AFTER@LHC: A Fixed Target ExpeRiment for hadron, heavy-ion and spin physics: Status and short-range plan

Jean-Philippe Lansberg
IPN Orsay, CNRS/IN2P3, Université Paris-Sud

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Part I

Why a new fixed-target experiment for High-Energy Physics now ?

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    [could be crucial to characterise possible BSM discoveries]
  - Proton charm content important to high-energy neutrino & cosmic-rays physics
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  - Explore the longitudinal expansion of QGP formation with new hard probes
  - Test the factorisation of cold nuclear effects from $p+A$ to $A+B$ collisions
  - Test the formation of azimuthal asymmetries: hydrodynamics vs. initial-state radiation

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- which are essential assets to study
  - rare proton fluctuations at large x
  - vector boson production near threshold and other rare processes
  - nuclear dependence in heavy-ion collisions
  - observables involving gluons and the proton spin

Part II

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

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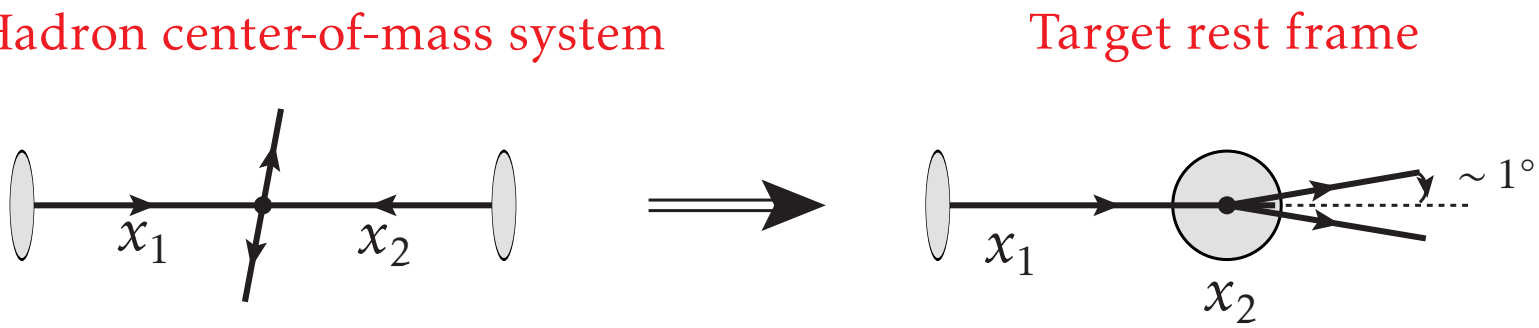

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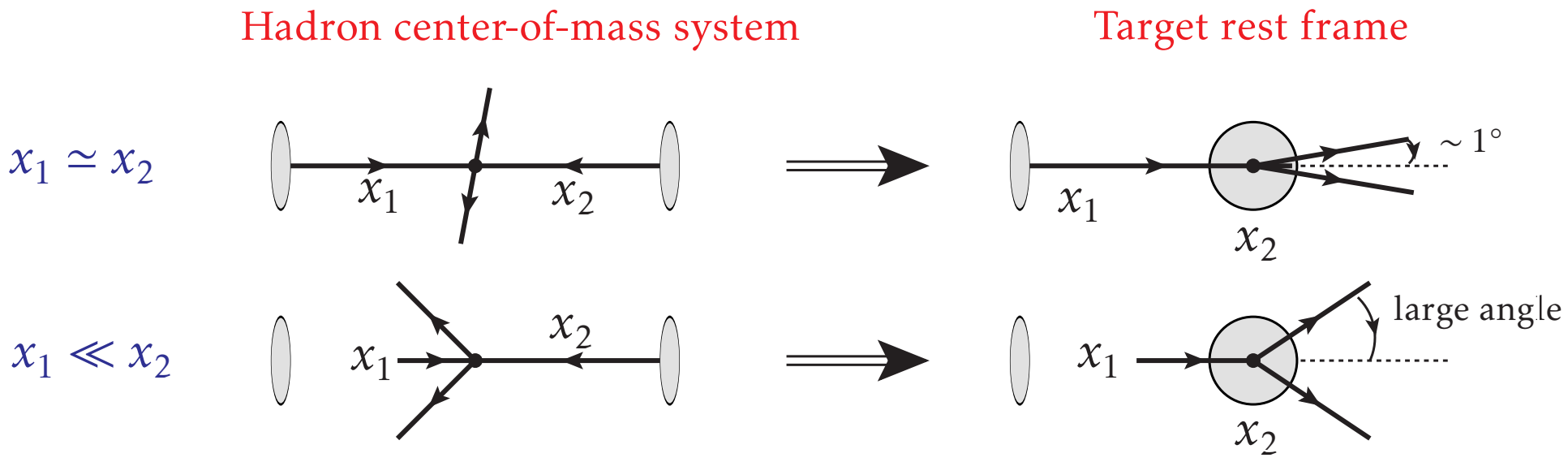

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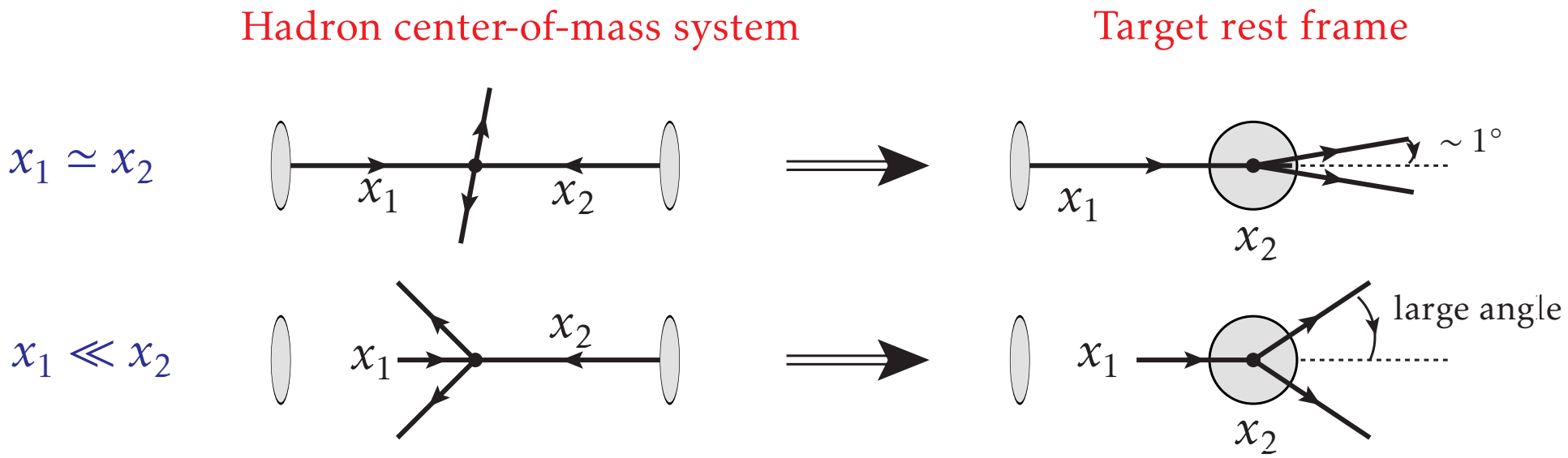

backward physics = large-x_2 physics

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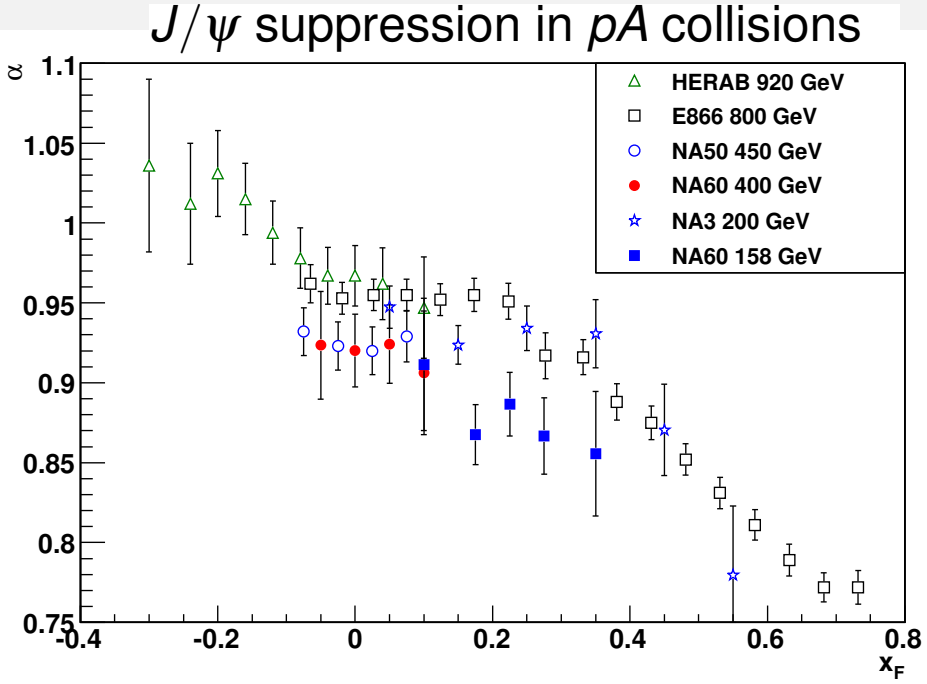

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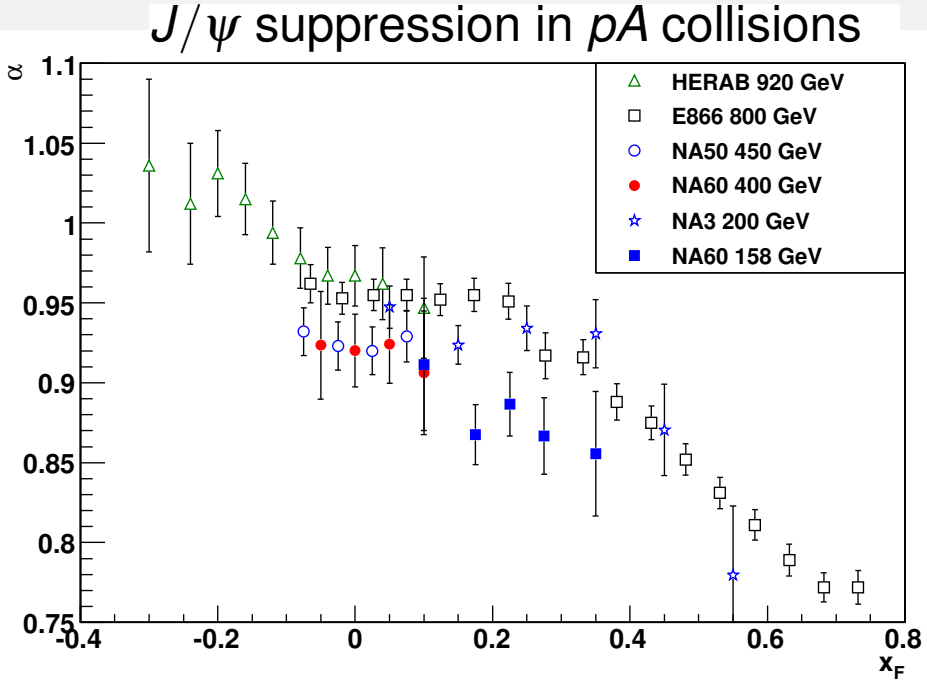

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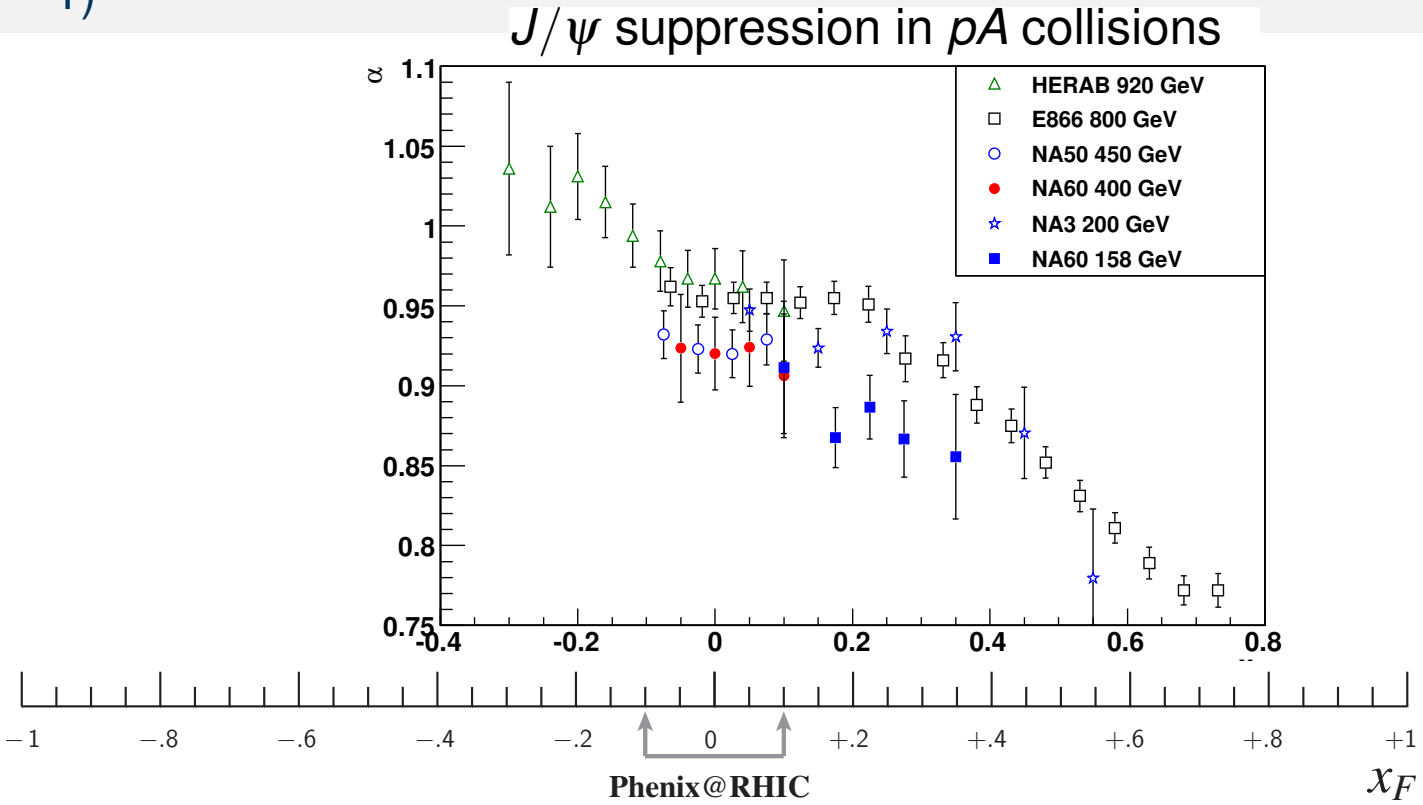

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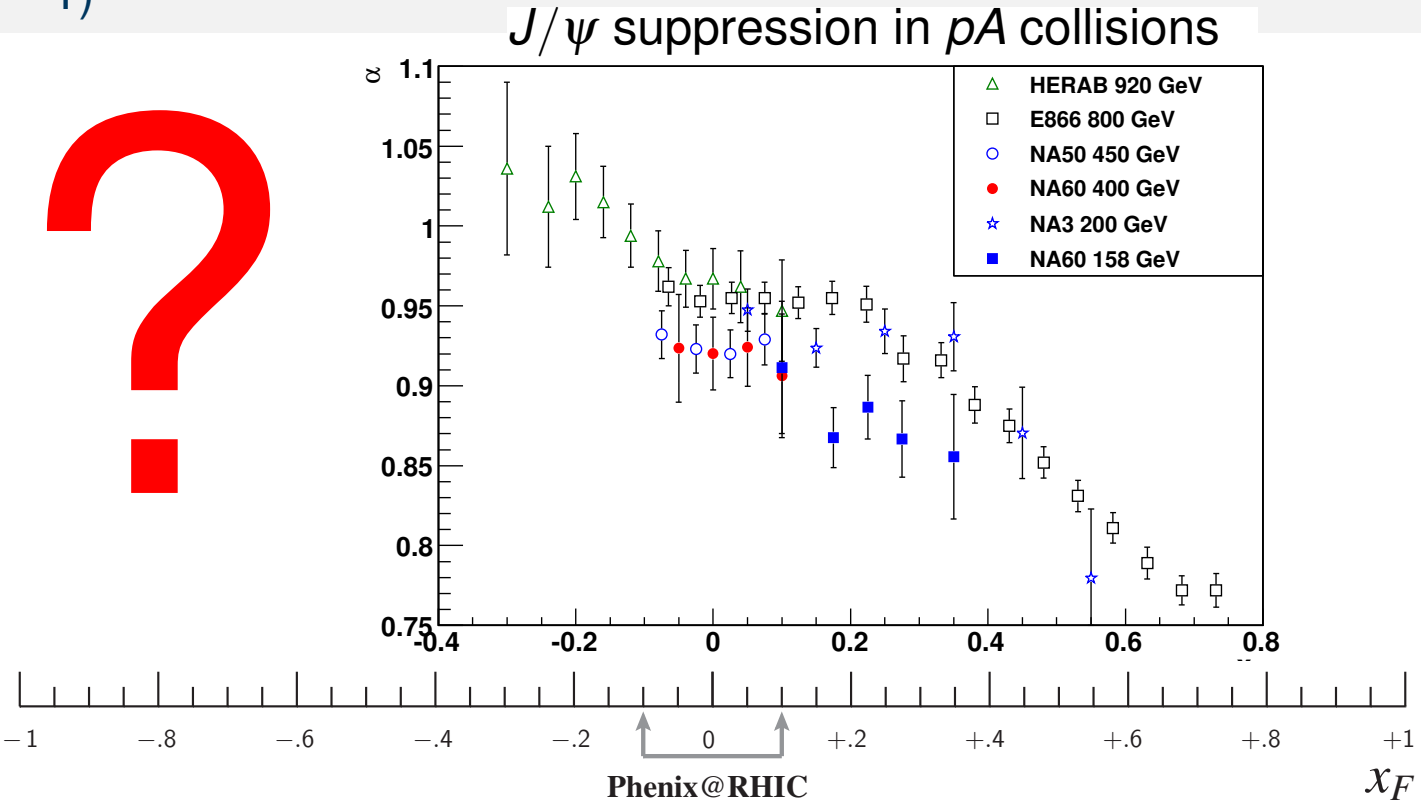

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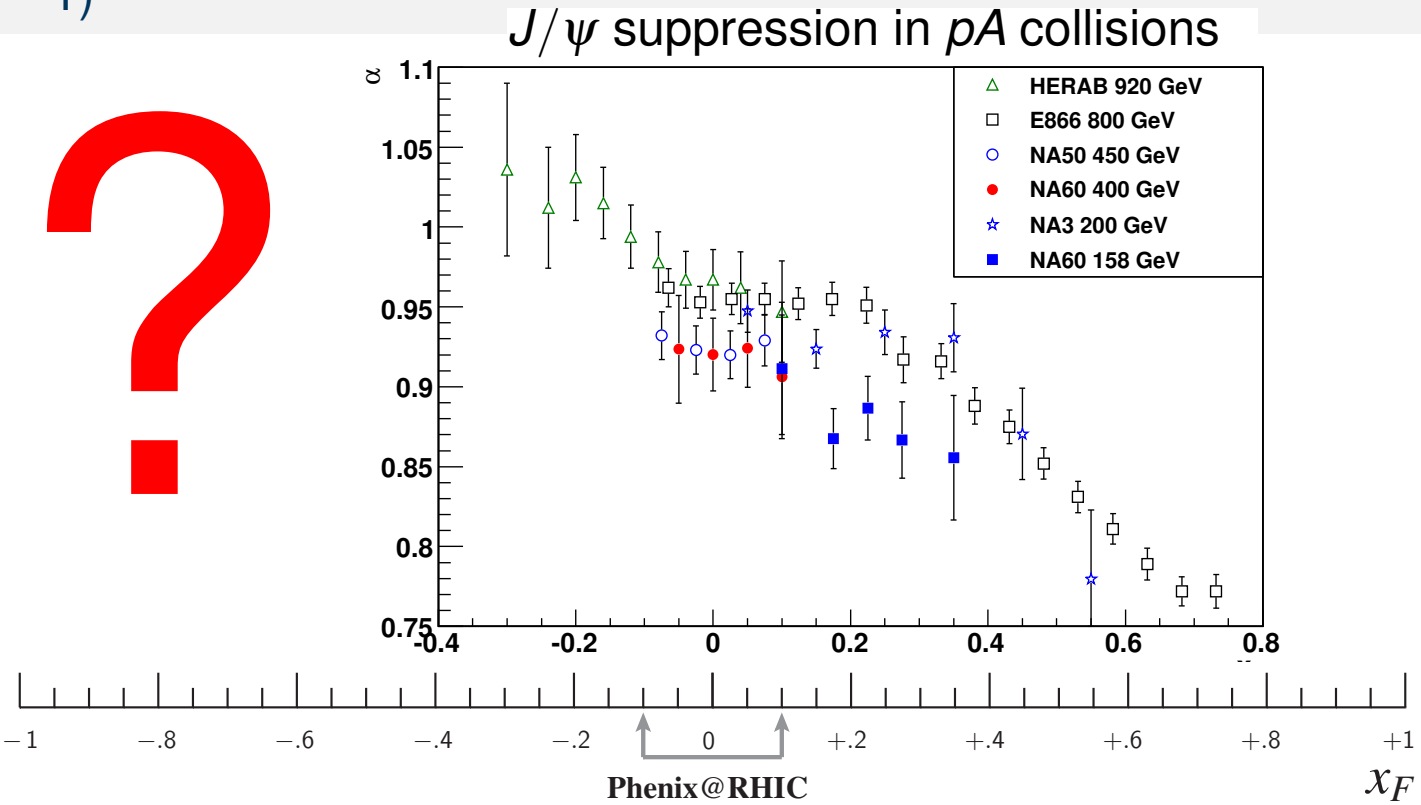

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- If we measure $\Upsilon(b\bar{b})$ at $y_{\rm cms} \simeq -2.5 \;\Rightarrow x_F \simeq \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{\rm cms}) \simeq -1$

The extracted-beam option

★ The LHC beam may be extracted using “Strong crystalline field”

without any decrease in performance of the LHC !

