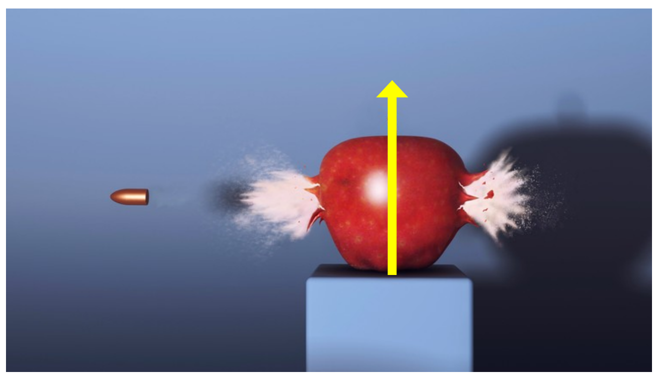
XXVII International Workshop on Deep Inelastic Scattering and Related Subjects
Torino – April 8-12 2019

The LHCSpin project



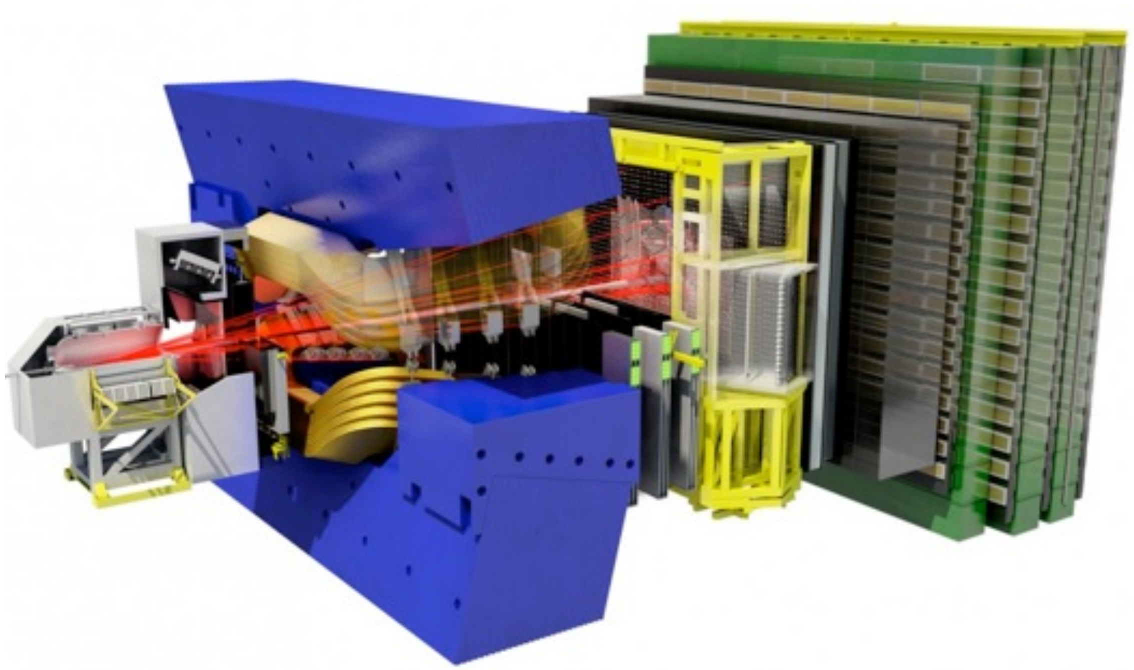
V. Carassiti[1]
G. Ciullo[1]
P. Di Nezza[2]
P. Lenisa[1]
L.L. Pappalardo[1]
E. Steffens[3]

[1] University of Ferrara and INFN, [2] INFN - Laboratori Nazionali di Frascati, [3] University of Erlangen

In collaboration with:
R.Engels (fz-juelich), J.Depner (Erlangen), K.Grigoryev (fz-juelich),
E.Maurice (CNRS/IN2P3, Orsay), A.Nass (fz-juelich), F.Rathmann (fz-juelich),
D.Reggiani (PSI-Zurich), A.Vasilyev (Gatchina),

The LHCSpin project

The **LHCSpin** project aims at bringing spin physics at the LHC through the implementation of a **polarized fixed target** in the **LHCb** spectrometer.



Fixed target kinematics at LHC

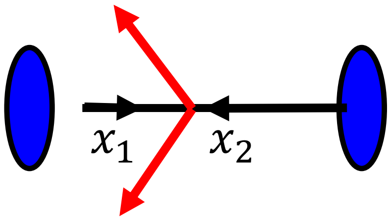
Kinematic conditions for fixed-target collisions at LHC

$E_p = 7$ TeV ⟹ $\gamma = \frac{\sqrt{s}}{2m_p} \approx 60$ **CM strongly boosted in the lab system!**

Kinematic conditions for fixed-target collisions at LHC

$E_p = 7$ TeV ⟹ $\gamma = \frac{\sqrt{s}}{2m_p} \approx 60$ **CM strongly boosted in the lab system!**

LHCb acceptance ($2 \lesssim y_{lab} \lesssim 5$) ⟺ $-3.0 \lesssim y_{CM} \lesssim 0$ **CM backward rapidity region**

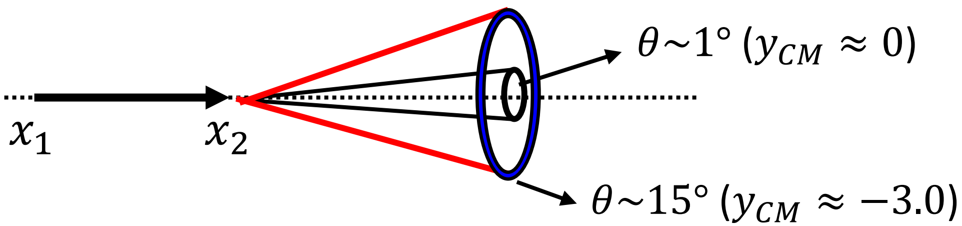


CM system

Kinematic conditions for fixed-target collisions at LHC

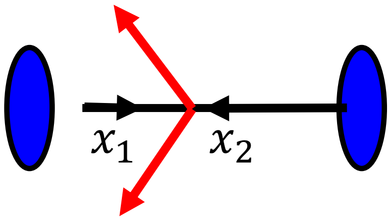
$E_p = 7$ TeV ⟹ $\gamma = \dfrac{\sqrt{s}}{2m_p} \approx 60$ **CM strongly boosted in the lab system!**

LHCb acceptance
$(2 \lesssim y_{lab} \lesssim 5)$ ⟺ $\boxed{-3.0 \lesssim y_{CM} \lesssim 0}$ **CM backward rapidity region**



Lab system

⟺



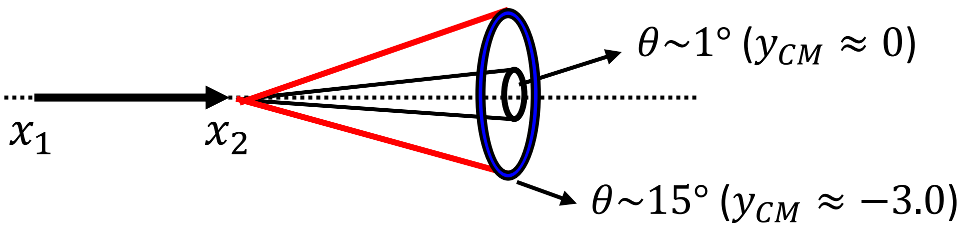
CM system

- **Bkw CM region is at reach of a forward spectrometer with reaction products at measurable forward angles**

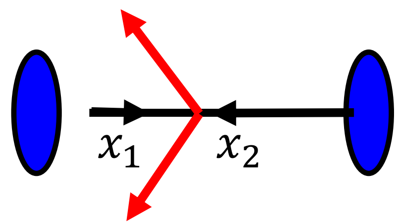
Kinematic conditions for fixed-target collisions at LHC

$E_p = 7$ TeV ⟹ $\gamma = \frac{\sqrt{s}}{2m_p} \approx 60$ **CM strongly boosted in the lab system!**

LHCb acceptance ($2 \lesssim y_{lab} \lesssim 5$) ⟺ $-3.0 \lesssim y_{CM} \lesssim 0$ **CM backward rapidity region**

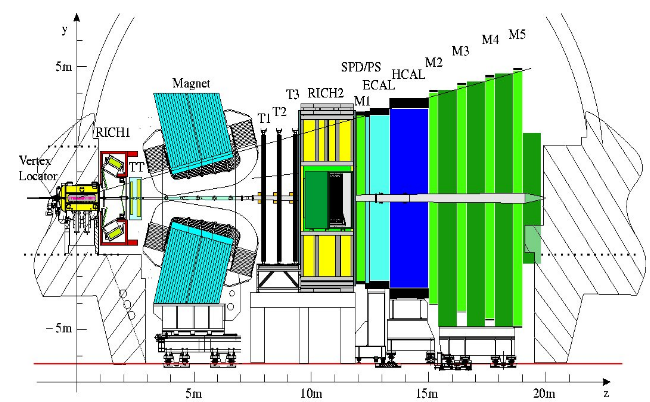


Lab system



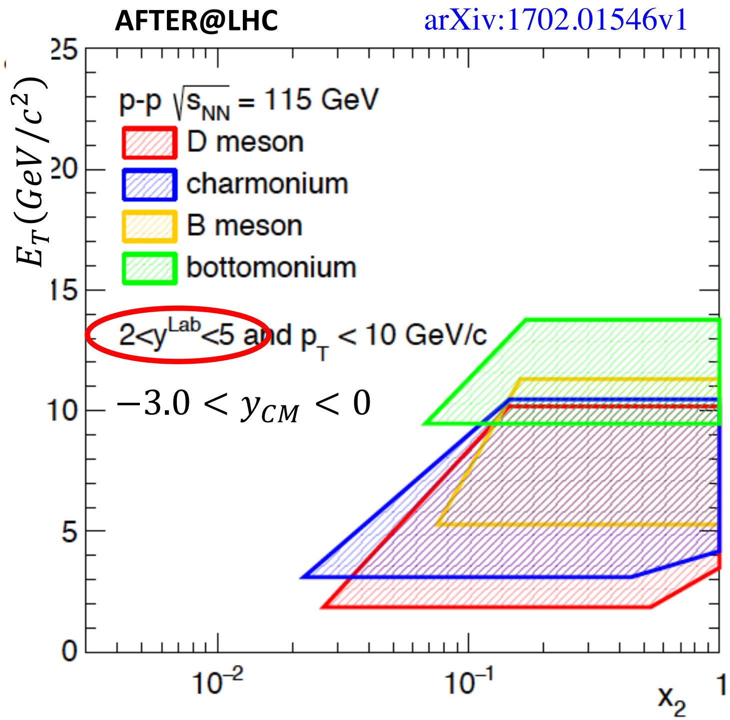
CM system

- **Bkw CM region is at reach of a forward spectrometer with reaction products at measurable forward angles**
- **LHCb ideal detector to host a fixed target at the LHC!**



Kinematic conditions for fixed-target collisions at LHC

$$-3.0 \lesssim y_{CM} \lesssim 0 \quad \Longrightarrow \quad x_2 = \frac{E_T}{\sqrt{s}} e^{-y_{CM}}$$

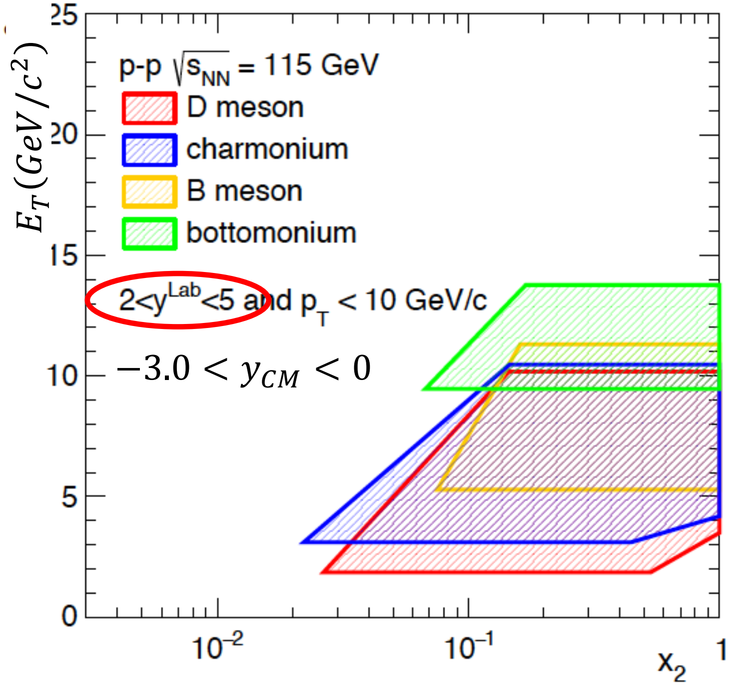


- **Sensitive to large x-Bjorken ($x_2 \to 1$)**
- **Access to target-fragmentation region** $(x_F \to -1)$

