The LHC spin project

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LHCb

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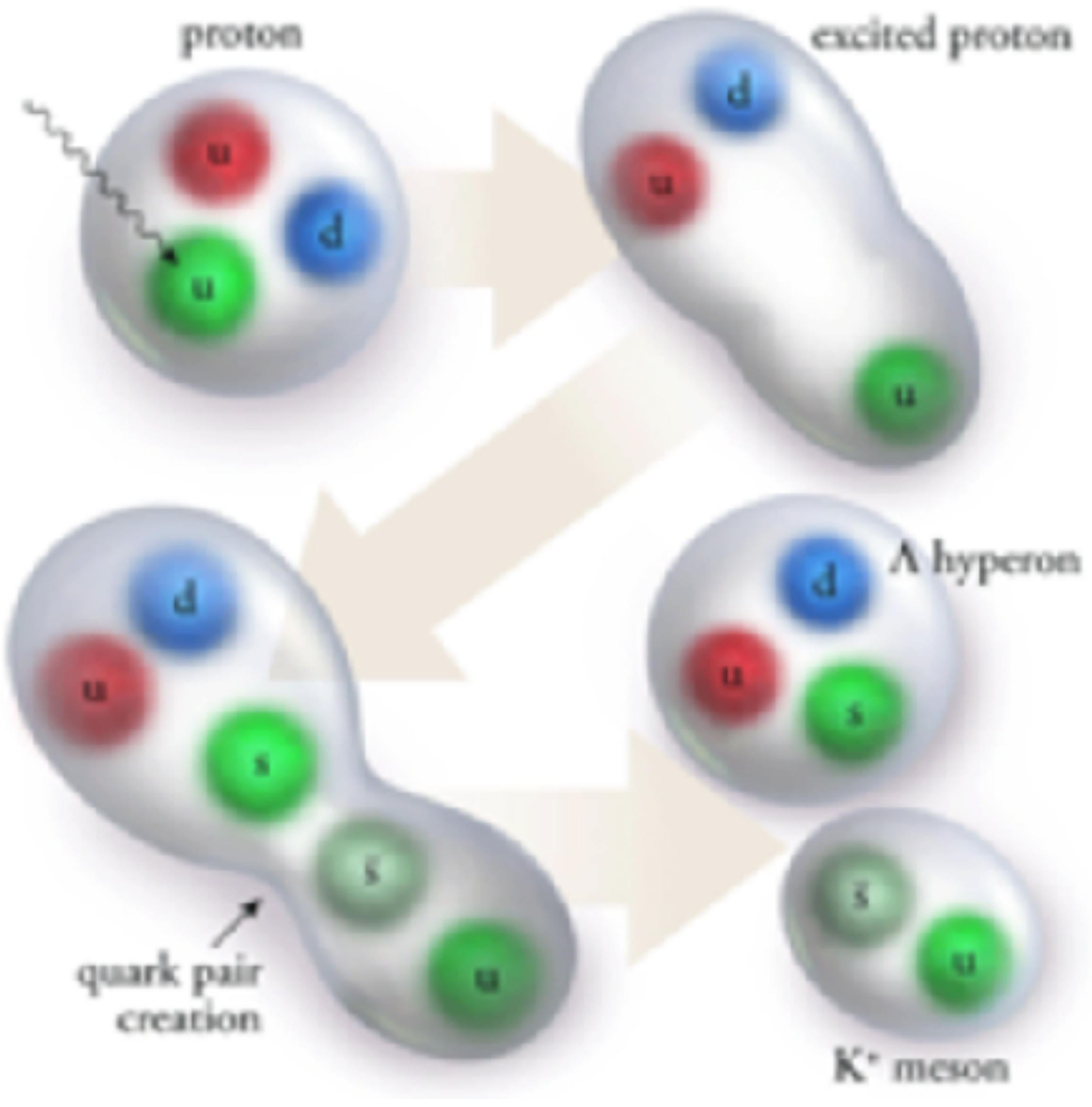
LPHE, 16/05/22

QCD

Quantum Chromodynamics is the theory of strong nuclear interactions. A fundamental field theory in hand since the early 1970s, but quarks and gluons (degrees of freedom in the theory) cannot be observed directly in experiments (color confinement)

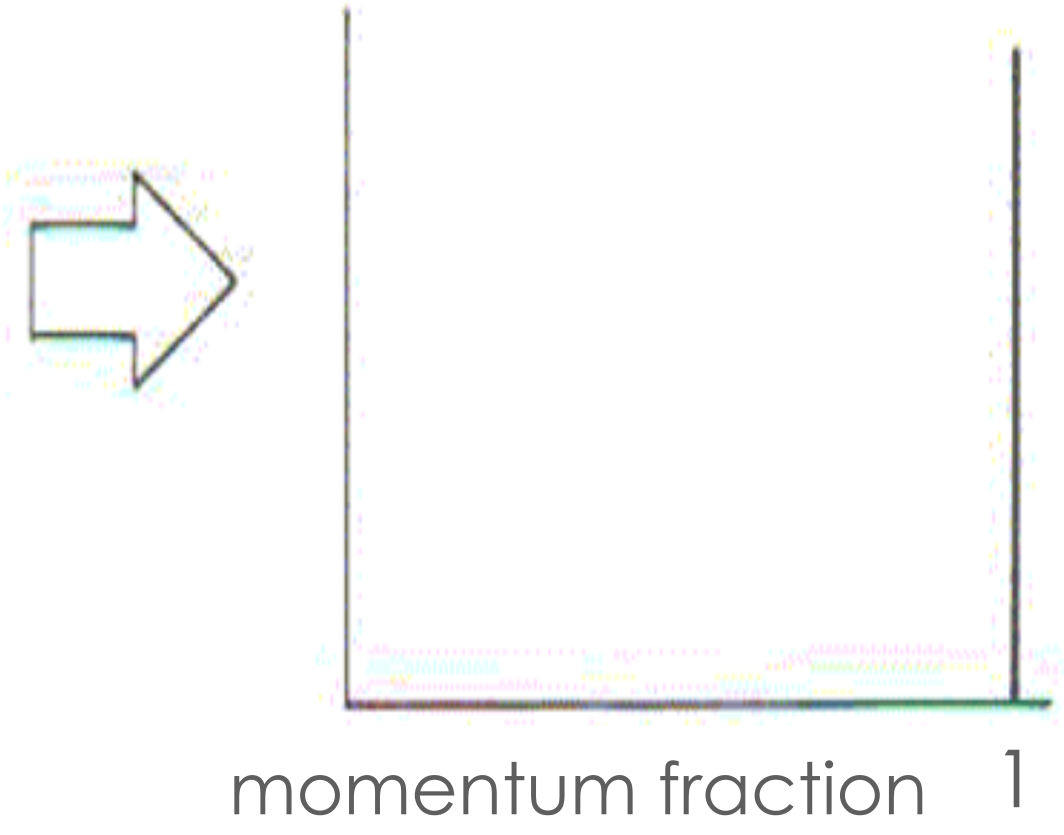
To study and understand fundamental aspects of QCD in terms of degrees of freedom we can start from the simplest stable QCD bound state: **the proton**



Unveiling the proton structure by scattering particles

momentum fraction that the scattering particle would carry if the proton were made of …

A point-like particle



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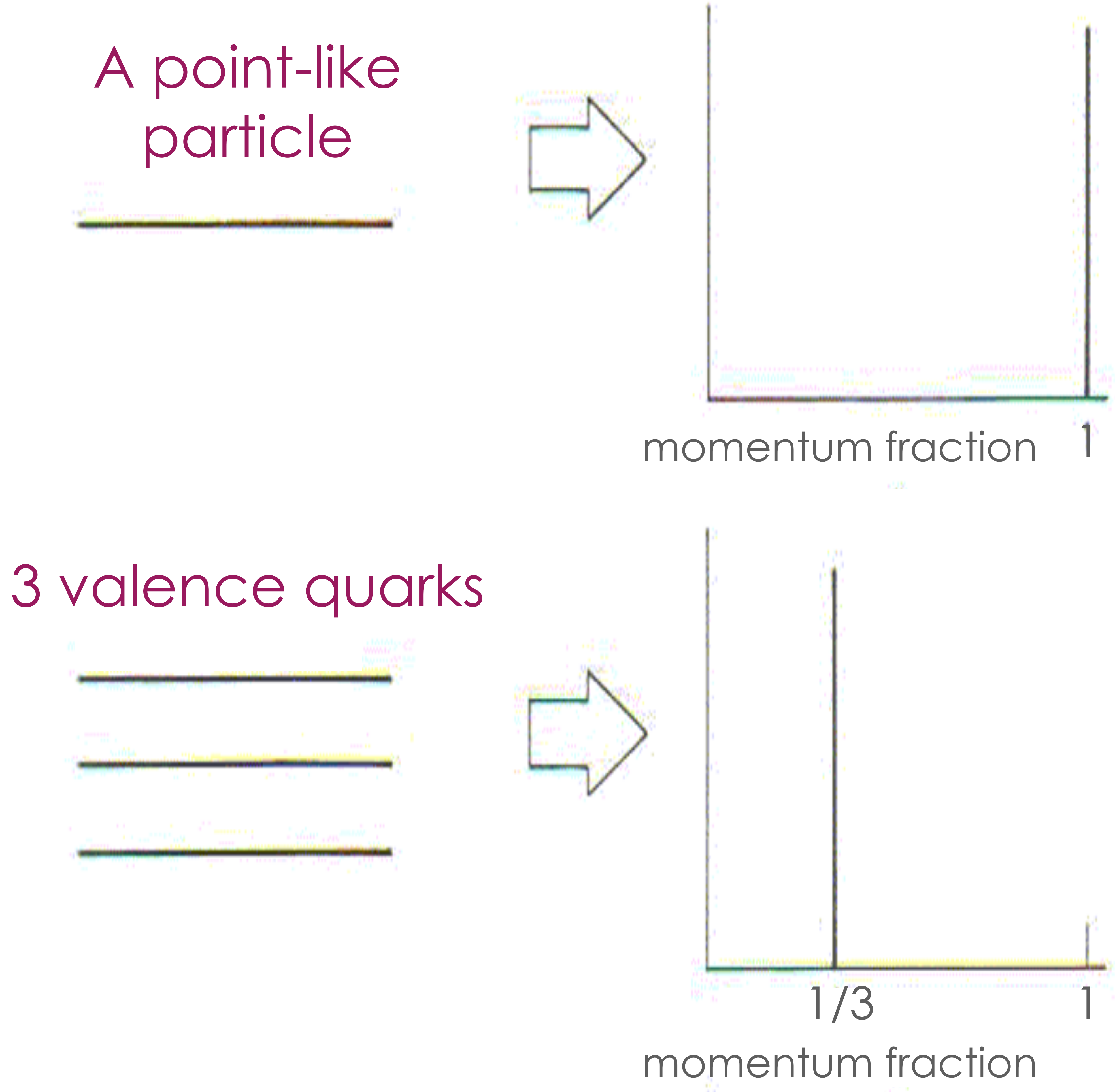

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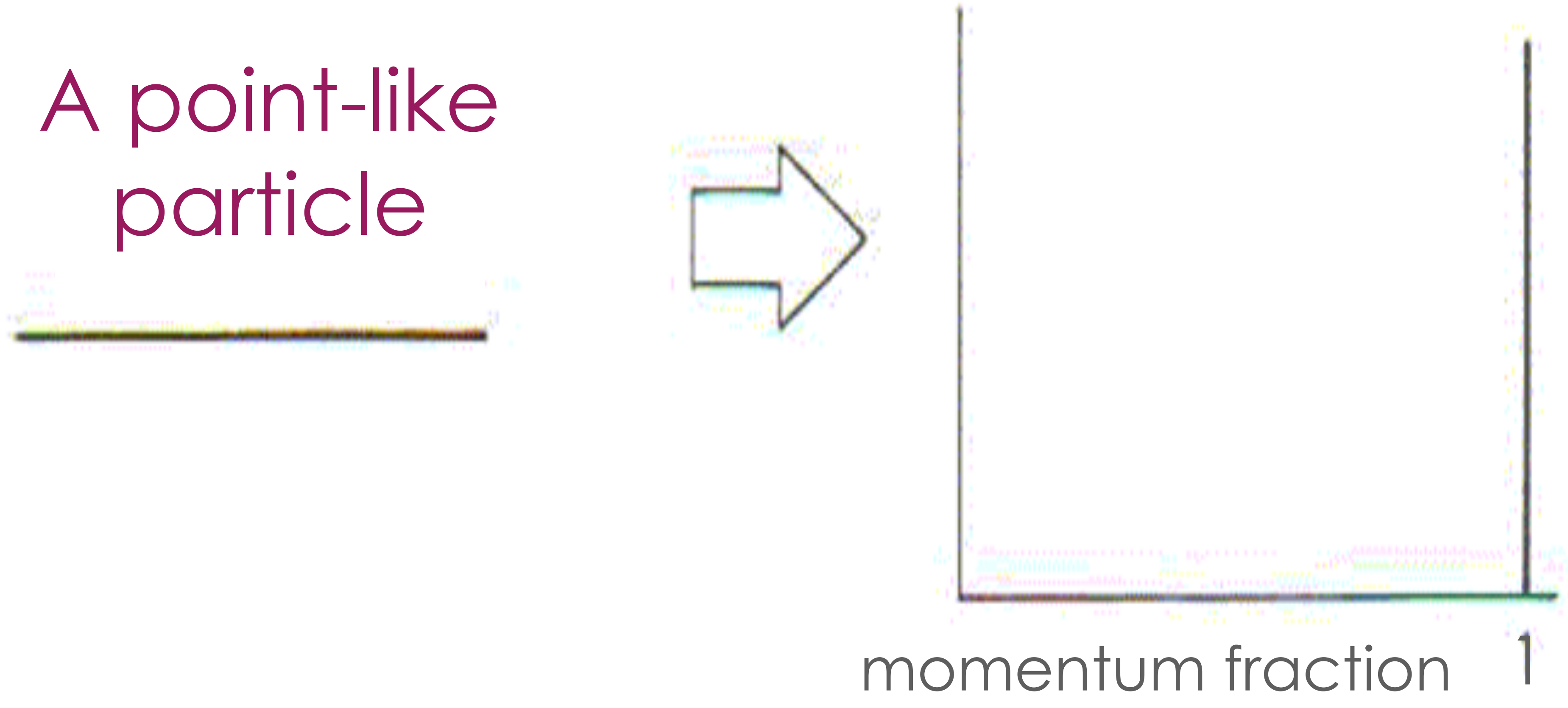
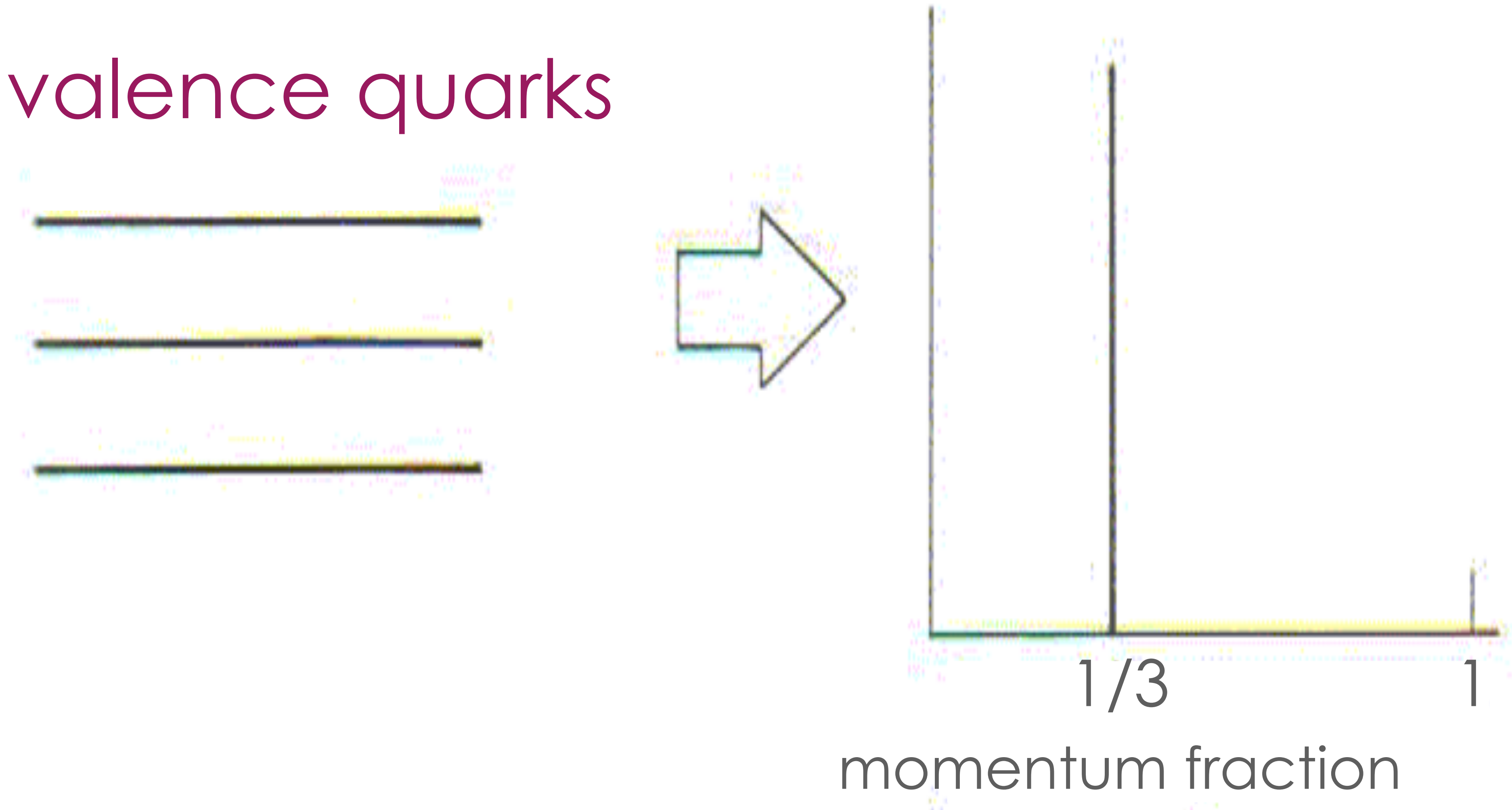
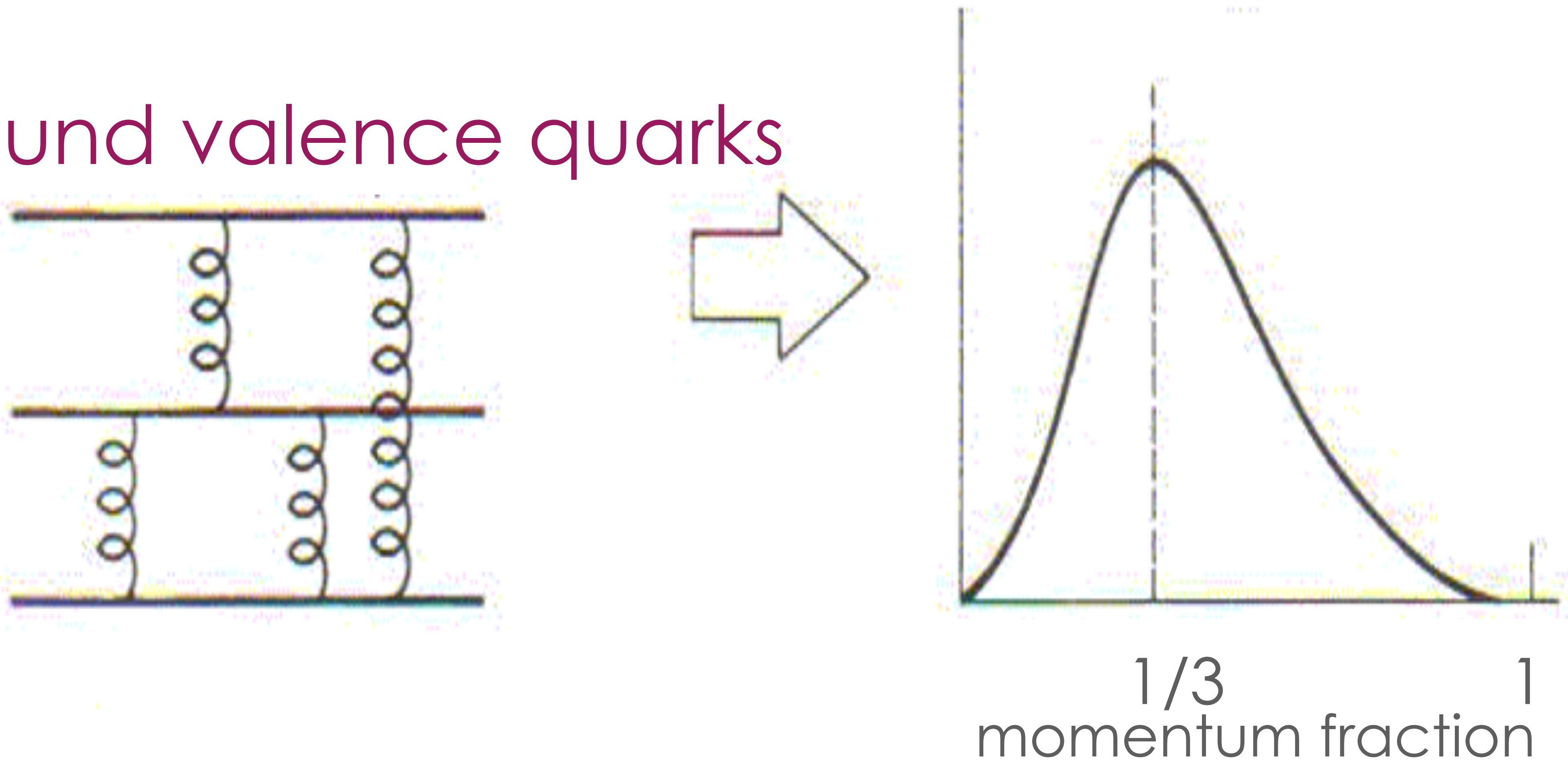


3 valence quarks



3 bound valence quarks



Unveiling the proton structure by scattering particles

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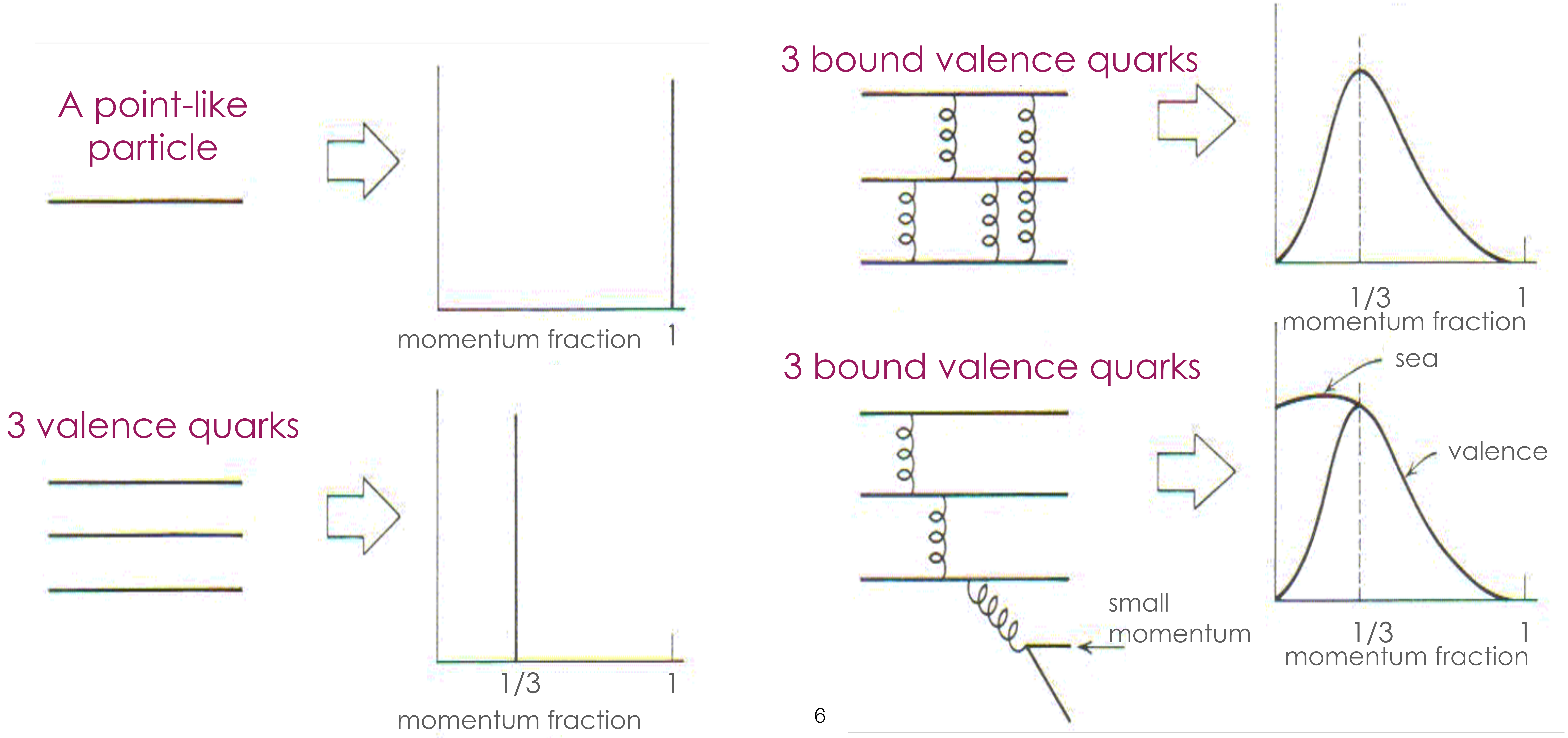
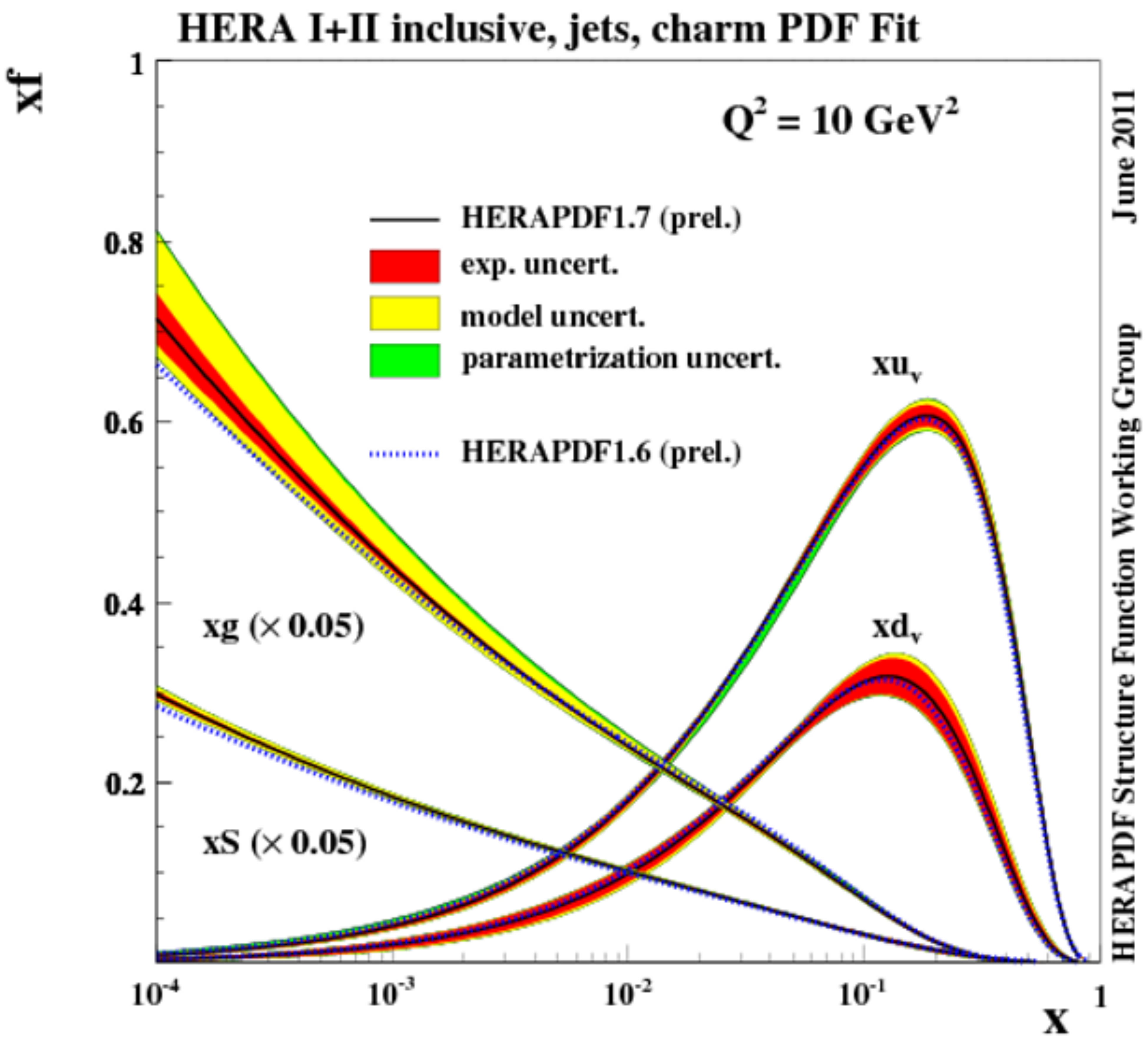
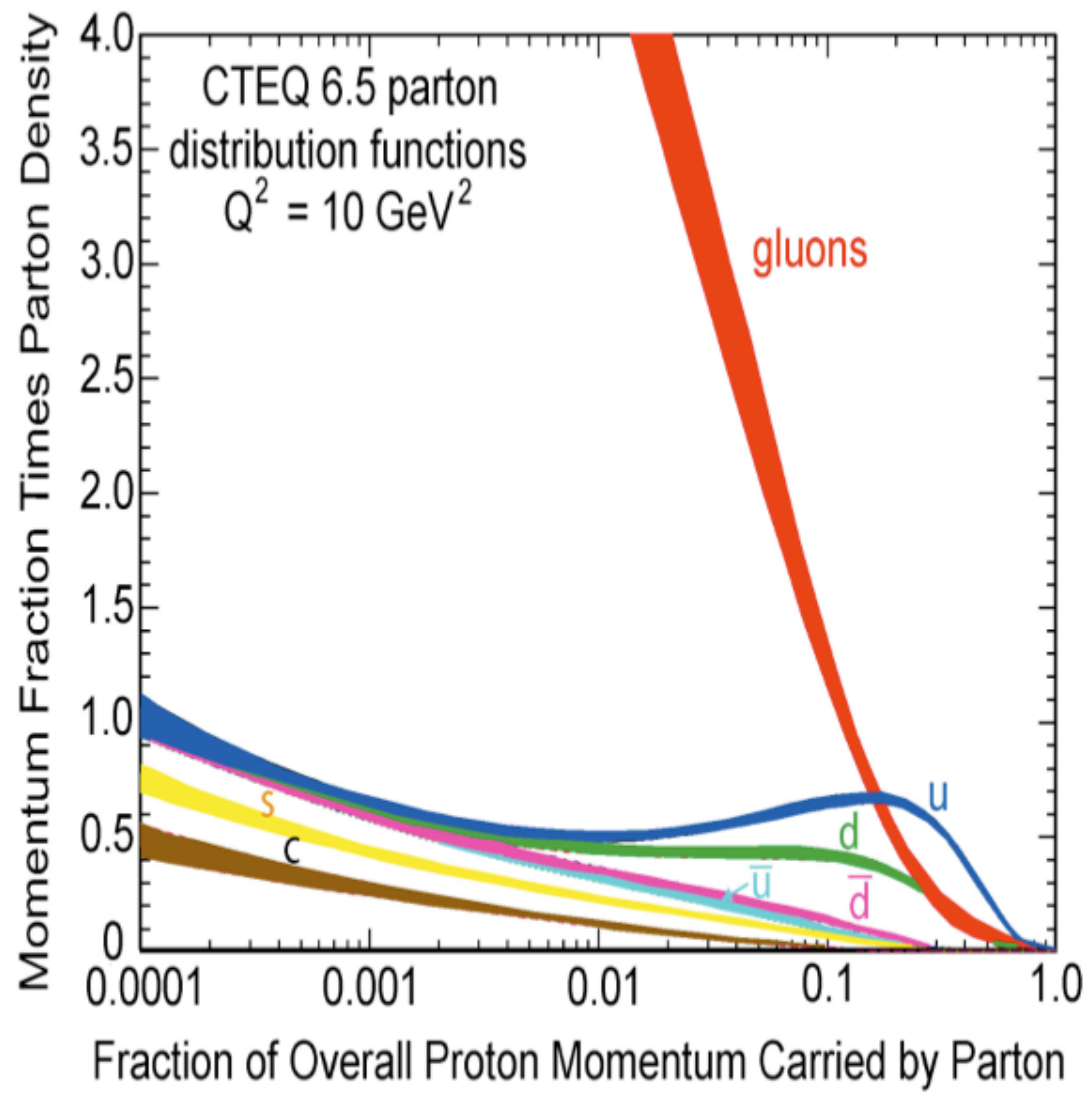


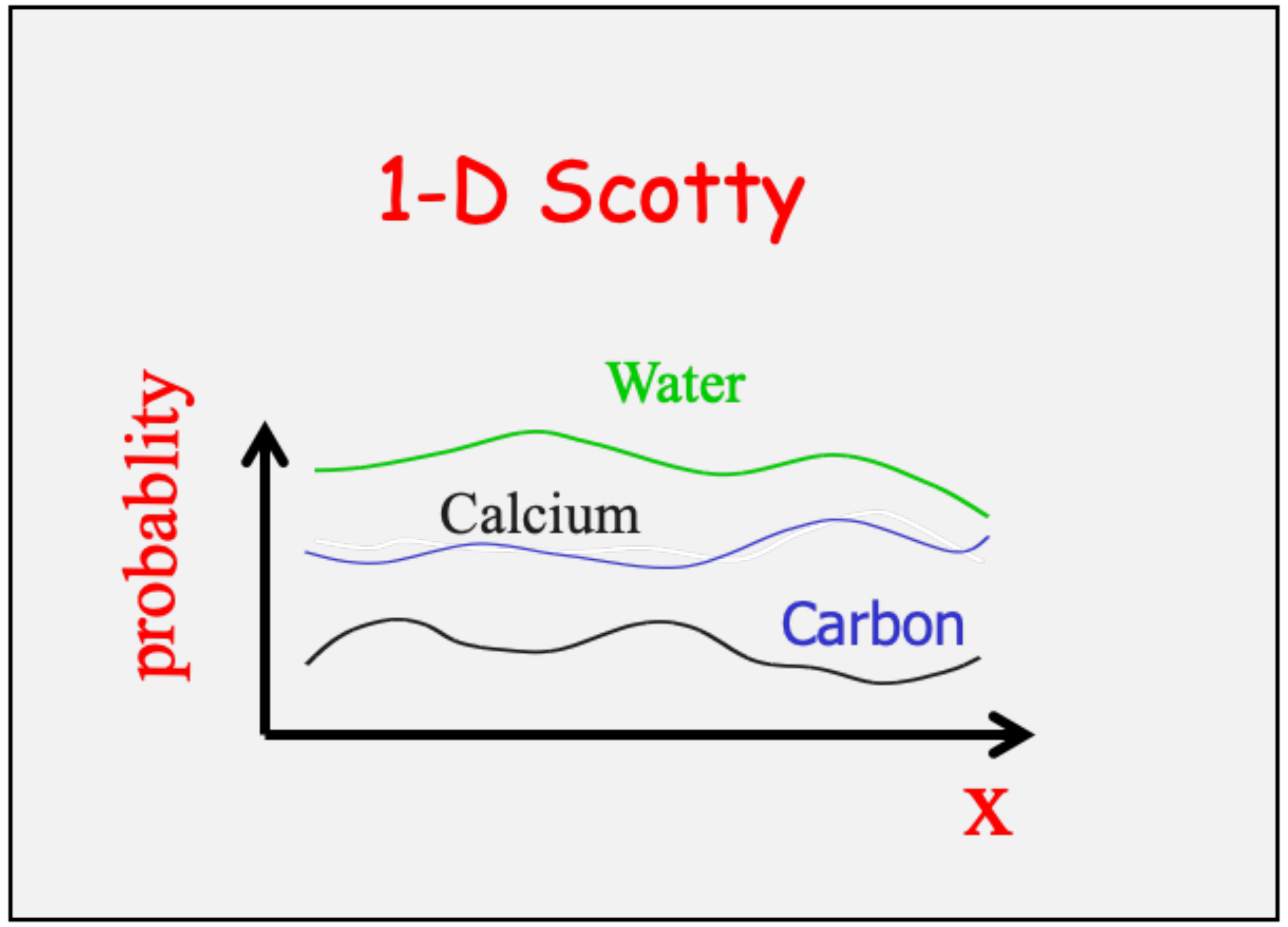
What have we learned in terms of this picture by now?

- Up and down quark “valence” distributions peaked ~1/3
- Lots of sea quark-antiquark pairs and even more gluons!





