

Unraveling the 3D/spin structure of the nucleons with a fixed-target experiment at the LHC

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On behalf of the
AFTER@LHC
study group



<http://after.in2p3.fr/after/index.php/Current author list>

Outline



Please refer to it for many more details, references,...

Also interesting: the input prepared for the ESPP update

- A combined effort of **experimentalists** and **theorists**
- Contains a **full Physics program** with projected performances, discussion of possible implementations and detectors
- AFTER@LHC study group is part of the CERN *Physics Beyond Colliders* QCD and Fixed-Target working groups, which analyze on behalf of CERN the different LHC fixed-target physics opportunities and the technological options in view of the coming **update of the European Particle Physics Strategy**

(Open Symposium in Granada in May 2019)

This talk: a selection of the **spin physics part**:

1. *Motivation, general ideas*
2. *q/g STSAs*
3. *q/g azimuthal asymmetries*
4. *s helicity/transversity at large x*
5. *Conclusions*

What for/Why/How of a fixed-target experiment at the LHC

Multi-purpose fixed target experiment using the multi-TeV proton and heavy-ion beams of the LHC, with 3 main physic objectives:

Advance our understanding of:

- The **high-x** gluon, antiquark and heavy-quark content in the nucleon and nucleus
- The **dynamics and spin of quarks and gluons** inside (un)polarized nucleons
- The **heavy-ion** collisions between SPS and RHIC energies towards large rapidities

Advantages of fixed-target mode w.r.t. collider mode:

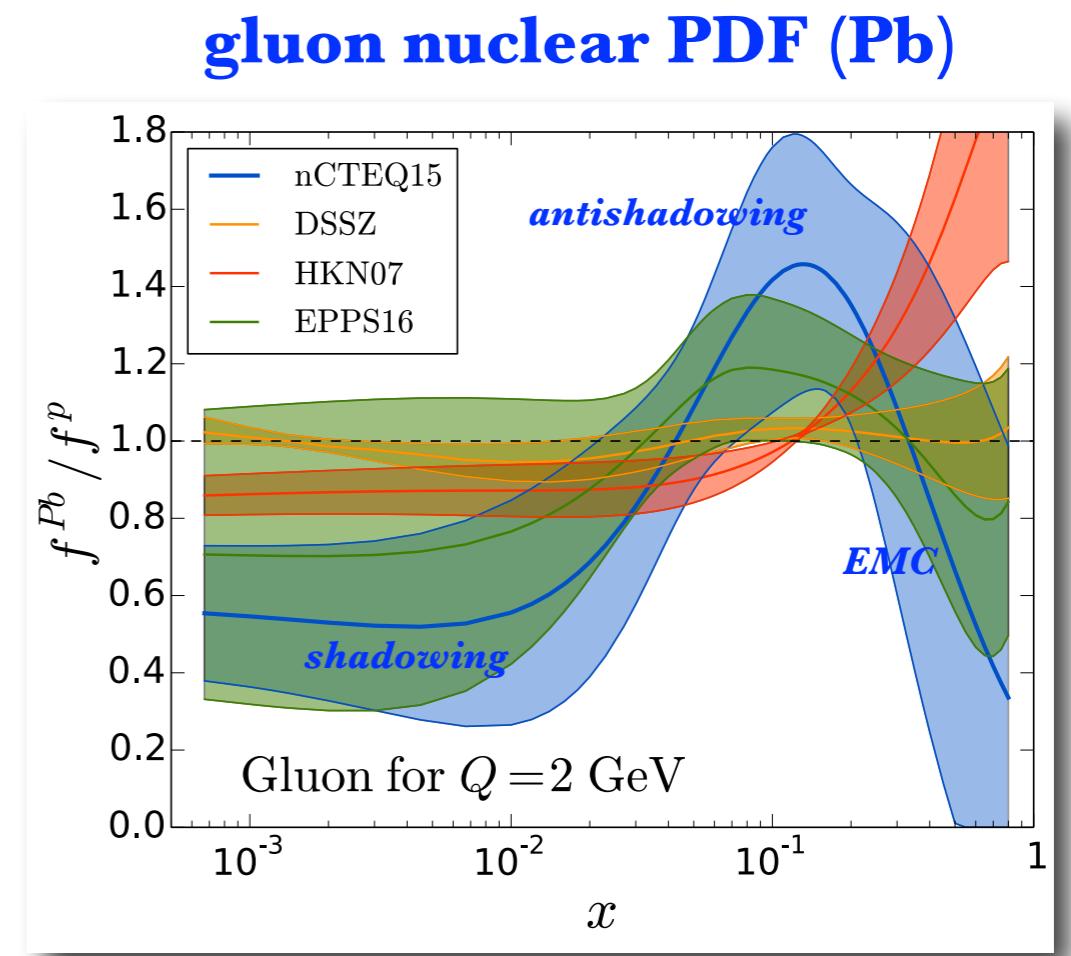
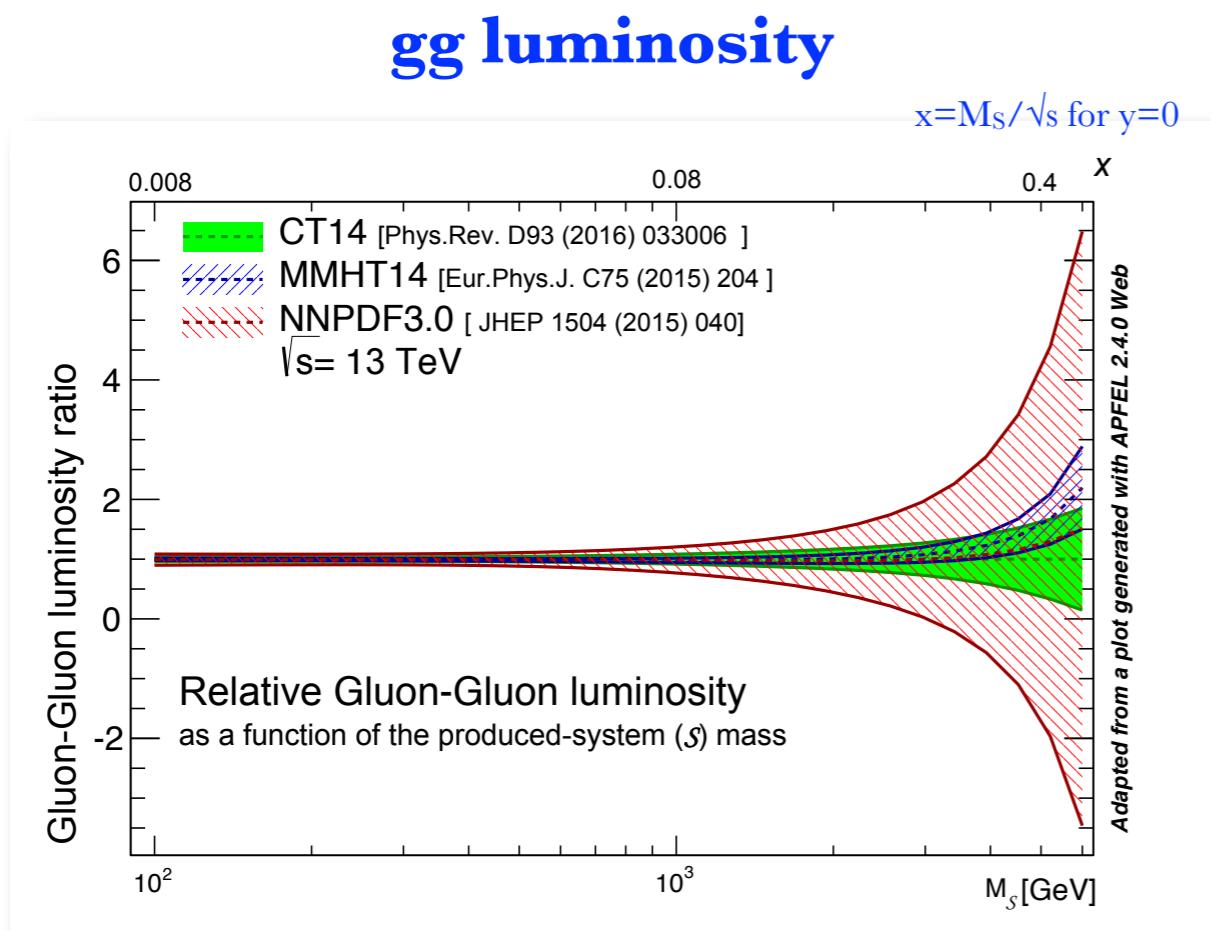
- Accessing the **high Feynman x_F** ($x_F \rightarrow -1$) domain
- Achieving **high luminosities** thanks to LHC beams and dense targets
- Possibility to **change the target** type (\neq atomic masses)
- Possibility to **polarize the target**
- It would be ***cheap***, given the huge amount of Physics we could obtain

In **parasitic mode** with most energetic beams ever, without affecting LHC performances:

- Internal solid/gas target + existing detectors (LHCb/ALICE)  *Nezza/Pappalardo (LHCSpin)*
- A bent crystal for a low extraction + new detectors

Physics case I: study the high- x frontier

- Very large PDF uncertainties for $x > 0.5$ [crucial to characterize possible BSM discoveries]
- Proton charm content important to high-energy neutrino & cosmic-rays physics
- EMC effect is still an open problem: studying a possible gluon EMC effect is essential
- Relevance of nuclear PDFs to understand the initial state of heavy-ion collisions



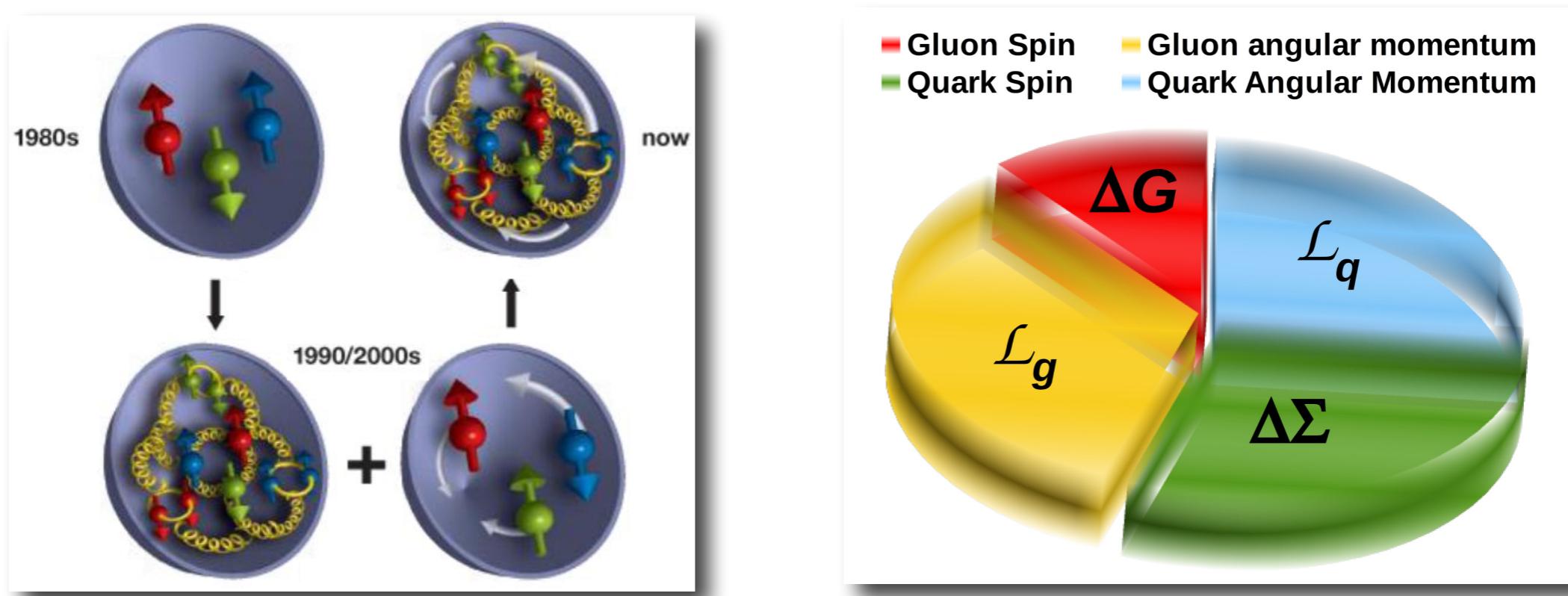
$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \frac{1}{s} \int_{\tau}^1 \frac{dx}{x} f_a(x, M_S^2) f_b(\tau/x, M_S^2), \quad \tau = M_S^2/s$$

For many more details:
[AFTER@LHC 1807.00603]

Physics case 2: unravelling the nucleon 3D/spin structure

- Test of QCD factorization framework [beyond the DY A_N sign change]
- Constrain non-perturbative functions: TMDs (Sivers, BM, lin. pol. gluons,...), twist-3,...
- Access OAM: indirectly through TMDs and directly through GPDs in UPC
- Strange quark helicity through DLL in Lambda production

