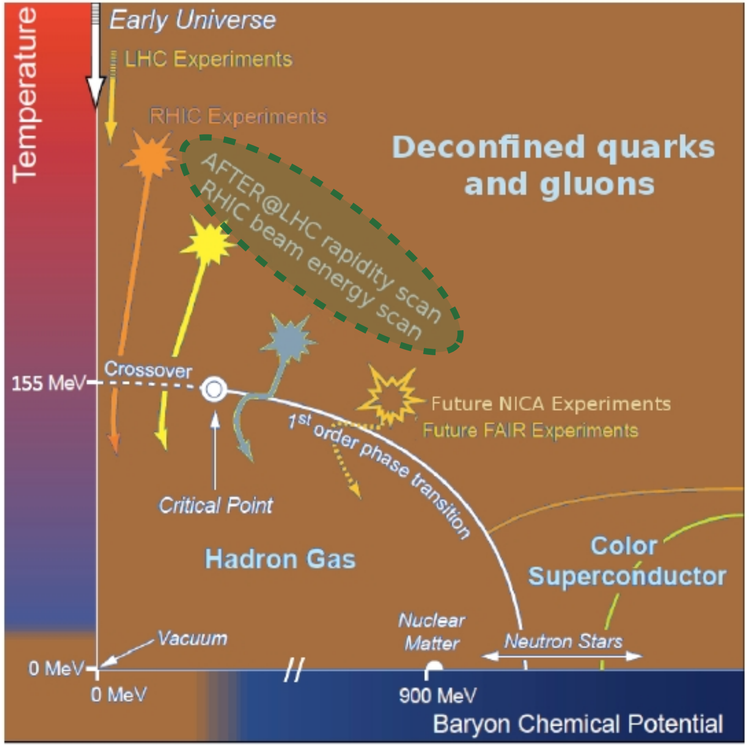
- Precise measurements of soft and hard probes of the QGP





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Summary

- AFTER@LHC: **high-statistics measurements in an energy domain between the SPS and top RHIC**, in an unexplored rapidity domain
- Three main physics motivations:
  - **High-x frontier**: nucleon and nuclear structure
  - **Spin of the nucleon** and the transverse dynamics of partons
  - **Quark-gluon plasma** over broad rapidity domain
- Experimental implementation possible based on the existing LHCb and ALICE detectors, two promising technical implementations:
  - **Internal gas target**
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Submitted to Physics Report

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Thank you!

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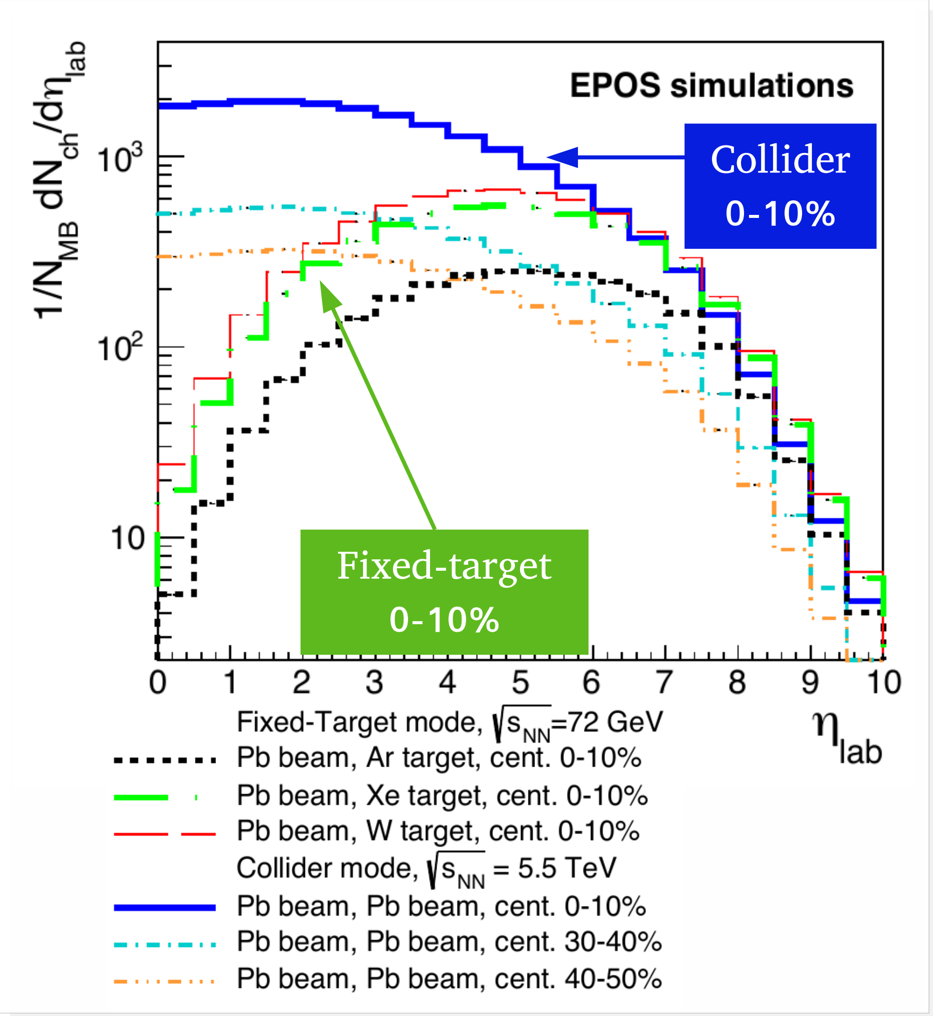
GRANTOVÁ AGENTURA ČESKÉ REPUBLIKY

