SPIN2021
Matsue, Japan
24th International Spin Symposium
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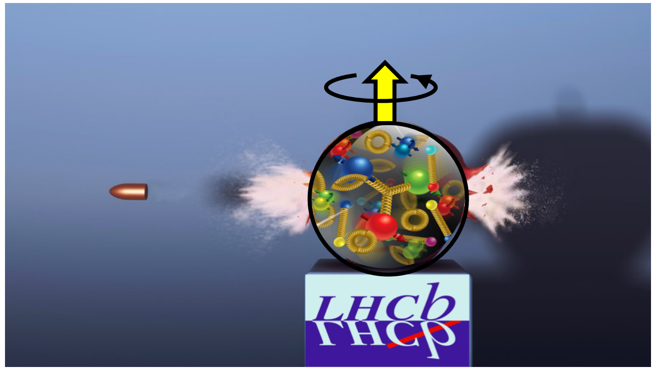
# Polarized target experiments at LHC

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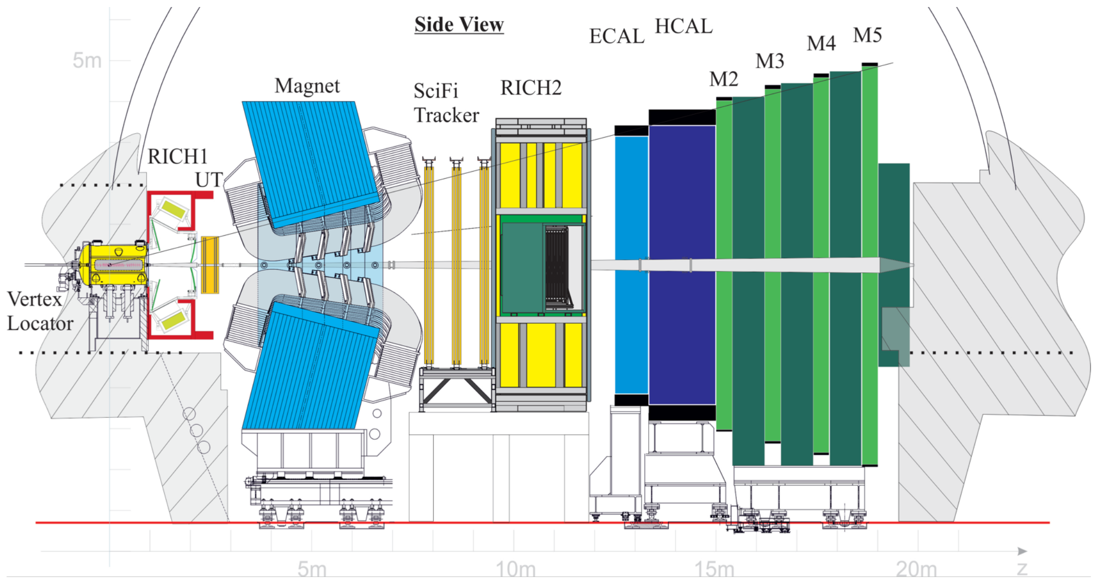
**Disclaimer:** the title of the talk ("Polarized target experiments at LHC") suggests the existence of several polarized-target experiments/projects at the LHC. However, at present, there is only one such proposal (**LHCspin**), to be operated in conjunction with the LHCb experiment.

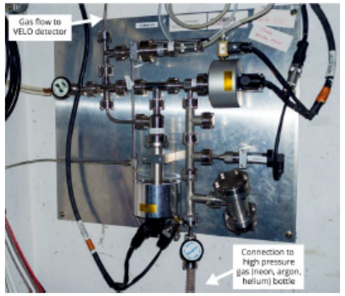
# The LHCb detector

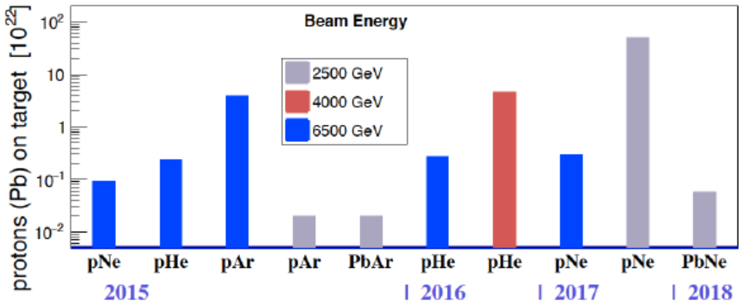
- LHCb is a **general-purpose single-arm spectrometer**, fully instrumented in $2 < \eta < 5$ and optimised for detection of charmed and beauty hadrons
[JINST 3 (2008) S08005] [IJMPA 30 (2015)1530022]




- **Excellent particle identification and momentum resolution:** $\sigma_p/p \leq 1.0\ \%$ ($p \in [2,200]$ GeV)
- **Major hardware upgrade to cope with the factor of 5 increase in lumi foreseen for the Run 3 (Feb. 2022)**

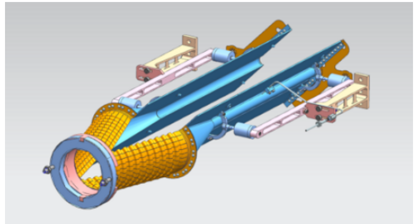
- Since 2015 can also be operated as a **fixed-target experiment** with the **SMOG system**

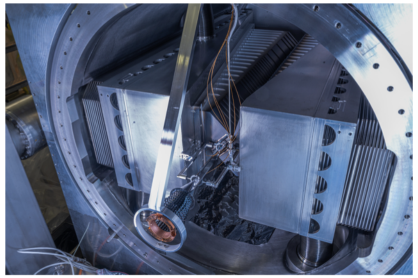



- **Unique opportunity to study pA/AA collisions on various targets exploiting the high-energy, high-intensity LHC beams!**

- **SMOG upgrade (SMOG2)**: a 20 cm long **storage cell** for the target gas has been **installed in 2020** upstream of the VELO





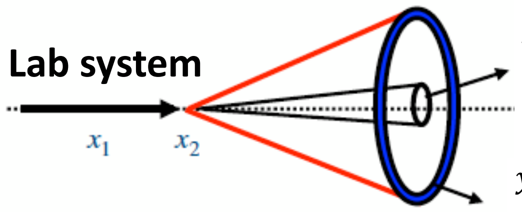
  - more gas species: $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
  - target density increased by large factor
  - Precise density (lumi) determination
  - Negligible impact on LHC beam lifetime and LHCb performance

# Kinematic conditions for fixed-target collisions at LHC

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

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

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



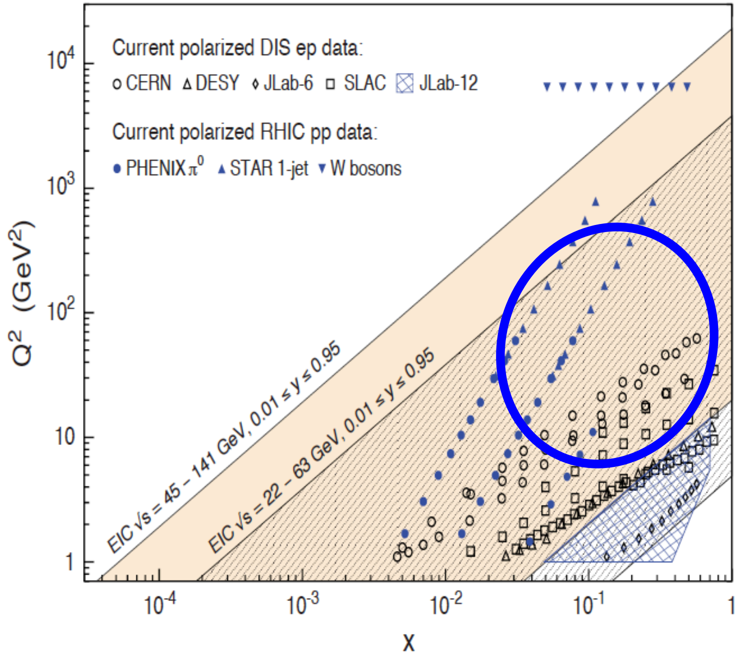

$y = 5\ (\theta \sim 1^\circ)$
$\implies y_{CM} \approx 0$

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

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

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

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

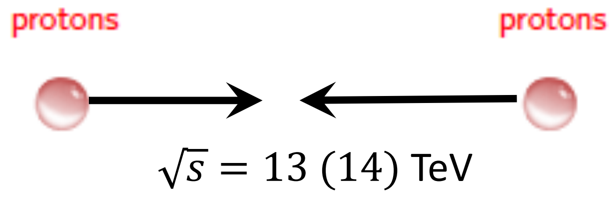


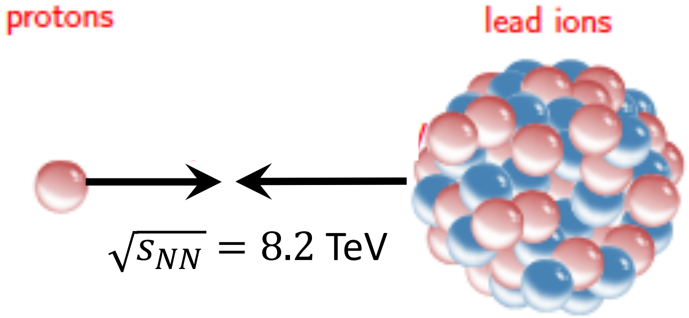

**Complementarity is the key!**

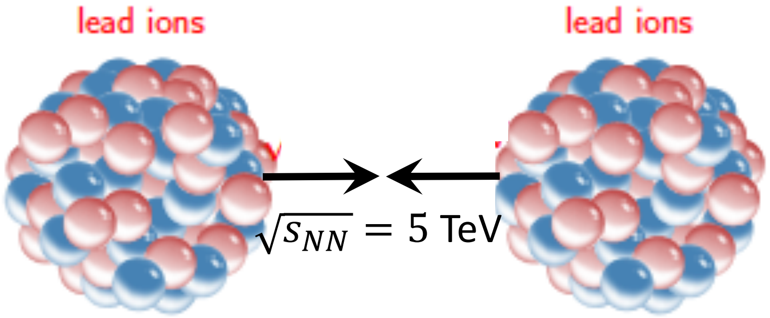
- Partial overlap with RHIC kinematics
- 12 GeV Jlab probes large-$x$ at small $Q^2$
- EIC will mainly focus at small-$x$ and large $Q^2$

# Types of collisions at LHCb

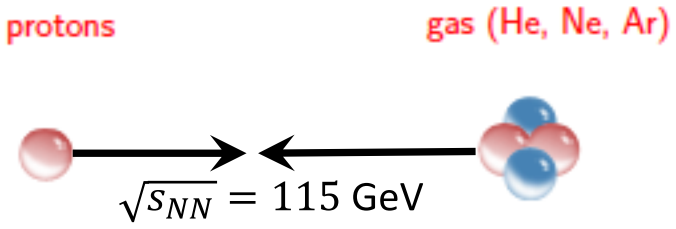
## Collider mode

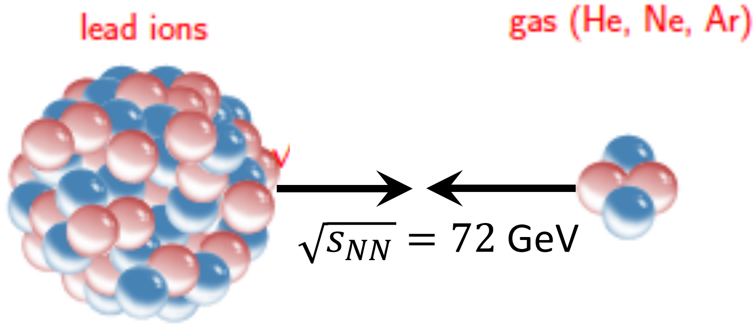


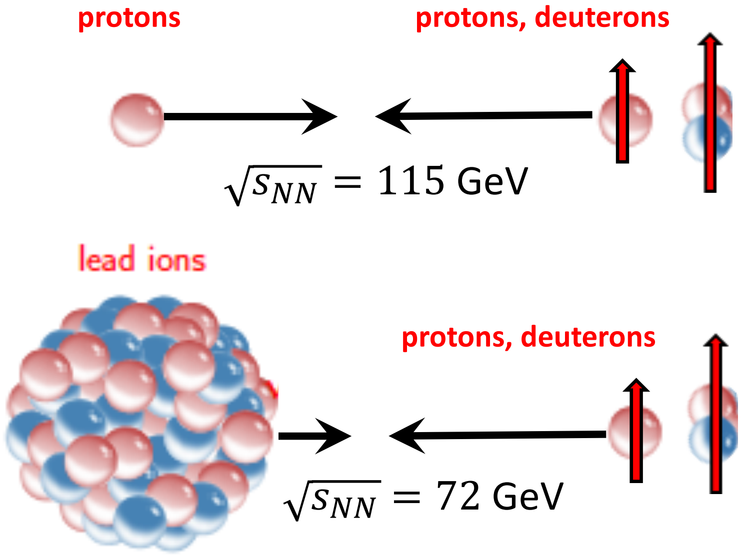




## Fixed-target mode (SMOG/SMOG2)




The SMOG program sets the basis for the development of a future **polarized gas target for LHCb:**




LHC spin

# The LHCspin project

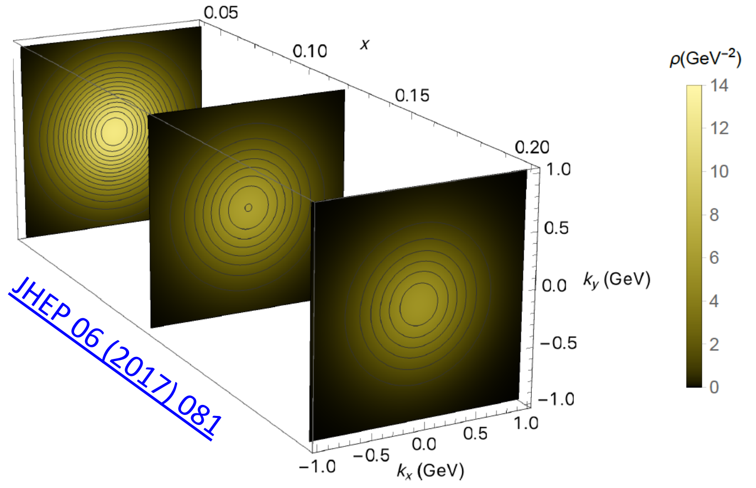
The **LHCspin** project aims to bring spin physics at the LHC through the implementation of a new-generation compact HERMES-like **polarized gaseous fixed target** in the **LHCb** spectrometer.

