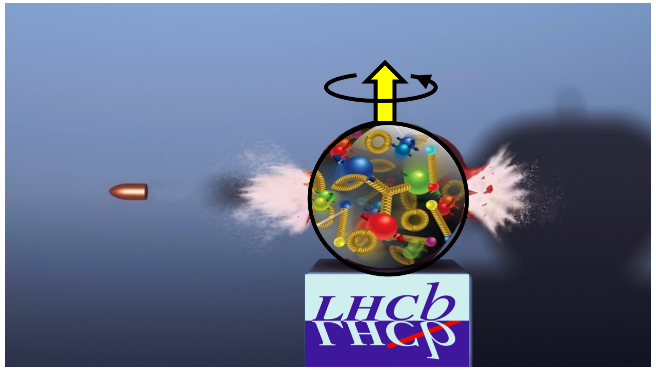
Fixed target experiments at LHC - strong2020 workshop

The LHCspin project



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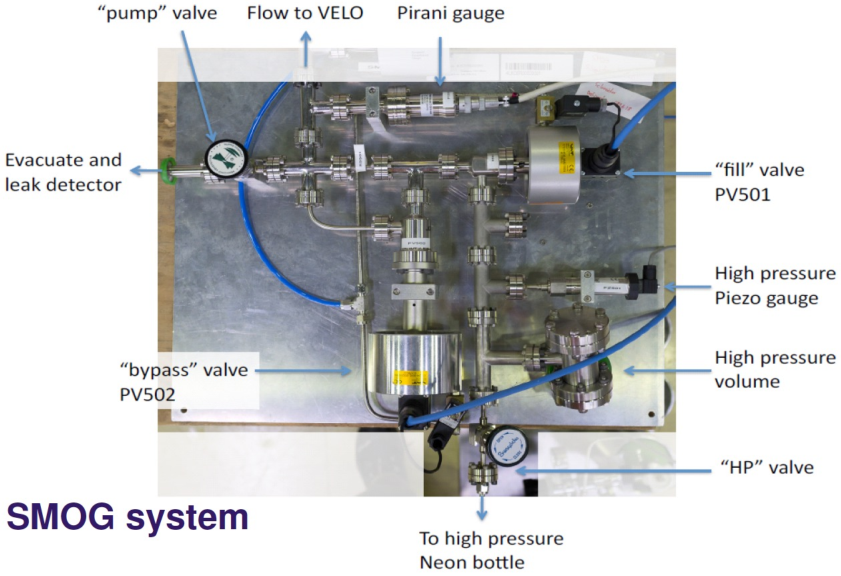
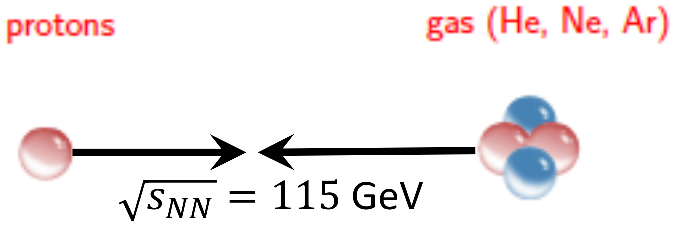
D.Reggiani (PSI-Zurich), M. Statera A.Vasilyev (Gatchina),

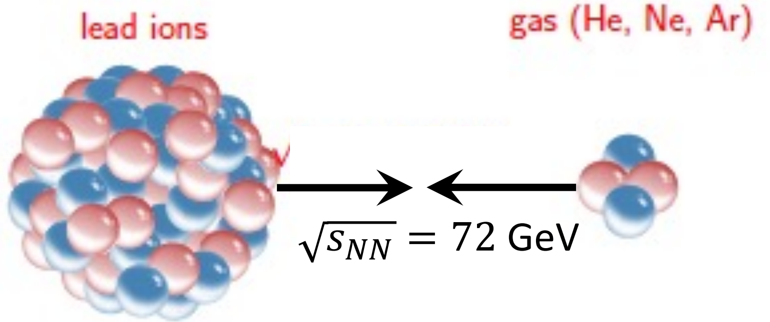
Fixed-Target collisions at LHCb



SMOG system

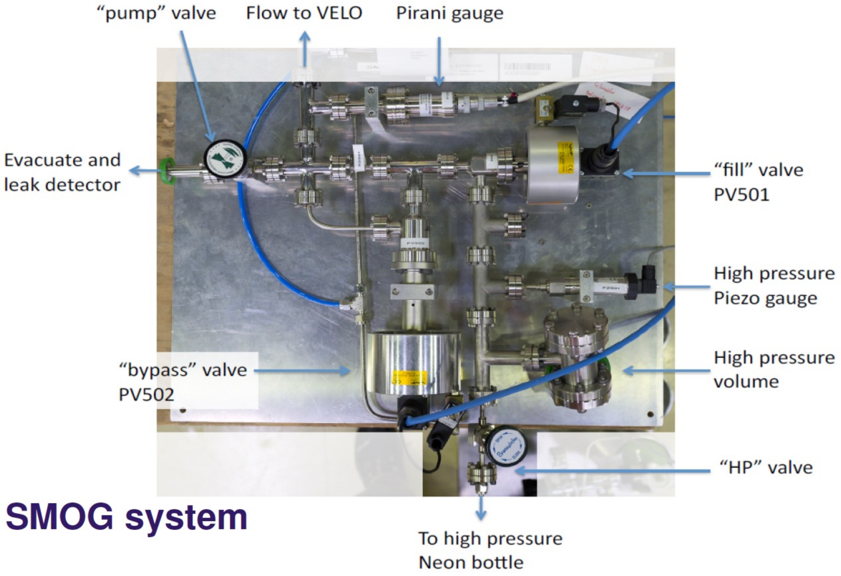


$\sqrt{s_{NN}} = 115$ GeV



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

Fixed-Target collisions at LHCb



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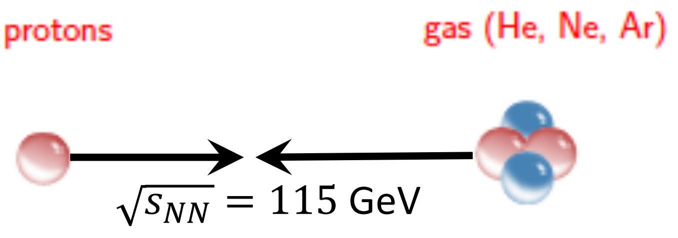
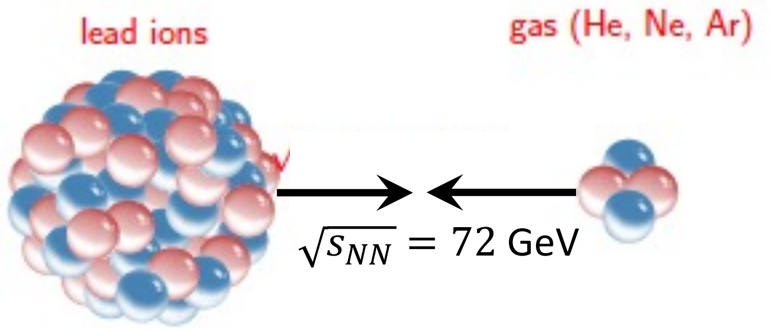
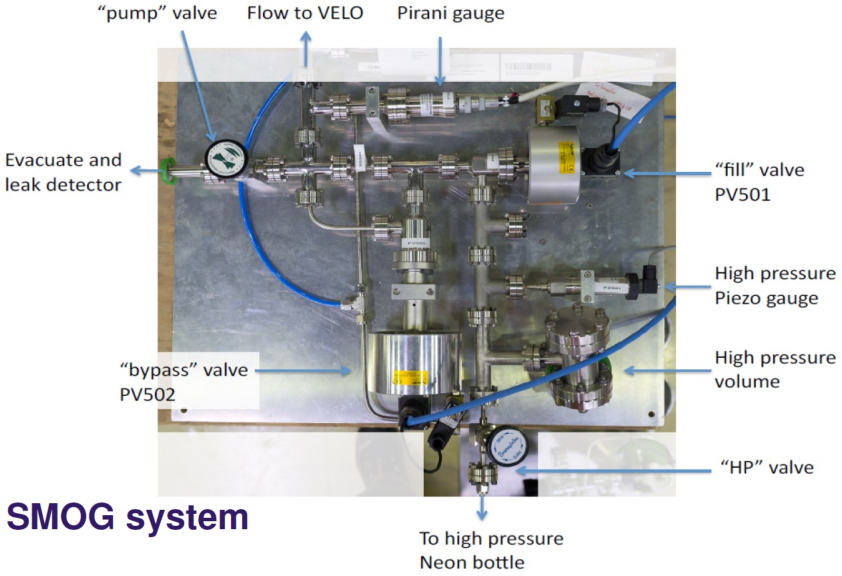




Already lots of interesting analyses with SMOG:

- ✓ Charm production in pHe and pAr
- ✓ **Charm production in pNe and PbNe** (→ **Emilie, Frederic**)
- ✓ **Prompt and detached antiproton production in pHe** (→ **Saverio**)
- ✓ Λ_c polarization in pNe
- ✓ Strangeness enhancement in PbNe vs pNe
- ✓ Cold Nuclear Matter effects in light-hadrons production in p-gas
- ✓ …

Fixed-Target collisions at LHCb



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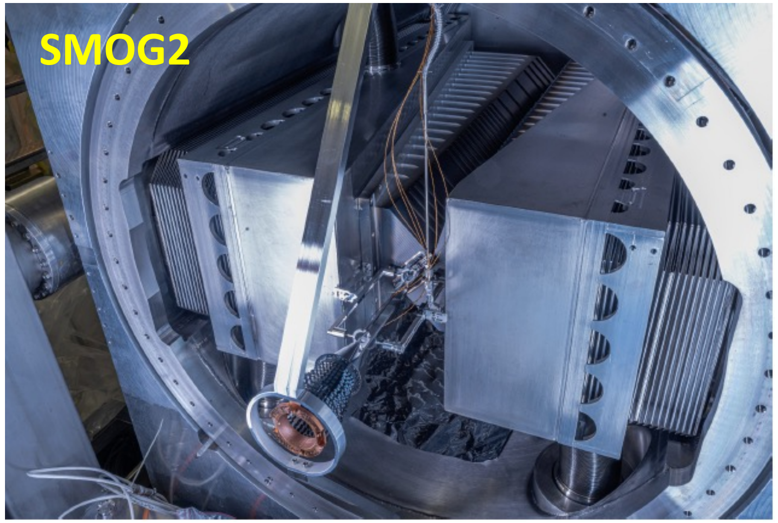

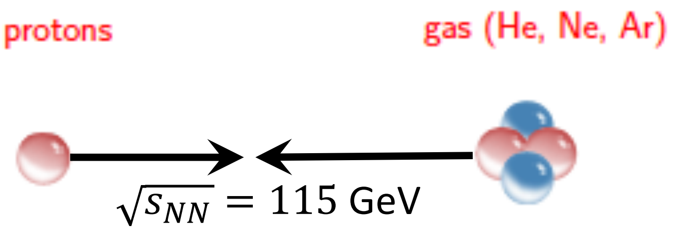

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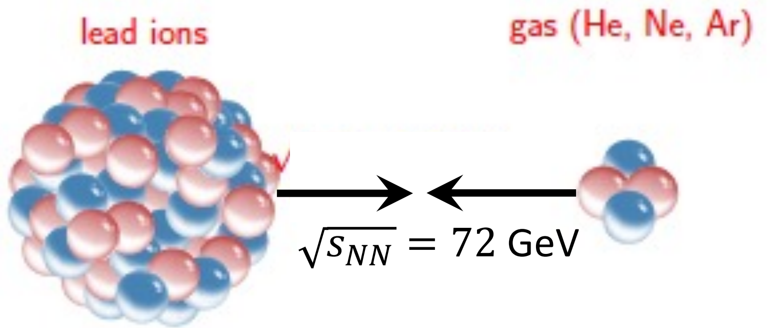

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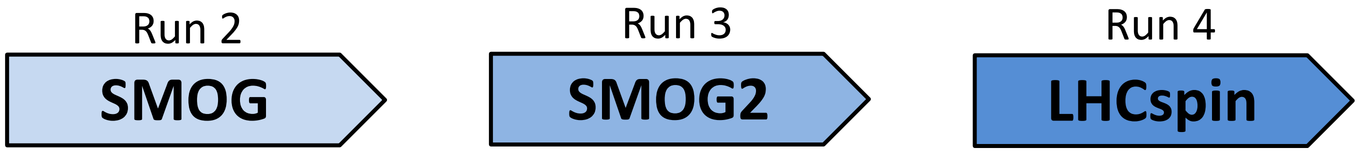
…and many more to come with SMOG2! (→ **Edoardo**)

The LHCspin project

The SMOG2 realization sets the basis for the development of a future **polarized gas target for LHCb**

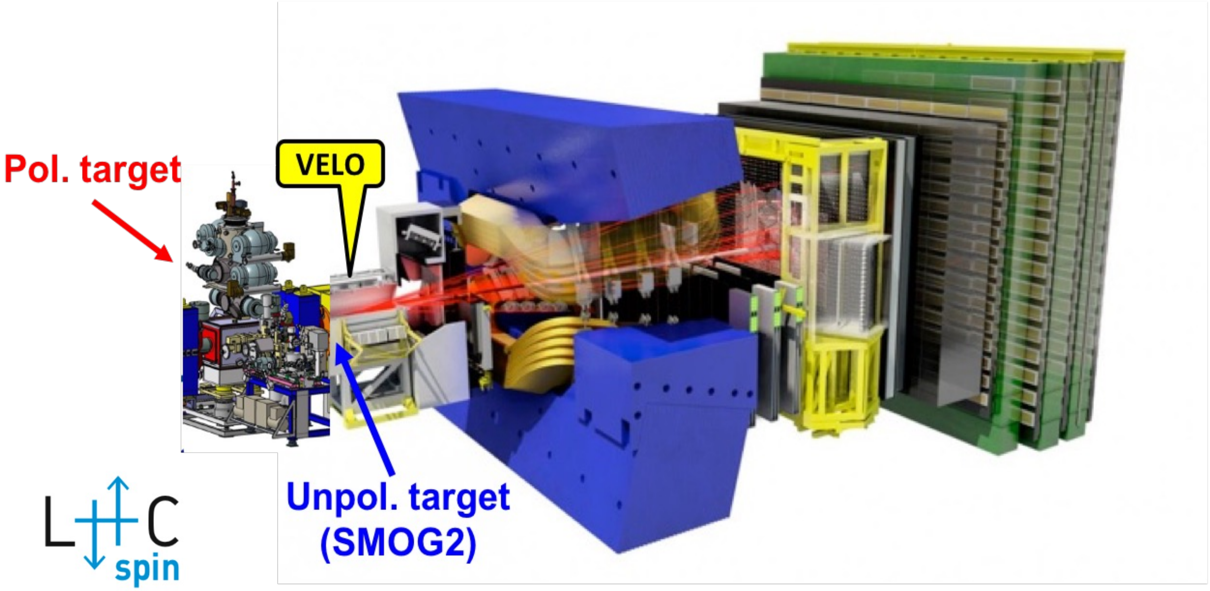


Run 2 — **SMOG**

Run 3 — **SMOG2**

Run 4 — **LHCspin**

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



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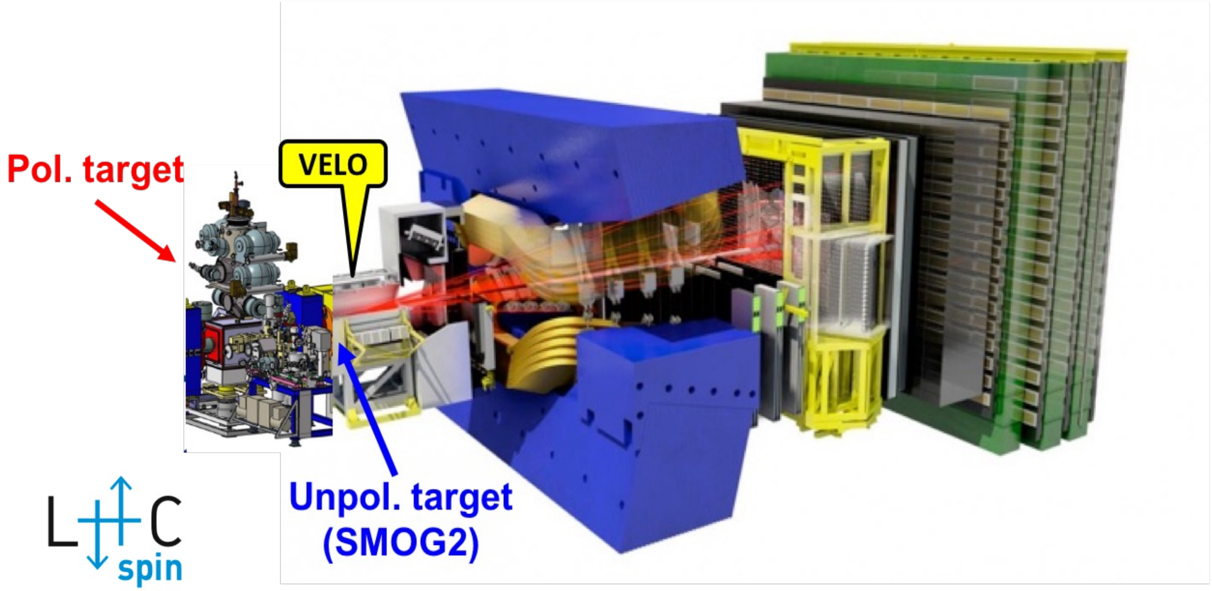
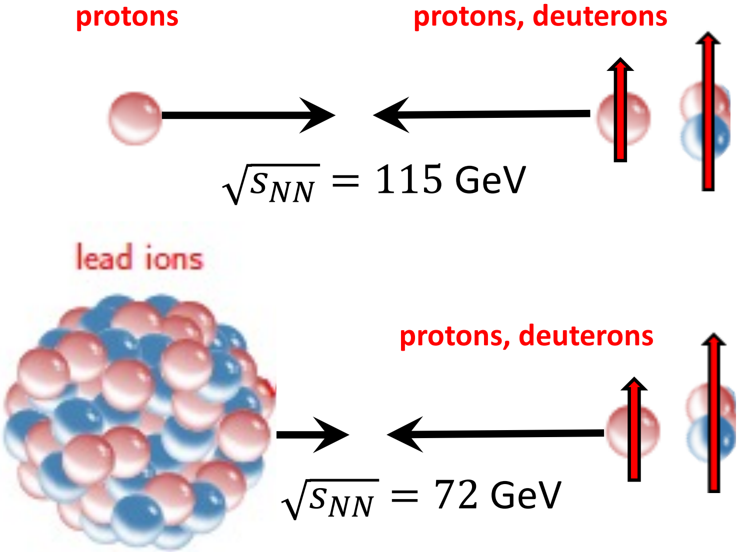
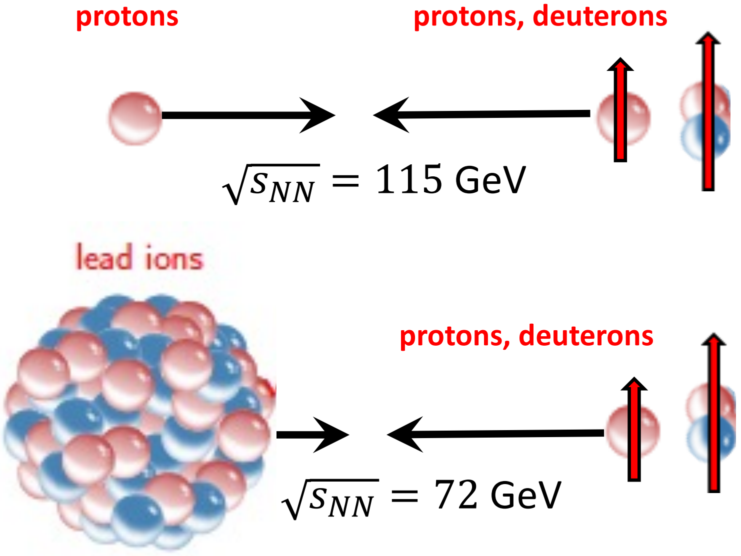




The LHCspin project

- ✓ **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 apparatus**
- ✓ **marginal impact on LHC beam lifetime and LHCb mainstream physics program and performances**
- ✓ **can run in parallel with collider mode** (interaction regions well displaced)
- ✓ **can benefit from both protons and heavy-ion beams**
- ✓ **allows also injection of unpolarized gases** $(H_2, D_2, He, N_2, O_2, Ne, Ar, \dots)$
- ✓ **broad physics program** (next slides)



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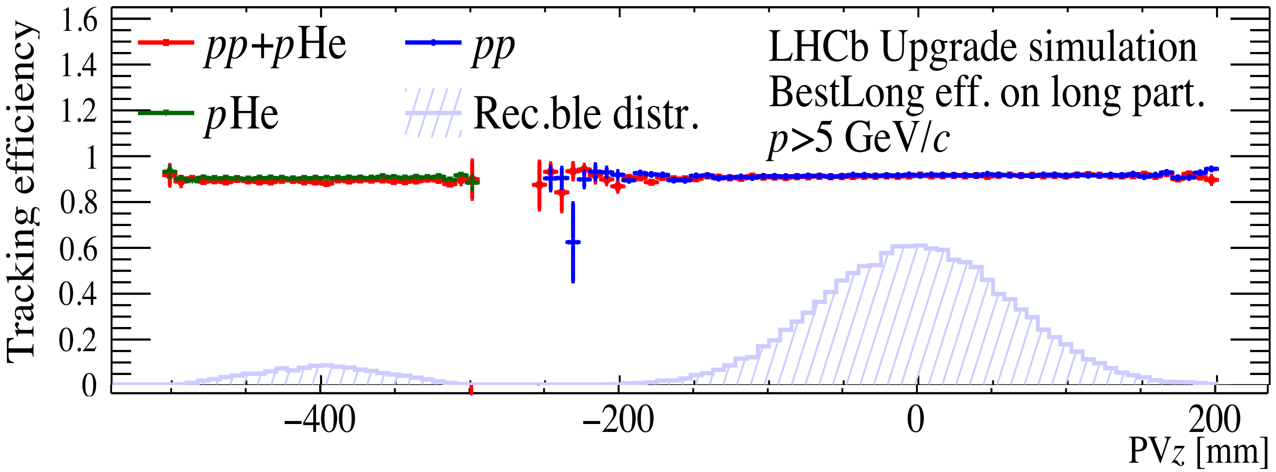
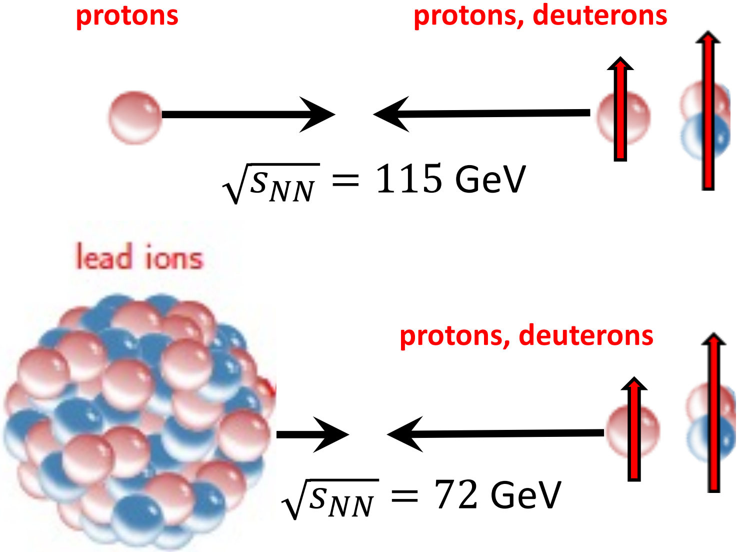




protons

protons, deuterons

$\sqrt{s_{NN}} = 115$ GeV

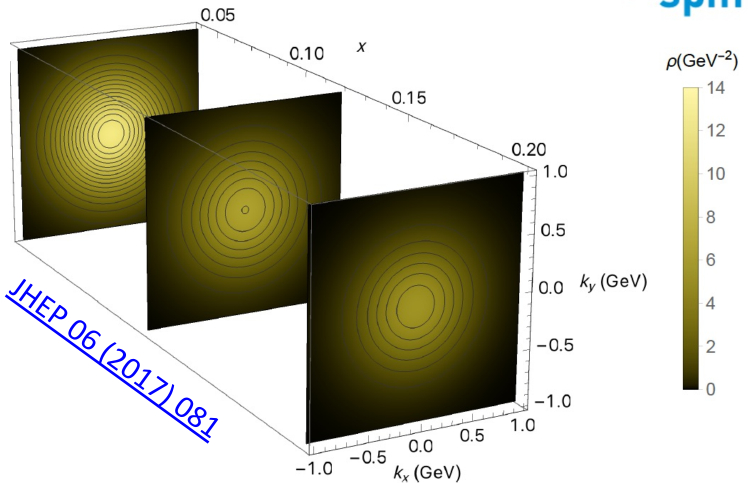
lead ions

protons, deuterons

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

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



JHEP 06 (2017) 081

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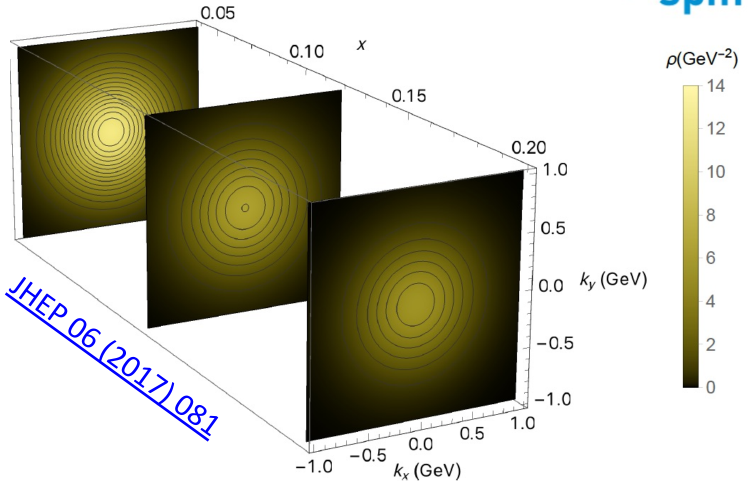

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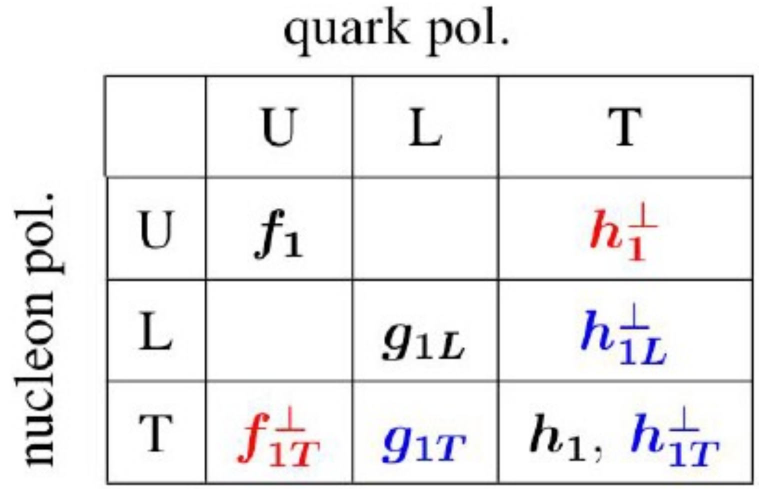


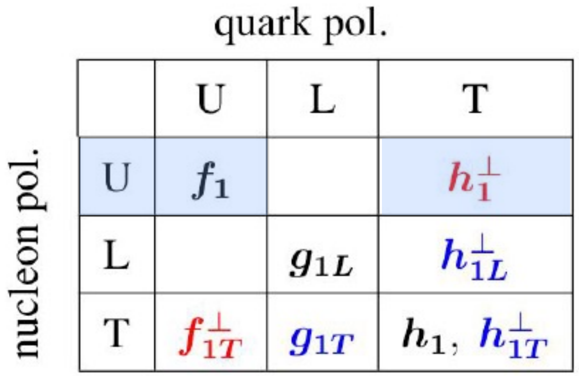
quark pol.