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_g + L_q$$

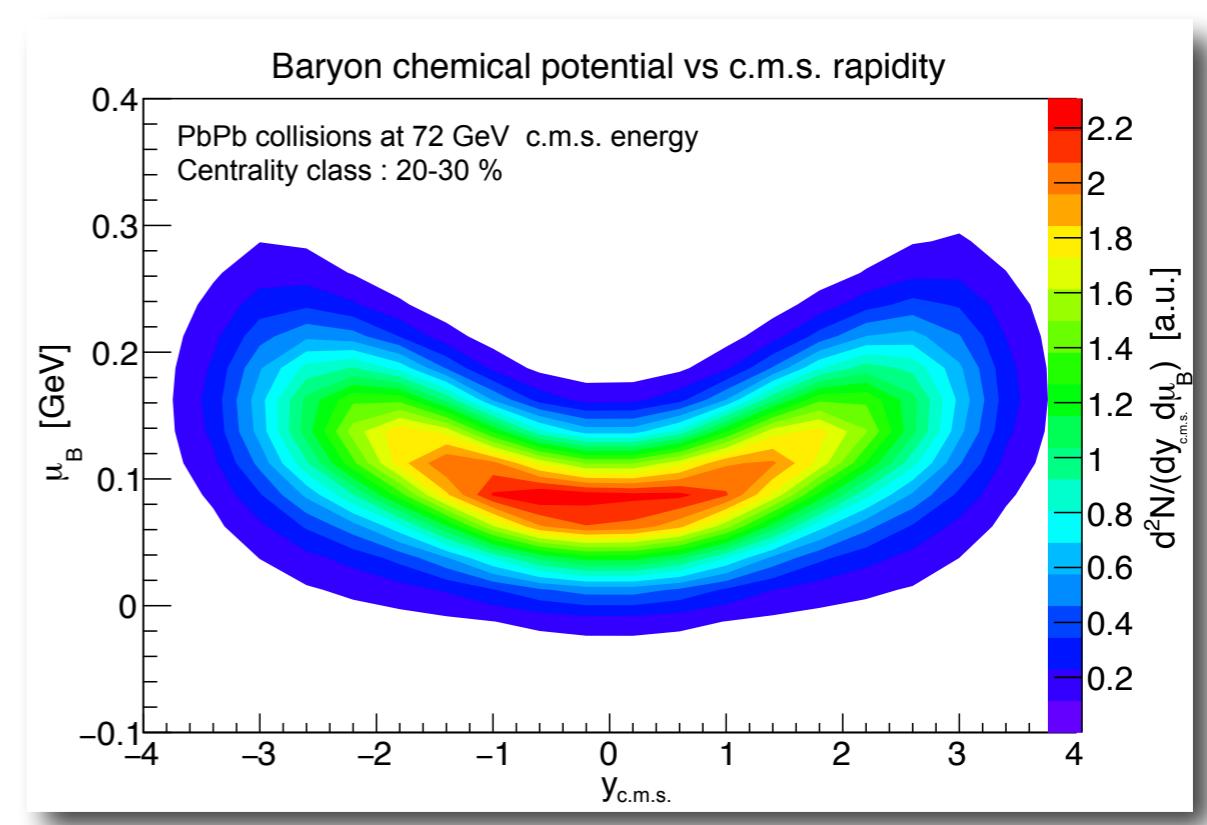
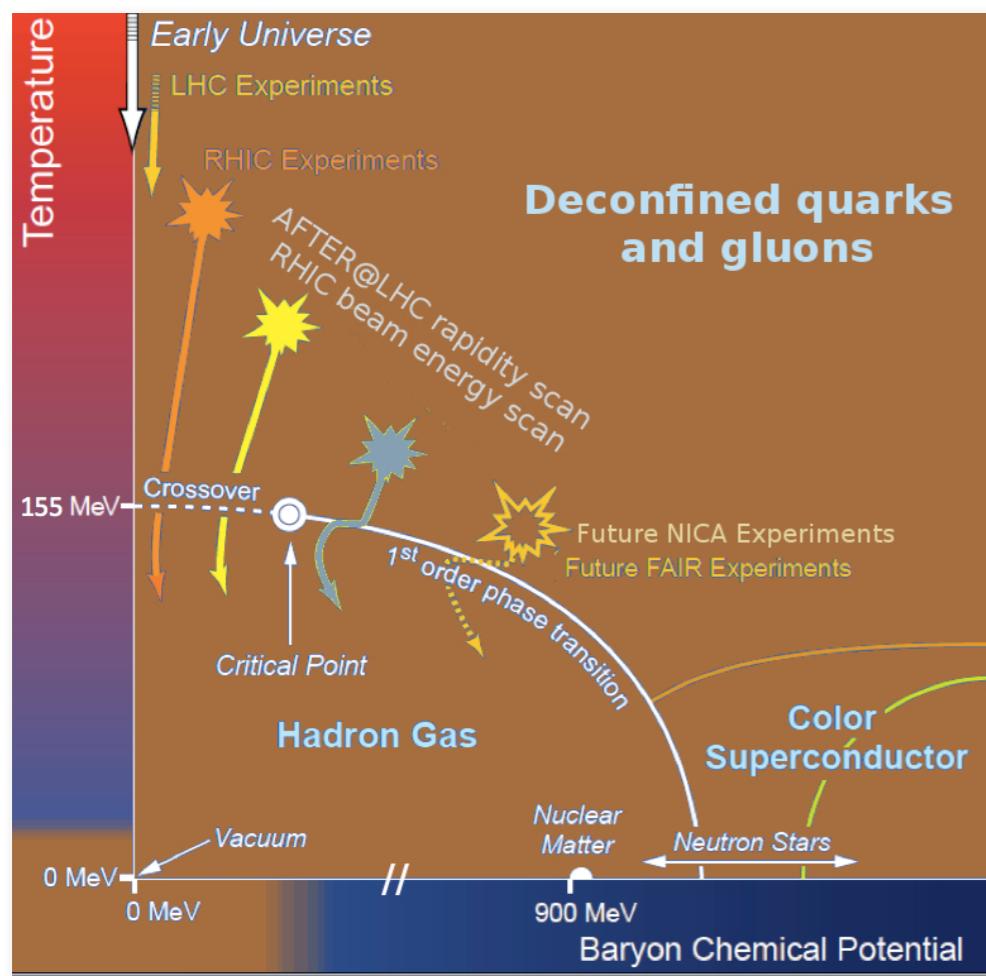


This talk: a selection of the spin physics part

For many more details:
[AFTER@LHC 1807.00603]

Physics case 3: heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies [needed to calibrate the “quarkonium thermometer” for the quark-gluon plasma (J/ψ , ψ' , χ_c , Υ , D ,...)]
- Test the formation of azimuthal asymmetries: hydrodynamics vs initial-state radiation
- Explore the longitudinal expansion of QGP formation
- Test the factorization of cold nuclear effects from $p+A$ to $A+B$ collisions



Rapidity scan
Complementary to RHIC energy scan

For many more details:

[AFTER@LHC 1807.00603]

Kinematics

Energy range

7 TeV proton beam on a fixed target

c.m.s. energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}$

Boost: $\gamma = \sqrt{s} / (2m_N) \approx 60$

Rapidity shift:

$$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$$

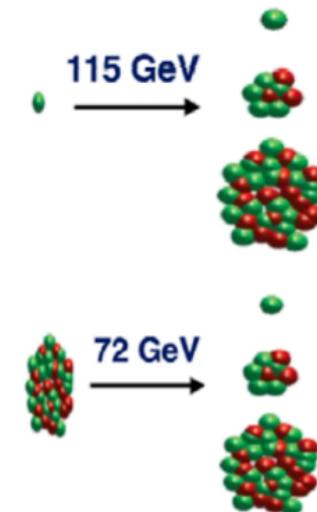
2.76 TeV Pb beam on a fixed target

c.m.s. energy: $\sqrt{s_{NN}} = \sqrt{2m_N E_{\text{Pb}}} \approx 72 \text{ GeV}$

Boost: $\gamma \approx 40$

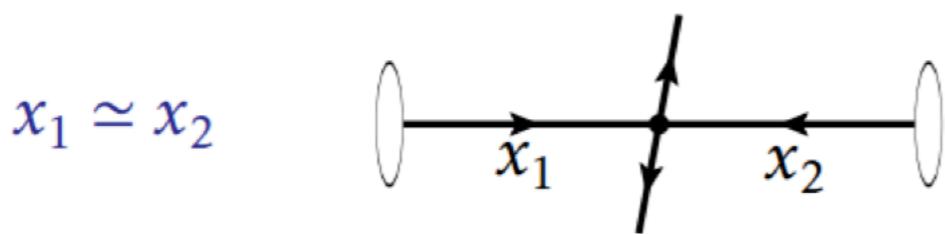
Rapidity shift:

$$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$$

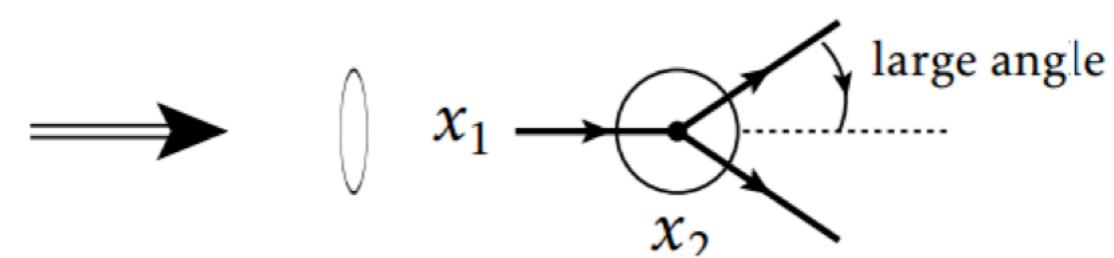
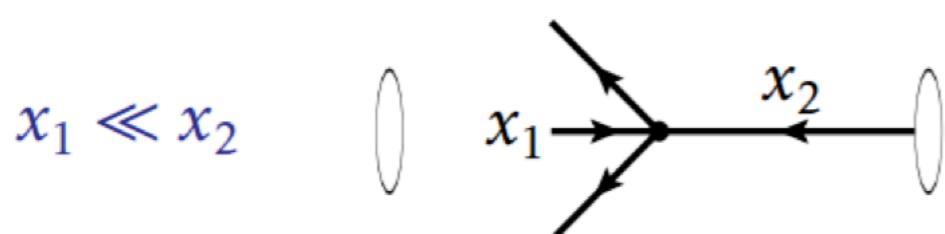
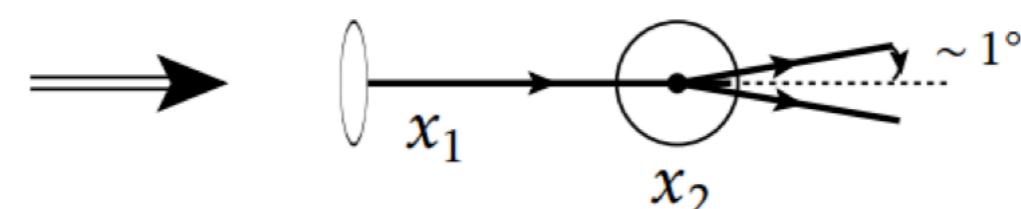


Boost effect:

Hadron center-of-mass system

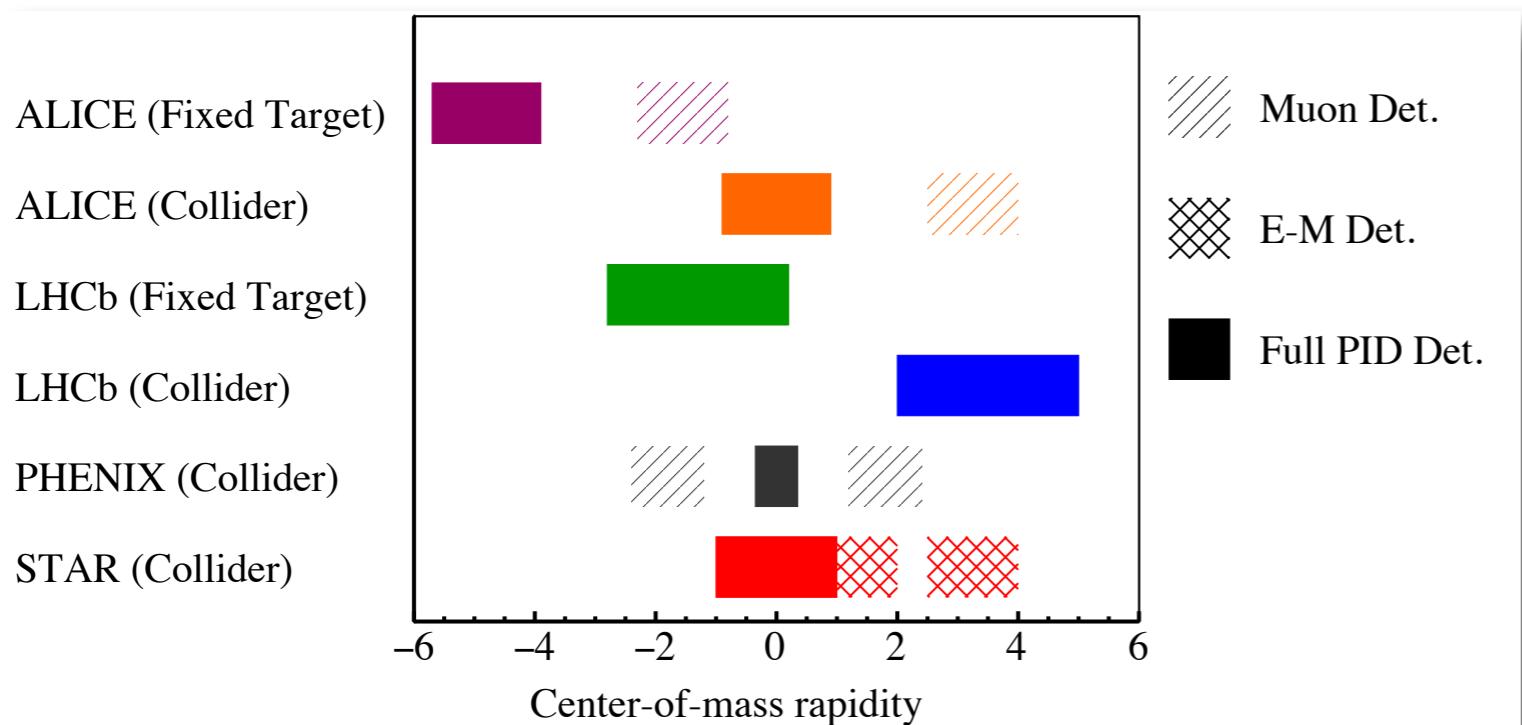


Target rest frame



Access to backward region: large x_2 ($x_F \rightarrow -1$)

Kinematics: LHCb-like and ALICE-like detectors



Acceptance of LHCb

$$2 < \eta_{\text{lab}} < 5$$

Acceptance of ALICE

$$\text{Muon arm: } 2.5 < \eta_{\text{lab}} < 4$$

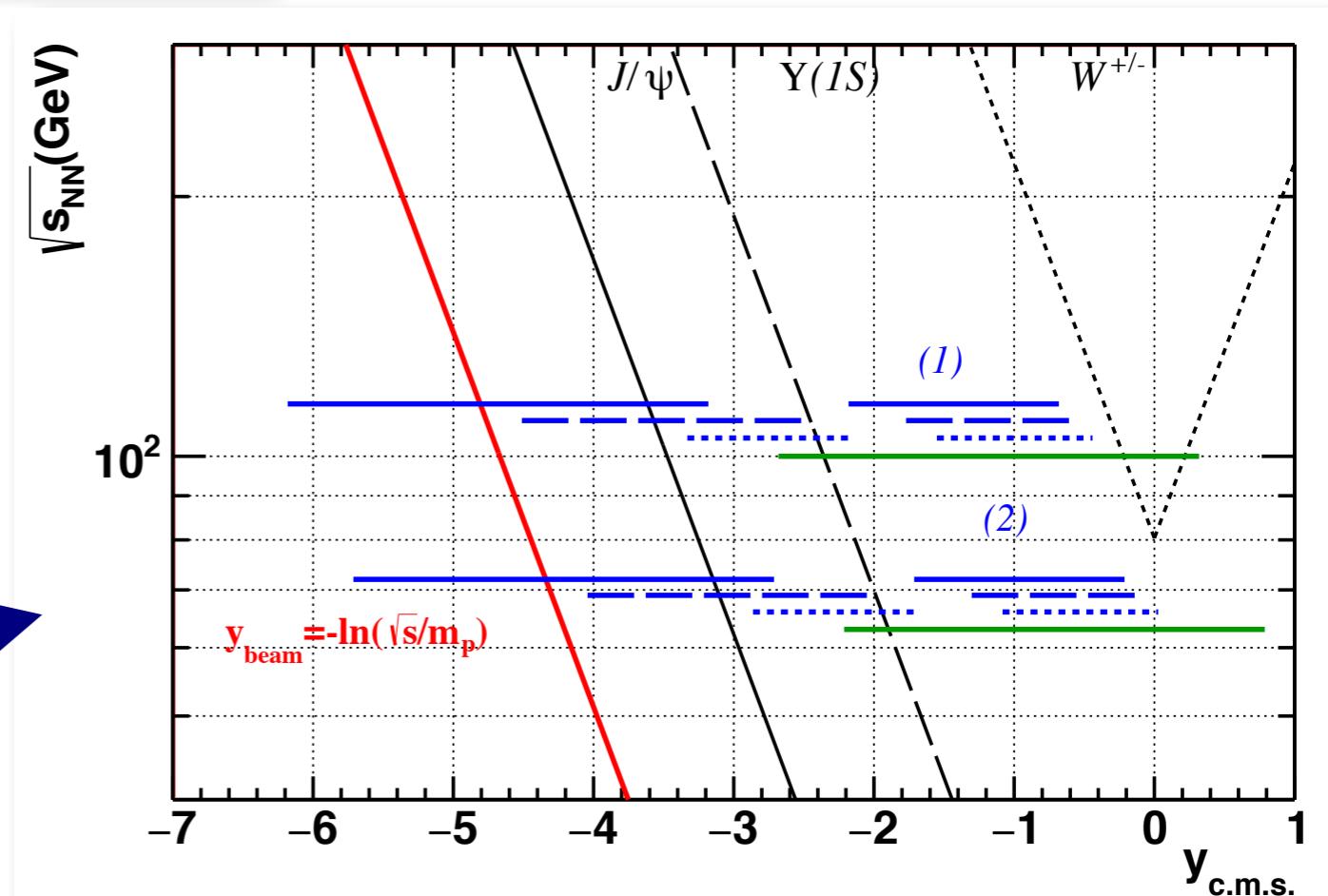
$$\text{Central barrel: } -0.9 < \eta_{\text{lab}} < 0.9$$

- LHCb and ALICE muon arm access the mid- to backward- rapidity region ($y_{\text{cms}} < 0$)
- ALICE central barrel probes very backward region (end of phase space)

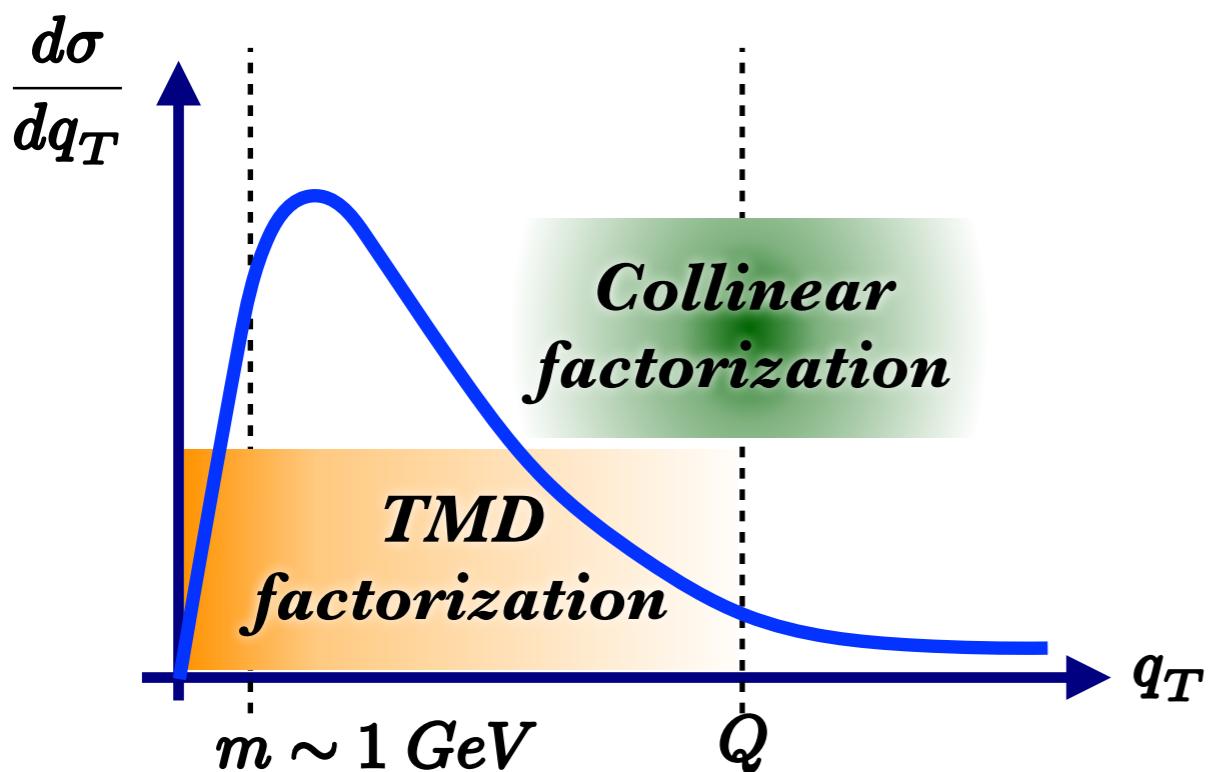
(1) $\sqrt{s}=115\text{GeV}$ and (2) $\sqrt{s}=72\text{GeV}$

{solid, dashed, dotted}: $z = \{0, 2.75, 4.7\}\text{m}$

Blue: ALICE; Green: LHCb



TMDs, twist-3, etc



OPE of TMDs onto integrated
counterparts
(too) Many non-perturbative
ingredients!!

For example:

$$\tilde{f}_{1T}^{\perp q/A(1)}(x, b_T; \zeta, \mu) = \sum_{j=q, \bar{q}, g} \int_x^1 \frac{d\bar{x}_1}{\bar{x}_1} \frac{d\bar{x}_2}{\bar{x}_2} \tilde{C}_{q/j}^{sivers}(\bar{x}_1, \bar{x}_2, b_T; \zeta, \mu) T_{Fj/A}(x_1/\bar{x}_1, x_2/\bar{x}_2; \mu)$$

$$\sigma(q_T, Q) \Big|_{q_T \leq Q} = \mathcal{W}(q_T, Q) + \left[\mathcal{O}\left(\frac{q_T}{Q}\right)^a + \mathcal{O}\left(\frac{m}{Q}\right)^{a'} \right] \sigma(q_T, Q)$$

$$\sigma(q_T, Q) \Big|_{q_T \sim Q \geq m} = \mathcal{Z}(q_T, Q) + \mathcal{O}\left(\frac{m}{q_T}\right)^b \sigma(q_T, Q)$$

- 2 scales $q_T < Q$: TMD factorization for small q_T & collinear factorization at large q_T
- 1 scale p_T : just collinear factorization

$$\begin{aligned} \tilde{T}_{i \leftrightarrow A}(x, b_T; \zeta, \mu) &= \sum_{j=q, \bar{q}, g} \tilde{C}_{i \leftrightarrow j}^T(x, \hat{b}_T; \mu_b^2, \mu_b) \otimes t_{j \leftrightarrow A}(x; \mu_b) \\ &\times \exp \left[\int_{\mu_b}^{\mu} \frac{d\hat{\mu}}{\hat{\mu}} \gamma_j \left(\alpha_s(\hat{\mu}), \ln \frac{\zeta}{\hat{\mu}^2} \right) \right] \left(\frac{\zeta}{\mu_b^2} \right)^{-D_j(\hat{b}_T; \mu_b)} \\ &\times \tilde{T}_{i \leftrightarrow A}^{NP}(x, b_T; \zeta) \end{aligned}$$

