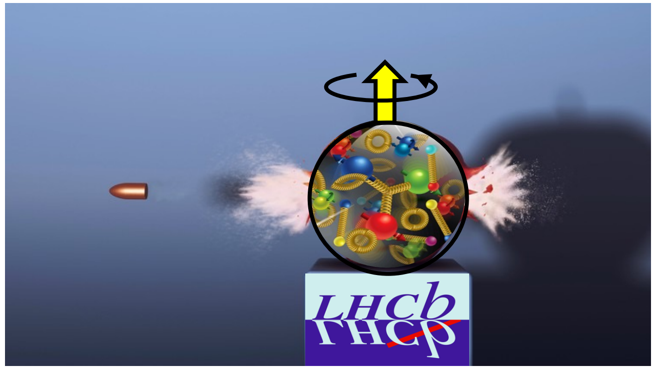
The LHCspin project:

a polarized target experiment at LHC



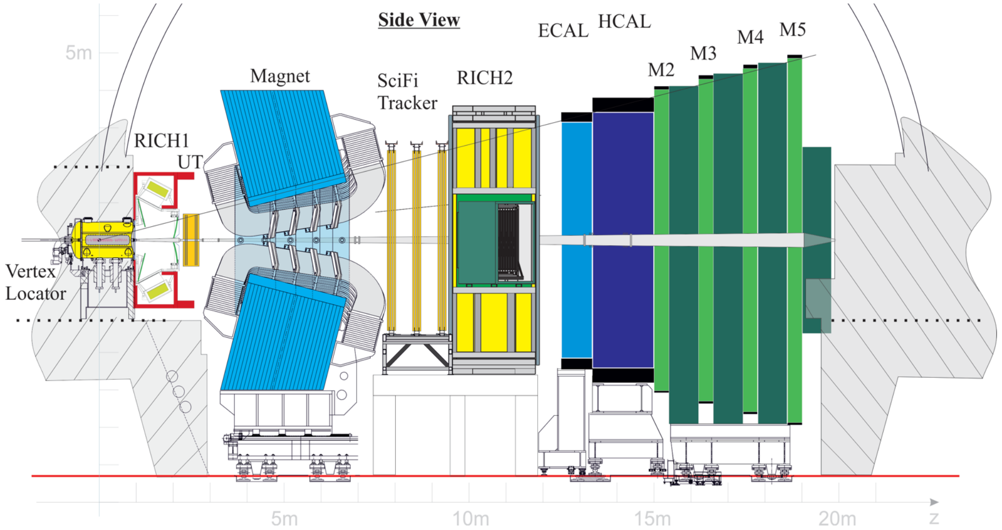
L. L. Pappalardo
(pappalardo@fe.infn.it)

HADRON 2023

LHCb detector and 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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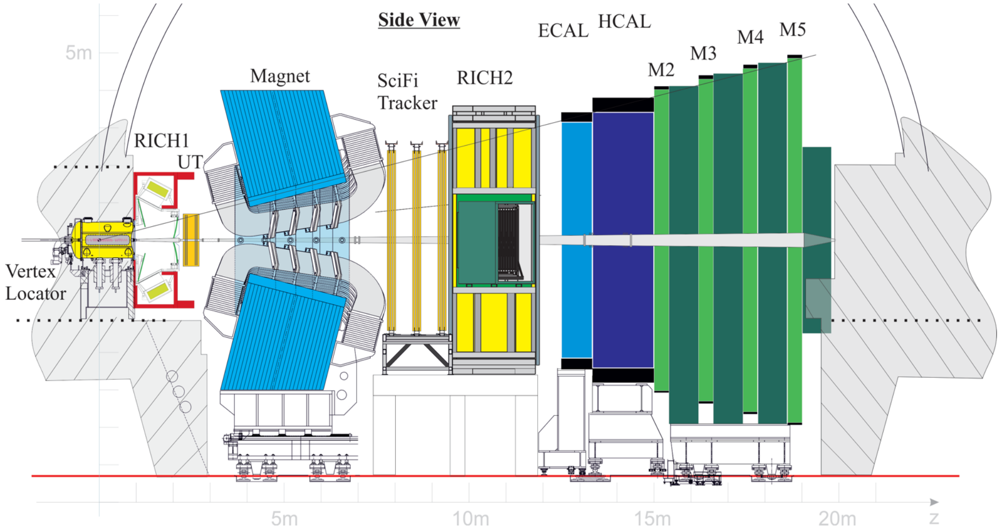

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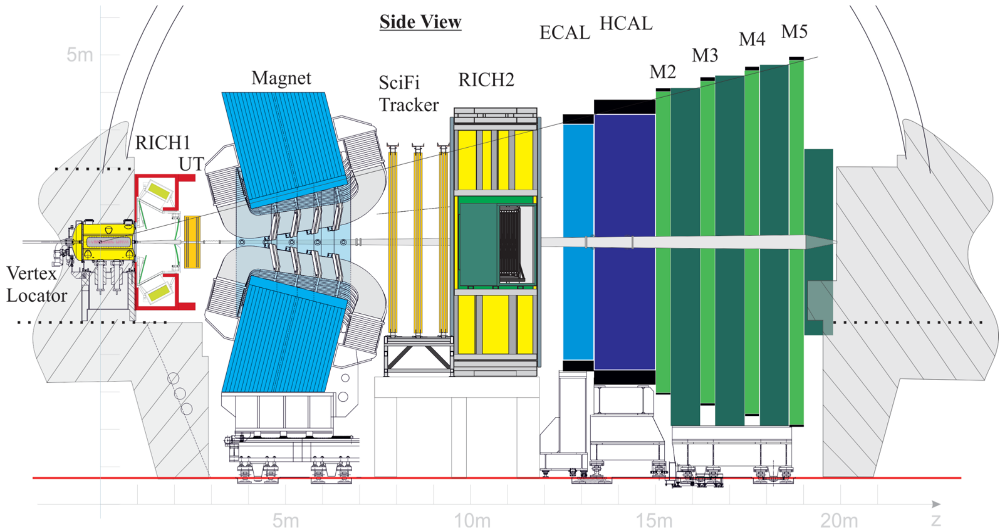

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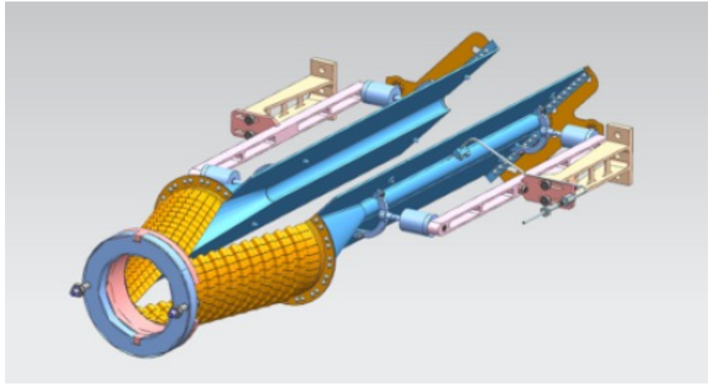

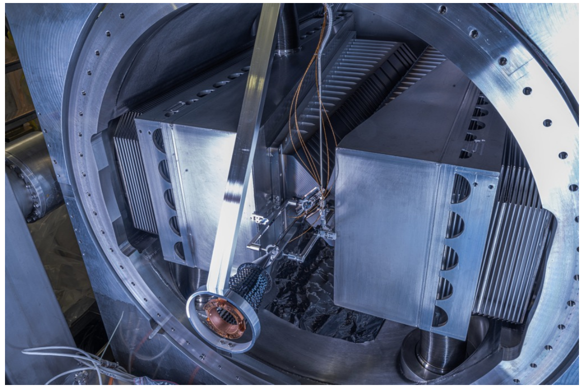

- more gas species: $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- target density increased by large factor
- Precise density (lumi) determination
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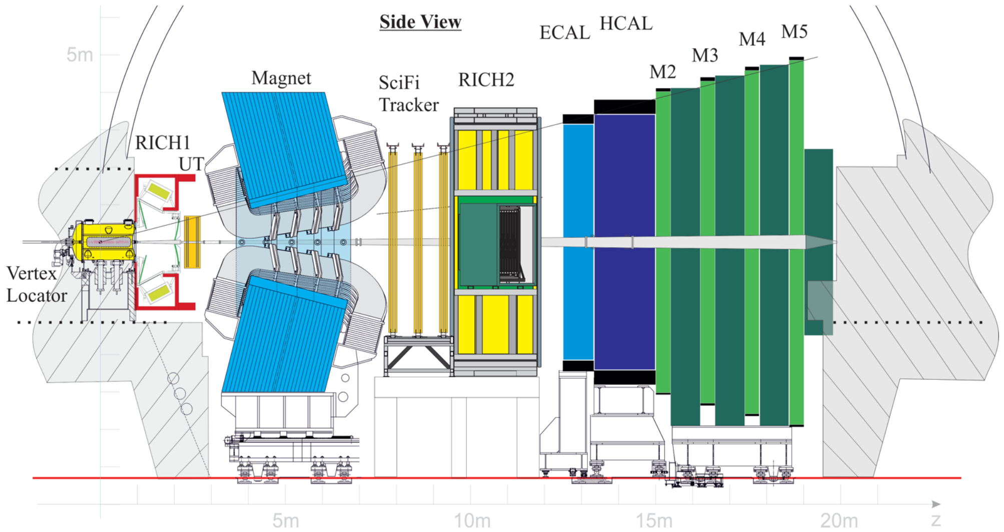

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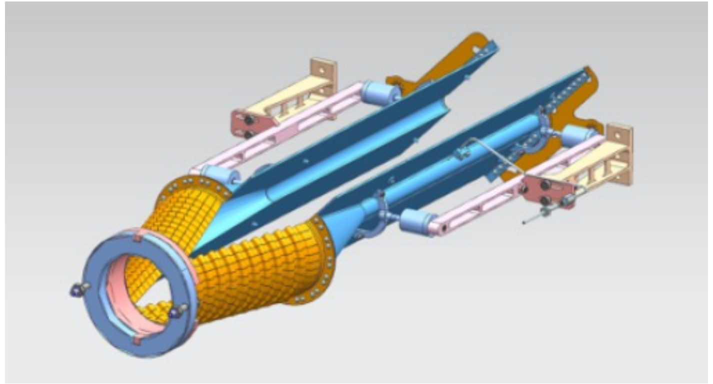
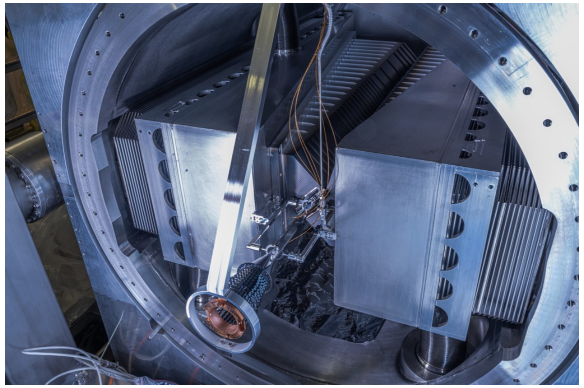

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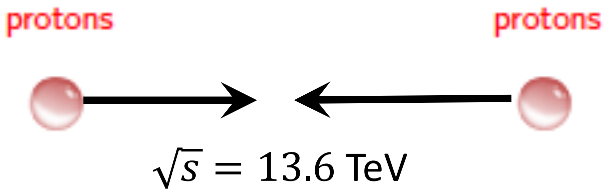
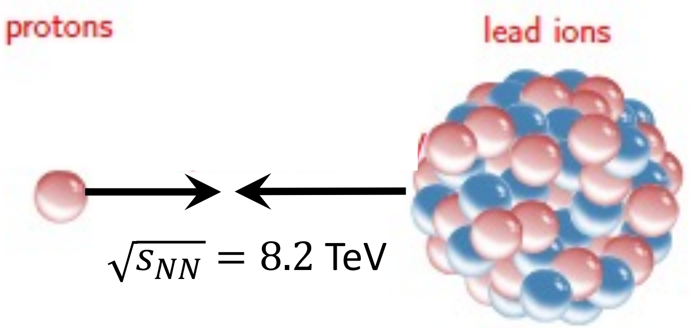
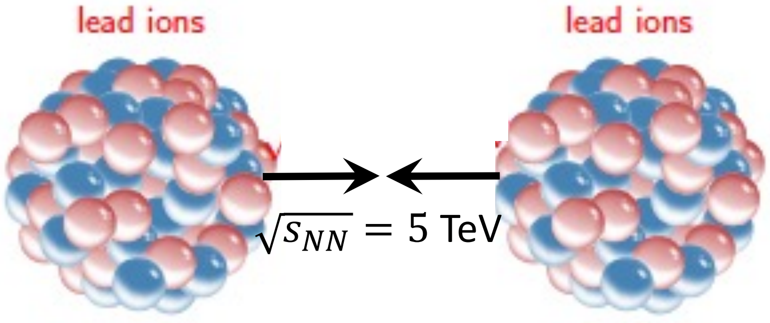
Find more on talk of L.P. Monday 5 (this parallel session)

Types of collisions at LHCb

Collider mode







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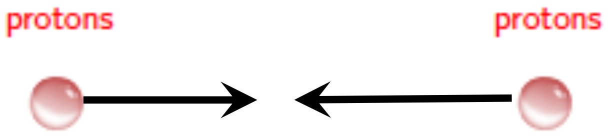
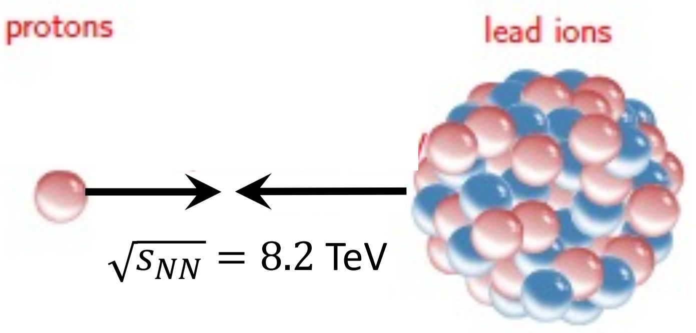
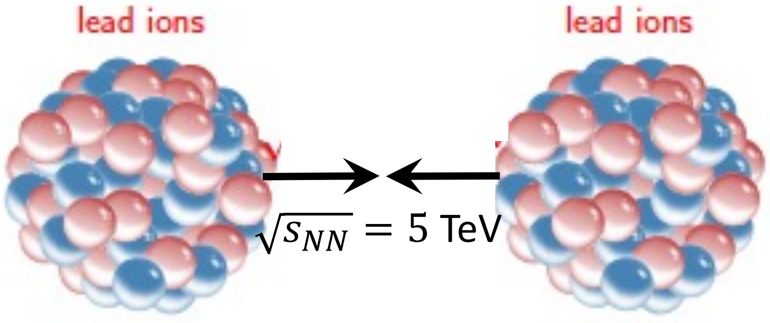


$\sqrt{s} = 13.6$ TeV

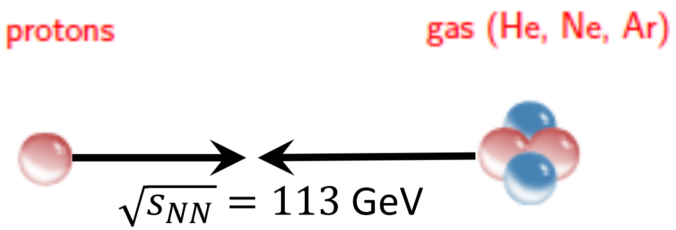


$\sqrt{s_{NN}} = 8.2$ TeV

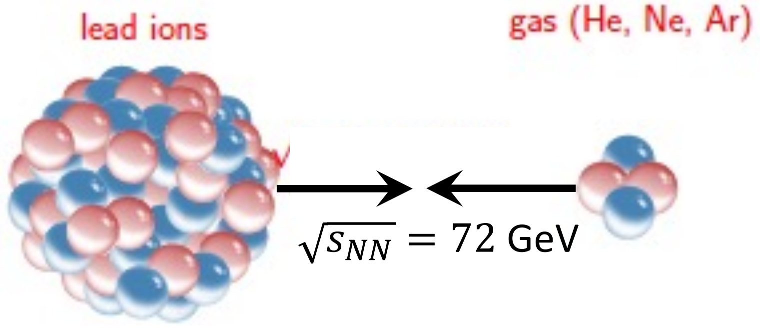


$\sqrt{s_{NN}} = 5$ TeV

Fixed-target mode (SMOG/SMOG2)



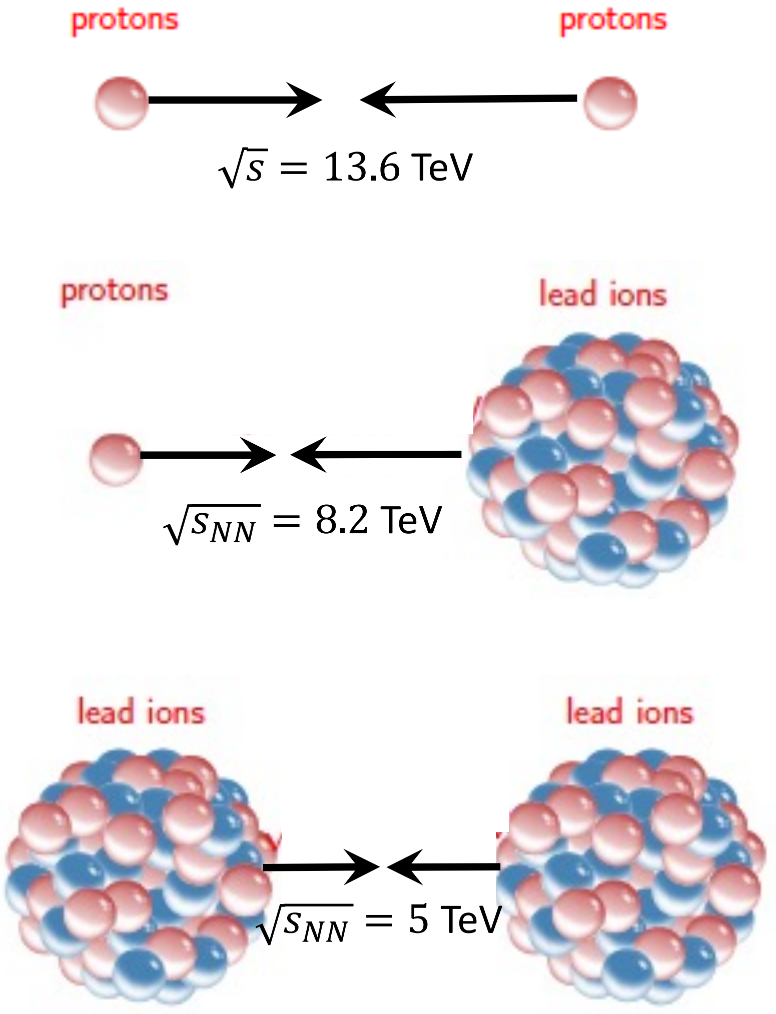
$\sqrt{s_{NN}} = 113$ GeV



$\sqrt{s_{NN}} = 72$ GeV

Types of collisions at LHCb

Collider mode



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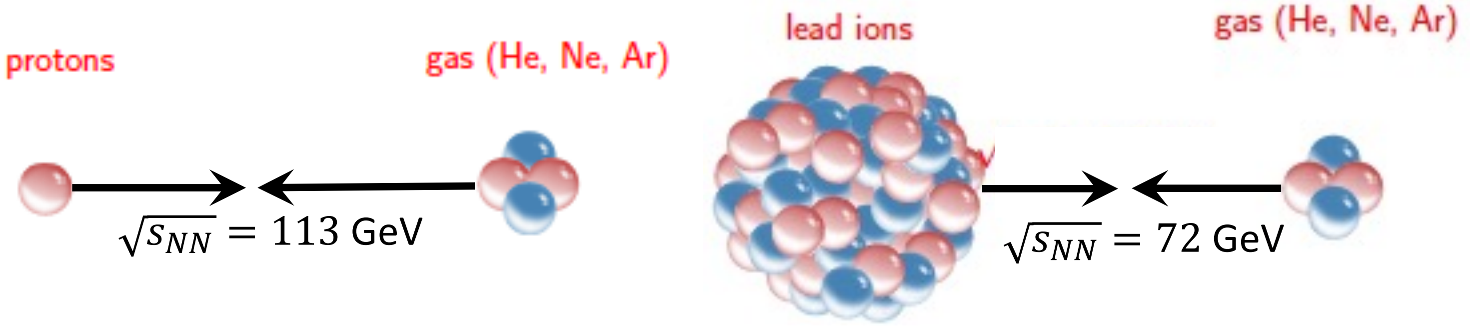
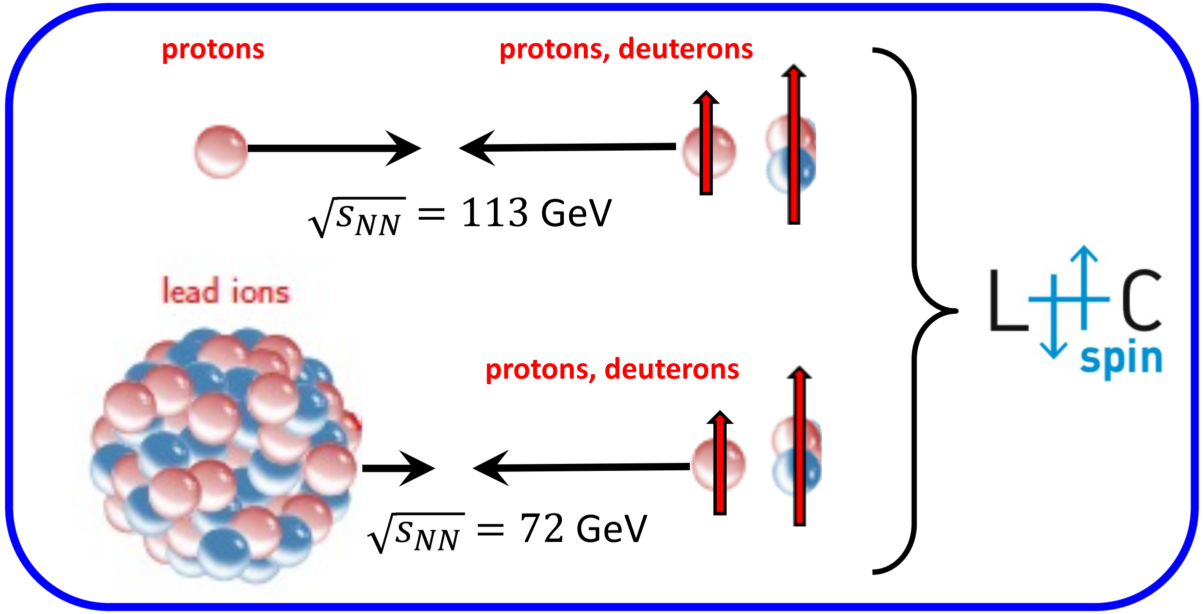


The SMOG program sets the basis for the development of a future **polarized gas target for LHCb:**



The LHCspin project

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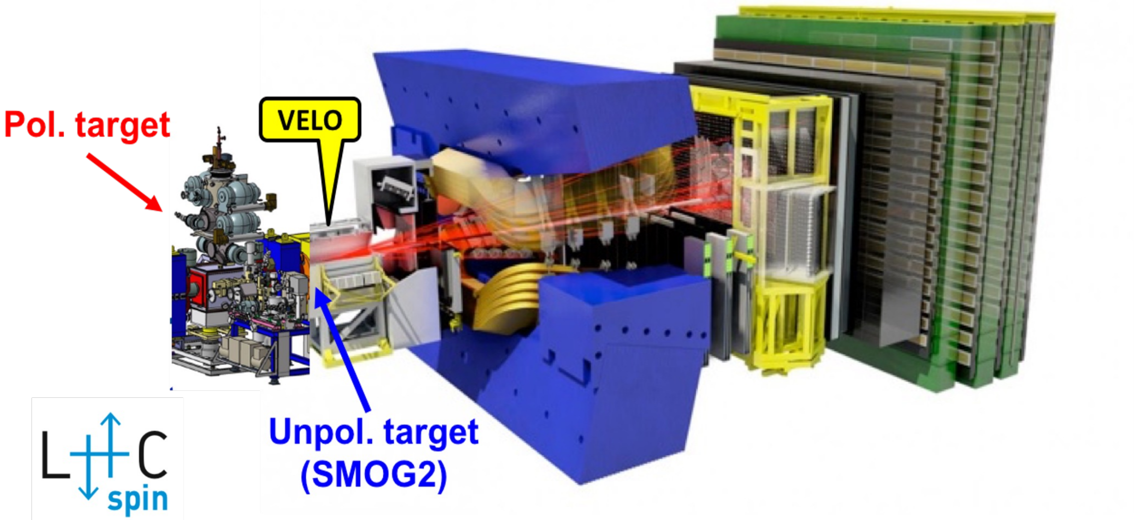

