8th COMPASS Analysis Phase mini-workshop (COMAP-VIII)
COMPASS - LHCspin – AMBER CERN- 22/05/2024

The physics case of LHCspin

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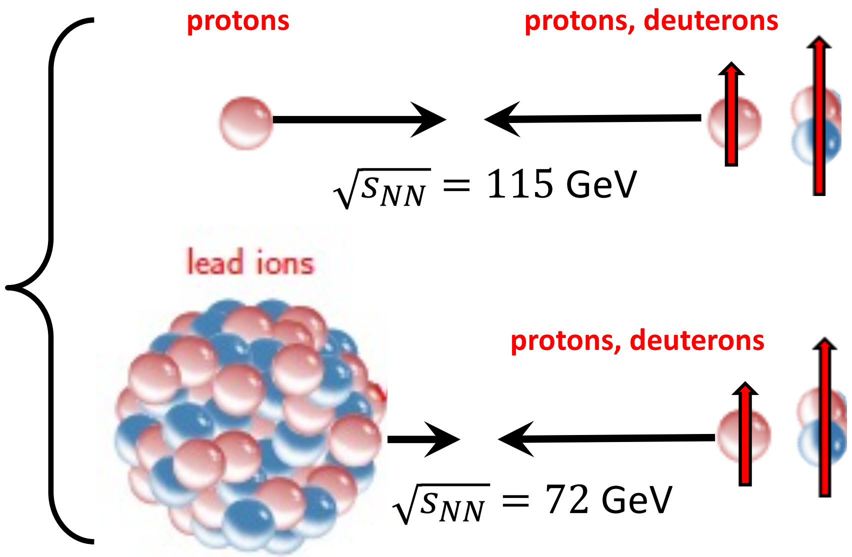
(1) CERN, (2) CNRS Saclay, (3) Duke University, (4) FZ Julich, (5) INFN Bari, (6) INFN Ferrara, (7) INFN Firenze, (8) INFN Frascati, (9) INFN Torino, (10) PSI Zurich, (11) TH Nuremberg, (12) University of Erlangen, (13) University of Ferrara, (14) University of Yamamata, (15) University of Yerevan

Kinematic conditions for fixed-target collisions at LHC



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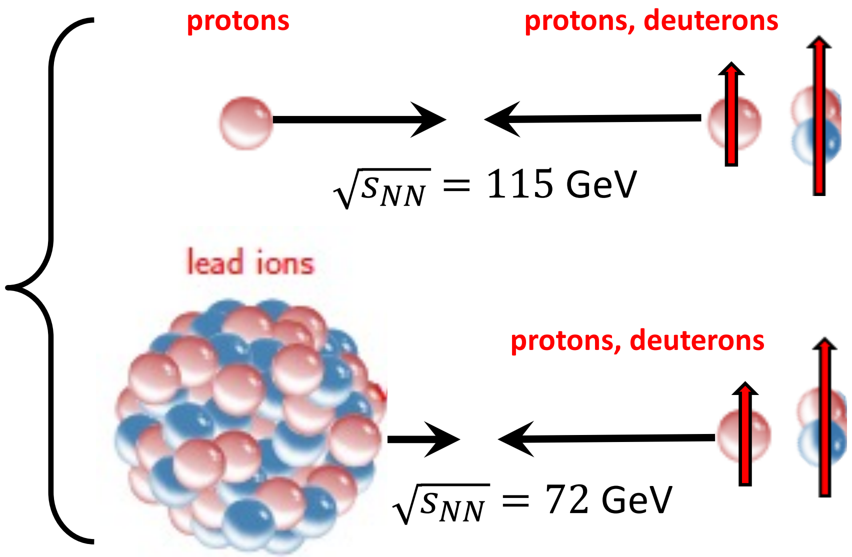
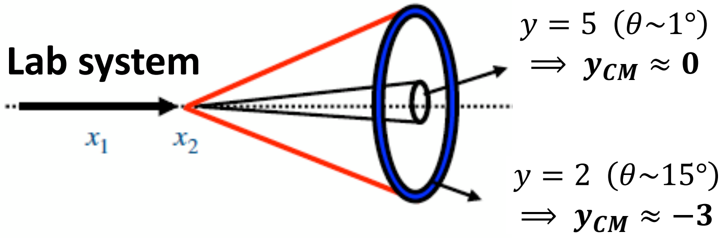


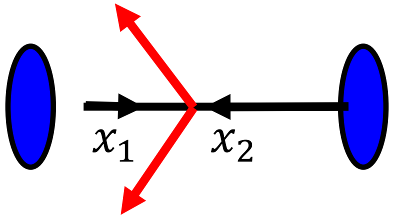
Assuming pA collisions with $E_p \approx 7\,TeV \implies \sqrt{s_{NN}} \approx \mathbf{115\ GeV}$

$$\boxed{\gamma = \frac{\sqrt{s_{NN}}}{2m_p} \approx 60} \implies$$



CM strongly boosted in the lab system!

$$2 \leq y_{LHCb} \leq 5 \implies -3 \leq y_{CM} \leq 0$$



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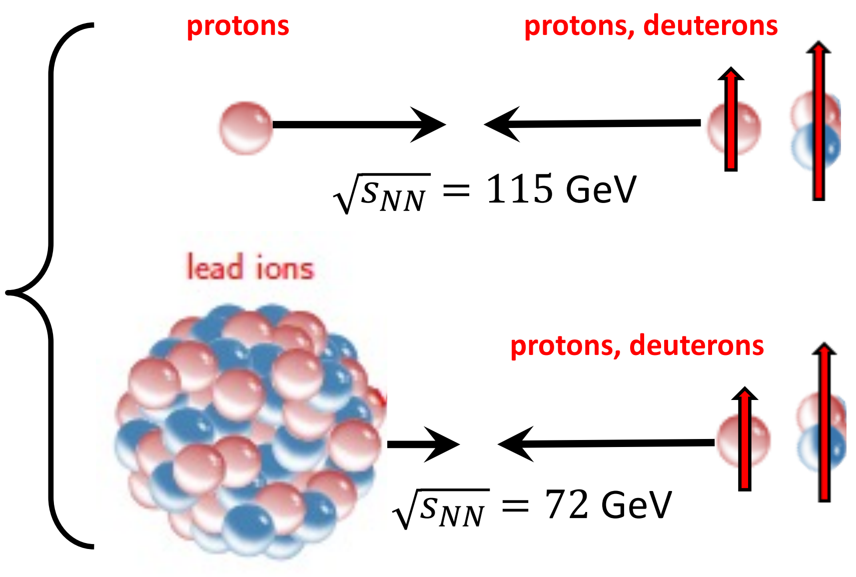

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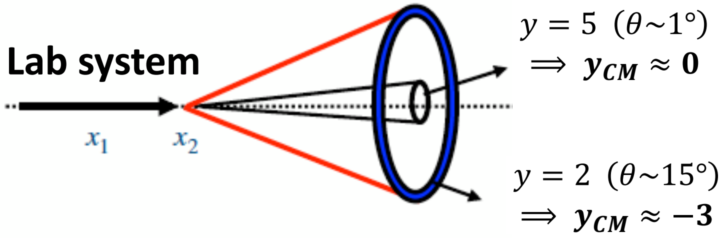

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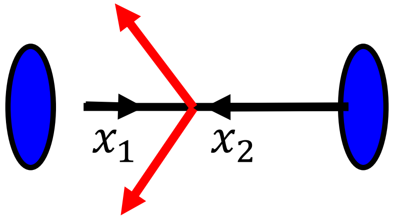
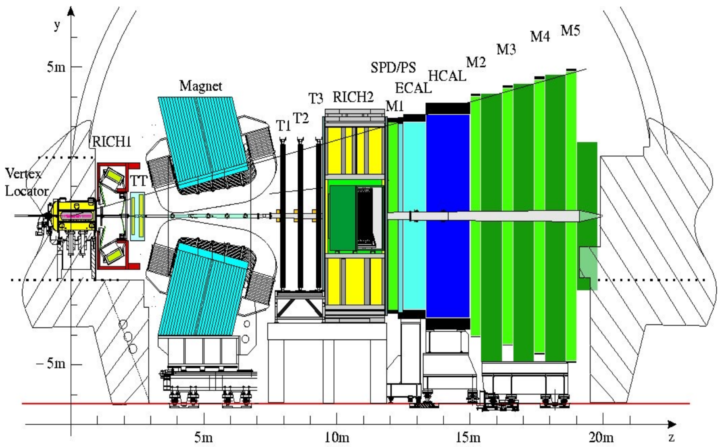


CM system

- **Bkw CM region is at reach of a forward spectrometer with reaction products at measurable forward angles**
- **LHCb ideal detector to host a fixed target at the LHC!**



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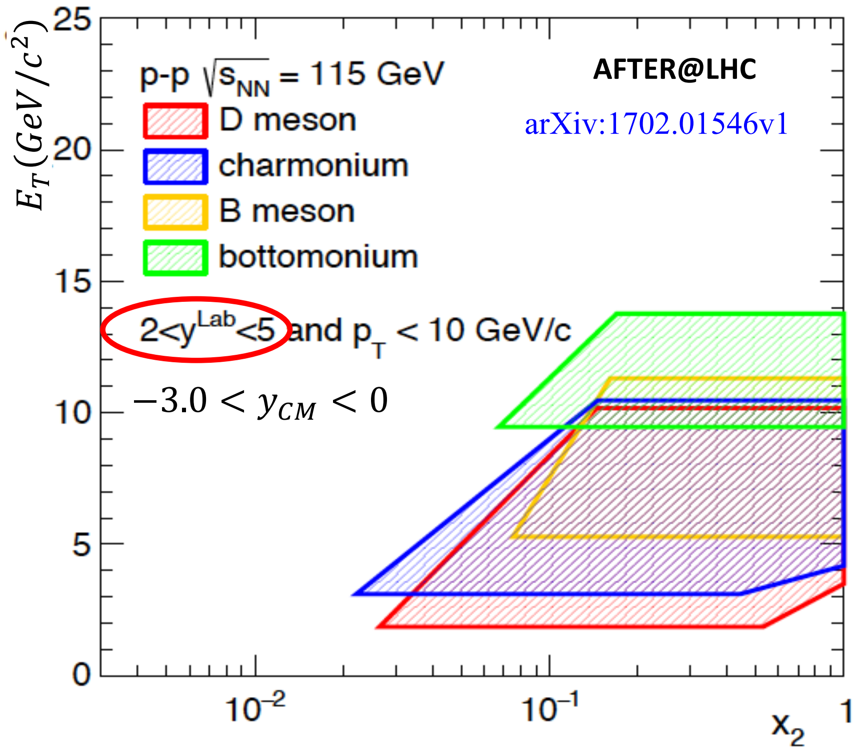
In the fixed-target configuration LHCb allows to cover **mid-to-large x at intermediate Q^2 and negative x_F**



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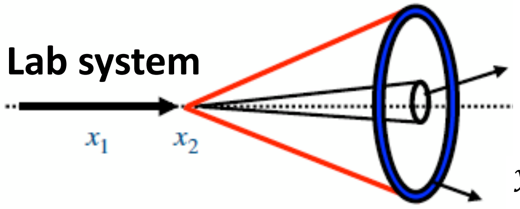

$y = 5\ (\theta \sim 1°)$
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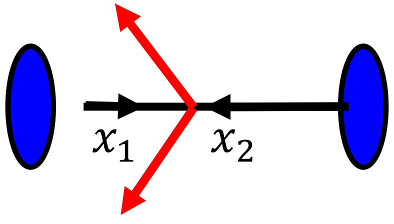

CM system

$$\boxed{x_2 \approx \frac{Q}{\sqrt{s_{NN}}} e^{-y_{CM}}} \Rightarrow \boxed{x_F = \frac{p_L^*}{|max(p_L^*)|} \sim x_1 - x_2 < 0}$$

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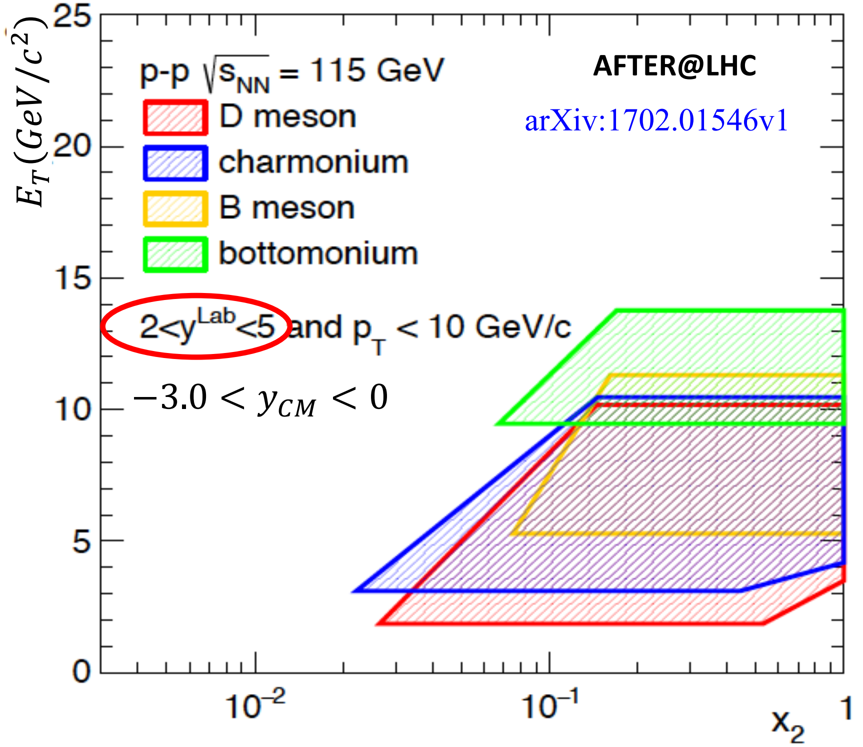

- Partial overlap with RHIC kinematics
- 12 GeV Jlab probes large-x at small Q^2
- EIC will mainly focus at small-x and large Q^2

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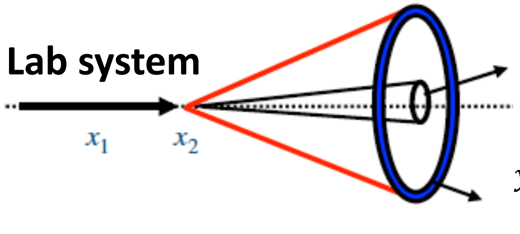

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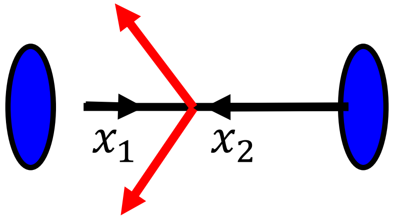

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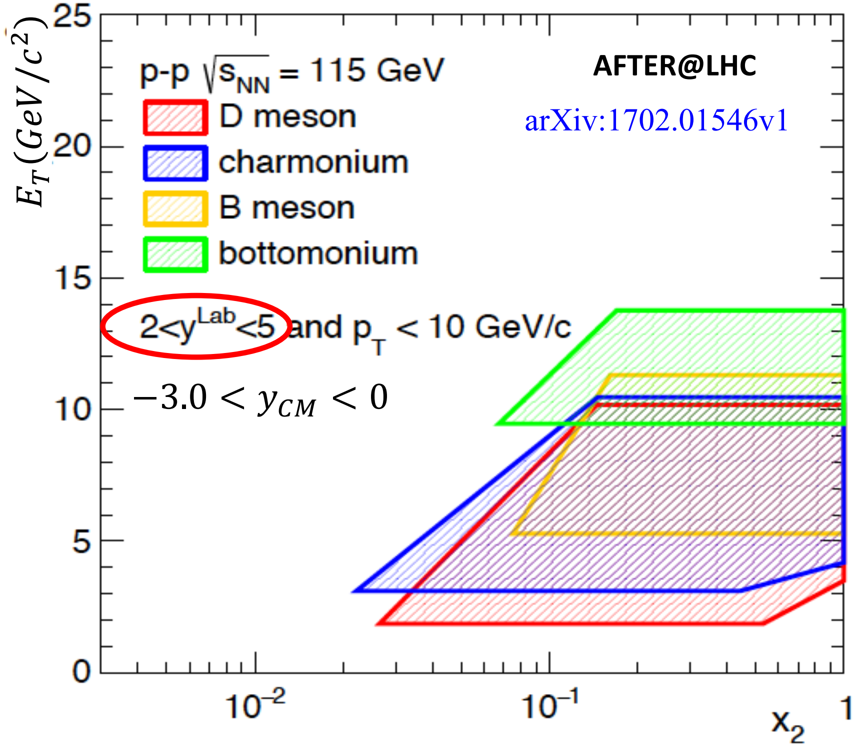

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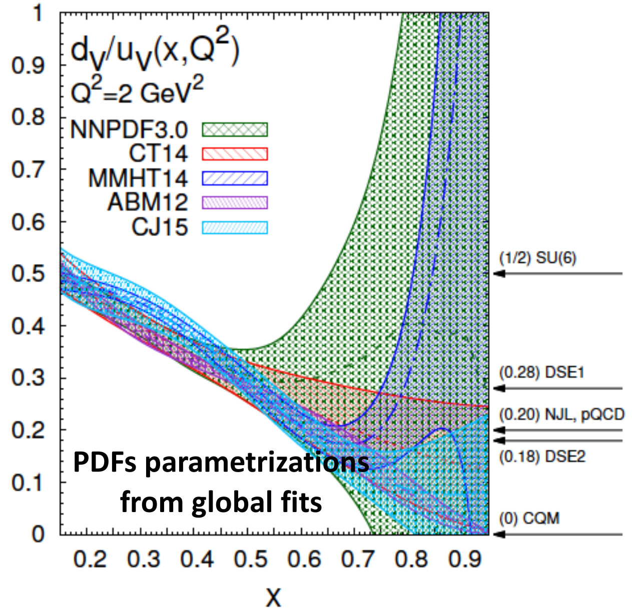
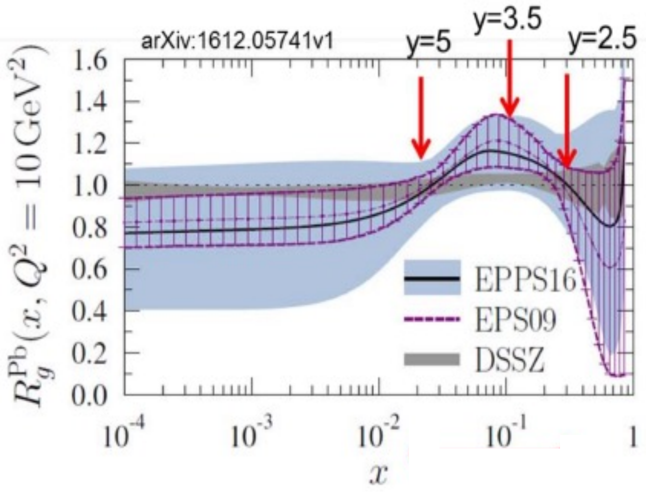
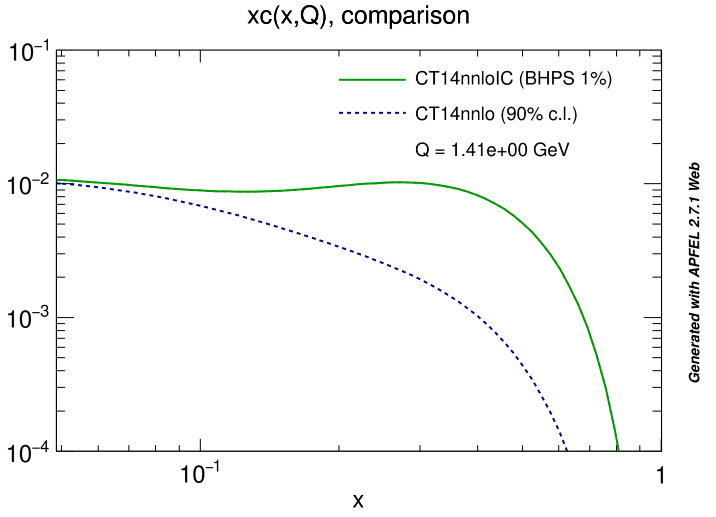


predictions from non-perturbative models

- Relevant for constraining PDFs and nPDFs at high-x
- Can also help to pin-down possible contributions from intrinsic charm at high-x





