

Quarkonium-physics case of the LHC in the fixed-target mode

-a short selection-

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Quarkonia as tools 2021

March 25, 2021



Part I

Introduction

Using the LHC beams in the fixed-target mode

Contributions to the ESPP update and other scientific sources

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3 ESPPU contributions submitted in Dec. 2019

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by J.D. Bjorken *et al.* [[inspirehep-1839432](#)]
- ▶ *Physics opportunities for a fixed-target programme in the ALICE experiment*
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Physics Beyond Colliders documents

- ▶ *Physics Beyond Colliders: QCD Working Group Report* - arXiv:1901.04482
- ▶ *Summary Report of Physics Beyond Colliders at CERN* - arXiv:1902.00260
- ▶ Summary by the PBC LHC FT Working Group:
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Reviews, special issues

- ▶ S.J. Brodsky *et al.*: Phys.Rept. 522 (2013) 239
- ▶ Adv. High En. Phys. Special issue
- ▶ AFTER@LHC Study Group Review: arXiv:1807.00603 [hep-ex]

The AFTER@LHC programme

A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

C. Hadjidakis^{a,1}, D. Kikola^{b,1}, J.P. Lansberg^{a,1,*}, L. Massacrier^{a,1}, M.G. Echevarria^{c,2}, A. Kusina^{d,2}, I. Schienbein^{e,2}, J. Seixas^{f,g,2}, H.S. Shao^{h,2}, A. Signori^{i,2}, B. Trzeciak^{j,2}, S.J. Brodsky^k, G. Cavoto^l, C. Da Silva^m, F. Donatoⁿ, E.G. Ferreiro^{o,p}, I. Hřivnáčová^a, A. Klein^m, A. Kurepin^q, C. Lorcé^r, F. Lyonnets^s, Y. Makdisi^t, S. Porteboeuf^u, C. Quintans^g, A. Rakotozafindrabe^v, P. Robbe^w, W. Scandale^x, N. Topilskaya^q, A. Uras^y, J. Wagner^z, N. Yamanaka^a, Z. Yang^{aa}, A. Zelenskiⁱ

Abstract

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in press in Physics Reports - DOI - 10.1016/j.physrep.2021.01.002

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Three main research axes

High- x partonic content of nucleons & nuclei

- Very large gluon PDF uncertainties for $x \gtrsim 0.5$.
- Gluon EMC effect to understand the quark EMC effect
- Proton charm content \leftrightarrow high-energy neutrino & cosmic-ray physics

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- proton spin decomposition and role of OAM $\mathcal{L}_{g;q}$
- test of the QCD factorisation framework
- role of the linearly polarised gluons in unpolarised protons

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Heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies
- Rapidity scan of the azimuthal asymmetries thanks to a broad rapidity reach
- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions with Drell-Yan

Kinematics

Kinematics

Energy range similar to RHIC

7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}$
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Boost:	$\gamma = \sqrt{s} / (2m_N) \approx 60$
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Rapidity shift:

$$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$$

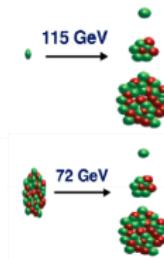
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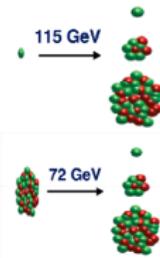
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Effect of boost :

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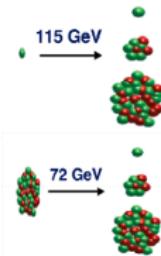
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- ▶ LHCb/ALICE muon arms become **backward detectors**: $[y_{c.m.s.} < 0]$
- ▶ ALICE central barrel becomes an **extreme backward detector**

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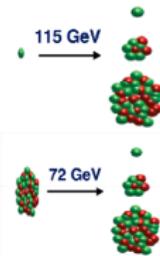
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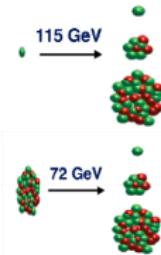
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- ▶ the rapidity coverage depends on the target location

Possible implementations

Internal gas target (with or without storage cell)

- can be installed in one of the existing LHC caverns, and **coupled to existing experiments**
- **validated by LHCb with SMOG** [their luminosity monitor used as a gas target]
- uses the high LHC particle current: p flux: $3.4 \times 10^{18} \text{ s}^{-1}$ & Pb flux: $3.6 \times 10^{14} \text{ s}^{-1}$
- **SMOG2 approved by LHCb**: open-end cell to increase the luminosity with the same gas flux
- **Storage cell with polarised gases** in LHCb: R&D needed for coating and polarisation performance
- A system like the polarised **H-jet RHIC polarimeter** (no storage cell) may also be used

Internal wire/foil target [used by Hera-B on the 920 GeV HERA p beam and by STAR at RHIC]

Bent crystal option: beam line vs split

- crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
- the LHC beam halo is recycled on dense target: proton flux: up to $5 \times 10^8 \text{ s}^{-1}$ & lead flux: up to $2 \times 10^5 \text{ s}^{-1}$
 - **Beam line** : provides a new facility with 7 TeV proton beam but requires civil engineering
 - **Beam split** : similar fluxes; less/no civil engineering; could be coupled to an existing experiment

- Luminosities with **internal gas target** or **crystal-based** solutions are not very different
- The beam line option is currently a little too ambitious (this could change with FCC)
- The gas targets are the **best polarised** targets and **satisfactory for heavy-ion** studies

(see also next talk by S. Mariani)

