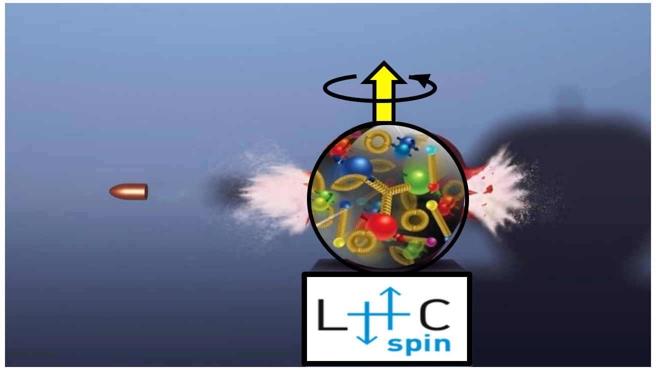
University of Ferrara

INFN

SAR WORS

LHCspin: a polarized fixed-target experiment at the LHC



L. L. Pappalardo
(pappalardo@fe.infn.it)

Sar WorS 2025 – 4° Sardinian Workshop on Spin

Spin physics at the LHC?

- World top energies
- high luminosity
- p and ion beams
- highly sophisticated state-of-the-art detectors
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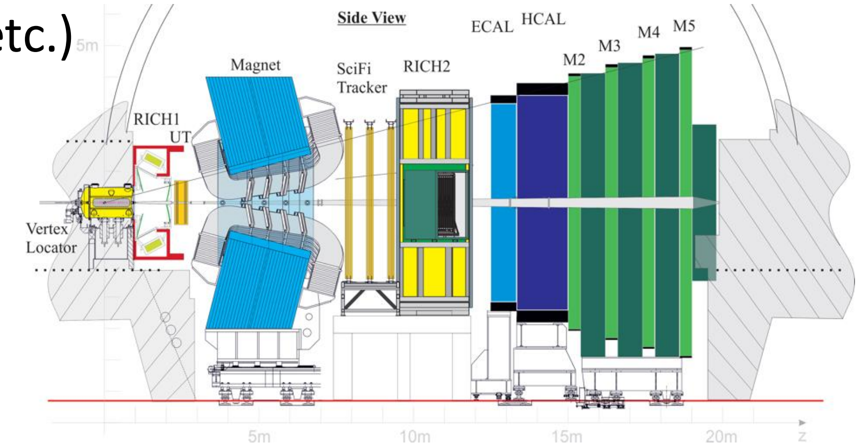
- **…and the LHCb spectrometer is the perfect place to host it.**



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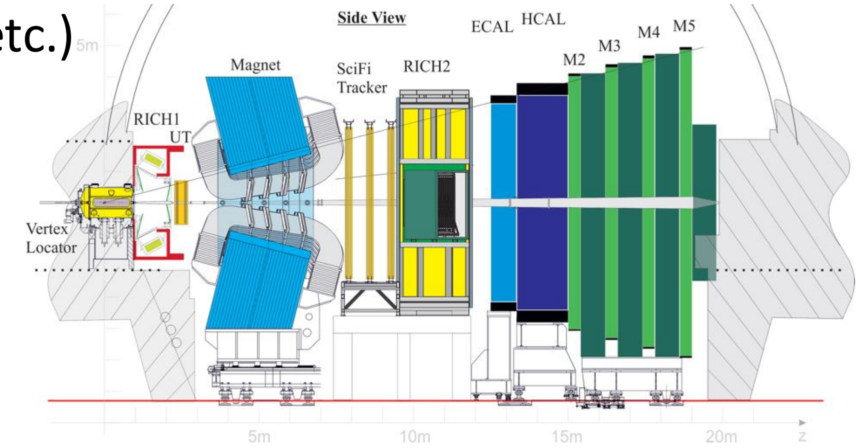
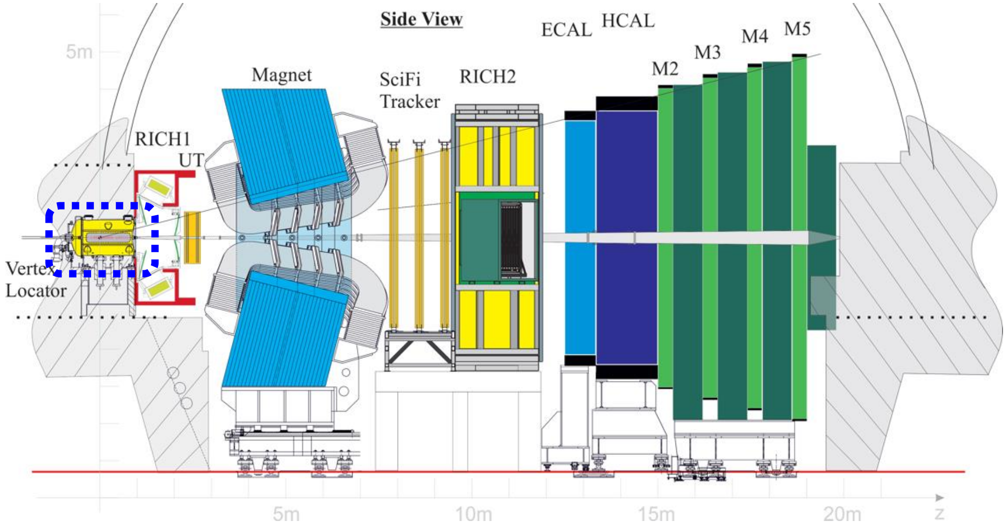
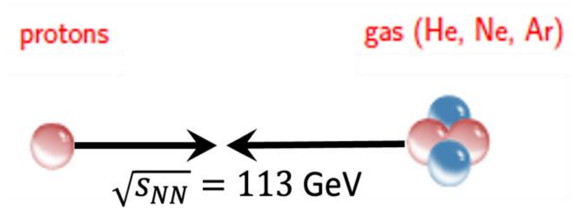


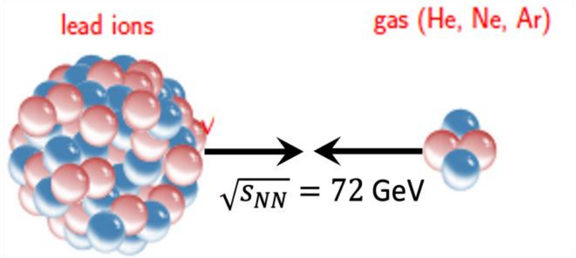
→ LHCspin **project!**

LHCb fixed-target setup

- Since 2015 LHCb can also be operated as a **fixed-target experiment** with the **SMOG system**, by injecting low pressure noble gases (He, Ne, Ar) into the VELO vessel.
- **Unique opportunity to study pA/AA collisions on various targets exploiting the high-energy, high-intensity LHC beams!**







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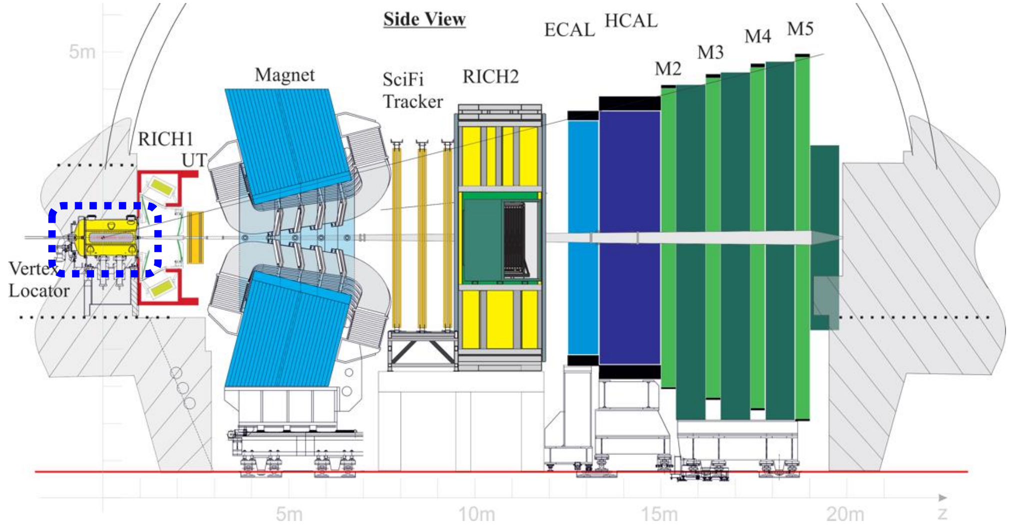

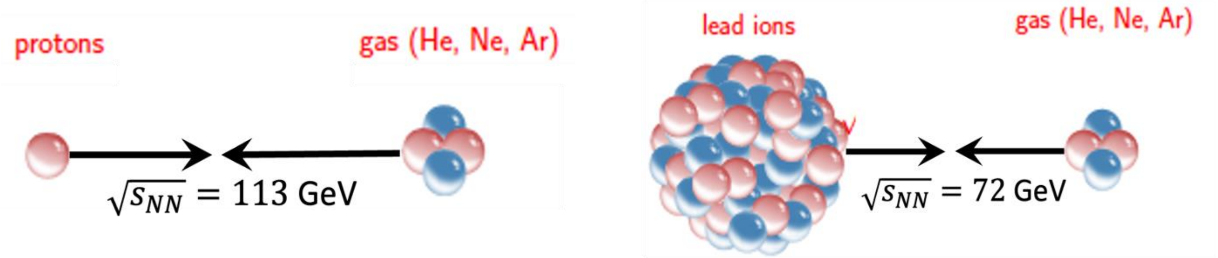

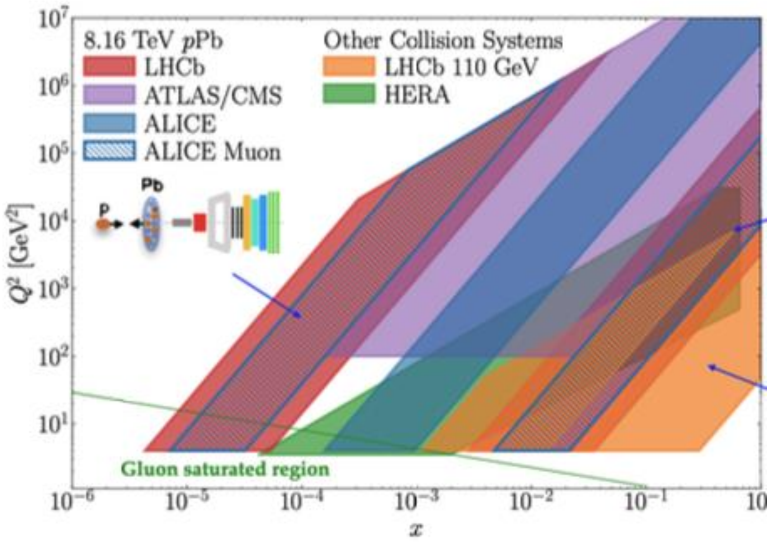

FT kinem. with $E_p = 6.8$ TeV:

- $\sqrt{s_{NN}} \approx 110\ GeV$
- $-3.0 \leq y_{CM} \leq 0$
- $x_F < 0$
- intermediate-large x_B
- intermediate Q^2

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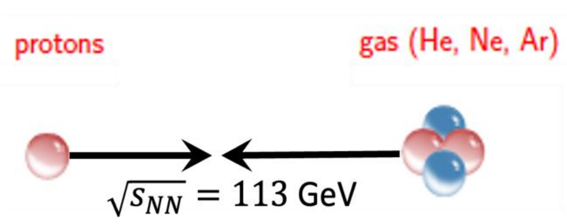

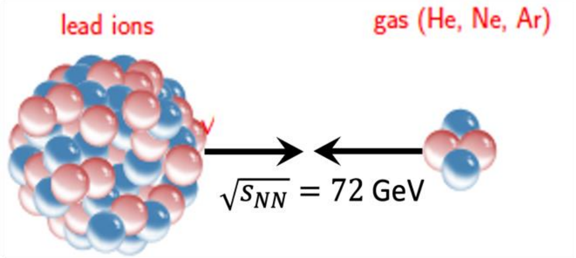

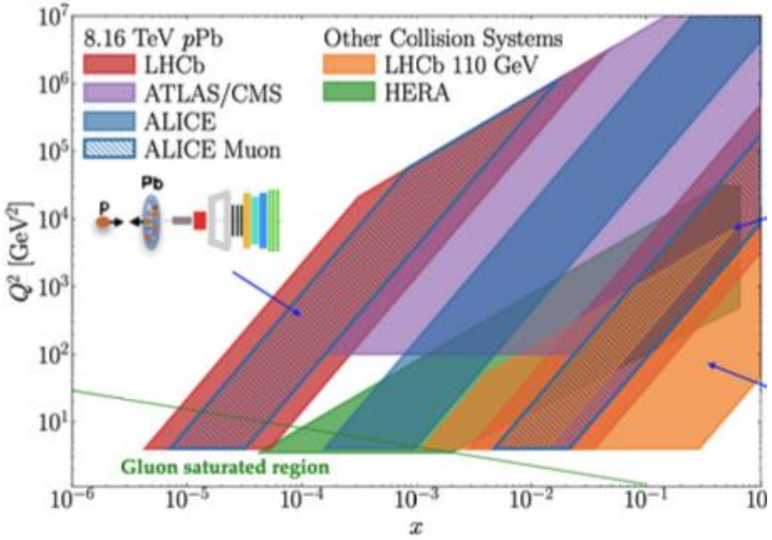

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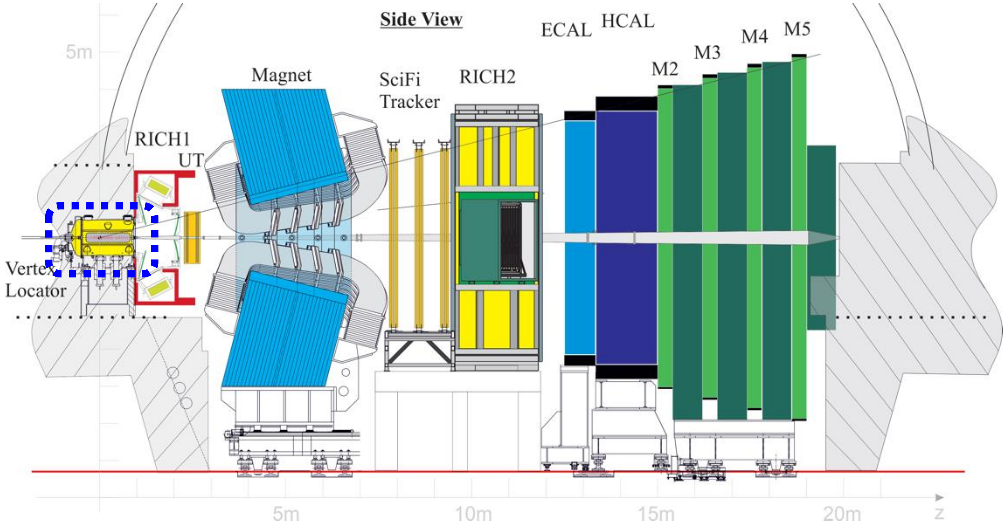
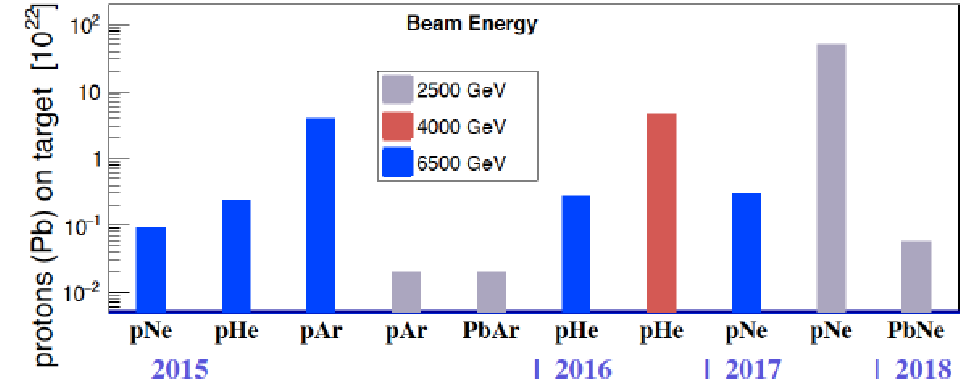




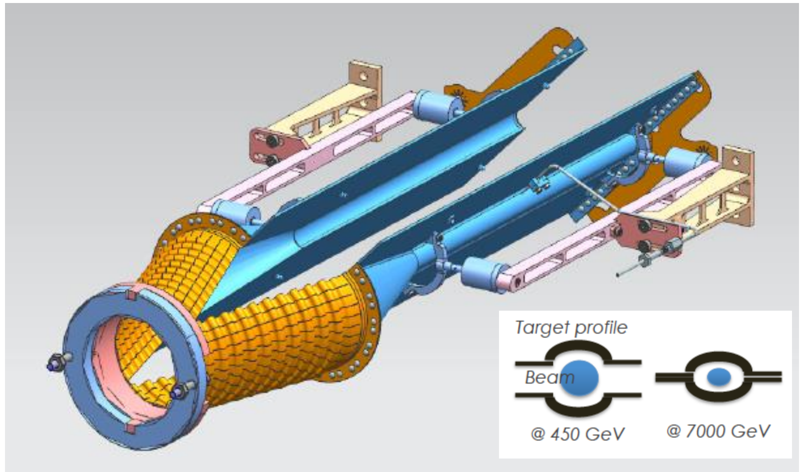
Many interesting published analyses:

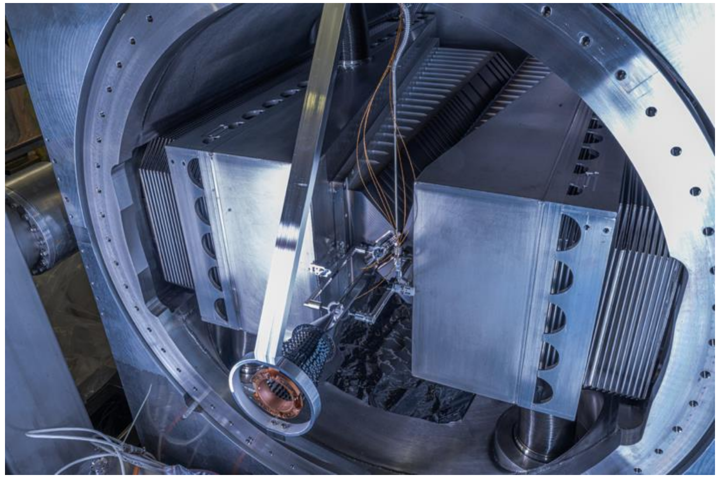
- Antiproton prod. cross section in p-He
- Charmonium production in p-Ne and Pb-Ne
- Open charm production in p-Ne and Pb-Ne

The SMOG2 upgrade

[SMOG2 TDR]

- 20 cm **storage cell** for the target gas **installed** upstream of the VELO
- Brand new, more flexible and sophisticated **Gas Feed System** (GFS)





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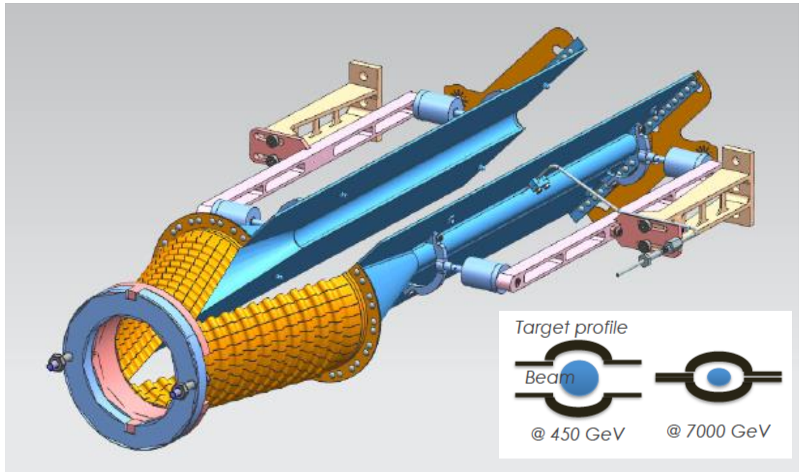
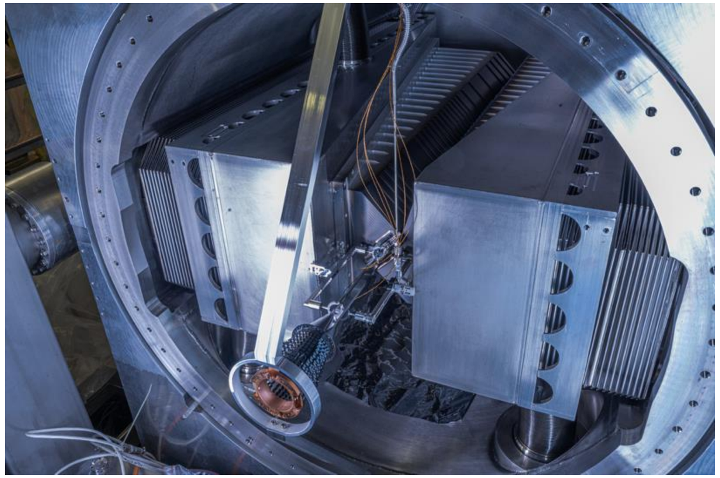
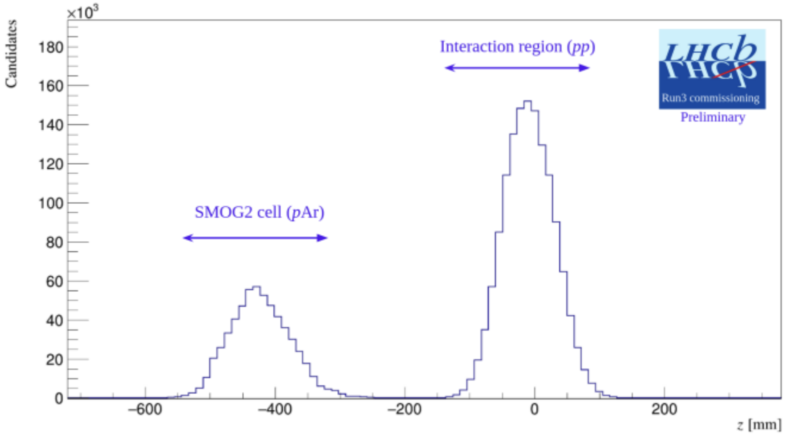




- more gas species: $H_2, D_2, He, N_2, O_2, Ne, Ar$ (Kr and Xe to be tested)
- target density increased by large factor (up to 30)
- precise density (luminosity) determination
- negligible impact on LHC and LHCb performance
- **can run un parallel with collider mode!**

Early 2024 SMOG2 data



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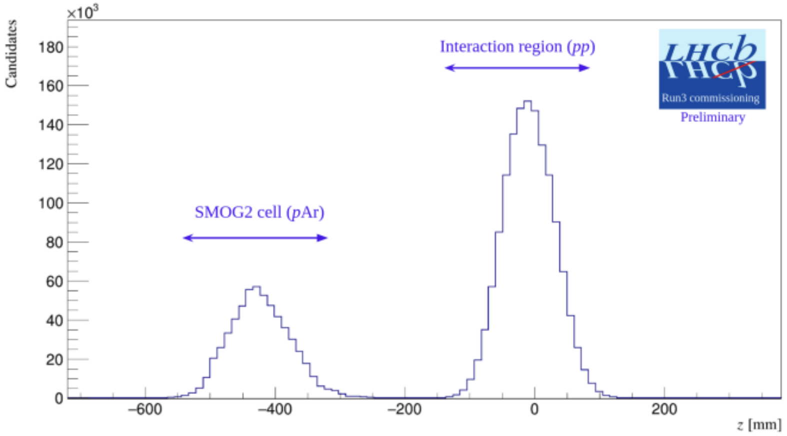

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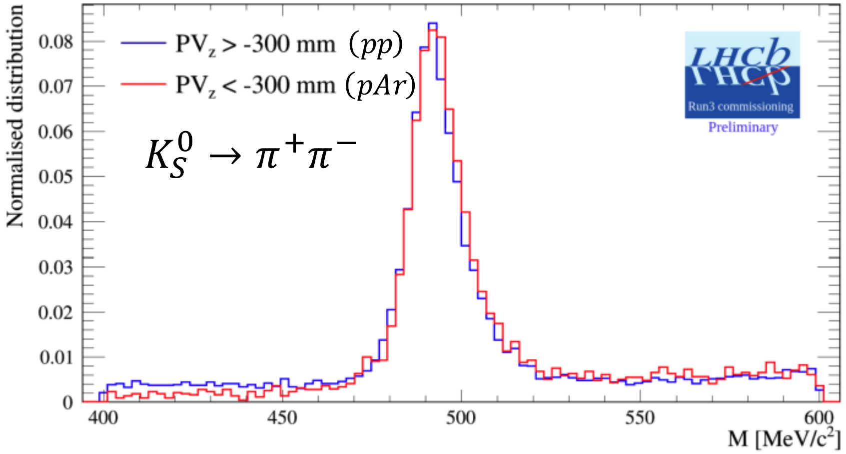

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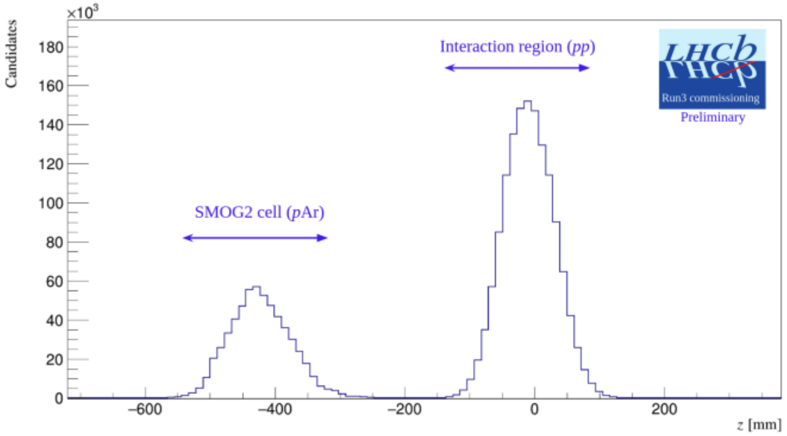