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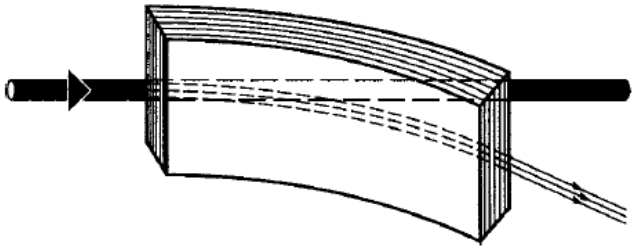

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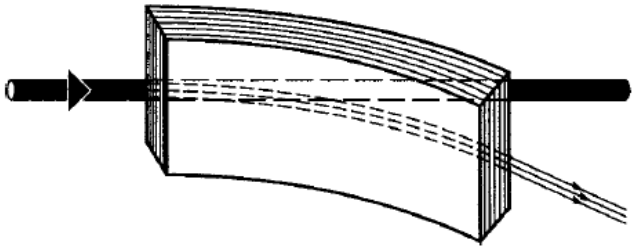

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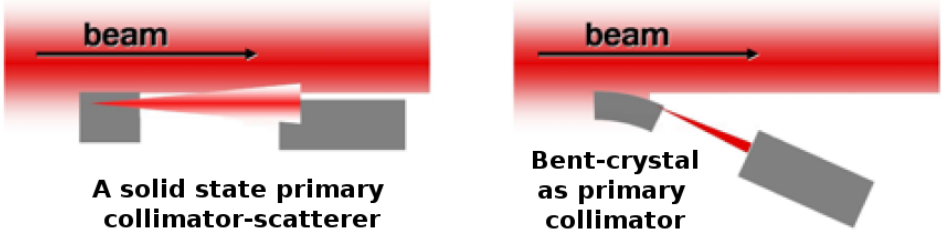

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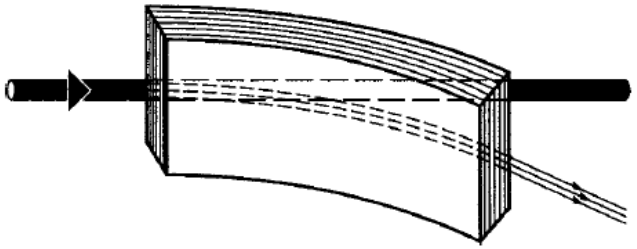

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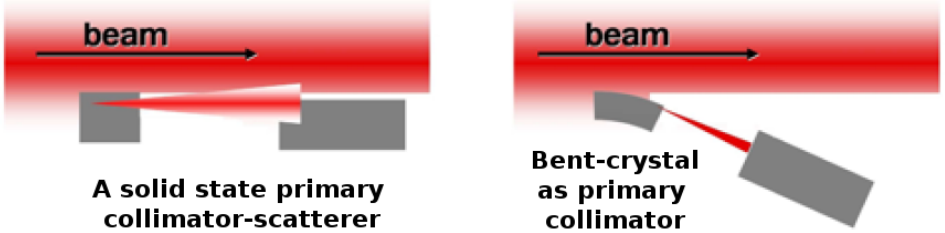

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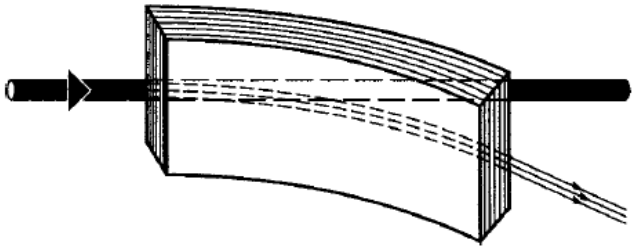

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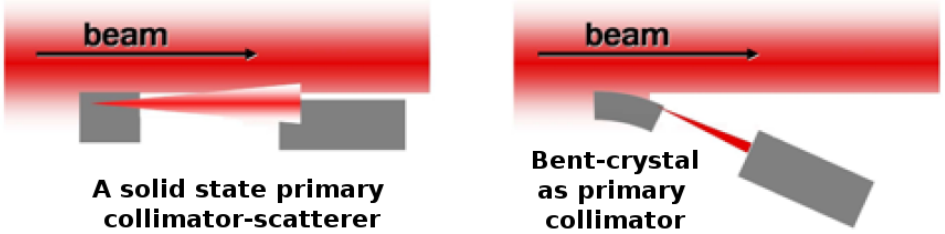

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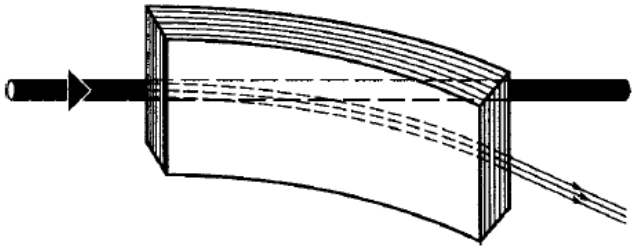

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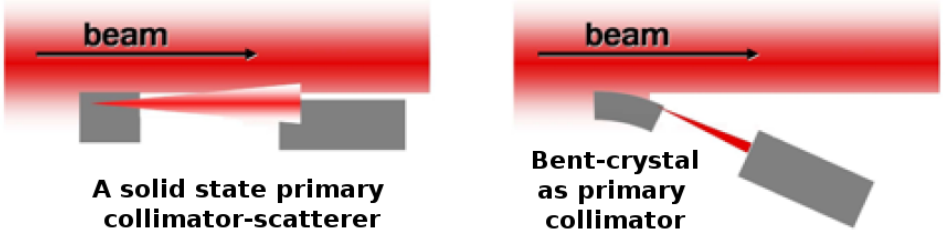

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★ CRYSBEAM: ERC funded project to extract the LHC beams

with a bent crystal

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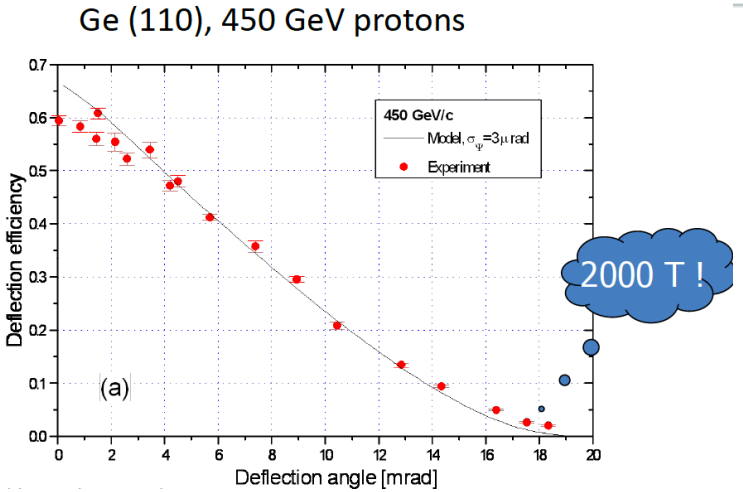

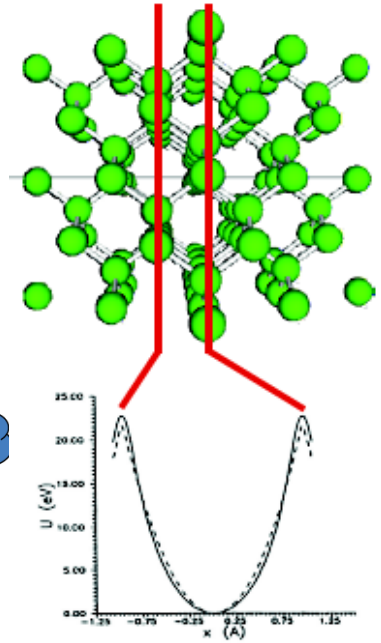

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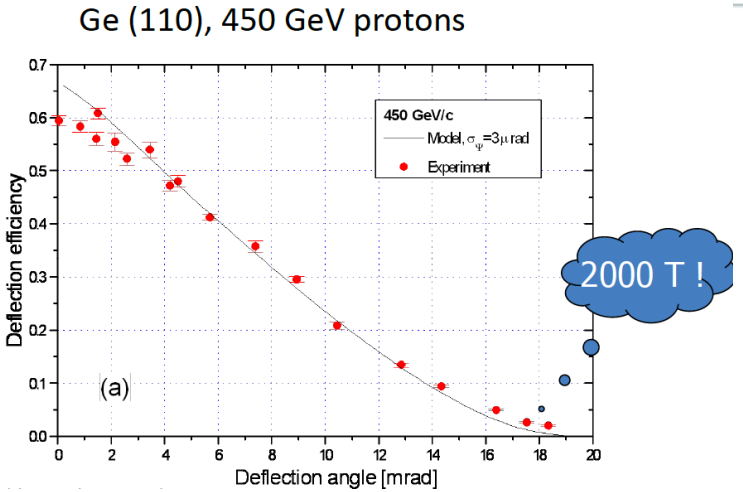

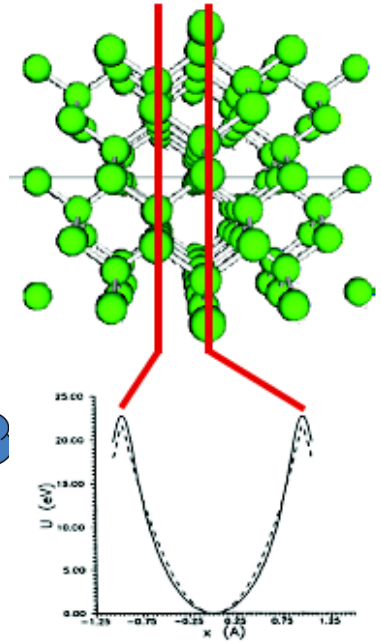

- The channeling efficiency is high for a deflection of a few mrad

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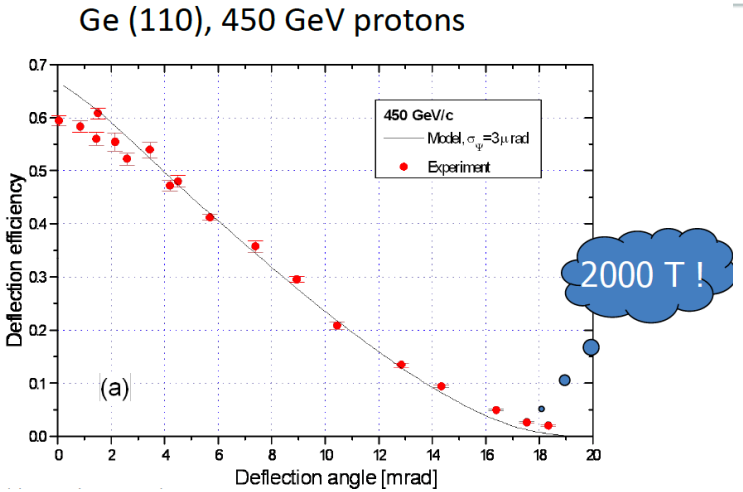

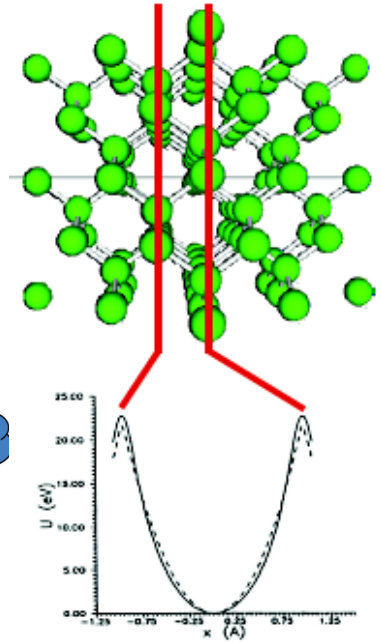

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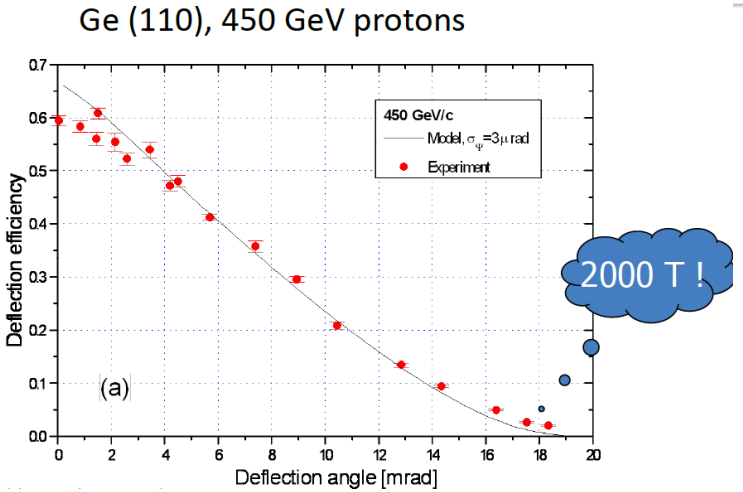

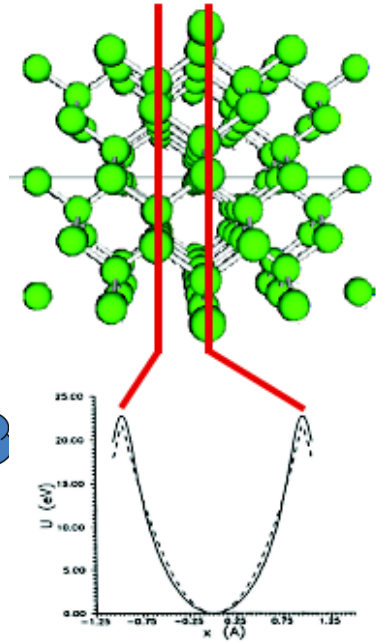

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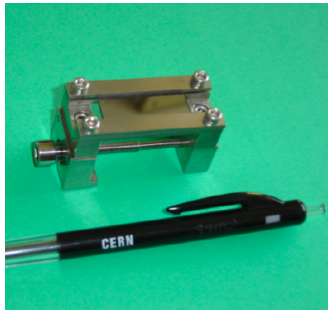
- Simple and robust way to extract the most energetic beam ever:



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★ ? : question mark on the limit on the gas pressure
Limitations likely not from a beam lifetime reduction

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- For *pp* and *pd* collisions : $\mathscr{L}_{H_2/D_2} \simeq 20\ \mathrm{fb}^{-1} y^{-1}$

3 orders of magnitude larger than RHIC

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- 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}

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- A specific gas target could provide a viable alternative to the beam extraction

Part III

AFTER@LHC: my (biased) selection of key measurements

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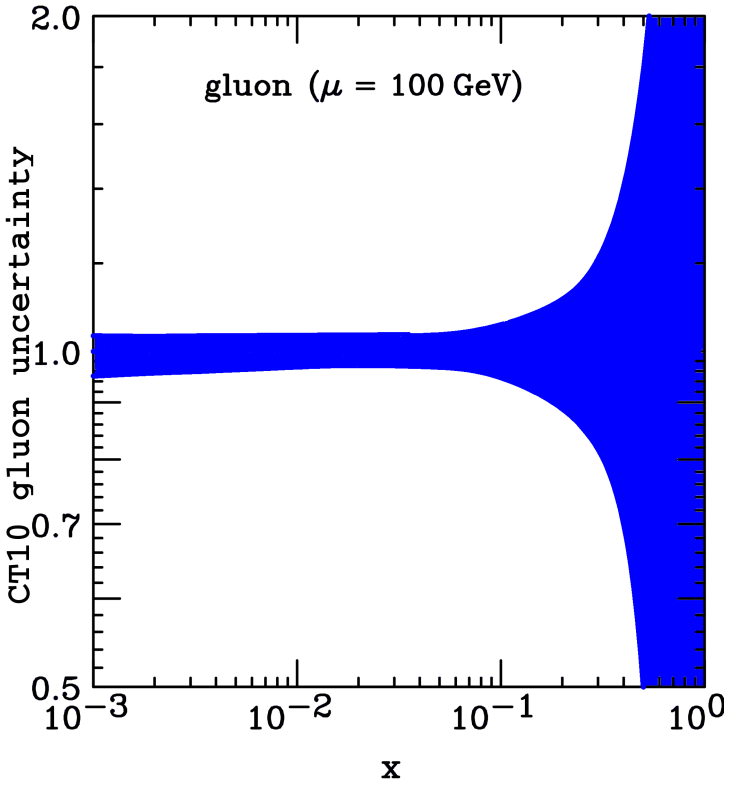