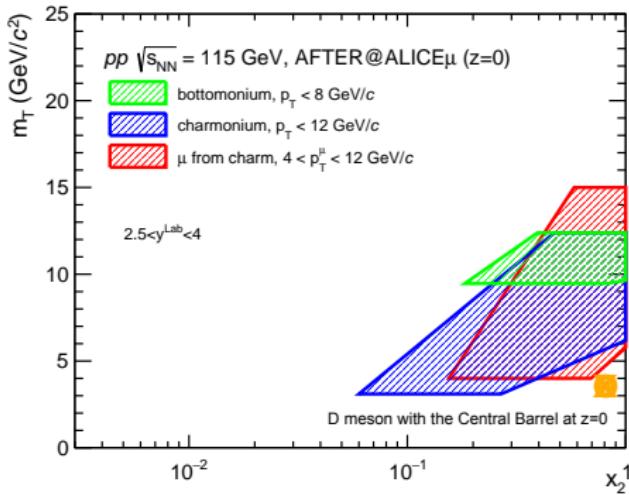
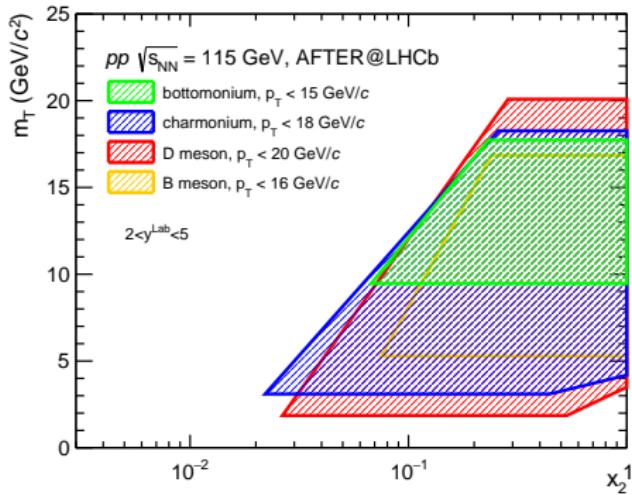
Part II

A selection of projected performances

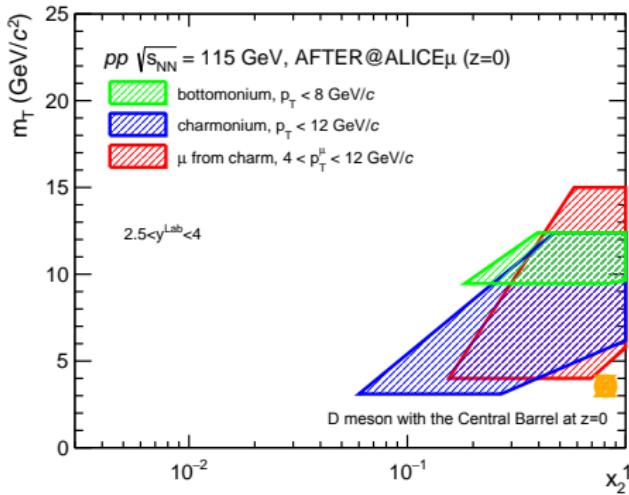
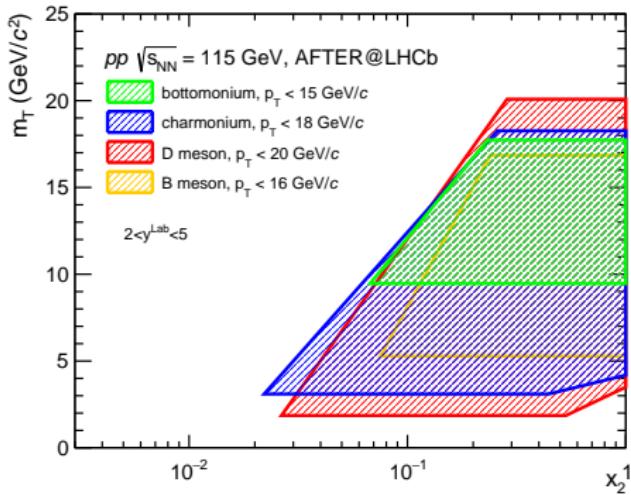
For what is not covered here see:

AFTER@LHC study group review - C. Hadjidakis *et al.* 1807.00603

Kinematical coverage for heavy flavours

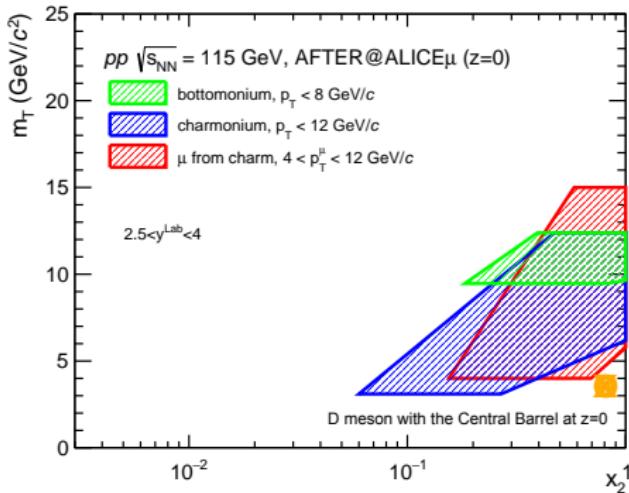
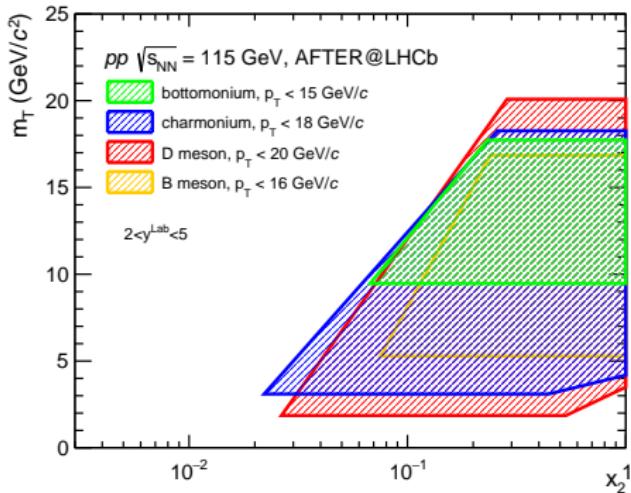


Kinematical coverage for heavy flavours



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Kinematical coverage for heavy flavours



- unprecedented access to gluon dynamics over broad x range
- Both for LHCb and ALICE, the coverage also depends on the target position

