AFTER @ LHC

A Fixed-Target ExpeRiment using the proton and lead LHC beams for quarkonium and many more physics studies

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AFTER @ LHC

on behalf of M. Anselmino (Torino), R. Arnaldi (Torino), S.J. Brodsky (SLAC), V. Chambert (IPNO), J.P. Didelez (IPNO), E.G. Ferreiro (USC), F. Fleuret (LLR), B. Genolini (IPNO), C. Hadjidakis (IPNO), C. Lorcé (IPNO),A. Rakotozafindrabe (CEA), P. Rosier (IPNO), I. Schienbein (LPSC), E. Scomparin (Torino), and U.I. Uggerhøj (Aarhus)

Part I

Why a new fixed-target experiment for HEP now ?

Decisive advantages of Fixed-target experiments

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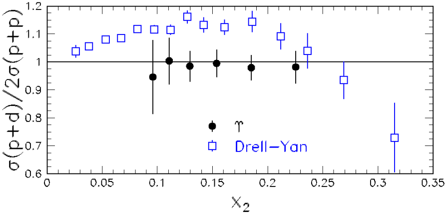
They exhibit 4 decisive features,

- 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.

E866 at Fermilab with the Tevatron beam

– **Precision Υ studies in *pp* and *pd* collisions** **E866 PRL 100 (2008) 062301**



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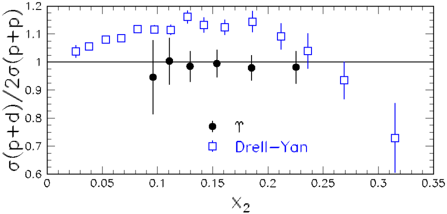

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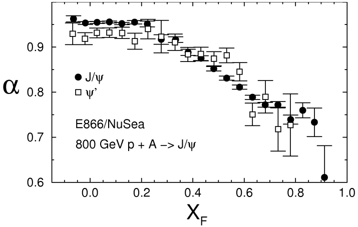

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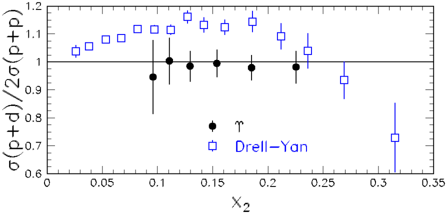

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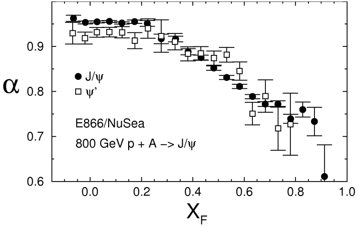

vs. 1 single preliminary $\psi(2S)$ point at $x_F \sim 0$ at RHIC in *d*Au collisions

Precision: necessary to show a different behaviour of $\psi(2S)$ vs. J/ψ

E866 and before

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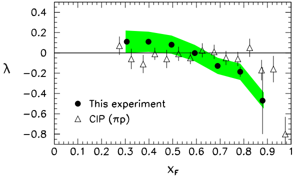

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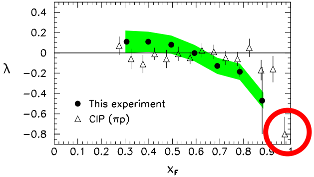

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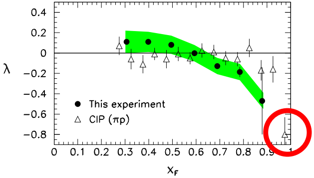

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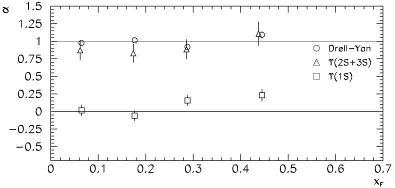

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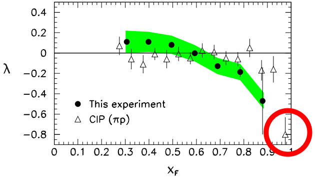

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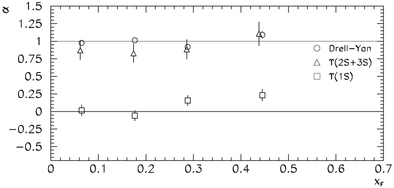

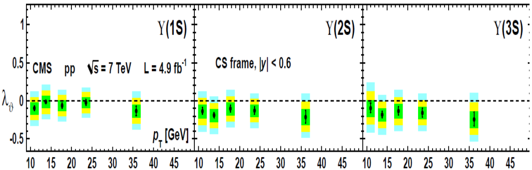

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Part II

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

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Generalities

- *pp* or *pA* with a 7 TeV *p* beam : $\sqrt{s} \simeq 115$ GeV
- For *pA*, a Fermi motion of 0.2 GeV would induce a spread of 10 % of $\sqrt{s}$

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without any performance decrease of the LHC !

