

Fixed-target experiment using LHC beams

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

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KEK

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?

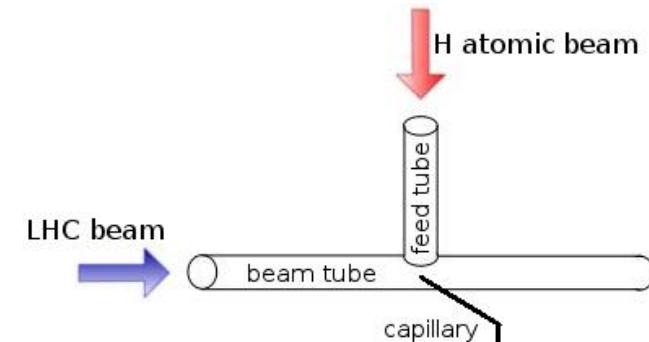


Despite the loss of E_{CM} , fixed-target experiment has its own advantages:

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

Three options

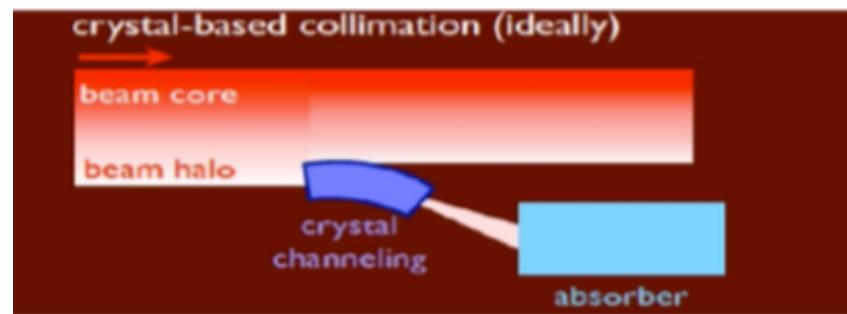
- Position target in beam pipe of LHCb
(c.f. SMOG@LHCb)



- Position target in beam pipe of ALICE

- Independent apparatus with new beam line

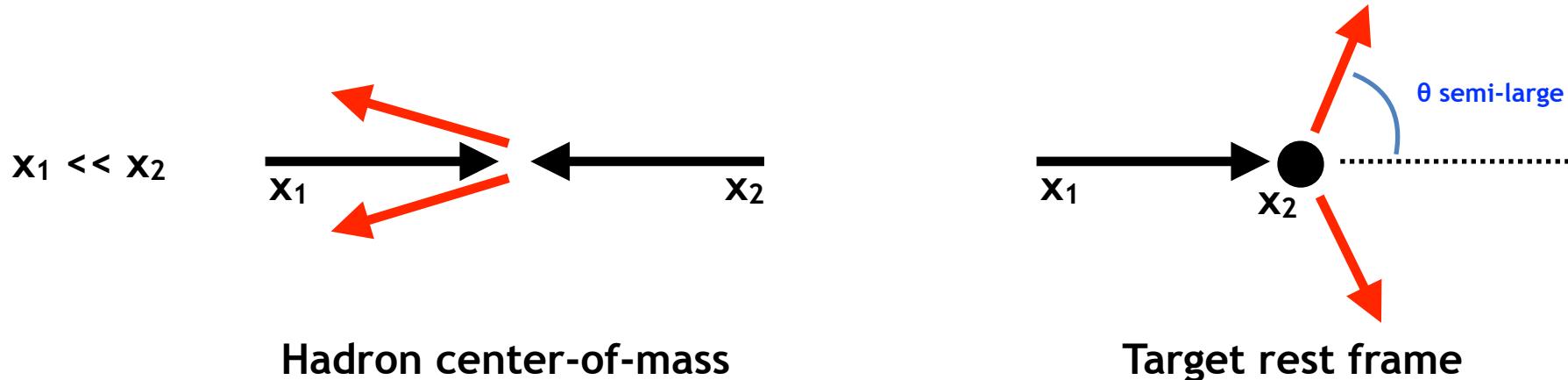
Beam halo is conducted to beam line with bent crystal
(application of the technology of beam collimation)



In any case, other LHC experiments will not be disturbed!

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 $p\bar{p}$
(Fixed target mode of LHCb)



Kinematics of bottomonium production: $x_{1,2} = \frac{m_{b\bar{b}}}{\sqrt{s}} e^{\pm y_{c.m.s.}}$

($\sqrt{s} = 115\text{GeV}$
for fixed-target)

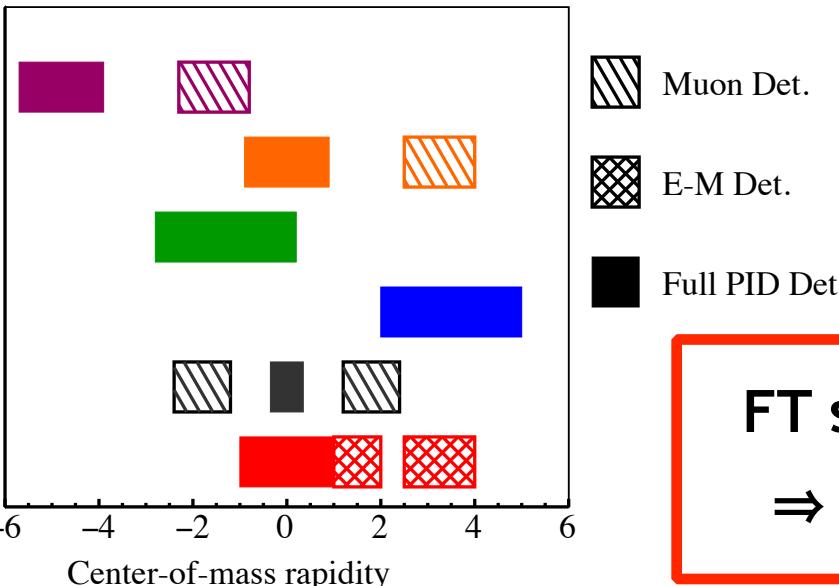
Production threshold at CM: $x_1 x_2 s = m_{b\bar{b}}^2$

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

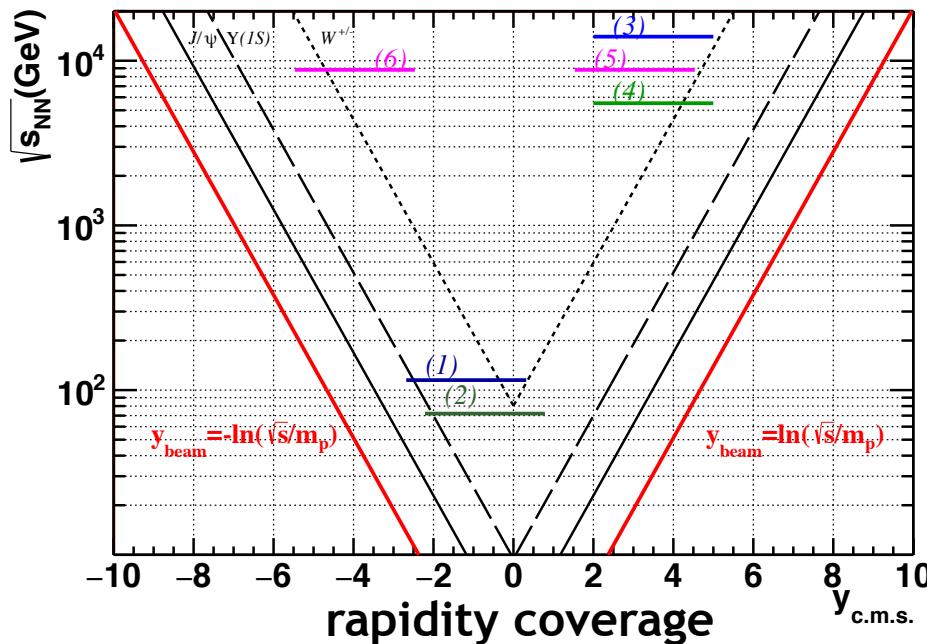
→ Can access up to “ x ” = 1.4 with
LHCb in the fixed-target mode

Expected performance with existing apparatus

ALICE (Fixed Target)