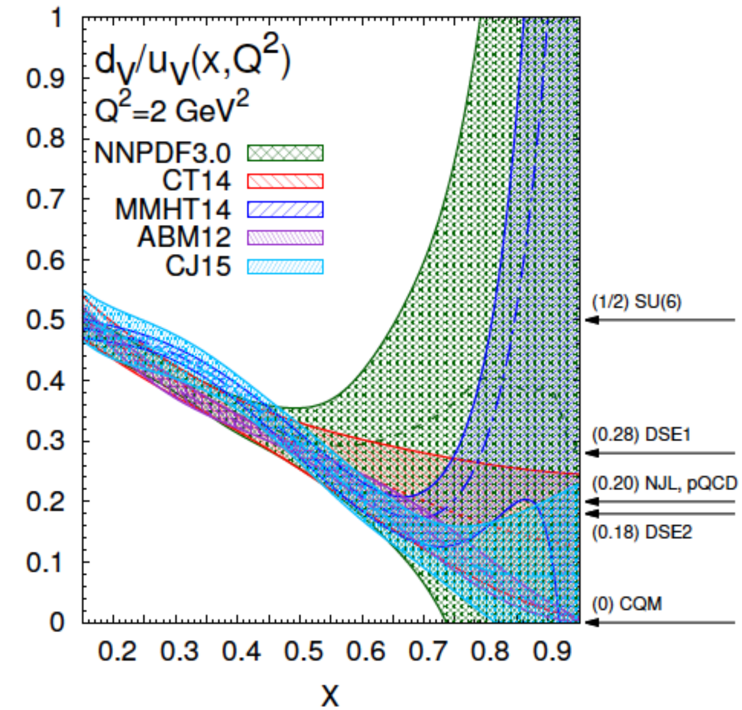
Kinematic conditions for fixed-target collisions at LHC

$$-3.0 \lesssim y_{CM} \lesssim 0 \quad \Longrightarrow \quad x_2 = \frac{E_T}{\sqrt{s}} e^{-y_{CM}}$$

AFTER@LHC arXiv:1702.01546v1

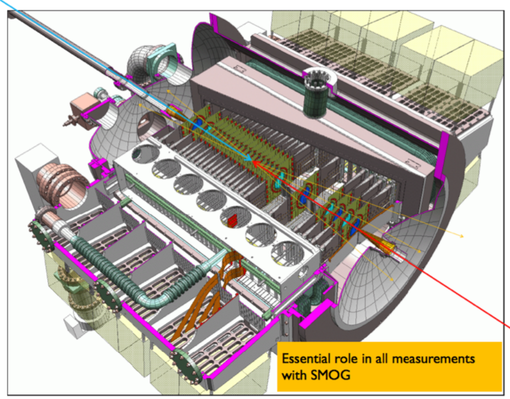


[R. D. Ball et al. Eur. Phys. J. C76 (2016) 383]



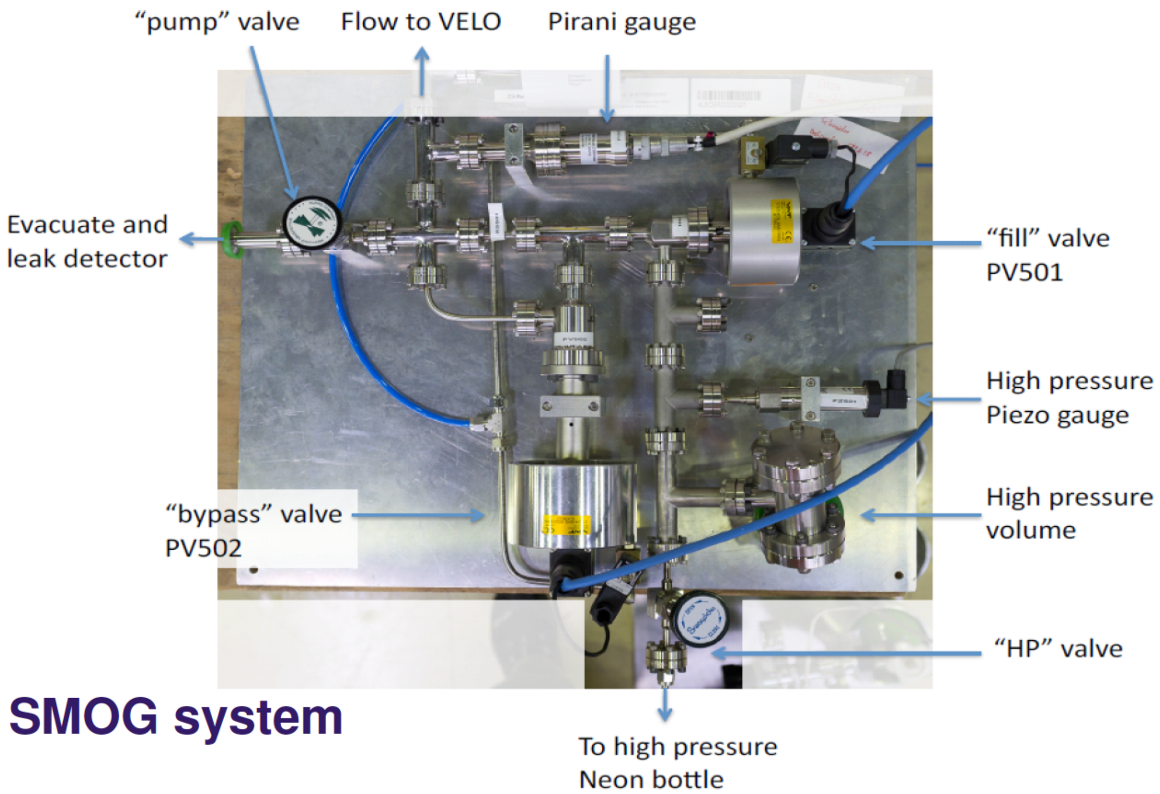
- **Sensitive to large x-Bjorken ($x_2 \to 1$)**
- **Access to target-fragmentation region** $(x_F \to -1)$

The LHCb fixed-target system



SMOG: System for Measuring Overlap with Gas:

- Low density noble gas injected in the VELO vessel ($\sim 10^{-7}$mbar)
- Gas pressure 2 orders of magnitude higher than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude

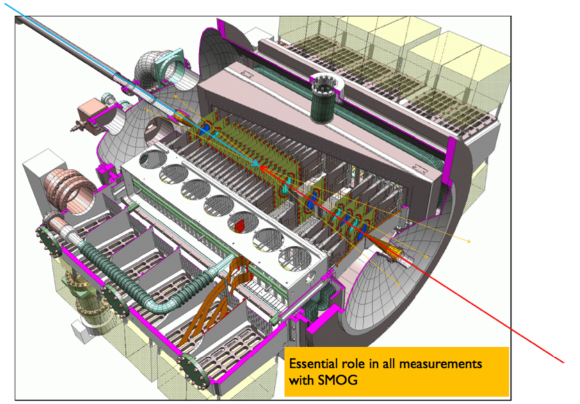


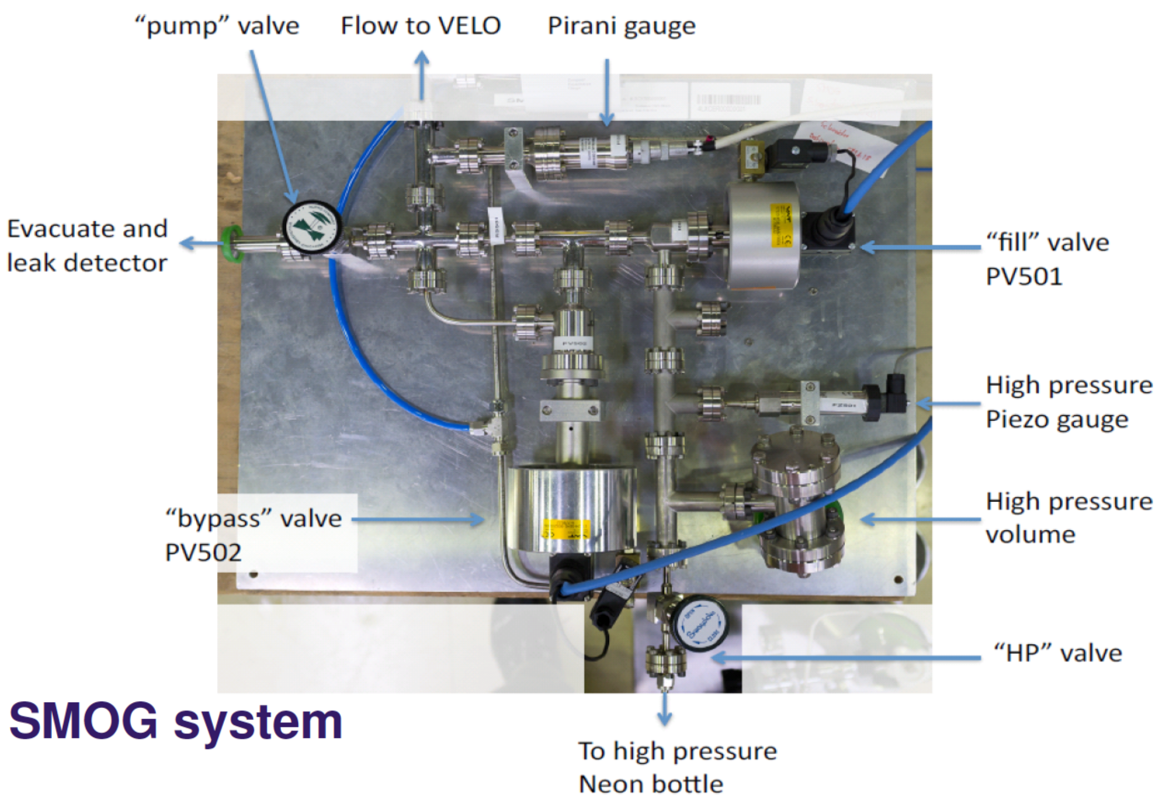
SMOG system

The LHCb fixed-target system

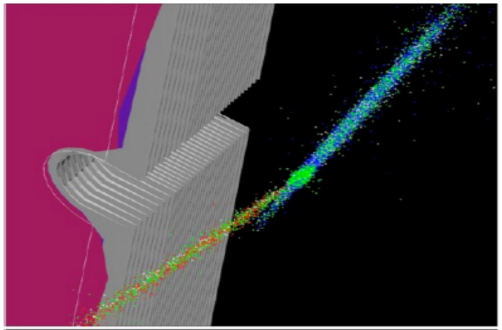
SMOG: System for Measuring Overlap with Gas:

- Low density noble gas injected in the VELO vessel ($\sim 10^{-7}$ mbar)
- Gas pressure 2 orders of magnitude higher than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude
- Conceived for **precise luminosity determination** (beam-gas imaging)





SMOG system

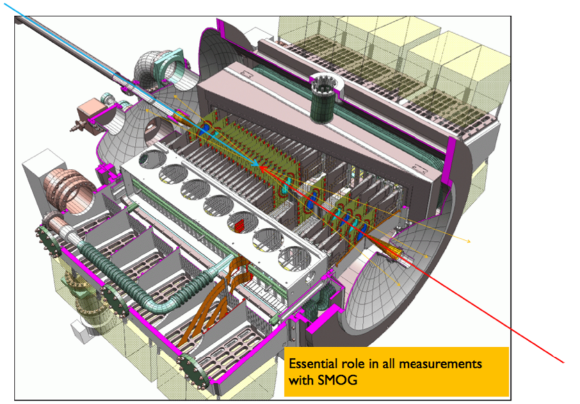


Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

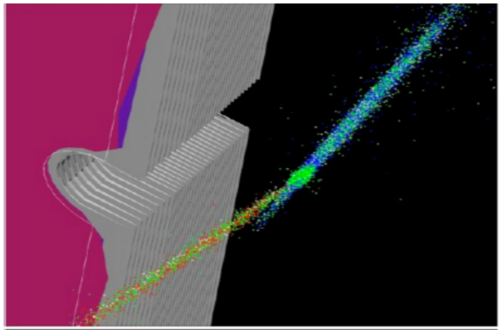
The LHCb fixed-target system

SMOG: System for Measuring Overlap with Gas:

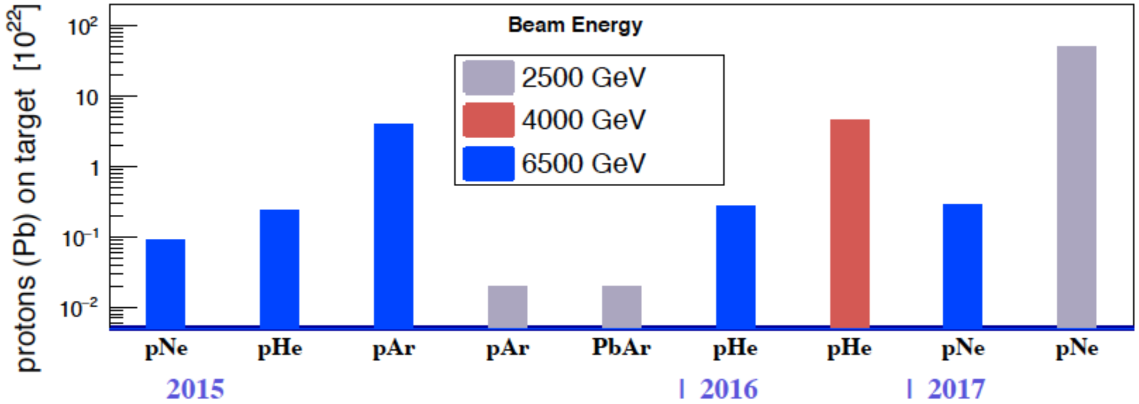
- Low density noble gas injected in the VELO vessel ($\sim 10^{-7}$mbar)
- Gas pressure 2 orders of magnitude higher than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude
- Conceived for **precise luminosity determination** (beam-gas imaging)



…but SMOG gives also the unique opportunity to operate an **LHC experiment in a fixed target mode** and to study pA and AA collisions on various targets!



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.



✓ First measurements of charm production in fixed-target configuration at the LHC, Phys. Rev. Lett. 122, 132002 (2019)

✓ Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV, Phys. Rev. Lett. 121, 222001 (2018)

Why a polarized fixed-target experiment at LHC?

✓ **Unique kinematic conditions**

- $E_p = 7\ \mathrm{TeV} \implies \sqrt{s} \approx 115\ \mathrm{GeV}$ (fills the gap between between SPS & RHIC)
- backward CM rapidity region ($x_F \to -1$)
- sensitive to poorly explored high x-Bjorken region

Why a polarized fixed-target experiment at LHC?

