AFTER@LHC : A fixed-target experiment using LHC beams

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(IPN Orsay, on behalf of the AFTER@LHC Study Group)

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INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

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

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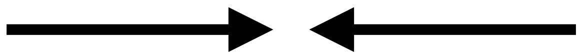
Abstract

We review the context, the motivations and the expected performances of a complete and ambitious fixed-target program using the multi-TeV proton and ion LHC beams. We also provide a detailed account of the different possible technical implementations ranging from an internal wire target to a full dedicated beam line extracted with a bent crystal. The possibilities offered by the use of the ALICE and LHCb detectors in the fixed-target mode are also reviewed.

C. Hadjidakis et al., arXiv:1807.00603 [hep-ex]
(submitted to Physics Reports)

Why fixed-target (FT) experiment?



7 TeV 7 TeV

Collider

E_{CM} = 14 TeV

7 TeV At rest

Fixed-target

E_{CM} = 115 GeV

Despite the loss of E_{CM}, fixed-target experiment has its own advantages:

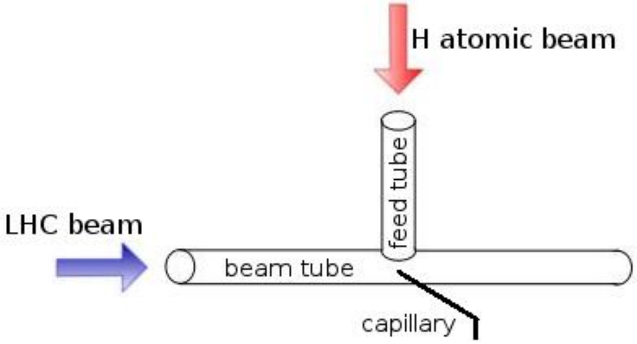
- High luminosity thanks to the high density of targets
- Accessibility to the far backward phase space (explained later)
- Large choice of the target nucleus
- E_{CM} = 115GeV (*pp*) , 72 GeV (*AA*) : energy between SPS and RHIC
- Target can be polarized : precision study of spin physics

Three options

- Position target in beam pipe of LHCb

  (c.f. SMOG@LHCb)

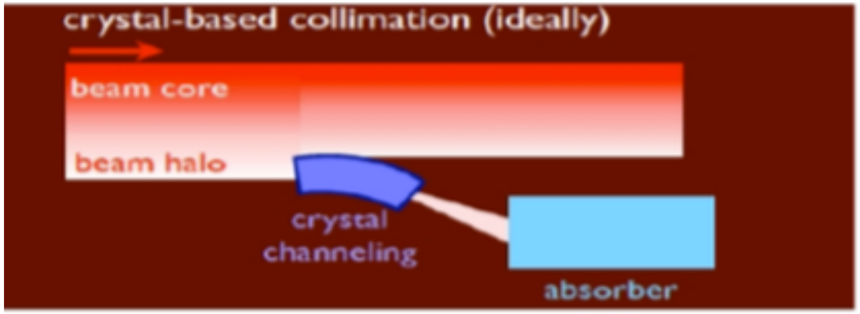
- Position target in beam pipe of ALICE



- Independent apparatus with new beam line

  Beam halo is conducted to beam line with bent crystal

  (application of the technology of beam collimation)

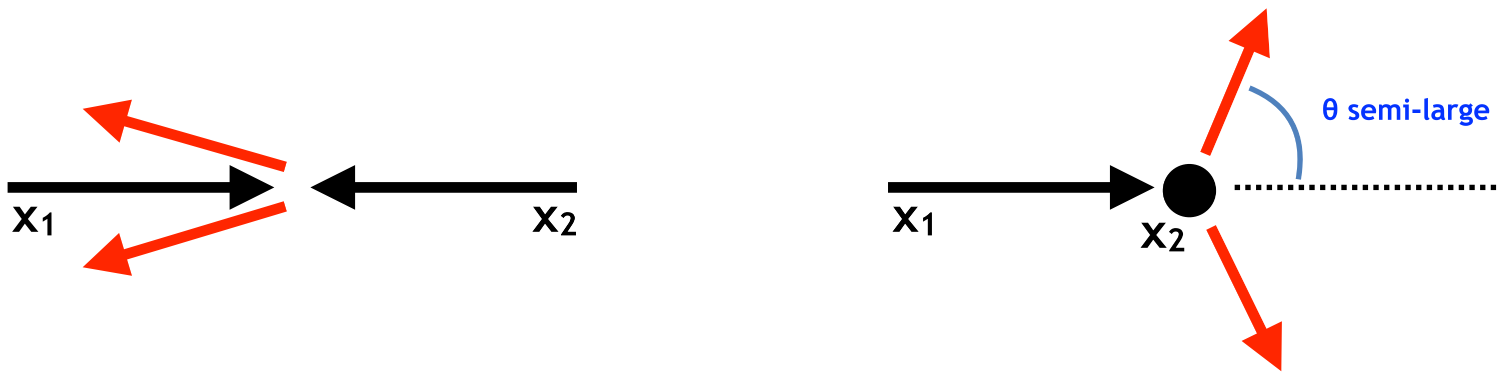


In any case, other LHC experiments will <u>not be disturbed</u>!

Kinematic coverage of $b\bar{b}$ production at AFTER@LHC

Let us estimate up to which x LHCb can cover with $b\bar{b}$ production off pp
(Fixed target mode of LHCb)

$x_1 << x_2$



Hadron center-of-mass

Target rest frame

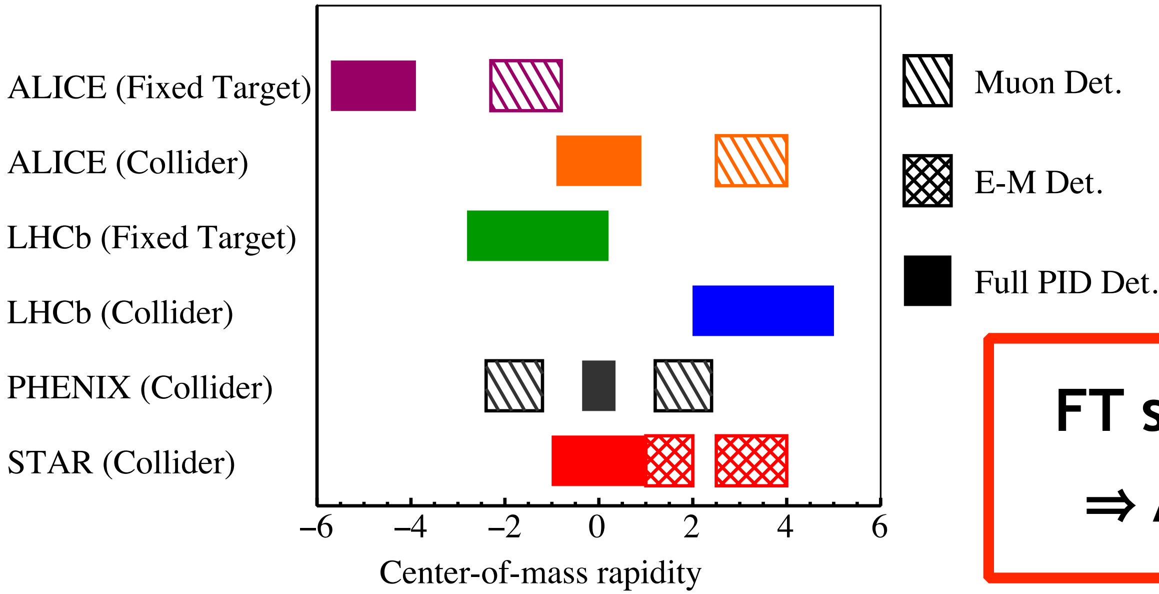
Kinematics of bottomonium production: $x_{1,2} = \frac{m_{b\bar{b}}}{\sqrt{s}} e^{\pm y_{\rm c.m.s.}}$ ($\sqrt{s}$ = 115GeV for fixed-target)

Production threshold at CM: $x_1 x_2 s = m^2_{b\bar{b}}$

LHCb rapidity coverage: $[2,5]_{\text{Lab frame}} = [-2.8,0.2]_{\text{c.m.s.}}$

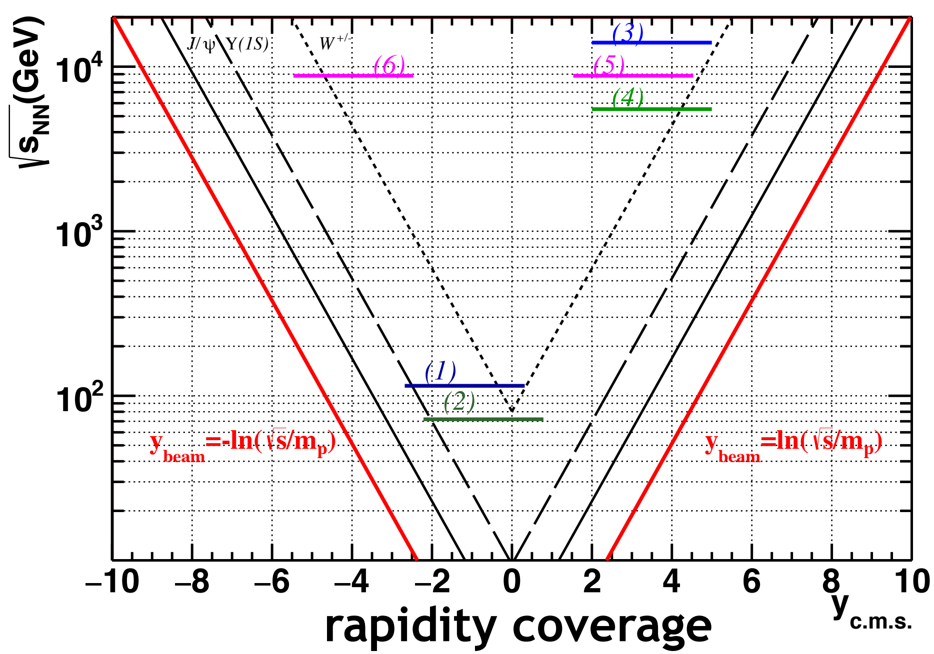
➡ **Can access up to "x" = 1.4 with LHCb in the fixed-target mode**

