Precision proton-proton and proton-nucleus collision studies at A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)

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Part I

Introduction

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- They exhibit 4 decisive features,
  - accessing the high Feynman x_F domain ($x_F \equiv \frac{p_z}{p_{z\,\max}}$)
  - achieving high luminosities with dense targets,
  - varying the atomic mass of the target almost at will,
  - polarising the target.

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- Good thing: small forward detector $\equiv$ large acceptance
- Bad thing: high multiplicity $\Rightarrow$ absorber $\Rightarrow$ physics limitation

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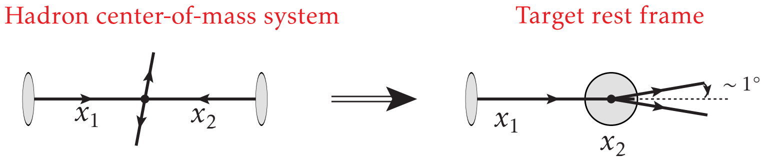

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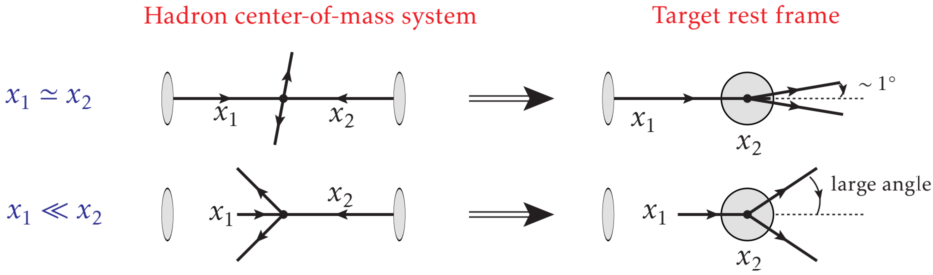

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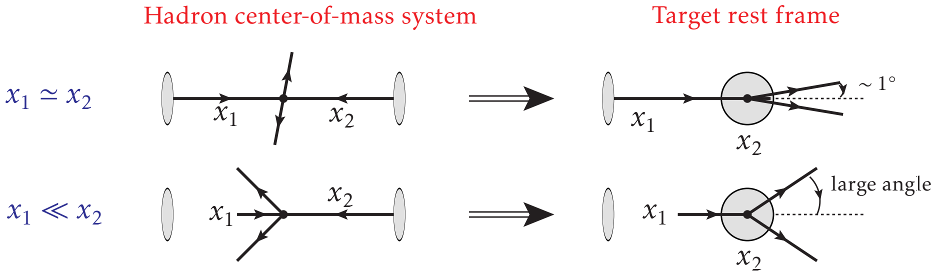

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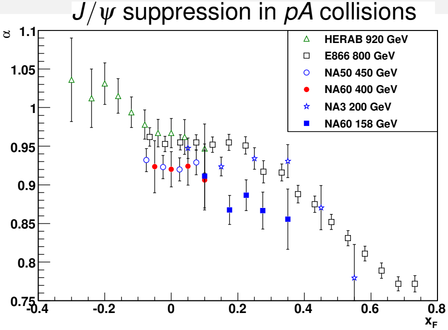

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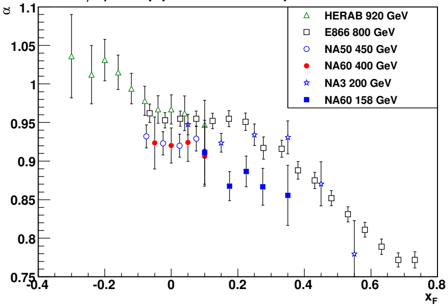

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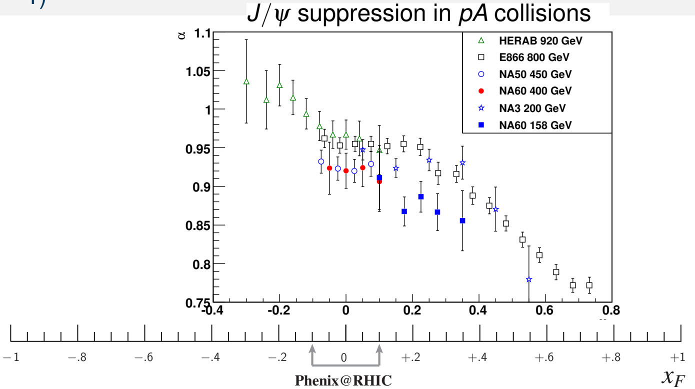

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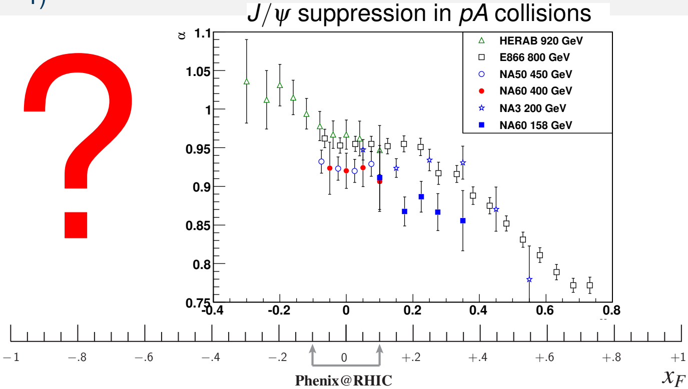

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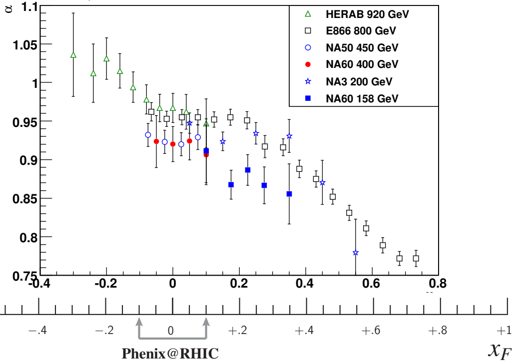

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- If we measure $\Upsilon(b\bar{b})$ at $y_{\rm cms} \simeq -2.5 \Rightarrow x_F \simeq \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{\rm cms}) \simeq -1$

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★ The LHC beam may be extracted using “Strong crystalline field” **without any decrease in performance of the LHC !**

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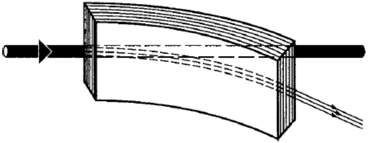

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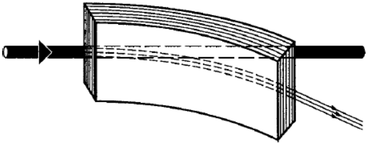

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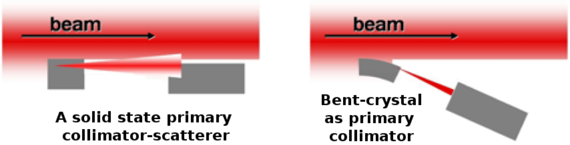