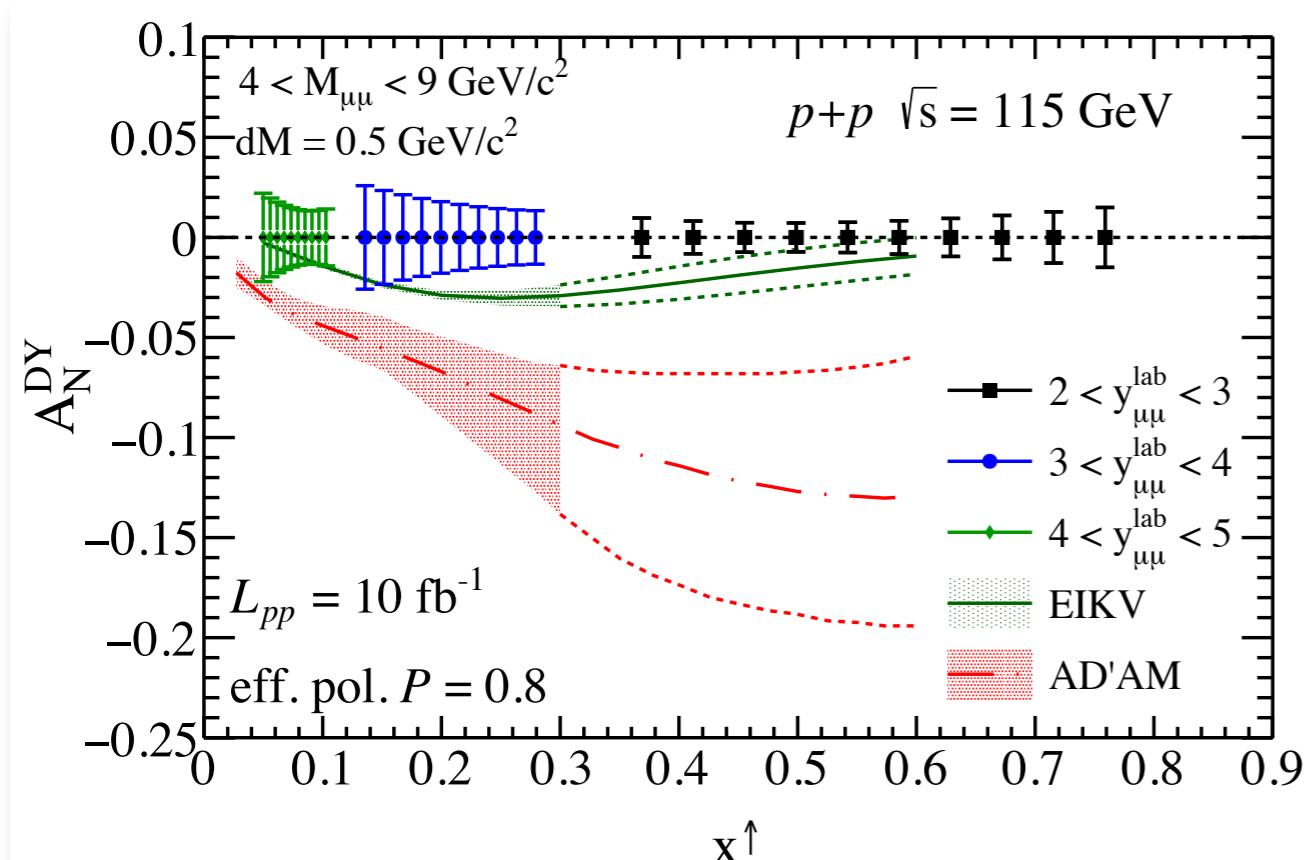
- **Generalized Parton Model (GPM)** is a useful way to get interesting results, but limited
- **Quarkonium/Heavy-flavour** in p: no proper TMD factorization yet

Quark Sivers effect: Drell-Yan A_N

In general: $A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$

For DY: $A_N \propto \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}$

Related to twist-3!

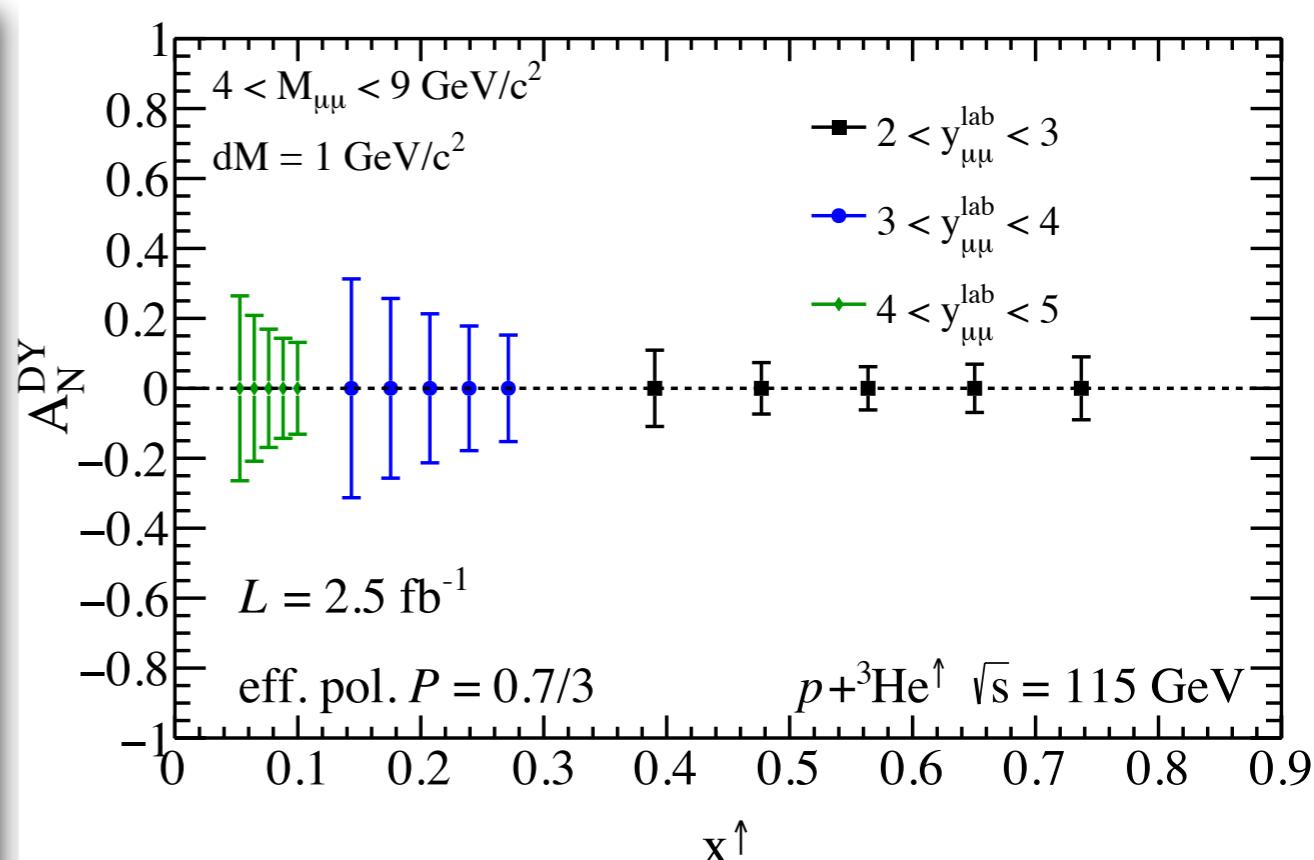


LHCb-like detector

AD'AM: [Anselmino, D'Alesio, Melis 1504.03791]

EIKV: [MGE, Idilbi, Kang, Vitev 1401.5078] + replicas

Both fits based on real SIDIS data only for $x < 0.3$
Predictions by changing Sivers sign from SIDIS
TMD evolution: EIKV yes; AD'AM no



LHCb-like detector

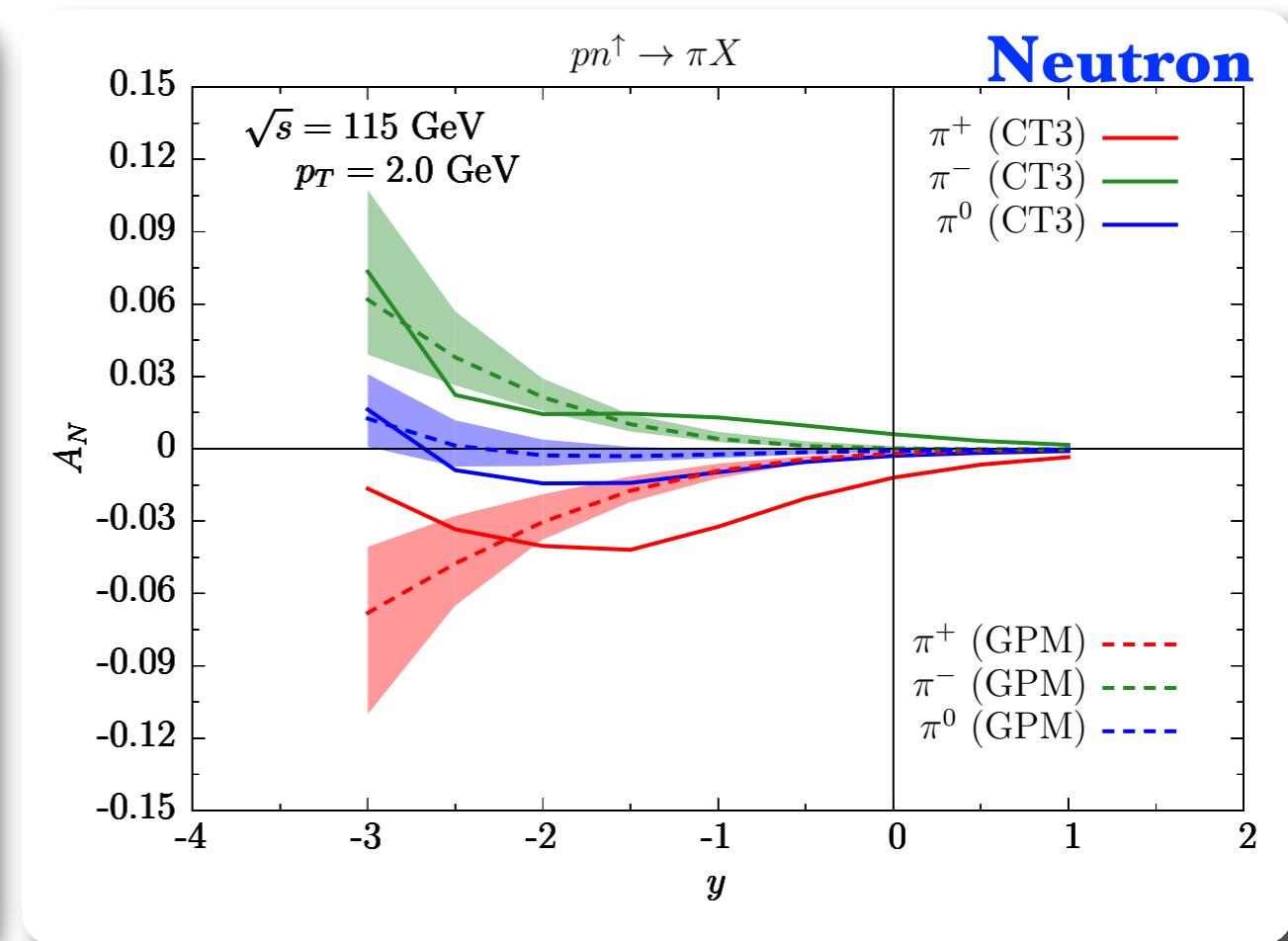
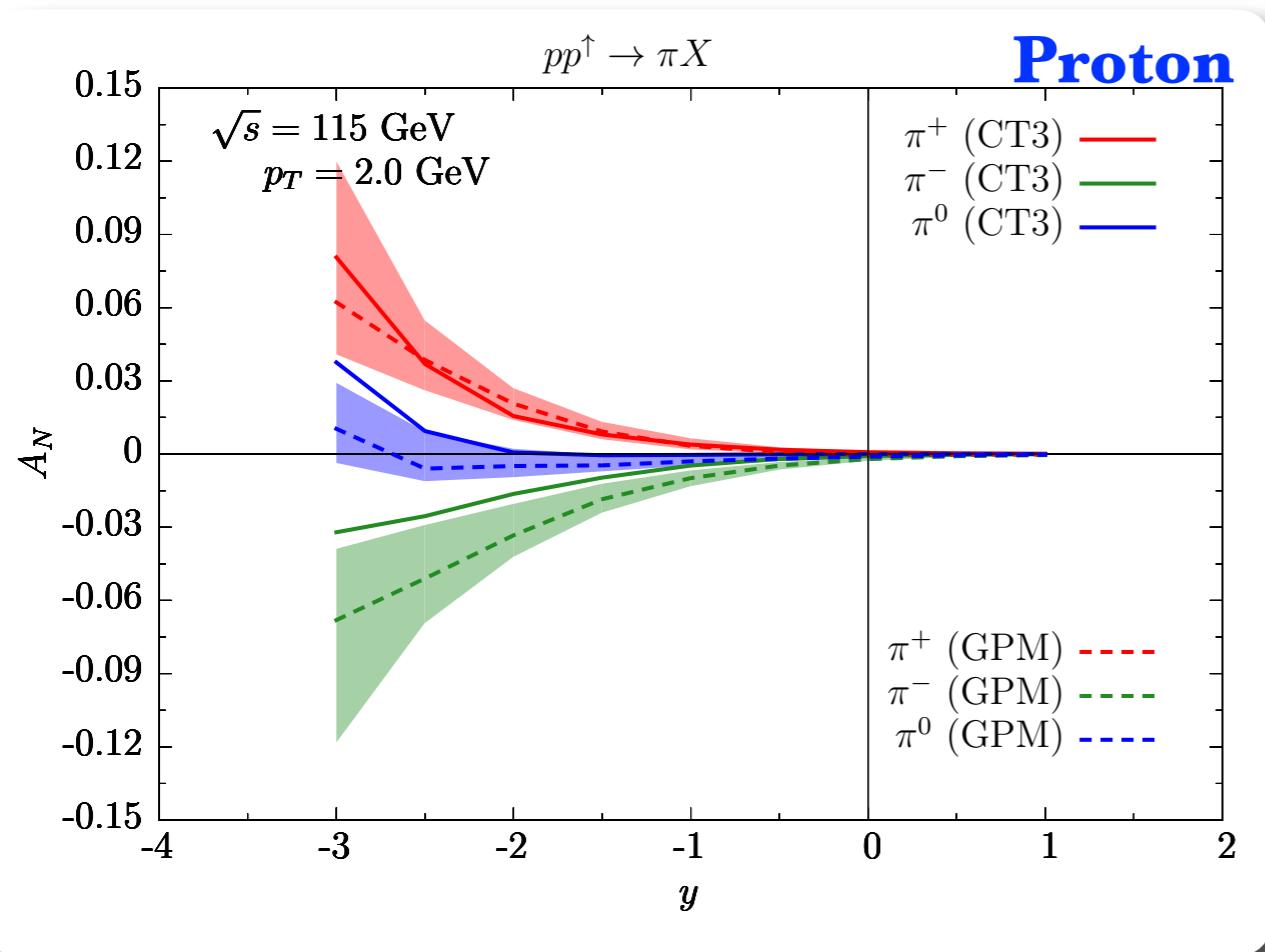
Worse statistics because of ${}^3\text{He} \leftrightarrow p$
But still, a unique opportunity to access neutron Sivers function!

