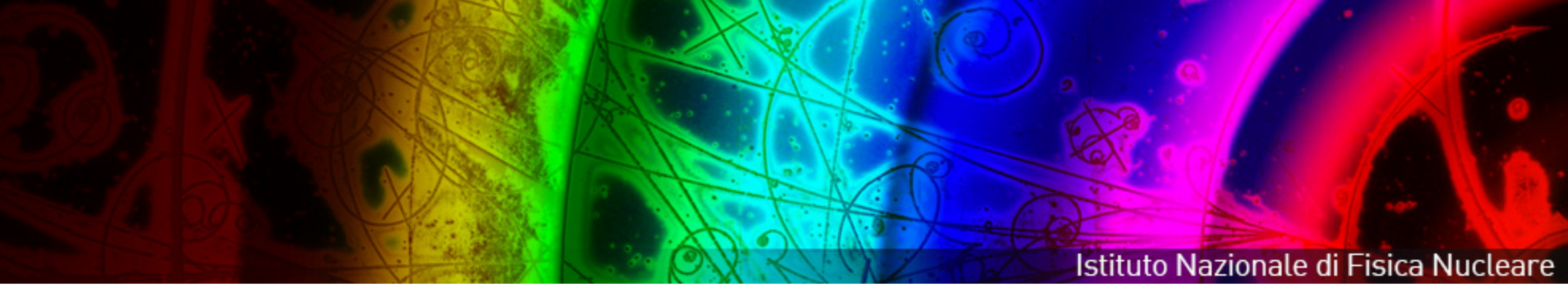


The LHCspin project

Pasquale Di Nezza

INFN LNF Istituto Nazionale di Fisica Nucleare

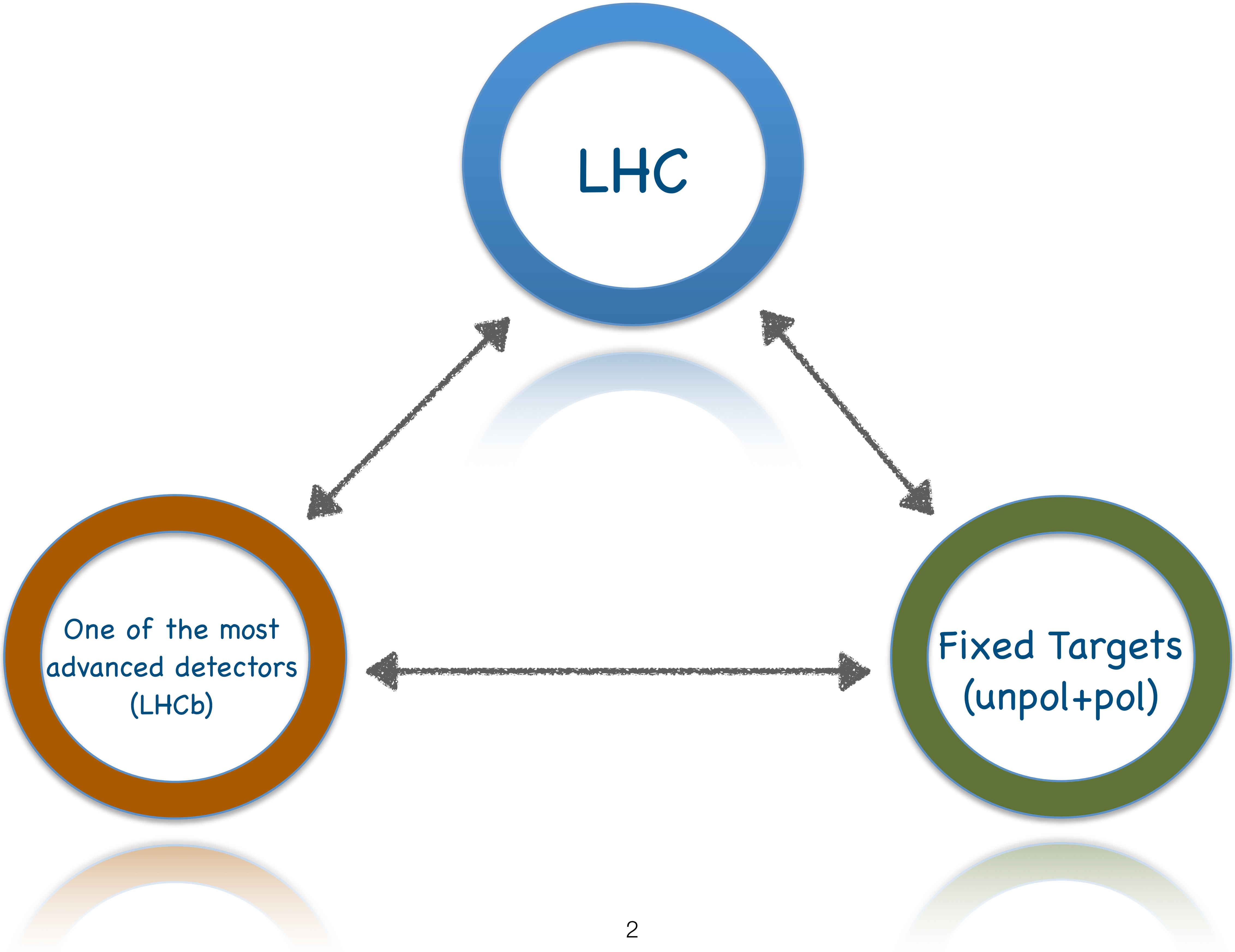
LHCb STRONG-2020

In collaboration with V.Carassiti, G.Ciullo, P.Lenisa, L.Pappalardo, E.Steffens

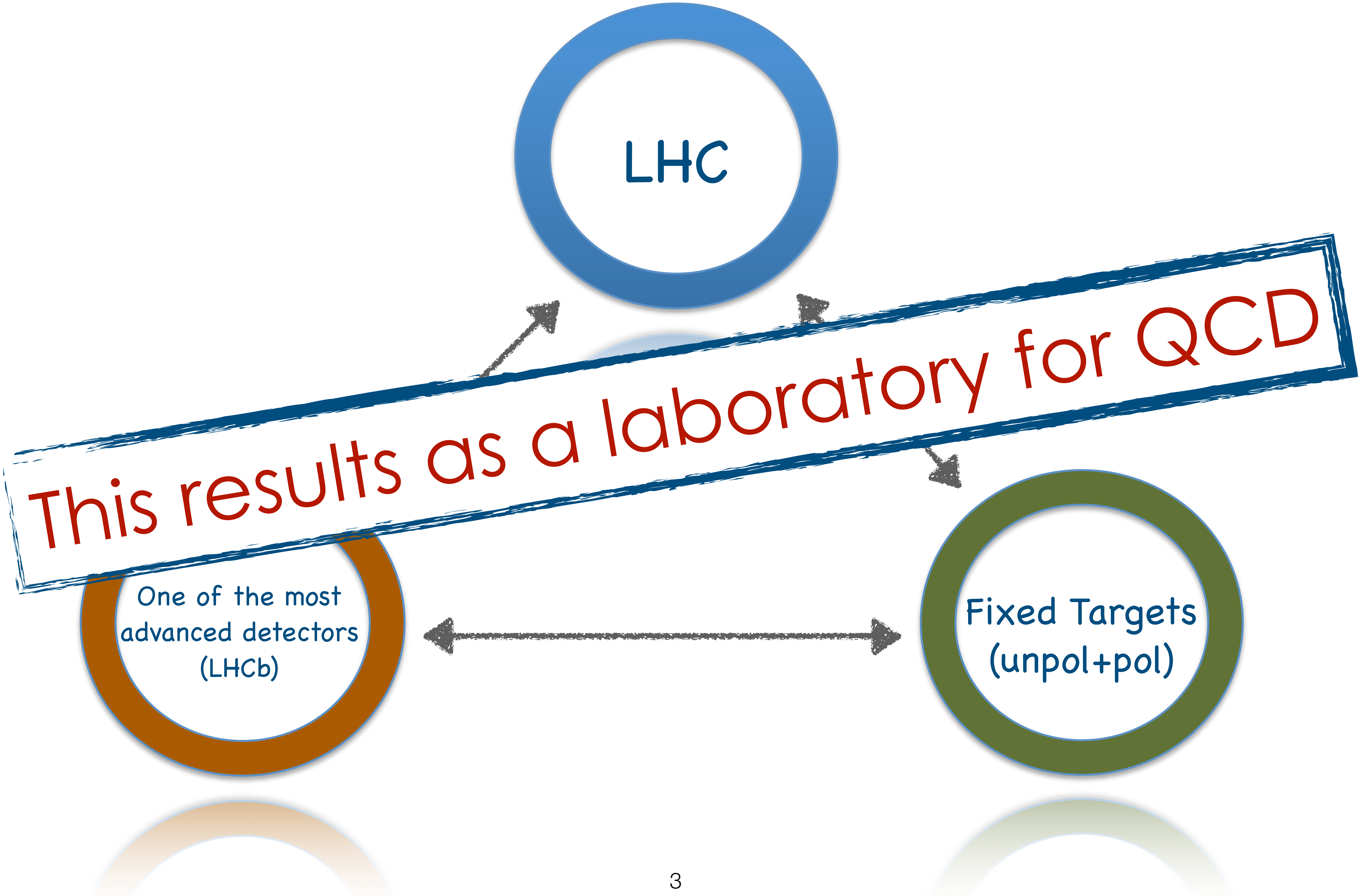
SPD NICA

30/09/20

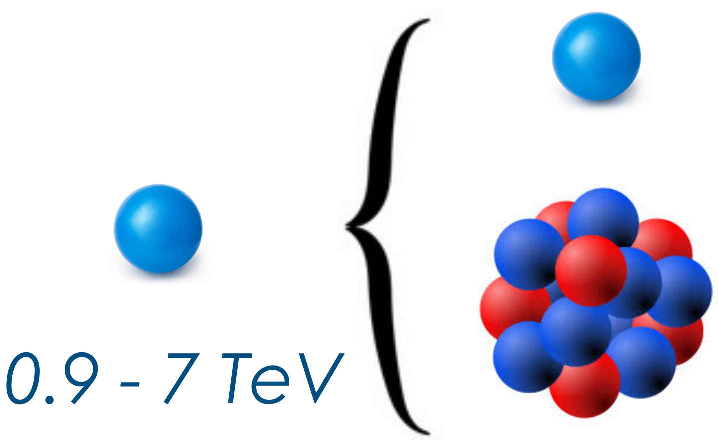
Merging 3 worlds for the first time



Merging 3 worlds for the first time



Kinematics on fixed target

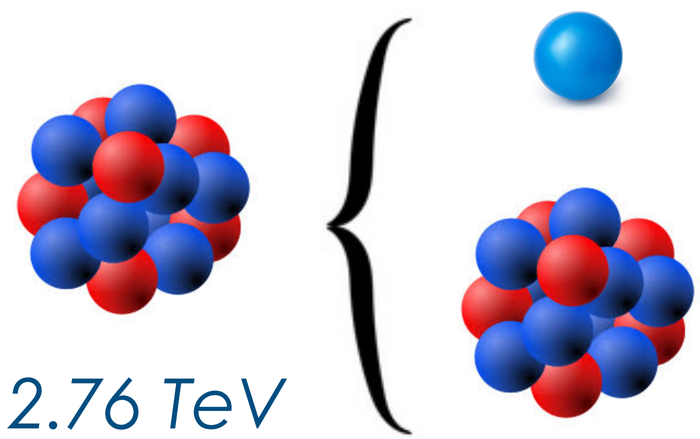


pp or pA collisions: 7 TeV beam on fix target

$$\sqrt{s} = \sqrt{2m_N E_p} = 115\ GeV$$

$$-3.0 \leq y_{CMS} \leq 0 \ \rightarrow \ 2 \leq y_{lab} \leq 5$$

between SPS & RHIC

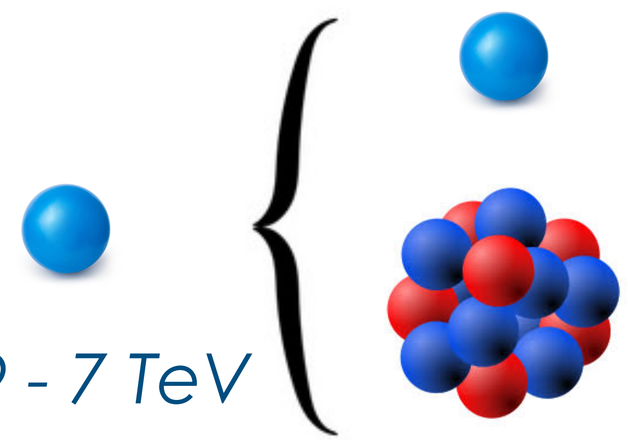


AA collisions: 2.76 TeV beam on fix target

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

$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

Kinematics on fixed target



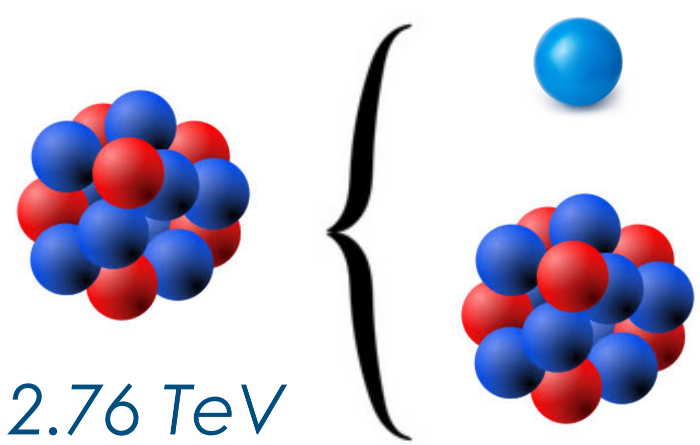
0.9 - 7 TeV

pp or pA collisions: 7 TeV beam on fix target

$$\sqrt{s} = \sqrt{2m_N E_p} = 115\ GeV$$

$$-3.0 \leq y_{CMS} \leq 0 \ \rightarrow \ 2 \leq y_{lab} \leq 5$$

between SPS & RHIC



2.76 TeV

AA collisions: 2.76 TeV beam on fix target

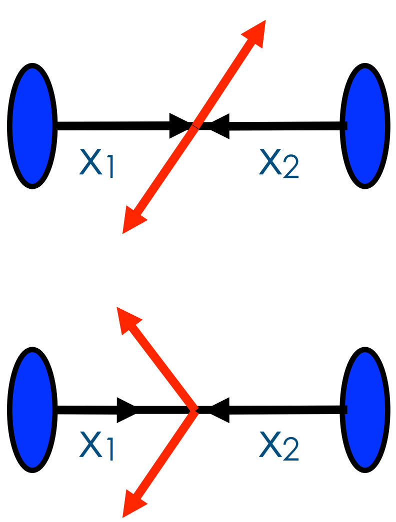
$$\sqrt{s_{NN}} \simeq 72\ GeV$$

$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

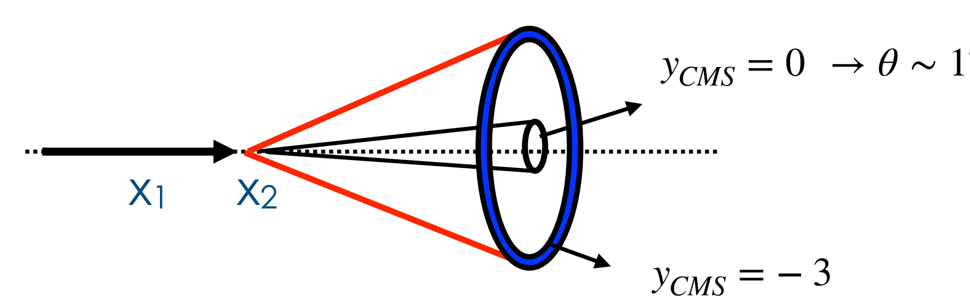
Boost effect $\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$ → access to large x_2 physics (x_F<0)

$x_1 \sim x_2$

$x_1 << x_2$

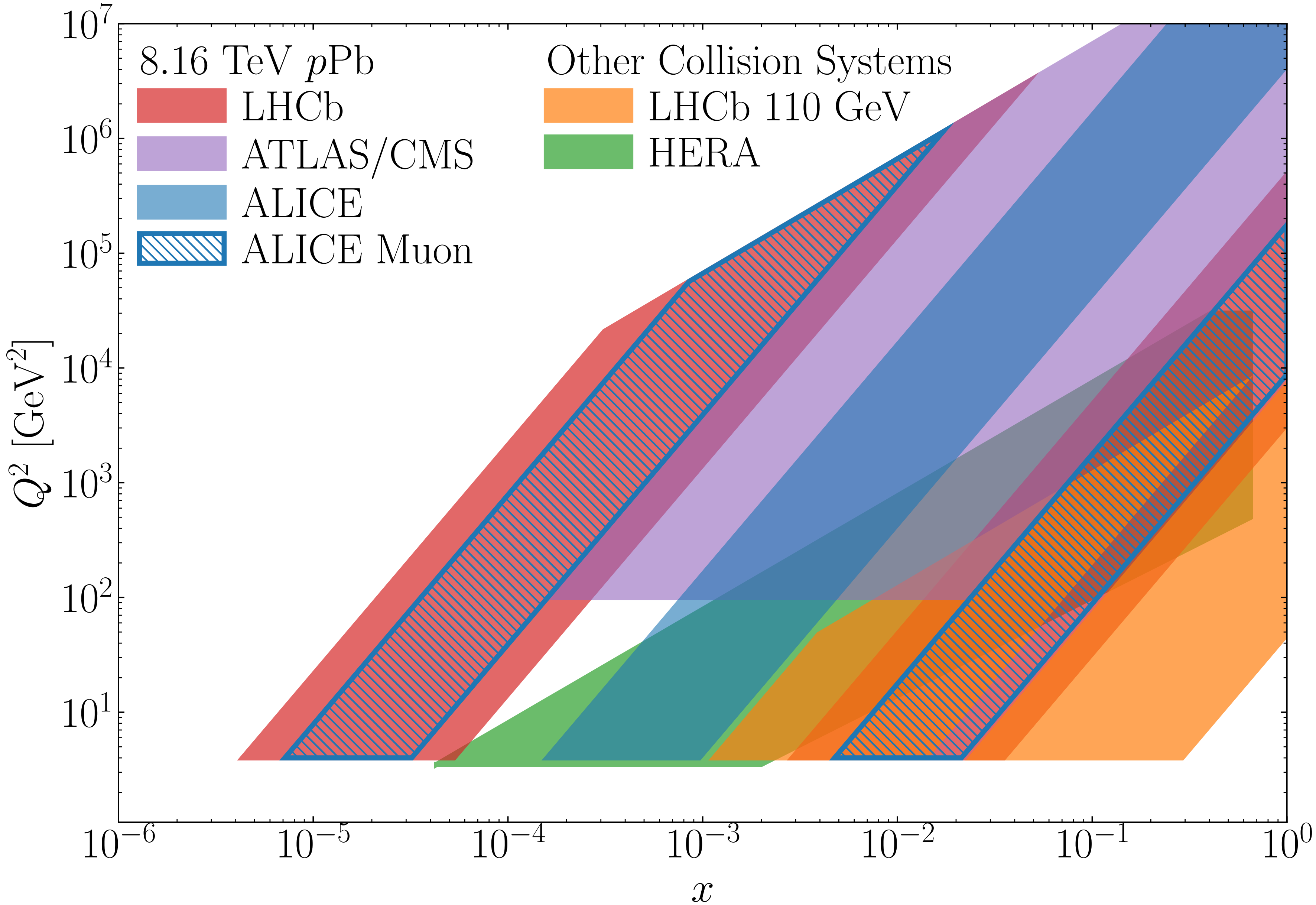


CMS → Target rest frame



Unique kinematical region

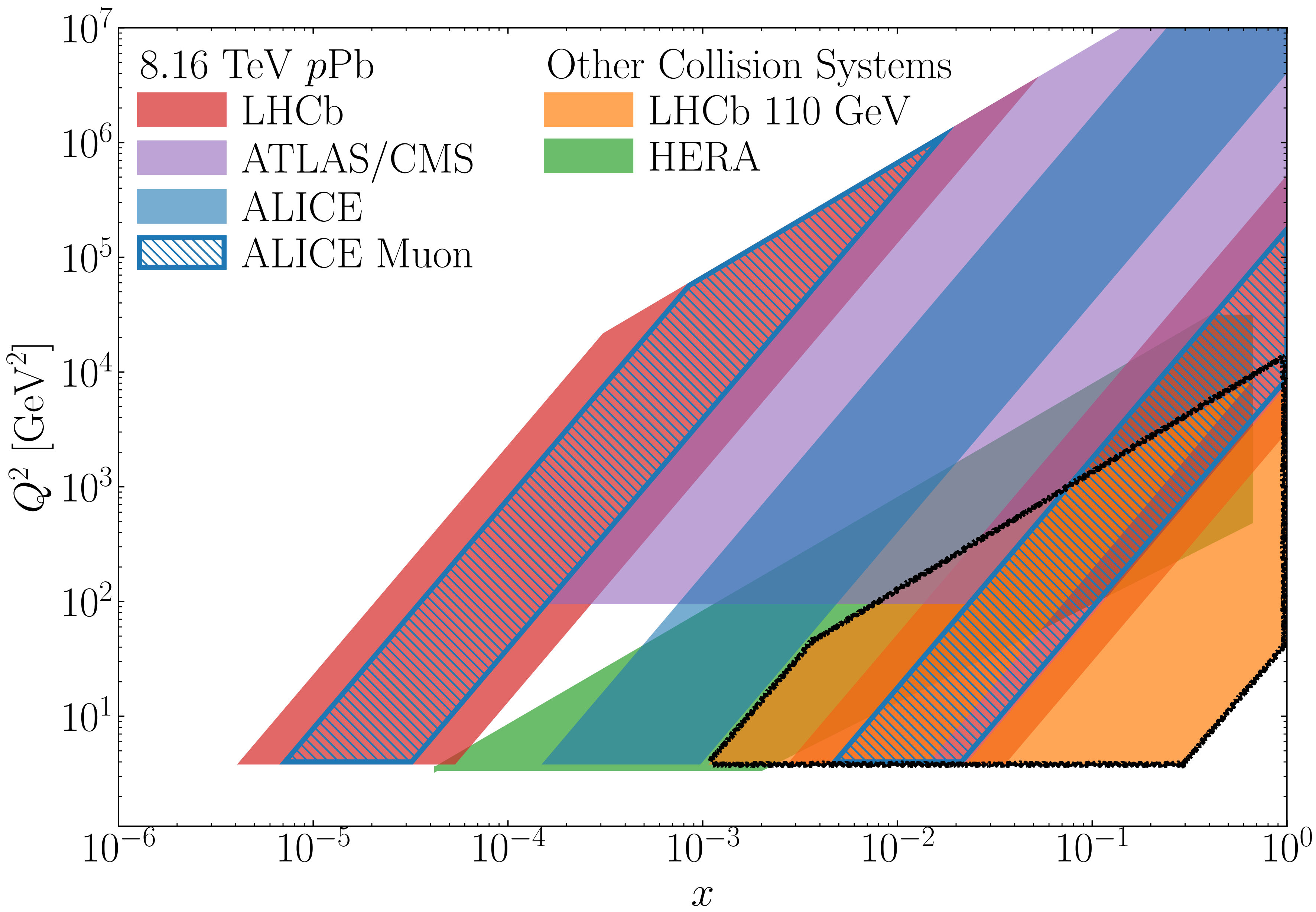
At the LHC fixed target pp, pp$^{\uparrow\downarrow}$, pA, Pb-p, Pb-p$^{\uparrow\downarrow}$ or Pb-A collisions, one has unique kinematic conditions at the poorly explored energy of √s ~ 100 GeV