✓ **Unique kinematic conditions**

- $E_p = 7\ \mathrm{TeV} \implies \sqrt{s} \approx 115\ \mathrm{GeV}$ (fills the gap between between SPS & RHIC)
- backward CM rapidity region ($x_F \to -1$)
- sensitive to poorly explored high x-Bjorken region

✓ **Broad variety of possible reactions**:

- polarized: $\mathrm{pp}^{\uparrow}$, $\mathrm{pd}^{\uparrow}$
- unpolarized: pA , PbA (A=H, D, He, O, Ne, Ar, Kr, Xe)

Why a polarized fixed-target experiment at LHC?

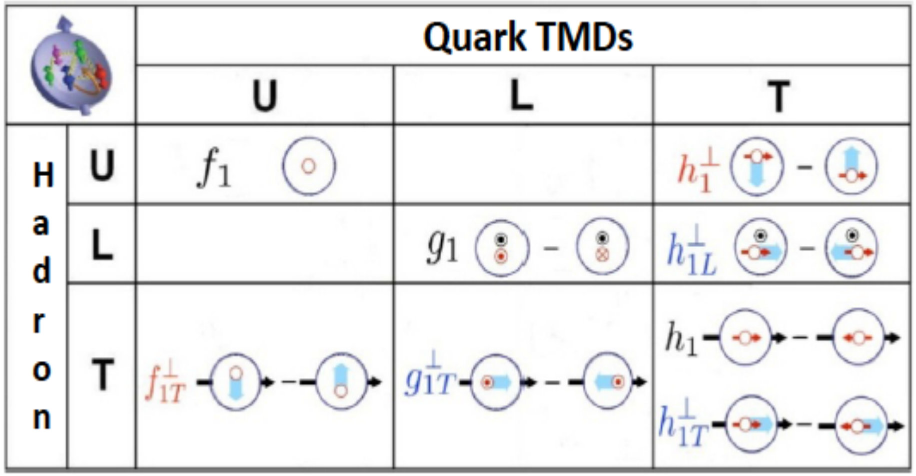
- ✓ **Unique kinematic conditions**
  - $E_p = 7\ \mathrm{TeV} \implies \sqrt{s} \approx 115\ \mathrm{GeV}$ (fills the gap between between SPS & RHIC)
  - backward CM rapidity region ($x_F \to -1$)
  - sensitive to poorly explored high x-Bjorken region
- ✓ **Broad variety of possible reactions**:
  - polarized: $\mathrm{pp}^{\uparrow}$, $\mathrm{pd}^{\uparrow}$
  - unpolarized: pA , PbA (A=H, D, He, O, Ne, Ar, Kr, Xe)
- ✓ **Marginal impact on LHC beam and mainstream physics at current experiments**
- ✓ **Polarized gas target technology well established (10 years @ HERMES)**
- ✓ **Very high performances ($\boldsymbol{P}\boldsymbol{\sim}\mathbf{80}\ \%$)**

Why a polarized fixed-target experiment at LHC?

- ✓ **Unique kinematic conditions**
  - $E_p = 7$ TeV $\Longrightarrow \sqrt{s} \approx 115$ GeV (fills the gap between between SPS & RHIC)
  - backward CM rapidity region ($x_F \to -1$)
  - sensitive to poorly explored high x-Bjorken region
- ✓ **Broad variety of possible reactions**:
  - polarized: $\mathrm{pp}^{\uparrow}$, $\mathrm{pd}^{\uparrow}$
  - unpolarized: pA , PbA (A=H, D, He, O, Ne, Ar, Kr, Xe)
- ✓ **Marginal impact on LHC beam and mainstream physics at current experiments**
- ✓ **Polarized gas target technology well established (10 years @ HERMES)**
- ✓ **Very high performances ($P \sim 80$ %)**
- ✓ **Broad and ambitious physics program**
  - 3D mapping of the nucleon structure (quark and gluon PDFs)
  - fundamental tests of QCD (universality, factorization, etc)
  - study of cold nuclear matter effects
  - search for intrinsic heavy quarks
  - study of QGP formation
- ... and much more!

Selected physics opportunities

Accessing the quark TMDs



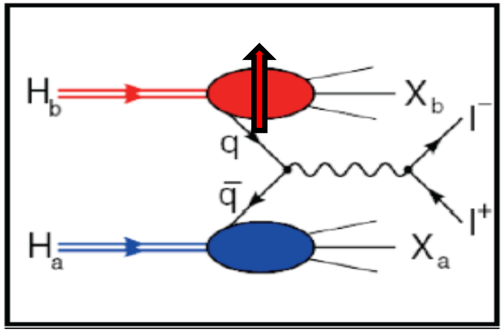
- **8 independent TMDs at twist-2**
- **Significant experimental progress in the last 15 years!**
- First extractions from global analyses

- So far, main results obtained in **SIDIS** measurements (HERMES, COMPASS, JLAB)
- **Drell-Yan** in hadron-hadron collisions represents a complementary approach
- Unique kinematic region with fixed-target collisions at LHC
- Comparison of results from SIDIS and DY will allow to set stringent tests on QCD: factorization, evolution, universality

Accessing the quark TMDs

Hadron	Quark TMDs: U	Quark TMDs: L	Quark TMDs: T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h_1 $h_{1T}^{\perp}$

Polarized Drell-Yan

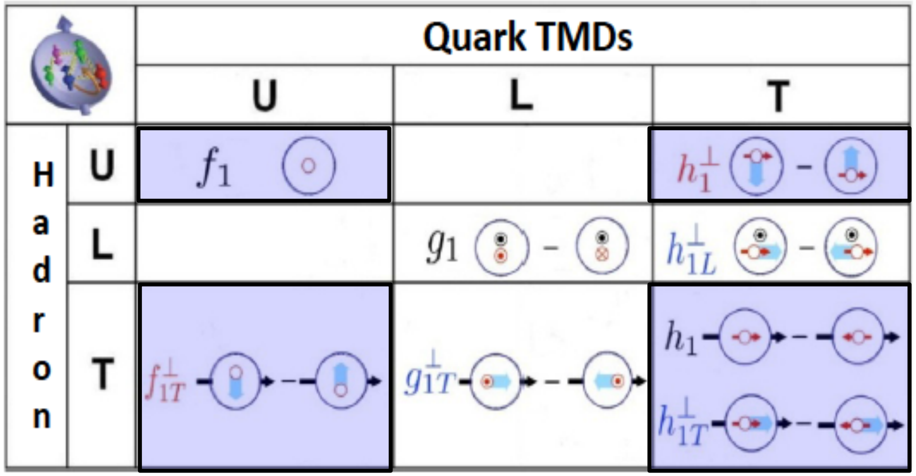


Sensitive to quark TMDs up to high $x_2^{\uparrow}$ through TSSAs

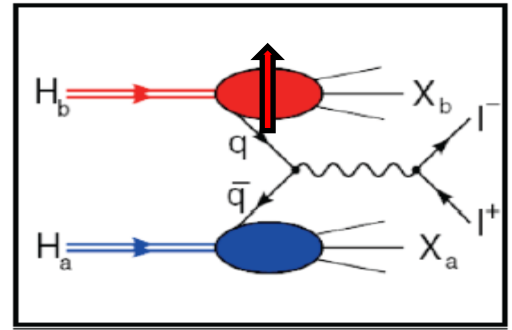
$$A_{UT}^{\sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{\sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{\sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}$$

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

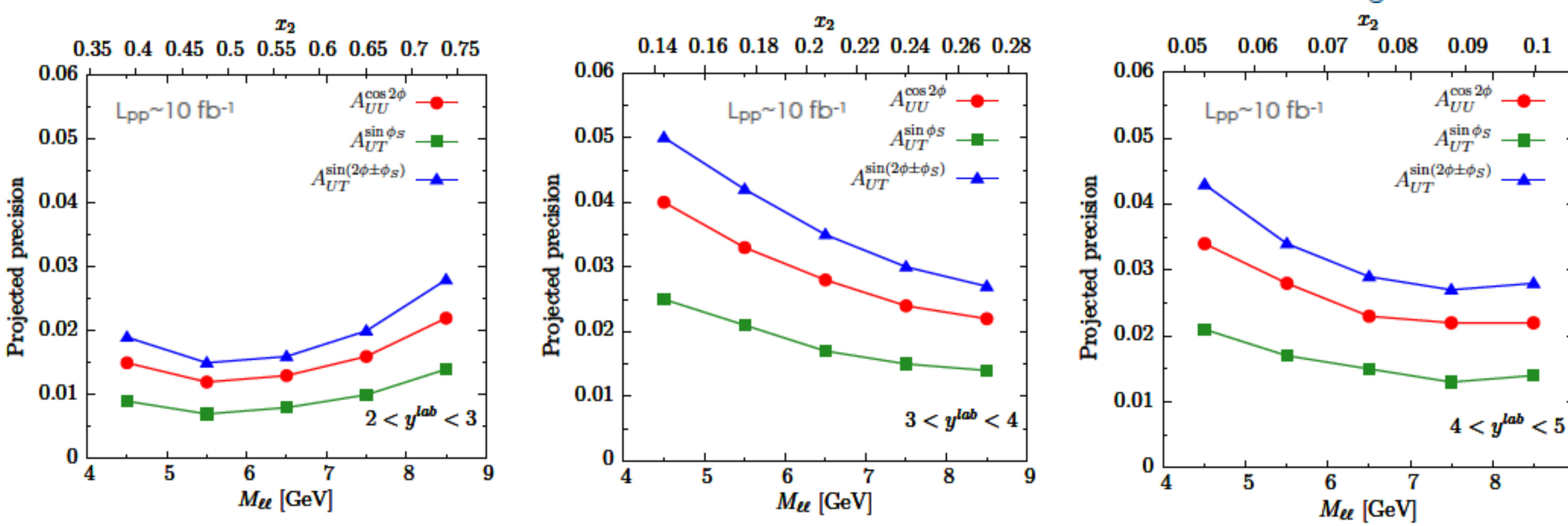
Accessing the quark TMDs



Polarized Drell-Yan



arXiv:1807.00603
and J.P.Lansberg, PBC CERN 2018



Probing the gluon TMDs with fixed-targets at LHC

		Gluon TMDs		
		Unpol	Circularly pol.	Linearly pol.
nucleon	U	f_1^g		$h_1^{\perp g}$
	L		g_1^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g
				$h_{1T}^{\perp g}$

Theory framework consolidated

…but experimental access still extremely limited!

Probing the gluon TMDs with fixed-targets at LHC

nucleon		Gluon TMDs: Unpol	Gluon TMDs: Circularly pol.	Gluon TMDs: Linearly pol.
	U	f_1^g		$h_1^{\perp g}$
	L		g_1^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

Theory framework consolidated

...but experimental access still extremely limited!

Gluon Sivers function:

- first hints by RHIC and COMPASS, but still basically unknown!
- shed light on spin-orbit correlations of gluons inside the proton
- sensitive to gluon orbital angular momentum!

Probing the gluon TMDs with fixed-targets at LHC

nucleon	Gluon TMDs: Unpol	Circularly pol.	Linearly pol.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g, $h_{1T}^{\perp g}$

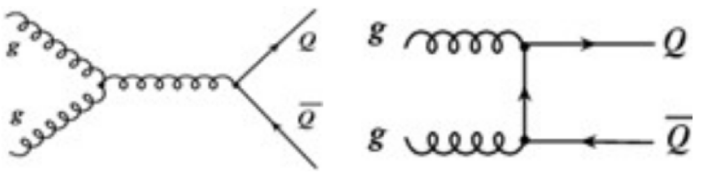
Theory framework consolidated

...but experimental access still extremely limited!

Gluon Sivers function:

- first hints by RHIC and COMPASS, but still basically unknown!
- shed light on spin-orbit correlations of gluons inside the proton
- sensitive to gluon orbital angular momentum!

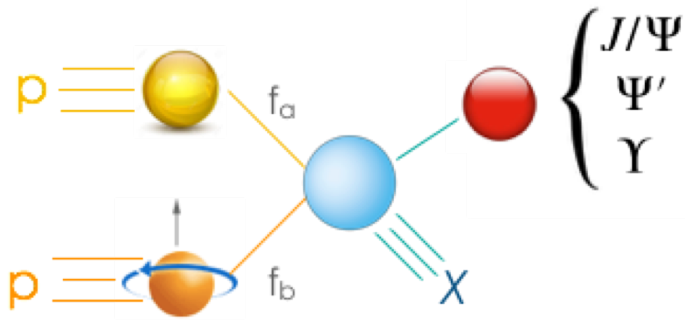
➢ In high-energy hadron collisions Heavy quarks dominantly produced through gg interactions:

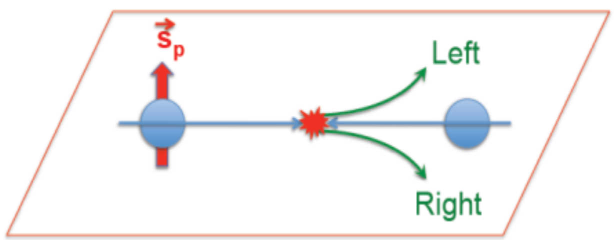


➢ The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-flavour observables**

Probing the gluon TMDs with fixed-targets at LHC

Inclusive quarkonia production in pp interaction turns out to be an ideal **gluon-sensitive observable!**

