A Fixed-Target Programme at the LHC

Future heavy-ion facilities

J.P. Lansberg

IPN Orsay – Paris-Sud U./Paris Saclay U. –CNRS/IN2P3

HARD PROBES 2018

International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
30 September 2018 to 5 October 2018 • Aix-Les-Bains • France

AFTER@LHC Study group: http://after.in2p3.fr

Part I

The AFTER@LHC programme

The Genesis

Physics Reports 522 (2013) 239–255

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ELSEVIER

Physics opportunities of a fixed-target experiment using LHC beams

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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
- Proton charm content

$\leftrightarrow$ high-energy neutrino & cosmic-ray physics

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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 $\mathcal{L}_{g;q}$:

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

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Heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies
- Test the formation of 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

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Part III

Possible Implementations and Luminosities

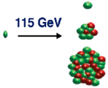
Fixed-target collisions at the LHC: main kinematical features

Fixed-target collisions at the LHC: main kinematical features

Energy range

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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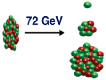

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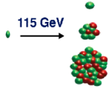

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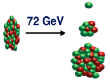

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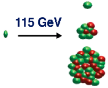

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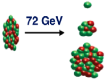

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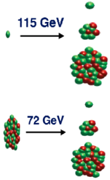

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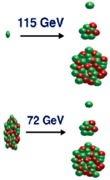

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- Allows for backward physics up to high x_2 [uncharted for proton-nucleus coll.; most relevant for $pp^{\uparrow}$ with large $x^{\uparrow}$]

Possible implementations

Talk by C. Hadjidakis this morning

Internal gas target (with or without storage cell)

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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: 3.4×10^{18} s^{-1} & Pb flux: 3.6×10^{14} s^{-1}
- Hermes storage cell proposed 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

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- 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: 5×10^{8} s^{-1} & lead flux: 2×10^{5} s^{-1}

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  - **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

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- 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: 5×10^{8} s^{-1} & lead flux: 2×10^{5} s^{-1}
  - **Beam line** : provides a new facility with 7 TeV proton beam but requires civil engineering
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→ Luminosities with internal gas target or crystal-based solutions are not very different

Possible implementations

Talk by C. Hadjidakis this morning

Internal gas target (with or without storage cell)

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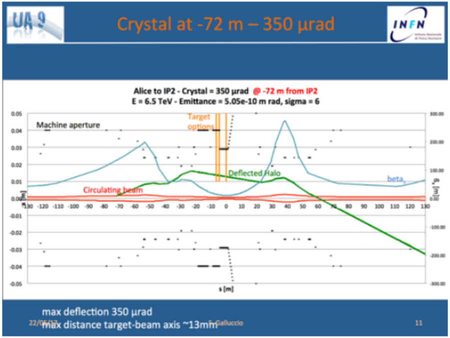
→ The gas targets are the best polarised targets and satisfactory for heavy-ion studies

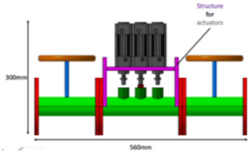
One example of the solutions reviewed by the PBC working group

Solid targets

Conceptual design work for a crystal beam-splitting scenario with in-beam solid targets in ALICE started by the proponents.
Compatibility with ALICE collider programme to be studied in detail.



Sketch of the internal solid target



- movable target with pneumatic system
- 2 valves on each side
- possibility to have several target types

- First study of single-crystal experiment at IP2 by F. Galluccio and W. Scandale
- Integration of a movable internal solid target with ALICE under study by K. Pressard

[Slide from S. Redealli, PBC workshop]

SMOG: more than a demonstrator ?