Expected performance with existing apparatus



FT shifts the rapidity

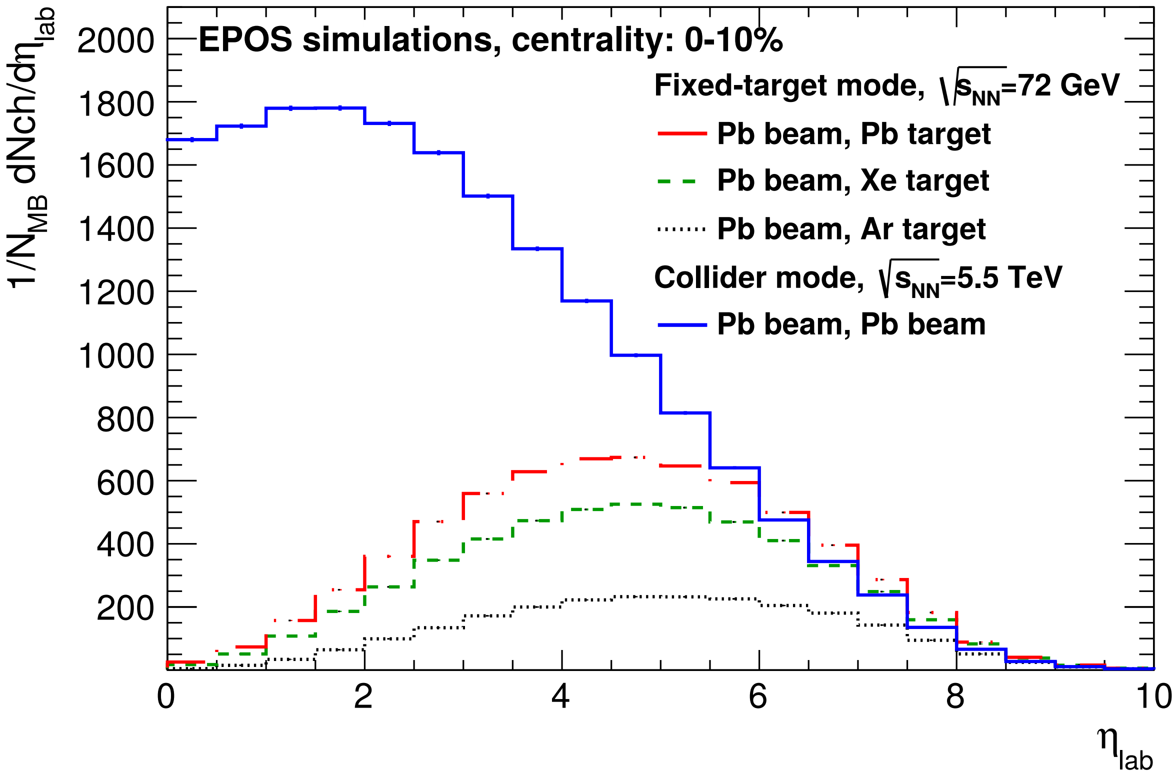
⇒ Access to far backward



Acceptances for:

(1) $\sqrt{s_{NN}}$=115 GeV pp, pA (FT)
(2) $\sqrt{s_{NN}}$=72 GeV pPb (FT)
(3) $\sqrt{s_{NN}}$=14 TeV pp (collider)
(4) $\sqrt{s_{NN}}$=5.5 TeV PbPb (collider)
(5) $\sqrt{s_{NN}}$=8.8 TeV pPb (collider)
(6) $\sqrt{s_{NN}}$=8.8 TeV Pbp (collider)

Charged particle multiplicity for heavy-ion collision



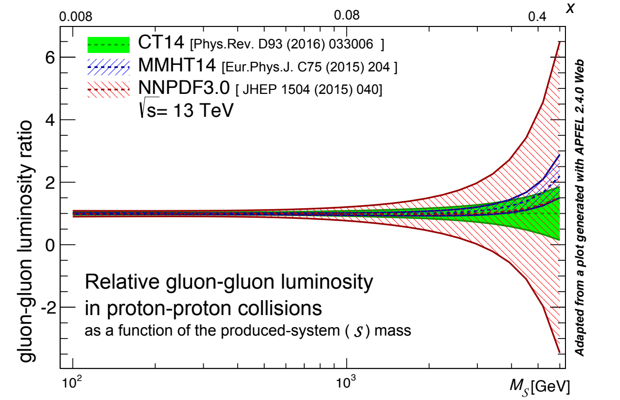
Assumed max. instantaneous luminosity : $3\times10^{28}cm^{-2}s^{-1}$

- Maximum of charged particles (for PbXe, $\sqrt{s_{NN}}$=72GeV) is near η_{lab}=4
- In any case, the multiplicity of AA collisions in FT mode does not exceed that of PbPb in collider mode

Physics covered by AFTER@LHC

- **High-x physics**
- **Spin physics**
- **Heavy ion collision**

High-x physics



High-x region is poorly known

Especially gluon PDF

High-x region is interesting because

- EMC effect, especially gluon EMC (almost unknown)

  Relation with the short-range correlation suggested, but what about gluons?

- Intrinsic charm, bottom : nonperturbative enhancement at high-x

- Hint to confinement in proton ?

  High-x gluon : almost all momentum of the proton carried by one gluon

  u/d ratio : no consensus between models → What is the true picture?

Applications:

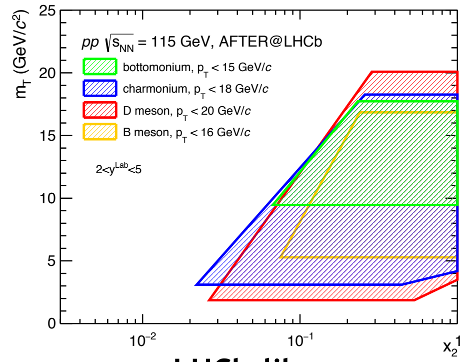
- Accuracy of PDFs needed for BSM search

- High energy astrophysics :
  cosmic ray spectrum, atmospheric neutrinos, etc (see later)

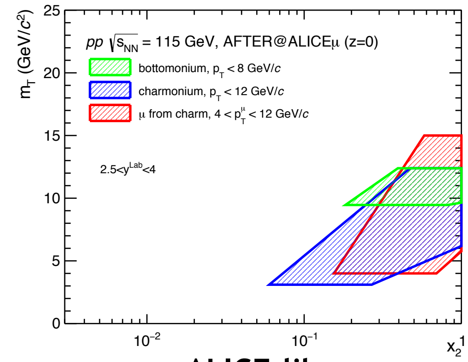
High-x physics

AFTER@LHC can uncover the high-x regime of

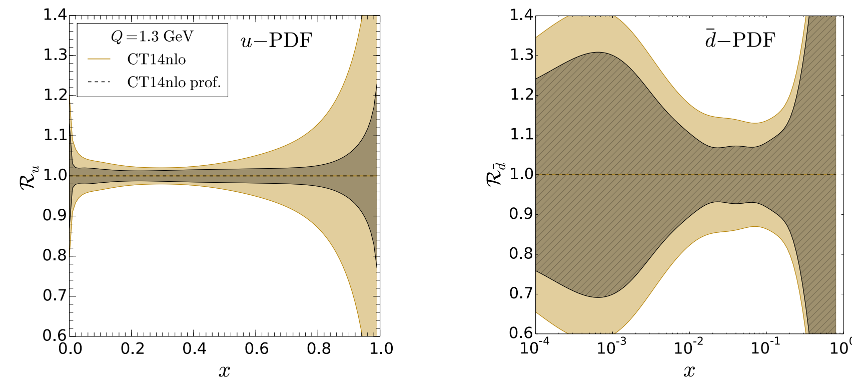
- **Light quark PDF**
  - **Drell-Yan**
- **Gluon PDF**
  - **Heavy quark production**
- **Intrinsic charm PDF**
  - **Inclusive D^0 production**



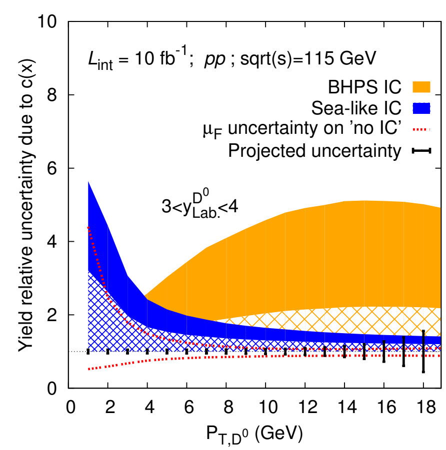
LHCb-like



ALICE-like



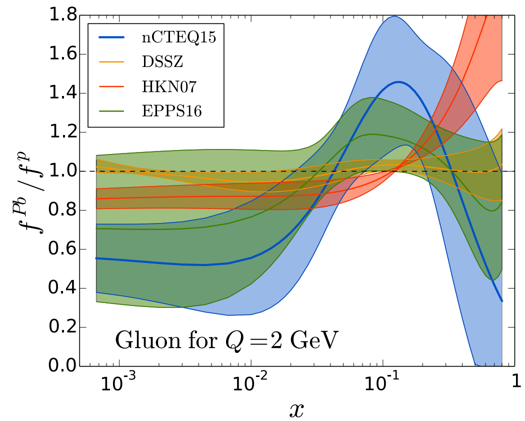
Improvement of light-quark PDF via Drell-Yan in AFTER@LHC



