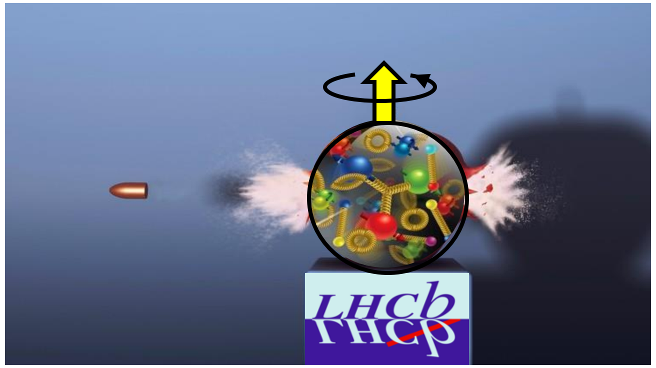
University
of Ferrara

The 12th Circum-Pan-Pacific Symposium on High Energy Spin Physics

LHCspin: a polarized fixed-target experiment at the LHC



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

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- World top energies
- high luminosity
- p and ion beams
- highly sophisticated state-of-the-art detectors
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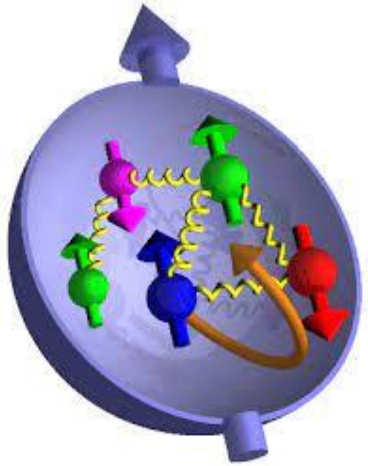

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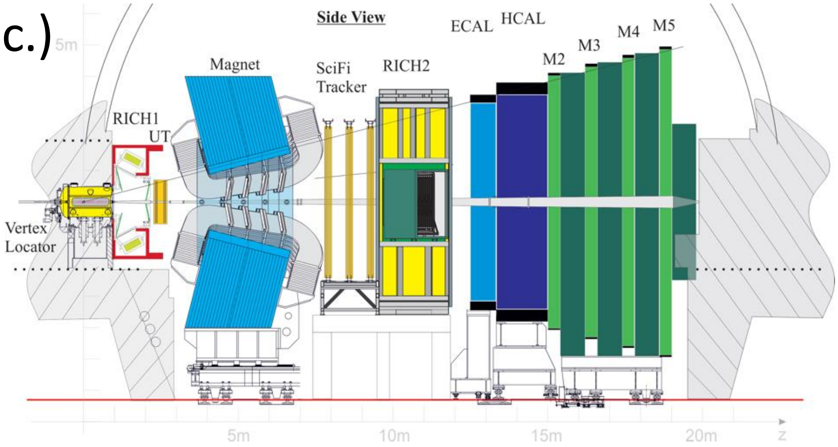
- ➢ **…and the LHCb spectrometer is the perfect place to host it.**



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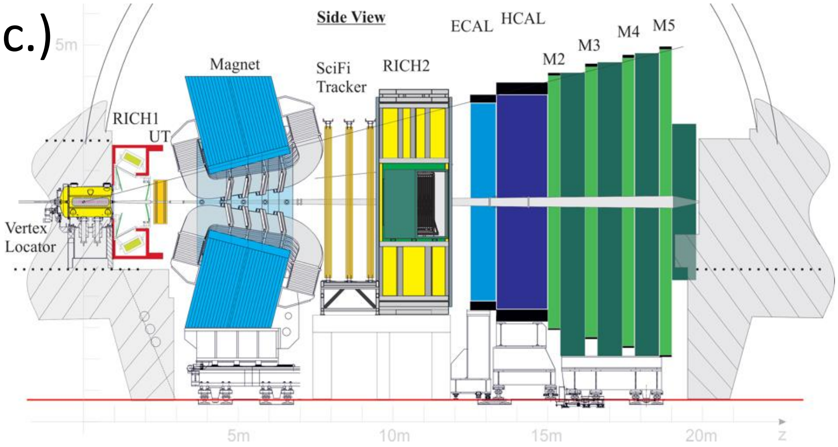
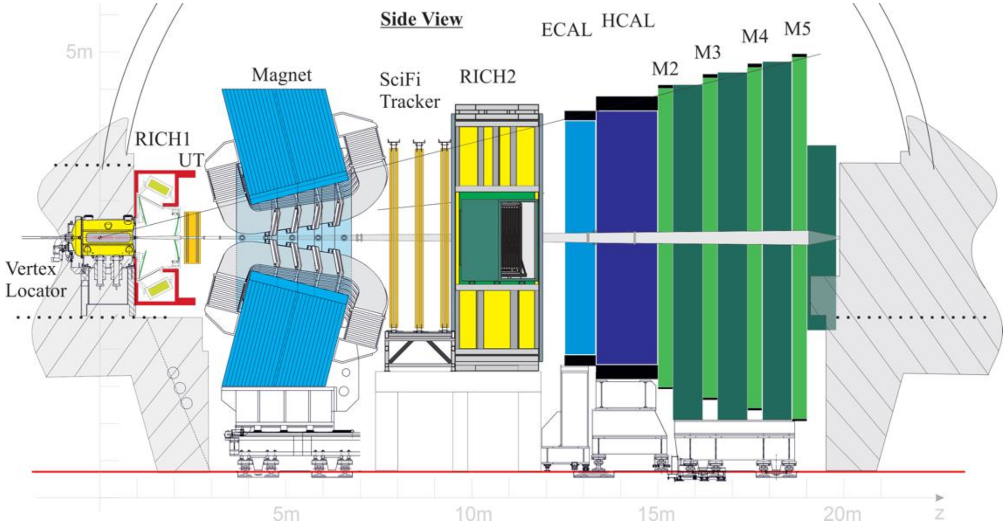


LHCspin **project!**

LHCb fixed-target setup

- 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]



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

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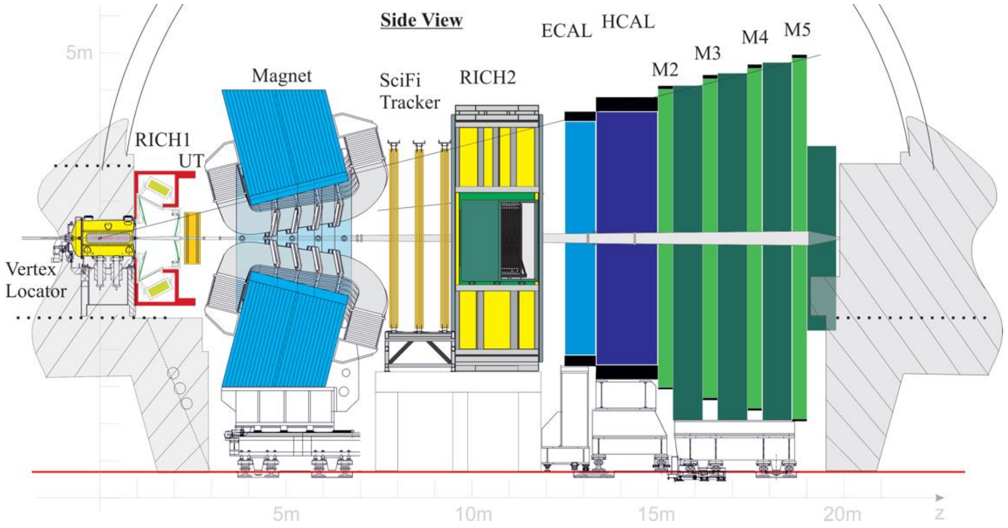

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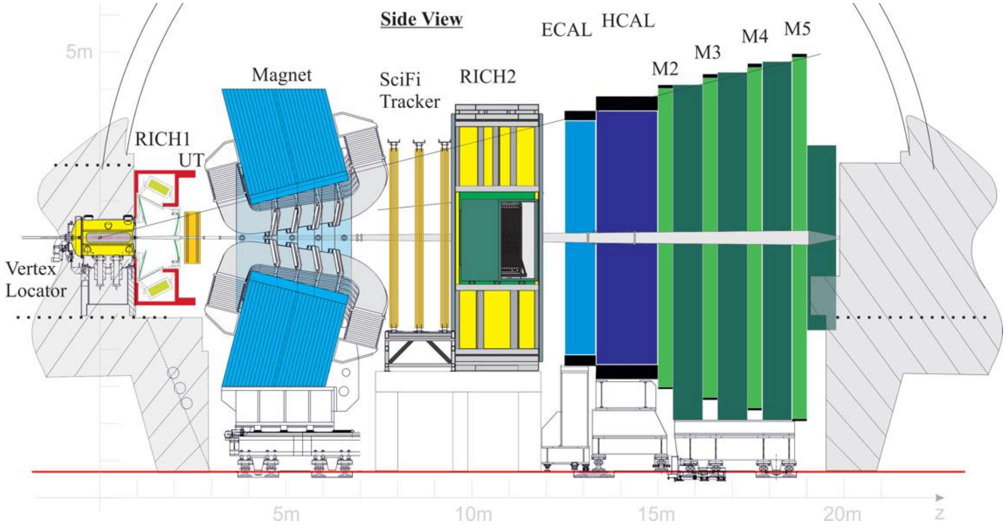
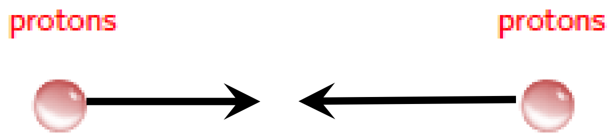
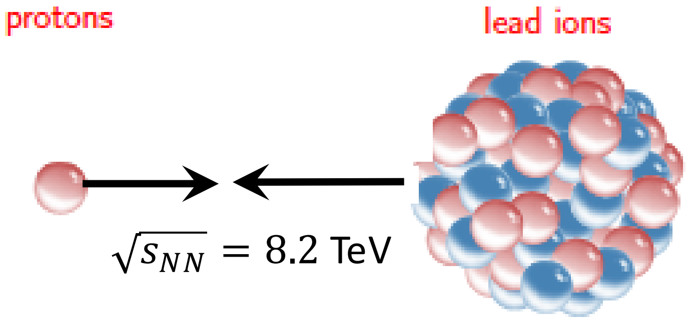


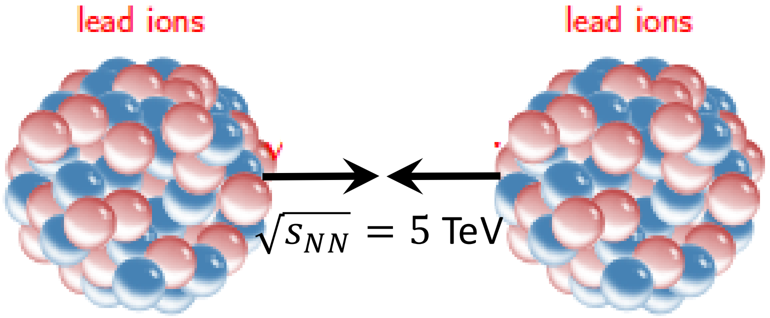
Types of collisions **(Collider mode):**



$\sqrt{s} = 13.6$ TeV



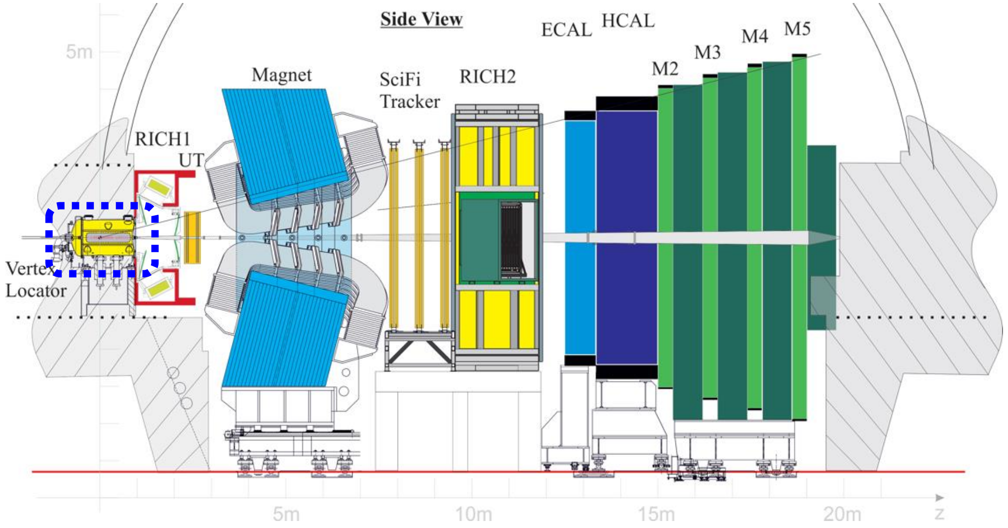
$\sqrt{s_{NN}} = 8.2$ TeV

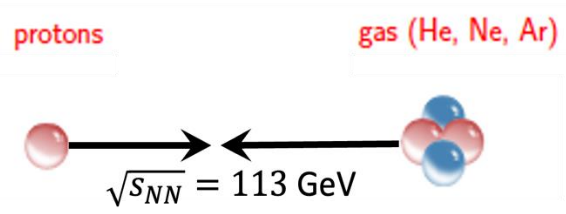


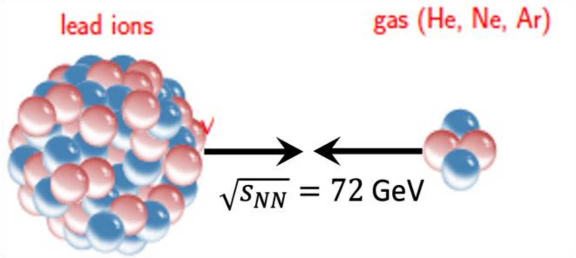
$\sqrt{s_{NN}} = 5$ TeV

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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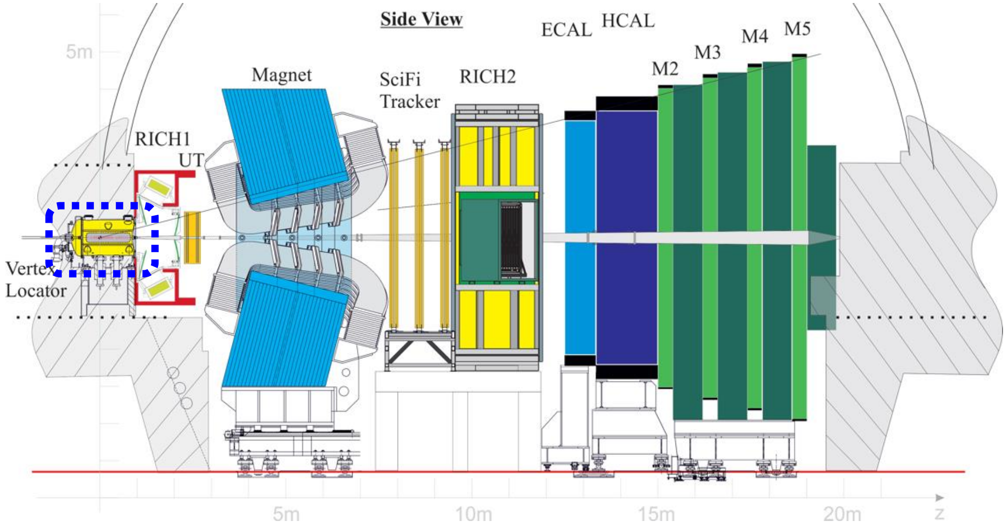

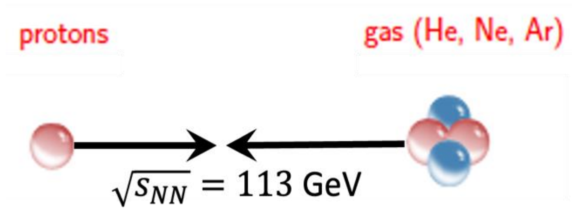

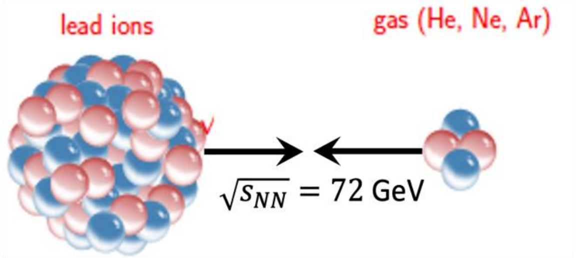

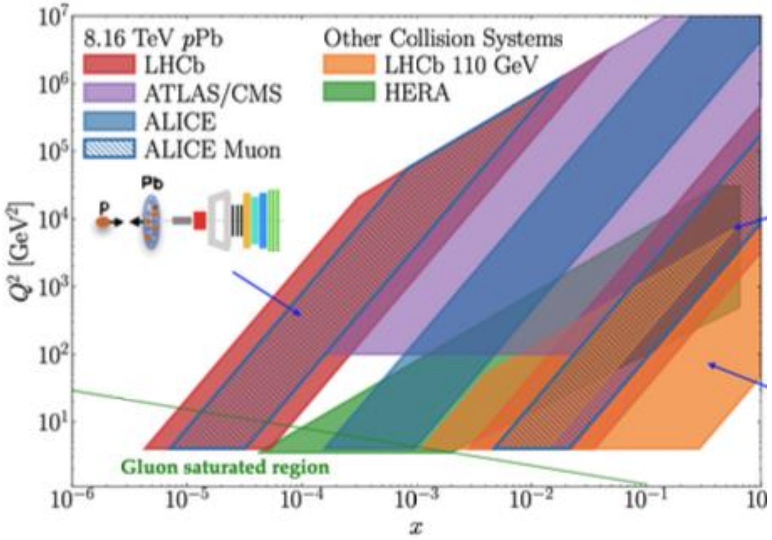

FT kinem. with $E_p = 6.8$ TeV:

- $\sqrt{s_{NN}} \approx 115\ GeV$
- $-3.0 \leq y_{CM} \leq 0$
- $x_F < 0$
- intermediate-large x_B
- intermediate Q^2

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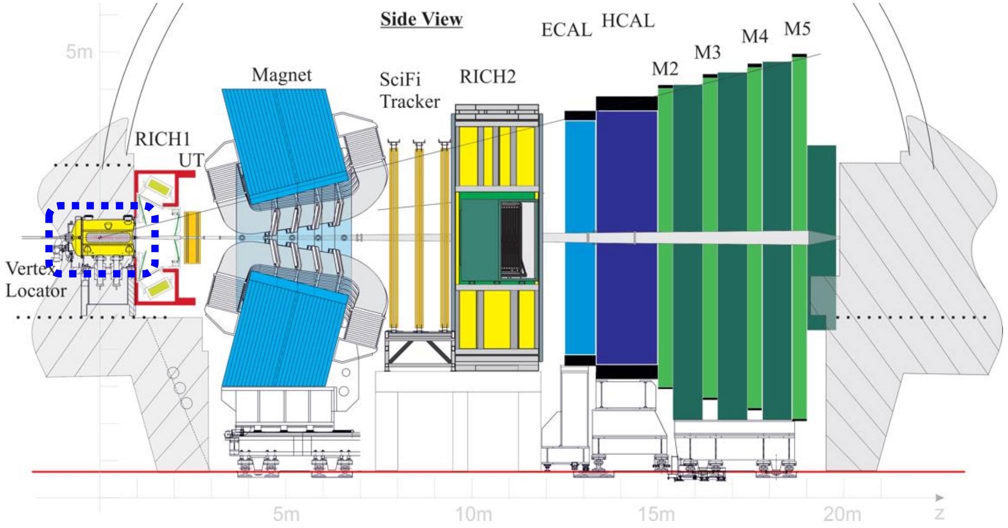

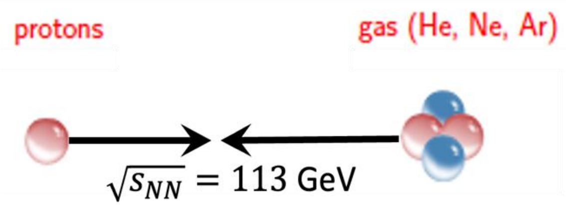

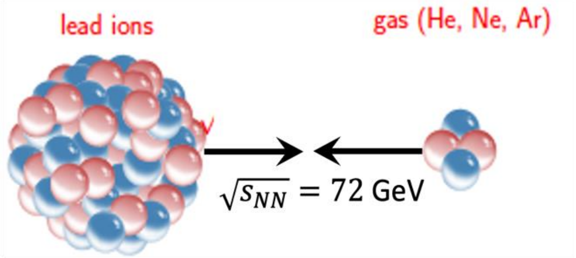

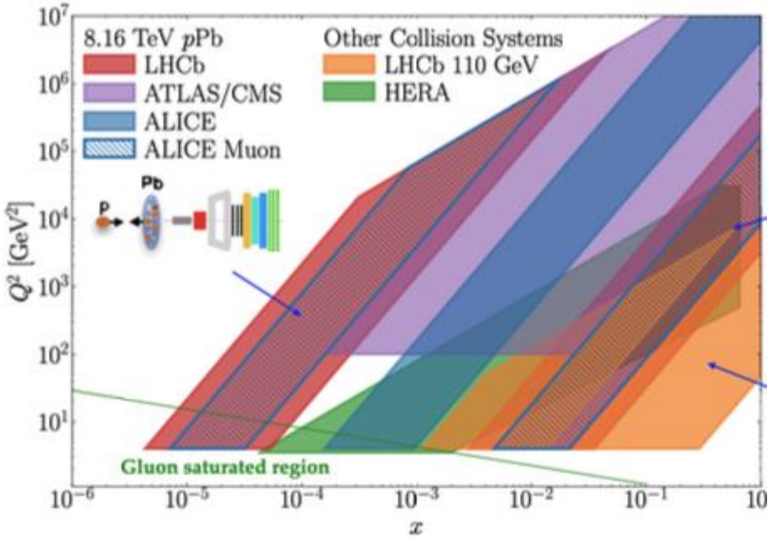

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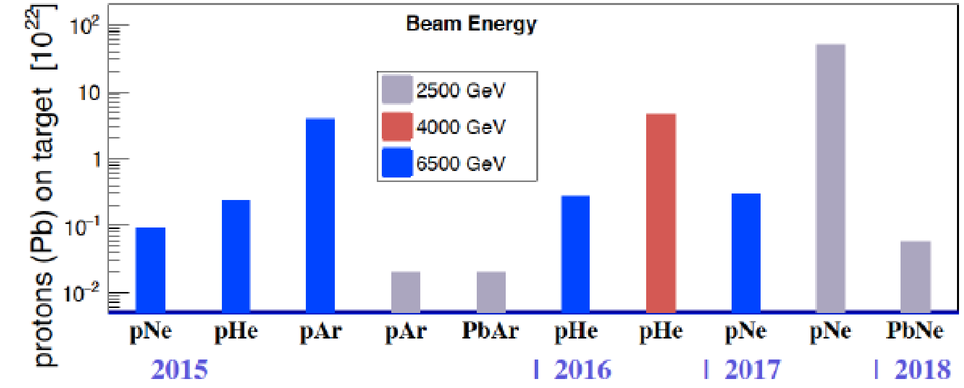


Many interesting published analyses:

- 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

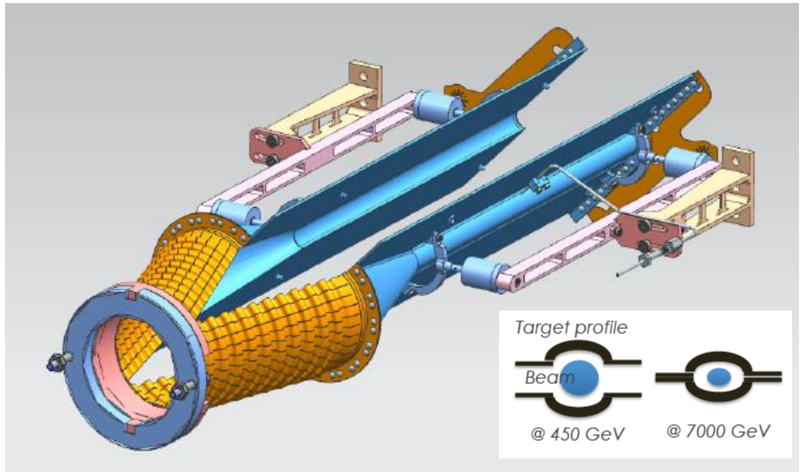
[SMOG2 TDR]

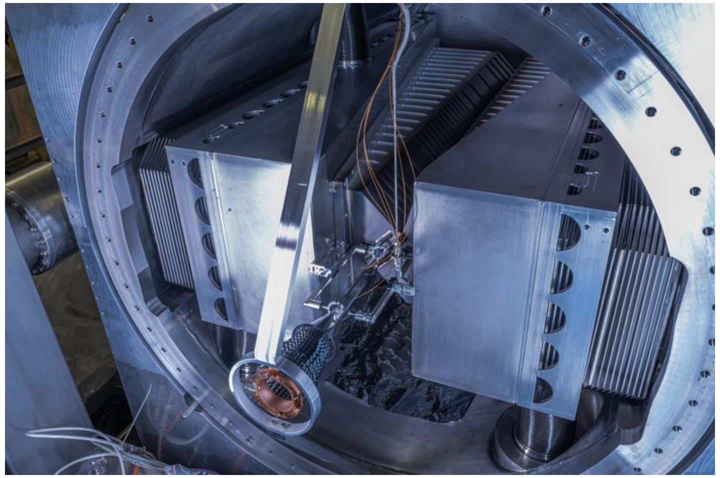
CERN/LHCC 2019-005
LHCb TDR 20
05 May 2019

UPGRADE
TDR
SMOG2

Technical Design Report

- 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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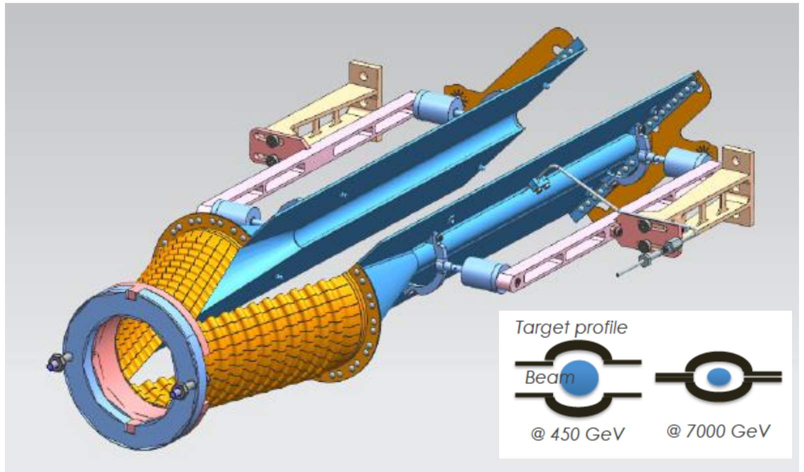
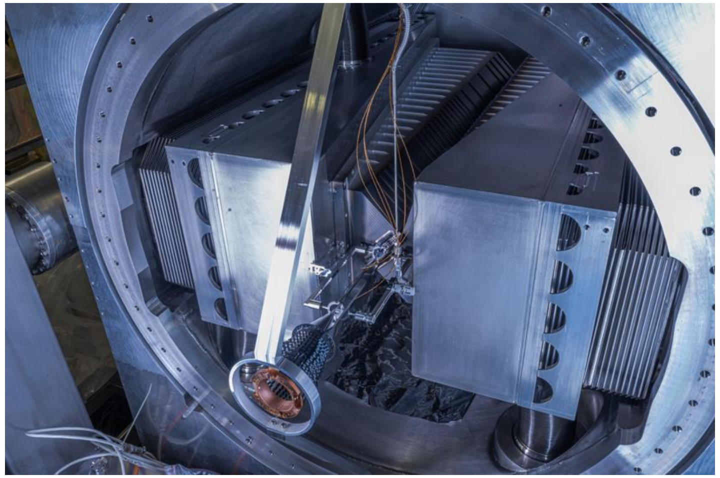
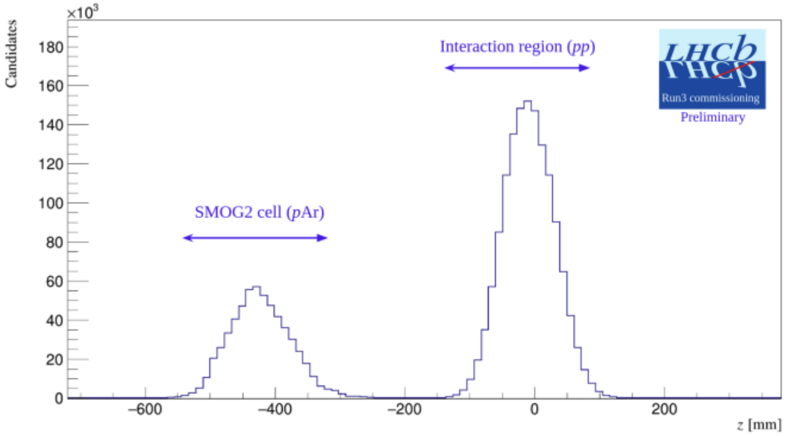