Quark Sivers effect: pion production

- Generalized Parton Model (GPM) and Collinear Twist-3 factorization (CT3) formalisms
- Test of the “flavor sign change” and thus isospin symmetry
- No simulations yet
- Potentially measurable $\sim 10\%$ STSA for backward rapidity!

$$A_N = \frac{[d\sigma^\uparrow - d\sigma^\downarrow]_{Sivers} + [d\sigma^\uparrow - d\sigma^\downarrow]_{Collins}}{d\sigma^\uparrow + d\sigma^\downarrow}$$

GPM: Sivers and Collins TMDs
 CT3: twist-3 functions
 Fragmentation dominates!



GPM: [Anselmino, D'Alesio, Melis 1504.03791]

CT3: [Gamberg, Kang, Pitonyak, Prokudin 1701.09170]

Isospin symmetry used.
E.g. for Sivers:

$$f_{1T}^{\perp u/\text{neutron}} = f_{1T}^{\perp d/\text{proton}}$$

$$f_{1T}^{\perp d/\text{neutron}} = f_{1T}^{\perp u/\text{proton}}$$

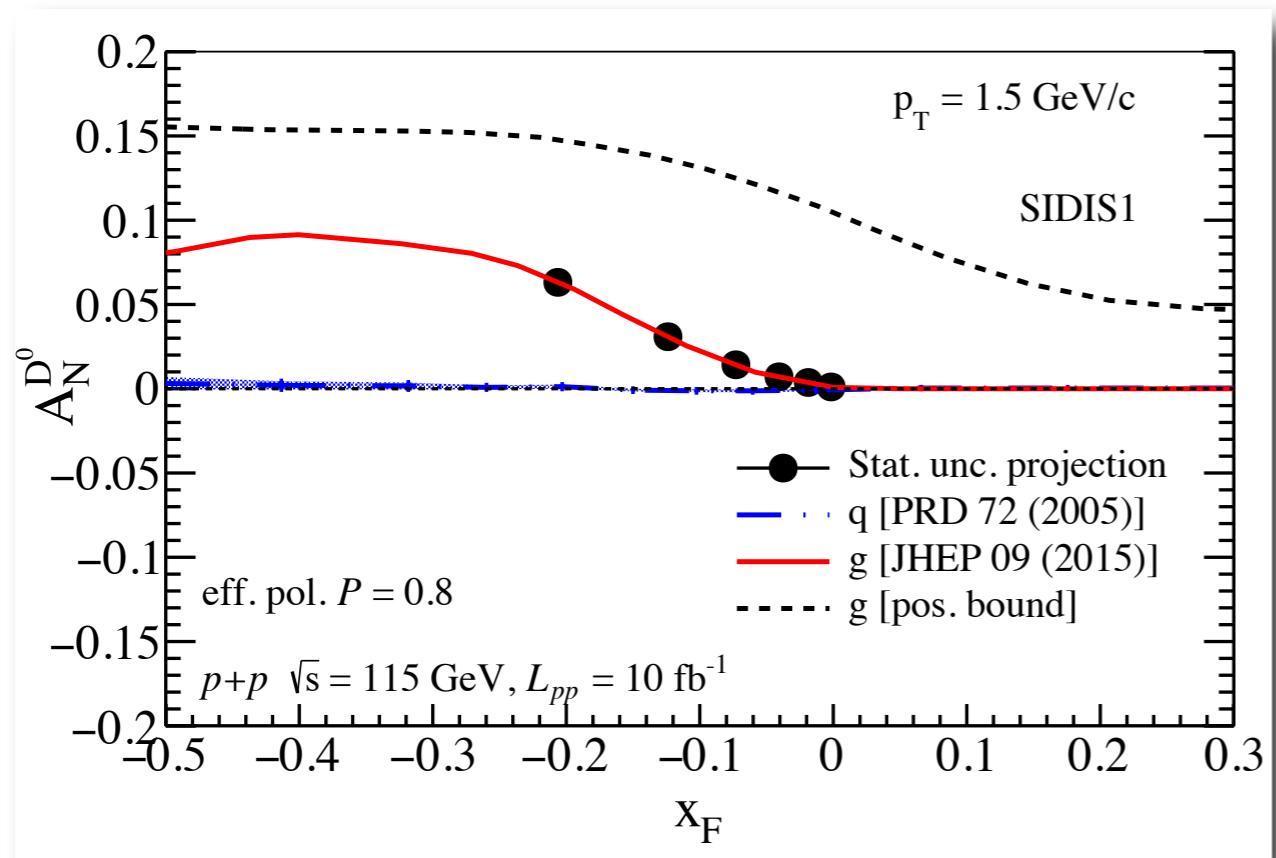
Gluon Sivers effect: open heavy-flavor production



TMD factorization for quarkonium/heavy-flavor production still to be obtained

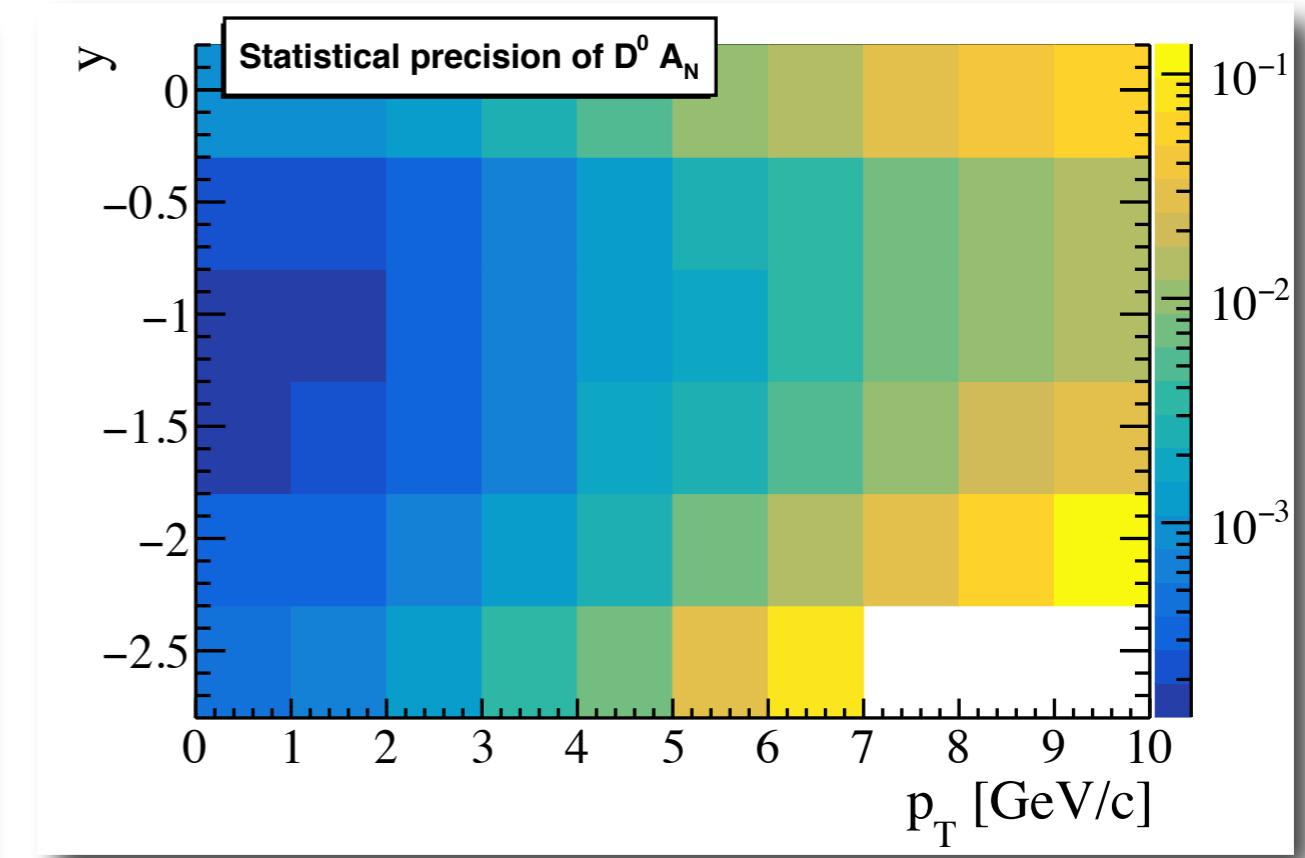
- D mesons can be collected with a transversely polarized target [never measured]
- Can constrain twist-3 tri-gluon correlation functions and gluon Sivers function
- Differences of $A_N^{\bar{D}^0}$ and $A_N^{D^0}$ give access to C-odd tri-gluon correlator T_G^d

[Kang, Qiu, Vogelsang, Yuan 0810.3333]



LHCb-like detector

Theory predictions with GPM factorization

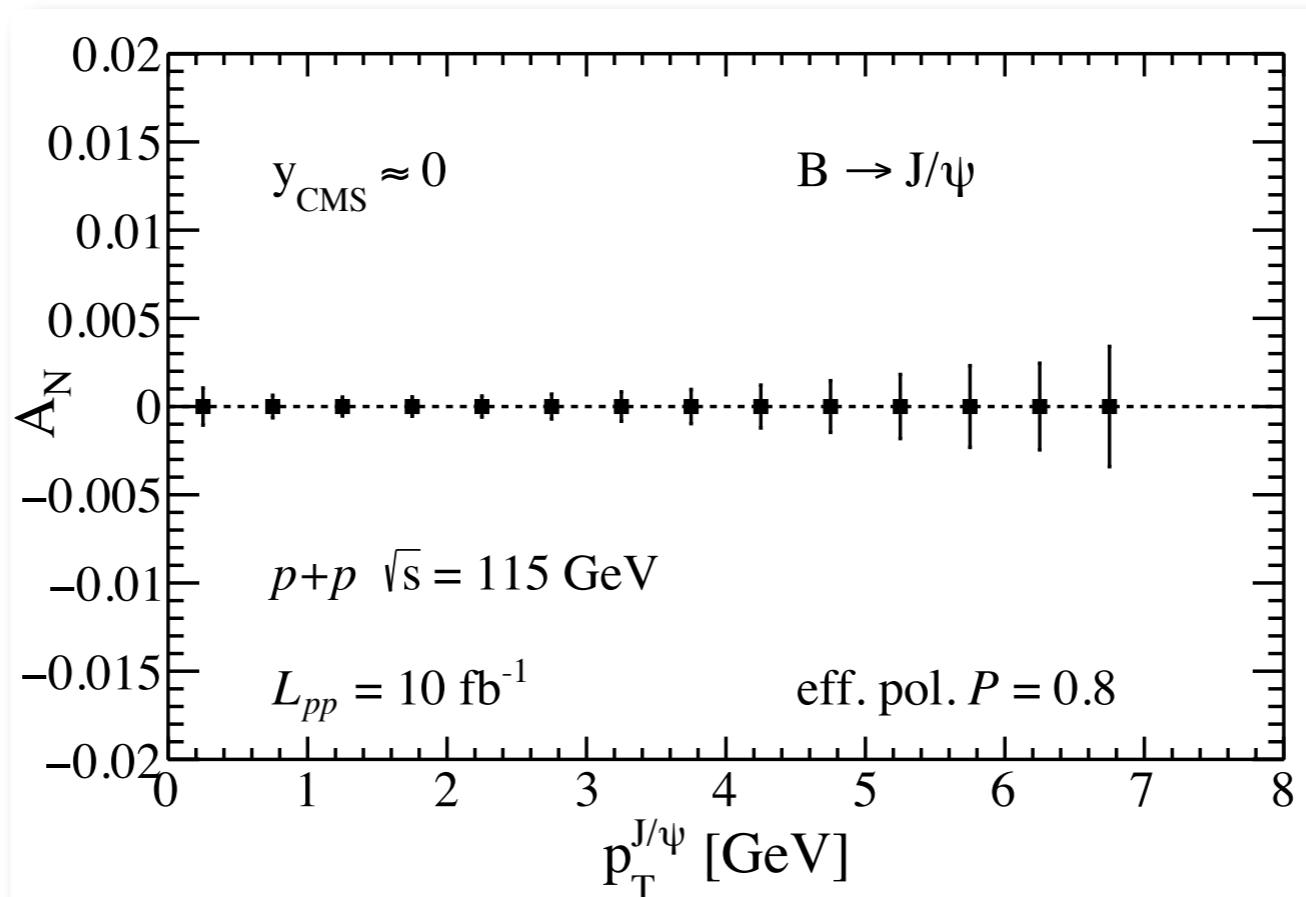


LHCb-like detector

Precision at the percent level!!