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- Crystal channeling is also possible for heavy-ion beams

Recent test with Pb at SPS: W. Scandale *et al.*, PLB 703 (2011) 547

- If required, bent diamonds may provide a crystal highly resistant to radiations

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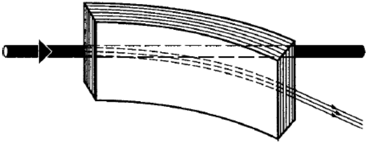

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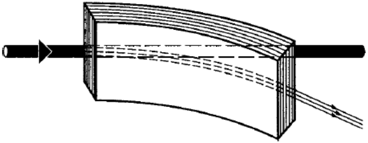

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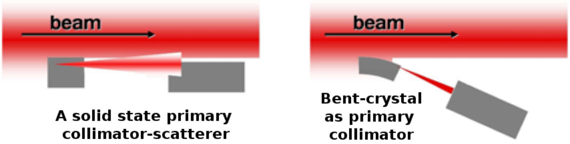

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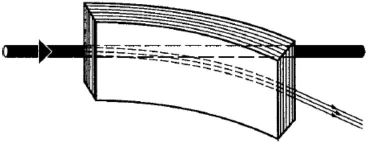

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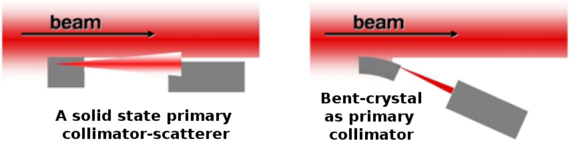

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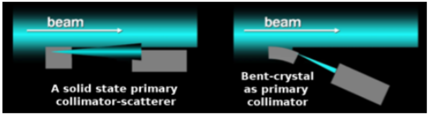
[S. Montesano, Physics at AFTER using LHC beams, ECT Trento, Feb. 2013]*

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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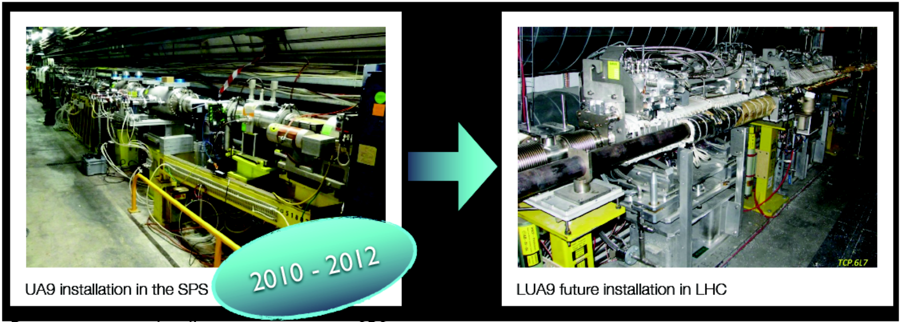

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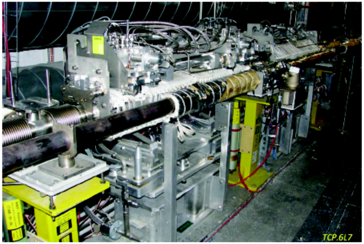

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Towards an installation in the LHC : propose and install during LS1 a min. number of devices

- 2 crystals

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

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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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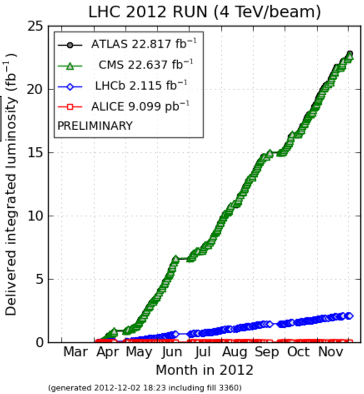

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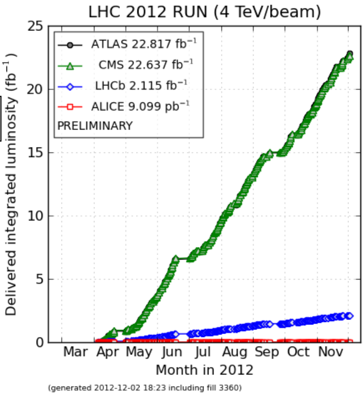

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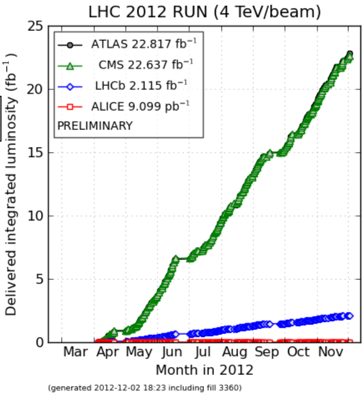

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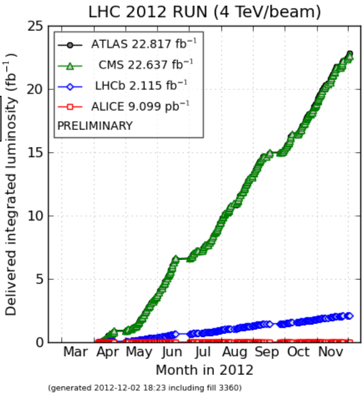
- Lumi for Pb runs in the backup slides

(roughly 10 times that planned for the LHC)