- more gas species: $H_2, D_2, He, N_2, O_2, Ne, Ar$ (Kr and Xe to be tested)
- target density increased by large factor (up to 30)
- precise density (luminosity) determination
- negligible impact on LHC and LHCb performance
- **can run un parallel with collider mode!**

Early 2024 SMOG2 data



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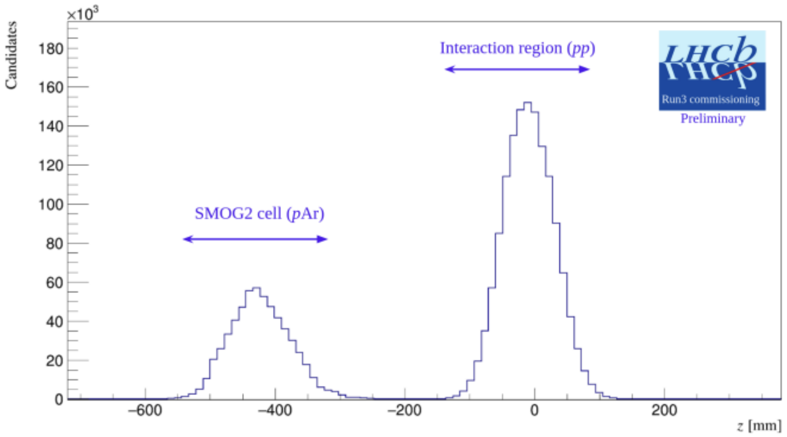

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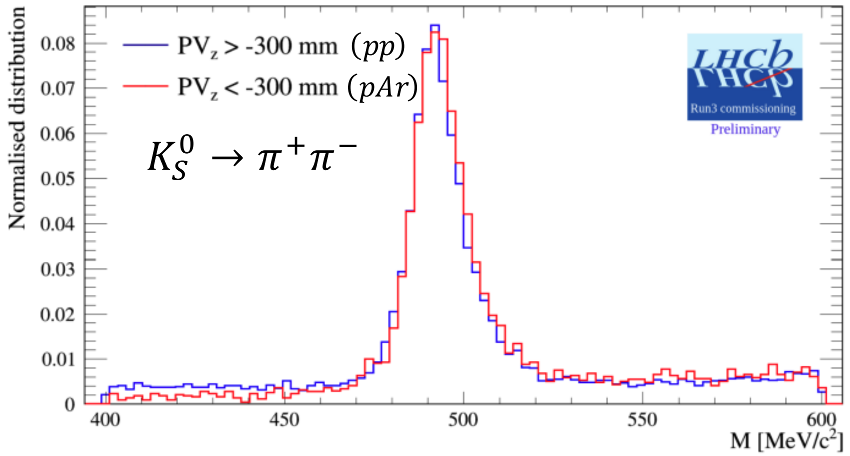

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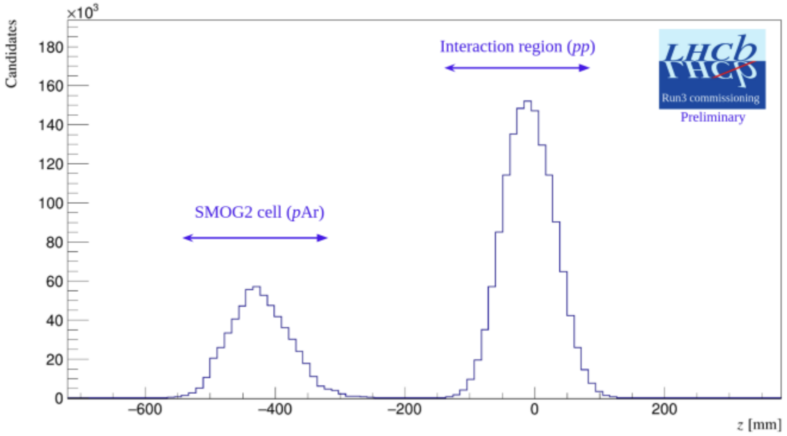

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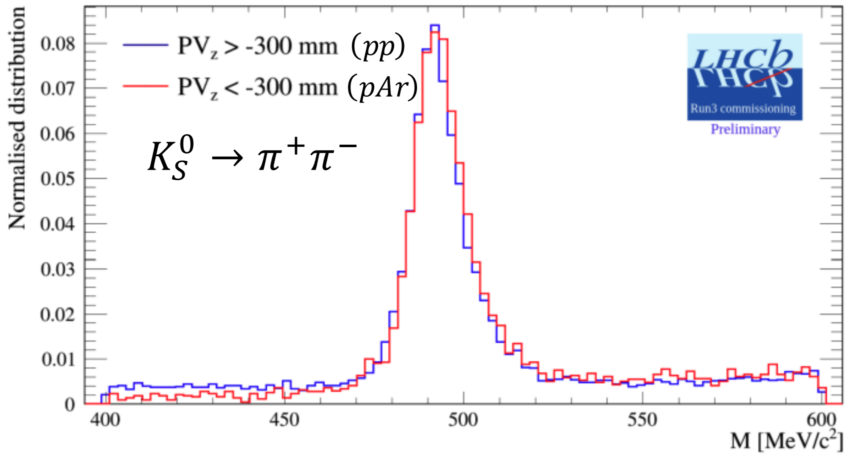

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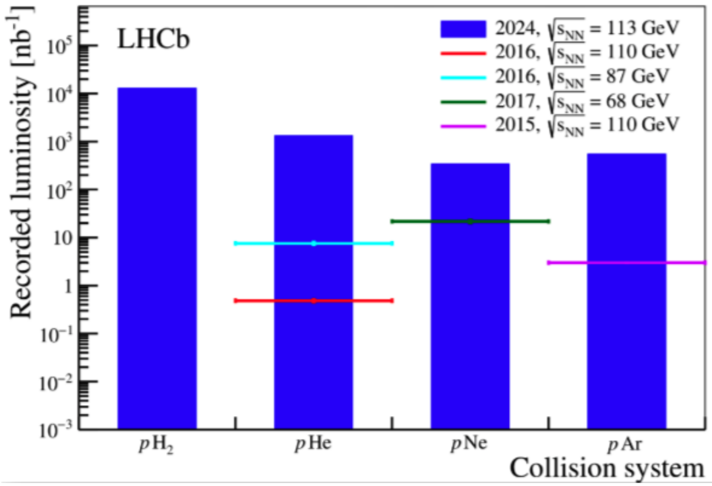

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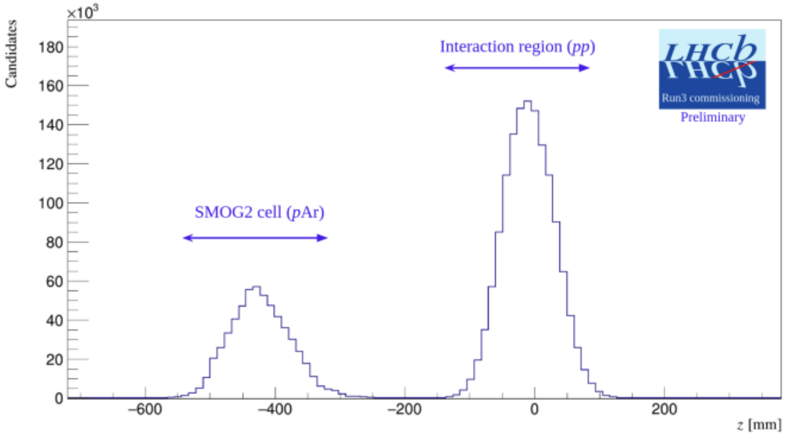

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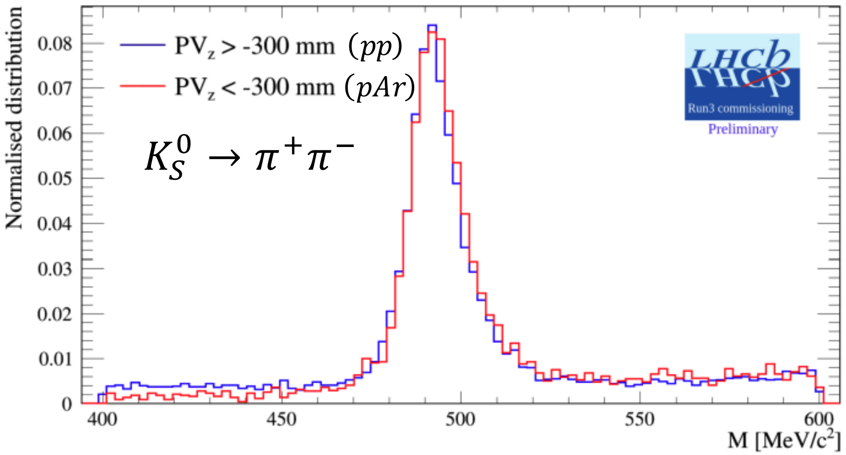

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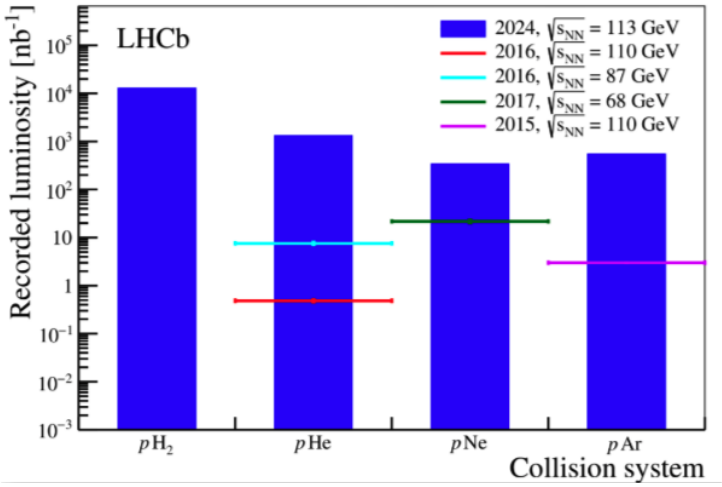
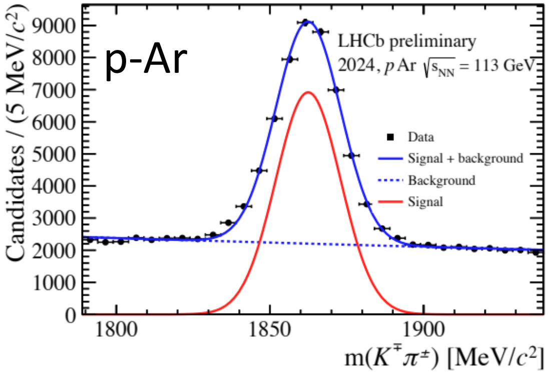
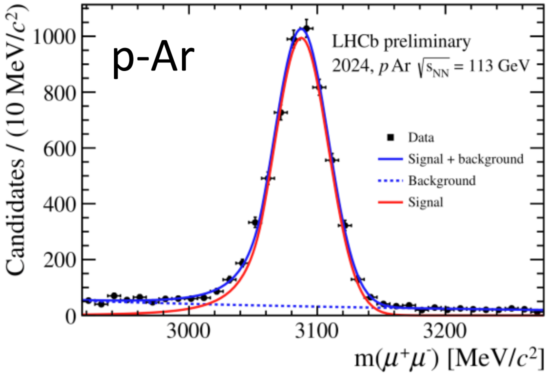


$D^0 \rightarrow K^-\pi^+$

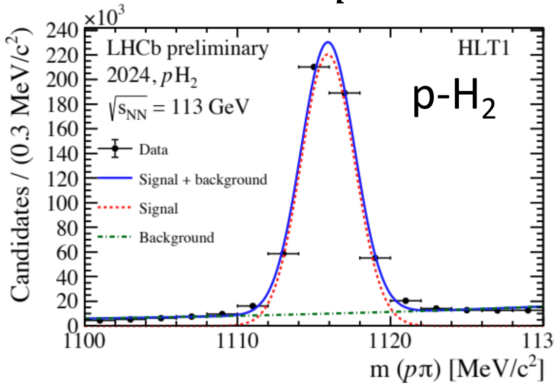


$J/\psi \rightarrow \mu^+\mu^-$



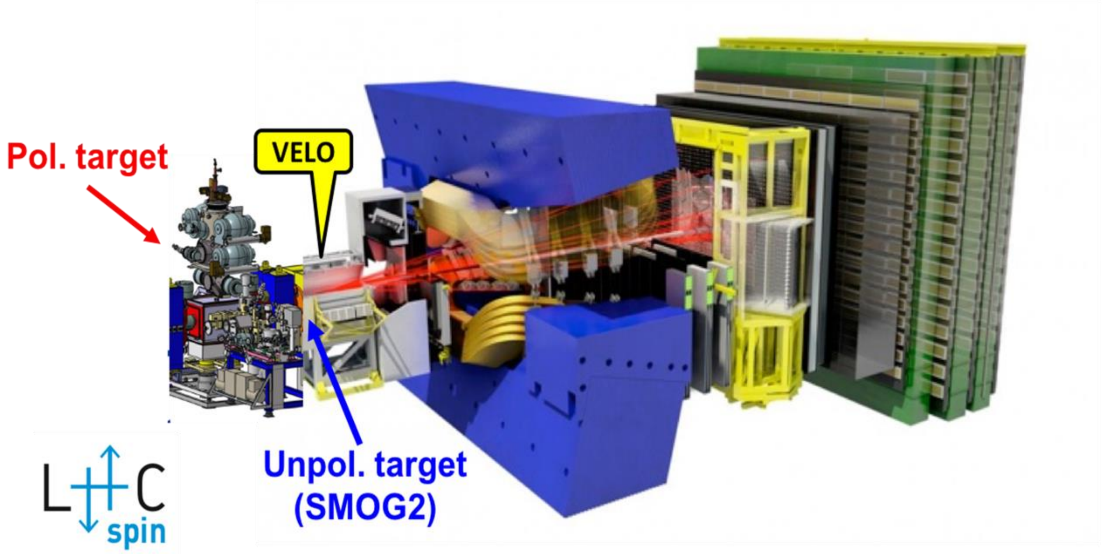
LHCB-FIGURE-2024-005

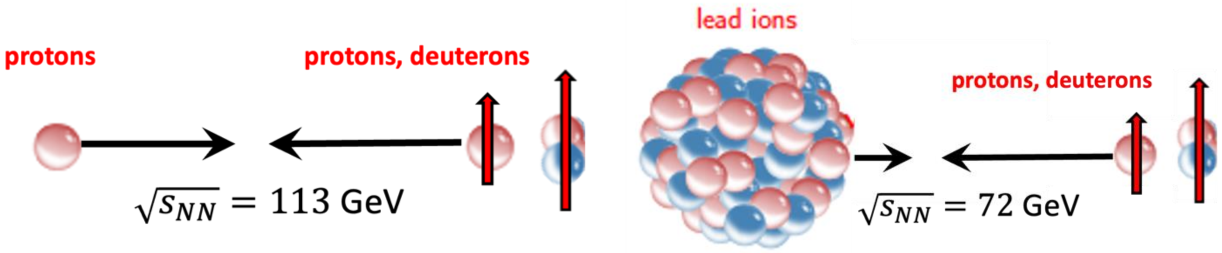
$\Lambda^0 \rightarrow p\pi^-$



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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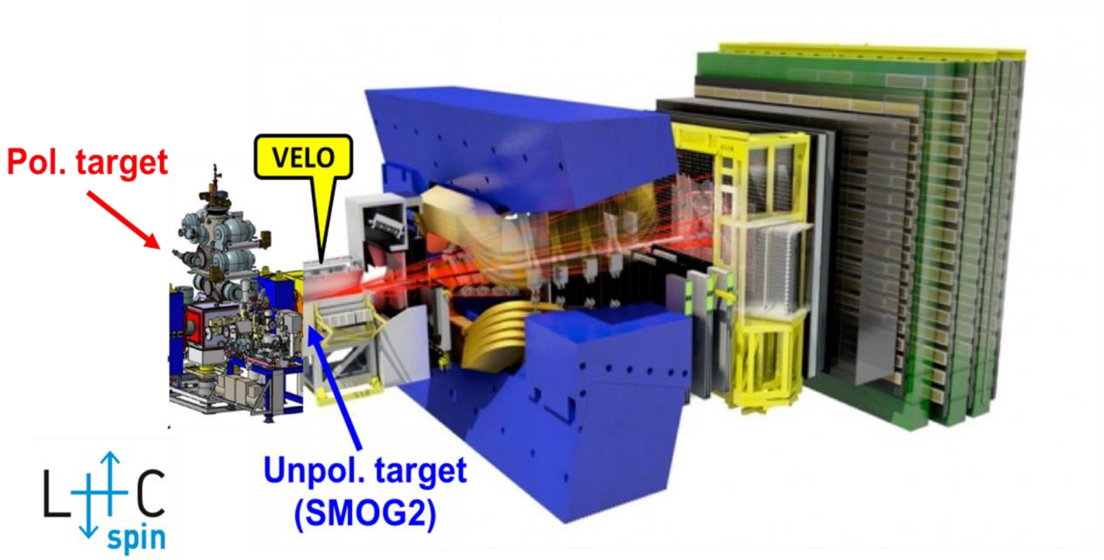

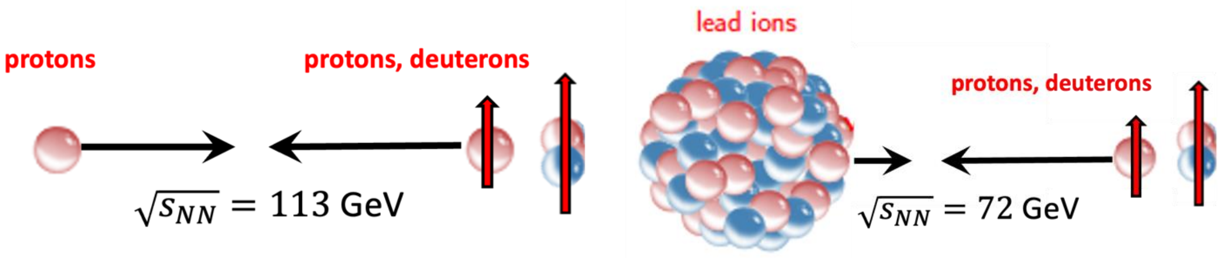

Physics Motivations

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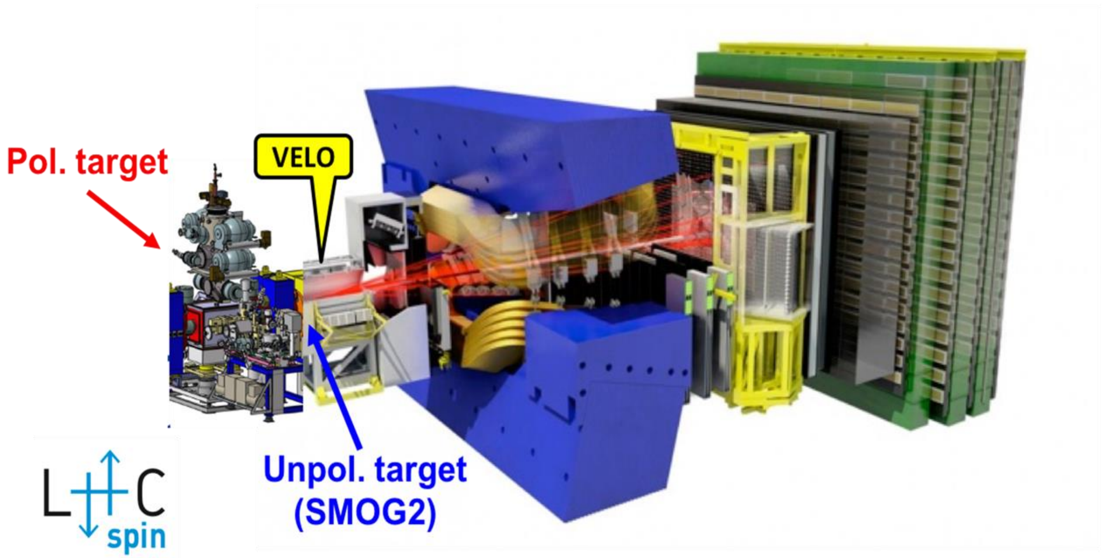
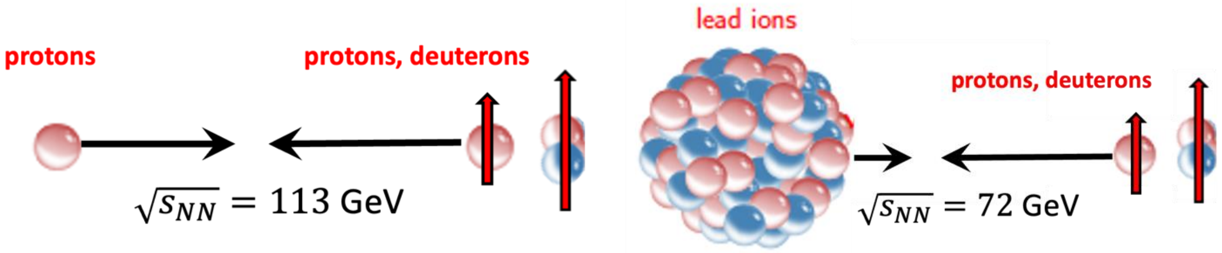


LHCspin



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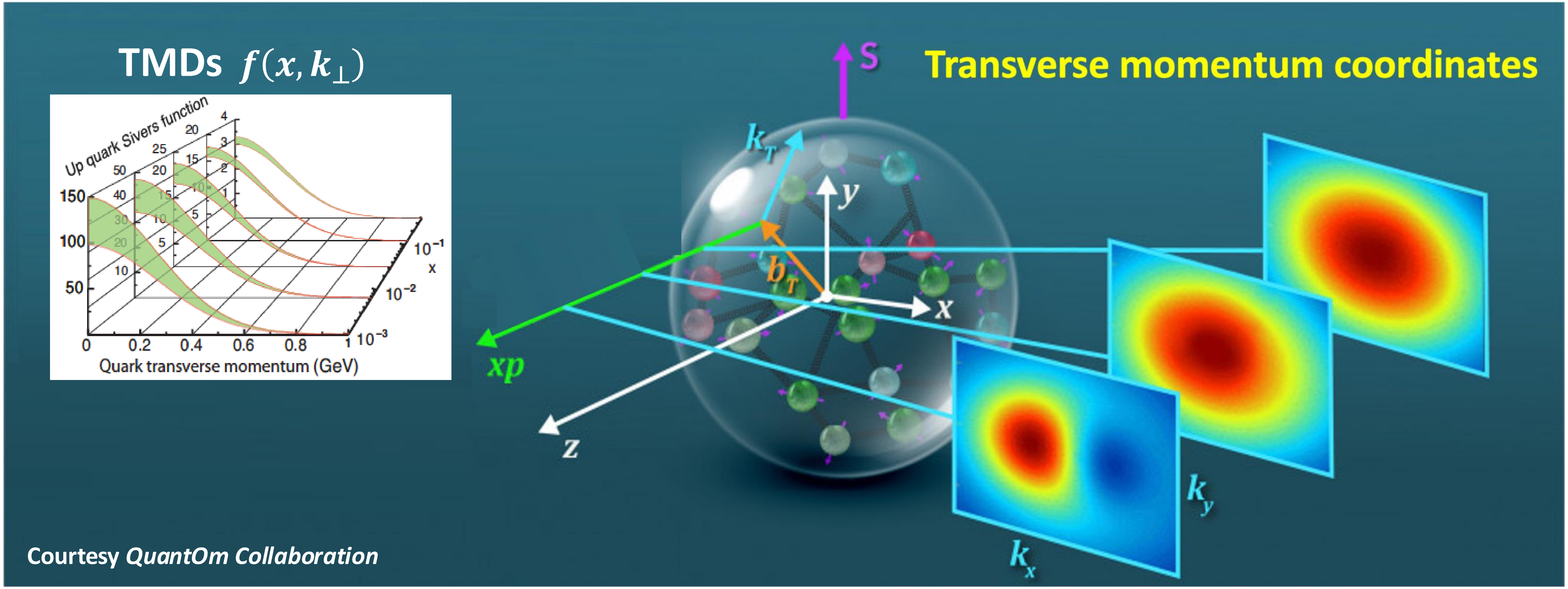
Points of strenght

- ✓ **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 heavy-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)

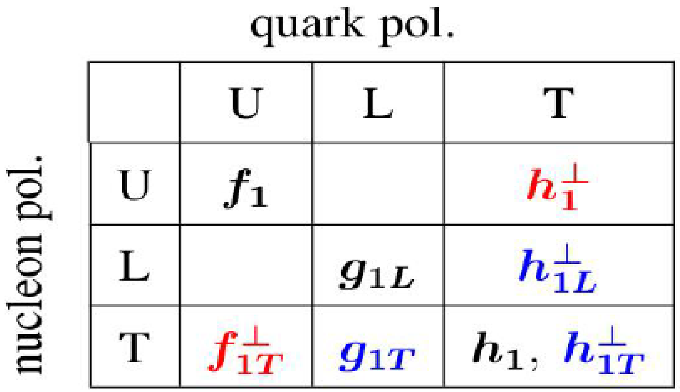
Nucleon tomography in momentum space: TMDs



Courtesy *QuantOm Collaboration*

- 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



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}	$h_1, \; h_{1T}^\perp$

- **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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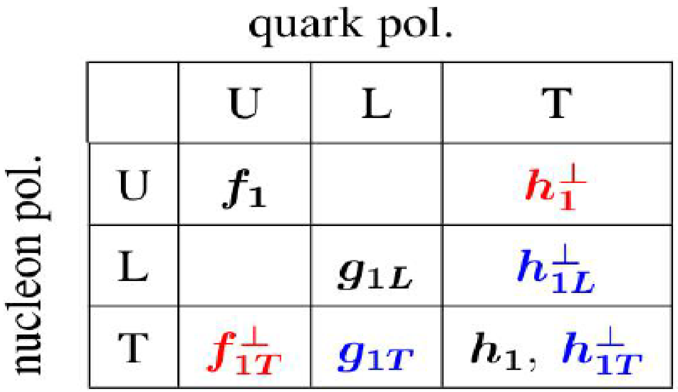

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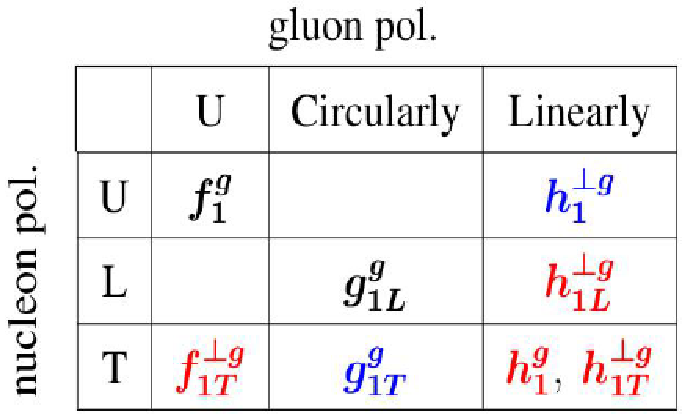


gluon pol.

