LHC-Fixed-Target Quarkonium Physics Case

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Quarkonia as tools, 12-18 Jan 2020, Aussois, France

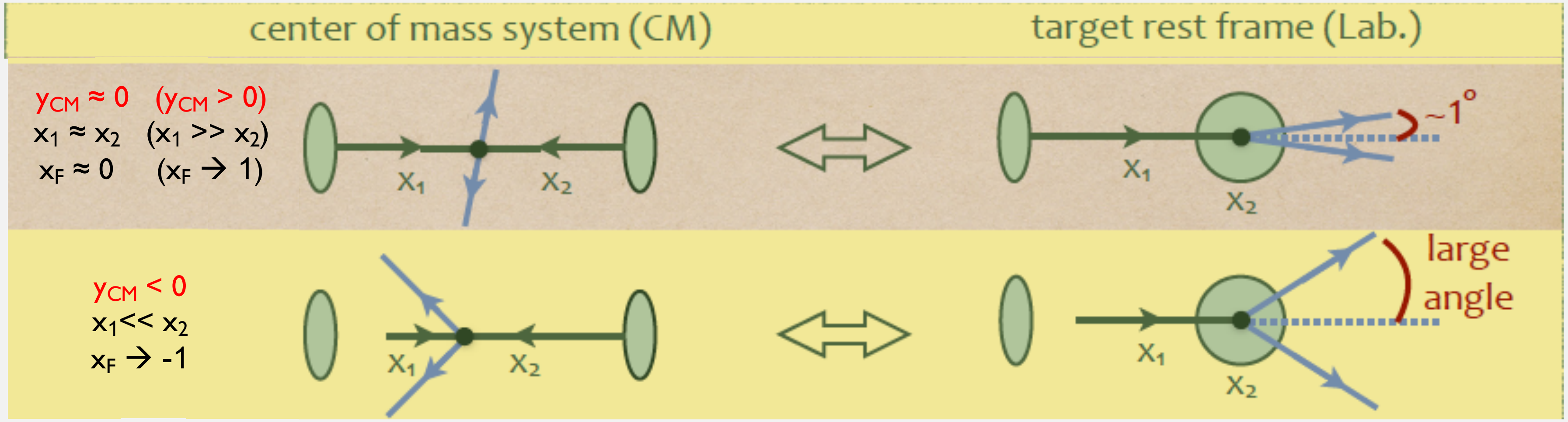
Outline

- ☐ Advantages of the fixed-target mode versus the collider mode
- ☐ Physics motivation for a fixed-target programme at the LHC
- ☐ Physics motivation: Spin and 3D nucleon structure
- ☐ A selection of projections for the FT@LHC spin physics case
  - ➢ Probing the quark Sivers effect with Drell-Yan
  - ➢ Probing the gluon Sivers effect with
    - Open Heavy Flavours
    - Vector quarkonium
    - C-even quarkonium
    - Quarkonium associated production
  - ➢ Access to linearly polarized partons in unpolarised protons
  - ➢ Exclusive quarkonium photoproduction to probe the GPDs

Advantages of the fixed-target mode versus the collider mode

❑ Several unique assets of the fixed-target mode w.r.t to the collider mode:

- ➢ **Accessing the high Feynman-x_F domain** ($x_F = p_z/p_{zmax} = x_1 - x_2$)



→ Entire CM forward hemisphere ($y_{CM} > 0$) within $0° < \theta_{lab} < 1°$ (high multiplicities → large detector occupancy)

→ Backward physics ($y_{CM} < 0$) : larger angle in the laboratory frame (lower detector occupancy) : access to parton with momentum fraction $x_2 \rightarrow 1$ in the target (ie. $x_F \rightarrow -1$)

Advantages of the fixed-target mode versus the collider mode

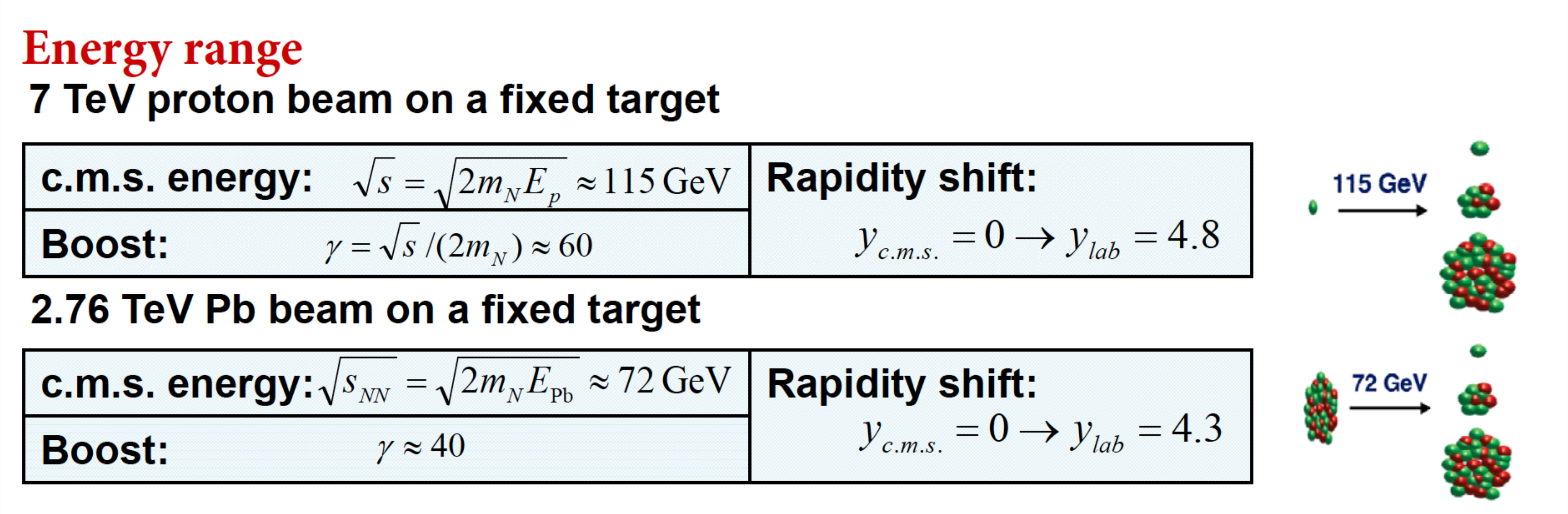
- **Target-species versatility :**
  - Change the target type in a reduced amount of time
  - Study the atomic-number dependence of nuclear effects
  - Isospin studies with deuteron and ^{3}He targets

- **Target polarisation (depending on the technology used) :**
  - The only way to make spin physics at the LHC complex
  - Access to single-spin asymmetries for several probes at large-x, where they are the largest
  - Polarised neutron studies with $D^\uparrow$, $^3He^\uparrow$

- **Outstanding luminosities :**
  - Thanks to high target density and large LHC beam luminosity
  - Without affecting the LHC performances (parasitic mode with respect to the collider mode)

Advantages of the fixed-target mode versus the collider mode

- **Probe a different energy range with the same accelerator :**
  - Same $\sqrt{s_{NN}}$ for pH, pd, pA systems (115 GeV) → interesting for R_{pA} measurements
  - Same $\sqrt{s_{NN}}$ for PbH, Pbd, PbA systems (72 GeV) → in between top SPS and RHIC energies



Energy range

7 TeV proton beam on a fixed target

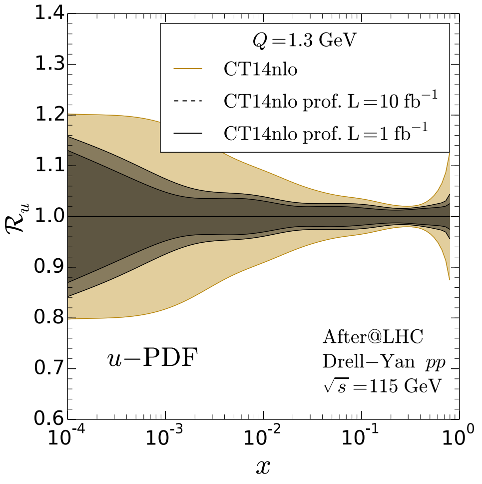
c.m.s. energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost: $\gamma = \sqrt{s}/(2m_N) \approx 60$	

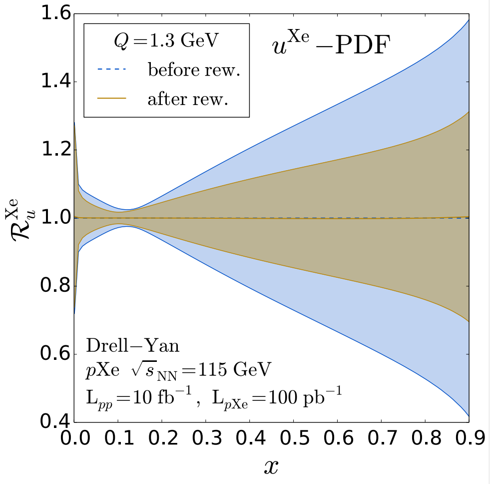
2.76 TeV Pb beam on a fixed target

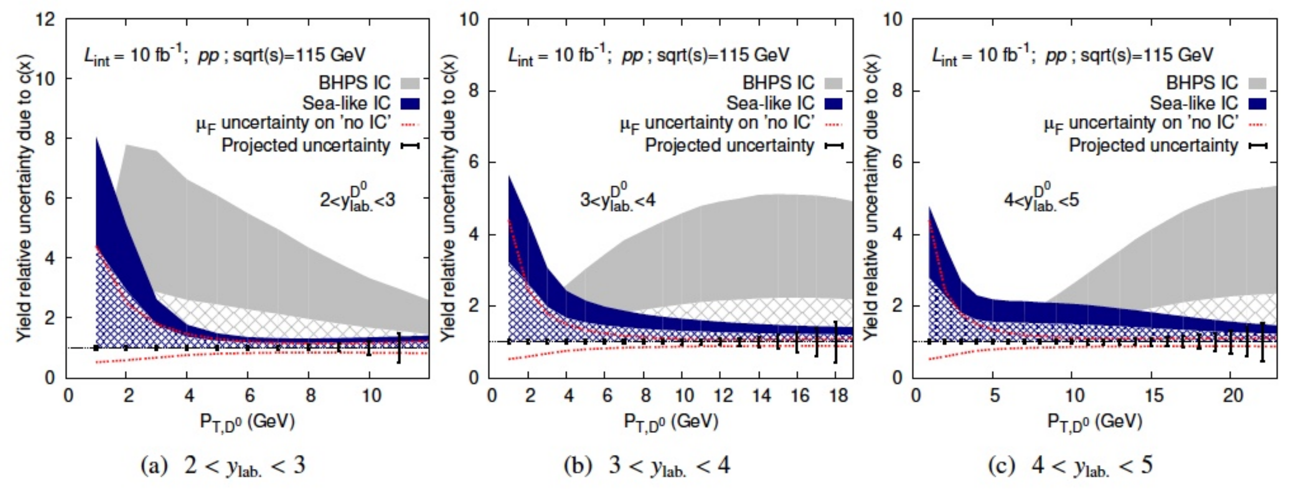
c.m.s. energy: $\sqrt{s_{NN}} = \sqrt{2m_N E_{\mathrm{Pb}}} \approx 72\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost: $\gamma \approx 40$	

Physics motivations for a fixed-target programme at the LHC
(focus on quarkonium, Open HF and Drell-Yan observables)

- ☐ **Advance our understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon & nucleus**
  - ➢ DY to probe the nucleon and nuclear structure → important impact on (anti)quarks PDFs and nPDFs at large-x
  - ➢ Open Heavy flavour to search for intrinsic charm in the proton at large-x → useful for HE neutrino and CR physics
  - ➢ Open HF, Quarkonia and associated production to probe the gluon distribution at large-x







(a) $2 < y_{\rm lab.} < 3$ (b) $3 < y_{\rm lab.} < 4$ (c) $4 < y_{\rm lab.} < 5$

- ☐ **Study Heavy-ion collisions between SPS and RHIC energies toward large rapidities (see B. Audurier talk)**
- ☐ **Advance our understanding of the dynamics and spin of gluons inside (un)polarised nucleons**

Physics motivations : Spin and 3D nucleon structure

☐ Unraveling the nucleon spin

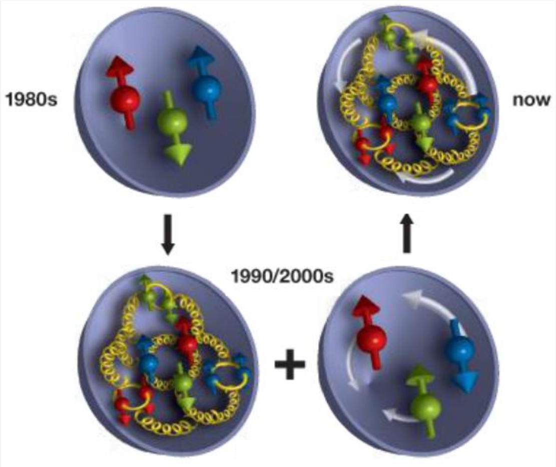
- From the spin crisis to the spin puzzle
- For longitudinally polarised nucleon, with helicity +1/2:

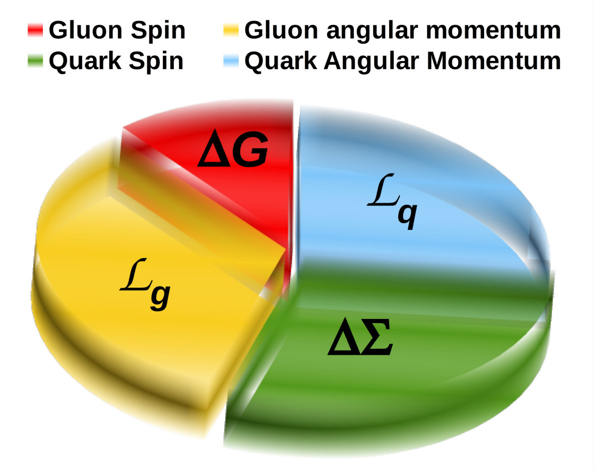
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \underbrace{\ell_g + \ell_q}$$

Spin of quarks and antiquarks

Spin of gluons

Orbital angular momentum (OAM) of quarks and gluons

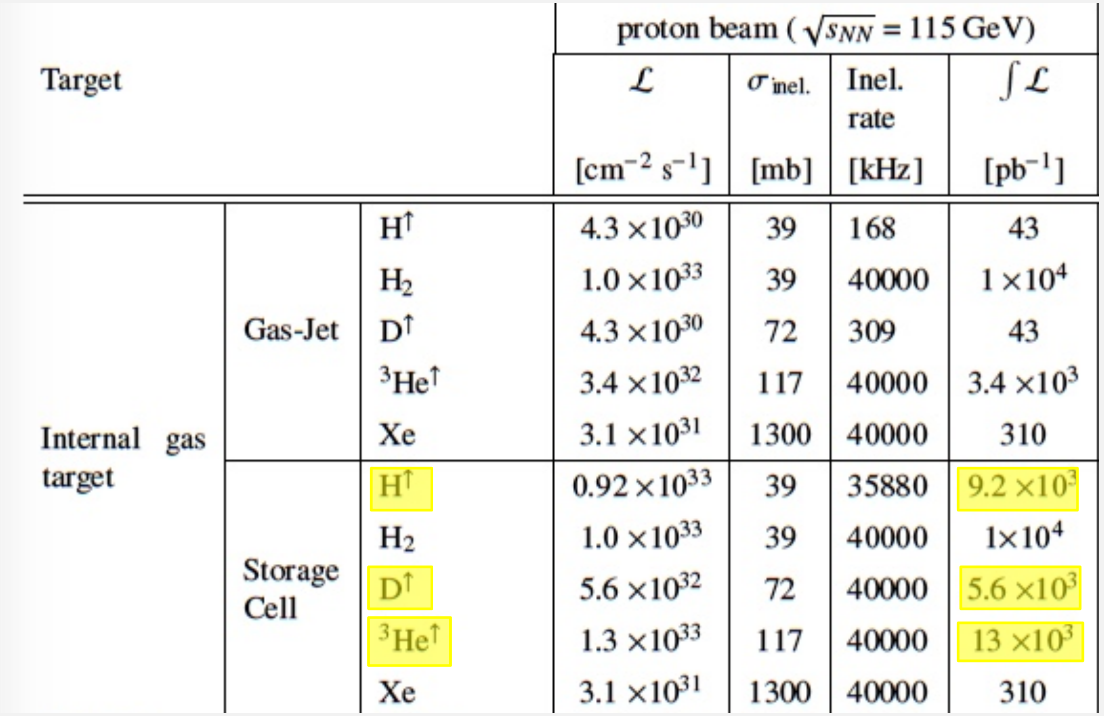




- OAM of quark and gluon still largely unknown → need observable sensitive to parton position and momentum
  - Indirect info on OAM via Single Transverse Spin Asymmetry measurements in hard-scattering processes with transv. polarised hadrons
  - Two formalisms to treat STSA : Collinear Twist-3 formalism (CT3) and Transverse-Momentum-Dependent factorization (TMD)
  - FT@LHC : high luminosity, highly polarized target, access to large-x → best suited for inclusive set of A_N measurements (including Open-HF and Quarkonia whose STSA are poorly known)
- Access to linearly polarised gluons in unpolarized nucleons: « Boer-Mulders » effect for gluons (using pseudo-scalar quarkonium production, associated quarkonium production)
- Importance of complementary measurements in pH (w.r.t lepto-induced reaction) since TMD are not universal

Implementations and luminosities (relevant for the spin physics case)

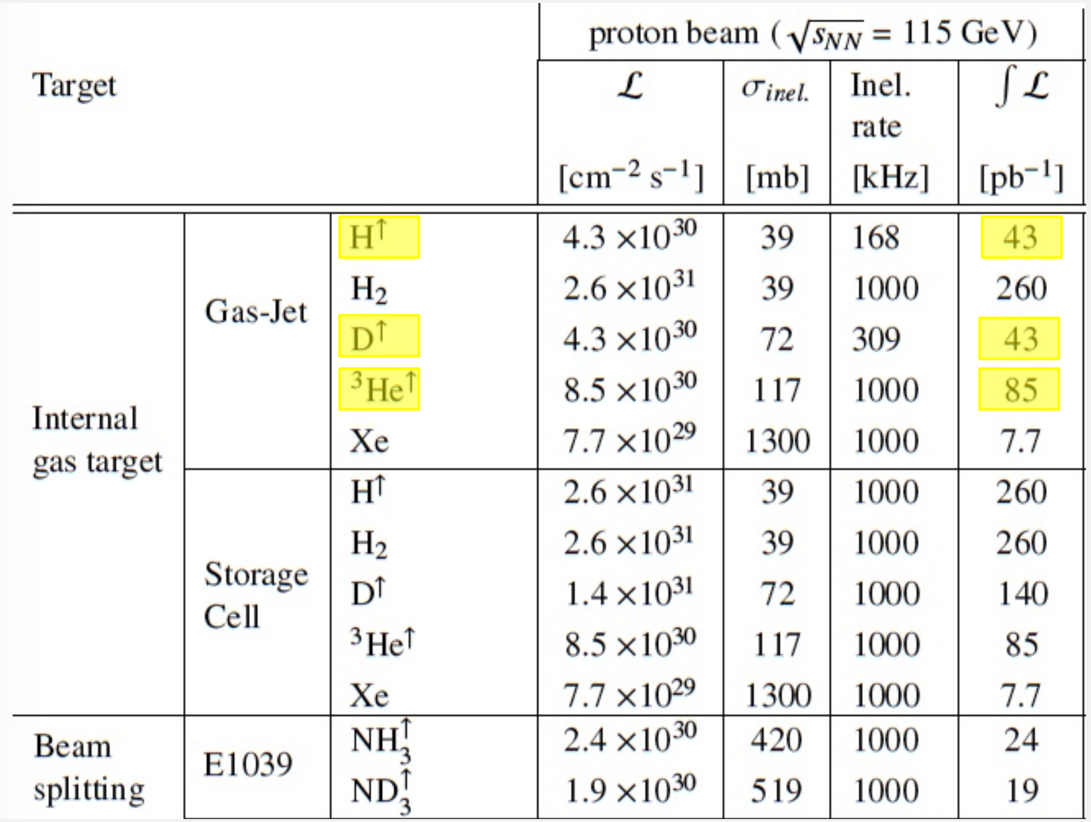
LHCb-like detector (with gas-jet or storage cell options)



Target			proton beam ($\sqrt{s_{NN}} = 115$ GeV)			
			$\mathcal{L}$ [cm^{-2} s^{-1}]	$\sigma_{\text{inel.}}$ [mb]	Inel. rate [kHz]	$\int\mathcal{L}$ [pb^{-1}]
Internal gas target	Gas-Jet	$H^{\uparrow}$	4.3×10^{30}	39	168	43
		H_2	1.0×10^{33}	39	40000	1×10^4
		$D^{\uparrow}$	4.3×10^{30}	72	309	43
		$^3He^{\uparrow}$	3.4×10^{32}	117	40000	3.4×10^3
		Xe	3.1×10^{31}	1300	40000	310
	Storage Cell	$H^{\uparrow}$	0.92×10^{33}	39	35880	9.2×10^3
		H_2	1.0×10^{33}	39	40000	1×10^4
		$D^{\uparrow}$	5.6×10^{32}	72	40000	5.6×10^3
		$^3He^{\uparrow}$	1.3×10^{33}	117	40000	13×10^3
		Xe	3.1×10^{31}	1300	40000	310

Assuming LHCb runs the full year in fixed target mode
The storage cell is considered to be 1m long.
Maximum readout rate considered: 40MHz in pp

ALICE-like detector (with gas-jet or pol. solid target options)



Target			proton beam ($\sqrt{s_{NN}} = 115$ GeV)			
			$\mathcal{L}$ [cm^{-2} s^{-1}]	$\sigma_{inel.}$ [mb]	Inel. rate [kHz]	$\int\mathcal{L}$ [pb^{-1}]
Internal gas target	Gas-Jet	$H^{\uparrow}$	4.3×10^{30}	39	168	43
		H_2	2.6×10^{31}	39	1000	260
		$D^{\uparrow}$	4.3×10^{30}	72	309	43
		$^3He^{\uparrow}$	8.5×10^{30}	117	1000	85
		Xe	7.7×10^{29}	1300	1000	7.7
	Storage Cell	$H^{\uparrow}$	2.6×10^{31}	39	1000	260
		H_2	2.6×10^{31}	39	1000	260
		$D^{\uparrow}$	1.4×10^{31}	72	1000	140
		$^3He^{\uparrow}$	8.5×10^{30}	117	1000	85
		Xe	7.7×10^{29}	1300	1000	7.7
Beam splitting	E1039	$NH_3^{\uparrow}$	2.4×10^{30}	420	1000	24
		$ND_3^{\uparrow}$	1.9×10^{30}	519	1000	19

Assuming ALICE runs the full year in fixed target mode
Proton flux considered for beam splitting option : ~ 5 x 10^8 p/s
Maximum readout rate considered 1MHz in pp/pA collisions

A selection of projections for the FT@LHC spin physics case (Drell-Yan, Open Heavy Flavour and Quarkonia)

Most of the material from the AFTER review : https://arxiv.org/abs/1807.00603

See also papers dedicated to the simulations performed by the AFTER@LHC study group:

Adv.High Energy Phys. 2015 (2015) 986348

Few Body Syst. 58 (2017) no.4, 139

Few Body Syst. 58 (2017) no.5, 148

Phys.Lett. B793 (2019) 33-40

Probing the quark Sivers effect with Drell-Yan

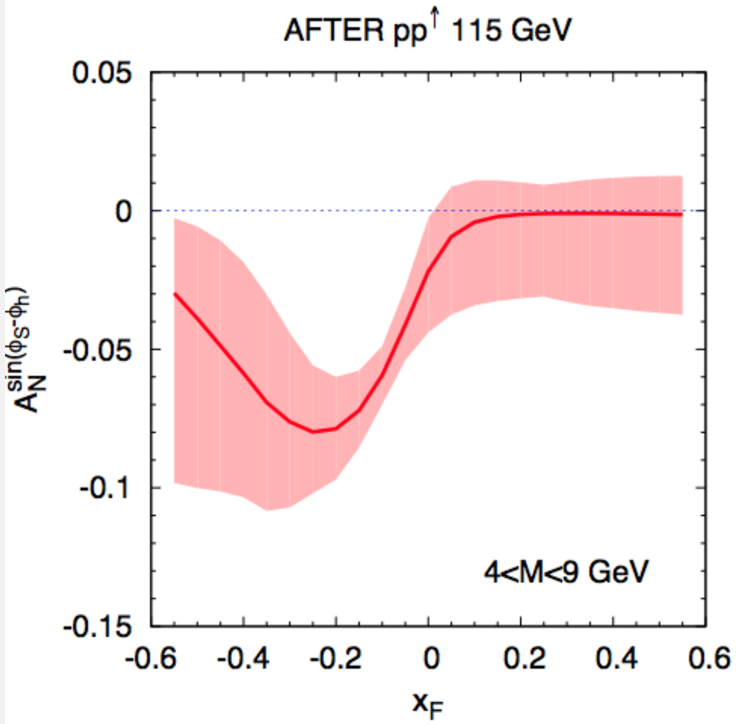
Quark Sivers effect: correlation between the quark transverse momentum k_T and the proton spin

❑ Can be probed with Drell-Yan process (unique tool theoretically well understood)
❑ Large STSA expected at high x_F for DY in polarised collisions at FT@LHC energies

$$A_N = \frac{1}{\mathcal{P}_{\mathrm{eff}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$\mathcal{P}_{\mathrm{eff}}$: effective polarization

$\sigma^{\uparrow(\downarrow)}$: cross section of particle produced with the target spin polarised upward (downward)