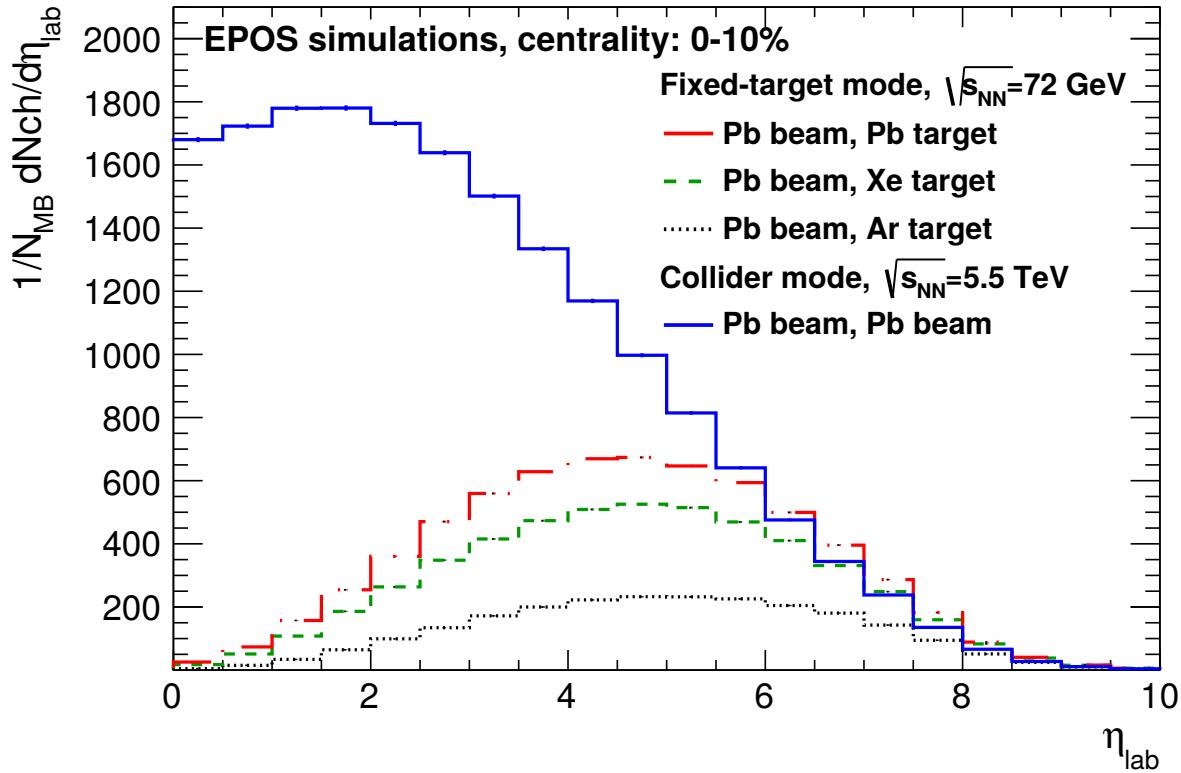


FT shifts the rapidity
⇒ Access to far backward



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

Charged particle multiplicity for heavy-ion collision



Assumed max. instantaneous luminosity : $3 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}$

- Maximum of charged particles (for PbXe, $\sqrt{s_{NN}}=72 \text{ GeV}$) is near $\eta_{lab}=4$
- 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

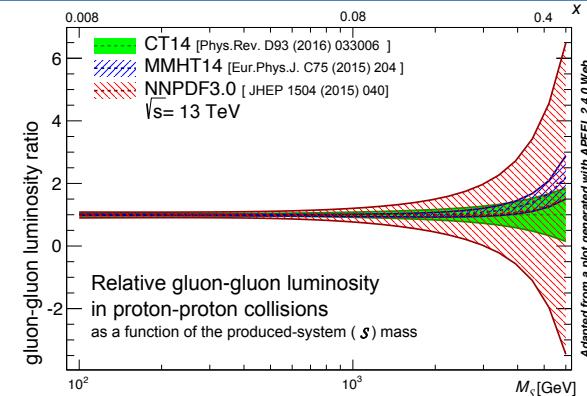
Especially gluon PDF

High-x region is interesting because

- ➊ EMC effect, especially gluon EMC (almost unknown)
Relation with the short-range correlation suggested, but what about gluons?
- ➋ Intrinsic charm, bottom : nonperturbative enhancement at high-x
- ➌ 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:

- ➊ Accuracy of PDFs needed for BSM search
- ➋ 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

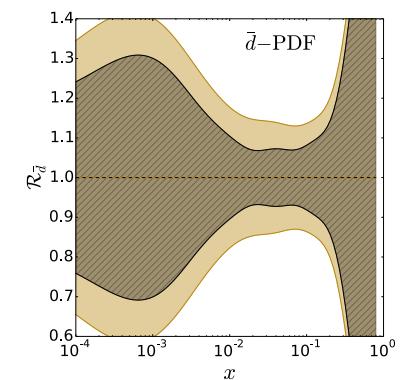
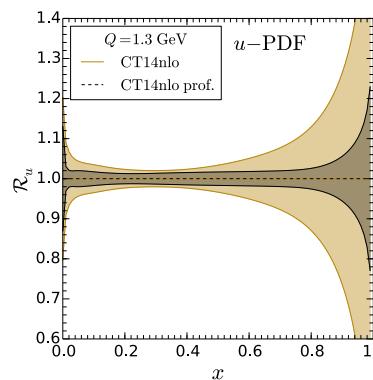
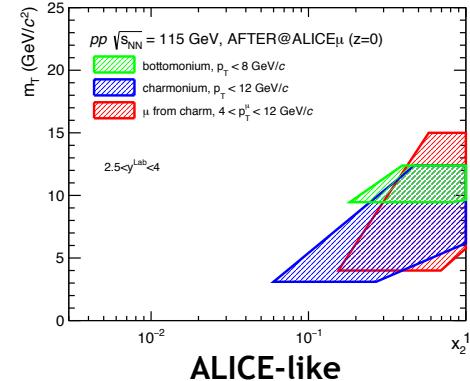
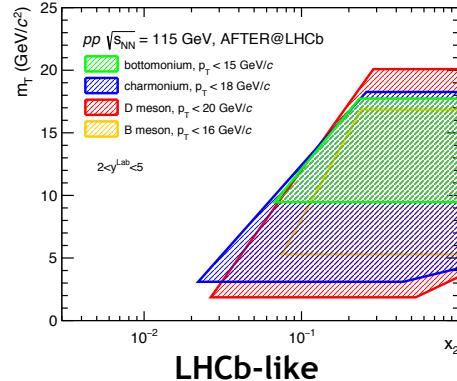
Drell-Yan

- Gluon PDF

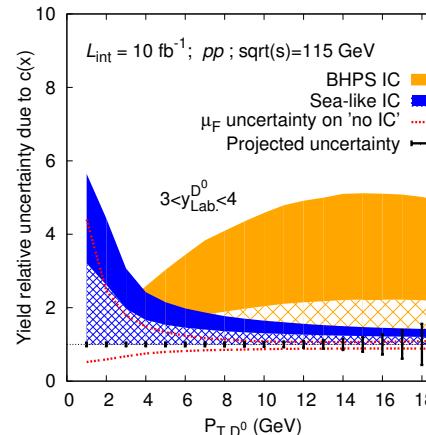
Heavy quark production

- Intrinsic charm PDF

Inclusive D^0 production



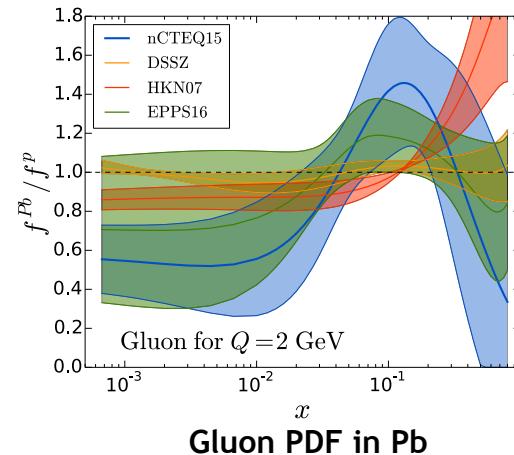
Improvement of light-quark PDF via Drell-Yan in AFTER@LHC



