The LHCspin project
A polarized internal target for the LHC

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on behalf of the LHCspin working group

PSTP2024

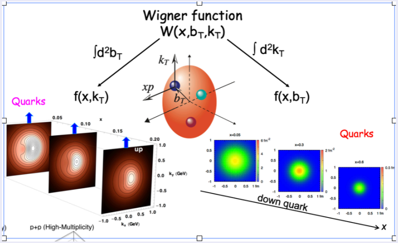
20^{th} *Workshop on Polarized Sources, Targets, and Polarimetry*

September 26^{th}, 2024

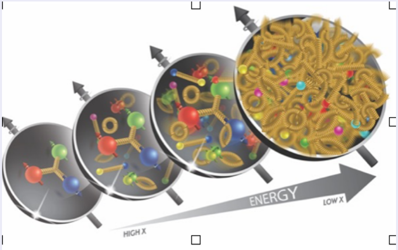
Motivation

Wide range of new physics scenarios with polarization at LHC

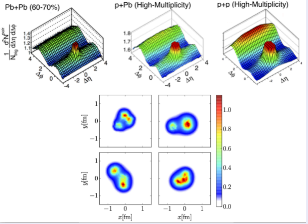
Hadron Tomography



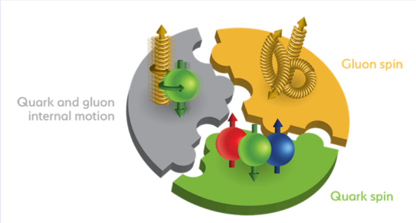
Hadron Structure



Collective Phenomena

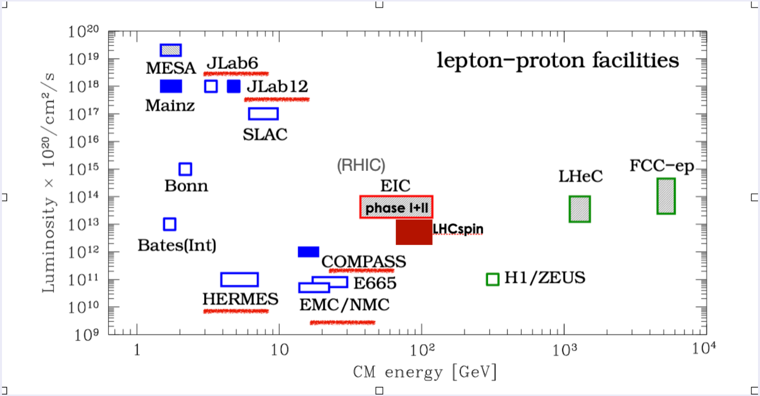


Spin Structure



Worldwide effort

Past present and future experiments with polarization



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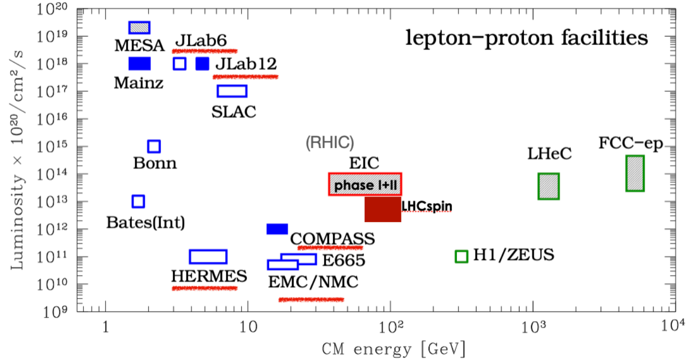
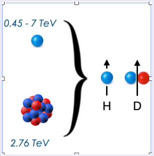


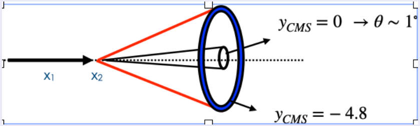
Issue at LHC

- LHC beams cannot be polarized.
- Polarized fixed-target: only option for polarized collisions

Kinematic plane for a fixed target experiment at LHC



- p-p: 0.45-7 TeV beam on fix target
  $\sqrt{s} = \sqrt{2m_N E_p}$: 41 – 115 GeV
- A-p: 2.76 TeV beam on fix target



- x_1: beam; x_2: target
- Large CM boost ($\gamma = \frac{\sqrt{s_{NN}}}{2m_p} \simeq 60$)
  large x_2 (X_F <0), small x_1

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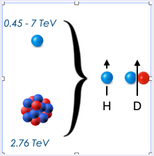

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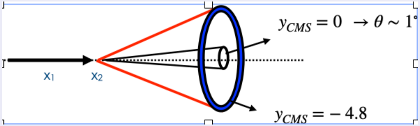

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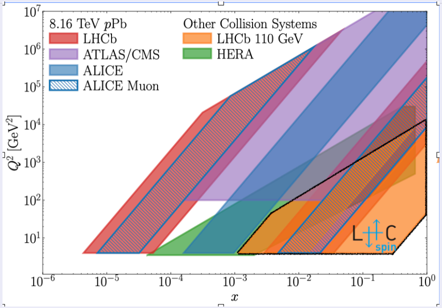


- Broad and poorly explored kinematic range

LHCb: a collider detector ...