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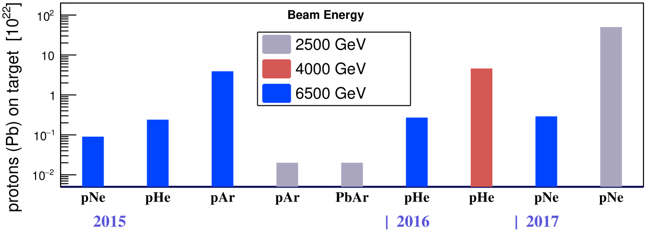

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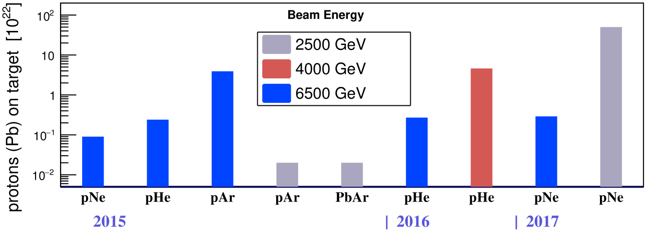

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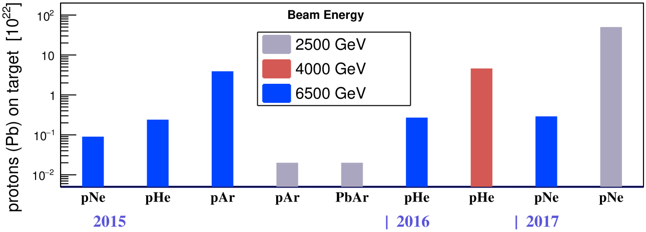

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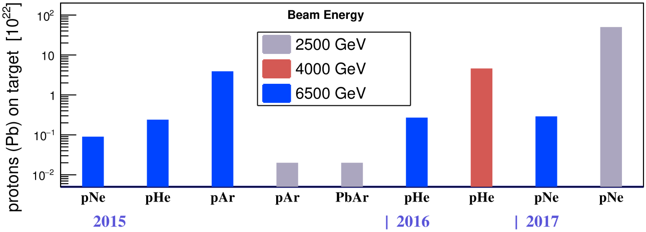

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My suggestion: slightly modify **during LS2** the beampipe to have a small vacuum zone between 2 valves [usable by a solid-target+crystal, a wire target or a gas target à la SMOG]

Luminosity comparison [w/o detector constraints]

Target			Beam: p $\mathcal{L}$ [cm^{-2}s^{-1}]	p Δt [s]	p $\int\mathcal{L}$ [nb^{-1}]	Pb $\mathcal{L}$ [cm^{-2}s^{-1}]	Pb Δt [s]	Pb $\int\mathcal{L}$ [nb^{-1}]
Internal gas target	SMOG	He, Ne, Ar	5.8×10^{29}	2.5×10^{5}	145	7.4×10^{25}	10^6	0.074
	Gas-Jet	$H^{\uparrow}$	4.3×10^{30}	10^7	4.3×10^{4}	5.6×10^{26}	10^6	0.56
		H_2	3.6 x (10^{33} -10^{34})	10^7	3.6 x (10^{7} -10^{8})	4.66 x (10^{29} -10^{30})	10^6	466-4660
		$D^{\uparrow}$	4.3×10^{30}	10^7	4.3×10^{4}	5.6×10^{26}	10^6	0.56
		$^3He^{\uparrow}$	3.6×10^{32}	10^7	3.6×10^{6}	4.66×10^{28}	10^6	47
	Storage Cell	$H^{\uparrow}$	0.92×10^{33}	10^7	9.2×10^{6}	1.18×10^{29}	10^6	118
		H_2	5.8×10^{33}	10^7	5.8×10^{7}	7.5×10^{29}	10^6	750
		$D^{\uparrow}$	1.1×10^{33}	10^7	1.1×10^{7}	1.4×10^{29}	10^6	140
		$^3He^{\uparrow}$	3.7×10^{33}	10^7	3.7×10^{7}	4.7×10^{29}	10^6	474
		Xe	2.34×10^{32}	10^7	2.34×10^{6}	3.0×10^{28}	10^6	30
Internal solid target with beam halo	Wire Target (0.5 mm)	C	2.8×10^{30}	10^7	2.8×10^{4}	5.6×10^{26}	10^6	0.56
		Ti	1.4×10^{30}	10^7	1.4×10^{4}	2.8×10^{26}	10^6	0.28
		W	1.6×10^{30}	10^7	1.6×10^{4}	3.1×10^{26}	10^6	0.31
Beam splitting	E1039	$NH_3^{\uparrow}$	7.2×10^{31}	10^7	7.2×10^{5}	1.4×10^{28}	10^6	14
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	Unpolarised solid target (5 mm)	C	2.8×10^{31}	10^7	2.8×10^{5}	5.6×10^{27}	10^6	5.6
		Ti	1.4×10^{31}	10^7	1.4×10^{5}	2.8×10^{27}	10^6	2.8
		W	1.6×10^{31}	10^7	1.6×10^{5}	3.1×10^{27}	10^6	3.1
Beam extraction	E1039	$NH_3^{\uparrow}$	7.2×10^{31}	10^7	7.2×10^{5}	1.4×10^{28}	10^6	14
		$ND_3^{\uparrow}$	7.2×10^{31}	10^7	7.2×10^{5}	1.4×10^{28}	10^6	14
	COMPASS	$NH_3^{\uparrow}$	1.0×10^{33}	10^7	1.0×10^{7}	2.0×10^{29}	10^6	200
		butanol $\uparrow$	2.7×10^{32}	10^7	2.7×10^{6}	5.3×10^{28}	10^6	53