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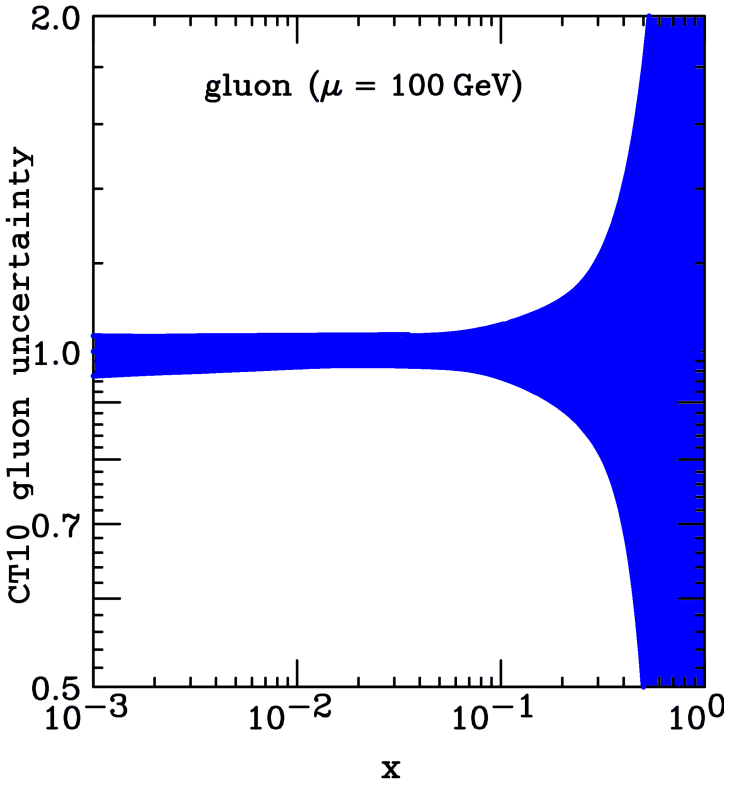

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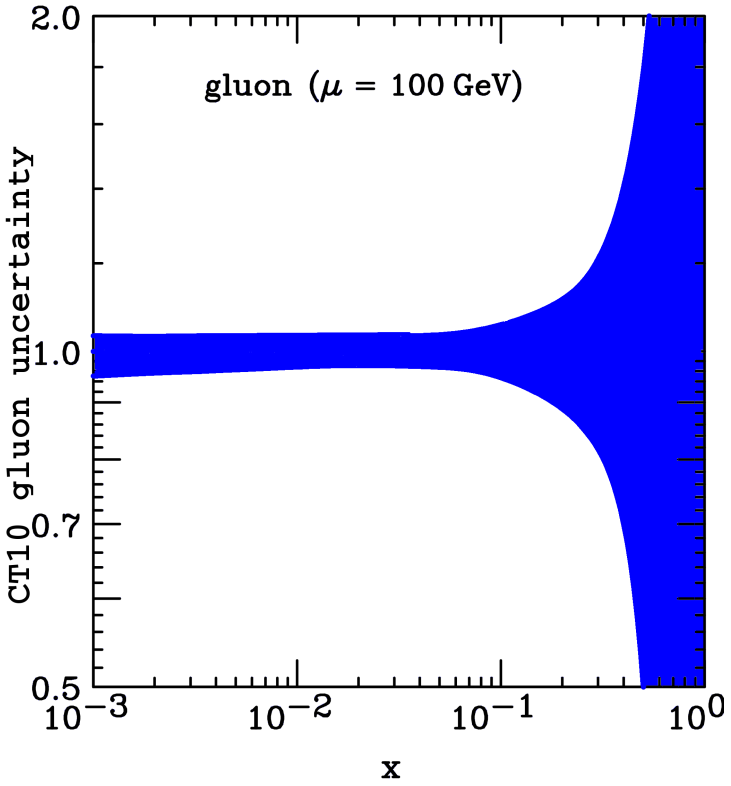

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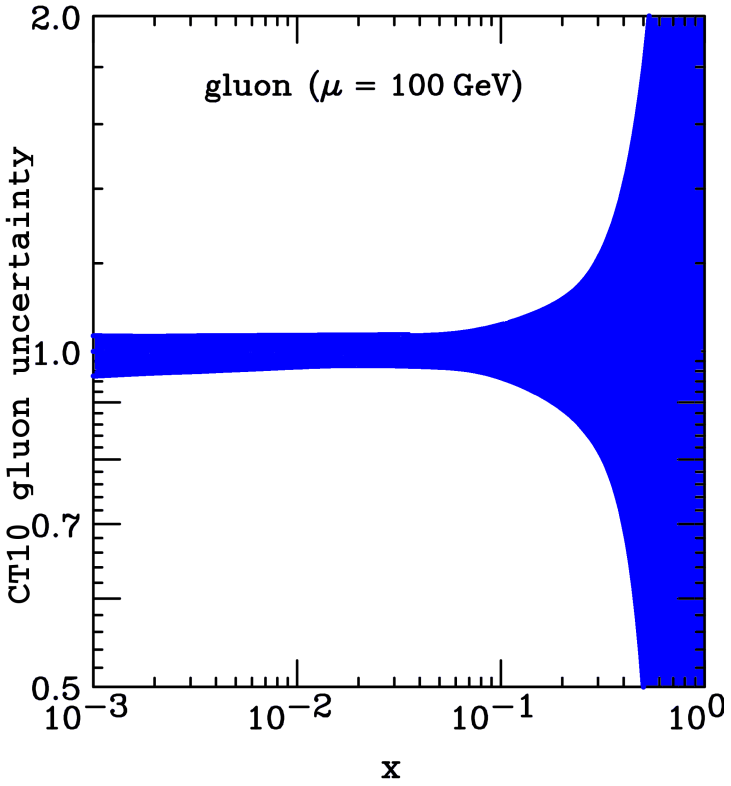

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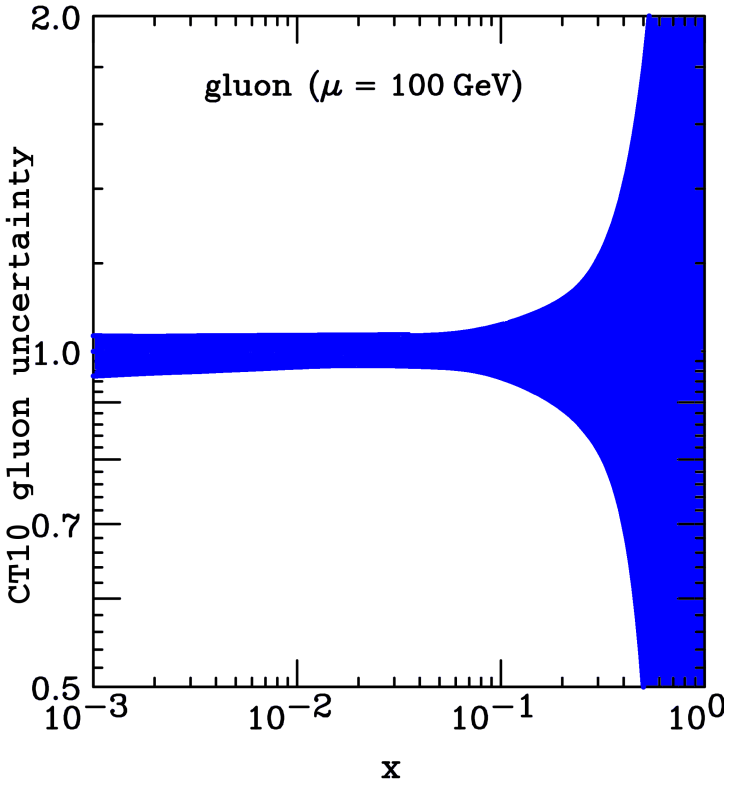

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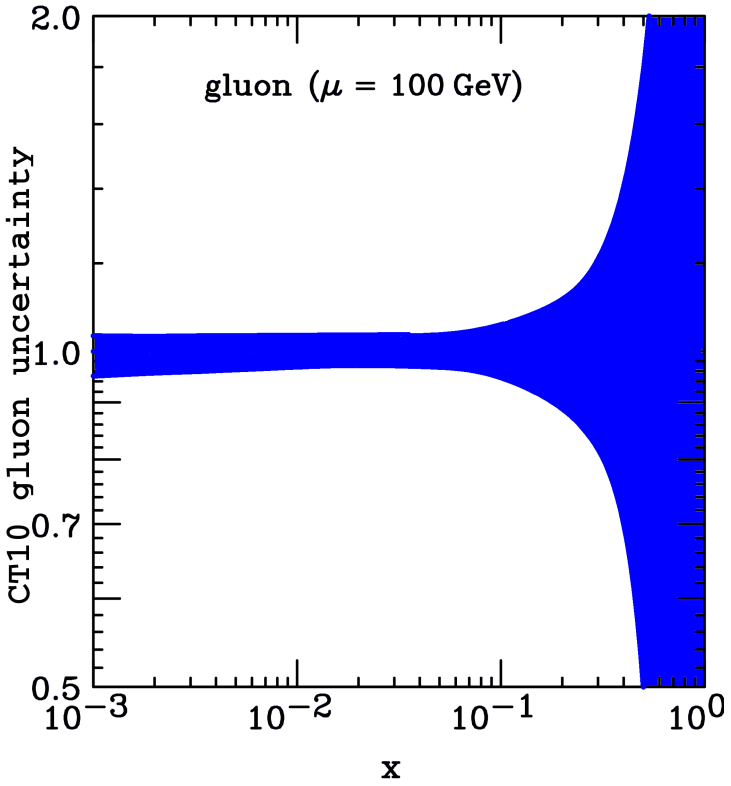

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Multiple probes needed to **check factorisation**

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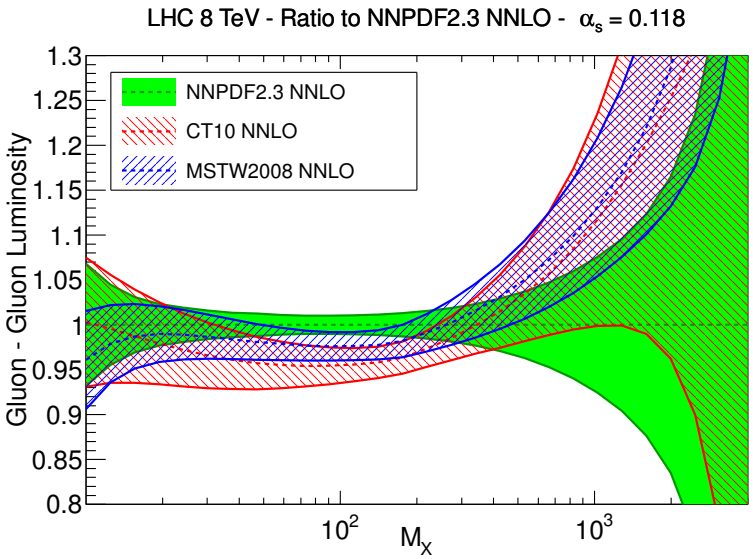

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Large-x gluons: important to characterise some possible BSM findings at the LHC

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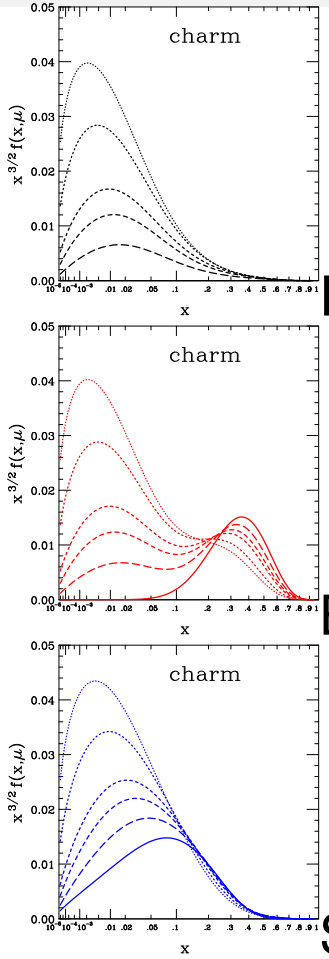

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BHPS

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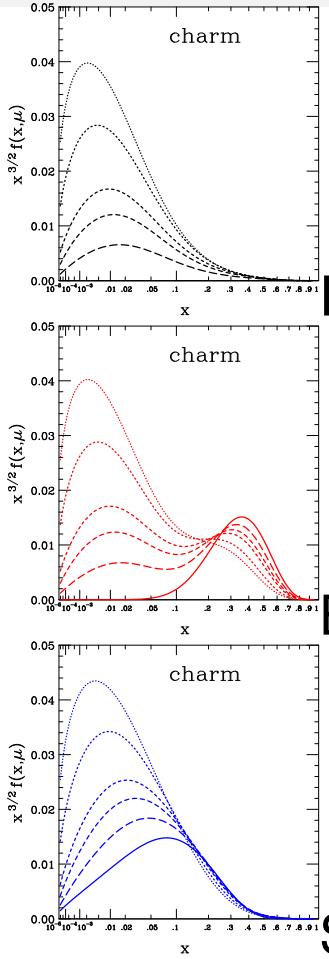

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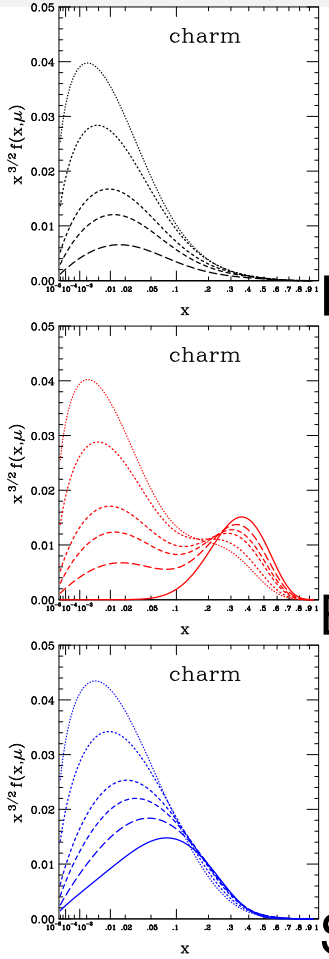

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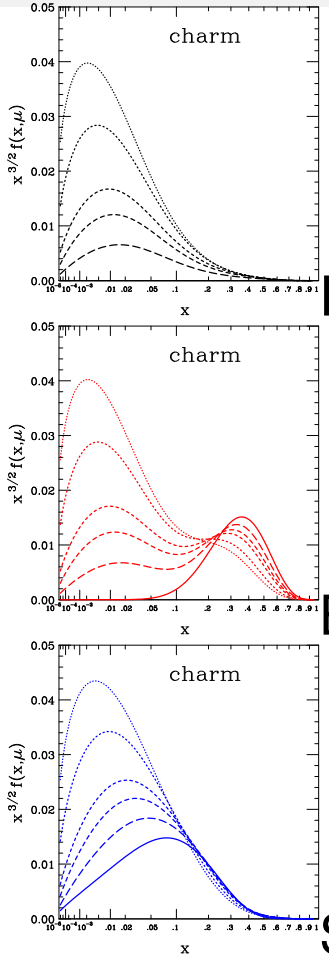

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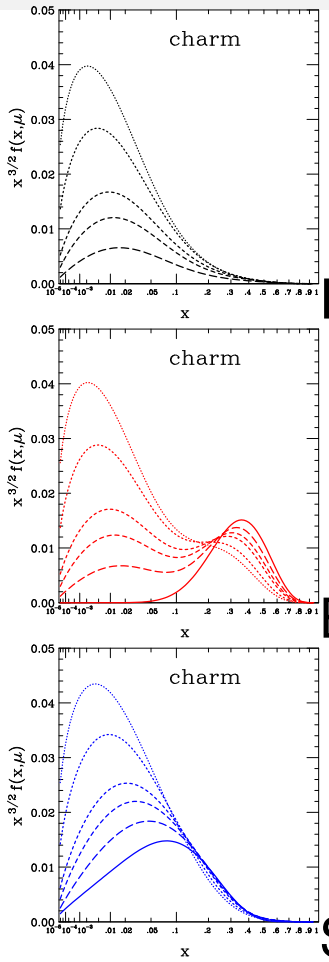

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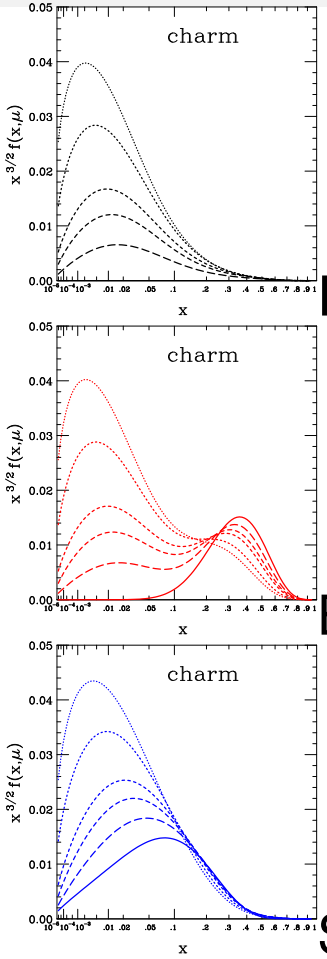

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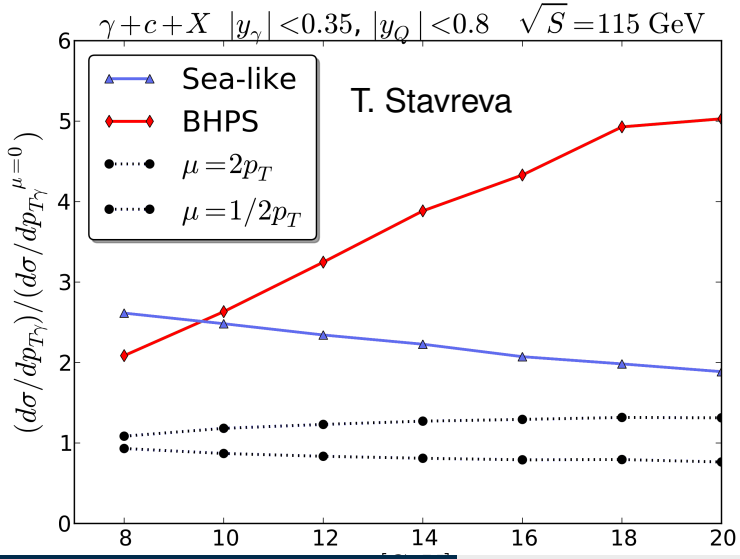

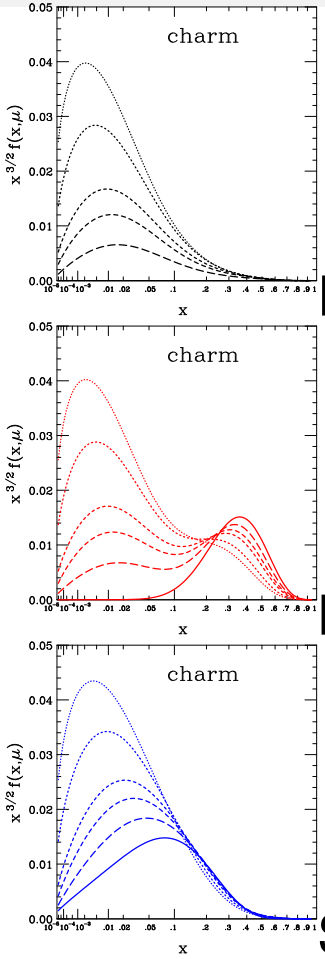

DGLAP

BHPS

Sea-like

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Distribution of linearly polarised gluons in unpolarised protons

