A Fixed-Target Program at the LHC (AFTER@LHC): where do we stand ?

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http://after.in2p3.fr/after/index.php/Current_member_list

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Outline

- Introduction: what and why
  - Kinematic features of AFTER@LHC
  - Physics opportunities
- Possible implementations
- Physics projections
- Summary

A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies, arXiv:1807.00603

http://after.in2p3.fr/after/index.php/Main_Page

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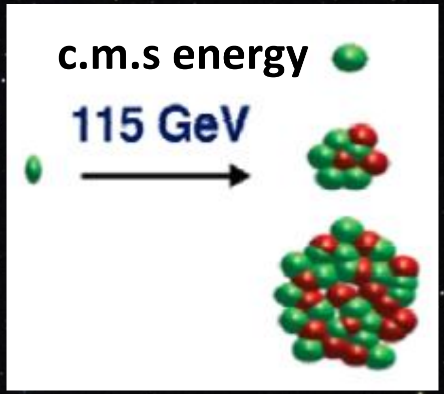
AFTER@LHC and its physics

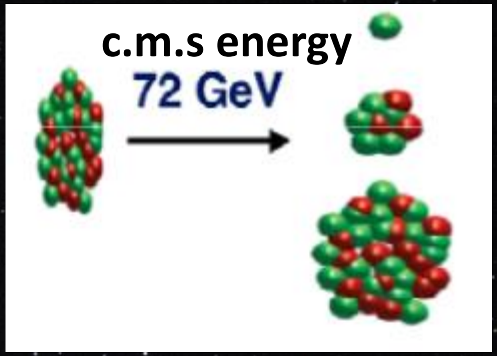
➢ A proposed fixed-target experiment using the multi-TeV proton or heavy-ion beams of the LHC

$$|x_F| \equiv \frac{|p_z|}{p_z^{\max}}$$

➢ Physics domains
- Frontier of high-x_F partons in nucleon and nucleus
- Unraveling the nucleon spin
- Nuclear matter in new rapidity and energy domains



➢ Assets
- Achieving high luminosities
- Varying different targets almost at will
- Polarising the target
- Accessing the high x_F partons



All these can be realised at the LHC in a parasitic mode, without affecting the performance of the LHC!

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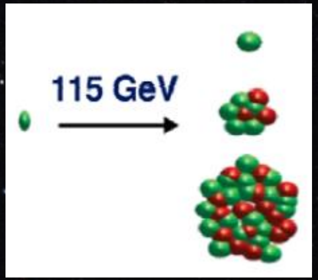
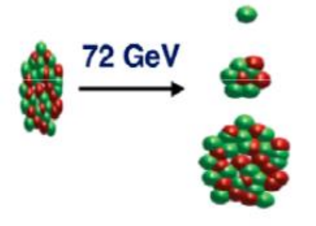
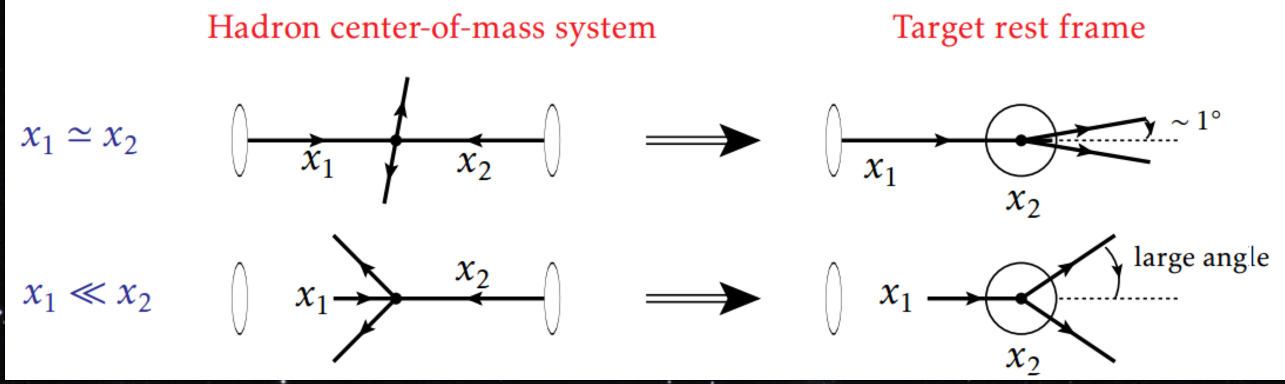
Main kinematic features

Beam energy	c.m.s energy $\sqrt{s_{NN}} = \sqrt{2m_N E_p}$	Lorentz boost $\gamma = \sqrt{s_{NN}}/(2m_N)$	Rapidity shift
7 TeV p beam	115 GeV	≈ 60	$y_{\mathrm{c.m.s.}} = y_{\mathrm{lab}} - 4.8$
2.76 TeV Pb beam	72 GeV	≈ 40	$y_{\mathrm{c.m.s.}} = y_{\mathrm{lab}} - 4.3$





- $\sqrt{s_{NN}}$ between SPS and RHIC and high luminosity
  - Allow, for the first time, for systematic studies of bottomonia and studies of W close to the threshold in fixed-target modes
- High boost between c.m.s and lab frames
  - Forward hemisphere ($y_{\mathrm{c.m.s.}} > 0$) is within $0^\circ < \theta_{\mathrm{lab}} < 1^\circ$
  - LHCb and the ALICE muon arm detect backward physics ($y_{\mathrm{c.m.s.}} < 0$)
    - ✓ Access to high x_2 (target), large angle in laboratory



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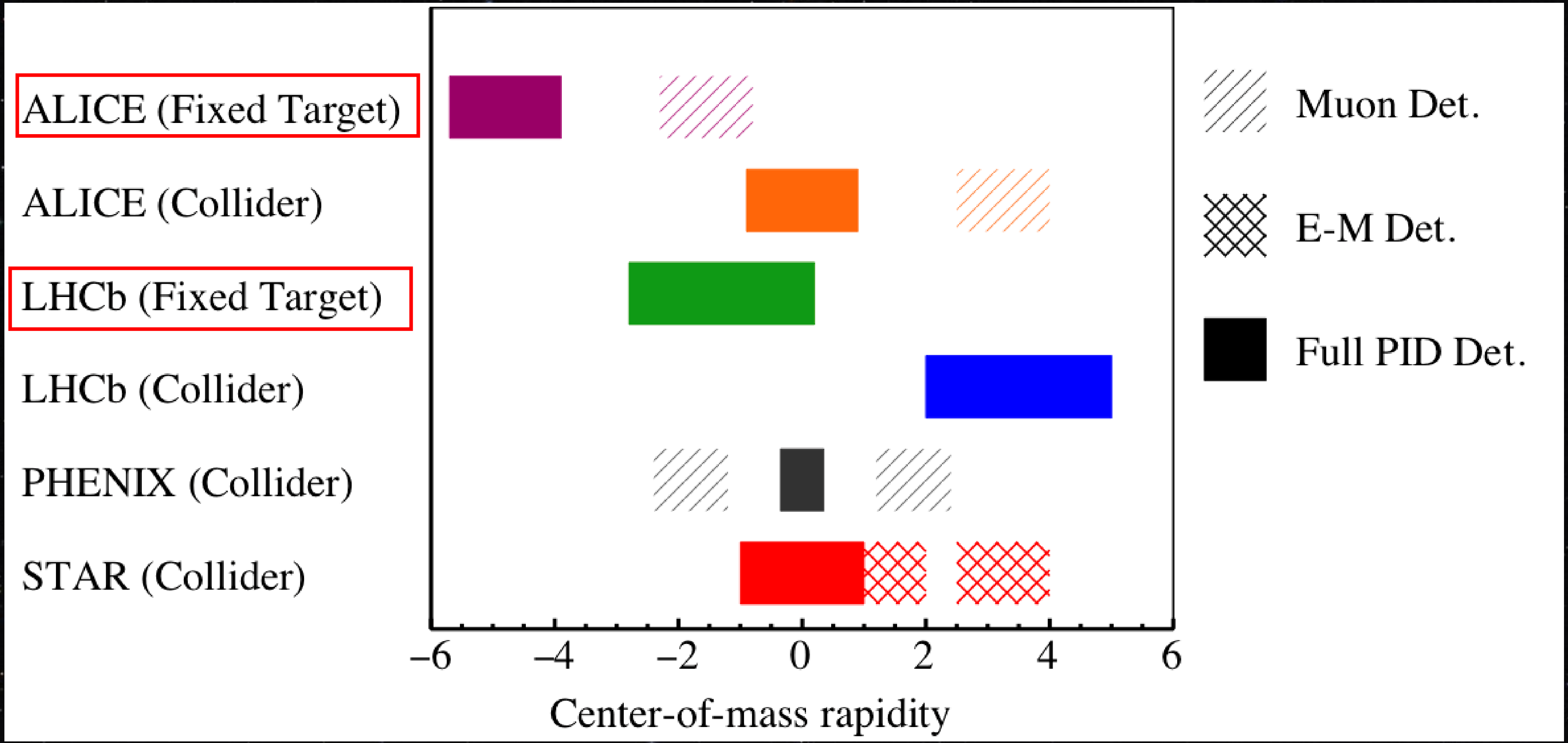
Rapidity coverage



- With 7 TeV proton beam
- Acceptance corresponds to a vertex position at the nominal Interaction Point

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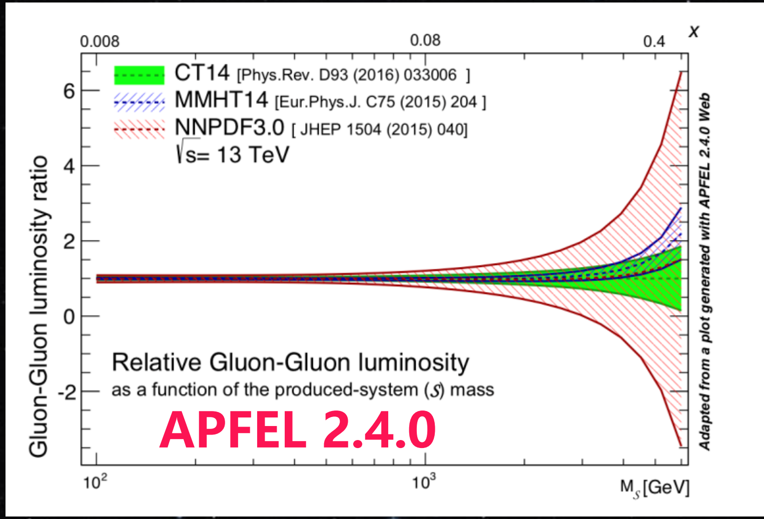
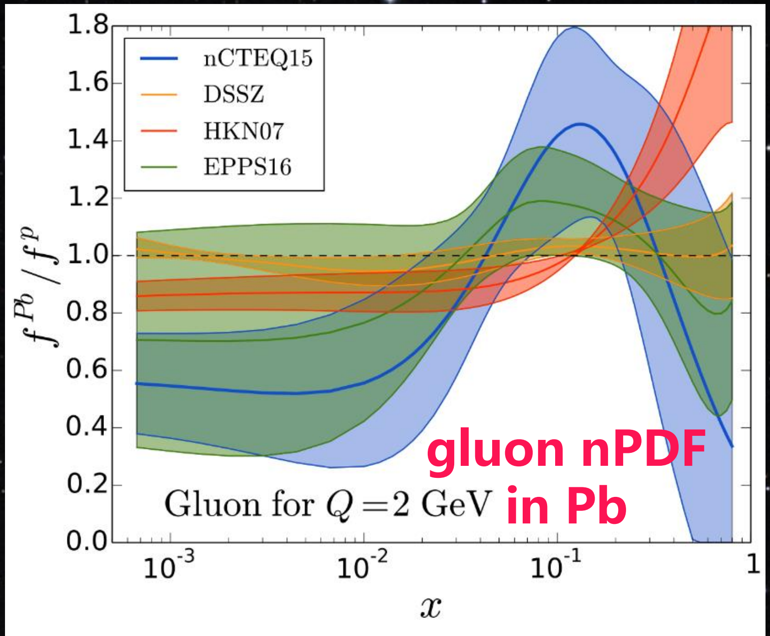
Physics motivation: high-x_F frontier

