A Fixed-Target Program at the LHC: the genesis

J.P. Lansberg

IJCLab Orsay – Paris Saclay U. – CNRS

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On behalf of the AFTER@LHC study group

Part I

Introduction

The Genesis

Physics Reports 522 (2013) 239–255

Contents lists available at SciVerse ScienceDirect

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Physics opportunities of a fixed-target experiment using LHC beams

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- 2018 : AFTER@LHC review out
- 2019 : PBC document out & ESPPU

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Community Support for A Fixed-Target Programme for the LHC

J.D. Bjorken[1], N. Brambilla[2], S.J. Brodsky[1], J. Cleymans[3], F. Donato[4], M.G. Echevarria[5], F. Halzen[6], P. Hoyer[7], A. Kusina[8], J.P. Lansberg[9], P.J. Mulders[10], C. Pajares[11], H. Satz[12], J. Seixas[13], A. Signori[14], D. Sivers[15], M. Strikman[16], and L. Szymanowski[17]

Abstract

This contribution aims at promoting the ground-breaking physics programme accessible with the multi-TeV LHC proton and ion beams used in the fixed-target mode. It can be realised in a parasitic mode for the LHC complex using existing detectors like those of the LHCb and ALICE collaborations or new dedicated systems during the LHC lifetime. It contains a brief description of the different technical implementations which are currently under investigation as well as the basic performances offered by the use of the ALICE and LHCb detectors in the fixed-target mode. In short, the multi-TeV LHC beams allow for the most energetic fixed-target experiment ever performed opening the way for unique studies of the nucleon and nuclear structure at high x, of the spin content of the nucleon and of the phases of the nuclear matter from a new rapidity viewpoint at seldom explored energies.

Contact: FTP4LHC-steering@ipno.in2p3.fr

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- CERN-PBC-Notes: e.g. 2019-003,2019-002,2019-001,2018-008,2018-007,2018-003,2018-001
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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

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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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The AFTER@LHC programme

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Version 2 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

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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
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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

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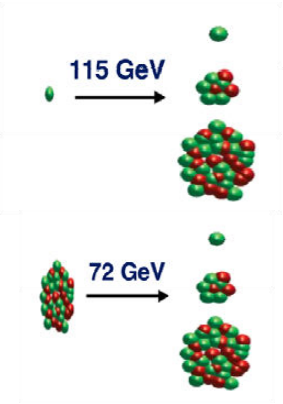

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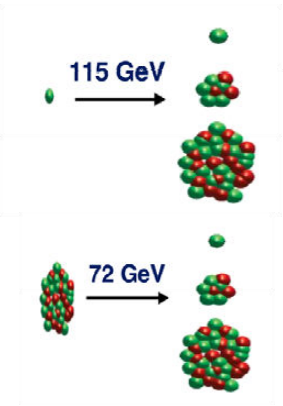

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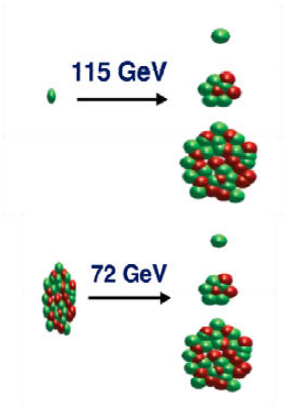

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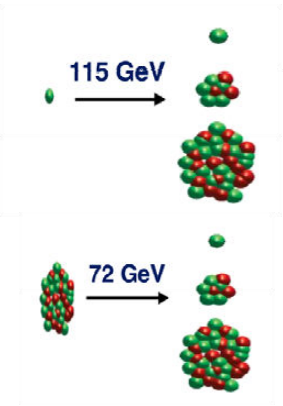

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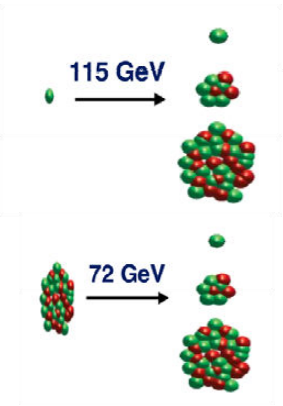

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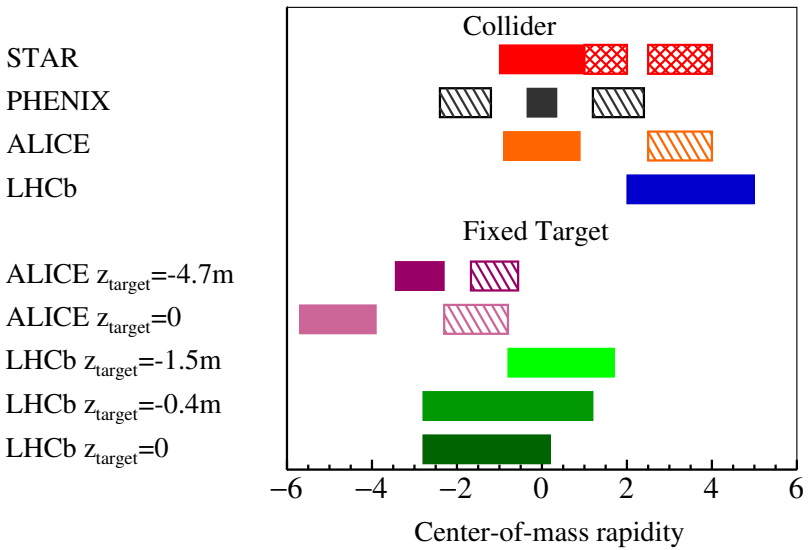
- Yet the rapidity coverage crucially depends on the target location

Effect of the target location



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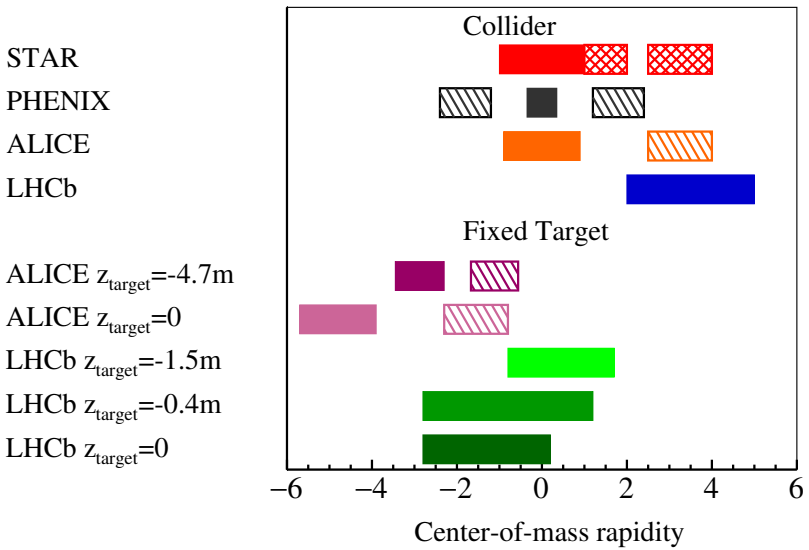
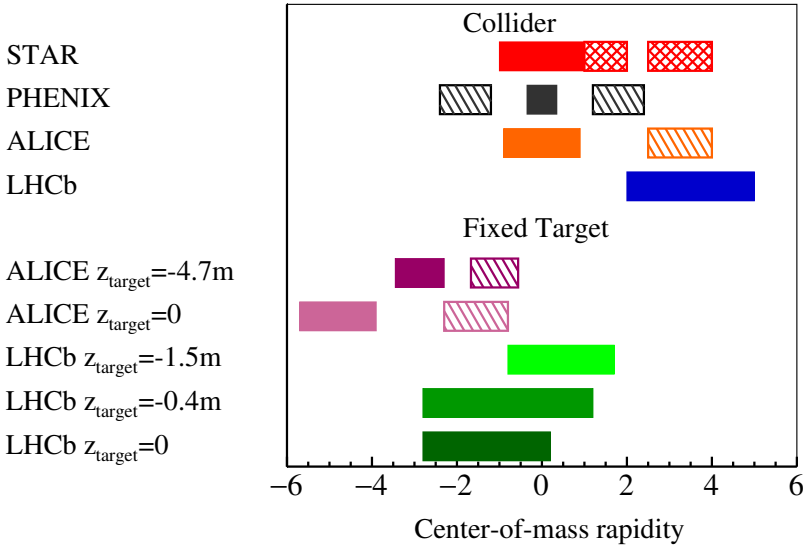


ALICE$_\mu$:

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

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

Effect of the target location



ALICE$_\mu$:

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

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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 …

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→ The gas targets are the best polarised targets and satisfactory for heavy-ion studies

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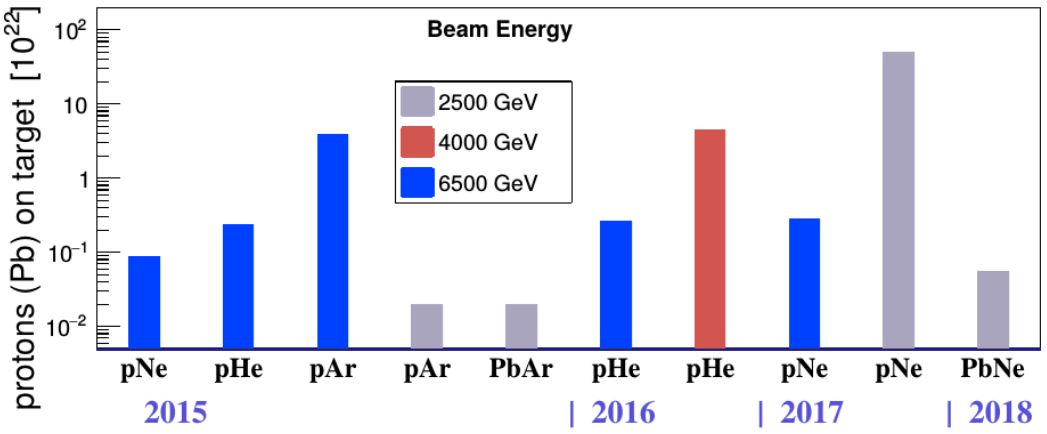

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Largest sample (pNe 2017) $\sim 100\ \mathrm{nb}^{-1}$

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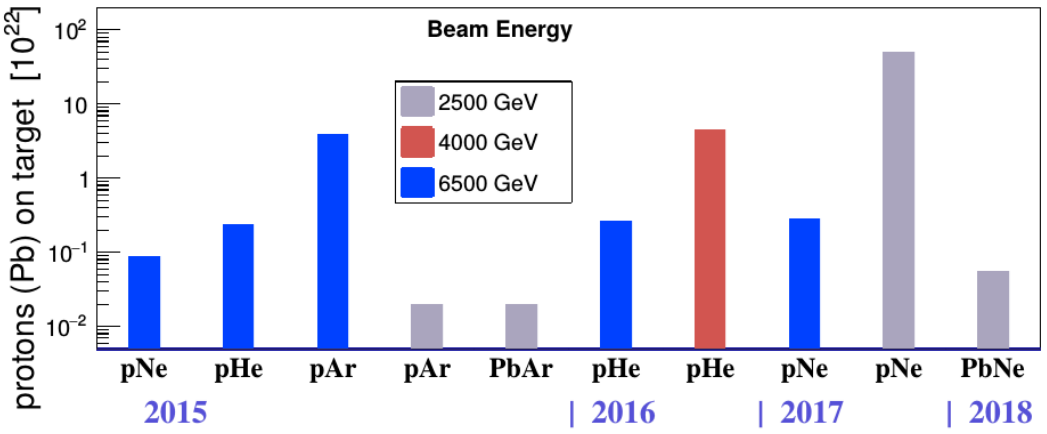

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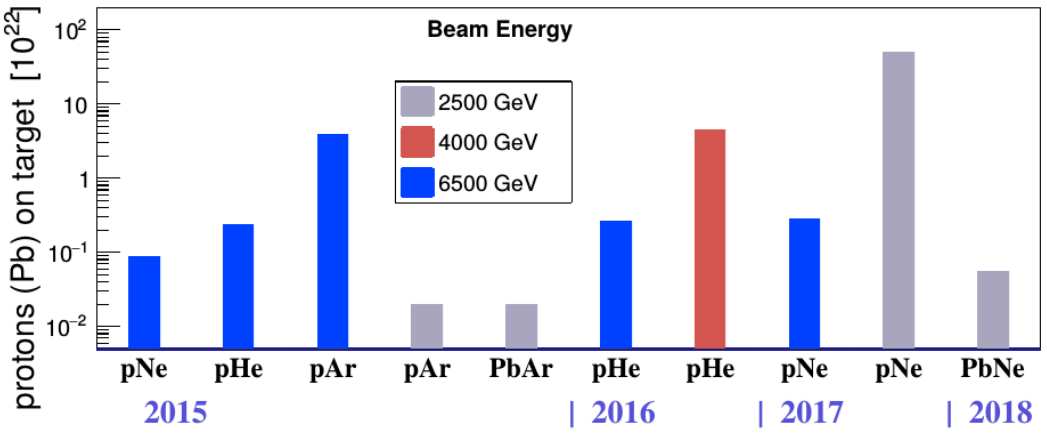

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- Different options discussed for future LHCb upgrades: No decision taken yet

Solutions within LHCb & reviewed by the PBC working group

SMOG 2: installation of an openable storage cell during LS2 [approved by LHCb]

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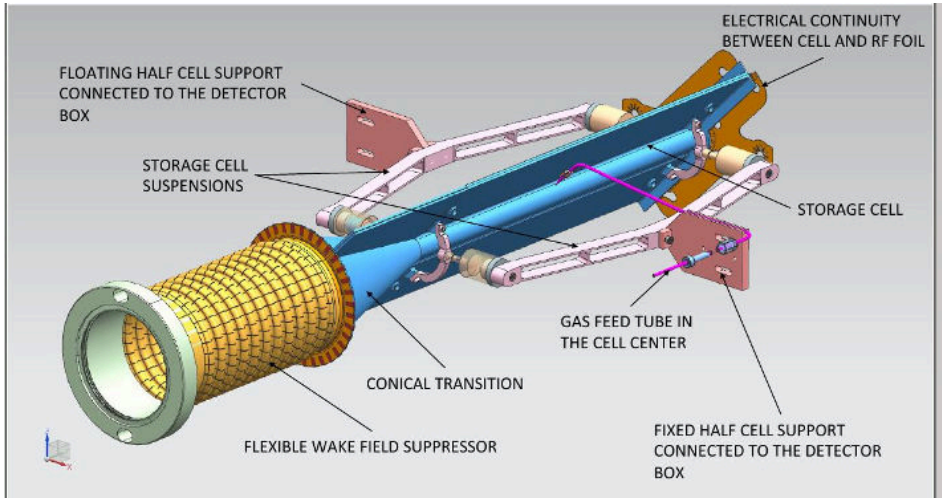

