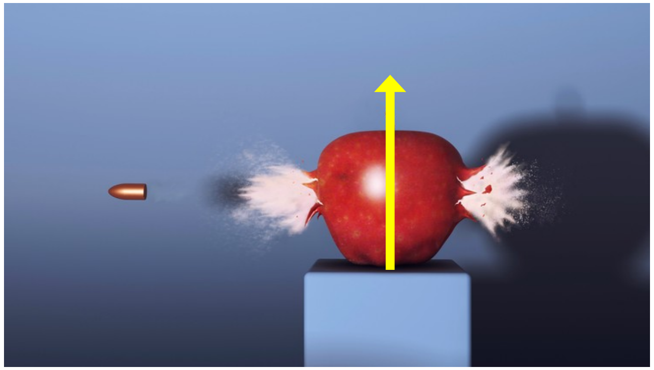
Correlations in Partonic and Hadronic Interactions 2018

Yerevan – September 24-28 2018

The LHCb fixed target project



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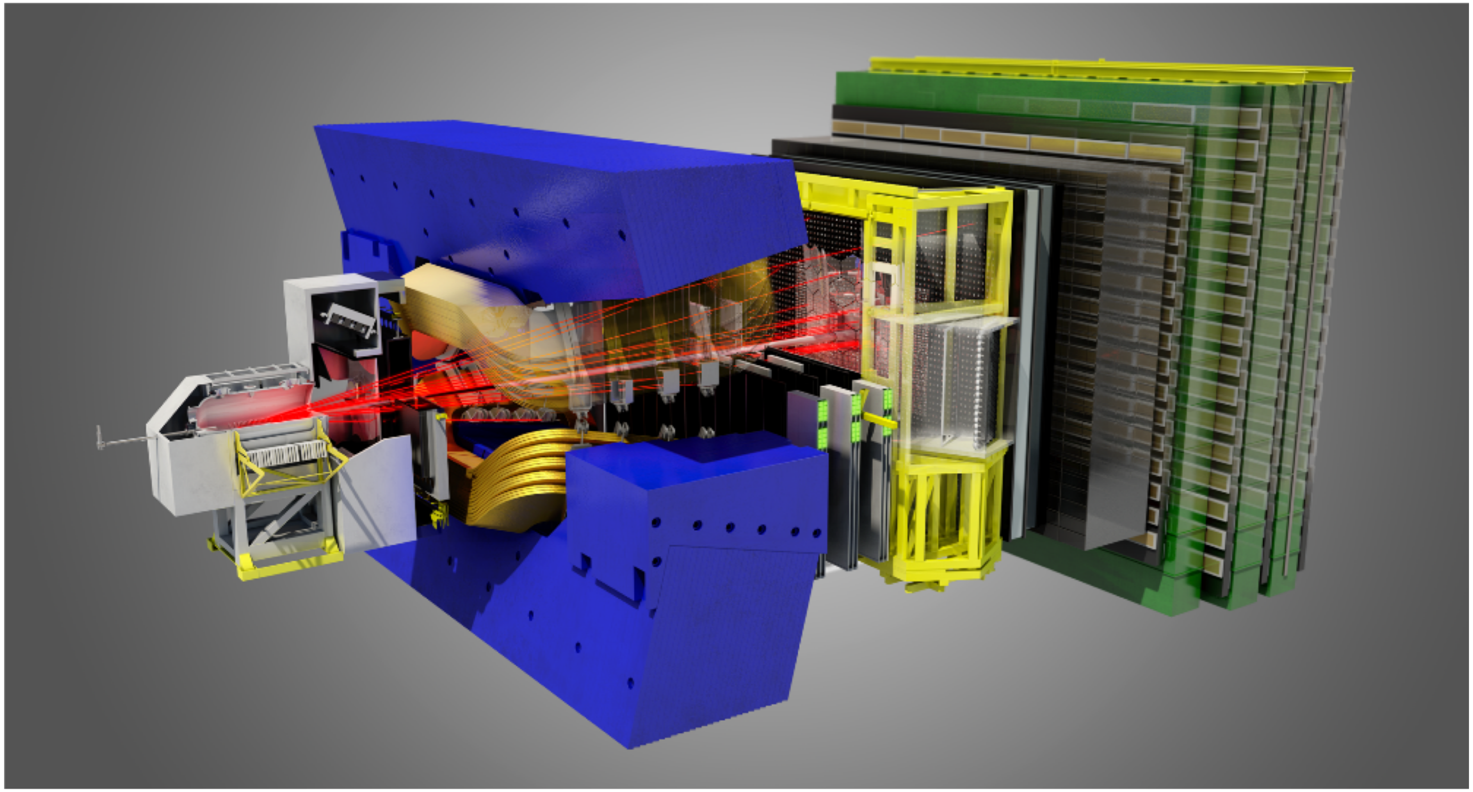
The LHCb detector

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



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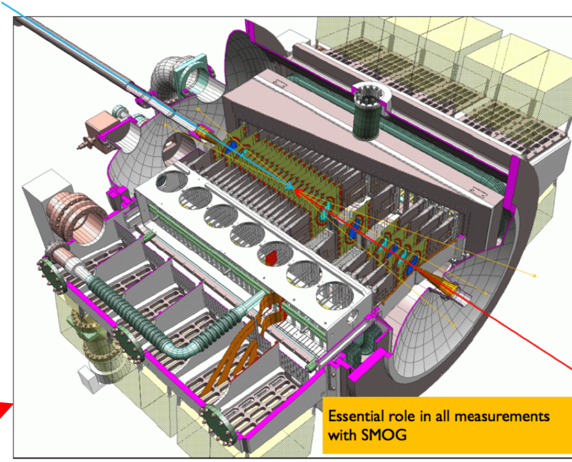
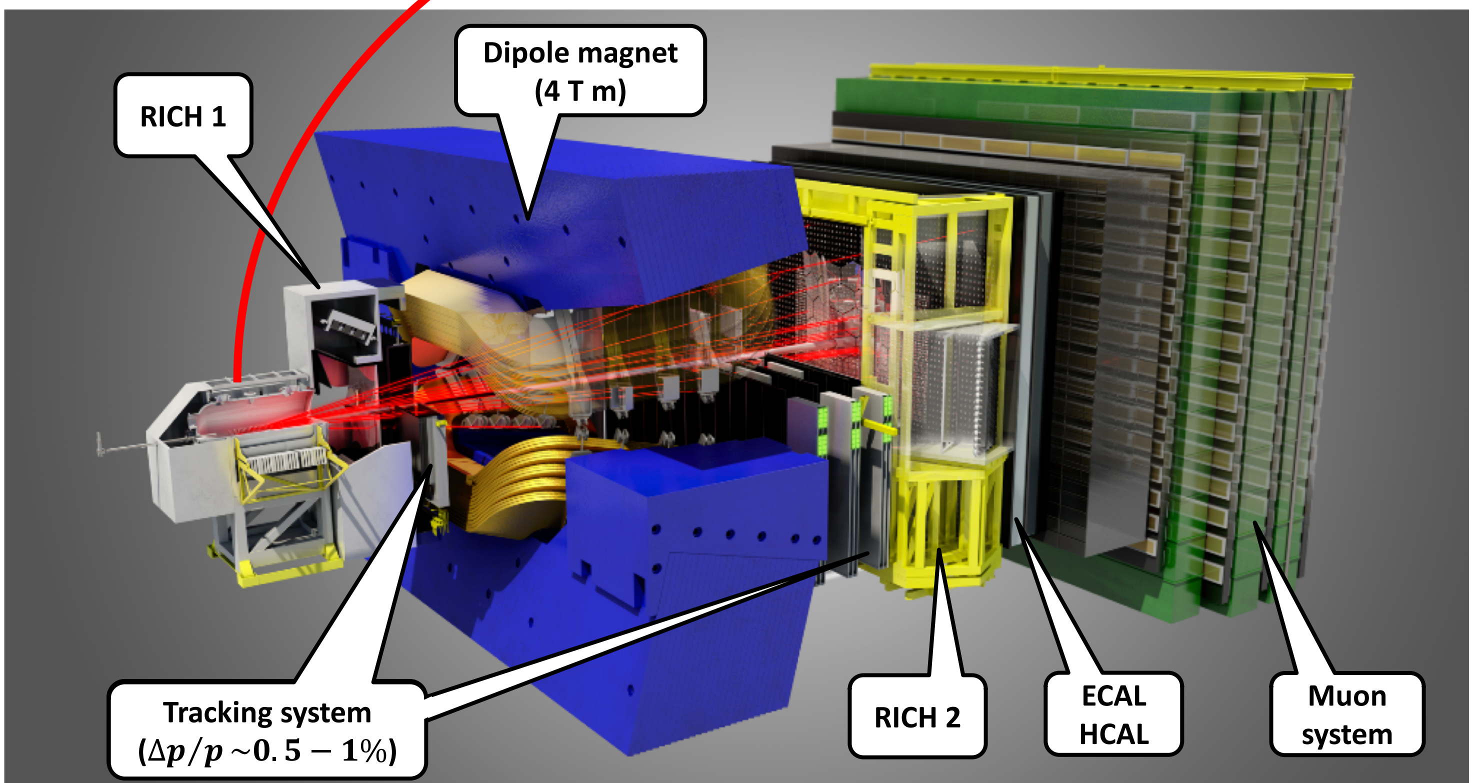


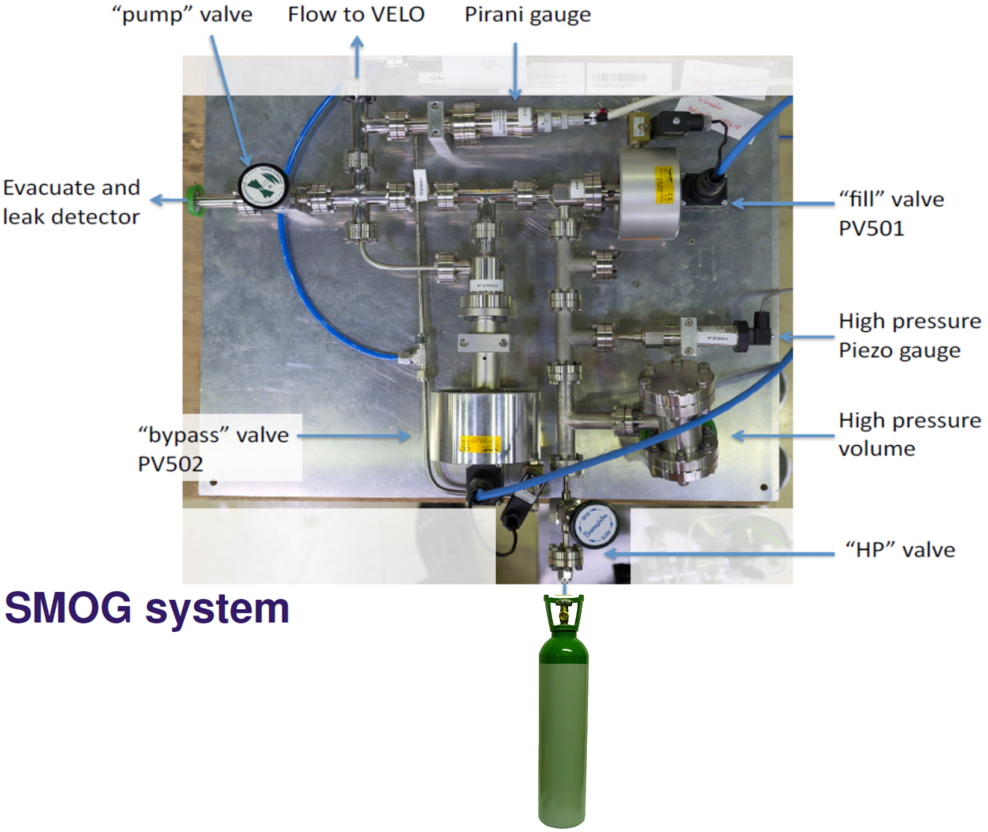
VELO (Vertex Locator)
- Vertex reconstruction
- IP resolution of 20 μm
- 21 stations of Si strip det.
- 2048 strips per sensor
- determines r and ϕ coord.



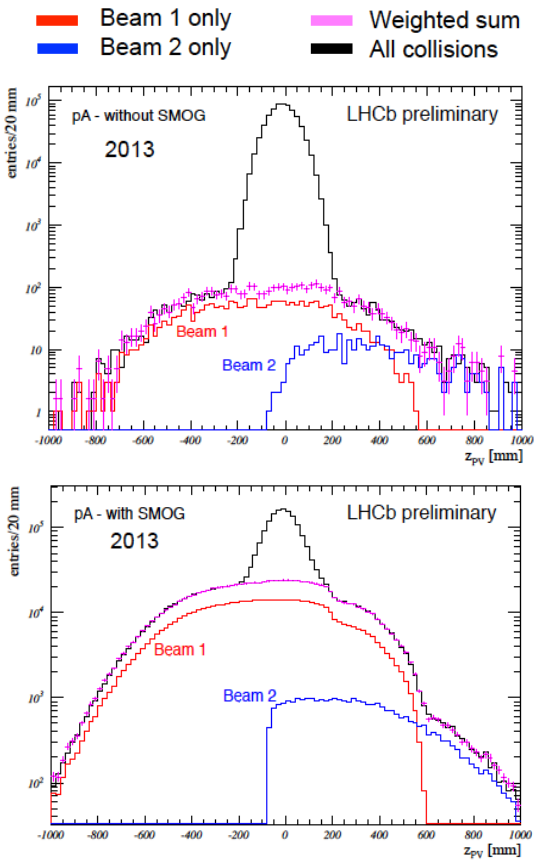
The LHCb fixed-target system

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 larger than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude



SMOG system



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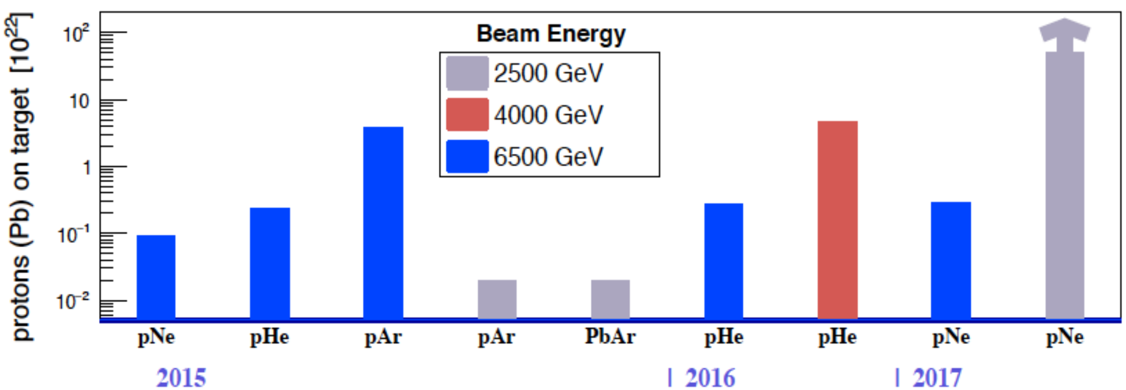
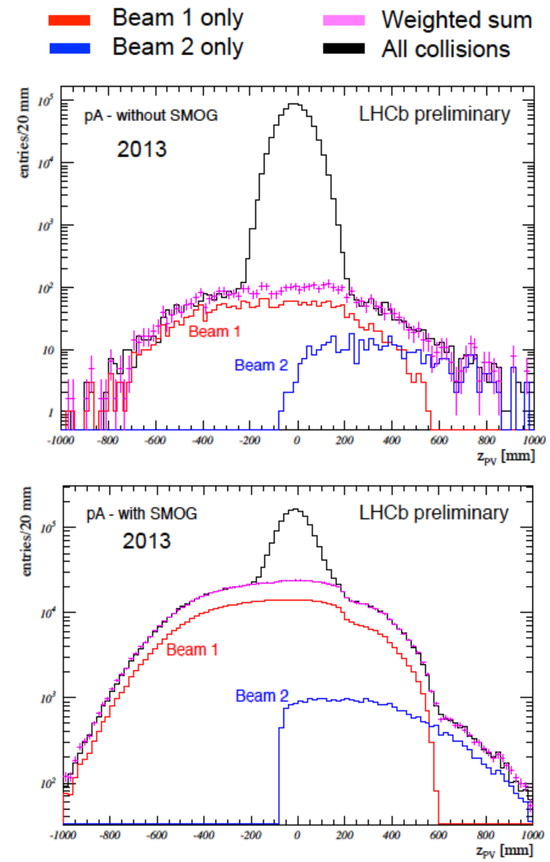
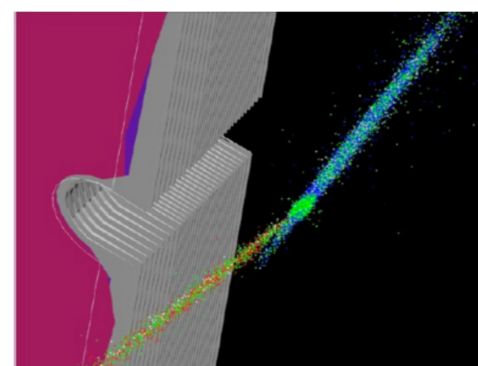
- Gas pressure 2 orders of magnitude larger than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude
- Conceived for **precise luminosity determination** (beam-gas imaging)

…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!