- LHCb is a general-purpose forward spectrometer, fully instrumented in $2 < \eta < 5$, and optimised for c and b hadron detection
- Excellent momentum resolution with VELO + tracking stations:

  $\sigma_p/p = 0.5 - 1.0\,\%$ $(p \in [2{,}200]$ GeV$)$
- Particle identification with RICH+CALO+MUON

$\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$

- Low momentum muon trigger:

  $p_{T_\mu} > 1.75$ GeV (2018)

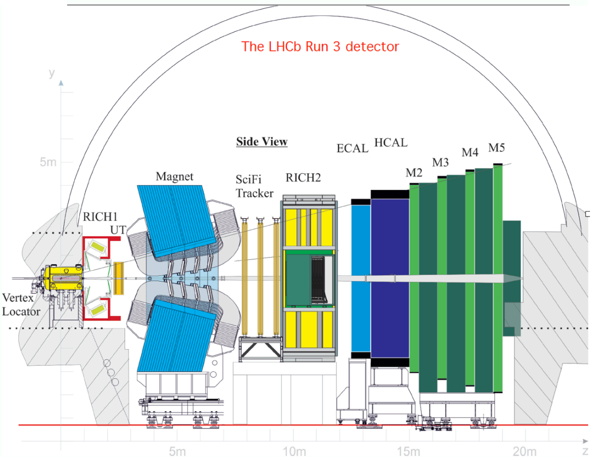
will be reduced thanks to the new fully-software trigger

- Major detector upgrades performed during LS2 for the Run 3 (5x luminosity)

[JINST 3 (2008) S08005]

[IJMP A 30, 1530022 (2015)]

[Comput Softw Big Sci 6, 1 (2022)]



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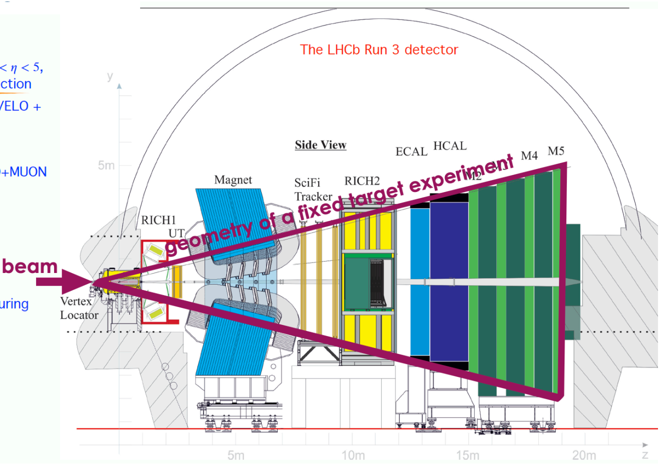
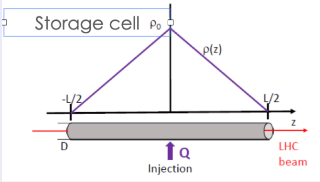
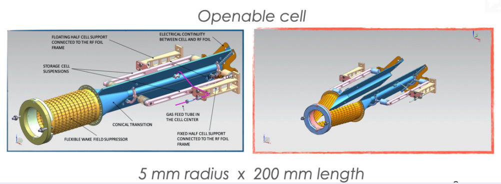


The SMOG2 apparatus

SMOG2 an unpolarized target at LHCb

- Openable storage cell installed in Autumn 2020 - operational since 2022





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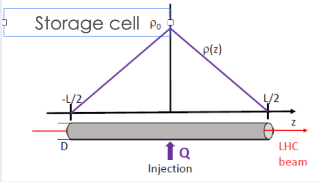
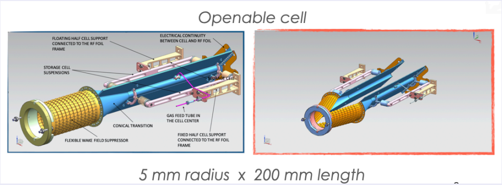
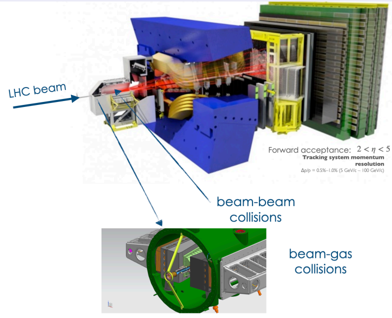


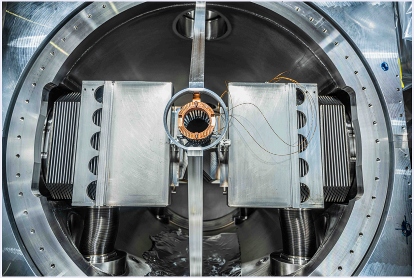


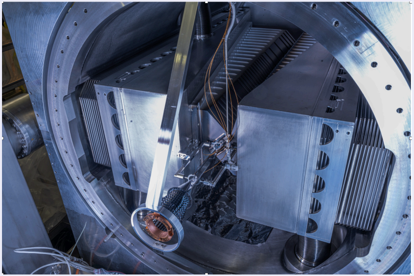
- LHCb successfully operating in both fixed target and collider modes