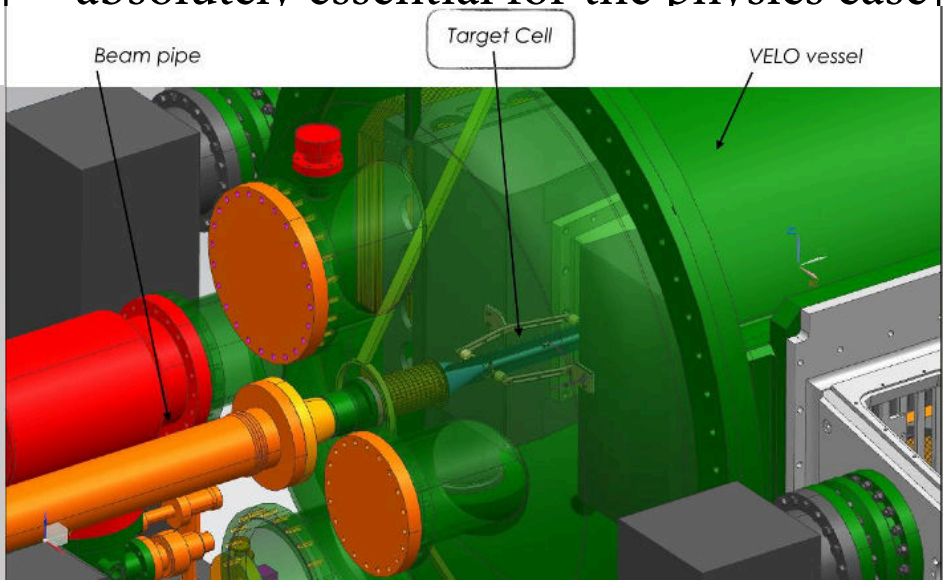

LHCb-PUB-2018-015 & CERN-PBC-Notes-2018-007

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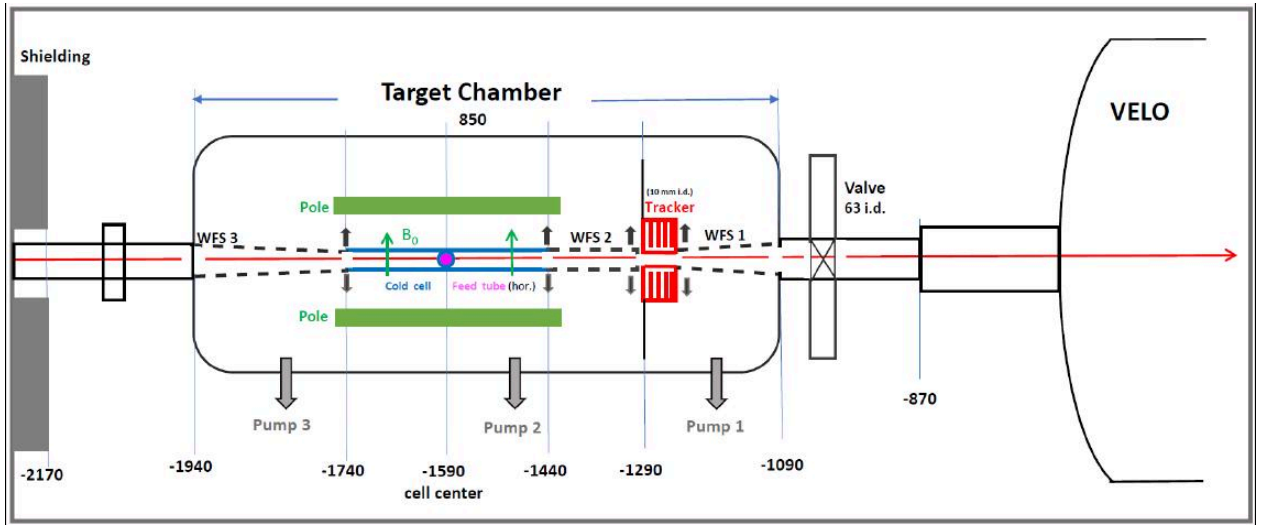

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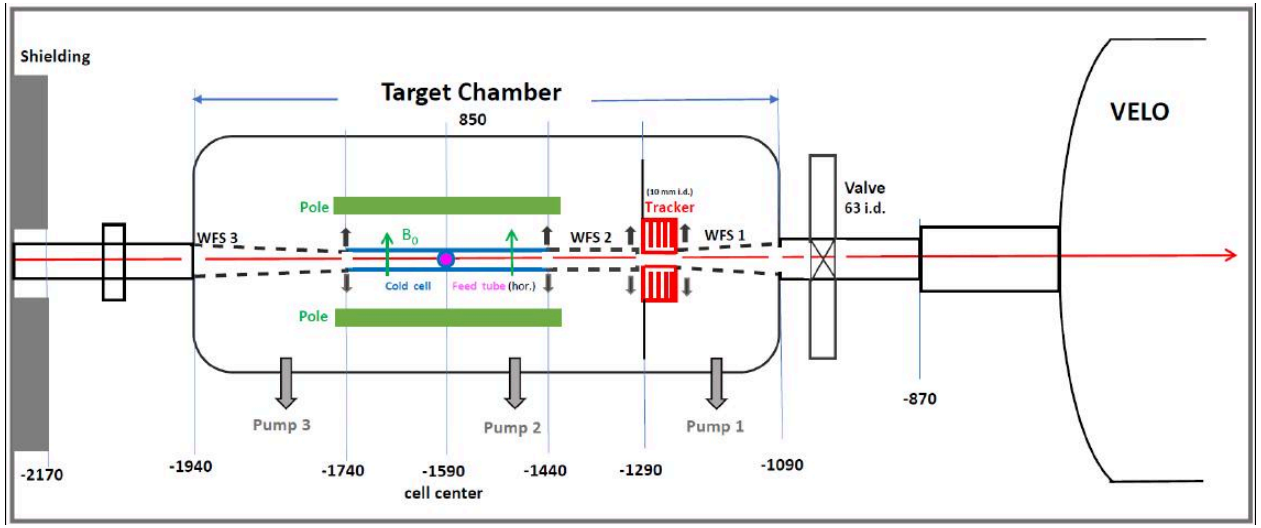

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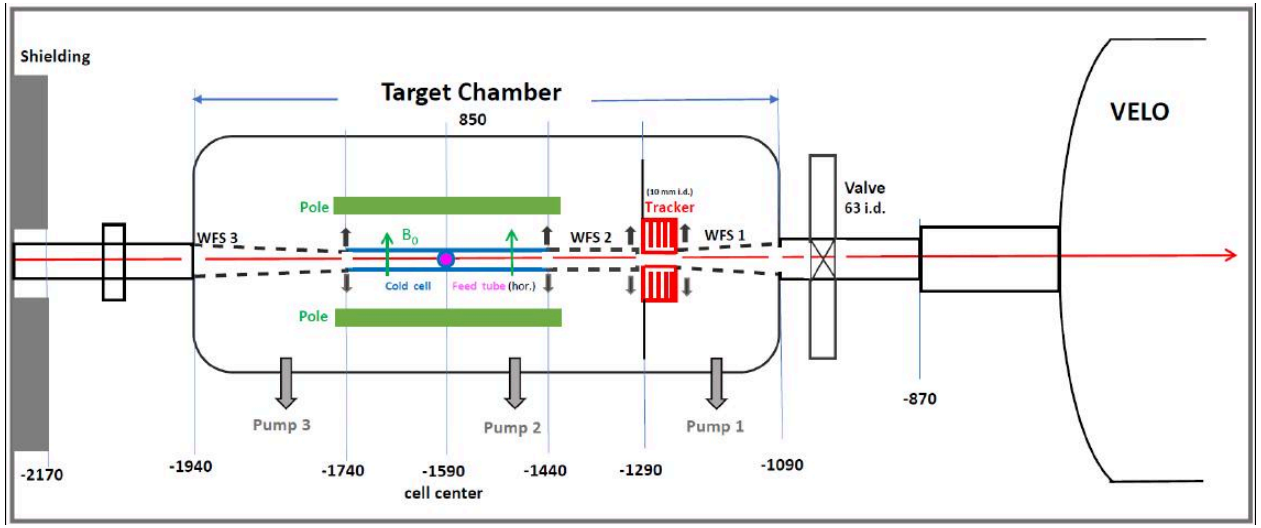

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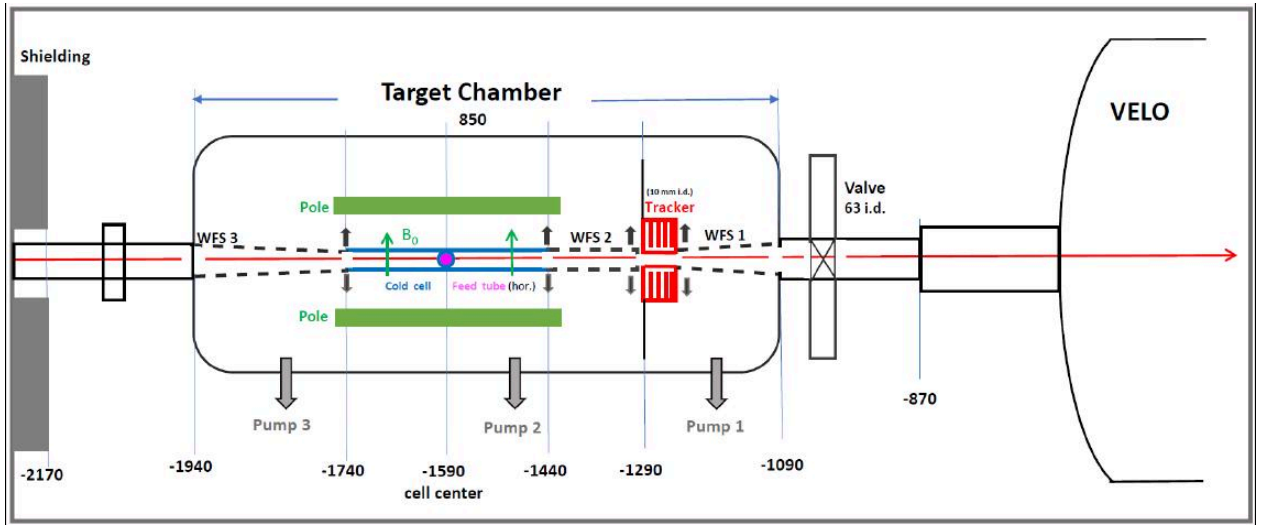

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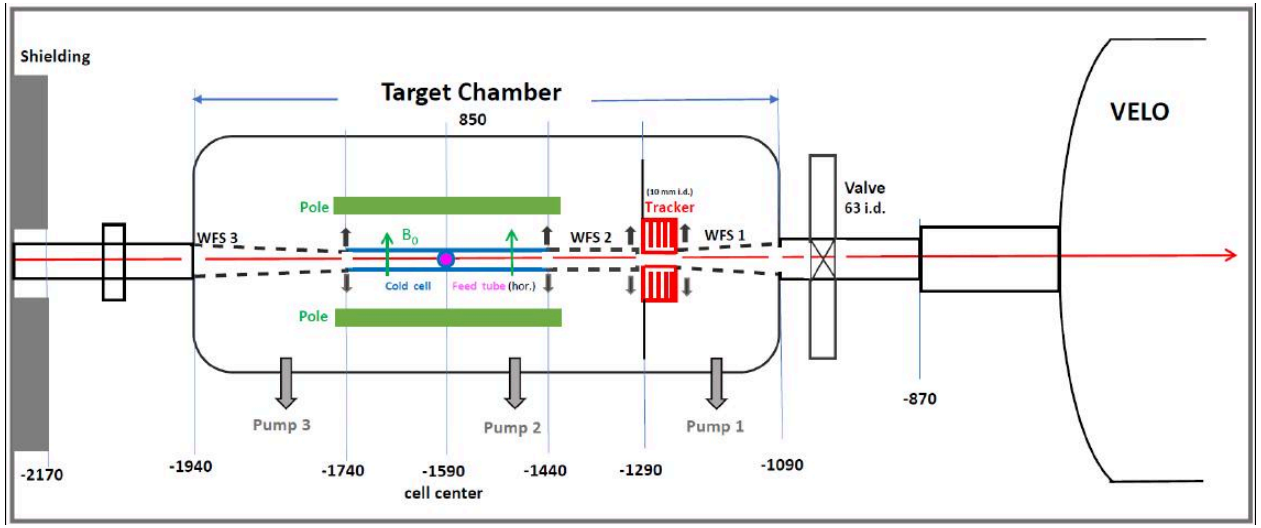

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Alternative: w/o storage cell like the RHIC H-jet polarimeter and/or modification of the VELO vessel

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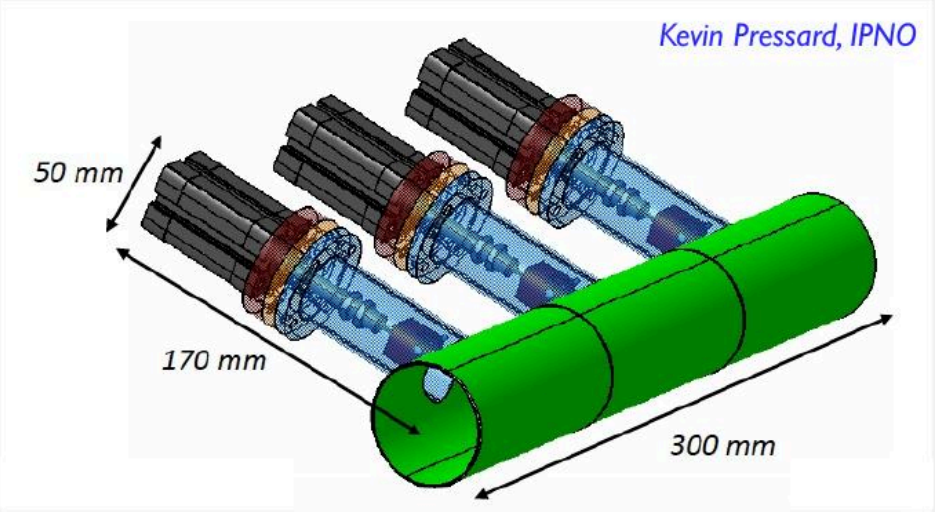

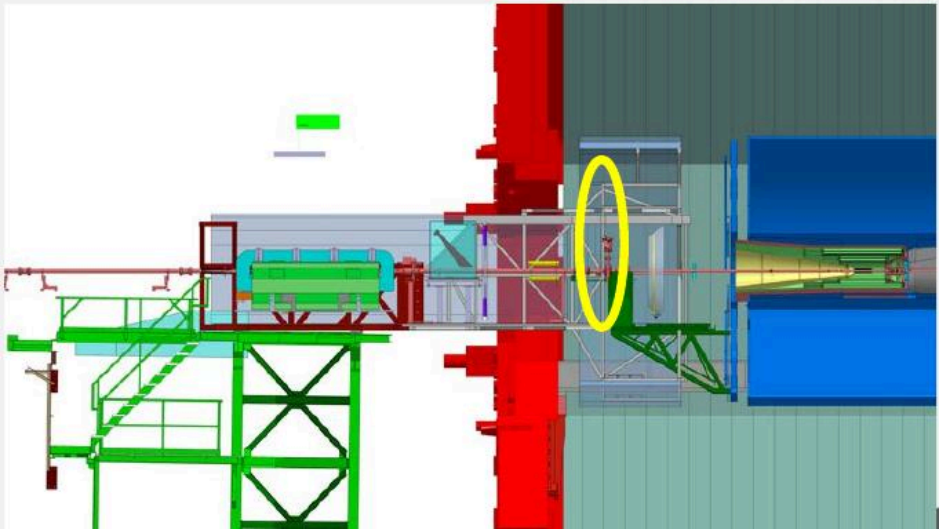

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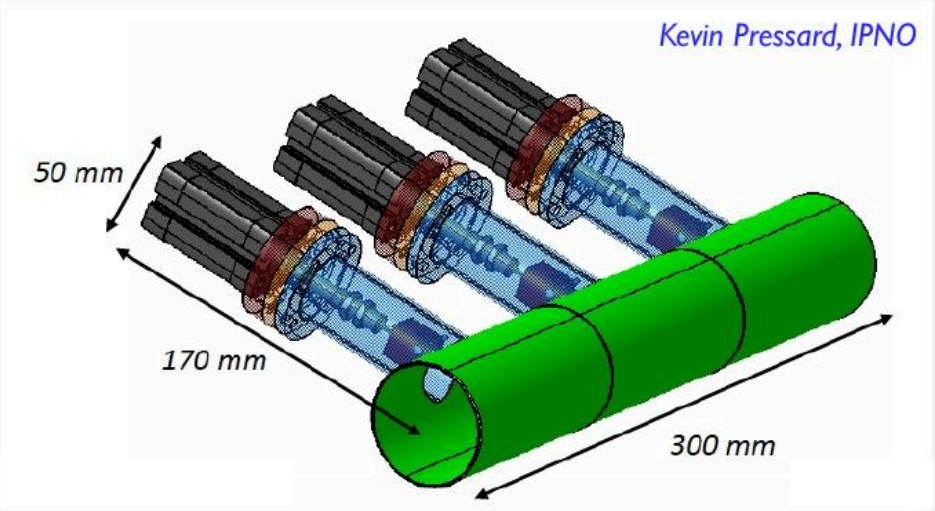

