





A Fixed-Target Programme at the LHC

J.P. Lansberg

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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

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The AFTER@LHC program

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Part I

The AFTER@LHC programme

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Physics Reports 522 (2013) 239-255



Physics opportunities of a fixed-target experiment using LHC beams

S.J. Brodsky^a, F. Fleuret^b, C. Hadjidakis^c, J.P. Lansberg^{c,*}

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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

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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.

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

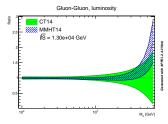
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Very large PDF uncertainties for $x \gtrsim 0.5$.

[could be crucial to characterise possible BSM discoveries]

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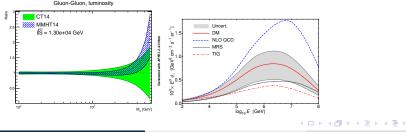


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· Proton charm content important to high-energy neutrino & cosmic-rays physics



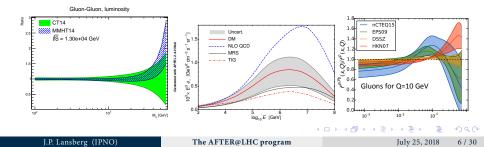
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- EMC effect is an open problem; studying a possible gluon EMC effect is essential
- · Relevance of nuclear PDF to understand the initial state of heavy-ion collisions



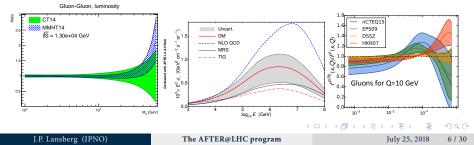
Advance our understanding of the high-x gluon, antiquark and heavy-quark content in the nucleon & nucleus

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

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where a single gluon carries most of its momentum



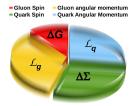
Advance our understanding dynamics and spin of gluons and quarks inside (un)polarised nucleons

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



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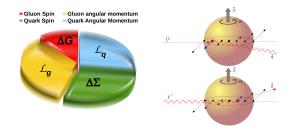
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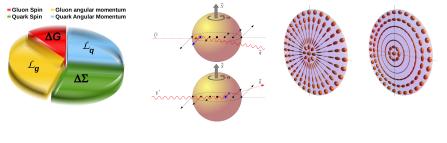
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Test of the QCD factorisation framework

Determination of the linearly polarised gluons in unpolarised protons

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

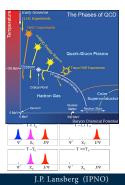


Heavy-ion collisions towards large rapidities

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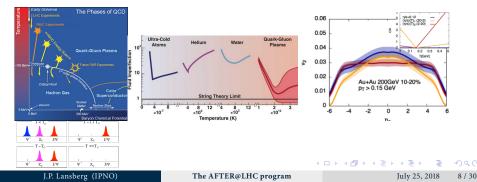
Heavy-ion collisions towards large rapidities

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



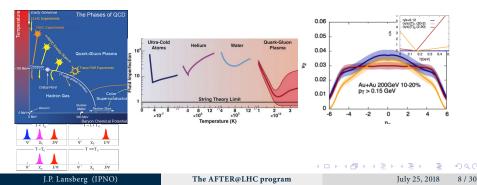
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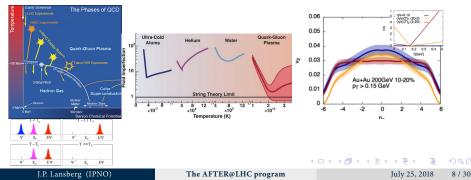
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- · Explore the longitudinal expansion of QGP formation
- Test the factorisation of cold nuclear effects from p + A to A + B collisions



Part III

Possible Implementations and Luminosities

J.P. Lansberg (IPNO)