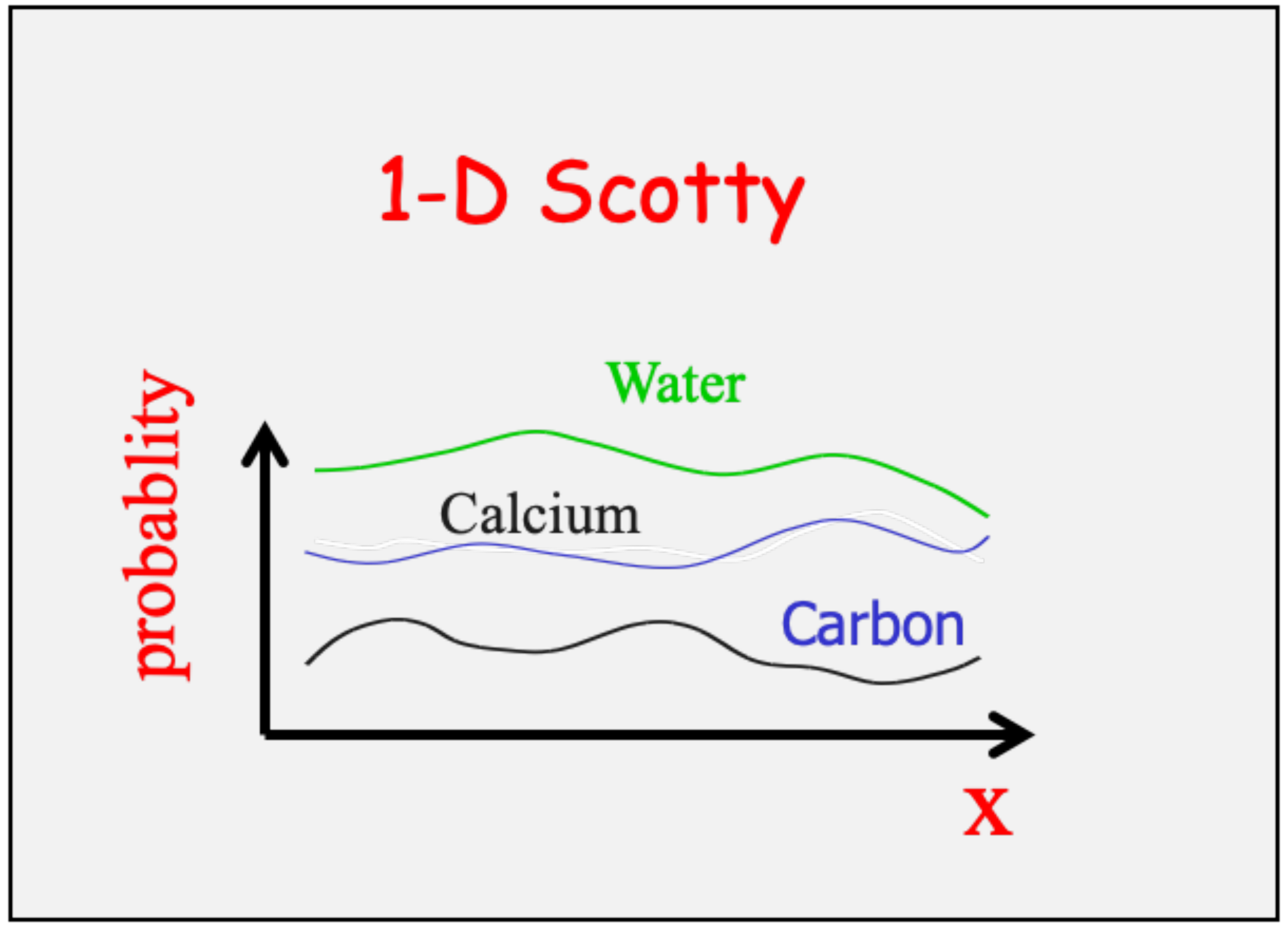
It is only a 1-dimensional description

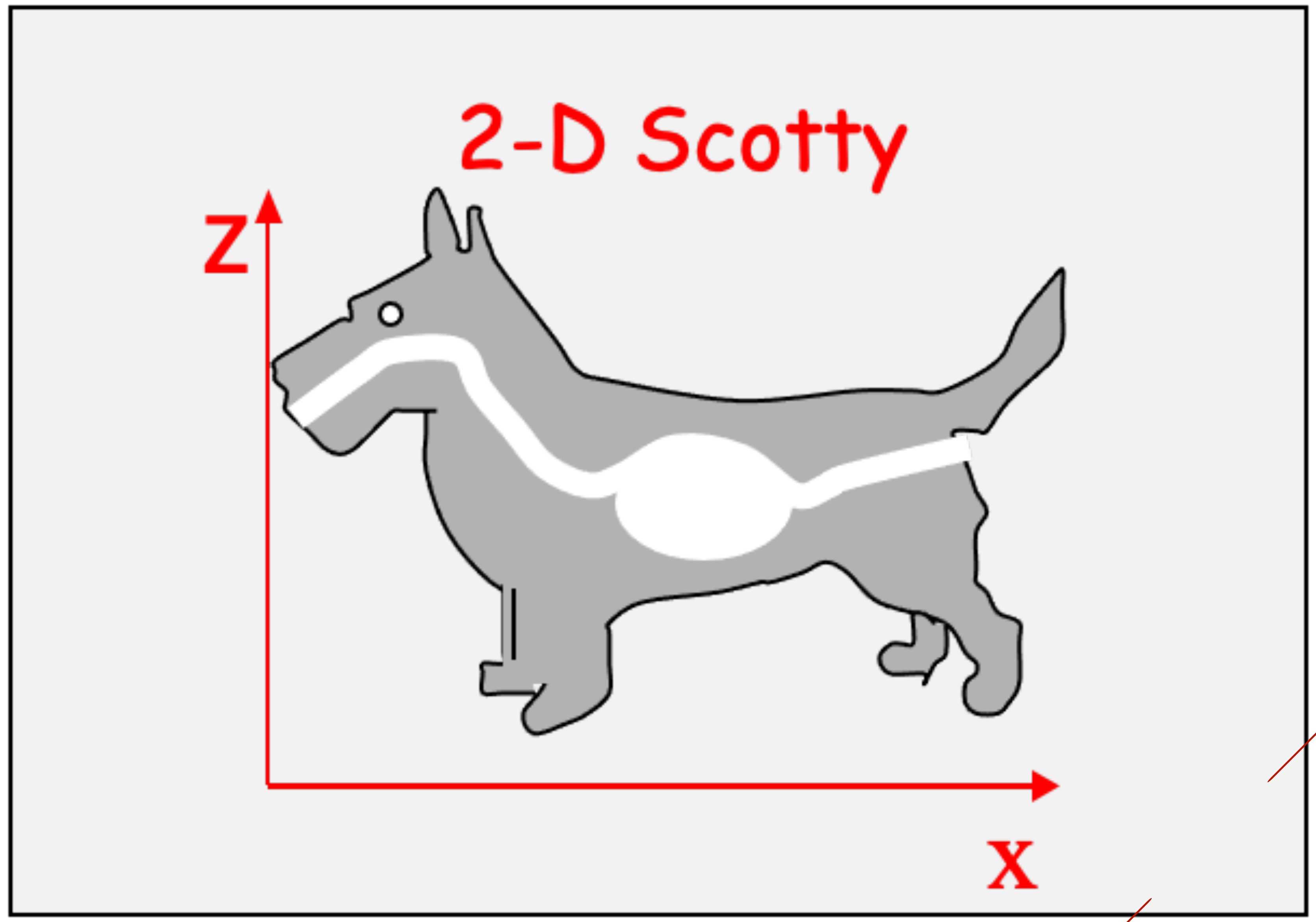


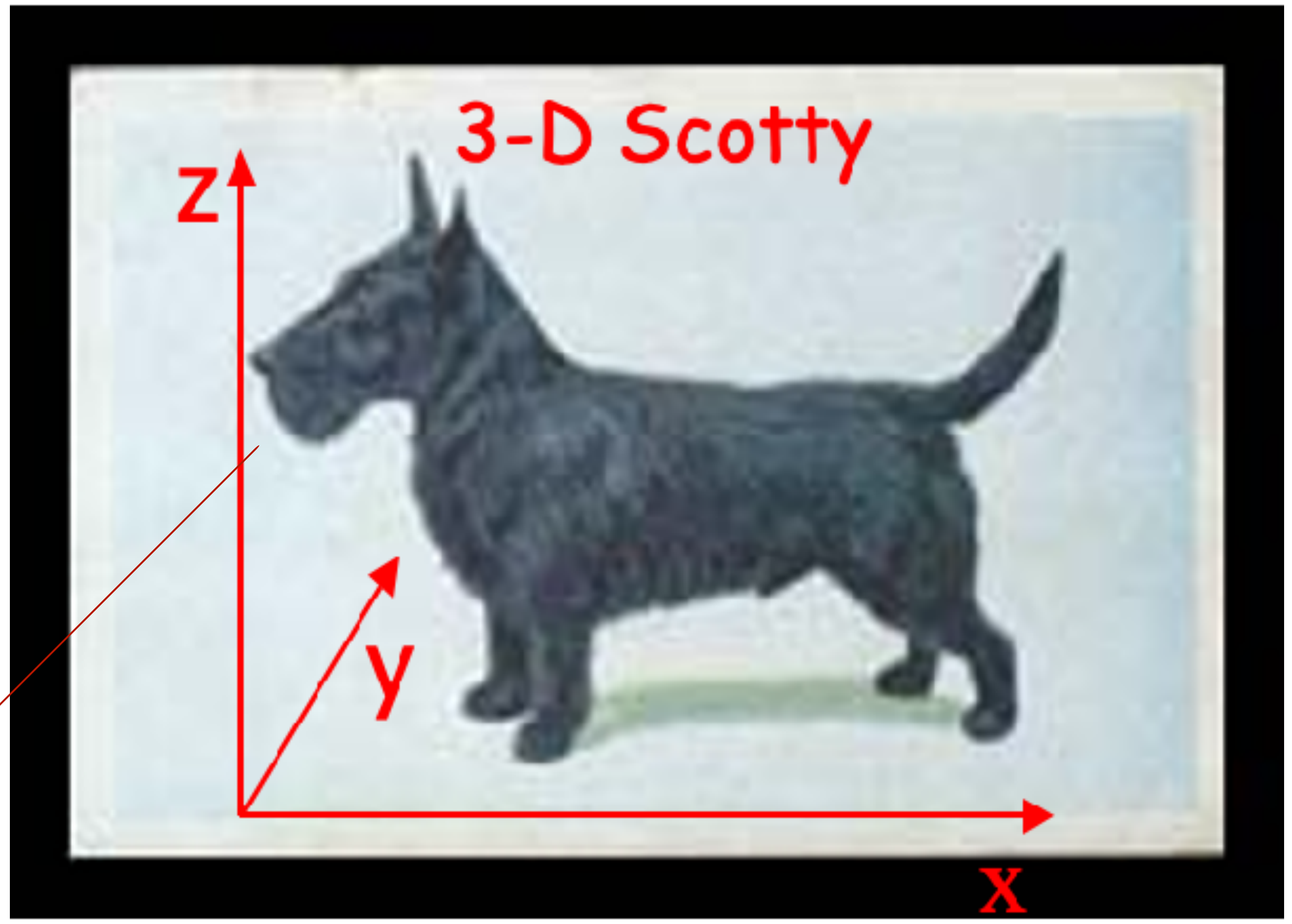
knowledge at Parton Distribution Function (PDF) level

What/who is Scotty?

It is only a 1-dimensional description







knowledge at Parton Distribution Function (PDF) level

knowledge introducing spin-spin and spin-momentum dependent PDFs

What/who is Scotty?

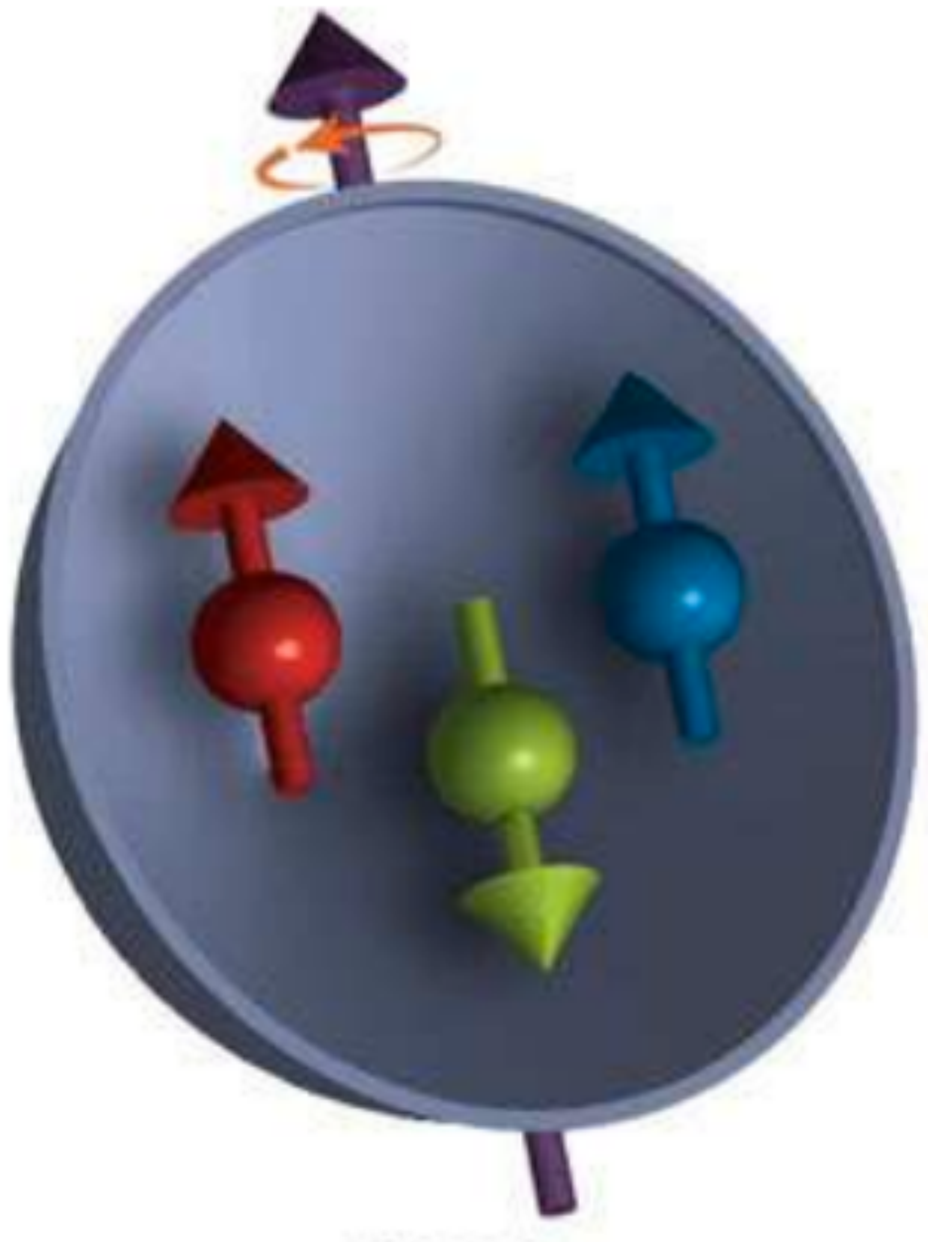
You believe you understood something

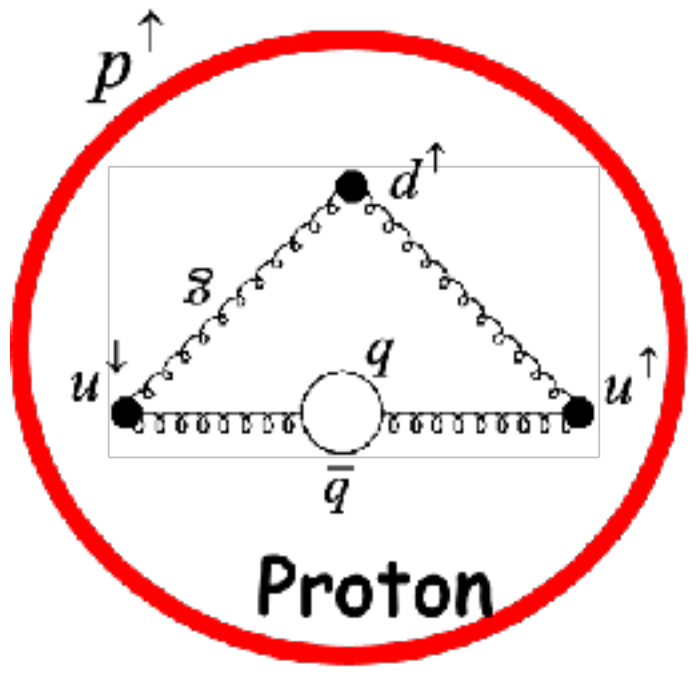
… now let’s add the spin

R.Jaffe

How much do we know about (proton) spin?

$$\frac{1}{2}\hbar =$$





A proton has a total spin +1/2 along some axis.
Most naively, you would expect it to contain two quarks with spin +1/2 and one with spin -1/2.
1/2 + 1/2 - 1/2 = +1/2

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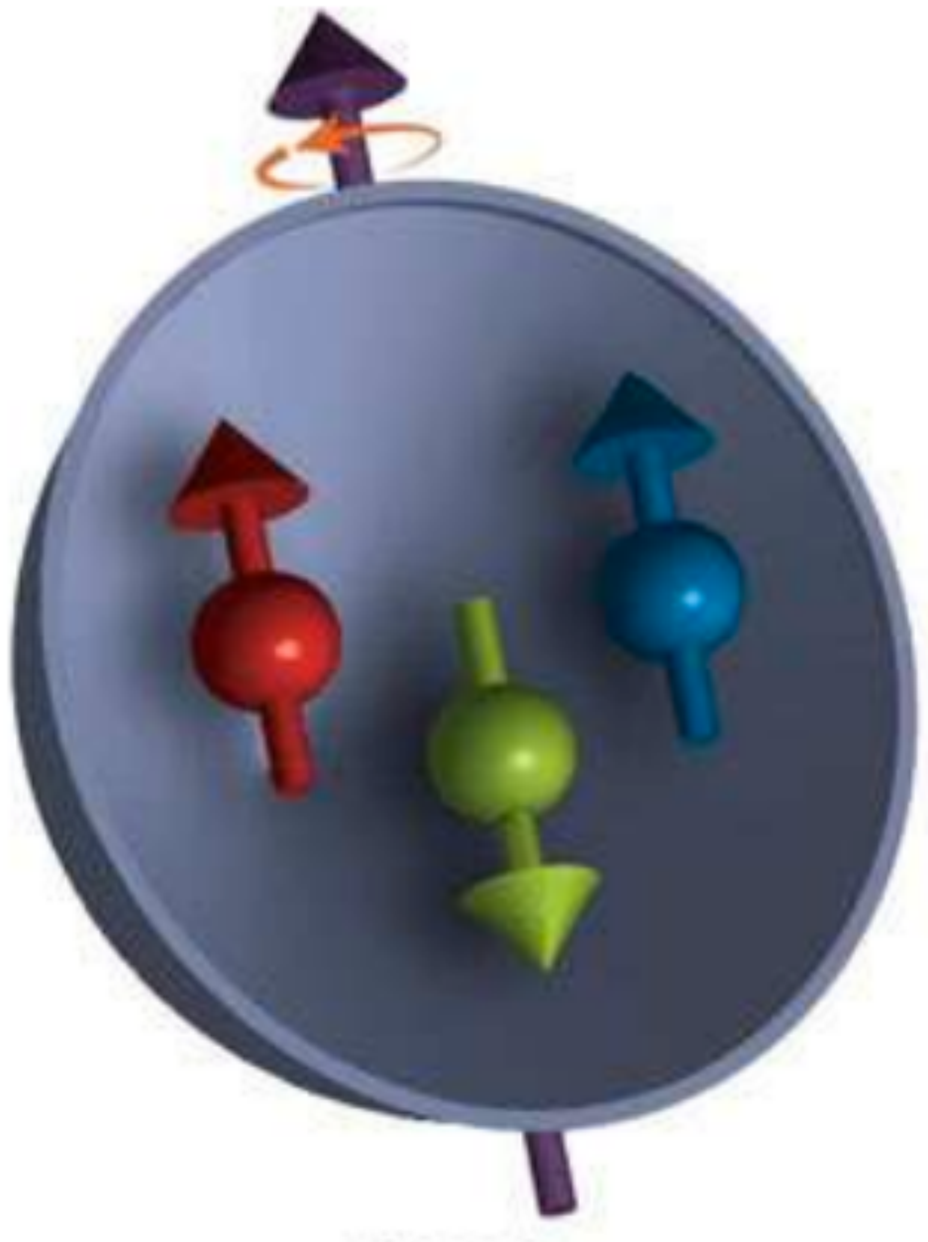

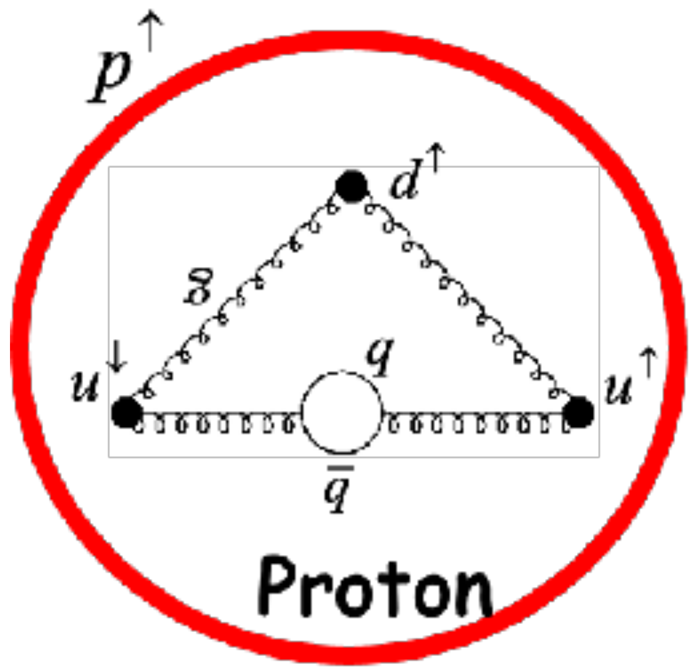

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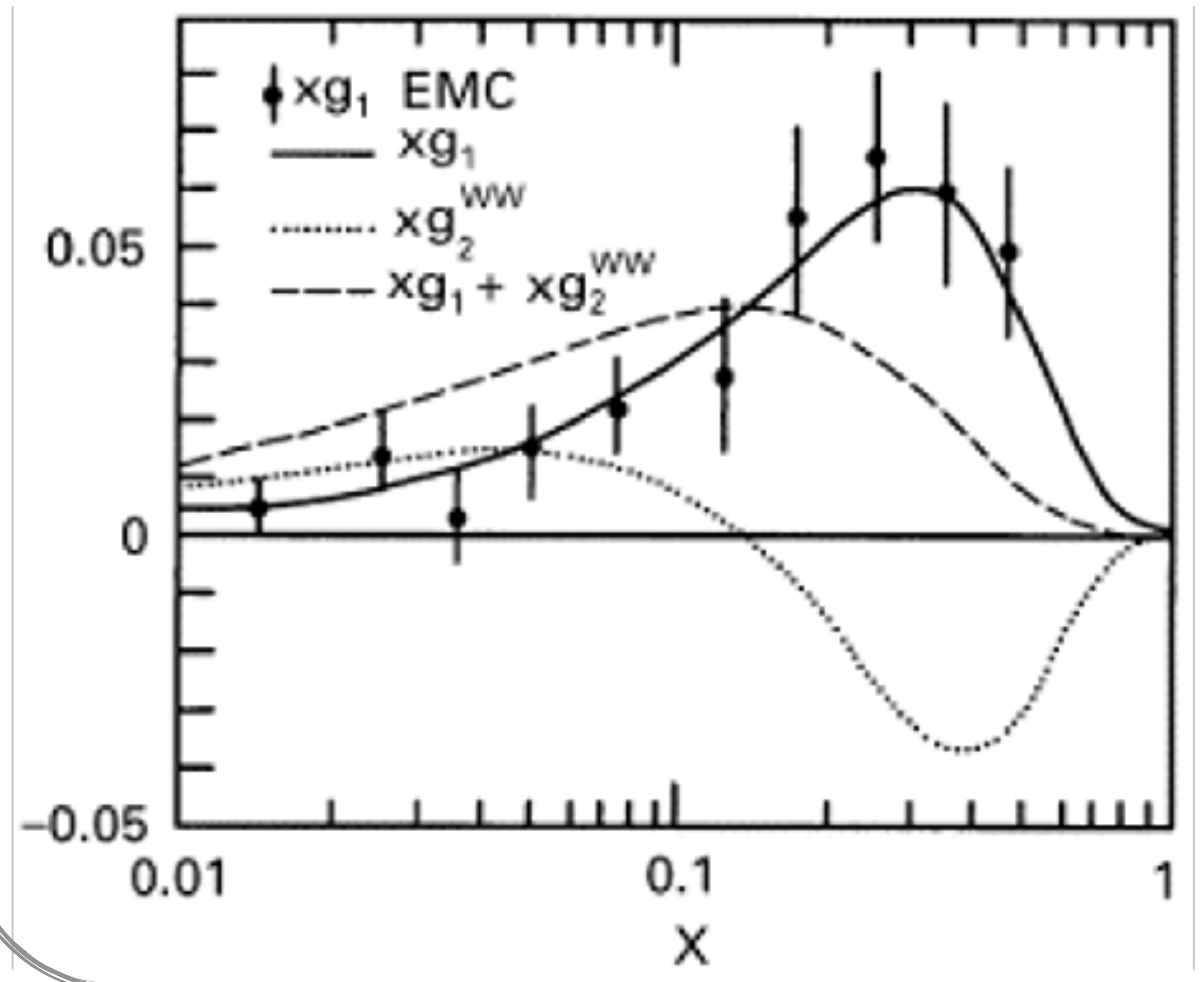
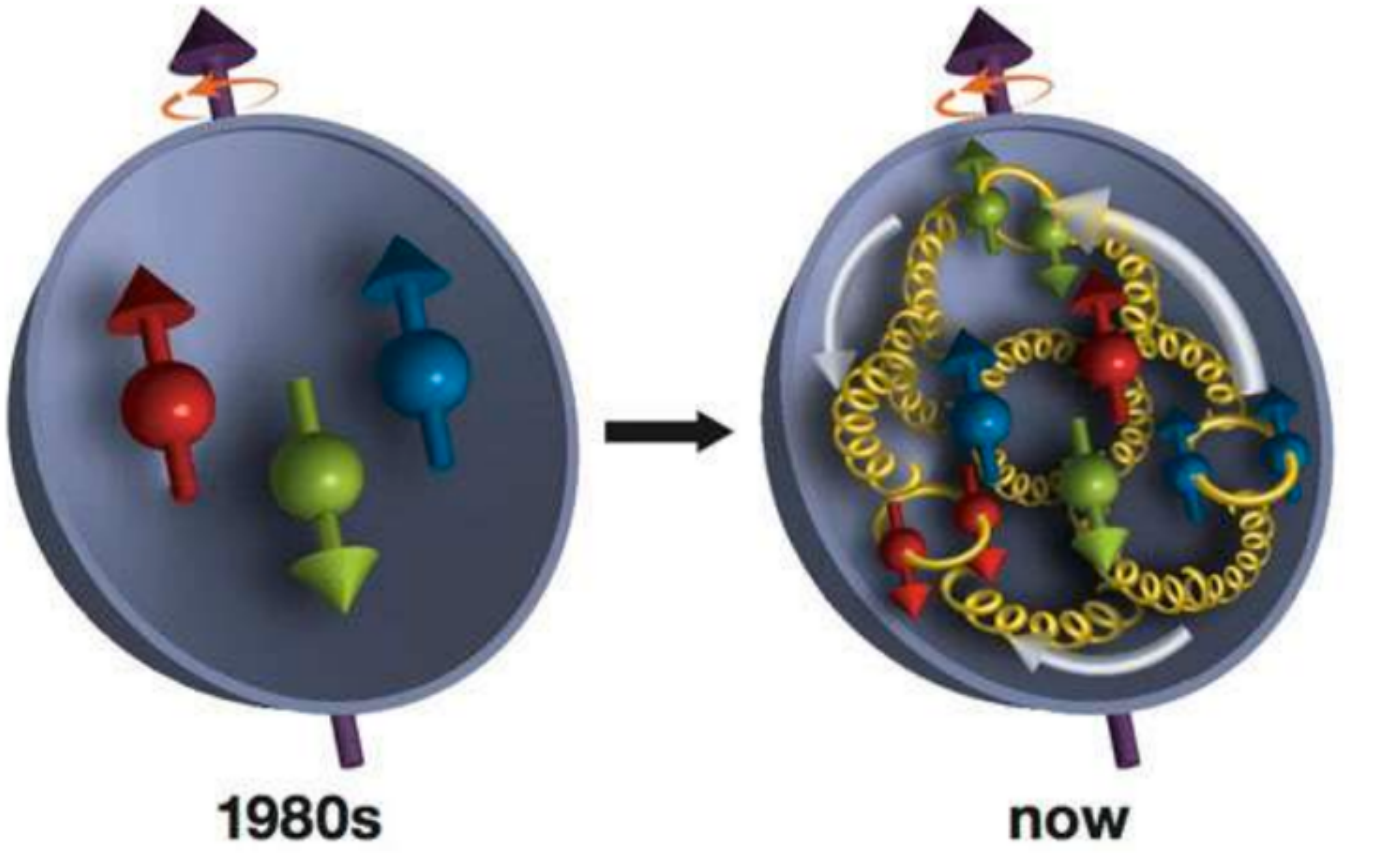


Surprising data from late 1980's!
Only ~12% of proton's spin carried by quarks' spins!

How much do we know about (proton) spin?

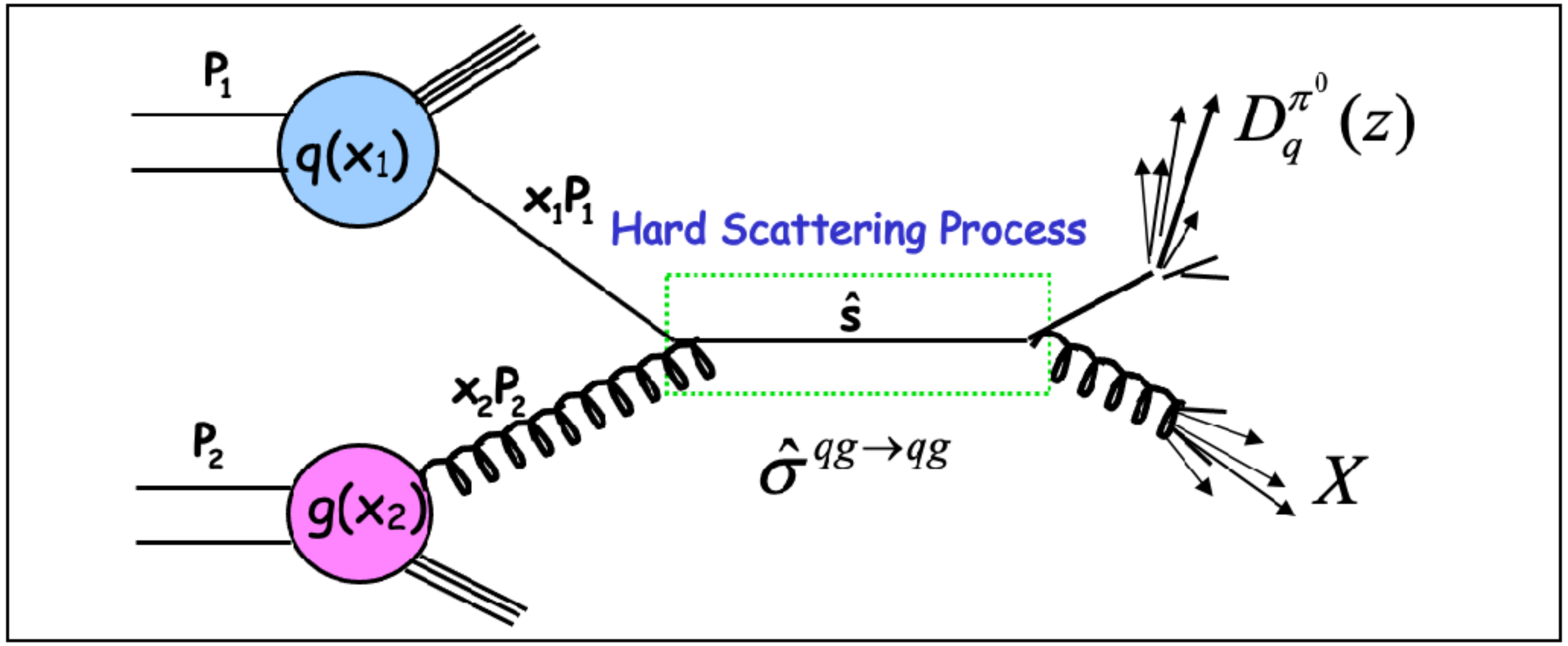
$$\frac{1}{2}\hbar =$$



Hence ~30% of the proton spin is carried by the spin of the quarks, the remaining spin must be carried by gluons or orbital angular momentum

$$\frac{1}{2}\hbar = \overbrace{\sum_q \frac{1}{2} S_q^z}^{\text{Total quark spin}} + \overbrace{S_g^z}^{\text{gluon spin}} + \overbrace{\sum_q L_q^z + L_g^z}^{\text{angular momentum}}$$

How to account for this?



$$\sigma\left(pp \to \pi^0 X\right) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

Particle production rates can be calculated using pQCD from:

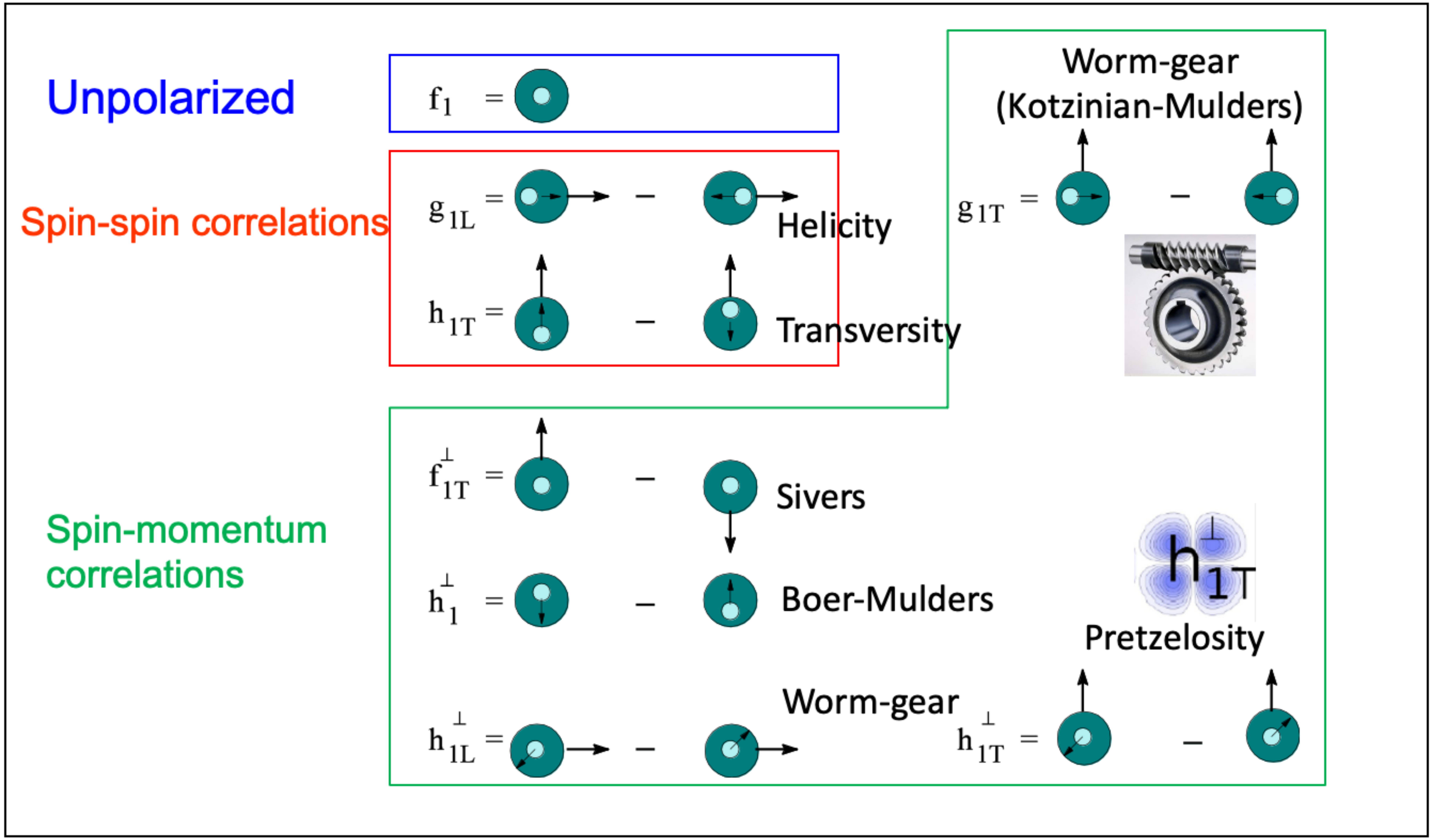
–Parton distribution functions (from experiment)
–pQCD partonic scattering rates (from theory)
–Fragmentation functions (from experiment)

We want a description - at Leading Order - that includes spin-spin and spin-momentum correlations

Unpolarized

f_1 = 

We want a description - at Leading Order - that includes spin-spin and spin-momentum correlations

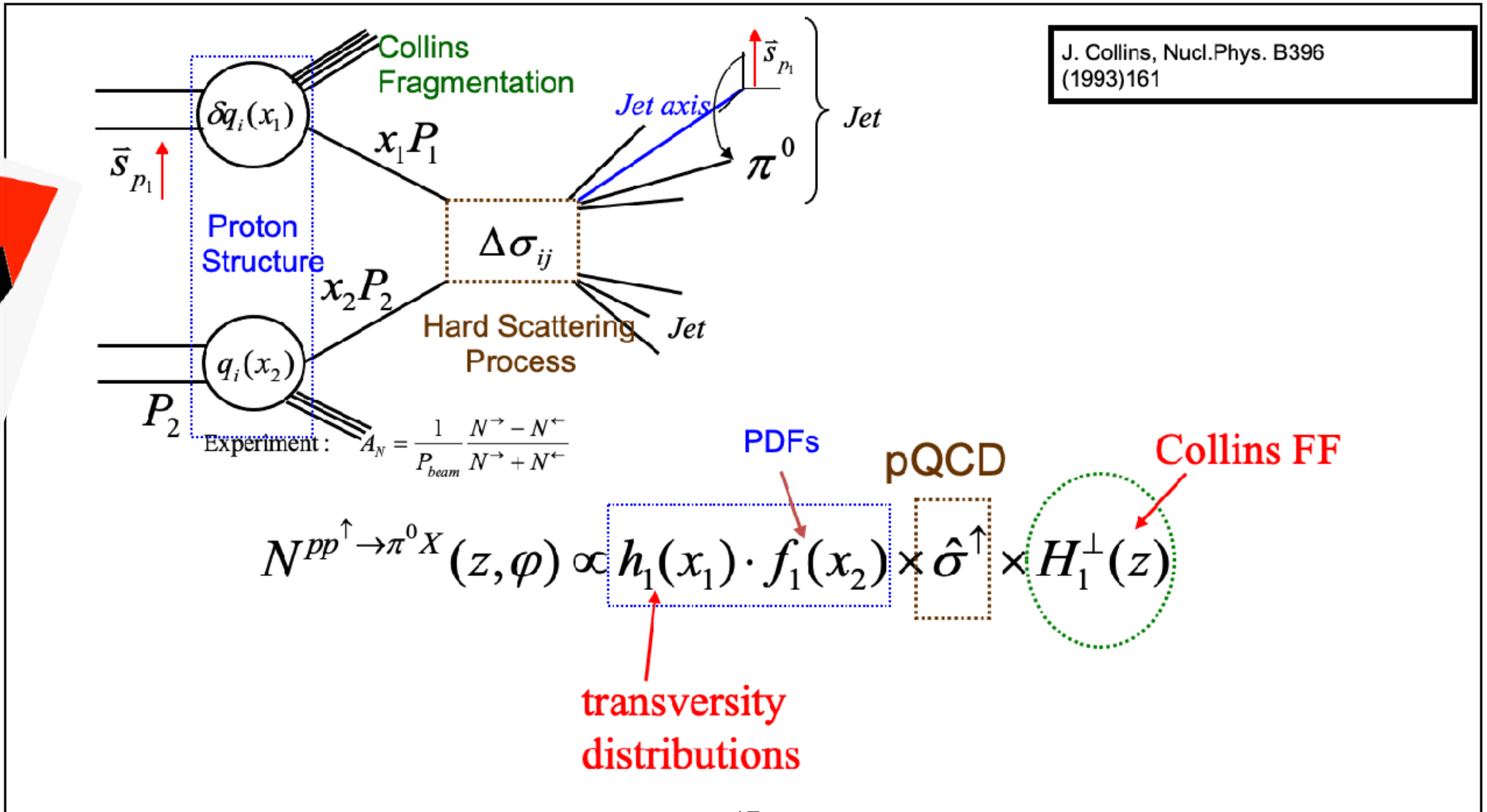


Transverse Momentum Distribution Functions (TMDs)