## Motivations and points of strenght

- ✓ **pretty unique kinematic conditions** (backward CM region, poorly explored large-$x$ region at intermediate $Q^2$)
- ✓ **exploit the world most powerfull particle accelerator and a state-of-the-art particle detector** (upgraded LHCb)
- ✓ **polarized gas target technology well established** (HERMES @ DESY, ANKE @ COSY with high performance)
- ✓ **marginal impact on LHC beam lifetime and LHCb mainstream physics program and performances**
- ✓ **can run in parallel with collider mode** (well displaced interaction regions)
- ✓ **can benefit from both protons and heavy-ion beams**
- ✓ **allows also injection of non-polarized gases:** $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- ✓ **broad and ambitious physics program** (next slides)

# The physics goals of LHCspin

- Multi-dimensional nucleon structure in a poorly explored kinematic domain
- Measure experimental observables sensitive to both **quarks and gluons TMDs**
- Make us of new probes (charmed and beauty mesons)
- Complement present and future SIDIS results
- Test non-trivial process dependence of quarks and (especially) gluons TMDs
- Extend our understanding of the strong force in the non-perturbative regime




JHEP 06 (2017) 081

quark pol.

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

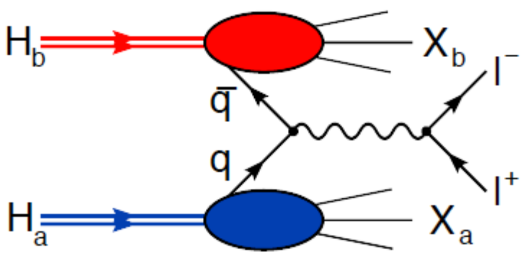
- **Significant experimental progress in the last 15 years!**
- **main results from SIDIS** (HERMES, COMPASS, JLAB, → EIC)
- **Drell-Yan** in h-h collisions offers a complementary approach (COMPASS, RHIC)
- Several extractions already available from global analyses
- Now entering the precision era

# 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**

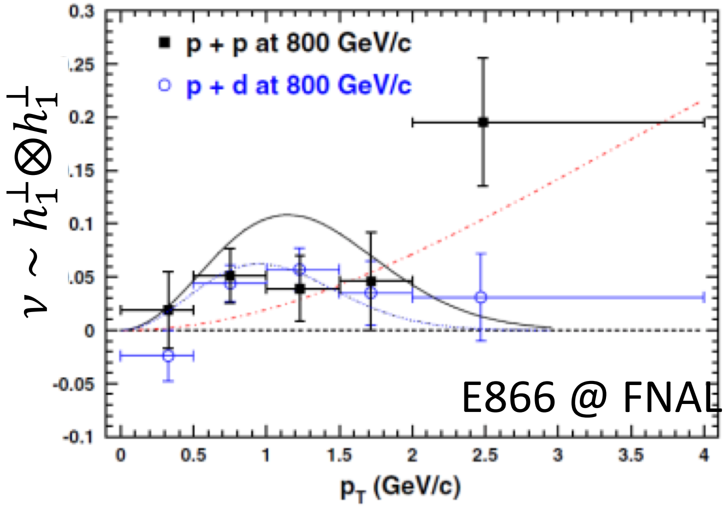



- Theoretically cleanest hard h-h scattering process
- LHCb has excellent $\mu$-ID & reconstruction for $\mu^+\mu^-$
- **dominant**: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$
- beam sea quarks probed at small $x$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

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

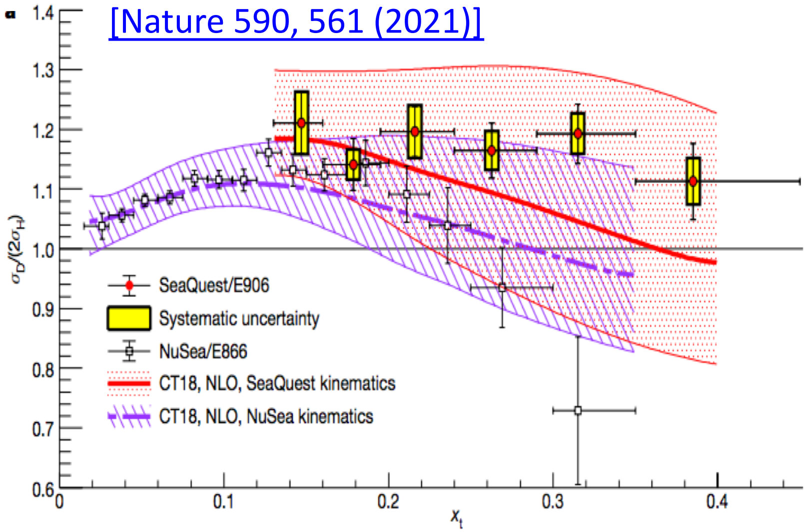
(violation of Lam-Tung relation)

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




[PRL 102 182001]

[Nature 590, 561 (2021)]



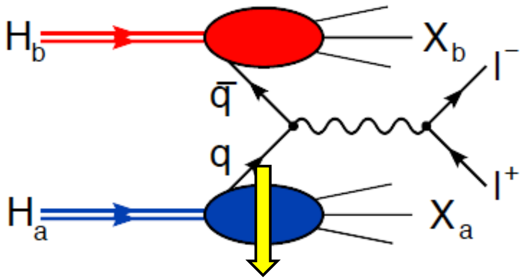

- Lattice QCD: $\bar{s}(x) \neq s(x)$ [arXiv:1809.04975]
- **proton sea more complex than originally thought!**
- **intrinsic heavy quarks**?
- Still a lot to be understood

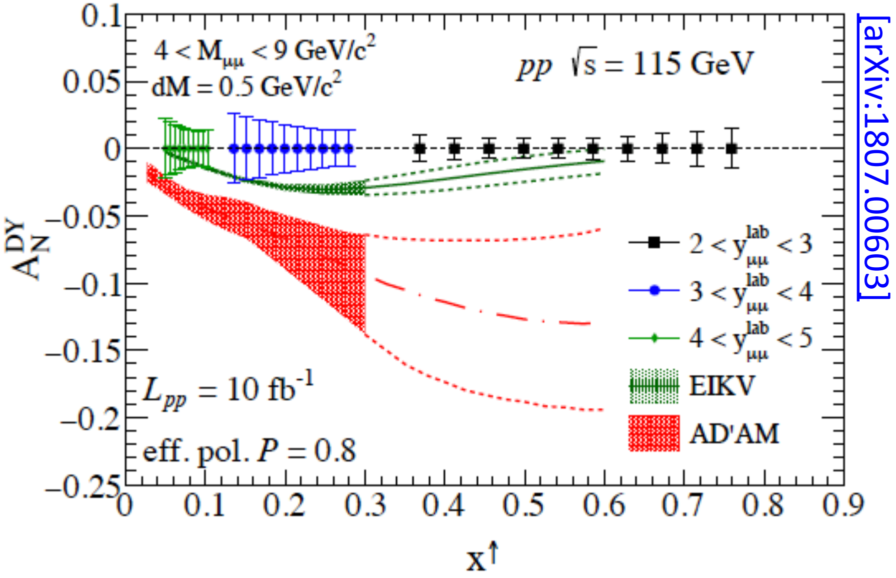
- H & D targets allow to study the **antiquark content of the nucleon**
- SeaQuest (E906): $\bar{d}(x) > \bar{u}(x) \implies$ **sea is not flavour symmetric!**

# Quark TMDs

| nucleon pol. \ quark 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**

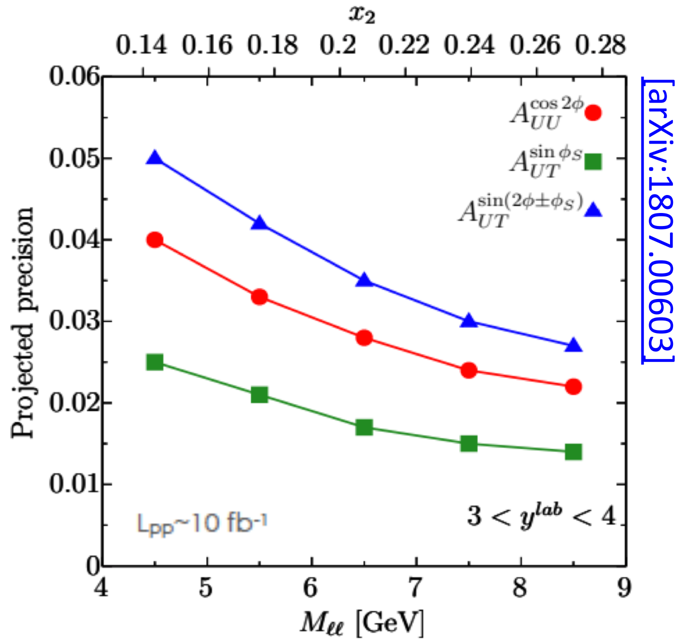
$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \Longrightarrow \quad A_{UT}^{\sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}, \quad A_{UT}^{\sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes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

($\phi$: 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

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

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

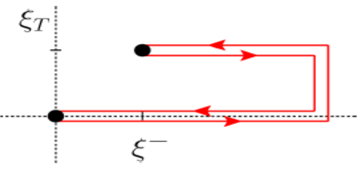
**Same naming/notation of quark TMDs, but there are important differences!**

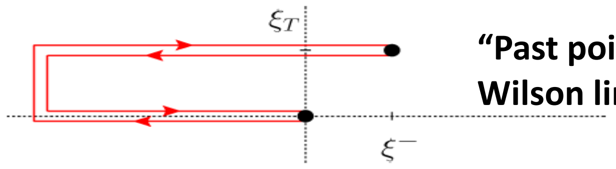
- the **linearity gTMD** ($h_1^g$) is completely unrelated to the quark transversity ($h_1^q$), and has no collinear counterpart
- **different naïve-time-reversal properties**

| | 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 ("+")**



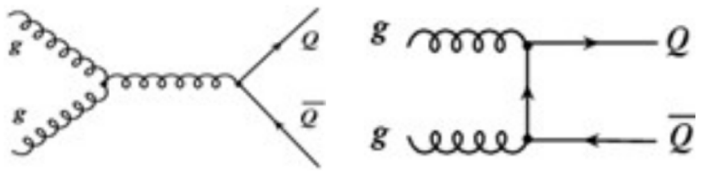




**"Past pointing" Wilson line ("−")**

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

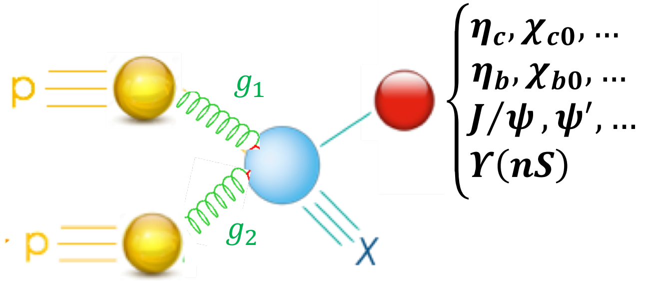
# Probing the gTMDs

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**

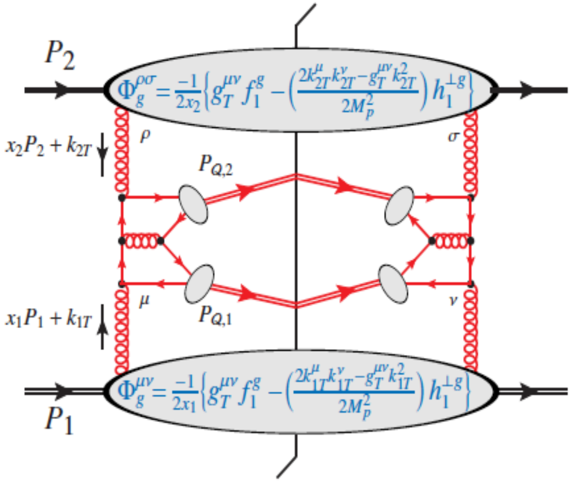
- **Inclusive quarkonia production in (un)polarized pp interaction** $(pp^{(\uparrow)} \rightarrow [Q\bar{Q}]X)$ turns out to be an ideal observable to access gTMDs (assuming TMD factorization)




- 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 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!)




