Depuis 80 ans, nos connaissances bâtissent de nouveaux mondes

Fixed-Target Opportunities at the (HL)LHC

J.P. Lansberg

Orsay (FLUO) – Paris Saclay U. – CNRS/IN2P3

Physics Beyond Colliders Working Group meeting

5-6 November 2019, CERN

On behalf of the AFTER@LHC study group

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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Physics Beyond Colliders documents

- *Physics Beyond Colliders: QCD Working Group Report* by the PBC QCD Working Group (A. Dainese *et al.*) : arXiv:1901.04482
- *Summary Report of Physics Beyond Colliders at CERN* by R. Alemany *et al.*: arXiv:1902.00260
- CERN-PBC-Notes: e.g. 2019-003,2019-002,2019-001,2018-008,2018-007,2018-003,2018-001
- Summary by the PBC LHC FT Working Group: CERN-PBC-REPORT-2019-001

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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. Kikoła[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. Donato[n], E.G. Ferreiro[o,p], I. Hřivnáčová[a], A. Klein[m], A. Kurepin[q], C. Lorcé[r], F. Lyonnet[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. Zelenski[t]

Abstract

We review the context, the motivations and the expected performances of a comprehensive and ambitious fixed-target program using the multi-TeV proton and ion LHC beams. We also provide a detailed account of the different possible technical implementations ranging from an internal wire target to a full dedicated beam line extracted with a bent crystal. The possibilities offered by the use of the ALICE and LHCb detectors in the fixed-target mode are also reviewed.

$\mathcal{O}(100)$ pages – *Submitted to Physics Reports*

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Version 2: to appear with updated FoM (luminosity, target location, ...)

3 main research axes:

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High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus

- Very large gluon PDF uncertainties for $x \gtrsim 0.5$.
- Gluon EMC effect to understand the quark EMC effect
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Dynamics and spin of gluons and quarks inside (un)polarised nucleons

- Possible missing contribution to the proton spin: Orbital Angular Momentum $\mathcal{L}_{g;q}$:

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q}$$

- Test of the QCD factorisation framework
- Determination 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

Part II

Kinematics, Possible Implementations and Luminosities

Fixed-target collisions at the LHC: main kinematical features

Fixed-target collisions at the LHC: main kinematical features

Energy range similar to RHIC

7 TeV proton beam on a fixed target

c.m.s. energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\text{GeV}$	**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: $\sqrt{s_{NN}} = \sqrt{2m_N E_{\text{Pb}}} \approx 72\,\text{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
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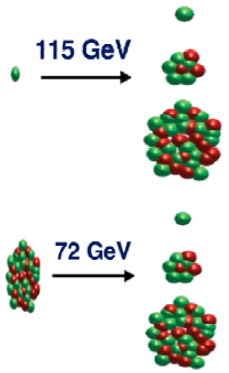

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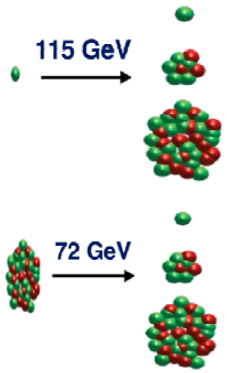

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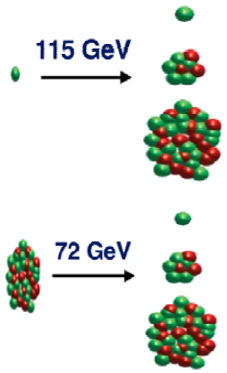

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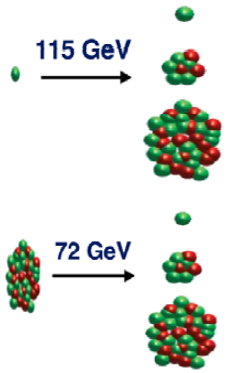

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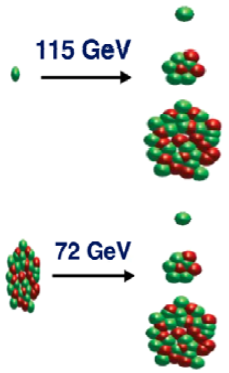

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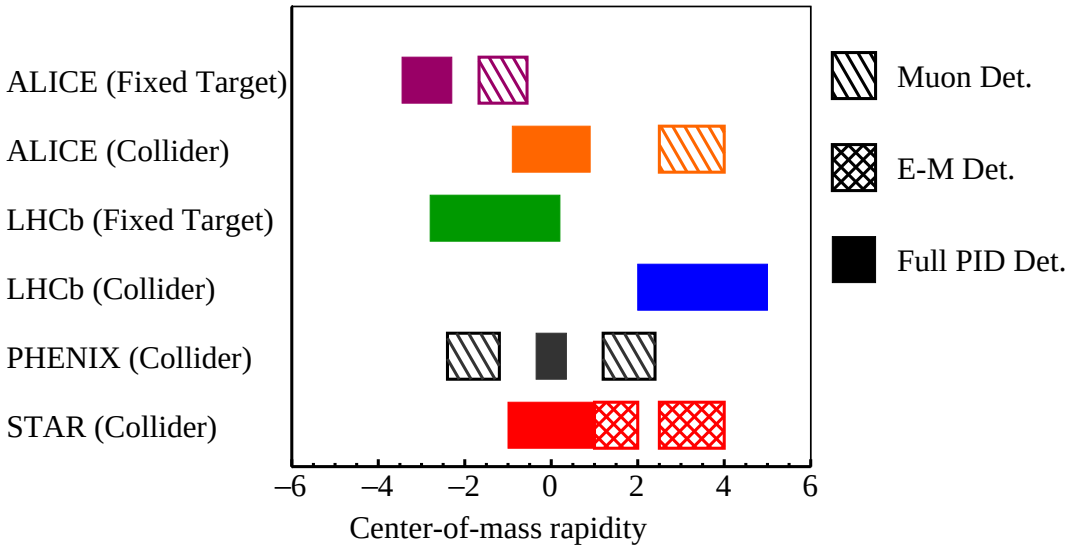
for $z = 0$