SMOG2 an unpolarized target at LHCb

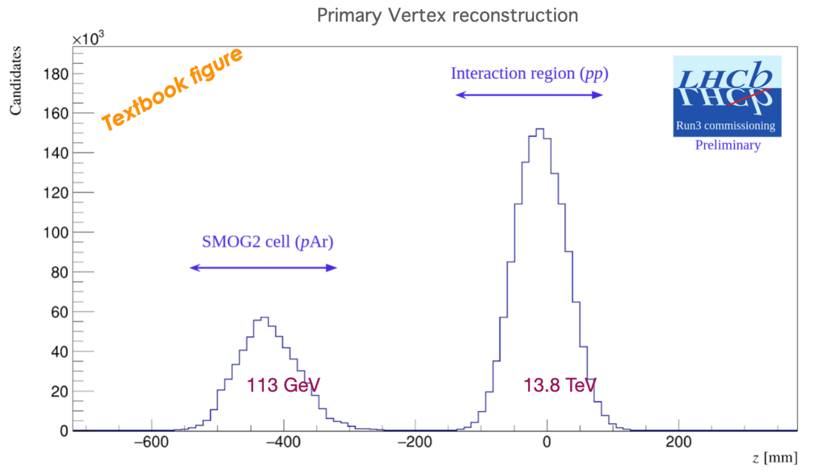
Only system in the LCH primary vacuum





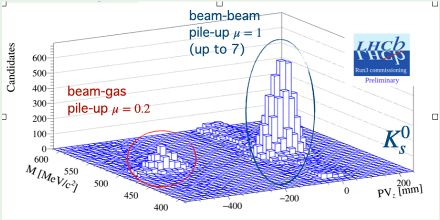
SMOG2 early results - 1

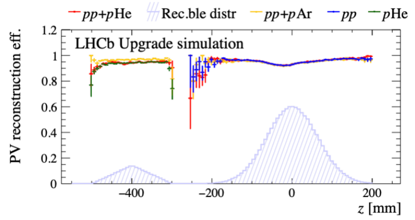
Two well separated and independent interaction points operaing simultaneously

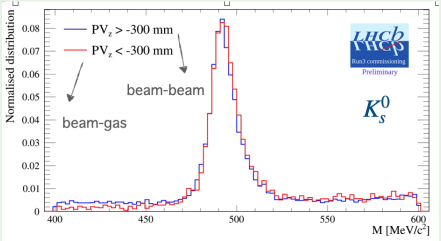


- *Selected for publication as Editor's suggestion on Phys. Rev A&B*

SMOG2 early results - 2







- beam-beam and beam-gas interactions well detached
- same resolution for beam-gas and beam-beam interactions

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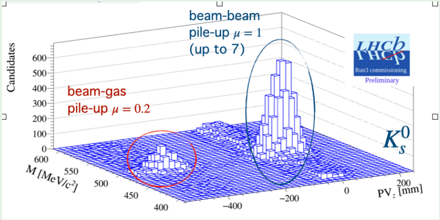
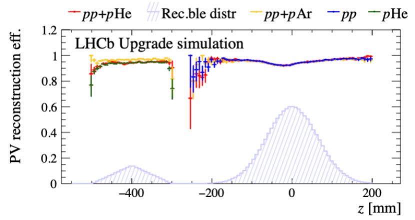
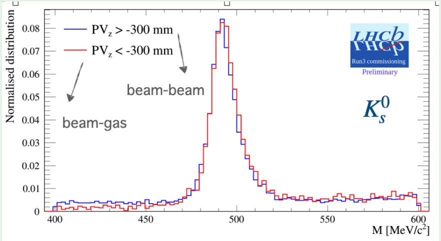






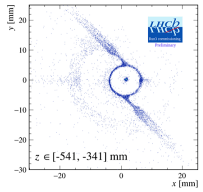
- beam-beam and beam-gas interactions well detached
- same resolution for beam-gas and beam-beam interactions

LHCb is the only experiment able to run in collider and fixed target mode simultanously

SMOG2 early results - 3

Cell tomography from residual gas and secondary interactions

2D



3D

SMOG2 early results - 3

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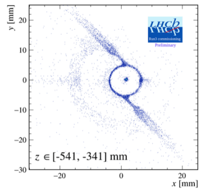
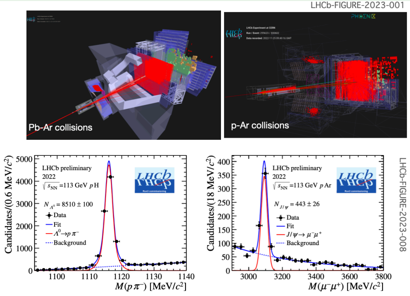


3D

Excellent results in only 18 minutes of data taking

- Λ and J/Ψ identification



LHCspin

Physics perspectives

Physics goals

- 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
- Measure exclusive processes to access GPD

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Event rates

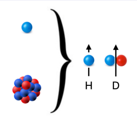
- Huge statistics
- Precise spin asymmetry on $J/\Psi \to \mu^+\mu^-$ and $D^0 \to K^+\pi^0$ for pH↑ collisions