NB: The storage-cell figures correspond to a 1-m long cell with a coating with the same performances as the HERMES-cell coating (a priori not compliant with the LHC requirement).

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	Unpolarised solid target (5 mm)	C	2.8×10^{31}	10^7	2.8×10^{5}	5.6×10^{27}	10^6	5.6
		Ti	1.4×10^{31}	10^7	1.4×10^{5}	2.8×10^{27}	10^6	2.8
		W	1.6×10^{31}	10^7	1.6×10^{5}	3.1×10^{27}	10^6	3.1
Beam extraction	E1039	$NH_3^{\uparrow}$	7.2×10^{31}	10^7	7.2×10^{5}	1.4×10^{28}	10^6	14
		$ND_3^{\uparrow}$	7.2×10^{31}	10^7	7.2×10^{5}	1.4×10^{28}	10^6	14
	COMPASS	$NH_3^{\uparrow}$	1.0×10^{33}	10^7	1.0×10^{7}	2.0×10^{29}	10^6	200
		butanol $^{\uparrow}$	2.7×10^{32}	10^7	2.7×10^{6}	5.3×10^{28}	10^6	53

NB: The storage-cell figures correspond to a 1-m long cell with a coating with the same performances as the HERMES-cell coating (a priori not compliant with the LHC requirement).

Luminosity comparison [w detector constraints]

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LHCb 'possible'

Assumption: Rates only constrained by the DAQ (40 MHz for *pp* coll.)
$\mathcal{L}_{pH_2/H^\uparrow}$: 10 $\text{fb}^{-1}\ \text{yr}^{-1}$; $\mathcal{L}_{\text{pXe}}$: 300 $\text{pb}^{-1}\ \text{yr}^{-1}$; $\mathcal{L}_{\text{PbXe}}$: 30 $\text{nb}^{-1}\ \text{yr}^{-1}$

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LHCb 'SMOG2' baseline for Run3

Assumption: Storage cell installed, very parasitic mode
$\mathcal{L}_{p\ \rm beam}$: 30 pb^{-1} (on H,D or Ar); $\mathcal{L}_{\rm Pb\ beam}$: 5 nb^{-1} (on Ar)

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ALICE ‘possible’ from Run4*

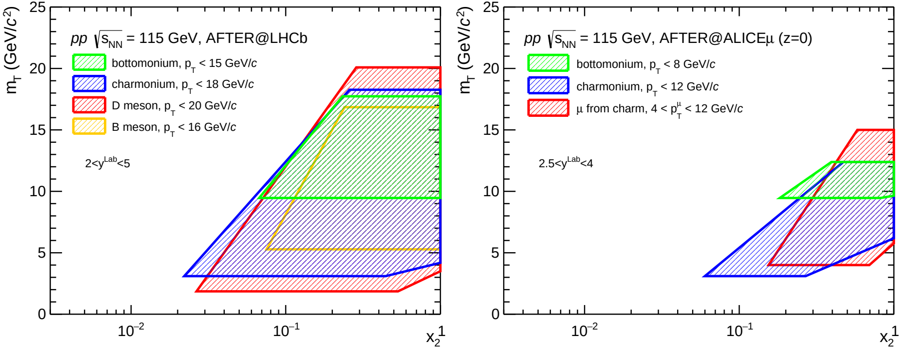
Assumption: Readout rate: 50 kHz in PbPb coll. and possibly up to 1 MHz in *pp* and *p*A coll.
With internal gas target: $\mathcal{L}_{pH_2/H^\uparrow}$: 250 pb^{-1}; $\mathcal{L}_{\rm PbXe}$: 8 nb^{-1}
With beam splitting and solid target: $\mathcal{L}_{p\rm W}$: 6 pb^{-1} ; $\mathcal{L}_{\rm PbW}$: 3 nb^{-1}

