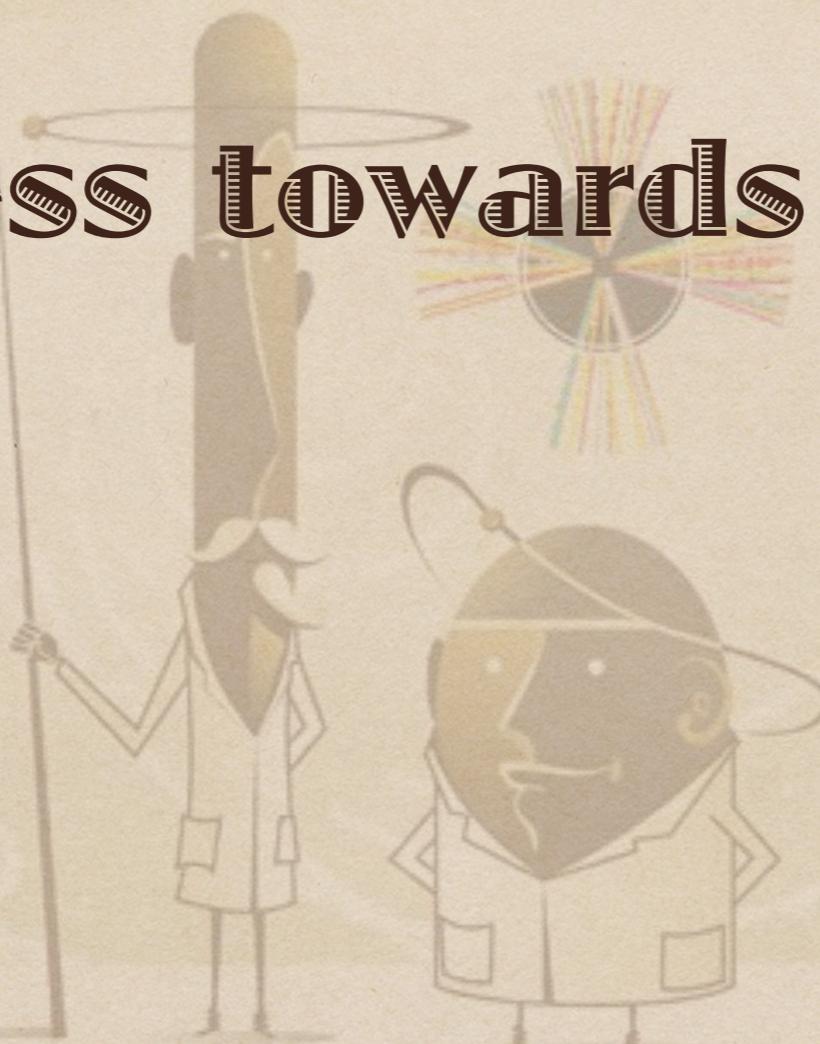


Progress towards AFTER@LHC



Andry Rakotozafindrabe
CEA (Saclay) IRFU



M. Anselmino (Torino), R. Arnaldi (Torino), S.J. Brodsky (SLAC), V. Chambert (IPN), J.P. Didelez (IPN), B. Genolini (IPN), E.G. Ferreiro (USC), F. Fleuret (LLR), Y. Gao (Tsinghua), C. Hadjidakis (IPN), J.P. Lansberg (IPN), C. Lorcé (IPN), R. Mikkelsen (Aarhus), A. Rakotozafindrabe (CEA), P. Rosier (IPN), I. Schienbein (LPSC), E. Scomparin (Torino), B. Trzeciak (CTU), U.I. Uggerhøj (Aarhus), R. Ulrich (Karlsruhe), Z. Yang (Tsinghua)

A Fixed Target Experiment using LHC beams

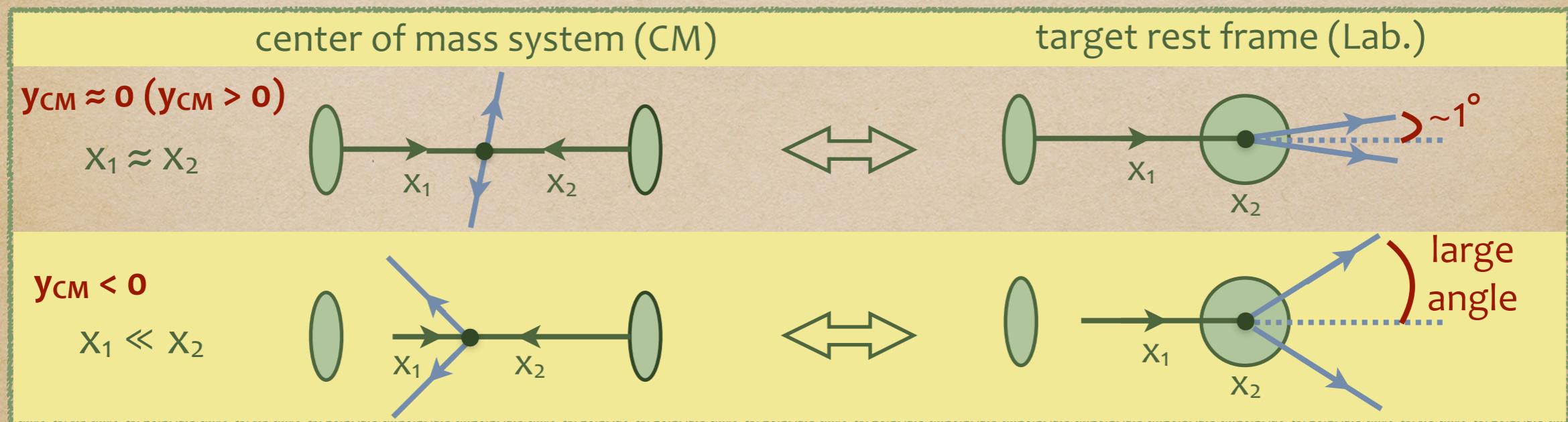
WHY A FIXED TARGET EXPERIMENT @ LHC ?

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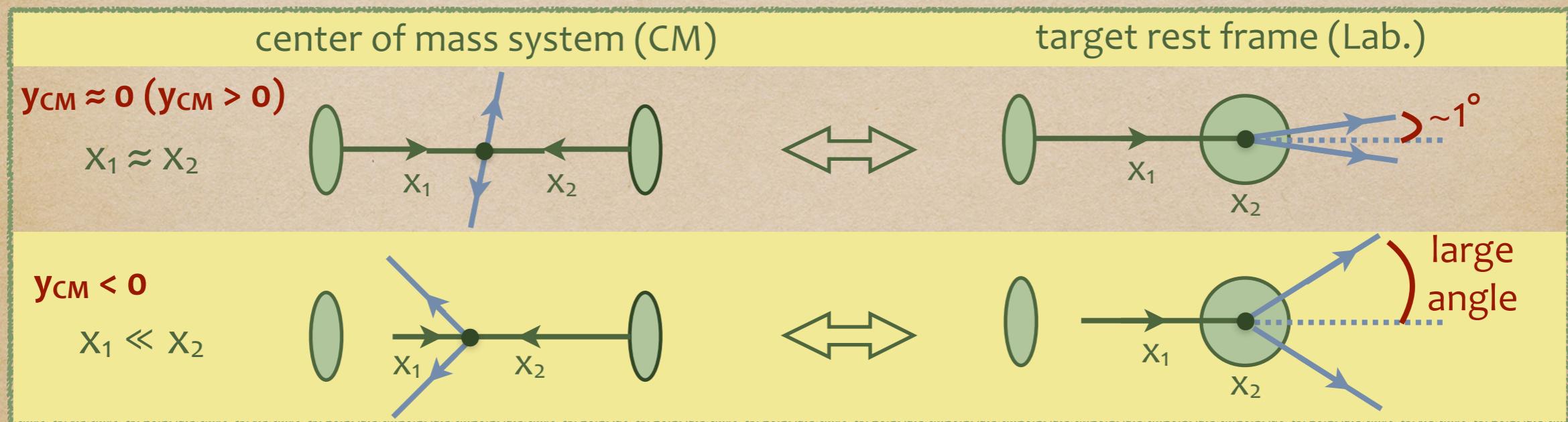
✓ provide a novel testing ground for QCD in the high x frontier :



- very energetic beam \Rightarrow boost \Rightarrow access to partons with $(x_2 \rightarrow 1)$ in the target, i.e. $(x_F \rightarrow -1)$ which is largely uncharted
- this corresponds to the region : $y_{CM} < 0$ i.e. **backwards physics**, large angles in the Lab. frame

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Some numbers : if using a 7 TeV p^+ beam on a fixed target ...

