AFTER @ LHC

(Quarkonium) Physics opportunities of a fixed-target experiment using LHC beams extracted by a bent crystal

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Part I

Why a new fixed-target experiment for HEP now ?

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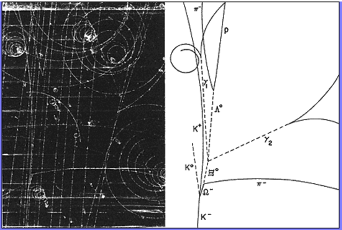

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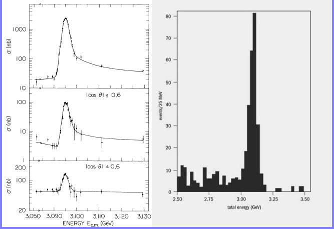

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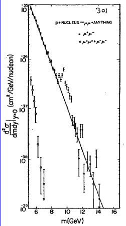

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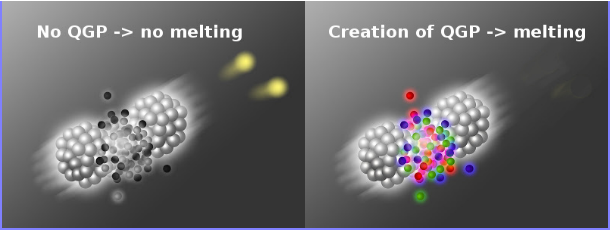

$J/\psi \to \mu\mu$ anomalous suppression @ CERN-SPS

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

Part II

A fixed-target experiment using the LHC beam(s): AFTER@LHC

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

Backward physics ?

- Let's adopt a different strategy and look at larger angles
  · particles with sufficient p_T to be detected
  · heavy particles whose decay product have enough p_T to be detected
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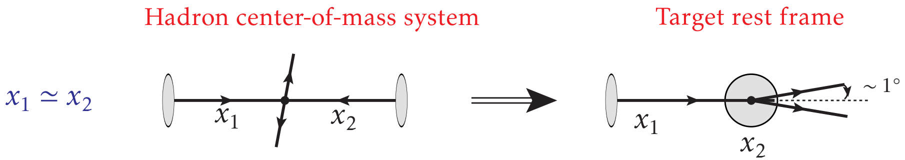

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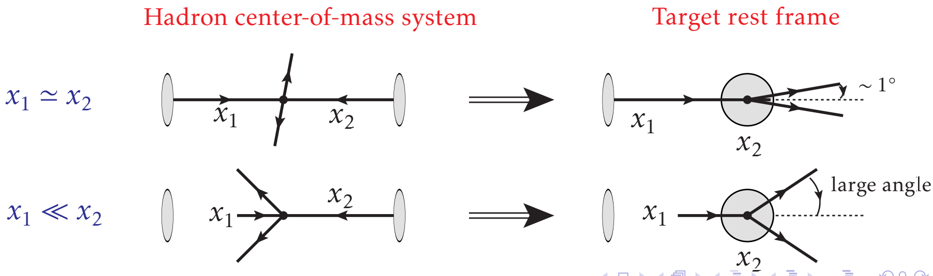

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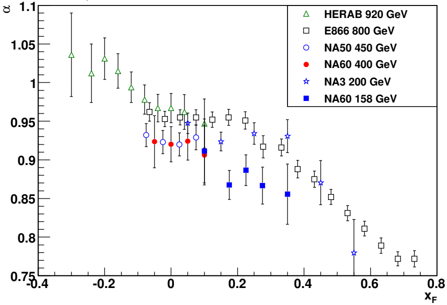
J/ψ suppression in pA collisions



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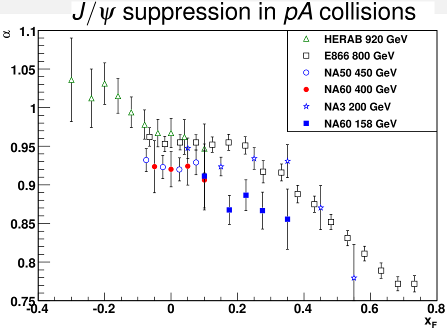