Backup

Detector requirements

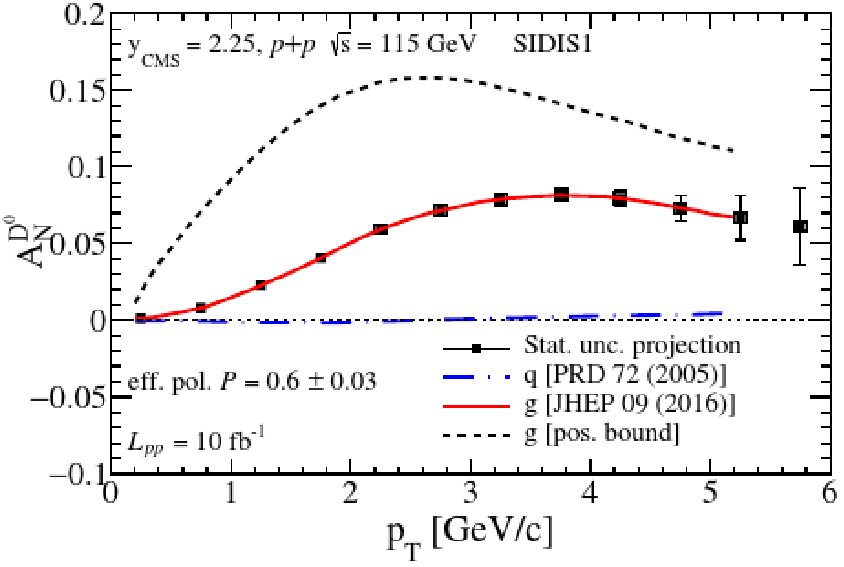


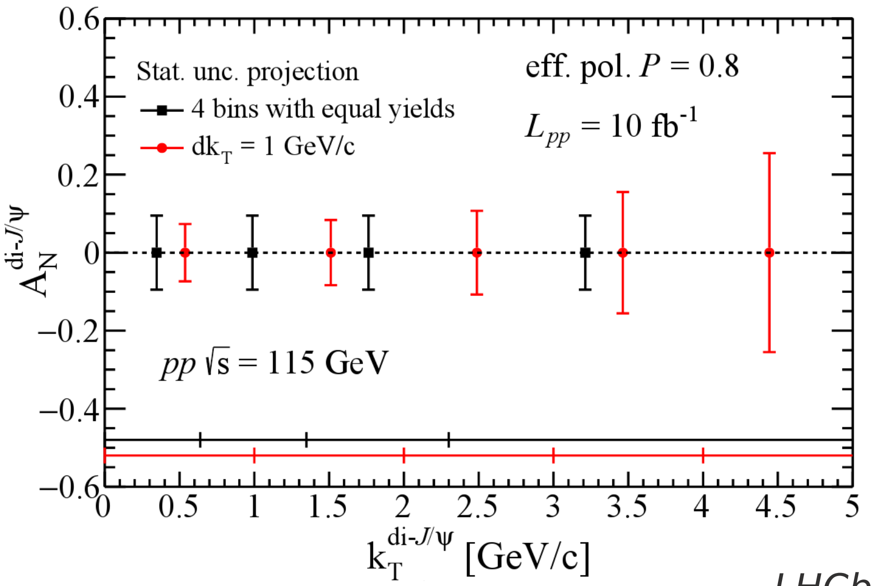
- **Wide rapidity coverage** of backward and mi-rapidity in $y_{c.m.s.}$
  p beam: $y_{lab.}$ range 0 – 4.8
  Pb beam: $y_{lab.}$ range 0 – 4.2
- With (low p_T) **PID and vertexing** capabilities
- Heavy-ion: good performance in **high-multiplicity events**, up to 600 – 700 charged tracks per unit of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

Spin projections

- Transversely polarised target
  - Gluon Sivers effect:
    - With D^0 – difference in A_N of D^0 vs $\bar{D}^0$ gives A_N of D^0 vs $\bar{D}^0$ 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

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





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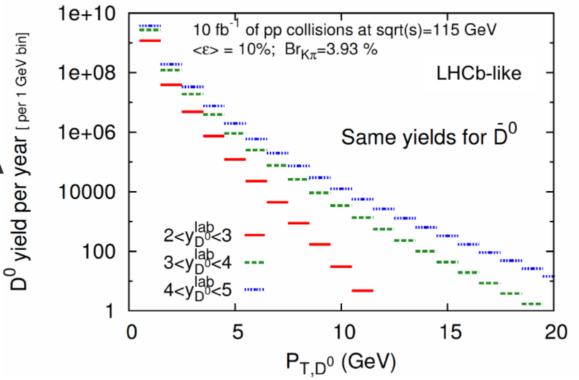
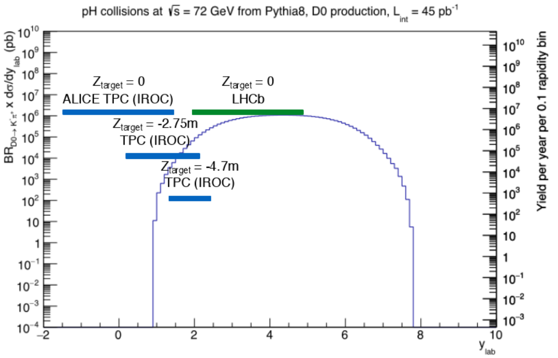
LHCb-like