► CM energy : $\sqrt{s} = \sqrt{2m_N E_p} \simeq 115 \text{ GeV}$

► boost : $\gamma_{CM}^{Lab} = \sqrt{s}/2m_p = 60$

► Rapidity shift :

$$y_{CM} = 0 \Leftrightarrow y_{Lab} = 4.8$$

A LARGE PALETTE OF MEASUREMENTS

✓ AFTER@LHC : decisive advantages of the fixed-target setup

- access to high $|x_F|$
- dense targets \Rightarrow high luminosities
- target versatility
- polarise (or not) the target

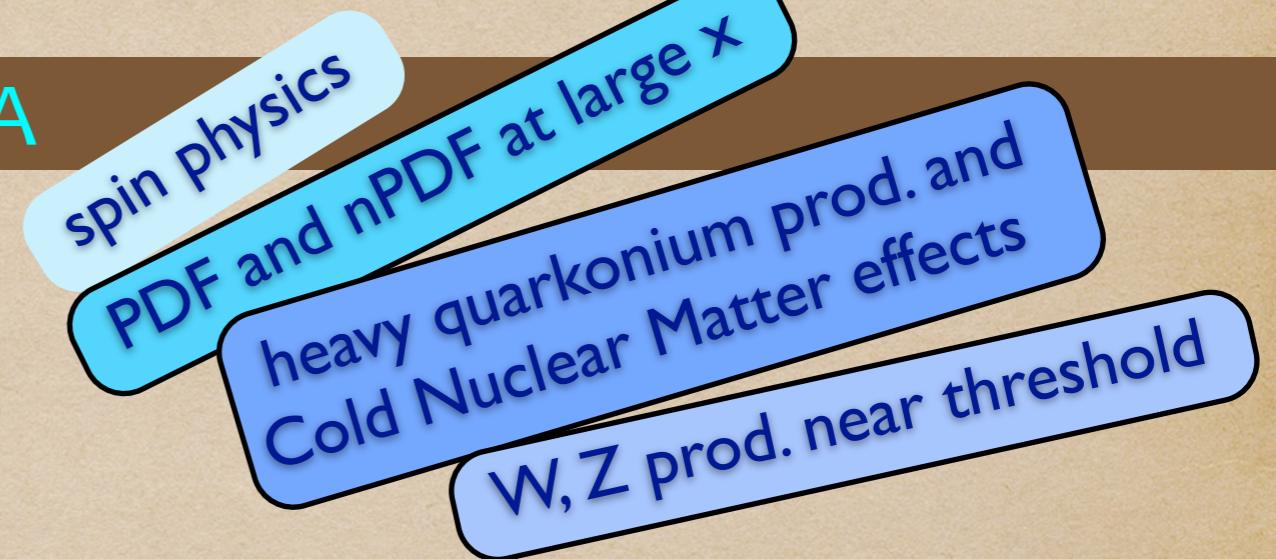
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spin physics

PDF and nPDF at large x

heavy quarkonium prod. and
Cold Nuclear Matter effects

W, Z prod. near threshold

► $\sqrt{s} \sim 72$ GeV : Pb-p, Pb-A

- using LHC 2.76 TeV Pb beam
- between SPS and top RHIC energies

Ultra Periph. Collisions

QGP studies, high precision heavy
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diffractive physics

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diffractive physics

> Only a few measurements will be presented here !

MORE DETAILS :

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► in Phys. Rept. :

[*S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239*]

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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,*}

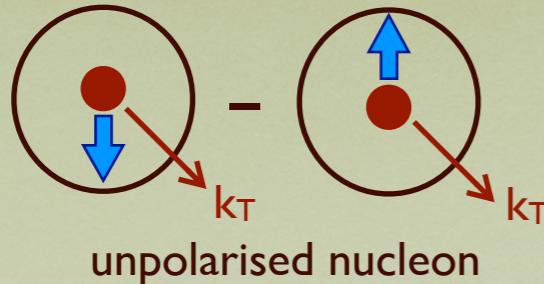
^a SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

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^c IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

► on the website :
after.in2p3.fr

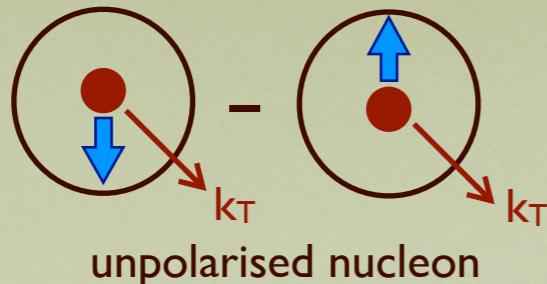
GLUON MOMENTUM TOMOGRAPHY



Boer-Mulders function:
Correlation between the gluon k_T and the gluon transverse spin

- Low p_T C-even quarkonium prod. is a good probe of the gluon « Boer-Mulders » functions

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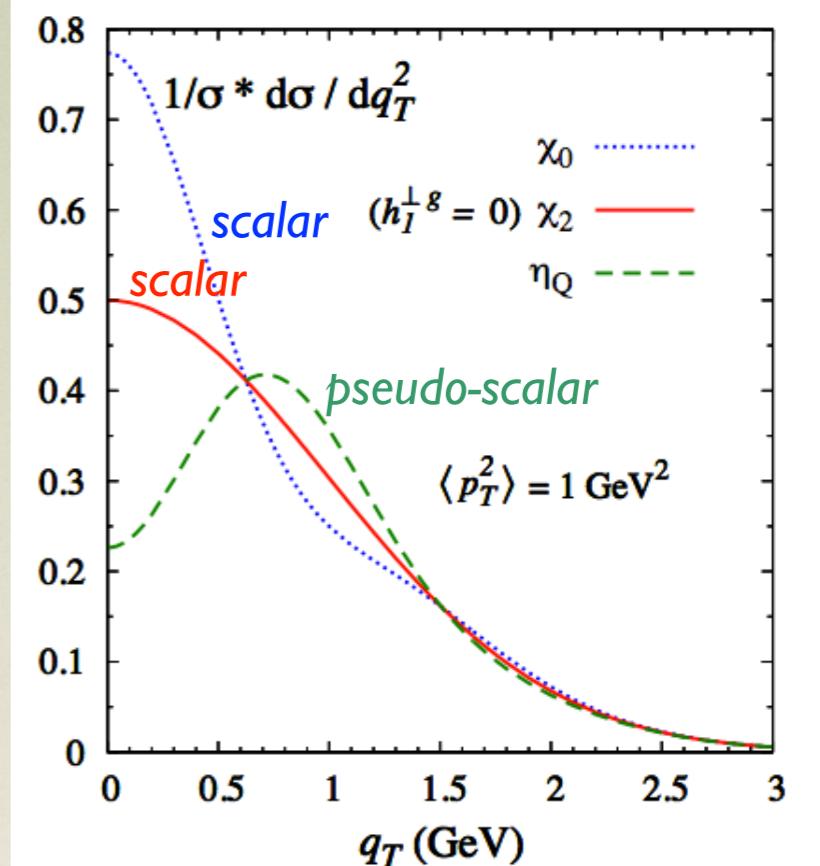


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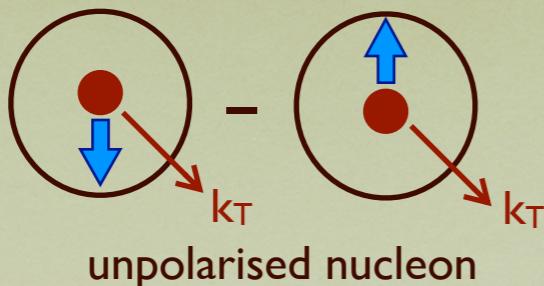
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- Linearly polarized gluon distr. in unpolarized N is unknown, but it is a tool to determine if Higgs is a scalar or pseudo-scalar boson

[Boer et al, PRL 108 (2012) 032002]

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GLUON MOMENTUM TOMOGRAPHY



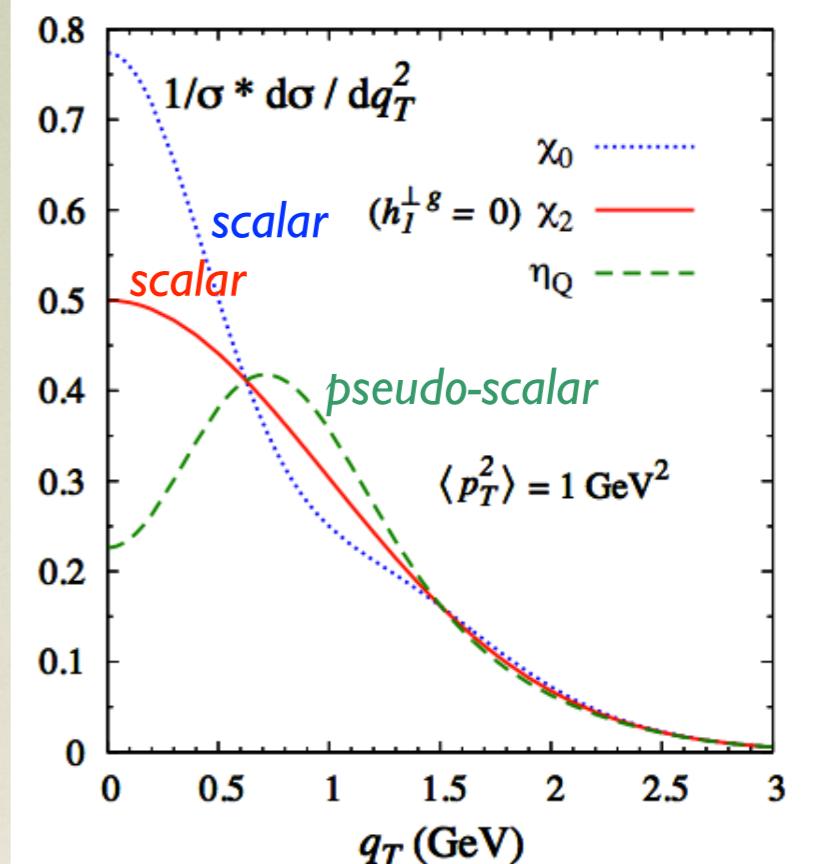
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- back to back $J/\Psi + \text{isolated } \gamma$ also a good probe of the gluon « Boer-Mulders » functions