Nuclear PDF

Nuclear PDF is poorly known at high-x

AFTER@LHC can improve PDFs at high-x
via Drell-Yan (u,d), heavy quark (g)

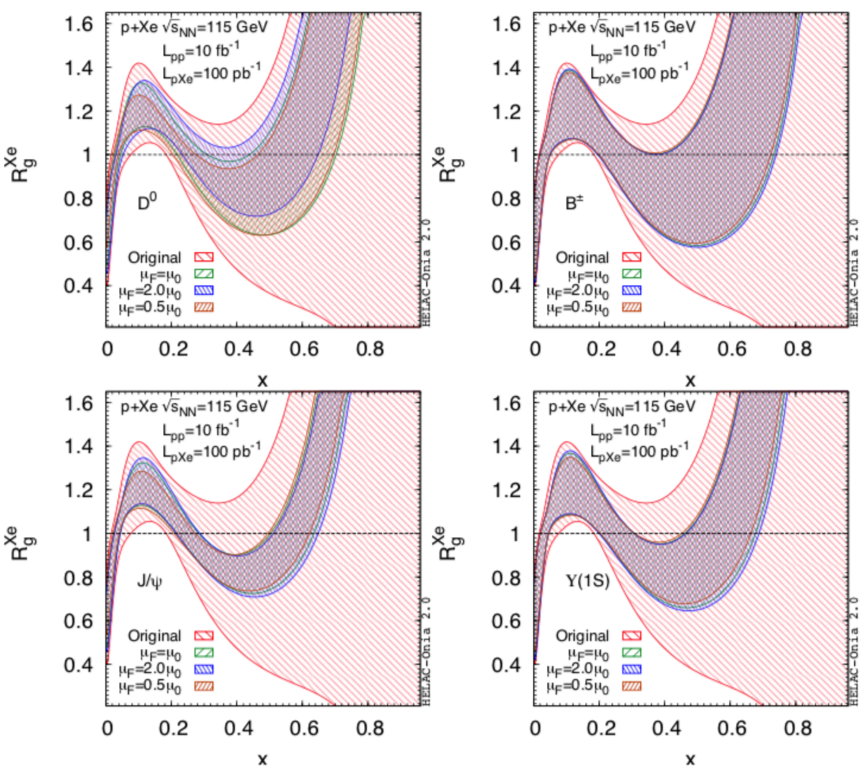


Gluon PDF in Pb

Projection of the nPDF accuracy

(Baysian-reweighting analysis,
assuming the luminosity 100 pb^{-1})

We must measure several mesons
final states at once
to remove nuclear systematics



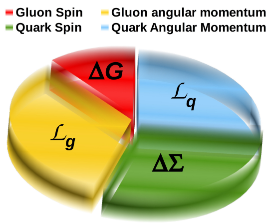
➡ We see a remarkable improvement at high-x

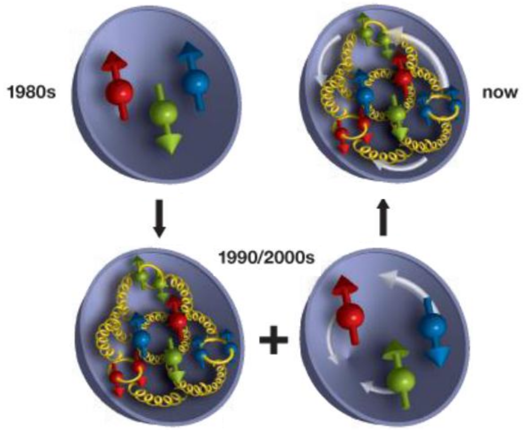
Spin physics

In fixed-target experiment, targets may be polarized: study of nucleon structure

<u>Proton spin decomposition:</u>

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}^g + \mathcal{L}^q$$





Quark spin contribution to nucleon spin is small (∼30%)

⇒ Proton spin puzzle (since 1980's)

Recent experimental data suggest the orbital angular momentum (OAM)

OAM ⇒ Transverse motion ⇒ TMD (k_T) or GPD

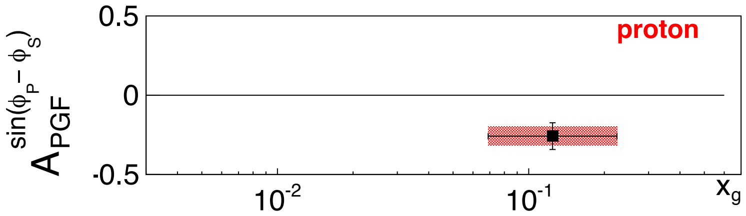
Probed with single transverse spin asymmetry (STSA)

In AFTER@LHC, the gluon STSA is determined via c, b quarks

We can also test the generalized universality
(sign change of Sivers function in SIDIS and DY),
strange quark helicity, transversity, …

Sivers function

Recently, COMPASS found nonzero gluon Sivers asymmetry :



COMPASS Collaboration, Phys. Lett. B **772**, 854 (2017).

⇒ $f_{1g}^{\perp} \neq 0$ **(gluon Sivers)**

⇒ **Hint of gluon OAM $\mathscr{L}^g \neq 0$!**

Sivers function

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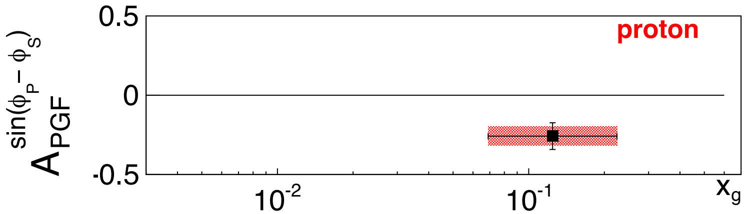
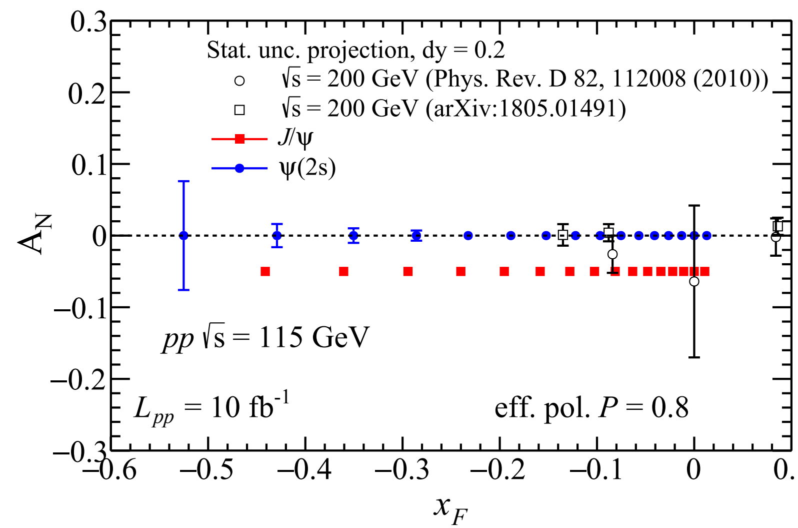


COMPASS Collaboration, Phys. Lett. B **772**, 854 (2017).

$\Rightarrow$ $f_{1g}^{\perp} \neq 0$ **(gluon Sivers)**

$\Rightarrow$ **Hint of gluon OAM $\mathcal{L}^g \neq 0$!**

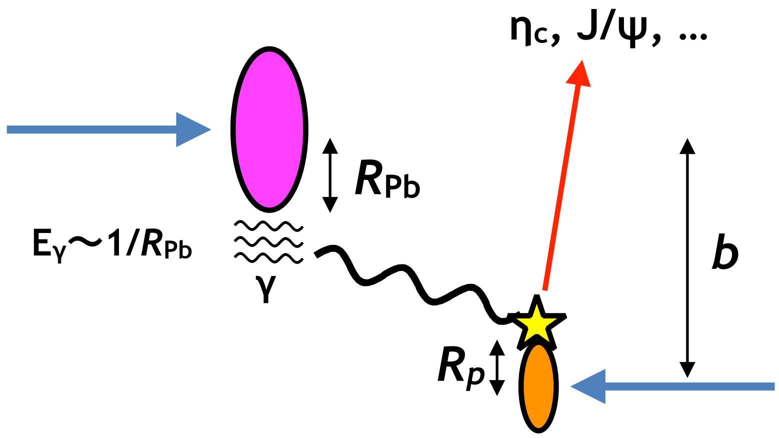
Gluon Sivers can also be indirectly accessed with inclusive quarkonia with AFTER@LHC with a much better accuracy than PHENIX



Access to gluon GPD via ultraperipheral collisions (UPCs)

Impact parameter $b > R_p + R_{Pb}$

⇒ Dominated by photon exchanges



(example of PbH)

Kinematics of UPC in fixed-target exp at LHC:

- **Boost of photon in projectile:**

$$\gamma_{\rm lab}^{\rm beam} = E_{\rm beam}/m_N \quad \begin{cases} 7000 \text{ for } p \\ 2500 \text{ for Pb} \end{cases}$$

- **Energy of photon :**

$$E_\gamma^{\rm max} \simeq \frac{\gamma_{\rm lab}^{\rm beam}}{R_{\rm Pb} + R_p} \simeq \gamma_{\rm lab}^{\rm beam} \times 30\,{\rm MeV}$$

- **C.M. energy of *γp* in fixed-target mode :**

$$\sqrt{s_{\gamma p,{\rm max}}} = \sqrt{2E_\gamma^{\rm max} m_p} \simeq 20\,{\rm GeV}$$

⇒ **First opportunity to study UPCs in the FT mode!**

Key figures of the UPC in FT at LHC (AFTER@LHC)

