



JSPS



# Ultra-peripheral-collision studies in the fixed-target mode with the proton and lead LHC beams

Nodoka Yamanaka

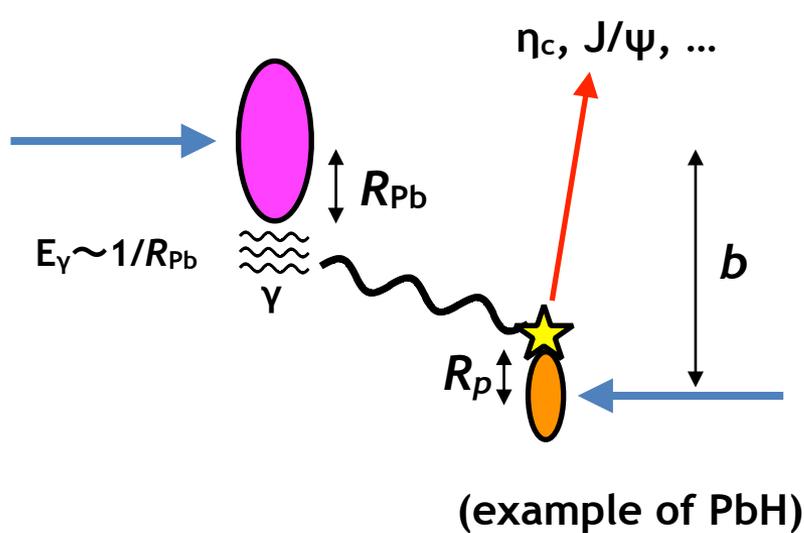
(IPN Orsay, on behalf of the  
AFTER@LHC Study Group)

2018/10/02  
Hard Probes 2018  
Aix-les-bains

# Ultra-peripheral collision in the fixed-target mode @ LHC

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

⇒ 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 :

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

- C.M. energy of  $\gamma p$  in fixed-target mode :

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

⇒ First opportunity to study **UPCs** in the **fixed-target (FT) mode!**

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

System	target thickness (cm)	$\sqrt{s_{NN}}$ (GeV)	$\mathcal{L}_{AB}^a$ ( $\text{pb}^{-1}\text{yr}^{-1}$ )	$E_A^{\text{lab}}$ (GeV)	$E_B^{\text{lab}}$ (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												
<i>pp</i>	100	115	$2.0 \times 10^4$	7000	$m_N$	61.2	7450	140	1050	44	8.5	17
<i>pPb</i>	1	115	$1.6 \times 10^2$	7000	$m_N$	61.2	7450	26	190	19	1.6	3.2
<i>pd</i>	100	115	$2.4 \times 10^4$	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	$1.2 \times 10^1$	100	100	106.4	22600	140	3150	77	15	30
<i>AuAu</i>	N/A	200	$2.8 \times 10^{-3}$	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

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

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

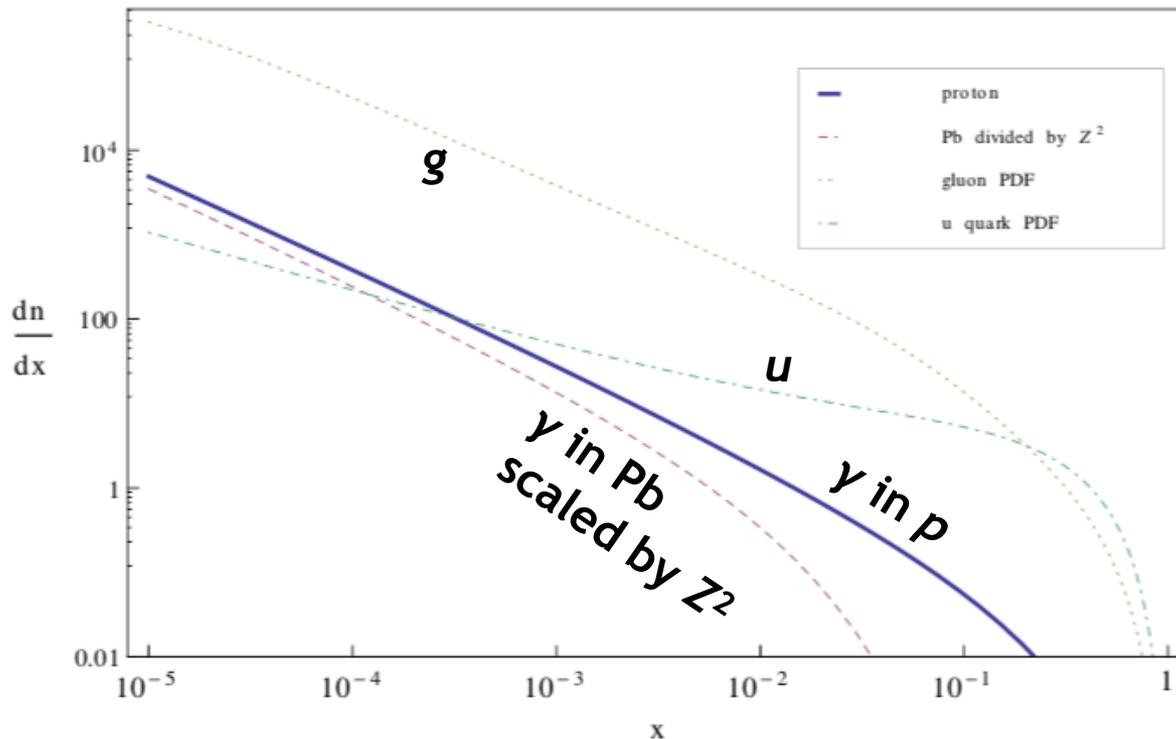
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# Photon flux and cross section in UPC

## Hadron-hadron cross section:

$$d\sigma^{h_A h_B} = \int dk_\gamma \left( \frac{dn^{h_A}}{dk_\gamma} d\sigma^{\gamma h_B}(s_{\gamma h_B}(k_\gamma)) + \frac{dn^{h_B}}{dk_\gamma} d\sigma^{\gamma h_A}(s_{\gamma h_A}(k_\gamma)) \right)$$

Convolution of photon-hadron collision (or photon-photon)