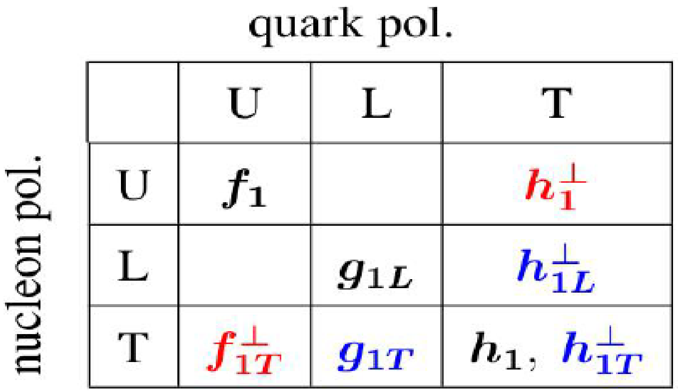
nucleon pol.

	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	$h_1^g,\ h_{1T}^{\perp g}$

- **8 independent gluon TMDs at leading-twist**
- Similar notation, but important differences!
- different naïve-time-reversal properties
- **Experimental access still very limited!**

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

Quark and gluon TMDs

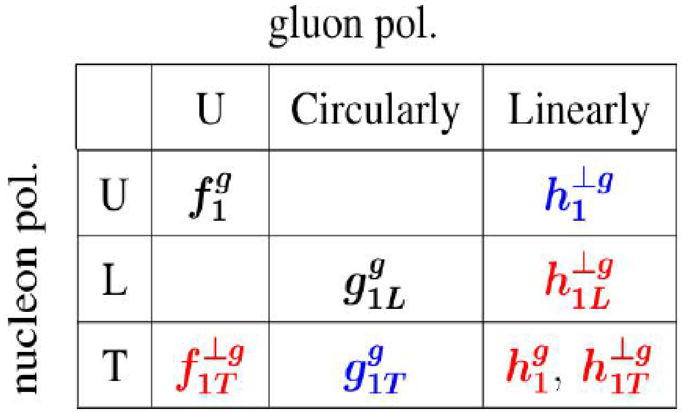


quark pol.

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, $h_{1T}^\perp$

- **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



gluon pol.

nucleon pol.

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- **8 independent gluon TMDs at leading-twist**
- Similar notation, but important differences!
- different naïve-time-reversal properties
- **Experimental access still very limited!**

	T-even	T-odd
q	$\mathbf{h_1^q}$	$\mathbf{h_1^{\perp q}}$
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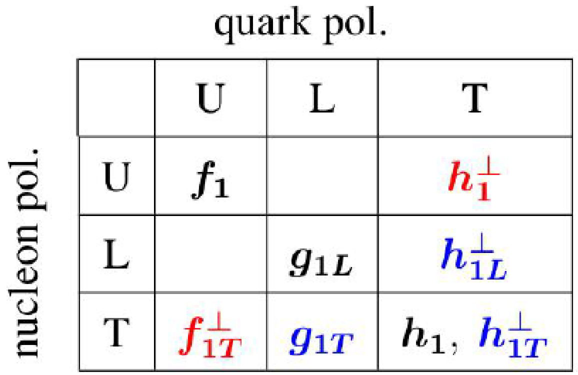
Polarized hadronic collisions with LHCspin offer a complementary approach

- 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

Quark TMDs



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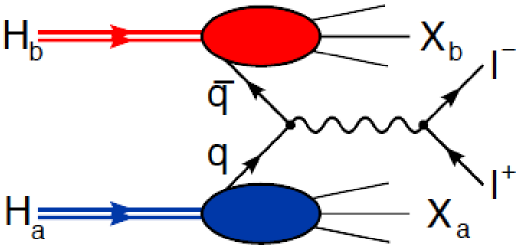
Transv. polarized Drell-Yan



- 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
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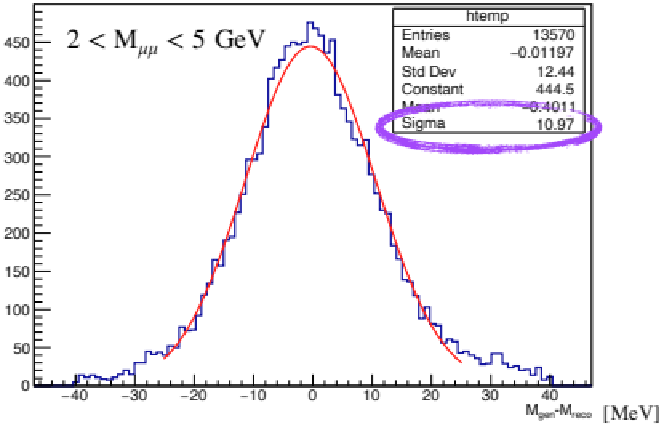
Expected mass resolution

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



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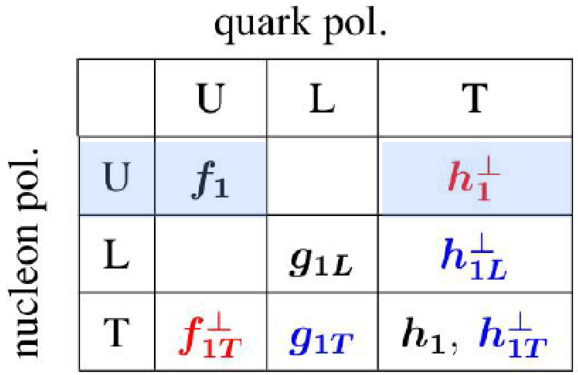

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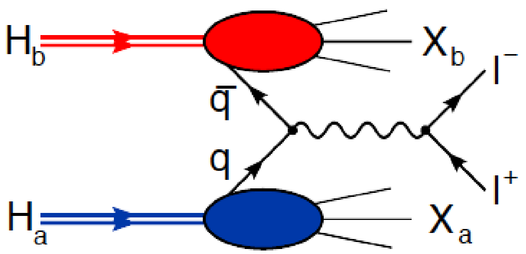

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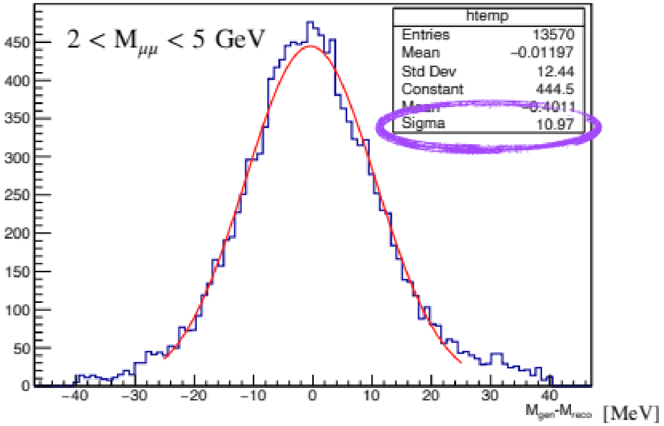
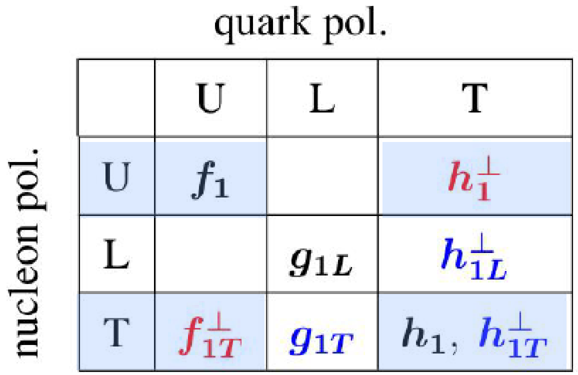


Sensitive to unpol. and BM TMDs

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

Quark TMDs



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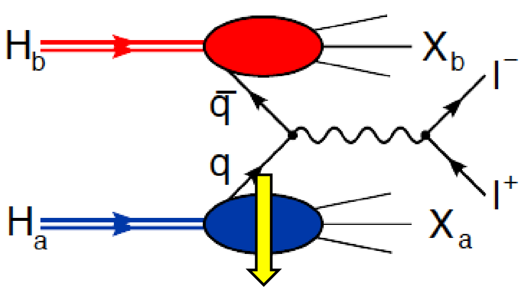

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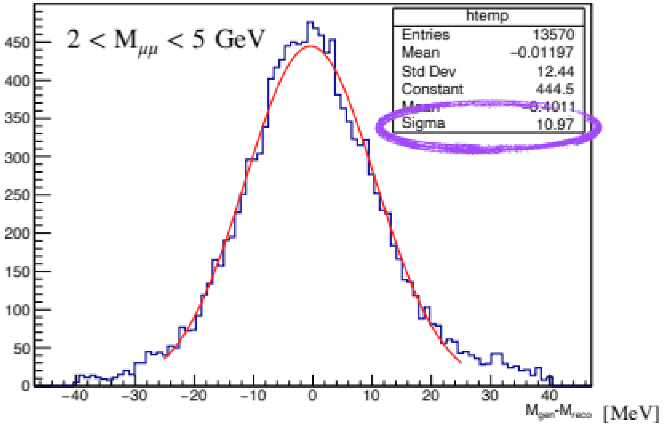

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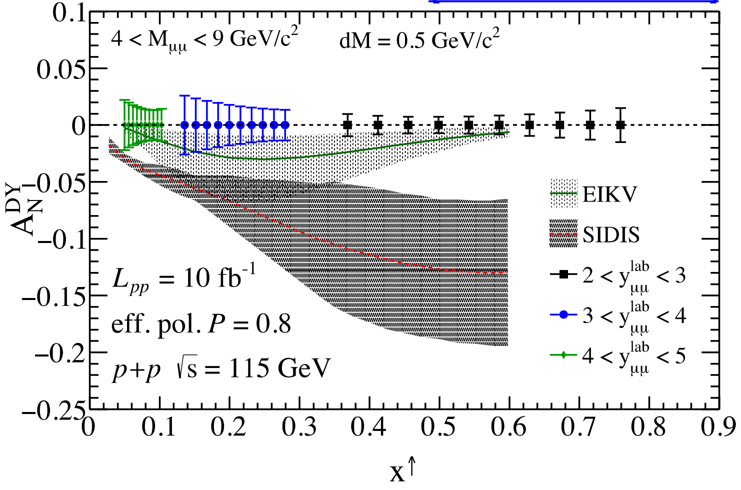
Sensitive to quark TMDs through TSSAs

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

[arXiv:1807.00603]



Quark TMDs

quark pol.

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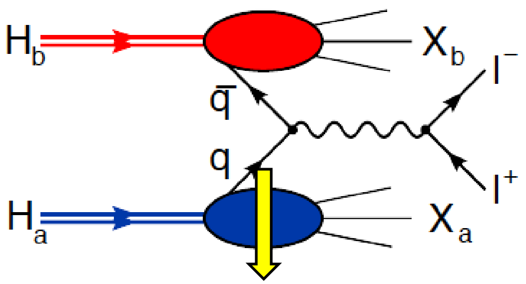

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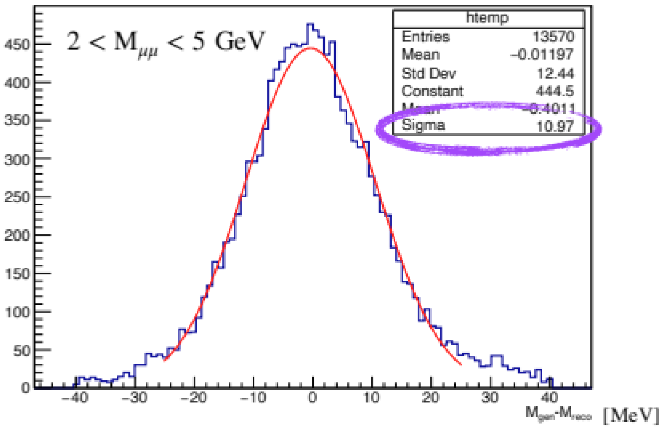

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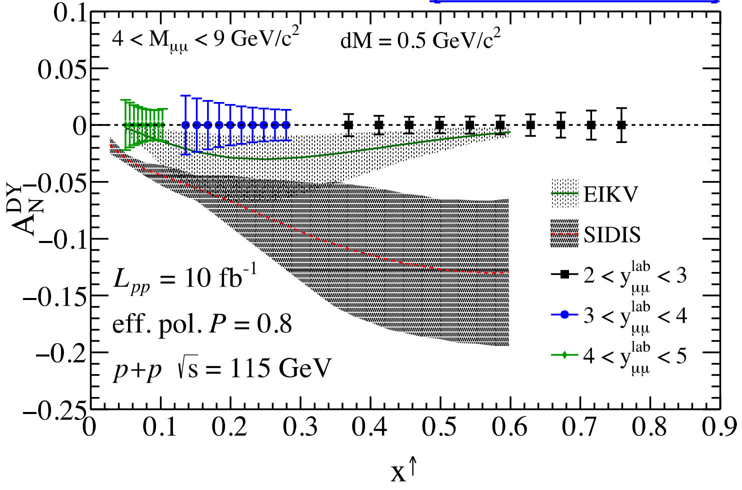
[arXiv:1807.00603]



- 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

Sensitive to unpol. and BM TMDs

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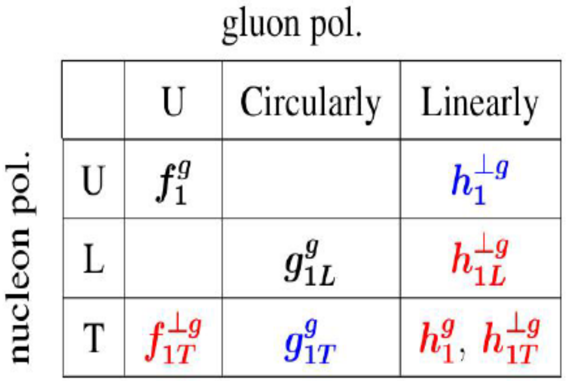
Gluon TMDs



nucleon pol. \ gluon pol.	U	Circularly	Linearly
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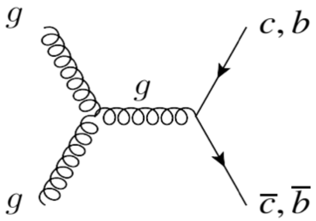
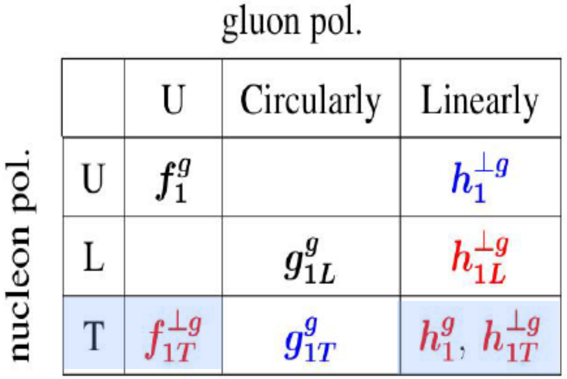
In high-energy hadron collisions, heavy quarks are dominantly produced through gg fusion:



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

Gluon TMDs



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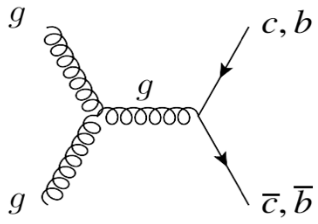

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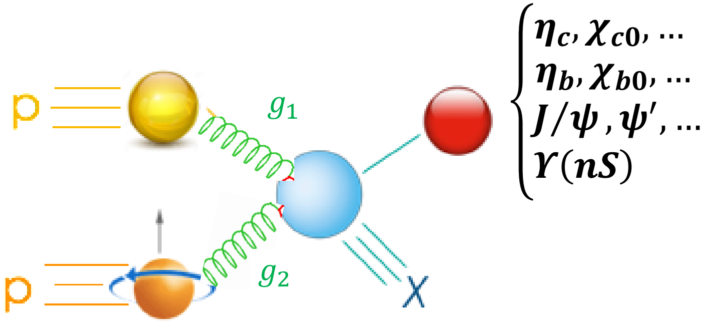
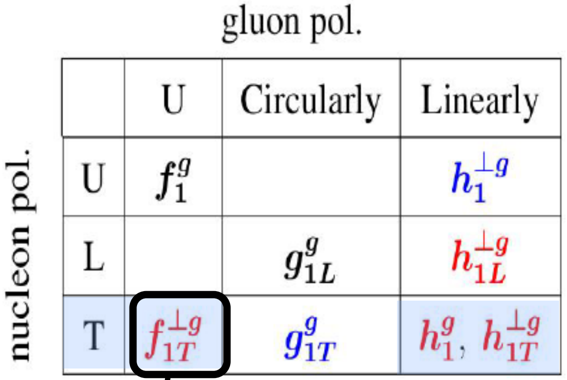


$$\begin{cases} \eta_c, \chi_{c0}, \ldots \\ \eta_b, \chi_{b0}, \ldots \\ J/\psi, \psi', \ldots \\ \Upsilon(nS) \end{cases}$$

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



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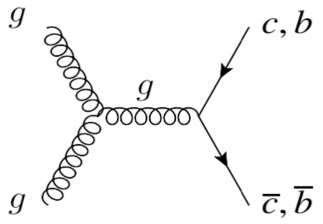
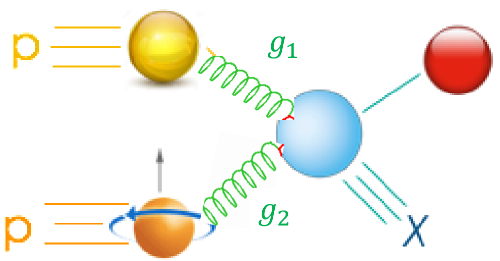


the most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-quark observables**



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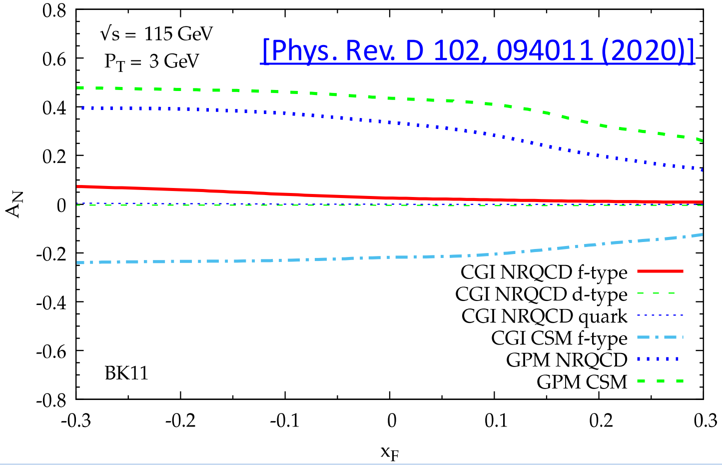
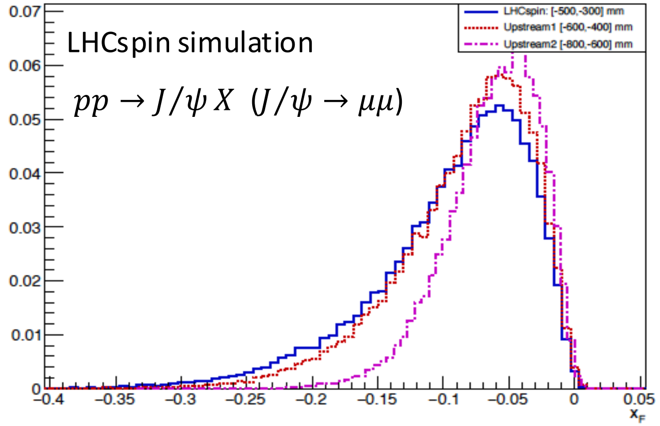
Gluon Sivers function:

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



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



LHCspin simulation

$pp \to J/\psi\, X\ \ (J/\psi \to \mu\mu)$

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

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

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

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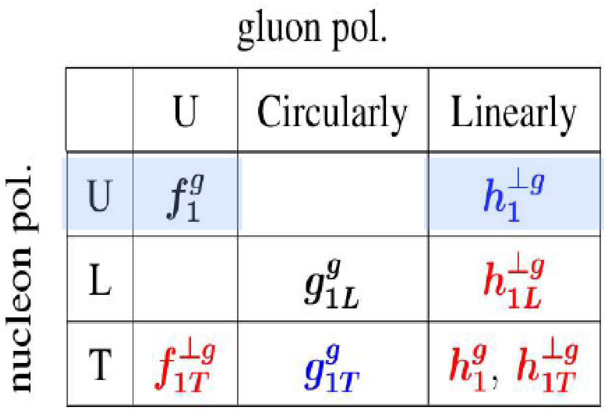

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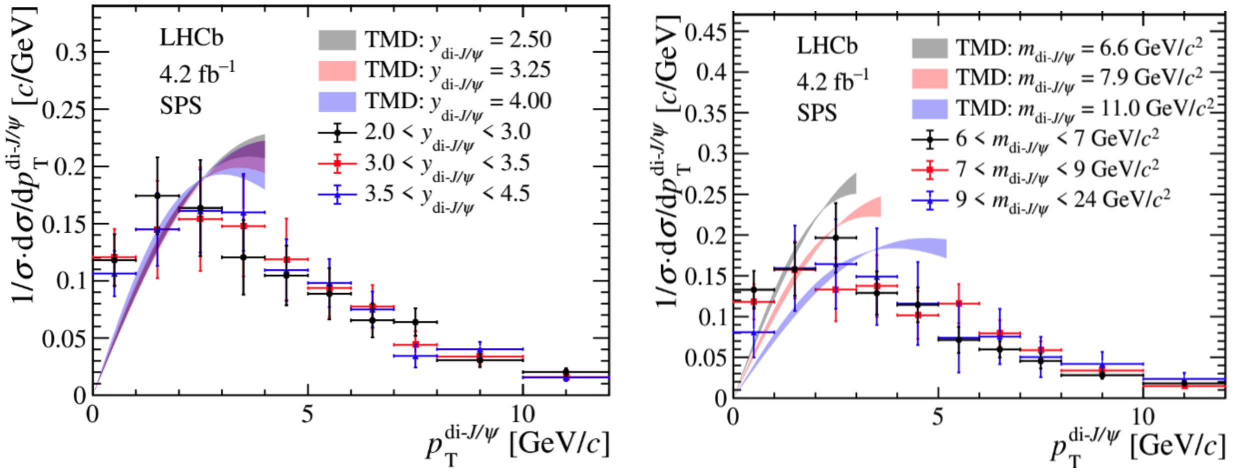
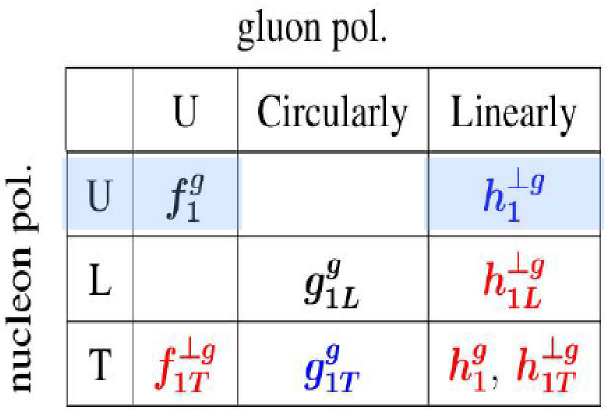
pp, 13 TeV JHEP 03 (2024) 088





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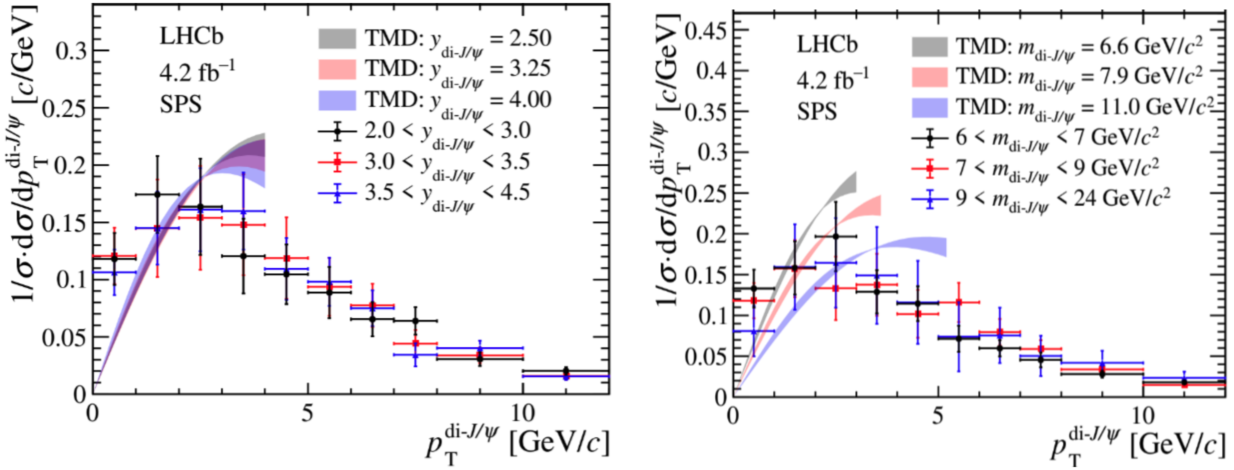
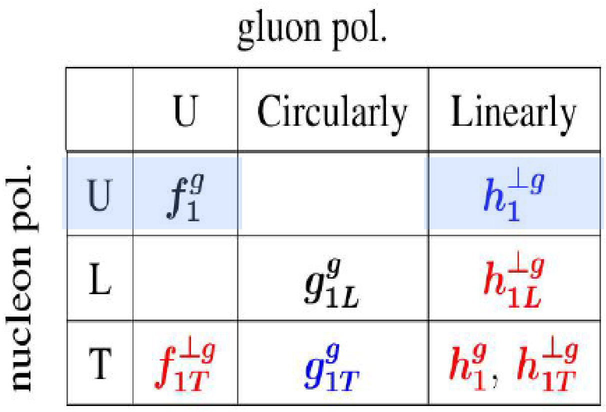
$pp, 13\ TeV$ JHEP 03 (2024) 088





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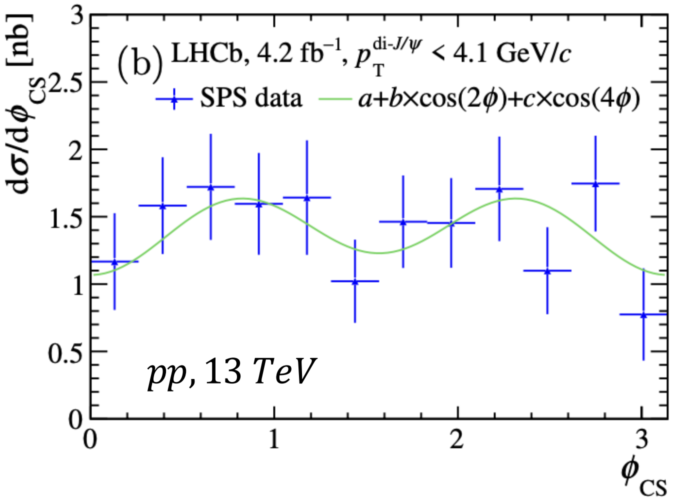


JHEP 03 (2024) 088

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

- 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

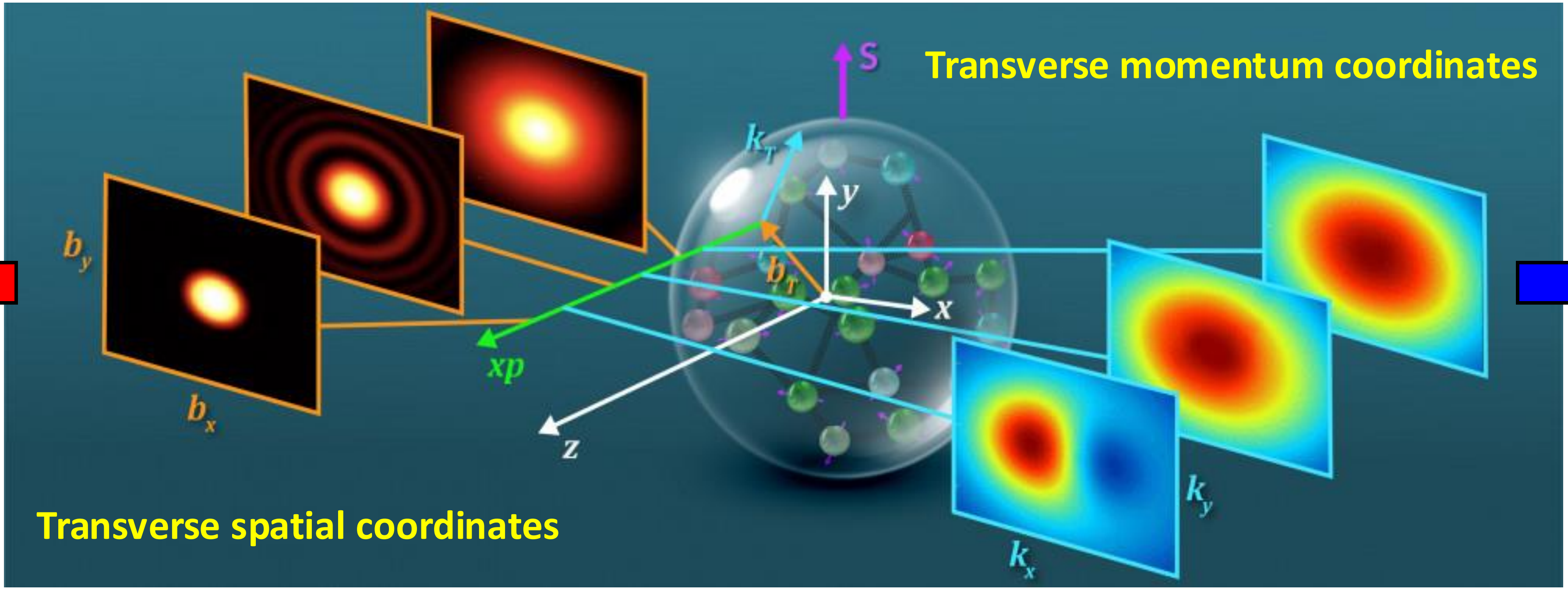
nucleon tomography in coord. space

$f(x, r_\perp)$

FT

GPDs

$H(x, \xi, t)$



nucleon tomography in mom. space

TMDs

$f(x, k_\perp)$

Courtesy *QuantOm Collaboration*

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.