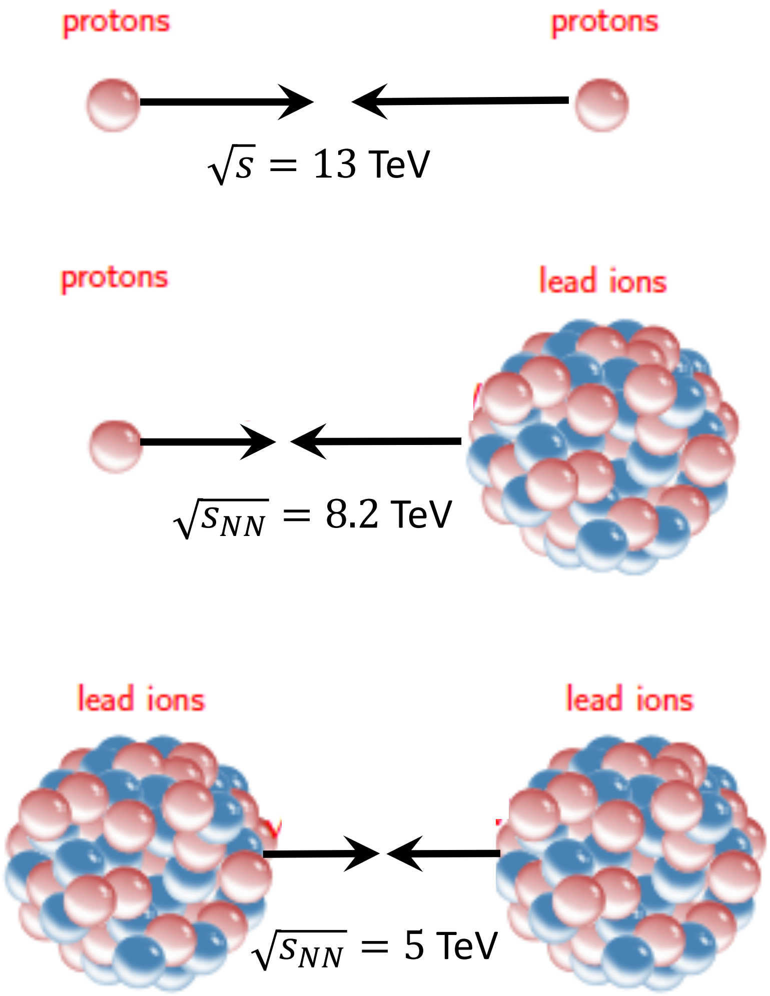




Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

Types of collisions at LHCb

Collider mode



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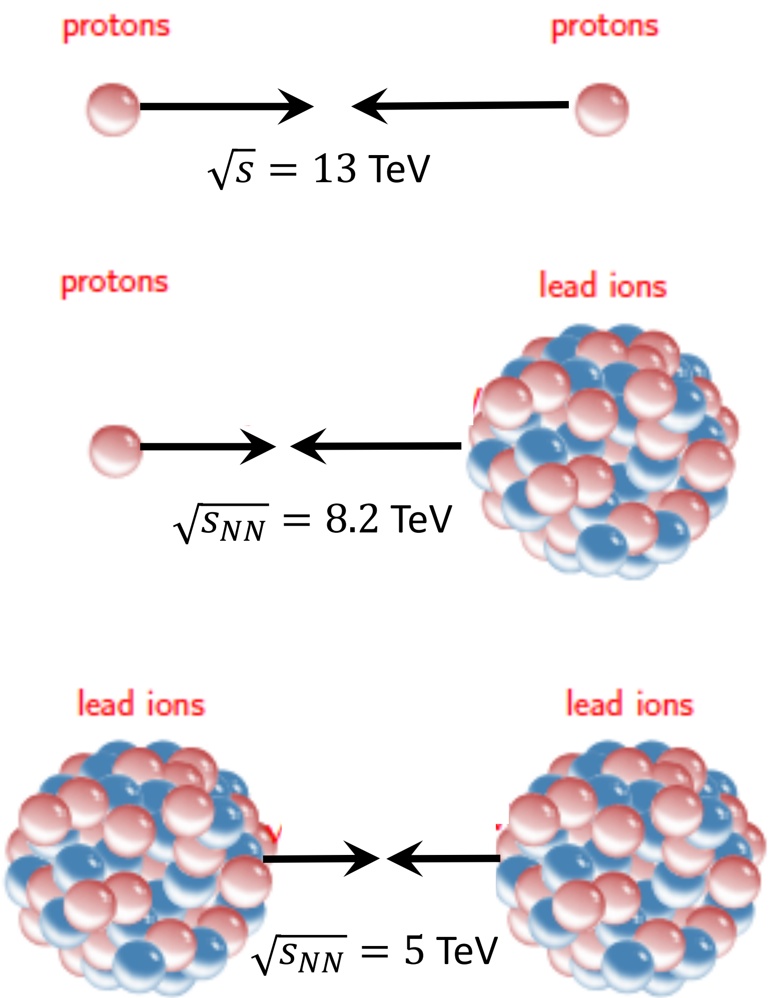
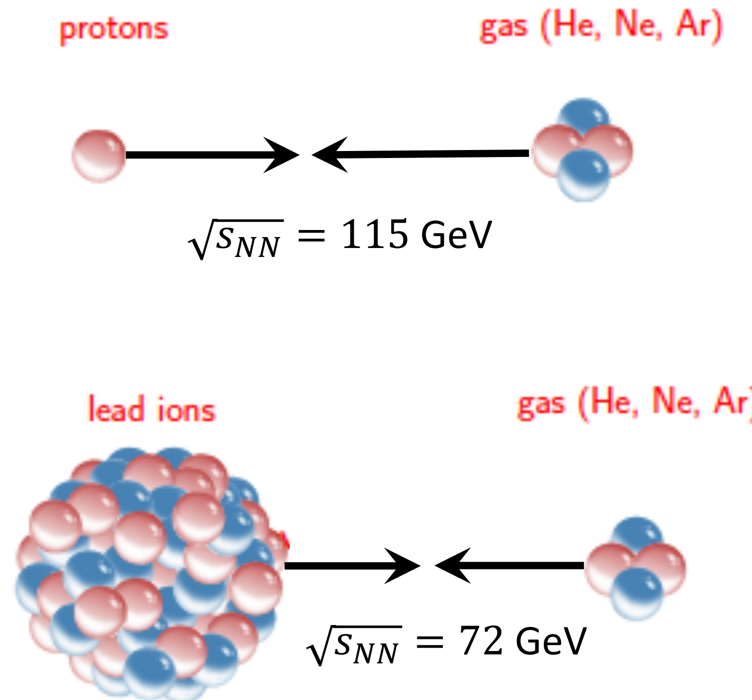


Fixed-target mode



Kinematic conditions for fixed-target collisions at LHC

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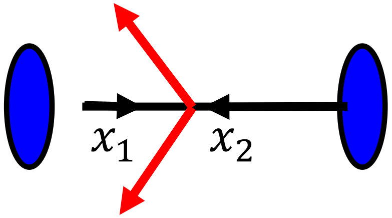

CM system

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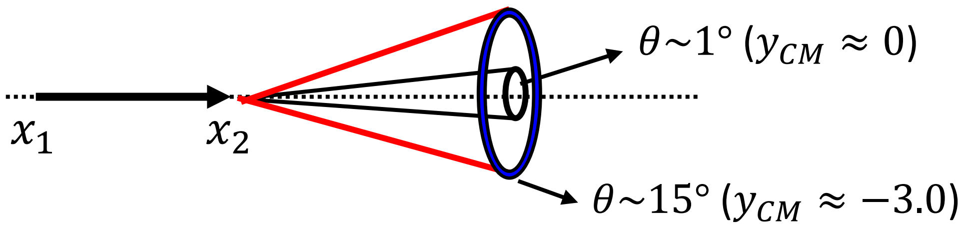
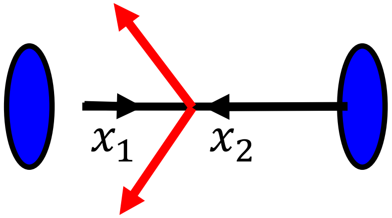


Lab system



CM system

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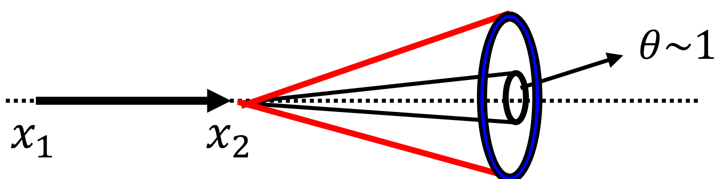
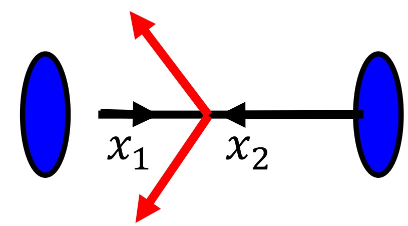


$\theta \sim 1^\circ$ $(y_{CM} \approx 0)$

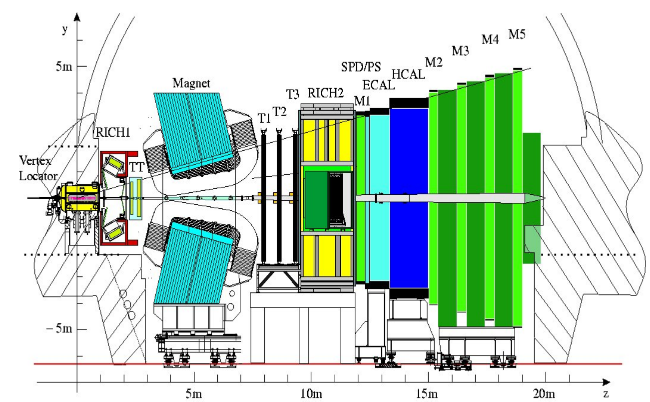
$\theta \sim 15^\circ$ $(y_{CM} \approx -3.0)$

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

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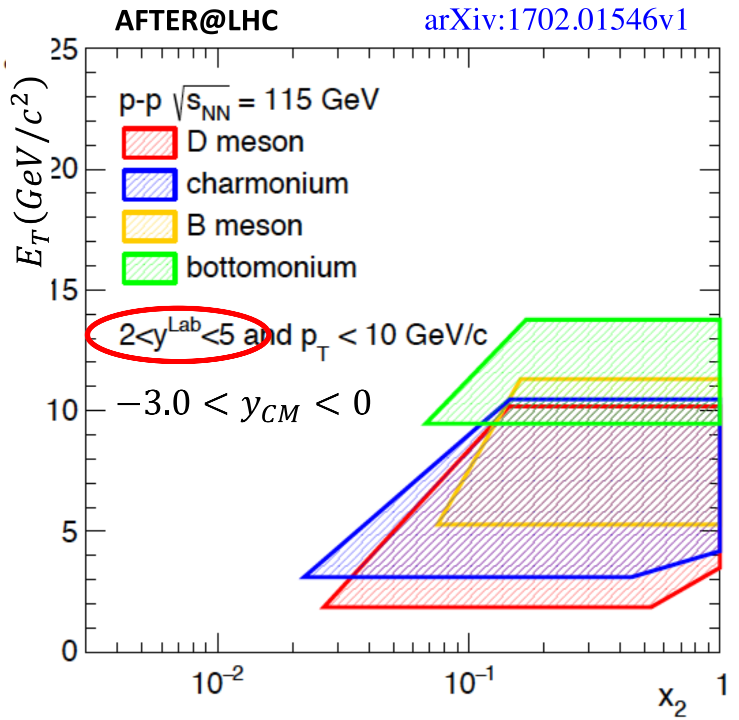

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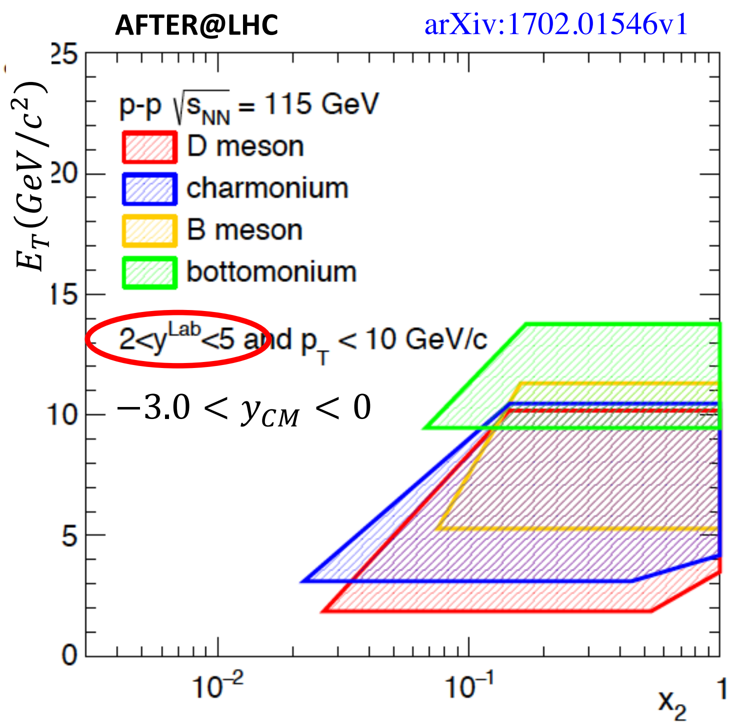
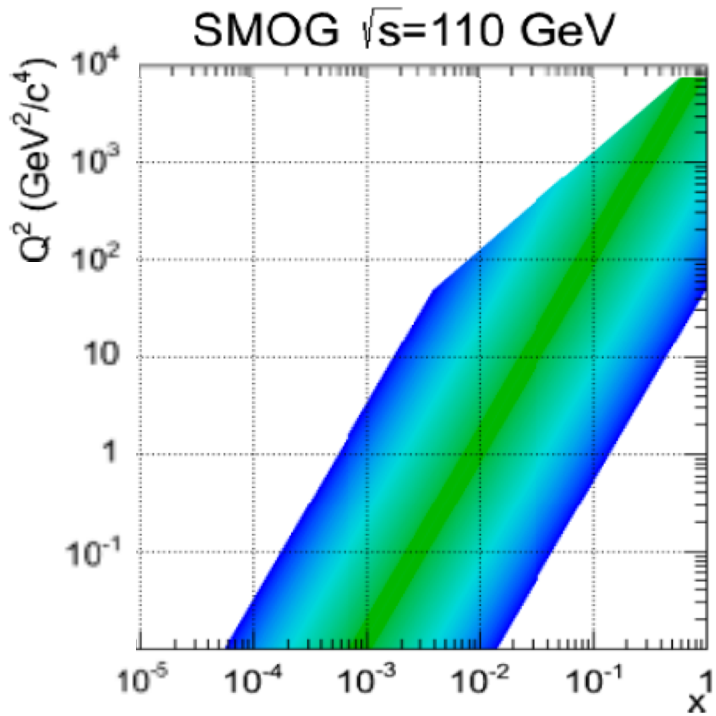
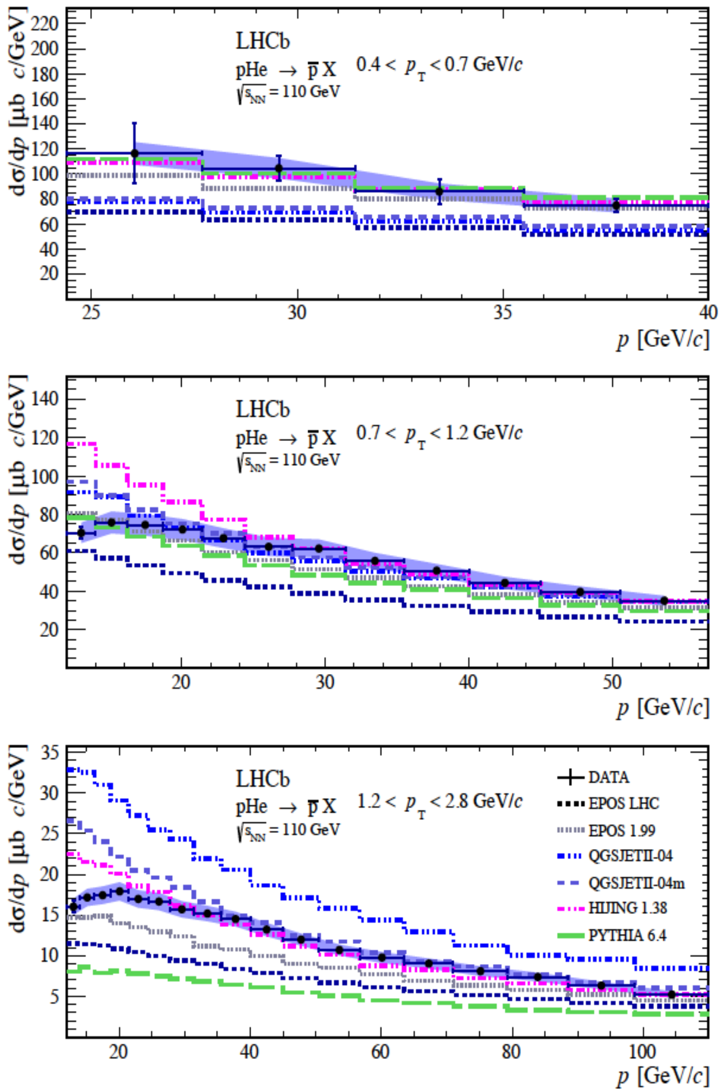




- ➢ **Sensitive to large x-Bjorken ($x_2 \to 1$)**
- ➢ **Access to target-fragmentation region** $(x_F \to -1)$

First physics results with SMOG

➢ **First measurement of $\overline{p}$ production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV** arXiv:1808.06127



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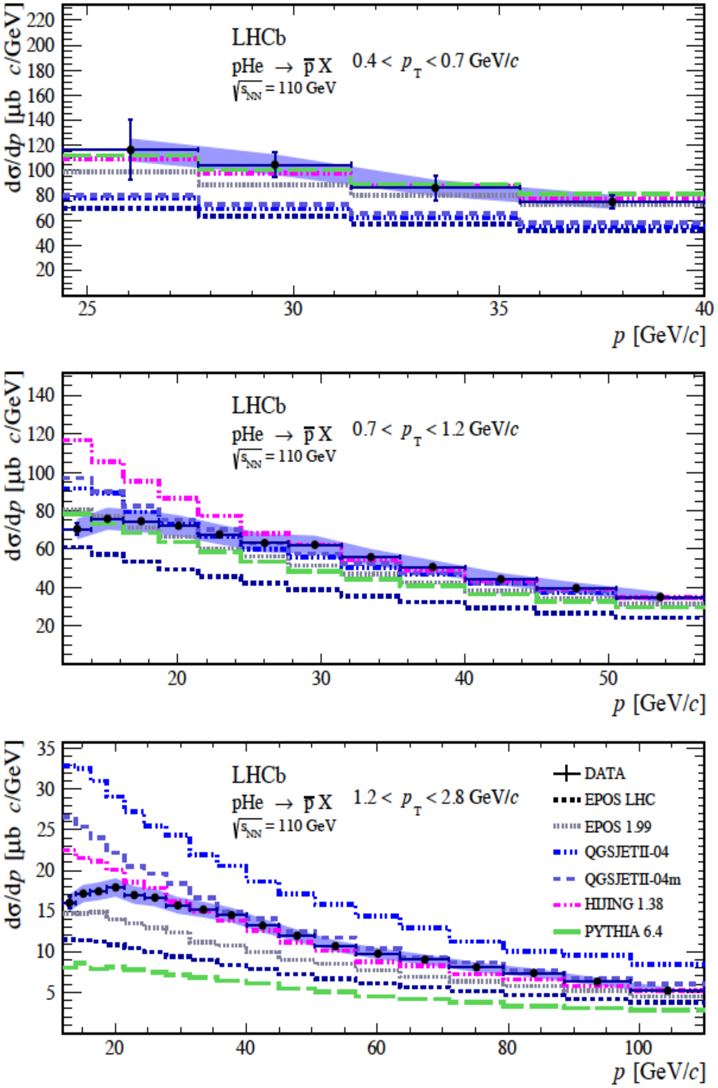
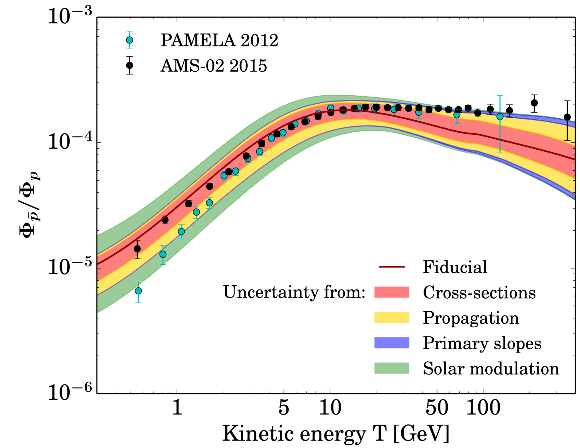


Relevant for cosmic-rays/DM physics: predictions for $\bar{p}/p$ flux ratio from spallation of primary cosmic rays on interstellar medium (H and He) are presently limited by large uncertainties on $\bar{p}$ production cross sections (especially from He)

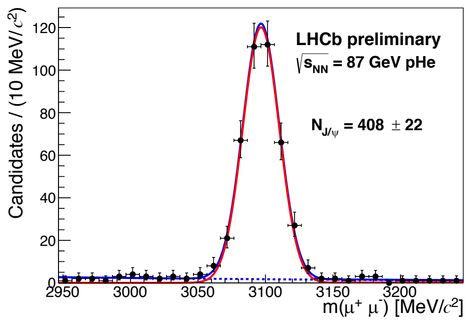


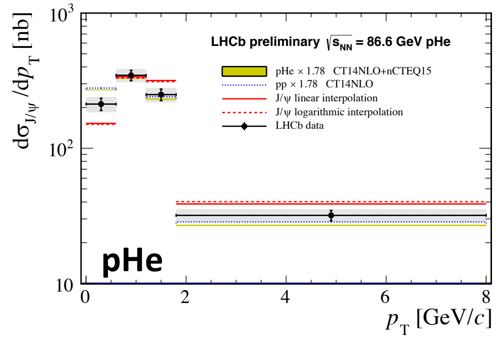
Unique analysis at LHC!