PDFs involving transversely polarised quarks are chiral-odd:

can only be observed experimentally in conjunction with a second chiral-odd function

polarised objects



From J.-C. Peng

$$d^6\sigma = \frac{4\pi\alpha^2 s x}{Q^4} \times$$

$f_1 =$

Boer-Mulders $h_1^{\perp} =$

$h_{1L}^{\perp} =$

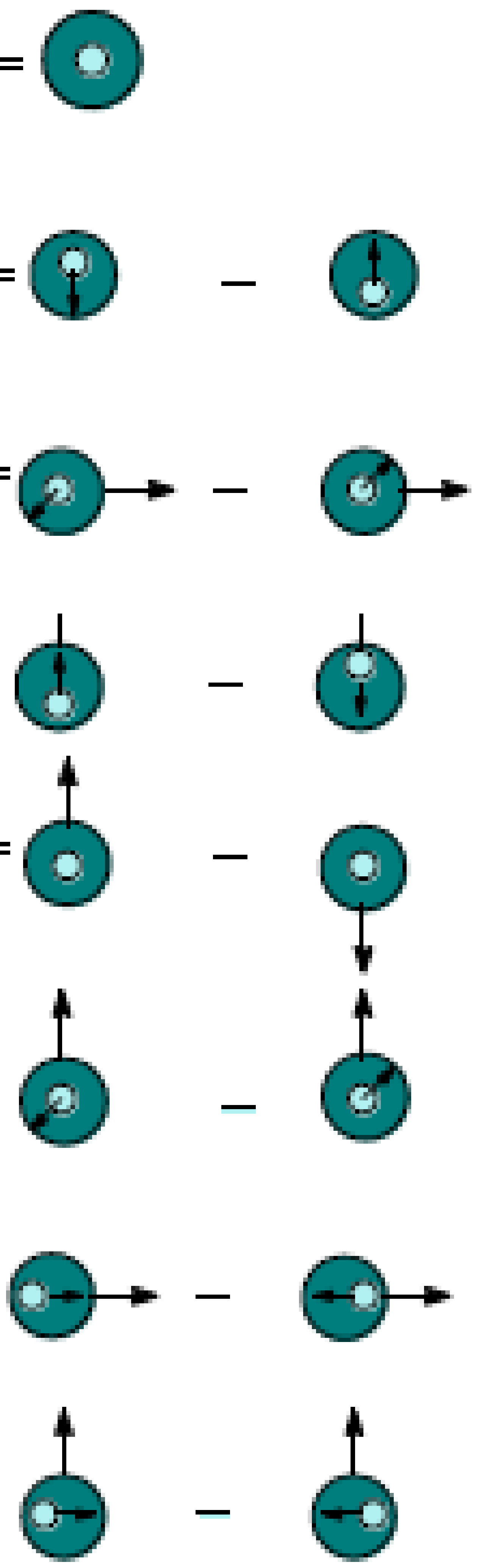
Transversity $h_{1T} =$

Sivers $f_{1T}^{\perp} =$

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

$g_{1L} =$

$g_{1T} =$



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2M_NM_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2M_NM_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3M_N^2M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

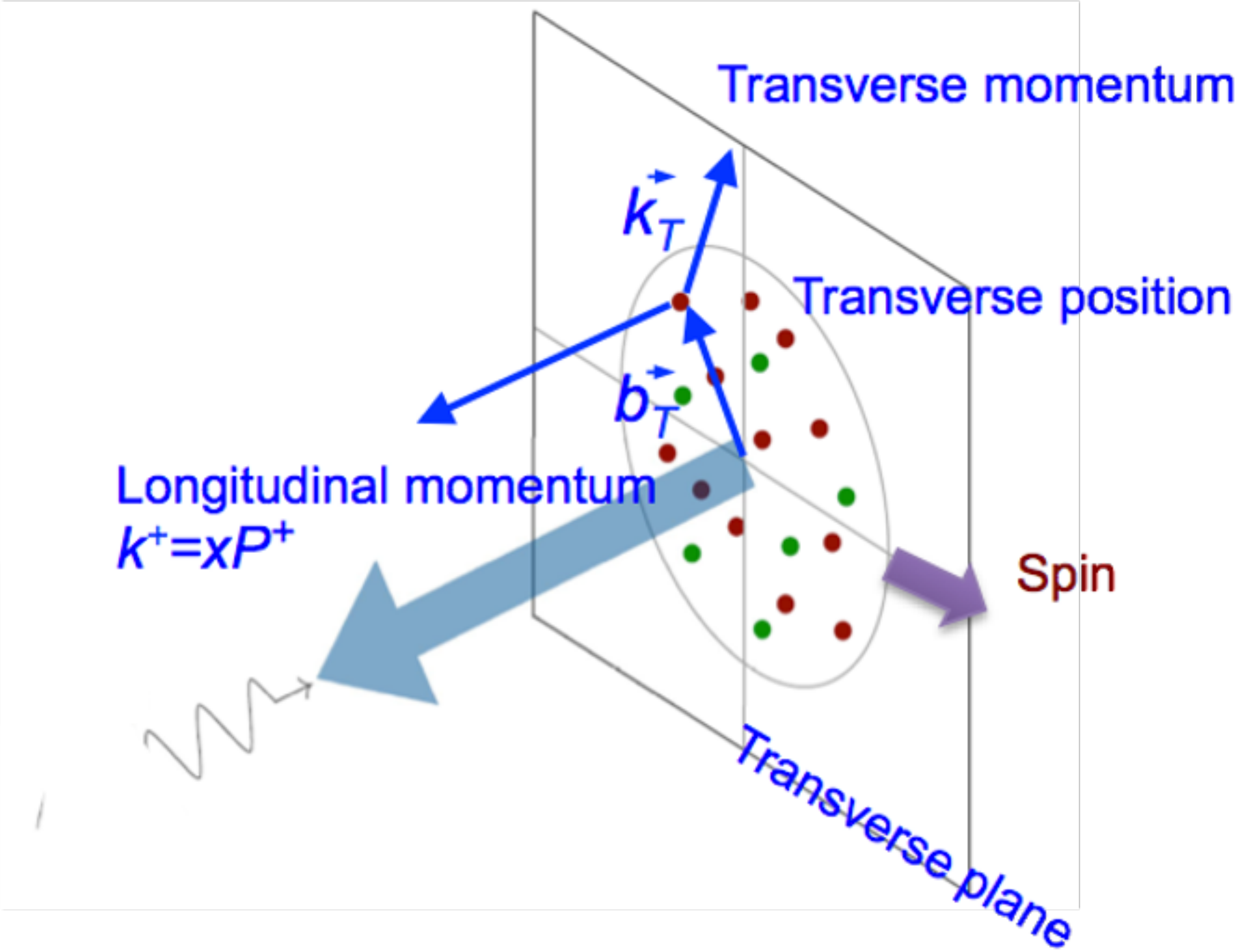
Polarzied beam and target

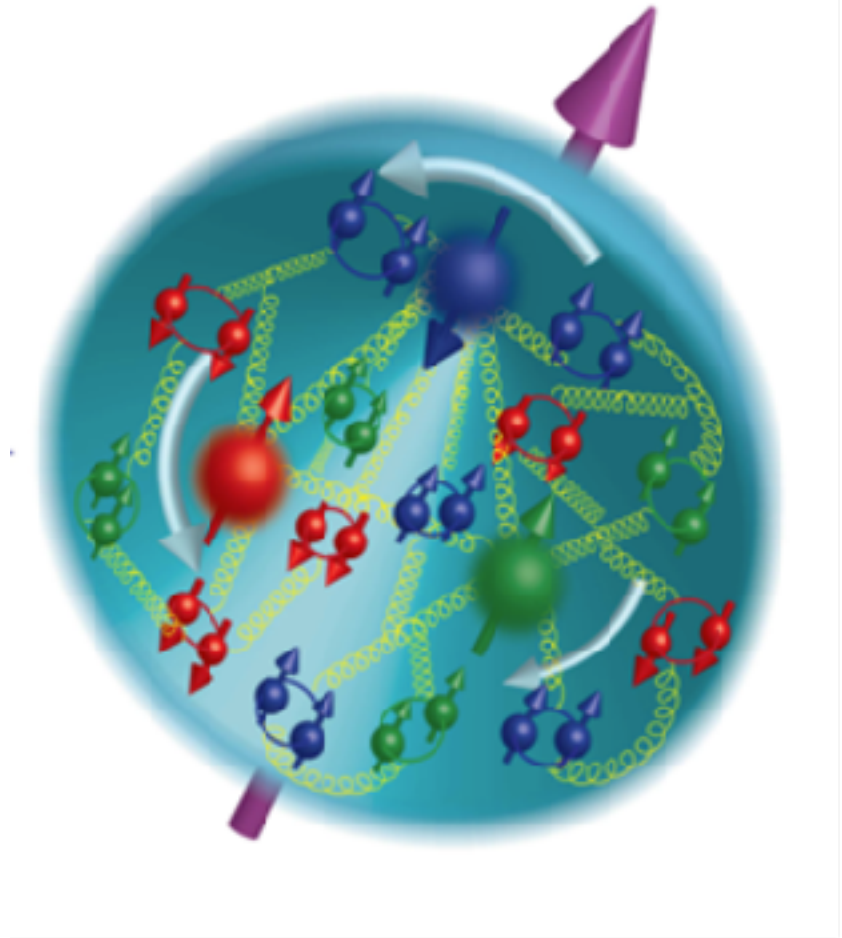
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

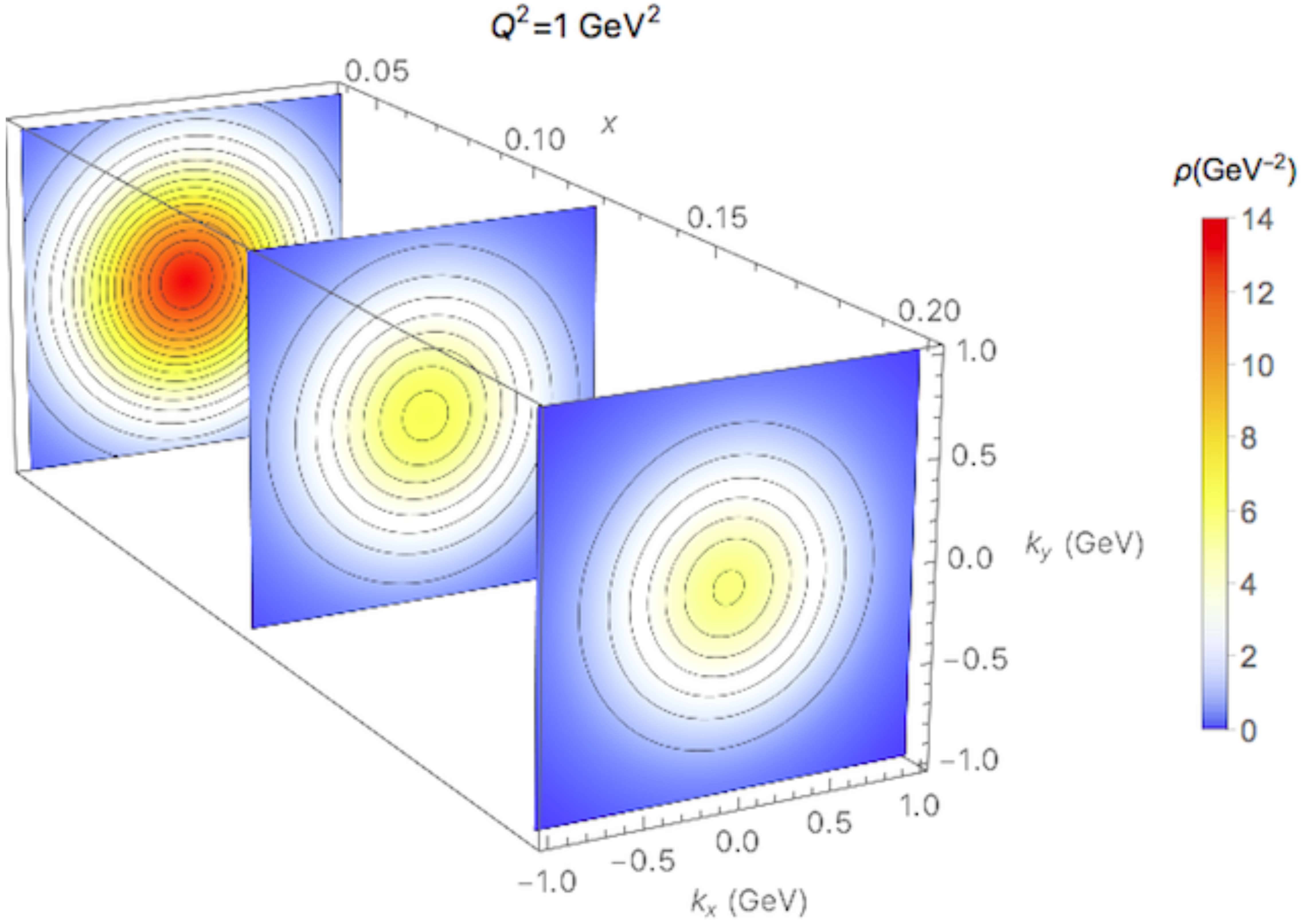
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

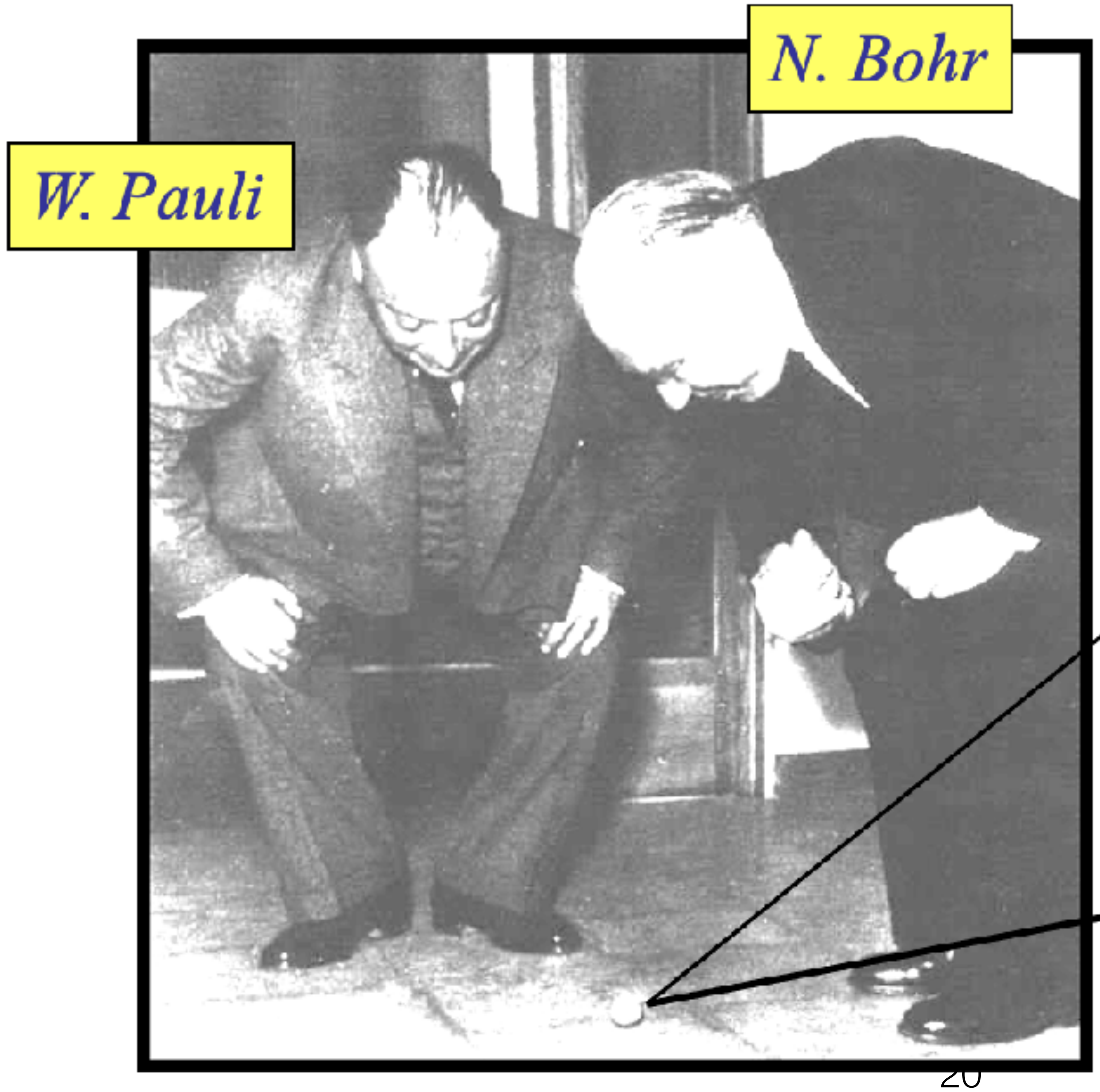
Hadron tomography

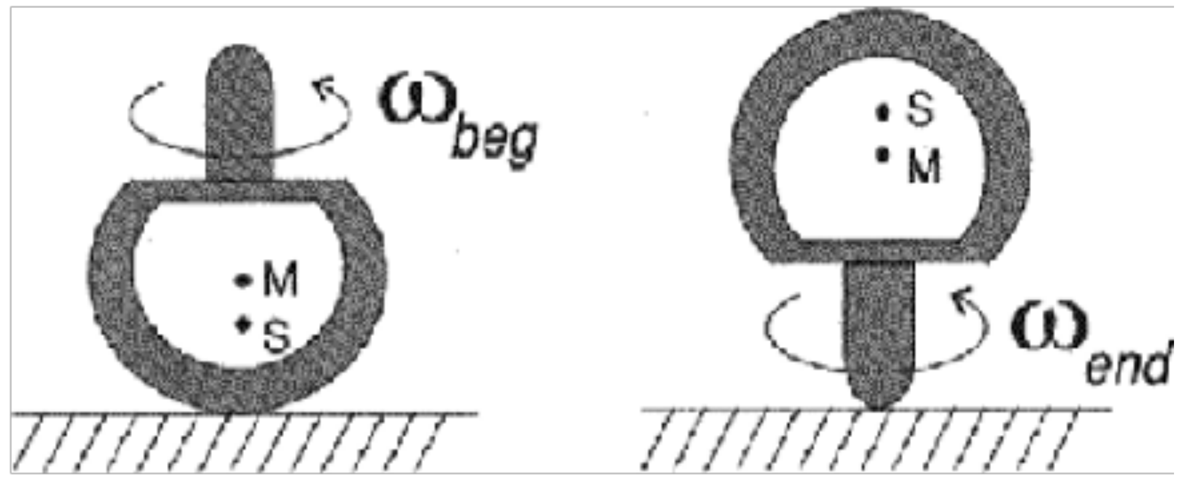




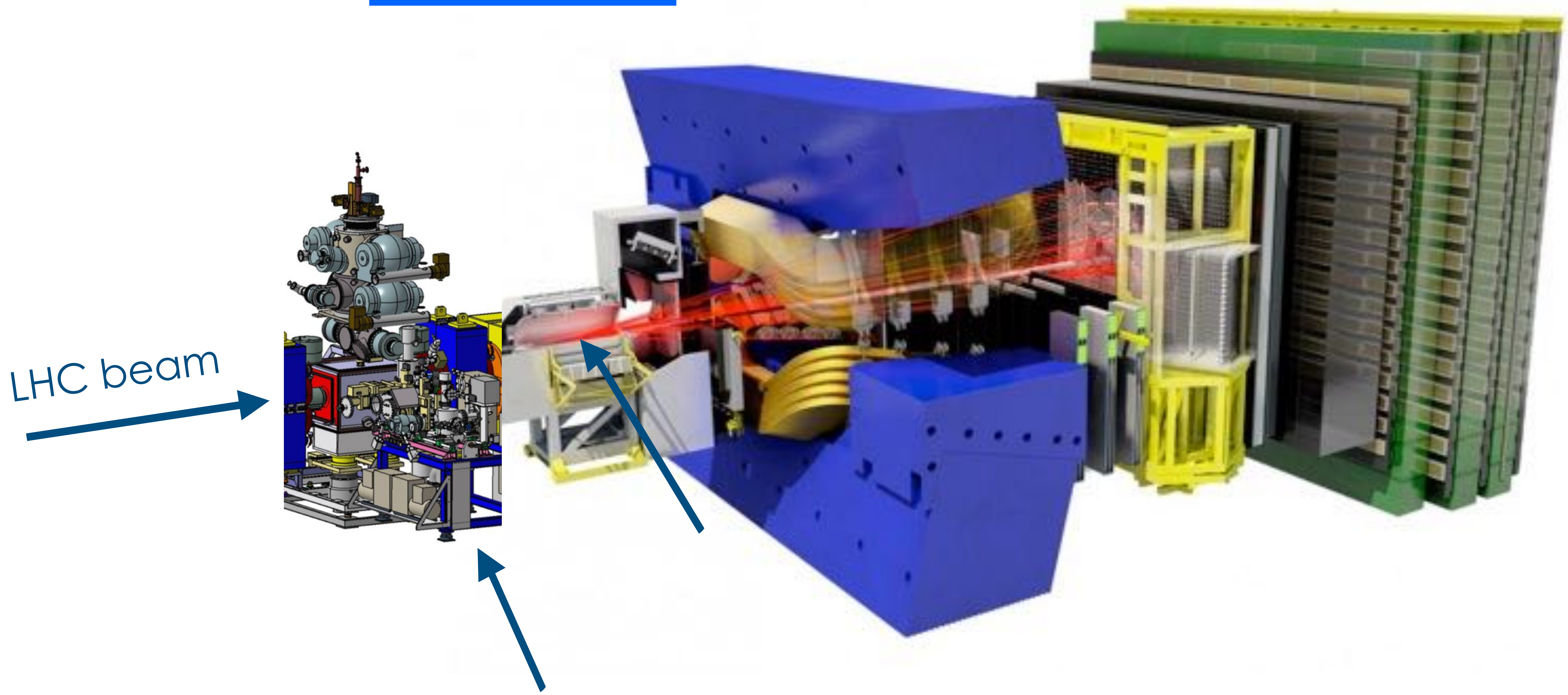


Now we need polarised protons meaning we need highly polarised H atoms





a polarised target at LHCb



The LHC beams cannot be polarised

$L\uparrow\downarrow C$ spin — a polarised target at LHCb

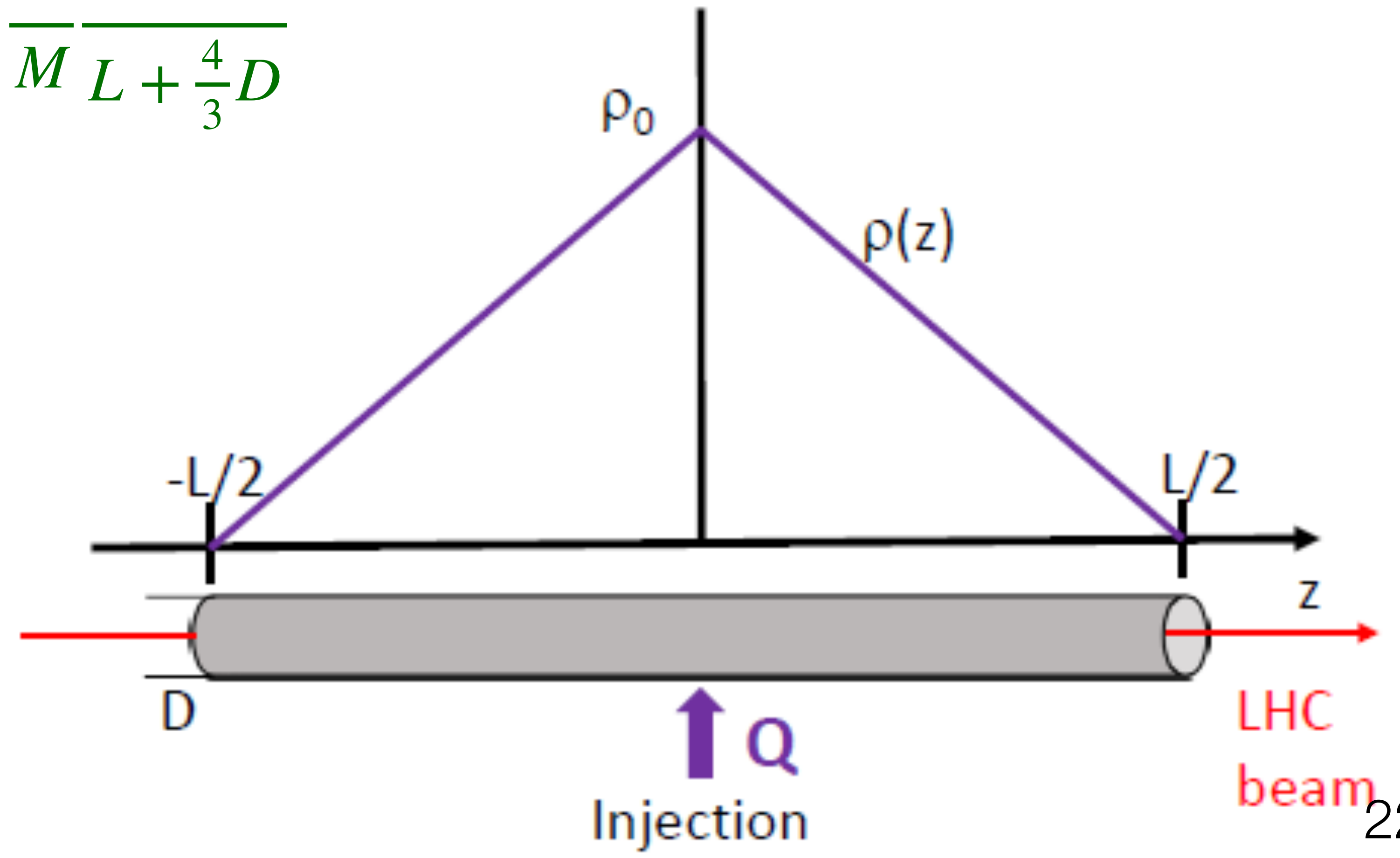
Luminosity

$$L_{ist} = \theta \, N_p \, f_{rev}$$

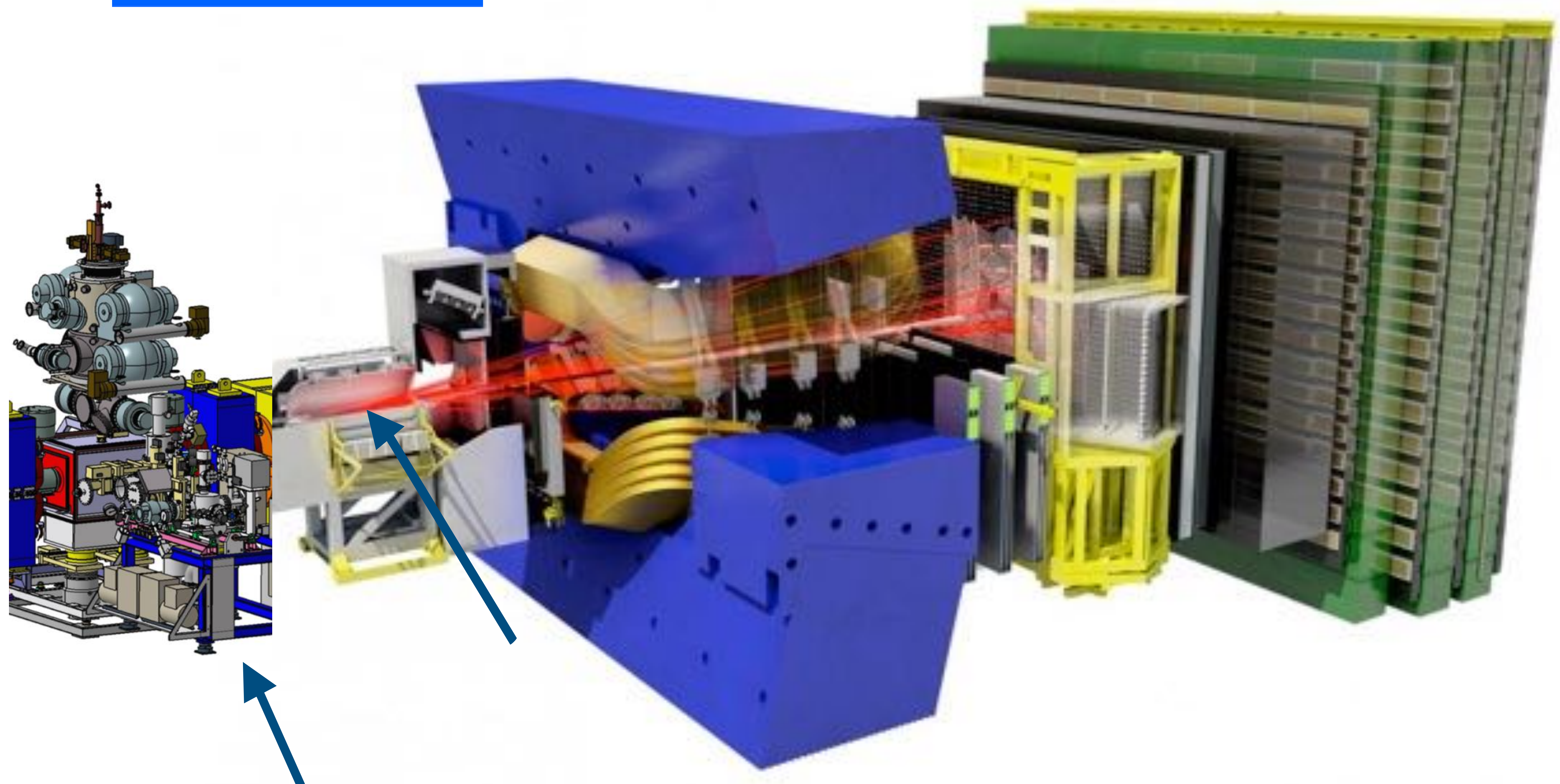
areal density → $\rho_0 \frac{L}{2} = \frac{\Phi}{C} \frac{L}{2}$ → $C = 3.81\sqrt{\frac{T}{M}} \frac{D^3}{L + \frac{4}{3}D}$

number of particles → $N_{p/b} \cdot N_b$

Storage cell concept



LHC beam



polarised target (beam-gas)

beam-beam collisions

LHCspin: a polarised target at LHCb

Luminosity

$$L_{ist} = \theta\ N_p\ f_{rev}$$

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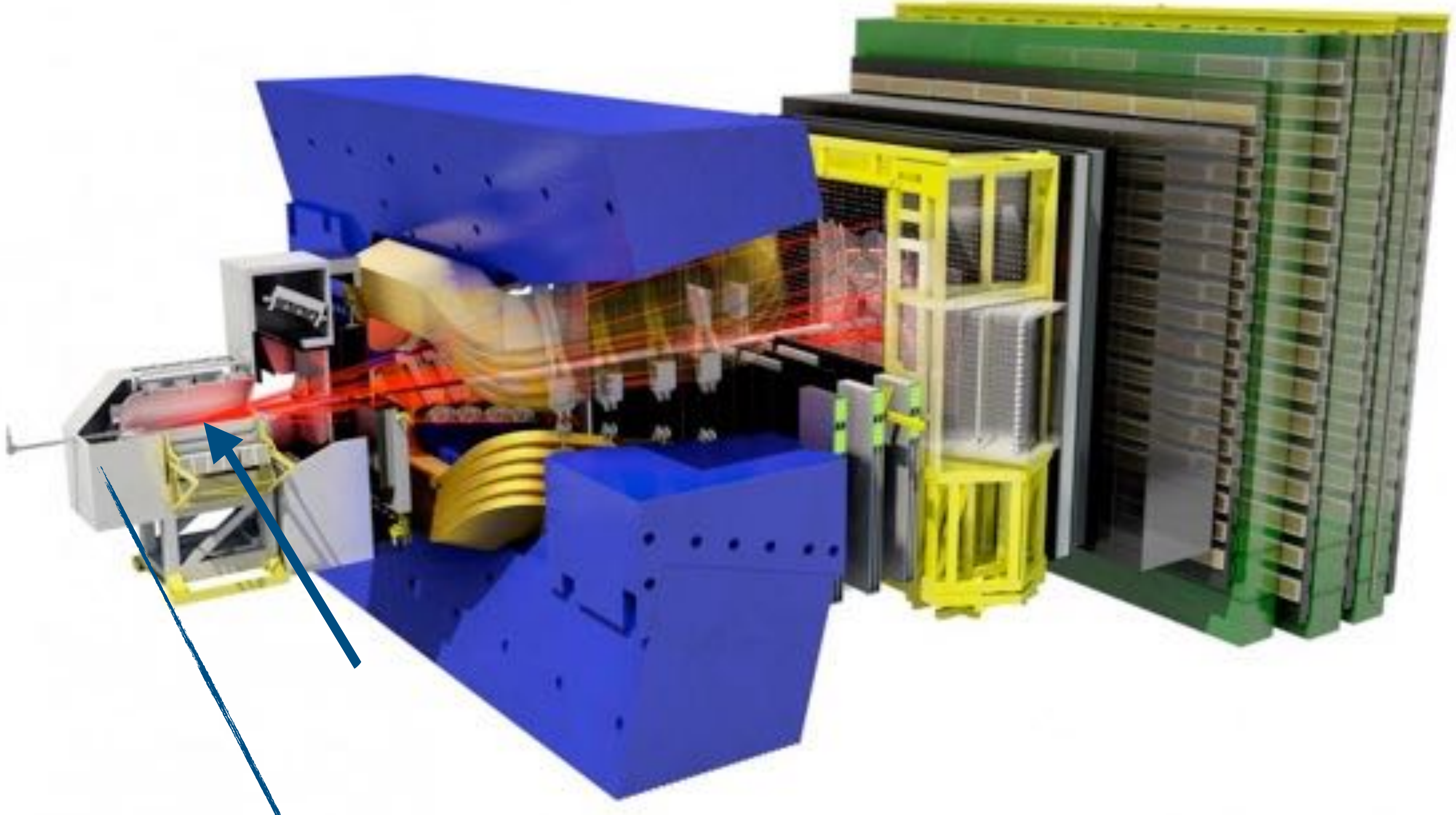
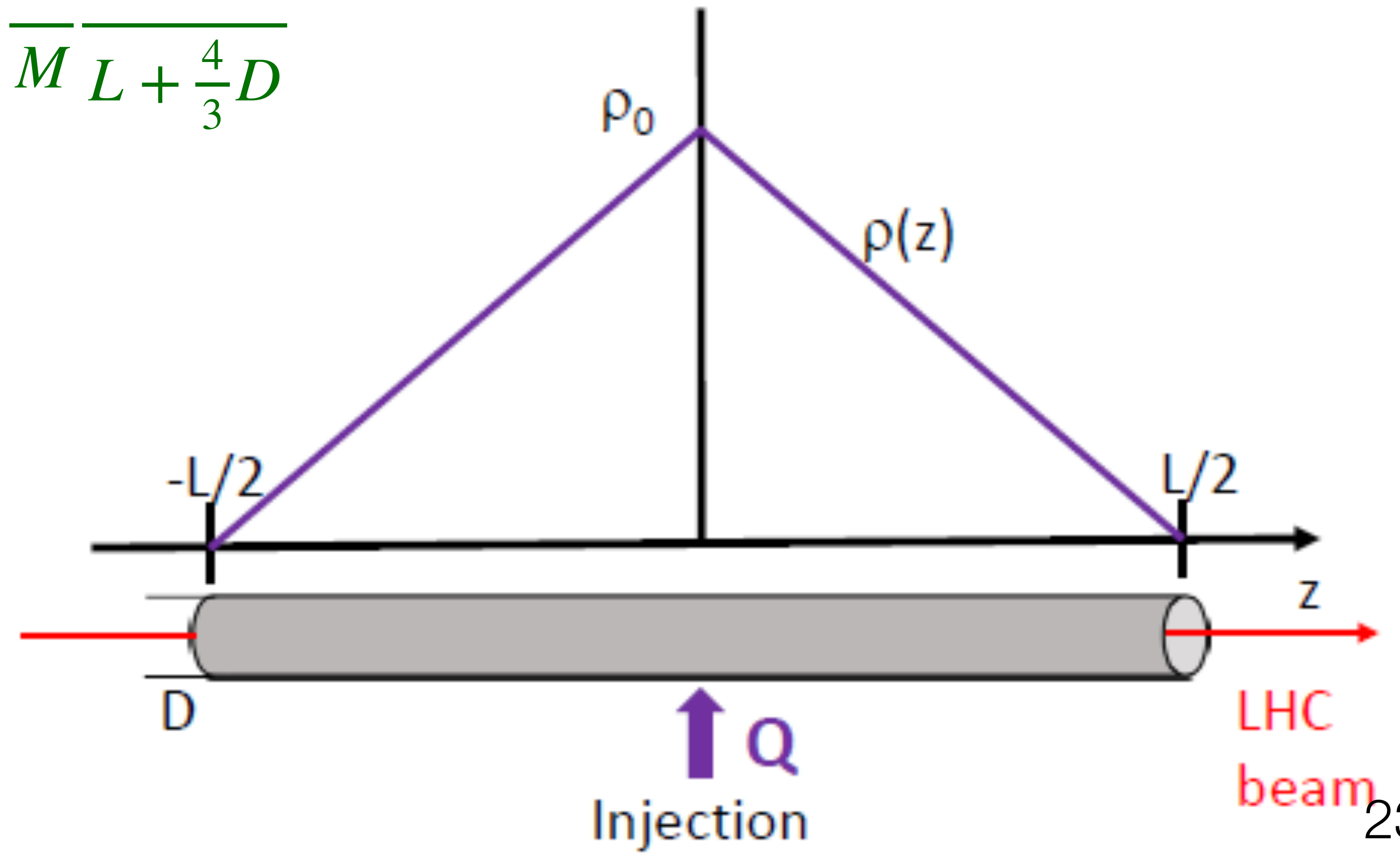
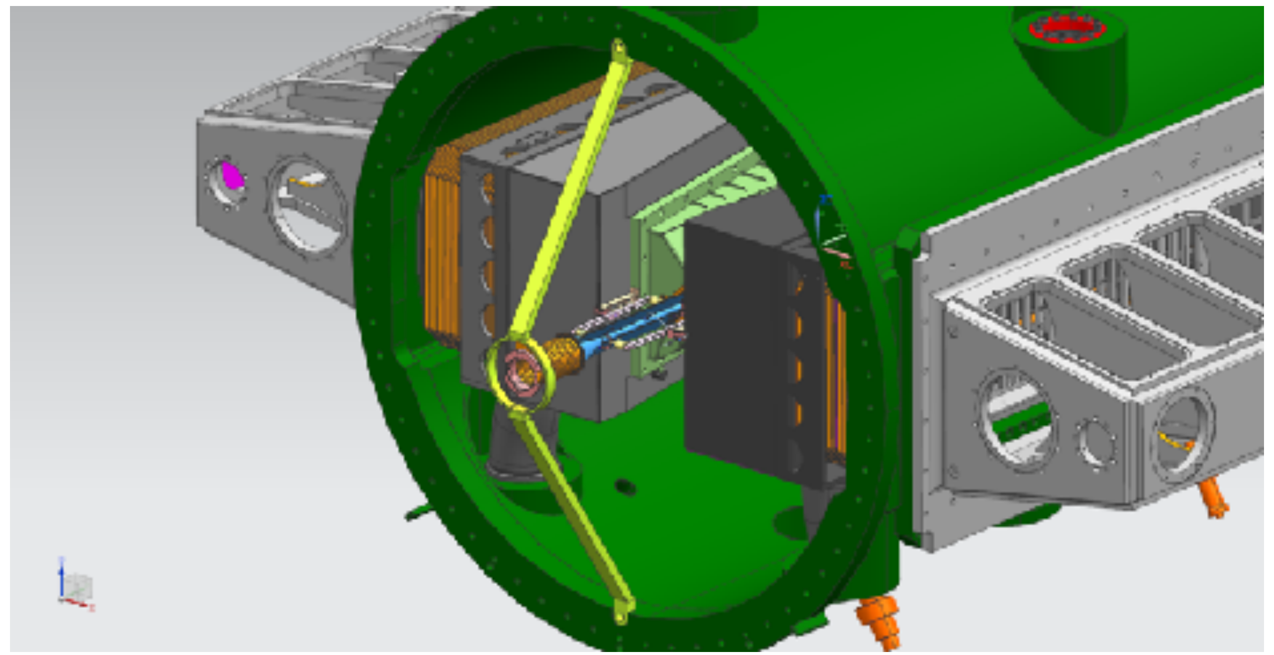
LHC beam