Nuclear PDF

Nuclear PDF is poorly known at high- x

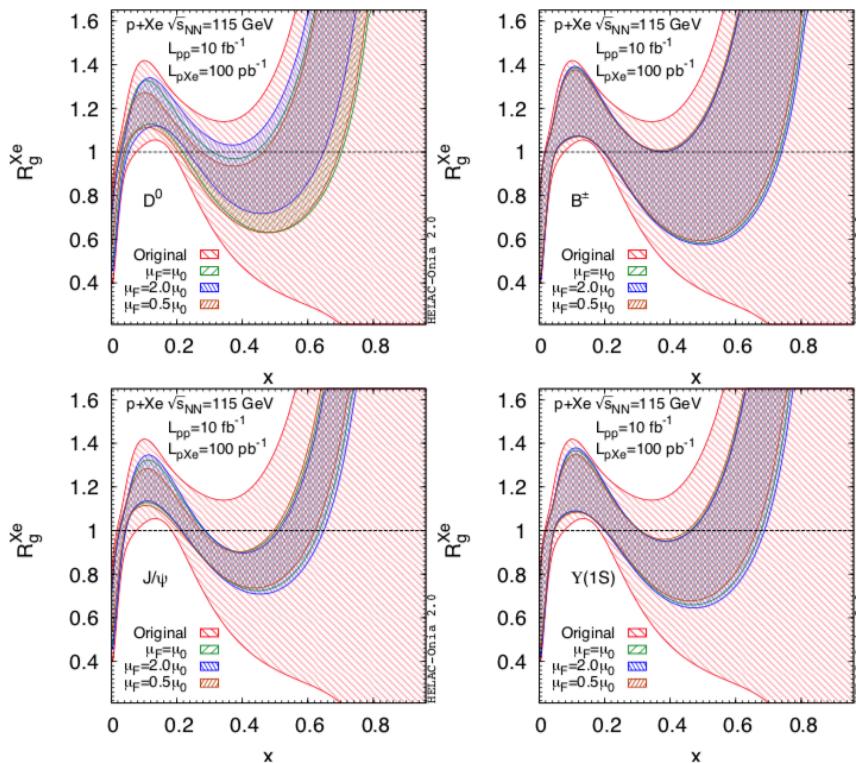
AFTER@LHC can improve PDFs at high- x
via Drell-Yan (u,d), heavy quark (g)



Projection of the nPDF accuracy

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

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



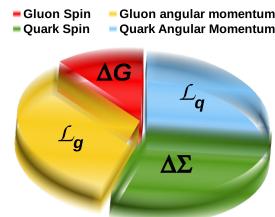
→ We see a remarkable
improvement at high- x

Spin physics

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

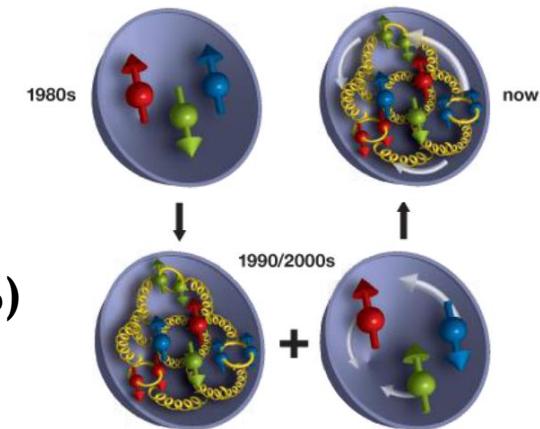
Proton spin decomposition:

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



Quark spin contribution to nucleon spin is small ($\sim 30\%$)

\Rightarrow Proton spin puzzle (since 1980's)



Recent experimental data suggest the **orbital angular momentum (OAM)**

OAM \Rightarrow Transverse motion \Rightarrow TMD (k_T) or GPD

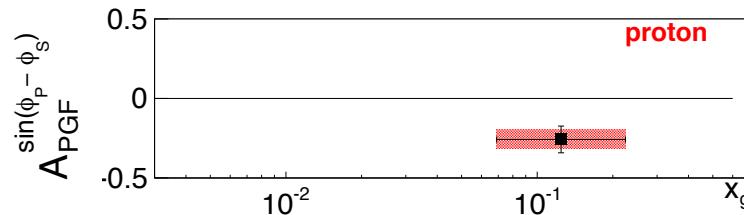
Probed with single transverse spin asymmetry (STSA)

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 :



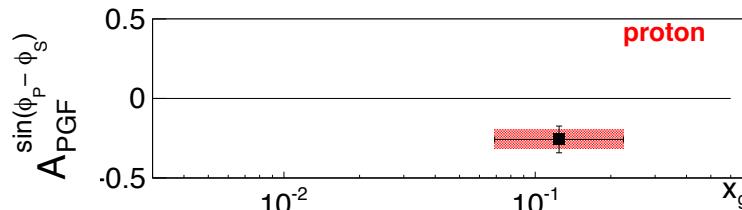
$$\Rightarrow f_{1g}^\perp \neq 0 \quad (\text{gluon Sivers})$$

\Rightarrow Hint of gluon OAM $\angle g \neq 0$!

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

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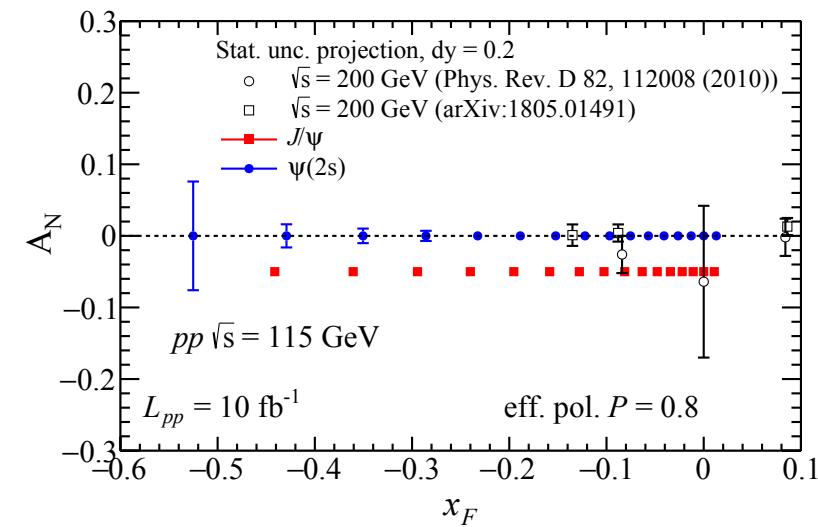


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$\Rightarrow f_{1g}^\perp \neq 0$ (gluon Sivers)

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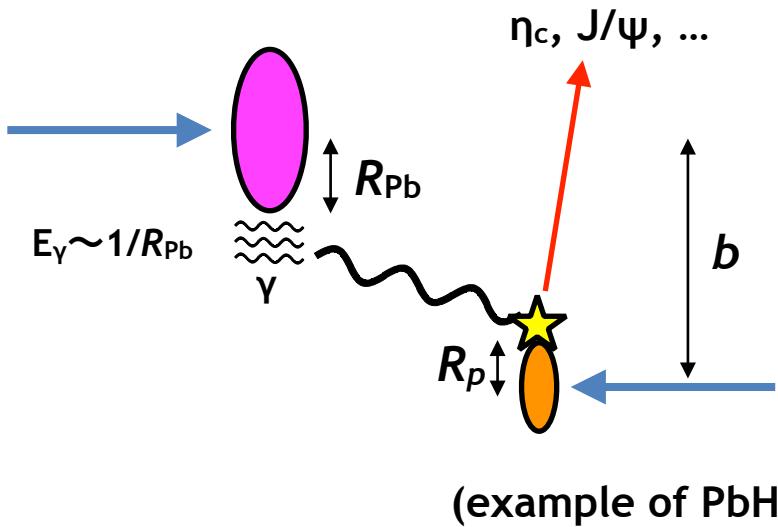
Gluon Sivers can also be indirectly accessed with **inclusive quarkonia** with AFTER@LHC with a much better accuracy than PHENIX



Access to gluon GPD via ultraperipheral collisions (UPCs)

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

⇒ Dominated by photon exchanges



Kinematics of UPC in fixed-target exp at LHC:

- Boost of photon in projectile:

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

- Energy of photon :

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

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

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

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

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

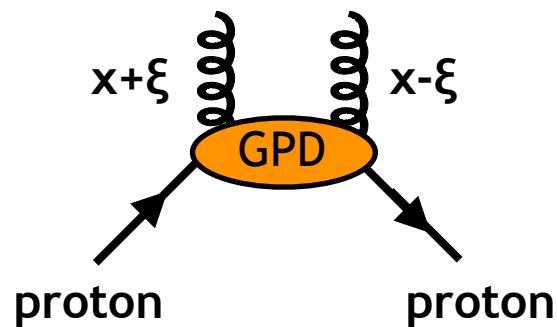
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Gluon generalized parton distribution (GPD)