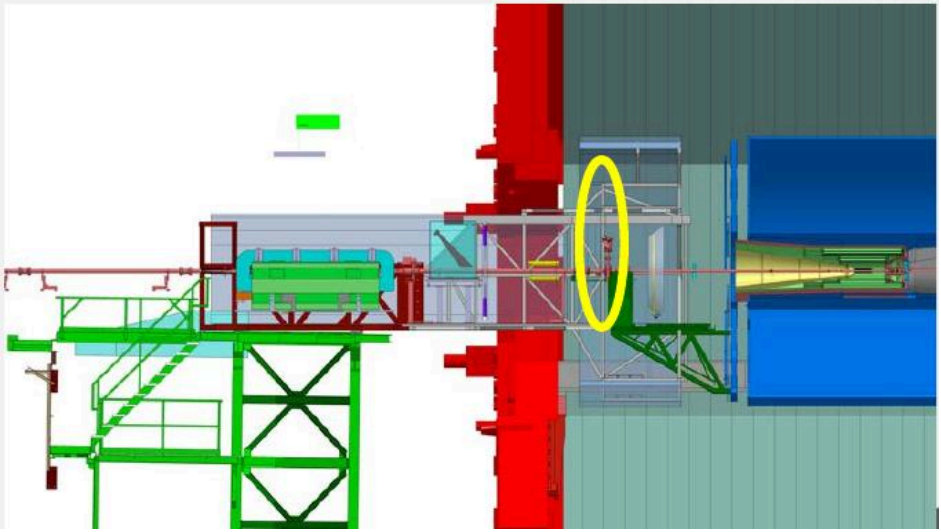

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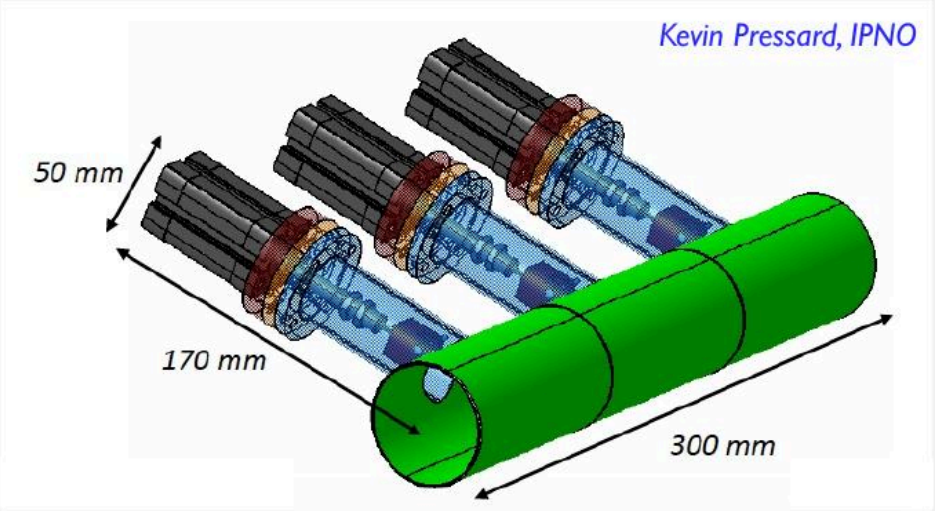

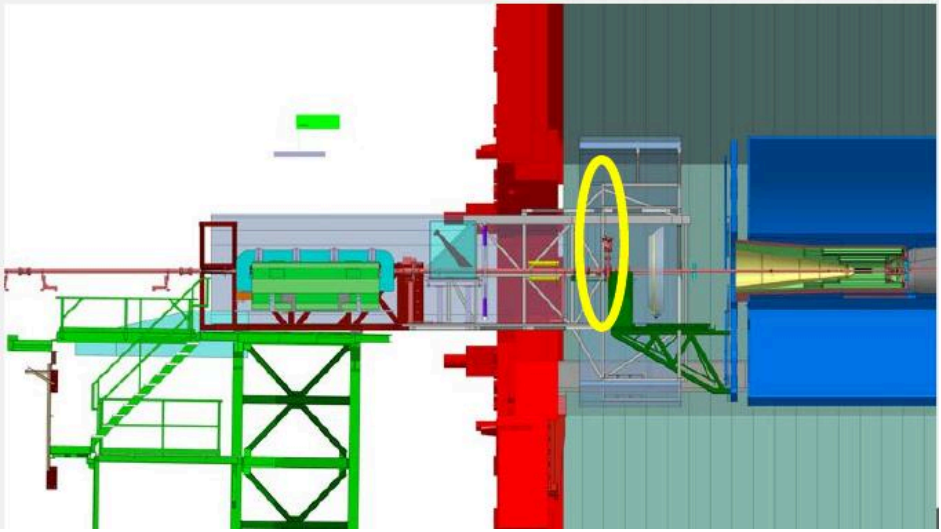

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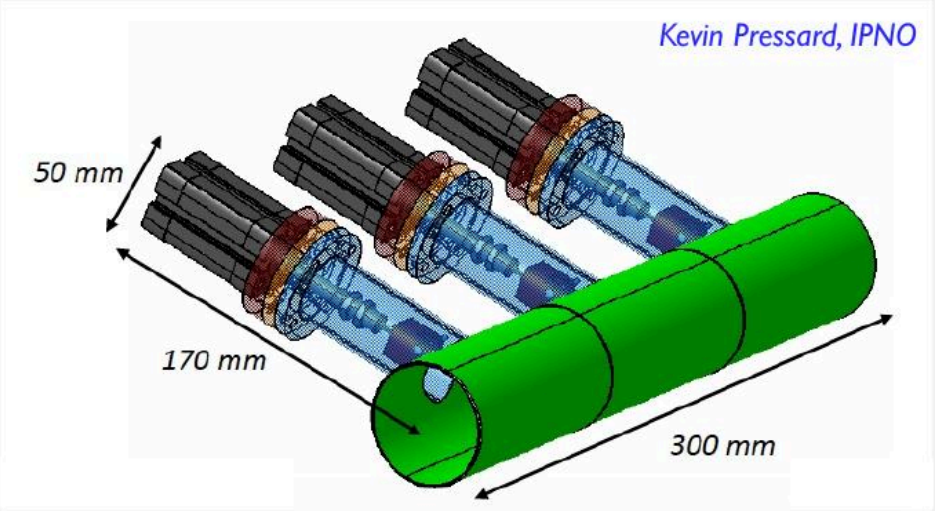

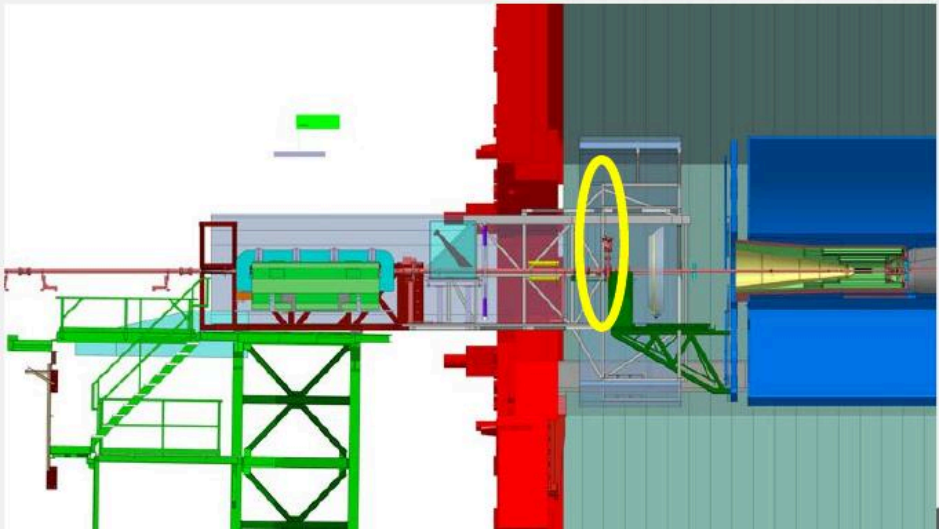

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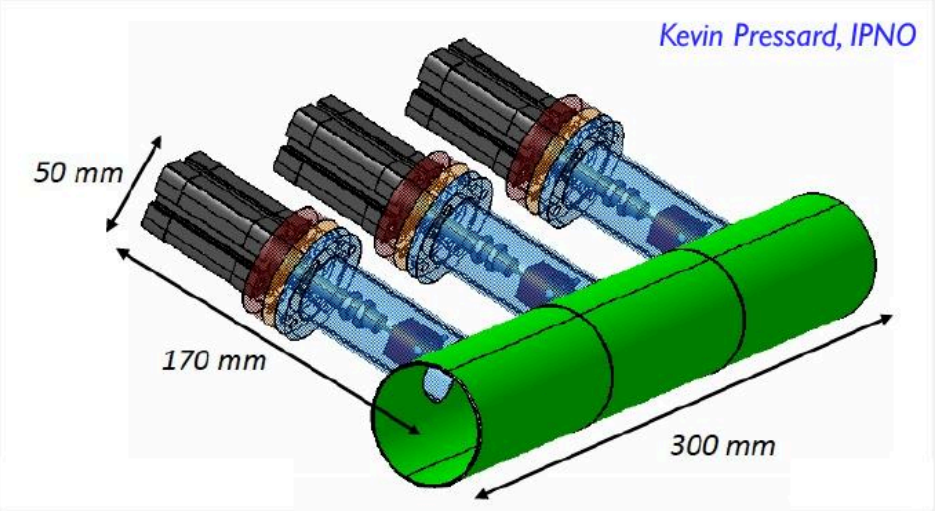

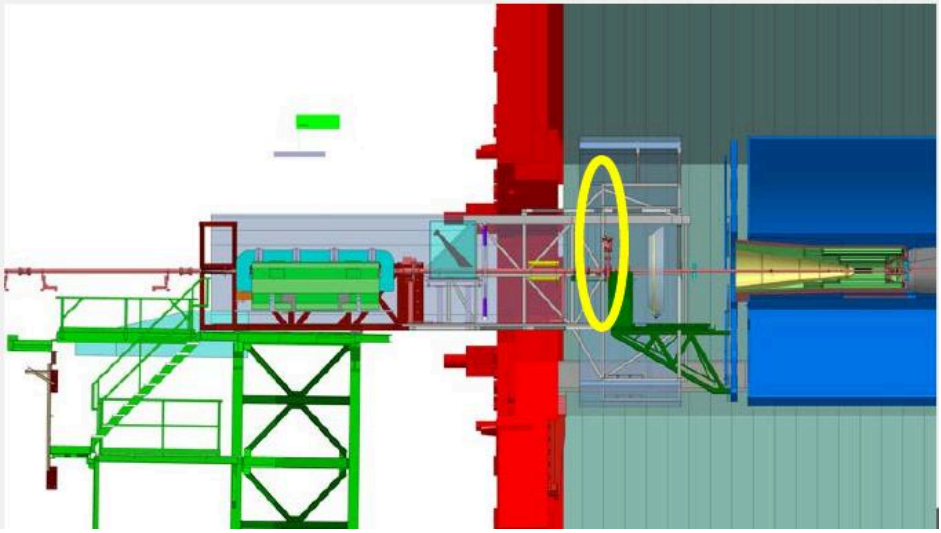

Luminosity comparison [w detector constraints]

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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 *p*A coll.
With internal gas target: $\mathcal{L}_{pH_2/H^\uparrow}$: 250 pb^{-1}; $\mathcal{L}_{PbXe}$: 8 nb^{-1}
With beam splitting and solid target: $\mathcal{L}_{pW}$: 0.6 ÷ 6 pb^{-1} ; $\mathcal{L}_{PbW}$: 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 Physics Studies

Drell-Yan

C. Hadjidakis *et al.*, **1807.00603**

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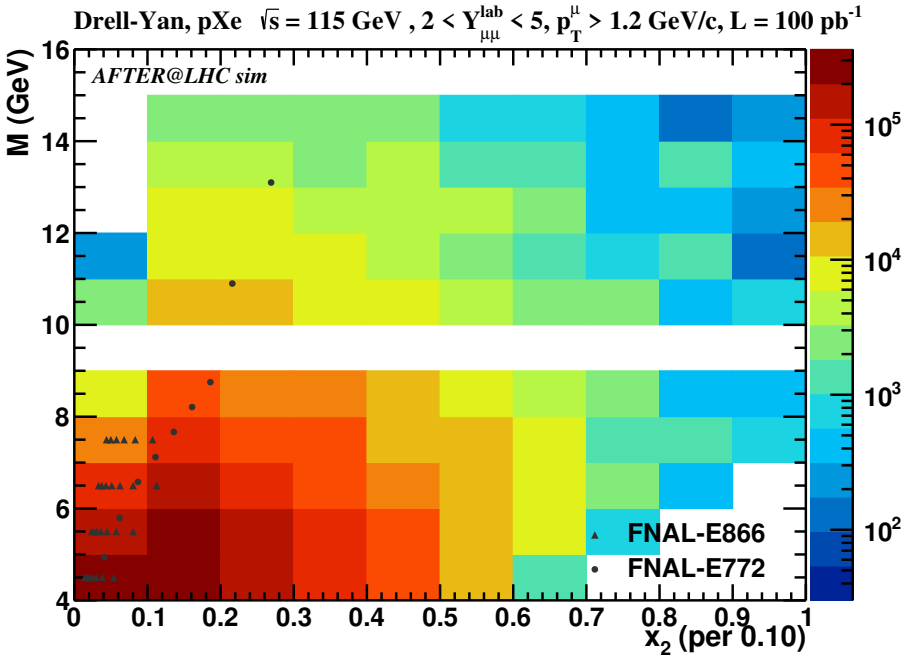
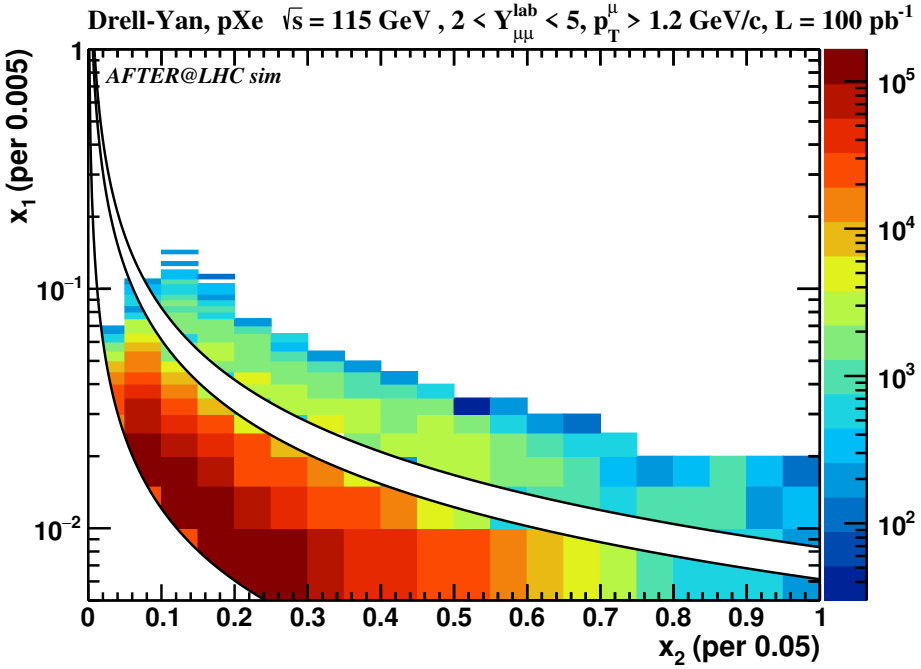
- Unique acceptance (with a LHCb-like detector) compared to existing DY *pA* data used for nuclear PDF fit (E866 & E772 @ Fermilab).