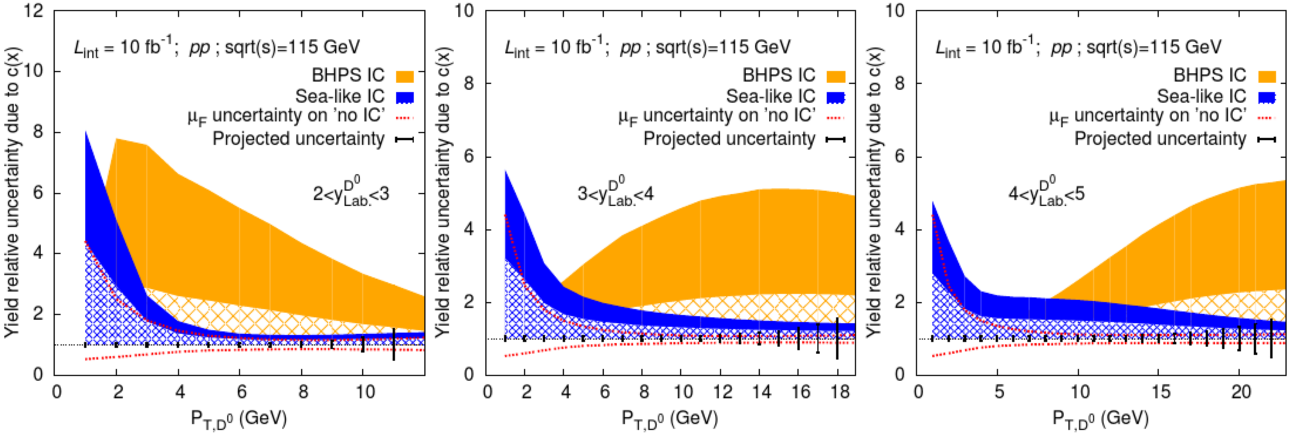
charm PDF (IC) with D

- 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

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





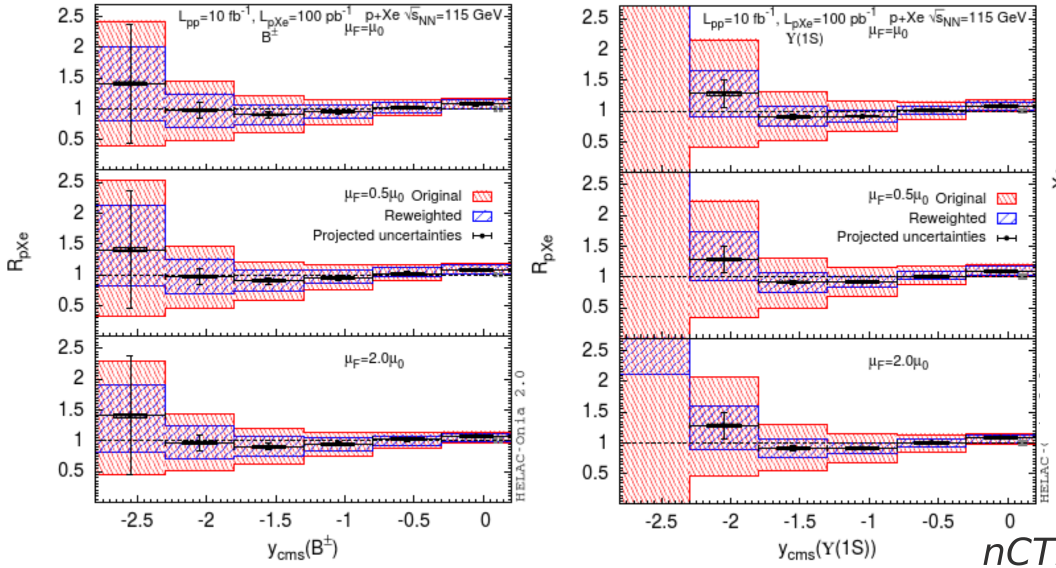


(a) $2 < y_{Lab} < 3$ (b) $3 < y_{Lab} < 4$ (c) $4 < y_{Lab} < 5$

arXiv: 1807.00603

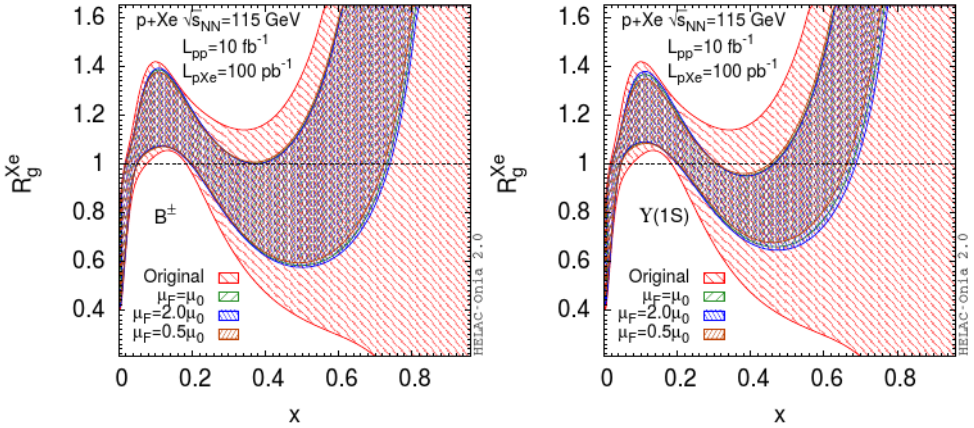
gluon nPDF with heavy-flavour

