Spin Physics with a fixed-target experiment at the LHC

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Outline

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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 comprehensive 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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[1] Editor
[2] Section editor

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[arXiv: 1807.00603]

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

Full review is (finally) out!!

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

This talk: a selection of the spin physics part:

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

What/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** ($x_F \to -1$) domain
- Achieving **high luminosities** thanks to LHC beams and dense targets
- Possibility to **change the target** type (≠ atomic masses)
- Possibility to **polarize the target**

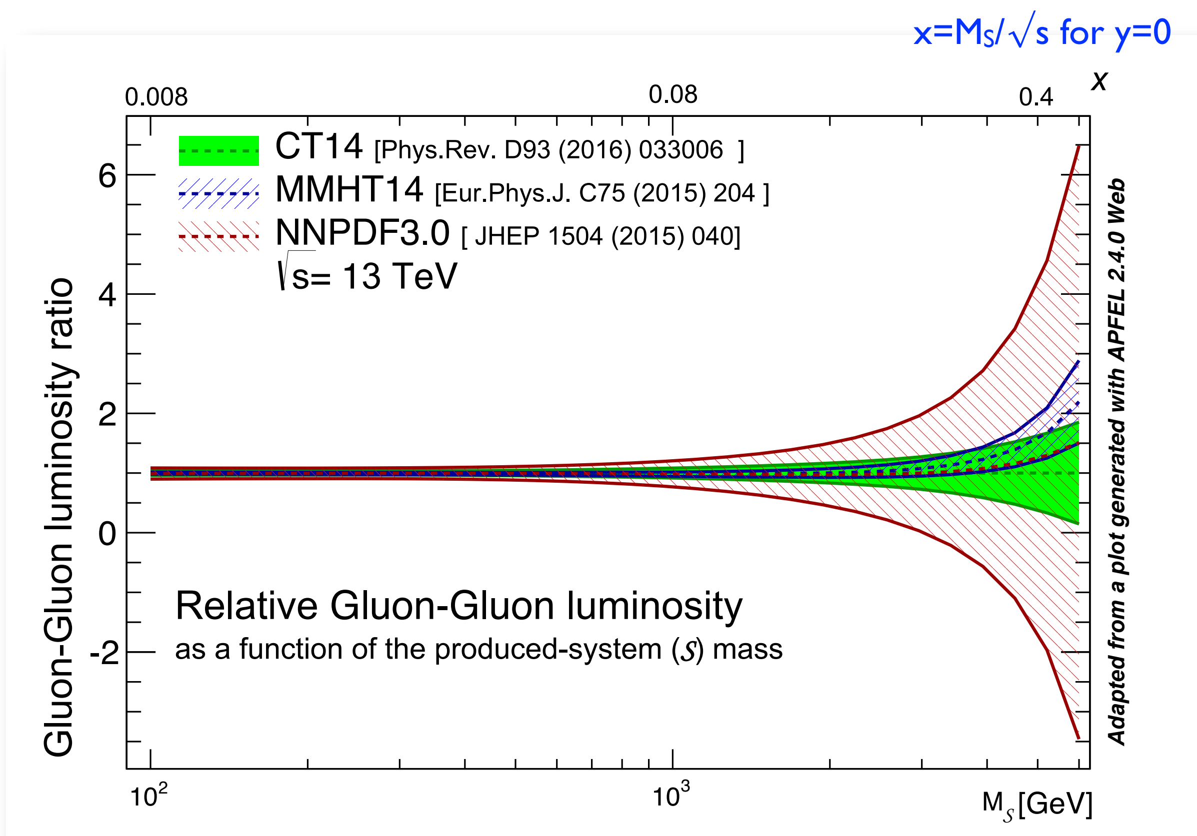
In **parasitic mode** with the most energetic beam ever, without affecting the LHC performances:
- Internal solid/gas target + existing detectors (LHCb/ALICE) ☞ *P. Di Nezza and E. Steffens*
- A bent crystal for a low extraction + new detectors

It would be "cheap"! :-)
Given the huge amount of Physics we could obtain…

Physics motivation I: study the high-x frontier

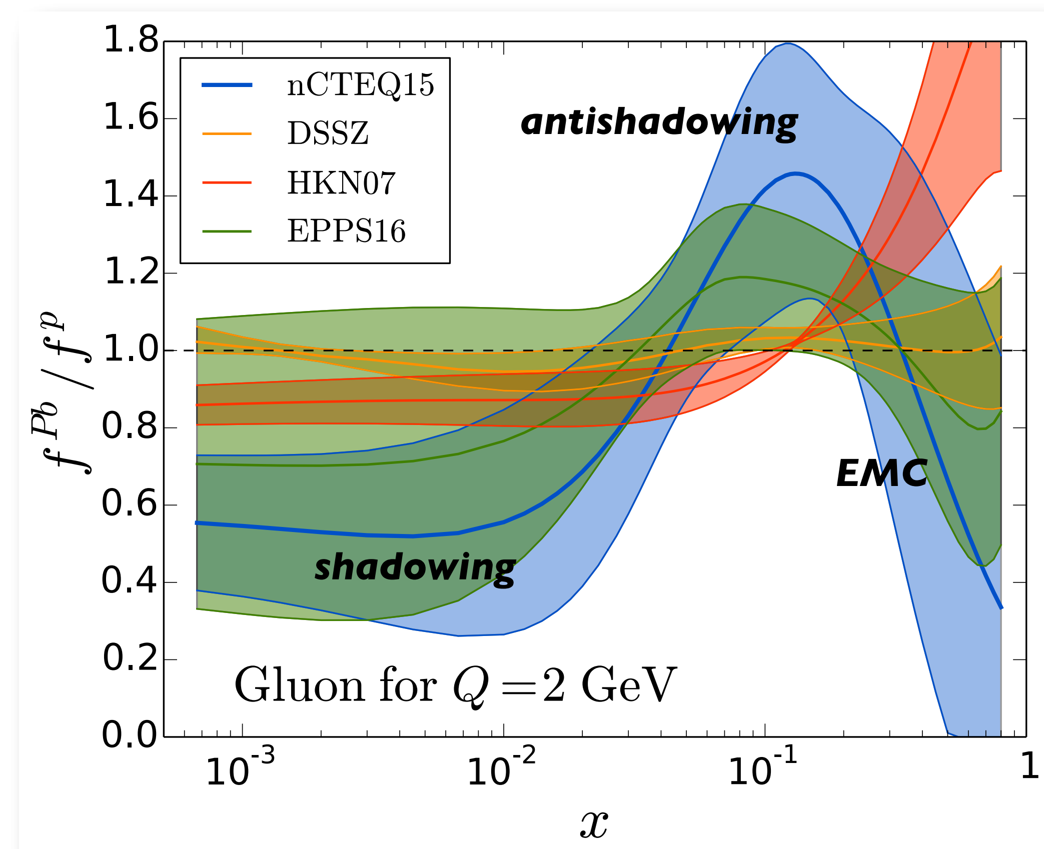
- Very large PDF uncertainties for x>0.5 [could be crucial to characterize possible BSM discoveries]
- Proton charm content important to high-energy neutrino & cosmic-rays physics
- EMC effect is still an open problem: studying a possible gluon EMC effect is essential
- Relevance of nuclear PDFs to understand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

gg luminosity



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

gluon nuclear PDF (Pb)

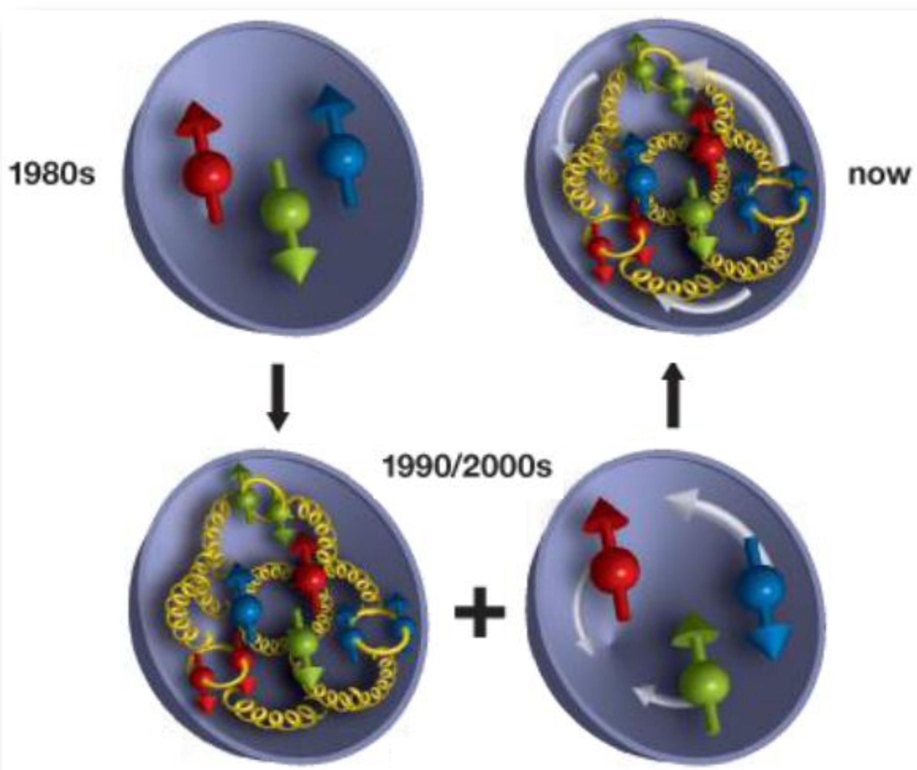


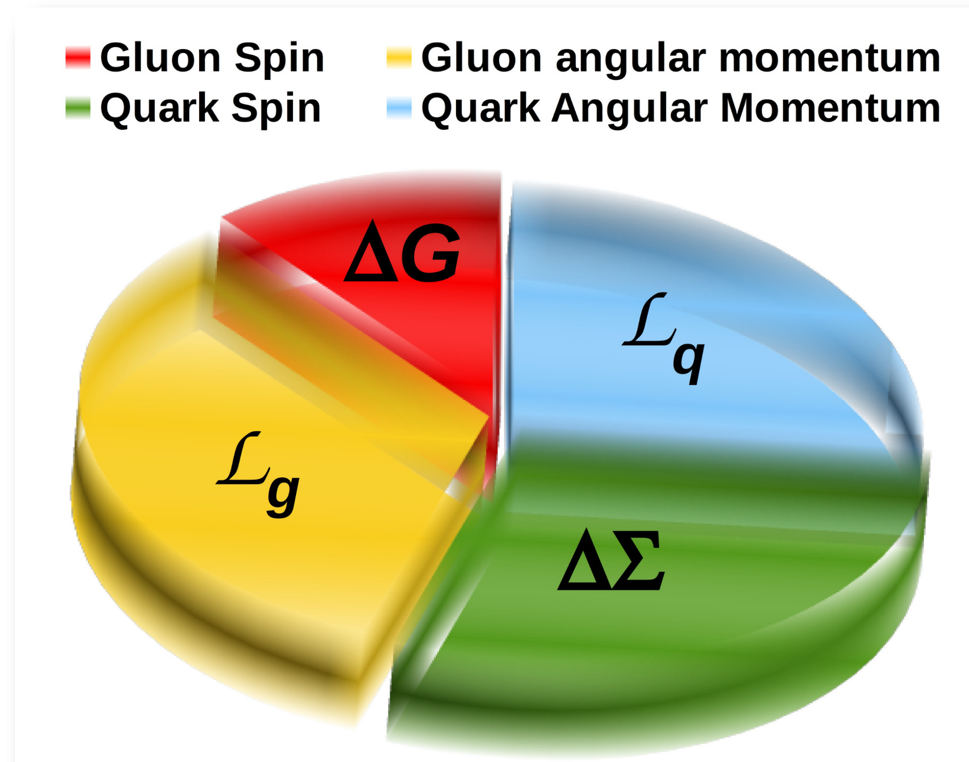
Check AFTER@LHC review ***[arXiv: 1807.00603]***
for many more details