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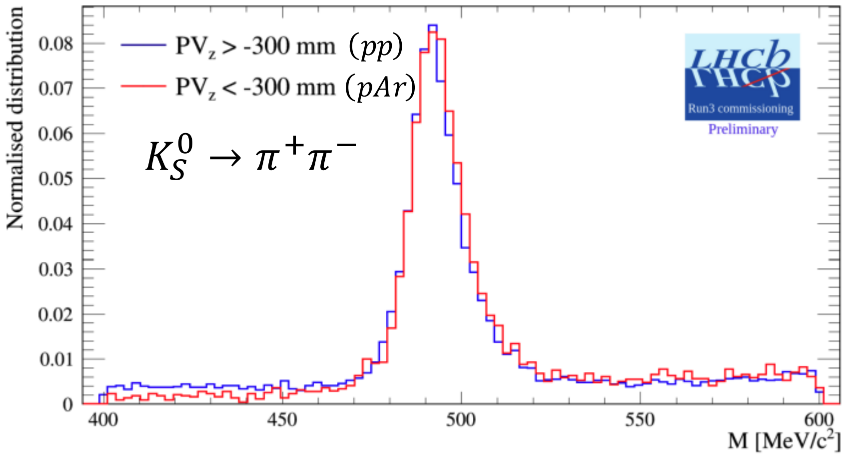

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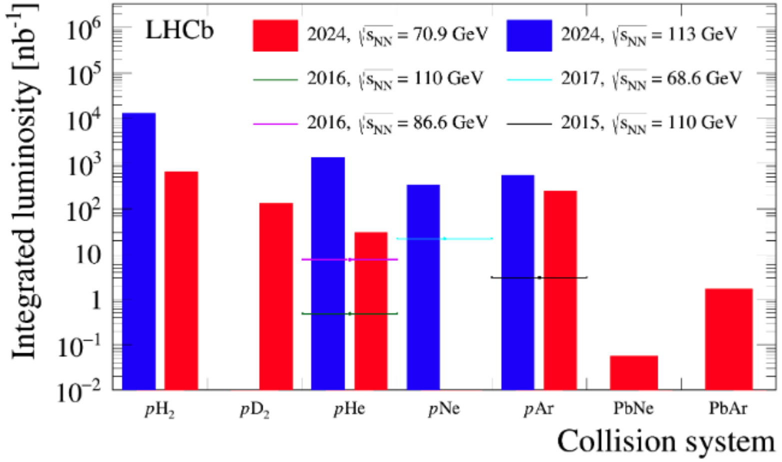
- ➢ **Large beam-gas samples already collected in 2024 with all available gases!**



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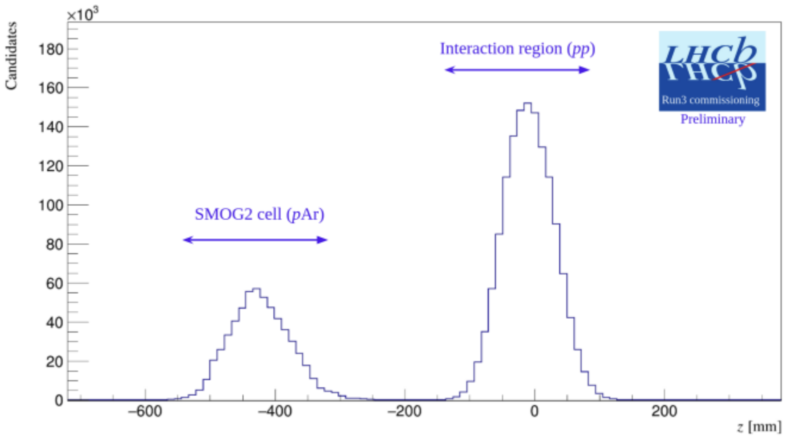

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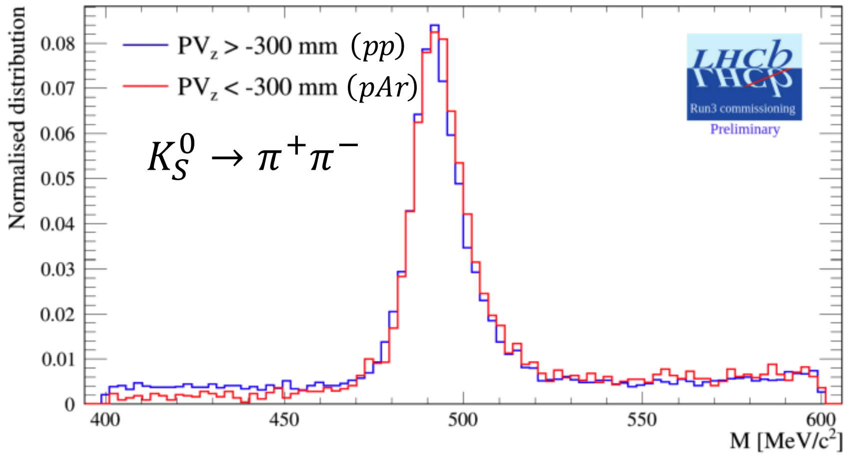

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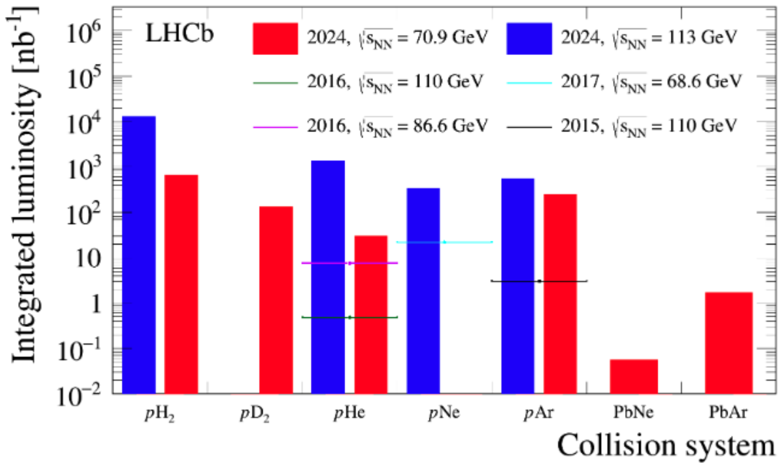
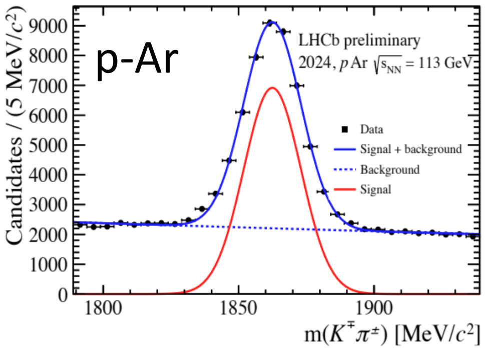
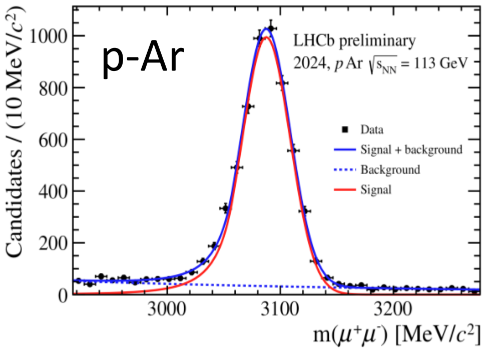


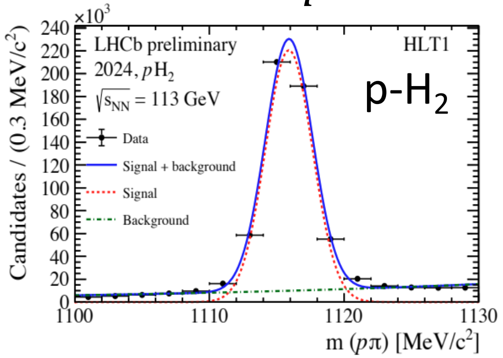
$D^0 \to K^-\pi^+$



$J/\psi \to \mu^+\mu^-$



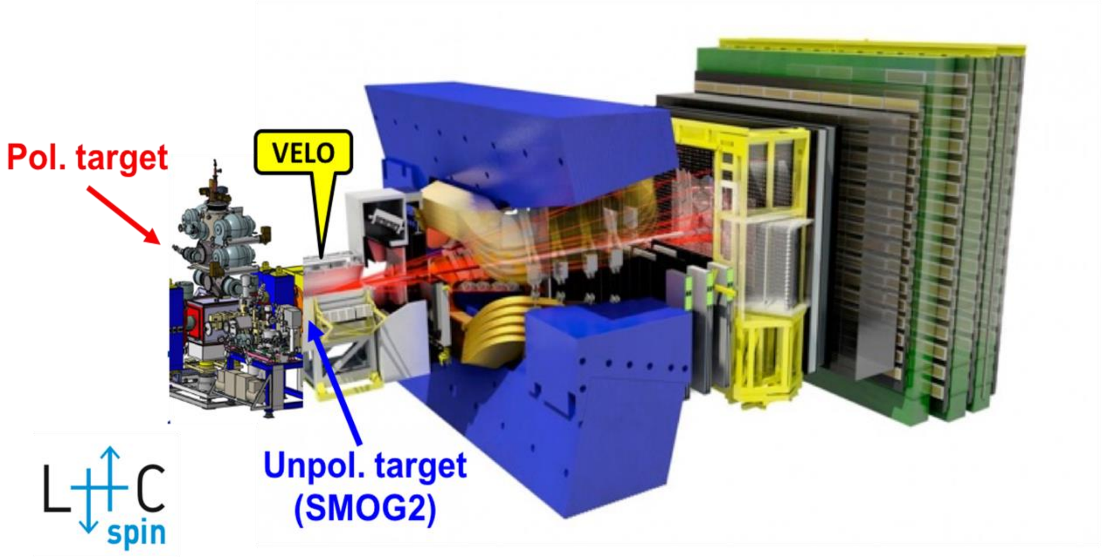
$\Lambda^0 \to p\pi^-$

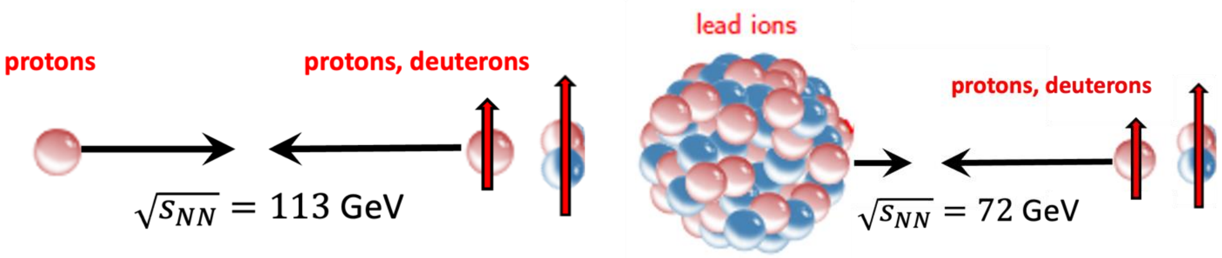


LHCB-FIGURE-2024-005

The LHCspin project

The **LHCspin** project represents the natural evolution of SMOG2 and will allow for the first time to perform **spin physics measurements at the LHC** through the implementation of a new-generation **polarized gaseous target** in the **LHCb** spectrometer.





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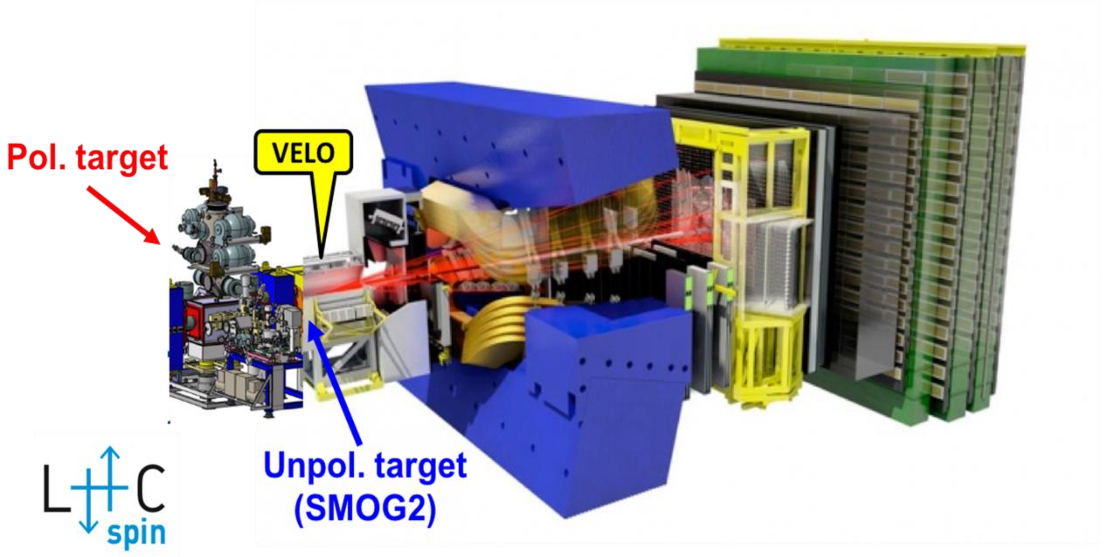

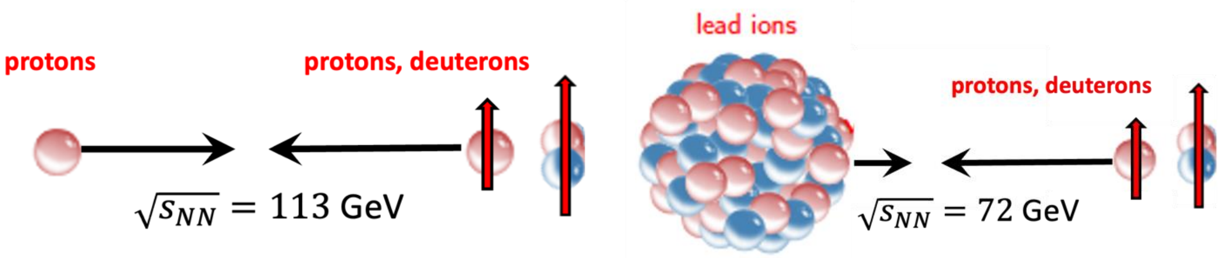

Physics Motivations

Study multi-dimensional nucleon structure at unique kinematic conditions (backward CM region, poorly explored large-x region at intermediate Q^2)

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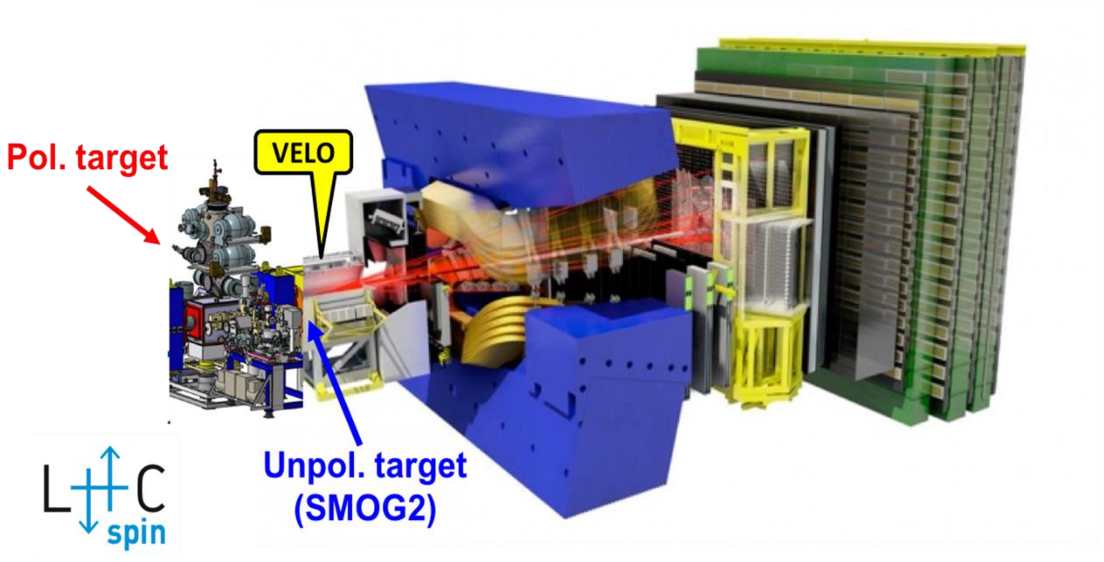

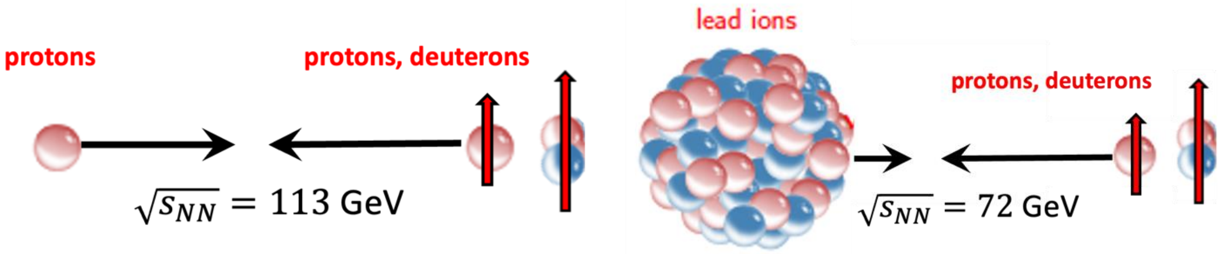

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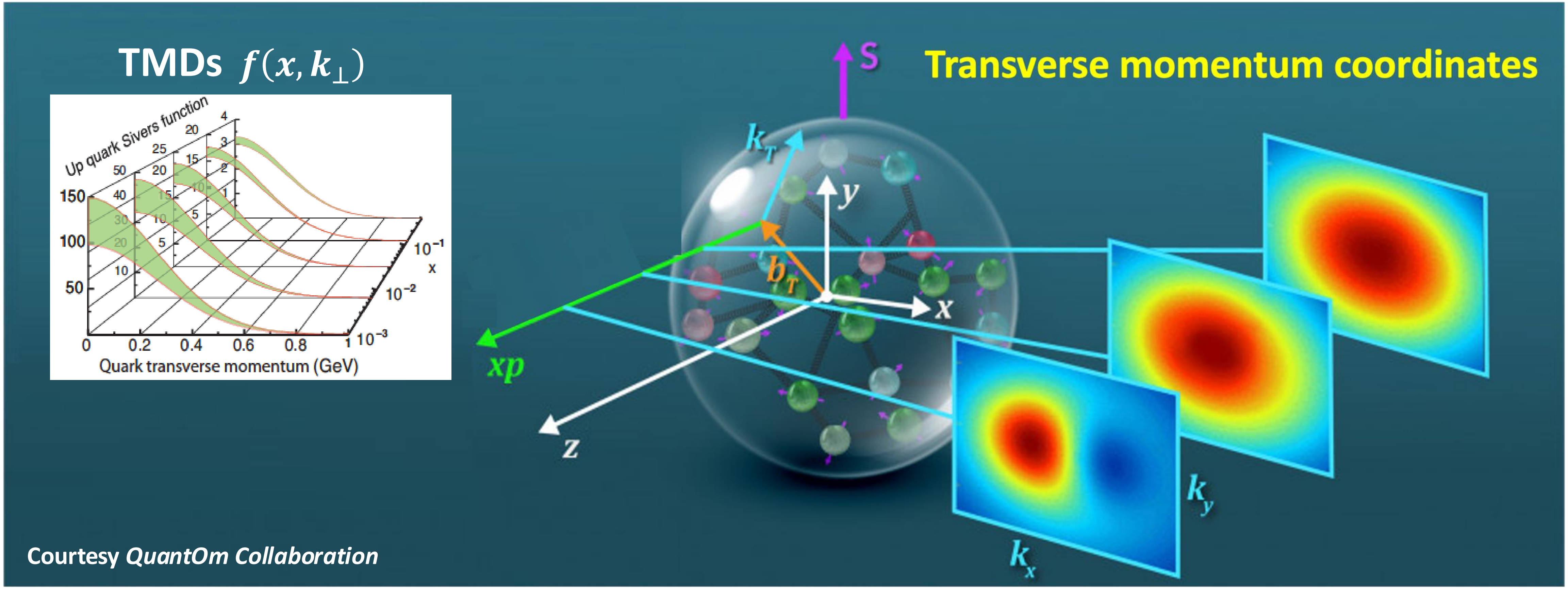
Points of strenght

- ✓ **use of well-established polarized gas target technology** (HERMES @ DESY, ANKE @ COSY,…)
- ✓ **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 ion beams**
- ✓ **allows also injection of non-polarized gases (a-la SMOG2):** $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- ✓ **broad and unique physics program** (next slides)

Nucleon tomography in momentum space: TMDs



- Describe **spin-orbit correlations of the form** $\vec{S} \cdot (\vec{p}_1 \times \vec{p}_2)$
- generate distorsions of the parton densities in transverse momentum plane (e.g. **Sivers effect**)
- can provide **sensitivity to unknown parton OAM!**

Quark and gluon 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}	$h_1,\ h_{1T}^\perp$

- **8 independent quark TMDs at leading-twist**
- **significant experimental progress in the last 20 years!**
- main results from SIDIS (HERMES, COMPASS, JLAB, → EIC)
- many phenomenological extractions available from global analyses

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- different naïve-time-reversal properties
- **Experimental access still very limited!**

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

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LHCspin

Polarized hadronic collisions with LHCspin offer a complementary approach!

- Measure experimental observables sensitive to both **quarks and gluons TMDs**
- Make use of new probes (charmed and beauty mesons)
- Test non-trivial process dependence of quarks and (especially) gluons TMDs

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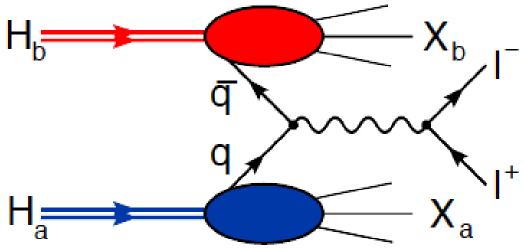
Unpolarized Drell-Yan



- Theoretically cleanest hard h-h scattering process
- LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$
- dominant: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- beam sea quarks probed at small x
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quark pol. (columns) / nucleon pol. (rows)

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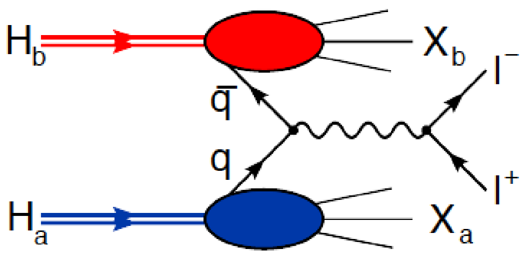

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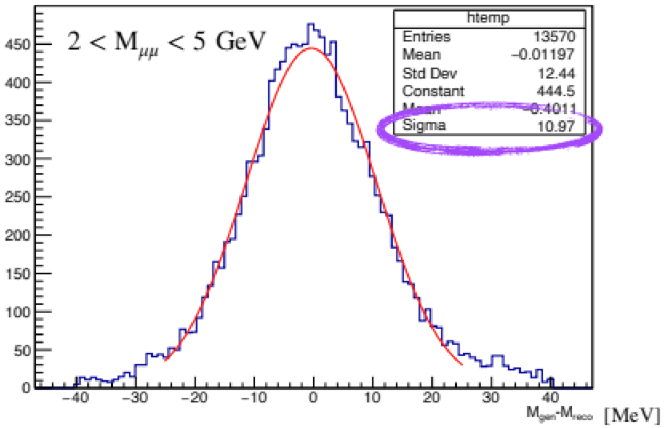
Expected mass resolution
$\sim 10\ MeV$ in $2 < M_{\mu\mu} < 5\ GeV$



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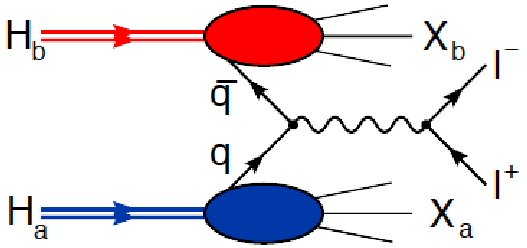

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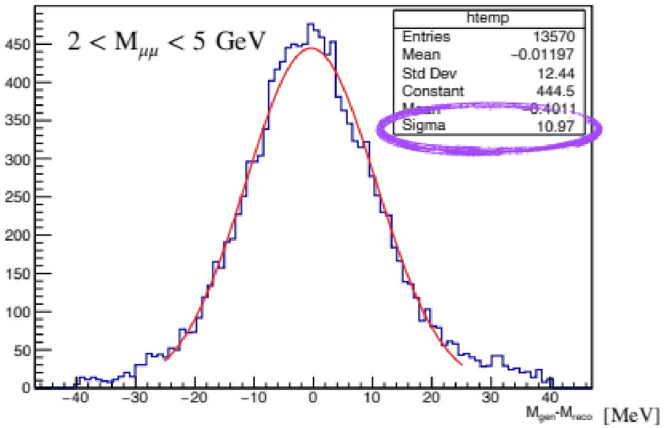

Sensitive to unpol. and BM TMDs

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

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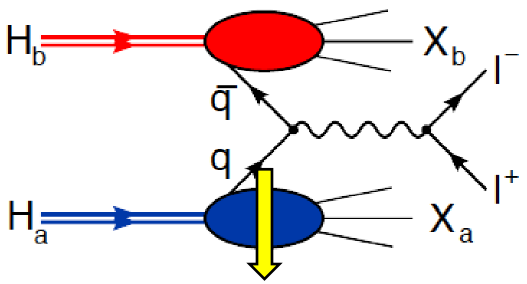
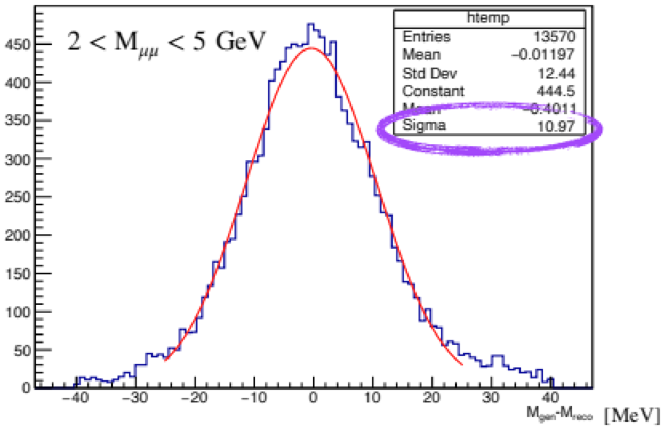
Transv. polarized Drell-Yan