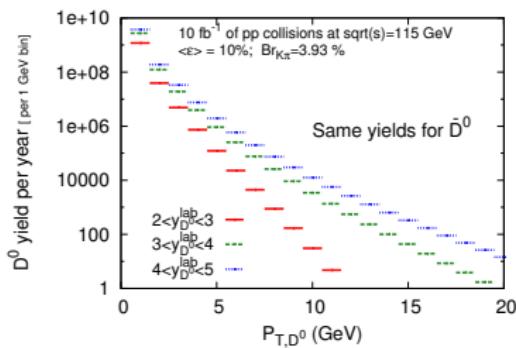
Charm prospects

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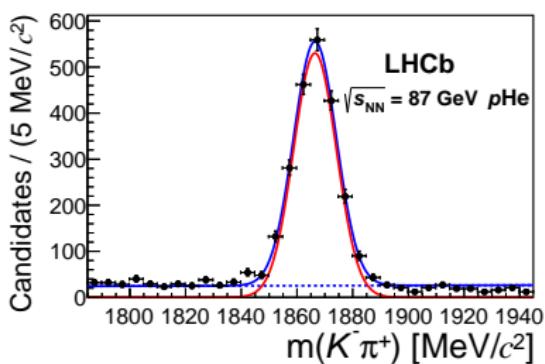
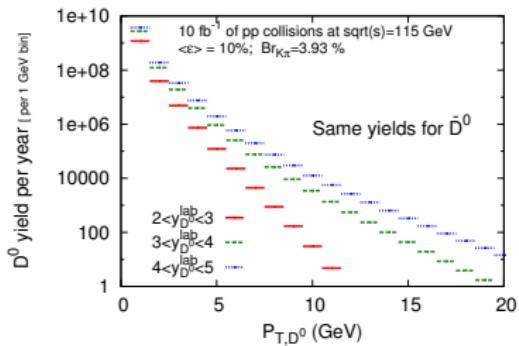
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 - Relevant for cosmic neutrinos



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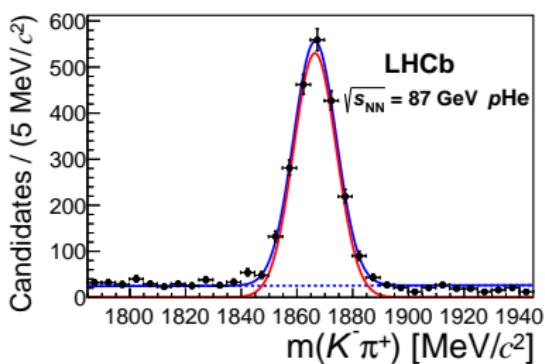
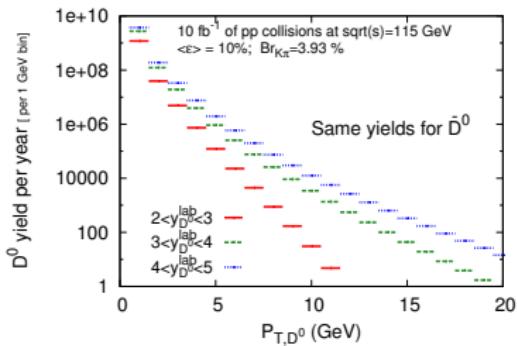
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- LHCb-like detector: the background is well under control [see below]

LHCb (SMOG) Phys. Rev. Lett. 122, 132002 (2019)



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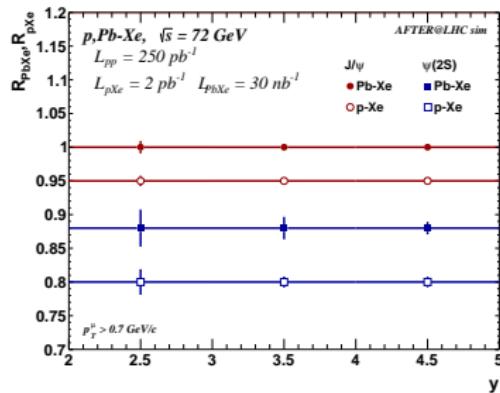
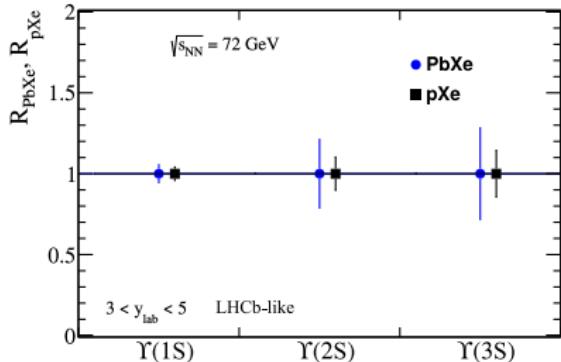
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- Looking at $D \rightarrow K\pi$ gives direct access to charm – anticharm asymmetries



Quarkonium Projections: heavy-ion collisions

C. Hadjidakis *et al.*, 1807.00603; B.Trzeciak *et al.* Few-Body Syst (2017) 58:148

- ▶ Like for nPDF studies (see later), multiple quarkonium studies are needed
- ▶ Clear need for a reliable pA baseline
- ▶ Statistical-uncertainty projections (accounting for background subtraction)