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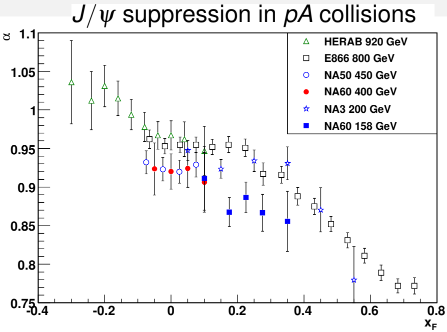

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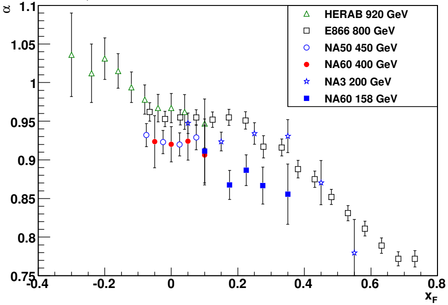

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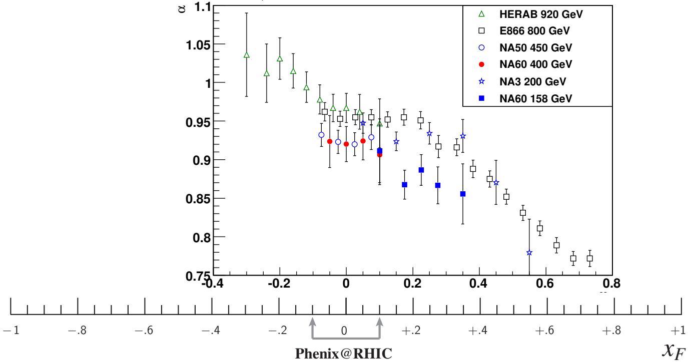

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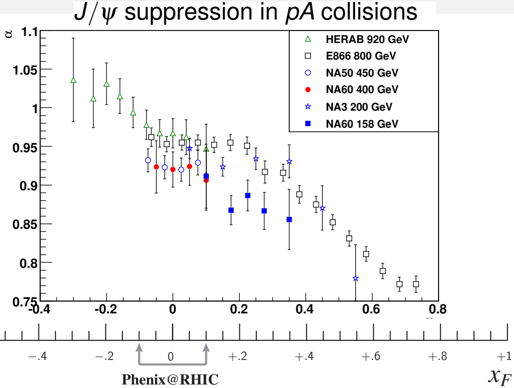

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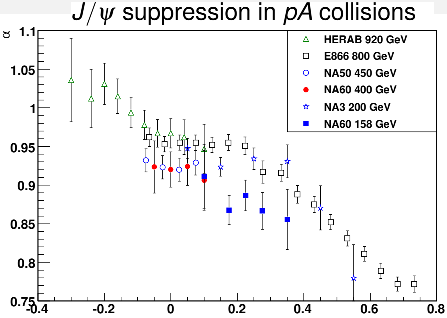

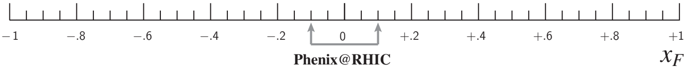

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- If we measure $\Upsilon(b\bar{b})$ at $y_{\rm cms} \simeq -2.5 \Rightarrow x_F \simeq \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{\rm cms}) \simeq -1$

Part III

AFTER: flagships measurements

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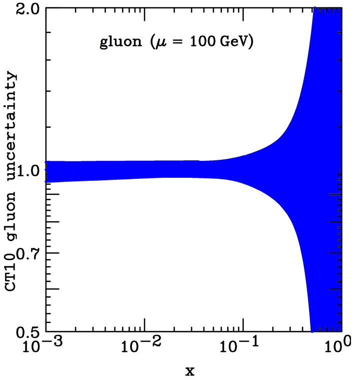

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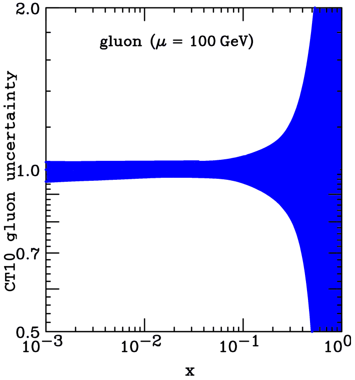

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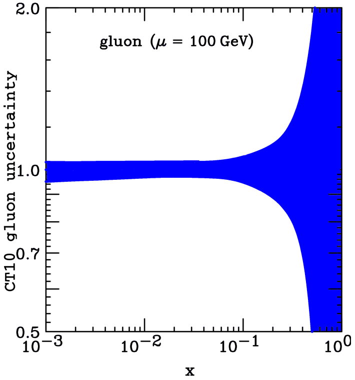

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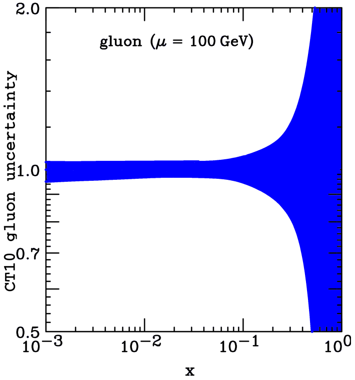