- Advance our understanding of **high-x_F gluon, antiquark and heavy-quark** contents in the nucleon and nucleus
  - Very large uncertainties of PDF for $x_F > 0.5$
    - ✓ Could be essential to possible discoveries of New Physics Beyond the Standard Model
  - Origin of the EMC effect in nuclei
    - ✓ Study of a possible gluon EMC effect is crucial
  - Possible non-perturbative source of c and b in protons
    - ✓ Important for HE neutrino and cosmic-ray physics
  - Search and study rare proton fluctuations where one gluon carries most of the proton momentum
    - ✓ Test QCD in a new limit unexplored so far

Uncertainties at high x_F could be largely reduced by measurements from AFTER@LHC



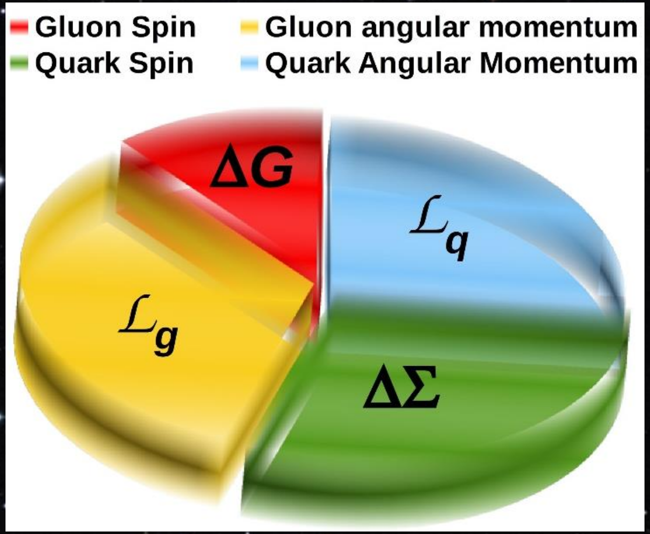


Physics motivation: unraveling the nucleon spin

- Advance our understanding of dynamics and spin of gluons and quarks inside (un)polarised nucleons
  - Possible missing contribution to the proton spin: Orbital Angular Momentum (OAM), $\mathcal{L}_g$ and $\mathcal{L}_q$

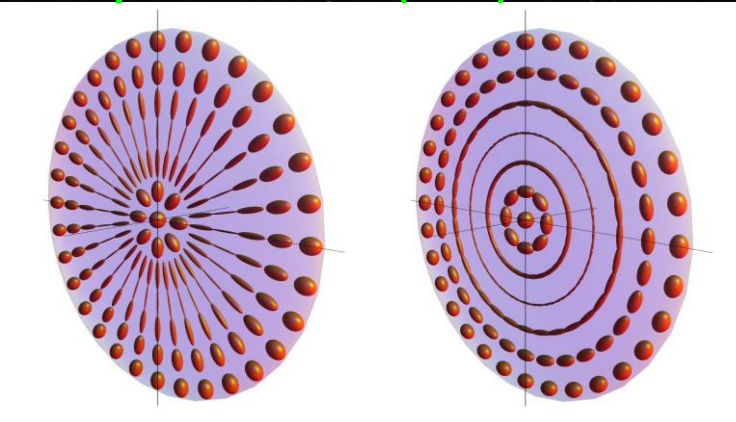
$$\boxed{\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{Spin of } q/\bar{q}} + \underbrace{\Delta G}_{\text{Spin of } g} + \underbrace{\mathcal{L}_g}_{\text{OAM of } g} + \underbrace{\mathcal{L}_q}_{\text{OAM of } q}}$$

First hint by COMPASS that $\mathcal{L}_q \neq 0$



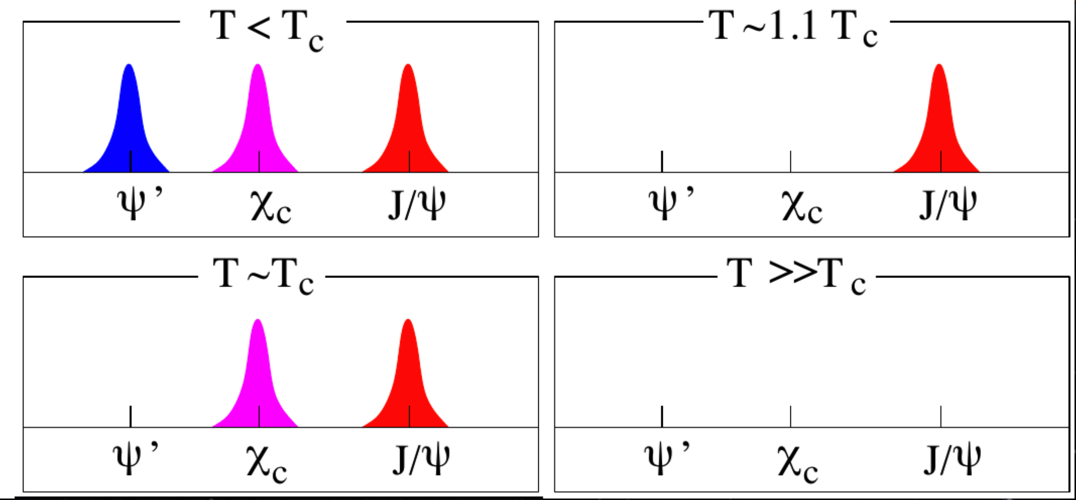
  - Access information on orbital motion of partons inside bound hadrons via Single Spin Asymmetry measurements
    - ✓ Sivers effect
  - Test TMD factorisation framework
    - ✓ Sign change of A_N between SIDIS and Drell-Yan
  - Determination of the linearly polarised gluons in unpolarised protons (Boer-Mulders effect)

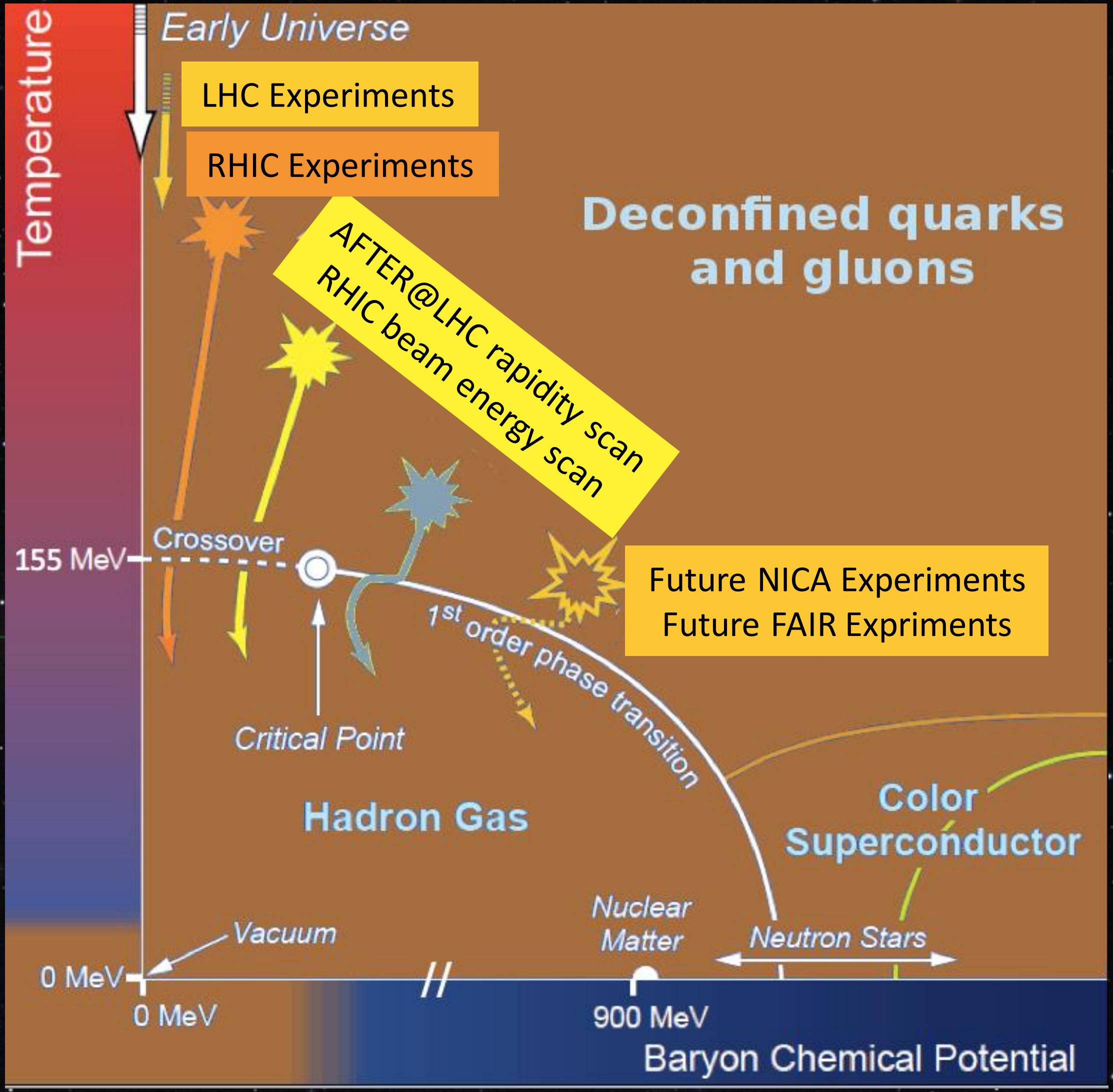
W. J. den Dunnen et al, Phys.Rev.Lett. 112 (2014) 212001



Physics motivation: heavy-ion collisions

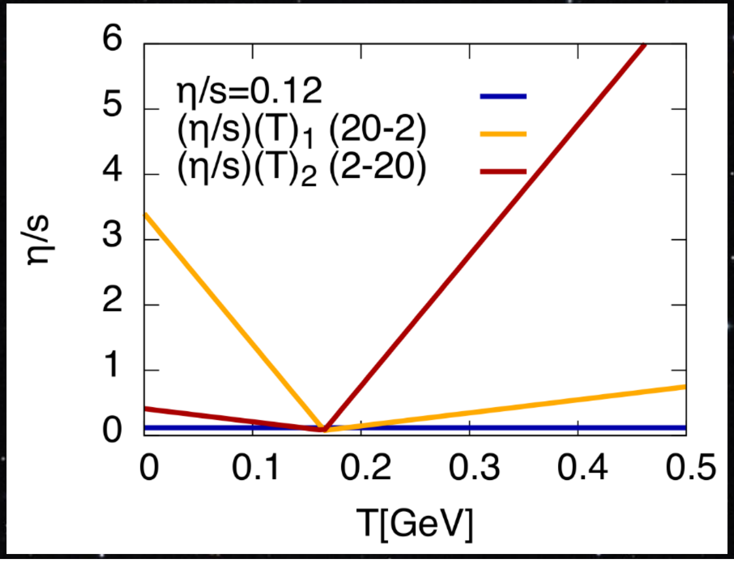
- **Heavy-ion collisions towards large rapidities**
  - A complete set of HF studies between SPS and RHIC energies
    - ✓ Needed to calibrate the quarkonium thermometer: $J/\psi, \psi(2S), \chi_c, \Upsilon, D, J/\psi$ from b, ...



