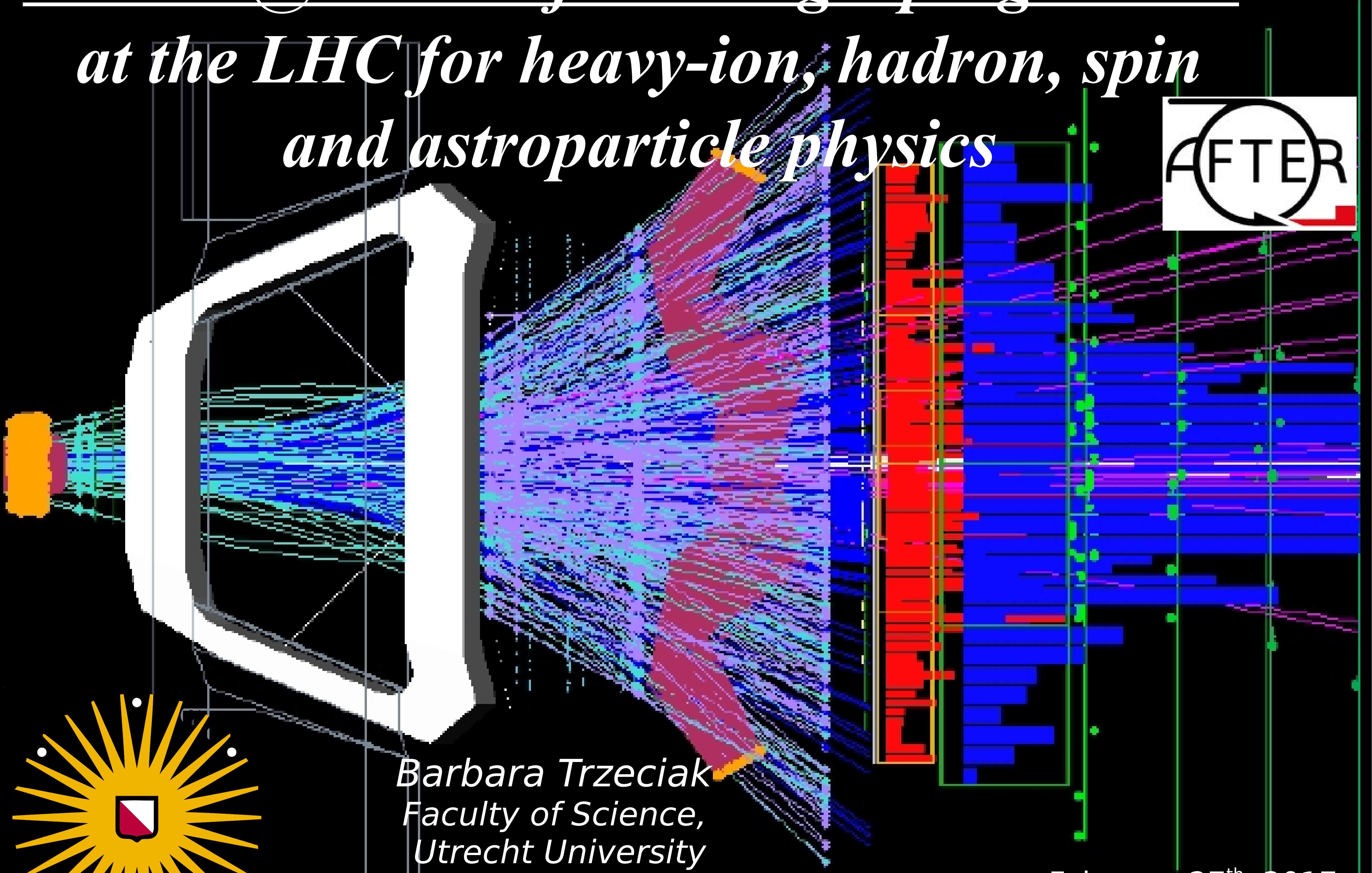
AFTER@LHC: A fixed-target programme at the LHC for heavy-ion, hadron, spin and astroparticle physics



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

February 27th, 2017
GGI, Florence

Outline

AFTER@LHC is a proposal for a multi-purpose fixed target experiment using the multi-TeV proton and heavy ion beams of the LHC

I. Kinematics, possible implementations and luminosities
II. Physics motivation
III. Projection studies
IV. Summary

Advantages of a fixed target mode with TeV beams

- access to large Feynman $|x_F|$ thanks to the boost $\left[|x_F| \equiv \frac{|p_z|}{p_{z\,\max}} \to 1\right]$
- target versatility (easy to change)
- possibility to polarize target
  - ambitious spin physics program
- high luminosities with either dense targets or high intensity beams
- all this in a parasitic mode !

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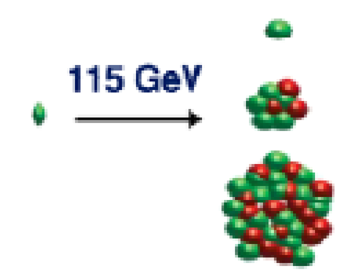
- With the LHC beams:

Energy range

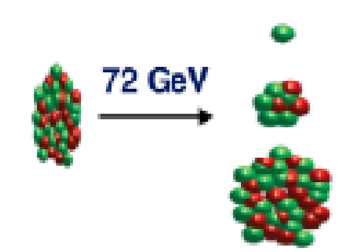
7 TeV proton beam on a fixed target

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



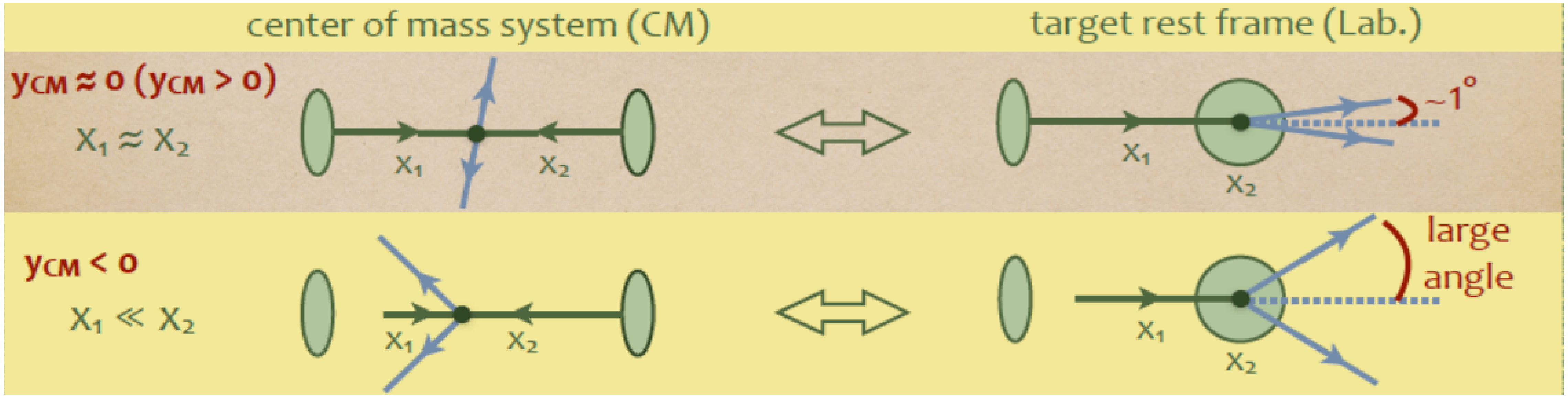
2.76 TeV Pb beam on a fixed target

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



Access to high x (backward physics)

Effect of boost



- Entire forward hemisphere – $y_{c.m.s.} > 0$ – within: $0° < \theta_{lab} < O(1°)$ - large occupancy – more challenging (only possible with an absorber - NA60)
- Backward region – $y_{c.m.s.} < 0$ – at large angles in the lab frame – low occupancy, no constrain from a beam pipe
  - backward physics fully accessible for the first time
  - access to partons with momentum fraction $x_2 \rightarrow 1$ in the target ($x_F \rightarrow -1$)

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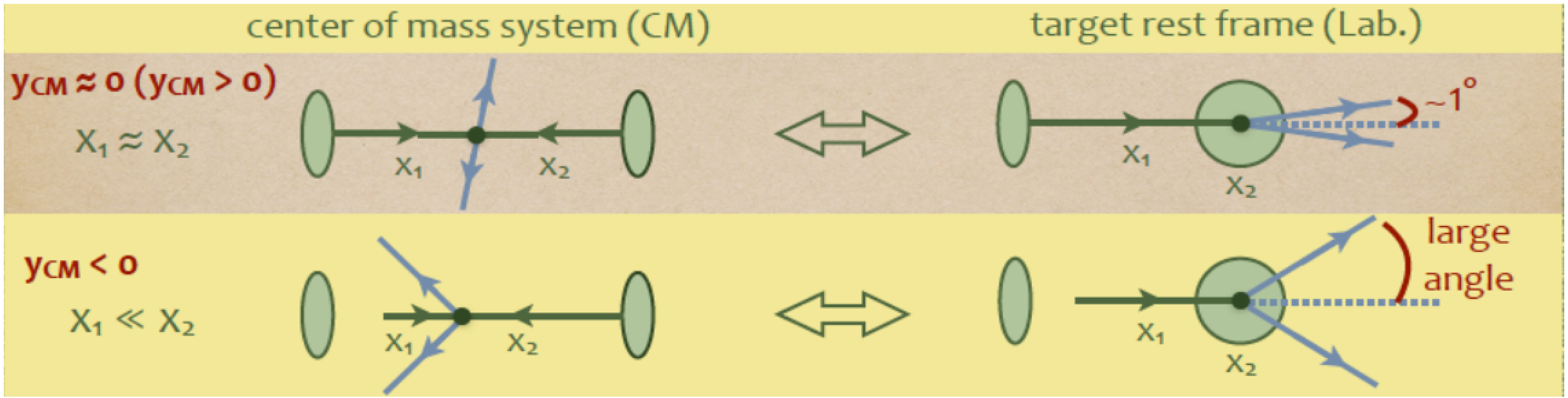

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- AFTER@LHC focuses on the backward region
  - LHCb and the ALICE muon arm become backward detectors
  - With the ~~reduces~~ √s their acceptance grows and covers ~half of the backward region

Possible implementations

- ✔ **Internal gas target similar to SMOG at LHCb / inspired by HERMES at HERA**
  - can be installed in one of the existing LHC caverns and coupled to existing experiments (or in a new one),
  - currently validated by the LHCb collaboration via a luminosity monitor (SMOG)
    - proton flux: 3.4 x 10^{18} p/s
    - Pb flux: 3.6 x 10^{14} Pb/s

High Intensity beams

- ✔ **Internal wire target** (used by Hera-B on the 920 GeV HERA p beam and by STAR at RHIC)
- ✔ **Beam line extracted with a bent crystal**
  - The most ambitious solution, provides ~~a new facility~~
  - The LHC beam halo is recycled
    - expected extracted p beam: 5 x 10^8 p/s (LHC beam loss: ~10^9 p/s)
    - expected extracted Pb beam: 2 x 10^5 Pb/s

Dense targets

- ✔ **Beam "split" with a bent crystal**
  - Intermediate option that reduces civil engineering
  - Might be coupled to an existing experiment
    - Similar flux

Luminosities

- ✔ **Internal gas target similar to SMOG at LHCb / inspired by HERMES at HERA**
- ✔ **Internal wire target**
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- ✔ **Beam "split" with a bent crystal**

High Intensity beams

Dense targets

➔ **Expected integrated luminosities:**

- Depends on the chosen implementation, pressure of the gas or target length ...

✗ pp

$\int \mathcal{L} \sim 10\ \mathrm{fb^{-1}yr^{-1}}$

✗ pA

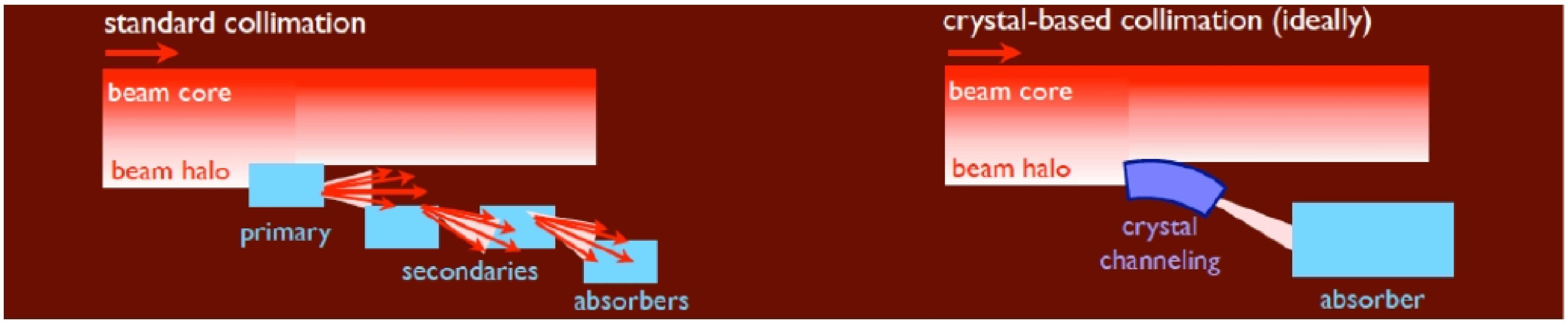
$\int \mathcal{L} = 0.1 - 2\ \mathrm{fb^{-1}yr^{-1}}$

✗ PbA

$\int \mathcal{L} = 1 - 50\ \mathrm{nb^{-1}yr^{-1}}$

Beam extraction using bent crystal

✓ **Motivated for collimation purposes**



Standard collimation today → Crystal-based collimation
- UA9 (@SPS)
- LUA9 (@LHC)

→ To beam extraction
- CRYSBEAM (@SPS then LHC)
- AFTER@LHC

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

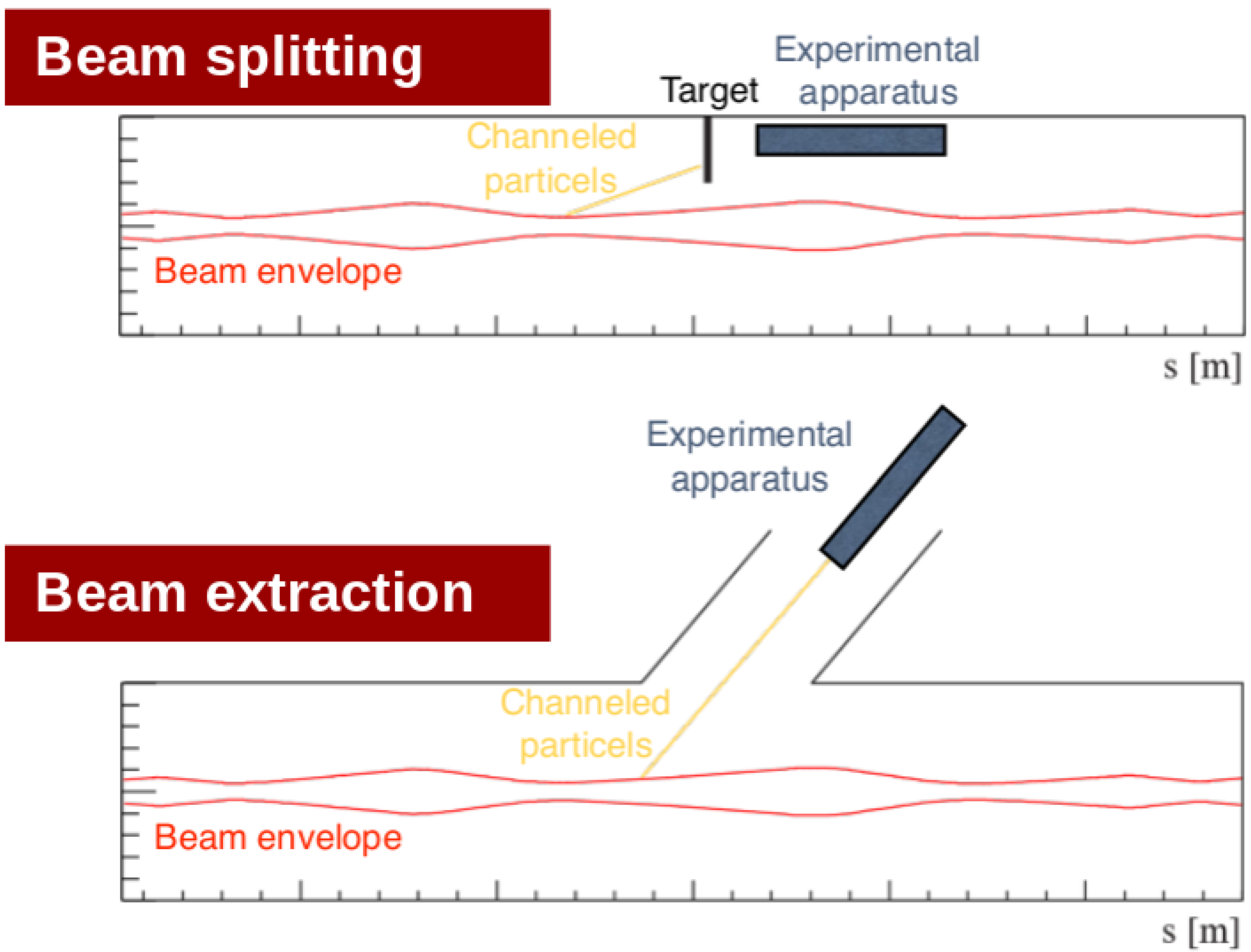
- LUA9 test in the LHC complex
- Deflecting the beam halo at 7σ distance to the beam

  Reduce the LHC beam loss

- New beam line + new experiment
- Beam extraction – requires civil engineering
- Beam splitting – an intermediate option that can be used with an existing experiment

Beam splitting using bent crystal

✓ **Beam splitting: an intermediate option**



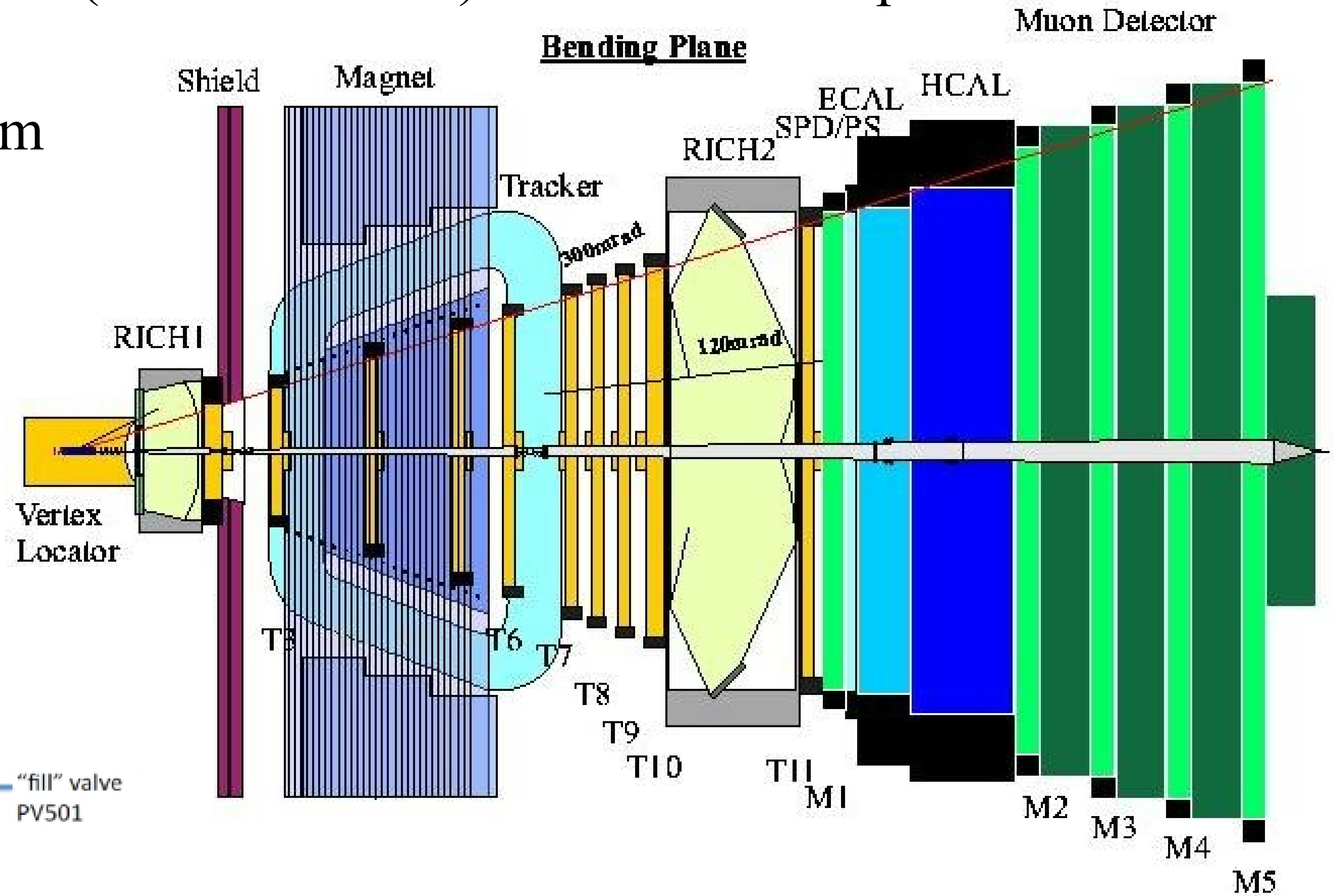
S. Redaelli, Physics Beyond Colliders, CERN, 06/09/2016

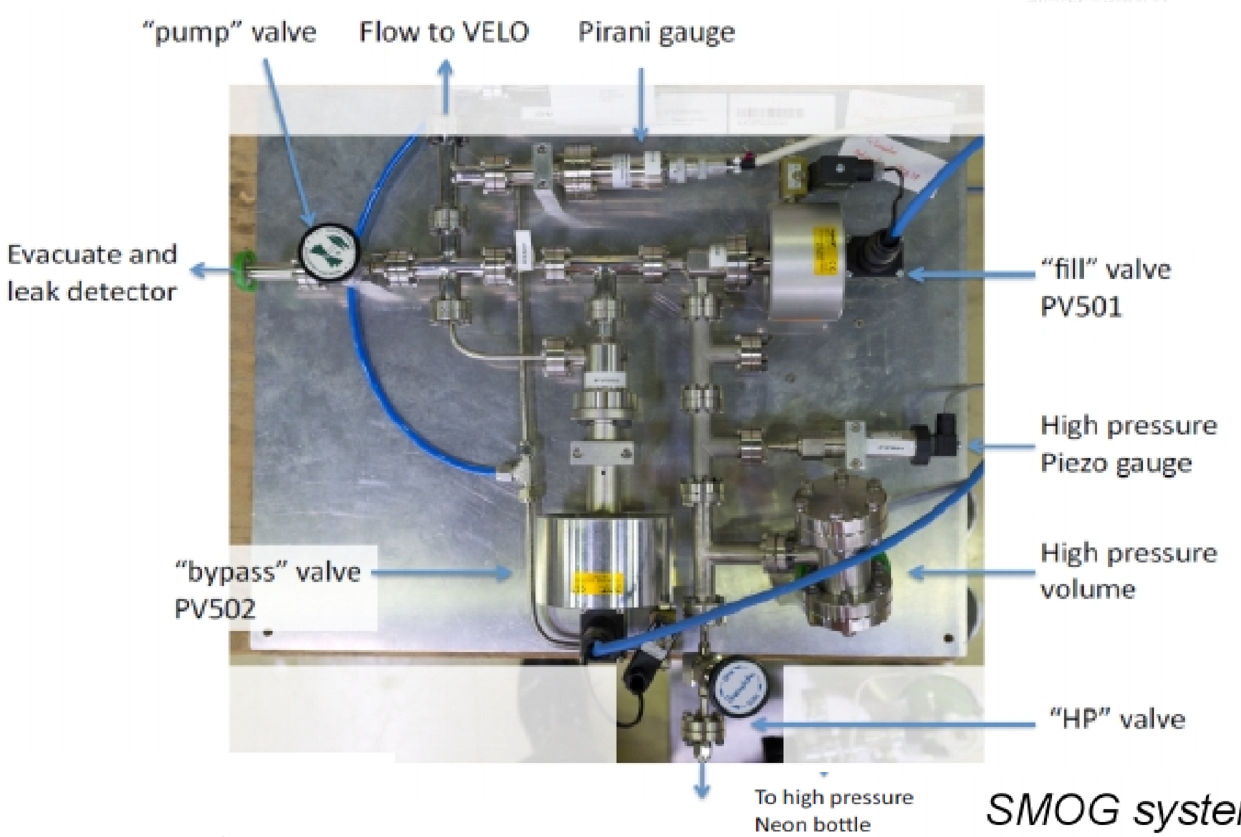
- Reduced civil engineering
- Similar fluxes as for the beam extraction option
- Might be coupled to an existing experiment