The physics goals of LHCspin

- Access the structure of nucleons in a poorly explored kinematic domain (large-x at intermediate Q^2)
- Measure experimental observables sensitive to **quarks and gluons TMDs and GPDs**
- Complement present and future SIDIS results (COMPASS/AMBER, Jlab, EIC)
- Test non-trivial process dependence of quarks and gluons TMDs
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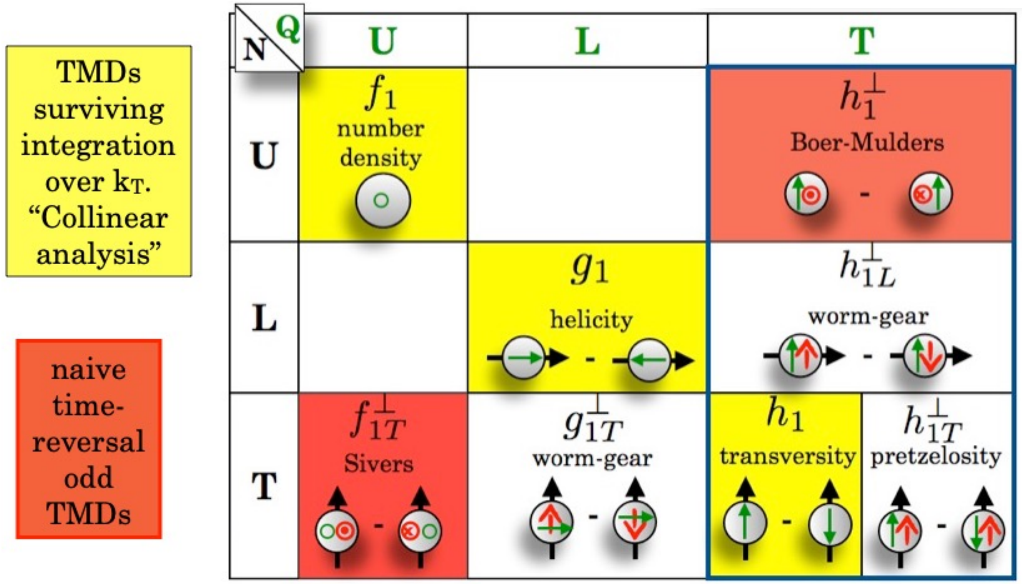

Courtesy C. Riedl

Quark TMDs:

- **significant experimental progress in the last 15 years!**
- many phenomenological extractions available from global analyses
- now entering the precision era
- **main results from SIDIS** (HERMES, COMPASS, JLAB, → EIC)

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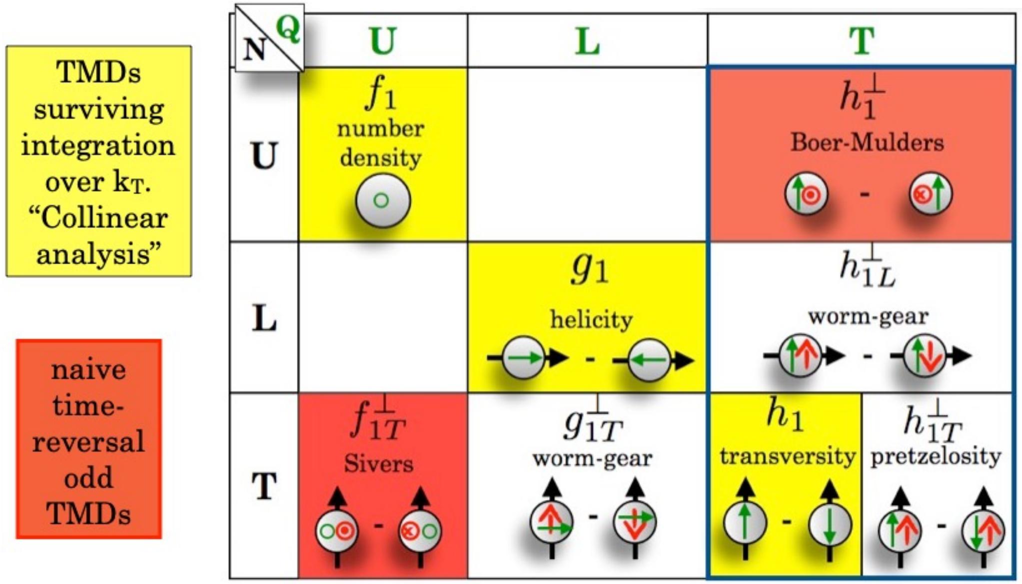

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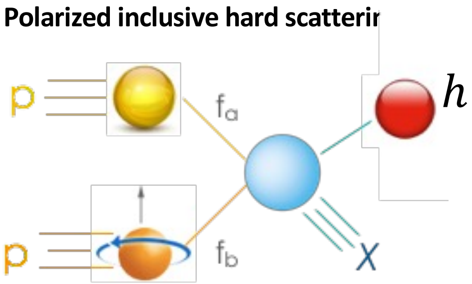
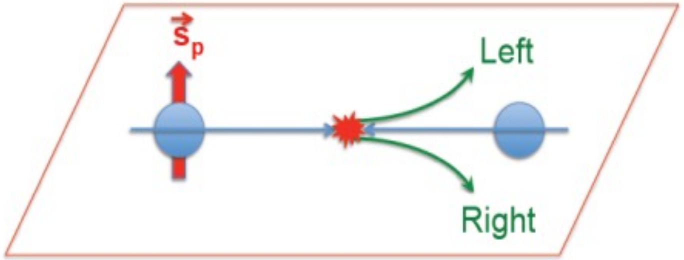
- **main results from SIDIS** (HERMES, COMPASS, JLAB, → EIC)
- **Inclusive hadron production and Drell-Yan** in (polarized) hadronic collisions offer complementary approaches

Probing quark TMDs in polarized pp collisions: inclusive hadron production





Main observables in pol. hadron collisions: **Single Transverse Spin Asymmetries (STSAs)**

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

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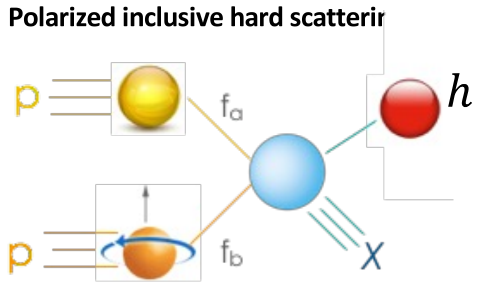

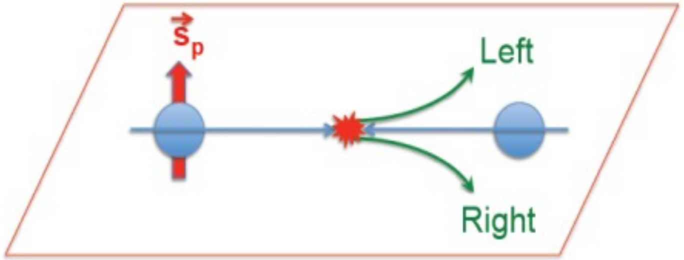

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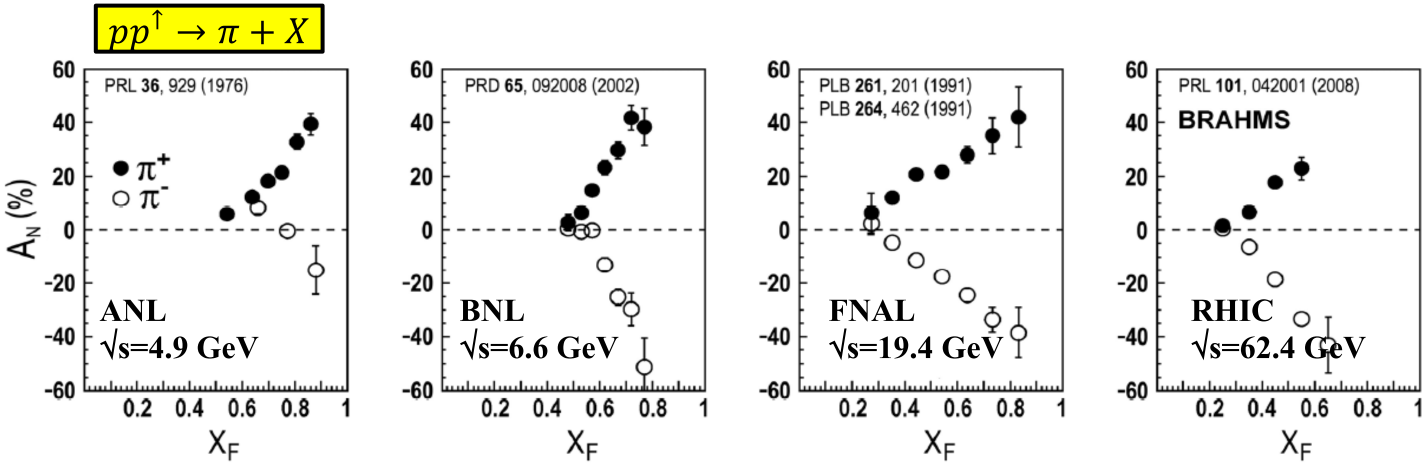
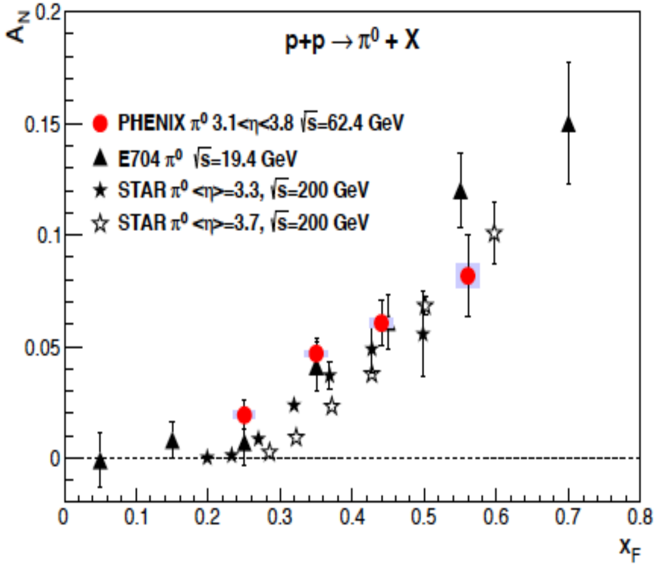
LO collinear pQCD predicts $A_N \sim O(10^{-4})$ but **asymmetries as large as 40% have been measured!**





- **Very large asymmetries persistent with energy, up to $\sqrt{s} = 200$ GeV !**
- Reproduced by various experiments over 40 years!

Probing quark TMDs in polarized pp collisions: inclusive hadron production

1. Collinear twist-3 approach (1 hard scale):
(Efremov-Taryaev, Qiu-Sterman, Kanazawa-Koike)
SSA arises from 3-parton (qgq, ggg) correlation function

2.Non-collinear leading twist approach (2 scales):
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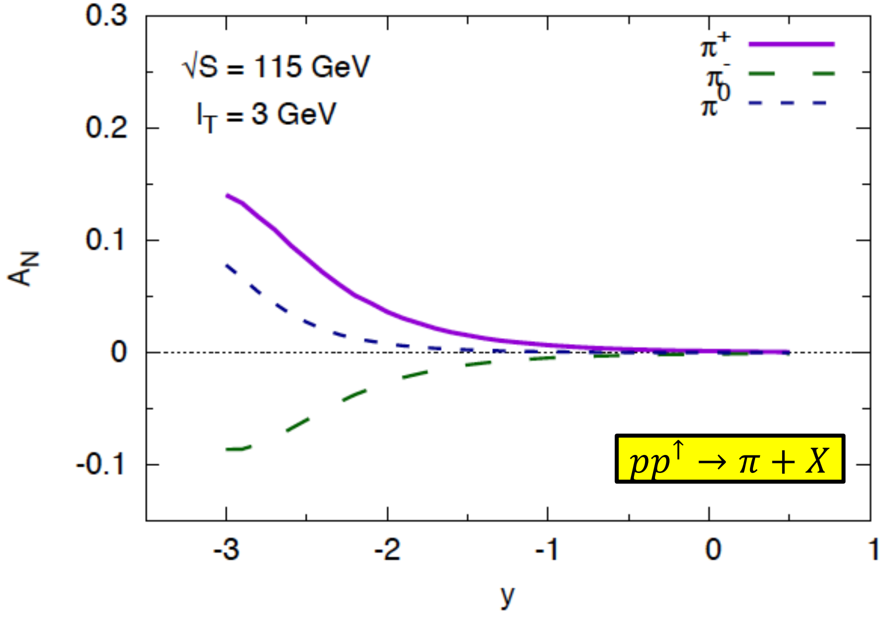

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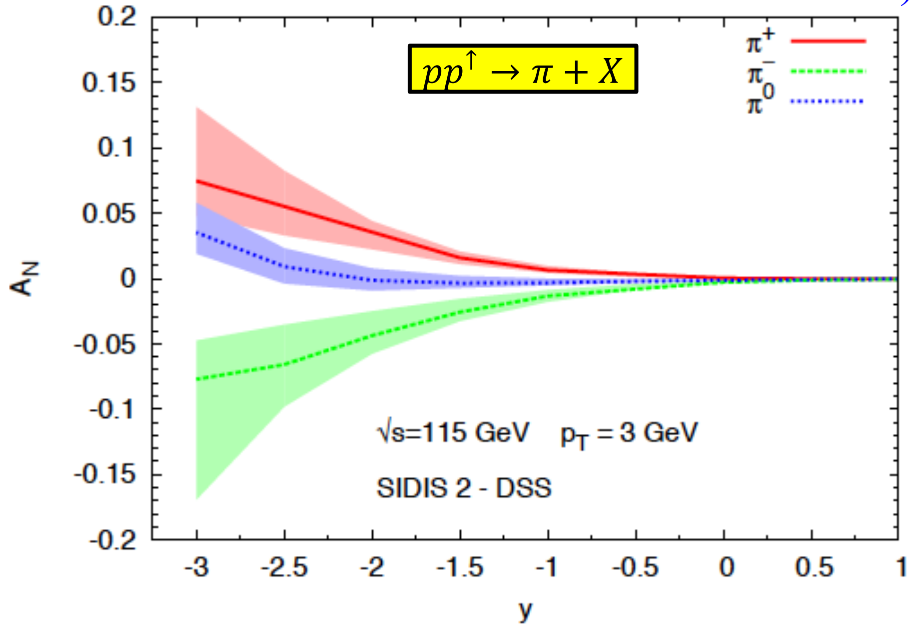

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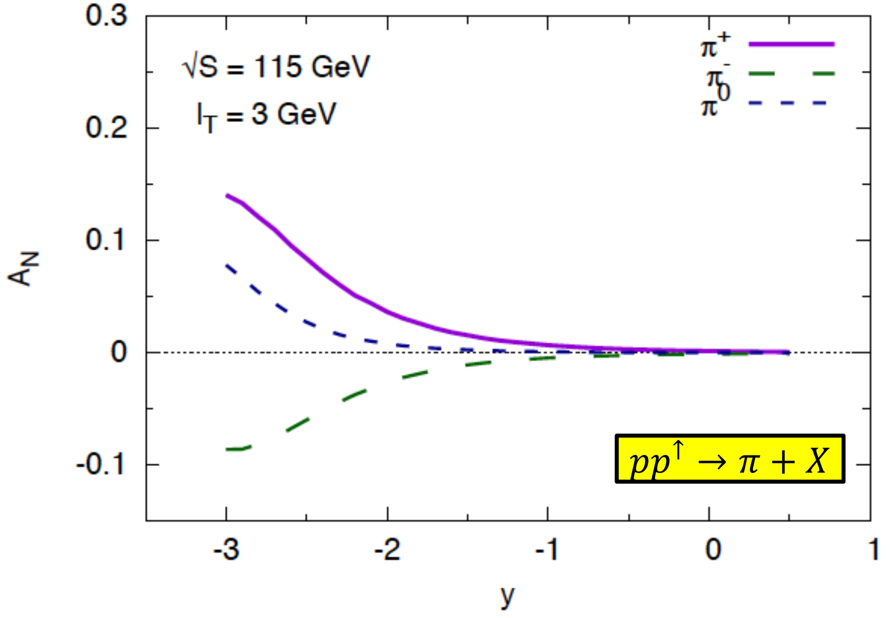

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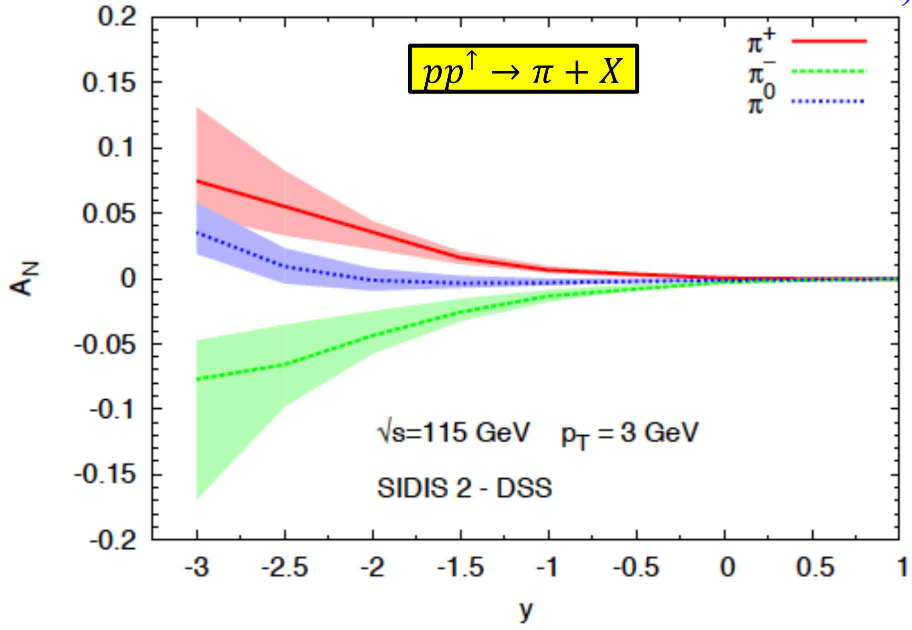
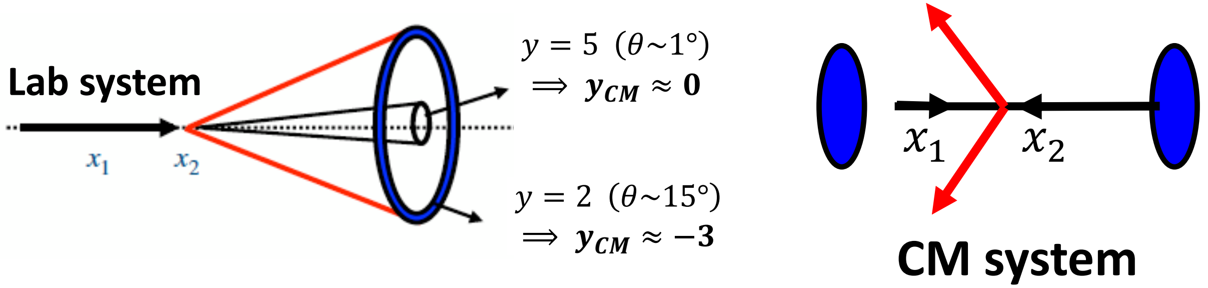


- **Asymmetries above 10 % → strong signature!!**
- The effect increases toward more negative CM rapidity
- Nicely matches LHCb acceptance with fixed target!