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

Expected mass resolution

$\sim 10\ MeV$ in $2 < M_{\mu\mu} < 5\ GeV$



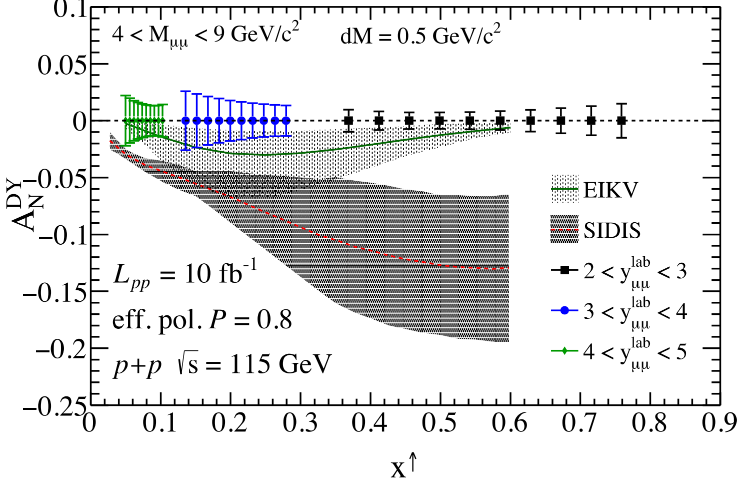
Sensitive to unpol. and BM TMDs

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

Sensitive to quark TMDs through TSSAs

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

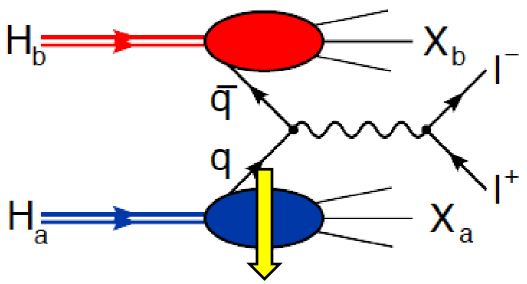
[arXiv:1807.00603]



Quark TMDs

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

Transv. polarized Drell-Yan



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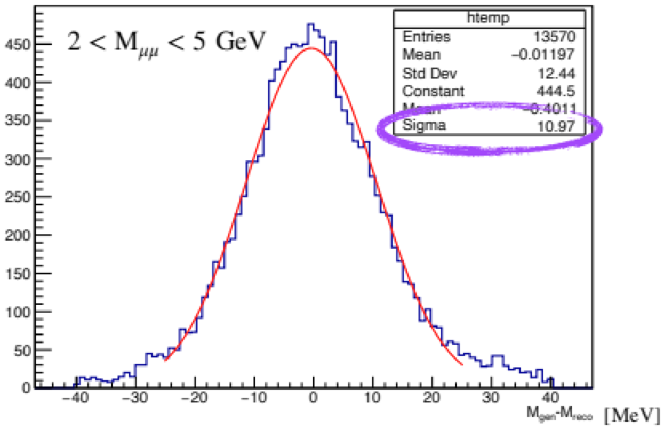

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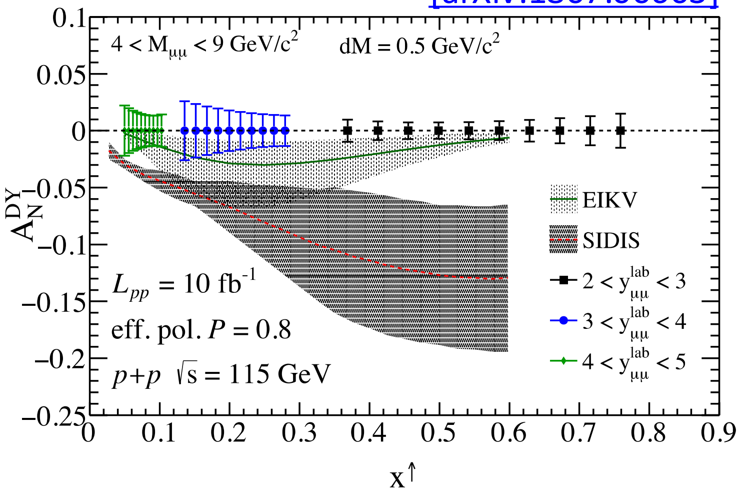


- In DY extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers func. wrt SIDIS

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

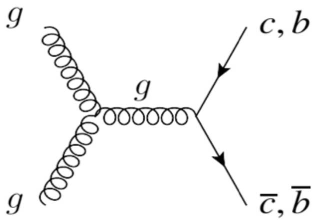
- Test flavour sensitivity using both H and D targets

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

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**

Gluon TMDs

gluon pol. (columns) / nucleon pol. (rows)

	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
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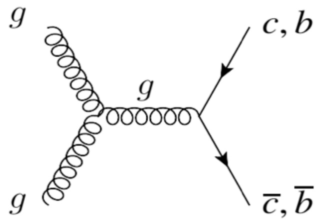

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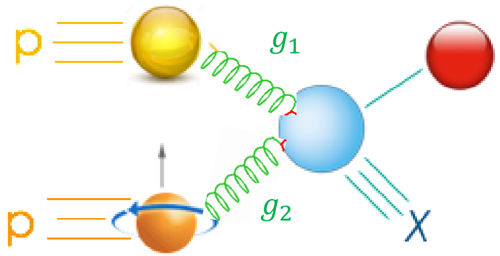

$$\begin{cases} \eta_c, \chi_{c0}, \dots \\ \eta_b, \chi_{b0}, \dots \\ J/\psi, \psi', \dots \\ \Upsilon(nS) \end{cases}$$

Polarized gTMDs can be accessed through TSSAs in **inclusive heavy meson production**

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

Gluon TMDs

gluon pol. / nucleon pol.

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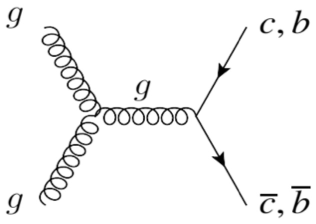

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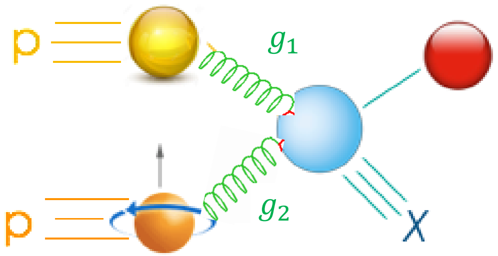

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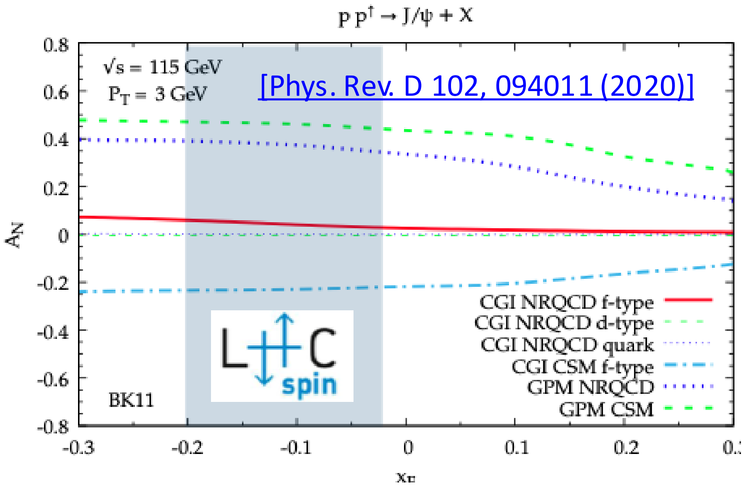
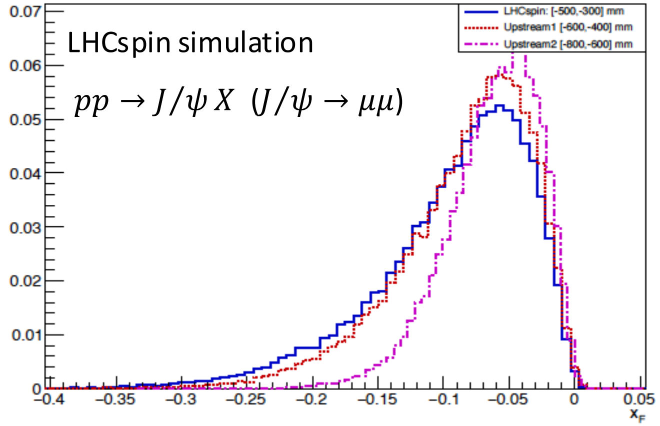
Gluon Sivers function:

- Sheds light on spin-orbit correlations of unpol. gluons inside a transv. pol. proton
- is sensitive to gluon OAM





Probing the gluon TMDs

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, e.g.: $pp^{(\uparrow)} \to J/\psi + J/\psi + X$

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$$\Big\{ F_1(M_{QQ},\theta_{CS})\, \mathcal{C}\left[f_1^g f_1^g\right](x_{1,2},\boldsymbol{P}_{QQ_T}) + F_2(M_{QQ},\theta_{CS})\, \mathcal{C}\left[w_2 h_1^{\perp g} h_1^{\perp g}\right](x_{1,2},\boldsymbol{P}_{QQ_T})$$

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gluon pol. / nucleon pol.

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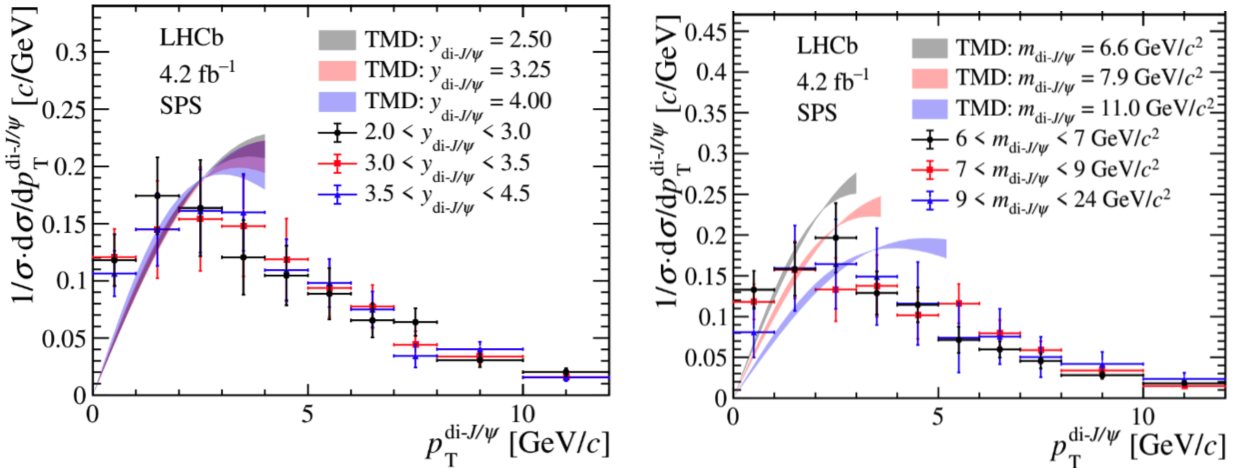
Probing the gluon TMDs

$pp, 13\ TeV$ JHEP 03 (2024) 088



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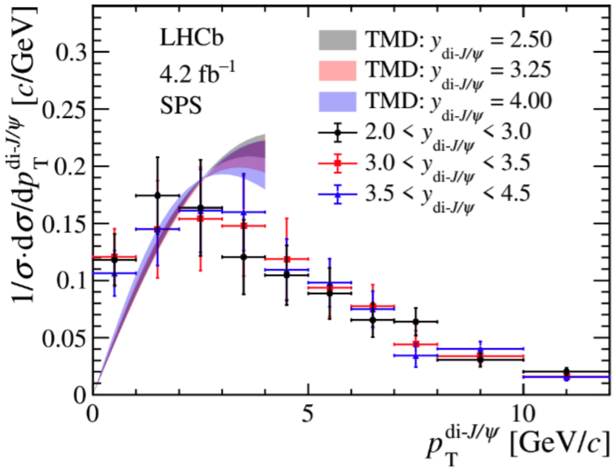

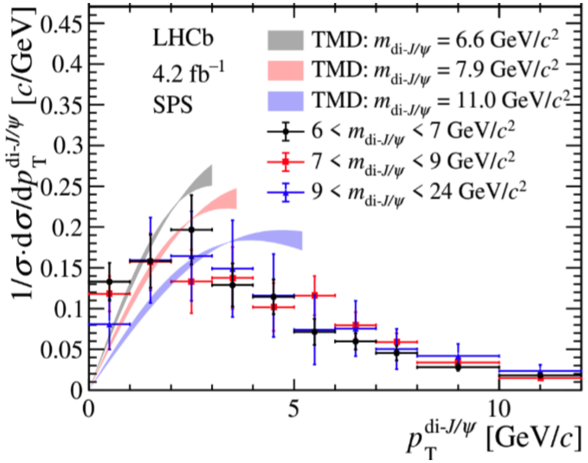

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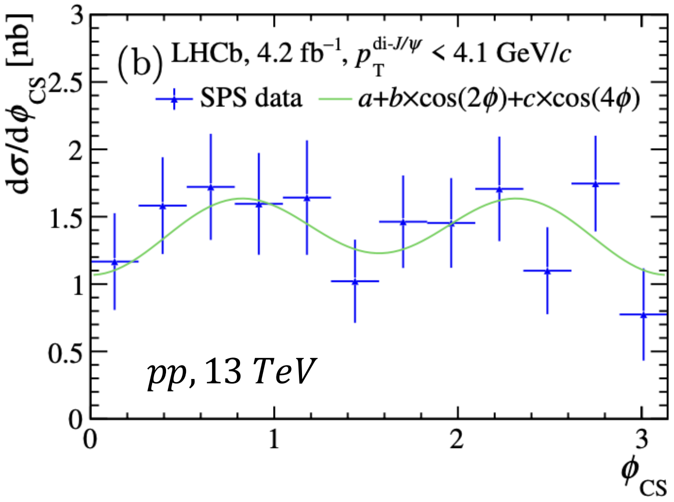


JHEP 03 (2024) 088

$$\langle \cos 2\phi_{CS} \rangle = -0.029 \pm 0.050\ (\text{stat}) \pm 0.009\ (\text{syst})$$
$$\langle \cos 4\phi_{CS} \rangle = -0.087 \pm 0.052\ (\text{stat}) \pm 0.013\ (\text{syst})$$

- azimuthal amplitudes consistent with zero
- a few-% asymmetry cannot be excluded
- uncertainties statistically dominated
- But very challenging at fixed-target kinematics

GPDs: a complementary approach to the nucleon tomography

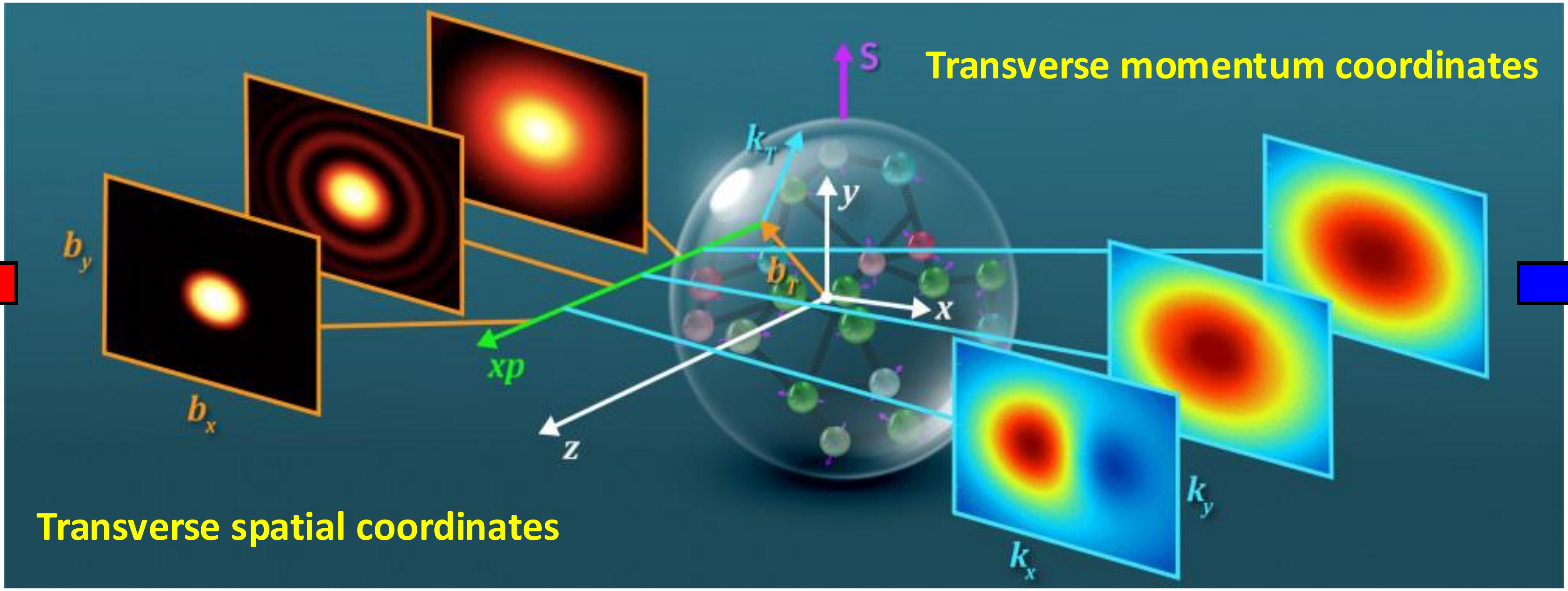
nucleon tomography in coord. space

$f(x, r_\perp)$

FT ↓

GPDs

$H(x, \xi, t)$



Courtesy *QuantOm Collaboration*

nucleon tomography in mom. space

TMDs

$f(x, k_\perp)$

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

quark pol.

nucleon pol.	U	L	T
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Gluon GPDs and UPC

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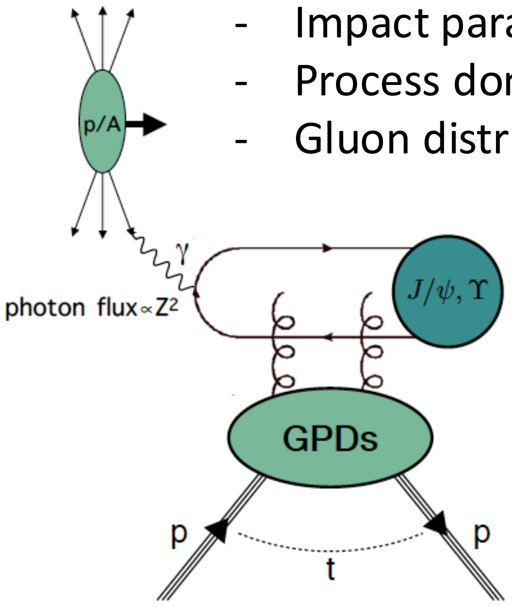
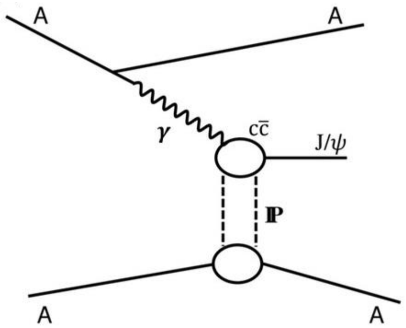
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

Gluon GPDs can be accessed at LHC in **Ultra-Peripheral collisions (UPC)** where a quasi-real photon is emitted by the relativistic beam particle [PRD 85 (2012), 051502]

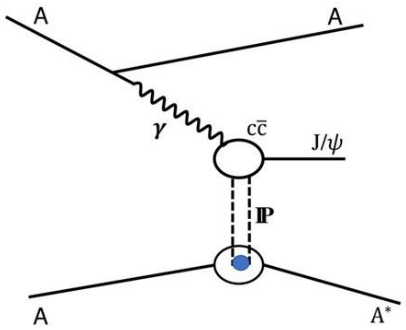
At LHC energies, these photons are energetic enough to trigger the production of hard dileptons and charmonia and bottomonia.

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





Coherent UPC:
pomeron emitted by entire nucleus



Incoherent UPC:
pomeron emitted by single nucleon

Gluon GPDs and UPC

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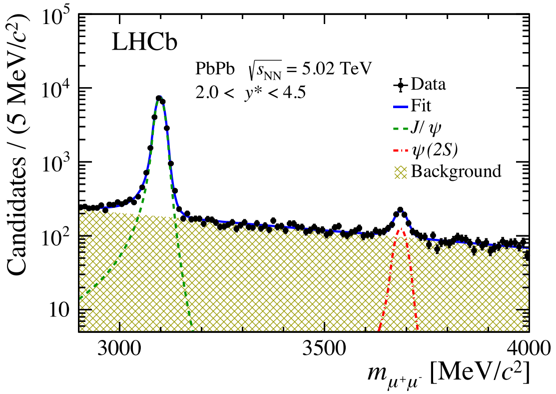
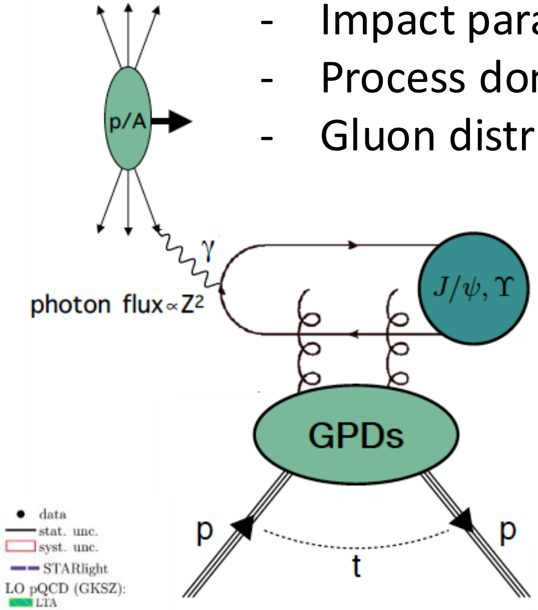


J. High Energ. Phys. 2023

Pb-Pb collisions

$\sqrt{s_{NN}} = 5.02\ TeV$



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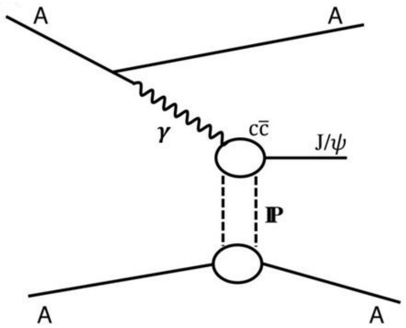
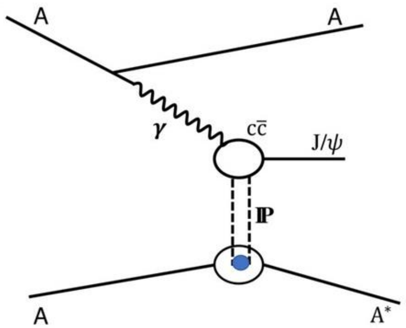
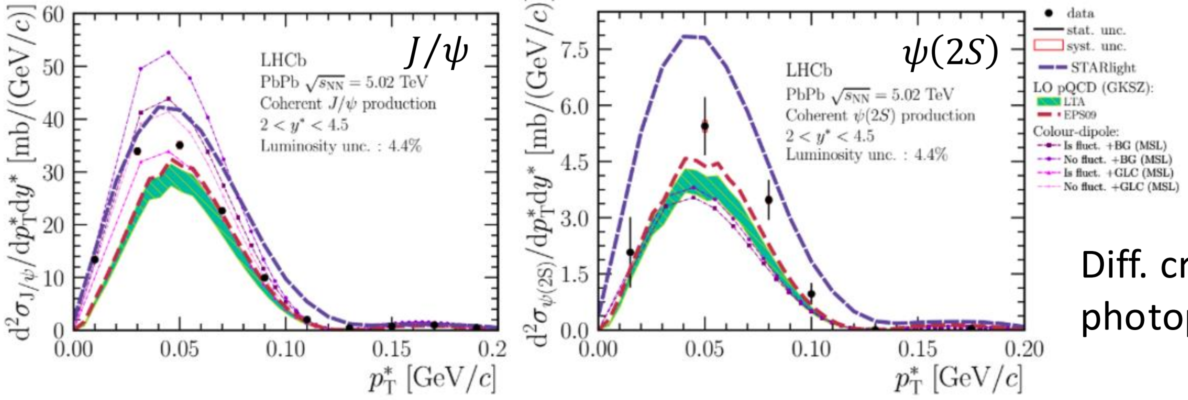


Coherent UPC: pomeron emitted by entire nucleus



Incoherent UPC: pomeron emitted by single nucleon



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

Gluon GPDs and UPC

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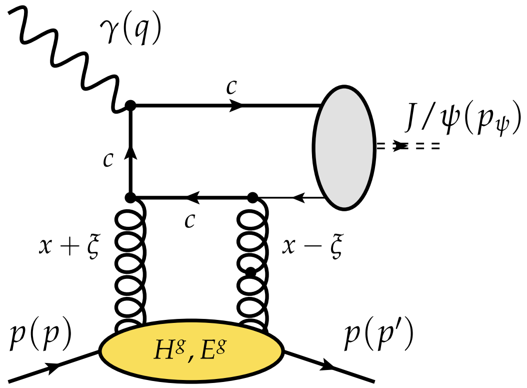
With LHCspin exclusive photo-production of J/ψ in UPC of proton (or lead) beams with polarized $H^{\uparrow}$ target can be studied, providing constraints to the essentially unknown **gluon GPD E_g** which plays a crucial role in the Ji sum rule:

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



Gluon GPDs and UPC

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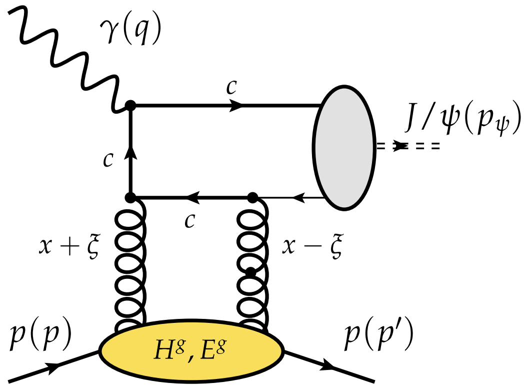
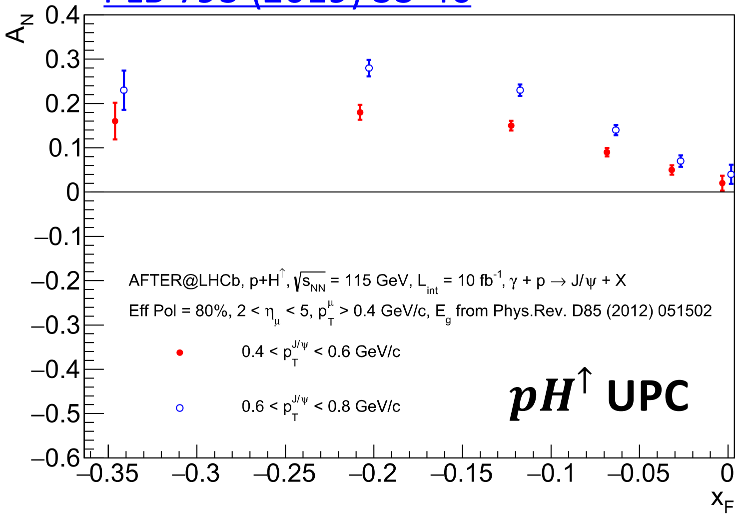
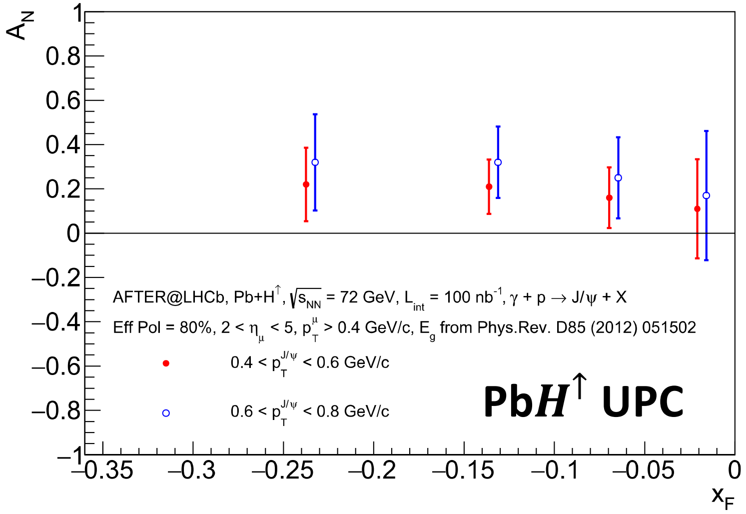


$$A_N = \frac{\sigma^{h_A h_B^\downarrow} - \sigma^{h_A h_B^\uparrow}}{\sigma^{h_A h_B^\downarrow} + \sigma^{h_A h_B^\uparrow}} = \frac{\int dk \frac{dn_A}{dk} A_N^\gamma\, \sigma^{\gamma h_B}}{\int dk \left[\frac{dn_A}{dk}\sigma^{\gamma h_B} + \frac{dn_B}{dk}\sigma^{\gamma h_A}\right]}$$

The hadronic STSA A_N can be parametrized in terms of the photonic STSA A_N^γ which incorporates the GPDs H^g and E^g through their gluonic CFFs $\mathcal{H}^g$ and $\mathcal{E}^g$

PLB 793 (2019) 33-40

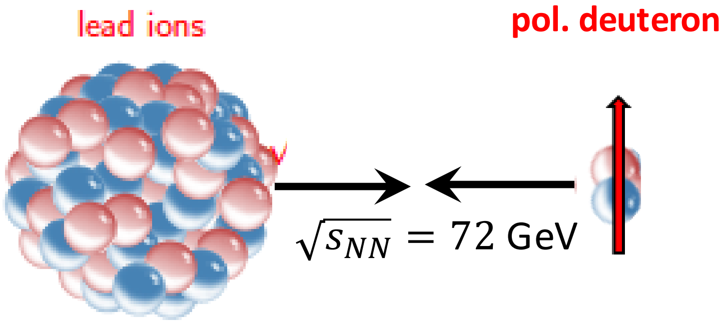




- Extraction based on models for the GPD H^g (Goloskokov-Kroll) and E^g (PRD 85, 051502 (2012))
- AFTER model-dependent predictions **very promising for $pH^\uparrow$ UPC**

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**).