$pp \rightarrow J/\psi J/\psi X$

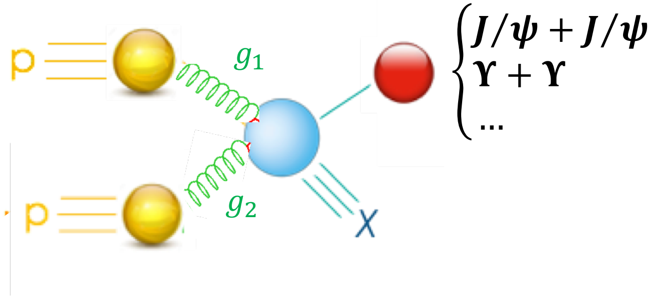
# Probing the gTMDs

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

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

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

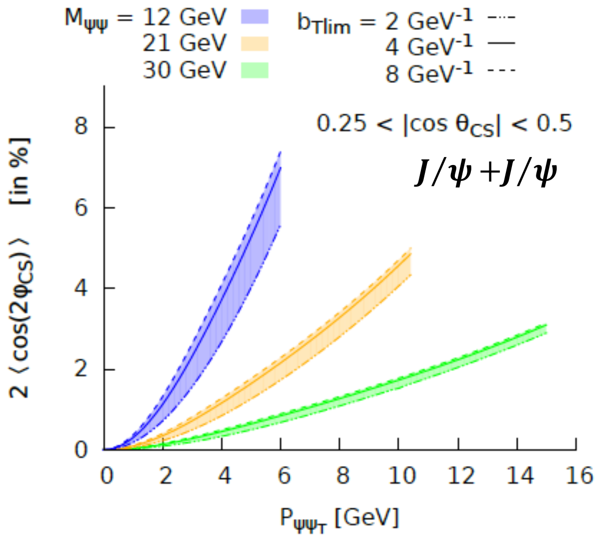
$$+\Big(F_3(M_{QQ},\theta_{CS})\,\mathcal{C}\Big[w_3 f_1^g h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T}) + F_3'(M_{QQ},\theta_{CS})\,\mathcal{C}\Big[w_3' h_1^{\perp g} f_1^g\Big](x_{1,2},\boldsymbol{P}_{QQ_T})\Big)\cos 2\phi_{CS} + F_4(M_{QQ},\theta_{CS})\,\mathcal{C}\Big[w_4 h_1^{\perp g} h_1^{\perp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



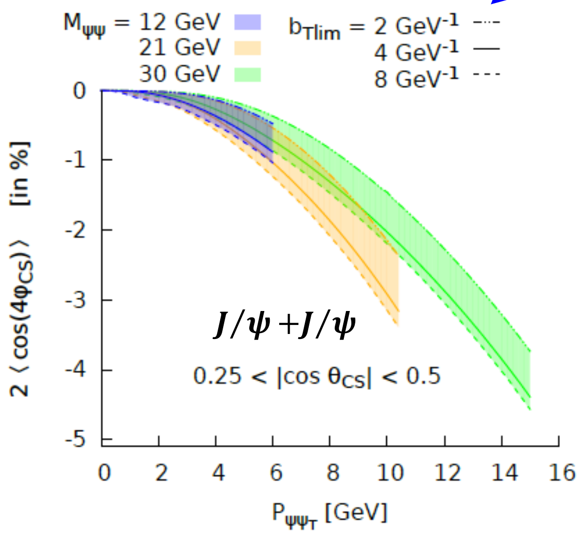

gluon pol.

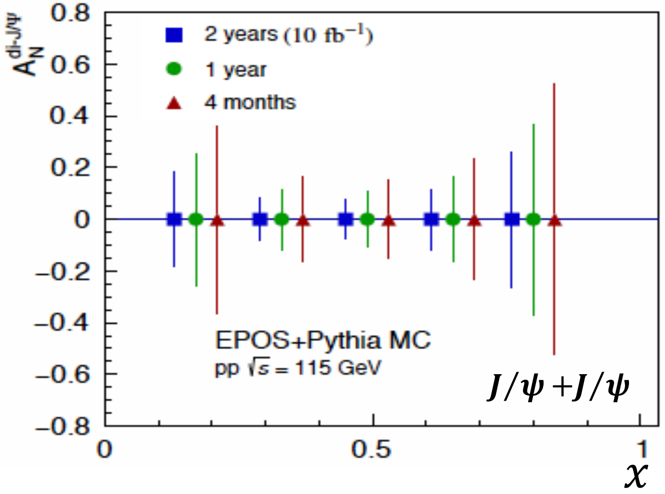
| nucleon pol. | U | Circularly | Linearly |
|---|---|---|---|
| U | $f_1^g$ | | $h_1^{\perp g}$ |
| L | | $g_{1L}^g$ | $h_{1L}^{\perp g}$ |
| T | $f_{1T}^{\perp g}$ | $g_{1T}^g$ | $h_1^g,\ h_{1T}^{\perp g}$ |

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



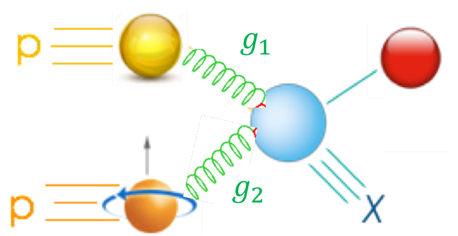

**Azimuthal amplitudes $\sim 5\%$!**



# Probing the gluon Sivers funct.

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



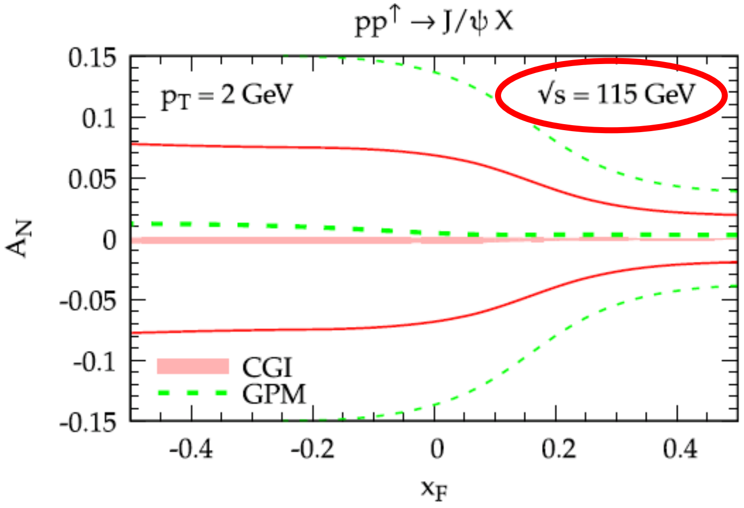

$\begin{cases} D^0, \bar{D}^0 \\ J/\psi, \psi' \\ \Upsilon \\ \ldots \end{cases}$

gluon pol.

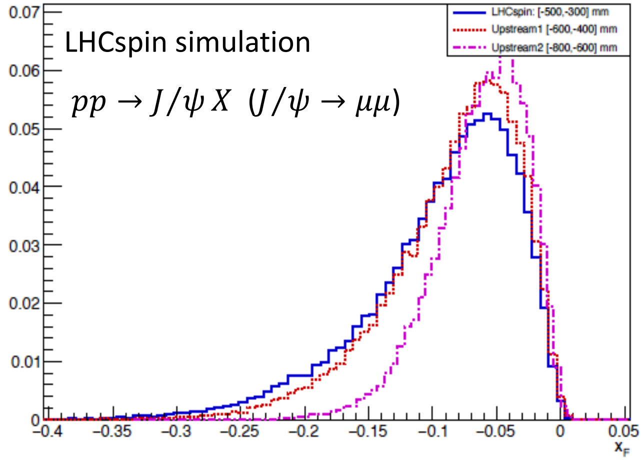
| nucleon pol. | U | Circularly | Linearly |
|---|---|---|---|
| U | $f_1^g$ | | $h_1^{\perp g}$ |
| L | | $g_{1L}^g$ | $h_{1L}^{\perp g}$ |
| T | $f_{1T}^{\perp g}$ | $g_{1T}^g$ | $h_1^g$, $h_{1T}^{\perp g}$ |

- Sheds light on spin-orbit correlations of unpol. gluons inside a transv. pol. proton
- sensitive to color exchange among IS and FS and gluon OAM
- expected to be small (quasi-saturation of Burkardt sum rule by $f_{1T}^{\perp q}$ and QCD predictions in large-$N_c$ limit)
- can be accessed through the Fourier decomposition of the TSSAs for **inclusive heavy meson production**

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




- **Predictions for pol. FT meas. at LHC (LHCspin-like)**
- [PRD 99, 036013 (2019)]
- $\boldsymbol{pp^\uparrow \to J/\psi + X}$
- **based on GPM & CGI-GPM**
- **Expected amplitudes could reach 5-10% in the $\boldsymbol{x_F < 0}$ region**



# A synergic attack to gTMDs

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

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

| | $pp \to \gamma\,\gamma\,X$ | $pA \to \gamma^*\,\text{jet}\,X$ | $e\,p \to e'\,Q\,\overline{Q}\,X$<br>$e\,p \to e'\,j_1\,j_2\,X$ | $pp \to \eta_{c,b}\,X$<br>$pp \to H\,X$ | $pp \to J/\psi\,\gamma\,X$<br>$pp \to \Upsilon\,\gamma\,X$ |
|---|---|---|---|---|---|
| $h_1^{\perp\,g\,[+,+]}$ (WW) | $\surd$ | $\times$ | $\surd$ | $\surd$ | $\surd$ |
| $h_1^{\perp\,g\,[+,-]}$ (DP) | $\times$ | $\surd$ | $\times$ | $\times$ | $\times$ |

| | DY | SIDIS | $p^\uparrow\,A \to h\,X$ | $p^\uparrow A \to \gamma^{(*)}\,\text{jet}\,X$ | $p^\uparrow p \to \gamma\,\gamma\,X$<br>$p^\uparrow p \to J/\psi\,\gamma\,X$<br>$p^\uparrow p \to J/\psi\,J/\psi\,X$ | $e\,p^\uparrow \to e'\,Q\,\overline{Q}\,X$<br>$e\,p^\uparrow \to e'\,j_1\,j_2\,X$ |
|---|---|---|---|---|---|---|
| $f_{1T}^{\perp\,g\,[+,+]}$ (WW) | $\times$ | $\times$ | $\times$ | $\times$ | $\surd$ | $\surd$ |
| $f_{1T}^{\perp\,g\,[+,-]}$ (DP) | $\surd$ | $\surd$ | $\surd$ | $\surd$ | $\times$ | $\times$ |

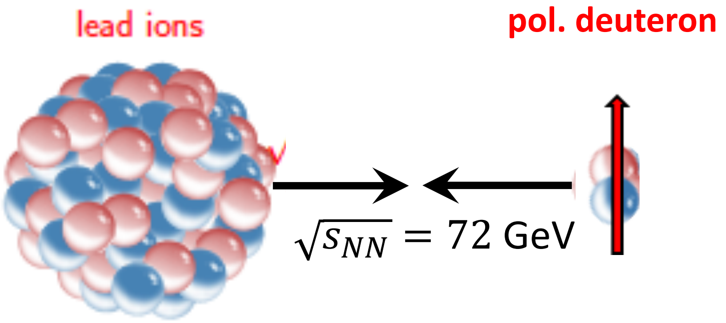
Can be measured at the EIC

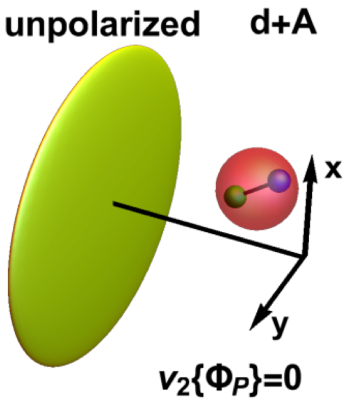
Can be measured at RHIC & LHC (including LHCb+SMOG2/LHCspin)

Can be measured at RHIC and LHCb+LHCspin

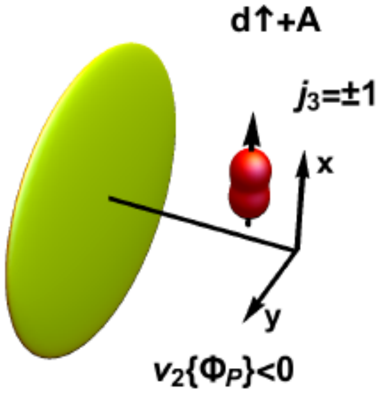
# Merging spin physics with heavy-ion physics

- 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**).

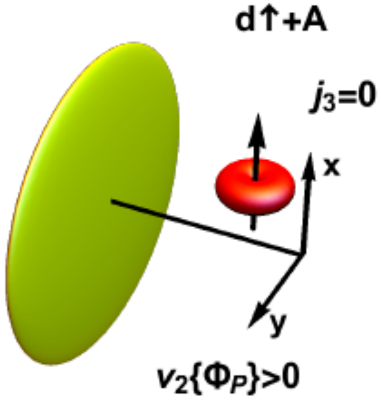



Unpol. deuterons: the **fireball is azimuthally symmetric** and $v_2 \approx 0$.