beam-beam collisions

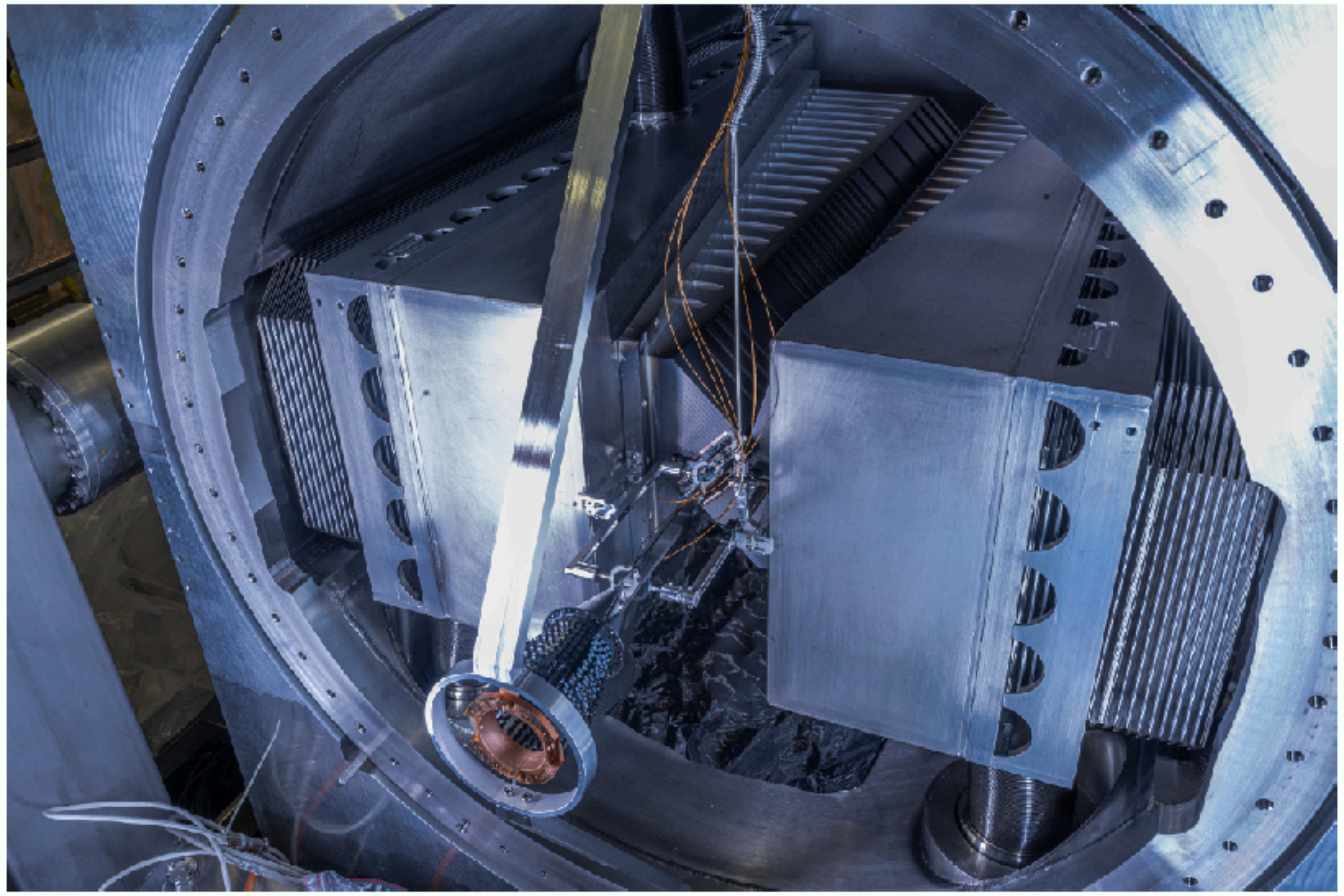
Storage cell concept

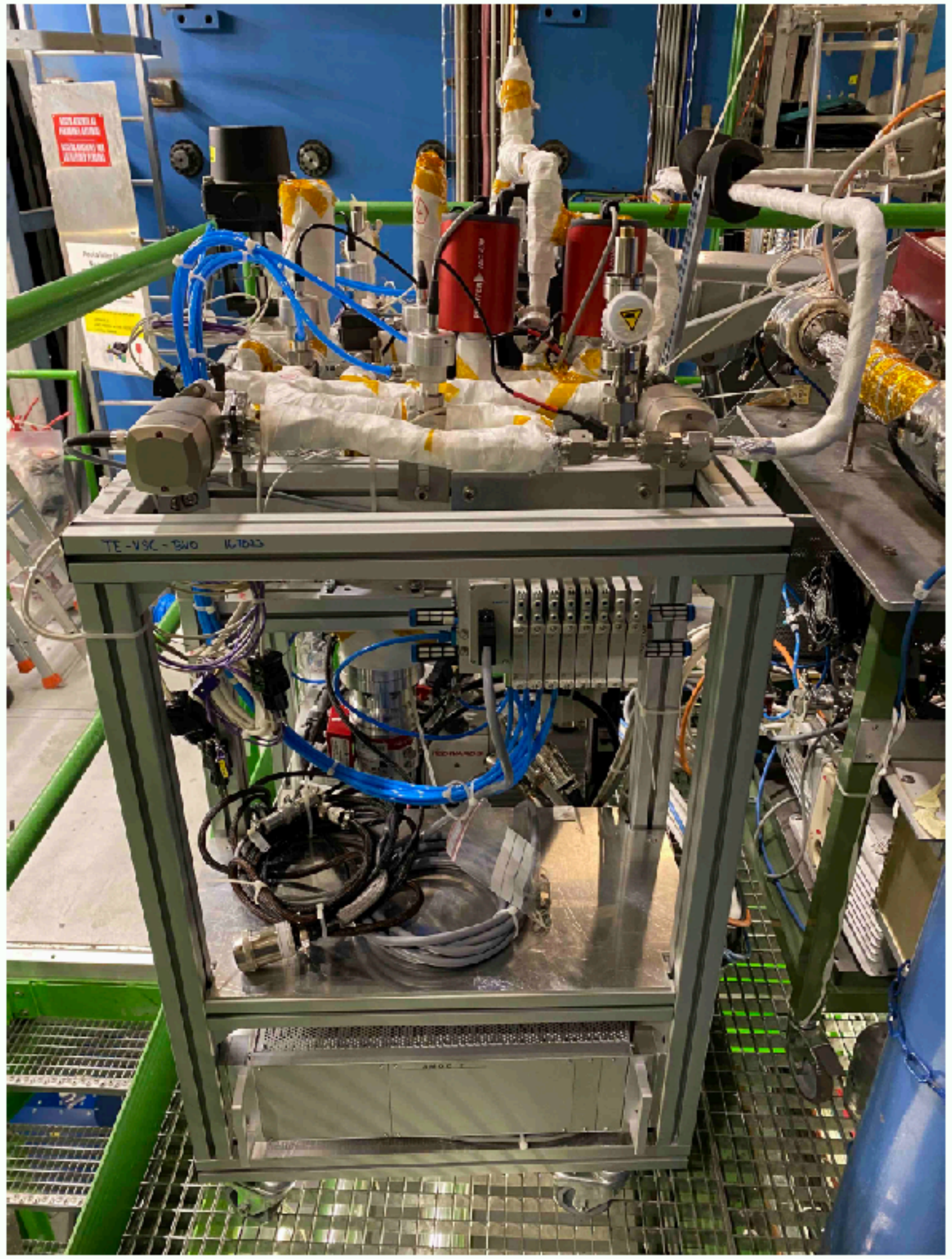




UNpolarised target (beam-gas)

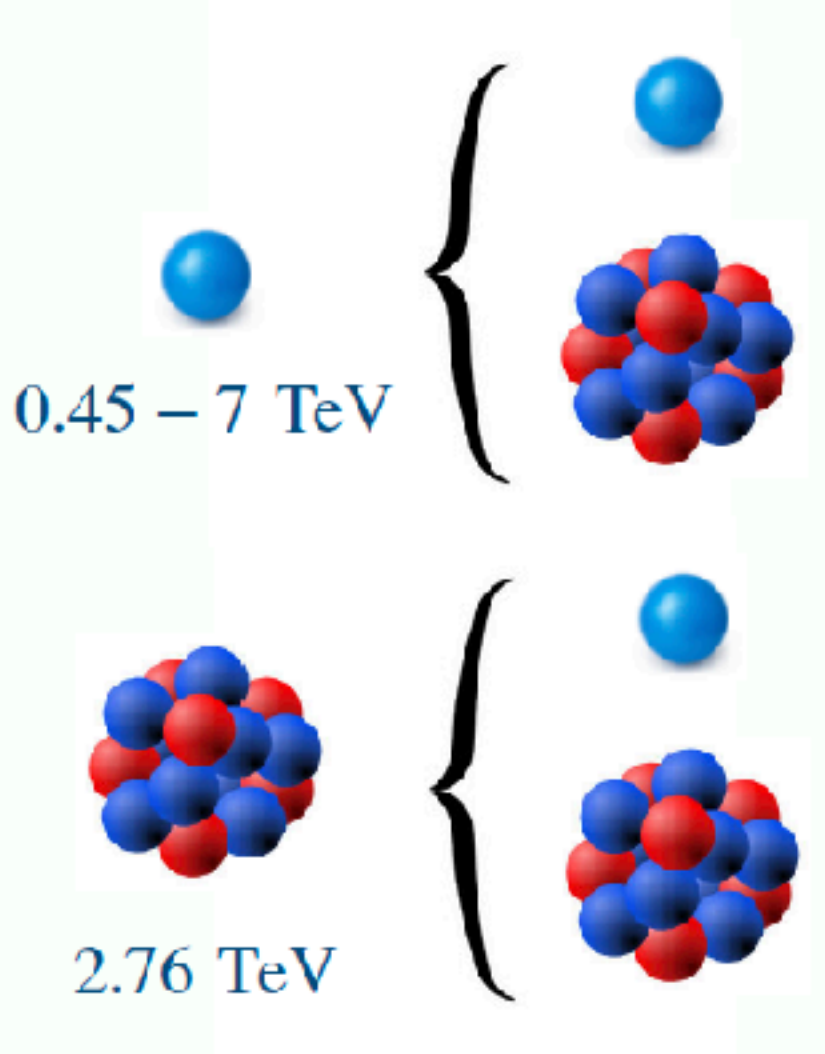
A unique project itself and a great playground





- Storage cell installed on 08/2020
- Boosts the density by $8 - 35$ X wrt SMOG
- Negligible impact on the beam lifetime: $\tau^{p-H_2}_{beam-gas} \sim 2000$ days , $\tau^{Pb-Ar}_{beam-gas} \sim 500$ h
- Temperature probes up and running

- GFS installed on 03/2022
- Can be filled with: He, Ne, Ar
- Under evaluation: H_2, D_2, N_2, O_2, Kr, Xe (e.g. can be injected at the end of a Run)



pp/pA collisions, 7 TeV beam:

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

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

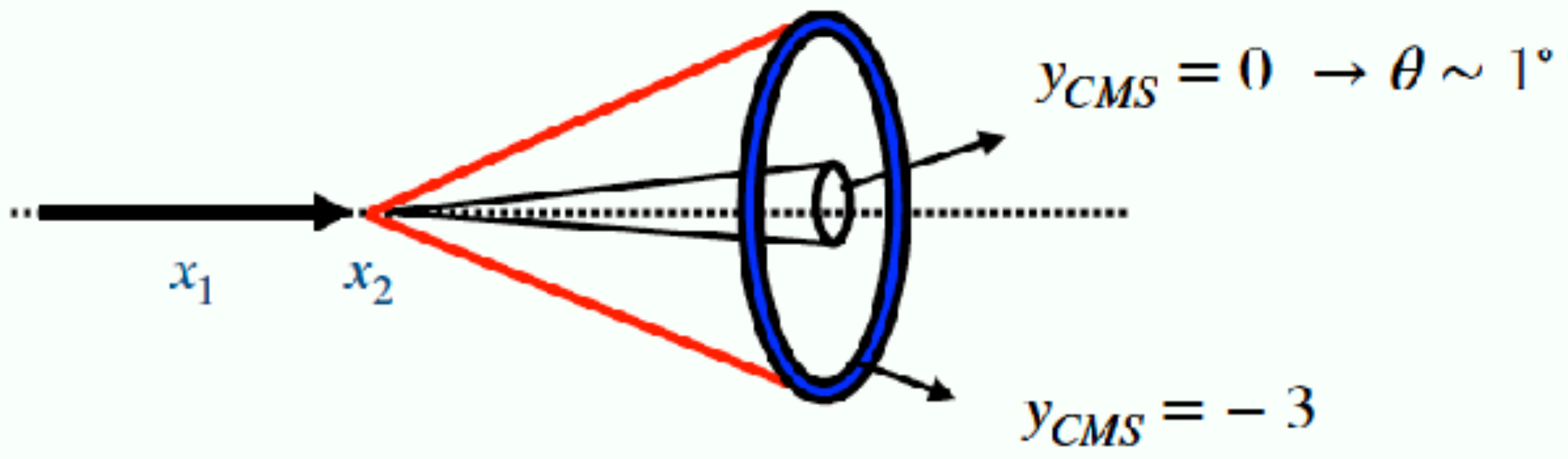
AA collisions, 2.76 TeV beam:

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

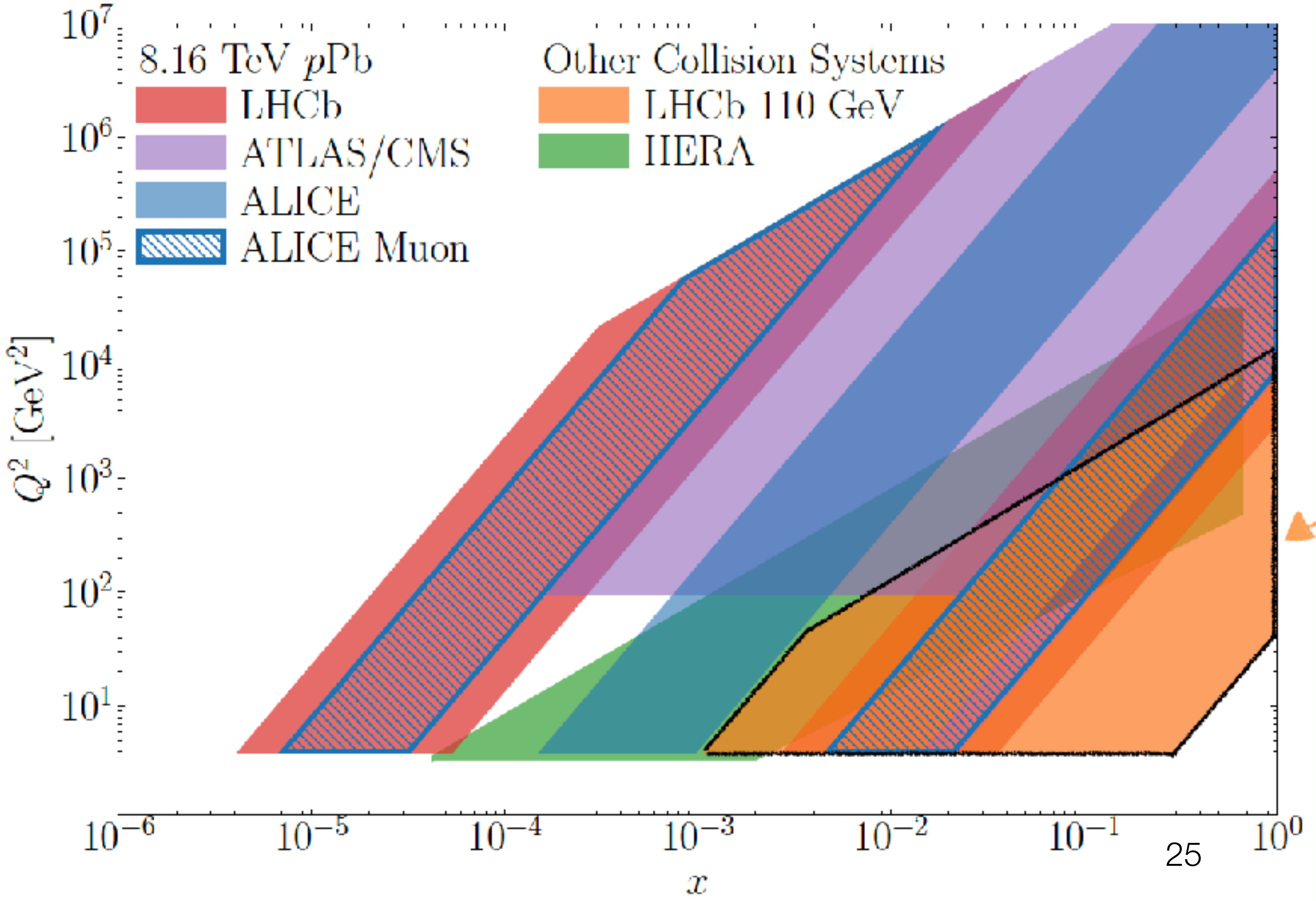
$y_{lab} = 4.3 \ \rightarrow \ y_{CMS} = 0$

1: beam, 2: target

Large CM boost : large x_2 values ($x_F < 0$) and small x_1



$$\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$$

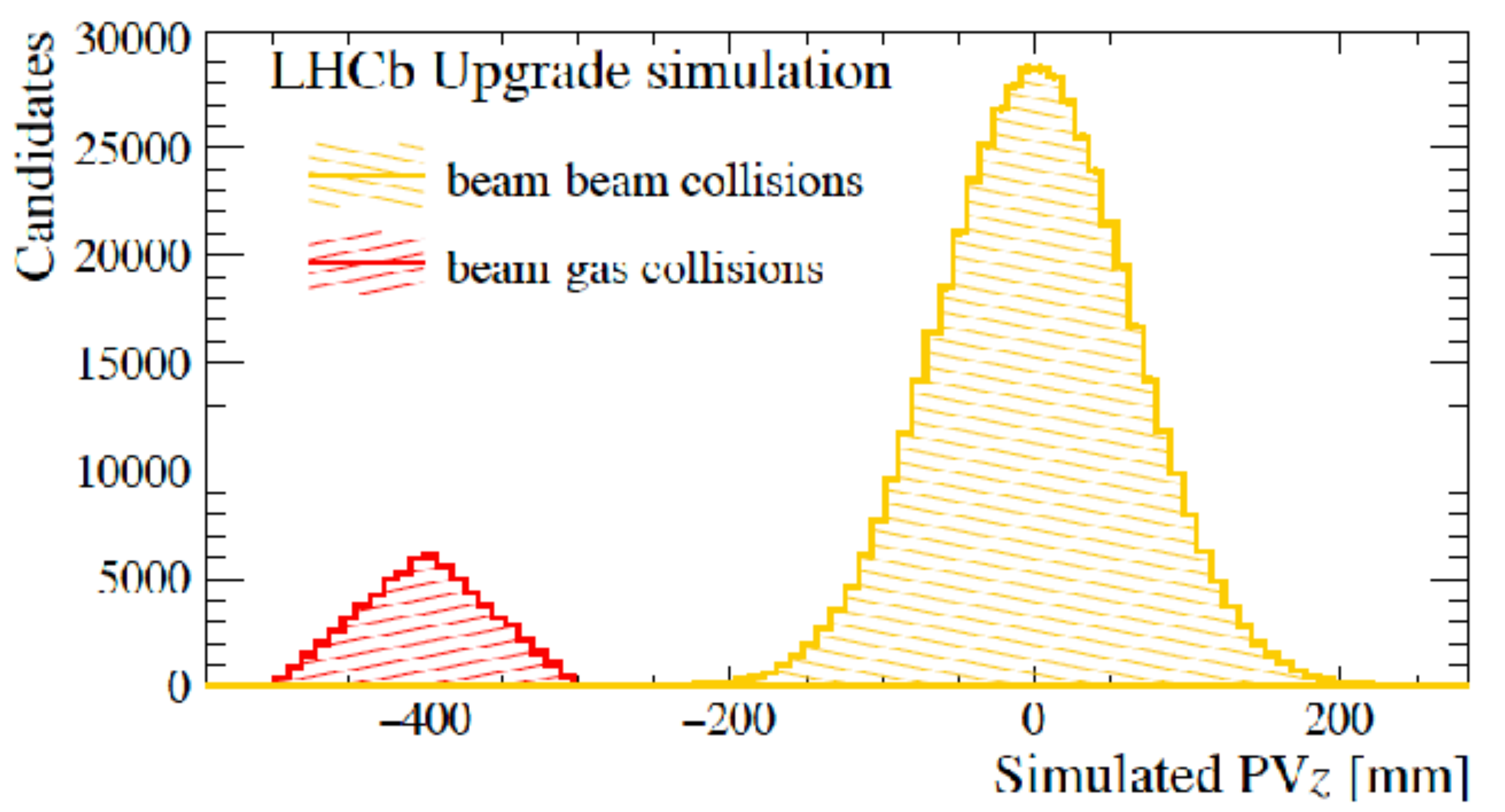


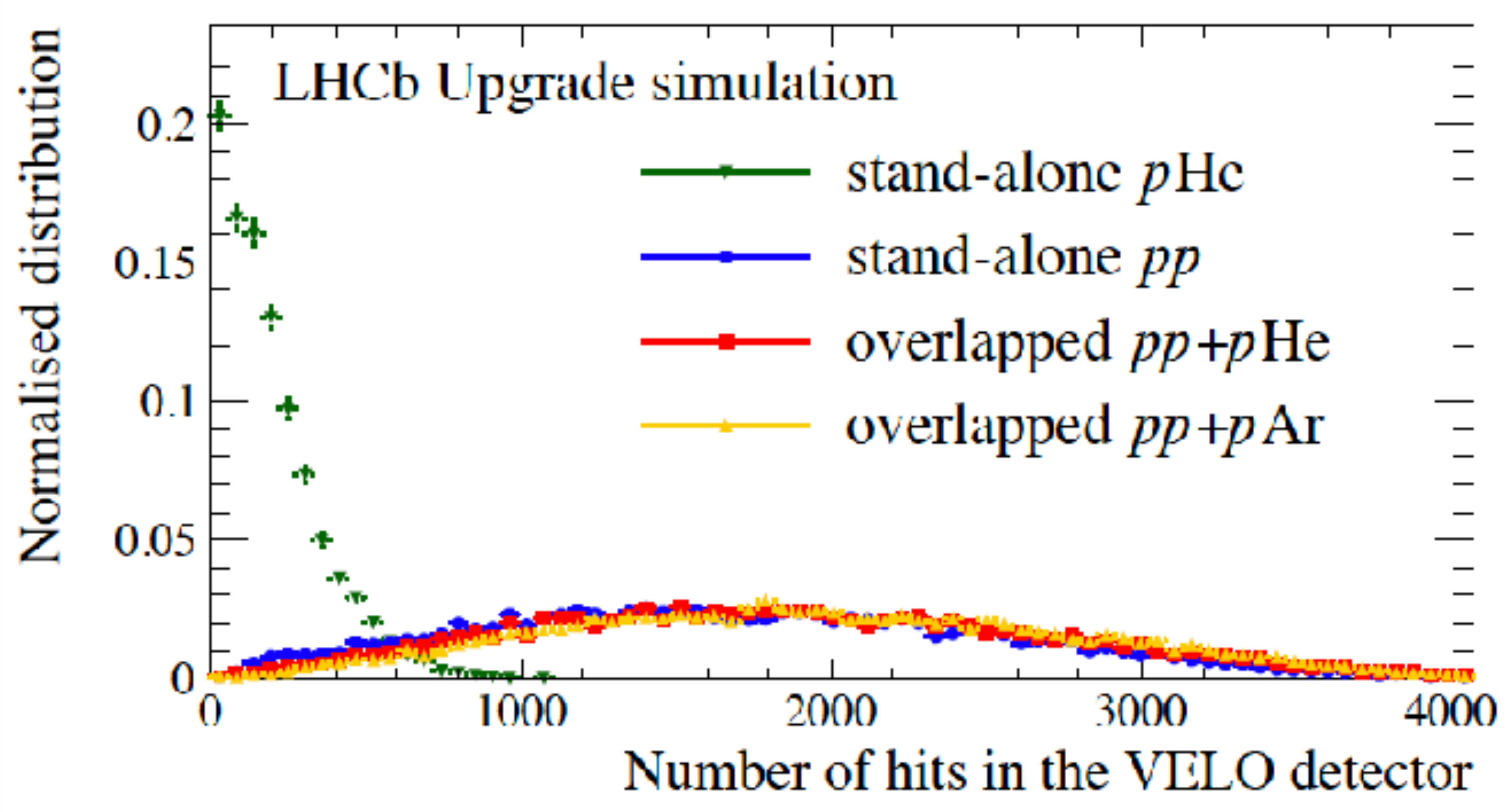
Unique QCD laboratory at LHC:

- Large-x content of g, $\bar{q}$ and heavy quarks in nucleons and nuclei
- Spin distributions of gluons inside unpolarised and polarised nucleons
- Heavy Ion FT collisions at an energy in between SPS and RHIC
- Broad and poorly explored kinematic range
- High luminosity, high resolution detectors: access to a large variety of probes incl. exotic
- Several unpolarised gas targets
- Polarised gas targets: $H^{\uparrow}, D^{\uparrow}$

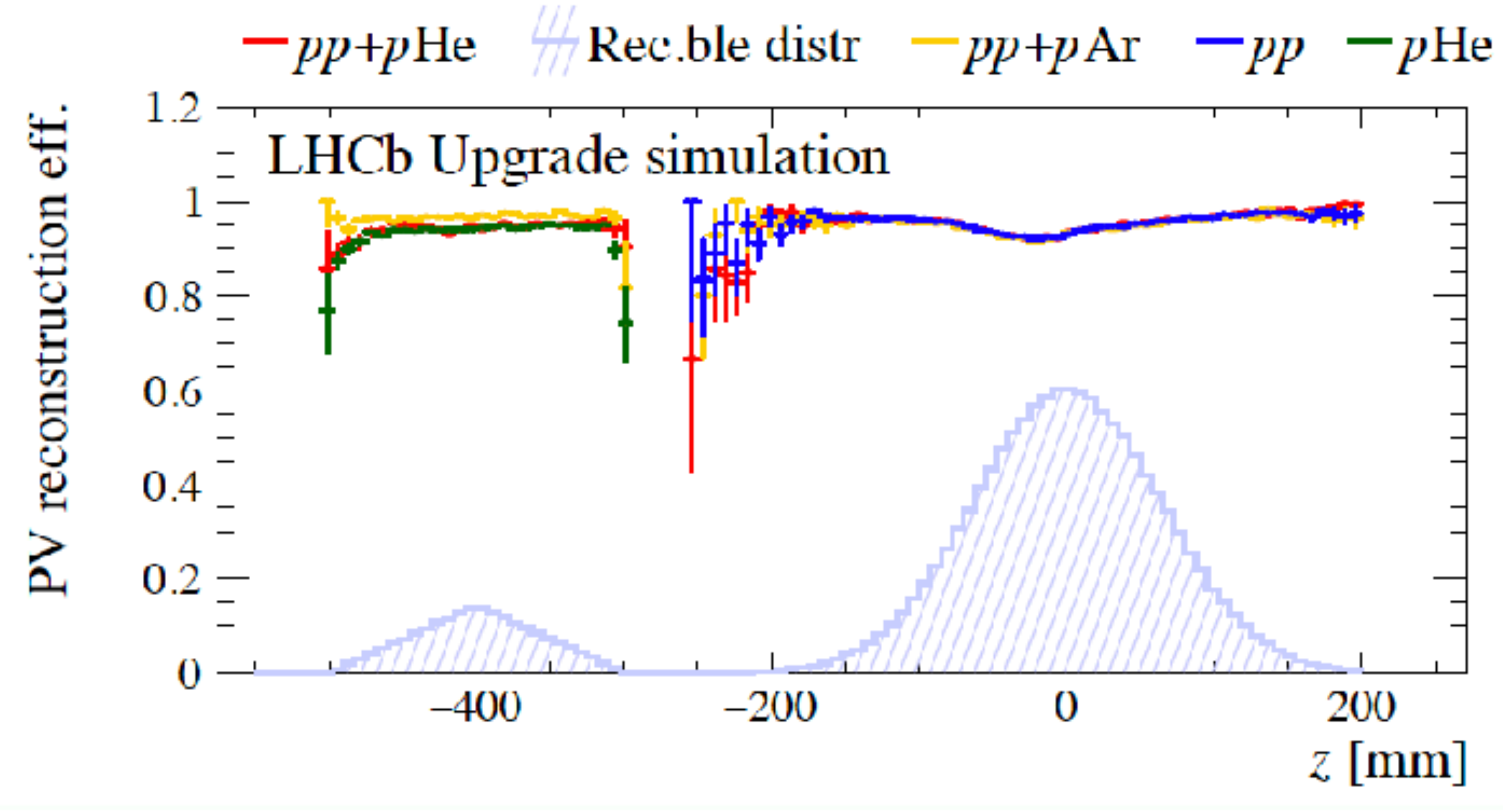
SMOG2 performances … similar to LHCspin

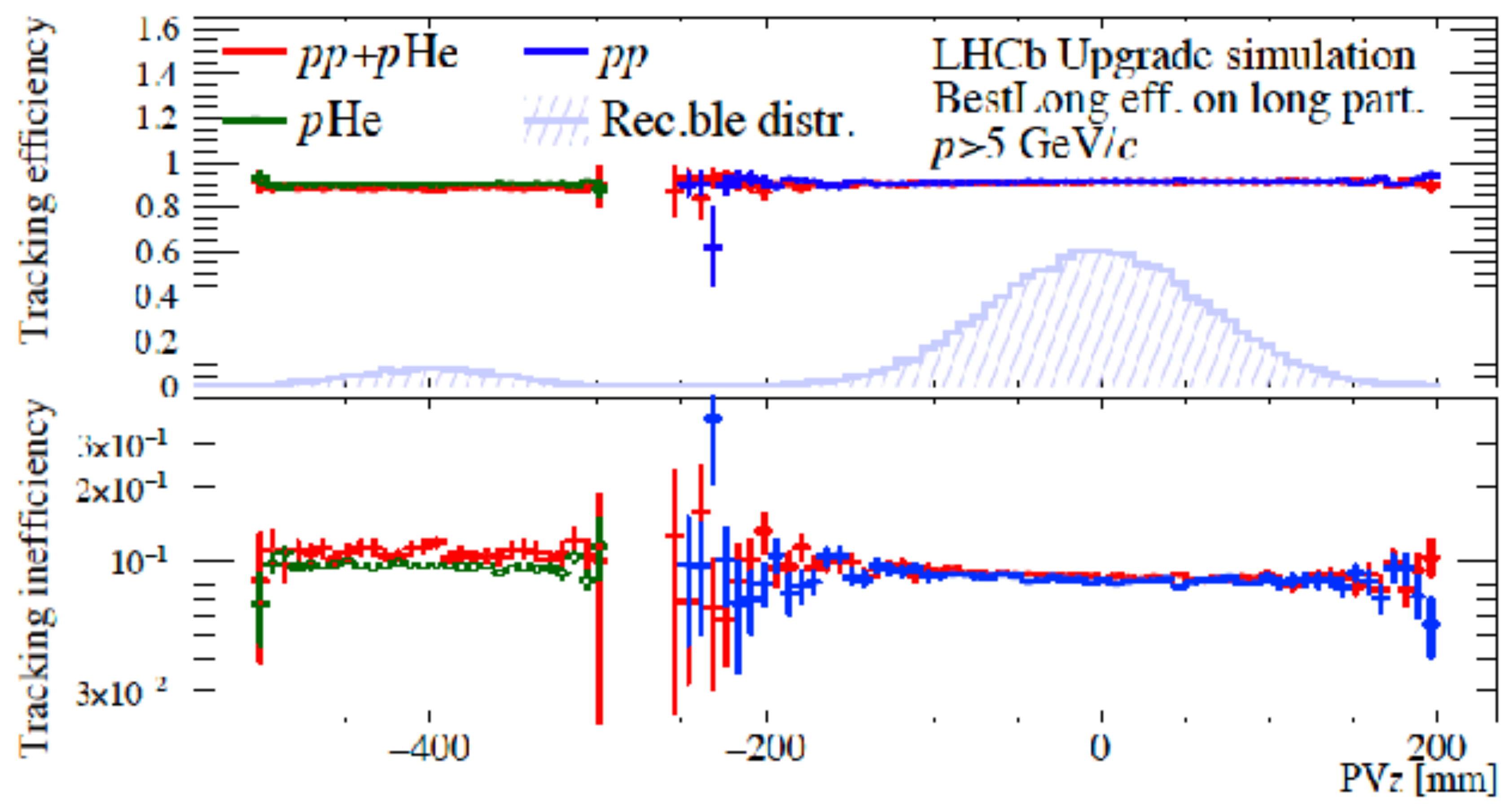
- beam-beam and beam-gas interaction regions are well detached ($\sigma_z = 0.1 - 1$ mm)
- Negligible increase of multiplicity
- $1-3\,\%$ throughput decrease when adding beam-gas to the LHCb event reconstruction sequence





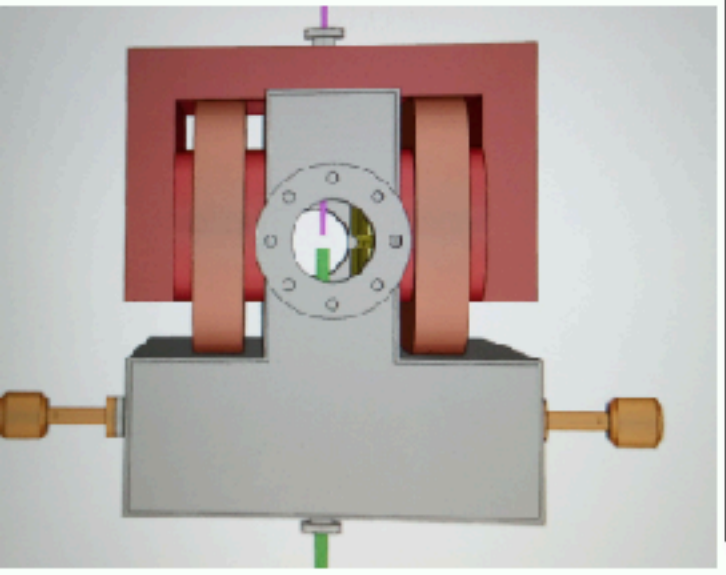
- Full reconstruction efficiency (PV & tracks) retained in the beam-gas region

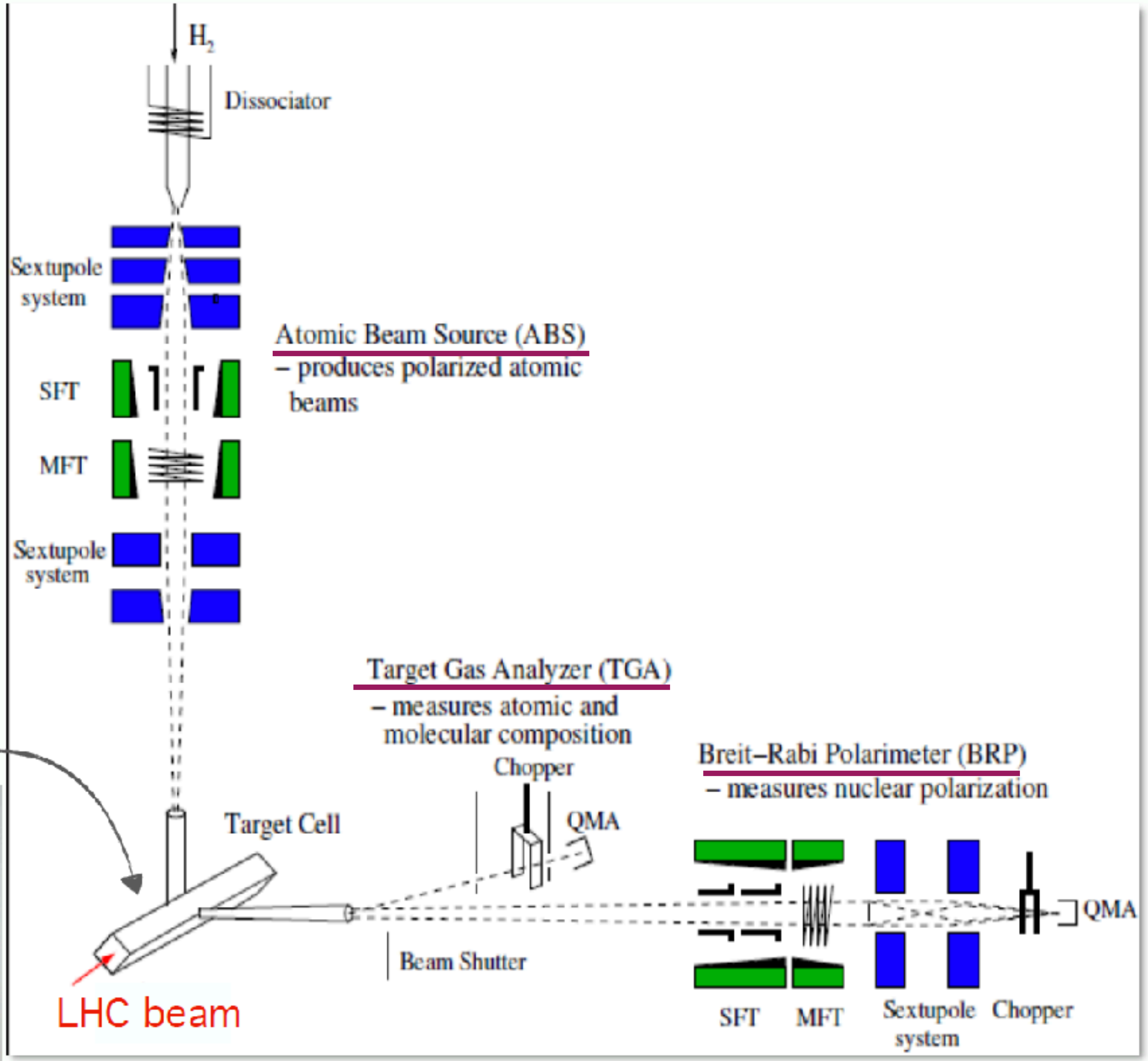




- LHCb will be the only experiment able to run in collider and fixed-target mode simultaneously!

LHCspin experimental setup



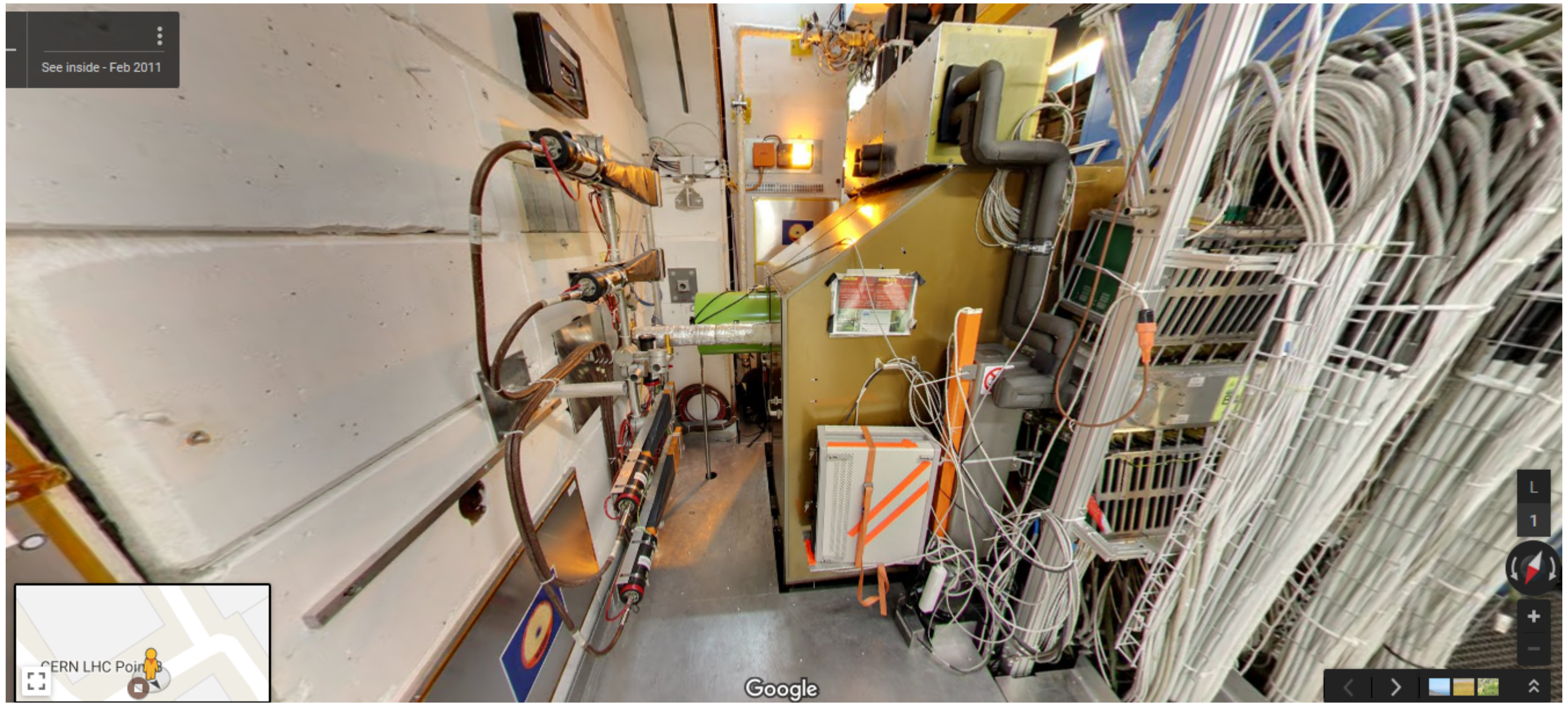


- Start from the well established HERMES setup @ DESY...
- ... to create the next generation of fixed target polarisation techniques!