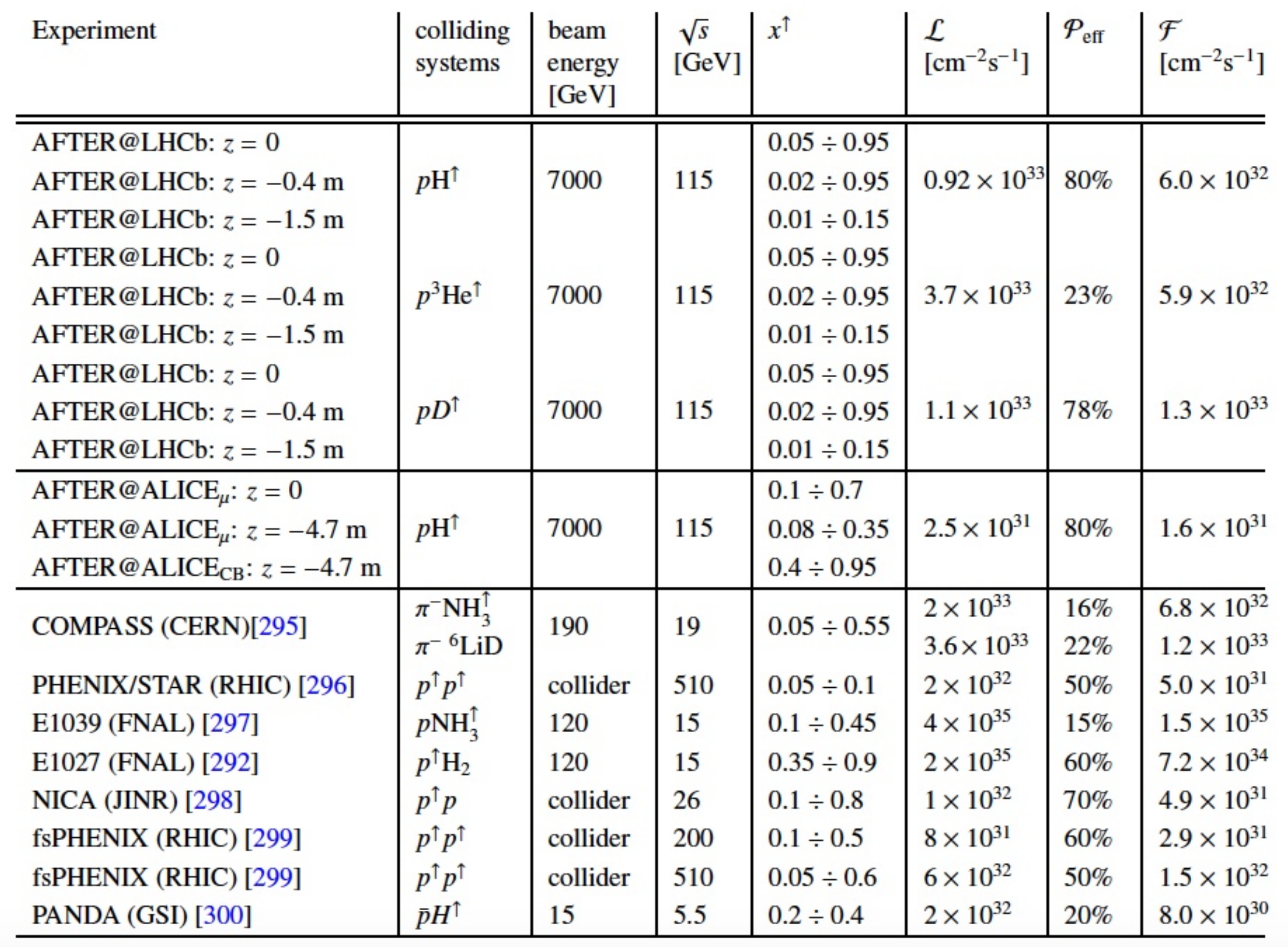


M. Anselmo, ECT*, Feb. 2013 (Courtesy U. d'Alessio)

❑ Important prediction shared by both CT3 and TMD formalisms : sign change of asymmetry between SIDIS and DY processes

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

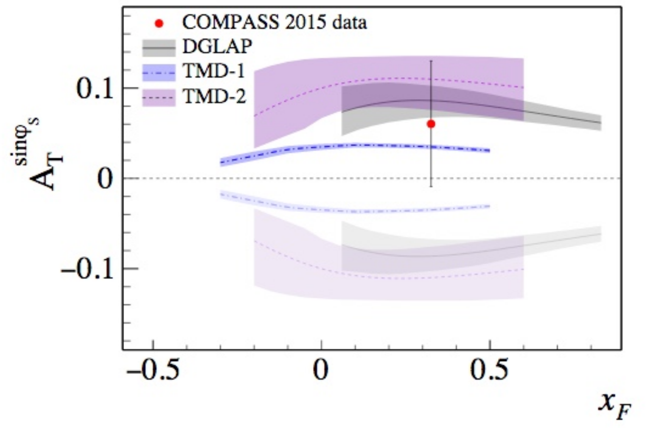
Probing the quark Sivers effect with Drell-Yan



Experiment	colliding systems	beam energy [GeV]	$\sqrt{s}$ [GeV]	$x^{\uparrow}$	$\mathcal{L}$ [cm^{-2}s^{-1}]	$\mathcal{P}_{\text{eff}}$	$\mathcal{F}$ [cm^{-2}s^{-1}]
AFTER@LHCb: $z = 0$	$pH^{\uparrow}$	7000	115	$0.05 \div 0.95$	0.92×10^{33}	80%	6.0×10^{32}
AFTER@LHCb: $z = -0.4$ m				$0.02 \div 0.95$			
AFTER@LHCb: $z = -1.5$ m				$0.01 \div 0.15$			
AFTER@LHCb: $z = 0$	$p^3\text{He}^{\uparrow}$	7000	115	$0.05 \div 0.95$	3.7×10^{33}	23%	5.9×10^{32}
AFTER@LHCb: $z = -0.4$ m				$0.02 \div 0.95$			
AFTER@LHCb: $z = -1.5$ m				$0.01 \div 0.15$			
AFTER@LHCb: $z = 0$	$pD^{\uparrow}$	7000	115	$0.05 \div 0.95$	1.1×10^{33}	78%	1.3×10^{33}
AFTER@LHCb: $z = -0.4$ m				$0.02 \div 0.95$			
AFTER@LHCb: $z = -1.5$ m				$0.01 \div 0.15$			
AFTER@ALICE$_{\mu}$: $z = 0$	$pH^{\uparrow}$	7000	115	$0.1 \div 0.7$	2.5×10^{31}	80%	1.6×10^{31}
AFTER@ALICE$_{\mu}$: $z = -4.7$ m				$0.08 \div 0.35$			
AFTER@ALICE$_{\text{CB}}$: $z = -4.7$ m				$0.4 \div 0.95$			
COMPASS (CERN)[295]	$\pi^{-}\text{NH}_3^{\uparrow}$ $\pi^{-}\,{}^6\text{LiD}$	190	19	$0.05 \div 0.55$	2×10^{33} 3.6×10^{33}	16% 22%	6.8×10^{32} 1.2×10^{33}
PHENIX/STAR (RHIC) [296]	$p^{\uparrow}p^{\uparrow}$	collider	510	$0.05 \div 0.1$	2×10^{32}	50%	5.0×10^{31}
E1039 (FNAL) [297]	$p\text{NH}_3^{\uparrow}$	120	15	$0.1 \div 0.45$	4×10^{35}	15%	1.5×10^{35}
E1027 (FNAL) [292]	$p^{\uparrow}\text{H}_2$	120	15	$0.35 \div 0.9$	2×10^{35}	60%	7.2×10^{34}
NICA (JINR) [298]	$p^{\uparrow}p$	collider	26	$0.1 \div 0.8$	1×10^{32}	70%	4.9×10^{31}
fsPHENIX (RHIC) [299]	$p^{\uparrow}p^{\uparrow}$	collider	200	$0.1 \div 0.5$	8×10^{31}	60%	2.9×10^{31}
fsPHENIX (RHIC) [299]	$p^{\uparrow}p^{\uparrow}$	collider	510	$0.05 \div 0.6$	6×10^{32}	50%	1.5×10^{32}
PANDA (GSI) [300]	$\bar{p}H^{\uparrow}$	15	5.5	$0.2 \div 0.4$	2×10^{32}	20%	8.0×10^{30}

$$\mathcal{F} = P_{eff}^2 \times \mathcal{L} \times \sum_i A_i$$

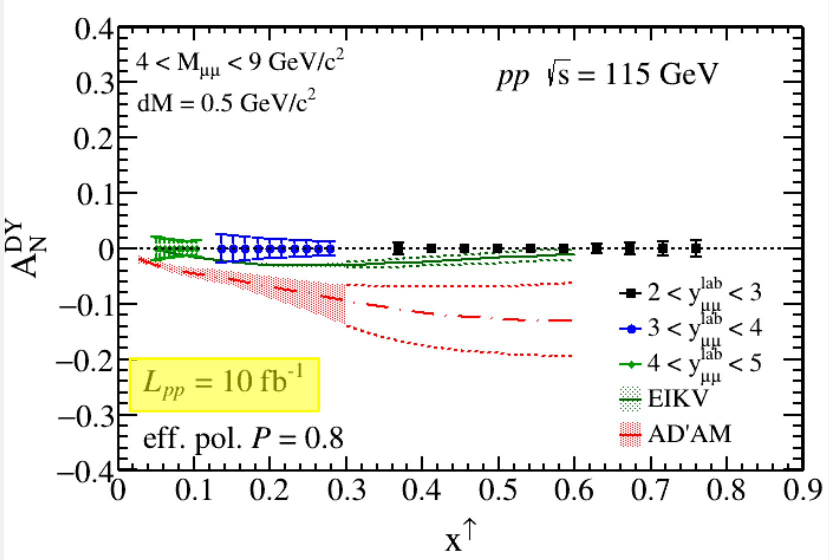
COMPASS Coll., arXiv:1704.00488

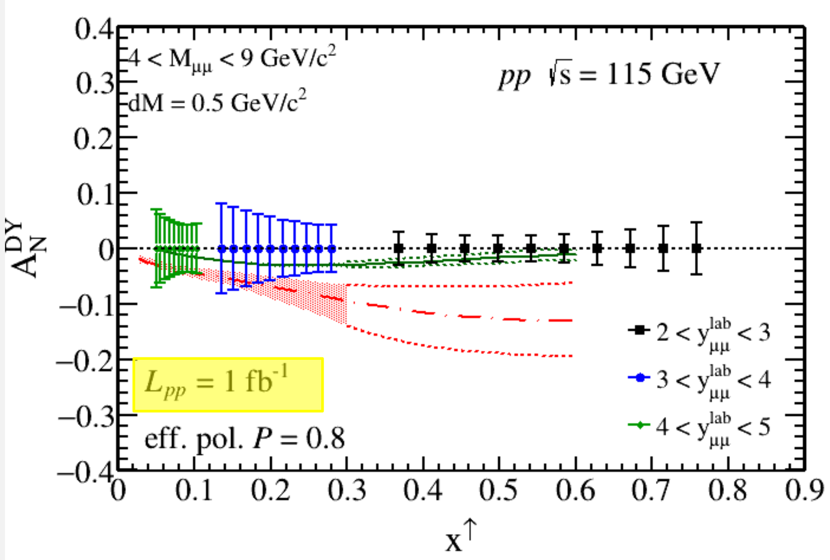


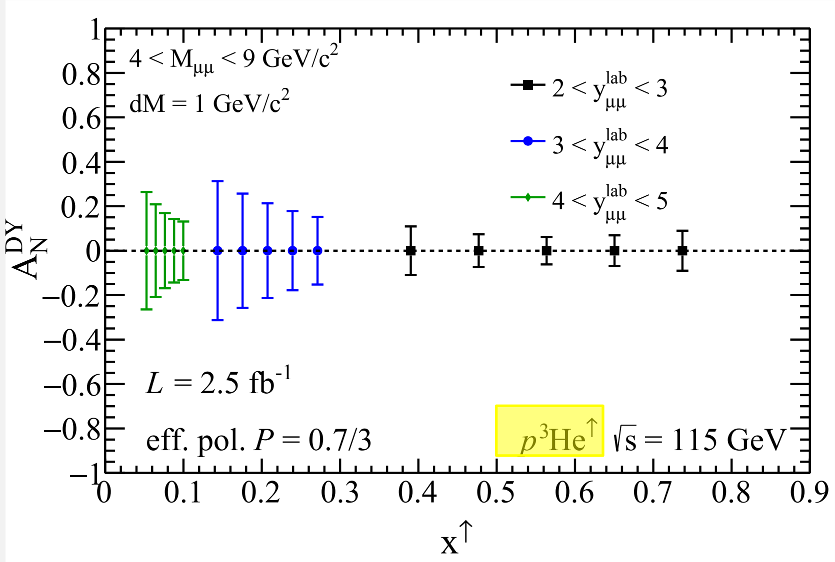
- ☐ First measurement of DY A_N by COMPASS
- ☐ FT@LHC : reach higher precision and perform measurements over a wide range of x_2 and masses
  - → towards accurate measurement of the Sivers function and confirmation/falsification of the sign change