* : Unless valves can be installed during LS2 (see my suggestion above)

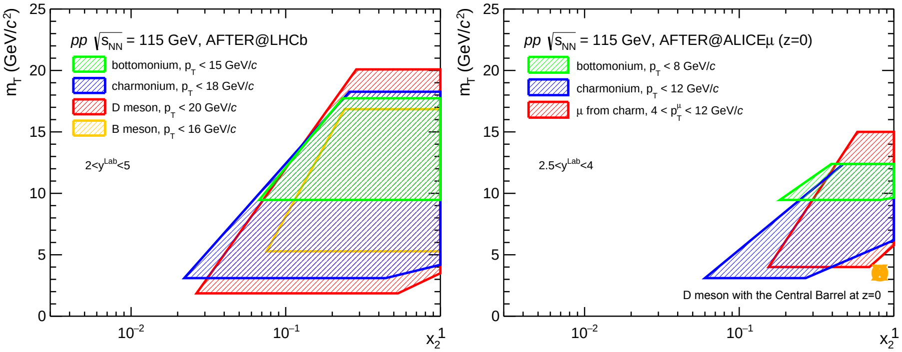
Part IV

Examples of Heavy-Ion Studies

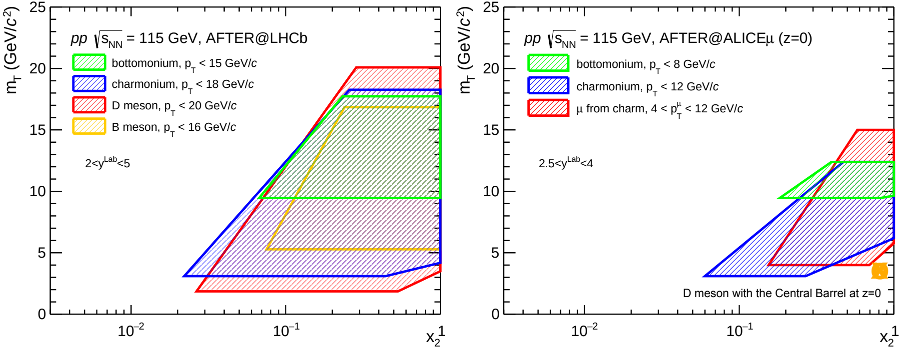
Kinematical coverage for heavy flavours



Kinematical coverage for heavy flavours



Kinematical coverage for heavy flavours



ALICE could also cover $\eta_{\mathrm{Lab}} \sim 1-2$ for quarkonia into dileptons with one muon in the muon arm and another in the central barrel

[done for UPCs in the collider mode, see C. Mayer at QM 2018]

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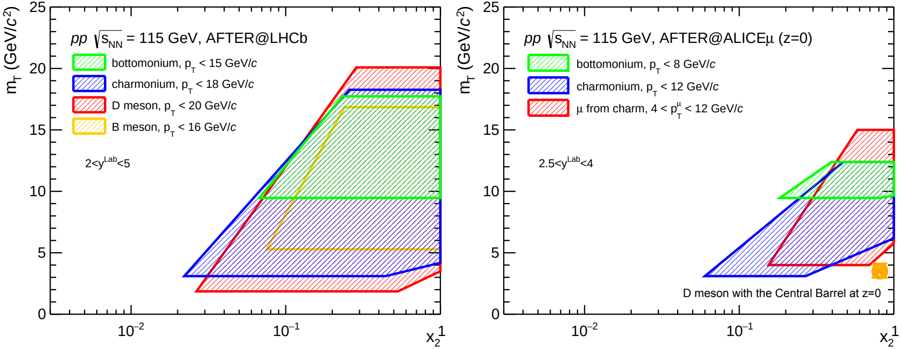

