A Fixed-Target Programme at the LHC

J.P. Lansberg

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

Hard-soft correlations in hadronic collisions - GDR QCD, LPC Clermont, 23-25 July 2018

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

Part I

The AFTER@LHC programme

The Genesis

Physics Reports 522 (2013) 239–255

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Physics opportunities of a fixed-target experiment using LHC beams

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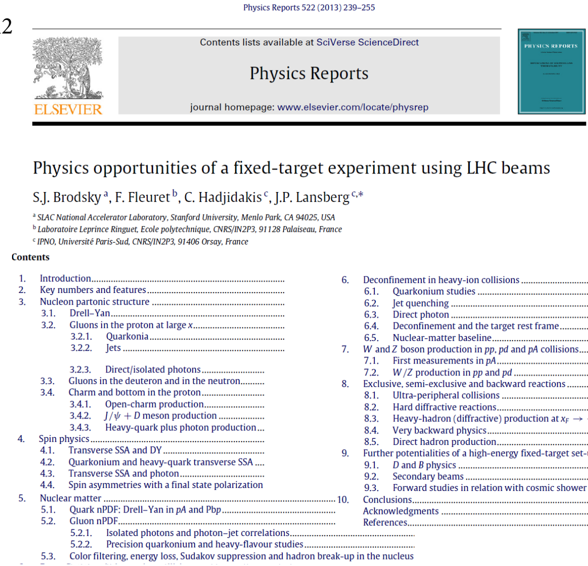

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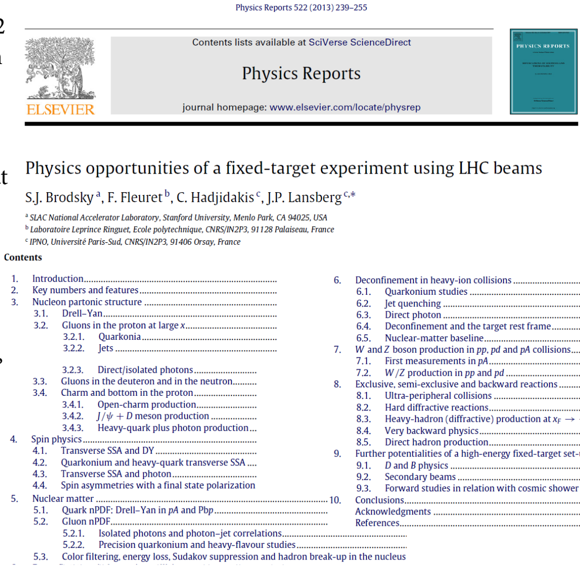
- September 2016: PBC kickoff, …



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- September 2016: PBC kickoff, …
- Finally the EoI, which became a review to motivate a full FT LHC program, is out !

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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.

The AFTER@LHC HIC programme

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High-x frontier

Advance our understanding of the high-x gluon, antiquark and heavy-quark content in the nucleon & nucleus

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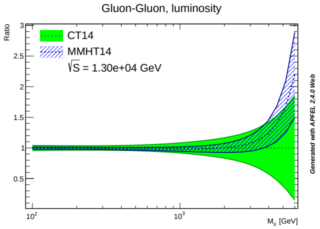
- Very large PDF uncertainties for $x \gtrsim 0.5$.

[could be crucial to characterise possible BSM discoveries]



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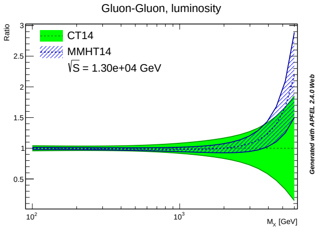

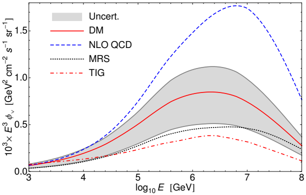

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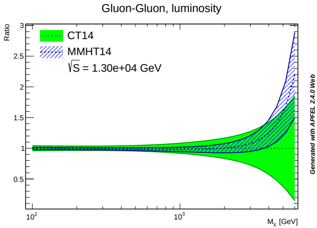
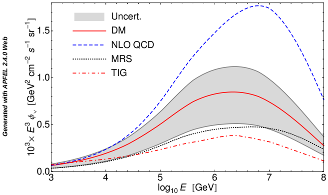
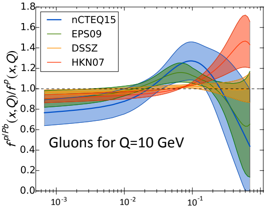
- Relevance of nuclear PDF to understand the initial state of heavy-ion collisions







