An experiment for LHCspin

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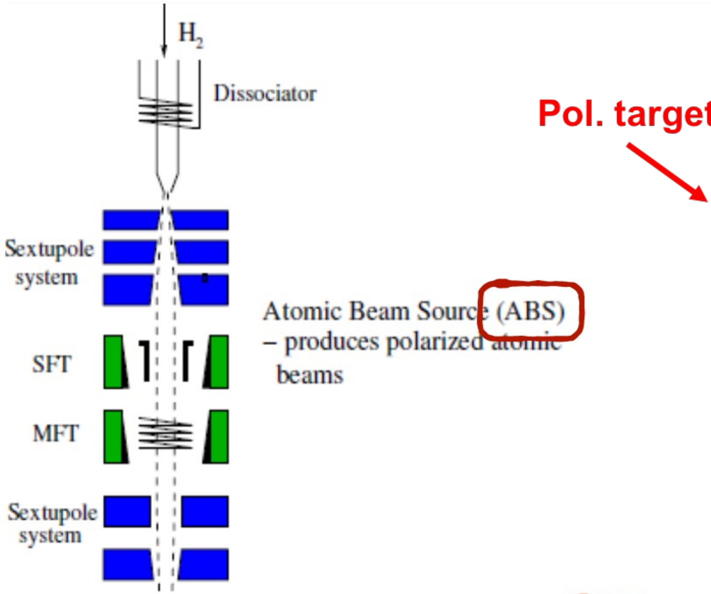
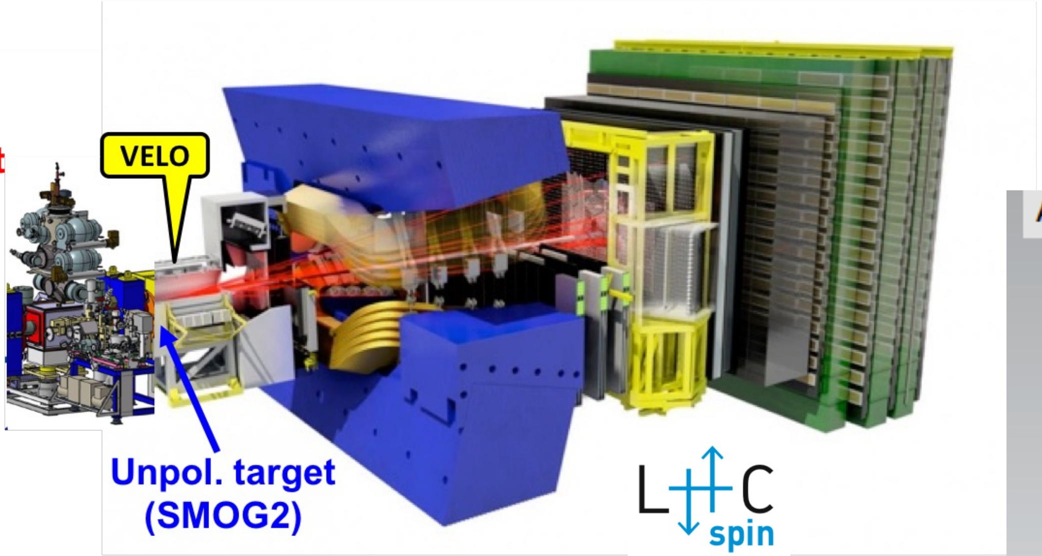
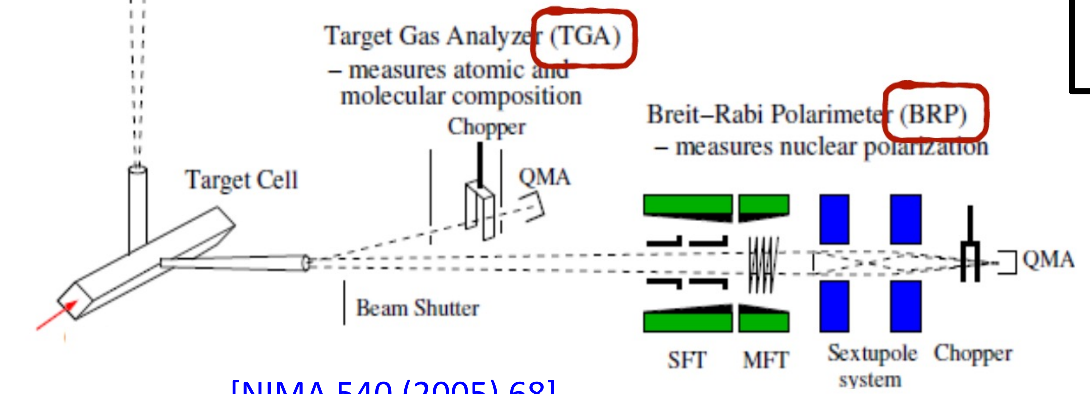
LHCspin Kick-off Meeting – December 18 2023

The LHCspin apparatus

The “final” LHCspin apparatus consists of a **new-generation polarized gaseous target** to be installed in the LHCb spectrometer usptream of the VELO



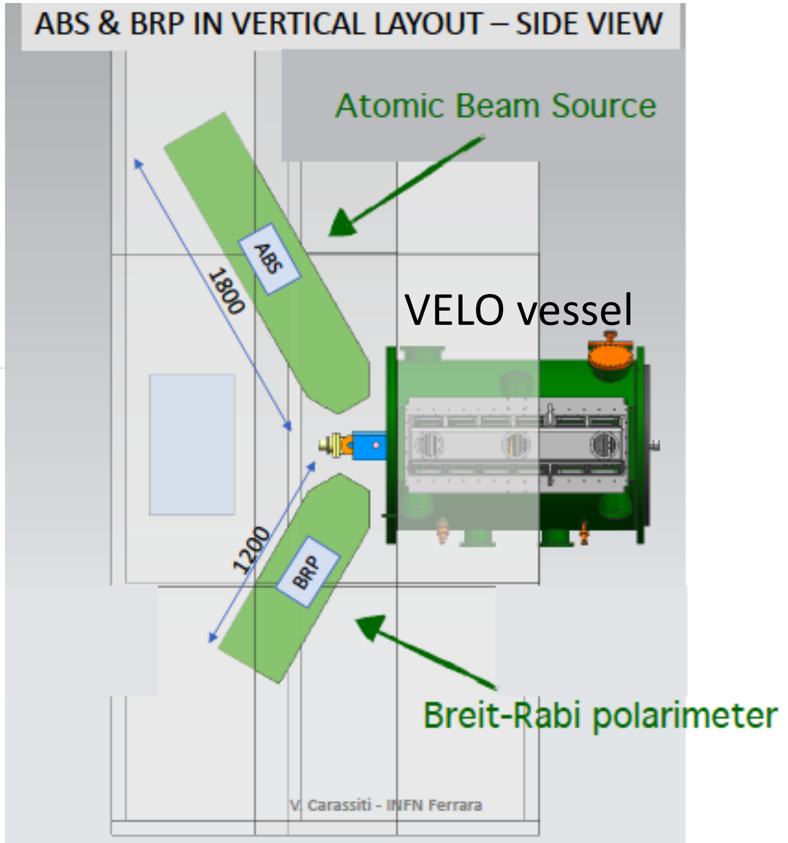




[NIMA 540 (2005) 68]

75-80% transverse polarization @ HERMES

See Alex talk!



The plan for the upcoming years

Necessary pre-requisites for the approval of the project at LHCb (Run5):

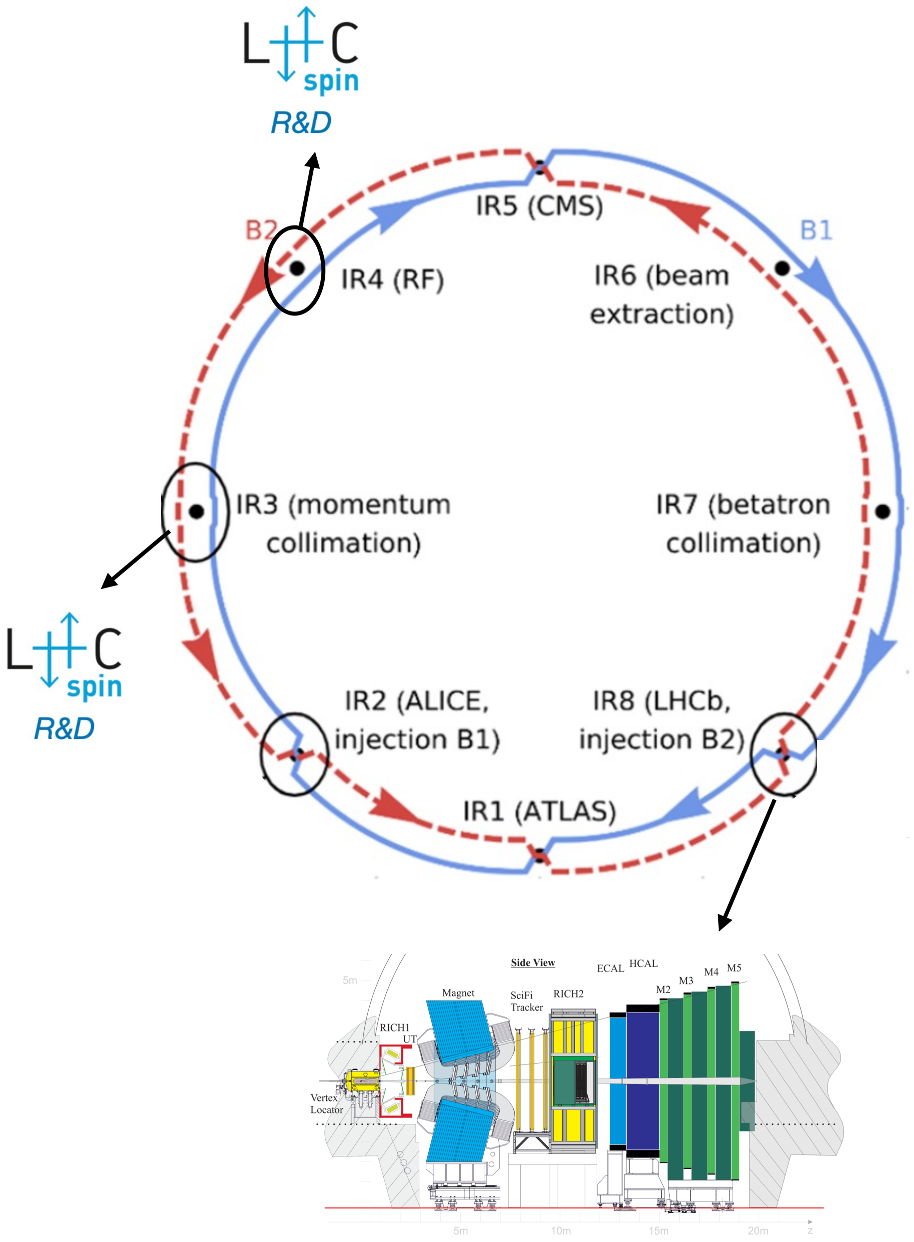
- R&D campaign for the apparatus towards the final setup for LHCb
- feasibility studies in a dedicated experimental area served by LHC beams

Plan:

- **LS3 (2026-28):** Installation of existing setup (ABS + polarimeter from COSY) + minimal spectrometer for simple (but unique!) physics measurements