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

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

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



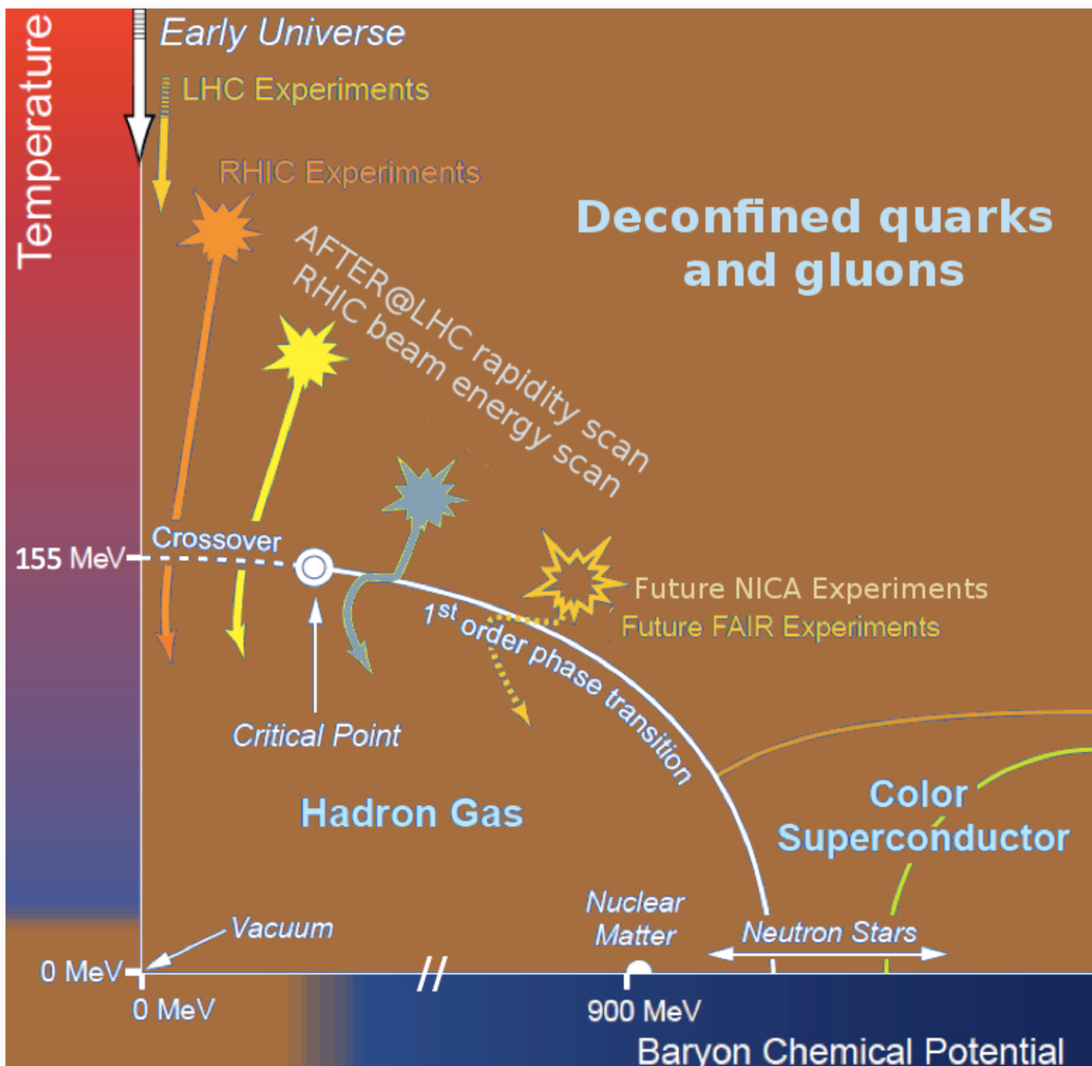


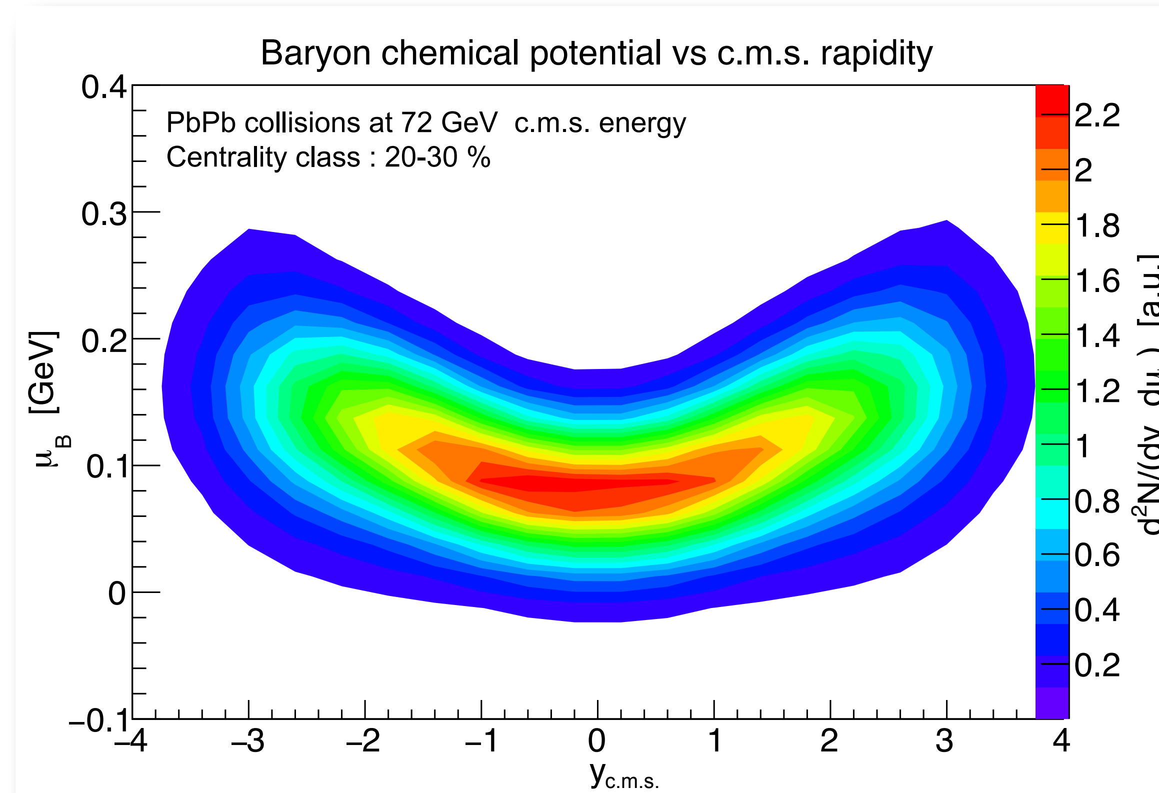
This talk: a selection of the spin physics part

Check AFTER@LHC review ***[arXiv: 1807.00603]***
for many more details

Physics motivation 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', χc, 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

Check AFTER@LHC review ***[arXiv: 1807.00603]*** for many more details

Kinematics

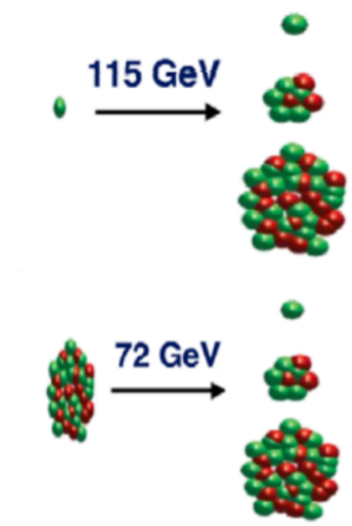
Energy range

7 TeV proton beam on a fixed target

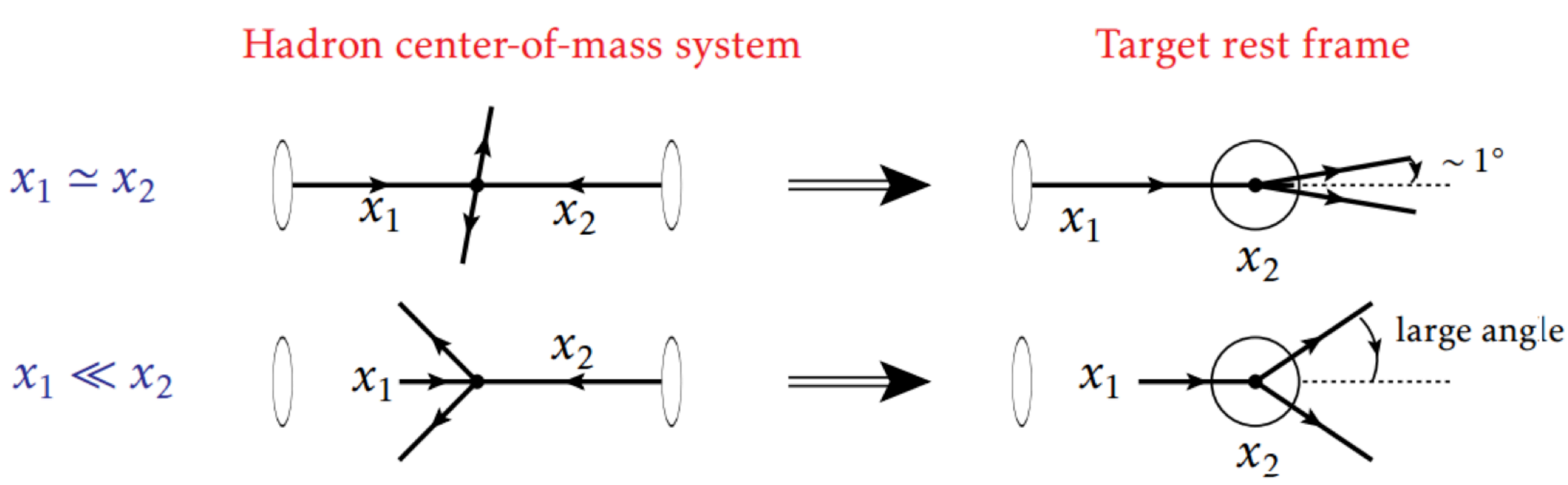
c.m.s. energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	