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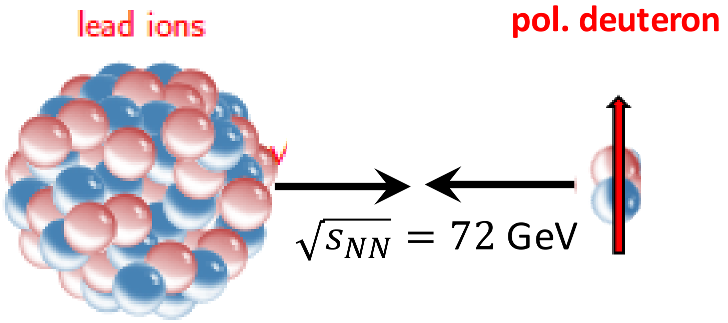

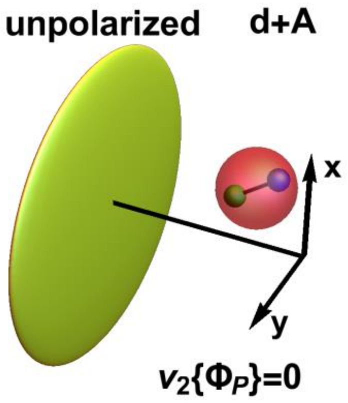

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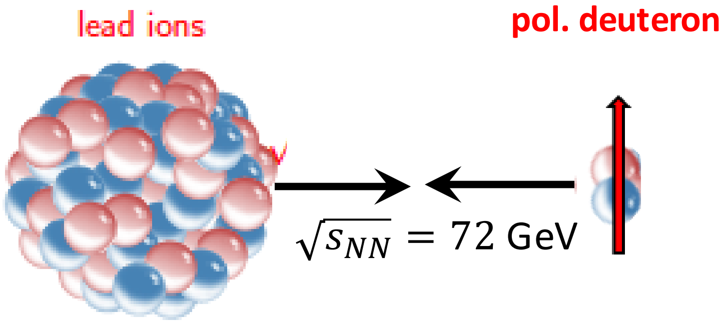

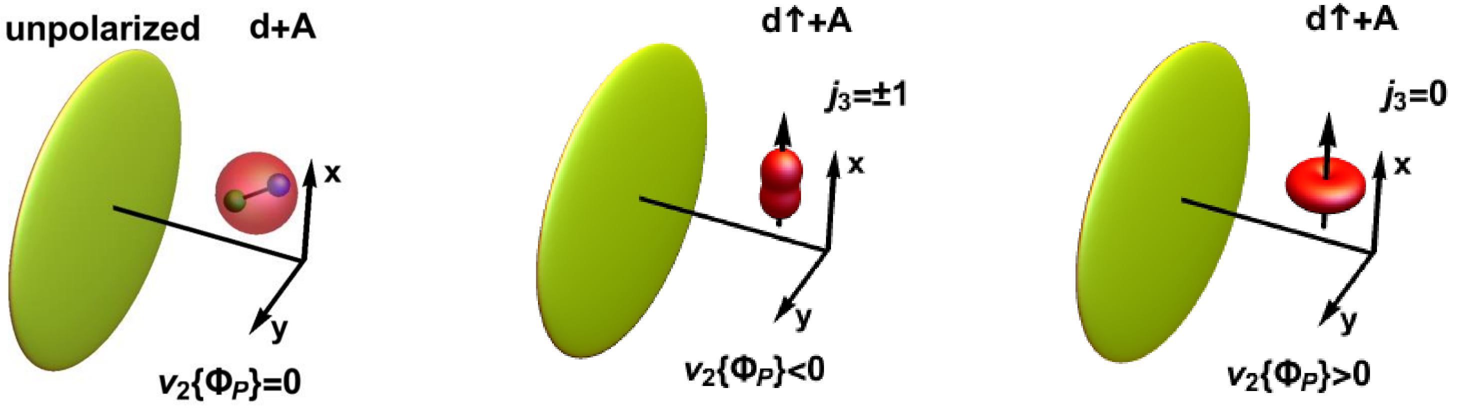

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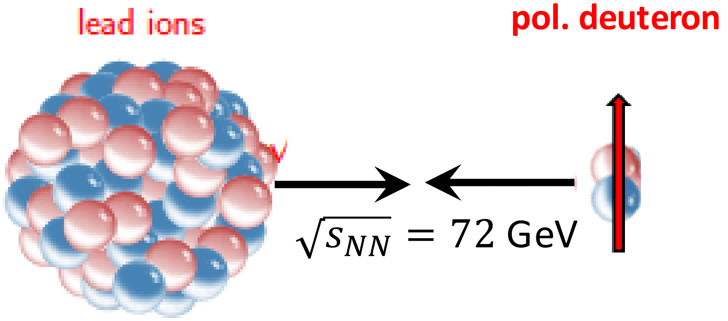

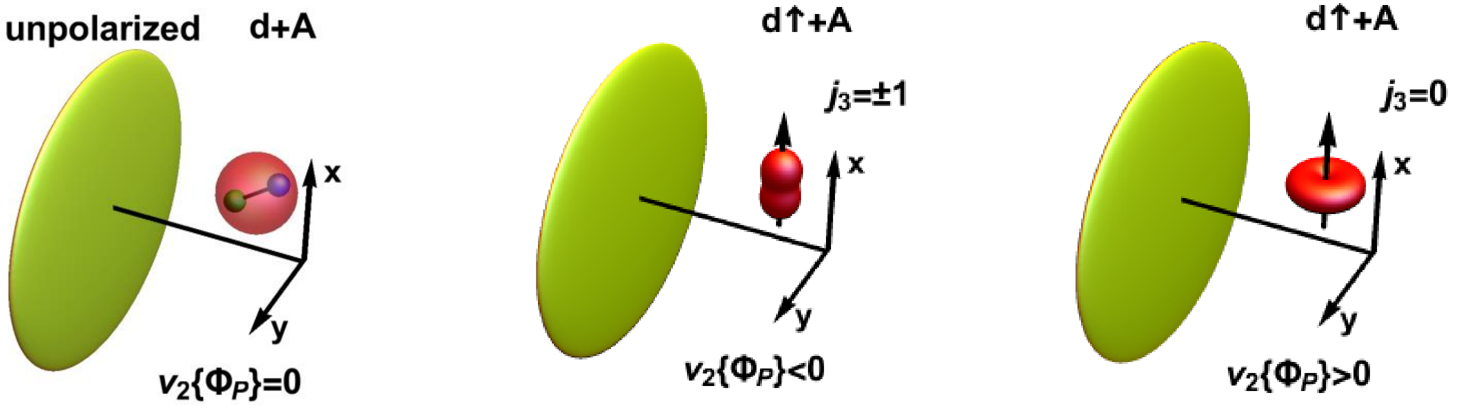

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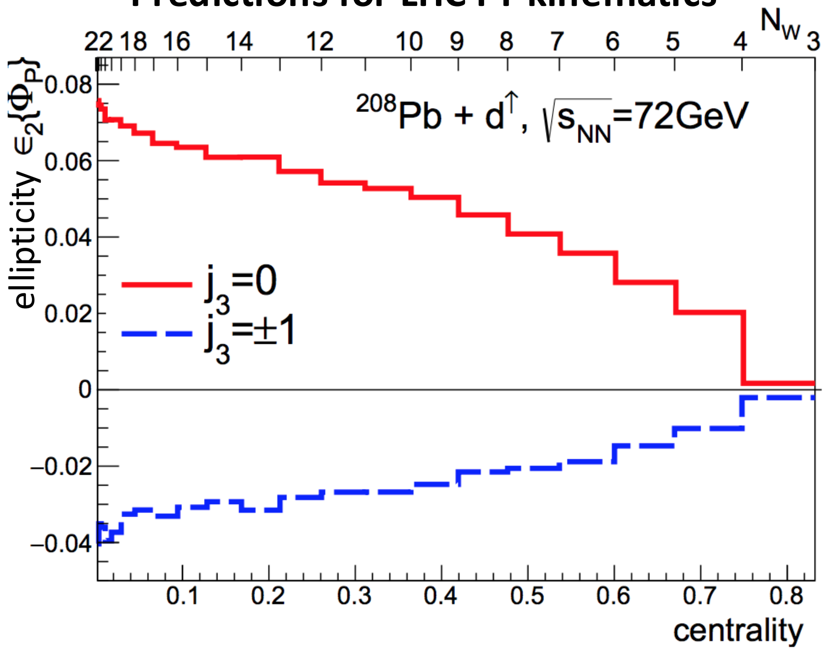
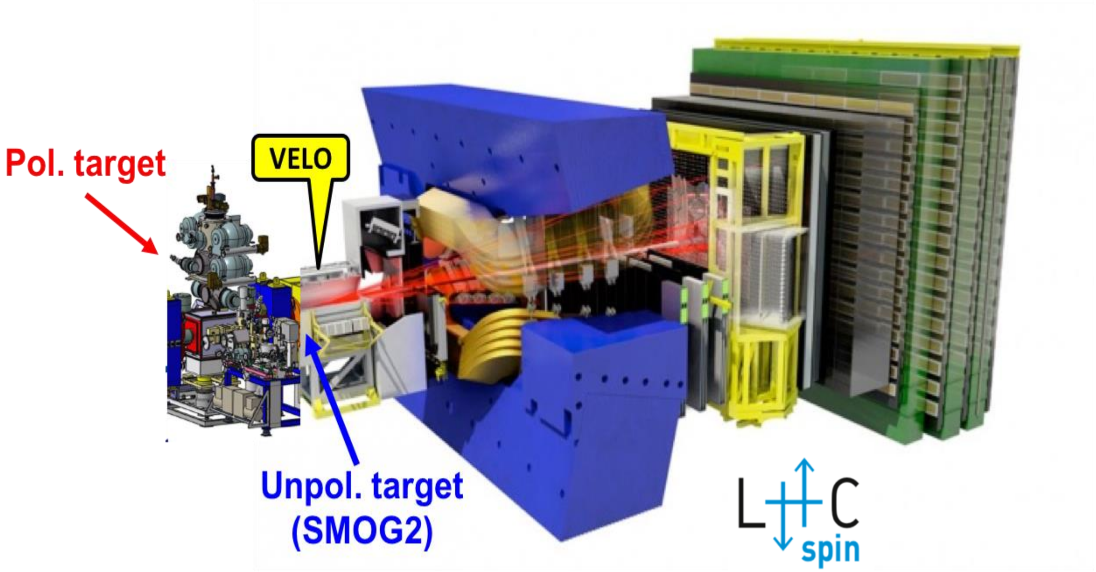
Predictions for LHC FT kinematics



[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



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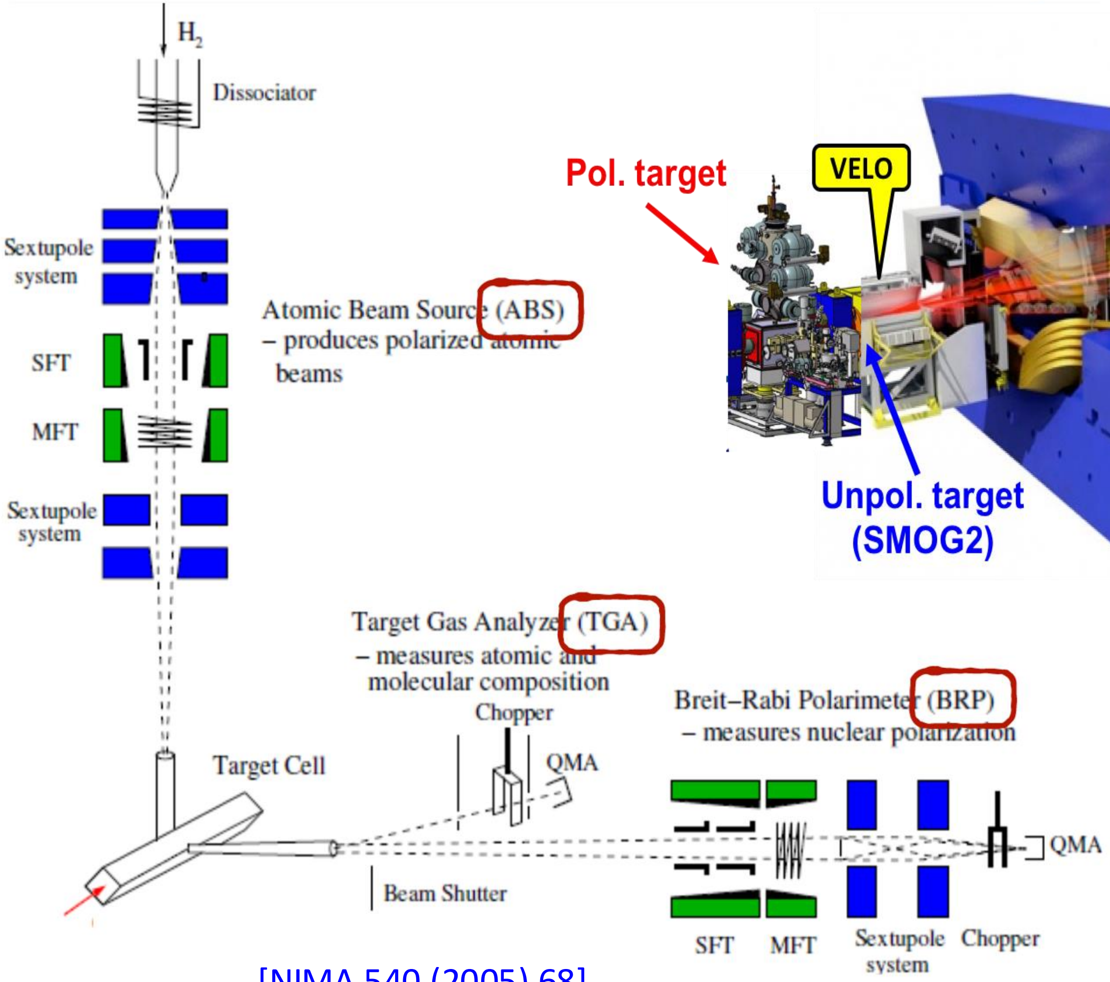

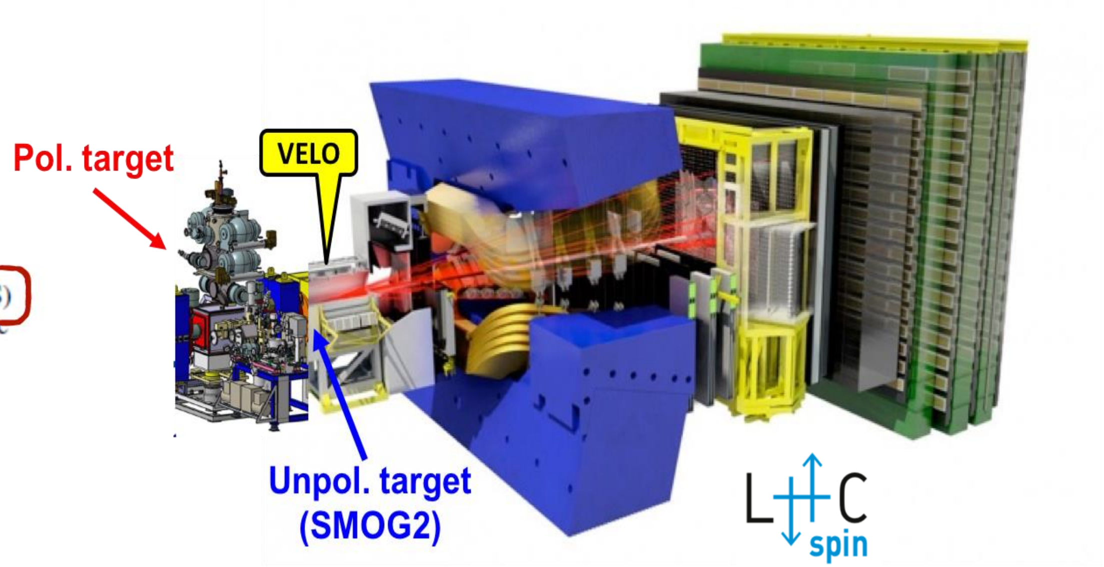

[NIMA 540 (2005) 68]

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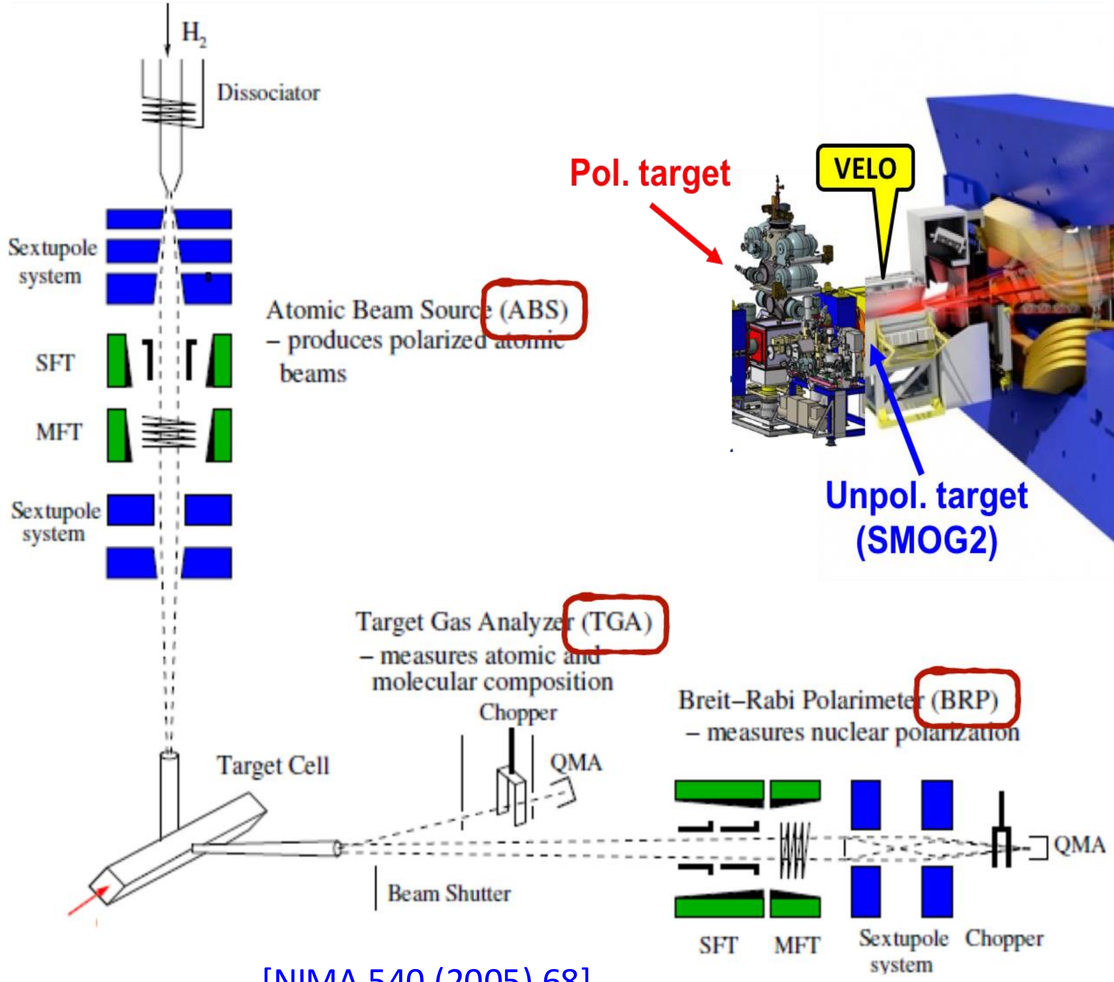

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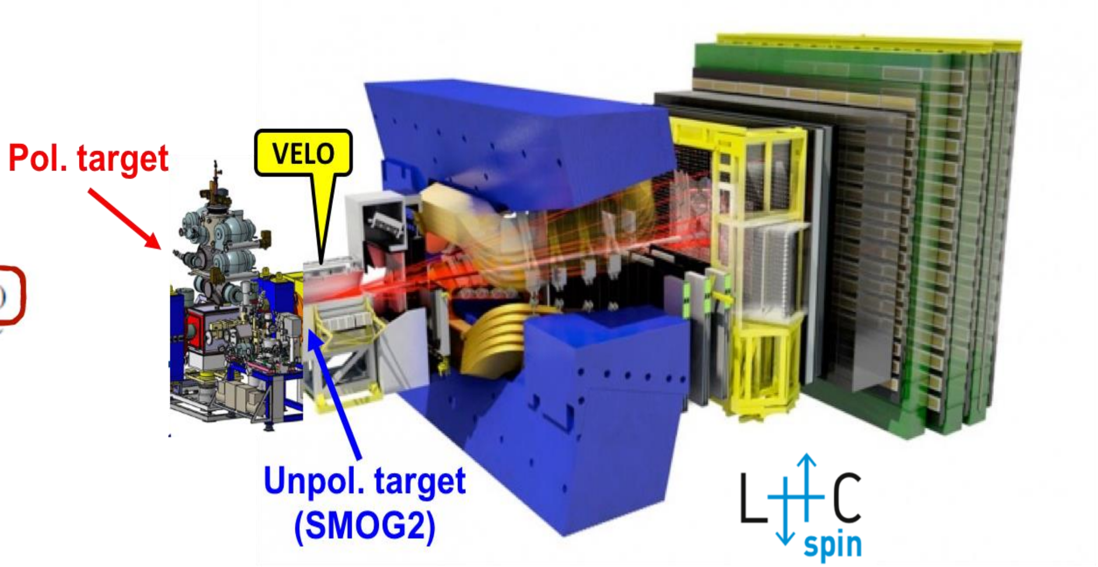