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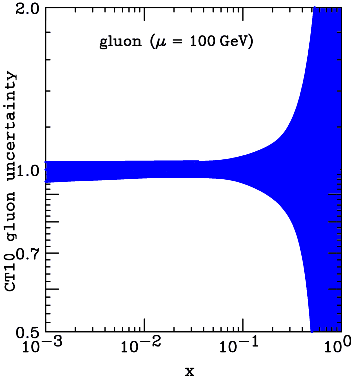

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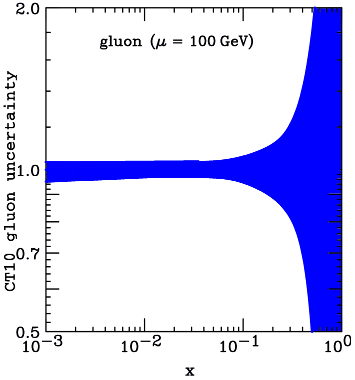

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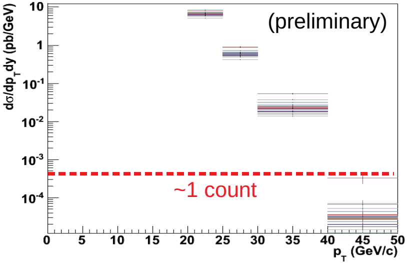
- jets ($P_T \in [20, 40]$ GeV)

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:

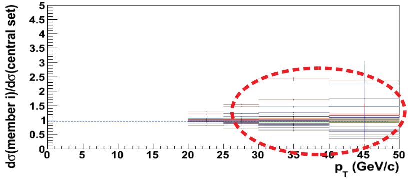
  p-p at √s=115 GeV
  |y|<0.5, p_T>20 GeV/c
  Isolation: R=0.4, E_T^{had}<5 GeV

  $\mathcal{L}$(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



Isolated-γ in p(7 TeV)-p(rest): $\sqrt{s}$ ~ 115 GeV

- p-p photon kinematics at fixed-target LHC (backwards rapidities):
  To access $x > 0.3$ one needs isolated-γ at: $p_T = x_T\sqrt{s}/2e^{-y} > 10$ GeV/c
- JETPHOX NLO pQCD calculations:

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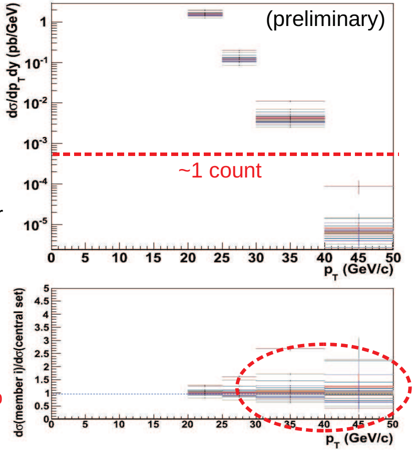


AFTER-LHC, ECT* Trento, Feb'13 28/31 David d'Enterria (CERN)

Accessing the large x glue with quarkonia

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

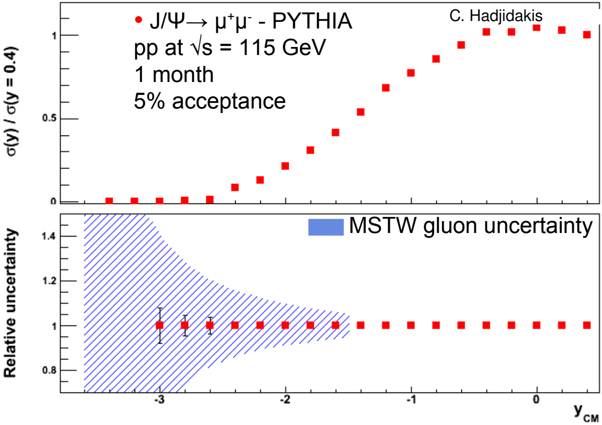
Statistical relative uncertainty
Large statistics allow to access very backward region

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

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

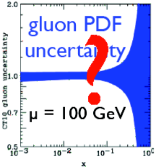
J/Ψ
$y_{CM} \sim 0 \rightarrow x_g = 0.03$
$y_{CM} \sim -3.6 \rightarrow x_g = 1$

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

Key studies: gluons in the neutron



gluon PDF unknown for neutron

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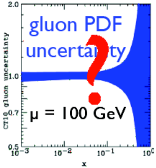

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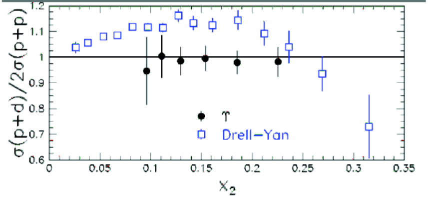
[E866, PRL 100 (2008) 062301]



Pioneering measurement by E866 @ Fermilab :

- using Υ
- at $Q^2 \sim 100$ GeV^2 similar gluon distribution in proton and neutron

could be extended using J/ψ :

- to (∼10x) lower x
- to lower Q^2

[Lansberg et al., FBS 53 (2012) 11]

target	yearly lumi(fb^{-1})	$B_{ll} \frac{dN_{J/\psi}}{dy}\Big\|_{y=0}$	$B_{ll} \frac{dN_{\Upsilon}}{dy}\Big\|_{y=0}$
1 m Liq. H_2	20	4.0 10^8	8.0 10^5
1 m Lid. D_2	24	9.6 10^8	1.9 10^6