Probing the quark Sivers effect with Drell-Yan

- DY production with an «LHCb-like» detector







- Comparison with theoretical predictions from AD'AM (Adv. High Energy Phys. 2015 (2015) 475040) and EIKV (Phys. Rev. D89 (2014) 074013), both based on fits of SIDIS data for $x \leq 0.3$
- High statistics of FT@LHC mandatory to discriminate between the theoretical approaches especially at large rapidity
- Test of TMD factorization and constrain on 3-parton correlation functions
- Also access to Sivers functions in the neutron thanks to polarized He target → isospin dependence of Sivers functions

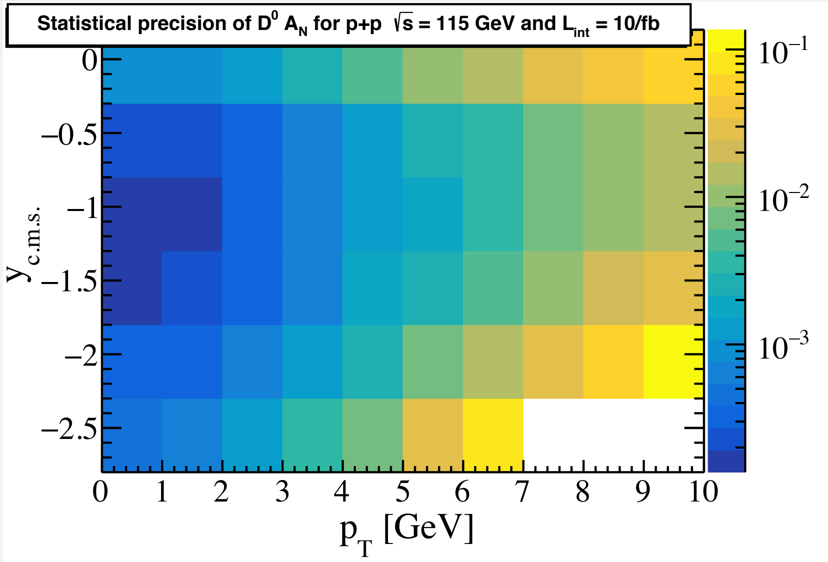
Probing the gluon Sivers effect

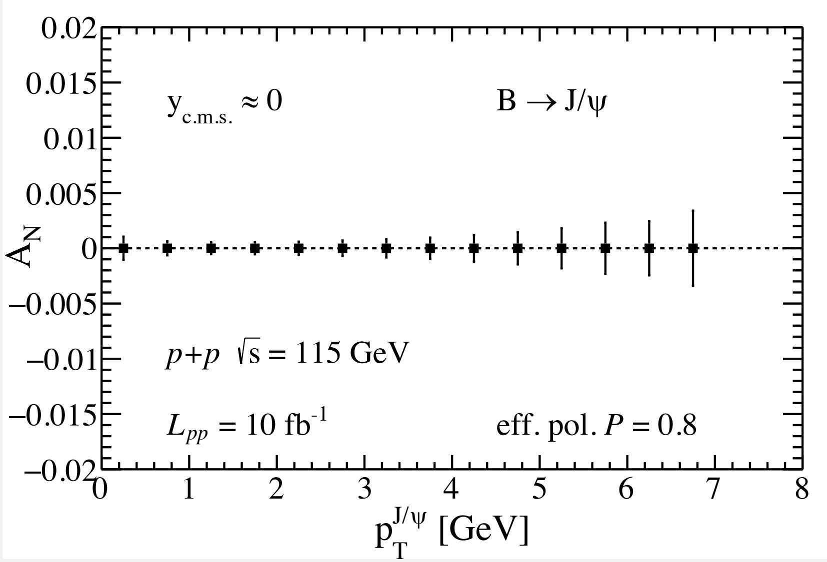
Gluon Sivers effect: correlation between the gluon transverse momentum k_T and the proton spin

- ❑ No analogous process to DY to probe the gluon content, being both experimentally clean and theoretically well-controlled
- ❑ Large yields in FT@LHC for several gluon sensitive probes (Open HF, quarkonia ~ 10^6 Υ and 10^9 J/Ψ per year)
- ❑ Gluon TMDs more « universal », gluon Sivers functions can be reduced to 2 independent ones

with Open Heavy Flavours

- ❑ Access to gluon Sivers effect and process dependence of A_N by measuring c & $\bar{c}$ quarks separately (C-odd correlators)
- ❑ « LHCb-like detector », precision at percent level on D^0 A_N for $p_T \leq 5$ GeV/c

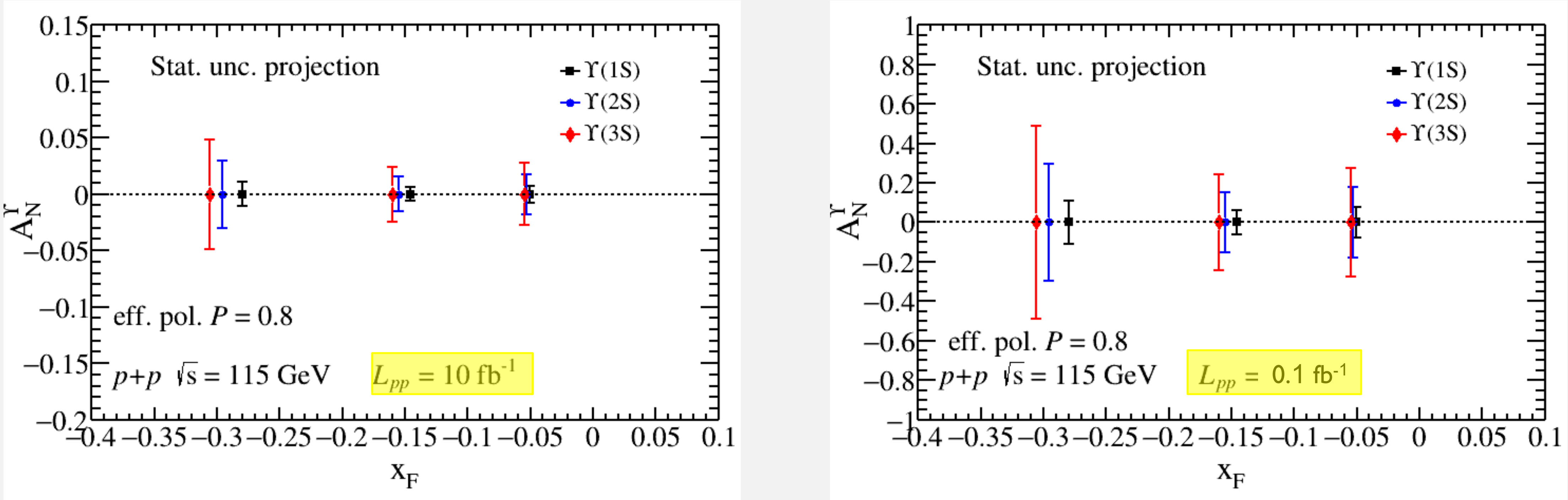




Probing the gluon Sivers effect with vector quarkonium production

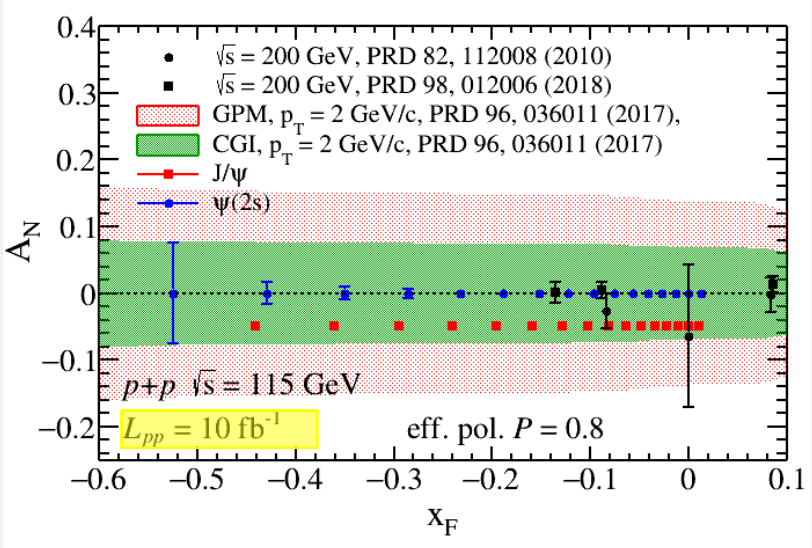
- Measurement of bottomonium A_N statistically doable with FT@LHC
- Large charmonium yields → precise access to gluon content of the proton over a much wider x-range than at RHIC
- Several possible explanations for current A_N measurements compatible with zero (gluon Sivers function might be zero, J/Ψ production mechanism via colour-octet transitions…) → new precise measurements needed

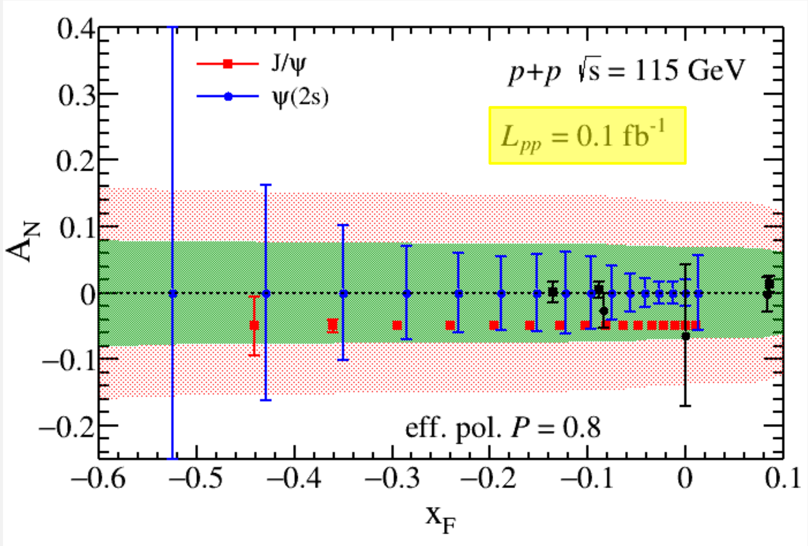
- Υ(nS) production with an « LHCb-like » detector



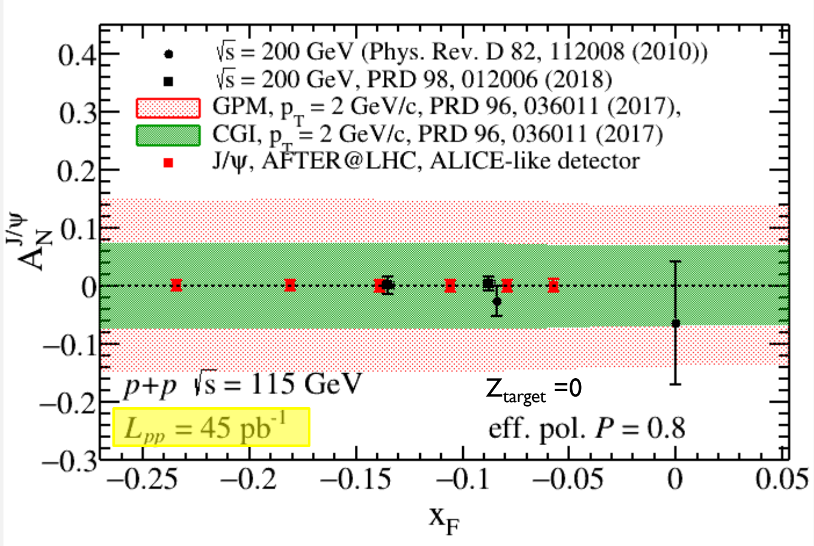
Probing the gluon Sivers effect with vector quarkonium production

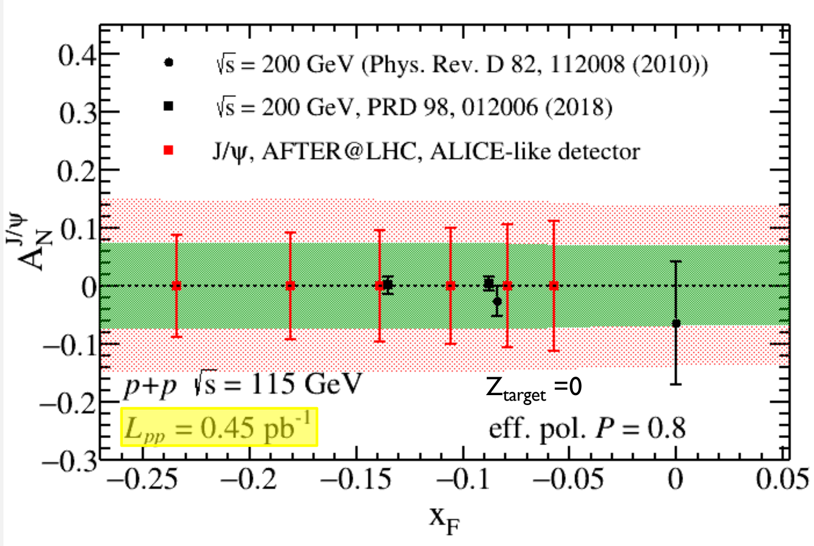
- J/Ψ and Ψ(2S) production with an « LHCb-like » detector, compared to PHENIX data
- Large integrated luminosity needed for Ψ(2S) A_N
- Comparison with 2 models :
    - Generalised parton model (GPM)
    - Color Gauge invariant version of GPM model(CGI)