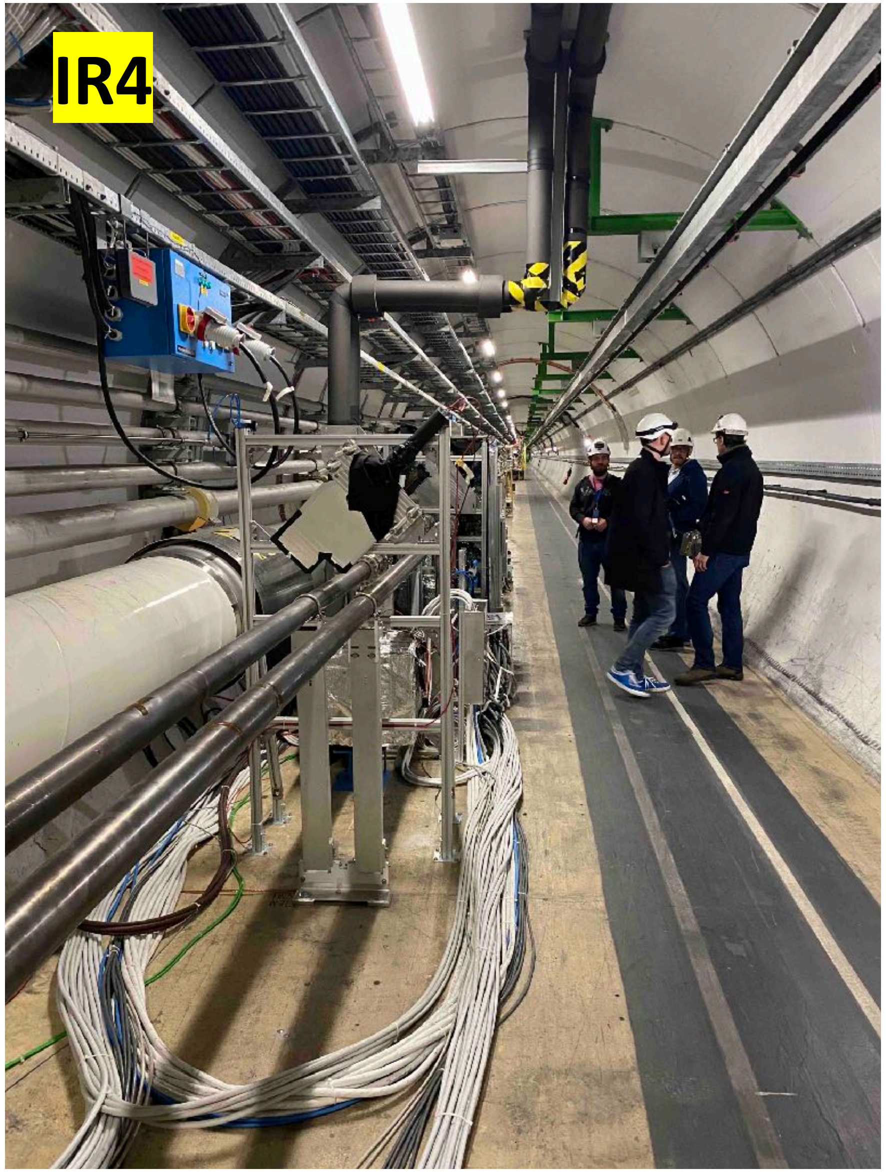
- **Run4 (2029-32):**
  - In-beam polarimetry studies (Paolo’s talk)
  - first polarized measurements at the LHC

- Two sites have been identified in the LHC tunnel (IR3, IR4)

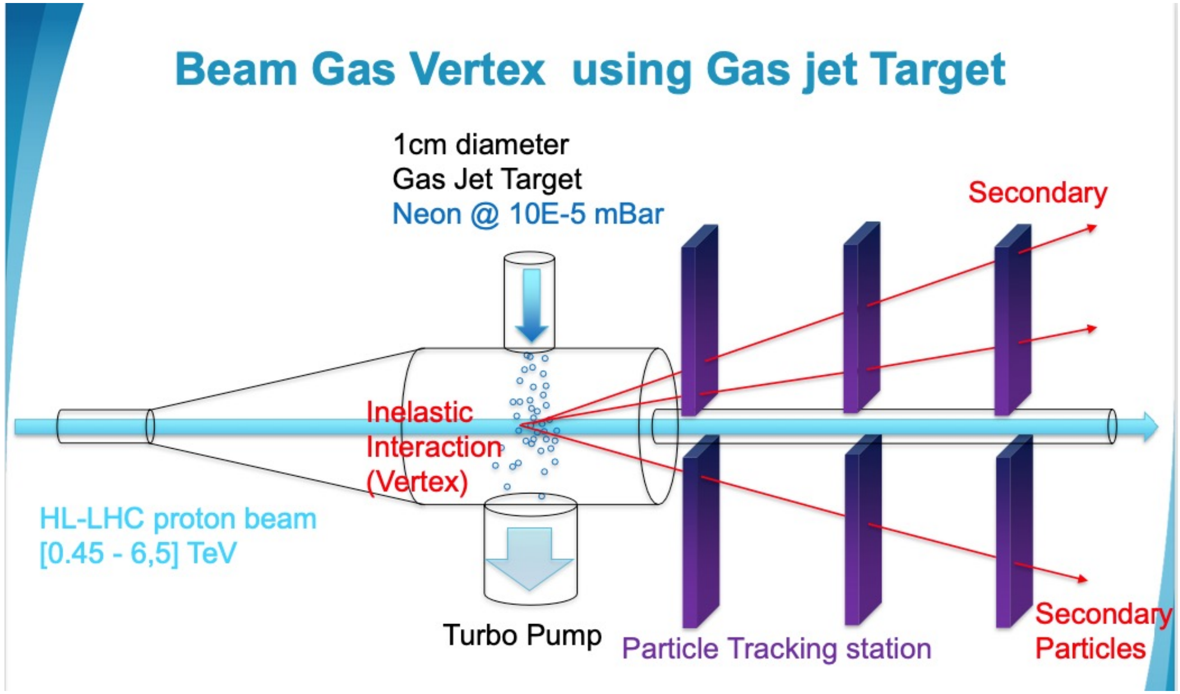


IR3 vs IR4

Essentially free from instrumentation



IR4 provides several advantages



Not in use, could be replaced by our apparatus

IR4 provides several advantages

Cables are available, as well as the rail for transporting the apparatus

There are racks available

Detector concept

In the following only some general ideas are presented. Detailed studies will follow once the consistency, the composition and the expertise of the proto-collaboration will be established.

Detector concept at IR4

Goals:

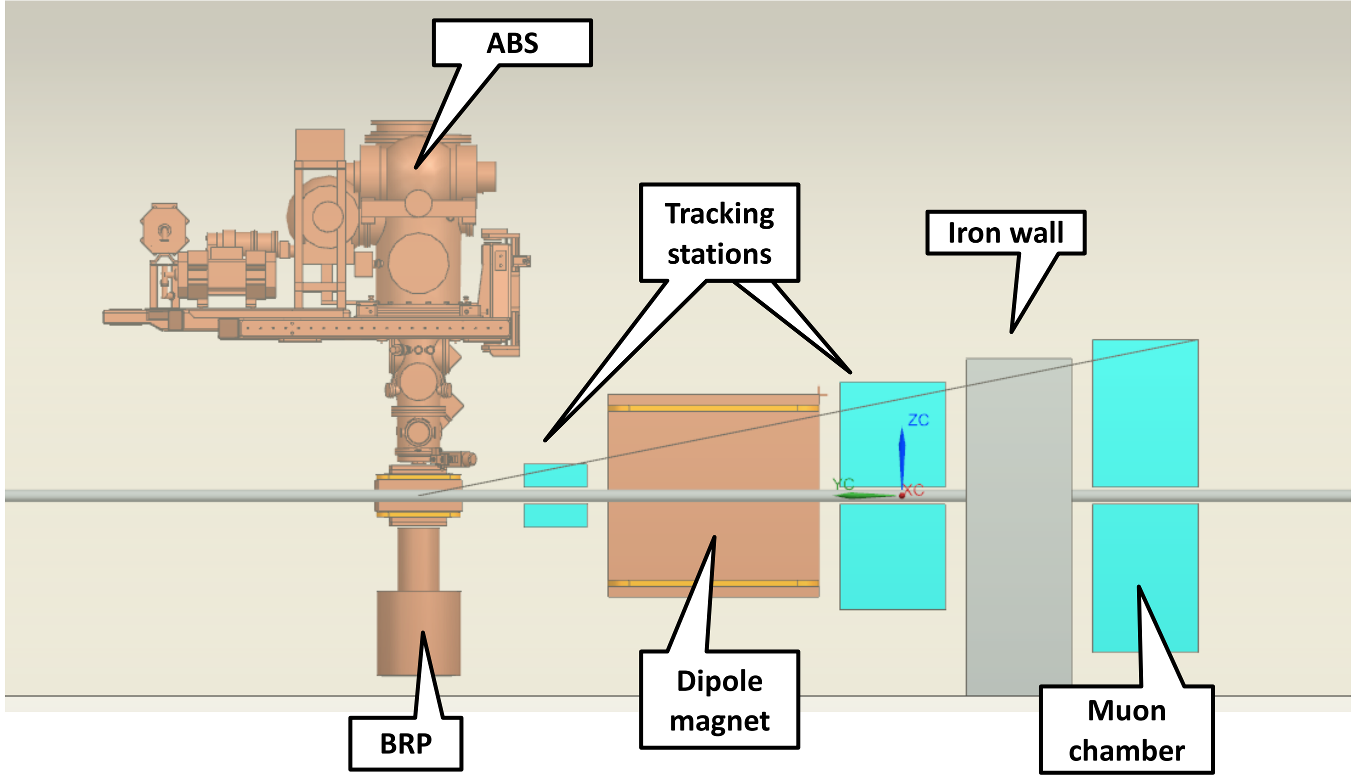
- proof of principle of the future (large-scale) experiment with LHCb.
- measurement of single-spin asymmetries in inclusive hadron production in $pH^{\uparrow}$ and $PbH^{\uparrow}$ (see next slides)

Apparatus:

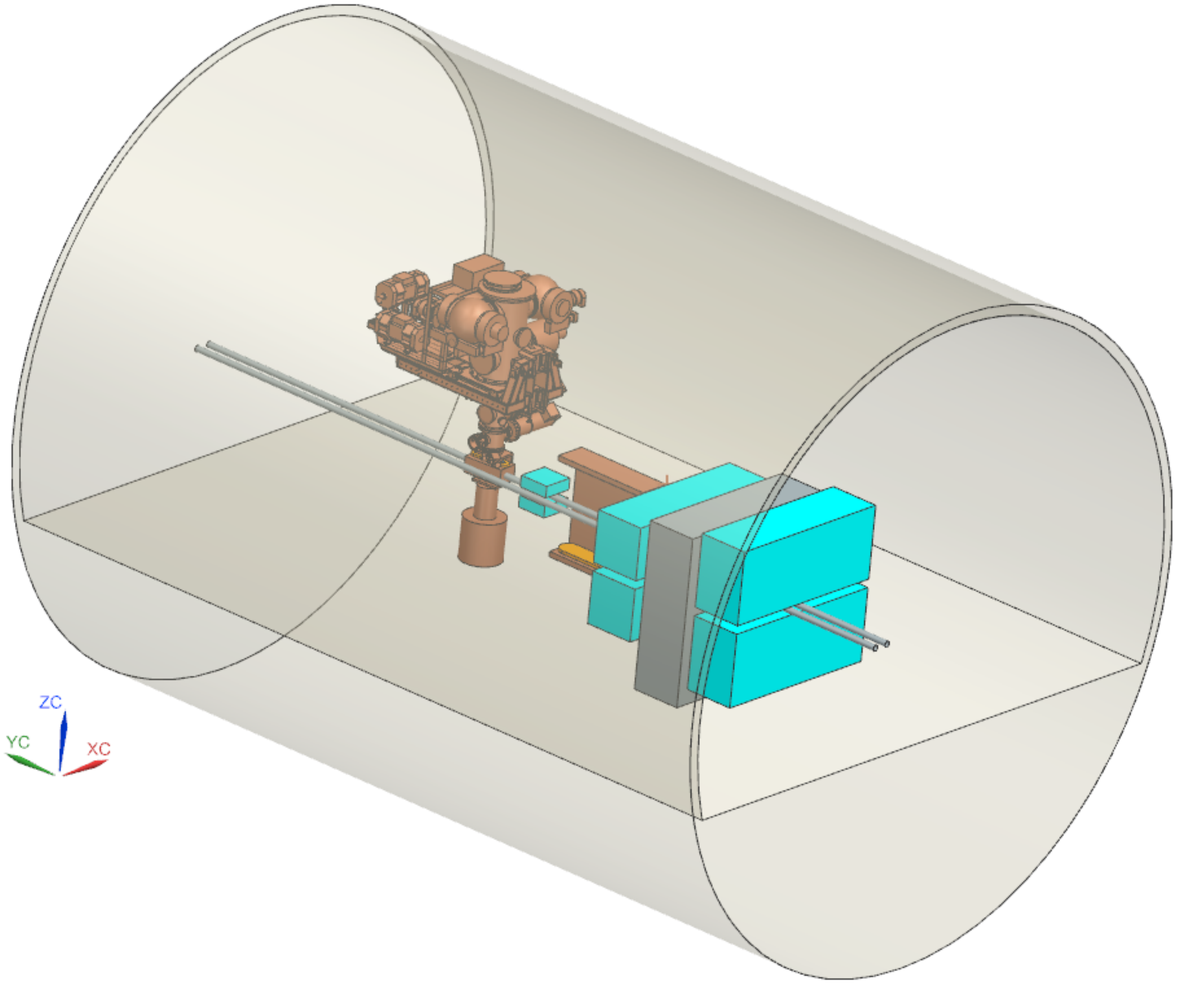
- jet-target (but could be done also with storage cell)
- full (minimal) spectrometer: dipole magnet, tracking stations, muon system
- simple PID detectors (Calo, RICH)?

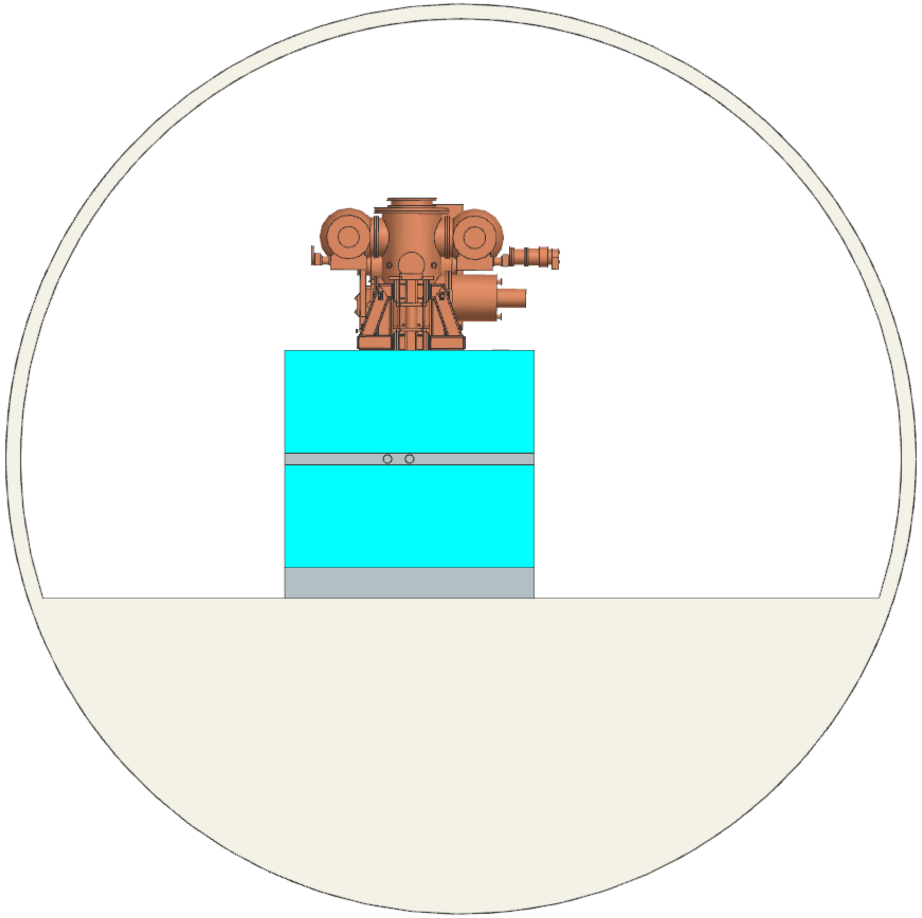
Needed expertise (apart from pol. target):

- dipole magnet
- tracking detectors (Si strip, SciFi, drift chambers?)
- muon chambers (MWPC?)
- electronics
- DAQ
- slow control
- tracking/reconstruction algorithms
- …



Detector concept at IR4





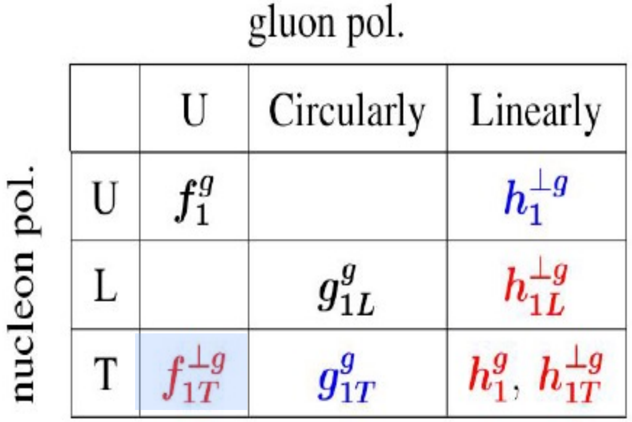
Some preliminary ideas for physics measurements

Possible physics measurements (I)

Single-spin asymmetries in inclusive J/ψ production in $pH^{\uparrow}$ and $pD^{\uparrow}$

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg\to QQg}\right] \sin\phi_S + \cdots$$

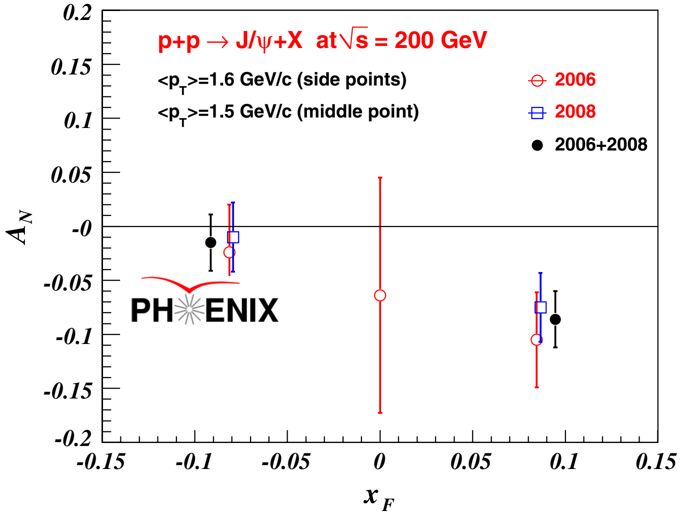
- ➢ provides access to polarized gluon TMDs (e.g. **gluon Sivers function $f_{1T}^{\perp g}$**)
  - describes spin-orbit correlations of unpol. gluons inside a transv. pol. proton
  - sensitive to (unknown) gluon OAM
- ➢ Presently only a few points measured by Phoenix (BNL)
- ➢ Promising predictions for full measurement with LHCb + pol. target
- ➢ find more in backup slides

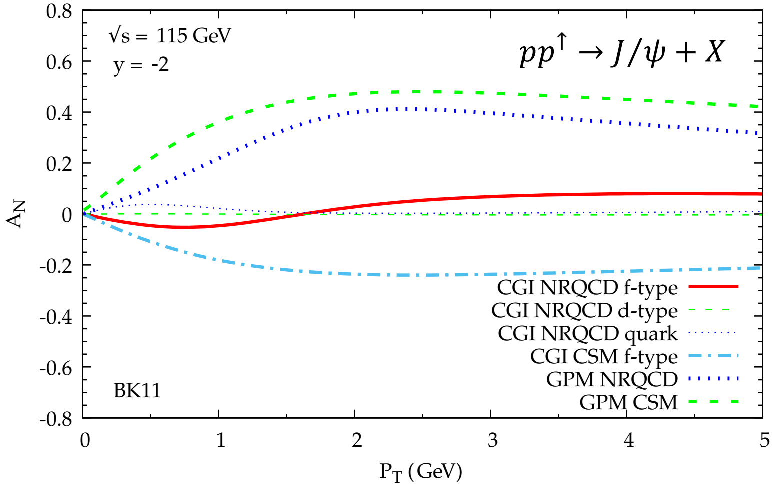


gluon pol.

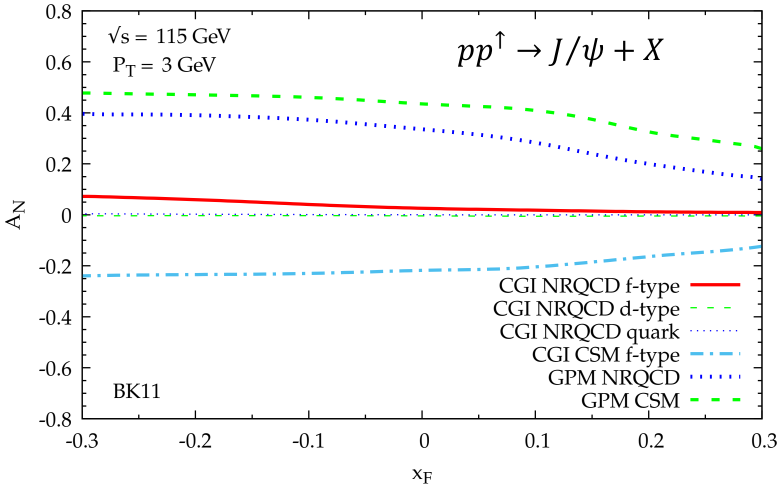
nucleon pol.