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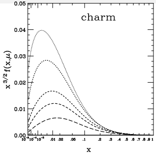

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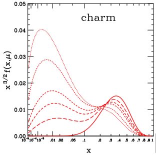

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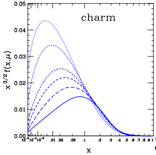

Sea-like

All 3 compatible with DIS data (Pumplin *et al.*)

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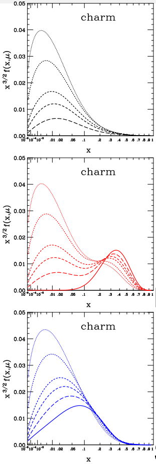

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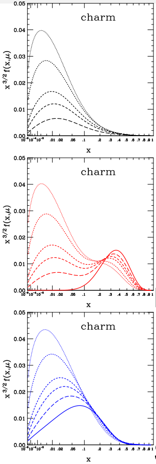

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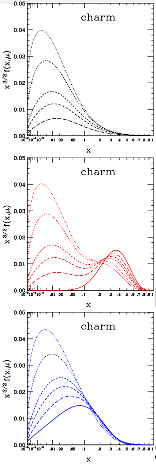

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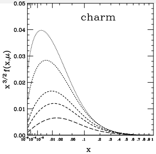

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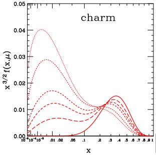

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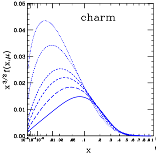

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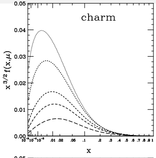

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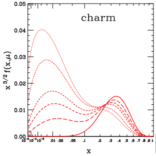

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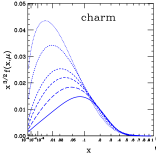

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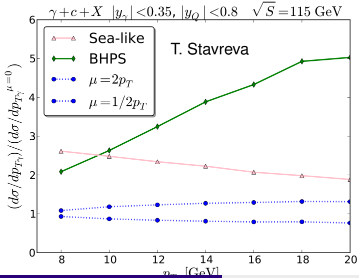

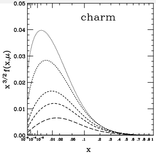

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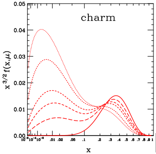

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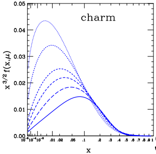

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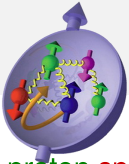

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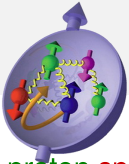

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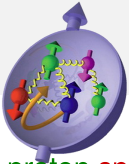

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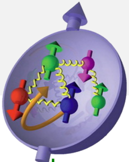

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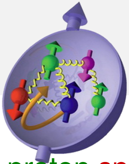

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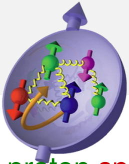

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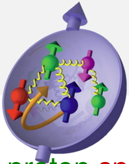

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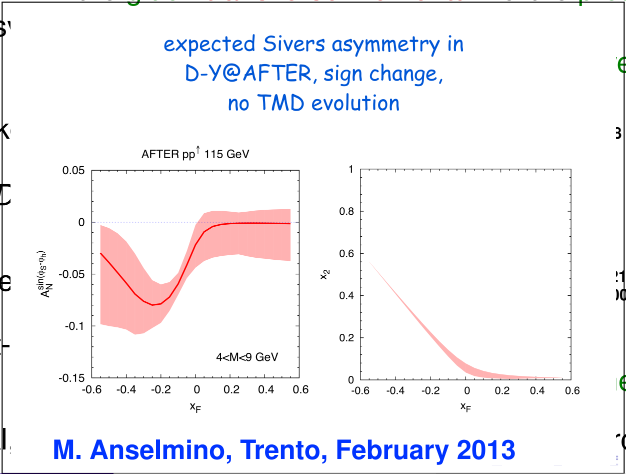

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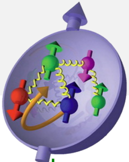

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PHYSICAL REVIEW D **86**, 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*
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Cristian Pisano†
Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

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Key studies: large-x gluon content of the nucleus

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- Large-*x* gluon nPDF: unknown

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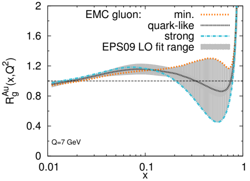

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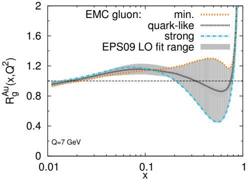

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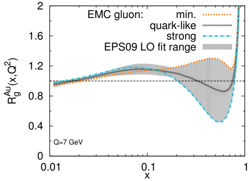