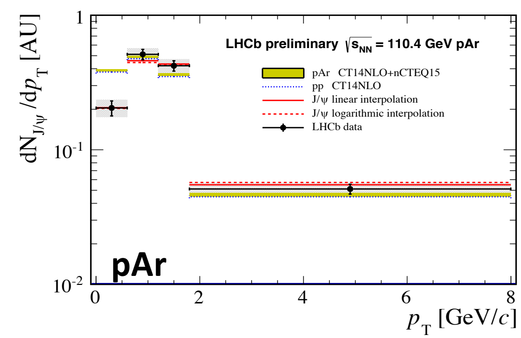
First physics results with SMOG

- **J/ψ and D^0 production in pAr and pHe collisions** LHCb-PAPER-2018-023 (in preparation)

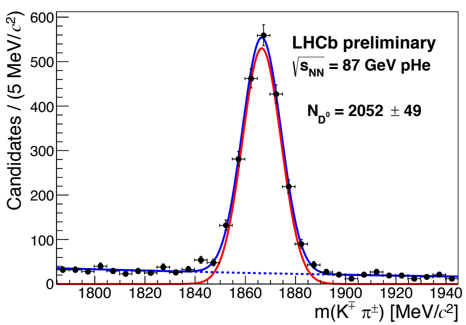
J/ψ

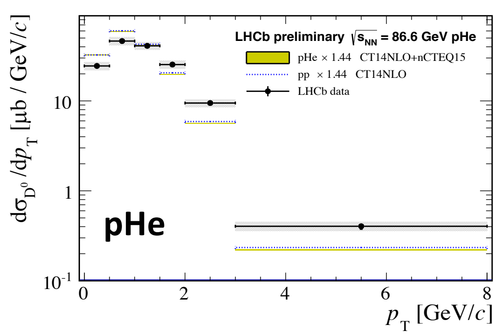


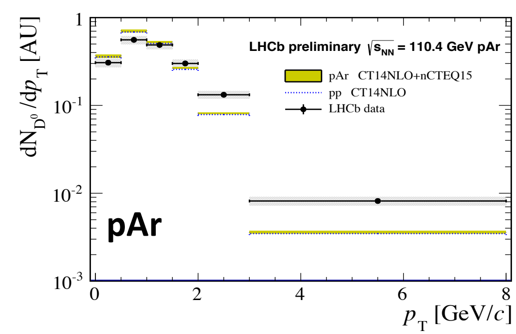




D^0







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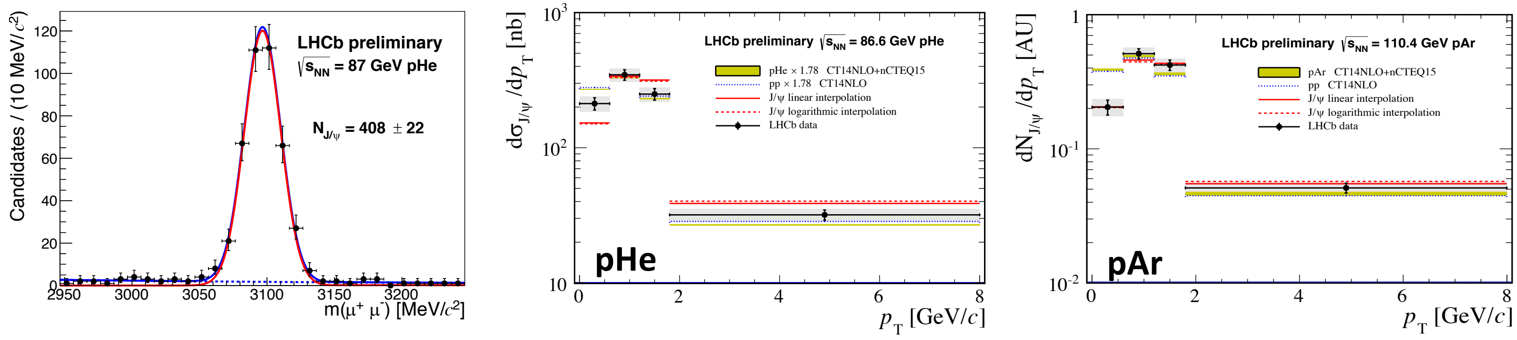
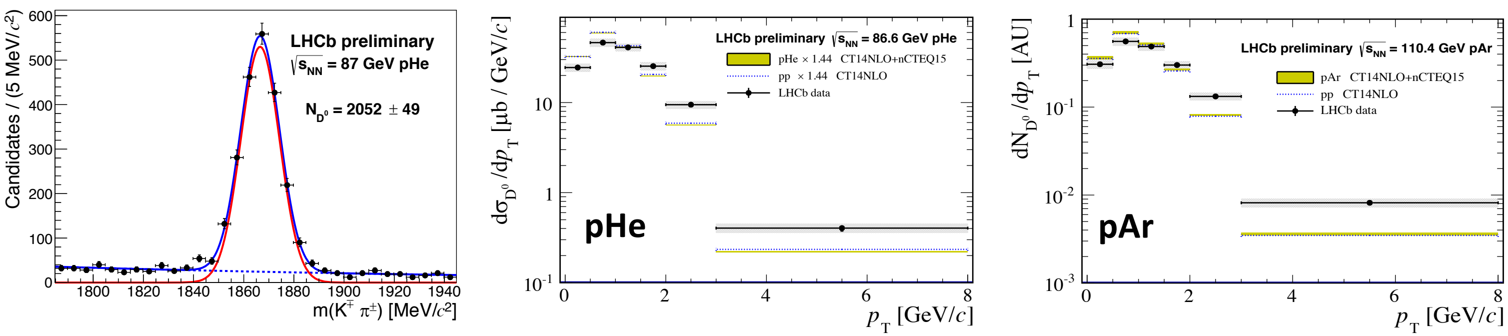
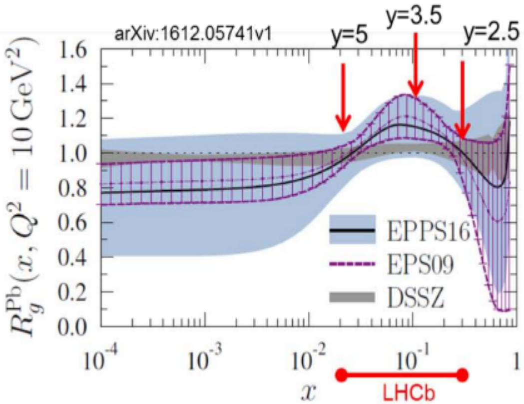
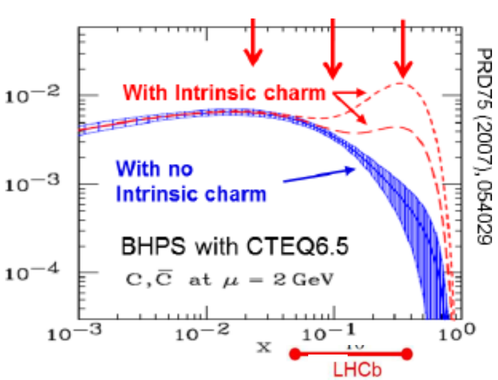


D^0



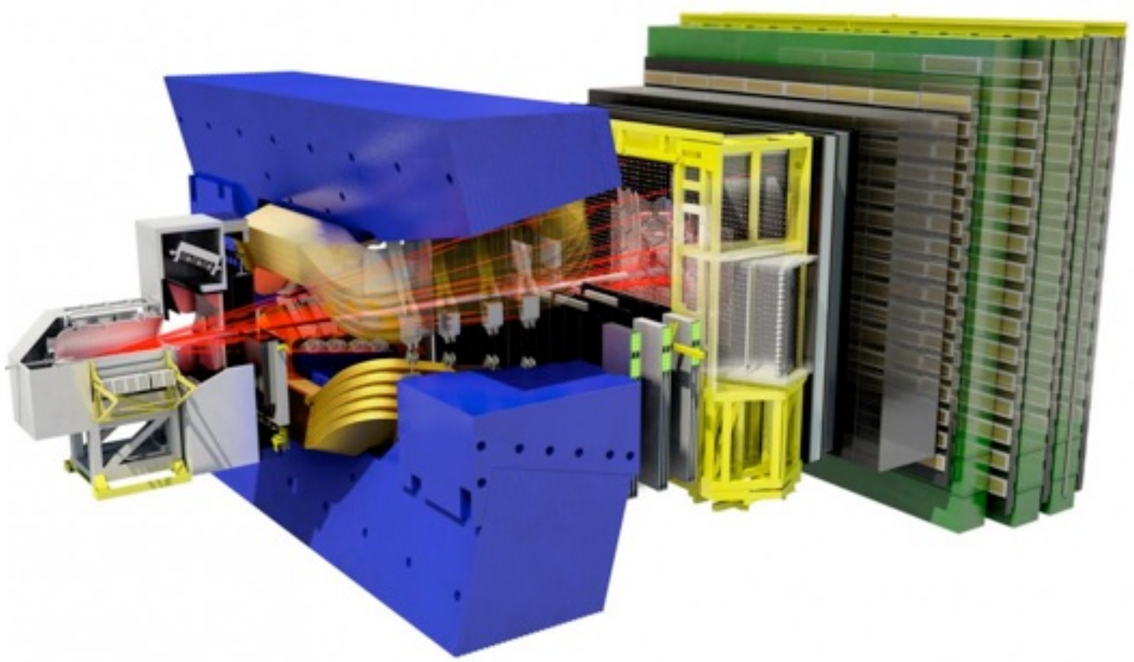
- Relevant for constraining nPDFs at high-x
- Can also help to pin-down possible contributions from intrinsic charm at high-x





The LHCSpin project

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



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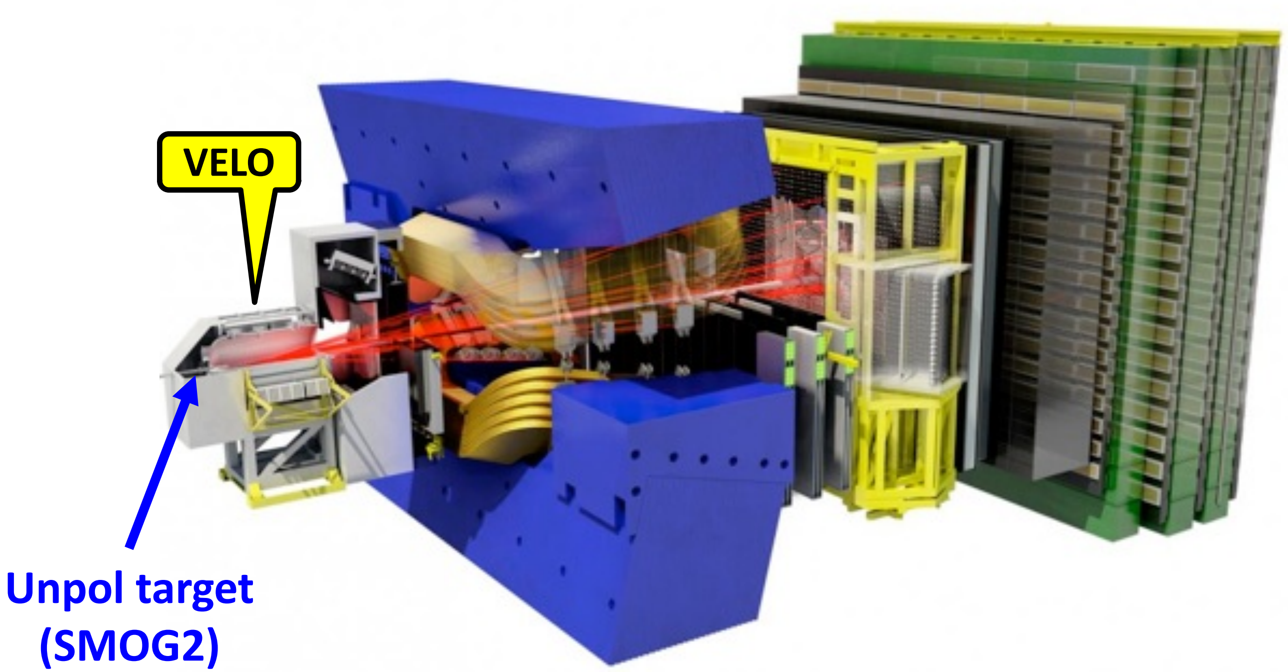
The project consists of **two phases**:

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**)



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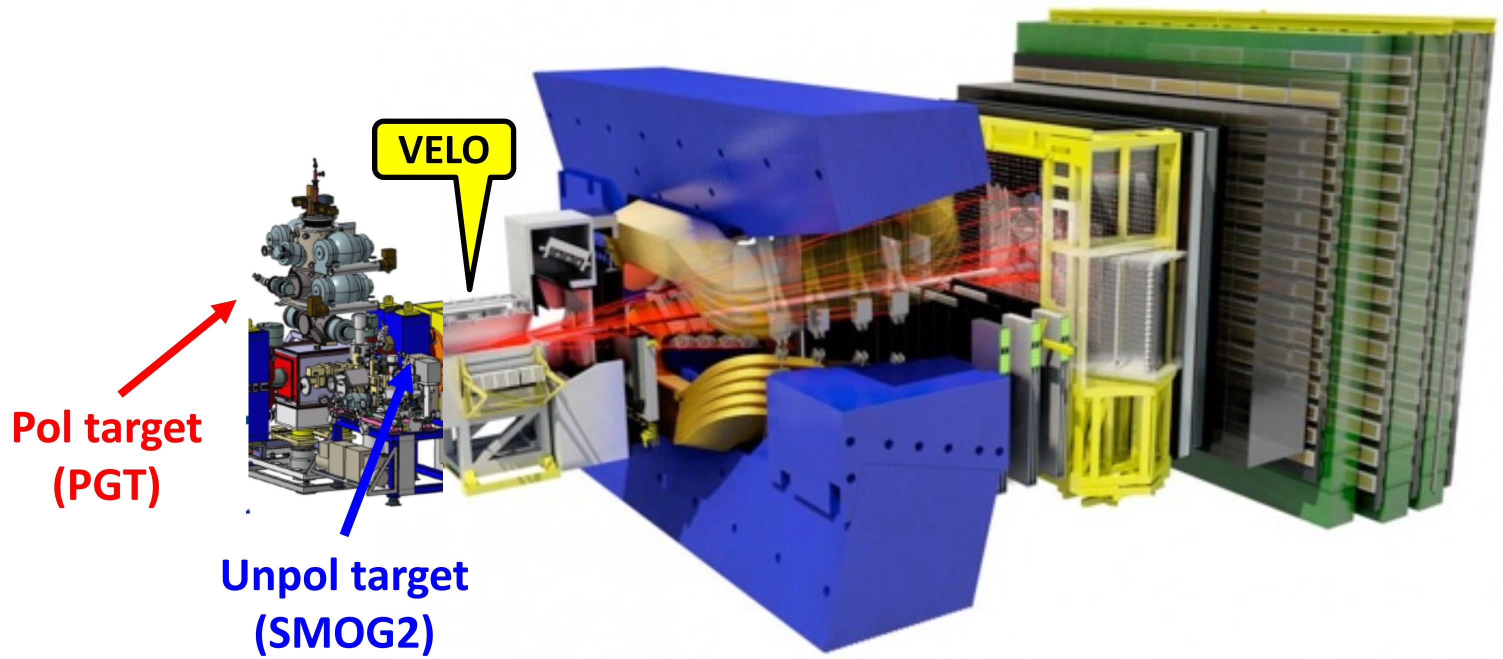
Phase II

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



Why LHCSpin?

✓ **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 ($x_F \to -1$)
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  - polarized: $\mathrm{pp}^{\uparrow}$, $\mathrm{pd}^{\uparrow}$
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- 3D nucleon structure (quark and gluon TMDs)
- fundamental tests of QCD (universality, factorization, etc)
- cold nuclear matter effects
- Intrinsic heavy quarks
- QGP formation

- ... and much more!