- J/Ψ production with an « ALICE-like » detector
- Large integrated luminosity needed to perform J/Ψ A_N measurement

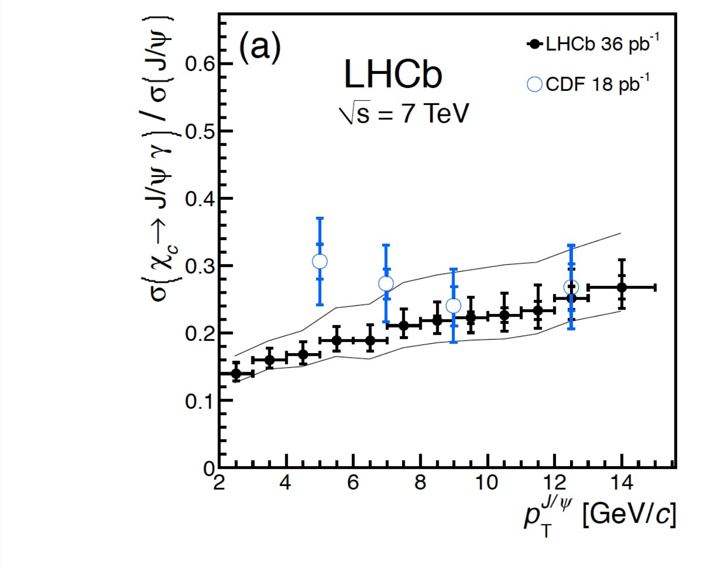




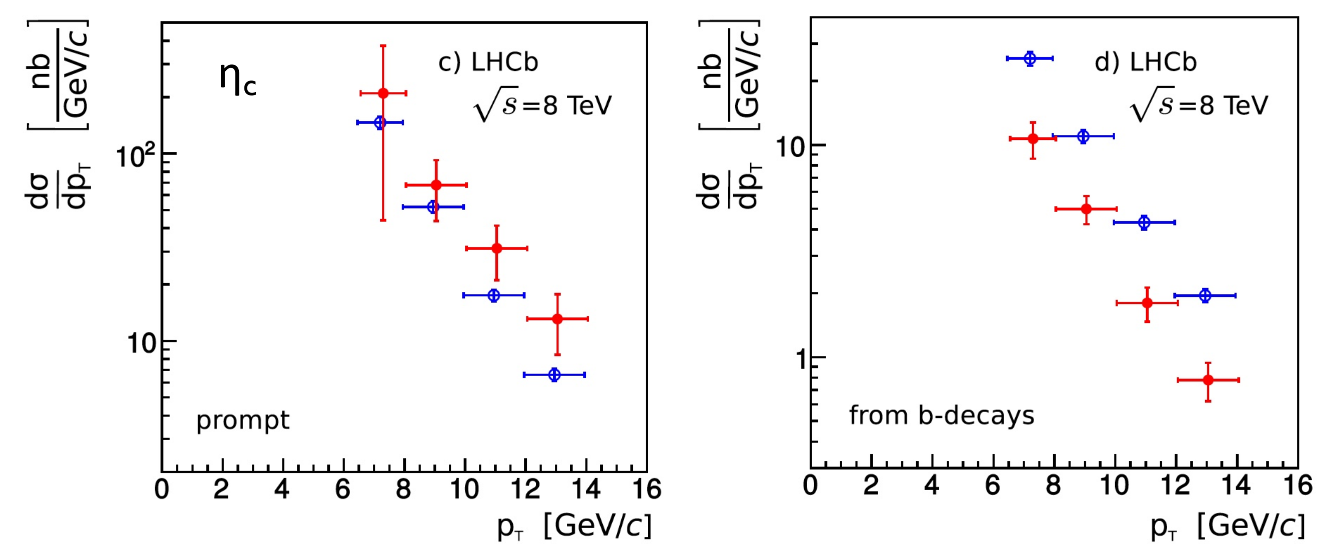
Probing the gluon Sivers effect with C-even quarkonium production

- Feasibility of the study of χ_c ($p_T \geq 2$ GeV/c) states and η_c ($p_T \geq 6$ GeV/c) already demonstrated by LHCb in busy collider environement
- Benefit at lower energy from the reduced combinatorial background → help access to lower p_T
- Similar yields expected as for vector quarkonia (but smaller branching ratio and efficiencies)

LHCb Collaboration, Phys.Lett. B718 (2012) 431-440



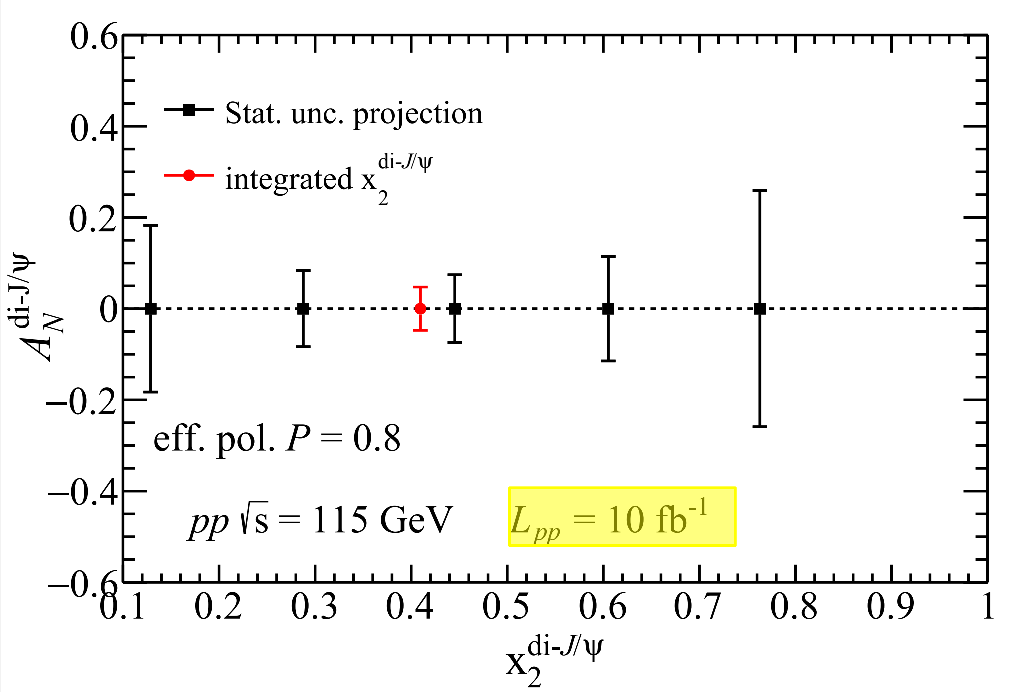
LHCb Collaboration, Eur. Phys. J. C75 no. 7, (2015), 311

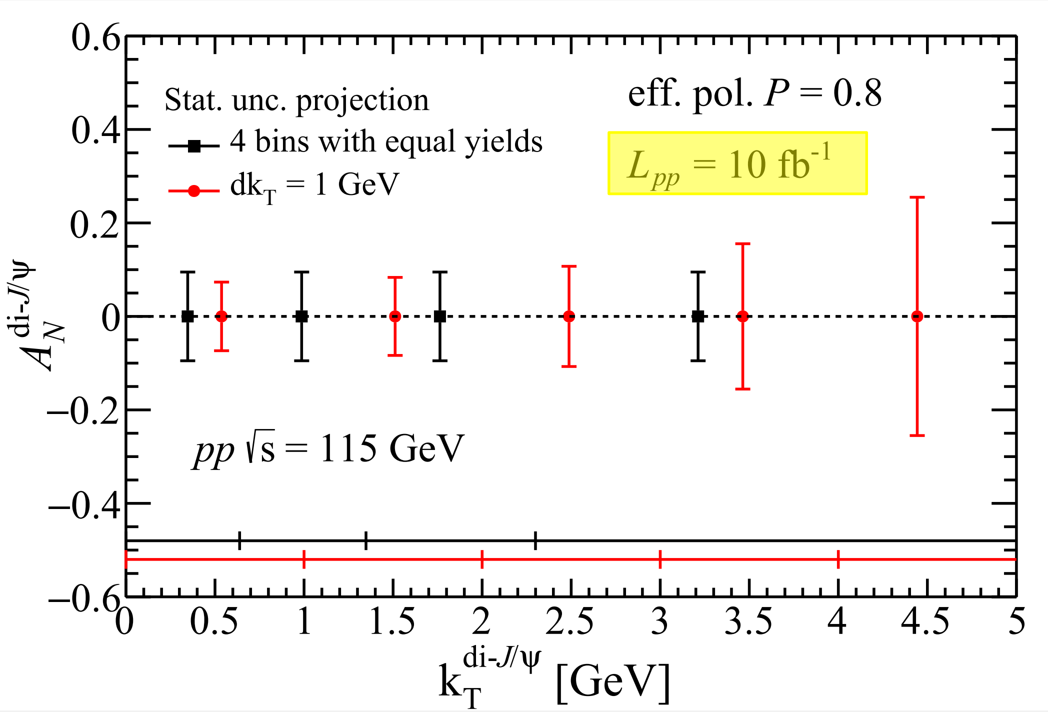


- STSA of η_c gives access to tri-gluon correlation functions
- Study as a function of p_T → transverse momentum dependence of the gluon Sivers function

Probing the gluon Sivers effect with associated quarkonium production

- Allow to probe TMD evolution mechanism by tuning the mass of the final state (J/ψ + J/ψ, J/ψ+γ, Y(nS) + γ)
- Thanks to large lumi in FT@LHC, large yearly double J/ψ yield (~ 300 to 1500)
- LHCb-like detector
  - Integrated di- J/ψ A_N of the order of few percent
  - $A_N(k_T)$: access for the first time to the k_T dependence of the gluon Sivers TMD up to k_T ~ 4 GeV

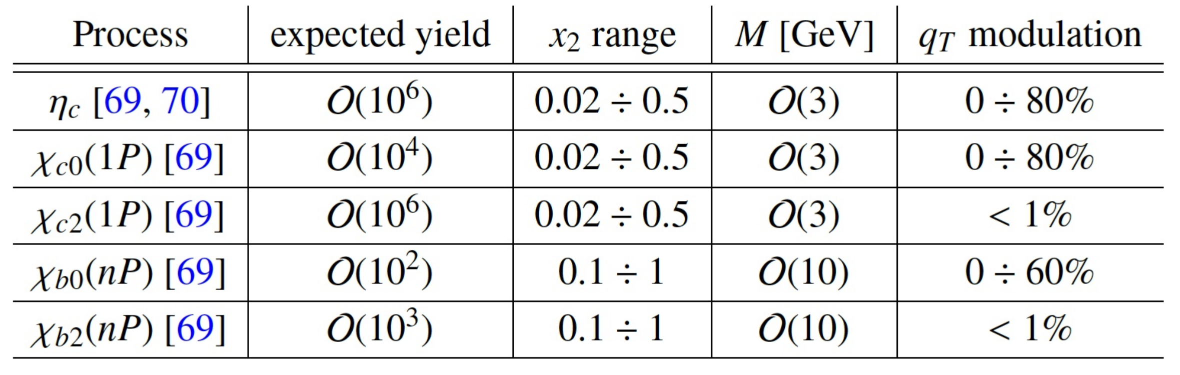




Access to the linearly polarised partons in unpolarised proton

« Boer-Mulders » effect: correlation between the parton transverse momentum k_T and its spin

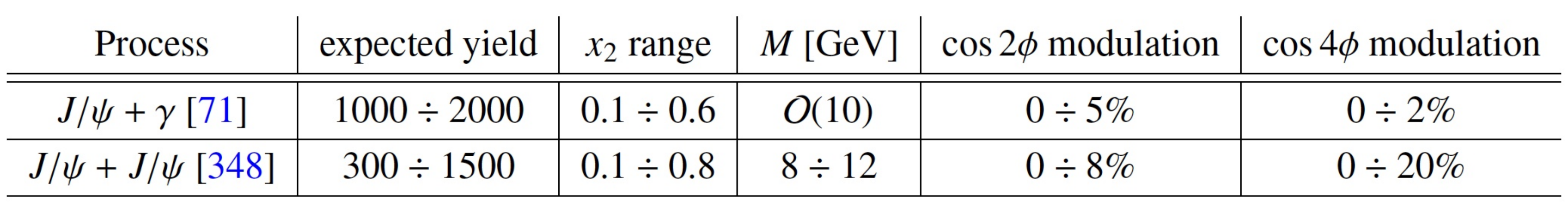
- For quarks, encoded in $h_1^{\perp q}$, sign change expected in SIDIS and DY
- For gluons, encoded in the distribution of linearly polarised gluons $h_1^{\perp g}$ → no experimental extraction performed so far
- Can be investigated with, for instance:
  - (pseudo)scalar quarkonium production → low-p_T spectra affected differently by $h_1^{\perp g}$
    → FT@LHC: Better access to low-p_T thanks to boost, though challenging