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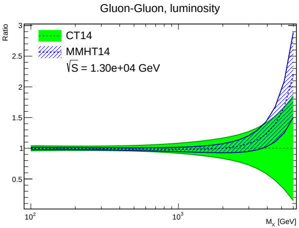
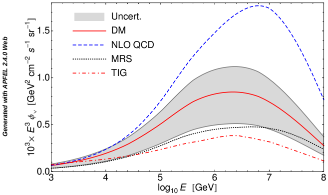
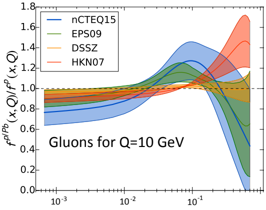
- Relevance of nuclear PDF to understand the initial state of heavy-ion collisions
- Search for and study rare proton/deuteron fluctuations
  where a single gluon carries most of its momentum







3D mapping of the parton momentum

Advance our understanding dynamics and spin of gluons and quarks inside (un)polarised nucleons

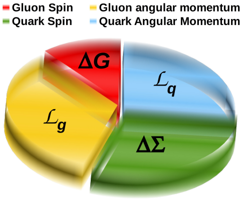
3D mapping of the parton momentum

Advance our understanding dynamics and spin of gluons and quarks inside (un)polarised nucleons

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

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

[First hint by COMPASS that $\mathcal{L}_g \neq 0$]



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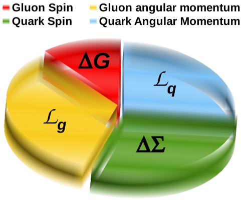

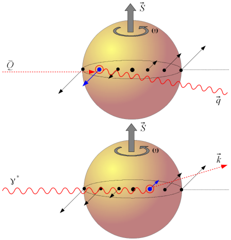

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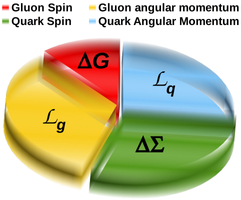
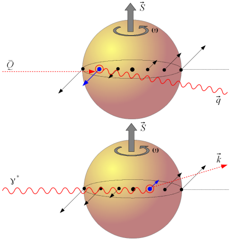
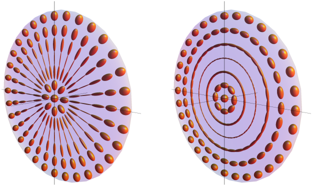
- Test of the QCD factorisation framework [beyond the DY A_N sign change]
- Determination of the linearly polarised gluons in unpolarised protons

[once measured, allows for spin physics without polarised proton, e.g. at the LHC]







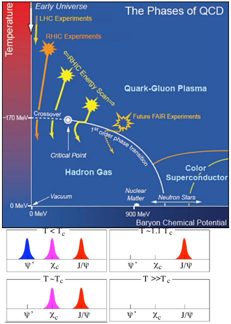
Heavy-ion collisions from one colliding nucleus rest frame

Heavy-ion collisions towards large rapidities

Heavy-ion collisions from one colliding nucleus rest frame

Heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies
  [needed to calibrate the quarkonium thermometer (J/ψ, ψ', χ_c, Υ, D, $J/\psi \leftarrow b$ + pairs)]



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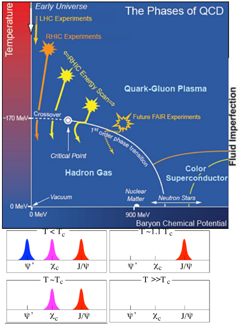

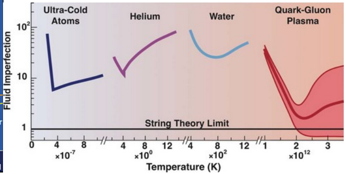

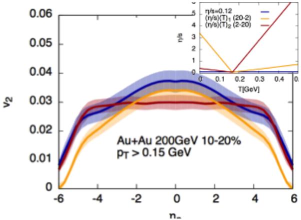

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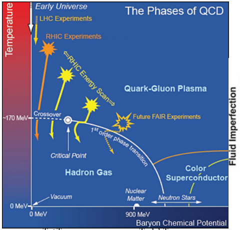
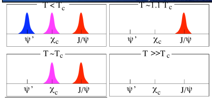
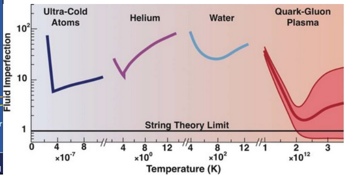
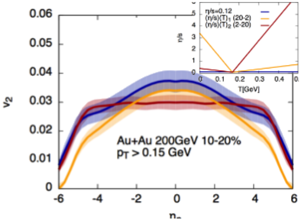
- Explore the longitudinal expansion of QGP formation