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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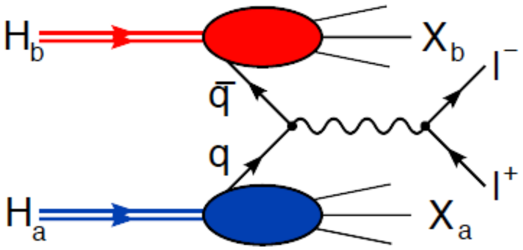
Unpolarized Drell-Yan



- Theoretically cleanest hard h-h scattering process
- LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$
- **dominant**: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
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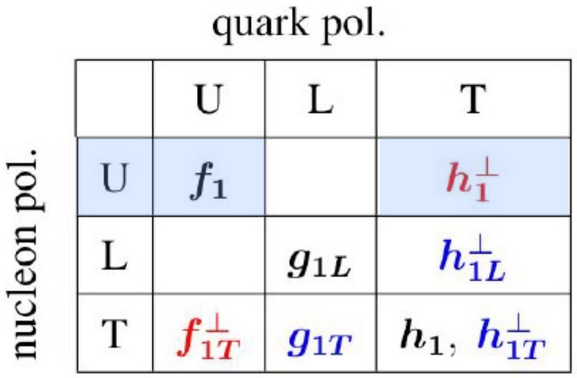

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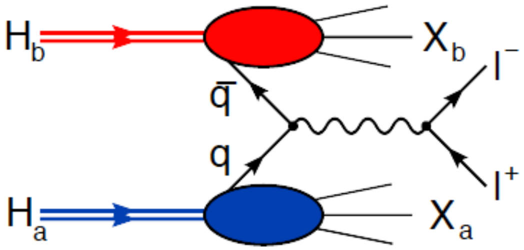

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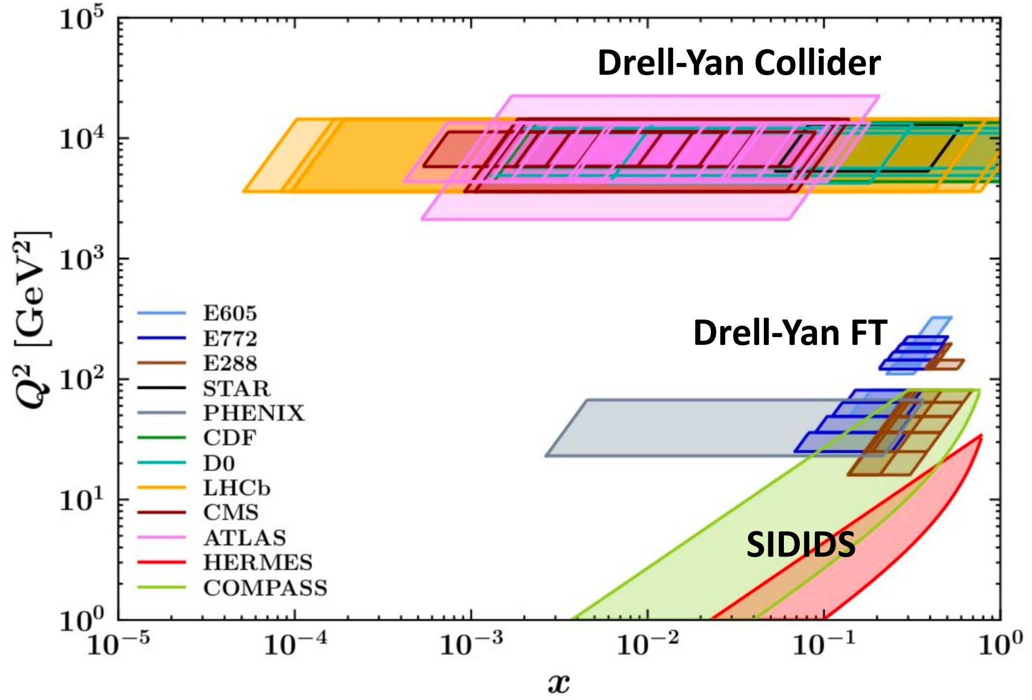
From Andrea's talk



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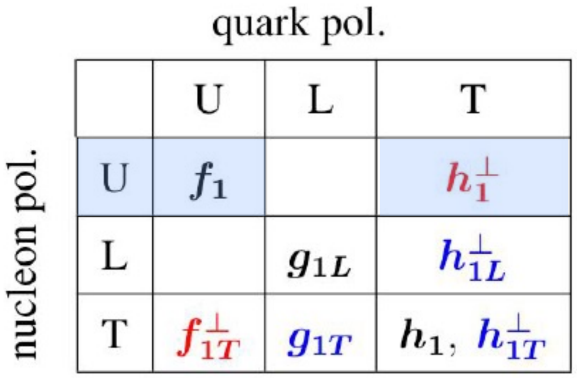

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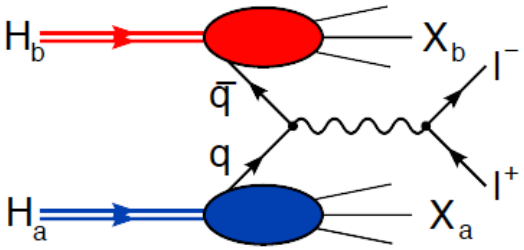

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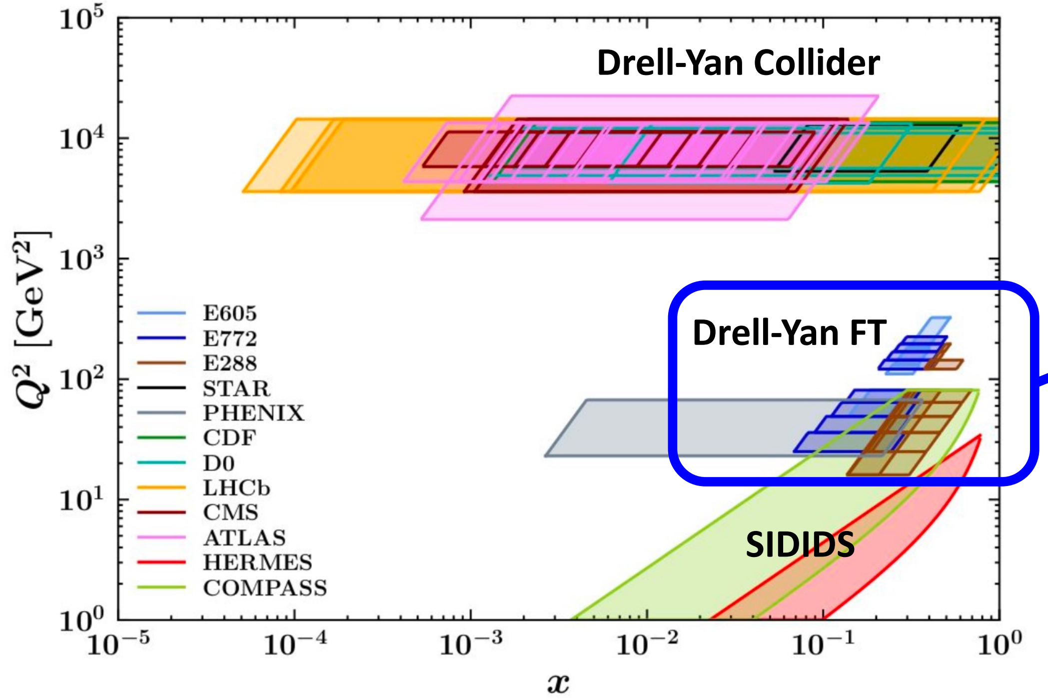
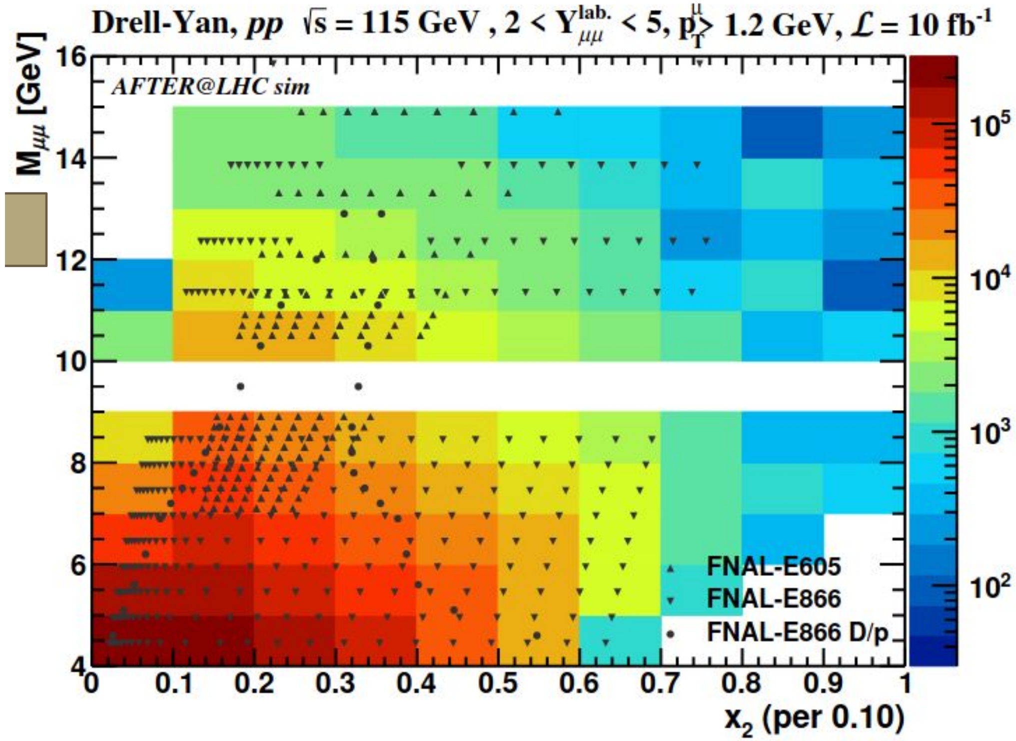
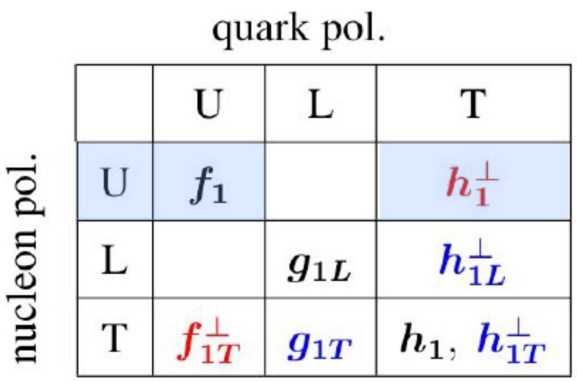




[arXiv:1807.00603]

Quark TMDs



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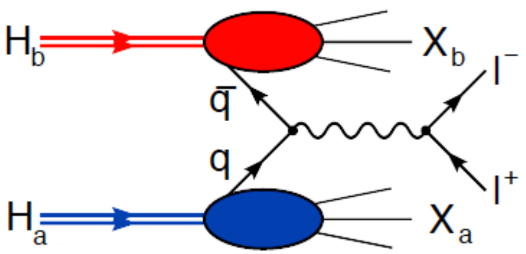

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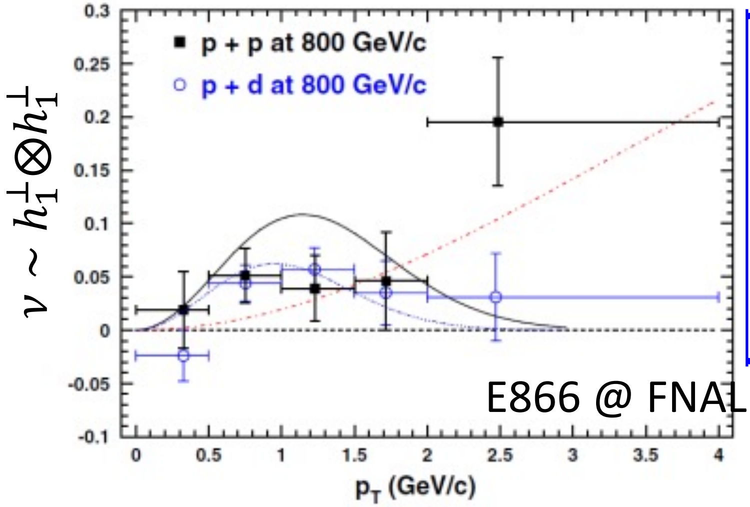
Sensitive to unpol. and BM TMDs for $q_T \ll M_{ll}$

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

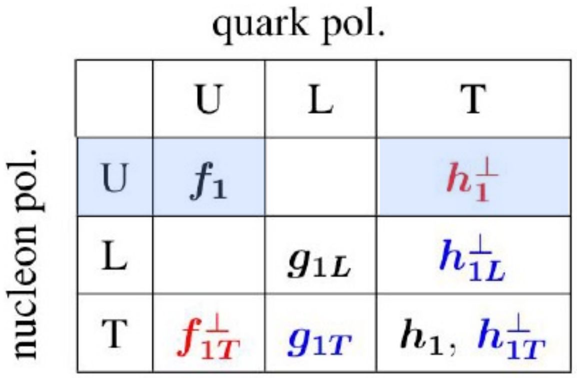
violation of Lam-Tung relation



E866 @ FNAL

[PRL 102 2009 182001]

Quark TMDs



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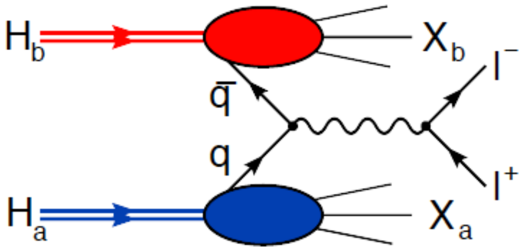

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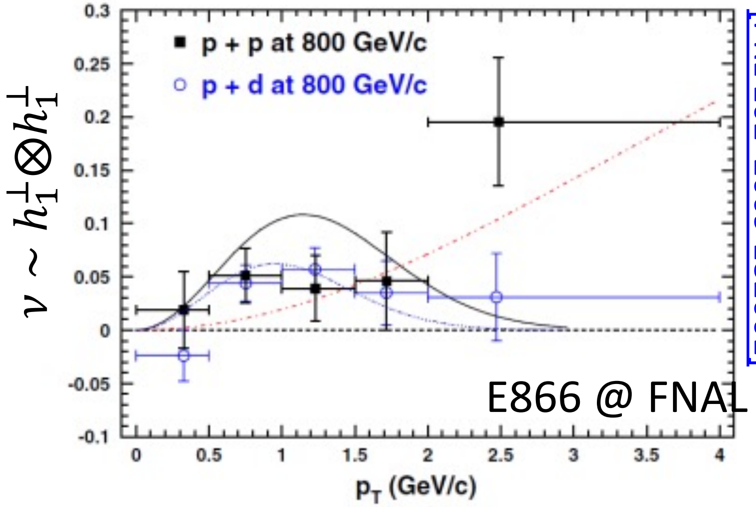
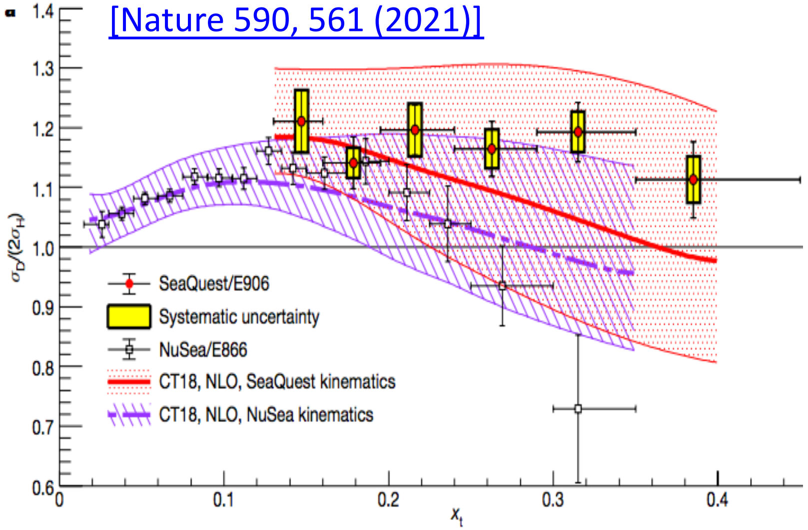


[PRL 102 2009 182001]

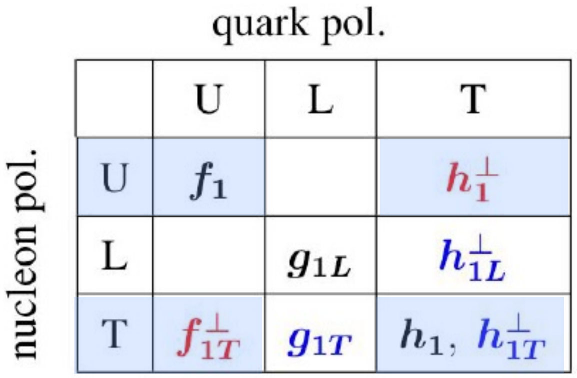
[Nature 590, 561 (2021)]



- Lattice QCD: $\bar{s}(x) \neq s(x)$ [arXiv:1809.04975]
- **proton sea more complex than originally thought!**

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

Quark TMDs



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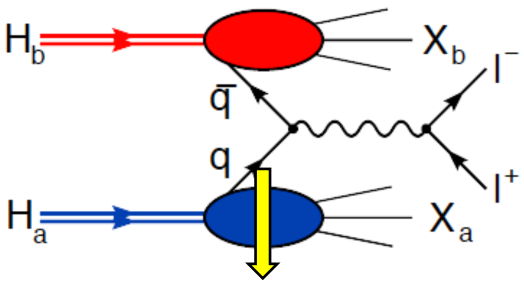
Transv. polarized Drell-Yan



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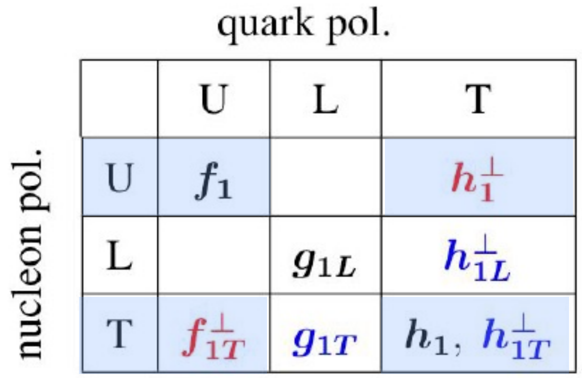

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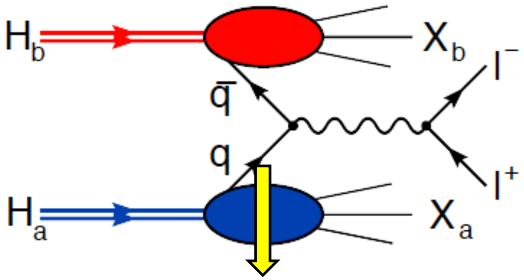
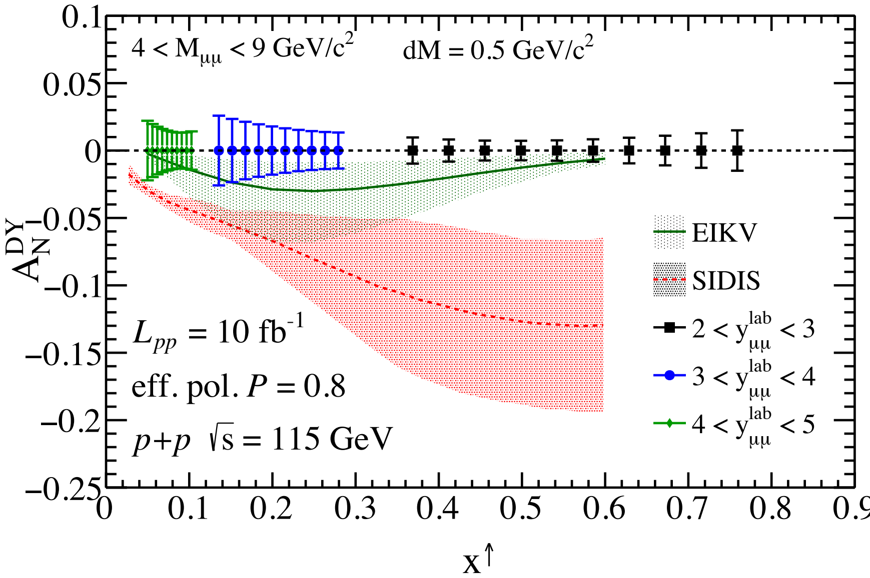


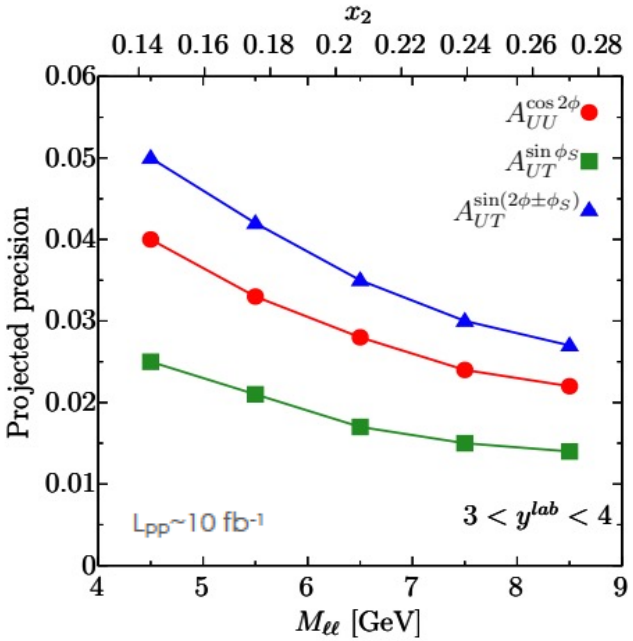


[arXiv:1807.00603]

- **Sensitive to quark TMDs through TSSAs**

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

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



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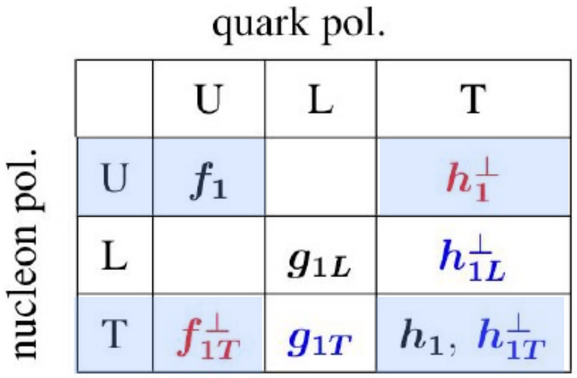

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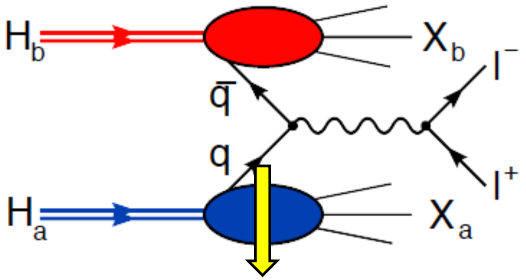
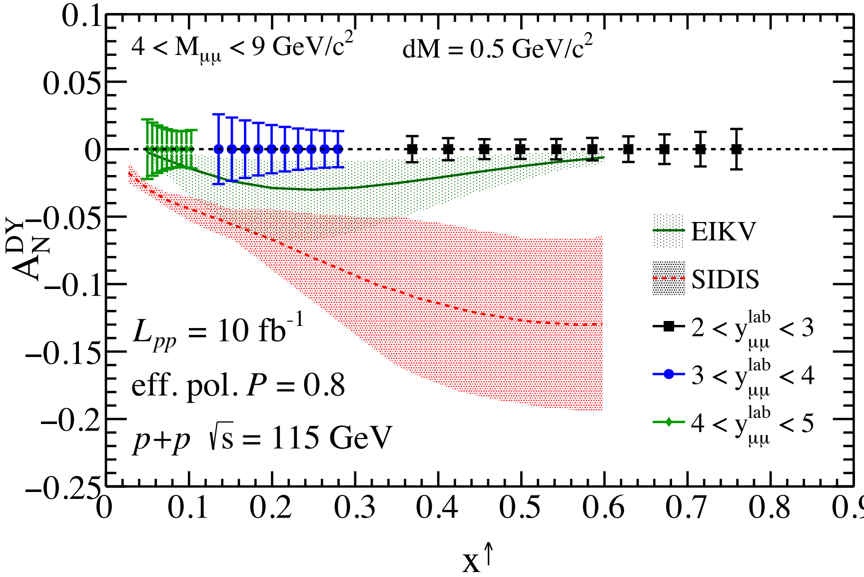
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transv. polarized Drell-Yan



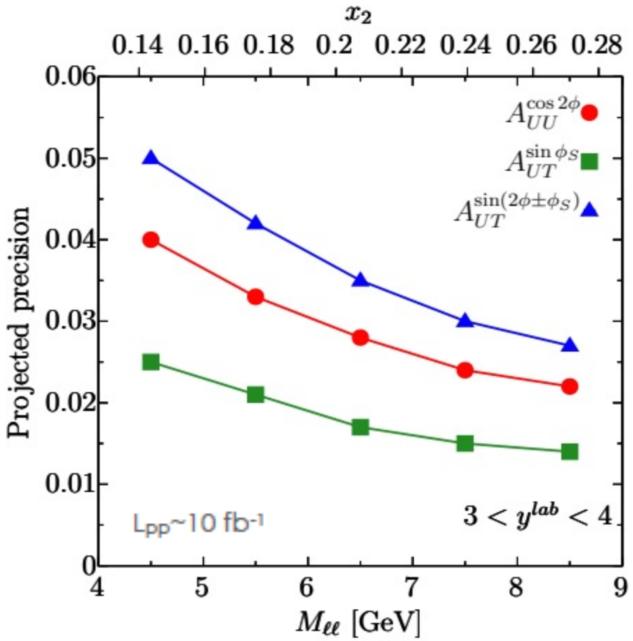


[arXiv:1807.00603]

- **Sensitive to quark TMDs through TSSAs**

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

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



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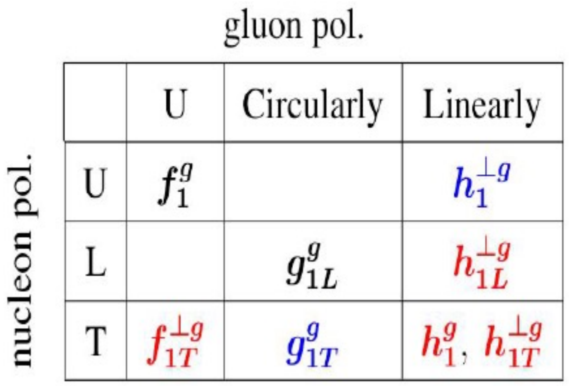
- Extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS

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

- Test flavour sensitivity using both H and D targets

Gluon TMDs



gluon pol.