[NIMA 540 (2005) 68–101]

HERMES PGT

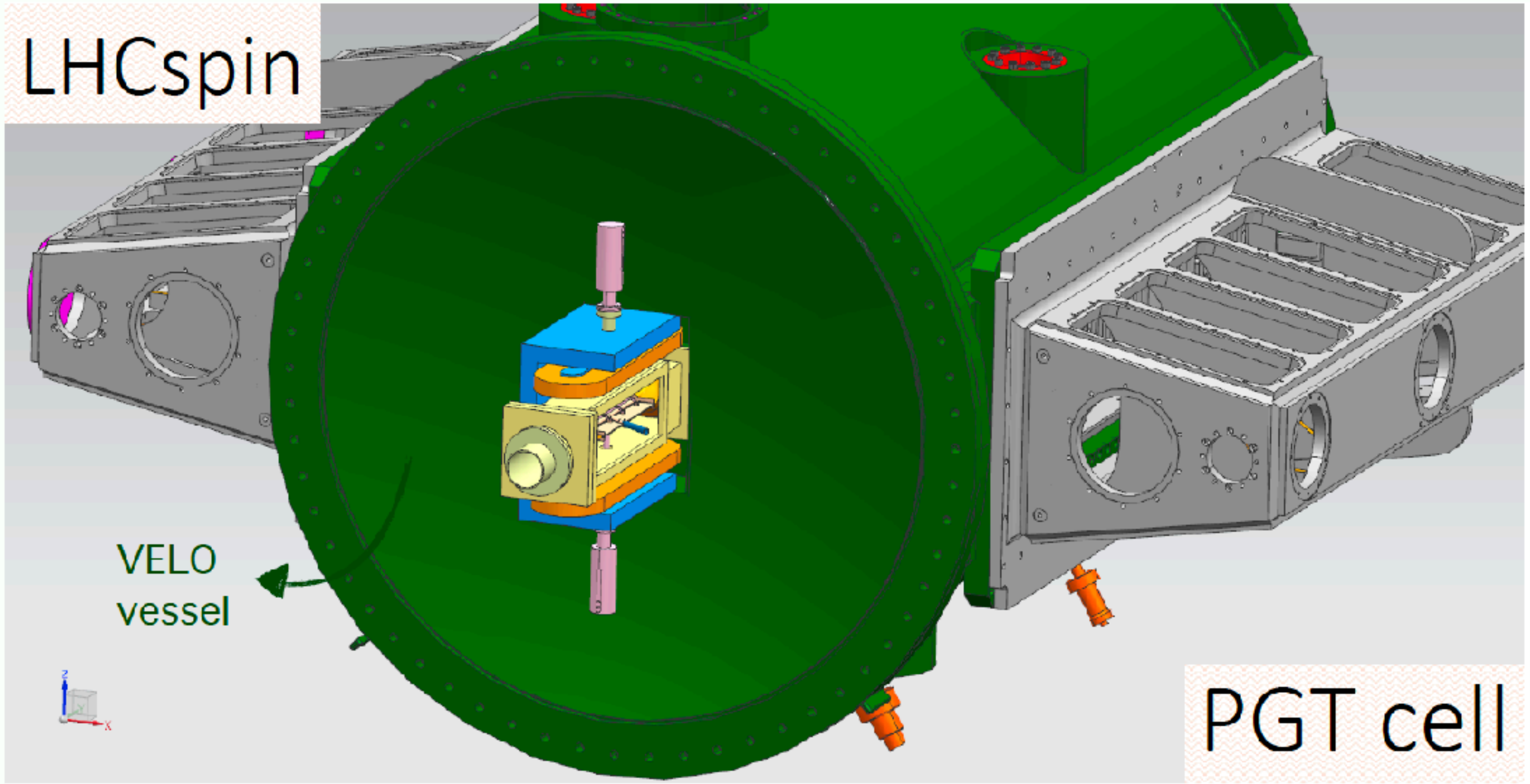
From here to here

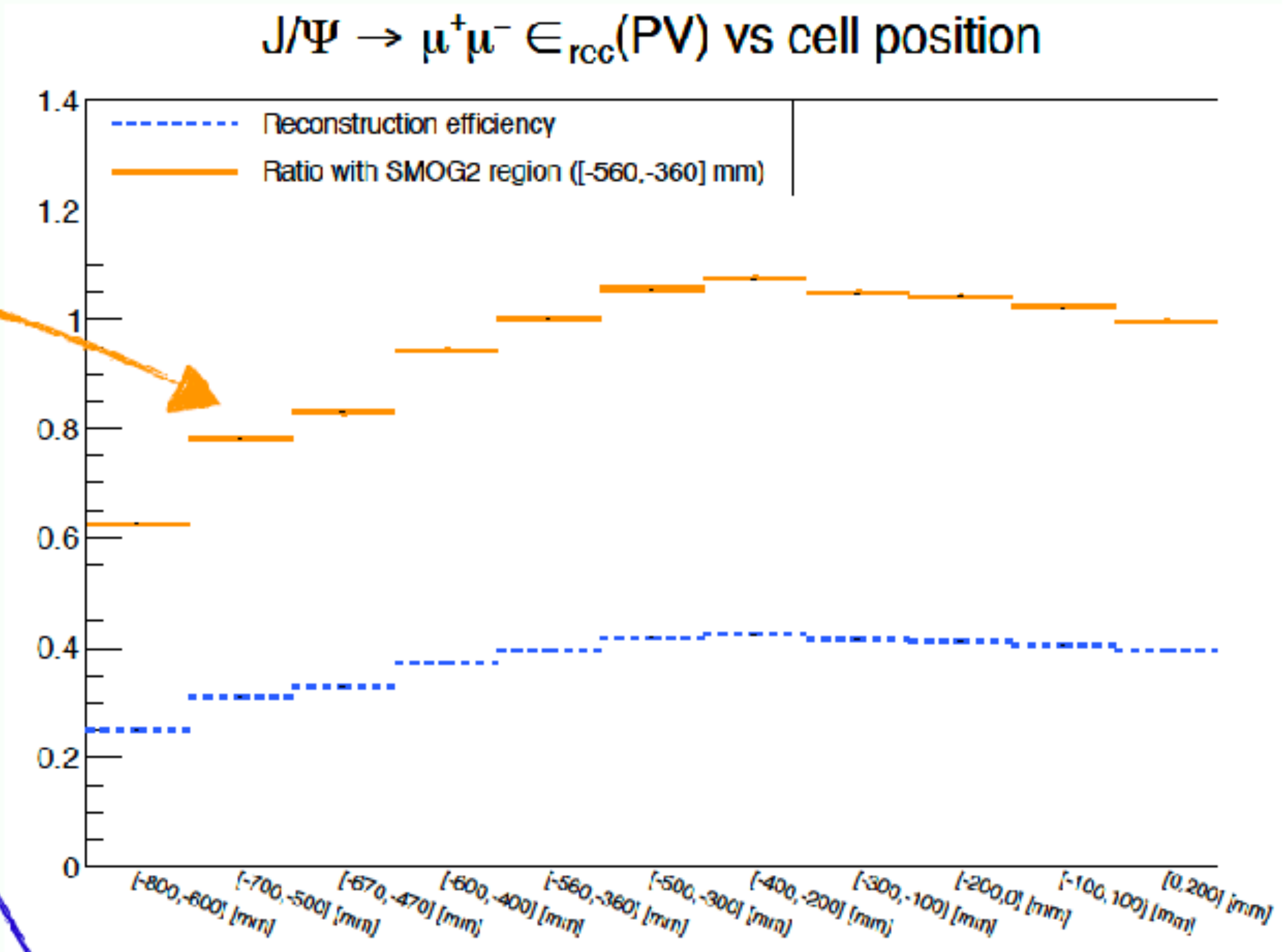


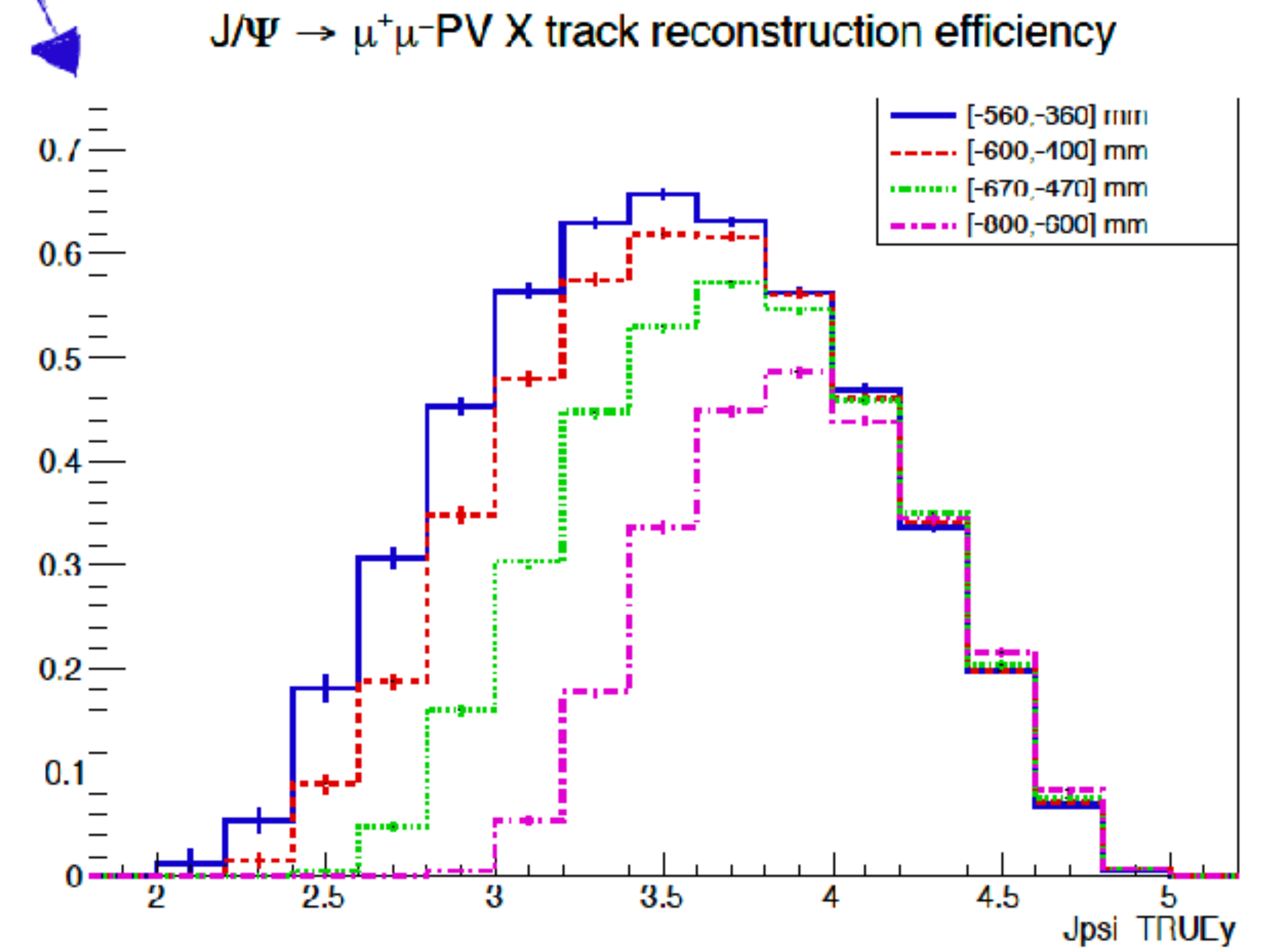
Space available in front of LHCb

PGT implementation into LHCb

- Cylindrical target cell with $L = 20$ cm and $D = 1$ cm
- LHCb simulations show broader kinematic acceptance & higher efficiency at the same position of the SMOG2 cell

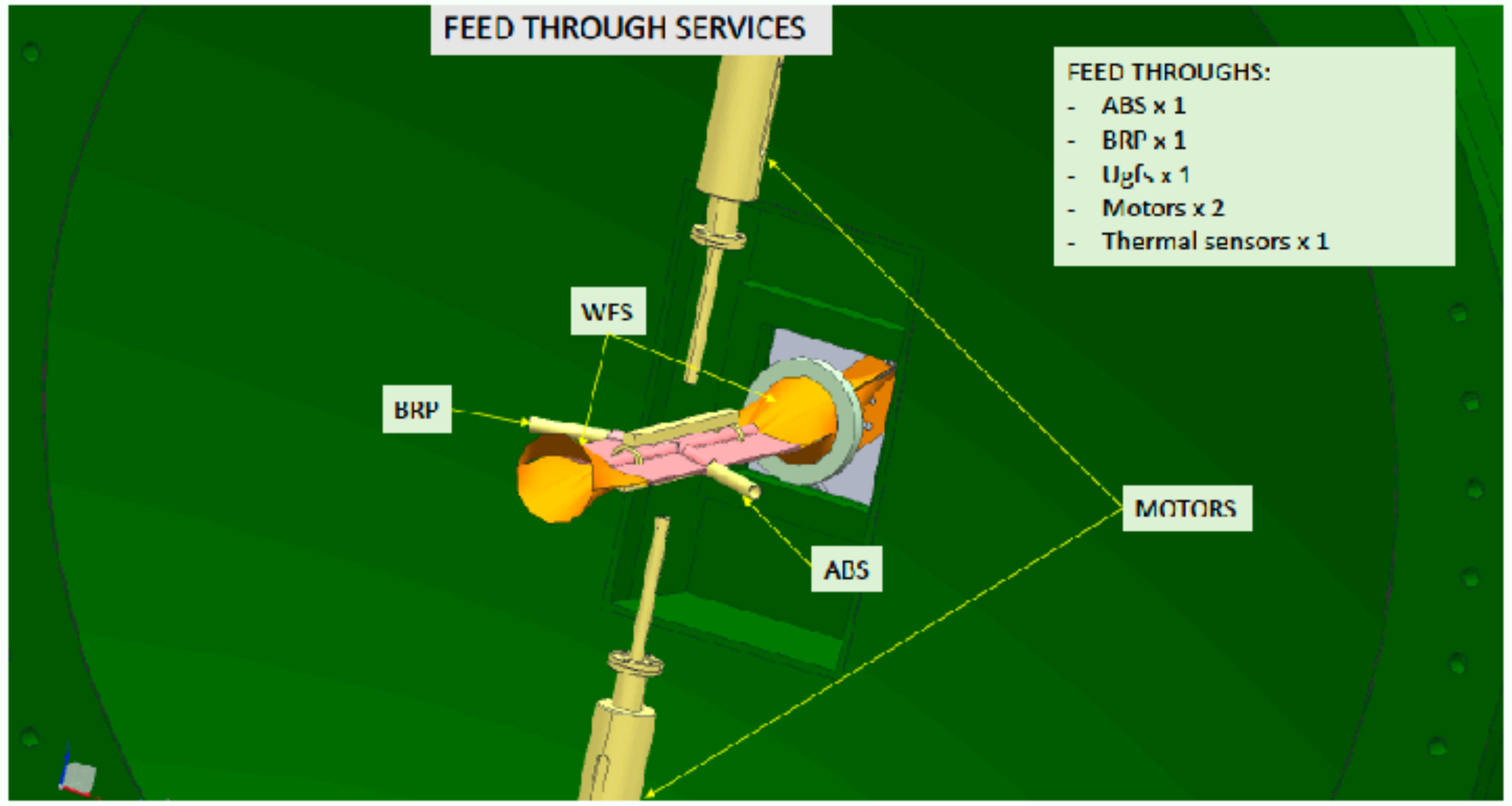


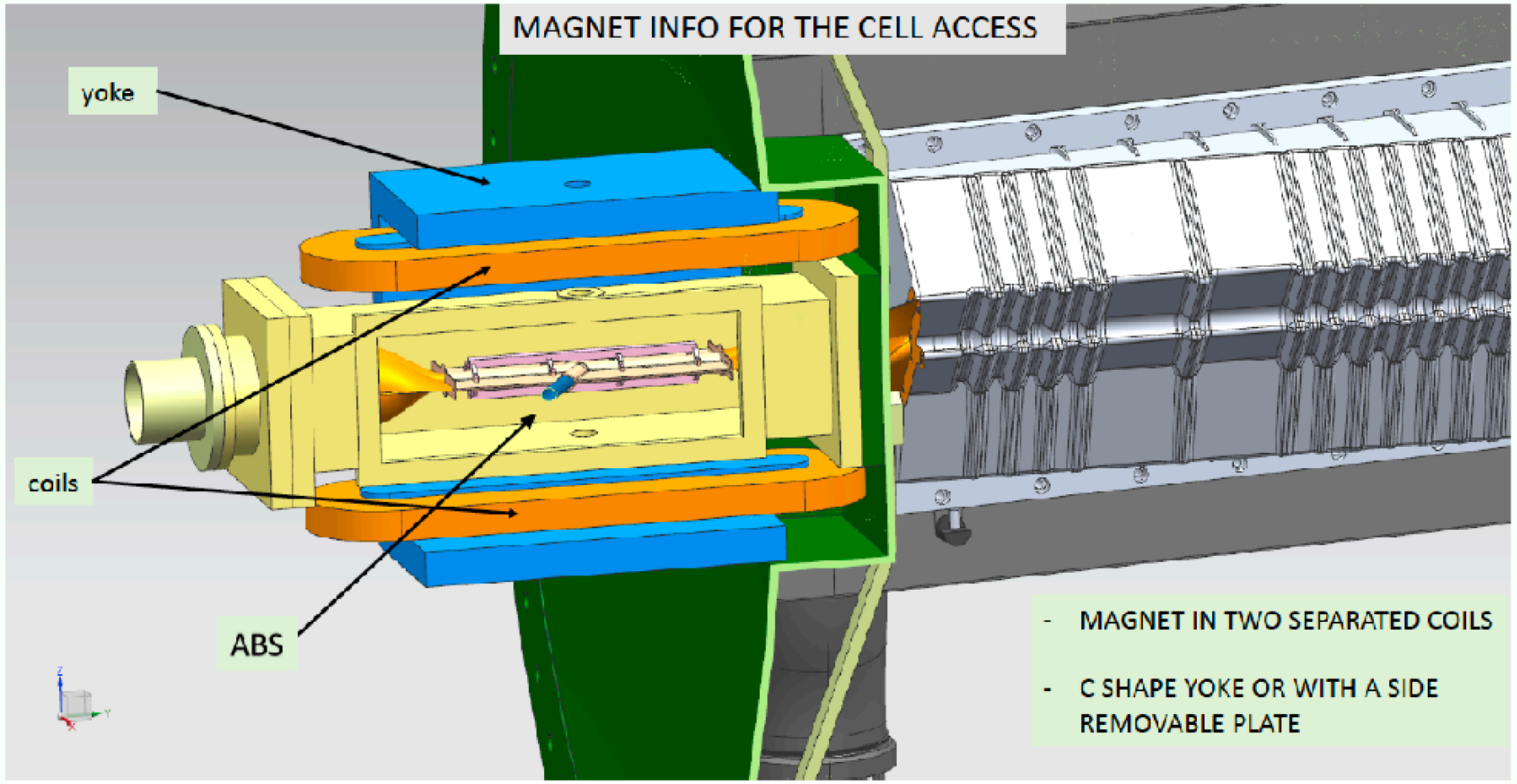




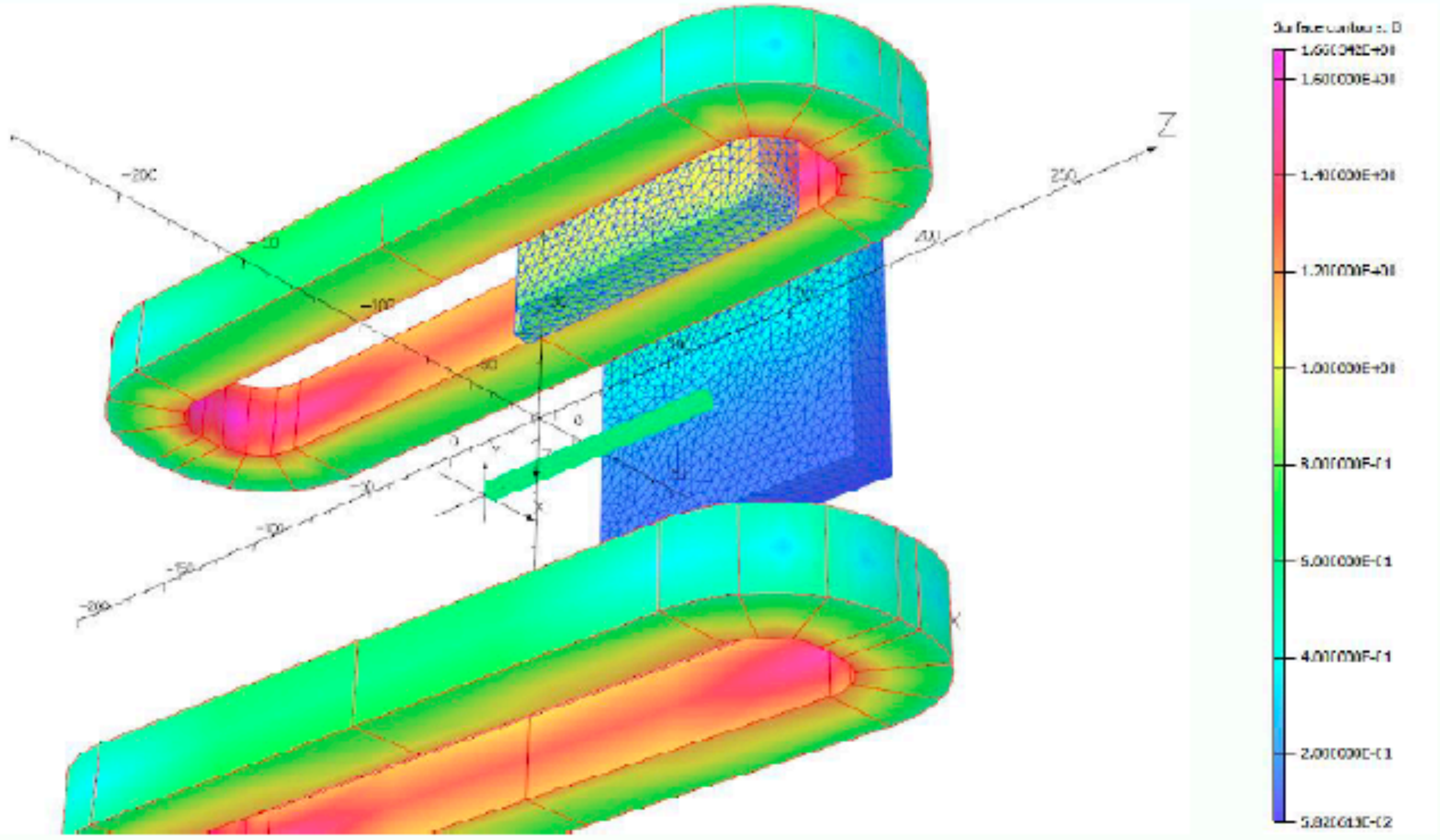
PGT implementation into LHCb

- Inject both polarised and unpolarised gases via ABS and UGFS

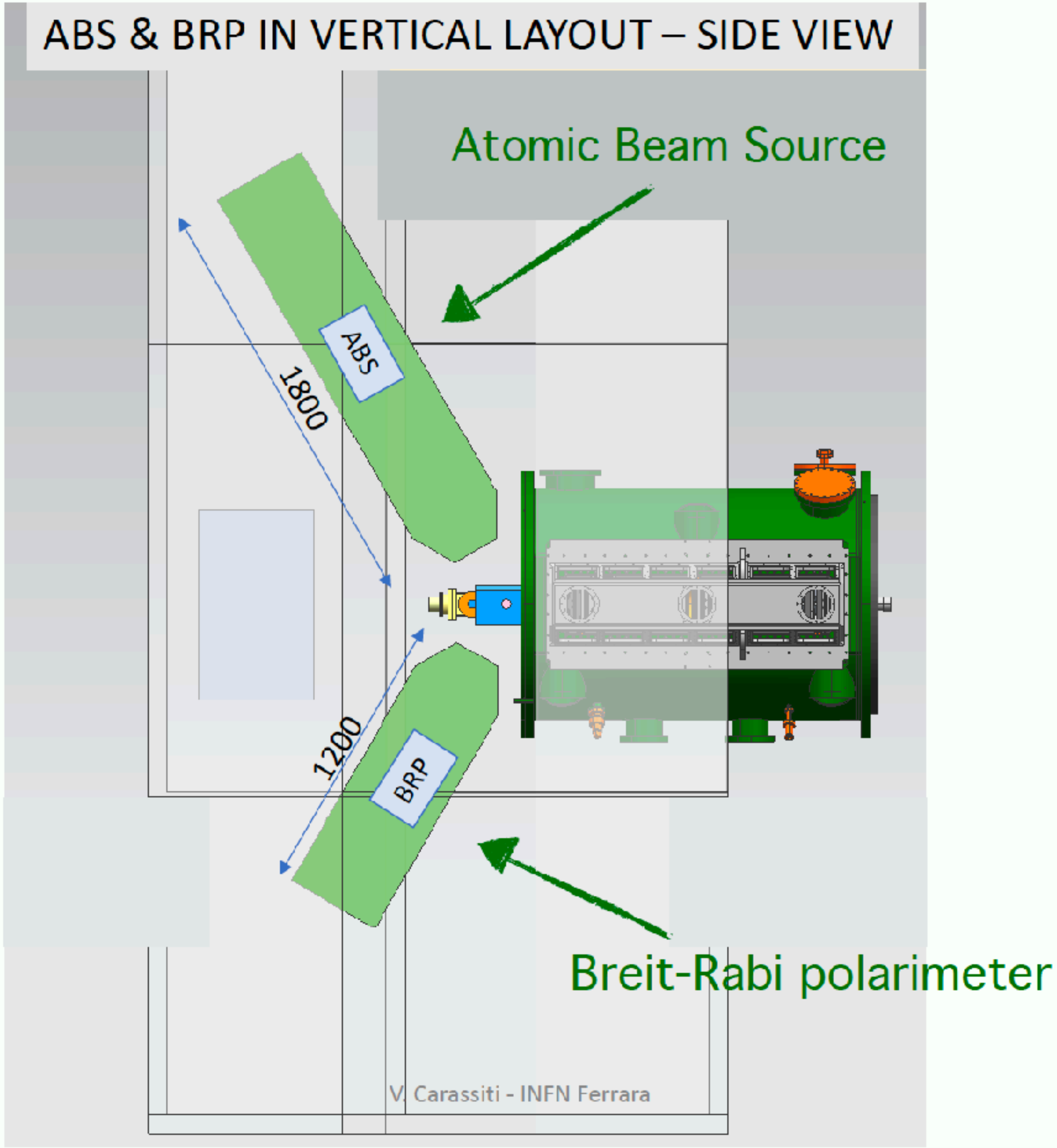




- Compact dipole magnet → static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300$ mT with polarity inversion
- $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation [PoS (SPIN2018)]
- Possibility to switch to a solenoid and provide longitudinal polarisation (e.g. in Run 5)



PGT implementation into LHCb



- Reduce the size of both ABS and BRP to fit into the available space in the LHCb cavern: a challenging R&D!
- No need for additional detectors to LHCb: only a modification of the VELO flange is required
- $P \simeq 85\,\%$ achieved at HERMES

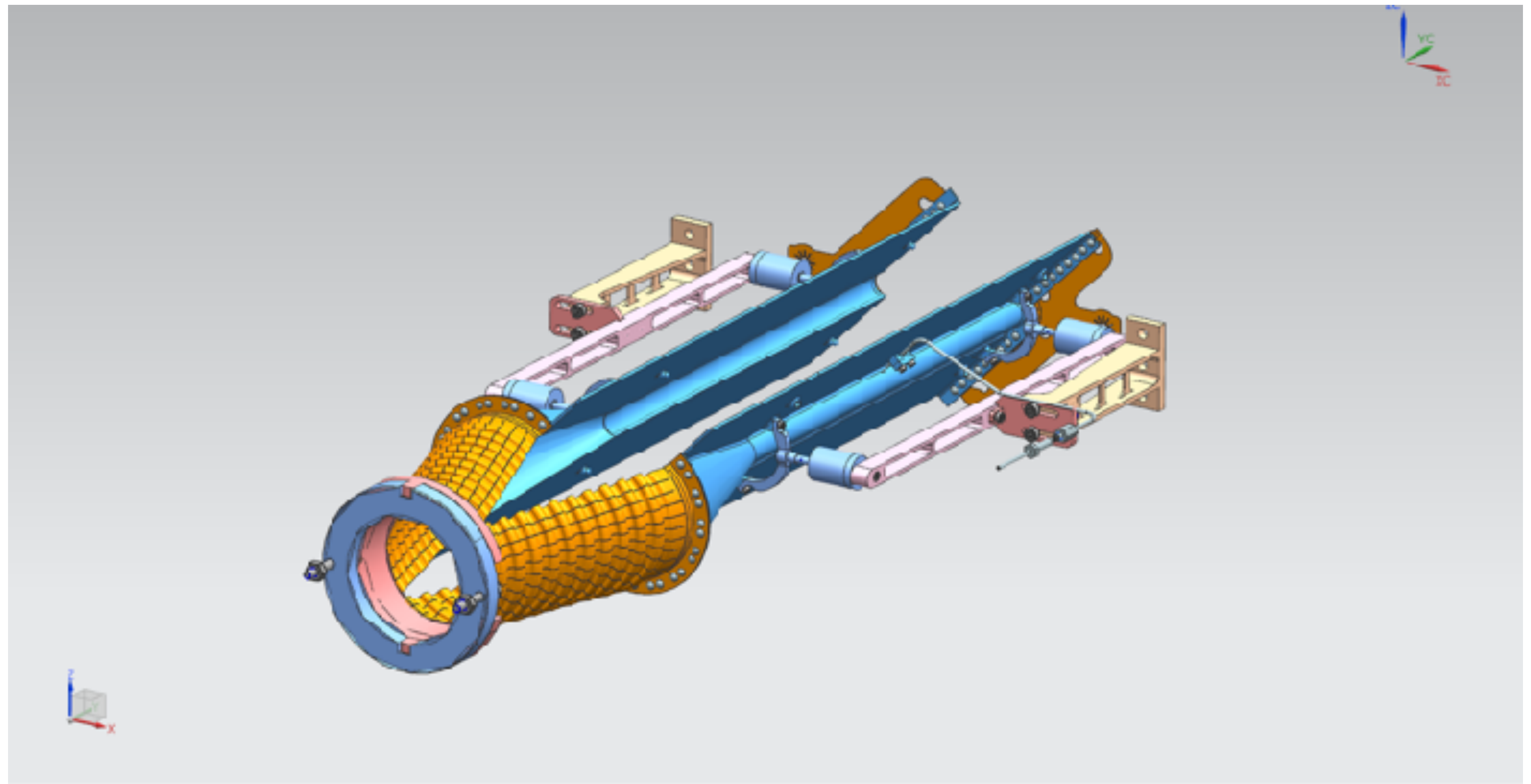
Injected intensity of H-atoms:
$6.5 \times 10^{16}\ \mathrm{s}^{-1}$

Achievable Luminosity (HL-LHC):
$\sim\ 8 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

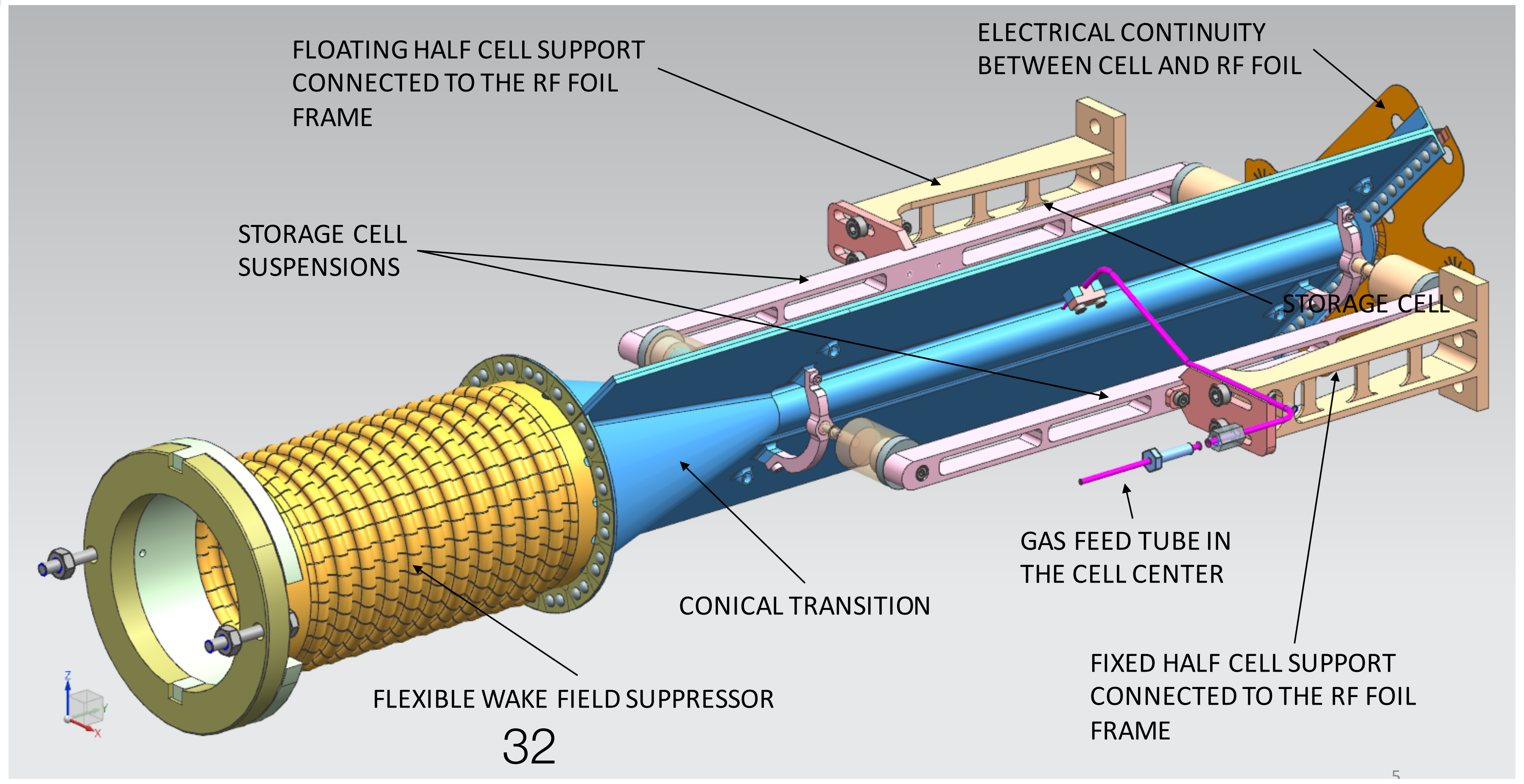
- Alternative solution is being investigated: a jet target provides lower density but higher polarisation degree

Some of the main requirements: openable cell

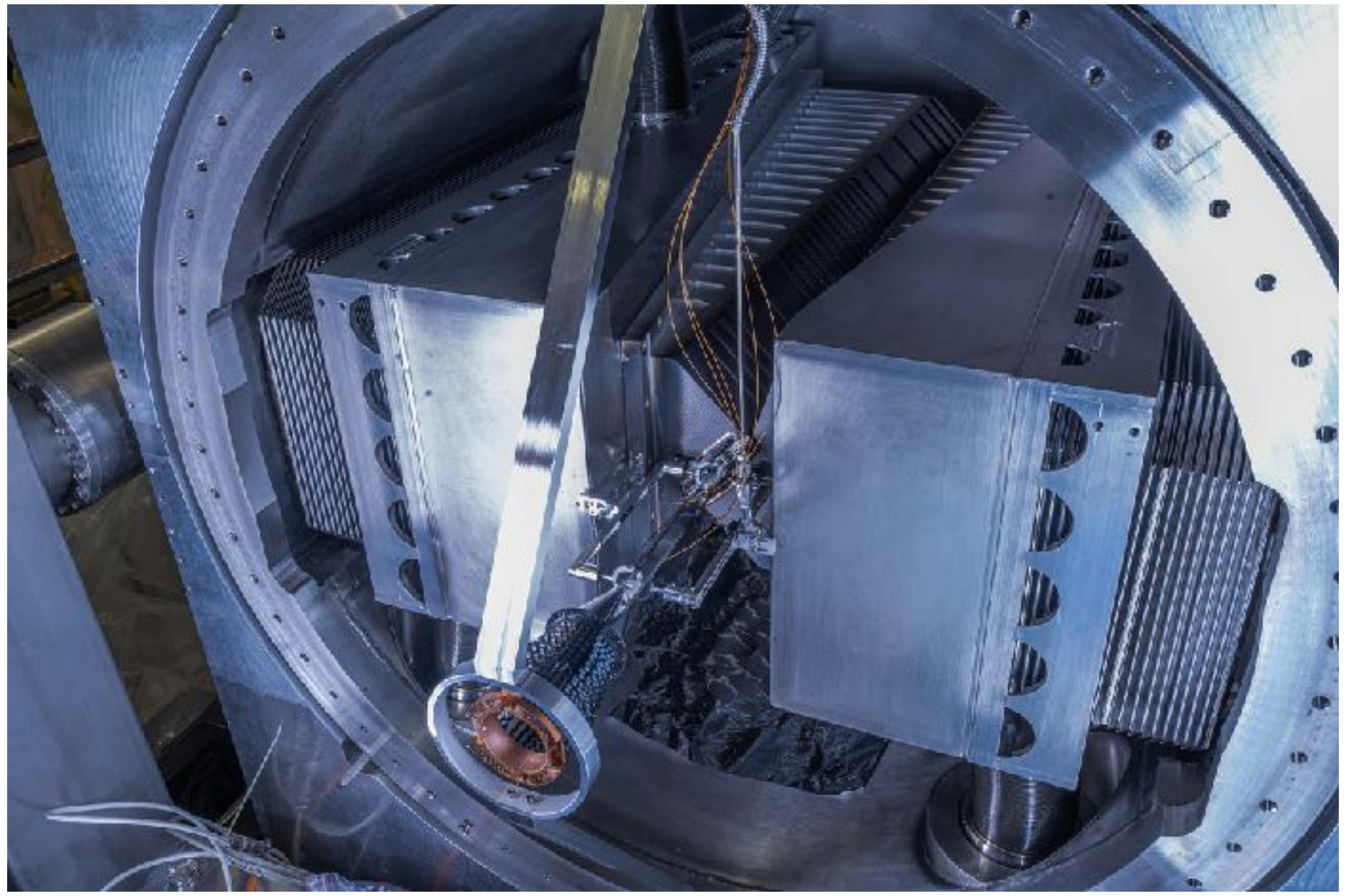
The transverse size of the LHC beam at injection (450 GeV) is much larger than at the lumi run (7 TeV)