SMOG@LHCb

- ✓ System for **M**easuring **O**verlap with **G**as
- ✓ Direct gas injection to VELO (Vertex Locator) motivated for a precise luminosity determination
- ✓ No specific pumping system
- ✓ Preferred gas targets:

	He	Ne	Ar	Kr	Xe
A	4	20	40	84	131





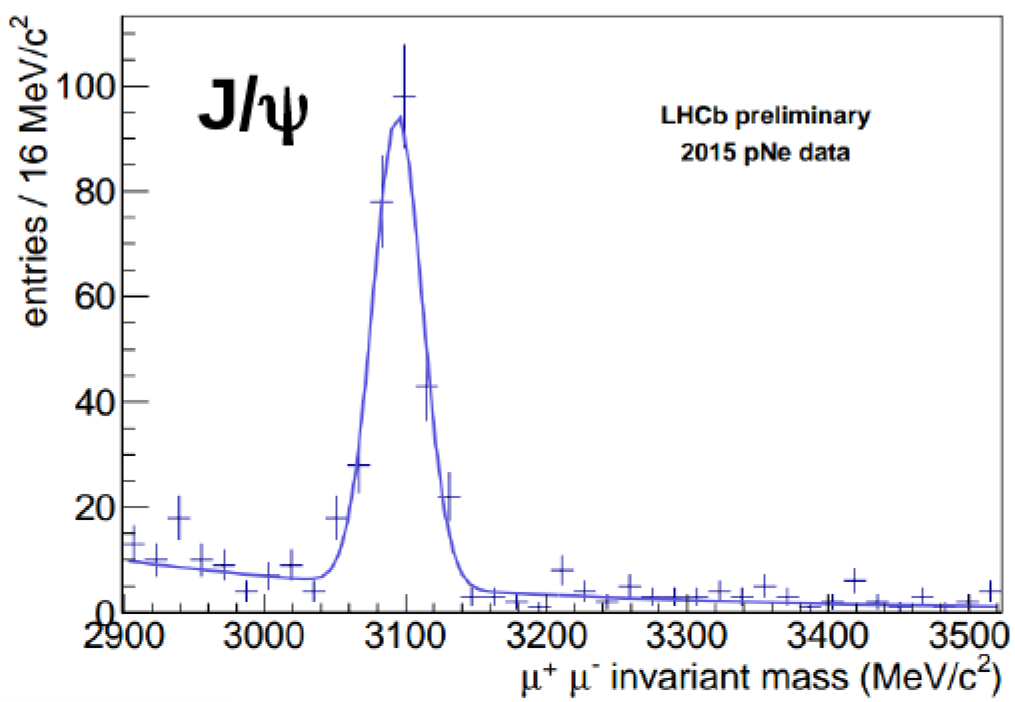
SMOG system

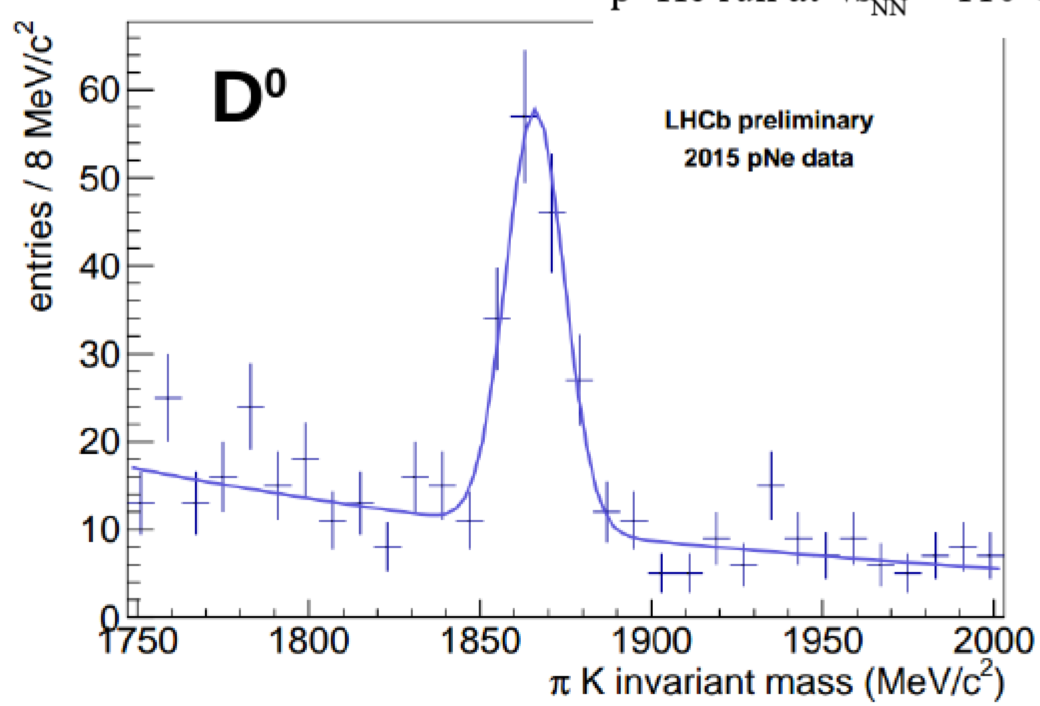
- So far only noble gases (NEG filter)

SMOG@LHCb - a working example

- Successful running, pA and AA data taking
- No decrease of LHC performances observed in the test runs
- Fixed target collisions can be separated
  → no need for dedicated physics runs
- Good performance:

p+Ne pilot run at $\sqrt{s_{NN}}$ = 87 GeV (2012) ~ 30 min
Pb+Ne pilot run at $\sqrt{s_{NN}}$ = 54 GeV (2013) ~ 30min
p+Ne run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 12h
p+He run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 8h
p+Ar run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 3 days
p+Ar run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ few hours
Pb+Ar run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ 1.5 week
p+He run at $\sqrt{s_{NN}}$ = 110 GeV (2016) ~ 2 days





$\sqrt{s_{NN}}$ = 110 GeV, about 12h of data taking (2015)

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

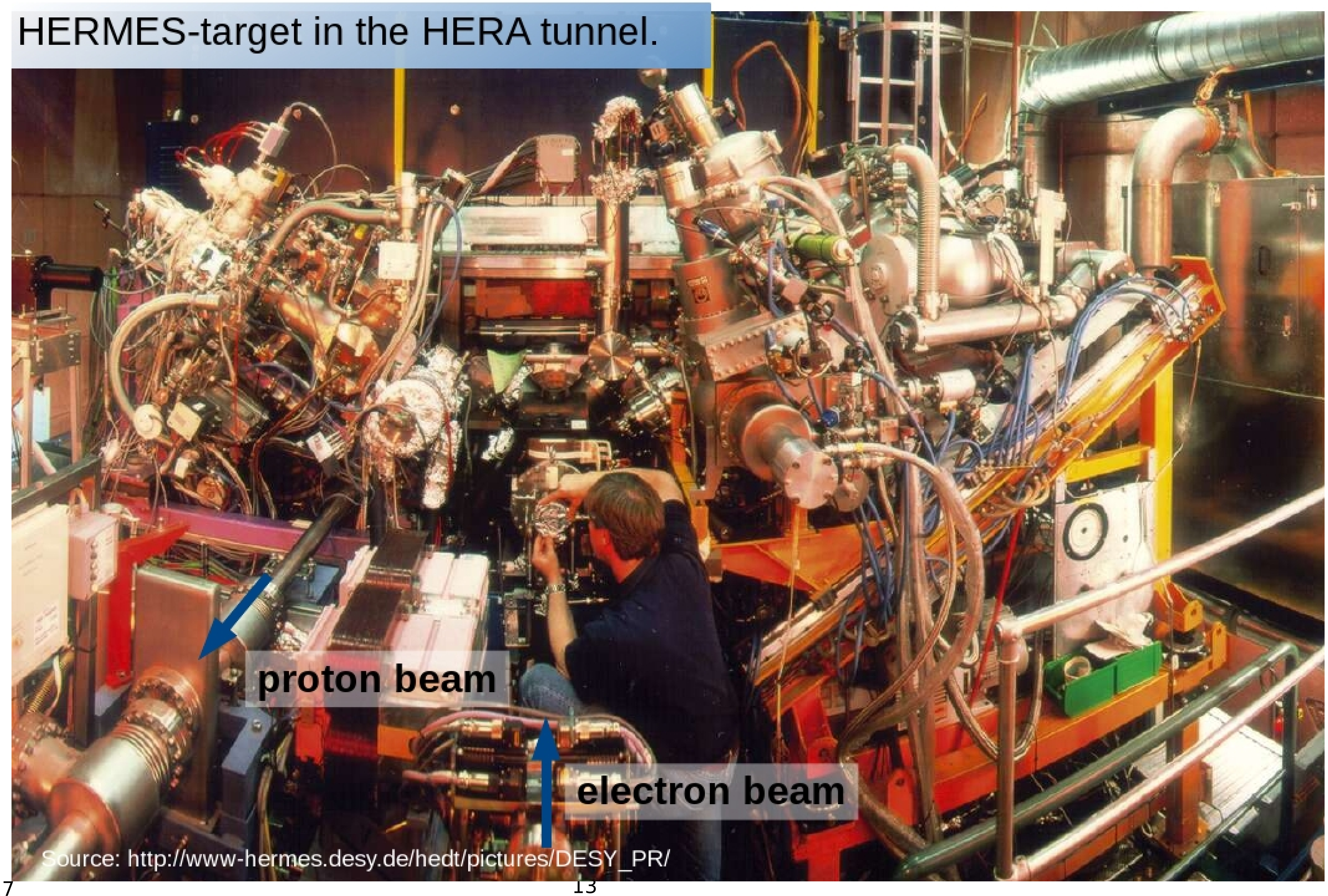
- ✗ Target polarization is not possible with SMOG
- ✗ So far only noble gases

➔ However internal gas target can be polarized, like HERMES target

Polarised target – HERMES system

Adv. High Energy Phys. 2015 (2015) 463141
E. Steffens, PoS (PSTP2015) 019

- Dedicated pumping system
- Polarised H and D injection in open-end storage cell - **polarisation of ~80%**
- Possibility to inject polarised ^3He or unpolarised heavy gas (Kr, Xe)



Internal gas targets

Two possible implementations

SMOG(-like) system

- SMOG: System for Measuring Overlap with Gas
- Designed for precise luminosity determination
- Noble gas directly injected in the VELO

✓ p(He,Ne,Ar), Pb(Ne,Ar) tested : completely parasitic [up to one week, so far]

✓ New pressure monitoring to be installed

✓ Could be coupled to ALICE: ideal demonstrator

✗ No specific pumping system: limit in the gas inject [pressure and duration]

✗ No possibility to use polarised gases

✗ Gas flows in the beampipe; pressure profile not optimised

✗ Kr and Xe maybe only at end of a run

HERMES(-like) system

- Injection of gas in an open-end storage cell
- Used e.g. at DESY for 10 years

✓ Dedicated pumping system [turbo-molecular pumps]

✓ Pressure in the cell significantly higher [diameter ≤ 2cm in the closed position]

✓ Polarised H and D can be injected ballistically with high polarisation

✓ Polarised ^{3}He or unpolarised heavy gas (Kr, Xe) can also be injected

✗ Not compatible with an injection inside ALICE; only upstream

✗ May need complementary vertexing capabilities

J.P. Lansberg, Physics Beyond Colliders Kickoff Workshop, 6-7 September 2016, CERN

Physics Highlights: AFTER@LHC

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- *Physics Reports 522 (2013) 239; Few Body Syst. 53 (2012) 11-25.*

Physics Reports 522 (2013) 239–255

Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

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Physics opportunities of a fixed-target experiment using LHC beams

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Contents

Expression of Interest in preparation

- *Many more ideas for a fixed target experiment at LHC in a Special Issue in Advances in High Energy Physics*

Advances in High Energy Physics

Hindawi

Special Issue on
Physics at a Fixed-Target Experiment Using the LHC Beams

CALL FOR PAPERS

- ***Heavy-ion physics***
- ***Exclusive reactions***
- ***Spin physics studies***
- ***Hadron structure***
- ***Feasibility study and technical ideas***

http://after.in2p3.fr/after/index.php/Recent_published_ideas_in_favour_of_AFTER@LHC

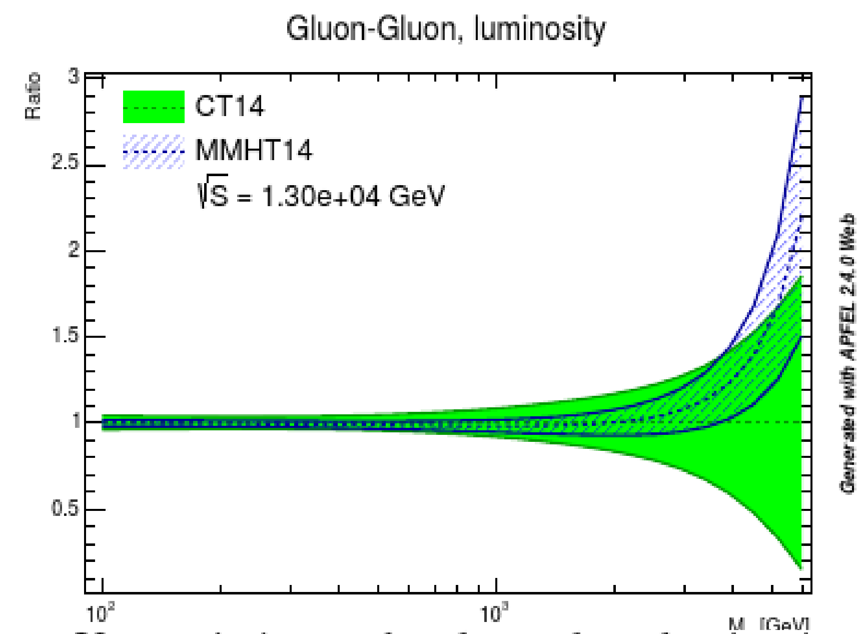
Physics Highlights: AFTER@LHC

➔ High-*x* frontier

- Advance our understanding of the **large-x gluon, antiquark** and **heavy-quark** content in the **nucleon** and **nucleus**

✔ **Nucleon partonic structure**

- Gluon pdf in the proton – large uncertainties at high x > 0.5
- $g_p(x) = g_n(x)$?



Uncertainties on the gluon-gluon luminosity at $\sqrt{s}$ = 13 TeV

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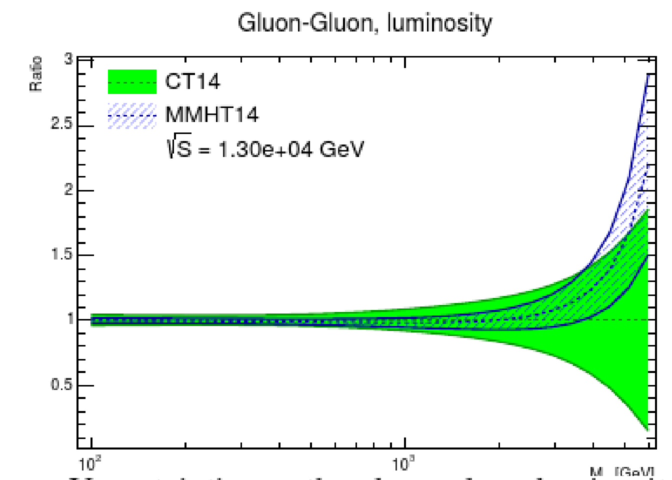

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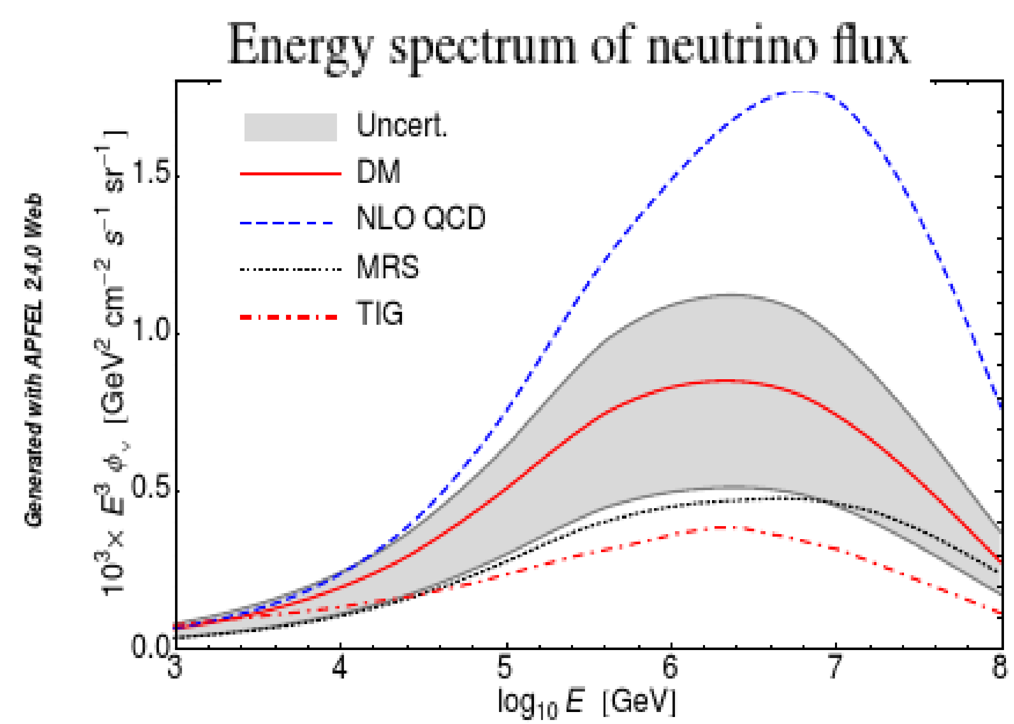
✔ **Heavy-quark distribution at large x in the proton**

- Proton **charm** content important to **high-energy neutrino and cosmic-ray** physics



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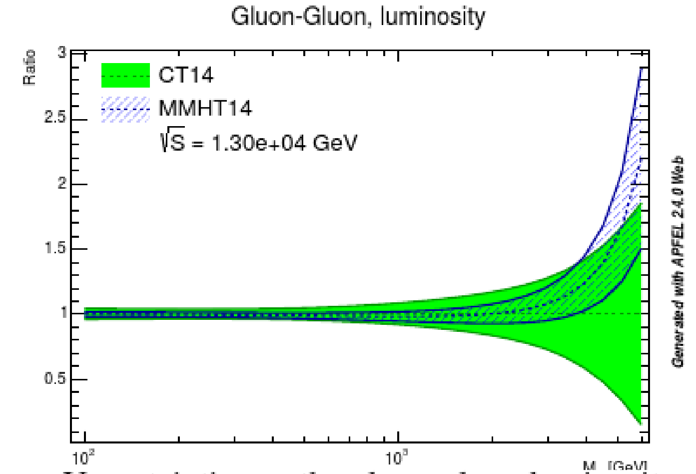

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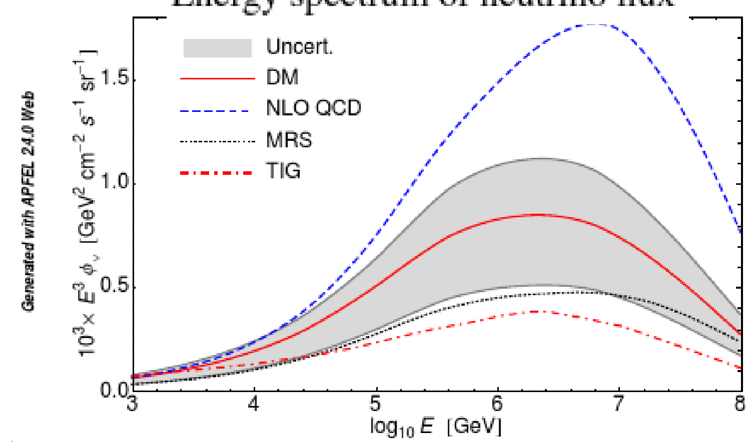
Energy spectrum of neutrino flux



✔ **Heavy-quark distribution at large x in the proton**

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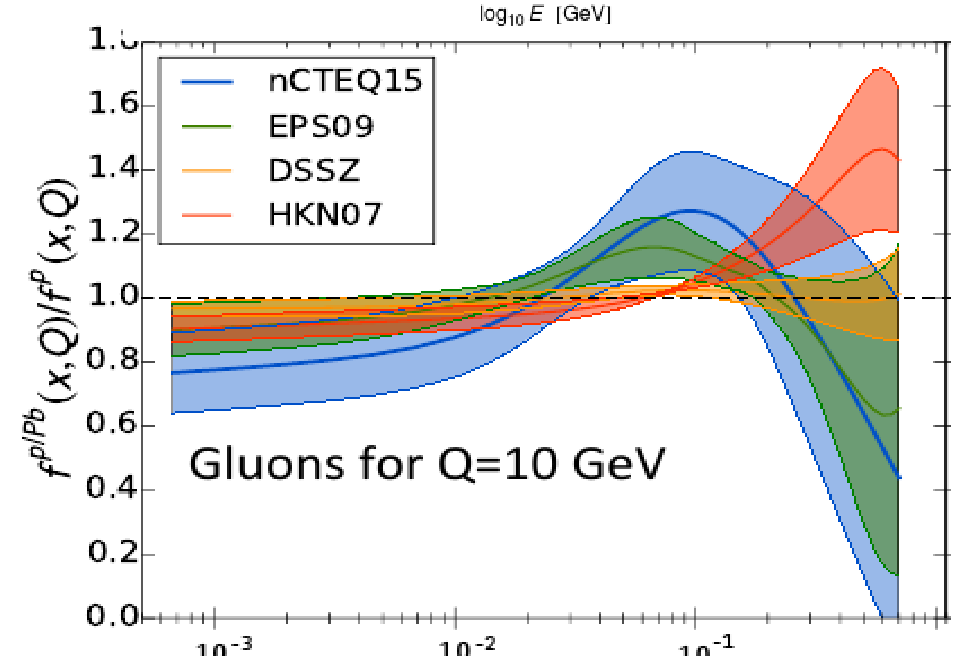
✔ **Nuclear structure – gluon distribution**

- Complementary to EIC, LHeC
- Large uncertainty in nuclei at large x, unknown **gluon EMC** effect
- Relevance of nuclear PDF to understand the **initial state of heavy-ion collisions**
- Search and study **rare proton fluctuations** where one gluon carries most of the proton momentum