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

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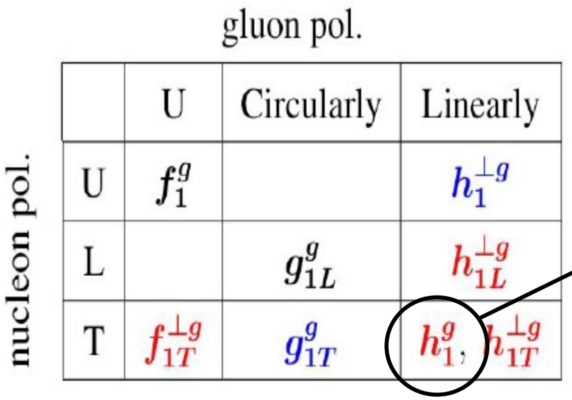

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- the **linearity gTMD** (h_1^g) is completely unrelated to the quark transversity (h_1^q), and has no collinear counterpart
- **different naïve-time-reversal properties**

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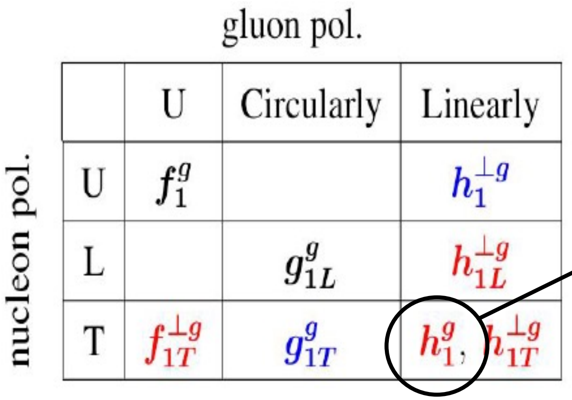

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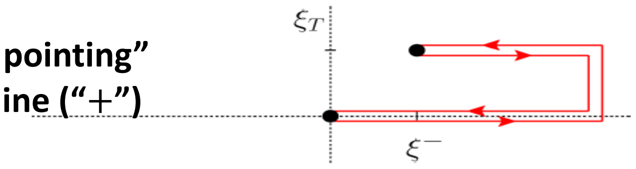
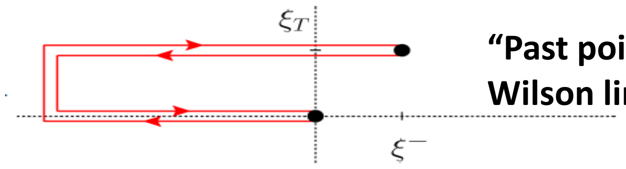
- **The gluon correlator depends on 2 path-dependent gauge links**, resulting in a more complex process dependence

"Future pointing"
Wilson line ("+")





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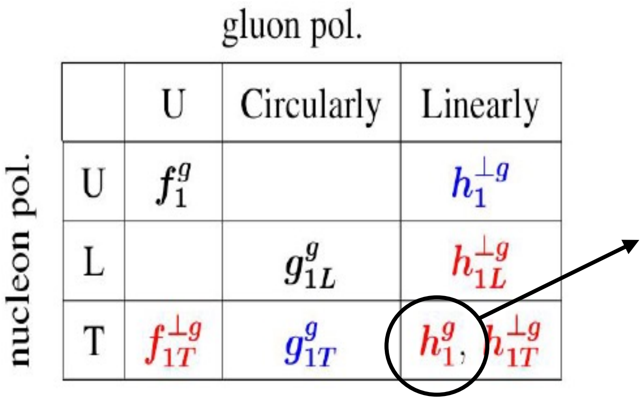

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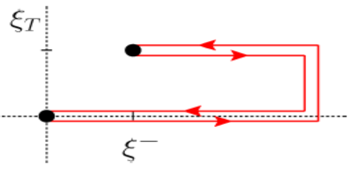

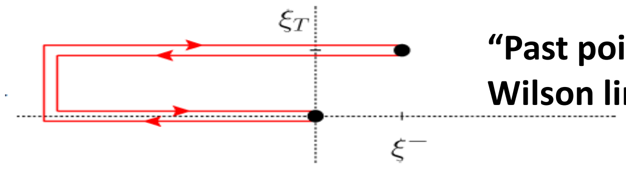

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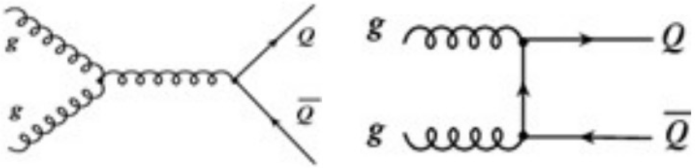
- Depending on their combinations, **there are 2 independent versions of each gTMD** that can probed in different processes and can have different magnitude and width and different x and k_T dependencies!
- E.g. there are 2 types of f_1^g and $h_1^{\perp g}$: $[+\,+] = [-\,-]$ Weizsacker-Williams (WW) ; $[+\,-] = [-\,+]$ 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 gTMDs

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



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Probing the gTMDs

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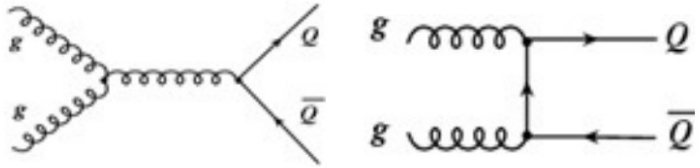

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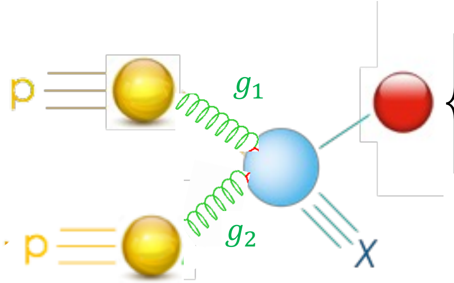

$$\begin{cases} \eta_c, \chi_{c0}, \ldots \\ \eta_b, \chi_{b0}, \ldots \\ J/\psi, \psi', \ldots \\ \Upsilon(nS) \end{cases}$$

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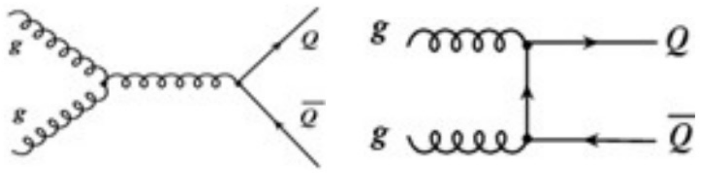

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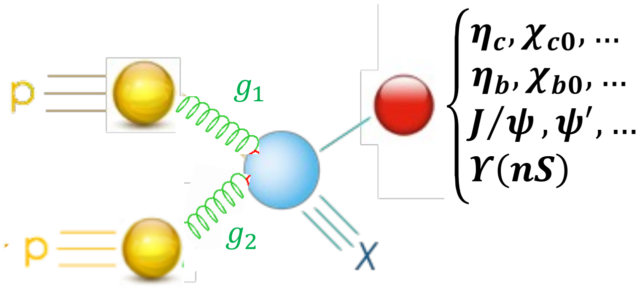

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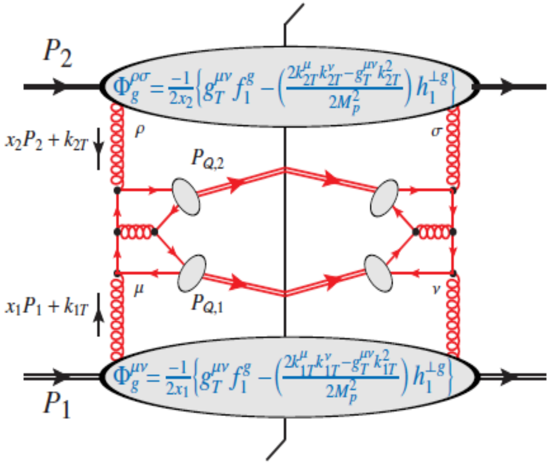
- TMD factorization requires $q_T(Q) \ll M_Q$. Can look at **associate quarkonia production**, where only the relative q_T needs to be small:

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



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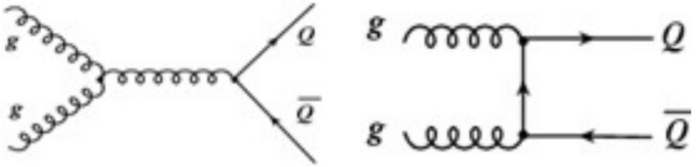

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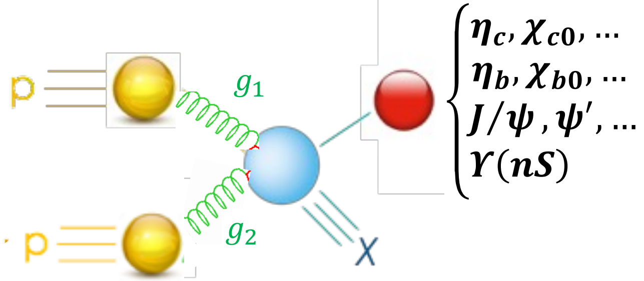

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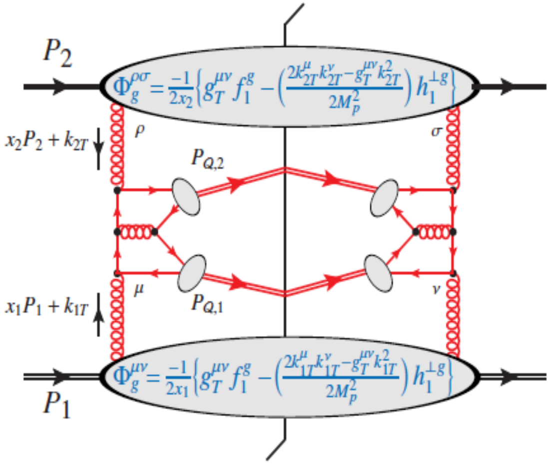
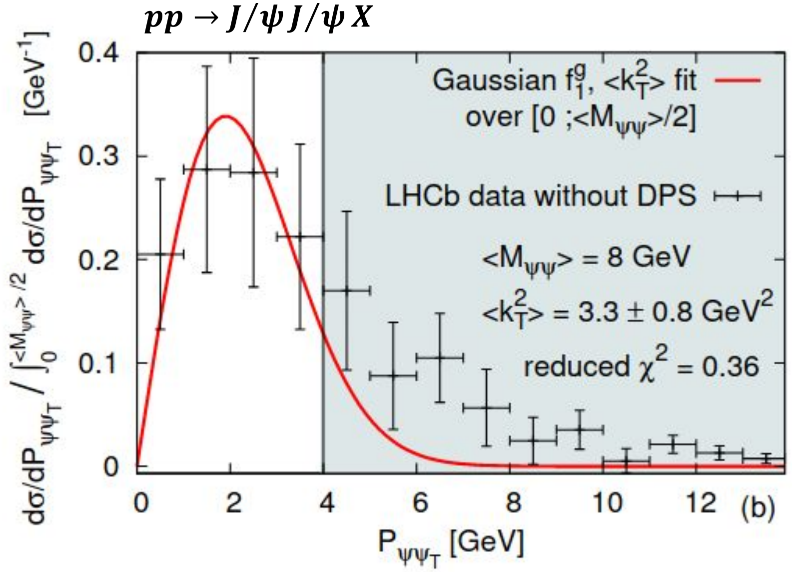
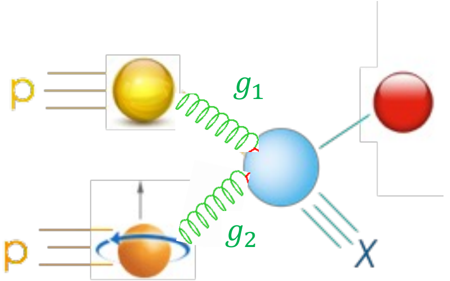




First extraction of f_1^g from LHCb di-J/ψ production data at 13 TeV [Lansberg et. al.]

Probing the gluon Sivers funct.

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



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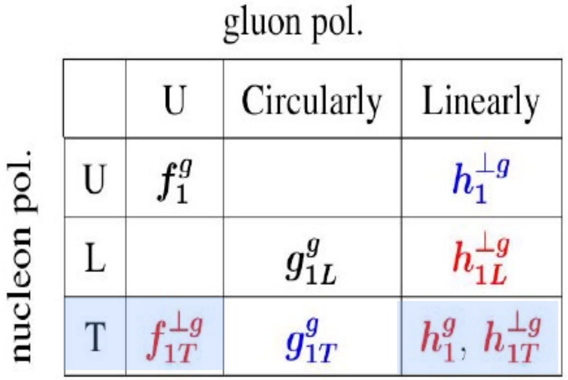

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nucleon pol.

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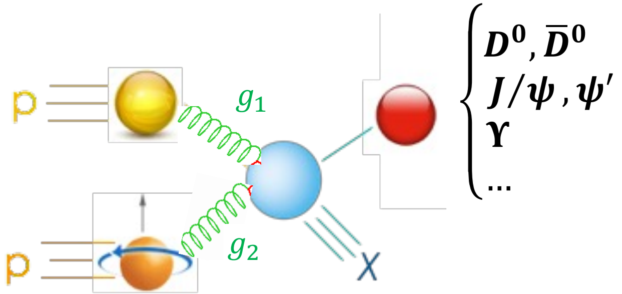

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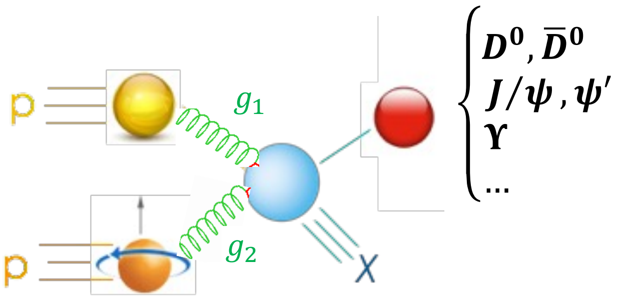

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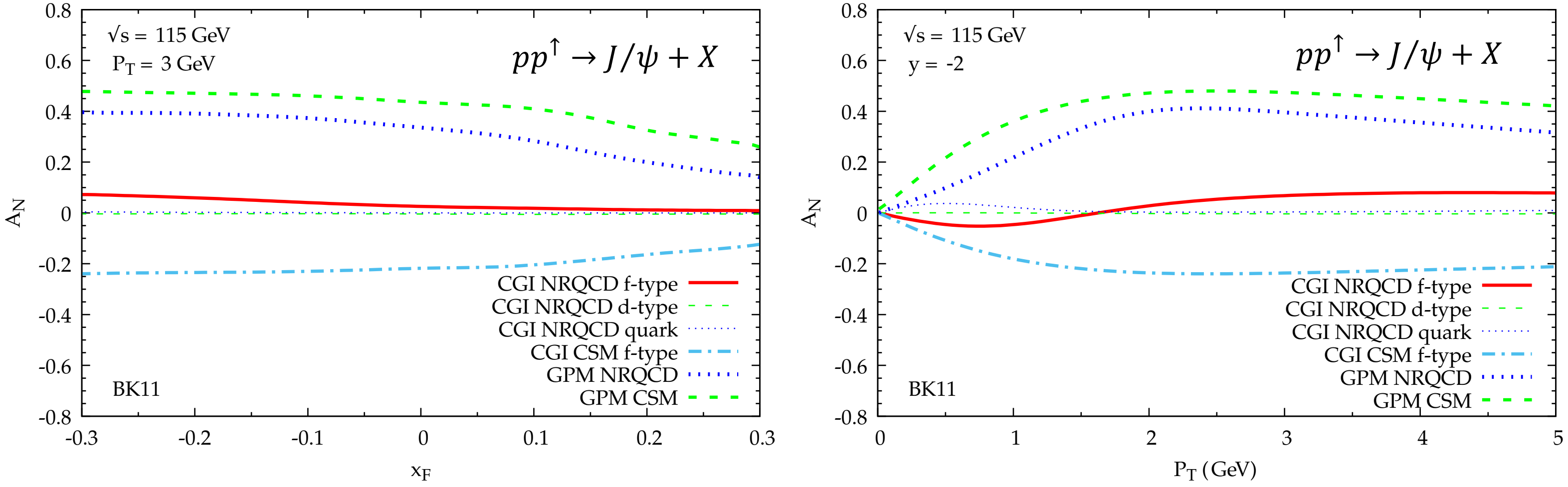
Predictions for pol. FT meas. at LHC (LHCspin-like) [Phys. Rev. D 102, 094011 (2020)]



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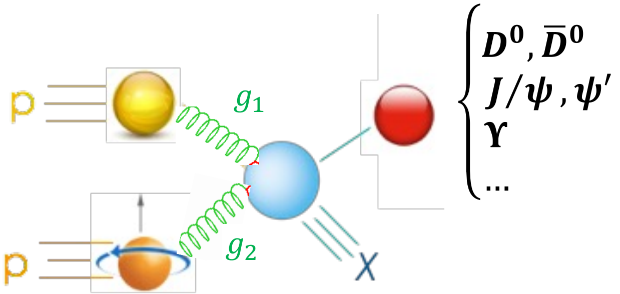

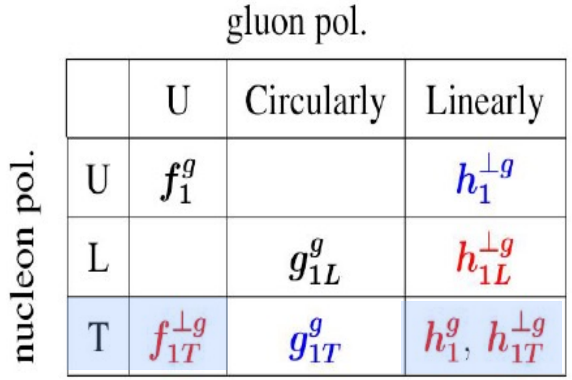

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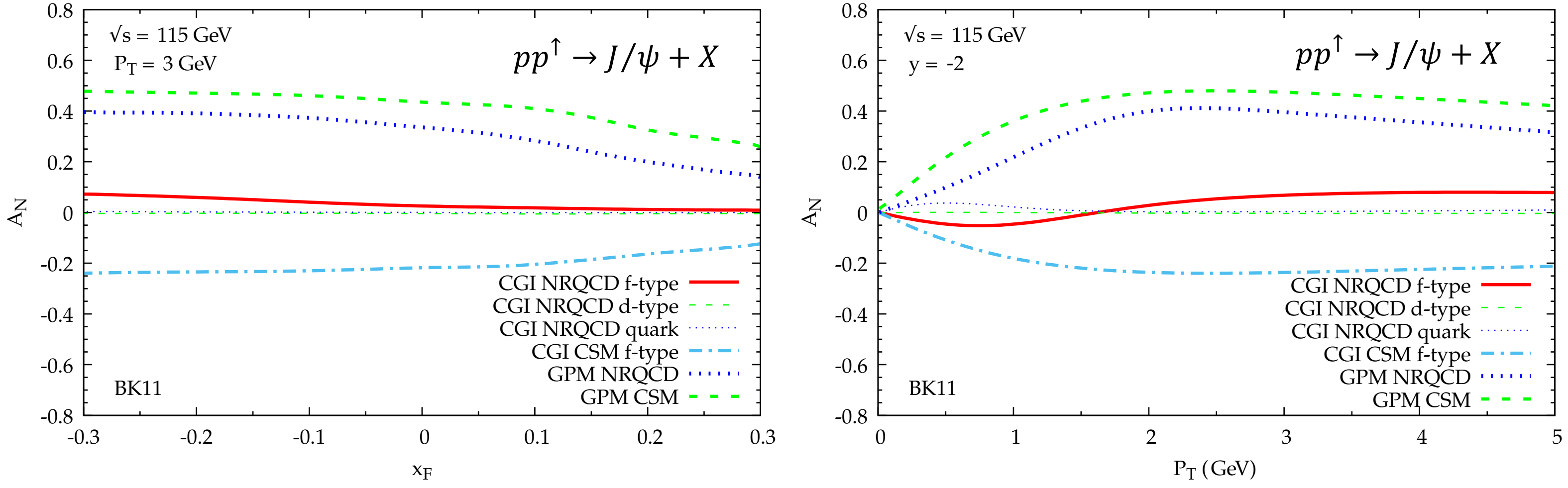
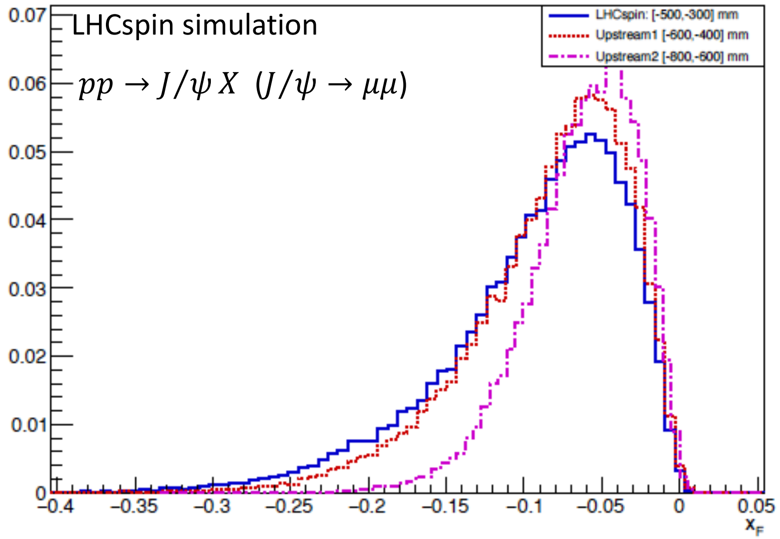
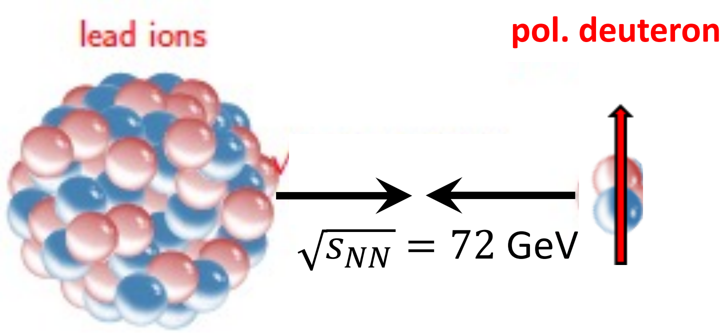




Merging spin physics with heavy-ion physics

- 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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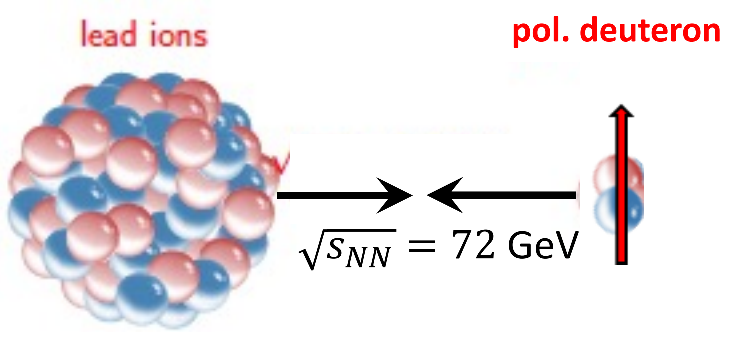

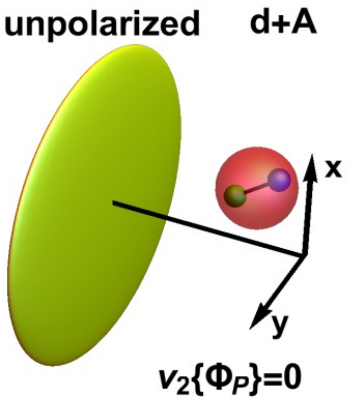

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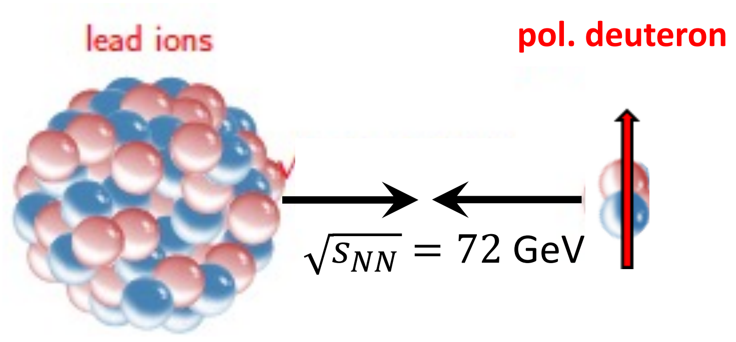

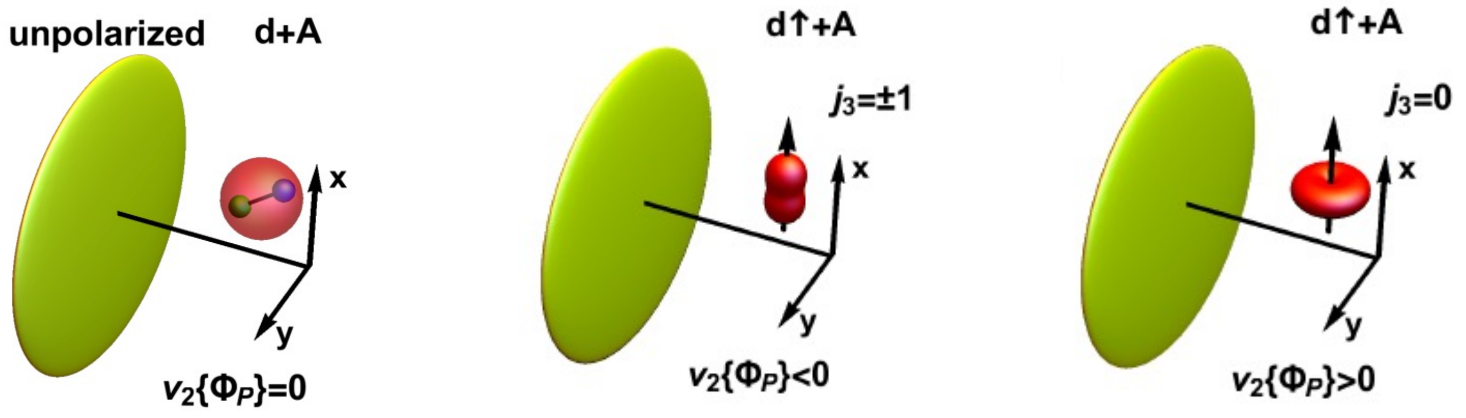

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$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