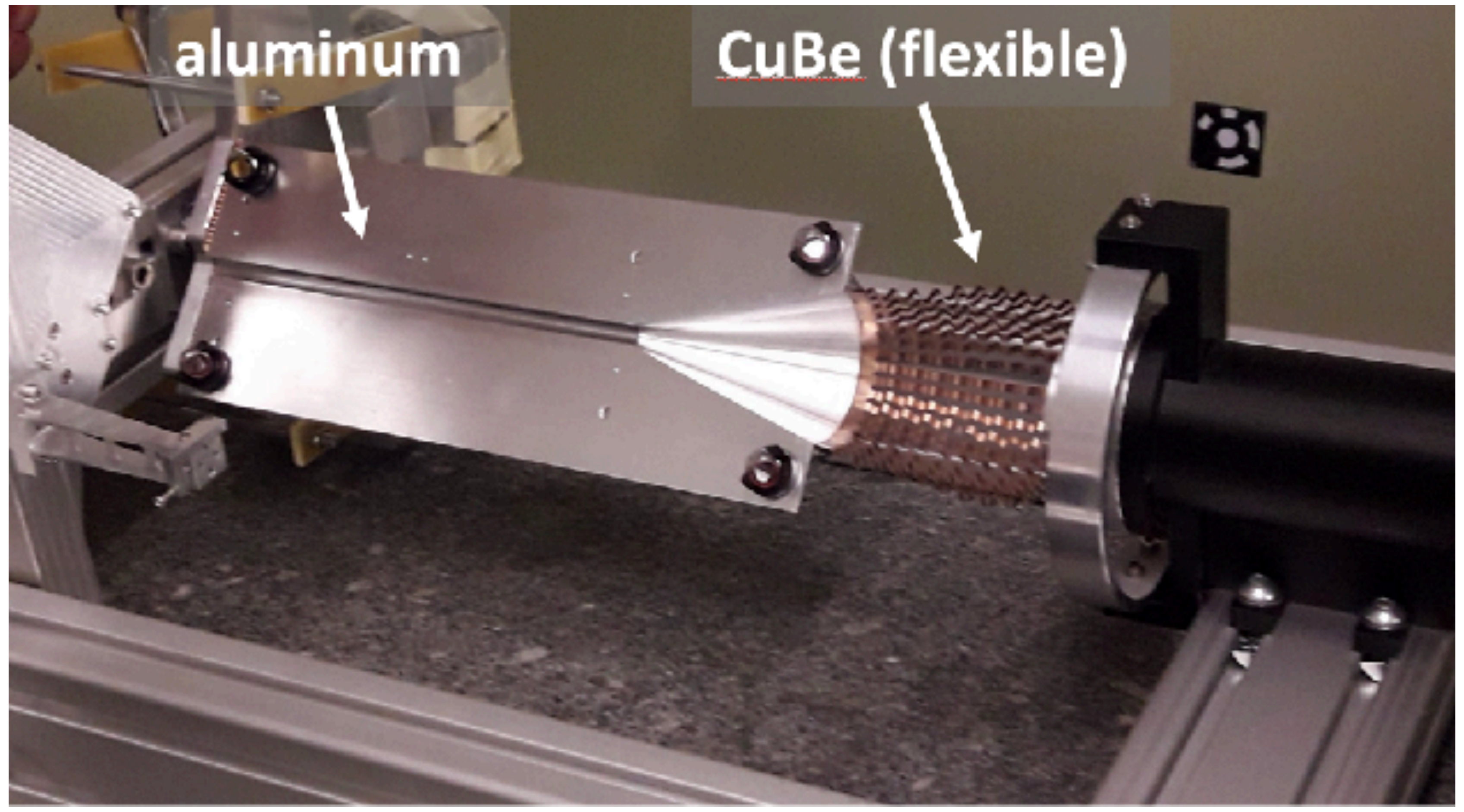
openable storage cell needed



Some of the main requirements: low Secondary Electron Yield



non coated



When primary incident particles hit a surface induce the emission of secondary particles creating beam instability and background

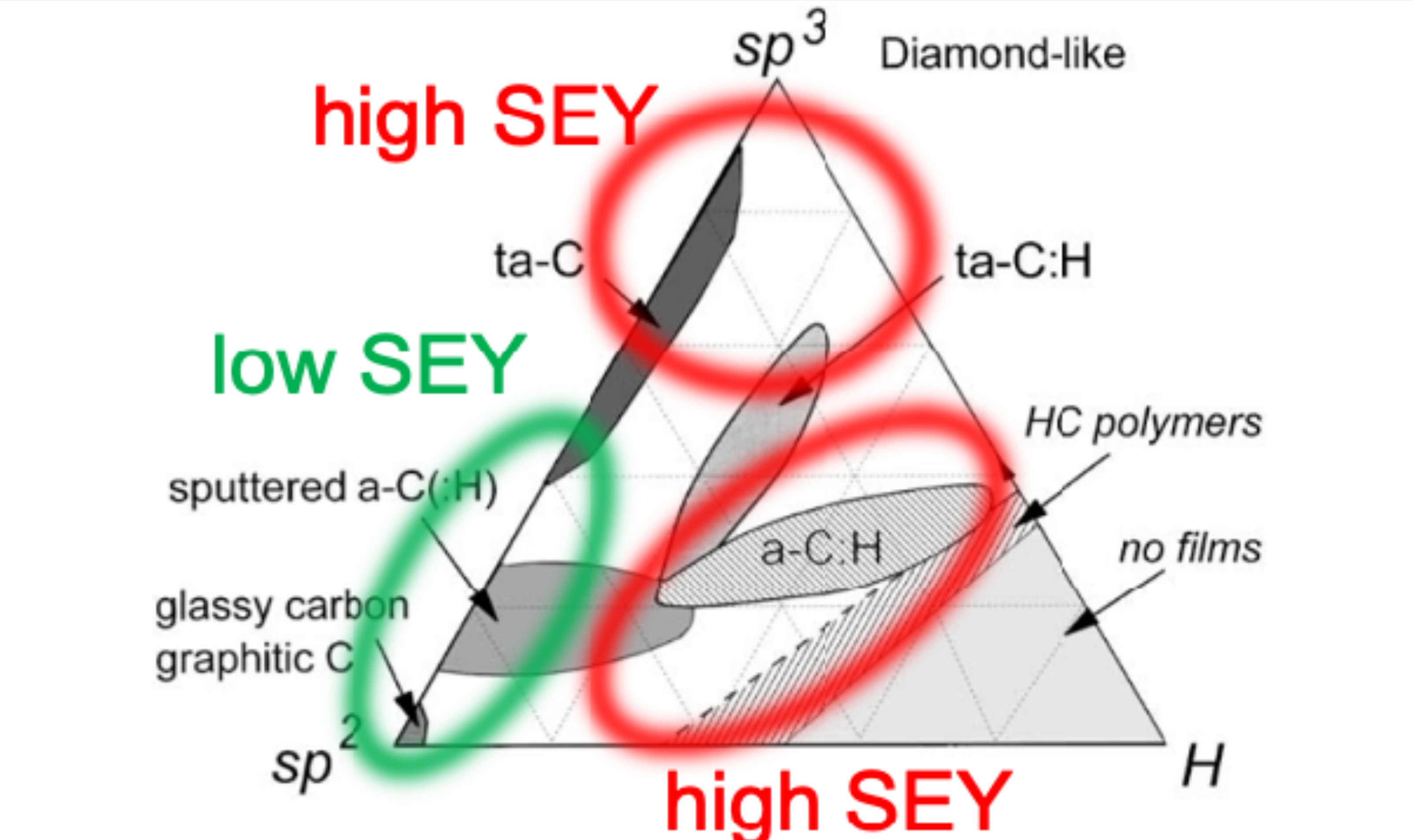
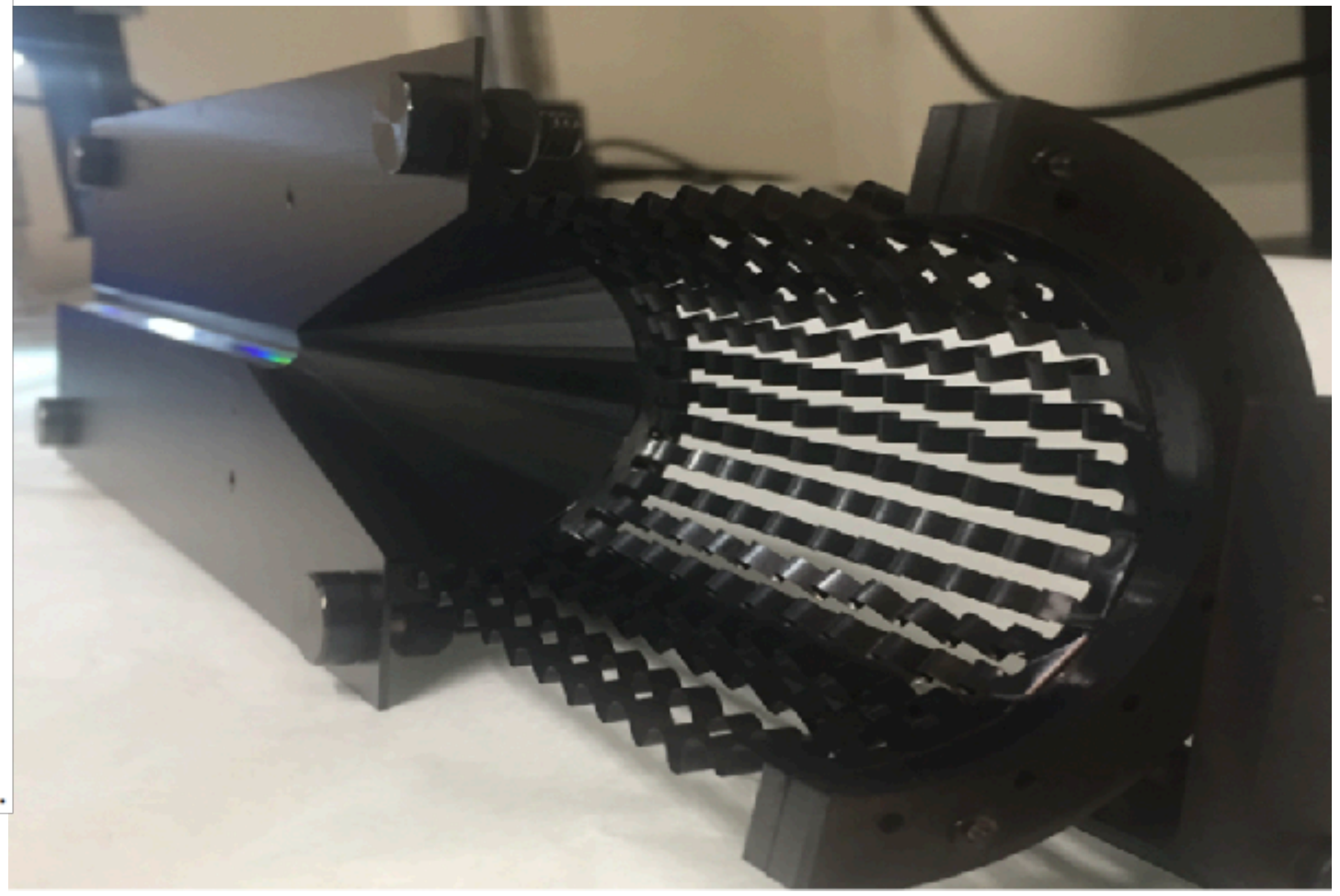


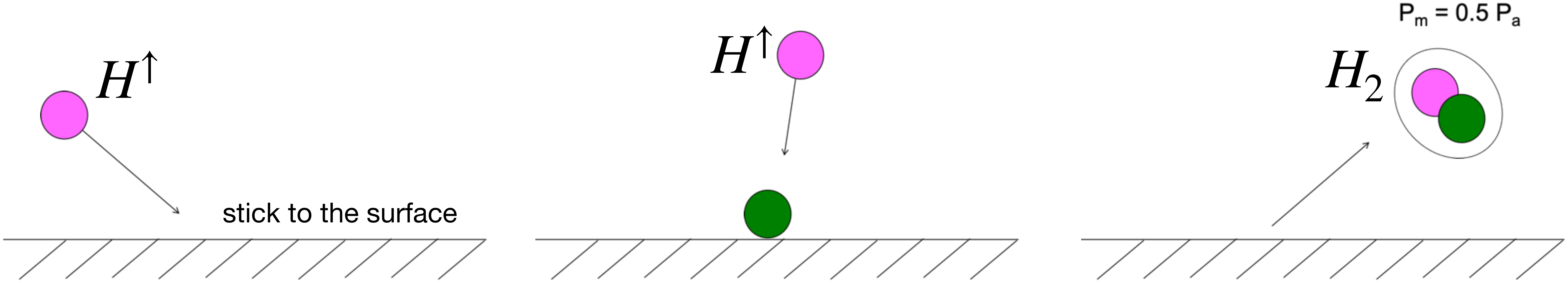
Fig. 2. Ternary phase diagram of bonding in amorphous carbon–hydrogen alloys.

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

amorphous Carbon coated



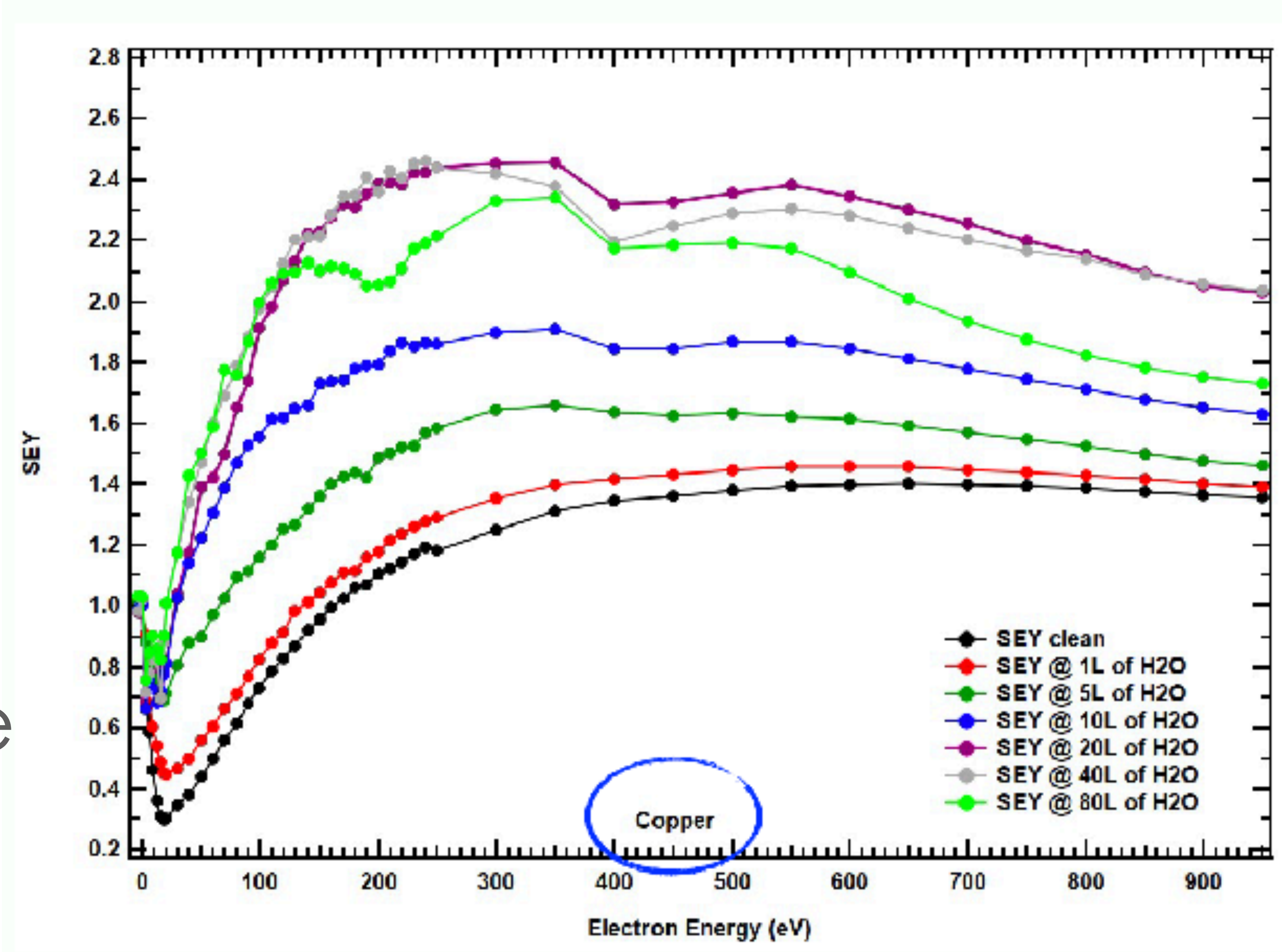
Some of the main requirements: low atomic recombination

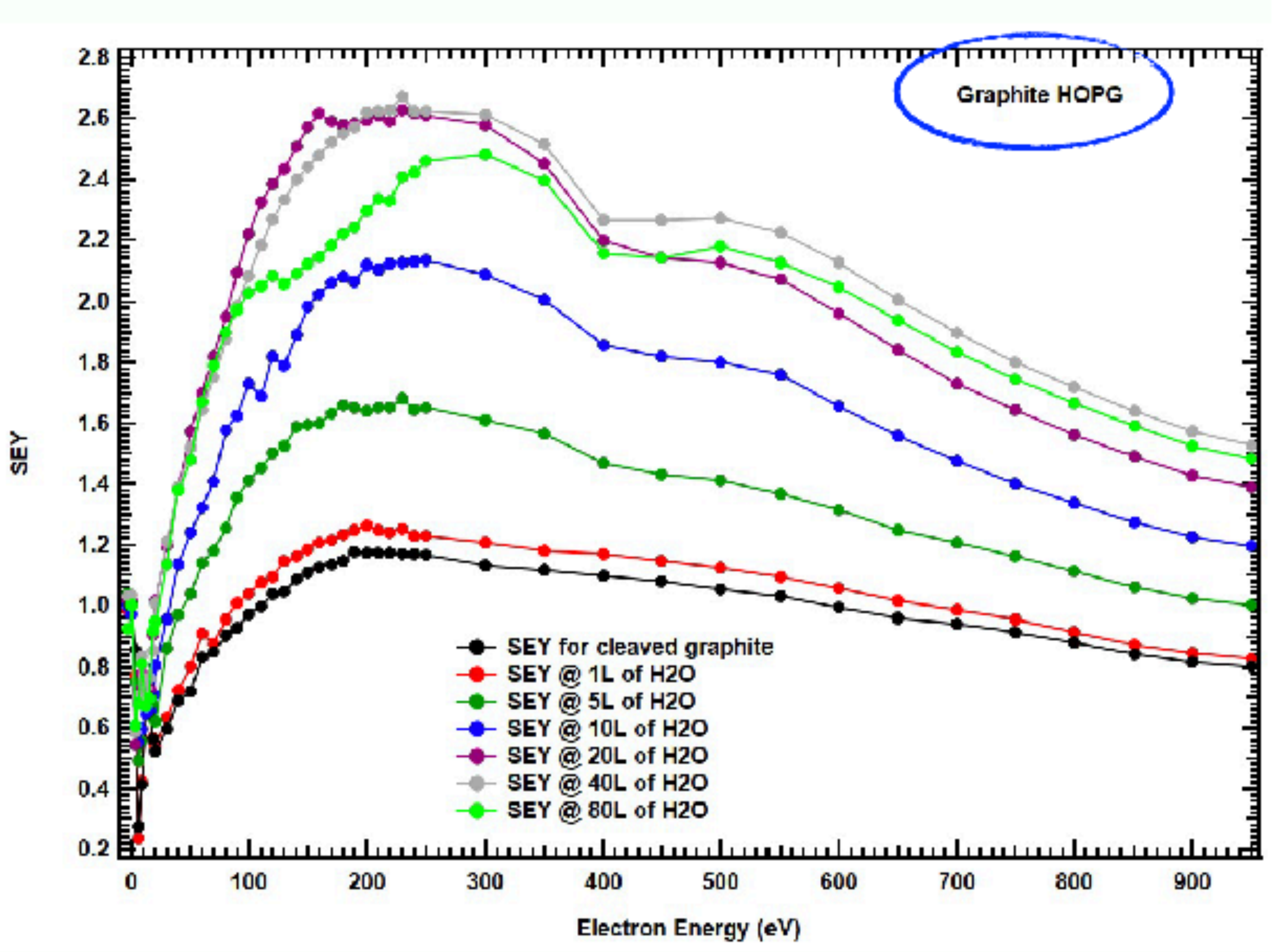


Avoid depolarisation avoiding sticking of particles with a proper coating
Materials used previously are not suitable at LHC

SEY behaviour (copper and ice) measured at the ARYA laboratory at INFN-Frascati laboratory

Copper: SEY ok, depol not-OK
Ice : SEY ok, depol ok … very difficult to have

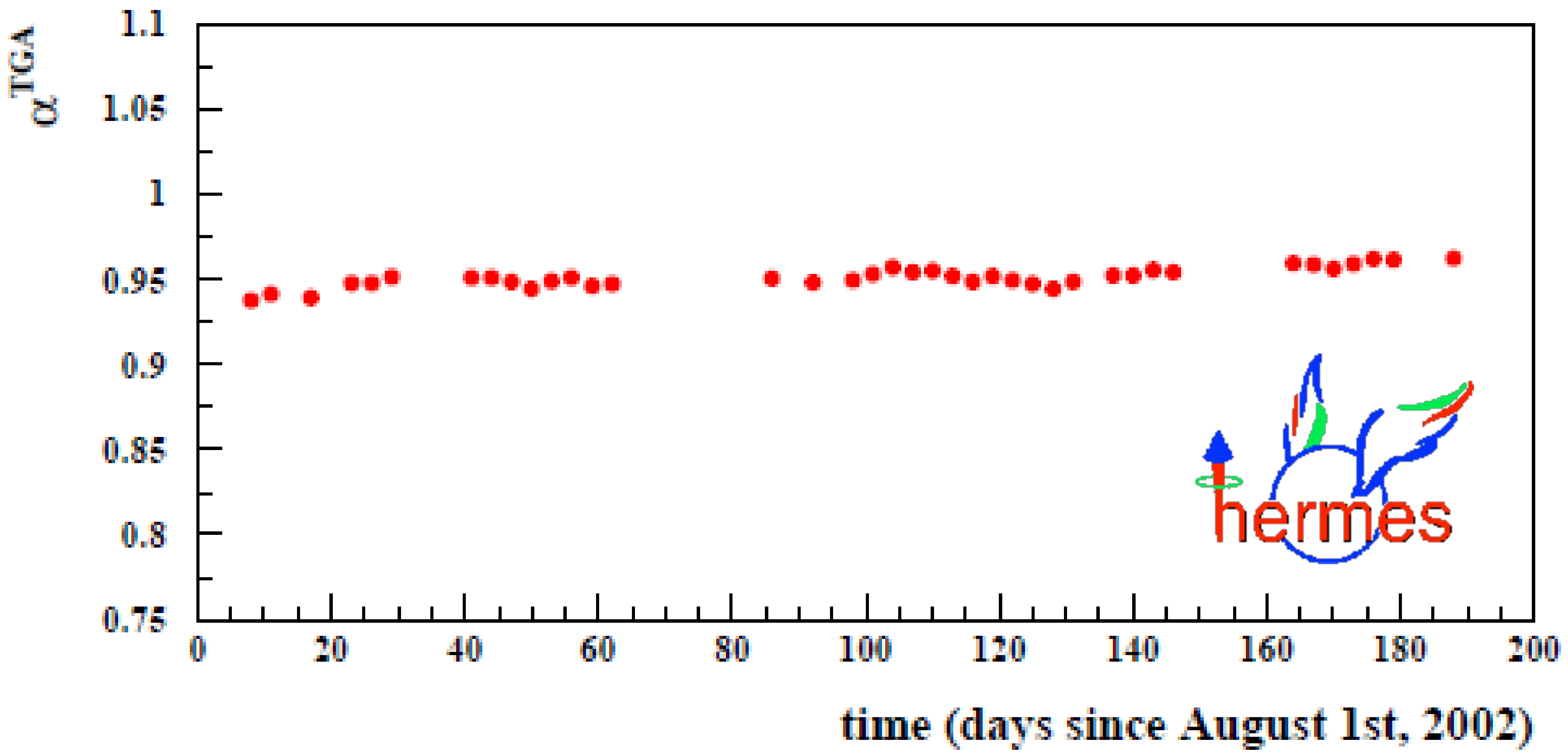




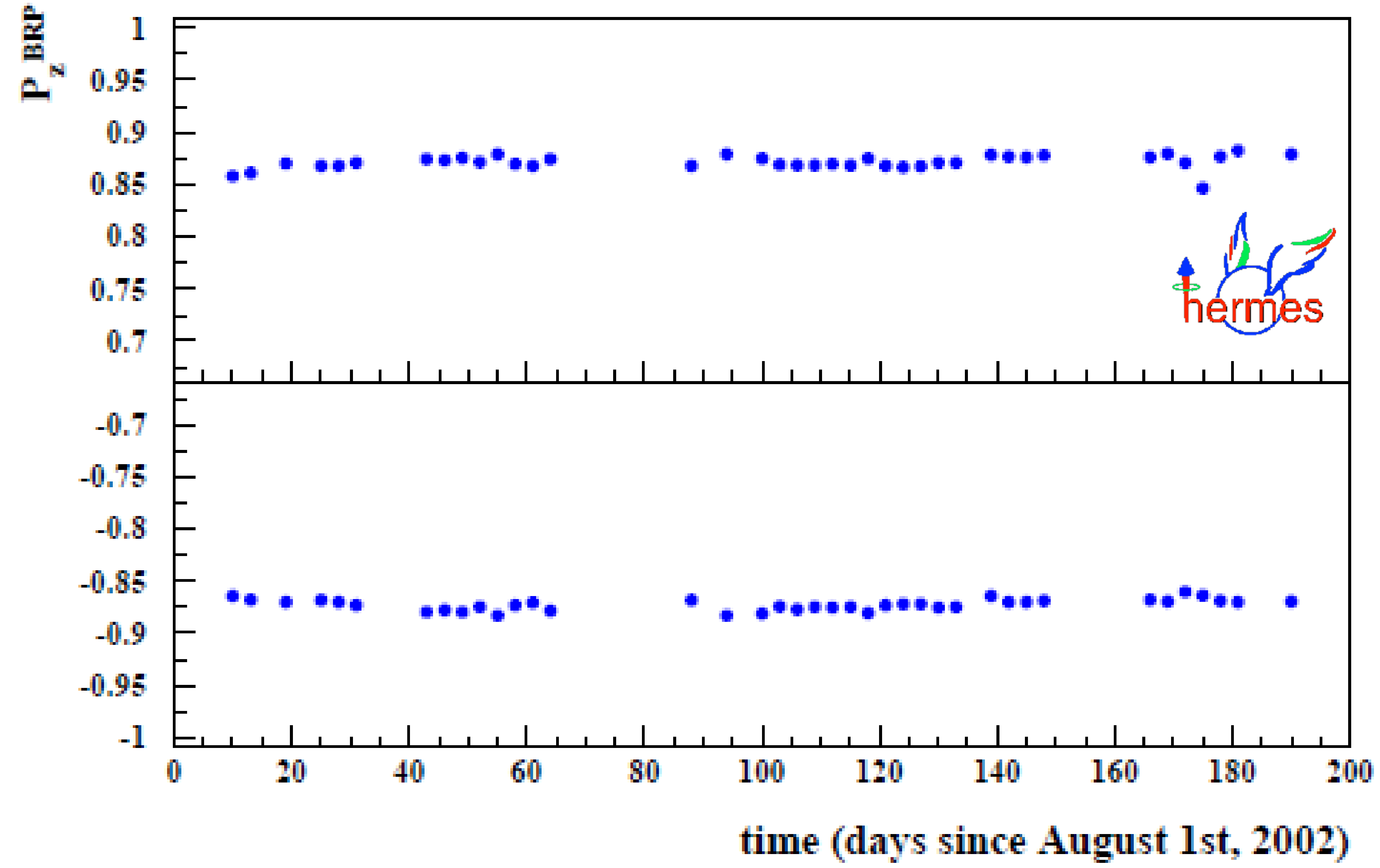
World best results reached

HERMES system
storage cell coated with Drifilm+ice @ 100 K

H recombination
(1-α)



H transverse
polarisation



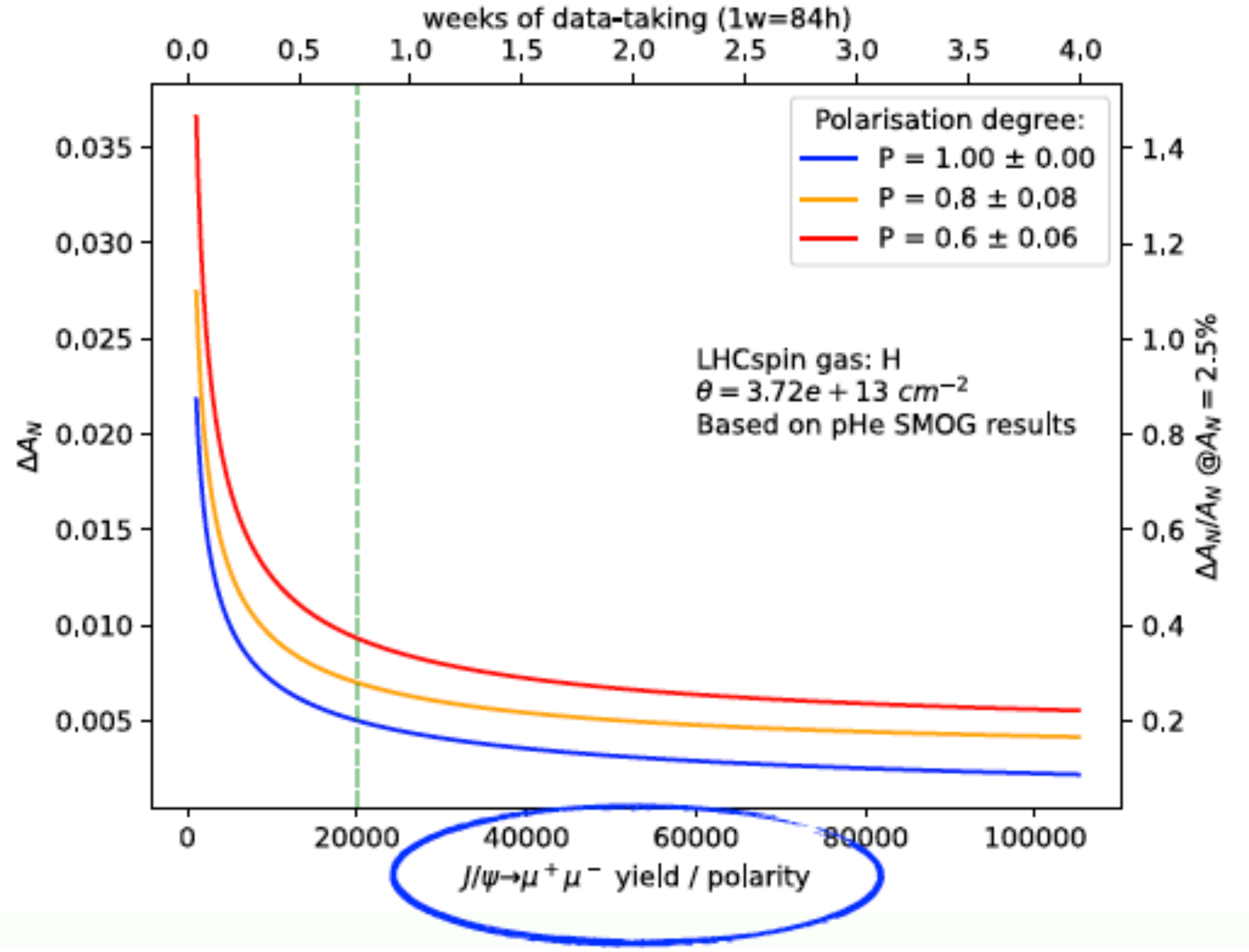
LHCspin event rates

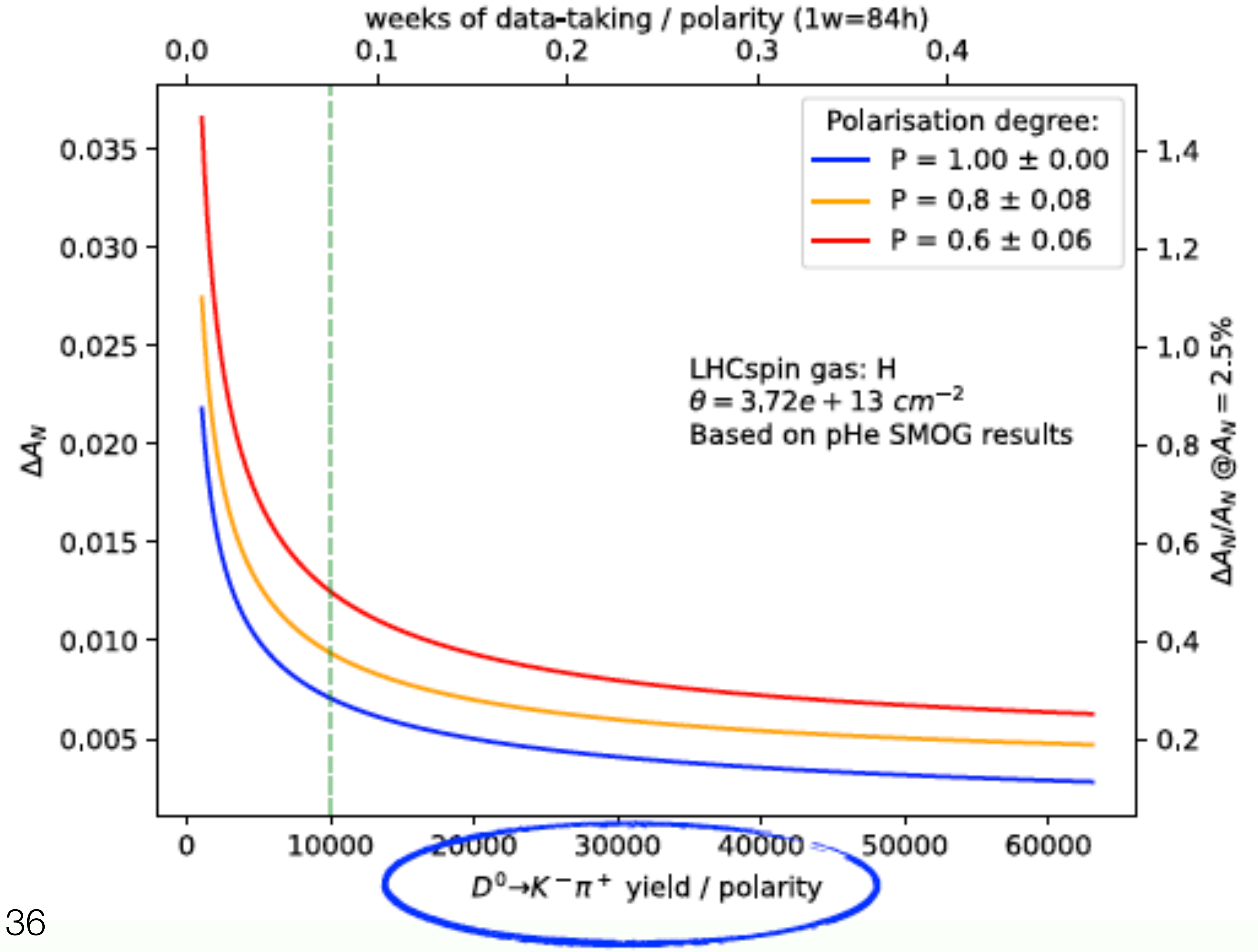
- First look at expected statistics (order of magnitude) in terms of a spin asymmetry:

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

- Projected uncertainty on TSSA with different polarisation degrees

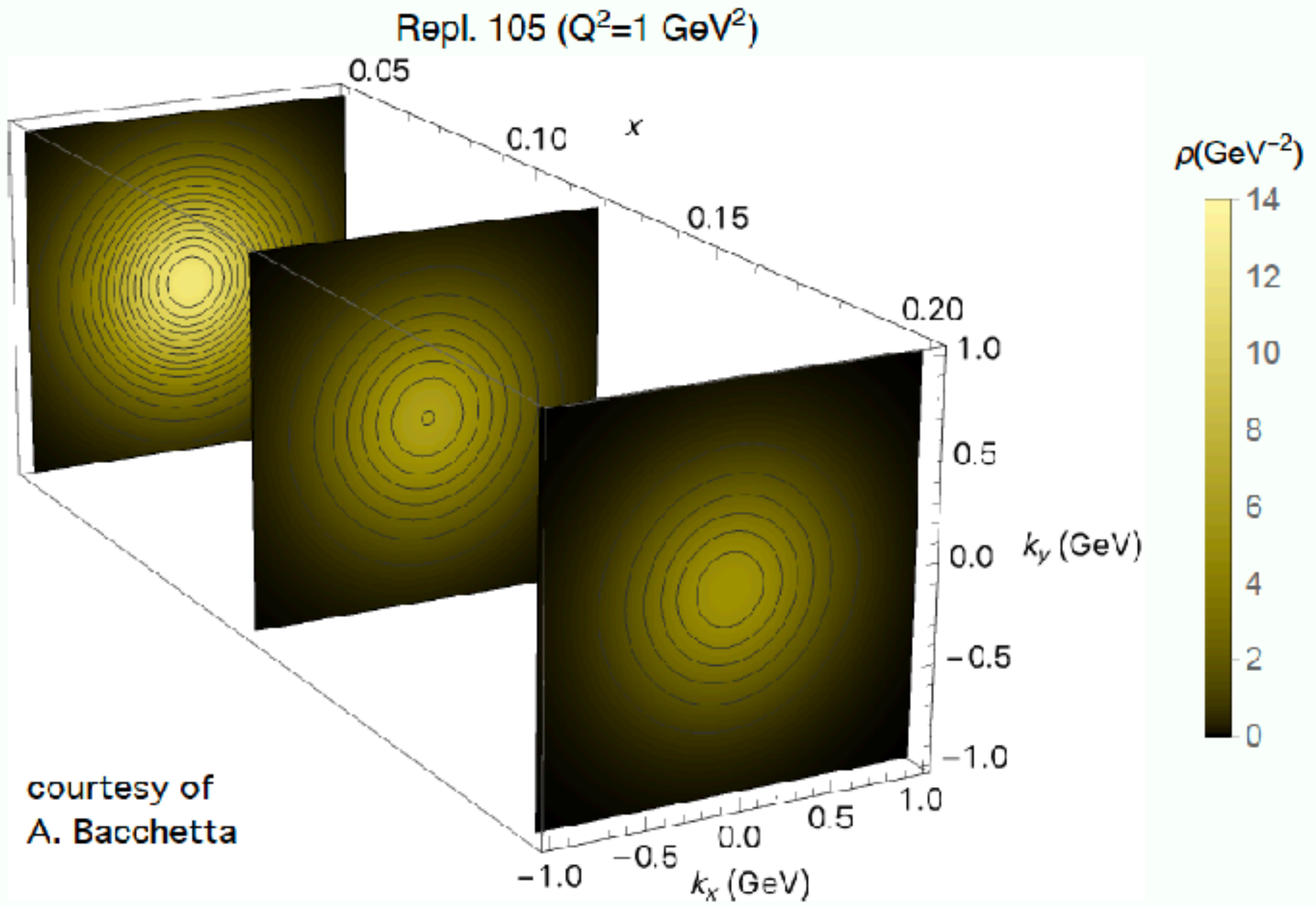
- Precise spin asymmetry on $J/\psi \to \mu^+\mu^-$ for $pH^{\uparrow}$ collisions in just a few weeks with Run 3 luminosity!
- Statistics further enhanced by a factor $\sim 3-5$ in Upgrade II