- 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

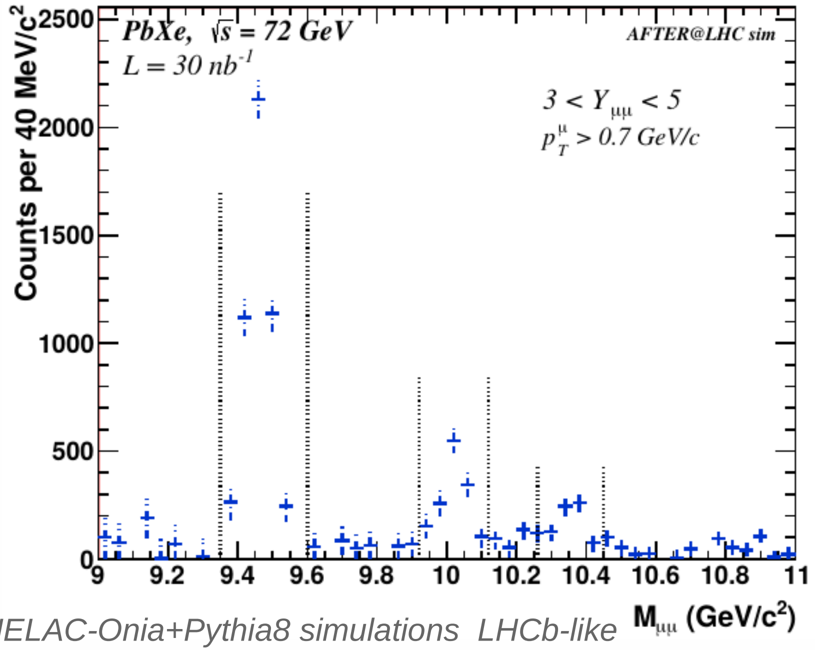


Impact on gluon nPDFs

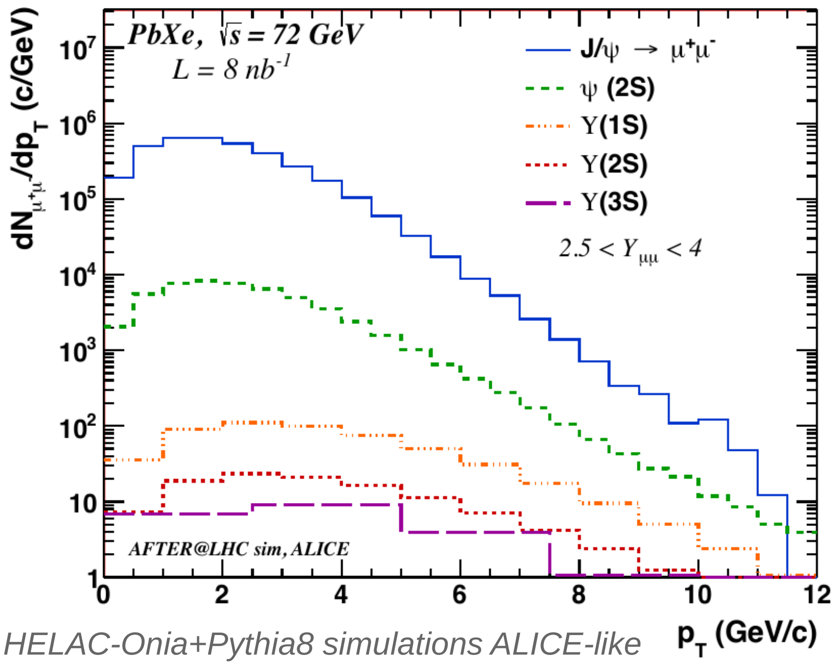
arXiv: 1807.00603

Quarkonium measurements

- Determination of the QGP thermodynamic properties
  - Measurements of ψ and Υ(nS) states down to 0 p_T, in pp, pA and PbA
  - Negligible contribution from recombination