2.76 TeV Pb beam on a fixed target

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

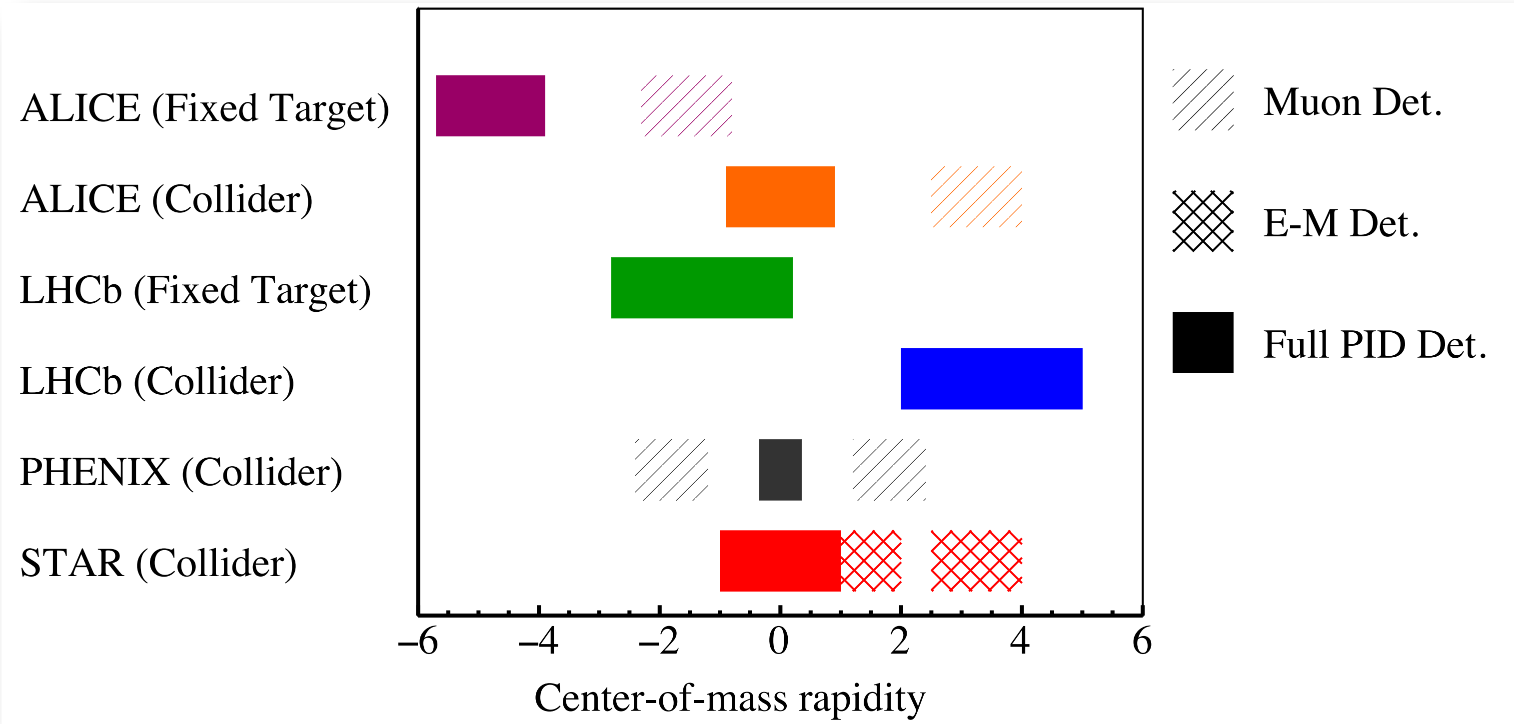


Boost effect:



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

Kinematics: LHCb-like and ALICE-like detectors



Acceptance of LHCb

$2 < \eta_{lab} < 5$

Acceptance of ALICE

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

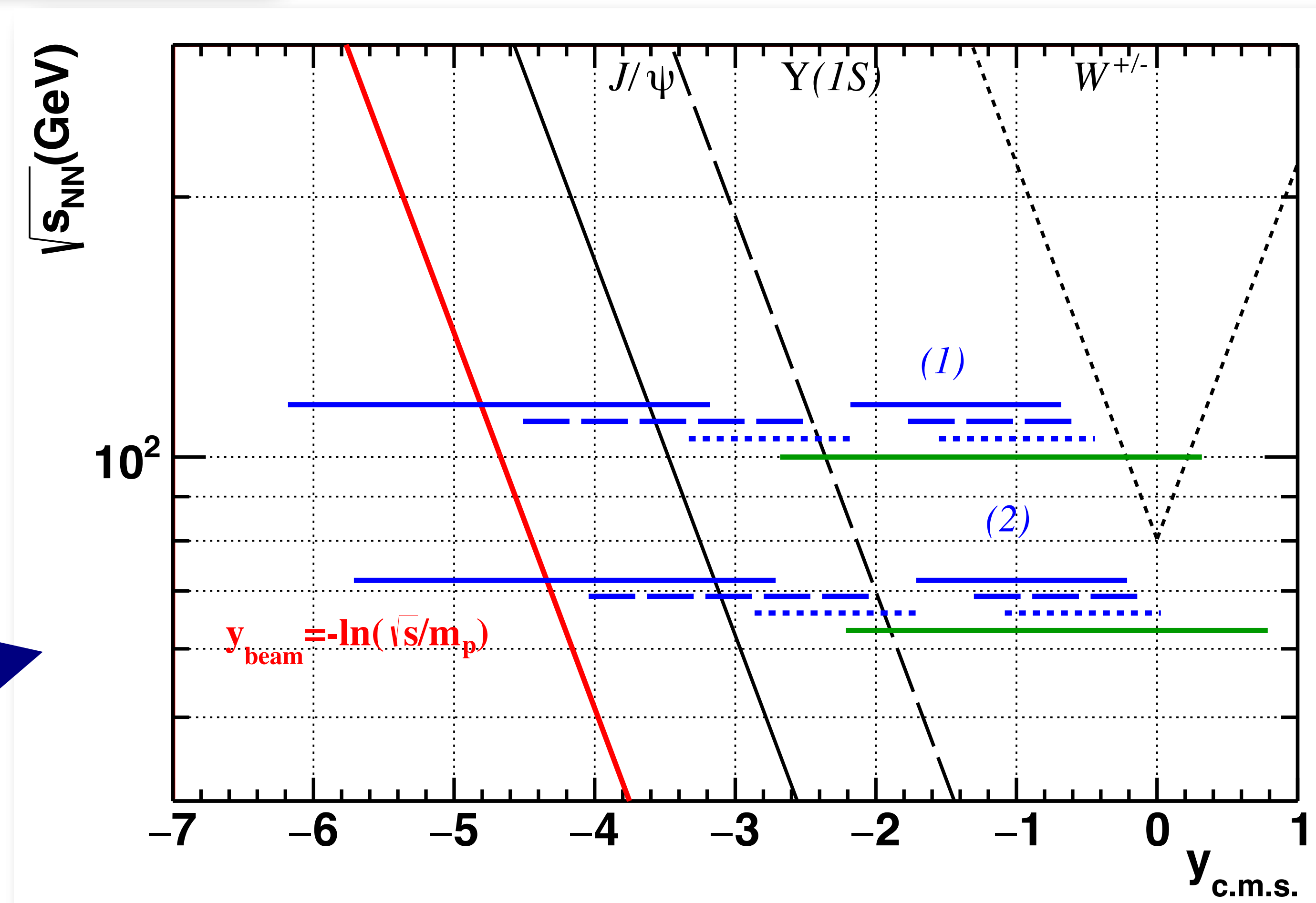
Central barrel: $-0.9 < \eta_{lab} < 0.9$

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

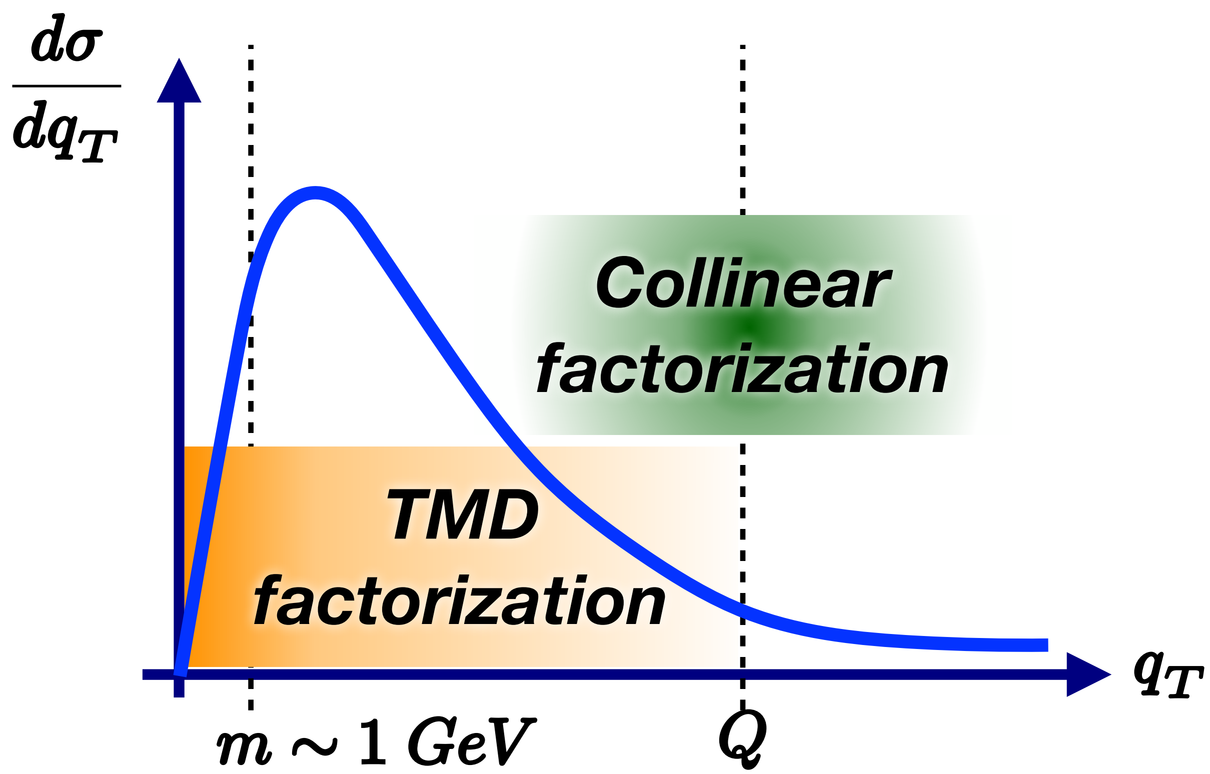
(1) $\sqrt{s}$=115GeV and (2) $\sqrt{s}$=72GeV

Solid, dashed, dotted: z= 0m, 2.75m, 4.7m

Blue: ALICE; Green: LHCb



Theory shot



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

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

- 2 scales qT<Q: TMD factorization for small qT & collinear factorization at large qT
- 1 scale pT: just collinear factorization

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

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

☞ A.Vladimirov

For example:

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

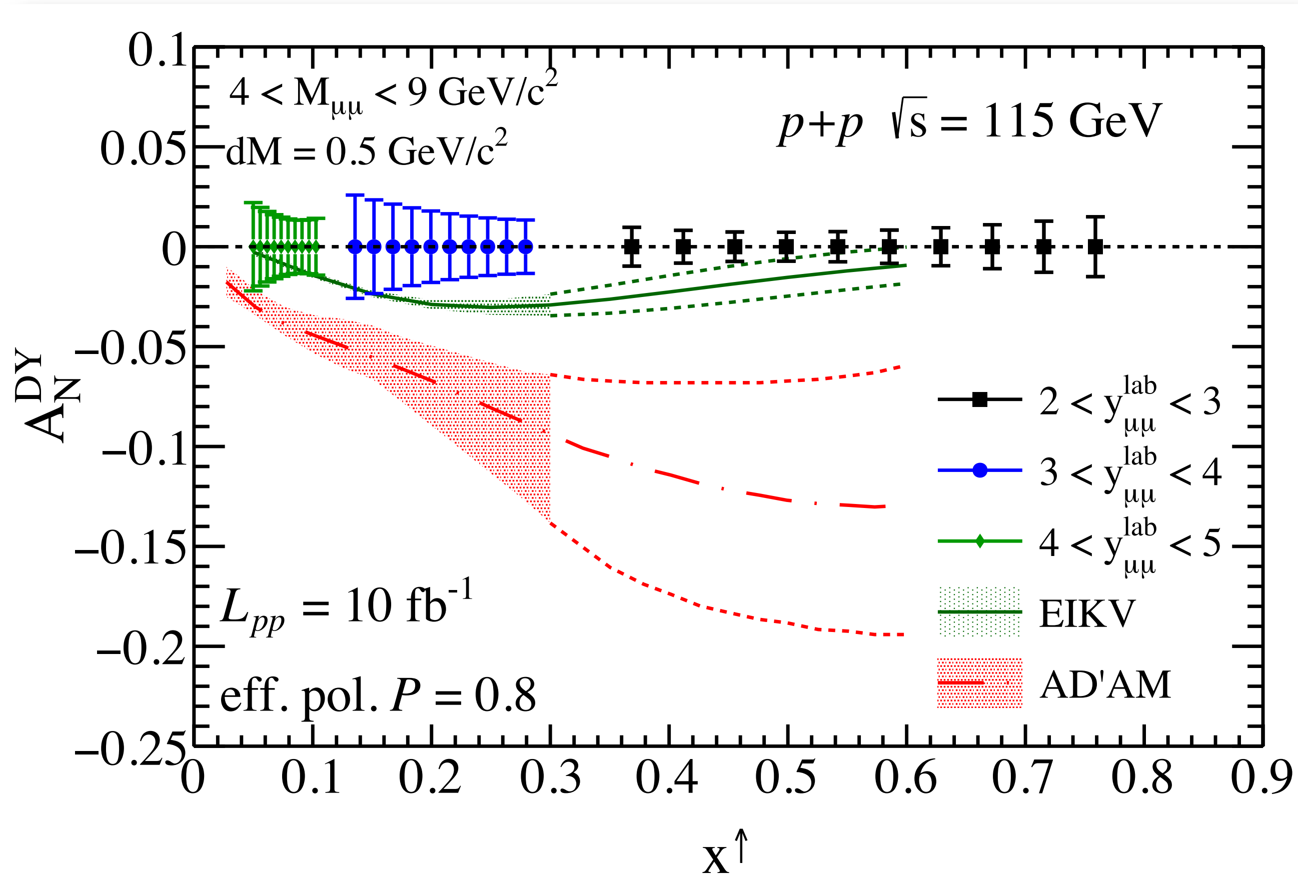
- **Generalized Parton *Model* (GPM)** is a useful way to get interesting results, but limited
- **Quarkonium/Heavy-flavour** in p: no proper TMD factorization yet…