**What can we study with the UPC  
in fixed-target mode at the LHC?**

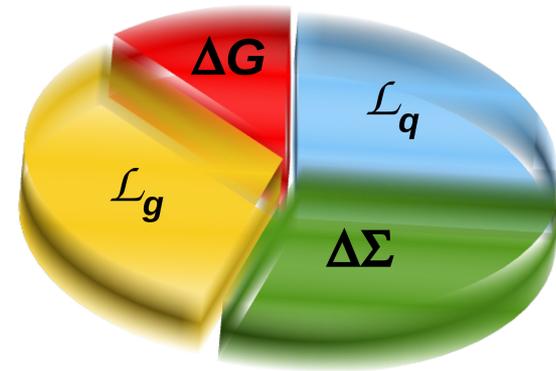
# Gluon orbital angular momentum (OAM)

## Proton spin decomposition:

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

gluon OAM

■ Gluon Spin    ■ Gluon angular momentum  
■ Quark Spin   ■ Quark Angular Momentum



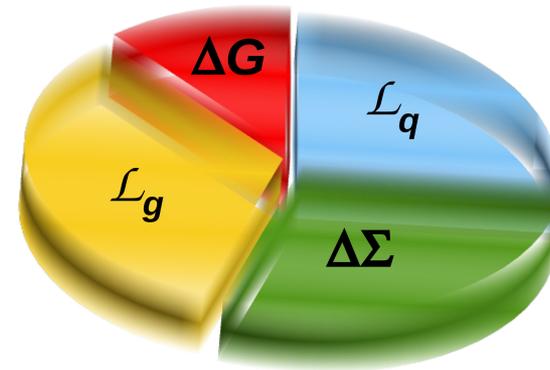
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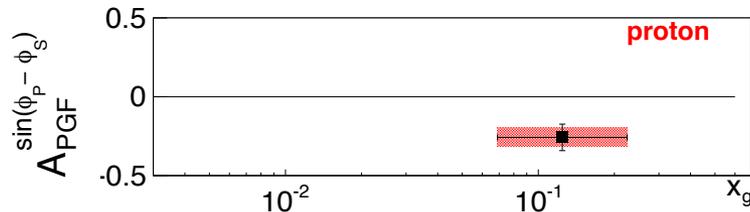
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Recently, COMPASS found nonzero gluon Sivers asymmetry :



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

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

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

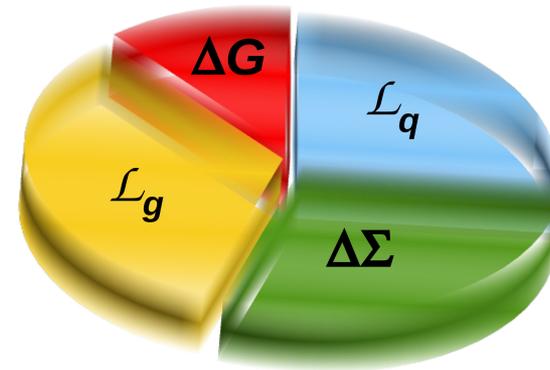
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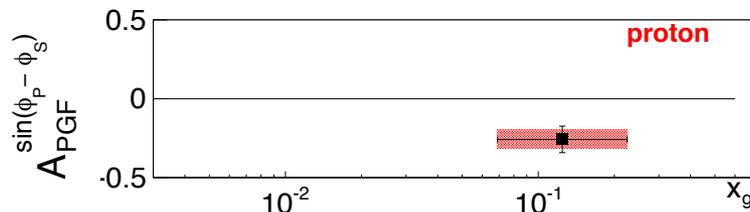
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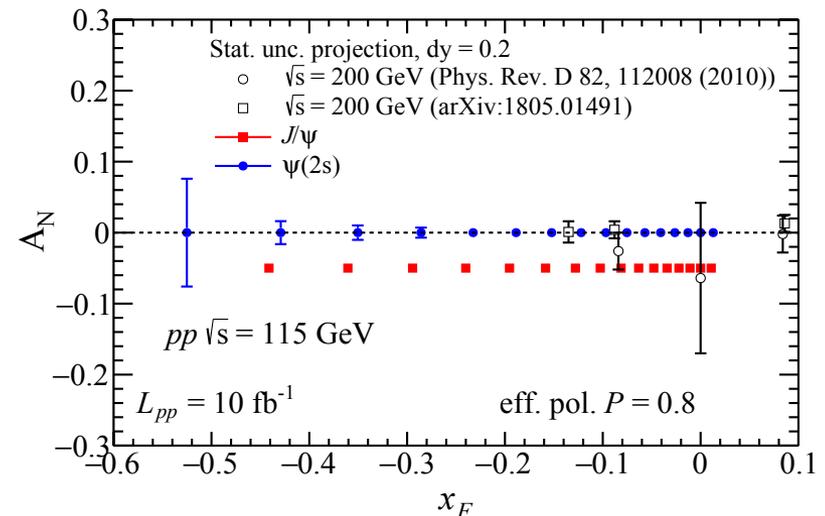
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Gluon Sivers can also be indirectly accessed with **inclusive** quarkonia with AFTER@LHC with a much better accuracy than PHENIX