Distribution of linearly polarised gluons in unpolarised protons

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

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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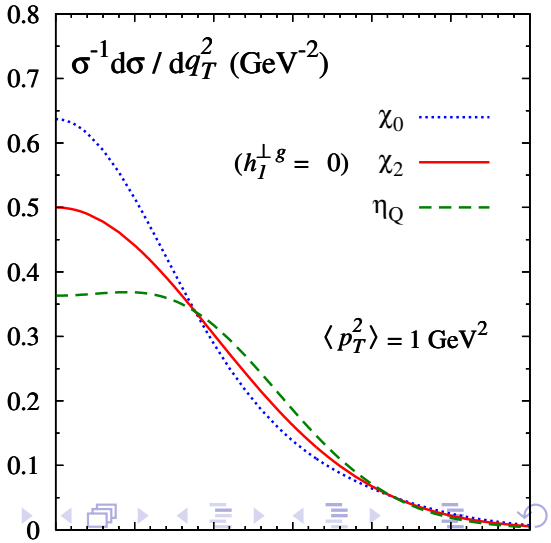

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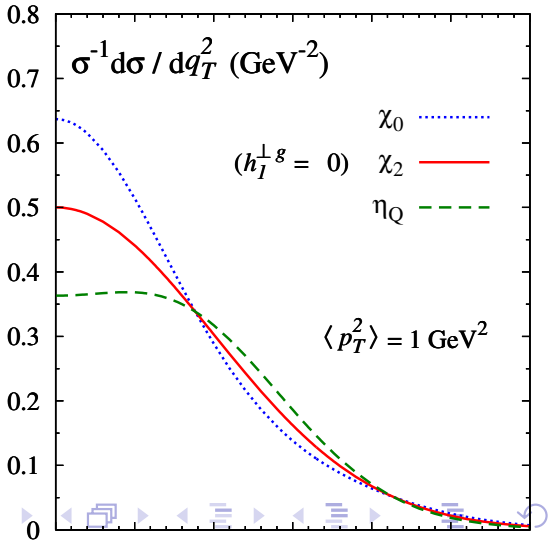

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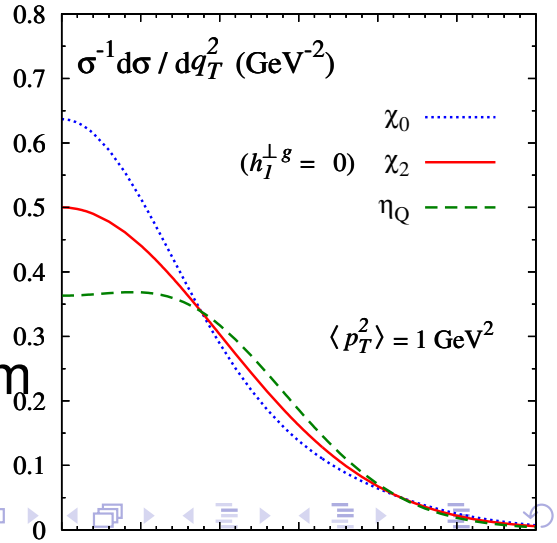
- $h_1^{\perp g}$ is connected to the Higgs transverse-momentum distribution **D. Boer,** *et al.* **PRL 108 (2012) 032002**



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PRL **112,** 212001 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

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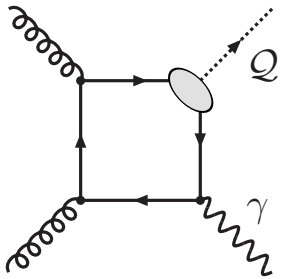

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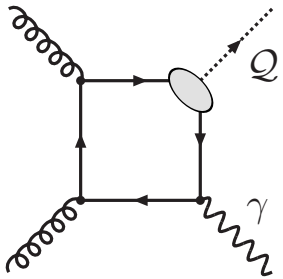

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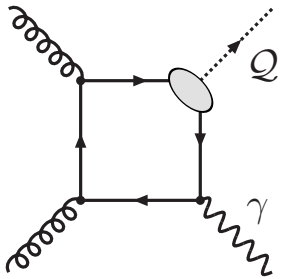

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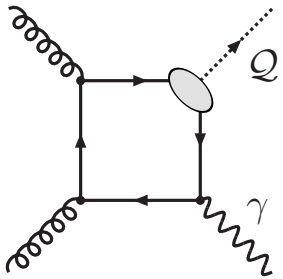

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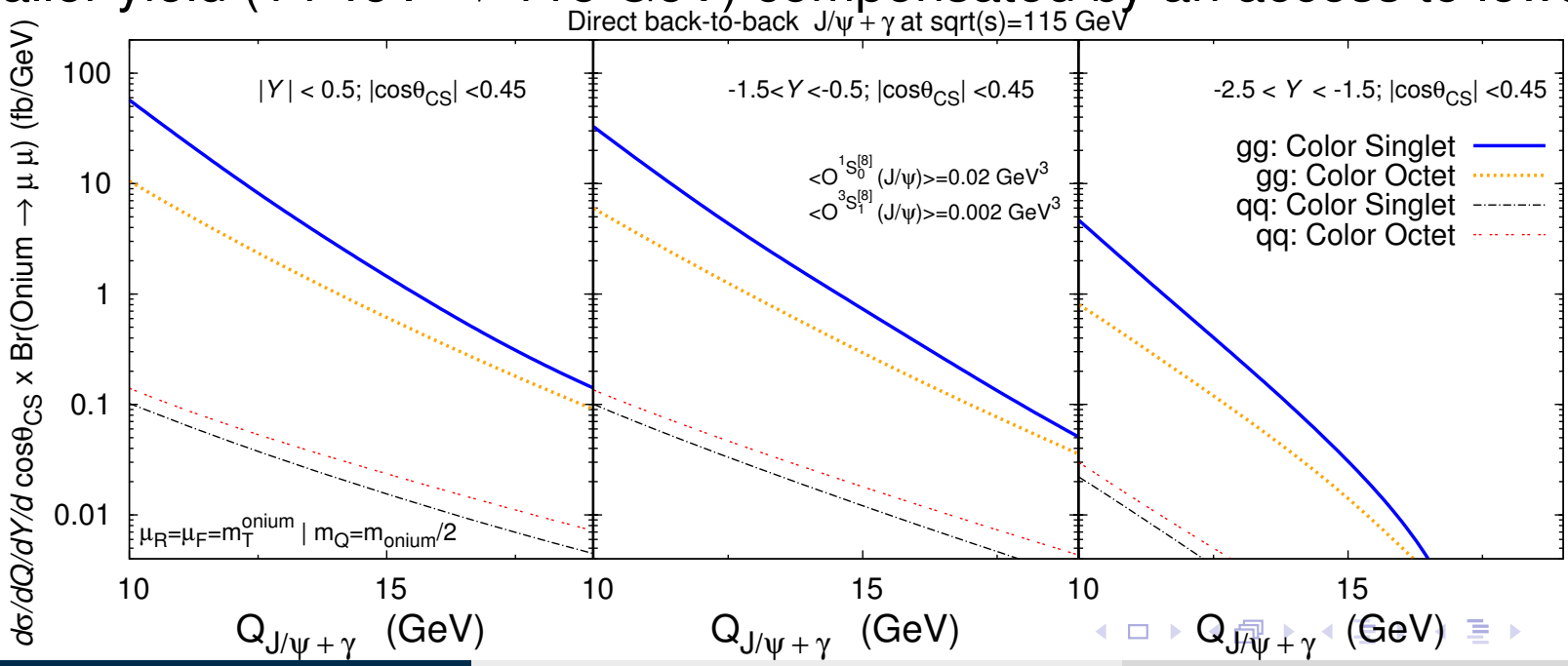

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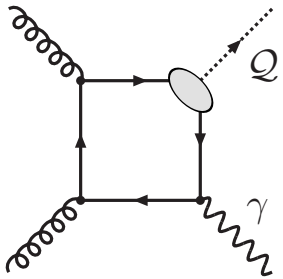

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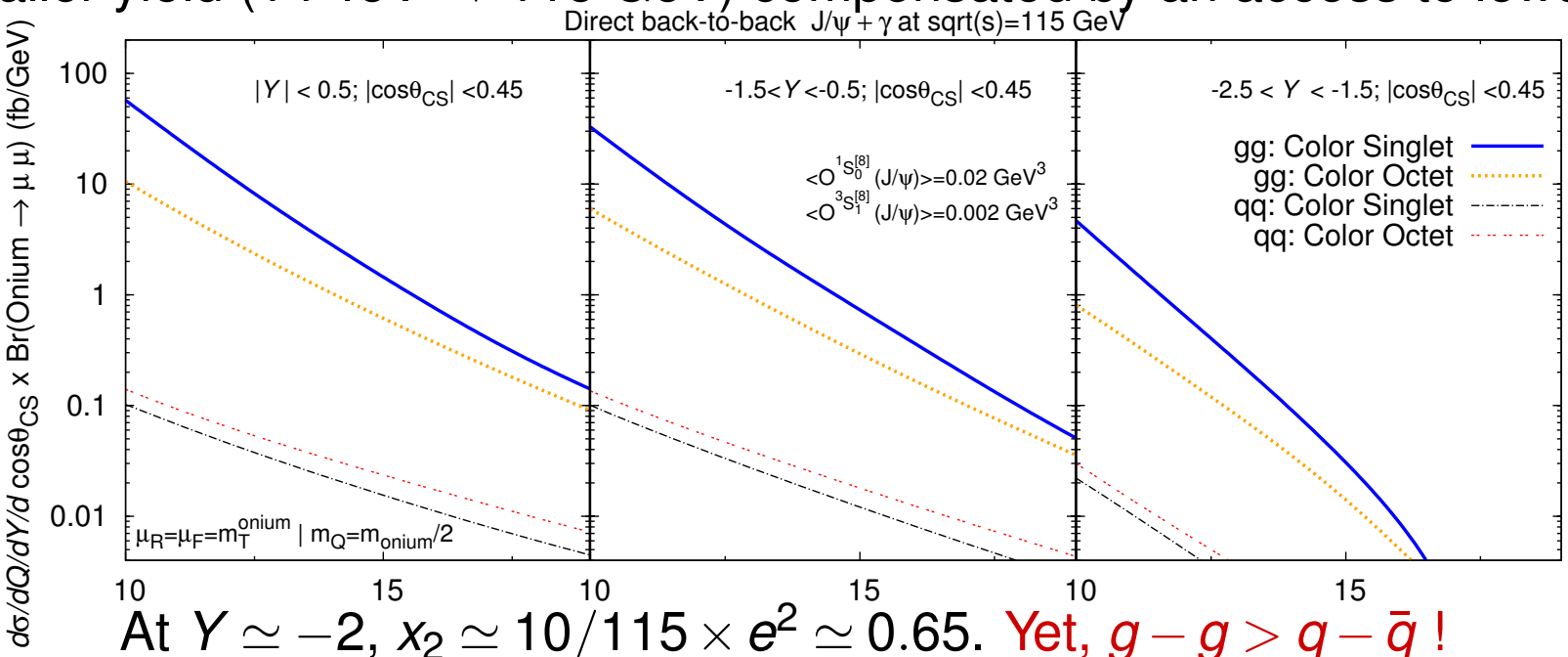

At $Y \simeq -2$, $x_2 \simeq 10/115 \times e^2 \simeq 0.65$. Yet, $g - g > q - \bar{q}$!

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)	$x_p^\uparrow$	$\mathscr{L}$ ($\mathrm{nb}^{-1}\mathrm{s}^{-1}$)
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
P1027	$p^\uparrow + p$	120	15	$0.35 \div 0.85$	400-1000
P1039	$p + p^\uparrow$	120	15	$0.1 \div 0.3$	400-1000

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

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

SSA in Drell-Yan studies with AFTER@LHC

➟ Relevant para ... its.

267.

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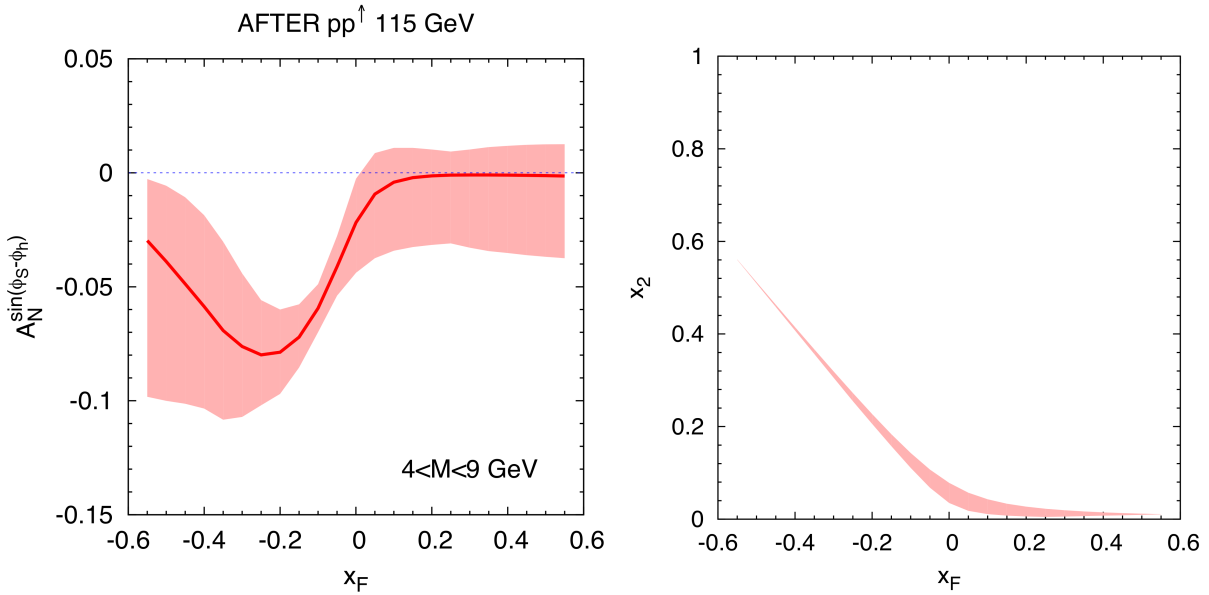
expected Sivers asymmetry in D-Y@AFTER, sign change, no TMD evolution



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

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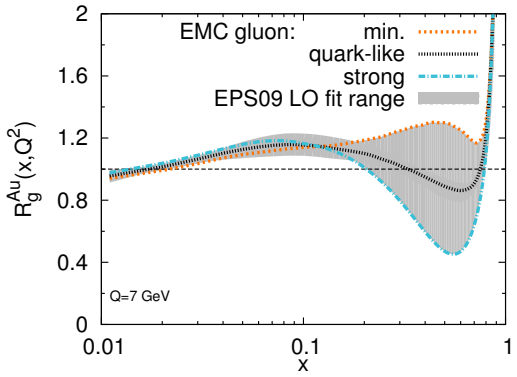

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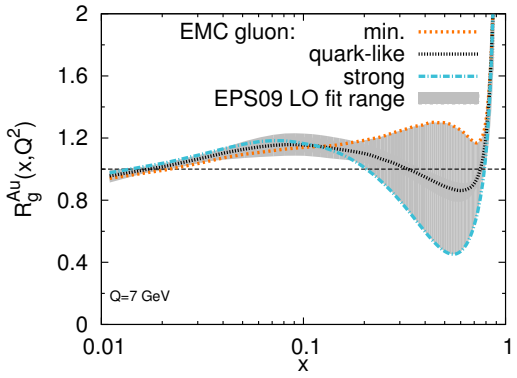

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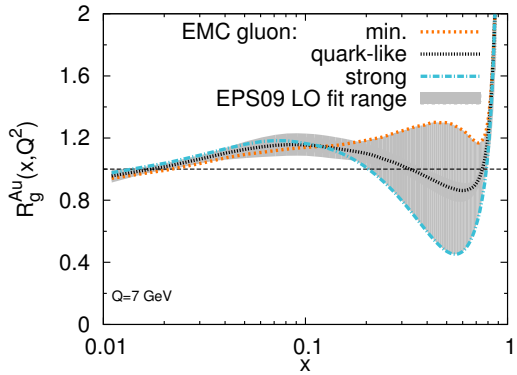

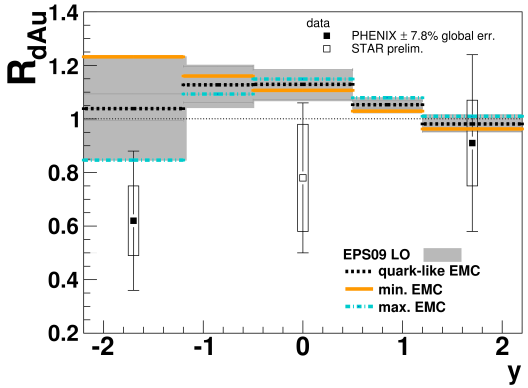

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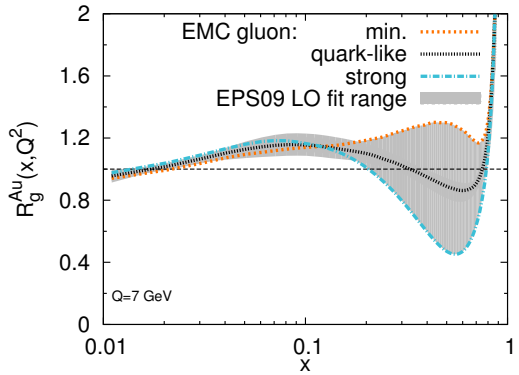

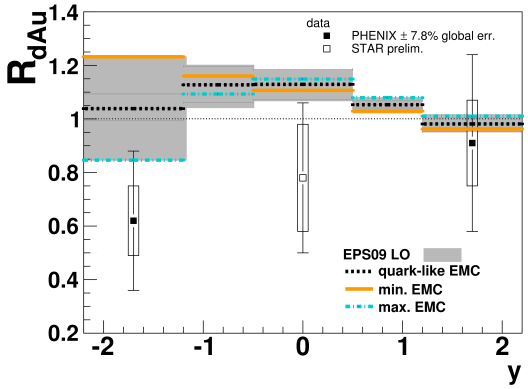

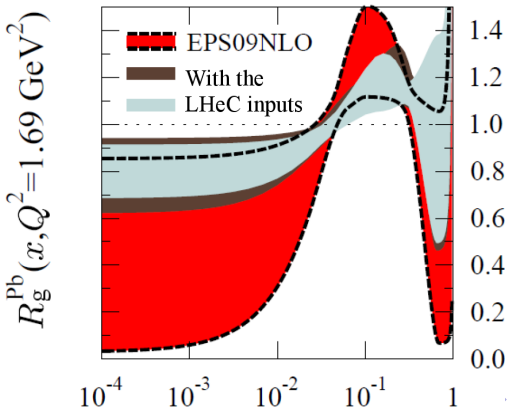

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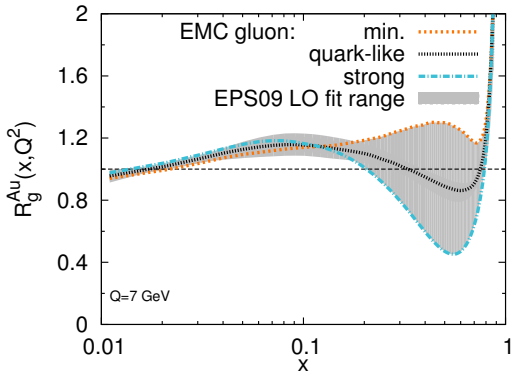