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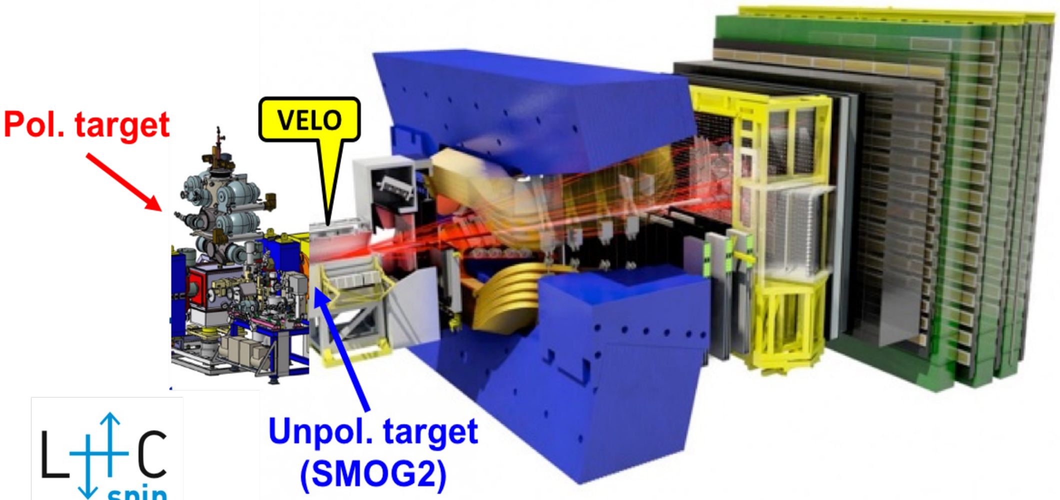
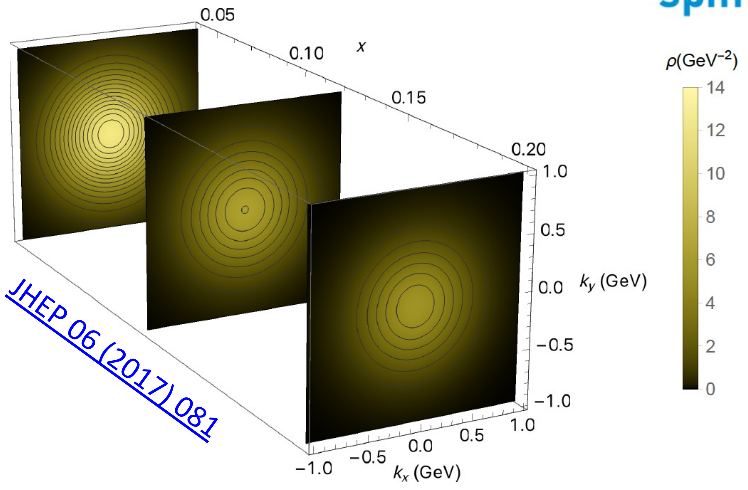


Motivations and points of strenght

- ✓ **unique kinematic conditions** (backward CM region, poorly explored large-x region at intermediate Q^2)
- ✓ **polarized gas target technology well established** (HERMES @ DESY, ANKE @ COSY with high performance)
- ✓ **target experts from HERMES and COSY involved in first person in the design of the LHCspin apparatus**
- ✓ **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)

The physics goals of LHCspin

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



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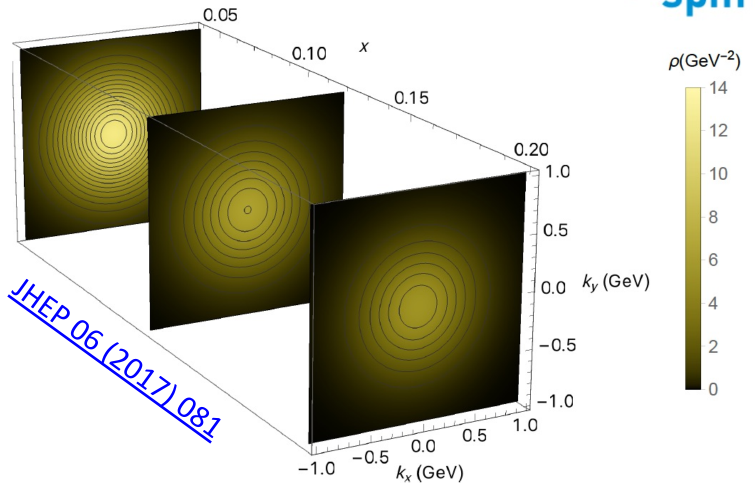

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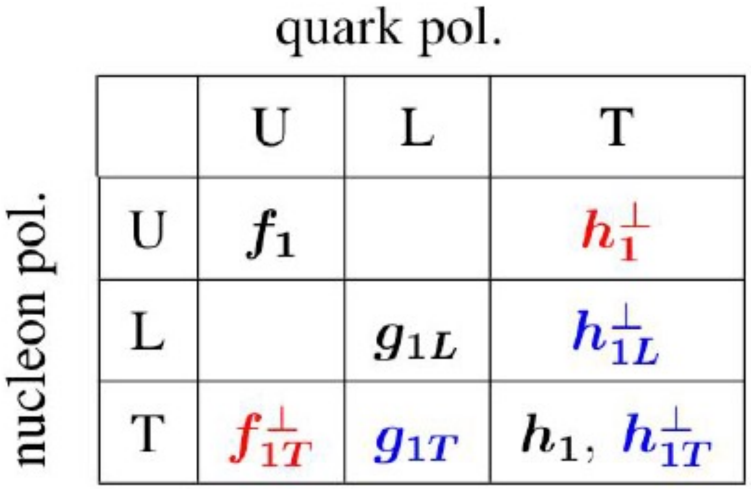


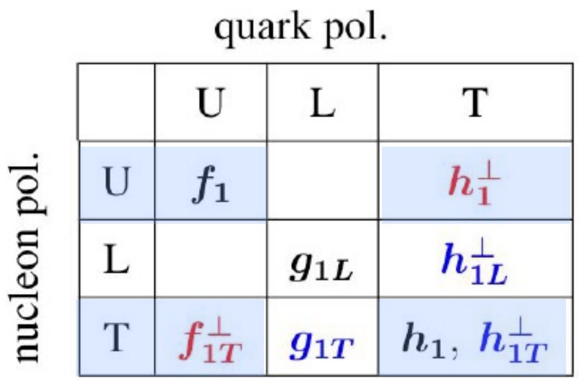
quark pol.

nucleon pol.

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

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

Quark TMDs



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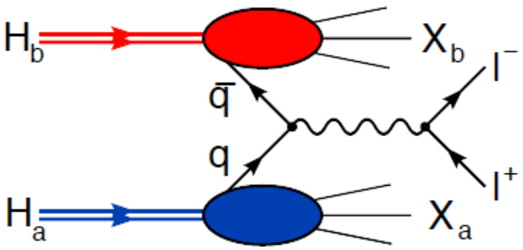
Transv. polarized Drell-Yan



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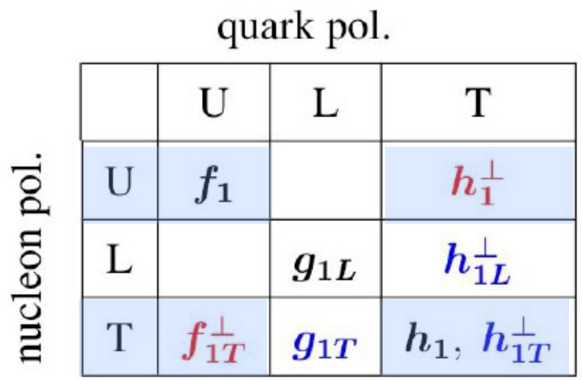

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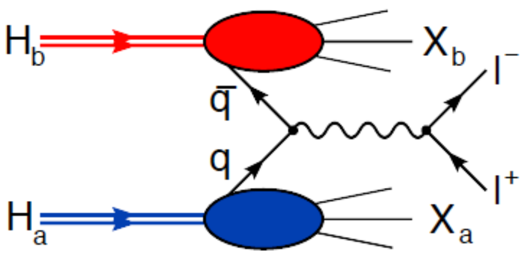

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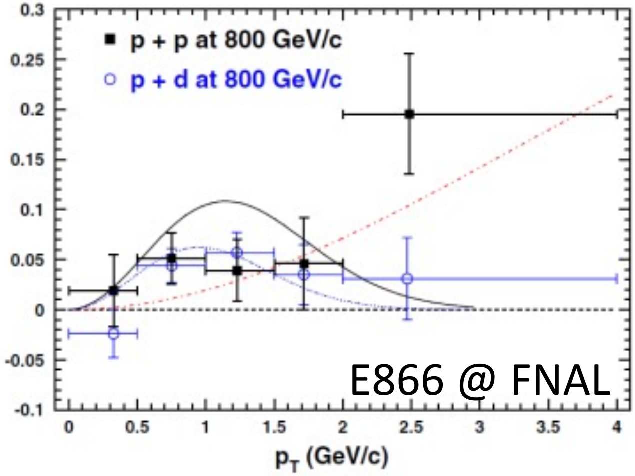
Sensitive to unpol. and BM TMDs

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

violation of Lam-Tung relation

$\nu \sim h_1^{\perp} \otimes h_1^{\perp}$



[PRL 102 2009 182001]

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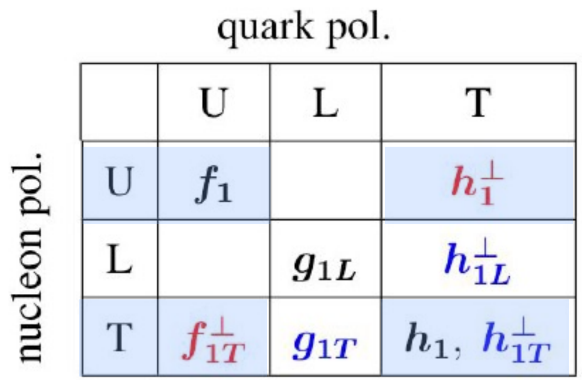

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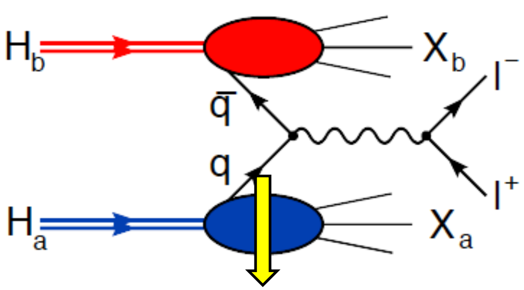

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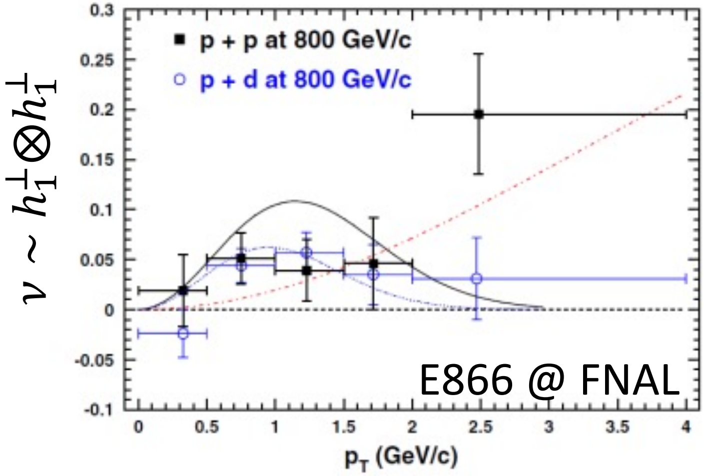

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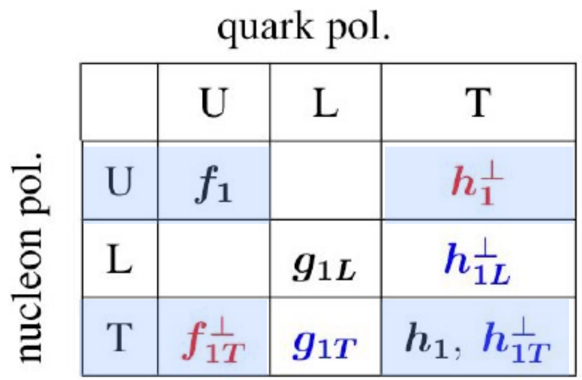

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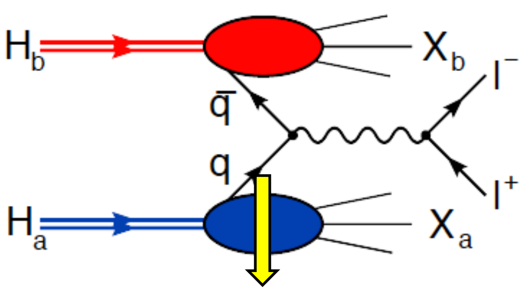

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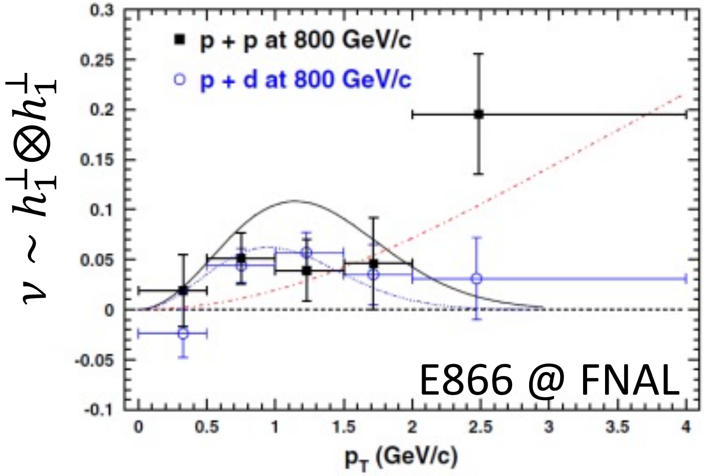

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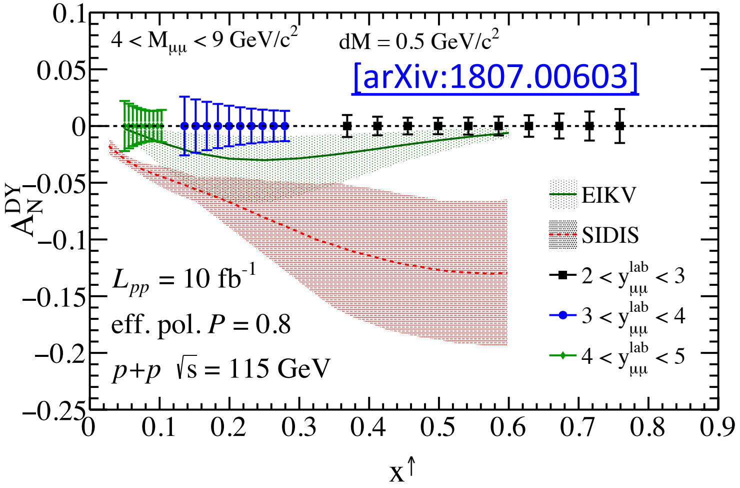

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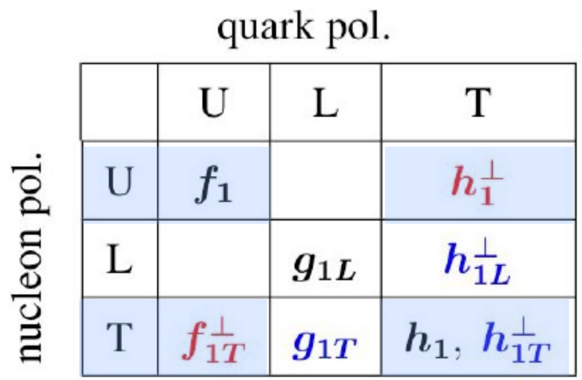

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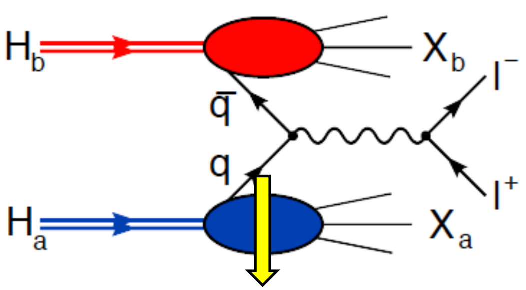

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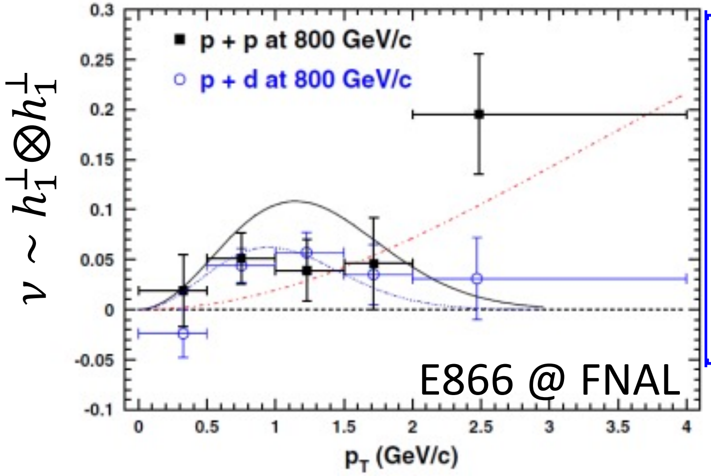

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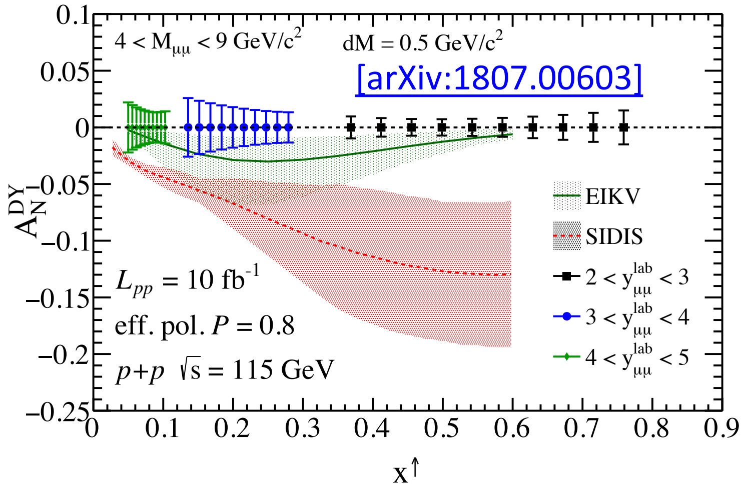


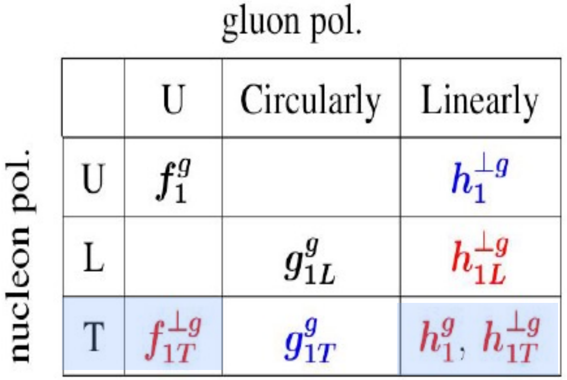
[arXiv:1807.00603]

- 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

Gluon TMDs

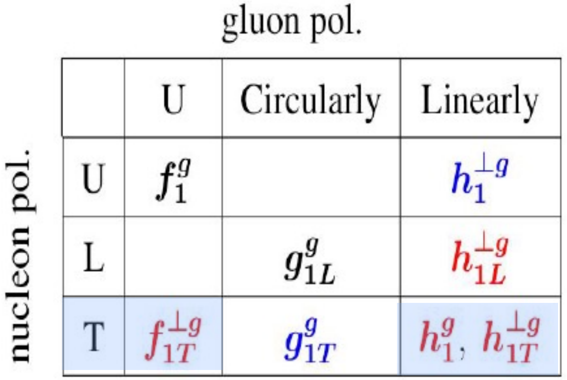


gluon pol.

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

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

Gluon TMDs



gluon pol.

nucleon pol.

	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
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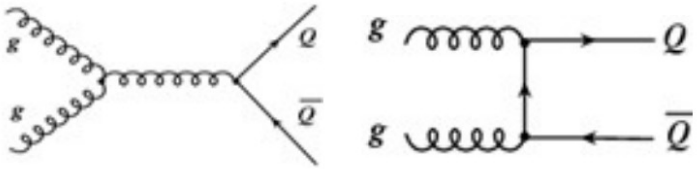

The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-quark observables**

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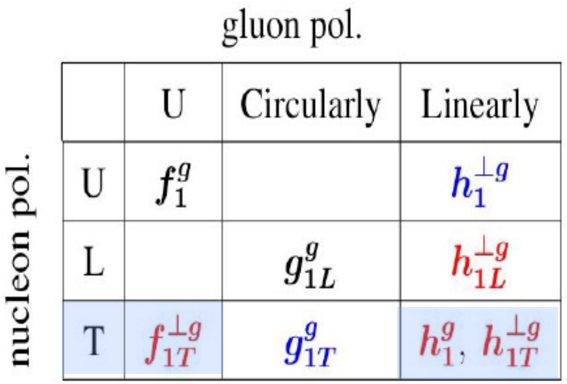

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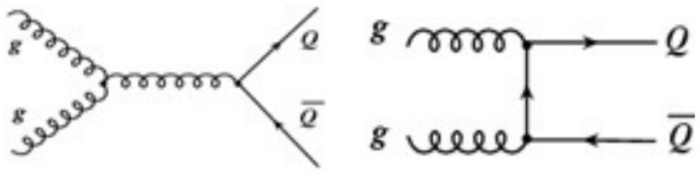

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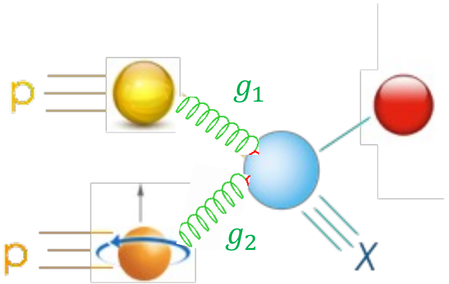
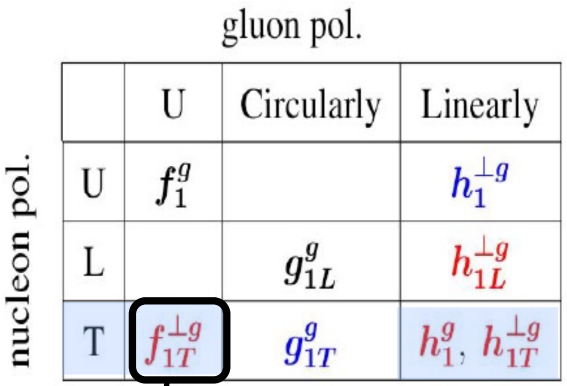


$$\begin{cases} \boldsymbol{D^0, \bar{D}^0} \\ \boldsymbol{J/\psi\,, \psi'} \\ \boldsymbol{\Upsilon} \\ \ldots \end{cases}$$

Gluon TMDs



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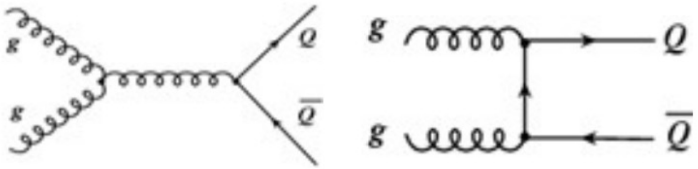

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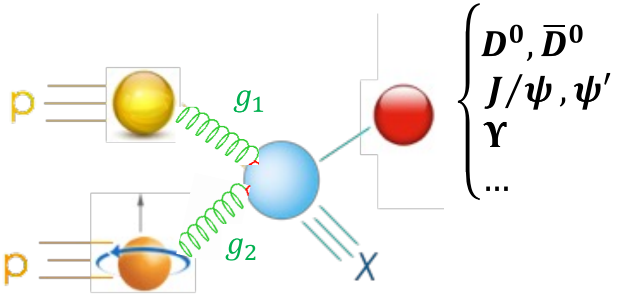