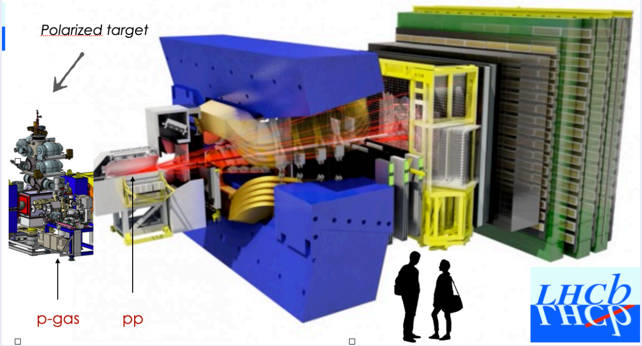
Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 <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

Statistics further enhanced by a factor 3-5 in LHCb upgrade II

A polarized target at LHCb

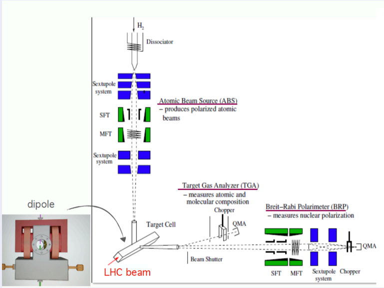
Successful technology based on HERA, COSY and RHIC experiments





Experimental setup

From the HERMES/PAX target setup



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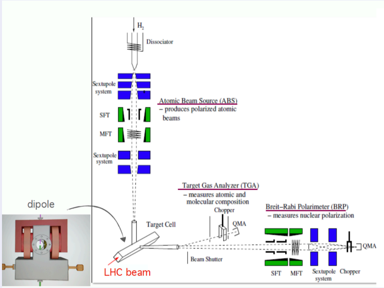
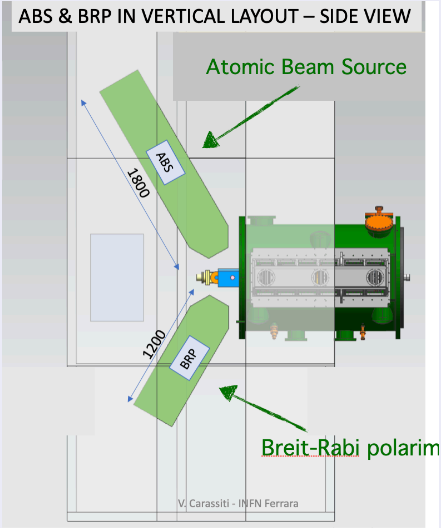


To a new generation of fixed target experiments

- Luminosity
  - Target density (H): $3.7 \times 10^{13} cm^{2}$
  - LHC beam (Run5): $6.8 \times 10^{18} ps^{-1}$
  - $L_{pH} = 2.5 \times 10^{32} cm^{-2} s^{-1}$
- Negligible impact on beam lifetime:
  - induced $\tau^{p-H}_{beam-gas} \sim 2000$ days;
  - typical τ_{LHC}: 10 h

Polarized gas target implementation

ABS + BRP polarmeter



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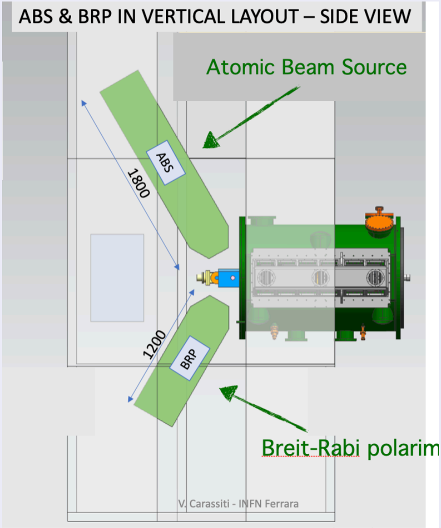
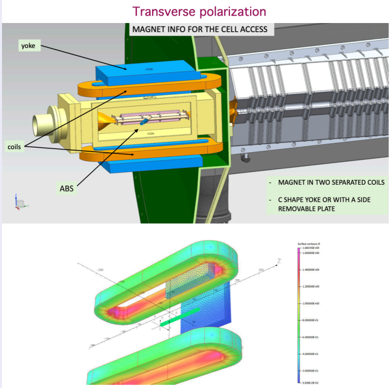


Holding field

- Compact dipole magnet
- B = 300 mT with polarity inversion
- Possibility to switch to a solenoid and provide long. polarization



Storage cell coating: amorphous carbon

Amorphous carbon as low emission yield material

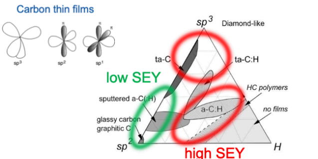
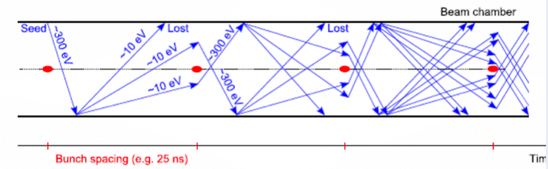


Fig. 2. Ternary phase diagram of bonding in amorphous carbon–hydrogen alloys.