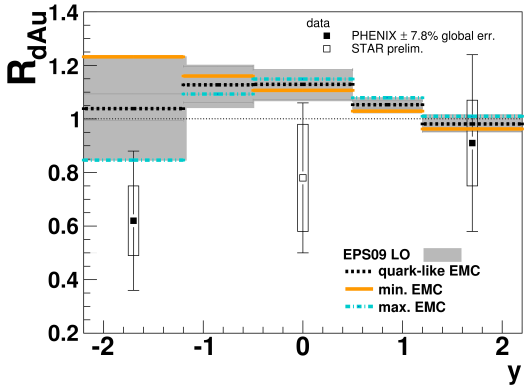

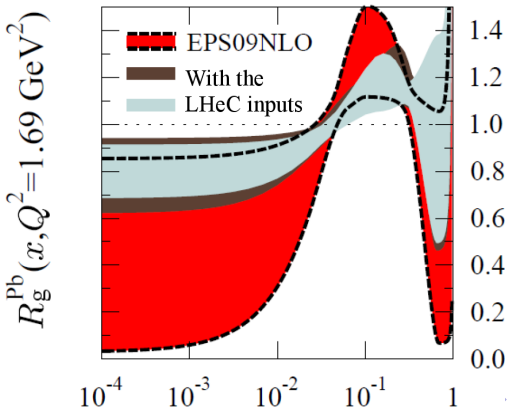

Physics with the lead-ion beam

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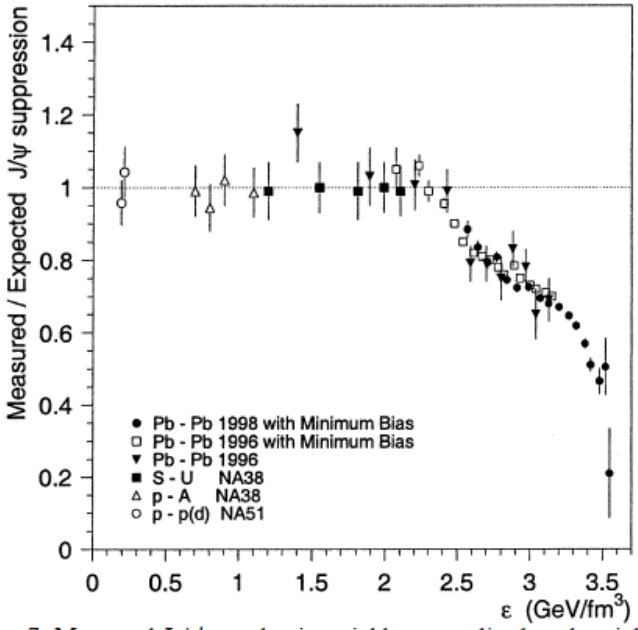

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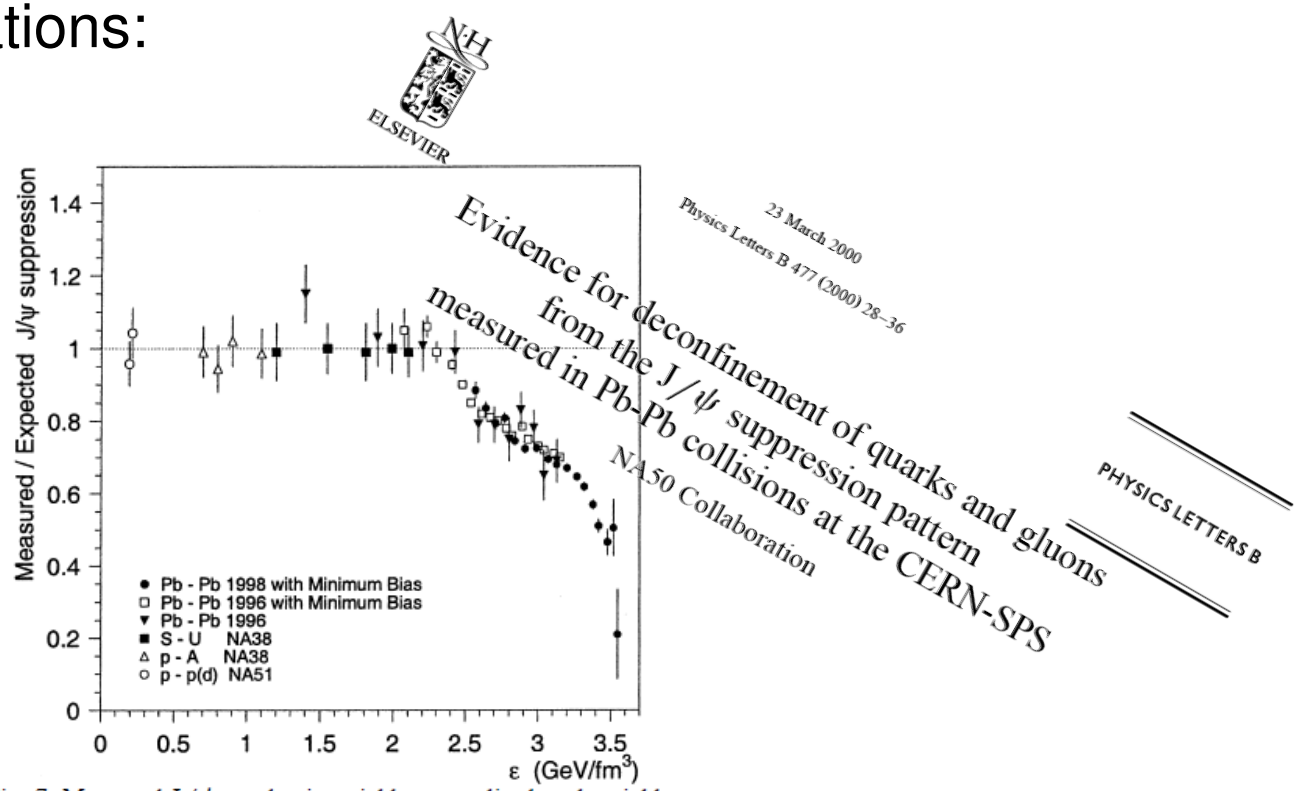

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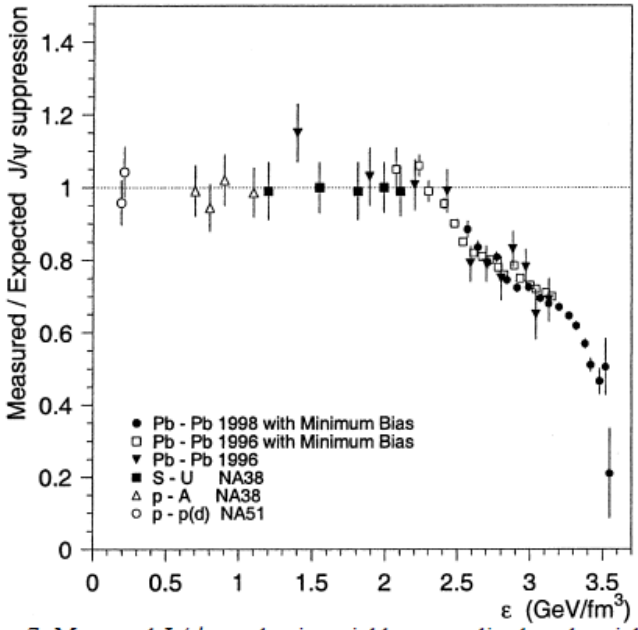

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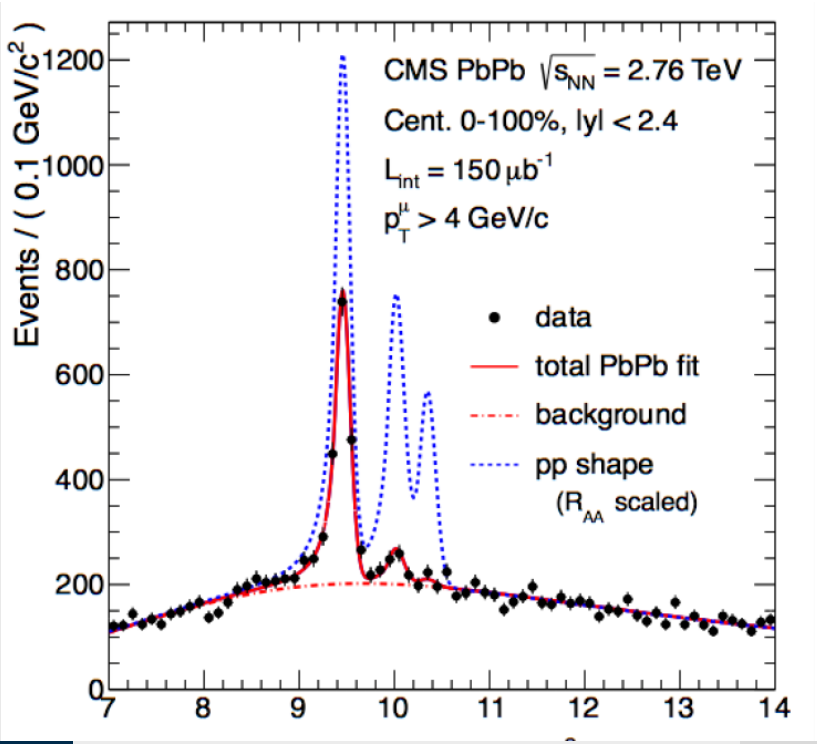

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Physics opportunities of a fixed-target experiment using LHC beams

S.J. Brodsky [a], F. Fleuret [b], C. Hadjidakis [c], J.P. Lansberg [c,*]

[a] SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA
[b] Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France
[c] IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

Contents

Part IV

Special Issue in Advances in High-Energy Physics & Workshop at CERN

Advances in High Energy Physics

Special Issue on
Physics at a Fixed-Target Experiment Using the LHC Beams

CALL FOR PAPERS

Fixed-target experiments (FTE) have brought essential contributions to particle and nuclear physics. They have led to particle discoveries (Ω, J/ψ, γ,...) and evidence for the novel dynamics of quarks and gluons in heavy-ion collisions. In accessing high x_F and in offering options for (un-) polarised proton and nuclear targets, they have also led to the observation of surprising QCD phenomena. They offer specific advantages compared to collider experiments: access to high x_F, high luminosities, target versatility, and polarisation.

The LHC 7 TeV protons on targets release a c.m.s. energy close to 115 GeV (72 GeV with Pb), in a range never explored so far, significantly higher than that at SPS and not far from RHIC. The production of quarkonia, DY, heavy flavours, jets, and γ in *pA* collisions can be studied with statistics previously unheard of and in the backward region, $x_F < 0$, which is uncharted. High precision QCD measurements can also obviously be carried out in *pp* and *pd* collisions with H_2 and D_2 targets. With the 50 TeV protons of the future circular collider (FCC), the c.m.s. energy could reach 300 GeV for original studies of W and Z boson, and perhaps H^0, production in *pp* and *pA* collisions.

With the LHC Pb beam, one can study the quark-gluon plasma (QGP) from the viewpoint of the nucleus rest frame after its formation. Thanks to modern technologies, studies of, for instance, direct γ and quarkonium *P*-waves production in heavy-ion collisions can be envisioned.

Polarising the target allows one to study single-spin correlations including the Sivers effect, hence, the correlation between the parton k_T and the nucleon spin.

We intend to publish a special issue on the physics at such a FTE using the LHC or FCC beams. The editors welcome original research articles and review articles from both theorists and experimentalists.

Potential topics include, but are not limited to:

- Heavy-quark and gluon content at large *x*
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- Simulation tools for high-energy physics
- Beam collimation and extraction with bent crystals
- Machine feasibility and radiological aspects
- Connection between UHECR studies and FTEs

Lead Guest Editor
Jean-Philippe Lansberg, Université Paris-Sud, Orsay, France
lansberg@in2p3.fr

Guest Editors
Gianluca Cavoto, Istituto Nazionale Di Fisica Nucleare, Roma, Italy
gianluca.cavoto@roma1.infn.it

Cynthia Hadjidakis, Université Paris-Sud, Orsay, France
cynthia@ipno.in2p3.fr

Jibo He, CERN, Geneva, Switzerland
jibo.he@cern.ch

Cédric Lorcé, Université de Liège, Liège, Belgium
c.lorce@ulg.ac.be

Barbara Trzeciak, Czech Technical University, Prague, Czech Republic
trzecbar@fjfi.cvut.cz

Manuscript Due
Friday, 20 March 2015

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Friday, 12 June 2015

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Advances in High Energy Physics

Hindawi

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Everybody is welcome to submit an individual contribution

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Part V

First simulations

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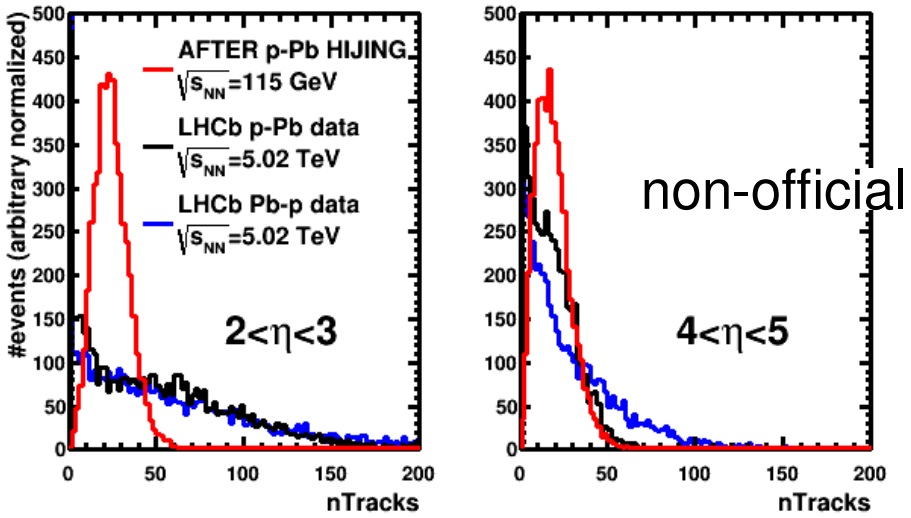

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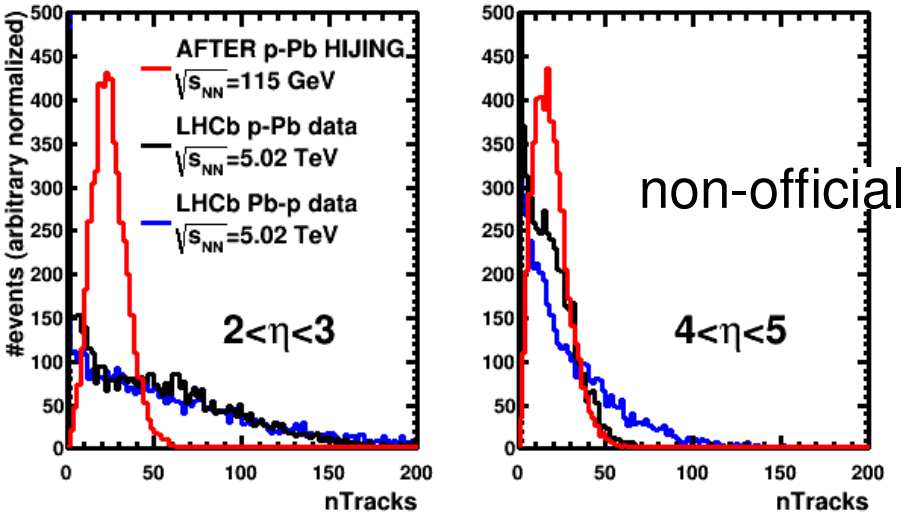


- Despite the boost, the number of tracks in the LHCb acceptance [forward η] is lower in the fixed mode than in the collider mode
- Very encouraging indication that the boost is not issue, but really an asset

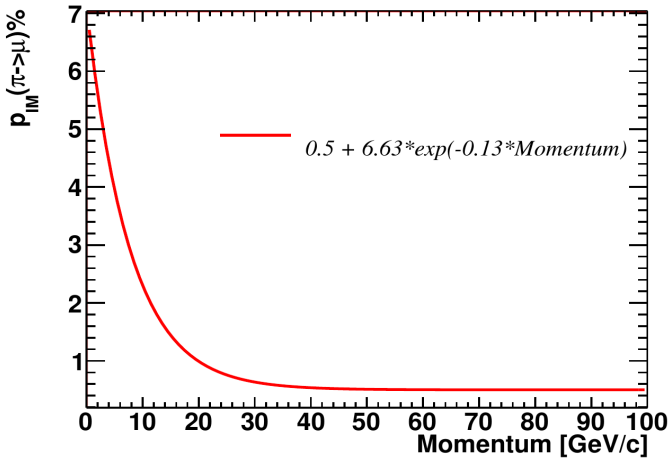
FAST SIMULATIONS FOR QUARKONIA (pp $\sqrt{s}$ = 115 GeV) USING LHCB RECONSTRUCTION PARAMETERS

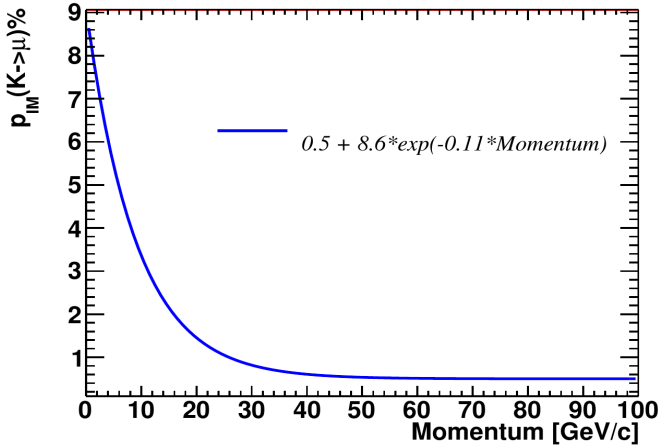
- Simulations with Pythia 8.185
- LHCb detector is NOT simulated but LHCb reconstruction parameters are introduced in the fast simulation (resolution, analysis cuts, efficiencies…)

Requirements
Momentum resolution : $\Delta p/p$ = 0.5%
Muon identification efficiency: 98%

Cuts at the single muon level
$2 < \eta_\mu < 5$
$p_T^\mu > 0.7$ GeV/c

Muon misidentification
If π and K decay before the calorimeters (12m), they are rejected by the tracking
Else a misidentification probability is applied