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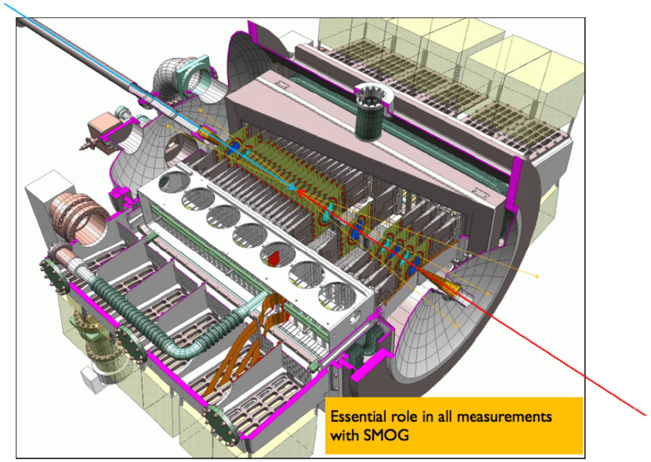
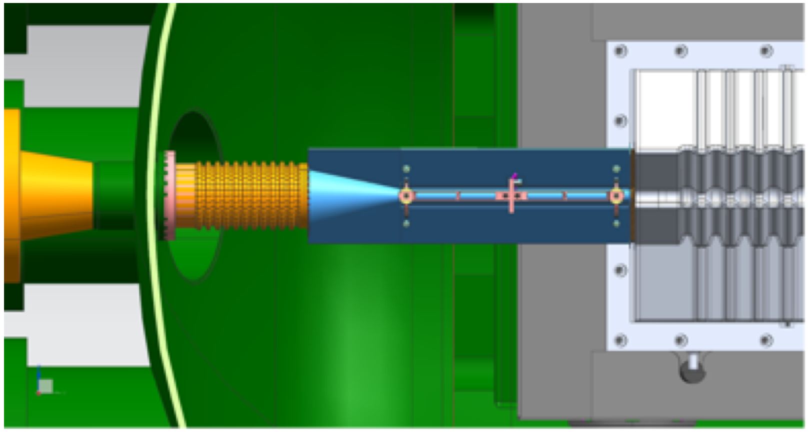
- ✓ **Polarized gas target technology well established (10 years @ HERMES)**
- ✓ **Very high performances (P~80 %)**

Phase I: SMOG2

The proposed SMOG2 setup





Internal side view

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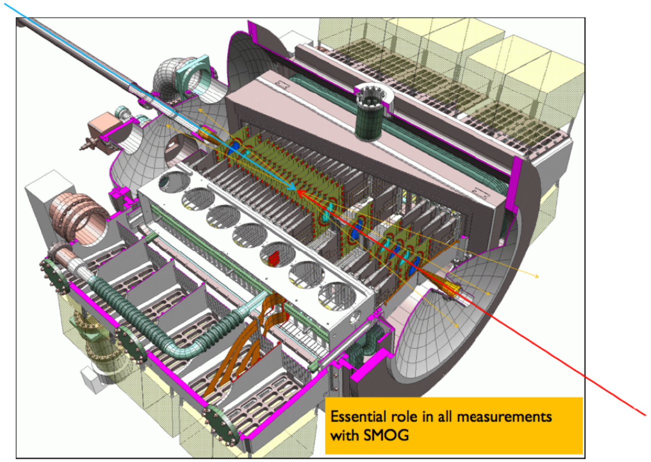

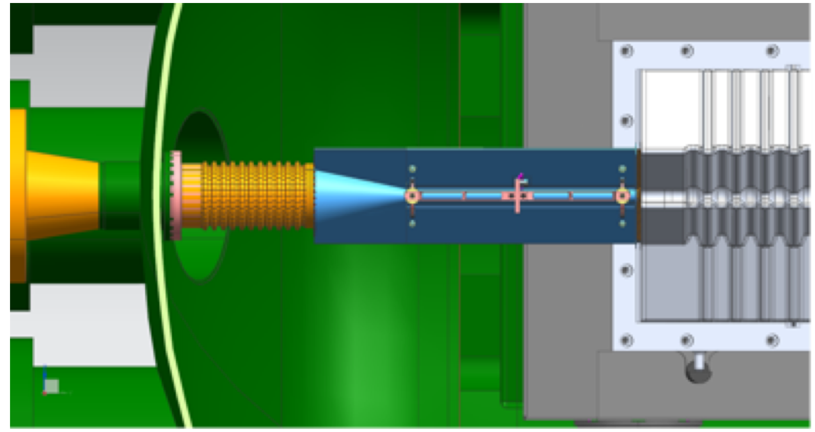

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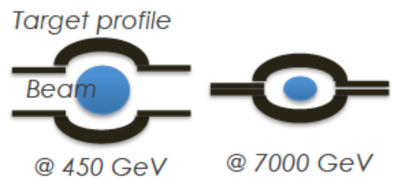
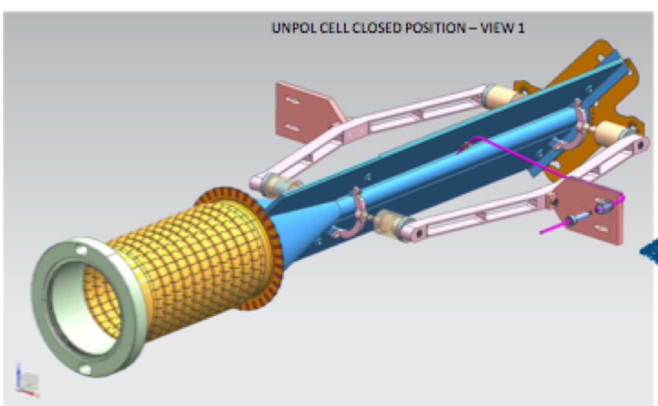
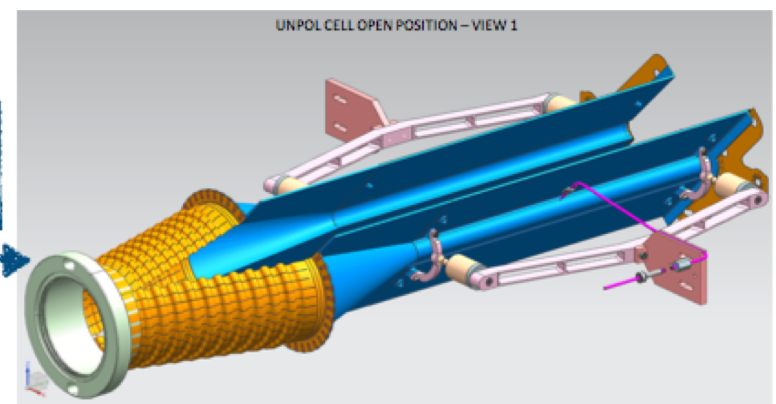




openable storage cell



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, N, 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)

- ✓ Preliminary MC simulations show **very similar reconstruction efficiencies** w.r.t SMOG despite IP is displaced w.r.t to VELO

SMOG2 vs. SMOG

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 vs. SMOG

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

Probing the gluon PDFs

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

- **Very significant progress in the last 15 years!**
- Many experiments involved: HERMES, COMPASS, JLAB, RHIC, BELLE, BABAR,..
- First extractions from global analyses
- **Now entering precision era!**

Probing the gluon PDFs

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 $h_{1T}^{\perp}$

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- First extractions from global analyses
- **Now entering precision era!**

Hadron	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!**

Probing the gluon PDFs

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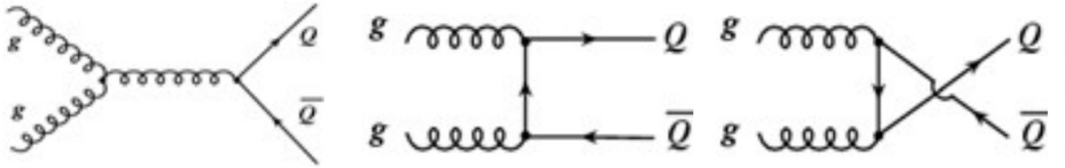
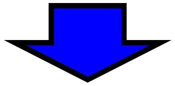
- Theory framework consolidated
- **...but experimental access still extremely limited!**
- **LHCSpin can provide a significant contribution to the field, already from Phase I (unpol target)**
- **Note: gluons with non-zero p_T inside an unpolarized hadron can be linearly polarized!**

Probing the gluon PDFs

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





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

Probing the gluon PDFs

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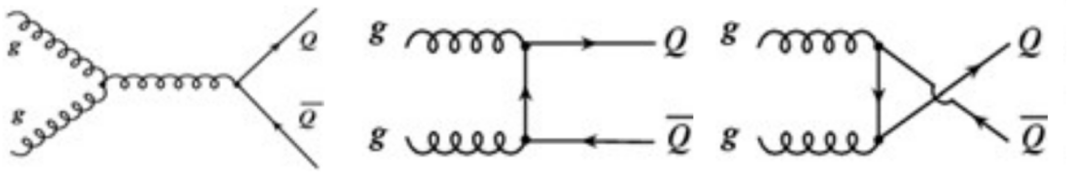
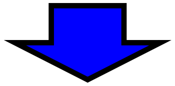
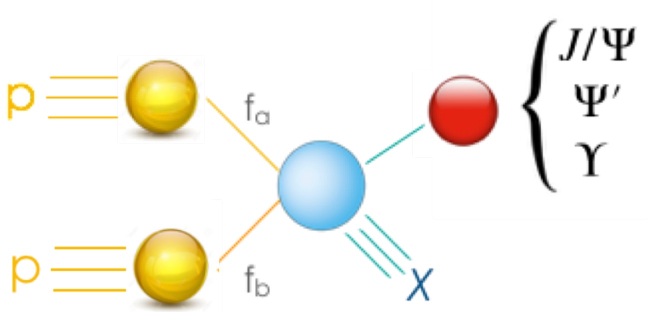




The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-flavour observables**

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



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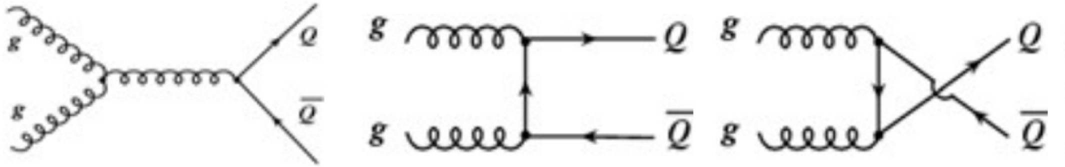

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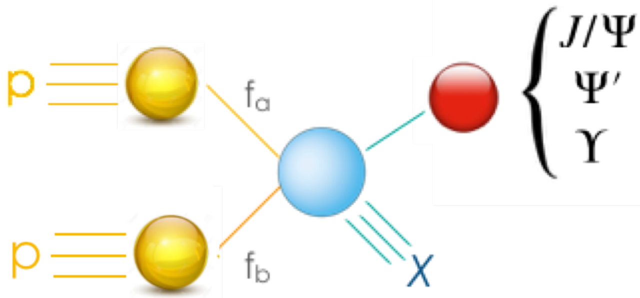
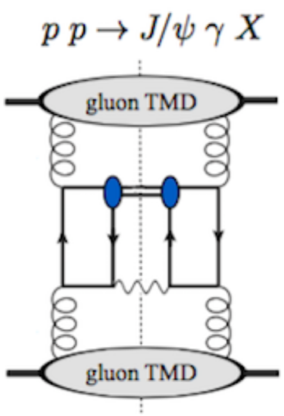




Caveat: TMD factorization requires $p_T(Q) \ll M_Q$. At LHC one can look at **back-to-back production of quarkonia and isolated photon or associate quarkonia production**, where only the relative p_T has to be small:

$$pp \to J/\psi + \gamma + X \qquad pp \to \Upsilon + \gamma + X \qquad pp \to J/\psi + J/\psi + X$$

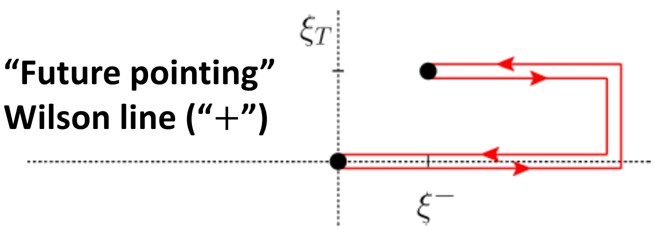
Probing the gluon PDFs

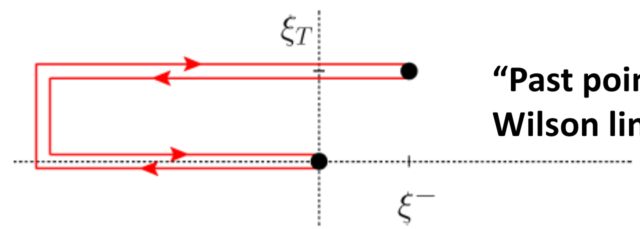
As for quark TMDs, also the gluon TMD phenomenology is enriched by the **process dependence** originating from ISI/FSI and encoded in the **gauge links**.

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

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

"Future pointing" Wilson line ("+")





"Past pointing" Wilson line ("−")

Probing the gluon PDFs

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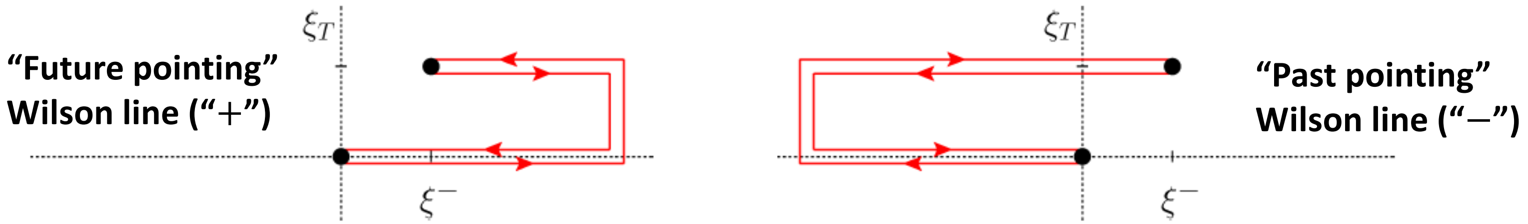


Both f_1^g and $h_1^{\perp g}$ are process dependent! Each of them can be of two types:

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

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

Probing the gluon PDFs

[D. Boer: arXiv:1611.06089]

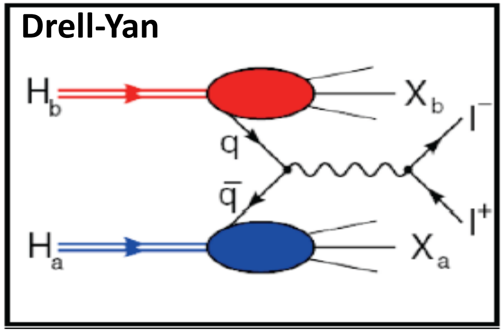
	DIS	DY	SIDIS	$pA \to \gamma\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$f_1^{g\,[+,+]}$ (WW)	×	×	×	×	√	√	√
$f_1^{g\,[+,-]}$ (DP)	√	√	√	√	×	×	×

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

(pink) Can be measured at the EIC

(blue) Can be measured at the LHC (and in particular at LHCb with SMOG2)

What about quark PDFs ?



- Clean process
- LHCb has excellent reconstruction capabilities for $\mu\mu$ channel!

- Dominant process: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu\mu$
- But also possible: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu\mu$

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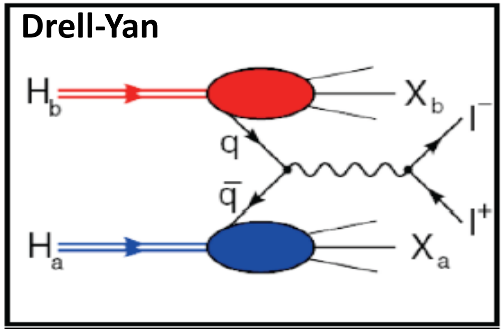

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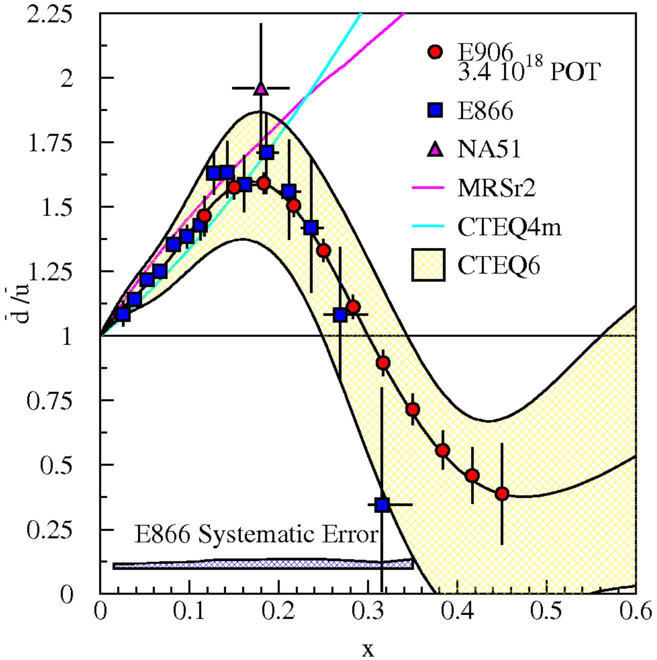
- Allows to study the **antiquark content of the nucleon!**



$\bar{d}(x) \neq \bar{u}(x)$!!

- sea is not flavour symmetric!
- hints that: $\bar{s}(x) \neq s\,(x)$
- Brodsky et al. arXiv:1809.04975
- **intrinsic sea quarks**?