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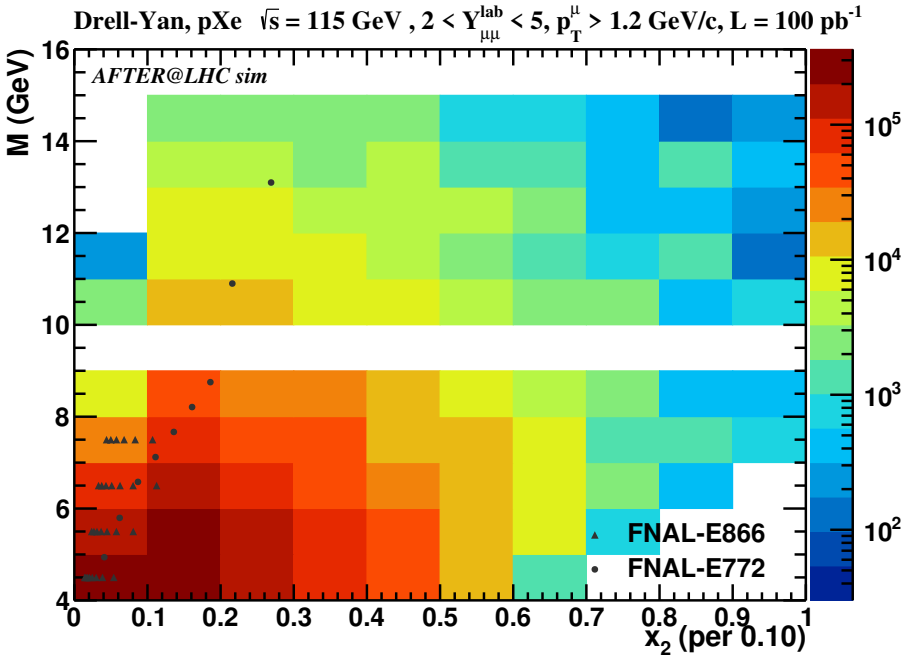

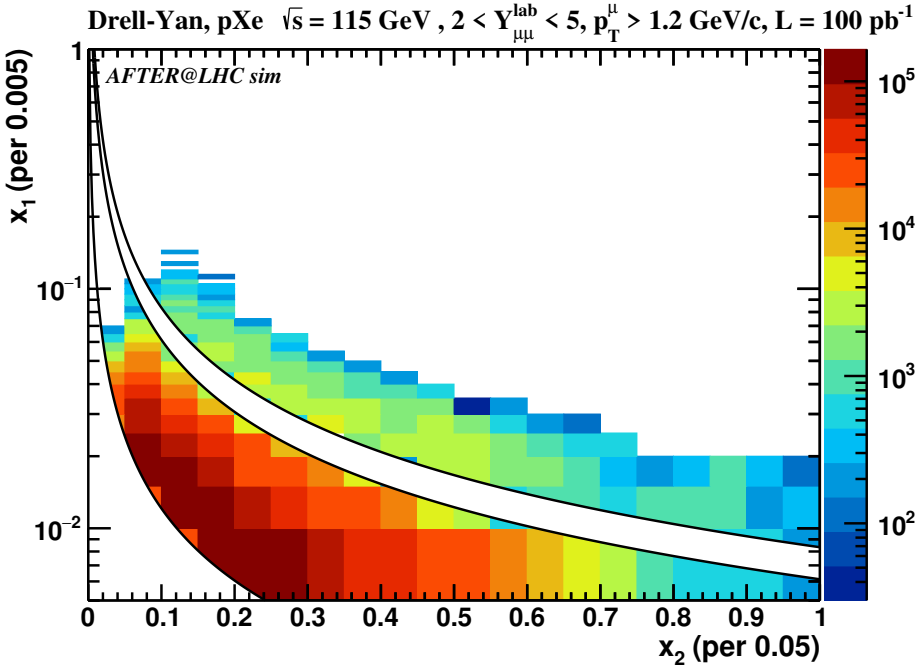

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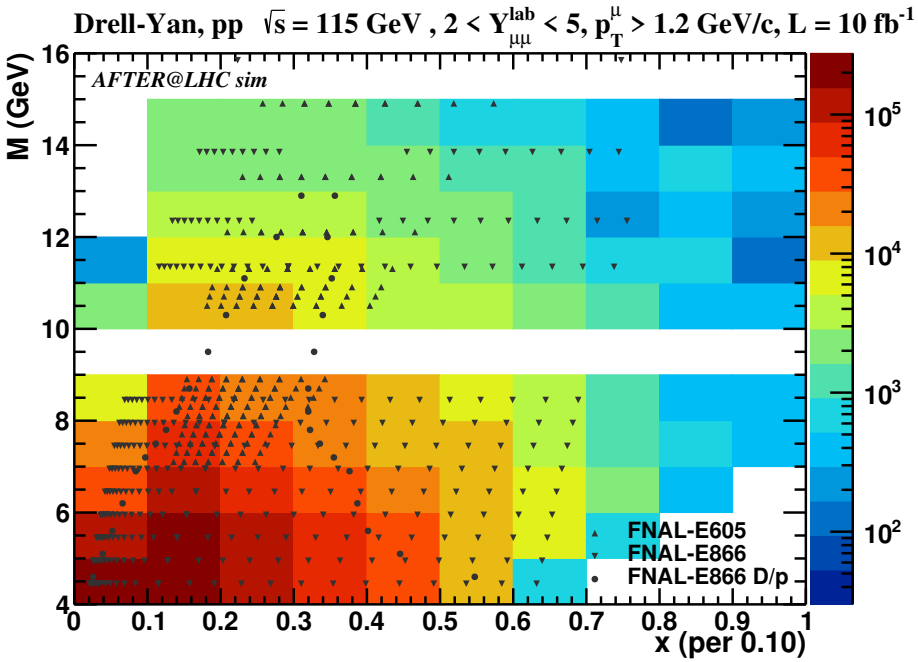

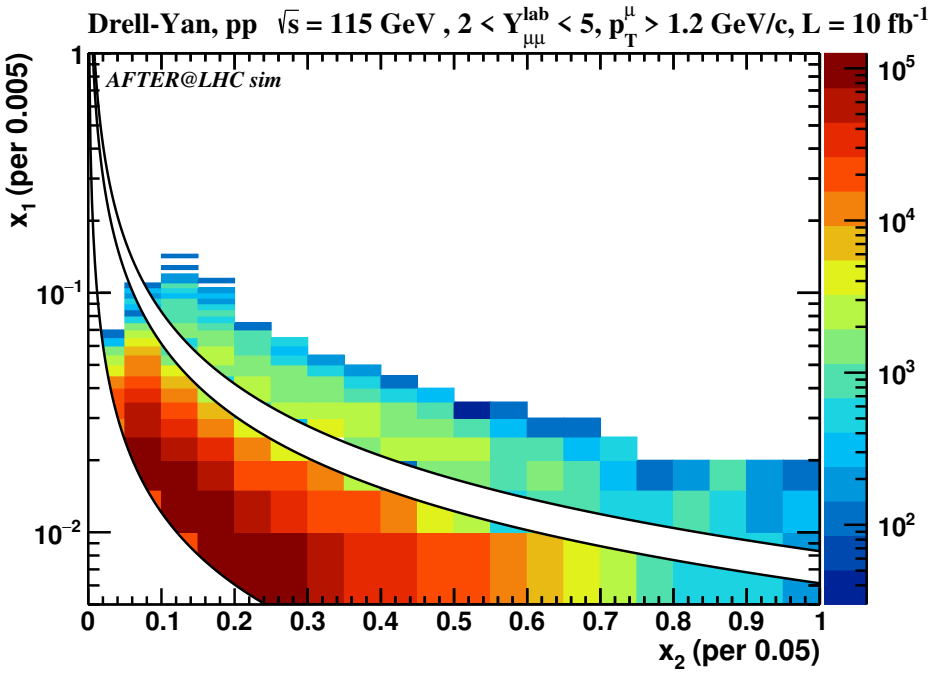

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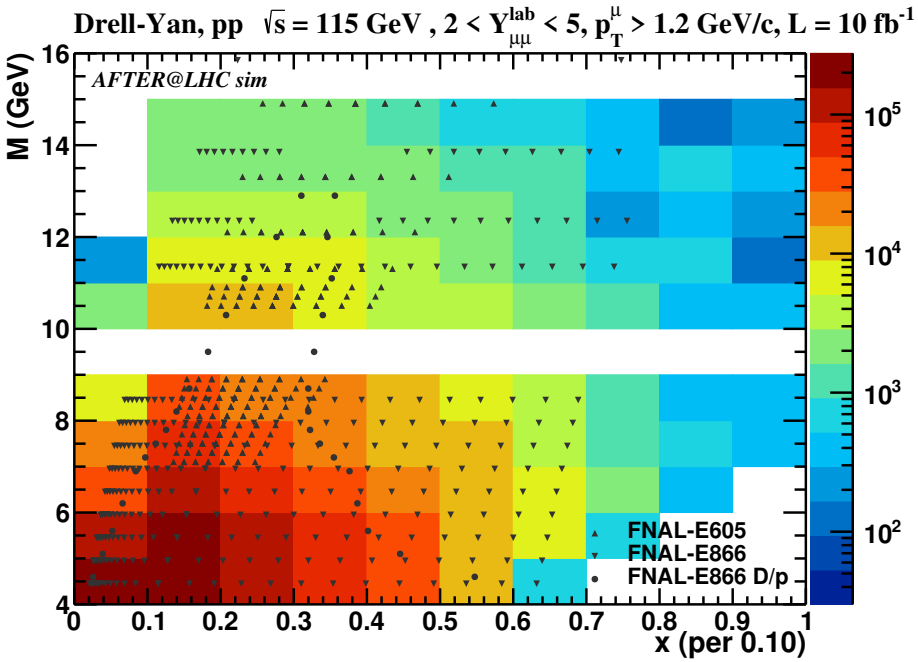

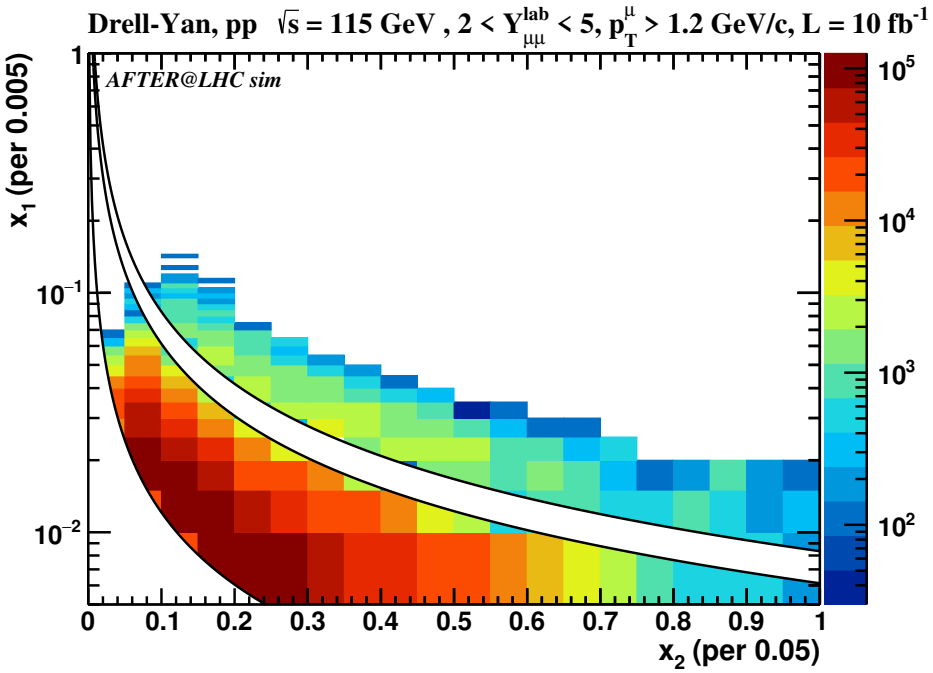

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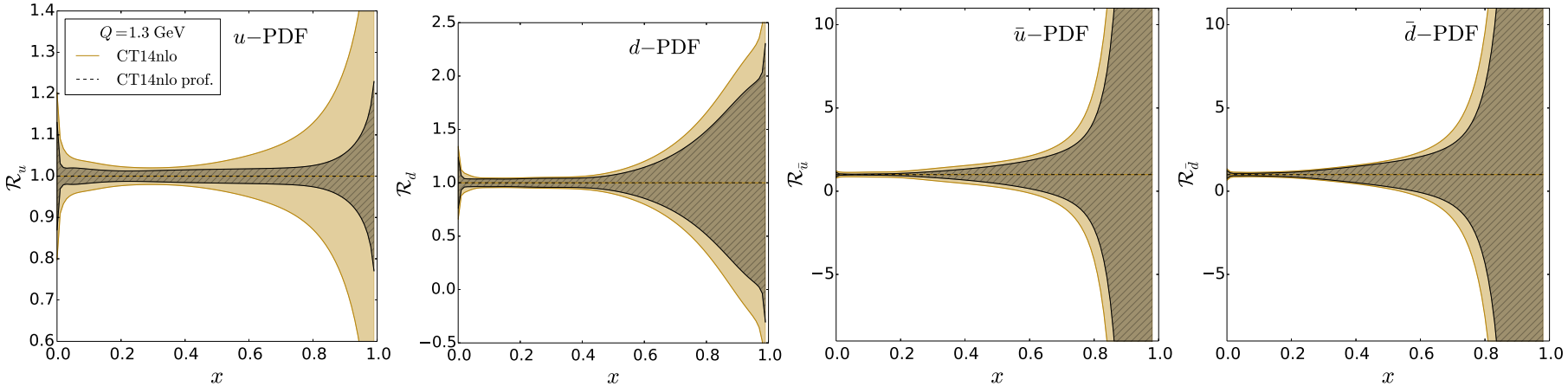

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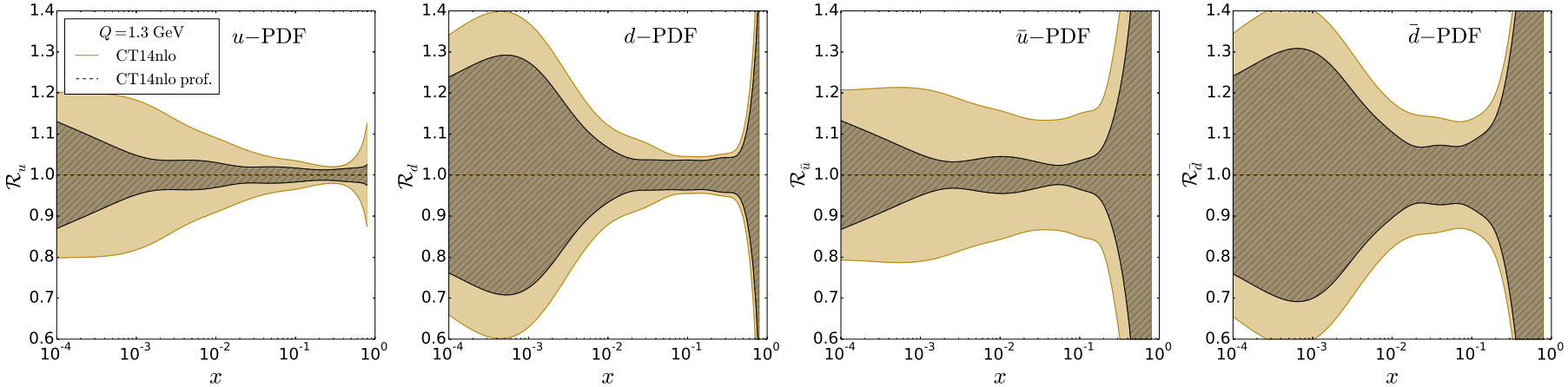

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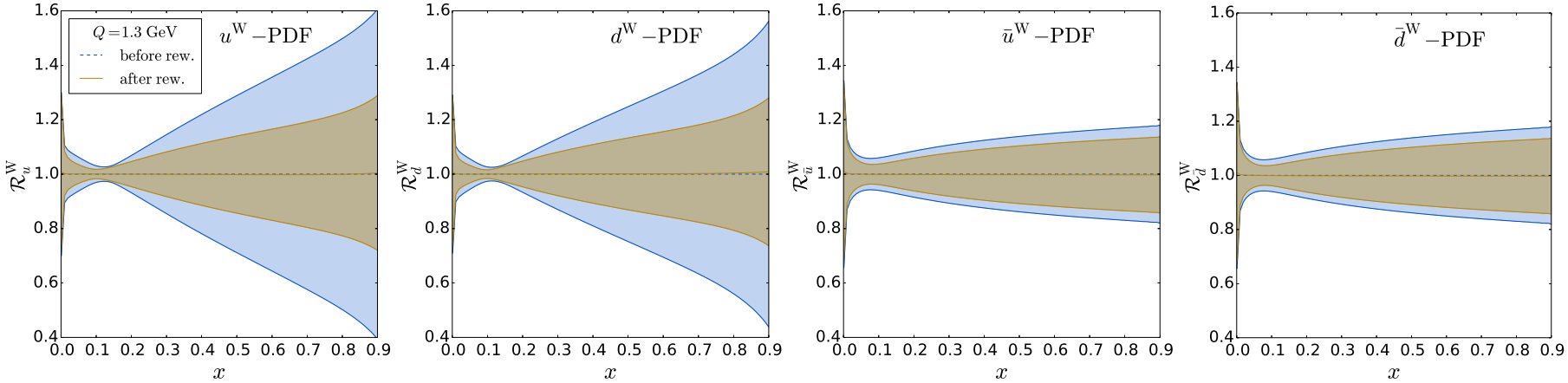