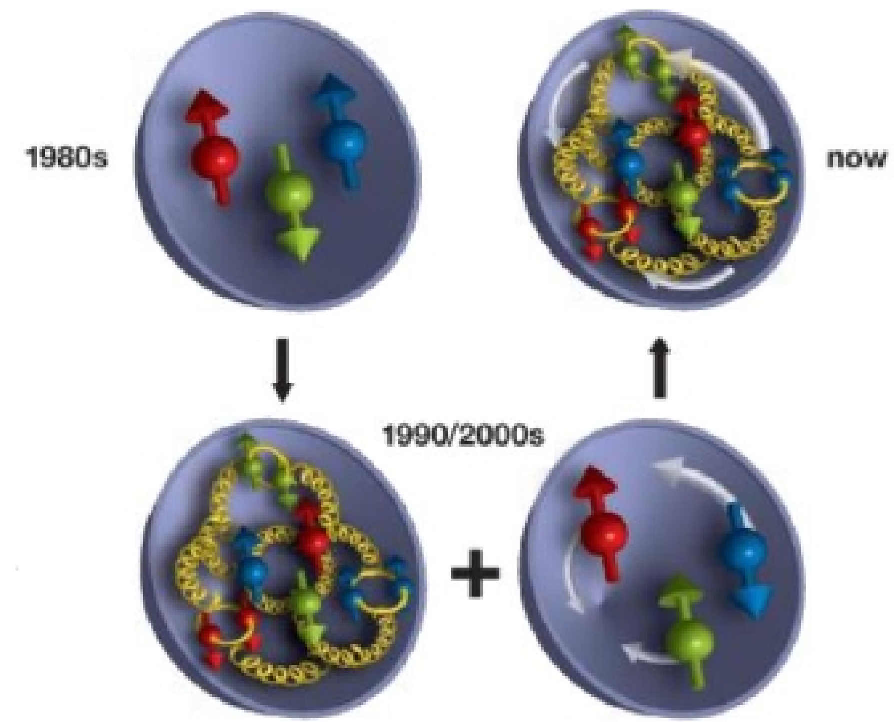


lack of knowledge in the gluon densities in nuclei for $x > 0.1$

Physics Highlights: AFTER@LHC

➔ Spin physics

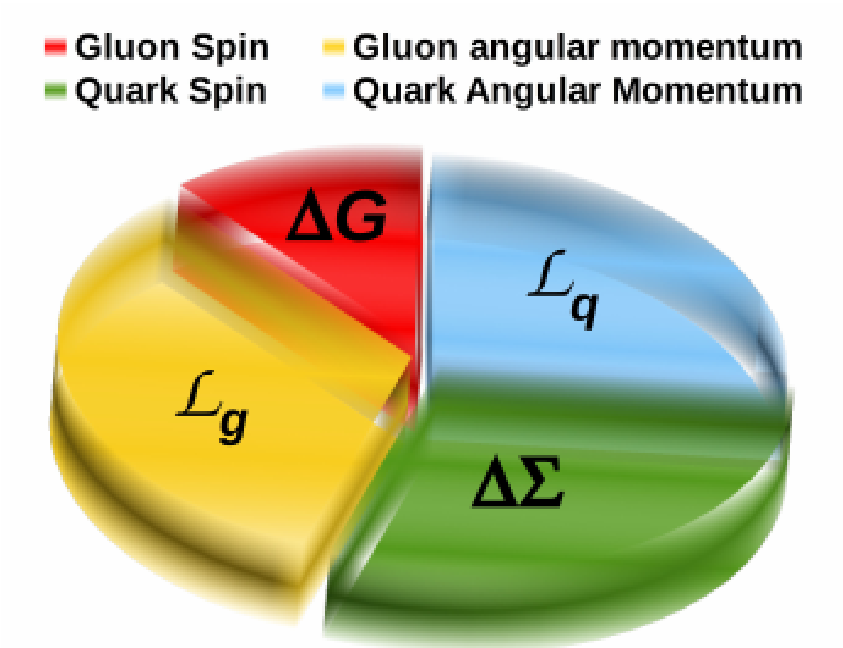
- Advance our understanding of **transverse dynamics and spin of gluons inside (un)polarised nucleons**



✔ **3D mapping of the proton momentum**

✔ Missing contribution to the **proton spin: gluon and quark Orbital Angular Momentum** $\mathcal{L}_{g;q}$

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



✔ **With a polarised target:**

→ p+p$^{\uparrow}$ → (indirect) access to quark L_q, gluon L_g and gluon TMDs

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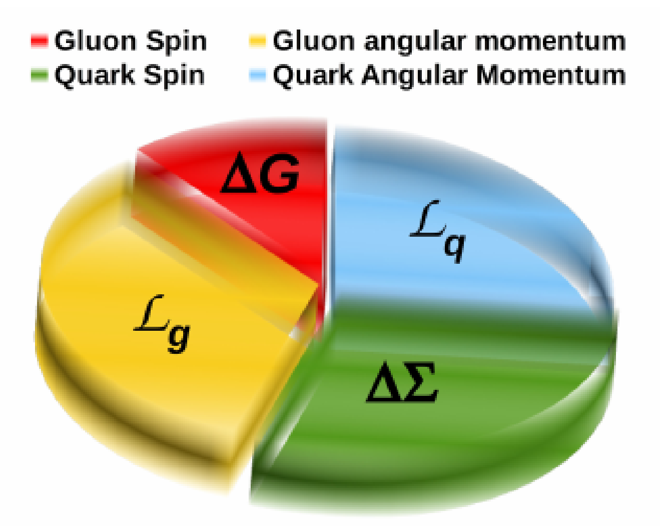

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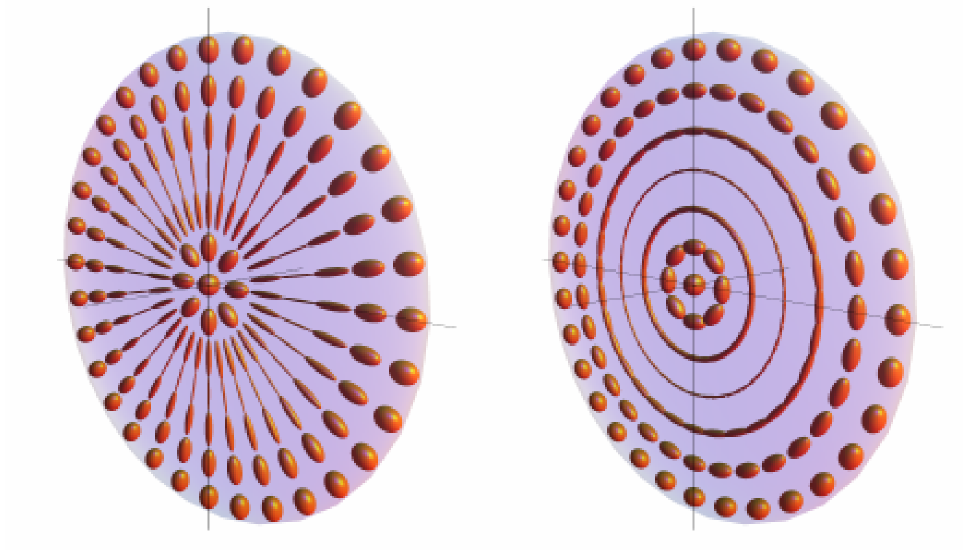
✔ Test of the **QCD factorisation** framework

✔ Determination of **linearly polarised gluons** in unpolarised protons: $h_1^{\perp g}$, "Boers-Mulder" effect



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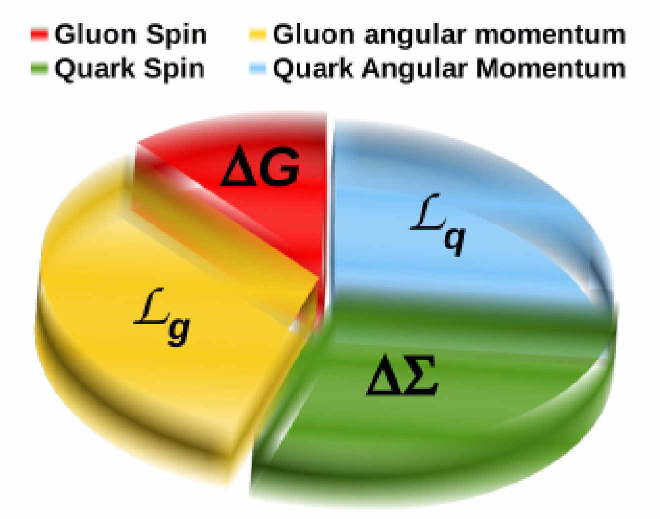

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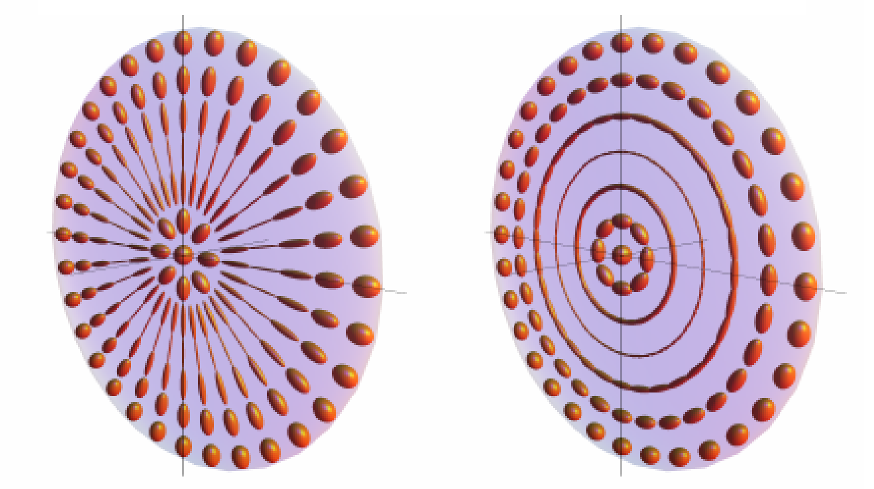


✔ With a polarised target:

- **Single Spin Asymmetries** (STSA) in hard-scattering processes, with a transversal polarised hadron: indirect access to the orbital motion of partons

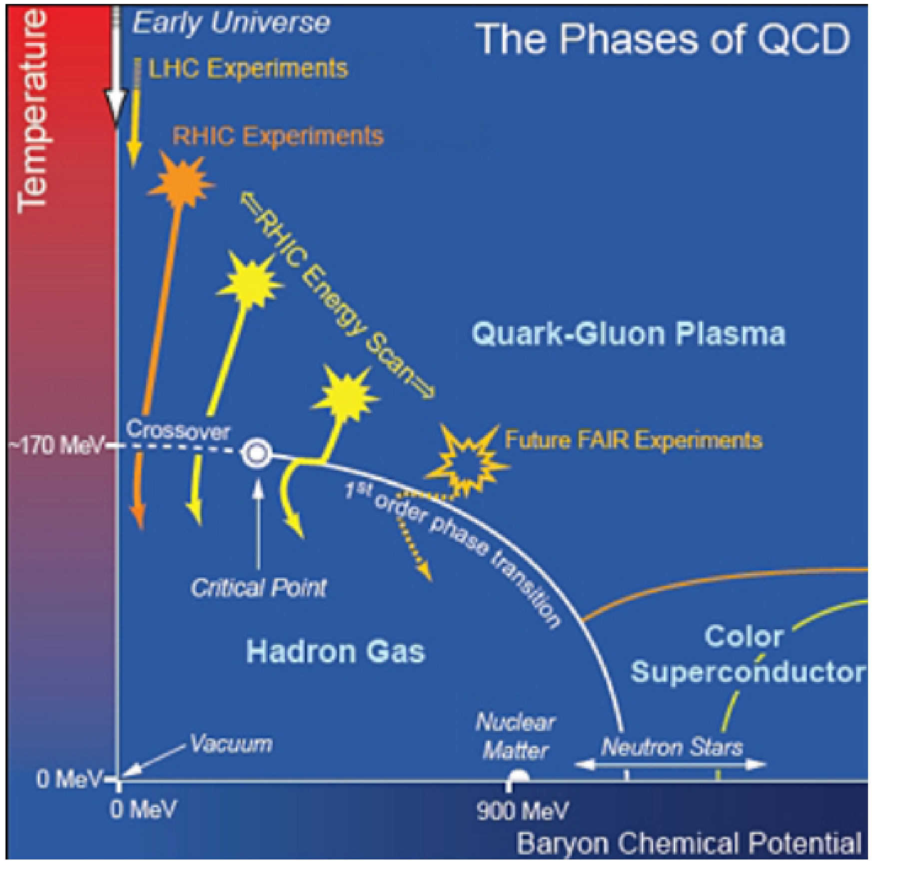
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

  - STSA: left-right asymmetries in parton distributions **Sivers effect**
  - **non-zero** quark/gluon **Sivers function** → **non-zero** quark/gluon **OAM** $f_{1T}^{\perp}(x,k_{\perp}^2)$

Physics Highlights: AFTER@LHC

✔ Heavy-Ion collisions from mid to large rapidities

- ✔ A complete set of heavy-flavour studies between SPS and RHIC energies
- ✔ Precise estimation of **Cold Nuclear Matter effects** from pA and AB – test of the **factorization**
  - In PbA, different nuclei, A-dependent studies
- ✔ **Quark-Gluon Plasma studies in heavy-ion collisions**



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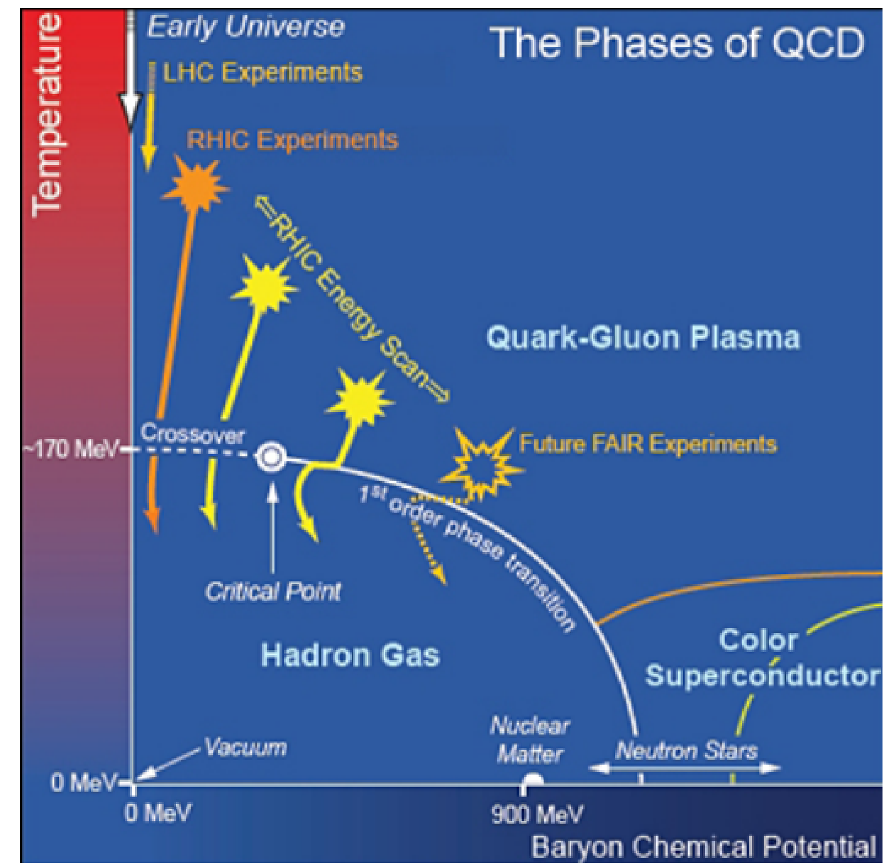
- In PbA, different nuclei, A-dependent studies

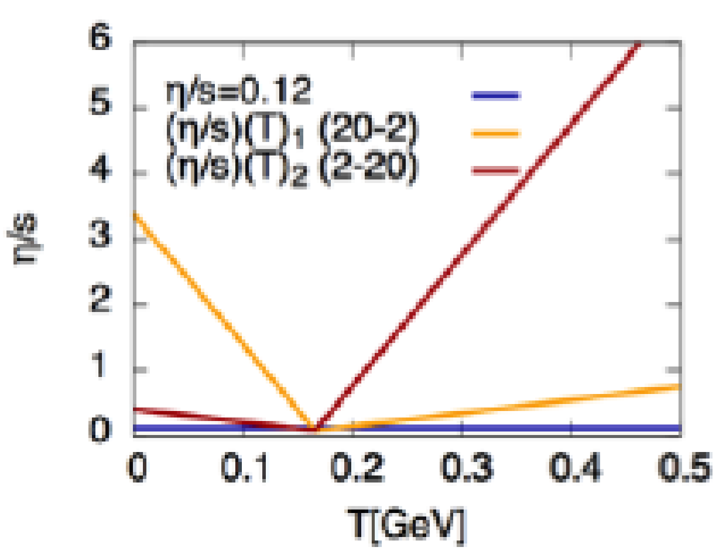
✔ **Quark-Gluon Plasma studies in heavy-ion collisions**

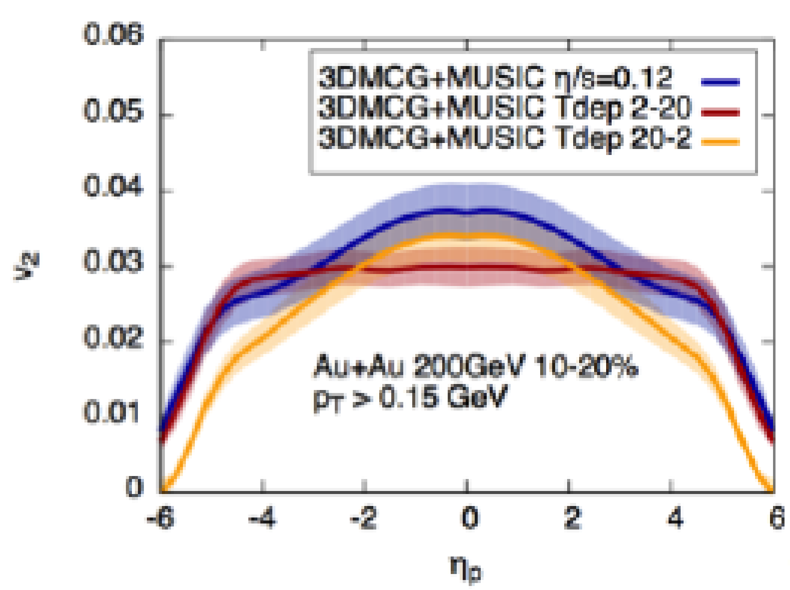
✔ Explore the **longitudinal expansion of QGP formation**

- Quarkonia, HF jets quenching, low mass lepton pairs, direct photons

✔ Test the formation of **azimuthal asymmetries**: hydrodynamics vs initial-state radiation





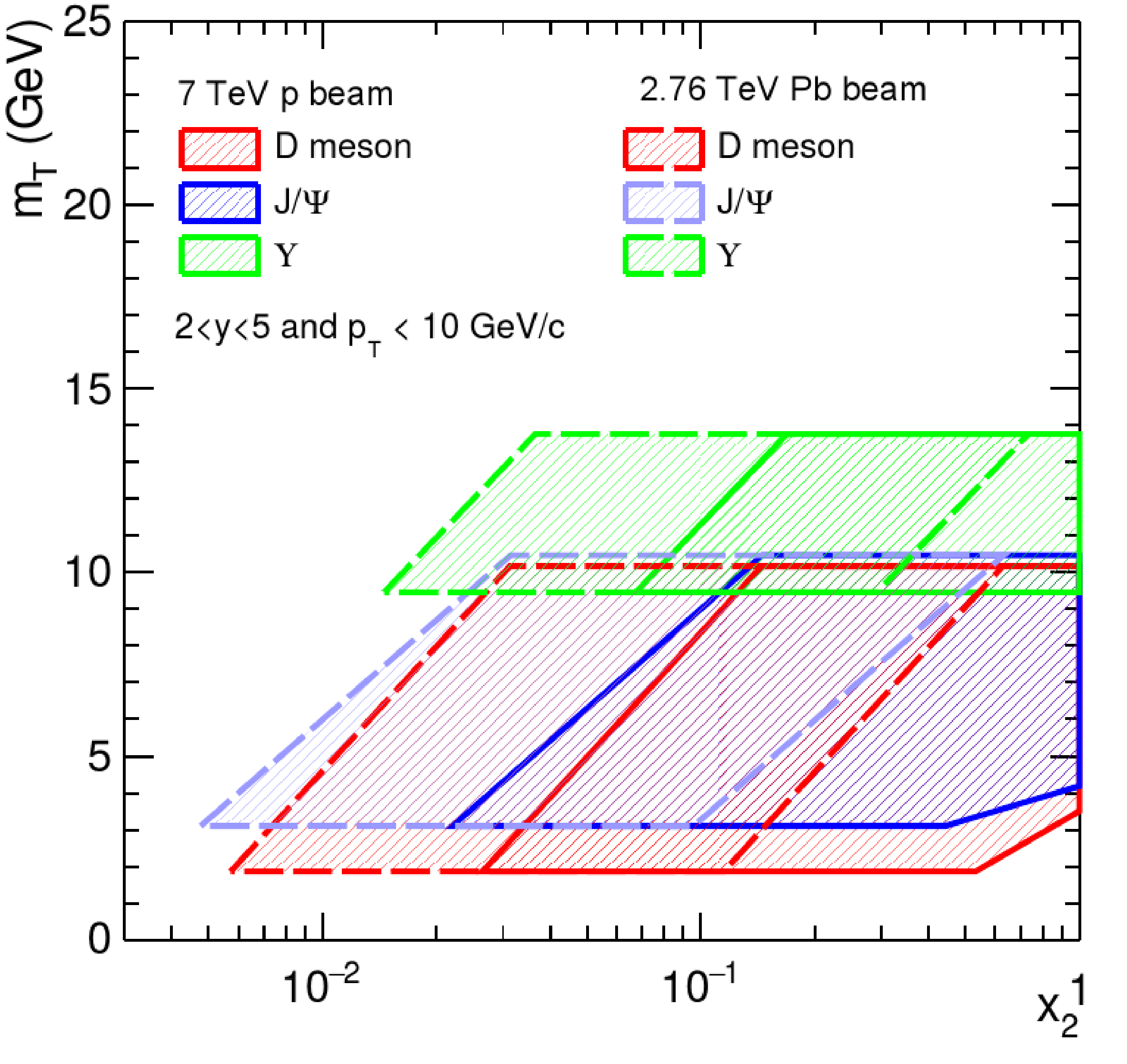


Feasibility studies

Projection studies

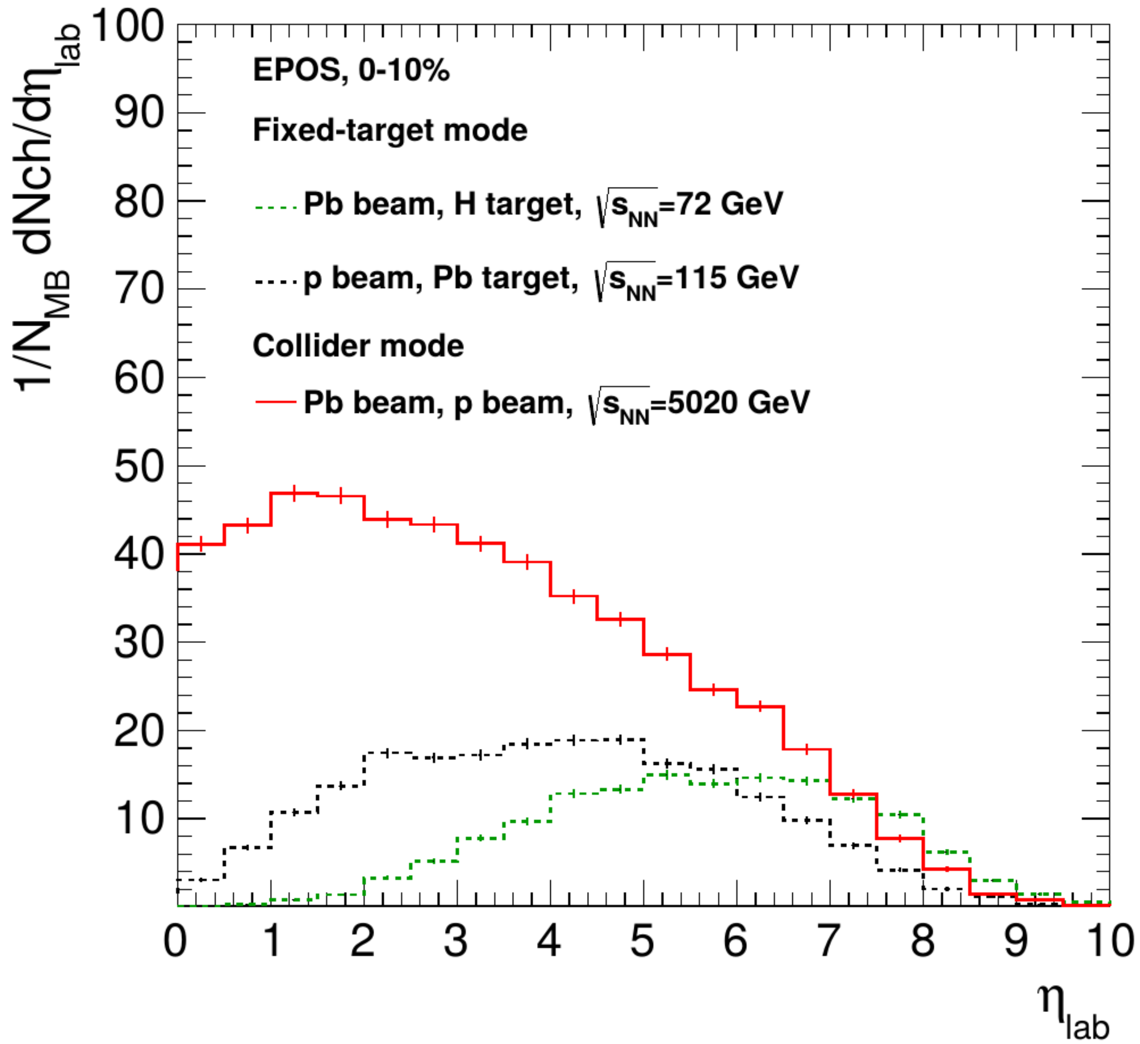
- Includes:
  - Drell-Yan
  - J/psi, Upsilon
  - Open Heavy Flavour

