High-x / Fixed targets

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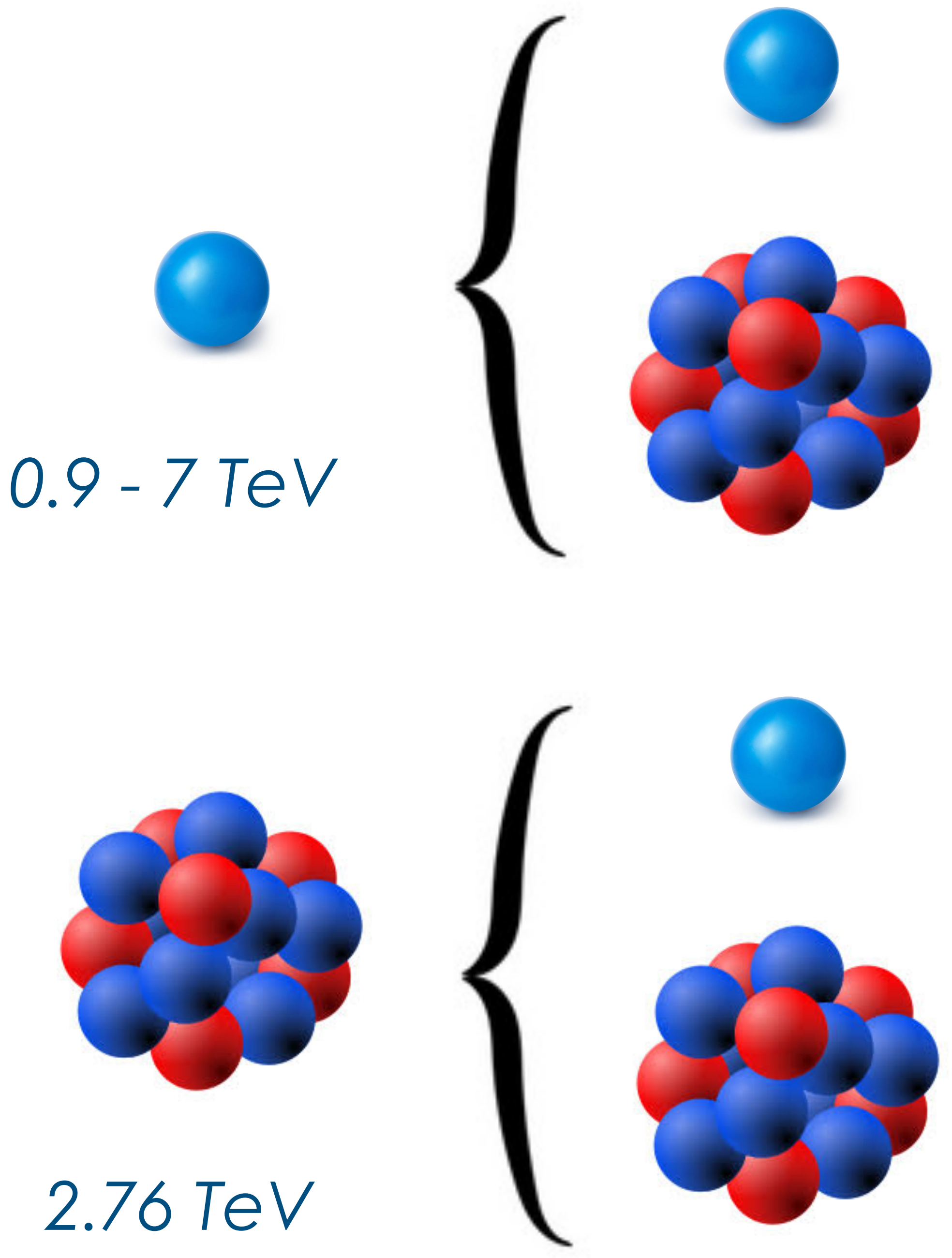
HADRON 2021

Round Table, 30/07/21

Kinematics on fixed target



pp or pA collisions: 7 TeV beam on fix target

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

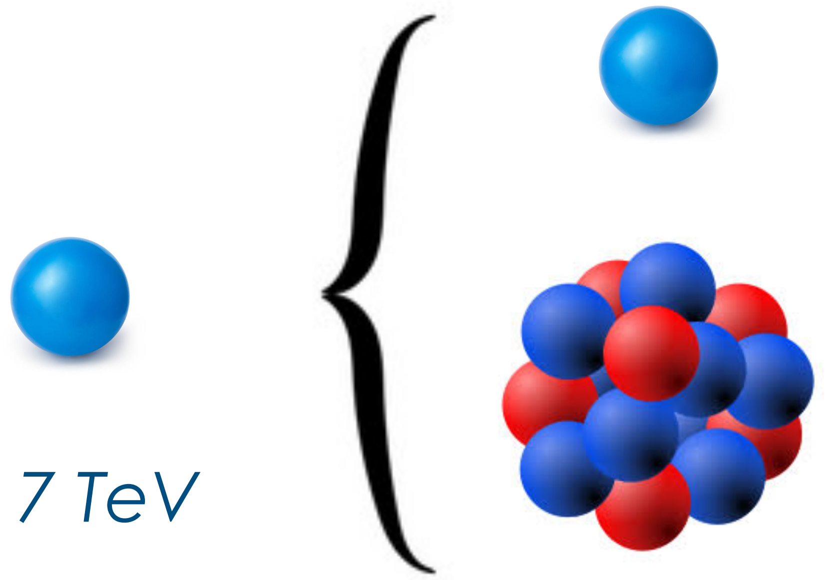
$$-3.0 \leq y_{CMS} \leq 0 \ \rightarrow \ 2 \leq y_{lab} \leq 5$$