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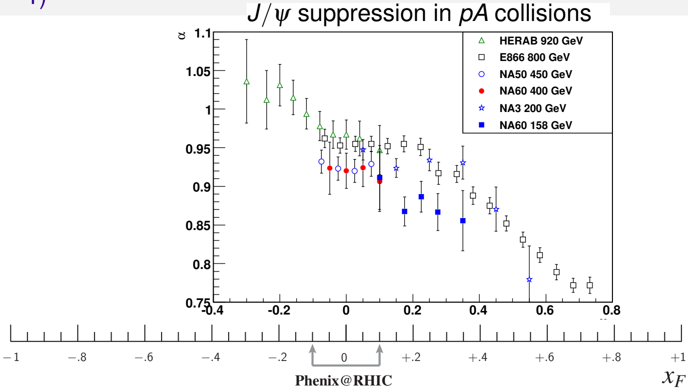

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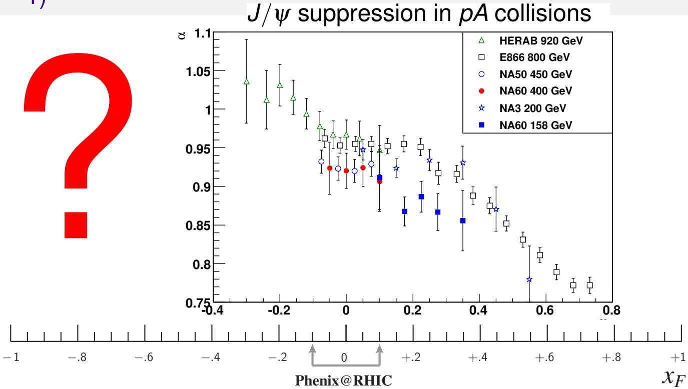

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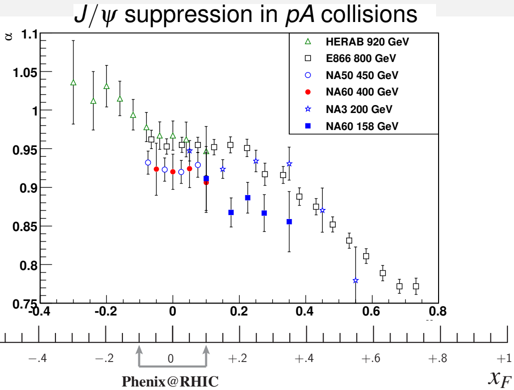

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- If we measure $\Upsilon(b\bar{b})$ at $y_{\rm cms} \simeq -2.5 \Rightarrow x_F \simeq \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{\rm cms}) \simeq -1$

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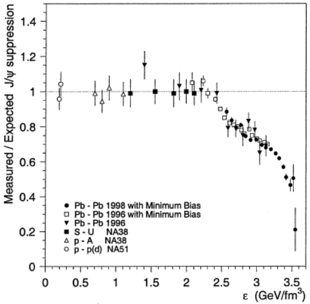

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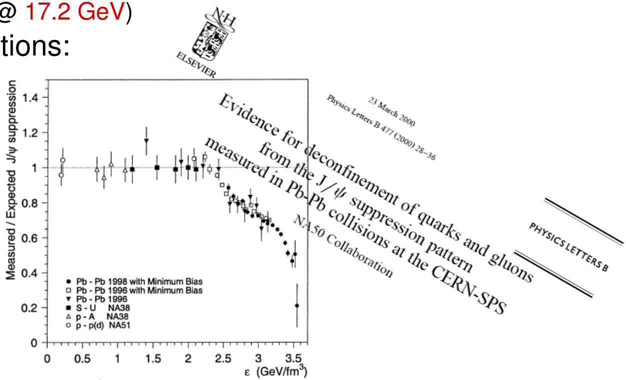

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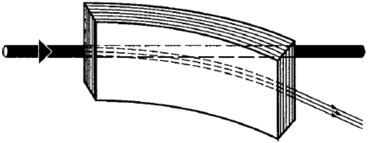

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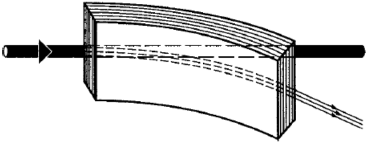

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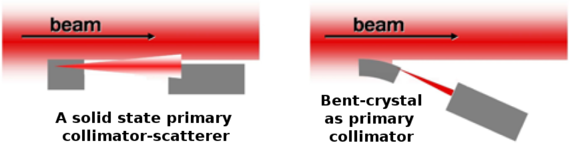