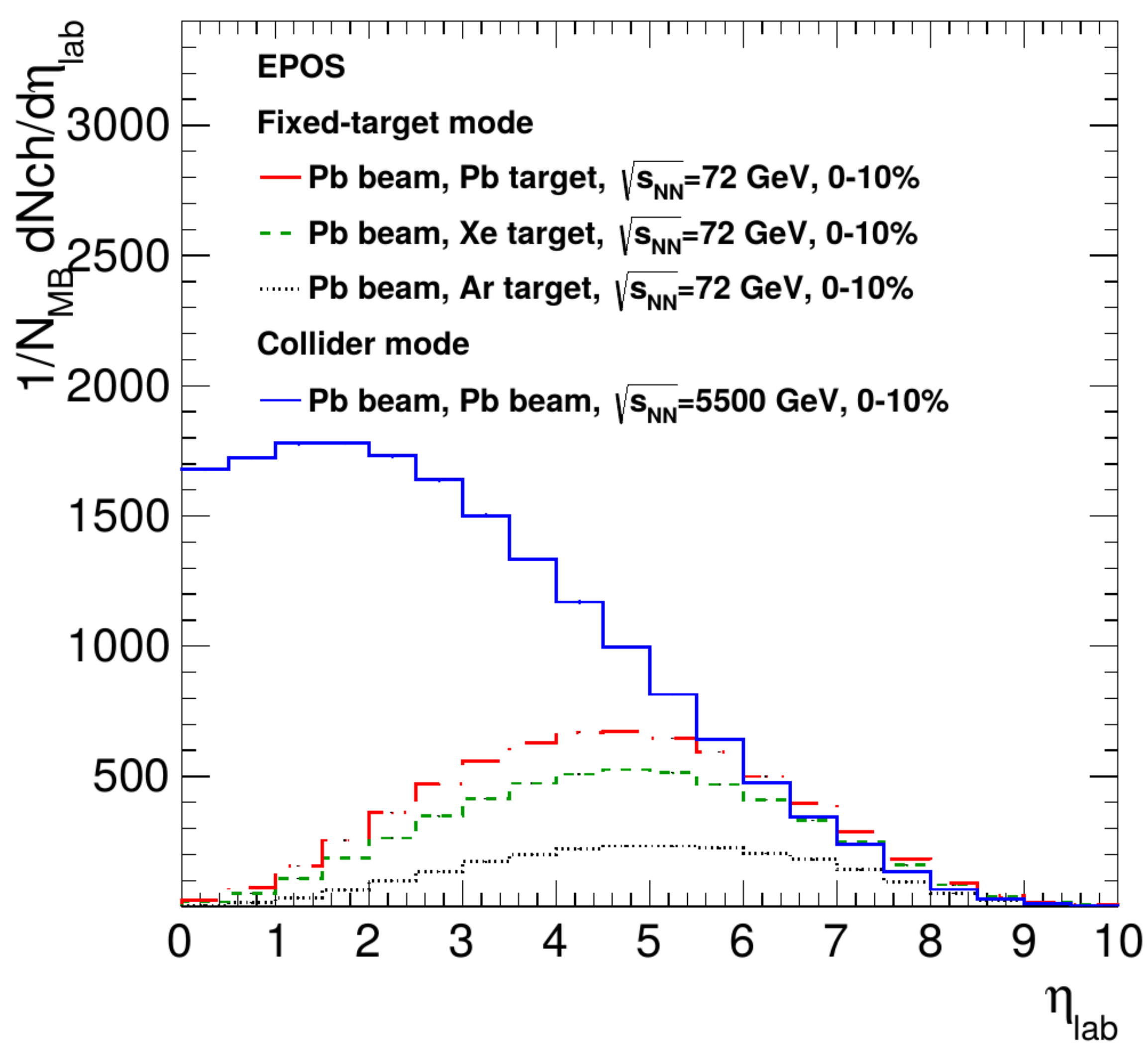
- Not covered here:
  - Azimuthal anisotropies
  - Photon related observable
  - $W^{+/-}$ boson
  - Other quarkonia, C-even
  - HF pairs, associated production
  - Ultra-peripheral collisions



Charge particle multiplicities in a fixed target mode

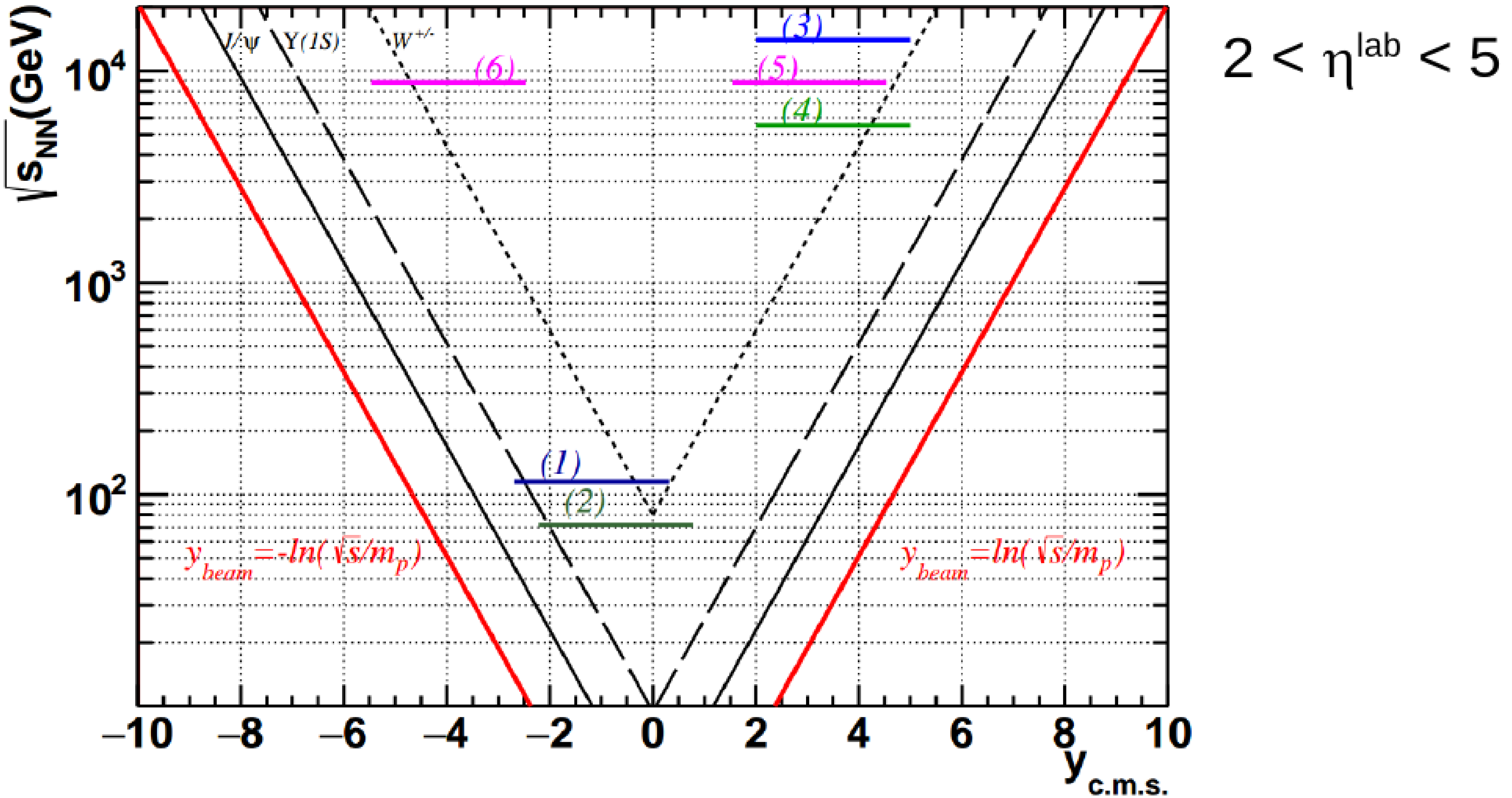
Advances in High Energy Physics, Volume 2015 (2015), Article ID 986348





- ✓ Charge particle multiplicities, for all possible fixed target modes, p+Pb, Pb+H, Pb+Pb, are smaller than the ones reached in the collider modes. A detector with the LHCb capabilities is able to reconstruct all event centralities up to Pb-Ar.

Acceptance for LHCb-like detector



(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

Nota: similar for the ALICE spectrometer

Projection studies with full background

- **Di-muon simulations**
- Separate simulations to have under control input p_T and y distributions and normalization of different sources

➔ **Input:**

✓ **Signal:**

- ➔ Quarkonia: J/ψ, ψ', Υ
- ➔ Drell-Yan pairs: $q\bar{q} \rightarrow \gamma^{\star}/Z \rightarrow \mu^+\mu^-$

✓ **Background sources:**

- ➔ Correlated background:

  $c+\bar{c} \rightarrow D^+ + D^- \rightarrow l^+l^-$

  $b+\bar{b} \rightarrow B^+ + B^- \rightarrow l^+l^-$

- ➔ Uncorrelated background:

  μ mostly from π/K decay

HELAC-Onia
(LO generator)
Les Houches Event Files

PYTHIA 8

p-p simulation

hadronisation, initial/final radiations, and resonance decays

PYTHIA 8

full minimum-bias Pythia 8 simulation

Fast simulation

- ➔ Realistic detector resolution
- ➔ Particle identification

Advances in High Energy Physics, Volume 2015 (2015), Article ID 986348

Projection studies with full background

- **Di-muon simulations**

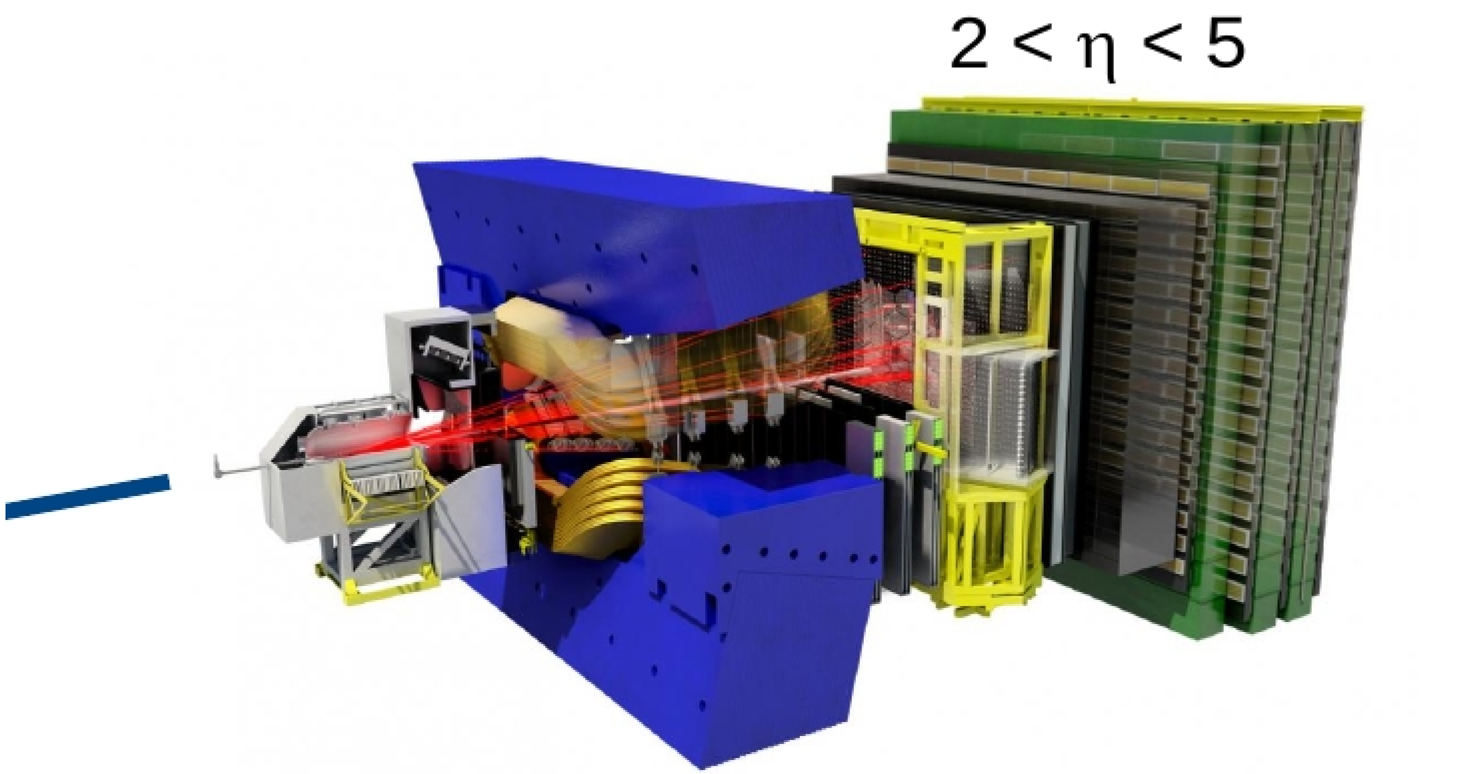
Fast simulation

- ➔ Realistic detector resolution
- ➔ Particle identification

LHCb-like detector setup

- ➔ momentum resolution: $\Delta p/p = 0.5\%$
- ➔ μ identification efficiency: 98%

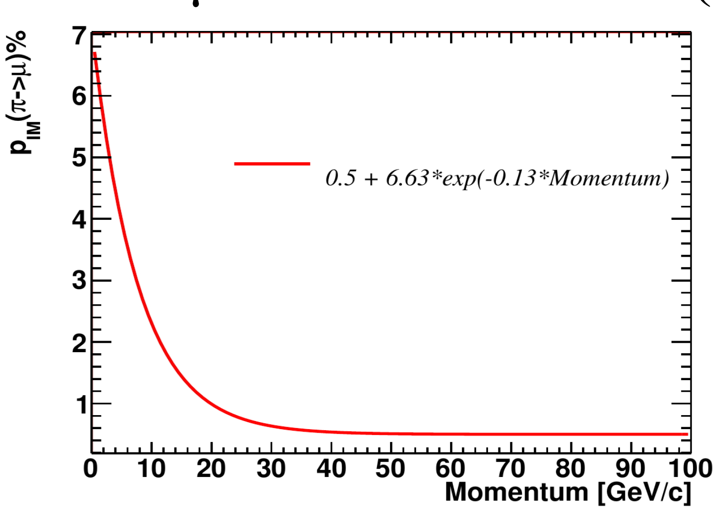
- Single μ cuts:
  - ➔ $\mathbf{2 < \eta_\mu^{lab} < 5}$
  - ➔ Minimum $p_T^\mu > 0.7$ GeV/c
  - ➔ μ misidentification (with π or K)

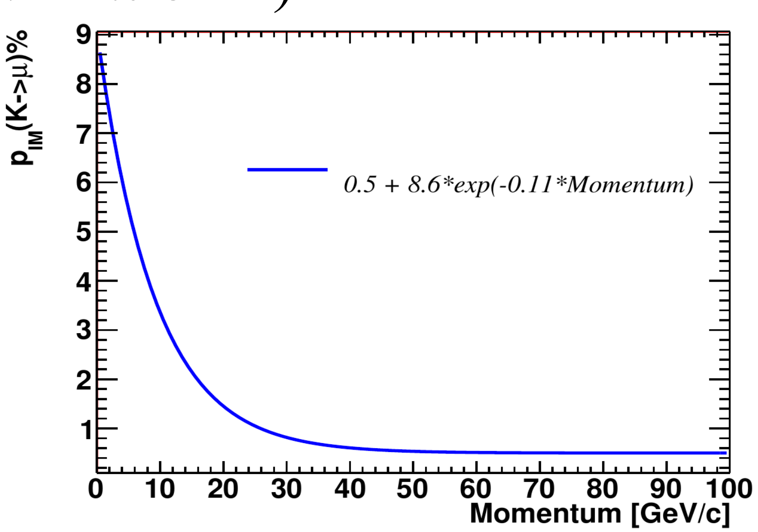


microvertexing, particle ID, μ ID, electromagnetic and hadonic cal.

HERMES-type target

- ➔ Polarisation: 80%





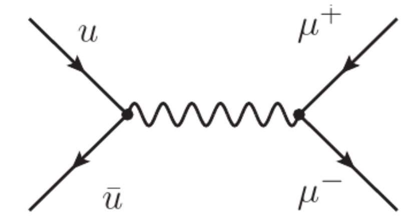
pA, AA studies:

- ➔ Nuclear scaling factor to pp cross-sections (accounting for a number of binary collisions)
- ➔ $R_{pA,AA} = 1$ – absence of hot/cold nuclear and isospin effects

F. Achilli et al, JINST 8 (2013) P10020
arXiv:1306.0249

Advances in High Energy Physics, Volume 2015 (2015), Article ID 986348

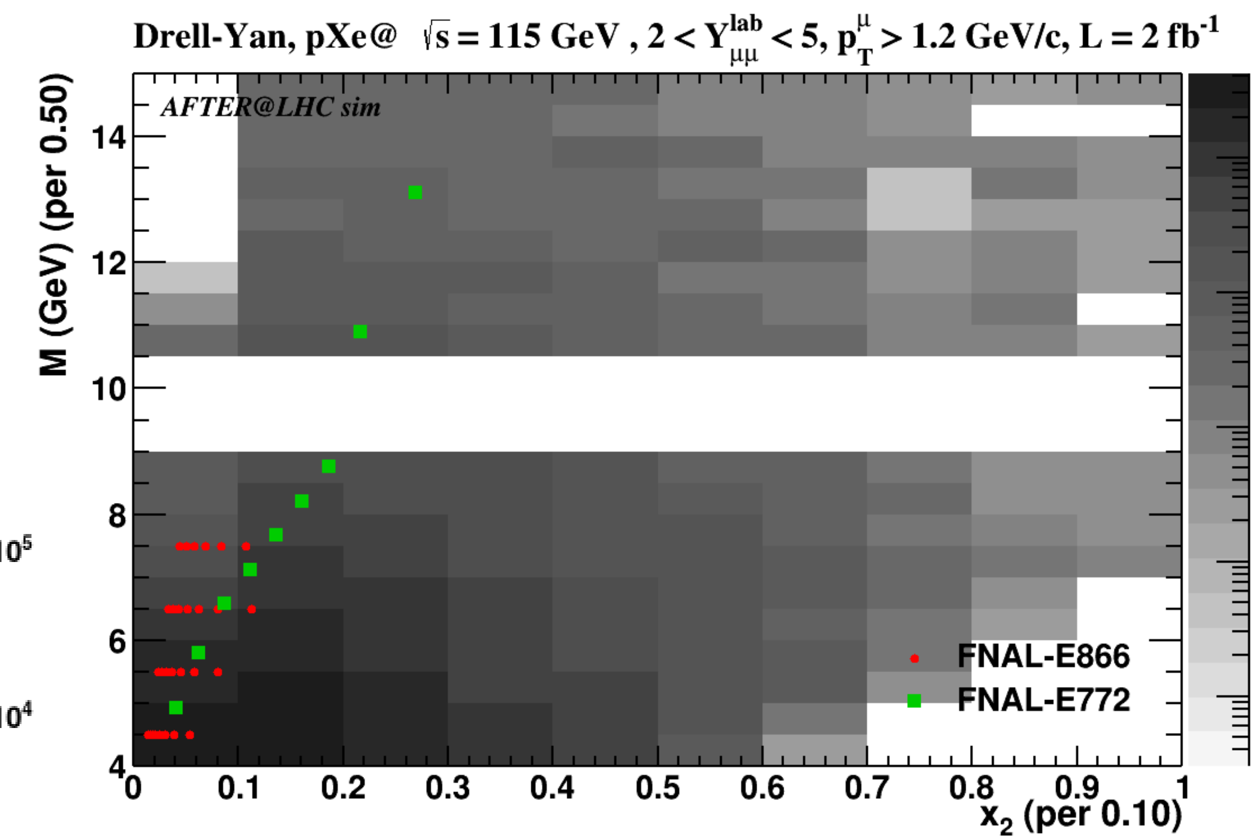
Drell-Yan simulations



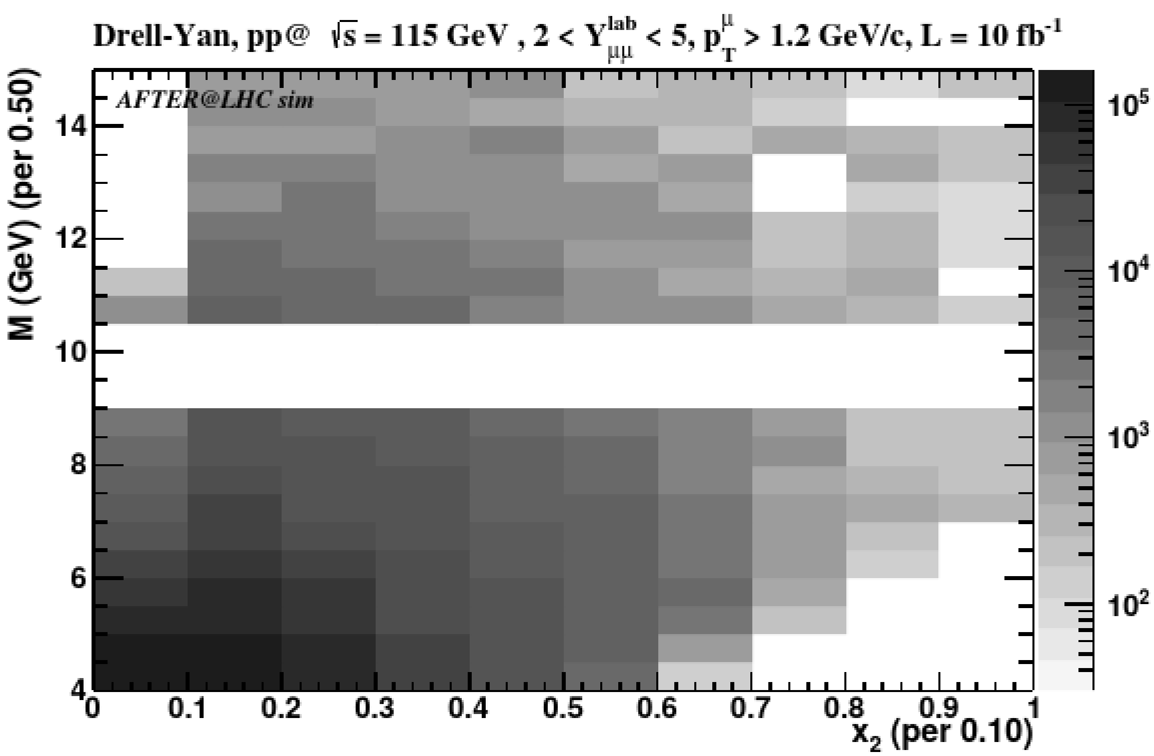
- **Unique acceptance** (with a LHCb-like detector) compared to existing Drell-Yan pA data used for nuclear PDF fits (E866 and E772 @ Fermilab)
- Projection for a Hermes like target

→ **Extremely large yields** up to $x_2 \rightarrow 1$

→ Unique coverage towards large x in pA, **the same acceptance for *pp* collisions**