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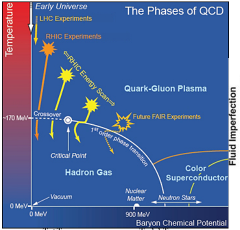
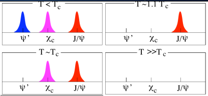
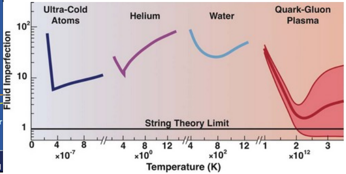
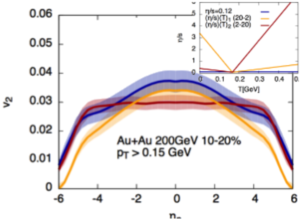
- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions









Part III

Possible Implementations and Luminosities

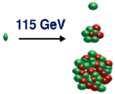
Fixed-target collisions at the LHC: main kinematical features

Fixed-target collisions at the LHC: main kinematical features

Energy range

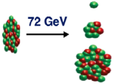
7 TeV proton beam on a fixed target

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



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:**
Boost: $\gamma \approx 40$	$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$



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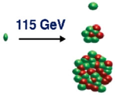

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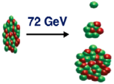
Boost:	$\gamma \approx 40$	



Such $\sqrt{s}$ allow, for the first time, for systematic studies of W boson, bottomonia, p_T spectra, associated production, ..., in the fixed target mode

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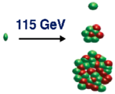
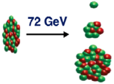


2.76 TeV Pb beam on a fixed target

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



Such $\sqrt{s}$ allow, for the first time, for systematic studies of W boson, bottomonia, p_T spectra, associated production, ..., in the fixed target mode

Effect of boost :

[particularly relevant for high energy beams]

- LHCb and the ALICE muon arm become backward detectors [$y_{\mathrm{c.m.s.}} < 0$]

Fixed-target collisions at the LHC: main kinematical features

Energy range

7 TeV proton beam on a fixed target

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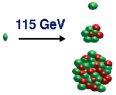

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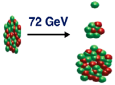

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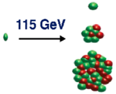

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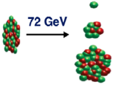

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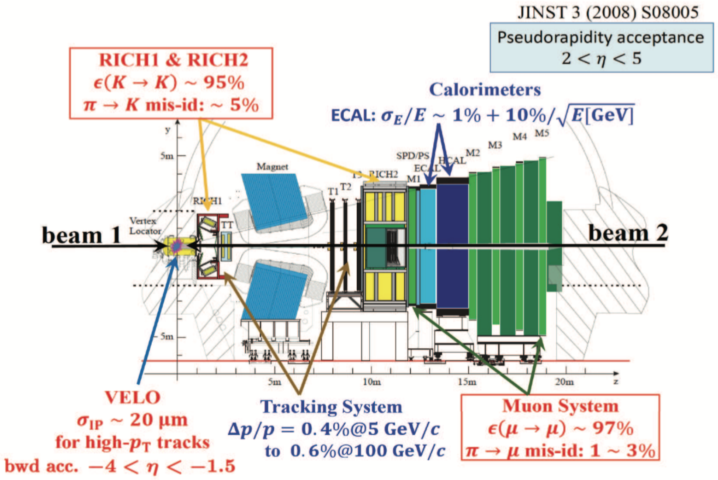
- With the reduced $\sqrt{s}$, their acceptance for physics grows and nearly covers half of the backward region for most probes [$-1 < x_F < 0$]
- Allows for backward physics up to high x_{target} ($\equiv x_2$) [uncharted for proton-nucleus; most relevant for p-p$^\uparrow$ with large $x^\uparrow$]