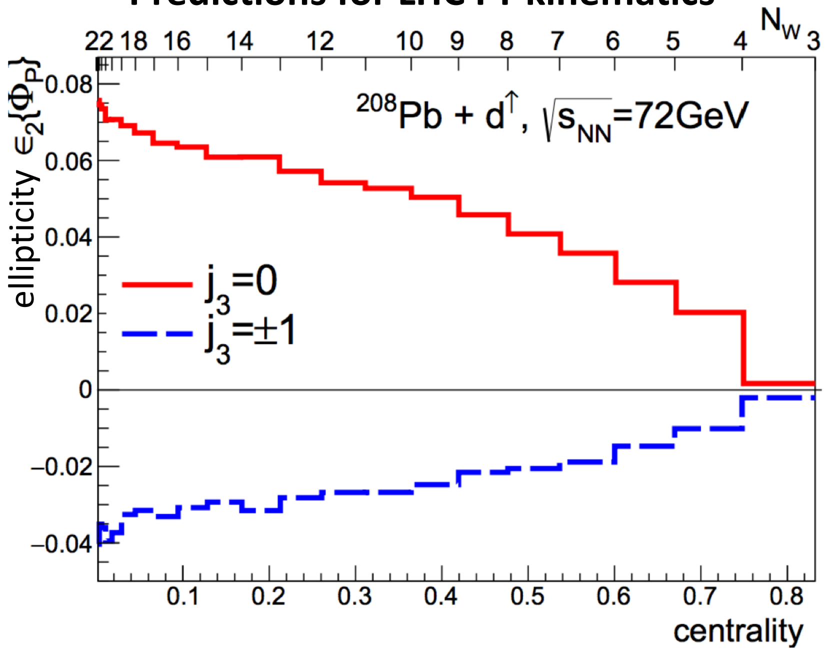



$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$




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

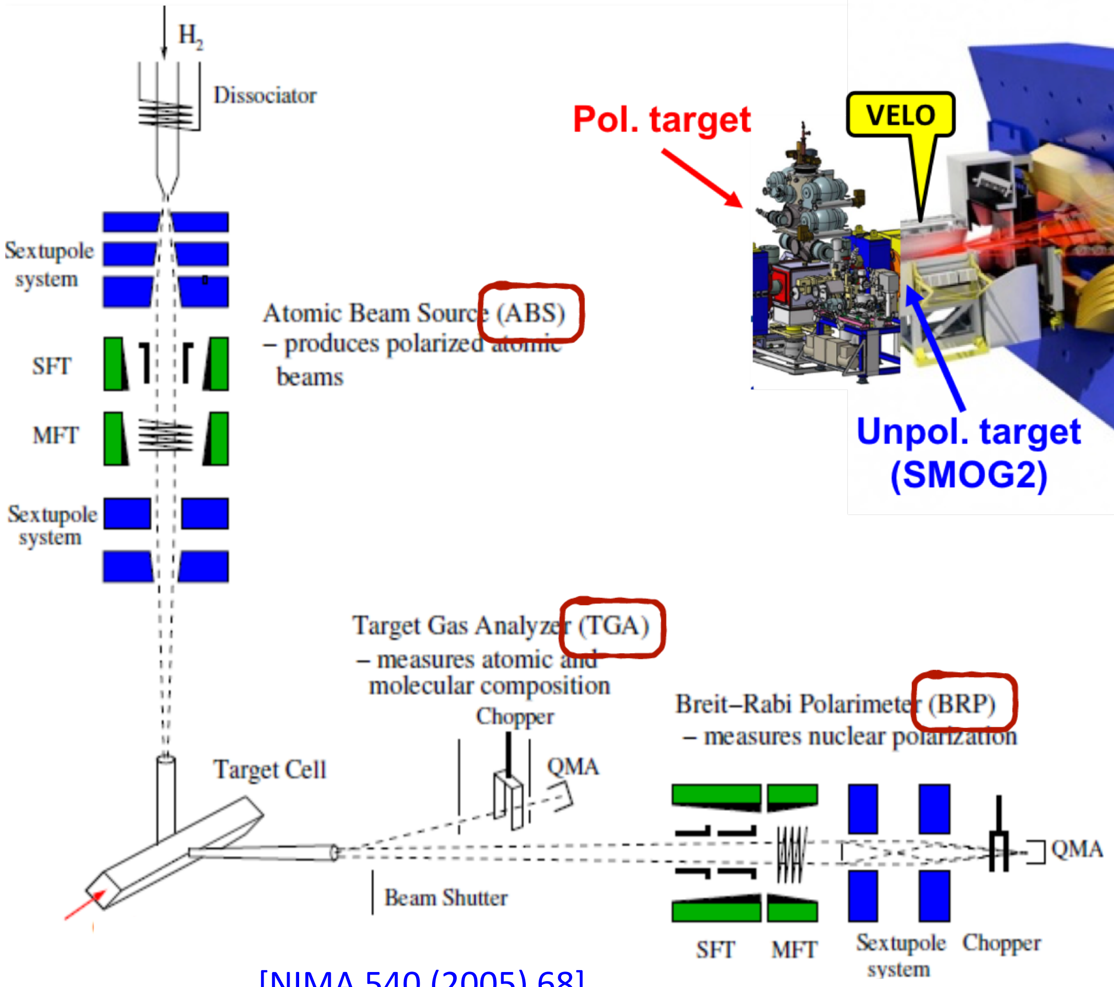
**Predictions for LHC FT kinematics**



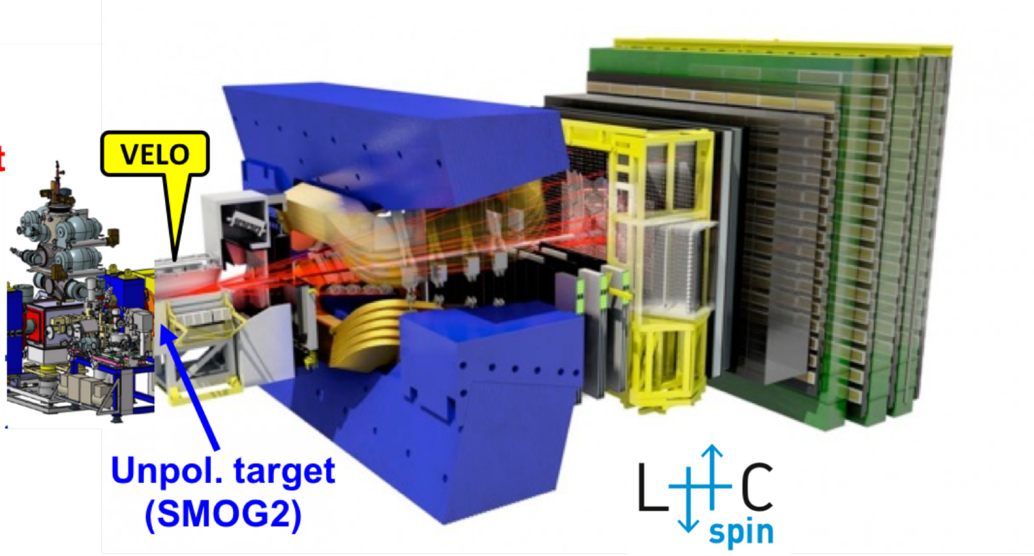

[PRC 101 (2020) 024901]

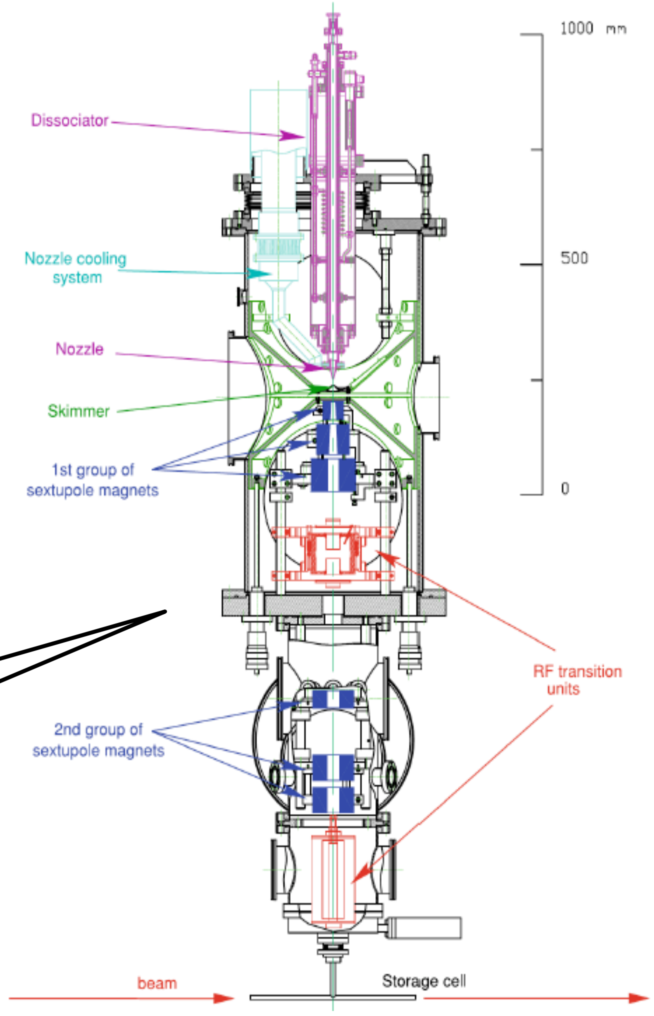
# The LHCspin apparatus

The LHCspin apparatus consists of a **new-generation HERMES-like polarized gaseous fixed target** to be installed usptream of the VELO




[NIMA 540 (2005) 68]