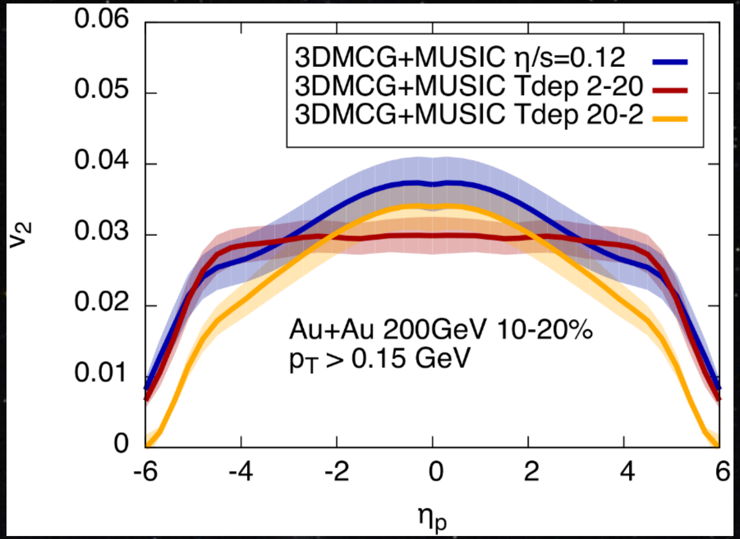


Physics motivation: heavy-ion collisions

- Heavy-ion collisions towards **large rapidities**
  - Test the formation of **azimuthal asymmetries**: hydrodynamics vs initial-state radiation
  - Explore **the longitudinal expansion** of QGP formation
    - ✓ Probe T dependence of the shear viscosity to entropy density ratio (η/s)
  - Test **the factorisation** of cold nuclear matter effects **from $p+A$ to $A+B$** collisions



$$(\eta T/(\varepsilon+P))(T) = 0.08 + a(T_c - T)\theta(T_c - T) + b(T - T_c)\theta(T - T_c)$$



B. Schenke, talk at QM2015

B. Schenke et al, Phys.Rev.Lett. 116 (2016) 212301

Possible implementations

- **Internal (gas or solid) target + existing detector**
  - (Un)polarised gas target + full LHC beam
  - Internal wire target intercepting the faint beam halo
  - Internal solid (polarised) target + beam splitting by bent-crystal
- **Beam extraction by bent crystal**
  - New beam line + new detector

Similar luminosities with an internal gas target or a bent crystal implementation

A single-year luminosity is similar to the nominal LHC luminosity, and much larger than those at SPS or RHIC

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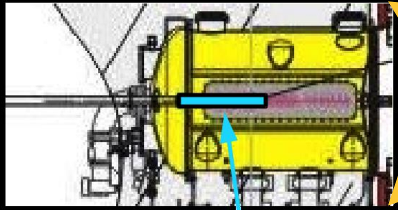
Internal gas target: LHCb-SMOG

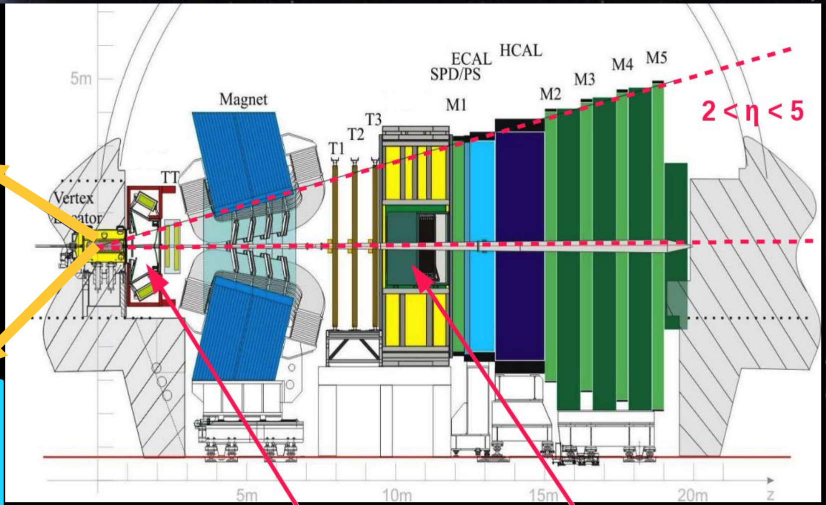
- System for Measuring Overlap with Gas (SMOG)
  - Initially designed for precise luminosity measurements
  - Noble gas injected inside the beam vacuum at the interacting point
  - $p+\mathrm{He(Ne,Ar)}$ and $\mathrm{Pb+Ne(Ar)}$ tested, completely parasitic
  - Could be coupled to ALICE

Typical integrated luminosity: $L_{\mathrm{int}} \sim \mathcal{O}\left(\mathrm{nb}^{-1}\right)$

VELO & SMOG



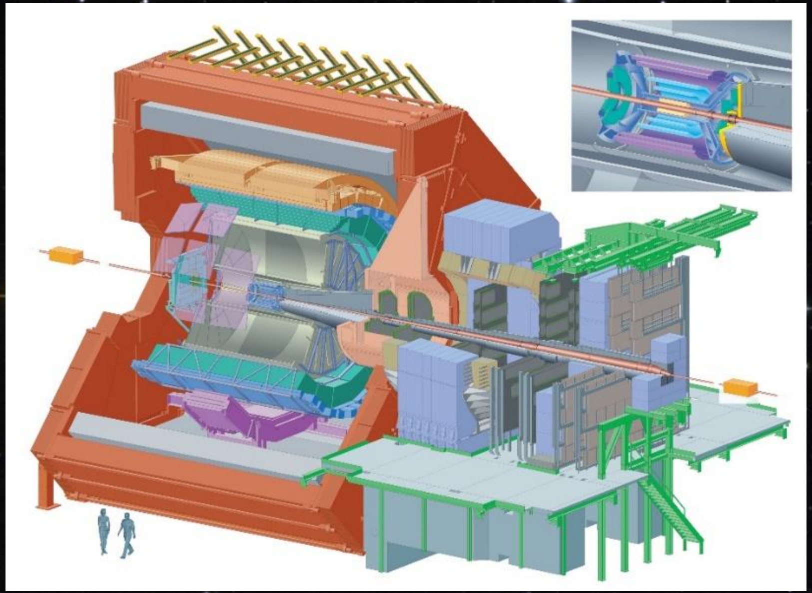
Gas target (He, Ne, Ar)



RICH1 $2.0 < \eta < 4.4$

RICH2 $3.0 < \eta < 5.0$

LHCb, JINST 3 (2008) S08005
M. Ferro-Luzzi, NIM A553 (2005) 388



ALICE, JINST 3 (2008) S08002

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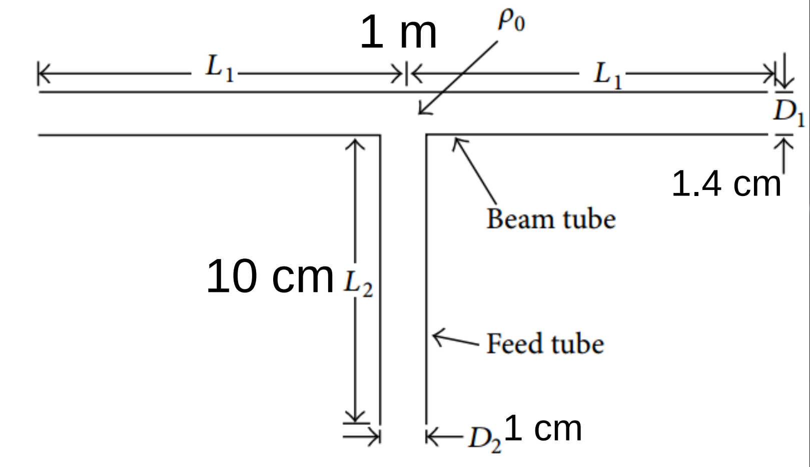
Internal gas target: HERMES-like & Gas jet

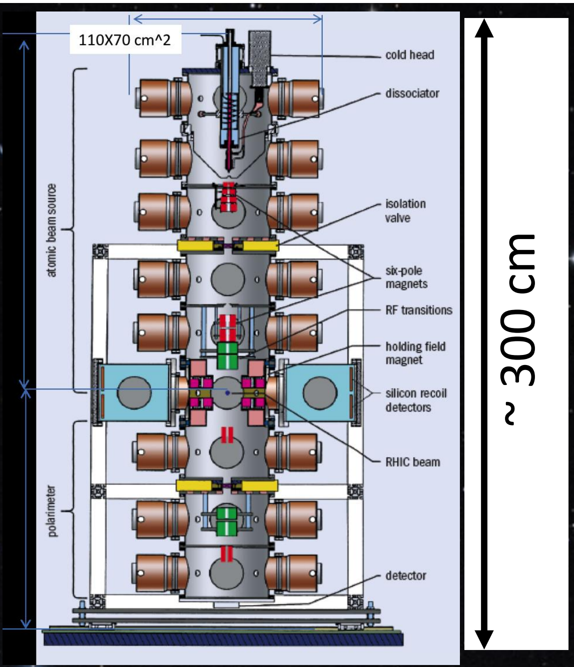
- **HERMES-type system:**
  injecting gas in an open-end storage cell
  - Dedicated pumping system, higher pressure
  - Polarised $\mathrm{H}^{\uparrow}$ and $\mathrm{D}^{\uparrow}$ with high polarisation
  - Implementations are under study
  - Typical luminosity: $\mathcal{L}_{\text{int}} \sim 10\ \mathrm{fb}^{-1}$ for $p + \mathrm{H}^{\uparrow}$
    $\sim 100\ \mathrm{nb}^{-1}$ for $\mathrm{Pb} + \mathrm{H}^{\uparrow}$
    $\sim 30\ \mathrm{nb}^{-1}$ for $\mathrm{Pb} + \mathrm{Xe}$