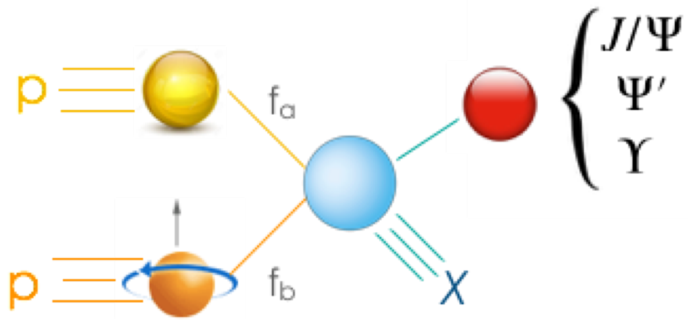


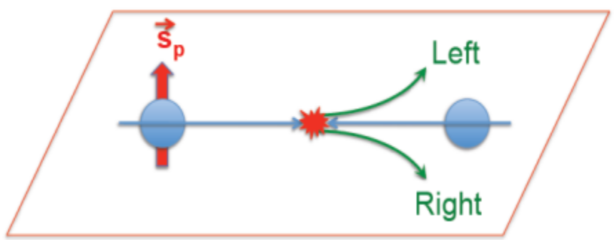


$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}}$$

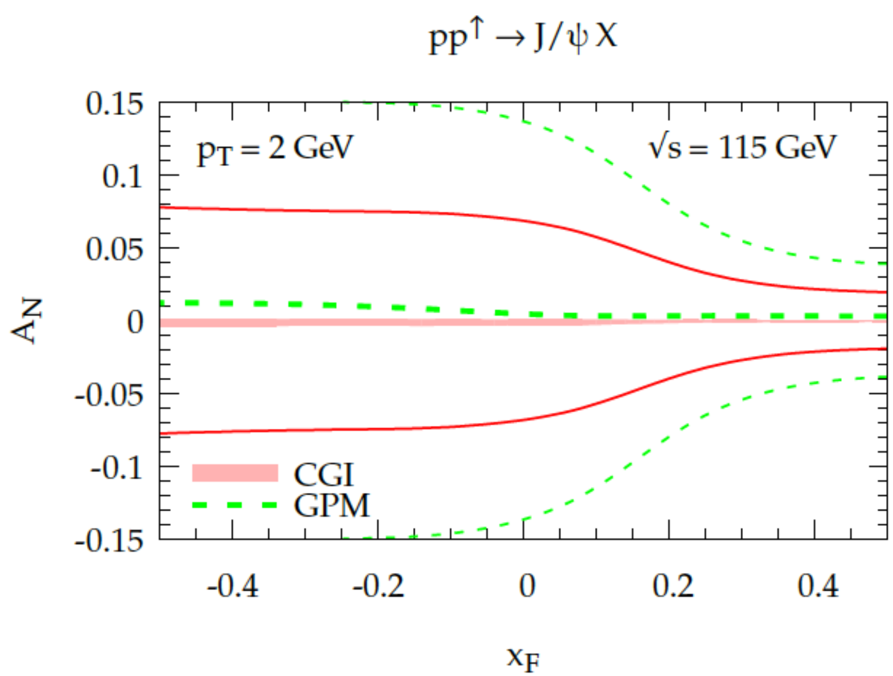
Probing the gluon TMDs with fixed-targets at LHC

Inclusive quarkonia production in pp interaction turns out to be an ideal **gluon-sensitive observable!**





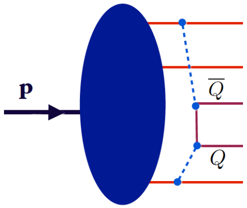
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}}$$



Phys. Rev. D 99, 036013 (2019)

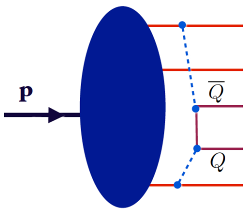
More physics reach with an unpolarized fixed target

- **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



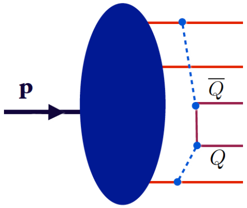
More physics reach with an unpolarized fixed target

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



- **pA collisions** (using unpolarized gas: He, O, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x!**)
  - studies of parton energy-loss and cold nuclear matter effects

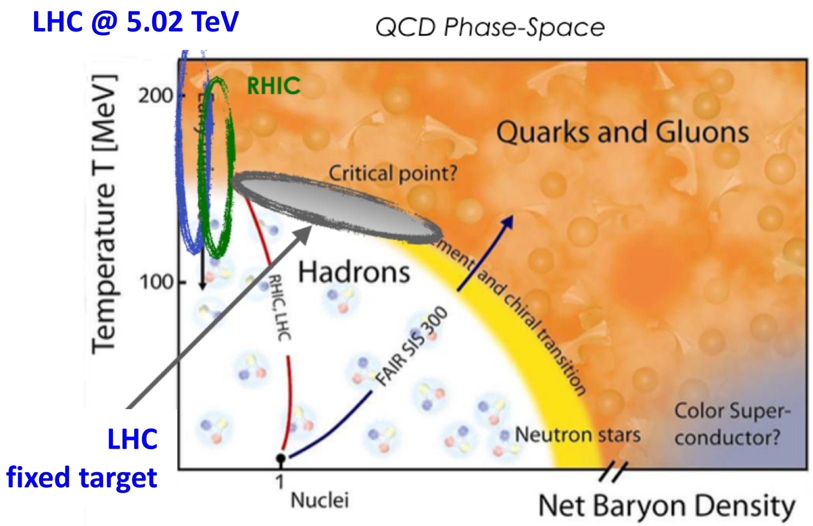
More physics reach with an unpolarized fixed target



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

- **pA collisions** (using unpolarized gas: He, O, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x!**)
  - studies of parton energy-loss and cold nuclear matter effects

- **PbA collisions at $\sqrt{s_{NN}} \approx 72$ GeV** (using unpolarized gas: He, O, Ne, Ar, Kr, Xe)
  - Study of **QGP formation**



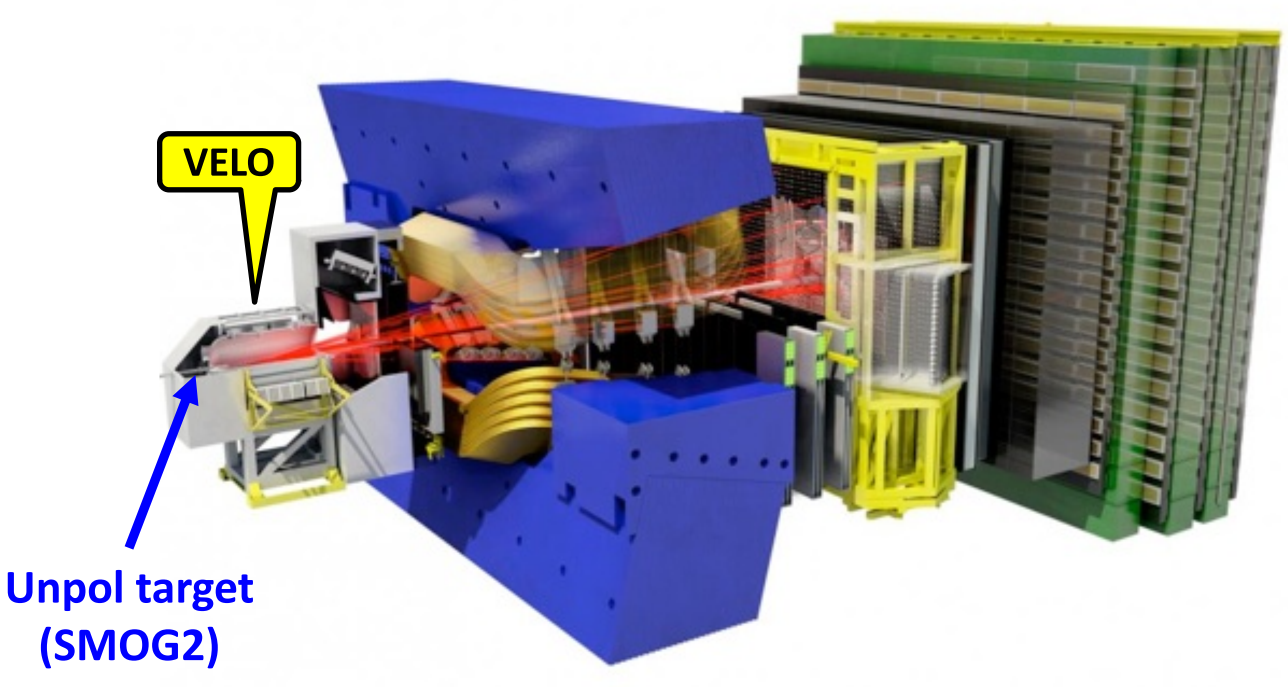
The LHCSpin project

The LHCSpin project

The project consists of **two phases**:

Phase I

Upgrade the present LHCb unpol. fixed-target system (**SMOG**) with the installation of a storage cell in the LHC beam pipe upstream of the VELO tracker (→ **SMOG2**)



The LHCSpin project

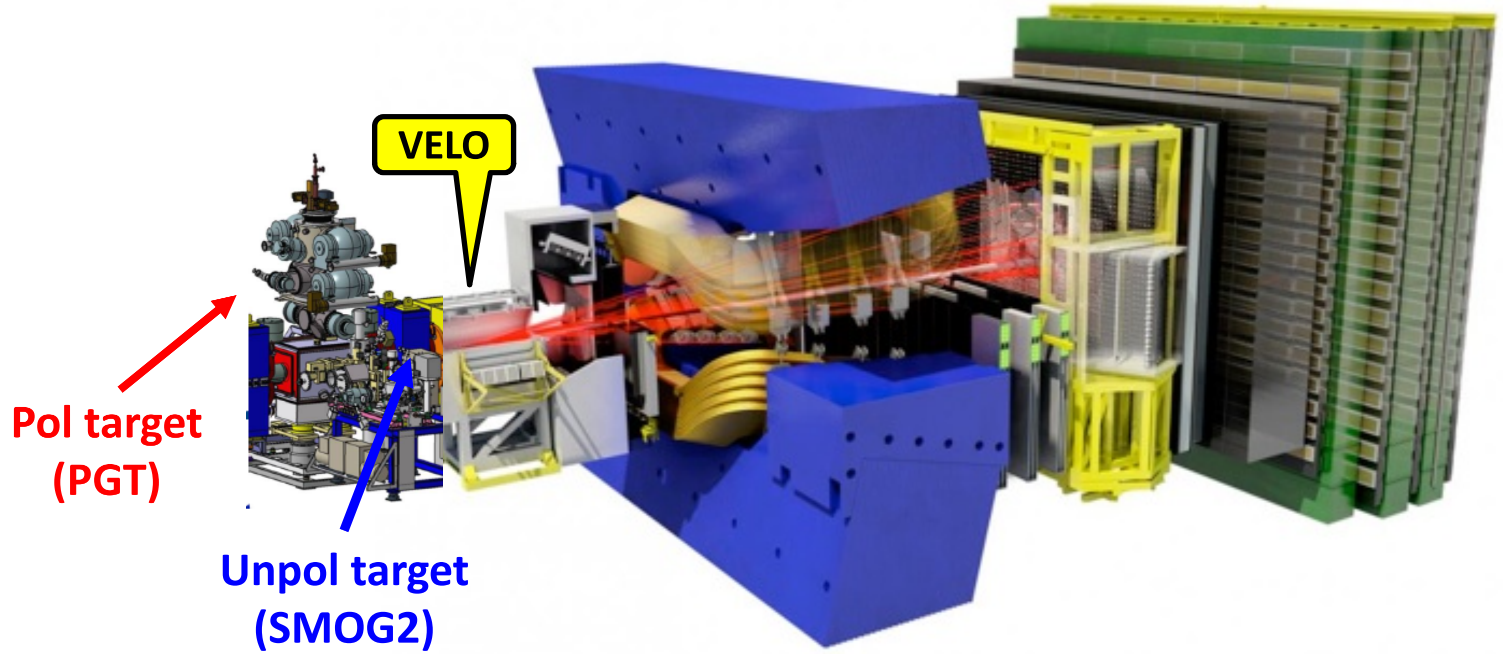
The project consists of **two phases**:

Phase I

Upgrade the present LHCb unpol. fixed-target system (**SMOG**) with the installation of a storage cell in the LHC beam pipe upstream of the VELO tracker (→ **SMOG2**)

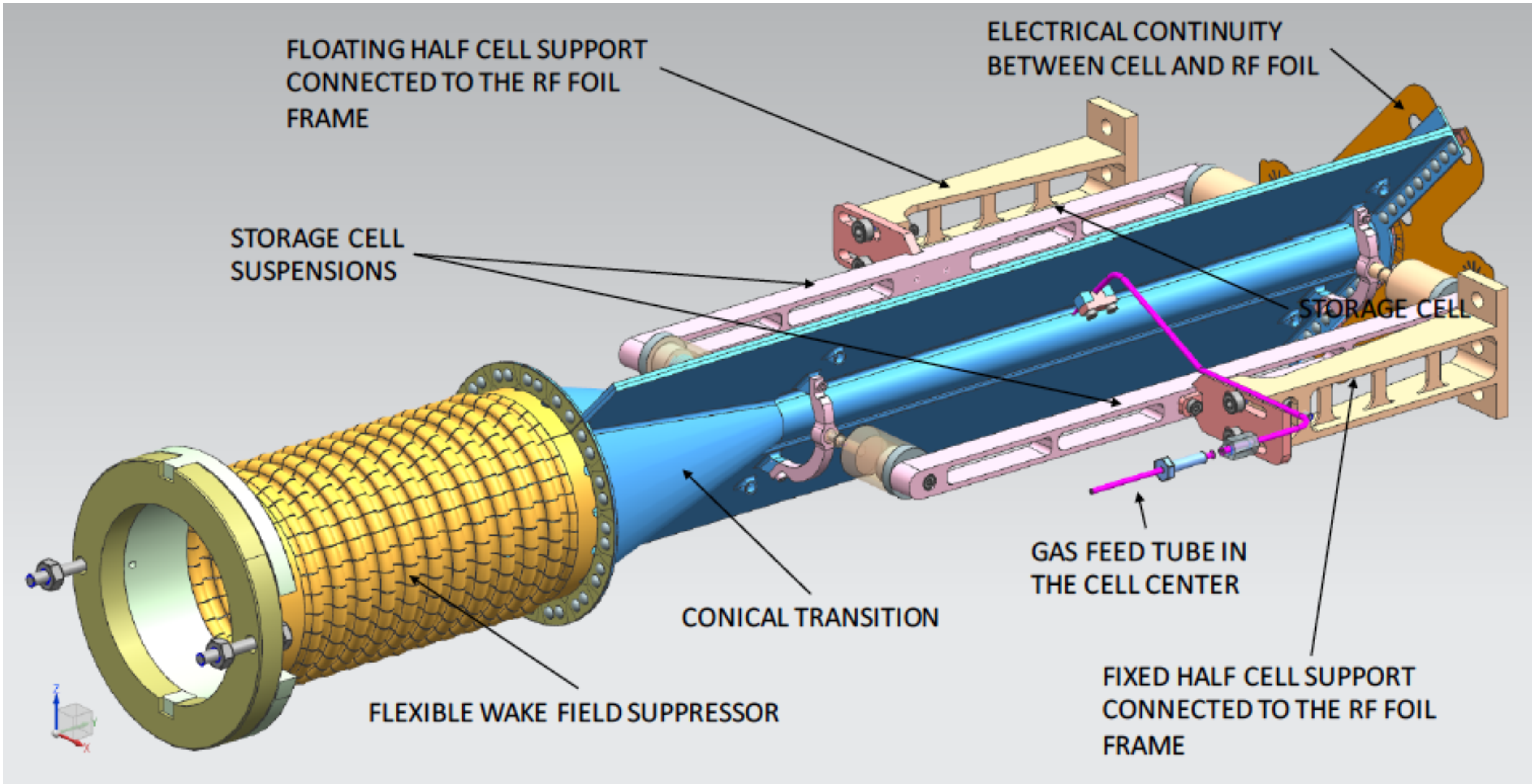
Phase II

Installation of a HERMES-like Polarized Gas Target system (**PGT**) in front of LHCb