C. Hadjidakis et al., arXiv:1807.00603 [hep-ex]

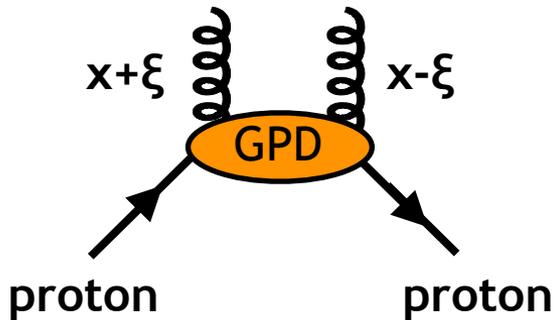


# Gluon generalized parton distribution (GPD)

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

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

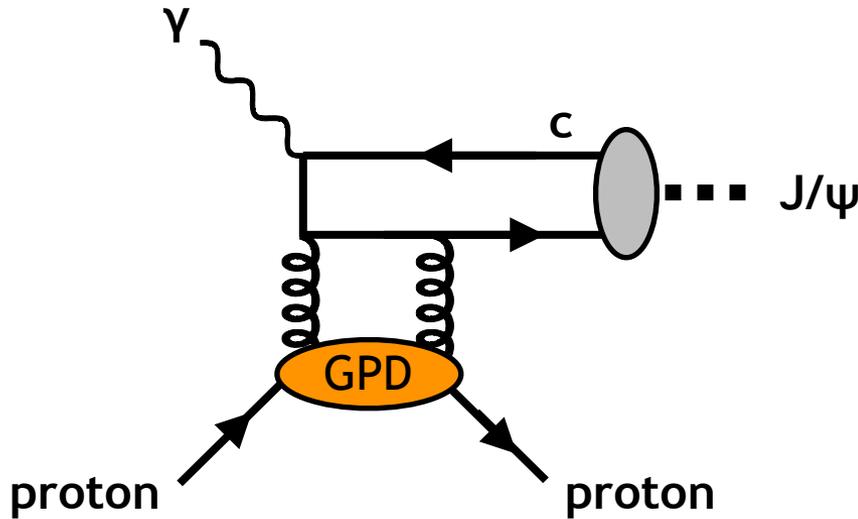
**Gluon GPD = “Pomeron form factor”**



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

# Extraction of GPD from $J/\psi$ photoproduction

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



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

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

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

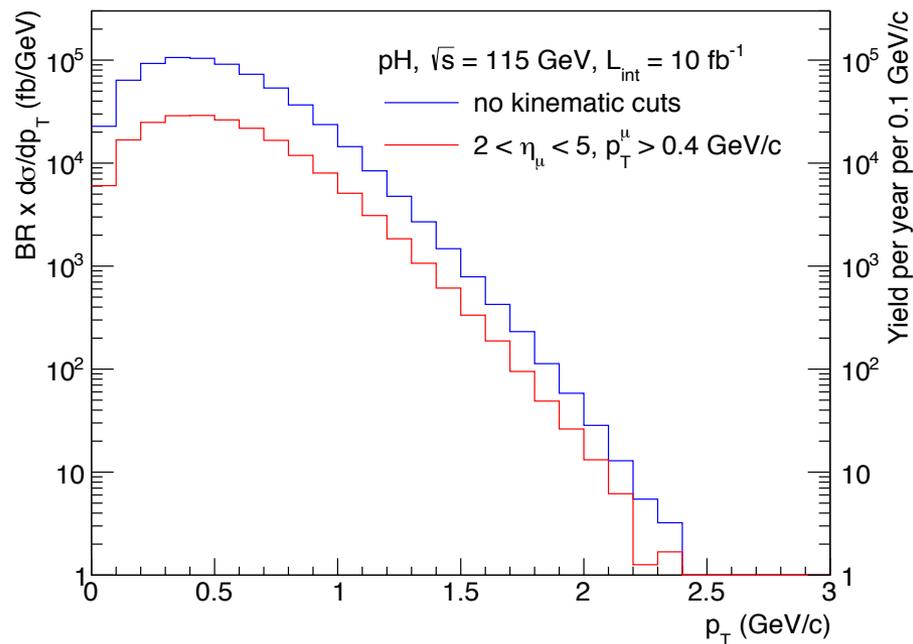
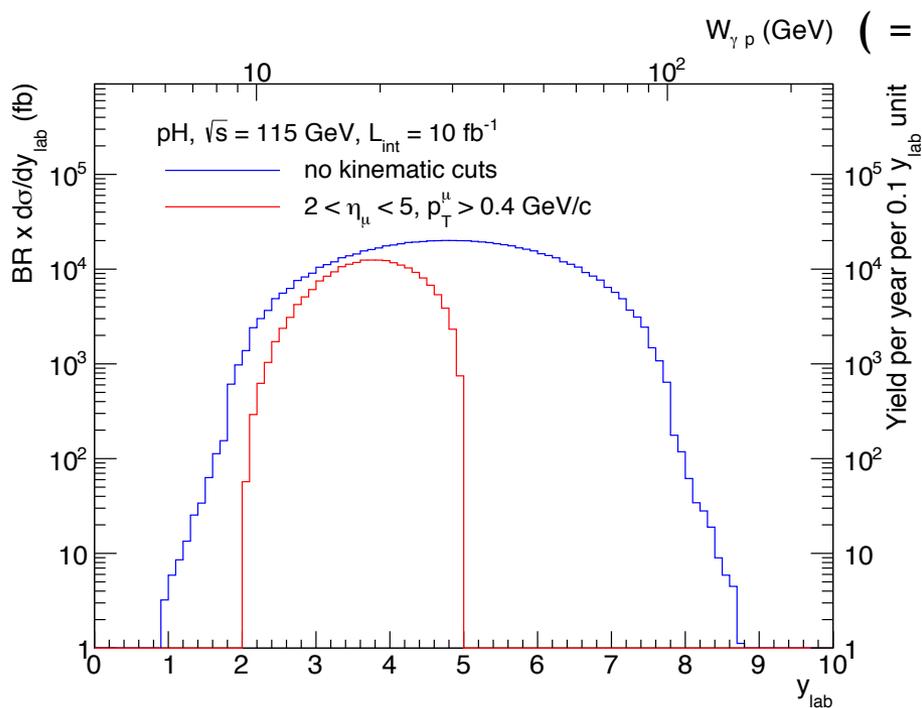
$$\text{with } T_g(x, \xi) = \frac{\xi}{(x - \xi + i\epsilon)(x + \xi - i\epsilon)} \alpha_s$$

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

# Number of $J/\psi$ expected from 1 year run (LHCb, pH)

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

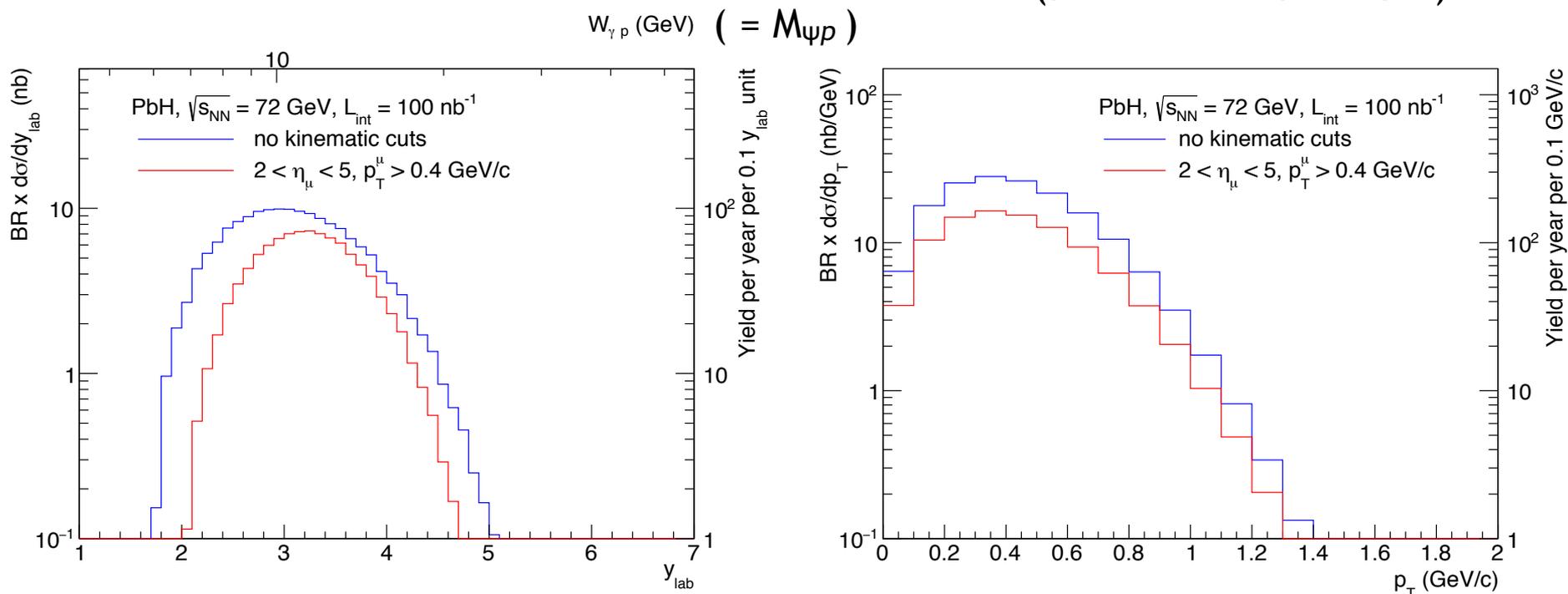
(Simulated with STARLIGHT)