E. Steffens,
Adv. High Energy Phys. 2015 (2015) 453141



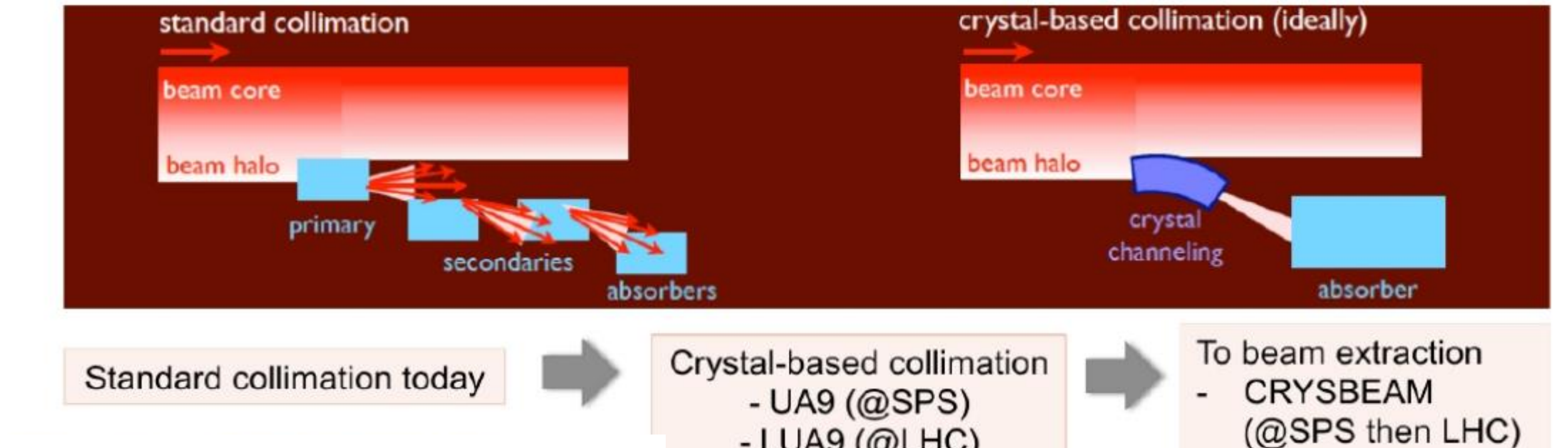
- **Polarised H-jet polarimeter used at RHIC**
  - To measure the proton beam polarisation
  - Polarised free atomic beam source (ABS)
  - Expected Integrated luminosity over one LHC year
    - ✓ $\mathcal{L}_{\text{int}} \sim 50\ \mathrm{pb}^{-1}$ for $p + \mathrm{H}^{\uparrow}$

Larger values with unpolarised H^2 target

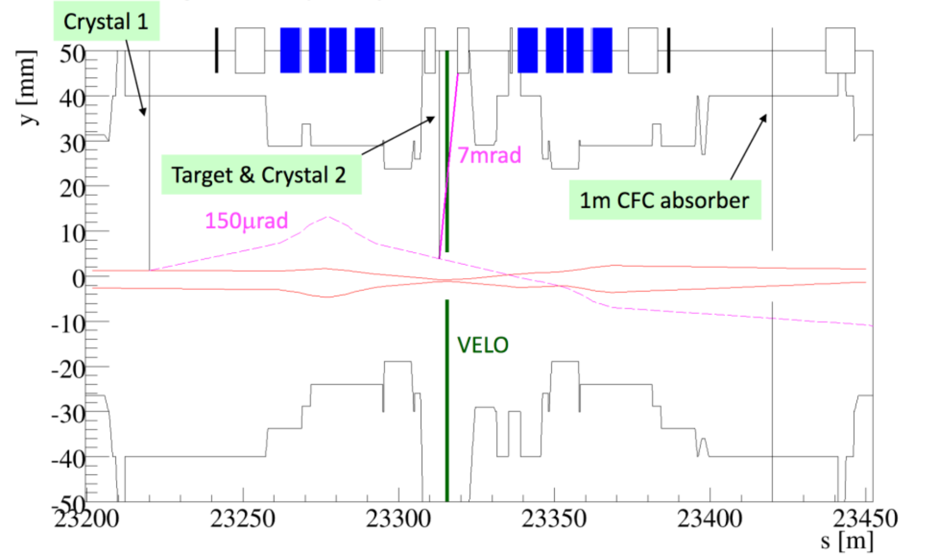


RHIC H-jet

Beam splitting/extraction using bent crystals



W. Scandale et al, JINST 6 (2011) T10002



- Bent crystals initially used for beam collimation
- Can be used to deflect beam halo at 7σ distance to the beam
  - Beam extraction: civil engineering required, new facility with 7 TeV proton beam
  - Beam splitting: could be used with existing experiment
- Typical luminosity over one year for 5 mm-thick targets

$$\mathcal{L}_{\text{int}} \sim 0.3\ \text{fb}^{-1}\ \text{for}\ p + \text{C}\quad (\text{A} = \text{C}, \text{W})$$
$$\sim 3\ \text{nb}^{-1}\ \text{for}\ \text{Pb} + \text{C}\ (\text{A} = \text{C}, \text{W})$$

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Selected physics projections

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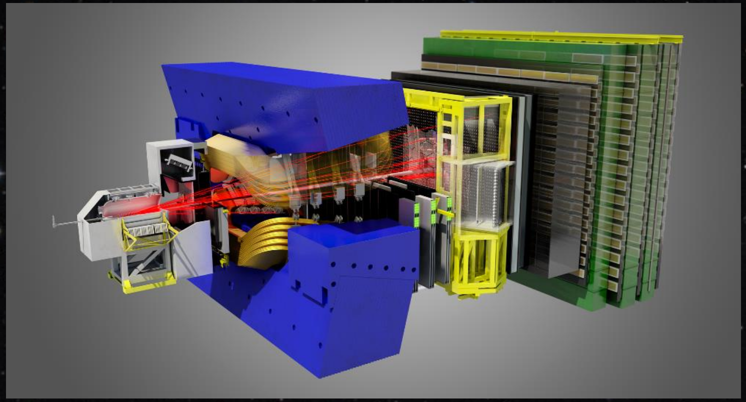
Assumptions of sensitivity study

➢ LHCb-like detector

- $\sqrt{s_{NN}} = 115\ \text{GeV},\ L_{\text{int}}(p\text{H}) = 10\ \text{fb}^{-1}/\text{y}$
- $\sqrt{s_{NN}} = 115\ \text{GeV},\ L_{\text{int}}(p\text{Xe}) = 100\ \text{fb}^{-1}/\text{y}$
- $\sqrt{s_{NN}} = \ 72\ \text{GeV},\ L_{\text{int}}(\text{PbXe}) = 30\ \text{nb}^{-1}/\text{y}$
- Reference at same energy:
  - ✓ $L_{\text{int}}(p\text{H}) = 250\ \text{pb}^{-1}$
  - ✓ $L_{\text{int}}(p\text{Xe}) = 100\ \text{pb}^{-1}$

$2 < \eta < 5$

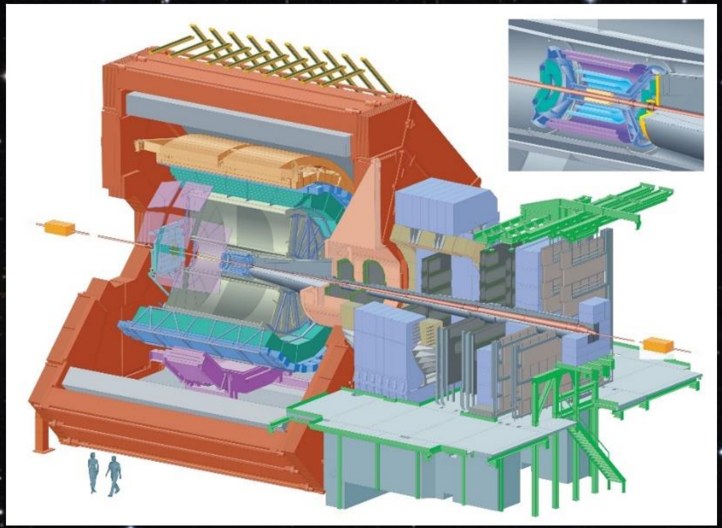


Precise vertexing, hadron ID, muon ID

➢ ALICE-like detector

- $\sqrt{s_{NN}} = \ 72\ \text{GeV},\ L_{\text{int}}(\text{PbA}) = 1.6\ \text{nb}^{-1}/\text{y}$
  $\text{A} = \text{W}$
- $\sqrt{s_{NN}} = 115\ \text{GeV},\ L_{\text{int}}(p\text{A}) = 6 - 40\ \text{pb}^{-1}/\text{y}$
  $\text{A} = \text{C or W}$

$-0.9 < \eta^{\text{TPC}} < 0.9$



Bent crystal + internal solid target:
$Z \sim 0$ + ALICE-like acceptance

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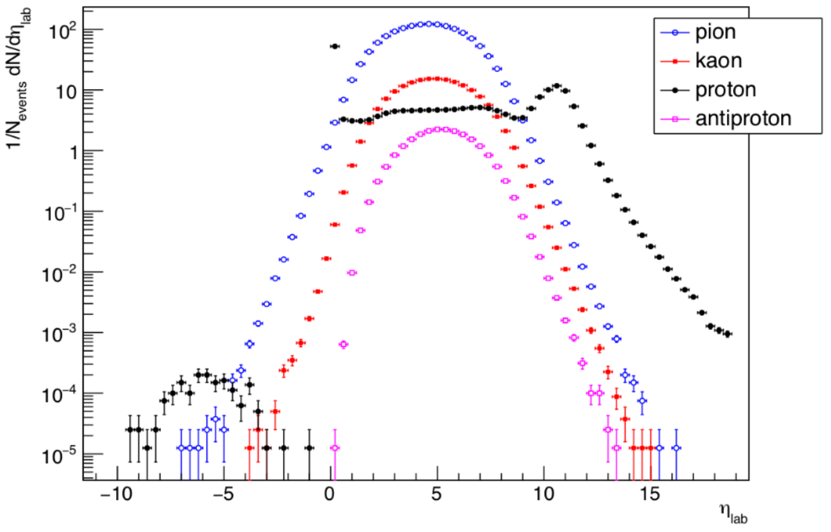
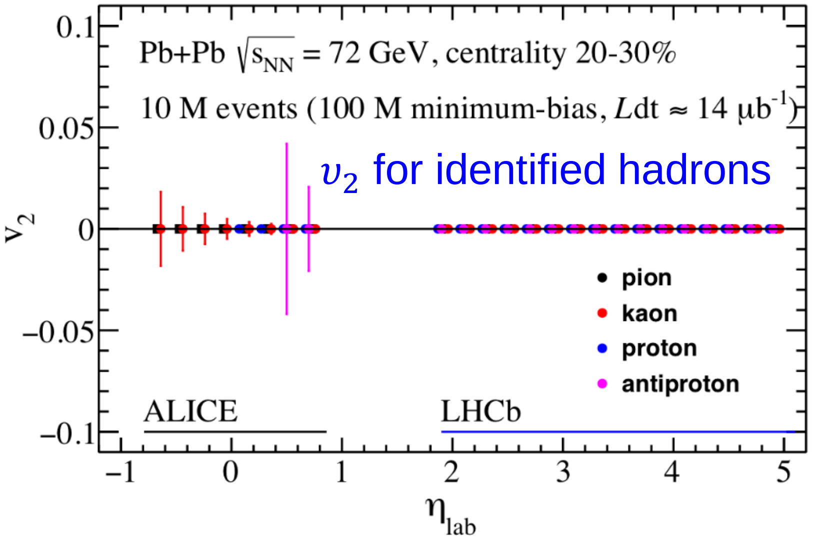
Heavy-ion physics: toward large rapidities