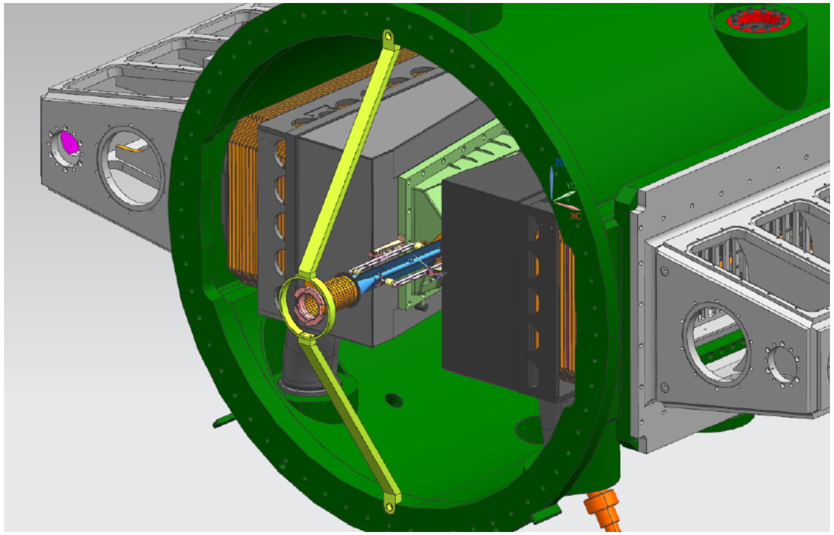


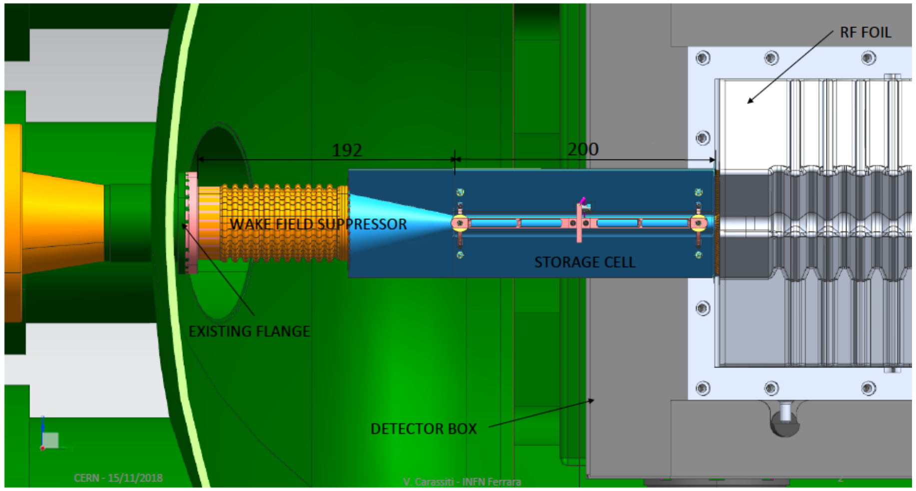
Phase I: the SMOG2 setup

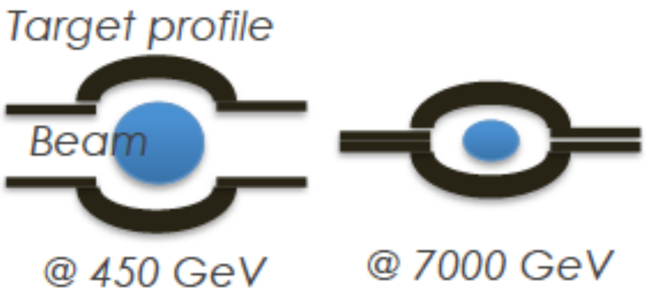
The SMOG2 setup

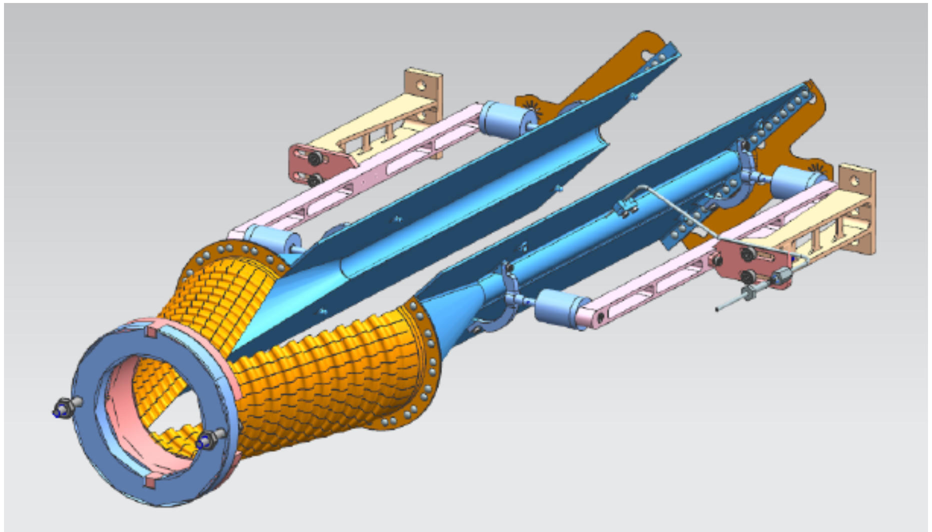


The SMOG2 setup









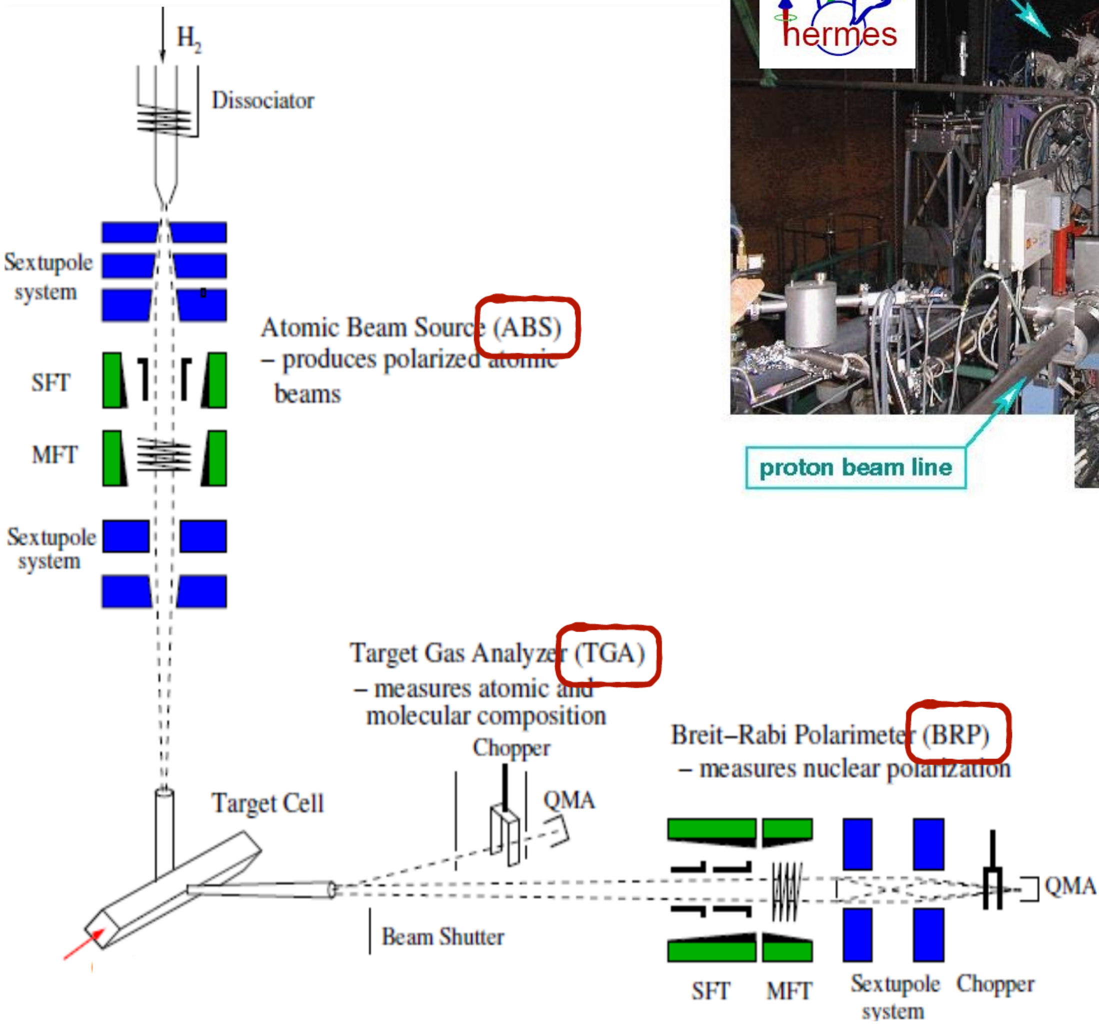
SMOG2 vs. SMOG

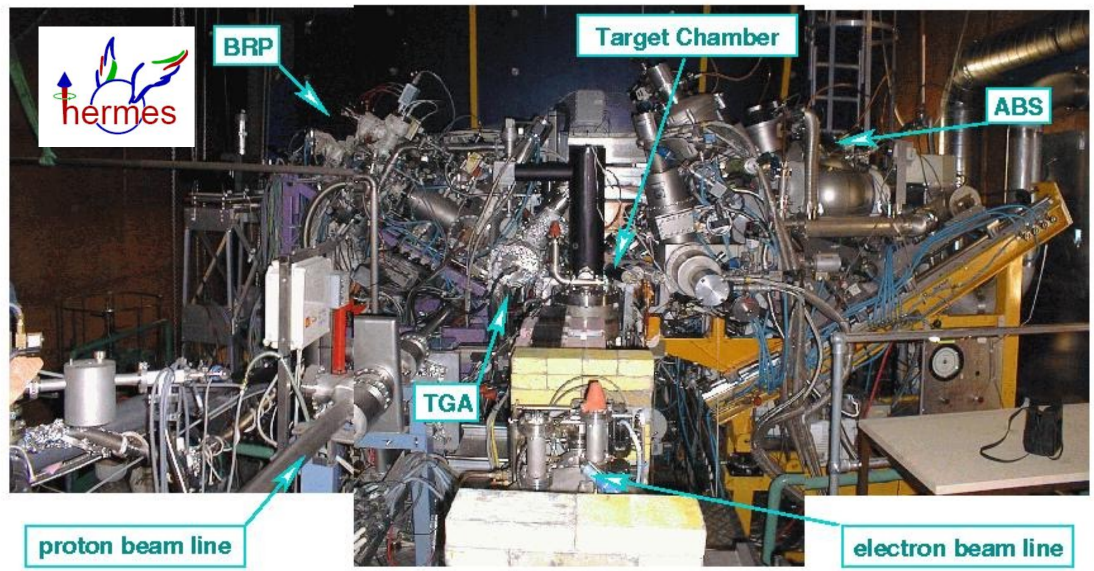
- ✓ **Increase of target density (luminosity)** by up to 2 orders of magnitude using the same gas load of SMOG ($\sim 10^{-7}$ mbar)
- ✓ Possibility to inject **more gas species**: H, D, He, O, Ne, Ar, Kr, Xe (SMOG: He, Ne, Ar)
- ✓ **More sophisticated Gas Feed System**: will allow to measure the target density with much higher precision
- ✓ Well **defined interaction region** upstream of the IP@13 TeV (limited to cell length: 20 cm)
- ✓ SMOG2 can (in principle) **run in parallel with collider mode** (well displaced IP)