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

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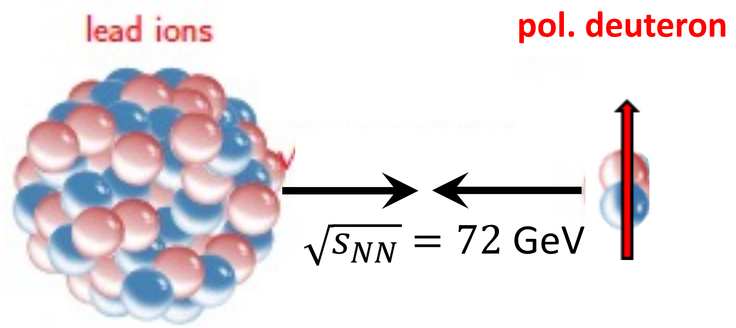
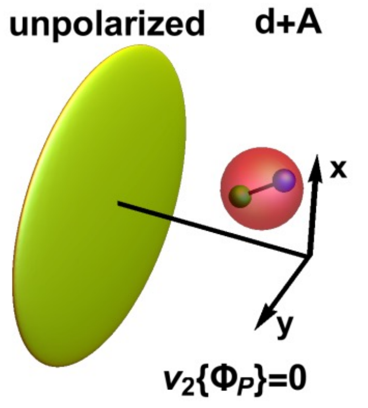
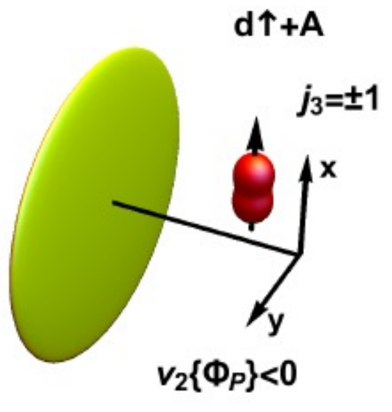
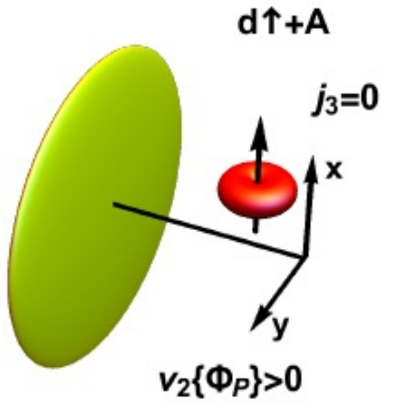




Unpol. deuterons: the **fireball is azimuthally symmetric** and $v_2 \approx 0.$

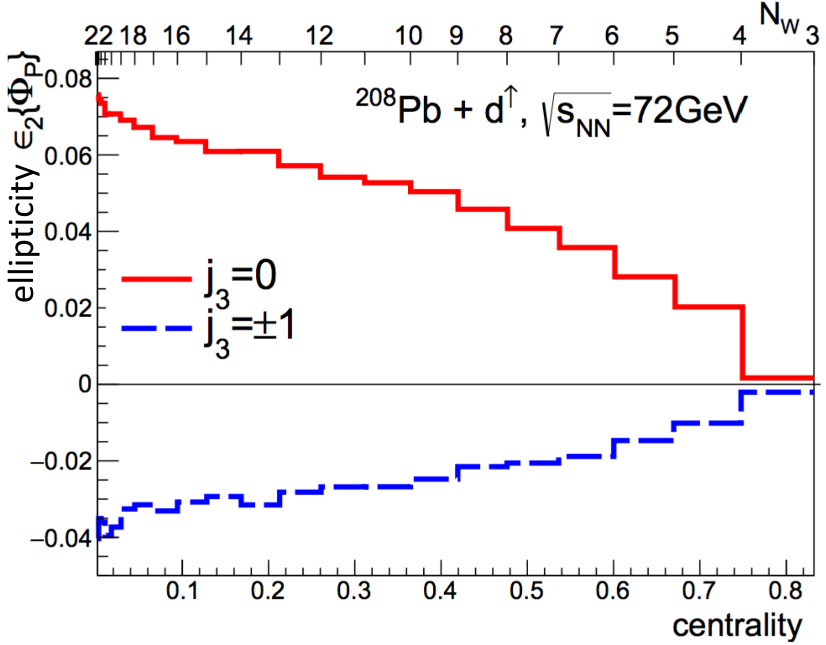


$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$



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

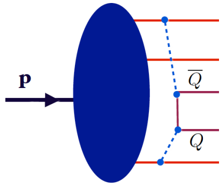
Predictions for LHC FT kinematics

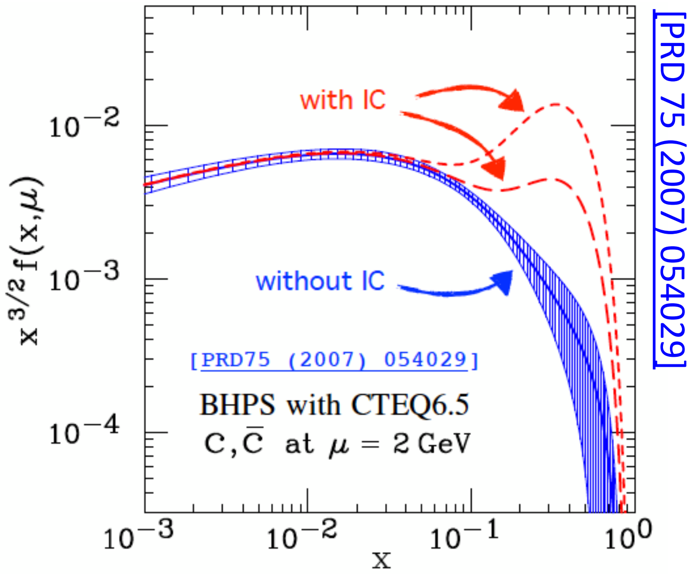


[PRC 101 (2020) 024901]

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





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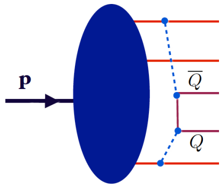

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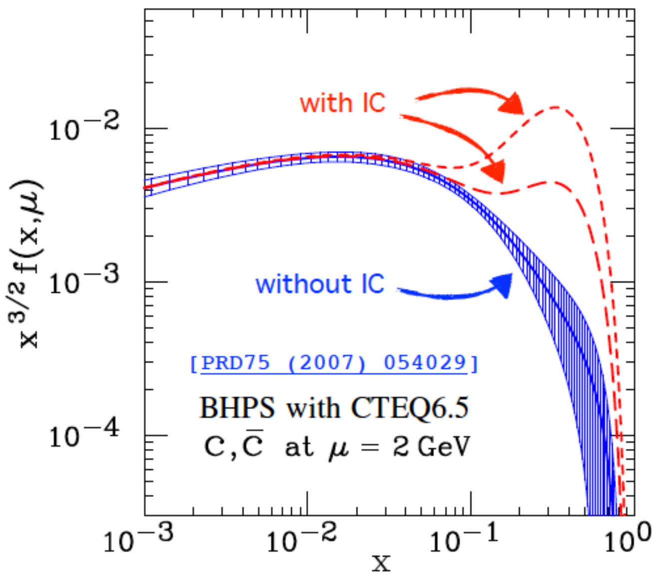
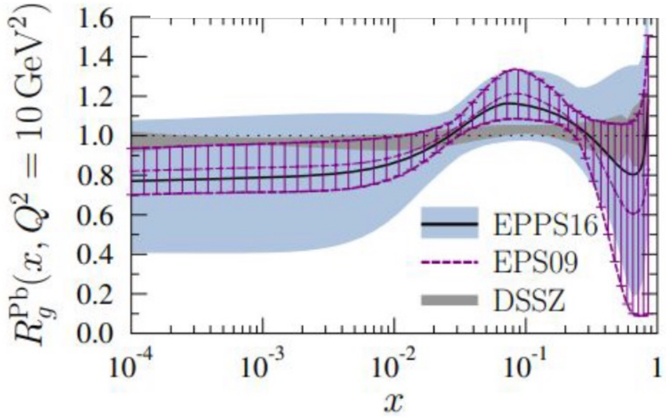


[PRD 75 (2007) 054029]

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



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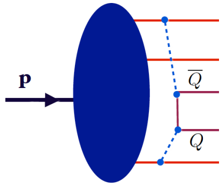

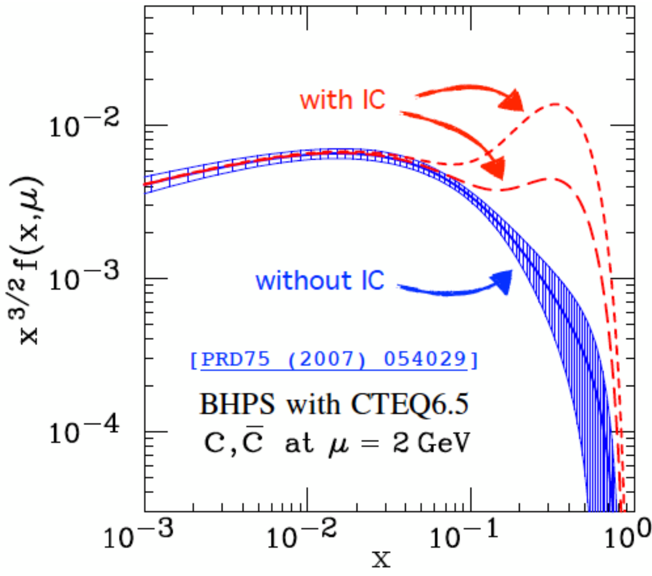

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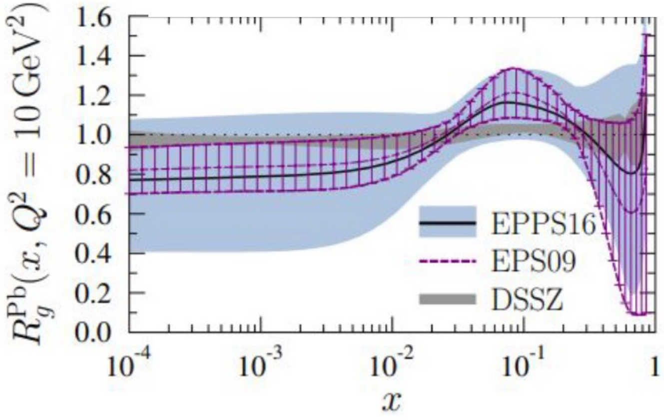
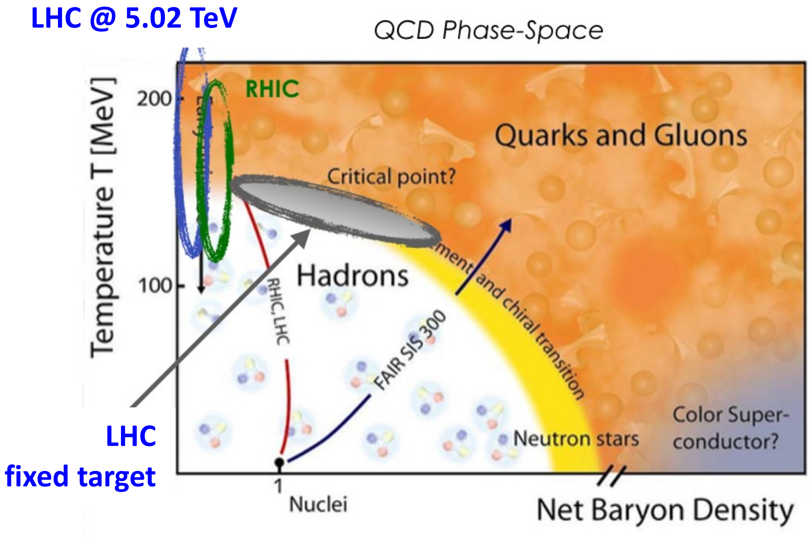
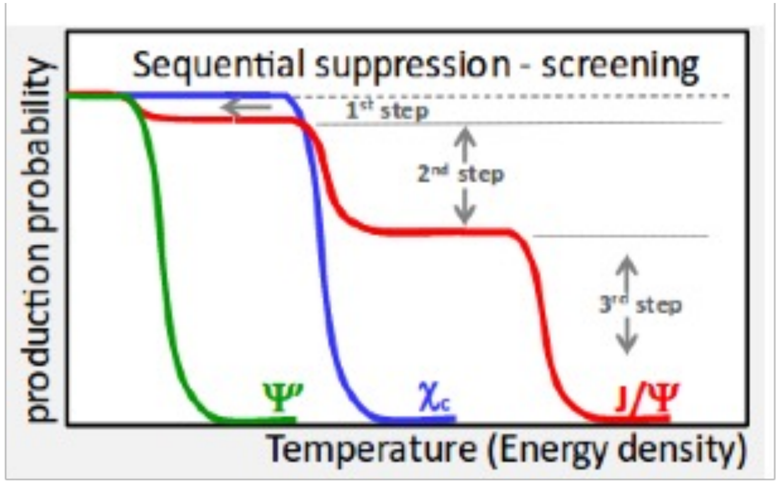
- **PbA collisions at $\sqrt{s_{NN}} \approx 72$ GeV** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - Study of **QGP formation** (search for predicted **sequential quarkonium suppression**)

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



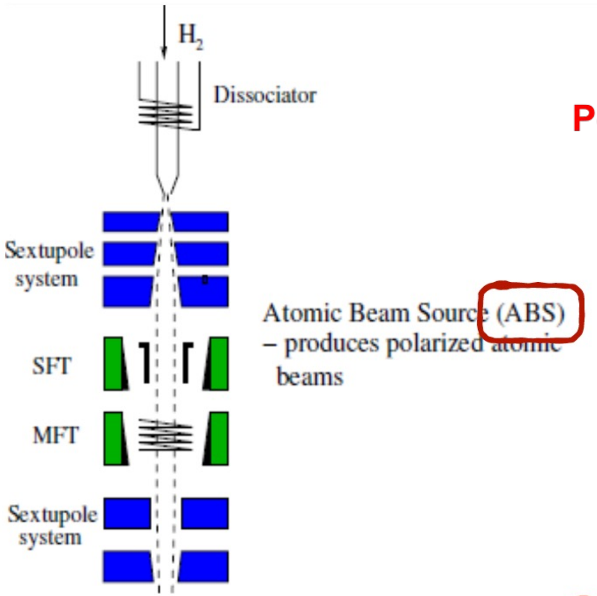


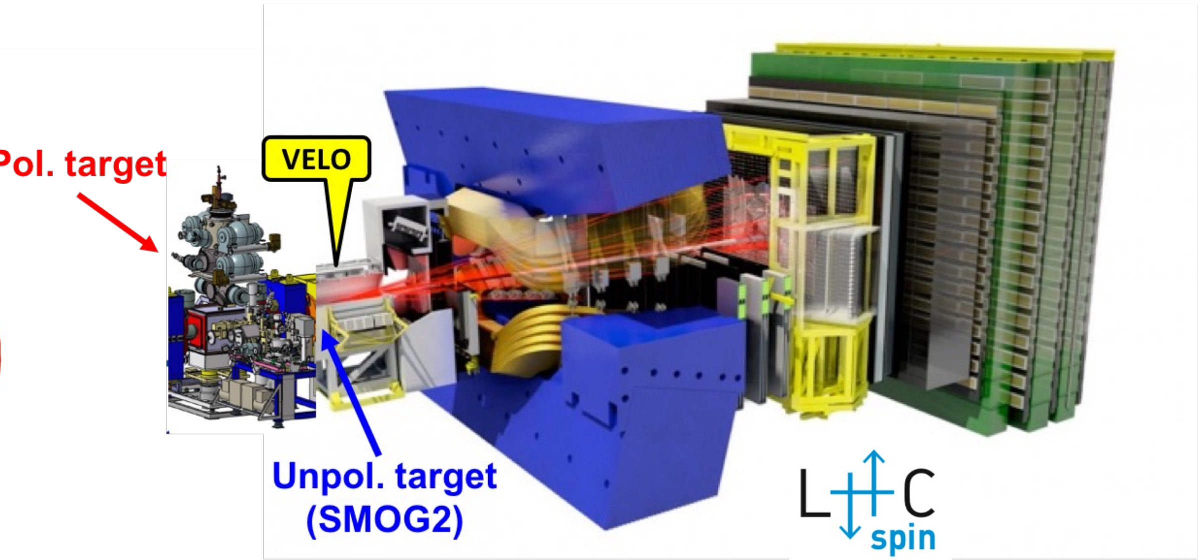


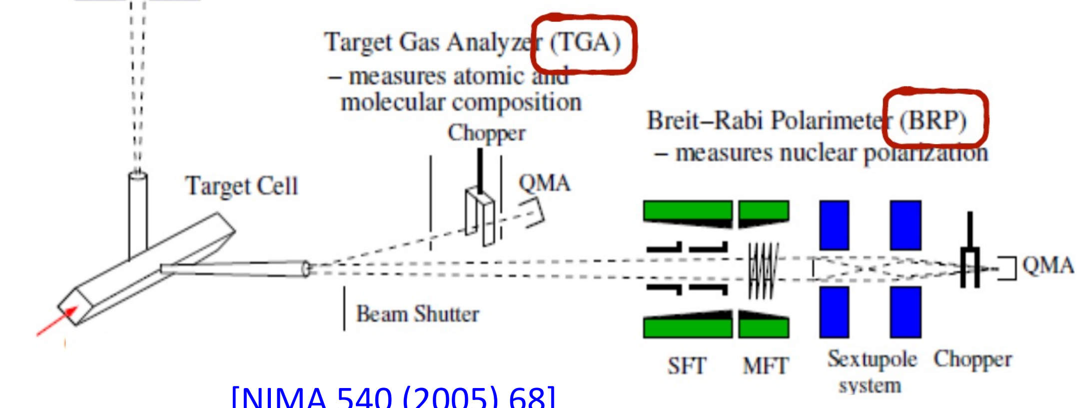
$c\bar{c}$ states: J/ψ , χ_c, ψ',...
Different binding energies, different dissociation temperatures → **medium thermometer**

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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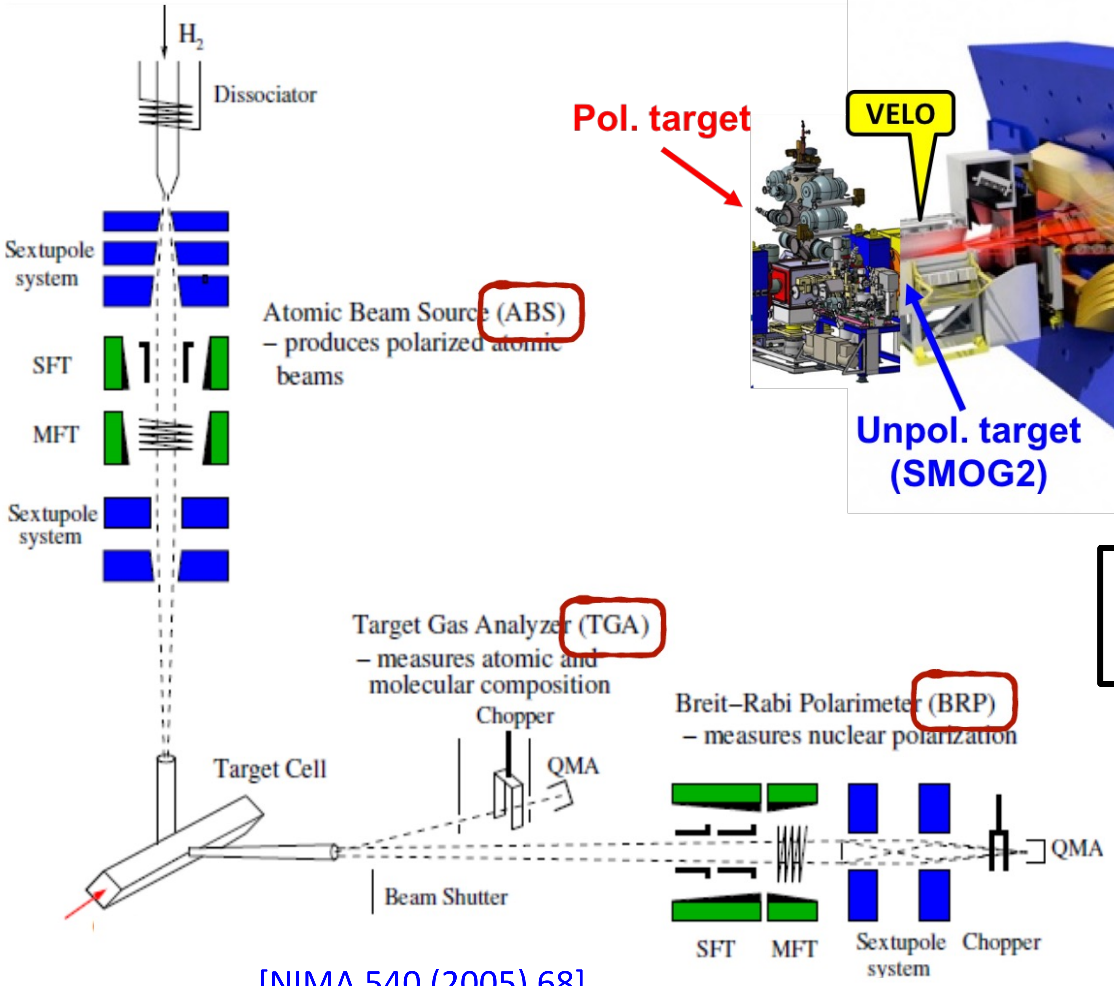

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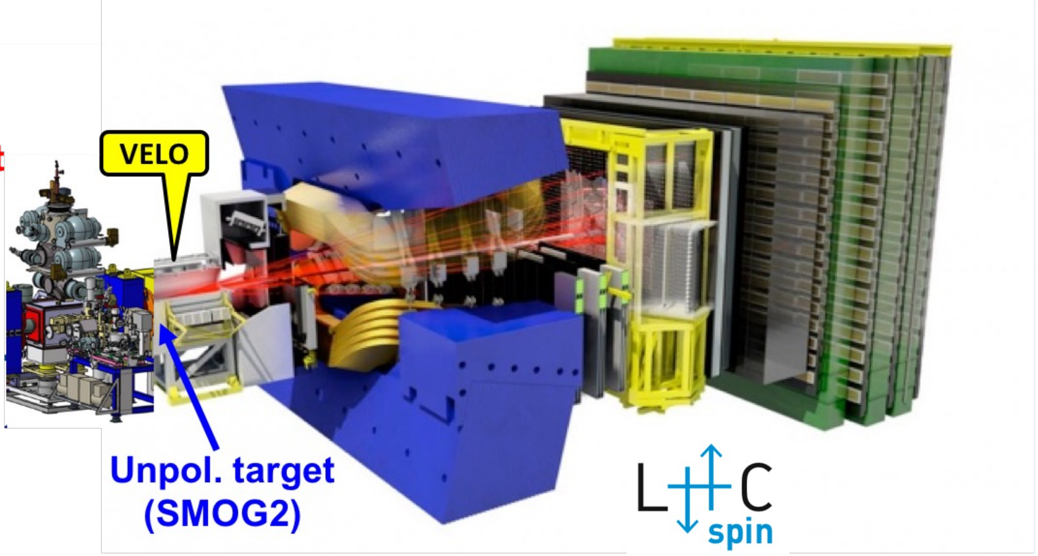

75-80% transverse polarization @ HERMES

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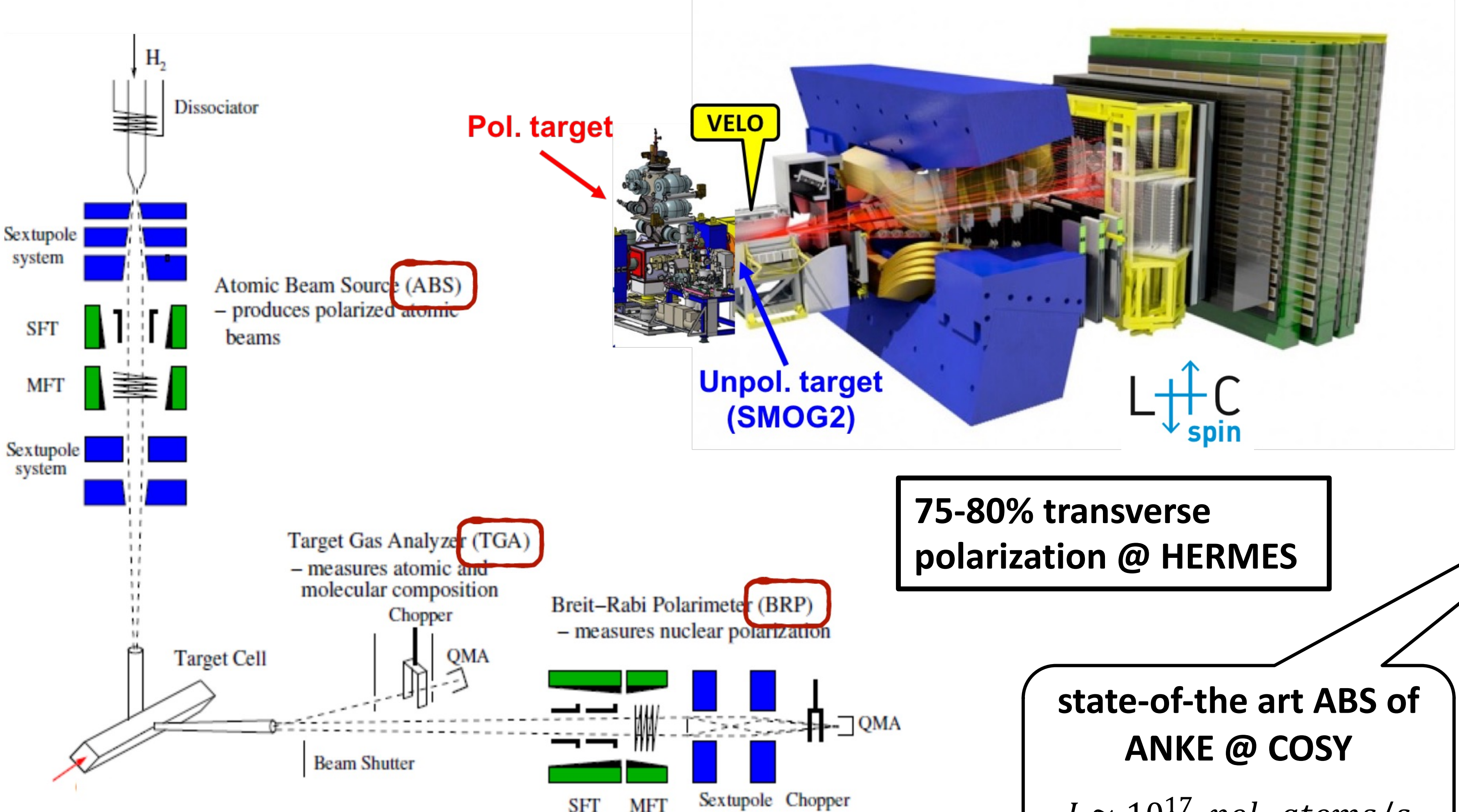
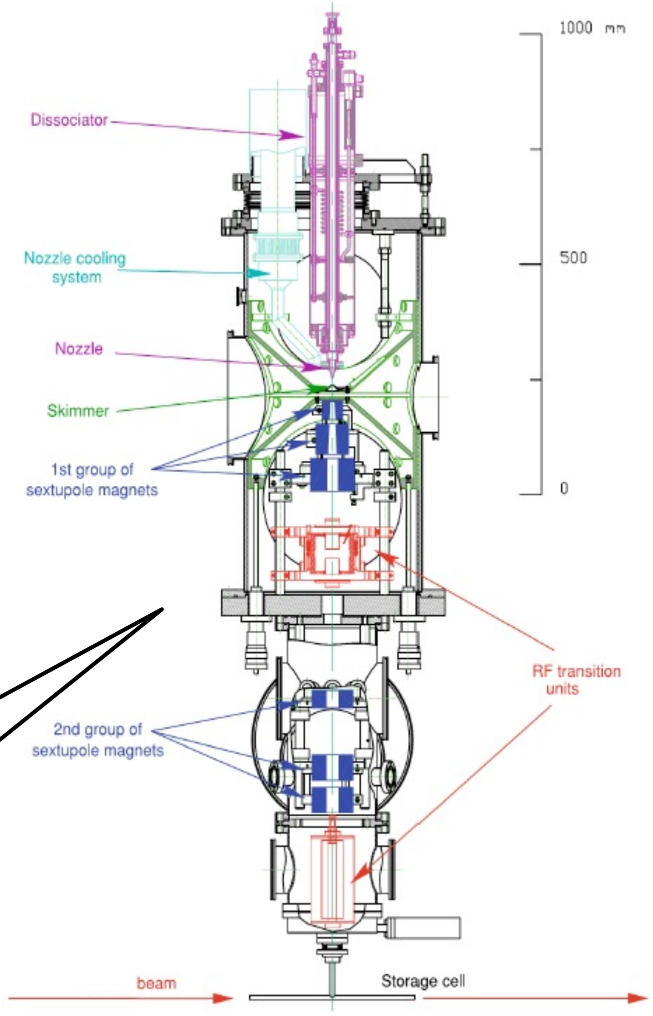