In addition the exotic region at x>1 can be accessed (Fermi motion) creating a bridge between QCD and nuclear physics

Unique kinematical region

At the LHC fixed target pp, pp$^{\uparrow\downarrow}$, pA, Pb-p, Pb-p$^{\uparrow\downarrow}$ or Pb-A collisions, one has unique kinematic conditions at the poorly explored energy of √s ~ 100 GeV

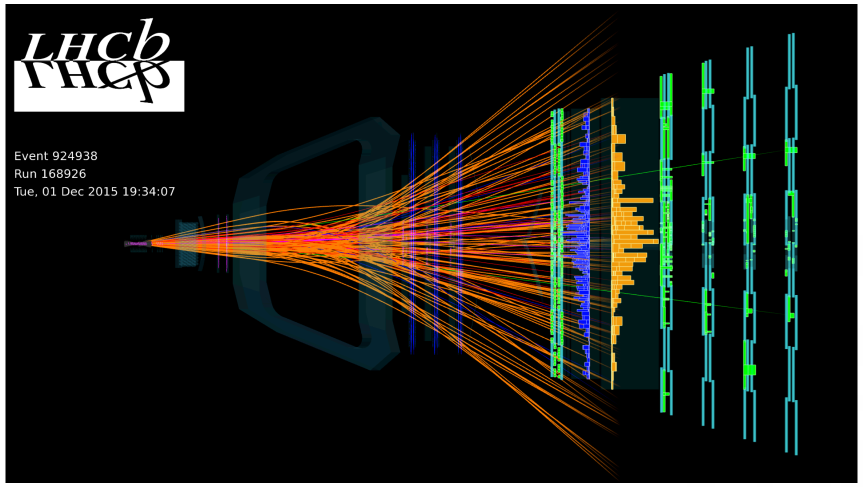


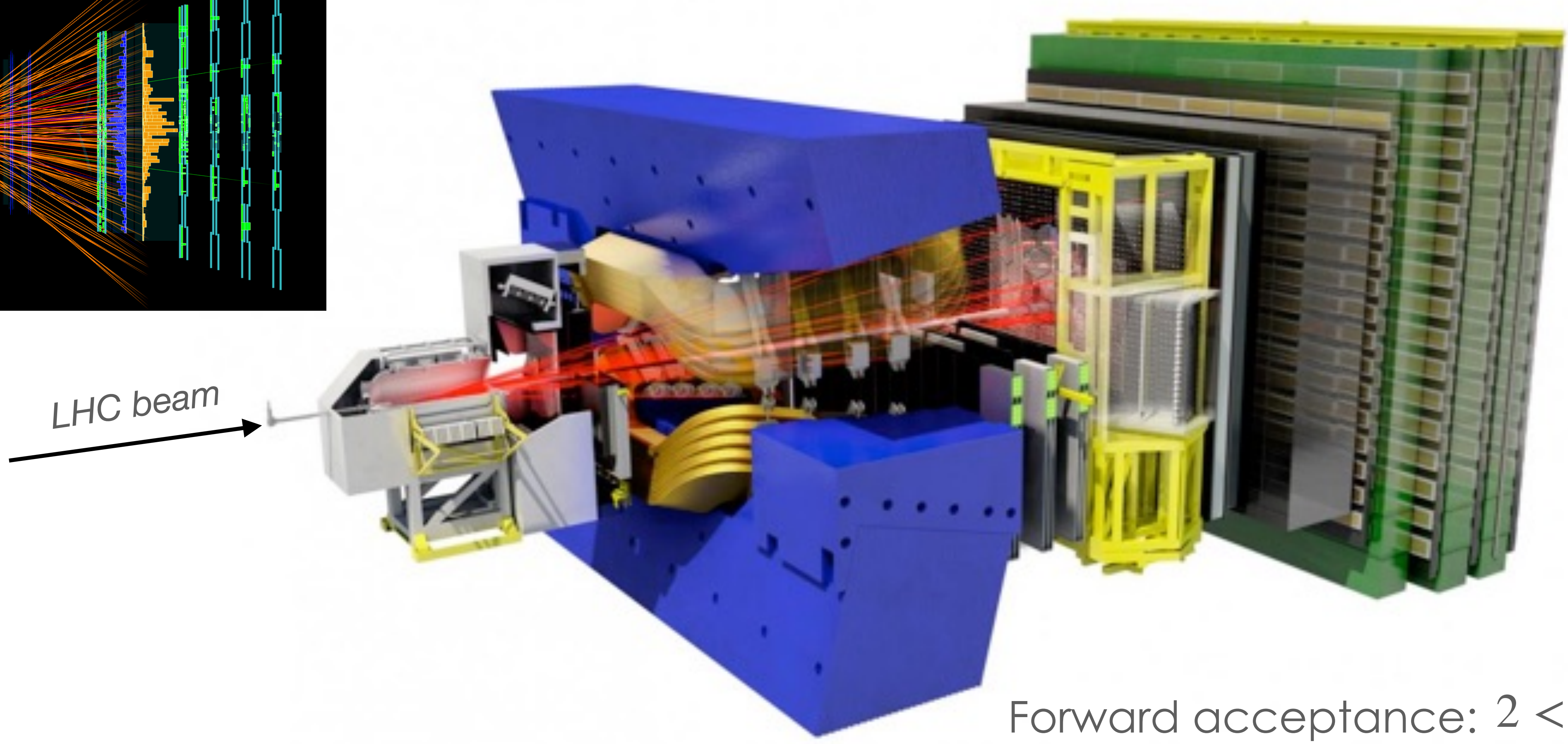
at moderate Q^2 and rapidity

In addition the exotic region at x>1 can be accessed (Fermi motion) creating a bridge between QCD and nuclear physics

LHCb, a single-arm forward spectrometer perfectly suited for fixed target collisions

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022





Forward acceptance: $2 < \eta < 5$

Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

optimised for studying particles containing c- and b-quarks

LHCb upgrade 2019-2020

- Collision rate at 40 MHz
- Pile-up factor $\mu \approx 5$
- Remove L0 triggers (software trigger)
- Read out the full detector at 40 MHz
- Replace the entire tracking system

LHCb, a single-arm forward spectrometer perfectly suited for fixed target collisions

JINST 3 (2008) S08005
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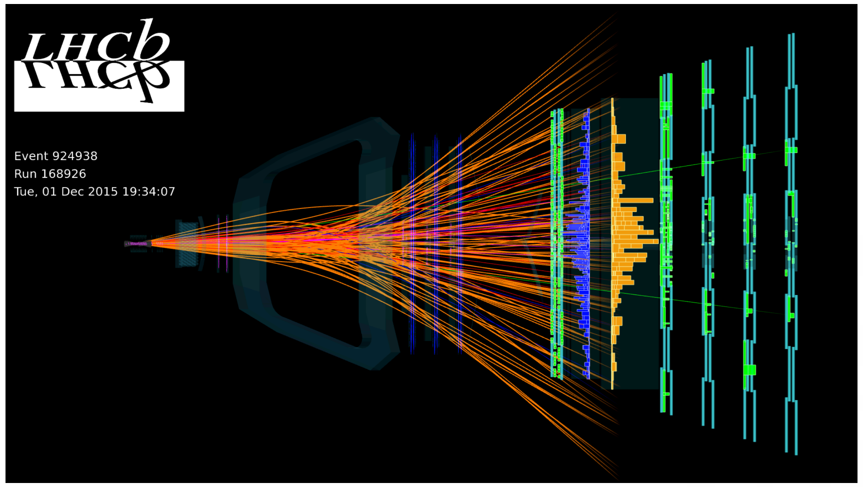

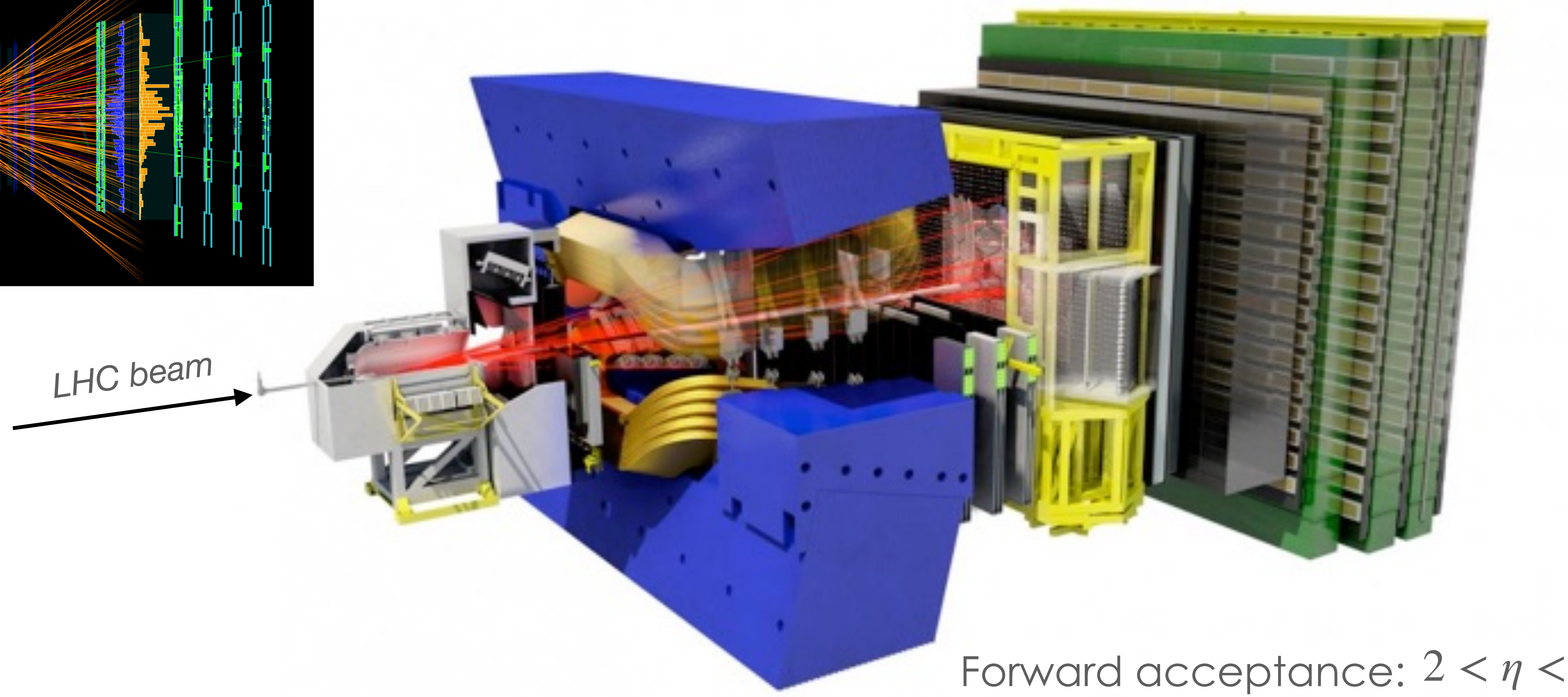

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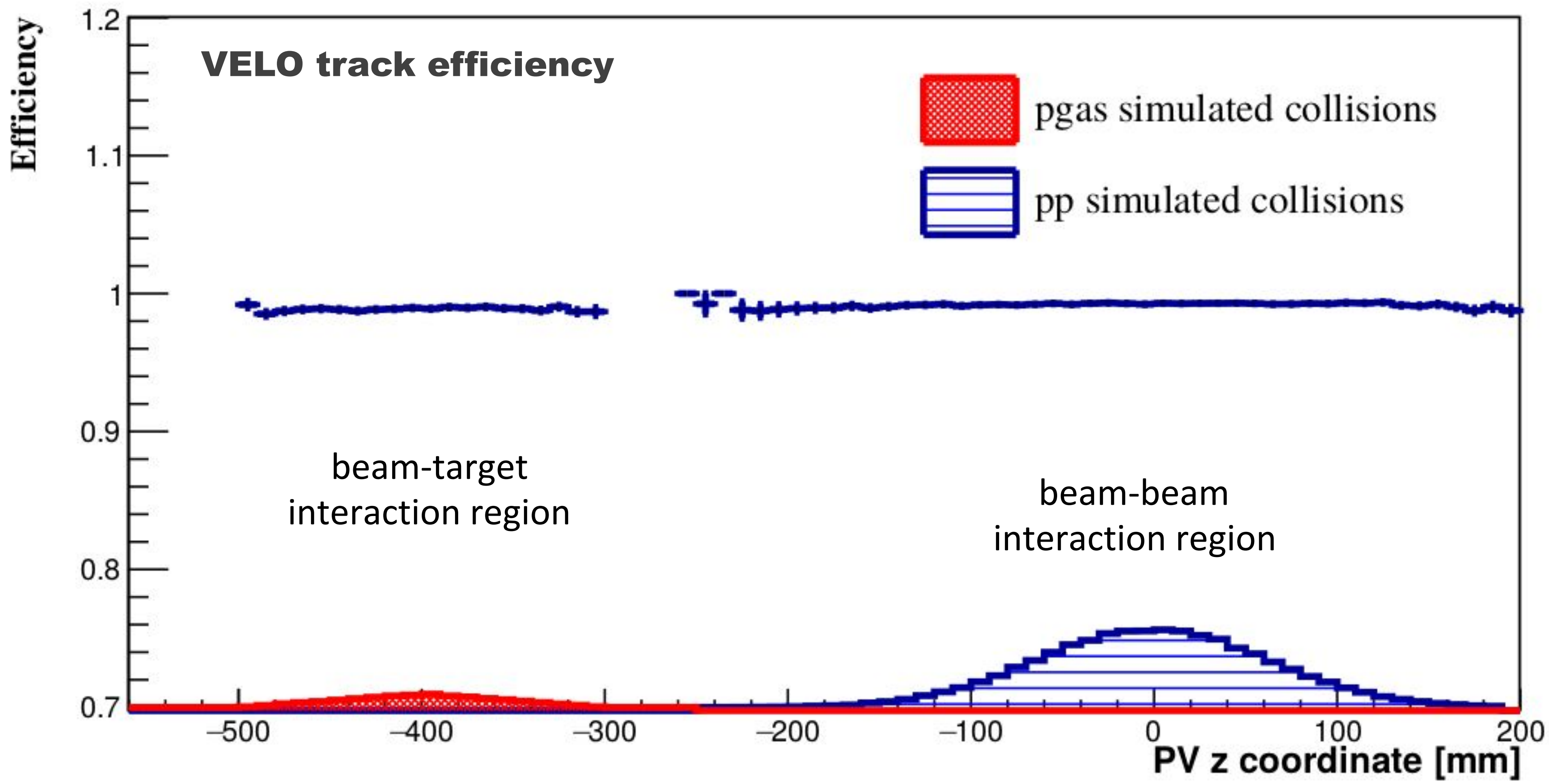
Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

LHCb is the only experiment able to run both in collider and in fixed-target mode … simultaneously!

Simultaneous run for p-gas @ 115 GeV and pp @ 14 TeV



The two systems don't interfere each other and the reconstruction efficiencies stay unchanged

The DAQ data flow increases of 1.3% only

Why

- Advance our understanding of the large-x gluon, antiquark and heavy quark content in nucleons and nuclei
- Advance our understanding of the dynamics and spin distributions of gluons inside (un)polarised nucleons
- Study heavy-ion collisions between SPS and RHIC energies at large rapidities

Why

- -Advance our understanding of the large-x gluon, antiquark and heavy quark content in nucleons and nuclei
- -Advance our understanding of the dynamics and spin distributions of gluons inside (un)polarised nucleons
- -Study heavy-ion collisions between SPS and RHIC energies at large rapidities

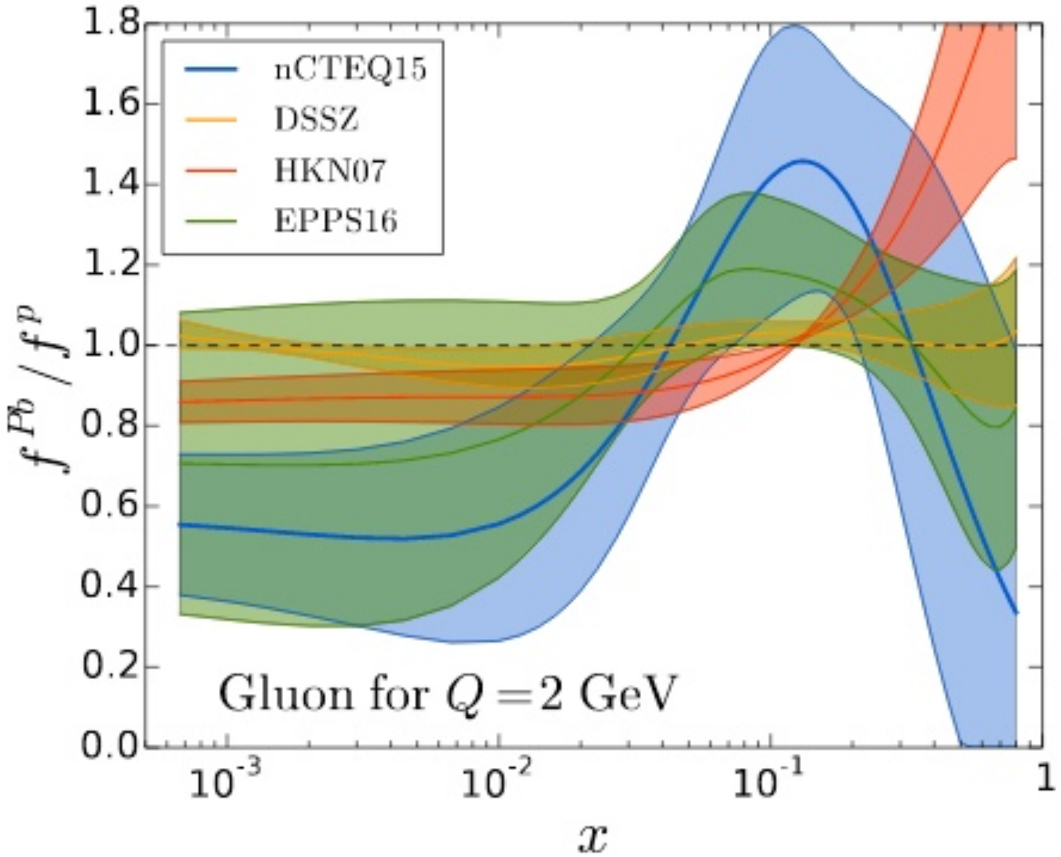
- Unique and large kinematic coverage
- High luminosity and high resolution detectors $\longrightarrow$ rare probes
- Proton or Heavy-Ion Beam
- Large variety of atomic gas targets: $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- Polarised targets: $H^{\uparrow}, D^{\uparrow}$
- Marginal impact on LHC beam and mainstream physics at current experiments

(for H: $1/e_{\text{lifetime}}$ > 2000 days)