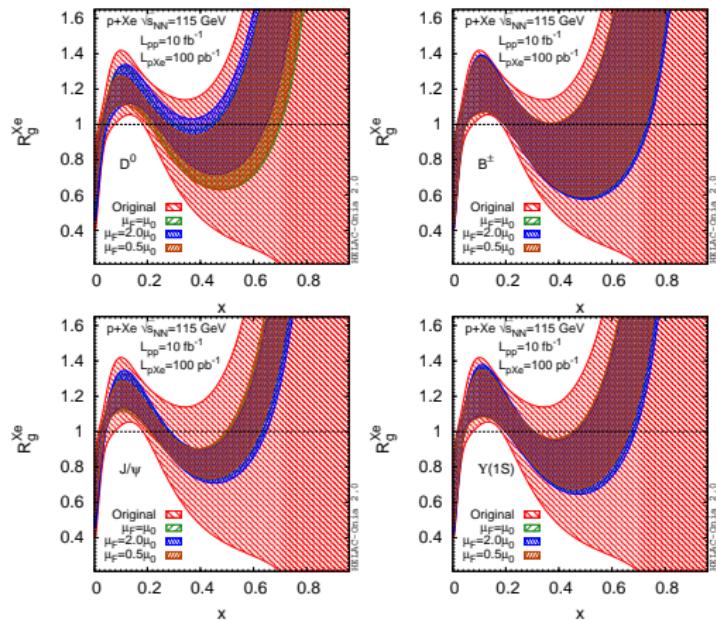


Gluons at the high- x frontier

using precision heavy-flavour-production data

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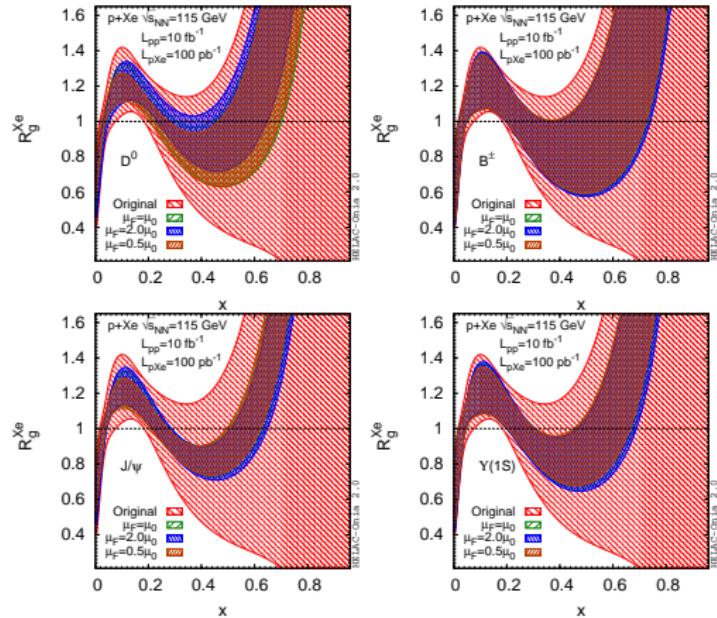
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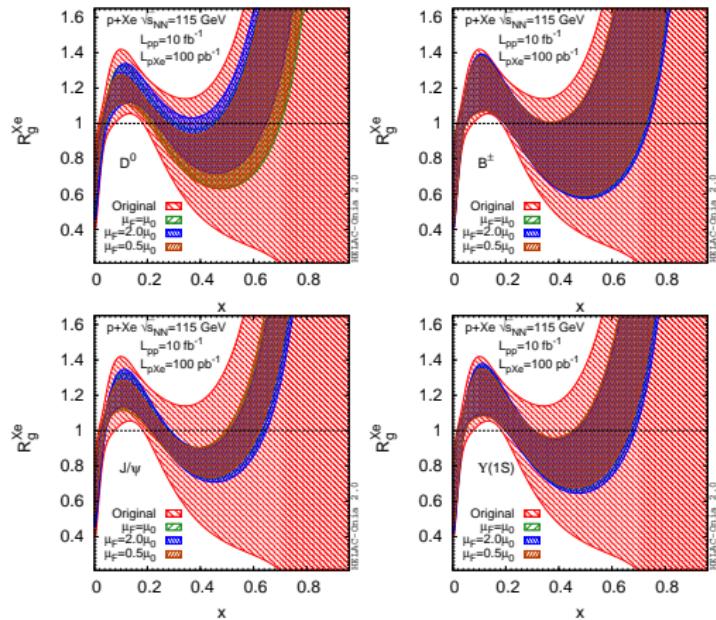
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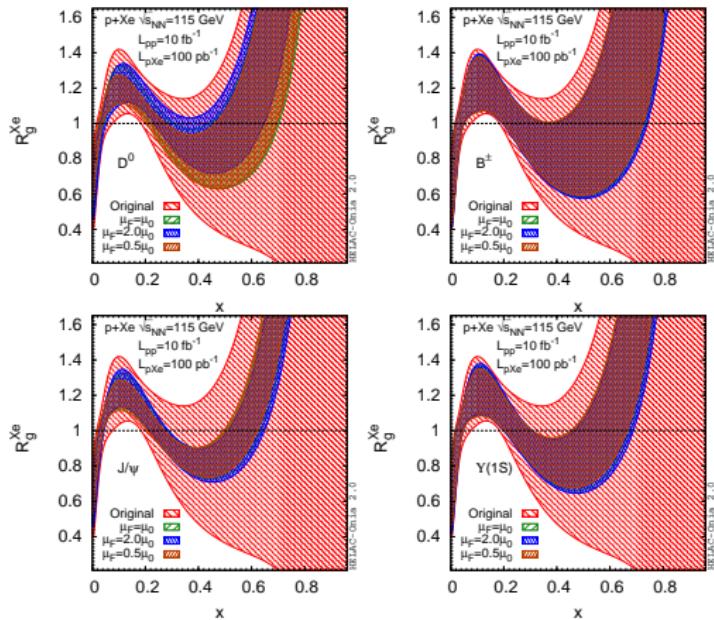
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- ▶ These projections assume that other nuclear effects are under control: different observables are thus needed
- ▶ Proton PDFs projections : yet to be done along the lines of the studies carried out for low- x gluon at the LHC

PROSA Coll. EPJC 75 (2015) 396; R. Gauld, J. Rojo PRL 118 (2017) 072001



unique constraints on gluon (n)PDFs
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A_N : quarkonium production

C. Hadjidakis *et al.*, 1807.00603; D. Kikola *et al.* Few Body Syst. 58 (2017) 139

- ▶ **A_N for all quarkonia** (J/ψ , ψ' , χ_c , $\Upsilon(nS)$, χ_b & η_c) can be measured
[So far, only J/ψ by PHENIX with larger uncertainties]