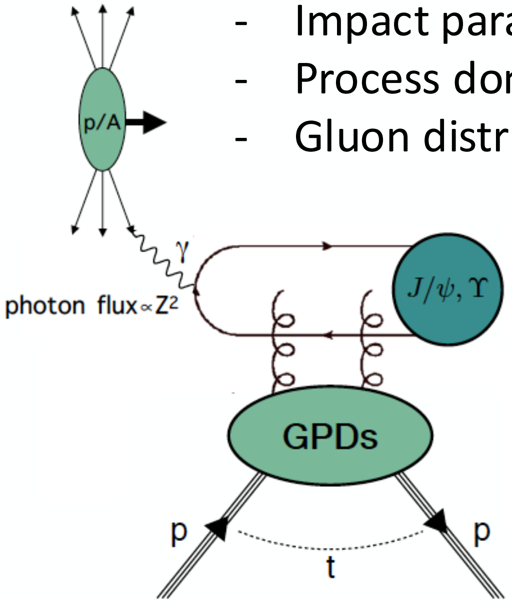
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Gluon GPDs and UPC

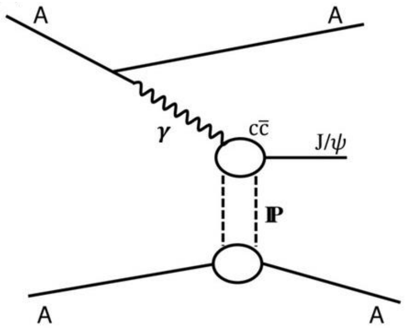
GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

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]

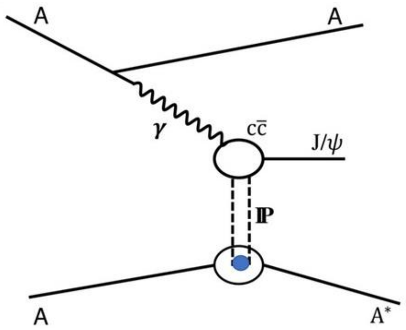
At LHC energies, these photons are energetic enough to trigger the production of hard dileptons and charmonia and bottomonia.



- 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
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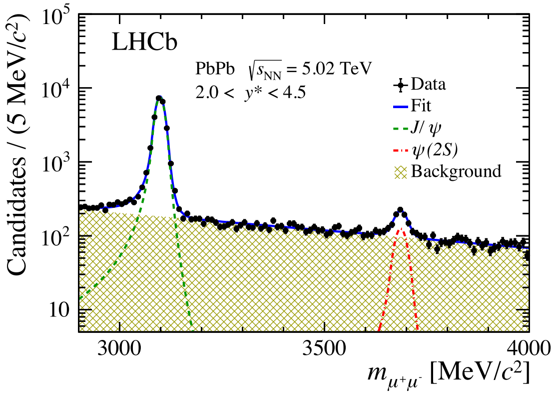
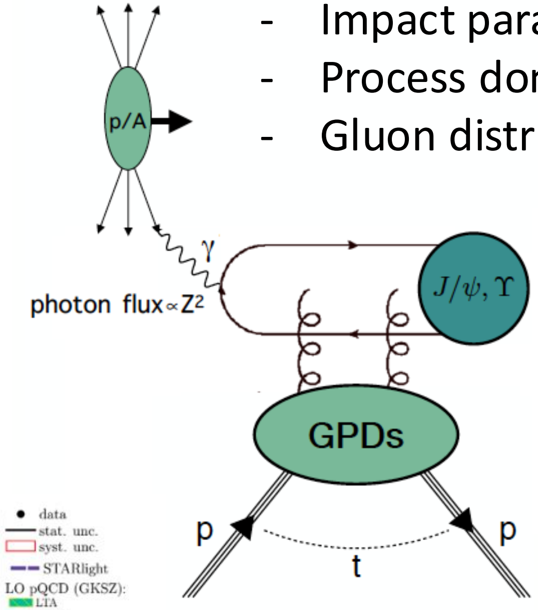


J. High Energ. Phys. 2023

Pb-Pb collisions

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



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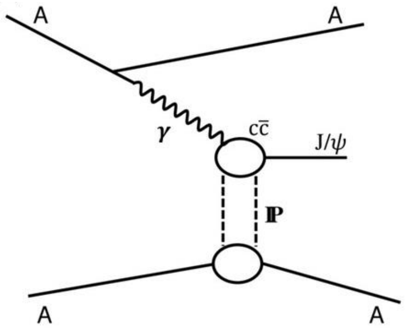

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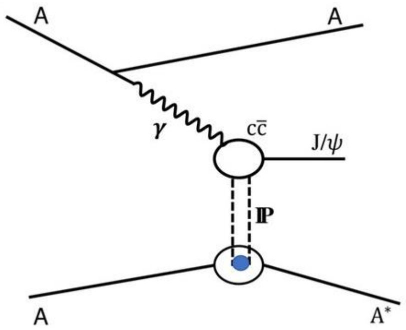

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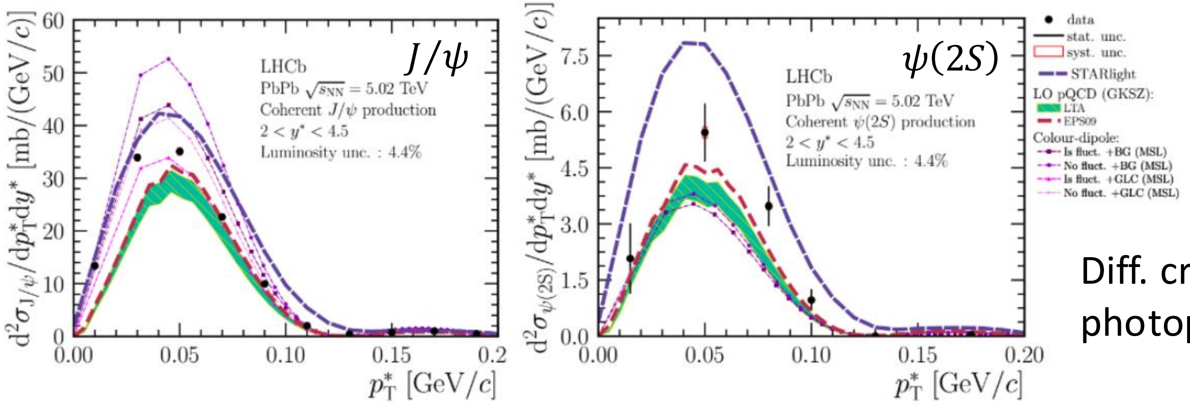

Diff. cross section vs. p_T for coherent J/ψ and $\psi(2S)$ photoproduction, compared with models

Gluon GPDs and UPC

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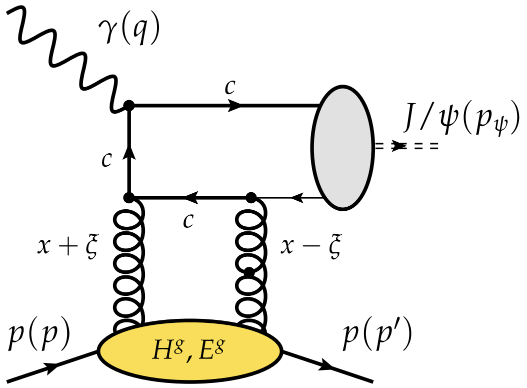
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T, \; \tilde{H}_T$

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

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



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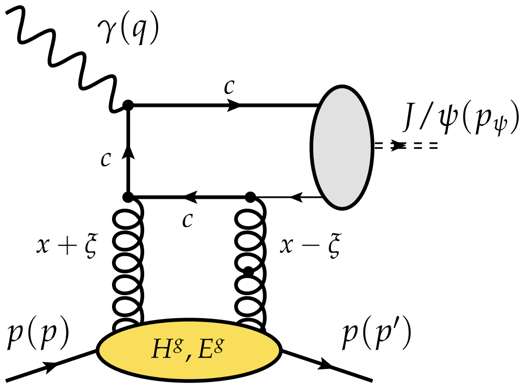
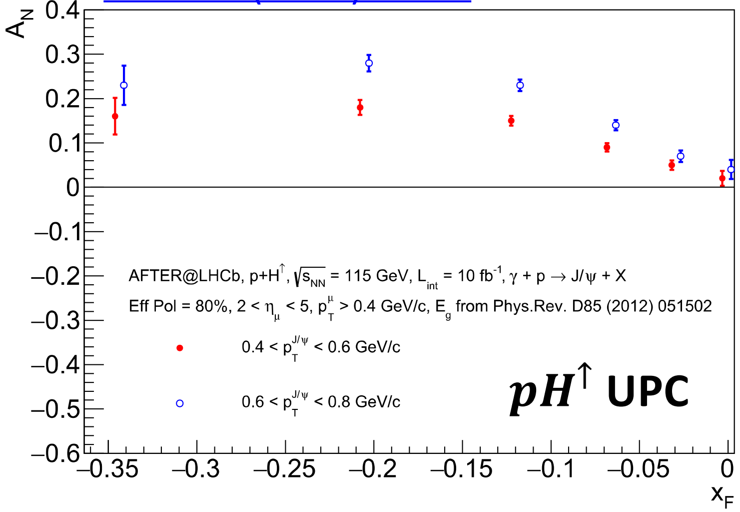
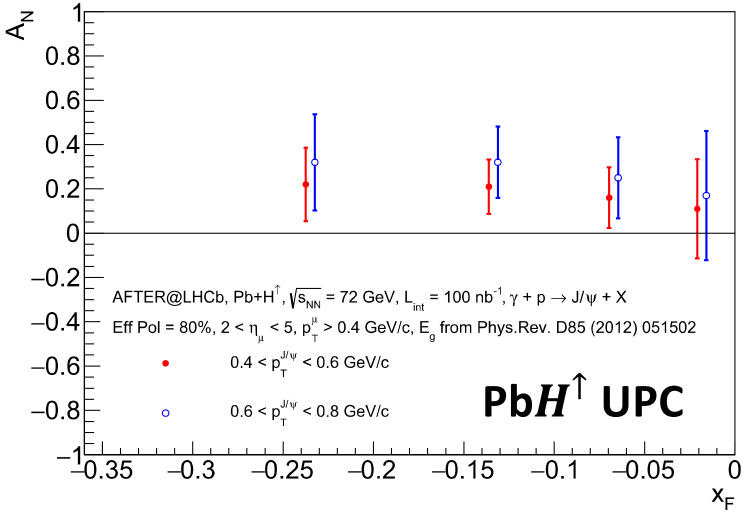


$$A_N = \frac{\sigma^{h_A h_B^{\downarrow}} - \sigma^{h_A h_B^{\uparrow}}}{\sigma^{h_A h_B^{\downarrow}} + \sigma^{h_A h_B^{\uparrow}}} = \frac{\int dk \frac{dn_A}{dk} A_N^{\gamma}\, \sigma^{\gamma h_B}}{\int dk \left[\frac{dn_A}{dk}\sigma^{\gamma h_B} + \frac{dn_B}{dk}\sigma^{\gamma h_A}\right]}$$

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



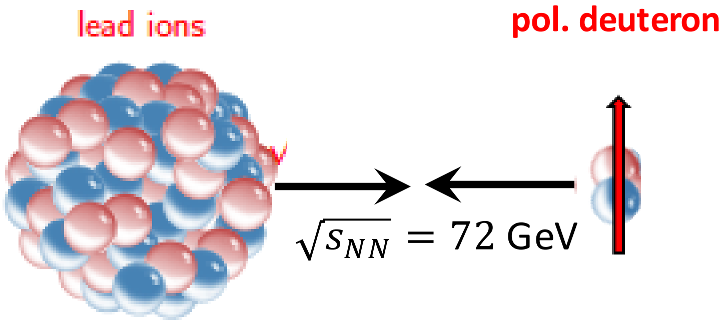


- Extraction based on models for the GPD H^g (Goloskokov-Kroll) and E^g (PRD 85, 051502 (2012))
- AFTER model-dependent predictions **very promising for $pH^{\uparrow}$ UPC**

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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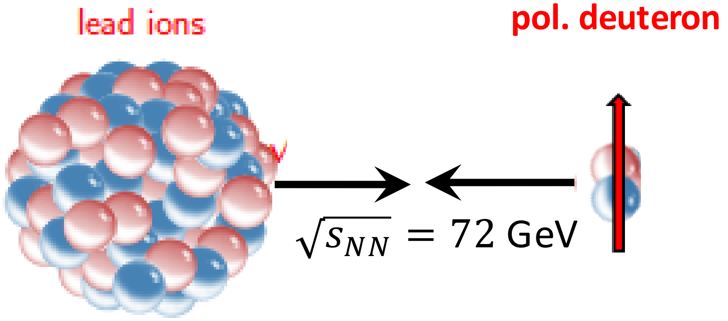

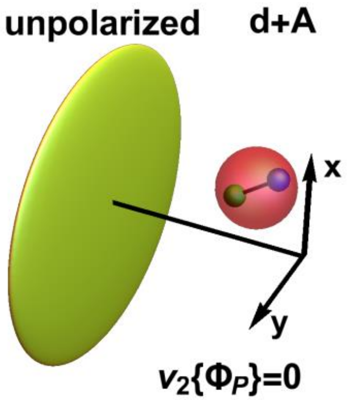

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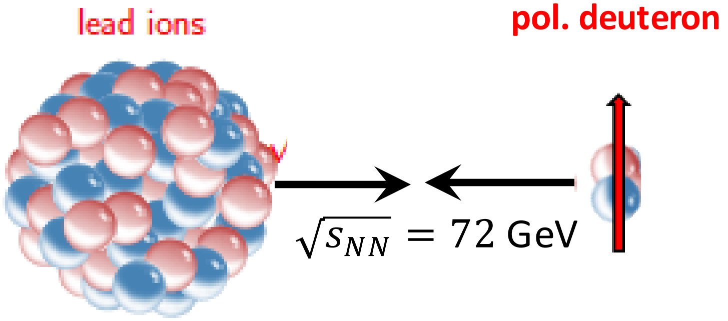

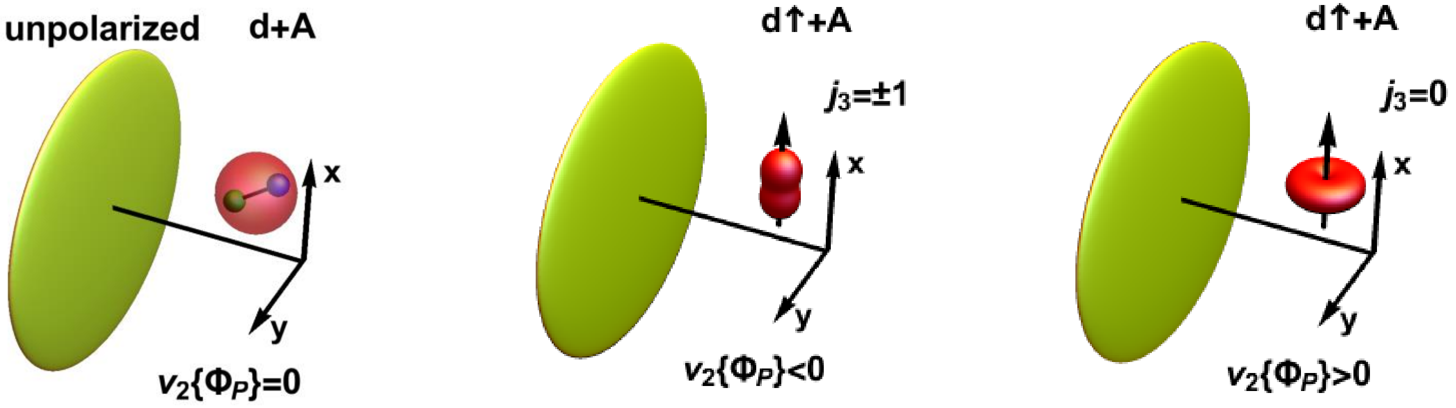

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$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

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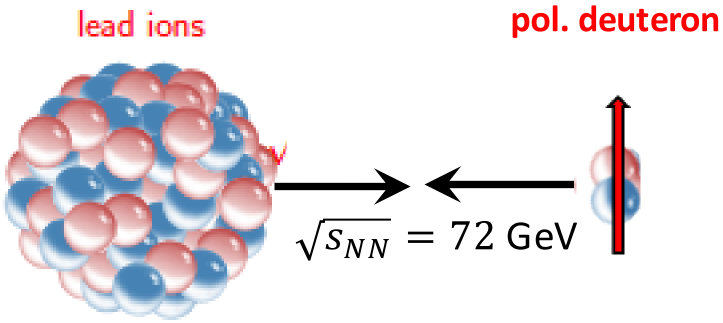

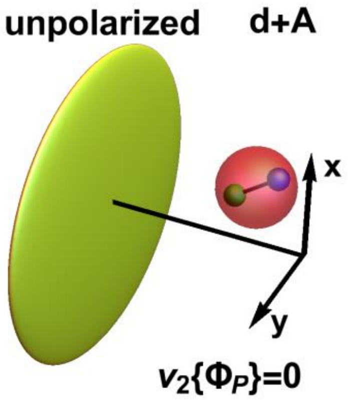

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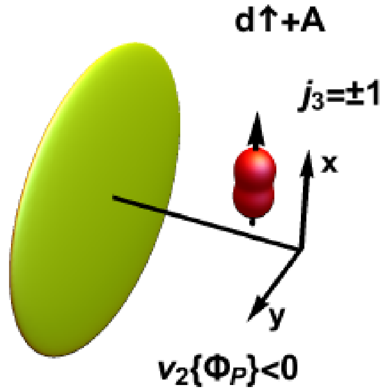

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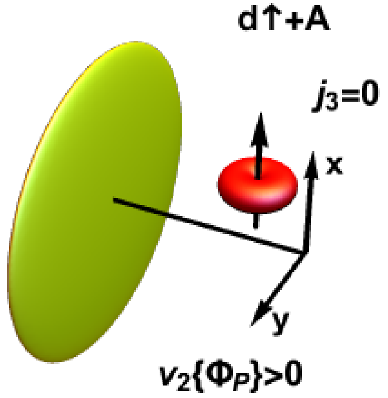

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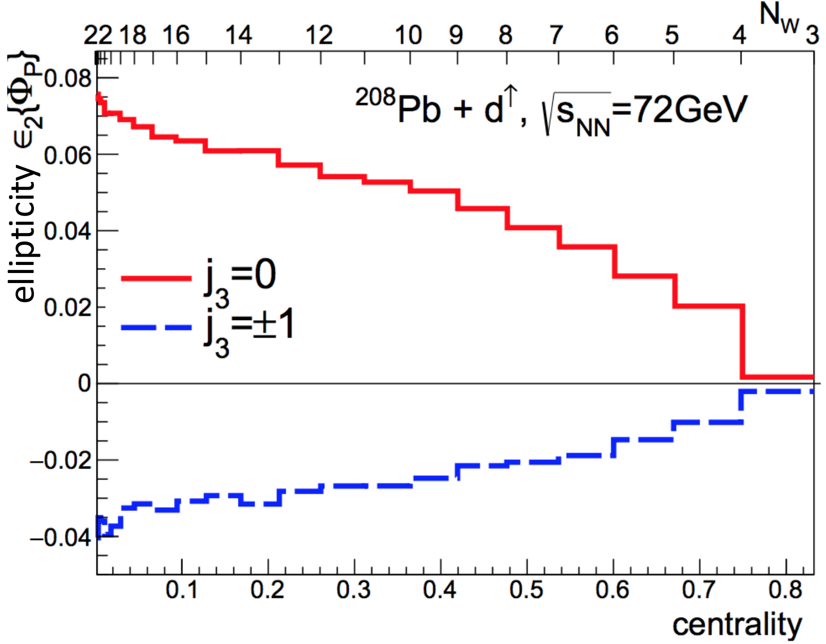
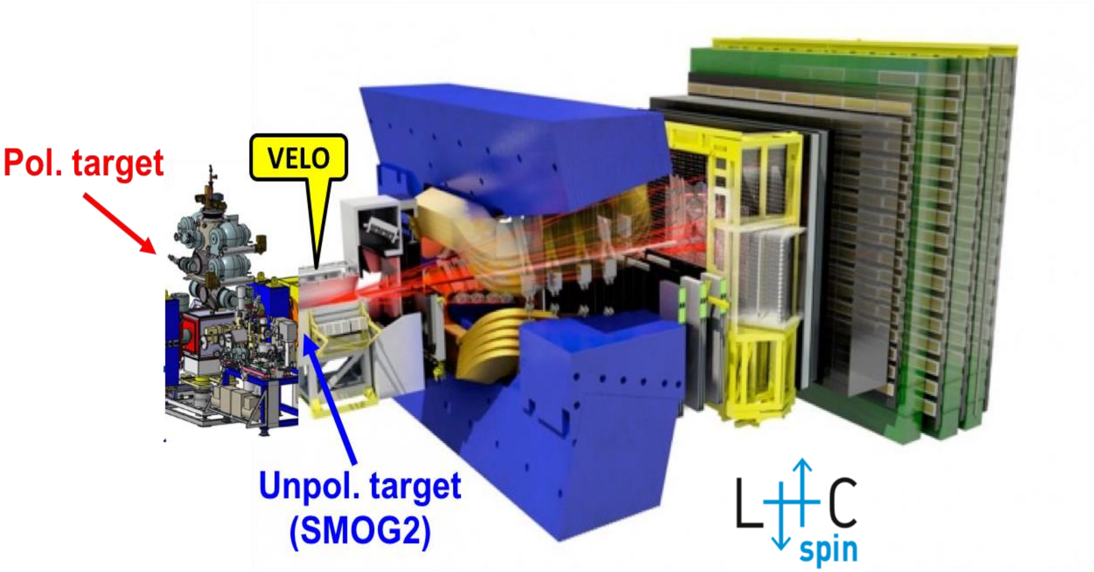
Predictions for LHC FT kinematics



[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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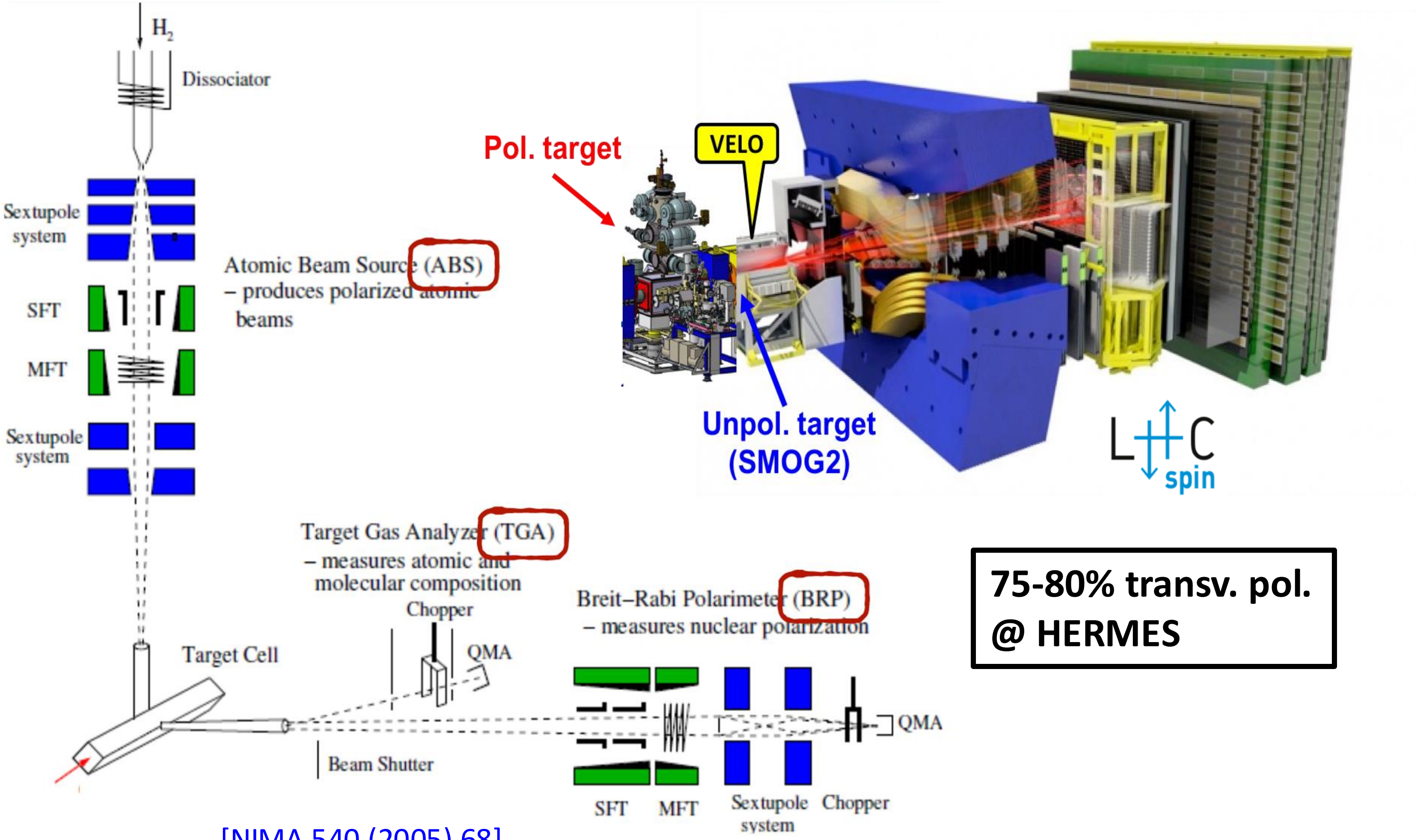