System	target thickness (cm)	$\sqrt{s_{NN}}$ (GeV)	$\mathcal{L}_{AB}{}^{a}$ ($\text{pb}^{-1}\text{yr}^{-1}$)	E_A^{lab} (GeV)	E_B^{lab} (GeV)	$\gamma^{\text{c.m.s.}}$ ($\frac{\sqrt{s_{NN}}}{2m_N}$)	$\gamma^{A\leftrightarrow B}$ ($\frac{s_{NN}}{2m_N^2}$)	$\frac{\hbar c}{R_A+R_B}$ (MeV)	$E_{\gamma\ \text{max}}^{A/B\ \text{rest}}$ (GeV)	$\sqrt{s_{\gamma N}^{\text{max}}}$ (GeV)	$E_{\gamma\ \text{max}}^{\text{c.m.s.}}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\text{max}}}$ (GeV)
AFTER												
pp	100	115	2.0×10^{4}	7000	m_N	61.2	7450	140	1050	44	8.5	17
pPb	1	115	1.6×10^{2}	7000	m_N	61.2	7450	26	190	19	1.6	3.2
pd	100	115	2.4×10^{4}	7000	m_N	61.2	7450	70	520	31	4.3	8.5
PbPb	1	72	$7.\times10^{-3}$	2760	m_N	38.3	2940	14	40	9	0.5	1.0
Pbp	100	72	1.1	2760	m_N	38.3	2940	26	76	12	1.6	3.2
Arp	100	77	1.1	3150	m_N	40.9	3350	41	140	16	2.5	5.0
Op	100	81	1.1	3500	m_N	43.1	3720	52	190	19	3.2	6.3
RHIC												
pp	N/A	200	1.2×10^{1}	100	100	106.4	22600	140	3150	77	15	30
AuAu	N/A	200	2.8×10^{-3}	100	100	106.4	22600	14	320	24	1.5	3.0
SPS												
InIn	.	17	.	160	m_N	9.22	170	17	2.9	2.5	0.15	0.31
PbPb	.	17	.	160	m_N	9.22	170	14	2.4	2.1	0.13	0.26

J.-P. Lansberg et al., JHEP **1509** (2015) 087

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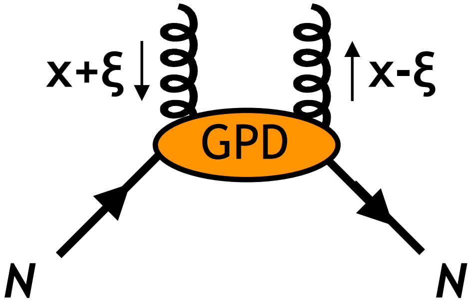
	$\sqrt{s_{NN}}$	E_{beam}	$\sqrt{s_{N\gamma}^{max}}$	$\sqrt{s_{\gamma\gamma}^{max}}$
pp	**115**	**7000**	**44**	**17**
Pb*p*	**72**	**2760**	**12**	**3.2**
PbPb	**72**	**2760**	**9**	**1.0**
***p*Pb**	**115**	**7000**	**19**	**3.2**

Gluon generalized parton distribution (GPD)

Direct access to the gluon OAM with GPDs (Ji sum rule)

$$L_z^g = \int dx\, x[H^g(x,0,0) + E^g(x,0,0)] - \int dx\, \tilde{H}^g(x,0,0)$$

Gluon GPD = "Pomeron form factor"



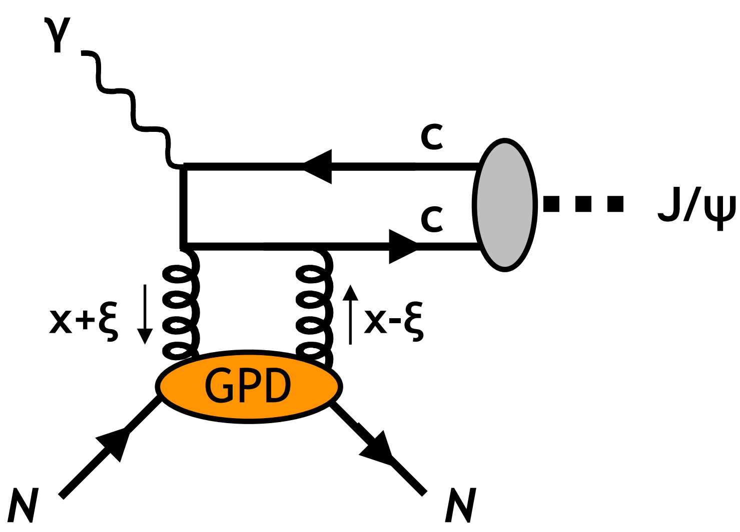
$$F^g(x,\xi,t)$$

$$= \frac{1}{(Pn_-)} \int \frac{d\lambda}{2\pi} e^{ix(Pz)} n_{-\alpha} n_{-\beta} \left\langle p' \left| G^{\alpha\mu}\left(-\frac{z}{2}\right) G^{\beta}_{\mu}\left(\frac{z}{2}\right) \right| p \right\rangle \Big|_{z=\lambda n_-}$$

$$= \frac{1}{2(Pn_-)} \left[H^g \bar{u}(p') \not{n}_- u(p) + E^g \bar{u}(p') \frac{i\sigma^{\alpha\beta} n_{-\alpha} \Delta_\beta}{2m_N} u(p) \right]$$

Extraction of GPD from J/ψ photoproduction

Exclusive J/ψ photoproduction : direct probe of gluon GPDs (*H^g*, *E^g*)!



A. J. Baltz, Phys. Rep. **458**, 1 (2008).

$$\mathcal{M} = \frac{2^3\sqrt{\pi} e e_q \epsilon^*(p_\psi)\cdot\epsilon(p_\gamma)}{M_\psi^{3/2}\sqrt{N_c}\xi}\cdot\frac{R(0)}{2(Pn_-)}$$

$$\left[\mathcal{H}^g \bar{u}(p')\not{n}_- u(p) + \mathcal{E}^g \bar{u}(p')\frac{i\sigma^{n_-\Delta}}{2m_N}u(p)\right]$$

$$\begin{cases} \mathcal{H}^g(\xi,t) \equiv \int_{-1}^{1} dx\, T_g(x,\xi) H^g(x,\xi,t) \\ \mathcal{E}^g(\xi,t) \equiv \int_{-1}^{1} dx\, T_g(x,\xi) E^g(x,\xi,t) \end{cases}$$

with $T_g(x,\xi) = \frac{\xi}{(x-\xi+i\epsilon)(x+\xi-i\epsilon)}\alpha_s$

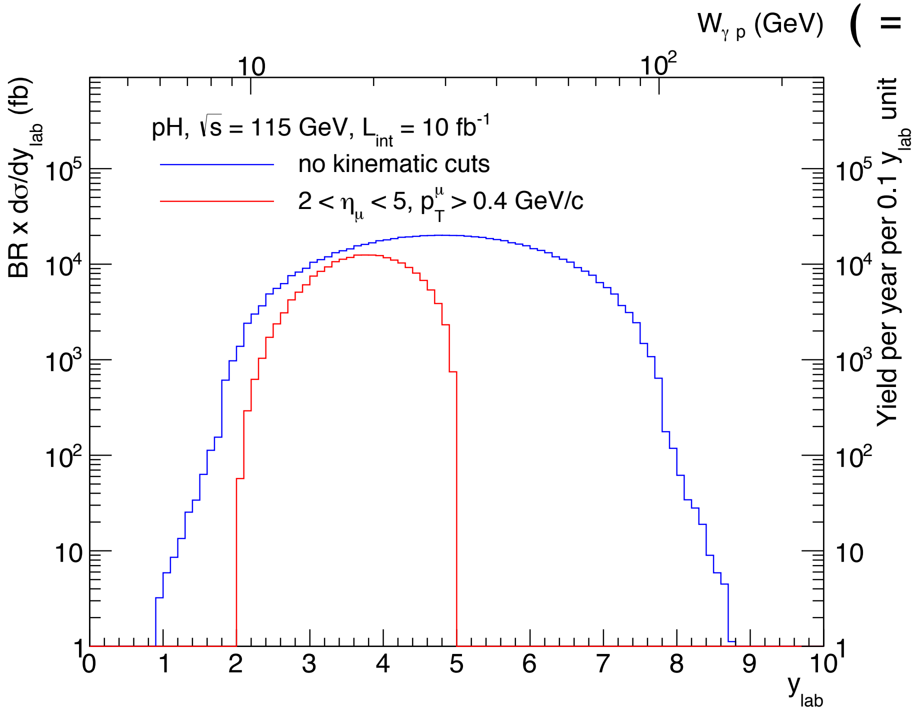
NB: to access *E^g*, one needs to polarize the proton