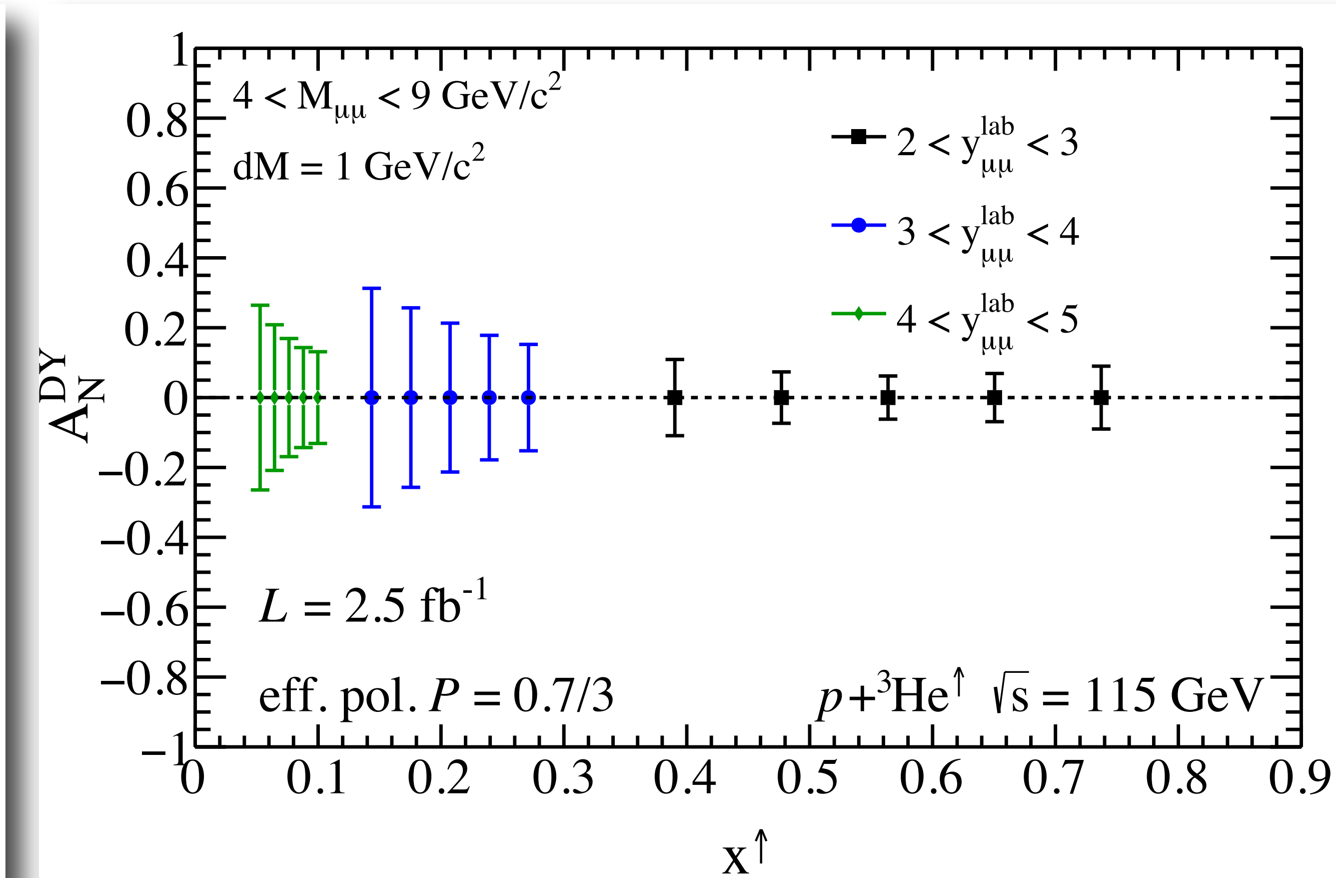
Quark Sivers effect: Drell-Yan A_N

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

LHCb-like detector

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

EIKV: MGE, Idilbi, Kang, Vitev [arXiv: 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

Worse statistics because of ³He↔p
But still, a unique opportunity to access neutron Sivers function!