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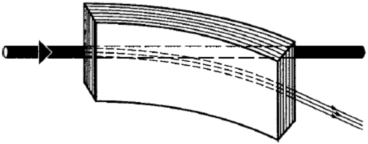

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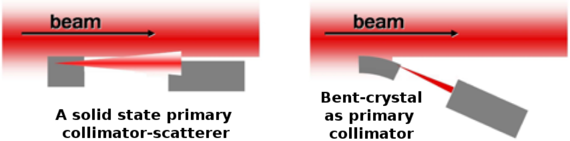

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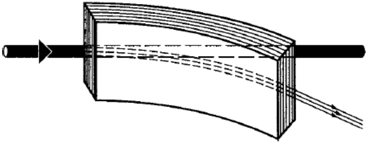

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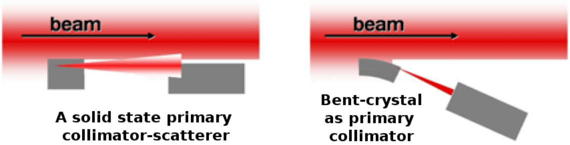

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★ 2 crystals to be installed in the LHC beampipe in 2014

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Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\int\mathcal{L}$ (pb^{-1}.yr^{-1})
Sol. H_2	0.09	1	**26**	**260**
Liq. H_2	0.07	1	**20**	**200**
Liq. D_2	0.16	2	**24**	**240**
Be	1.85	9	**62**	**620**
Cu	8.96	64	**42**	**420**
W	19.1	185	**31**	**310**
Pb	11.35	207	**16**	**160**

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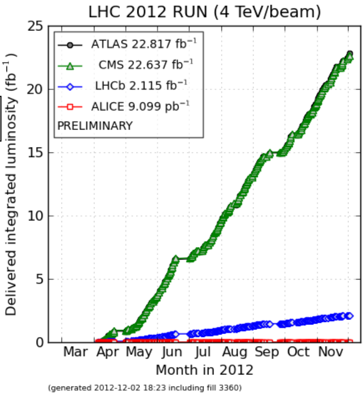

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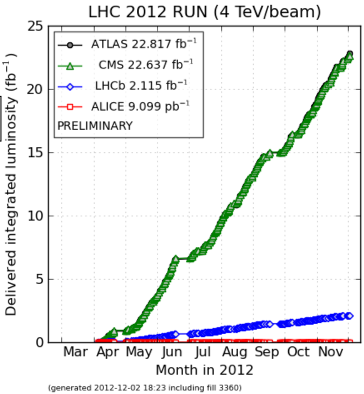

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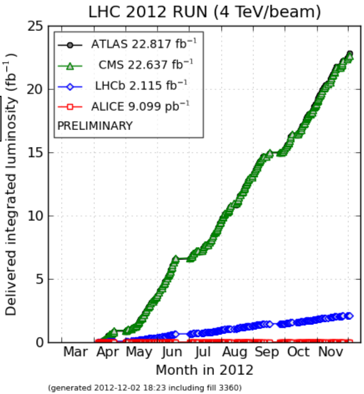

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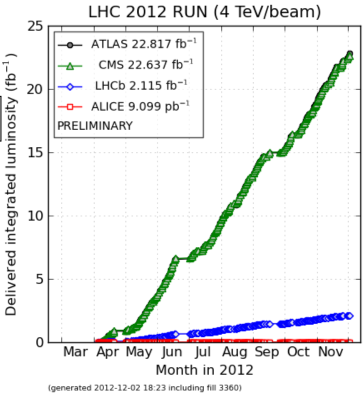
(roughly 10 times that planned for the LHC)



Part II

AFTER: flagship measurements

Key studies: gluons in the proton

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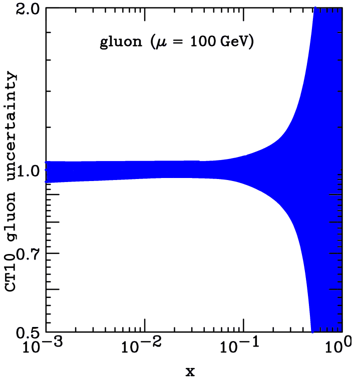

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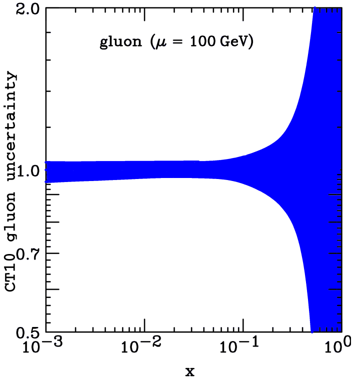

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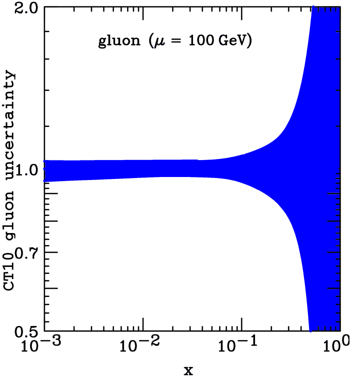

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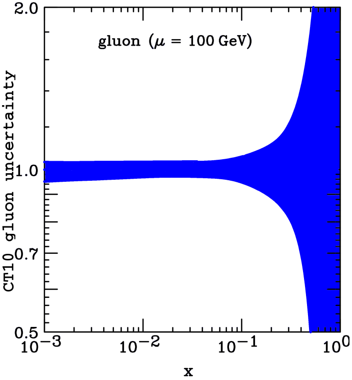

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- Isolated photon

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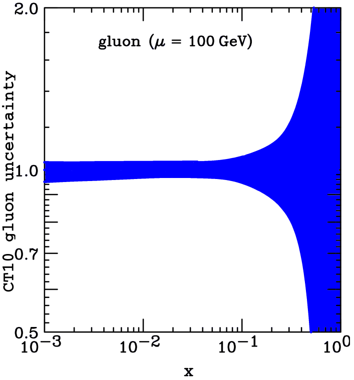

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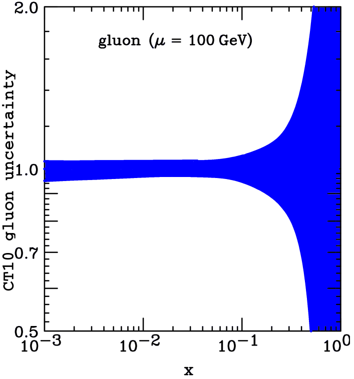

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Multiple probes needed to **check factorisation**

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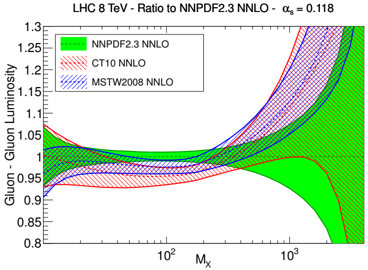

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Large-x gluons: important for BSM searches at the LHC

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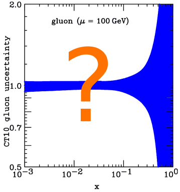

Gluon PDF for the neutron unknwon

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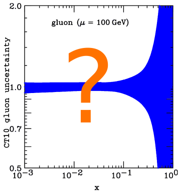