PDF world

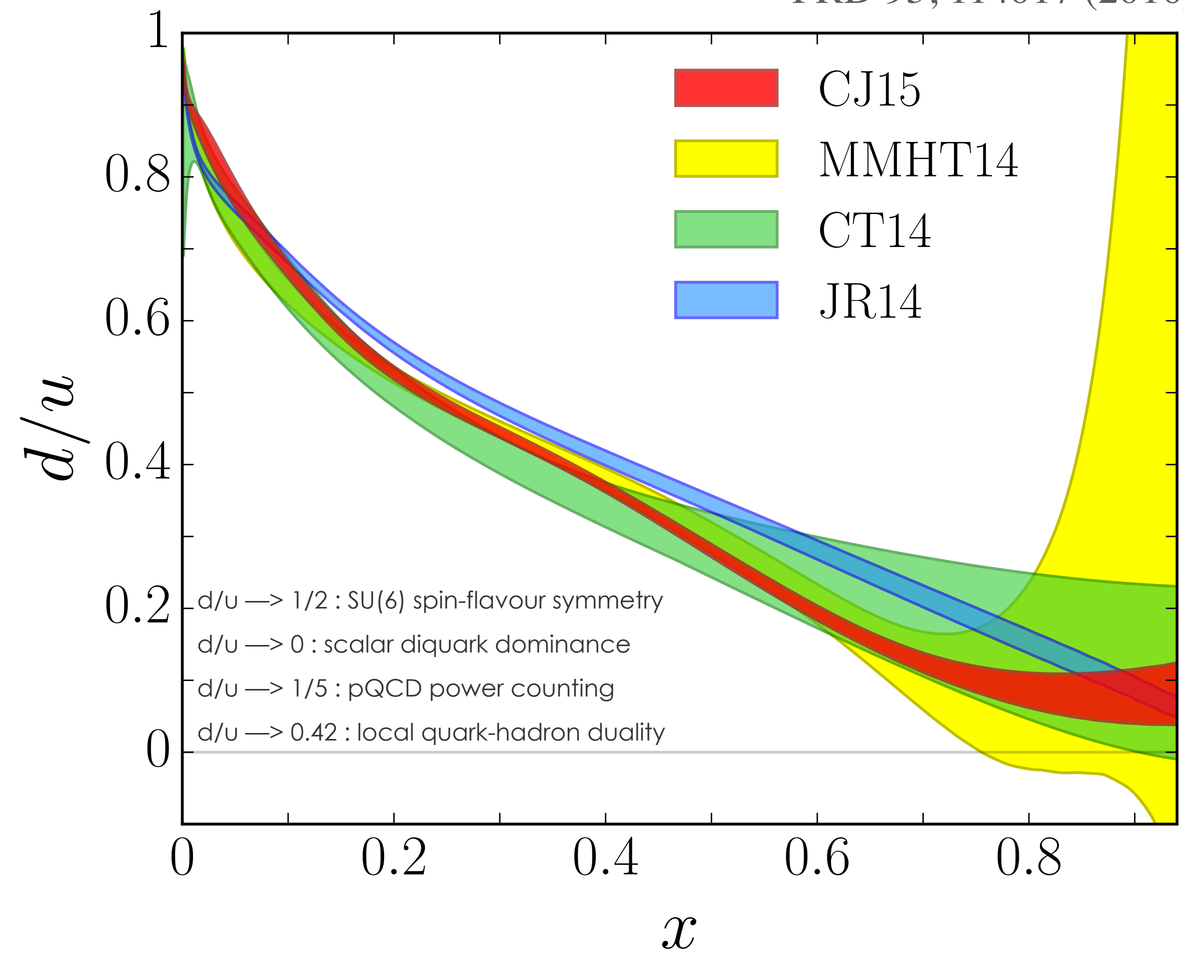
High-x physics

Gluon density in Pb



Quark density in p

PRD 93, 114017 (2016)

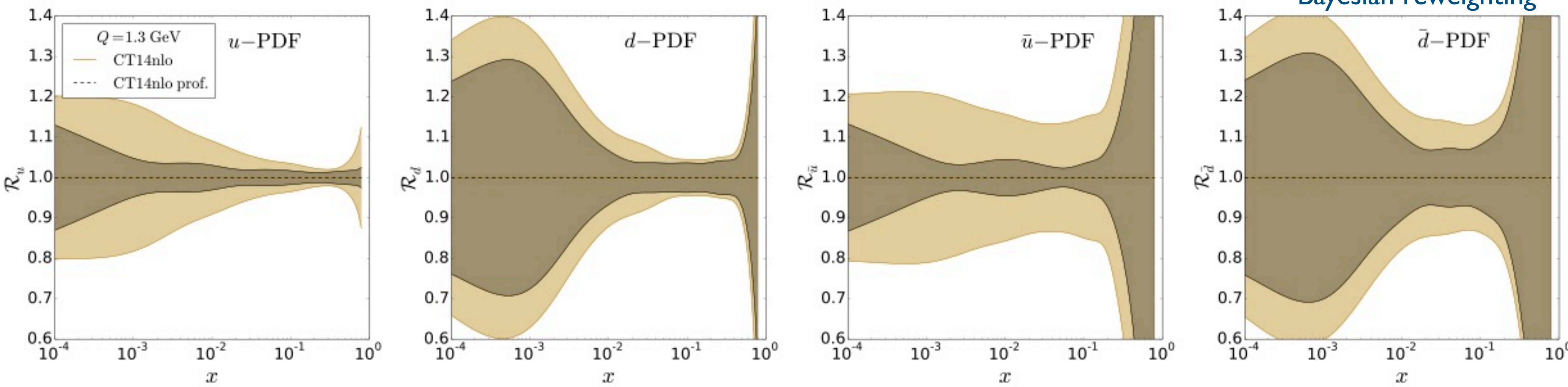


- Reduce the uncertainties on PDFs goes beyond the "simple" knowledge. Among others, it is a crucial ingredient for HEP measurements (even FCC) and predictions of physics processes BSM (e.g. heavy partners of the gauge bosons)
- Cosmic Ray Physics (e.g. to reduce the uncertainties on the prompt atmospheric neutrino flux)
- More insight into EMC effect

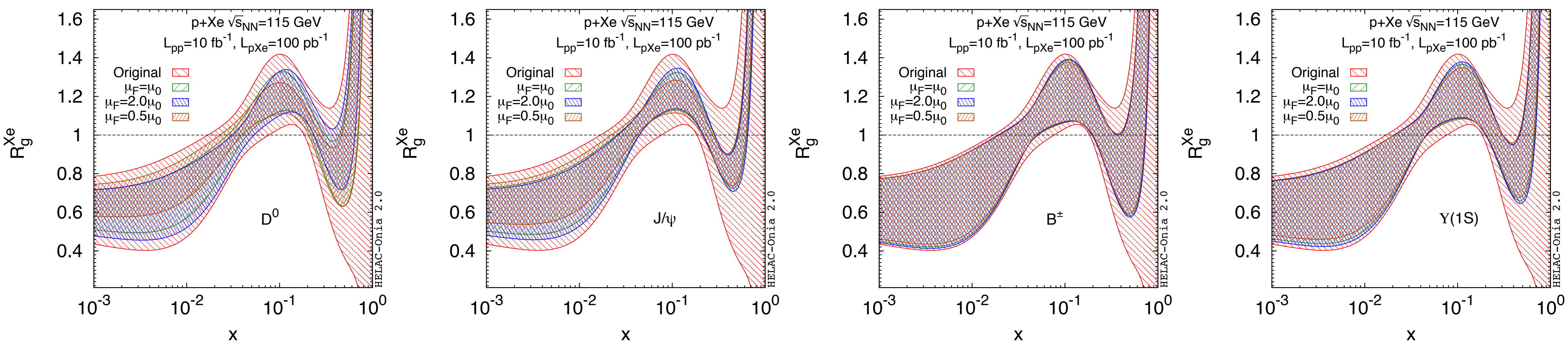
High-x physics

arXiv:1807.00603

Bayesian reweighting



PDF



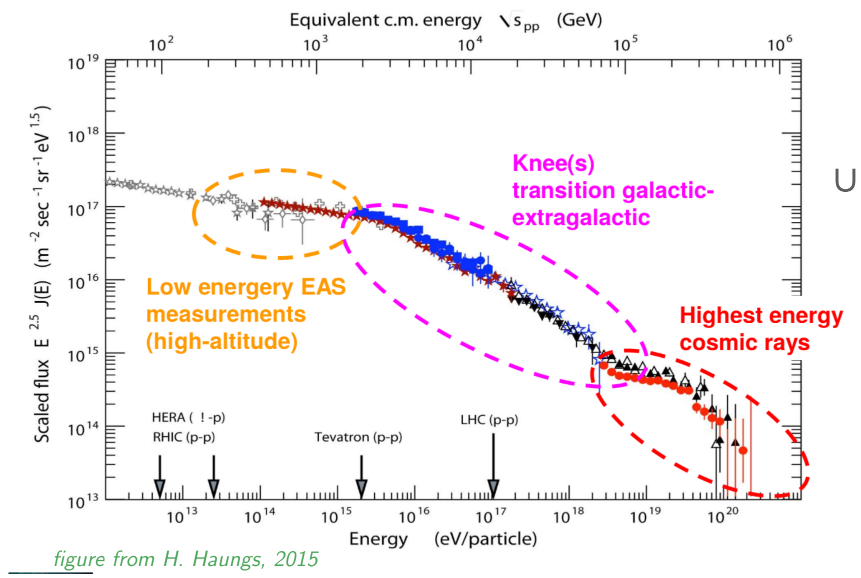
nPDF
(gluon)

Unique constraints on gluon nPDFs at high-x and low scales

Substantial improvement of the uncertainties

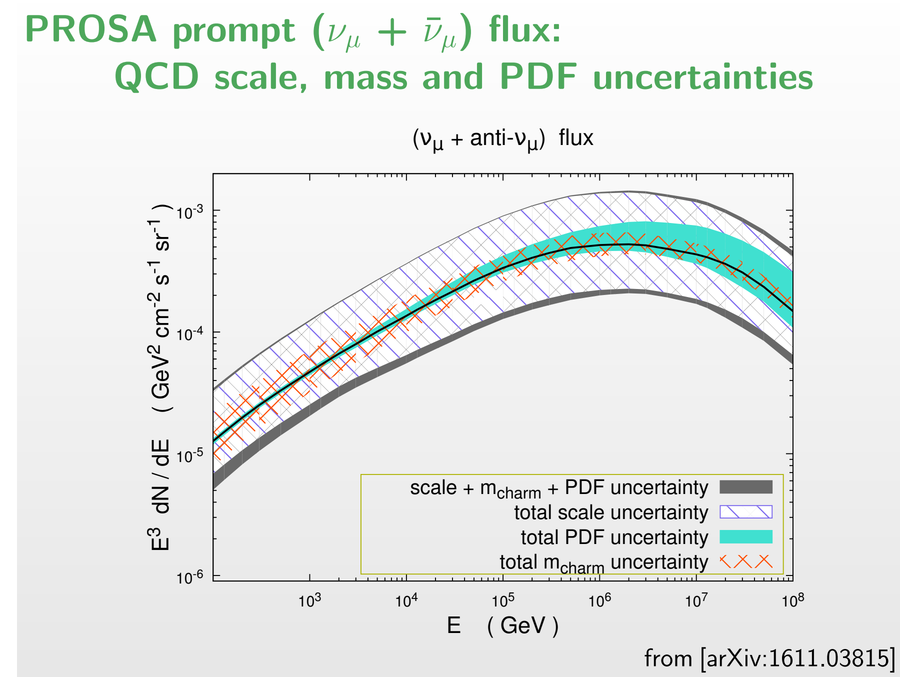
estimation with 10 fb^{-1}

Cosmic Rays and DM



pHe, pO, pN

unique opportunities



UHE CR composition (strongly model dependent) is still very uncertain! Solving the **composition problem** would be important to understand the CR production mechanisms

Big uncertainties from PDF

Antiproton issue: **Dark Matter** annihilation (primary), scatter on interstellar matter (secondary)

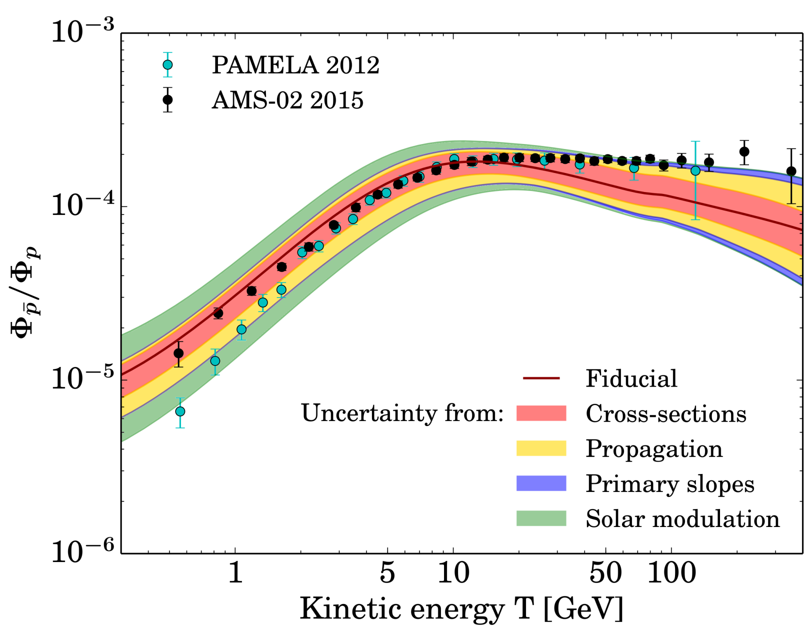
$$\sigma = \sigma^0_{\bar{p}} + \sigma^{\Lambda}_{\bar{p}} + \sigma^0_{\bar{n}} + \sigma^{\mathrm{Hep,pHe,HeHe}}$$

measure + scaling

ignored

$= \sigma^0_{\bar{p}}$ assumed

MC or simple scaling factors



Crucial inputs from LHCb data (FT)

-(n)PDF on nuclei present in interstellar medium

-validation of the theory used to describe HF hadroproduction

-cold and hot nuclear matter effects (in pA and AA collisions)

LHCb paper: Phys. Rev. Lett. 121 (2018), 222001 (arXiv:1808.06127)

Cosmic Rays and DM

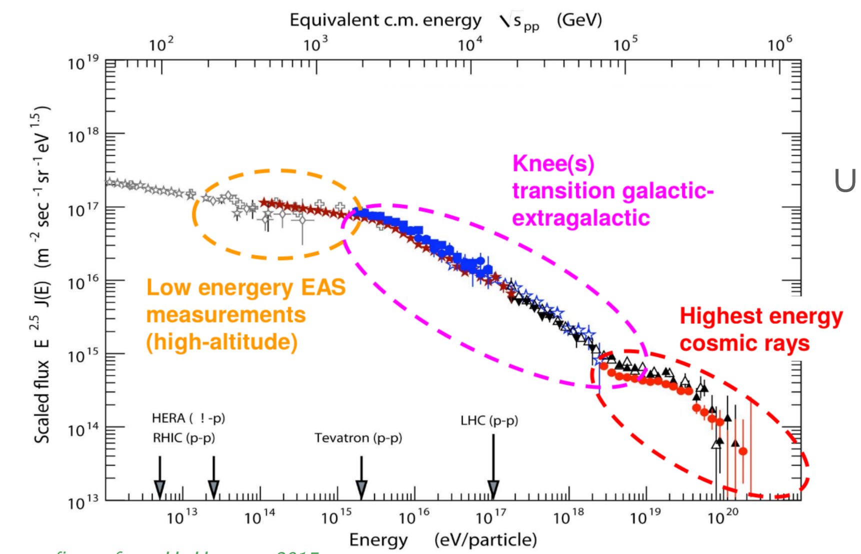
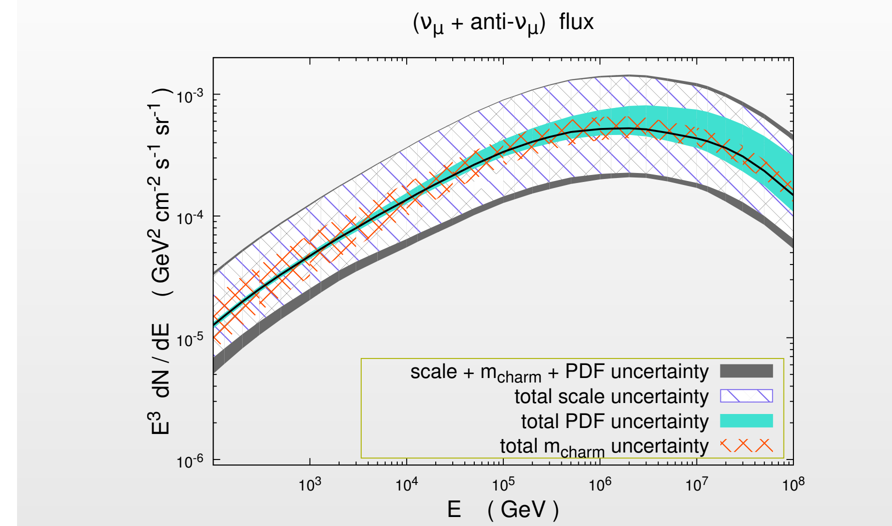


figure from H. Haungs, 2015

pHe, pO, pN

unique opportunities

PROSA prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux:
QCD scale, mass and PDF uncertainties



from [arXiv:1611.03815]

UHE CR composition (strongly model dependent) is still very uncertain! Solving the **cor** important to understand t

Big uncertainties from PDF

Wishlist for fixed target measurements at LHCb from the CR community

1) p He $\rightarrow \bar{\Lambda}, \bar{\Sigma}$ from existing run

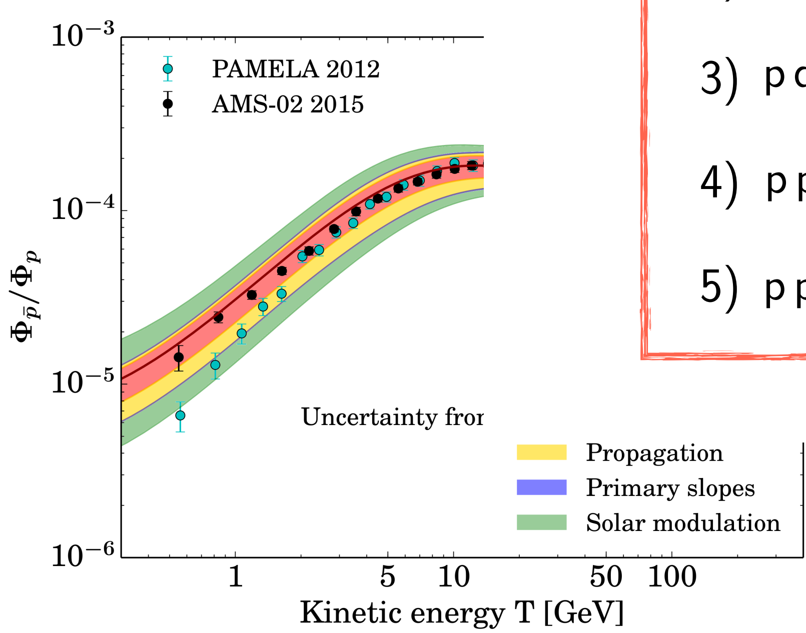
2) p p (H_2) $\rightarrow \bar{p}$ to test scaling violation in forward hemisphere

3) p d $\rightarrow \bar{p}$ to test isospin effects

4) p p, p He $\rightarrow \bar{d}, \bar{He}$ to determine coalescence momentum

5) p p, p He $\rightarrow \pi$, K to model positron source term

Antiproton issue: **Dark M** scatter on interstellar m



,pHe,HeHe

MC or simple scaling factors

Cb data (FT)

nterstellar medium

validation of the theory used to describe HF hadroproduction

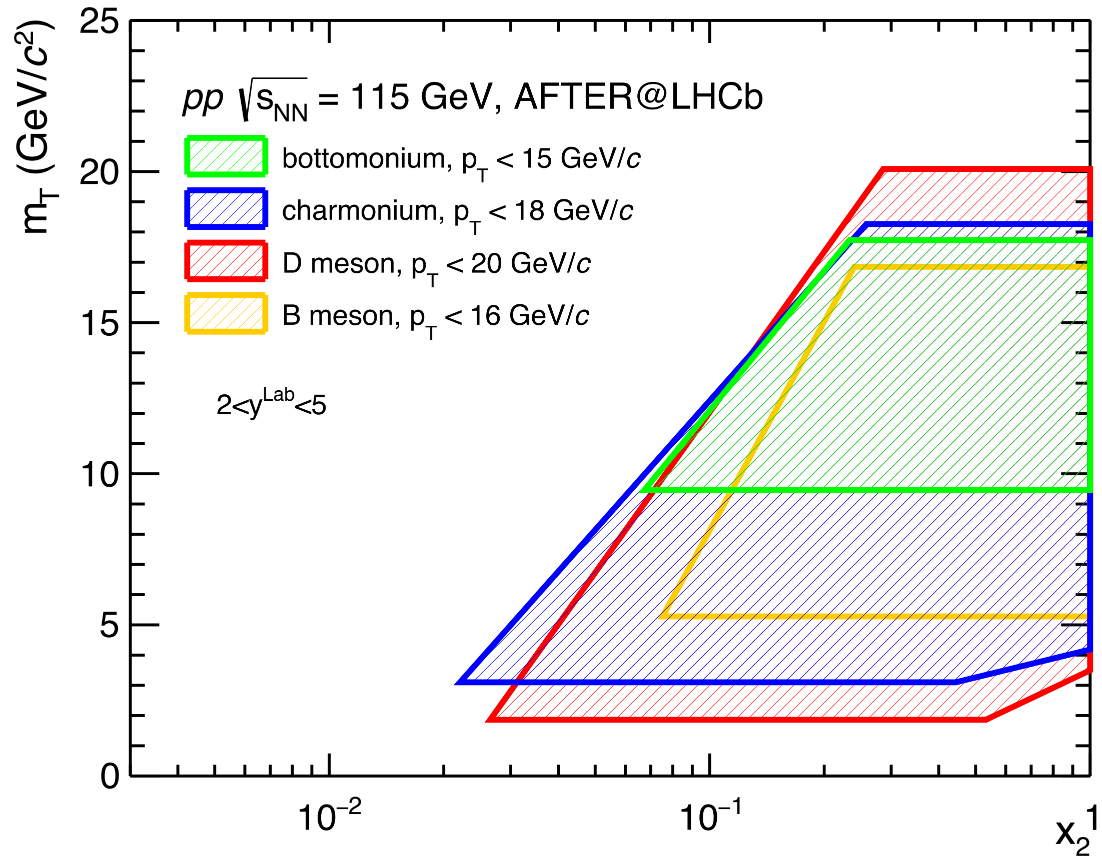
-cold and hot nuclear matter effects (in pA and AA collisions)