[NIMA 540 (2005) 68]

75-80% transverse polarization @ HERMES

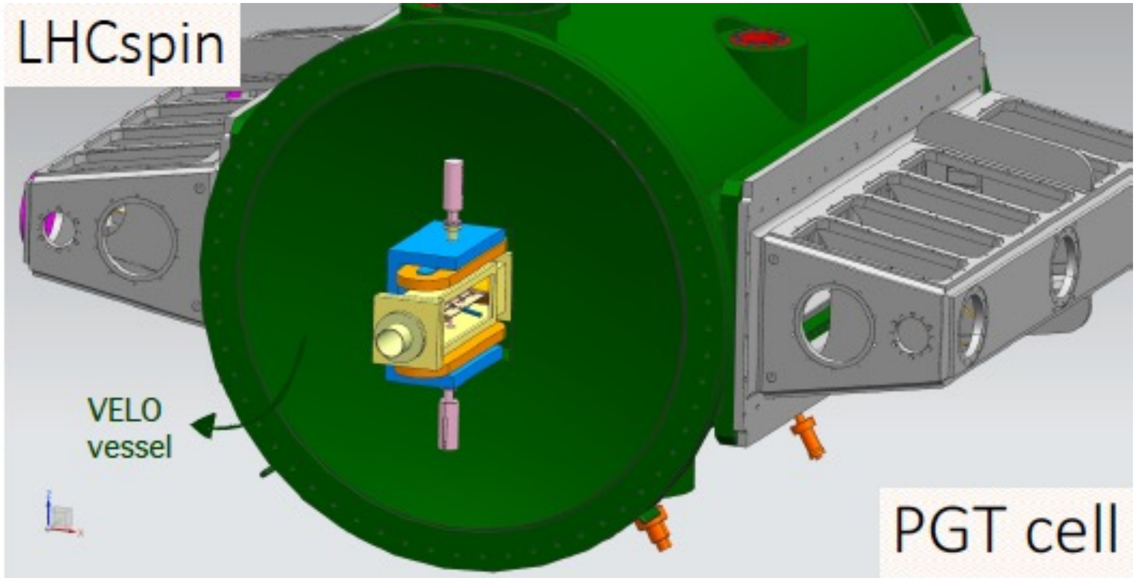
state-of-the art ABS of ANKE @ COSY

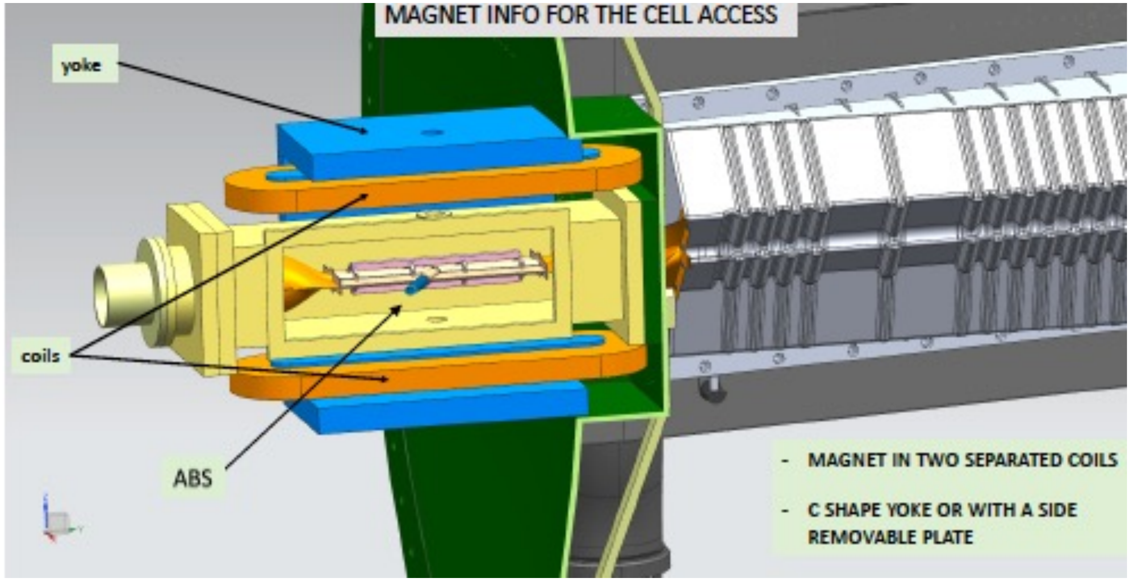
$I \simeq 10^{17}\ pol.atoms/s$

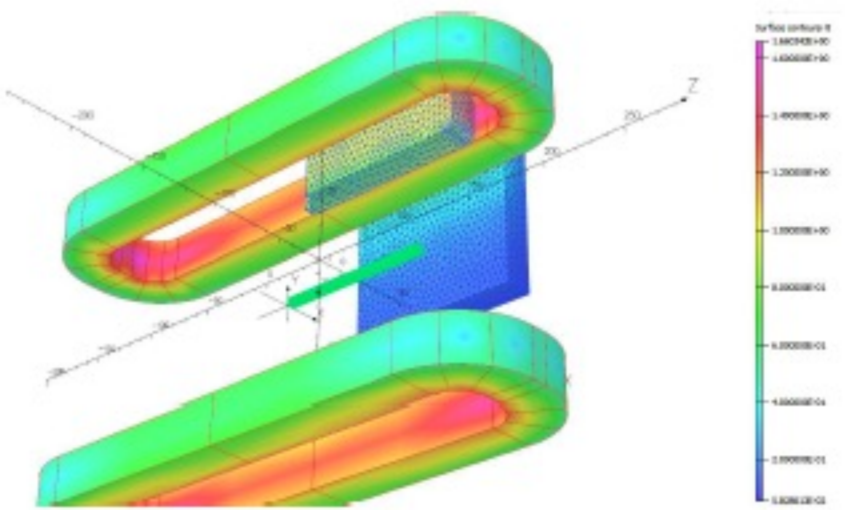


[NIM A 721, 83 (2013)]

The LHCspin apparatus [PoS (SPIN2018)]







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

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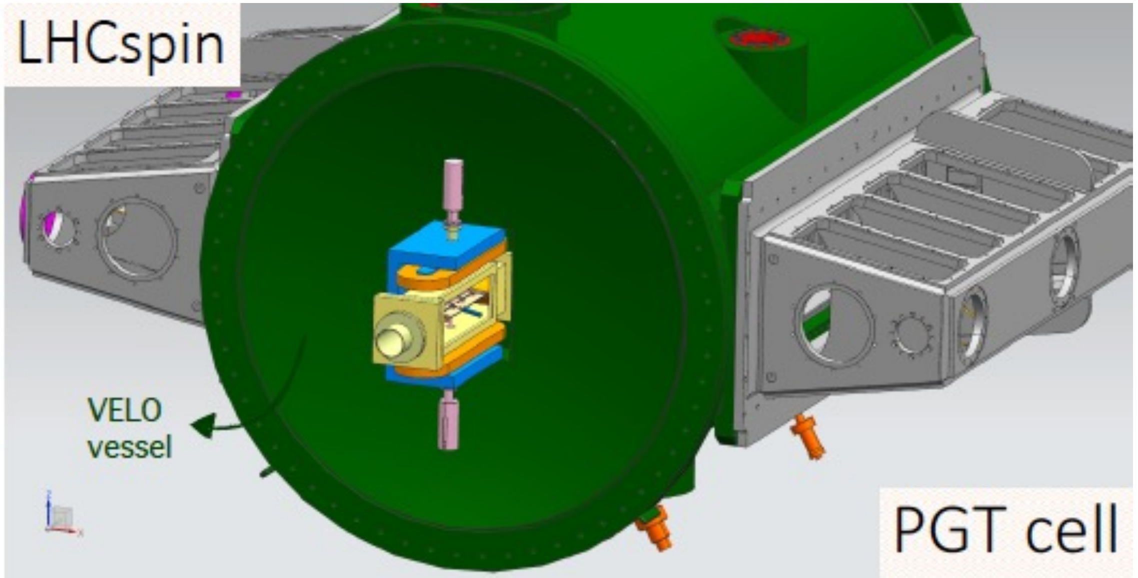

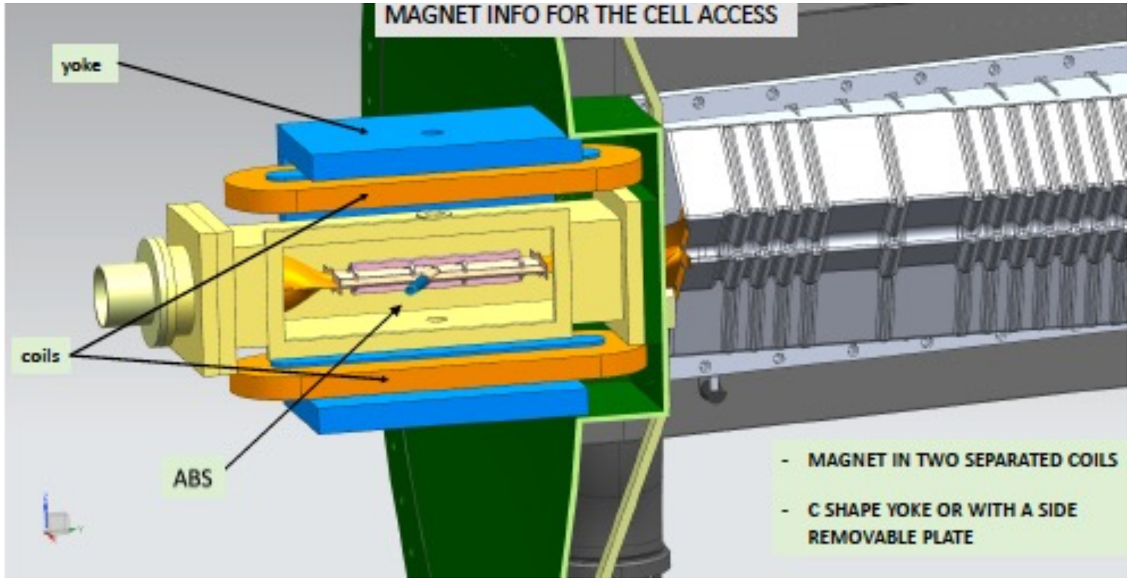

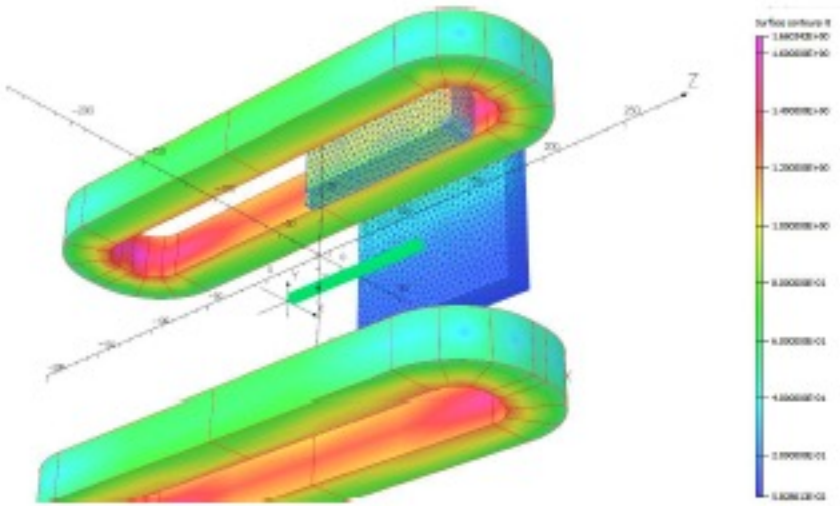

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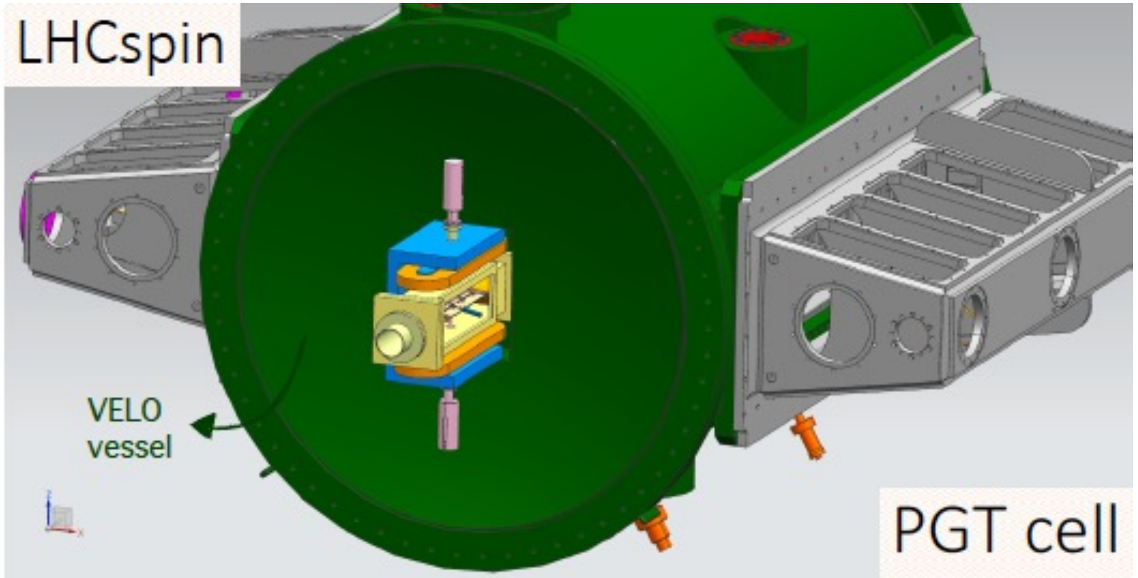

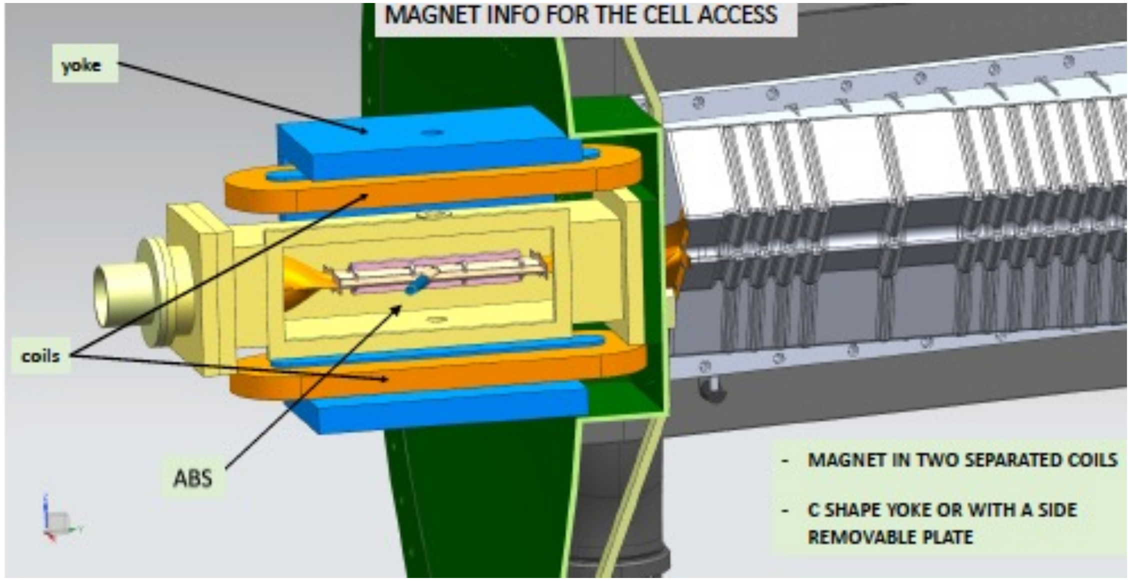

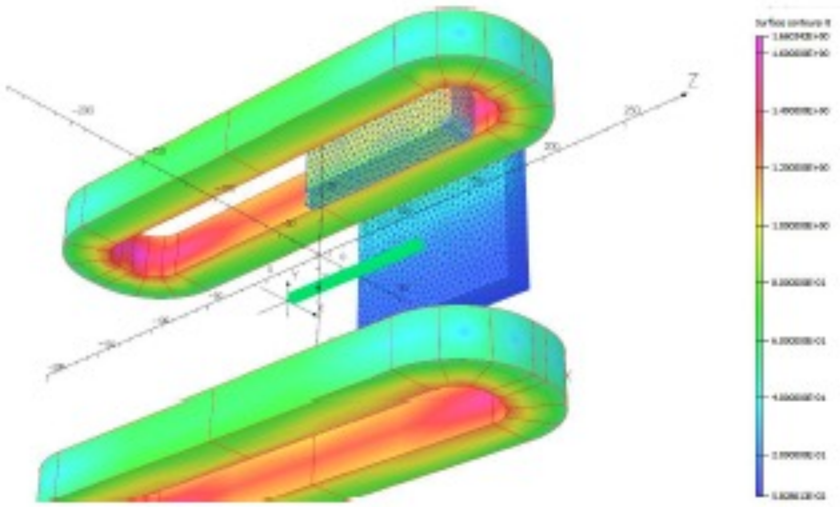

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- **Possibility to switch from dipole magnet to solenoid to realize a Longitudinal polarized target in Run5**

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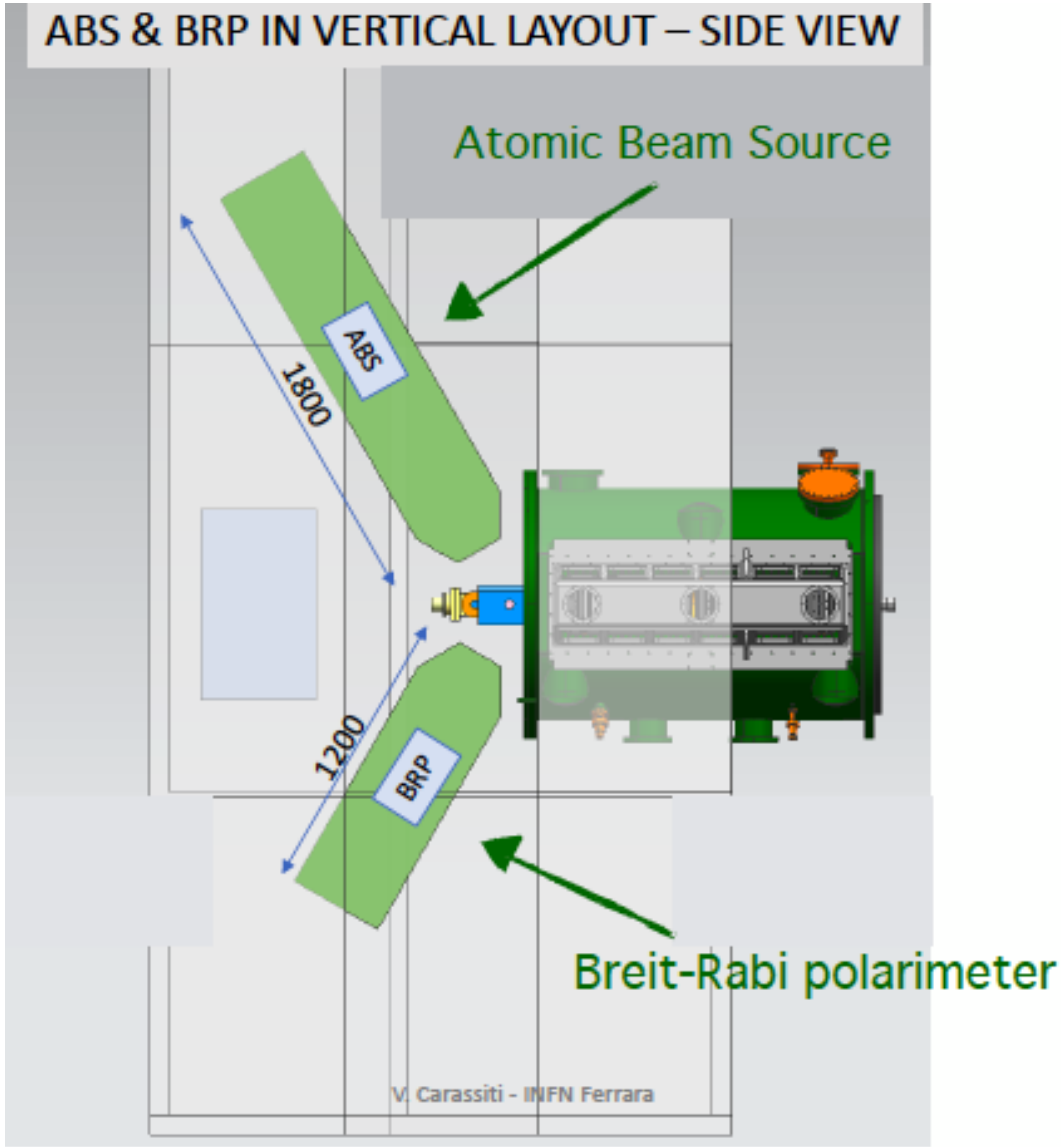

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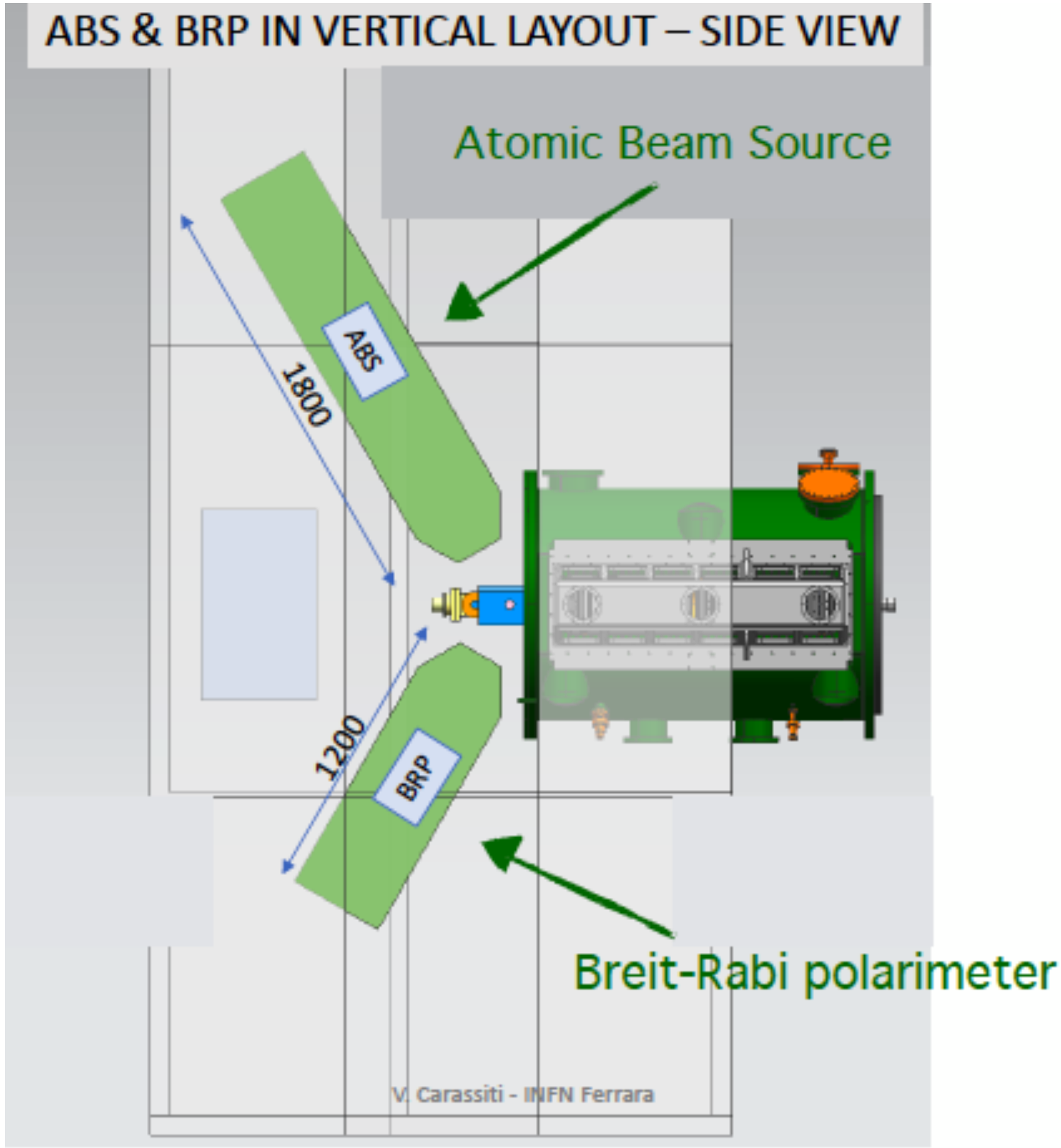

- **Need to develop a new-generation compact ABS and diagnostic system to fit into the limited available space in the VELO alcove**
- **Coating studies for the cell walls are ongoing. Crucial for target polarization (back-up slides)**

The jet target hypothesis

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

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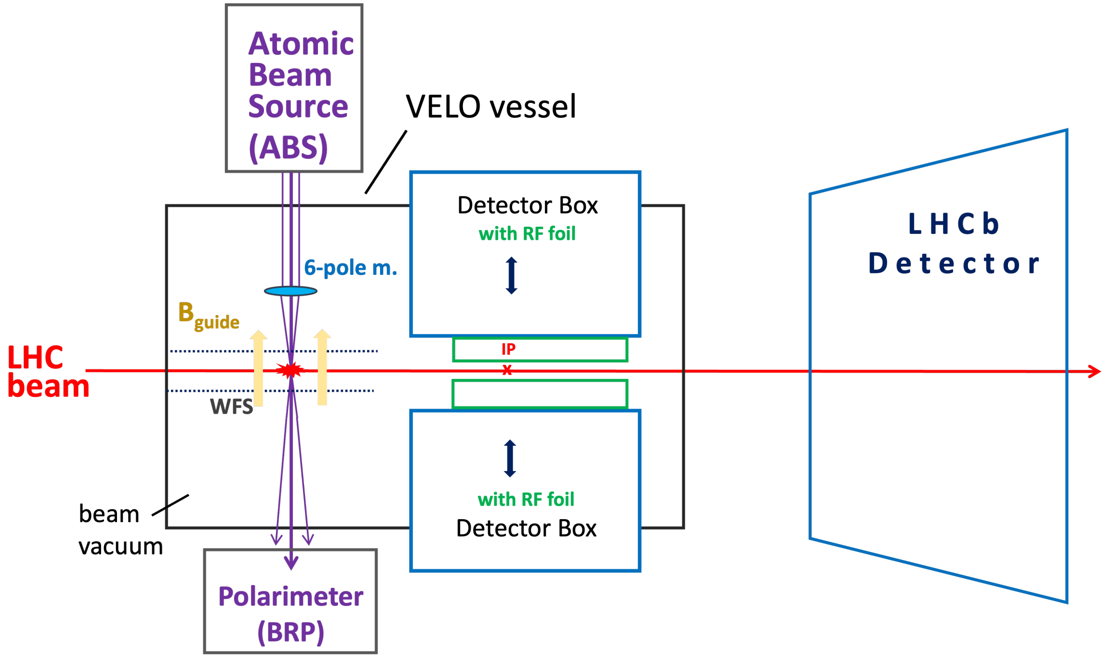