	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, $h_{1T}^{\perp g}$





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



Possible physics measurements (II)

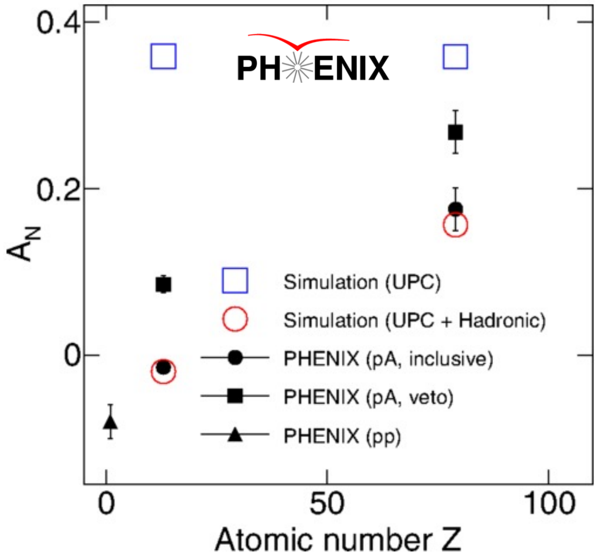
Measurement of A_N single-spin asymmetries for hadron production in $PbH^{\uparrow}$ UPC ($p^{\uparrow}Pb \rightarrow hPbX$)

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

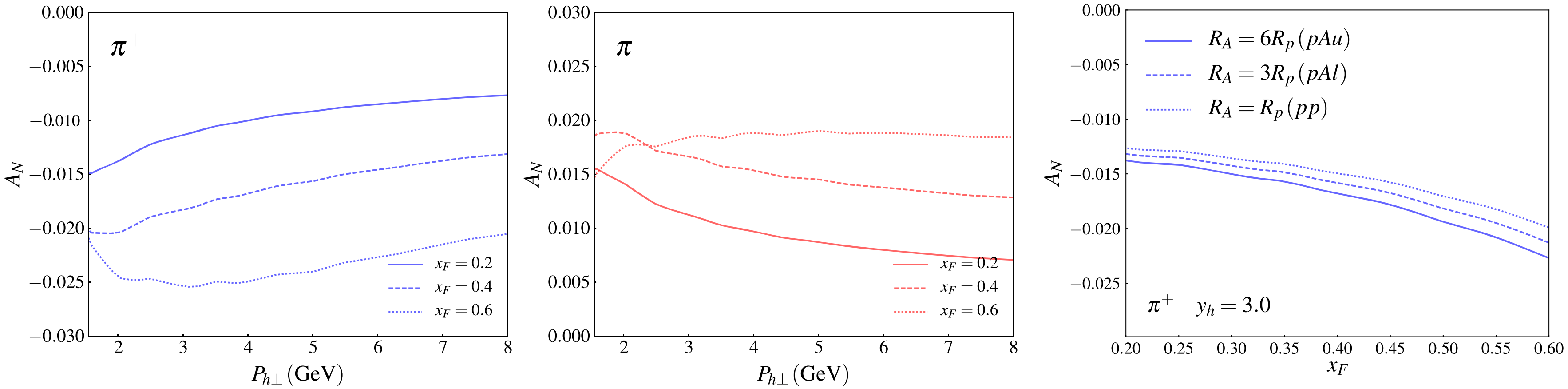
- A Phoenix measurement exists on forward neutron production in $p^{\uparrow}Al$ and $p^{\uparrow}Au$ UPC at $\sqrt{s_{NN}} = 200\ GeV$

- Predictions available (based on twist-3 approach)

Phys. Rev. C95, 044908 (2017)



Phys. Rev. D98, 094025 (2018)



More ideas for physics measurements will be considered once the features of the apparatus will be more definite.

Conclusions

- LHCspin allows for a rich and peculiar physics program at LHC at unique conditions (backup slides)
- Full-scale experiment with LHCb proposed for Run5
- Exploit Run4 for R&D and first polarized measurements
- Experimental setup to be installed during LS3 at IR3 or IR4
- Complexity of the apparatus (and physics goals) critically dependent on the consistency and expertise of proto-collaboration

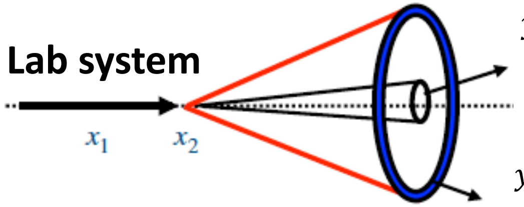
Backup

Kinematic conditions for fixed-target collisions at LHC

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

$$x_2 \approx \frac{Q}{\sqrt{s_{NN}}} e^{-y_{CM}}$$

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



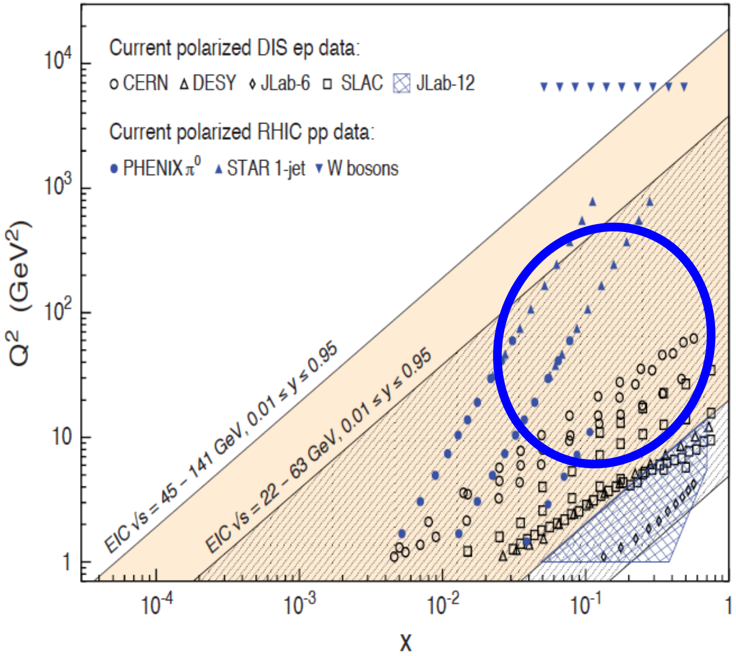
$y = 5\ (\theta \sim 1°)$
$\implies y_{CM} \approx 0$

$y = 2\ (\theta \sim 15°)$
$\implies y_{CM} \approx -3$

$$x_F = \frac{p_L^*}{|max(p_L^*)|} \sim x_1 - x_2 < 0$$

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

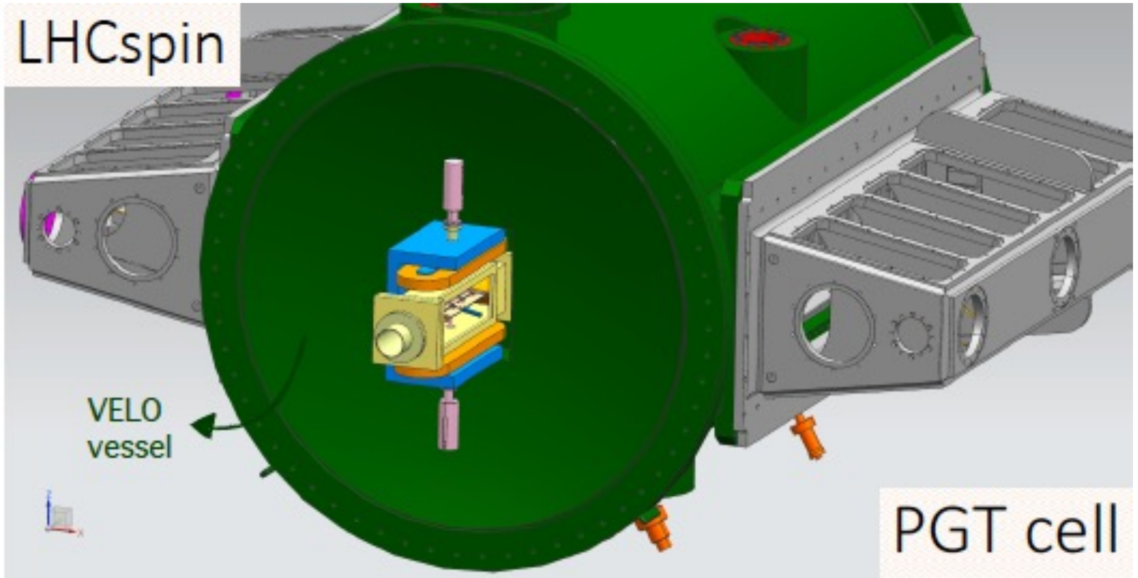
In the fixed-target configuration LHCb allows to cover **mid-to-large x at intermediate Q^2 and negative x_F.**

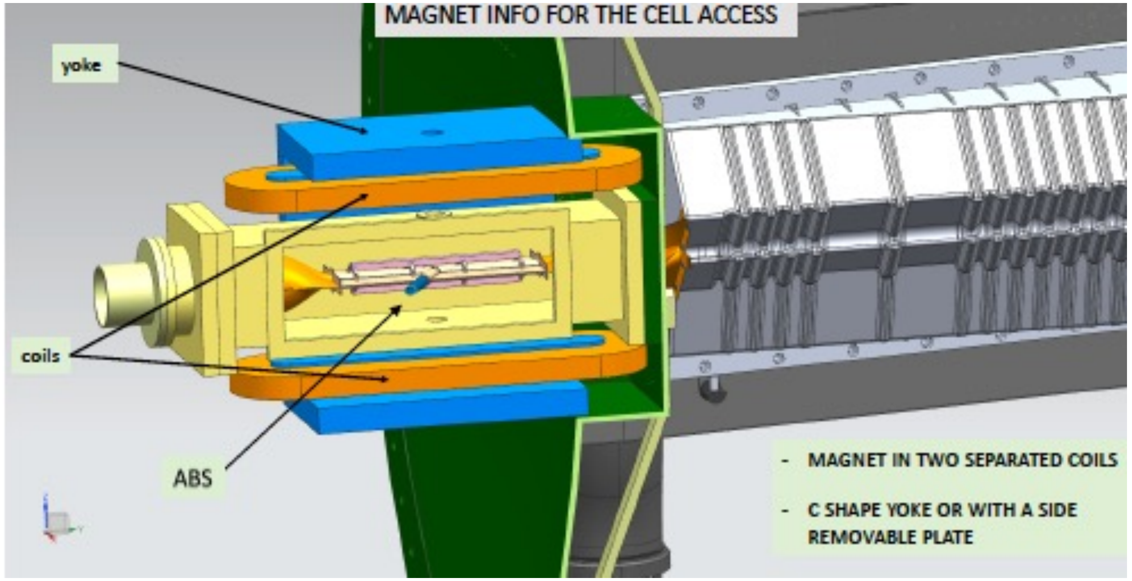


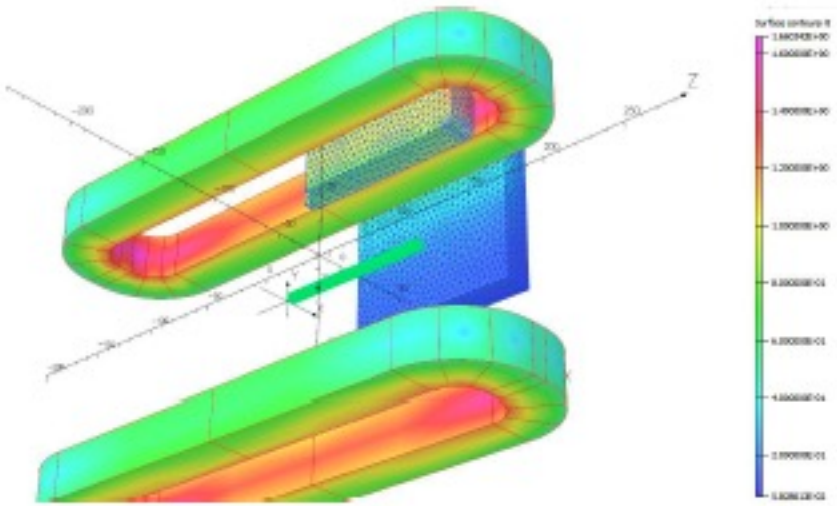
Complementarity is the key!