Probing quark TMDs in polarized pp collisions: Drell-Yan

quark pol. / nucleon pol.

nucleon pol.	U	L	T
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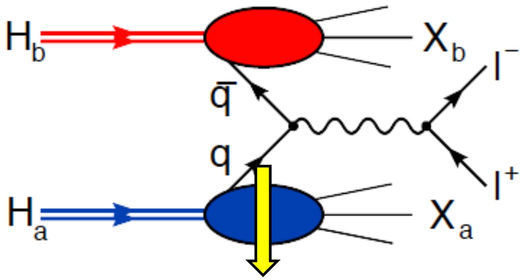
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Transv. polarized Drell-Yan



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- **dominant**: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$
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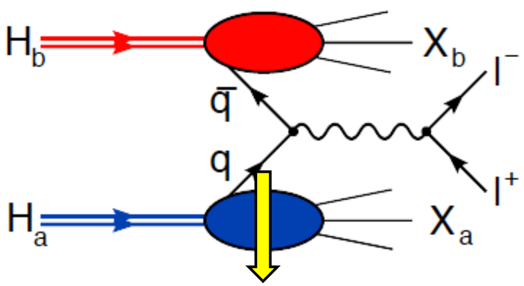

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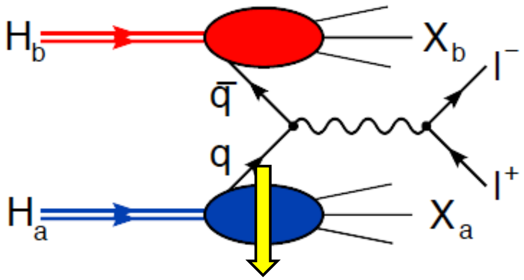

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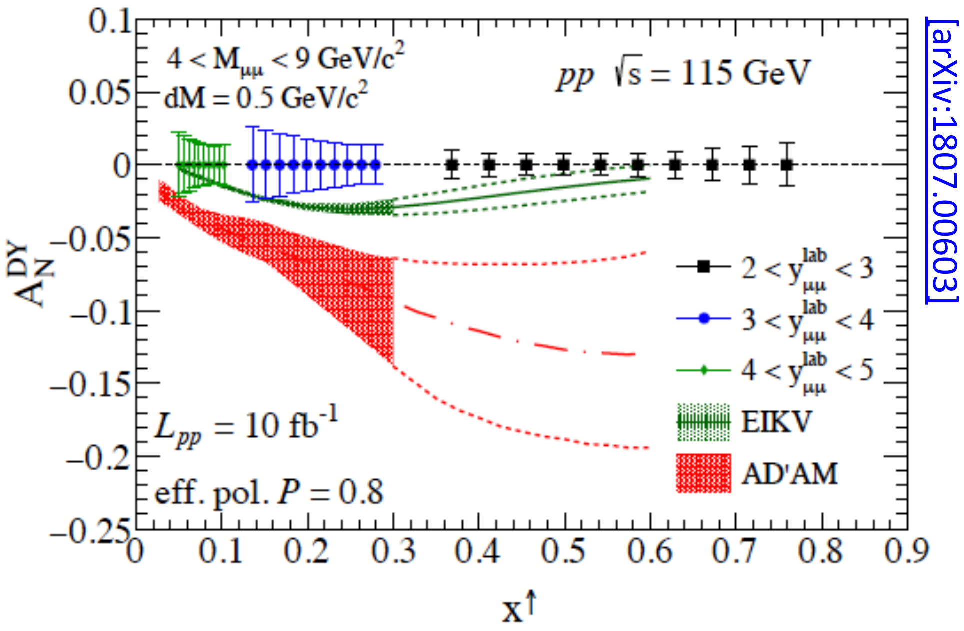

[arXiv:1807.00603]

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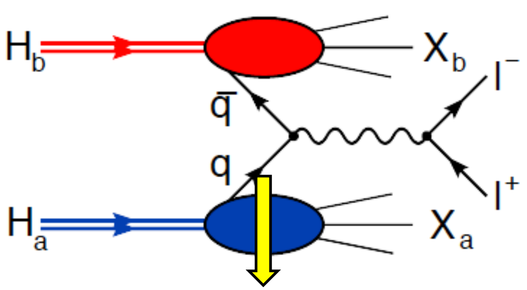

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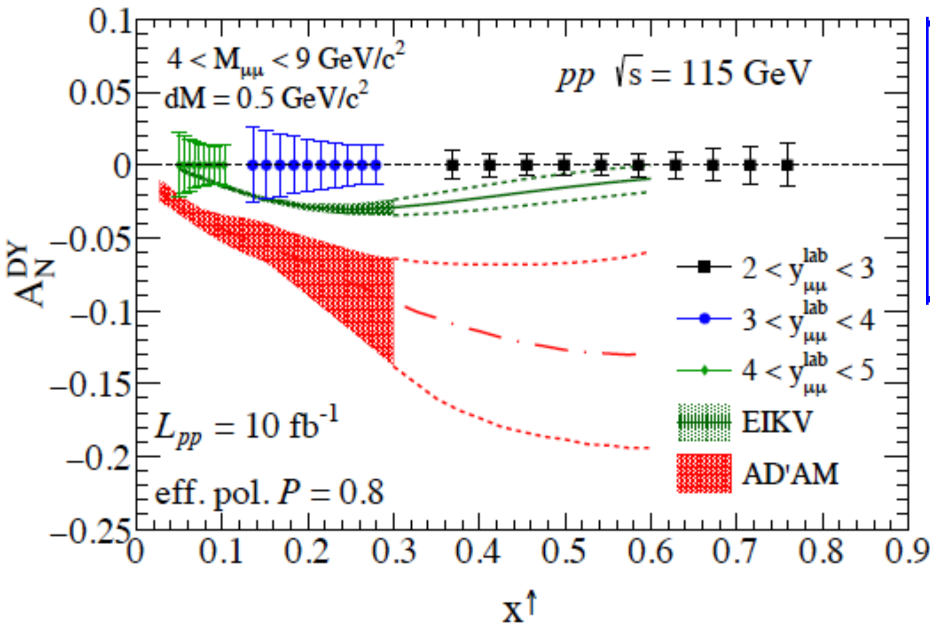
- Extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS

$$f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{SIDIS}$$

- Test flavour sensitivity using both H and D targets



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gluon TMDs

gluon pol.

nucleon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

Theory framework well consolidated **…but experimental access still extremely limited!**

gluon TMDs

gluon pol.

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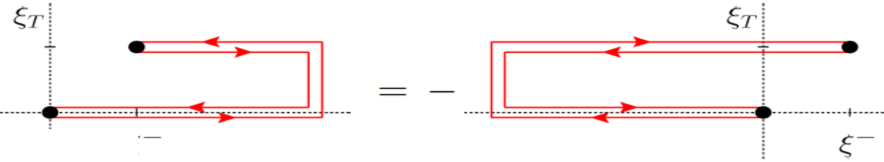
Wilson line ("+")
FSI (SIDIS)



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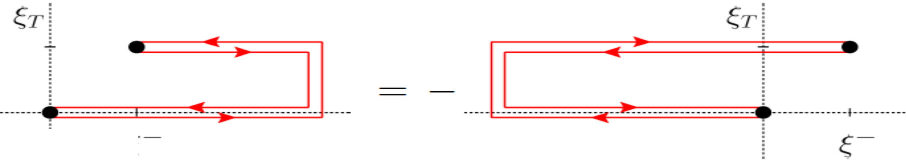

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$$[+,+] \quad \boxed{f_{1T}^{\perp g[e\,p^\uparrow \to e'\,Q\bar{Q}\,X]}(x,p_T^2) = -f_{1T}^{\perp g[p^\uparrow\,p \to \gamma\,\gamma\,X]}(x,p_T^2)} \quad [-,-]$$

Sign-change relation expected for the other T-odd gTMDs h_1^g and $h_{1T}^{\perp g}$!

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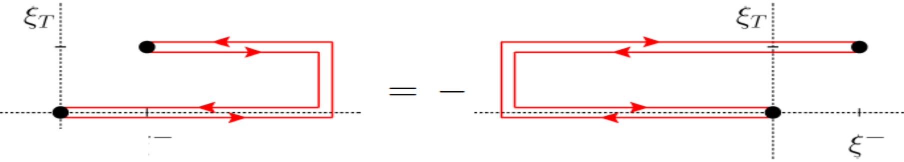

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gluon TMDs

gluon pol. / nucleon pol.

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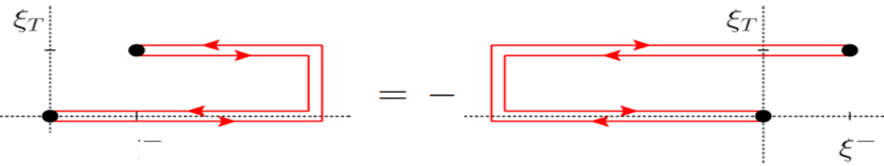

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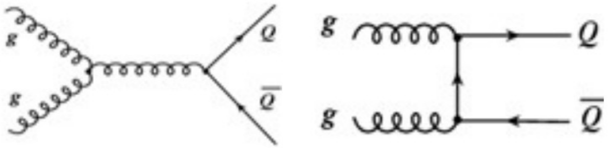
- E.g. there are 2 types of f_1^g and $h_1^{\perp g}$: $[+\,+] = [-\,-]$ Weizsacker-Williams (WW) ; $[+\,-] = [-\,+]$ DiPole (DP)

- 2 indep. GSF: $f_{1T}^{\perp g[+,+]}$ **"f-type"** → antisymm. colour structure ; $f_{1T}^{\perp g[+,-]}$ **"d-type"** → symm. colour structure

Probing gluon TMDs in polarized pp collisions

In high-energy hadron collisions, heavy quarks are dominantly produced through gg fusion:



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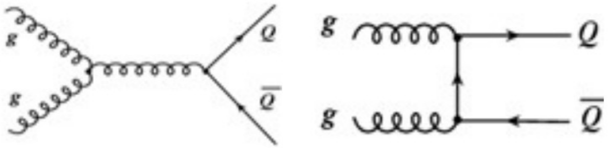

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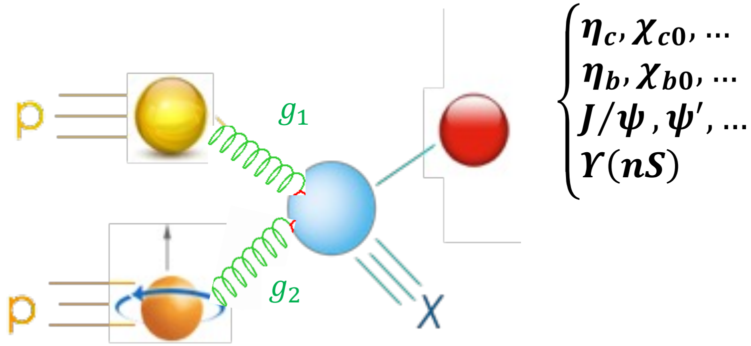

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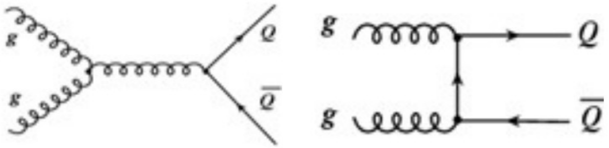

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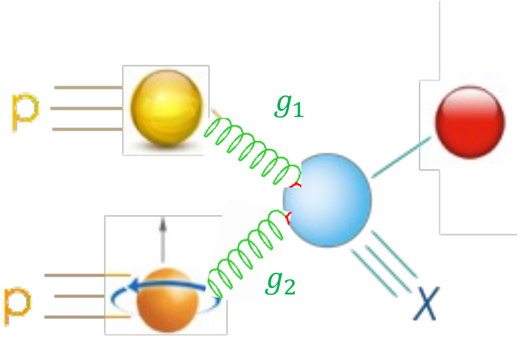

$$\begin{cases} \eta_c, \chi_{c0}, \dots \\ \eta_b, \chi_{b0}, \dots \\ J/\psi, \psi', \dots \\ \Upsilon(nS) \end{cases}$$

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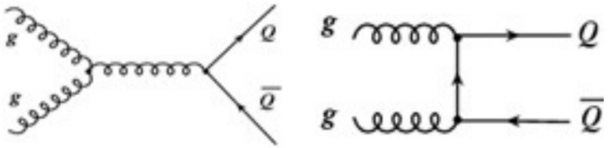

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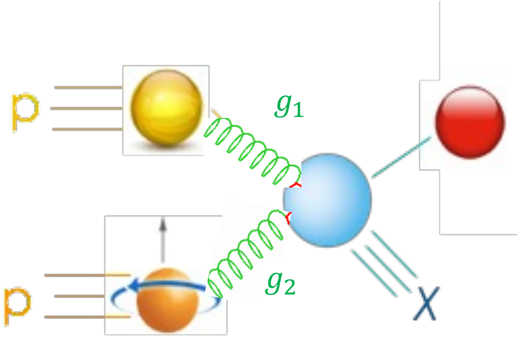

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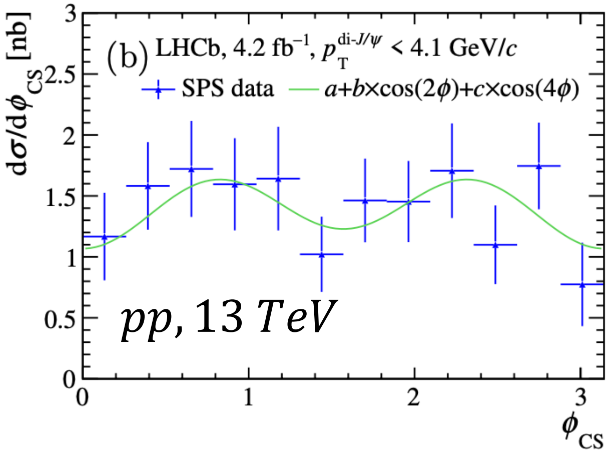

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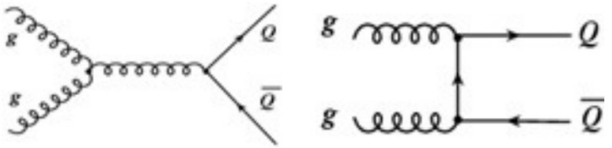

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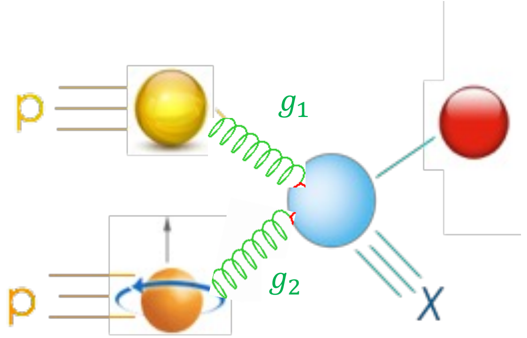

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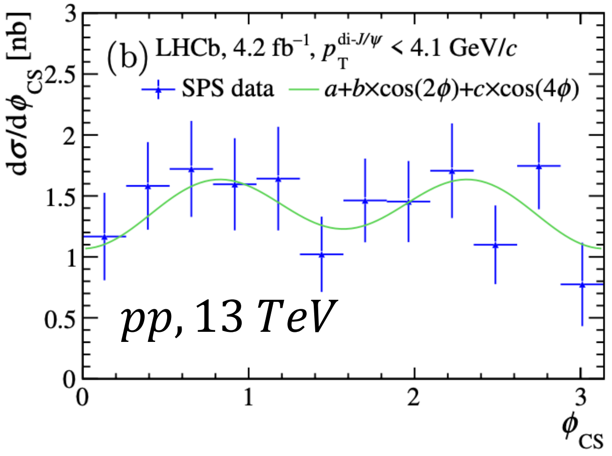

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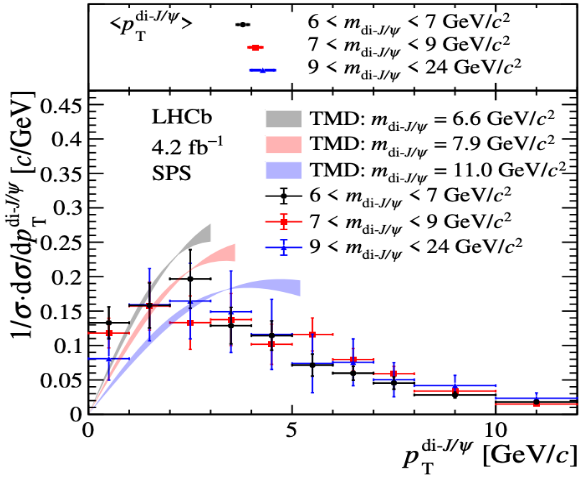

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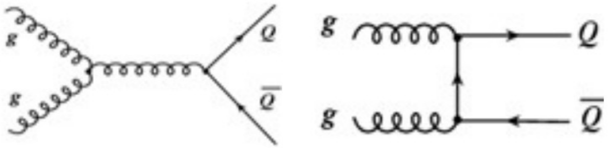

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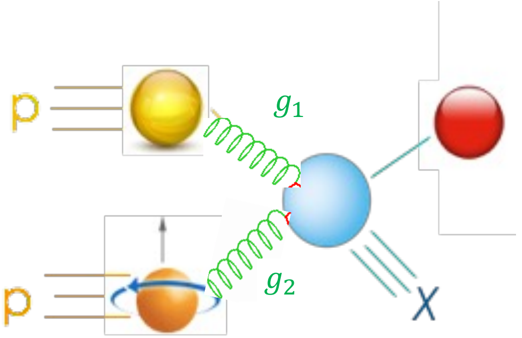

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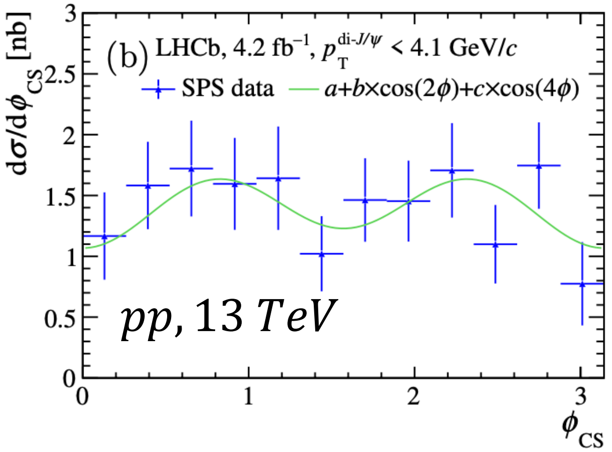
[JHEP 03 (2024) 088](https://doi.org/)



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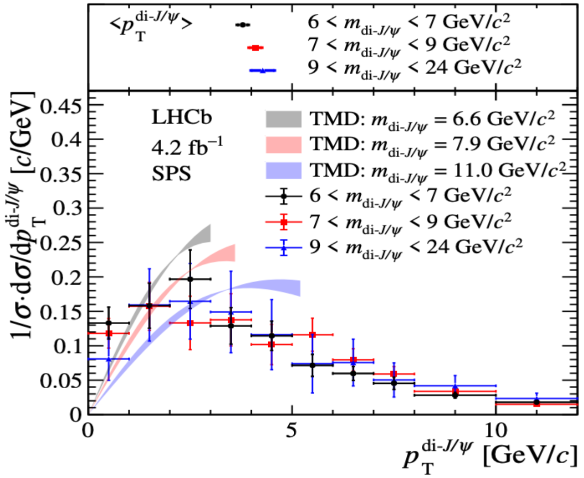

...but very challenging at fixed-target kinematics!