LHCb acceptance for various colliding modes



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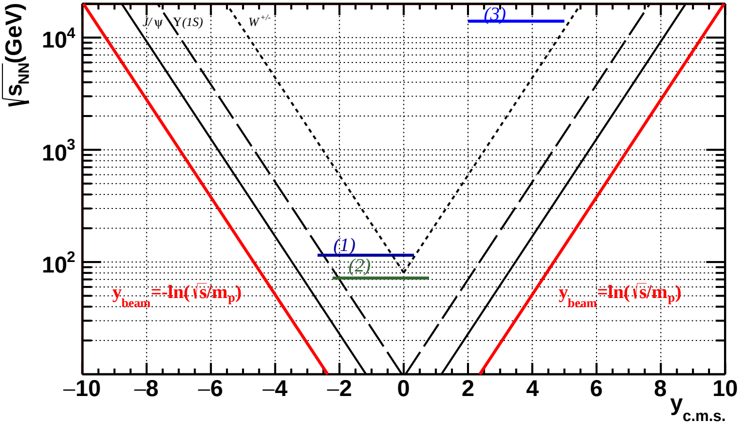
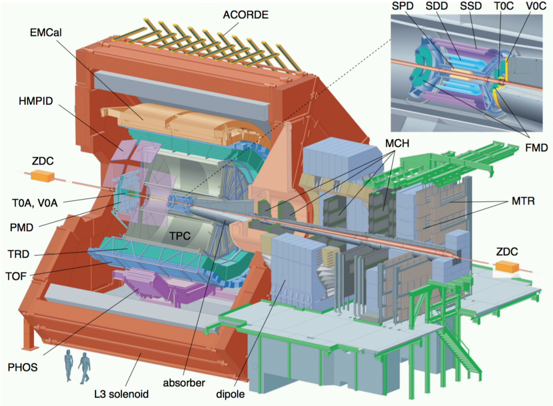


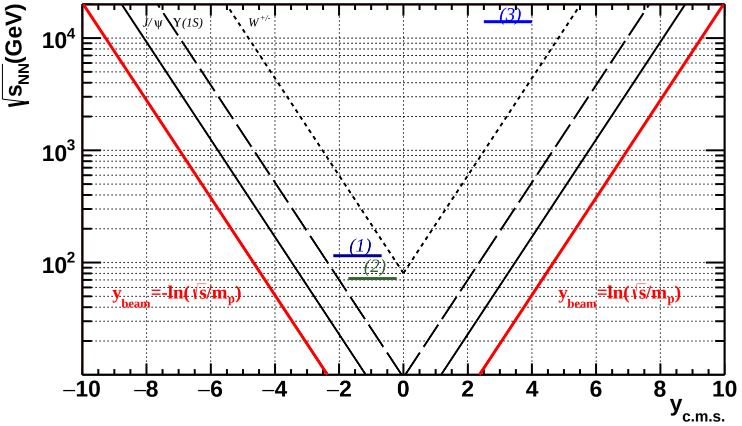
- (1) Fixed-target using p beam, $E_p = 7$ TeV
- (2) Fixed-target using Pb beam, $E_{Pb} = 2.76$ A.TeV
- (3) Collider using p beams, $E_p = 7$ TeV

ALICE muon acceptance for various colliding modes



- Central barrel: $-0.9 < \eta < 0.9$
- Muon spectrometer acceptance: $2.5 < \eta < 4$

ALICE muon acceptance for various colliding modes



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- Internal gas target (with or without storage cell)
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  - currently validated by the LHCb collaboration 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}
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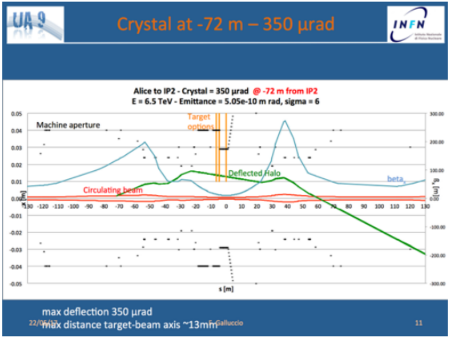
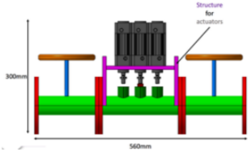
pp	pA	PbA
$\mathcal{O}(0.1-10\ \text{fb}^{-1}\text{yr}^{-1})$	$\mathcal{O}(0.1-1\ \text{fb}^{-1}\text{yr}^{-1})$	$\mathcal{O}(1-50\ \text{nb}^{-1}\text{yr}^{-1})$

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 pumping 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

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.