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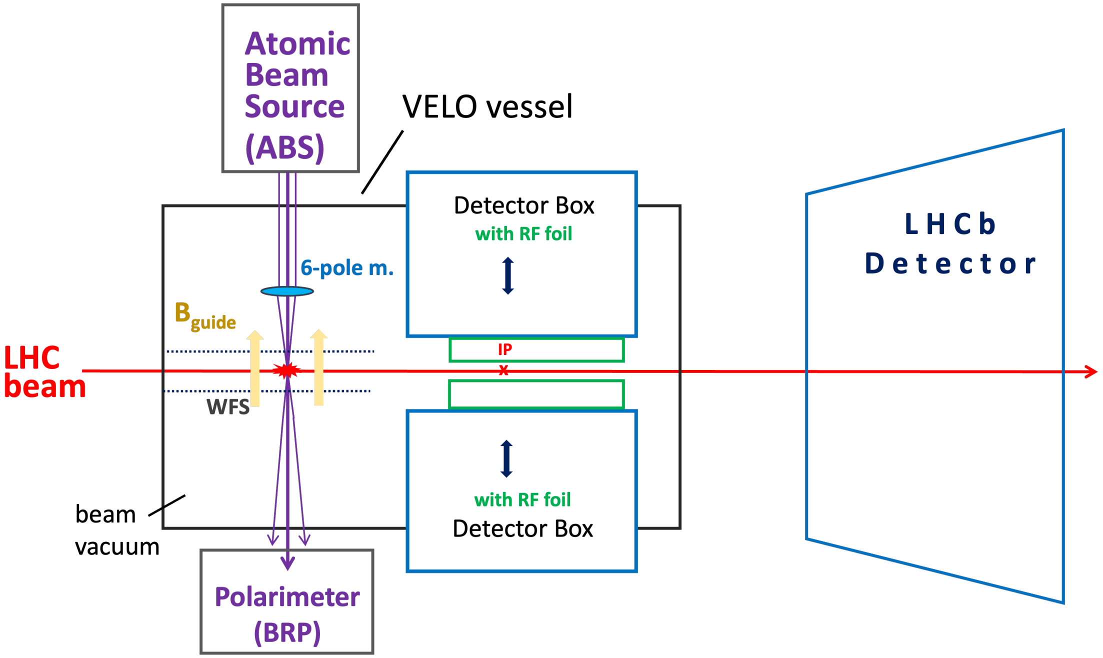
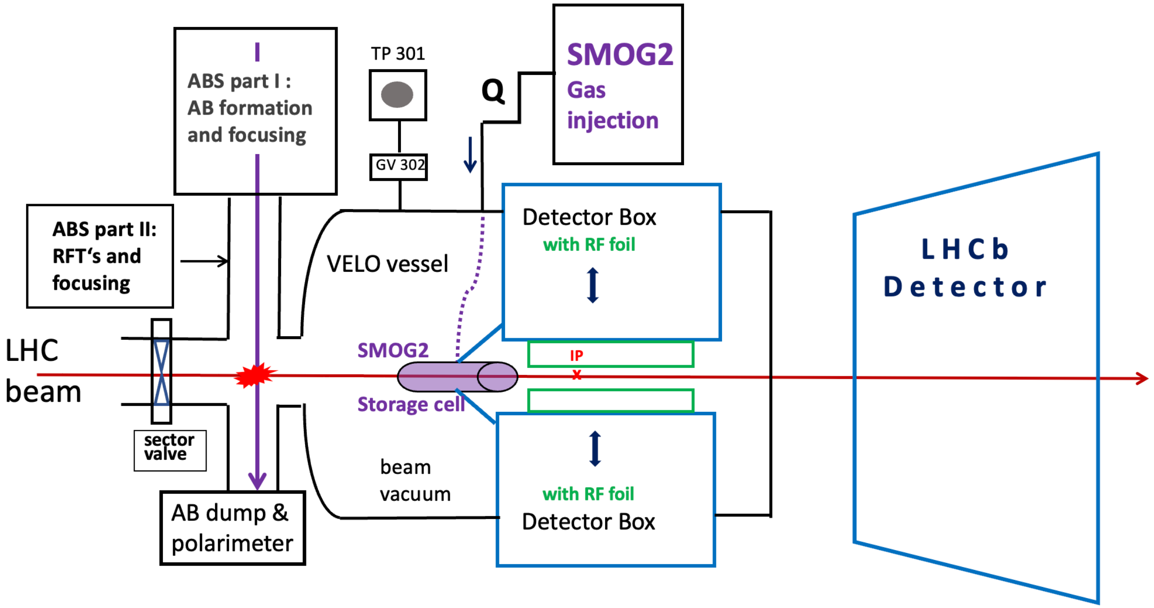


Jet Target + SMOG2



Expected performance

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

- $1.2 \cdot 10^{11}$ p/bunch (RUN3)
- 2808 bunches
- $\boldsymbol{I_{beam} = 3.8 \cdot 10^{18}\ p/s}$

$$\mathcal{L}_{pH}(\mathbf{300}\ \boldsymbol{K}) \approx \mathbf{1.4 \cdot 10^{32}\ cm^{-2}s^{-1}}$$

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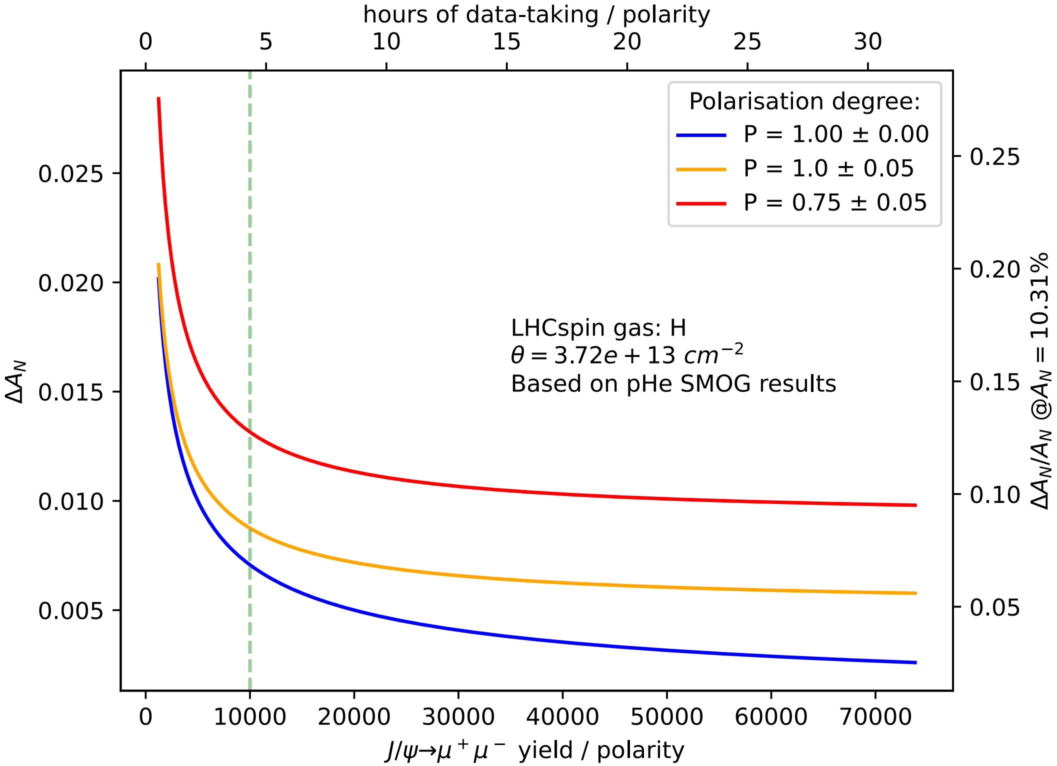

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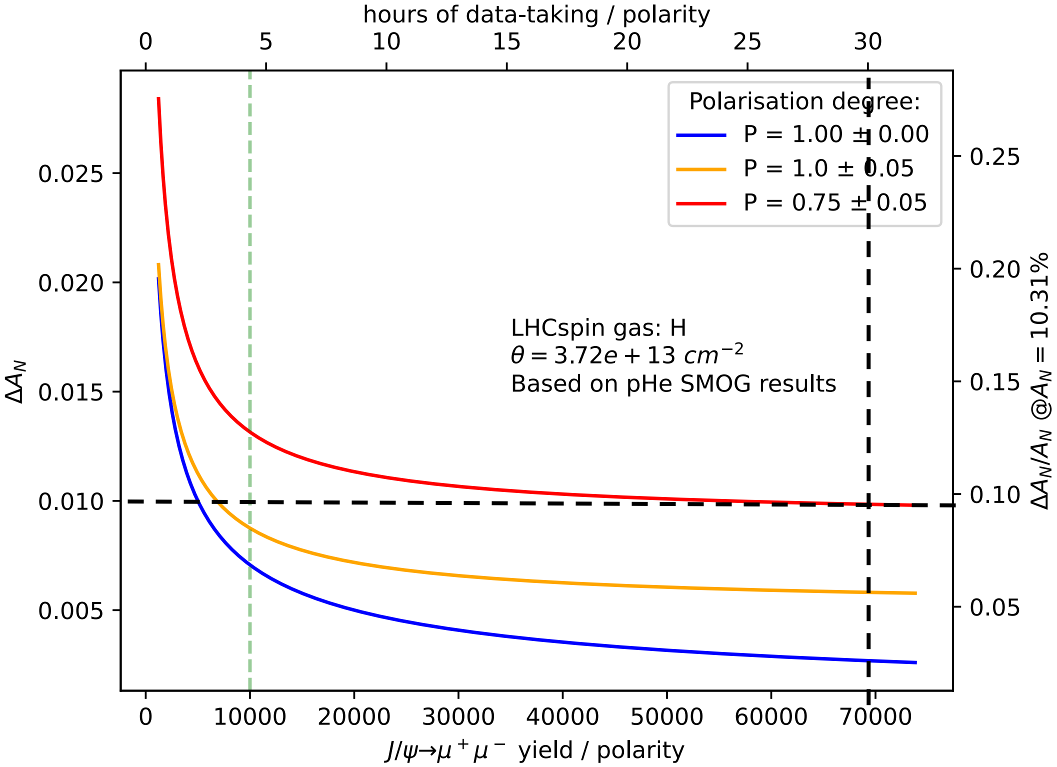

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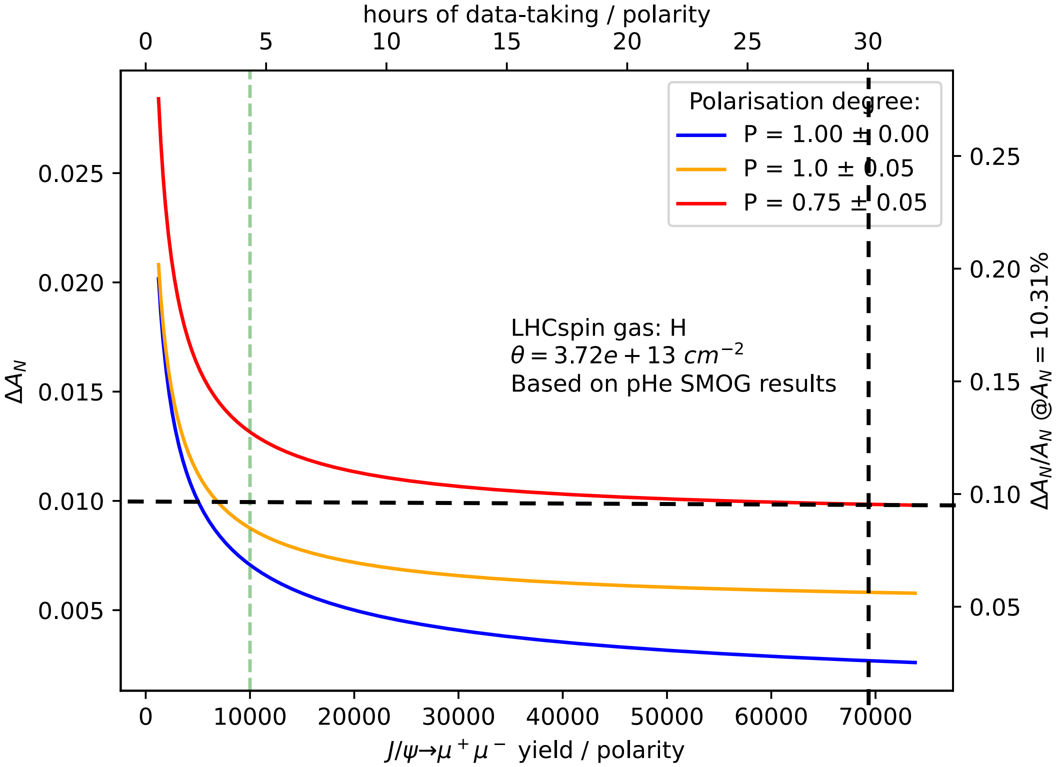


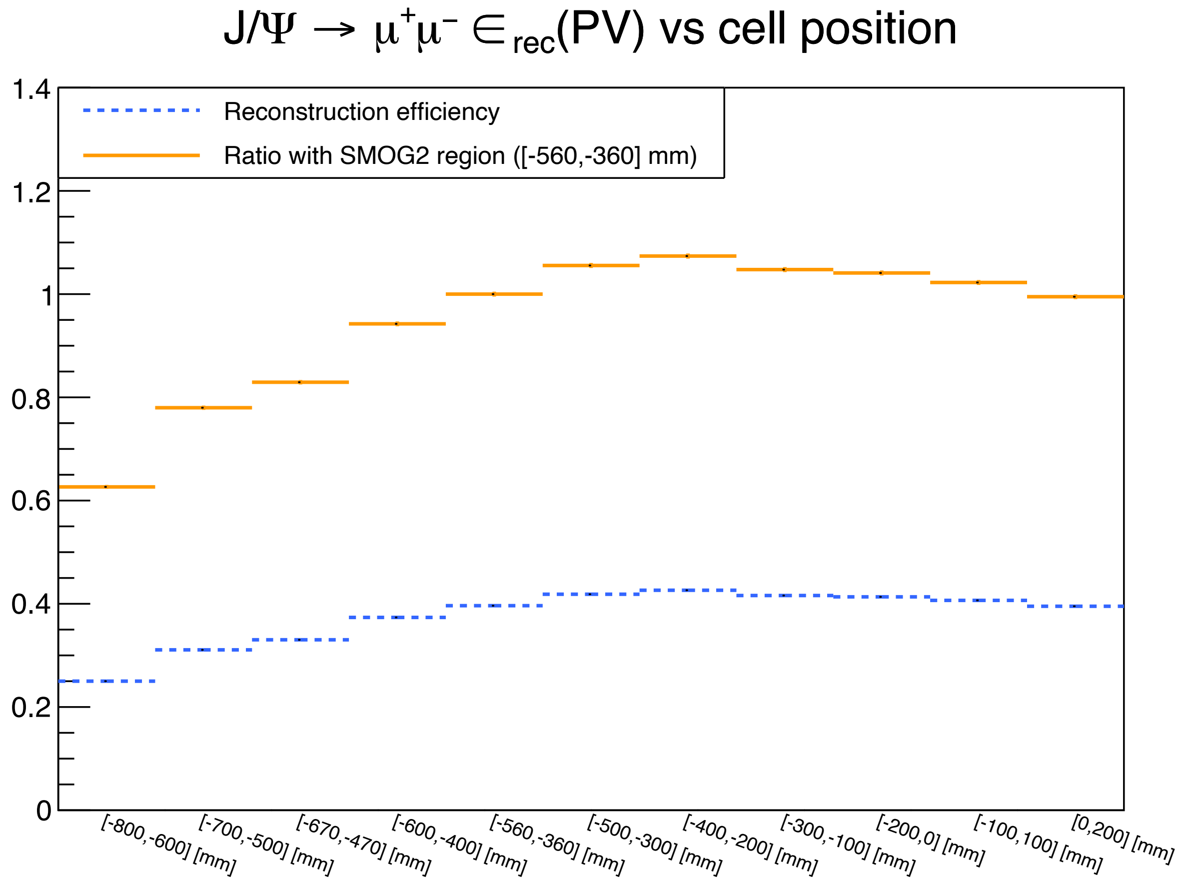
Expected yields for Run4 (Run4+Run5):

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
- $Stat(Run5) \sim \sqrt{5}\, Stat(Run4)$

Reconstruction efficiencies



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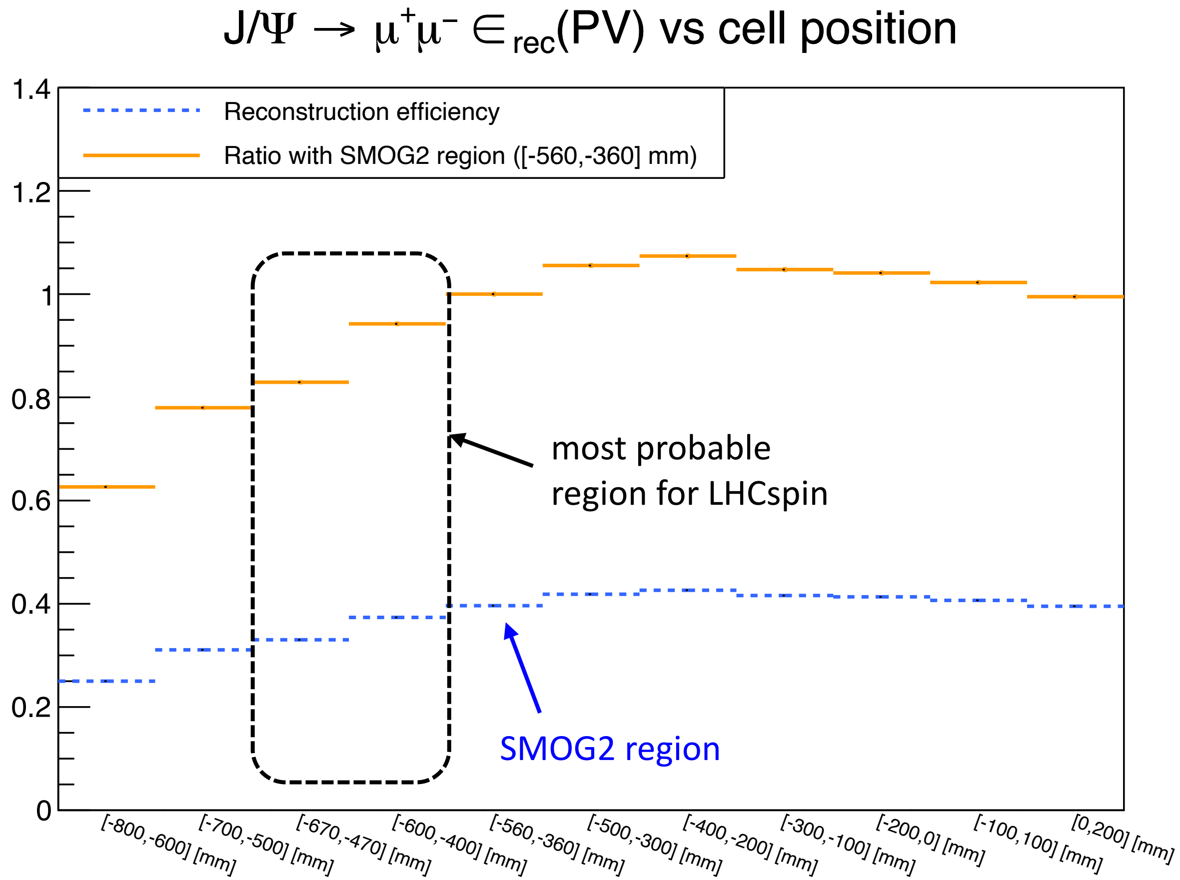
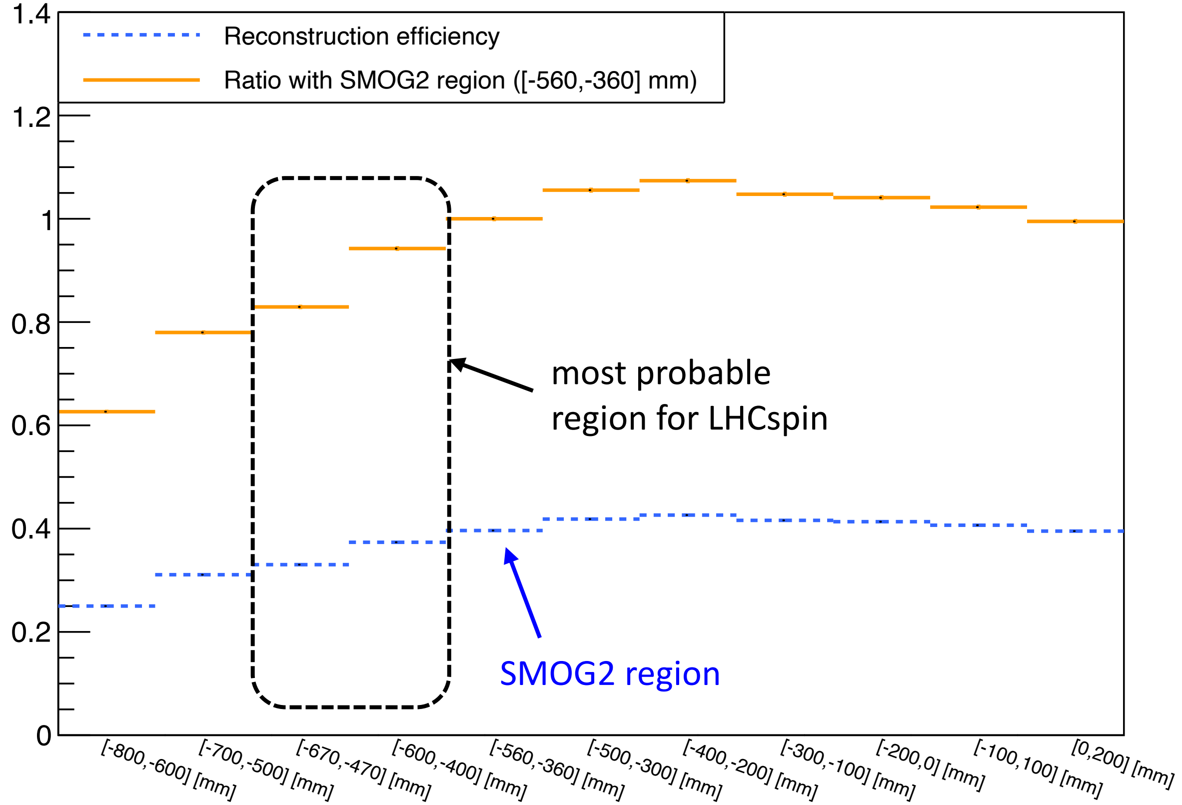


most probable region for LHCspin

SMOG2 region

Reconstruction efficiencies

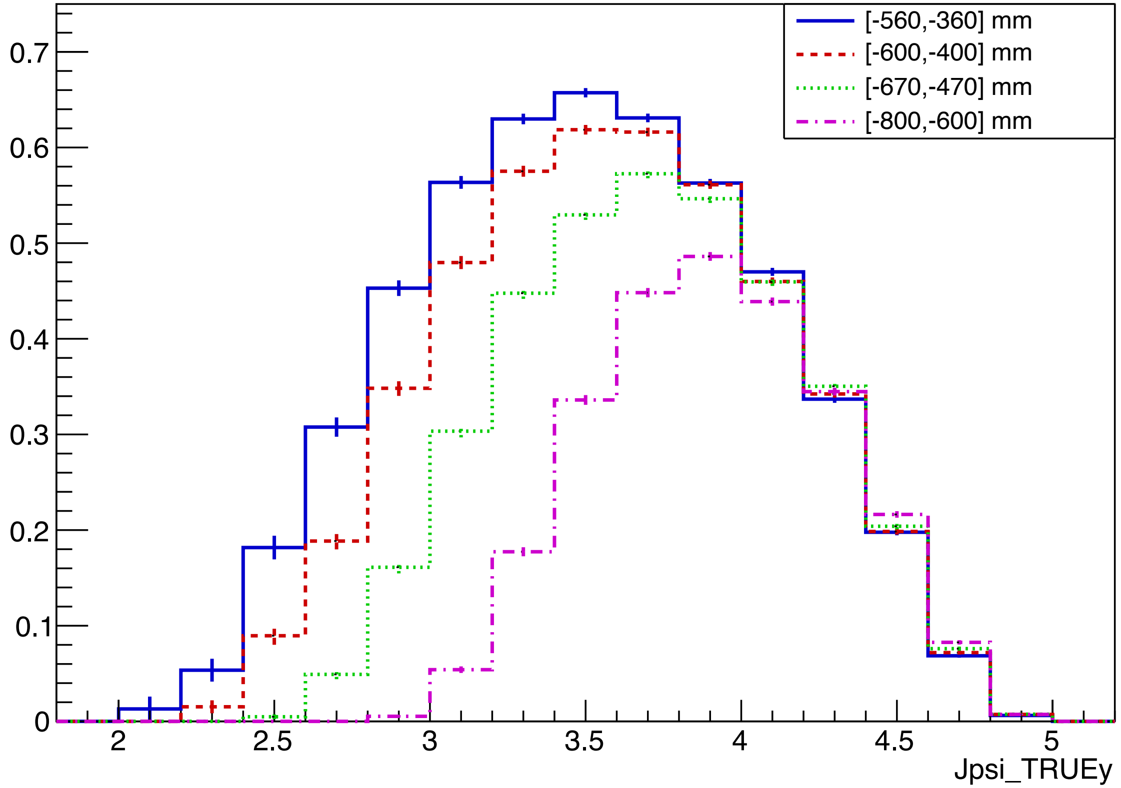
$J/\Psi \to \mu^+\mu^- \in_{rec}(PV)$ vs cell position