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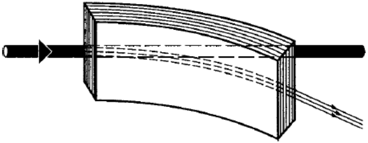

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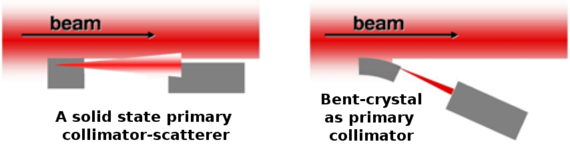

★ Tests will be performed on the LHC beam:
LUA9 proposal approved by the LHCC

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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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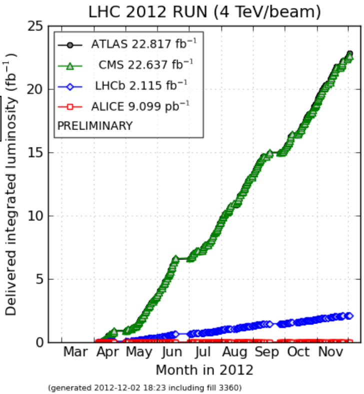

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- PHENIX lumi in their decadal plan
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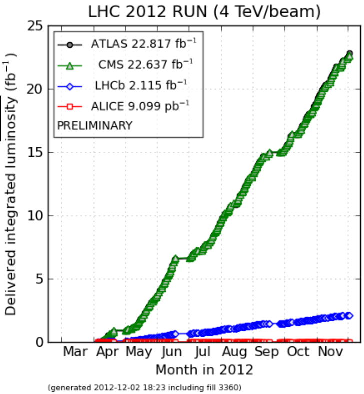

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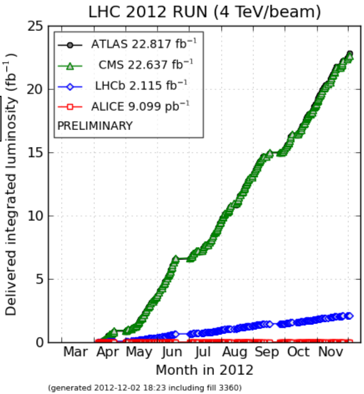

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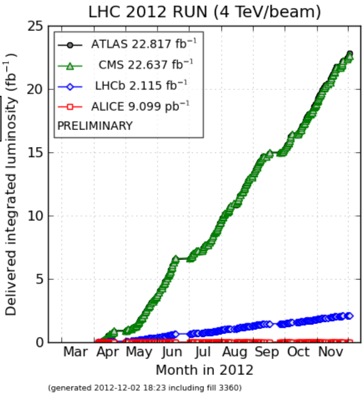

Part III

AFTER: flagships measurements

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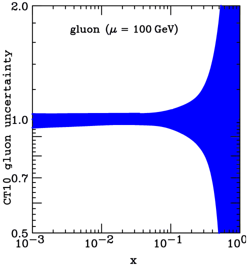

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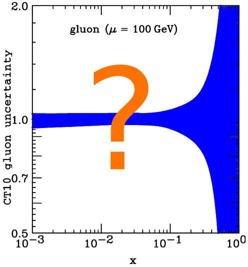

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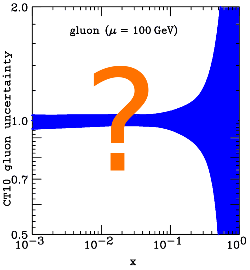

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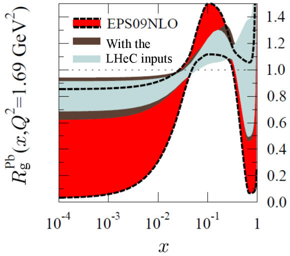

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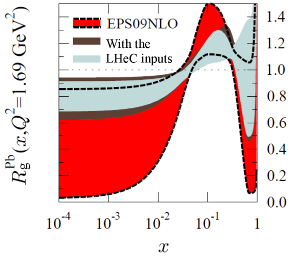

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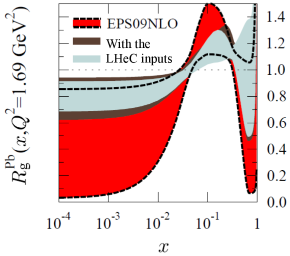