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Υ
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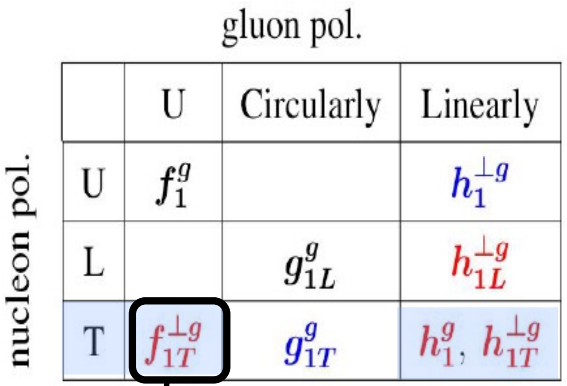

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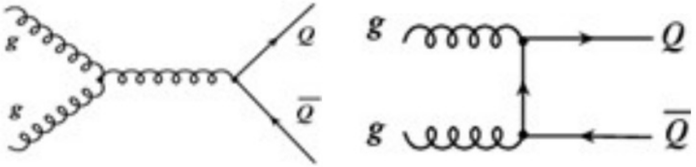

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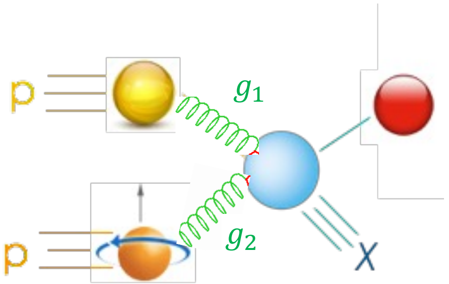

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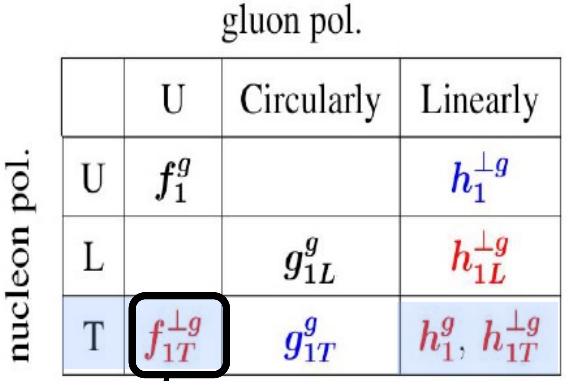
$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg\to Q\bar{Q}g}\right] \sin\phi_S + \cdots$$

Gluon TMDs



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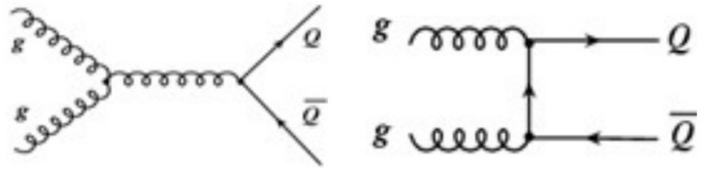

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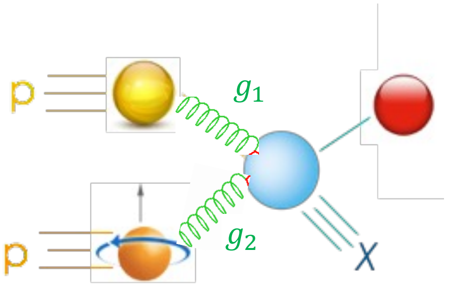

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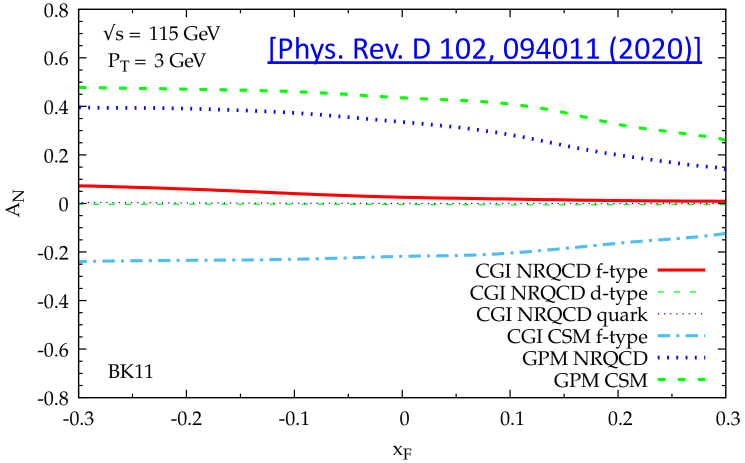
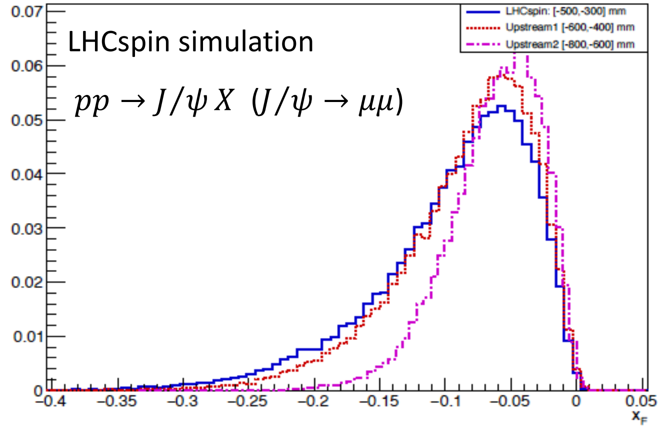


[Phys. Rev. D 102, 094011 (2020)]



LHCspin simulation

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

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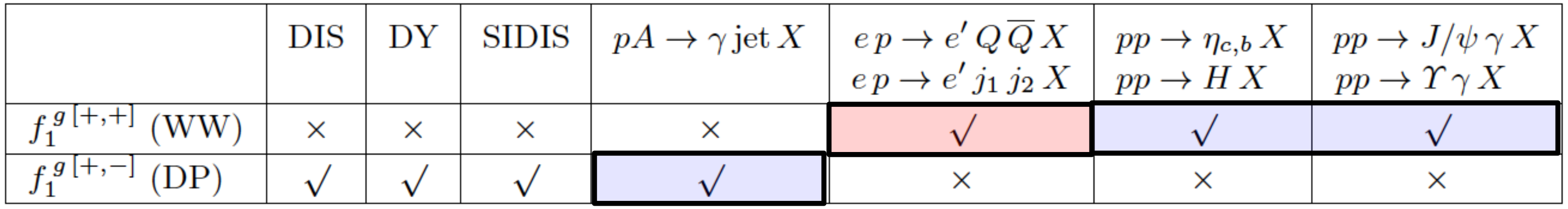
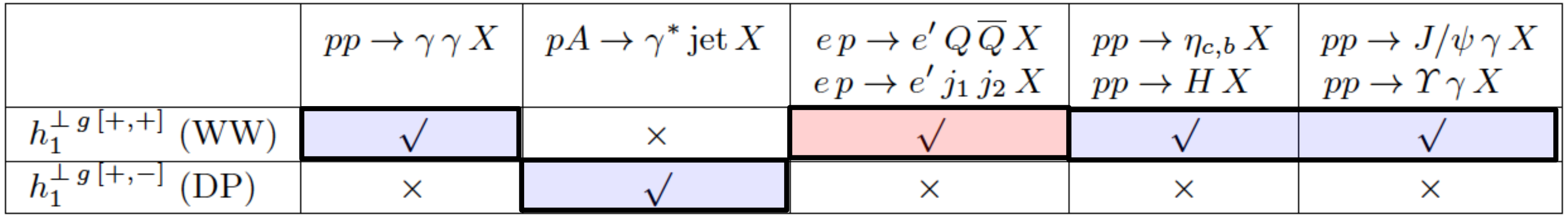
A synergic attack to gTMDs

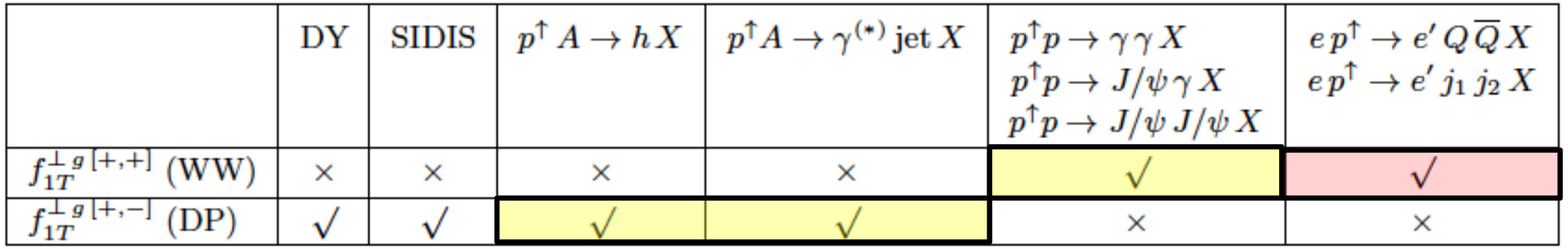
[D. Boer: Few-body Systems 58, 32 (2017)]



	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

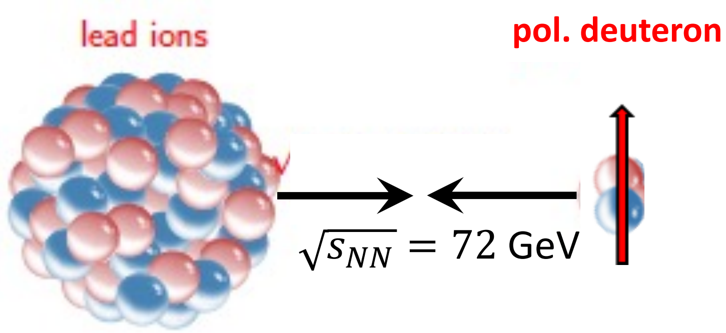
🟦 Can be measured at RHIC & LHC (including LHCb+SMOG2/LHCspin)

🟨 Can be measured at RHIC and LHCb+LHCspin

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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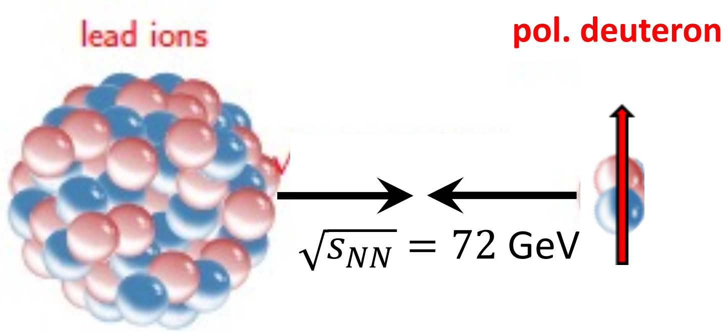

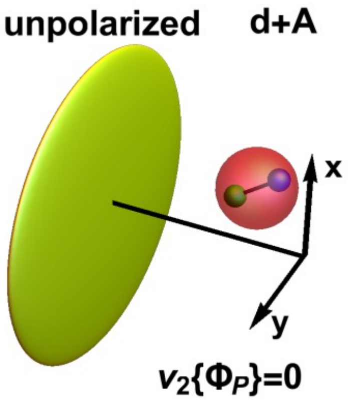

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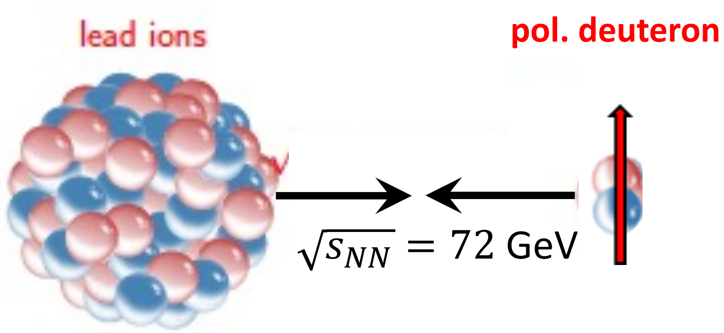

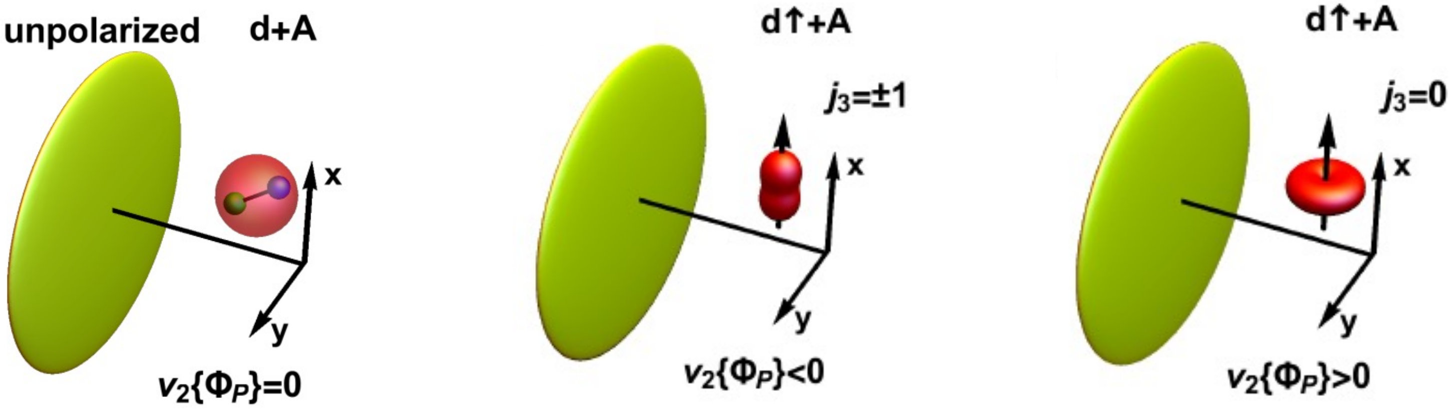

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$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

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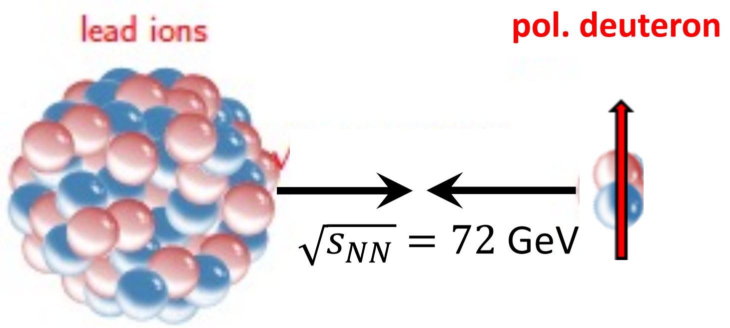

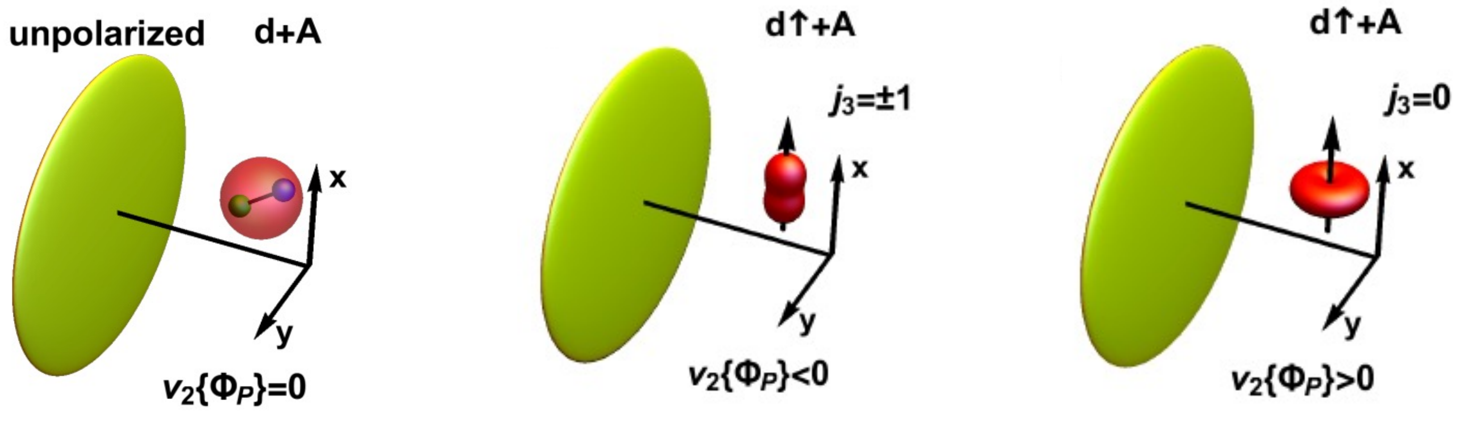

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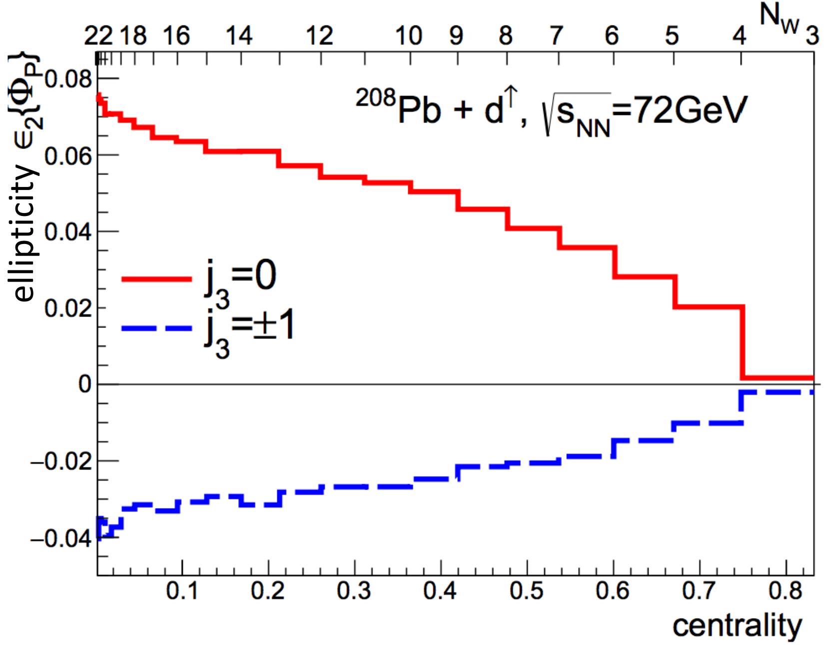
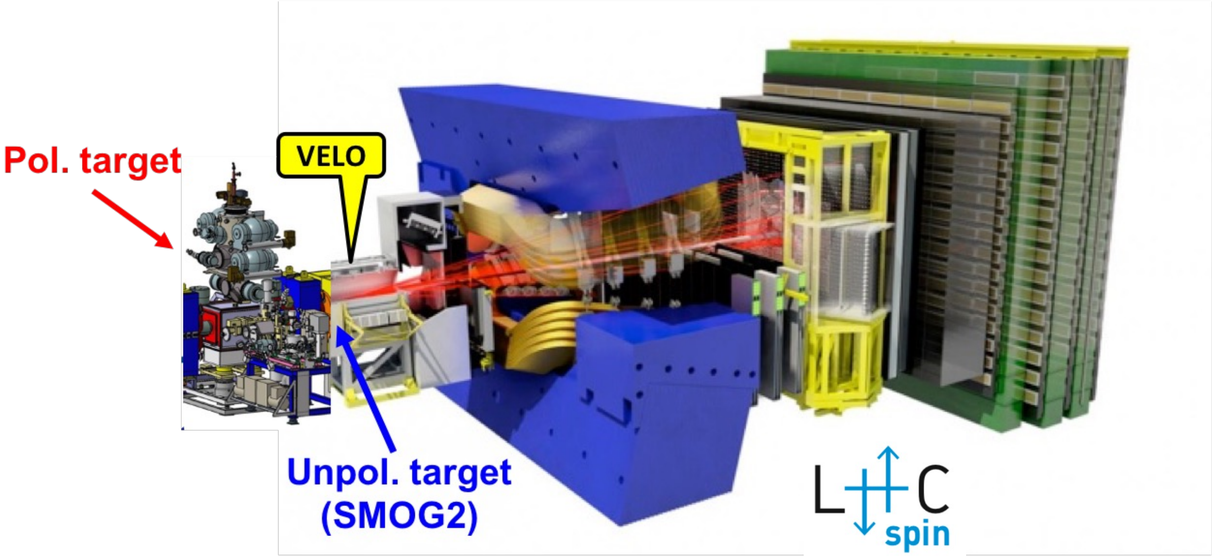
Predictions for LHC FT kinematics



[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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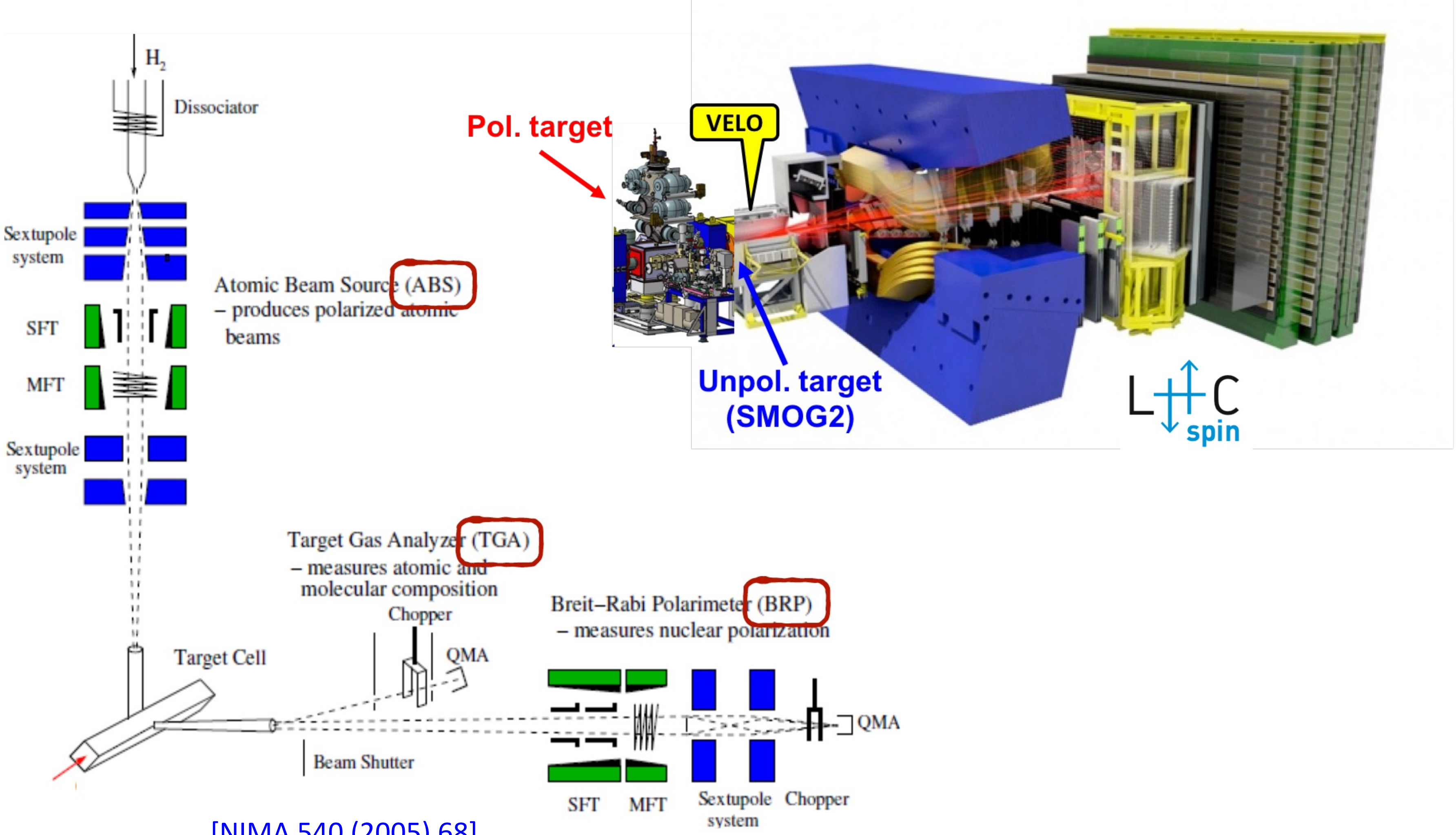

[NIMA 540 (2005) 68]