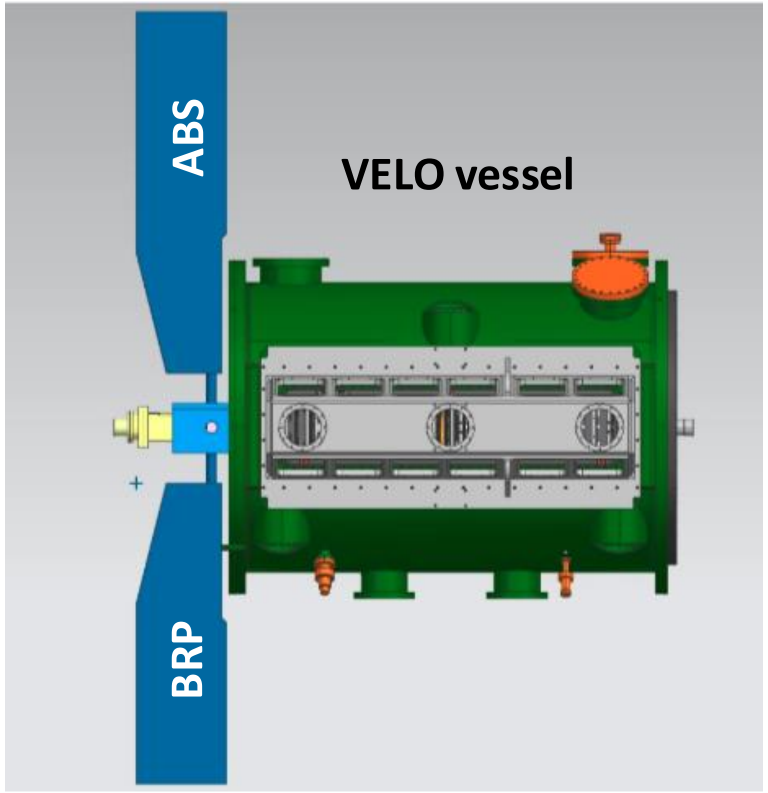

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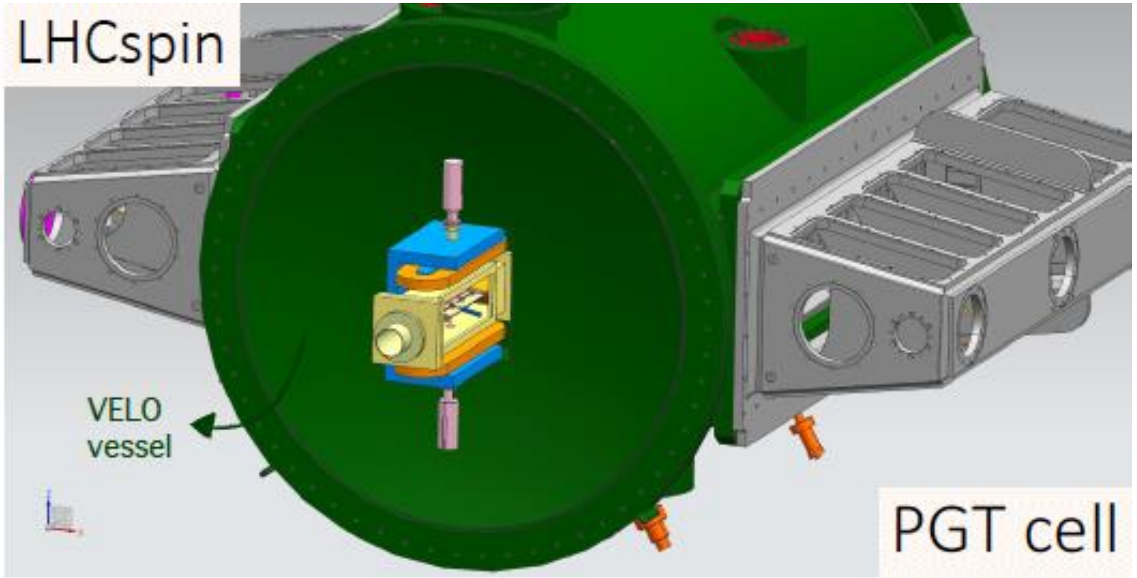

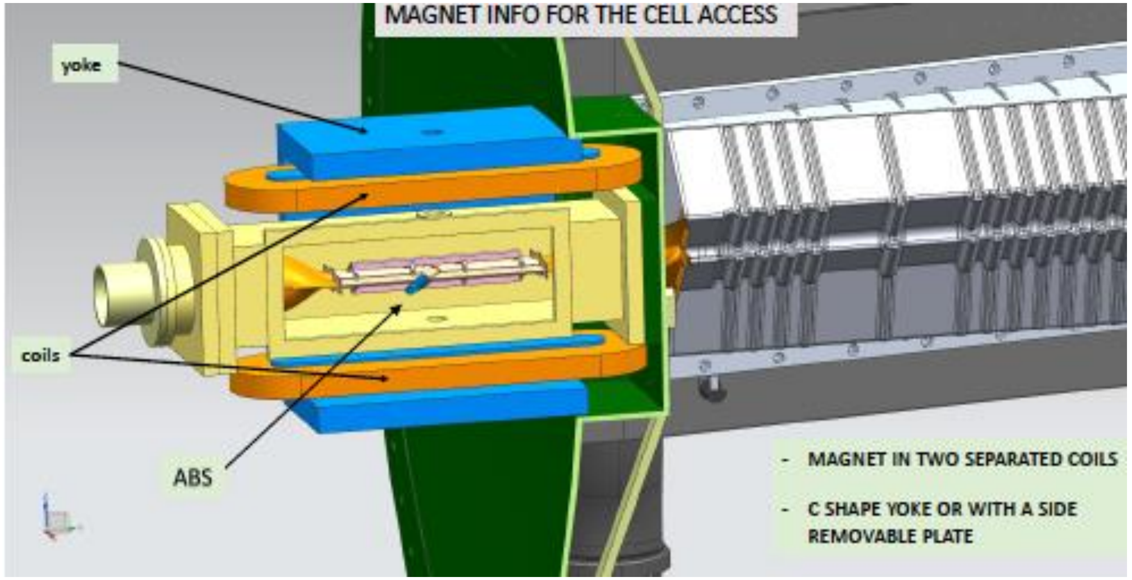

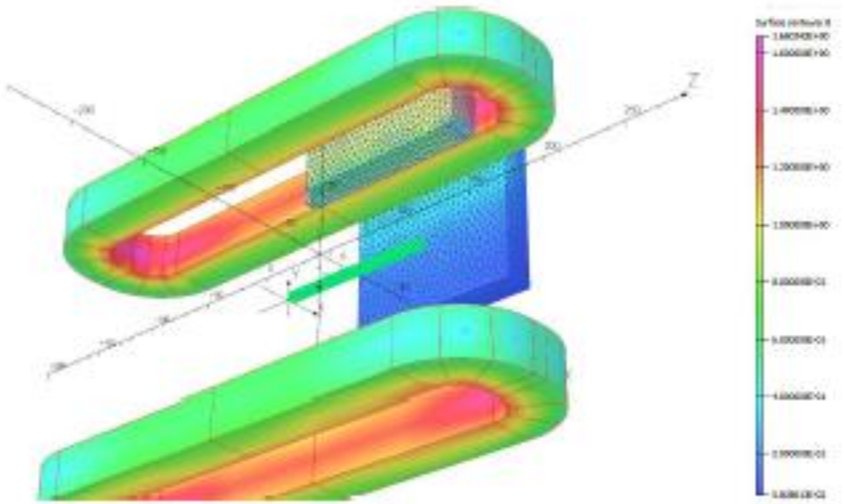

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- **Required $B = 300\ mT$ with $\Delta B/B \sim 10\%$**

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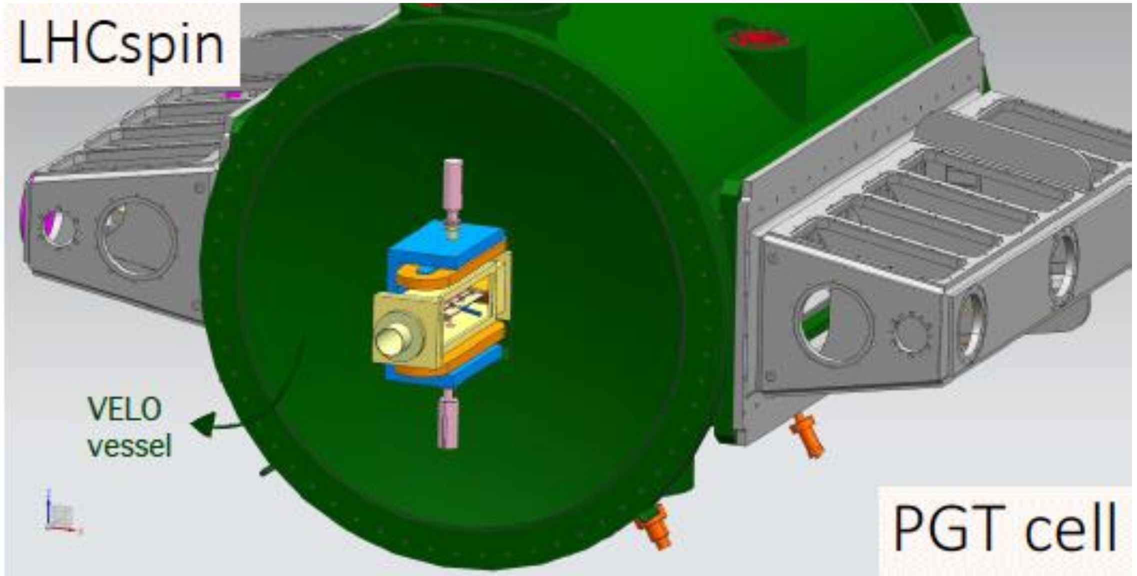

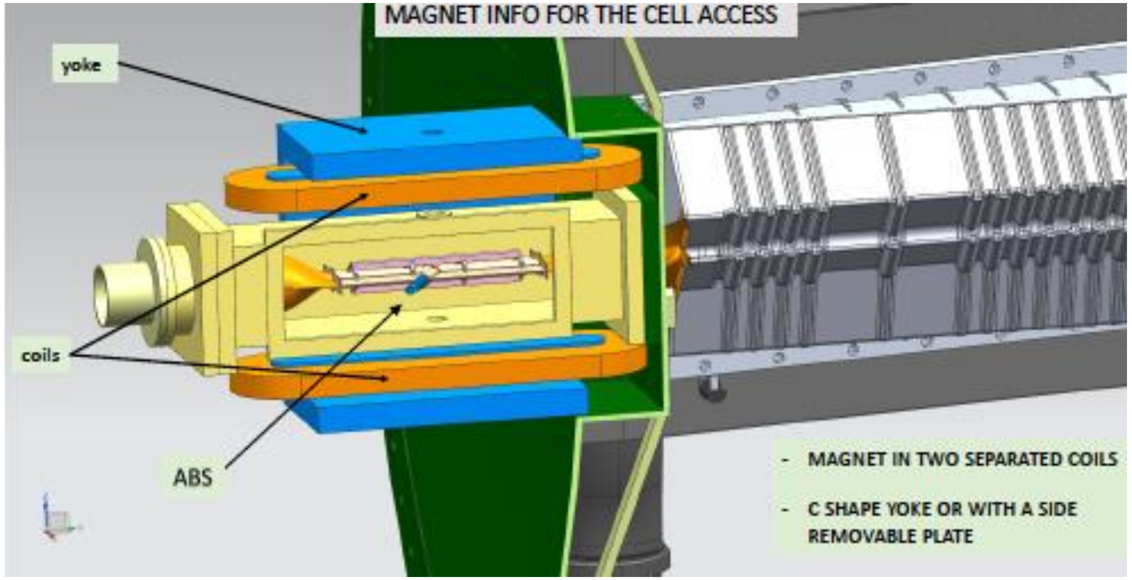

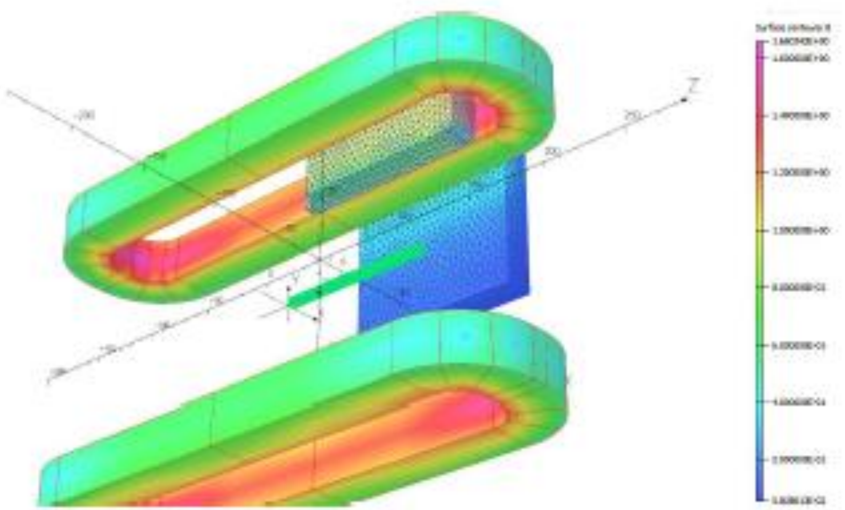

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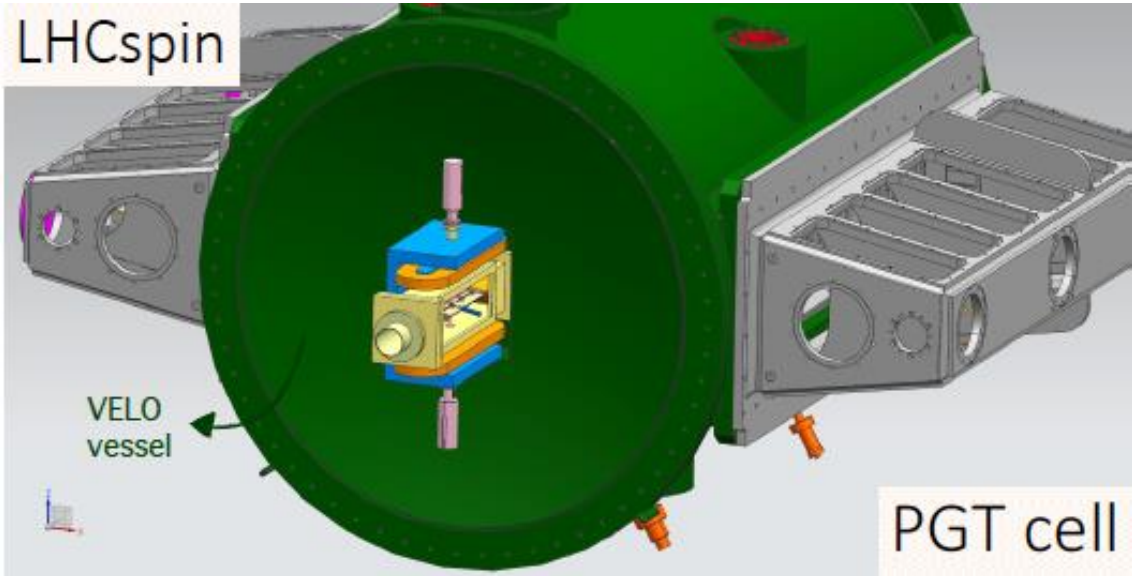

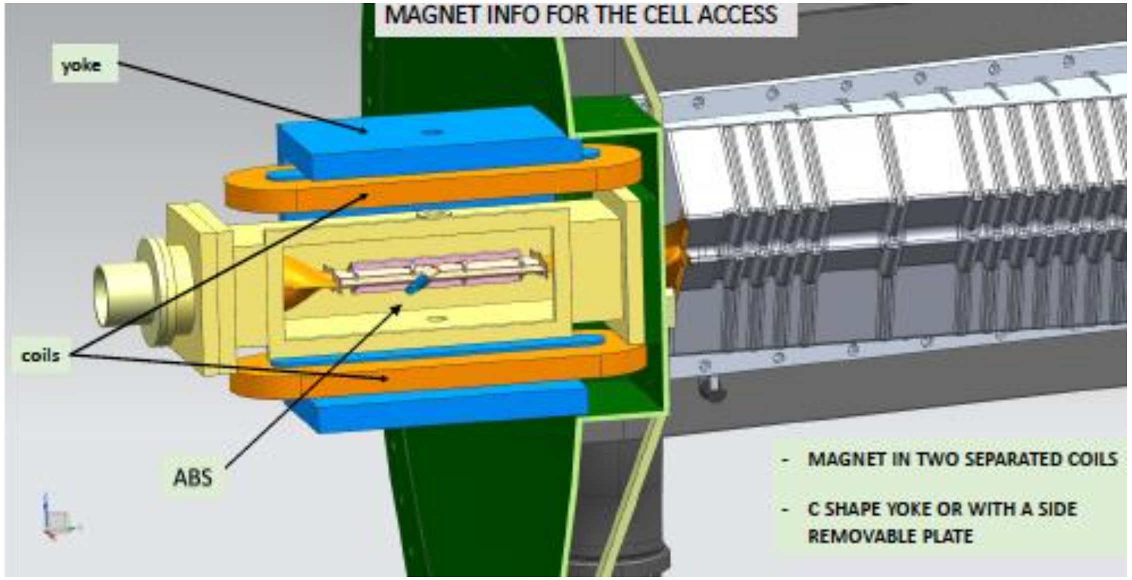

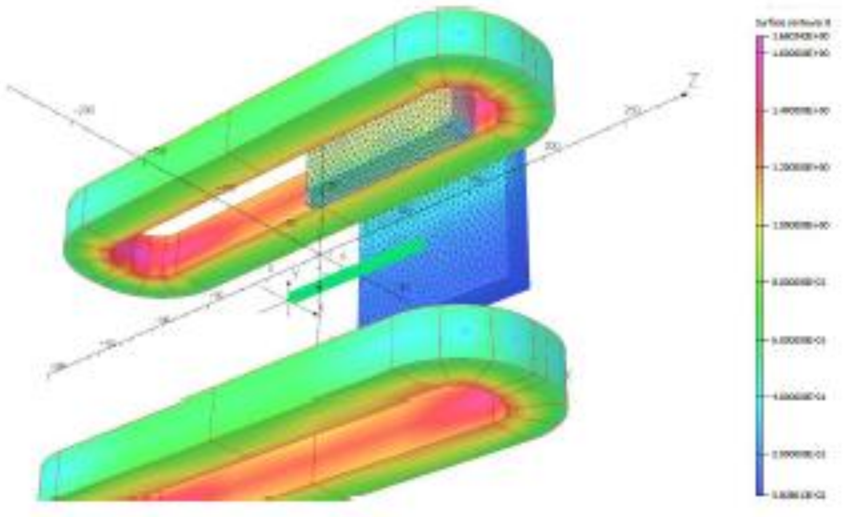

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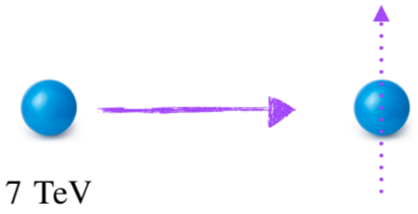
- **Possibility to switch from dipole magnet to solenoid to realize a Longitudinal polarized target in a future phase**

Kinematic coverage



$$\sqrt{s} = \sqrt{2 m_N E_p} = 115\ GeV$$

$$x_F = 2\, E_T / \sqrt{s}\ \sinh(y^*) \qquad E_T = \sqrt{M^2 + p_T^2}$$

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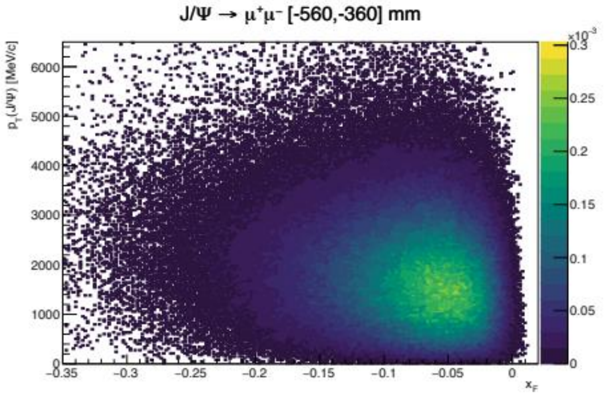
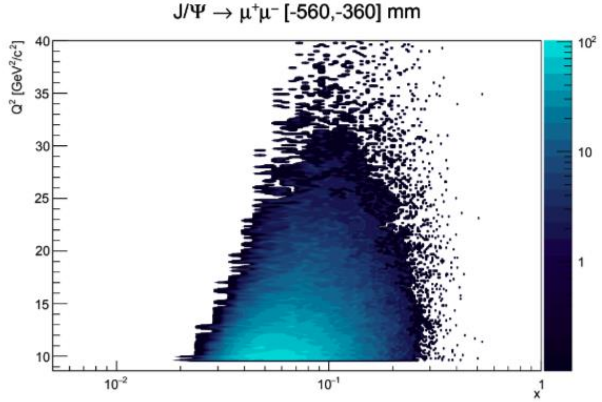
The kinematic coverage **depends on the cell position:**

- SMOG2 cell position: [-560,-360] mm





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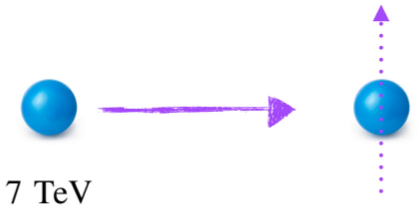

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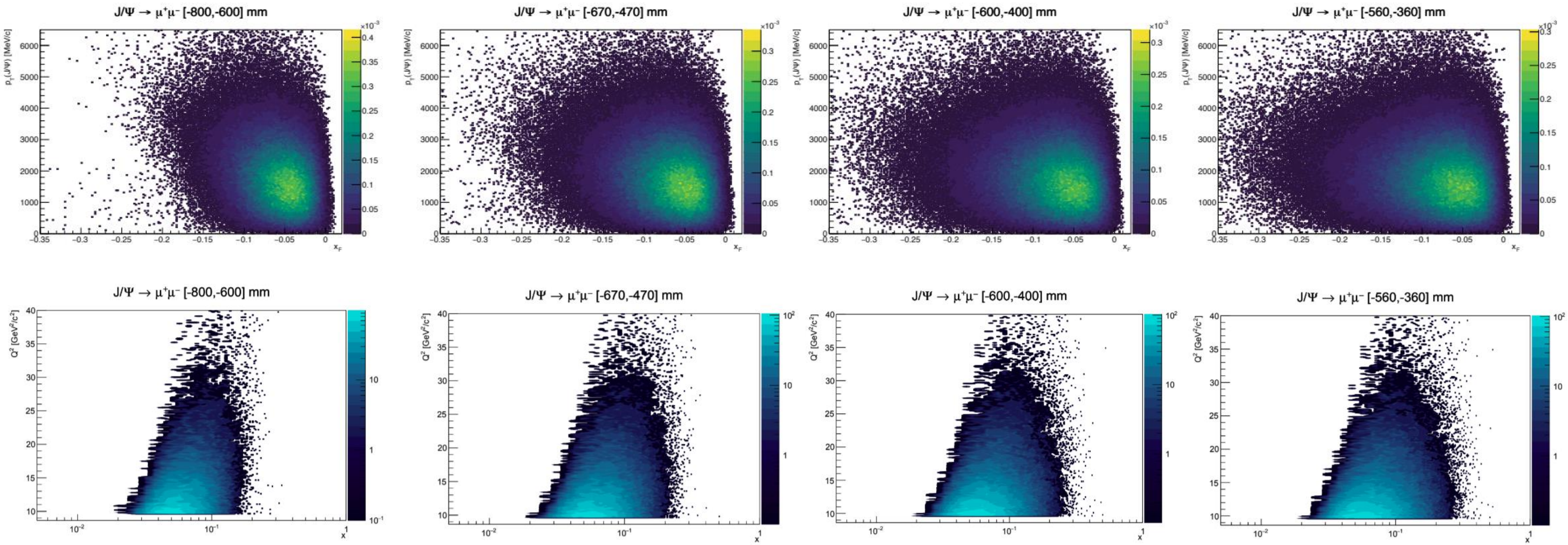

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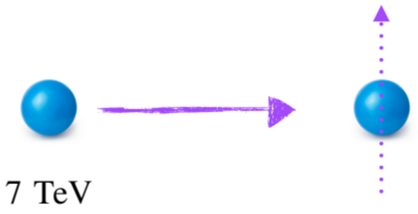

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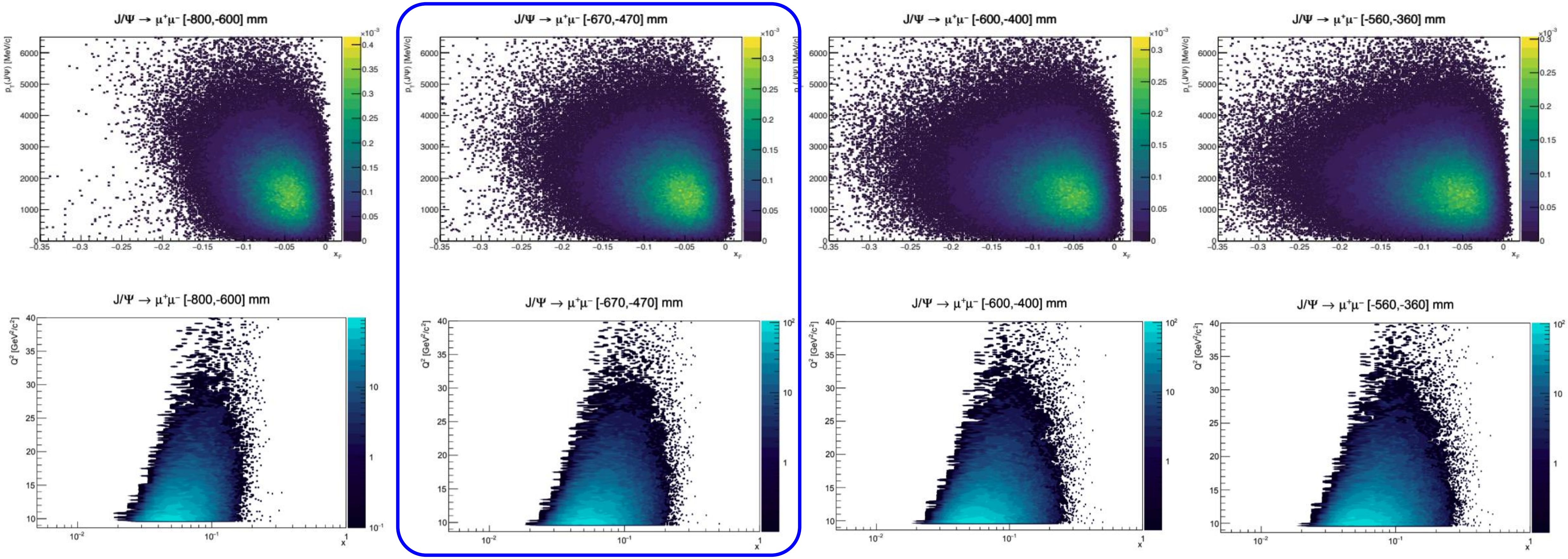
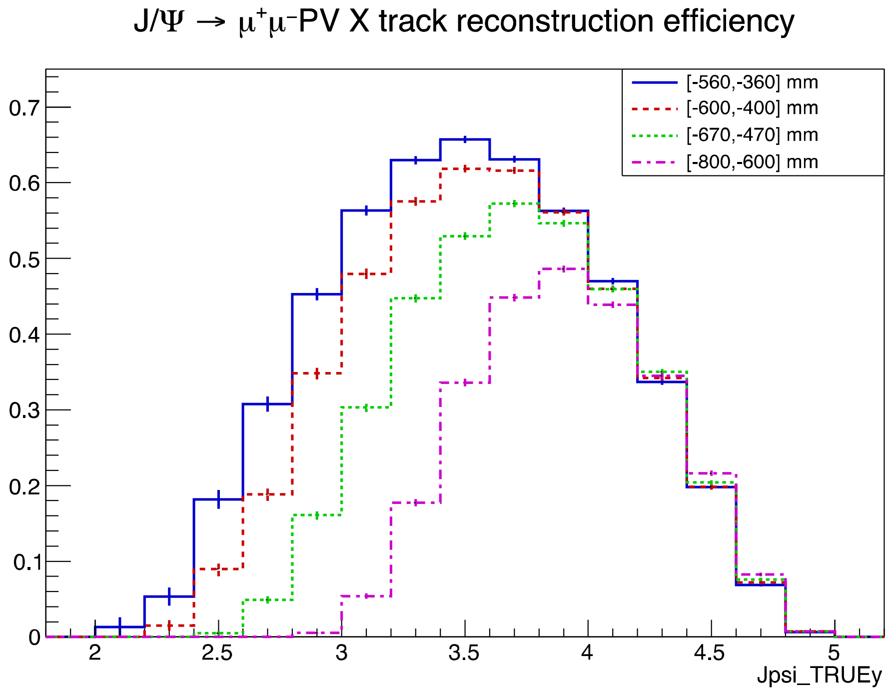