# Number of $J/\psi$ expected from 1 year run (LHCb, PbH)

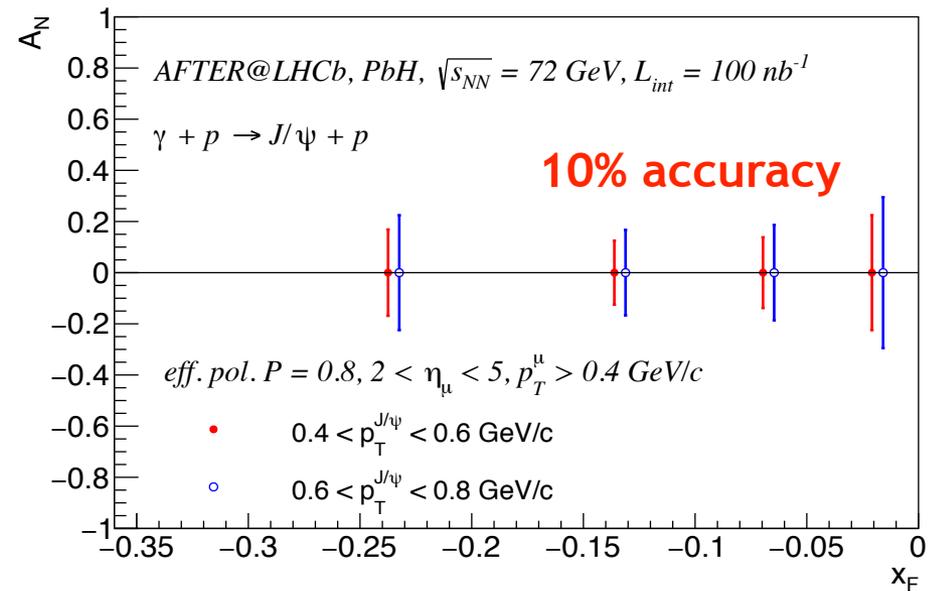
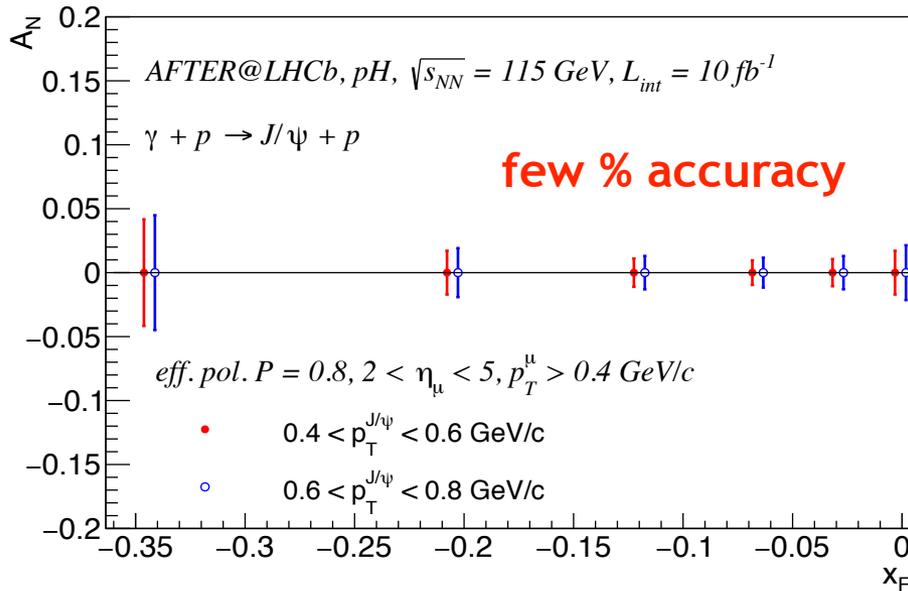
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# Projection of sensitivity to STSA ( $A_N$ ) with AFTER@LHC