- T **dependence of shear viscosity to entropy density ratio** η/s
  - One of the most fundamental properties of QGP
  - Still poorly understood
  - Particle yields and azimuthal anisotropy coefficients v_n measured at large rapidities are powerful tools to η/s
  - A small data sample will allow for a precision study of v_n over a very broad rapidity range

EPOS Pb+Pb @ $\sqrt{s_{NN}} = 72$ GeV





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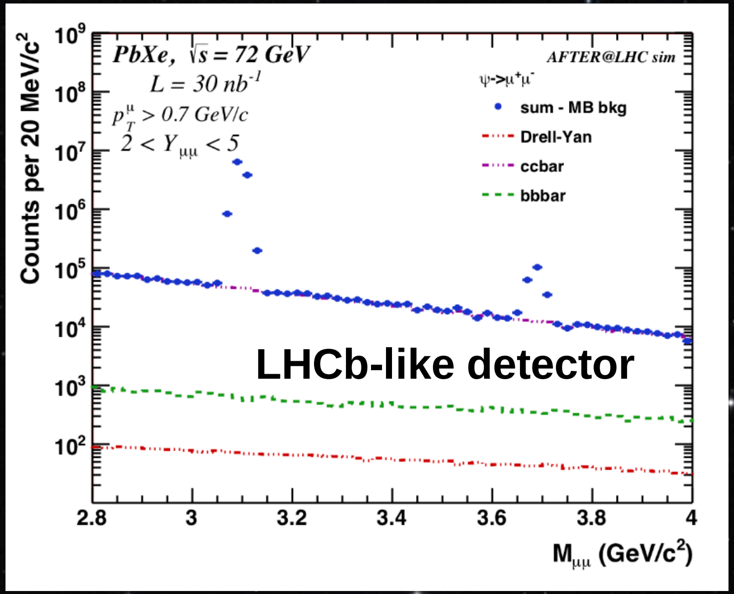
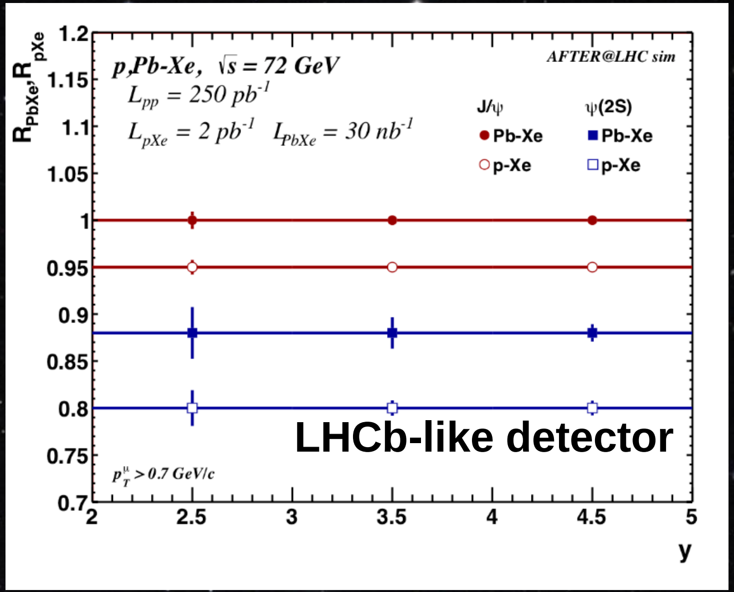
Heavy-ion physics: toward large rapidities

- **Precise quarkonium studies: J/ψ and $\psi(2S)$**
  - Probe large gluon x_2 in the target
  - Constrain gluon antishadowing, EMC effects, and other CNM effects with pA
  - Study colour screening from QGP in AA
  - Wide rapidity coverage with p_T down to zero GeV
  - Full background simulations show very good prospects for all systems with LHCb-like performances
  - $\psi(2S)$ measurement in PbXe with a statistical uncertainty from 10-30%

Nuclear modification factor

$$R_{\mathrm{AA'}} \equiv \frac{dN_{\mathrm{AA'}}}{\langle N_{\mathrm{coll}}\rangle dN_{pp}}$$





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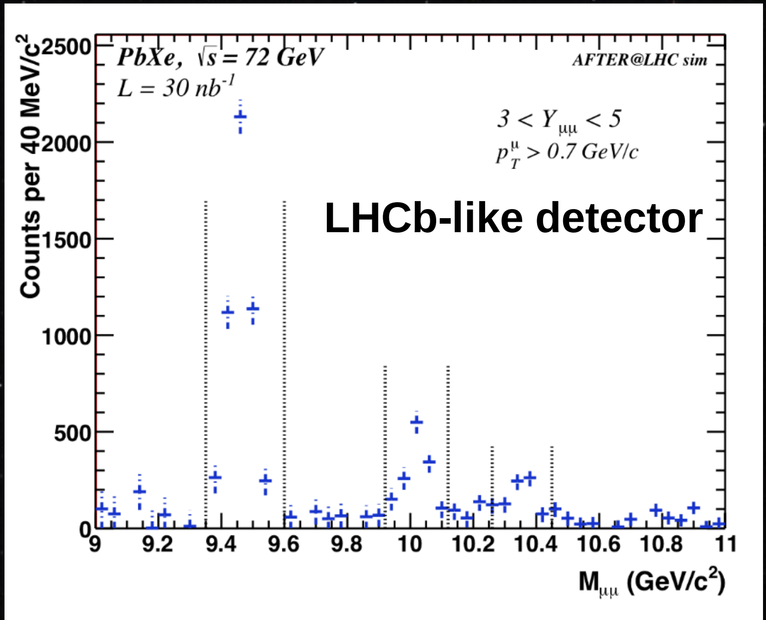
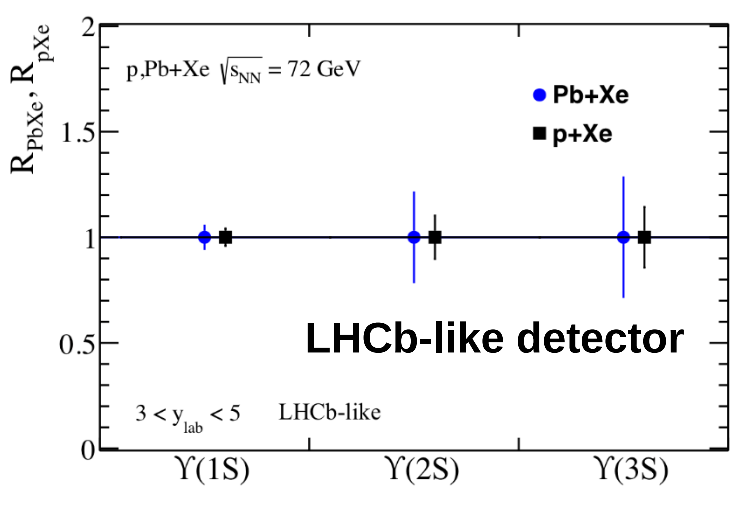
Heavy-ion physics: toward large rapidities

- **Precise quarkonium studies: $\Upsilon(nS)$**
  - **Determination of thermodynamic properties of QGP + CNM effects with $\Upsilon(nS)$ in pp, pA and AA**
  - Search for phase transition with $\Upsilon(nS)$ suppression as a function of y and system size
  - Large $\Upsilon(nS)$ yields in one LHC year of PbXe data taking with LHCb-like performance
  - **Statistical uncertainty ~7% on $R_{AA}(\Upsilon(1S))$**





(a)			(b)			(c)		
$\Upsilon(1S)$	S	S/B	$\Upsilon(2S)$	S	S/B	$\Upsilon(3S)$	S	S/B
pp	1.33×10^3	29.0	pp	2.92×10^2	8.2	pp	1.37×10^2	10.3
pXe	1.39×10^3	7.8	pXe	3.06×10^2	2.2	pXe	1.44×10^2	2.8
PbXe	4.33×10^3	1.8×10^{-1}	PbXe	9.56×10^2	5.0×10^{-2}	PbXe	4.49×10^2	6.2×10^{-2}