Probing gluon TMDs in polarized pp collisions: inclusive J/ψ

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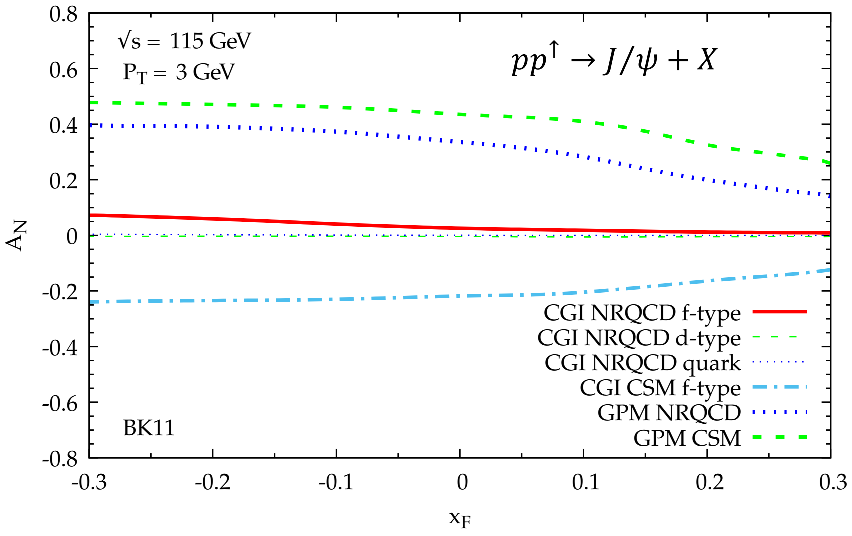
[Phys. Rev. D 102, 094011 (2020)]



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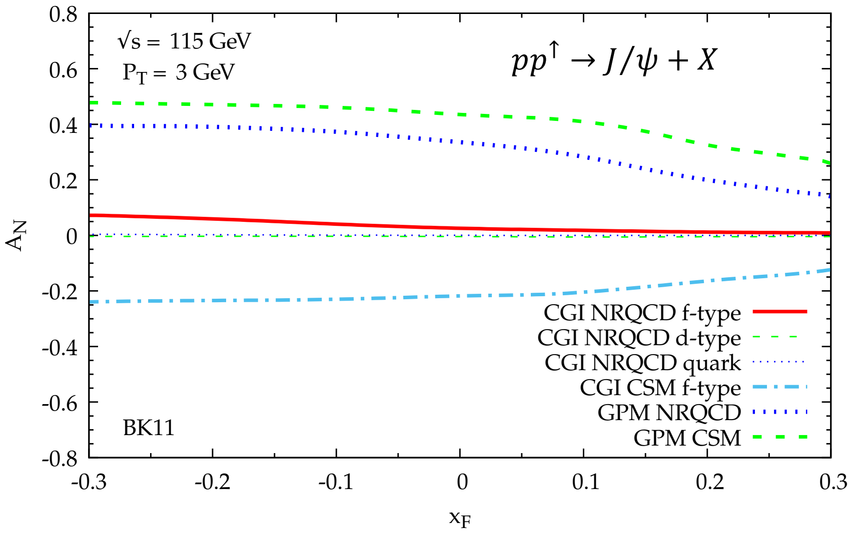

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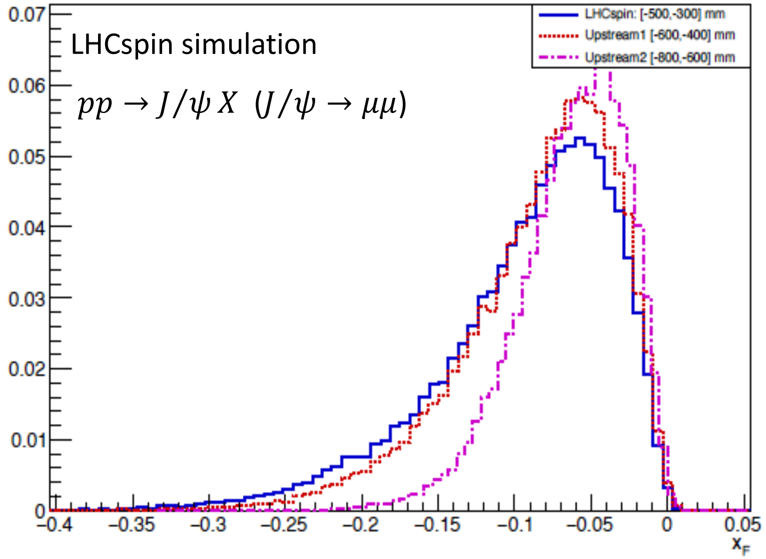

gluon TMDs: a synergic attack

Gluon TMDs are difficult to measure. A synergic effort from complementary approaches is necessary.

[D. Boer: Few-body Systems 58, 32 (2017)]

	DIS	DY	SIDIS	$pA \to \gamma\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$f_1^{g\,[+,+]}$ (WW)	×	×	×	×	√	√	√
$f_1^{g\,[+,-]}$ (DP)	√	√	√	√	×	×	×

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
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$f_{1T}^{\perp\,g\,[+,+]}$ (WW)	×	×	×	×	√	√
$f_{1T}^{\perp\,g\,[+,-]}$ (DP)	√	√	√	√	×	×

Can be measured at the EIC

Can be measured at RHIC & LHC (including LHCb+SMOG2/LHCspin)

Can be measured at RHIC and LHCb+LHCspin

Gluon GPDs and UPC

GPD	U	L	T
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3D maps of parton densities in coordinate space

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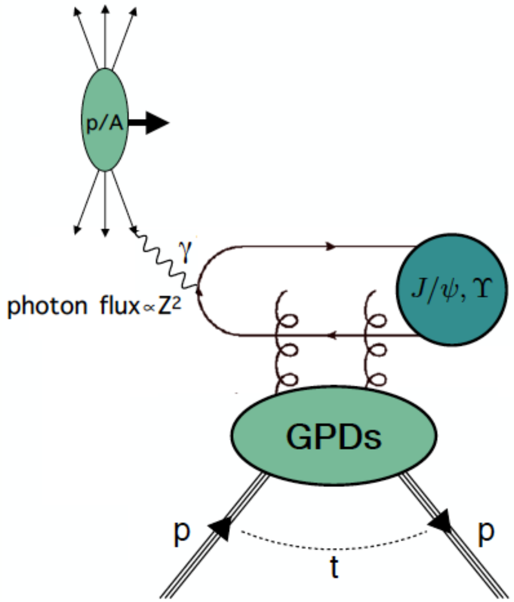

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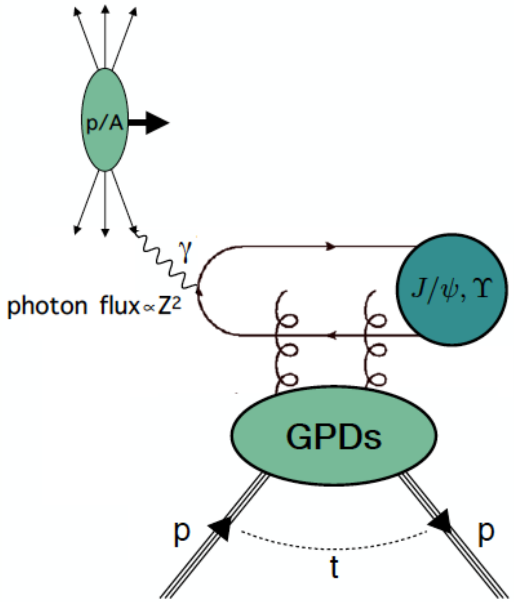

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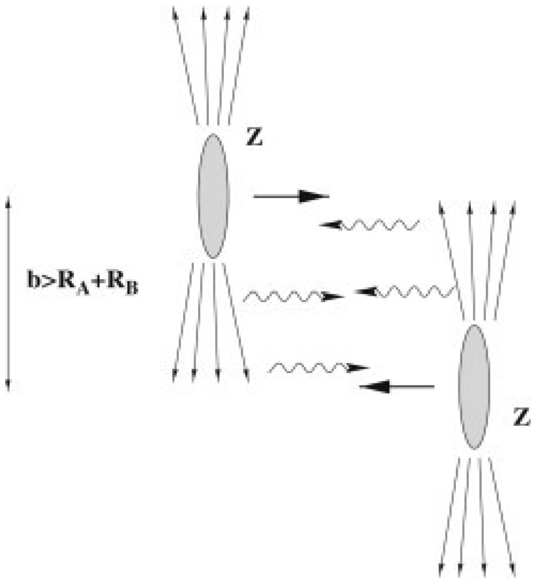

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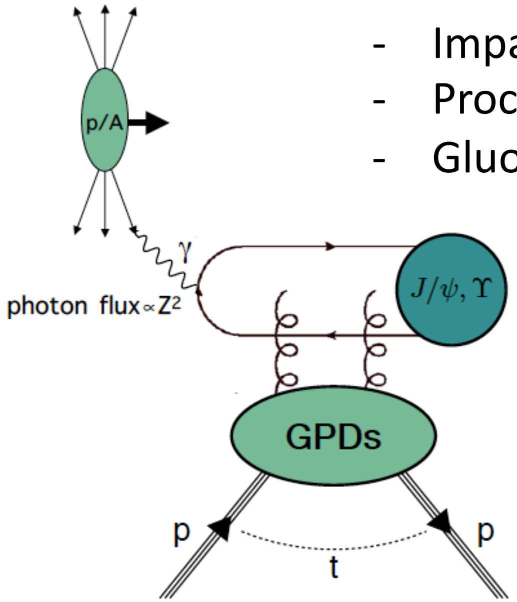
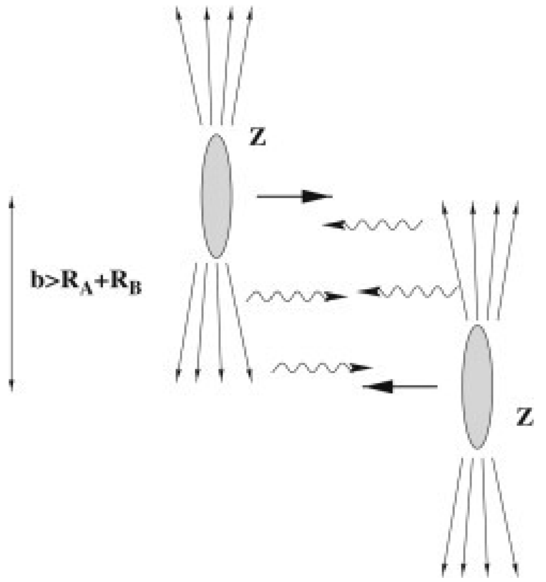


- Impact parameter larger than sum of radii
- Process dominated by EM interaction
- Gluon distributions probed by pomeron exchange

Gluon GPDs and UPC

GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T, \ \tilde{H}_T$

3D maps of parton densities in coordinate space



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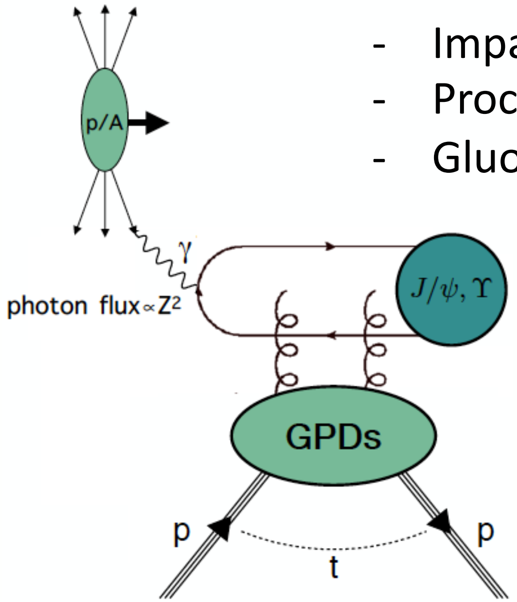

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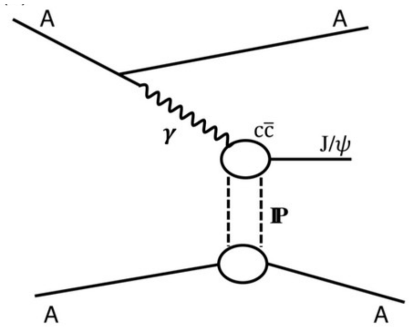
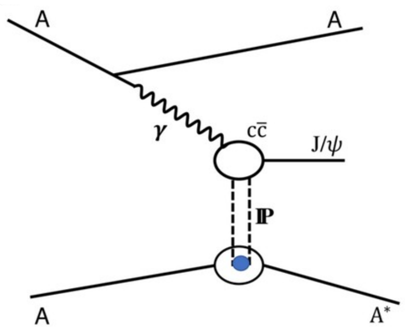


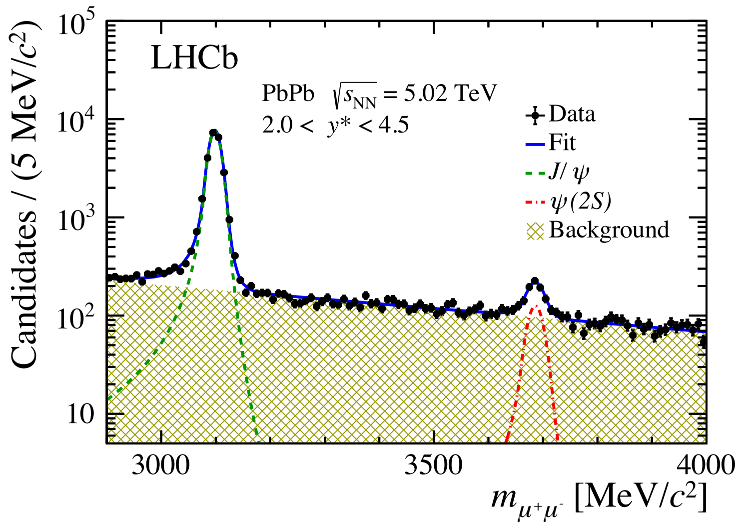
Coherent UPC:
pomeron emitted
by entire nucleus



Incoherent UPC:
pomeron emitted
by single nucleon

Exlcusive quarkonia production in UPC provides sensitivity to **gluon GPDs** [PRD 85 (2012), 051502]

Recent LHCb UPC results in PbPb [JHEP 2023, 146 (2023)]



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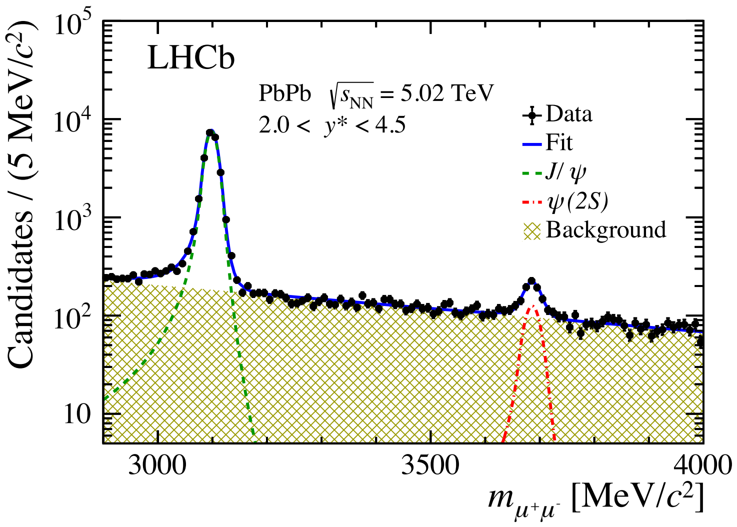
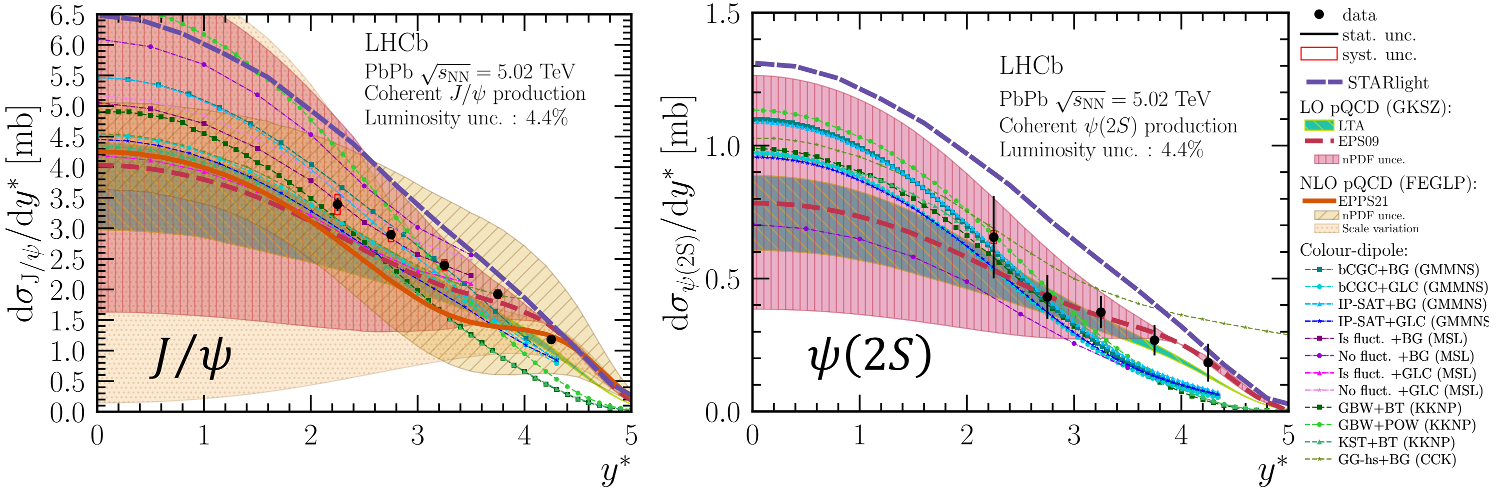


Diff. cross section vs. y^* for coherent J/ψ and $\psi(2S)$ photoproduction, compared with models



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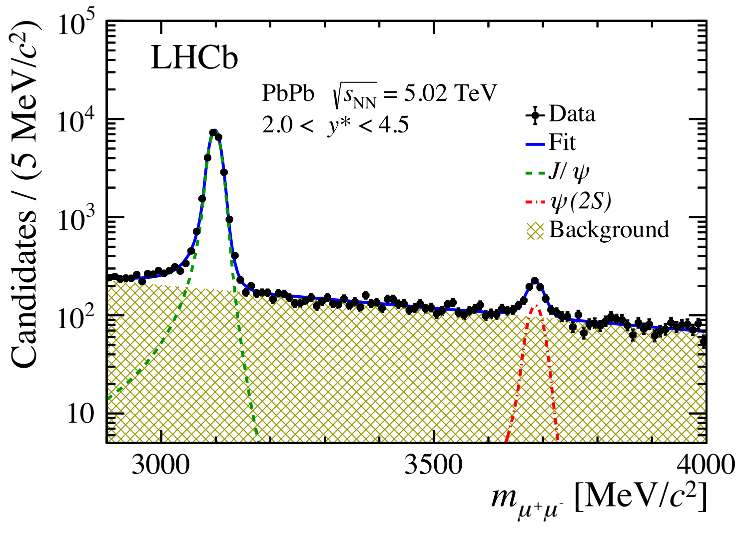