J. Robertson / Materials Science and Engineering R 37 (2002) 129–281



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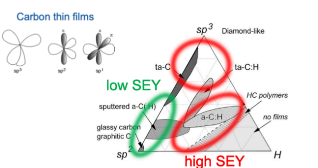

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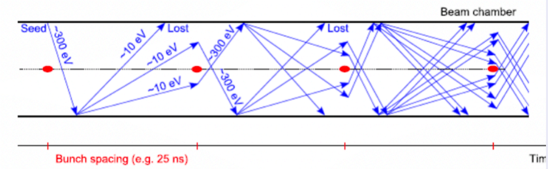
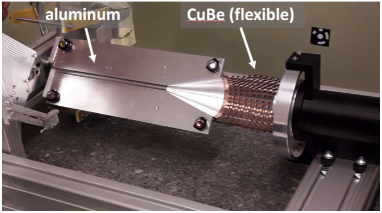
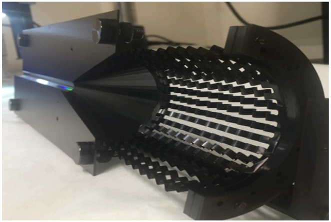


SMOG2 cell coating

SMOG2 non coated cell



SMOG2 amorphous Carbon coated cell



Coating issues for a polarized storage cell

Previous experience

- HERA and COSY: Drifilm (silicon) or Teflon (fluoride) coatings combined with ice layers, kept SEY low and prevented recombination
- LHC: no fluoride or silicon materials allowed

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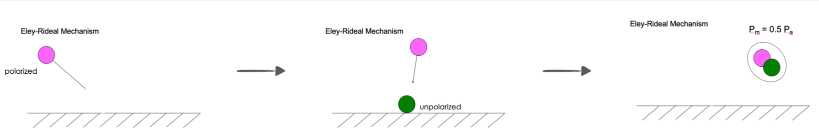
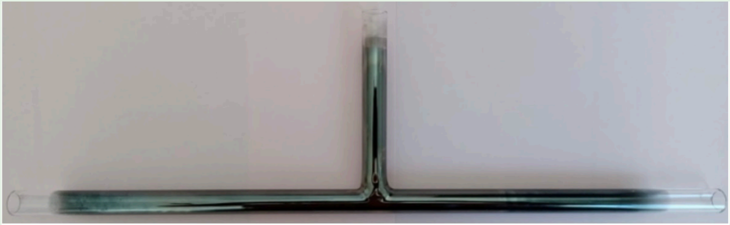
Amorphous carbon properties

- Amorphous carbon: excellent for low SEY
- What about recombination?
- Eley-Rideal recombination mechanism:



Polarization measurement on an amorphous carbon coated cell

Quartz cell coated with amorphous carbon



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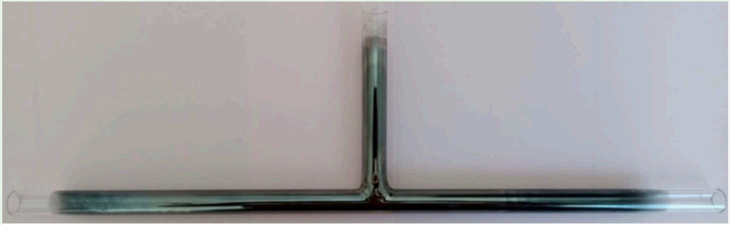
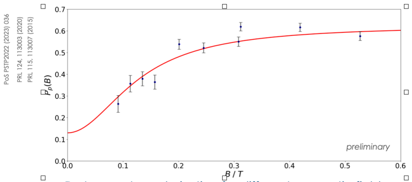


Measurements with Lamb-shift polarimeter setup at FZ-Jülich



Proton vector polarization for different magnetic fields
- aC coating -

Initial atomic polarisation $P_a = 0.90$
Recombination rate 95.8 - 100 %

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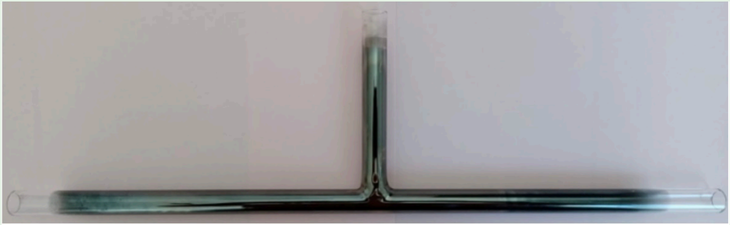

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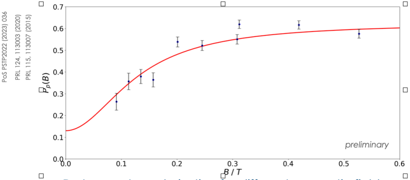

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Result: recombined molecules preserve polarization! → talk by R. Engels

Inverting the paradigm: a polarized molecular target

- Exploitation of recombination effects. Possible if:
  1. Recombination "fast enough" to recombine two polarized atoms
  2. Recombination rate high
- Development of a new storage cell with polarized molecules
  - High density
  - Better polarization preservation

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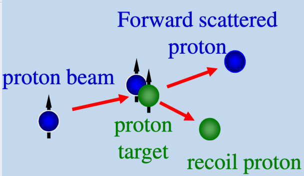
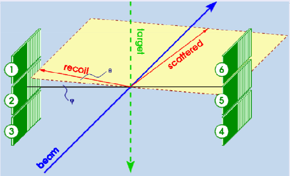
Problem

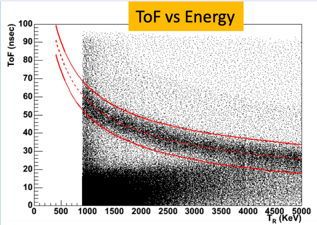
- Breit-Rabi polarimeter cannot measure molecular polarization
- Absolute polarimeter required!