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- On-going theory study for $W^{\pm}$ production accounting for threshold resummation

Drell-Yan Intermediate-Mass-Region acceptance

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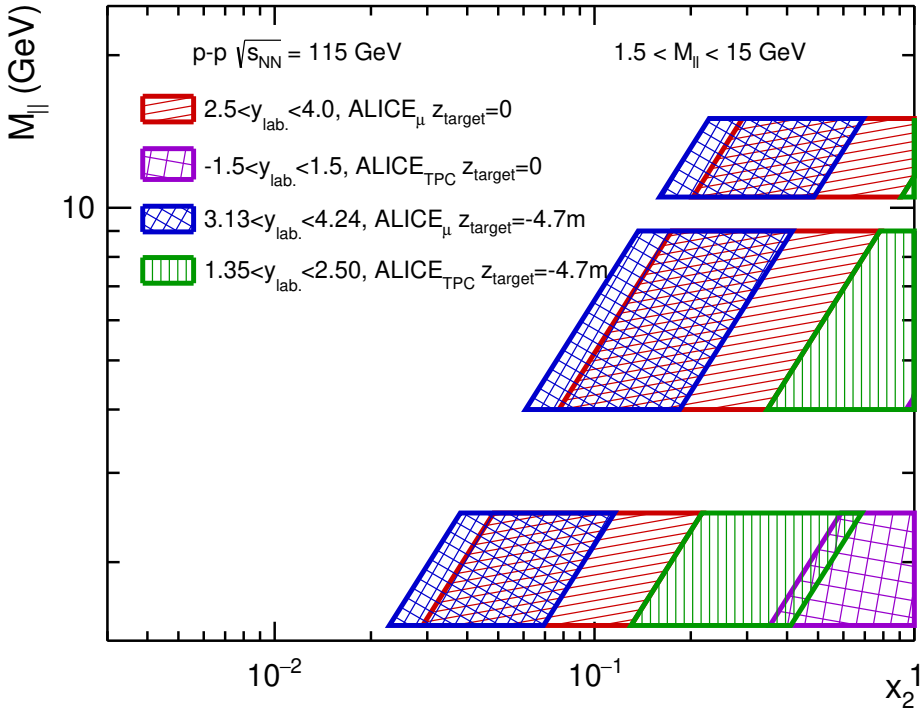

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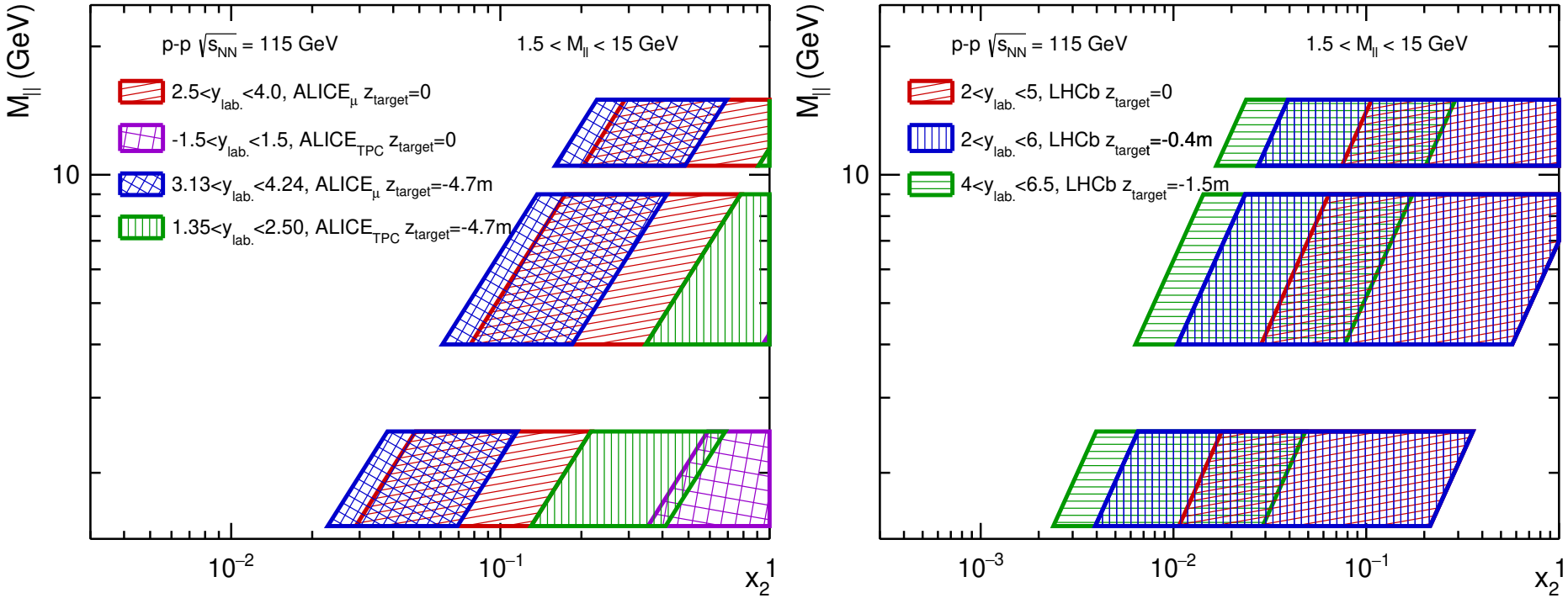
- For LHCb with $z = -1.5$m (right plot, green), the acceptance is significantly shifted to lower x ($0.003 < x_2 < 0.04$ for $M_{\ell\ell} = 2$ GeV)



Drell-Yan STSAs & the target location

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

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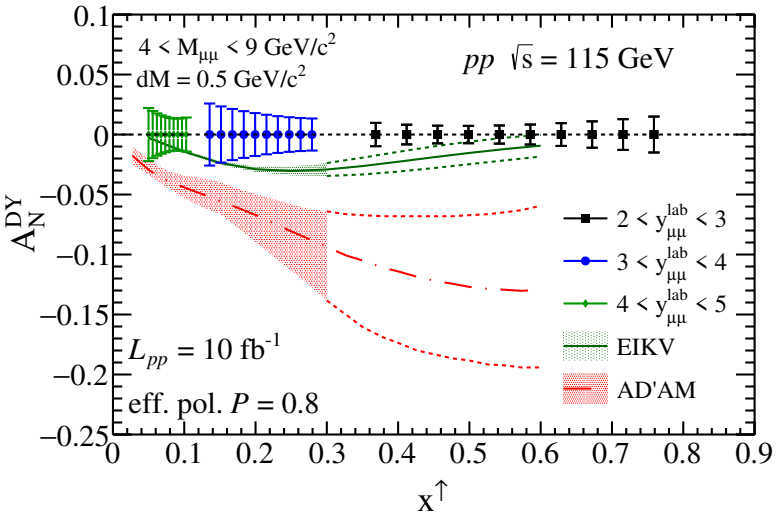

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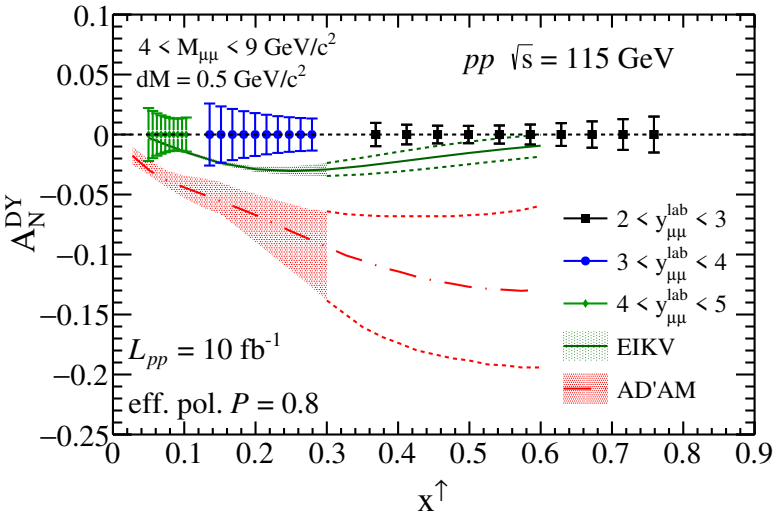

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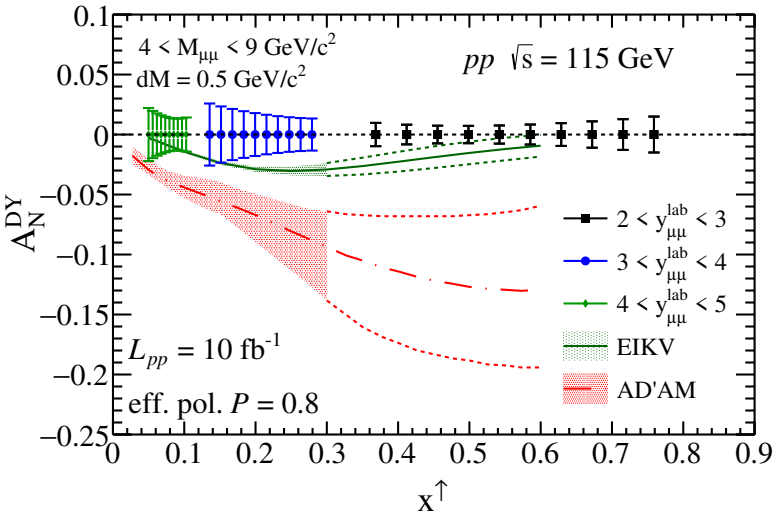

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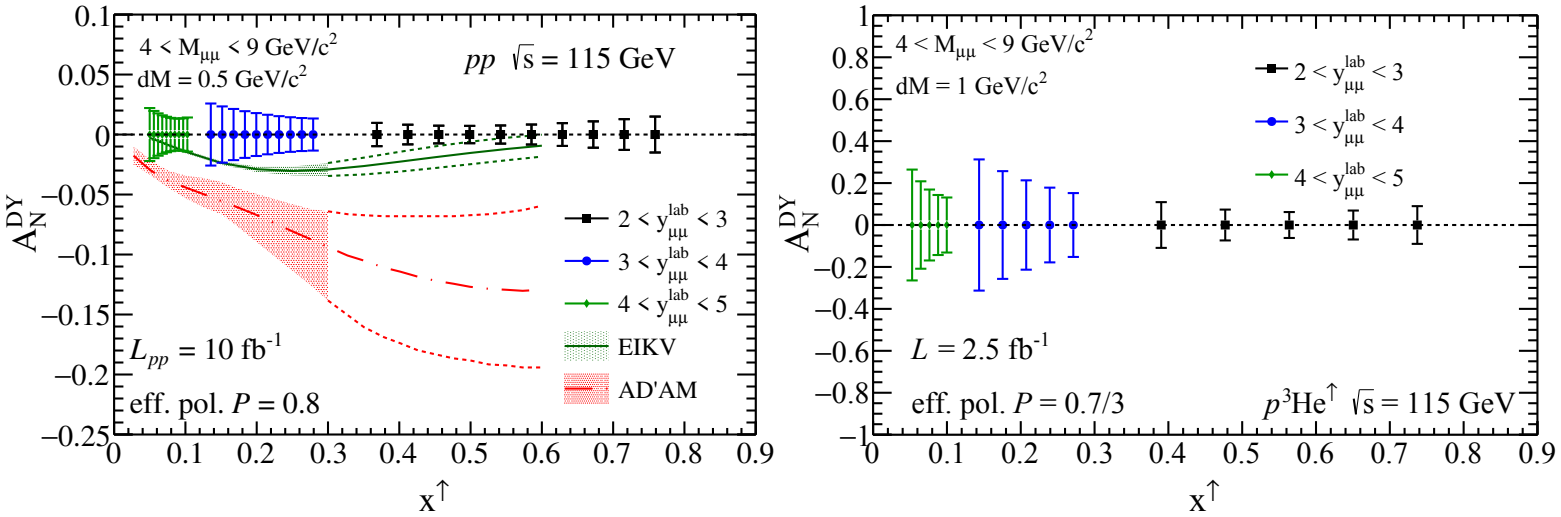

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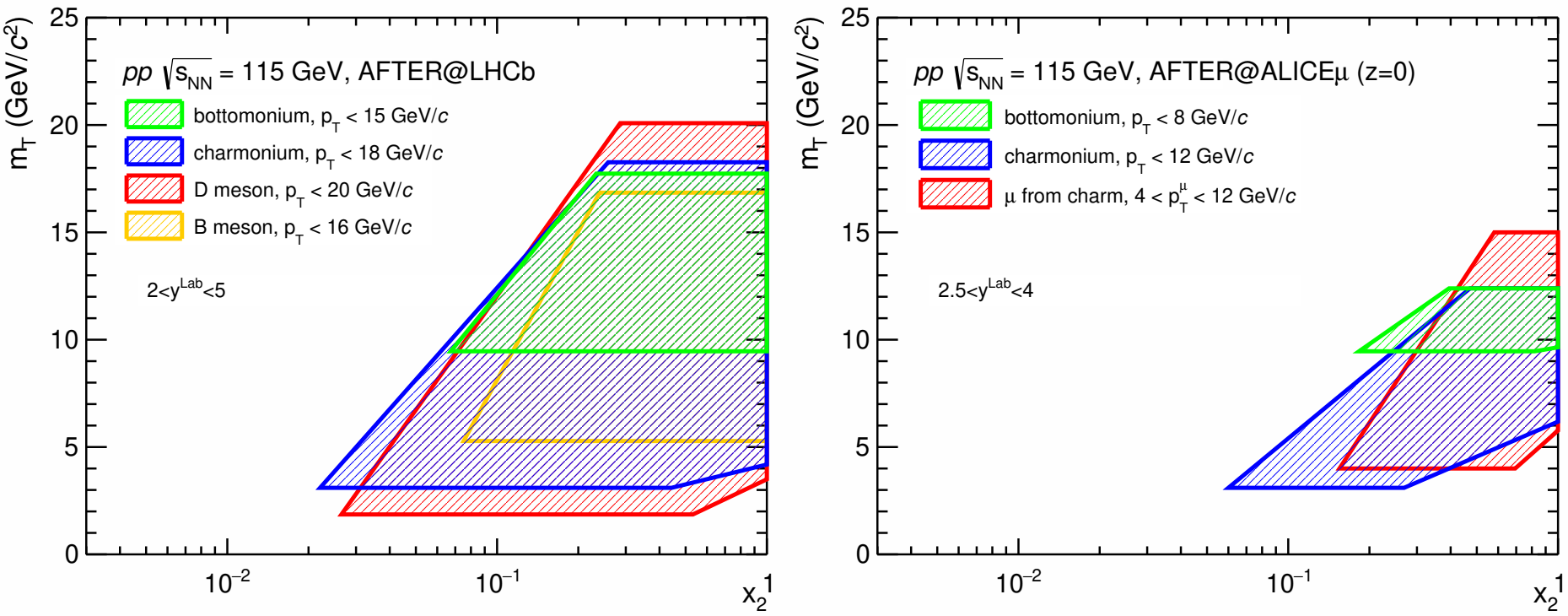
- Might be worth considering the gas-jet option allowing for a less remote target (here for He)