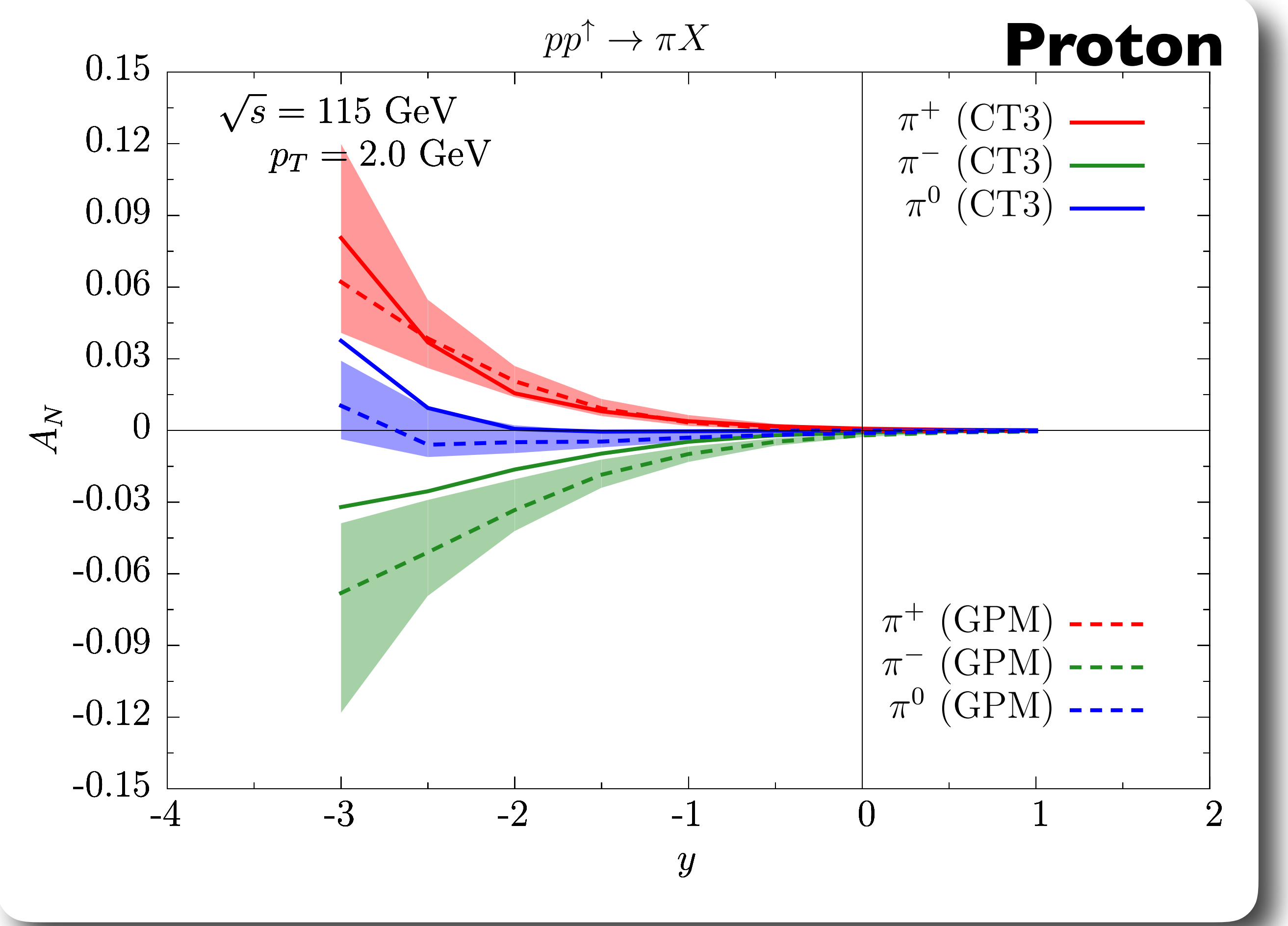
Quark Sivers effect: pion production

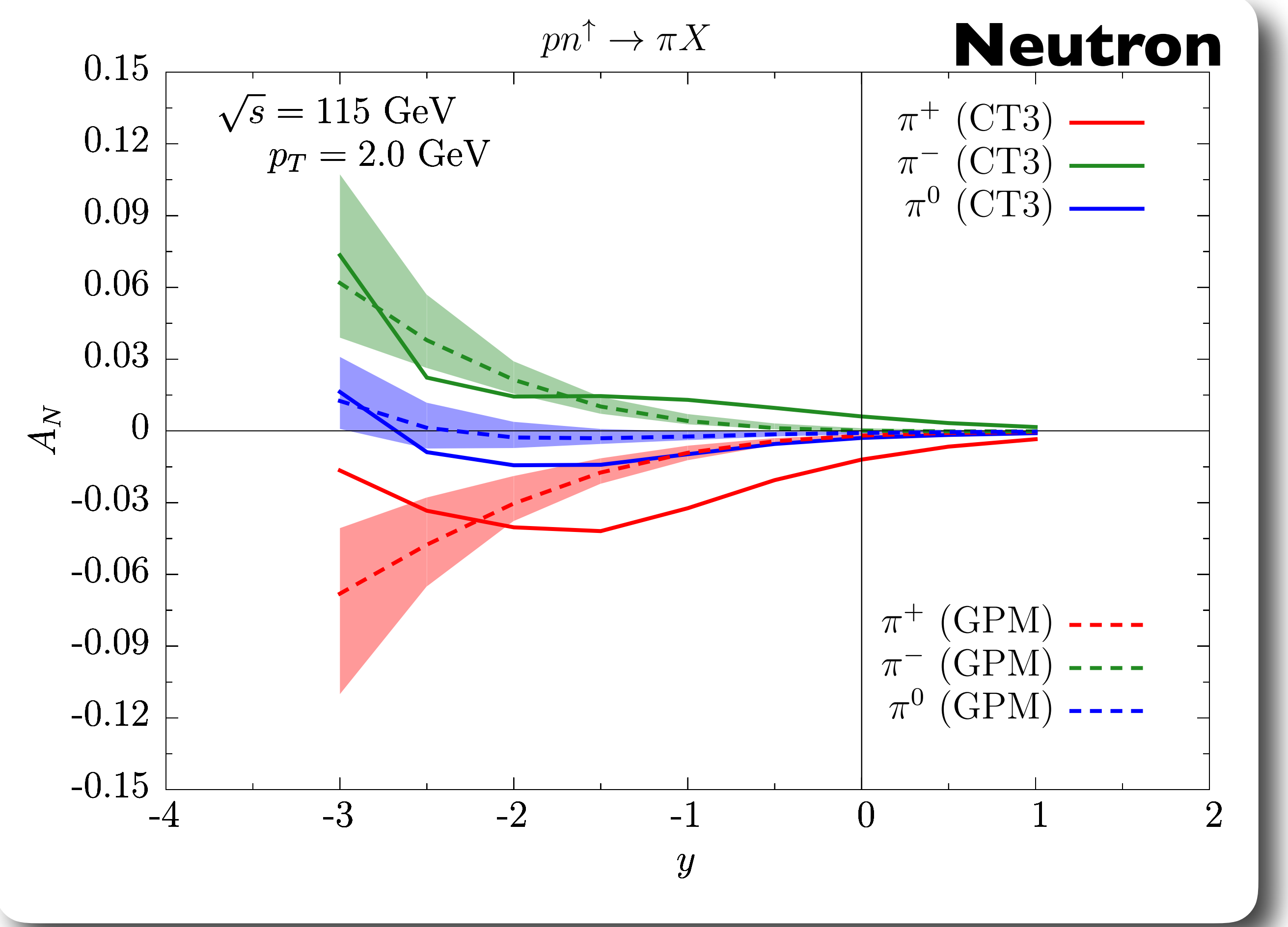
- Generalized Parton *Model* (GPM) and Collinear Twist-3 factorization (CT3) formalisms
- Test of the "flavor sign change" and thus isospin symmetry
- No simulations yet
- Potentially measurable ~10% STSA for backward rapidity!

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

→ GPM: Sivers and Collins TMDs

→ CT3: twist-3 functions
Fragmentation dominates!





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

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

Isospin symmetry used.
E.g. for Sivers:

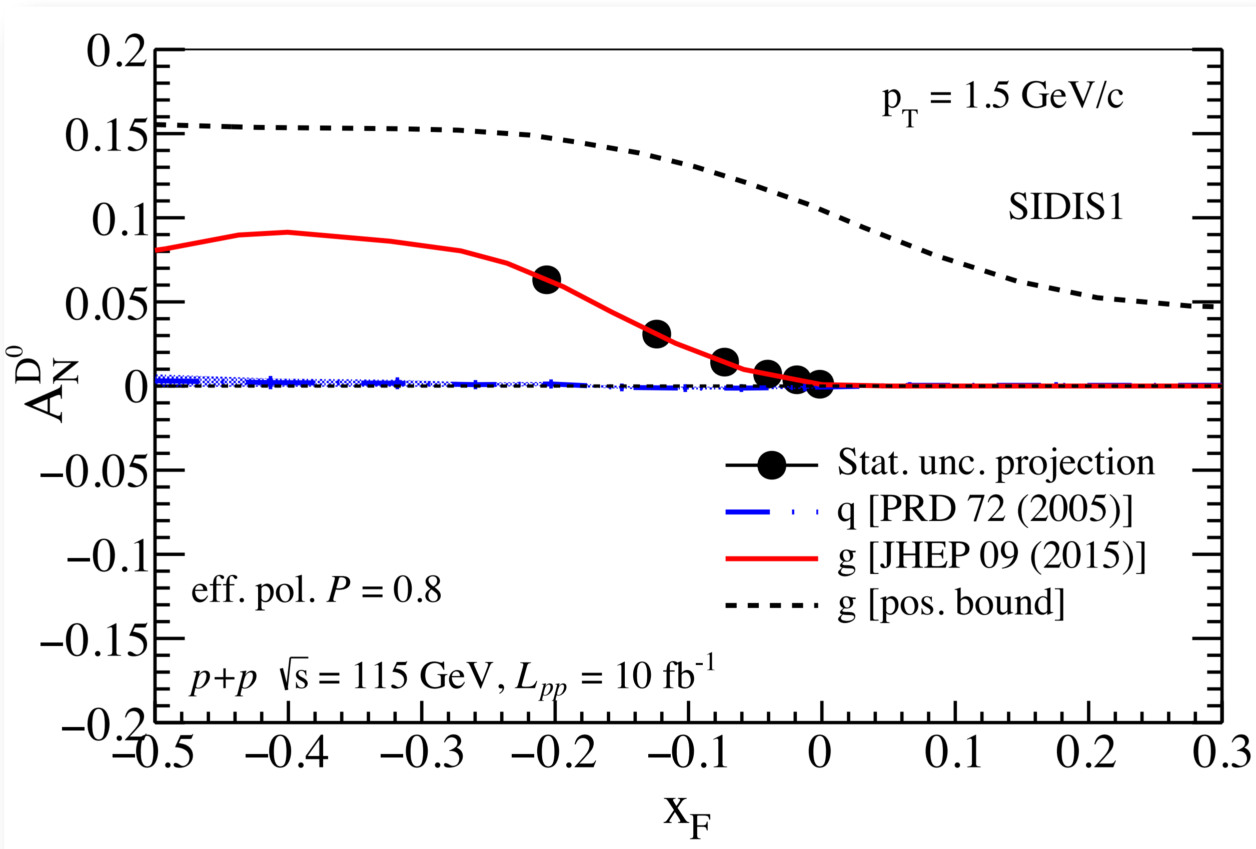
$$f_{1T}^{\perp u/neutron} = f_{1T}^{\perp d/proton}$$
$$f_{1T}^{\perp d/neutron} = f_{1T}^{\perp u/proton}$$

Gluon Sivers effect: open heavy-flavor production

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

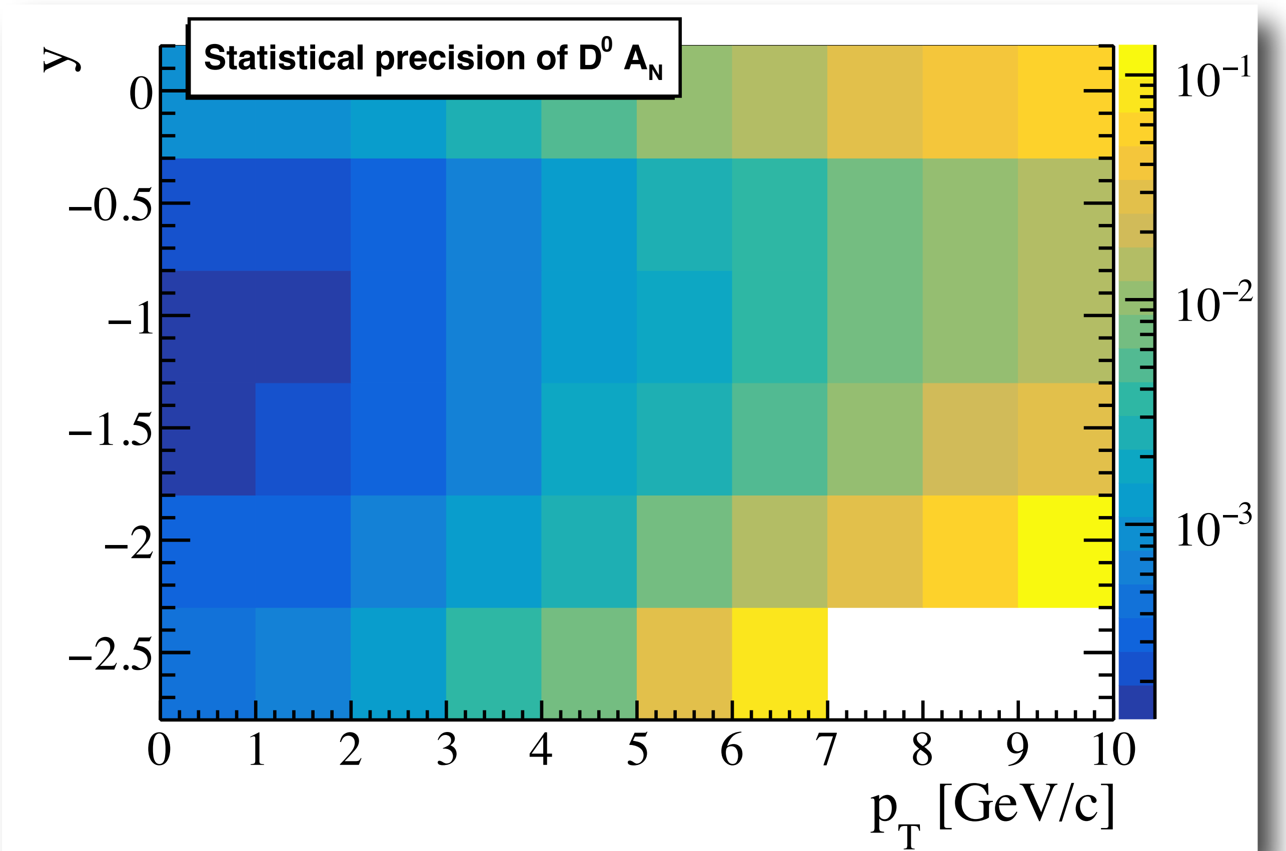
- D mesons can be collected with a transversely polarized target [never measured]
- Can constrain twist-3 tri-gluon correlation functions and gluon Sivers function
- Differences of $A_N^{\bar{D}^0}$ and $A_N^{D^0}$ give access to C-odd tri-gluon correlator T_G^d

Kang, Qiu, Vogelsang, Yuan [arXiv: 0810.3333]