[NIMA 540 (2005) 68]

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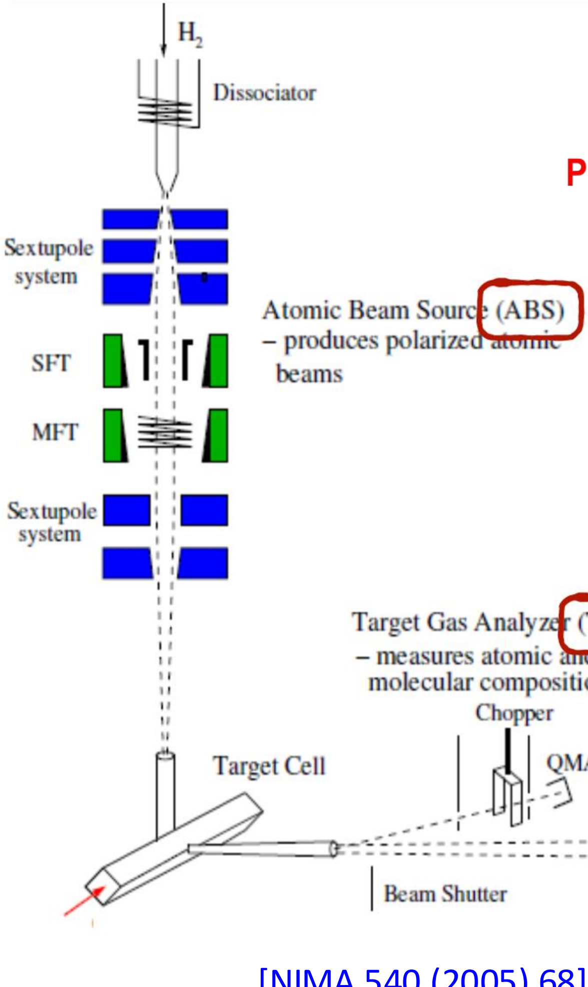

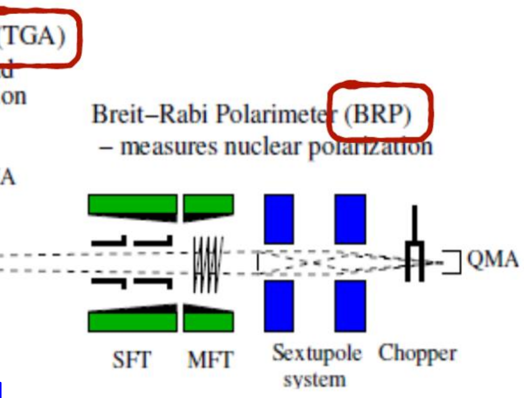

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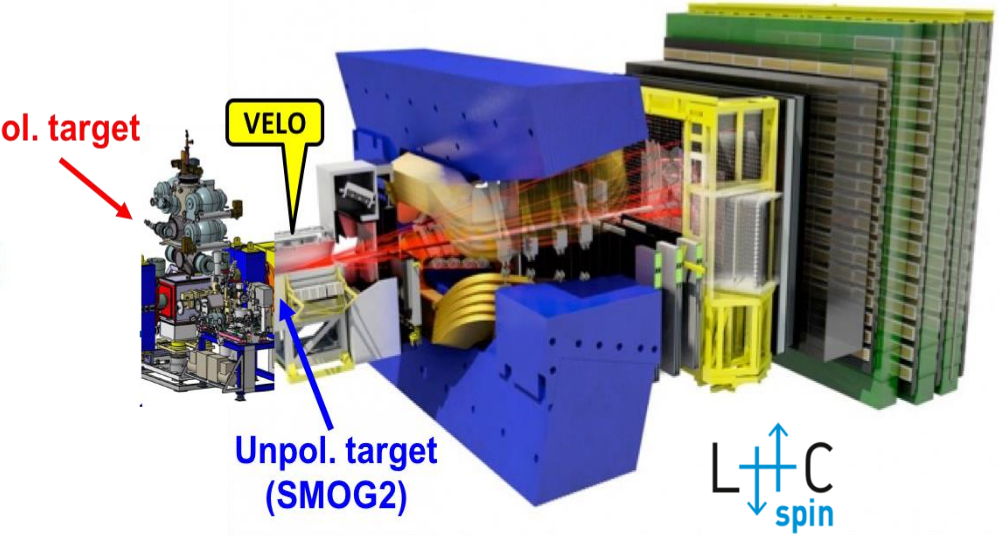

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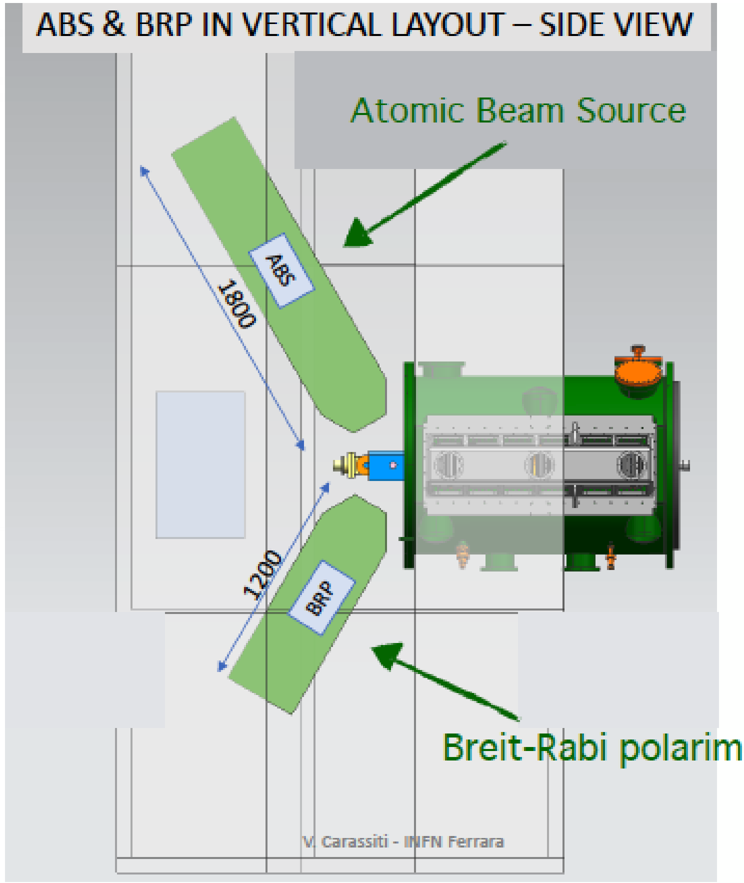

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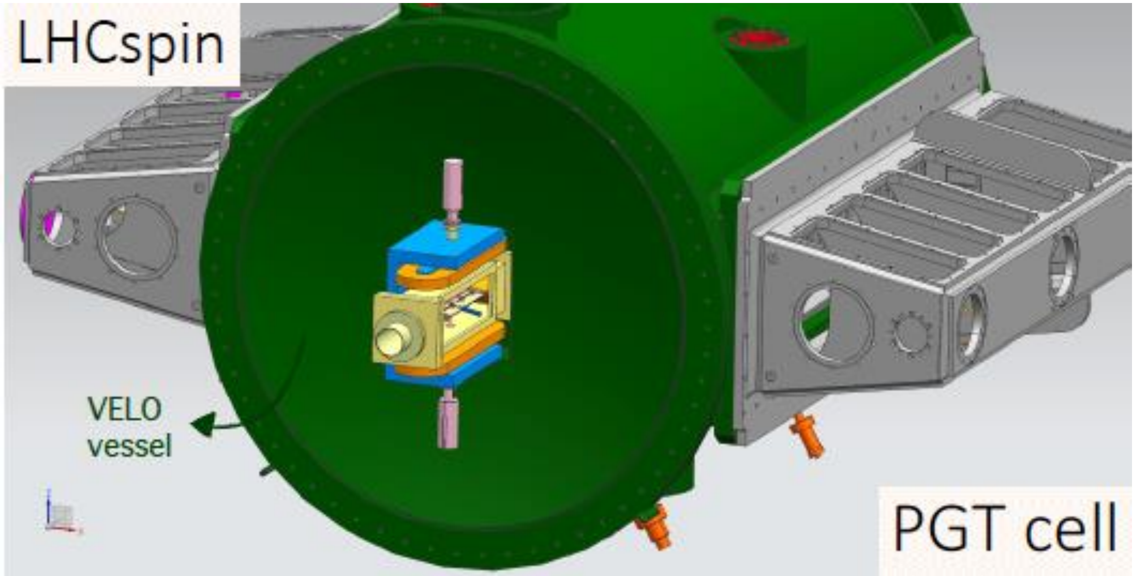

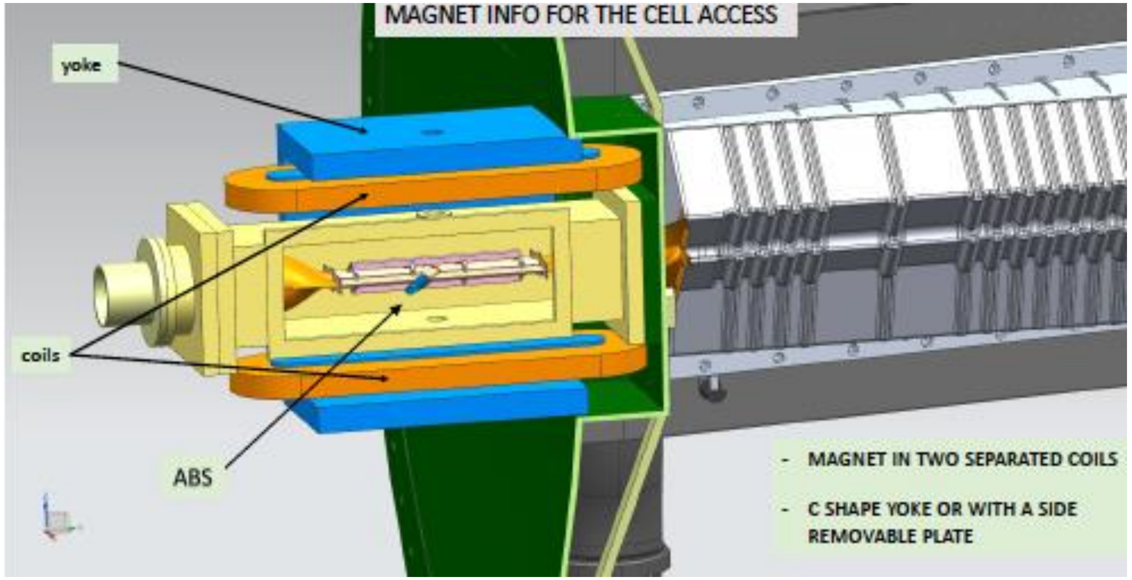

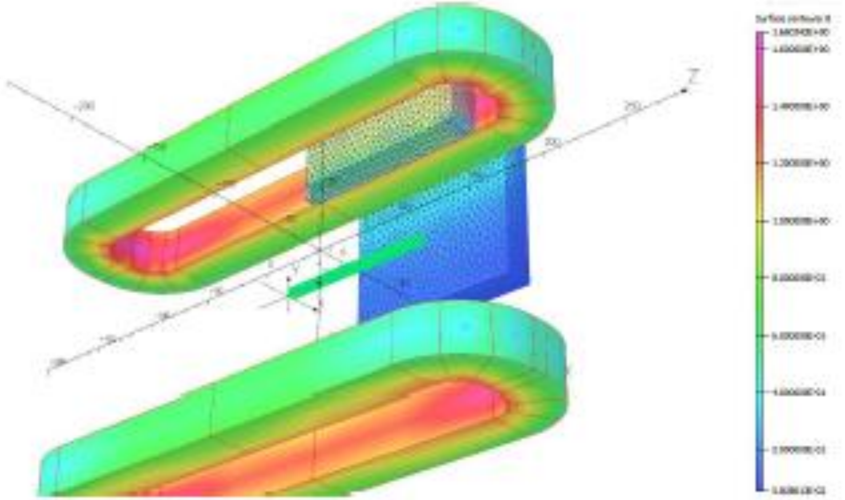

- **Compact SC dipole magnet for static transverse field to maintain polarization inside the cell**
- **Required $B = 300\ mT$ with $\Delta B/B \sim 10\%$**

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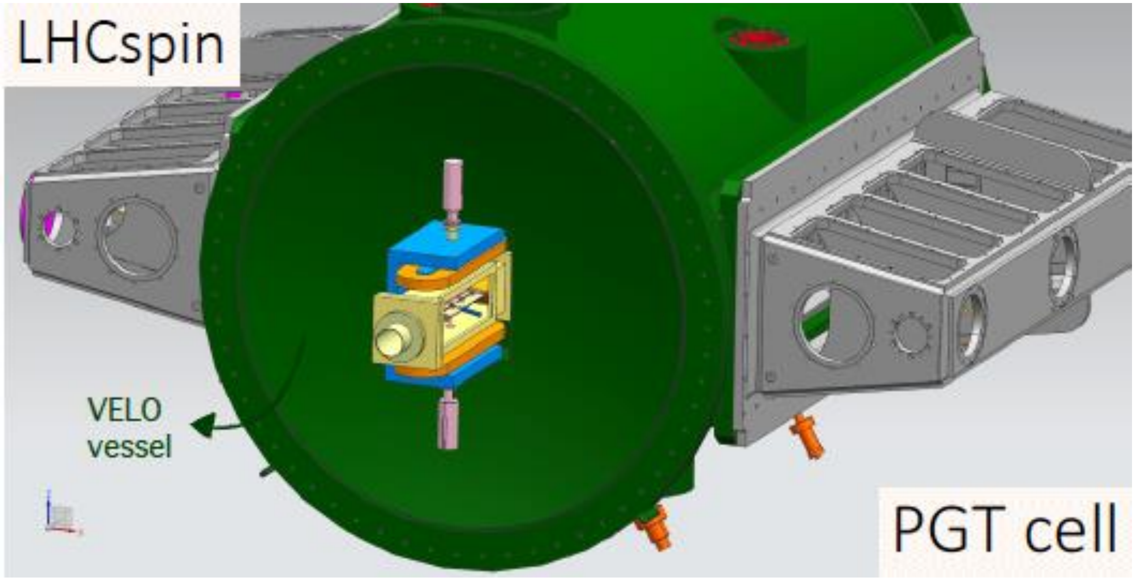

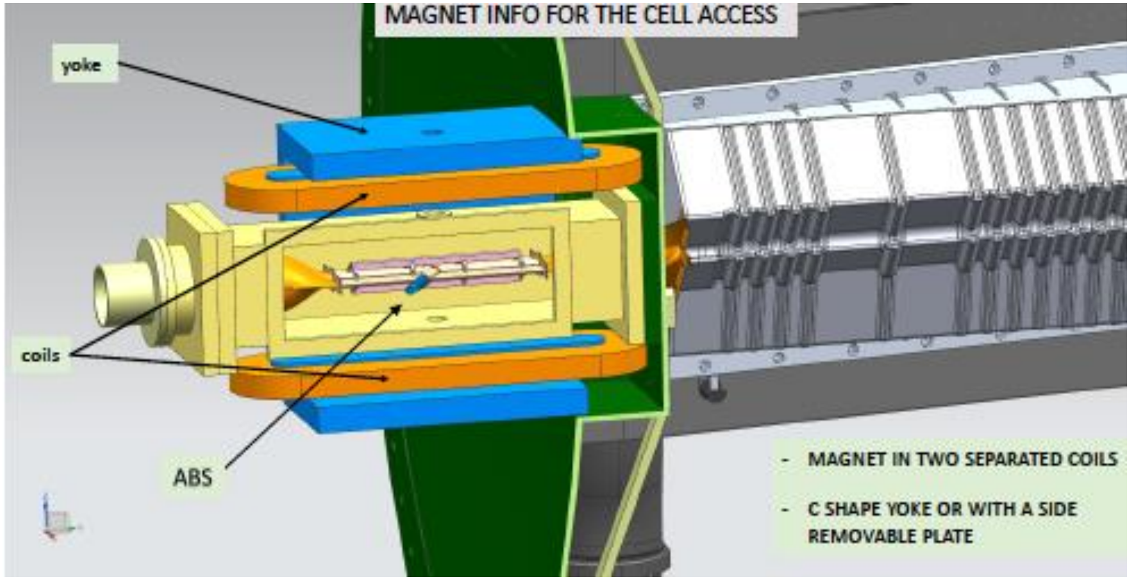

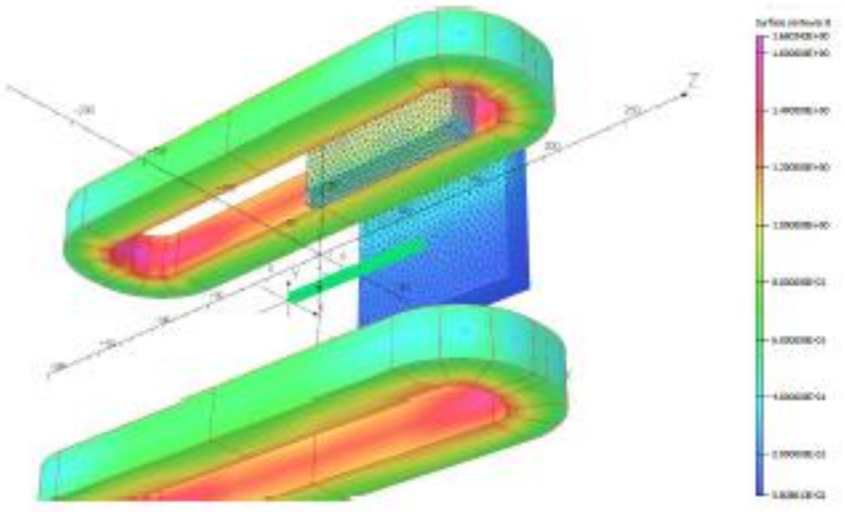

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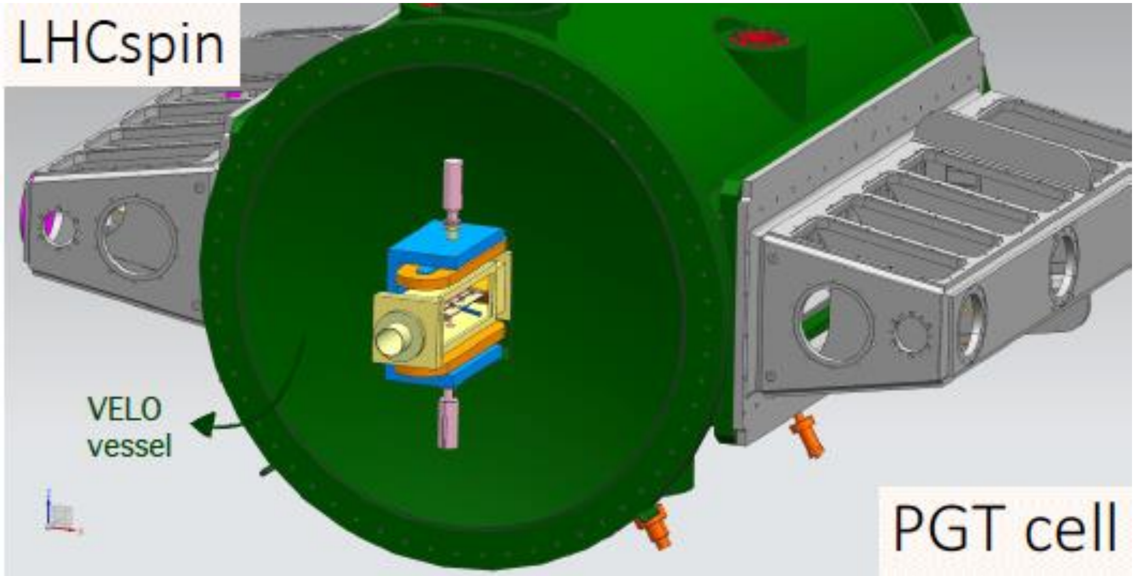

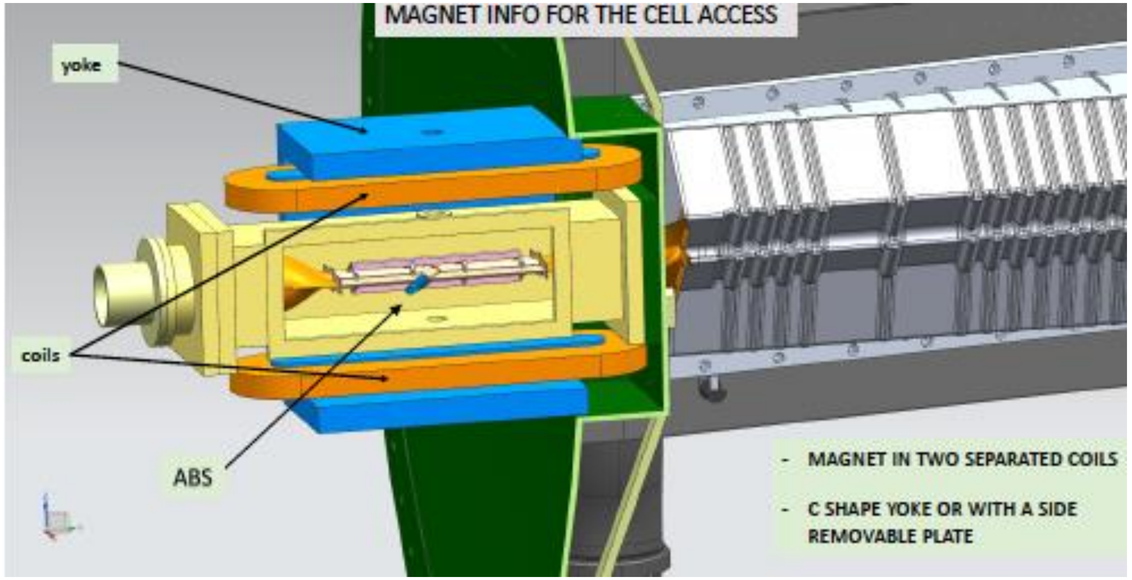

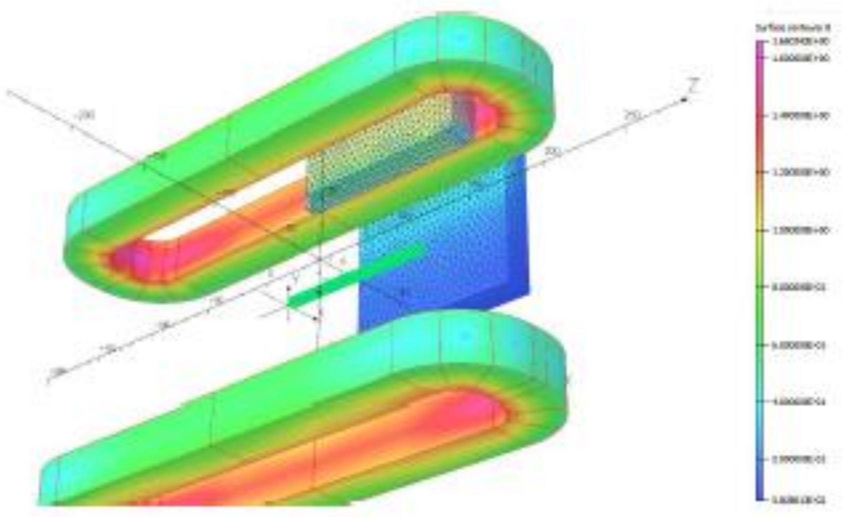

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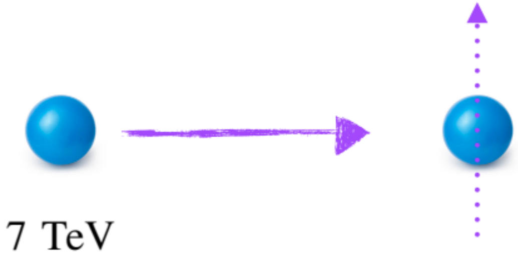
- **Possibility to switch from dipole magnet to solenoid to realize a Longitudinal polarized target in a future phase**

Kinematic coverage



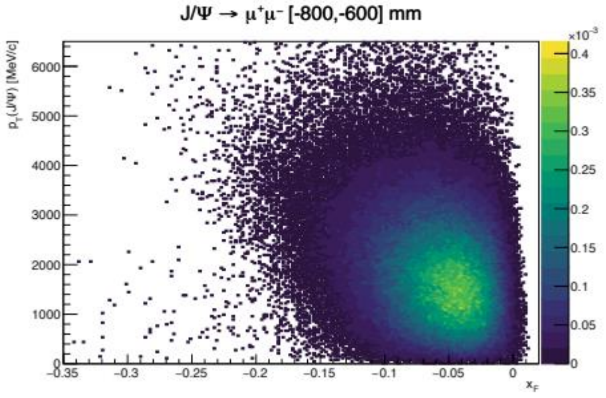
$$\sqrt{s} = \sqrt{2m_N E_p} = 115 \text{ GeV}$$

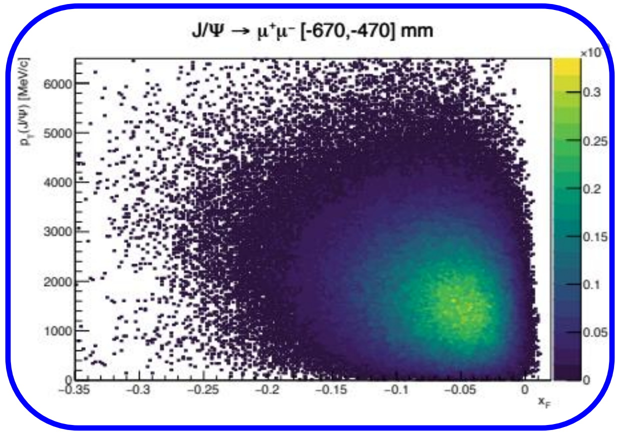
Using $x_F = 2E_T/\sqrt{s_{NN}}\ \sinh(y^*)$

with $E_T^2 = M^2 + P_T^2$

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

- x_B/ x_F ranges shrink towards larger backward distances
- SMOG2 cell position: [-560,-360] mm
- Probable position of LHCspin cell: [-670,-470] mm