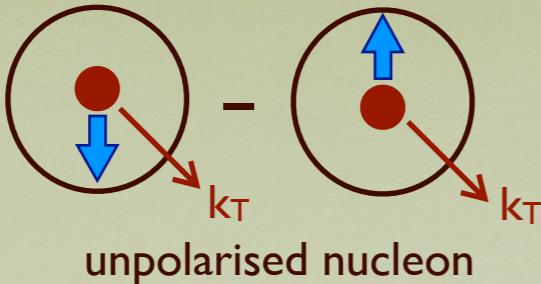
[Boer et al, PRL 108 (2012) 032002]

[den Dunnen et al., PRL 112 (2014) 212001,
J.P. Lansberg, Transversity 2014]

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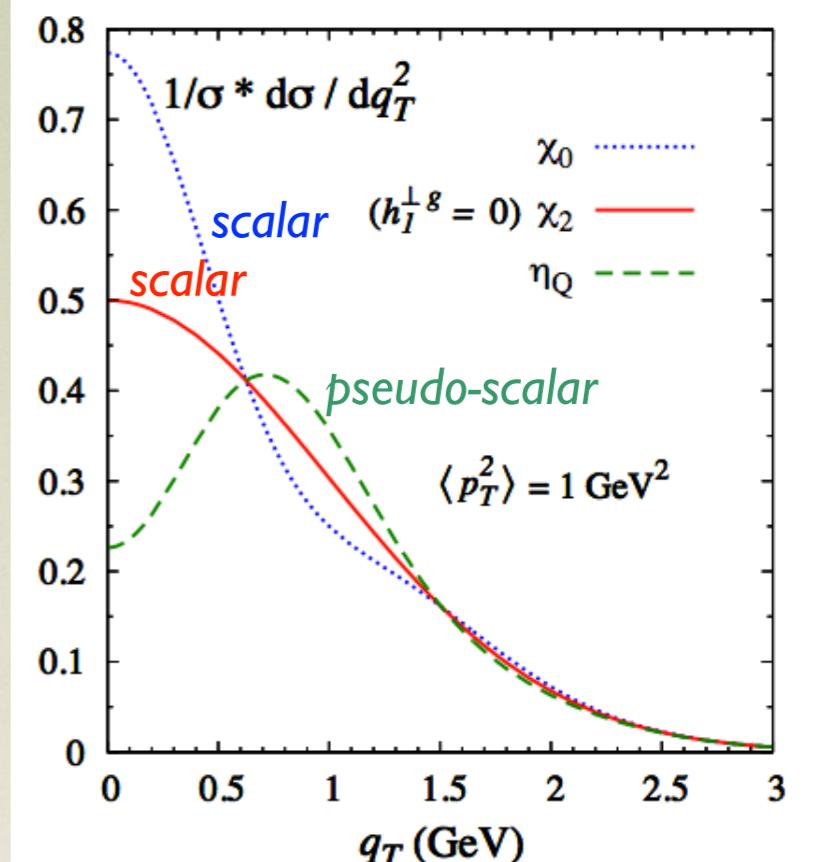
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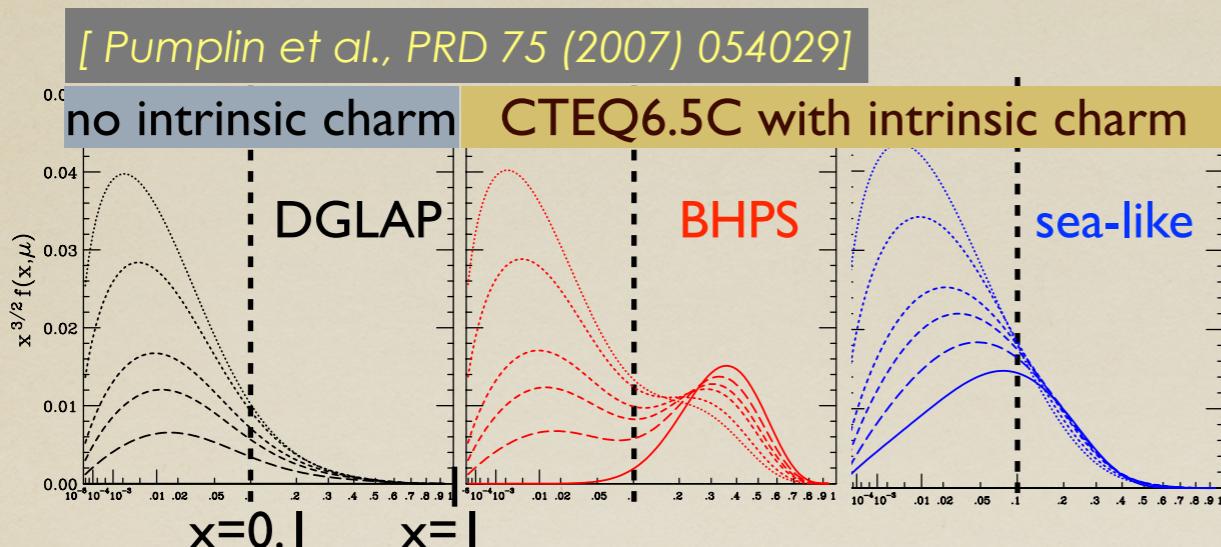
AFTER :

- ✓ boost \Rightarrow easier access to low p_T C-even quarkonia
- ✓ large quarkonium yields + modern calorimetry (χ_Q detection)

[Boer, Pisano, PRD 86 (2012) 094007]



HEAVY QUARKS AT HIGH X

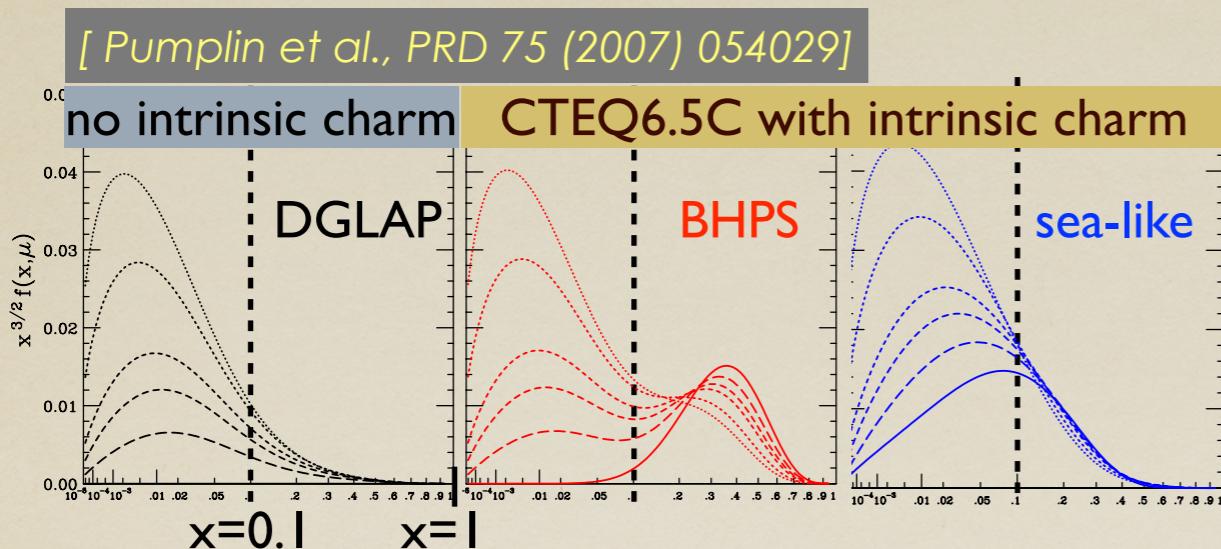


charm (and bottom) PDF at high x :

- first hint of intrinsic charm at large x in F_2^C data from μ^+ -Fe scattering
- [EMC Collaboration, NPB 213 (1983) 31]
- but with large uncertainties on the derived IC probability (0.86 ± 0.60)%

[Harris et al., NPB 461 (1996) 181]