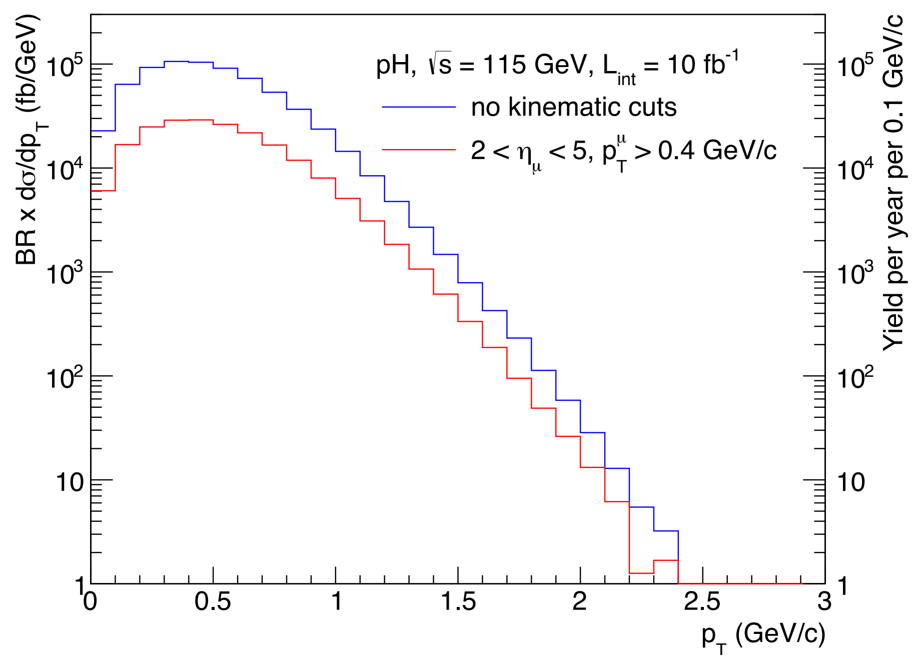
Number of J/ψ expected from 1 year run (LHCb, pH)

	pH	PbH
Photon-emitter	proton	Lead
$\sigma^{tot}_{J/\psi}$ (pb)	1.18×10^3	276.77×10^3
$\sigma_{J/\psi\to l^+l^-}$ (pb)	70.10	16.50×10^3
$\sigma_{J/\psi\to l^+l^-}$ (with LHCb η_μ cut) (pb)	20.65	9.81×10^3
$\sigma_{J/\psi\to l^+l^-}$ (with LHCb η_μ and p_T^μ cut) (pb)	20.64	9.81×10^3
# events	200 000	1000

(Simulated with STARLIGHT)

(= $M_{\psi p}$)





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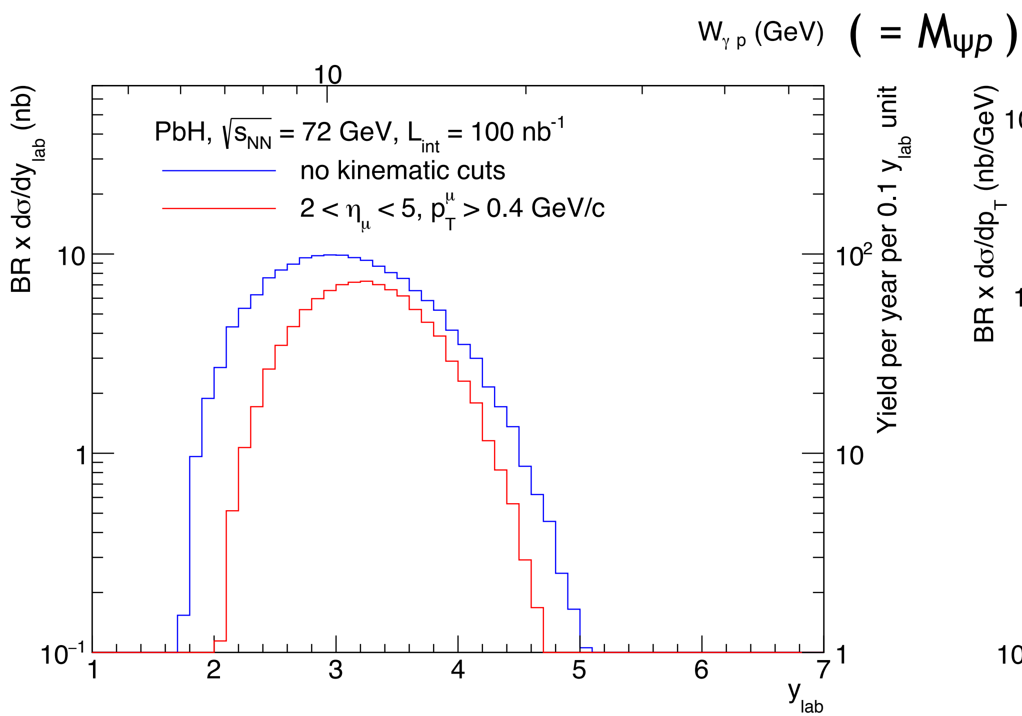
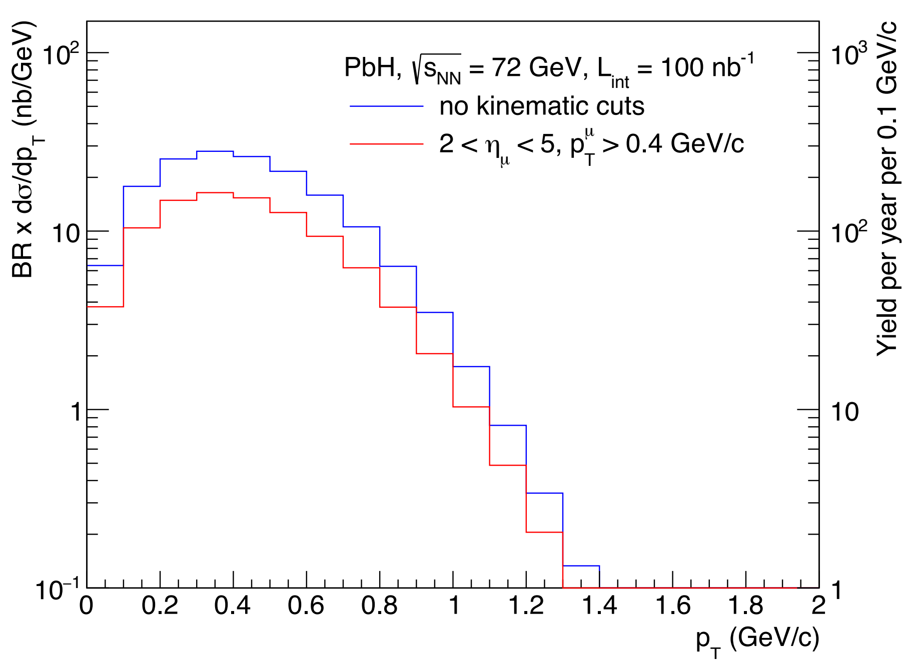
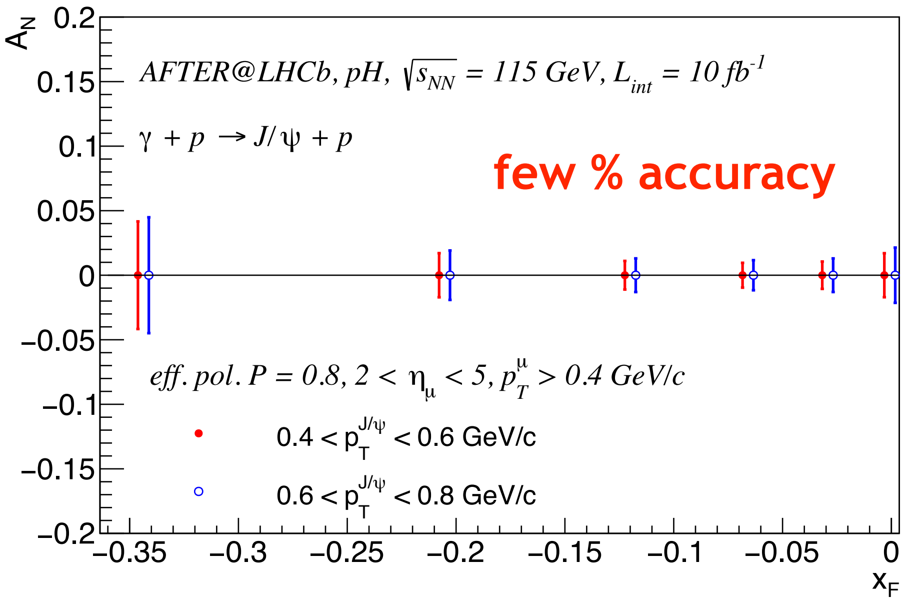
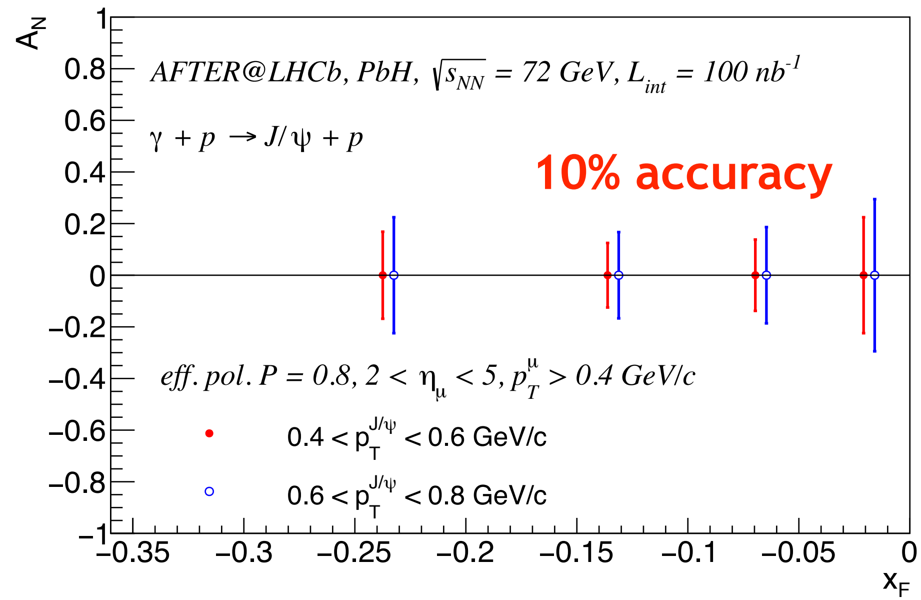




Projection of sensitivity to STSA (A_N) with AFTER@LHC

Assuming a target polarization of 80%
(compatible with H-jet system from RHIC or HERMES-like storage cell)





$$A_N^{\gamma p^{\uparrow} \to J/\psi\, p} \propto (1+\xi)\,\mathrm{Im}\left(\mathcal{E}^{g*}\mathcal{H}^{g}\right)$$