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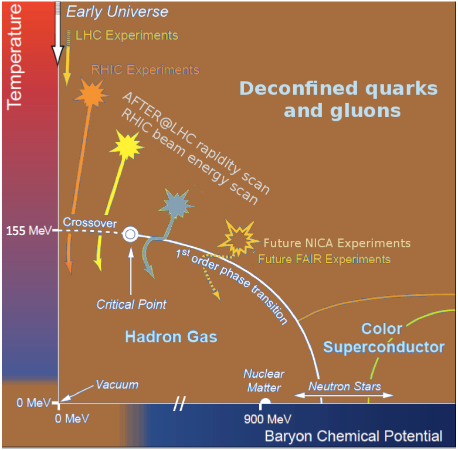
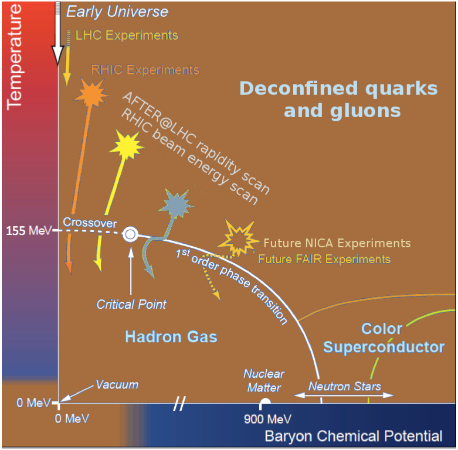
NB: The coverage depends on the target position

Heavy ions: rapidity scan & quarkonium precision studies



Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain: between SPS and RHIC



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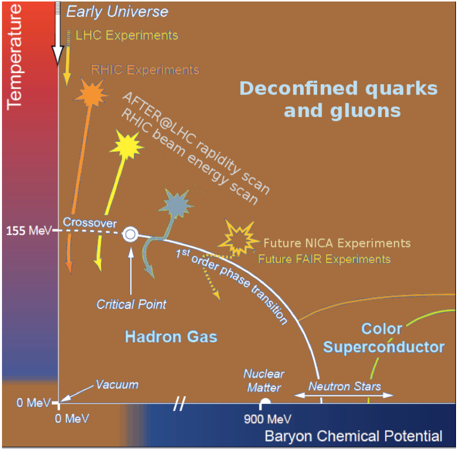

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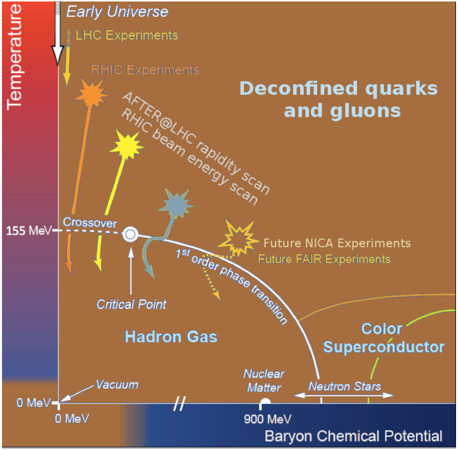
- Handle on more quarkonium states (e.g. $\chi_{c,b}$, η_c) and on open charm and beauty



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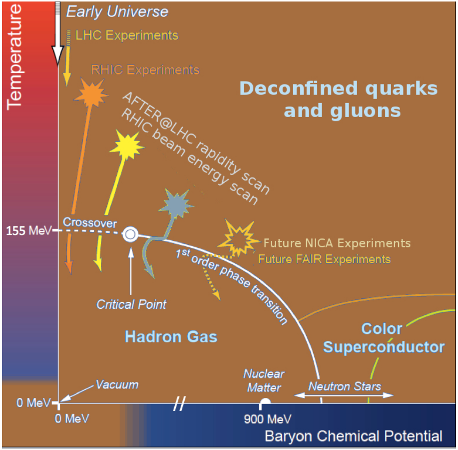