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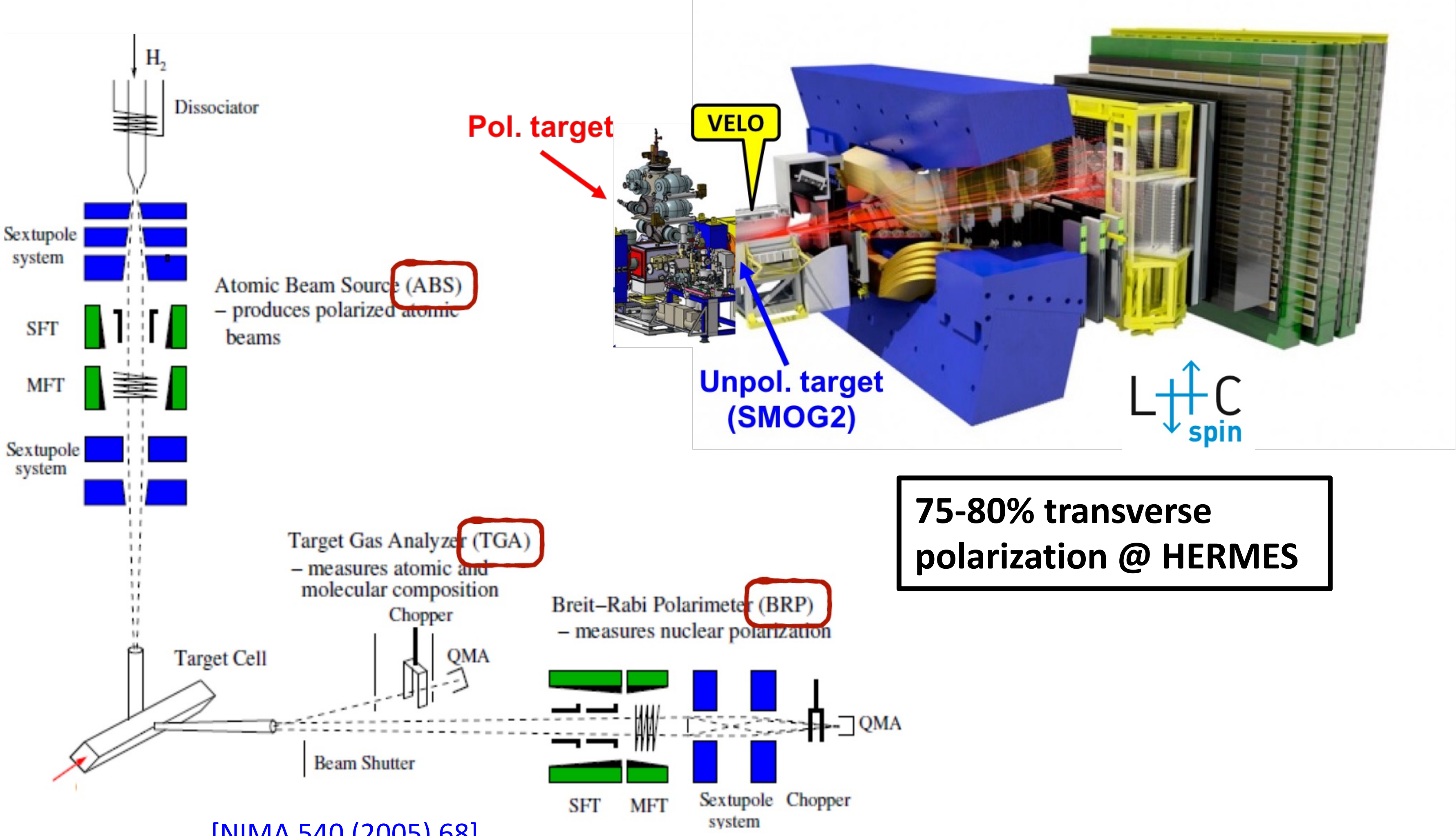

75-80% transverse polarization @ HERMES

[NIMA 540 (2005) 68]

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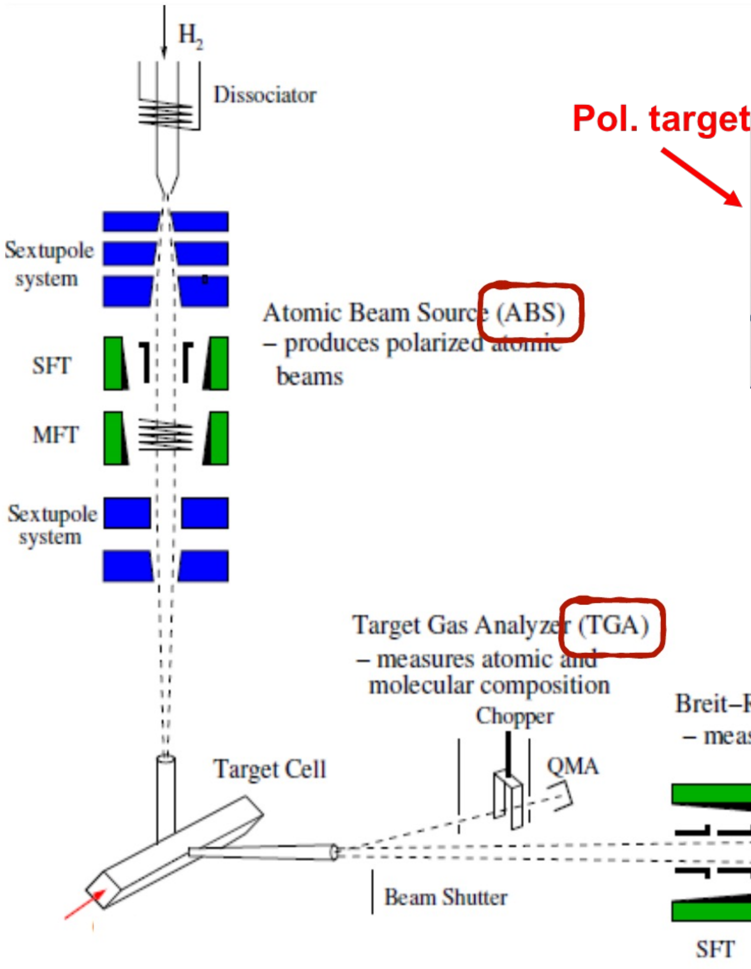

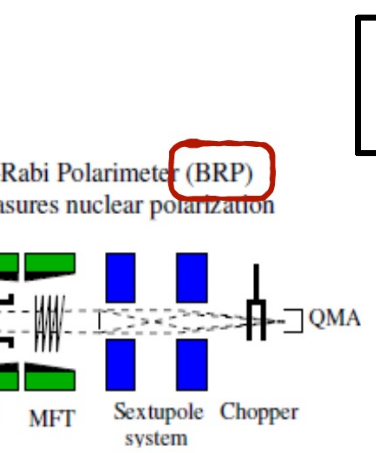

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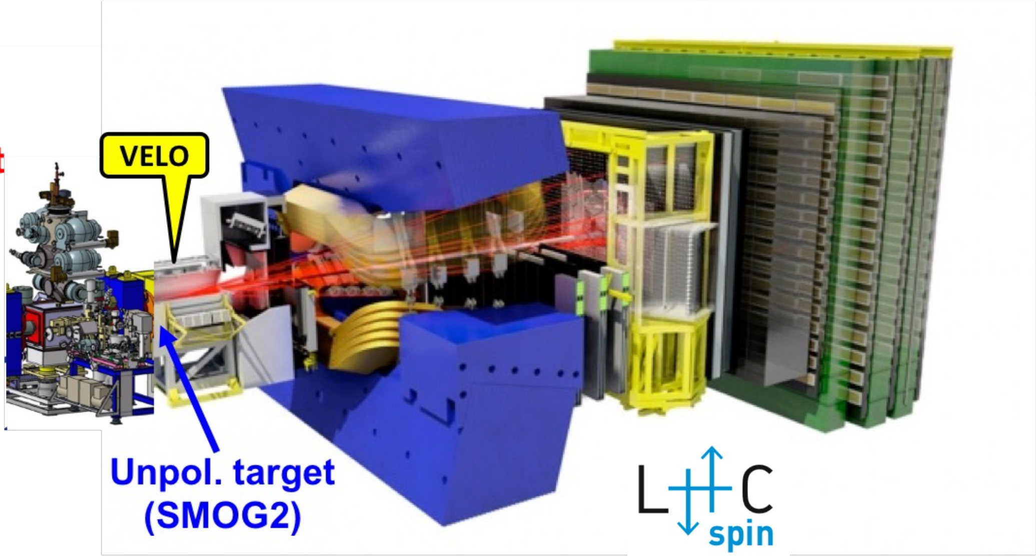

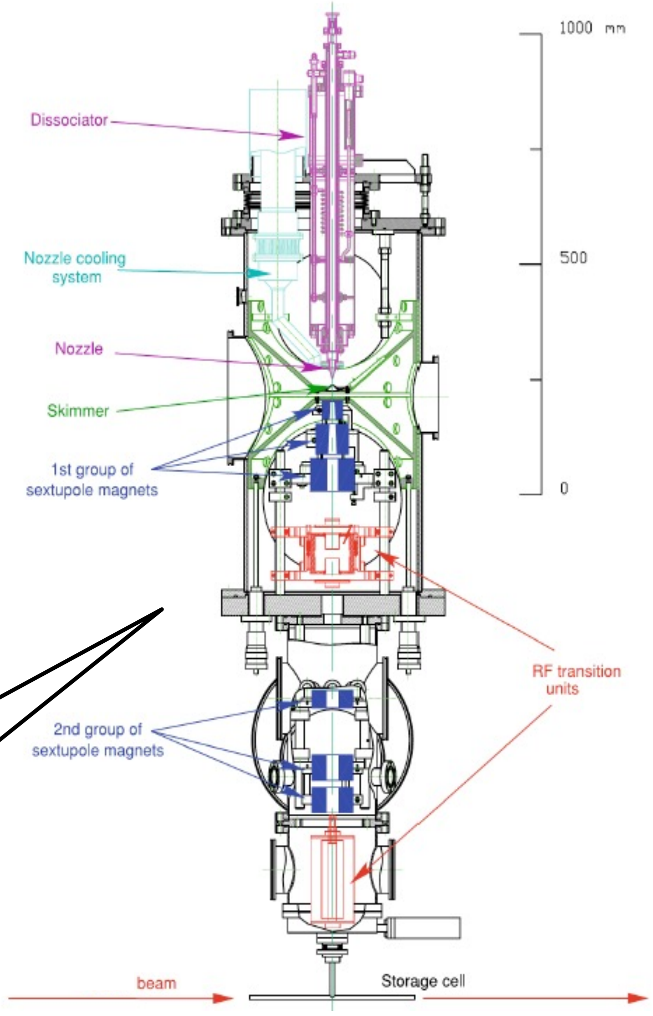

[NIM A 721, 83 (2013)]

75-80% transverse polarization @ HERMES

state-of-the art ABS of ANKE @ COSY

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

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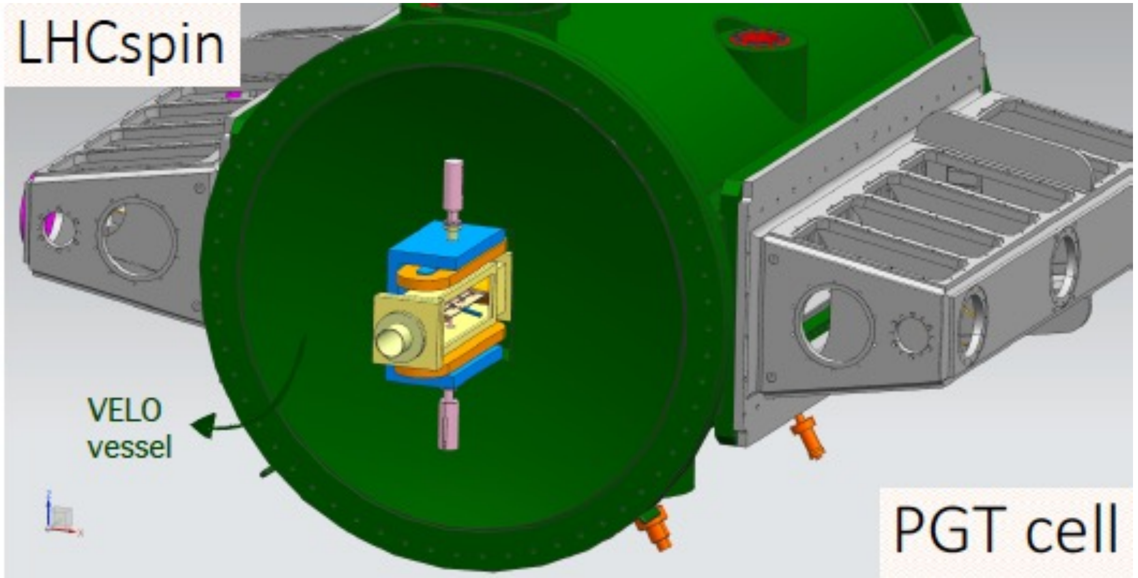
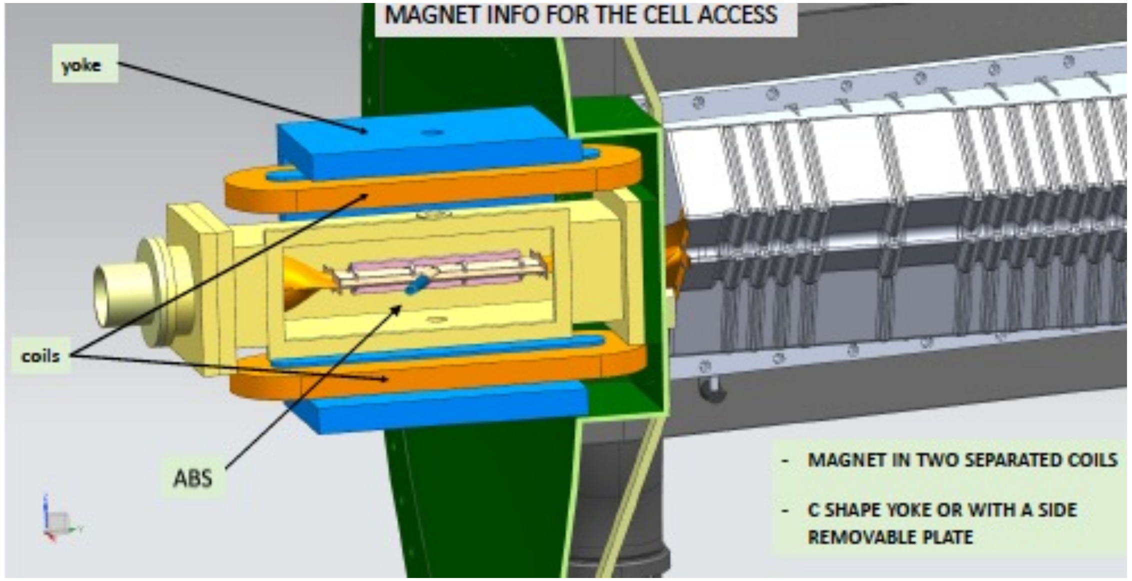
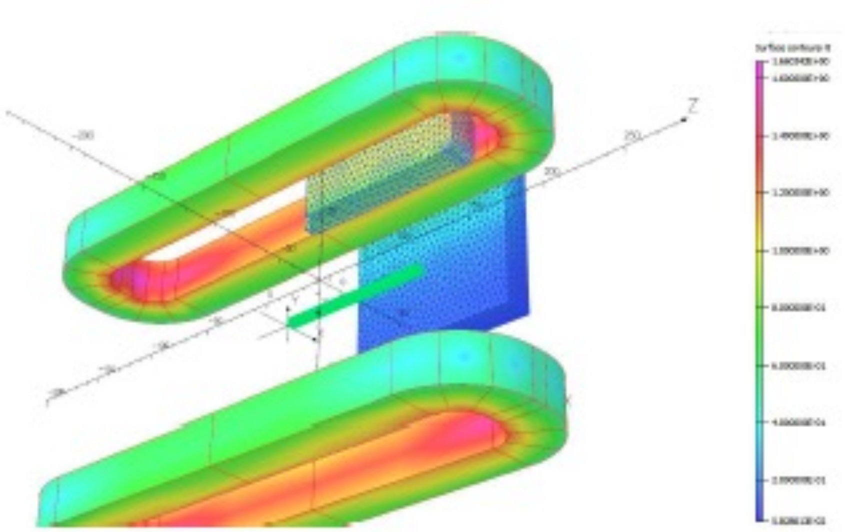


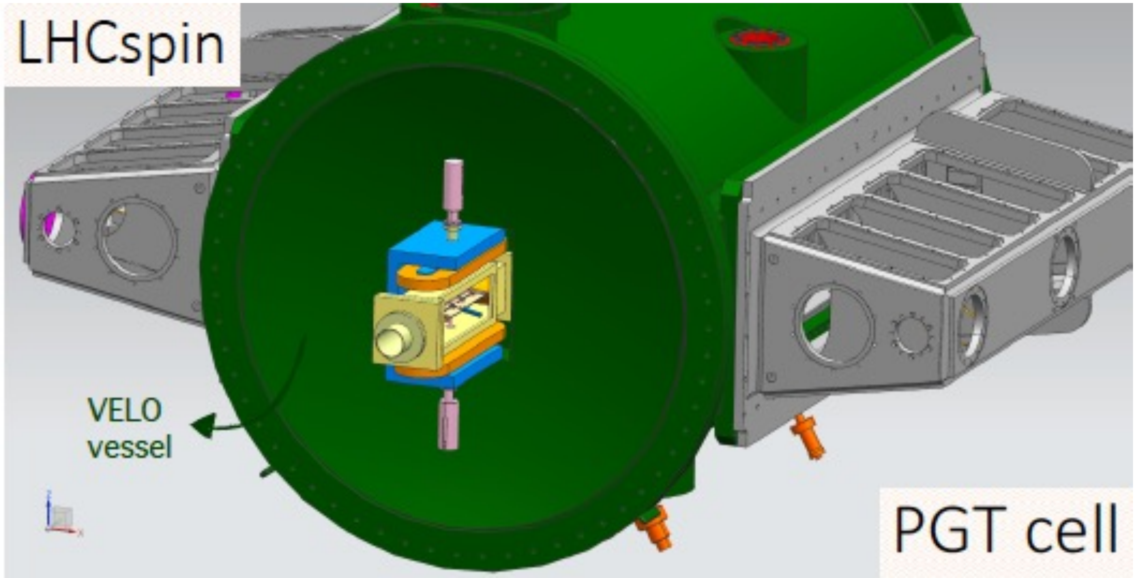


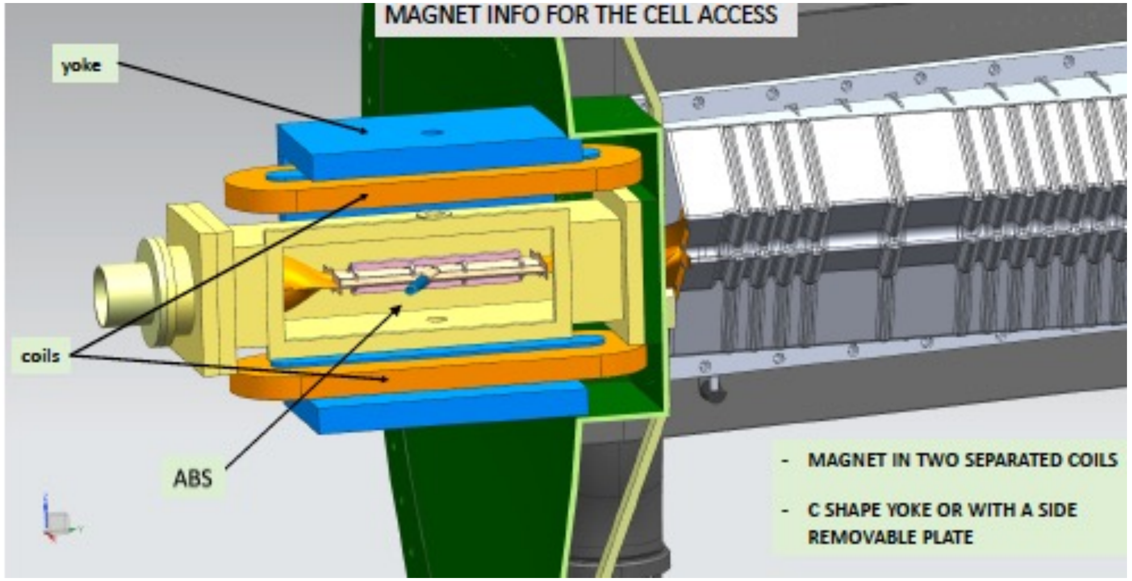
- MAGNET IN TWO SEPARATED COILS
- C SHAPE YOKE OR WITH A SIDE REMOVABLE PLATE

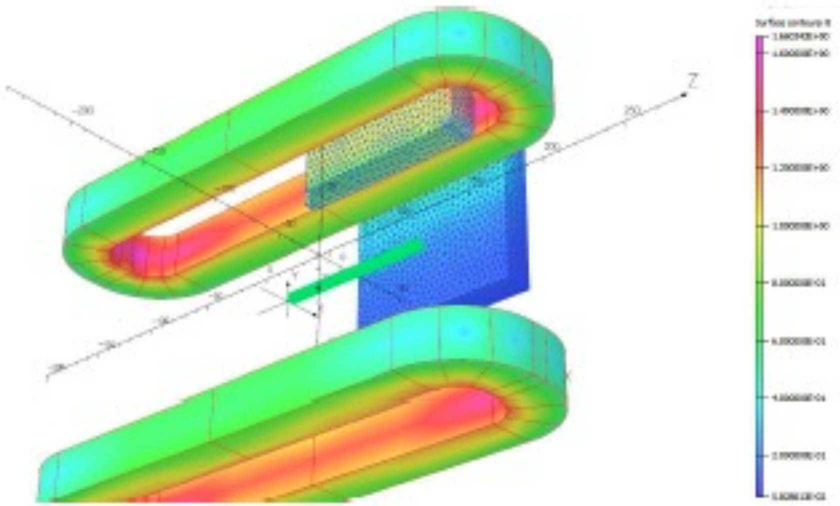


- **Compact superconductive dipole magnet for static transverse field to maintain polarization inside the cell and avoid beam-induced depolarization**
- **Required $B = 300\ mT$ with $\Delta B/B \sim 10\%$**

The LHCspin apparatus







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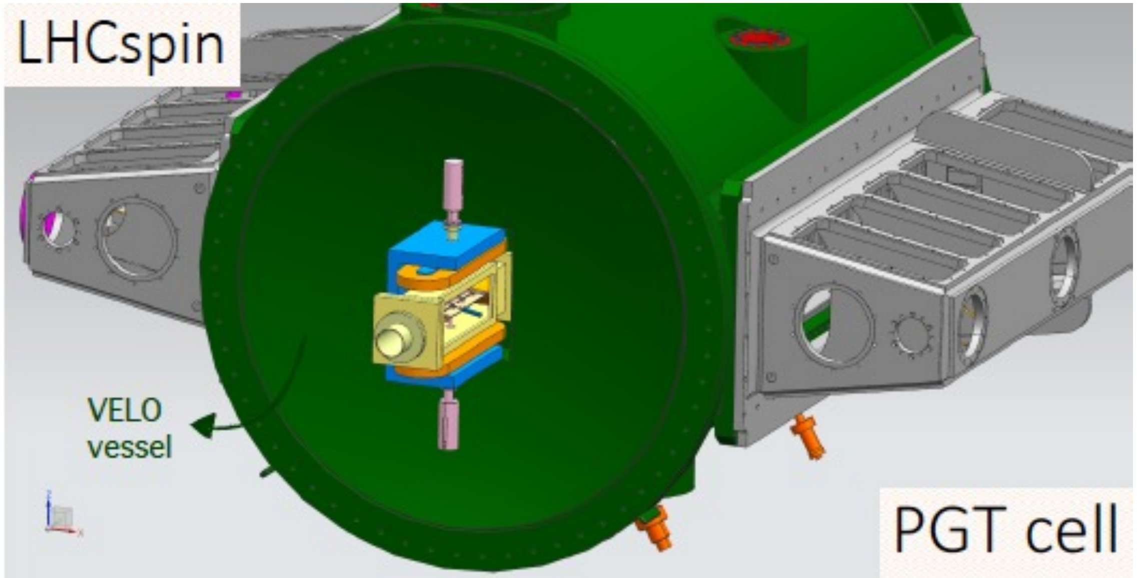