HELAC-Onia+Pythia8 simulations LHCb-like

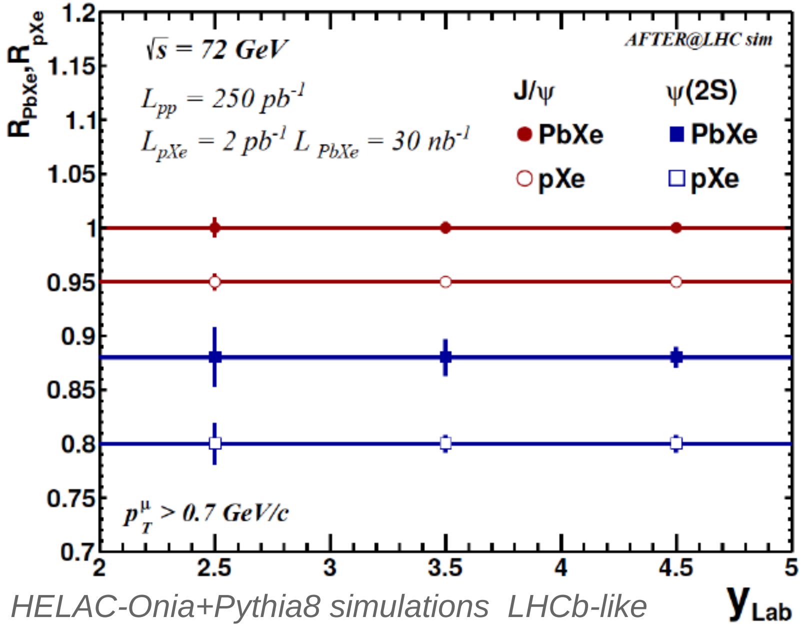


HELAC-Onia+Pythia8 simulations ALICE-like

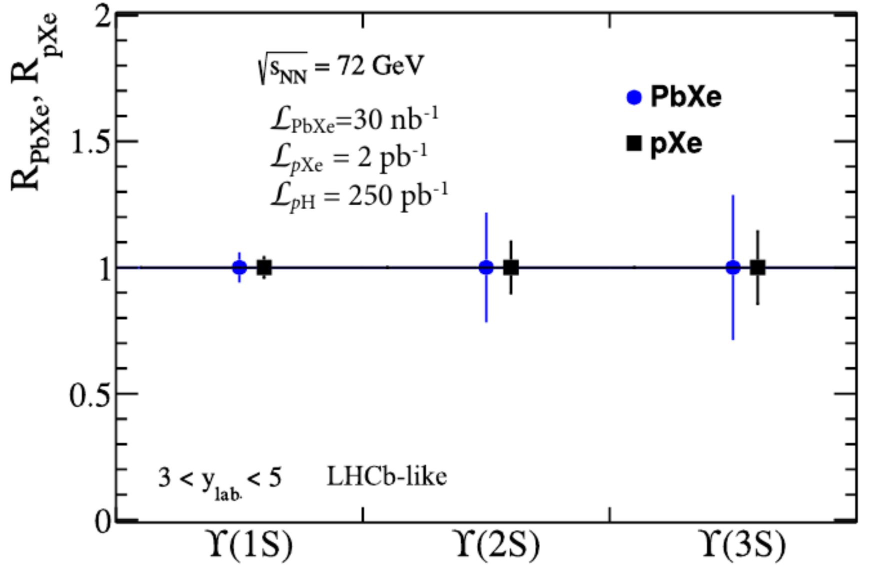
Few Body Syst. 58 (2017) 5, 148

Quarkonium R_{AA}

- Precise measurements of charmonium states vs rapidity
- Measurement of the 3 $\Upsilon(\mathrm{nS})$ state suppression



HELAC-Onia+Pythia8 simulations LHCb-like



HELAC-Onia+Pythia8 simulations LHCb-like

- Possibility to access χ_C and η_C, J/ψ – J/ψ and J/ψ – D correlations

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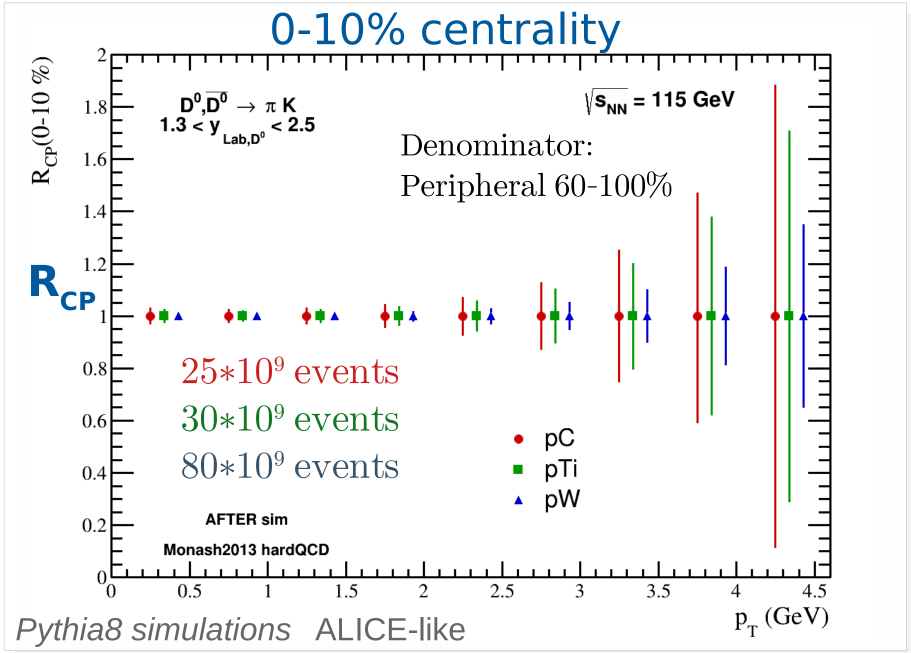
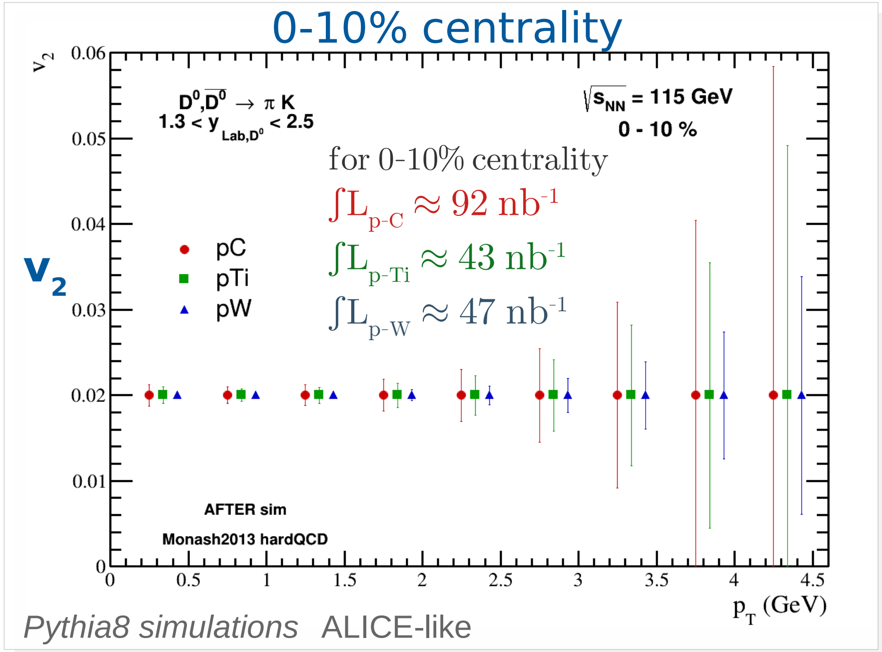
arXiv: 1807.00603