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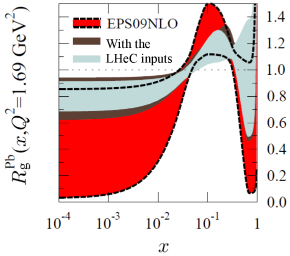

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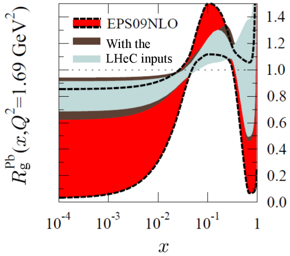

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- jets (we should access $P_T \in [20, 40]$ GeV)

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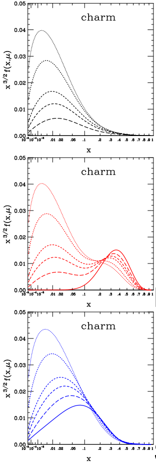

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BHPS

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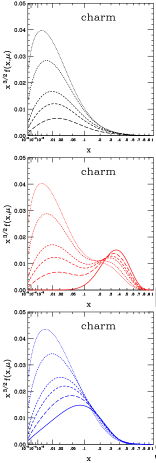

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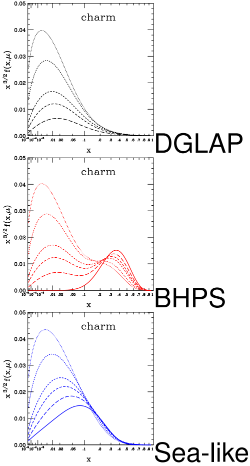

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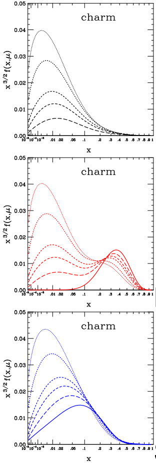

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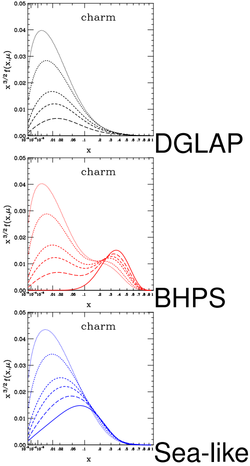

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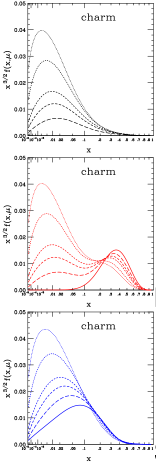

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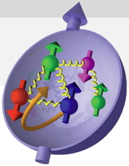

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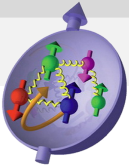

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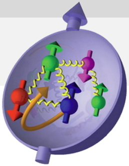

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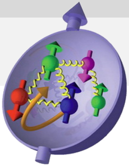

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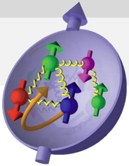

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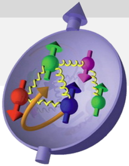

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- In general, one can carry out an *extensive spin-physics program*

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  - Reconstructed rate are most likely between a few dozen to a few thousand / year
- Multiply heavy baryons: discovery potential ? ($\Omega^{++}(ccc)$, ...)
- Very forward (backward) physics:
  - semi-diffractive events
  - Ultra-peripheral collisions, etc.

Part IV

AFTER and the heavy flavours

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

- Interpolating the world data set:

Target	$\int \mathcal{L}$ ($fb^{-1}.yr^{-1}$)	$N(J/\Psi)\ yr^{-1}$ $= A\mathcal{L}\mathcal{B}\sigma_{\Psi}$	$N(\Upsilon)\ yr^{-1}$ $= A\mathcal{L}\mathcal{B}\sigma_{\Upsilon}$
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- Probe of the (very) large *x* in the target