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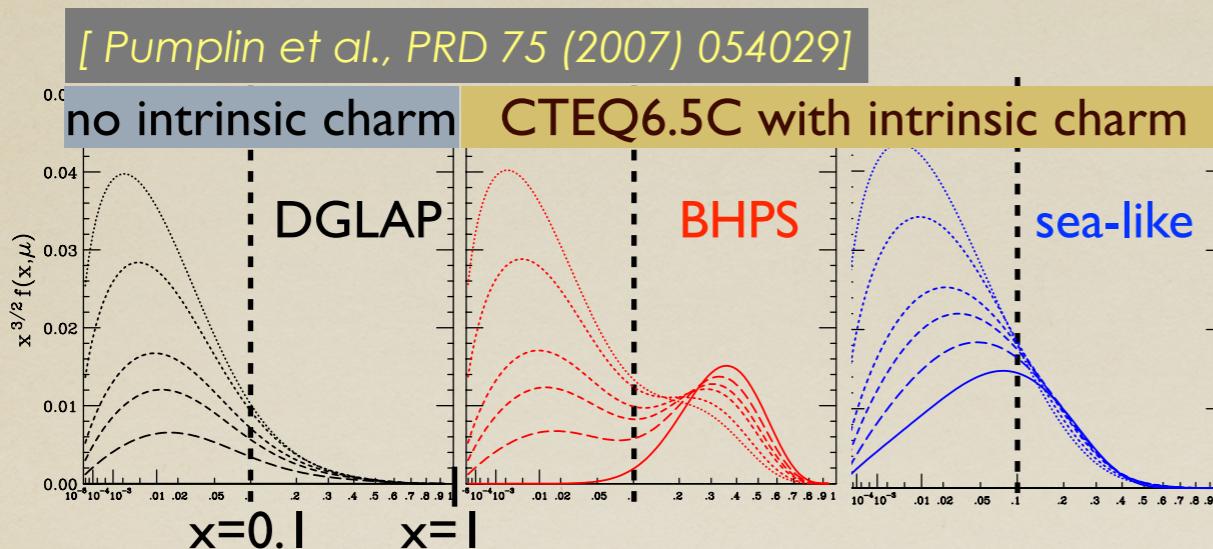
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exp. probes :

- ▶ open charm, open beauty
- ▶ new open c, b hadrons at high x_F ?

[Chang and Peng, PLB 704 (2011) 197]

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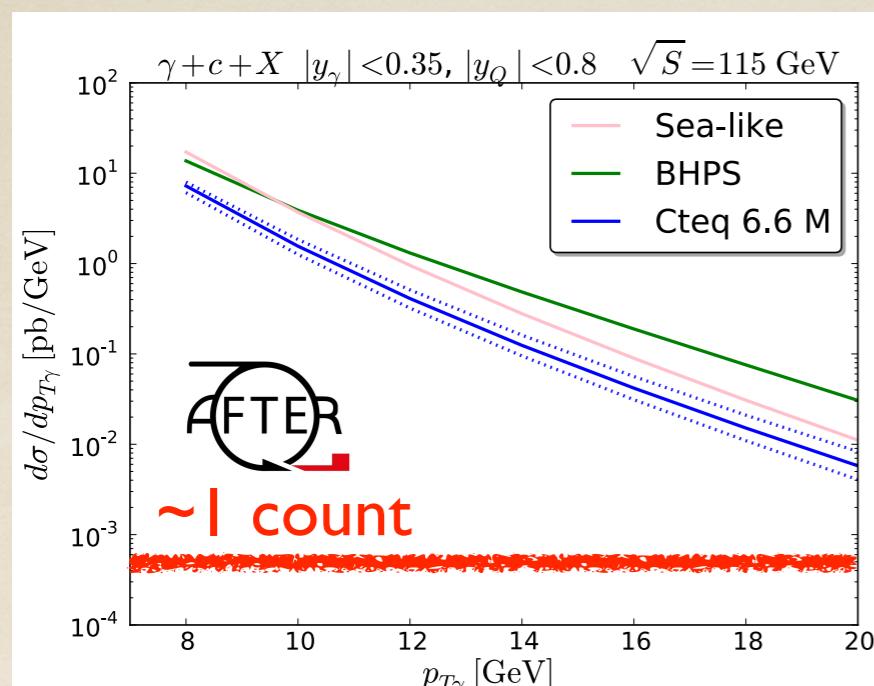
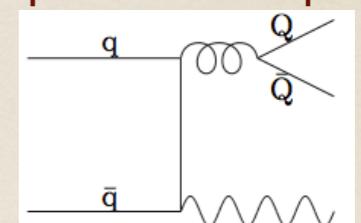
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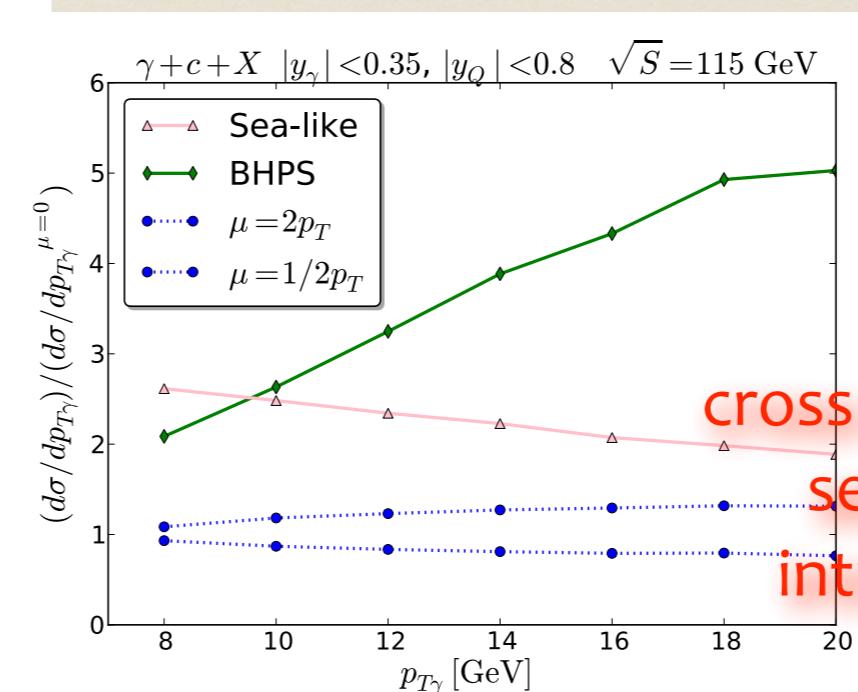
[Chang and Peng, PLB 704 (2011) 197]

- ▶ $\gamma + c, \gamma + b$ production

dominant diagram : photon couples to initial quarks



[T. Stavreva, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013]



cross section : good sensitivity to intrinsic charm

GLUON PDF IN FREE AND BOUND NUCLEON

✓ AFTER@LHC : precision studies of gluon sensitive probes

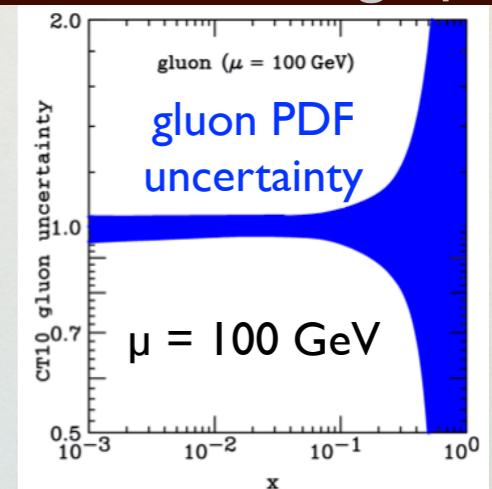
quarkonia, isolated photon, photon-jet correlation, high pT jets

P-P

P-d

P-n

- * gluon PDF at high x :
 - not easily accessible in DIS
 - large uncertainties for the proton (unknown for the neutron)
 - limit the precision on reference processes used for BSM searches at LHC