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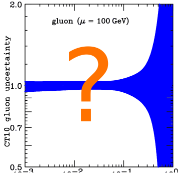

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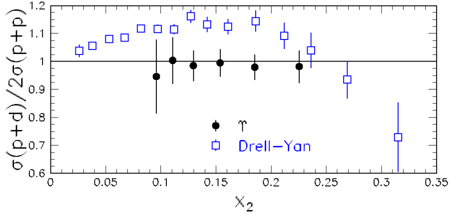

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- using $\Upsilon \to Q^2 \simeq 100$ GeV^2
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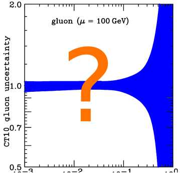

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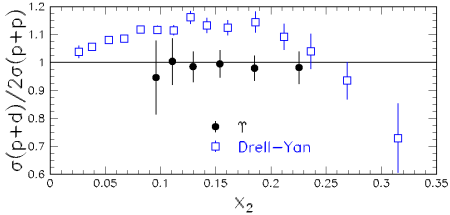

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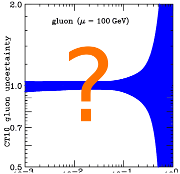

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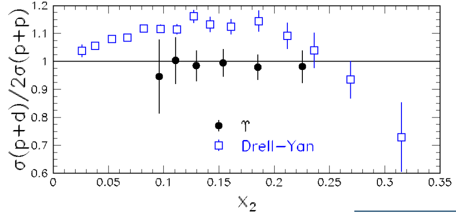

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target	yearly lumi	$\mathcal{B}\frac{dN_{J/\psi}}{dy}$	$\mathcal{B}\frac{dN_{\Upsilon}}{dy}$
1m Liq. H_2	20 fb^{-1}	4.0×10^8	9.0×10^5
1m Liq. D_2	24 fb^{-1}	9.6×10^8	1.9×10^6

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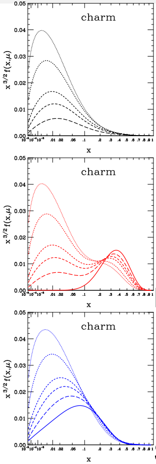

DGLAP

BHPS

Sea-like

3 sets from CTEQ6c (Pumplin *et al.*)

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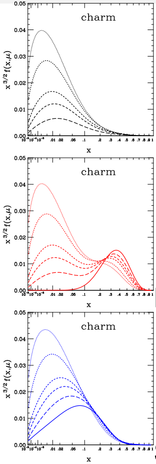

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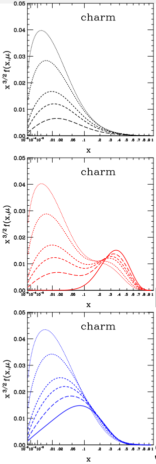

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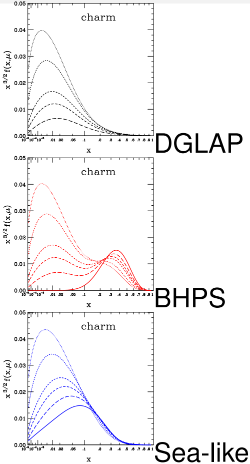

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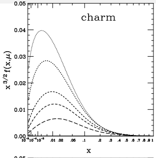

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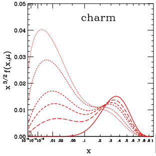

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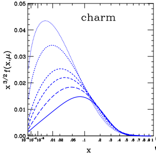

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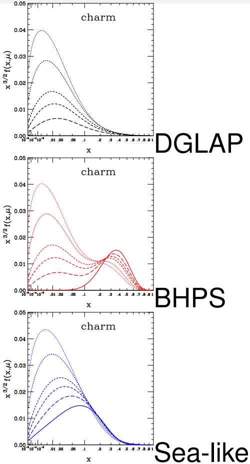

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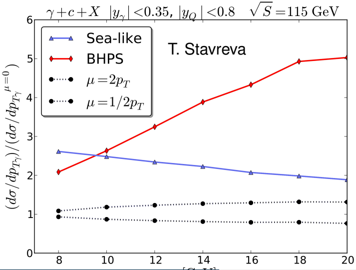

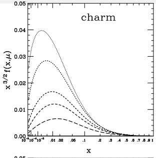

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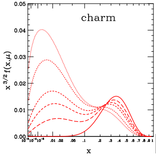

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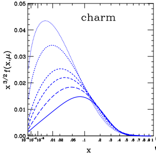

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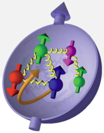

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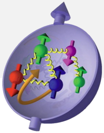

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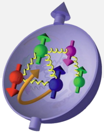

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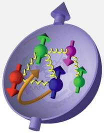

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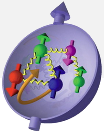

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Access to gluon Boer-Mulder functions

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PHYSICAL REVIEW D **86**, 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
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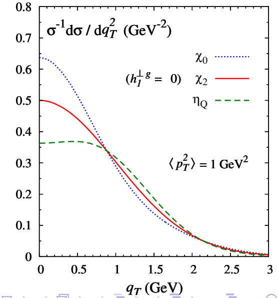

SSA in Drell-Yan studies with AFTER@LHC

➟ Relevant parameters for the future proposed polarized DY experiments.

S.J. Brodsky, F. Fleuret, C. Hadjidakis, JPL, Phys. Rep. 522 (2013) 239
V. Barone, F. Bradamante, A. Martin, Prog. Part. Nucl. Phys. 65 (2010) 267.

Experiment	particles	energy (GeV)	$\sqrt{s}$ (GeV)	$x_p^{\uparrow}$	$\mathscr{L}$ ($\text{nb}^{-1}\text{s}^{-1}$)
AFTER	$p+p^{\uparrow}$	7000	115	$0.01 \div 0.9$	1
COMPASS	$\pi^{\pm}+p^{\uparrow}$	160	17.4	$0.2 \div 0.3$	2
COMPASS (low mass)	$\pi^{\pm}+p^{\uparrow}$	160	17.4	~ 0.05	2
RHIC	$p^{\uparrow}+p$	collider	500	$0.05 \div 0.1$	0.2
J–PARC	$p^{\uparrow}+p$	50	10	$0.5 \div 0.9$	1000
PANDA (low mass)	$\bar{p}+p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	0.2
PAX	$p^{\uparrow}+\bar{p}$	collider	14	$0.1 \div 0.9$	0.002
NICA	$p^{\uparrow}+p$	collider	20	$0.1 \div 0.8$	0.001
RHIC Int.Target 1	$p^{\uparrow}+p$	250	22	$0.2 \div 0.5$	2
RHIC Int.Target 2	$p^{\uparrow}+p$	250	22	$0.2 \div 0.5$	60

➟ For AFTER, the numbers correspond to a 50 cm polarized *H* target.