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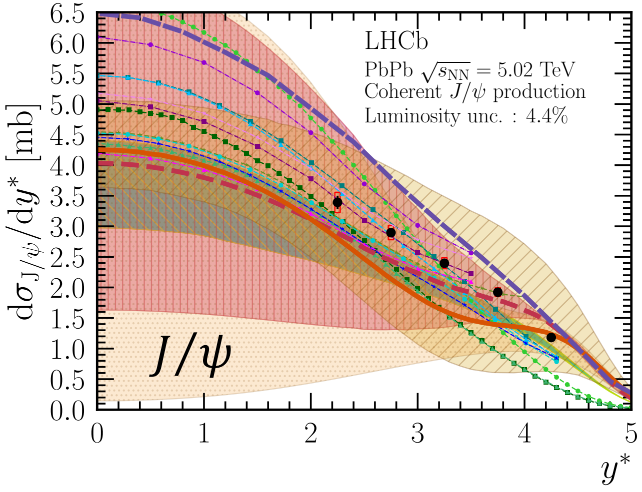

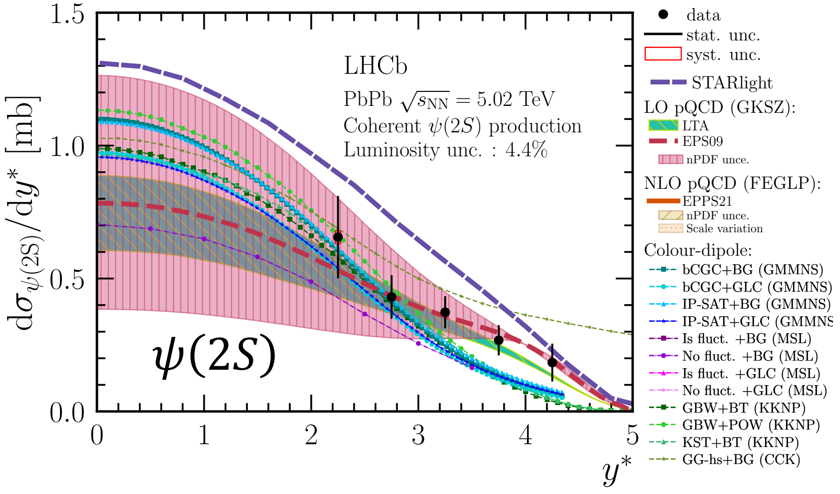

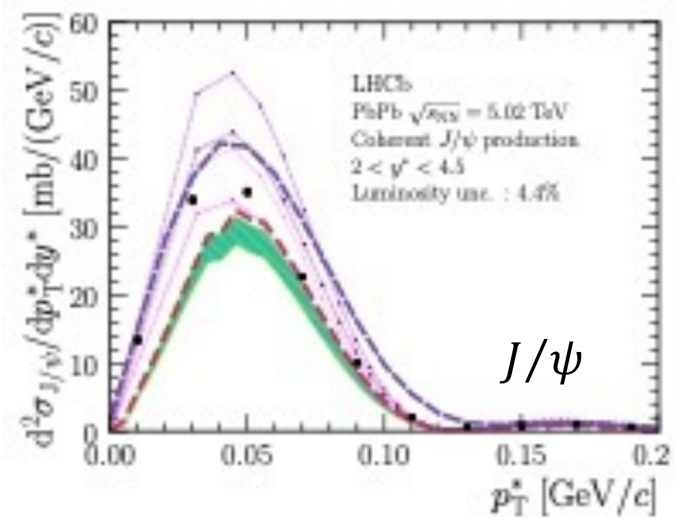

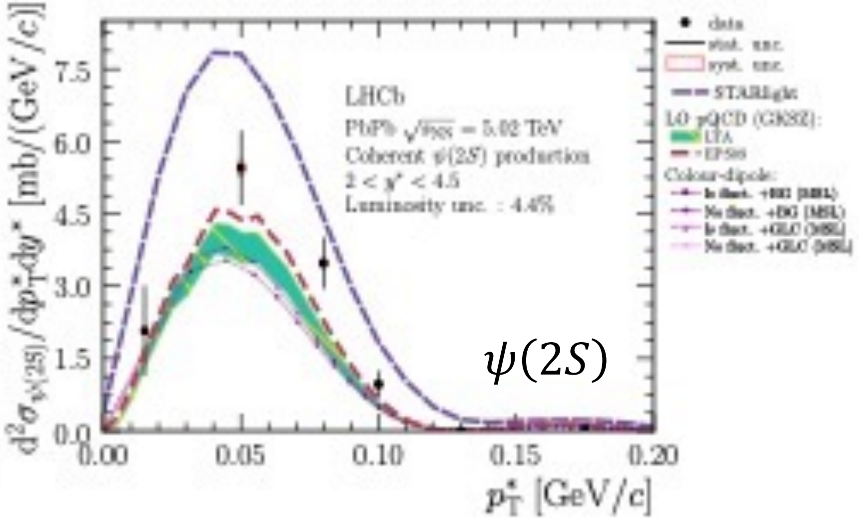

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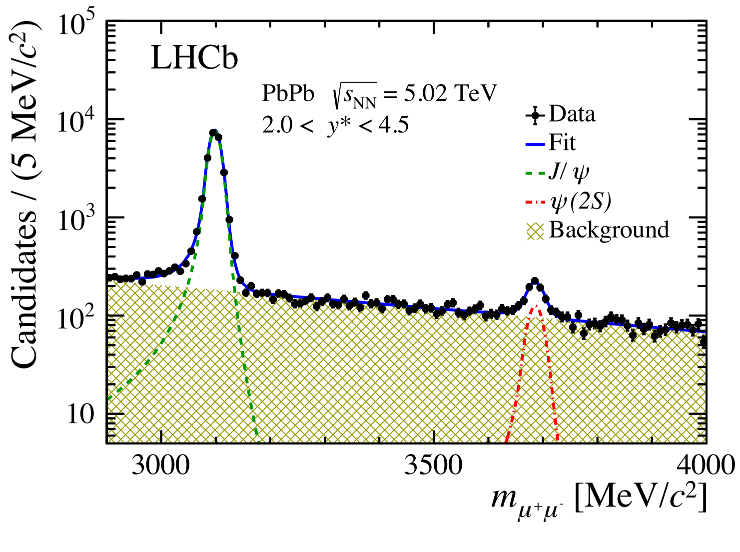

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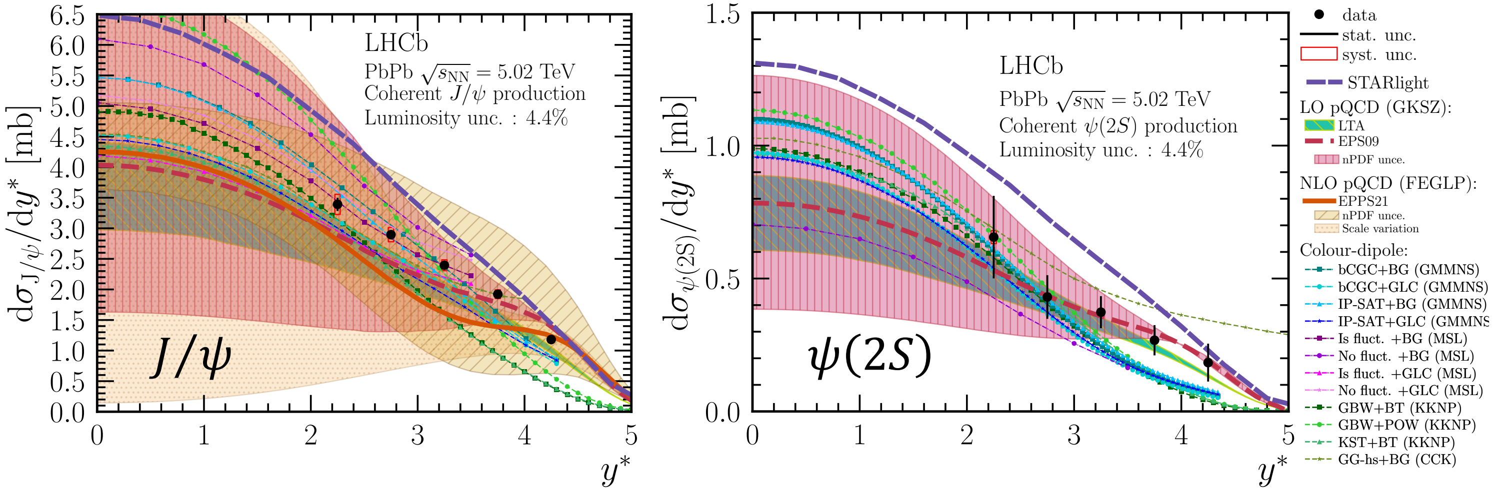
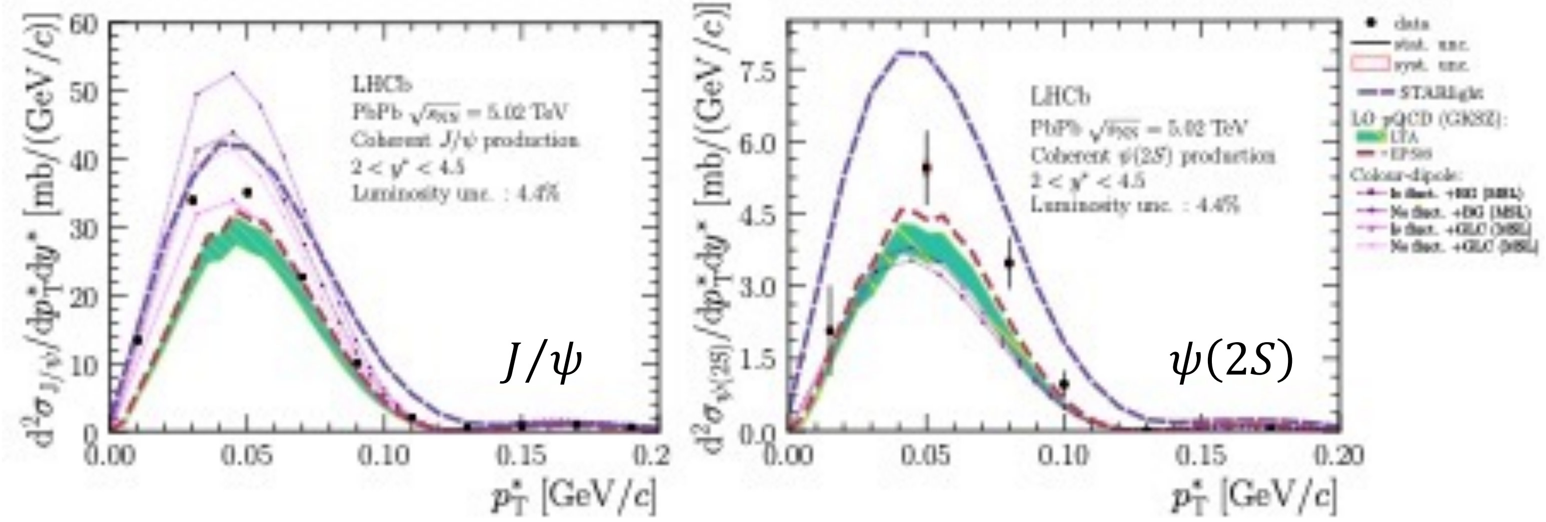


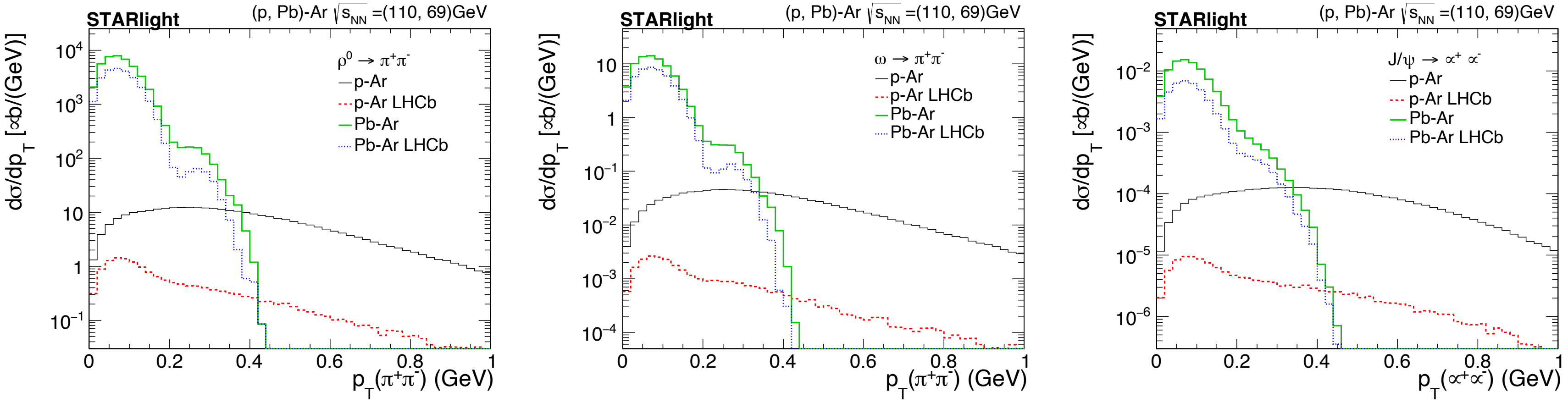


Diff. cross section vs. p_T for coherent J/ψ and $\psi(2S)$ photoproduction, compared with models

Many other ongoing UPC analyses at LHCb based on collider PbPb data

Gluon GPDs and UPC

UPC can be studied also in **fixed-target mode at LHCb** using the LHC beams at energies up to $\sqrt{S_{\gamma p}} \approx 40\ GeV$.



p_T distributions for the exclusive vector meson ($\rho^0, \omega, J/\psi$) photoproduction in:

- pAr ($\sqrt{s_{NN}} = 110$ GeV)
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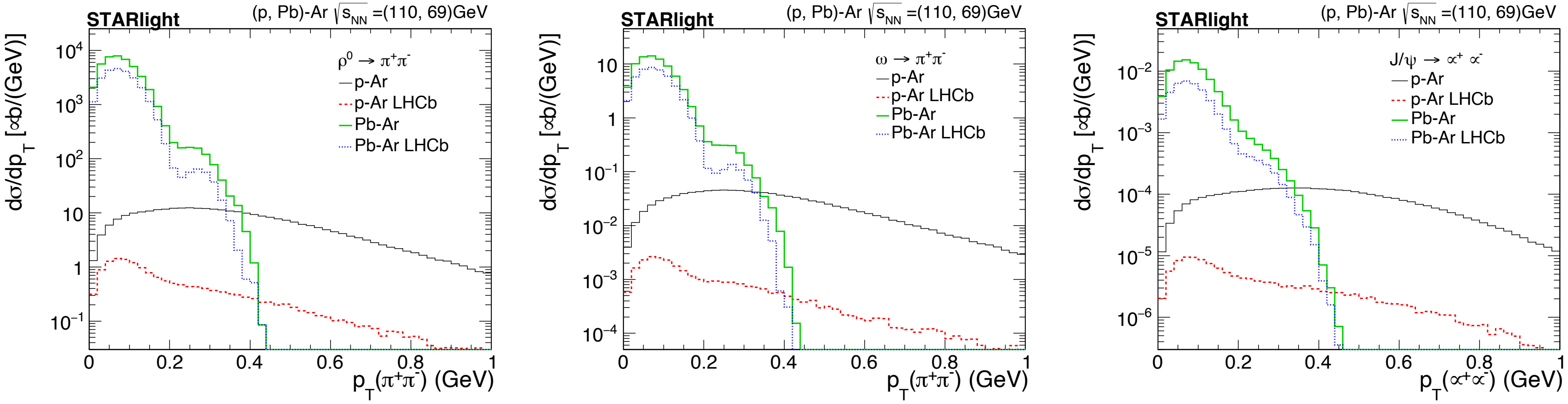

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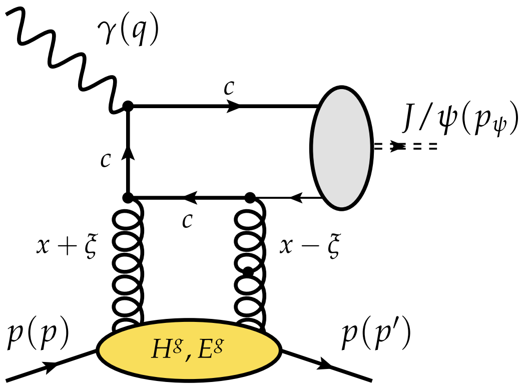
With LHCspin photo-production of J/ψ in polarized UPC of proton (or lead) beams with $H^{\uparrow}$ target can be studied, providing constraints to the essentially unknown **gluon GPD E_g** which plays a crucial role in the Ji sum rule:

$$J^g = \frac{1}{2}\int_0^1 dx\Big(H^g(x,\xi,0) + E^g(x,\xi,0)\Big)$$



Constrainig gluon GPDs in polarized UPC

Using the STARLIGHT MC generator, the **AFTER** collaboration has studied the $J/\psi \rightarrow \mu\mu$ differential photo-production cross section for **polarized UPC at LHCb fixed-target kinematics** (LHCspin conditions)

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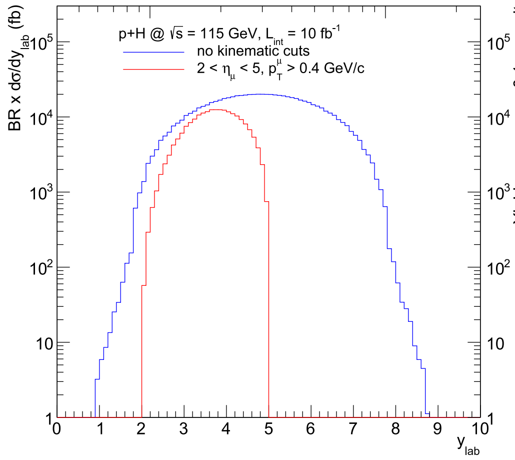
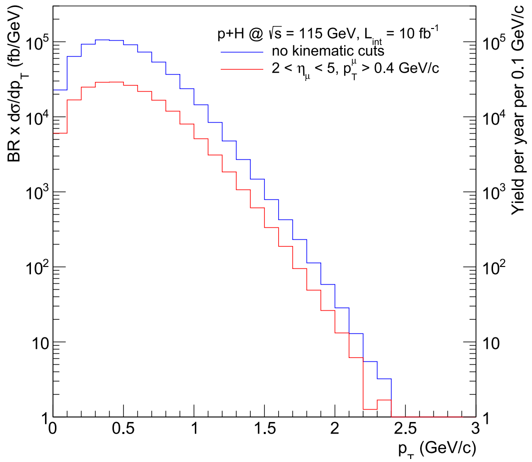
PLB 793 (2019) 33-40





Ultra-Peripheral $pH^{\uparrow}$ collisions:

- $\sqrt{s_{NN}} = 115\ GeV$
- $p_T^{\mu} > 0.4\ GeV$
- $2 < \eta_{\mu} < 5$

Assuming $10\ fb^{-1}$ corresponds to a yearly yield of $\sim 2\times10^5$ photo-produced J/ψ in the LHCb acceptance.