LHCb paper: Phys. Rev. Lett. 121 (2018), 222001 (arXiv:1808.06127)

Heavy Flavour

- Complementary D and B-physics done at high energies

arXiv:1807.00603



- Wide kinematical range
- Unique possibility to probe HF channels with the:

-same spectrometer

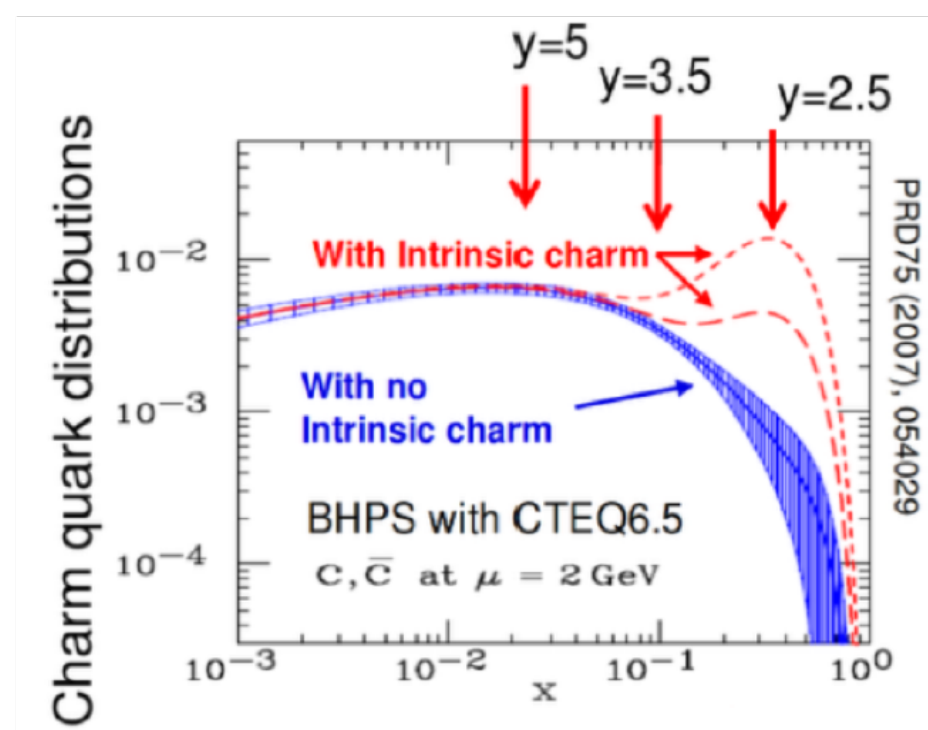
-same beam

-at $\sqrt{s} = 115\ GeV$ and $\sqrt{s} = 14\ TeV$

- Intrinsic heavy-quark:

-non-perturbative intrinsic charm
(already hints from LHCb-FT PRL 122, 132002 (2019))

-5-quark Fock state (uudQQ) of the proton at high-x



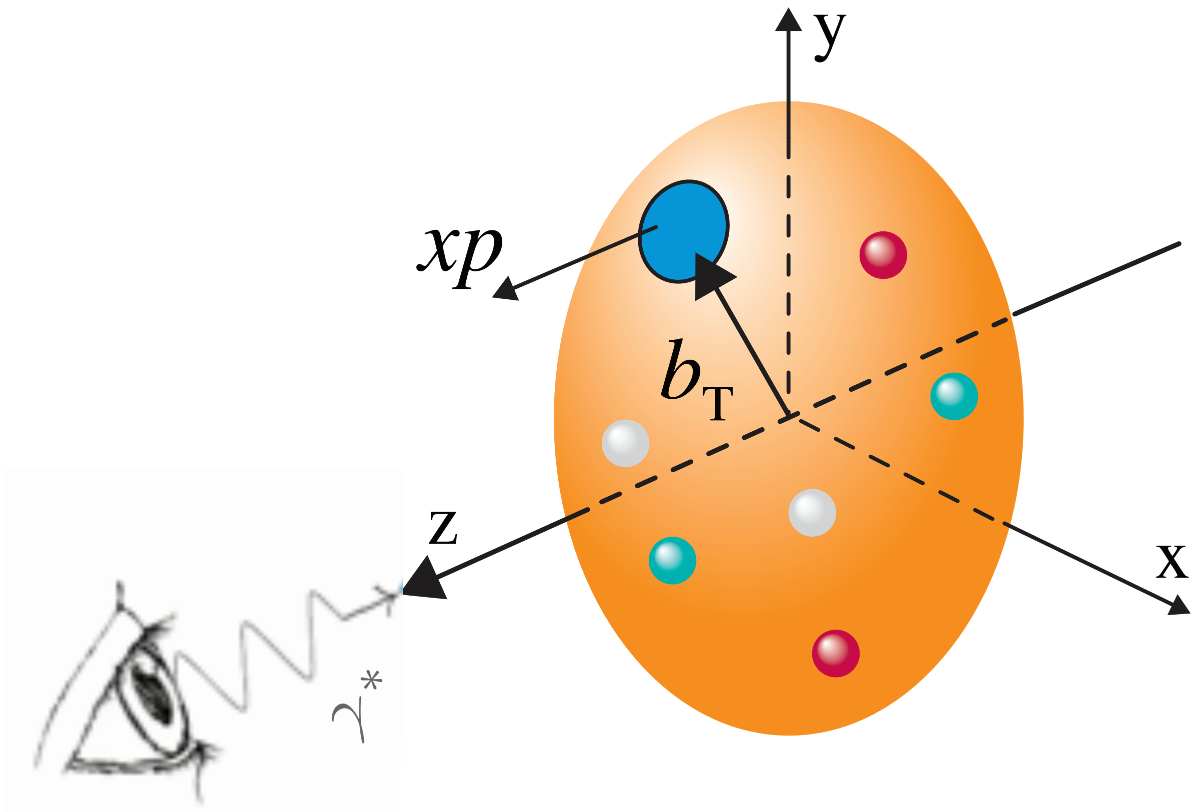
Statistics in full synergy mode (1 yr data taking)

LHCb-PUB-2018-015

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})
Unpolarised gas	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

		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

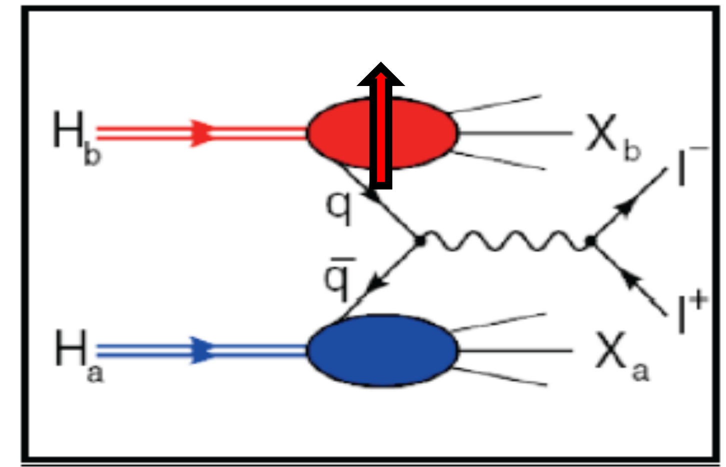
Deep in the hadronic structure



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 $h_{1T}^\perp$

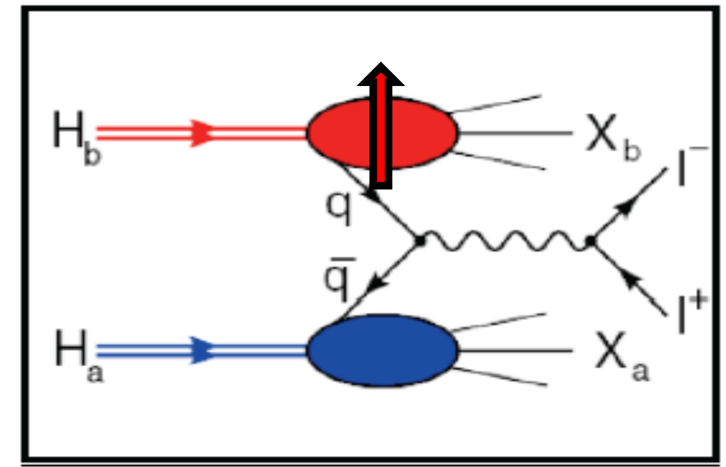
Polarized Drell-Yan



Accessing the quark TMDs

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

Polarized Drell-Yan

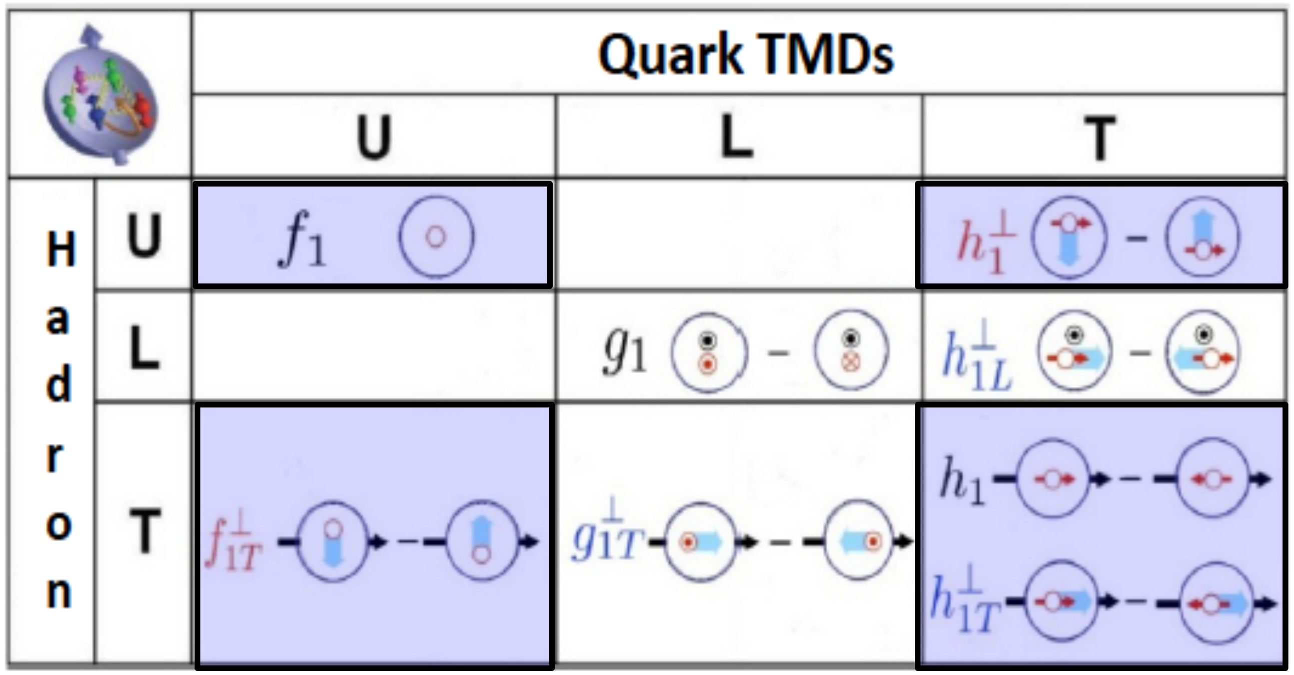


Sensitive to quark TMDs up to high $x_2^{\uparrow}$ through TSSAs

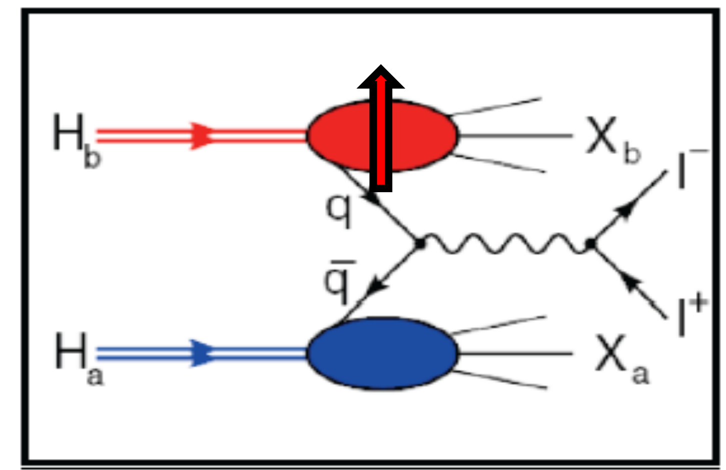
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_{1T}^{\perp q}}{f_1^q \otimes f_1^q} \qquad A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}$$

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

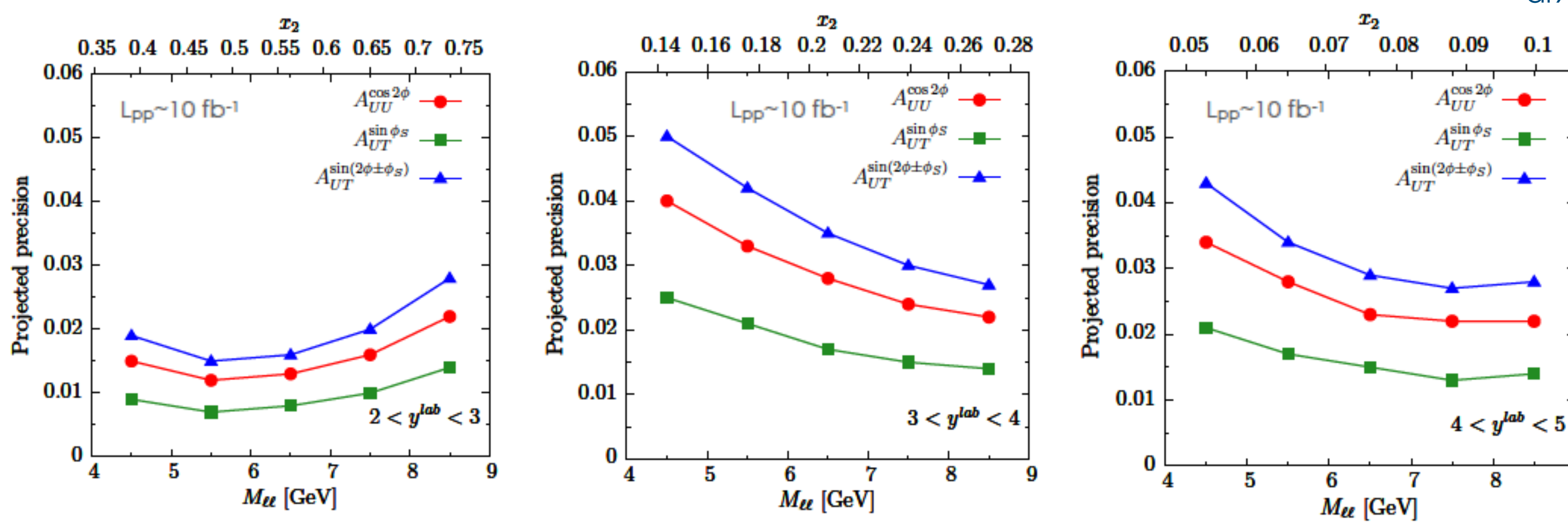
Accessing the quark TMDs



Polarized Drell-Yan



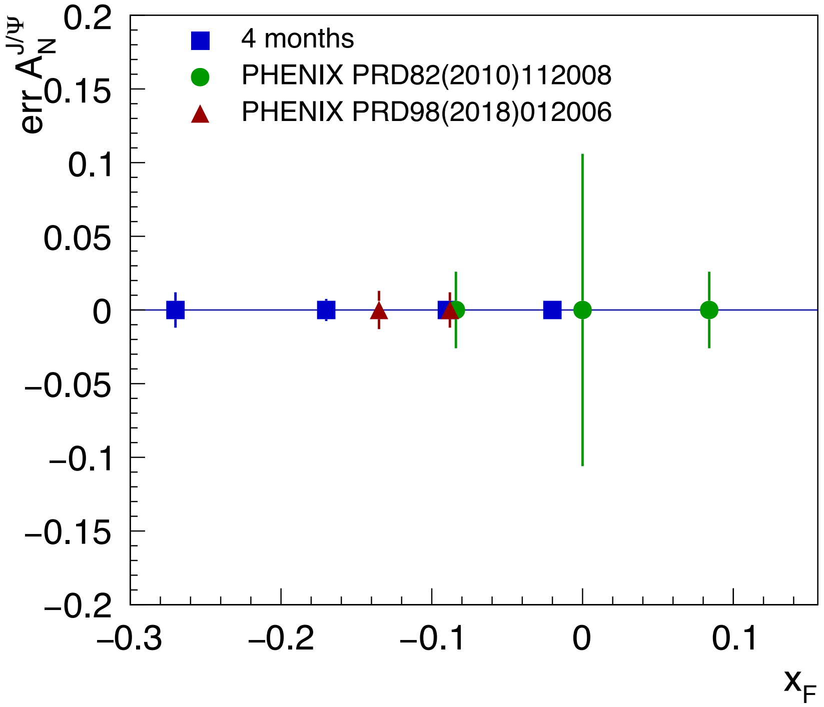
arXiv:1807.00603



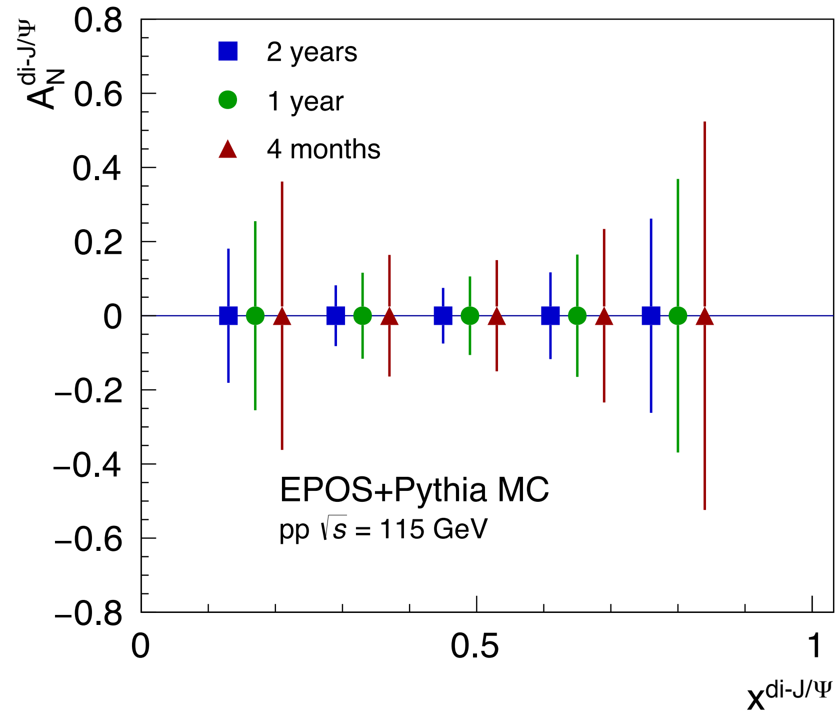
High precision achievable for observables connected to (i.e.) the transversity, the Boer-Mulders function, the pretzelosity and the Sivers TMDs