Open HF in small systems

- p-A collisions: cold nuclear matter effects, collectivity in small systems, QGP ?
- Simultaneous measurements of D meson elliptic flow and nuclear modification factor, in different systems

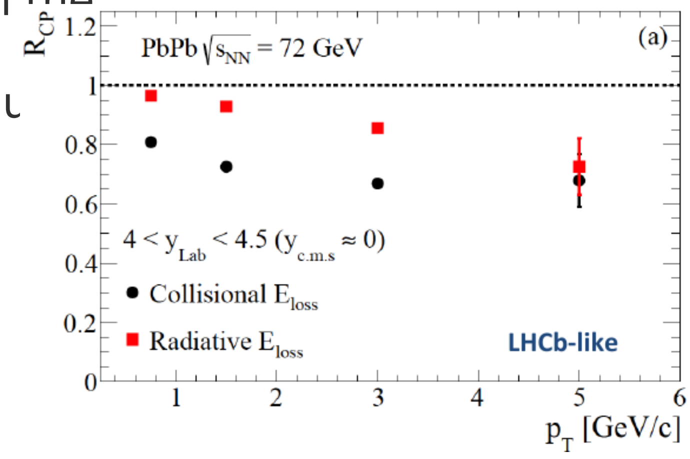


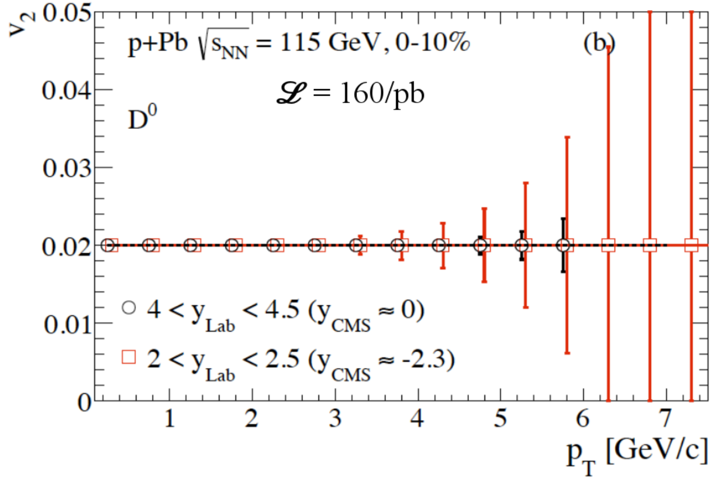


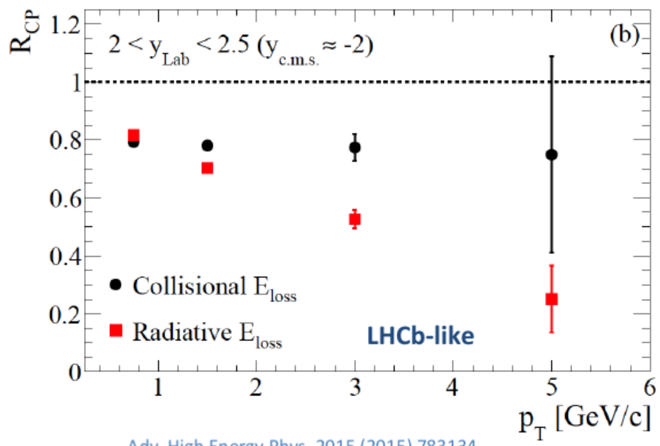
- ALICE: target at z = -4.7 m, with 1cm long solid targets
- Similar precision expected in 10-20, 20-40% centrality intervals
- Quarkonia and HF μ can be studied with ALICE muon arms at: $-1.6 < y_{CMS} < -0.5$

QGP: Open Heavy-Flavour

- Open heavy-flavour in A-A → heavy-quark energy loss in the medium
- Precise suppression measurements of charm and beau 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