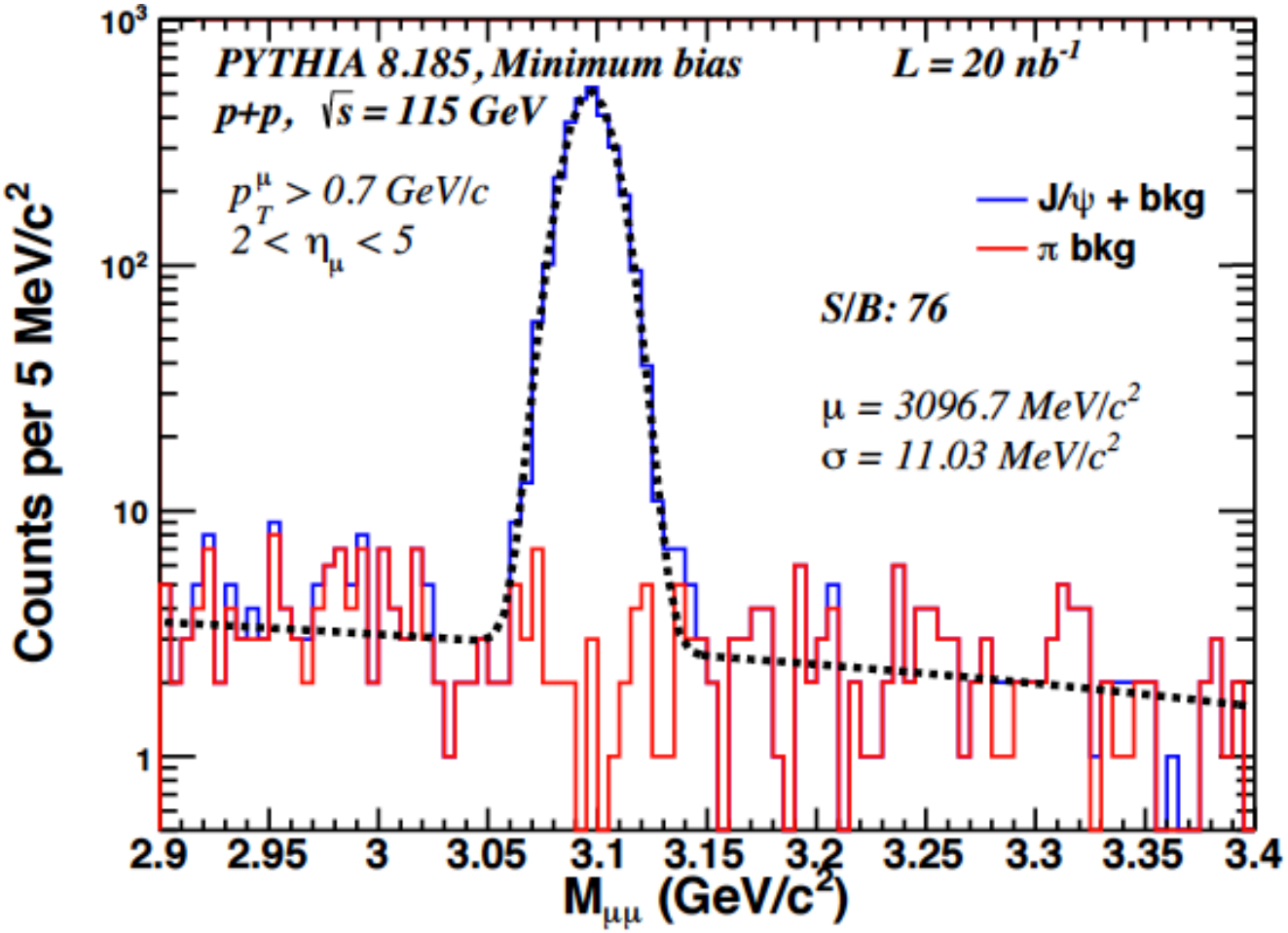
R. Mikkelsen, B. Trzeciak

Performance of the muon identification at LHCb, F. Achilli et al, arXiv:1306.0249

J/Ψ →μ⁺μ⁻ IN MB pp @ 115 GEV

- For 1m of H target and few tens of seconds of data taking

B. Trzeciak, July 2014, Orsay



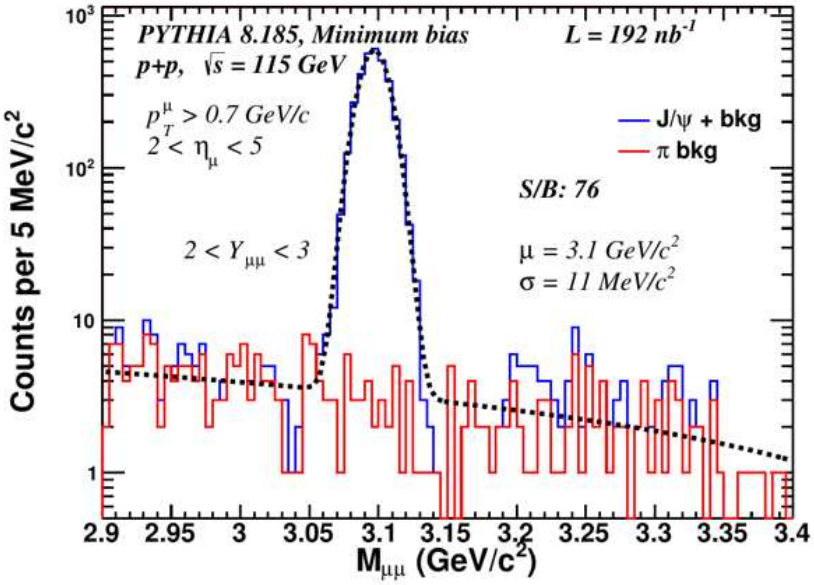
Misidentified pions is the dominant source of background

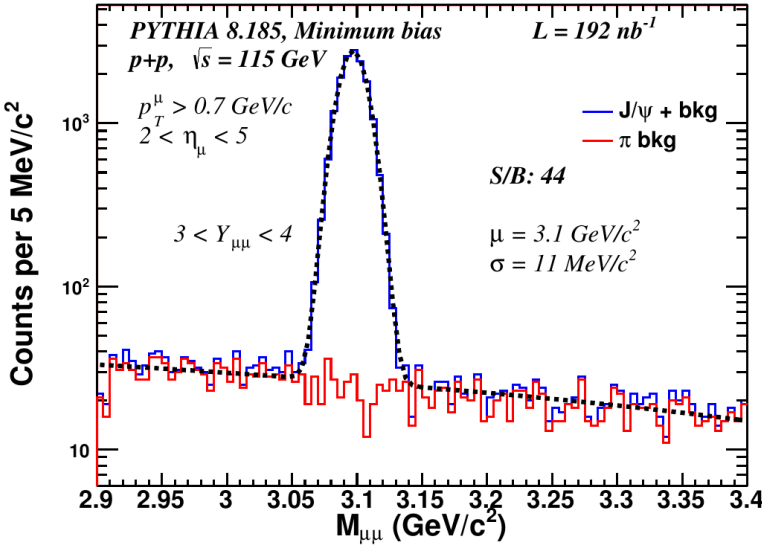
R. Mikkelsen, B. Trzeciak

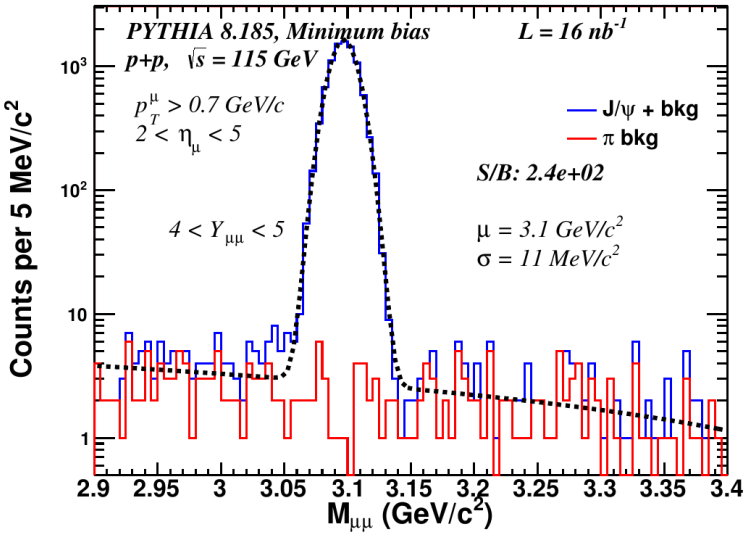
J/Ψ →μ⁺μ⁻ IN MB pp @ 115 GEV (BINS IN RAPIDITY)

- For 1m of H target and few minutes of data taking

B. Trzeciak, July 2014, Orsay







R. Mikkelsen, B. Trzeciak

Accessing the large *x* glue with quarkonia:

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

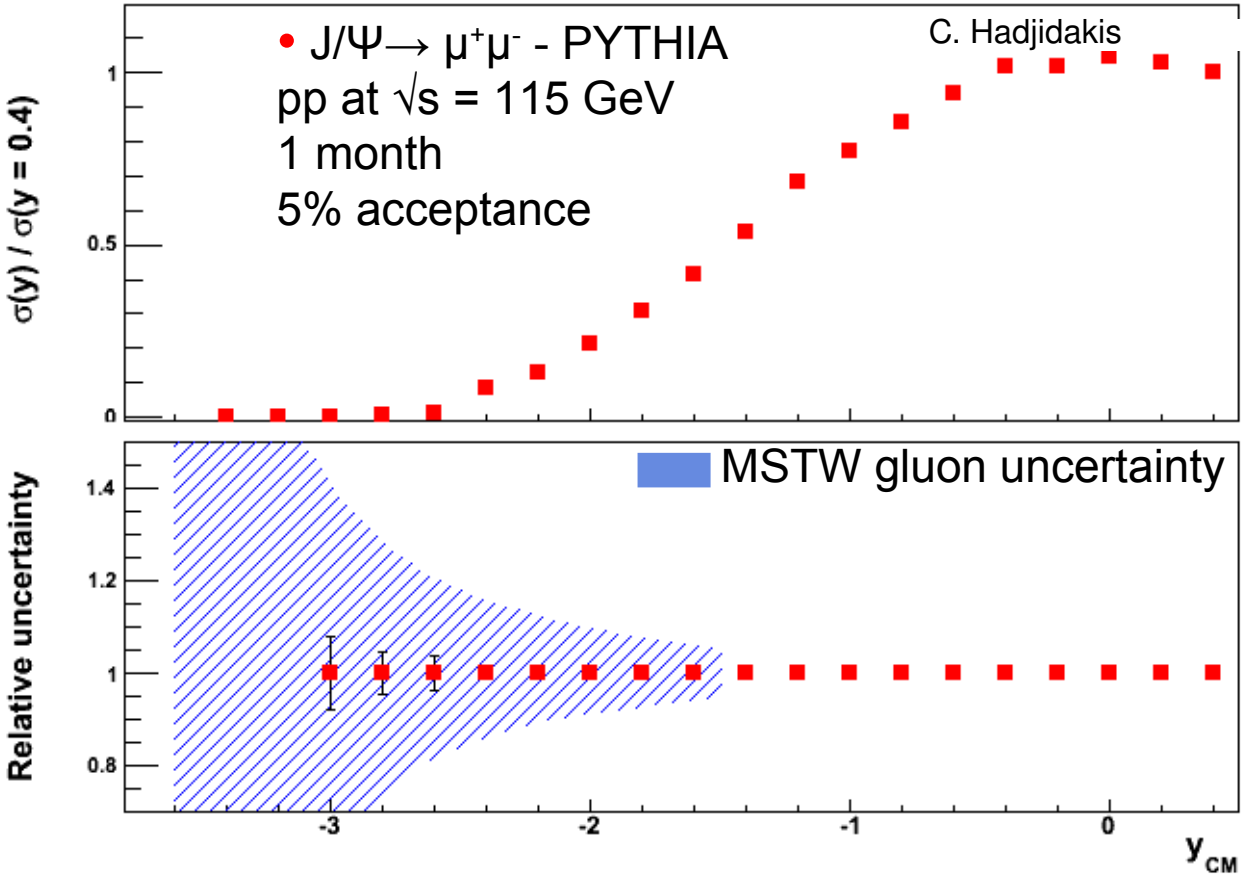
Statistical relative uncertainty
Large statistics allow to access very backward region

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

Y: 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 VI

Conclusion and outlooks

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- A wealth of possible measurements:
  DY, Open b/c, jet correlation, UPC... (not mentioning secondary beams)

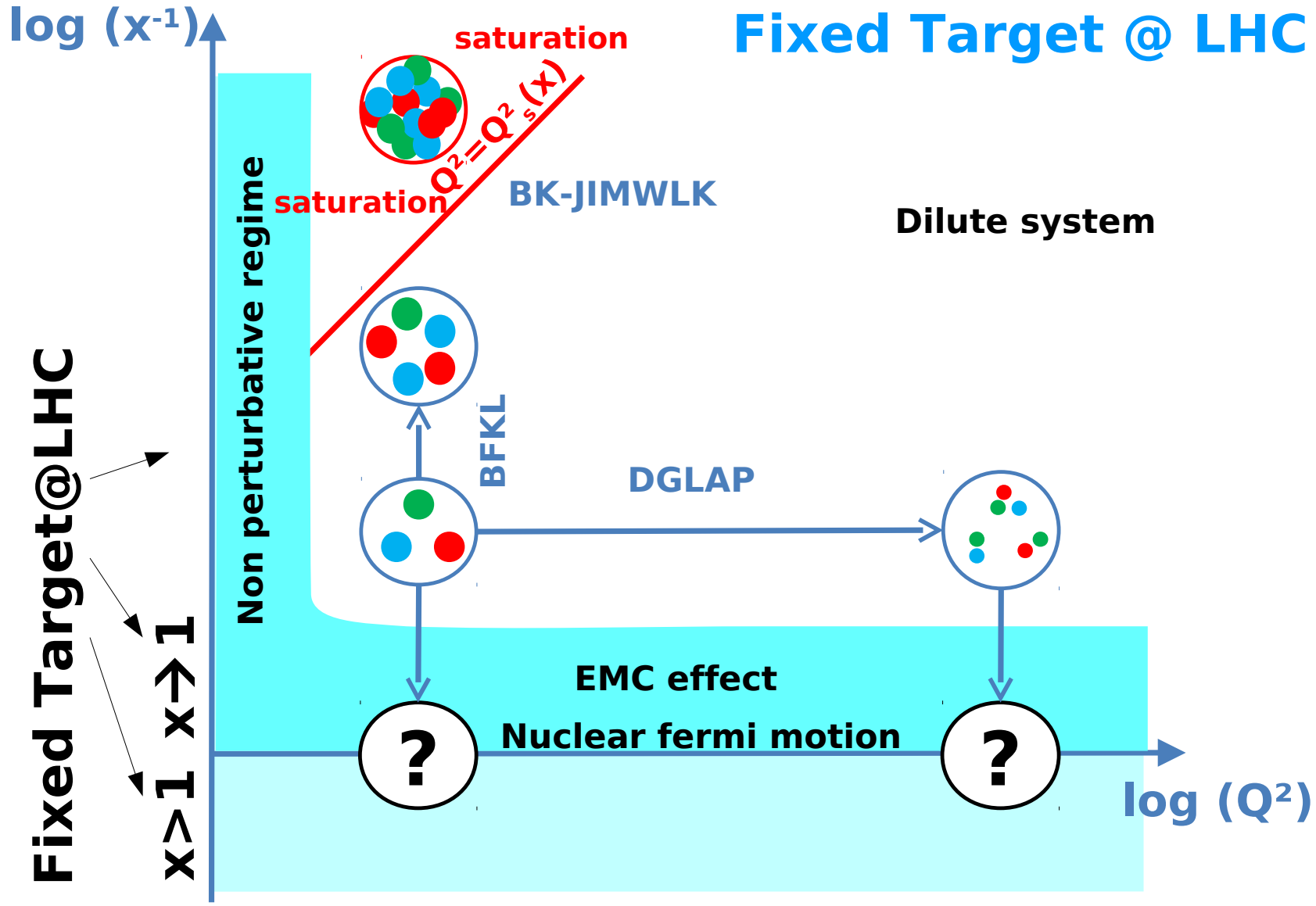
Part VII

Backup slides

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.