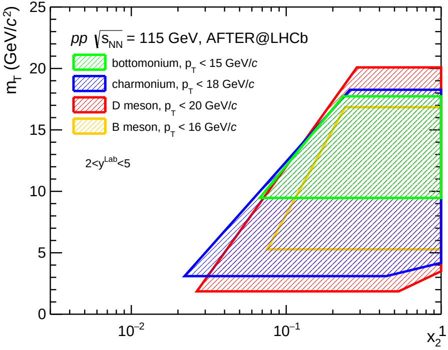
Luminosity comparison

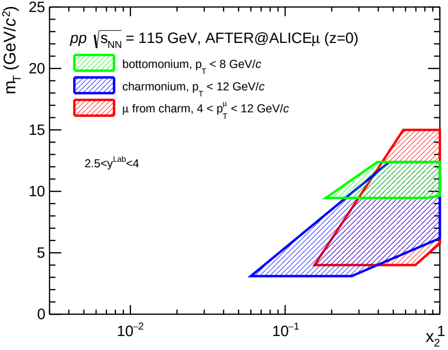
Target			Beam					
			p			Pb		
			$\mathcal{L}$ [cm^{-2}s^{-1}]	Δt [s]	$\int\mathcal{L}$ [nb^{-1}]	$\mathcal{L}$ [cm^{-2}s^{-1}]	Δt [s]	$\int\mathcal{L}$ [nb^{-1}]
Internal gas target	SMOG	He, Ne, Ar	5.8×10^{29}	2.5×10^{5}	145	7.4×10^{25}	10^{6}	0.074
	Gas-Jet	$H^{\uparrow}$	4.3×10^{30}	10^{7}	4.3×10^{4}	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
		$ND_3^{\uparrow}$	7.2×10^{31}	10^{7}	7.2×10^{5}	1.4×10^{28}	10^{6}	14
	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

Part IV

Some FoM for Heavy-Ion Studies

Kinematical coverage



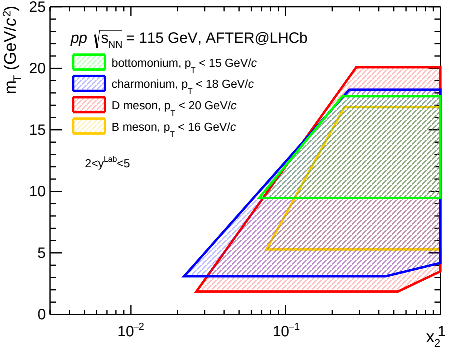


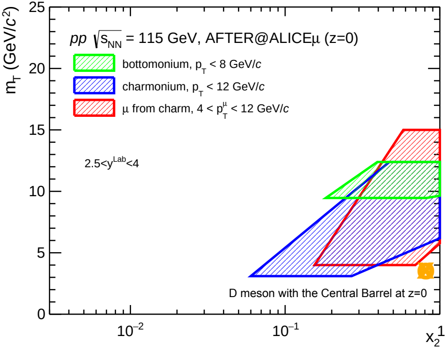
ALICE could cover $\eta \sim 1-2$ for quarkonium into dileptons with one muon in the muon arm and another in the central barrel

[done for UPCs in the collider mode]

NB: The coverage depends on the target position

Kinematical coverage





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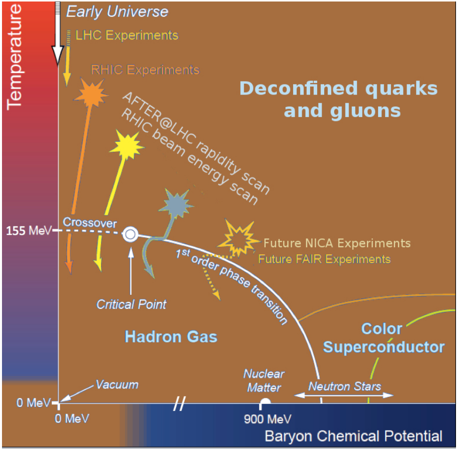
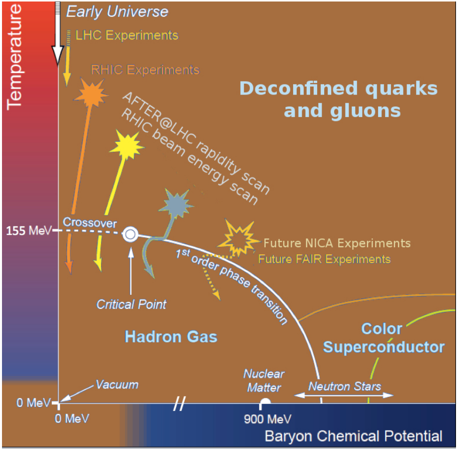
Heavy ions: rapidity scan & quarkonium precision studies



Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain between SPS and RHIC



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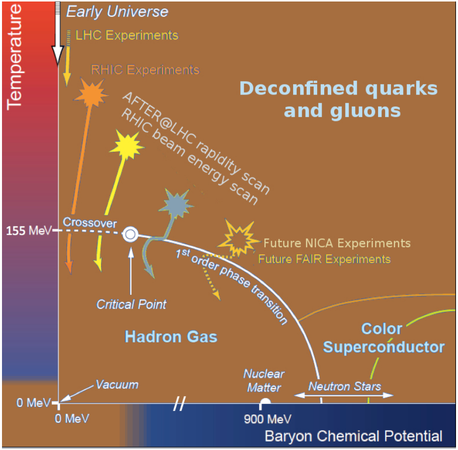