➟ $\ell^+\ell^-$ angular distribution: separation Sivers vs. Boer-Mulders effects

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Expe
AFT
COM
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PAX
NICA
RHI Int.T
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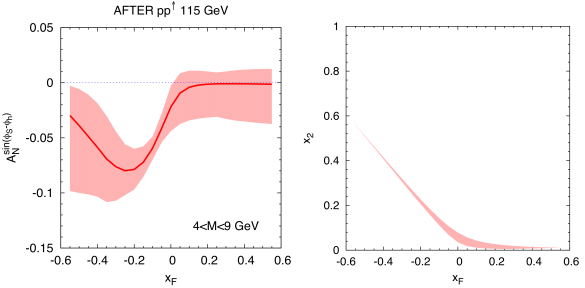
expected Sivers asymmetry in
D-Y@AFTER, sign change,
no TMD evolution



M. Anselmino, ECT*, Feb. 2013 (Courtesy U. d'Alessio)

➟ For AFTER, t

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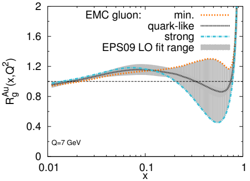

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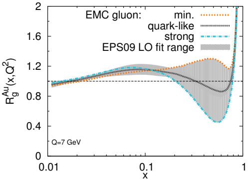

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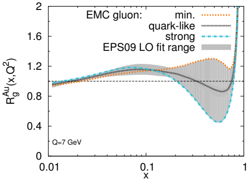

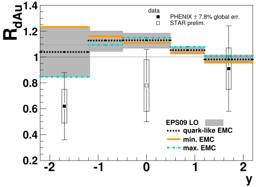

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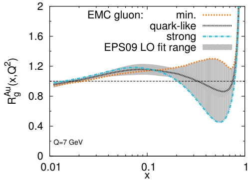

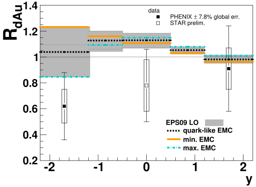

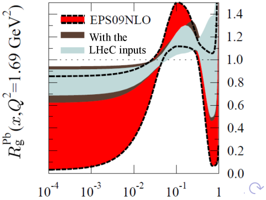

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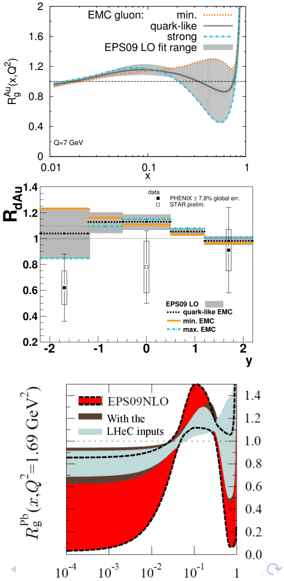
- Unique potential for gluons at $x > 0.1$



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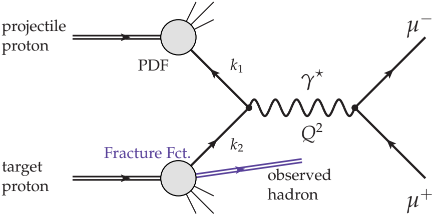

L. Trentadue, G. Veneziano, PLB 323 (1994) 201
F. Ceccopieri, L. Trentadue, PLB 668 (2008) 319

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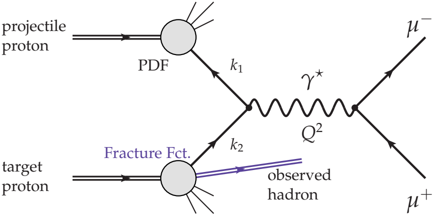

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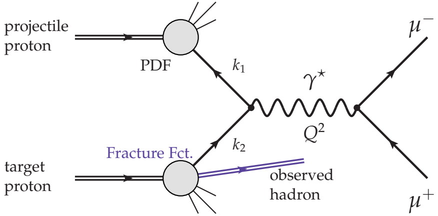

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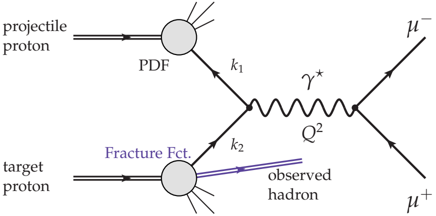

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- good prospects for fracture-function studies with AFTER

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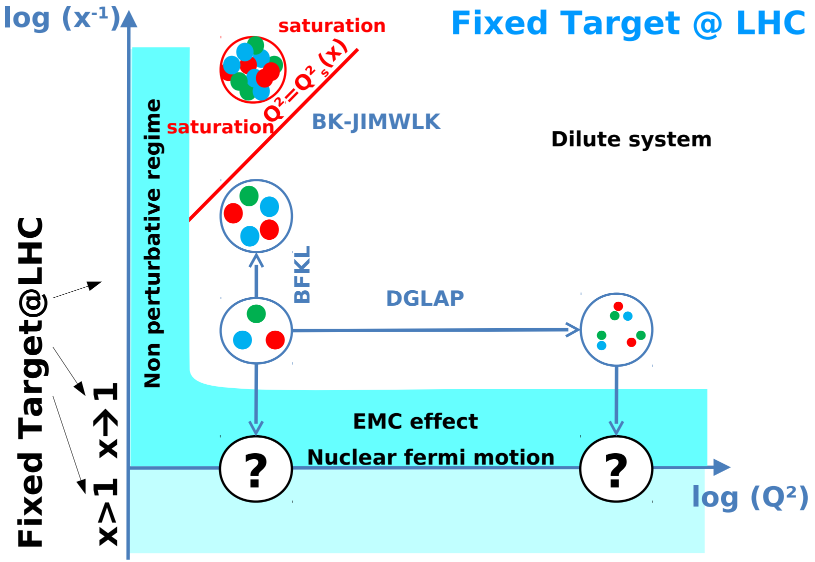

log (x⁻¹)
saturation
Fixed Target @ LHC
$Q^2=Q^2_s(x)$
saturation
BK-JIMWLK
Dilute system
Non perturbative regime
Fixed Target@LHC
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x>1 x→1
EMC effect
Nuclear fermi motion
?
?
log (Q²)