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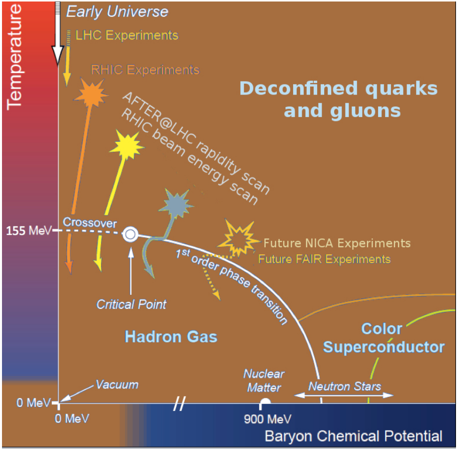
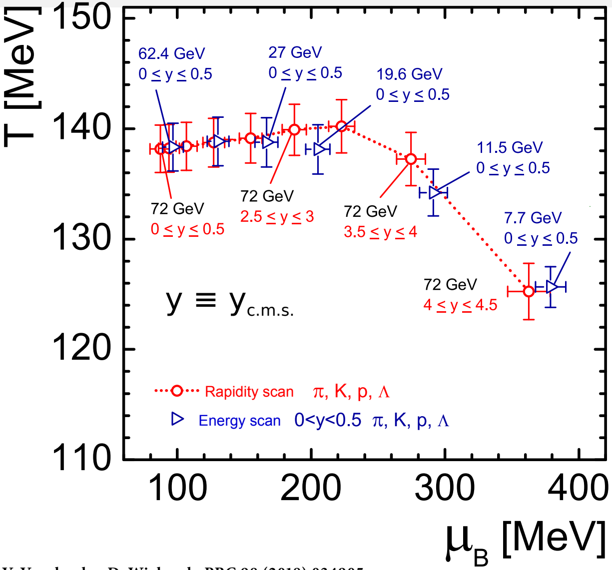


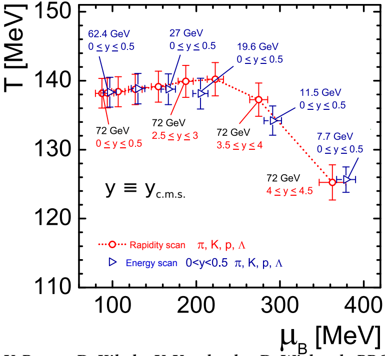
Even with 1 billion J/ψ's, the *direct* J/ψ yield will remain unprecise by 30 % !

Rapidity scan



V. Begun, D. Kikola, V. Vovchenko, D. Wielanek, PRC 98 (2018) 034905

Rapidity scan



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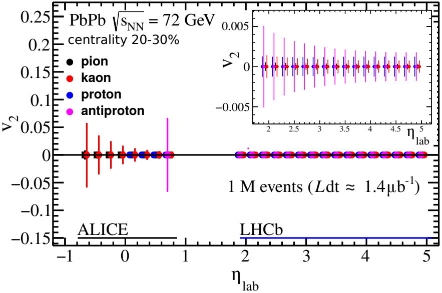

Quarkonium Projections: heavy-ion collisions

B.Trzeciak *et al.***Few-Body Syst (2017) 58:148**

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Quarkonium Projections: heavy-ion collisions

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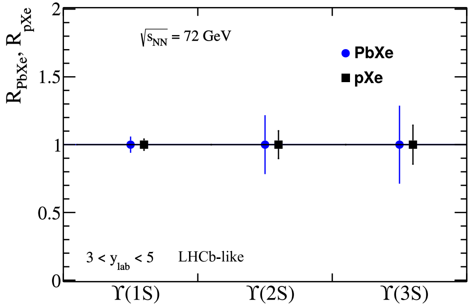
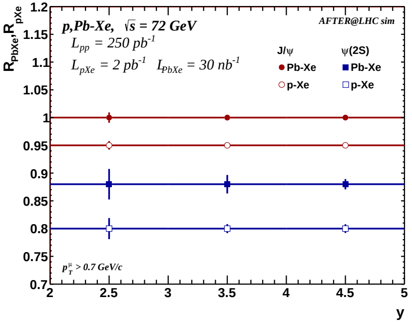
- Like for nPDF studies (see later), multiple quarkonium studies are needed
- Clear need for a reliable *pA* baseline
- Statistical-uncertainty projections (accounting for background subtraction)