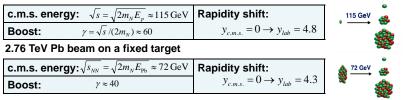
The AFTER@LHC program

July 25, 2018 9 / 30

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Energy range

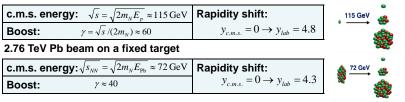
7 TeV proton beam on a fixed target



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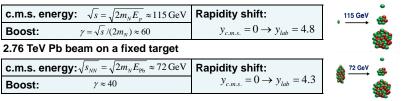


Such \sqrt{s} allow, for the first time, for systematic studies of *W* boson, bottomonia, p_T spectra, associated production, ..., in the fixed target mode

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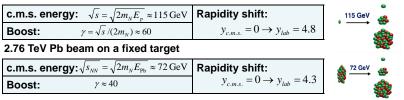
[particularly relevant for high energy beams]

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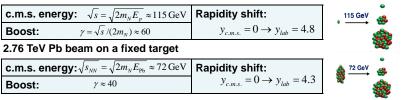
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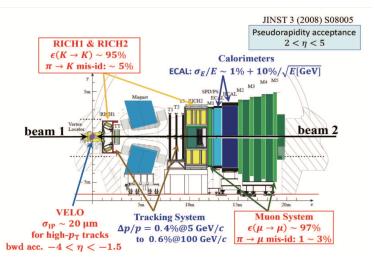
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• Allows for backward physics up to high $x_{target} (\equiv x_2)$ [uncharted for proton-nucleus; most relevant for p-p[†], with large $x^{\frac{1}{2}}$] [UPL Lansberg (IPNO)] The AFTER@LHC program July 25, 2018 10/30

LHCb acceptance for various colliding modes

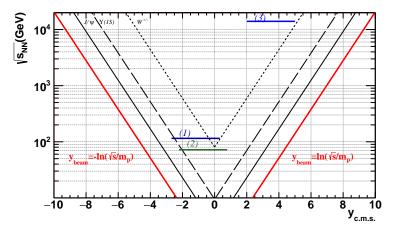


J.P. Lansberg (IPNO)

July 25, 2018 11 / 30

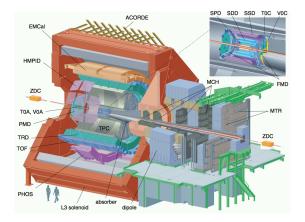
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LHCb acceptance for various colliding modes



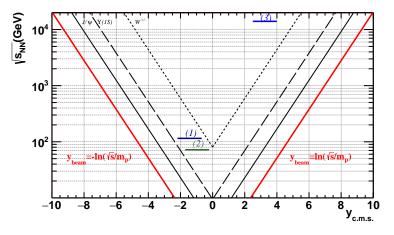
- (1) Fixed-target using p beam, $E_p = 7$ TeV
- (2) Fixed-target using Pb beam, $E_{Pb} = 2.76$ A.TeV
- (3) Collider using p beams, $E_p = 7$ TeV

ALICE muon acceptance for various colliding modes



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

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 - · can be installed in one of the existing LHC caverns, and coupled to existing experiments
 - · 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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- \rightarrow The internal solid target & beam split option: similar possibilities; the latter is cleaner
- \rightarrow The gas target is the best for polarised target and satisfactory for heavy-ion studies

$$\begin{array}{ccc} pp & pA & PbA \\ \mathcal{O}(0.1 - 10 \text{ fb}^{-1}\text{yr}^{-1}) & \mathcal{O}(0.1 - 1 \text{ fb}^{-1}\text{yr}^{-1}) & \mathcal{O}(1 - 50 \text{ nb}^{-1}\text{yr}^{-1}) \end{array}$$