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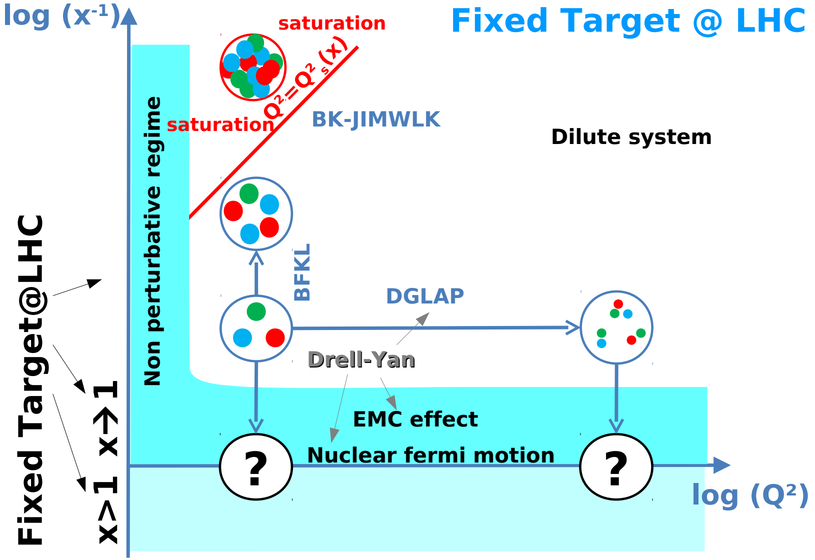
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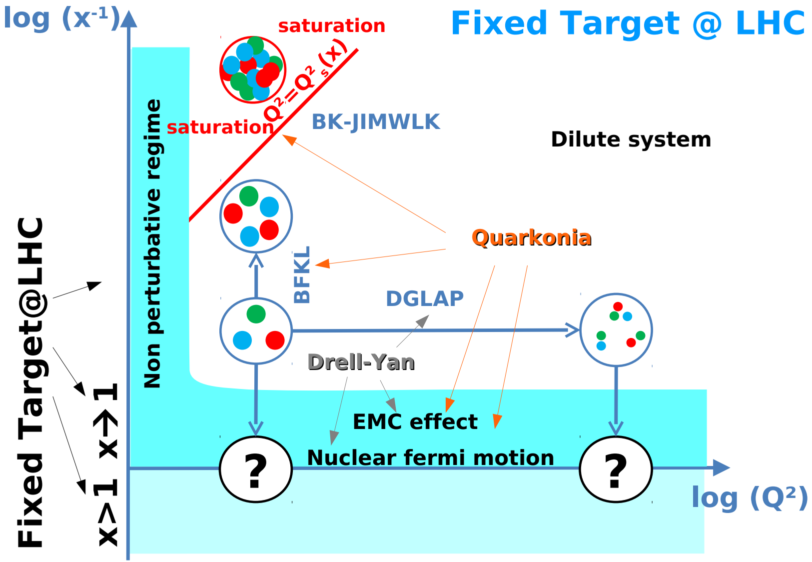

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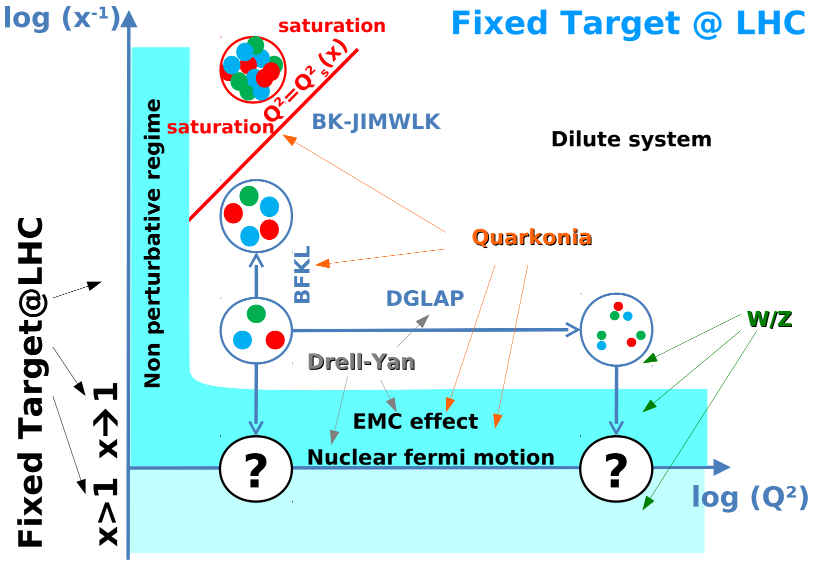
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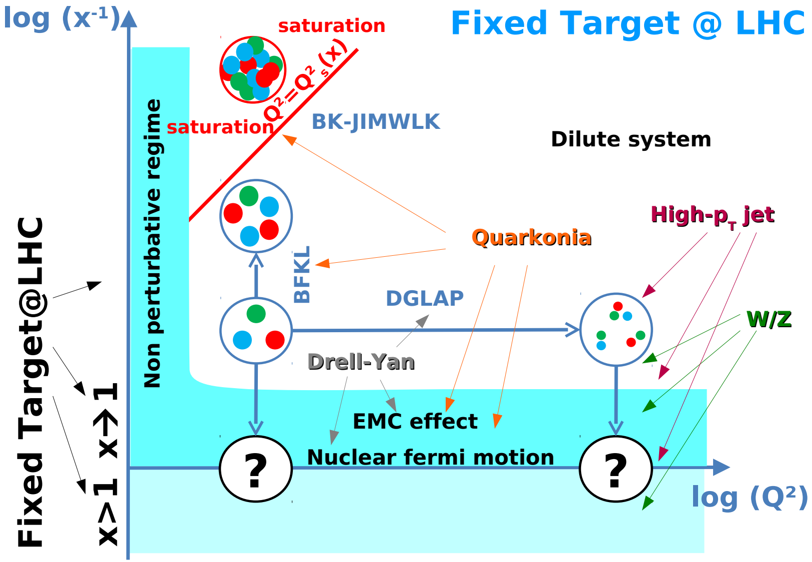

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More details in

Physics Reports 522 (2013) 239–255

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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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[b] Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France
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      3.2.2. Jets
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Part III

First simulations

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See e.g. M. Adinolfi's talk, WG2, Thursday at 8H50

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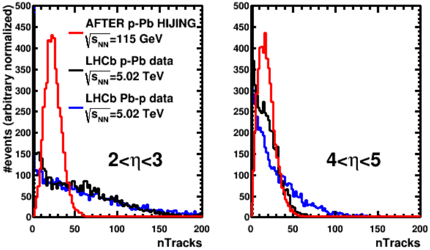

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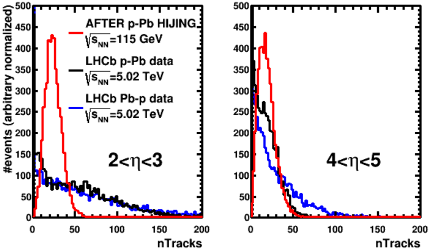

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- Very encouraging indication that the boost is not issue, but really an asset

Some quarkonium and decay-product distributions at 115 GeV in the backward hemisphere ($y_{\rm Lab} < 4.8$)

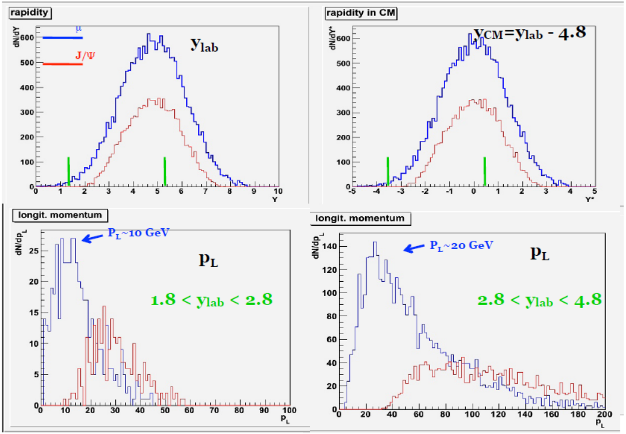
Pythia 6.4.21: p (7 TeV) + p → J/ψ (isub=86)