J/Ψ → μ⁺μ⁻ [-800,-600] mm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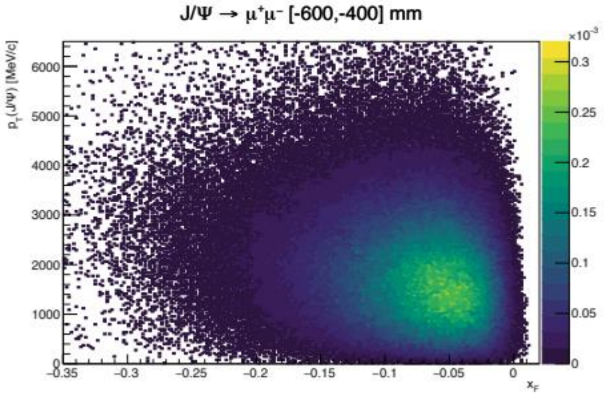
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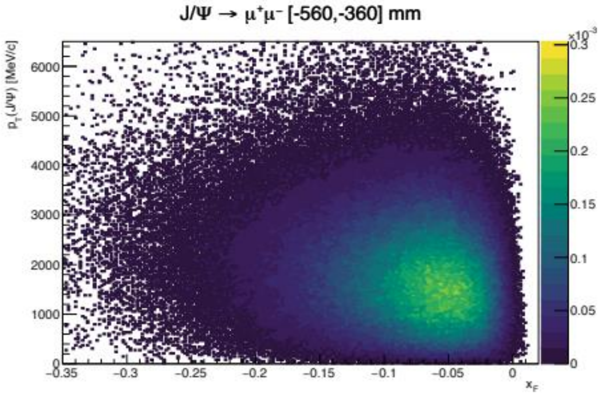
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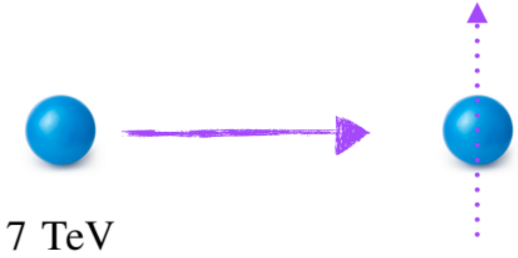

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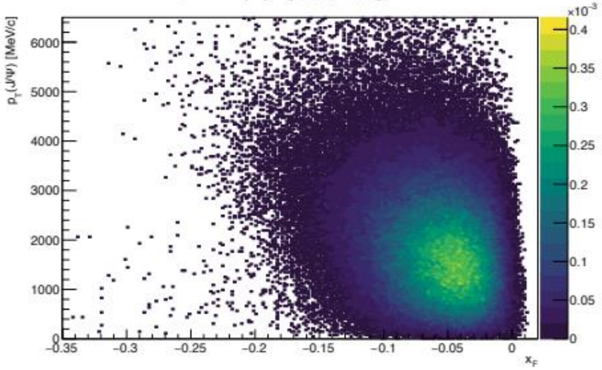
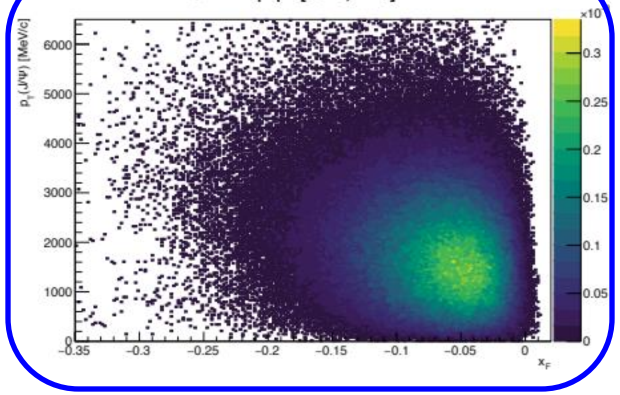


$J/\Psi \to \mu^+\mu^-$ [-670,-470] mm



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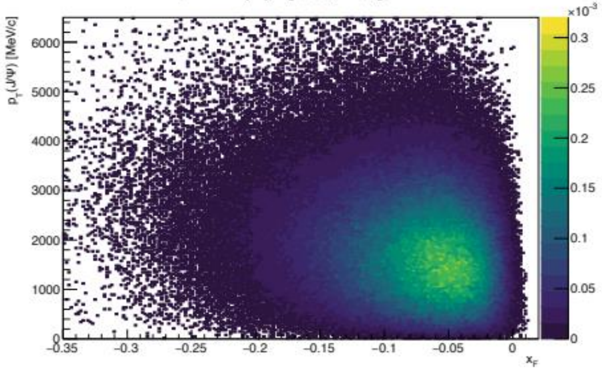

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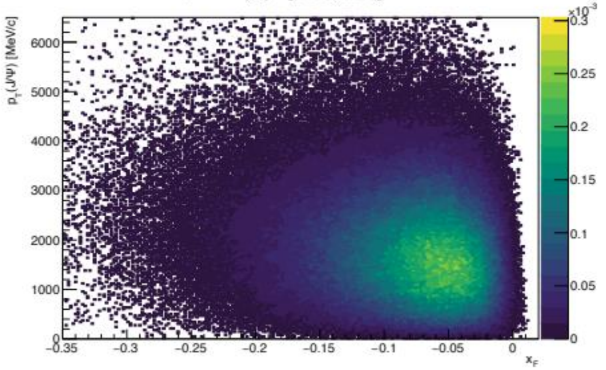
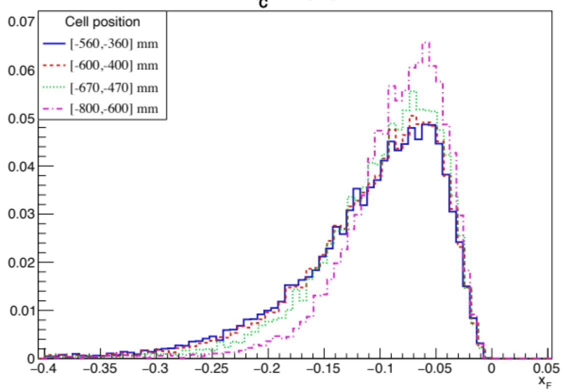
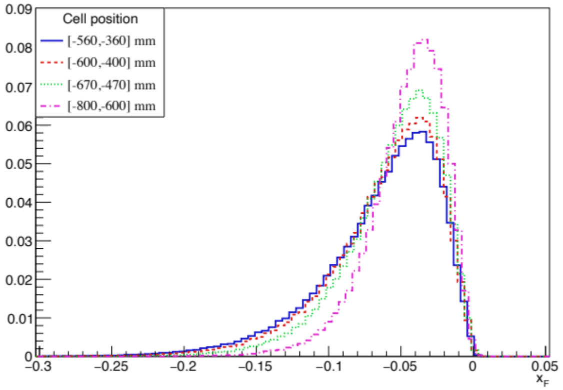


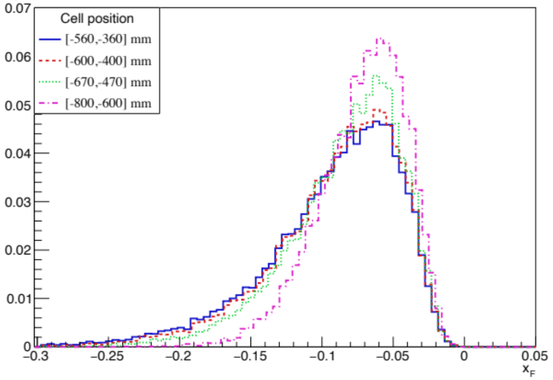
$\eta_c \to p\,\bar{p}$



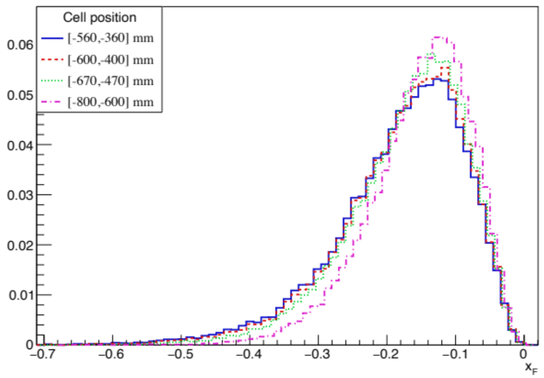
$D^0 \to K^-\pi^+$



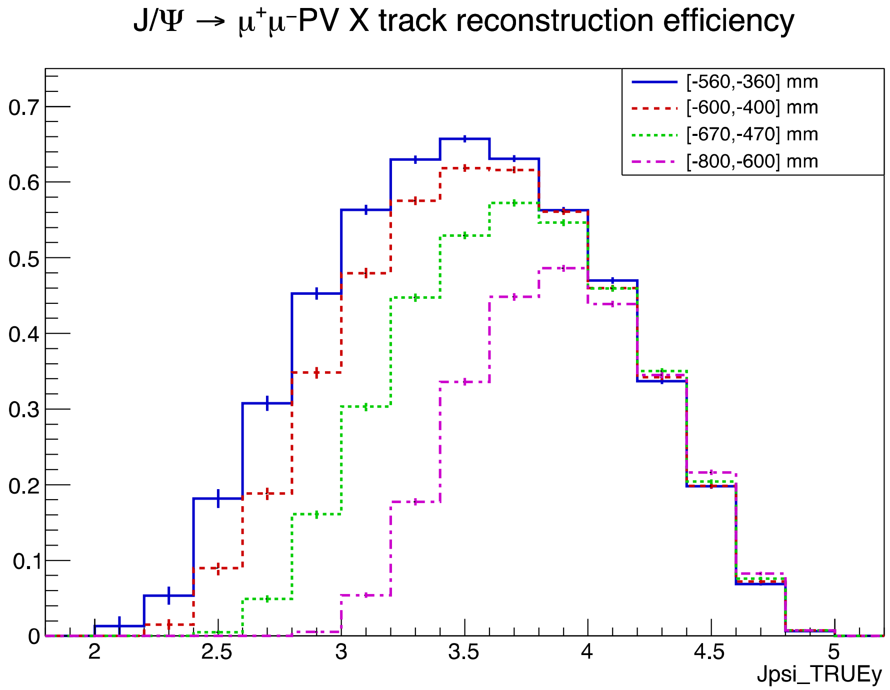
$\Lambda_c^+ \to p\,K^-\pi^+$



$\Upsilon \to \mu^+\mu^-$



Expected performance



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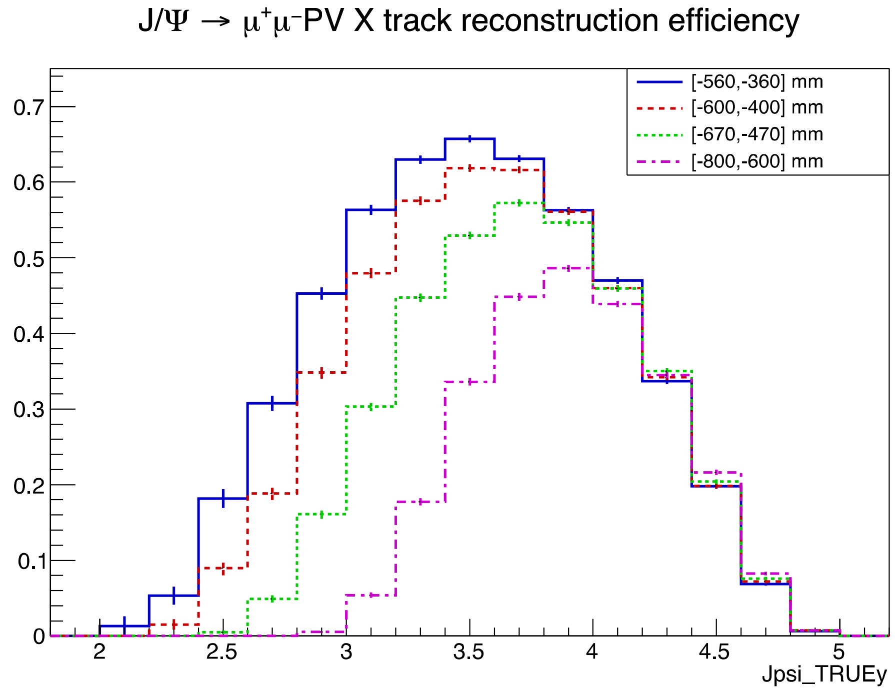


Target

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

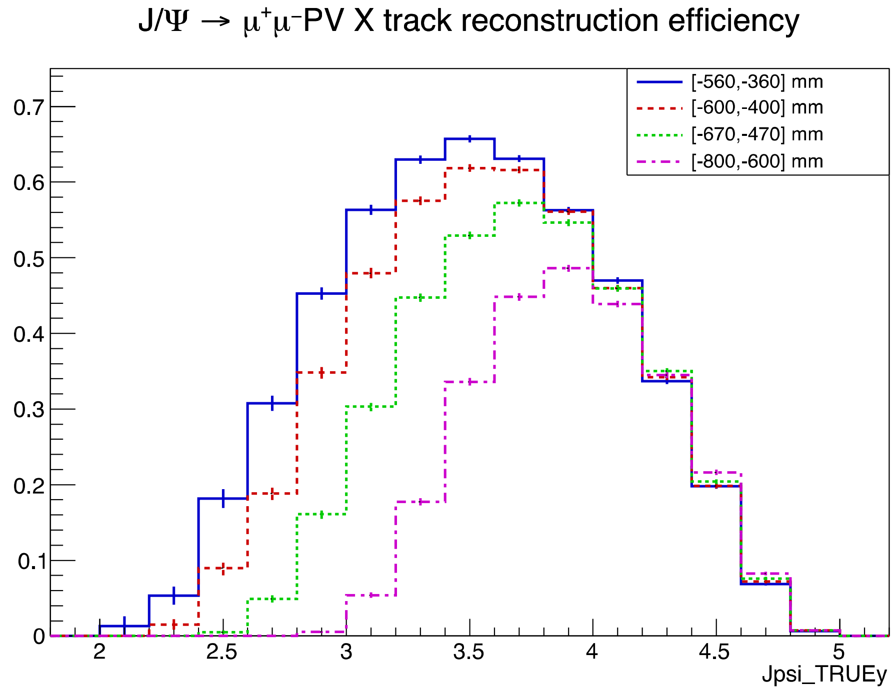
Beam (Run4)

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

$$\boldsymbol{\mathcal{L}_{pH}(300\ K) \approx 2.5 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

$$\boldsymbol{L_{pH}(Run) \approx 5\ fb^{-1}}$$

Expected performance


J/Ψ → $\mu^+\mu^-$PV X track reconstruction efficiency

Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 < M_{\mu\mu} < 9$ GeV)	7.4×10^3	8.8×10^5
$\Upsilon \to \mu^+\mu^-$	5.6×10^3	6.7×10^5
$\Lambda_c^+ \to pK^-\pi^+$	1.3×10^6	1.5×10^8

- fully reconstructed and selected events!
- based on extrapolation of current SMOG2 performance

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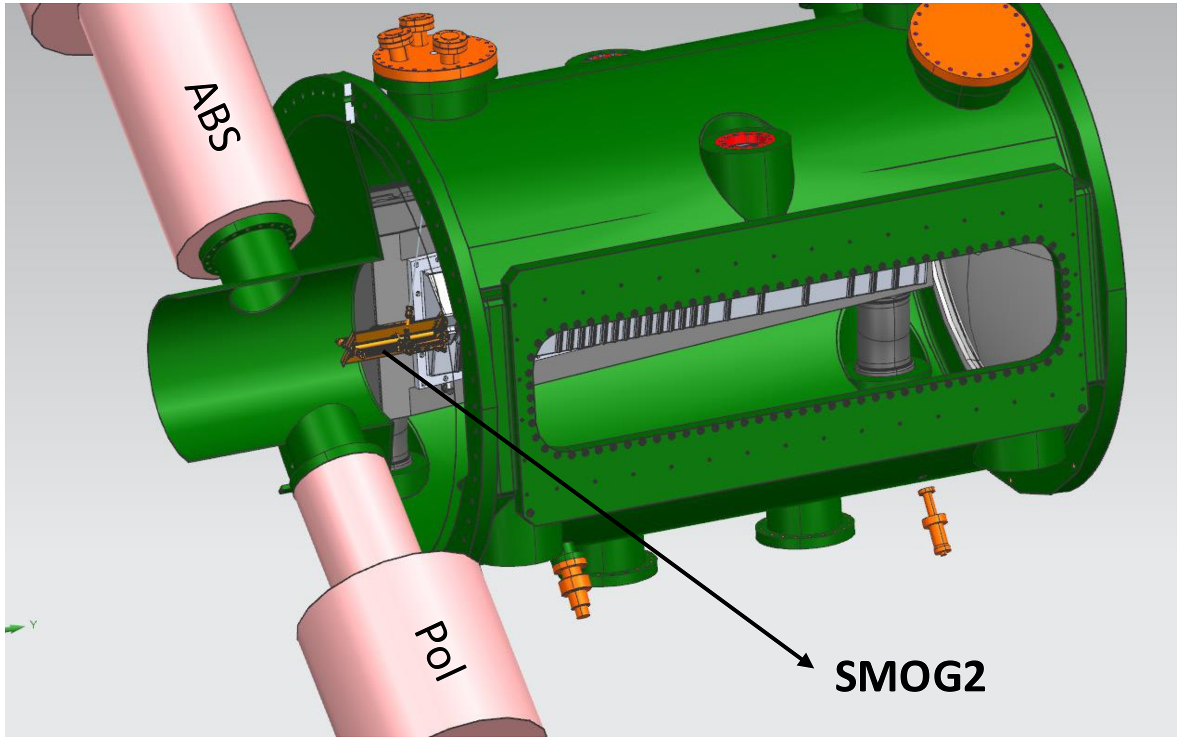
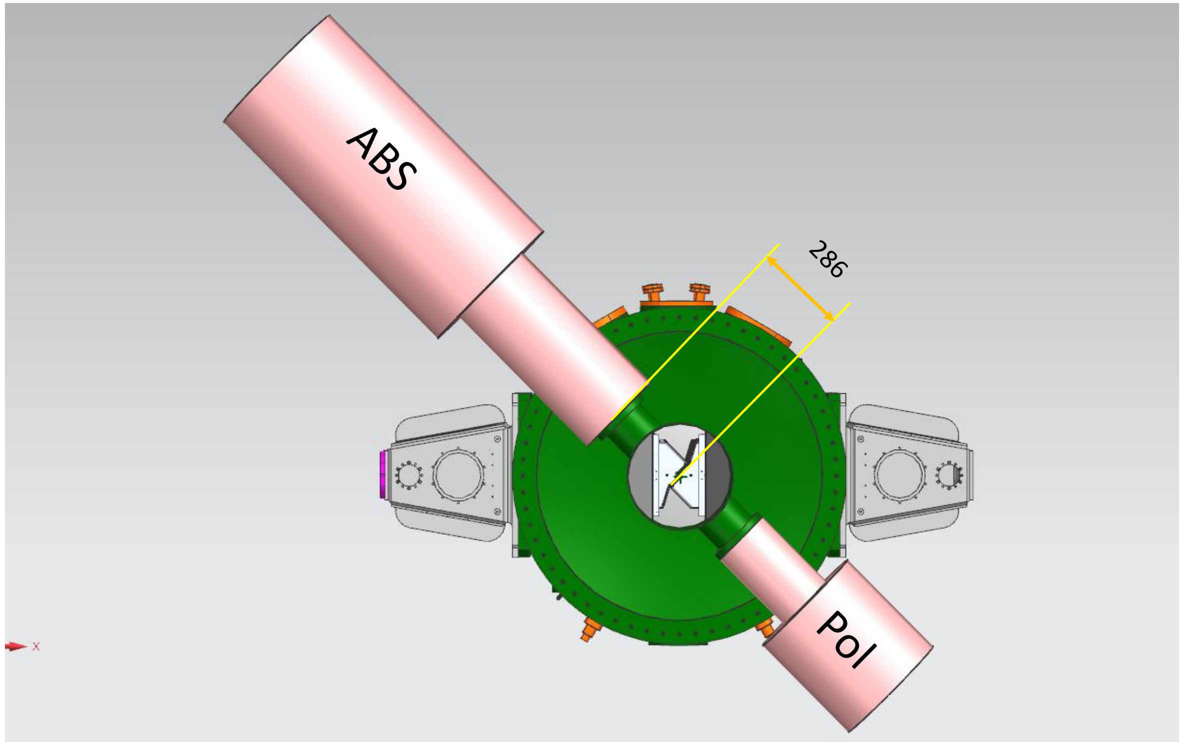
The jet target option

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

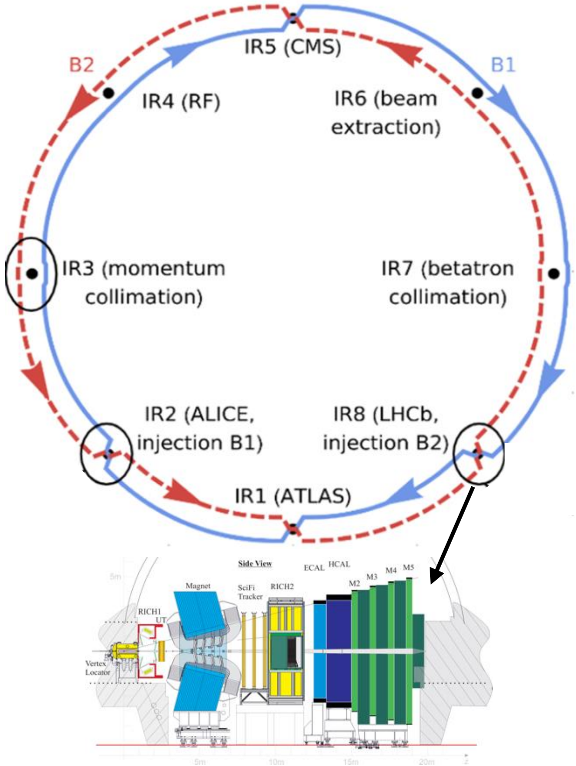




The plan for the upcoming years

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



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- R&D campaign for the apparatus towards the final setup for LHCb
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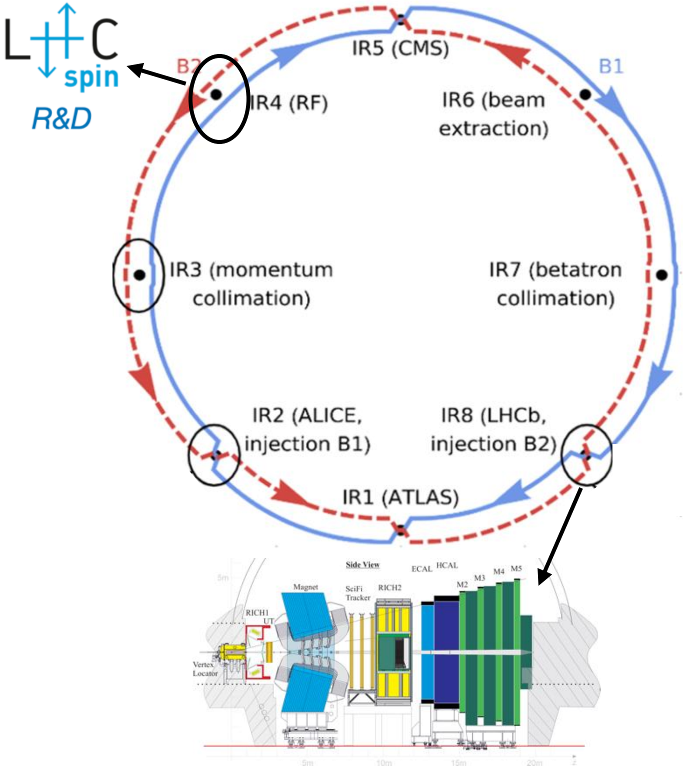
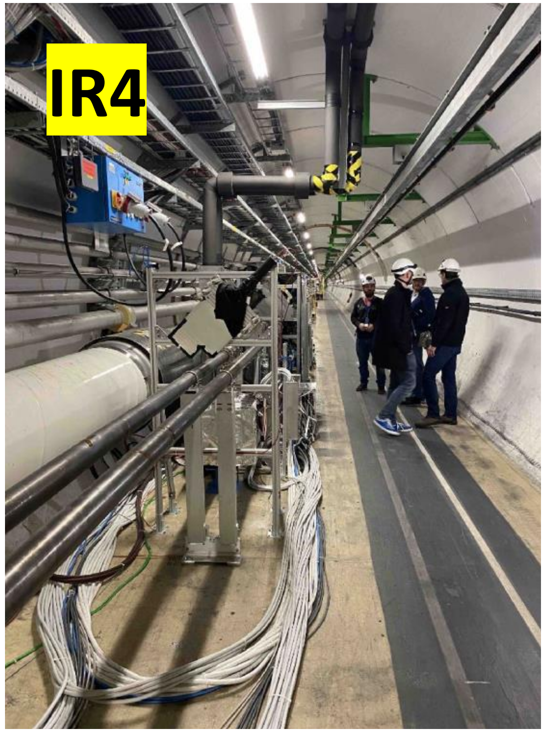
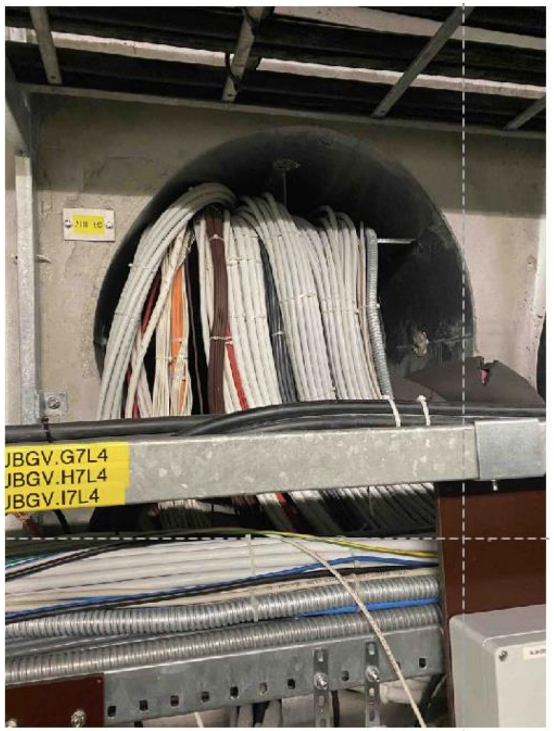
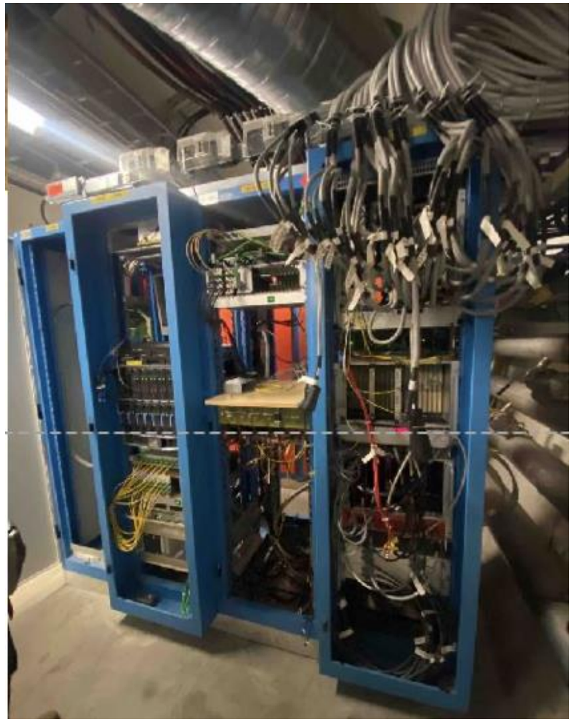
IR4 is the ideal place for our R&D:

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









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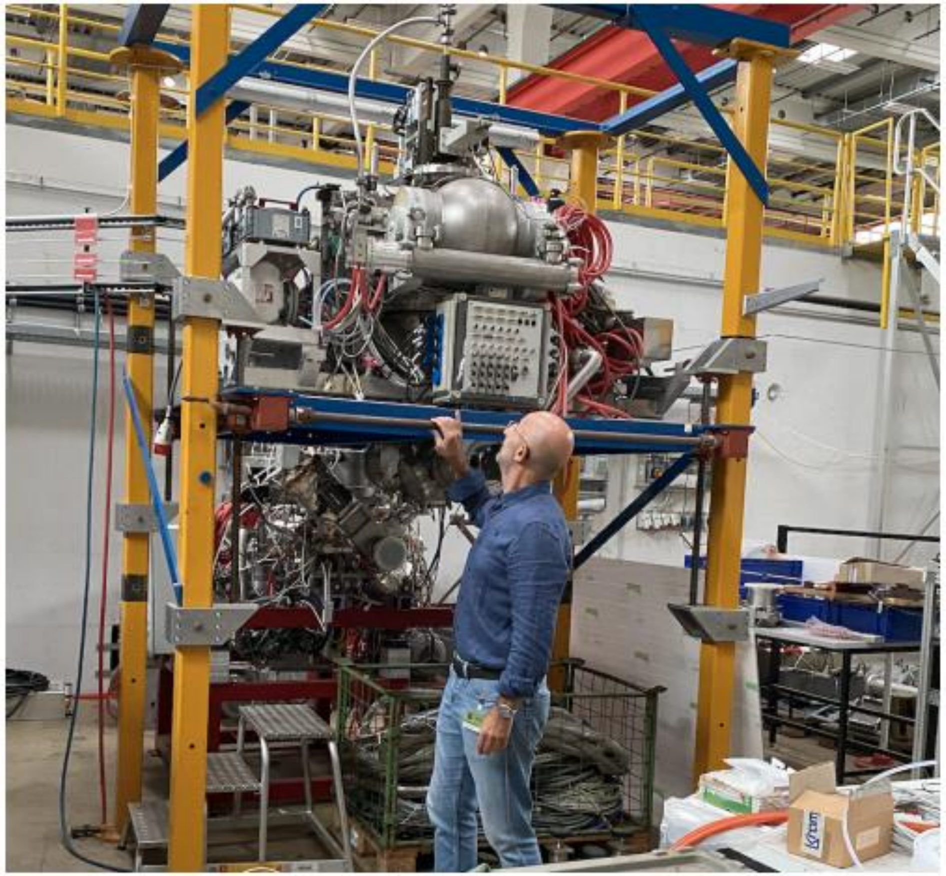

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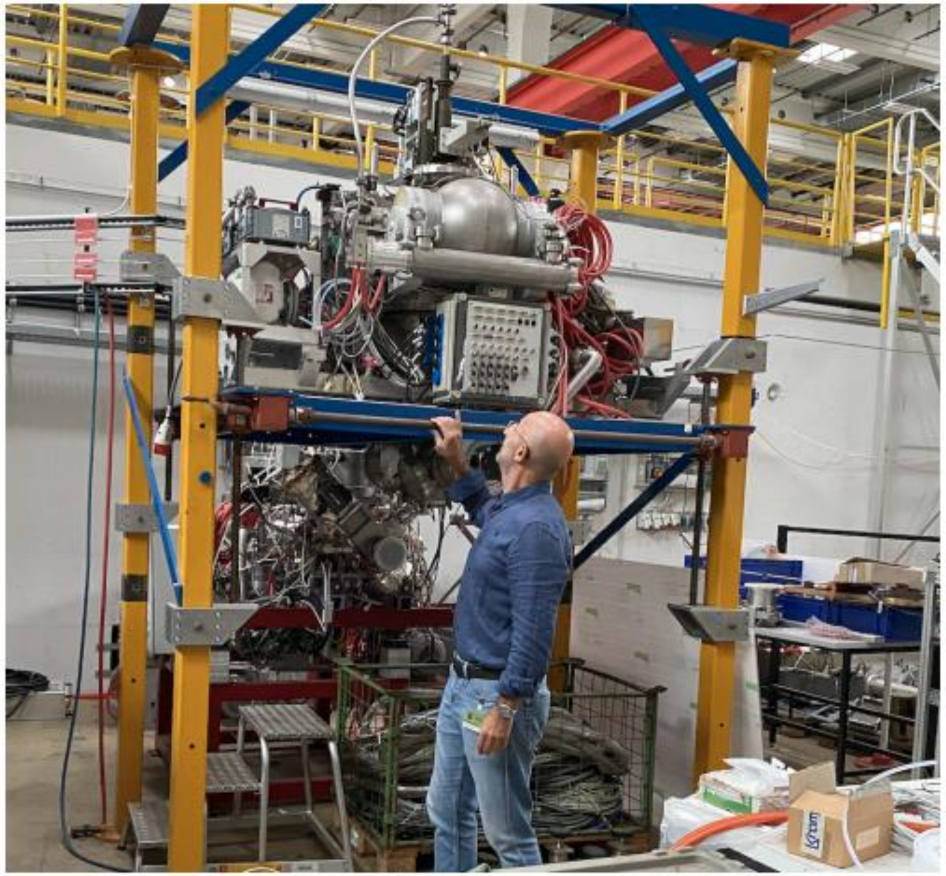
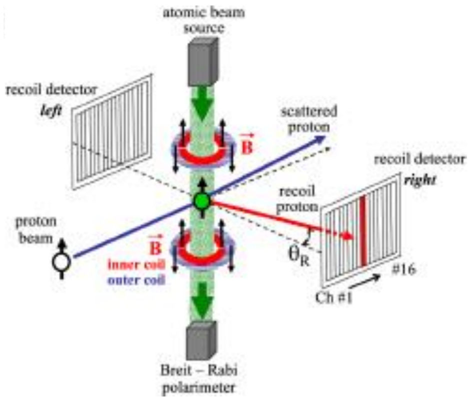
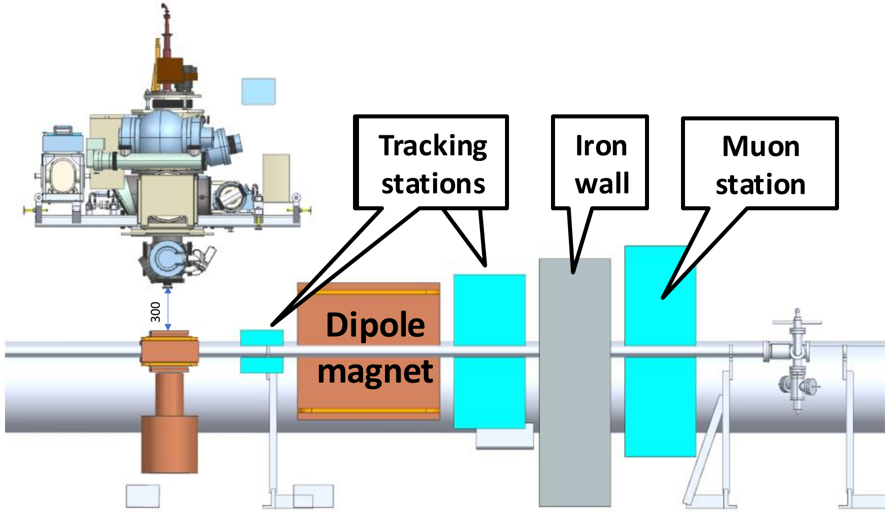


LS3 (2026-30):

- **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 be used for absolute calibration of BRP and measure of molecular polarization.
- **Possibility to implement a minimal spectrometer**





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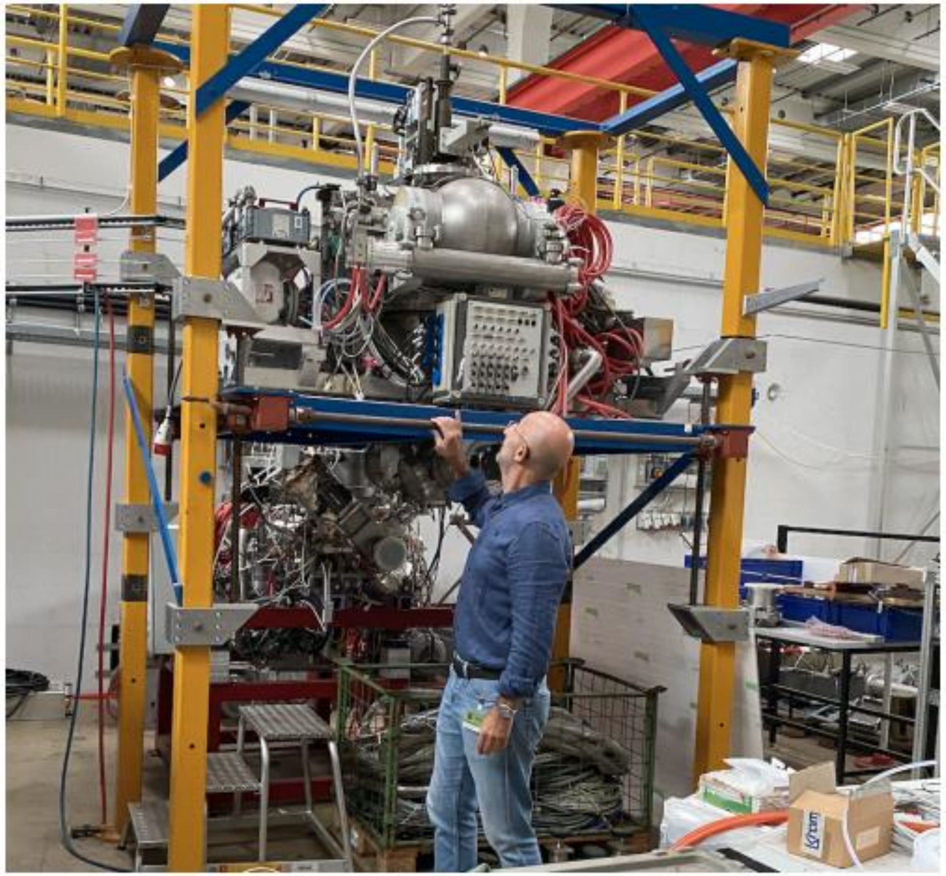

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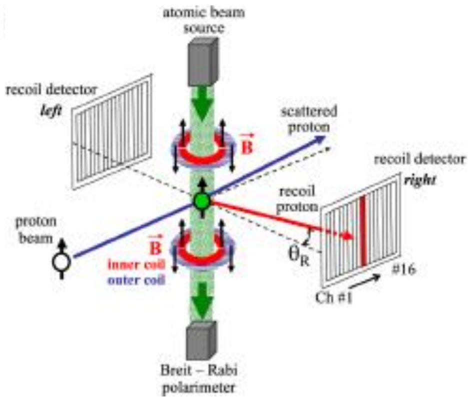
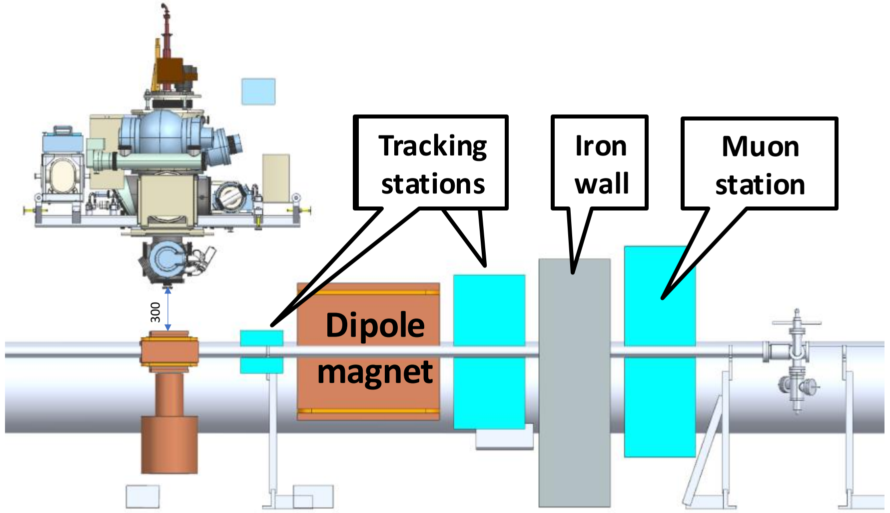
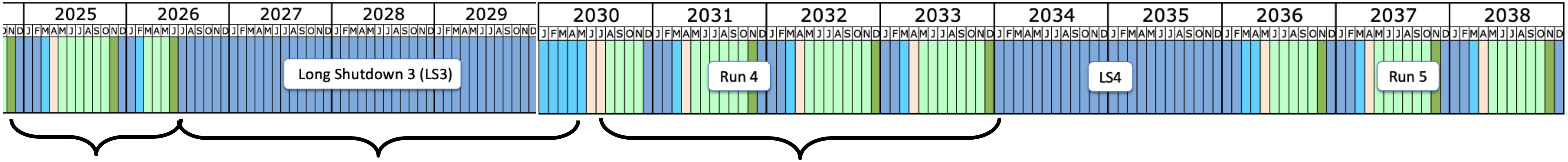




Run4 (2030-33):

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

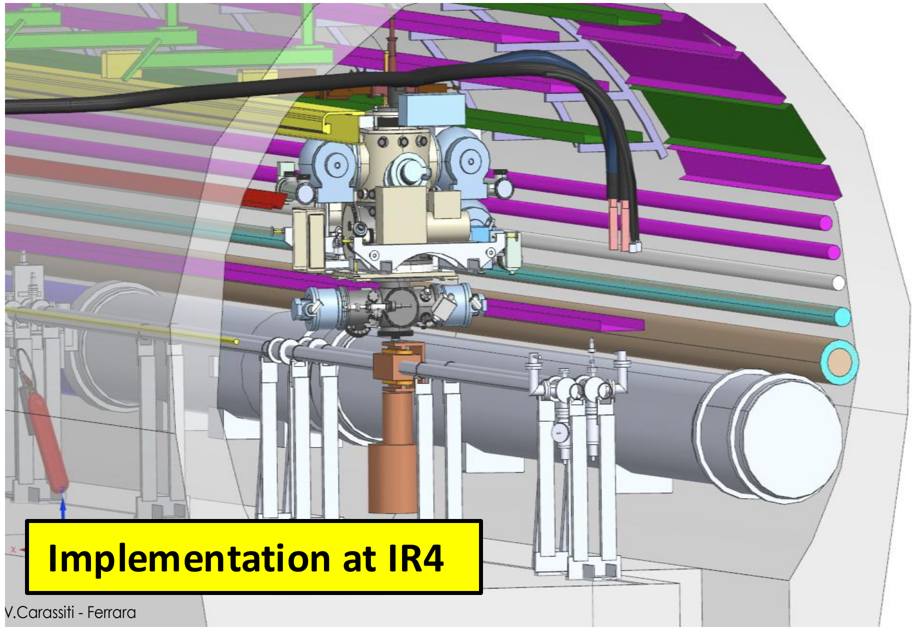
Timeline of the project



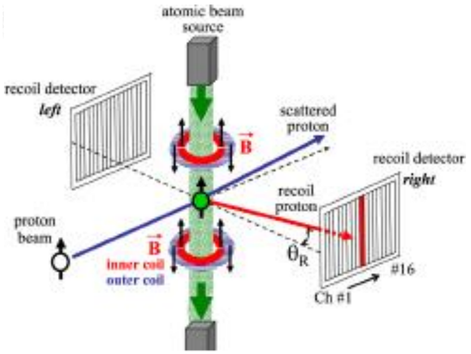
First tests and characterization in Ferrara

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

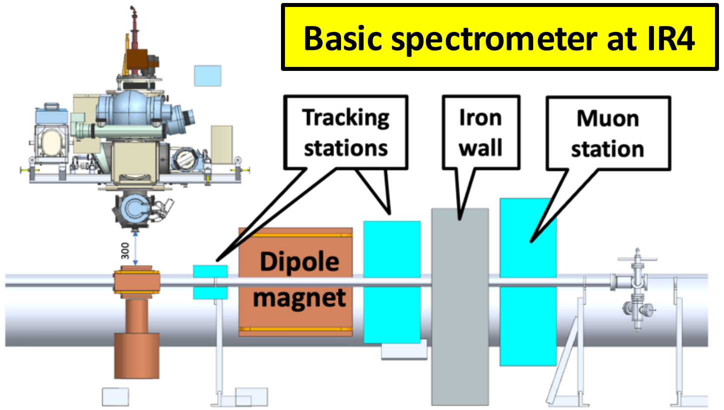
- Absolute calibration of BR polarimeter
- Polarimetry measurements
- First physics measurements (SSAs)


Implementation at IR4

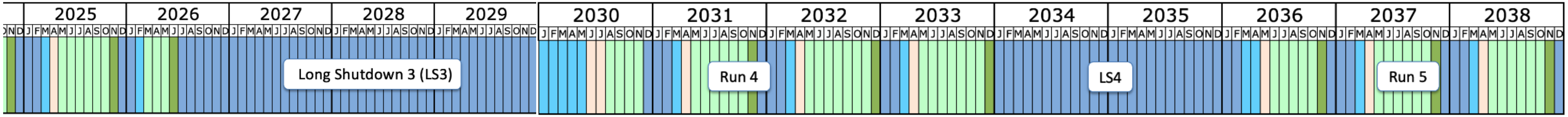
V.Carassiti - Ferrara



Absolute polarimeter


Basic spectrometer at IR4

Timeline of the project



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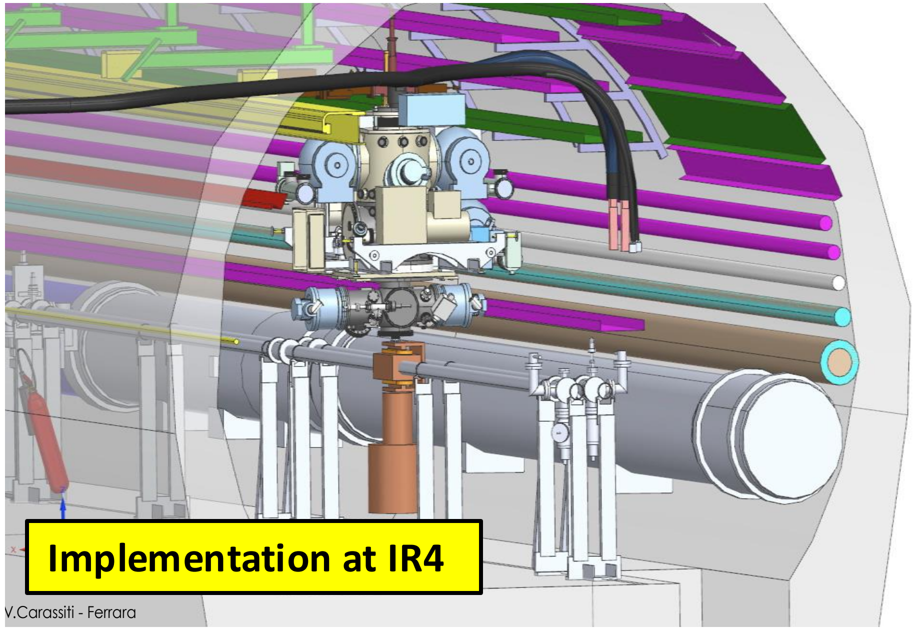
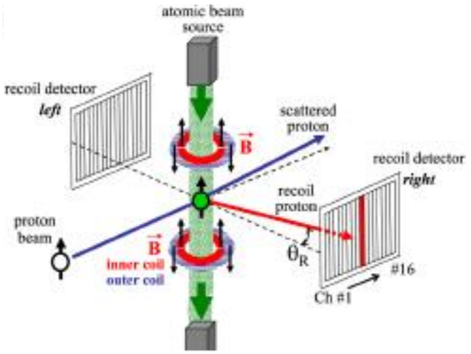
Move apparatus from IR4 to LHCb

Data taking with LHCb

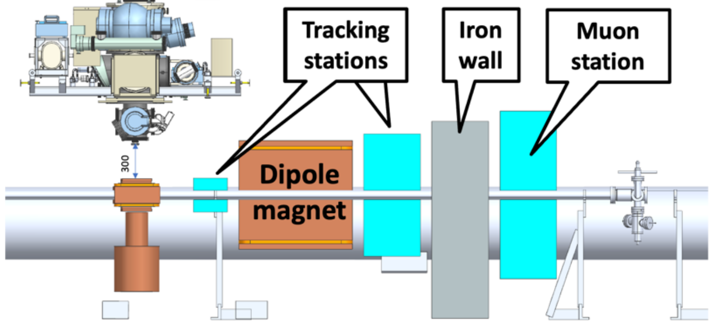

Implementation at IR4

V.Carassiti - Ferrara

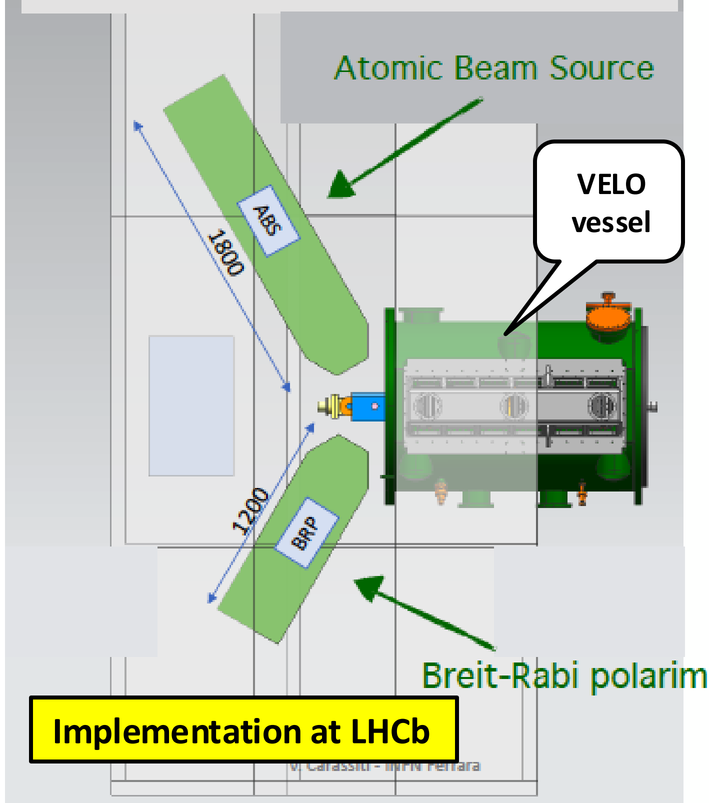


Absolute polarimeter

Basic spectrometer at IR4



ABS & BRP IN VERTICAL LAYOUT – SIDE VIEW



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

Conclusions

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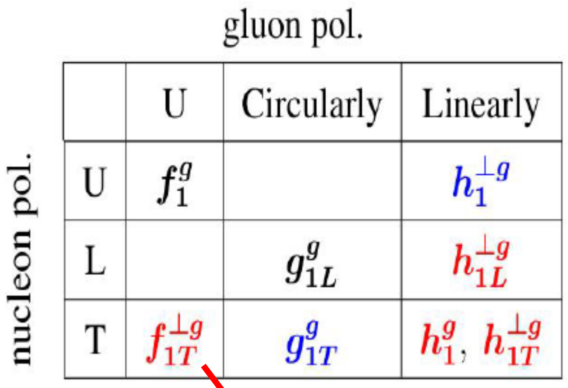
If approved, LHCspin will make LHCb the first experiment simultaneously running in collider and fixed-target mode with unpolarized and polarized targets, opening a whole new range of explorations at the LHC!

Backup

gluon TMDs



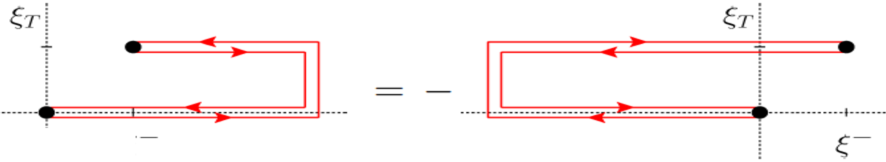
gluon pol.

nucleon pol.

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

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

Gluon 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))

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

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

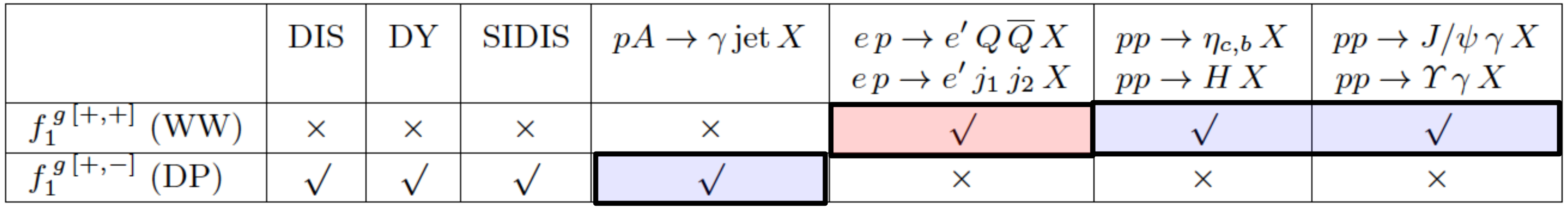
- Depending on their combinations, **there are 2 independent versions of each gTMD** that can be probed in different processes and can have different magnitude and widths and different x and k_T dependencies!