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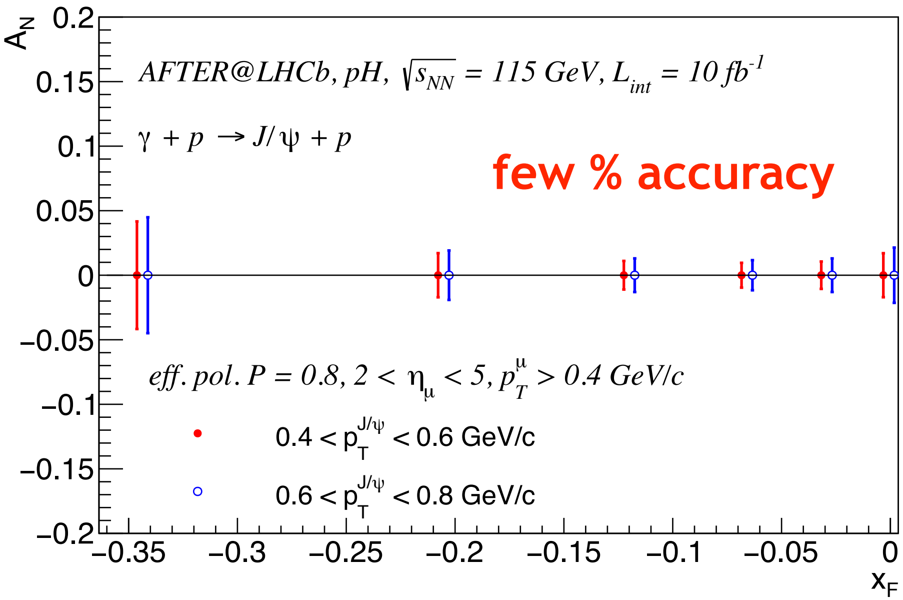
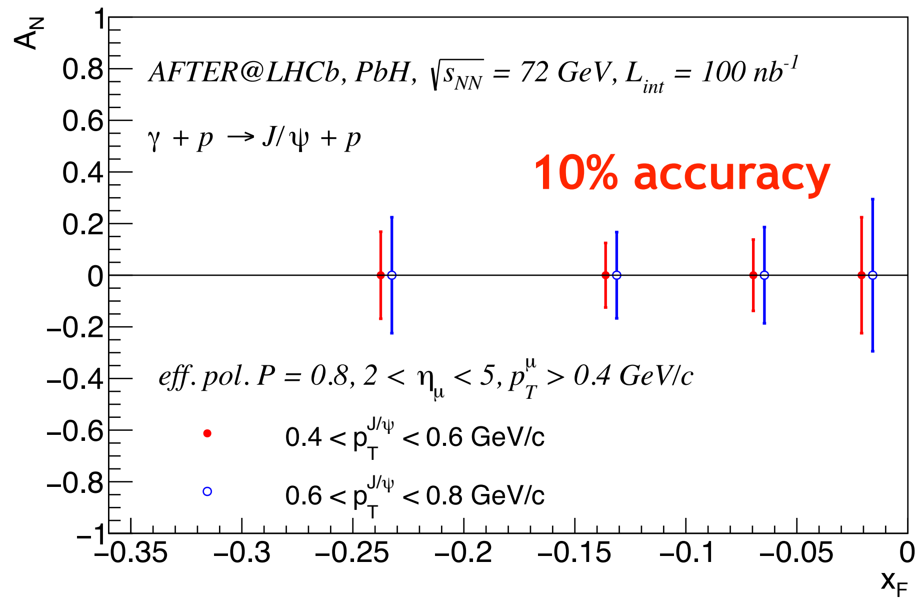
(compatible with H-jet system from RHIC or HERMES-like storage cell)





$$A_N^{\gamma p^{\uparrow} \to J/\psi\, p} \propto (1+\xi)\,\mathrm{Im}\left(\mathcal{E}^{g*}\mathcal{H}^{g}\right)$$

- **PbH is better than *p*H since we know the source of emitted photon**
- **Might be feasible with a polarized deuteron target**

⇒ probe deuteron GPD

E. R. Berger et al., Phys. Rev. Lett. **87**, 142302 (2001)

Heavy-ion physics

Objects:

- Nature of the QCD phase transition
- Thermodynamic properties of hot QCD medium (transport properties, etc)
- Interaction of hard partons with the medium

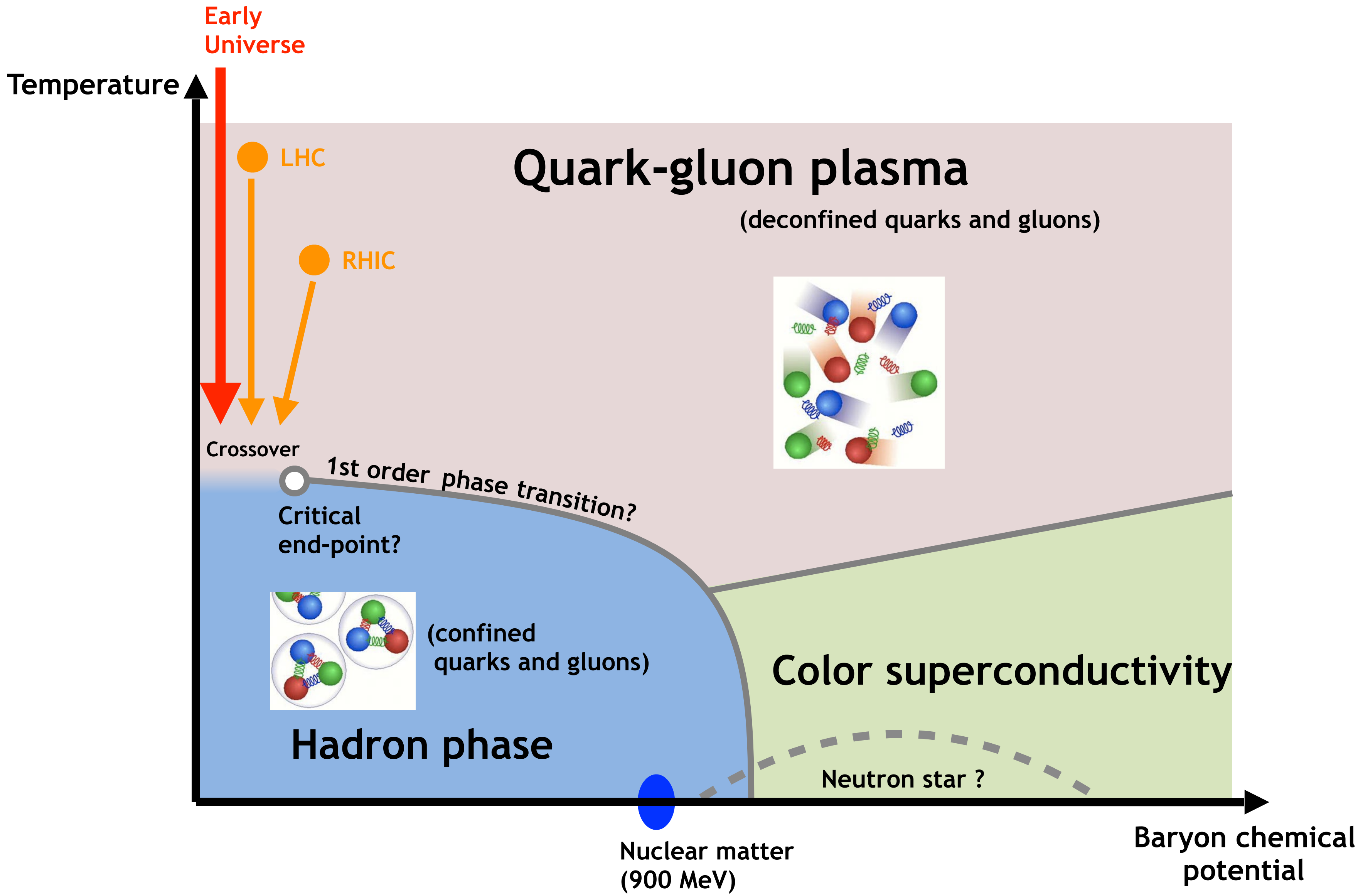
Important observables:

- Azimuthal angular distribution of hadrons in the final state
- Nuclear modification (R_{AA}, R_{pA})