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1cm Cu	64	**0.42**	**5.3 10^8**	**1.1 10^6**
1cm W	185	**0.31**	**1.1 10^9**	**2.3 10^6**
1cm Pb	207	**0.16**	**6.7 10^8**	**1.3 10^6**
LHC pPb 8.8 TeV	207	**10^{-4}**	**1.0 10^7**	**7.5 10^4**
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1cm W	185	**0.31**	**1.1 10^9**	**2.3 10^6**
1cm Pb	207	**0.16**	**6.7 10^8**	**1.3 10^6**
LHC pPb 8.8 TeV	207	**10^{-4}**	**1.0 10^7**	**7.5 10^4**
RHIC dAu 200GeV	198	**1.5 10^{-4}**	**2.4 10^6**	**5.9 10^3**
RHIC dAu 62GeV	198	**3.8 10^{-6}**	**1.2 10^4**	**18**

- In principle, one can get 300 times more J/ψ –not counting the likely wider y coverage– than at RHIC, allowing for
  - χ_c measurement in *pA* via $J/\psi + \gamma$ (extending Hera-B studies)
  - Polarisation measurement as the centrality, y or P_T
  - Ratio ψ' over direct J/ψ measurement in *pA*
  - not to mention ratio with **open charm, Drell-Yan,** etc ...

AFTER: also an heavy-flavour observatory in *PbA*

- Luminosities and yields with the extracted 2.76 TeV Pb beam ($\sqrt{s_{NN}} = 72$ GeV)

Target	A.B	$\int \mathcal{L}$ ($nb^{-1}.yr^{-1}$)	N(J/Ψ) yr^{-1} = $AB\mathcal{L}\mathcal{B}\sigma_{\Psi}$	N(ϒ) yr^{-1} = $AB\mathcal{L}\mathcal{B}\sigma_{\Upsilon}$
1 m Liq. H_2	207.1	800	$3.4\ 10^6$	$6.9\ 10^3$
1cm Be	207.9	25	$9.1\ 10^5$	$1.9\ 10^3$
1cm Cu	207.64	17	$4.3\ 10^6$	$0.9\ 10^3$
1cm W	207.185	13	$9.7\ 10^6$	$1.9\ 10^4$
1cm Pb	207.207	7	$5.7\ 10^6$	$1.1\ 10^4$
LHC PbPb 5.5 TeV	207.207	0.5	$7.3\ 10^6$	$3.6\ 10^4$
RHIC AuAu 200GeV	198.198	2.8	$4.4\ 10^6$	$1.1\ 10^4$
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The same picture also holds for open heavy flavour

New quarkonium observables at LHC and AFTER

Aim: pin down the production mechanism

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- η_c: soon (?) LHCb, then AFTER@LHC
  - gluon polarisation studies e.g. **D. Boer, C. Pisano, Phys.Rev. D86 (2012) 094007**
  - gluon PDF extraction: e.g. **D. Diakonov, M.G. Ryskin, A.G. Shuvaev. JHEP 02 (2013) 069.**

Part V

Outlooks

Outlooks on AFTER

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Part VI

FCPPL & AFTER

FCPPL, quarkonium and AFTER

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→ 3 new Chinese experimental partners: USTC (Tang), Tsinghua (Gao) & Peking U. (Mao)

→ 2 new French experimental partners: IRFU (Rakotozafindrabe) & IPNO (Hadjidakis)

FCPPL, quarkonium and AFTER: what for ?

Phenomenology $\leftrightarrow$ Experiment

FCPPL, quarkonium and AFTER: what for ?

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- Master students to make first fast simulations for inclusive quarkonium with existing set-up (e.g. LHCb) and PYTHIA "out of the box"

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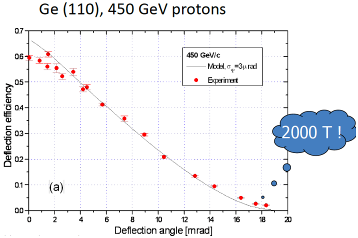
- Theoretical study of the yield close the edge of the phase space ($|x_F| \to 1$)
- Improve the predictions for e.g. η_c

Part VII

Backup slides

The beam extraction

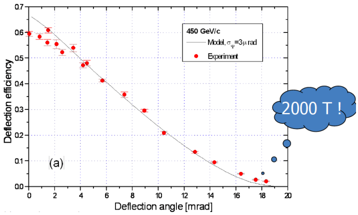
- Inter-crystalline fields are huge



The beam extraction

- Inter-crystalline fields are huge

Ge (110), 450 GeV protons



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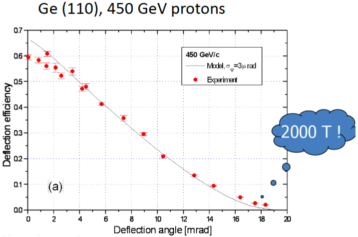