Gluon Sivers effect: open heavy-flavor production

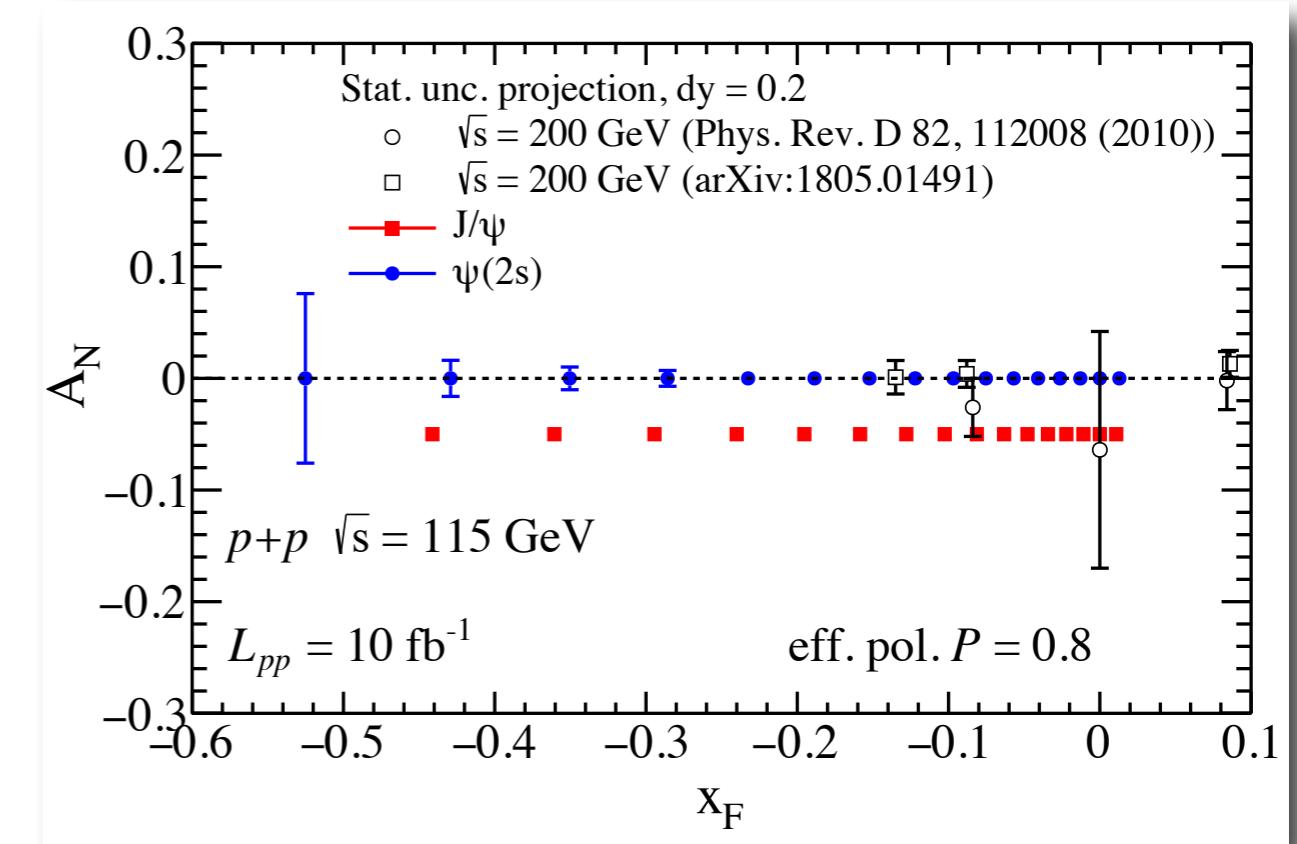
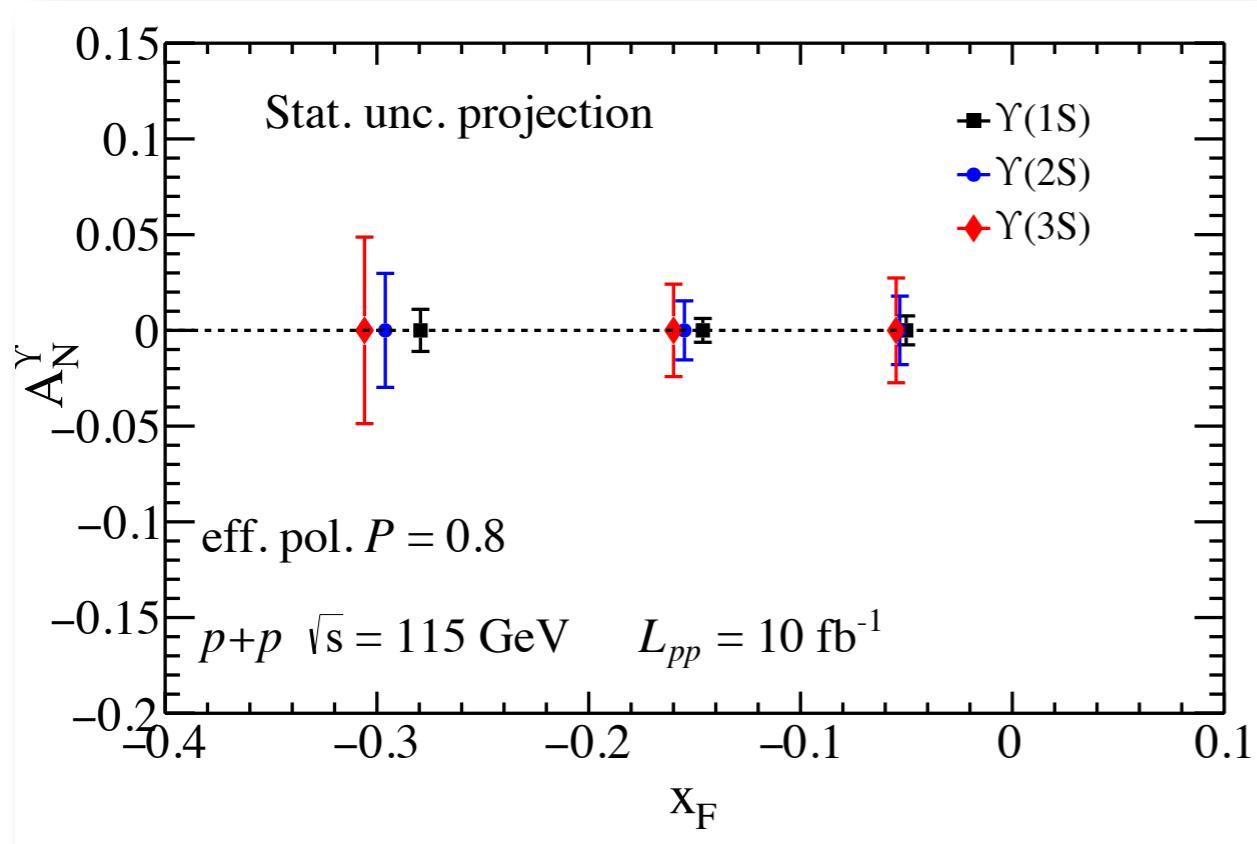
Projected statistical precision for B meson STSA (through its decay in J/Psi)



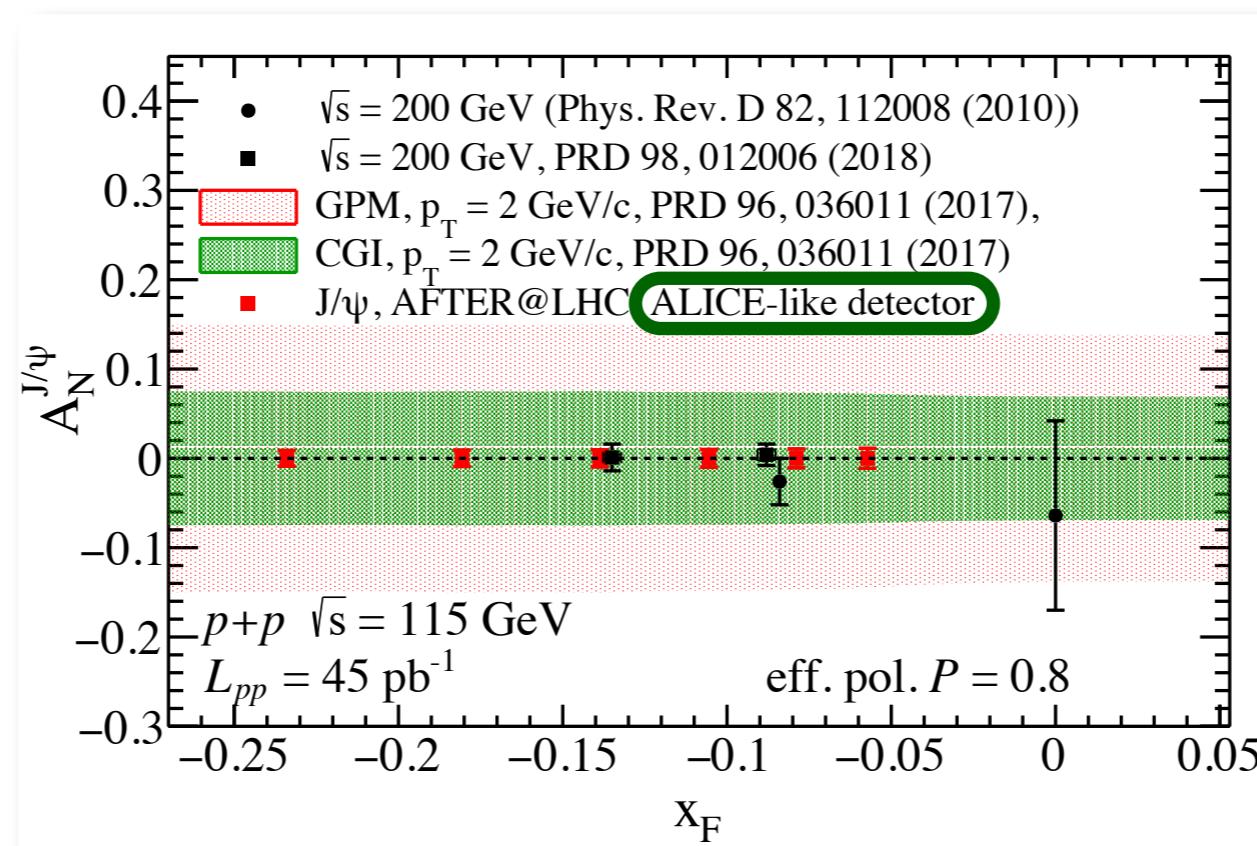
LHCb-like detector

Precision at the per mile level!!