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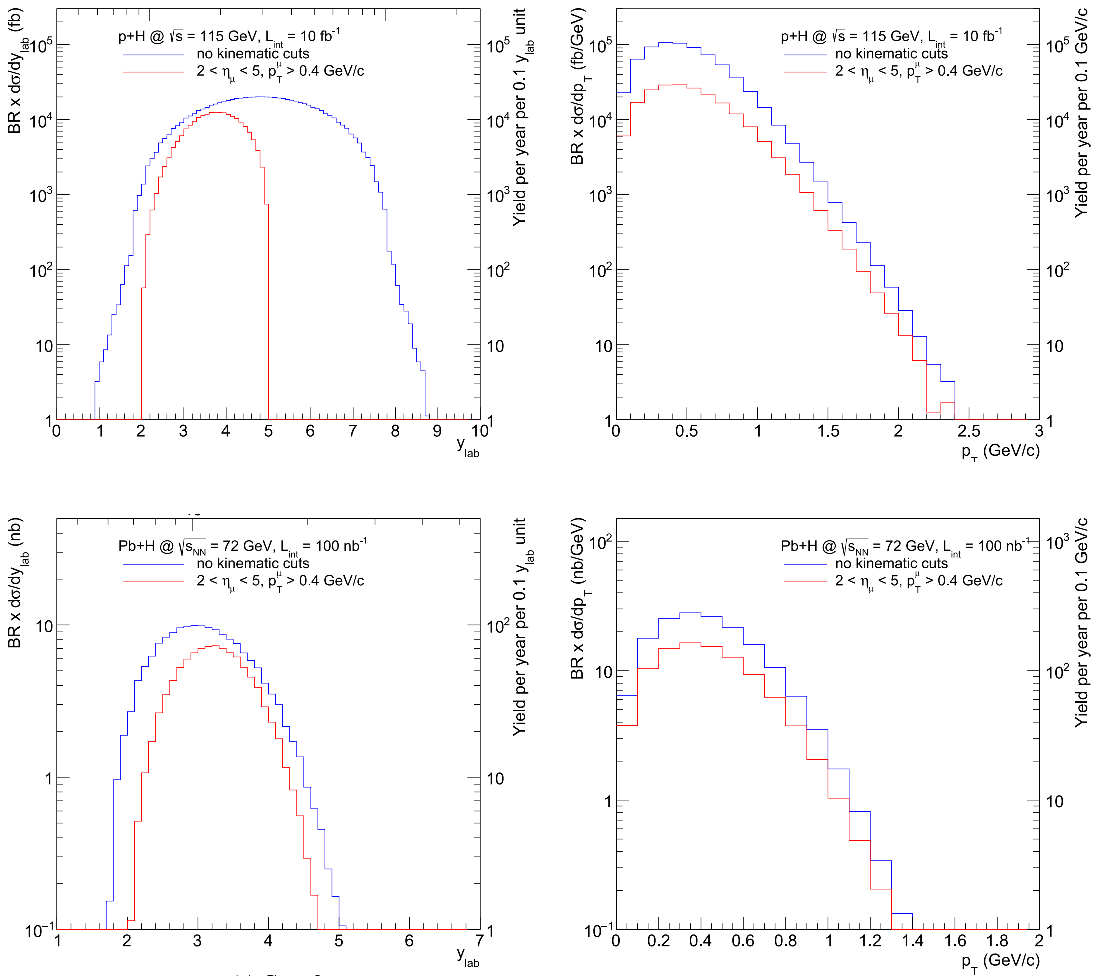

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Ultra-Peripheral Pb$H^{\uparrow}$ collisions:

- $\sqrt{s_{NN}} = 72\ GeV$
- $p_T^{\mu} > 0.4\ GeV$
- $2 < \eta_{\mu} < 5$

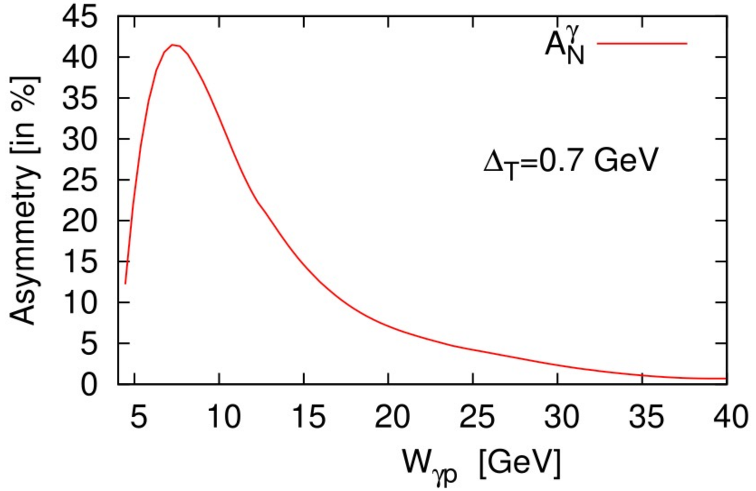
Assuming $0.1\ pb^{-1}$ corresponds to a yearly yield of $\sim 10^3$ photo-produced J/ψ in the LHCb acceptance (challenging).

Constrainig gluon GPDs in polarized UPC

Considering UPC between nuclei A and B, with the B nucleus (proton) polarized, the hadronic STSA A_N can be expressed in terms of the photonic STSA A_N^γ

$$A_N = \frac{\sigma^{h_A h_B^\downarrow} - \sigma^{h_A h_B^\uparrow}}{\sigma^{h_A h_B^\downarrow} + \sigma^{h_A h_B^\uparrow}} = \frac{\int dk \frac{dn_A}{dk} A_N^\gamma \, \sigma^{\gamma h_B}}{\int dk \left[\frac{dn_A}{dk} \sigma^{\gamma h_B} + \frac{dn_B}{dk} \sigma^{\gamma h_A} \right]}$$

where A_N^γ incorporates the GPDs H^g and E^g through their gluonic CFFs $\mathcal{H}^g$ and $\mathcal{E}^g$, and is pretty large at moderate $W_{\gamma p}$



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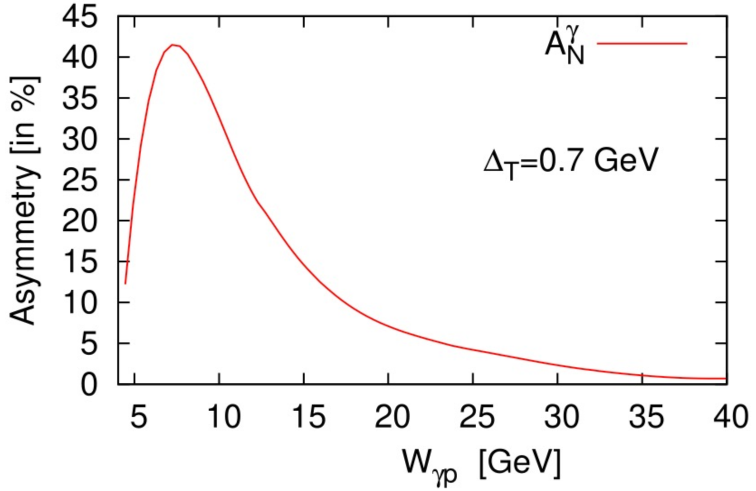
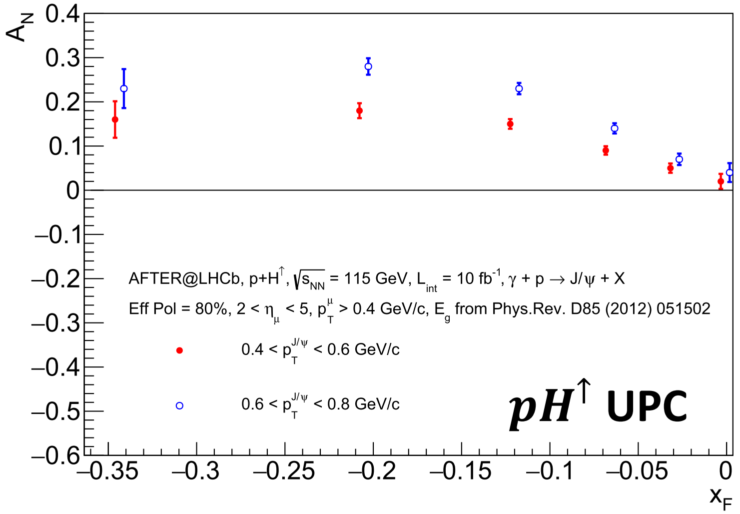
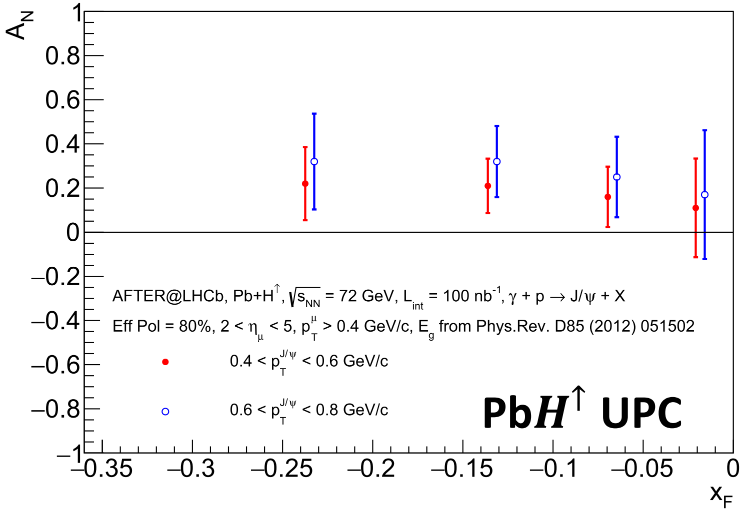


PLB 793 (2019) 33-40





- Extraction based on models for the GPD H^g (Goloskokov-Kroll) and E^g (PRD 85, 051502 (2012))
- AFTER model-dependent predictions **very promising for $pH^\uparrow$ UPC**

SSAs in polarized UPC

Measurement of A_N single-spin asymmetries for hadron production in $PbH^{\uparrow}$ UPC ($Pbp^{\uparrow} \rightarrow hPbX$) is also possible

- Two mechanisms can contribute:
  - TMD approach: process dominated by Sivers function
  - collinear twist-3 approach: process dominated by twist-3 fragmentation functions

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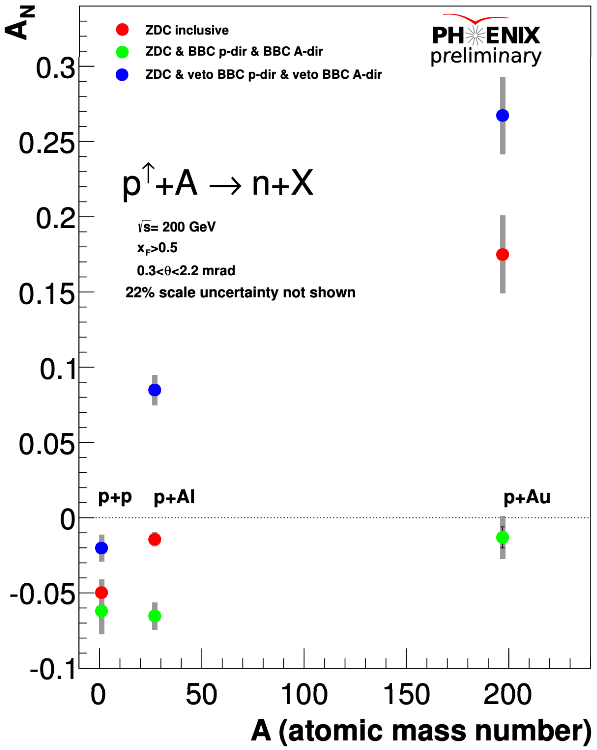
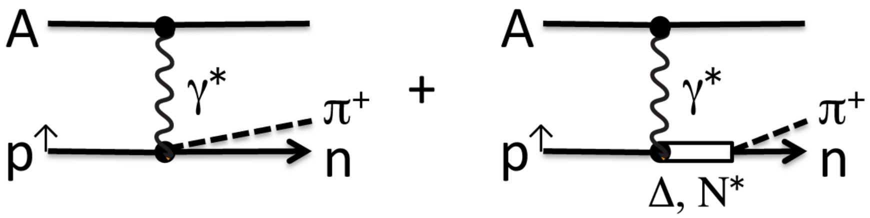
- Phoenix has recently measured large transverse SSAs in forward neutron production in $Alp^{\uparrow}$ and $Aup^{\uparrow}$ UPC at $\sqrt{s_{NN}} = 200\ GeV$

J. Phys.: Conf. Ser. 736 012017





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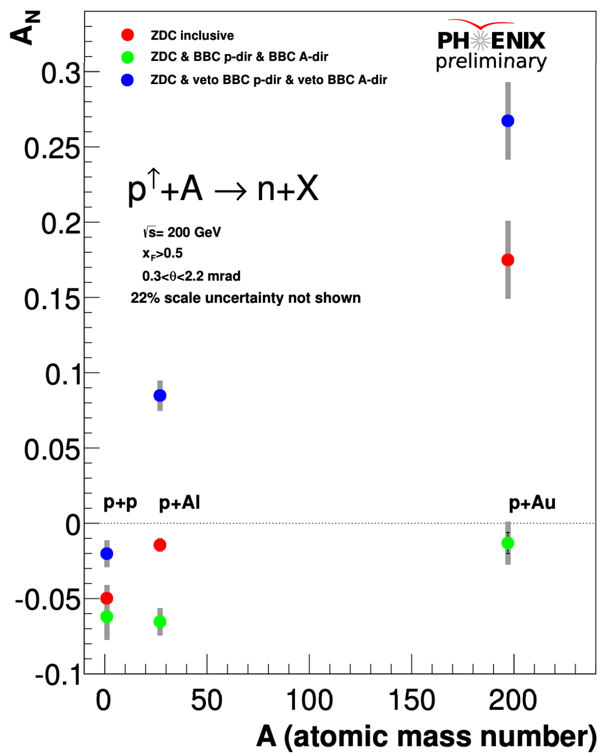
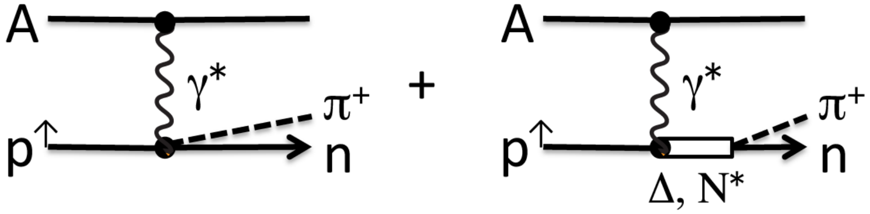
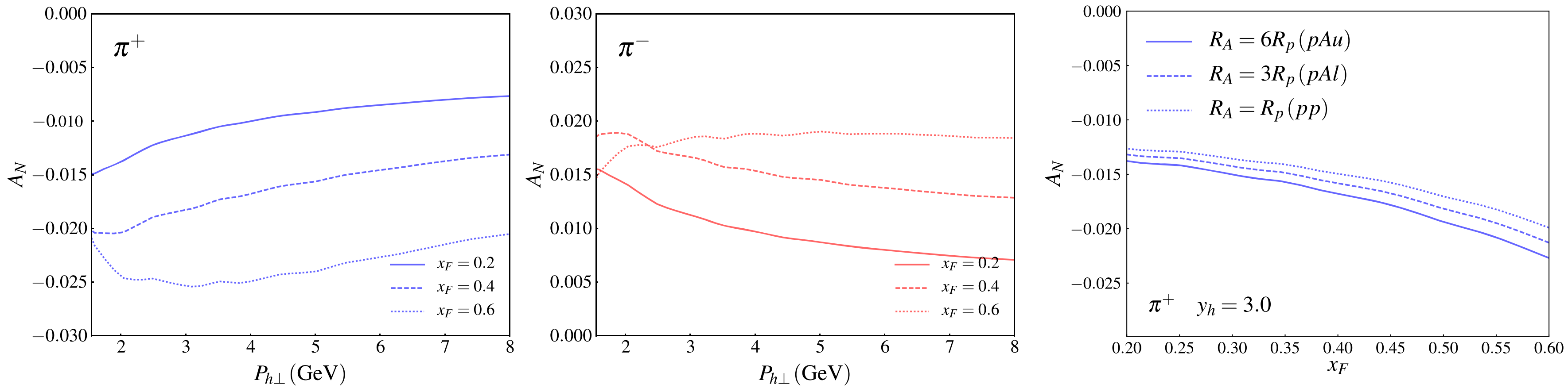




- Predictions available (based on twist-3 approach)

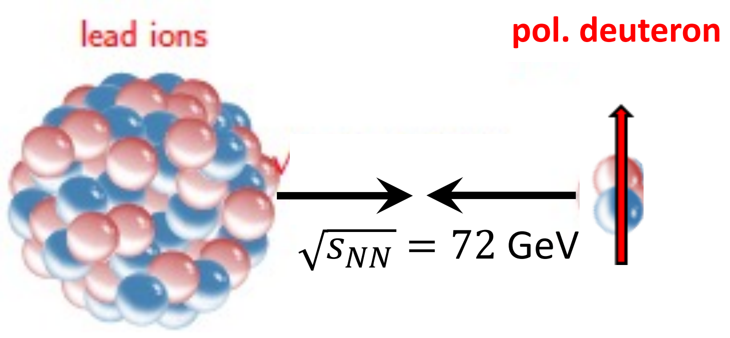
Phys. Rev. D98, 094025 (2018)



Merging spin physics with heavy-ion physics

- probe collective phenomena in heavy-light systems by exploiting **ultra-relativistic collisions of heavy nuclei with trasv. pol. deuterons**

- polarized light target nuclei offer a unique opportunity to control the orientation of the formed fireball by measuring the **elliptic flow** relative to the polarization axis (**ellipticity**).



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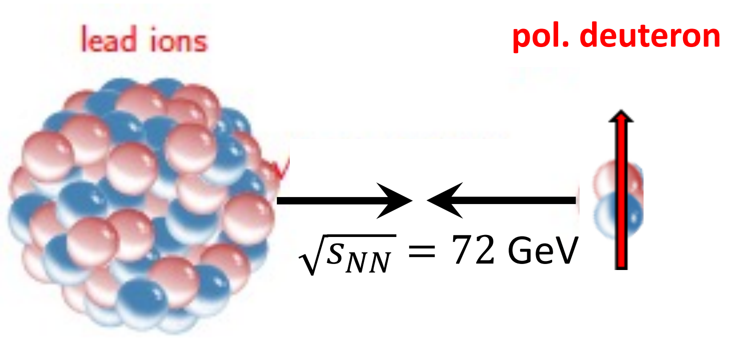

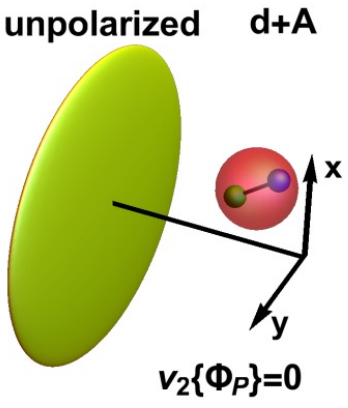

Unpol. deuterons: the **fireball is azimuthally symmetric** and $\boldsymbol{v_2 \approx 0}$.