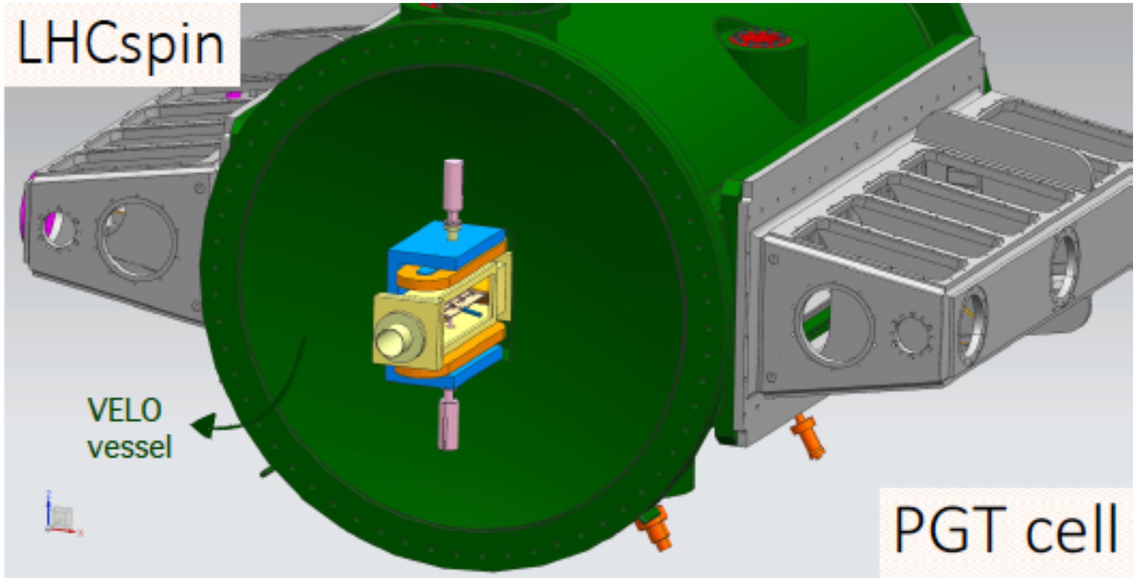



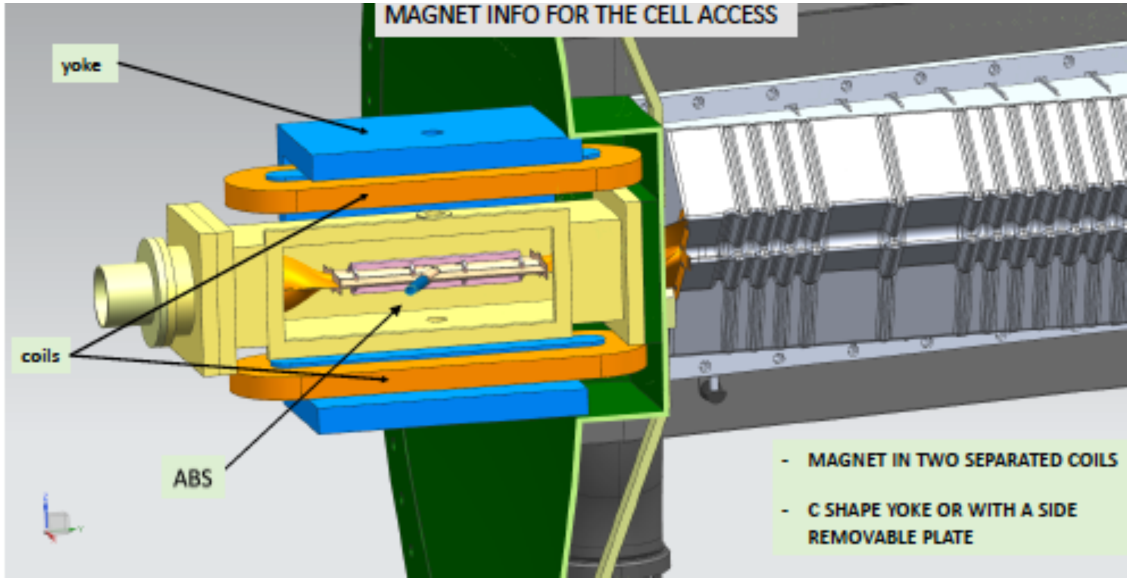

**state-of-the art ABS of ANKE @ COSY**

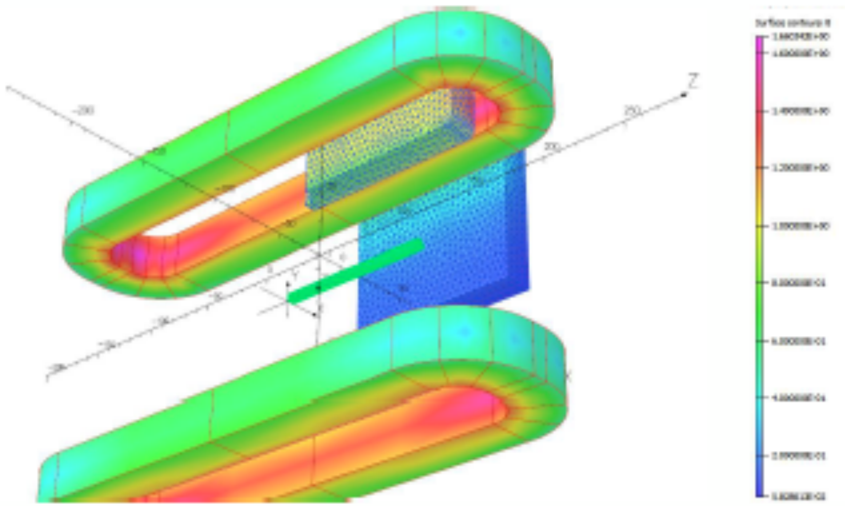
$I \simeq 10^{17}\ pol.atoms/s$

[NIM A 721, 83 (2013)]

# The LHCspin apparatus [PoS (SPIN2018)]

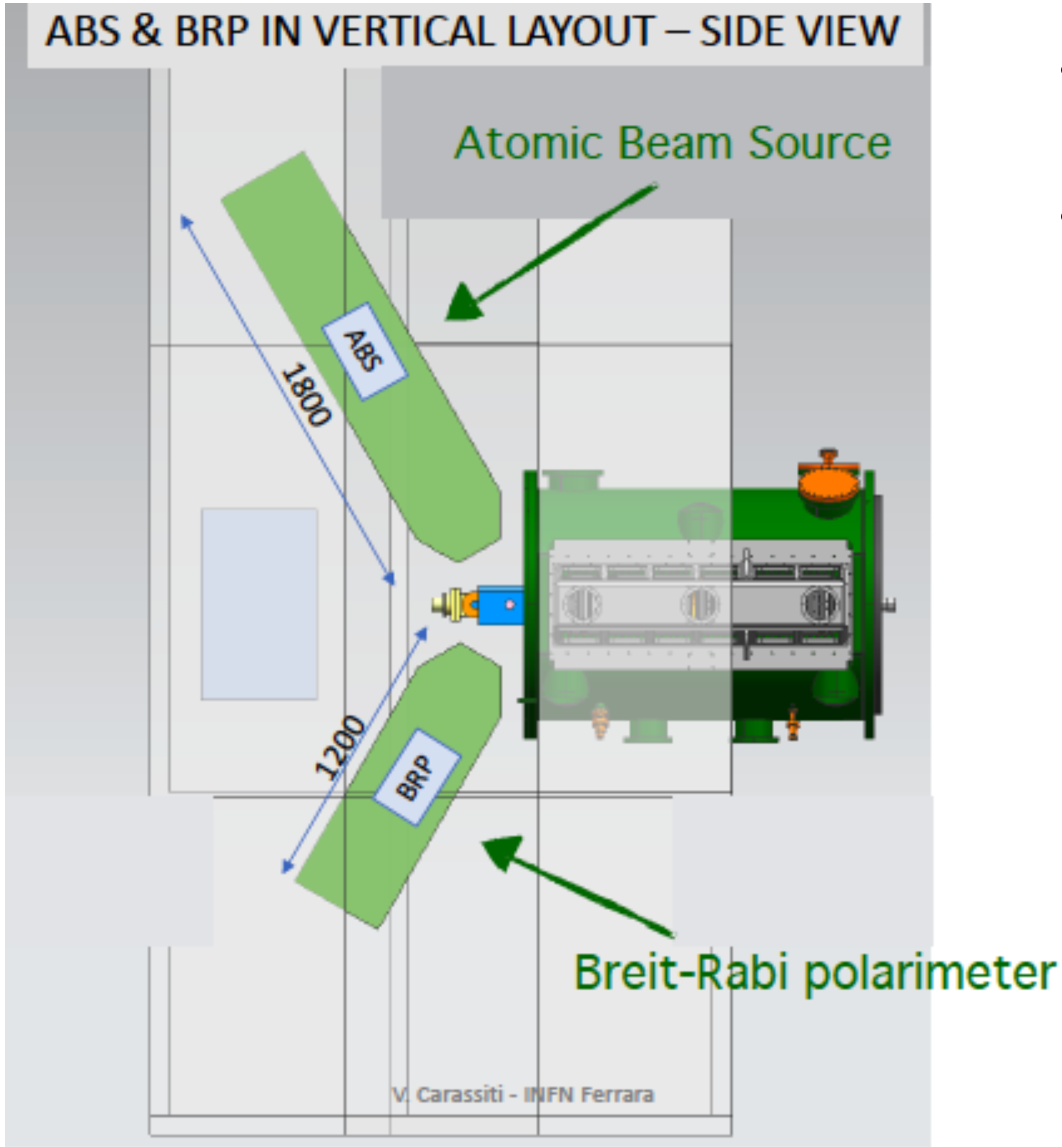


- **Compact dipole magnet for static transverse field to maintain polarization inside the cell and avoid beam-induced depolarization**
- **Required $B = 300\ mT$ with $\Delta B/B \sim 10\%$**
- **Superconductive coils + iron yoke fits the constraints**
- **No need for additional detectors**

# The LHCspin apparatus [PoS (SPIN2018)]

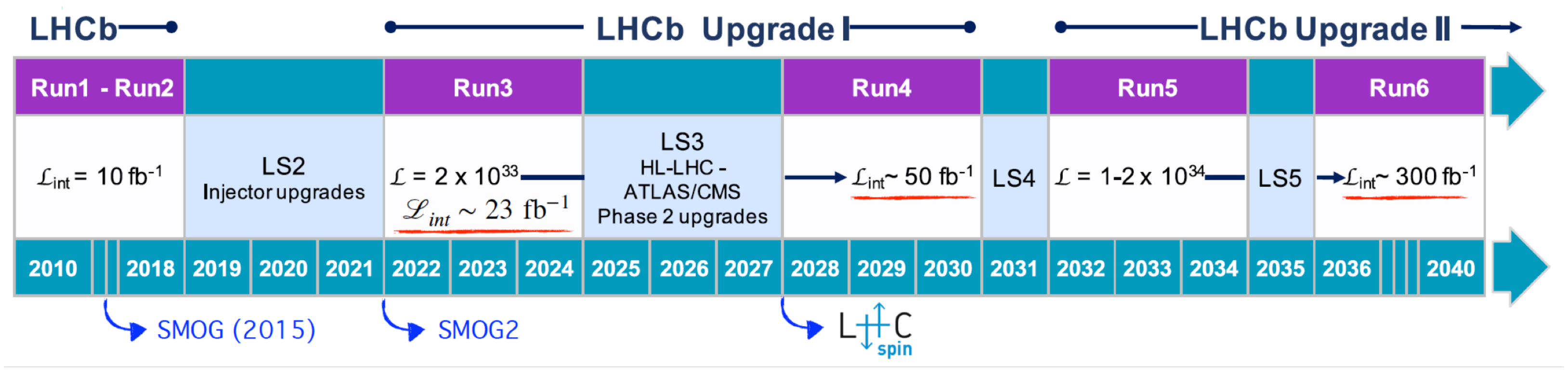



- **Need to develop a new-generation compact ABS and diagnostic system to fit into the limited available space in the VELO alcove**
- Alternative solution with jet target also under evaluation: lower density but higher polarization degree

**…a challenging R&D, but worth the effort!**

# 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
- Cutting-edge unpolarized physics will also be at reach (cold nuclear matter effects, intrinsic charm, QGP studies, etc.)



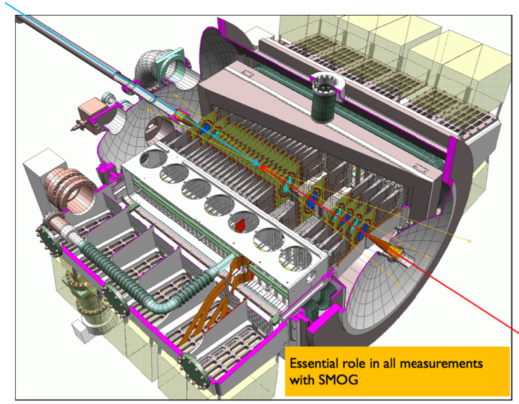

**If approved, LHCspin will bring for the first time spin physics to the LHC, and LHCb will become the first experiment simultaneously running in collider and fixed-target mode with polarized targets, opening a whole new range of explorations.**

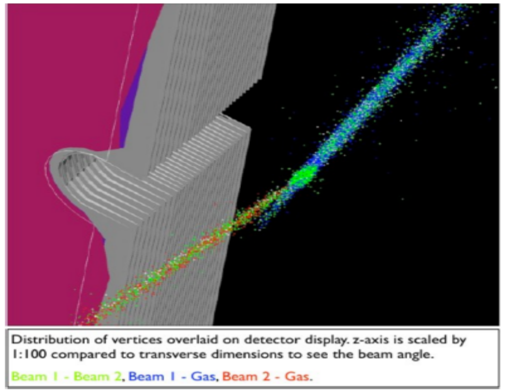
# Backup

# The SMOG system

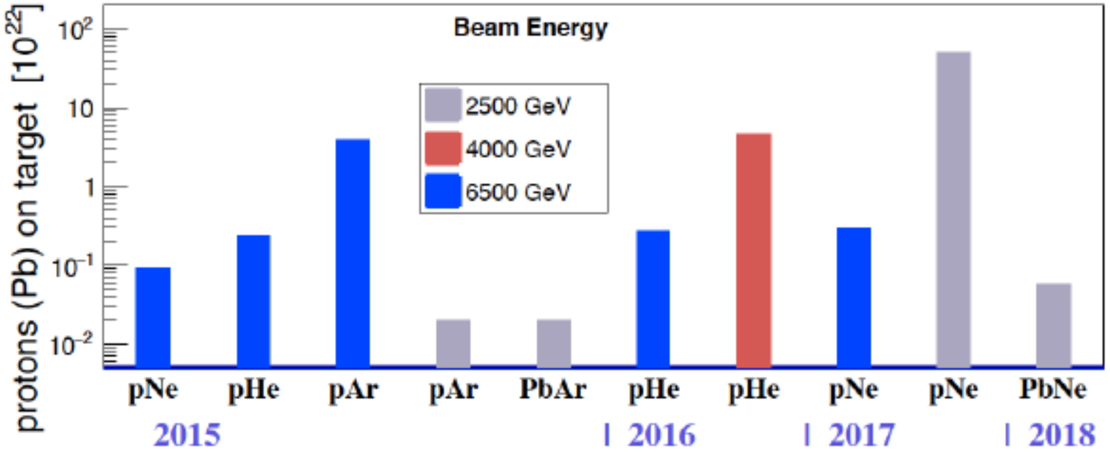
SMOG: System for Measuring Overlap with Gas:

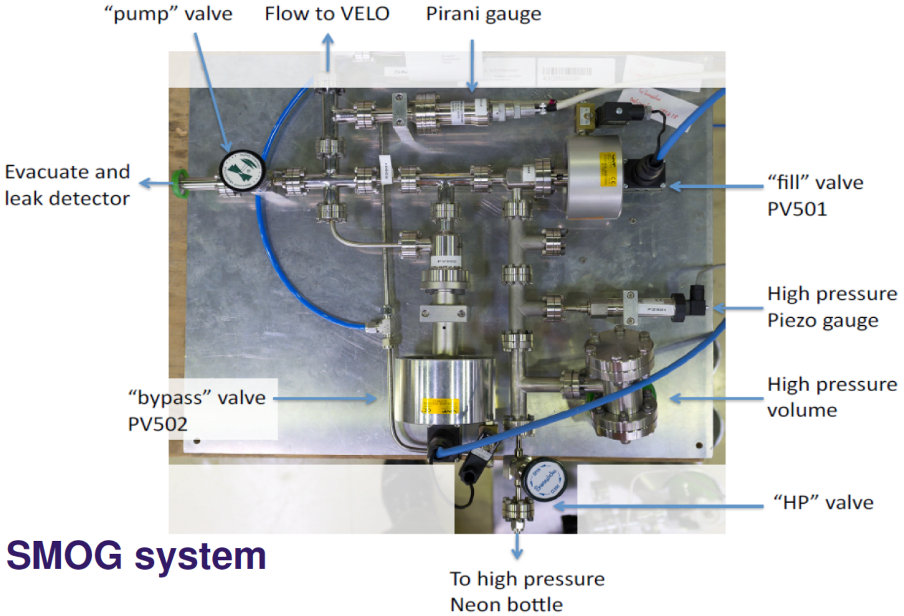
- Low density noble gas injected in the VELO vessel ($\sim 10^{-7}$mbar)
- Gas pressure 2 orders of magnitude higher than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude
- Conceived for **precise luminosity determination** (beam-gas imaging)




…but SMOG gives also the unique opportunity to operate an **LHC experiment in a fixed target mode** and to study pA and AA collisions on various targets!