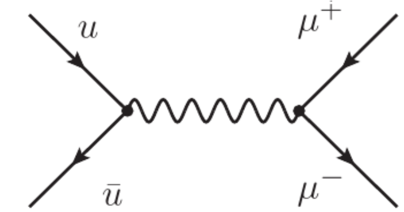


p+Xe 115 GeV



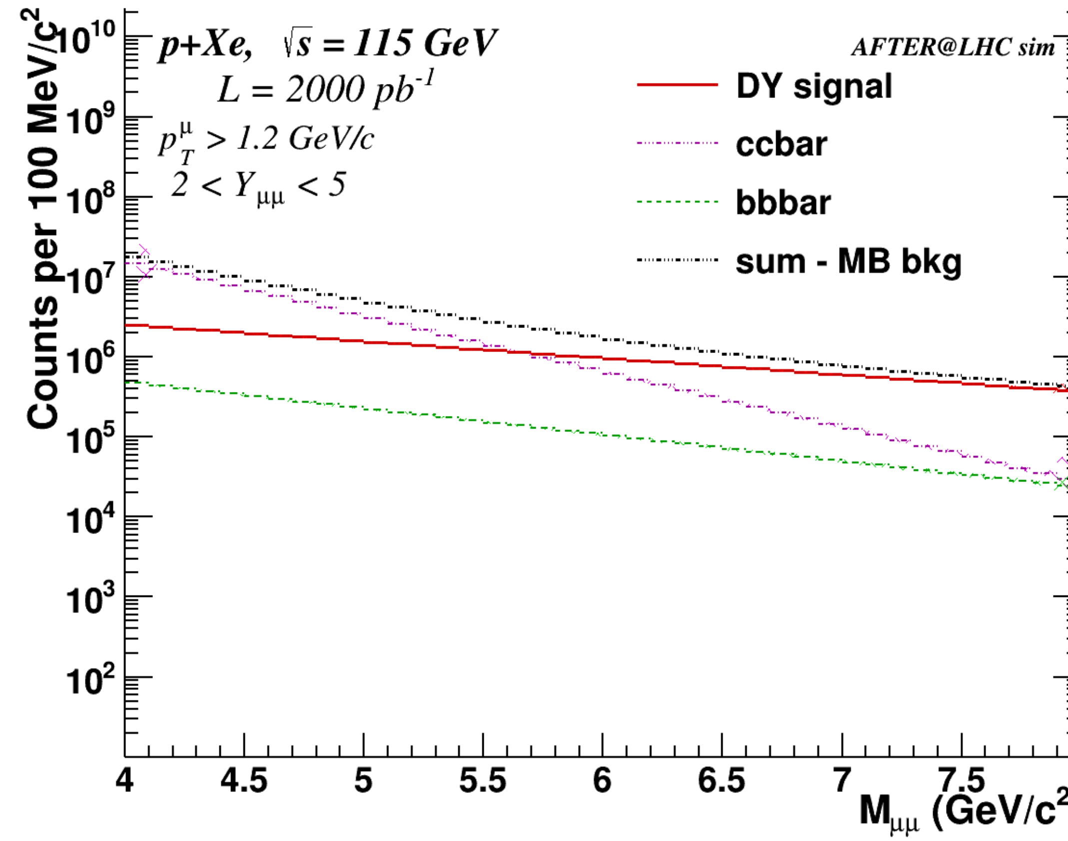
p+p 115 GeV

Drell-Yan simulations with full background

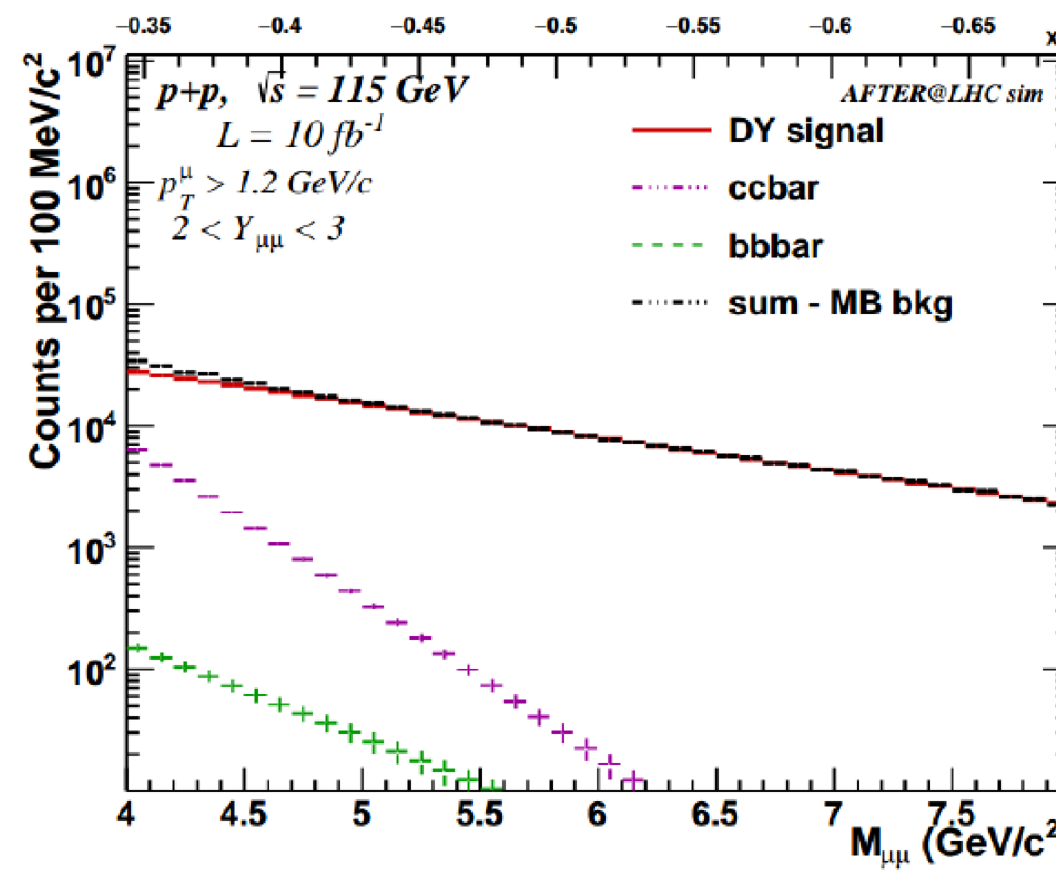


- Charm and beauty backgrounds can be reduced (a secondary vertex cut),
  however interesting on their own
- Combinatorial background under control
  - easily subtracted, one can refine with mixed-event technique (needed for PbA systems)
- At **backward** rapidities **quark-induced processes are favoured**
  → background gets smaller

- No existing measurements at RHIC



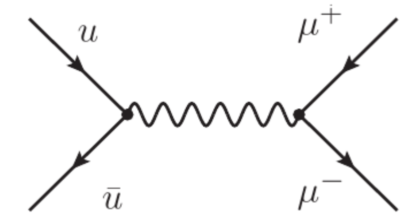
p+Xe 115 GeV



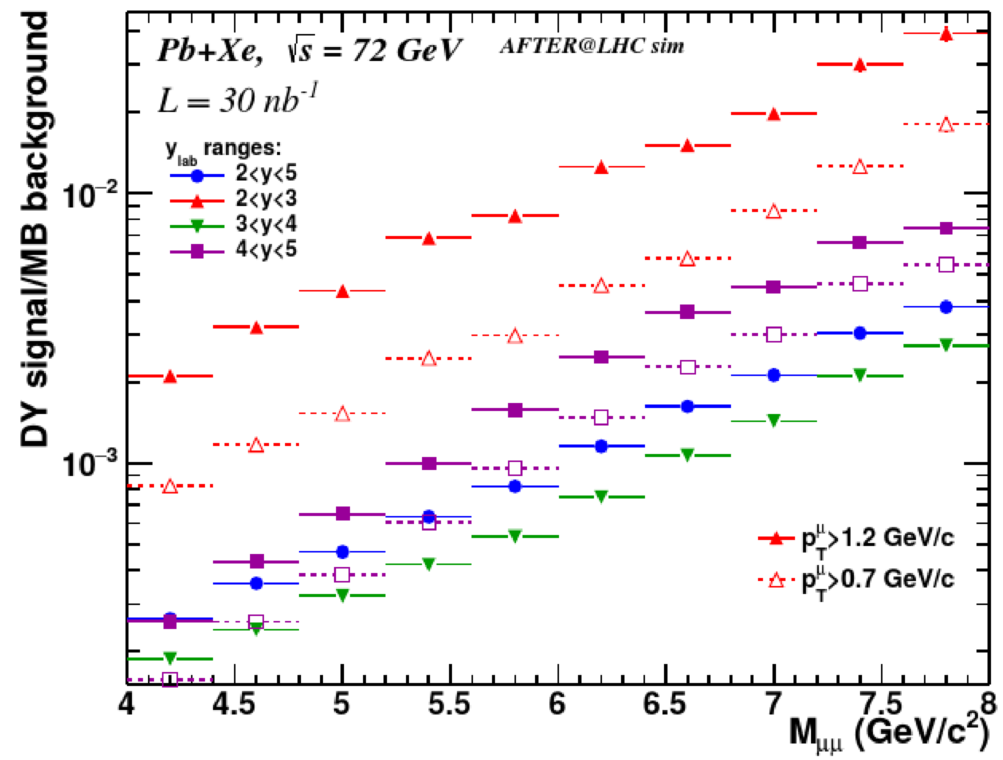
p+p 115 GeV

Combinatorial background subtracted with the like-sign method

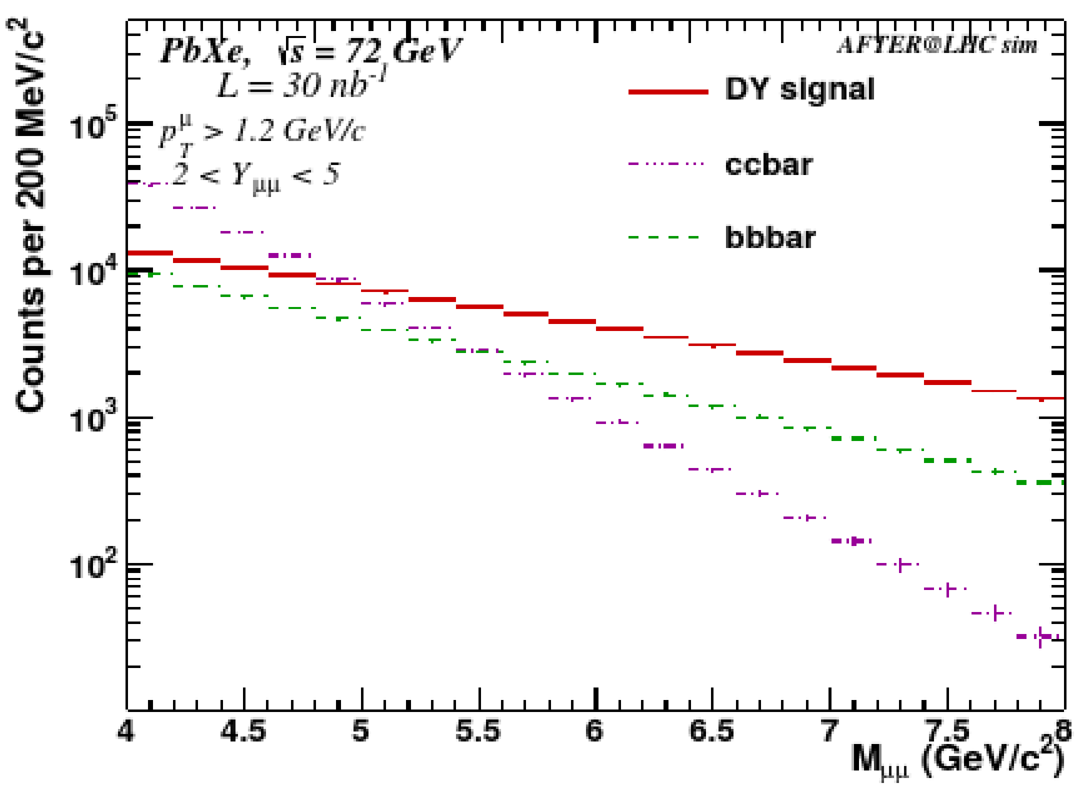
Drell-Yan simulations with full background

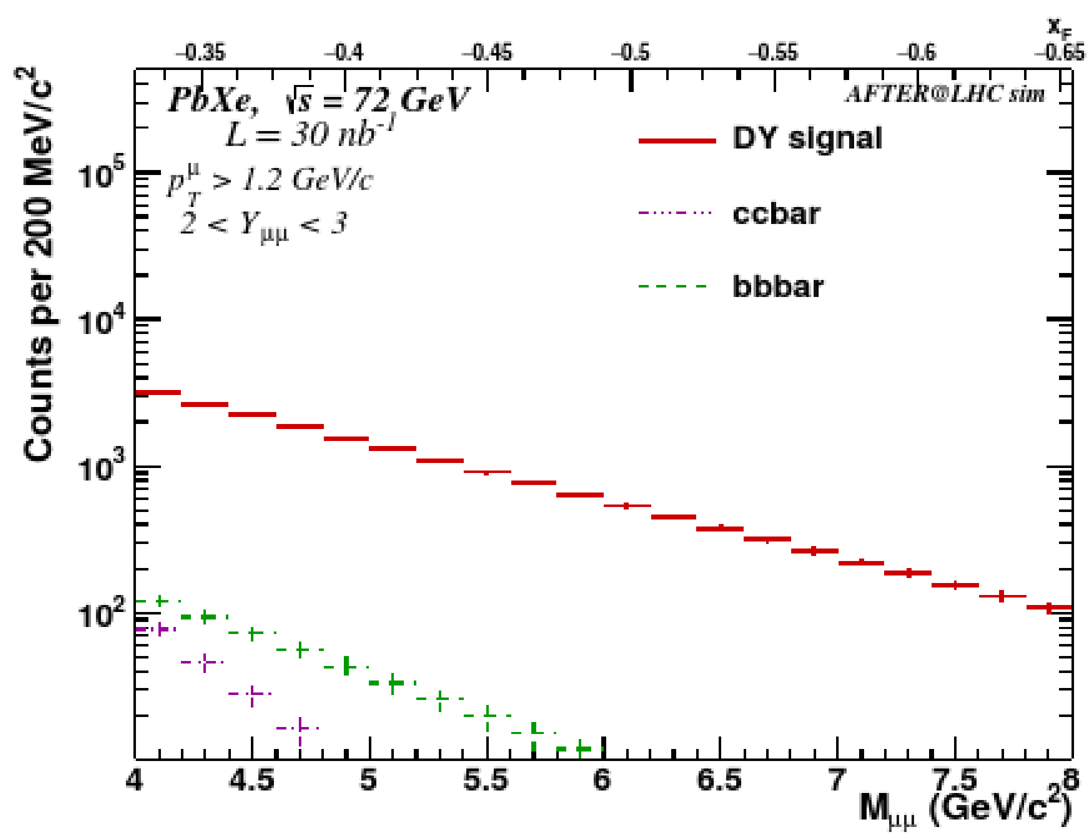


- Drell-Yan measurements also in **heavy-ion collisions**
- Reasonable combinatorial background (S/B)
  - Can be extracted with mixed-event technique
- At **backward** rapidities **quark-induced processes are favoured**



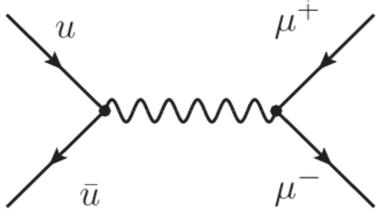
Pb+Xe 72 GeV





Uncertainties for the combinatorial background subtraction not taken into account

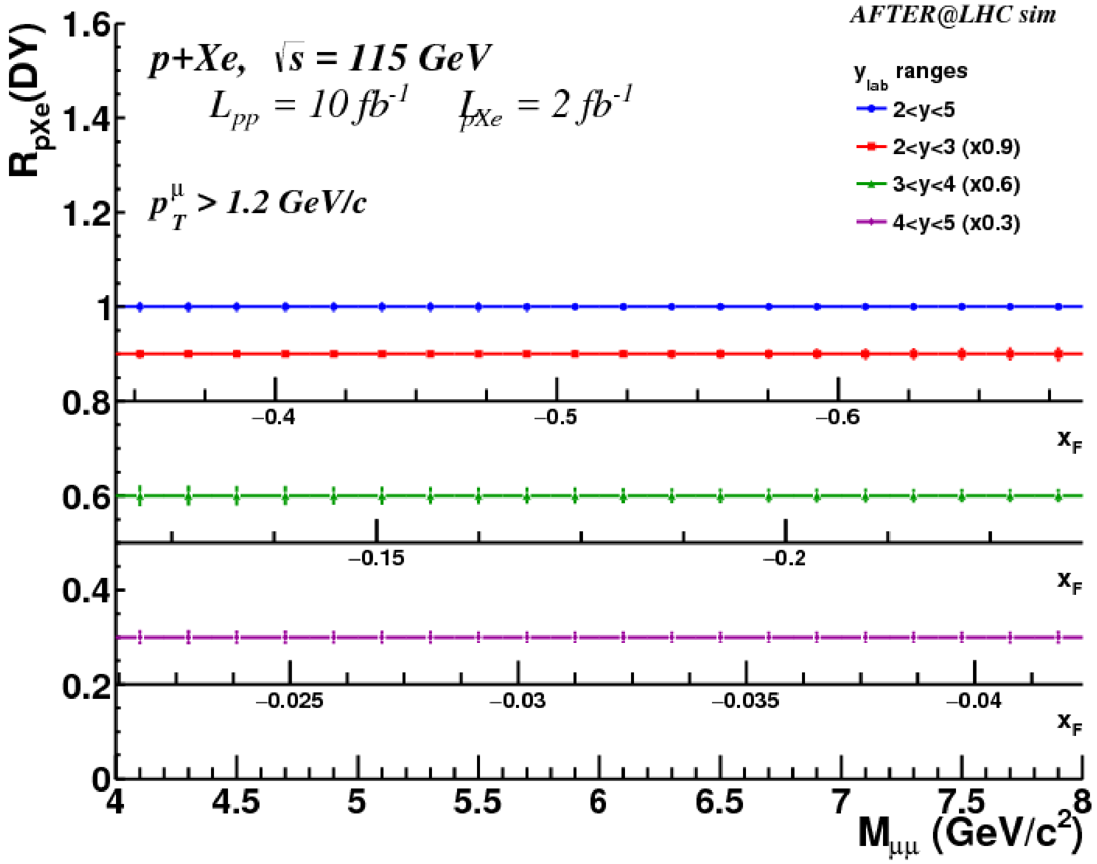
Drell-Yan projections



■ Nuclear Modification Factor

- Precise measurement of R_{pA}^{DY} up to high x_F

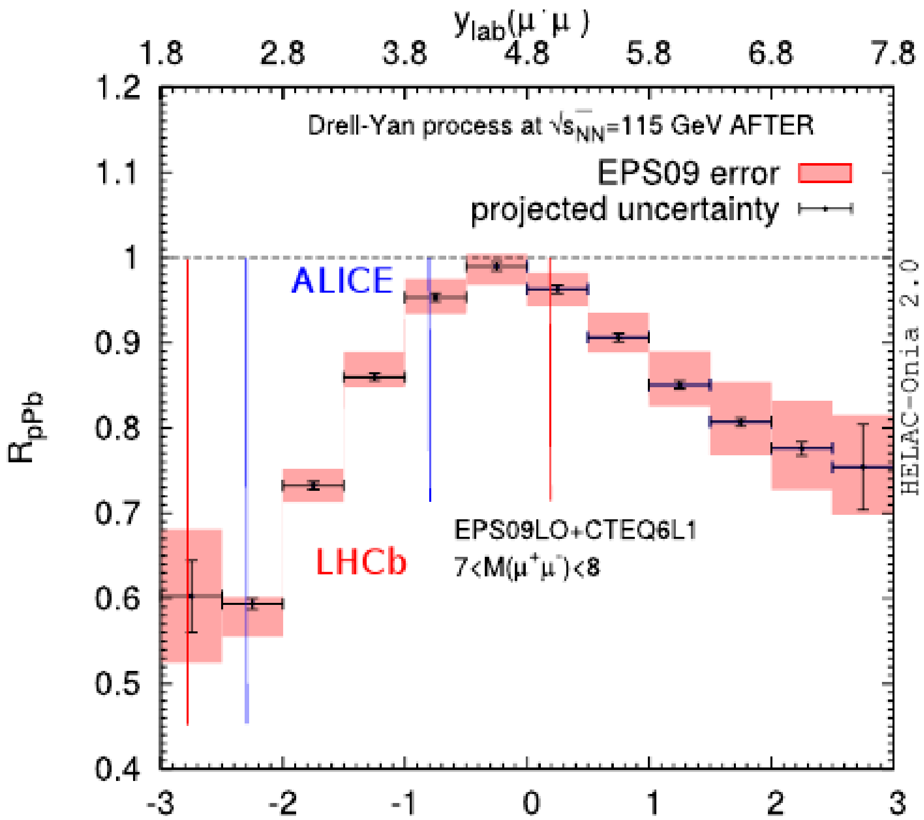
p+Xe 115 GeV



- Combinatorial background subtracted with the like-sign method

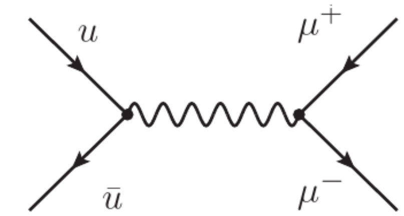
- Novel constraints on the quark nuclear PDF with DY in pA collisions

→ **Statistical uncertainties smaller than nPDF uncertainties** – good discrimination power