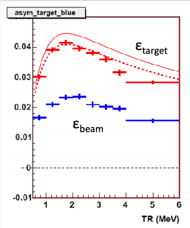
Absolute Polarimetry with Carbon Nuclear Interference (CNI)

Recoil spectrometer at RHIC







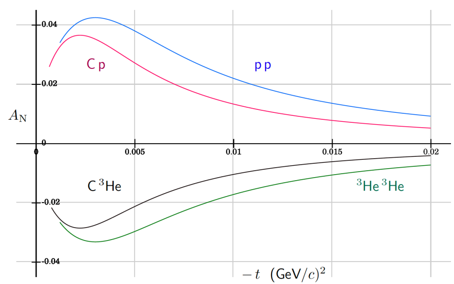


- Array of Si detectors measures T_R & ToF of recoil proton.
- Channel no corresponds to recoil angle θ_R.
- Correlations (T_R & ToF) and (T_R & θ_R) $\rightarrow$ elastic process
- $A_N \rightarrow$ beam/target polarization

Recoil polarimetry at LHCspin

Estimations from N. Buttimore (Trinity College)

- Analyzing power:



- Cross section at 7 TeV: σ_{tot} = 47 mb (255 GeV: σ_{tot} = 39.2 mb)
- Recoil energies at 7 TeV: 1.7 MeV $< T_R <$4.6 MeV
- Recoil angles at 90^o: 30 mrad $< \theta <$ 50 mrad

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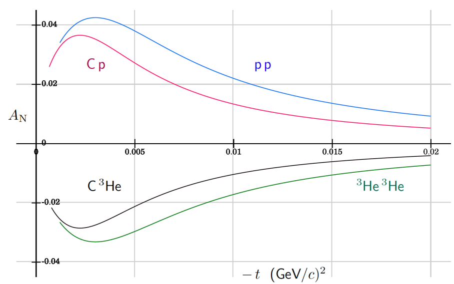

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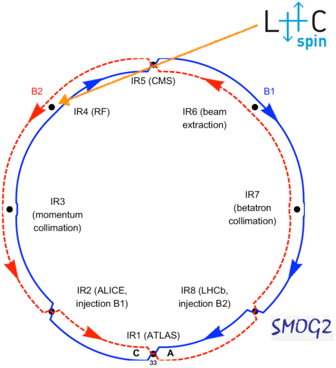
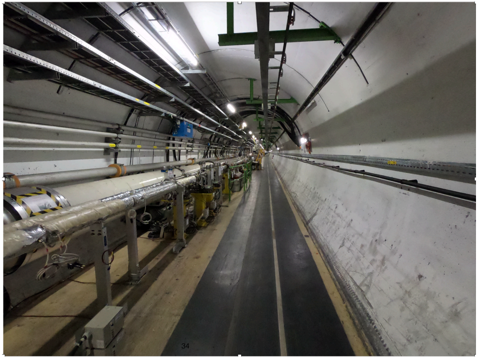
To validate the predictions of A_N at 7 TeV, the absolute polarimeter must be installed in coincidence with the BRP polarimeter along the beamline at LHC

Installation of a polarized jet target at LHC Interaction Region 4





Other options

- IR3
- IR8 before or after LHCb (beyond the wall)

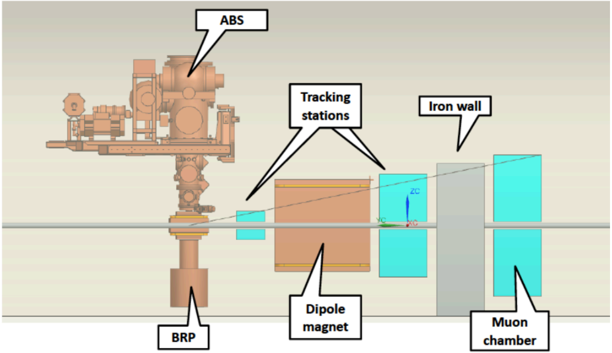
Objectives of the installation at the IR4

Apparatus

- Jet target
- Absolute polarimeter & BRP
- Full (minimal) spectrometer: dipole mag., track. stations, muons syst.
- Simple PID detector (Calo, RICH)