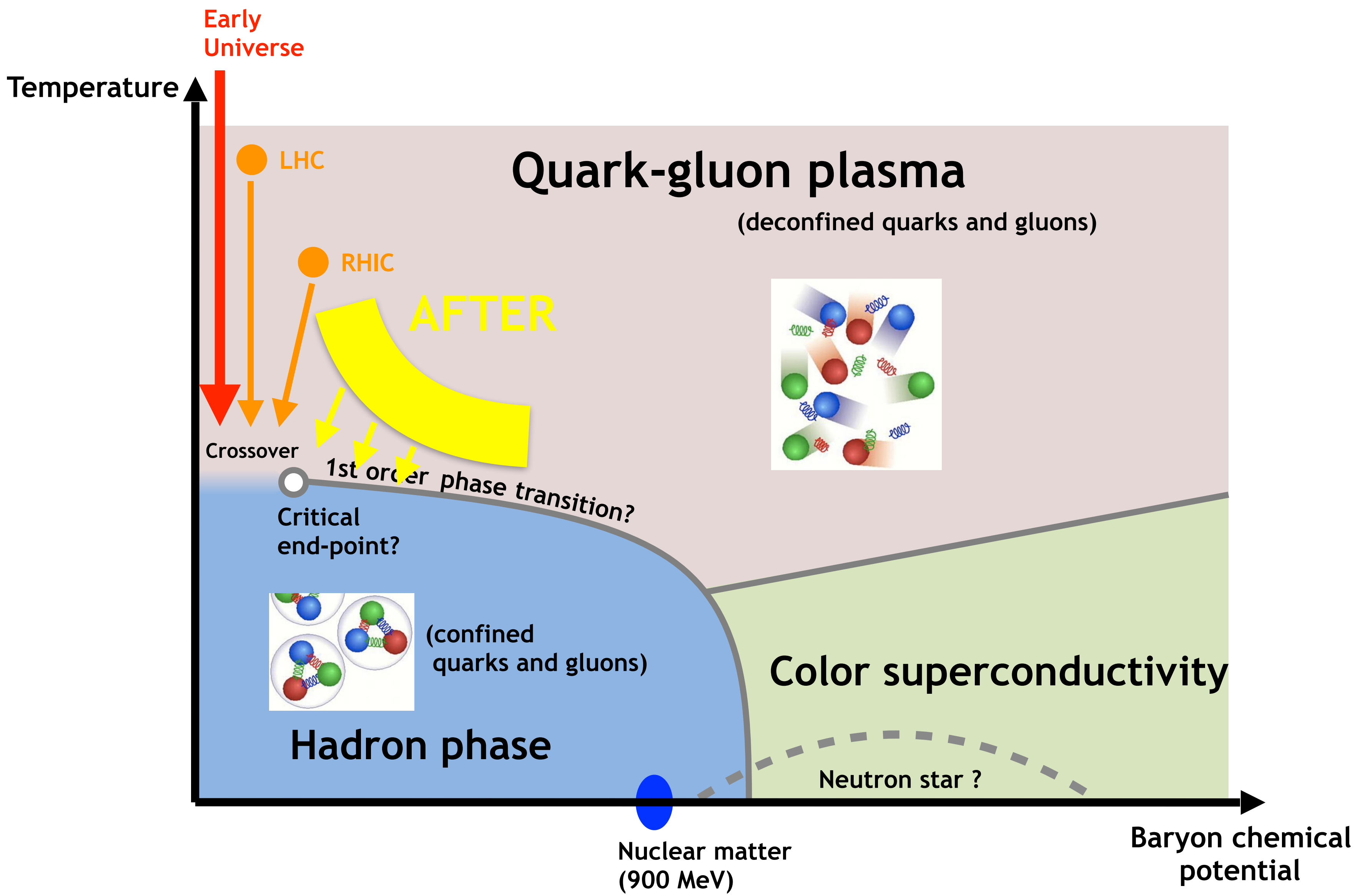
Advantages of AFTER@LHC:

- E_{CM} between those of RHIC and SPS
- Large rapidity coverage

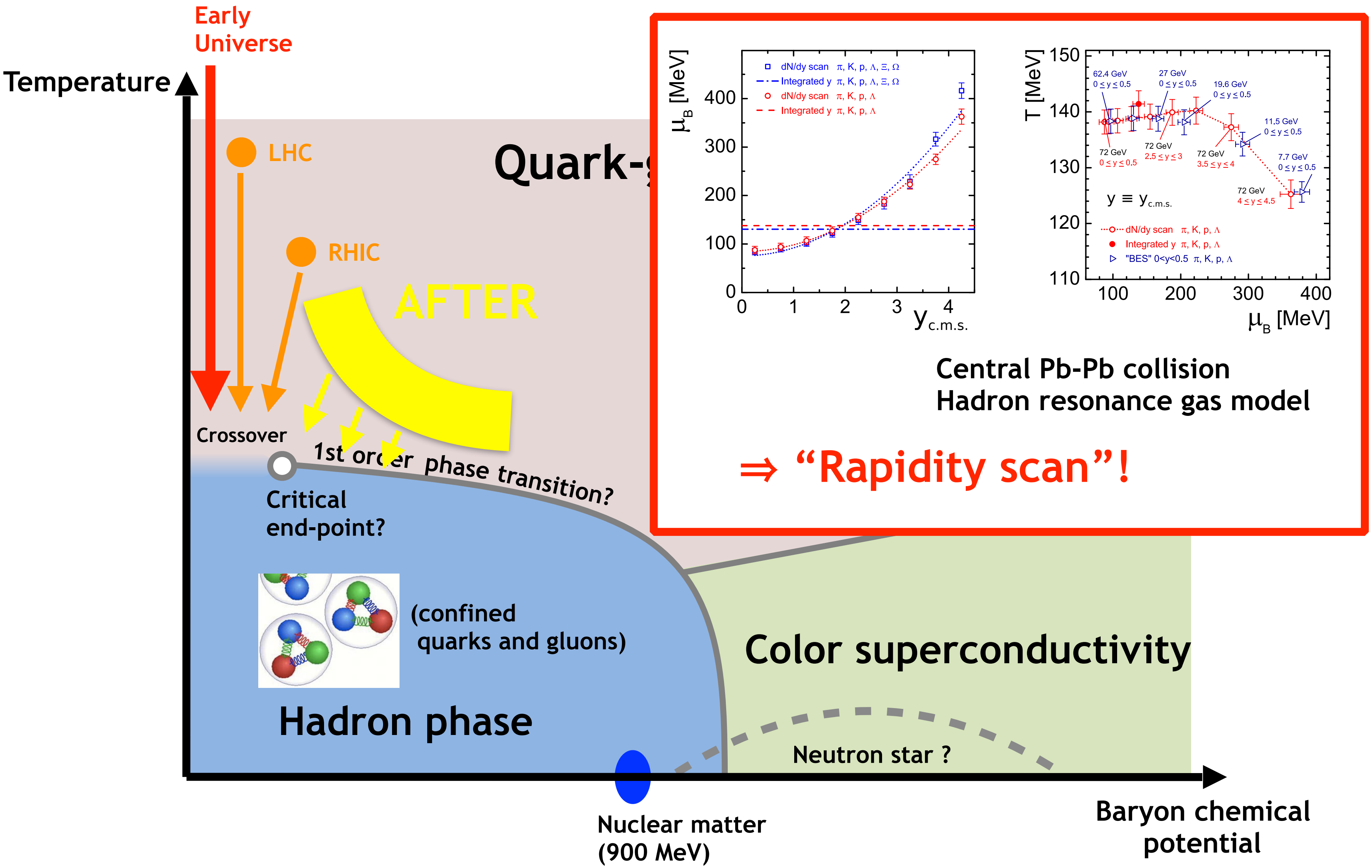
Heavy-ion physics : AFTER vs QCD phase diagram



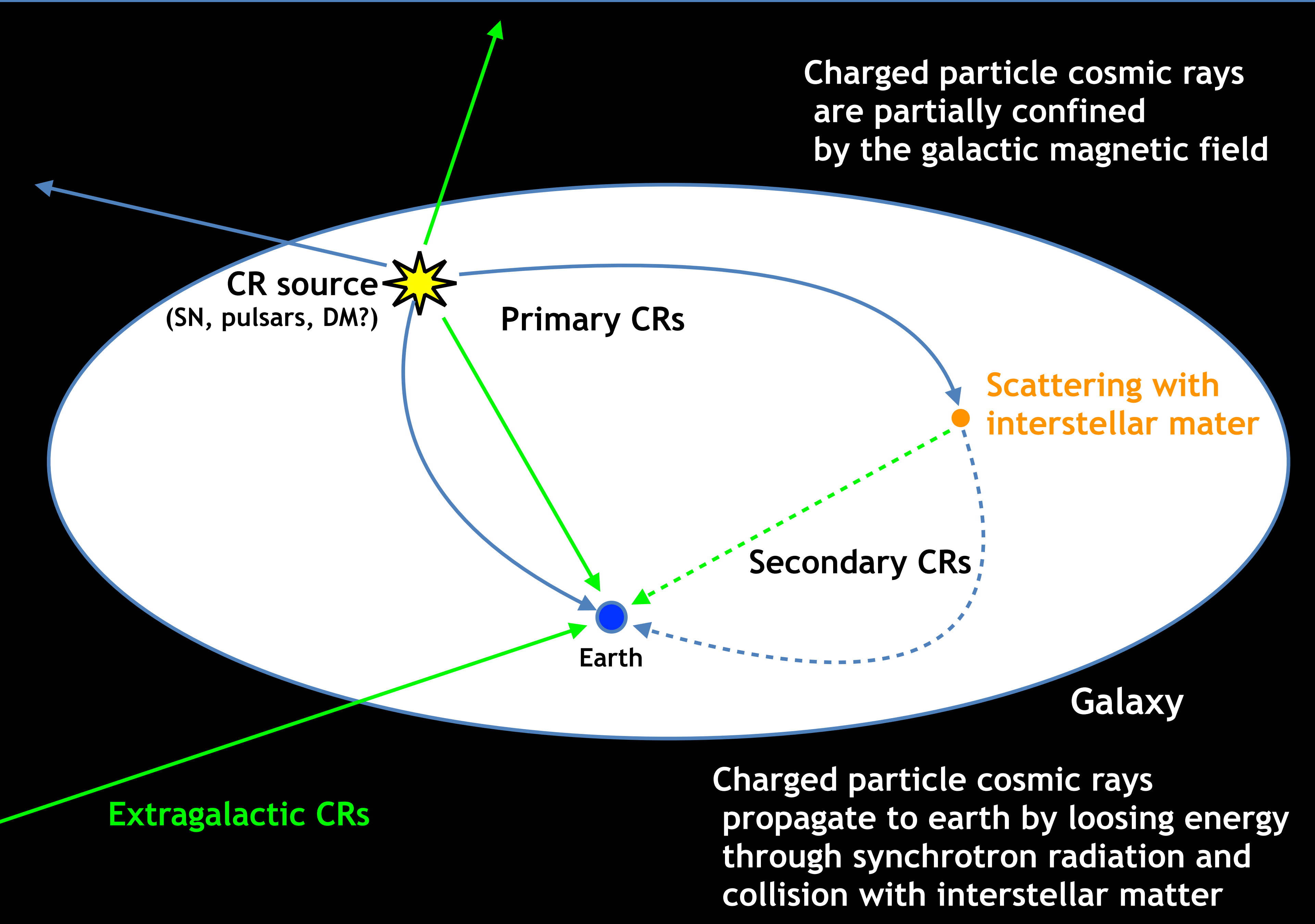
Heavy-ion physics : AFTER vs QCD phase diagram