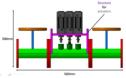
Solid targets



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

اس Crystal at -72 m – 350 µrad	
	SI
Alice to iP2 - Crystal = 350 µrad <mark>⊕ -72 m from iP2</mark> E = 6.5 TeV - Emittance = 5.05e-10 m rad, sigma = 6	
005 Target 004 Machine aperture options	300.00
	236.00
est Circulating berm	10000
	-100.00
	-200.00
4.65 s(m)	-305.00
max deflection 350 µrad ^{22/7} ññäx distance target-beam axis ~13mn ^{Galaxco}	11

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

	Internal gas target			Internal solid target	Beam splitting	Beam extraction	
Characteristics	aracteristics SMOG Gas Jet Stor		Storage Cell	with beam halo			
Run duration ¹⁴	*	**	**	*	**	* * *	
Parasiticity ¹⁵	***	**	**	*	**	* * *	
Integrated lumi- nosity ¹⁶	*	**	**	*	**	* * *	
Absolute lumi- nosity determina- tion ¹⁷	*	**	**	*	**	* * *	
Target versality ¹⁸	**	**	***	**	**	* * *	
Target polarisa- tion 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

			Beam					
Target			р			Pb		
			L	Δt	∫L	L	Δt	∫£
		$[cm^{-2}s^{-1}]$	[s]	[nb ⁻¹]	$[cm^{-2}s^{-1}]$	[s]	$[nb^{-1}]$	
Internal gas target -	SMOG	He, Ne, Ar	5.8 ×10 ²⁹	2.5×10^5	145	7.4 ×10 ²⁵	10 ⁶	0.074
		H^{\uparrow}	4.3 ×10 ³⁰	107	4.3×10^{4}	5.6 ×10 ²⁶	10 ⁶	0.56
	Gas-Jet	H_2	$3.6 \ge (10^{33} - 10^{34})$	107	$3.6 \ge (10^7 - 10^8)$	$4.66 \ge (10^{29} - 10^{30})$	106	466-4660
		\mathbf{D}^{\uparrow}	4.3 ×10 ³⁰	107	4.3×10^{4}	5.6×10^{26}	10^{6}	0.56
		³ He [↑]	3.6 ×10 ³²	107	3.6×10^{6}	4.66×10^{28}	10^{6}	47
	Storage Cell	H^{\uparrow}	0.92×10^{33}	107	9.2×10^{6}	1.18 ×10 ²⁹	106	118
		H_2	5.8 ×10 ³³	107	5.8×10^{7}	7.5×10^{29}	10^{6}	750
		\mathbf{D}^{\uparrow}	1.1 ×10 ³³	107	1.1×10^{7}	1.4×10^{29}	106	140
		³ He [↑]	3.7 ×10 ³³	107	3.7×10^{7}	4.7×10^{29}	10^{6}	474
		Xe	2.34×10^{32}	107	2.34×10^{6}	3.0×10^{28}	10^{6}	30
Internal solid	Wire	С	2.8 ×10 ³⁰	107	2.8×10^{4}	5.6 ×10 ²⁶	106	0.56
target with	Target	Ti	1.4×10^{30}	107	1.4×10^4	2.8×10^{26}	10^{6}	0.28
beam halo	(0.5 mm)	W	1.6 ×10 ³⁰	107	1.6×10^4	3.1×10^{26}	10^{6}	0.31
Beam splitting	E1039	NH_3^{\uparrow}	7.2 ×10 ³¹	107	7.2×10^{5}	1.4×10^{28}	10 ⁶	14
		ND_3^{\uparrow}	7.2×10^{31}	107	7.2×10^{5}	1.4×10^{28}	10^{6}	14
	Unpolarised	С	2.8 ×10 ³¹	107	2.8×10^{5}	5.6 ×10 ²⁷	106	5.6
	solid	Ti	1.4×10^{31}	107	1.4×10^{5}	2.8×10^{27}	10^{6}	2.8
	target (5 mm)	W	1.6×10^{31}	107	1.6×10^{5}	3.1×10^{27}	10^{6}	3.1
Beam extraction	E1039	NH_3^{\uparrow}	7.2 ×10 ³¹	107	7.2×10^{5}	1.4 ×10 ²⁸	106	14
		ND_3^{\uparrow}	7.2×10^{31}	107	7.2×10^5	1.4×10^{28}	10^{6}	14
	COMPASS	NH_3^{\uparrow}	1.0 ×10 ³³	107	1.0×10^{7}	2.0×10^{29}	106	200
		butanol [↑]	2.7 ×10 ³²	107	2.7×10^{6}	5.3 ×10 ²⁸	10^{6}	53