Phase II: the polarized target setup

A new design for a compact polarized gas target

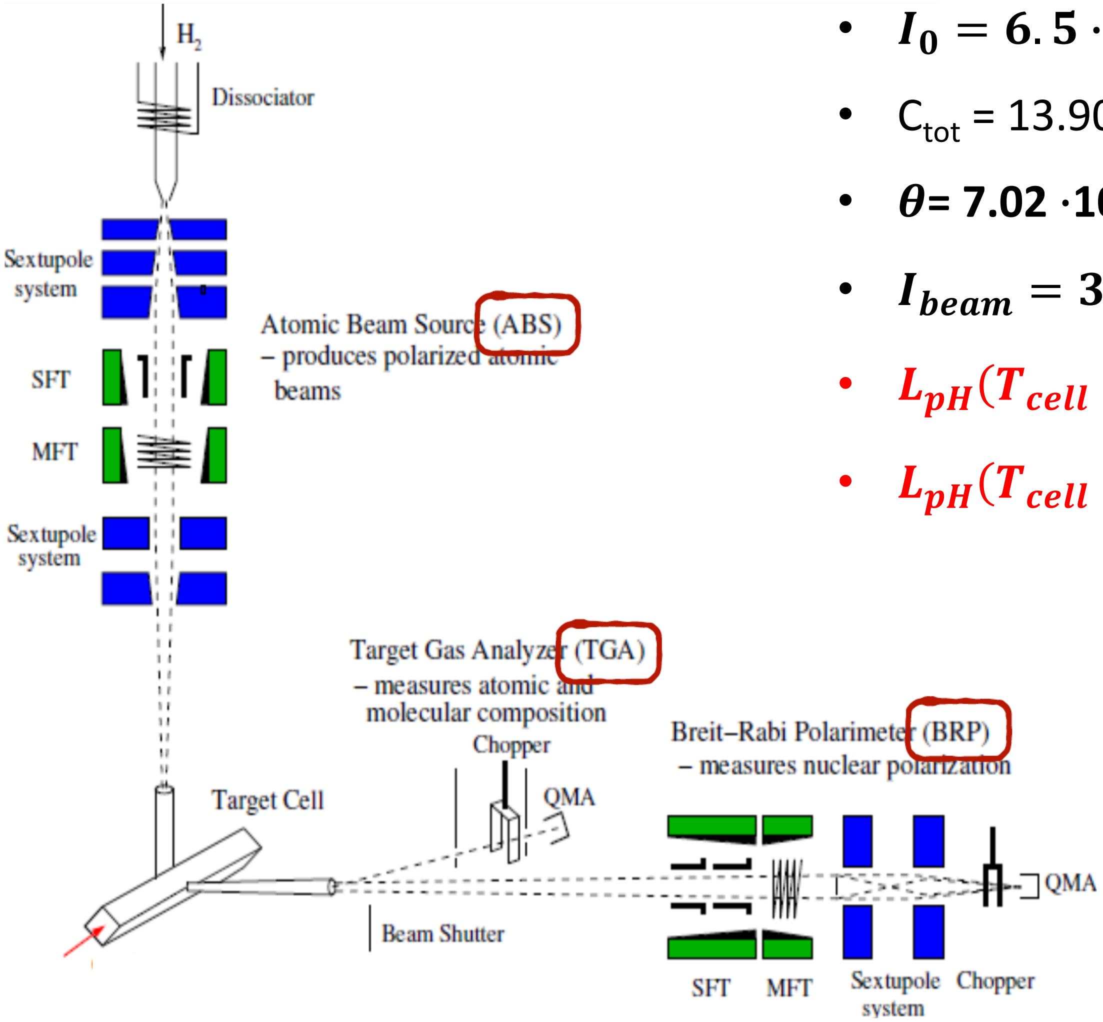
Same principle of Hermes





A new design for a compact polarized gas target

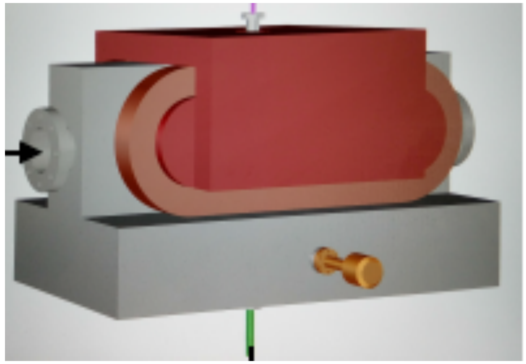
Same principle of Hermes

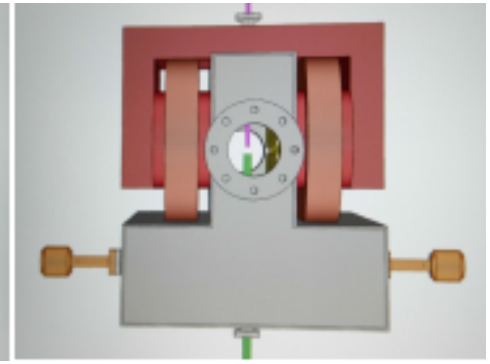


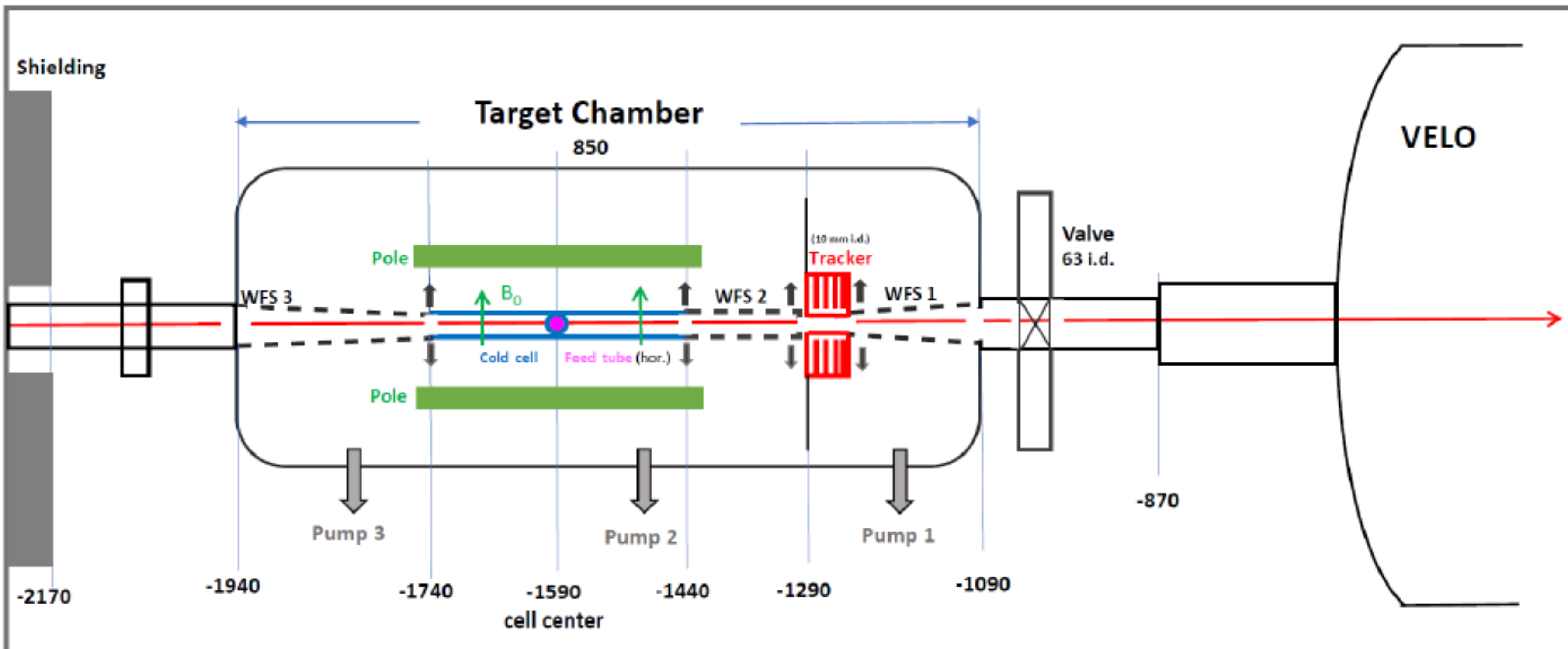
Some numbers:

- $I_0 = 6.5 \cdot 10^{16} s^{-1}$
- C_{tot} = 13.90 l/s
- θ = 7.02 $\cdot 10^{13}/\mathrm{cm}^2$
- $I_{beam} = 3.8 \cdot 10^{18}\ p/s$ (very conservative!)
- $L_{pH}(T_{cell} = 300\ K) = 2.7 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $L_{pH}(T_{cell} = 100\ K) = 4.6 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

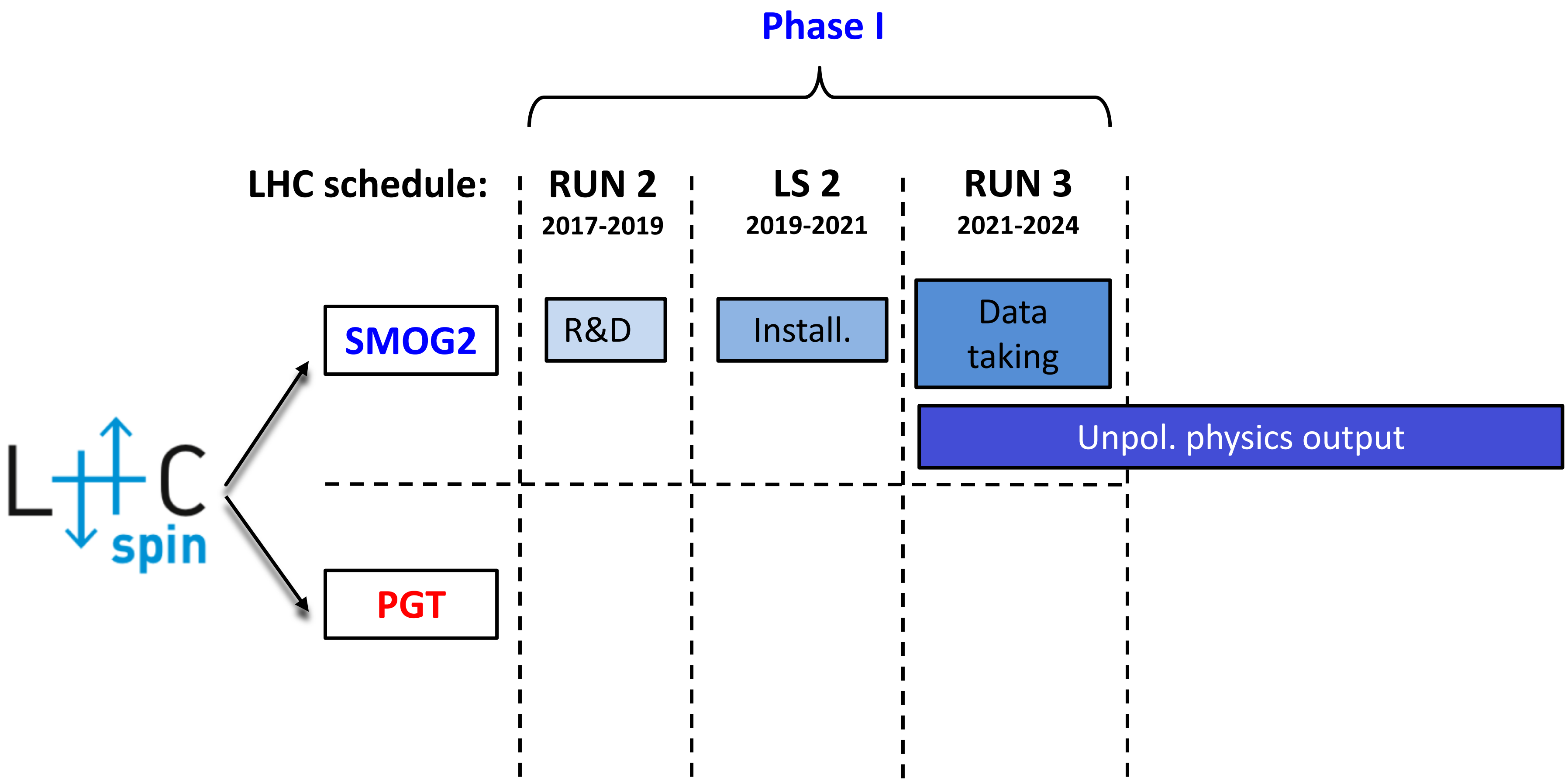
A new design for a compact polarized gas target