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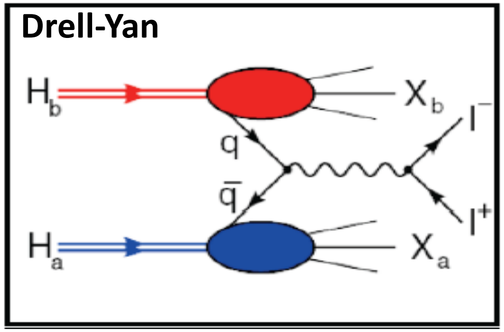

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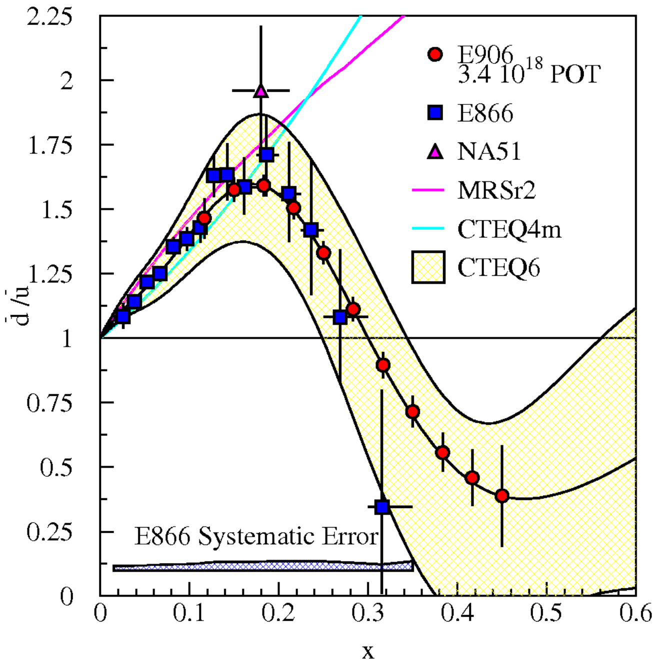

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- Allows to study the **antiquark content of the nucleon!**

- **Provides sensitivity to unpolarized and BM TMDs up to high x_2**

$$\sigma_{UU} \propto f_1 f_1 + \cos 2\phi \, h_1^\perp h_1^\perp$$

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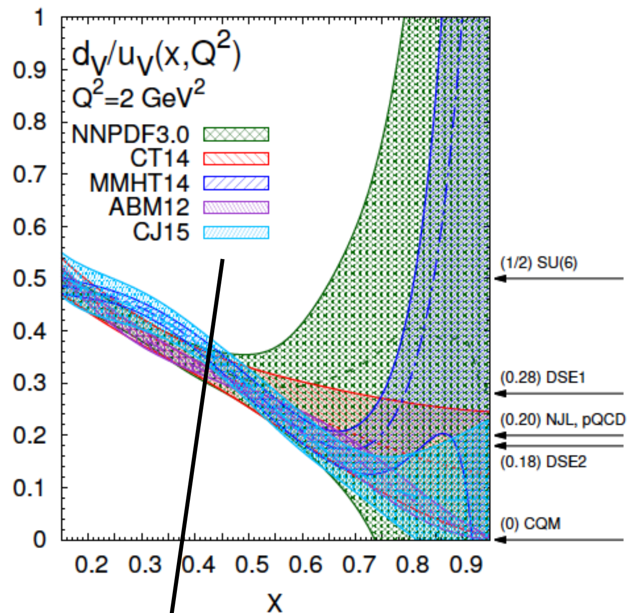
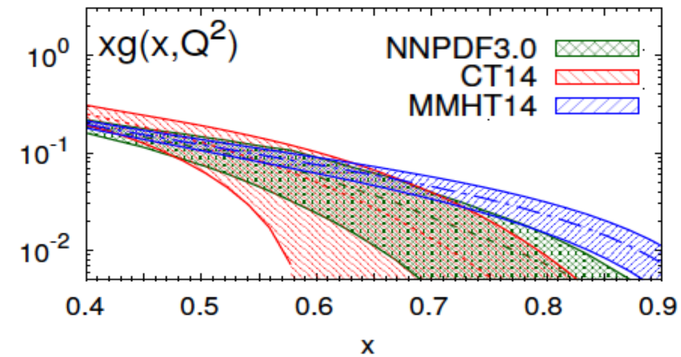
The high-x frontier

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



predictions from non-perturbative models

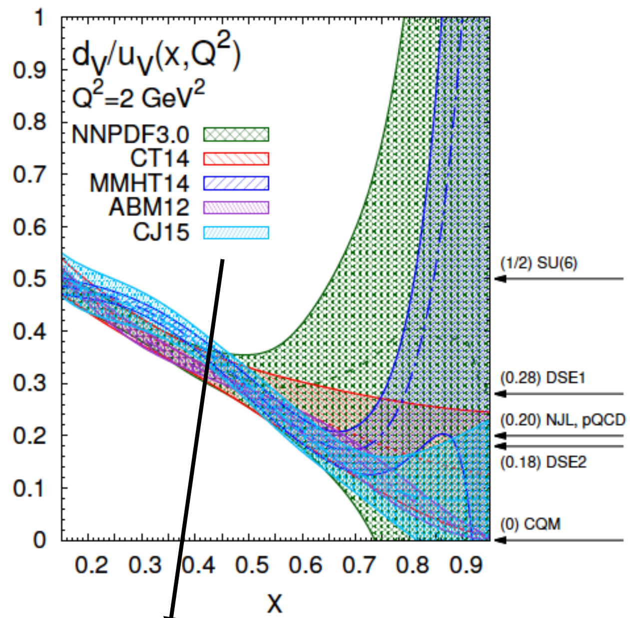
PDFs parametrizations from global fits



- Huge uncertainties at very large x
- **Quest for data at $x > 0.5$**

The high-x frontier

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



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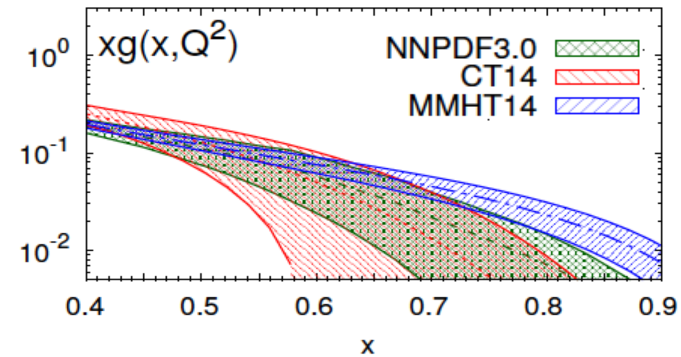

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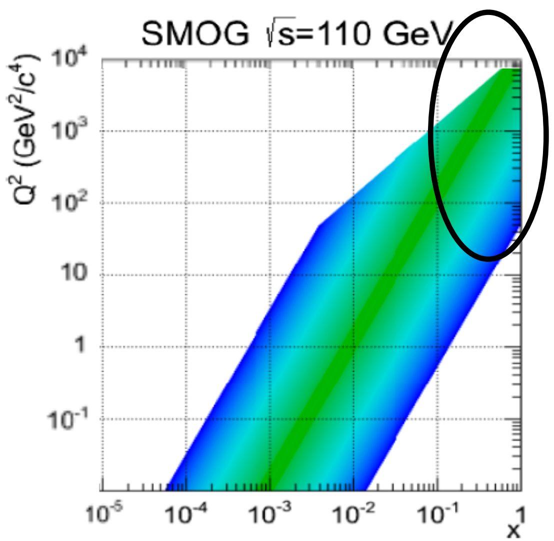
- $q(x_{targ})$ **with H and D at SMOG2**



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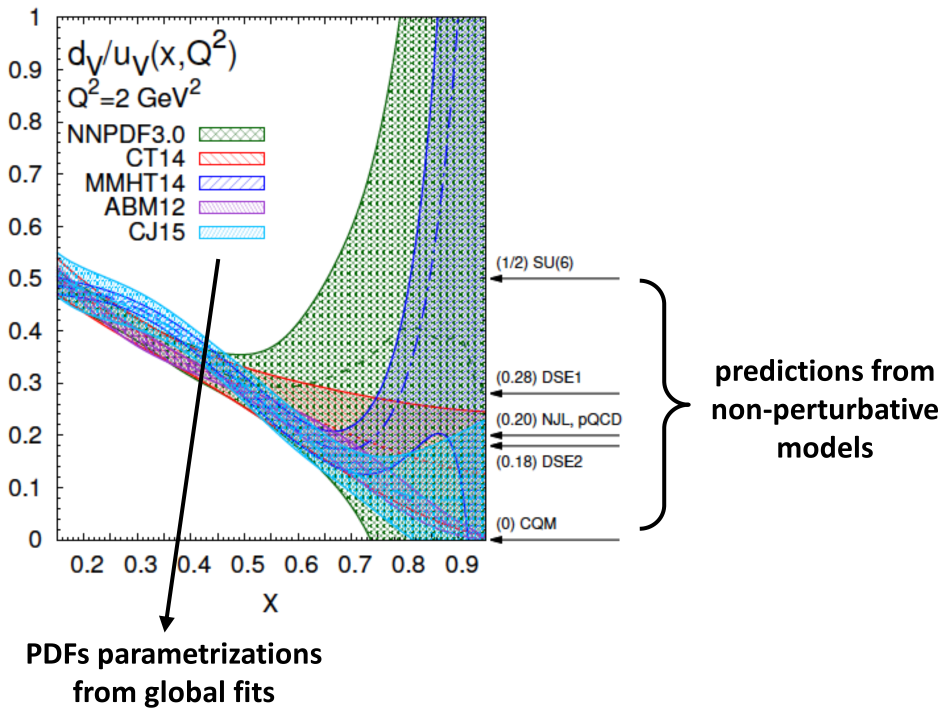

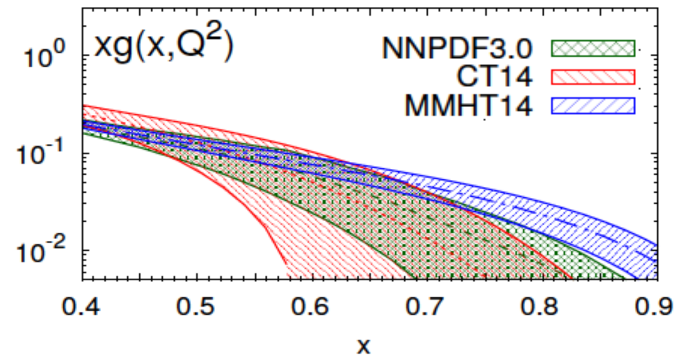

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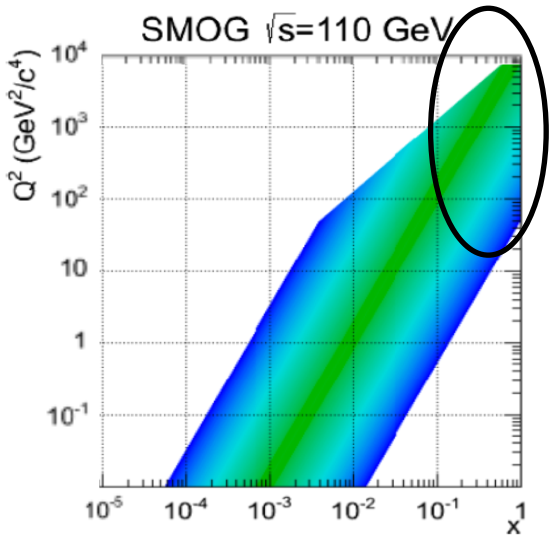
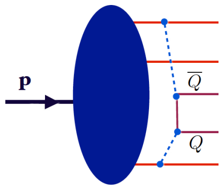


Fermi motion in the nucleus can allow to access the **exotic $x > 1$ region**, where parton dynamics depends on the interaction between the nucleons within the nucleus (**unexplored bridge between QCD and nuclear physics!**)

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



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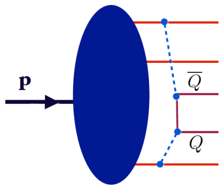

- **pA collisions** (using unpolarized gas: He, N, Ne, Ar, Kr, Xe)
  - constraints on nPDFs (e.g. on poorly understood **gluon antishadowing at high x!**)
  - studies of parton energy-loss and cold nuclear matter effects

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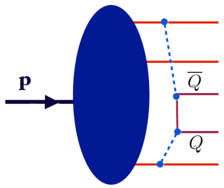

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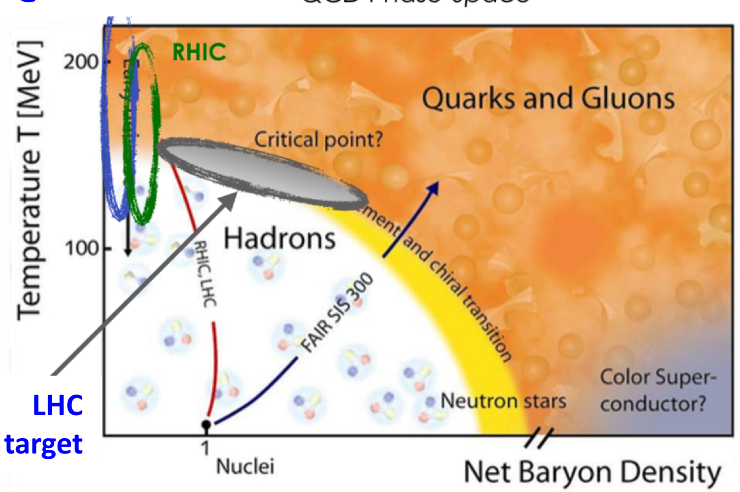
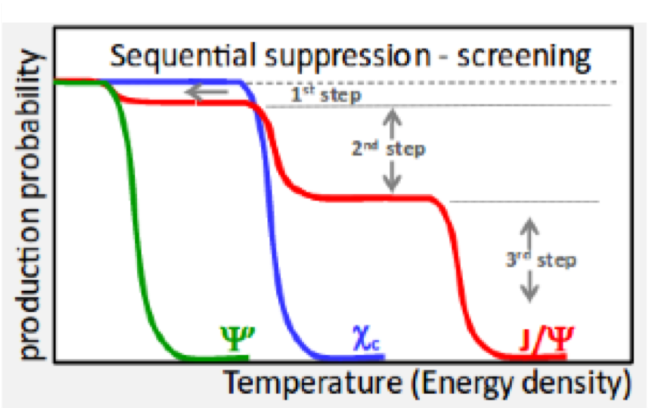
  - studies of parton energy-loss and cold nuclear matter effects

- **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**)





$c\bar{c}$ states: J/ψ, χ_c, ψ',...
Different binding energy, different dissociation temp.

R&D

SMOG2

not only a project itself

LHCspin

Phase II transversely polarised H and D target

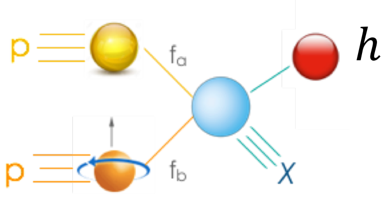
... at LHCb

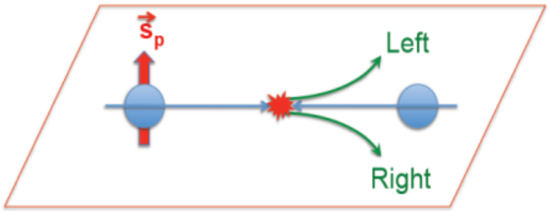
Phase II: polarized gas target

STSAs in pp collisions

Main observables in pol. hadron collisions: **Single Transverse Spin Asymmetries (STSAs)**

Polarized inclusive hard scattering





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

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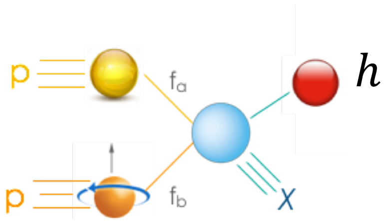
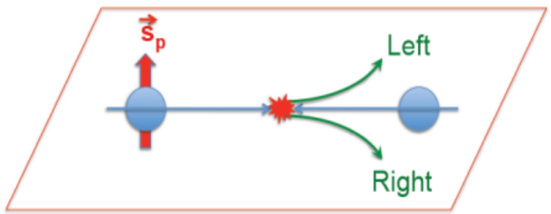
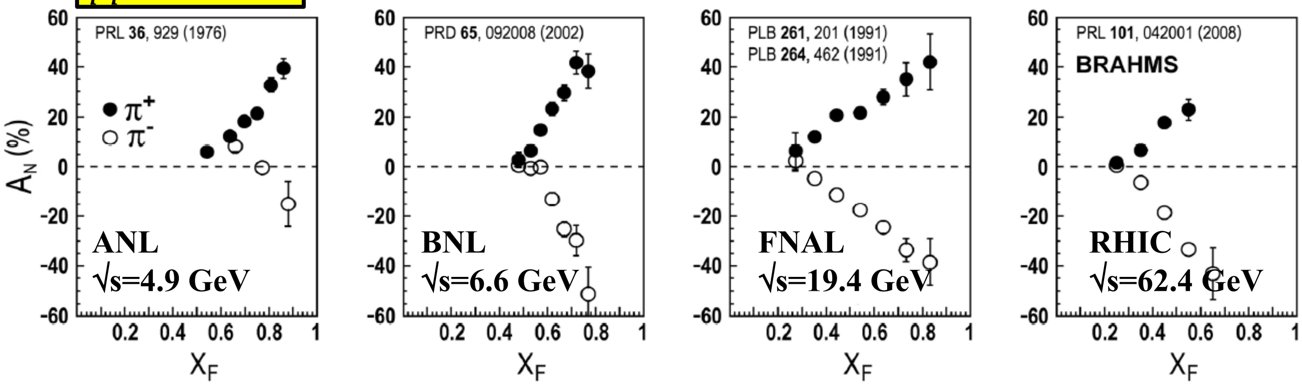


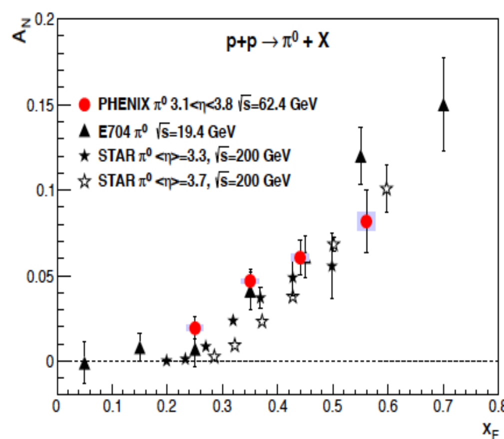


$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow}-N_h^{\downarrow}}{N_h^{\uparrow}+N_h^{\downarrow}}$$

LO collinear pQCD predicts $A_N \sim O(10^{-4})$ but **asymmetries as large as 40%** have been measured!

$pp^{\uparrow} \rightarrow \pi + X$





- **Very large asymmetries persistent with energy !**
- Reproduced by various experiments over 40 years!
- Large asymmetries up to $\sqrt{s} = 500$ GeV, where the applicability of pQCD issestablished.