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

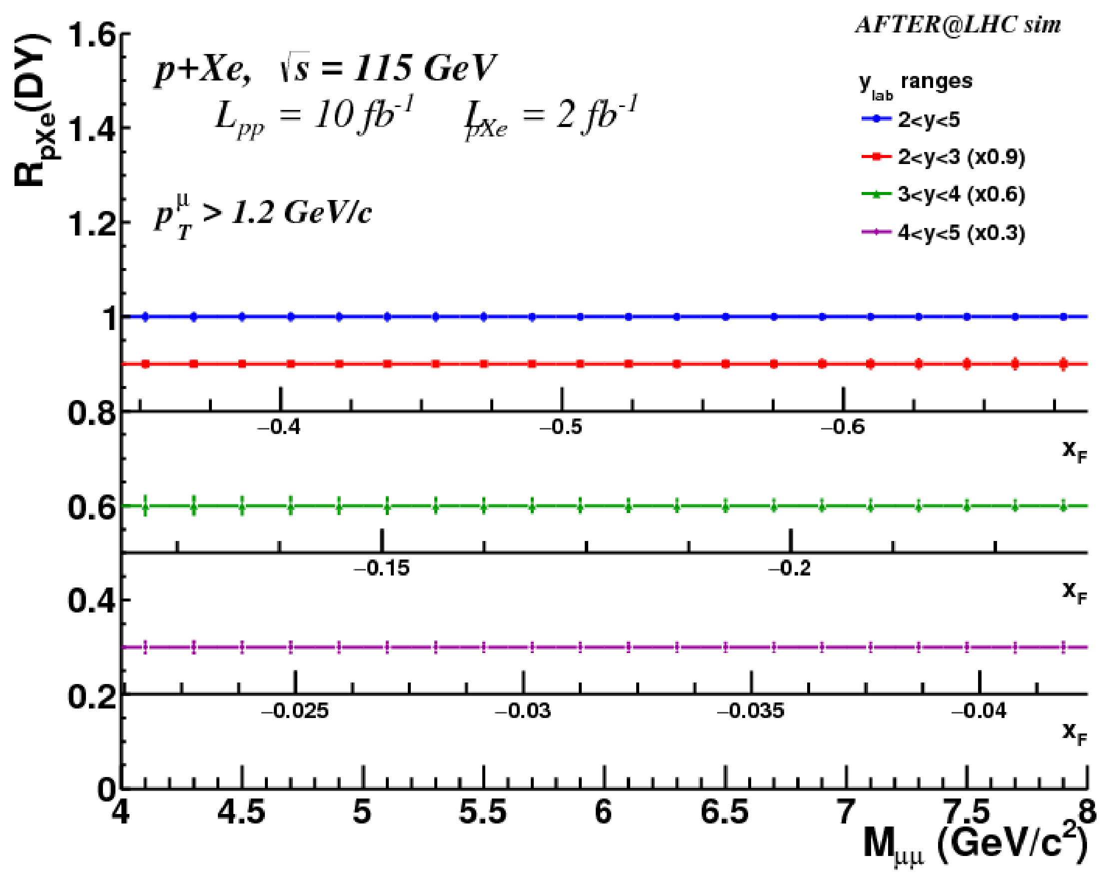
Drell-Yan projections



■ Nuclear Modification Factor

- Precise measurement of R_{pA}^{DY} up to high x_F – **nPDF constraints**

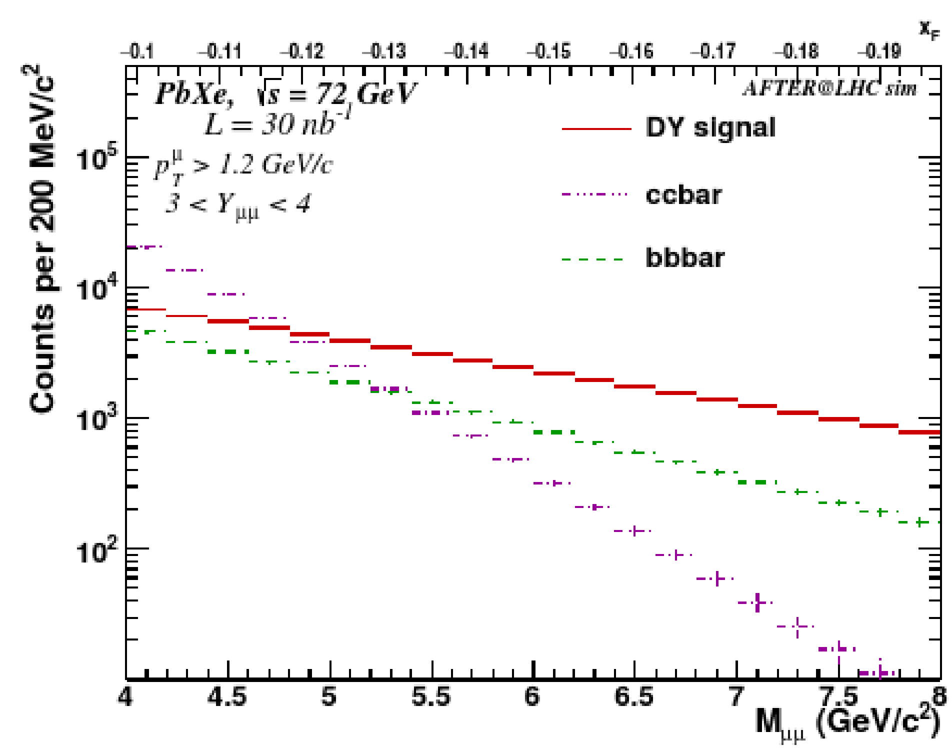
p+Xe 115 GeV



- Combinatorial background subtracted with the like-sign method

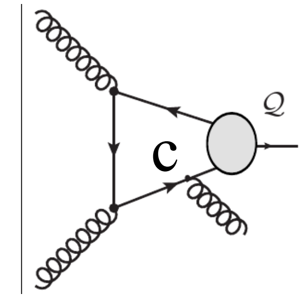
- Test of (linear) factorisation of initial-state effects in pA collisions to AA collisions
  - Electromagnetic probes, like Drell-Yan (produced from initial-state partons, immune to final-state effects)
  - Needs to be performed in a broad x_B range, where nuclear modifications are expected to be more significant in p-A

→ Precise measurements with AFTER@LHC – probe initial-state effects on quarks in different AA collisions



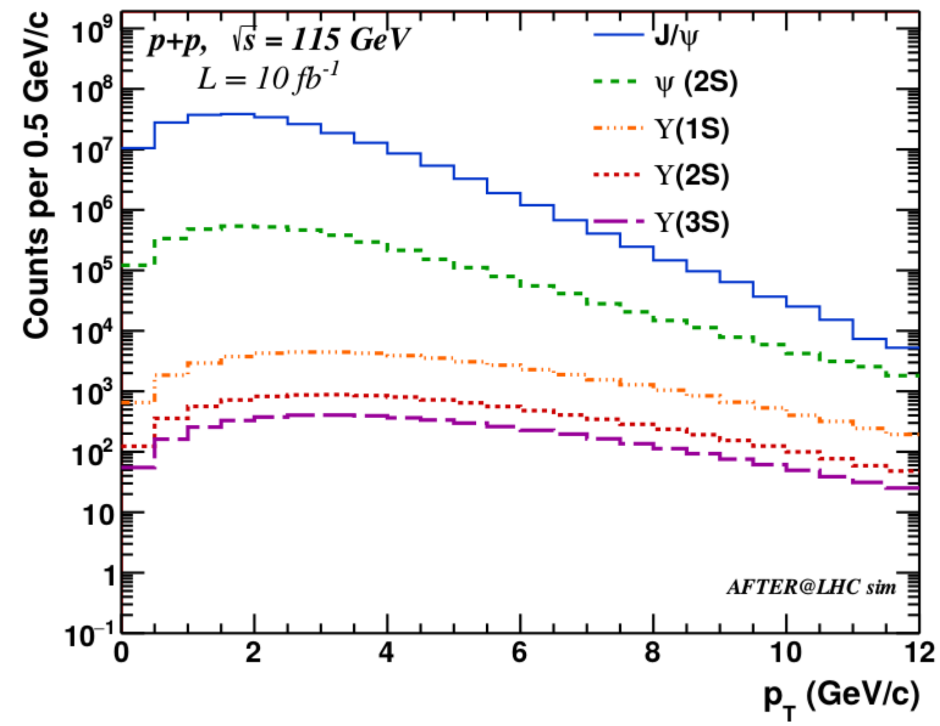
Pb+Xe 72 GeV

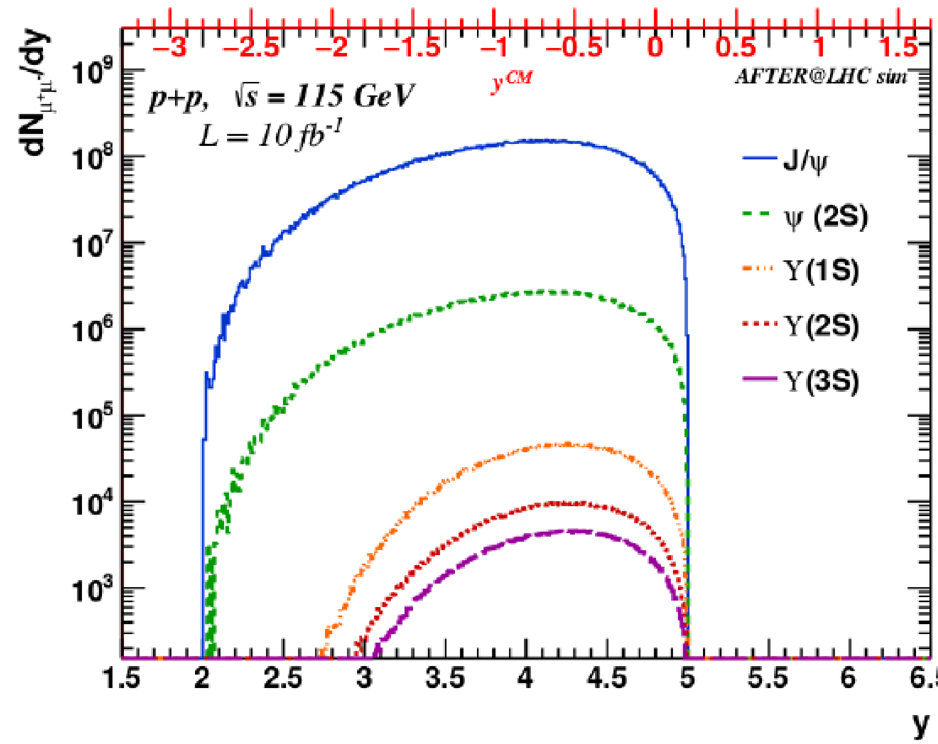
Quarkonium simulations with full background



- **Large yields of quarkonia**
  - J/ψ and ψ(2S) signals can be studies up to ~ 15 GeV/c, ϒ(nS) up to ~ 10 GeV/c
  - Down to 0 GeV/c
  - Similar p_T reach expected for pA
  - J/ψ / ψ(2S): 2 < y < 5
  - ϒ(nS) is ~ 2.5-3 < y < 5

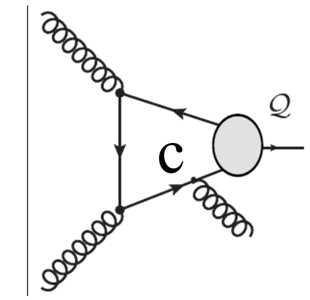
- **Aim is to measure a complete set of heavy-flavours to use them as tools** (gluon luminometers, TMDs, PDFs, nPDFs – QGP effects)
- Unique opportunity to access **C-even quarkonia + associated production**





p+p 115 GeV

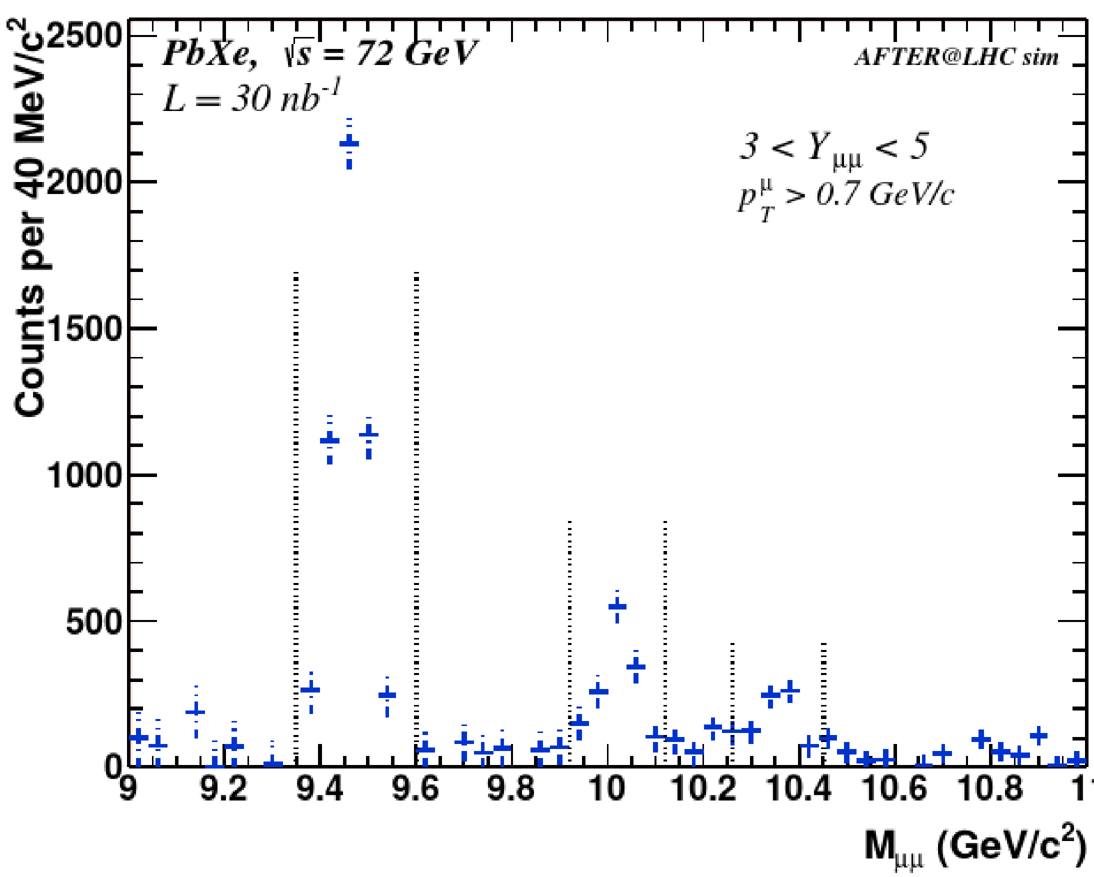
Quarkonium simulations with full background - heavy-ion collisions

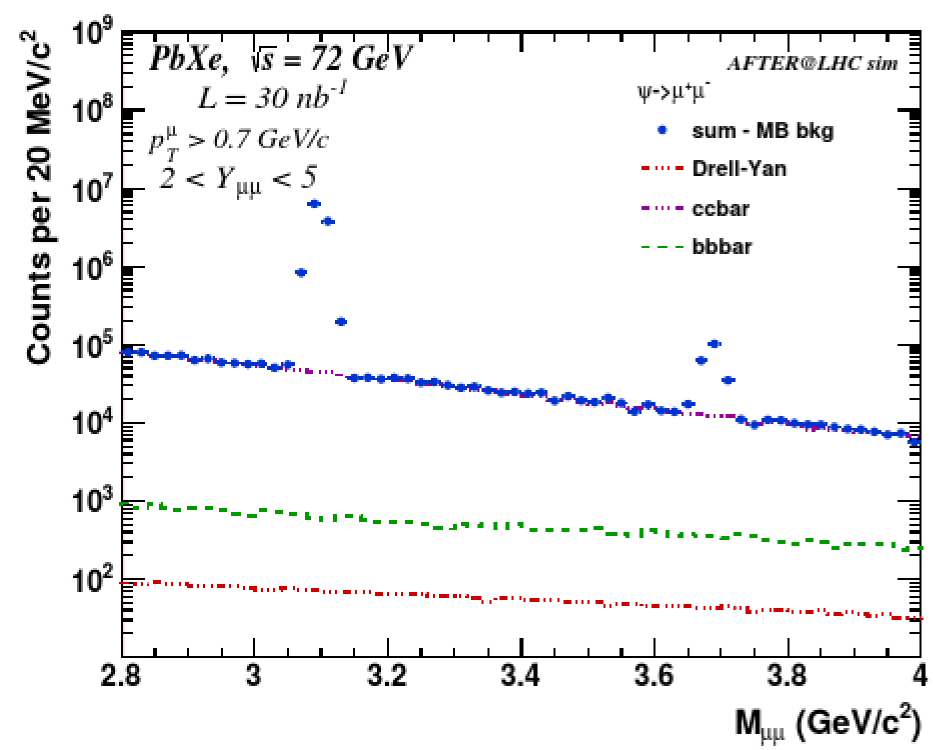


- **Large yields of quarkonia**
  - First simulations for PbXe at 72 GeV with the full background, and baseline pp, pA collisions at 72 GeV
  - Good handle on the background
  - **Good separation of different Upsilon states**

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

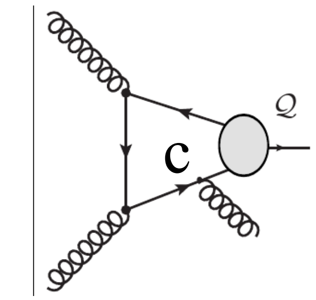
Pb+Xe 72 GeV





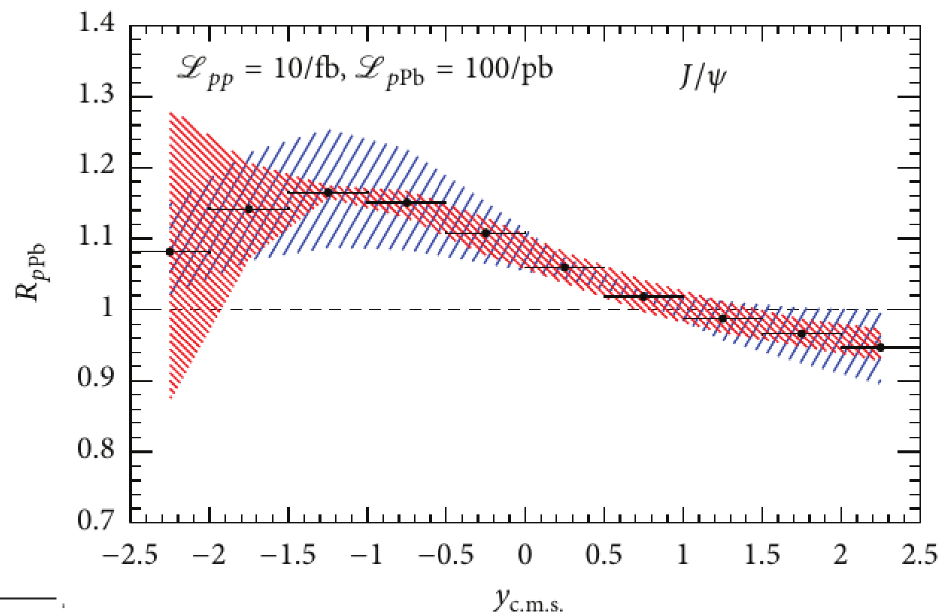
- No nuclear effects assumed
- Combinatorial background subtracted with the like-sign method

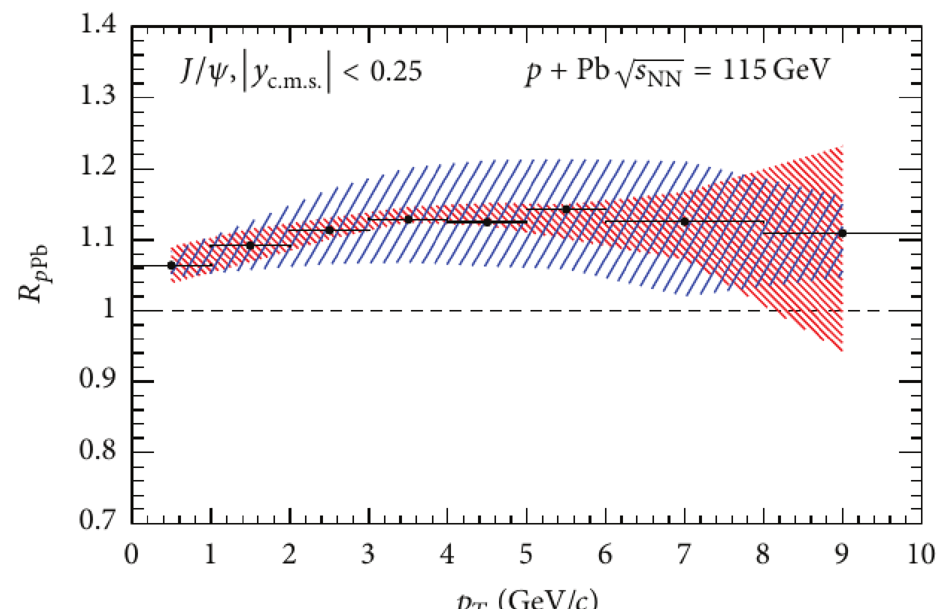
Quarkonium projections



- **Nuclear Modification Factor**

  Combination of measurements of $\Upsilon(nS)$, J/ψ and ψ(2S) for $-3 < y_{CMS} < 0$ will allow to pin down **the gluon EMC and antishadowing effect**