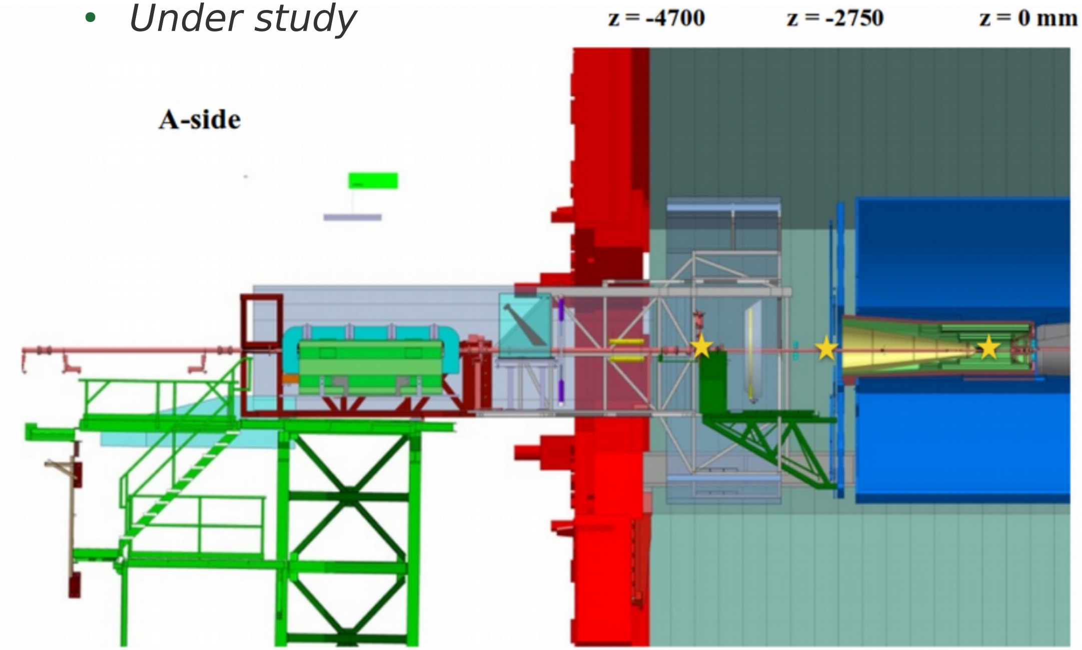


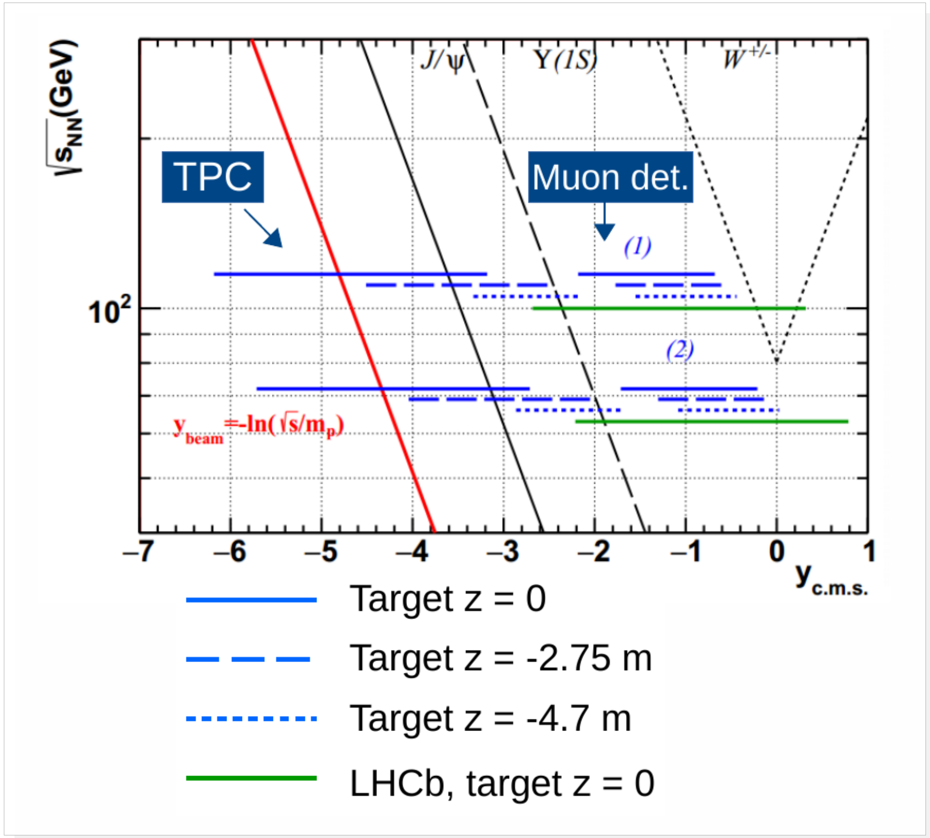
LHCb-like

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

Possible implementation: ALICE

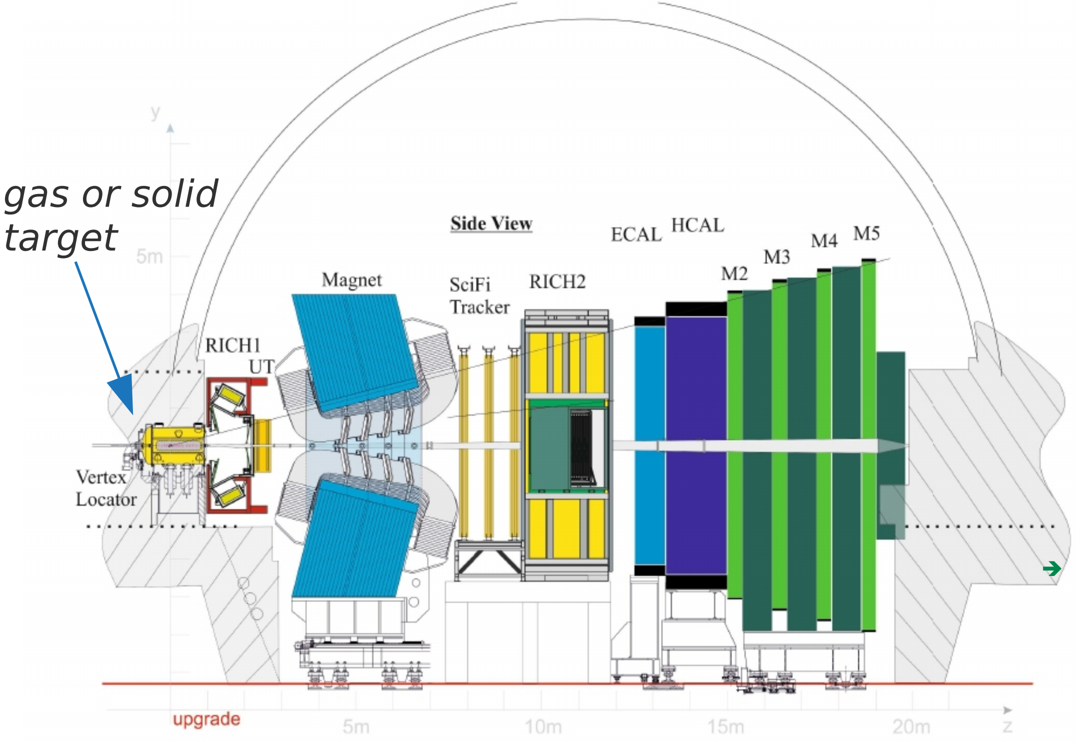
- **Beam splitting with bent crystal + internal target**
  - Crystal installed prior of the IP2 (ALICE), at ~70m
  - Deviates the beam halo onto a solid target in L3 magnet
  - Target *z* position< 4.8m
- **Gas storage cell target**
  - *Under study*