Kinematical coverage for heavy flavours



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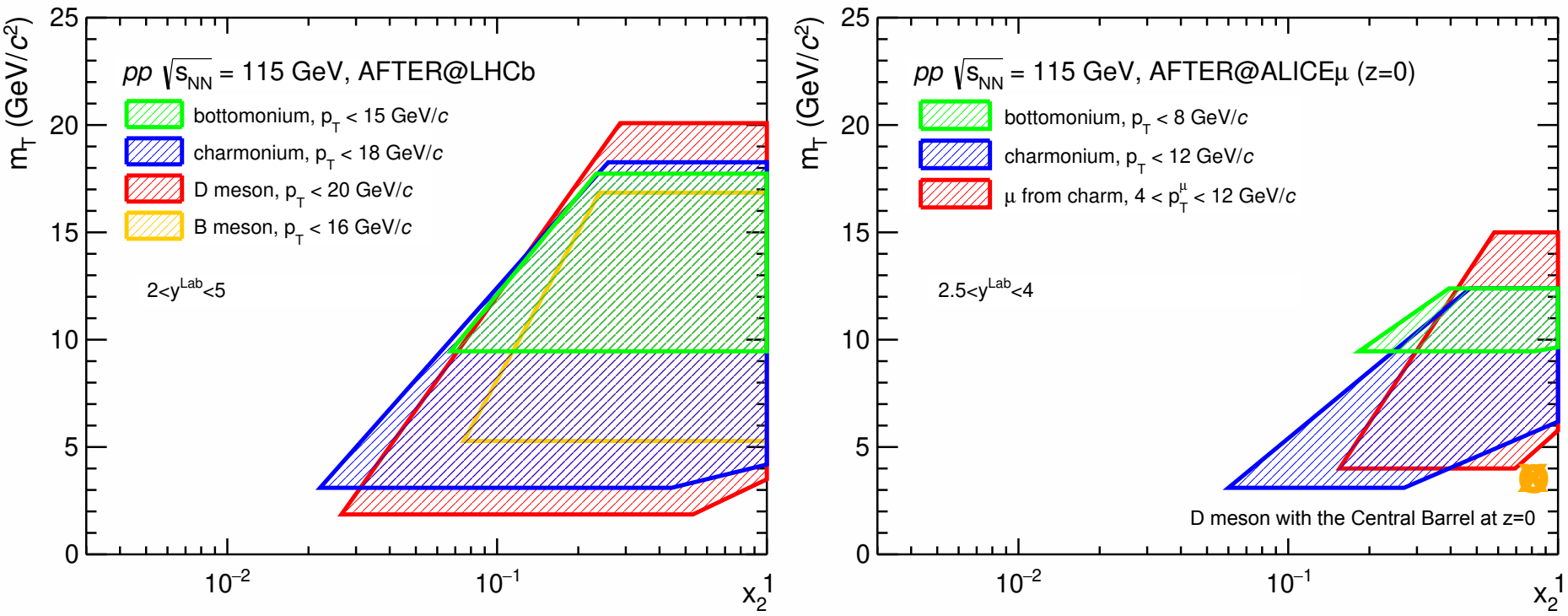

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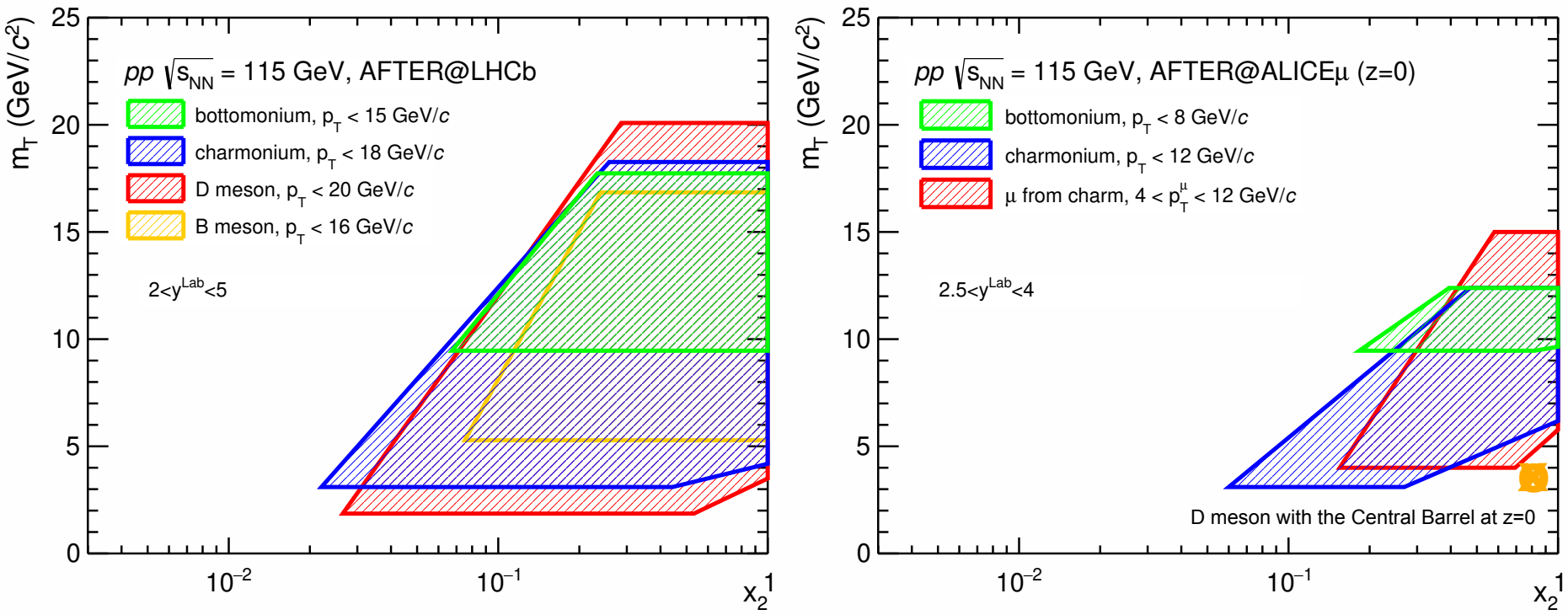

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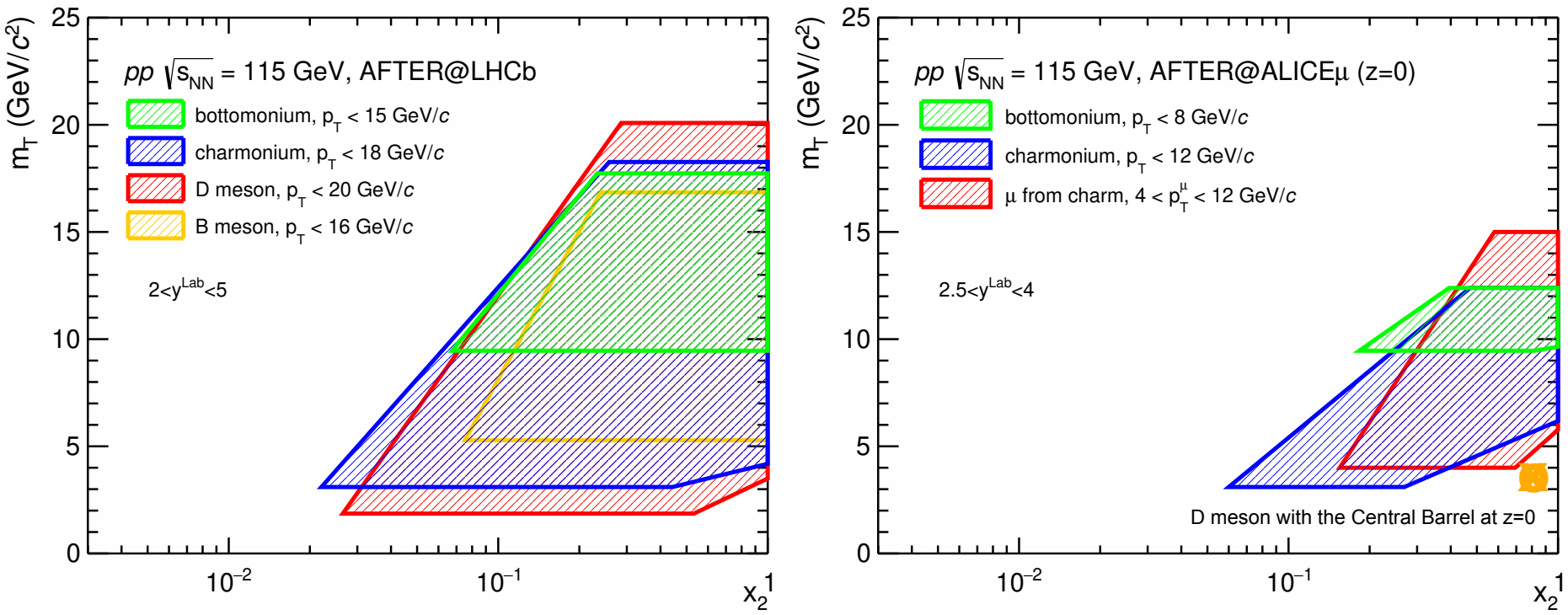

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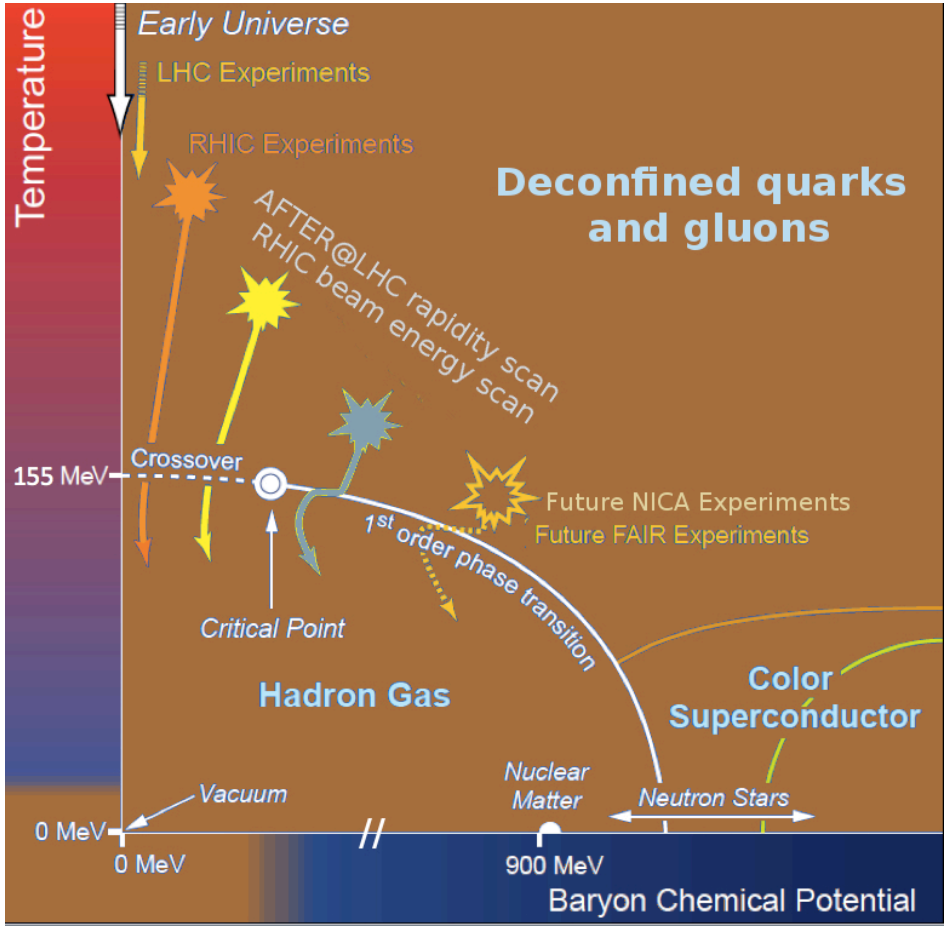
- Both for LHCb and ALICE, the coverage also depends on the target position

Heavy ions: rapidity scan & heavy-flavour precision studies



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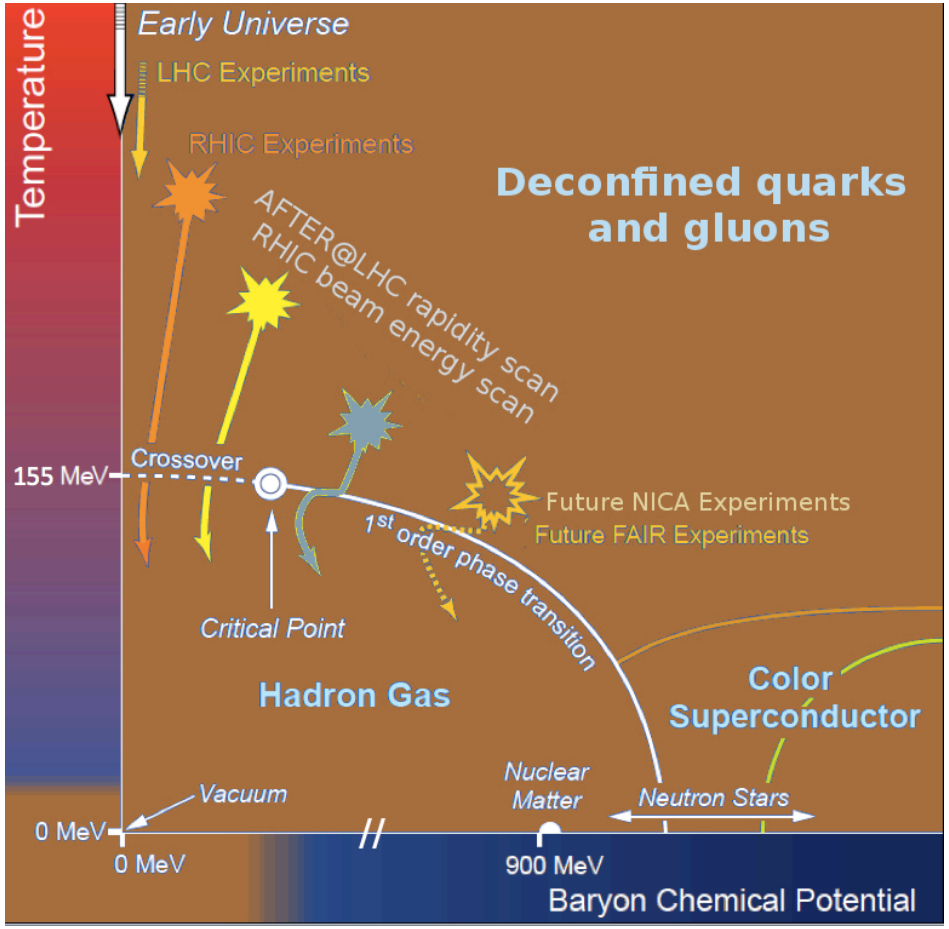

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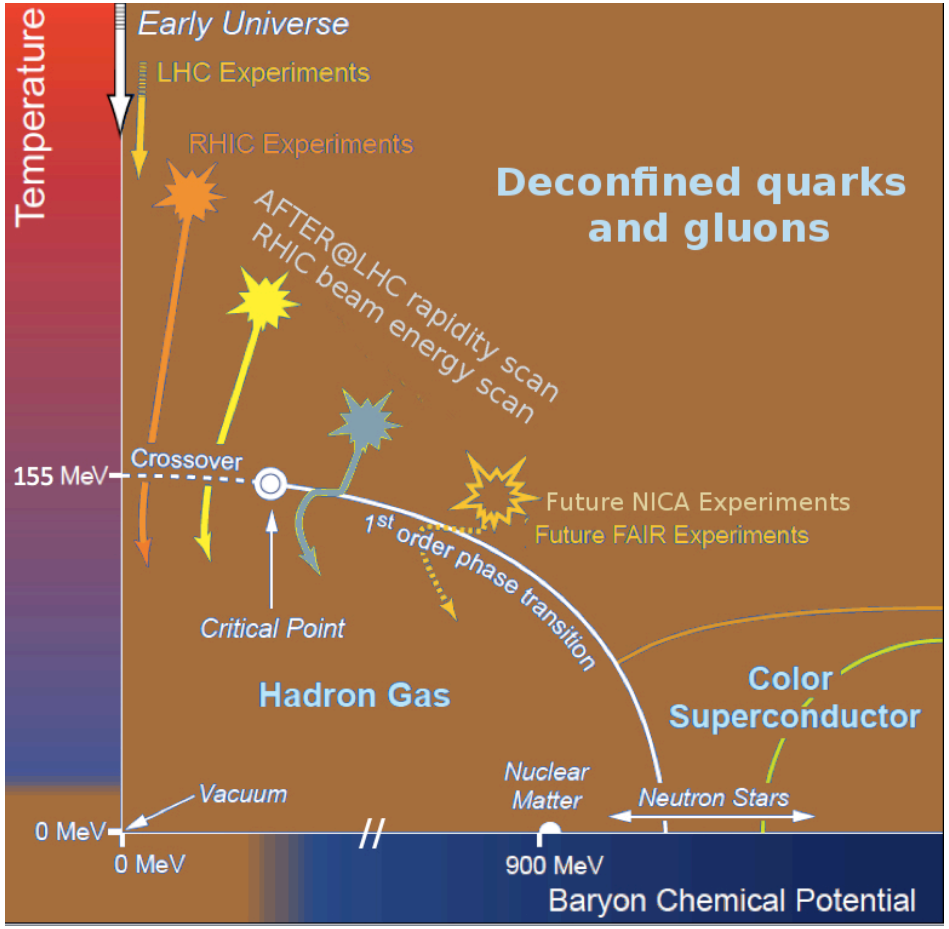