Overall


log (x⁻¹)
Fixed Target @ LHC
saturation
Q²=Q²s(x)
saturation
BK-JIMWLK
Dilute system
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BFKL
DGLAP
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?
?
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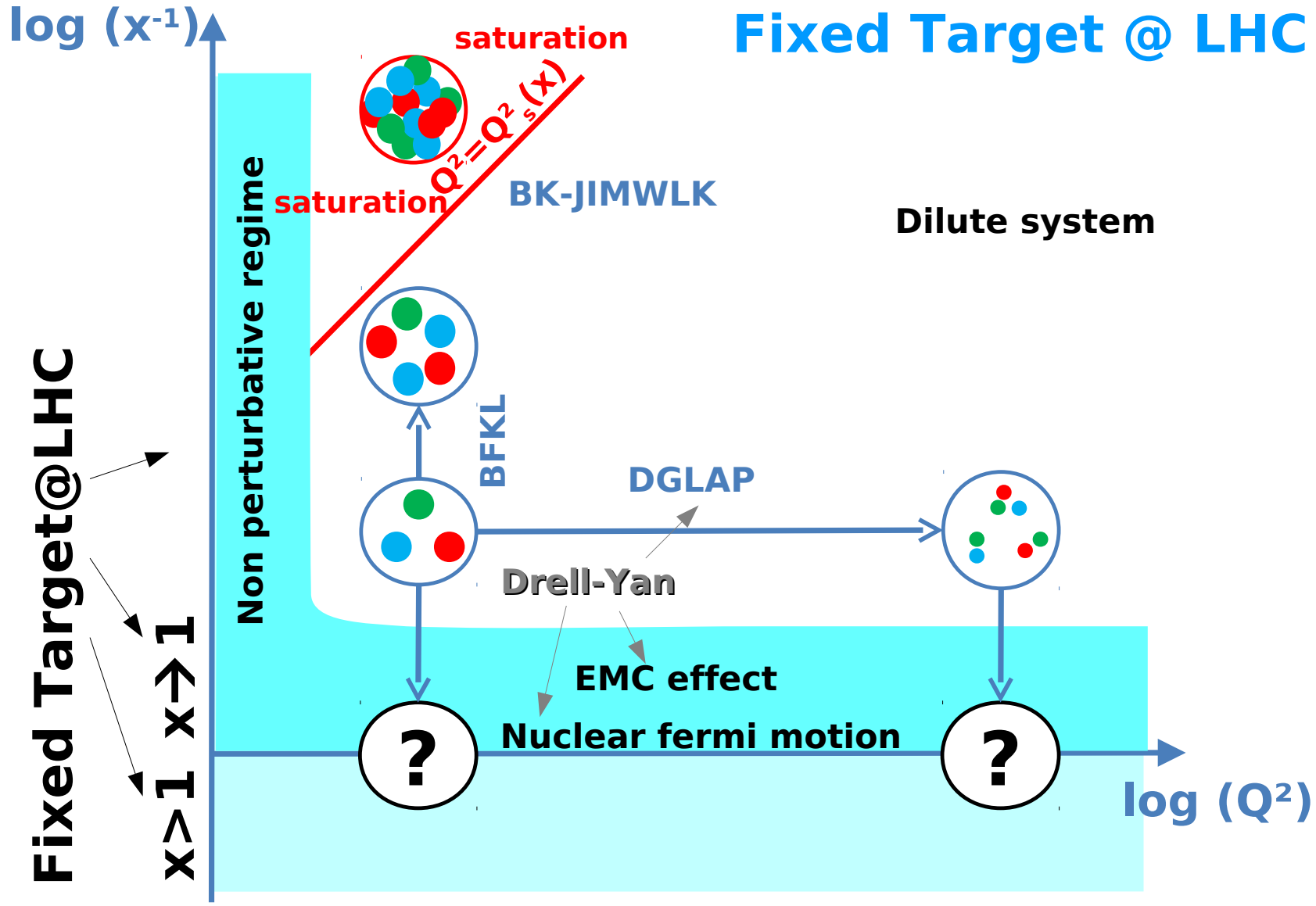
Overall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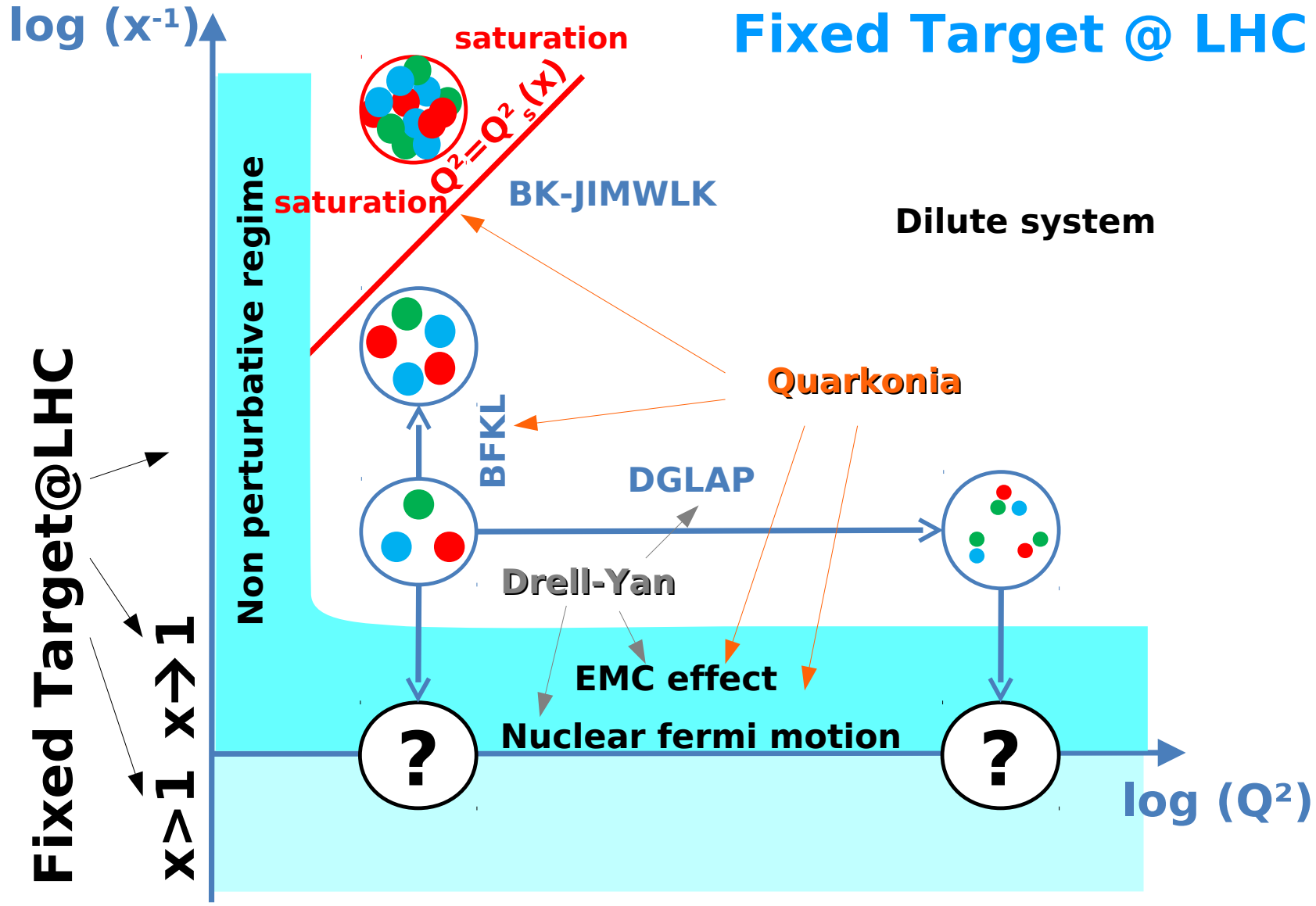
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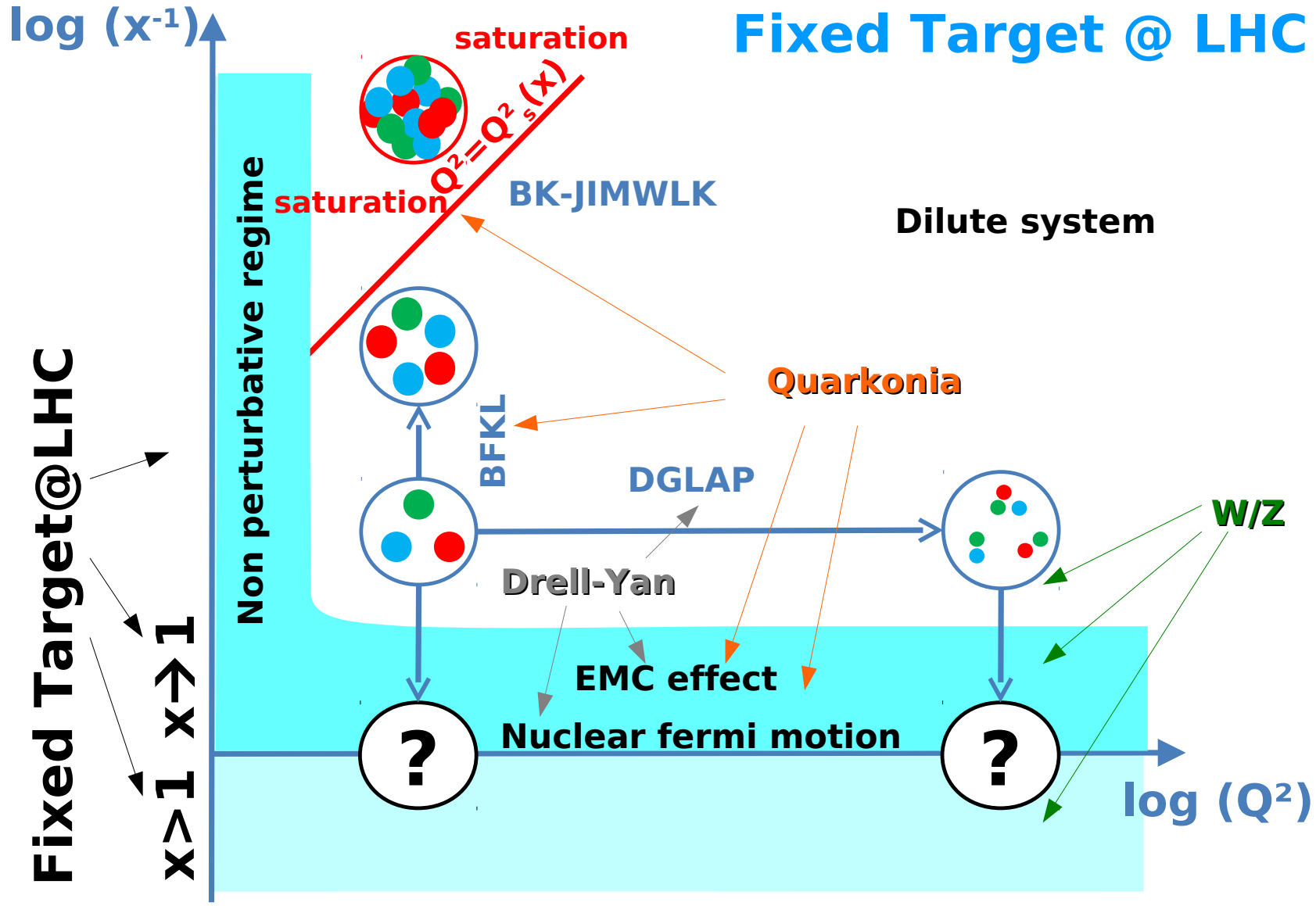
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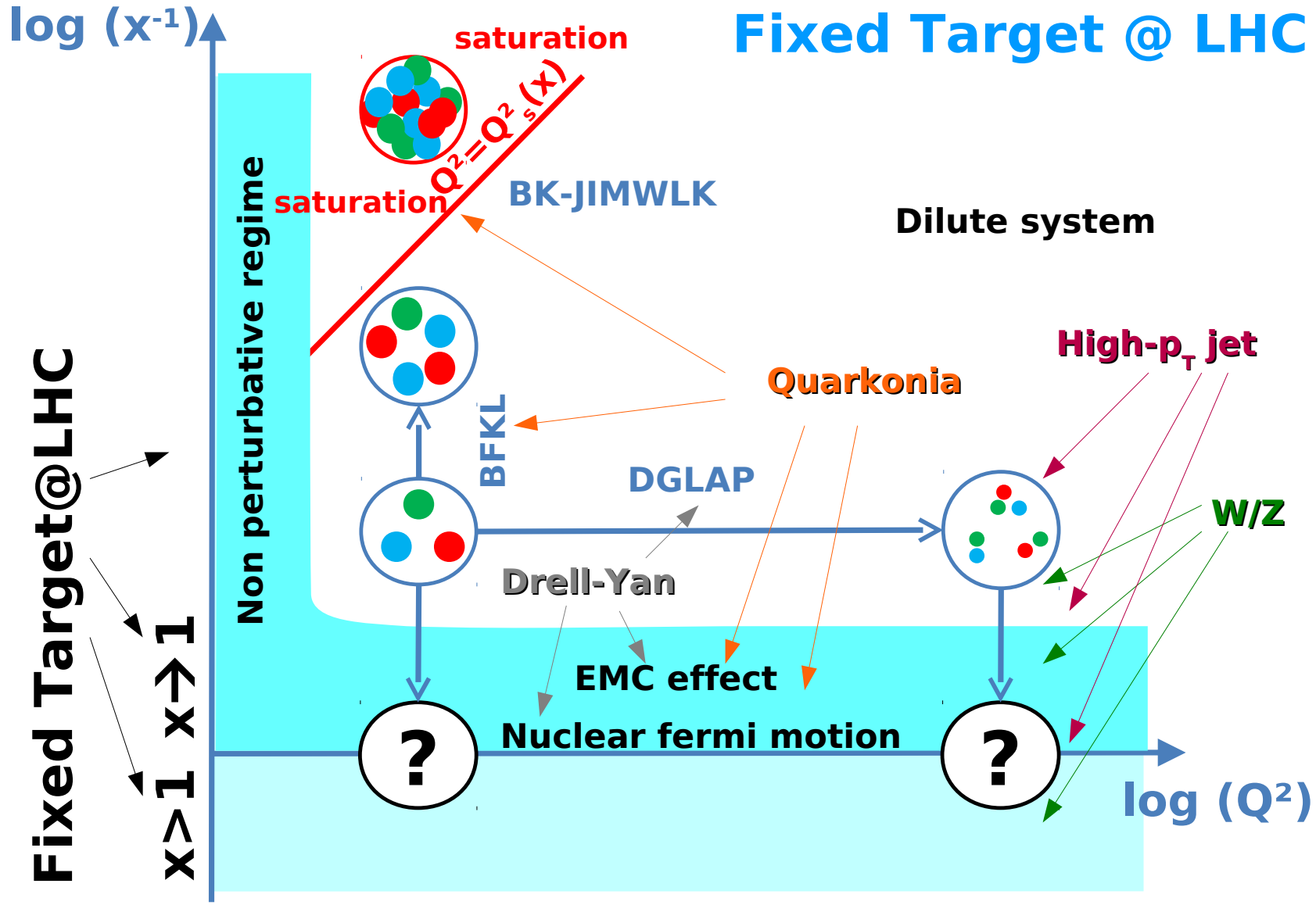
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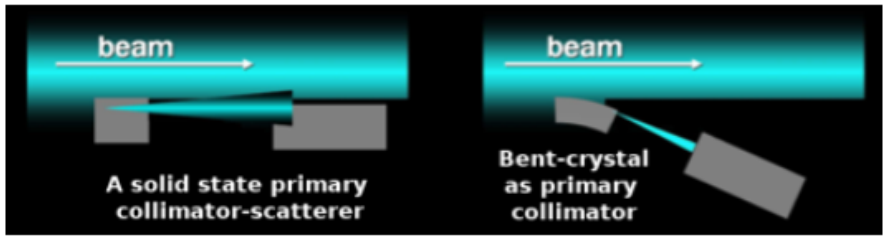
The beam extraction: news

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

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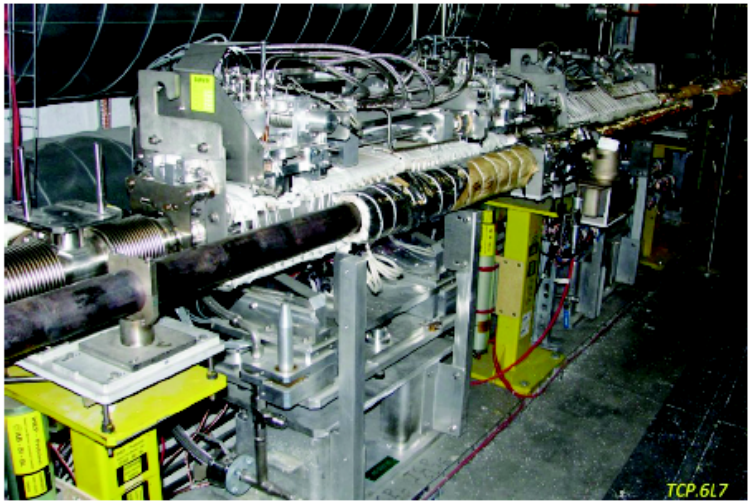

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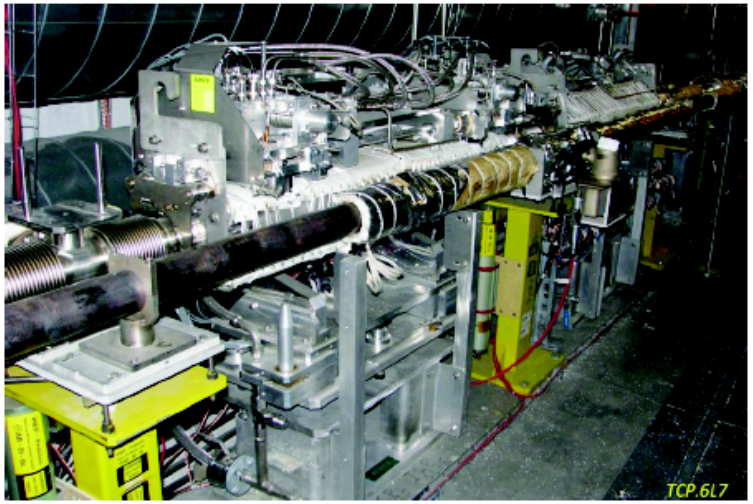

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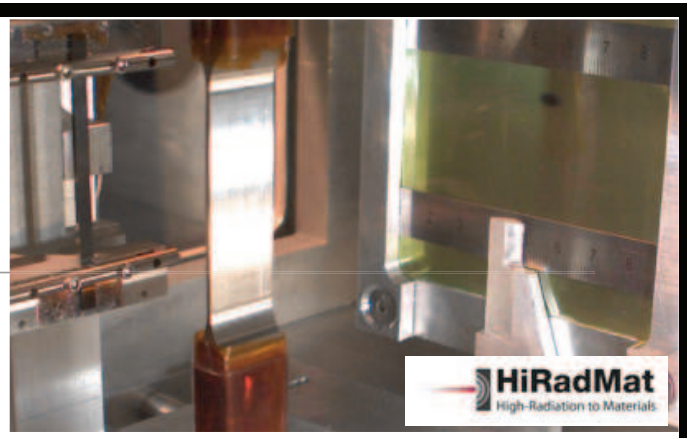
Towards an installation in the LHC : propose and install during LS1 a min. number of devices

- 2 crystals

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

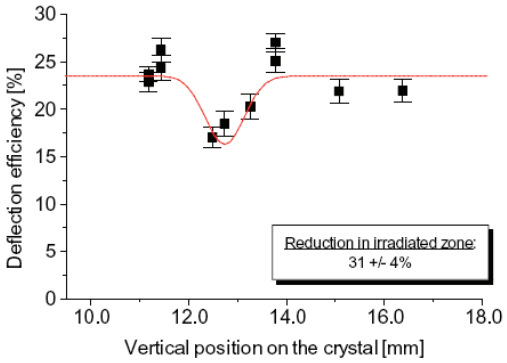
Simone Montesano - February 11th, 2013 - Physics at AFTER using the LHC beams

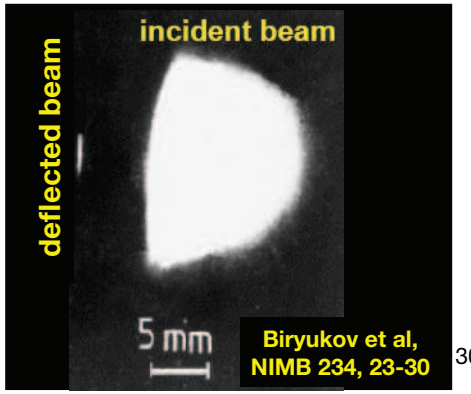
Crystal resistance to irradiation



- **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

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





30

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

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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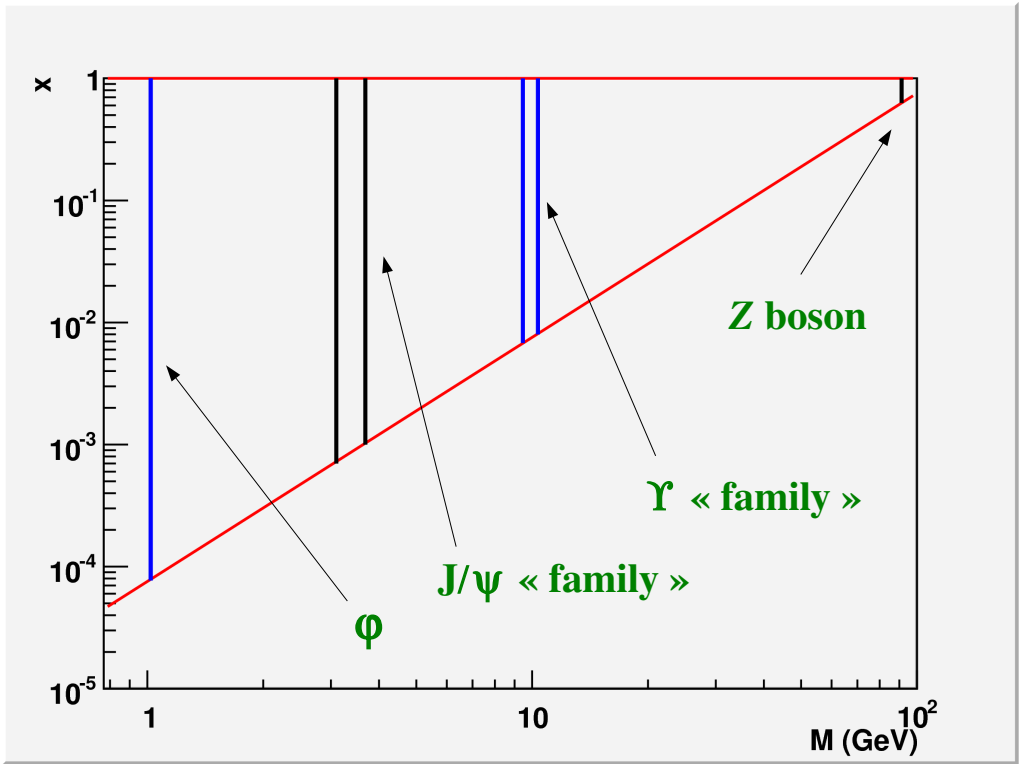
AFTER@LHC: A dilepton observatory ?