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

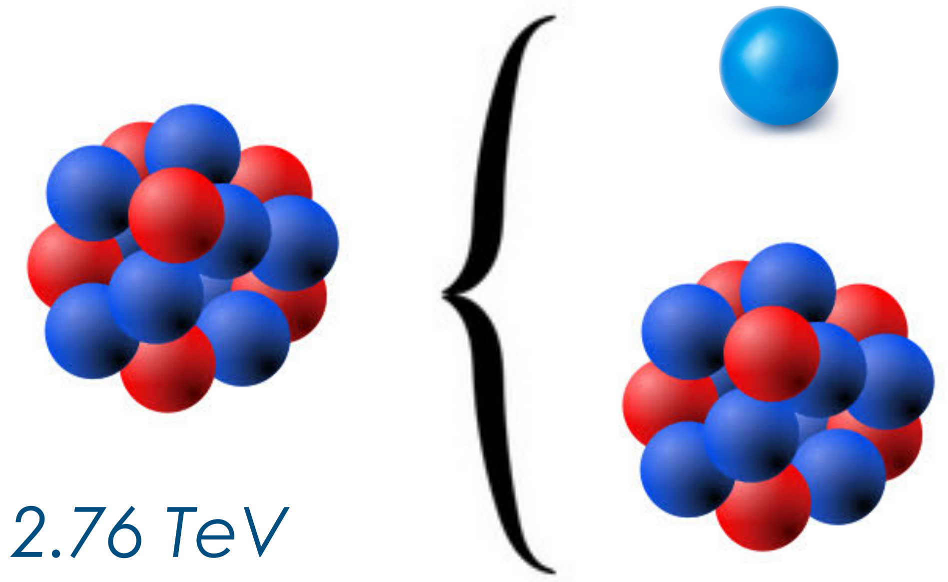


0.9 - 7 TeV

pp or pA collisions: 7 TeV beam on fix target

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

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



2.76 TeV

AA collisions: 2.76 TeV beam on fix target

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

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

$H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$

SMOG2 @ LHCb

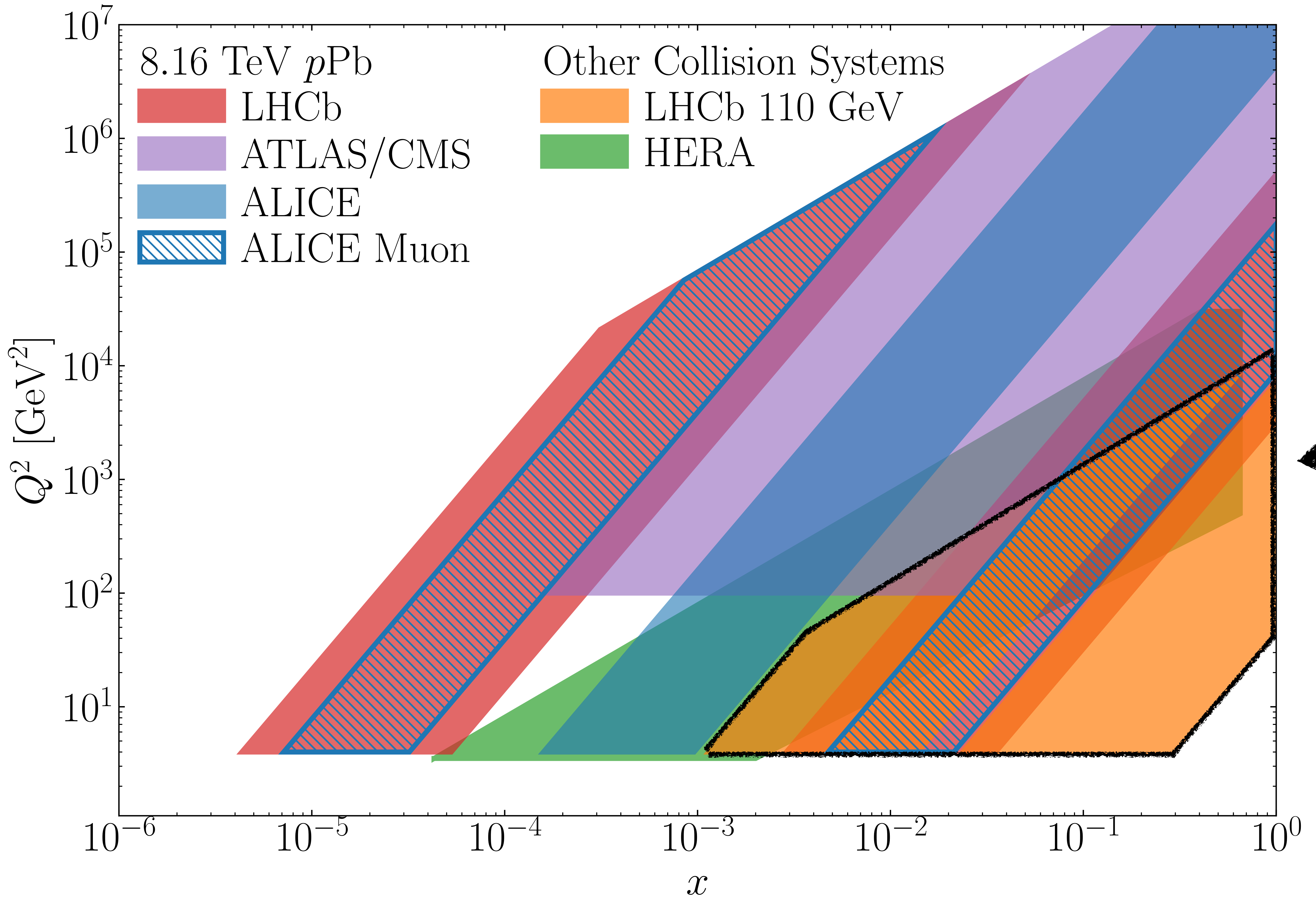
$H^{\uparrow}, D^{\uparrow}$

LHC spin

$Be, Ca, C, Ti, Ni, Cu, Os, Ir, W$

FT @ ALICE

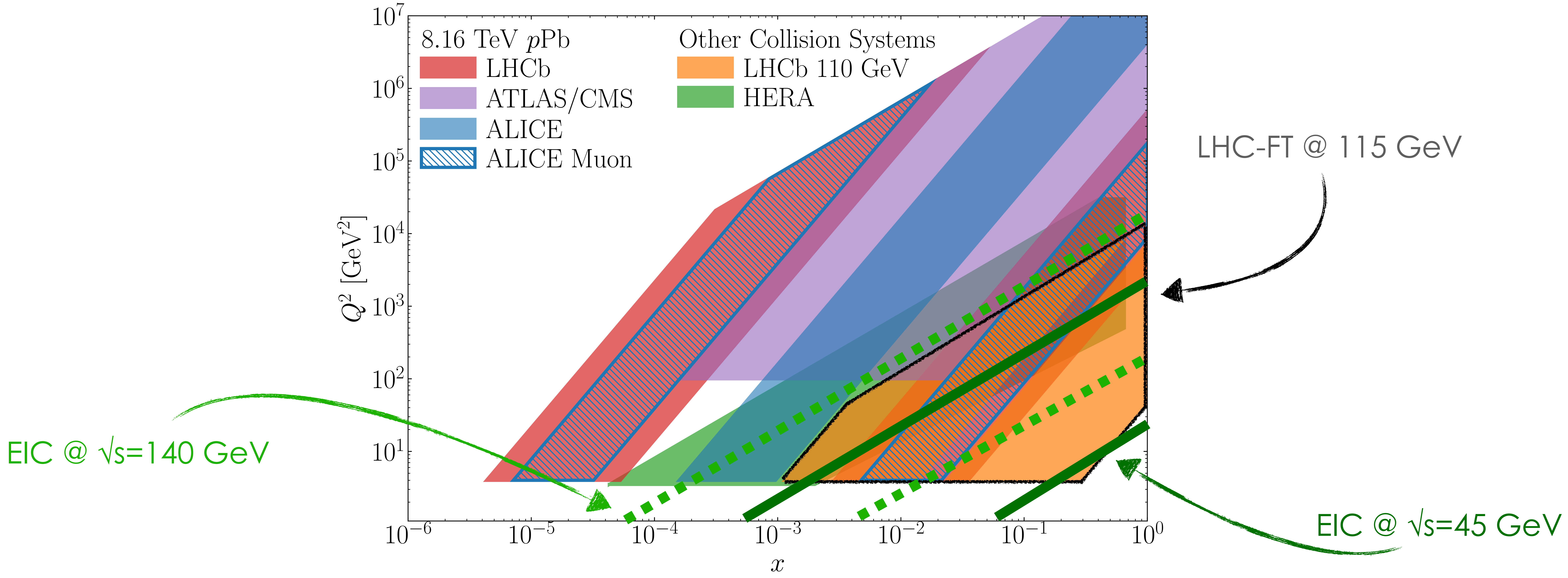
Unique kinematical regions



LHC-FT @ 115 GeV

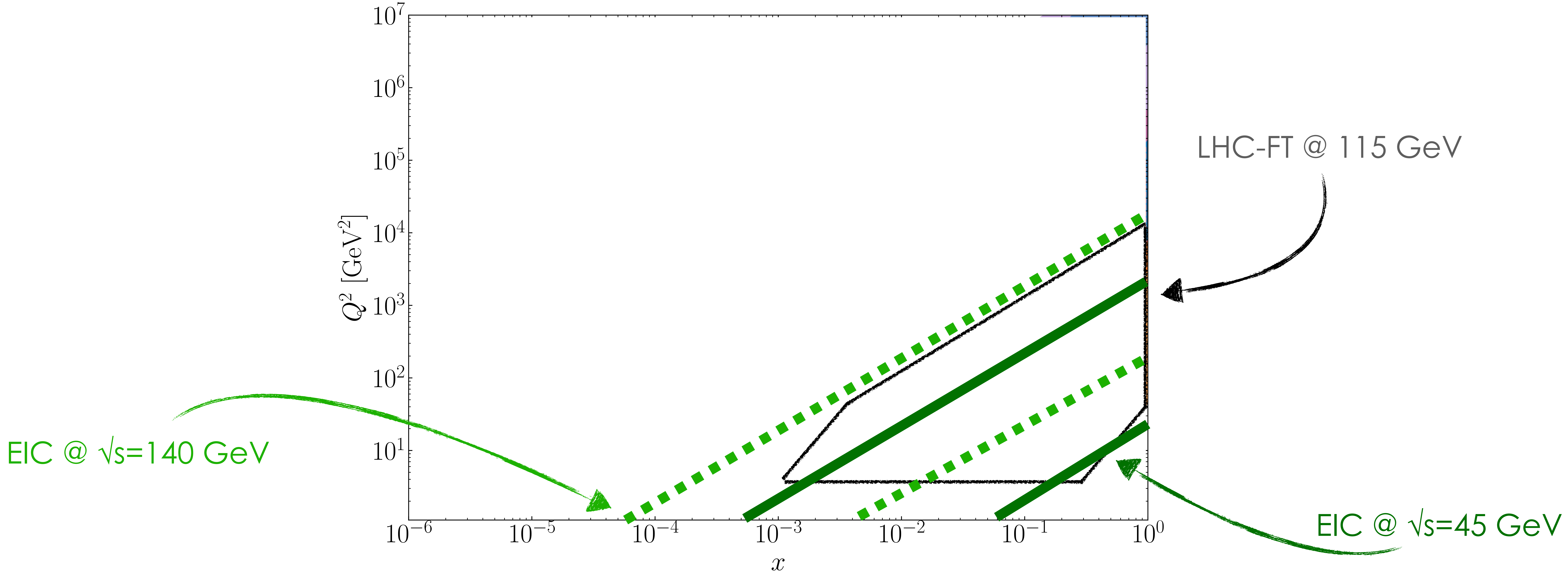
at moderate Q^2 and rapidity

Unique kinematical regions



EIC ref
arXiv:1602.03922

Unique kinematical regions



EIC ref
arXiv:1602.03922

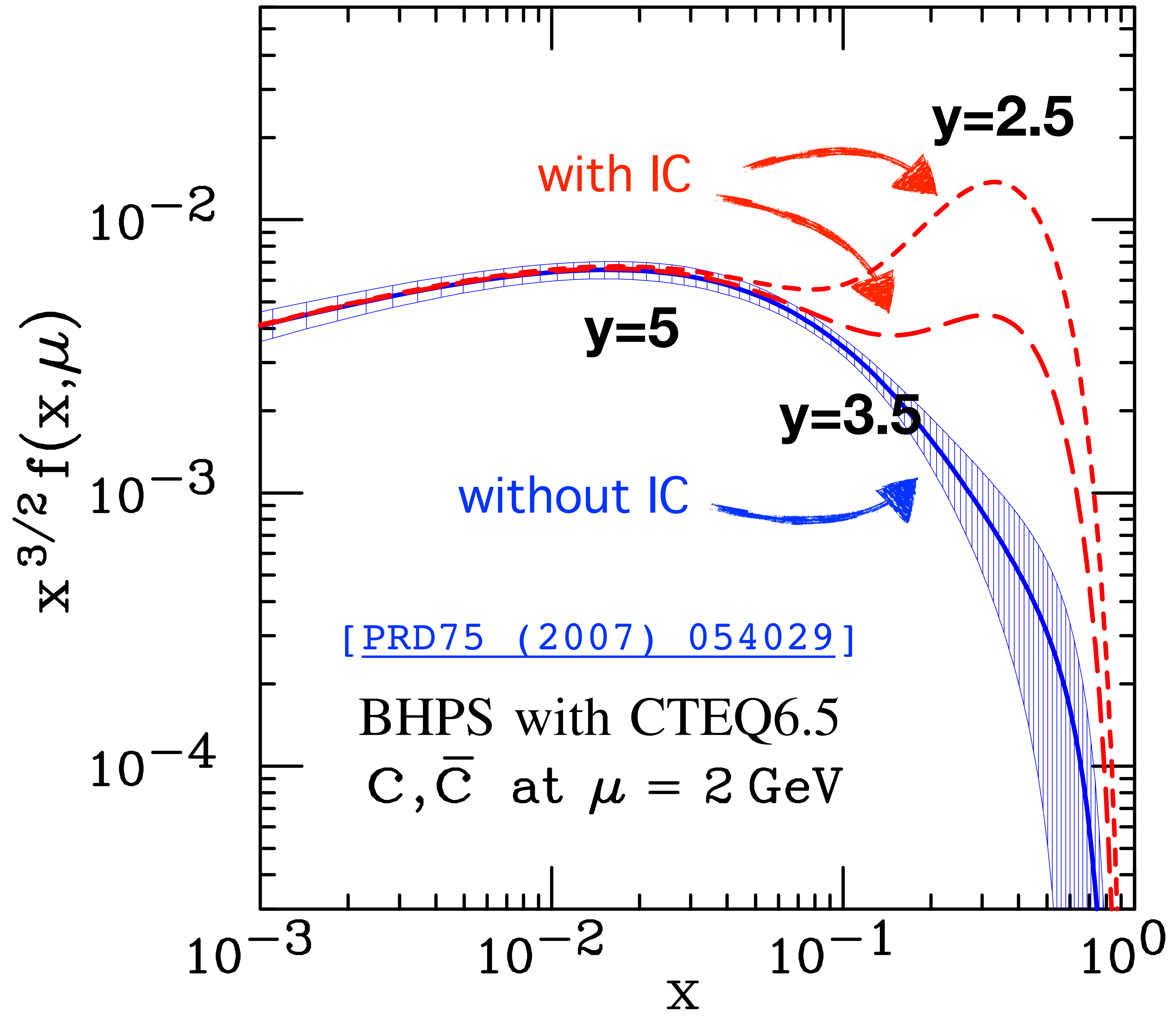
Heavy Flavour

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

-same spectrometer

-same beam

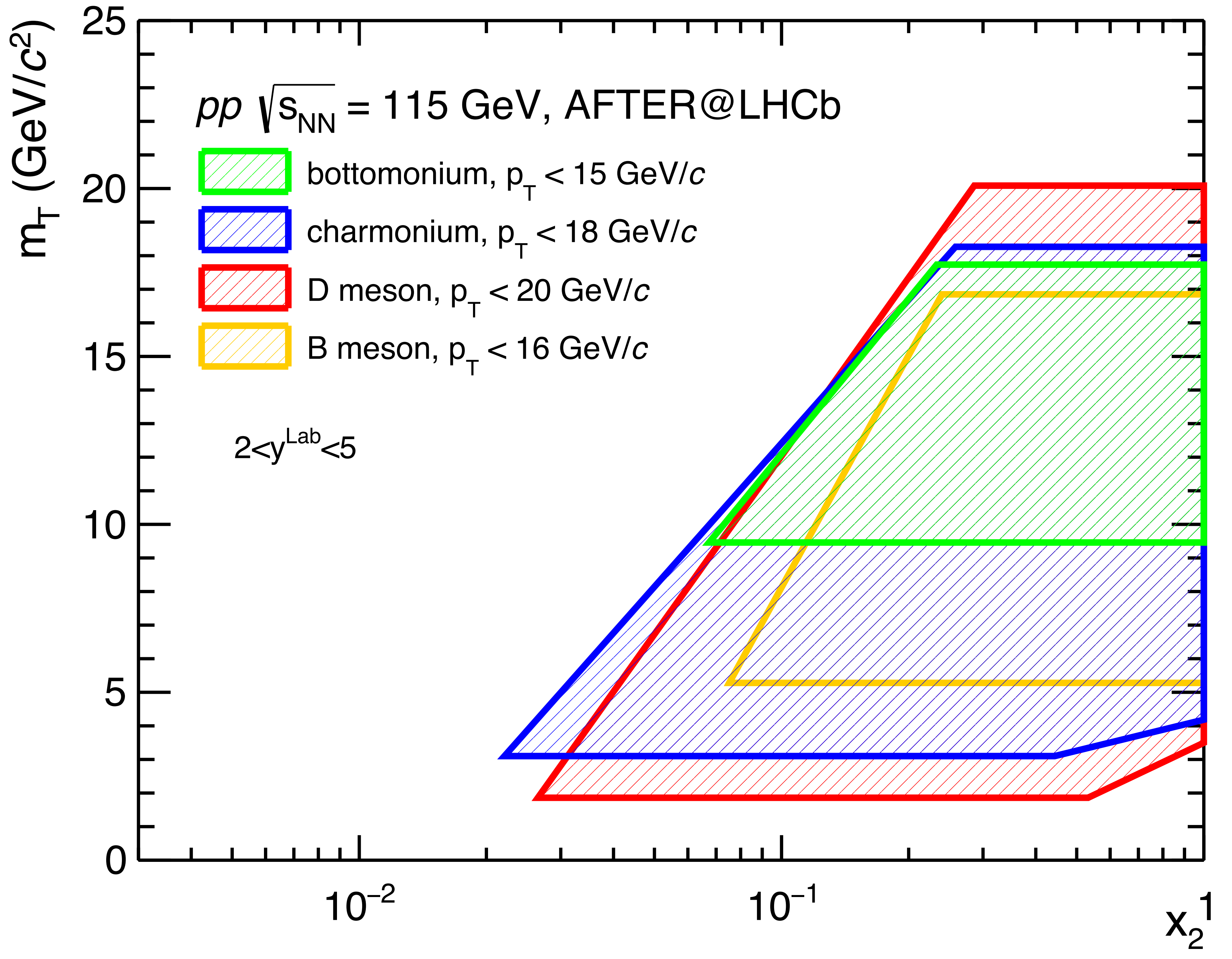
-at $\sqrt{s} = 115\ GeV$ and $\sqrt{s} = 14\ TeV$



- Hints of an Intrinsic Charm (IC) component in the proton
- First search performed with SMOG: [PRL 122 (2019) 132002]
- Still to be investigated