… heavy quark sector

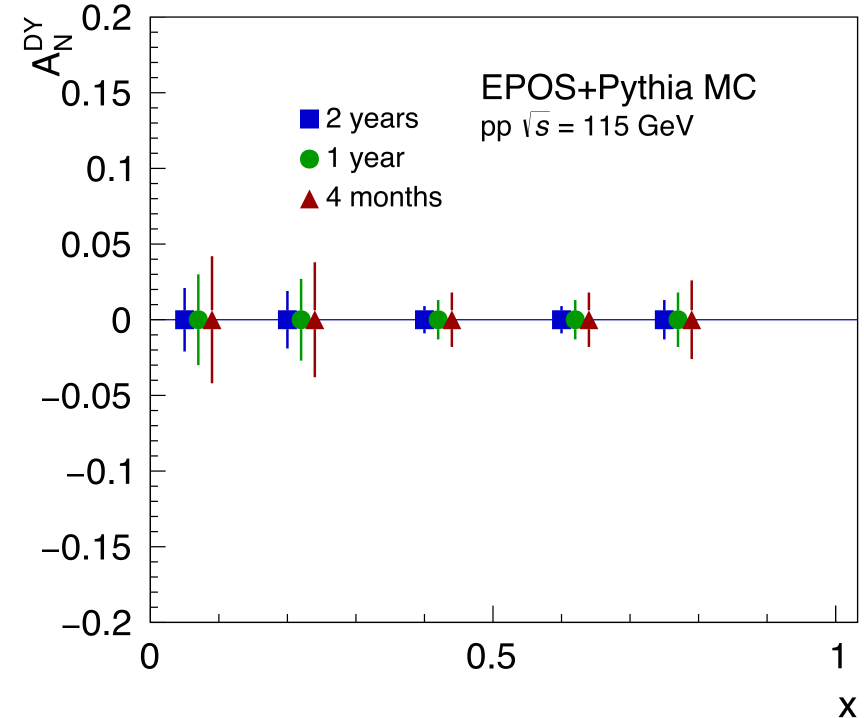
J/Ψ

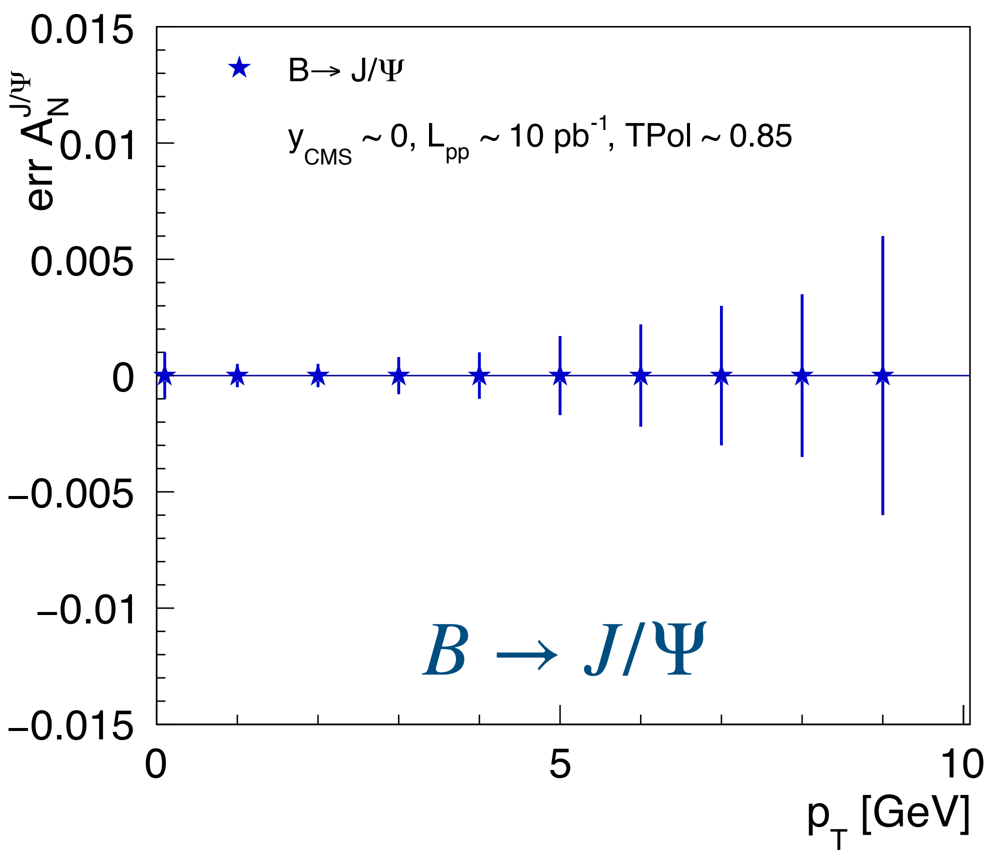


$di - J/\Psi$



DY



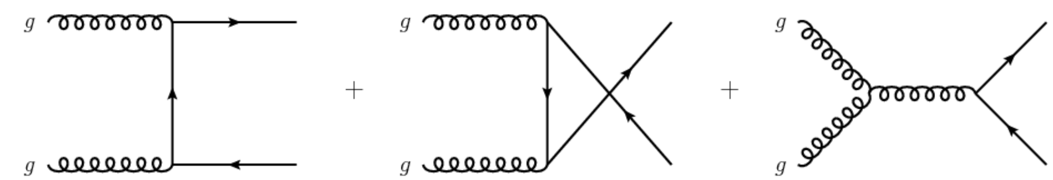


Such measurement would open a new era of precision measurements in spin physics using heavy-quark probes

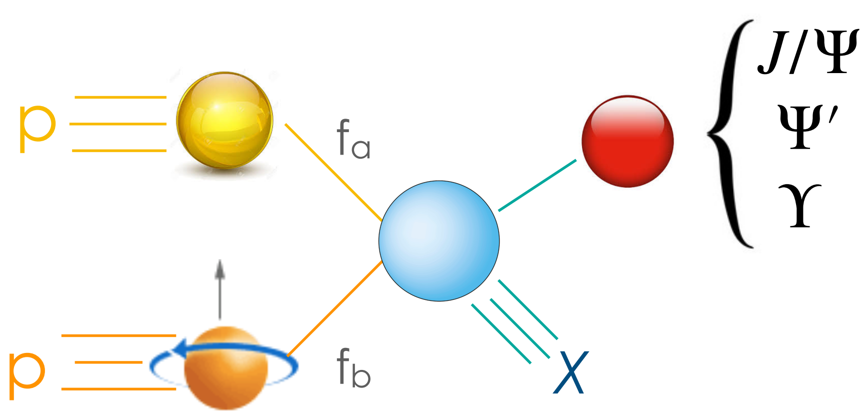
Accessing the gluon TMDs

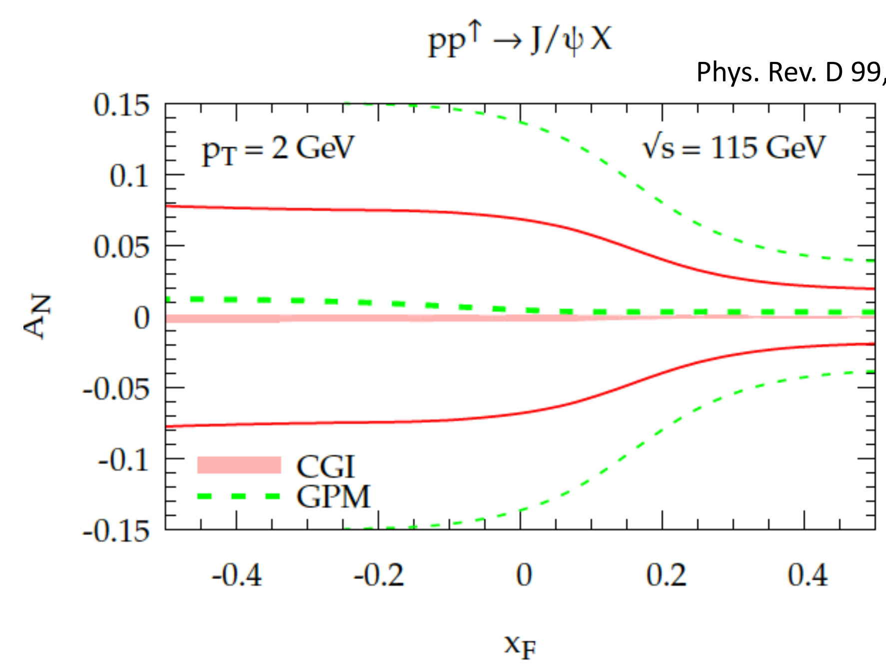
		Gluon TMDs		
		Unpol	Circularly pol.	Linearly pol.
nucleon	U	f_1^g		$h_1^{\perp g}$
	L		g_1^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	$g_{1T}^{\perp g}$	h_{1T}^g, $h_{1T}^{\perp g}$

In high-energy hadron collisions Heavy Quarks are 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





Phys. Rev. D 99, 036013 (2019)

LHCb can measure nearly all quarkonia states (including C-even) with high precision!
The expected yields are much larger than previous fixed-target experiments.
Heavy mesons are unique observables, poorly accessible from other hadron-hadron experiments
[unique channels: pseudoscalar quarkonia (η, η_c, $\eta_c(2S)$, $\chi_{c,b}$), Υ, J/Ψ, Ψ', di–J/Ψ, $\Upsilon(1,2,3S)$, D, B-mesons, DY ($\mu^+\mu^-$)]

Accessing the gluon TMDs

[D. Boer: arXiv:1611.06089]

Weizsacker-Williams (WW) gluon distributions

dipole (DP) gluon distributions

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)	×	√	×	×	×

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

TMDs (Sivers)

	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

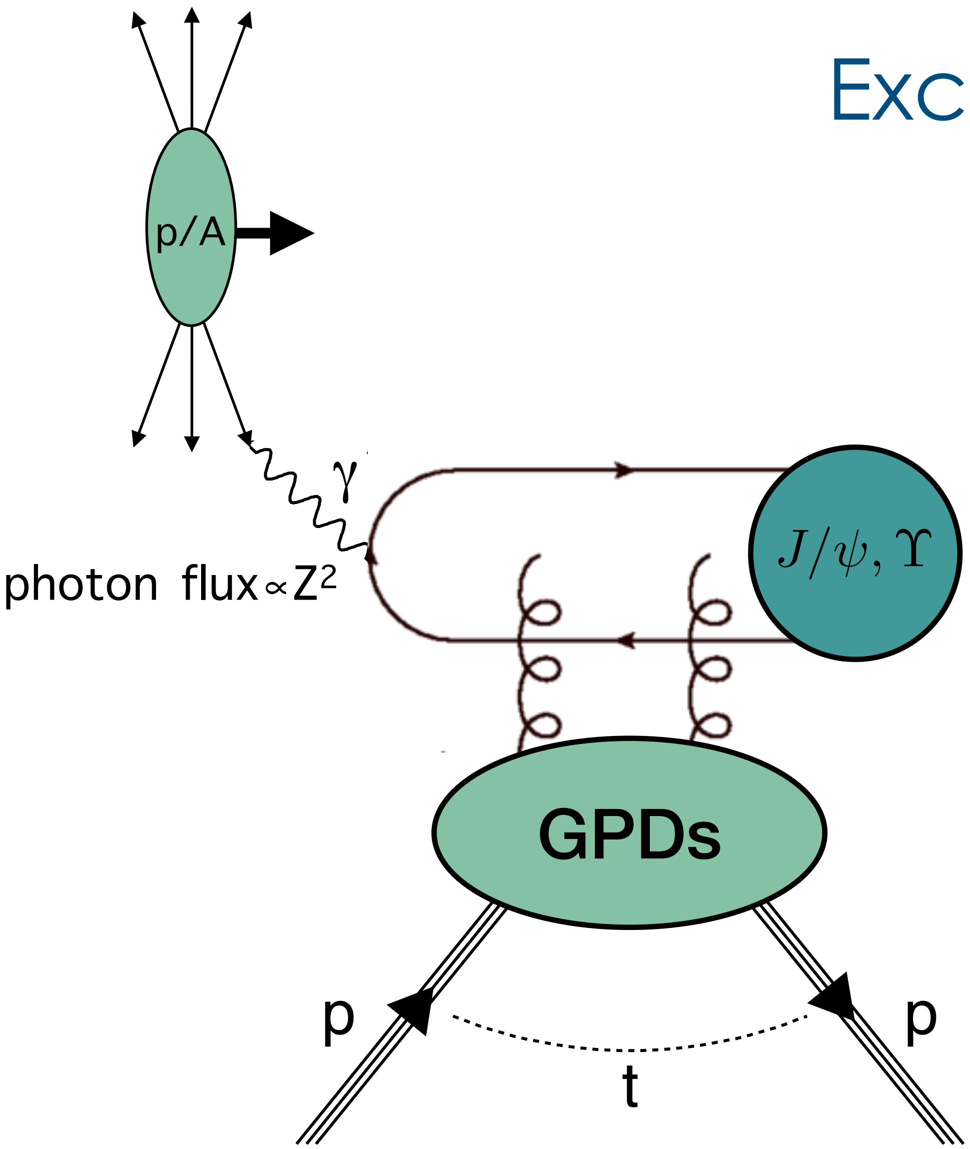
$f_{1T}^{\perp g[+,-]}$ (Dipole s type or "**d-type**") → symmetric colour structures

Sign change:
Universality of QCD
(indication from COMPASS and RHIC)

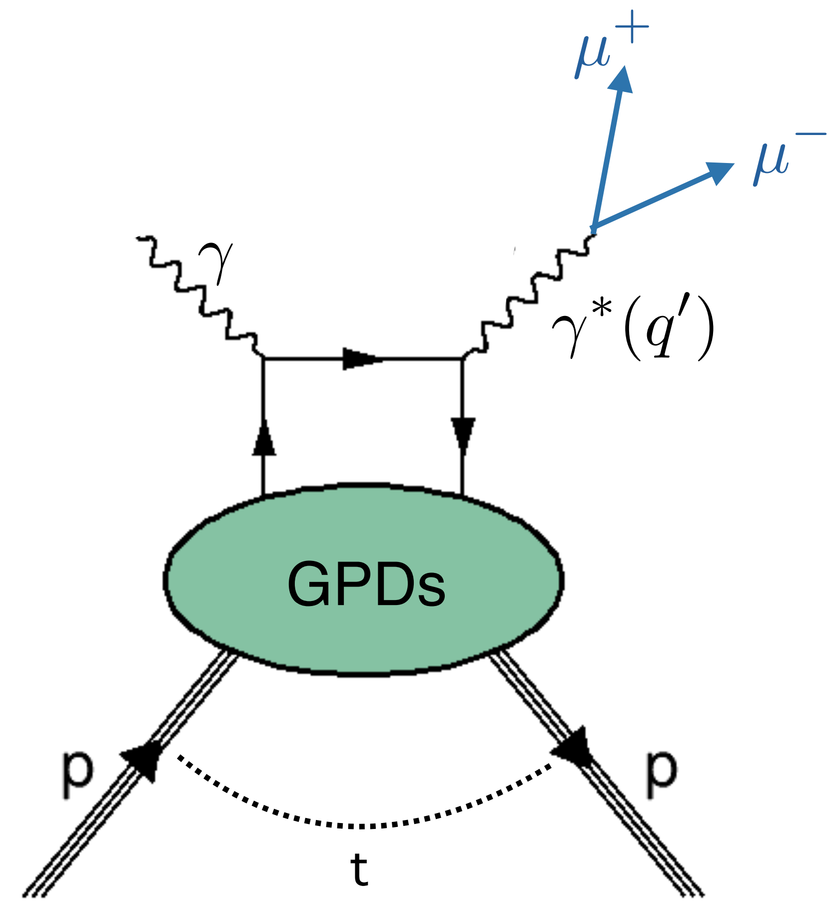
Can be measured at the Electron Ion-Collider (EIC)

Can be measured at FT-LHCb

Exclusive physics via UPC



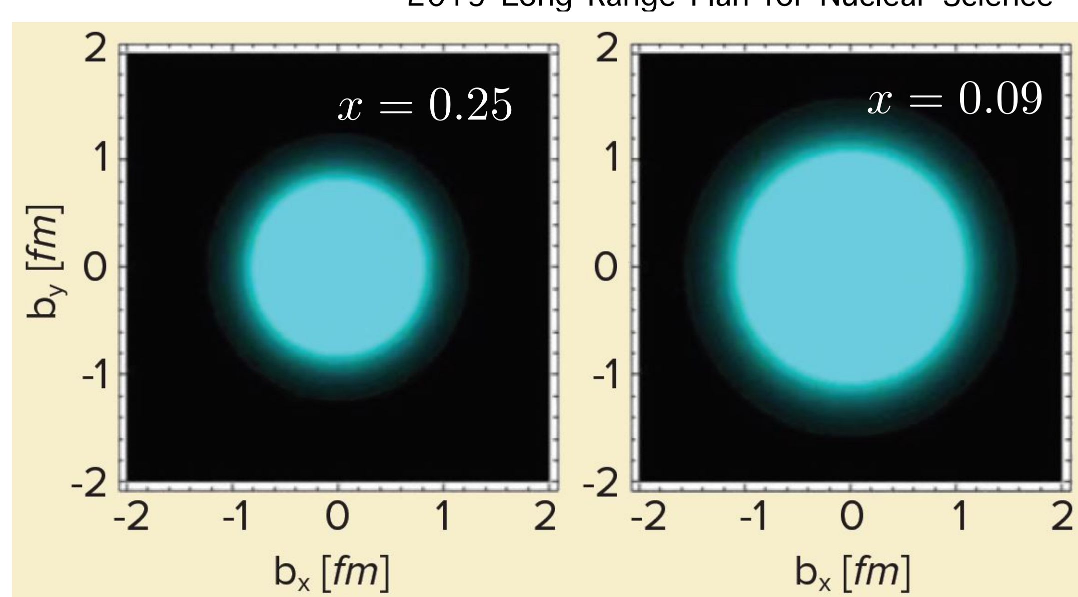
Exclusive meson production



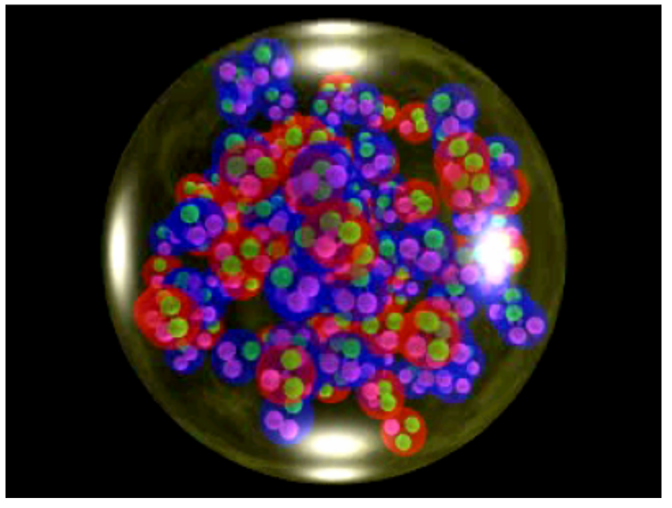
Timelike Compton scattering

One of the objectives:
3D pictures in coordinate (impact parameter) space

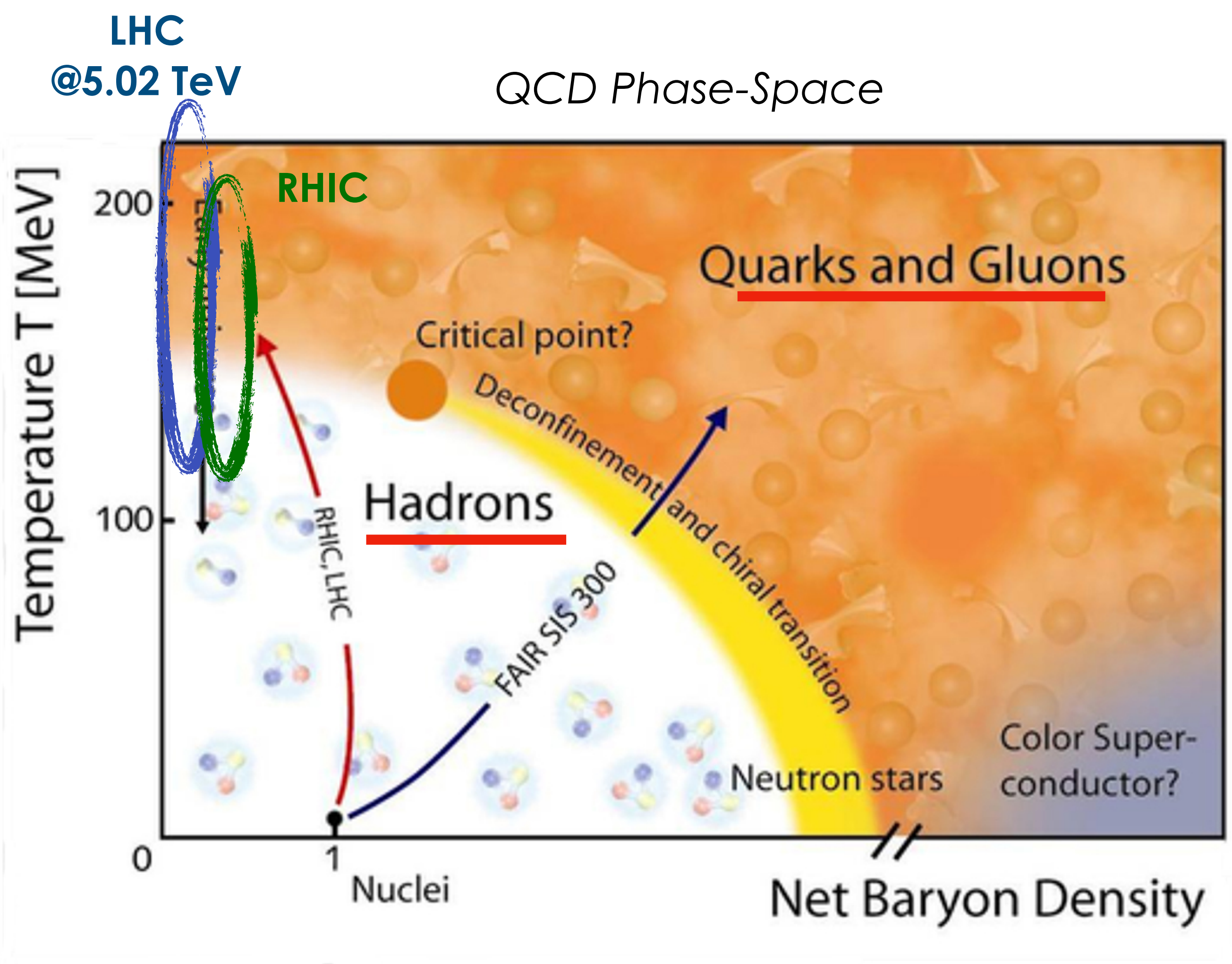
2015 Long Range Plan for Nuclear Science