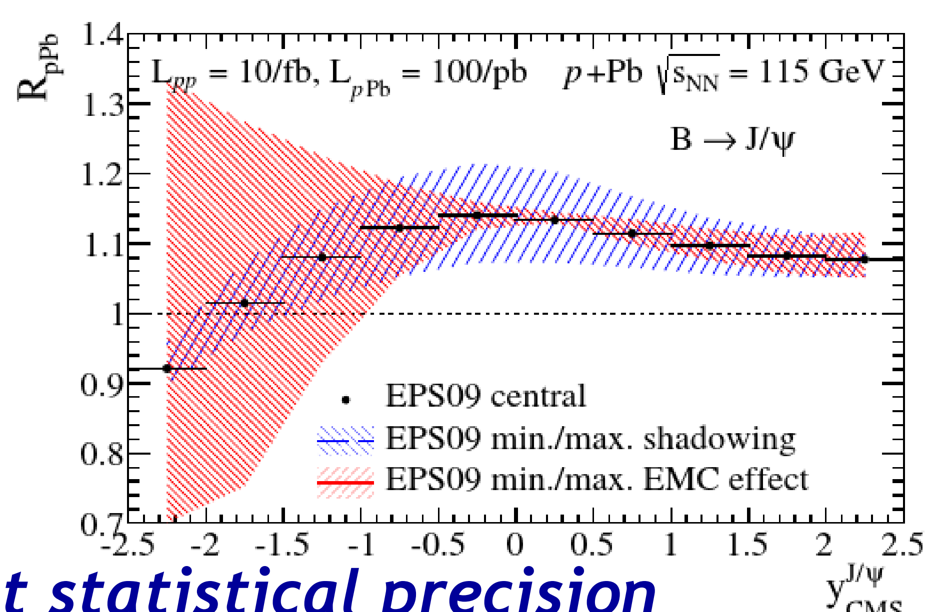


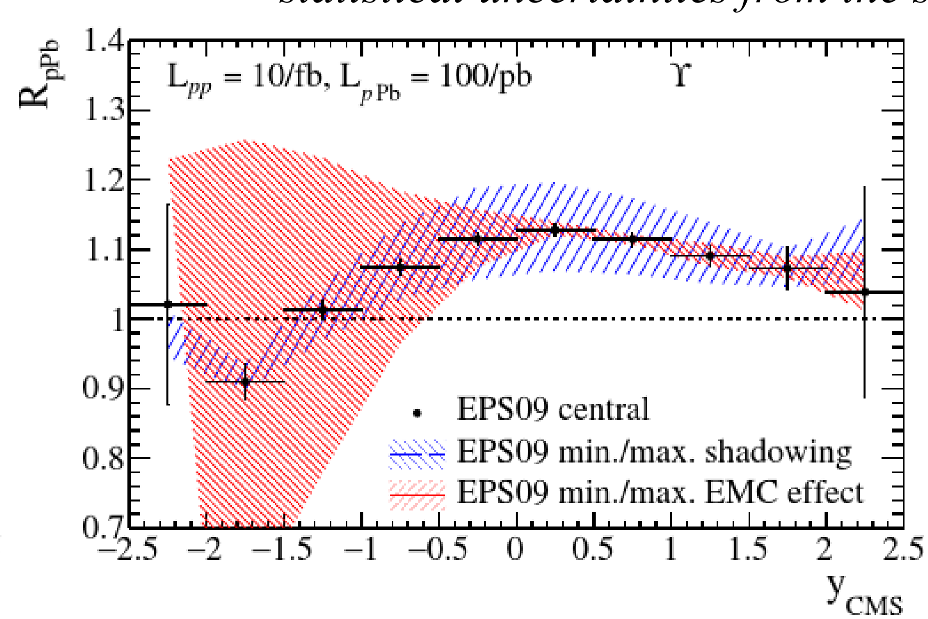


charm

$$R_{pA} = \frac{dN_{pA}}{\langle N_{coll}\rangle\, dN_{pp}}$$

statistical uncertainties from the signal yield only





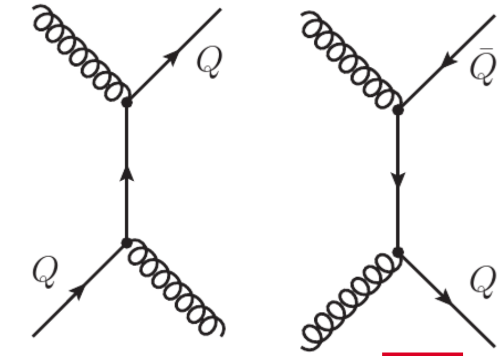
beauty

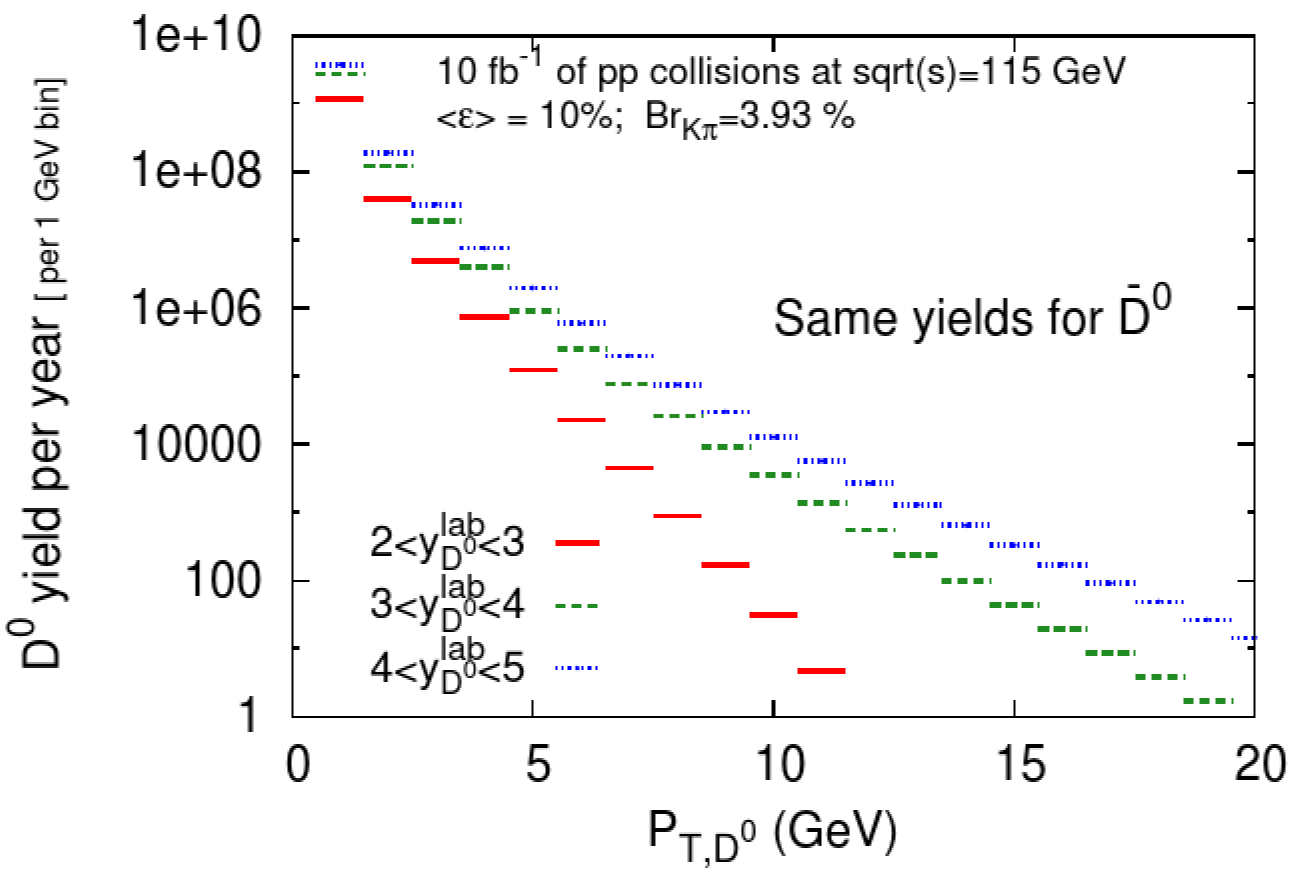
p+Pb 115 GeV

Excellent statistical precision

Open Heavy Flavour simulations

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





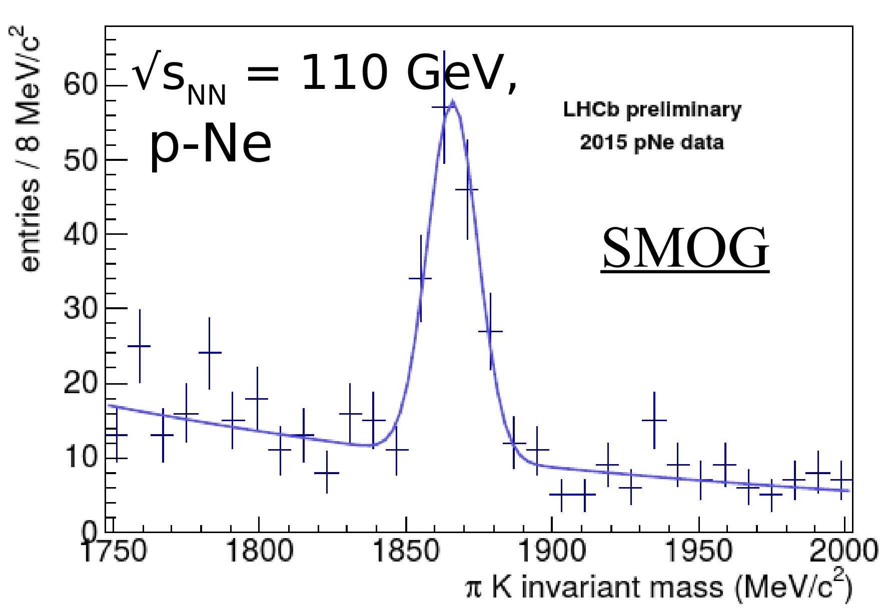
- Charm can easily be measured down to 0 p_T [total x-section]
- Over a wider rapidity coverage [$x_F \rightarrow -1$]

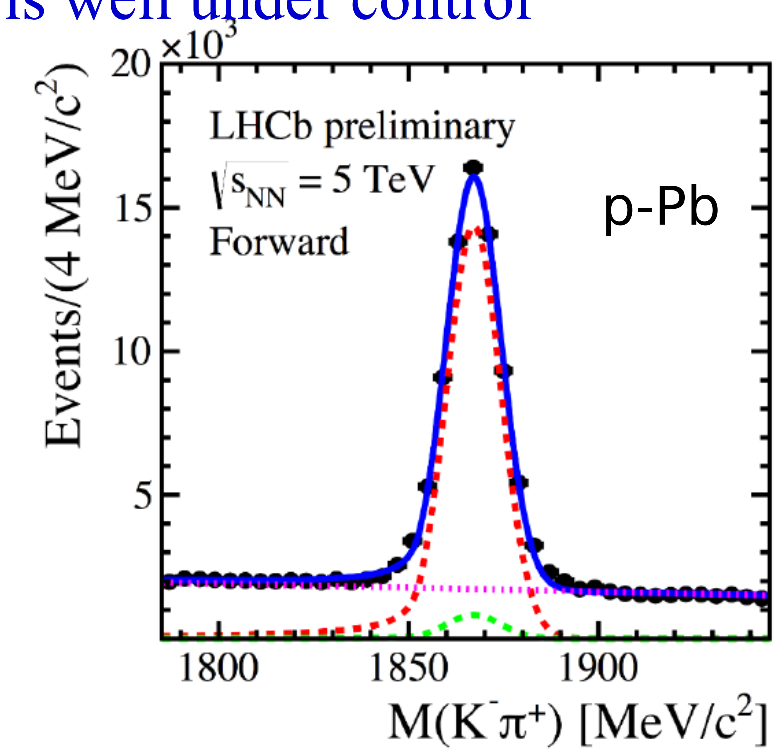
Extremely high statistical precision in pp, pA and AA collisions

- **Charm-anticharm asymmetry** accessible
- Unique handle on the **charm content in the proton at high x** - long standing debate: perturbative vs non-perturbative origin

p+p 115 GeV

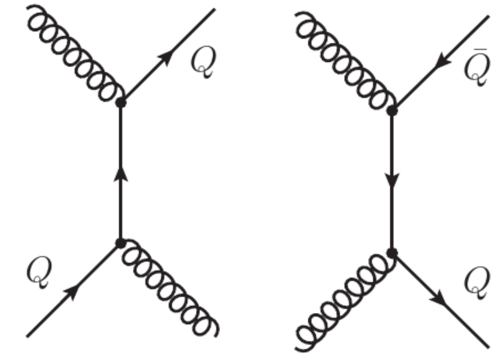
- With a LHCb-like detector the background is well under control





LHCb

Open heavy-flavour projections

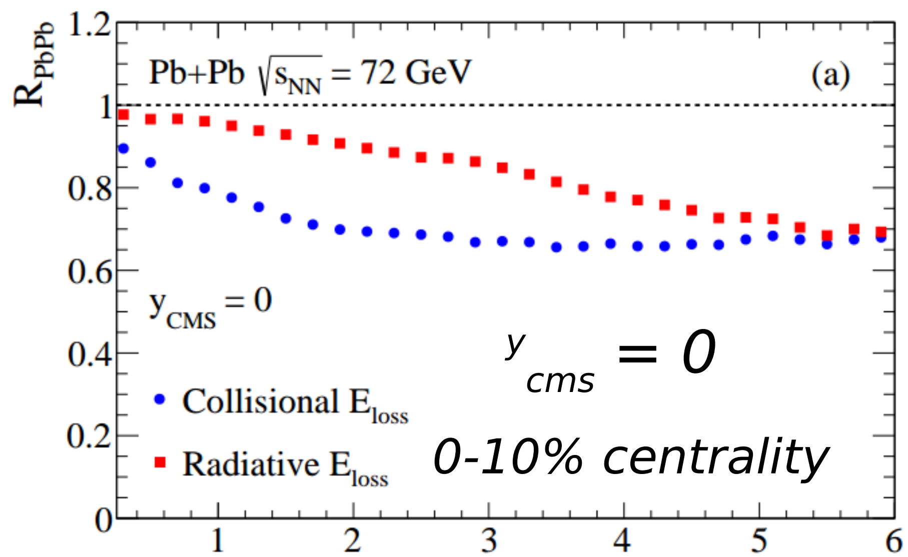


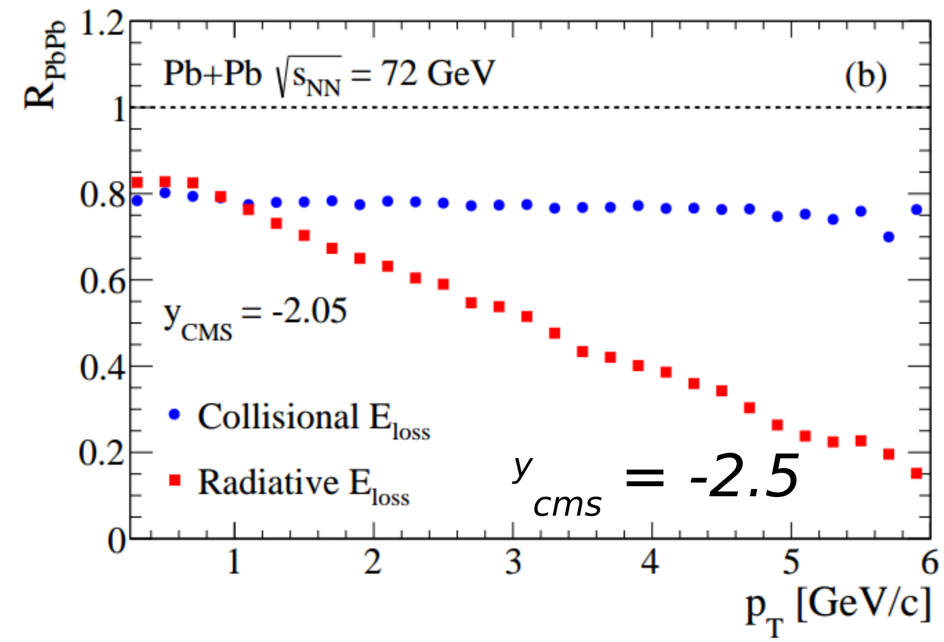
- Nuclear Modification Factor

What is the source of the heavy-quark energy loss ? **QGP properties**

R_{AA} vs y and p_T → *Collisional vs. radiative energy loss*

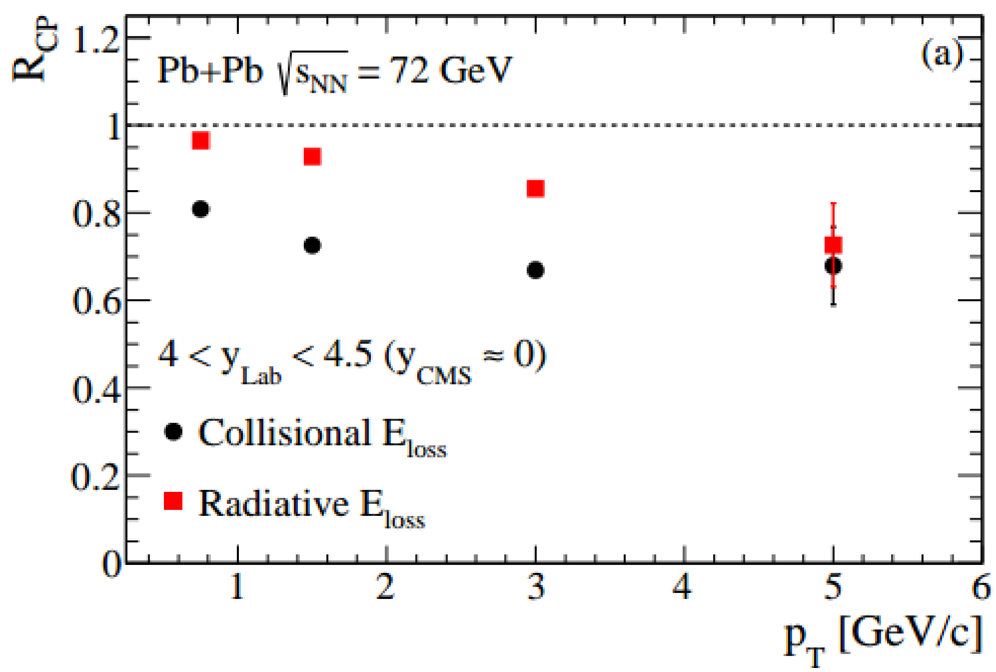
$D^0 \to K^- \pi^-$

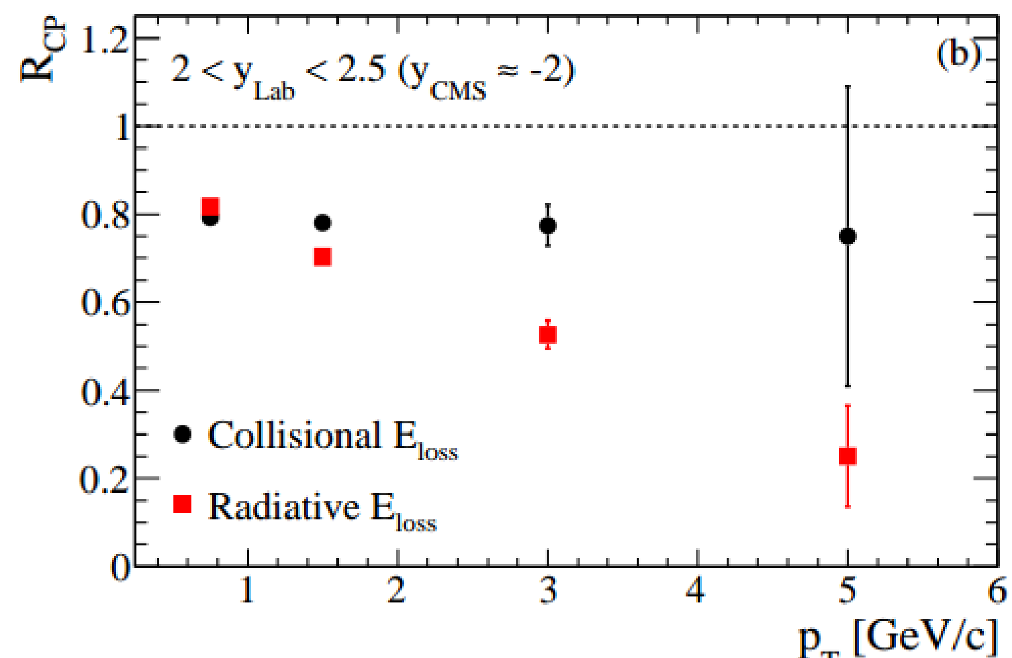




statistical uncertainties from the signal yield only

Pb+Pb 72 GeV



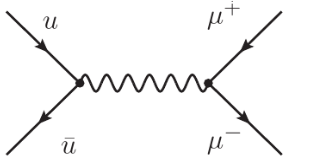


Excellent statistical precision, **also for azimuthal anisotropies (v_2) measurements**

Spin physics - projections

p+p 115 GeV

Single spin asymmetry (SSA)

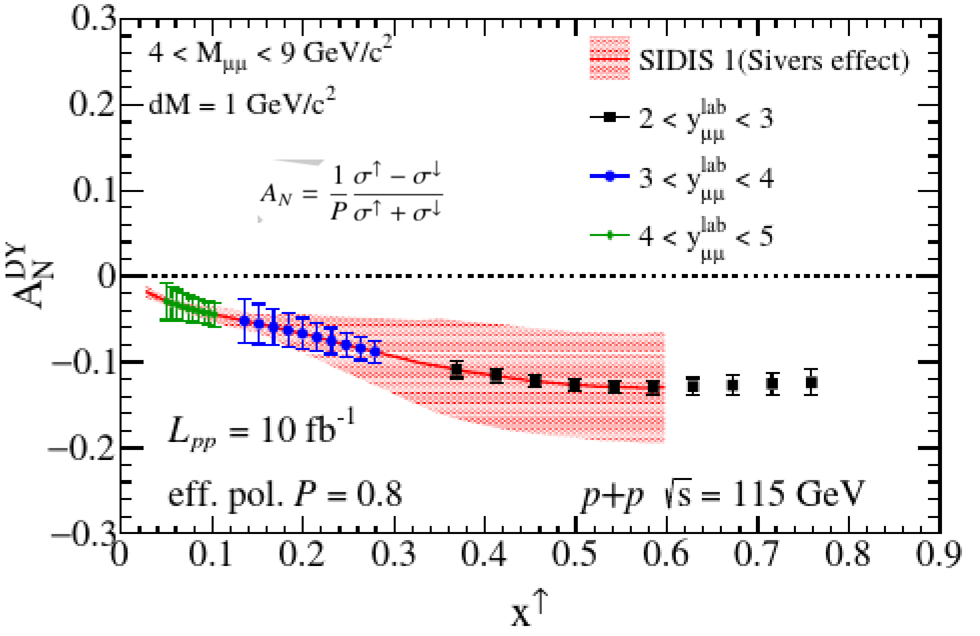


non-zero quark/gluon Sivers function → non-zero quark/gluon OAM

- **Drell-Yan SSA → Quark Sivers effect**

The target rapidity region ($x_F < 0$) corresponds to high $x^{\uparrow}$ ($x_F \rightarrow -1$) where the k_T - spin correlation is the largest

➔ **Precise measurements of A_N^{DY} at high x**



➔ DY pair production on a transversely polarised target of interest of many experiments

➔ Check the sign change in A_N DY vs SIDIS

➔ Process dependence predicted:

$$f_{1T}^{\perp,q}(x,k_{\perp}^2)_{\text{Drell-Yan}} = -f_{1T}^{\perp,q}(x,k_{\perp}^2)_{\text{Semi-Inclusive DIS}}$$

- *With a highly polarised gas target: from an exploration phase to a consolidation phase*

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

P – effective polarisation

STSA predictions for the AFTER@LHC kinematics:

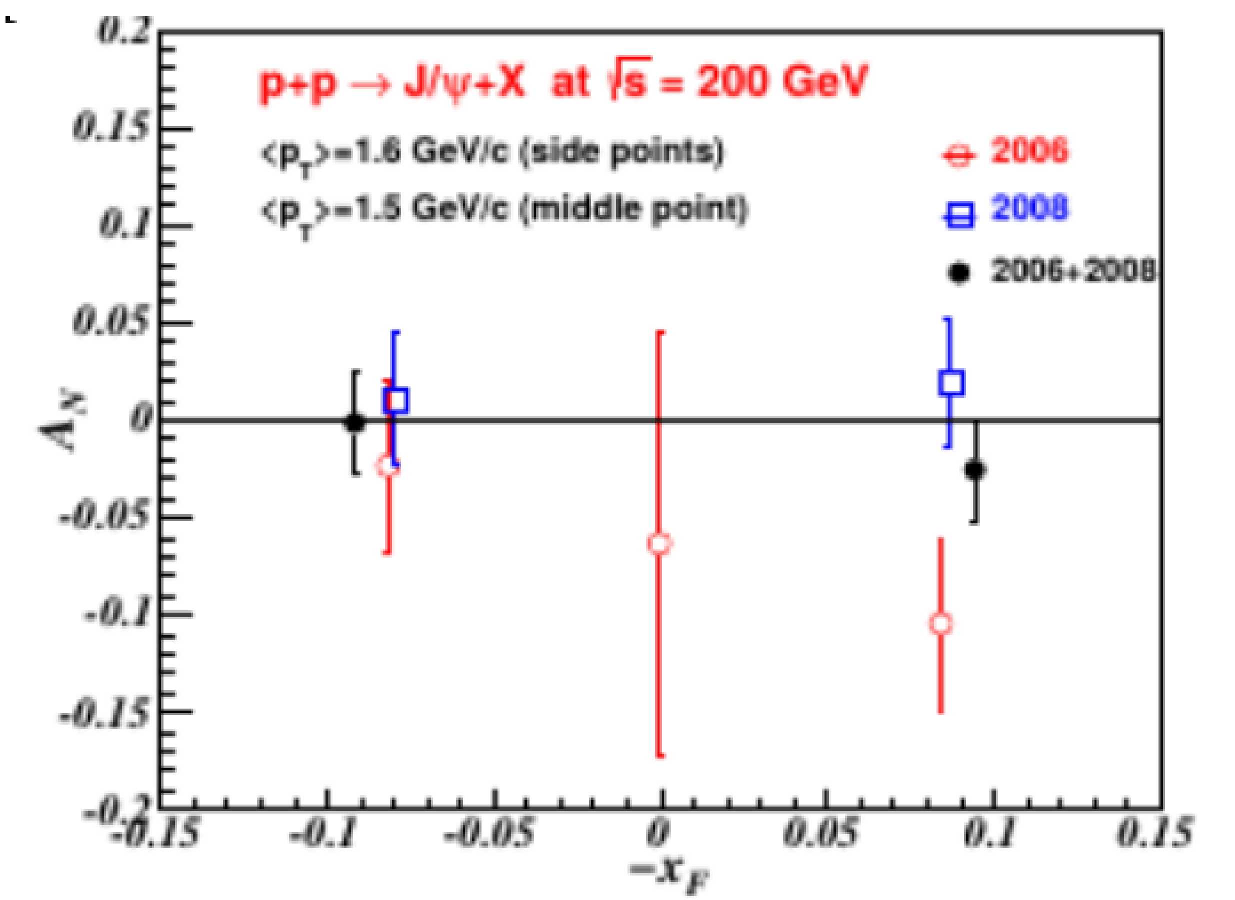
- M. Anselmino, U. D'Alesio, and S. Melis. Adv. Hi. En. Phys. (2015) 475040.
- K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak. Adv. Hi. En. Phys. (2015) 257934.
- T. Liu, B.Q. Ma. Eur. Phys. J. C72 (2012) 2037

Spin physics - projections

Single spin asymmetry (SSA)

- **Gluon Sivers effect essentially unconstrained**
  - ✔ Can be measured via A_N of gluon sensitive probes
  - ✔ Theoretical complication suggest to analyse multiple probes
    - ➔ quarkonia – J/ψ, ϒ, χ_c,, hc,…
    - ➔ B and D meson production
    - ➔ γ, γ–jet, γ–γ
    - ➔ J/ψ + γ–: the cleanest

✗ *Only existing measurement*



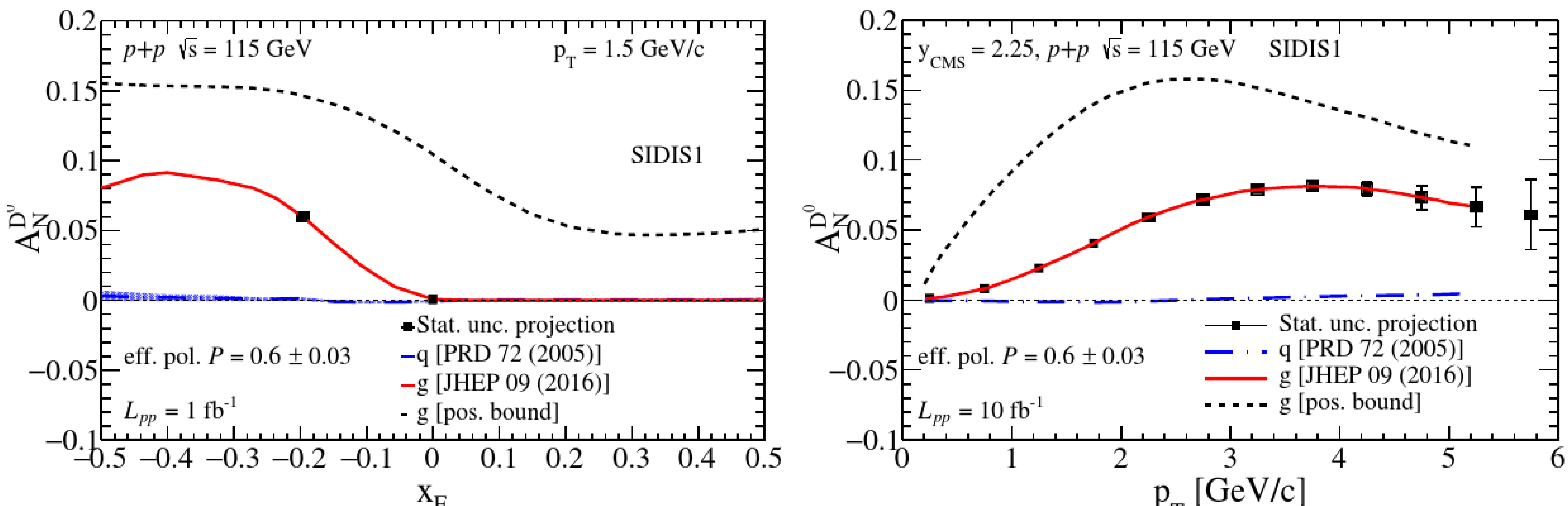
Spin physics - projections

p+p 115 GeV

Single spin asymmetry (SSA)