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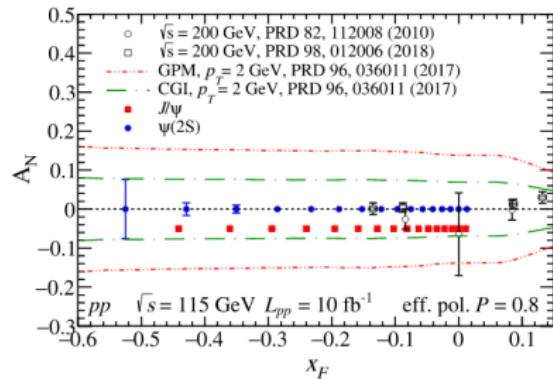
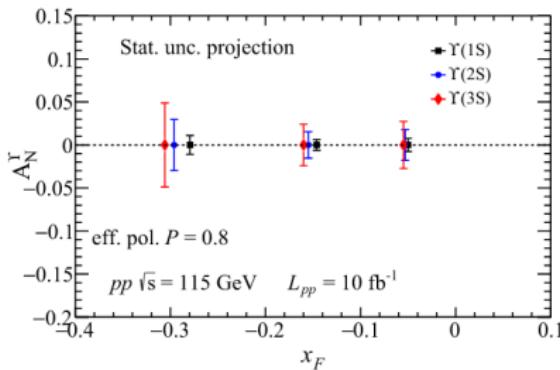
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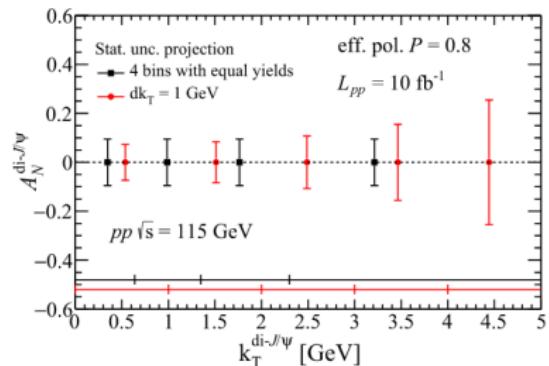
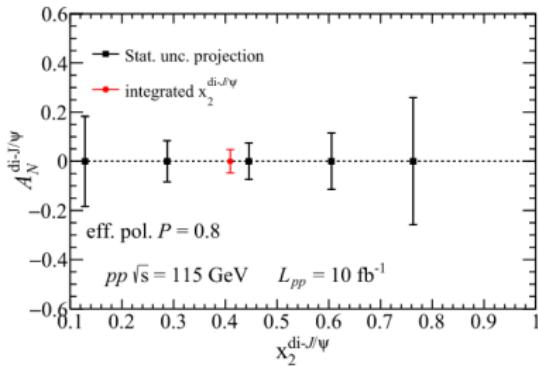
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A_N : quarkonium production

C. Hadjidakis *et al.*, 1807.00603; D. Kikola *et al.* Few Body Syst. 58 (2017) 139

- A_N for all quarkonia (J/ψ , ψ' , χ_c , $\Upsilon(nS)$, χ_b & η_c) can be measured
[So far, only J/ψ by PHENIX with larger uncertainties]
- Also access to polarised neutron (${}^3\text{He}^\uparrow$) at the per cent level for J/ψ
- Completely new perspectives to study the gluon Sivers effect
- Di- J/ψ allow one to study the k_T dependence of the gluon Sivers function for the very first time



Linearly polarised gluon TMD PDF

Extracting the distribution of linearly polarised gluons in an unpolarised proton: $h_1^{\perp g}$

C. Hadjidakis *et al.*, 1807.00603

Linearly polarised gluons alter the q_T distribution of (pseudo)scalar mesons and generates azimuthal asymmetries in pair production

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

Table 17: Expected q_T modulations generated by $h_1^{\perp g}$ for a selection of quarkonium-production observables, along with the expected yields and x_2 ranges derived from $x_2 = M e^{Y_{\text{c.m.s.}}} / \sqrt{s}$ for a rapidity coverage $-2.8 < Y_{\text{c.m.s.}} < 0.2$ and $\sqrt{s} = 115$ GeV.

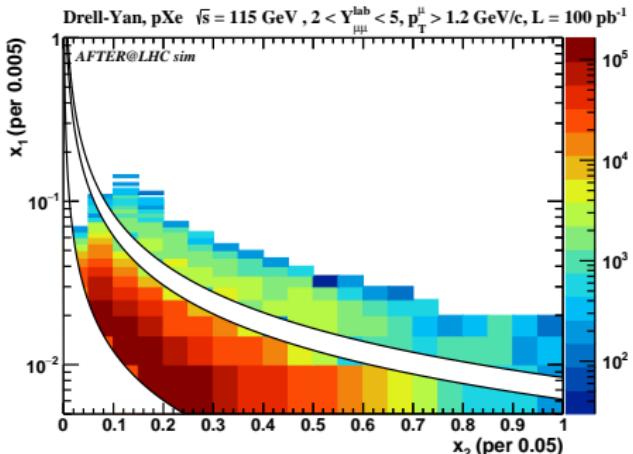
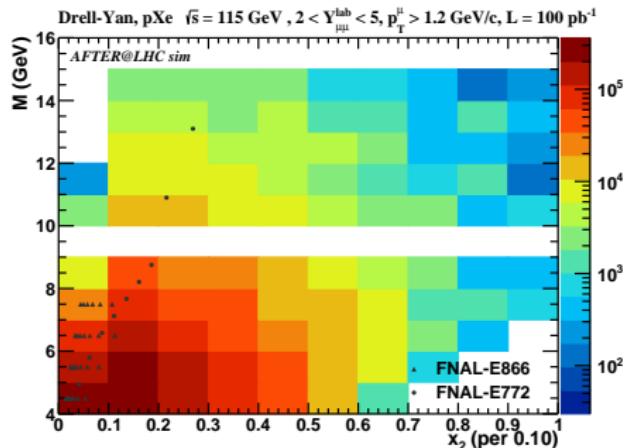
Process	expected yield	x_2 range	M [GeV]	$\cos 2\phi$ modulations	$\cos 4\phi$ modulations
$J/\psi + \gamma$ [60]	$1000 \div 2000$	$0.1 \div 0.6$	$O(10)$	$0 \div 5\%$	$0 \div 2\%$
$J/\psi + J/\psi$ [312]	$300 \div 1500$	$0.1 \div 0.8$	$8 \div 12$	$0 \div 8\%$	$0 \div 20\%$