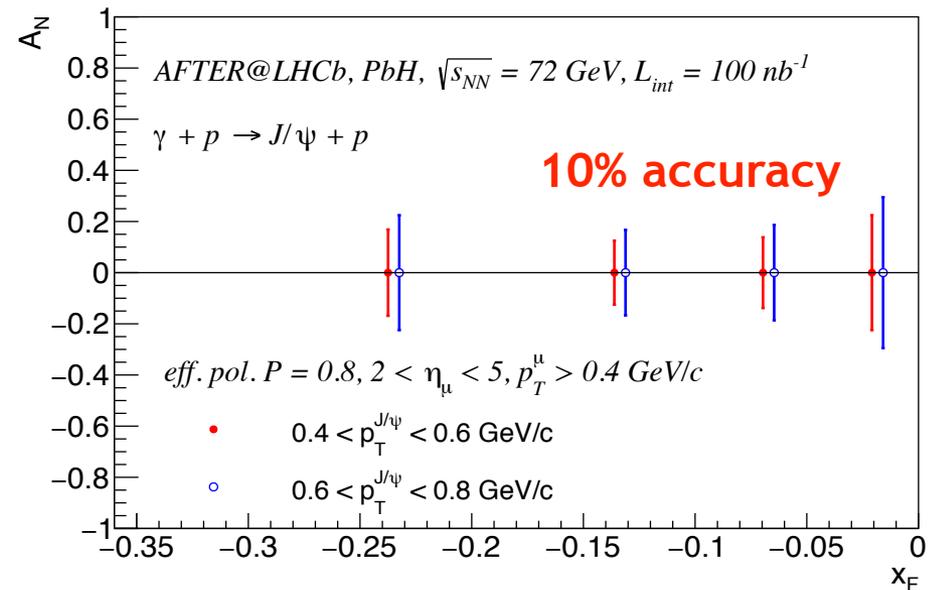
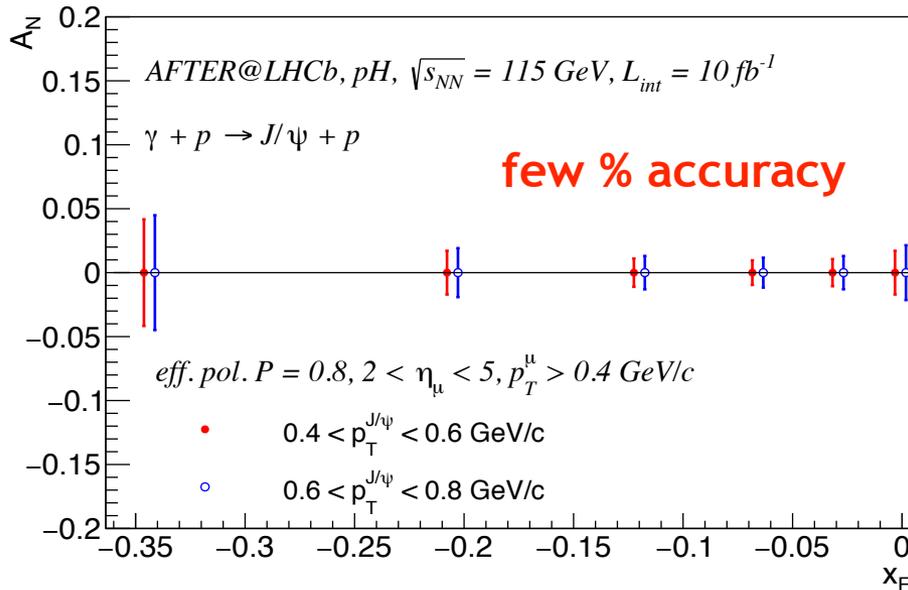
Assuming a target polarization of 80%  
(compatible with H-jet system from RHIC or HERMES-like storage cell)



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

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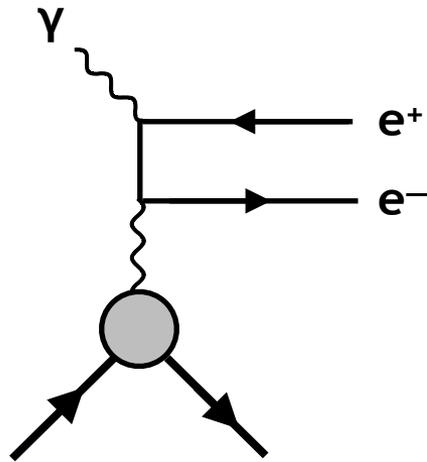


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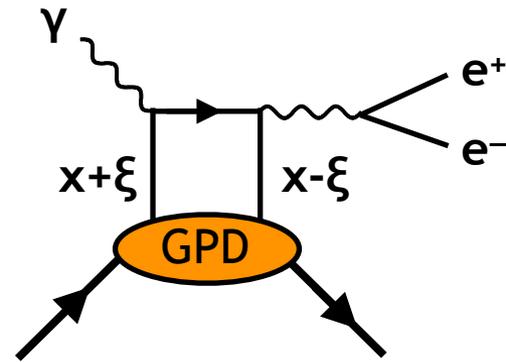
- **PbH is better than pH** since we know the source of emitted photon
- **Might be feasible with a polarized deuteron target**

⇒ probe **deuteron GPD**

# Exclusive dilepton photoproduction via UPC



Bethe-Heitler (BH) scattering



Timelike Compton scattering (TCS)

The BH-TCS interference gives access to quark GPDs via azimuthal asym.  
It can be as large as 10% of the sum for AFTER@LHC energies

	$\sigma_{BH}(\text{pb})$	luminosity	events yr <sup>-1</sup>
p on Pb	1940 pb	0.16 fb <sup>-1</sup> yr <sup>-1</sup>	3 × 10 <sup>5</sup>
p on H	7.1 pb	20 fb <sup>-1</sup> yr <sup>-1</sup>	1.4 × 10 <sup>5</sup>
Pb on H	5500 pb	11 nb <sup>-1</sup> yr <sup>-1</sup>	6 × 10 <sup>3</sup>

# Light-by-light scattering

Light-by-light (LbL) scatterings ( $\gamma\gamma \rightarrow \gamma\gamma$ ) have been observed

ATLAS Collaboration, Nature Phys. 13, 852 (2017)

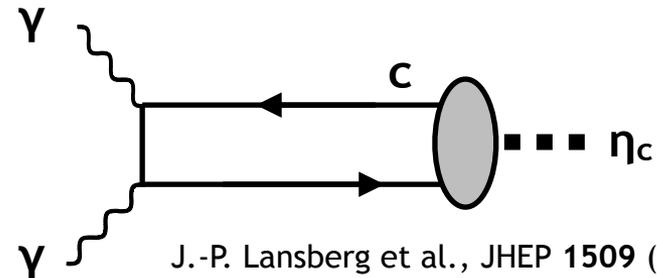
CMS Collaboration, CMS-FSQ-16-012 (talk of Niedziela)

With AFTER@LHC, we can also look for LbL scatterings via UPCs.

We are especially interested in :

## ● $\eta_c$ photoproduction:

We can access to  
the photon flux of  $p$ , Pb



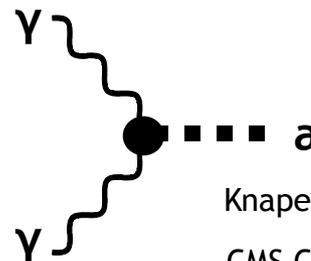
J.-P. Lansberg et al., JHEP 1509 (2015) 087

Goncalves and Sauter, PRD 91, 094014 (2015)

See however S. Klein, arXiv:1808.08253 [hep-ph]

## ● Axion search:

MeV – GeV axions are  
not constrained.



Knapen et al., PRL 118, 171801 (2017)

CMS Collaboration, CMS-FSQ-16-012 (talk of Niedziela)

Feasibility study remains to be done for AFTER@LHC

# 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.

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C. Hadjidakis et al., arXiv:1807.00603 [hep-ex]  
(to be submitted in Phys. Rep.)