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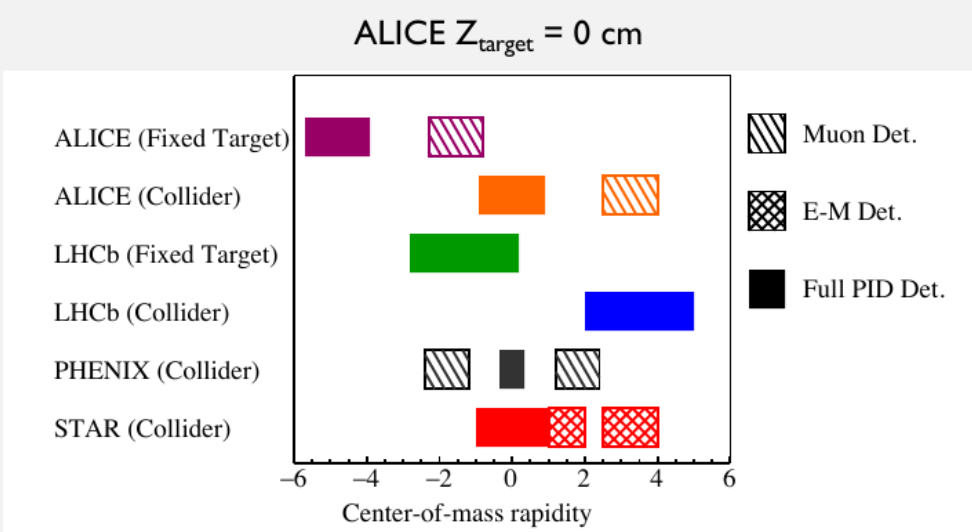
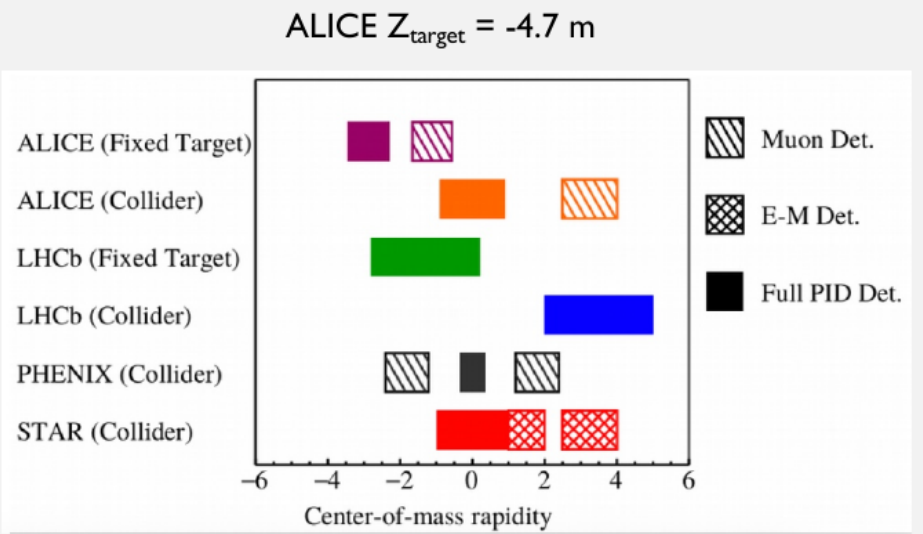
Effect of the target location

ALICE_{μ}:

$z = 0 : 2.5 < \eta < 4$ approx. leads to $-2.3 < y_{\text{cms}} < -0.8$

$z = -4700$ mm $: 3.1 < \eta < 4.2$ approx. leads to $-1.7 < y_{\text{cms}} < -0.6$





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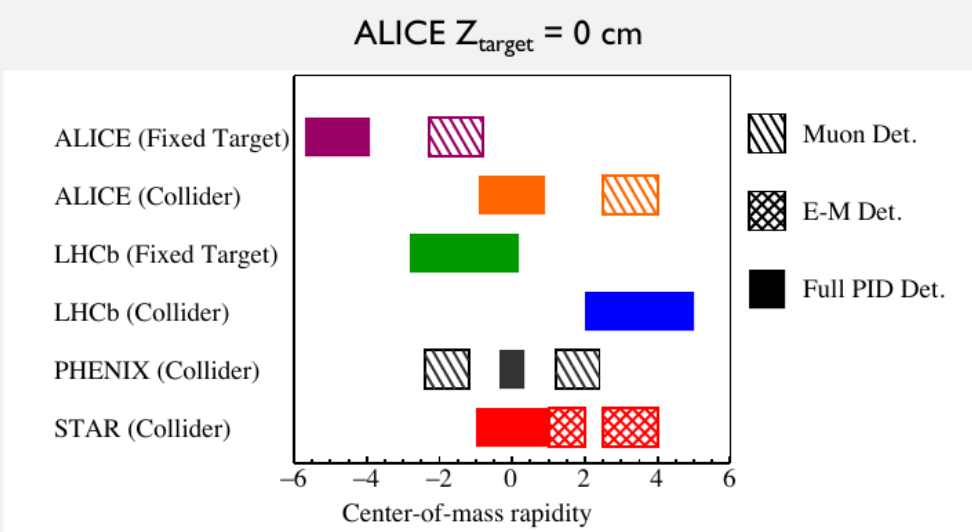

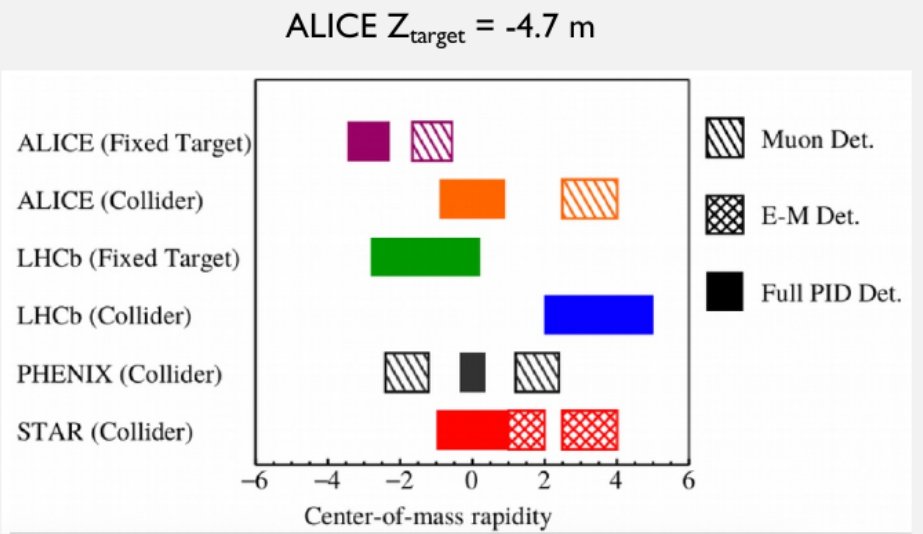

LHCb:

$z = 0$ (~ SMOG) : $2 < \eta < 5$ approx. leads to $-2.8 < y_{\rm cms} < 0.2$

$z = -1500$ mm (~ LHCSpin): $4 < \eta < 6.5$ approx. leads to $-0.8 < y_{\rm cms} < 1.7$

not so backward anymore …

Luminosity comparison [w detector constraints]

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LHCb 'possible'

Assumption: Rates only constrained by the DAQ (40 MHz for pp coll.)
$\mathcal{L}_{p\mathrm{H}_2/\mathrm{H}^\uparrow}$: 10 fb^{-1} yr^{-1}; $\mathcal{L}_{\mathrm{pXe}}$: 300 pb^{-1} yr^{-1}; $\mathcal{L}_{\mathrm{PbXe}}$: 30 nb^{-1} yr^{-1}

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LHCb 'SMOG2' baseline for Run3

Assumption: Storage cell installed, very parasitic mode
$\mathcal{L}_{p\ \mathrm{beam}}$: 150 pb^{-1} on H, 10 pb^{-1} on D or 45 pb^{-1} on Ar; $\mathcal{L}_{\ \mathrm{Pb\ beam}}$: 5 nb^{-1} on Ar

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ALICE 'possible' from Run4*

Assumption: Readout rate: 50 kHz in PbPb coll. and possibly up to 1 MHz in pp and pA coll.
With internal gas target: $\mathcal{L}_{p\mathrm{H}_2/\mathrm{H}^\uparrow}$: 250 pb^{-1}; $\mathcal{L}_{\mathrm{PbXe}}$: 8 nb^{-1}
With beam splitting and solid target: $\mathcal{L}_{p\mathrm{W}}$: 0.6 ÷ 6 pb^{-1} ; $\mathcal{L}_{\mathrm{PbW}}$: 3 nb^{-1}

Qualitative comparison

Characteristics	Internal gas target			Internal solid target with beam halo	Beam splitting	Beam extraction
	SMOG	Gas Jet	Storage Cell			
Run duration	★	★★	★★	★	★★	★★★
Parasiticity	★★	★★	★★	★	★★	★★★
Integrated luminosity	★	★★★	★★★	★	★★	★★★
Absolute luminosity determination	★	★★	★★	★	★★	★★★
Target versatility	★	★★	★★	★	★★	★★★
(Effective) target polarisation	-	★★★	★★	-	- / ★	★
Use of existing experiment	★★★	★★	★	★★	★★	-
Civil engineering or R&D	★★★★	★★★	★★	★★	★★	★
Cost	★★★	★★	★★	★★★	★★	★
Implementation time	★★★	★★	★★	★★★	★★	★
High x	★	★★★	★★★★	★	★★	★★★★
Spin Physics	-	★★★	★★★	-	- / ★★	★★★
Heavy-Ion	★	★★★	★★★	★★	★★	★★★★

Part III

Examples of Updates of Physics Studies

Drell-Yan acceptance

C. Hadjidakis *et al.*, **1807.00603 (v2)**

Drell-Yan acceptance

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- Intermediate Mass Region ($1 < M_{\ell\ell} < 2.5$ GeV) DY dominated by combinatorial background: difficult to simulate: no FoM

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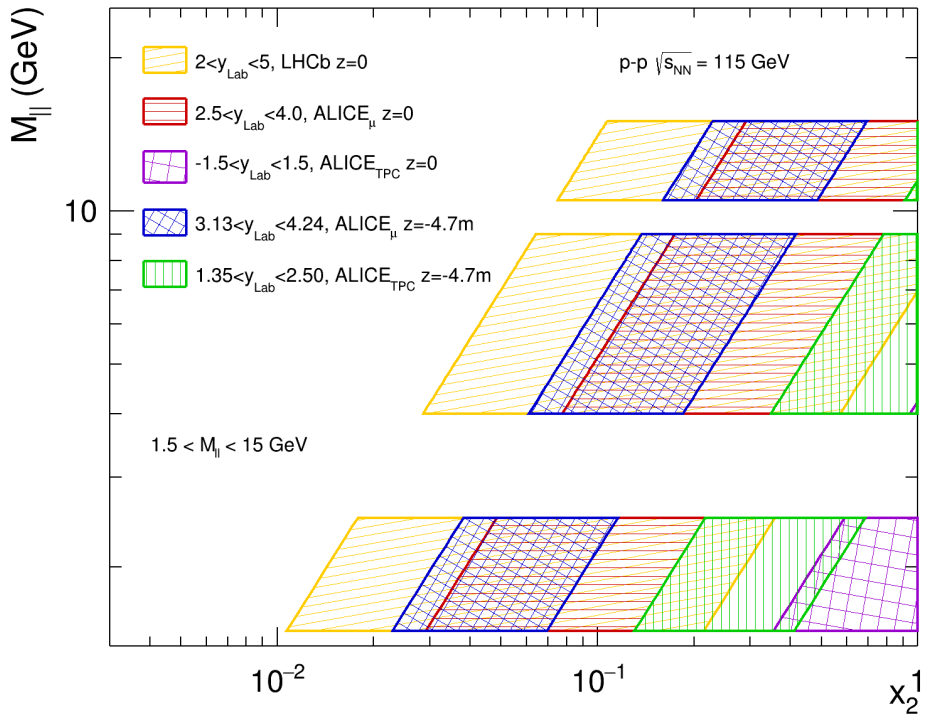