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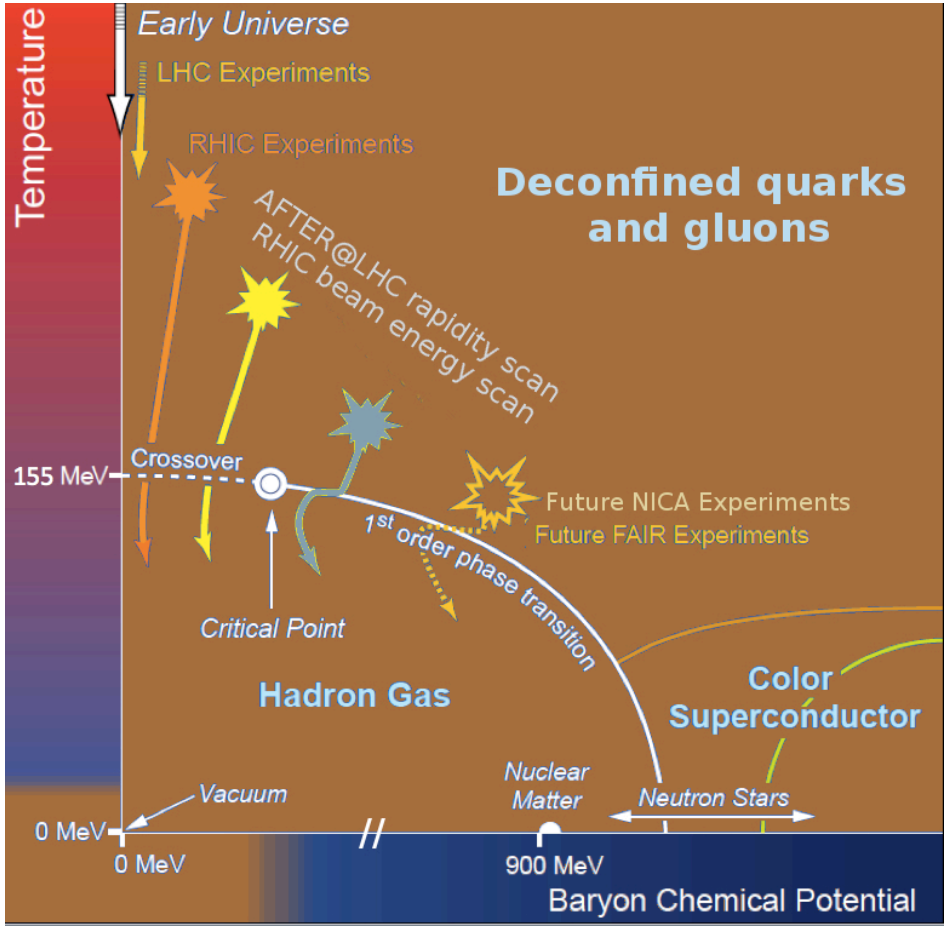

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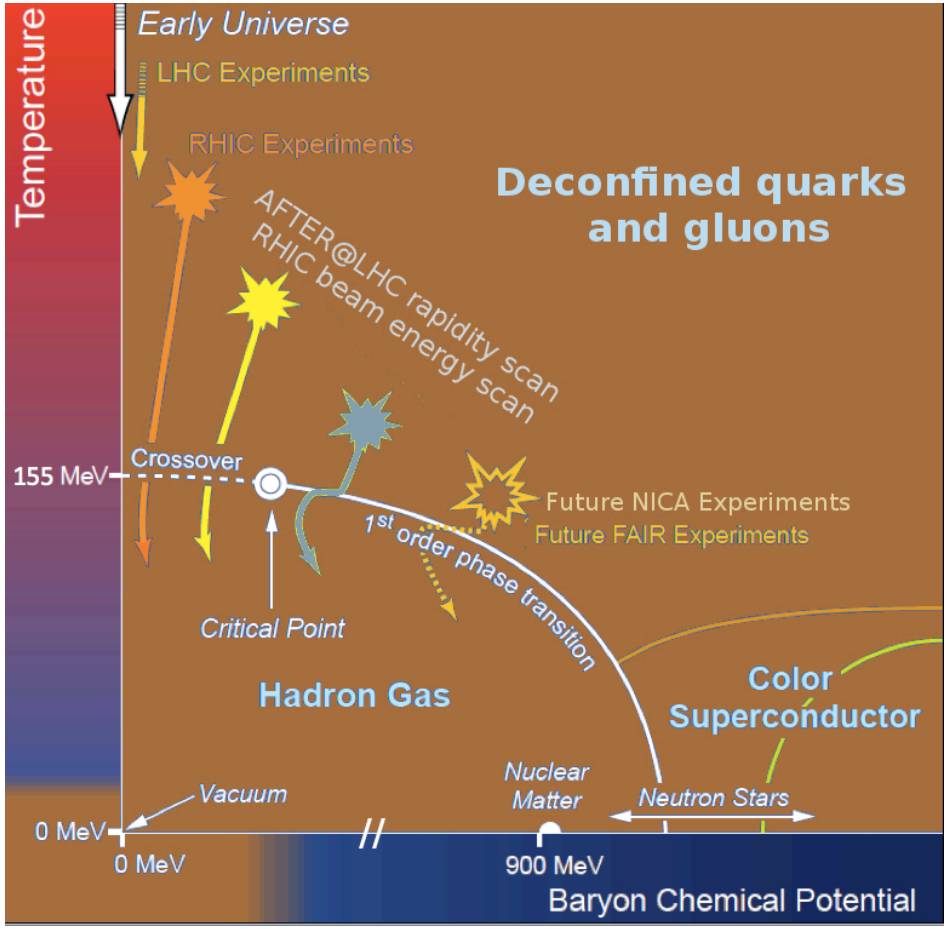
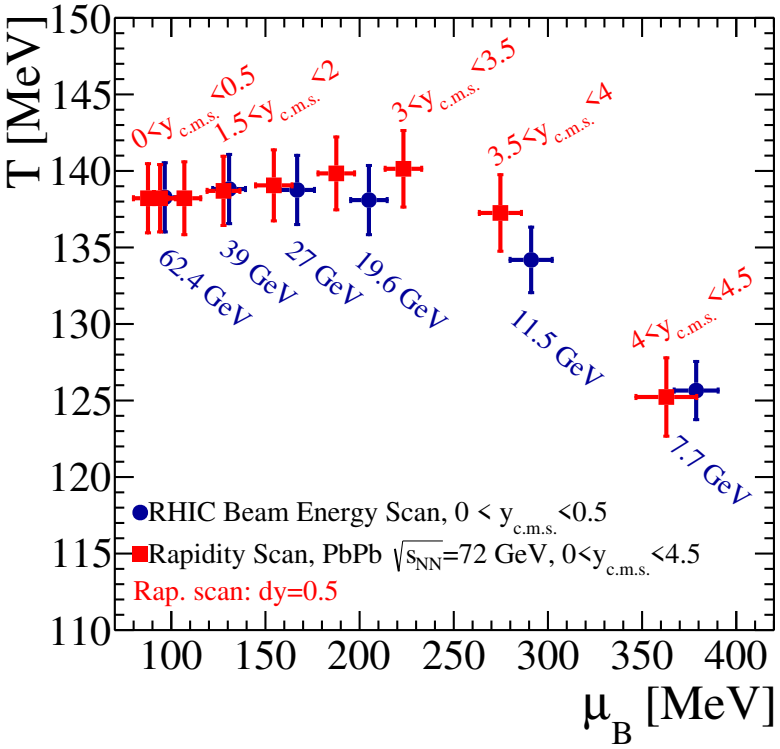
- FoMs for $\chi_{c,b}$ and η_c to be done in cooperation with the LHCb and ALICE collaborations with advanced simulations



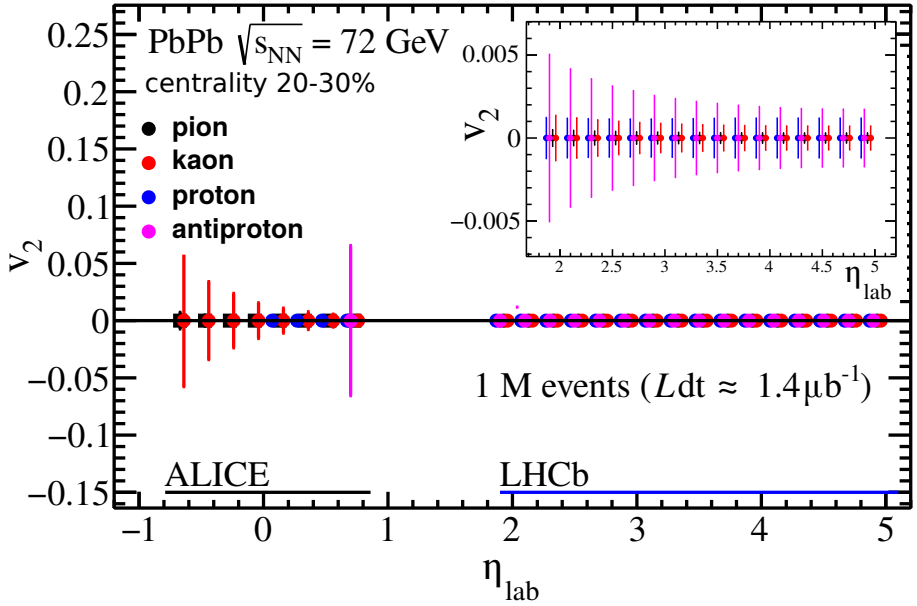
Rapidity scan

Illustration of the ALICE-LHCb complementarity

C. Hadjidakis *et al.*, 1807.00603



V. Begun, D. Kikola, V. Vovchenko, D. Wielanek, PRC 98 (2018)



Quarkonium Projections: heavy-ion collisions

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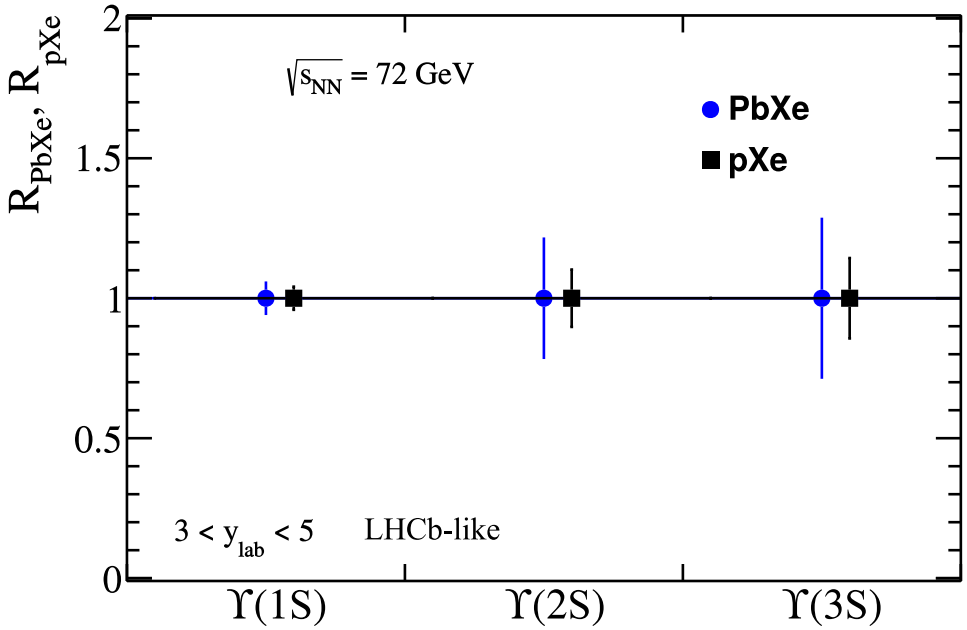

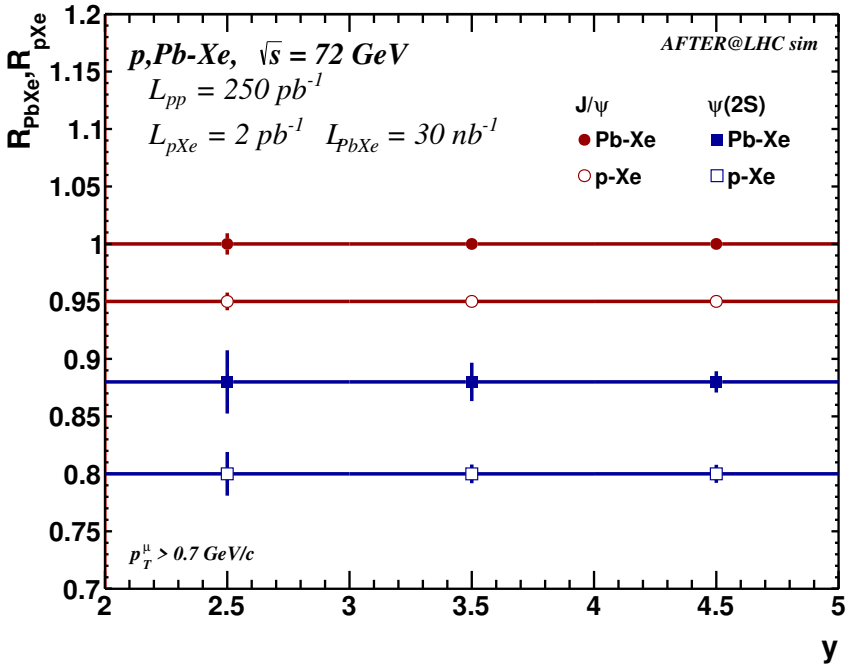

Gluons at the high-x frontier using precision heavy-flavour-production data

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- Extremely promising first projections using Bayesian reweighting
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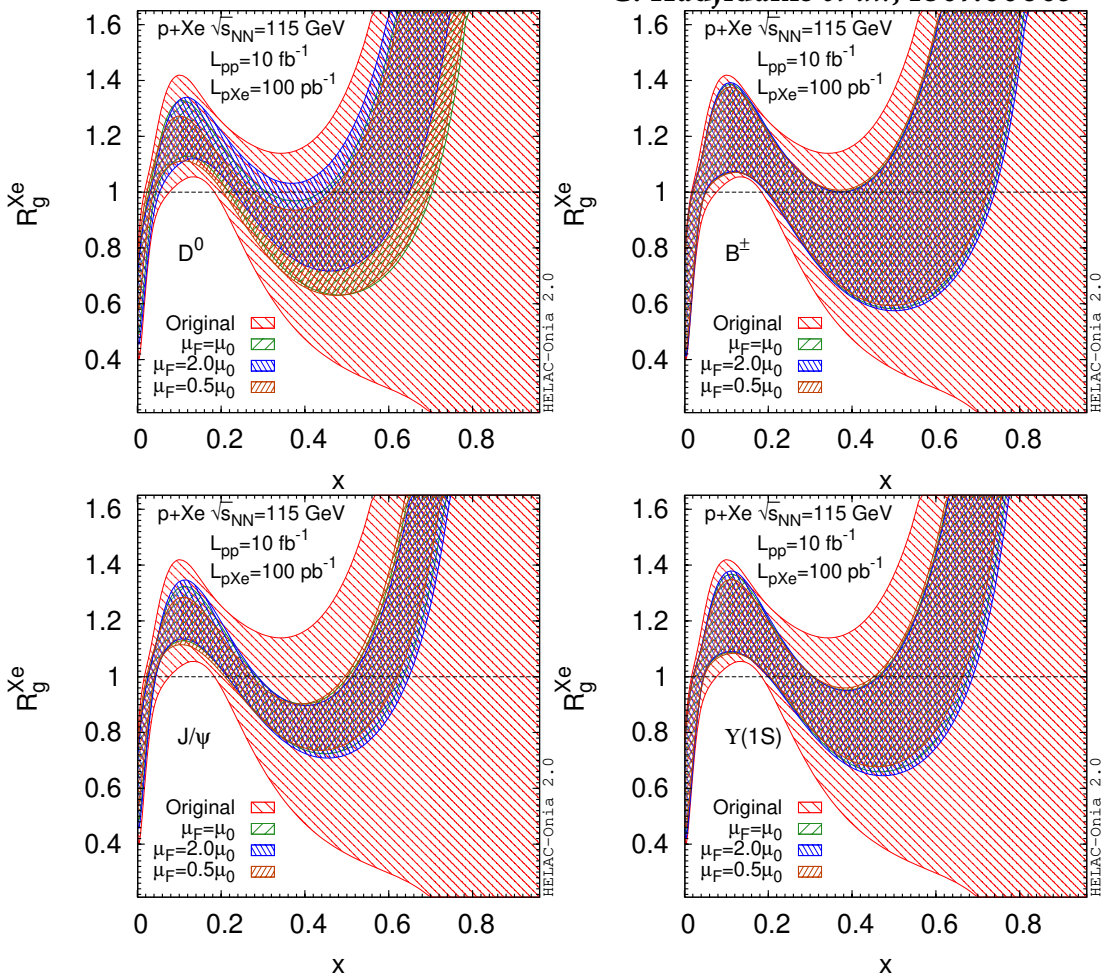