Complementary D and B-physics done at high energies

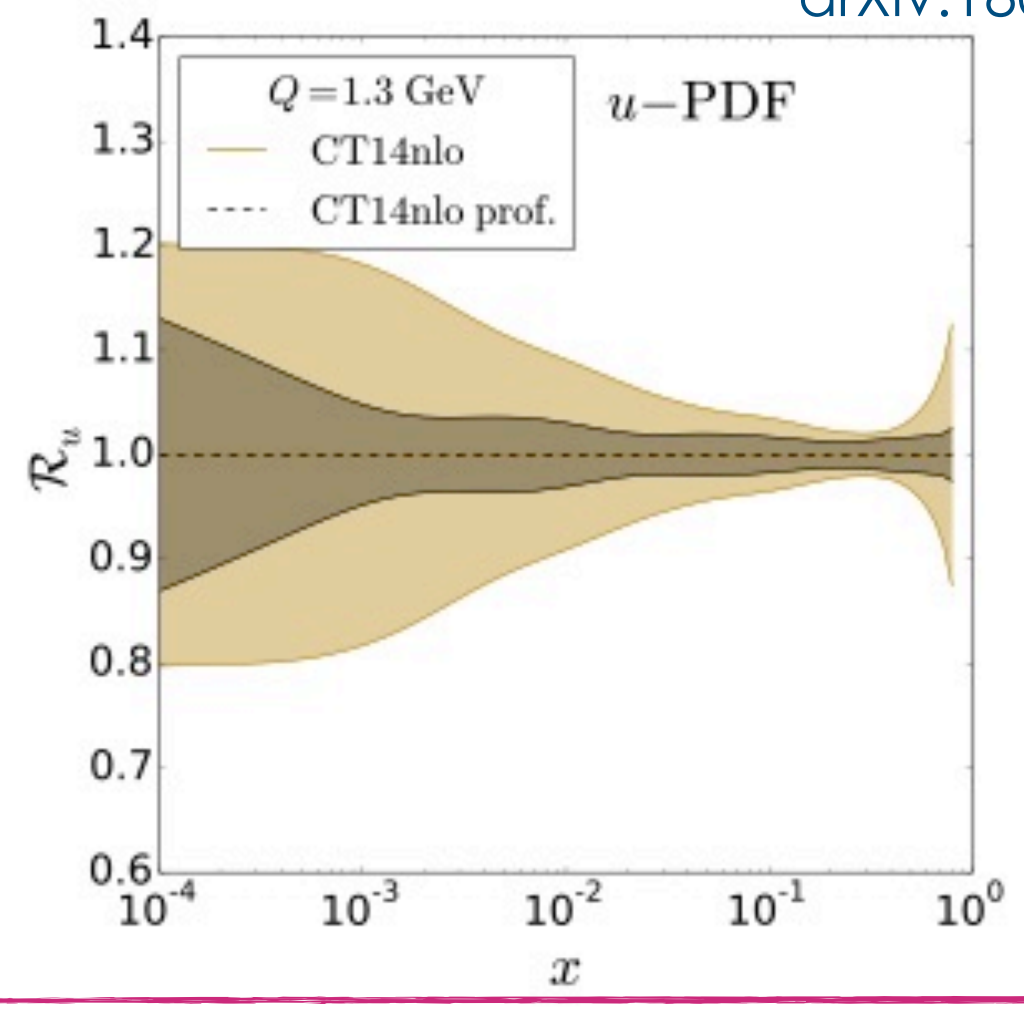
arXiv:1807.00603



arXiv:1807.00603

light-q PDFs

10 fb^{-1}



Accessing the gluon TMDs

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

Gluon TMDs

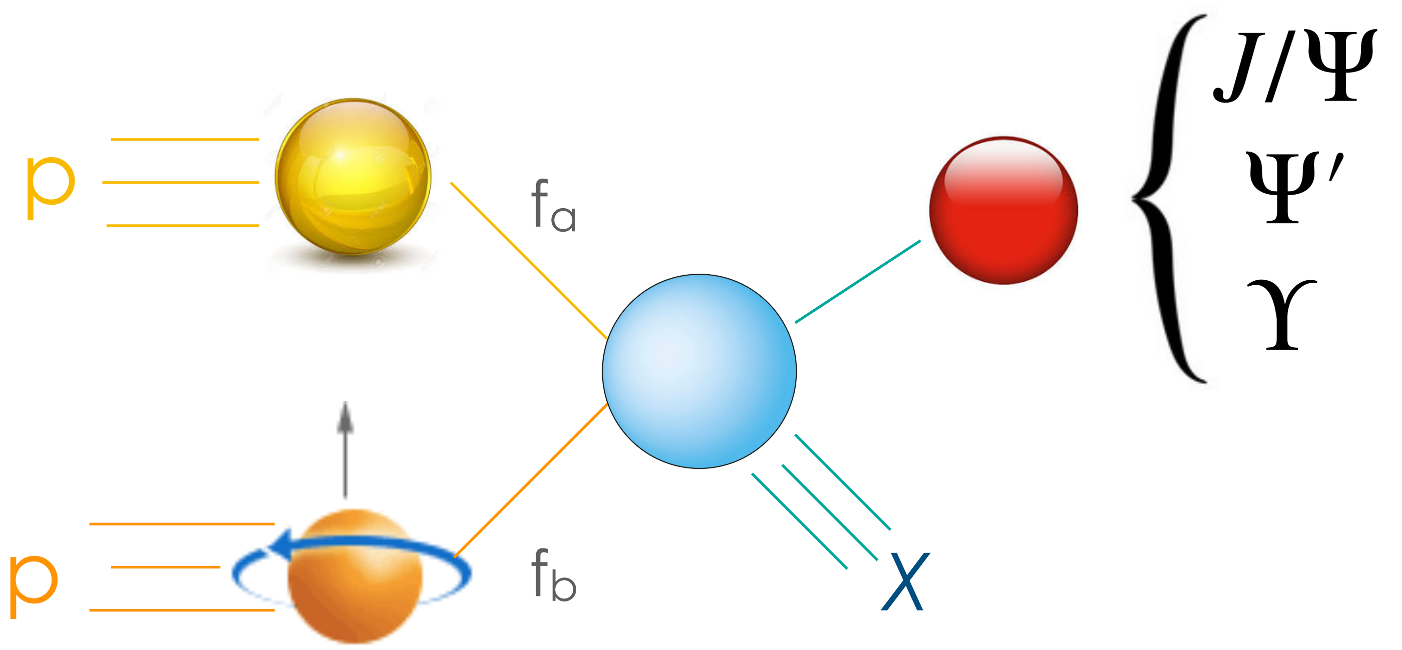
The most efficient way to access the gluon dynamics inside the proton at LHC is to measure Heavy Flavour observables, dominantly produced through gg interactions

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

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

Weizsacker-Williams (WW) gluon distributions

dipole (DP) gluon distributions



[D. Boer: arXiv:1611.06089]

unpolarized gluon TMD

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

linearly polarized gluon TMD

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

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

TMDs (Sivers)

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

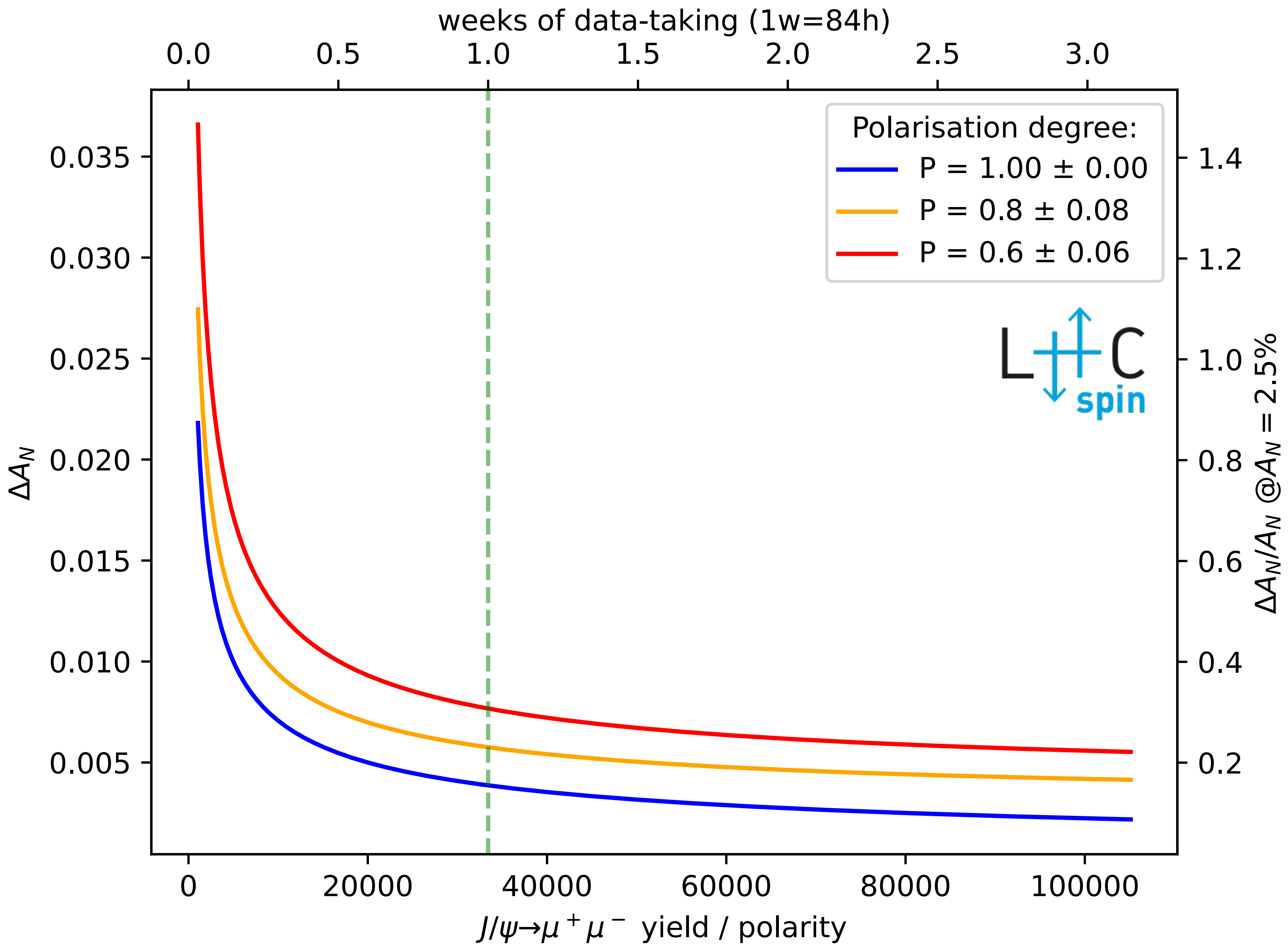
Sign change: *Universality of QCD*

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

Can be measured at FT-LHC

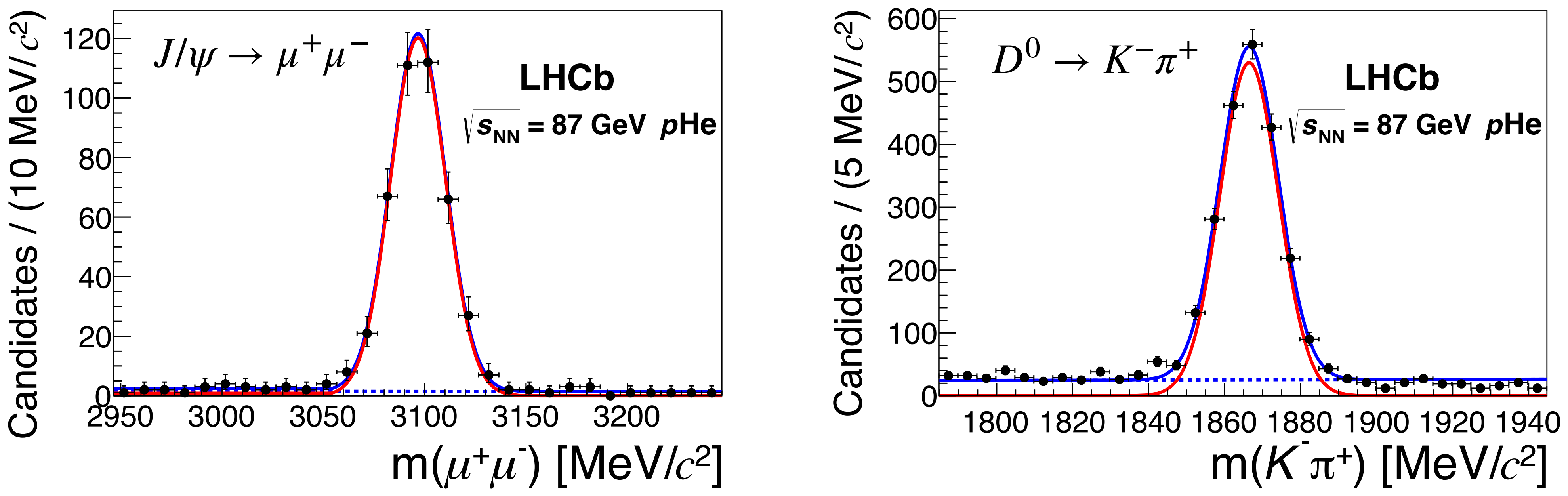
LHCb can measure nearly all quarkonia states with high precision!
[unique channels: pseudoscalar quarkonia (η, η_c, $\eta_c(2S)$, $\chi_{c,b}$), Υ, J/Ψ, Ψ', di–J/Ψ, Υ(1,2,3S), D, B-mesons, DY ($\mu^+\mu^-$)]

Single Spin Asymmetries



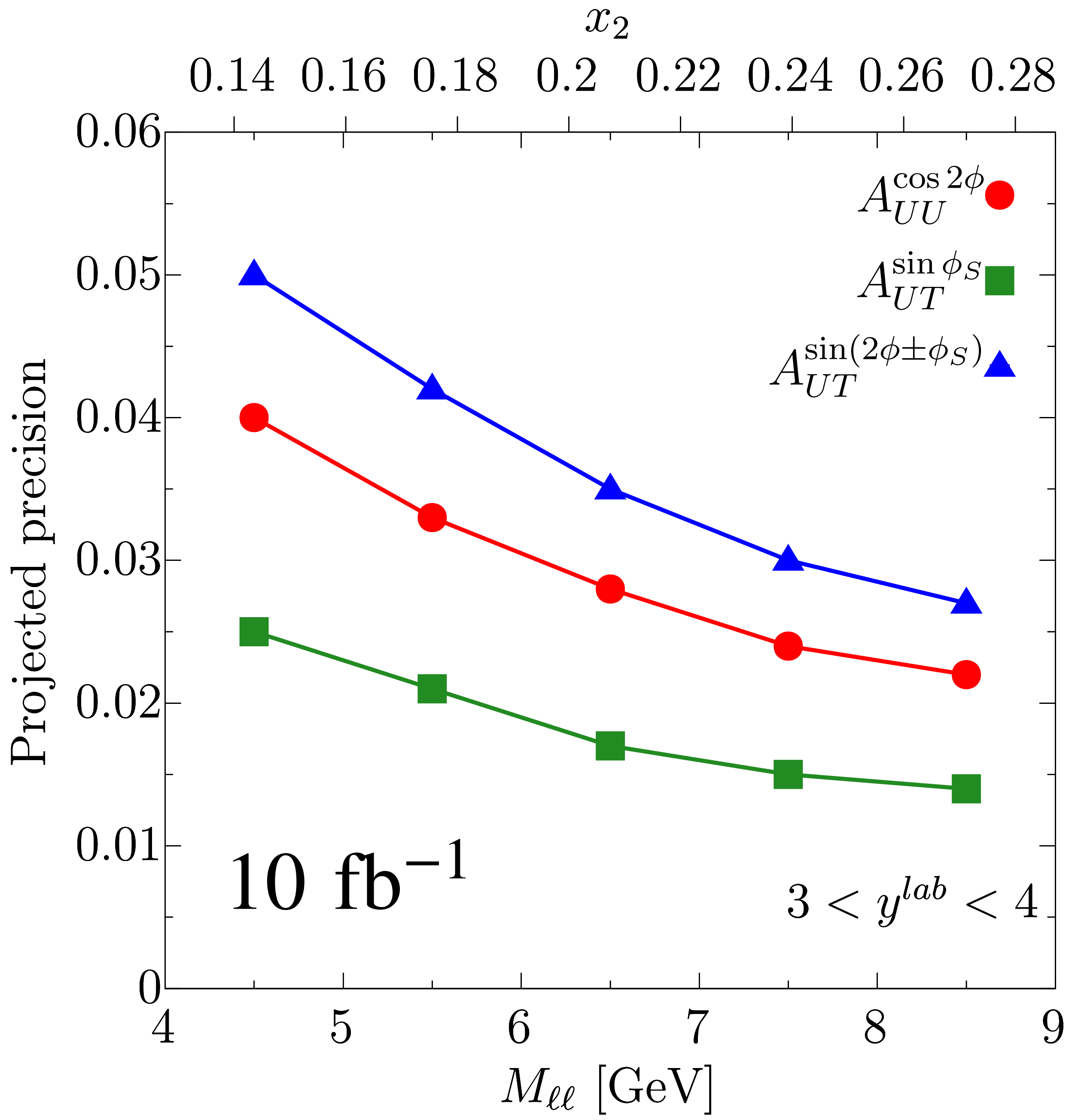
Excellent precision in integrated observables
EIC will access the multidimensional phase-space

- An example of SMOG data from 2016: $7.6\ \mathrm{nb}^{-1}$ in just $87\ \mathrm{h}$