Drell-Yan acceptance

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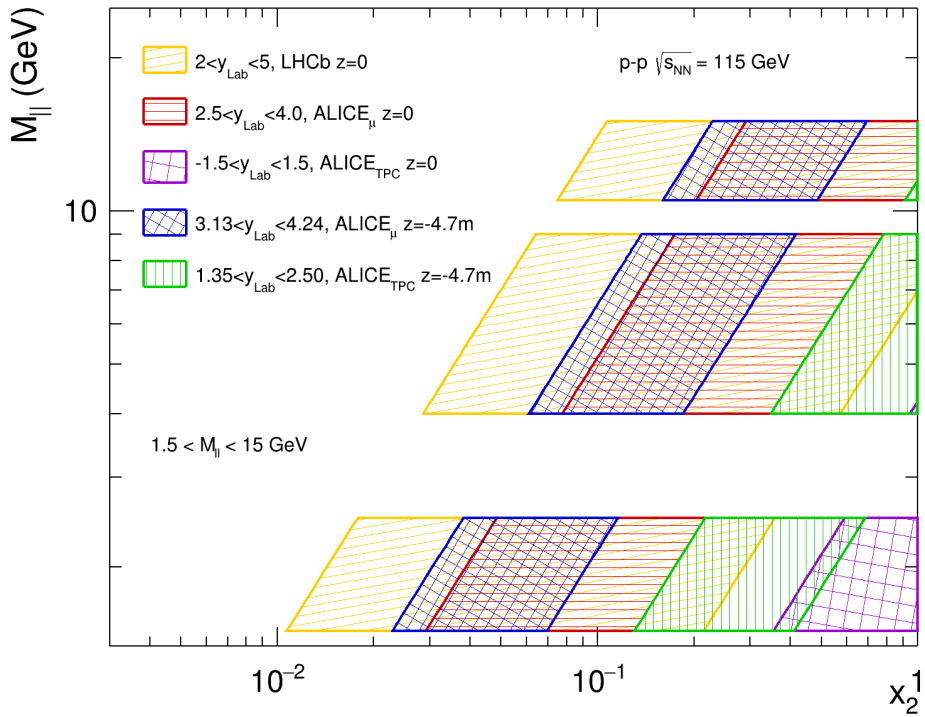
- But rather easy to access: high rates and good acceptance
- For LHCb with $z = -1.5$m (not shown), the acceptance is significantly shifted to lower x ($0.003 < x_2 < 0.04$ for $M_{\ell\ell} = 2$ GeV)



Drell-Yan STSAs & the target location

C. Hadjidakis *et al.*, 1807.00603 (v2)

As aforementioned, without additional detector:
$z = -1500$ mm (~ LHCSpin): $4 < \eta_{(\mathrm{lab})} < 6.5$

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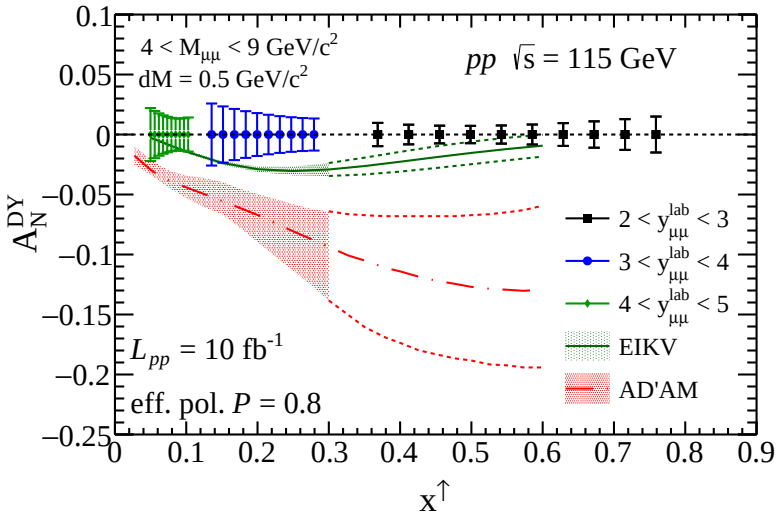

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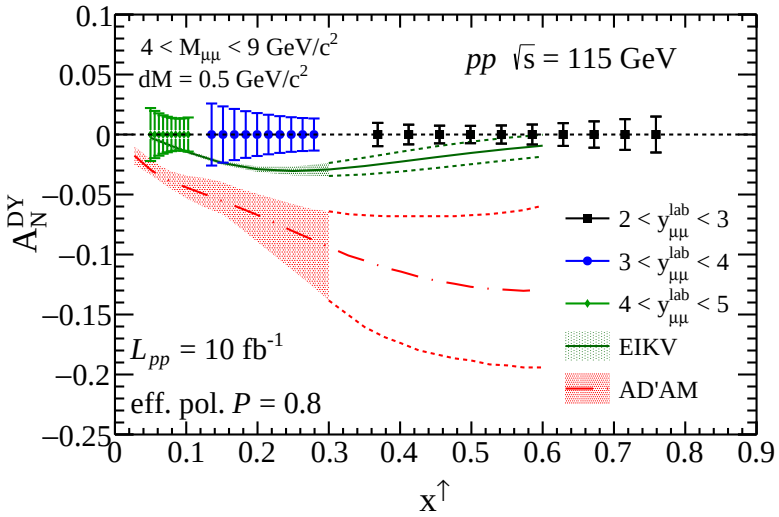

- Only the green points remain accessible for these masses

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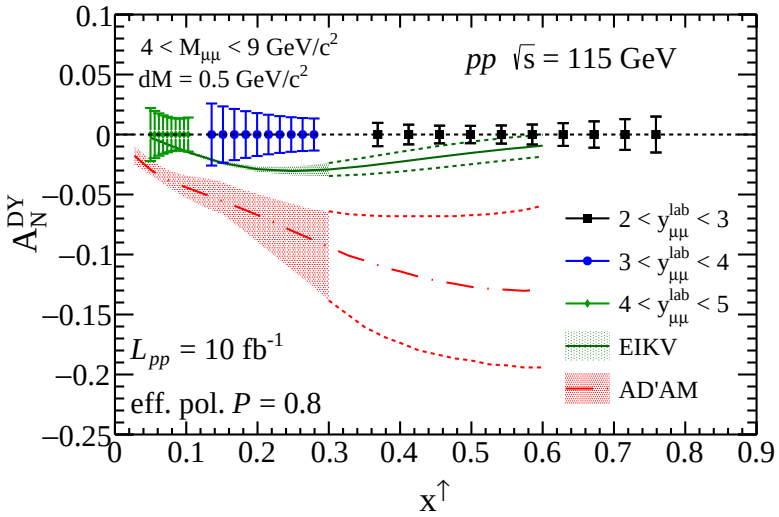

- Only the green points remain accessible for these masses
- For larger masses, the STSAs may be reduced by the evolution