Process	expected yield	x_2 range	M [GeV]	q_T modulation
η_c [69, 70]	$\mathcal{O}(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c0}(1P)$ [69]	$\mathcal{O}(10^4)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$0 \div 80\%$
$\chi_{c2}(1P)$ [69]	$\mathcal{O}(10^6)$	$0.02 \div 0.5$	$\mathcal{O}(3)$	$< 1\%$
$\chi_{b0}(nP)$ [69]	$\mathcal{O}(10^2)$	$0.1 \div 1$	$\mathcal{O}(10)$	$0 \div 60\%$
$\chi_{b2}(nP)$ [69]	$\mathcal{O}(10^3)$	$0.1 \div 1$	$\mathcal{O}(10)$	$< 1\%$

Modulation of the transverse momentum spectrum induced by $h_1^{\perp g}$

- $J/\psi + \gamma$, $J/\psi + J/\psi$ → final states with different inv. mass (test of TMD evolution)

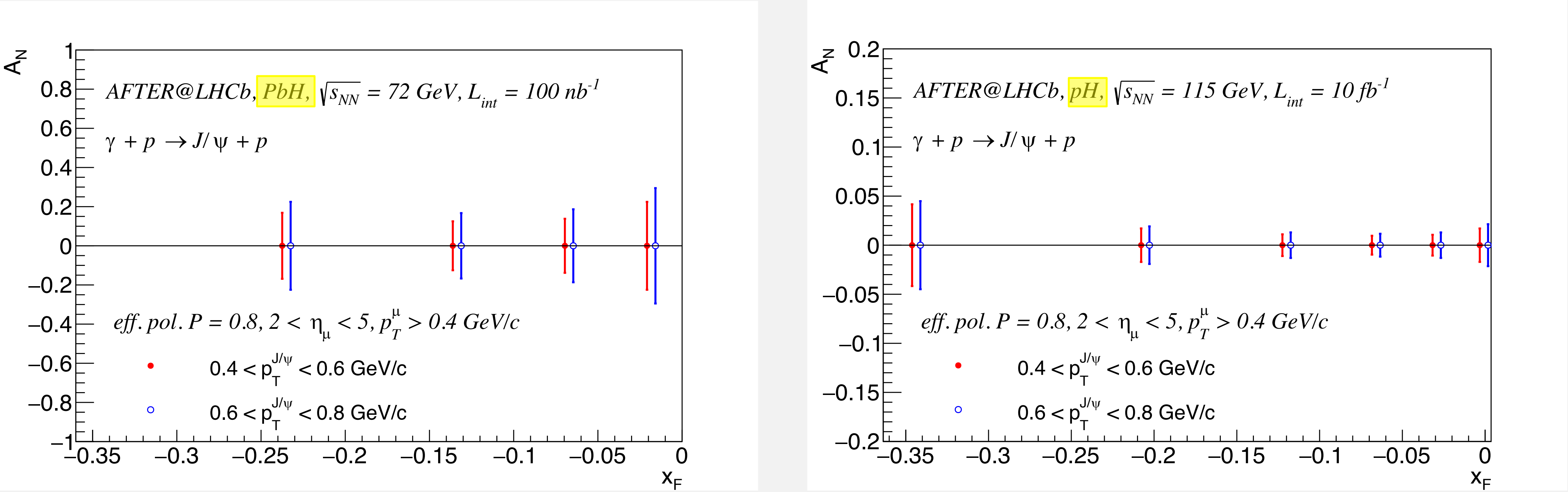


Process	expected yield	x_2 range	M [GeV]	$\cos 2\phi$ modulation	$\cos 4\phi$ modulation
$J/\psi + \gamma$ [71]	$1000 \div 2000$	$0.1 \div 0.6$	$\mathcal{O}(10)$	$0 \div 5\%$	$0 \div 2\%$
$J/\psi + J/\psi$ [348]	$300 \div 1500$	$0.1 \div 0.8$	$8 \div 12$	$0 \div 8\%$	$0 \div 20\%$

Azimuthal modulations of the spectrum induced by $h_1^{\perp g}$

Exclusive quarkonium photoproduction to probe the GPDs

- ☐ Exclusive photoproduction studied in « UPC » probes the internal structure of hadrons in terms of GPDs → related to the OAM carried by quarks and gluons via Ji's sum rule
- ☐ Exclusive J/Ψ production sensitive to gluon GPDs, STSA sensitive to yet unknown GPD E_g (importance piece of spin sum rule)
- ☐ Enough precision at FT@LHC to perform a first extraction of E_g



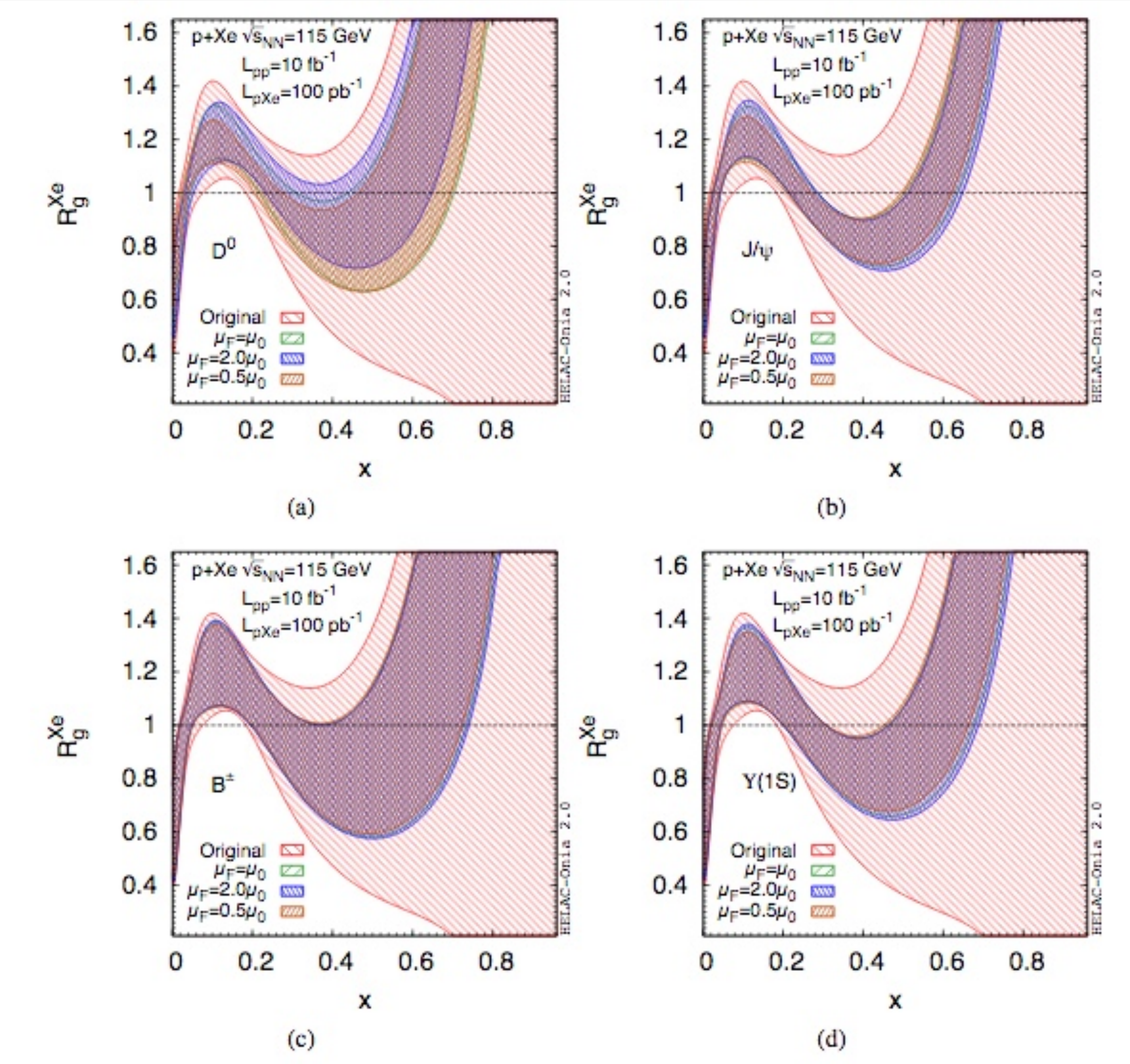
Conclusion

- ❑ A fixed-target programme at the LHC will provide a unique playground to explore the connection between the TMD and CT3 approaches, in particular in the gluon sector where the study of quarkonia can play an important role
- ❑ A fixed-target programme at the LHC will open the way for a full three dimensional mapping of the parton momentum, and in turn, for more insights on the orbital angular momentum of the quarks and gluons
- ❑ Since LHC beams are not polarised, it is a unique opportunity to perform a spin physics programme at the LHC!

BACKUP

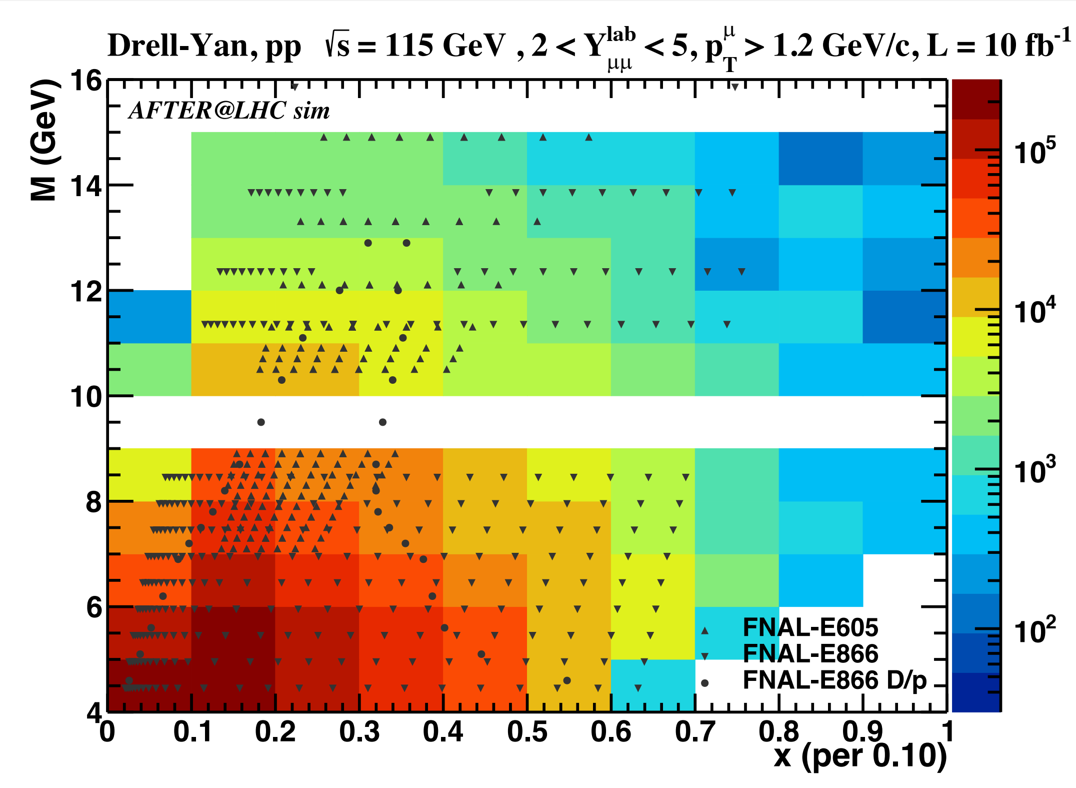
Open-HF and quarkonia to constrain high-x nuclear gluon distributions

- ❑ LHCb-like detector, pXe collisions
- ❑ Extremely promising first projections using Bayesian reweighting
- ❑ Assume that other nuclear effects are under control : different observables are thus needed
- ❑ Unique constraints on gluon nPDFs at high-x and low scales

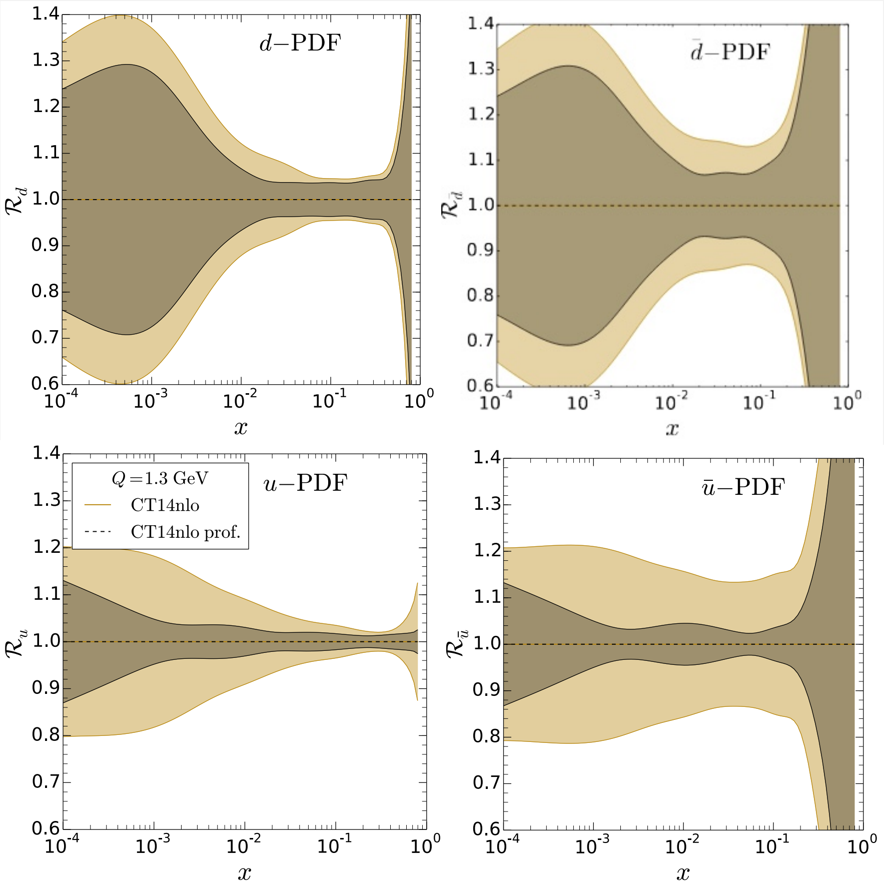


Drell-Yan process to probe the nucleon structure at large-x

- LHCb-like detector, pp collisions
- Extension of the measurement to larger x_2 w.r.t existing Fermilab data (suffering from limited statistical precision at kinematic boundaries)