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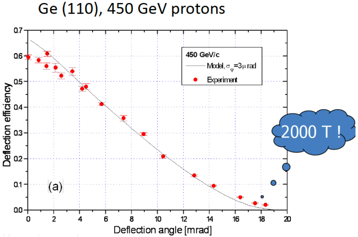
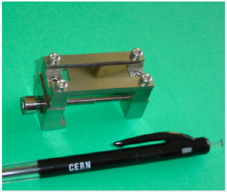


- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:



Luminosities

- Instantaneous Luminosity:
  $\mathscr{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times \mathcal{N}_A)/A$
  $\Phi_{beam} = 2 \times 10^5$ 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}

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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- Revolution frequency: Each bunch passes the extraction point at a rate of 3.10^5 km.s^{-1}/27 km $\simeq$ 11 kHz

A few figures on the (extracted) proton beam

- Beam loss: $10^9\ p^+ \mathrm{s}^{-1}$
- Extracted intensity: $5 \times 10^8\ p^+ \mathrm{s}^{-1}$ (1/2 the beam loss) **E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31**
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  - one extracts $5.10^8/3.10^7 \simeq 16 p^+$ from each bunch at each pass
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- similar figures for the Pb-beam extraction

Need for a quarkonium observatory

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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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Department of Physics, University of Durham, Durham, England

R. G. Roberts
Rutherford Appleton Laboratory, Didcot, Oxon, England

W. J. Stirling
Department of Physics, University of Durham, Durham, England
(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

High precision quarkonium studies in pA: What for ?

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  - Is there an EMC effect for gluon ? (reminder: EMC region $0.3 < x < 0.7$)
- One should be careful with factorization breaking effects:

This calls for multiple measurements to (in)validate factorization

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Observation of J/ψ sequential suppression seems to be hindered by

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  - χ_c never studied in AA collisions
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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 ...

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 $B^0 \to J/\psi + K_s^0$, $B^0 \to \pi^+\pi^-$. 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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1. Introduction

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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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LETTER OF INTENT

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- 10^{20} particles/cm^2 : one year of operation for realistic conditions
- After a year, one simply moves the crystal by less than one mm ...

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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NIM B Beam Interactions with Materials & Atoms
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Strong crystalline fields – a possibility for extraction from the LHC

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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.

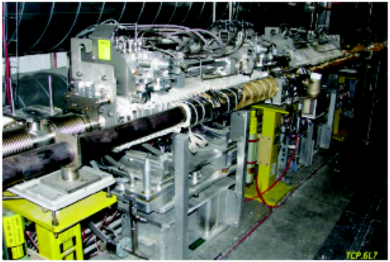
UA9 → LUA9

[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

2010 - 2012



LUA9 future installation in LHC

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
- halo extraction efficiency 70÷80% for protons (50÷70% for Pb)

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

- 2 crystals
- tests during LS2

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

NEW !

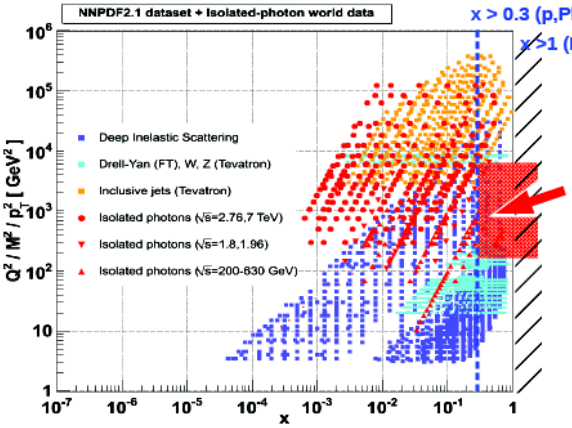
P–P

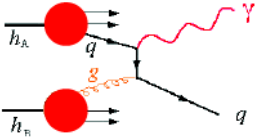
(x,Q^2) map of AFTER isolated-γ

[D.d'E & J.Rojo, NPB 860 (2012) 311]

- p-p kinematics at fixed-target LHC:

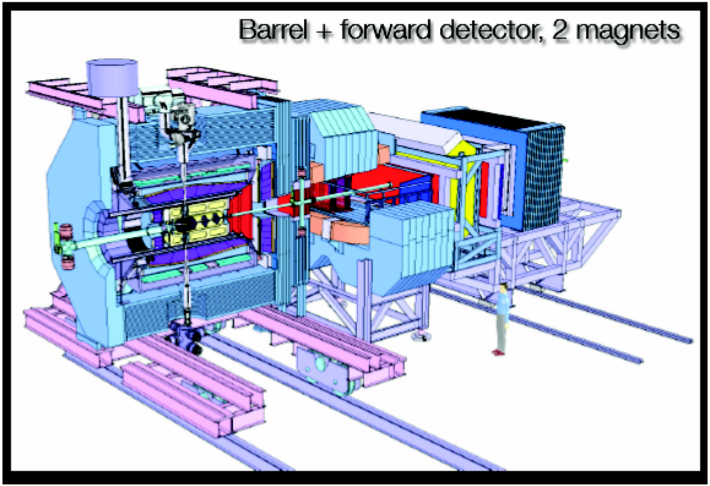
To access x > 0.3 one needs isolated-γ with: $p_T = x_T\sqrt{s}/2$ > 10-20 GeV/c





[D. D'Enterria, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013]

Detector : could be inspired by PANDA

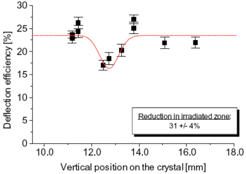


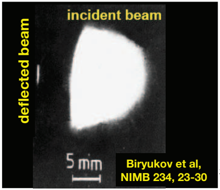
EmCal could be based on ultragranular CALICE, developed for ILC

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

NA48 - Biino et al, CERN-SL-96-30-EA





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

Accessing the large *x* glue

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

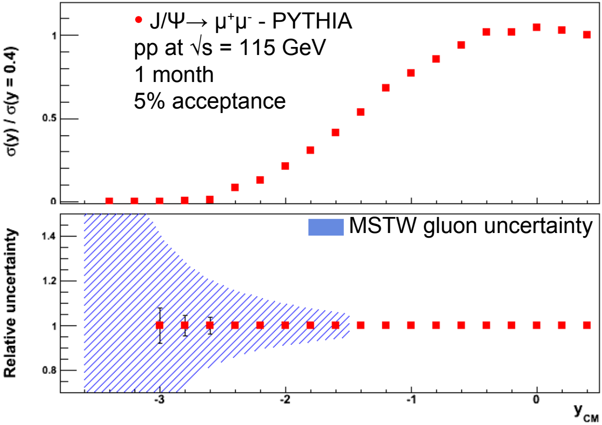
Statistical relative uncertainty
Large statistics allow to access very backward region

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

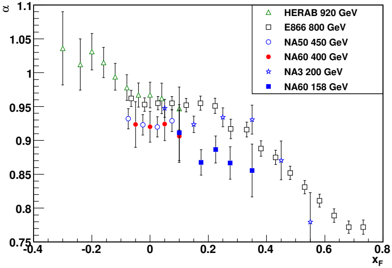
Υ: larger x_g for same y_{CM}
$y_{CM} \sim\ 0 \rightarrow x_g = 0.08$
$y_{CM} \sim -2.4 \rightarrow x_g = 1$



⇒ Backward measurements allow to access large x gluon pdf

SPS and Hera-B

– J/ψ data in pA collisions



NA60 Phys.Lett. B 706 (2012) 263
NA 50 Eur.Phys.J. C48 (2006) 329
NA 3 Z.Phys. C20 (1983)
HERA-B Eur.Phys.J. C60 (2009) 525

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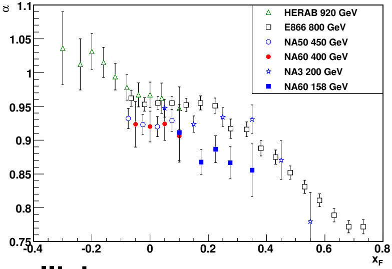

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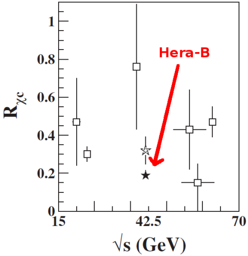
– χ_c **data in** pA **collisions**



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