Part V

One example of Cold Nuclear Matter Study

Gluons at the high-x frontier

Talk by A. Kusina on Wednesday

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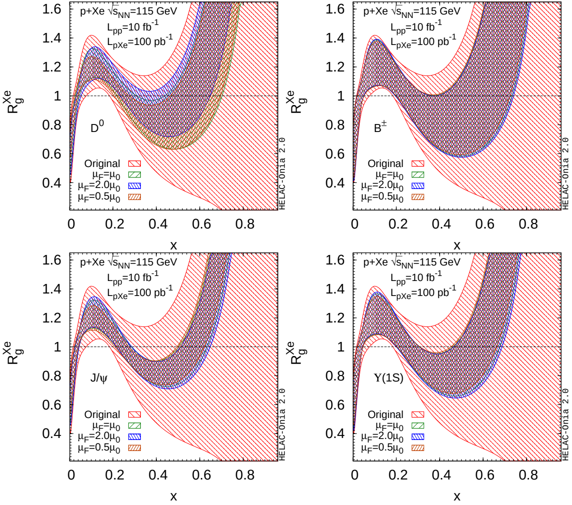
- First extremely promising projections
  [NB: *initial nPDF uncertainties for* $x > 0.1$ *(red band) are underestimated; simply no data exist there. Projection done assuming that other nuclear effect are under control.]*



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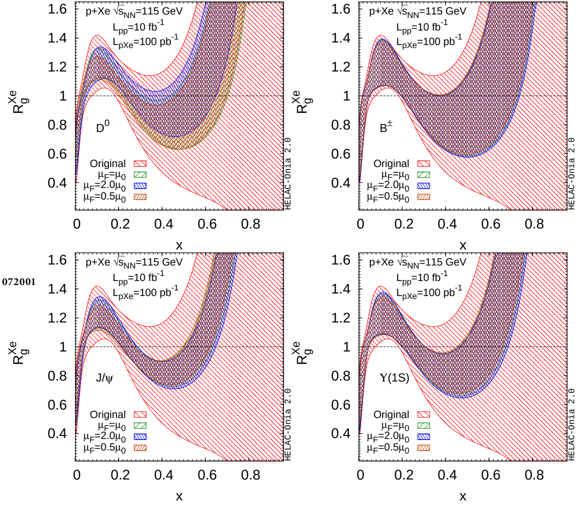
PROSA Coll. Eur.Phys.J. C75 (2015) 396; R. Gauld, J. Rojo PRL 118 (2017) 072001



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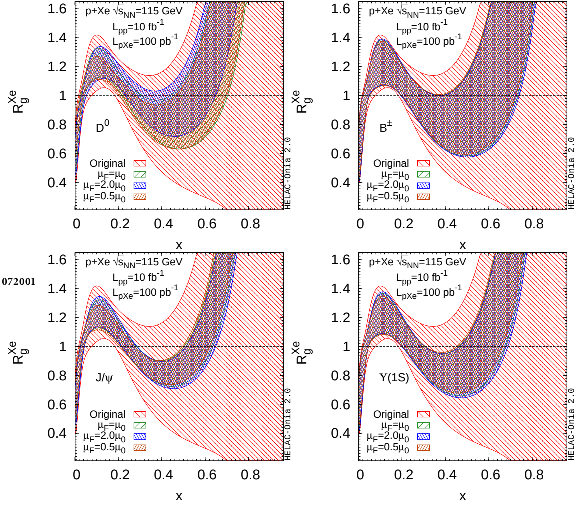

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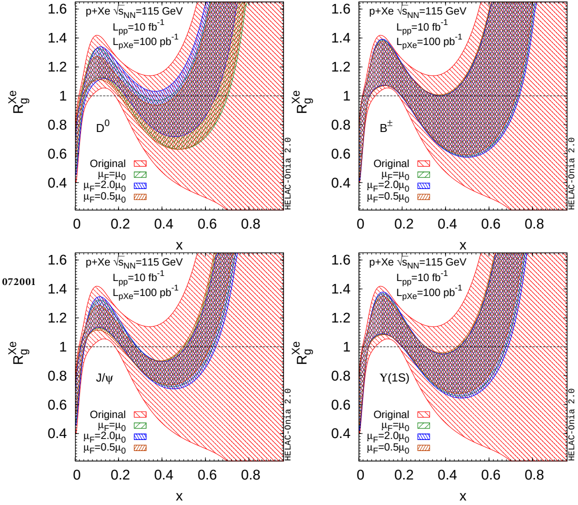