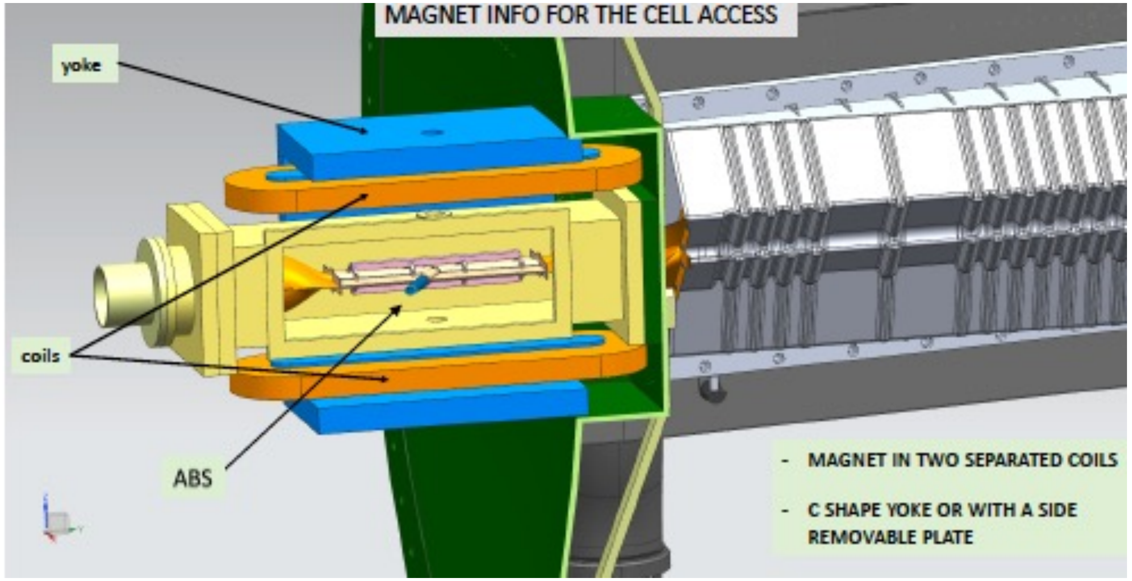

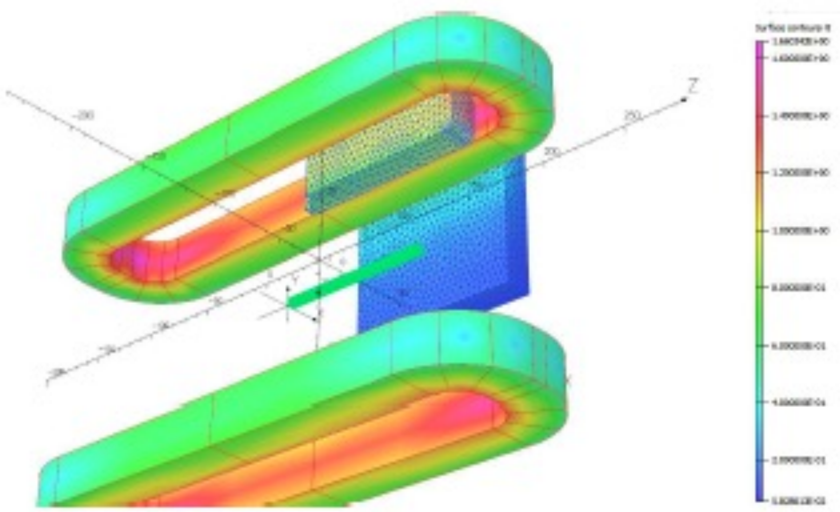

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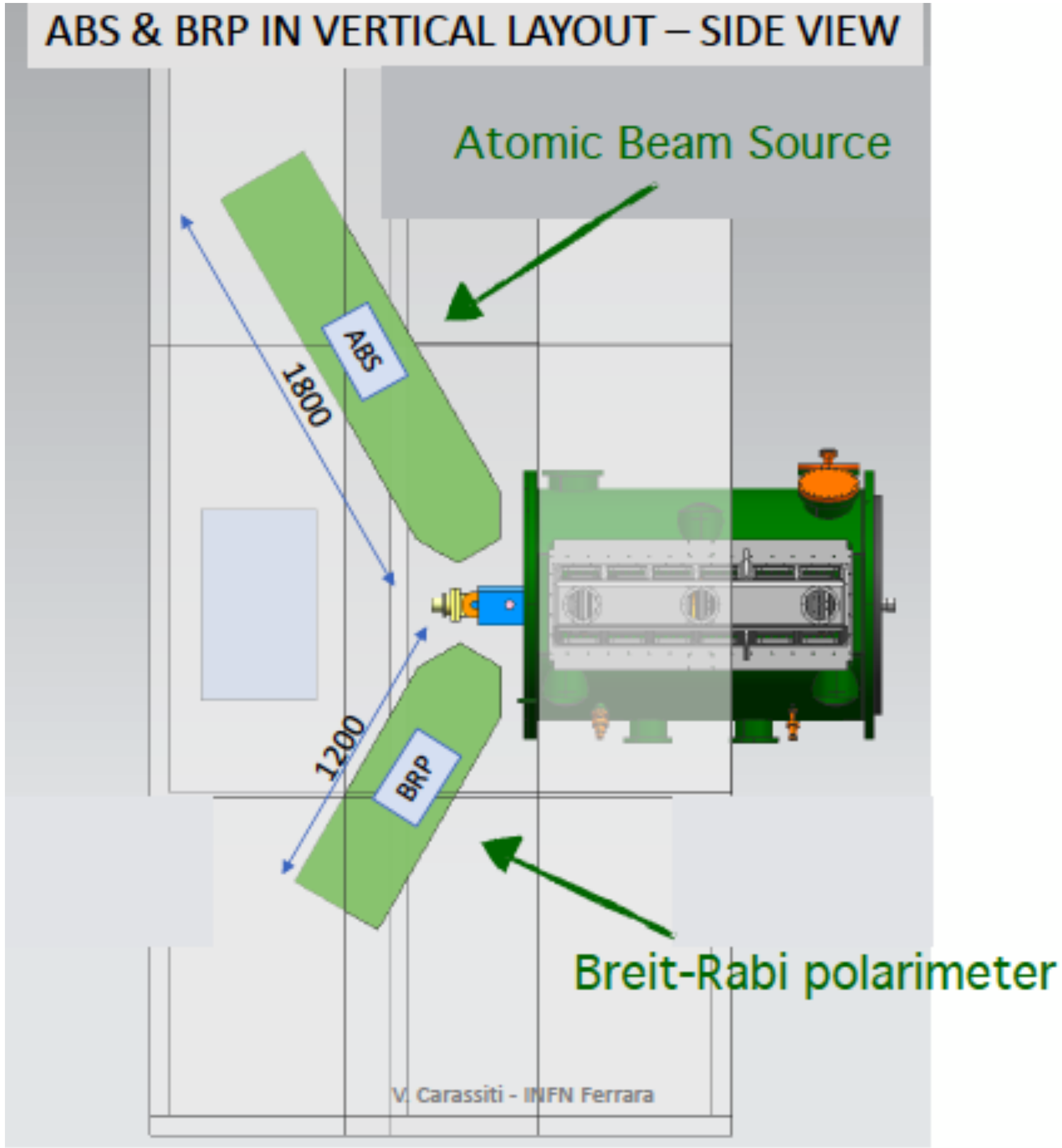
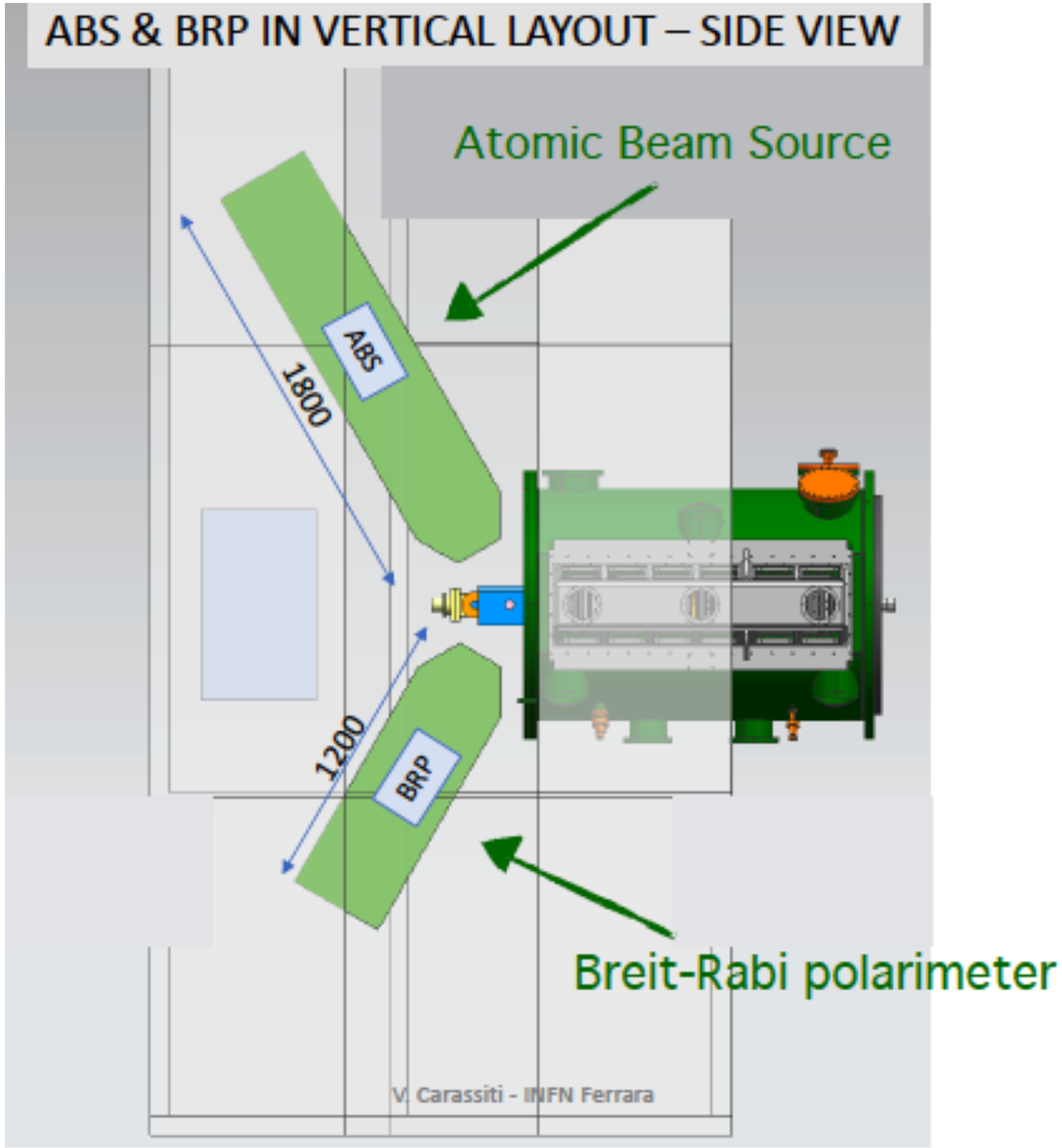
- **Possibility to switch from dipole magnet to solenoid to realize a Longitudinal polarized target**

The LHCspin apparatus



Need to develop a new-generation compact ABS and diagnostic system to fit into the limited available space in the VELO alcove

The LHCspin apparatus



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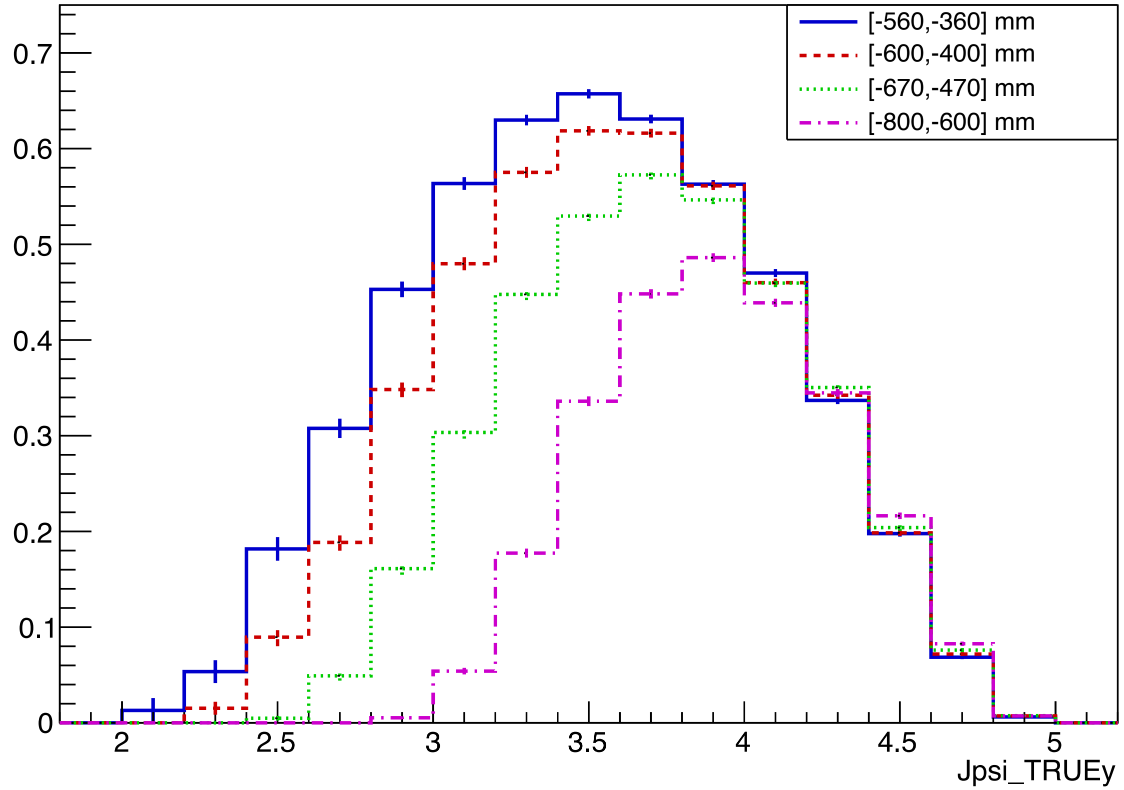
J/Ψ → $\mu^+\mu^-$PV X track reconstruction efficiency



Expected performance

Target

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

Beam (Run4)

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

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

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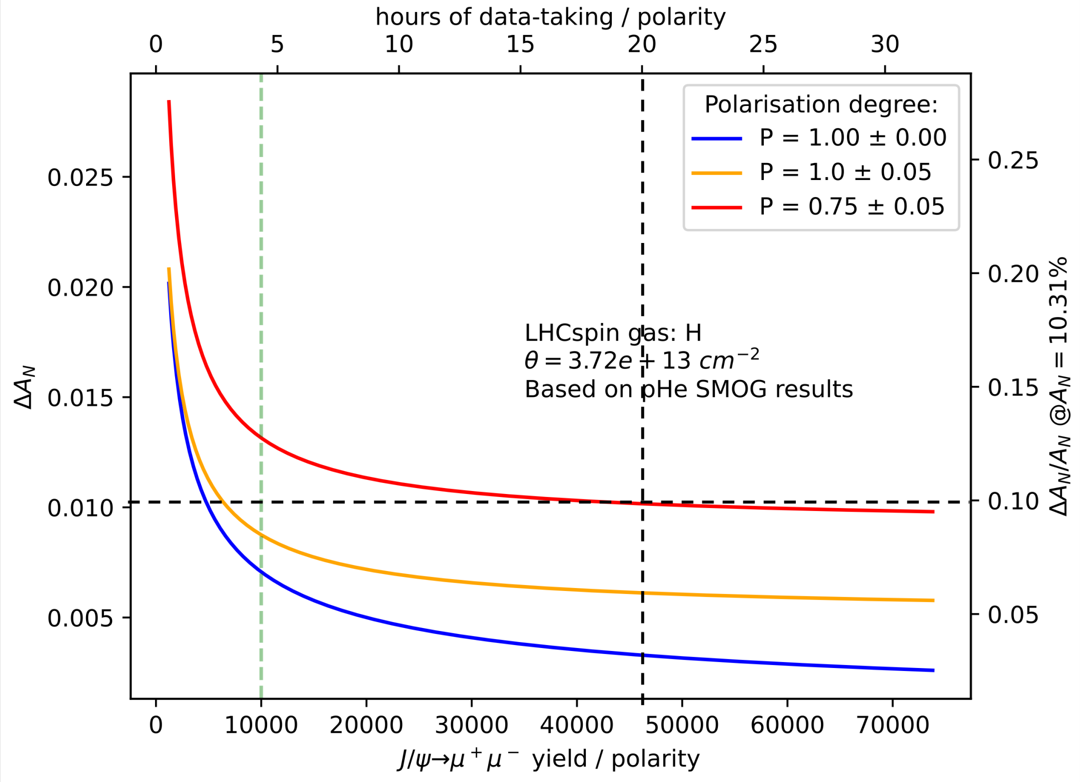

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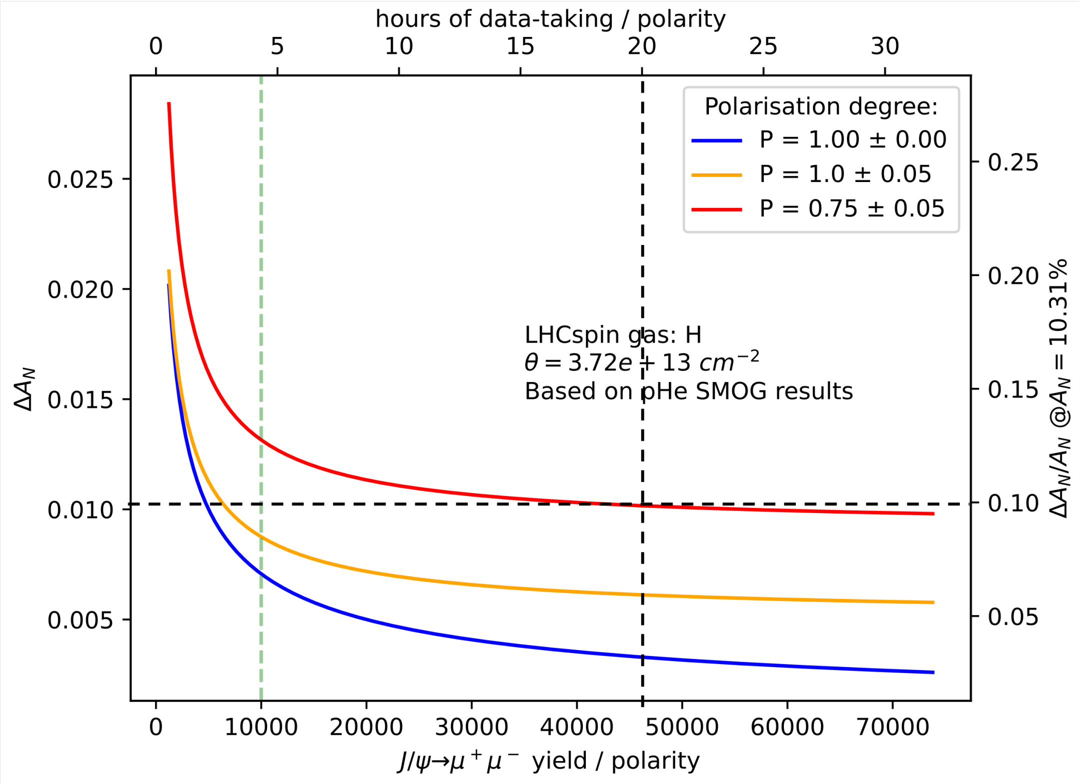


Expected yields for Run4 (Run4+Run5):

Channel	Events / week	Total events
$J/\psi \to \mu^+\mu^-$	194k (434k)	23M (75M)
$\psi(2S) \to \mu^+\mu^-$	3.5k (7.7k)	414k (1.3M)
$D^0 \to K^-\pi^+$	976k (2.2M)	117M (380M)
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$	77 (170)	930 (3000)
Drell Yan ($5 < M_{\mu\mu} < 9$ GeV)	110 (250)	13k (43k)
$\Upsilon \to \mu^+\mu^-$	83 (187)	10k (32k)
$\Lambda_c^+ \to pK^-\pi^+$	19k (43k)	2.3M (7.5M)

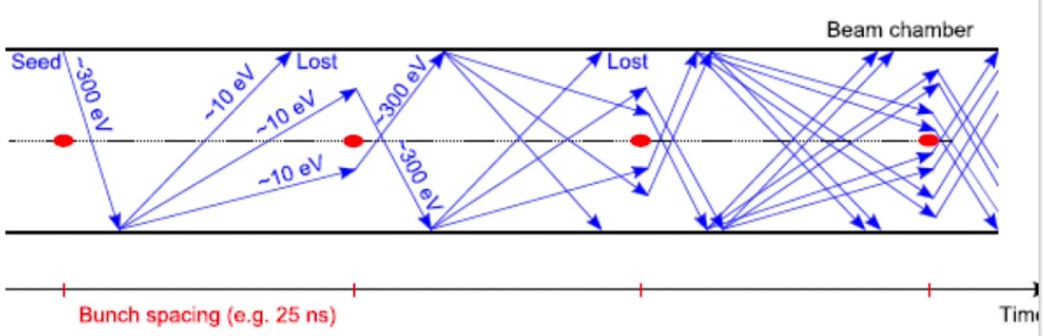
assumptions:

- 120 weeks/RUN
- 84h/week
- $Stat(Run5) \sim \sqrt{5}\, Stat(Run4)$

Recombination and cell coating

The inner coating of the storage cell is a crucial aspect of the R&D. It is needed to:

✓ **minimize e-cloud** related beam instabilities



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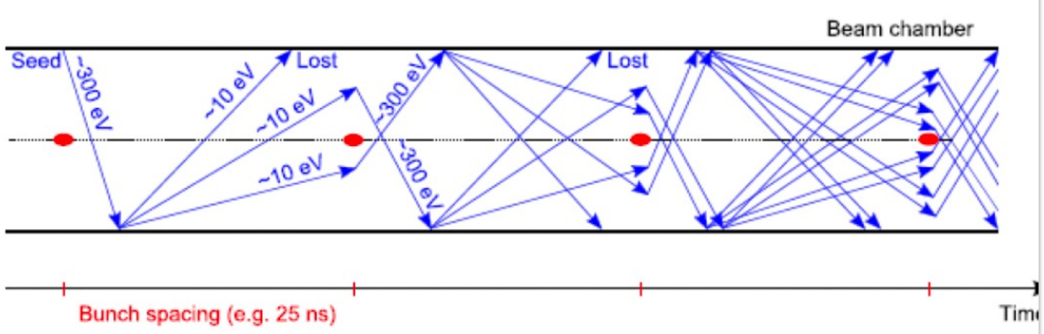

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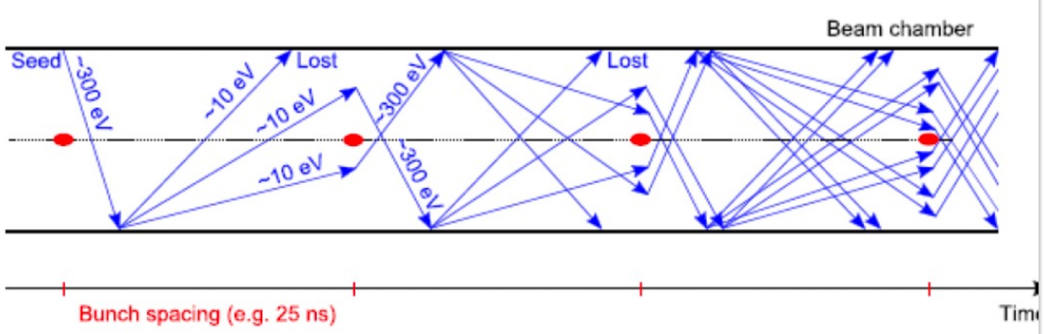

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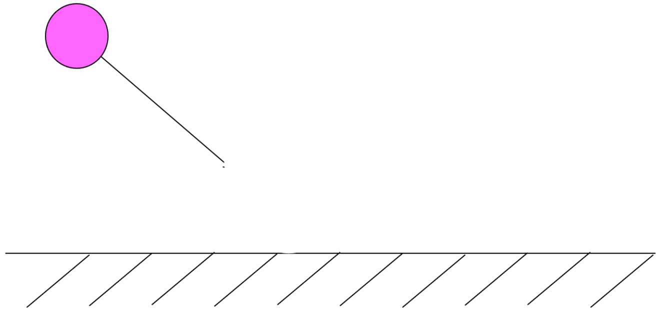
Eley-Rideal Mechanism