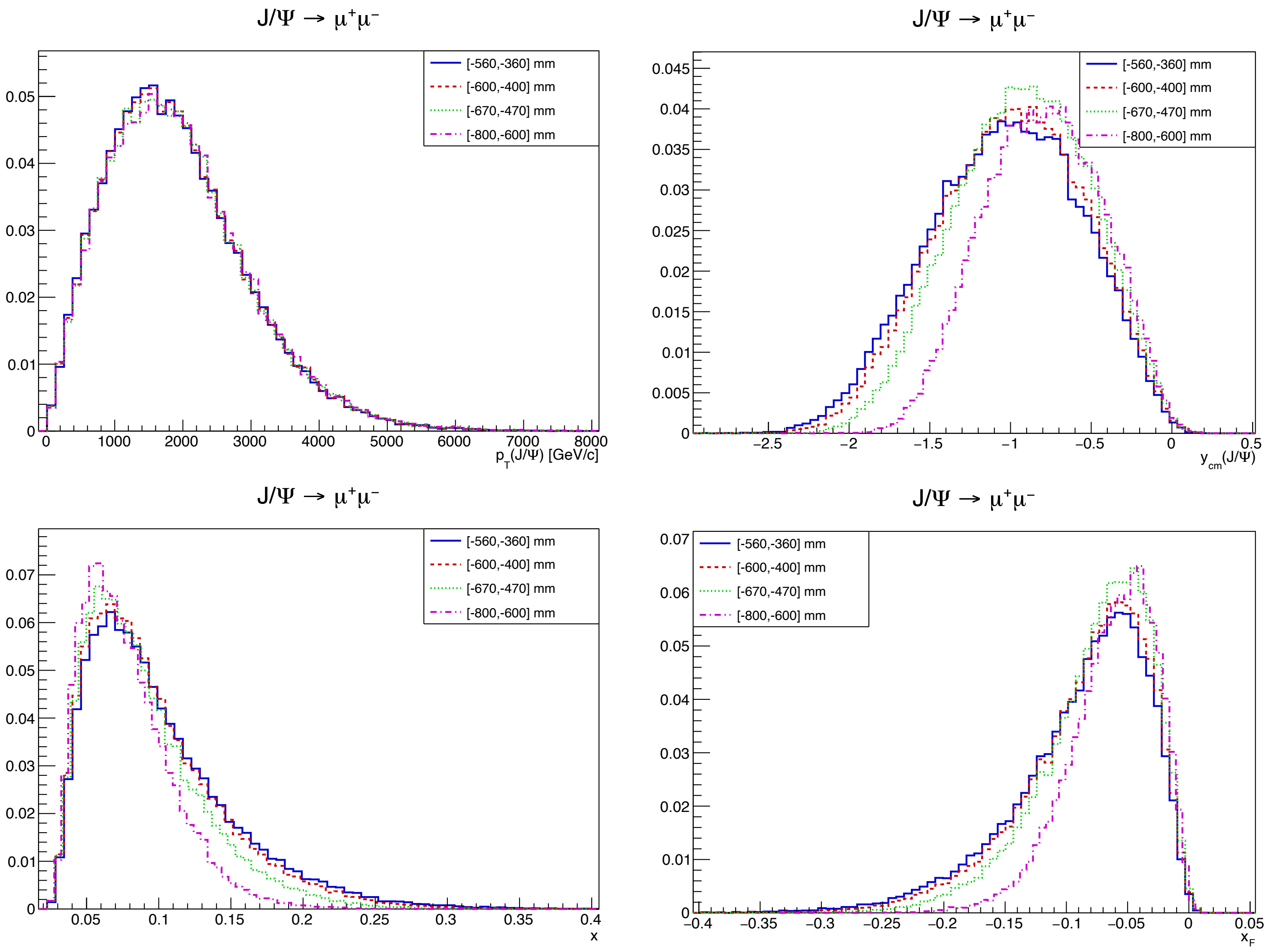
most probable region for LHCspin

SMOG2 region

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



Kinematic coverage



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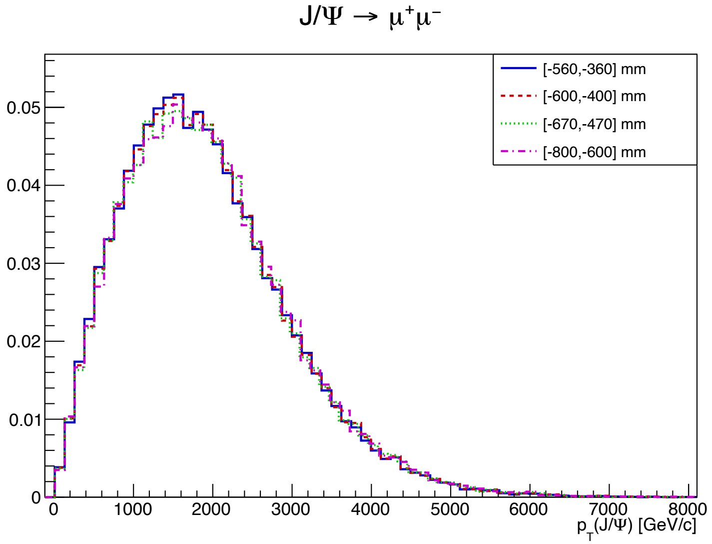
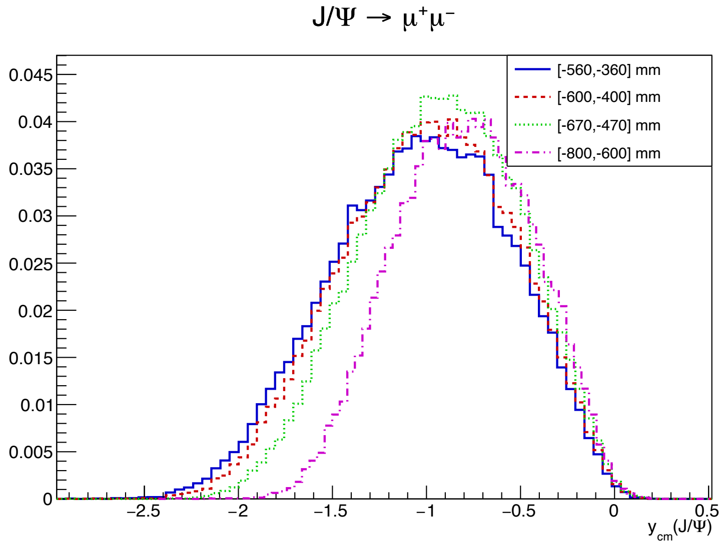

$J/\Psi \to \mu^+\mu^-$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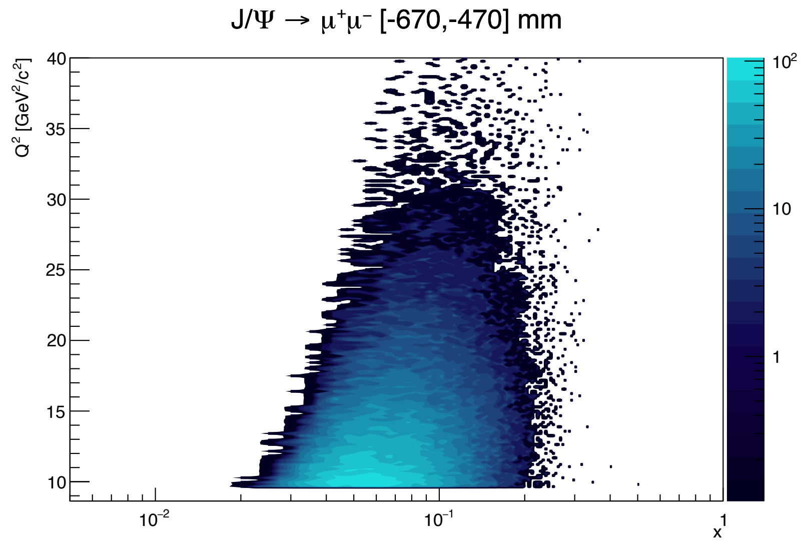
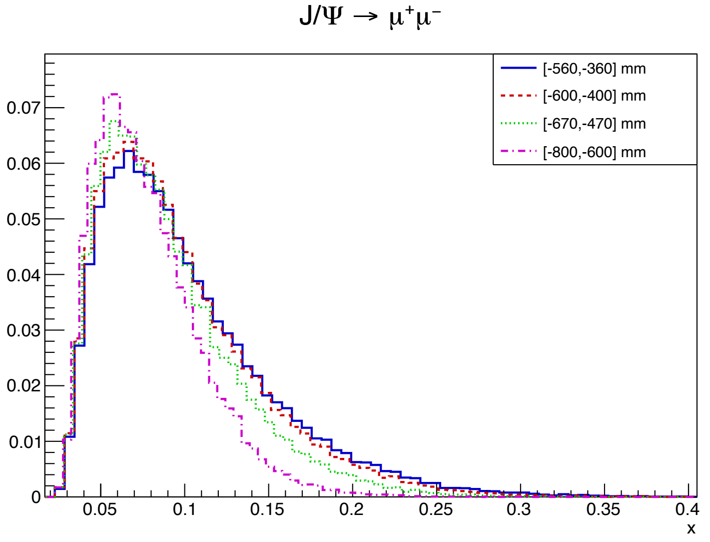

$J/\Psi \to \mu^+\mu^-$ [-670,-470] mm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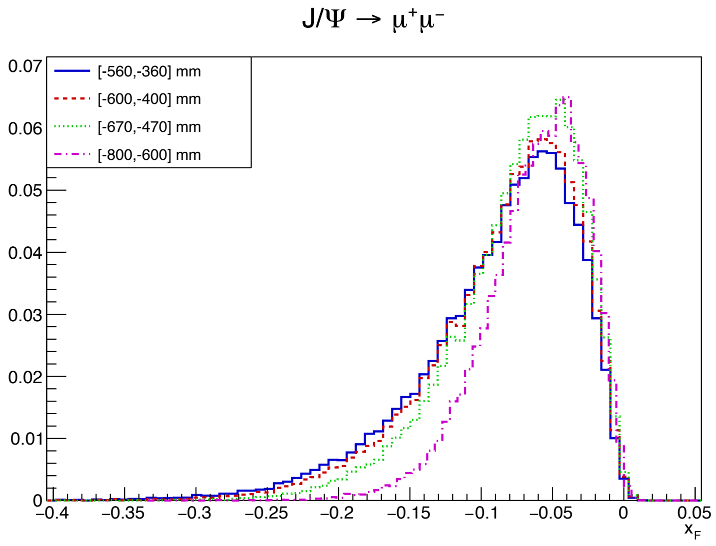
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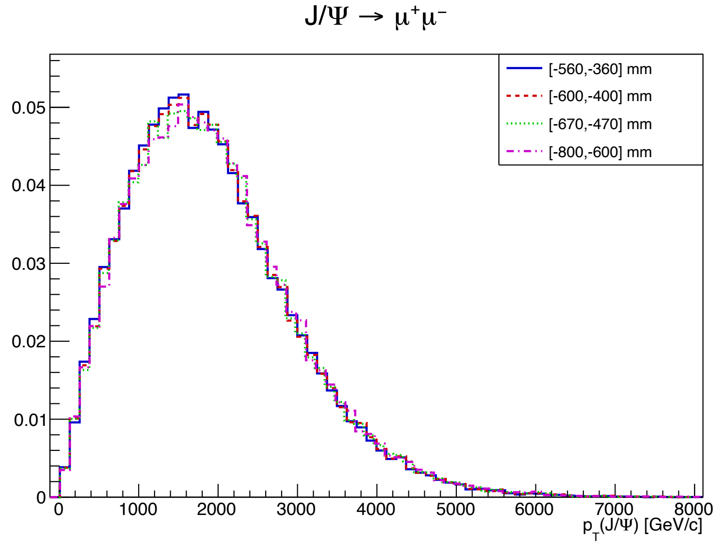

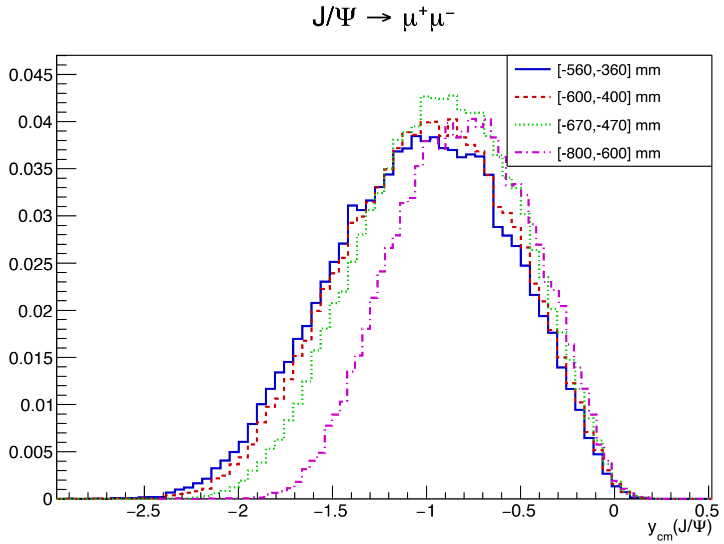

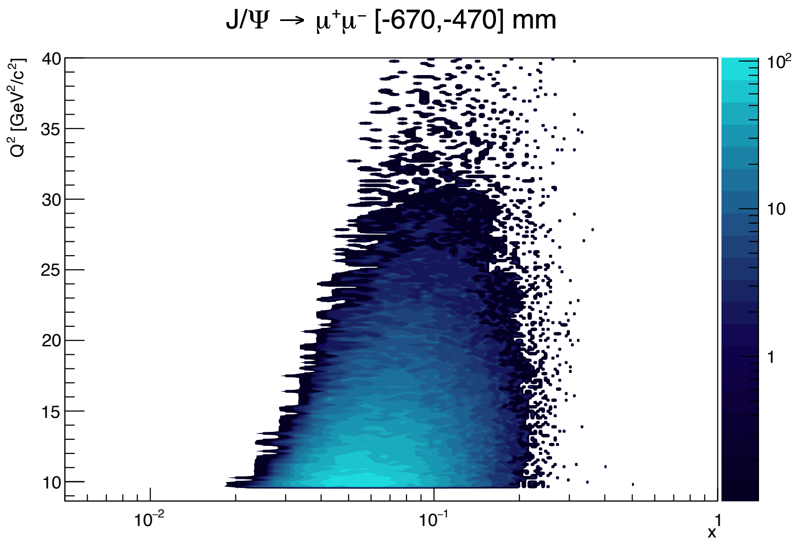

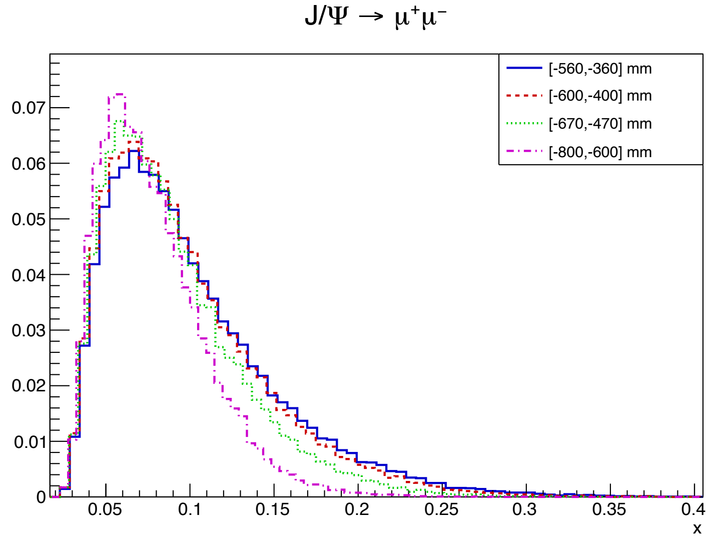

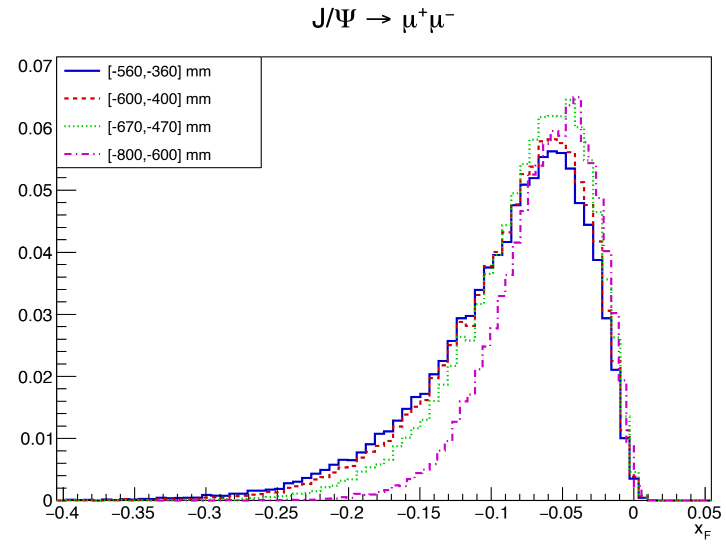

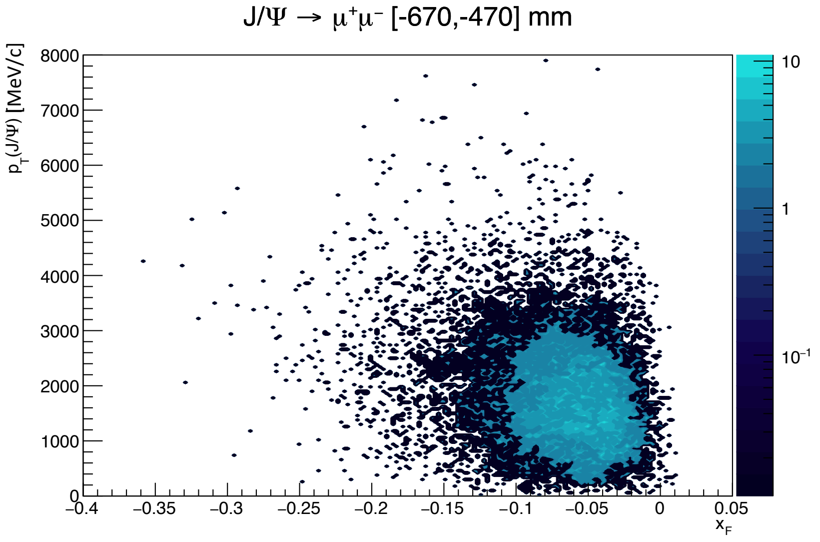

A preliminary analysis tool for pseudo-data

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

A preliminary analysis tool for pseudo-data

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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)
- Assign to each simulated event a target polarization state (↑ or ↓) using a random extraction modulated with a model for the cross section (in this way we introduce a spin-dependence in the simulation)
- 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):

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

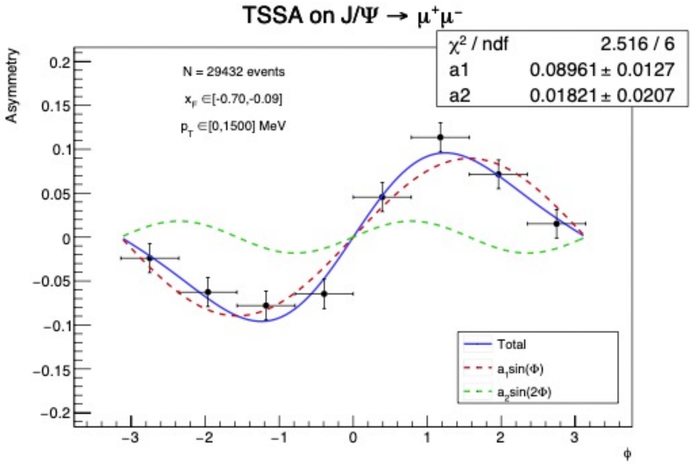
- Using these pseudo-data the TSSA is computed in the usual way:

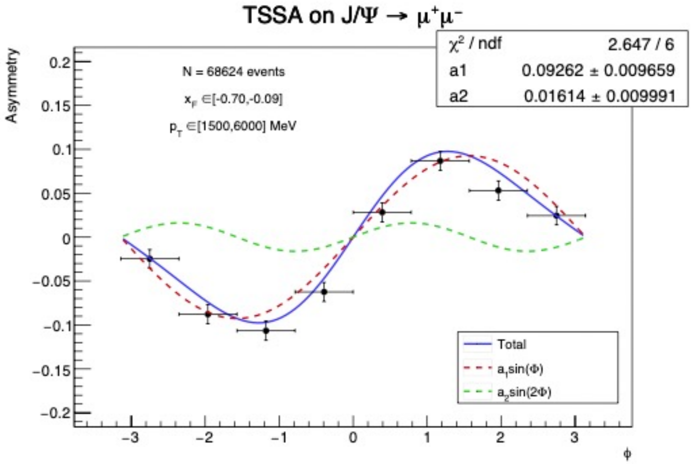
$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

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 of 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

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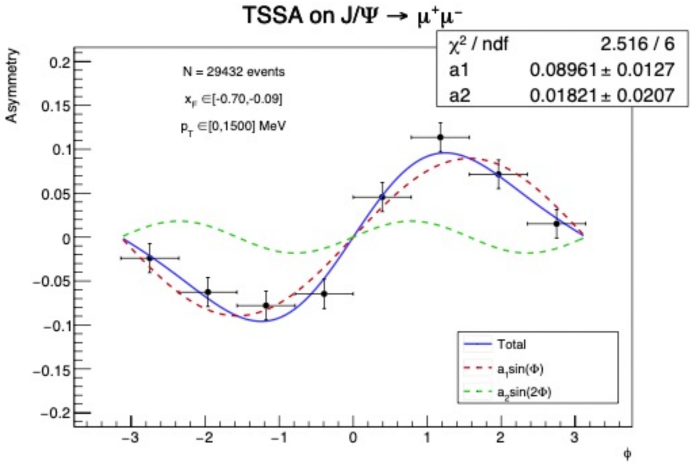

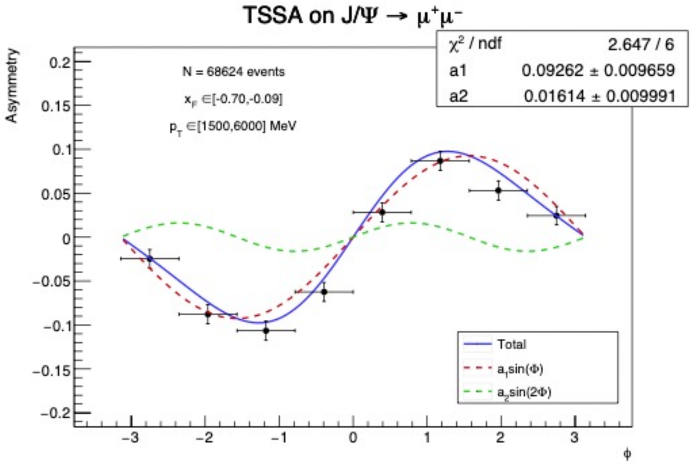

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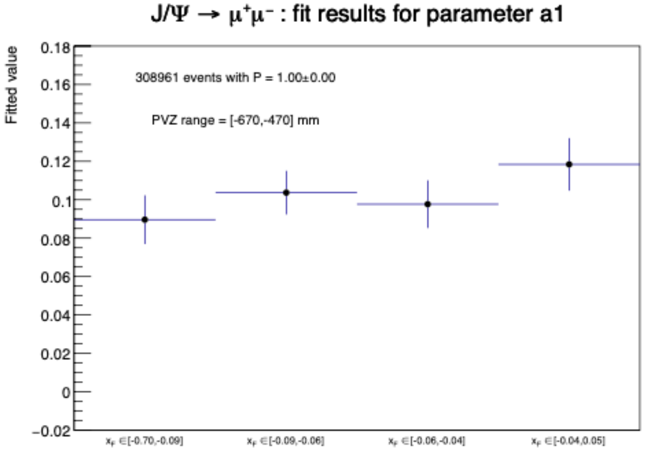
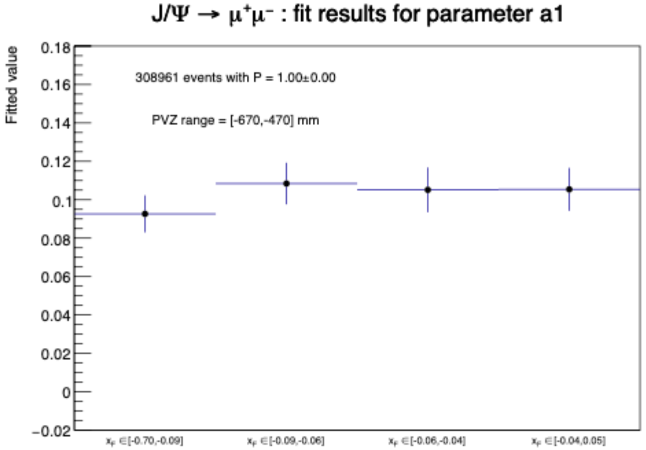
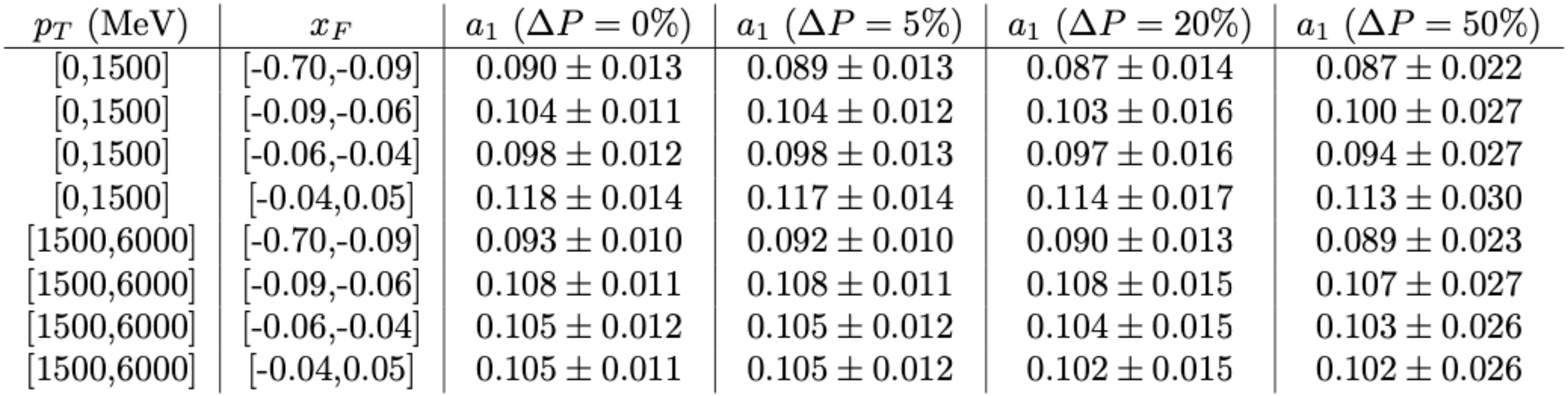




- The amplitudes a_1 are the reported vs. x_F in bins of p_T (and vice-versa)
- A mild kinematic dependence is observed consistent with the model