Please see other talks on AFTER@LHC:

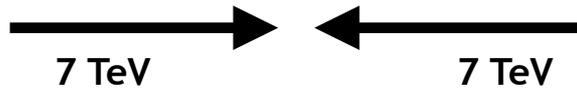
- [Future heavy-ion facilities: FT LHC \(AFTER\) \(J.P. Lansberg\)](#)
- [High-luminosity fixed-target experiments at the LHC \(C. Hadjidakis\)](#)
- [Probing the high-x content of the nuclei in the FT mode \(A. Kusina\)](#)
- [Heavy-flavour-production studies ...in the FT mode \(A. Uras\)](#)

## Summary

- We studied the potentiality of **AFTER@LHC** to measure the **UPC** : for the 1st time we can study UPC in the fixed-target mode.
- We showed that we can probe the **gluon GPDs** via **quarkonium exclusive photoproductions**.
- Using a **polarized target** one can access  $E_g$  and thus the **gluon orbital angular momentum**.
- With  $10\text{fb}^{-1}(\text{pH})$ , we can measure  $A_N^{J/\psi}$  with a few % of accuracy.
- The quark GPDs can also be accessed with exclusive dilepton photoproductions.
- Opportunity to study light-by-light scattering below 3 GeV using fixed-target experiment.

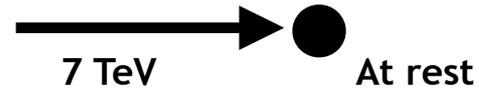
**End**

# Why fixed-target experiment?



Collider

$$E_{CM} = 14 \text{ TeV}$$



Fixed-target

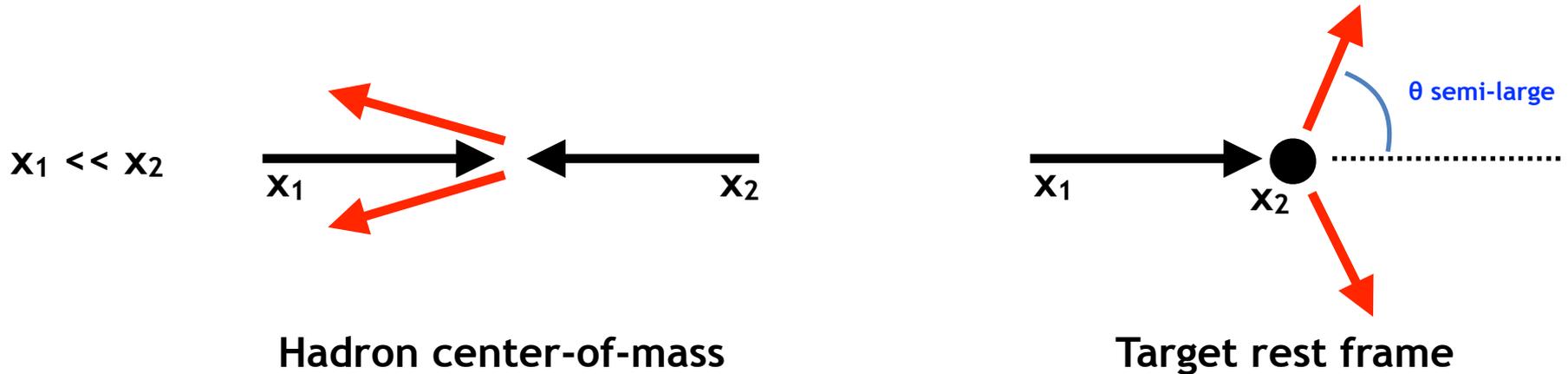
$$E_{CM} = 115 \text{ GeV}$$

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
- Arbitrary 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

# 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)



Kinematics of bottomonium production:  $x_{1,2} = \frac{m_{b\bar{b}}}{\sqrt{s}} e^{\pm y_{\text{c.m.s.}}}$  ( $\sqrt{s} = 115\text{GeV}$   
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**

High-x region is interesting because

- Fundamental aspect of QCD (gluon carrying 40%, intrinsic heavy quarks, etc)
- Important for BSM search, astrophysics, etc

But the high-x behavior of nucleon/nuclear PDF is poorly or not known

AFTER@LHC can uncover

- Light quark PDF

Drell-Yan

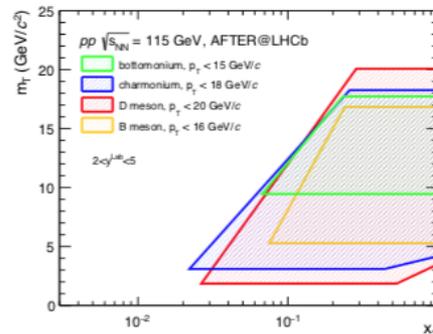
- Gluon PDF

Quarkonium production

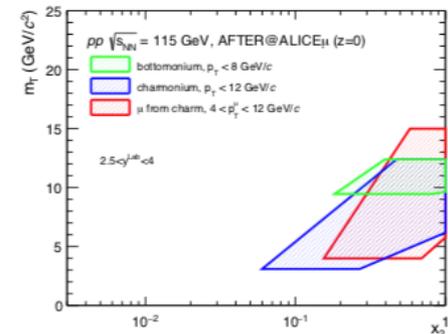
- Intrinsic charm PDF

Inclusive  $D^0$  production

- Double parton scattering



LHCb-like



ALICE-like

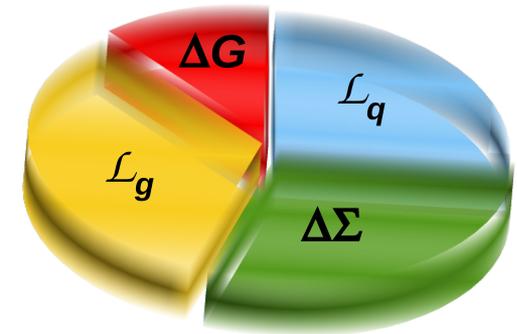
In fixed-target experiment, targets may be polarized: study of nucleon structure

## Proton spin puzzle (since 1987):

Quark spin contribution to nucleon spin is small

Quark and gluon orbital angular momenta are important, but not well understood

■ Gluon Spin    ■ Gluon angular momentum  
■ Quark Spin    ■ Quark Angular Momentum



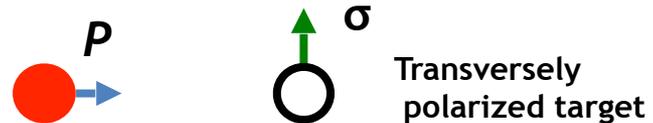
Orbital angular momentum  $\Rightarrow$  Transverse motion ( $k_T$ )