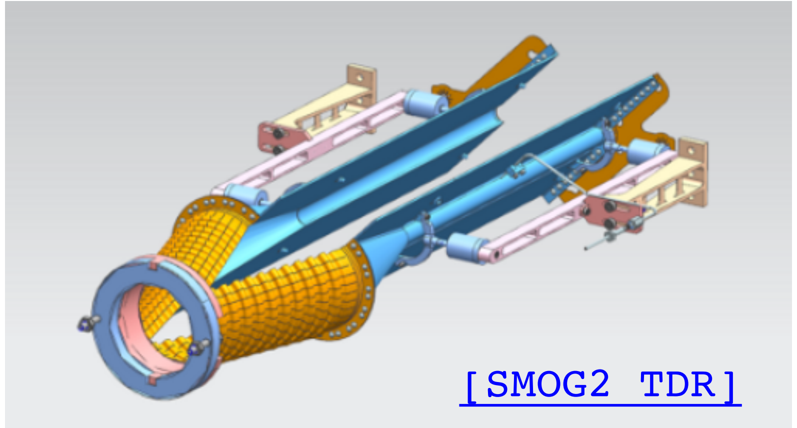



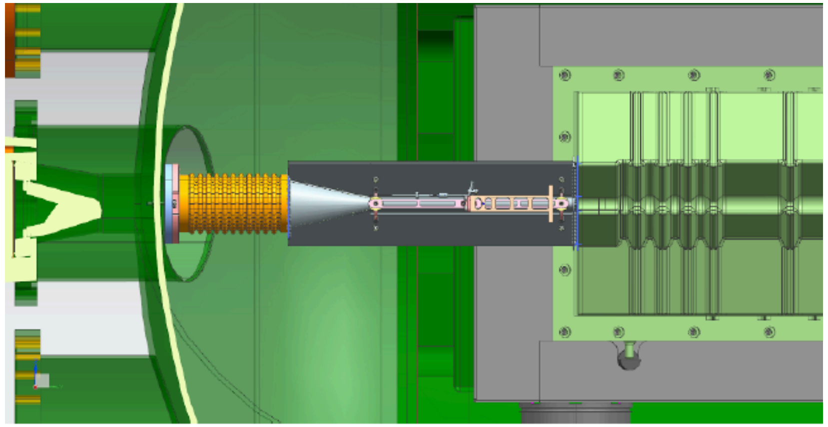

SMOG system

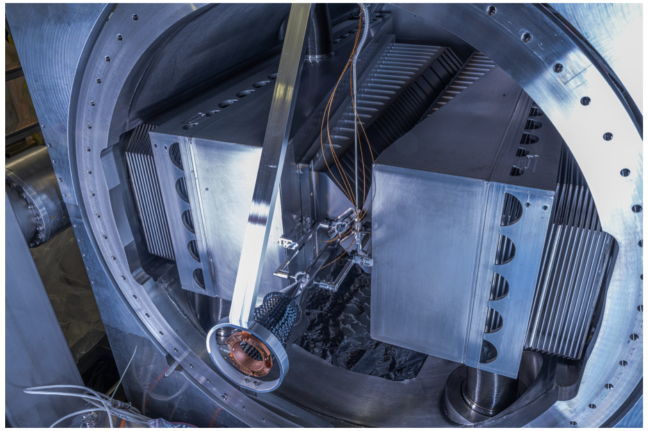
- ✓ First measurements of charm production in fixed-target configuration at the LHC [Phys. Rev. Lett. 122, 132002 (2019)]
- ✓ Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV [Phys. Rev. Lett. 121, 222001 (2018)]

# The SMOG2 upgrade

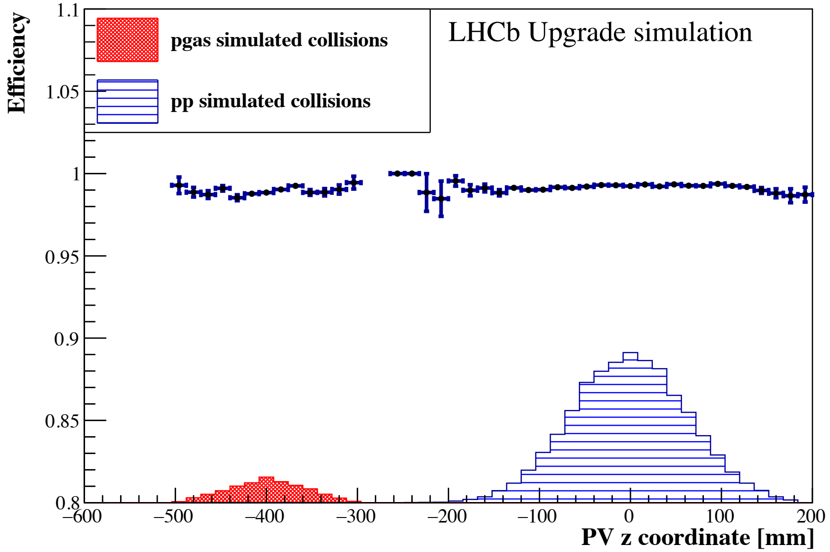
A 20 cm long **storage cell** for the target gas has been installed in 2020 next to the VELO





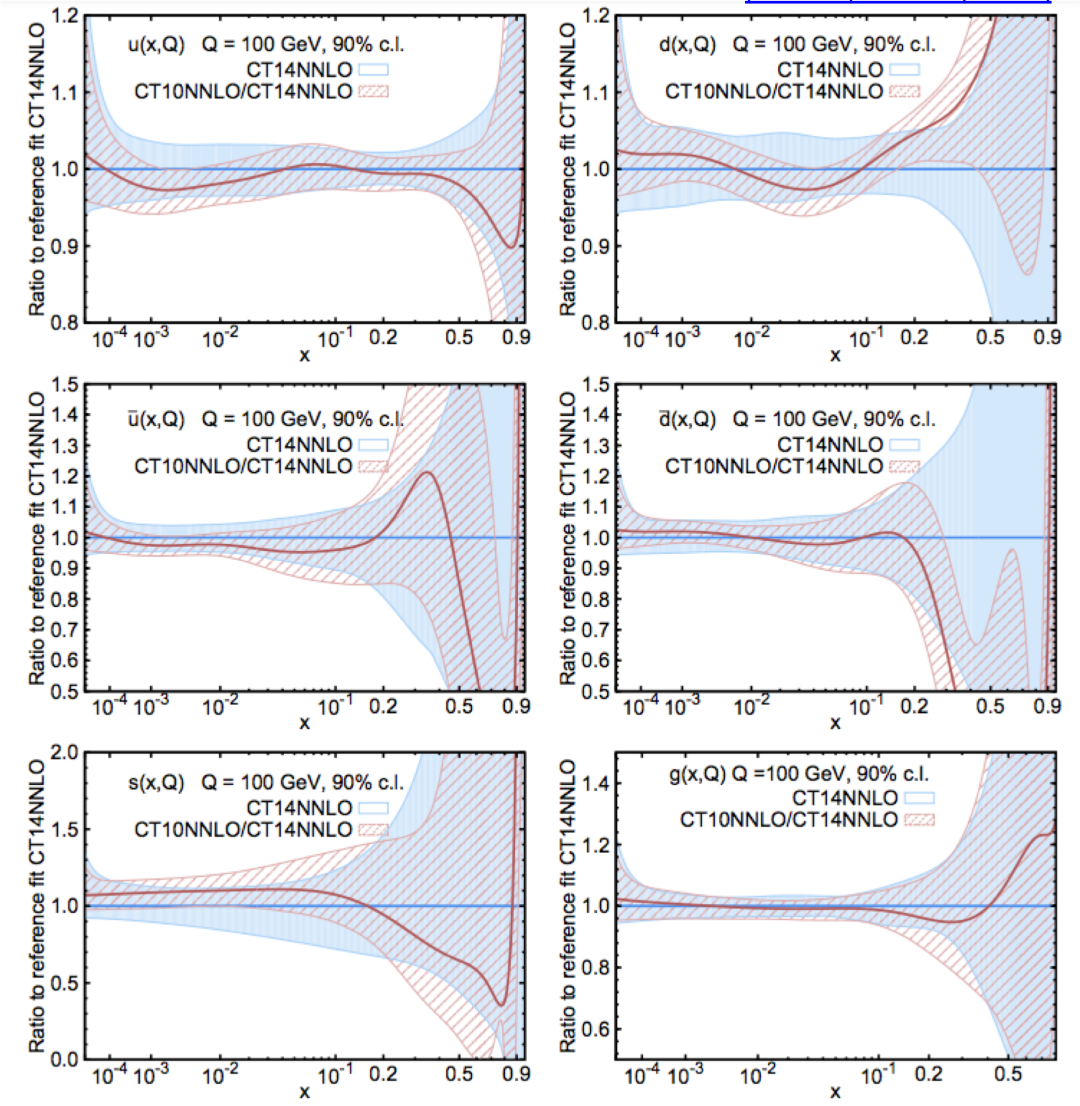
- Can be filled with unpolarised $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- Boosts the taregt density by factor 8-30 wrt SMOG
- Negligible impact on the beam lifetime ($\tau^{H_2}_{beam-gas} \sim$ 2000 days)
- A trigger for simultaneous p-p ($\sqrt{s} = 14\, TeV$) and p-gas ($\sqrt{s_{NN}} = 115\, GeV$) data-taking is already in place for SMOG2
- 1-3% throughput decrease when adding p-gas to the LHCb event reconstruction sequence
- **LHCb will be the only experiment able to run in collider- and fixed-target mode simultaneously!**



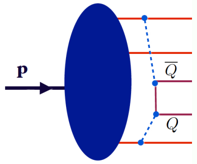

[LHCb-FIGURE-2019-007]

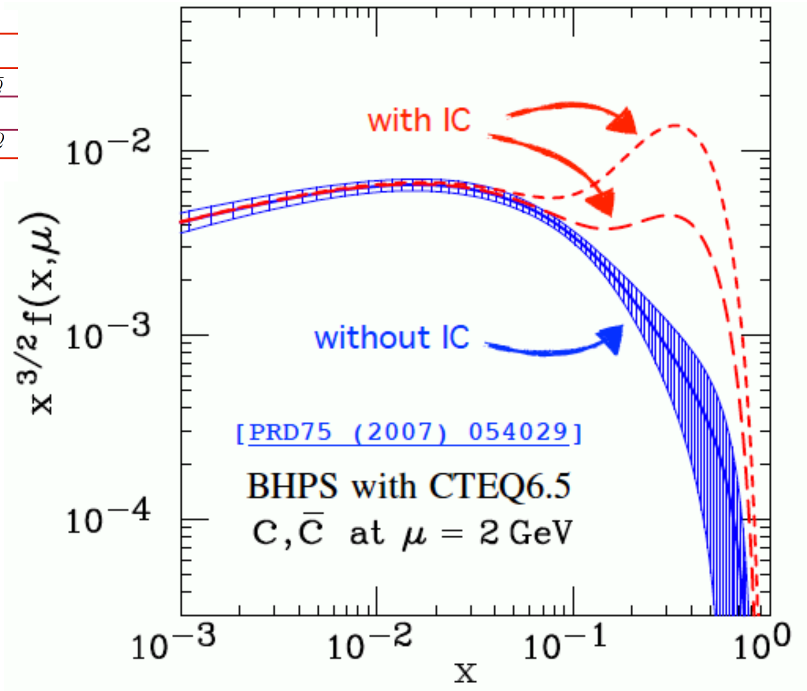
# Kinematic conditions for fixed-target collisions at LHC

[PRD 93, 033006, 2016]

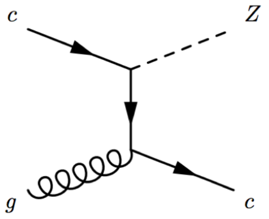



[PRD 75 (2007) 054029]




- **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!