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

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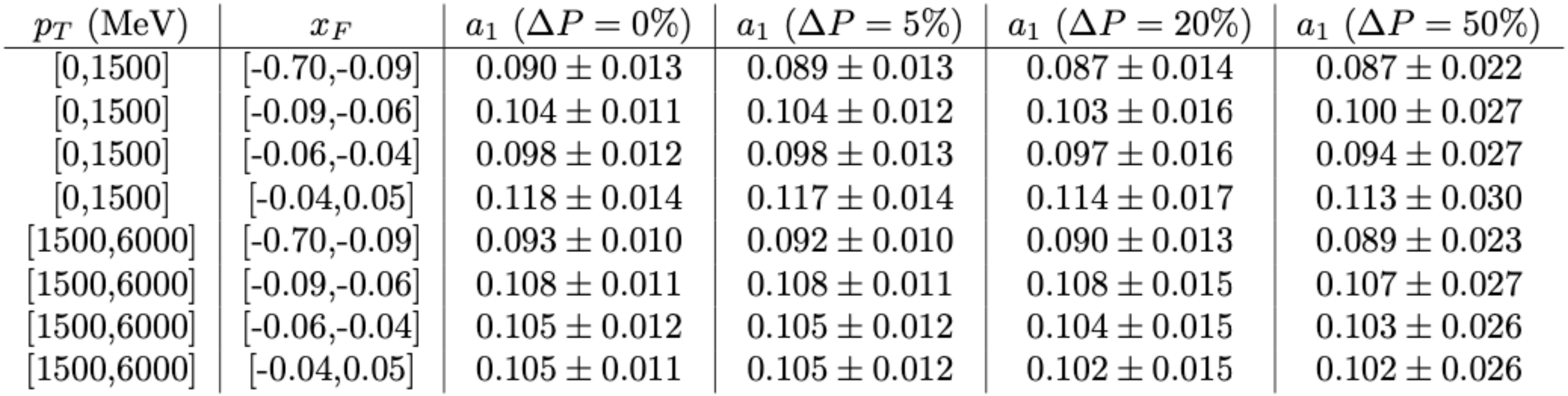

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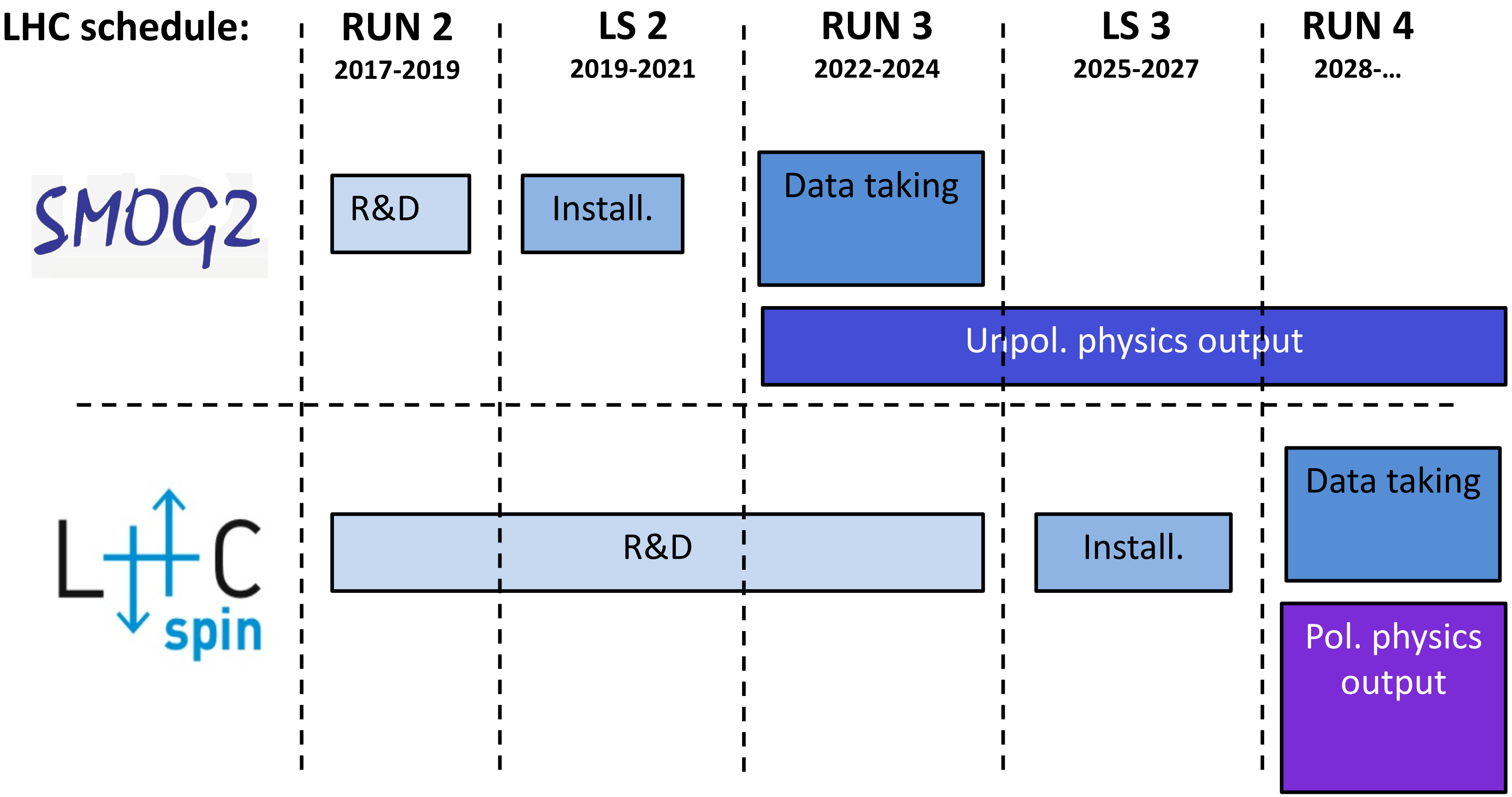
[1500,6000]	[-0.04,0.05]	0.105 ± 0.011	0.105 ± 0.012	0.102 ± 0.015	0.102 ± 0.026

- 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 $\Delta P \approx 10 - 15\%$ for the storage cell hypothesis (and close to 0 for the jet target hypothesis)**

The time schedule of the project



Conclusions

- The FT 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 ambitious physics program
- Novel approaches and reactions will be exploited for studies of the 3D nucleon structure
- First insights into the yet unknown gluon TMDs (such as the GSF) will be possible thanks to the excellent capabilities of LHCb in reconstructing quarkonia states and heavy mesons.
- Cutting-edge unpolarized physics will also be at reach (cold nuclear matter effects, intrinsic charm, QGP studies, etc.)
- The R&D calls for a new generation of polarized gas targets. A very challenging but worth the effort!

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

Backup

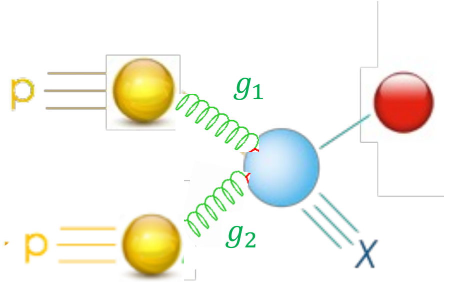
Probing the gTMDs

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

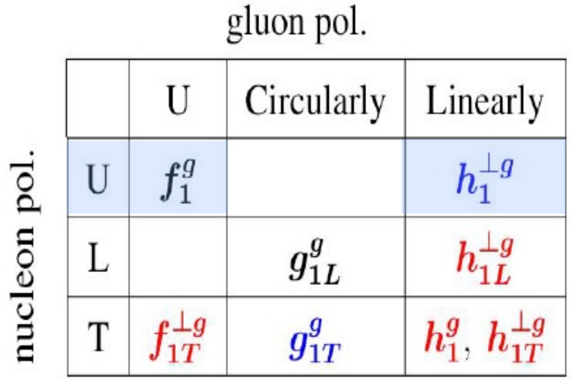
$$\Big\{F_1(M_{QQ},\theta_{\rm CS})\,\mathcal{C}\Big[f_1^g f_1^g\Big](x_{1,2},\boldsymbol{P}_{QQ_T})$$

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

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

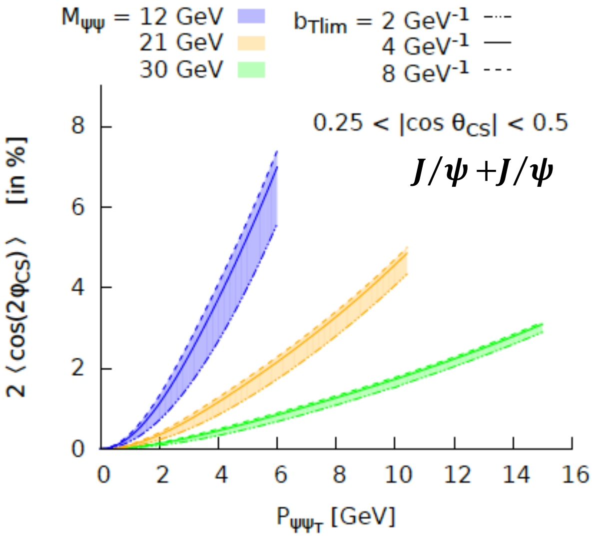


$$\begin{cases} J/\psi + J/\psi \\ \Upsilon + \Upsilon \\ \dots \end{cases}$$

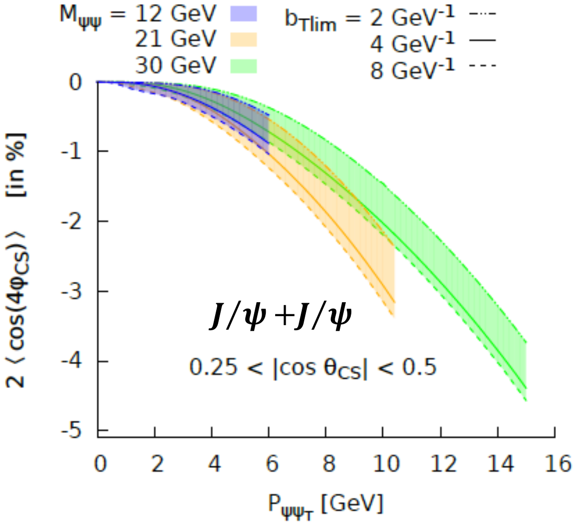


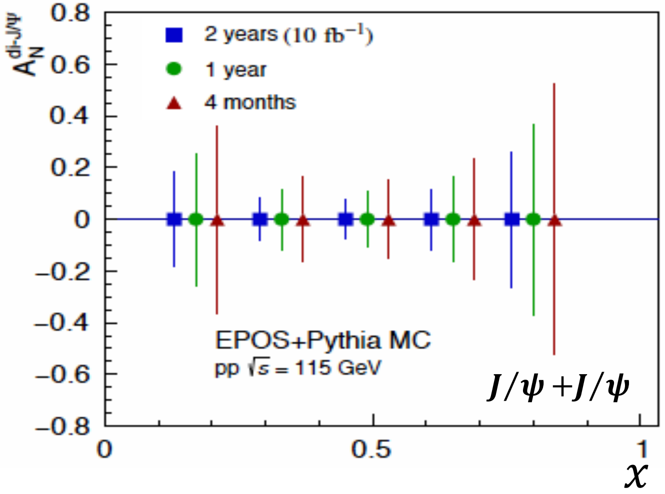
nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

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%!





A synergic attack to gTMDs

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

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

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

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

🟥 Can be measured at the EIC

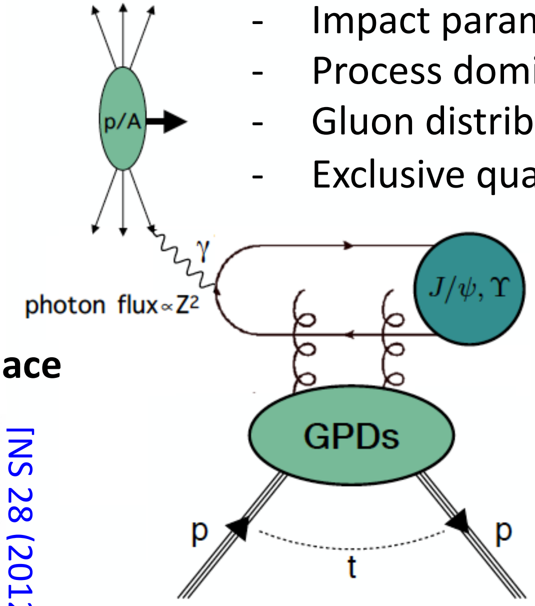
🟦 Can be measured at RHIC & LHC (including LHCb+SMOG2/LHCspin)

🟨 Can be measured at RHIC and LHCb+LHCspin

UPC and gGPDs

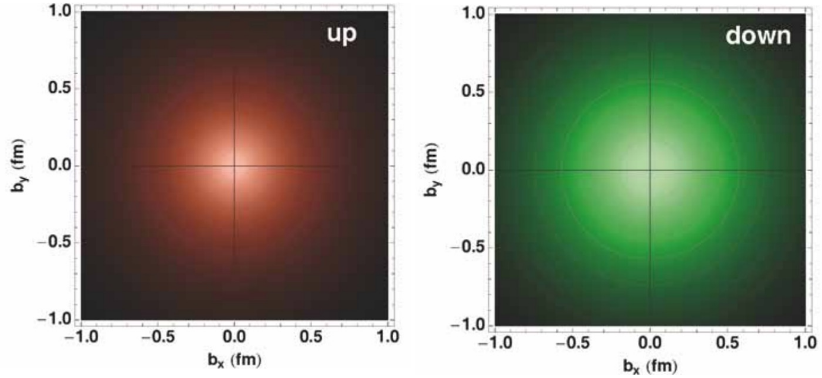
GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

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

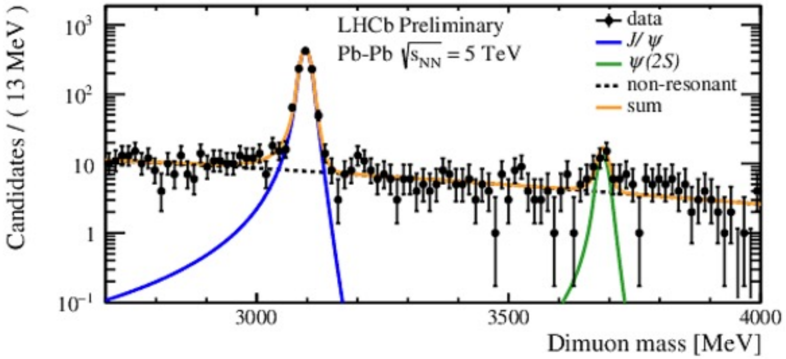


- Impact parameter larger than sum of radii
- Process dominated by EM interaction
- Gluon distributions probed by pomeron exchange
- Exclusive quarkonia prod. sensitive to gluon GPDs [PRD 85 (2012), 051502]

3D maps of parton densities in coordinate space

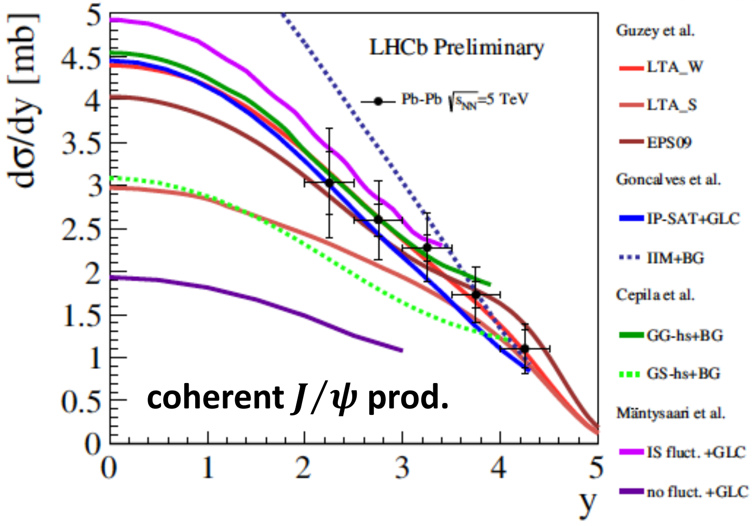


[NS 28 (2012), 1]



[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)

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

Cell coating R&D

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

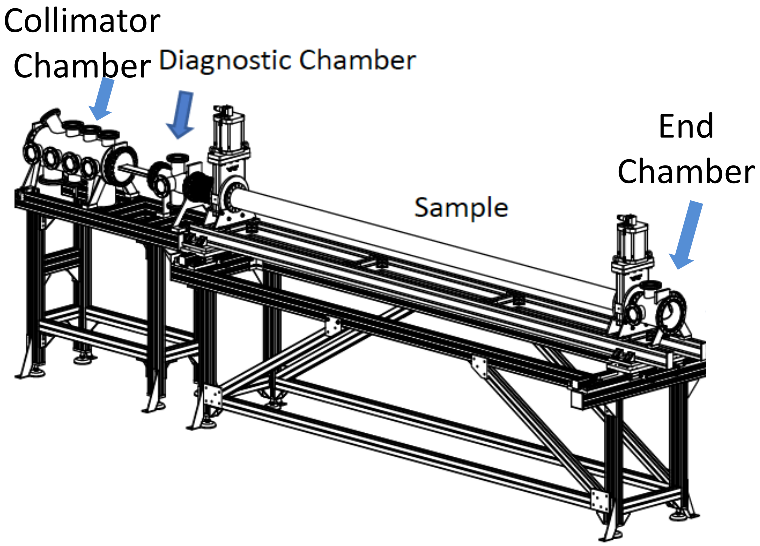
- ✓ **minimize e-cloud** related beam instabilities → ensure low Secondary Elecron Yield (SEY)
- ✓ **minimize H depolarization** due to wall collisions → can be monitored through measurement of H recombination

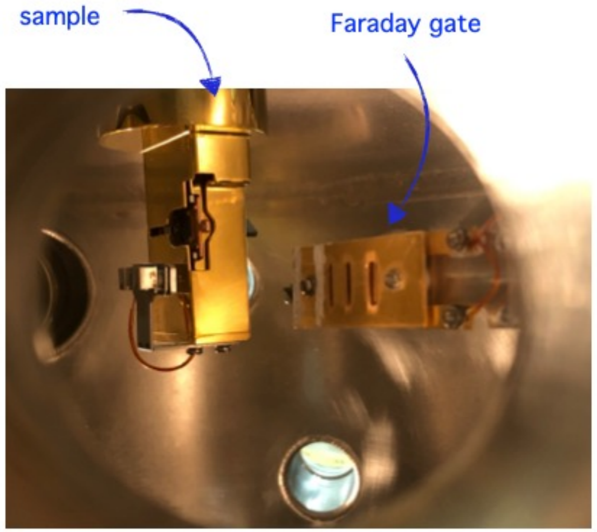
Teflon and Drifilm (HERMES) not compatible with LHC requirements. **Amorfous Carbon** (a-C) is allowed but may induce depolarization. Possible solution (a-la HERMES): generate a **thin layer of ice on top of a-C coating**

- reduces the depolarization
- ensures a renewable surface
- requires to cool down the cell to $\sim 100\ K$
- could cause a larger SEY
- Need to be investigated → **dedicated R&D**

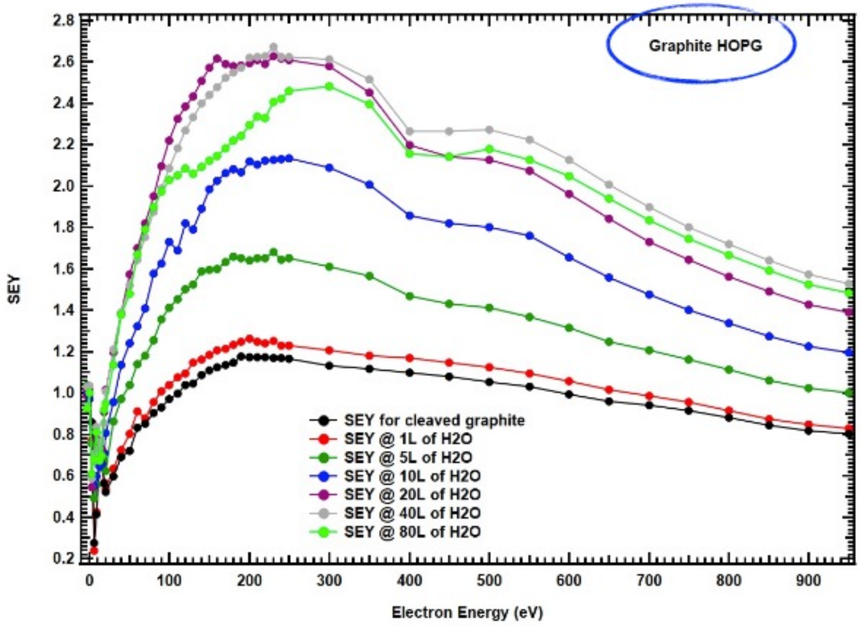
The **ARYA project at INFN-LNF**:

- existing surface-coating laboratory has been equipped with UHV ultrapure water dosing system
- SEY measurement through electron gun on target vs H_2O dose

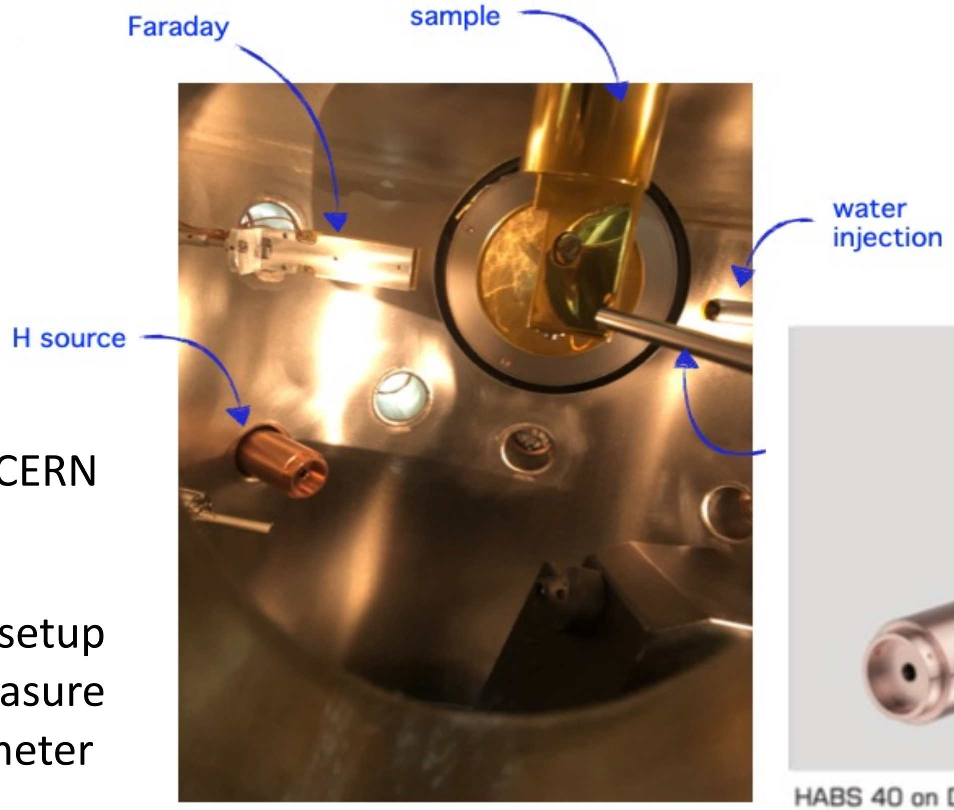




Cell coating R&D



- SEY measurements on grafite vs incident electron energy with 1, 4, 10, 20, 40, 80 monolayers of H_2O at 90K
- Max SEY = 2.6: impact on LHC is under evaluation



HABS 40 on DN40CF (O.D. 2.75") flange

Next steps:

- Measurement on the actual a-C sample from CERN
- **Measurement of H recombination**

H recombination studies: with the same setup inject H by means of an atomic source and measure H/H_2 fraction vs H_2O dose with a mass spectrometer

Independent depolarization studies on a-C ongoing in Juelich (dedicated laboratory)

Main reactions or interest (…an incomplete wishlist)

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

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

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

☛ **TMDs of valence and sea quarks**

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

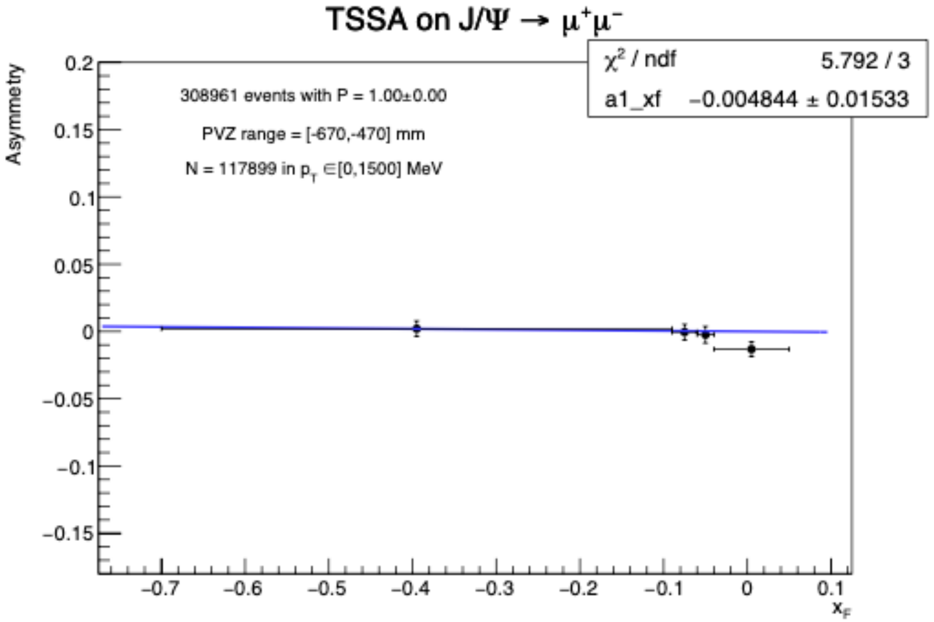
☛ **Pol and unpol gluon PDFs**

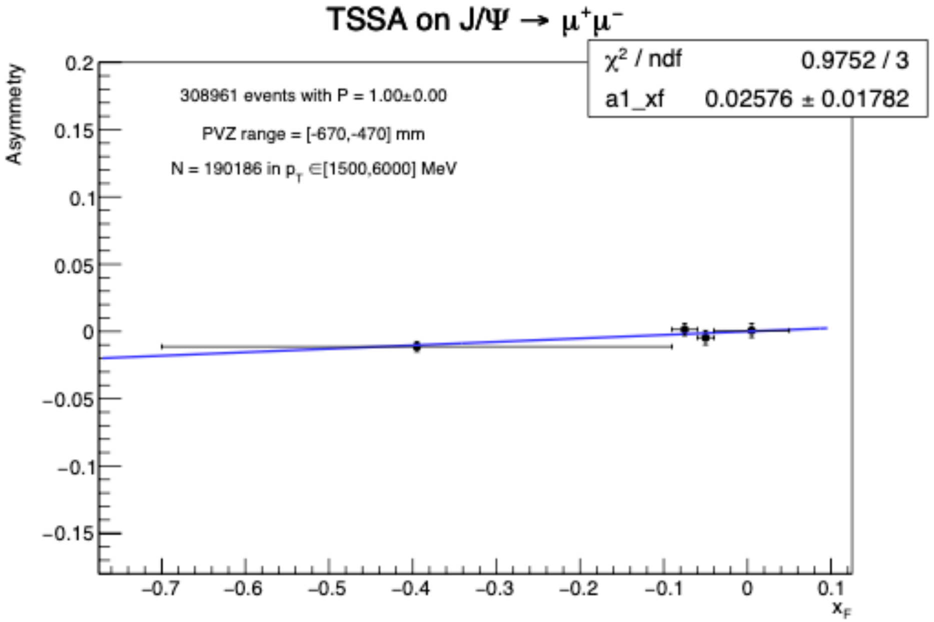
- pA, PbA $\ (A = He, Ne, Ar, Kr, \ldots)$

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

A preliminary analysis tool for pseudo-data

- A simpler approach is also developed which consists in evaluating the TSSA directly from the yields in each 2D bin





- A linear fit is also shown to quantify the mild kinematic dependence of the asymmetry