Goals

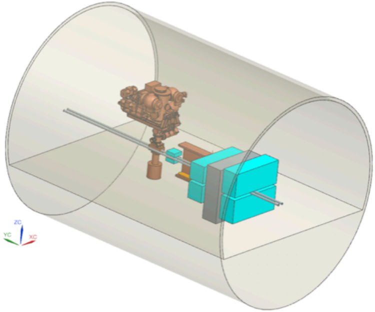
- PoP absolute polarimeter
- PoP future experiment at LHCb
- Single spin asymmetries in inclusive hadron production in $pH\uparrow$ and $PbH\uparrow$



Project development in two phases

Phase 1 - Test installation at IR4

- Develop a compact - LHCb independent apparatus at IR4
- conduct R&D for a PGT for Run5
- feasibility of absolute polarimetry
- perform new physics measurements



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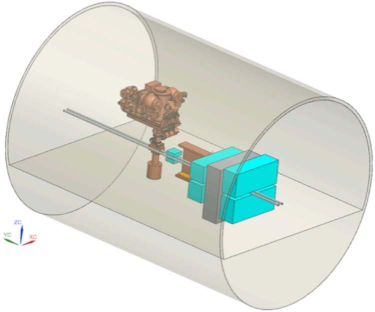
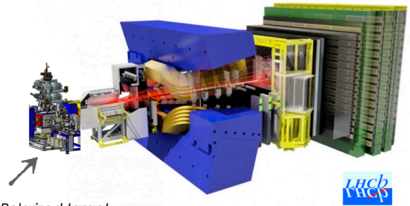


Phase 2 - Installation at LHCb

- Install the PGT in LHCb for Run5
- exploit the potentialities of LHCb (upgrade II): c-. b- quark reconstruction, rare probes

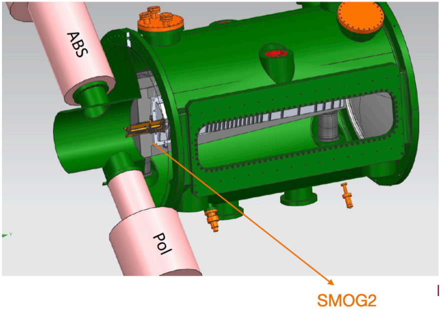


Polarized target

Backup solution: polarized jet target

Jet target option

- Lower density ($\sim 10^{12}$ at/cm^2)
- Higher polarization ($\sim$ 90 %)
- Small Helmholtz coil with no impact on LHCb current and future setup



Backup solution: polarized jet target

Jet target option

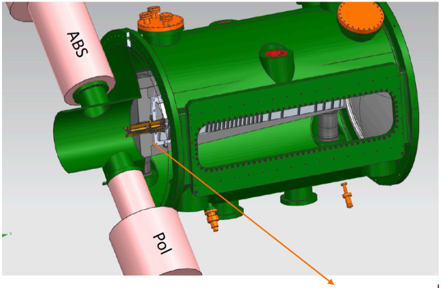
- Lower density ($\sim 10^{12}$ at/cm^2)
- Higher polarization ($\sim$ 90 %)
- Small Helmholtz coil with no impact on LHCb current and future setup

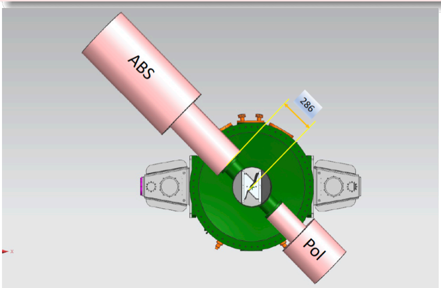
Pro

- no recombination
- high polarization
- small systematics in P meas.

Contra

- $\times$ 40 lower luminosity
- tolerable for standard channels
- relevant for rare probes





Perspectives

LHCspin is complementary to EIC

[D. Boer: arXiv:1611.06089]

unpolarized gluon TMD

	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)	√	√	√	√	×	×	×

linearly polarized gluon TMD

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

TMDs (Sivers) [D. Boer: arXiv:1611.06089, D. Boer et al. HEPJ 08 2016 001]

	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)	√	√	√	√	×	×

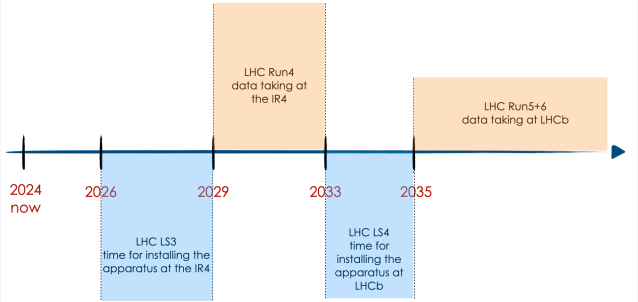
$f_{1T}^{\perp g[+,+]}$ (Weizsacker-Williams type or "**f-type**") → antisymmetric colour structures

$f_{1T}^{\perp g[+,-]}$ (Dipole s type or "**d-type**") → symmetric colour structures

Can be measured at the Electron Ion-Collider (EIC)