J/Ψ → $\mu^+\mu^-$

μ from J/ψ for $1.3 < y_{lab} < 5.3$

$P_T \sim$ 1.7 GeV

$P_L \sim$ 62 GeV



Longitudinal muon momentum

$1.3 < y_{lab} < 3.3$

p_L(max) ~ 16 (50) GeV

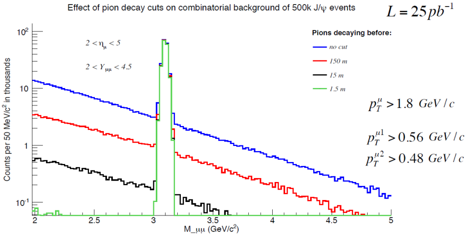
$3.3 < y_{lab} < 4.3$

p_L(max)~ 45 (150) GeV

$4.3 < y_{lab} < 5.3$

p_L(max)~ 120 (300) GeV

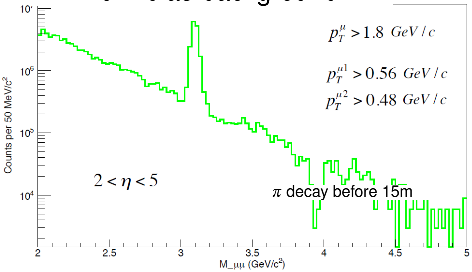
First look at some backgrounds



A few hours of data taking with 1 m H2 target

PYTHIA v. 8.183, process: Charmonium:gg2QQbar[3Si(1)]g at $\sqrt{s} = 115 GeV$

Minimum bias background



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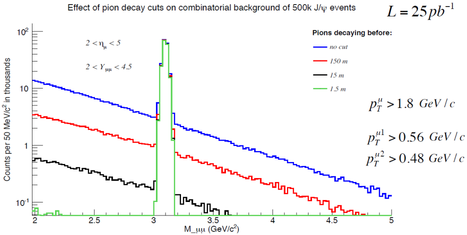

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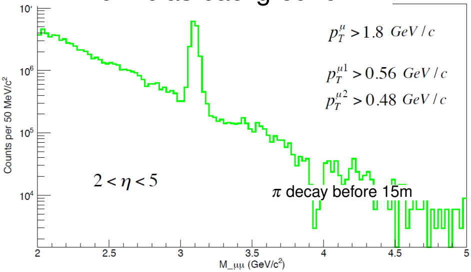
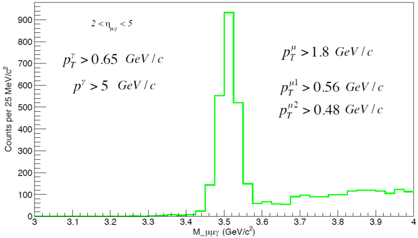


60000 χ_c events



$\chi_c \to \gamma J/\psi \to (\gamma)\mu\mu$

$3.062 GeV/c^2 < M_{\mu\mu} < 3.12 GeV/c^2$

Additional cuts can be added (vertex, etc.)

Accessing the large *x* glue with quarkonia:

PYTHIA simulation
$\sigma(y) / \sigma(y=0.4)$
statistics for one month
5% acceptance considered

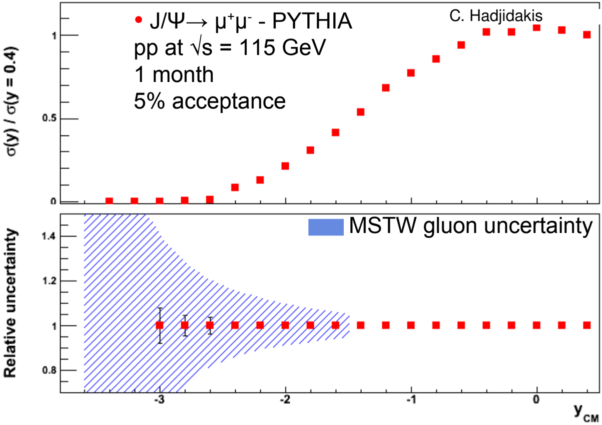
Statistical relative uncertainty
Large statistics allow to access very backward region

Gluon uncertainty from MSTWPDF
- only for the gluon content of the target
- assuming

$$x_g = M_{J/\psi}/\sqrt{s}\, e^{-y_{CM}}$$

J/Ψ
$y_{CM} \sim 0 \rightarrow x_g = 0.03$
$y_{CM} \sim -3.6 \rightarrow x_g = 1$

Υ: larger x_g for same y_{CM}
$y_{CM} \sim 0 \rightarrow x_g = 0.08$
$y_{CM} \sim -2.4 \rightarrow x_g = 1$



⇒ Backward measurements allow to access large x gluon pdf

Assuming that we understand the quarkonium-production mechanisms

Part IV

Conclusion and outlooks

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- Very good complementarity with electron-ion programs

Outlooks

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  Webpage: **http://after.in2p3.fr**

Further readings

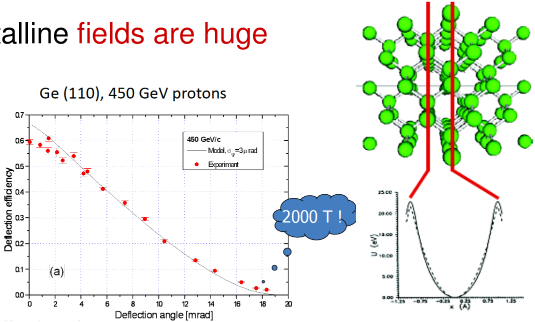
- *Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC*
  By G. Chen *et al.*. [arXiv:1401.6269 [hep-ph]]. Phys.Rev. D89 (2014) 074020.
- *Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams.*
  By J.P. Lansberg, S.J. Brodsky, F. Fleuret, C. Hadjidakis. [arXiv:1204.5793 [hep-ph]]. Few Body Syst. 53 (2012) 11.
- *Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)*
  By T. Liu, B.Q. Ma. [arXiv:1203.5579 [hep-ph]]. Eur.Phys.J. C72 (2012) 2037.
- *Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER*
  By D. Boer, C. Pisano. [arXiv:1208.3642 [hep-ph]]. Phys.Rev. D86 (2012) 094007.
- *Ultra-relativistic heavy-ion physics with AFTER@LHC*
  By A. Rakotozafindrabe, *et al.* . [arXiv:1211.1294 [nucl-ex]]. Nucl.Phys. A904-905 (2013) 957c.
- *Spin physics at A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)*
  By A. Rakotozafindrabe, *et al.* .[arXiv:1301.5739 [hep-ex]]. Phys.Part.Nucl. 45 (2014) 336.
- *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.