Table 18: Expected azimuthal asymmetries generated by $h_1^{\perp g}$ for a selection of quarkonium-associated-production observables, along with the expected yields and x_2 ranges derived from $x_2 = M e^{Y_{\text{c.m.s.}}} / \sqrt{s}$ for a rapidity coverage $-2.8 < Y_{\text{c.m.s.}} < 0.2$ and $\sqrt{s} = 115$ GeV.

Drell-Yan

C. Hadjidakis *et al.*, 1807.00603

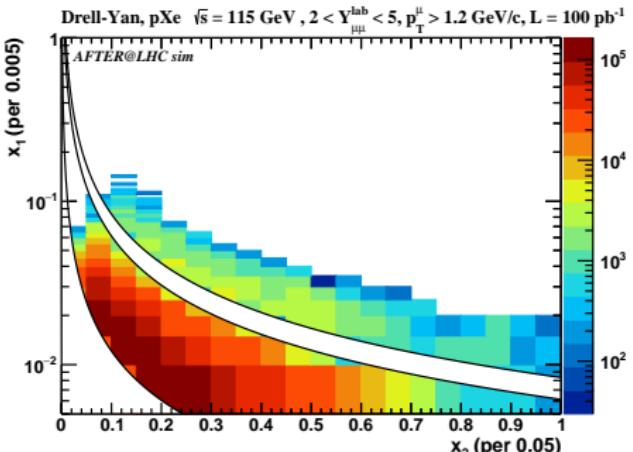
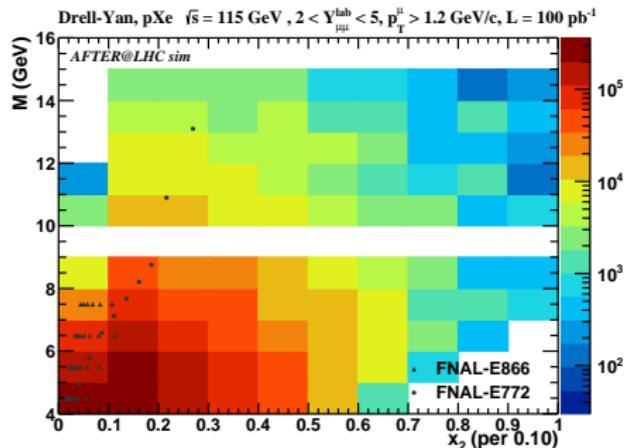
- Unique acceptance (with a LHCb-like detector) compared to existing DY pA data used for nuclear PDF fit (E866 & E772 @ Fermilab).



Drell-Yan

C. Hadjidakis *et al.*, 1807.00603

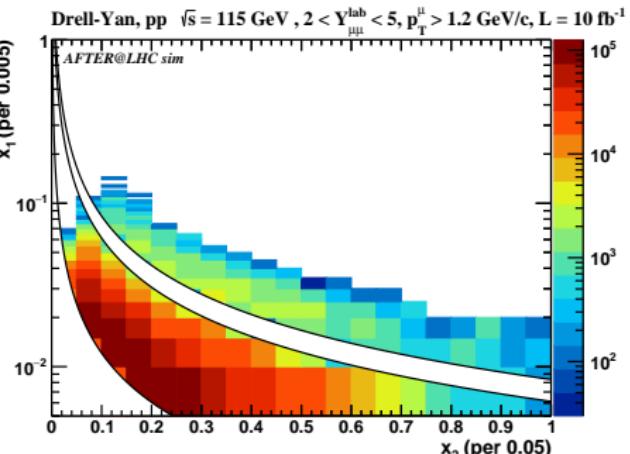
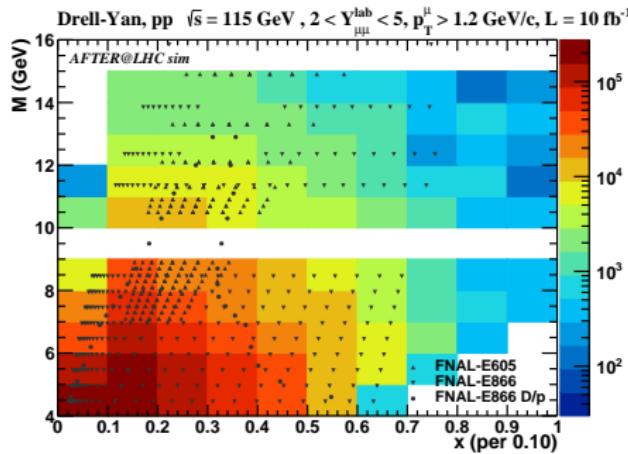
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- Extremely large yields up to $x_2 \rightarrow 1$