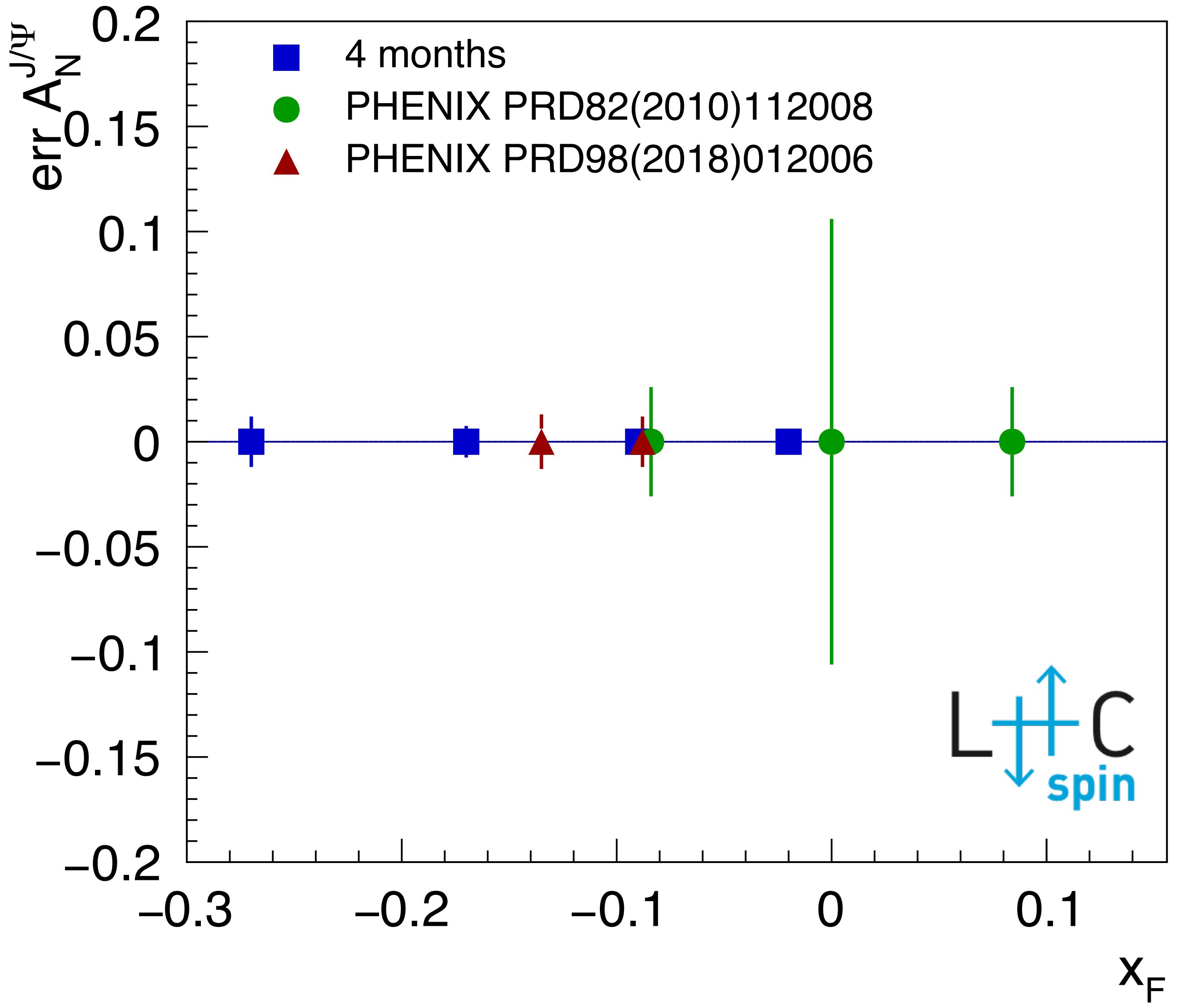
[PRL 122 (2019) 132002]

- Polarised DY

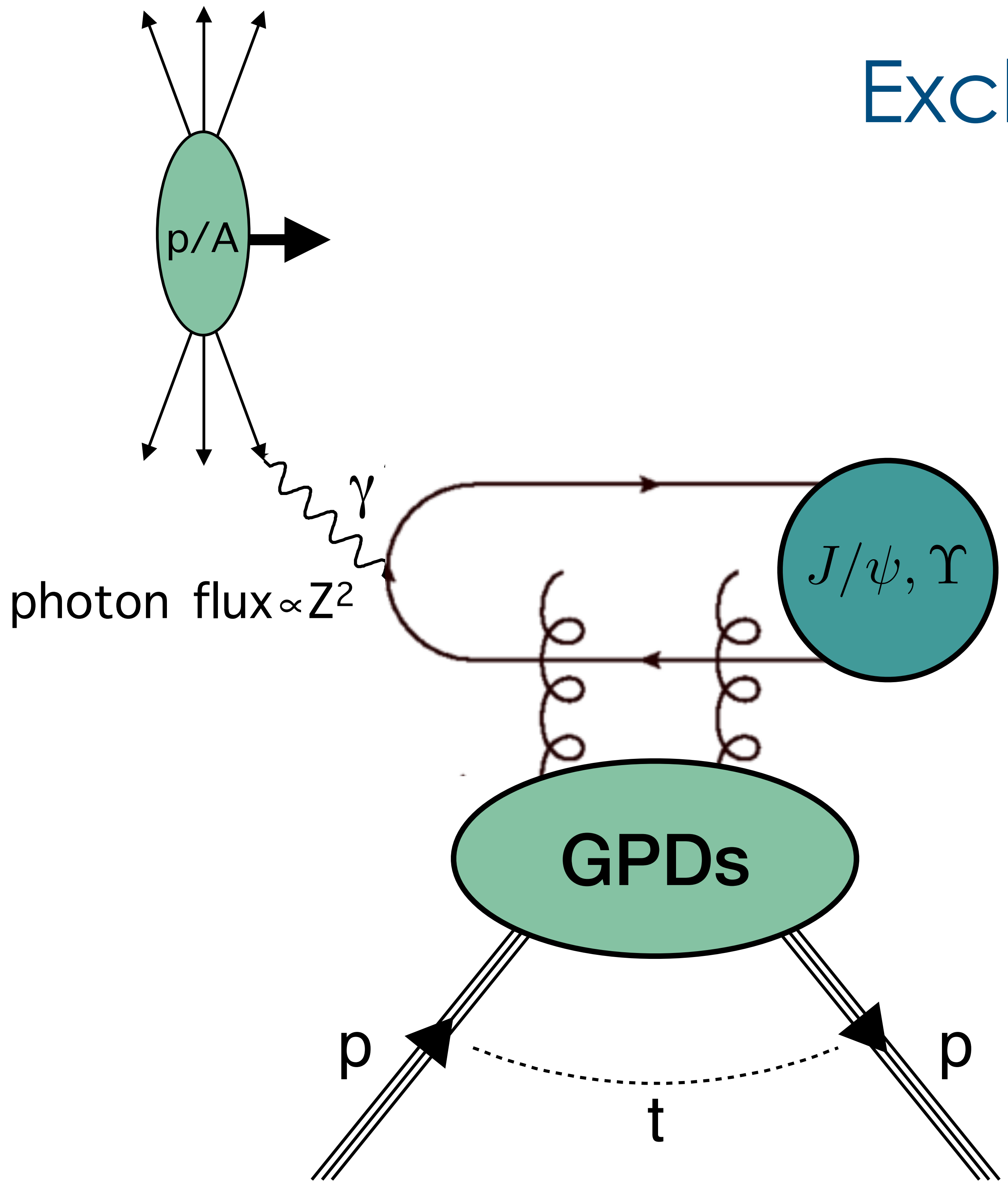


[ArXiv:1807.00603]

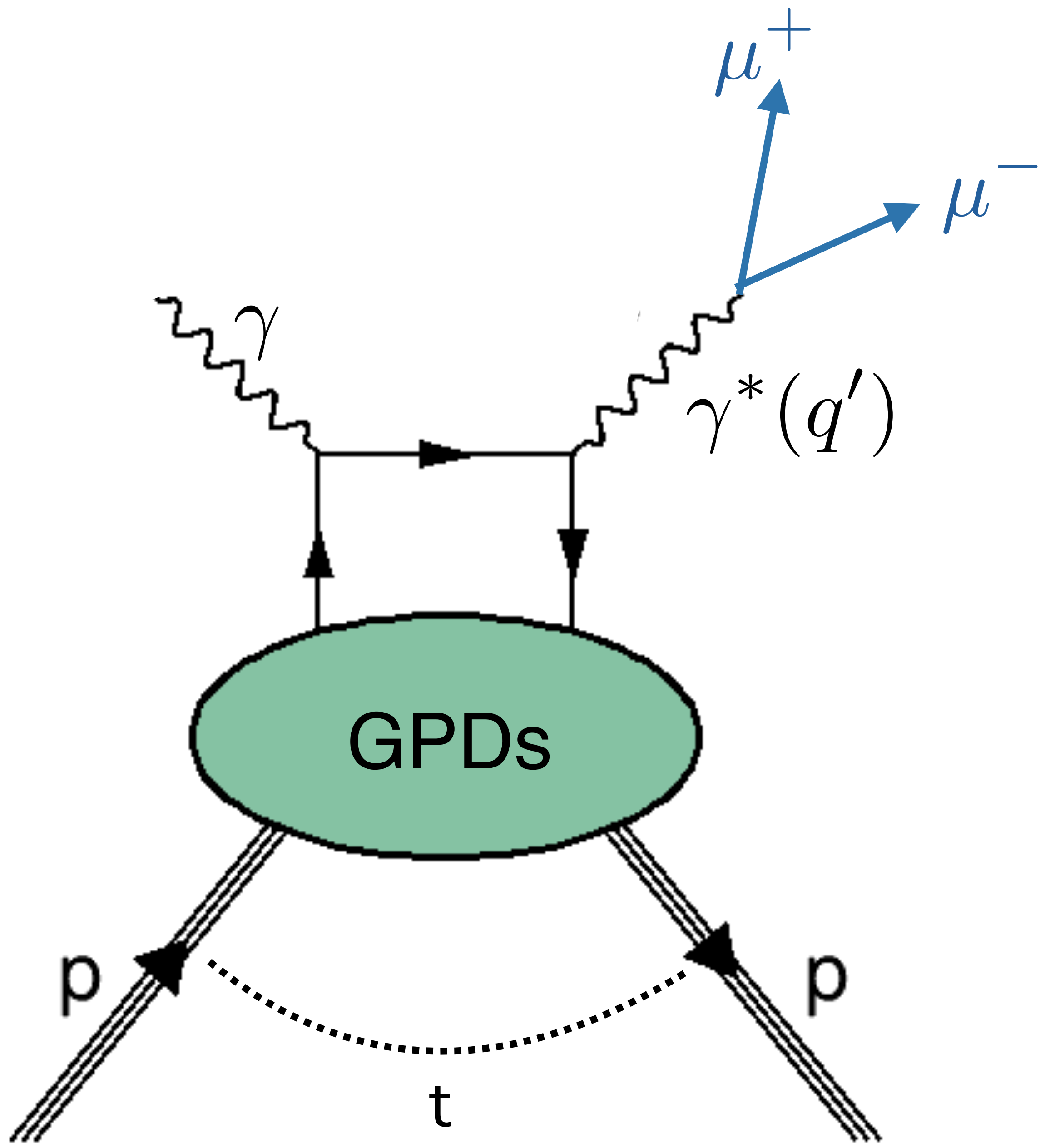
- Heavy Quark probes e.g. J/ψ, di-J/ψ



Exclusive physics via UPC



Exclusive meson production

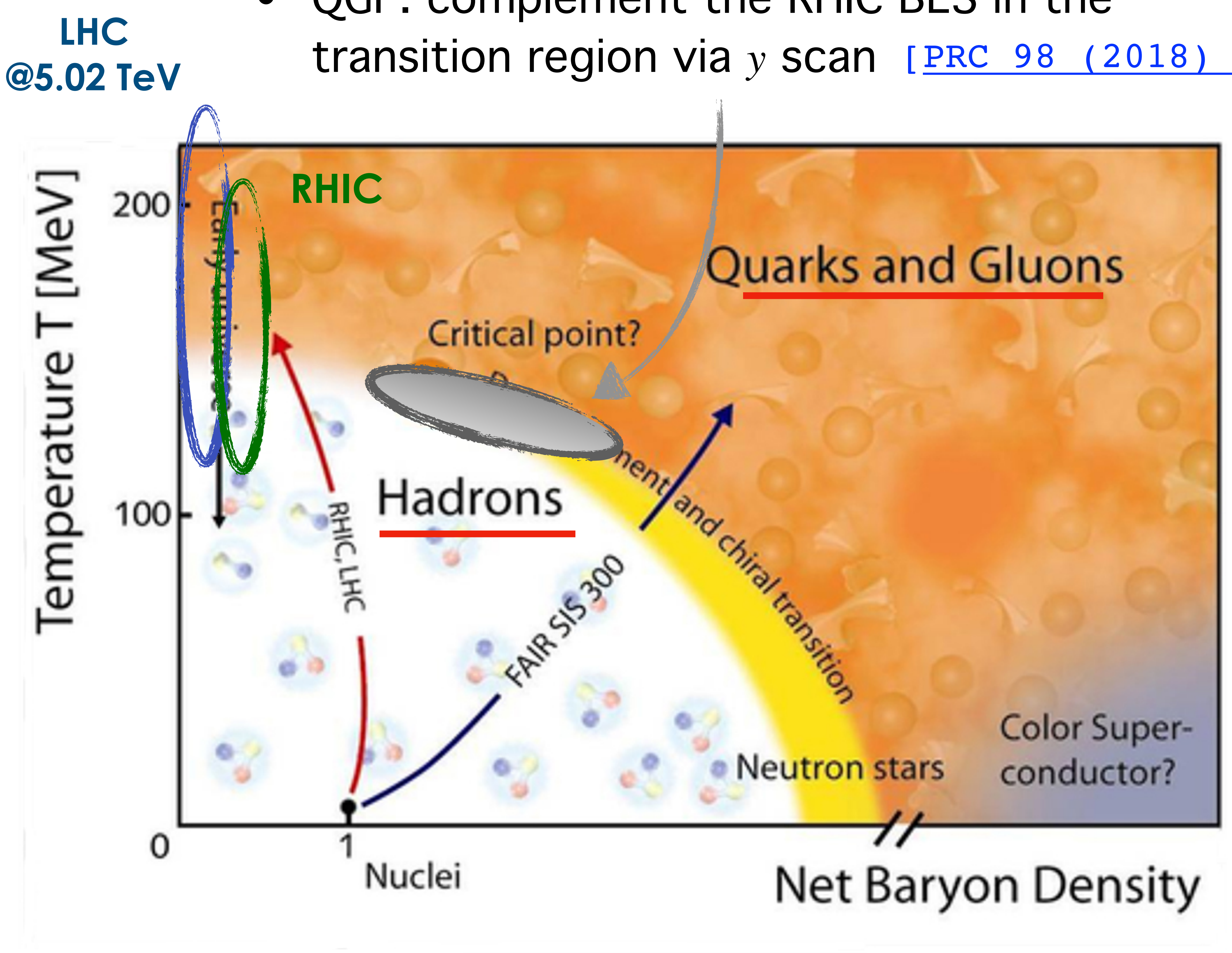


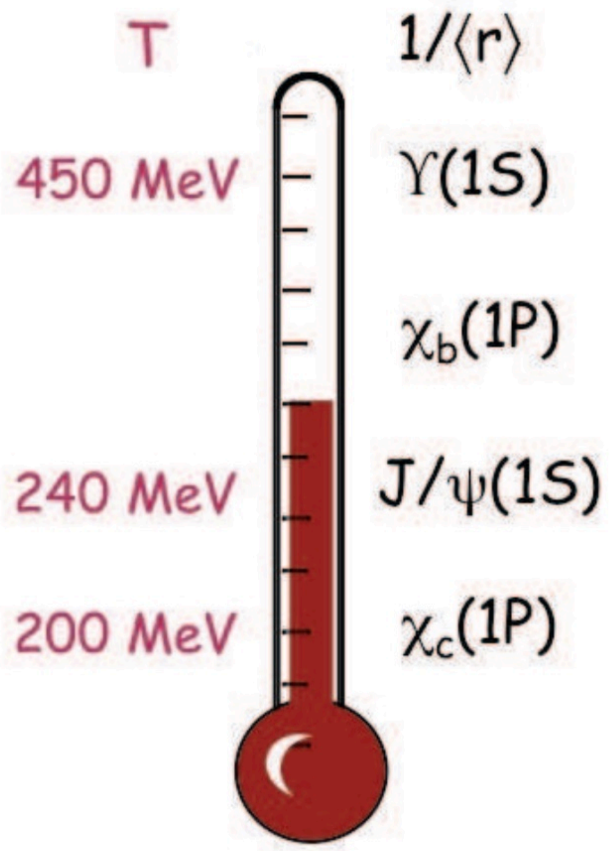
Timelike Compton scattering

	$pp,$	$pAr,$	$pKr,$	$pXe,$	$PbAr$
Statistical uncertainty on the cos(ϕ) modulation of the continuum 2 muons →	30%	10%	20%	15%	30%
Statistical uncertainty on the J/Ψ xsection →	10%	5%	5%	5%	5%