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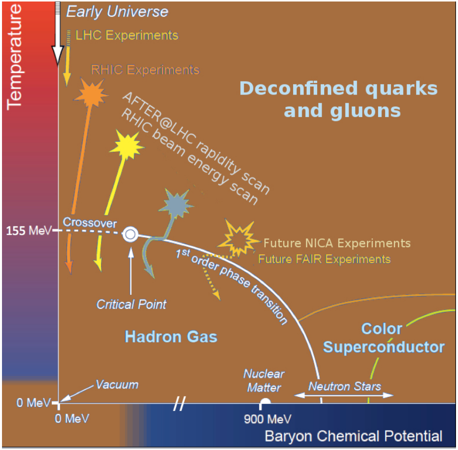
- Energy domain between SPS and RHIC
- Rapidity scan to scan through μ_B & T (e.g. $v_2(y) \leftrightarrow \eta/s$) wit a good PID (LHCb and ALICE)
- At backward rapidities, the background for $\mu^+\mu^-$ is tractable even without absorber
- Handle on more quarkonium states (e.g. $\chi_{c,b}$, η_c) and on open charm and beauty



Heavy ions: rapidity scan & quarkonium precision studies

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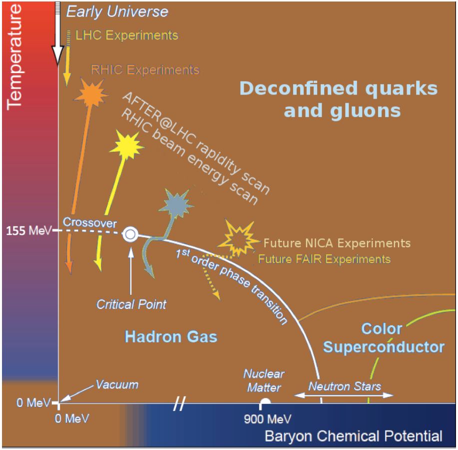

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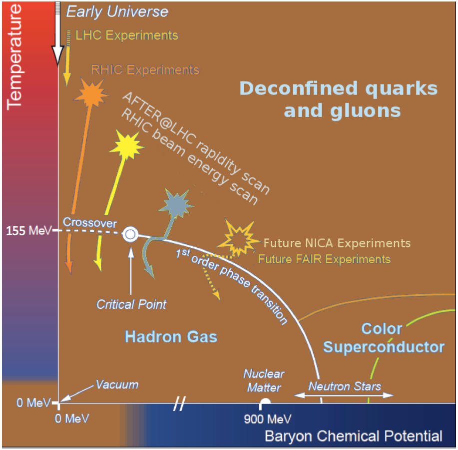
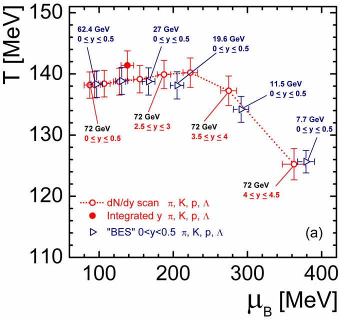
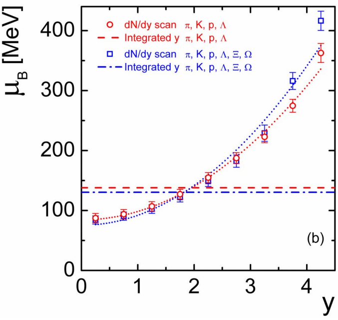
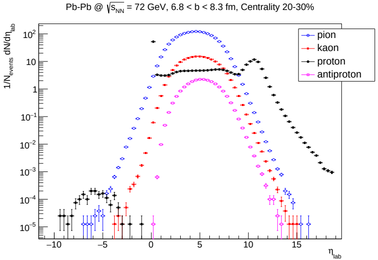


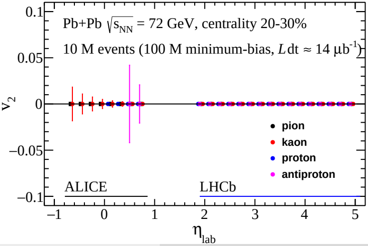
Even with 1 billion J/ψ's, the *direct* J/ψ yield will remain unprecise by 30 % !