LHCb-like detector

Theory predictions with GPM factorization

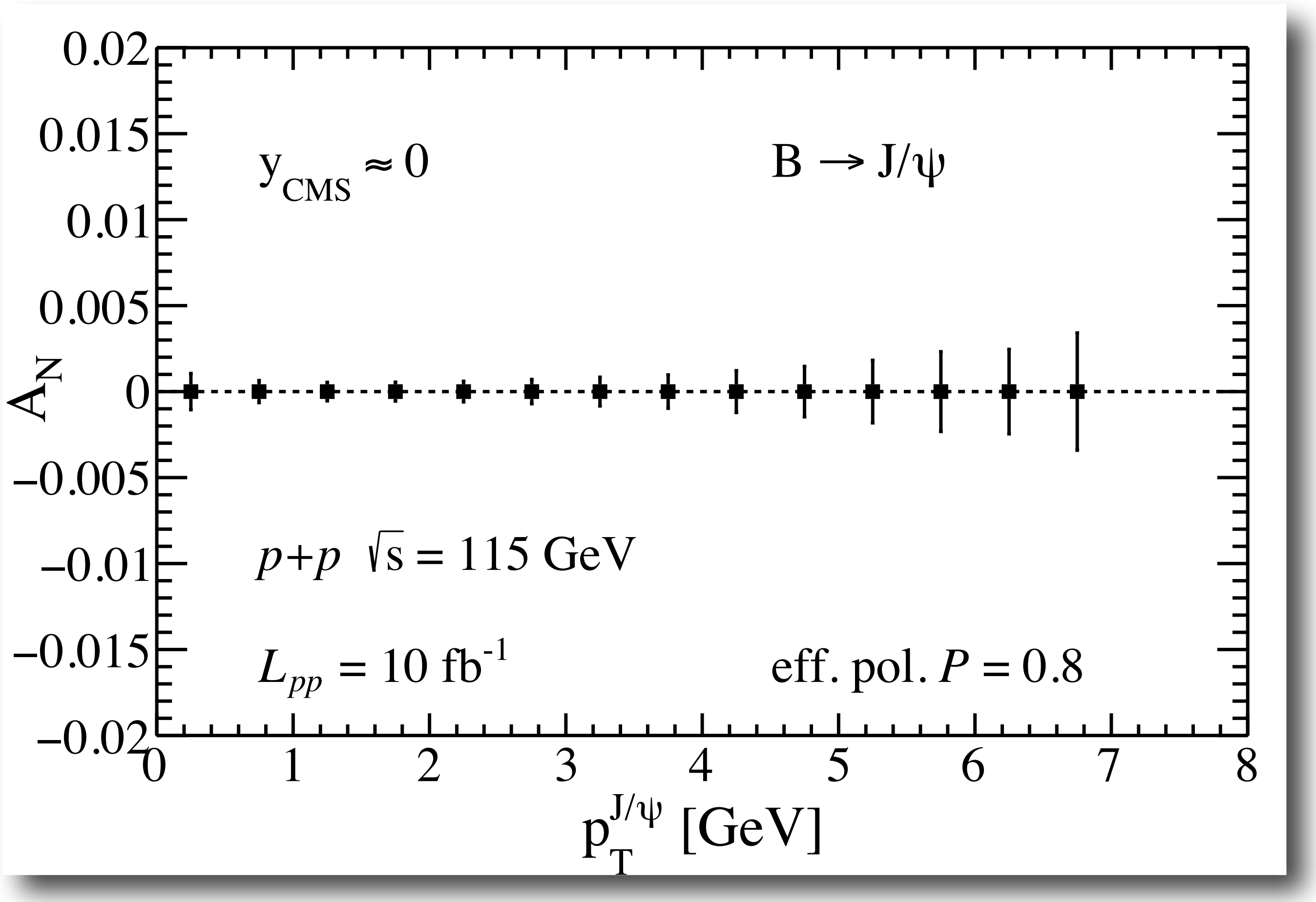


LHCb-like detector

Precision at the percent level!!

Gluon Sivers effect: open heavy-flavor production

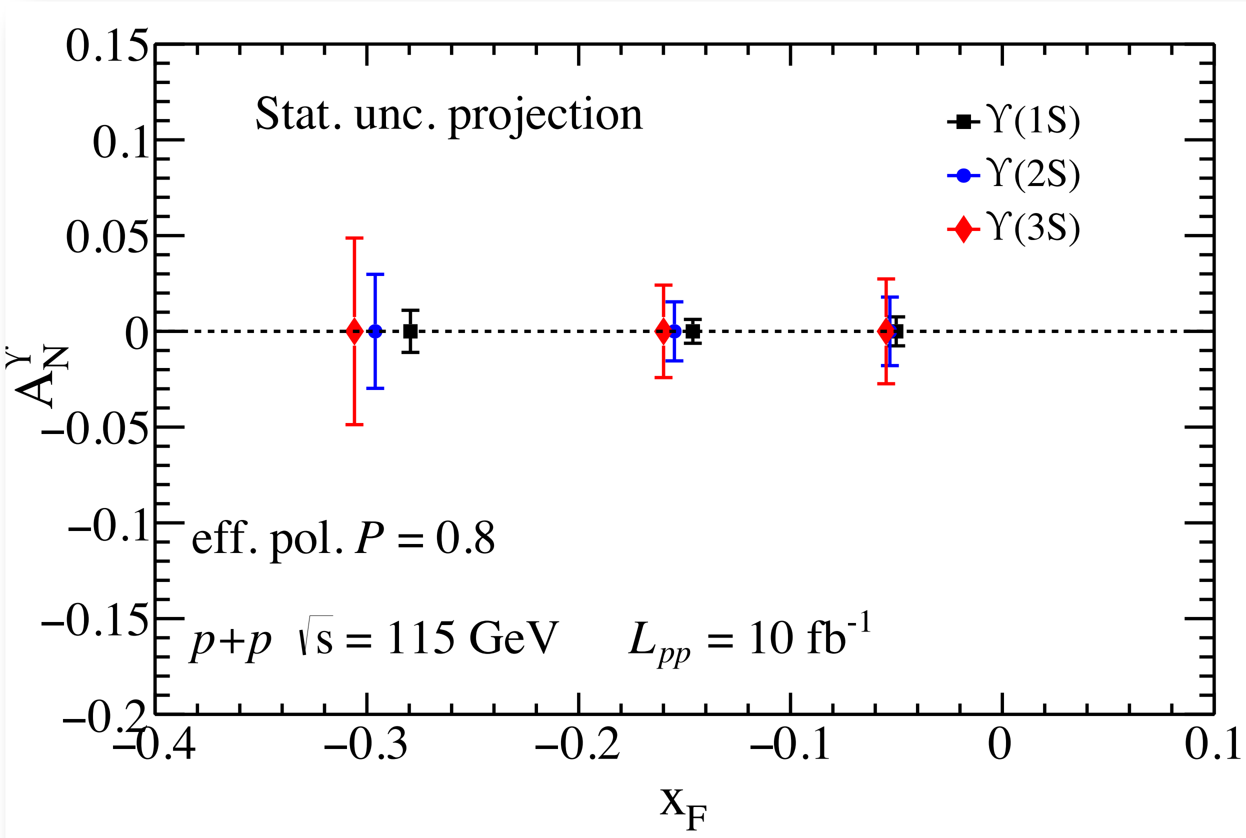
Projected statistical precision for B meson STSA (through its decay in J/Psi)



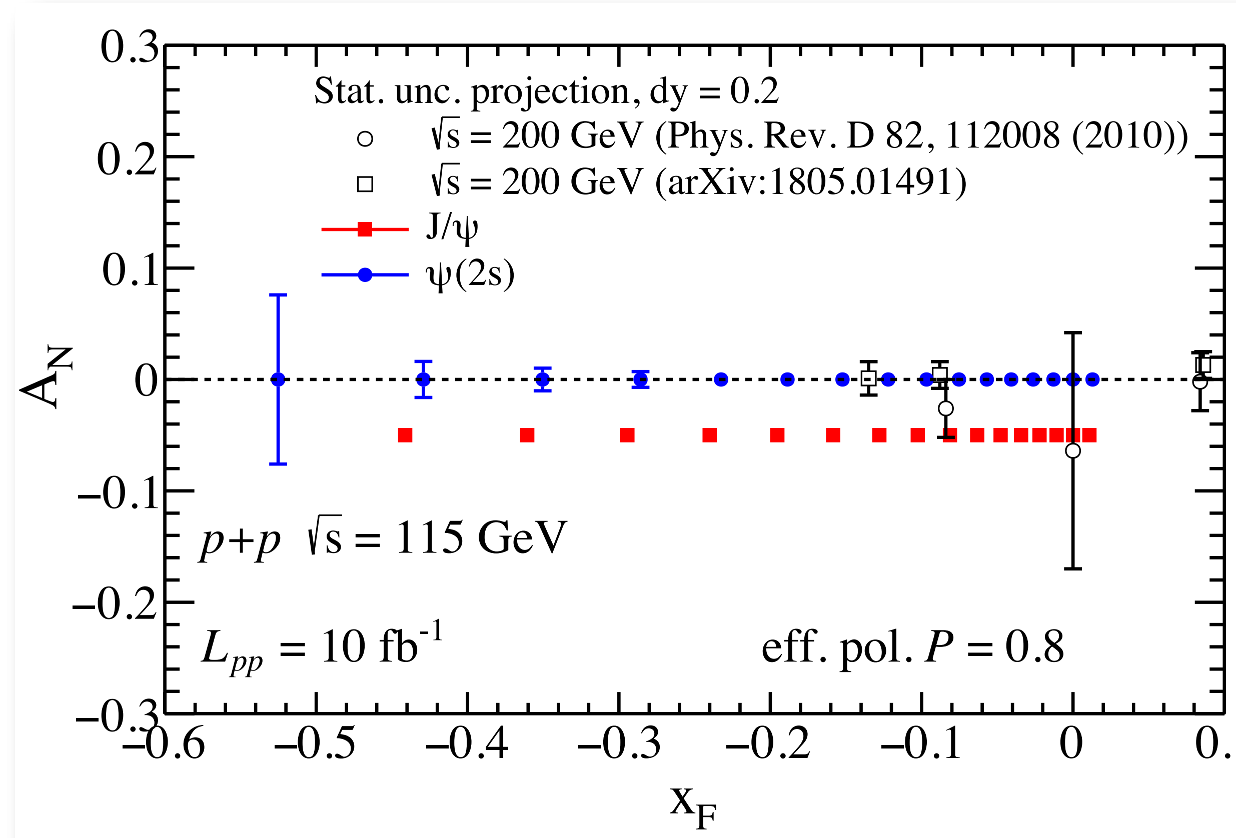
LHCb-like detector

Precision at the per mile level!!

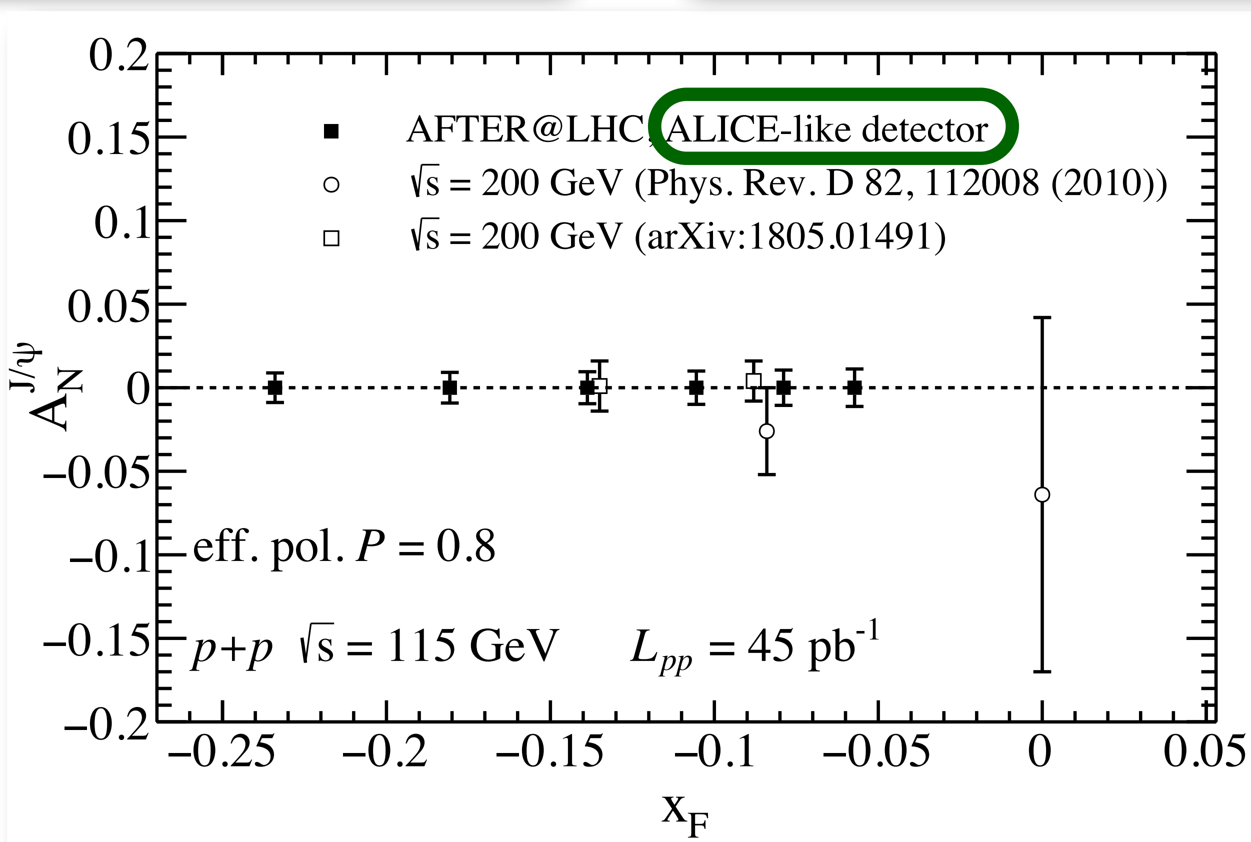
Gluon Sivers effect: vector quarkonium production