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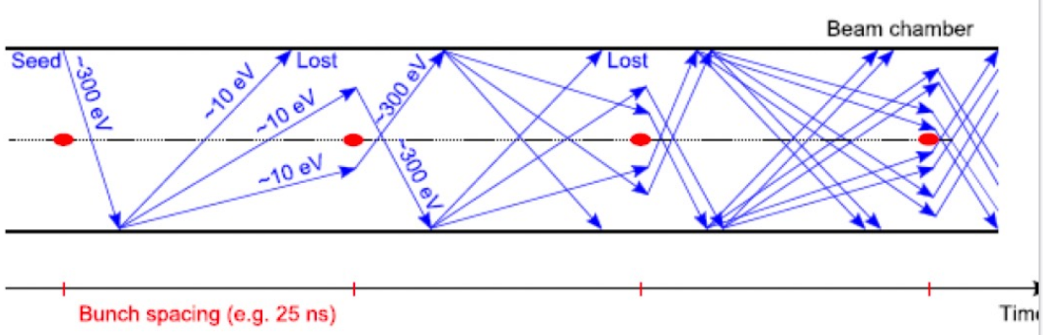

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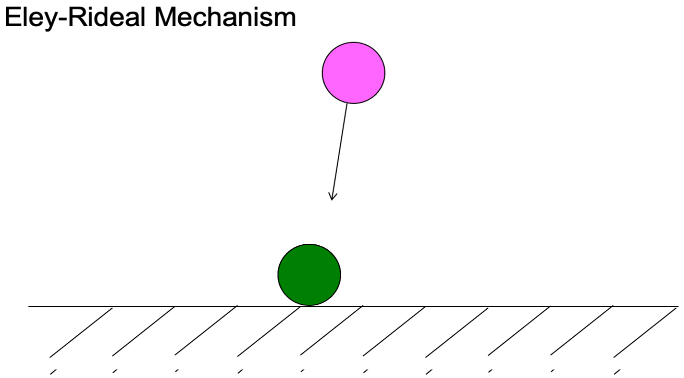

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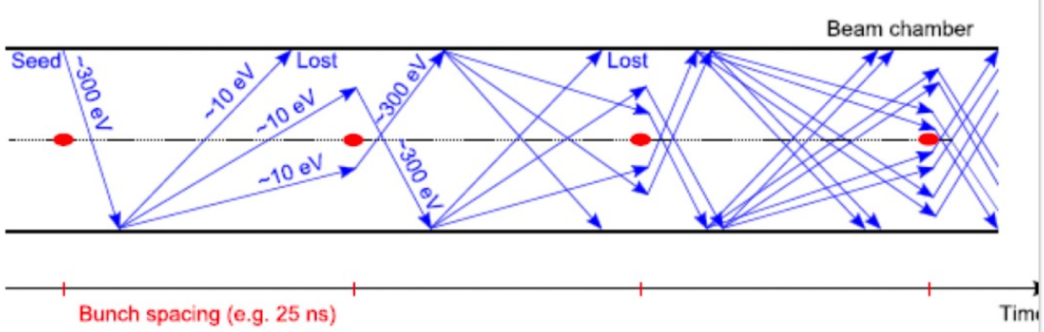

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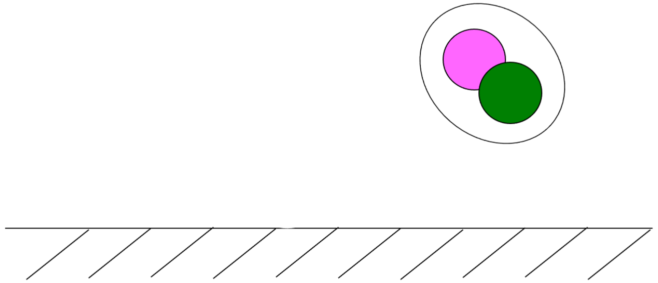

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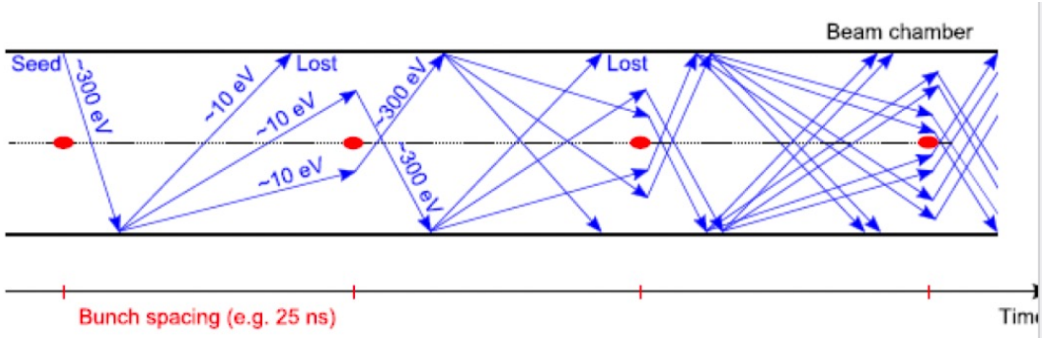

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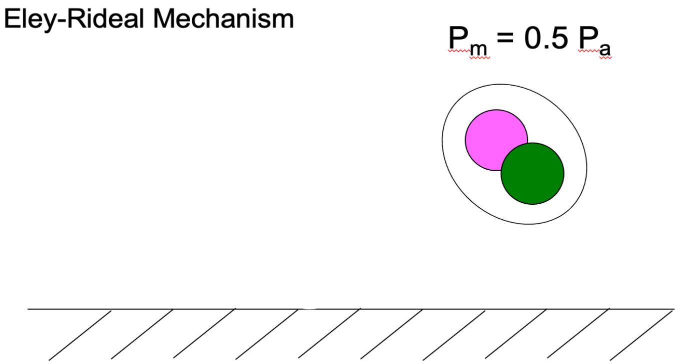

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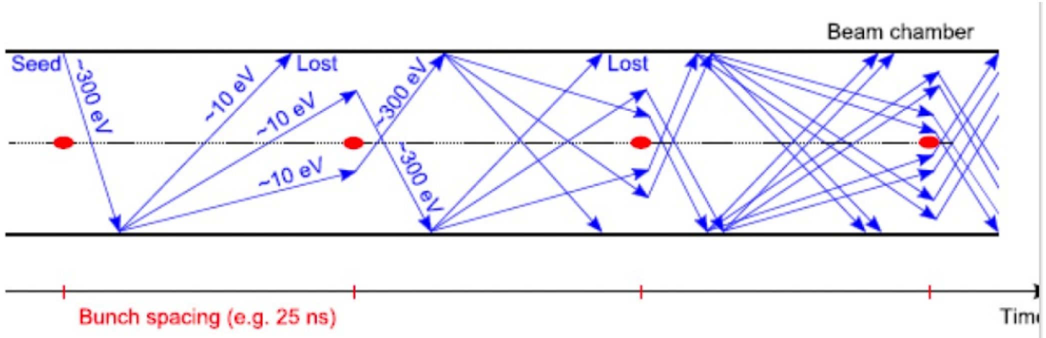

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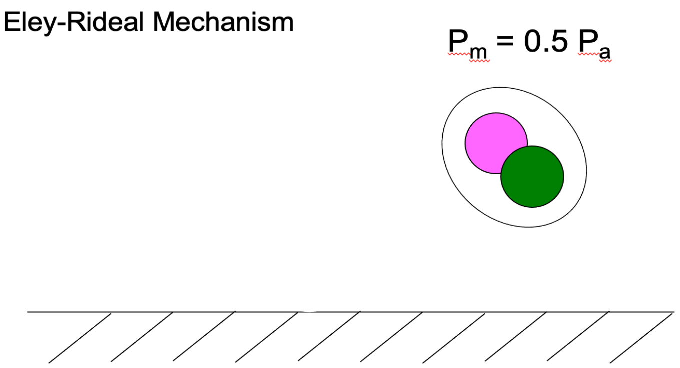

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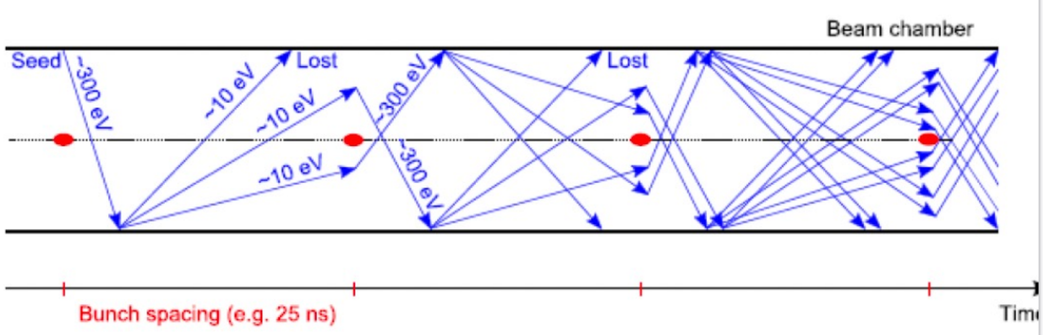

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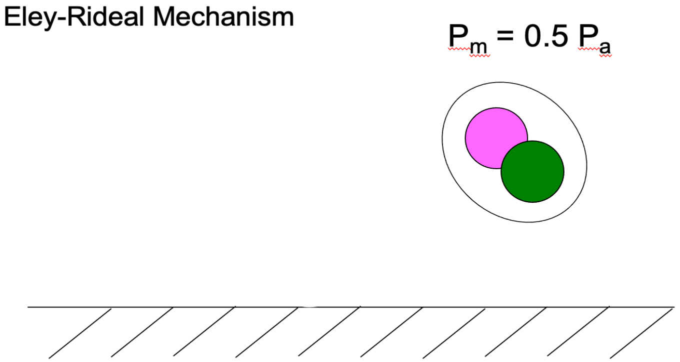
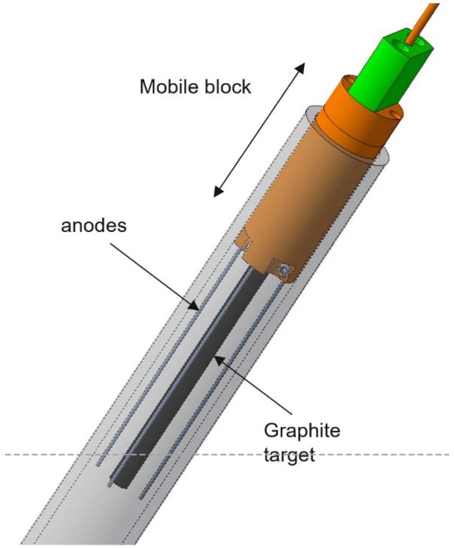
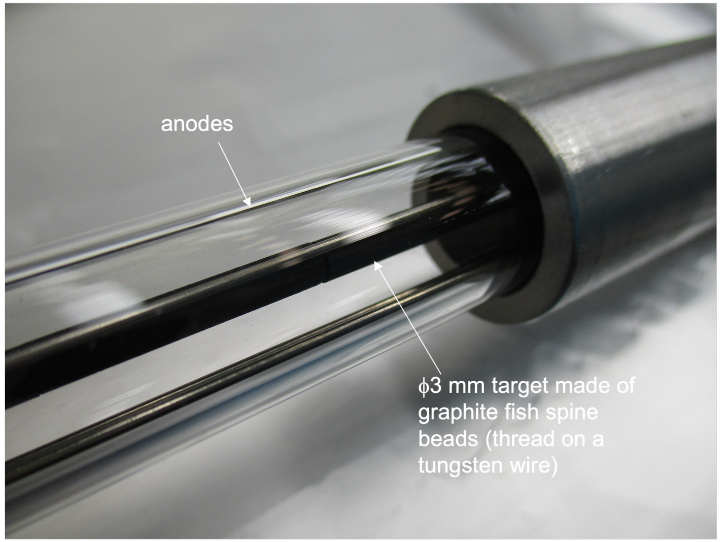


- ✓ Studies are ongoing in order to understand if carbon films with low SEY cope with the required recombination rate of polarized H atoms injected in the storage cell

- ✓ Carbon coated cell prototypes have been produced at CERN and are being analysed at Juelich Forschungszentrum.





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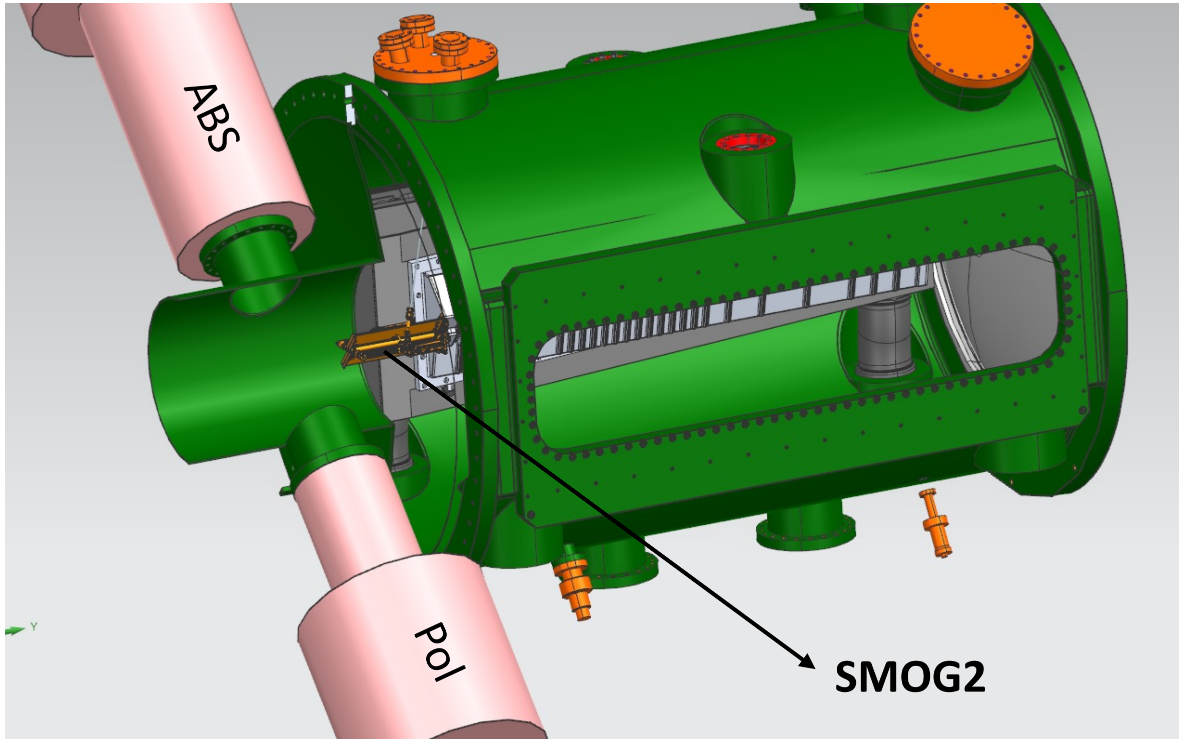
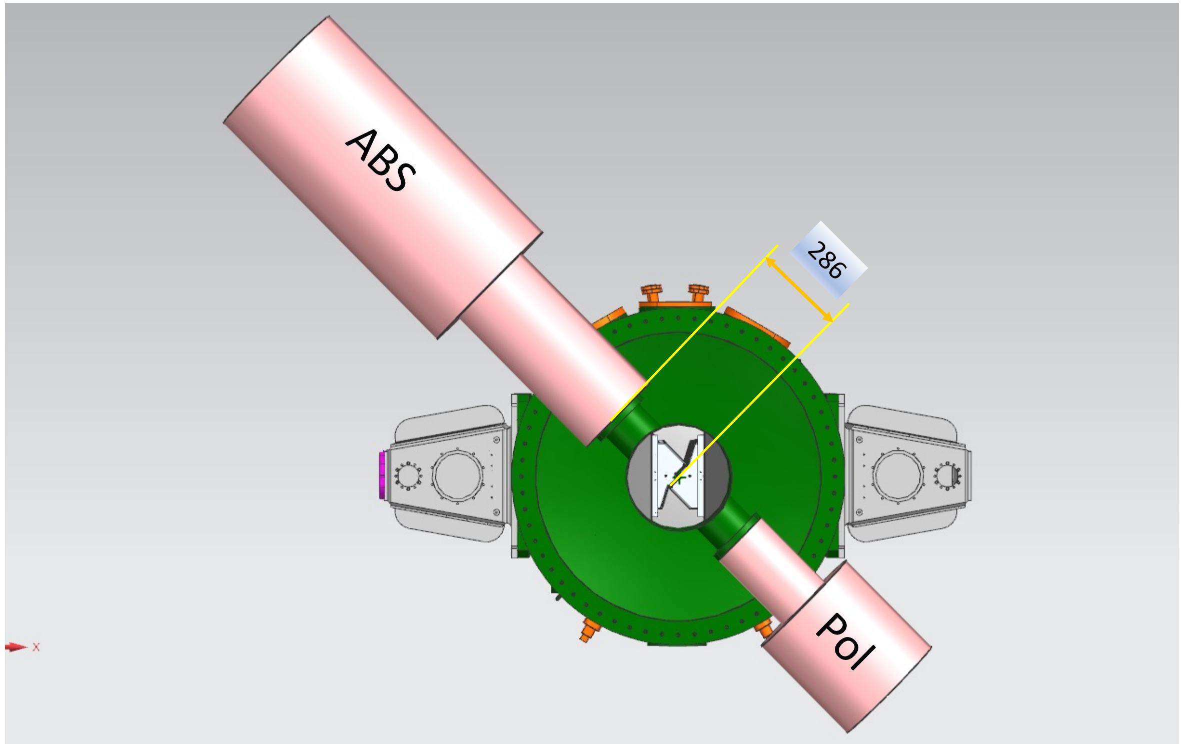
The jet target option

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

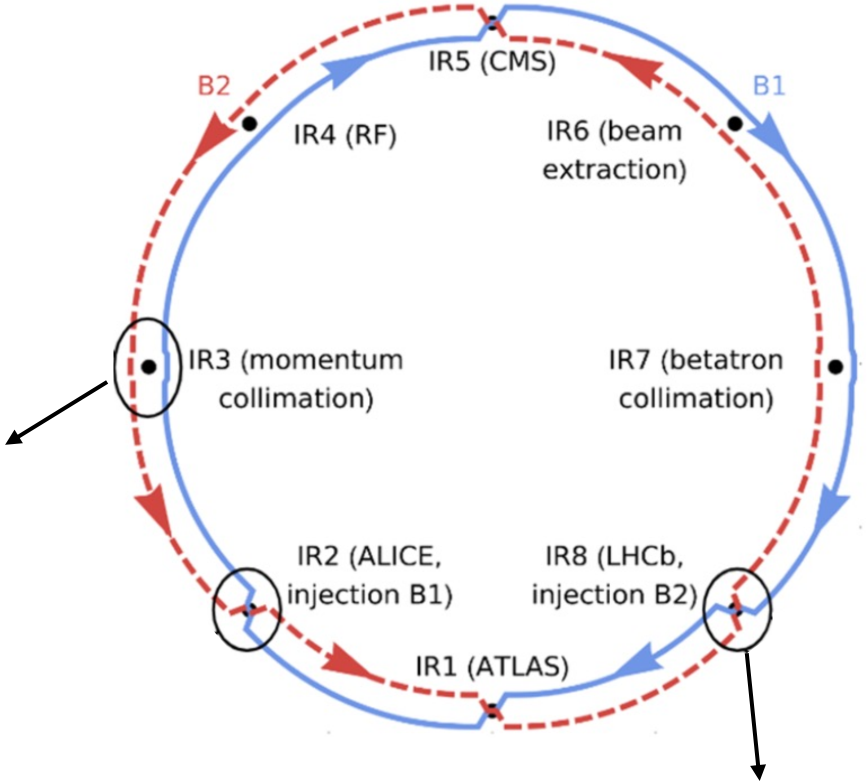
- lower density ($\sim 10^{12}\ \mathrm{atoms}/cm^{2}$) → about a factor of 40 smaller
- higher polarization (up to 90%)
- lower systematics in P measurement (virtually close to 0)
- Compatible with SMOG2 setup





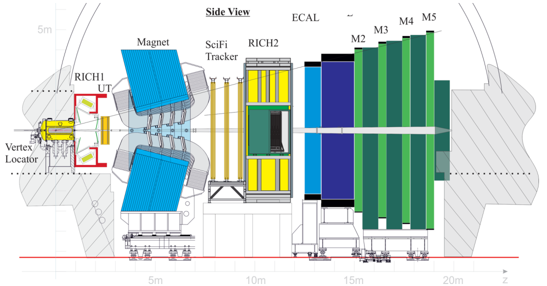
The plan for the upcoming years

The IR3 area is a straight sector of LHC, presently free from instrumentation



LHCspin

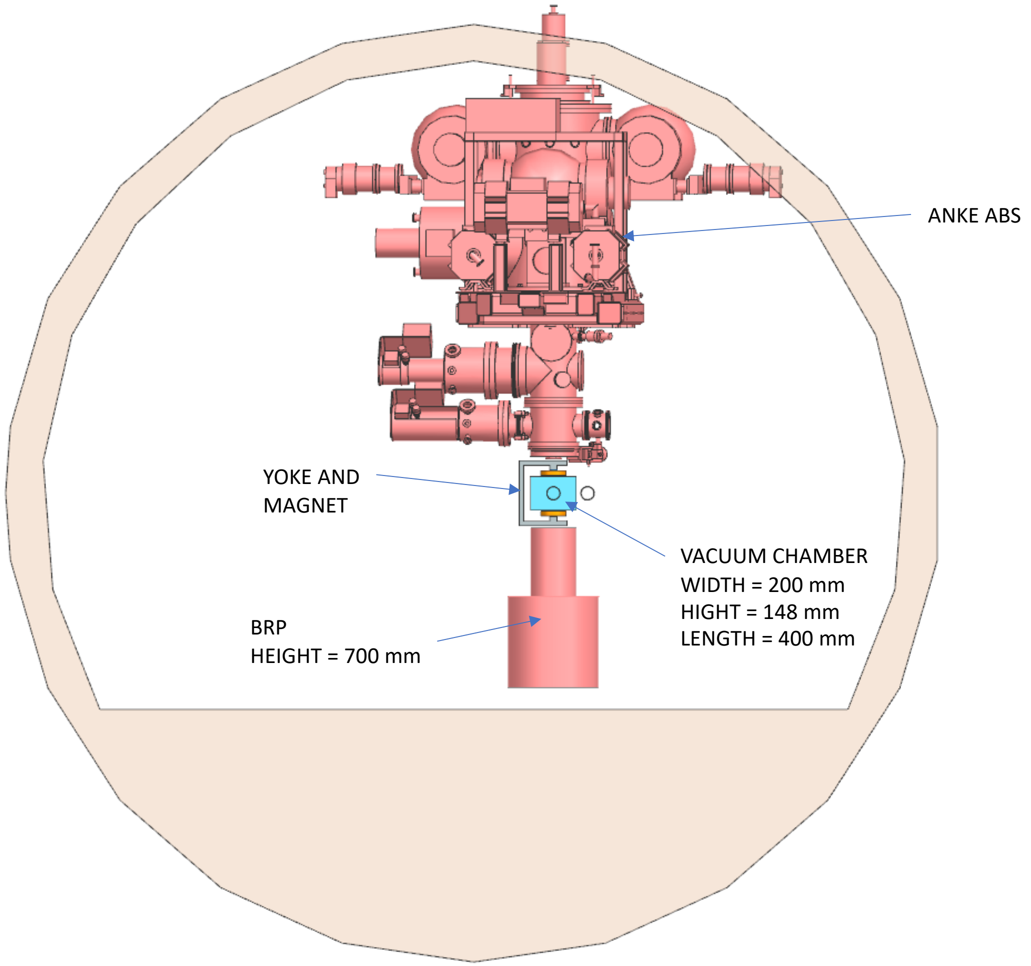
R&D

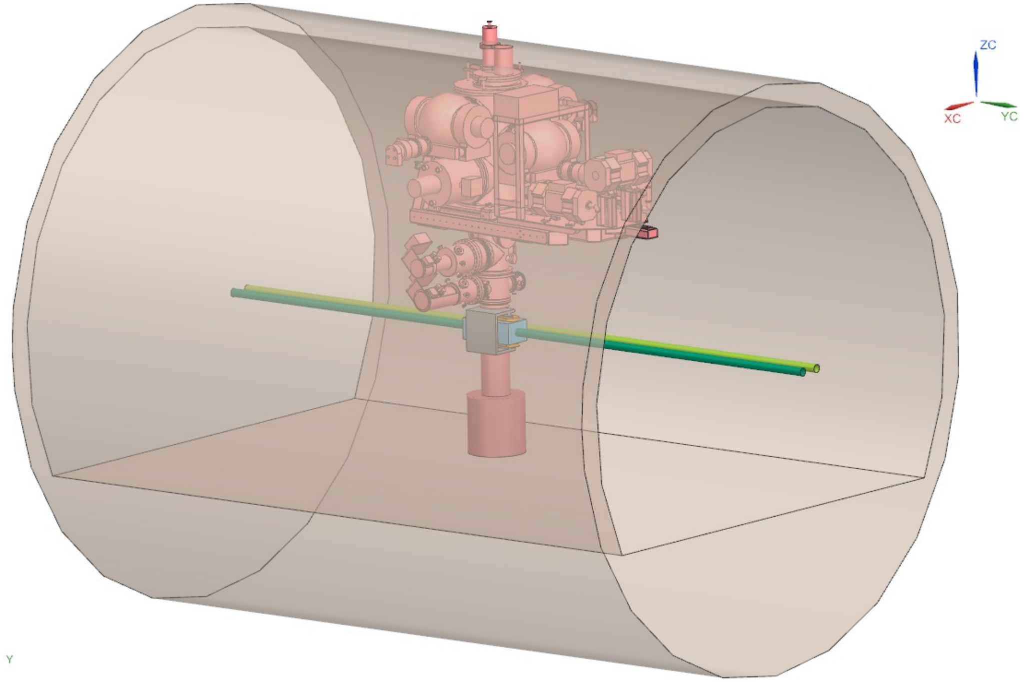


- Explore the possibility to use this site for an in-depth **on-beam R&D for LHCspin**
- Installation of existing setup (ABS and polarimeter from COSY) during LS3
- Possibility to realize **proof-of-principle prototype experiment** during Run4