Extension of PDF with transverse motion (3D-tomography of partons):

$$\hat{f}(x, \mathbf{k}_\perp^2; \sigma_p) = \underbrace{f_1(x, \mathbf{k}_\perp^2)}_{\text{TMD PDF}} + \underbrace{f_{1T}^\perp(x, \mathbf{k}_\perp^2)}_{\text{Sivers function}} \frac{\mathbf{P}_p \cdot \sigma_p \times \mathbf{k}_\perp}{M_p}$$

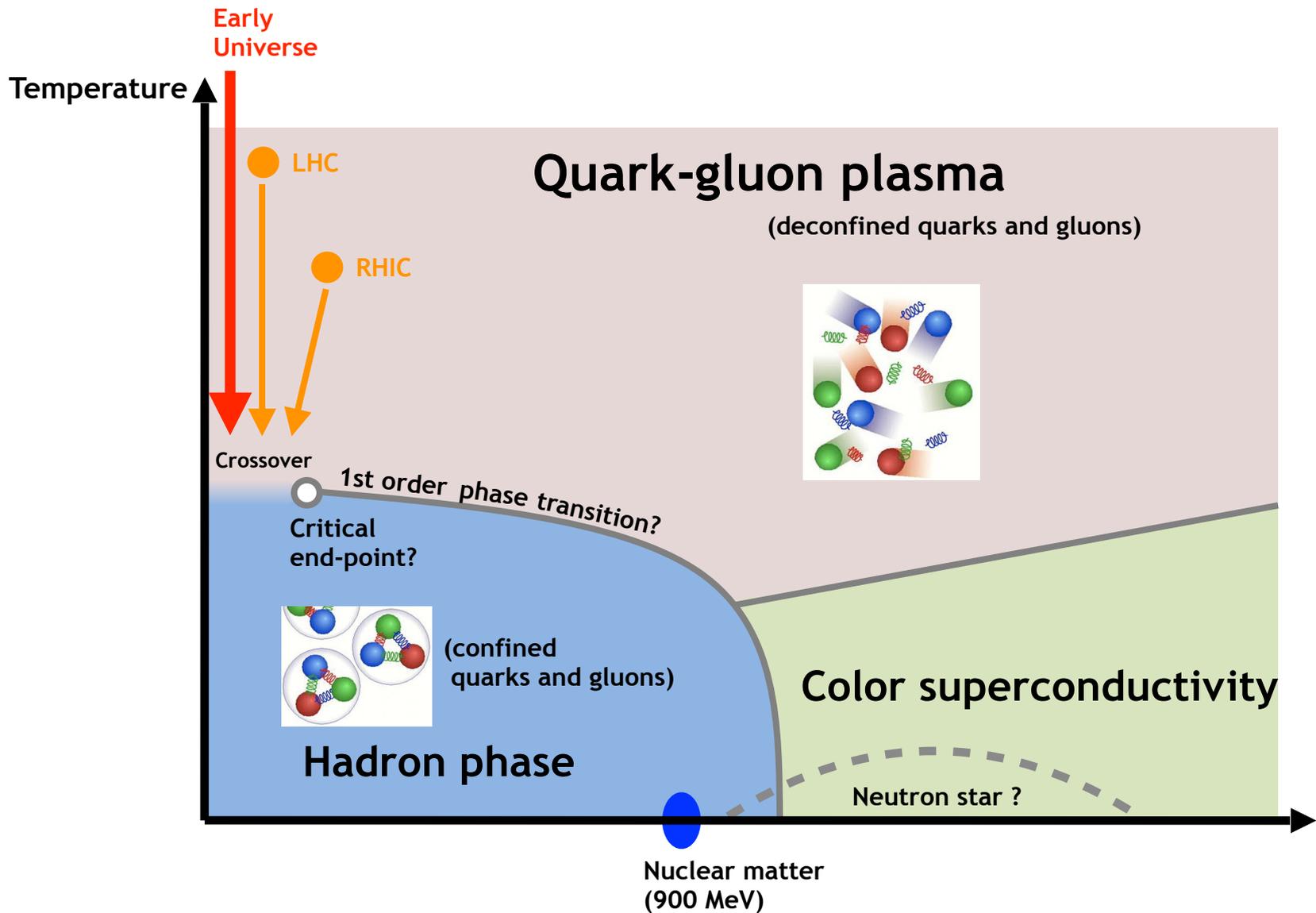
How to extract :Single spin asymmetry