Can be measured at LHCspin

Timetable



Spare

Rates

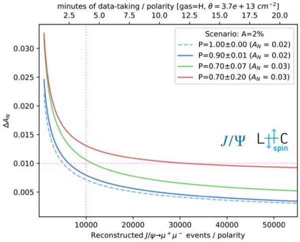
LHCspin event rates

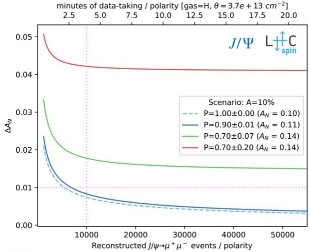
Precise *spin asymmetry* on $J/\Psi \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow K^-\pi^+$ for $pH^\uparrow$ collisions in just few weeks

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

Statistics further enhanced by a factor 3-5 in LHCb upgrade II

Huge statistics

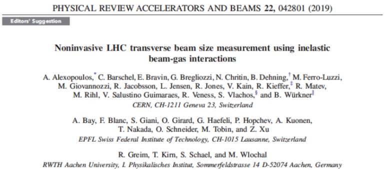




reconstructed particles

Beam Gas Vertex Instrument

https://indico.cern.ch/event/817655/contributions/3442649/attachments/1861615/3059737/2019_06_BGV_GasJetTarget.pdf



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 042801 (2019)

Editors' Suggestion

Noninvasive LHC transverse beam size measurement using inelastic beam-gas interactions

A. Alexopoulos,* C. Barschel, E. Bravin, G. Bregliozzi, N. Chritin, B. Dehning,† M. Ferro-Luzzi, M. Giovannozzi, R. Jacobsson, L. Jensen, R. Jones, V. Kain, R. Kieffer,‡ R. Matev, M. Rihl, V. Salustino Guimaraes, R. Veness, S. Vlachos,§ and B. Würkner‖
CERN, CH-1211 Geneva 23, Switzerland

A. Bay, F. Blanc, S. Giani, O. Girard, G. Haefeli, P. Hopchev, A. Kuonen, T. Nakada, O. Schneider, M. Tobin, and Z. Xu
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R. Greim, T. Kirn, S. Schael, and M. Wlochal
RWTH Aachen University, I. Physikalisches Institut, Sommerfeldstrasse 14 D-52074 Aachen, Germany

This apparatus is not used and could be replaced by LHCspin

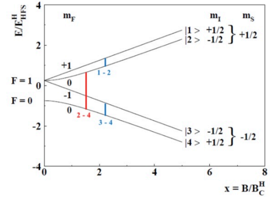
Beam Induced Depolarization

Beam-induced depolarization (BID)

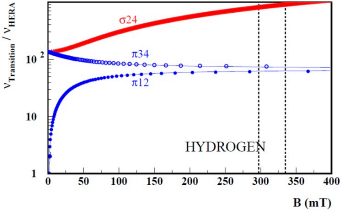
- After its 1st observation at VEPP-3, this effect has been studied at HERMES, see first measurement with B_{long} publ. in PRL **82** (1999) 1164, and analyzed together with B_{transv} in diss. Ph. Tait, Erlangen (2006): http://www.hermes.desy.de/notes/pub/06LIB/pntait.06-060.thesis.ps.gz .
- BID is based on resonant transitions caused by the beam field acting on the polarized H-atoms in an external guide field $B_0 \approx 300$ mT. There are different classes of transitions, depending on the relative orientation of the guide field $\mathbf{B_0}$ and $\mathbf{B_1}$, the beam field component.

  π resonances for $B_1 \perp B_0$ $\Delta F = 0, \pm 1$ $\Delta_{mF} = \pm 1$, and

  σ resonances for $B_1 = B_0$ $\Delta F = \pm 1$ $\Delta_{mF} = 0$.
- Some of these resonances change nuclear polarization. For longitudinal guide field, only the π resonances are present. For transverse field, like at LHCspin, both types of resonances are present. The σ resonances, interchanging states 2 and 4, are densely spaced, i.e. its prevention requires a very high homogeneity of the guide field.



Hydrogen hfs diagram
$B_{crit} = 50.7$ mT



Beam Induced Depolarization: HERA vs LHC

Beam-induced depolarization (BID)

Machine	N_{Bunch}	f_{Bunch} MHz	I_{beam} A	σ_z cm	σ_t ps	α ps^{-2}	$1/e$ *width Fourier Sp.*	I_0 *peak* current(A)
HERA-e	210	10.41	0.04	0.93	31	$5.203 \cdot 10^{-4}$	5.1 GHz	36.4
LHC	2600	40.08	1.0	7.55	253	$7.81 \cdot 10^{-6}$	0.63 GHz	55.7

Main differences between HERA-e and LHC:

1. **Bunch frequency f_B:** 10.41 MHz vs. 40.08 MHz. This results for the LHC in a 4x larger spacing of the ‘resonant B-values’, i.e. it reduces requirements on field quality.
2. **Width of the Fourier spectrum:** 5.1 GHz vs. 0.63 GHz. This leads to a rapid fall-off of the relevant Fourier amplitudes of the $\sigma_{2\text{-}4}$ resonance (8.54 GHz) at the LHC.

This naïve comparison suggests that BID at the LHC is probably less dangerous as at HERA-e, thanks to the higher bunch frequency and the much longer bunches, and despite the 25 times higher beam current! – Clearly, this needs to be confirmed by a systematic study of BID at the LHC!

2019-06-04 PREFER-2019 Petersburg E. Steffens (FAU): Design of a PGT for the LHC 14