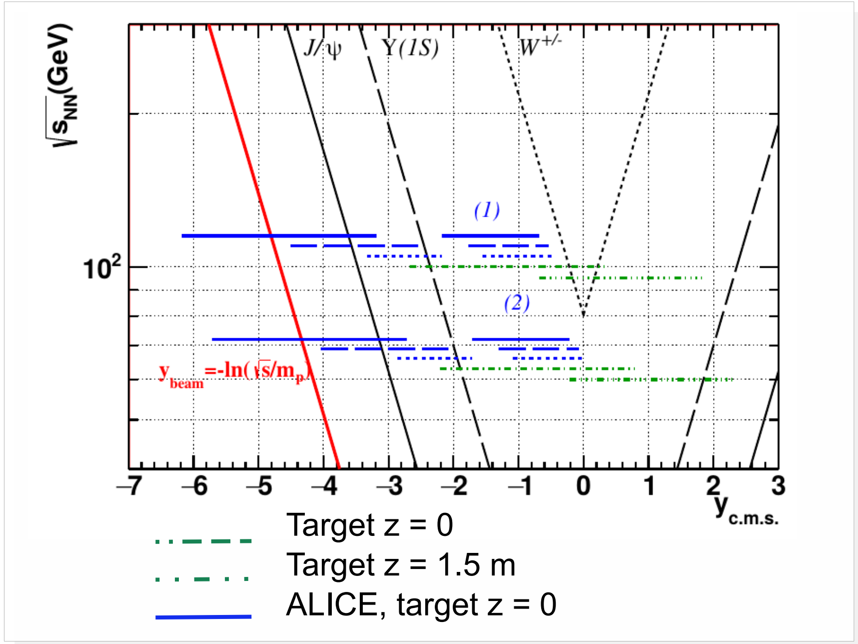




Possible implementation: LHCb

- 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)





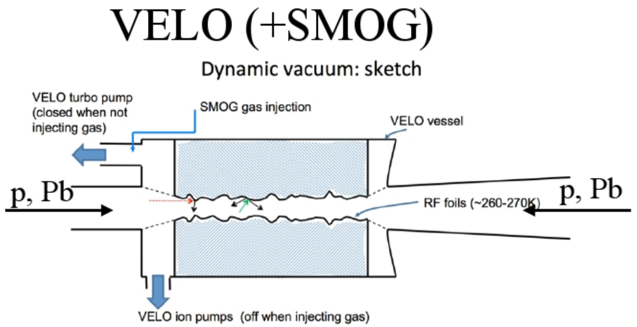
- **LHCb:**
  - Forward detector with full PID, $2 < \eta_{lab} < 5$
  - Precision tracking system, vertex locator
  - Limitation in high-multiplicity event reconstruction
  - New VELO: high readout rate, higher multiplicities

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

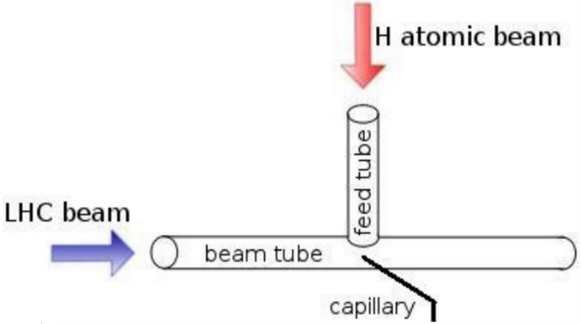
SMOG@LHCb

System for Measuring Overlap with Gas



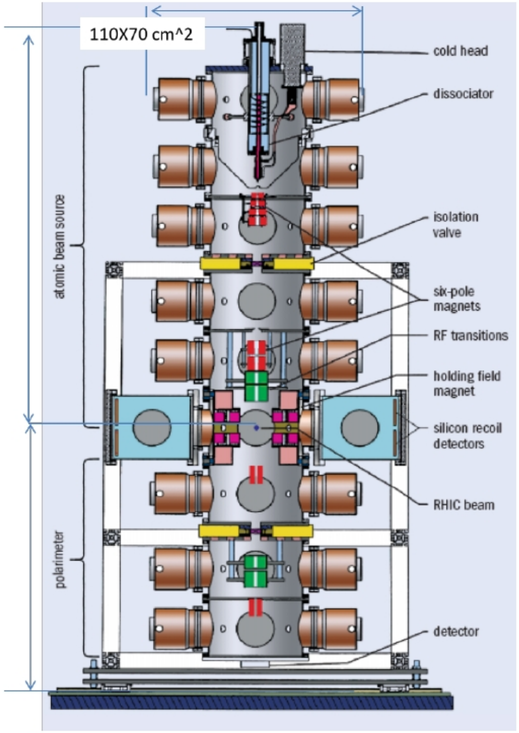
- Unpolarised noble gases
- Gas injected into vertex locator (VELO) vacuum
- Low gas pressure

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