- 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

The LHCspin apparatus





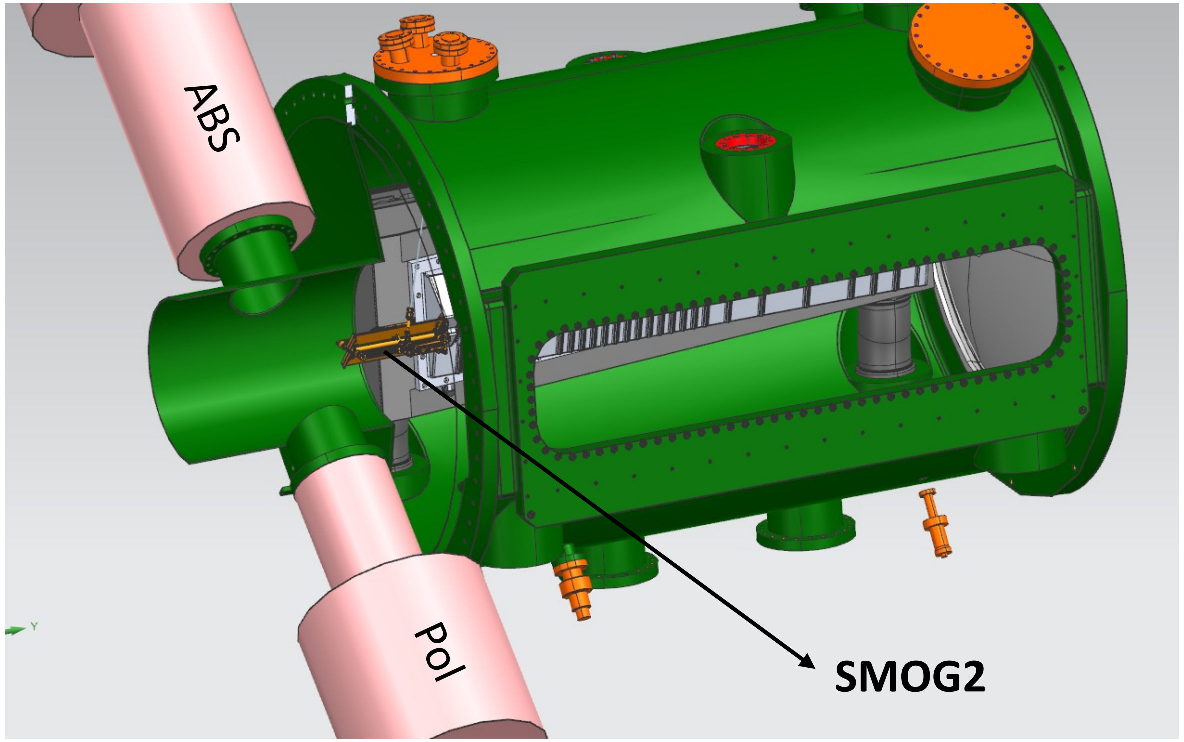


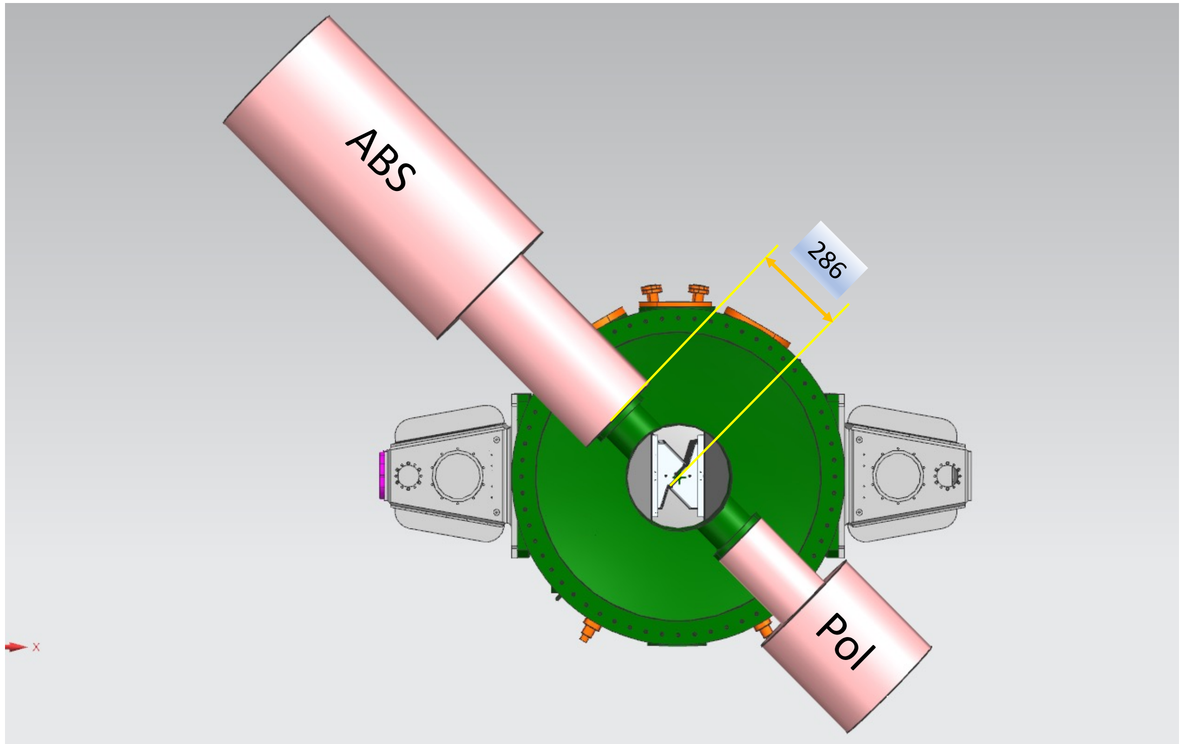
- **Compact superconductive dipole magnet for static transverse field to maintain polarization inside the ($B = 300\ mT$; $\Delta B/B \sim 10\%$)**
- **Need to modify main flange of VELO vessel (inward)**
- **No need for additional detectors!**
- **Possibility to switch from dipole magnet to solenoid to realize a Longitudinal polarized target**

The jet target option

Alternative solution with **jet target** also under evaluation:

- lower density ($\sim 10^{12}$ atoms$/cm^2$) → about a factor of 40 smaller
- higher polarization (up to 90%)
- lower systematics in P measurement (virtually close to 0)
- Compatible with SMOG2 setup





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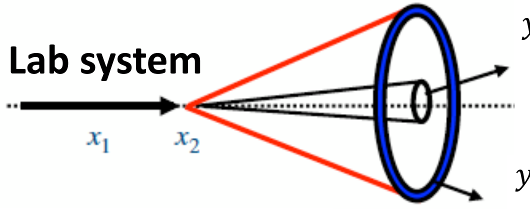

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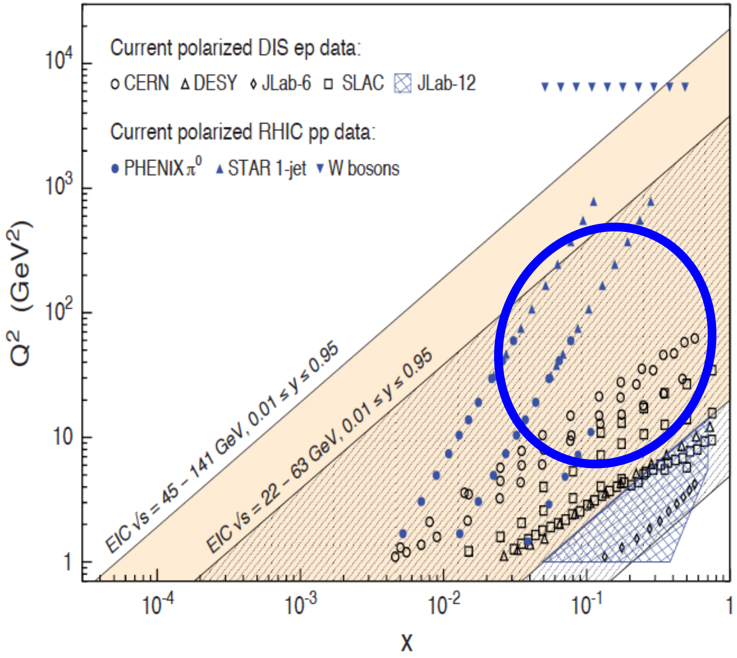

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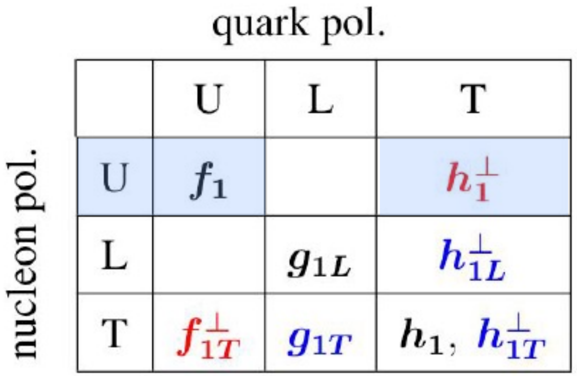
Quark TMDs

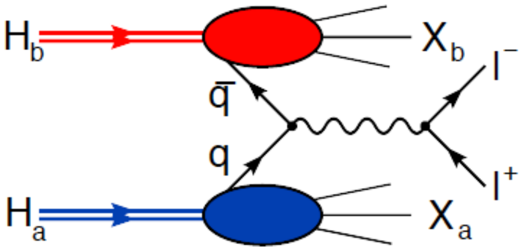


quark pol.

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

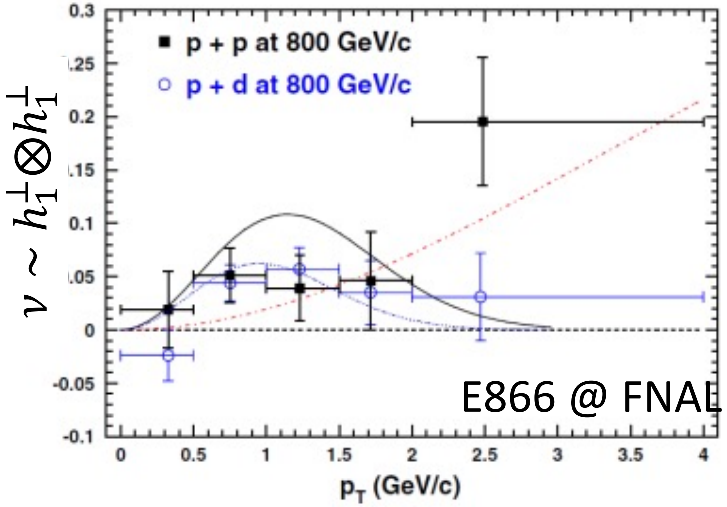


- Theoretically cleanest hard h-h scattering process
- LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$
- **dominant**: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$
- beam sea quarks probed at small x
- target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

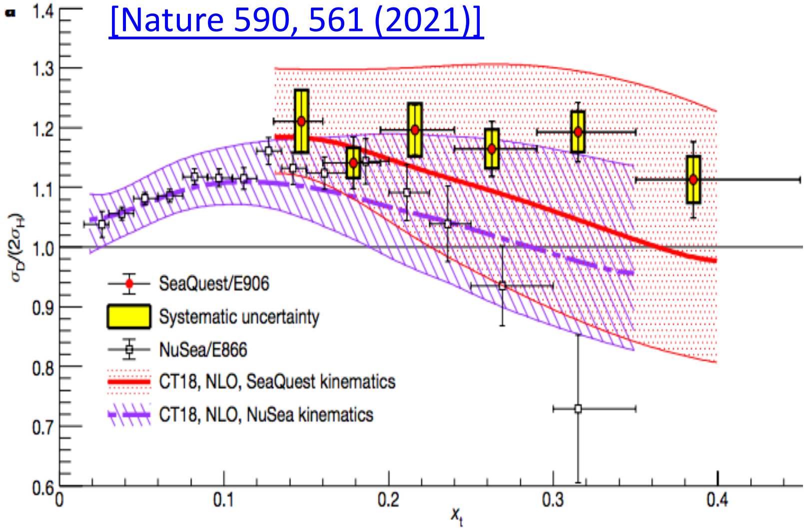
Sensitive to unpol. and BM TMDs for $q_T \ll M_{ll}$

(violation of Lam-Tung relation)

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



[PRL 102 2009 182001]