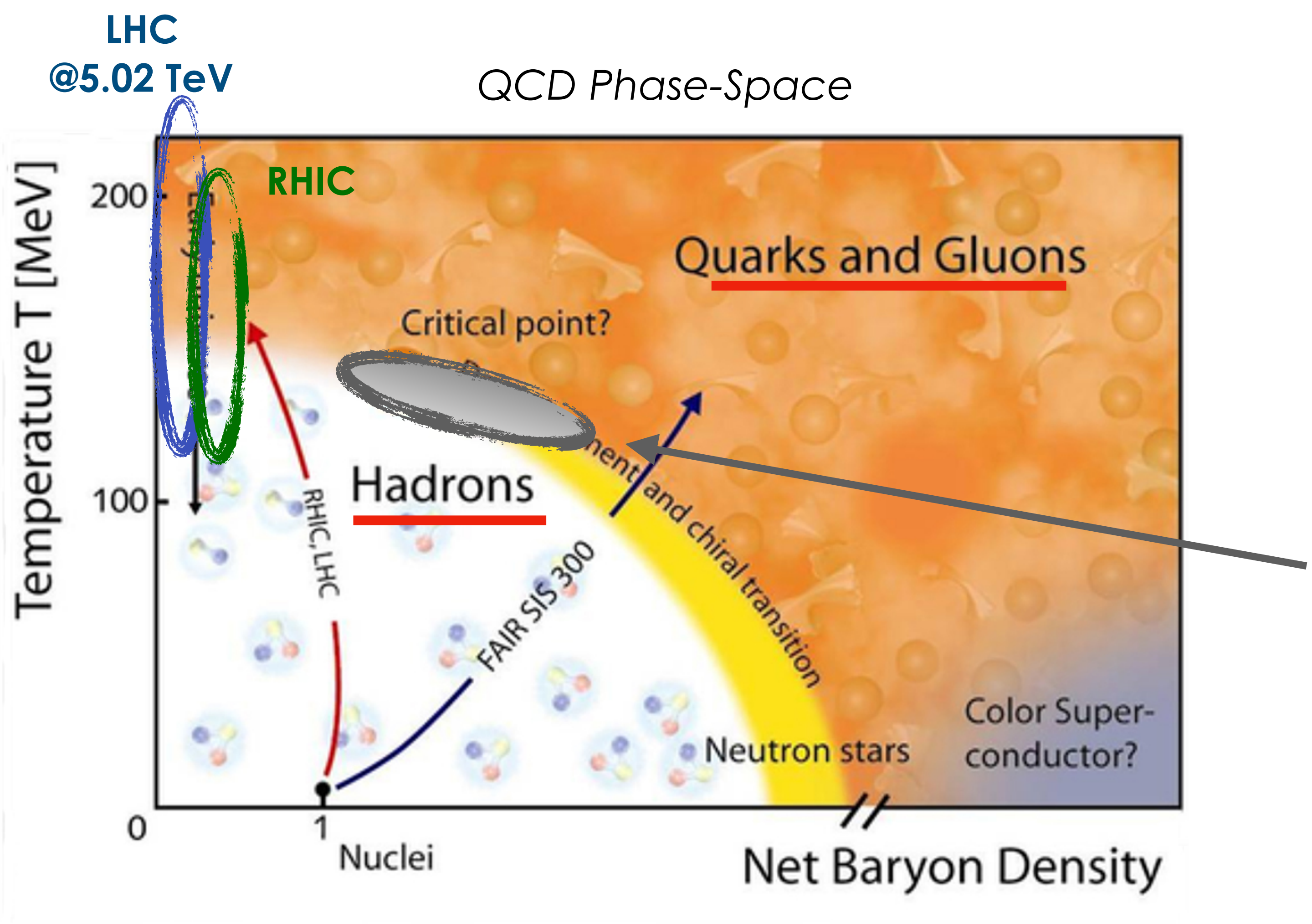
Heavy-Ion world



Heavy-Ion collision: QGP and phase transition



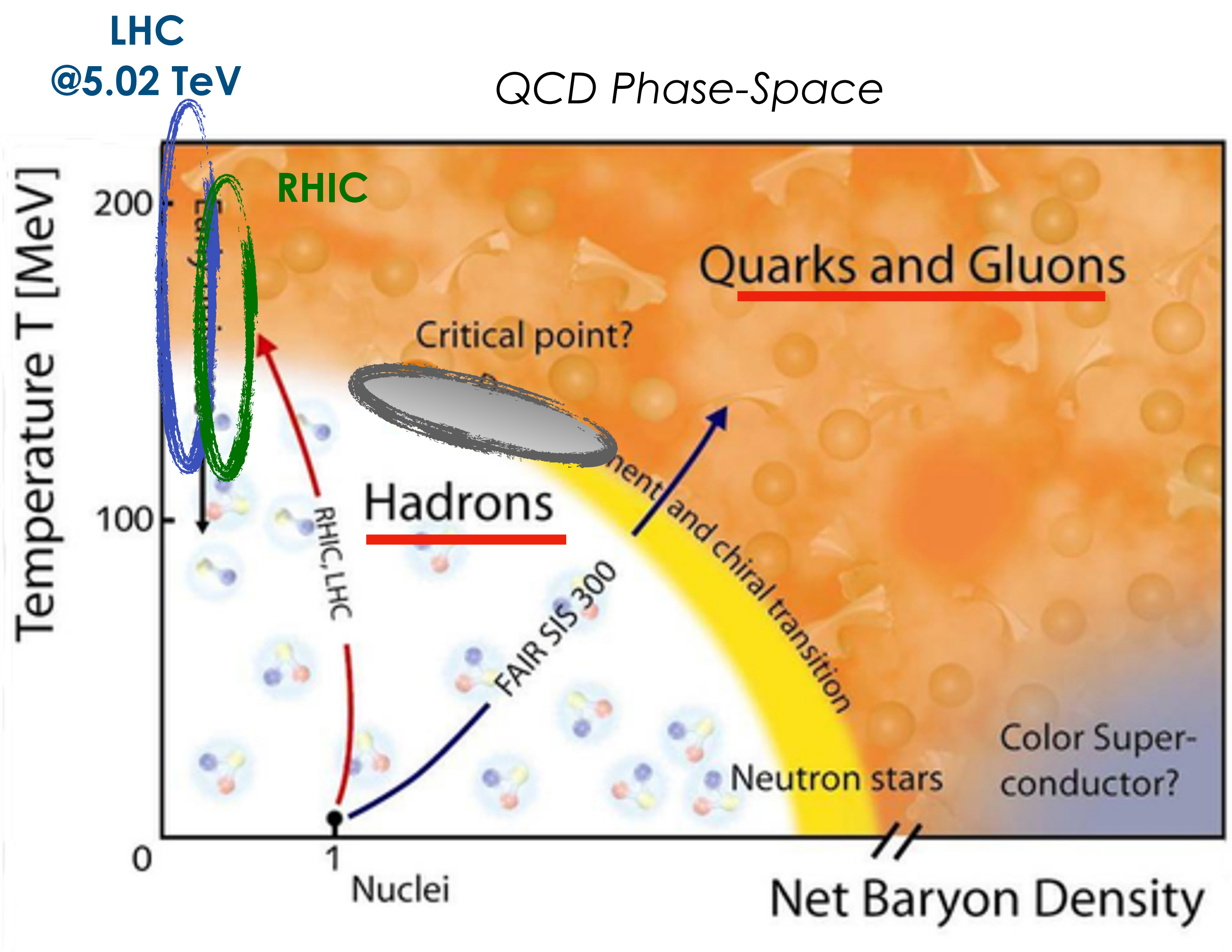
Heavy-Ion collision: QGP and phase transition



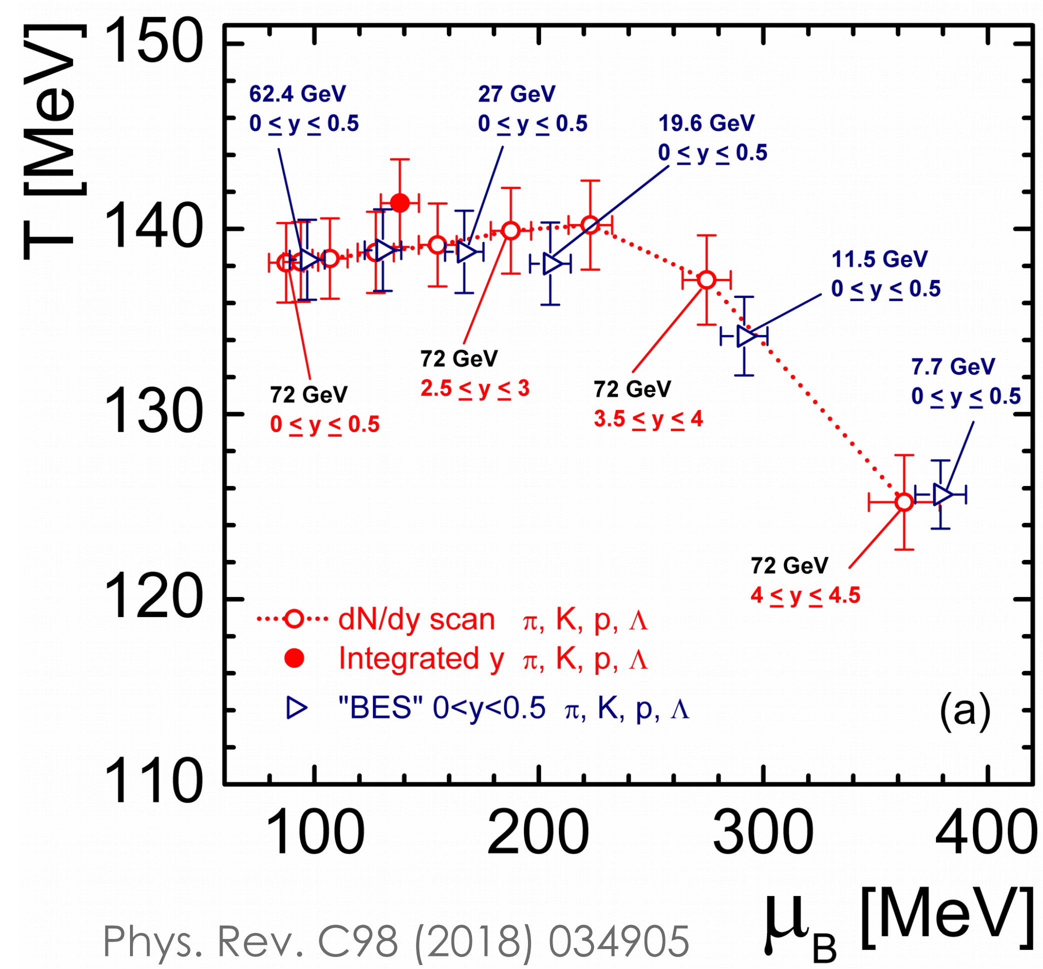
Region potentially
covered by HI-FT collisions

Heavy-Ion collision: QGP and phase transition

QCD Phase-Space



how to scan the phase space



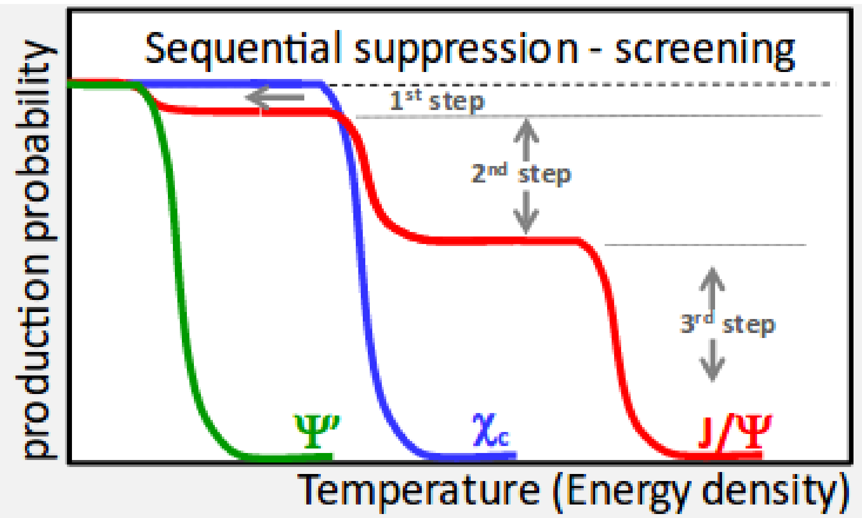
Phys. Rev. C98 (2018) 034905

<u>3 experimental degrees of freedom</u>: rapidity scan, different colliding systems, centrality dependence

Rapidity scan at 72 GeV with FT@LHC can complement the RHIC beam energy scan from 62.4 GeV down to 7.7 GeV (at $y_{cms} \sim 0$)

Color screening and sequential suppression

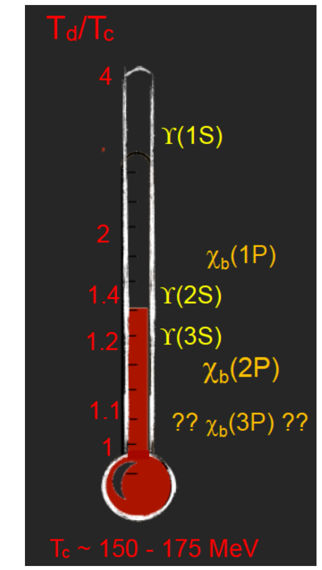
- Color Screening in hot nuclear matter prevents formation of $c\bar{c}$ bound states



$c\bar{c}$ bound states: J/ψ, χ_c , ψ', … different binding energy, different dissociation temperature

sequential suppression pattern

Phys. A28(2013) 1340012



Dissociation temperature from lattice QCD (+hydro)

- QGP tomography

Probing:

-the longitudinal extension of the hot medium (high rapidities)

-the colliding systems of different sizes

-the centrality dependence

-with and w/o HF probes

Temperature dependence of the shear viscosity to entropy density ratio (η/s) by measuring the rapidity dependence of the anisotropic flow

3D+1 viscous hydrodynamic calculations

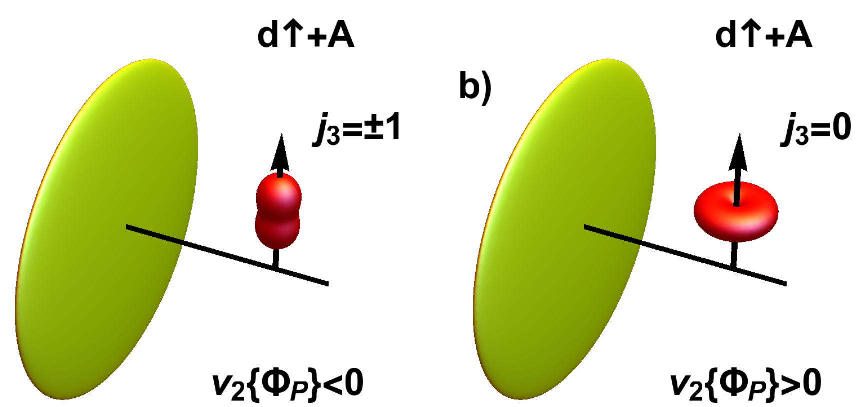
Elliptic flow in ultra-relativistic collisions with polarised deuterons

arXiv:1906.09045, 2001.10260

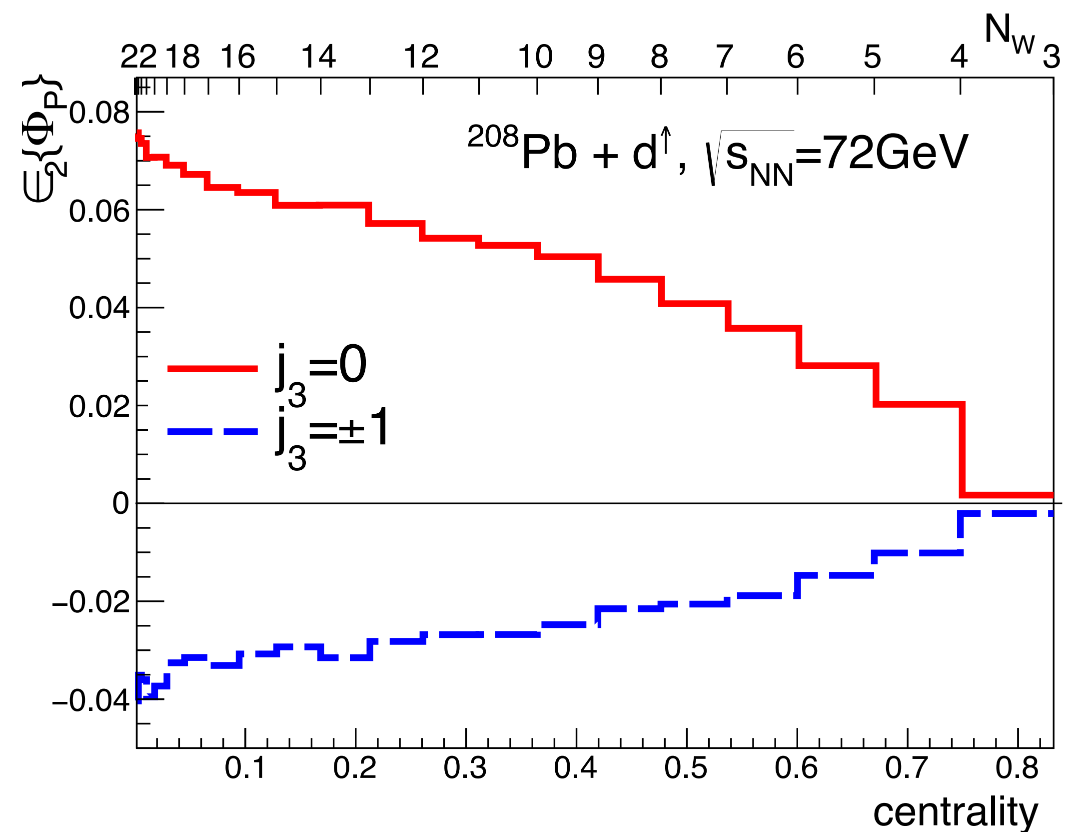
Ridge and flow measurements, connected to collectivity phenomena, are among the most interesting results achieved in the last years in the QGP physics.