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

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

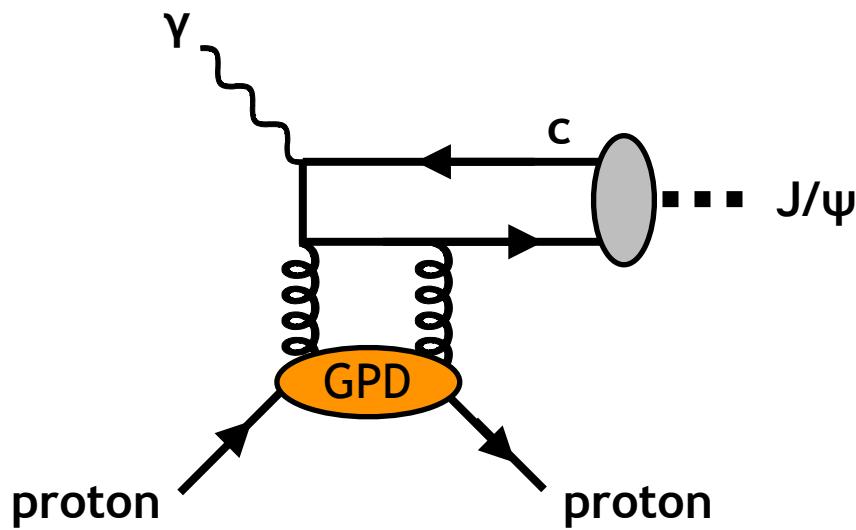
Gluon GPD = “Pomeron form factor”



$$\begin{aligned} F^g(x, \xi, t) &= \frac{1}{(P n_-)} \int \frac{d\lambda}{2\pi} e^{ix(Pz)} n_{-\alpha} n_{-\beta} \left\langle p' \left| G^{\alpha\mu} \left(-\frac{z}{2}\right) G_\mu^\beta \left(\frac{z}{2}\right) \right| p \right\rangle \Big|_{z=\lambda n_-} \\ &= \frac{1}{2(P n_-)} \left[H^g \bar{u}(p') \gamma_\perp u(p) + E^g \bar{u}(p') \frac{i\sigma^{\alpha\beta} n_{-\alpha} \Delta_\beta}{2m_N} u(p) \right] \end{aligned}$$

Extraction of GPD from J/ ψ photoproduction

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



$$\mathcal{M} = \frac{2^3 \sqrt{\pi} e e_q \epsilon^*(p_\psi) \cdot \epsilon(p_\gamma)}{M_\psi^{3/2} \sqrt{N_c} \xi} \cdot \frac{R(0)}{2(P n_-)} \left[\mathcal{H}^g \bar{u}(p') \not{\eta}_- u(p) + \mathcal{E}^g \bar{u}(p') \frac{i \sigma^{n-\Delta}}{2m_N} u(p) \right]$$

$$\left\{ \begin{array}{l} \mathcal{H}^g(\xi, t) \equiv \int_{-1}^1 dx T_g(x, \xi) H^g(x, \xi, t) \\ \mathcal{E}^g(\xi, t) \equiv \int_{-1}^1 dx T_g(x, \xi) E^g(x, \xi, t) \end{array} \right.$$

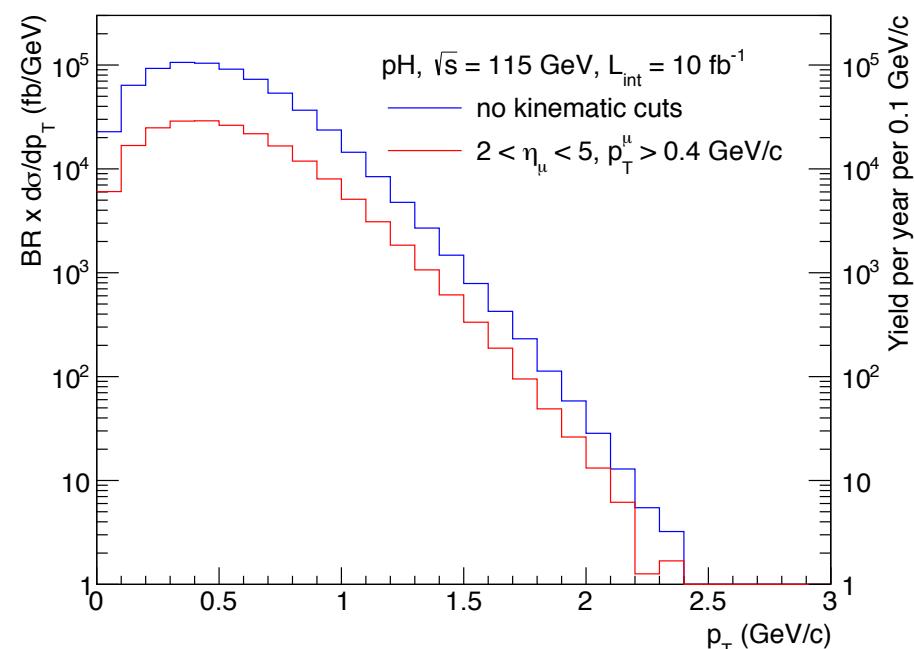
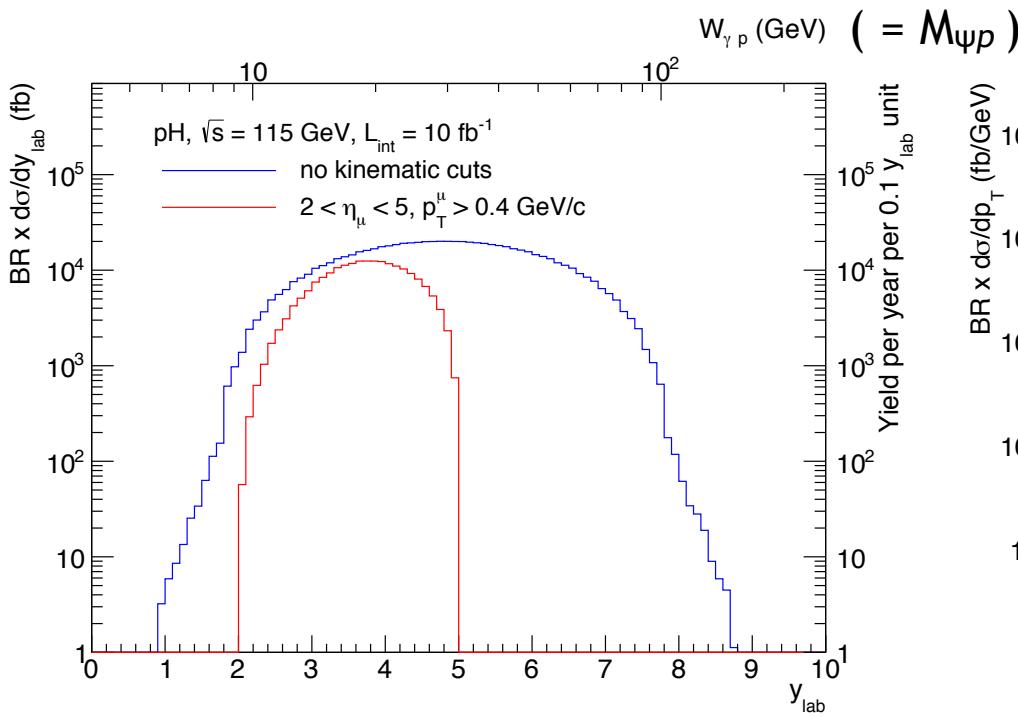
$$\text{with } T_g(x, \xi) = \frac{\xi}{(x - \xi + i\epsilon)(x + \xi - i\epsilon)} \alpha_s$$