Rapidity scan









Quarkonium Projections: heavy-ion collisions

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

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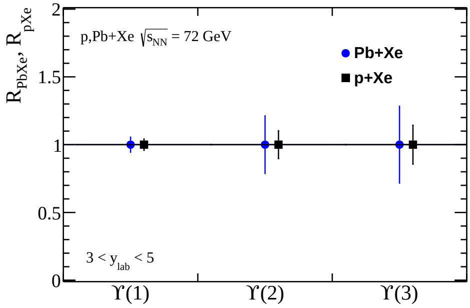
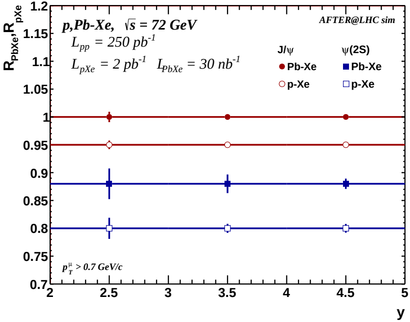
- Clear need for a reliable baseline with *pA* systems
- Statistical-uncertainty projections (accounting for background subtraction)

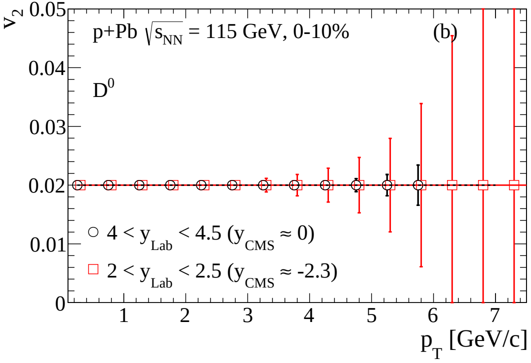




Part V

Some FoM for Cold Nuclear Matter Studies

First look at small systems or new look at Cold Nuclear Matter effects



For *pp* collisions, multiplicity studies will be done soon !

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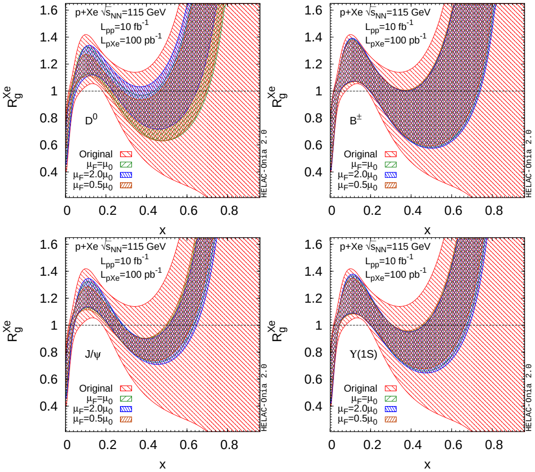

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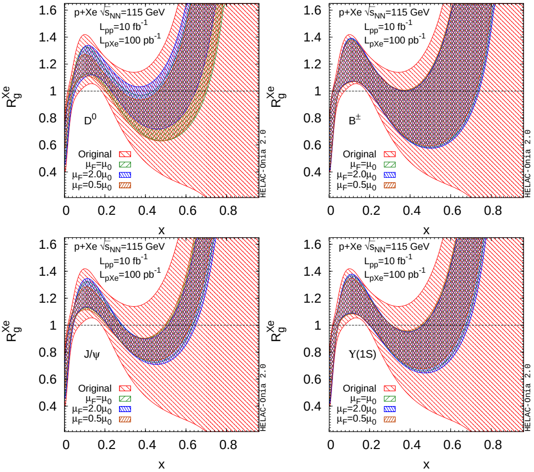

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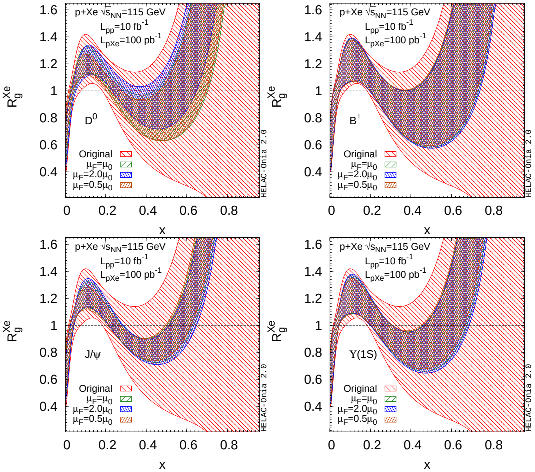
- Contrary to nPDF studies bearing on nuclear modification factors, one needs ways to reduce the systematical theory uncertainties