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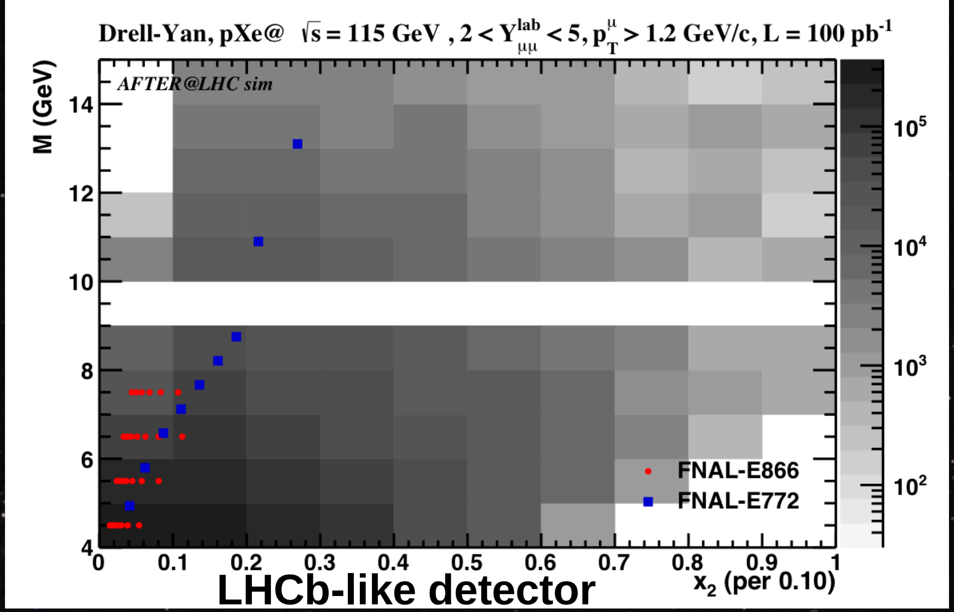
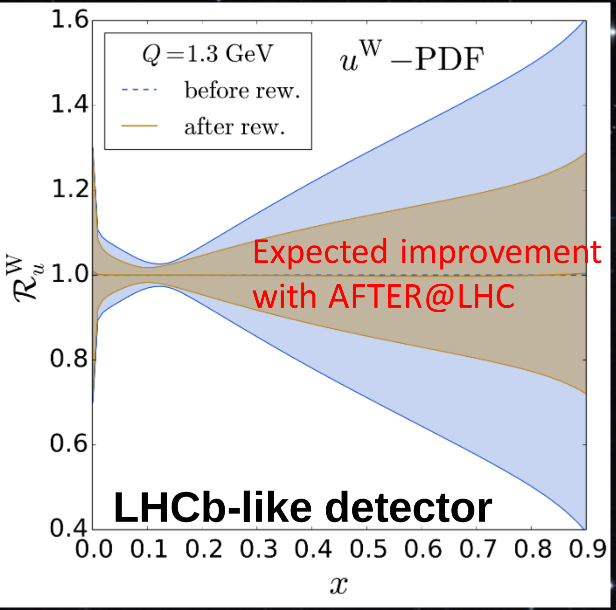
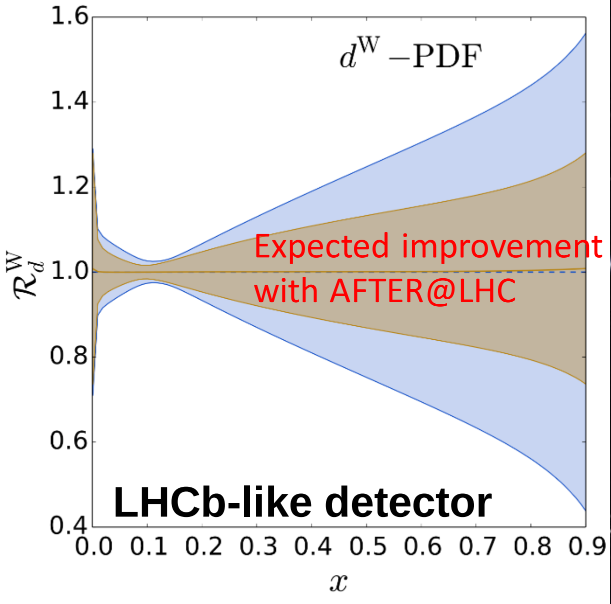
High-x frontier: Drell-Yan

- **Unique acceptance** (with an LHCb-like detector) compared to existing DY pA data used for nuclear PDF fit
- Extremely large yields up to $x_2 \to 1$ (pXe simulation), various targets
- Potential impact of DY measurements on nPDFs
- **Significant decrease of the uncertainties of u and d distributions**







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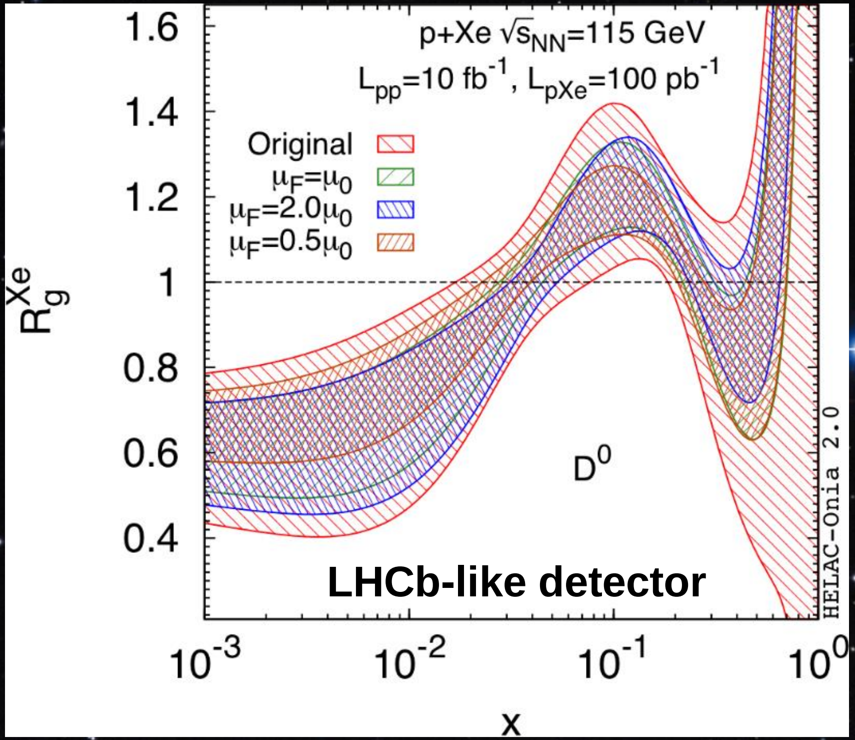
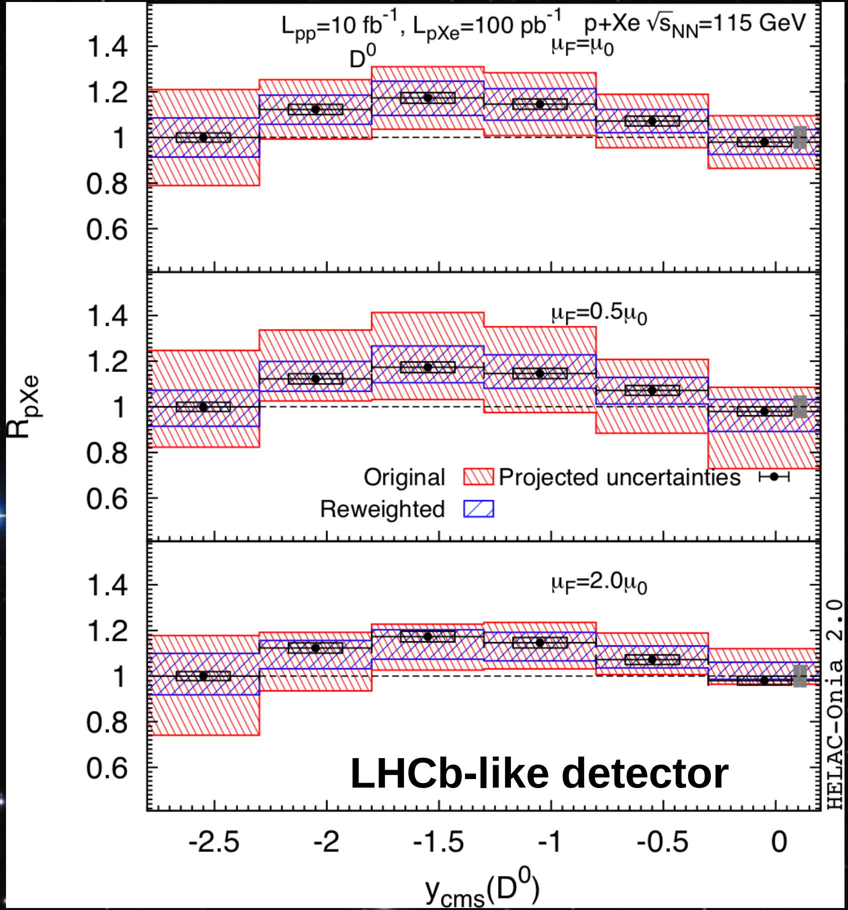
High-x frontier: constraining gluon nPDF

- **Gluon nPDF at high-x is among the least known**
- **Uncertainties could be significantly reduced by measurements at AFTER@LHC (e.g. R_{pXe})**
- **LHCb-like simulation**

Nuclear modification factor

$$R_{pA} \equiv \frac{dN_{pA}}{\langle N_{\rm coll}\rangle dN_{pp}}$$





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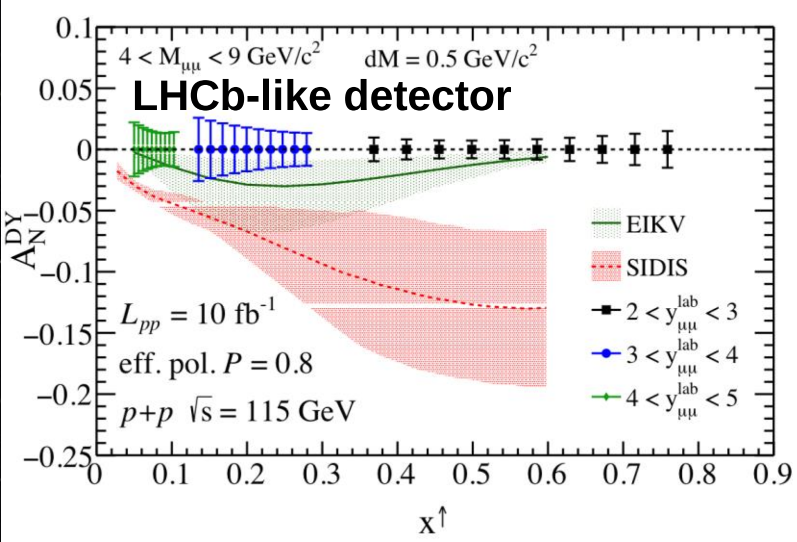
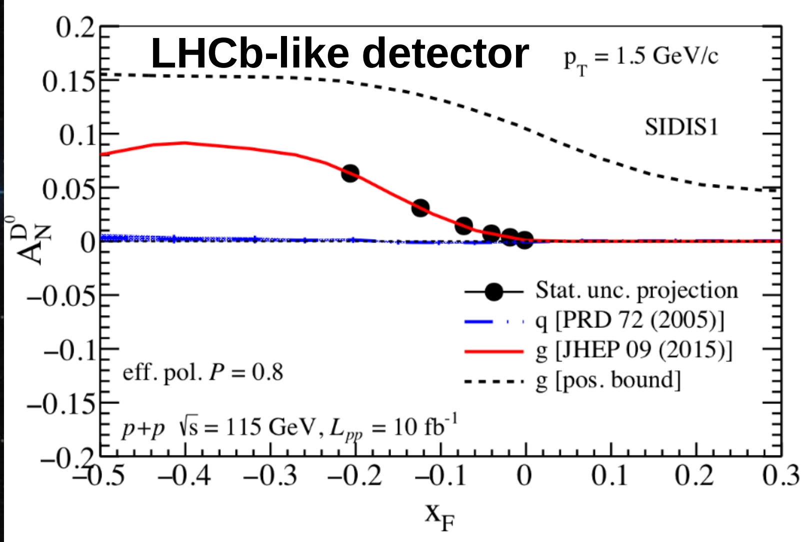
Spin physics: single transverse spin asymmetry

- The single transverse spin asymmetry (STSA) A_N defined as

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

- The A_N was predicted to be small in the collinear pQCD approach at leading twist, but measured to be large at high x in polarised collisions
- $A_N^{\text{Drell-Yan}}$ at AFTER@LHC will put strict constraints on the Sivers effect for quarks
- A_N for open heavy-flavour production gives access to the Sivers effect for gluons