Physics potentiality with a polarized target @LHCb

Collinear (twist-3) approach:
Kanazawa et al. arXiv:1502.04021v3

Non-collinear (leading twist) approach:
Anselmino et al. arXiv:1504.03791v2)

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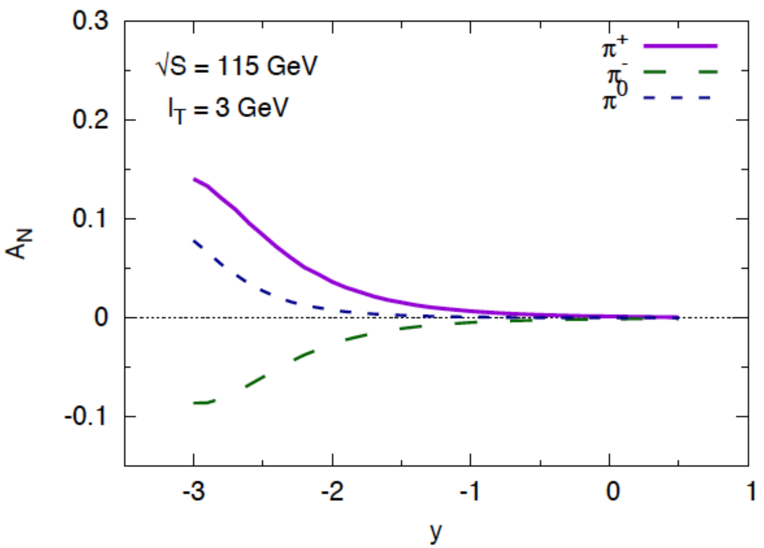

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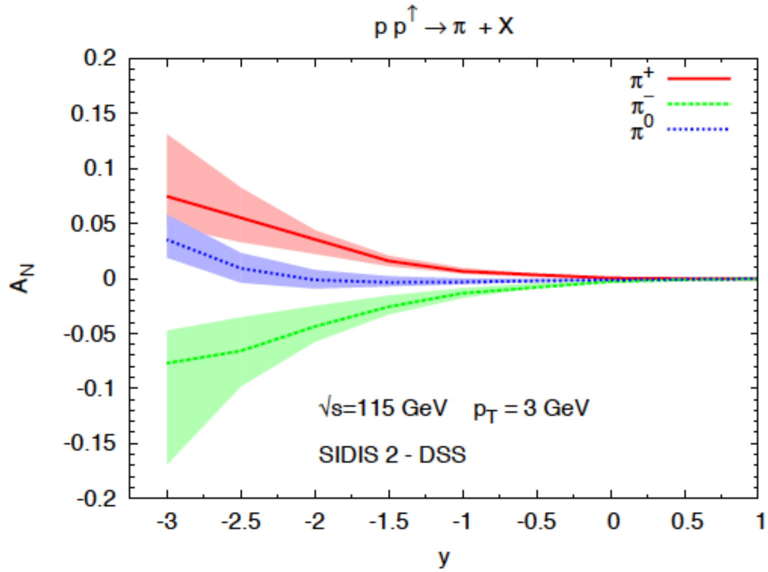

Physics potentiality with a polarized target @LHCb

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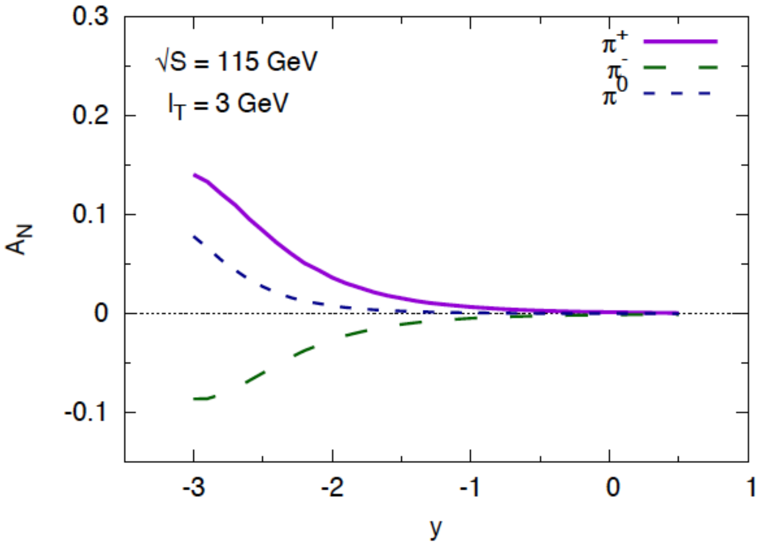

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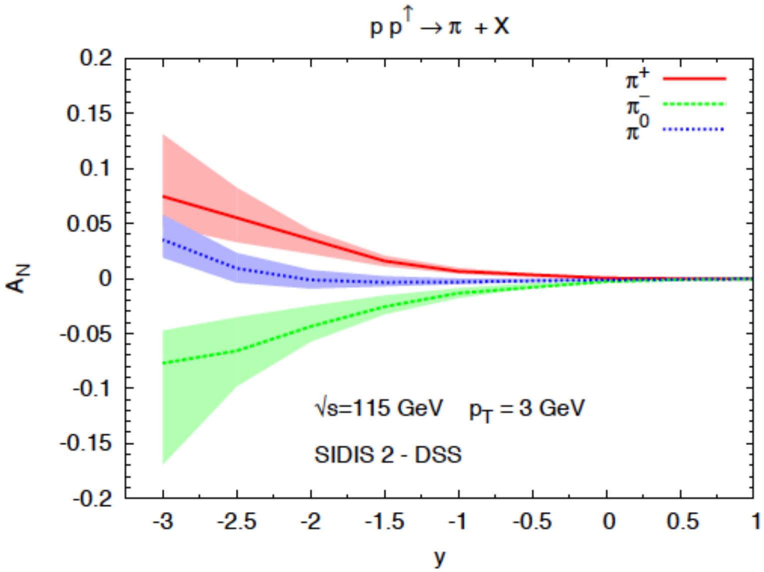
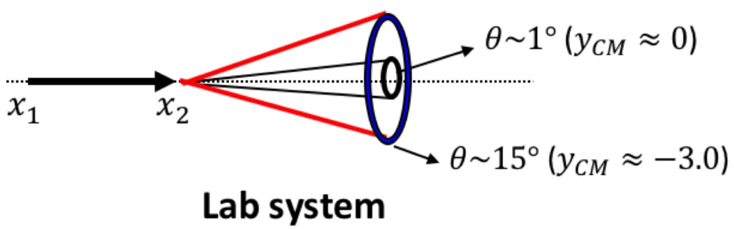


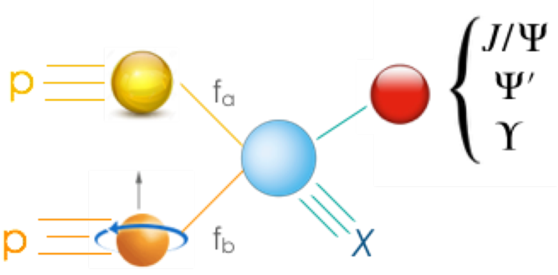
- **Asymmetries above 10 %! Big signature!!**
- The effect increases with more negative CM rapidity
- Nicely matches LHCb acceptance with fixed target!



Probing the polarized gluon PDFs

Inclusive pion production provides sensitivity to the quark PDFs, but a fixed polarized target at LHC can also open the way to the **extraction of polarized gluon PDFs through heavy-flavour observables:**

Polarized inclusive hard scattering



Hadron	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 $h_{1T}^{\perp g}$

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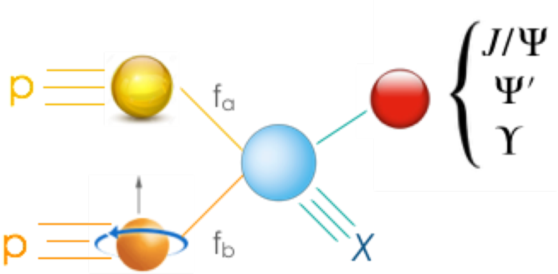

		Gluon TMDs		
		Unpol	Circularly pol.	Linearly pol.
Hadron	U	f_1^g		$h_1^{\perp g}$
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	T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g $h_{1T}^{\perp g}$

One main achievement would be accessing the **gluon Sivers function through STSAs:**

- 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!

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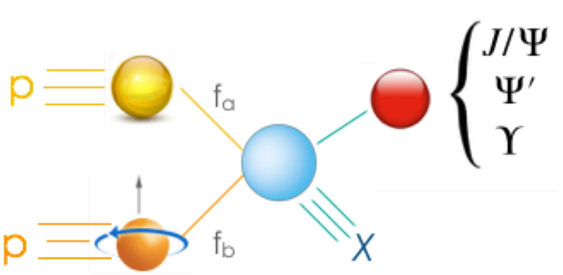

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- sensitive to gluon orbital angular momentum!

The measured STSAs can be related (GPM) to the convolution of the gluon Sivers function for the target proton and the unpolarized gluon pdf for the beam proton:

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

Process dependence of the GSF

Two independent gluon Sivers functions can be defined from the different combinations of Wilson lines in the gluon correlator:

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

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

Can differ in magnitude and width (!)

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[D. Boer: arXiv:1611.06089, D. Boer et al. HEPJ 08 2016 001]

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

Can be measured at the EIC — Can be measured at the LHCb with a PGT

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$f_{1T}^{\perp g\,[+,+]}$ (WW)	×	×	×	×	√	√
$f_{1T}^{\perp g\,[+,-]}$ (DP)	√	√	√	√	×	×

Can be measured at the EIC

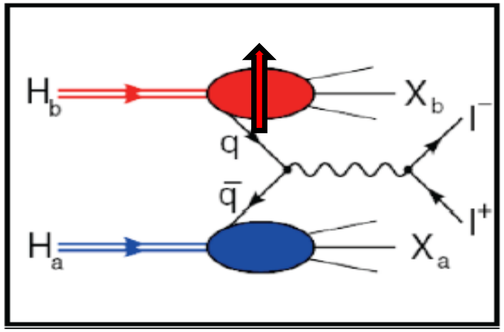
Can be measured at the LHCb with a PGT

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

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

What about quark TMDs ?

Polarized Drell-Yan



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

$$A_{UU}^{\cos 2\phi} \sim \frac{h_1^{\perp q} \otimes h_1^{\perp q}}{f_1^q \otimes f_1^q}$$

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

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

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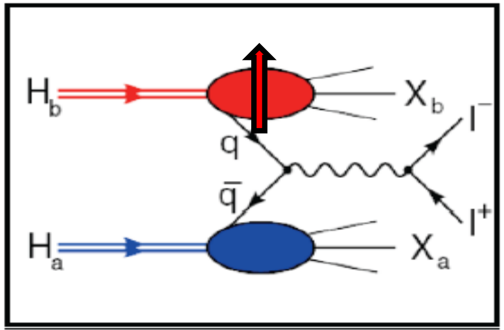

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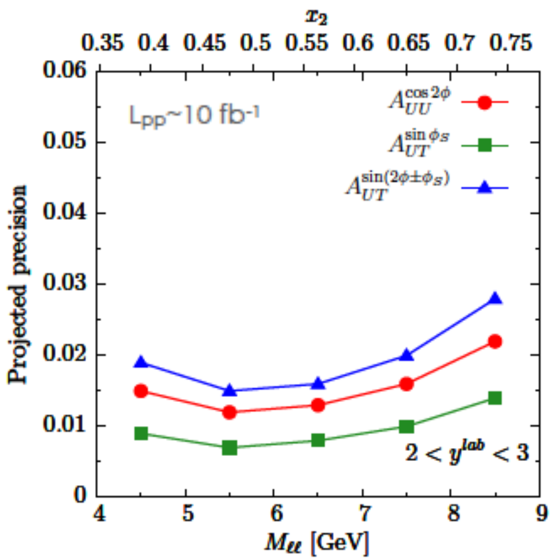
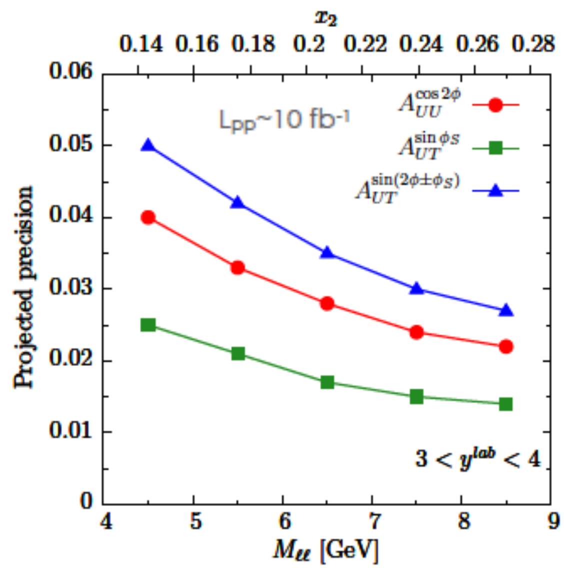
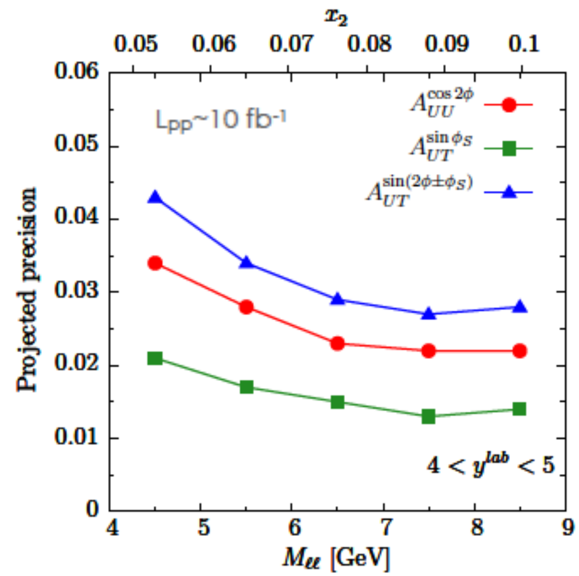




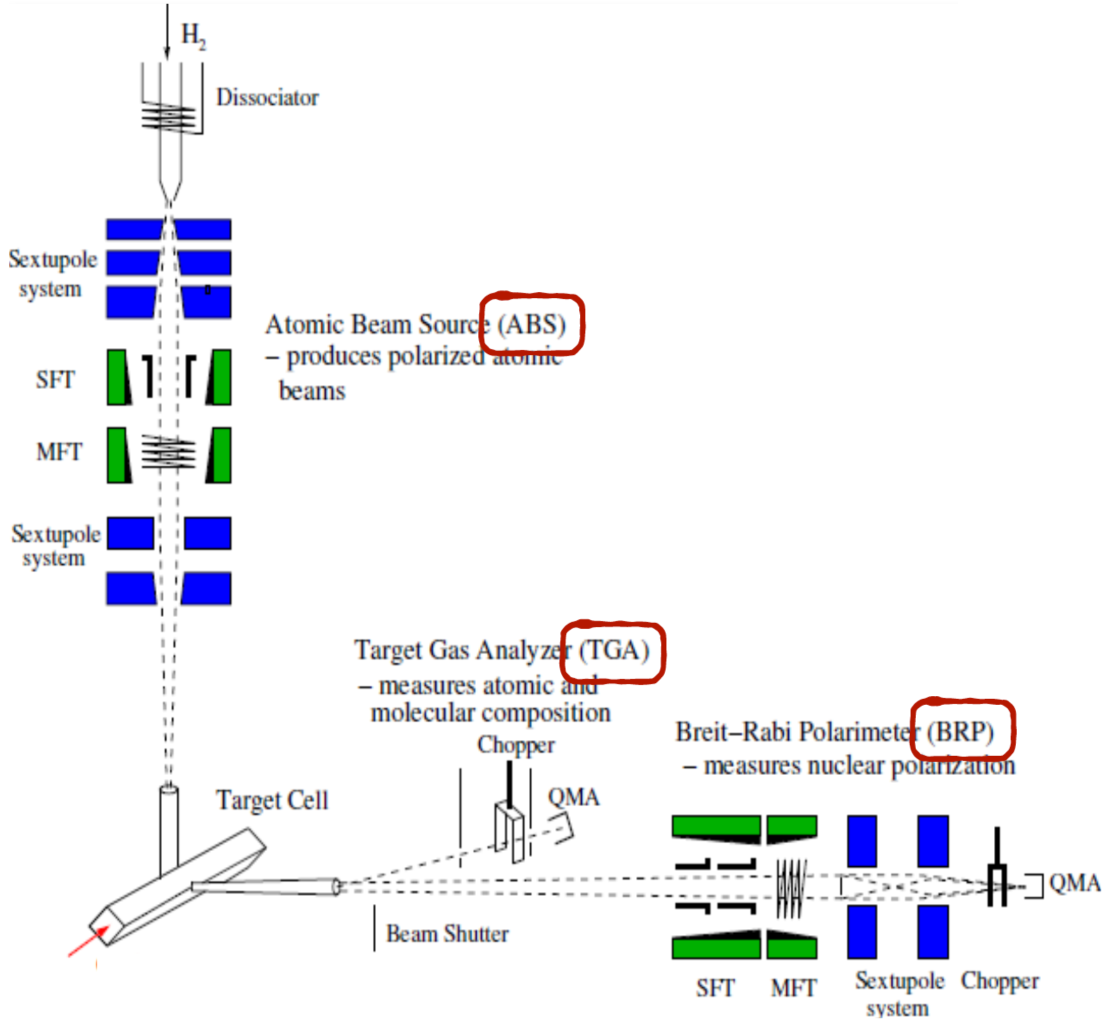


AFTER@LHC arXiv:1807.00603
and J.P.Lansberg, PBC CERN 2018

The polarized target Setup

A new design for a compact polarized gas target

Same principle of Hermes



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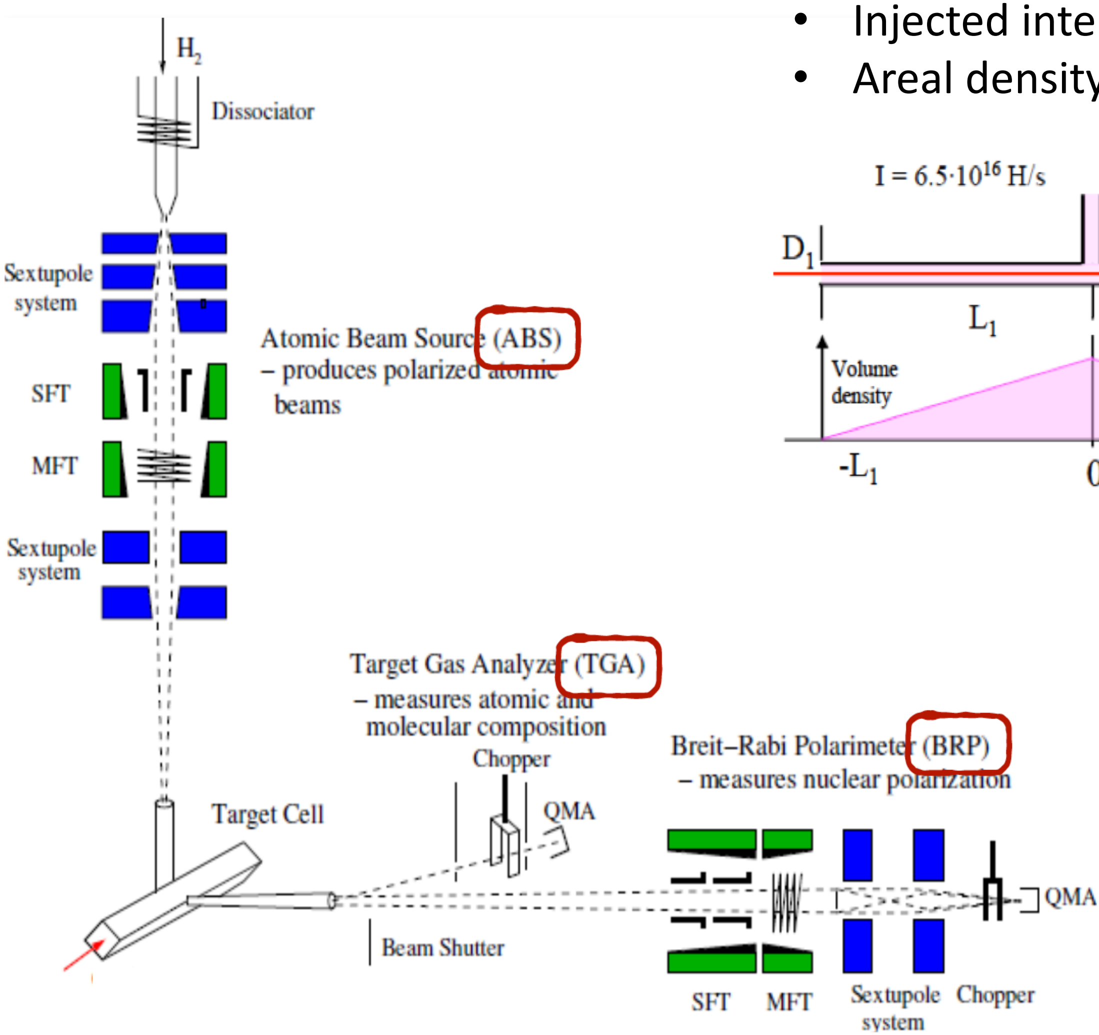
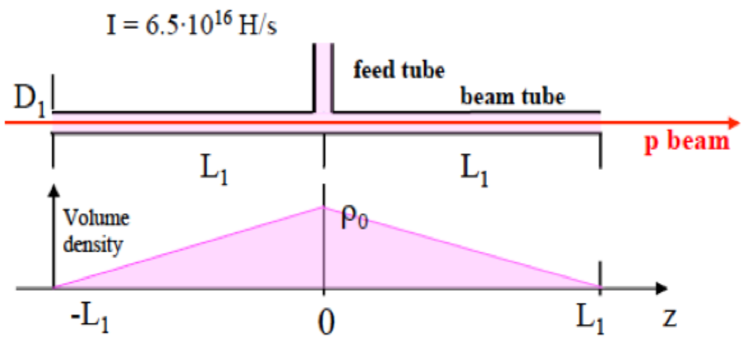