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P-P

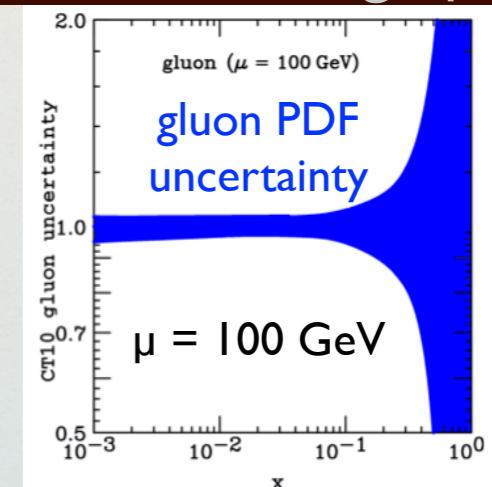
P-d

P-n

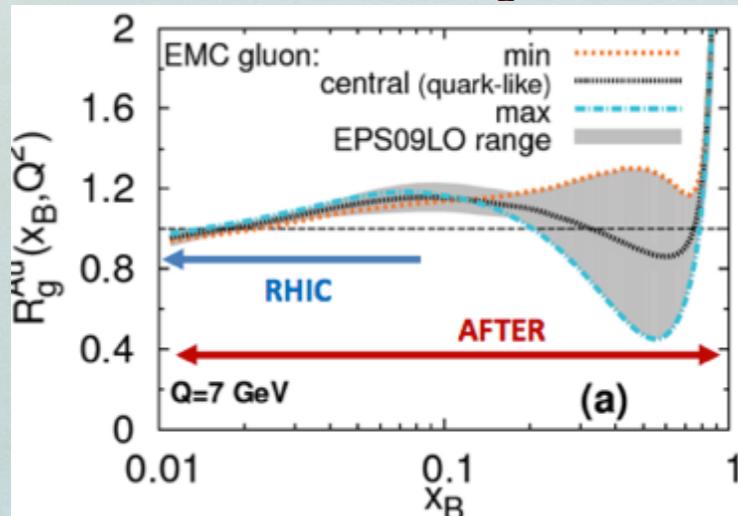
P-A

Pb-p

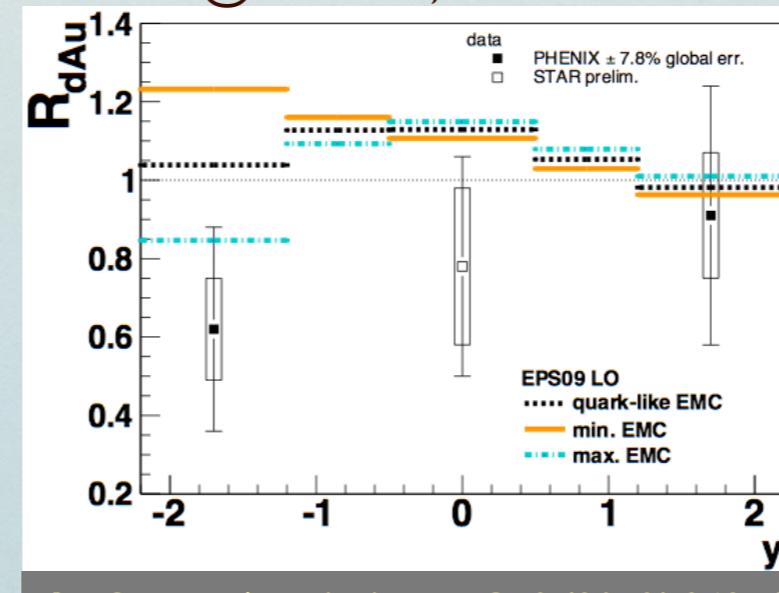
- * gluon PDF at high x :
 - not easily accessible in DIS
 - large uncertainties for the proton (unknown for the neutron)
 - limit the precision on reference processes used for BSM searches at LHC
- * gluon nuclear PDF at large x :
 - unknown gluon EMC effect
 - hint from Υ data from RHIC, strongly limited by the statistics
 - AFTER : **complementarity with LHeC** (focus at low x)



nuclear modification of g PDF in Au

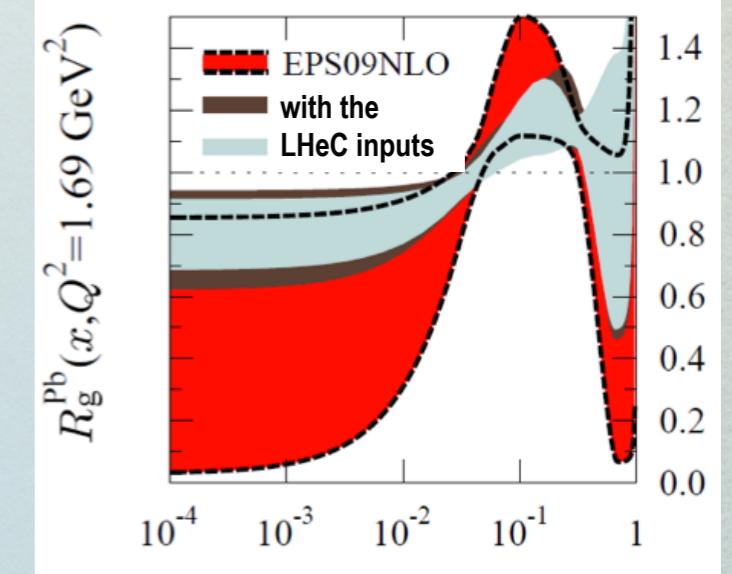


Υ in dAu @ 200 GeV, STAR and PHENIX



[E.G. Ferreiro et al., EPJ C73 (2013) 2427]

nuclear modification of g PDF in Pb

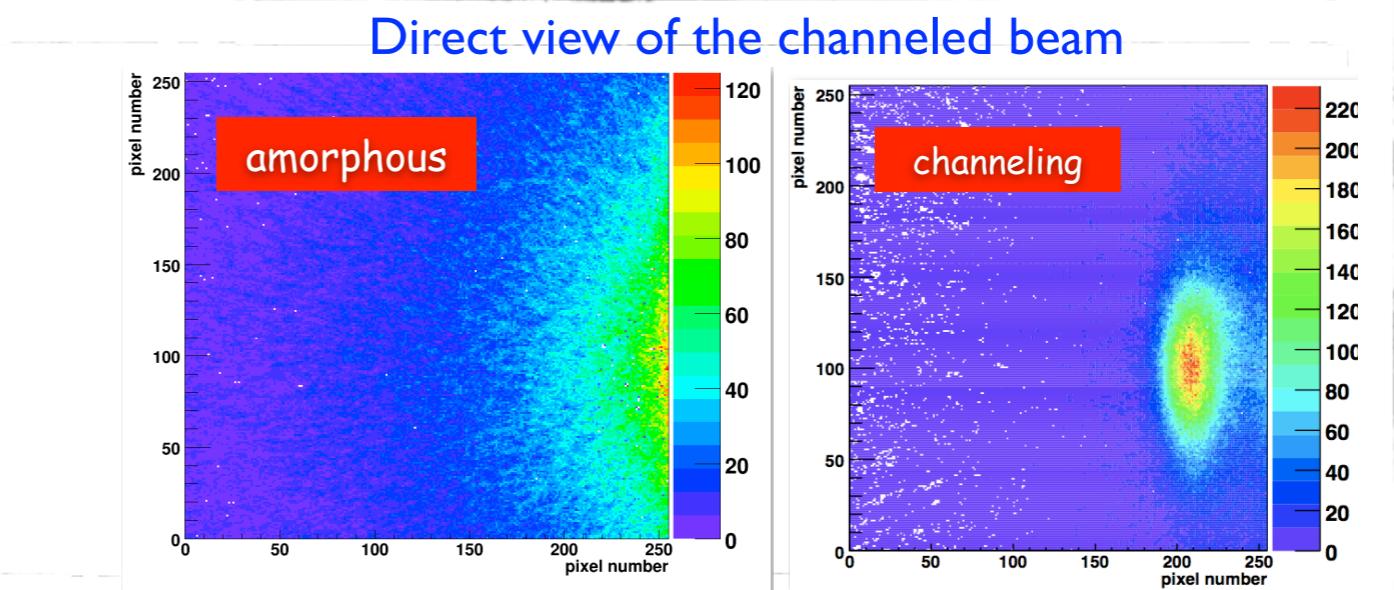


[LHeC CDR, J. Phys. G 39 (2012) 075001]

BEAM EXTRACTION : THE PARASITIC MODE



- From standard collimation, to crystal-based collimation ... and to beam extraction
- today
- SPS (UA9)
LHC (LUA9)
- CRYSBEM (SPS then LHC)
AFTER (LHC)



[S. Montesano, W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013]

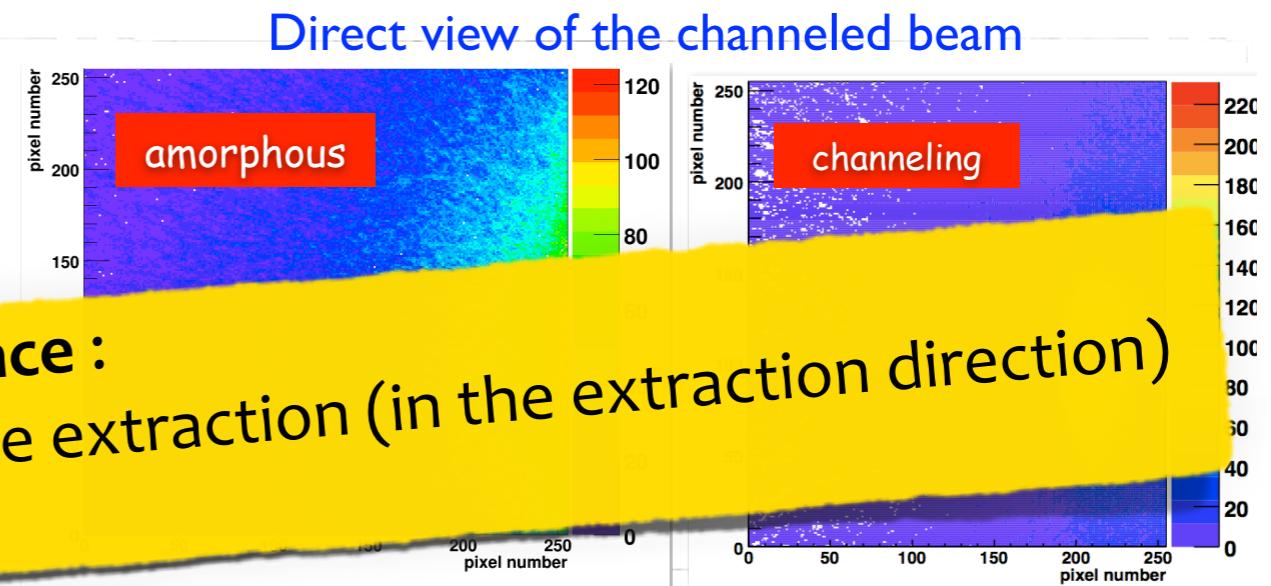
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LHC (LUA9)
- CRYSBEM (SPS then LHC)
AFTER (LHC)