- Impact on quark PDFs evaluated with Bayesian reweighting



Drell-Yan process to probe the nucleon structure at large-x

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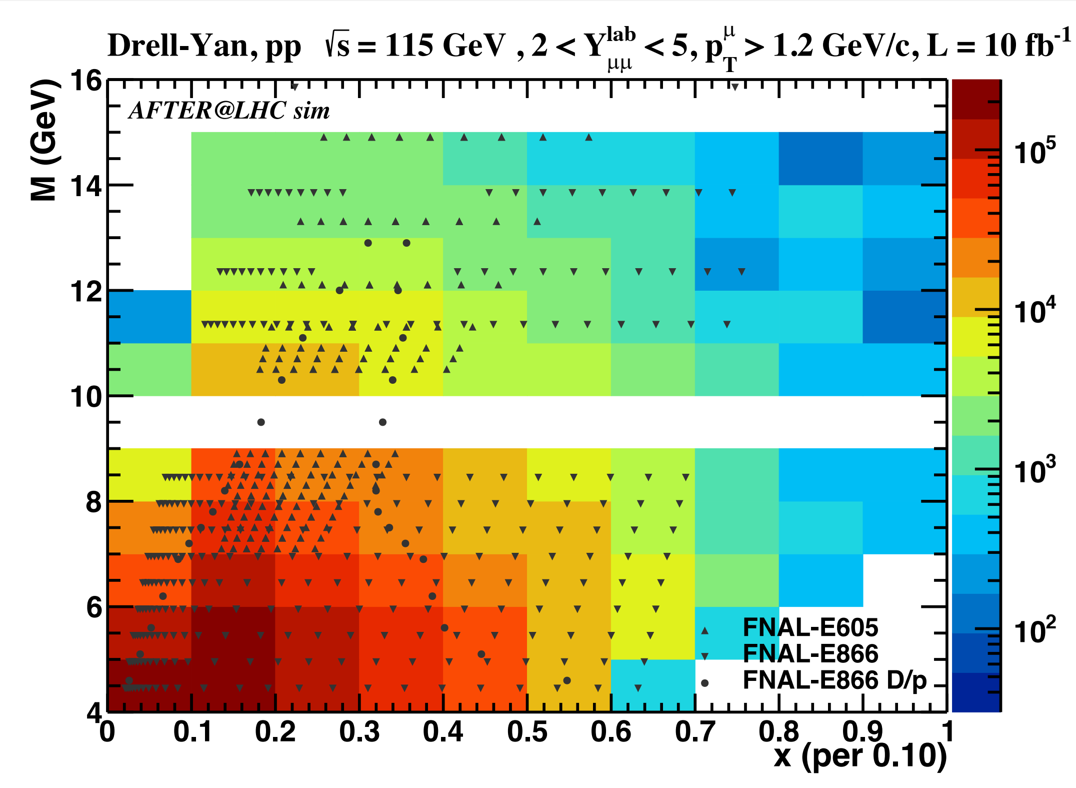
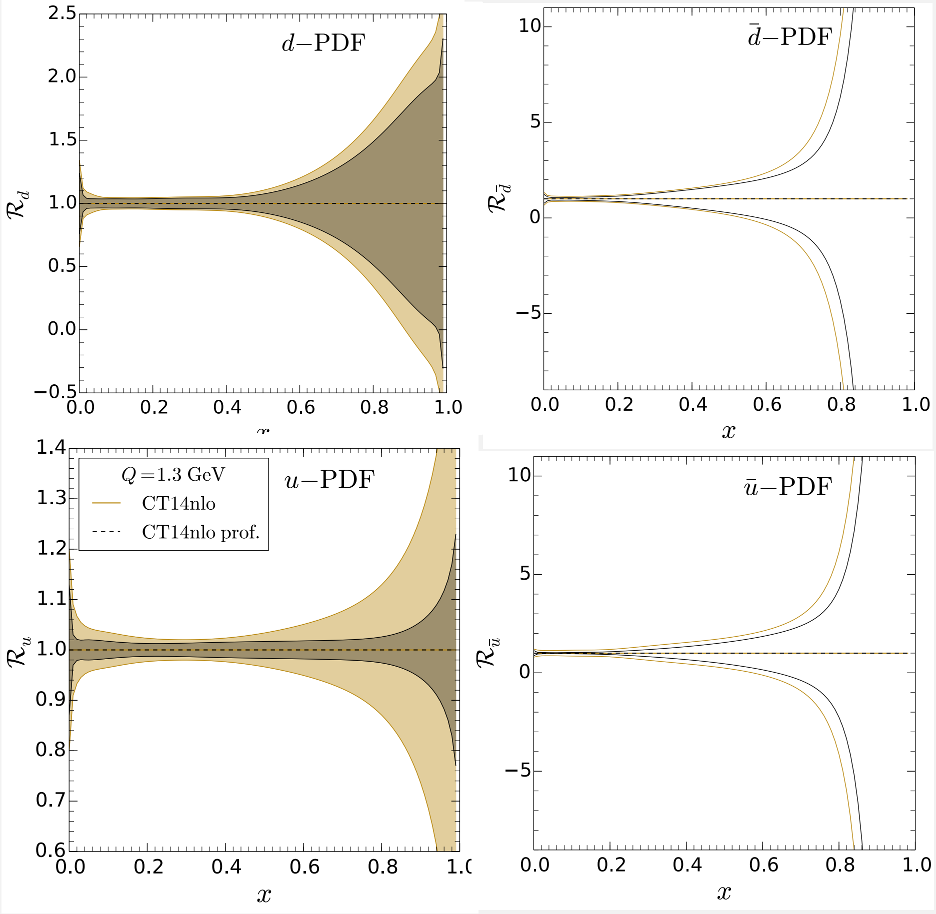
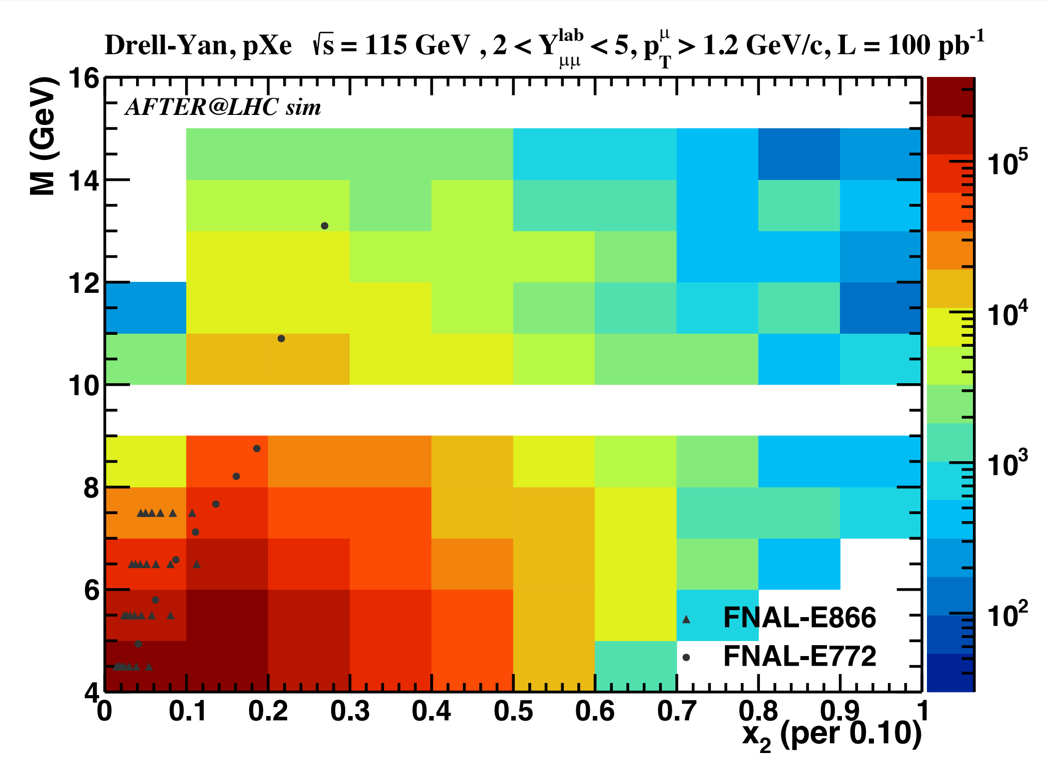


- Impact on quark PDFs evaluated with Bayesian reweighting
- Knowledge of valence quarks distribution considerably improved for x > 0.4 (esp. for u quark)

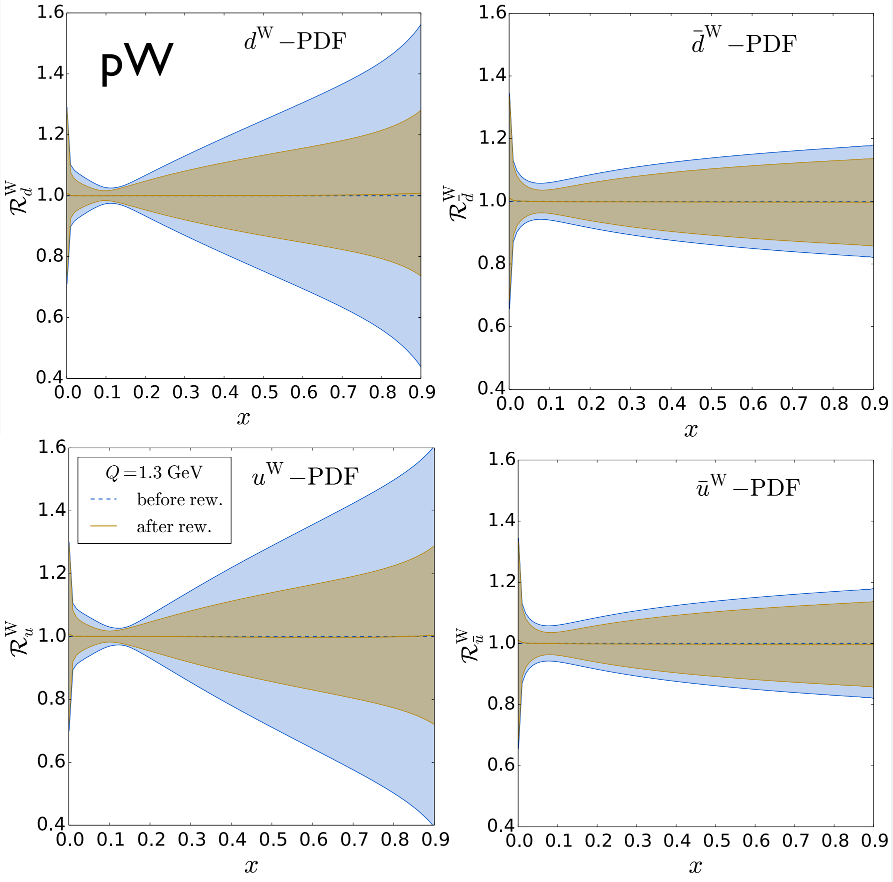


Drell-Yan process to probe the nuclear structure at large-x

- LHCb-like detector, pXe collisions
- Unique acceptance compared to existing DY pA data (E866 & E772 @Fermilab)
- Same coverage in pp and pA
- Large yields up to $x_2 \rightarrow 1$