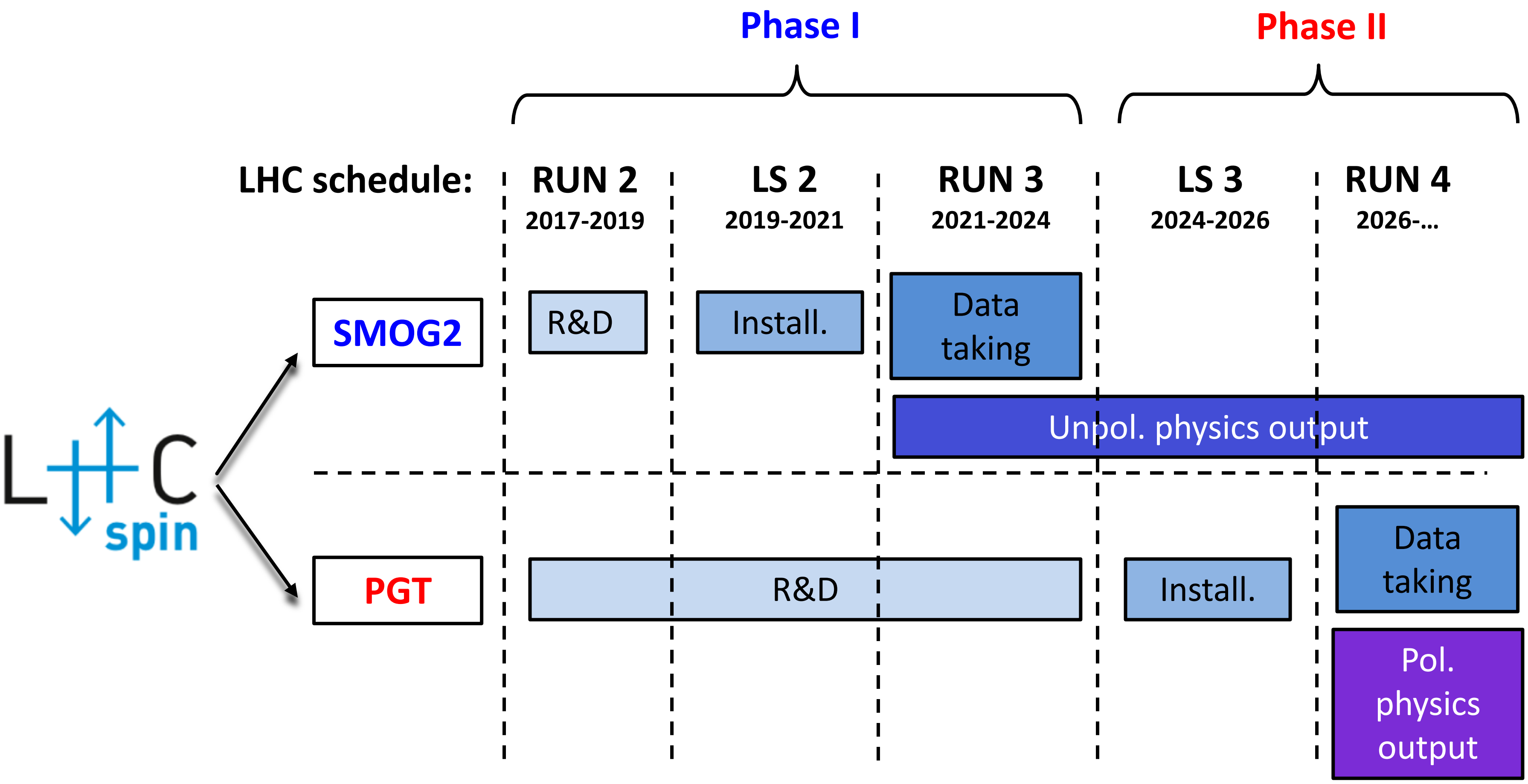




Time schedule of the project



Time schedule of the project



Conclusions

- A fixed-target experiment at the LHC will provide unique kinematic conditions for a broad and ambitious physics program!
- A fixed-target physics program is already ongoing at LHCb with SMOG
- **The proposed upgrade of SMOG (SMOG2) is now approved and in production phase. Installation during LS2.**
- **The polarized target option is the natural evolution of SMOG2**. It is taken into serious consideration by the LHCb Collaboration and LHC machine experts! A review process has been initiated and R&D is ongoing. Expected installation during LHC LS3 (2024-2026).

Conclusions

- A fixed-target experiment at the LHC will provide unique kinematic conditions for a broad and ambitious physics program!
- A fixed-target physics program is already ongoing at LHCb with SMOG
- **The proposed upgrade of SMOG (SMOG2) is now approved and in production phase. Installation during LS2.**
- **The polarized target option is the natural evolution of SMOG2**. It is taken into serious consideration by the LHCb Collaboration and LHC machine experts! A review process has been initiated and R&D is ongoing. Expected installation during LHC LS3 (2024-2026).

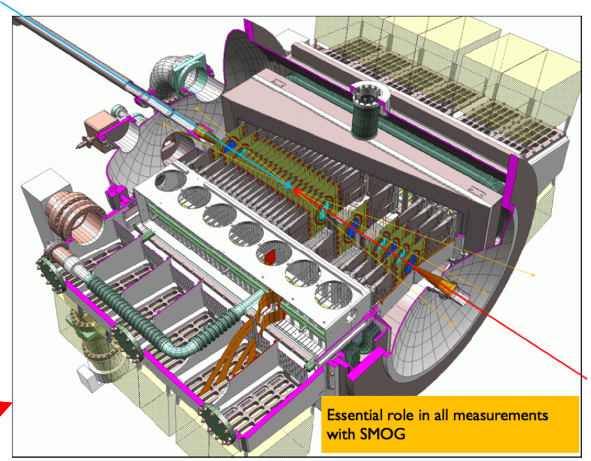
We are working to bring spin physics at the most powerful particle accelerator!

Anyone interested to contribute to this fascinating challenge is welcome to join us!!

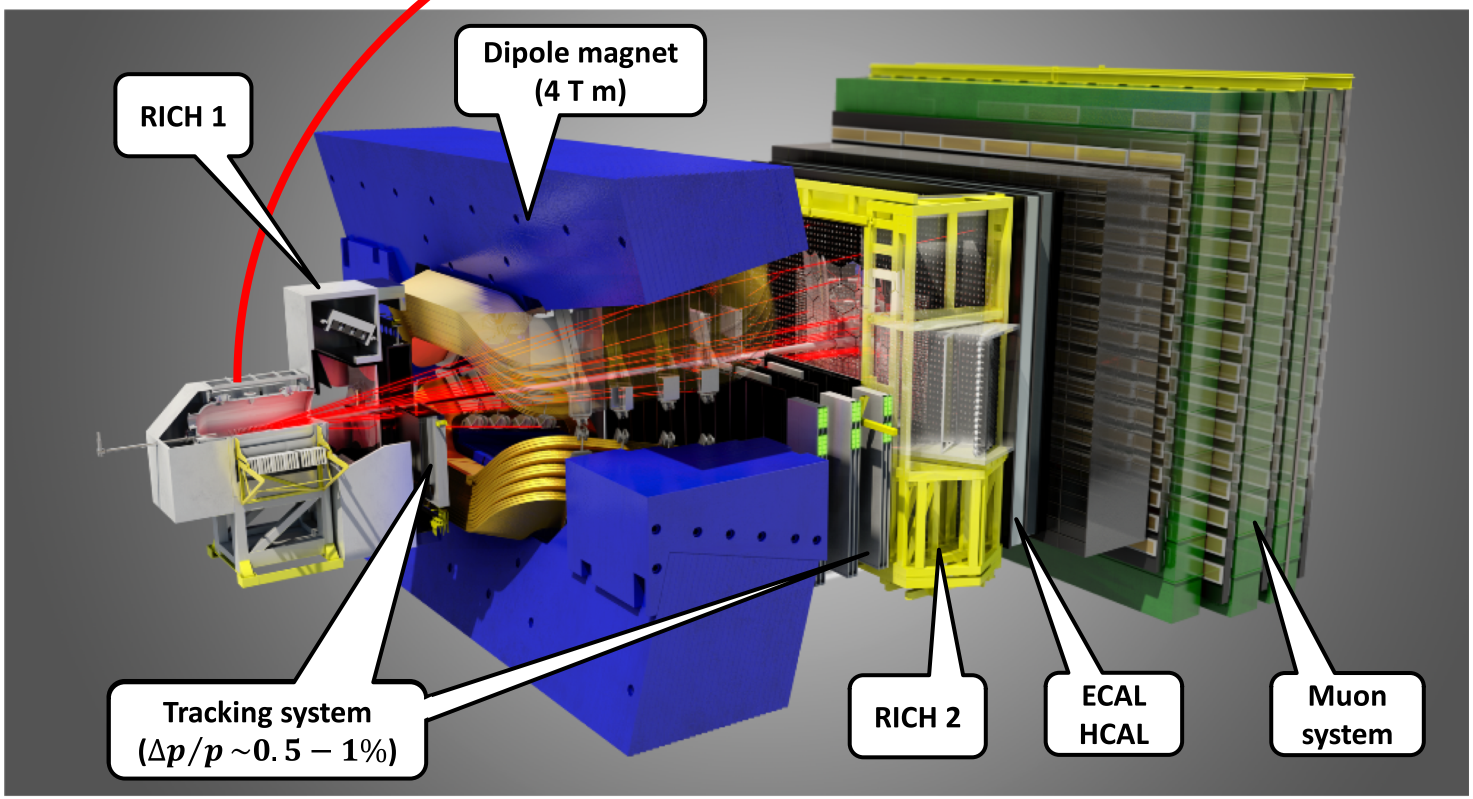
Backup

The LHCb detector

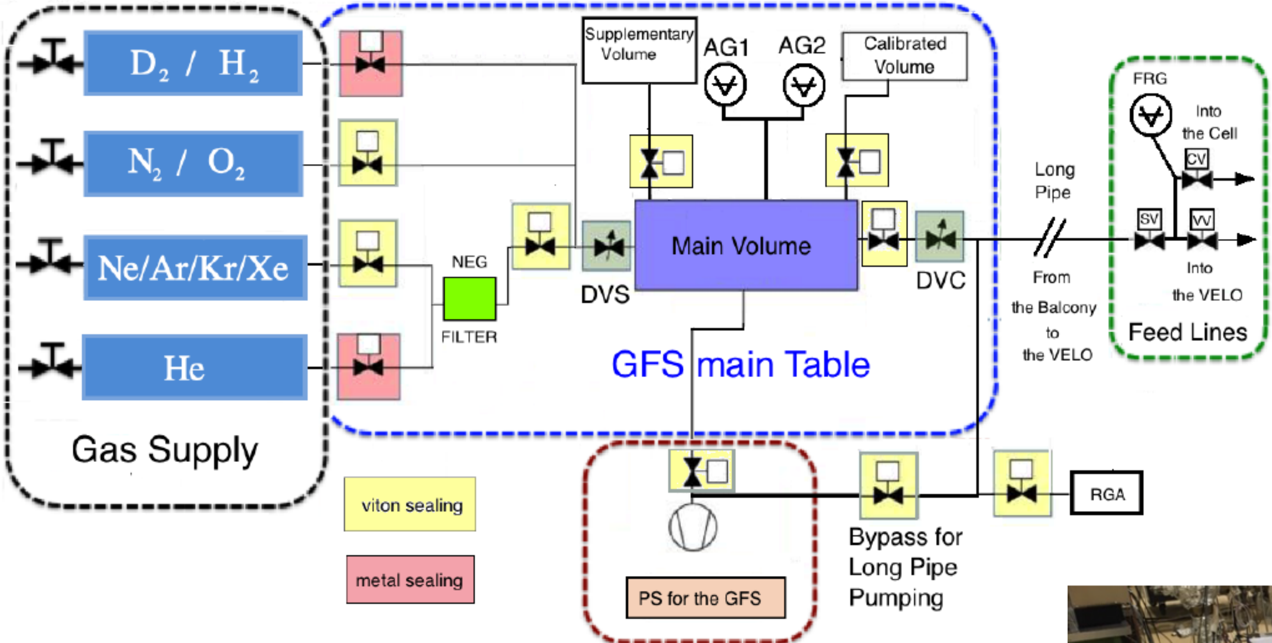
- A single-arm spectrometer designed for the study of particles containing c or b quarks
- **Forward acceptance:** $2 < \eta < 5$



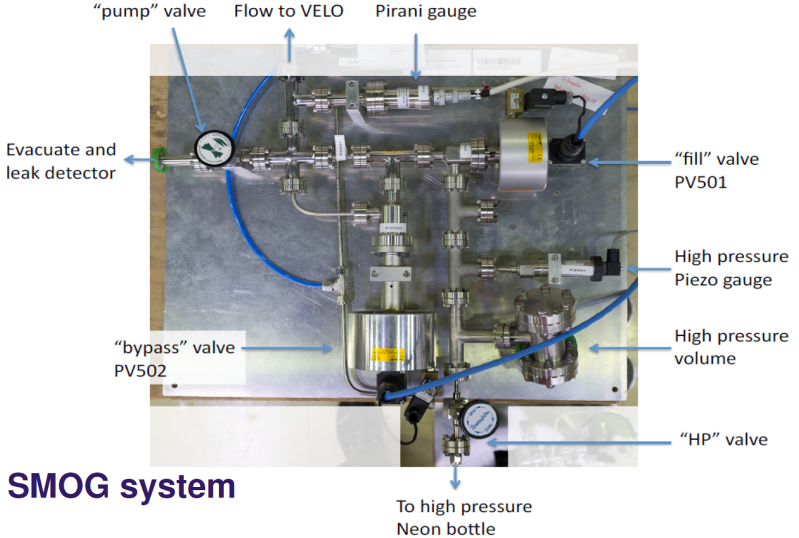
VELO (Vertex Locator)
- Vertex reconstruction
- IP resolution of 20 μm
- 21 stations of Si strip det.
- 2048 strips per sensor.