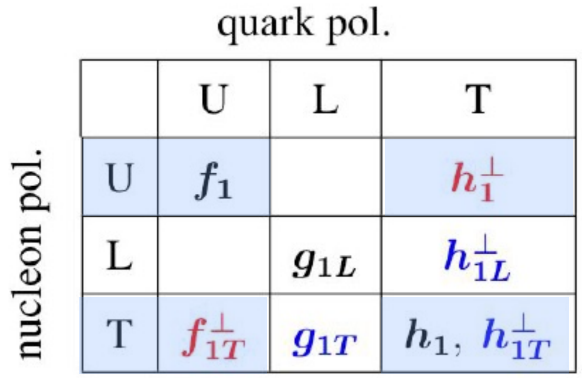


[Nature 590, 561 (2021)]

- 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!**

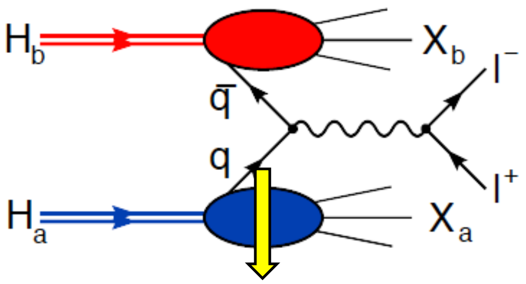
Quark TMDs

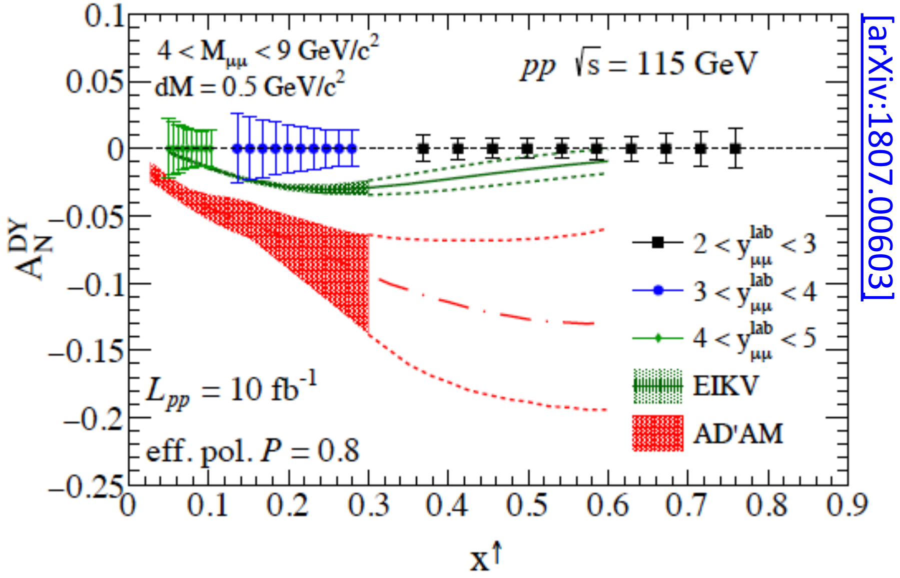


quark pol.

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

Transv. polarized Drell-Yan

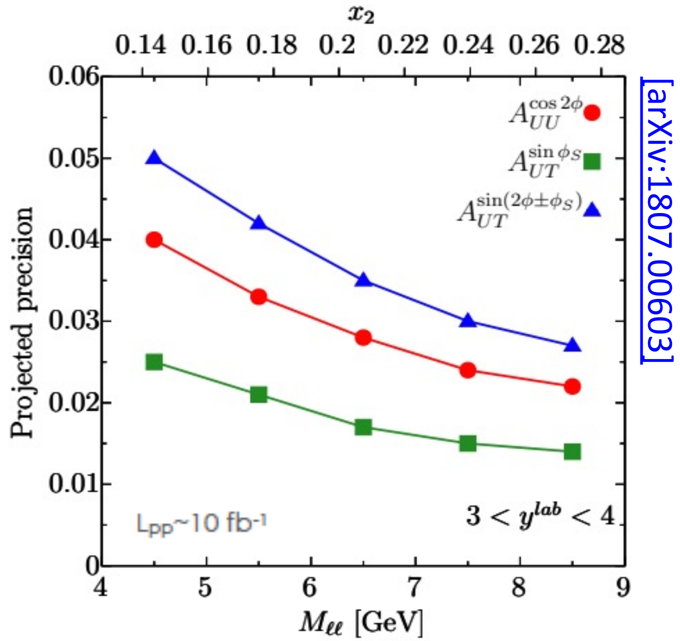




- **Sensitive to quark TMDs through TSSAs**

$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \Longrightarrow A_{UT}^{sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}, \quad A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}, \ldots$$

(ϕ: azimuthal orientation of lepton pair in dilepton CM)

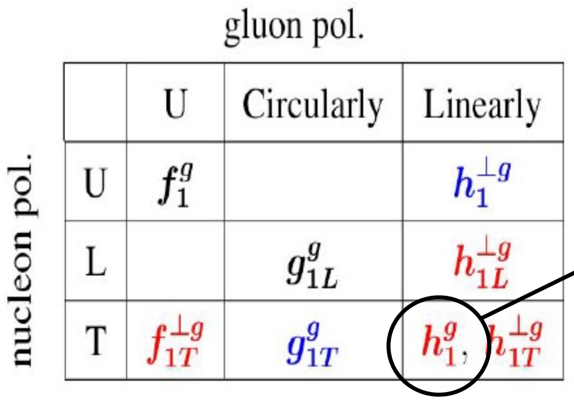


- Extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS

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

- Test flavour sensitivity using both H and D targets

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!**

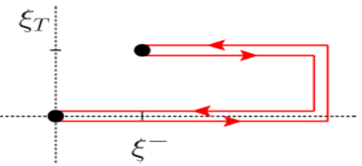
Similar naming/notation of quark TMDs, but there are important differences!

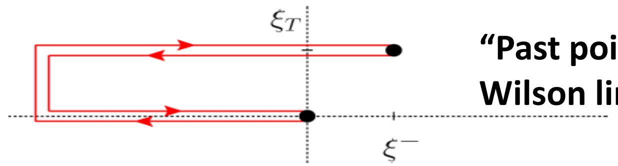
- the **linearity gTMD** (h_1^g) is completely unrelated to the quark transversity (h_1^q), and has no collinear counterpart
- **different naïve-time-reversal properties**

	T-even	T-odd
q	$\mathbf{h_1^q}$	$\mathbf{h_1^{\perp q}}$
g	$\mathbf{h_1^{\perp g}}$	$\mathbf{h_1^g}$

- Also the gTMD phenomenology is enriched by the **process dependence** originating by ISI/FSI encoded in the **gauge links**.
- **The gluon correlator depends on 2 path-dependent gauge links**, resulting in a more complex process dependence

"Future pointing" Wilson line ("+")



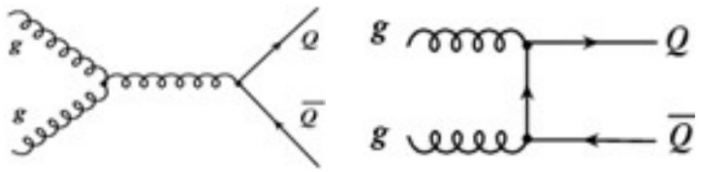


"Past pointing" Wilson line ("−")

- Depending on their combinations, **there are 2 independent versions of each gTMD** that can probed in different processes and can have different magnitude and width and different x and k_T dependencies!
- 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

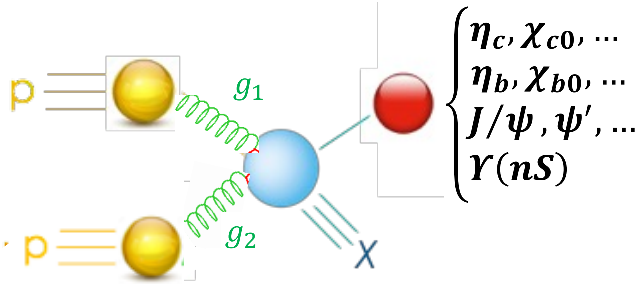
Probing the gluon TMDs

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



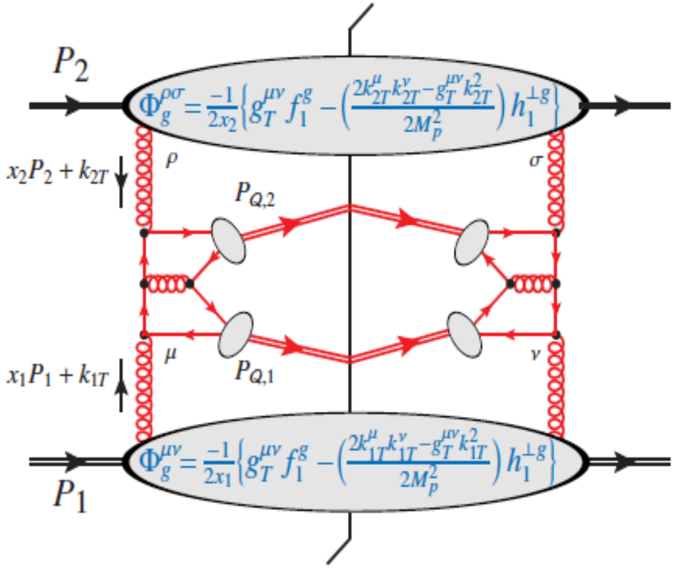
The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-quark observables**

- **Inclusive quarkonia production in (un)polarized pp interaction** $(pp^{(\uparrow)} \rightarrow [Q\bar{Q}]X)$ turns out to be an ideal observable to access gTMDs (assuming TMD factorization)



- TMD factorization requires $q_T(Q) \ll M_Q$. Can look at **associate quarkonia production**, where only the relative q_T needs to be small:

$$\text{E.g.:} \quad pp^{(\uparrow)} \rightarrow J/\psi + J/\psi + X$$



- Due to the larger masses this condition is more easily matched in the case of **bottomonium**, where TMD factorization can hold at larger q_T (although very challenging for experiments!)

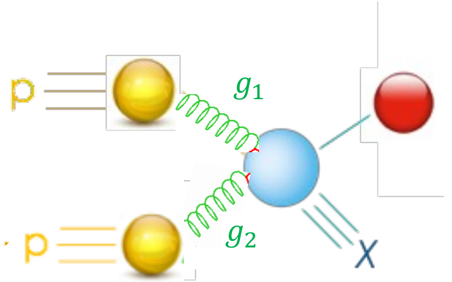
Probing the gluon TMDs: inclusive quarkonia-pair production

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

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

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

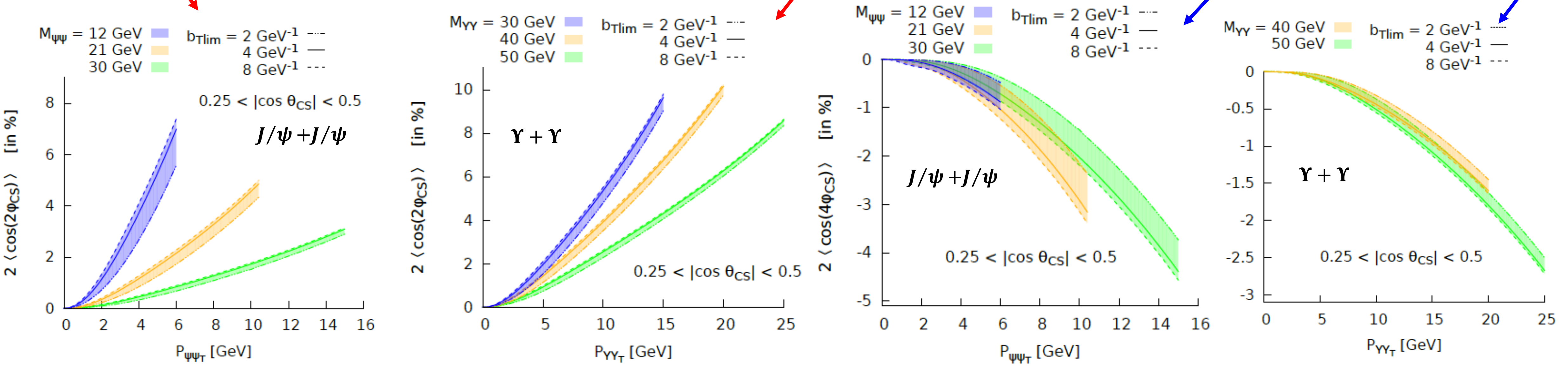
$$+\boxed{\Big(F_3(M_{QQ},\theta_{CS})\,\mathcal{C}\Big[w_3 f_1^g h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T}) + F_3'(M_{QQ},\theta_{CS})\,\mathcal{C}\Big[w_3' h_1^{\perp g} f_1^g\Big](x_{1,2},\boldsymbol{P}_{QQ_T})\Big)\cos 2\phi_{CS}}\ \boxed{+F_4(M_{QQ},\theta_{CS})\,\mathcal{C}\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T})\cos 4\phi_{CS}\Big\}}$$



$\left\{\begin{array}{l} J/\psi + J/\psi \\ \Upsilon + \Upsilon \\ \ldots \end{array}\right.$

gluon pol.