Part V

Backup slides

The beam extraction

- Inter-crystalline fields are huge



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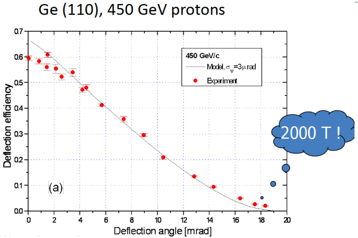

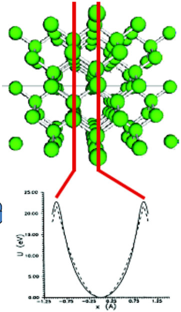

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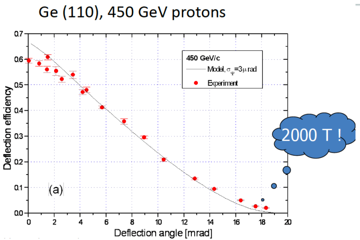

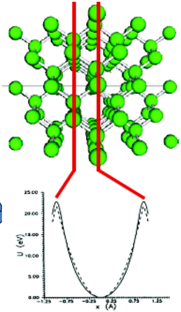

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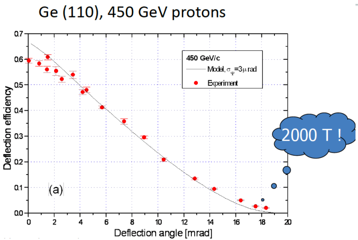
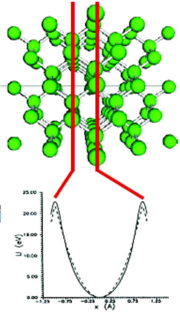
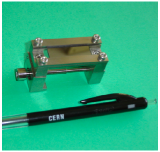




- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:



Beam extraction

- **Beam extraction @ LHC**

… there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

… The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of $\simeq 7\sigma$ to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

… ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies

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Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39
NIM B Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *
Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, Aarhus C DK-8000, Denmark

Received 9 September 2004; received in revised form 6 January 2005
Available online 24 February 2005

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

A few figures on the (extracted) proton beam

- Beam loss: $10^9\ p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8\ p^+ s^{-1}$ (1/2 the beam loss) **E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31**

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  - the crystal sees 2808×11000 s^{-1} $\simeq 3.10^7$ bunches s^{-1}
  - one extracts $5.10^8/3.10^7 \simeq 15p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%,

no pile-up !

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  - $5 \times 10^8 p^+ \times 3600$ s h^{-1} $\times 10$ h $= 1.8 \times 10^{13} p^+$ fill^{-1}
  - This means $1.8 \times 10^{13}/3.2 \times 10^{14} \simeq$ 5.6% of the p^+ in the beam

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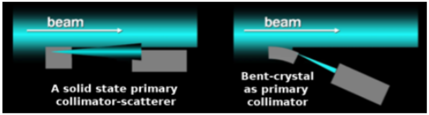
- similar figures for the Pb-beam extraction

The beam extraction: news

[S. Montesano, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013]

Goal : assess the possibility to use bent crystals as primary collimators in hadronic accelerators and colliders

UA9 installation in the SPS



Prototype crystal collimation system at SPS :

- local beam loss reduction (5÷20x reduction for proton beam)
- beam loss map show average loss reduction in the entire SPS ring
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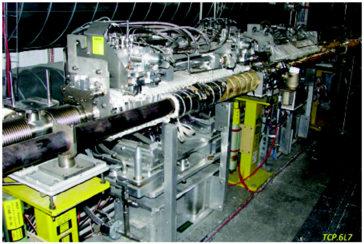

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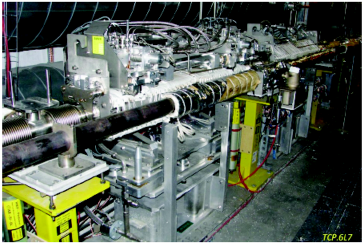

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Towards an installation in the LHC : propose and install during LS1 a min. number of devices

- 2 crystals

Long term plan is ambitious : propose a collimation system based on bent crystals for the upgrade of the current LHC collimation system

Luminosities

- Instantaneous Luminosity:
  $\mathscr{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times \mathscr{N}_A)/A$
  $\Phi_{beam} = 2 \times 10^5$ Pb s^{-1}, $\ell = 1$ cm (target thickness)
- Integrated luminosity $\int dt \mathscr{L} = \mathscr{L} \times 10^6$ s for Pb
- Expected luminosities with 2×10^5Pb s^{-1} extracted (1cm-long target)

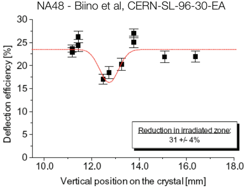
Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (mb^{-1}.s^{-1})=$\int\mathcal{L}$ (nb^{-1}.yr^{-1})
Sol. H_2	0.09	1	**11**
Liq. H_2	0.07	1	**8**
Liq. D_2	0.16	2	**10**
Be	1.85	9	**25**
Cu	8.96	64	**17**
W	19.1	185	**13**
Pb	11.35	207	**7**

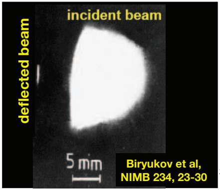
- Planned lumi for PHENIX Run15AuAu 2.8 nb^{-1} (0.13 nb^{-1} at 62 GeV)
- Nominal LHC lumi for PbPb 0.5 nb^{-1}

Simone Montesano - February 11th, 2013 - Physics at AFTER using the LHC beams

Crystal resistance to irradiation

- **IHEP U-70** (Biryukov et al, NIMB 234, 23-30):
  - 70 GeV protons, 50 ms spills of **10^{14} protons every 9.6 s**, several minutes irradiation
  - equivalent to 2 nominal LHC bunches for 500 turns every 10 s
  - 5 mm silicon crystal, **channeling efficiency unchanged**
- **SPS North Area - NA48** (Biino et al, CERN-SL-96-30-EA):
  - 450 GeV protons, 2.4 s spill of 5 x 10^{12} protons every 14.4 s, one year irradiation, **2.4 x 10^{20} protons/cm^2** in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - 10 x 50 x 0.9 mm^3 silicon crystal, 0.8 x 0.3 mm^2 area irradiated, **channeling efficiency reduced by 30%**.
- **HRMT16-UA9CRY** (HiRadMat facility, November 2012):
  - 440 GeV protons, up to 288 bunches **in 7.2 μs**, 1.1 x 10^{11} protons per bunch (**3 x 10^{13} protons** in total)
  - energy deposition comparable to an asynchronous beam dump in LHC
  - 3 mm long silicon crystal, **no damage to the crystal after accurate visual inspection**, more tests planned to assess possible crystal lattice damage
    - **accurate FLUKA simulation of energy deposition** and residual dose





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S. Montesano (CERN - EN/STI) @ ECT* Trento workshop, Physics at AFTER using the LHC beams (Feb. 2013)

The lead-ion beam

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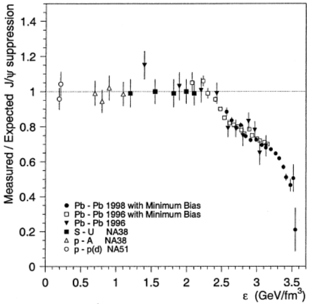

Fig. 7. Measured J/ψ production yields, normalised to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. The data is shown as a function of the energy density reached in the several collision systems.