■ Open charm SSA → **Gluon Sivers effect and quark-gluon correlations**

- D^0 collected with a transversely polarised target [Never measured]
- Access to the tri-gluon correlation and (indirectly) the gluon Sivers effect (→ L_g)
  [First hint by COMPASS that $L_g \neq 0$, J. Phys.: Conf. Ser. 678 012055]
- Unique study: A_N of D^0 vs $\overline{D^0}$ → access to C-odd correlators
  [NPRD 78, 114013 (2008)]



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

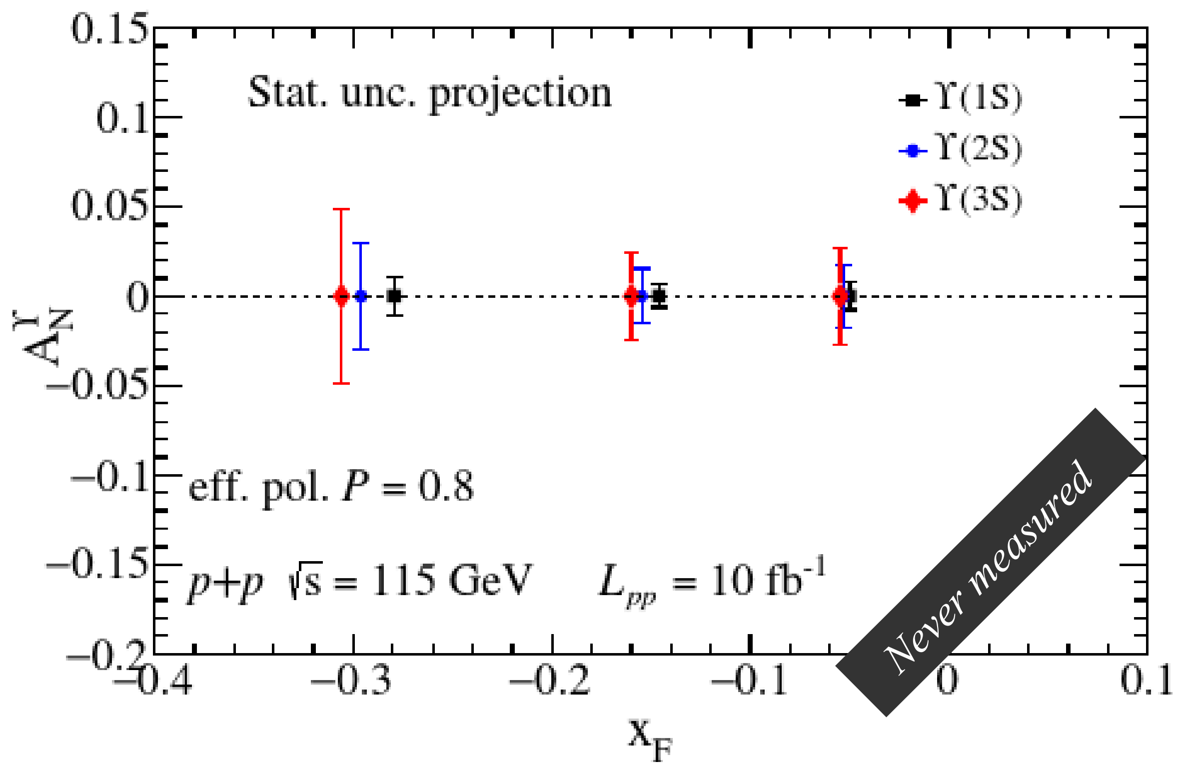
Excellent statistical precision at a per-cent level

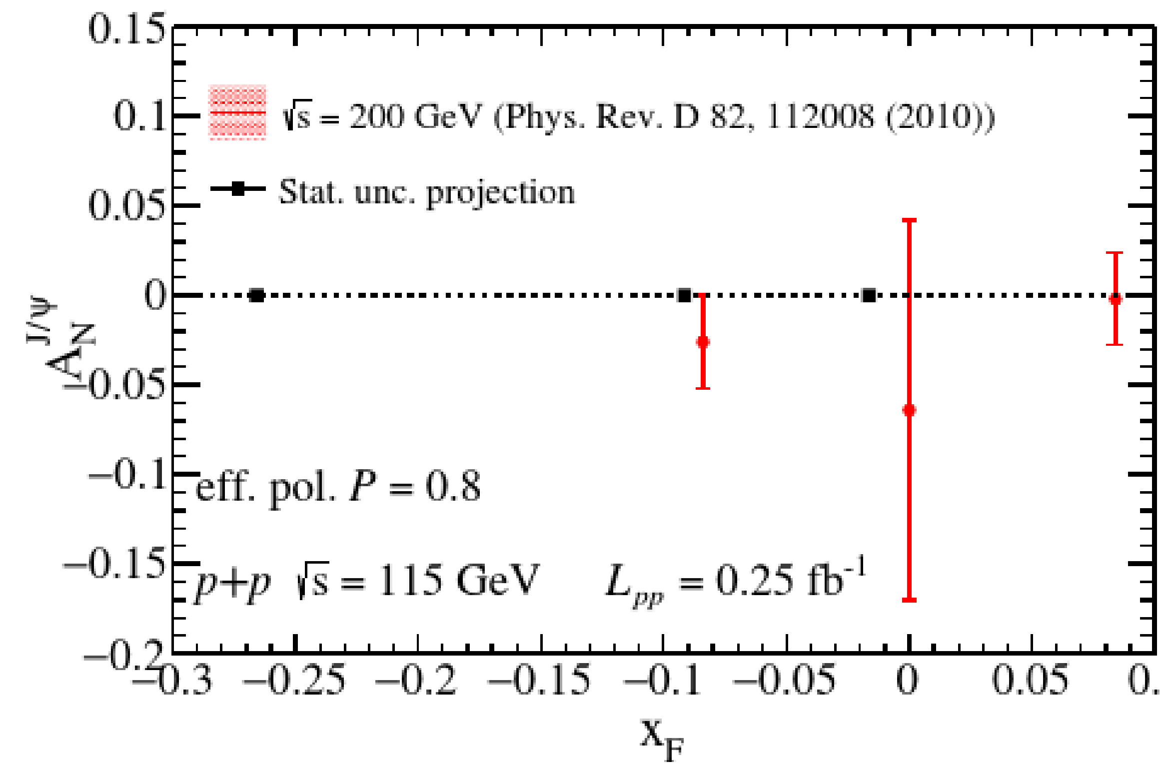
Spin physics - projections

p+p 115 GeV

Single spin asymmetry (SSA)

- Quarkonia SSA → **Gluon Sivers effect** (hint from COMPASS)





Excellent statistical precision

- A_N for all quarkonia can be measured with great precision
- Unique access to C-even quarkonia and associated production
- *Completely new perspective to study the gluon Sivers effect*

- Similar statistical precision with polarised ^{3}He target

Conclusions

AFTER@LHC is a proposal for a multi-purpose fixed target experiment using the multi-TeV proton and heavy ion beams of the LHC

- Three main subjects push for a fixed-target program at the LHC
  (no interference with other programs)
  - The high-x frontier: new probes of the confinement and connections with astroparticles
  - The nucleon spin and the transverse dynamics of the partons
  - The approach to the deconfinement phase transition: new energy, wide rapidity domain and new probes
- 2 ways towards fixed-target collisions with the LHC beams
  - A slow extraction with a bent crystal
  - An internal gas target inspired by SMOG@LHCb/Hermes/...
- New papers:

An Expression of Interest to be submitted to the LHCC is being written

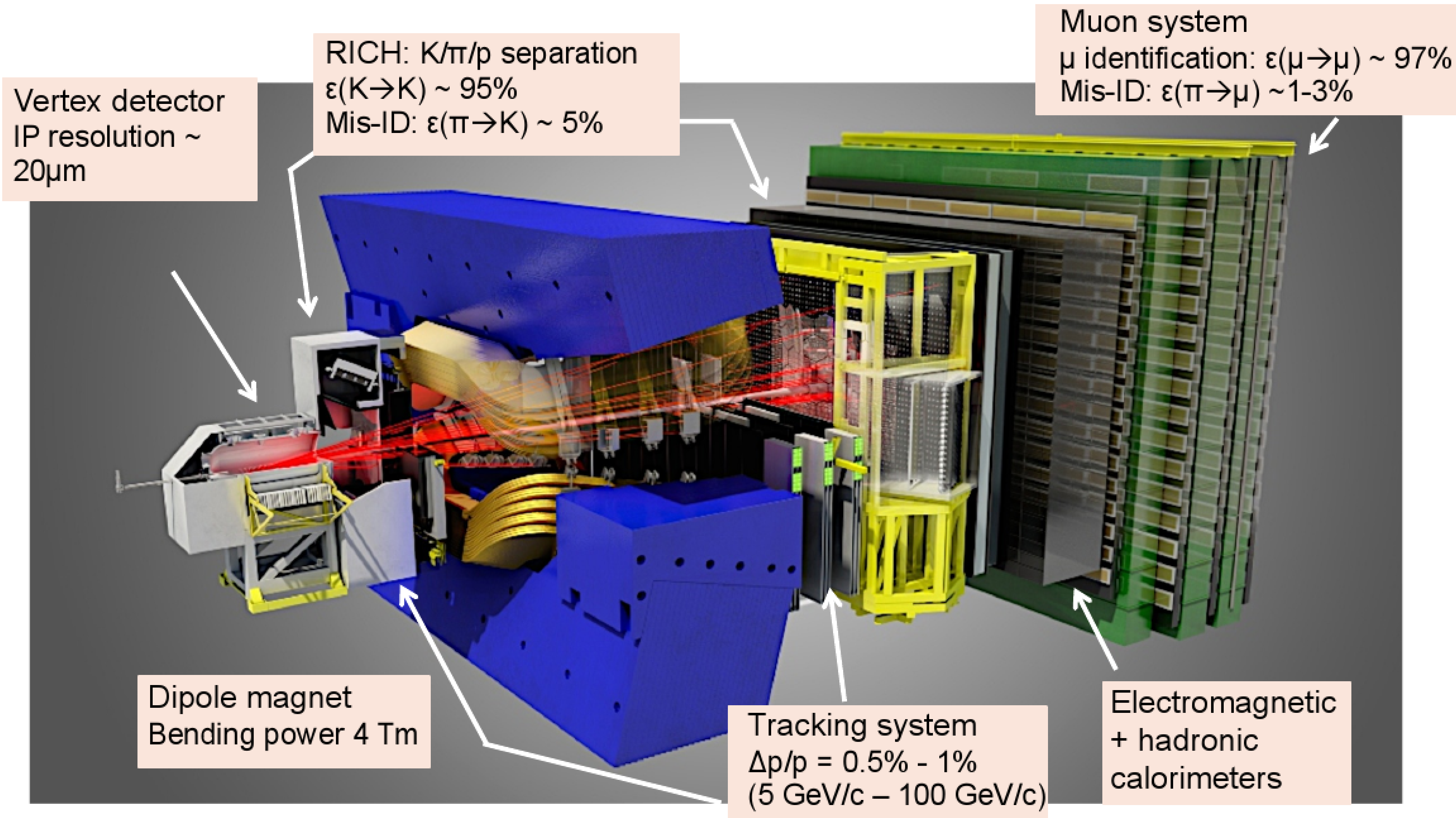
after.in2p3.fr

Thank you !

BACKUP

The LHCb detector

- Single arm spectrometer in the forward region
- **Fully instrumented in its angular acceptance (2 < η < 5)**

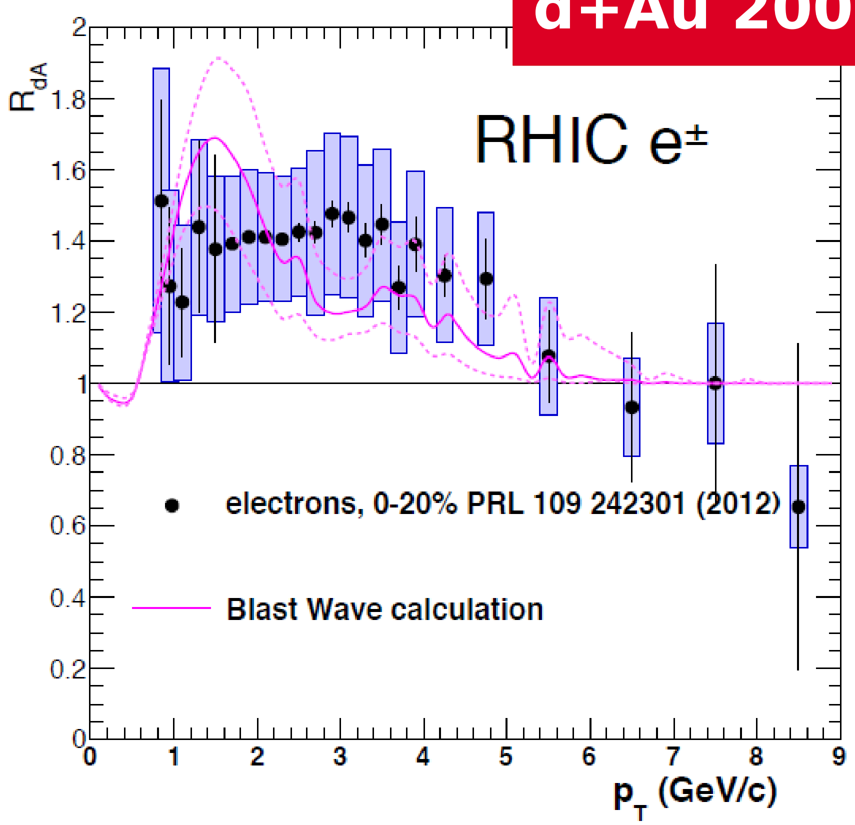


Open Heavy Flavour in pA collisions

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

- Heavy quarks in pA

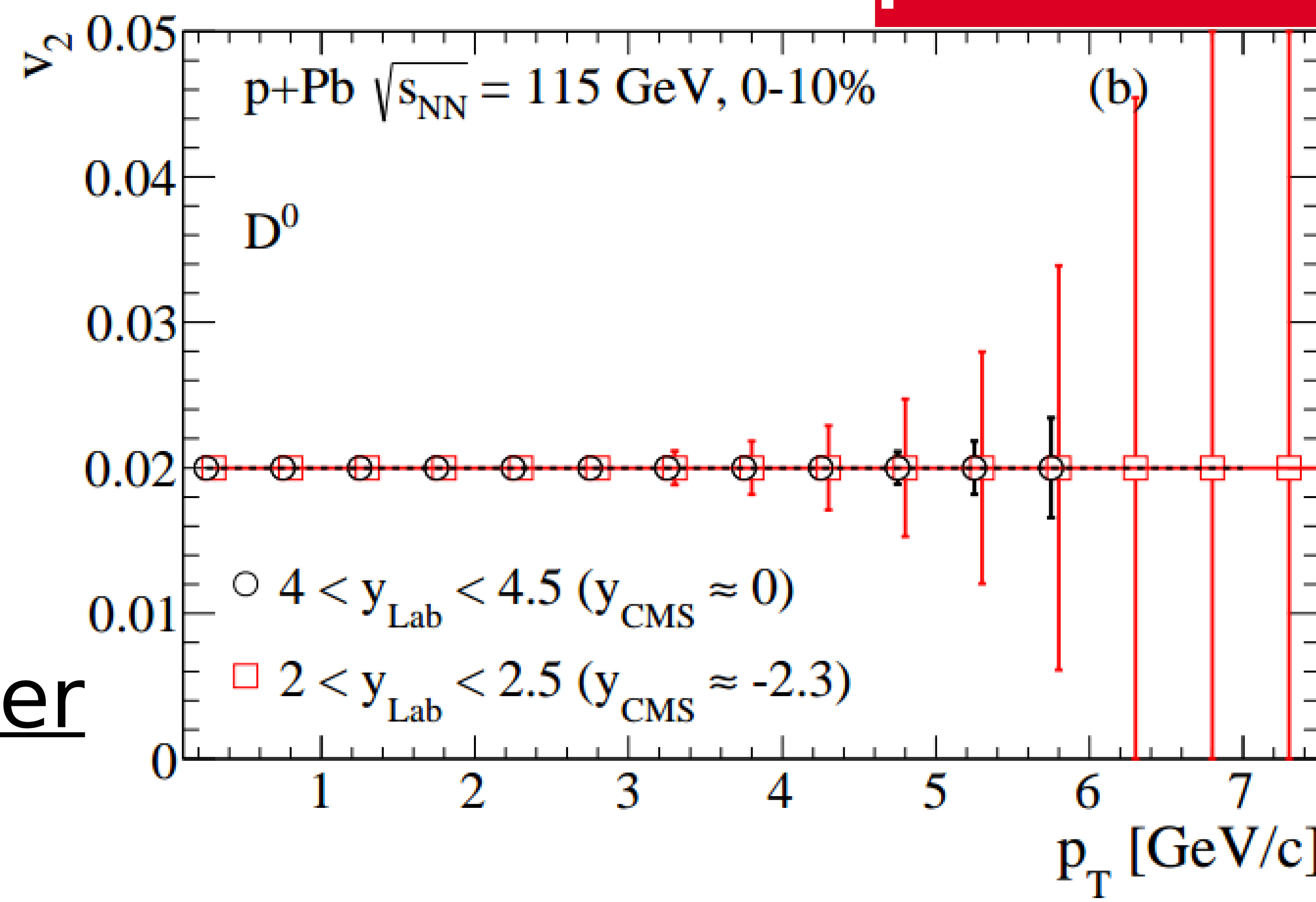
d+Au 200 GeV



Cronin effect ?
Collective effects (radial flow)?

„Possible evidence for radial flow of heavy mesons in d+Au collisions" Phys. Lett. B731 51-56 (2014)

p+A 115 GeV



AFTER → definitive answer

Ideas in favour of AFTER@LHC

Future Reading

Heavy-Ion Physics

- *Gluon shadowing effects on J/ψ and Υ production in p+Pb collisions at $\sqrt{s_{NN}}$ = 115 GeV and Pb+p collisions at $\sqrt{s_{NN}}$ = 72 GeV at AFTER@LHC* by R. Vogt. Adv.Hi.En.Phys. (2015) ID:492302.
- *Prospects for open heavy flavor measurements in heavy-ion and p+A collisions in a fixed-target experiment at the LHC* by D. Kikola. Adv.Hi.En.Phys. (2015) ID:783134
- *Quarkonium suppression from coherent energy loss in fixed-target experiments using LHC beams* by F. Arleo, S.Peigné. [arXiv:1504.07428 [hep-ph]]. Adv.Hi.En.Phys. (2015) ID:961951
- *Anti-shadowing Effect on Charmonium Production at a Fixed-target Experiment Using LHC Beams* by K. Zhou, Z. Chen, P. Zhuang. arXiv:1507.05413 [nucl-th].
- *Lepton-pair production in ultraperipheral collisions at AFTER@LHC*
  By J.P. Lansberg, L. Szymanowski, J. Wagner. arXiv:1504.02733 [hep-ph]. To appear in JHEP
- *Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams.* By J.P. Lansberg, S.J. Brodsky, F. Fleuret, C. Hadjidakis. [arXiv:1204.5793 [hep-ph]]. Few Body Syst. 53 (2012) 11.

Future Reading

Spin physics

- *Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment* by K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak. [arXiv:1502.04021 [hep-ph]. Adv.Hi.En.Phys. (2015) ID:257934.
- *Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment in a TMD factorisation scheme* by M. Anselmino, U. D'Alesio, and S. Melis. [arXiv:1504.03791 [hep-ph]]. Adv.Hi.En.Phys. (2015) ID:475040.
- *The gluon Sivers distribution: status and future prospects* by D. Boer, C. Lorcé, C. Pisano, and J. Zhou. [arXiv:1504.04332 [hep-ph]]. Adv.Hi.En.Phys. (2015) ID:371396
- *Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)* By T. Liu, B.Q. Ma. [arXiv:1203.5579 [hep-ph]]. Eur.Phys.J. C72 (2012) 2037.
- *Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER* By D. Boer, C. Pisano. [arXiv:1208.3642 [hep-ph]]. Phys.Rev. D86 (2012) 094007.

Future Reading

Hadron structure

- *Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC).* by J.P. Lansberg, H.S. Shao. [arXiv:1504.06531 [hep-ph]]. To appear in Nucl. Phys. B
- *Next-To-Leading Order Differential Cross-Sections for Jpsi, psi(2S) and Upsilon Production in Proton-Proton Collisions at a Fixed-Target Experiment using the LHC Beams (AFTER@LHC)* by Y. Feng, and J.X. Wang. Adv.Hi.En.Phys. (2015) ID:726393, in press.
- *η_c production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon* By V.P. Goncalves, W.K. Sauter. arXiv:1503.05112 [hep-ph].Phys.Rev. D91 (2015) 9, 094014.
- *A review of the intrinsic heavy quark content of the nucleon* by S. J. Brodsky, A. Kusina, F. Lyonnet, I. Schienbein, H. Spiesberger, and R. Vogt. Adv.Hi.En.Phys. (2015) ID:231547, in press.
- *Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC* By G. Chen *et al.*. [arXiv:1401.6269 [hep-ph]]. Phys.Rev. D89 (2014) 074020.

Future Reading

Feasibility study and technical ideas

- *Feasibility studies for quarkonium production at a fixed-target experiment using the LHC proton and lead beams (AFTER@LHC)* by L. Massacrier, B. Trzeciak, F. Fleuret, C. Hadjidakis, D. Kikola, J.P.Lansberg, and H.S. Shao arXiv:1504.05145 [hep-ex]. Adv.Hi.En.Phys. (2015) ID:986348
- *A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions* by C. Barschel, P. Lenisa, A. Nass, and E. Steffens. Adv.Hi.En.Phys. (2015) ID:463141
- *Quarkonium production and proposal of the new experiments on fixed target at LHC* by N.S. Topilskaya, and A.B. Kurepin. Adv.Hi.En.Phys. (2015) ID:760840

Generalities

- *Physics Opportunities of a Fixed-Target Experiment using the LHC Beams*
  By S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. [arXiv:1202.6585 [hep-ph]]. Phys.Rept. 522 (2013) 239.

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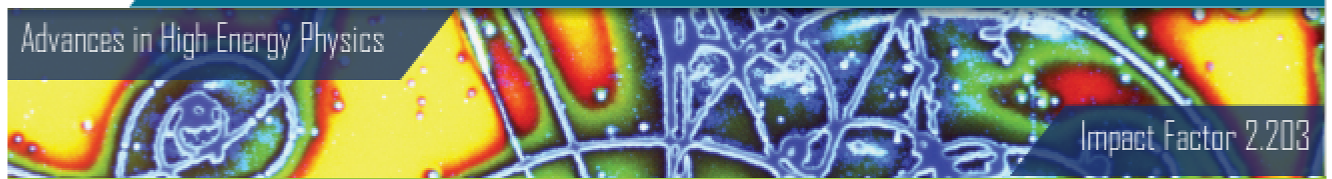

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Physics at a Fixed-Target Experiment Using the LHC Beams

Guest Editors: Jean-Philippe Lansberg, Gianluca Cavoto, Cynthia Hadjidakis, Jibo He, Cédric Lorcé, and Barbara Trzeciak