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Summary

- A rich and unique physics program has been proposed with a fixed-target experiment at the LHC (AFTER@LHC), using the multi-TeV proton and lead beams
  - Large-x frontiers, spin physics, and heavy-ion physics
  - can be realised in a parasitic mode, without affecting the performance of the LHC
- Possible technical implementations are discussed
  - Beam extraction with bent crystal coupled to a solid target
  - Internal gas target inspired from SMOG@LHCb/HERMES/RHIC
- Physics projection studies with LHCb-and ALICE-like detectors
- Review on physics case and projected performances available (arXiv:1807.00603)

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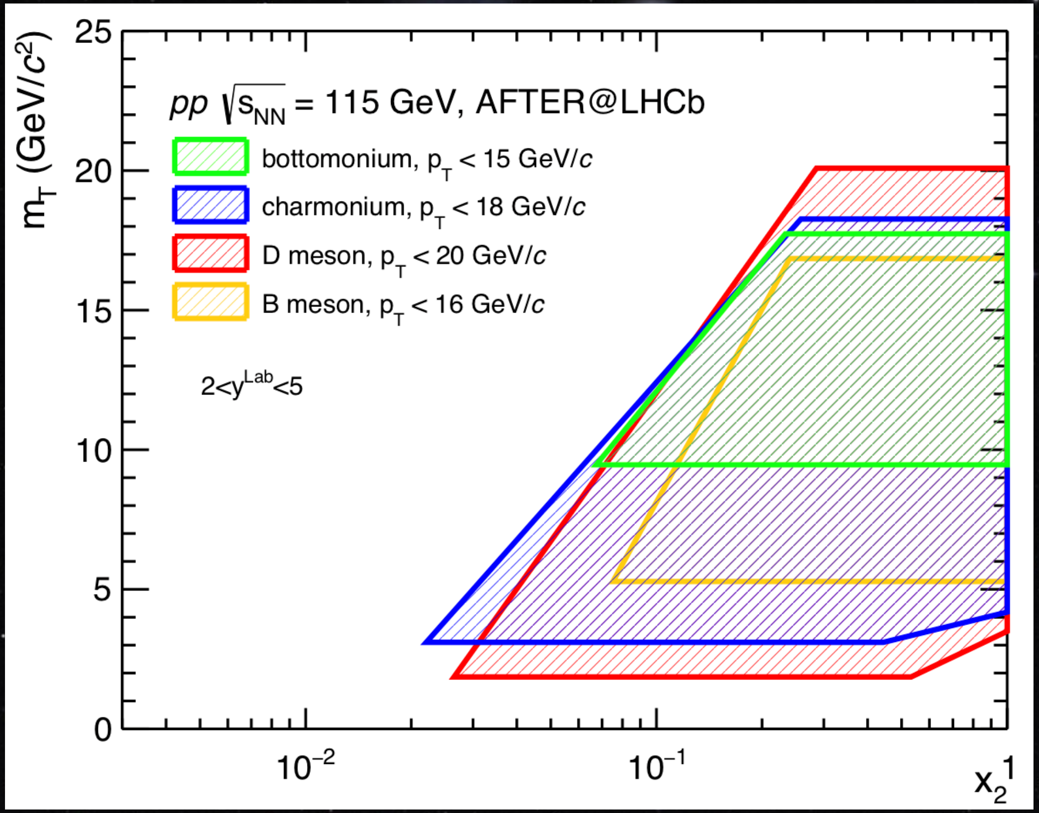
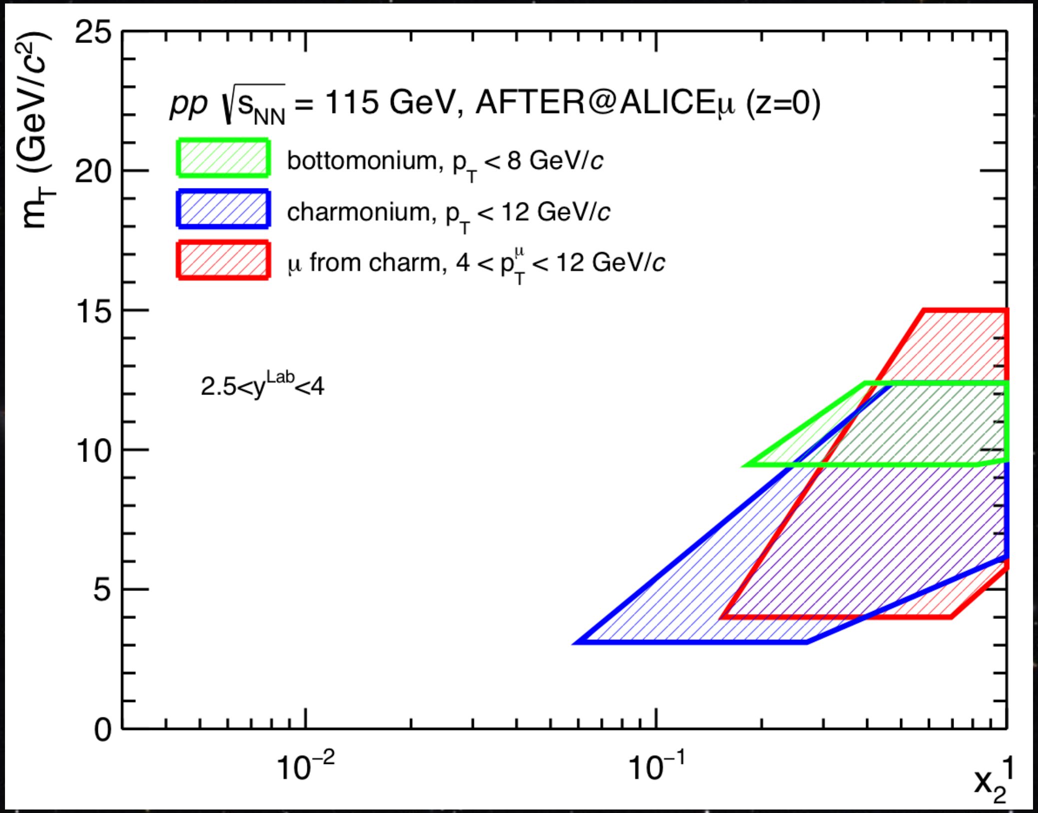
Backup slides

Typical kinematic reach in x_2 and the scale m_T





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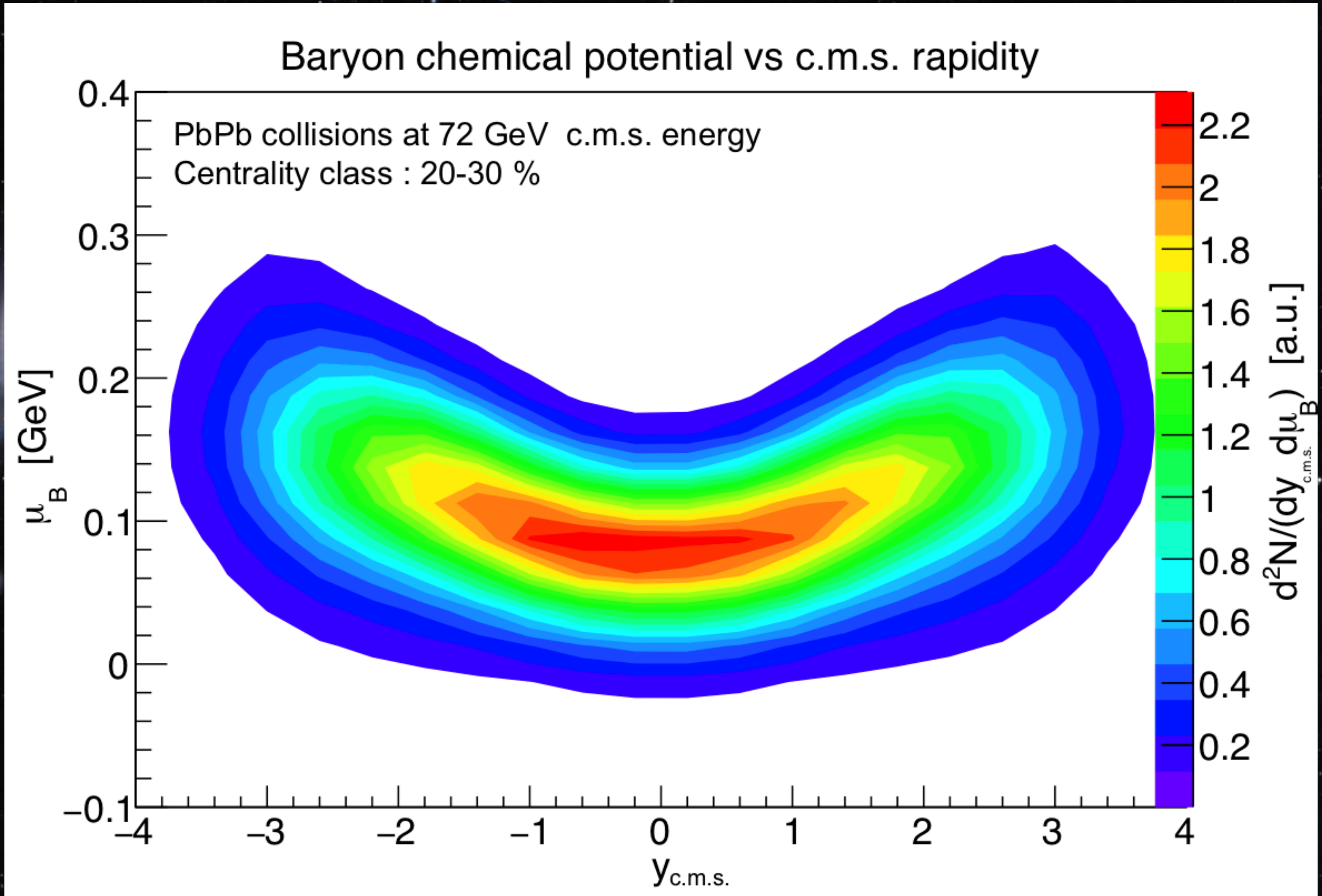
$d^2N/dyd\mu_B$ in the $(\mu_B, y_{\text{c.m.s.}})$ plane