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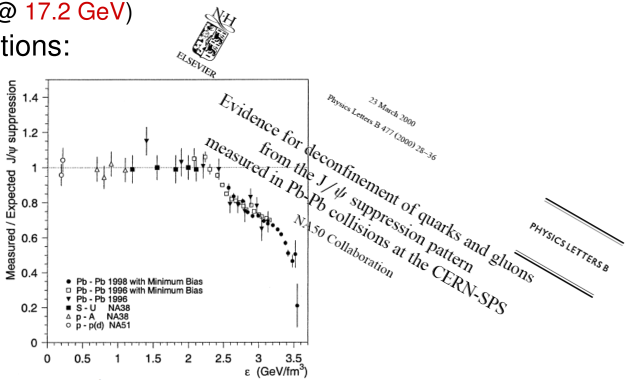

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AFTER, among other things, a quarkonium observatory in *pp*

- Interpolating the world data set:

Target	$\int\mathcal{L}$ ($fb^{-1}.yr^{-1}$)	N(J/Ψ) yr^{-1} = $A\mathcal{L}\mathcal{B}\sigma_\Psi$	N(Υ) yr^{-1} = $A\mathcal{L}\mathcal{B}\sigma_\Upsilon$
1 m Liq. H_2	20	$4.0\ 10^8$	$8.0\ 10^5$
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- Probe of the (very) large *x* in the target

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PHYSICAL REVIEW D VOLUME 37, NUMBER 5 1 MARCH 1988

Structure-function analysis and ψ, jet, W, and Z production: Determining the gluon distribution

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(Received 27 July 1987)

We perform a next-to-leading-order structure-function analysis of deep-inelastic μN and νN scattering data and find acceptable fits for a range of input gluon distributions. We show three equally acceptable sets of parton distributions which correspond to gluon distributions which are (1) “soft,” (2) “hard,” and (3) which behave as $xG(x) \sim 1/\sqrt{x}$ at small x. J/ψ and prompt photon hadroproduction data are used to discriminate between the three sets. Set 1, with the “soft”-gluon distribution, is favored. W, Z, and jet production data from the CERN collider are well described but do not distinguish between the sets of structure functions. The precision of the predictions for σ_W and σ_Z allow the collider measurements to yield information on the number of light neutrinos and the mass of the top quark. Finally we discuss how the gluon distribution at very small x may be directly measured at DESY HERA.

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- Production puzzle $\rightarrow$ quarkonium not used anymore in global fits
- With systematic studies, one would restore its status as gluon probe

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  - not to mention ratio with **open charm, Drell-Yan,** etc ...

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- One should be careful with factorization breaking effects:

This calls for multiple measurements to (in)validate factorization

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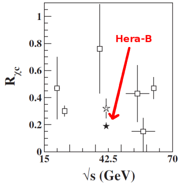

HERA-B PRD 79 (2009) 012001, and ref. therein

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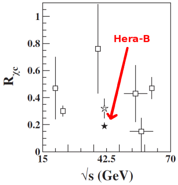

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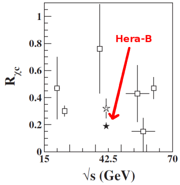

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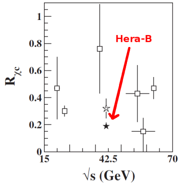

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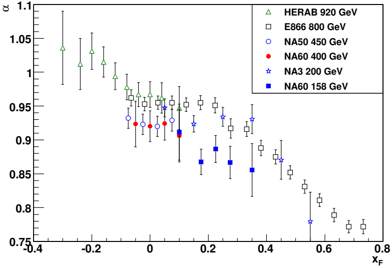
- the possibilities for $c\bar{c}$ recombination
  - Open charm studies are difficult where recombination matters most
    i.e. at low P_T
  - Only indirect indications –from the y and P_T dependence of R_{AA}–
    that recombination may be at work
  - CNM effects may show a non-trivial y and P_T dependence . . .

SPS and Hera-B

– J/ψ data in pA collisions



NA60 Phys.Lett. B 706 (2012) 263
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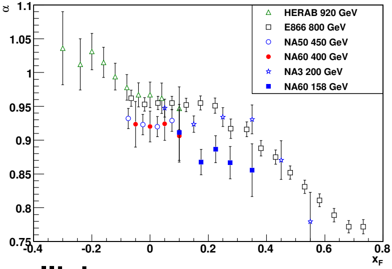

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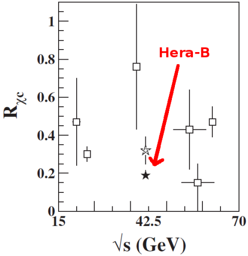

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LHB

Our idea is not completely new

Nuclear Instruments and Methods in Physics Research A 333 (1993) 125–135
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

LHB, a fixed target experiment at LHC to measure CP violation in B mesons

Flavio Costantini

University of Pisa and INFN, Italy

A fixed target experiment at LHC to measure CP violation in B mesons is presented. A description of the proposed apparatus is given together with its sensitivity on the CP violation asymmetry measurement for the two benchmark decay channels $B^0 \to J/\psi + K^0_s$, $B^0 \to \pi^+\pi^-$. The possibility of obtaining an extracted LHC beam hinges on channeling in a bent silicon crystal. Recent results on beam extraction efficiencies measured at CERN SPS based on this technique are presented.

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This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about 10^8 protons/s allowing the production of as many as 10^{10} $B\overline{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an e^+e^- asymmetric B factory with 10^{34} $cm^{-2}s^{-1}$ luminosity [5].

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- For LHCb, typically 1 fb^{-1} means $\simeq 2 \times 10^{11} B\bar{B}$ pairs at 14 TeV

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This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about 10^8 protons/s allowing the production of as many as 10^{10} $B\bar{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an e^+e^- asymmetric B factory with 10^{34} cm^{-2}s^{-1} luminosity [5].

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LARGE HADRON BEAUTY FACTORY
LETTER OF INTENT

- B-factories: 1 ab^{-1} means $10^9 B\bar{B}$ pairs
- For LHCb, typically 1 fb^{-1} means $\simeq 2 \times 10^{11} B\bar{B}$ pairs at 14 TeV
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- After a year, one simply moves the crystal by less than one mm ...

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  - they should also be calculated for $x_F \to -1$

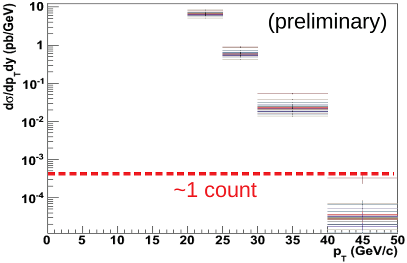
    where IQ could dominate

Isolated-γ in p(7 TeV)-p(rest): √s ~ 115 GeV

- p-p photon kinematics at fixed-target LHC (central rapidities):
  To access x > 0.3 one needs isolated-γ at: $p_T = x_T\sqrt{s}/2 > 20$ GeV/c
- JETPHOX NLO pQCD calculations:

  p-p at √s=115 GeV
  |y|<0.5, p_T>20 GeV/c
  Isolation: R=0.4, E_T^{had}<5 GeV

  $\mathcal{L}$(10 cm H_2-target) ~ 2•10^3 pb^{-1}/year



PDF: CT10 52 eigenval. (90% CL)
Scales: $\mu_i = p_T$
FF = BFG-II
x-section uncertainties(*) of ±150%

(*) (68%CL)/(90% CL) ~ 1.65