# Probing the gTMDs

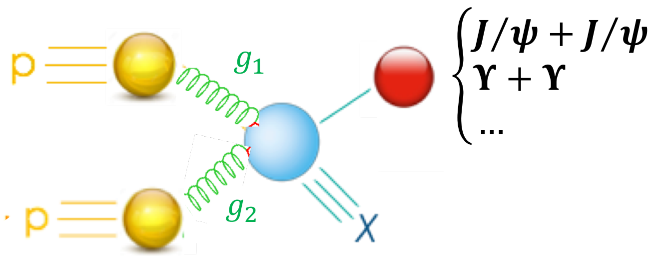
$$\frac{d\sigma}{dM_{QQ}dY_{QQ}d^2\boldsymbol{P}_{QQ_T}d\Omega} = \frac{\sqrt{M_{QQ}^2 - 4M_Q^2}}{(2\pi)^2 8s\, M_{QQ}^2}$$

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

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

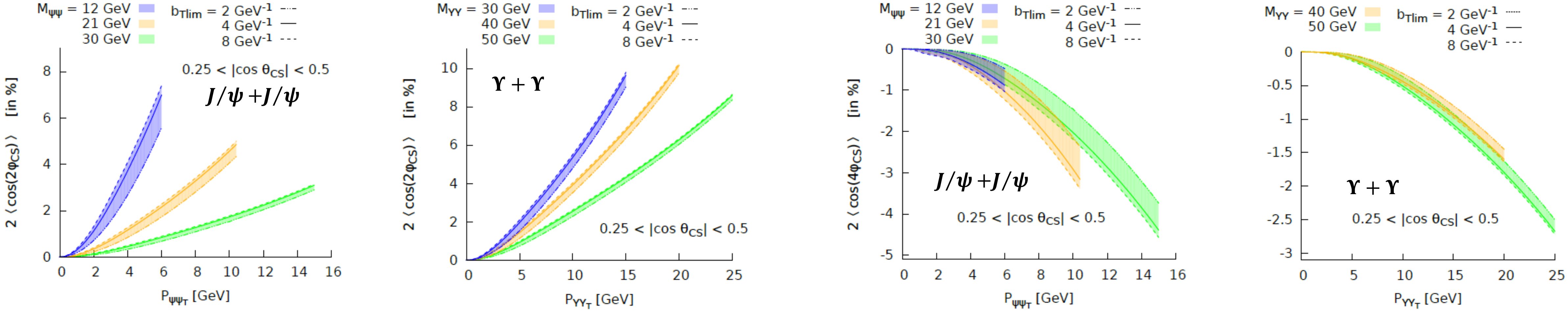
$$+\Big(F_3(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[w_3 f_1^g h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T}) + F_3'(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[w_3' h_1^{\perp g} f_1^g\Big](x_{1,2},\boldsymbol{P}_{QQ_T})\Big)\cos 2\phi_{CS}$$

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




gluon pol.

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

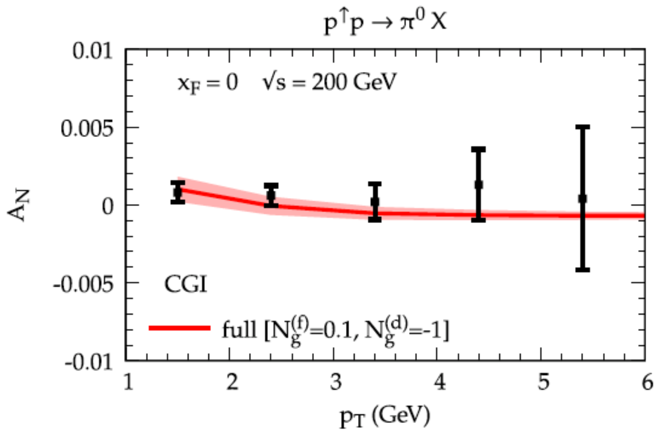


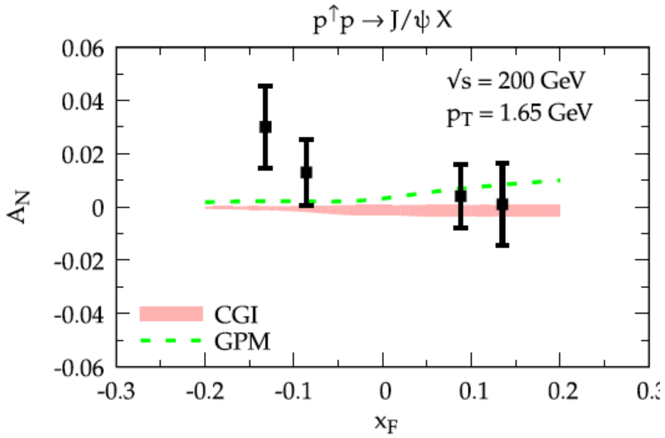

Predictions based on CSM + TMD evolution for $x_1 \sim x_2 \sim 10^{-3}$ at forward rapidity [EPJ C 80, 87 (2020)]

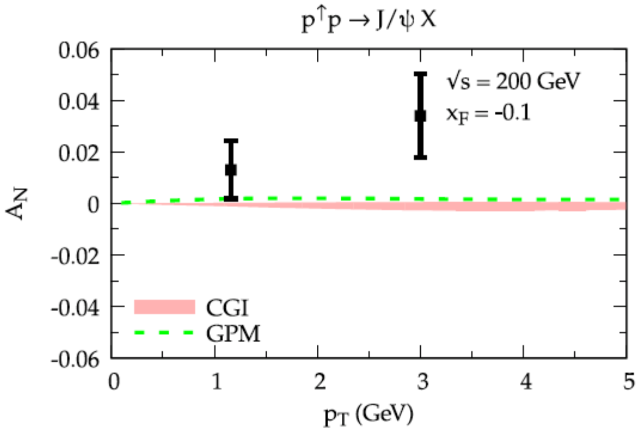
**Azimuthal amplitudes ~ 5%!!**

# Probing the gluon Sivers funct.

- First extraction using GPM [JHEP 09 (2015) 119] from SSAs measured at PHENIX in $p^{\uparrow}p \rightarrow \pi^0 X$ at central rapidities
- New extractions on inclusive $\pi, D^0, J/\psi$ PHENIX data based on (improved) CGI-GPM model (process dependence introduced through ISI and FSI)

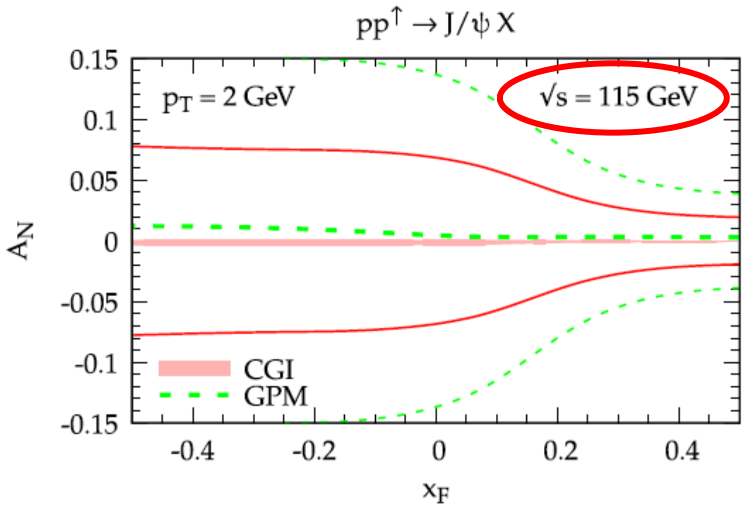


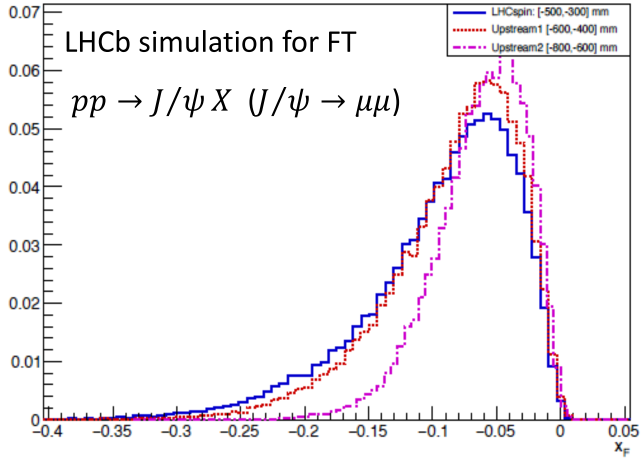




[PRD 99, 036013 (2019)]

- predictions are small
- Limited-precision PHENIX data are non-zero at $x_F < 0$



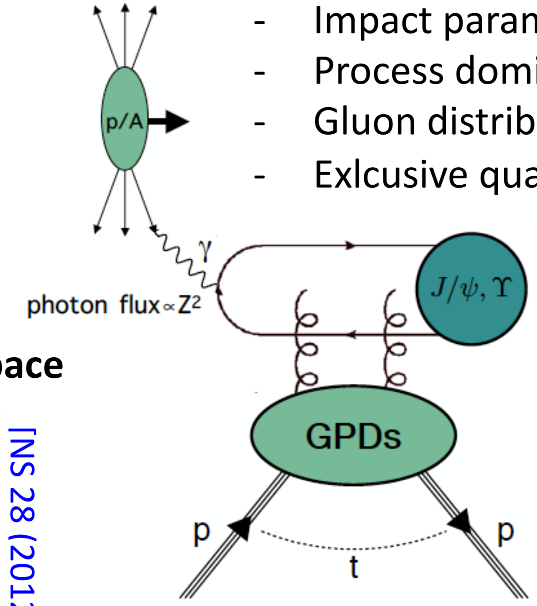

- **Predictions for pol. FT meas. at LHC (LHCspin-like)**
- $\boldsymbol{pp^{\uparrow} \rightarrow J/\psi + X}$
- **Based on GPM & CGI-GPM**
- **Expected amplitudes could reach 5-10% in the backward region ($\boldsymbol{x_F < 0}$)**



# gGPDs

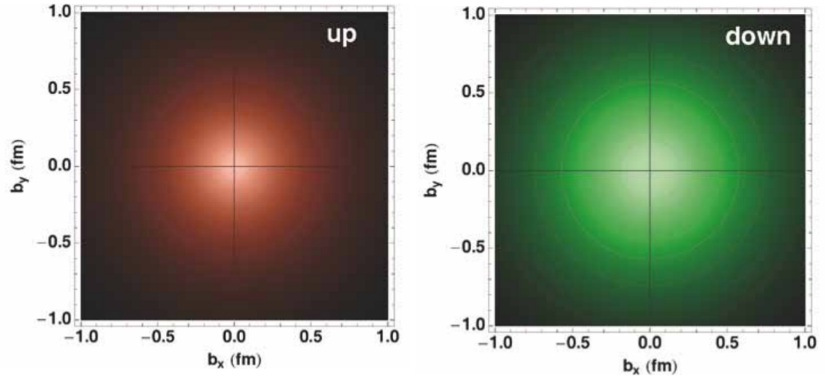
| GPD | $U$ | $L$ | $T$ |
|---|---|---|---|
| $U$ | $H$ | | $\mathcal{E}_T$ |
| $L$ | | $\tilde{H}$ | $\tilde{E}_T$ |
| $T$ | $E$ | $\tilde{E}$ | $H_T, \ \tilde{H}_T$ |

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

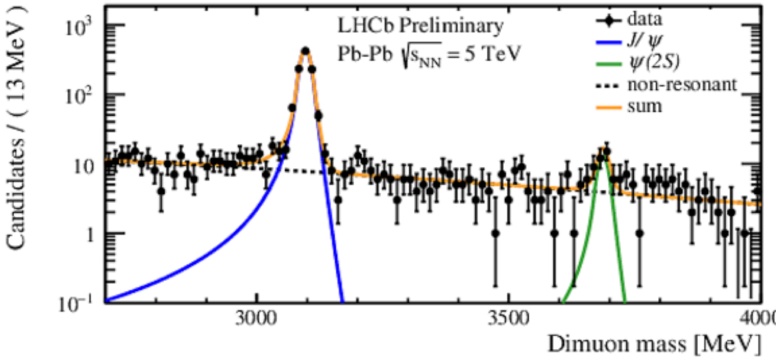



- Impact parameter larger than sum of radii
- Process dominated by EM interaction
- Gluon distributions probed by pomeron exchange
- Exlcusive quarkonia prod. sensitive to gluon GPDs [PRD 85 (2012), 051502]

**3D maps of parton densities in coordinate space**

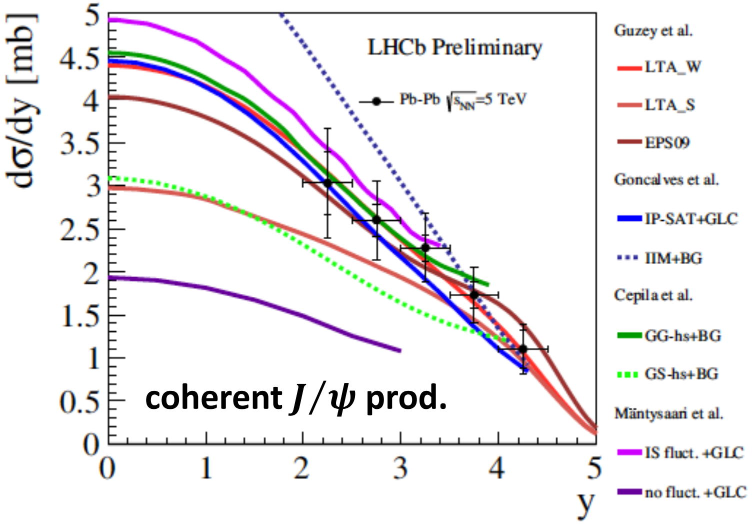



[NS 28 (2012), 1]