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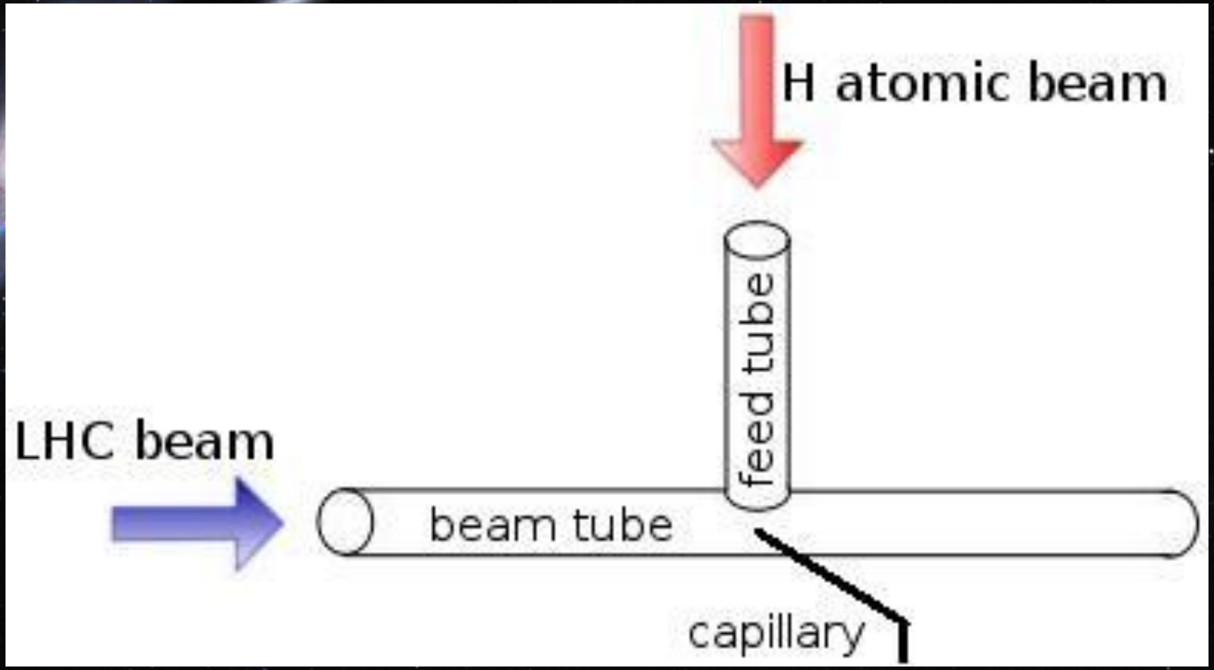
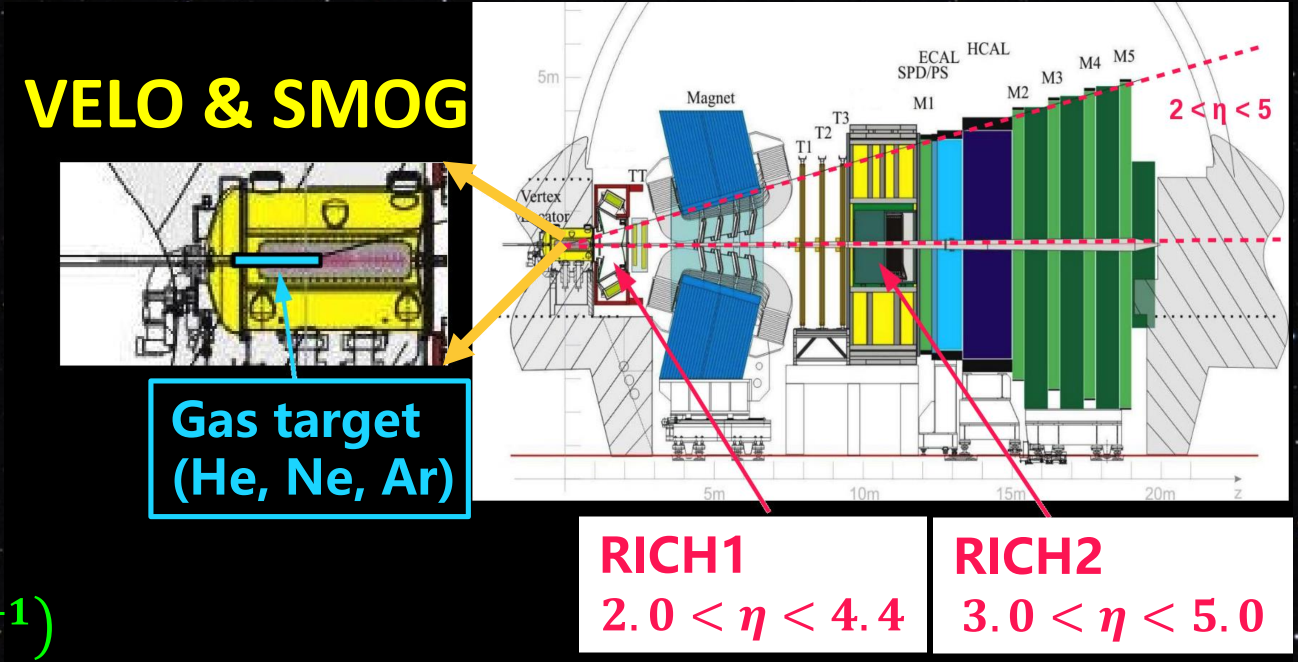
Target cell for polarised gas



Internal gas target: LHCb-SMOG

- System for Measuring Overlap with Gas (SMOG)
  - Initially designed for precise luminosity measurements
  - Noble gas injected inside the beam vacuum at the interacting point
  - $p + \mathrm{He}(\mathrm{Ne}, \mathrm{Ar})$ and $\mathrm{Pb} + \mathrm{Ne}(\mathrm{Ar})$ tested, completely parasitic
  - Could be coupled to ALICE

- Current limitation
  - No specific pumping system
  - Polarised gases cannot be used
  - Gas flows in the beam pipe
  - Kr/Xe maybe only at end of runs

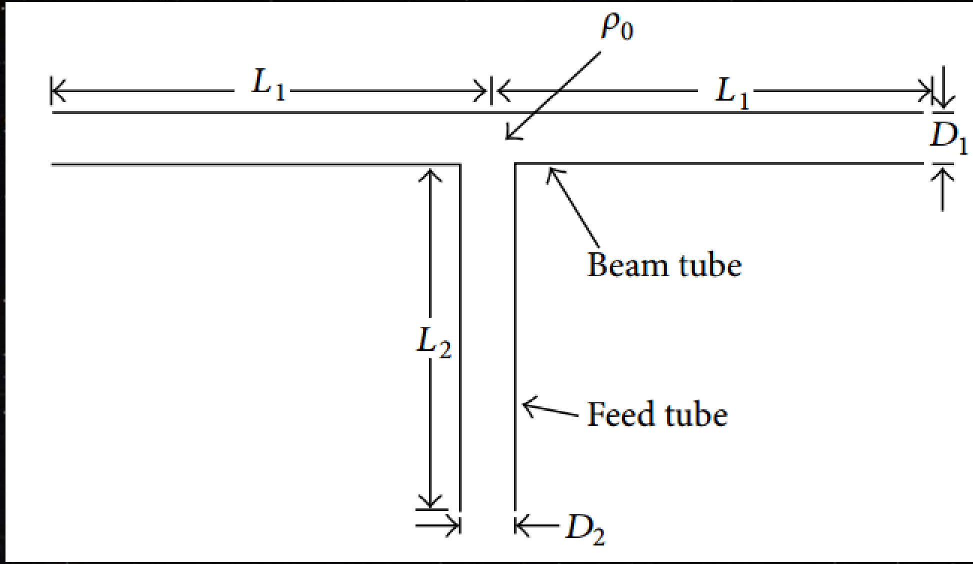


Typical integrated luminosity: $L_{\mathrm{int}} \sim \mathcal{O}\left(\mathrm{nb}^{-1}\right)$

Internal gas target: HERMES(-like) system

- Injecting gas in an open-end storage cell, used e.g. for more than 10 years at DESY
  - Dedicated pumping system
  - Pressure in the cell significantly higher
  - Polarised $\mathrm{H}^{\uparrow}$ and $\mathrm{D}^{\uparrow}$ can be injected ballistically with high polarisation
  - Possible for polarised $^{3}\mathrm{He}^{\uparrow}$ or unpolarised heavy gas (Kr, Xe)
  - Implementation at LHCb under study
  - Could be used in ALICE, most likely very upstream of the current IP
    - ✓May need complementary vertexing capabilities

E. Steffens,
Adv. High Energy Phys. 2015 (2015) 453141



Typical luminosity: $L_{\text{int}} \sim 10\ \text{fb}^{-1}$ for $p + \mathrm{H}$
$\sim 100\ \text{nb}^{-1}$ for Pb+H

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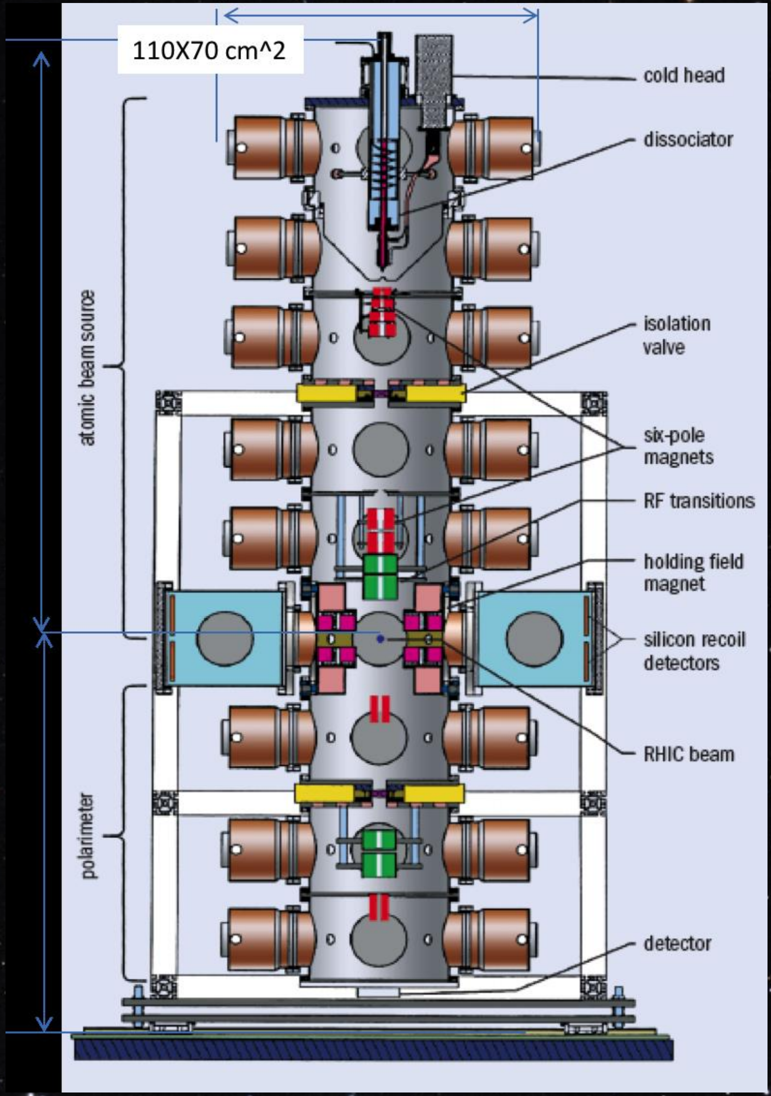
Gas-jet target

- Polarised H-jet polarimeter used at RHIC
  - To measure the proton beam polarisation
  - Compact device
  - 9 vacuum chambers → 9 stages of differential pumping
  - Polarised free atomic beam source (ABS)



- Expected Integrated luminosity over one LHC year
  - $L_{\text{int}} \sim 50\ \text{pb}^{-1}$ for $p + \text{H}$

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