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

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

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

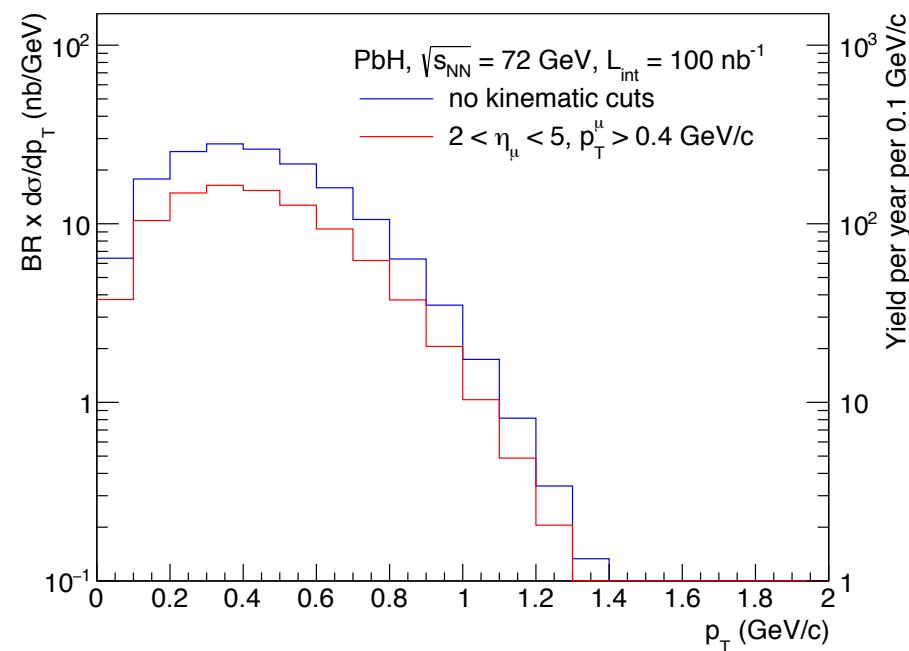
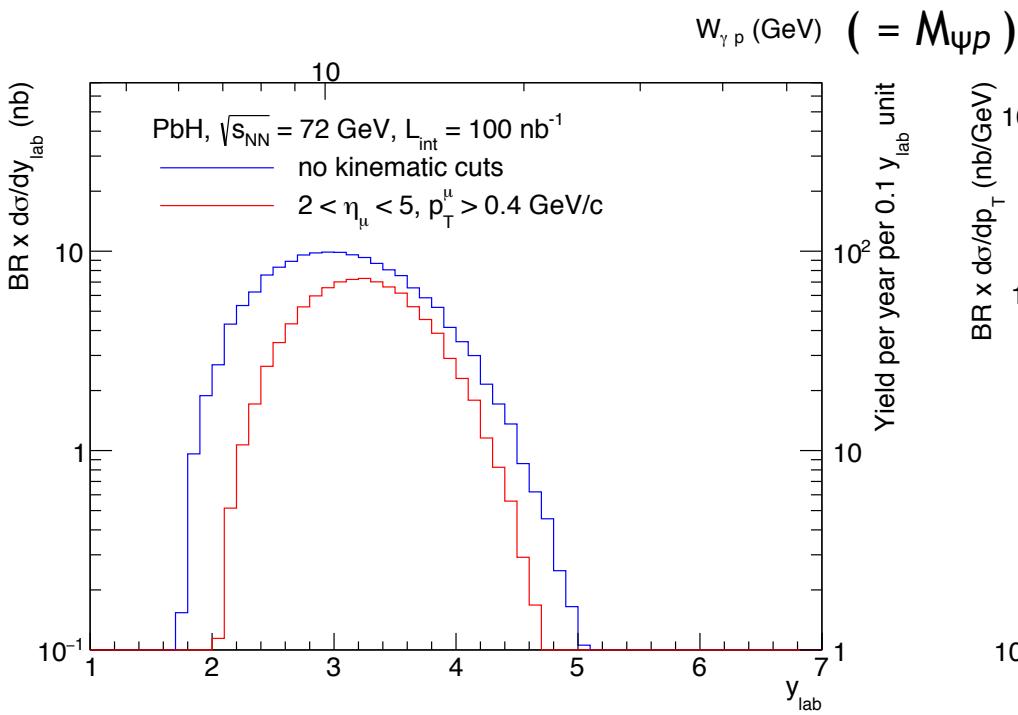
(Simulated with STARLIGHT)



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

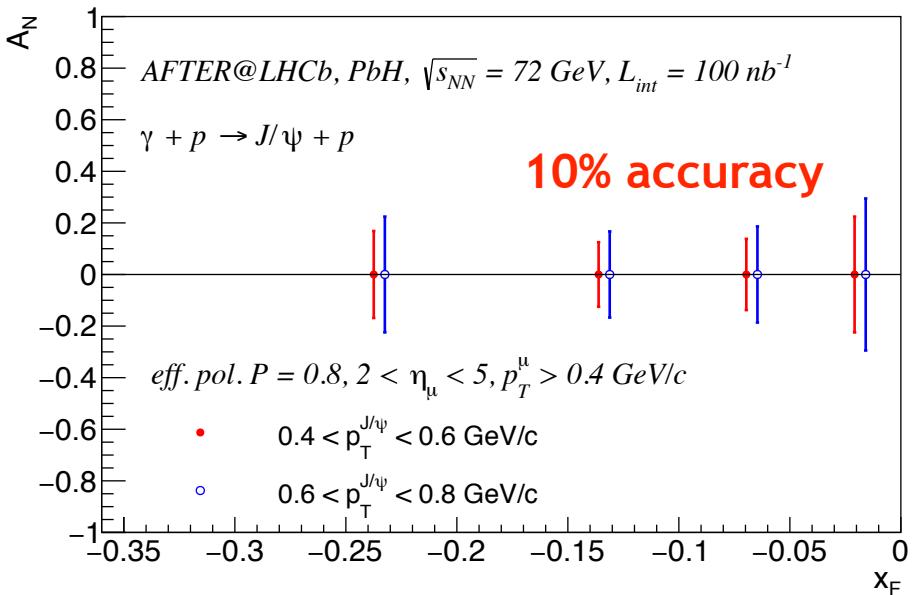
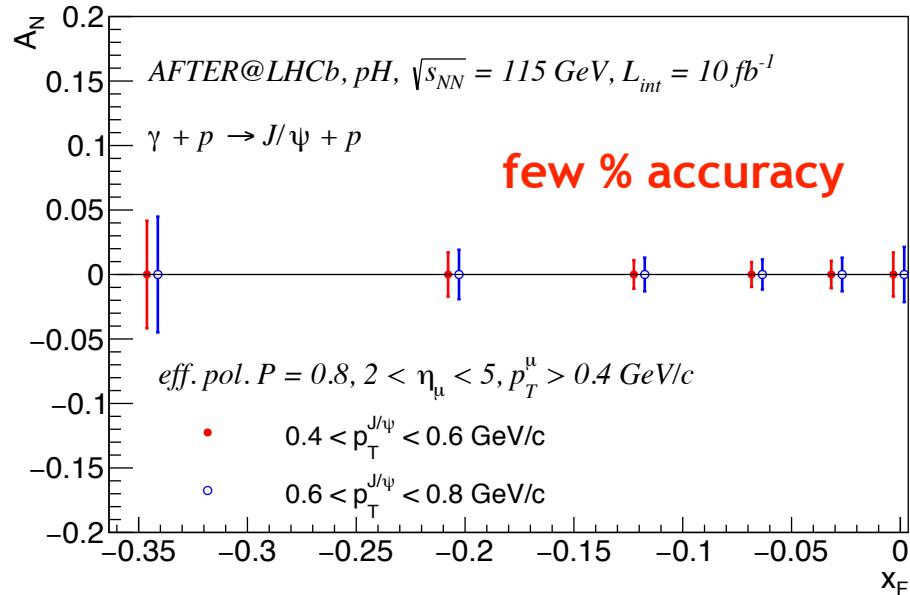
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$\sigma_{J/\psi \rightarrow l^+l^-}$ (with LHCb η_μ and p_T^μ cut) (pb)	20.64	9.81×10^3
# events	200 000	1000

(Simulated with STARLIGHT)



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

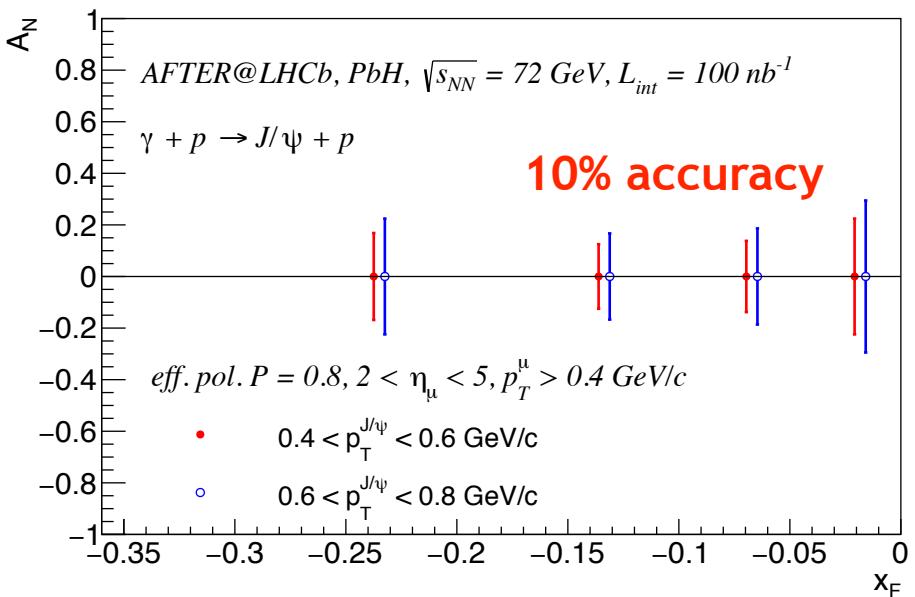
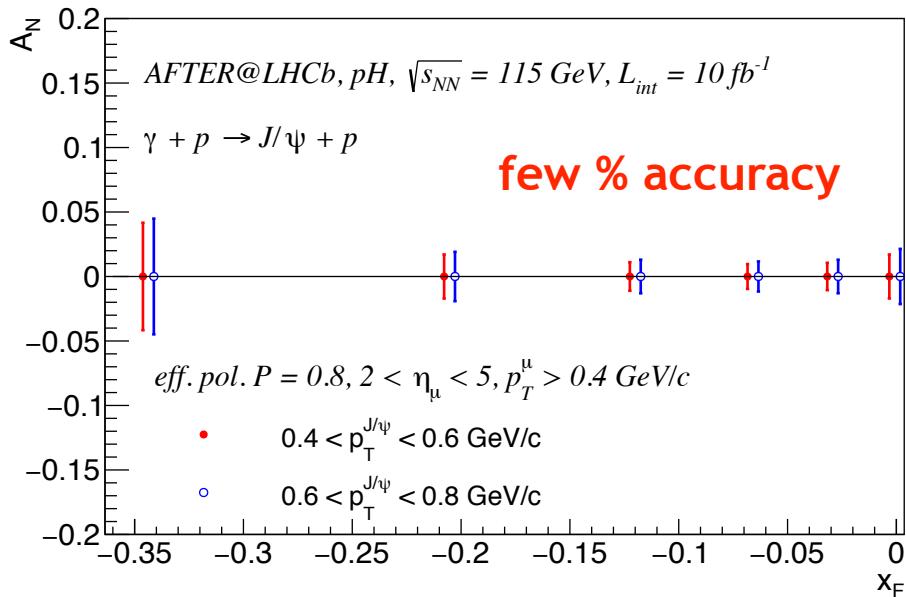
Assuming a target polarization of 80%
 (compatible with H-jet system from RHIC or HERMES-like storage cell)