Expected performance



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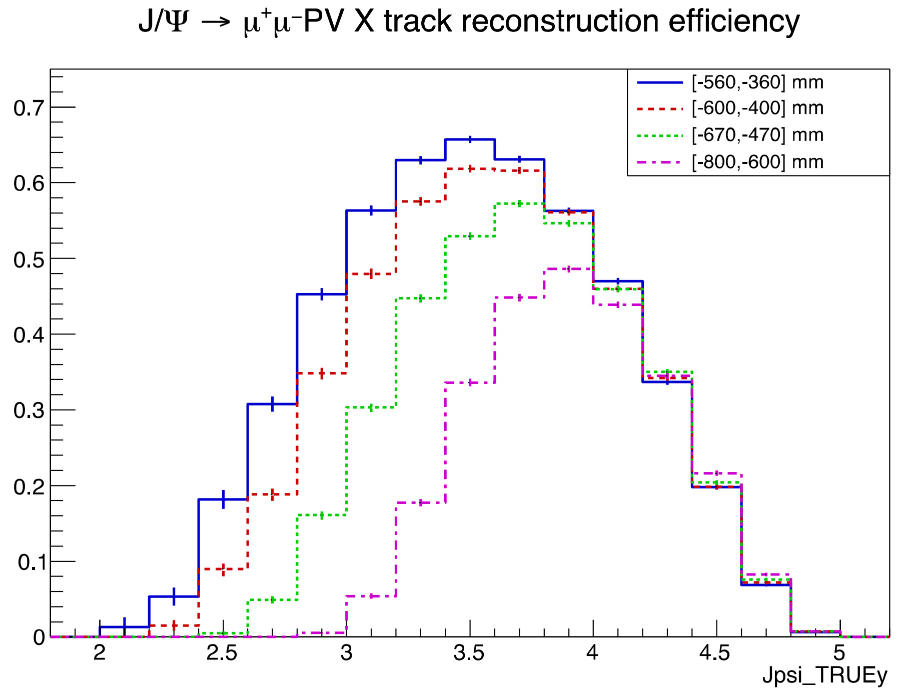

Target

- $I_0 = 6.5 \cdot 10^{16} s^{-1}$ (HERMES)
- C_{tot} = 17.4 l/s (20 cm cell)
- **θ= 3.7 ·10^{13} atoms/cm^2**

Beam (Run4)

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

$$\boldsymbol{\mathcal{L}_{pH} \approx 2.5 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

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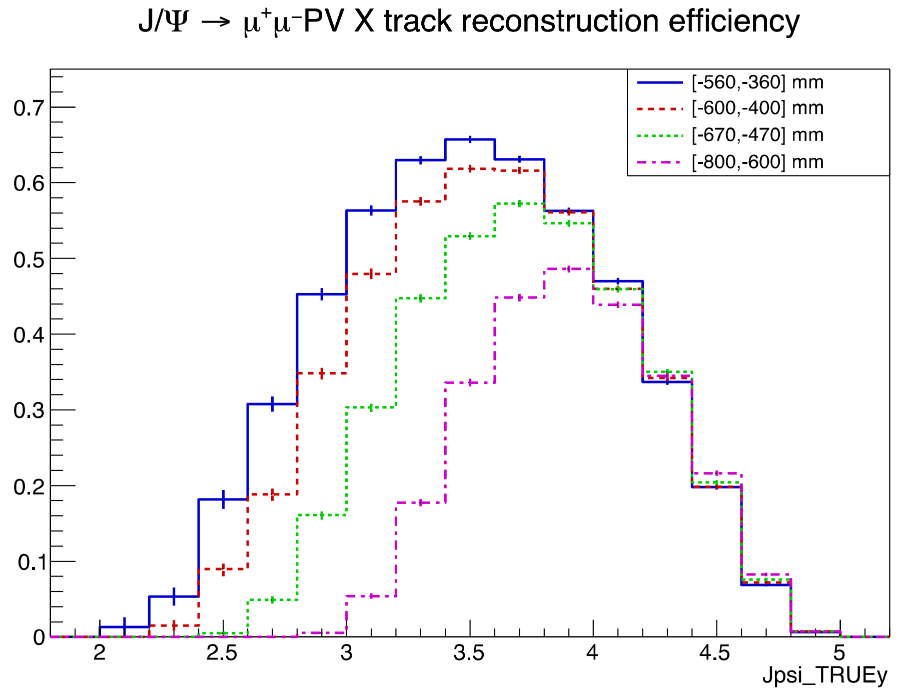

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$\psi(2S) \to \mu^+\mu^-$	4.6×10^5	5.5×10^7
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- fully reconstructed and selected events (after cuts)!
- based on extrapolation of current SMOG2 performance

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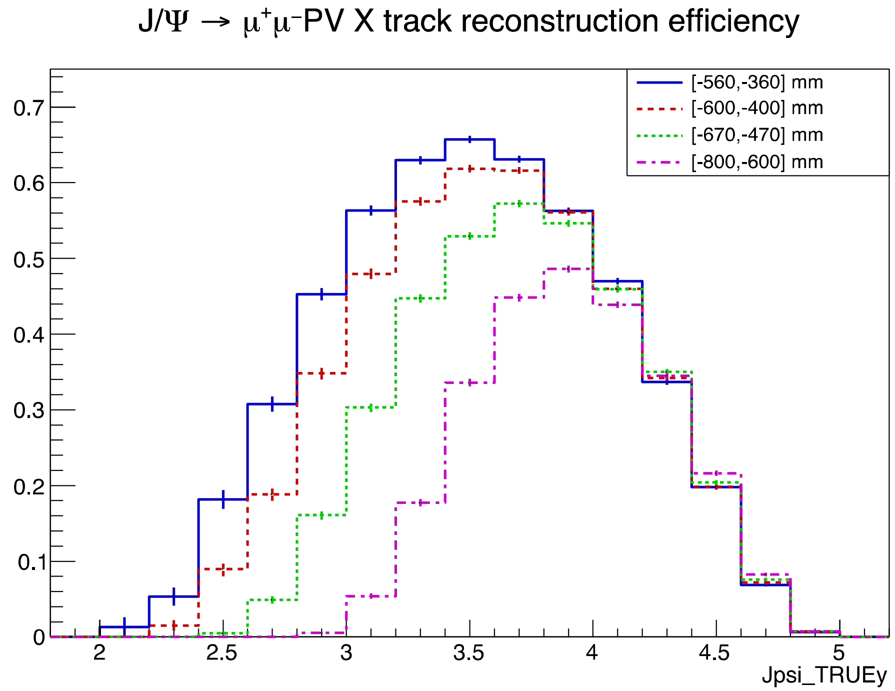

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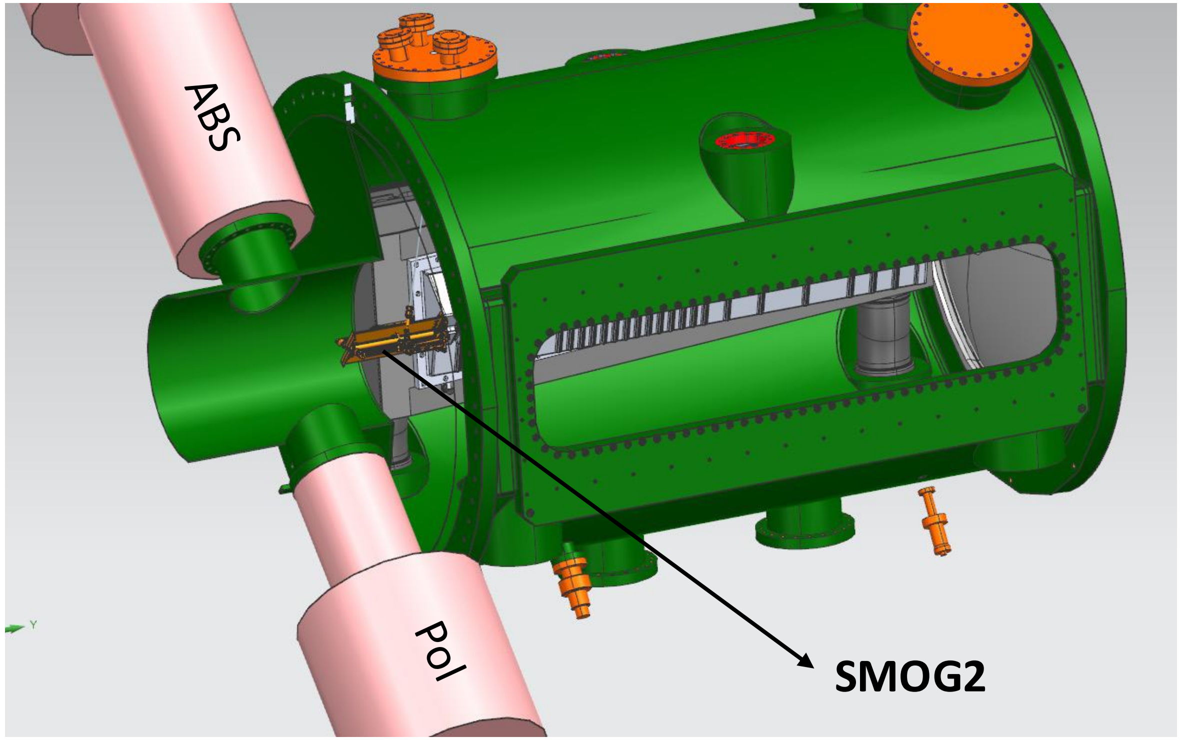
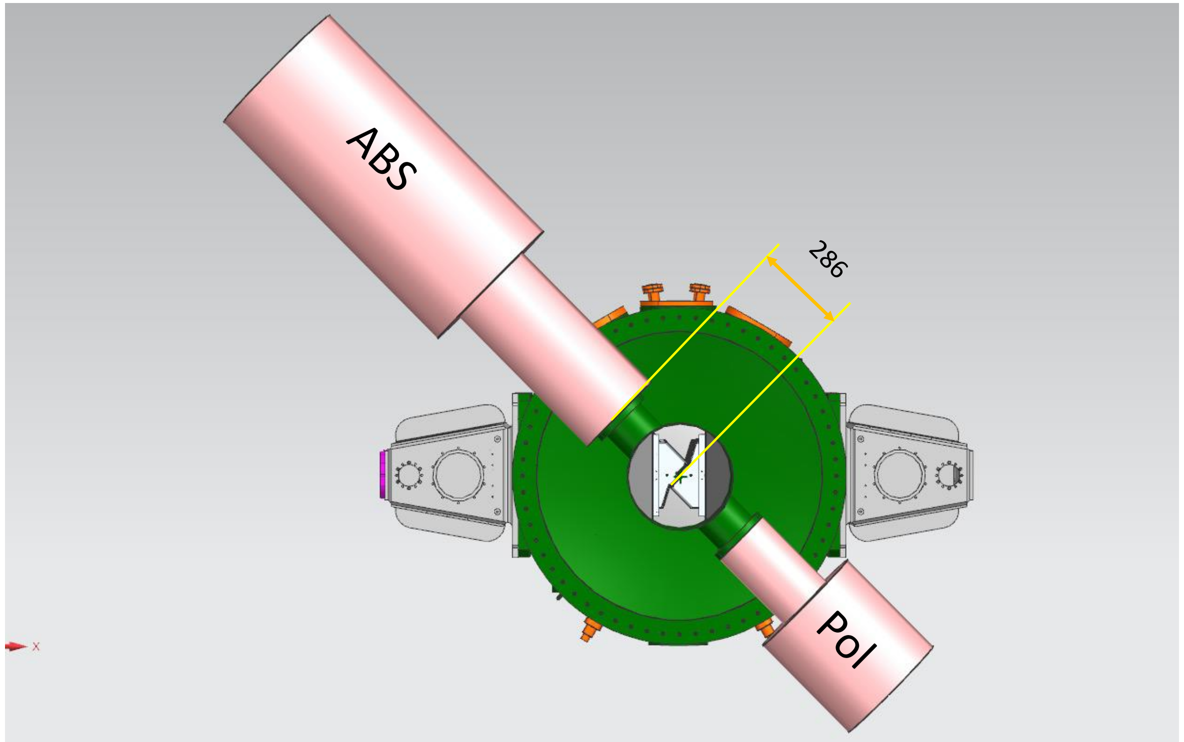
Will be much higher in Run5 (HL-LHC)!!

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

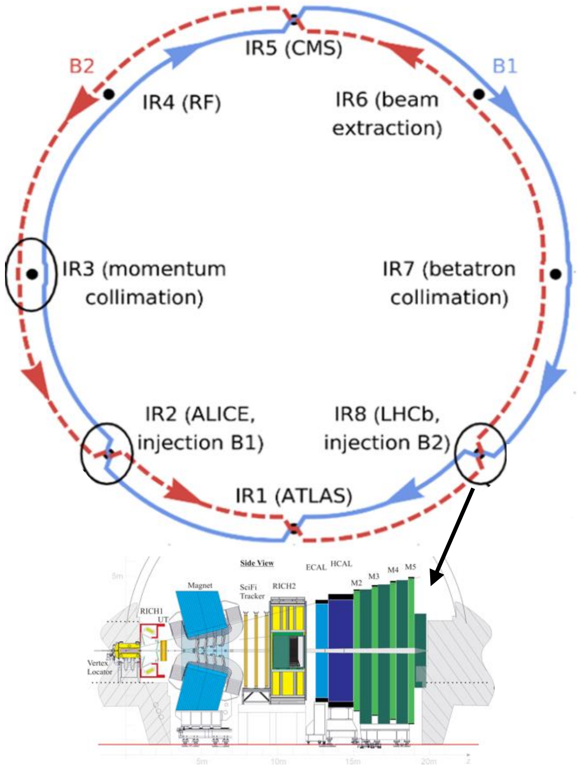




The plan for the upcoming years

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

- R&D campaign for the apparatus towards the final setup for LHCb
- feasibility studies in a dedicated exp. area served by LHC beams
- Develop and test a RHIC-like absolute polarimeter



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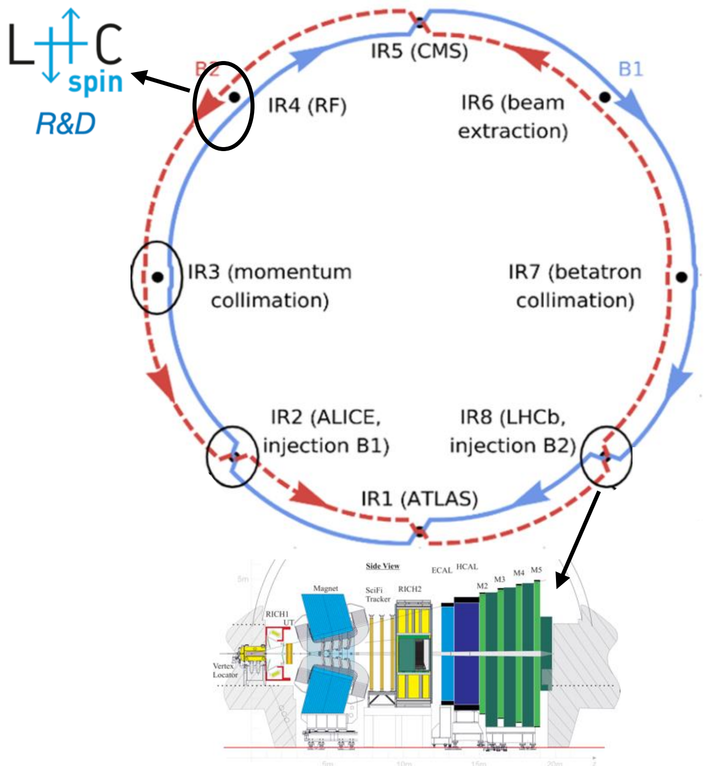
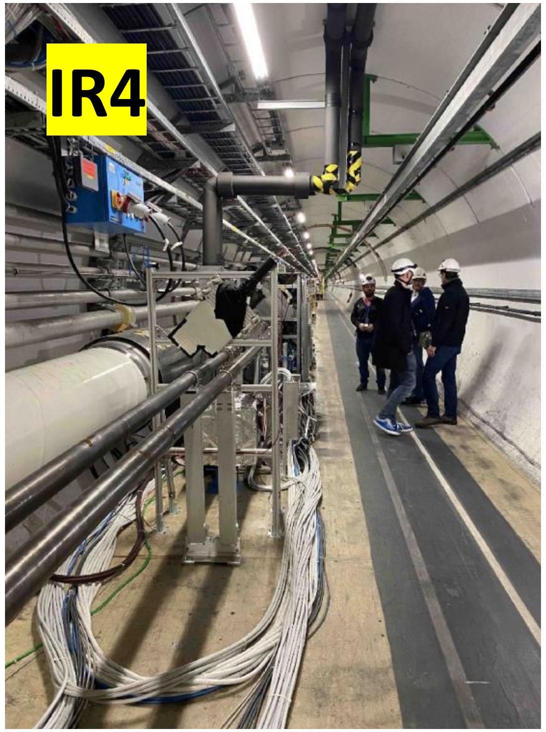
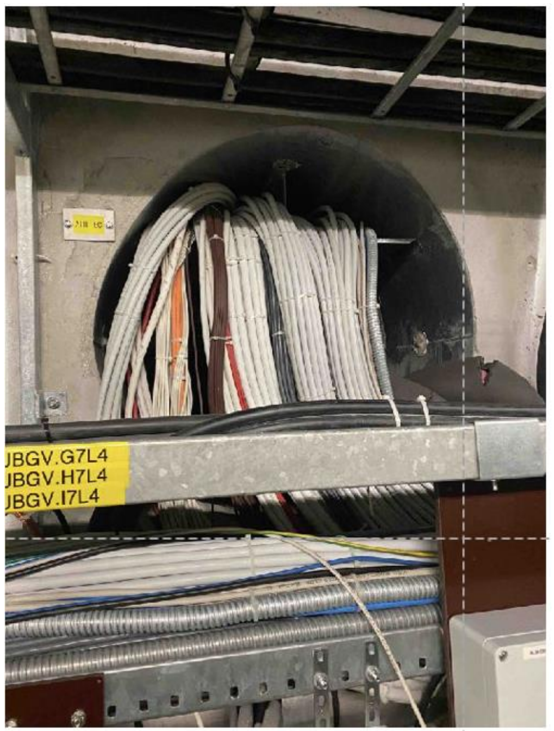
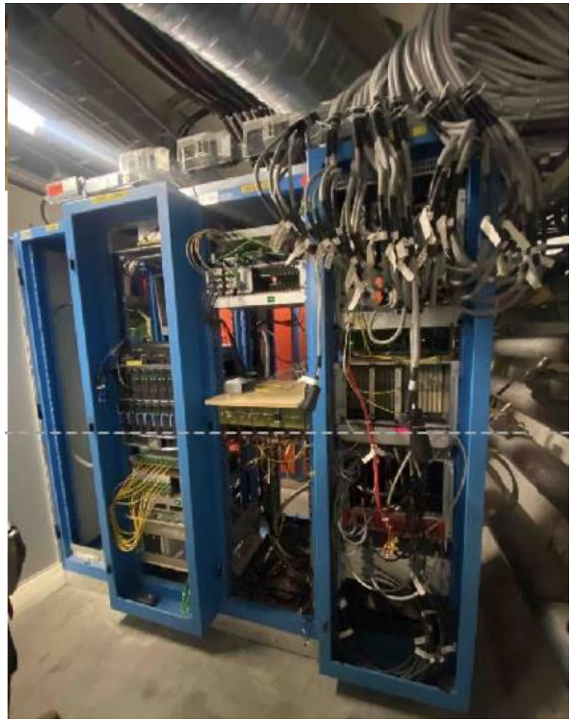
IR4 is the ideal place for our R&D:

- Lots of free space for our instrumentation
- Rails, cables and racks already available in-situ









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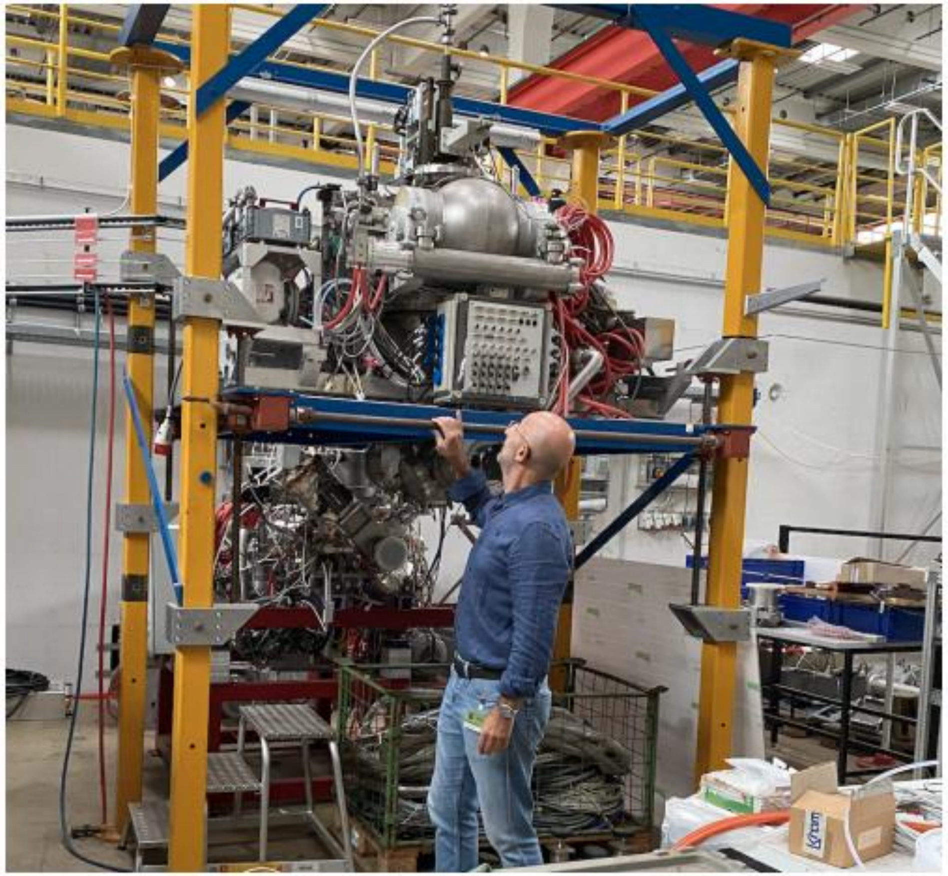
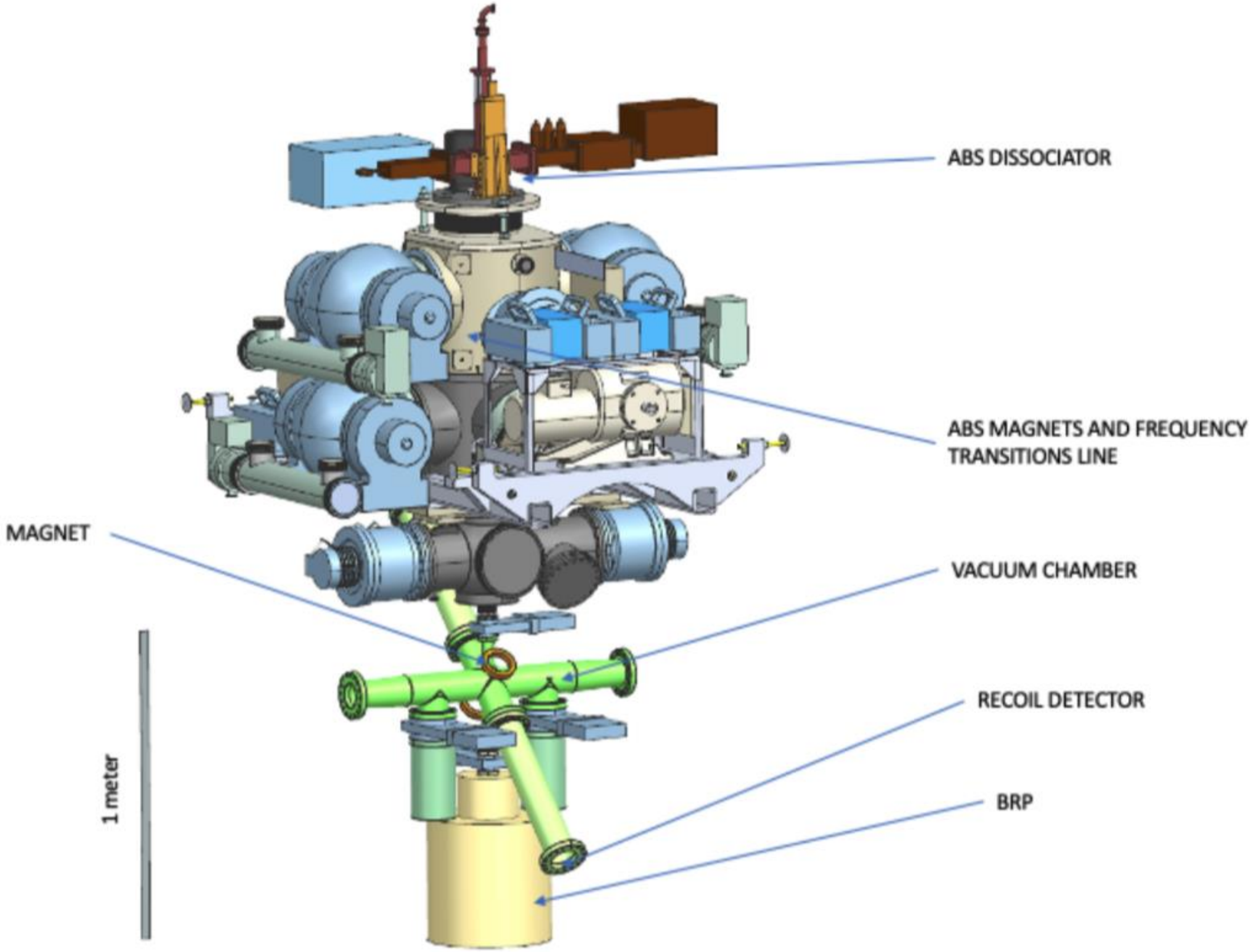
ABS and BR-polarimeter have already been moved to Ferrara for first tests and optimization prior to full installation at IR4.