Drell-Yan

C. Hadjidakis *et al.*, 1807.00603

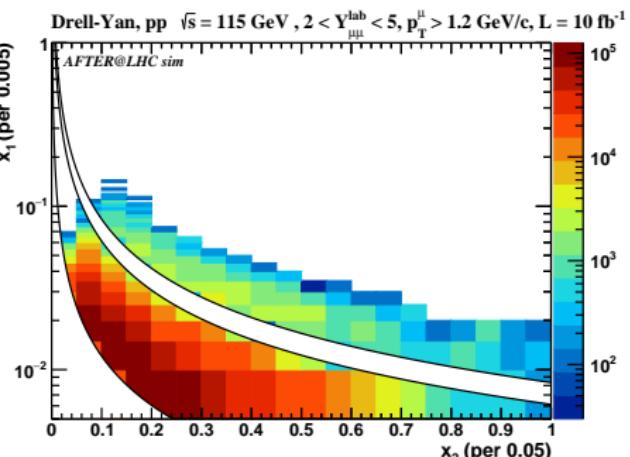
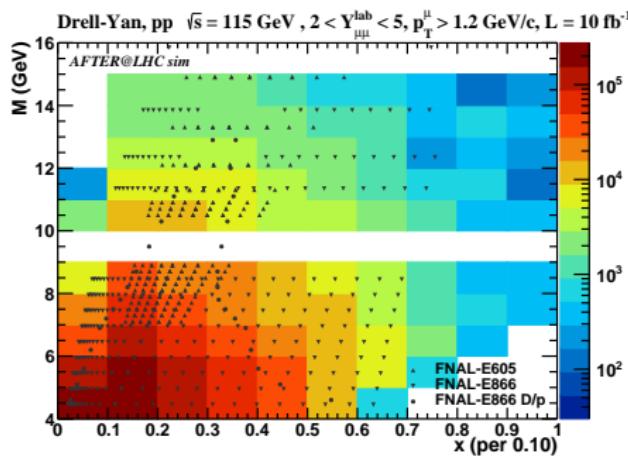
- Unique acceptance (with a LHCb-like detector) compared to existing DY pA data used for nuclear PDF fit (E866 & E772 @ Fermilab).
- Extremely large yields up to $x_2 \rightarrow 1$
- Same acceptance for pp collisions



Drell-Yan

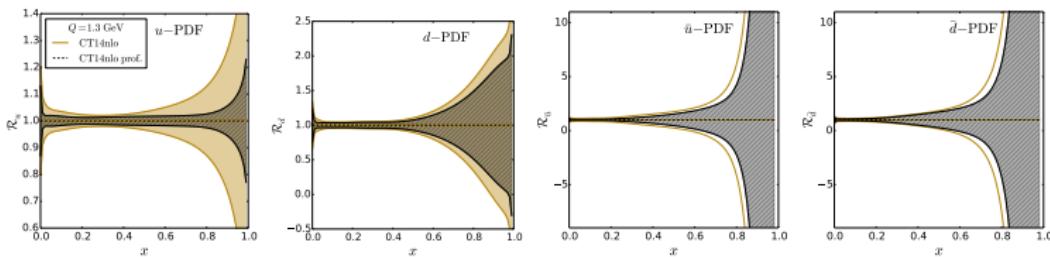
C. Hadjidakis *et al.*, 1807.00603

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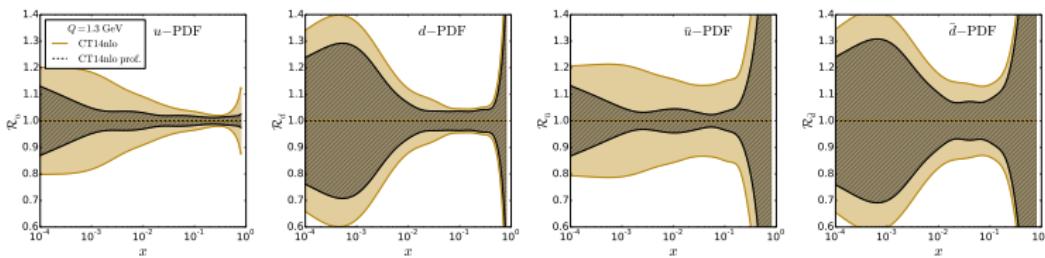
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- Same acceptance for pp collisions
- Decrease of the proton PDF uncertainties : FoM using Bayesian reweighting

pp case



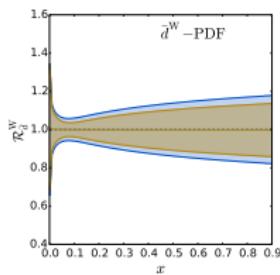
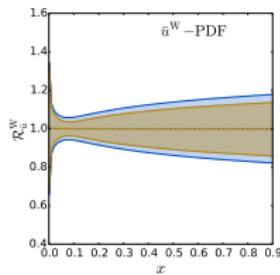
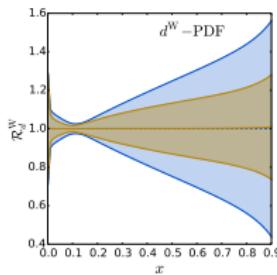
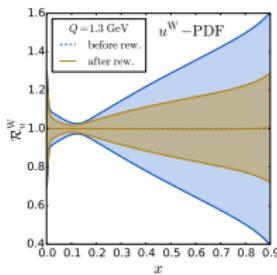
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- Decrease of the proton PDF uncertainties : FoM using Bayesian reweighting

pp case



- Unique acceptance (with a LHCb-like detector) compared to existing DY pA data used for nuclear PDF fit (E866 & E772 @ Fermilab).
- Extremely large yields up to $x_2 \rightarrow 1$
- Same acceptance for pp collisions
- Decrease of the proton PDF uncertainties : FoM using Bayesian reweighting
- as well as the nuclear PDF uncertainties

pW case



A_N : Drell-Yan

[LHCb-like detector]

- DY pair production on a **transversely polarised** target is the aim of several experiment (COMPASS, E1039, STAR, E1027)

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A_N : Drell-Yan

[LHCb-like detector]

- DY pair production on a **transversely polarised** target is the aim of several experiment (COMPASS, E1039, STAR, E1027)
- Check the **sign change** in A_N DY vs SIDIS: hot topic in spin physics !

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A_N : Drell-Yan

[LHCb-like detector]

- DY pair production on a **transversely polarised** target is the aim of several experiment (COMPASS, E1039, STAR, E1027)
- Check the **sign change** in A_N DY vs SIDIS: hot topic in spin physics !
- ${}^3\text{He}^\uparrow$ target → quark Sivers effect in the **neutron via DY**: unique !