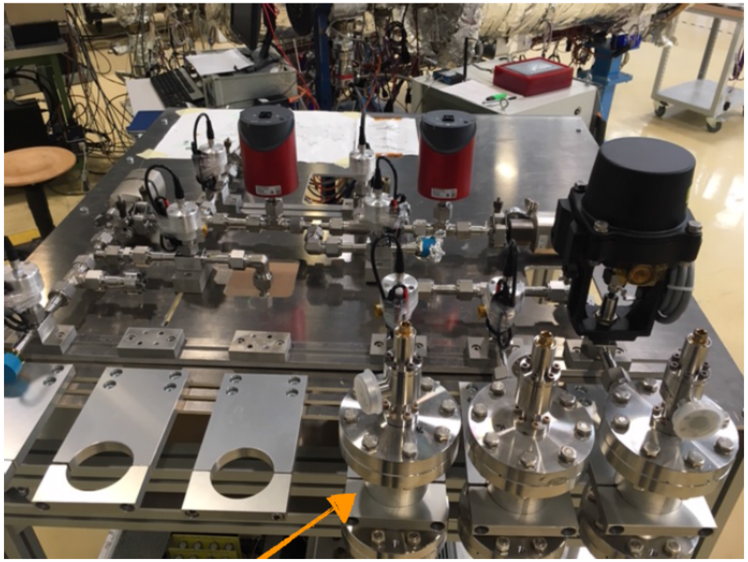
The SMOG2 setup



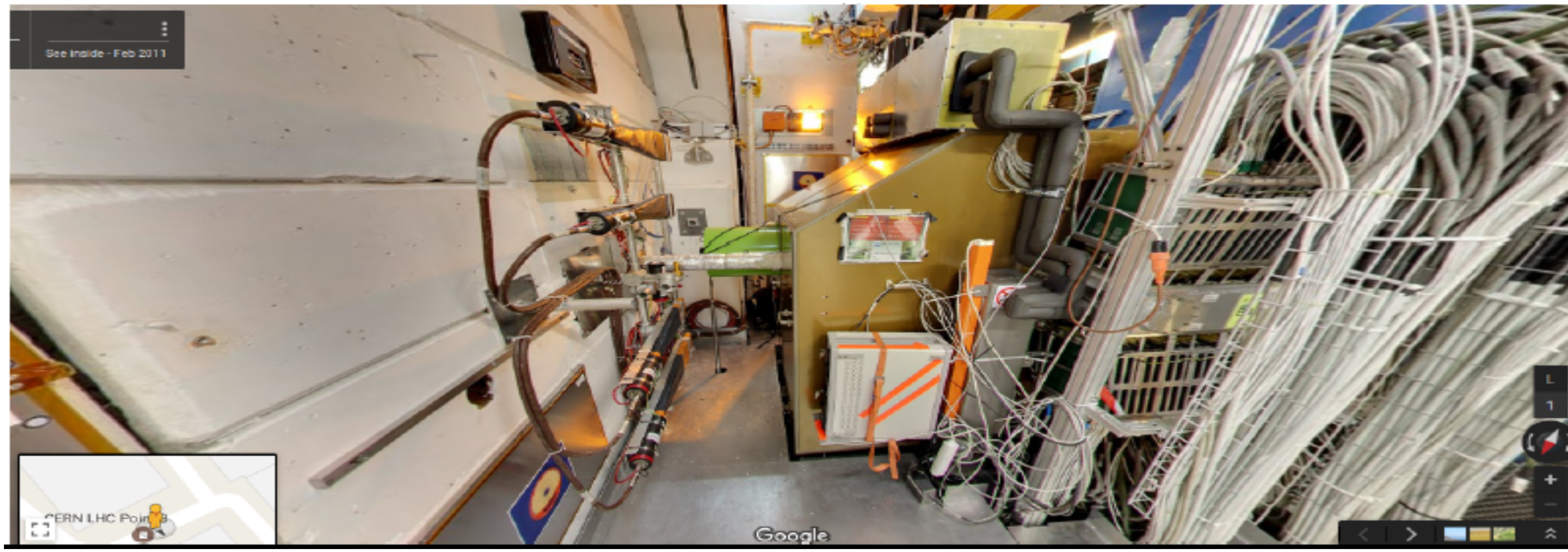
SMOG2 gas feed system

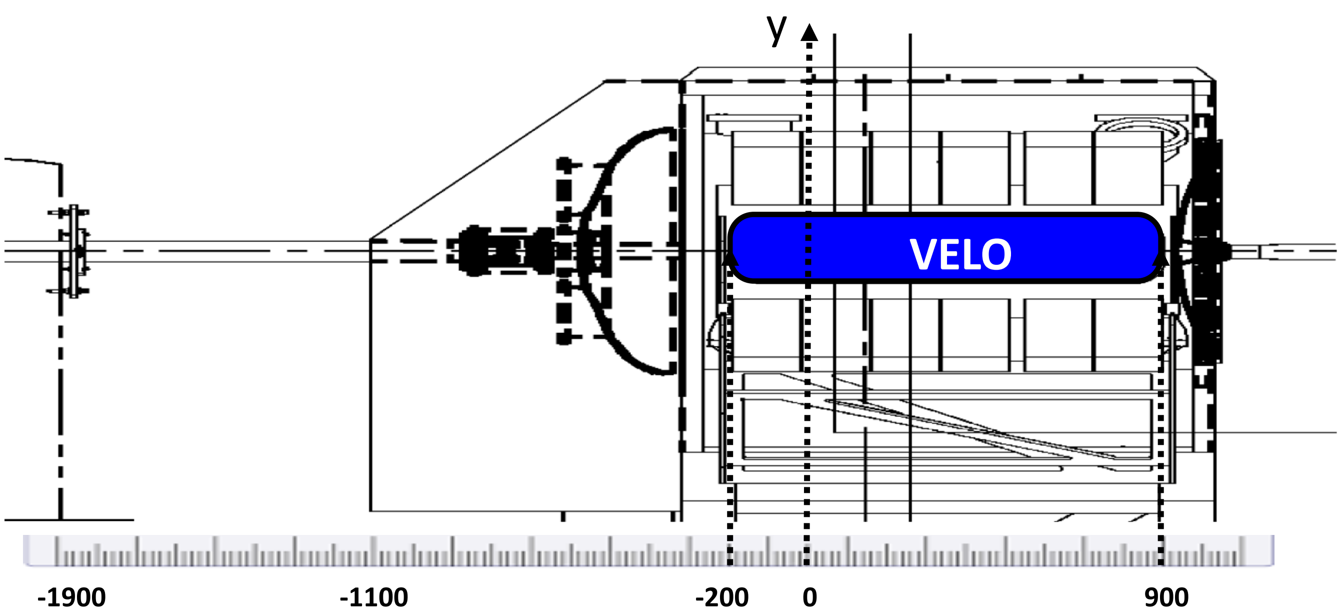


SMOG system



There is sufficient room beyond the VELO…



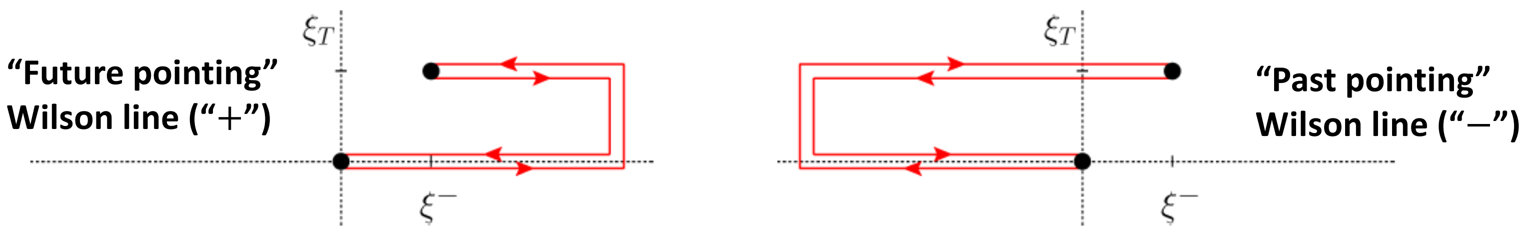


Process dependence

As for quark TMDs, also the gluon TMD phenomenology is enriched by the **process dependence** originating from ISI/FSI and encoded in the **gauge links**.

The gluon correlator depends on two path-dependent gauge links [D. Boer: arXiv:1611.06089]

$$\Gamma^{\mu\nu\,[\mathcal{U},\mathcal{U}']}(x,\boldsymbol{k}_T) \equiv \int \frac{d(\xi\cdot P)\,d^2\xi_T}{(P\cdot n)^2(2\pi)^3} e^{i(xP+k_T)\cdot\xi} \langle P|\mathrm{Tr}_c\left[F^{n\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{n\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$



Both f_1^g and $h_1^{\perp g}$ are process dependent! Each of them can be of two types:

$[+\,+] = [-\,-]$ Weizsacker-Williams (WW) $[+\,-] = [-\,+]$ DiPole (DP)

- **can differ in magnitude and width (!)**
- **can be probed by different processes**

Process dependence

Can be measured at the EIC

Can be measured at the LHC with FT

[D. Boer: arXiv:1611.06089]

	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)	√	√	√	√	×	×	×

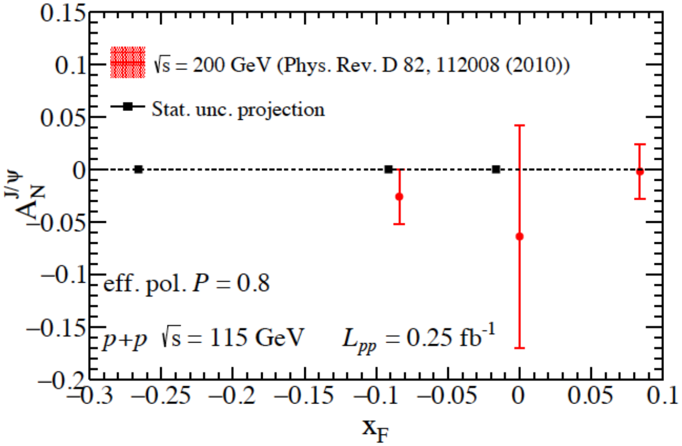
	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	√	×	√	√	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×	√	×	×	×

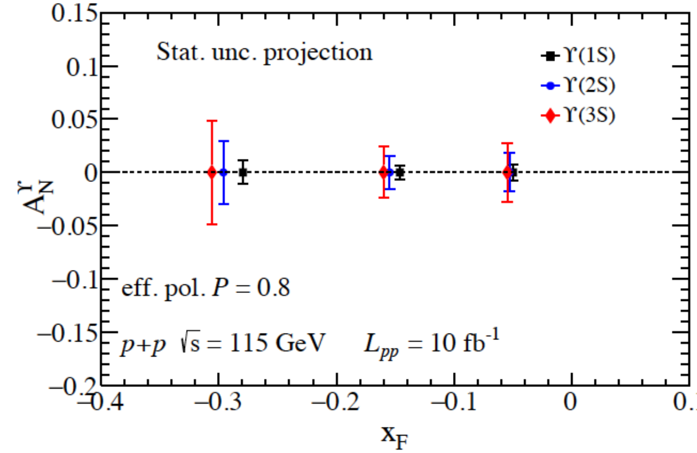
	DY	SIDIS	$p^\uparrow\,A \to h\,X$	$p^\uparrow A \to \gamma^{(*)}\,\text{jet}\,X$	$p^\uparrow p \to \gamma\,\gamma\,X$ $p^\uparrow p \to J/\psi\,\gamma\,X$ $p^\uparrow p \to J/\psi\,J/\psi\,X$	$e\,p^\uparrow \to e'\,Q\,\overline{Q}\,X$ $e\,p^\uparrow \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[+,+]}$ (WW)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

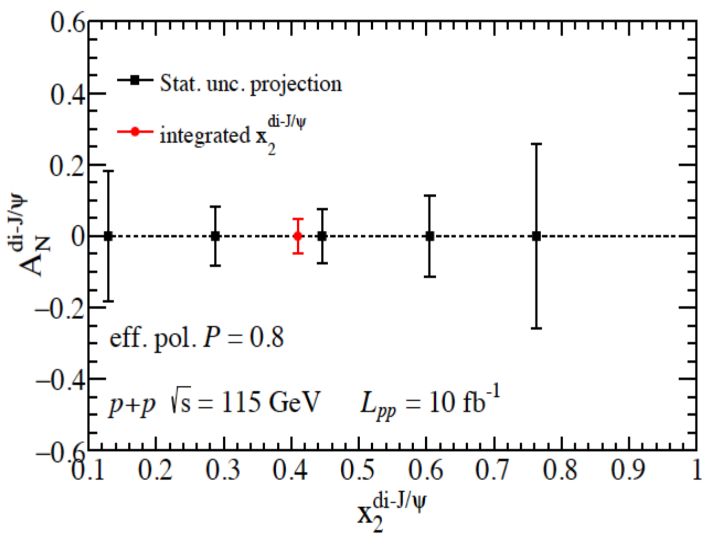
$$[+,+] \quad f_{1T}^{\perp\,g[e\,p^\uparrow \to e'\,Q\bar{Q}\,X]}(x, p_T^2) = -f_{1T}^{\perp\,g[p^\uparrow\,p \to \gamma\,\gamma\,X]}(x, p_T^2) \quad [-,-]$$

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

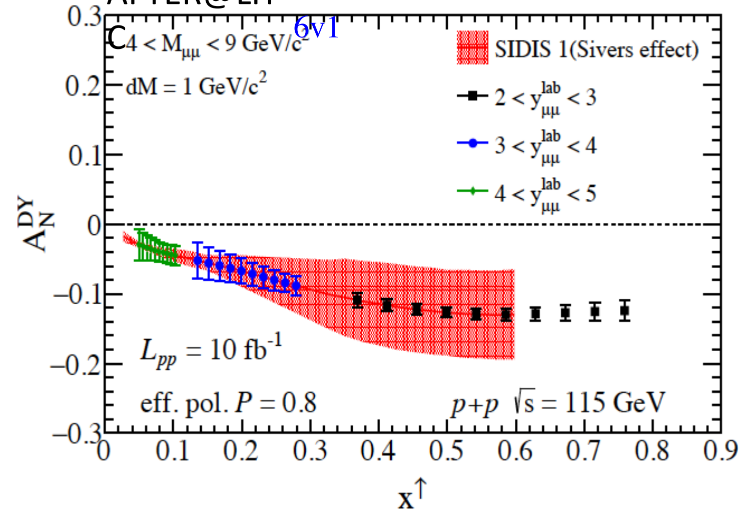
(projected results from **AFTER@LHC** arXiv:1702.01546v1)







AFTER@LHC arXiv:1702.01546v1



Main reactions of interest

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

☛ **Pol and unpol gluon PDFs**

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

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

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

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

We warmly encourage our theory colleagues to propose new physics cases and new reactions of interest for LHCSpin!

SMOG2 projections for LHC Run3

Storage cell assumptions	gas type	gas flow (s^{-1})	peak density (cm^{-3})	areal density (cm^{-2})	time per year (s)	int. lum. (pb^{-1})
SMOG2 SC	He	1.1×10^{16}	10^{12}	10^{13}	3×10^{3}	0.1
	Ne	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	Ar	2.4×10^{15}	10^{12}	10^{13}	2.5×10^{6}	80
	Kr	8.5×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	Xe	6.8×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	H_2	1.1×10^{16}	10^{12}	10^{13}	5×10^{6}	150
	D_2	7.8×10^{15}	10^{12}	10^{13}	3×10^{5}	10
	O_2	2.7×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	N_2	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1

SMOG2 example pAr @115 GeV

Int. Lumi.		80/pb
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k