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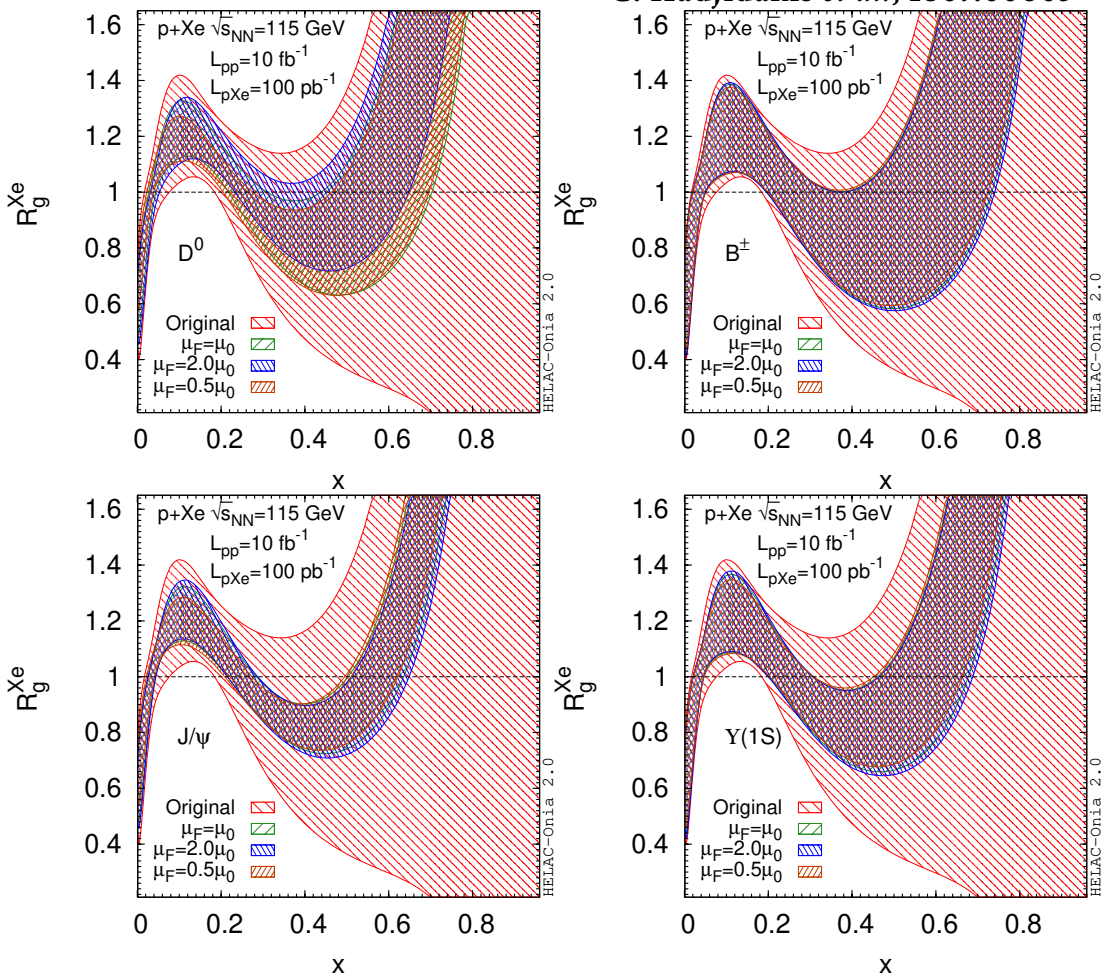

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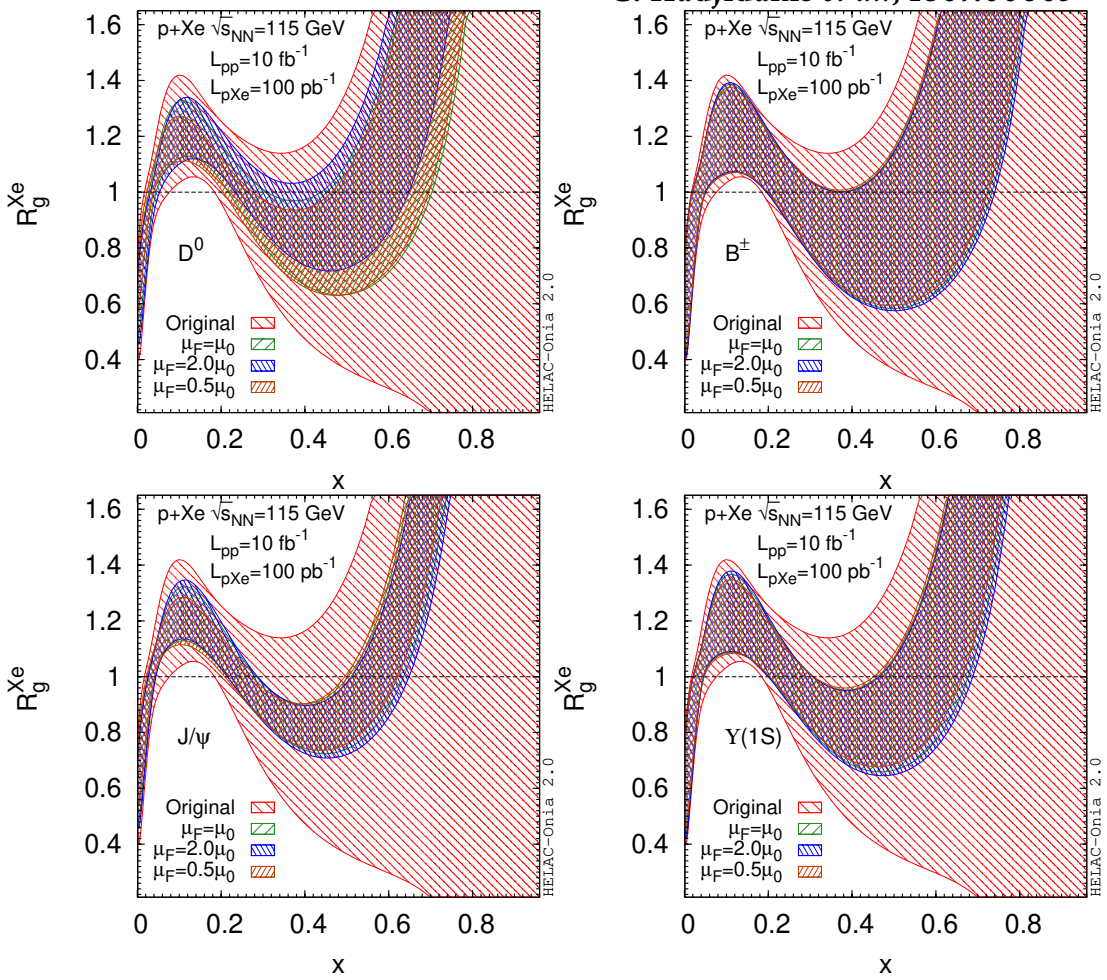

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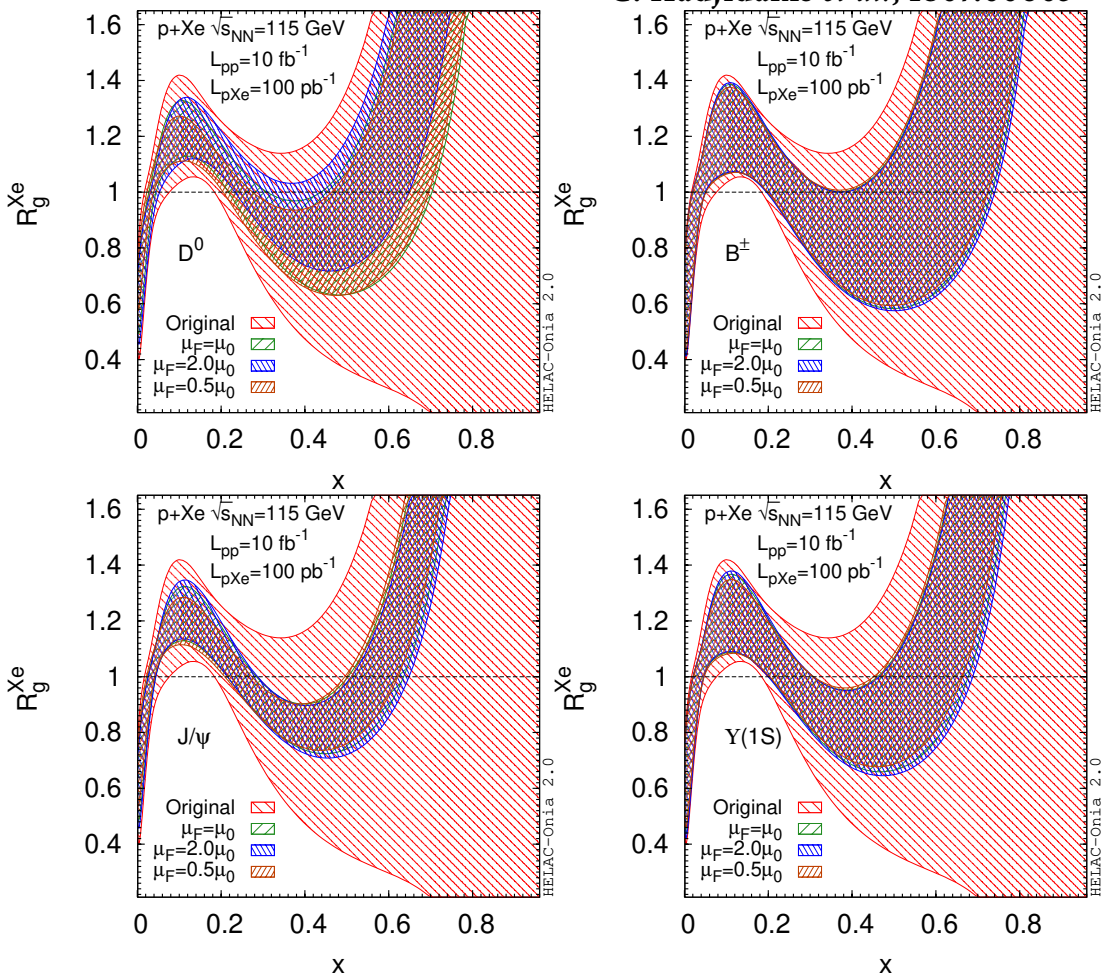

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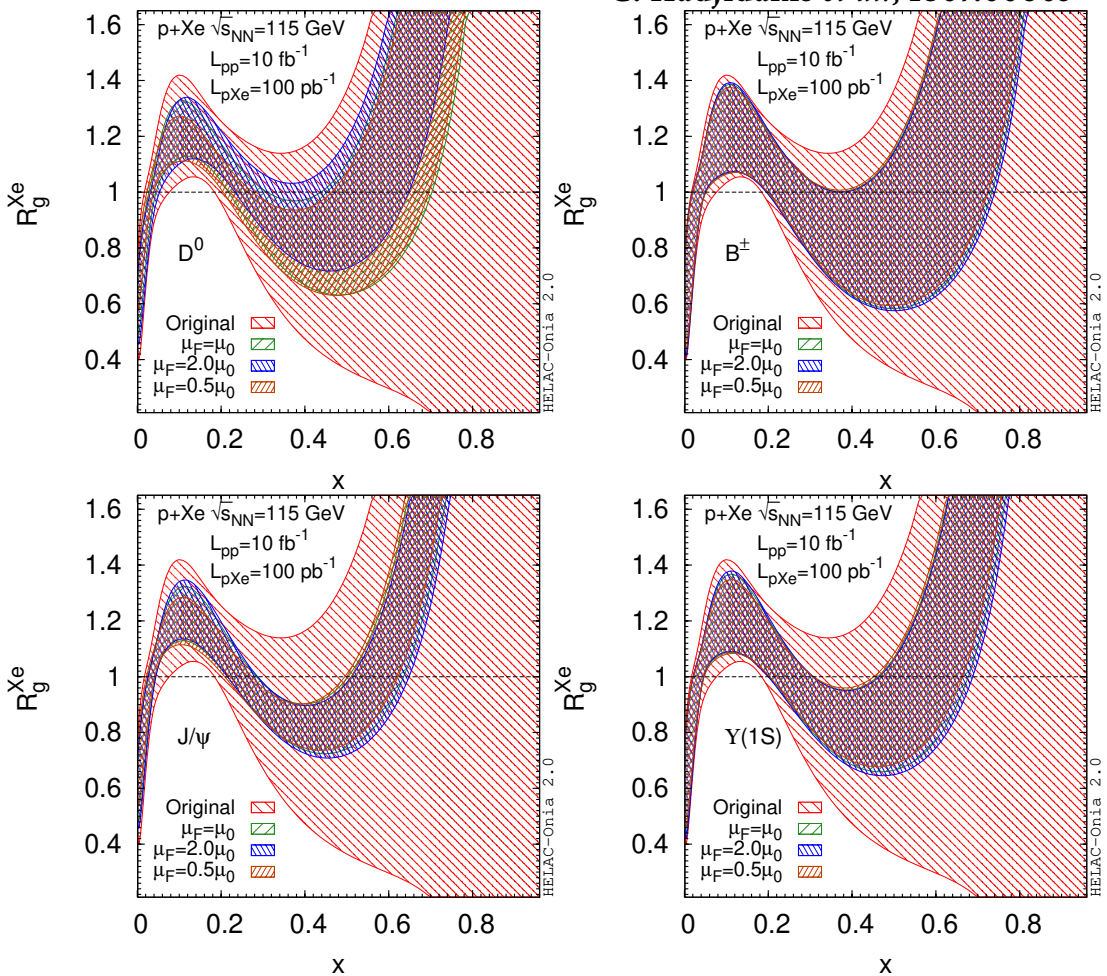

Reward: unique constraints on gluon (n)PDFs at high x and low scales

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* $\sqrt{s_{\mathrm{NN}}}$ = 72 *GeV using a viscous hydro + cascade model* by I. Karpenko: Acta Phys. Polon. B50 (2019), 141
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- *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
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- *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

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- *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.
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- *Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC*
  By G. Chen *et al.*. Phys.Rev. D89 (2014) 074020.

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- *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
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Generalities

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