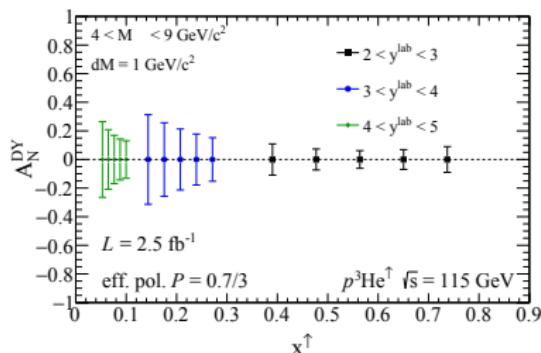
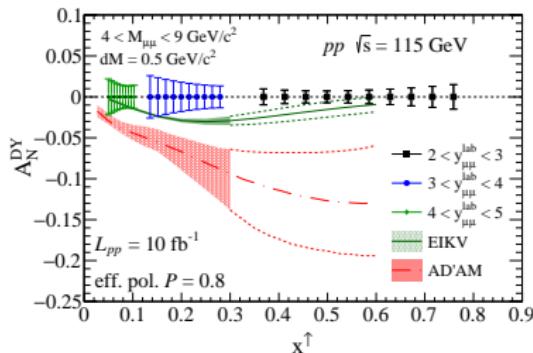
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A_N : Drell-Yan

[LHCb-like detector]

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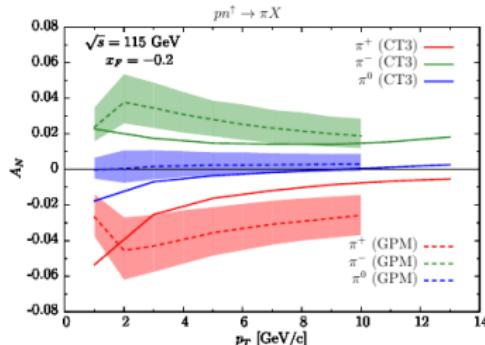
D. Kikola et al. Few Body Syst. 58 (2017) 139



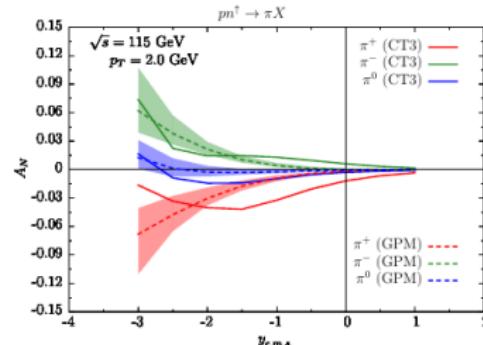
A_N : light mesons

"Flavour sign" change

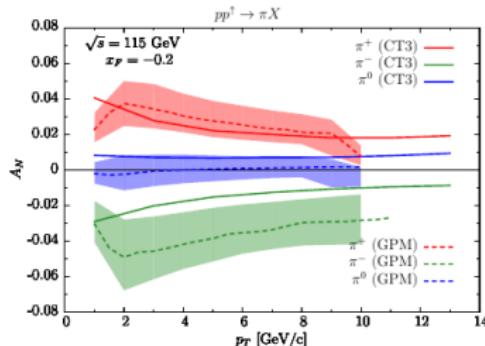
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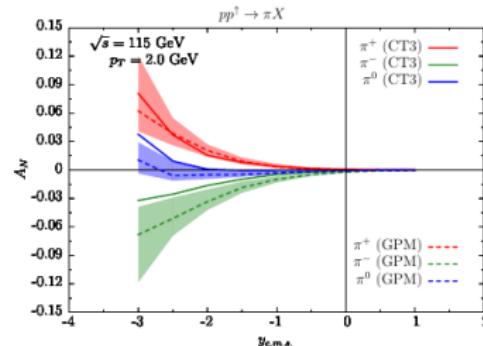
(a)



(b)

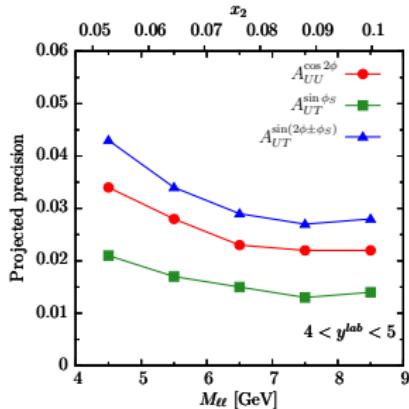
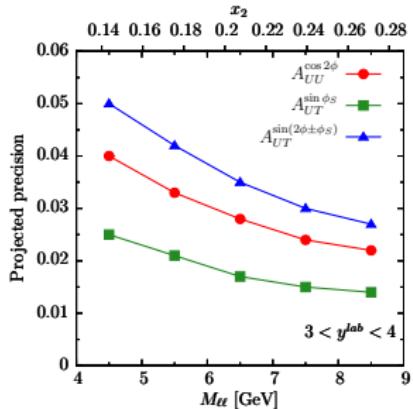
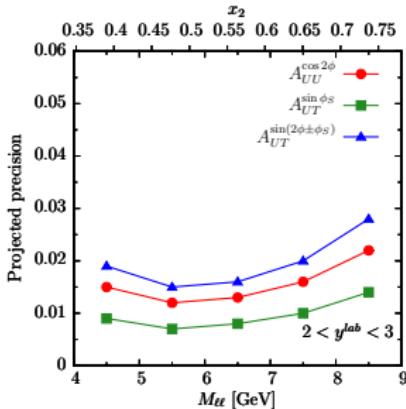


(c)



(d)

More about polarised Drell-Yan



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

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

$$A_{UT}^{\sin \phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}$$

$$A_{UT}^{\sin(2\phi - \phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}$$

Conclusions and outlook

- THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC
 - The high x frontier: new probes of the confinement
and connections with astroparticles
 - The nucleon spin and the transverse dynamics of the partons
 - Heavy-ion studies new energy, new rapidity domain and new probes
- 2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS
 - A slow extraction with a bent crystal
 - An internal gas target inspired from SMOG@LHCb/Hermes/H-Jet, ...

The physics reach of the LHC complex can greatly be extended at a very limited cost with the adjunction of an ambitious and long term research program using the LHC beams in the fixed-target mode.