Reward: unique constraints on gluon PDFs at high x and low scales

Part VI

Conclusion

Conclusions

- Three main themes push for a fixed-target program at the LHC

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- Based on fast simulations, the AFTER@LHC study group has made FoMs for LHCb and ALICE in the FT mode which clearly support a full physics program
- Our review is now out [arXiv:1807.00603] and will feed in the European Strategy via the Physics Beyond Colliders Working Group

Part VII

Backup slides

Qualitative comparison

Characteristics	Internal gas target: SMOG	Internal gas target: Gas Jet	Internal gas target: Storage Cell	Internal solid target with beam halo	Beam splitting	Beam extraction
Run duration[14]	⋆	⋆⋆	⋆⋆	⋆	⋆⋆	⋆⋆⋆
Parasiticity[15]	⋆⋆⋆	⋆⋆	⋆⋆	⋆	⋆⋆	⋆⋆⋆
Integrated luminosity[16]	⋆	⋆⋆	⋆⋆	⋆	⋆⋆	⋆⋆⋆
Absolute luminosity determination[17]	⋆	⋆⋆	⋆⋆	⋆	⋆⋆	⋆⋆⋆
Target versality[18]	⋆⋆	⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆⋆
Target polarisation[19]	-	⋆⋆	⋆⋆	-	- / ⋆[20]	⋆
Use of existing experiment[21]	⋆⋆	⋆	⋆	⋆	⋆	-
Civil engineering or R&D [22]	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆
Cost	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆
Implementation time	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆⋆	⋆
High x[23]	⋆	⋆⋆	⋆⋆⋆	⋆	⋆/ ⋆⋆	⋆⋆⋆
Spin Physics[24]	-	⋆⋆⋆	⋆⋆⋆	-	- / ⋆⋆	⋆⋆⋆
Heavy-Ion[25]	⋆	⋆⋆	⋆⋆	⋆/ ⋆⋆	⋆⋆	⋆⋆⋆

Table 8: Qualitative comparison of the various technological solutions.

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 $\sqrt{s_{NN}}$ = 72 GeV using a viscous hydro + cascade model* by I. Karpenko: arXiv:1805.11998 [nucl-th]
- *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
- *Lepton-pair production in ultraperipheral collisions at AFTER@LHC* By J.P. Lansberg, L. Szymanowski, J. Wagner. JHEP 1509 (2015) 087
- *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.

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
- *Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC).* by J.P. Lansberg, H.S. Shao. [arXiv:1504.06531 [hep-ph]]. 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. arXiv:1503.05112 [hep-ph].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

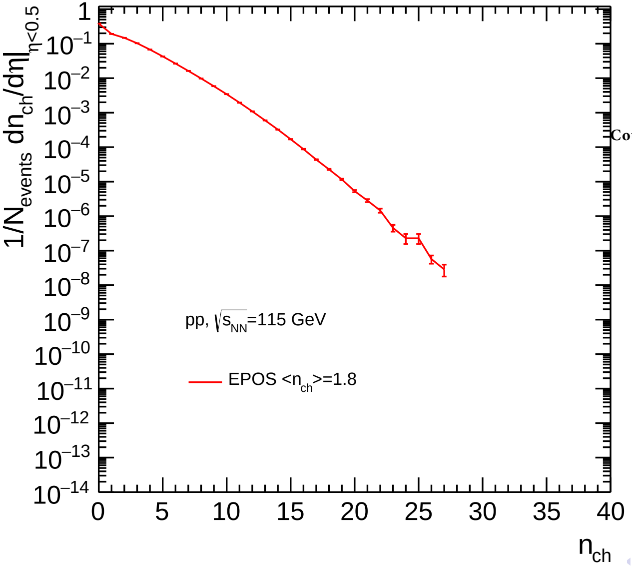
Feasibility study and technical ideas

- *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.

High multiplicity *pp* at low energies



Courtesy of T. Pierog