$$A_N^{\gamma p^\uparrow \rightarrow J/\psi p} \propto \sqrt{t_0 - t} \operatorname{Im} (\mathcal{E}^{g*} \mathcal{H}^g)$$

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

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$$A_N^{\gamma p^\uparrow \rightarrow J/\psi p} \propto \sqrt{t_0 - t} \operatorname{Im} (\mathcal{E}^{g*} \mathcal{H}^g)$$

- ➊ PbH is better than pH since we know the source of emitted photon
- ➋ 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

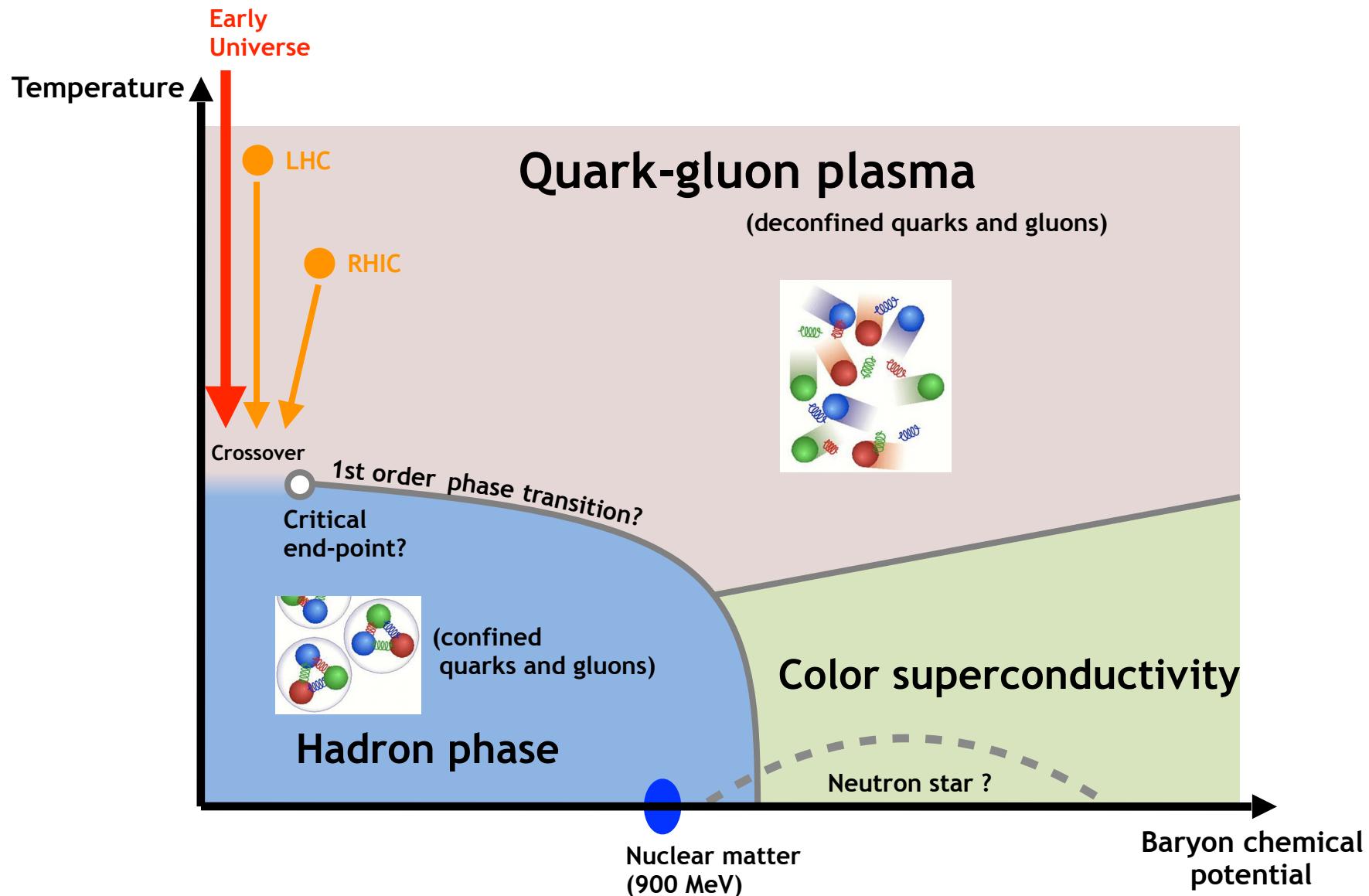
Important observables:

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

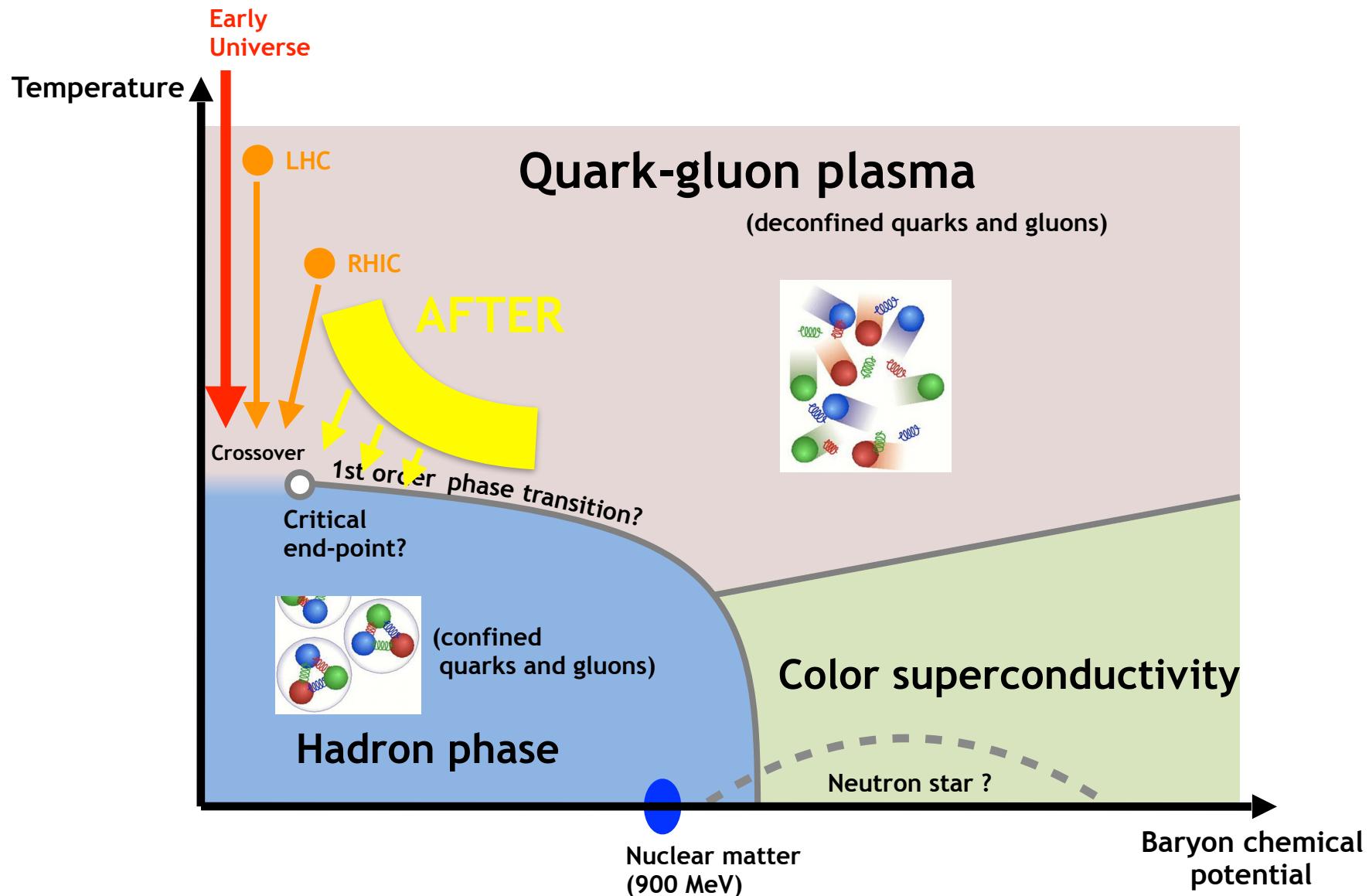
Advantages of AFTER@LHC:

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

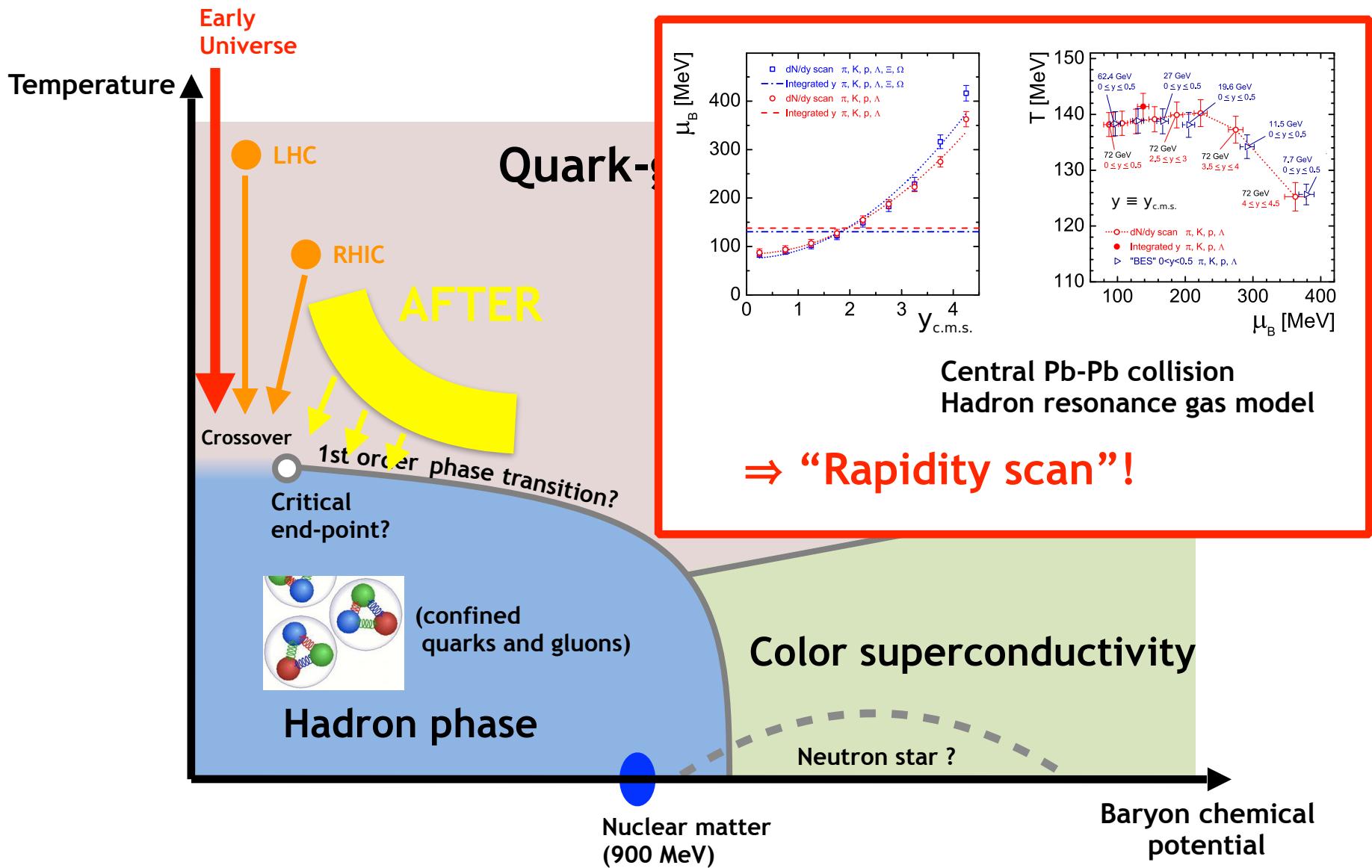
Heavy-ion physics : AFTER vs QCD phase diagram



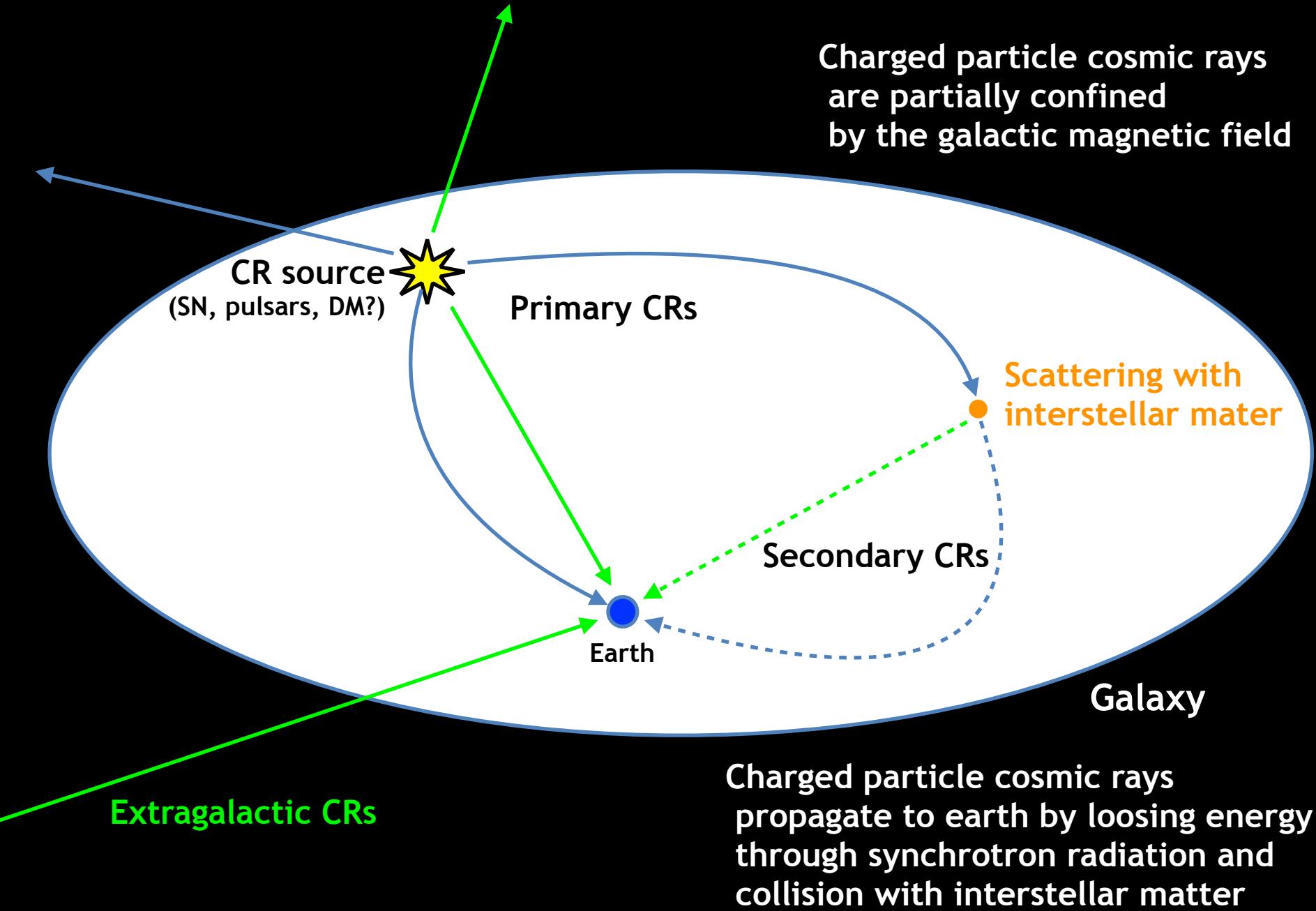
Heavy-ion physics : AFTER vs QCD phase diagram