We can put this in connection with spin clarifying the nature of dynamics in small systems

its experimental confirmation would prove the presence of the shape-flow transmutation mechanism, typical of hydrodynamic expansion, or rescattering in the later stages of the fireball evolution



ultra-relativistic d+A collision, where the deuteron is polarised along the axis Φ_P perpendicular to the beam



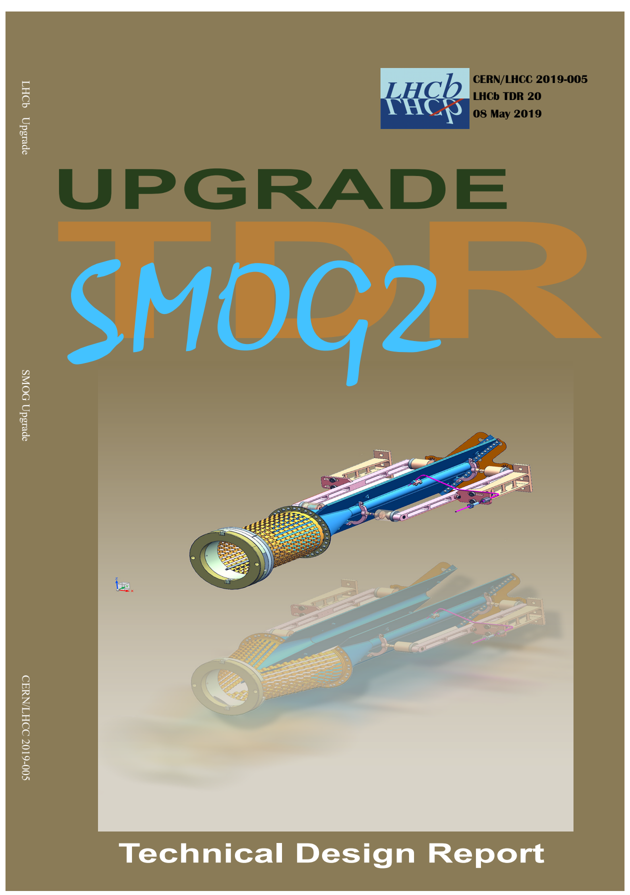
Ellipticities of the fireball

A polarised target at LHC can easily provide Pb $D^{\uparrow}$ collisions

This is going to happen at LHCb

LHCspin

Phase I
unpolarised target

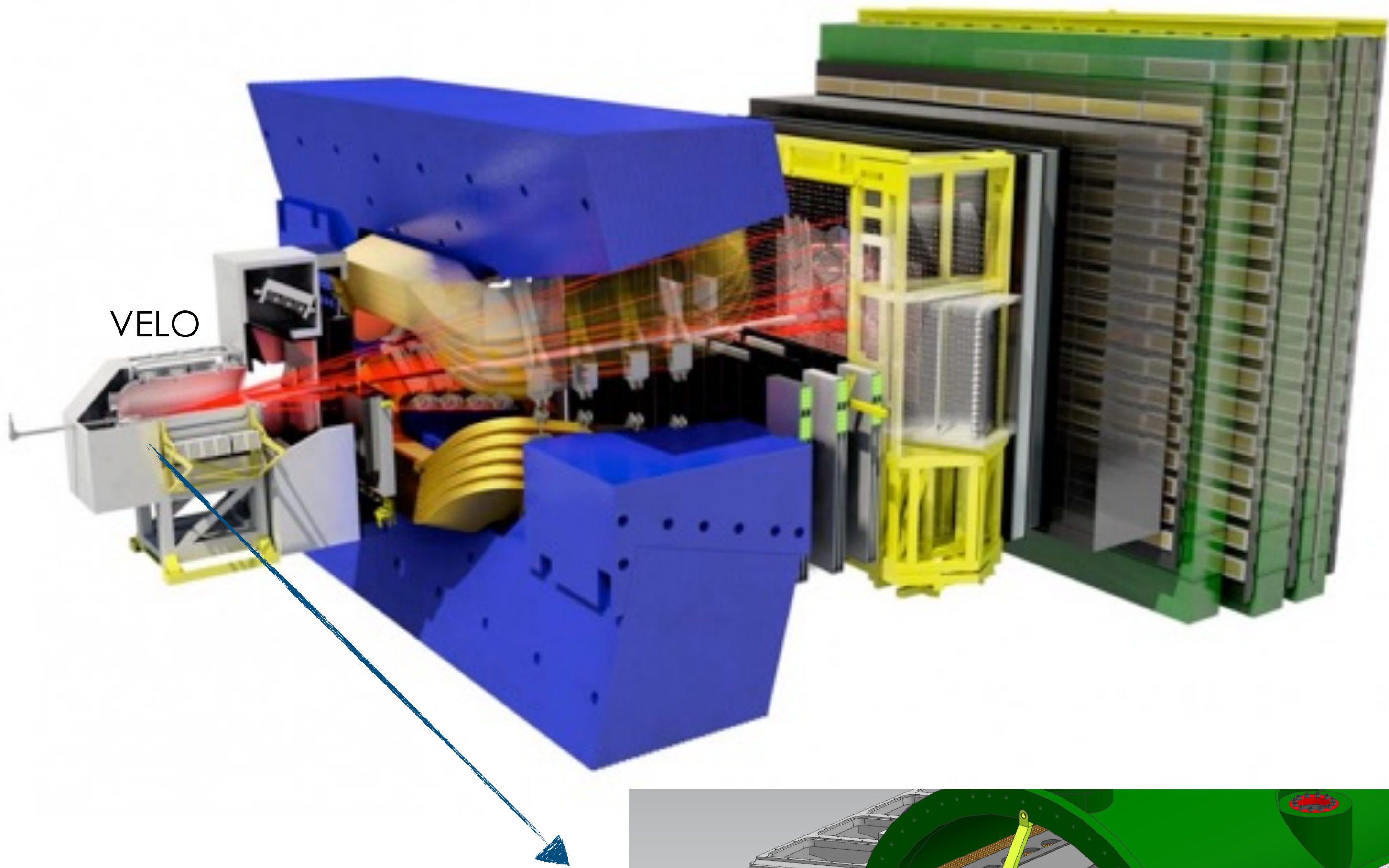


Now!

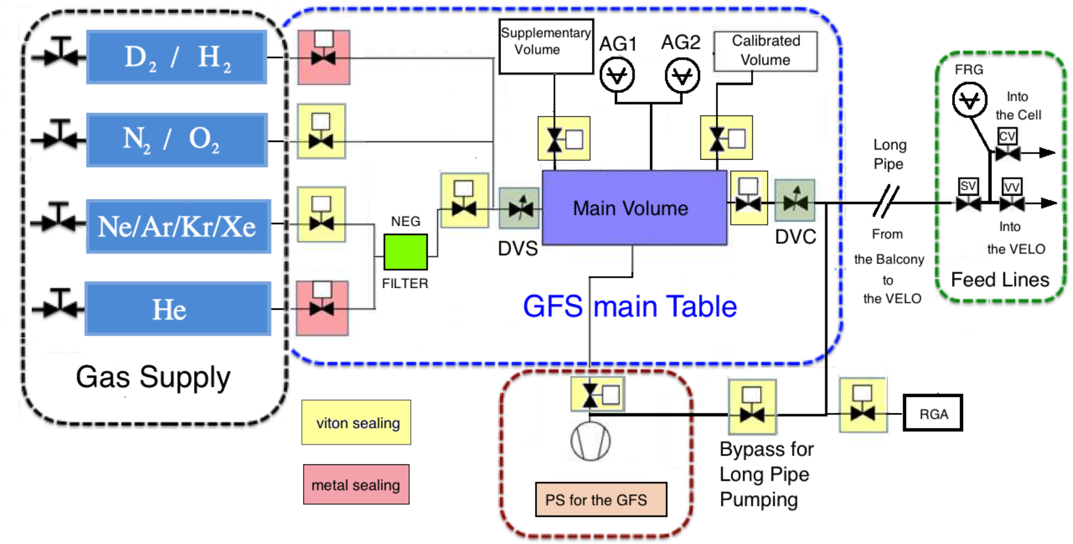
Installation in August 2020
Data taking during LHC Run3 2022-2024

Phase II
transversely polarised H and D target

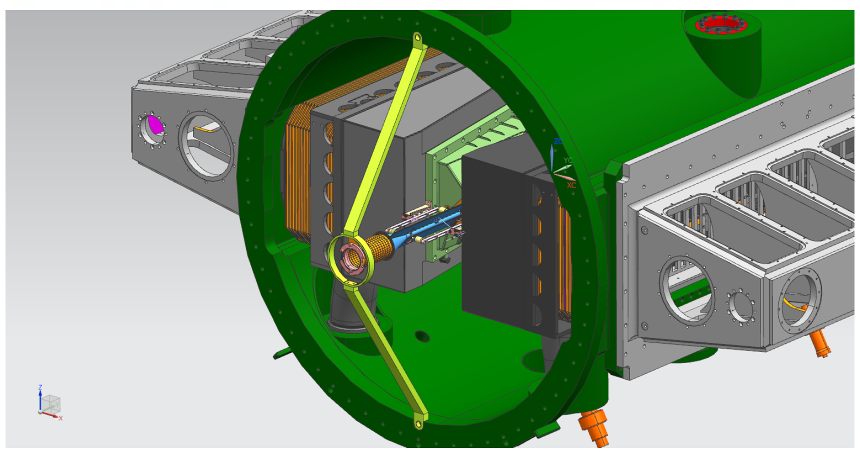
We aim at installing it in the LHC LS3 (2025-…)



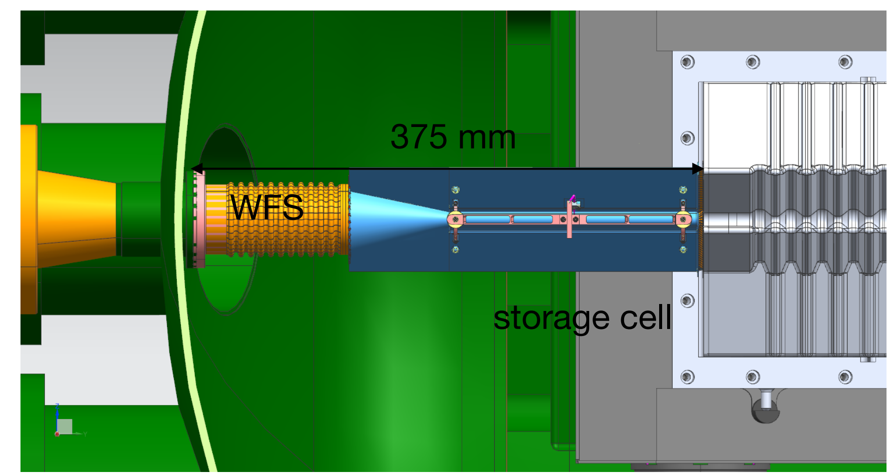
Gas Feed System

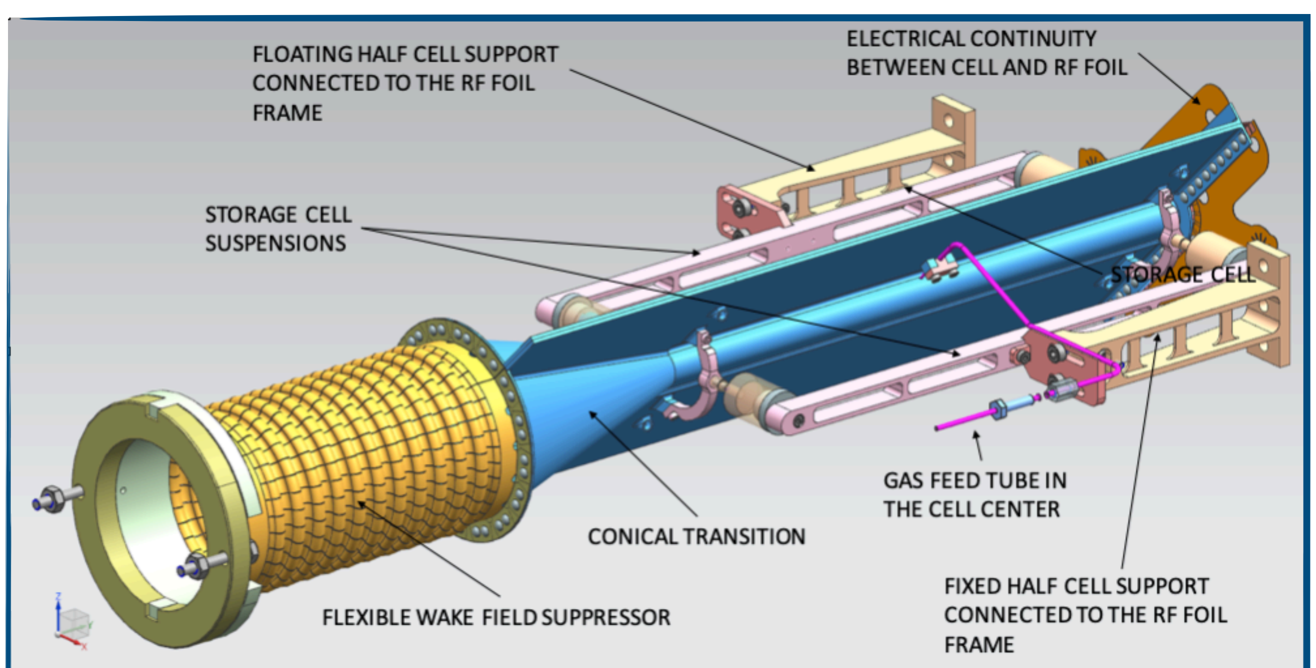


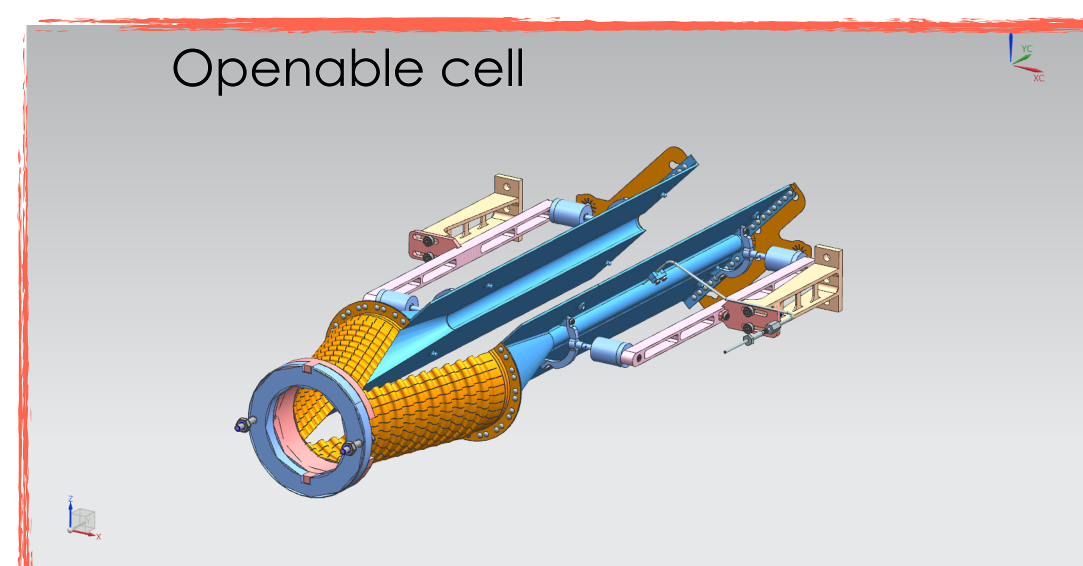
It is the only object into the LHC primary vacuum