Drell-Yan STSAs & the target location

C. Hadjidakis *et al.*, 1807.00603 (v2)

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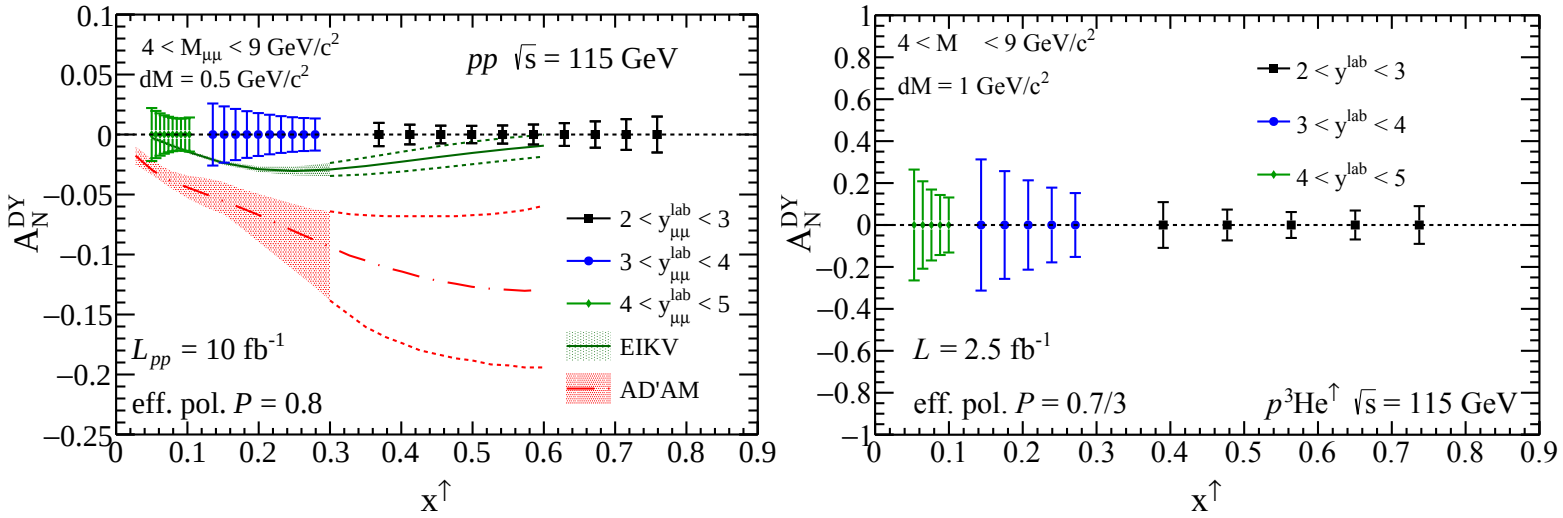
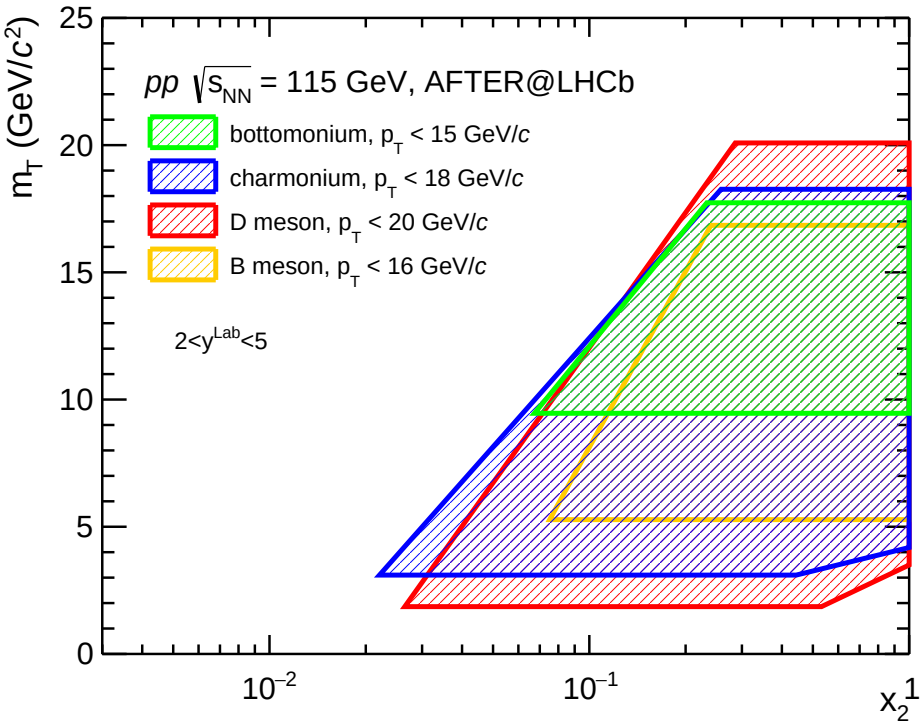
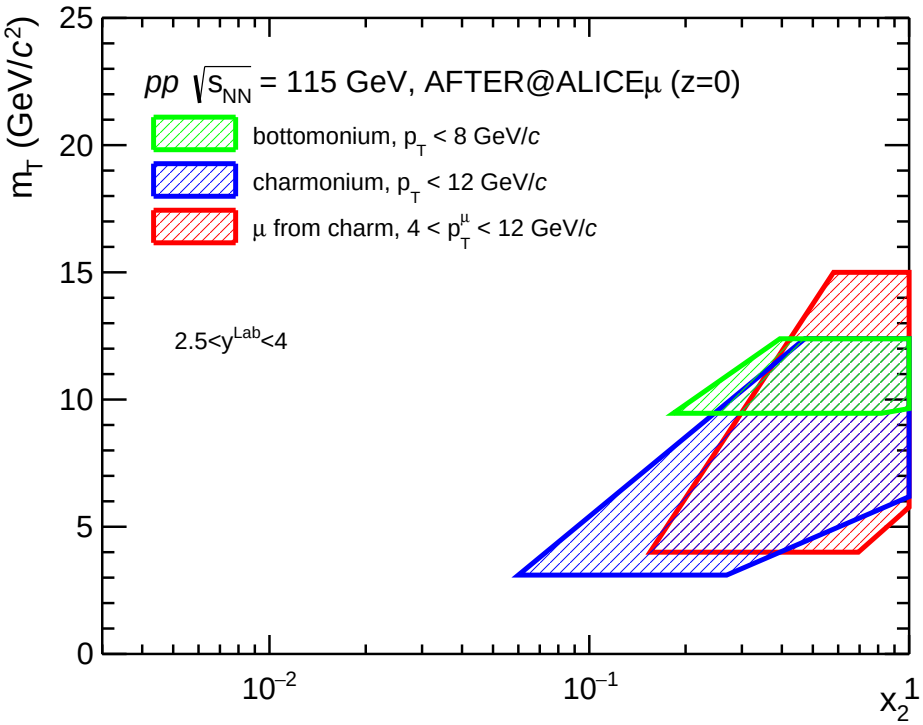