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

Ultra-Peripheral Collisions in the FT mode and J/ψ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner, arXiv:1709.09044 & in progress

	pH	PbH
Photon-emitter	proton	Lead
$\sigma^{tot}_{J/\psi}$ (pb)	1.18×10^3	276.77×10^3
$\sigma_{J/\psi\to l^+l^-}$ (pb)	70.10	16.50×10^3
$\sigma_{J/\psi\to l^+l^-}$ (with LHCb η_μ cut) (pb)	20.65	9.81×10^3
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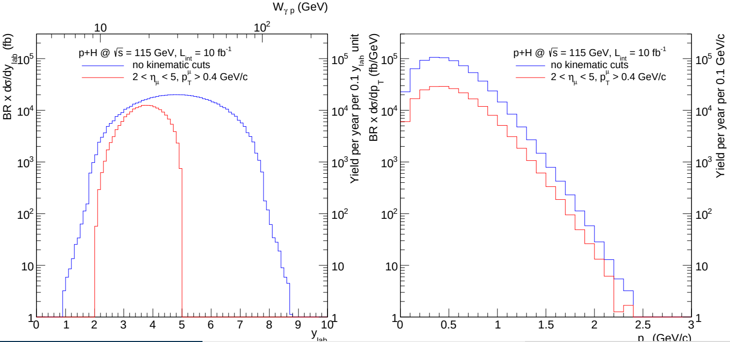

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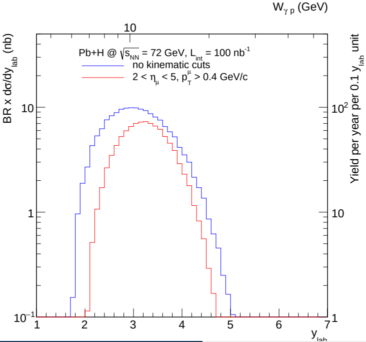

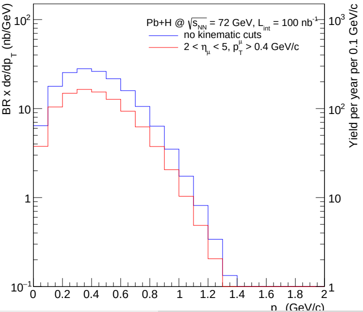

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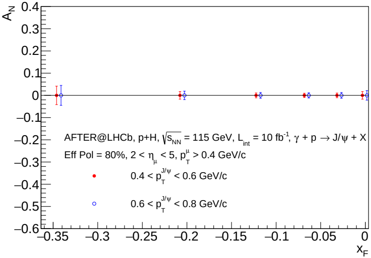
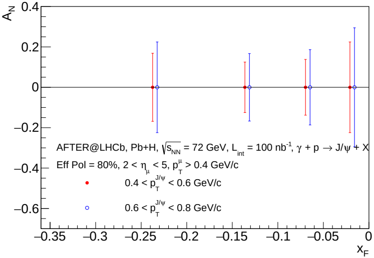
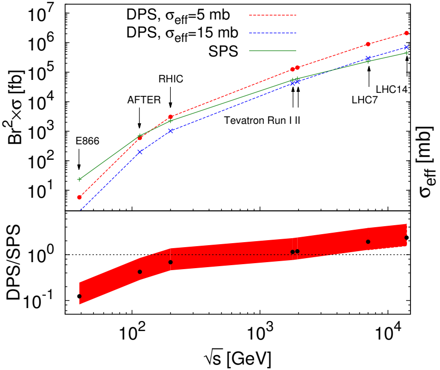


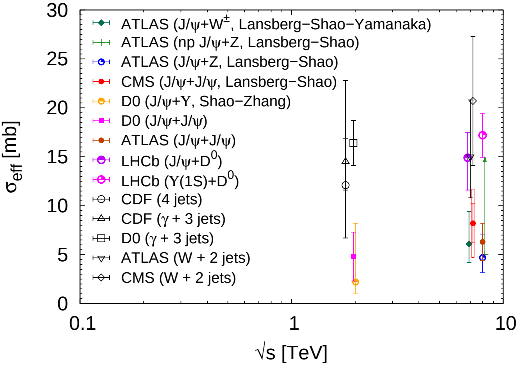


$A_N^{\gamma p^\uparrow \to J/\psi p} \propto \sqrt{t_0 - t} Im(\mathcal{E}_g^* \mathcal{H}_g) \to$ access to the GPD E_g and the gluon OAM

DPS studies in a new energy regime

Di-ψ production at $\sqrt{s}$ = 115 GeV





About 1000 SPS events (incl. Branching) expected per year (10 fb^{-1})

Part VI

Conclusion

Conclusions

- THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

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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 and will feed in the European Strategy via the Physics Beyond Collider WG

Part VII

Backup slides

Further readings

Heavy-Ion Physics

- *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

- *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.