TMDs

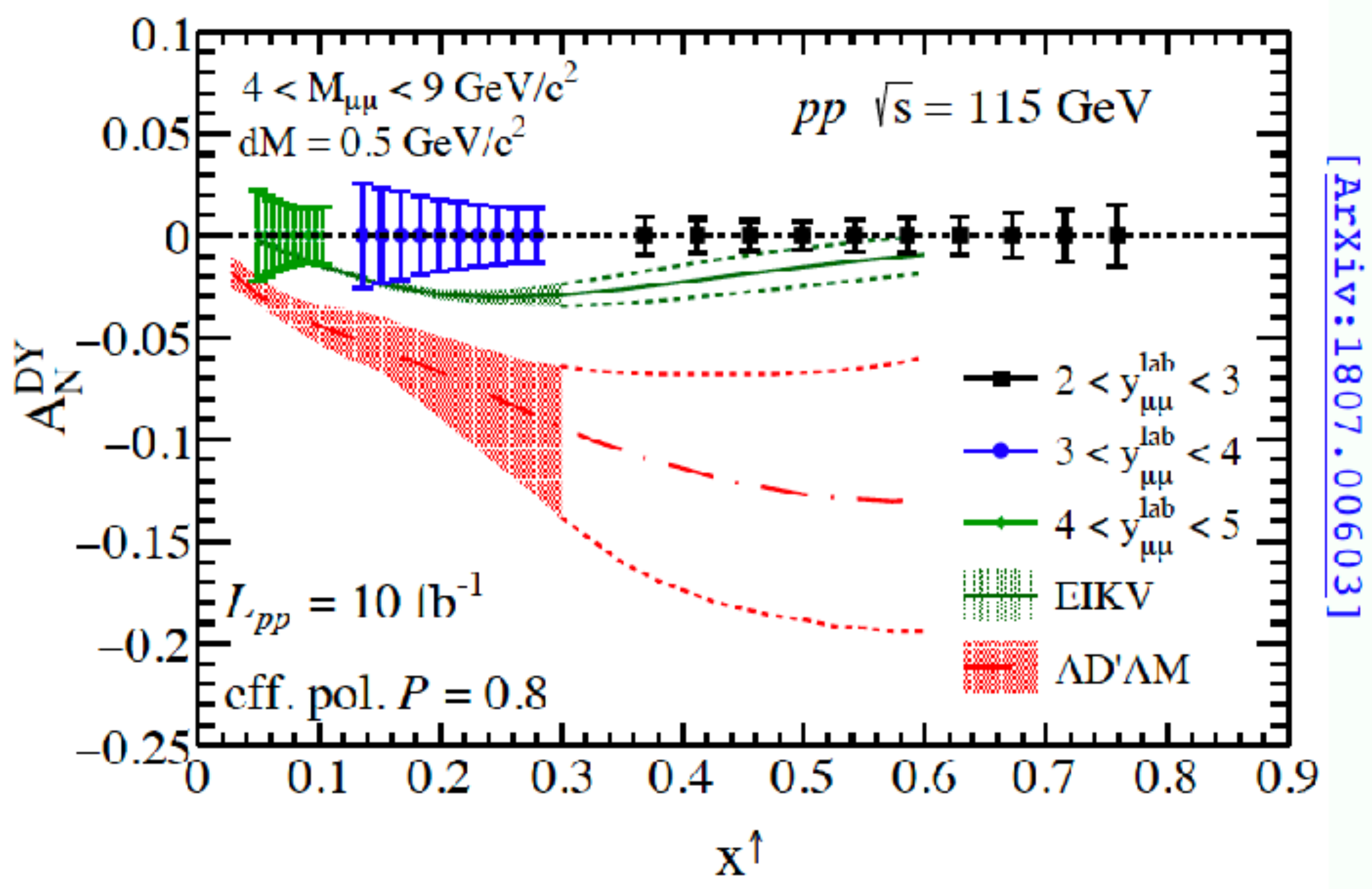
- 3D momentum "tomography" of hadrons:



- To access the transverse motion of partons inside a polarised nucleon: measure TMDs via TSSAs at high $x_2^\uparrow$ (and low x_1)

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \longrightarrow A_N \sim \frac{f_1^q(x_1, k_{T1}^2) \otimes f_{1T}^{\perp\bar{q}}(x_2, k_{T2}^2)}{f_1^q(x_1, k_{T1}^2) \otimes f_1^q(x_2, k_{T2}^2)}$$

- Projections of polarised Drell-Yan data with $10\ \mathrm{fb}^{-1}$



- Verify the sign change of the Sivers TMD in DY wrt SIDIS:

$$f_{1T}^{\perp q}(x, k_T^2)_{\mathrm{DY}} = -f_{1T}^{\perp q}(x, k_T^2)_{\mathrm{SIDIS}}$$

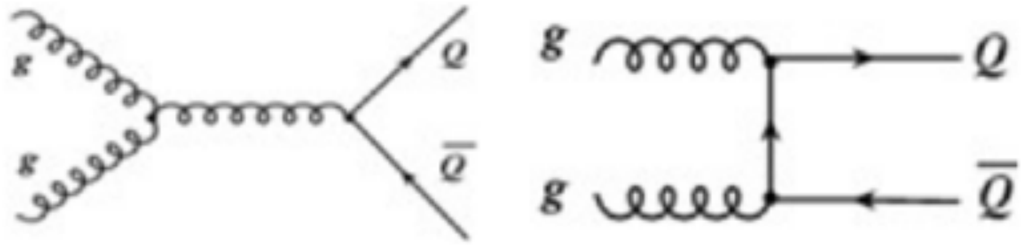
- + isospin effect with polarised deuterium

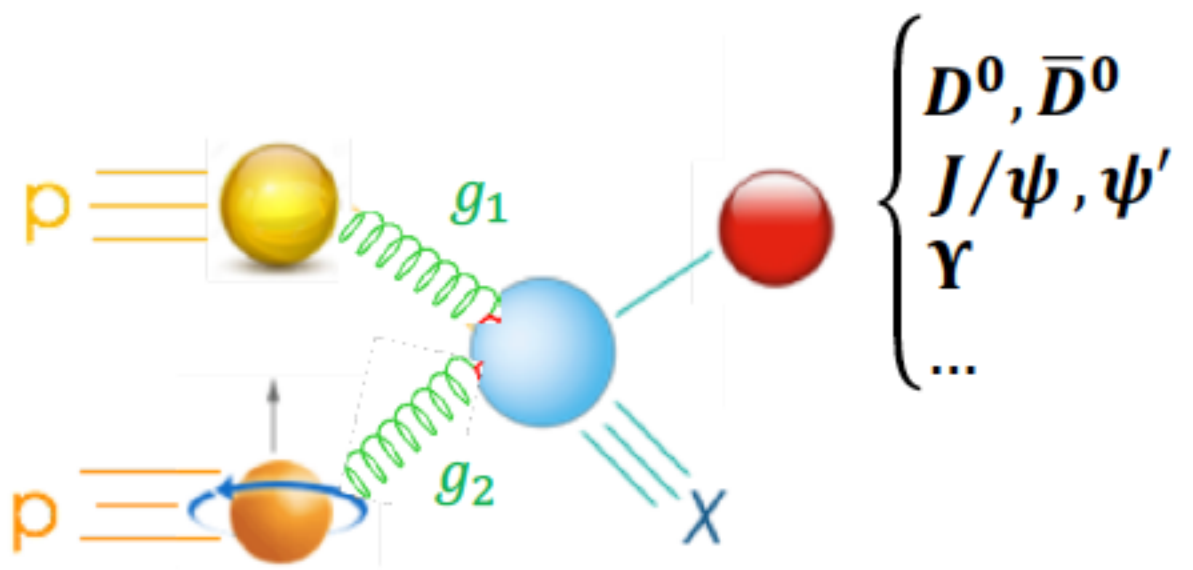
- Sea-quark component accessed via $W^\pm$ boson production, with $\Delta A_N \sim 0.1 - 0.2$ complementing RHIC [PRL 116 (2016) 132301]

The gluon Sivers function

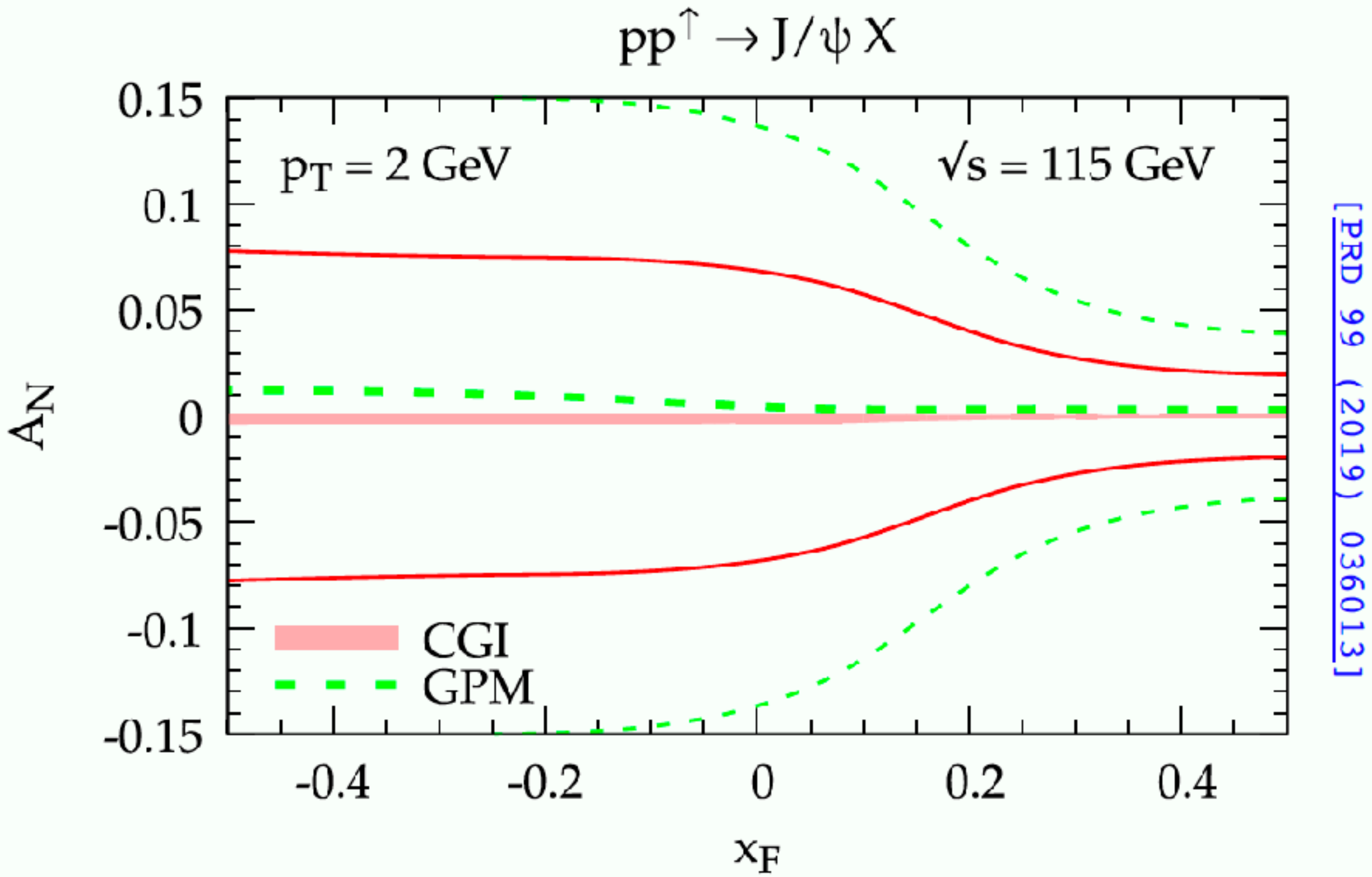
Completely unconstrained!

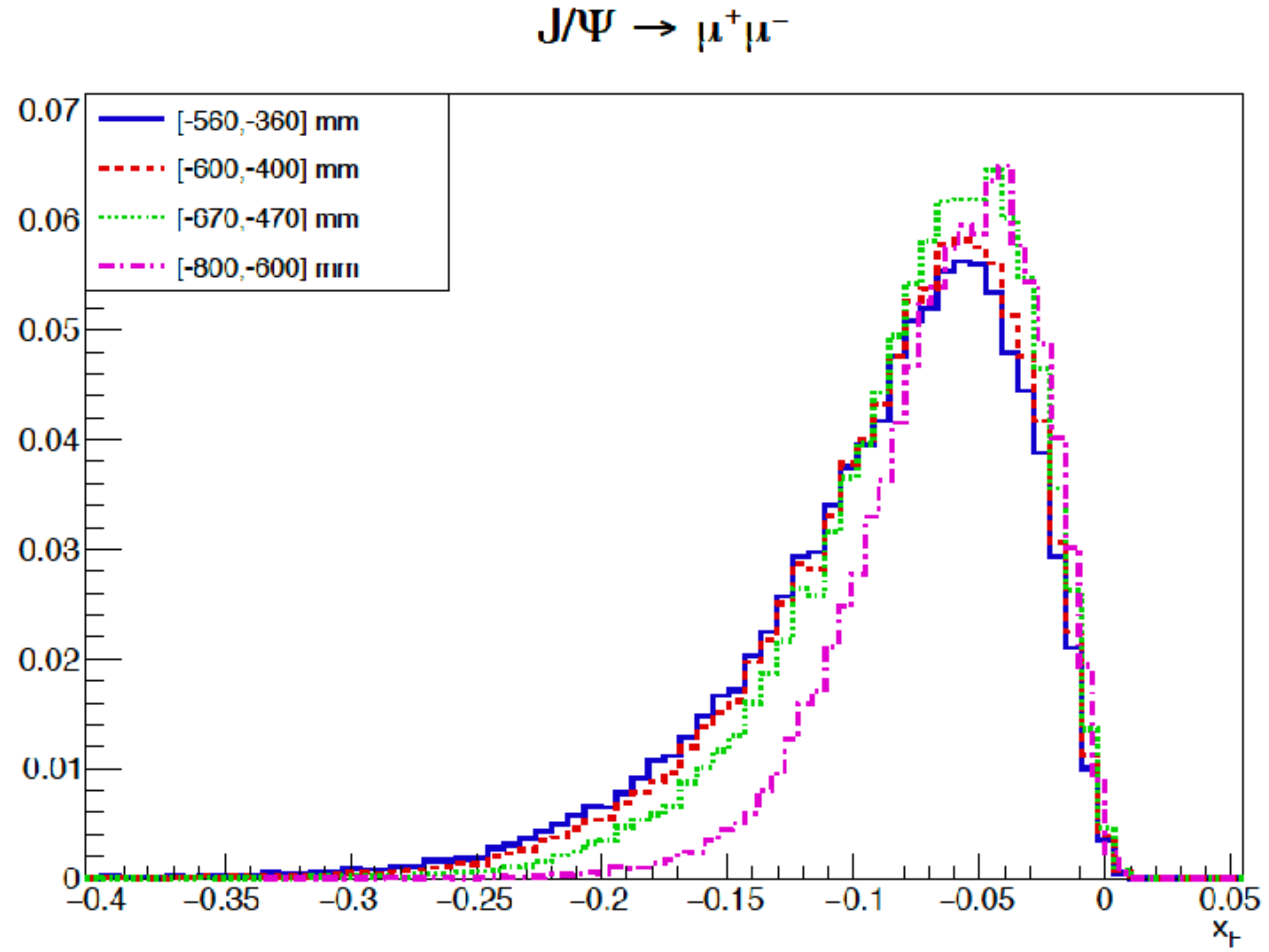
dominant process at LHC





- $pp^{\uparrow} \to Q\bar{Q}_{[HF]}X$ is the ideal observable to access gTMDs ($q_T(Q) << M_Q$)
- Deep insight into the nucleon gluon dynamics
- Sheds light on spin-orbit correlations
- Sensitive to the totally unknown gluon Orbital Angular Momentum





TMDs

- Plenty of observables with polarised DY: azimuthal asymmetries of the dilepton pair to probe TMDs
- h_q^1 : transversity → difference in densities of quarks having T pol. ↑↑ or ↑↓ in T pol. nucleon
- $f_{1T}^{\perp q}$: Sivers → dependence on p_T orientation wrt T pol. nucleon
- $h_1^{\perp q}$: Boer-Mulders → dependence on p_T orientation wrt T pol. quark in unp. nucleon
- $h_{1T}^{\perp q}$: pretzelosity → dependence on p_T and T. pol of both T pol. quark and nucleon
- f_1^q : unpolarised TMD, always present at the denominator

$$A_{UU}^{cos2\phi} \sim \frac{h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_1^{\perp \bar{q}}(x_2, k_{2T}^2)}{f_1^q(x_1, k_{1T}^2) \otimes f_1^{\bar{q}}(x_2, k_{2T}^2)}$$

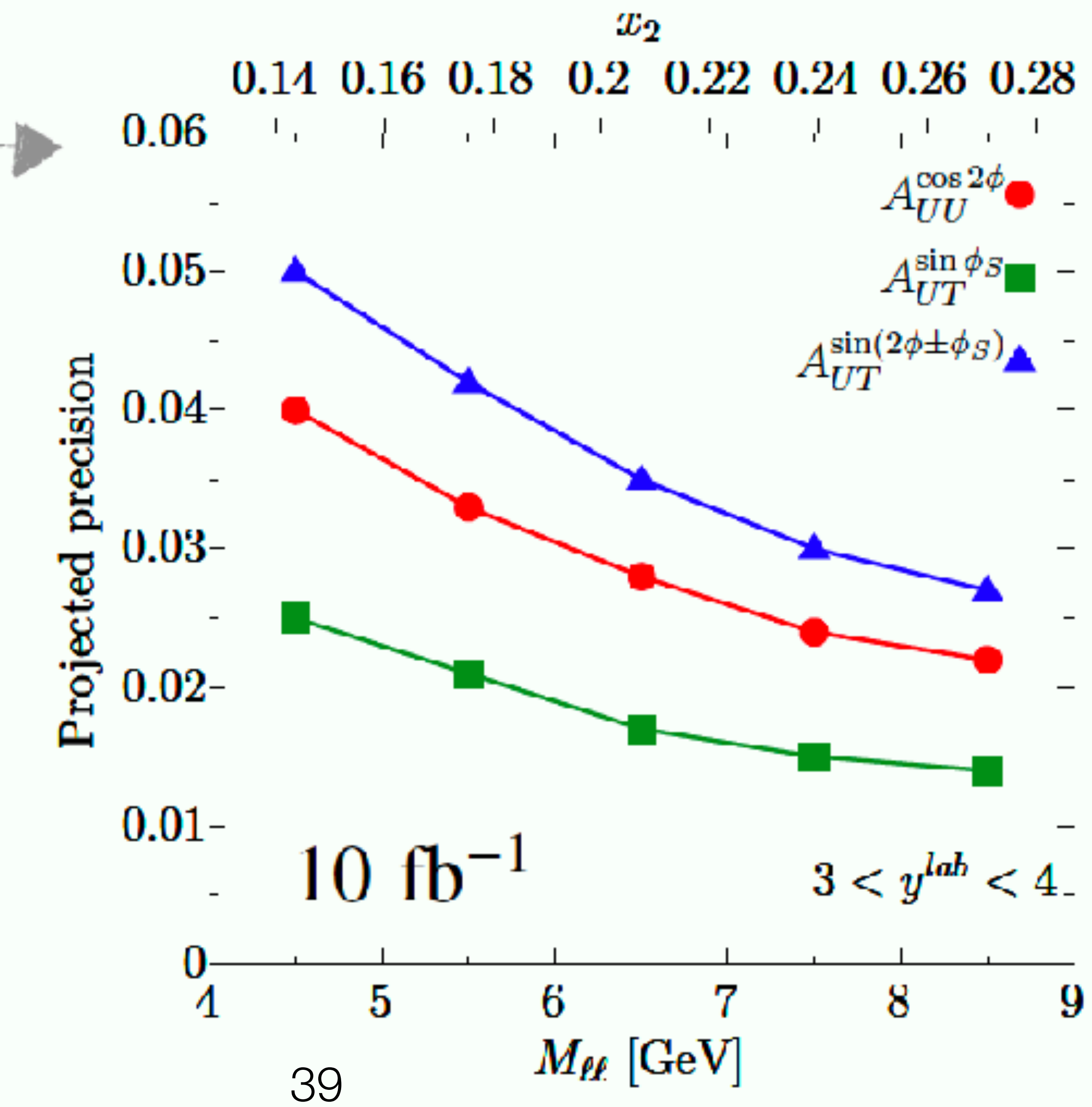
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q(x_1, k_{1T}^2) \otimes f_{1T}^{\perp \bar{q}}(x_2, k_{2T}^2)}{f_1^q(x_1, k_{1T}^2) \otimes f_1^{\bar{q}}(x_2, k_{2T}^2)}$$

$$A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_{1T}^{\perp \bar{q}}(x_2, k_{2T}^2)}{f_1^q(x_1, k_{1T}^2) \otimes f_1^{\bar{q}}(x_2, k_{2T}^2)}$$

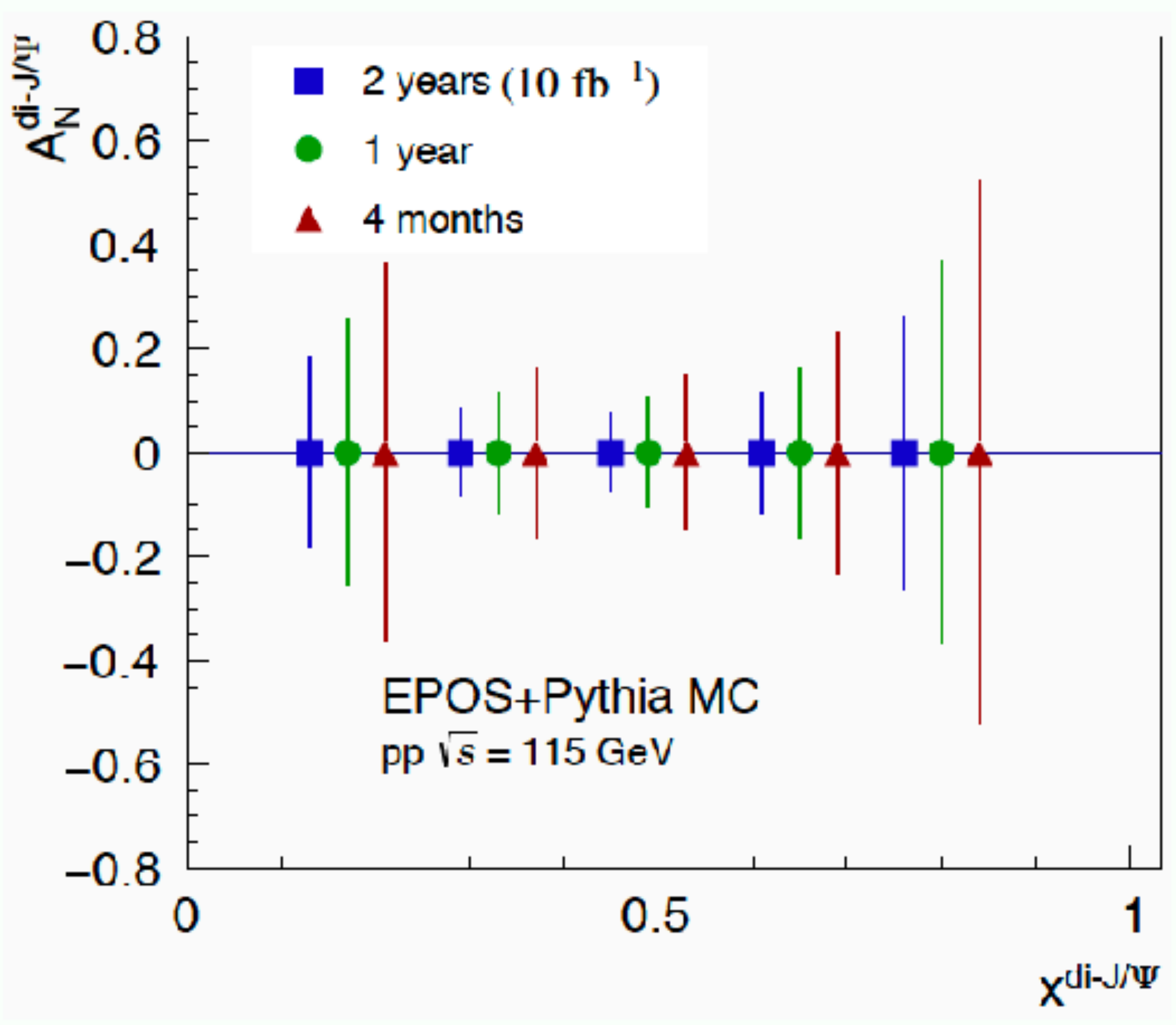
$$A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q}(x_1, k_{1T}^2) \otimes h_1^{\bar{q}}(x_2, k_{2T}^2)}{f_1^q(x_1, k_{1T}^2) \otimes f_1^{\bar{q}}(x_2, k_{2T}^2)}$$

- polarised Drell-Yan to access unpolarised TMDs of sea quarks and polarised TMDs in the valence region
- gluon-induced asymmetries: $h_1^{\perp g}$ never measured, can be accessed together with the f_1^g TMD (also unconstrained) in di-J/ψ and Υ production

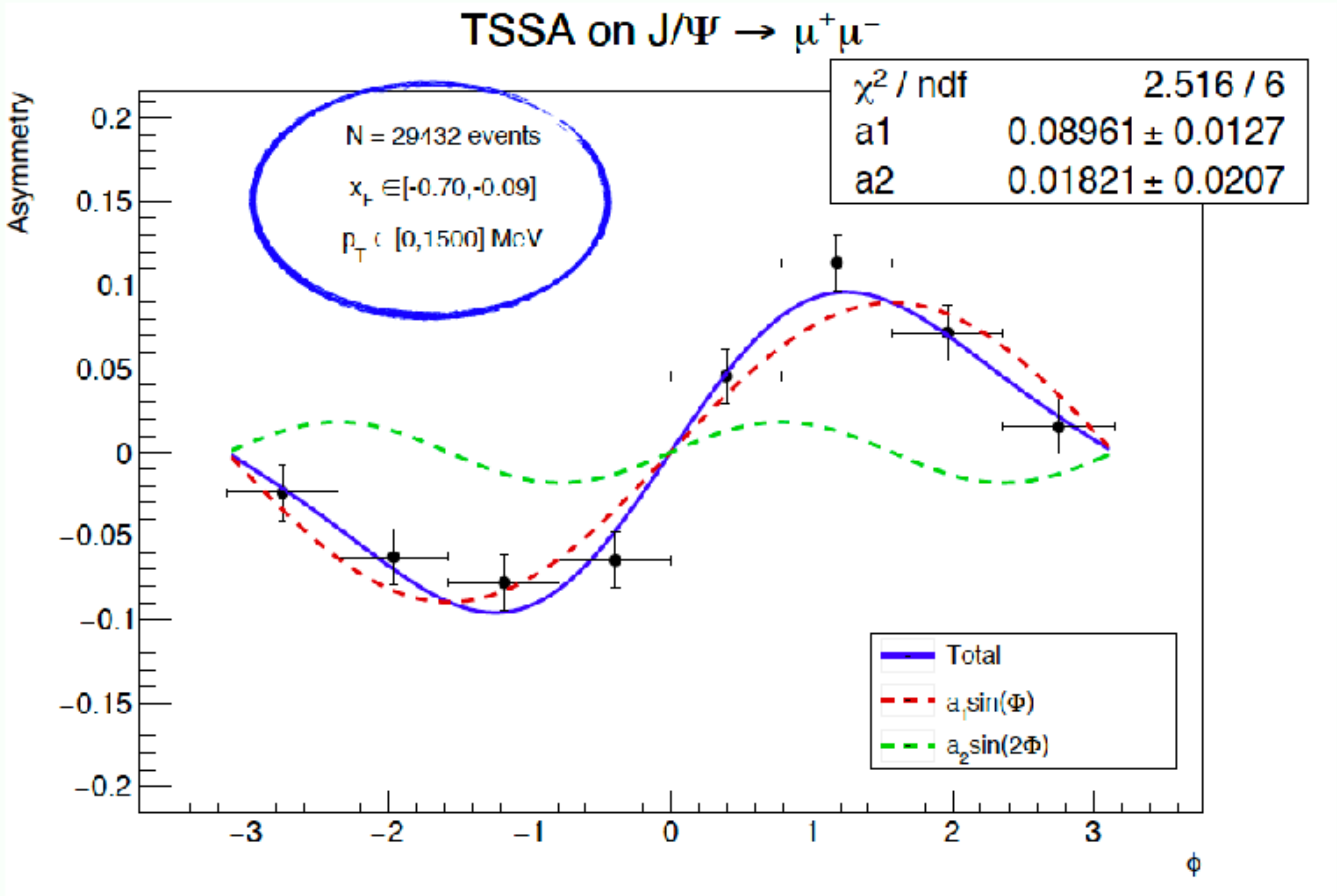
[ArXiv:1807.00603] [PLB 784 (2018) 217-222]

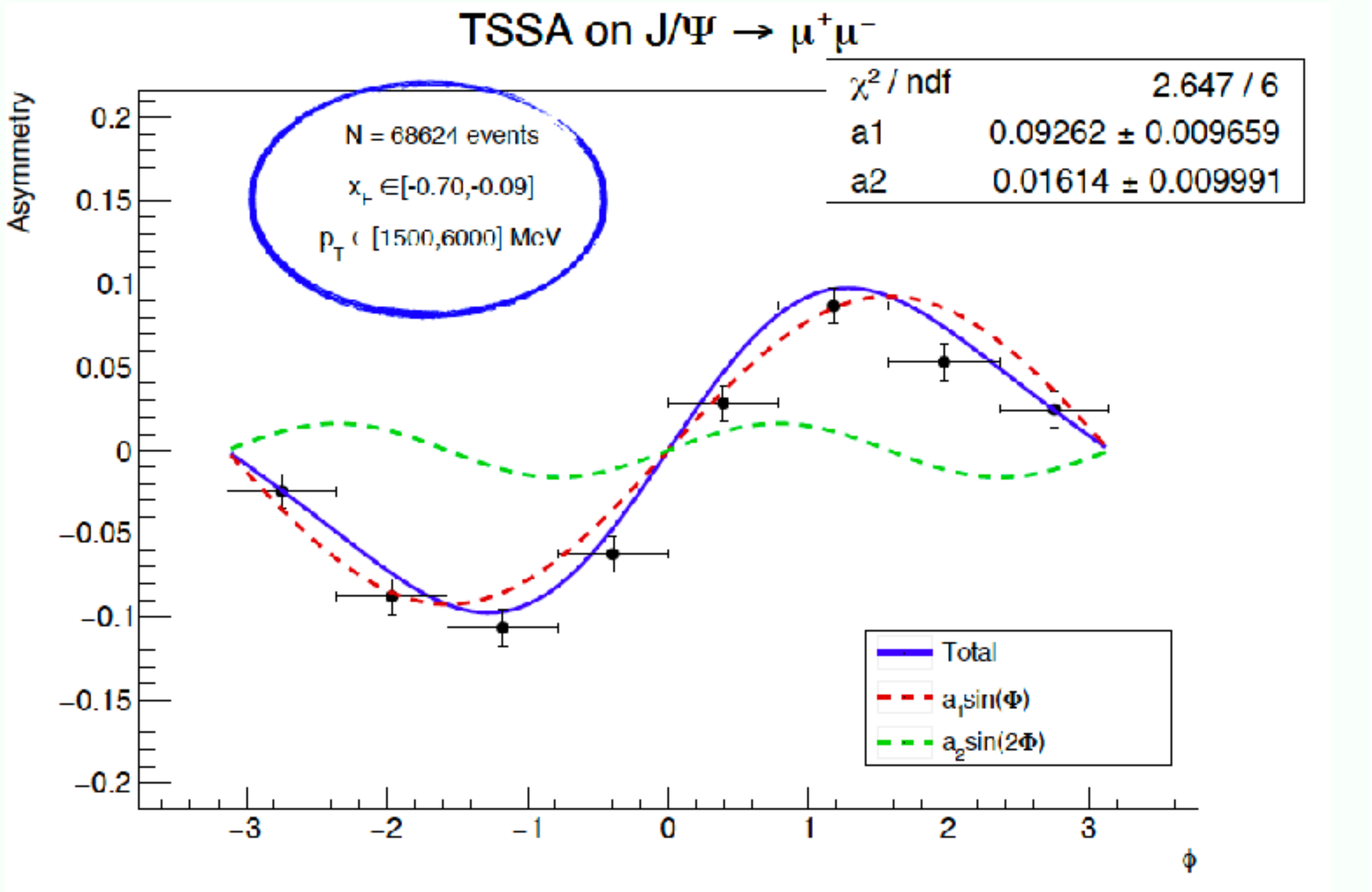


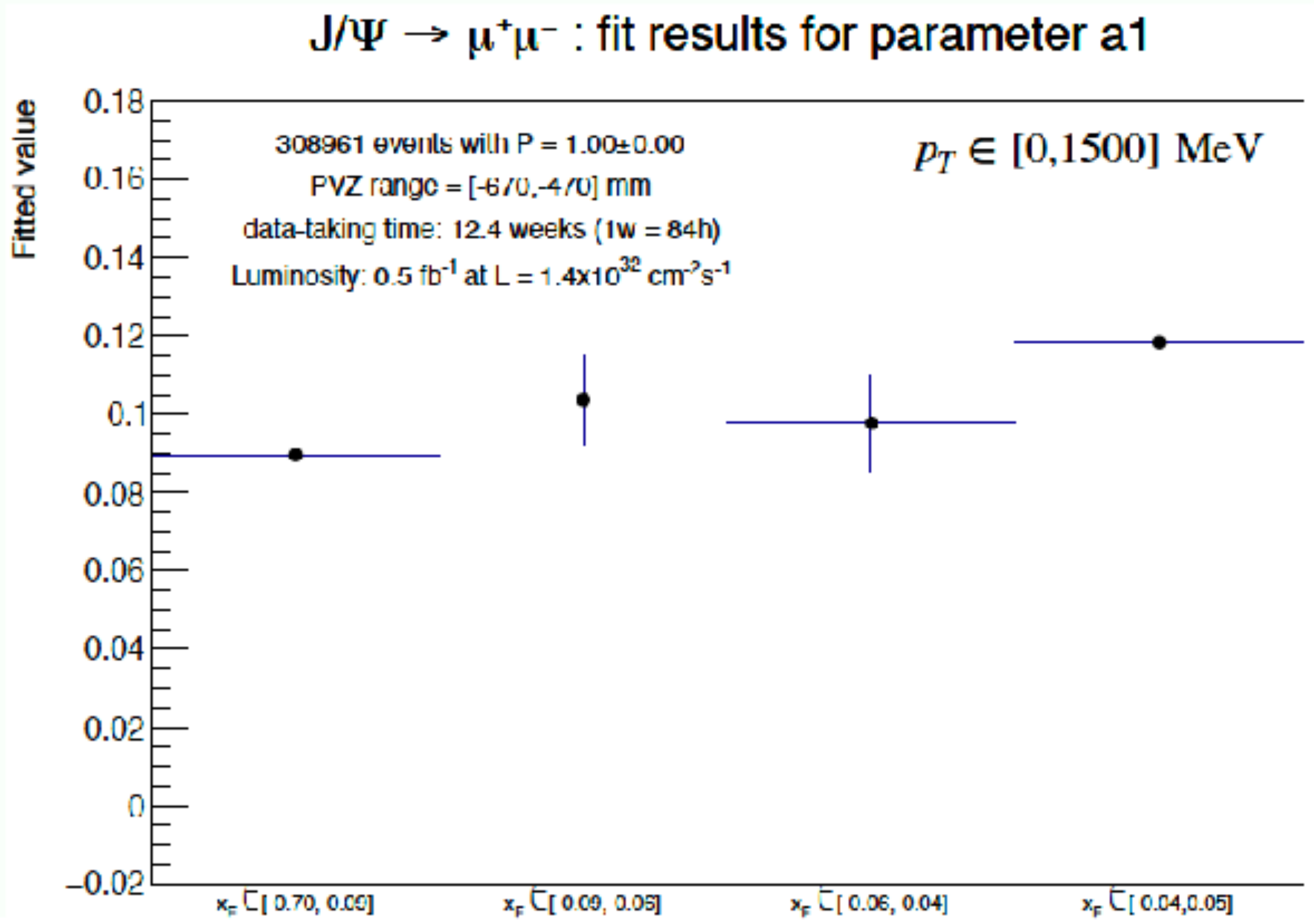
- J/Ψ J/Ψ channel



A TSSA analysis at LHCspin



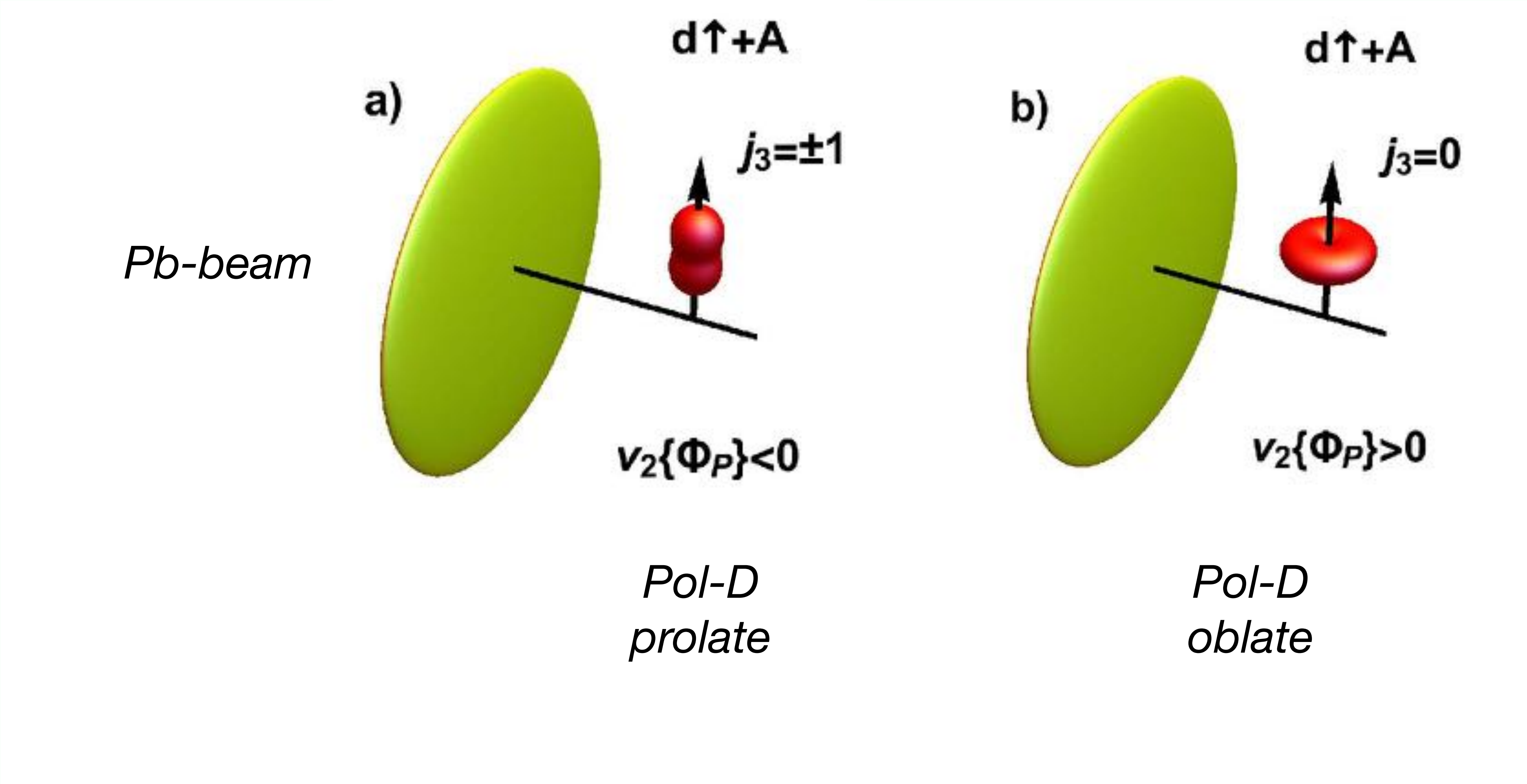




- Full LHCb simulations → emulate the target polarisation by assigning a ↑↓ tag according to a model. In this example: 10% asymmetry $\sin\phi$, 2% on $\sin 2\phi$ with mild x_F, p_T dependence [JHEP 12 (2020) 010]
- Fit the polarised data with the sum of two Fourier amplitudes
- Within this statistics (~ 3 months of data-taking): $A_N \sim 0.1 \pm 0.01$ with $4\ x_F \times 2\ p_T \times 8\ \phi$ bins on $J/\Psi \to \mu^+\mu^-$
- Work ongoing on other channels