1 yr of data taking

- QGP: complement the RHIC BES in the transition region via y scan [PRC 98 (2018) 034905]



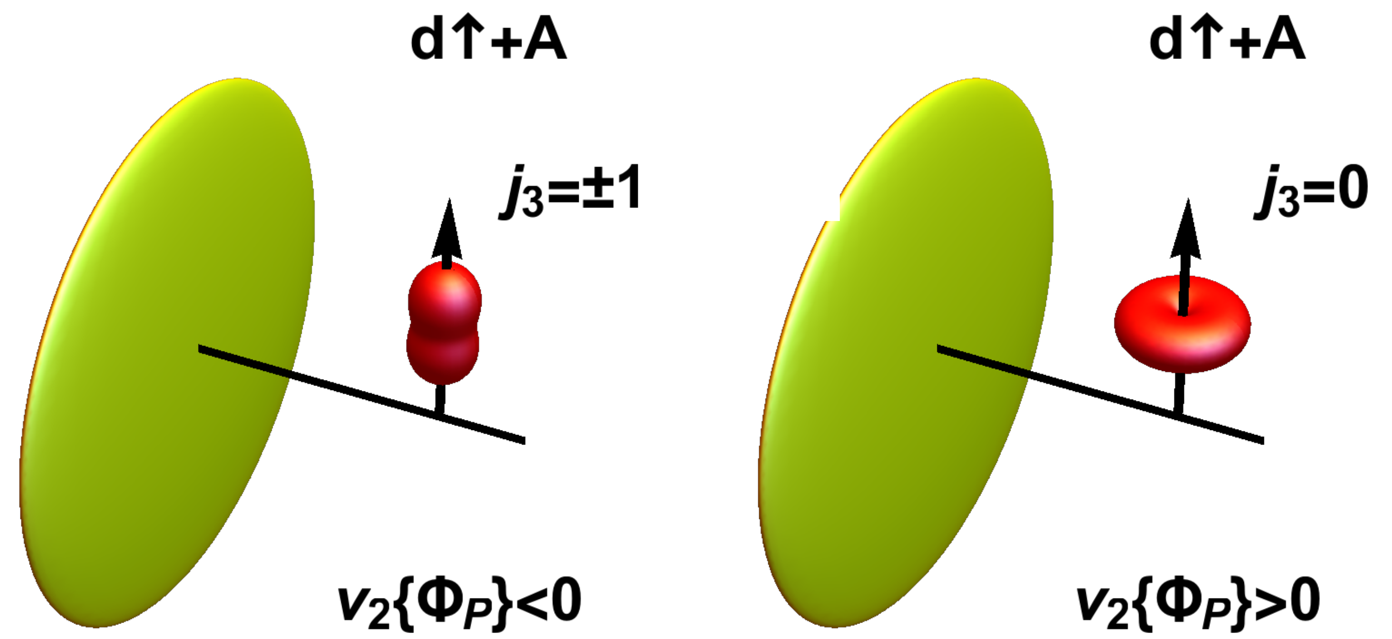


- Suppression of $c\bar{c}$ bound states as QGP thermometer
- Different binding energy → different dissociation temperature

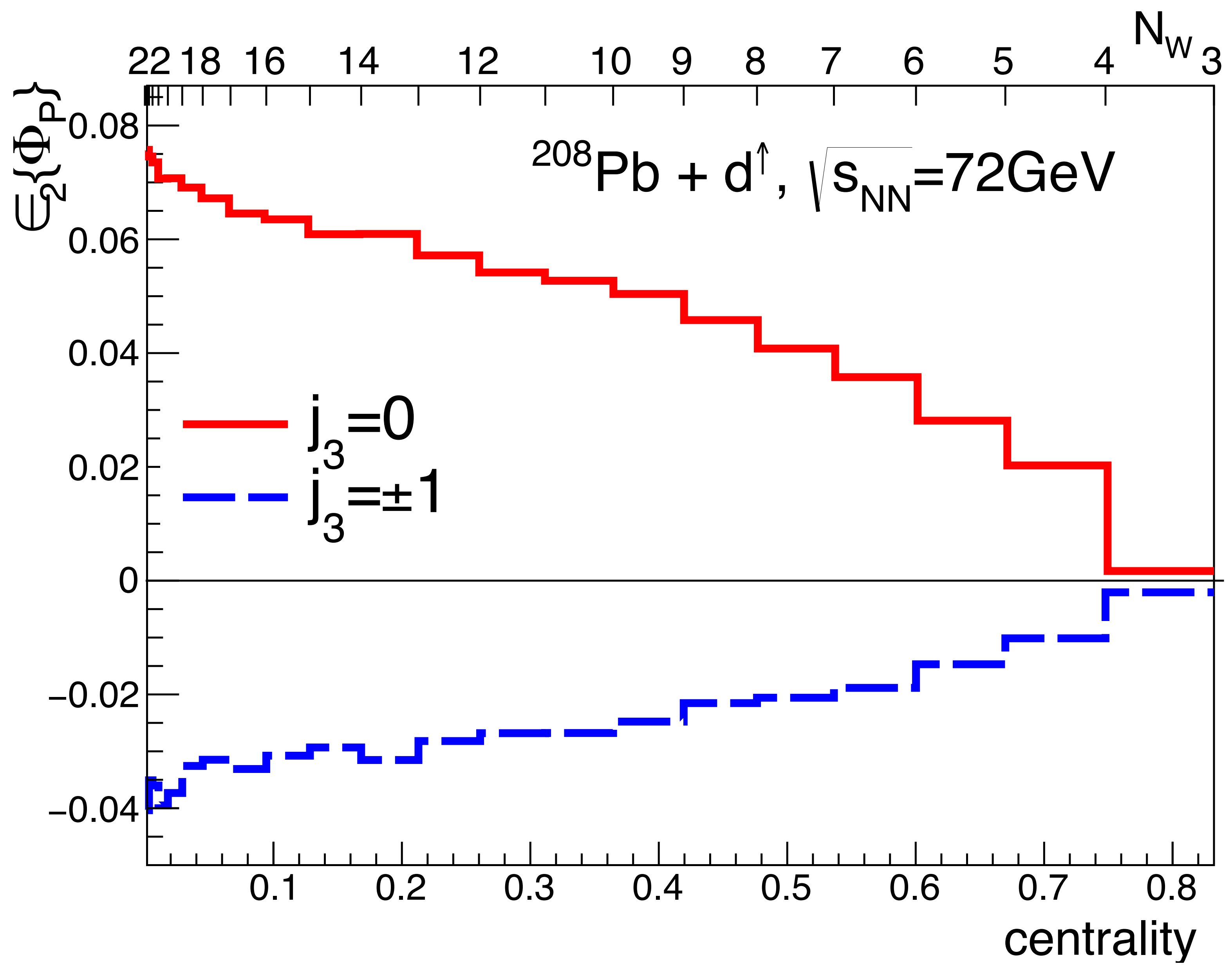
[IJMPA 28 (2013) 1340012]

- Ultra-relativistic collisions of heavy nuclei on T polarised deuterons to probe the dynamics of small systems
- Deformation of $D^{\uparrow}$ is reflected in the orientation of the created fireball in the transverse plane

D polarised along Φ_p , perpendicular to the beam



- Quantified by the ellipticity (ϵ_2 wrt Φ_p)



[PRC 101 (2020) 024901]