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Part IV

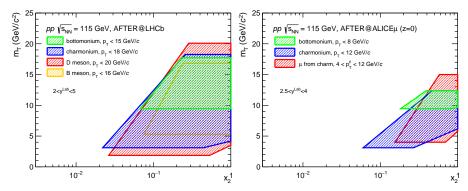
Some FoM for Heavy-Ion Studies

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The AFTER@LHC program

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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]

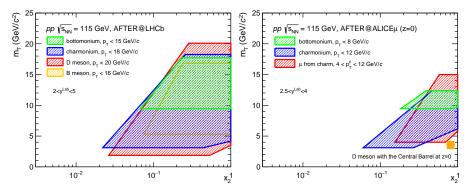
NB: The coverage depends on the target position

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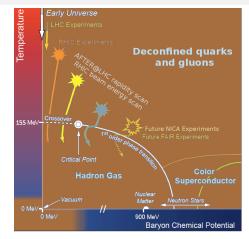
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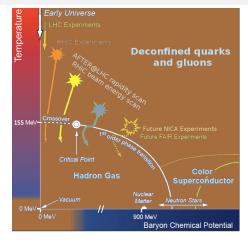
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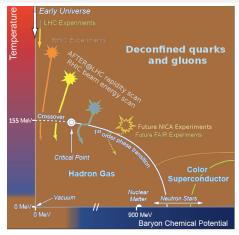
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• Energy domain between SPS and RHIC



July 25, 2018 21 / 30

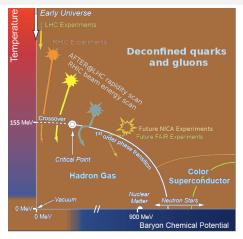
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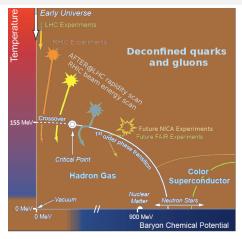
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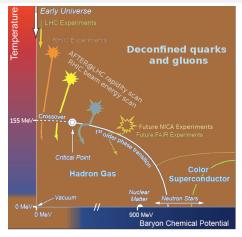
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- Handle on more quarkonium states
 (e.g. χ_{c,b}, η_c) and on open charm and beauty



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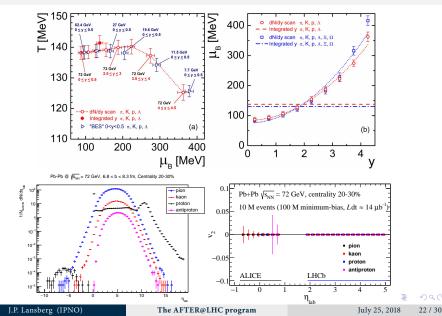
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Even with 1 billion J/ψ 's, the *direct* J/ψ yield will remain unprecise by 30 % !