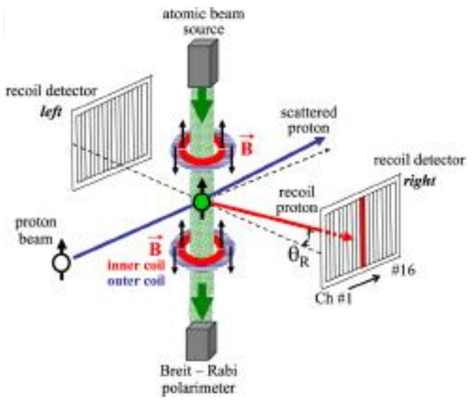


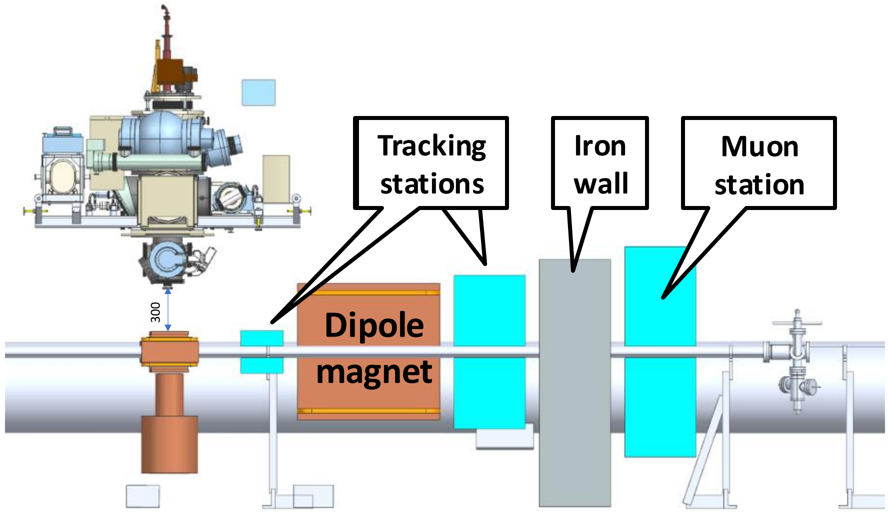


The plan for the upcoming years

LS3 (2027-30):

- **Installation at IR4 of existing setup** (ABS + BR polarimeter)
- **Implementation of a RHIC-like absolute polarimeter:** exploits Coulomb-Nuclear Interference in beam-target scattering to measure of molecular polarization (to be calibrated with the BRP)
- **Possibility to implement a minimal spectrometer**





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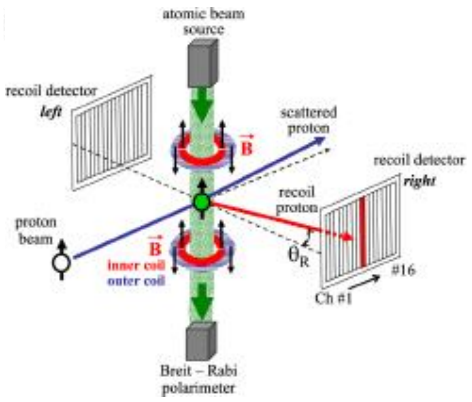

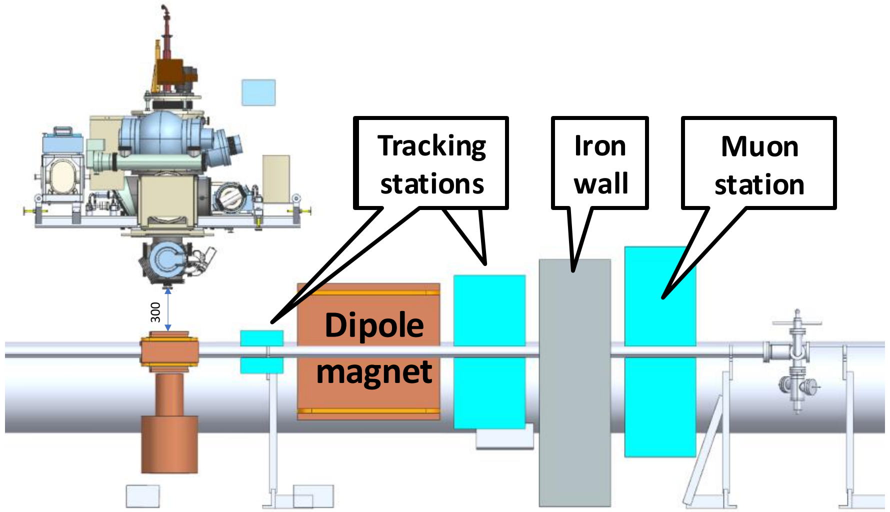

Run4 (2030-33):

- **In-beam polarimetry studies**
- **proof-of-principle prototype experiment: first pol. meas. at the LHC** (SSAs in inclusive light hadron production)

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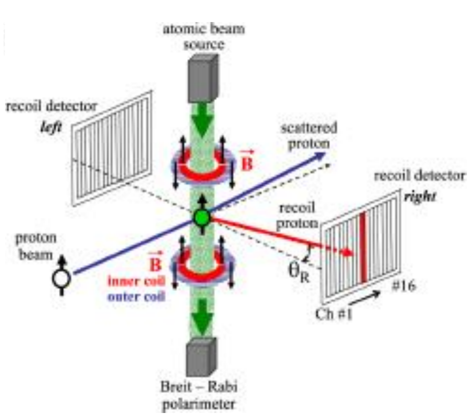
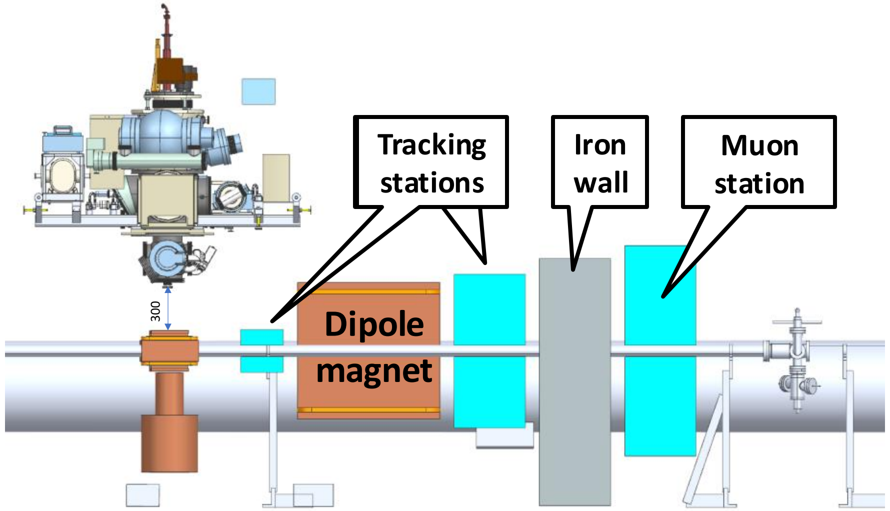
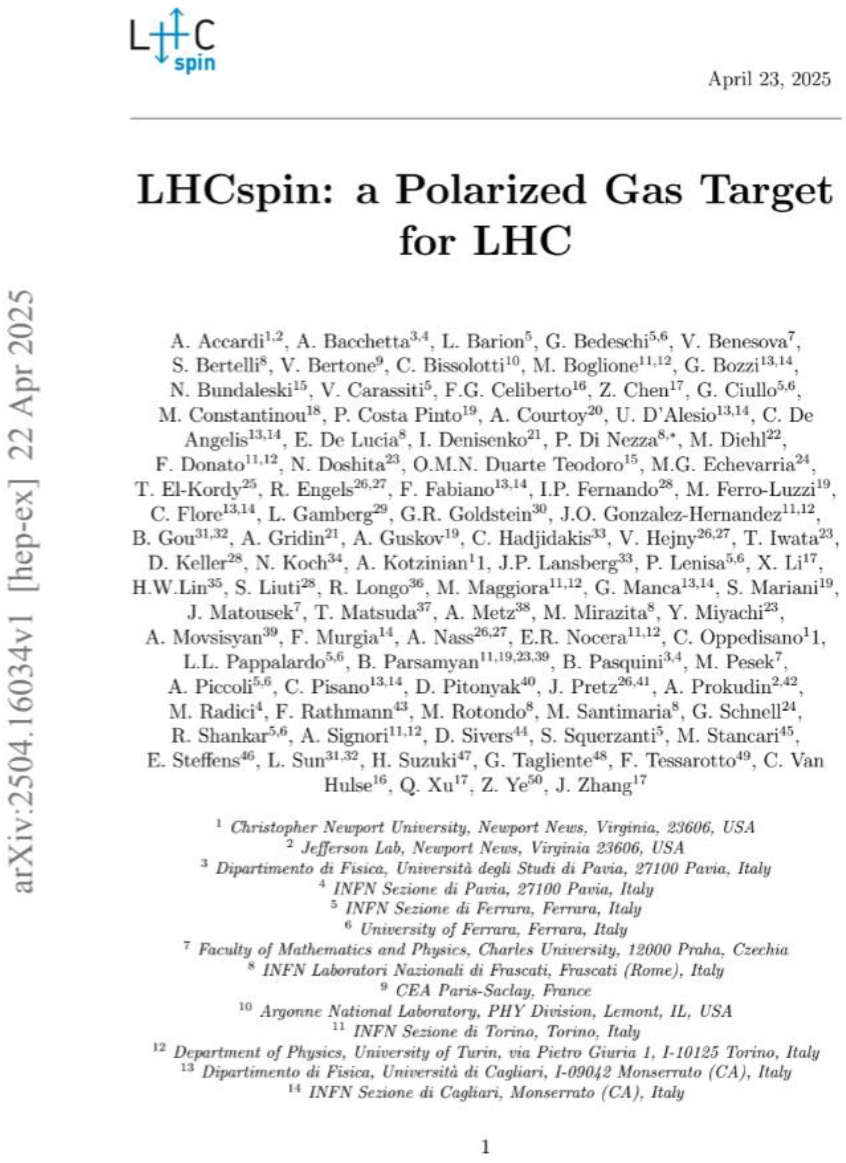
- **Possibility to implement a minimal spectrometer**





Run4 (2030-33):

- **In-beam polarimetry studies**
- **proof-of-principle prototype experiment: first pol. meas. at the LHC** (SSAs in inclusive light hadron production)



LHC spin

April 23, 2025

arXiv:2504.16034v1 [hep-ex] 22 Apr 2025

LHCspin: a Polarized Gas Target for LHC

A. Accardi[1,2], A. Bacchetta[3,4], L. Barion[5], G. Bedeschi[5,6], V. Benesova[7], S. Bertelli[8], V. Bertone[9], C. Bissolotti[10], M. Boglione[11,12], G. Bozzi[13,14], N. Bundaleski[15], V. Carassiti[5], F.G. Celiberto[16], Z. Chen[17], G. Ciullo[5,6], M. Constantinou[18], P. Costa Pinto[19], A. Courtoy[20], U. D'Alesio[13,14], C. De Angelis[13,14], E. De Lucia[8], I. Denisenko[21], P. Di Nezza[8,*], M. Diehl[22], F. Donato[11,12], N. Doshita[23], O.M.N. Duarte Teodoro[15], M.G. Echevarria[24], T. El-Kordy[25], R. Engels[26,27], F. Fabiano[13,14], I.P. Fernando[28], M. Ferro-Luzzi[19], C. Flore[13,14], L. Gamberg[29], G.R. Goldstein[30], J.O. Gonzalez-Hernandez[11,12], B. Gou[31,32], A. Gridin[21], A. Guskov[19], C. Hadjidakis[33], V. Hejny[26,27], T. Iwata[23], D. Keller[28], N. Koch[34], A. Kotzinian[1]1, J.P. Lansberg[33], P. Lenisa[5,6], X. Li[17], H.W.Lin[35], S. Liuti[28], R. Longo[36], M. Maggiora[11,12], G. Manca[13,14], S. Mariani[19], J. Matousek[7], T. Matsuda[37], A. Metz[38], M. Mirazita[8], Y. Miyachi[23], A. Movsisyan[39], F. Murgia[14], A. Nass[26,27], E.R. Nocera[11,12], C. Oppedisano[1]1, L.L. Pappalardo[5,6], B. Parsamyan[11,19,23,39], B. Pasquini[3,4], M. Pesek[7], A. Piccoli[5,6], C. Pisano[13,14], D. Pitonyak[40], J. Pretz[26,41], A. Prokudin[2,42], M. Radici[4], F. Rathmann[43], M. Rotondo[8], M. Santimaria[8], G. Schnell[24], R. Shankar[5,6], A. Signori[11,12], D. Sivers[44], S. Squerzanti[5], M. Stancari[45], E. Steffens[46], L. Sun[31,32], H. Suzuki[47], G. Tagliente[48], F. Tessarotto[49], C. Van Hulse[16], Q. Xu[17], Z. Ye[50], J. Zhang[17]

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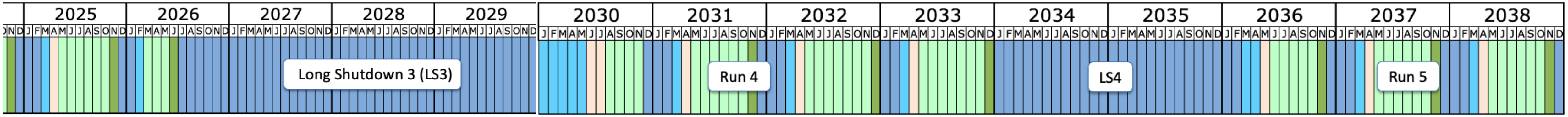
1

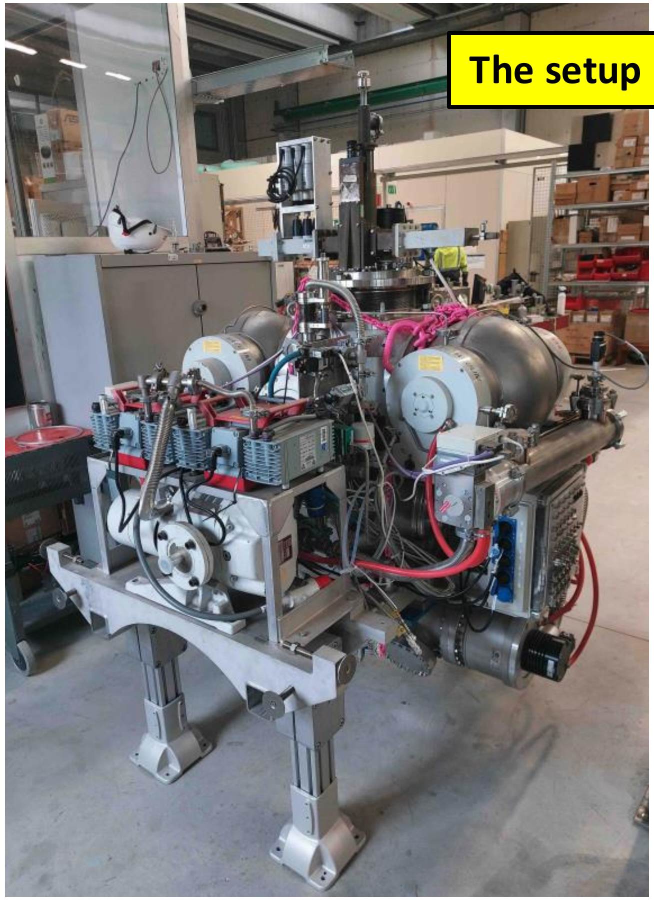
https://arxiv.org/abs/2504.16034

Timeline of the project

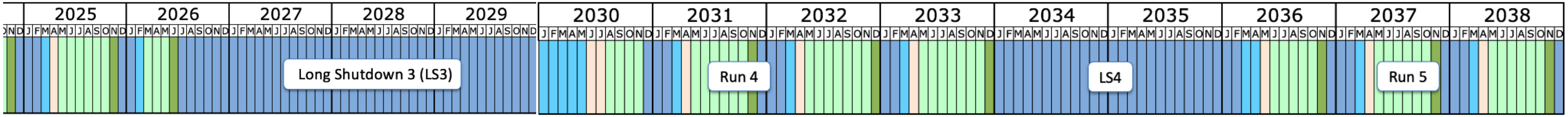


First tests and characterization in Ferrara

The setup @ Ferrara

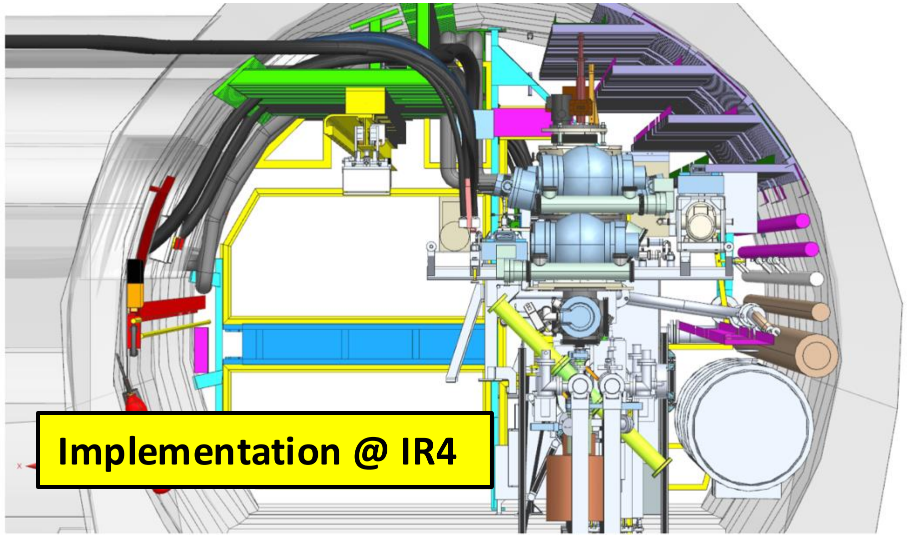


Timeline of the project

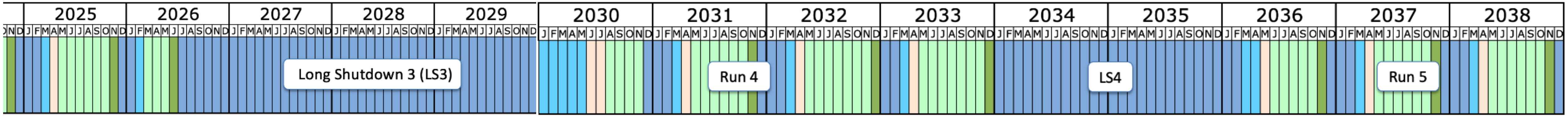


First tests and characterization in Ferrara

Installation at IR4 (LHC):
- ABS + Breit-Rabi polarimeter
- Absolute polarimeter
- minimal spectrometer ?



Timeline of the project



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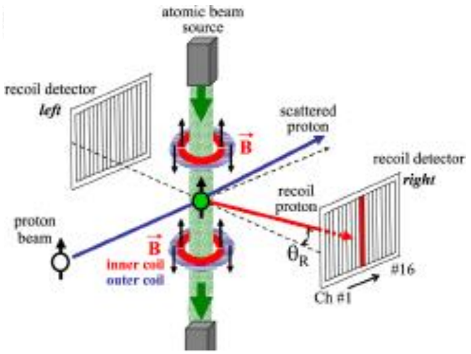
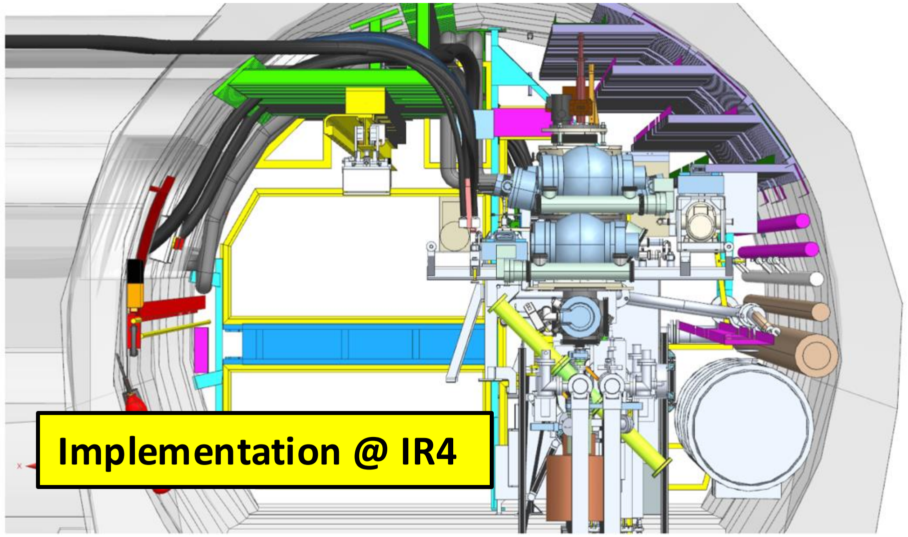
- Absolute polarimeter
- minimal spectrometer ?

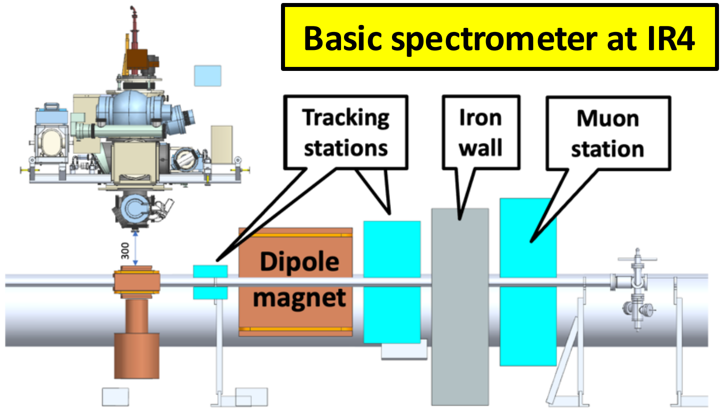
- Polarimetry measurements
- First physics measurements (SSAs)?



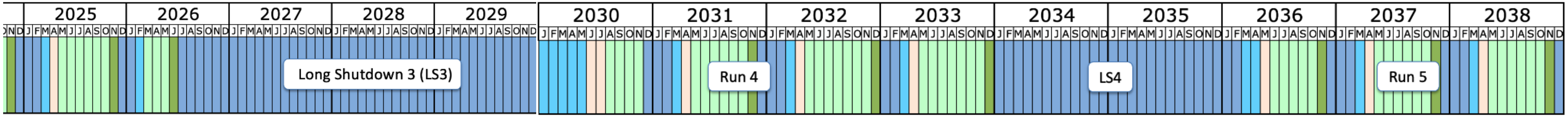
Absolute polarimeter



Basic spectrometer at IR4



Timeline of the project



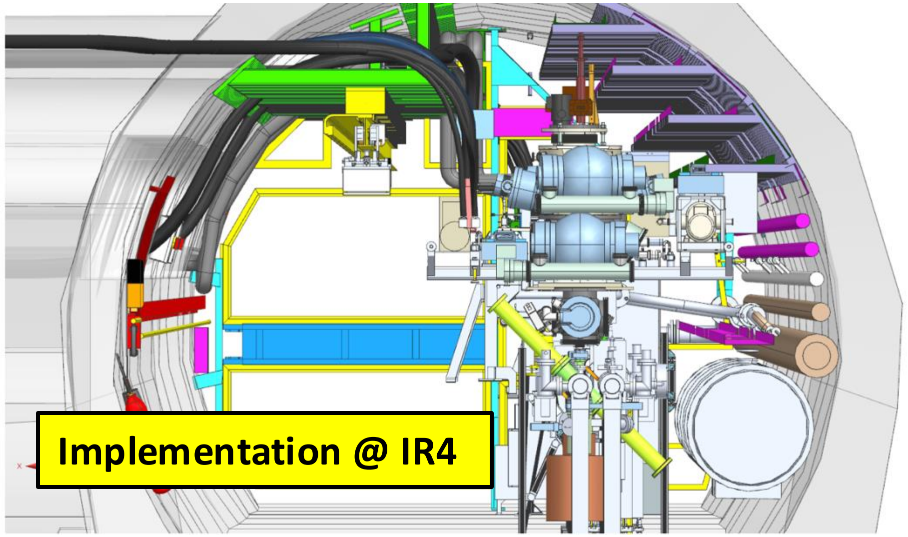
First tests and characterization in Ferrara

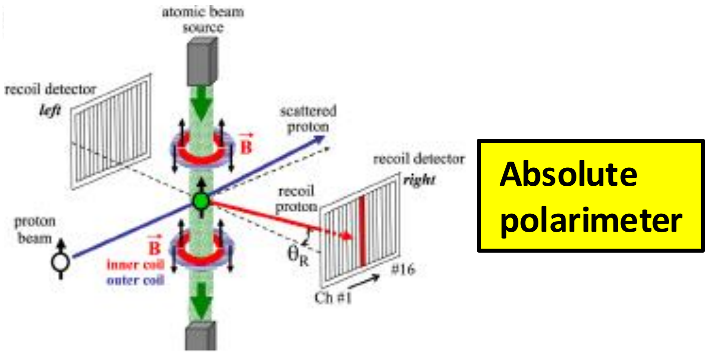
Installation at IR4 (LHC):
- ABS + Breit-Rabi polarimeter
- Absolute polarimeter
- minimal spectrometer ?

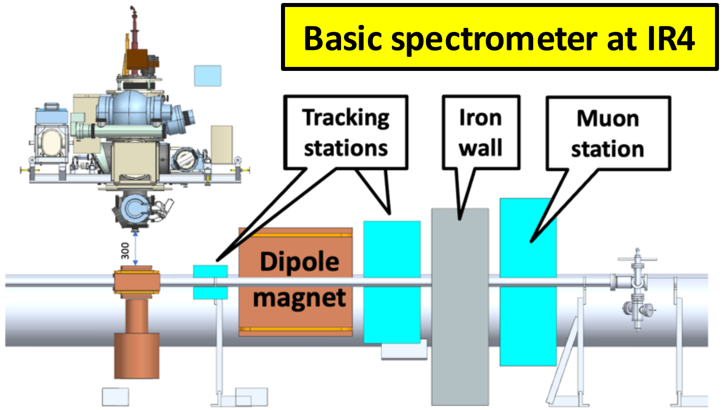
- Polarimetry measurements
- First physics measurements (SSAs)?