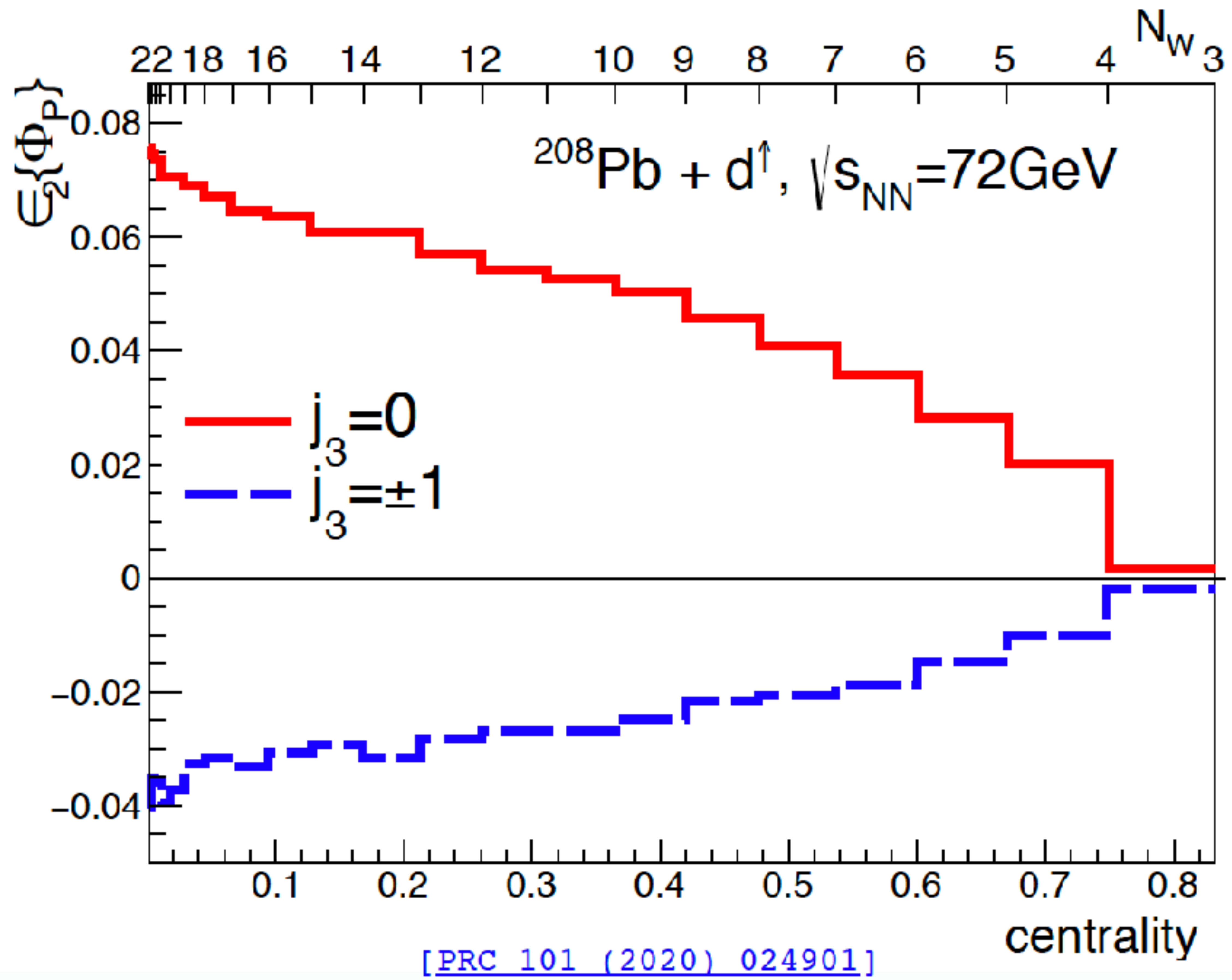
Polarised Heavy-Ion collisions

- Interesting topic joining heavy ions and polarisation: probing the dynamics of small systems
- Ultra-relativistic collisions of heavy nuclei (Pb) on transversely polarised deuterons ($D^{\uparrow}$)
- Deformation of $D^{\uparrow}$ is reflected in the orientation of the generated fireball in the transverse plane



D polarised along Φ_p , perpendicular to the beam

- Quantified by the ellipticity, ϵ_2 wrt Φ_p
- Can be easily performed on minimum bias data!



[PRC 101 (2020) 024901]

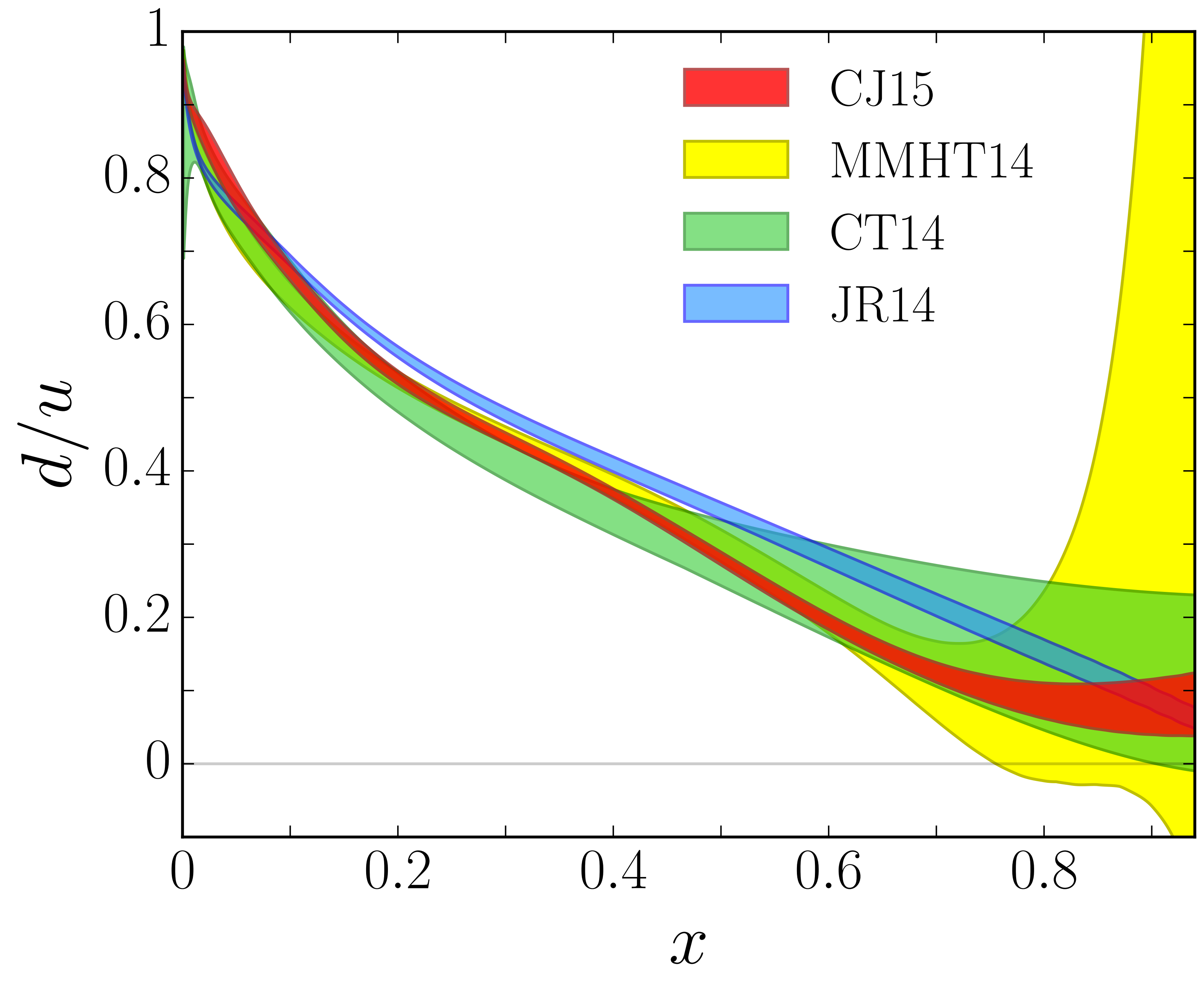
Additional Physics Motivations ...

we can measure already with SMOG2

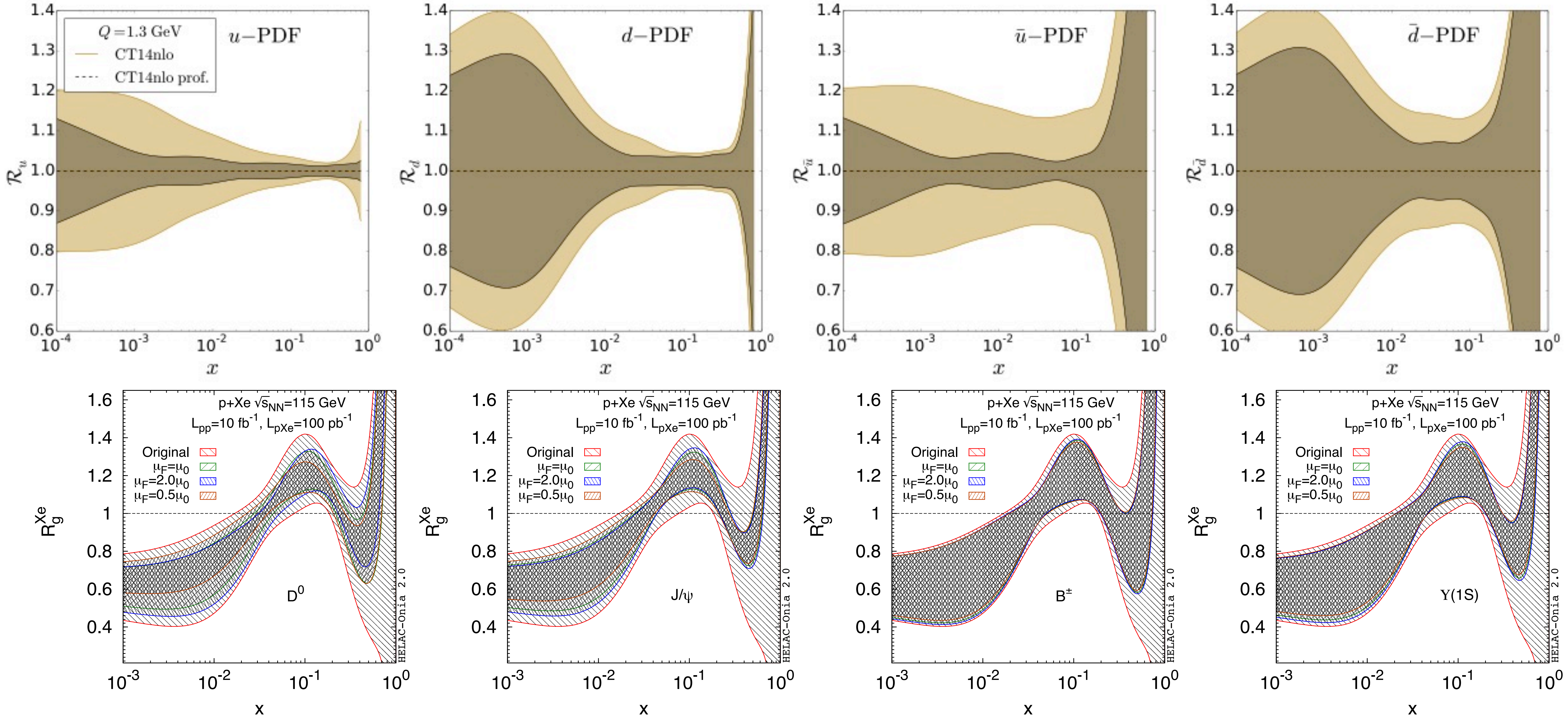
High-x

Smaller uncertainty could better constraint models on hadron structure, e.g. for x—>1

- d/u —> 1/2 : SU(6) spin-flavour symmetry
- d/u —> 0 : scalar diquark dominance
- d/u —> 1/5 : pQCD power counting
- d/u —> 0.42 : local quark-hadron duality



Substantial improvement of the uncertainties



PDF

nPDF
(gluon)

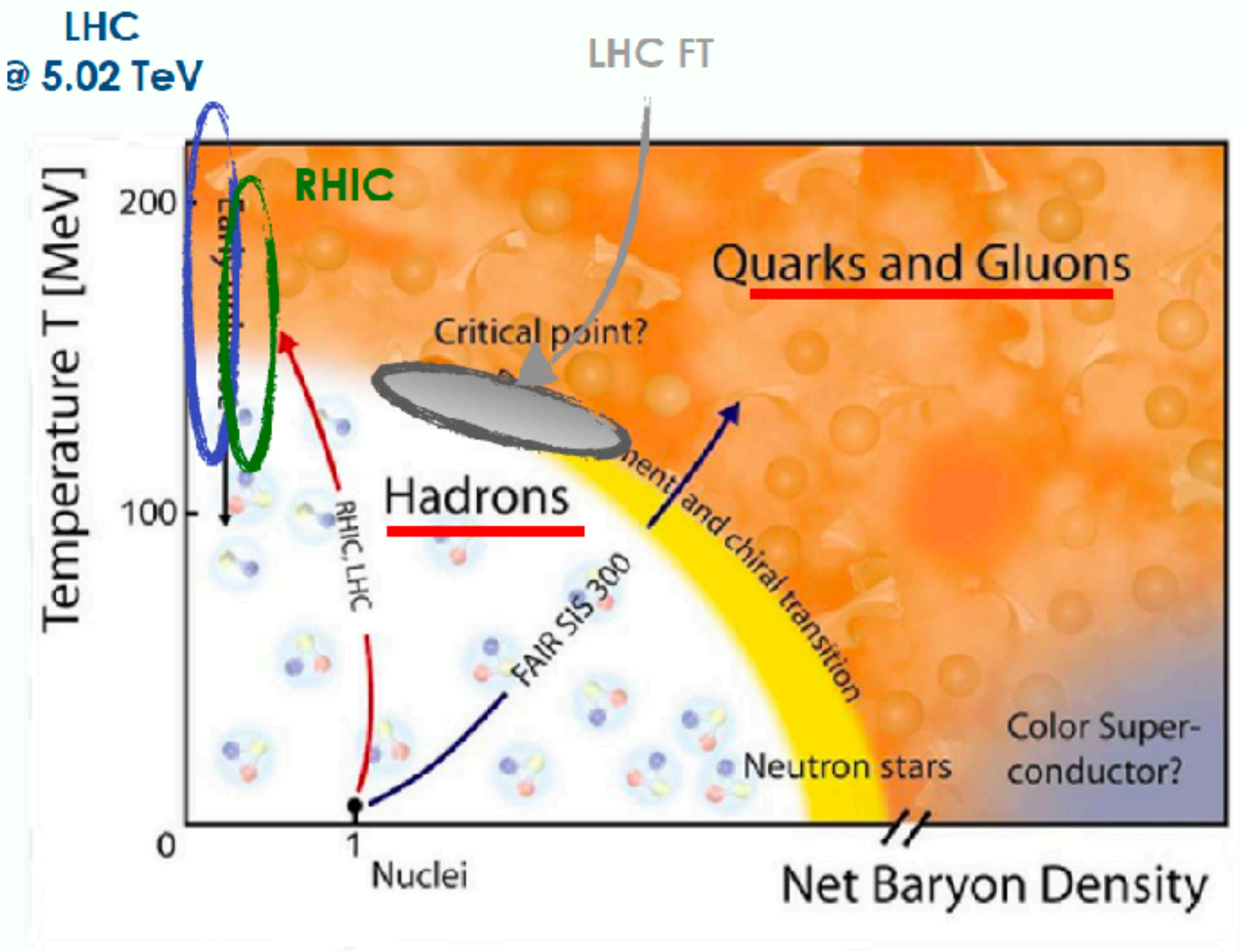
arXiv:1807.00603

estimation with 10 fb^{-1}

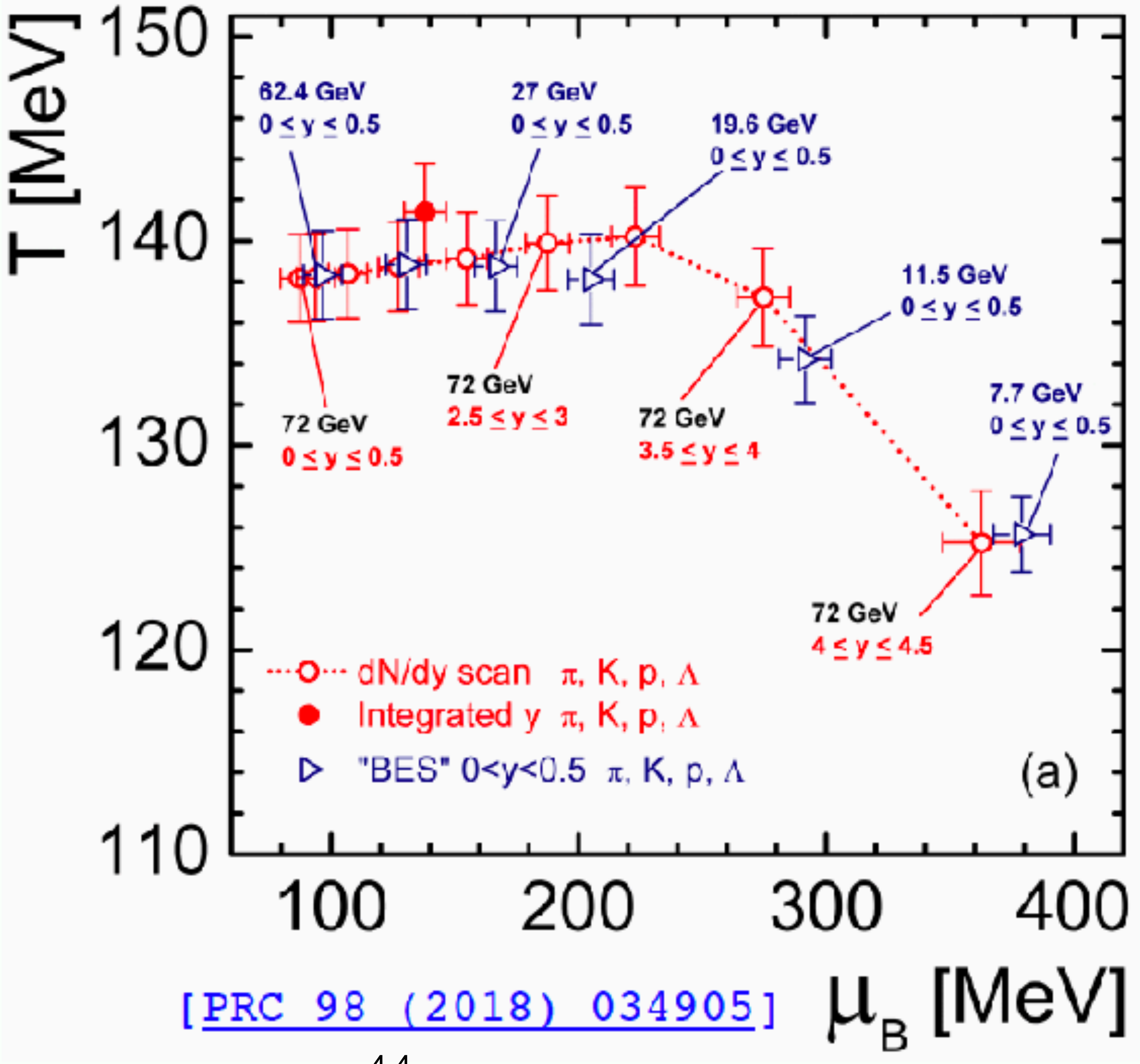
Heavy-Ion collisions

- LHC delivers proton beam at $7\ \mathrm{TeV}$ and lead beam at $2.76\ \mathrm{TeV}$, while the storage cells technology allows for an easy target change
- Great opportunities to probe nuclear matter over a new rapidity domain at $\sqrt{s} = 72\ \mathrm{GeV}$

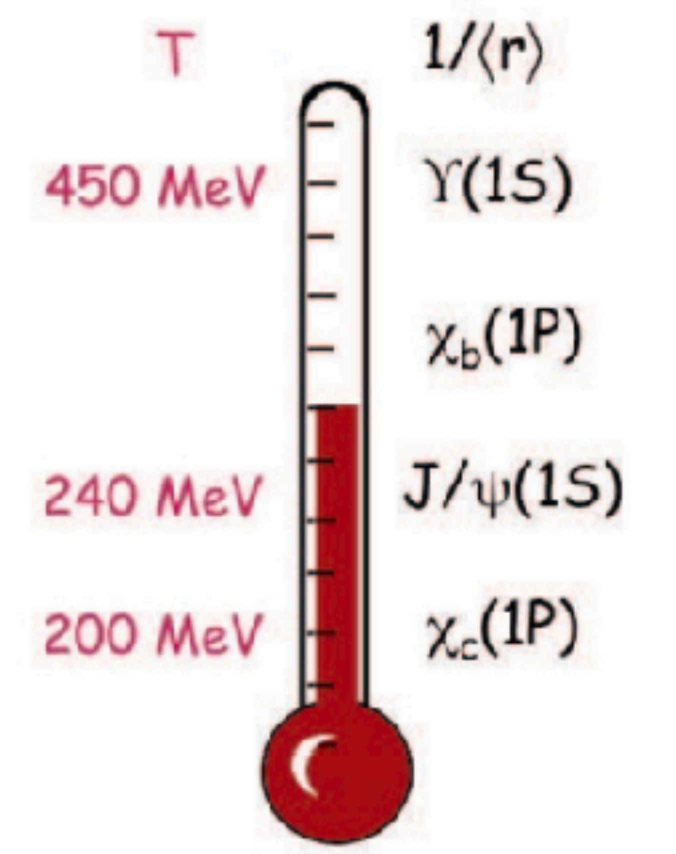
- Hints for deconfinement at this energy: FT collisions to explore the transition region



- Complement the RHIC Beam Energy Scan (BES) with a y scan



[PRC 98 (2018) 034905]

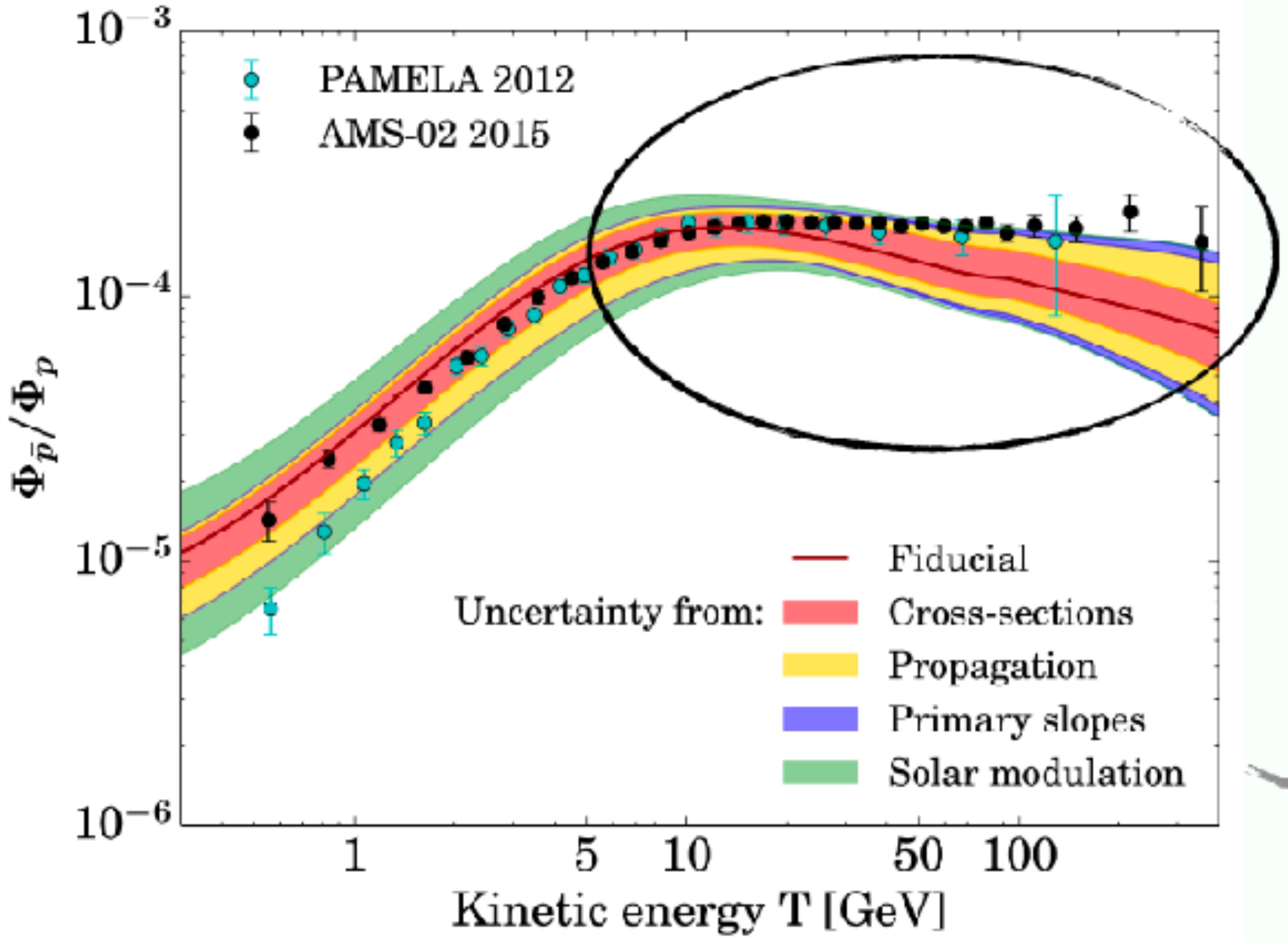


- Suppression of $c\bar{c}$ bound states as QGP thermometer
- States with different binding energy → different dissociation temperature
- LHCspin to access unique/heavy probes [IJMPA 28 (2013) 1340012]

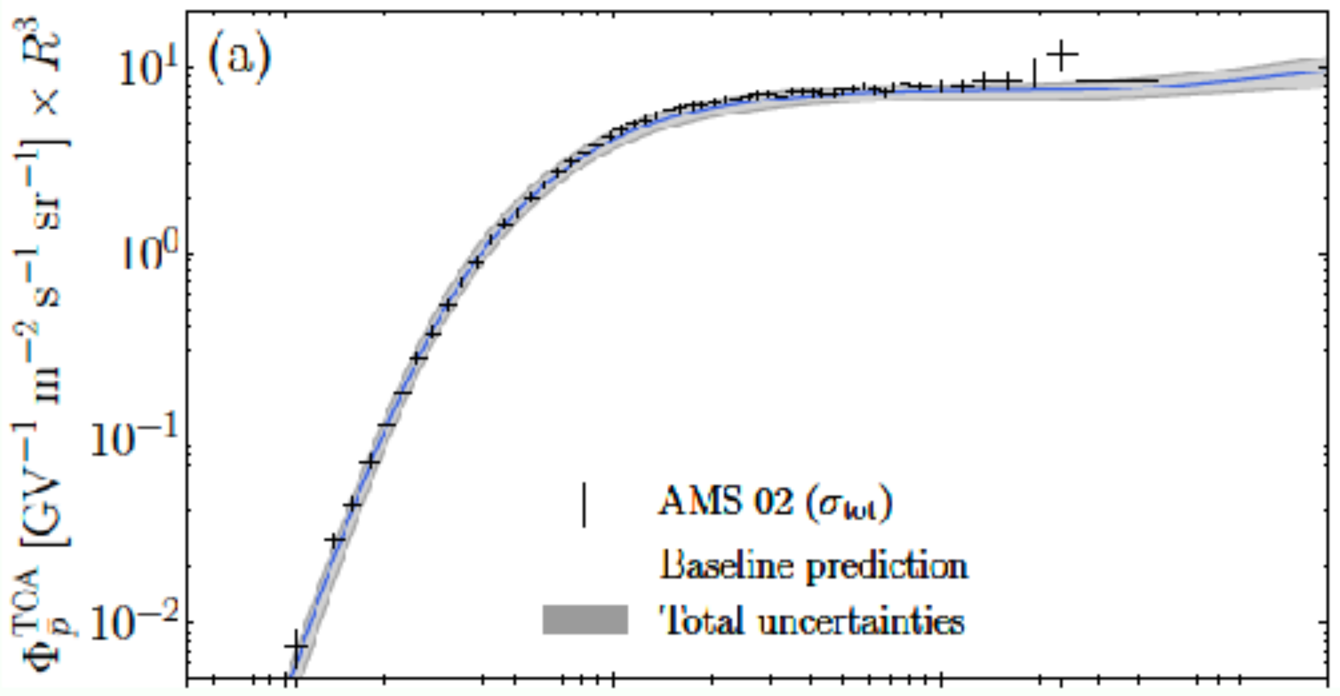
Astroparticle

- $\bar{p}$ production on pHe collisions, first measurement from SMOG helped the interpretation of DM annihilation [PRL 121 (2018) 222001]

[JCAP09 (2015) 023]

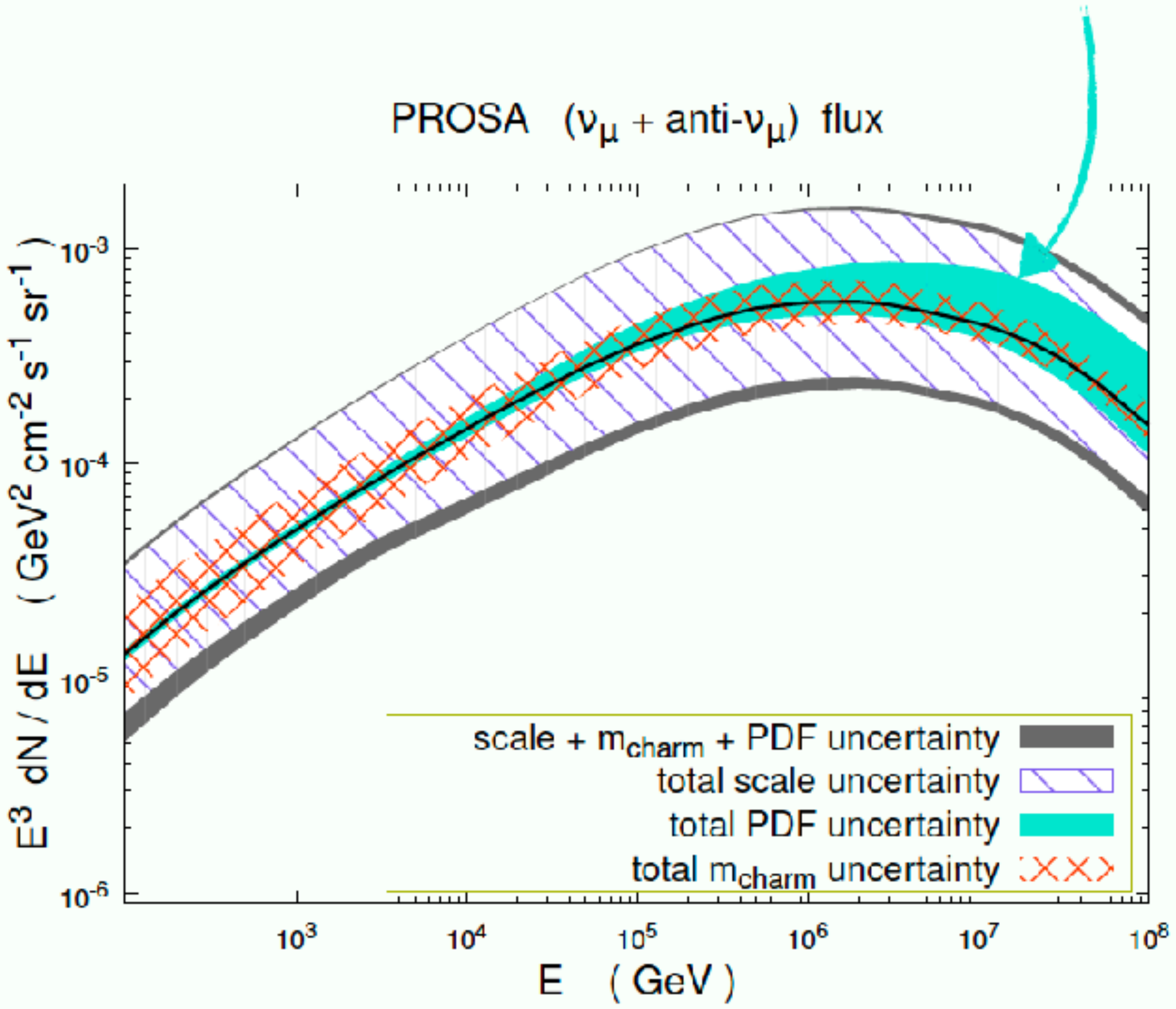


[ArXiv:1906.07119]



- Main uncertainty still due to cross sections!

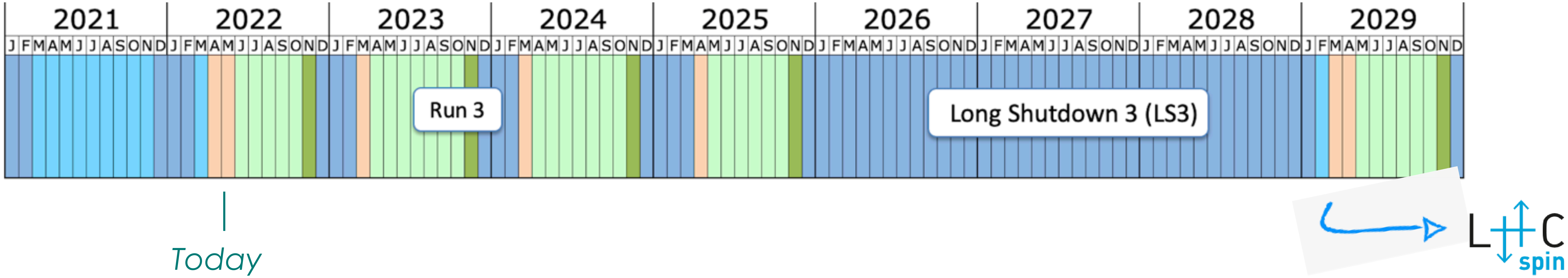
- heavy-flavour hadroproduction measurements needed to improve the prompt ν_μ flux prediction at high energy



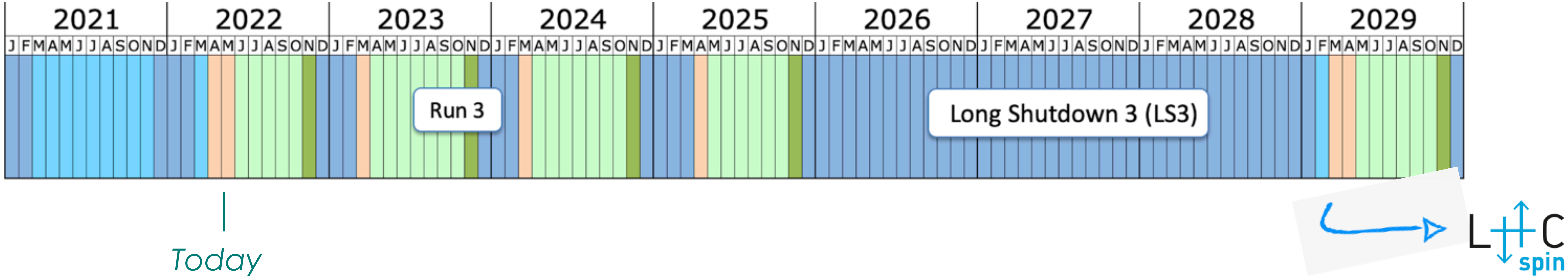
[JHEP 05 (2017) 004]

- Inputs for UHECR flux composition with pHe, pO, pN data
- ^{16}O beam foreseen for Run 3, would reproduce the actual processes:
- $^{16}\mathrm{O} + \mathrm{p} \to \bar{\mathrm{p}} + \mathrm{X}$ and $^{16}\mathrm{O} + {}^{4}\mathrm{He} \to \bar{\mathrm{p}} + \mathrm{X}$ [CERN-LPCC-2018-07]

Conclusions

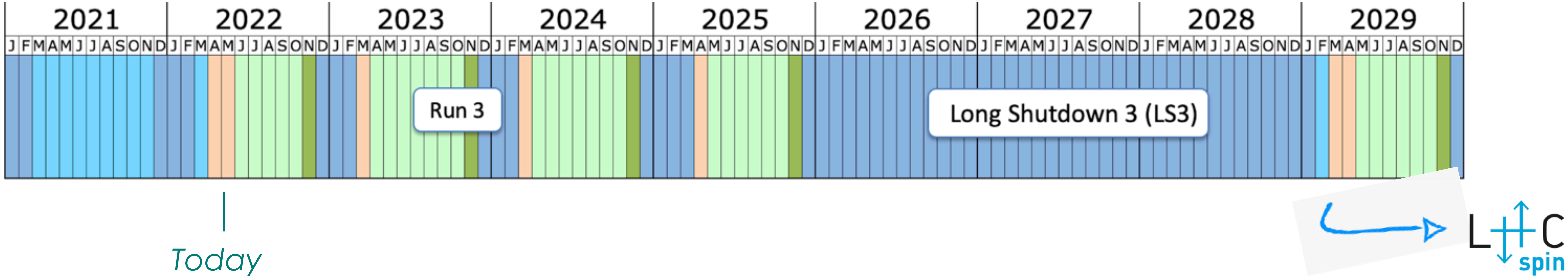


Conclusions



- LHCspin is an innovative project conceived to bring polarized physics at the most powerful collider (LHC) exploiting the unique kinematic conditions provided by a TeV-scale beam, with one of the most advanced fully instrumented forward spectrometer (LHCb)
- The installation of the first storage cell target for unpolarized gases (SMOG2) already happened, it will start taking data from LHC Run3 (2022), and is a fantastic playground for the LHCspin R&D
- LHCspin is extremely ambitious in terms of both physics reach and technical complexity

Conclusions



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- LHCspin is extremely ambitious in terms of both physics reach and technical complexity

LHCspin represents a unique possibility … in a realistic time schedule and costs