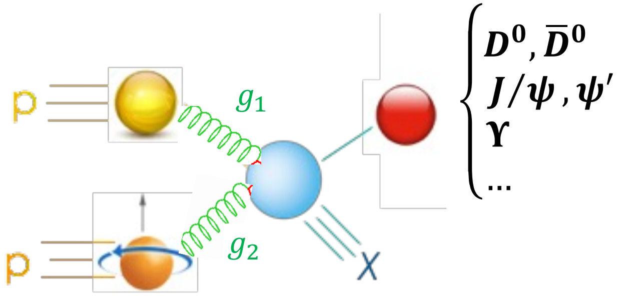
nucleon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$



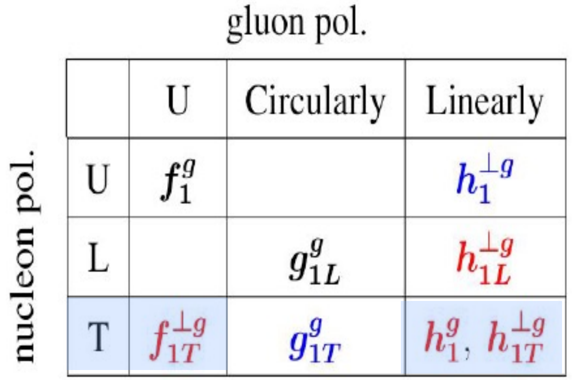
Predictions based on CSM + TMD evolution for $x_1 \sim x_2 \sim 10^{-3}$ at forward rapidity [EPJ C 80, 87 (2020)] ➡ **Azimuthal amplitudes ~ 5%!!**

Probing the gluon Sivers funct.

$$\Gamma_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{x}{2}\left\{ g_T^{\mu\nu}\,\frac{\epsilon_T^{\rho\sigma}\, p_{T\rho}\, S_{T\sigma}}{M_p}\boxed{f_{1T}^{\perp g}(x,\boldsymbol{p}_T^2)} + \dots \right\}$$



$$\begin{cases} D^0, \bar{D}^0 \\ J/\psi\,, \psi' \\ \Upsilon \\ \dots \end{cases}$$



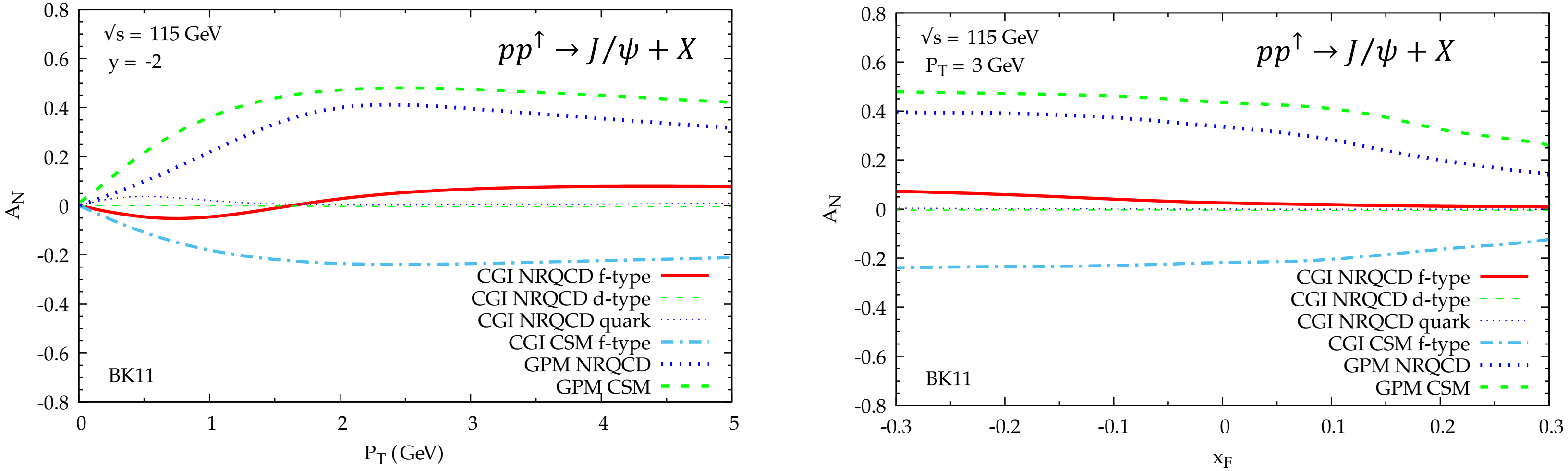
gluon pol.

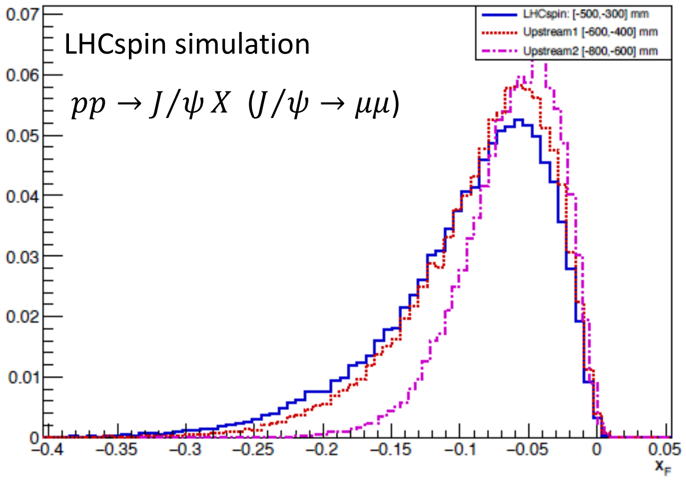
nucleon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

- Sheds light on spin-orbit correlations of unpol. gluons inside a transv. pol. proton
- sensitive to gluon OAM
- can be accessed through the measurement of the TSSAs in **inclusive heavy meson production**

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} \propto \left[f_{1T}^{\perp g}(x_a,k_{\perp a})\otimes f_g(x_b,k_{\perp b})\otimes d\sigma_{gg\to Q\bar{Q}g}\right]\sin\phi_S + \cdots$$

Predictions for pol. FT meas. at LHC (LHCspin-like) [Phys. Rev. D 102, 094011 (2020)]





A synergic attack to gTMDs

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

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

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\mathrm{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	🟦 √	×	🟥 √	🟦 √	🟦 √
$h_1^{\perp\,g\,[+,-]}$ (DP)	×	🟦 √	×	×	×

	DY	SIDIS	$p^\uparrow\,A \to h\,X$	$p^\uparrow A \to \gamma^{(*)}\,\mathrm{jet}\,X$	$p^\uparrow p \to \gamma\,\gamma\,X$ $p^\uparrow p \to J/\psi\,\gamma\,X$ $p^\uparrow p \to J/\psi\,J/\psi\,X$	$e\,p^\uparrow \to e'\,Q\,\overline{Q}\,X$ $e\,p^\uparrow \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[+,+]}$ (WW)	×	×	×	×	🟨 √	🟥 √
$f_{1T}^{\perp\,g\,[+,-]}$ (DP)	√	√	🟨 √	🟨 √	×	×

🟥 Can be measured at the EIC

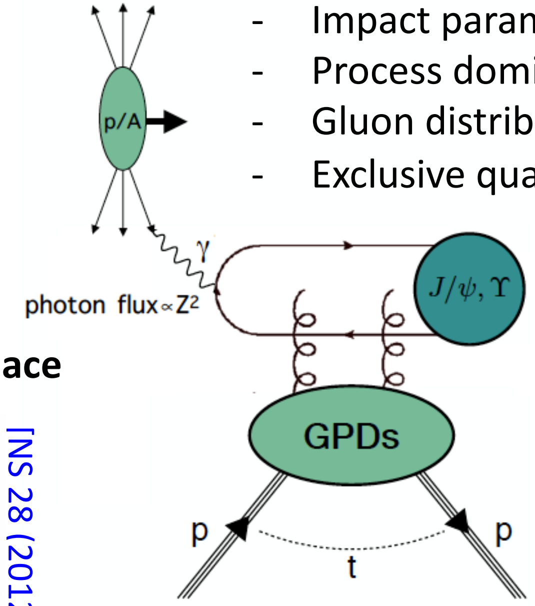
🟦 Can be measured at RHIC & LHC (including LHCb+SMOG2/LHCspin)

🟨 Can be measured at RHIC and LHCb+LHCspin

UPC and gGPDs

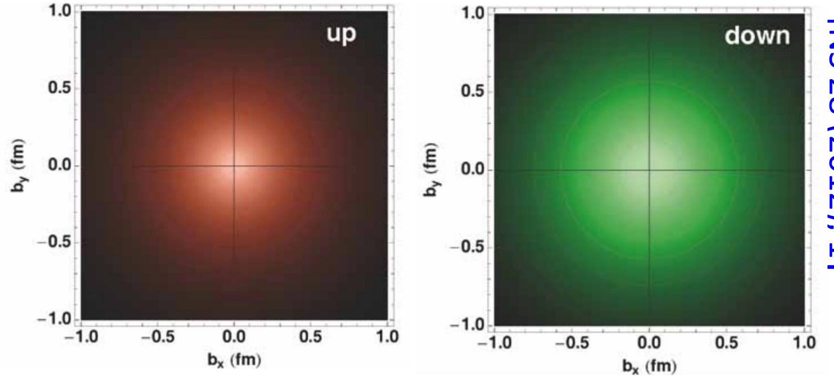
GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	H_T, $\tilde{H}_T$

Can be accessed at LHC in **Ultra-Peripheral collisions (UPC)**



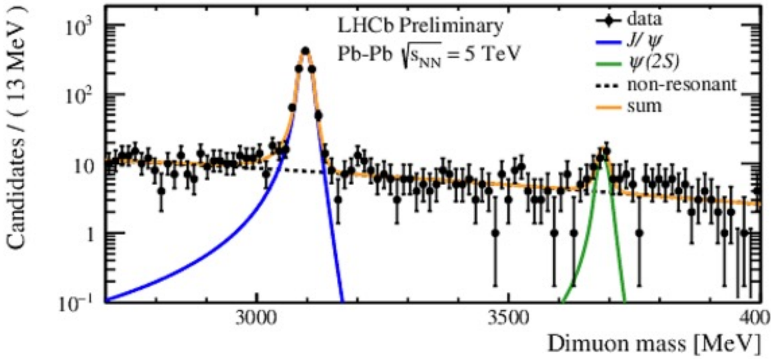
- Impact parameter larger than sum of radii
- Process dominated by EM interaction
- Gluon distributions probed by pomeron exchange
- Exclusive quarkonia prod. sensitive to gluon GPDs [PRD 85 (2012), 051502]