Extremely small emittance :
beam size 950m after the extraction (in the extraction direction)
~0.3 mm



[S. Montesano, W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013]

BEAM EXTRACTION : THE PARASITIC MODE



- From standard collimation, to crystal-based collimation ... and to beam extraction today
 - SPS (UA9)
 - LHC (LUA9)
 - CRYSBEM (SPS then LHC)
 - AFTER (LHC)
- UA9 : a complete crystal collimation prototype is installed in the SPS
 - ✓ Multi-turn channeling efficiency : 70÷80% for protons, 50÷70% for ions
 - ✓ Loss reduction rate at crystal : 20× for protons, 7× for ions
 - ✓ Off-momentum loss reduction : 6× for protons, 7× for ions (currently, LHC is limited by dispersion losses)
- LUA9 : approved by the LHCC
 - ✓ 2 crystals already installed in the LHC beam pipe
 - ✓ first tests with beam possibly in 2015/2016

[S. Montesano, Joint LUA9-AFTER meeting, Nov. 2013]

BEAM EXTRACTION : THE PARASITIC MODE



- From standard collimation, to crystal-based collimation ... and to beam extraction today
 - SPS (UA9)
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 - ✓ Multi-turn channeling efficiency : 70÷80% for protons, 50÷70% for ions
 - ✓ Loss reduction rate at crystal : 20× for protons, 7× for ions
 - ✓ Off-momentum loss reduction
- Proposal :
recycle the beam loss by inserting the crystal **in the halo (7σ)** of the LHC beam [E Uggerhoj and U.I. Uggerhoj, NIM B 234 (2005) 31]
- LUA9
 - ✓ 2014 tests with beam
 - ✓ first tests with beam possibly in 2015/2016

LUMINOSITIES

$\sqrt{s} = 115 \text{ GeV}$

Estimates based on :

- extraction eff. (multi pass) ~50% LHC beam loss $\Rightarrow 5 \cdot 10^8 \text{ p}^+/\text{s}$ extracted
- 1 year = 10^7 s for p^+ beam

✓ AFTER@LHC : outstanding luminosities \Rightarrow precision studies

Target	Luminosity / year	yield / unit of rapidity at $y=0$	
	fb^{-1}	J/ψ	Υ
10 cm solid H	2.6	$5.2 \cdot 10^7$	$1.0 \cdot 10^5$
10 cm liquid H	2.0	$4.0 \cdot 10^7$	$8.0 \cdot 10^4$
10 cm liquid D	2.4	$9.6 \cdot 10^7$	$1.9 \cdot 10^5$
1 cm Be	0.62	$1.1 \cdot 10^8$	$2.2 \cdot 10^5$
1 cm Cu	0.42	$5.3 \cdot 10^8$	$1.1 \cdot 10^6$
1 cm W	0.31	$1.1 \cdot 10^9$	$2.3 \cdot 10^6$
1 cm Pb	0.16	$6.7 \cdot 10^8$	$1.3 \cdot 10^6$

P-H

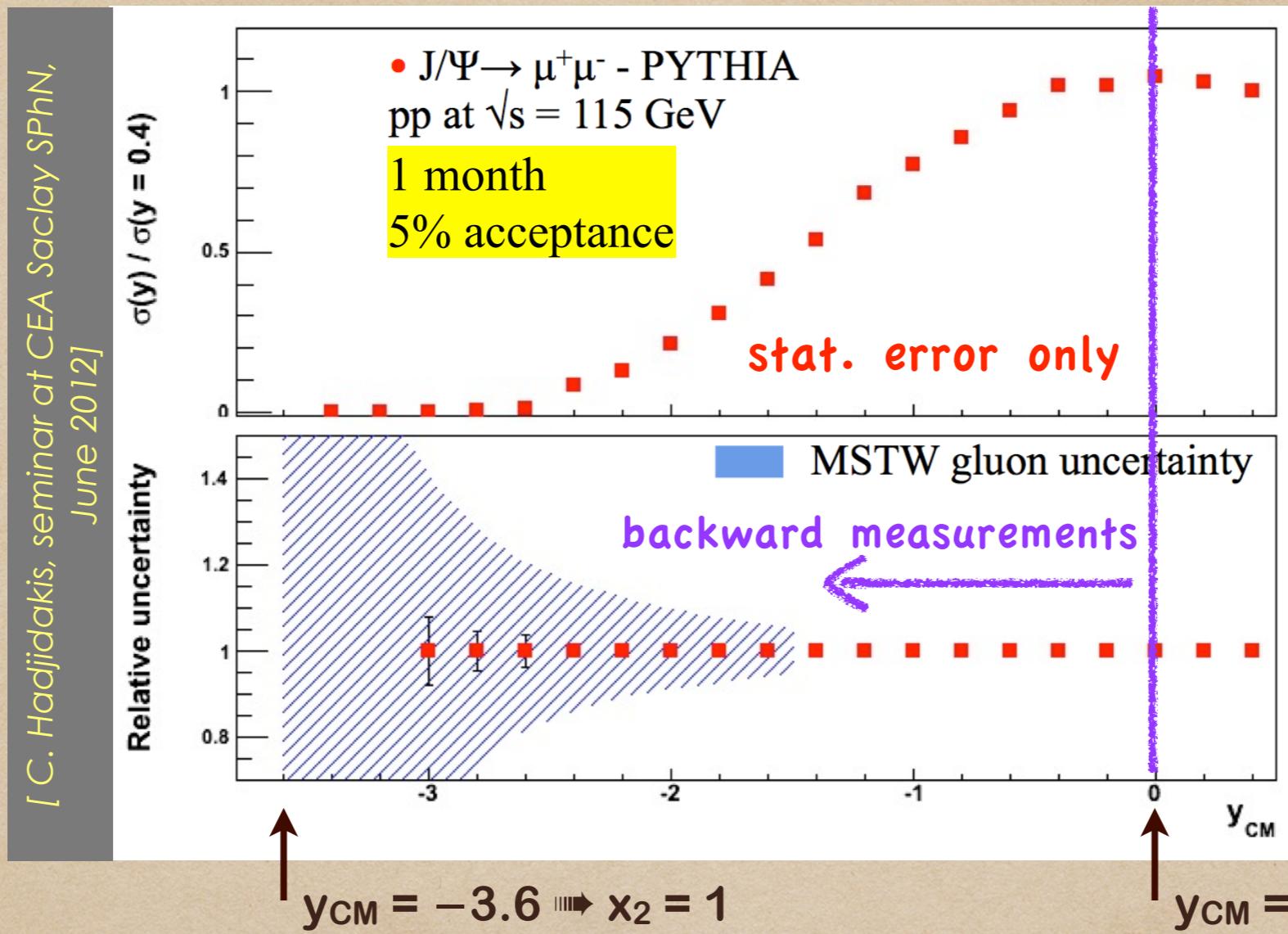
P-A

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

Compare to :

- LHC 2012 Run (4 TeV p^+ beam), delivered luminosity at **LHCb 2.115 fb^{-1}**
- **RHIC** expected luminosity (PHENIX decadal plan) in 2014
 $\text{pp} @ 200 \text{ GeV } 1.2 \cdot 10^{-2} \text{ fb}^{-1}$, $\text{dAu} @ 200 \text{ GeV } 1.5 \cdot 10^{-4} \text{ fb}^{-1}$