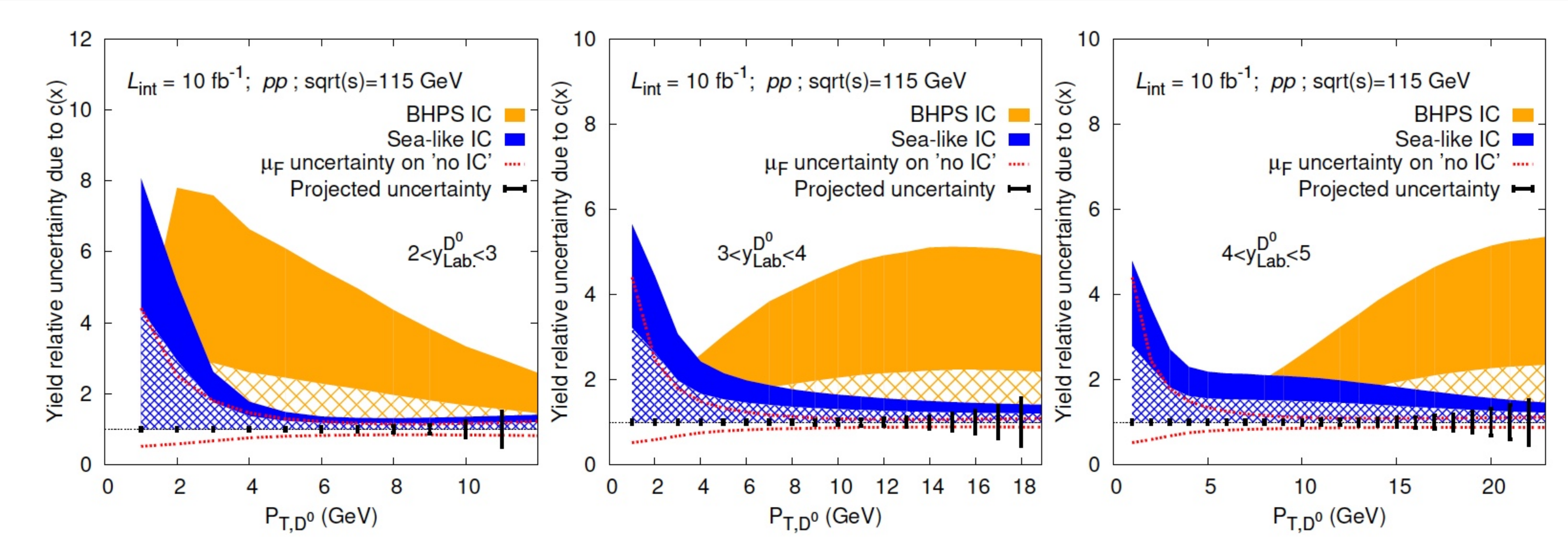


- Decrease of the nuclear PDF uncertainties
- Significant impact for u and d quark nPDFs at large x



Open-HF at large-x to study intrinsic charm in the proton

- ❑ LHCb-like detector, pp colisions

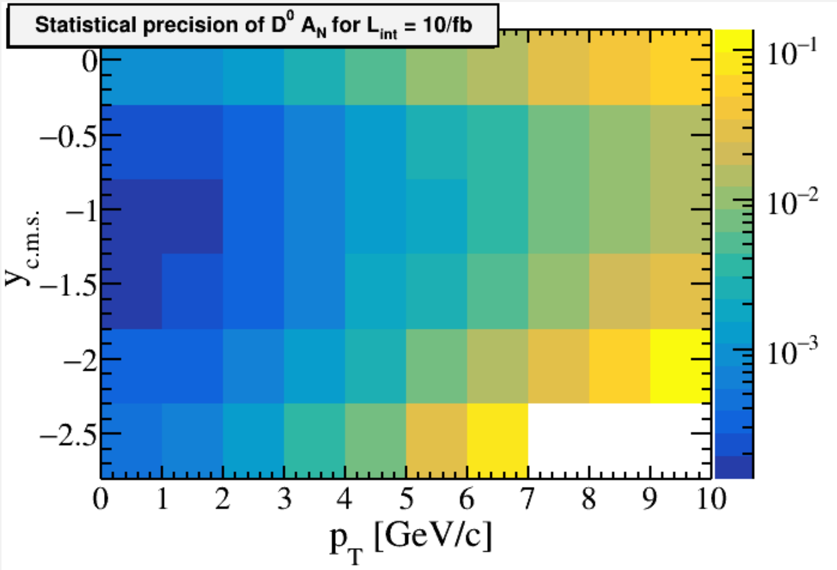


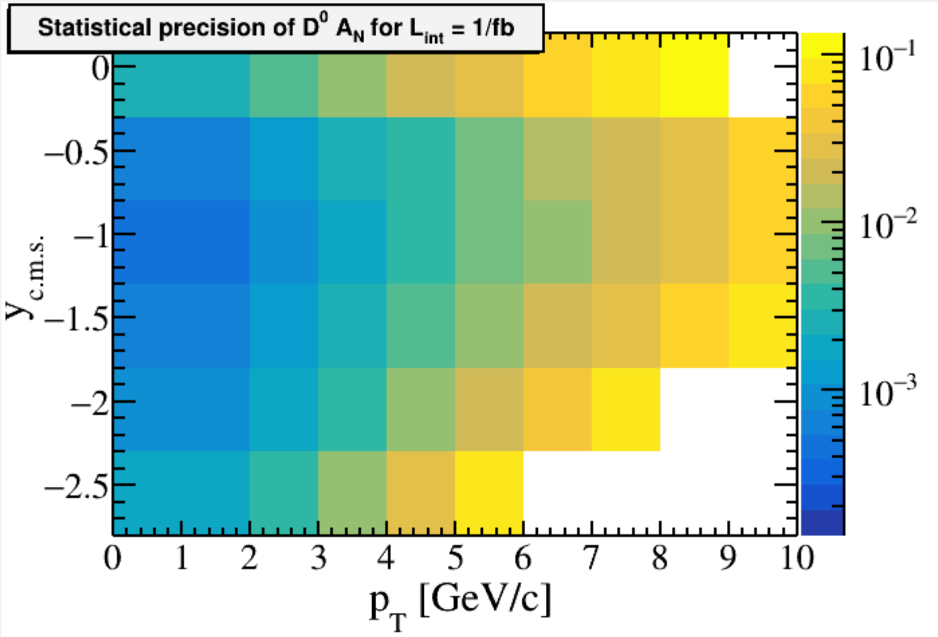
(a) $2 < y_{Lab} < 3$ (b) $3 < y_{Lab} < 4$ (c) $4 < y_{Lab} < 5$

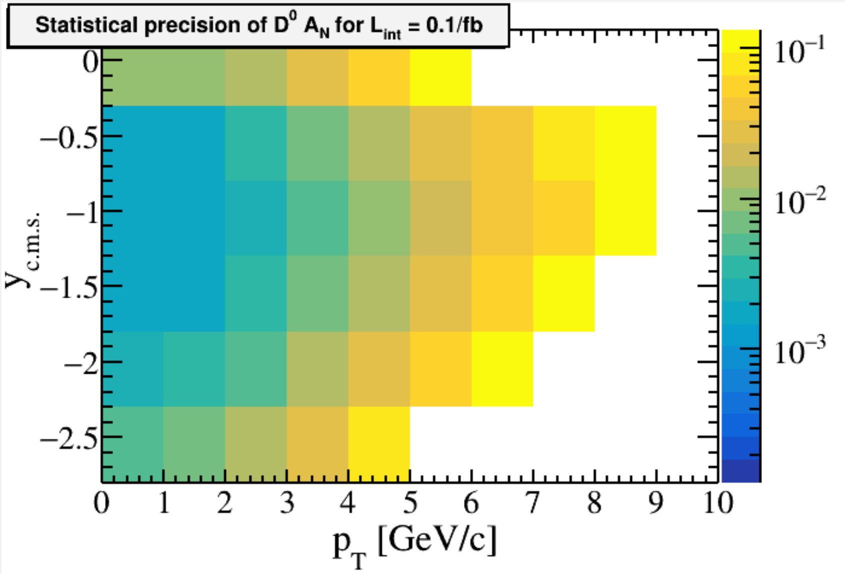
➡ Experimental precision in this p_T/y range should provide strong constraints on intrinsic charm model

Probing the gluon Sivers effect with Open HF

- ☐ Access to gluon Sivers effect and process dependence of A_N by measuring c & $\bar{c}$ quarks separately (C-odd correlators)
- ☐ « LHCb-like detector »

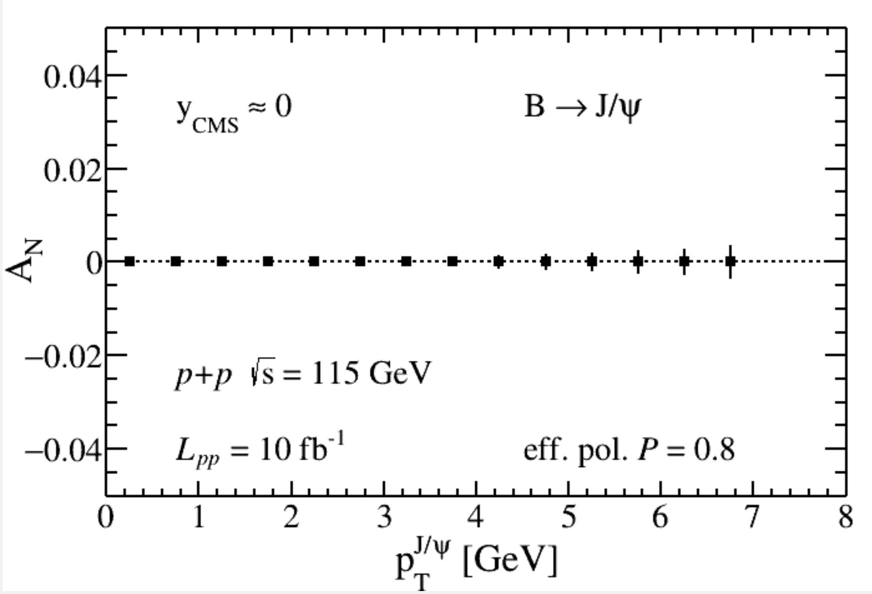


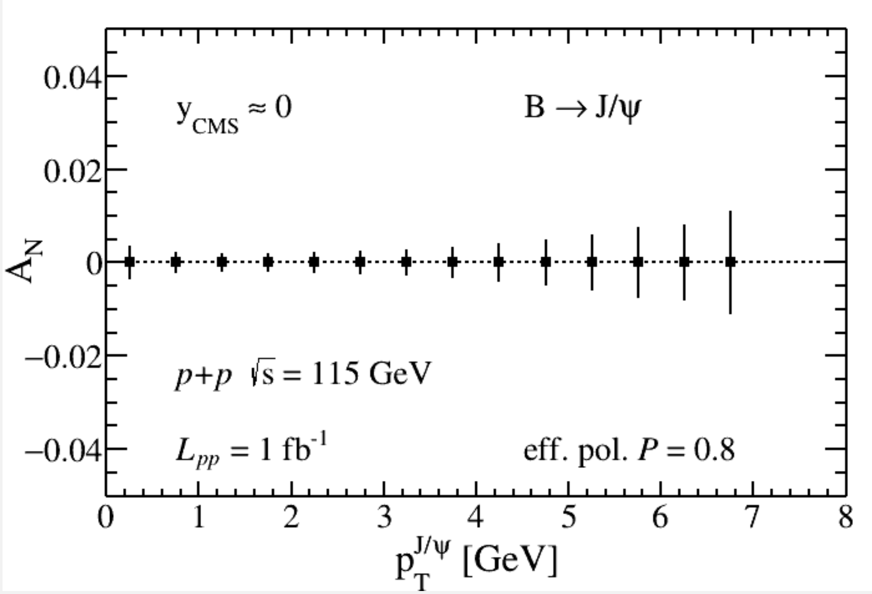


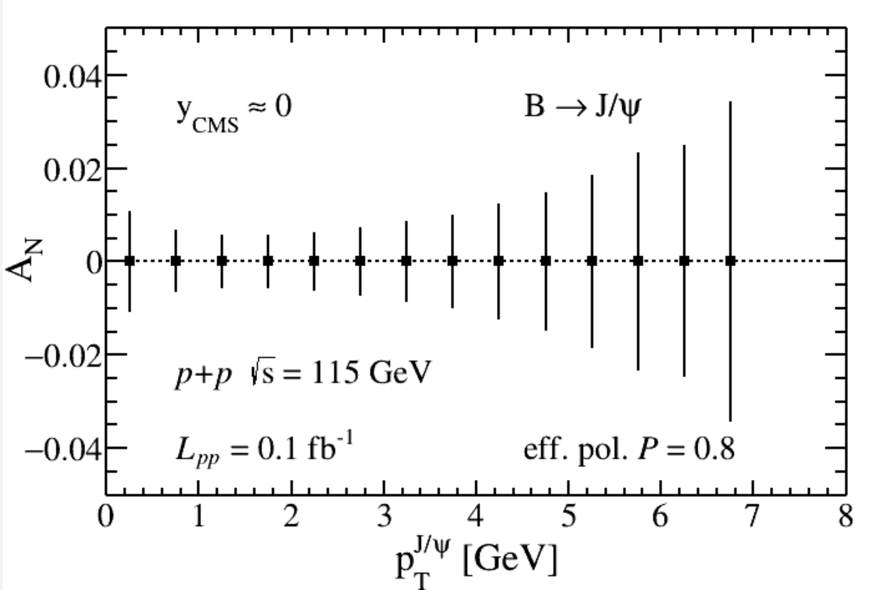


Probing the gluon Sivers effect with Open HF

- ☐ « LHCb-like detector », B → J/Ψ







Probing the quark Sivers effect with Drell-Yan