3D maps of parton densities in coordinate space

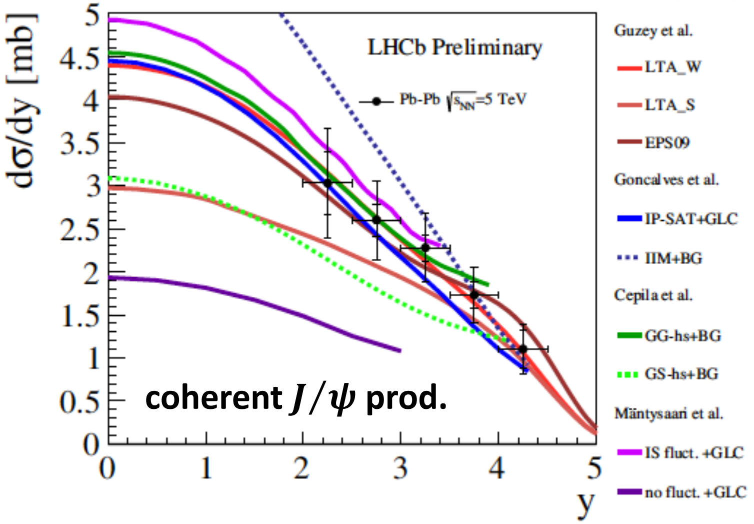


[NS 28 (2012), 1]

First results from LHCb in PbPb UPC



[NPA 982 (2019) 247]



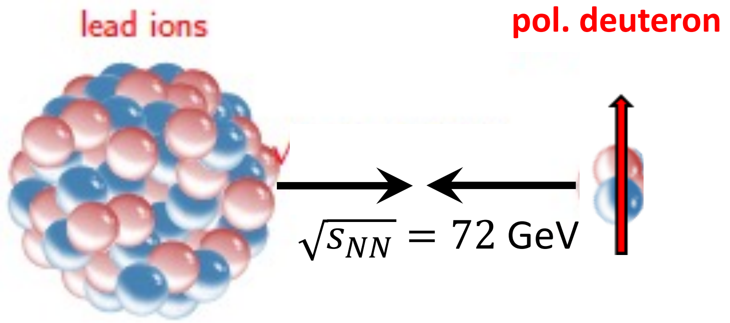
coherent J/ψ prod.

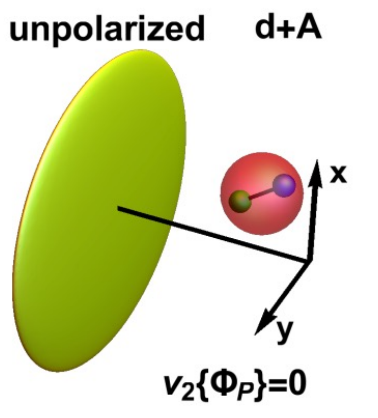
LHCspin could allow to access the GPD E^g (a key ingredient of the Ji sum rule)

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

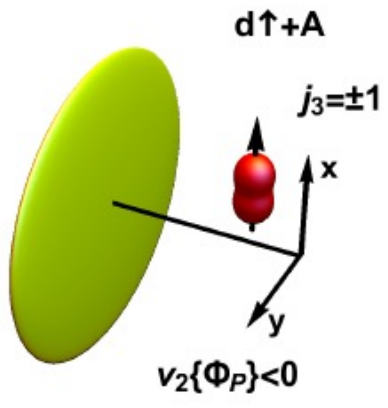
Merging spin physics with heavy-ion physics

- probe collective phenomena in heavy-light systems through **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**).

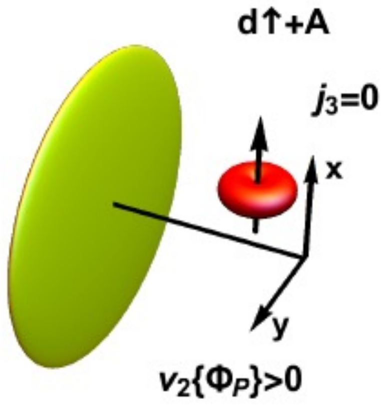




Unpol. deuterons: the **fireball is azimuthally symmetric** → $v_2 \approx 0$.

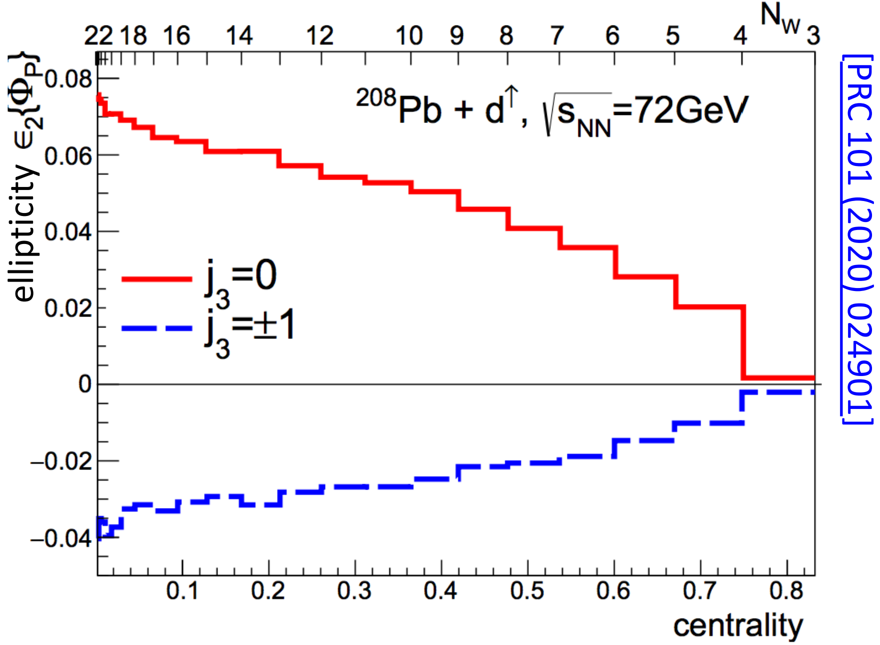


$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$



$j_3 = 0$ → **oblate fireball** corresponds to $v_2 > 0$

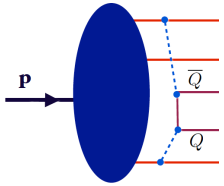
Predictions for LHC FT kinematics

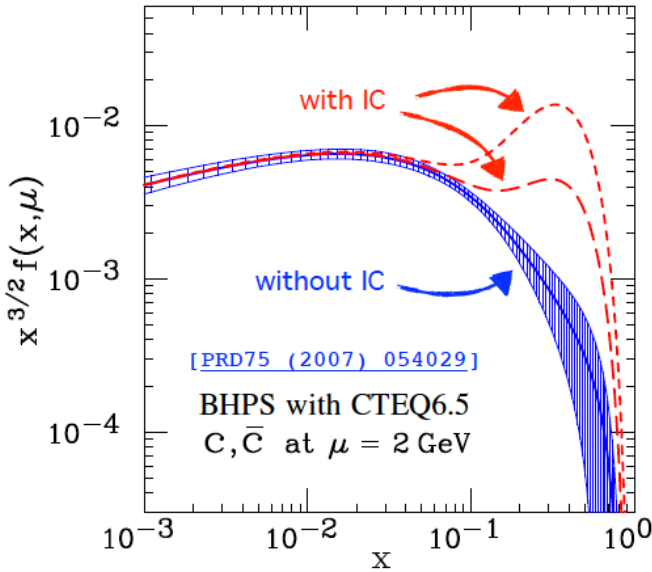


[PRC 101 (2020) 024901]

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



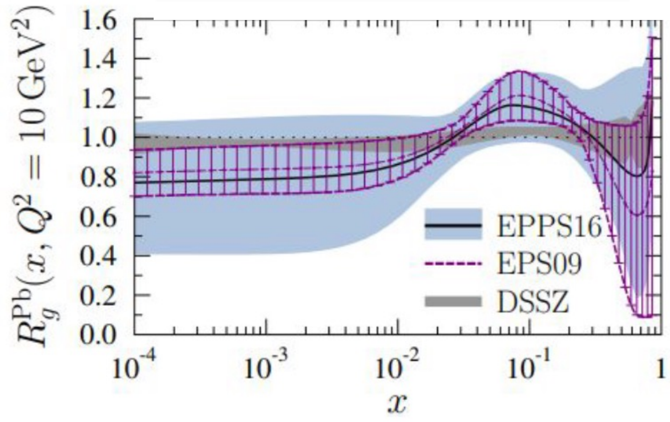


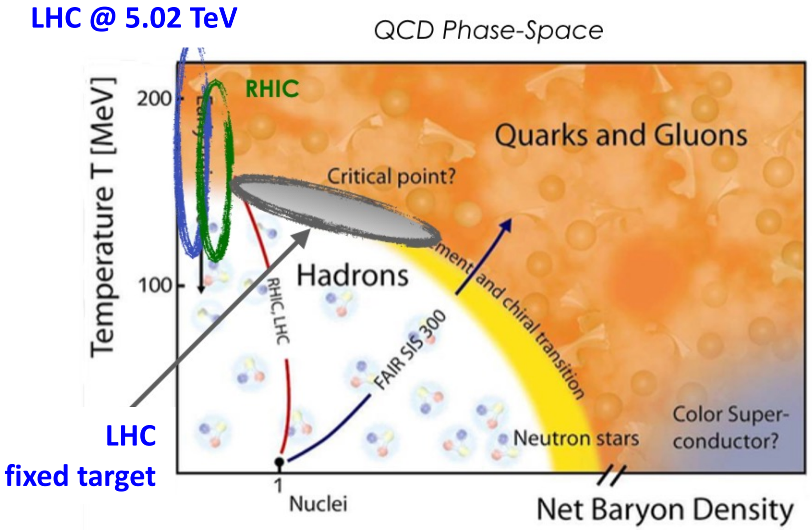
[PRD 75 (2007) 054029]

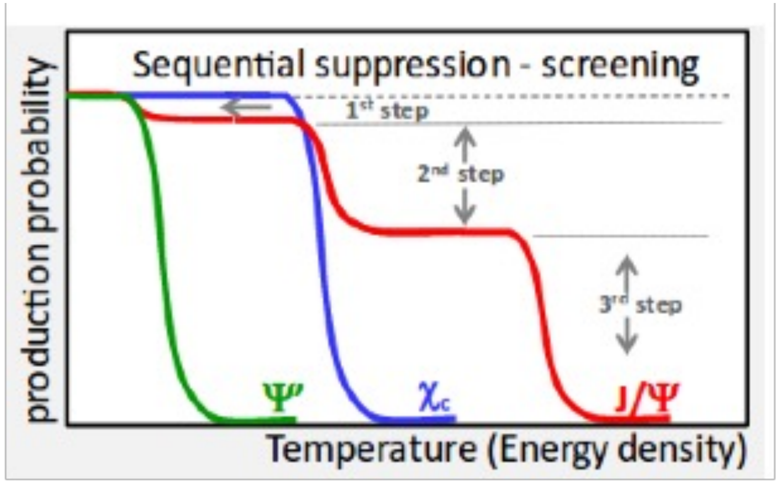
- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium
  - reactions of interest for cosmic-ray physics and DM searches

- **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**)

Eur. Phys. J. C 77, 163 (2017)







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