- Only the green points remain accessible for these masses
- For larger masses, the STSAs may be reduced by the evolution
- Might be worth considering the gas-jet option allowing for a less remote target (here for He)

Kinematical coverage for heavy flavours





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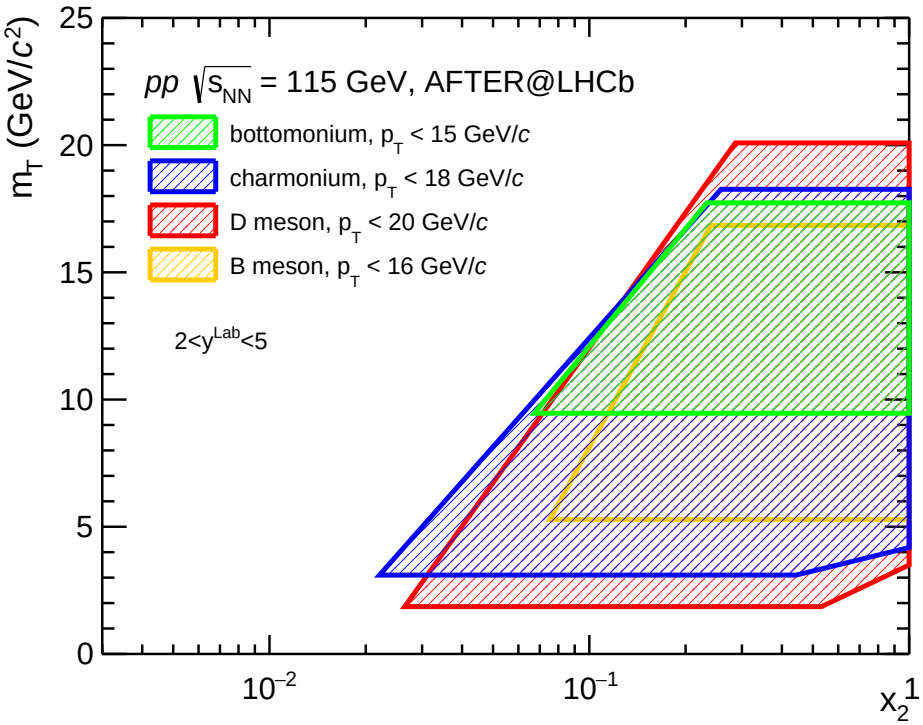
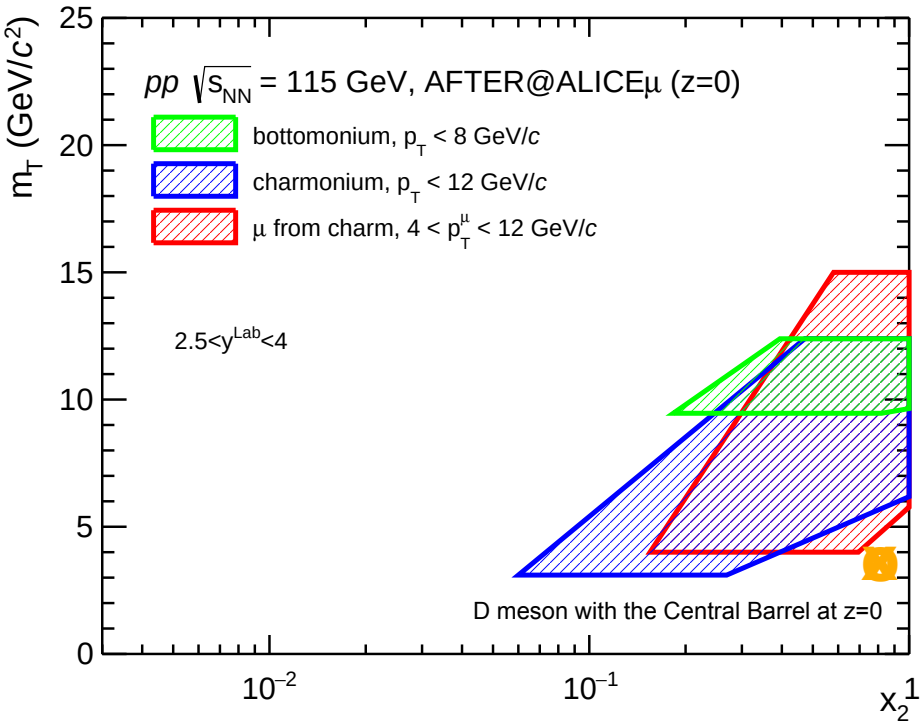
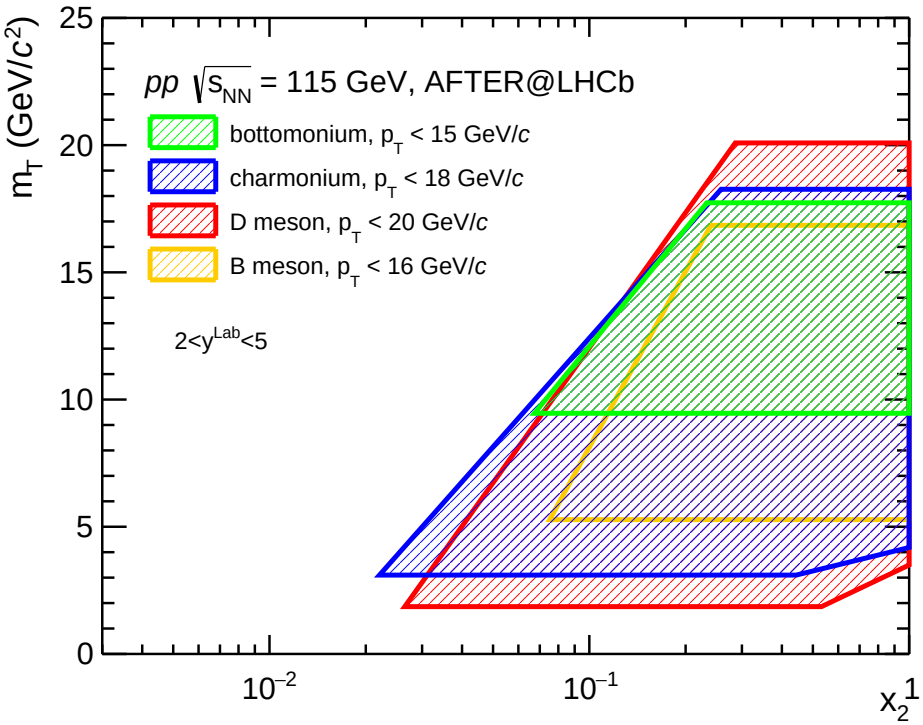
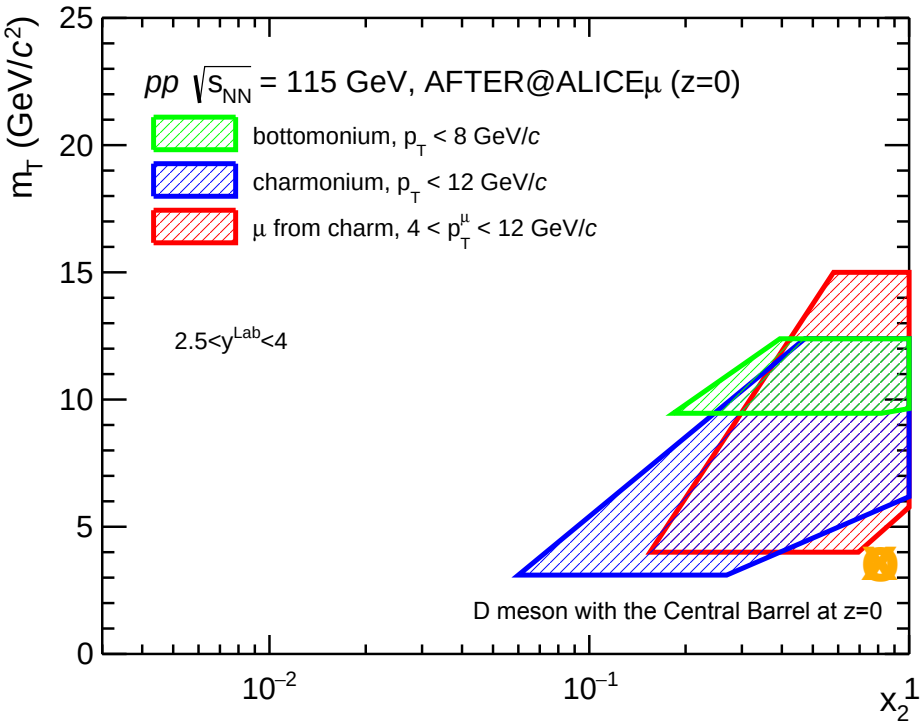