LHCb-like detector



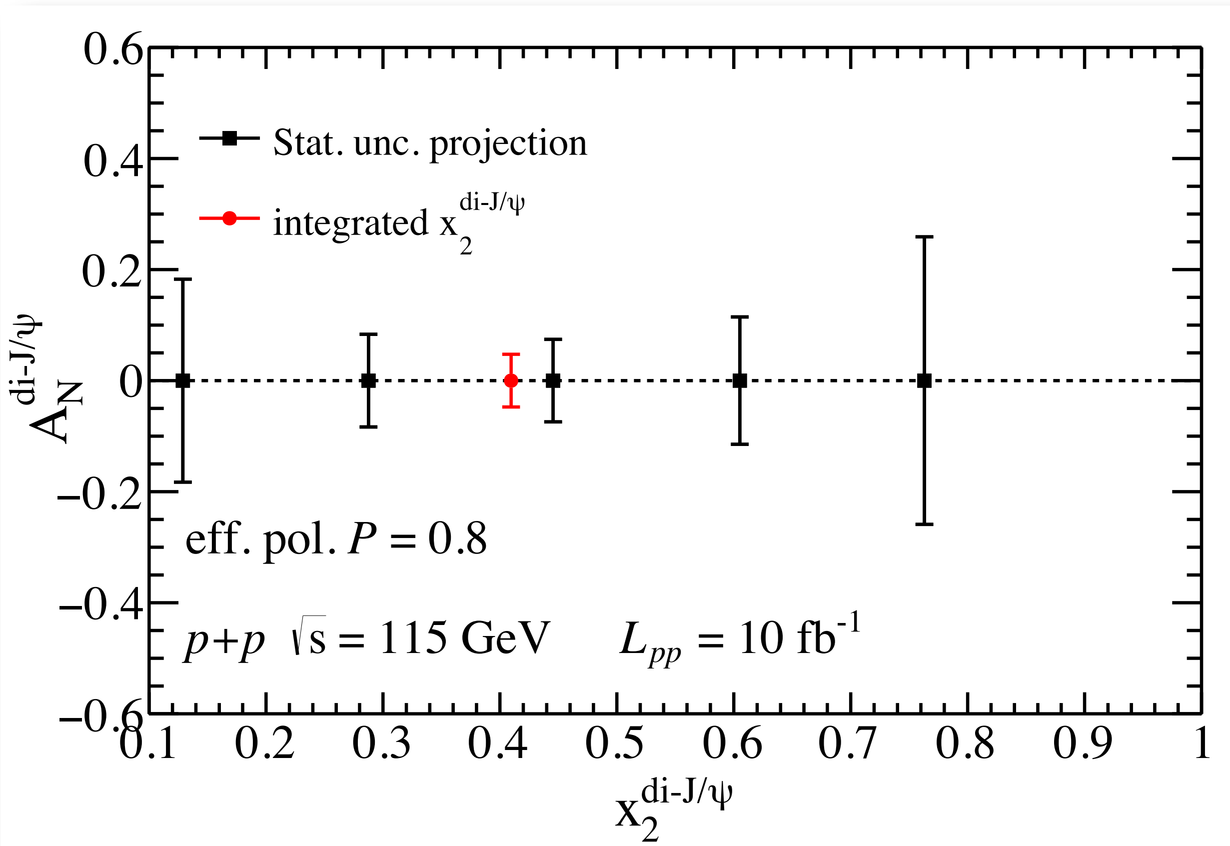
LHCb-like detector



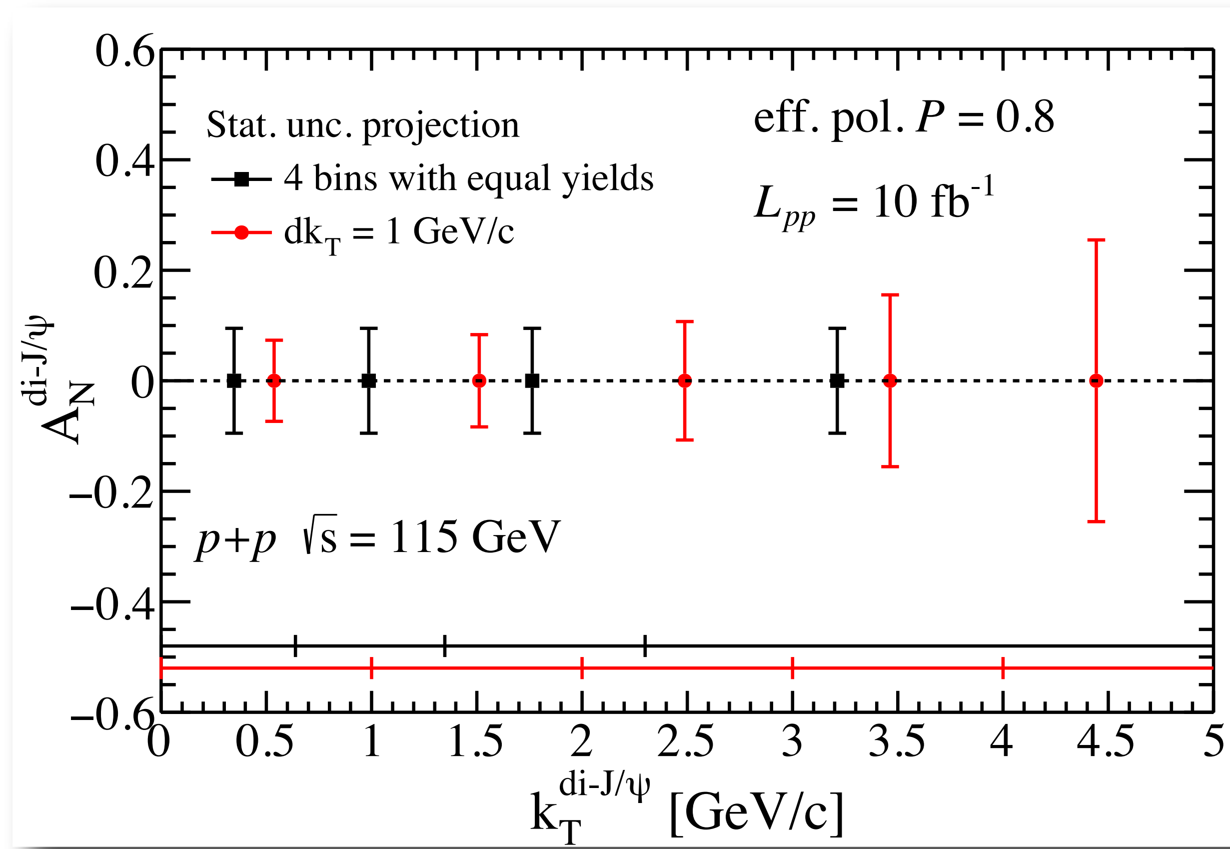
Precision at the percent level!!

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!
- They are 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:

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \Big\{ (1 + D_{[\sin^2\theta]} A_{UU}^{\cos 2\phi} \cos 2\phi) + |\vec{S}_T| \Big[A_{UT}^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \Big(A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \Big) \Big] \Big\}$$

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

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

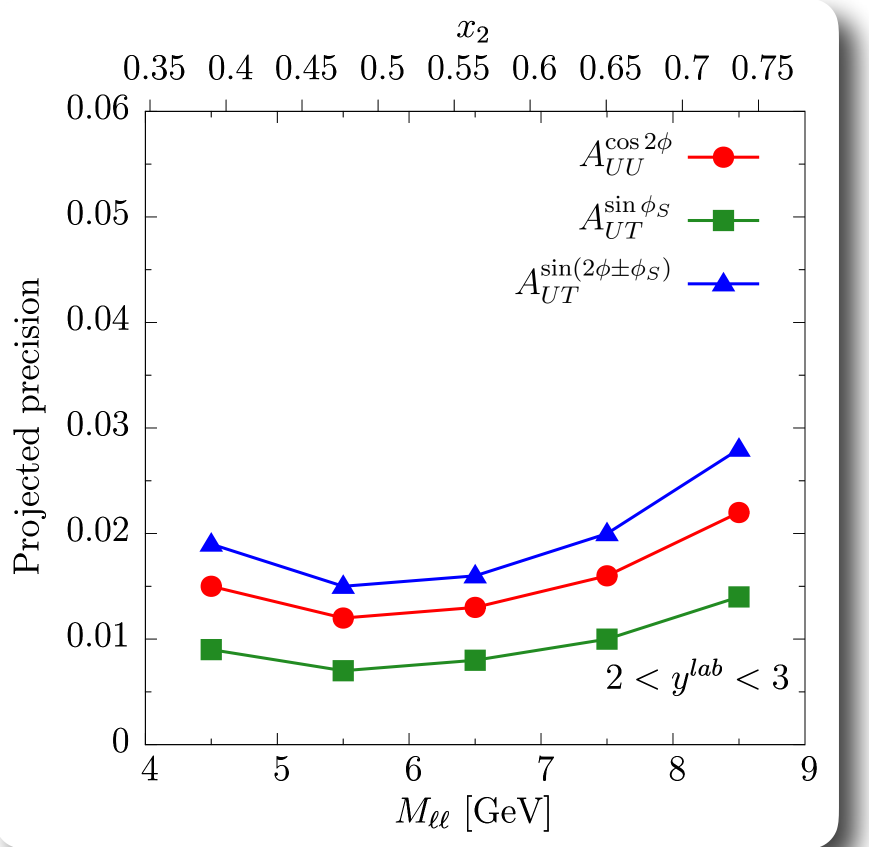
$$A_{UT}^{\sin(2\phi+\phi_S)} \sim h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_{1T}^{\perp \bar{q}}(x_2, k_{2T}^2)$$

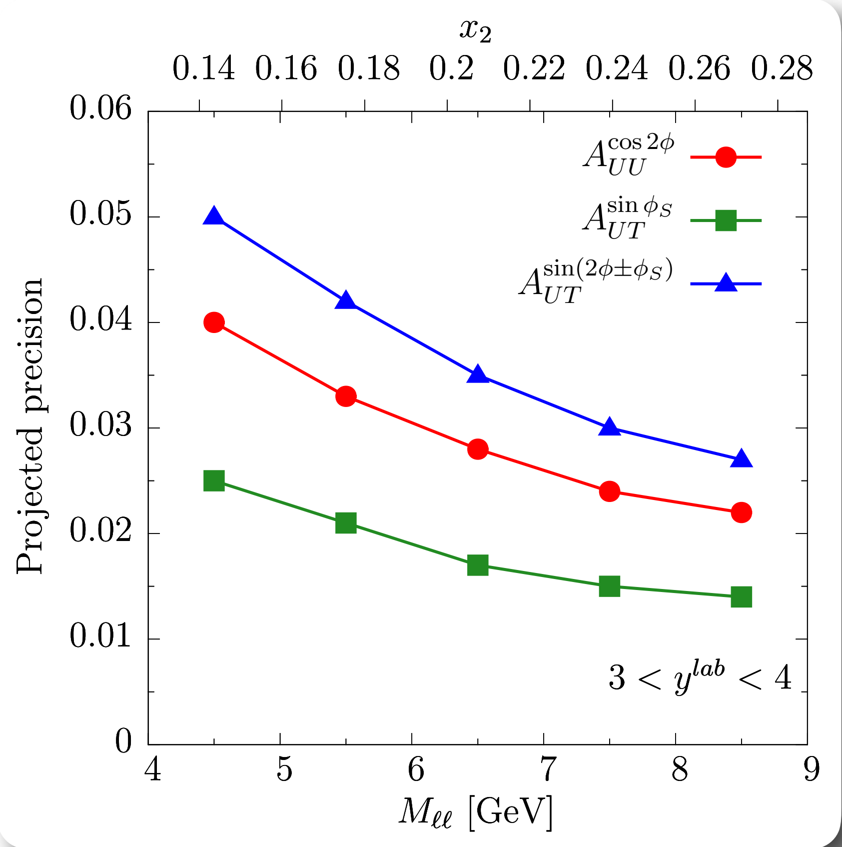
$$A_{UT}^{\sin(2\phi-\phi_S)} \sim h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_1^{\bar{q}}(x_2, k_{2T}^2)$$