Cosmic Rays and DM

pHe, pO, pN … and also Op, OO
unique opportunities

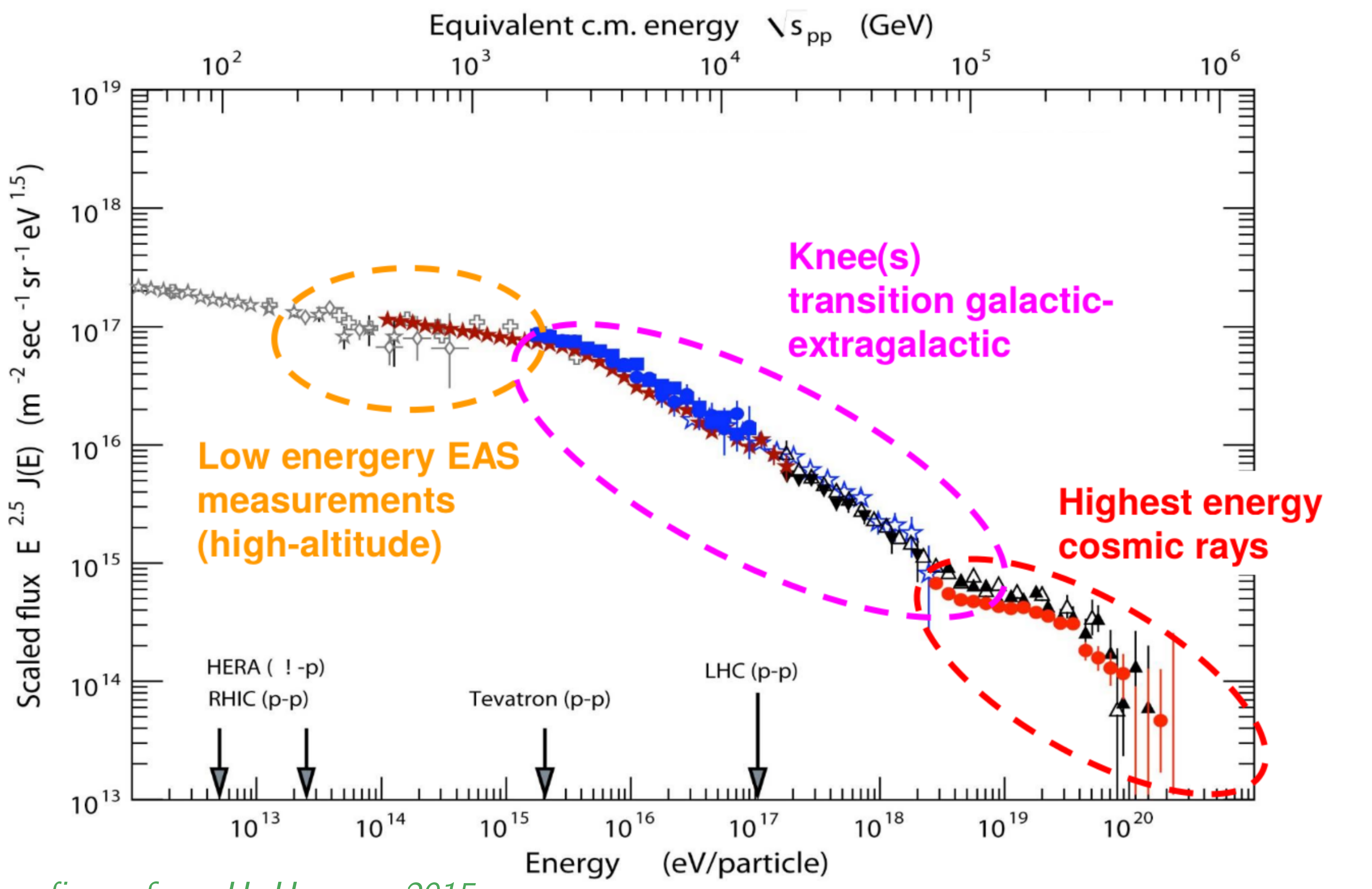


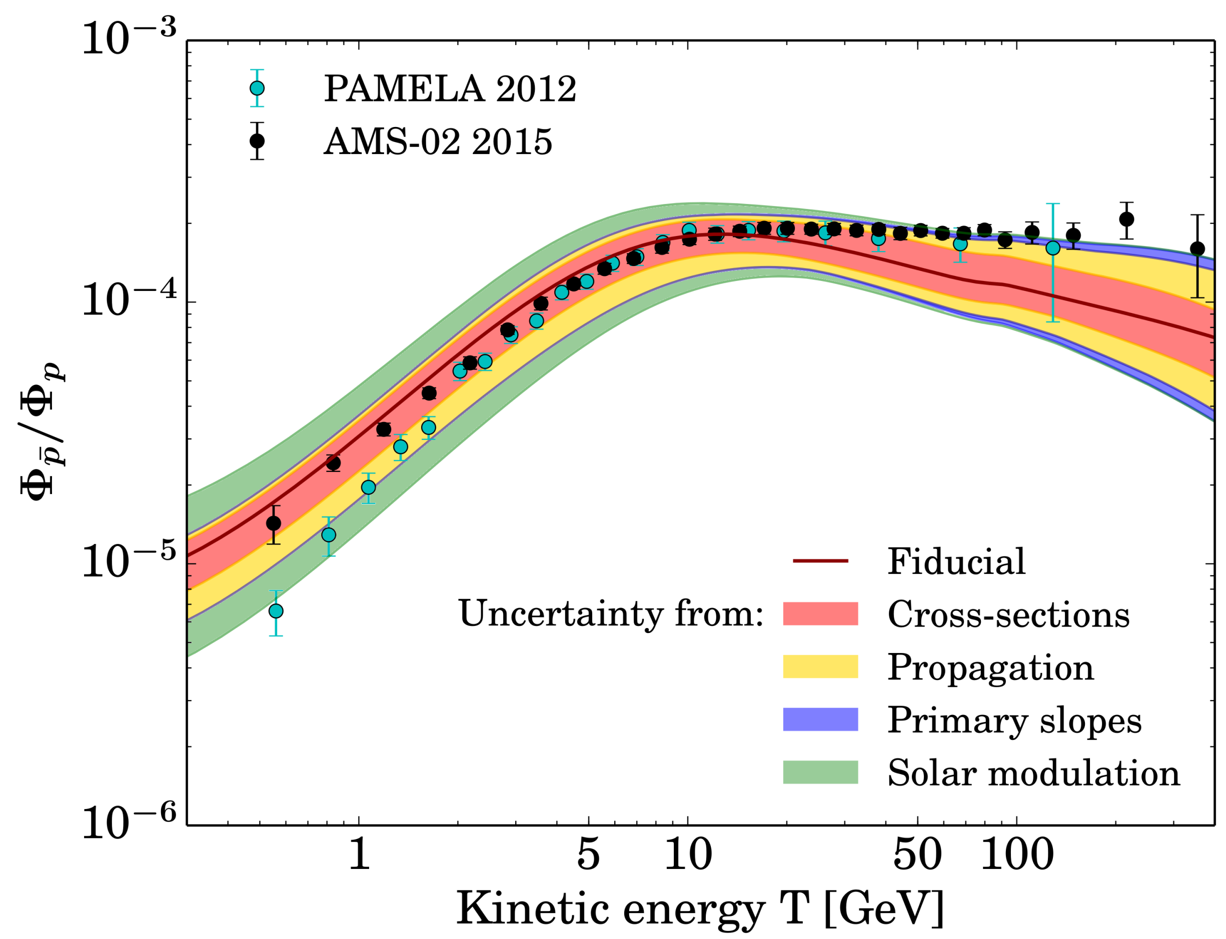
figure from H. Haungs, 2015

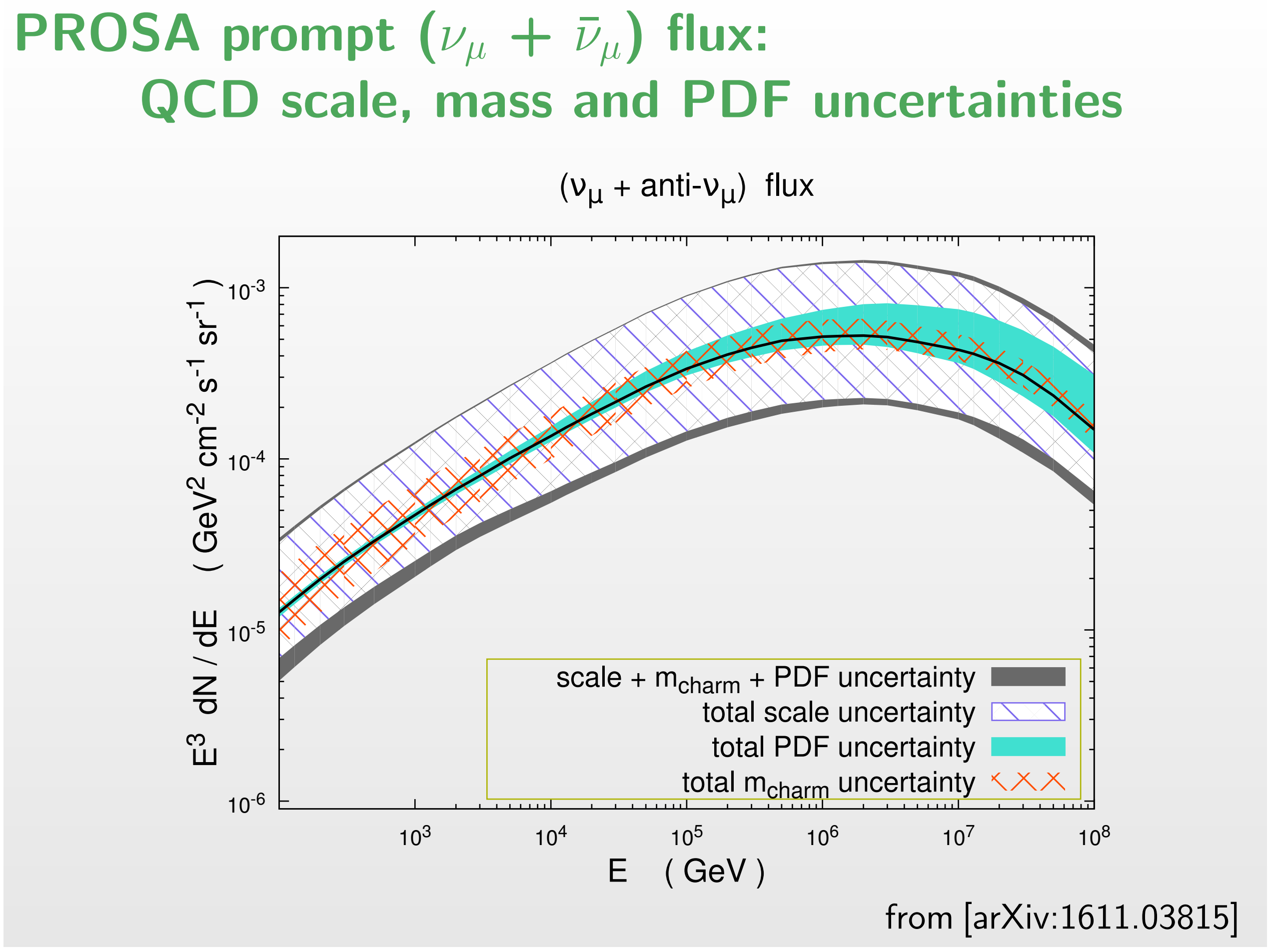
composition problem

Crucial inputs from FT data

- -(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)

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





Big uncertainties from PDF

<u>Wishlist for FT measurements at LHC from the CR community</u>

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 $\rightarrow \bar{d}, \overline{He}$ to determine coalescence momentum
5) p p, p He $\rightarrow \pi$, K to model positron source term

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

SMOG2@LHCb - Statistics in full synergy mode (1 yr data taking)

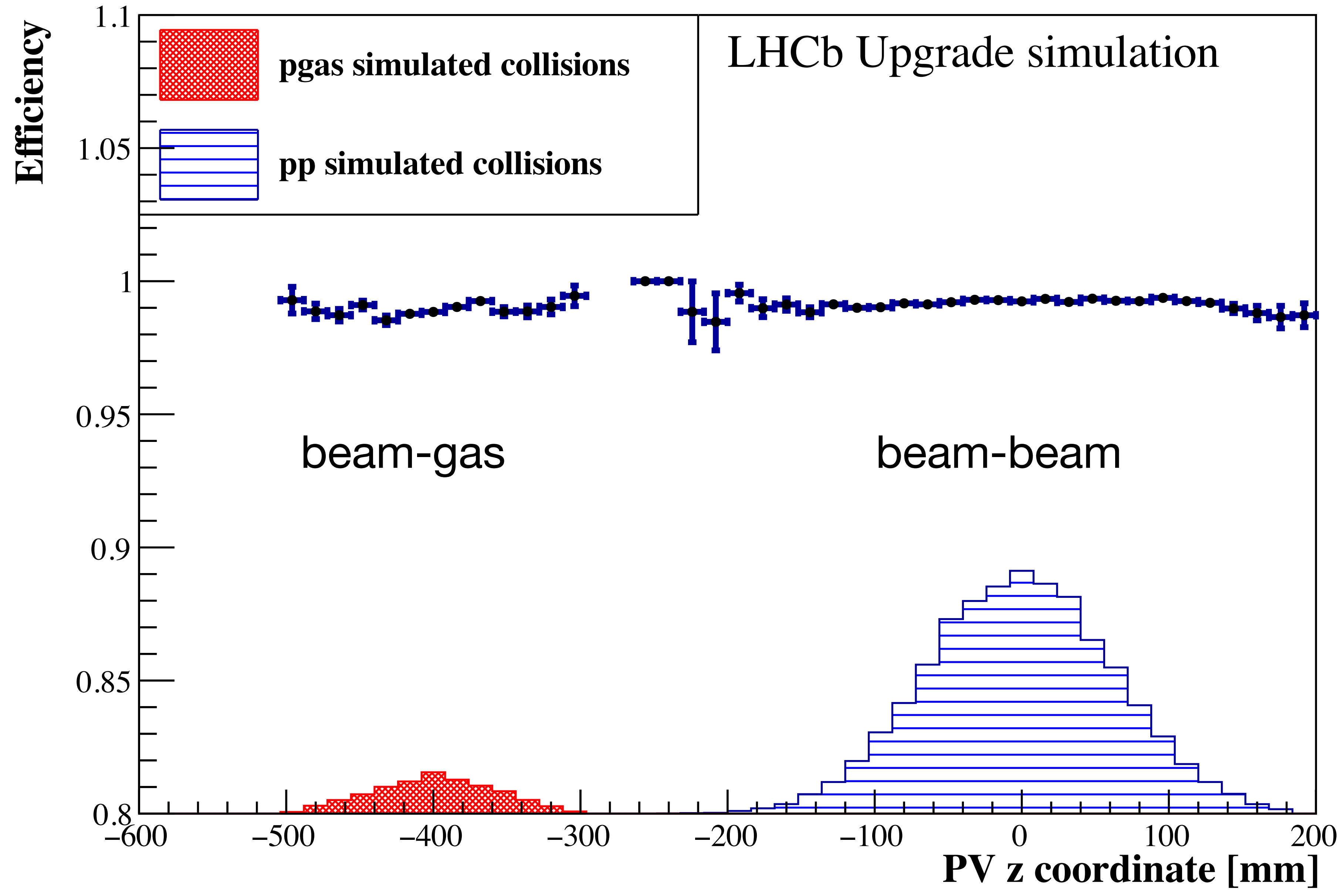
LHCb-PUB-2018-015

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

Large statistics in short time, without interfering with the beam-beam LHC operations

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



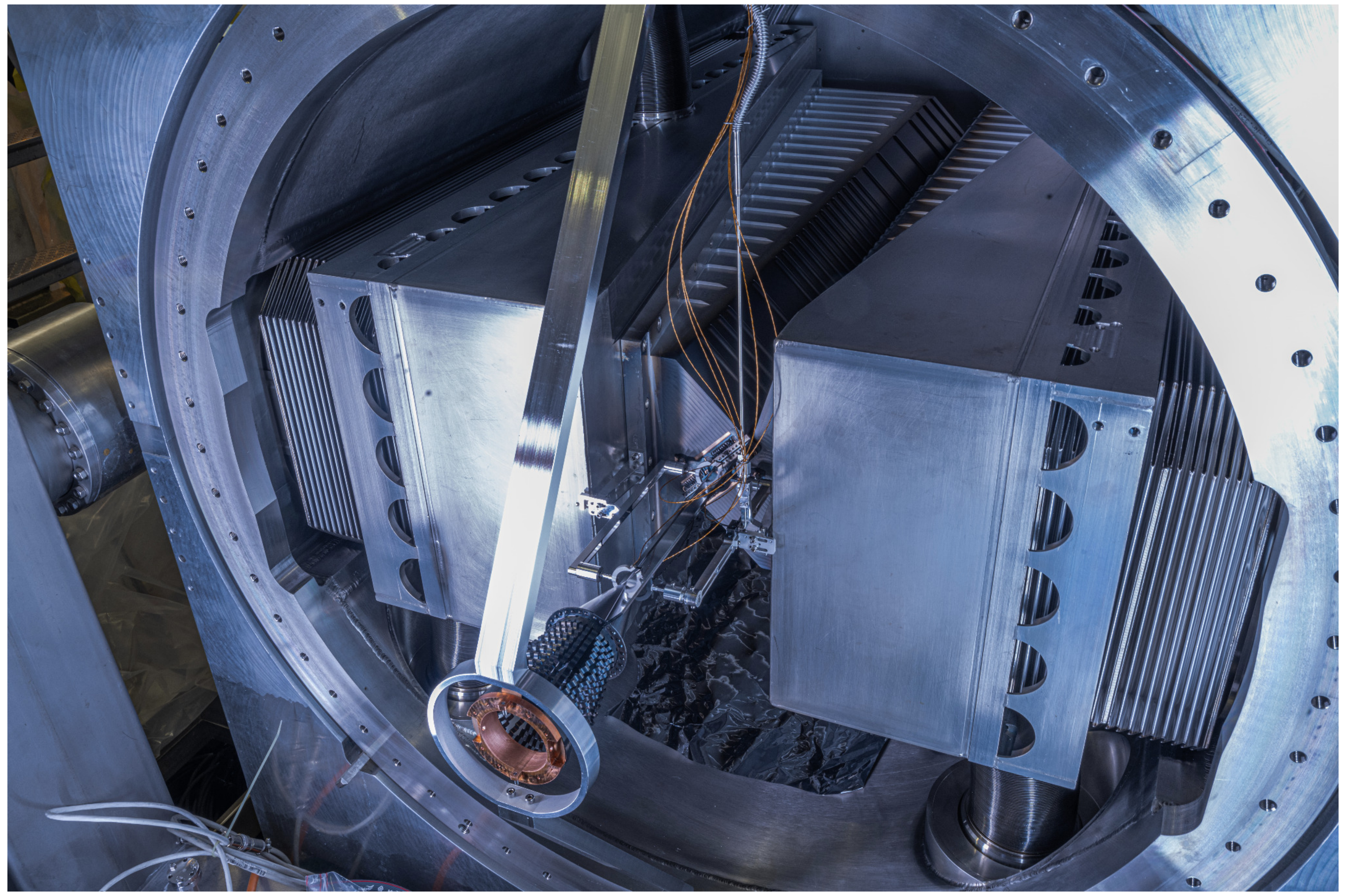
LHCb-FIGURE-2019-007

On the road … where are we at the LHC?