FOR E.G. STATISTICAL PRECISION ON LARGE X GLUON PDF



Gluon uncertainty from MSTW PDF : only for the gluon content in the target

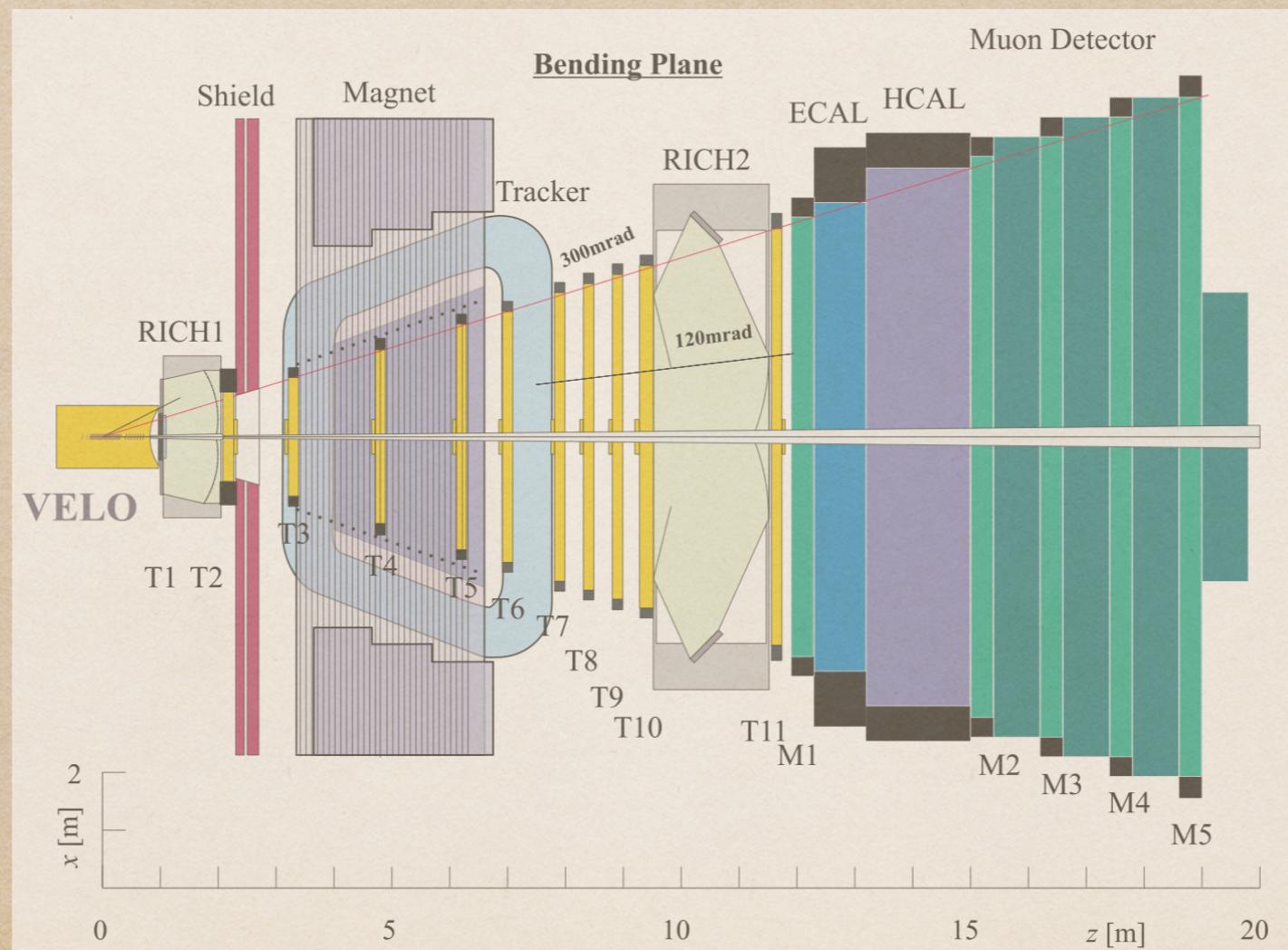
- Using **J/ Ψ as a probe of the gluon PDF**
- assuming initial gluon in the target $x_2 = (M_{J/\psi}/\sqrt{s}) \exp^{-y_{CM}}$
- **stat. error only** (no propagation of the uncertainties that originate from our understanding of the J/ Ψ production mechanism)
- **similar measurements can/should be done with other states to reduce the model dependence**

TOWARDS A FORWARD DETECTOR

- ♦ Focus on ($y_{CM} < 0$) i.e. « large » angles ($\theta > 1^\circ$) but still forward angles in the Lab.
- ♦ What needs to be improved w.r.t. known detector performances ?

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- ♦ for e.g. a LHCb-like detector : $2 < \eta < 5$

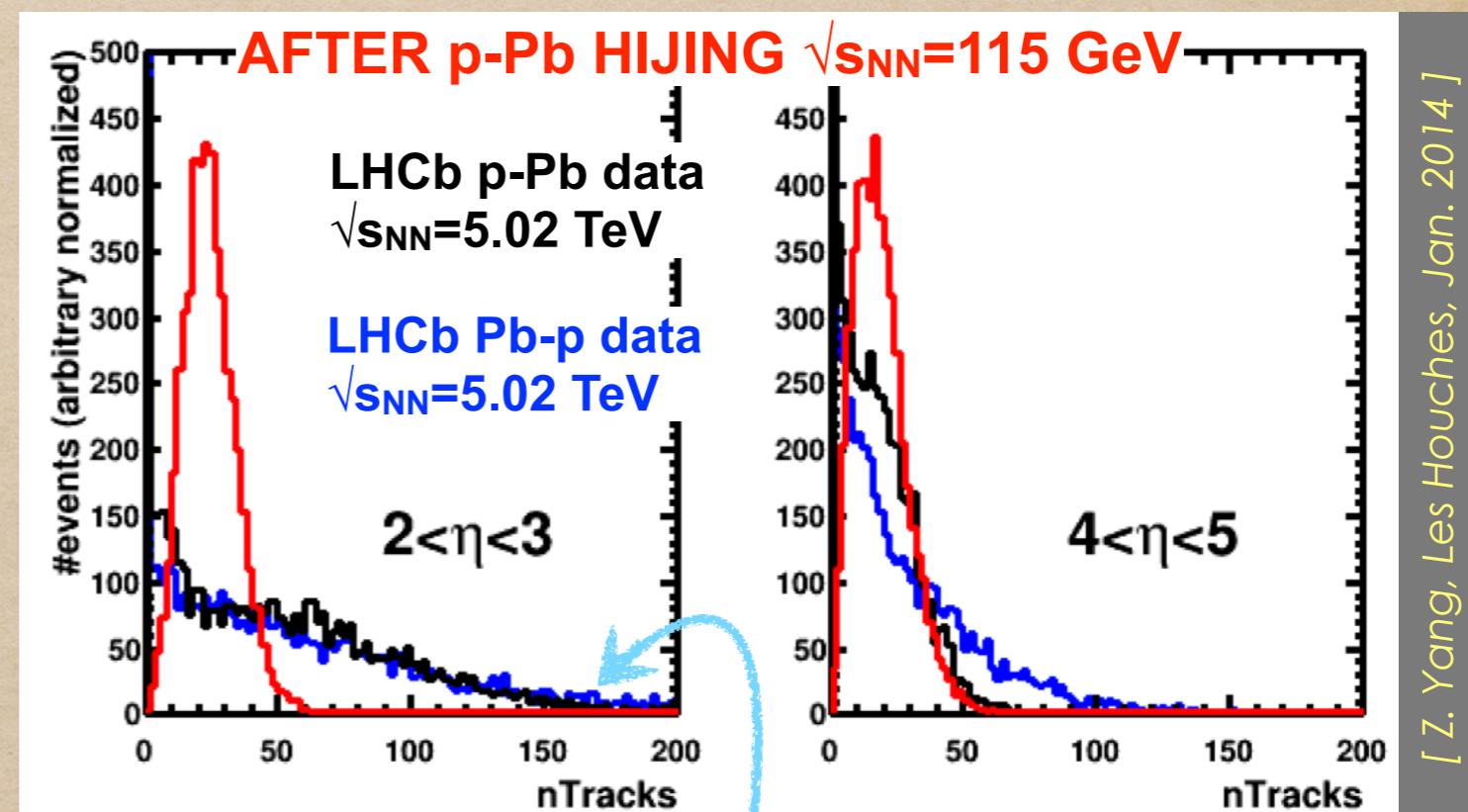


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- ♦ for e.g. a LHCb-like detector : $2 < \eta < 5$

✓ Track multiplicity : cope with the boost

Despite the boost, the track multiplicity is lower in the **fixed target mode** than in the collider mode



highest multiplicity/event ever experienced so far by LHCb

[Z. Yang, Les Houches, Jan. 2014]

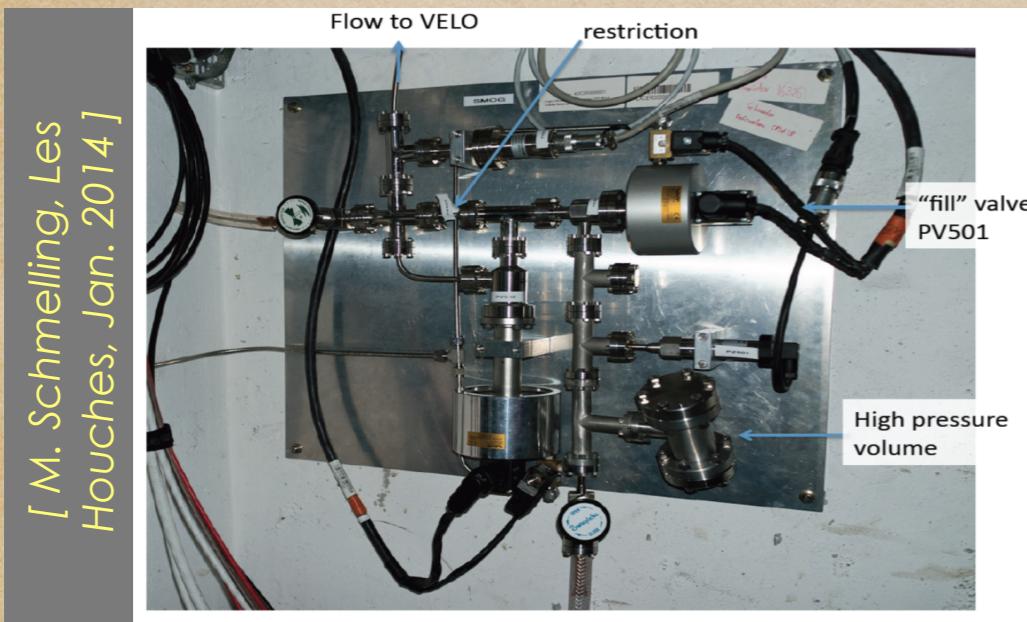
TOWARDS A FORWARD DETECTOR

- ♦ Focus on ($y_{CM} < 0$) i.e. « large » angles ($\theta > 1^\circ$) but still forward angles in the Lab.
- ♦ What needs to be improved w.r.t. known detector performances ?
- ♦ for e.g. a LHCb-like detector : $2 < \eta < 5$