[NPA 982 (2019) 247]

**First results from LHCb in PbPb UPC**

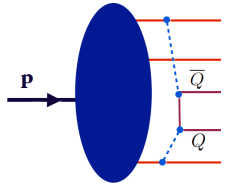



**LHCspin could allow to access the GPD $E^g$ (a key ingredient of the Ji sum rule)**

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

# More physics reach with unpolarized FT reactions

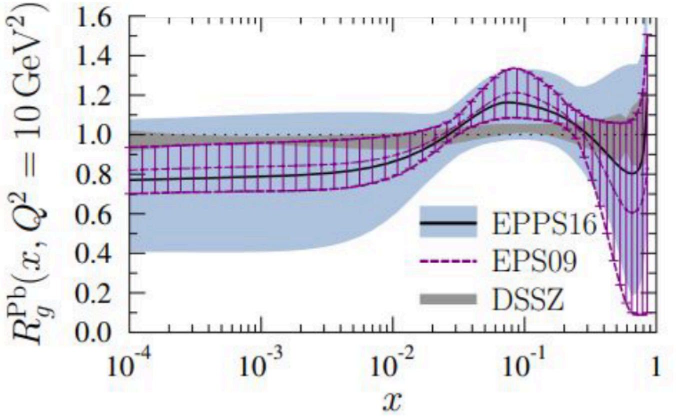
- **Intrinsic heavy-quark** **[S.J. Brodsky et al.,** Adv.High Energy Phys. 2015 (2015) 231547]
  - 5-quark Fock state of the proton may contribute at high $x$!
  - **charm PDFs** at large $x$ could be larger than obtained from conventional fits




- **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

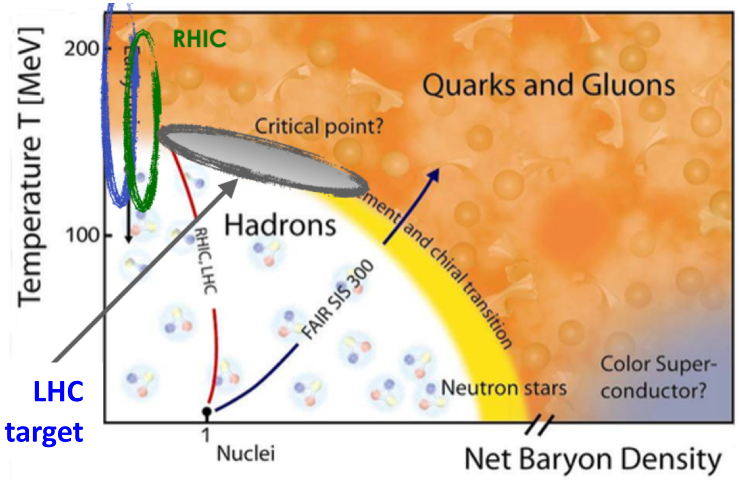
- **PbA collisions at** $\sqrt{s_{NN}} \approx \mathbf{72\ GeV}$ (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - Study of **QGP formation** (search for predicted **sequential quarkonium suppression**)

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

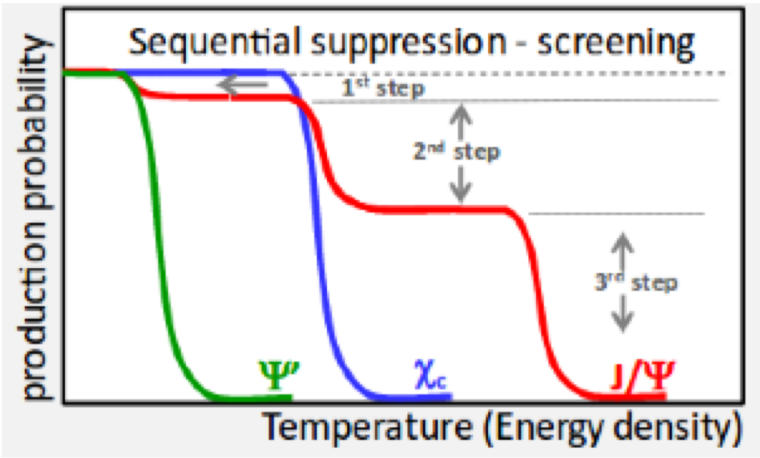



LHC @ 5.02 TeV

QCD Phase-Space




LHC
fixed target




$c\bar{c}$ states: $J/\psi$, $\chi_c$, $\psi'$,…
Different binding energy, different dissociation temp.

# Main reactions or interest (…an incomplete wishlist)

- $pp \to \mu^+\mu^- + X \quad (pp \to e^+e^- + X)$
- $pd \to \mu^+\mu^- + X \quad (pd \to e^+e^- + X)$

☛ **unpolarized TMDs of valence and sea quarks and momentum distrib. of sea quarks**

- $pp^\uparrow \to \mu^+\mu^- + X \quad (pp^\uparrow \to e^+e^- + X)$
- $pd^\uparrow \to \mu^+\mu^- + X \quad (pd^\uparrow \to e^+e^- + X)$

☛ **TMDs of valence and sea quarks**

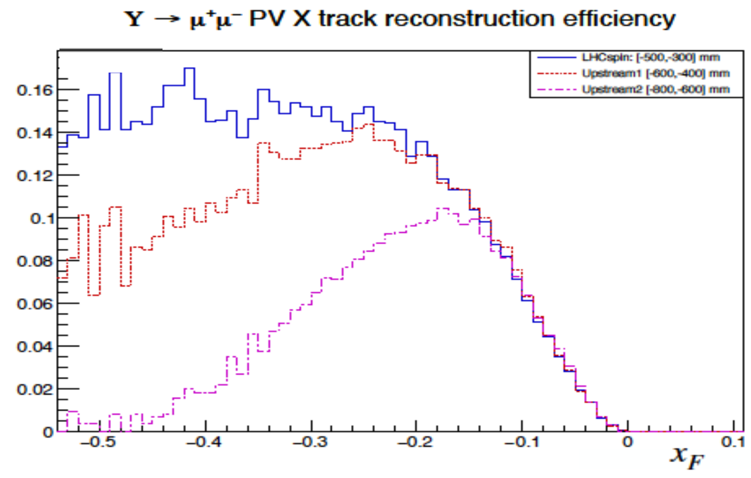
- $pp^{(\uparrow)} \to \eta_c + X \quad (pp^{(\uparrow)} \to \chi_{c,b} + X)$
- $pp^{(\uparrow)} \to J/\psi + X$
- $pp^{(\uparrow)} \to \Upsilon + X$
- $pp^{(\uparrow)} \to J/\psi + J/\psi + X$
- $pp^{(\uparrow)} \to J/\psi + \gamma + X$
- $pp^{(\uparrow)} \to \Upsilon + \gamma + X$

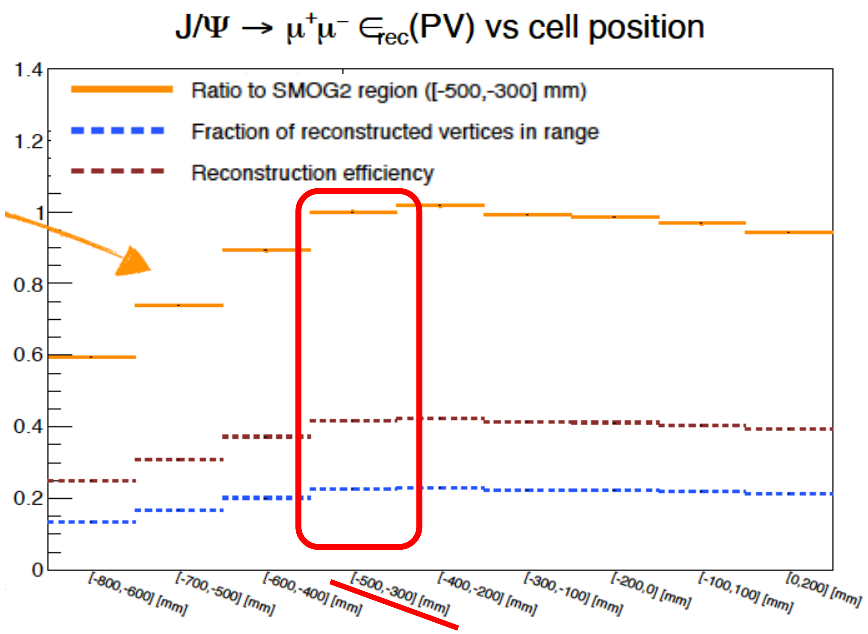
☛ **Pol and unpol gluon PDFs**

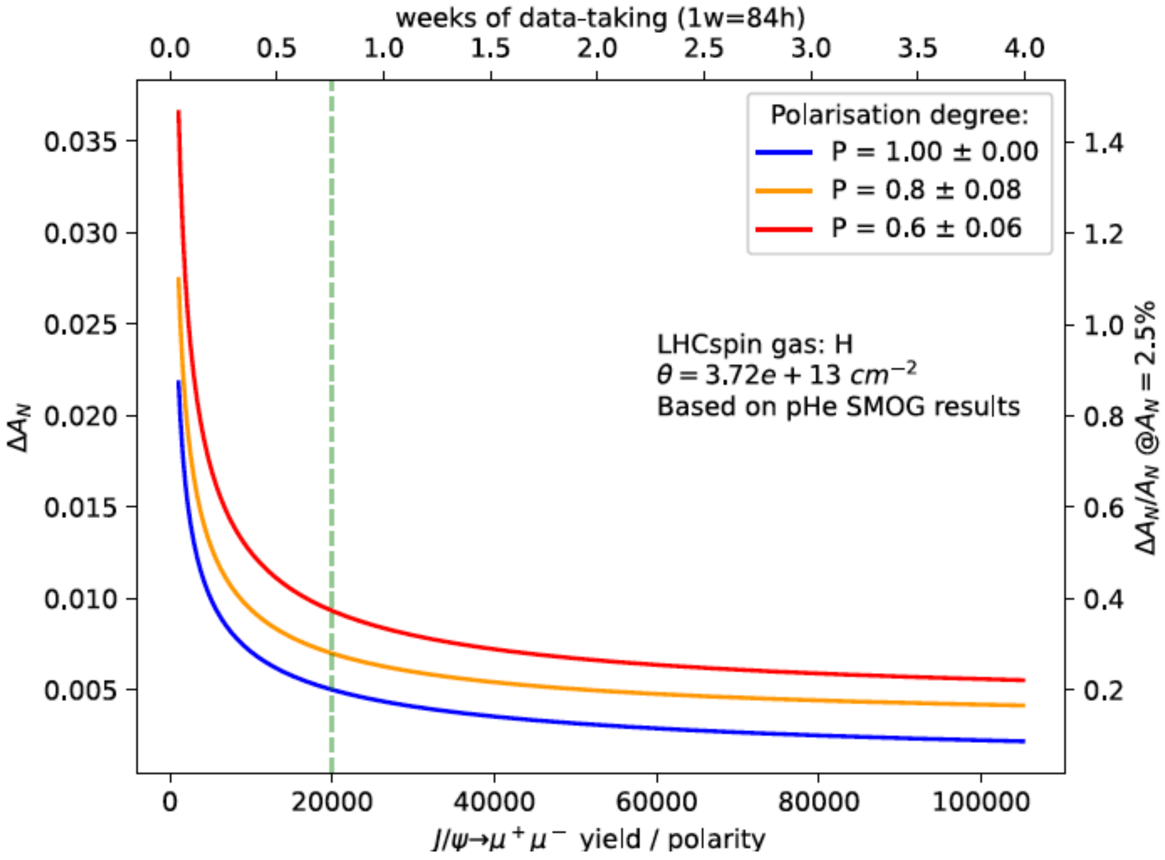
- pA, PbA $(A = He, Ne, Ar, Kr, \ldots)$

☛ **Nuclear matter effects, QGP, etc**

# Expected performances




- Precise spin asymmetries for inclusive $J/\psi \to \mu^+\mu^-$ in $pH^\uparrow$ collisions in a few weeks of data taking

- Statistics further enhanced by a factor 3-5 during the LHC upgrade II phase

# Expected performances

- The LHC beam runs through the target cell and experiences an **Areal density**: $\theta = ½ \rho_0 L$
- **Volume density**: $\rho_0 = I_0/(2C_1 + C_2)$ where: $C = 3.81\sqrt{\frac{T(K)}{M}\frac{D^3}{L+1.33D}}\ \left(\frac{l}{s}\right)$

P
G
T

- $\boldsymbol{I_0 = 6.5 \cdot 10^{16} s^{-1}}$
- $C_{tot}$ = 13.90 l/s
- $\boldsymbol{\theta}$**= 7.02 ·$10^{13}$/cm$^2$**

B
e
a
m

- $2.2 \cdot 10^{11}$ p/bunch
- 2760 bunches
- $\boldsymbol{I_{beam} = 6.8 \cdot 10^{18}\ p/s}$

- $\boldsymbol{L_{pH}(T_{cell} = 300\ K) = 4.8 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$
- $\boldsymbol{L_{pH}(T_{cell} = 100\ K) = 8.3 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$

# The time schedule of the project