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Rapidity scan



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

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

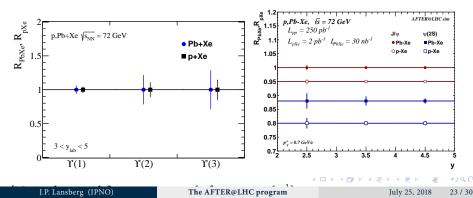
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B.Trzeciak et al.Few-Body Syst (2017) 58:148

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

- Like for nPDF studies, multiple quarkonium studies are needed to study the QGP formation at a new energy range between SPS and RHIC
- Clear need for a reliable baseline with *pA* systems
- Statistical-uncertainty projections (accounting for background subtraction)



Part V

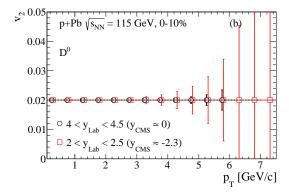
Some FoM for Cold Nuclear Matter Studies

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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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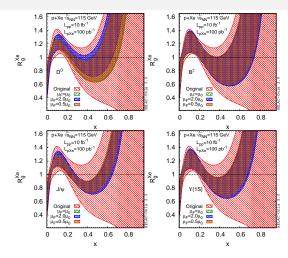
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[NB: initial nPDF uncertainties for *x* > 0.1 are underestimated; simply no data exist there]

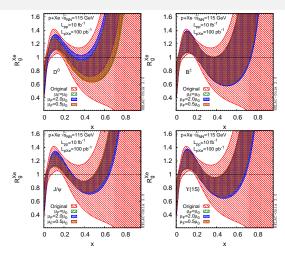


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• Similar studies for the proton PDFs are yet to be done along the lines of the studies carried out for low-*x* gluon at the LHC PROSA Coll. Eur.Phys.J. C75 (2015)

396; R. Gauld, J. Rojo PRL 118 (2017) 072001



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High-*x* frontier

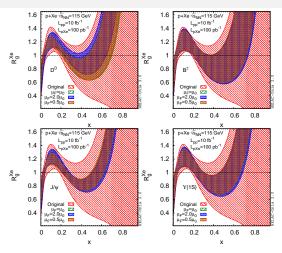
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396; R. Gauld, J. Rojo PRL 118 (2017) 072001

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



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

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	pН	PbH
Photon-emitter	proton	Lead
$\sigma_{J/\psi}^{tot}$ (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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# events	200 000	1000

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

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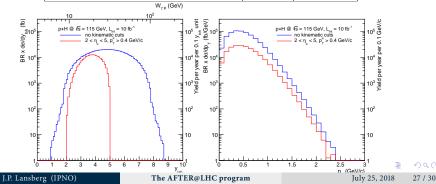
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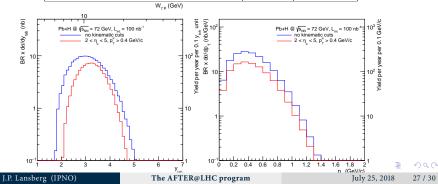
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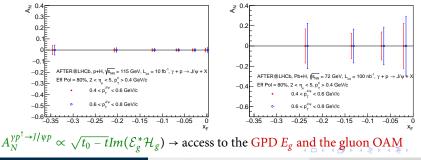
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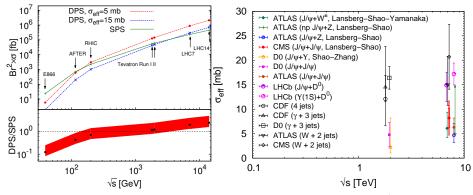
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DPS studies in a new energy regime

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



About 1000 SPS events (incl. Branching) expected per year (10 fb⁻¹)

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Part VI

Conclusion

J.P. Lansberg (IPNO)

The AFTER@LHC program

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July 25, 2018 29 / 30

• 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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• Our review is now out and will feed in the European Strategy via the Physics Beyond Collider WG

Part VII

Backup slides

J.P. Lansberg (IPNO)

The AFTER@LHC program

 Image: Image:

Heavy-Ion Physics

- Gluon shadowing effects on J/ψ and Y production in p+Pb collisions at √s_{NN} = 115 GeV and Pb+p collisions at √s_{NN} = 72 GeV at AFTER@LHC by R. Vogt. Adv.Hi.En.Phys. (2015) 492302.
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The AFTER@LHC program

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