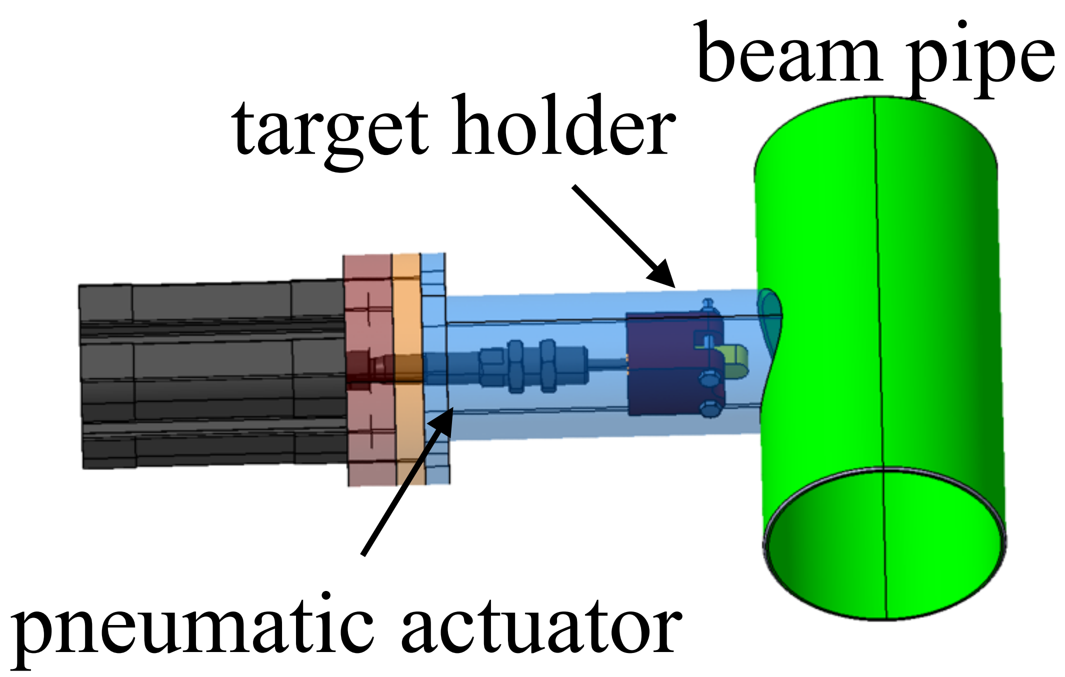
SMOG2 @ LHCb, the unpolarised gas target has been installed and ready to work from the LHC Run3

The polarised upgrade of SMOG2 is in the R&D phase. Aiming at installing during the LHC LS3 (~2027)

Solid target at ALICE in the R&D phase



LHC spin



$H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$

$H^{\uparrow}, D^{\uparrow}$

$Be, Ca, C, Ti, Ni, Cu, Os, Ir, W$

Fixed Target physics at the LHC opens new physics frontiers, exploiting even more the potentialities of the existent most powerful collider and using the most advanced detectors

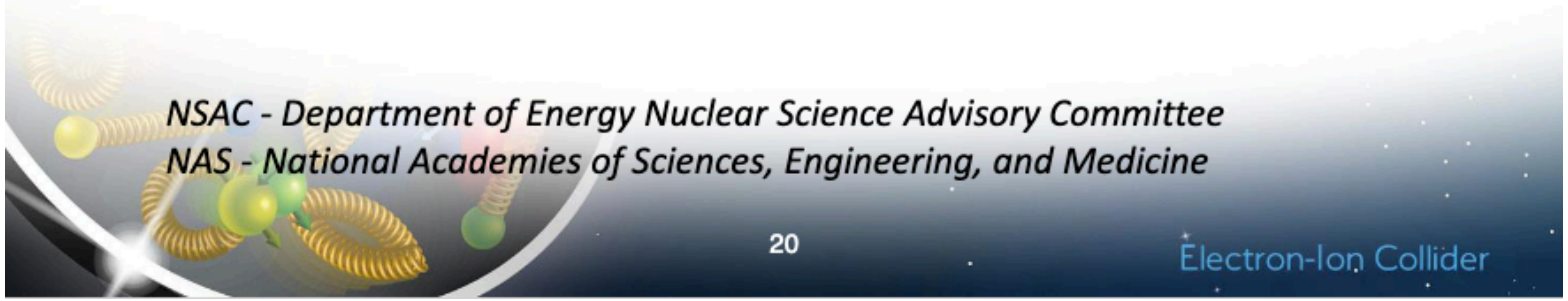
Part of this (unpolarized gas target) is already happening now
The other projects could start at LHC Run4

These programs are, not only, complementary to EIC, but they could constitute test-benches for the future measurements

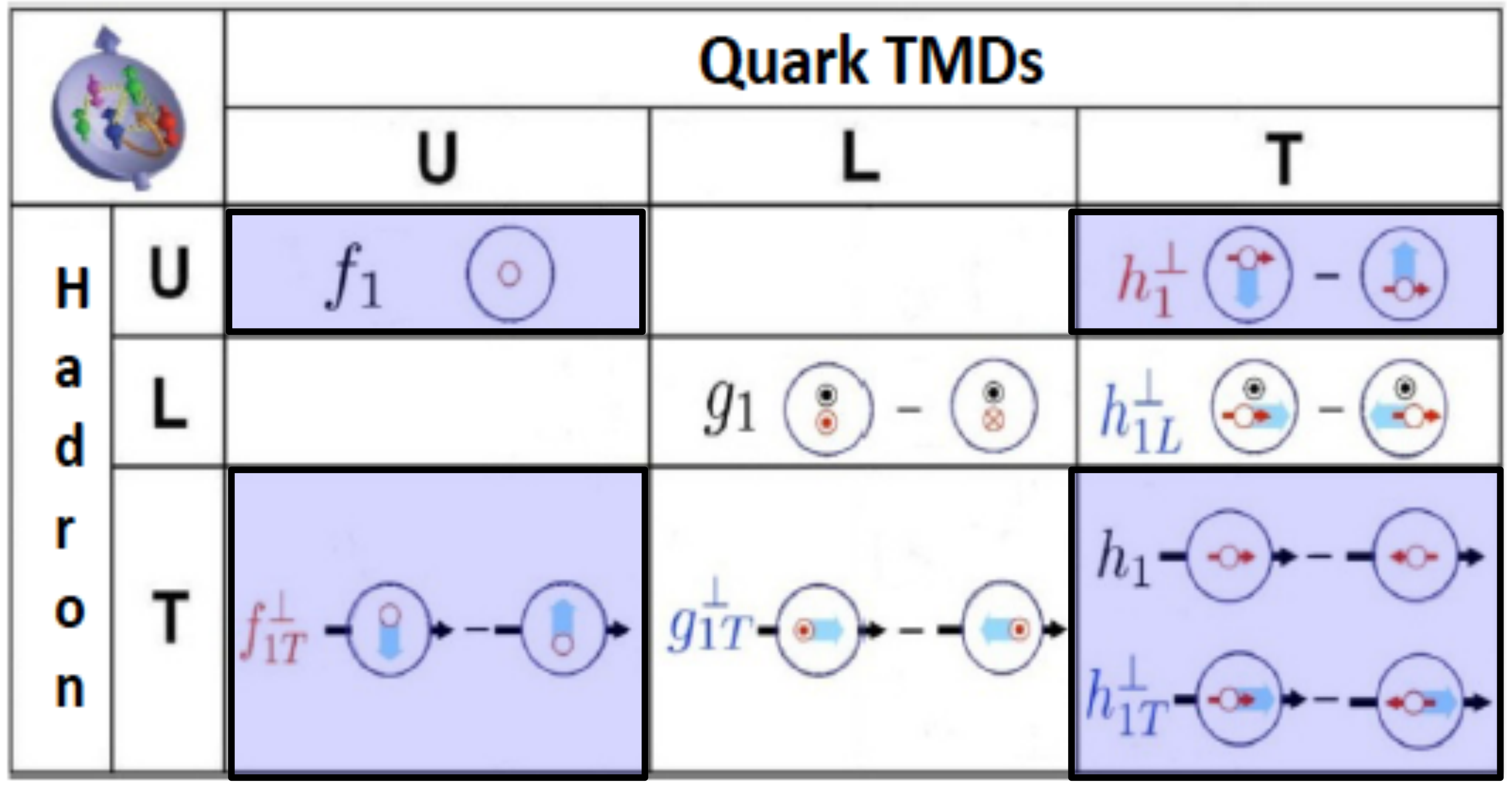
EIC designed to meet NSAC and NAS Requirements

LHC spin

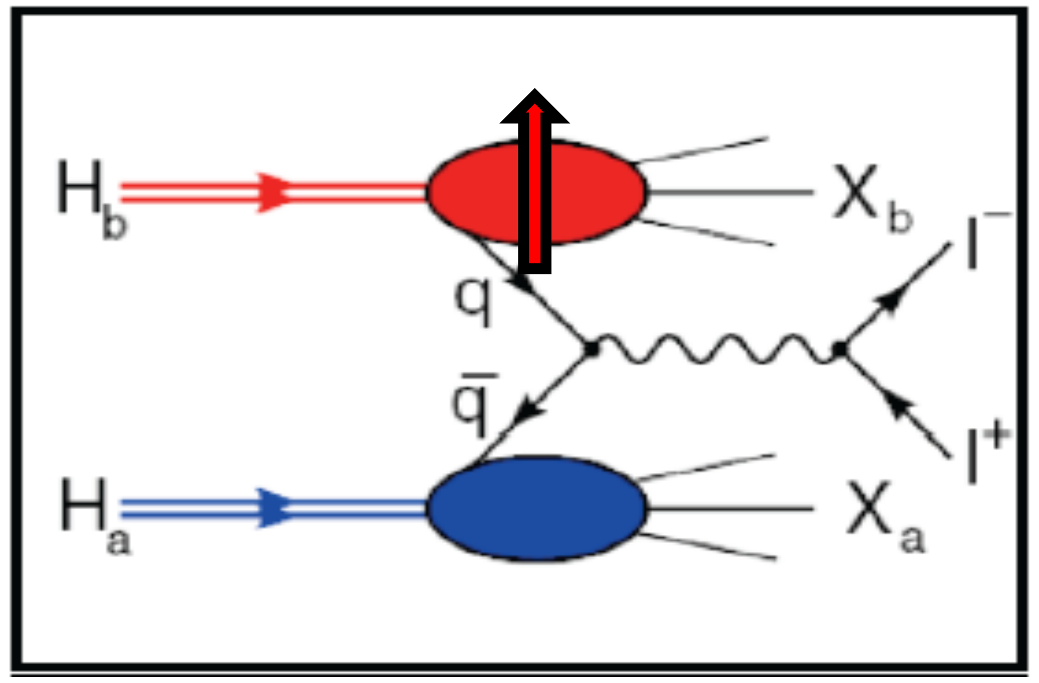
• Center of Mass Energies	45 GeV – 140 GeV	up to 115 GeV
• Maximum Luminosity	10^{34} cm^{-2}s^{-1}	8 x 10^{32} cm^{-2} s^{-1}
• Hadron Beam Polarization	>70%	~85 % (target)
• Electron Beam Polarization	>70%	— (no double spin asymmetries)
• Ion Species Range	p to Uranium	$H^{\uparrow\downarrow}, D^{\uparrow\downarrow}, H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
• Number of interaction regions	up to two	1

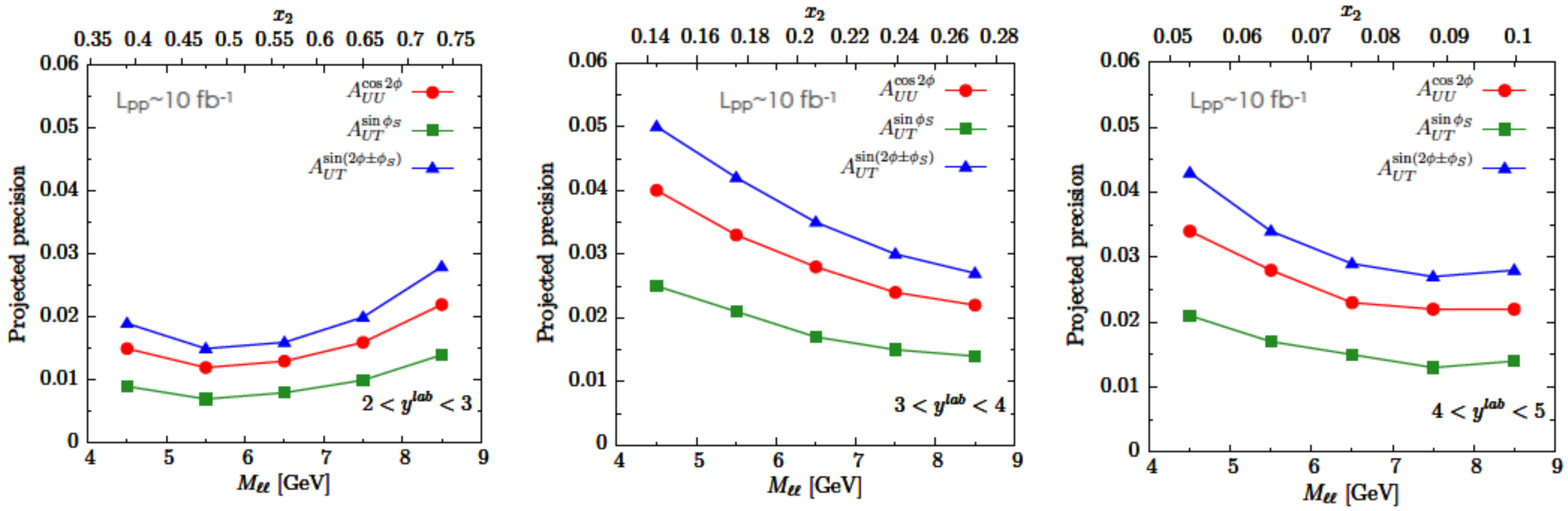


Accessing the quark Transverse Momentum Distribution functions (TMDs)