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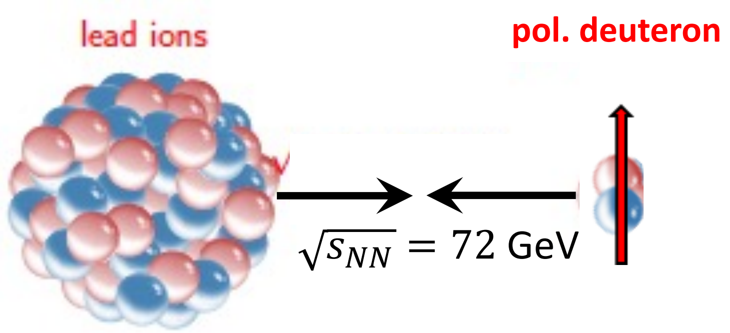

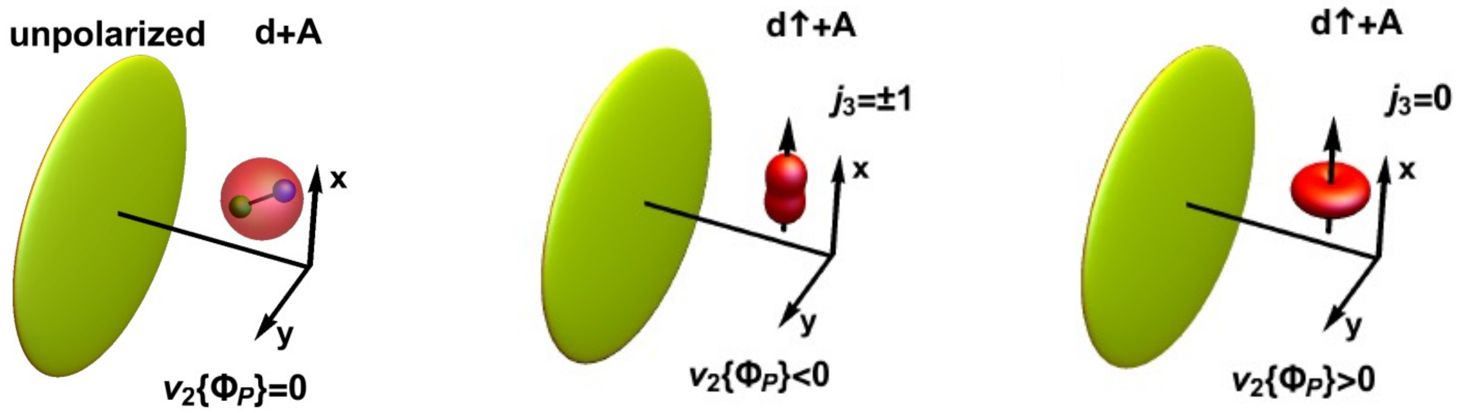

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$j_3 = \pm 1 \rightarrow$ **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

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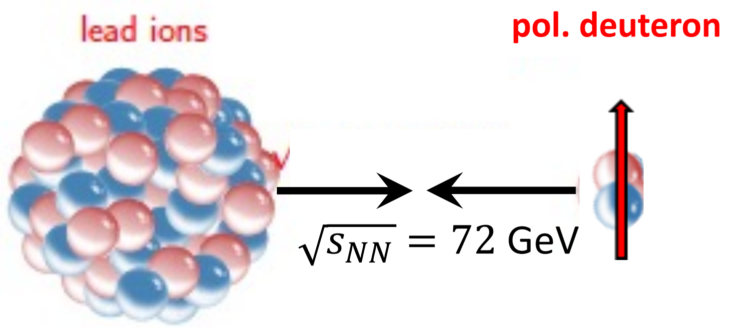

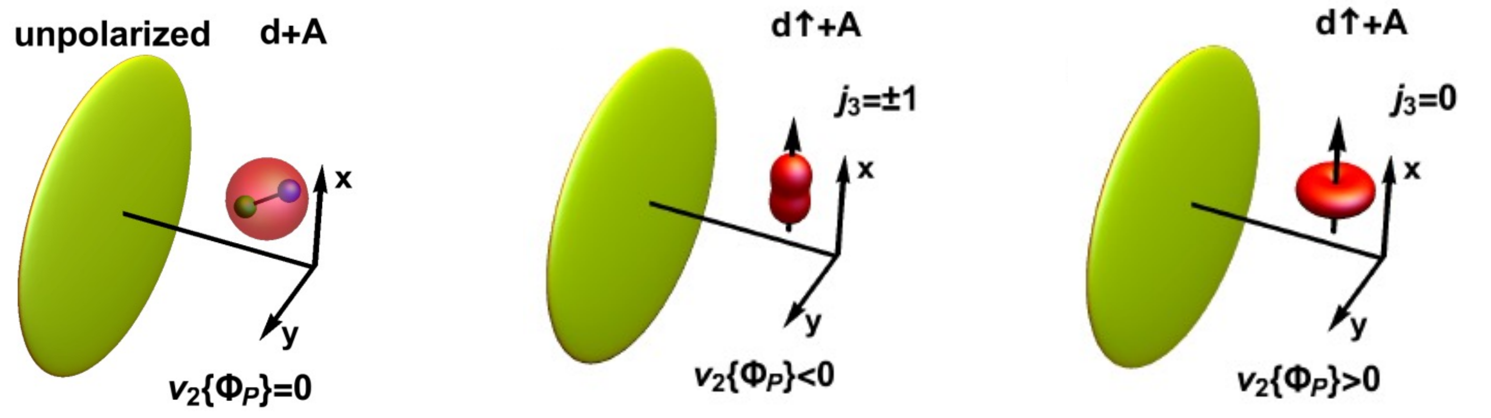

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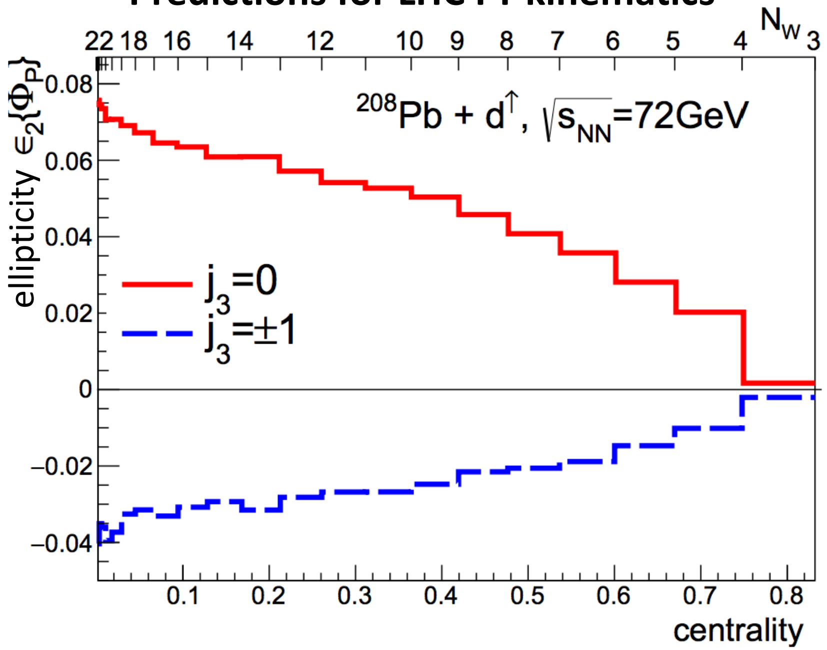
Predictions for LHC FT kinematics



[PRC 101 (2020) 024901]

Main reactions or interest (…an incomplete wishlist)

- $pp\ (pd) \rightarrow \mu^+\mu^-\quad (e^+e^-)$ ☛ **unpol DY: unpolarized TMDs of valence and sea quarks**
- $pp^{\uparrow}(pd^{\uparrow}) \rightarrow \mu^+\mu^-\quad (e^+e^-)$ ☛ **pol. DY: polarized TMDs of valence and sea quarks**
- $pp^{\uparrow}\ (pd^{\uparrow}) \rightarrow \pi\ (K) + X$ ☛ **inclusive production of light hadrons: polarized TMDs of valence and sea quarks**

- $pp^{\uparrow}(pd^{\uparrow}) \rightarrow \eta_c\ (\chi_{c,b}) + X$
- $pp^{\uparrow}\ (pd^{\uparrow}) \rightarrow J/\psi + X$
- $pp^{\uparrow}(pd^{\uparrow}) \rightarrow \Upsilon + X$
- $pp^{\uparrow}(pd^{\uparrow}) \rightarrow J/\psi + J/\psi + X$
- $pp^{\uparrow}(pd^{\uparrow}) \rightarrow J/\psi + \gamma + X$
- $pp^{\uparrow}(pd^{\uparrow}) \rightarrow \Upsilon + \gamma + X$

☛ **inclusive production of quarkonia: pol. and unpol. gluon TMDS**

- $A + p^{\uparrow} \rightarrow A + p^{\uparrow} + J/\psi$ ☛ **exclusive charmonia production in polarized UPC: gluon GPDs**
- pA, PbA $(A = He, Ne, Ar, Kr, \ldots)$ ☛ **Nuclear matter effects, QGP, etc**

Conclusions

- A polarized fixed target at LHCb will open the way to a broad and ambitious physics program
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure
- First insights into the yet unknown gluon TMDs (such as the GSF) will be possible thanks to the excellent capabilities of LHCb in reconstructing quarkonia states and heavy mesons.
- Comparison with results from present and future SIDIS experiments will shed light on the process-dependence of T-odd TMDs
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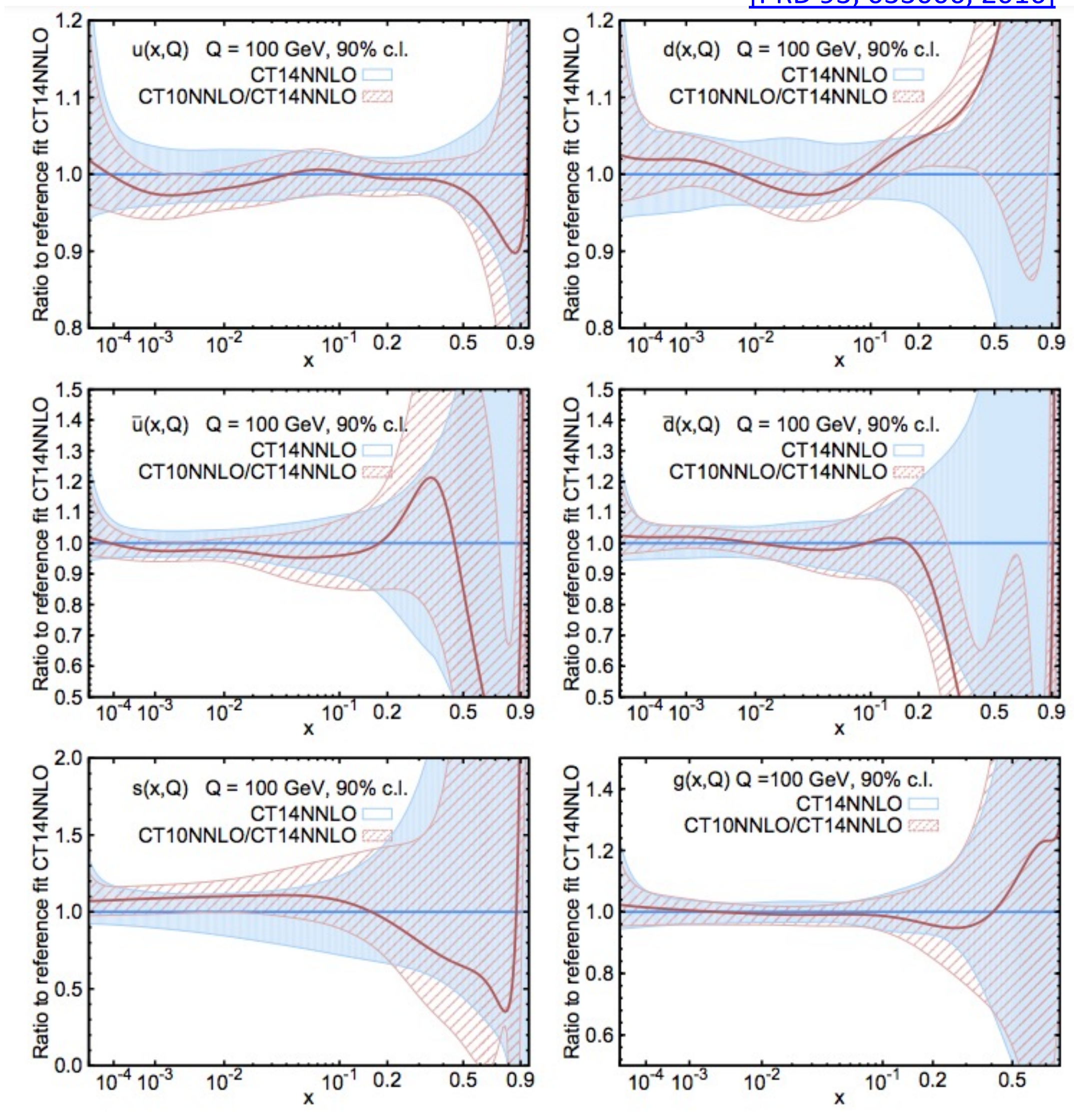
- See Marco’s talk for simulation of physics channels and expected performance

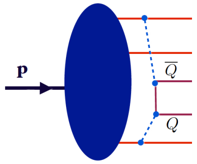
Backup

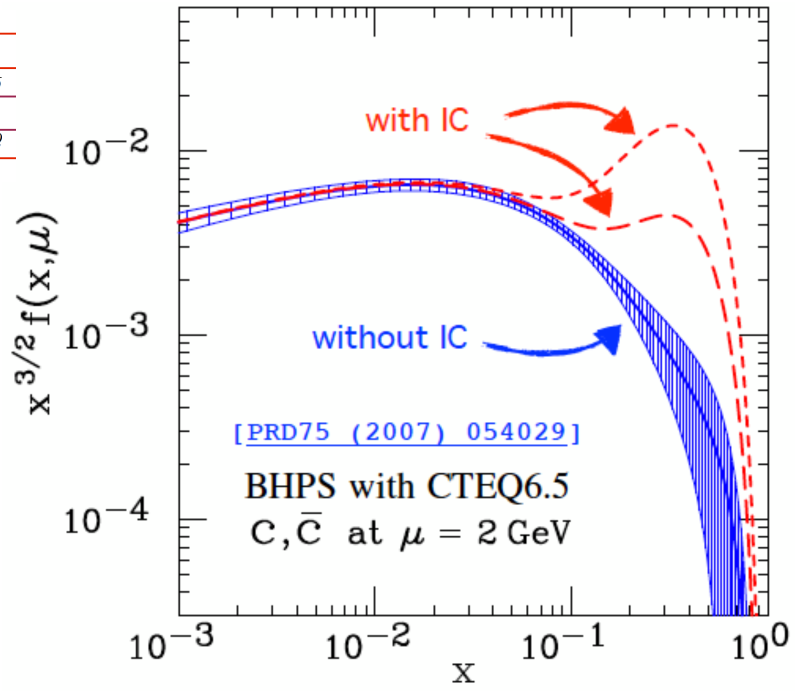
Kinematic conditions for fixed-target collisions at LHC

[PRD 93, 033006, 2016]

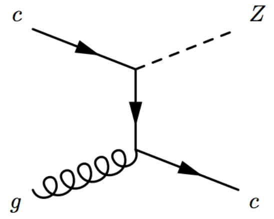


[PRD 75 (2007) 054029]





- **Significant contributions of IC expected at large x**
- First search performed with SMOG [PRL 122 (2019)]
- New intriguing LHCb results with pp collisions at large rapidity [arXiv:2109.08084]
- Still to be investigated!



Accessing quark TMDs in polarized pp collisions: inclusive hadron production

Collinear (twist-3) approach: (Efremov-Taryaev, Qiu-Sterman, Kanazawa-Koike)

- based on collinear QCD factorization (1 hard scale: works for $p_T, Q \gg \Lambda_{QCD}$)
- exchange of a gluon between the active parton and the color field of the IS or FS hadron
- gluon exchange generates the interference between different partonic scattering amplitudes
- this interference, described by a **3-parton (e.g. qgq, ggg) correlation function**, generates the SSA
- interestingly, the Qiu-Sterman correlator $T_{q(G)}(x,x)$ can be related at tree level to the 1^{st} transverse moment of the **Sivers function**:

$$f_{1T}^{\perp(1)q(g)}(x) = \int d^2k_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q(g)}(x, k_\perp^2) \ \propto T_{q(G)}(x,x)$$

- the Sivers function can arise from a combination of several Qiu-Sterman functions, but other twist-3 objects can contribute to A_N

Non-collinear (leading-twist) approach: (Anselmino, D'Alesio et al.)

- involves TMD PDFs and FFs
- works in the limit $p_T \ll$ Q (2 energy scales), but is not supported by TMD factorization
- can be considered as an effective model description (Generalized Parton Model)
- SSAs arise mainly from **Sivers effects**

➢ **The two approaches correspond exactly** in the overlap region $\Lambda_{QCD} \ll p_T \ll Q$ (proved for SSAs in Drell-Yan: Ji, Qiu, Vogelsang, Yuan, PRL, 2006)

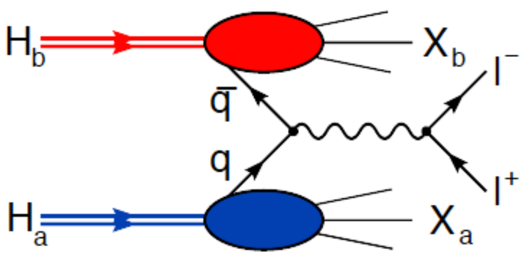
➢ …but very little is presently known about **tri-gluon correlation functions** and **gluon TMDs**.