Kinematical coverage for heavy flavours





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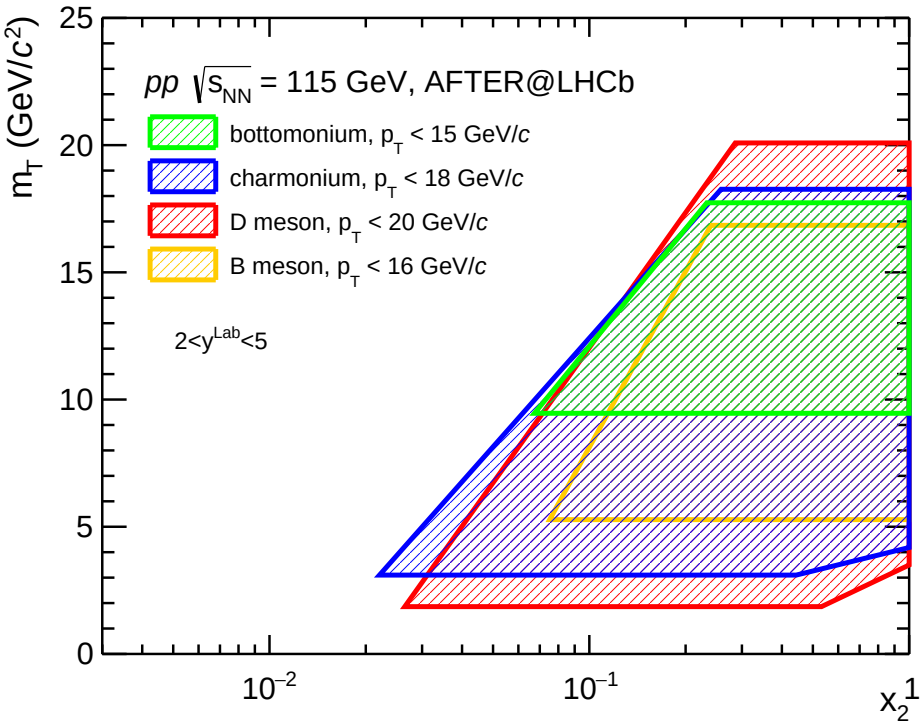

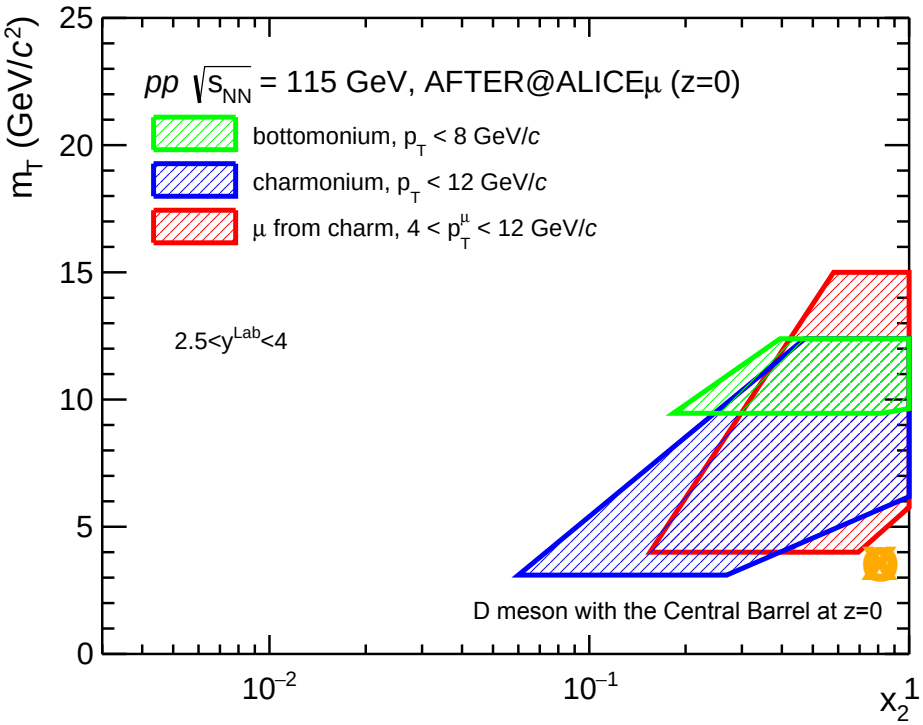

- ALICE could extend its coverage with $\eta_{\rm Lab} \sim 1 - 2$ for quarkonia into dileptons with one muon in the muon arm and another in the central barrel
- Both for LHCb and ALICE, the coverage also depends on the target position