- Cell dimensions: 30 cm x 1 cm
- Injected intensity of H-atoms = $6.5 \cdot 10^{16}\ \mathrm{s}^{-1}$
- Areal density $\sim 1.2 \cdot 10^{14}\ \mathrm{cm}^{-2}$



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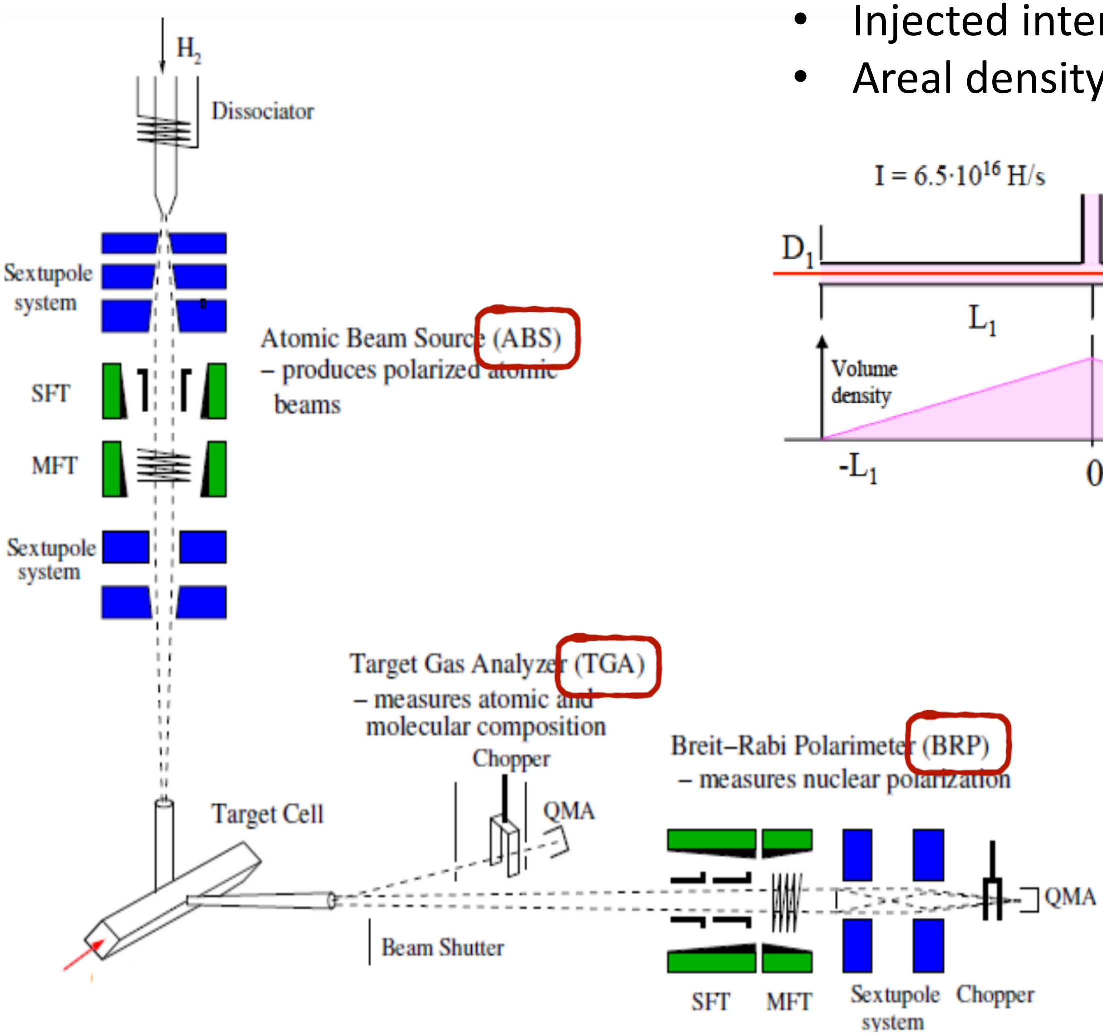

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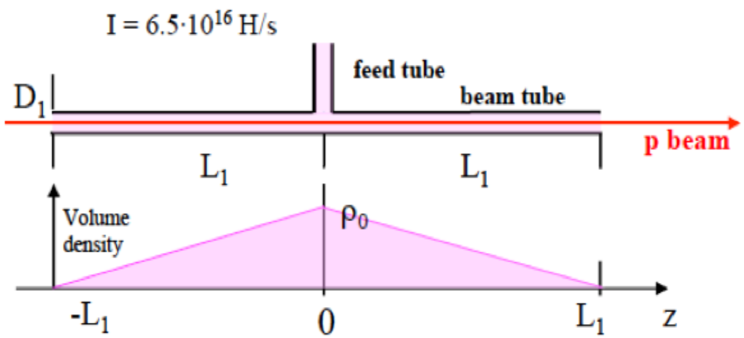

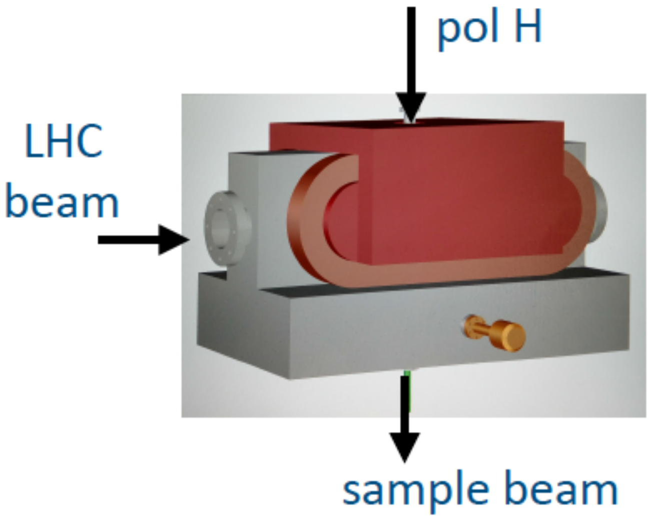

Expected performance for the PGT

- The LHC beam runs through the target cell and experiences an **Areal density**: $\theta = ½ \rho_0 L$
- **Volume density**: $\rho_0 = I_0/(2C_1 + C_2)$ where: $C = 3.81\sqrt{\frac{T(K)}{M}\frac{D^3}{L+1.33D}}\left(\frac{l}{s}\right)$

$I_0 = 6.5 \cdot 10^{16} s^{-1}$ $C_{tot} = 13.90$ l/s $\rho_0 = 4.68 \cdot 10^{12}/cm^3$ ⟹ $\boldsymbol{\theta = 7.02 \cdot 10^{13}/cm^2}$

$$\begin{cases} N_{p/bunch} = 1.15 \cdot 10^{11} \\ N_{bunch} = 2800 \\ f_{rev} = 11245\ Hz \end{cases} \Longrightarrow \boldsymbol{I_{beam} = 3.6 \cdot 10^{18}\ s^{-1}}$$

$$\boldsymbol{L(T_{cell} = 300\ K) = I_{beam} \cdot \theta = 2.5 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

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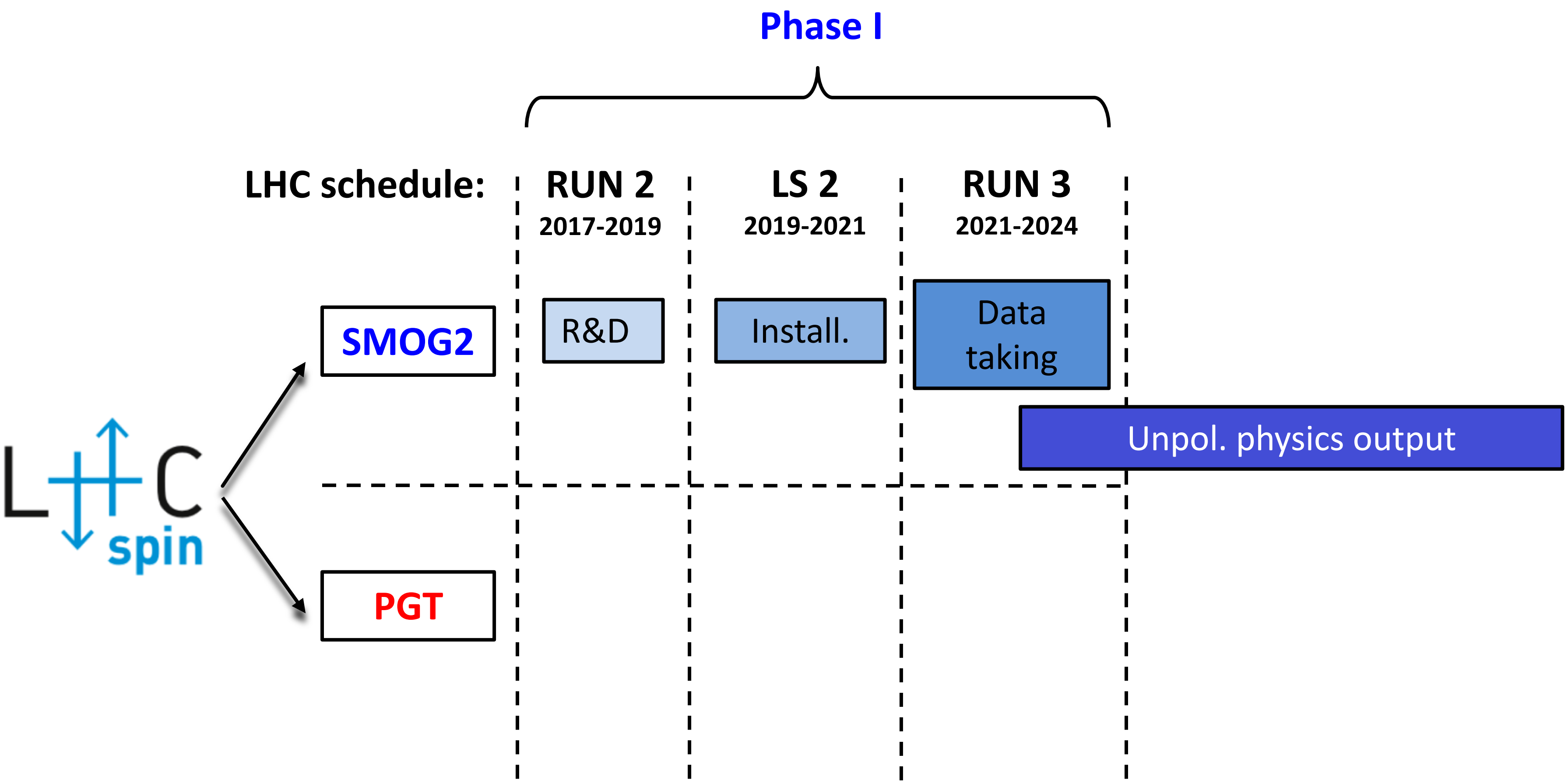
- ➢ The pressure in the LHC beam pipe outside the target region would be $\sim 10^{-7}$ mbar, one order of magnitude lower than the maximum pressure allowed by LHC
- ➢ Parallel operation will cause marginal reduction of beam half-life!

Time schedule of the project



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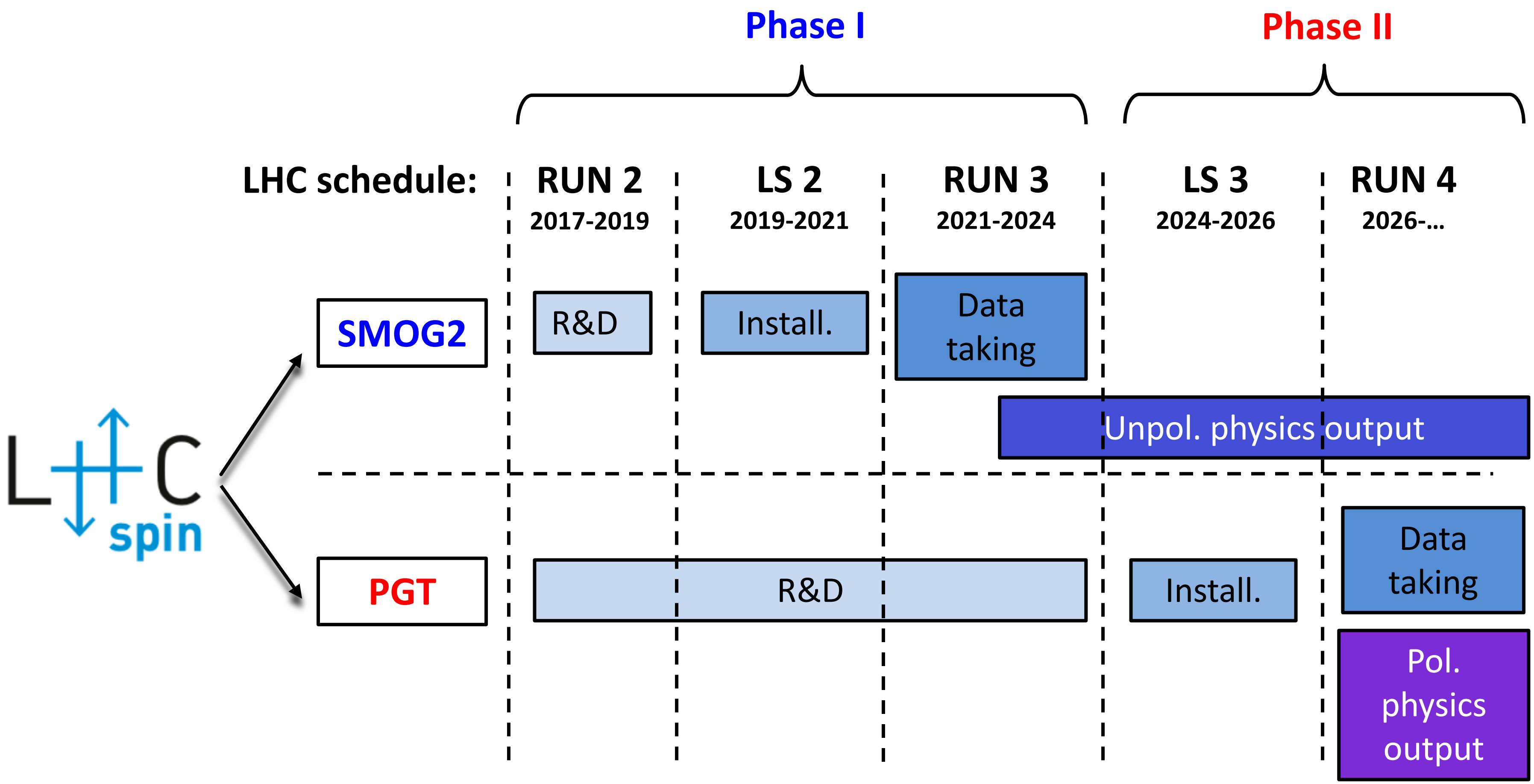

Conclusions

- A fixed-target physics program is already ongoing at LHCb with SMOG
- Our proposal for an upgrade of SMOG is in advanced stage of R&D and well endorsed by the Collaboration. We expect a formal approval by LHCb/LHC/CERN by the end of the year and full installation by 2020.
- The expected performances of SMOG2 will allow to greatly expand the physics reach of SMOG!
- A polarized fixed target at LHC will provide unique kinematic conditions for a broad and ambitious physics program!
- The LHCSpin project is taken into serious consideration by the LHCb Collaboration and LHC machine experts! A review process has been initiated.

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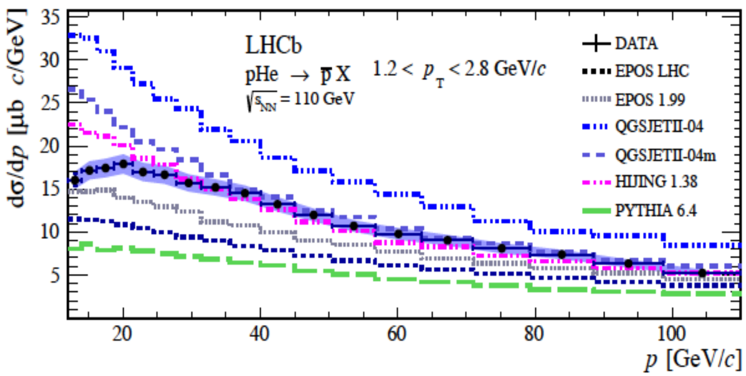
We are working to bring spin physics at the most powerful particle accelerator!

Anyone interested to contribute to this fascinating challenge is more than welcome!!

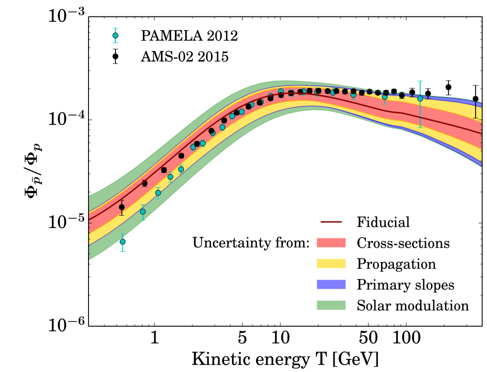
Backup

First physics results with SMOG

- **First measurement of $\bar{p}$ production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV** arXiv:1808.06127

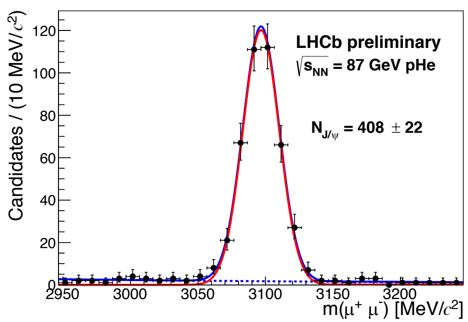


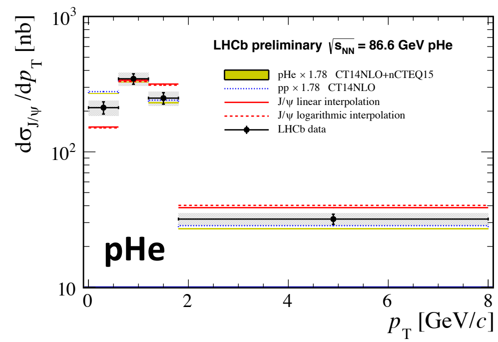
Relevant for cosmic-rays/DM physics: predictions for $\bar{p}/p$ flux ratio from spallation of primary cosmic rays on interstellar medium (H and He) are presently limited by uncertainties on $\bar{p}$ production cross sections.