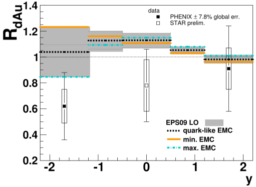

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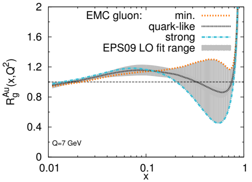
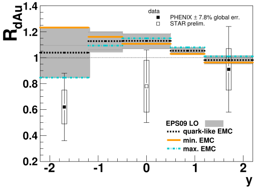
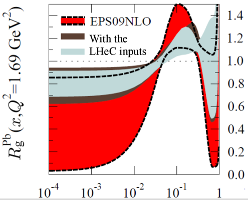
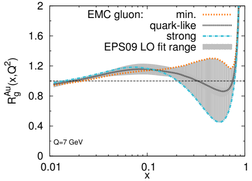


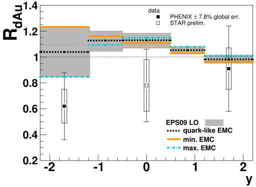


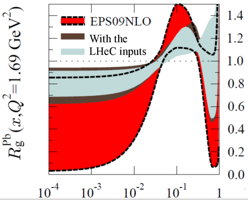


Key studies: large-x gluon content of the nucleus

- Large-x gluon nPDF: unknown
- Gluon EMC effect ?
- Hint from Υ data at RHIC
- Strongly limited in terms of statistics after 10 years of RHIC:
- DIS contribution expected for low x mainly projected contribution of LHeC:
- AFTER allows for extensive studies of gluon sensitive probes in pA
- Unique potential for gluons at $x > 0.1$







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  - Reconstructed rate are most likely between a few dozen to a few thousand / year

Further key studies ?

- Multiply heavy baryons: discovery potential ? ($\Omega^{++}(ccc)$, ...)

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- Semi-diffractive events
- Ultra-peripheral collisions via γp interaction
  - $\gamma_{\rm lab}^{\rm beam} \simeq 7000$
  - $E_{\gamma,\rm lab}^{\rm max} \simeq \gamma_{\rm lab}^{\rm beam} \times 30$ MeV
  - $\sqrt{s_{\gamma p}} = \sqrt{2 m_p E_\gamma}$ up to 20 GeV

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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Contents

Part IV

Back to the future ...

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.

LHB

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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} $B\bar{B}$ 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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LETTER OF INTENT

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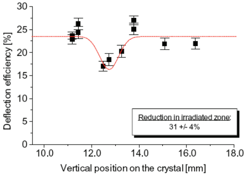
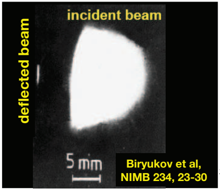
- 10^{20} particles/cm^2 : one year of operation for realistic conditions
- After a year, one simply moves the crystal by less than one mm ...

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





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

Part V

Conclusion and outlooks

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Part VI

Backup slides

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
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Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *
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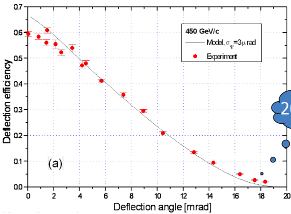
Received 9 September 2004; received in revised form 6 January 2005
Available online 24 February 2005

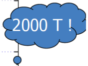
If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

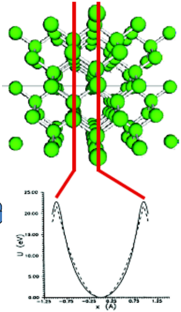
The beam extraction

- Inter-crystalline fields are huge

Ge (110), 450 GeV protons







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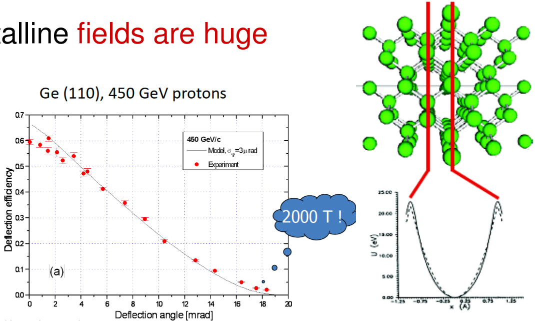

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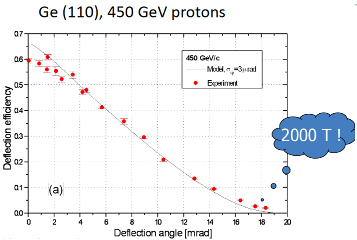
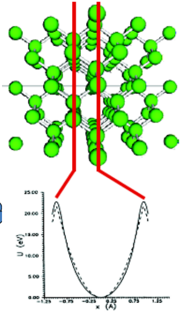
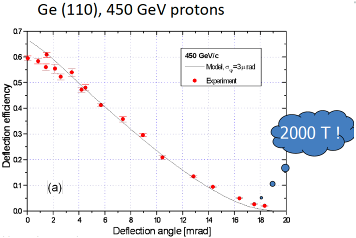


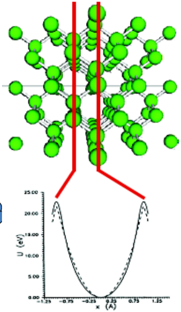


- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)

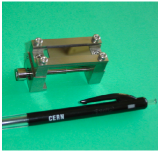
The beam extraction

- Inter-crystalline fields are huge





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

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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- Extraction over a 10h fill:
  - $5 \times 10^8 p^+ \times 3600$ 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

These protons are lost anyway !