Gluon Sivers effect: vector quarkonium production



LHCb-like detector

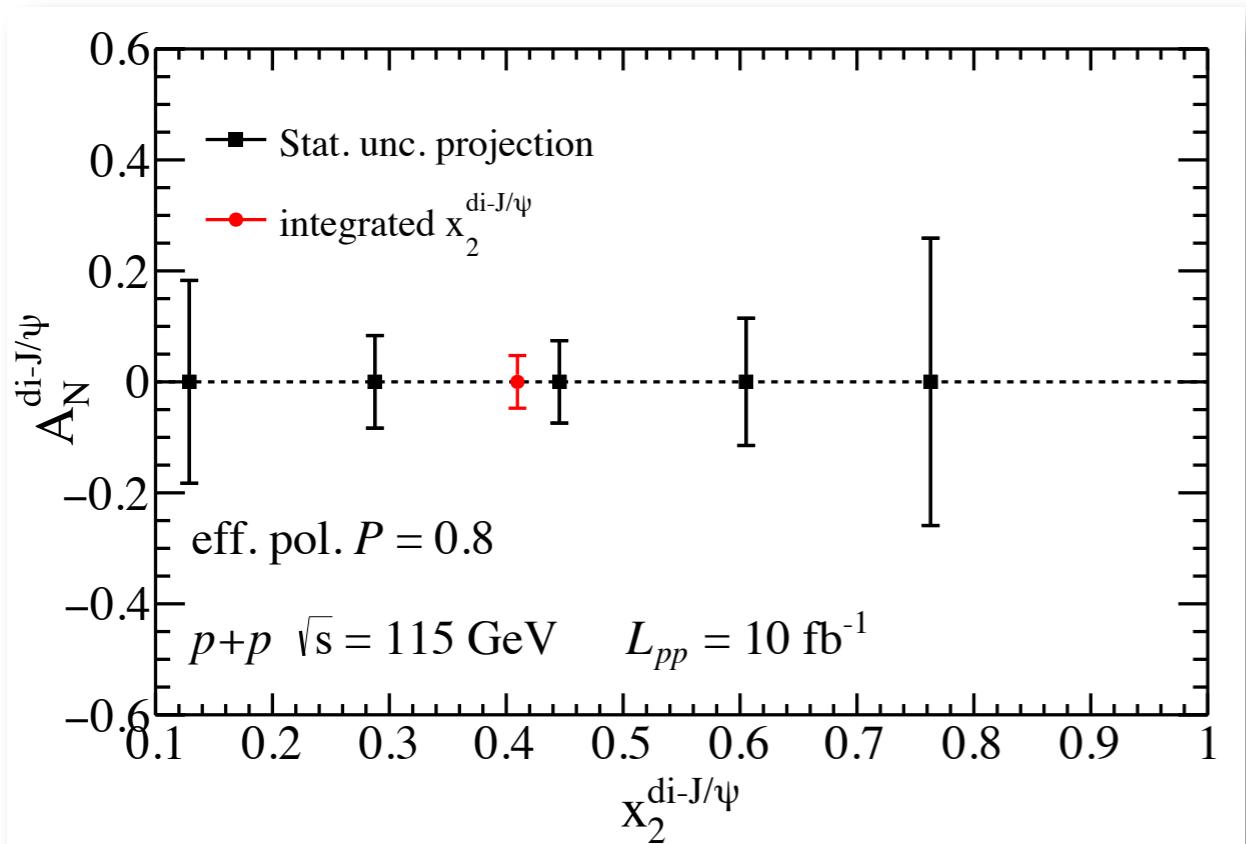


LHCb-like detector

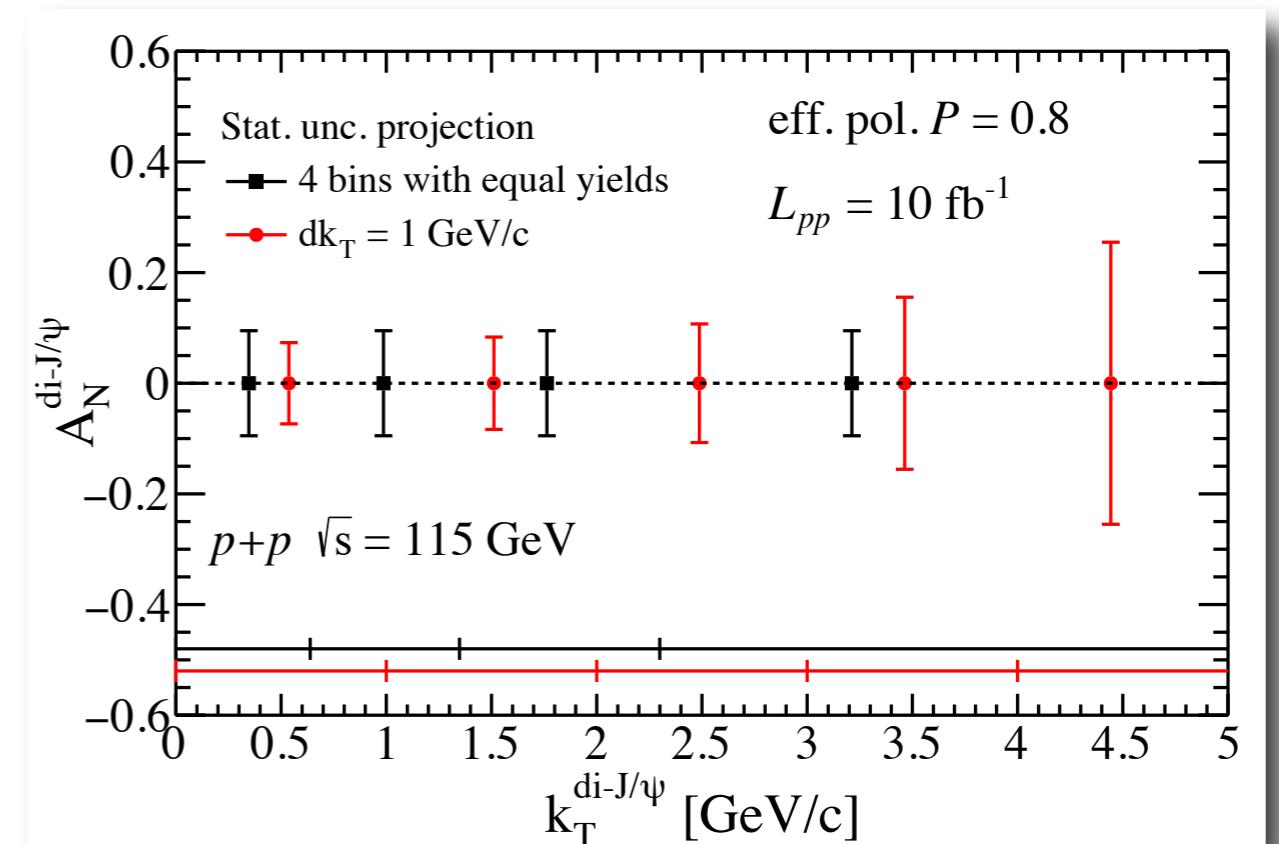
Precision at the percent level!!

Gluon Sivers effect: associated production

- Momentum imbalance observables, e.g. di-J/Psi, allow one to study the k_T dependence of the gluon Sivers function for the very first time!
- Fundamental tools to access gluon Sivers effect and probe **gluon TMD evolution**



LHCb-like detector



LHCb-like detector

Precision at the level of ~10%!!

Quark induced azimuthal asymmetries

Drell-Yan cross section for a transversely polarized target has several modulations:

$$A_{UU}^{\cos 2\phi} \sim h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_1^{\perp \bar{q}}(x_2, k_{2T}^2)$$

$$A_{UT}^{\sin \phi_S} \sim f_1^q(x_1, k_{1T}^2) \otimes f_{1T}^{\perp \bar{q}}(x_2, k_{2T}^2)$$

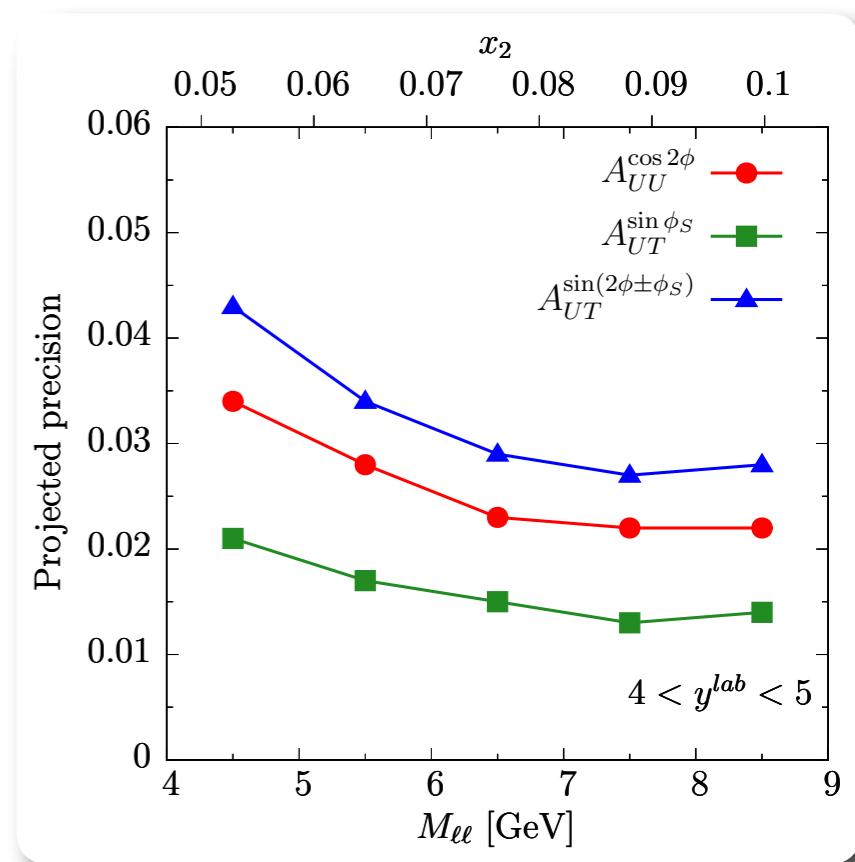
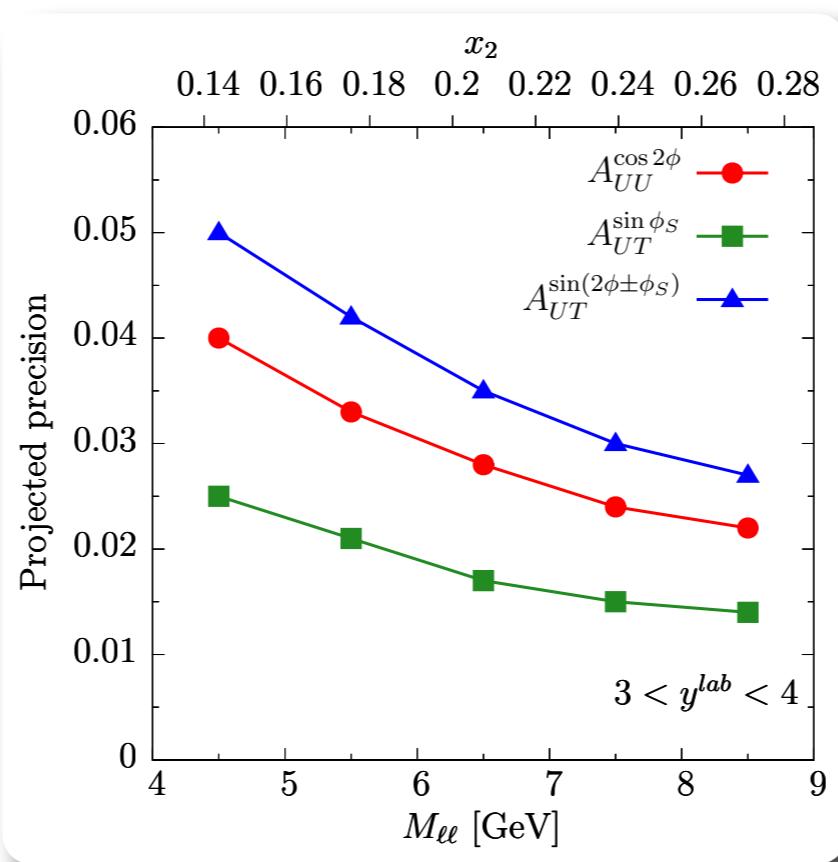
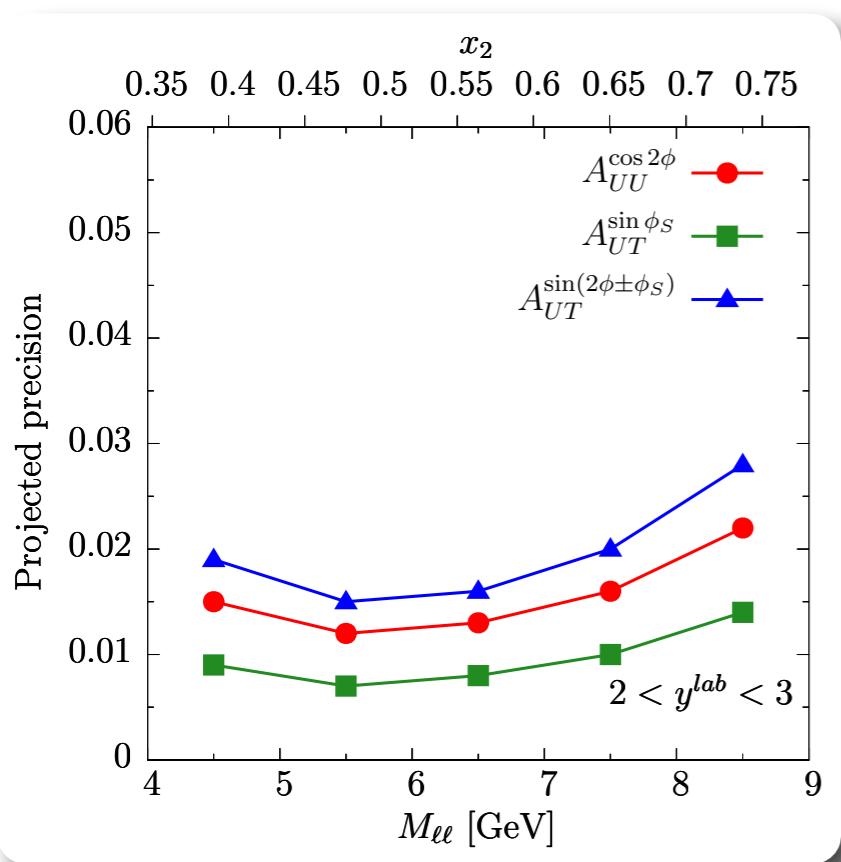
$$A_{UT}^{\sin(2\phi + \phi_S)} \sim h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_{1T}^{\perp \bar{q}}(x_2, k_{2T}^2)$$

$$A_{UT}^{\sin(2\phi - \phi_S)} \sim h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_1^{\bar{q}}(x_2, k_{2T}^2)$$