The plan for the upcoming years

Rendering view of the LHCspin setup installed on the LHC beam pipe at IR3





The existing equipment (ABS & polarimeter) requires some modification to fit into the available space in the tunnel

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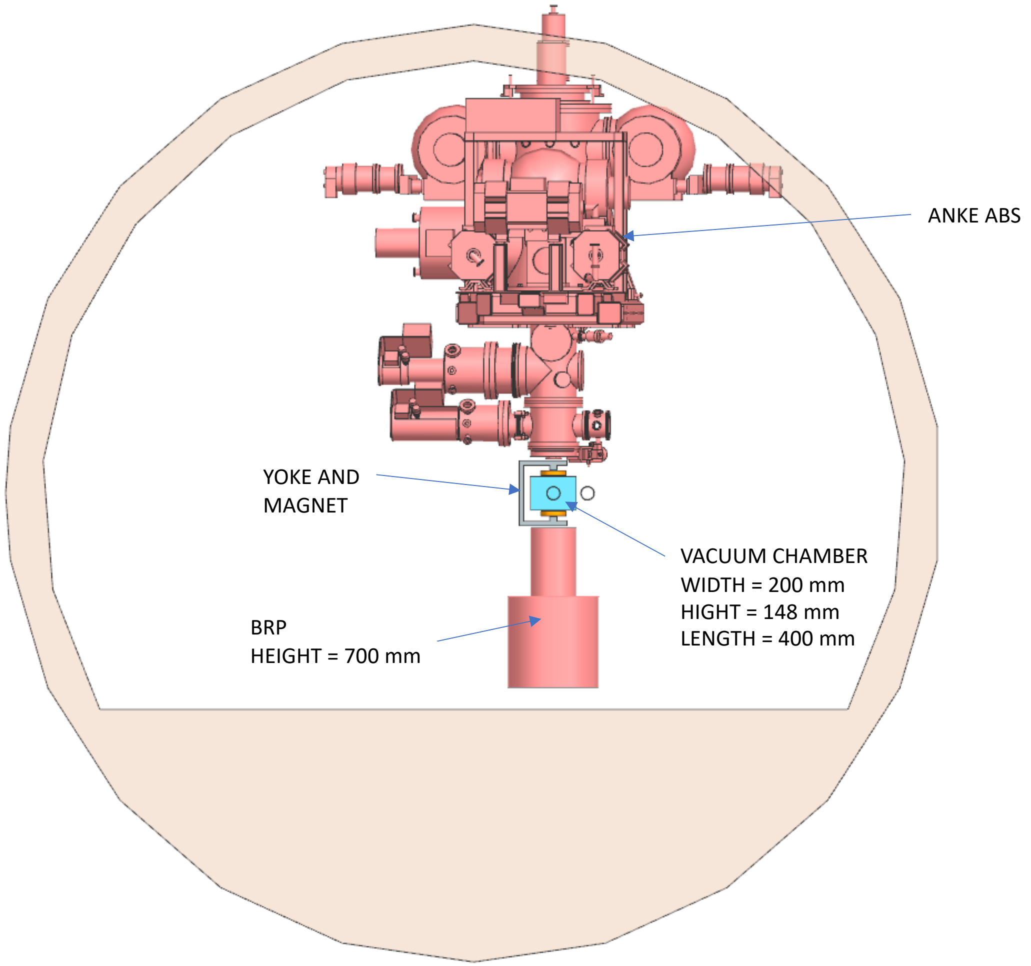

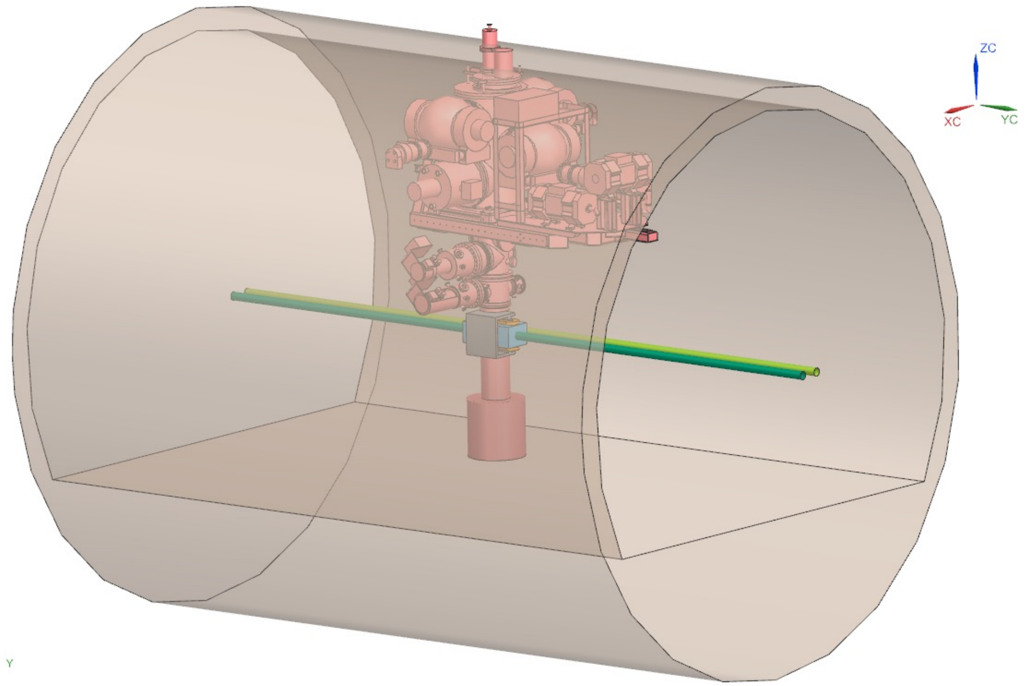

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- In the next years, the IR3 site will be exploited for proof-of-principle test for the charm-baryon dipole-moment experiment with bent crystals.
- Discussions are already ongoing to address possible synergies and interferences.

The plan for the upcoming years

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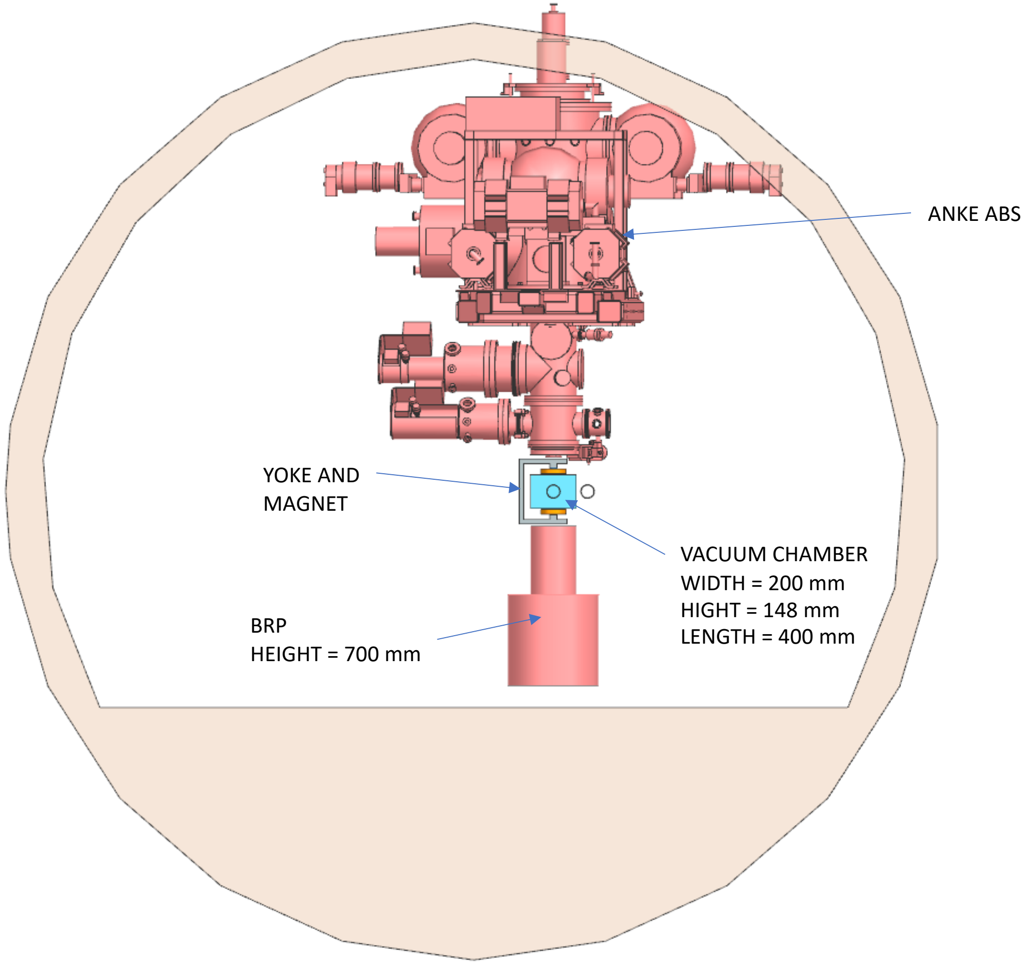

Need to develop a simple detector setup with a few tracking stations and possibly a dipole magnet (one is already available at IR3).

The plan for the upcoming years

Possible measures that we could perform at IR3 include:

1) **study of beam-target interactions**: beam-induced depolarization, impedance, aperture, etc…

2) **absolute calibration of the Breit-Rabi polarimeter** with polarimetry measurements based on Coulomb beam-target scattering (this would require the installation of two small Si (strip/pixel) detectors within the primary vacuum of LHC);

3) **study of recombination/depolarization** at the cell walls (in case we can install a cell);

4) **measurement of basic left-right asymmetries** in inclusive light-hadron production (in case we can use the dipole magnet), as a proof of principle of the future (large-scale) experiment with LHCb. This does not strictly require a target cell and can be performed with a jet target provided by the ABS.

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- Several internal (LHCb) and external groups have shown interest in contributing to this venture
- A kick-off meeting with all the interested actors will be organized in the upcoming months in view of building a proto-collaboration with all the necessary expertise (detectors, DAQ, vacuum, polarimetry, magnets, etc.)

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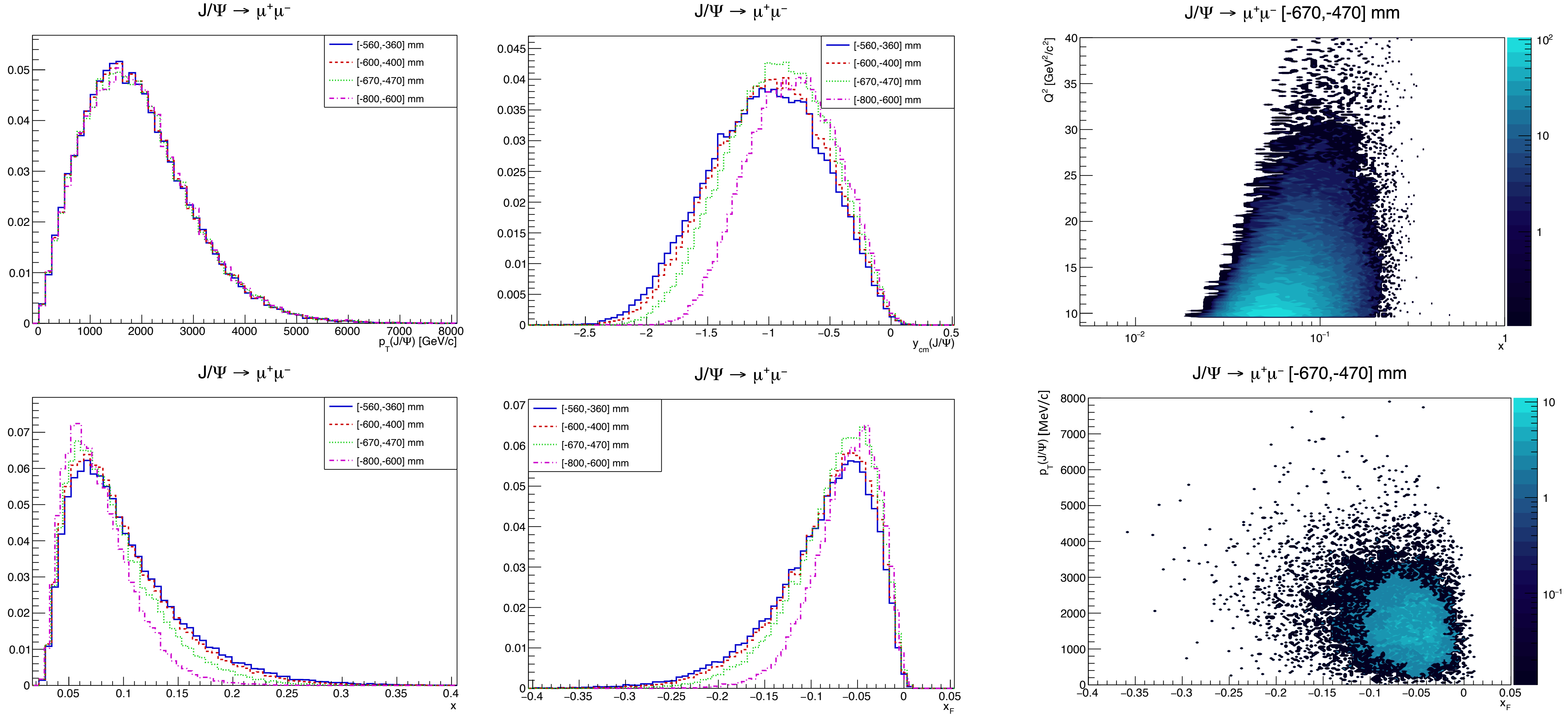
If approved, LHCspin will make LHCb the first experiment simultaneously running in collider and fixed-target mode with unpolarized and polarized targets, opening a whole new range of explorations at the LHC!

Backup

Kinematic coverage


J/Ψ → μ⁺μ⁻

J/Ψ → μ⁺μ⁻

J/Ψ → μ⁺μ⁻ [-670,-470] mm

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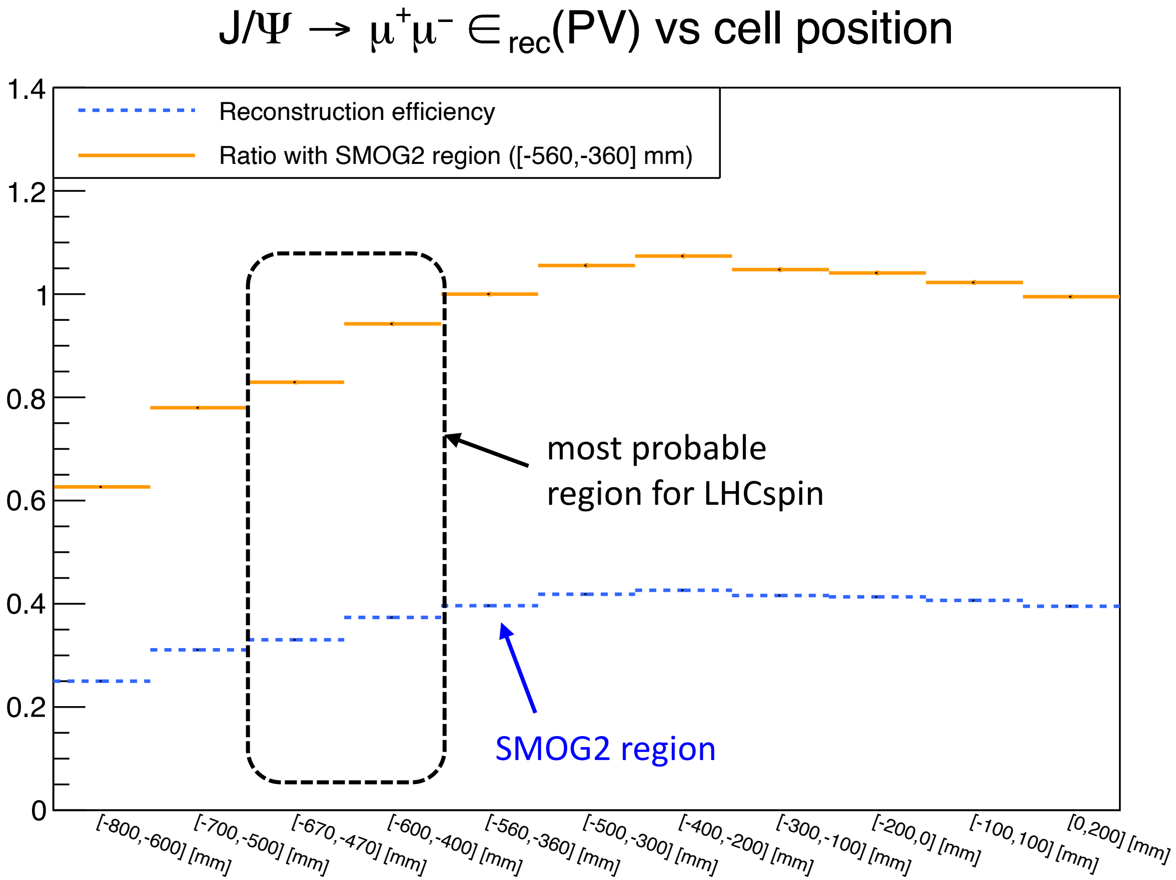
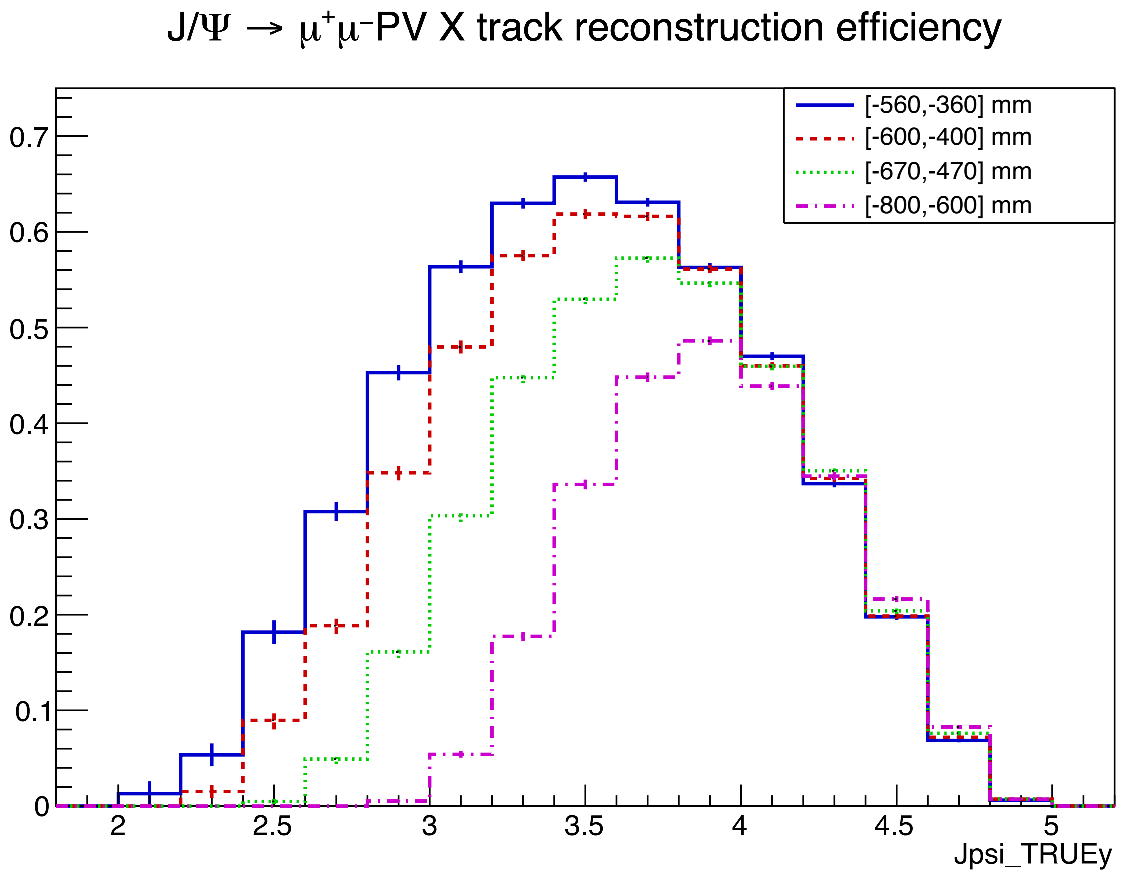
Reconstruction efficiencies



$J/\Psi \rightarrow \mu^+\mu^- \in_{rec}(PV)$ vs cell position

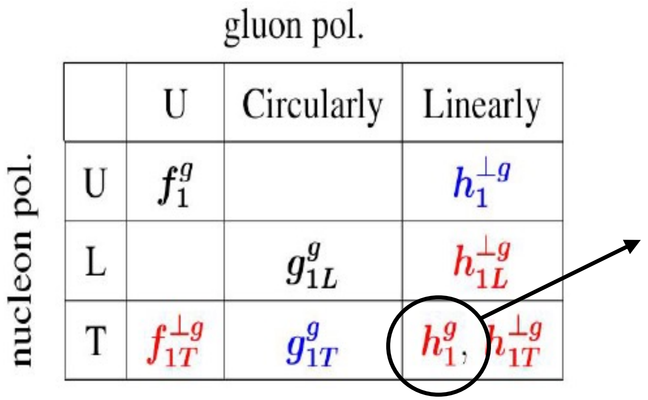
most probable region for LHCspin

SMOG2 region



$J/\Psi \rightarrow \mu^+\mu^-$PV X track reconstruction efficiency

Gluon TMDs



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

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

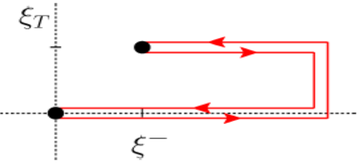
Similar naming/notation of quark TMDs, but there are important differences!