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    These protons are lost anyway !
- similar figures for the Pb-beam extraction

NEW !

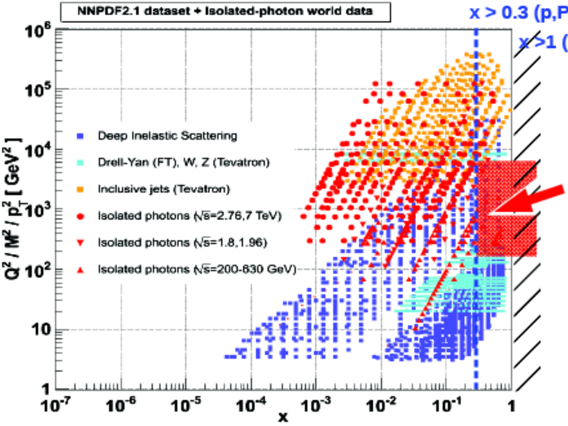
p−p

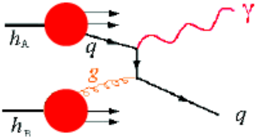
(x,Q^2) map of AFTER isolated-γ

[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: $p_T = x_T\sqrt{s}/2 > 10\text{-}20$ GeV/c





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

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} = $A\mathcal{L}\mathcal{B}\sigma_\Upsilon$
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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

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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

AFTER: also a quarkonium observatory in *pA*

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

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  - What is the amount of Intrinsic charm ? Is it color filtered ?
  - 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

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

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

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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
RHIC AuAu 62GeV	198.198	0.13	4.0 10^4	61

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	$\int \mathcal{L}$ ($nb^{-1}.yr^{-1}$)	$N(J/\Psi)$ yr^{-1} = $AB\mathcal{L}\mathcal{B}\sigma_{\Psi}$	$N(\Upsilon)$ 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
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1 m Liq. H_2	207.1	800	3.4 10^6	6.9 10^3
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The same picture also holds for open heavy flavour

What for ?

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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 . . .

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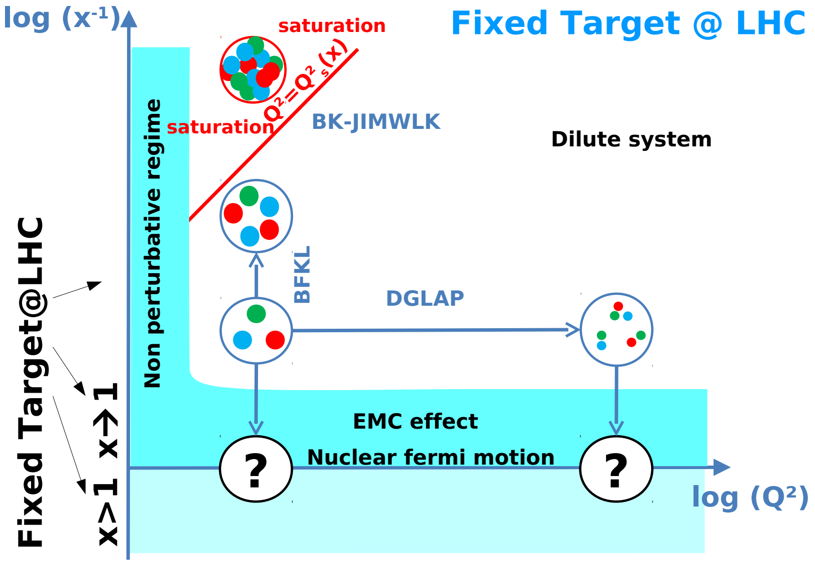
- without target-species limitation
- with an outstanding luminosity
- with virtually no limit on particle-species studies (except top quark)
- with modern detection techniques

Overall


Fixed Target @ LHC
log (x⁻¹)
saturation
Q²=Q²s(x)
saturation
BK-JIMWLK
Dilute system
Non perturbative regime
BFKL
DGLAP
Fixed Target@LHC
x→1
x>1
EMC effect
Nuclear fermi motion
?
?
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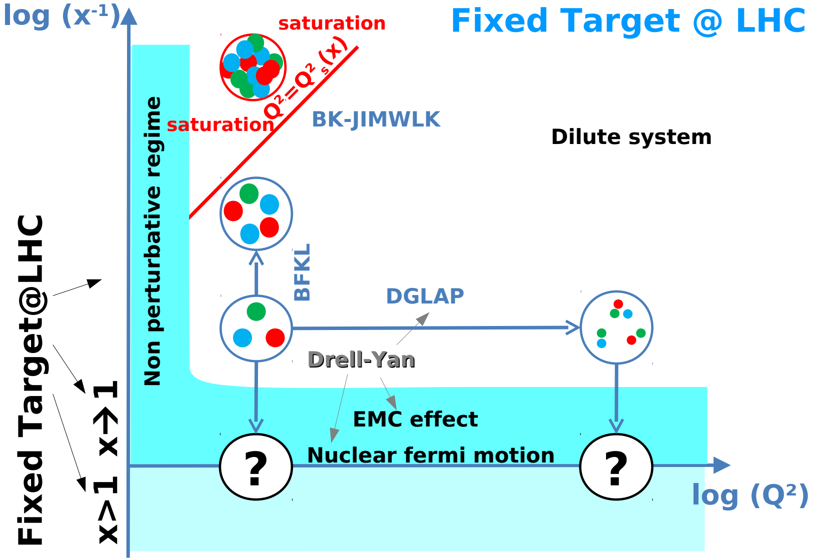
Overall