Possible to constrain different TMDPDFs:

- Unpolarized Sivers** (T-odd)
- Boer-Mulders** (T-odd)
- Pretzelosity**
- Transversity**

[Arnold, Metz, Schlegel 0809.2262]



Linearly polarized gluon TMDPDF

- It is matched onto twist-2 g/q PDFs: simpler pheno than Boer-Mulders (T-odd)!
- No experimental extraction whatsoever (first attempt from di-J/Psi in [\[arXiv:1710.01684\]](#))
- Affects several quarkonium production qT spectra

[\[Lansberg, Pisano, Schlegel 1702.00305\]](#)

$$\frac{d\sigma(\eta_Q)}{dq_T} \propto f_1^g \otimes f_1^g - h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\frac{d\sigma(\chi_{Q0})}{dq_T} \propto f_1^g \otimes f_1^g + h_1^{\perp g} \otimes h_1^{\perp g}$$

$$\frac{d\sigma(\chi_{Q2})}{dq_T} \propto f_1^g \otimes f_1^g$$

[\[Boer, Pisano 1208.3642\]](#)

$$\frac{d\sigma(2 \text{ colorless})}{dq_T d\Omega} \propto F_1 f_1^g \otimes f_1^g + F_2 h_1^{\perp g} \otimes h_1^{\perp g}$$

$$+ \cos(2\phi_{CS}) (F_3 f_1^g \otimes h_1^{\perp g} + F'_3 h_1^{\perp g} \otimes f_1^g)$$

$$+ \cos(4\phi_{CS}) F_4 h_1^{\perp g} \otimes h_1^{\perp g}$$

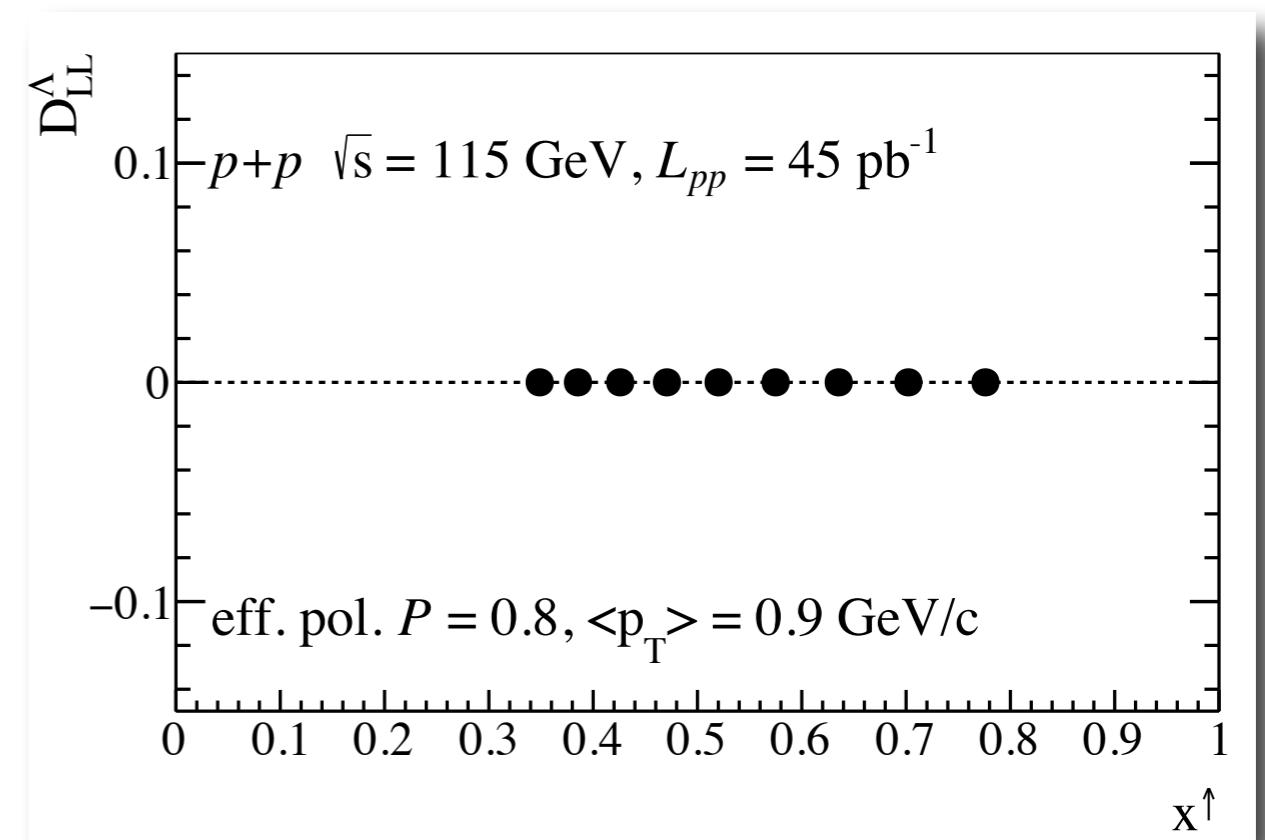
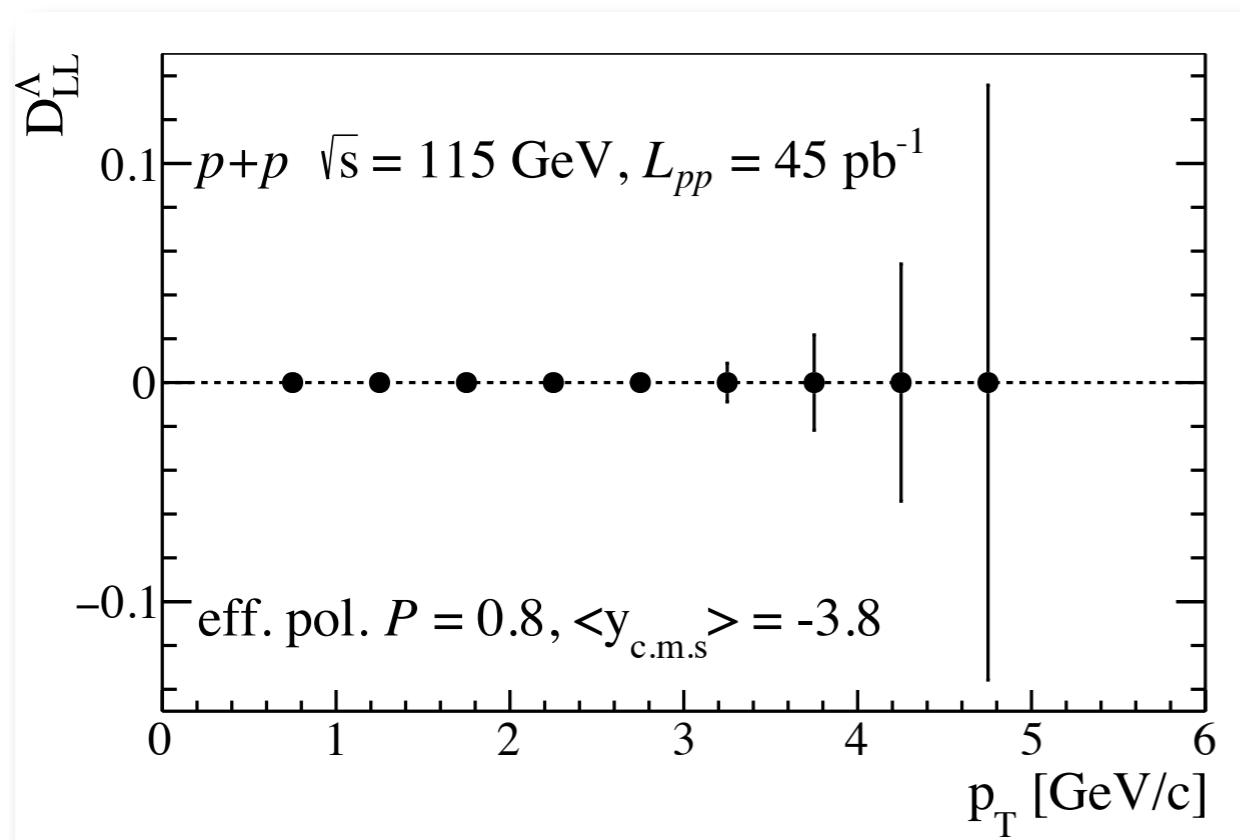
Process at AFTER@LHC	expected yield	x_2 range	M [GeV]	q_T modulation
η_c	$O(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c0}(1P)$	$O(10^4)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c2}(1P)$	$O(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$< 1\%$
$\chi_{b0}(nP)$	$O(10^2)$	$0.1 \div 1$	$\mathcal{O}(10)$	$0 \div 60\%$
$\chi_{b2}(nP)$	$O(10^3)$	$0.1 \div 1$	$\mathcal{O}(10)$	$< 1\%$

Process at AFTER@LHC	expected yield	x_2 range	M [GeV]	$\langle \cos 2\phi \rangle$	$\langle \cos 4\phi \rangle$
$J/\psi + \gamma$	$1000 \div 2000$	$0.1 \div 0.6$	$\mathcal{O}(10)$	$0 \div 5\%$	$0 \div 2\%$
$J/\psi + J/\psi$	$300 \div 1500$	$0.1 \div 0.8$	$8 \div 12$	$0 \div 15\%$	$0 \div 20\%$

[\[Lansberg, Pisano, Scarpa, Schlegel 1710.01684\]](#)

Strange quark helicity/transversity at high x

$$D_{LL} \equiv \frac{\sigma_{pp^+ \rightarrow \Lambda^+} - \sigma_{pp^+ \rightarrow \Lambda^-}}{\sigma_{pp^+ \rightarrow \Lambda^+} + \sigma_{pp^+ \rightarrow \Lambda^-}}$$



Great statistical precision expected for longitudinal spin transfer D_{LL} to Λ hyperons with ALICE-like detector and a target located ahead from the ALICE TPC at $z=4.7\text{m}$

Similar precision can be achieved for D_{TT} , which would give a handle on the **strange quark transversity** and thus on the **tensor charge**

Conclusions

• **3 main themes** would greatly benefit from a fixed-target program at the LHC:

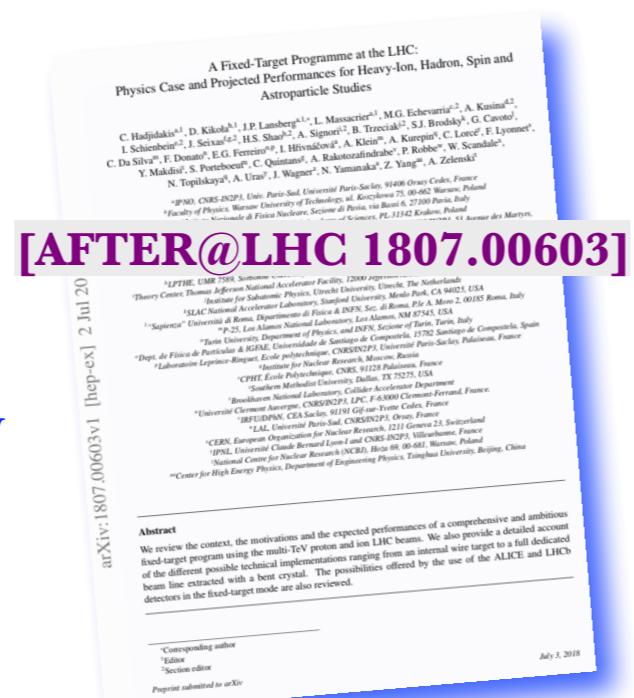
- **High-x frontier**: probe of confinement and connected to astroparticles
- **Nucleon 3D/spin structure**: access large x_F and great precision
- **Heavy-ion Physics**: new energy, new rapidity domain and new probes

• **2 ways to realize** a fixed-target experiment using the LHC beams:

- **A bent crystal** for a low extraction + new detectors
- **Internal solid/gas target** + existing detectors

☞ Nezza/Pappalardo (*LHCSpin*)

• Based on fast simulations, the **AFTER@LHC study group** has made FoMs for LHCb and ALICE in the FT mode which clearly **support a full physics program** carried out **at a fixed-target experiment at the LHC**



*It is doable, “cheap”
and very very useful!
So the sooner it is built,
the better! :-)*

Check **AFTER@LHC** review
for many more details

Thank you!