Accessing quark TMDs in polarized pp collisions: Drell-Yan

quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Unpolarized Drell-Yan

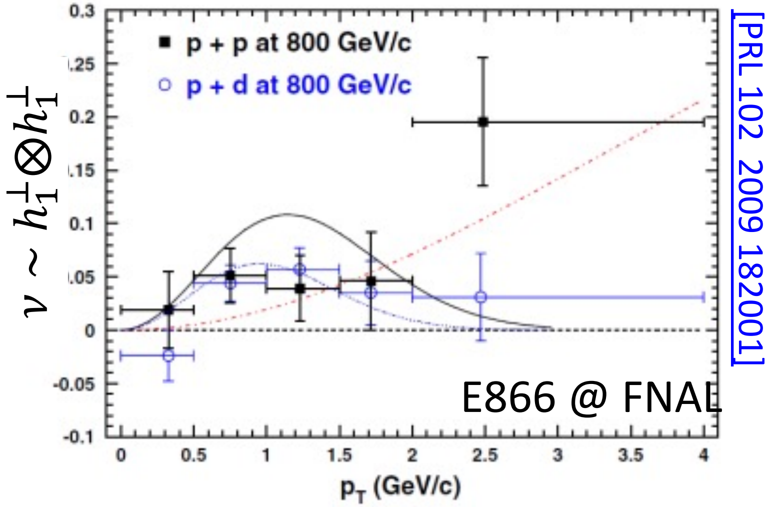


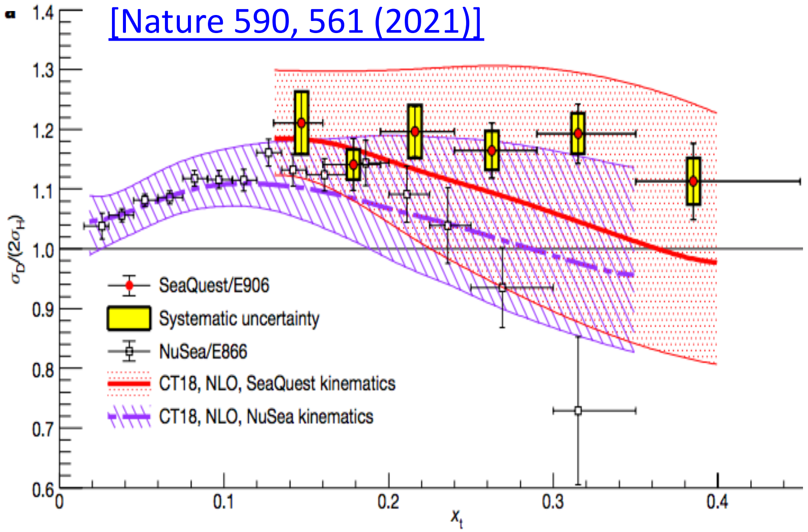
- Theoretically cleanest hard h-h scattering process
- LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$
- **dominant**: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$
- beam sea quarks probed at small x
- target valence quarks probed at large x

Sensitive to unpol. and BM TMDs for $q_T \ll M_{ll}$

(violation of Lam-Tung relation)

$$d\sigma_{UU}^{DY} \propto f_1^{\bar{q}} \otimes f_1^{q} + \cos 2\phi \ h_1^{\perp,\bar{q}} \otimes h_1^{\perp,q}$$

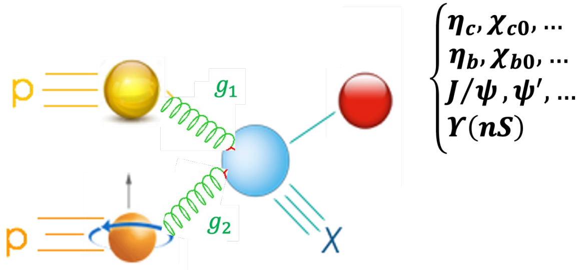




- Lattice QCD: $\bar{s}(x) \neq s\,(x)$ [arXiv:1809.04975]
- **proton sea more complex than originally thought!**
- **intrinsic heavy quarks**?
- Still a lot to be understood

- H & D targets allow to study the **antiquark content of the nucleon**
- SeaQuest (E906): $\bar{d}(x) > \bar{u}(x) \implies$ **sea is not flavour symmetric!**

Probing gluon TMDs in polarized pp collisions



Two main production mechanisms with different description of the hadronization:

- **Colour-Octet Model**: all colours and J^{PC} assignments are possible for the intermediate $Q\bar{Q}$ state.
- **Colour-Singlet Model**: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} of final-state quarkonium

Only quarkonia states produced in a color singlet state can provide clean access to gTMDs

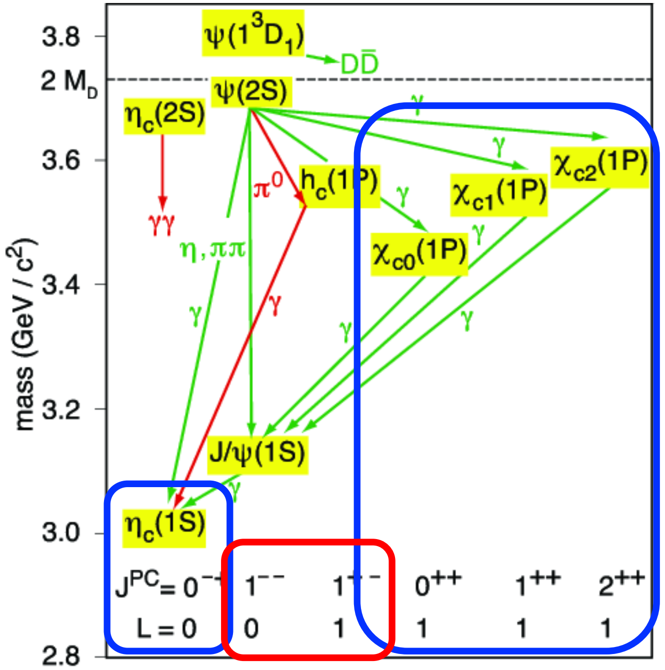
- **C-even quarkonia states ($J^{PC} = 0^{\pm,+}$: $\eta_c, \chi_{c0}, \eta_b, \chi_{b0}, \ldots$) can be formed in gluon-gluon in a color singlet state**
- **C-odd quarkonia states (e.g. J/ψ , $\psi(2S), \Upsilon(nS)$) can be formed in gluon-gluon fusion only in a color octet state**
- **Landau-Yang theorem: production of C-odd quarkonia states in a color singlet state requires a third gluon**, which:
  - causes a non-trivial TMD interpretation
  - dilutes the TMD information (e.g. the gluon Sivers function could be much larger than can be extracted from inclusive J/ψ production). This could explain the very small asymmetries measured by PHENIX.

➡ **Best channel would be inclusive η_c production** (although the few existing results rely on J/ψ production)

[D. Boer: Few-body Systems 58, 32 (2017)] [Boer, Pisano: arXiv:1208.3642v2] W. Beenakker, arXiv:1508.07115

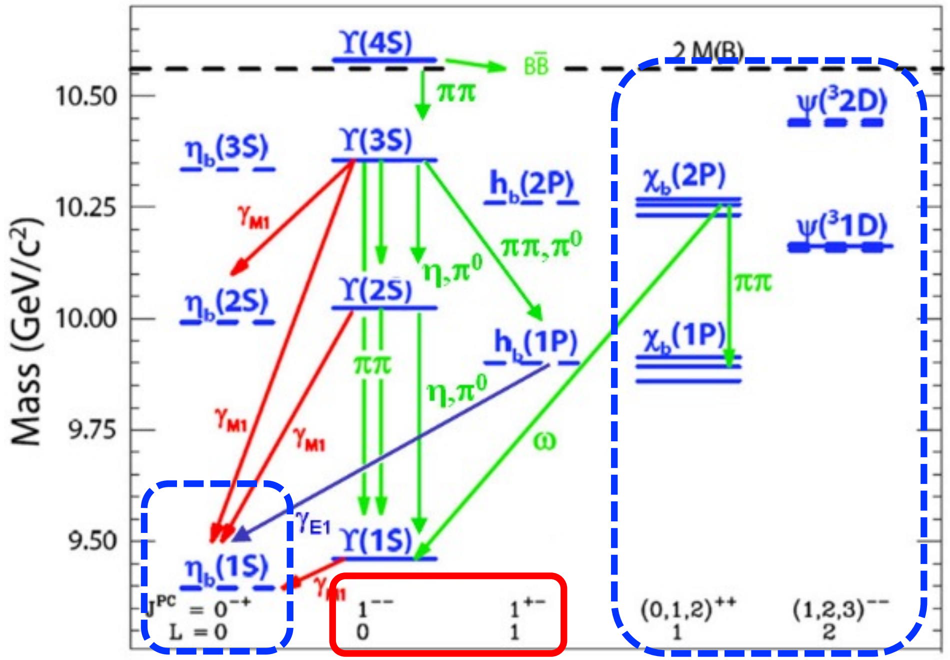
Motivations for $\eta_c \to p\bar{p}$ channel

Charmonium

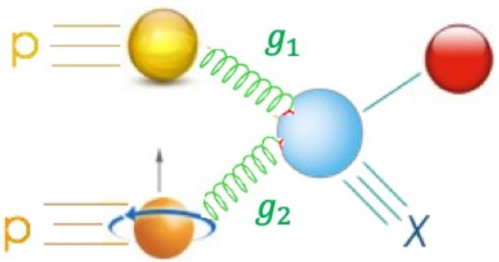


C-even C-odd C-even

Bottomonium



C-even C-odd C-even



$$\begin{cases} \boxed{\eta_c, \chi_{c0},} \dots \\ \eta_b, \chi_{b0}, \dots \\ J/\psi + J/\psi \\ J/\psi + \gamma \\ \dots \end{cases}$$

→ **best channels**

→ statistically suppressed

→ requires CALO info

Probing the gTMDs

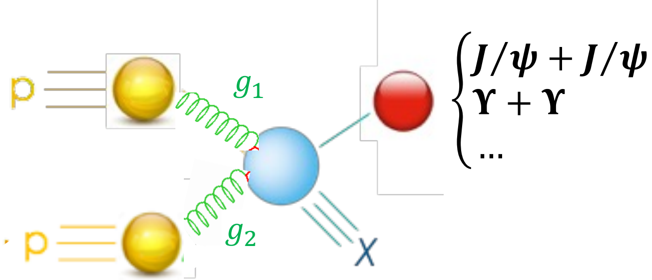
$$\frac{d\sigma}{dM_{QQ}\,dY_{QQ}\,d^2\boldsymbol{P}_{QQ_T}\,d\Omega} = \frac{\sqrt{M_{QQ}^2 - 4M_Q^2}}{(2\pi)^2 8s\, M_{QQ}^2}$$

$$\Big\{ F_1(M_{QQ},\theta_{CS})\,\mathcal{C}\left[f_1^g f_1^g\right](x_{1,2},\boldsymbol{P}_{QQ_T})$$

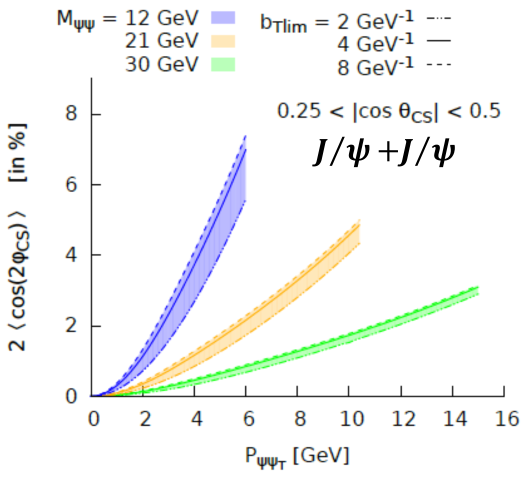
$$+F_2(M_{QQ},\theta_{CS})\,\mathcal{C}\left[w_2 h_1^{\perp g} h_1^{\perp g}\right](x_{1,2},\boldsymbol{P}_{QQ_T})$$

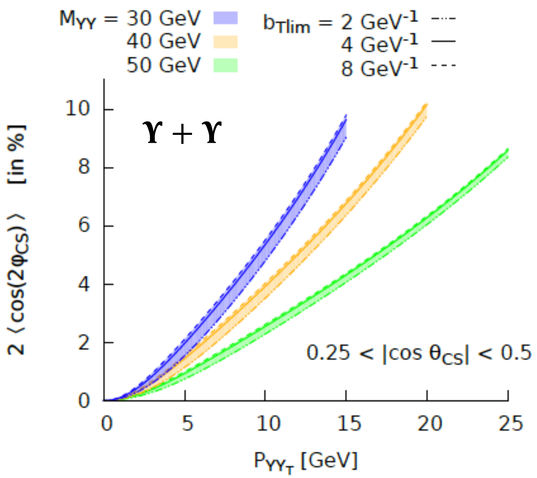
$$\boxed{+\Big(F_3(M_{QQ},\theta_{CS})\,\mathcal{C}\left[w_3 f_1^g h_1^{\perp g}\right](x_{1,2},\boldsymbol{P}_{QQ_T})+ F_3'(M_{QQ},\theta_{CS})\,\mathcal{C}\left[w_3' h_1^{\perp g} f_1^g\right](x_{1,2},\boldsymbol{P}_{QQ_T})\Big)\cos 2\phi_{CS}}$$

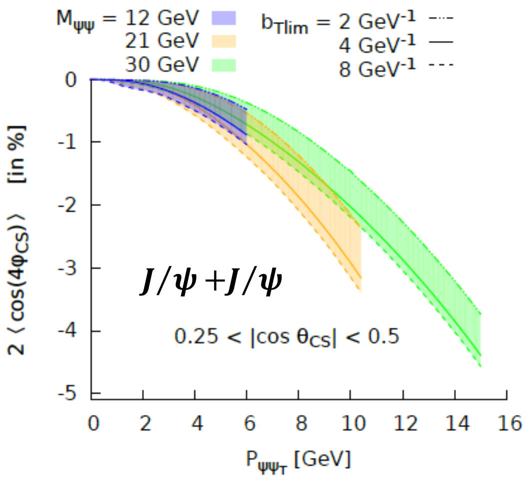
$$\boxed{+F_4(M_{QQ},\theta_{CS})\,\mathcal{C}\left[w_4 h_1^{\perp g} h_1^{\perp g}\right](x_{1,2},\boldsymbol{P}_{QQ_T})\cos 4\phi_{CS}}\Big\}$$

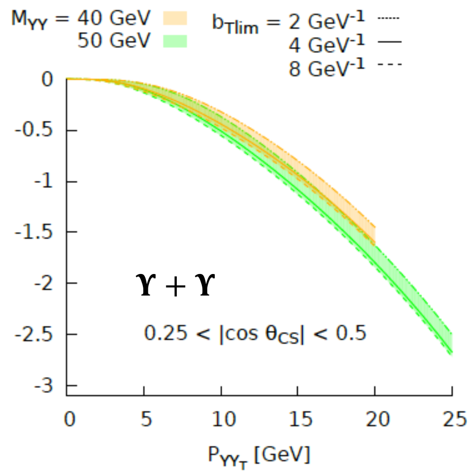


nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$





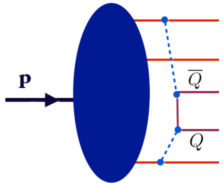


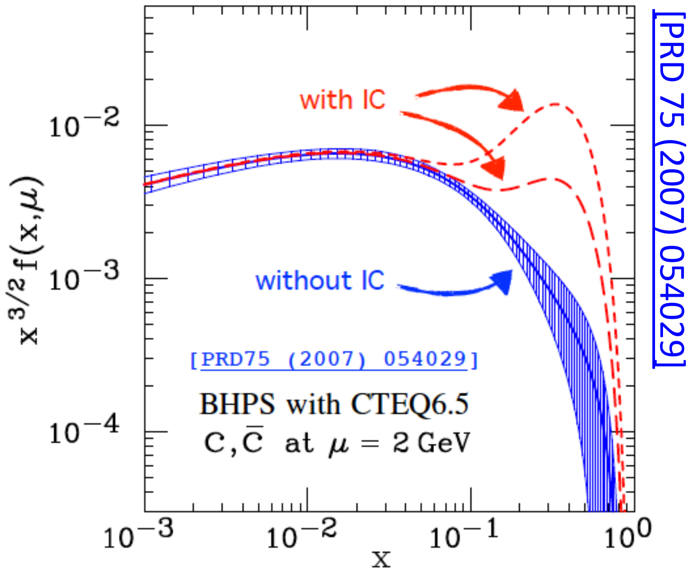


Predictions based on CSM + TMD evolution for $x_1 \sim x_2 \sim 10^{-3}$ at forward rapidity [EPJ C 80, 87 (2020)] ➡ **Azimuthal amplitudes ~ 5%!!**

More physics reach with unpolarized FT reactions

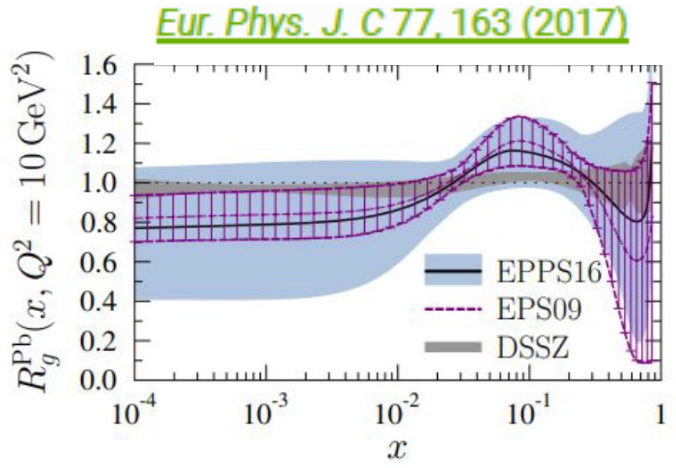
- **Intrinsic heavy-quark** **[S.J. Brodsky et al.,** Adv.High Energy Phys. 2015 (2015) 231547]
  - 5-quark Fock state of the proton may contribute at high x!
  - **charm PDFs** at large x could be larger than obtained from conventional fits

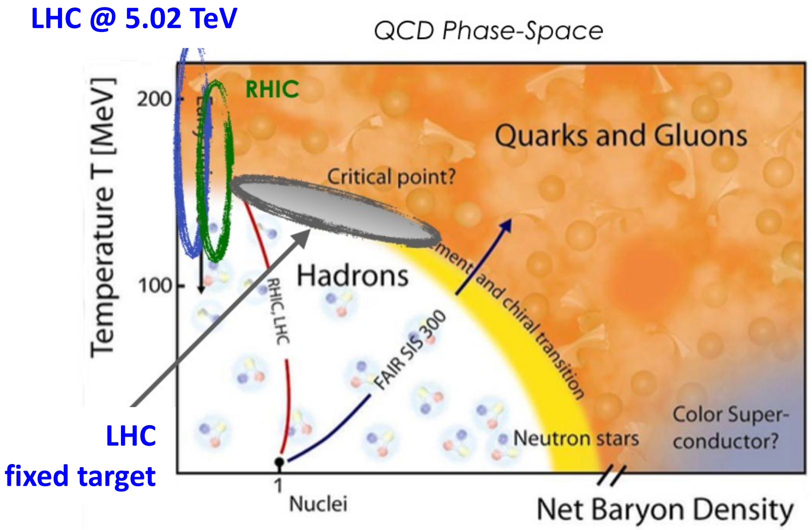


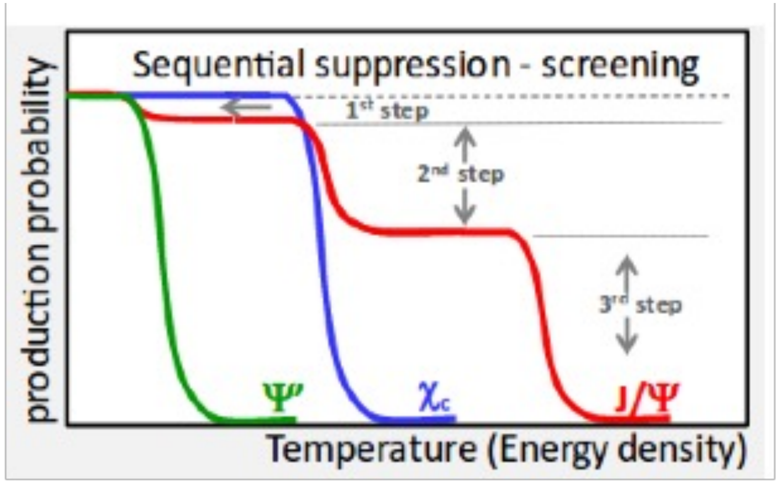


- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium
  - reactions of interest for cosmic-ray physics and DM searches

- **PbA collisions at $\sqrt{s_{NN}} \approx 72$ GeV** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - Study of **QGP formation** (search for predicted **sequential quarkonium suppression**)







$c\bar{c}$ states: J/ψ, χ_c, ψ',…
Different binding energies, different dissociation temperatures → **medium thermometer**

Expected luminosity

- The LHC beam runs through the target cell and experiences an **Areal density**: $\theta = \frac{1}{2} \rho_0 L$
- **Volume density**: $\rho_0 = I_0/(2C_1 + C_2)$ where: $C = 3.81\sqrt{\frac{T(K)}{M}}\frac{D^3}{L+1.33D}\left(\frac{l}{s}\right)$

$I_0 = 6.5 \cdot 10^{16} s^{-1}$ C_{tot} = 13.90 l/s ρ_0 = 4.68 $\cdot 10^{12}/\text{cm}^3$ ➡ $\boxed{\theta = 3.7 \cdot 10^{13}/\text{cm}^2}$

$$\left\{\begin{array}{l} N_{p/bunch} = 2.2 \cdot 10^{11} \\ N_{bunch} = 2760 \\ f_{rev} = 11245\ Hz \end{array}\right. \Longrightarrow \boxed{I_{beam} = 6.8 \cdot 10^{18}\ s^{-1}}$$

$$\boxed{L(T_{cell} = 300\ K) = I_{beam} \cdot \theta = 2.5 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}}$$

- ➢ The pressure in the LHC beam pipe outside the target region would be $\sim 10^{-7}$ mbar, one order of magnitude lower than the maximum pressure allowed by LHC
- ➢ Parallel operation will cause marginal reduction of beam half-life!