Part IV

Conclusions

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- See also the Physics Briefing Book : arXiv:1910.11775 [hep-ex]

Part V

Backup slides

Further readings

Heavy-Ion Physics

- *Estimation of the freeze-out parameters reachable in the AFTER@LHC project* by V. Begun, D. Kikola, V. Vovchenko, D. Wielanek, Phys. Rev. C 98 (2018)
- *Rapidity scan in heavy ion collisions at* $\sqrt{s_{\rm NN}}$ = 72 *GeV using a viscous hydro + cascade model* by I. Karpenko: Acta Phys. Polon. B50 (2019), 141
- *Gluon shadowing effects on* J/ψ *and* Υ *production in p+Pb collisions at* $\sqrt{s_{NN}}$ = 115 *GeV and Pb+p collisions at* $\sqrt{s_{NN}}$ = 72 *GeV at AFTER@LHC* by R. Vogt. Adv.Hi.En.Phys. (2015) 492302.
- *Prospects for open heavy flavor measurements in heavy-ion and p+A collisions in a fixed-target experiment at the LHC* by D. Kikola. Adv.Hi.En.Phys. (2015) 783134
- *Quarkonium suppression from coherent energy loss in fixed-target experiments using LHC beams* by F. Arleo, S.Peigne. [arXiv:1504.07428 [hep-ph]]. Adv.Hi.En.Phys. (2015) 961951
- *Anti-shadowing Effect on Charmonium Production at a Fixed-target Experiment Using LHC Beams* by K. Zhou, Z. Chen, P. Zhuang. Adv.High Energy Phys. 2015 (2015) 439689
- *Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams.* By J.P. Lansberg, S.J. Brodsky, F. Fleuret, C. Hadjidakis. [arXiv:1204.5793 [hep-ph]]. Few Body Syst. 53 (2012) 11.

Further readings

Spin physics

- *Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment* by K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak. [arXiv:1502.04021 [hep-ph]. Adv.Hi.En.Phys. (2015) 257934.
- *Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment in a TMD factorisation scheme* by M. Anselmino, U. D'Alesio, and S. Melis. [arXiv:1504.03791 [hep-ph]]. Adv.Hi.En.Phys. (2015) 475040.
- *The gluon Sivers distribution: status and future prospects* by D. Boer, C. Lorcé, C. Pisano, and J. Zhou. [arXiv:1504.04332 [hep-ph]]. Adv.Hi.En.Phys. (2015) 371396
- *Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)* By T. Liu, B.Q. Ma. Eur.Phys.J. C72 (2012) 2037.
- *Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER* By D. Boer, C. Pisano. Phys.Rev. D86 (2012) 094007.
- *Single-Transverse-Spin Asymmetries in Exclusive Photo-production of J/ψ in Ultra-Peripheral Collisions in the Fixed-Target Mode at the LHC and in the Collider Mode at RHIC*
By J.P. Lansberg, L. Massacrier, L. Szymanowski, J. Wagner, Phys.Lett. B793 (2019) 33

Further readings

Hadron structure

- *Exclusive vector meson photoproduction in fixed - target collisions at the LHC* by V.P. Goncalves, M.M. Jaime. Eur.Phys.J. C78 (2018) no.9, 693
- *Lepton-pair production in ultraperipheral collisions at AFTER@LHC*
  By J.P. Lansberg, L. Szymanowski, J. Wagner. JHEP 1509 (2015) 087
- *Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC).*
  by J.P. Lansberg, H.S. Shao. Nucl.Phys. B900 (2015) 273-294
- *Next-To-Leading Order Differential Cross-Sections for Jpsi, psi(2S) and Upsilon Production in Proton-Proton Collisions at a Fixed-Target Experiment using the LHC Beams (AFTER@LHC)*
  by Y. Feng, and J.X. Wang. Adv.Hi.En.Phys. (2015) 726393.
- *η_c production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon*
  By V.P. Goncalves, W.K. Sauter.Phys.Rev. D91 (2015) 9, 094014.
- *A review of the intrinsic heavy quark content of the nucleon*
  by S. J. Brodsky, A. Kusina, F. Lyonnet, I. Schienbein, H. Spiesberger, and R. Vogt. Adv.Hi.En.Phys. (2015) 231547.
- *Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC*
  By G. Chen *et al.*. Phys.Rev. D89 (2014) 074020.

Further readings

Feasibility study and technical ideas

- *Feasibility Studies for Single Transverse-Spin Asymmetry Measurements at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC)* by Daniel Kikola et al. [arXiv:1702.01546 [hep-ex]]. Few Body Syst. 58 (2017) 139.
- *Heavy-ion Physics at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC): Feasibility Studies for Quarkonium and Drell-Yan Production* by B. Trzeciak et al. [arXiv:1703.03726 [nucl-ex]] Few Body Syst. 58 (2017) 148
- *Feasibility studies for quarkonium production at a fixed-target experiment using the LHC proton and lead beams (AFTER@LHC)* by L. Massacrier, B. Trzeciak, F. Fleuret, C. Hadjidakis, D. Kikola, J.P.Lansberg, and H.S. Shao arXiv:1504.05145 [hep-ex]. Adv.Hi.En.Phys. (2015) 986348
- *A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions* by C. Barschel, P. Lenisa, A. Nass, and E. Steffens. Adv.Hi.En.Phys. (2015) 463141
- *Quarkonium production and proposal of the new experiments on fixed target at LHC* by N.S. Topilskaya, and A.B. Kurepin. Adv.Hi.En.Phys. (2015) 760840

Generalities

- *Physics Opportunities of a Fixed-Target Experiment using the LHC Beams*
  By S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. [arXiv:1202.6585 [hep-ph]]. Phys.Rept. 522 (2013) 239.