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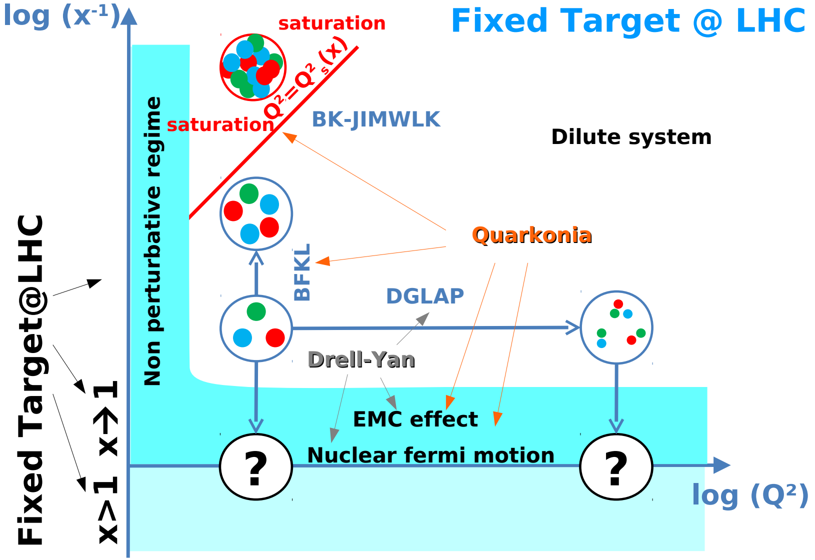
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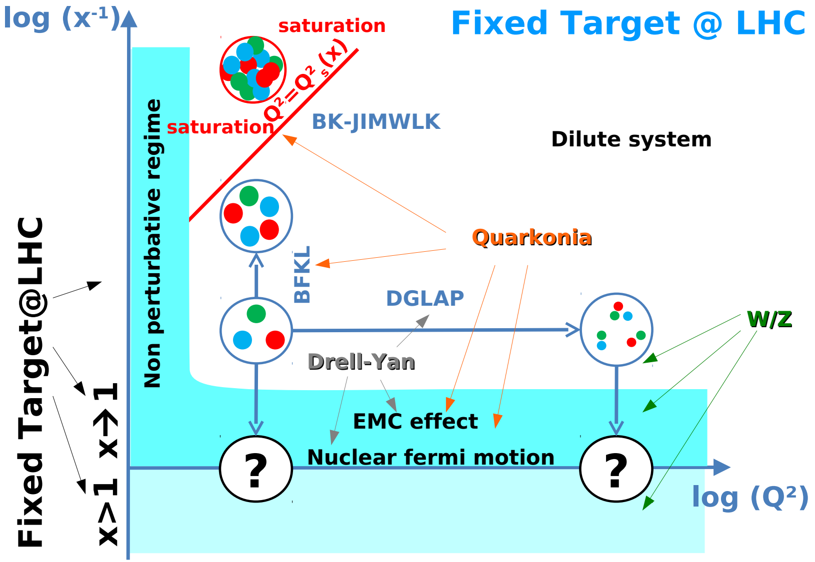
log (x-1)
saturation
Fixed Target @ LHC
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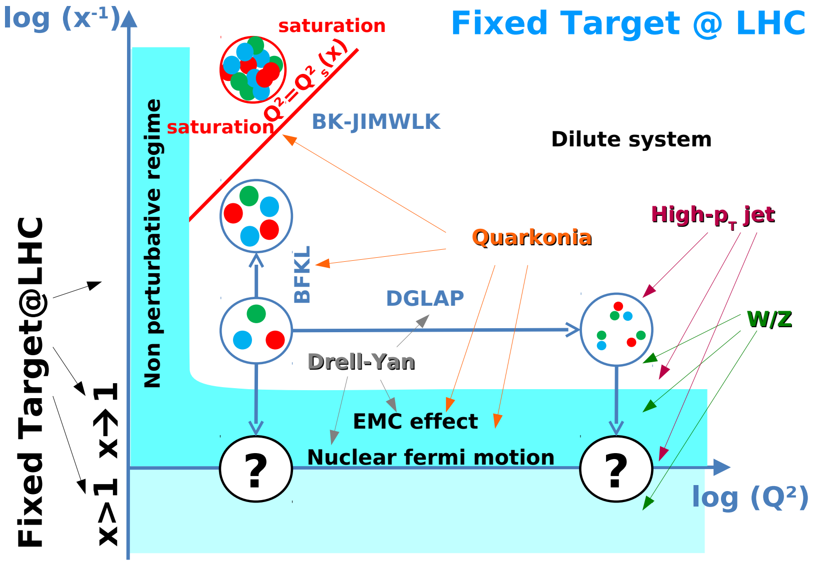

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