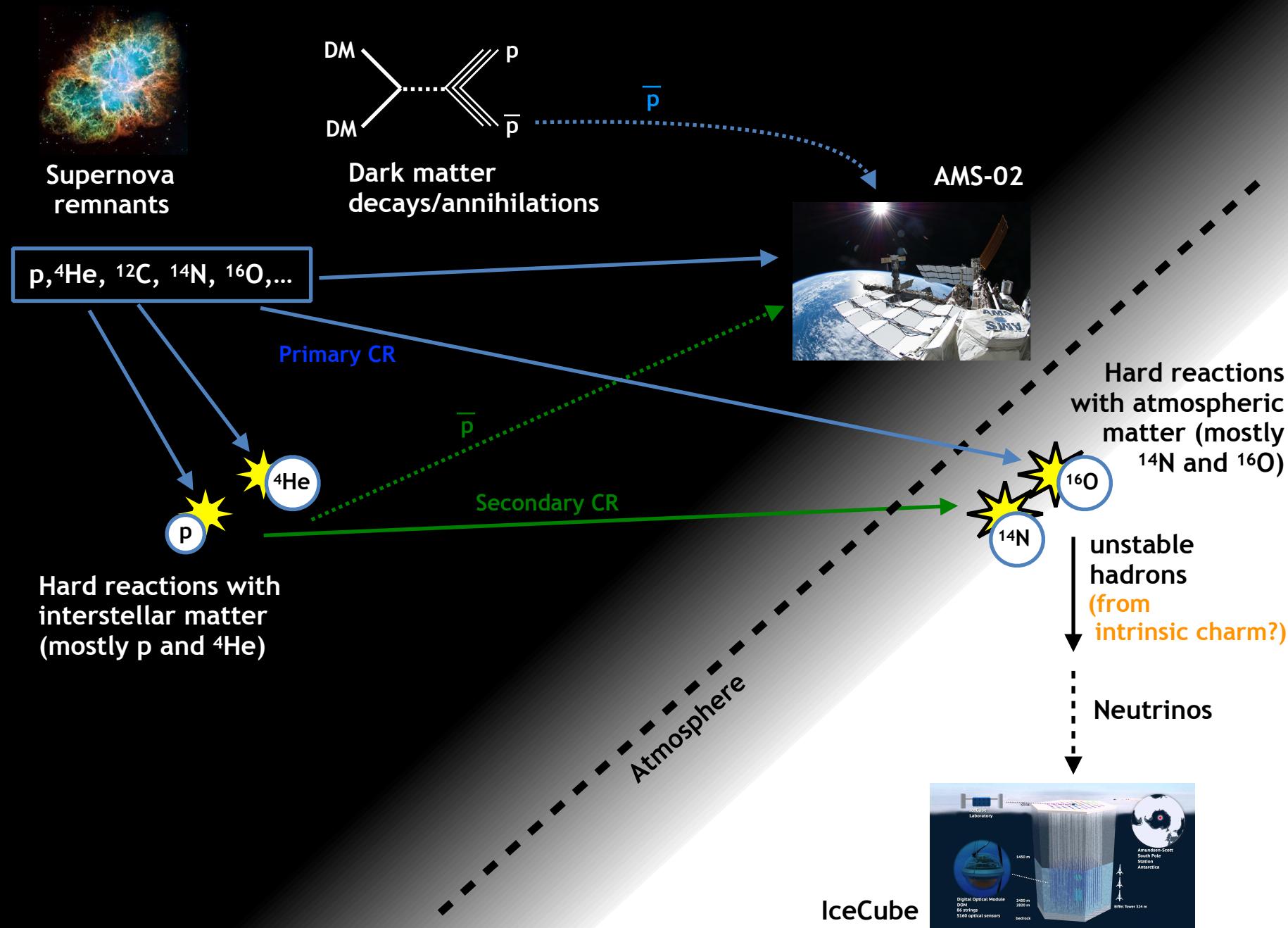
Heavy-ion physics : AFTER vs QCD phase diagram



Astrophysics and cosmic rays



Application to astrophysics :cosmic antiprotons, neutrinos



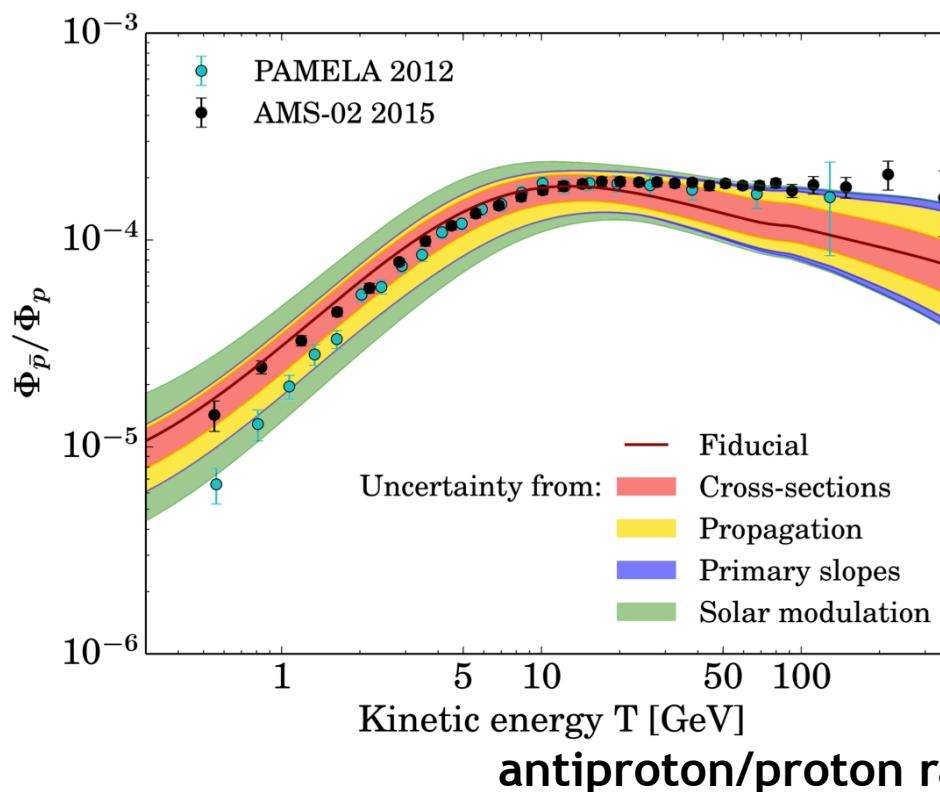
Cosmic antiprotons and antihelia

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

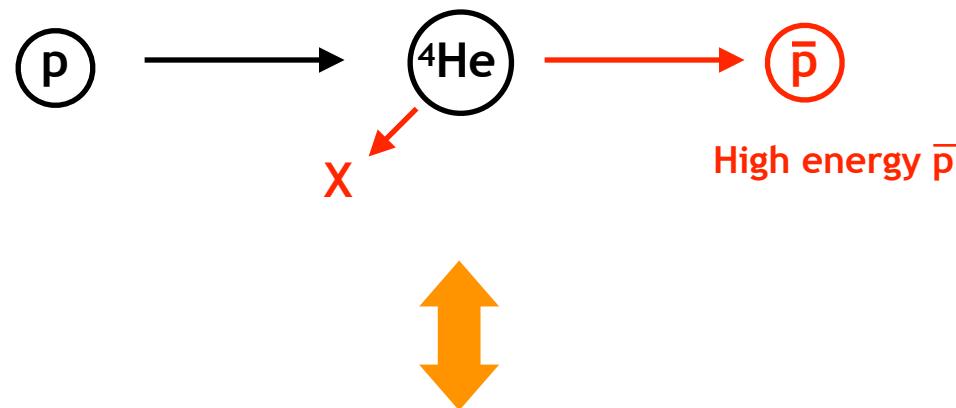


Inverse kinematics in the antiproton production in FT mode

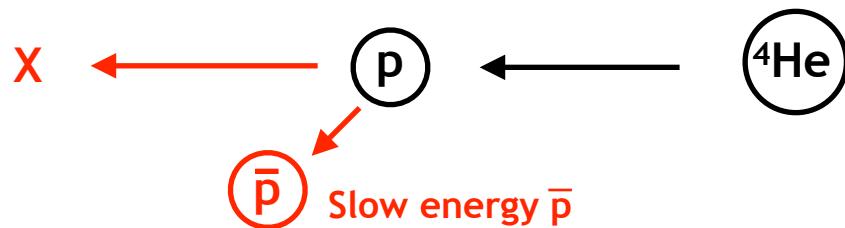
p beam to ${}^4\text{He}$ targets can probe ${}^4\text{He}$ beam to p targets with inverse kinematics



Laboratory frame:



Inverted frame:



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