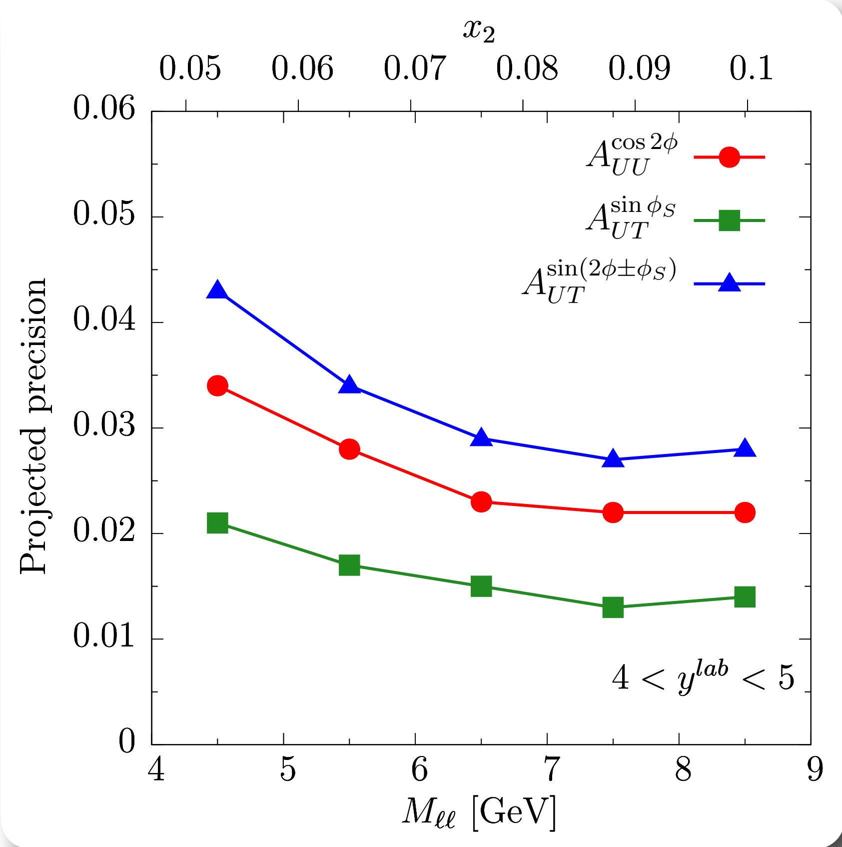
Arnold, Metz, Schlegel [arXiv: 0809.2262]

Possible to constrain: unpolarized, Sivers, Boer-Mulders, pretzelosity and tranversity TMDs!

T-odd *T-odd*







LHCb-like detector

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

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

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

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

Boer, Pisano [arXiv: 1208.3642]

Lansberg, Pisano, Schlegel [arXiv: 1702.00305]

$$\frac{d\sigma(2\text{ colorless})}{dq_T d\Omega} \propto F_1 f_1^g \otimes f_1^g + F_2 h_1^{\perp g} \otimes h_1^{\perp g} + \cos(2\phi_{CS})\left(F_3 f_1^g \otimes h_1^{\perp g} + F_3' h_1^{\perp g} \otimes f_1^g\right) + \cos(4\phi_{CS}) F_4 h_1^{\perp g} \otimes h_1^{\perp g}$$

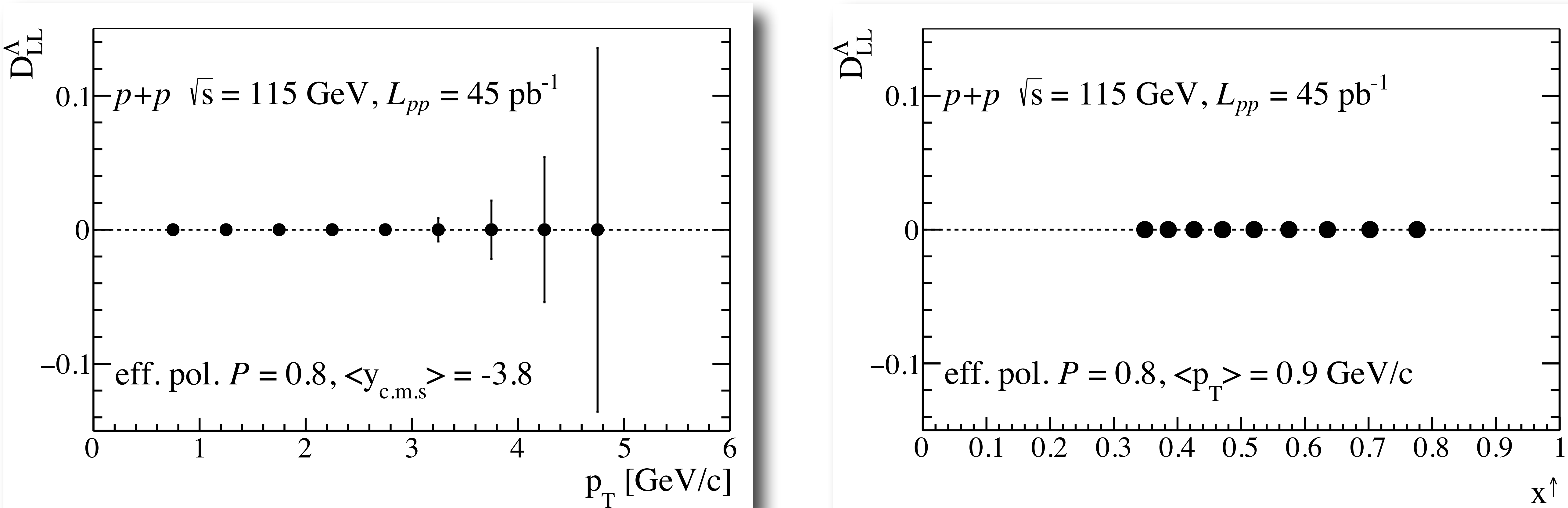
Process at AFTER@LHC	expected yield	x_2 range	M [GeV]	q_T modulation
η_c	$O(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c0}(1P)$	$O(10^4)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c2}(1P)$	$O(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$< 1\%$
$\chi_{b0}(nP)$	$O(10^2)$	$0.1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

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 [arXiv: 1710.01684]

Strange quark helicity/transversity at high x

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



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*=4.7m

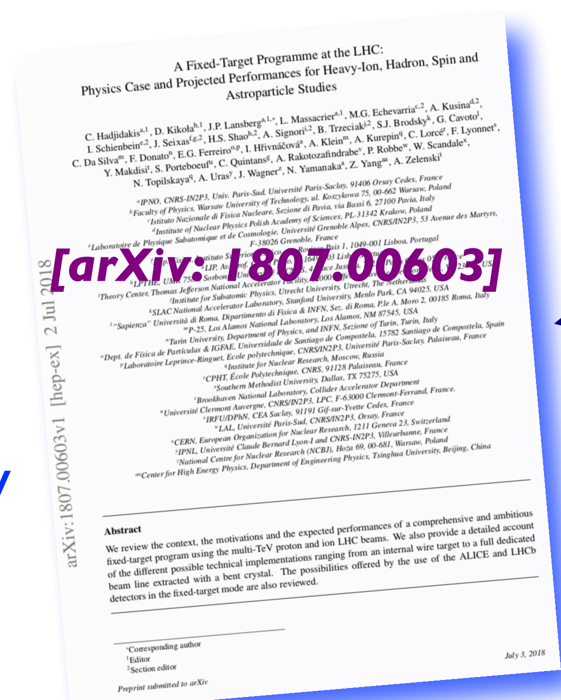
Similar precision can be achieved for $\mathbf{D_{TT}}$, which would give a handle on the **strange quark transversity** and thus on the **tensor charge**

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 → *talks by P. Di Nezza and E. Steffens*

- 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**


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 comprehensive 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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[1] Editor
[2] Section editor

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[arXiv: 1807.00603]

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

Check AFTER@LHC review for many more details

Backup

Relevant parameters for future/planned experiments

Experiment	particles	beam energy (GeV)	$\sqrt{s}$ (GeV)	$x^{\uparrow}$	$\mathcal{L}$ (cm^{-2}s^{-1})	$\mathcal{P}_{\rm eff}$	$\mathcal{F}$ (cm^{-2}s^{-1})
AFTER@LHCb	$p + p^{\uparrow}$	7000	115	$0.05 \div 0.95$	$1 \cdot 10^{33}$	80%	$6.4 \cdot 10^{32}$
AFTER@LHCb	$p + {}^3\mathrm{He}^{\uparrow}$	7000	115	$0.05 \div 0.95$	$2.5 \cdot 10^{32}$	23%	$1.4 \cdot 10^{31}$
AFTER@ALICE$_{\mu}$	$p + p^{\uparrow}$	7000	115	$0.1 \div 0.3$	$2.5 \cdot 10^{31}$	80%	$1.6 \cdot 10^{31}$
COMPASS (CERN)	$\pi^- + p^{\uparrow}$	190	19	$0.05 \div 0.55$	$2 \cdot 10^{33}$	14%	$4.0 \cdot 10^{31}$
PHENIX/STAR (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.1$	$2 \cdot 10^{32}$	50%	$5.0 \cdot 10^{31}$
E1039 (FNAL)	$p + p^{\uparrow}$	120	15	$0.1 \div 0.45$	$4 \cdot 10^{35}$	15%	$9.0 \cdot 10^{33}$
E1027 (FNAL)	$p^{\uparrow} + p$	120	15	$0.35 \div 0.9$	$2 \cdot 10^{35}$	60%	$7.2 \cdot 10^{34}$
NICA (JINR)	$p^{\uparrow} + p$	collider	26	$0.1 \div 0.8$	$1 \cdot 10^{32}$	70%	$4.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	200	$0.1 \div 0.5$	$8 \cdot 10^{31}$	60%	$2.9 \cdot 10^{31}$
fsPHENIX (RHIC)	$p^{\uparrow} + p^{\uparrow}$	collider	510	$0.05 \div 0.6$	$6 \cdot 10^{32}$	50%	$1.5 \cdot 10^{32}$
PANDA (GSI)	$\bar{p} + p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	$2 \cdot 10^{32}$	20%	$8.0 \cdot 10^{30}$

Table 16: Compilation inspired from [1, 19] of the relevant parameters for the future or planned polarised DY experiments. The effective polarisation ($\mathcal{P}_{\rm eff}$) is a beam polarisation (where relevant) or an average polarisation times a (possible) dilution factor (for a gas target, similar to the one developed for HERMES [87, 264]) or a target polarisation times a dilution factor (for the NH_3 target used by COMPASS and E1039). For the AFTER@LHC lines, the numbers correspond to a gas target. $\mathcal{F}$ is the (instantaneous) spin figure of merit of the target defined as $\mathcal{F} = \mathcal{P}_{\rm eff}^2 \times \mathcal{L}$, with $\mathcal{L}$ being the instantaneous luminosity.