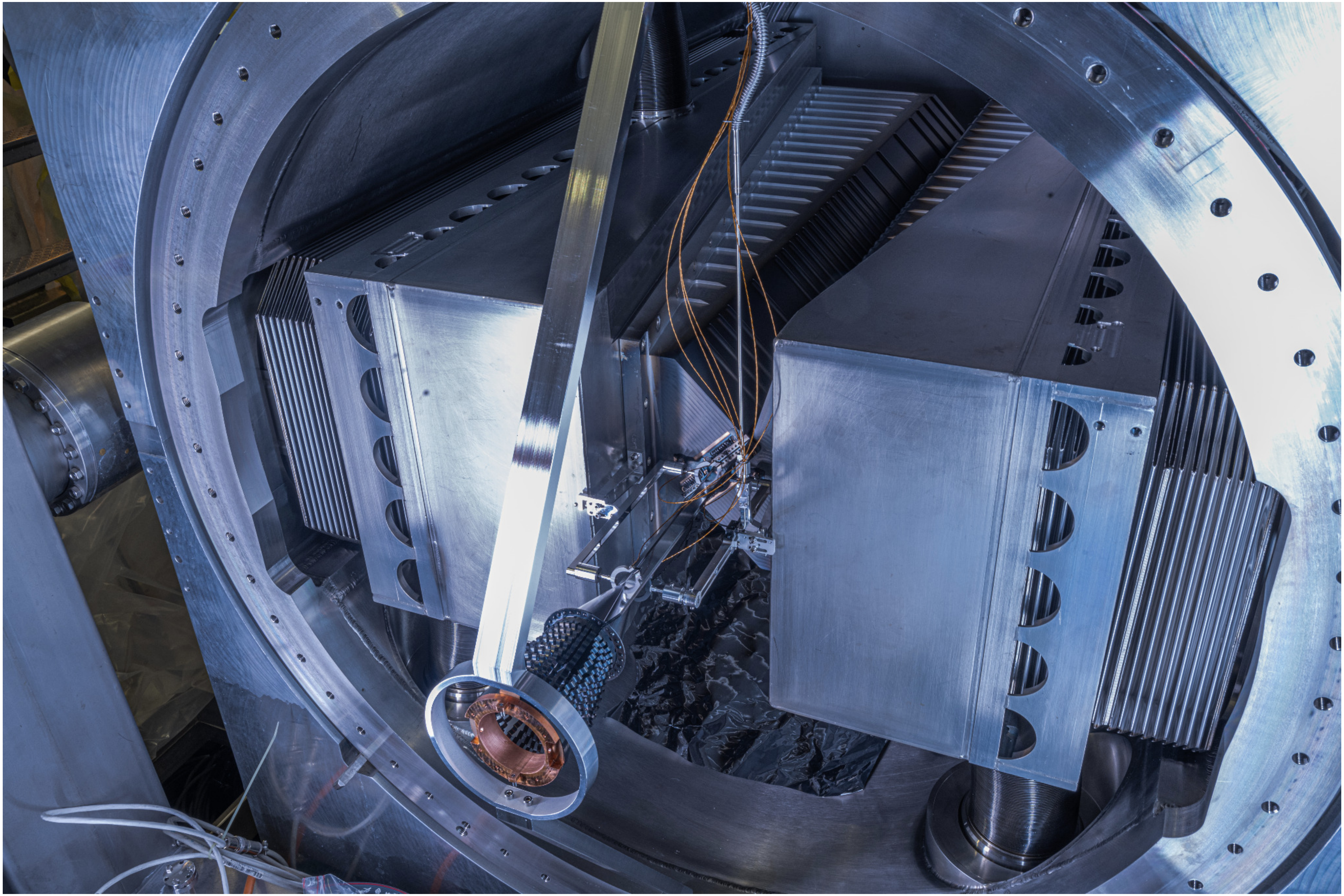


Internal side view





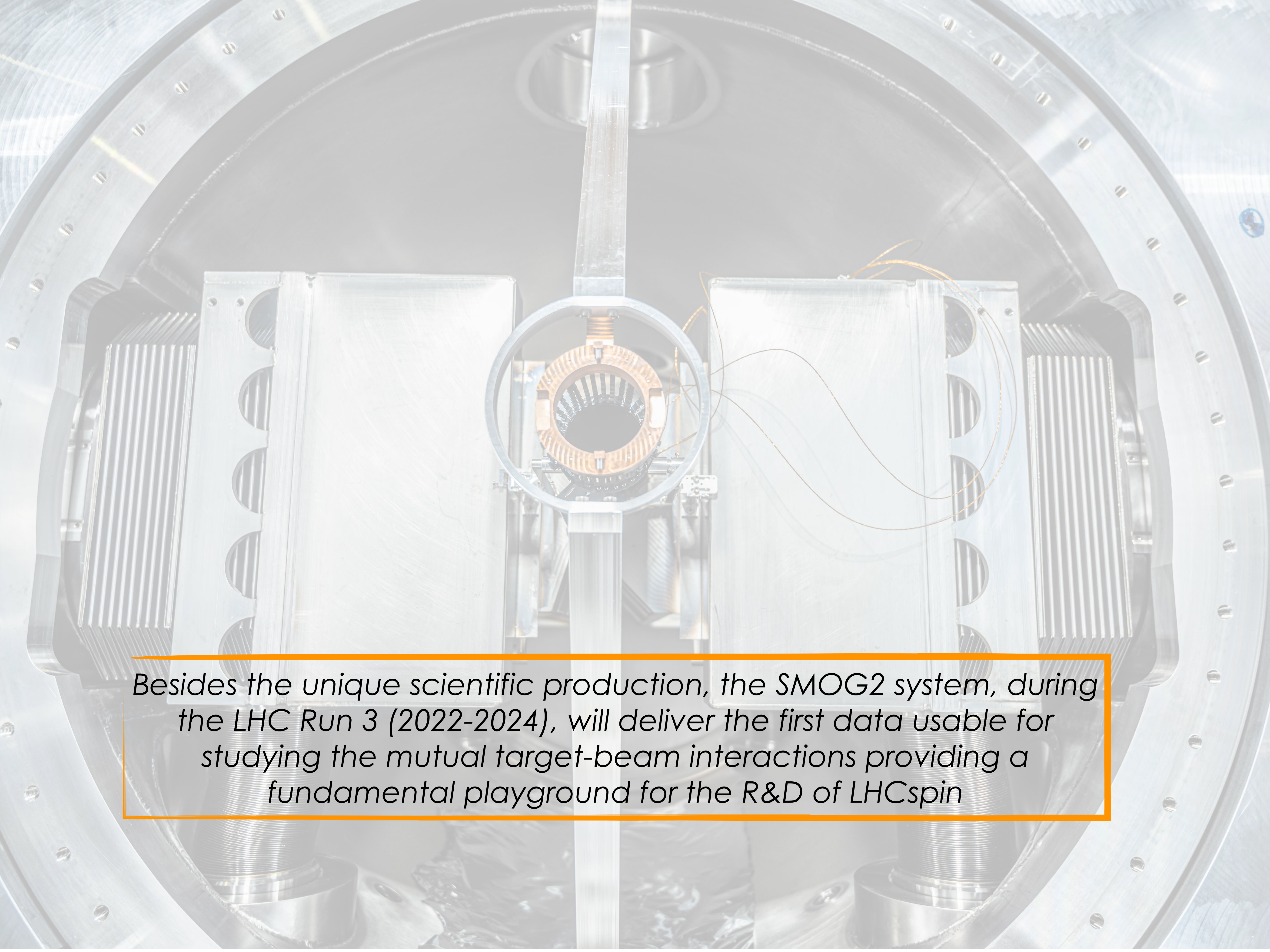




The storage cell … the only object in the LHC primary vacuum

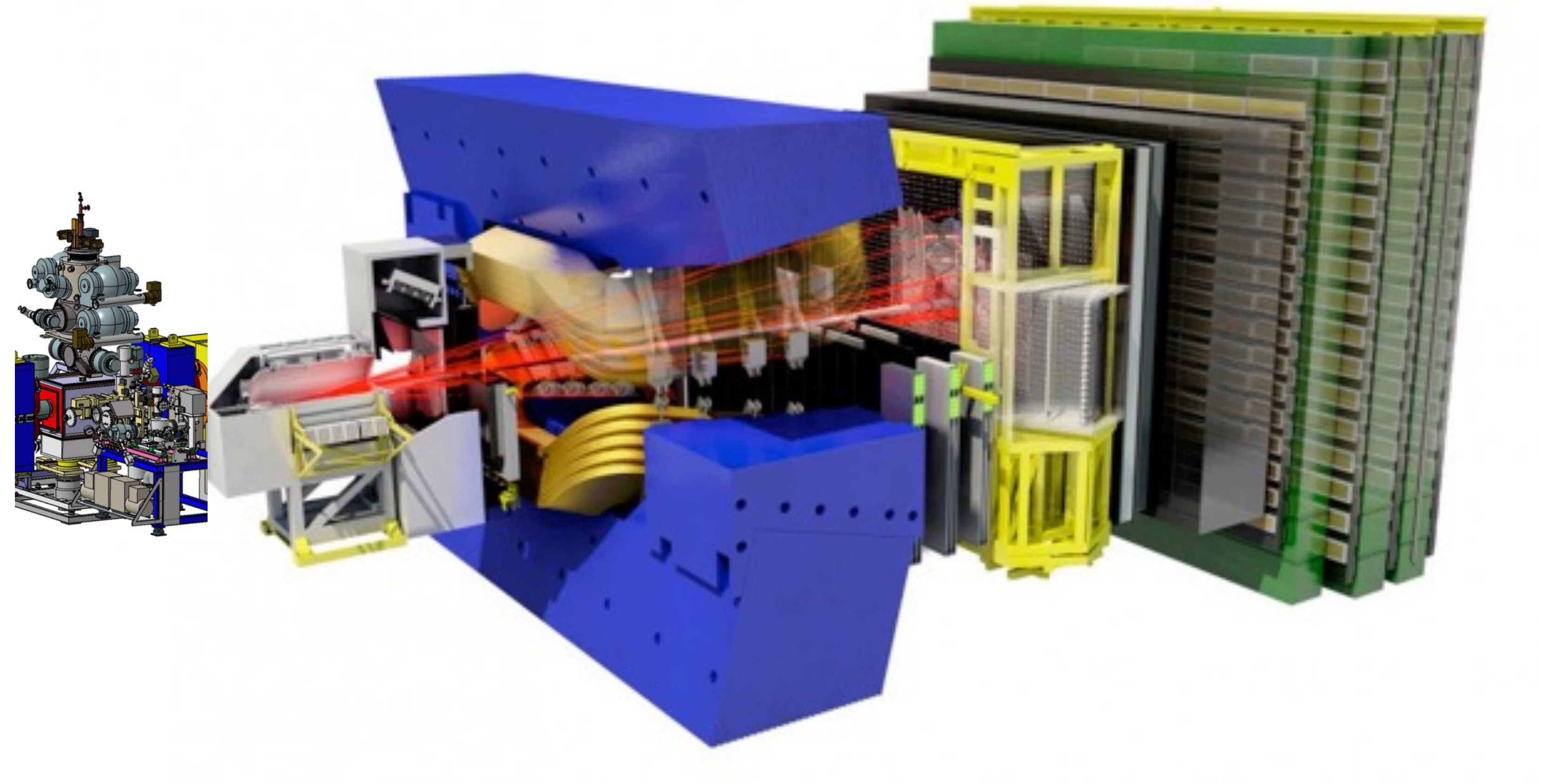
During the installation

The Gas Feed System that will be completed and installed in 2021



Besides the unique scientific production, the SMOG2 system, during the LHC Run 3 (2022-2024), will deliver the first data usable for studying the mutual target-beam interactions providing a fundamental playground for the R&D of LHCspin

LHCspin



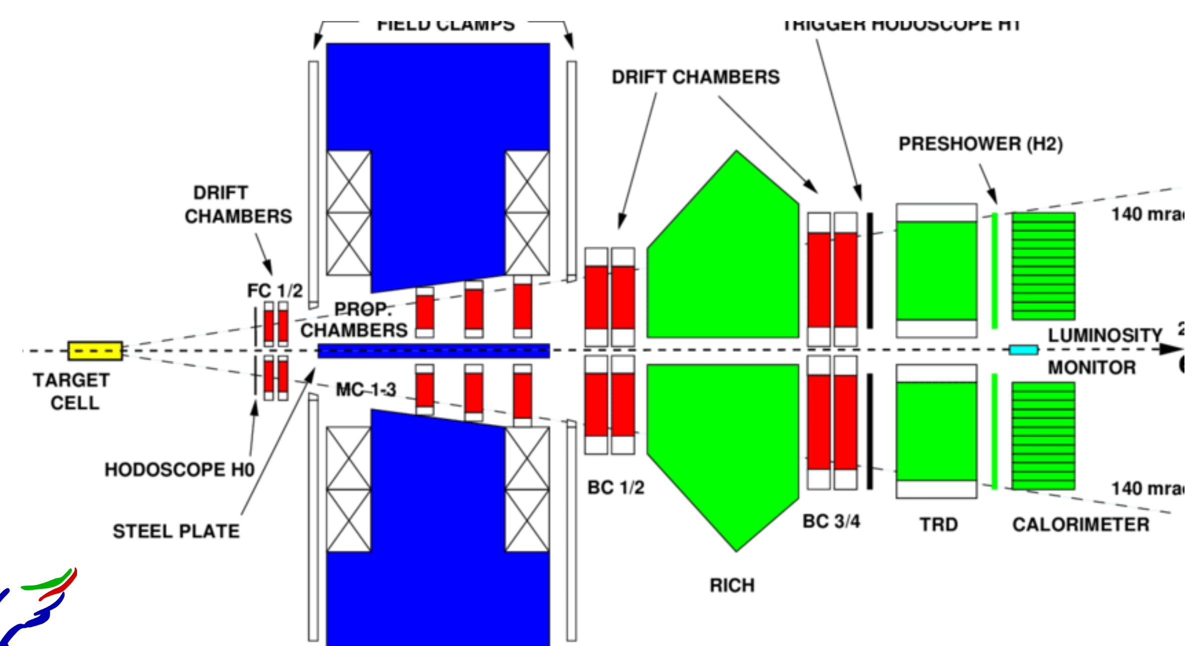
Polarised target

The technique proposed is well consolidated

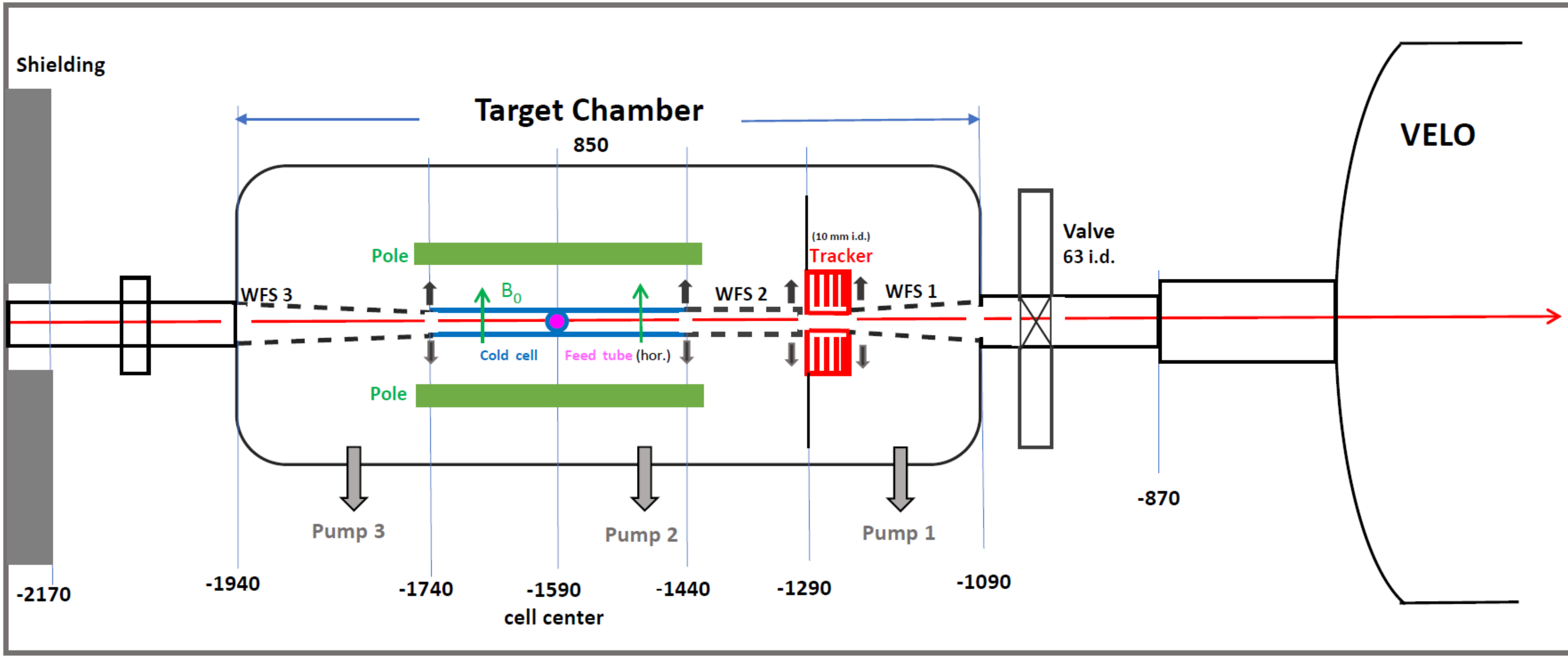
Design follows the successful HERMES Polarised Gas Target which ran at HERA 1996 – 2005, and the follow-up PAX target operational at COSY (FZ Jülich)

However the R&D is complex and needs several innovative developments

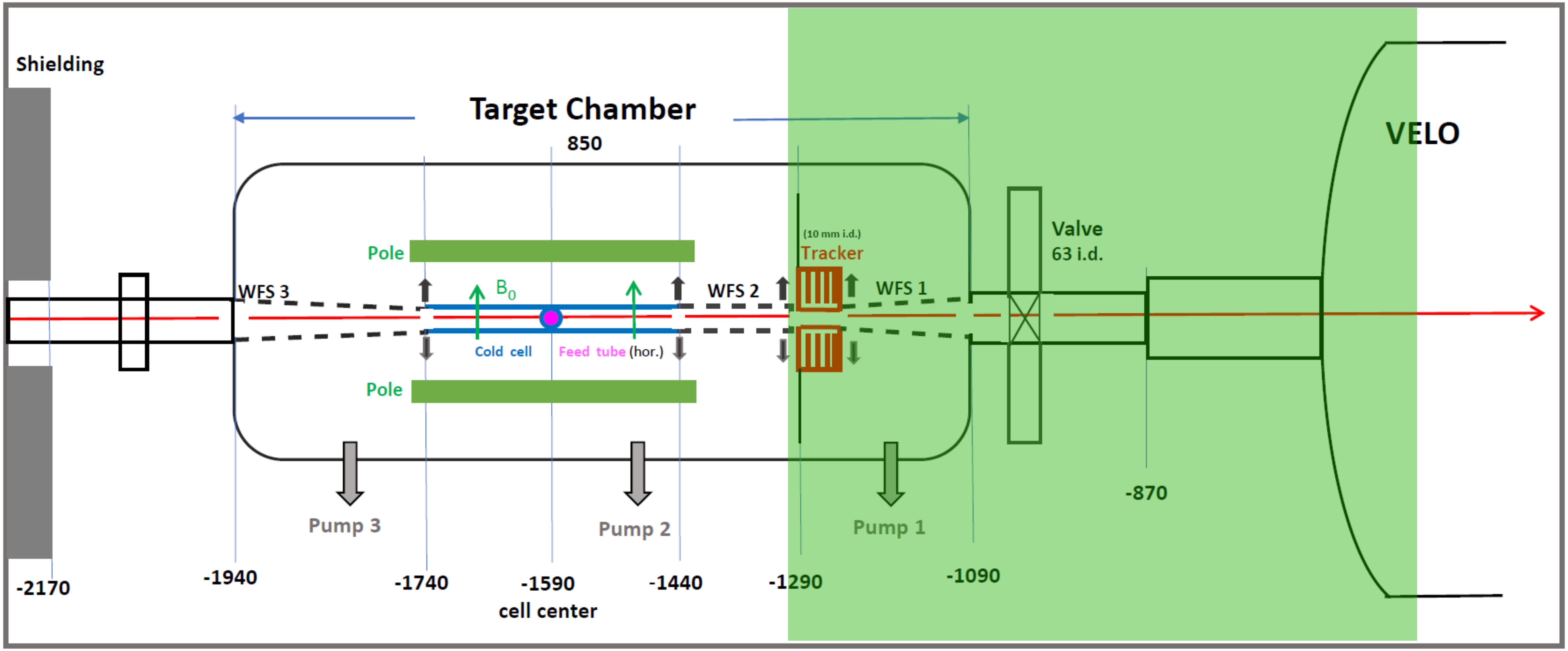
hermes



Polarised Gas Target (PGT) topology – a schematic view

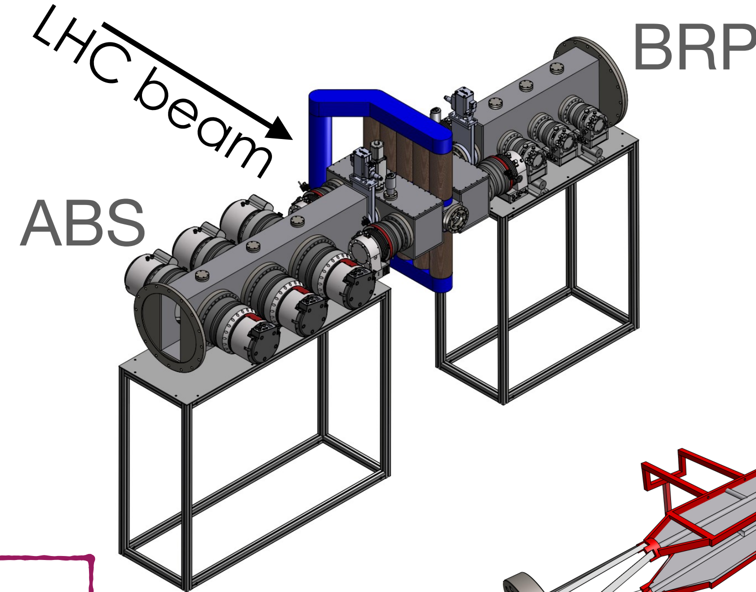


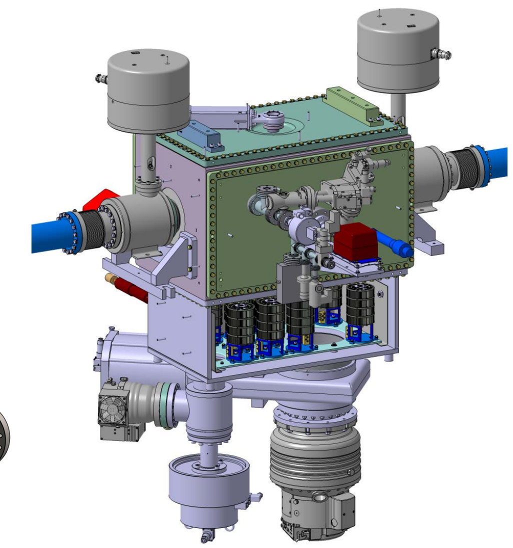
Polarised Gas Target (PGT) topology – a schematic view



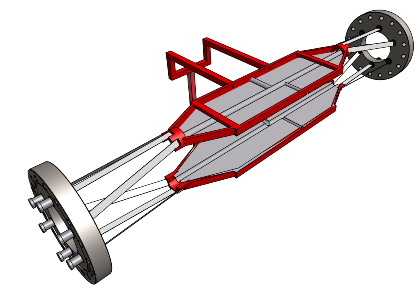
Another option is to cut all this part and put the PGT closer to the VELO tracker

PGT: R&D schematic status

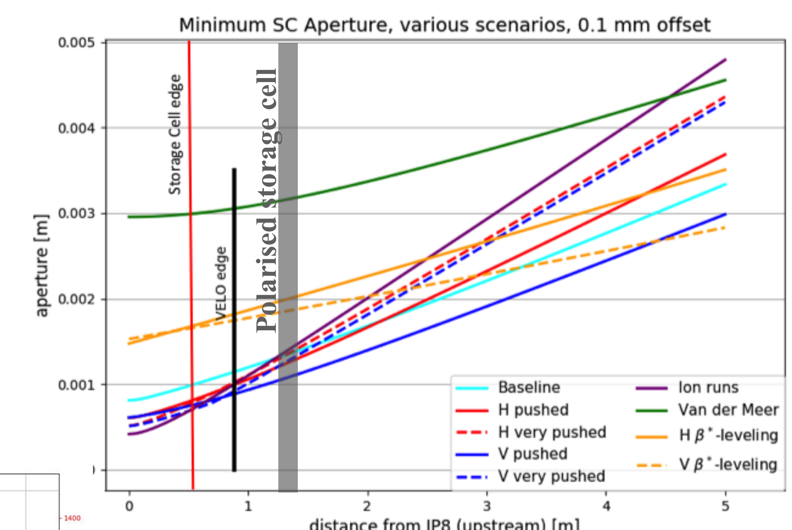




- Storage cell drawing: ADVANCED
- Aperture studies: FINALIZED

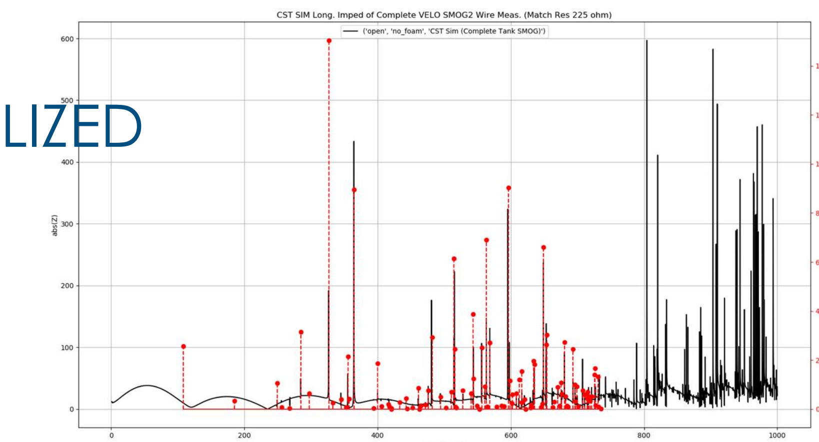


At HL-LHC-25ns, LHCspin can reach $L=8.3 \cdot 10^{32}$ cm^{-2}s^{-1}



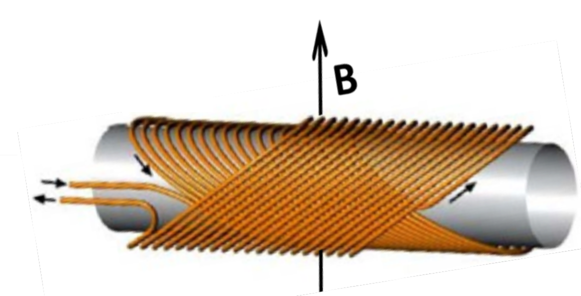
- Electron clouds: FINALIZED
- Coating: IN PROGRESS
- Impedance and beam stability: ADVANCED

Section with cell

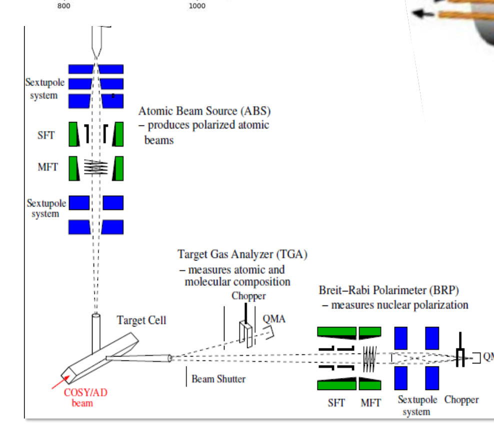


- Beam Induced Depolarization: FINALIZED
- Transverse Magnet: IN PROGRESS

Canted cosine theta



- Compact ABS+BRP: IN PROGRESS
- Additional tracker: TO BE STARTED



At the moment common efforts on the R&D from CERN, INFN-Frascati, Ferrara, Erlangen, Julich, PNPI

Conclusions

- A lively and fast-growing fixed-target program is being developed at LHCb, exploiting the unique kinematic conditions provided by a TeV-scale beam and a fully instrumented forward spectrometer
- The installation of the first storage cell target for unpolarized gases happened in August 2020. The PGT could come few years later.

Conclusions

- A lively and fast-growing fixed-target program is being developed at LHCb, exploiting the unique kinematic conditions provided by a TeV-scale beam and a fully instrumented forward spectrometer
- The installation of the first storage cell target for unpolarized gases happened in August 2020. The PGT could come few years later.

Fixed target collisions at the LHC represent a unique possibility for *a laboratory for QCD and astroparticle* in unexplored kinematic regions … in a realistic time schedule