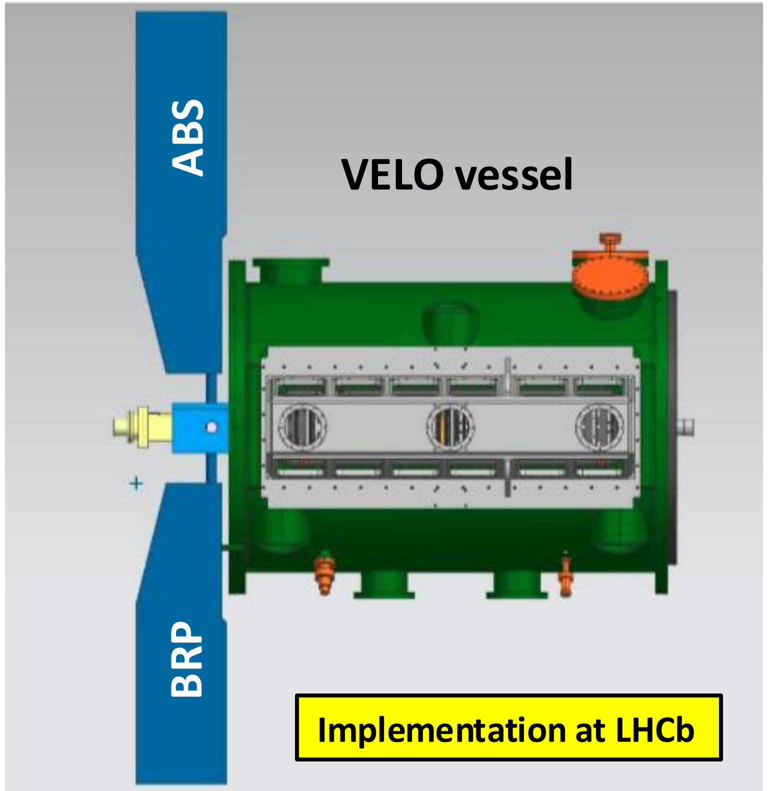
Move apparatus from IR4 to LHCb

Data taking with LHCb









Conclusions

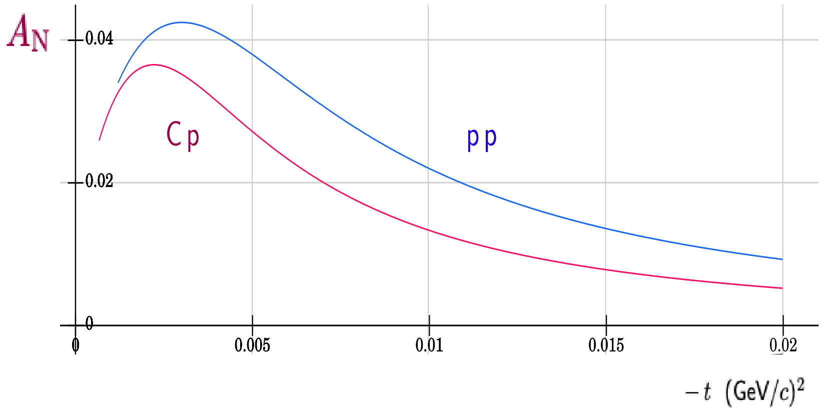
- **The Fixed-Target program at LHCb is active since Run 2, now greatly enriched with SMOG2**
- LHCspin is the natural evolution: **a polarized fixed target at LHCb will bring spin-physics for the first time at the LHC and will open the way to a broad and unique physics program!**
- Novel approaches and reactions will be exploited to study 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.
- The approval process of the first phase (R&D at IR4) is in progress.

Backup

Absolute polarimetry

Under **Coulomb-Nuclear Interference** (CNI) conditions one can measure L-R asymmetries in elastic $pH^{\uparrow}$ scattering:

$$A_N(t) = \frac{\mu_p - 1}{m_p}\sqrt{-3t_e}\,\frac{(t/t_e)^{3/2}}{3(t/t_e)^2+1} \qquad t_e = -\frac{8\pi\sqrt{3}\alpha_{EM}|ZZ'|}{\sigma_{tot}(s)}$$

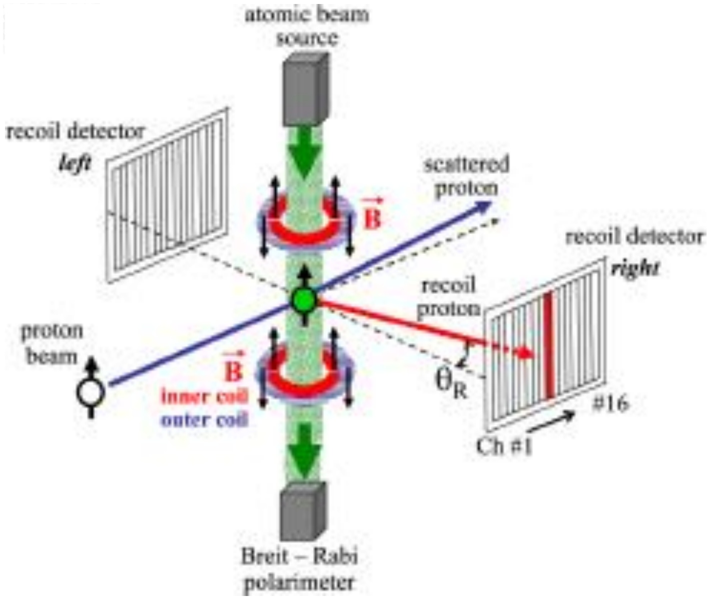


Analyzing power is maximal (4-5%) **for $t = t_e$**

For a 7 TeV proton beam:

- $\sigma_{tot} \approx 47\ mb$
- proton recoil energies: 1.7 – 4.6 MeV
- proton recoil angles $87° < \theta_{lab} < 89°$

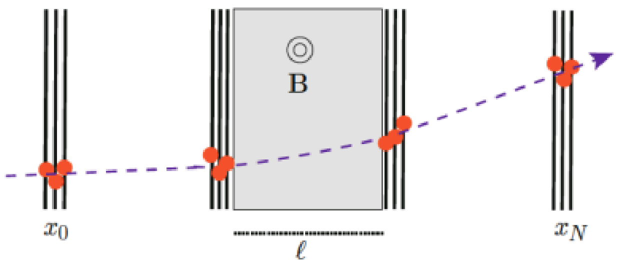
➢ Technique used for polarimetry at RHIC with p-C scattering
(A. Poblaguev et al., PoS PSTP 2017 (2018) 022)



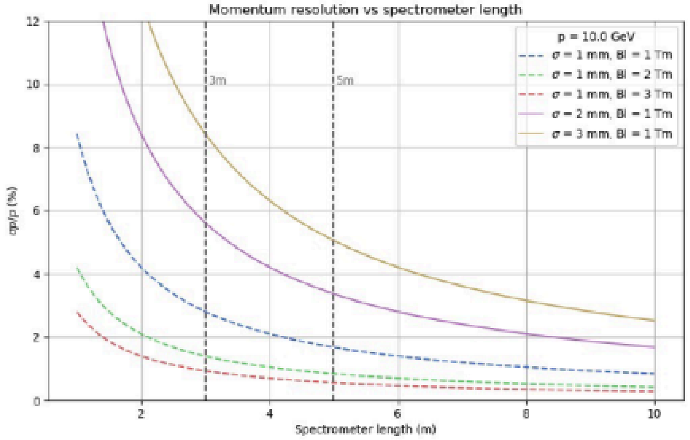
➢ Find more here: https://www.maths.tcd.ie/~nhb/talks/2019_07_16_nhb.pdf

Physics measurements at IR4

Even though the focus will be on polarimetry and beam interactions, we performed preliminary calculations to determine if a simple detector could meet our needs



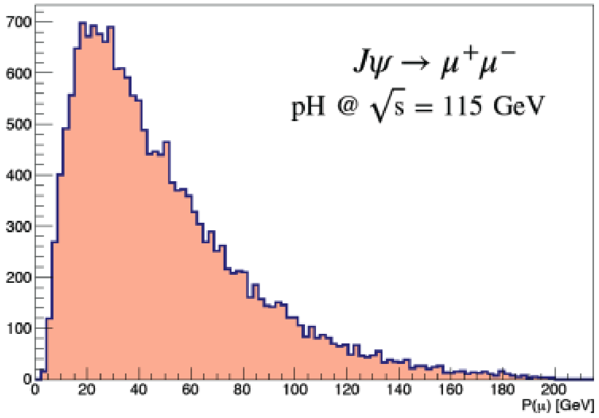
$$\frac{\delta p}{p} = \frac{8\sigma}{\sqrt{N+1}} \frac{1}{0.3z \cdot Bl \cdot L} p$$



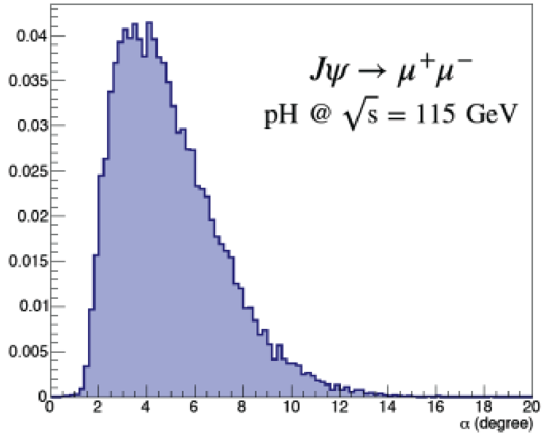
we can achieve a resolution $\delta p/p < 1\,\%$ within a few meters of lever arm (depending on space constraints) for momenta up to a few GeV and with N = 10 hit measurements

with $\delta p/p \sim 1\,\%$ we have $\delta m \sim 40$ MeV, excellent for any other measurement

momentum



opening angle



it is even possible to have a ToF PID @3σ level for $\pi - K$
$p \sim 1\ GeV \to \sigma_T \mathcal{O}(100)\ ps$

Anything we measure is new

A synergic attack to gTMDs

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

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

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

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

Can be measured at the EIC (pink)

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

Can be measured at RHIC and LHCb+LHCspin (yellow)

gluon TMDs

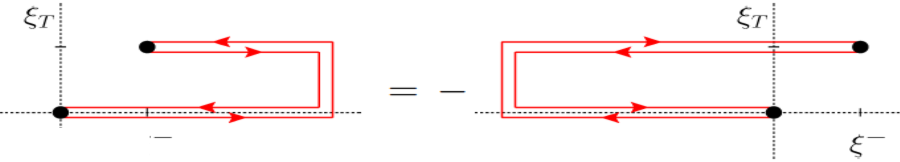
gluon pol. (columns) / nucleon pol. (rows)

	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 correlator depends on 2 path-dependent gauge links, different for ISI and FSI:

"Future pointing" Wilson line ("+") FSI (SIDIS)



"Past pointing" Wilson line ("−") ISI (DY))

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

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

- Depending on their combinations, **there are 2 independent versions of each gTMD** that can be 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

A preliminary analysis tool for pseudo-data

A pseudo-data set based on a Transversely Pol. H target has been generated to study the interplay between statistical and systematic uncertainties (due to the measurement of the polarization).

Similar approach used at HERMES (Appendix C of [JHEP, 12:010, 2020]):

- Use official LHCb MC data for inclusive production of $J/\psi \to \mu^+\mu^-$ in fixed-target configuration (PYTHIA8 + EPOS)
- **Introduce a spin-dependence in the simulation:** assign to each simulated event a target polarization state (↑ or ↓) using a random extraction modulated with a model for the cross section
- The model assumes a dominant $\sin\phi$ modulation (e.g. sensitive to the gluon Sivers) plus a suppressed $\sin 2\phi$ modulation (to account e.g. for possible higher-twist contributions). Both terms depend mildly on the kinematics (x, p_T):

$$\rho = \frac{1}{2}\left[1 + \left(a_1 + a_2\frac{x-\overline{x}}{x_{max}} + a_3\frac{p_T-\overline{p_T}}{p_{T\ max}}\right)\sin\phi + \left(b_1 + b_2\frac{x-\overline{x}}{x_{max}} + b_3\frac{p_T-\overline{p_T}}{p_{T\ max}}\right)\sin 2\phi\right]$$

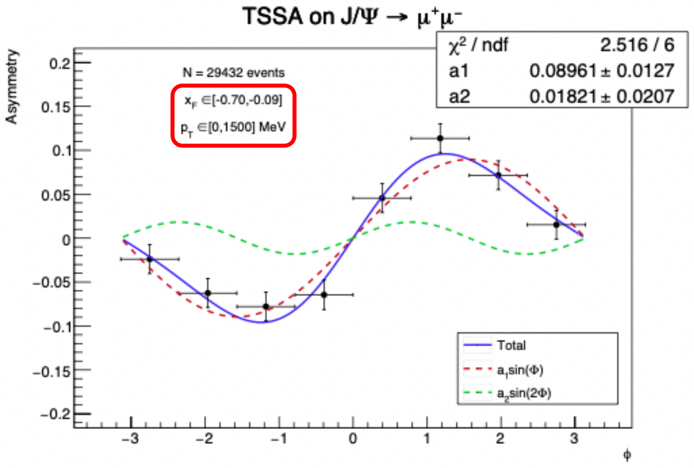
- Using these pseudo-data the TSSA is computed in the usual way:

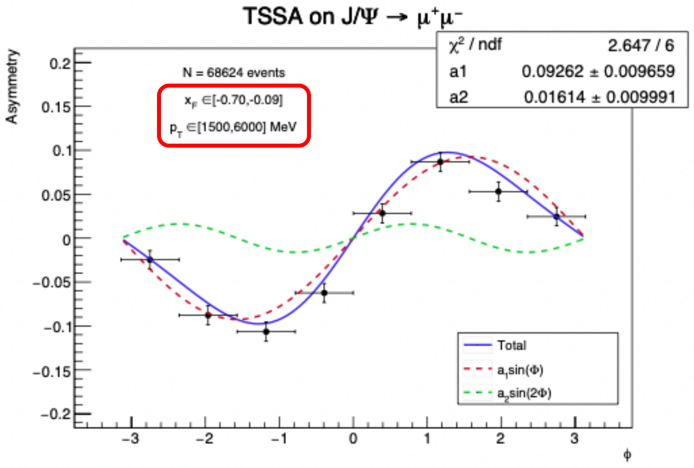
$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

and the uncertainties on $N^{\uparrow(\downarrow)}$ (Poisson) and P (systematic) propagated accordingly.

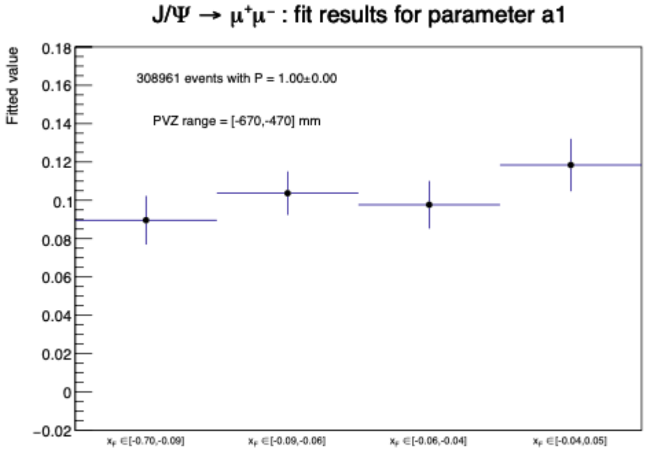
A preliminary analysis tool for pseudo-data

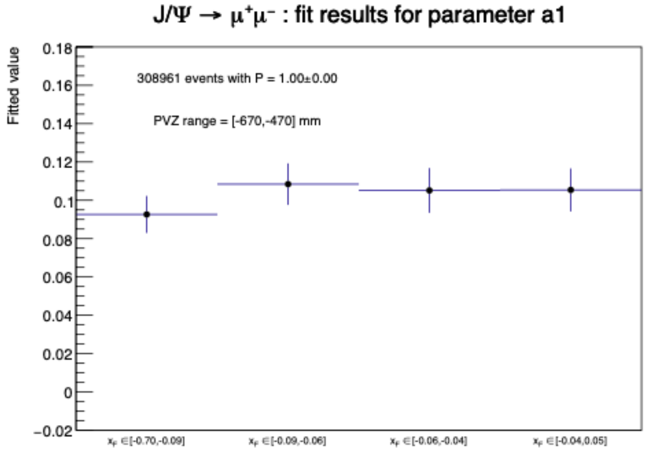
- The data points are binned in x_F and p_T (2D binning), represented vs. ϕ and fitted with $f = a_1 \sin\phi + a_2 \sin 2\phi$ where the free parameters a_1 and a_2 represent the amplitude of the corresponding azimuthal modulation





- The extracted parameters a_1 and a_2 are consistent with those used to generate the model (no bias is observed)
- With the available MC statistics (corresponding to 2 weeks of data-taking) there is no sensitivity for the $\sin 2\phi$ term





- The amplitudes a_1 are reported vs. x_F in bins of p_T (and vice-versa)
- A mild kinematic dependence is observed consistent with the model

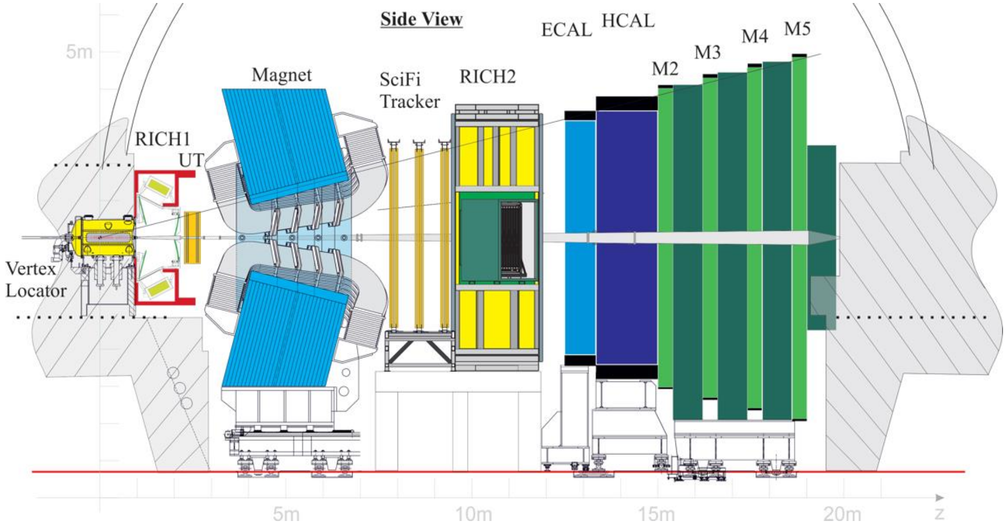
Statistical vs Systematics uncertainties

- The analysis tool described above allows to study the interplay between statistical uncertainties and systematic uncertainties (due to the measurement of the polarization) under different data-taking scenarios

p_T (MeV)	x_F	a_1 ($\Delta P = 0\%$)	a_1 ($\Delta P = 5\%$)	a_1 ($\Delta P = 20\%$)	a_1 ($\Delta P = 50\%$)
[0,1500]	[-0.70,-0.09]	0.090 ± 0.013	0.089 ± 0.013	0.087 ± 0.014	0.087 ± 0.022
[0,1500]	[-0.09,-0.06]	0.104 ± 0.011	0.104 ± 0.012	0.103 ± 0.016	0.100 ± 0.027
[0,1500]	[-0.06,-0.04]	0.098 ± 0.012	0.098 ± 0.013	0.097 ± 0.016	0.094 ± 0.027
[0,1500]	[-0.04,0.05]	0.118 ± 0.014	0.117 ± 0.014	0.114 ± 0.017	0.113 ± 0.030
[1500,6000]	[-0.70,-0.09]	0.093 ± 0.010	0.092 ± 0.010	0.090 ± 0.013	0.089 ± 0.023
[1500,6000]	[-0.09,-0.06]	0.108 ± 0.011	0.108 ± 0.011	0.108 ± 0.015	0.107 ± 0.027
[1500,6000]	[-0.06,-0.04]	0.105 ± 0.012	0.105 ± 0.012	0.104 ± 0.015	0.103 ± 0.026
[1500,6000]	[-0.04,0.05]	0.105 ± 0.011	0.105 ± 0.012	0.102 ± 0.015	0.102 ± 0.026

- A 5% systematic uncertainty on P has no impact on the total uncertainty on a_1
- For $\Delta P = 20\%$ the systematic uncertainty amounts to 30-40% of the statistical uncertainty
- For $\Delta P = 50\%$ the systematic uncertainty approximately equals the statistical uncertainty
- **We expect $\boldsymbol{\Delta P \approx 10 - 15\%}$ for the storage cell hypothesis (and close to 0 for the jet target hypothesis)**

The LHCb detector



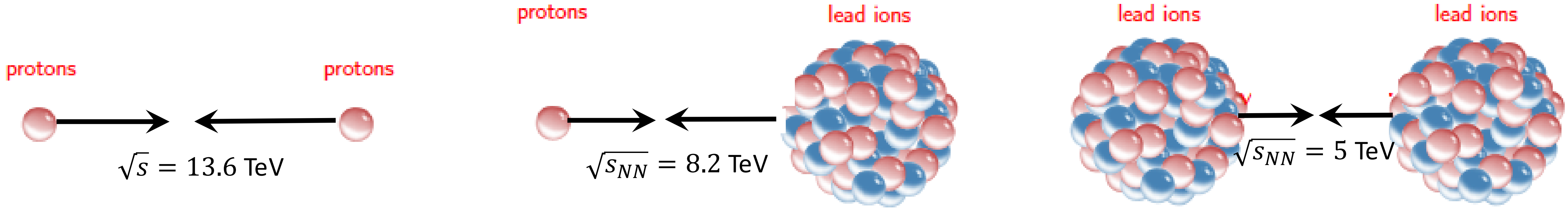
- LHCb is a **general-purpose single-arm spectrometer**, fully instrumented in $2 < \eta < 5$ and optimised for detection of charmed and beauty hadrons
  [JINST 3 (2008) S08005] [IJMPA 30 (2015)1530022]

- **Excellent particle identification and momentum resolution**: $\sigma_p/p \leq 1.0\ \%$ ($p \in [2,200]$ GeV)

- **Precise primary and secondary vertex reconstruction (VELO)**

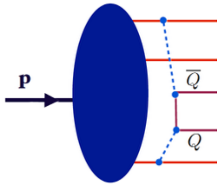
- **During LS2 major hardware upgrade to cope with the factor of 5 increase in luminosity starting from the Run 3**
  [http://arxiv.org/abs/2305.10515]

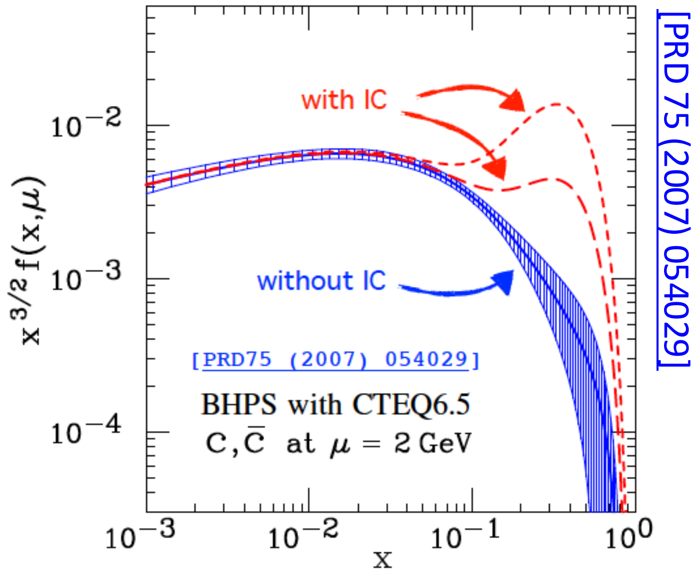
Types of collisions (Collider mode):



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

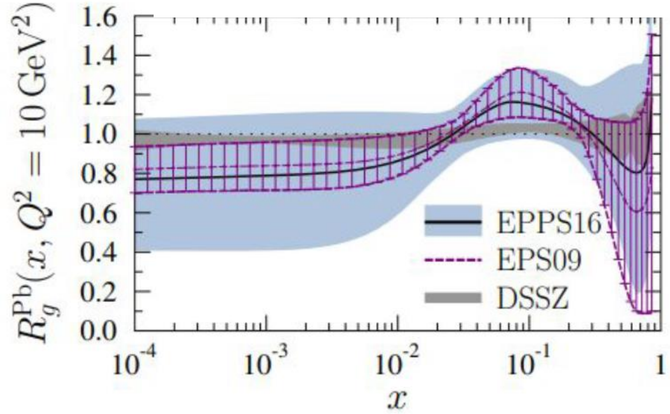


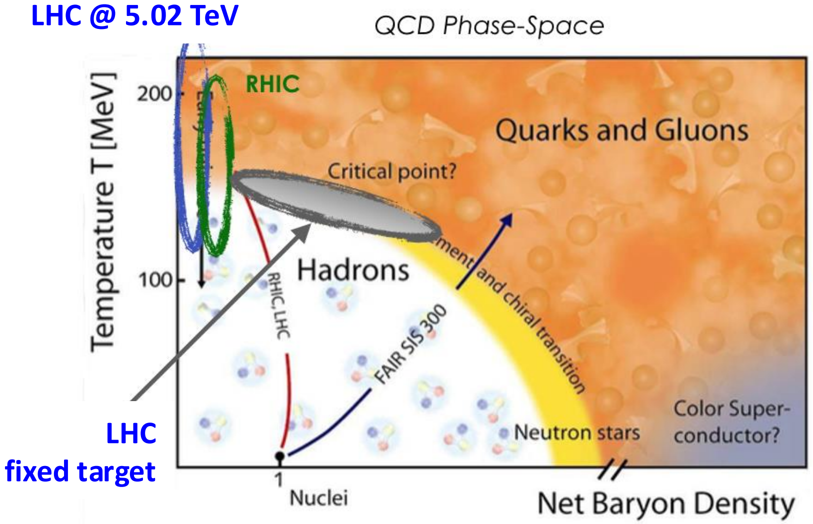


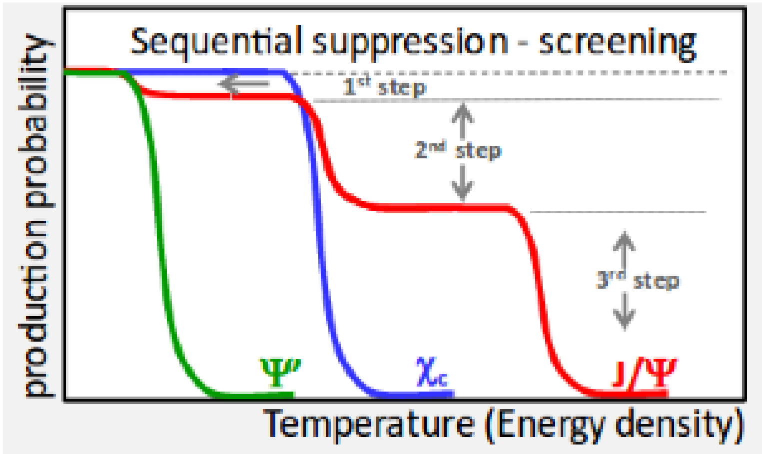
- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium
  - reactions of interest for cosmic-ray physics and DM searches

- **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**)

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







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