Polarized Drell-Yan



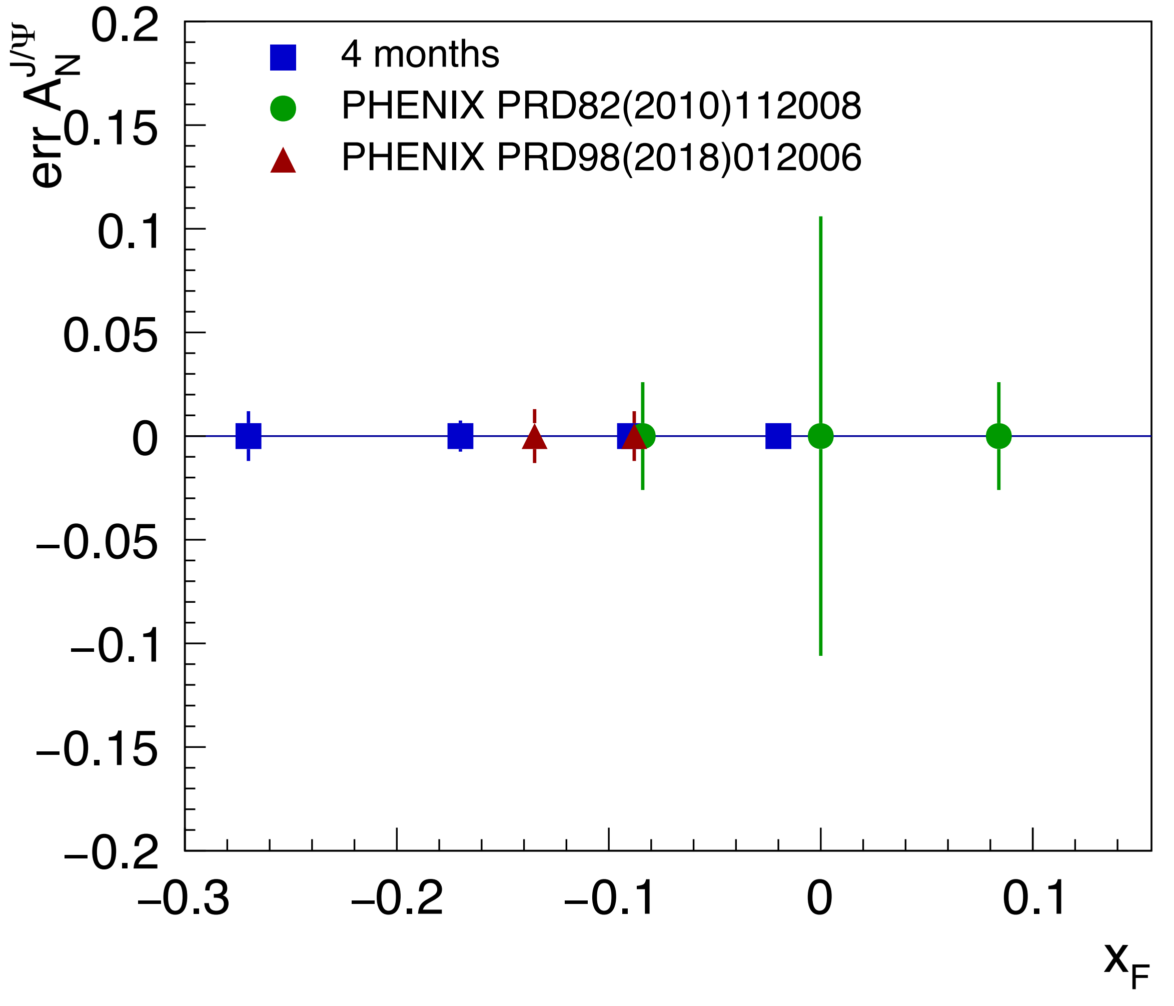


arXiv:1807.00603

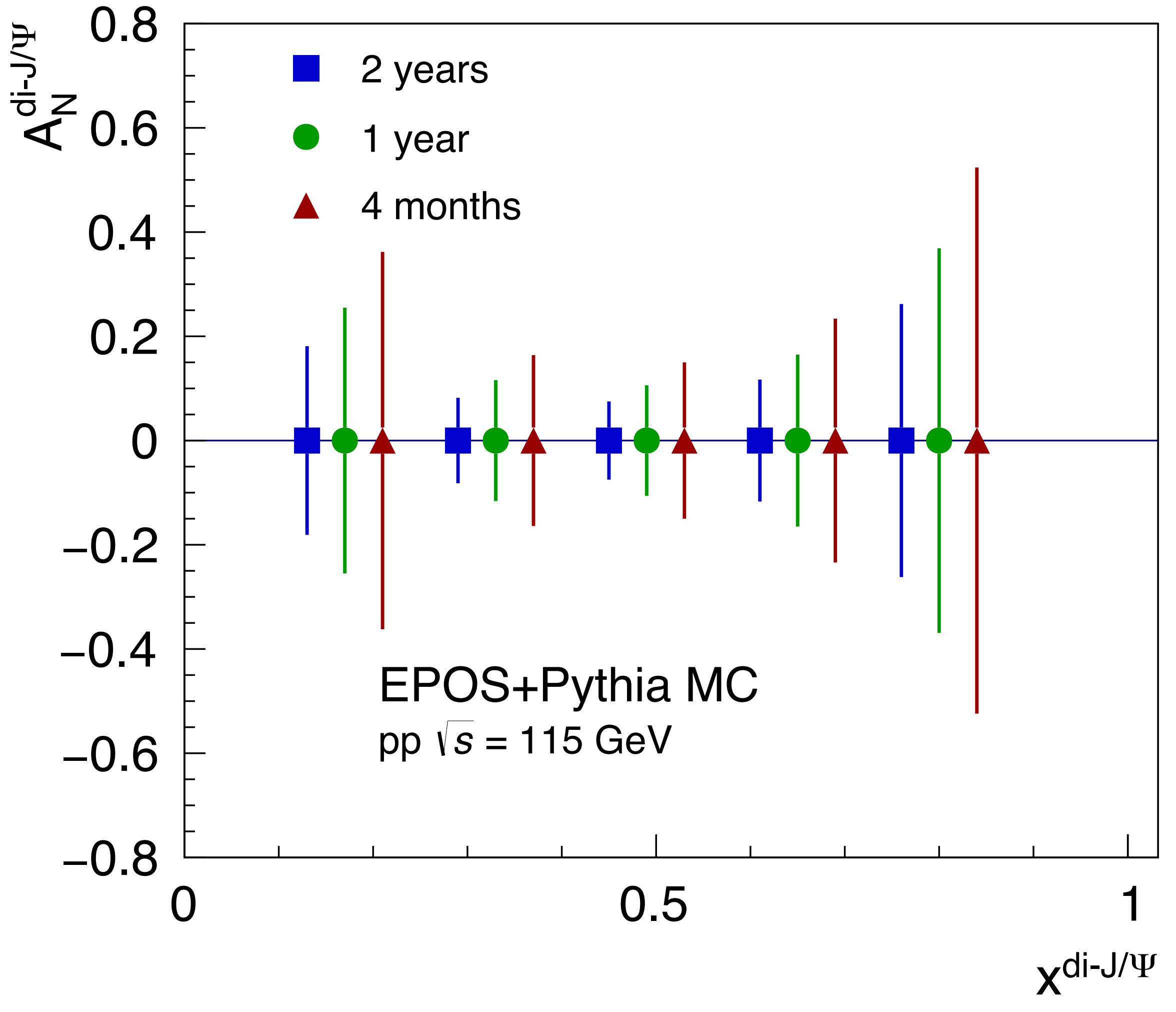
High precision achievable for observables connected to (e.g.) the transversity, the Boer-Mulders function, the pretzelosity and the Sivers TMDs

… heavy quark sector

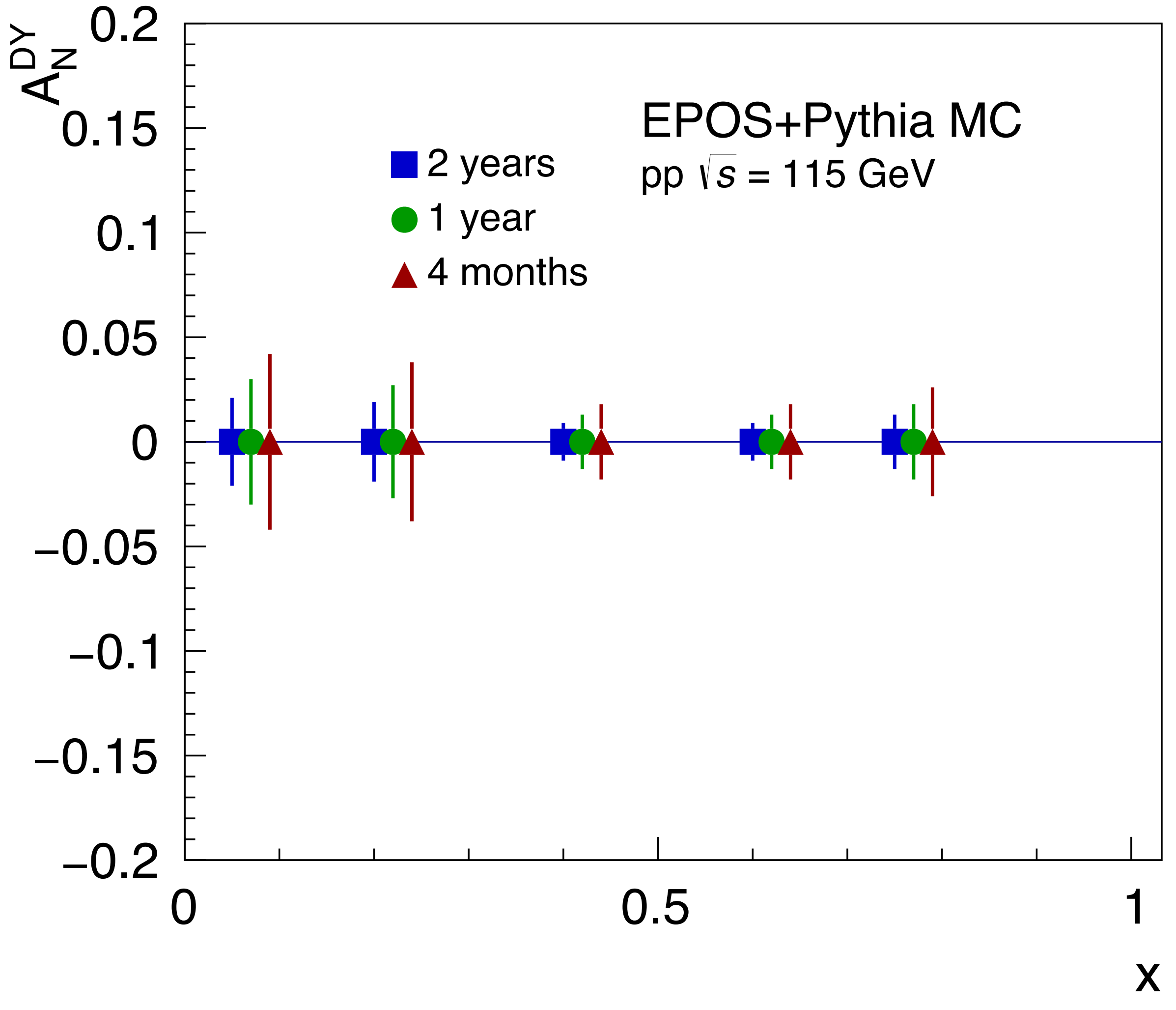
J/Ψ

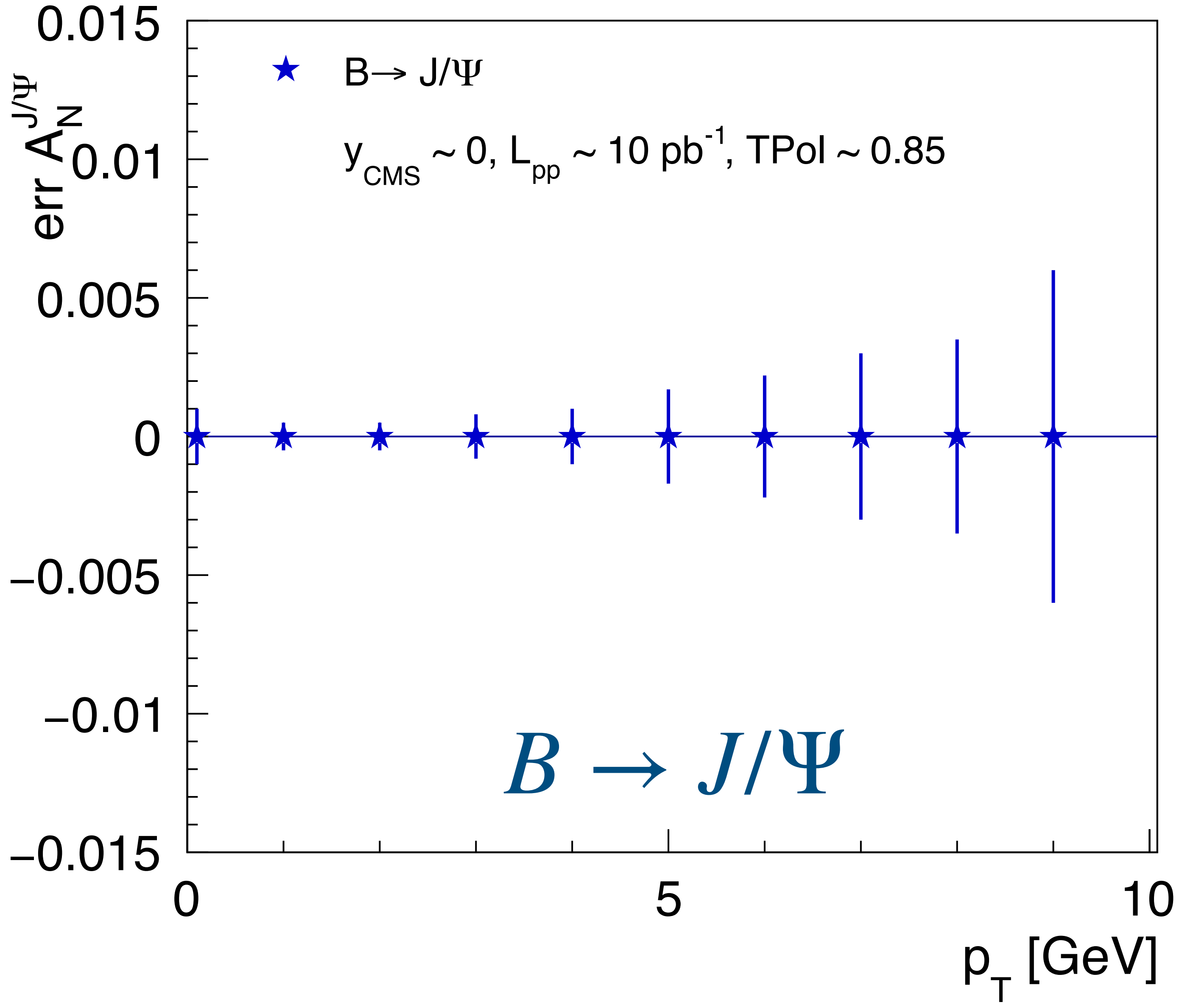


$di-J/\Psi$



DY





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