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

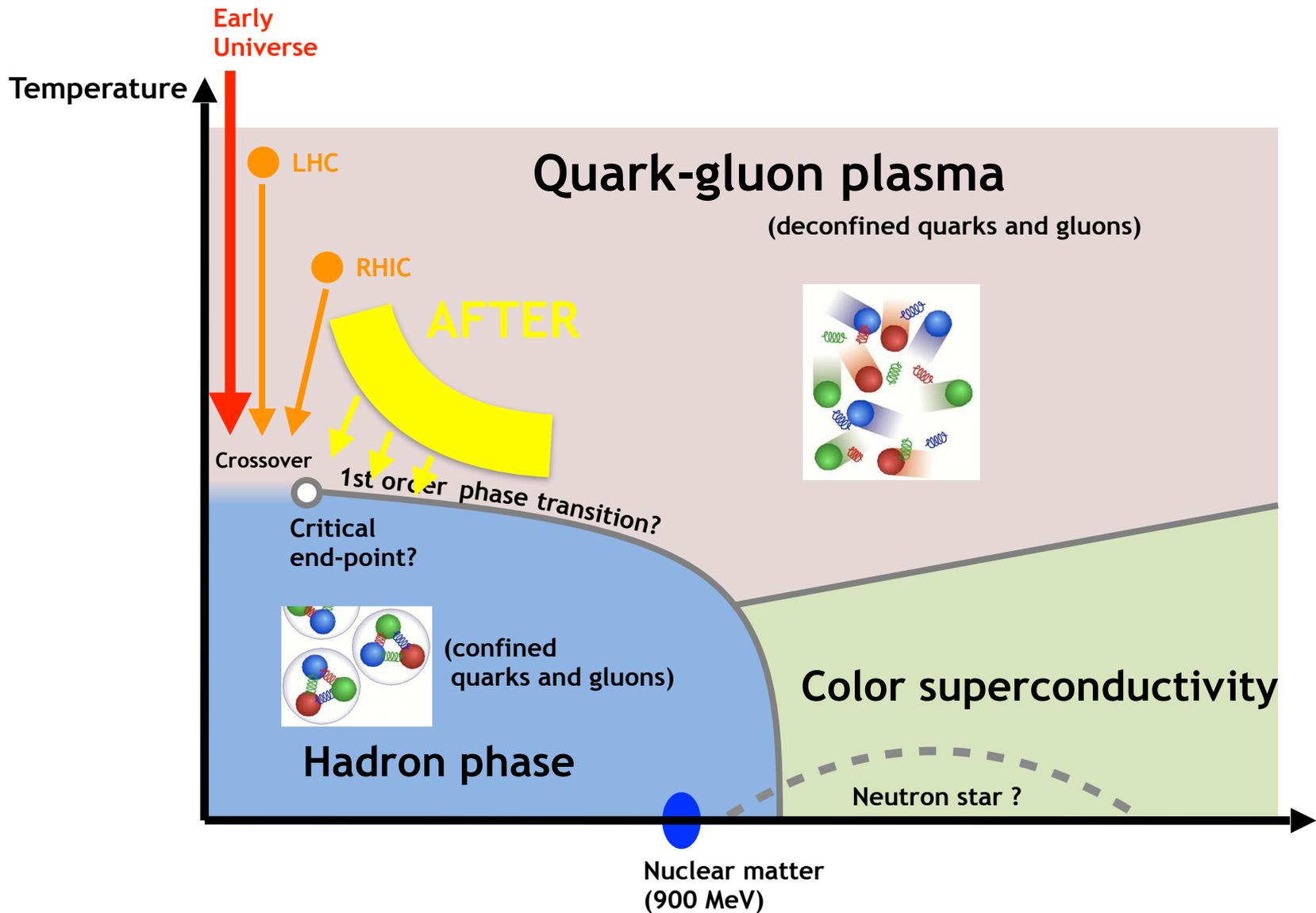


With AFTER@LHC, we can access at high-x, also for gluon TMD/Sivers

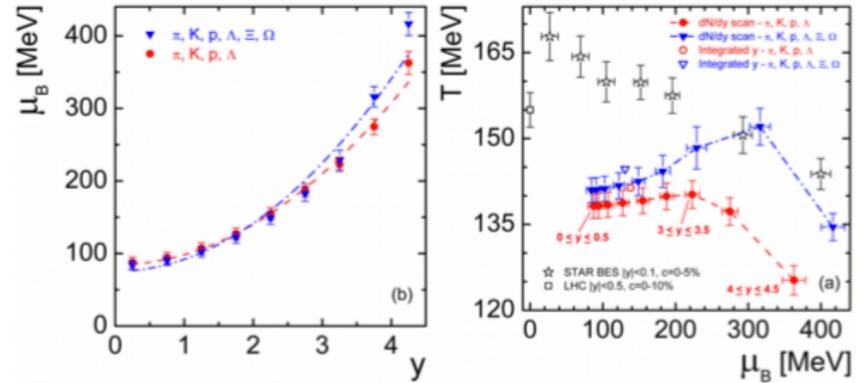
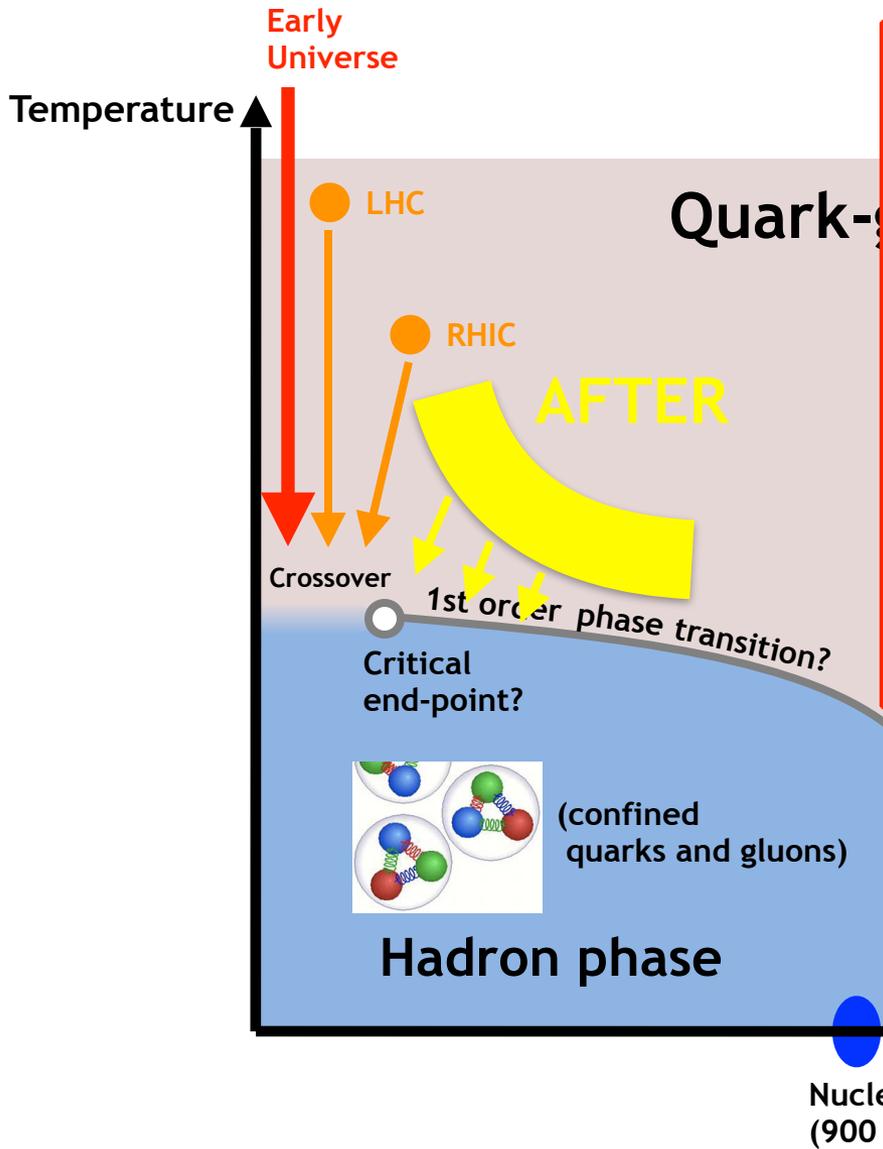
# Heavy ion collision : AFTER vs QCD phase diagram



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# Heavy ion collision : AFTER vs QCD phase diagram



⇒ “Rapidity scan”!