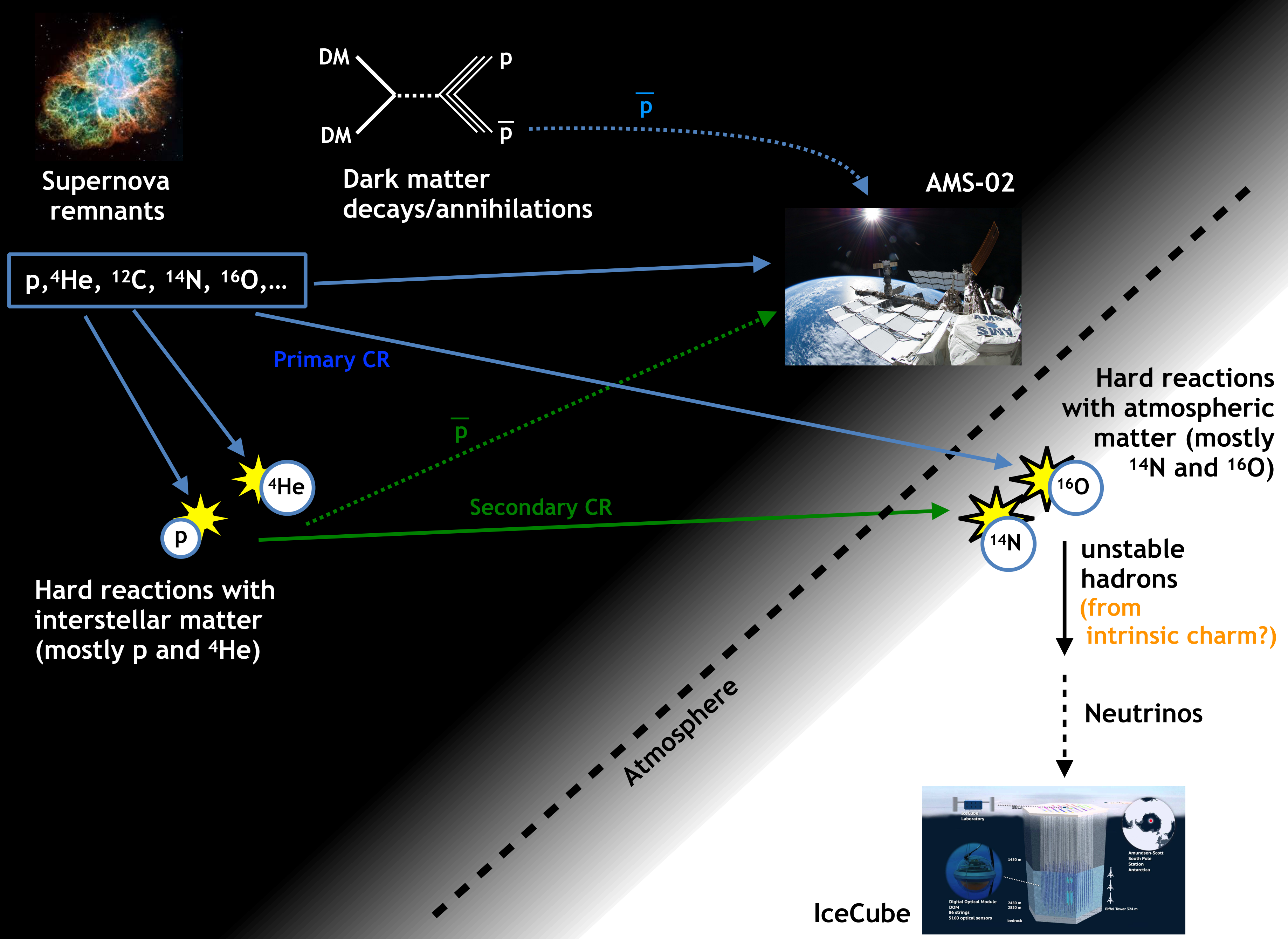
Heavy-ion physics : AFTER vs QCD phase diagram



Astrophysics and cosmic rays



Application to astrophysics :cosmic antiprotons, neutrinos



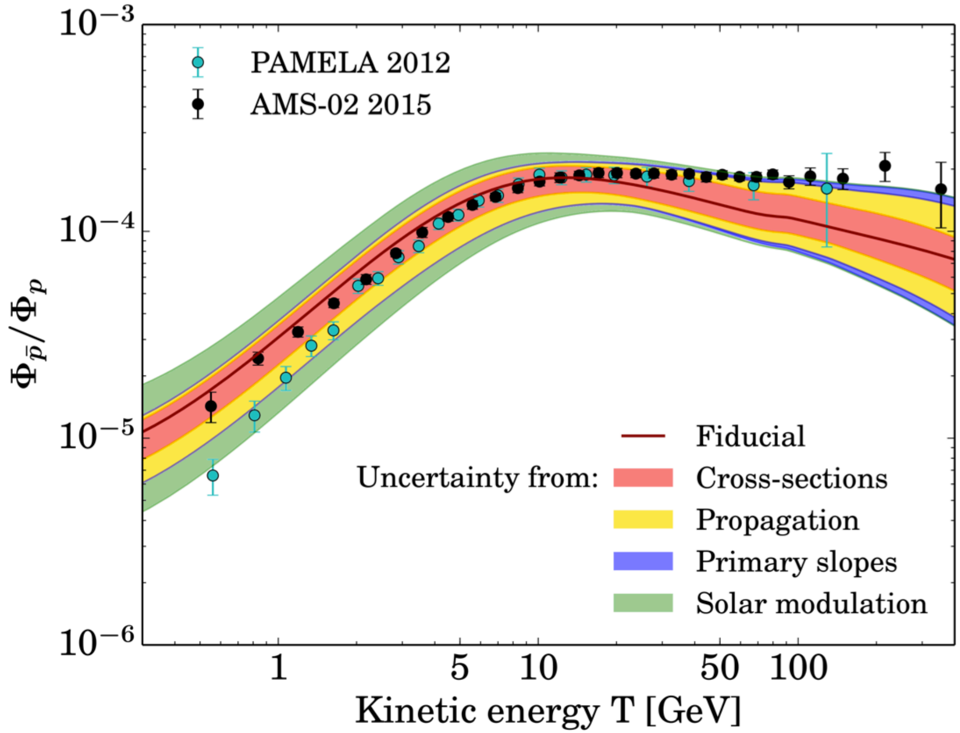
Cosmic antiprotons and antihelia

Antiprotons are secondary CR (created by scattering of high energy CR with interstellar protons or nuclei)

⇒ Good probe of CR generation mechanism, especially DM

Problem :

Accuracy of the creation production cross section



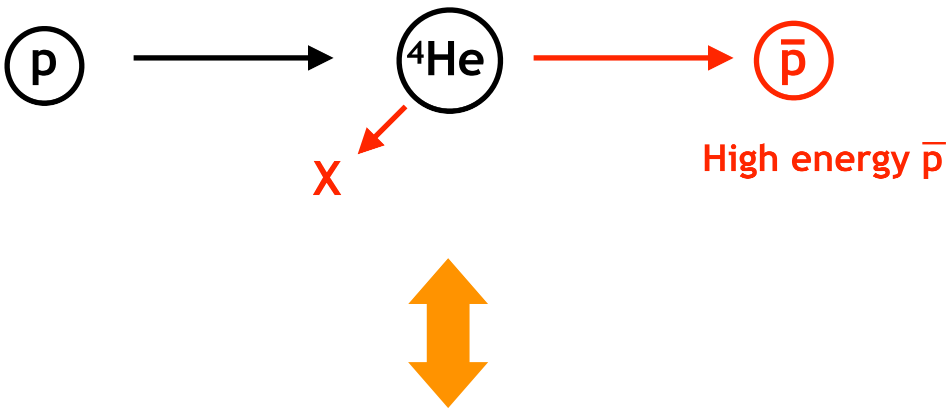
antiproton/proton ratio, AMS-02 (2015)

Inverse kinematics in the antiproton production in FT mode

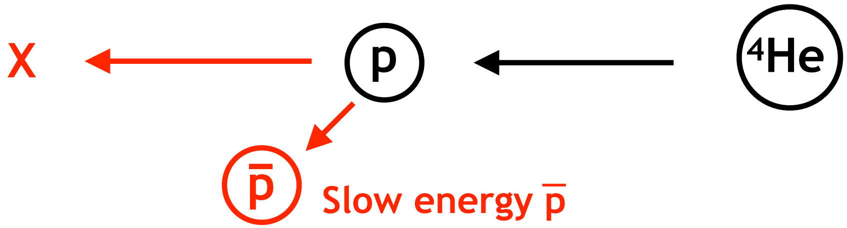
p beam to ^{4}He targets can probe ^{4}He beam to p targets with inverse kinematics

$p + {}^4He \rightarrow p + X$

<u>"Normal" frame:</u>



<u>Inverted frame:</u>



ALICE can measure slow antiproton!

Summary

- AFTER@LHC : we are promoting fixed-target experiment using LHC beam.
- Keywords : large rapidity, heavy quarks.
- Three important motivations:
  (1) High-x physics,
  (2) Spin physics,
  (3) Heavy ion physics.
- High-x physics : reduce gluon PDF uncertainty, probe intrinsic heavy quarks.
- Spin physics : probe parton OAM, indirectly with TMD, directly with GPD via UPC.
- Heavy-ion physics : rapidity scan can access finite density QCD.
- Application to astrophysics : cosmic antiproton spectrum, atmospheric neutrinos.

Backup