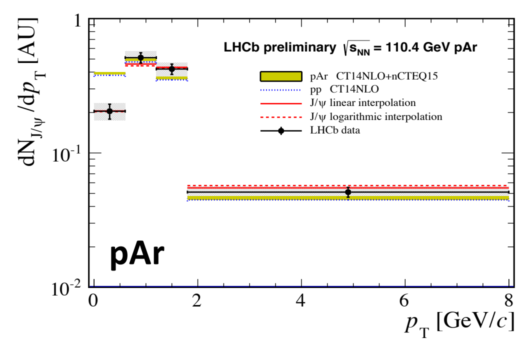


- ***J/ψ* and *D*⁰ production in pAr and pHe collisions** LHCb-PAPER-2018-023 (in preparation)

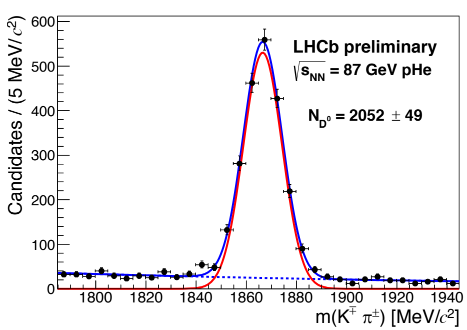
J/ψ

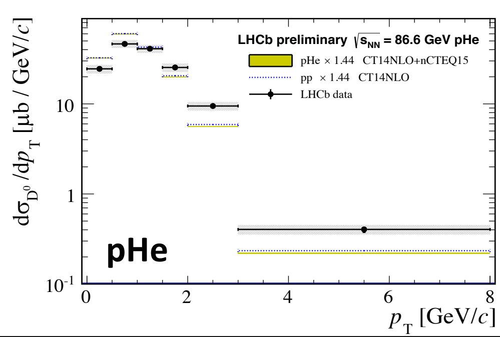


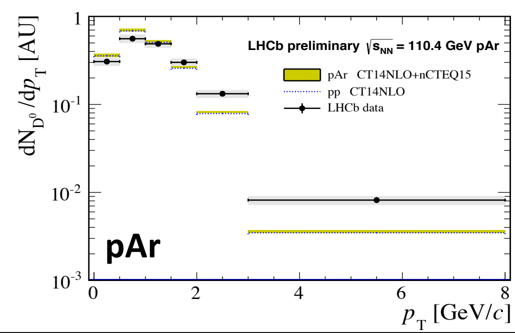




***D*⁰**







The LHCSpin project

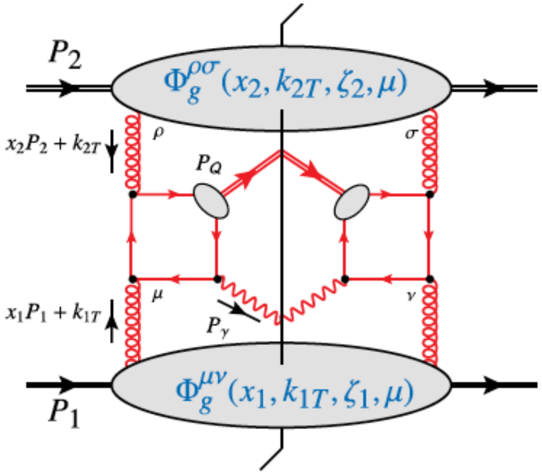
A growing motivated collaboration:

Christian Baumgarten	(PSI Zurich)
Vito Carassiti	(INFN and University of Ferrara)
Giuseppe Ciullo	(INFN and University of Ferrara)
Pasquale Di Nezza	(INFN Laboratori Nazionali di Frascati, LHCb)
Ralf Engels	(IKP - Forschungszentrum Jülich)
Kirill Grigoryev	(IKP - Forschungszentrum Jülich)
Paolo Lenisa	(INFN and University of Ferrara)
Emilie Maurice	(CNRS, Saclay, LHCb)
Alexander Nass	(IKP - Forschungszentrum Jülich)
Luciano Pappalardo	(INFN and University of Ferrara, LHCb)
Frank Rathmann	(IKP - Forschungszentrum Jülich)
Davide Reggiani	(PSI Zurich)
Marco Statera	(INFN and University of Milano)
Erhard Steffens	(University of Erlangen-Nürnberg)
Michael Winn	(CNRS, Saclay, LHCb)

Other groups from EU and US have informally expressed their interest in the project!

Probing the gluon PDFs

[Dunnen et al., PRL 112, 212001]



$$\Phi_g^{\mu\nu}(x, \boldsymbol{k}_T, \zeta, \mu) \equiv \int \frac{d(\xi\cdot P)\, d^2\xi_T}{(xP\cdot n)^2 (2\pi)^3} e^{i(xP+k_T)\cdot\xi} \times \langle P | F_a^{n\nu}(0) \left(\mathcal{U}^{n[-]}_{[0,\xi]}\right)_{ab} F_b^{n\mu}(\xi) | P \rangle |_{\xi\cdot P'=0}$$

$$= -\frac{1}{2x}\left\{ g_T^{\mu\nu} f_1^g - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu} \frac{\boldsymbol{k}_T^2}{2M_p^2} \right) h_1^{\perp g} \right\}$$

Unpol. gluon distrib. funciton

Linearly pol. gluon distrib. function (requires non-zero gluon p_T)

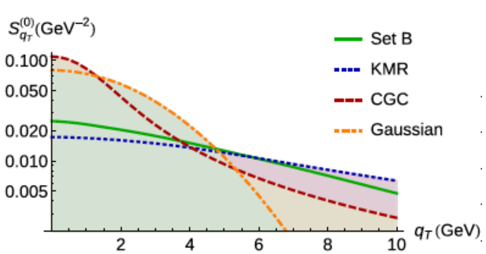
$$\frac{d\sigma}{dQ\,dY\,d^2\boldsymbol{q}_T\,d\Omega} = \frac{C_0(Q^2 - M_Q^2)}{sQ^3 D}\{F_1\mathcal{C}[f_1^g f_1^g] + F_3\cos(2\phi)\times \mathcal{C}[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2] + F_4\cos(4\phi)\times\mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]\} + \mathcal{O}\left(\frac{\boldsymbol{q}_T^2}{Q^2}\right)$$

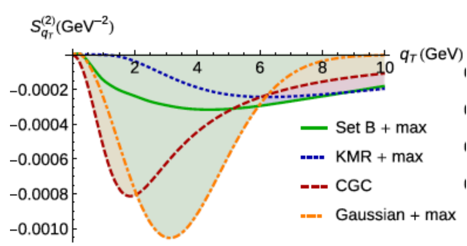
$$S_{q_T}^{(n)} \equiv \frac{\int d\phi \cos(n\phi) \frac{d\sigma}{dQ\,dY\,d^2\boldsymbol{q}_T\,d\Omega}}{\int d\boldsymbol{q}_T^2 \int d\phi \frac{d\sigma}{dQ\,dY\,d^2\boldsymbol{q}_T\,d\Omega}}$$

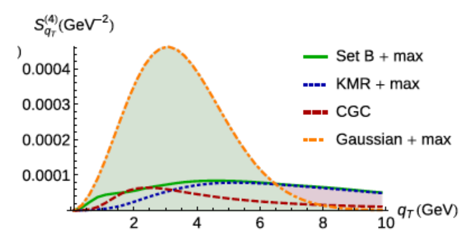
$$S_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int d\boldsymbol{q}_T^2 \mathcal{C}[f_1^g f_1^g]}$$

$$S_{q_T}^{(2)} = \frac{F_3 \mathcal{C}[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2]}{2F_1 \int d\boldsymbol{q}_T^2 \mathcal{C}[f_1^g f_1^g]}$$

$$S_{q_T}^{(4)} = \frac{F_4 \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]}{2F_1 \int d\boldsymbol{q}_T^2 \mathcal{C}[f_1^g f_1^g]}$$







STSAs in pp collisions

Collinear (twist-3) approach: (Efremov-Taryaev, Qiu-Sterman, Kanazawa-Koike)

- based on collinear QCD factorization (1 hard scale: works for $p_T, Q \gg \Lambda_{QCD}$)
- SSAs arise from interference between partonic amplitudes (3-parton correlators) generated by gluon exchange with IS or FS hadron

Non-collinear (leading-twist) approach: (Anselmino, Boglione et al.)

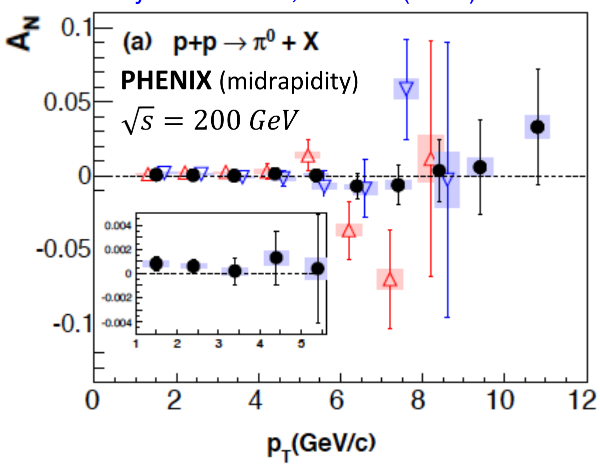
- involves TMD PDFs and FFs
- works in the limit $p_T \ll$ Q (2 energy scales), but is not supported by TMD factorization
- can be considered as an effective model description (**Generalized Parton Model**)
- SSAs arise mainly from **Sivers effects**

➢ **The two approaches correspond exactly** in the overlap region $\Lambda_{QCD} \ll p_T \ll Q$ (proved for SSAs in Drell-Yan: Ji, Qiu, Vogelsang, Yuan, PRL, 2006)

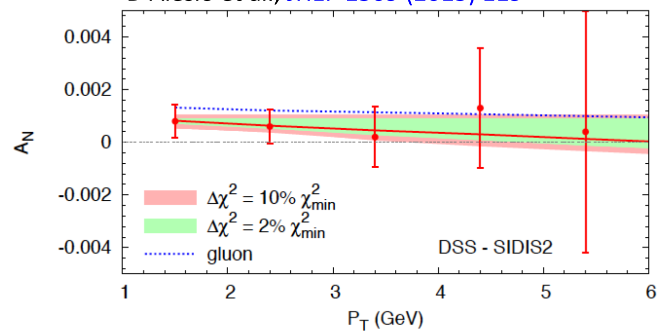
➢ …very little is presently known about **tri-gluon correlation functions** and **polarized gluon TMDs!**

Probing the GSF (from RHIC data)

Phys. Rev. D 90, 012006 (2014)

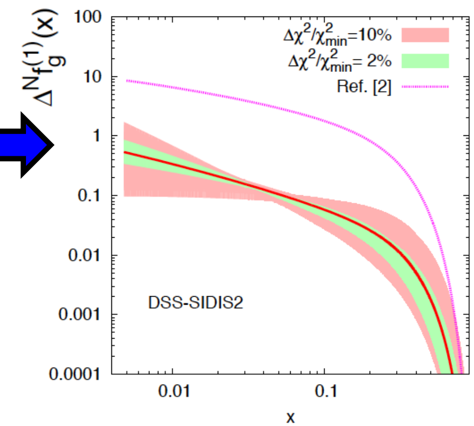


D'Alesio et al., JHEP 1509 (2015) 119

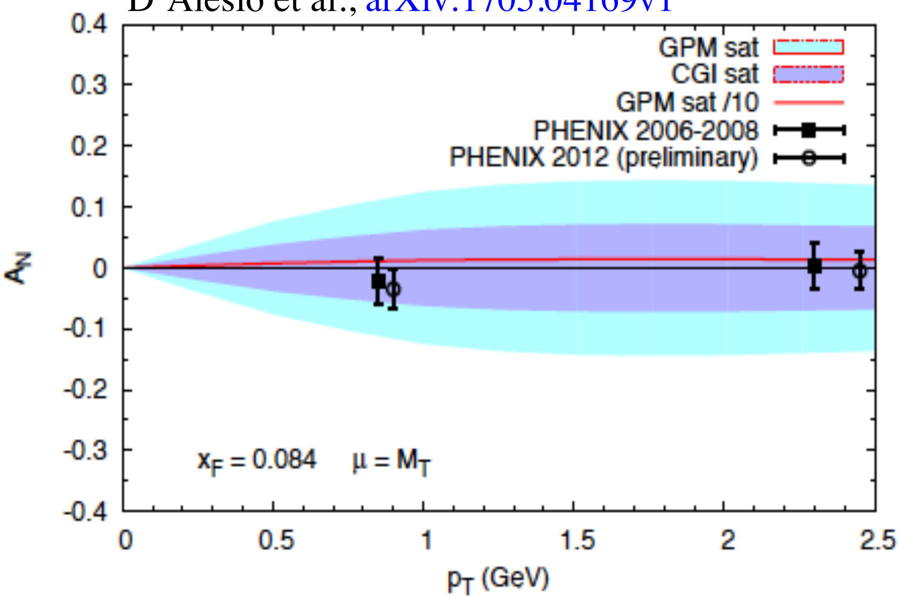


A_N estimate in the frame of GPM, based on param. from SIDIS data + FFs from DSS

First $k_\perp$-moment of the gluon Sivers function (small positive)

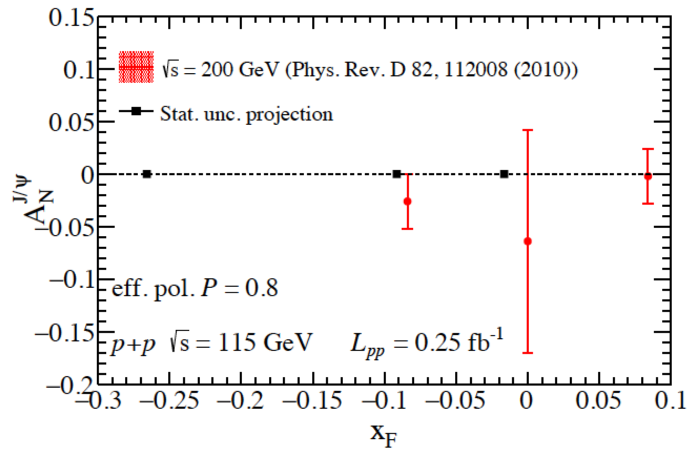


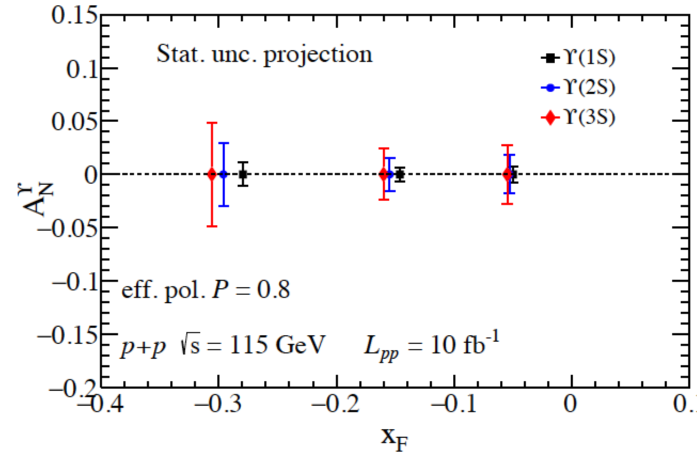
D'Alesio et al., arXiv:1705.04169v1

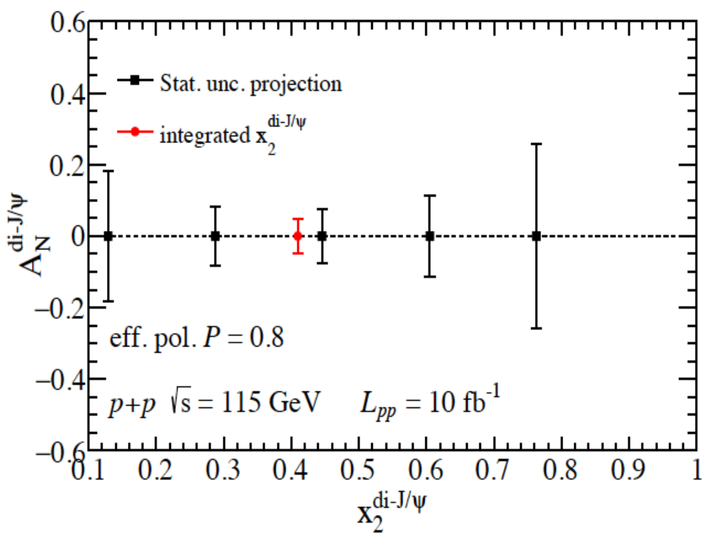


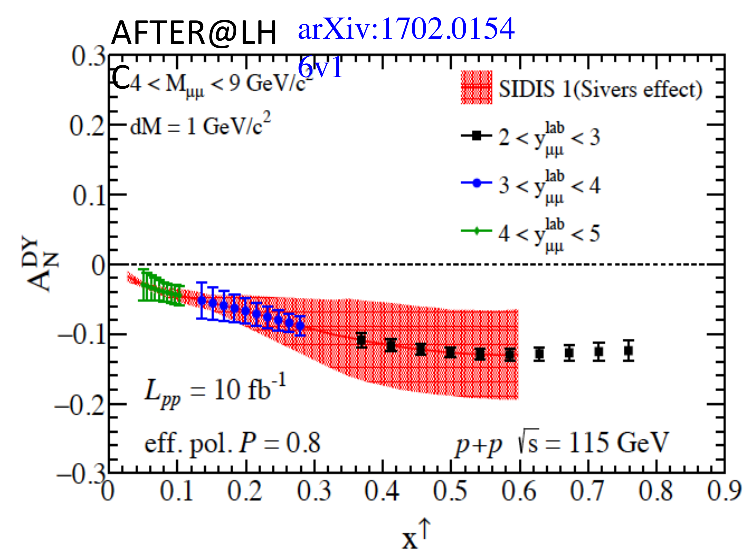
- **Existing quarkonia results only from PHENIX**
- First measurement of A_N for $\boldsymbol{pp^{\uparrow} \rightarrow J/\psi X}$
- Sensitive to f-type gluon Sivers funciton
- A very recent prediction of A_N from Color-Gauge Invariant GPM **(CGI-GPM)**: takes into account the process dependence of the GSF

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









Main reactions or interest

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

☛ **Pol and unpol gluon PDFs**

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

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

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

☛ **TMDs of valence and sea quarks**

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

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

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

There is some room beyond the VELO…