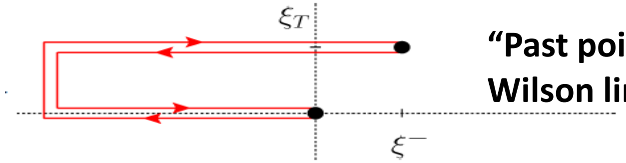
- the **linearity gTMD** (h_1^g) is completely unrelated to the quark transversity (h_1^q), and has no collinear counterpart
- **different naïve-time-reversal properties**

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

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

"Future pointing" Wilson line ("+")



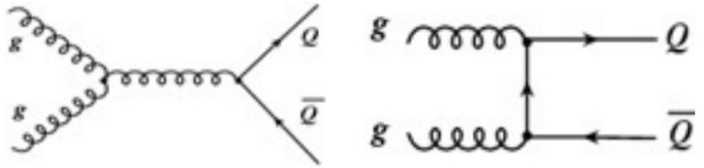


"Past pointing" Wilson line ("−")

- Depending on their combinations, **there are 2 independent versions of each gTMD** that can probed in different processes and can have different magnitude and width and different x and k_T dependencies!
- E.g. there are 2 types of f_1^g and $h_1^{\perp g}$: $[+\,+] = [-\,-]$ Weizsacker-Williams (WW) ; $[+\,-] = [-\,+]$ DiPole (DP)
- 2 indep. GSF: $f_{1T}^{\perp g[+,+]}$ **"f-type"** → antisymm. colour structure ; $f_{1T}^{\perp g[+,-]}$ **"d-type"** → symm. colour structure

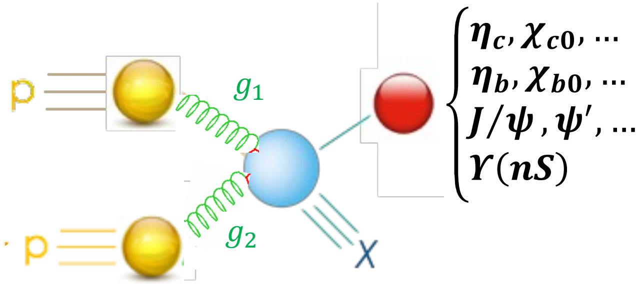
Probing the gluon TMDs

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



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

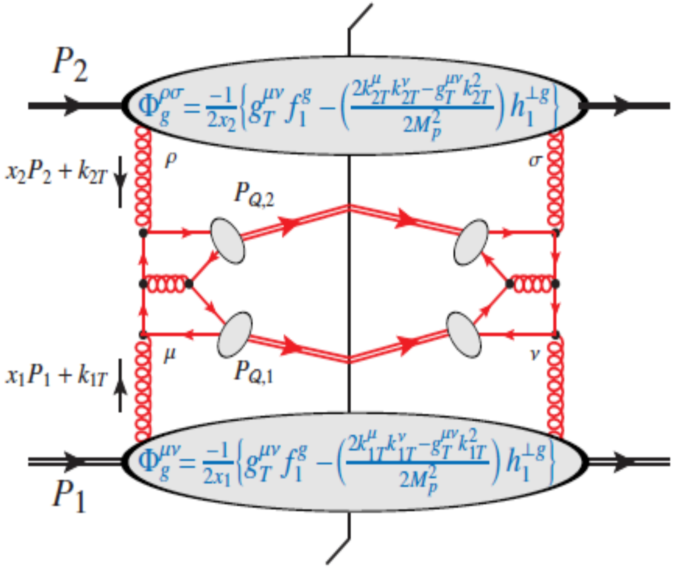
- **Inclusive quarkonia production in (un)polarized pp interaction** ($pp^{(\uparrow)} \rightarrow [Q\bar{Q}]X$) turns out to be an ideal observable to access gTMDs (assuming TMD factorization)



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

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

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



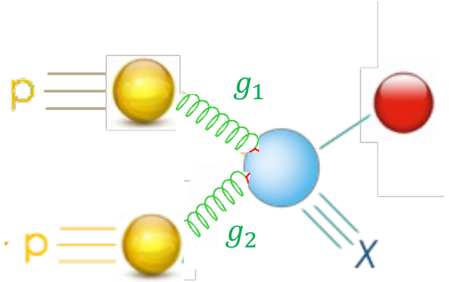
Probing the gluon TMDs: inclusive quarkonia-pair production

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

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

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

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



$$\begin{cases} J/\psi + J/\psi \\ \Upsilon + \Upsilon \\ \ldots \end{cases}$$

gluon pol.

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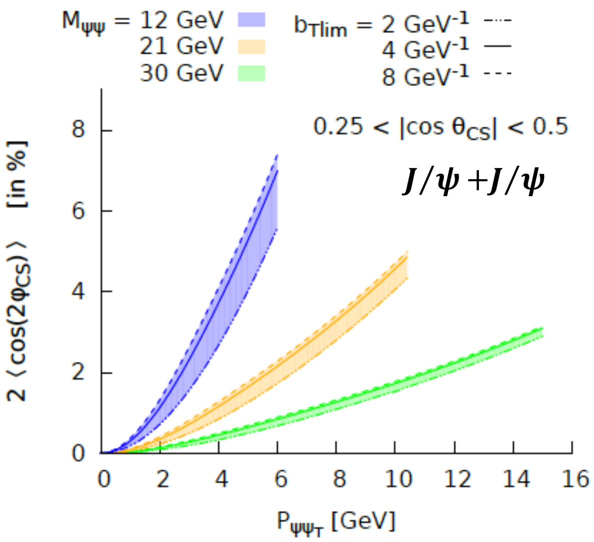
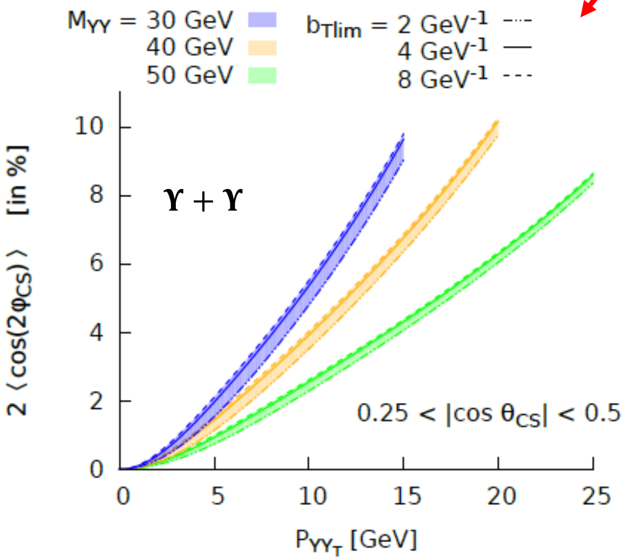
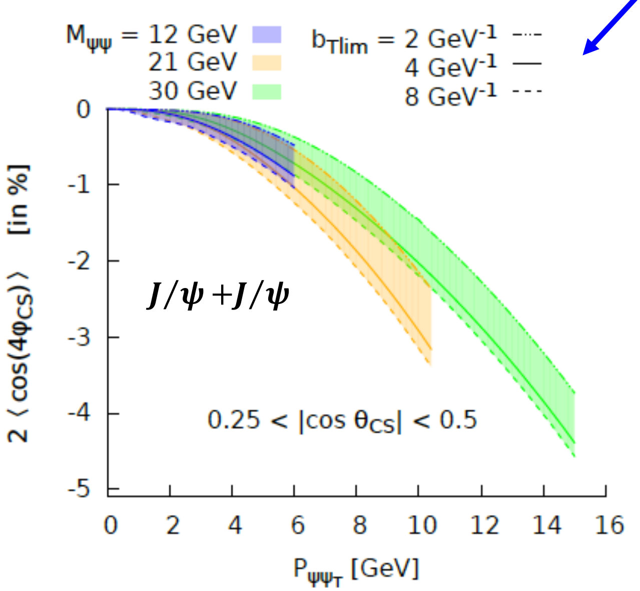
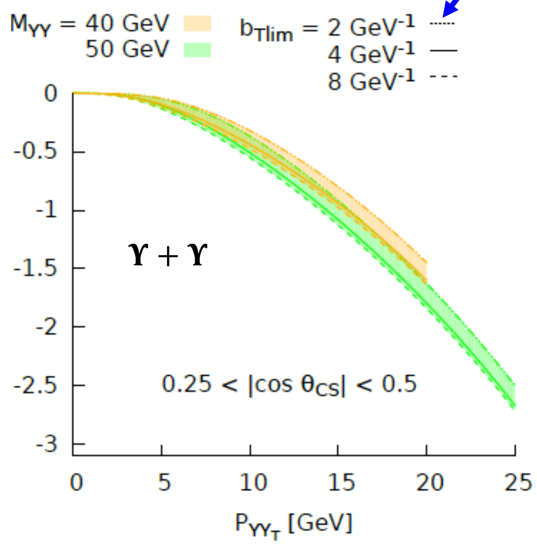
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$







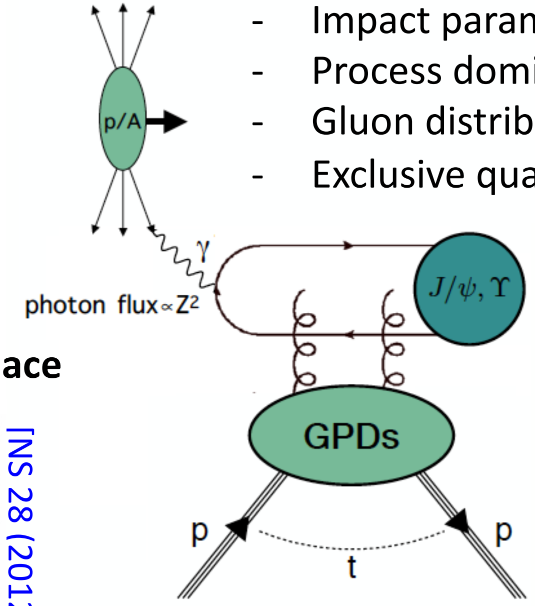


Predictions based on CSM + TMD evolution for $x_1 \sim x_2 \sim 10^{-3}$ at forward rapidity [EPJ C 80, 87 (2020)] ➡ **Azimuthal amplitudes ~ 5%!!**

UPC and gGPDs

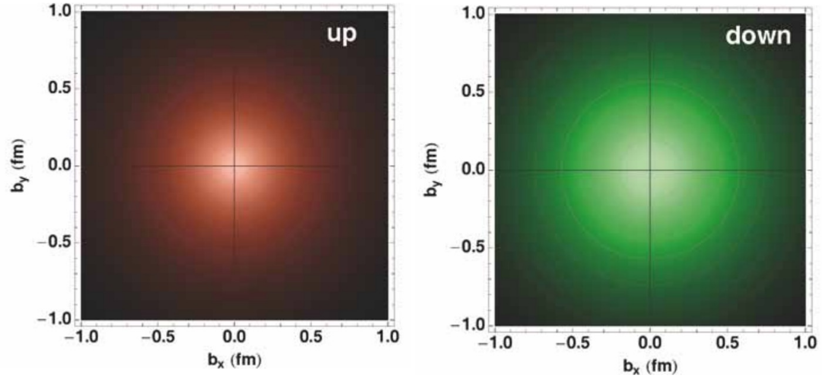
GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

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

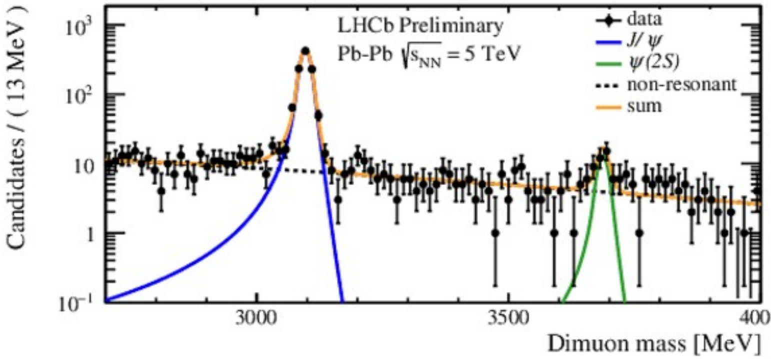


- Impact parameter larger than sum of radii
- Process dominated by EM interaction
- Gluon distributions probed by pomeron exchange
- Exclusive quarkonia prod. sensitive to gluon GPDs [PRD 85 (2012), 051502]

3D maps of parton densities in coordinate space

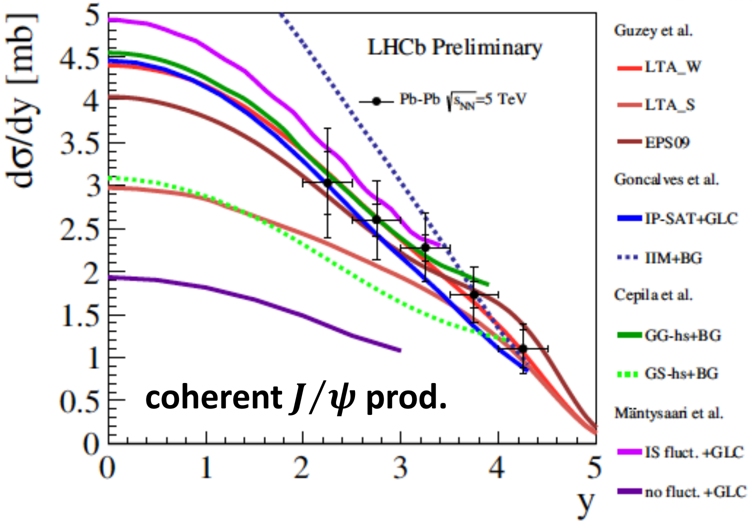


[NS 28 (2012), 1]



[NPA 982 (2019) 247]

First results from LHCb in PbPb UPC



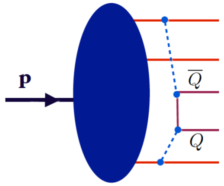
coherent J/ψ prod.

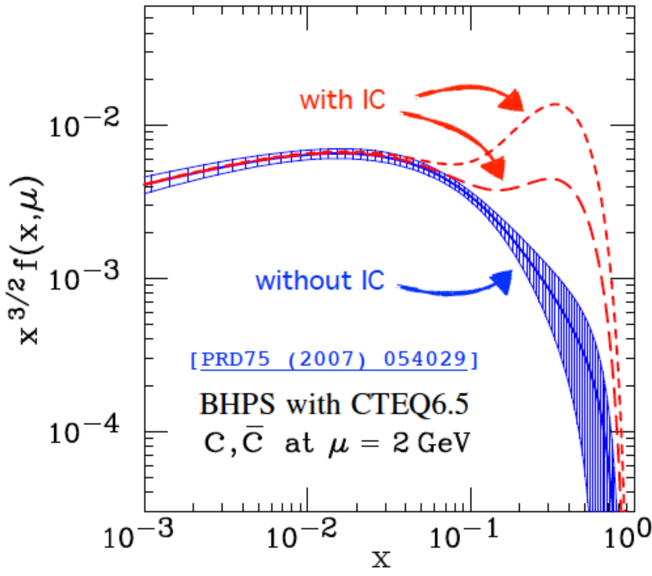
LHCspin could allow to access the GPD E^g (a key ingredient of the Ji sum rule)

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

More physics reach with unpolarized FT reactions

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



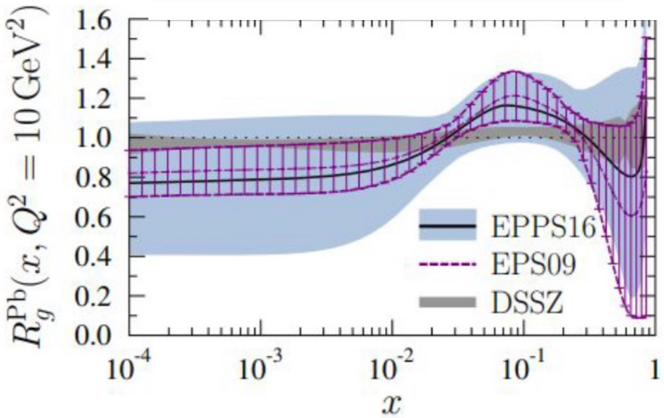


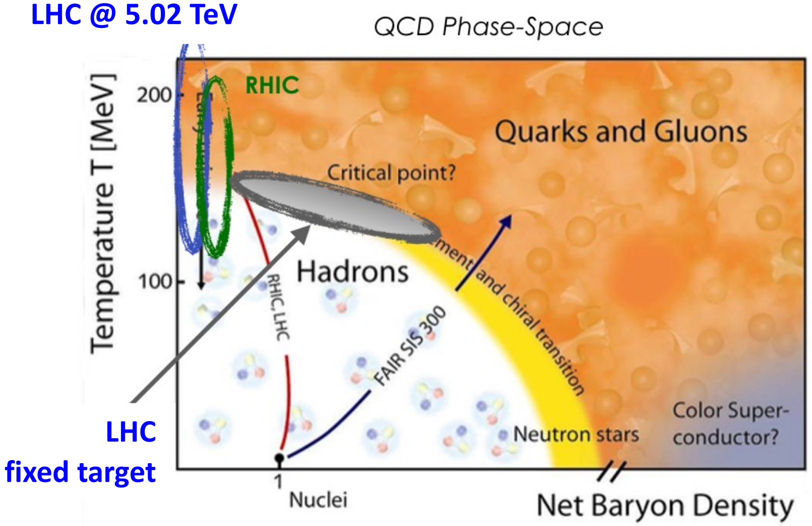
[PRD 75 (2007) 054029]

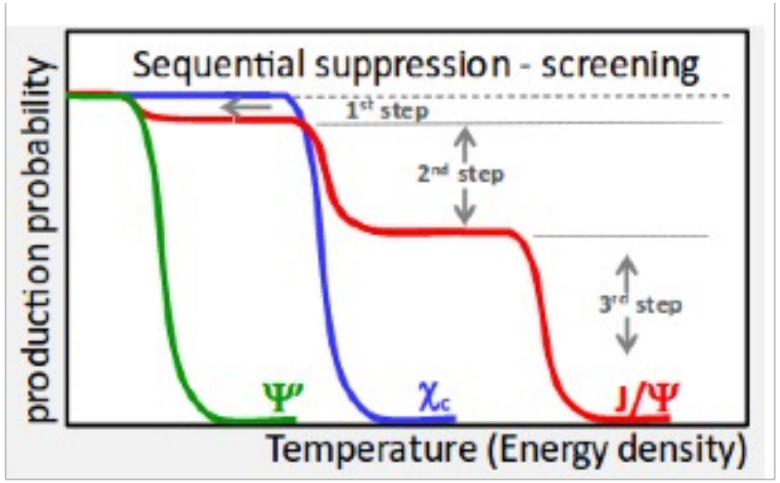
- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x**)
  - studies of parton energy-loss and absorption phenomena in the cold medium
  - reactions of interest for cosmic-ray physics and DM searches

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

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







$c\bar{c}$ states: $J/\psi, \chi_c, \psi'$,...
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 $J/\psi \rightarrow \mu^+\mu^-$ 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):

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

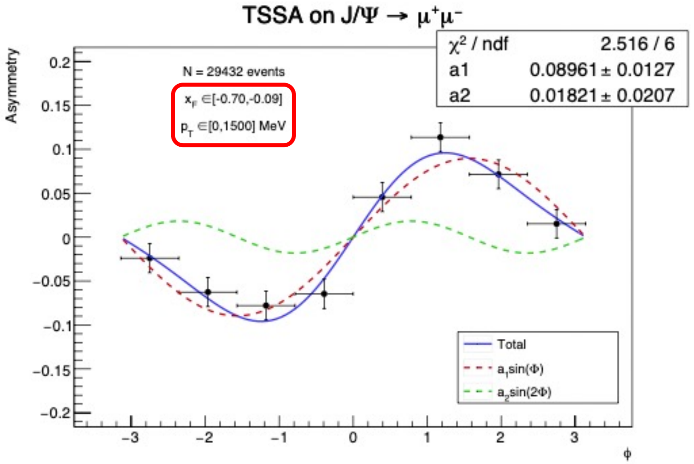
- Using these pseudo-data the TSSA is computed in the usual way:

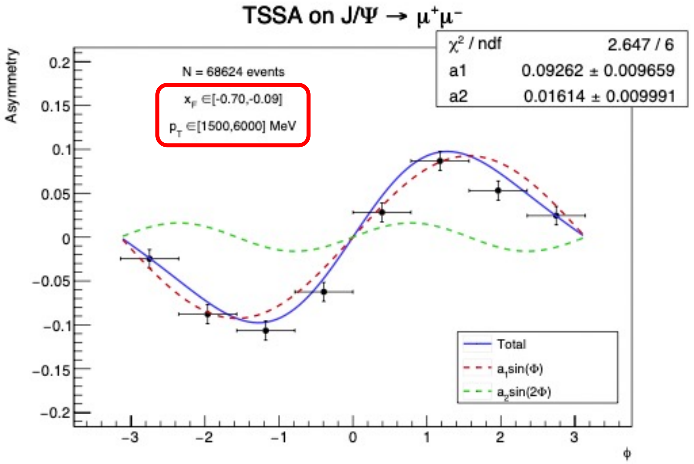
$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

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

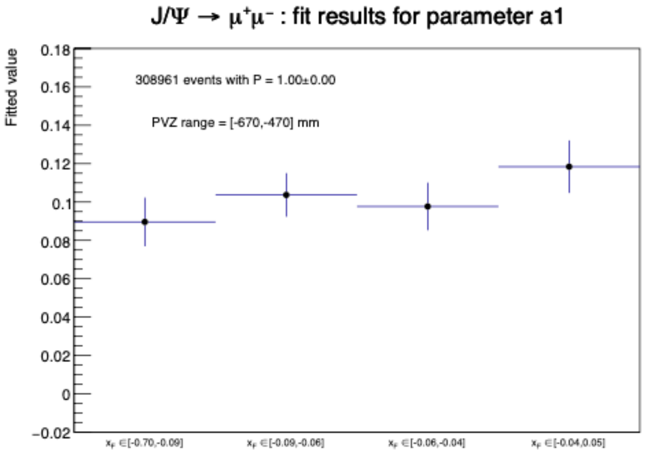
A preliminary analysis tool for pseudo-data

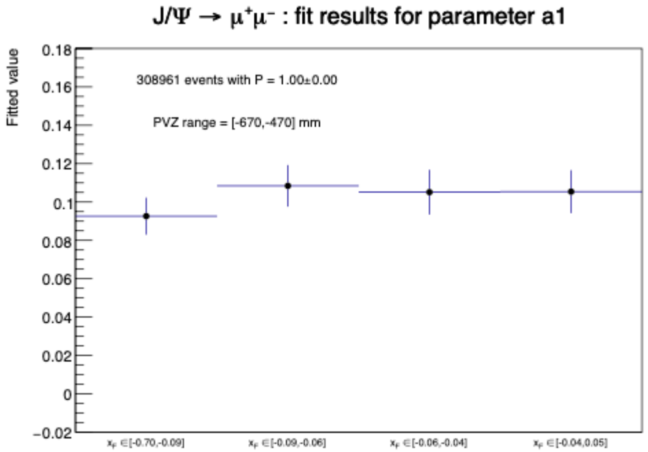
- The data points are binned in x_F and p_T (2D binning), represented vs. ϕ and fitted with $f = a_1 \sin\phi + a_2 \sin 2\phi$ where the free parameters a_1 and a_2 represent the amplitude of the corresponding azimuthal modulation





- 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

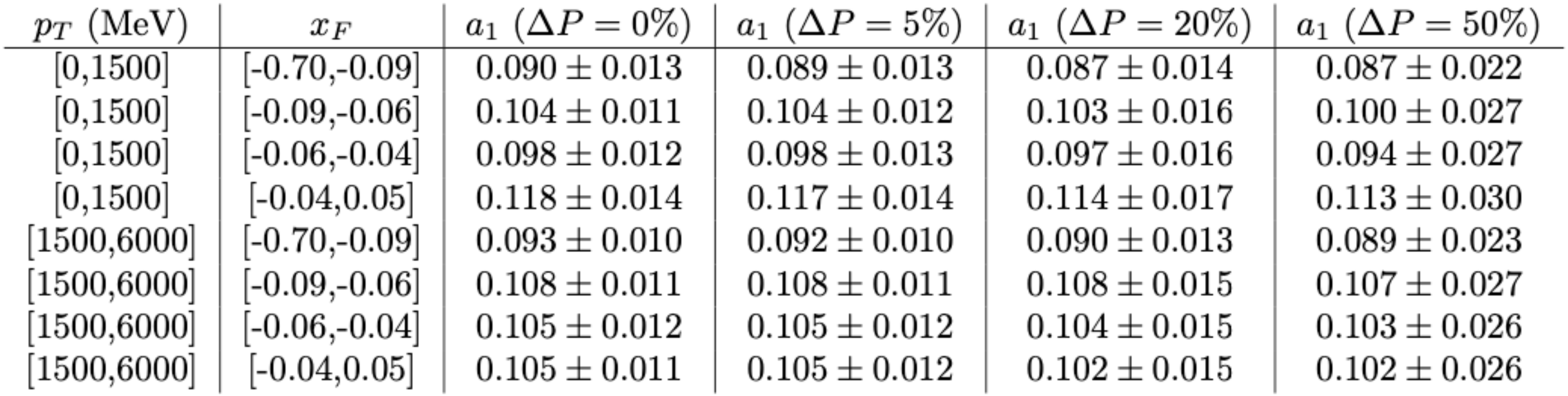




- The amplitudes a_1 are the reported vs. x_F in bins of p_T (and vice-versa)
- A mild kinematic dependence is observed consistent with the model

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)**