➟ Region in x probed by dilepton production as function of $M_{\ell\ell}$



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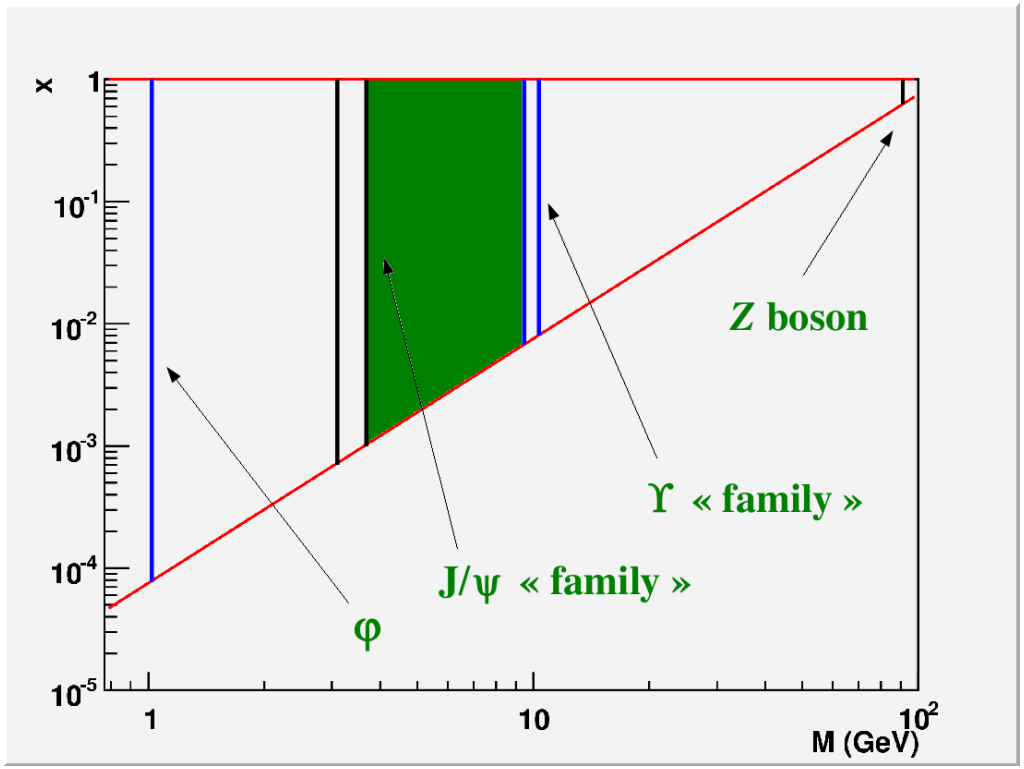

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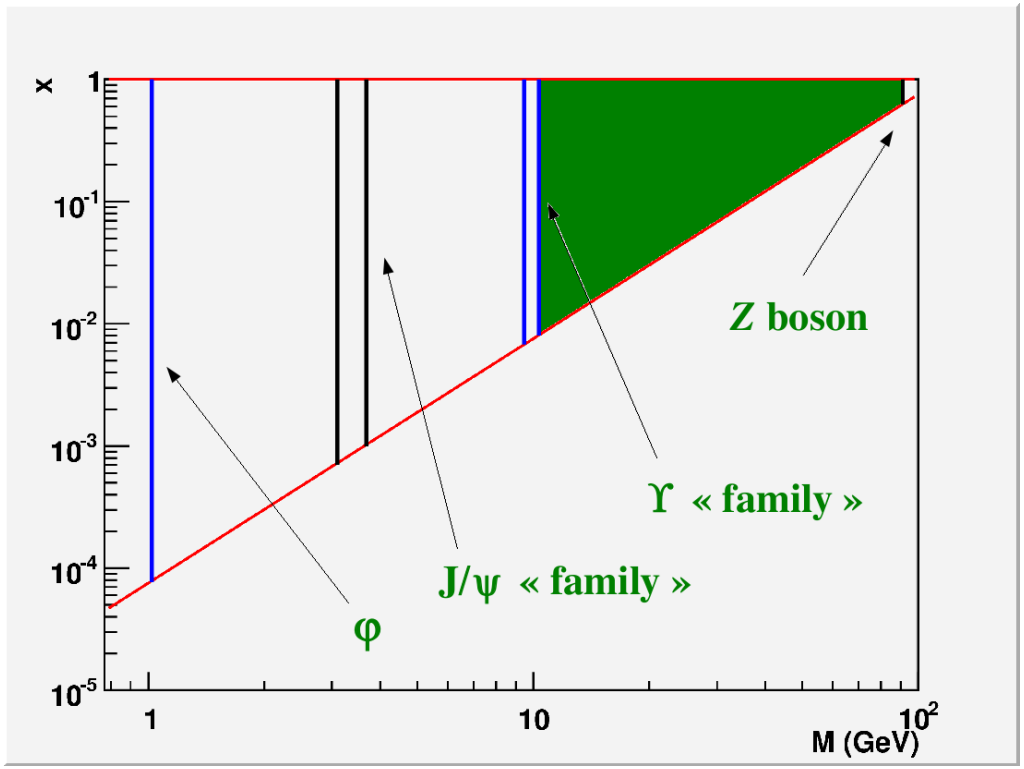

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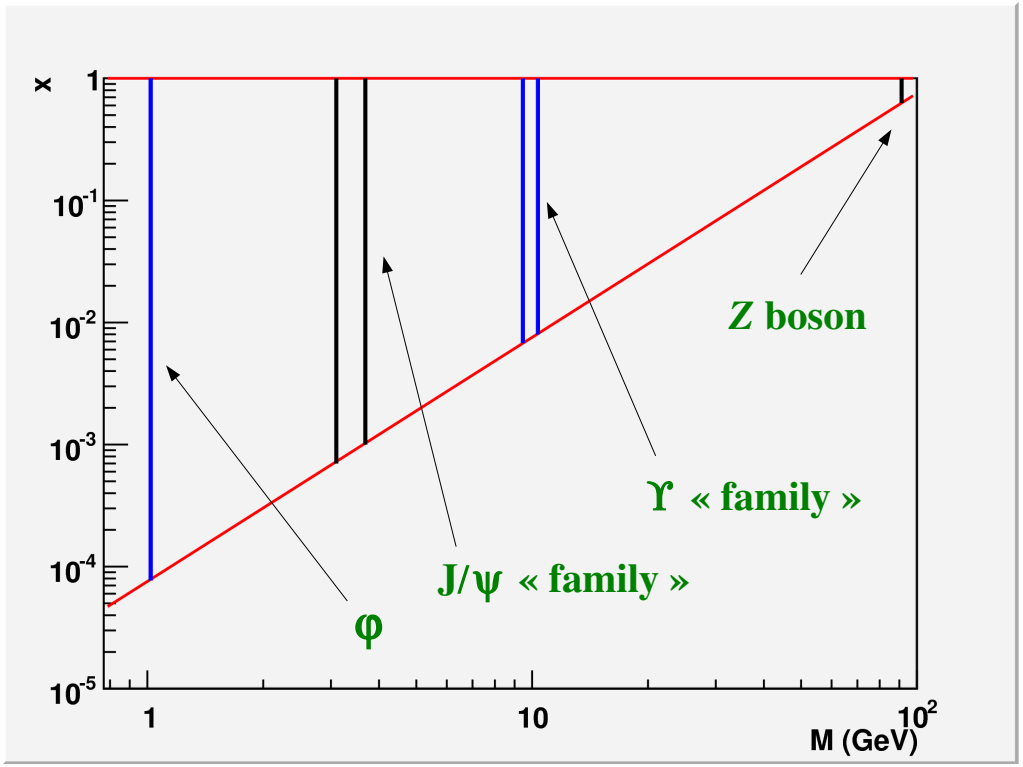

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via p and d studies

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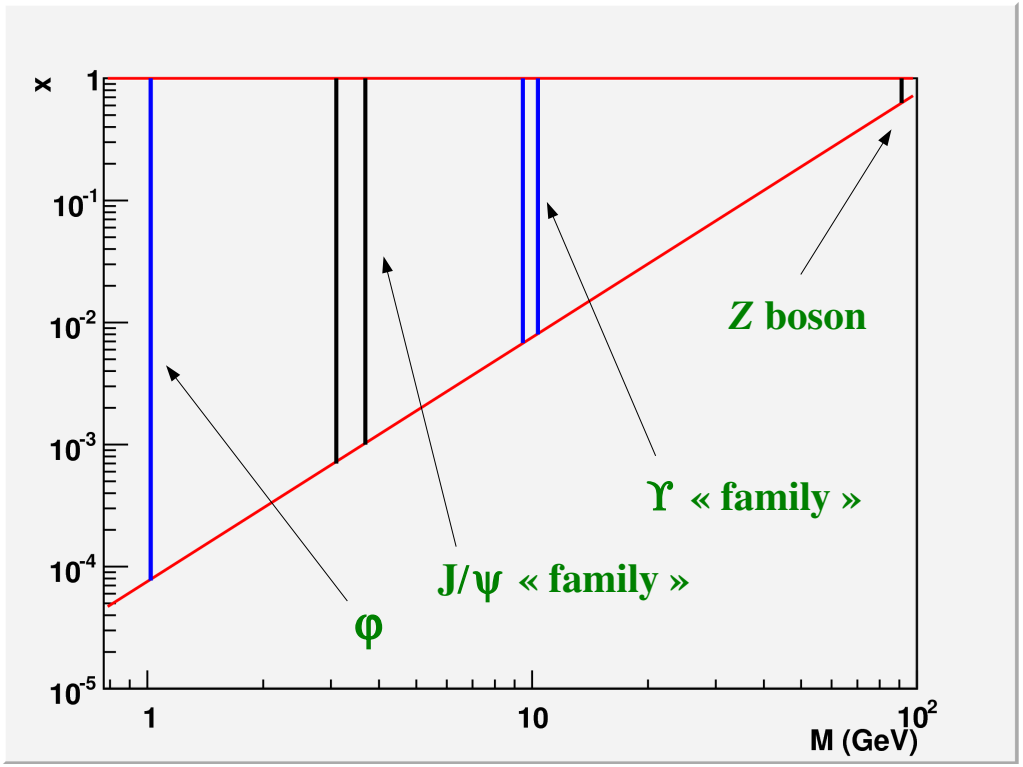
- at small(est) x: forward (need to stop the (extracted) beam)



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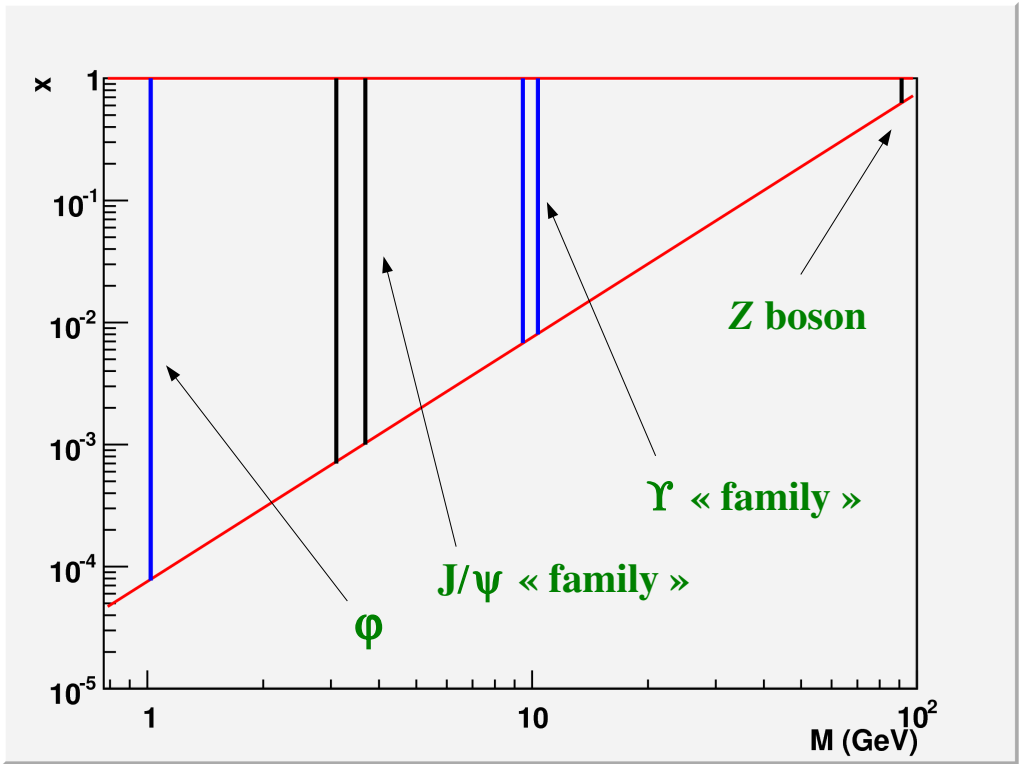

➠ To do: to look at the rates to see how competitive this will be

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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1 m Liq. D_2	24	$9.6\ 10^8$	$1.9\ 10^6$
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- Unique access in the backward region

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	$4.0\ 10^8$	$8.0\ 10^5$
1 m Liq. D_2	24	$9.6\ 10^8$	$1.9\ 10^6$
LHC pp 14 Tev (low pT)	0.05 (ALICE) 2 LHCb	$3.6\ 10^7$ $1.4\ 10^9$	$1.8\ 10^5$ $7.2\ 10^6$
RHIC pp 200GeV	$1.2\ 10^{-2}$	$4.8\ 10^5$	$1.2\ 10^3$

- 1000 times higher than at RHIC;comparable to ALICE/LHCb at the LHC
- Numbers are for only one unit of rapidity about 0
- Unique access in the backward region
- 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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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

AFTER: also a quarkonium observatory in *pA*

Target	A	$\int \mathcal{L}$ (fb^{-1}.yr^{-1})	N(J/Ψ) yr^{-1} = $A\mathcal{L}\mathcal{B}\sigma_\Psi$	N(ϒ) yr^{-1} =$A\mathcal{L}\mathcal{B}\sigma_\Upsilon$
1cm Be	9	**0.62**	**1.1 10^8**	**2.2 10^5**
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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 factorisation

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$\mathcal{L}\mathcal{B}\sigma_{\Upsilon}$
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The same picture also holds for open heavy flavour

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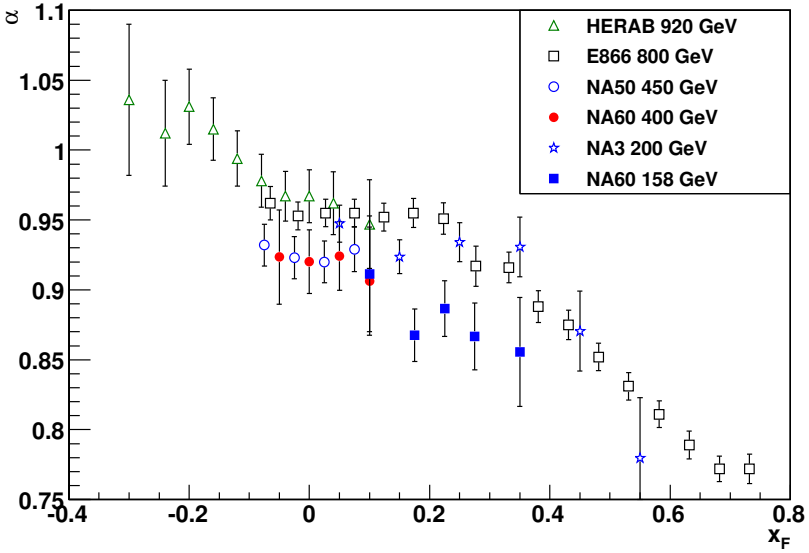
- the possibilities for $c\bar{c}$ recombination
  - Open charm studies are difficult where recombination matters most
    i.e. at low P_T
  - Only indirect indications –from the y and P_T dependence of R_{AA}–
    that recombination may be at work
  - CNM effects may show a non-trivial y and P_T dependence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

SPS and Hera-B

– J/ψ **data in** pA **collisions**



NA60 Phys.Lett. B 706 (2012) 263
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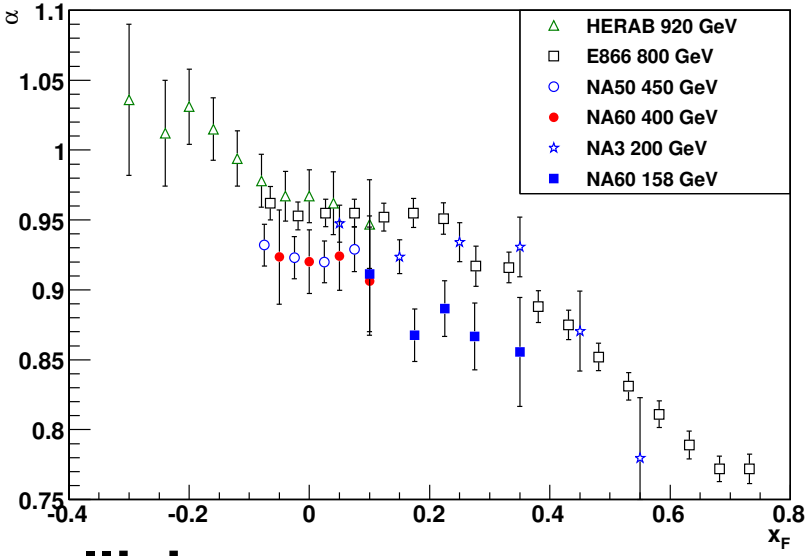

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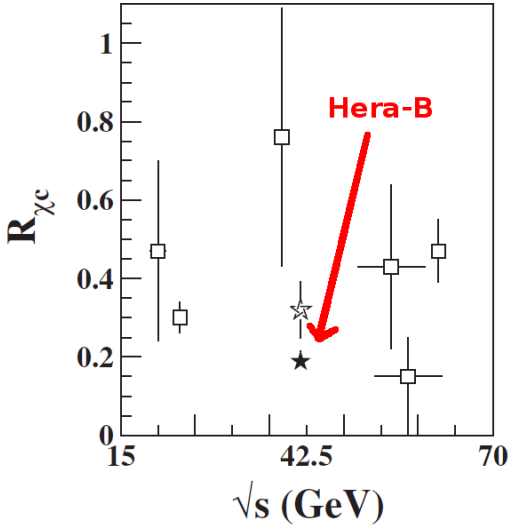

HERA-B PRD 79 (2009) 012001, and ref. therein

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].

LARGE HADRON BEAUTY FACTORY
LETTER OF INTENT

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- LHB turned down in favour of LHCb mainly because of the fear of a premature degradation of the bent crystal due to radiation damages.

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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
- LHB turned down in favour of LHCb mainly because of the fear of a premature degradation of the bent crystal due to radiation damages.
- Nowadays, degradation is known to be $\simeq 6\%$ per 10^{20} particles/cm^2
- 10^{20} particles/cm^2 : one year of operation for realistic conditions

LHB

Our idea is not completely new

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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 $x_F \to -1$

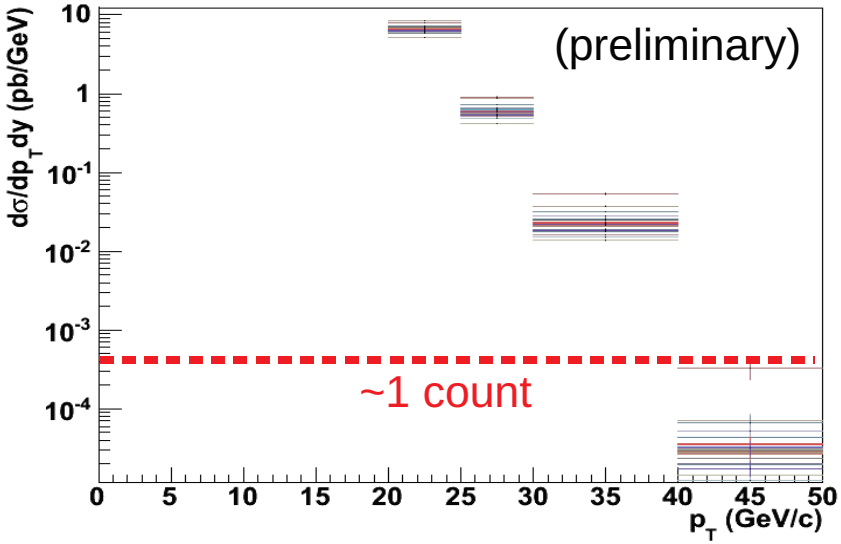
    where IQ could dominate

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) ~ $2 \bullet 10^3$ 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