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

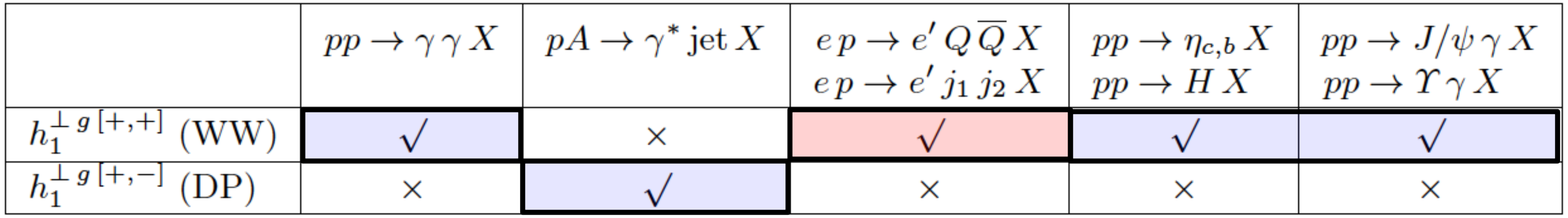
- 2 indep. GSF: $f_{1T}^{\perp g[+,+]}$ **"f-type"** → antisymm. colour structure ; $f_{1T}^{\perp g[+,-]}$ **"d-type"** → symm. colour structure

A synergic attack to gTMDs

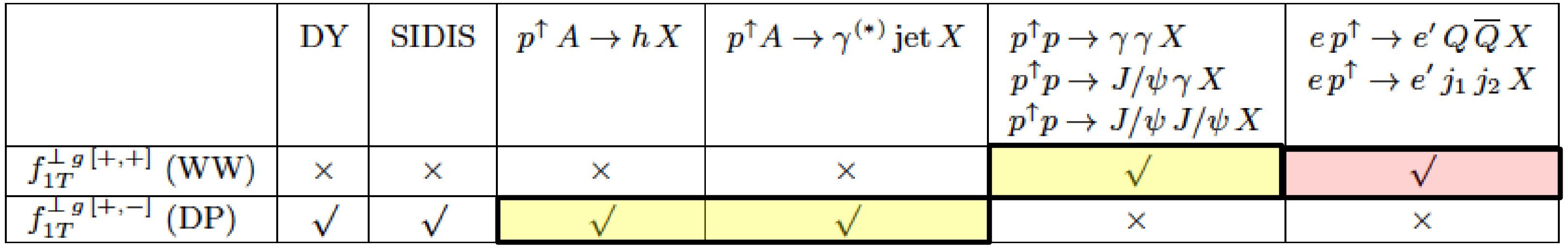
[D. Boer: Few-body Systems 58, 32 (2017)]



	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)	√	√	🟨 √	🟨 √	×	×

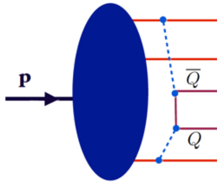
🟥 Can be measured at the EIC

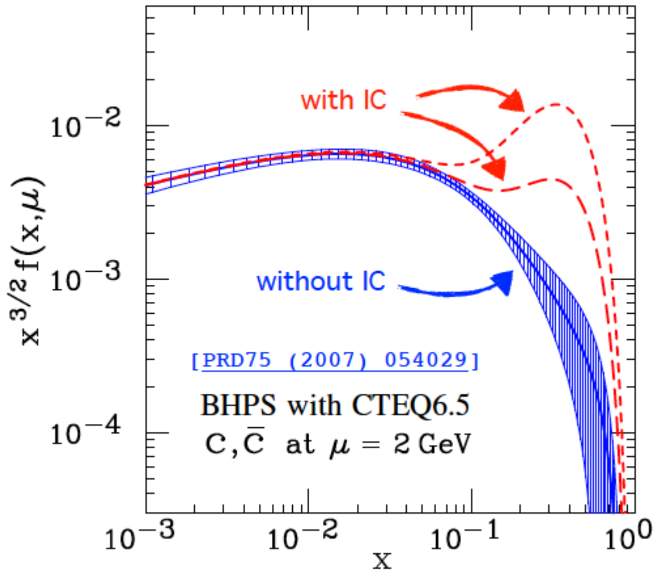
🟦 Can be measured at RHIC & LHC (including LHCb+SMOG2/LHCspin)

🟨 Can be measured at RHIC and LHCb+LHCspin

More physics reach with unpolarized FT reactions

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



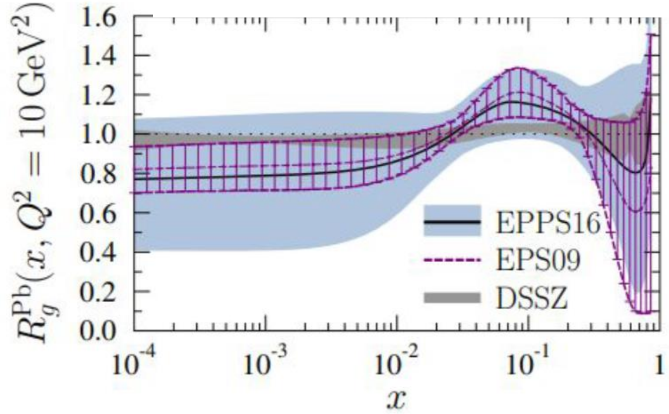


[PRD 75 (2007) 054029]

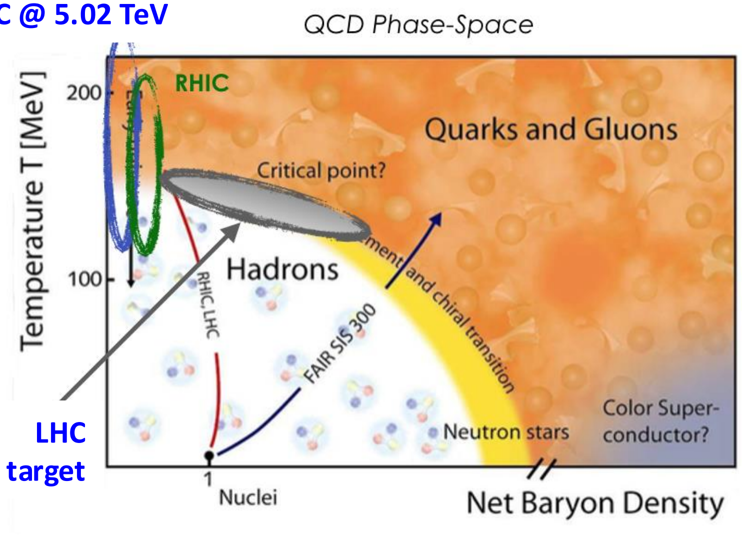
- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium
  - reactions of interest for cosmic-ray physics and DM searches

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

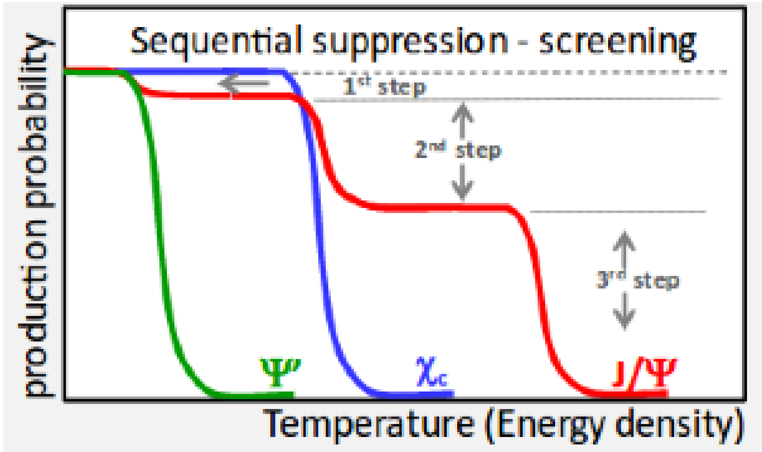
Eur. Phys. J. C 77, 163 (2017)



LHC @ 5.02 TeV



LHC fixed target



$c\bar{c}$ states: $J/\psi, \chi_c, \psi'$,...
Different binding energies, different dissociation temperatures → **medium thermometer**

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):

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

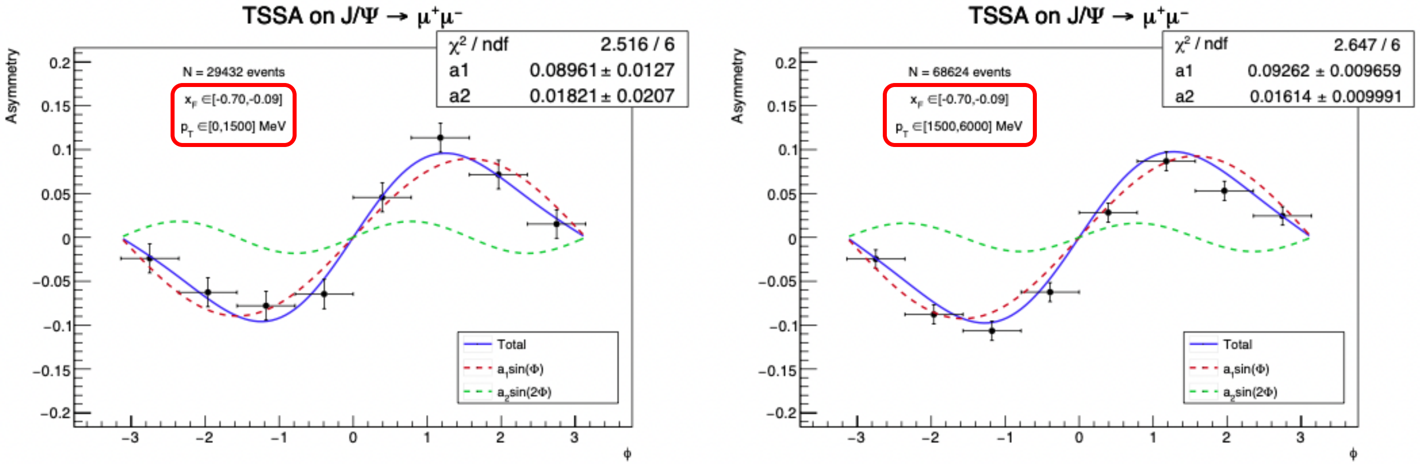
- Using these pseudo-data the TSSA is computed in the usual way:

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

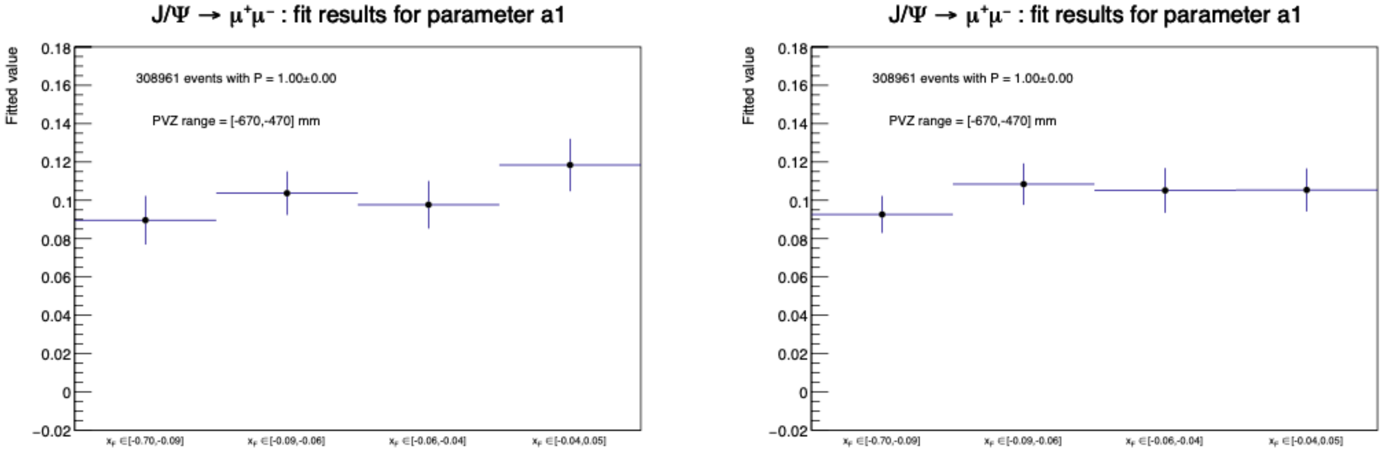
and the uncertainties on $N^{\uparrow(\downarrow)}$ (Poisson) and P (systematic) propagated accordingly.

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



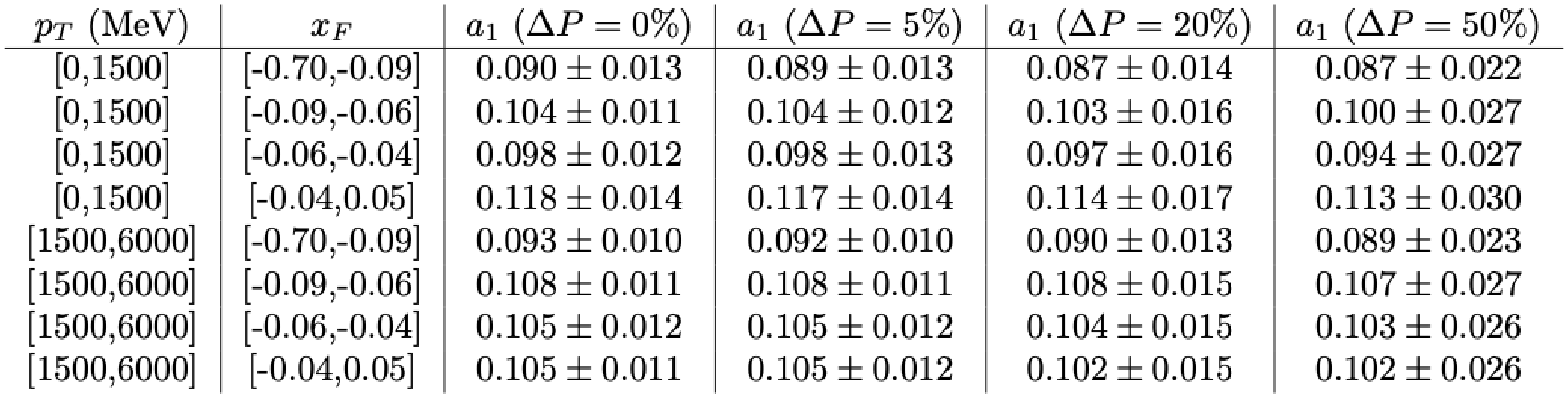
- The extracted parameters a_1 and a_2 are consistent with those used to generate the model (no bias is observed)
- With the available MC statistics (corresponding to 2 weeks of data-taking) there is no sensitivity for the $\sin 2\phi$ term



- The amplitudes a_1 are the 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 plan for the upcoming years

Plan:

- Installation of existing setup (ABS + polarimeter from COSY) + minimal detection apparatus during LS3 (2026-28)
- **R&D and proof-of-principle experiment** during Run4 (2029-2032)
- Three levels of complexity (depending on effective manpower, involved expertise and fundings):

Option 1 (minimal): pol. get targt (no storage cell) for polarimetry measurements with $pH^{\uparrow}$ elastic scattering

Option 2 (intermediate): implementation of an openable storage cell along the beam-pipe (a-la SMOG2) for:

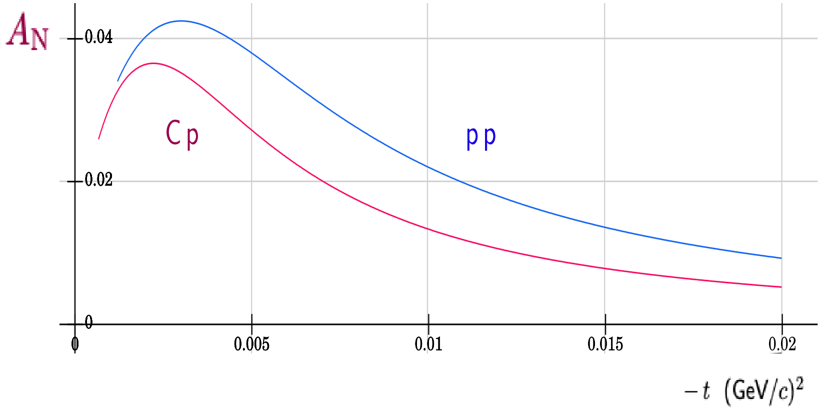
- polarimetry measurements ($pH^{\uparrow}$ elastic scattering)
- study of recombination/depolarization at the cell walls
- study of beam-target interactions

Option 3 (full small-scale experiment): implementation of a minimal spectrometer (in conjunction with get-target or storage cell) for simple (but unique!) physics measurements (spin asymmetries).

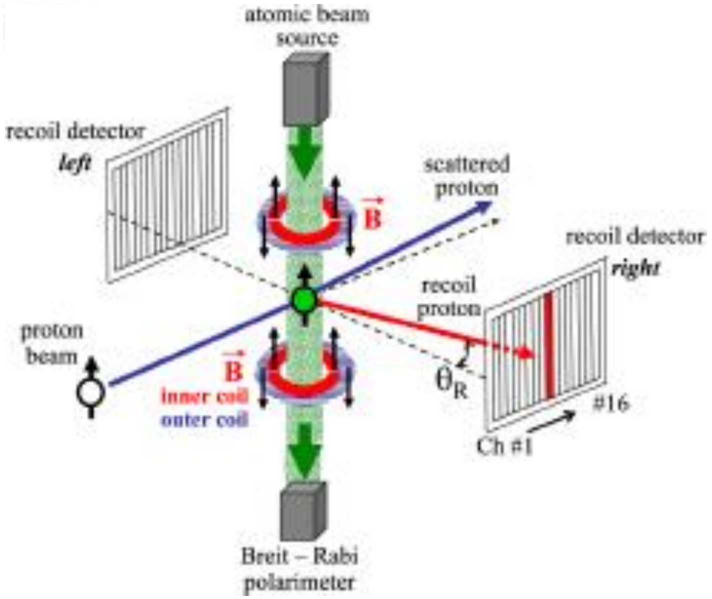
Option 1 (minimal)

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

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



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



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

For a 7 TeV proton beam:

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

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

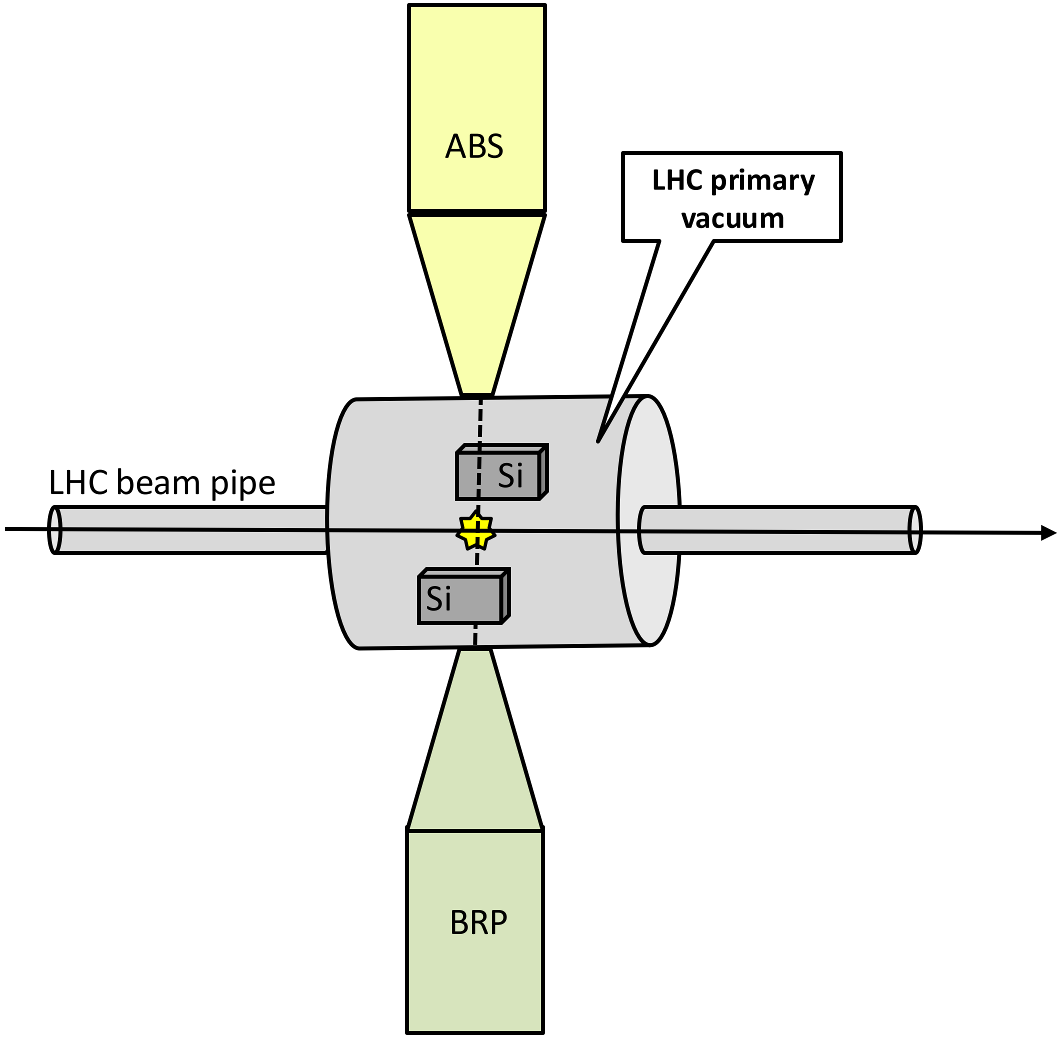
Option 1 (minimal)

Goals:
- First absolute polarimetry measurements with elastic beam-target scattering at LHC energies
- test model predictions for Coulomb-Nuclear Interference
- allow for absolute calibration of the Breit-Rabi polarimeter

Tasks and challenges:
- detect small (<5%) Left-Right asymmetry of elastically scattered low-energy protons at large angles ($\sim 90°$)
- due to very small recoil energies (< 5 MeV), need to place **detectors in primary vacuum**

Apparatus:
- target system: jet target (ABS) + Breit-Rabi Polarimeter (BRP)
- detection system: pairs of small-area Si (strip/pixel) detectors in LHC primary vacuum (angular coverage: 30-50 mrad around $90°$

Needed expertise (apart from pol. target):
- Si detectors (to be operated in primary vacuum)
- electronics + DAQ
- …



Option 2 (intermediate)

Goals:

- those of Option 1 (but using a storage cell)
- study of recombination/depolarization at the cell walls (coatings)
- study of beam-target interactions (under realistic conditions for future use at LHCb): beam-induced depolarization, aperture, impedance, etc.

Apparatus:

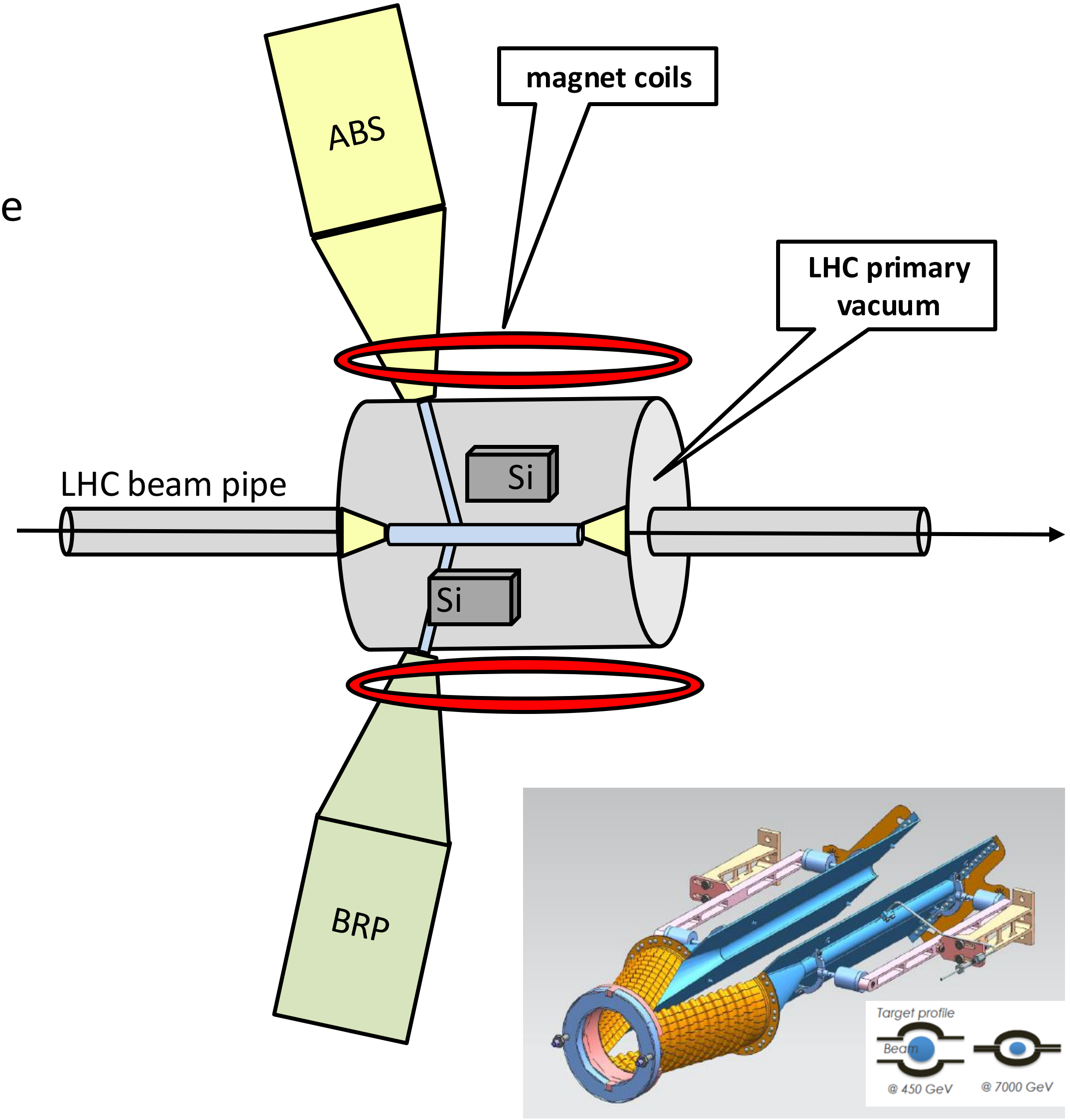
- same as previous + storage cell
- 300 mT transverse magnet to maintain polarization inside the cell

Challenges:

- cell must be openable (with independent motor) to avoid interference with beam during injection/tuning
- cell lateral walls must be very thin to allow passage of low-energy recoiling protons (for polarimetry measurement)

Needed expertise (apart from pol. target):

- Si detectors (to be operated in primary vacuum)
- electronics + DAQ
- transverse magnet
- cryogenics (for SC magnet)
- …



Option 3 (full small-scale experiment)

Goals:

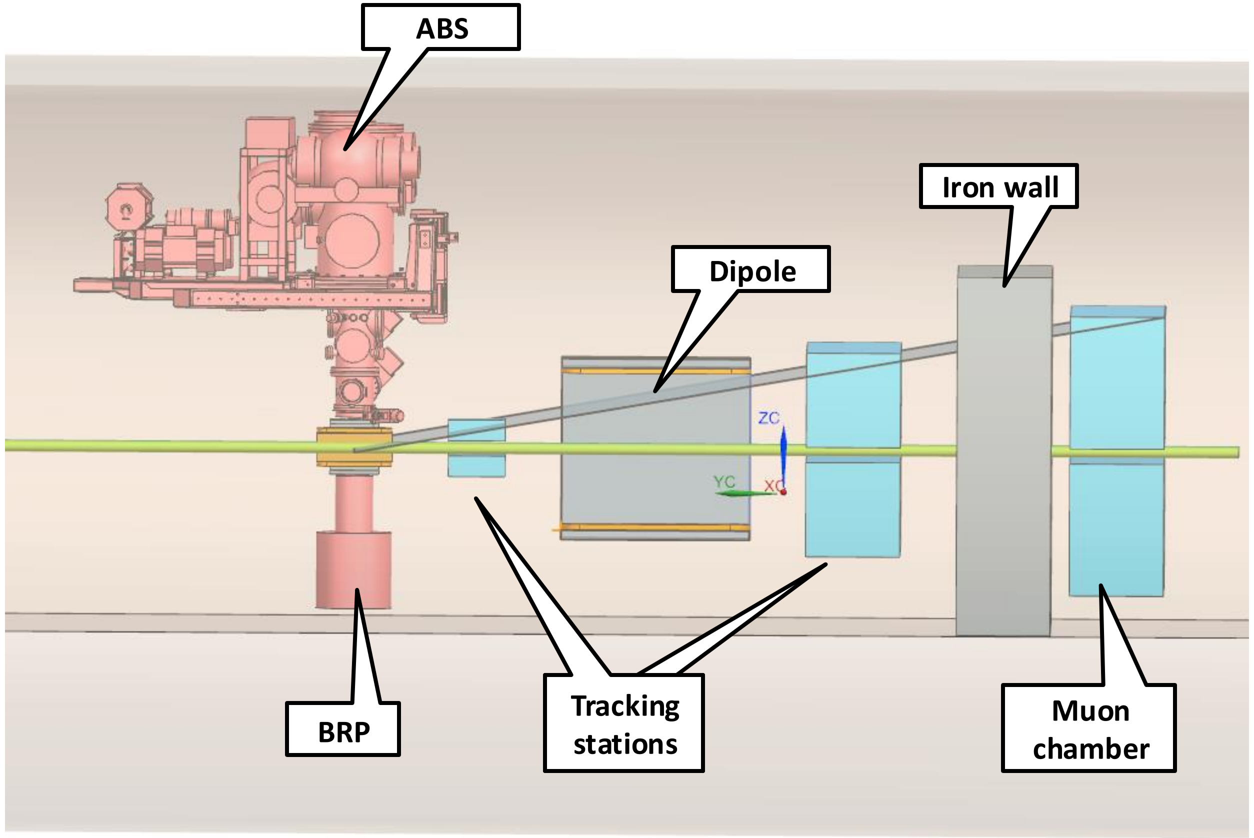
- Those of option 1 (polarimetry measurements)
- measurement of single-spin asymmetries in inclusive hadron (e.g. $J/\psi \to \mu^+\mu^-$) production in $pH^\uparrow, pD^\uparrow, AH^\uparrow, AD^\uparrow$
- proof of principle of the future (large-scale) experiment with LHCb.

Needed expertise (apart from pol. target):

- Si detectors (to be operated in primary vacuum)
- dipole magnet
- tracking detectors (SciFi, Si strip, drift chamber?)
- muon chambers (MWPC?)
- DAQ + electronics
- slow control
- tracking/reconstruction algorithms
- …

Apparatus:

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



Instrumentation at IR4

- A **Beam-Gas Vertex** (BGV) apparatus, based on a **gas get target** and used in the past for beam emittance measurements (currently not in use), could be replaced by our apparatus
- **LHCspin could also serve as a new BGV**

BGV