✓ Track multiplicity : cope with the boost

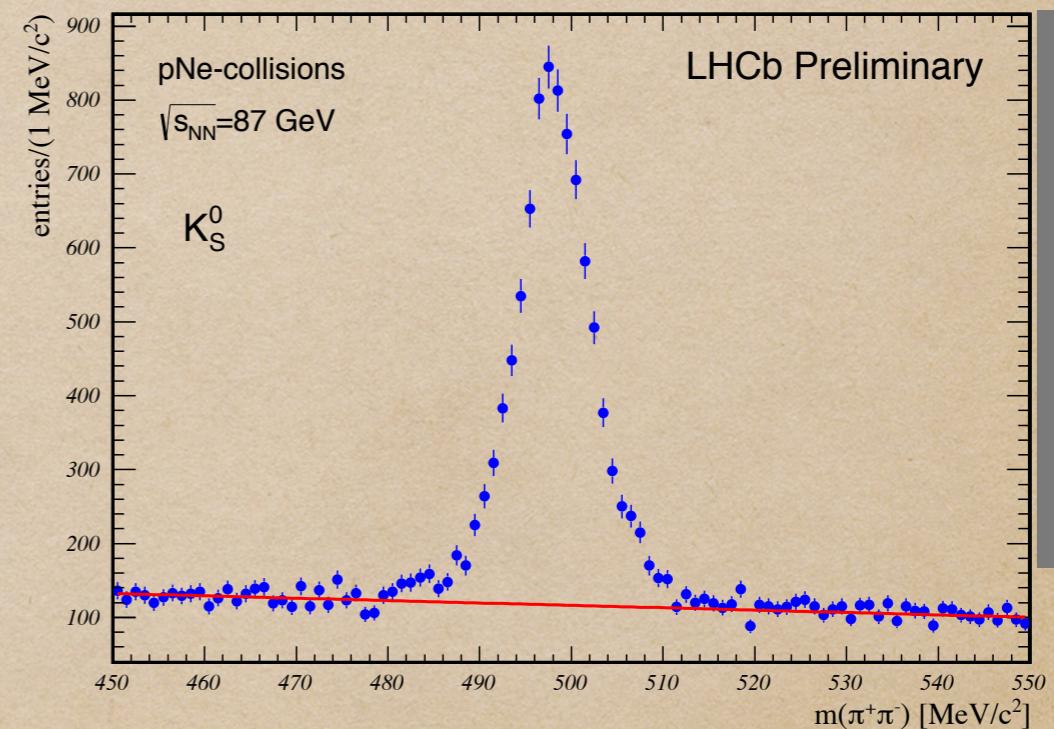
✓ SMOG pilot run : a proof of principle

System for Measuring Overlap with Gas



[M. Schmeling, Les Houches, Jan. 2014]

Inject rare gas (Ne) in the VELO, for luminosity measurements \Rightarrow **LHCb taking data in fixed-target mode, with gaseous target**



Strangeness production (for .e.g K_S^0)
4 TeV proton beam on gaseous Ne target

[LHCb-Conf-2012-034]

TOWARDS A FORWARD DETECTOR

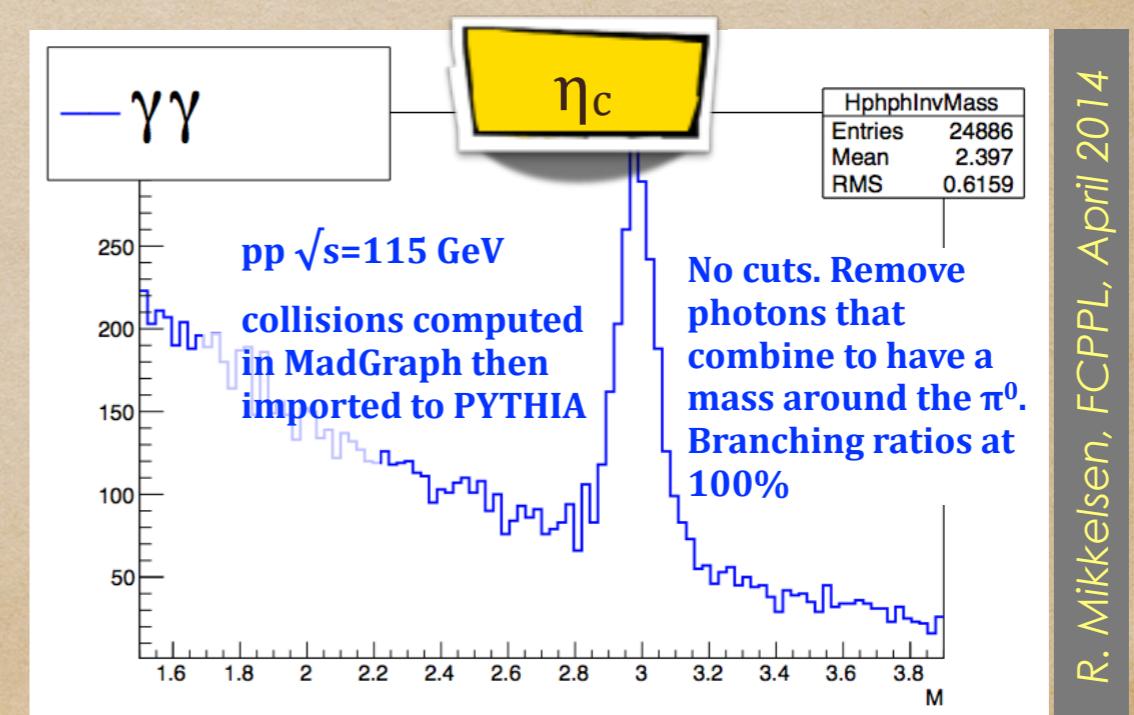
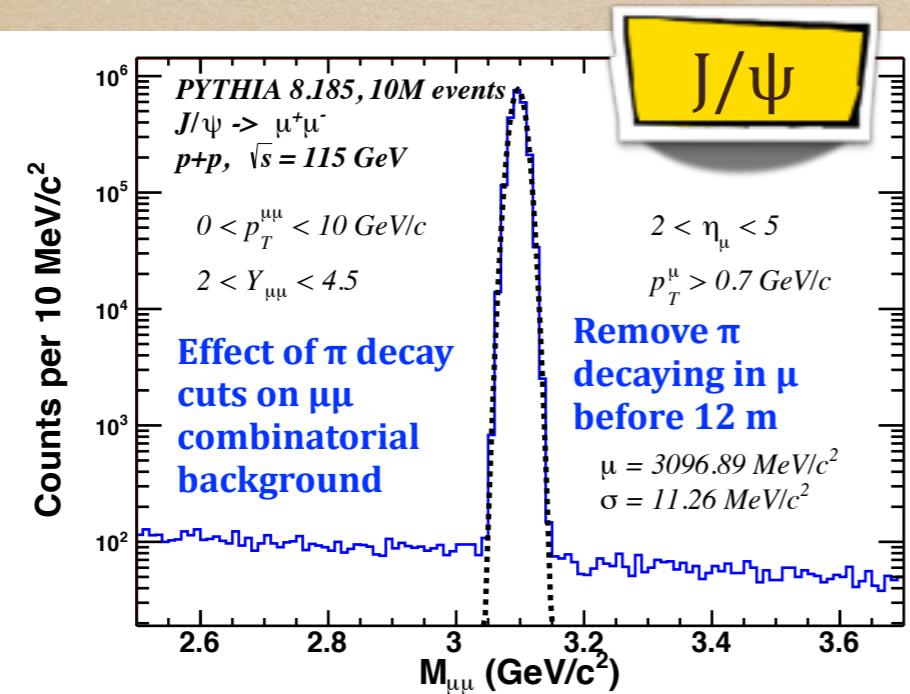
- Focus on ($y_{CM} < 0$) i.e. « large » angles ($\theta > 1^\circ$) but still forward angles in the Lab.
- What needs to be improved w.r.t. known detector performances ?
- for e.g. a LHCb-like detector : $2 < \eta < 5$

✓ Track multiplicity : cope with the boost

✓ SMOG pilot run : a proof of principle

✓ Fast simulations : first look at the background for quarkonium

Using η coverage, photon $\Delta E/E$, muon $\Delta p/p$ of LHCb detector, + their usual cuts on muon p_T to improve the S/B ratio



SUMMARY

AFTER : A Fixed-Target ExpeRiment using LHC beams

- provide a novel testing ground for QCD in the high-x frontier
- despite recycling the LHC beam loss, outstanding luminosities are achievable in pp, pA at $\sqrt{s_{NN}} = 115$ GeV and in PbA at $\sqrt{s_{NN}} = 72$ GeV, thanks to high density targets
- high-x frontier \Leftrightarrow backward physics ($y_{CM} < 0$) \Leftrightarrow forward detector in the Lab.
- first simulation studies using a LHCb-like detector : promising setup !

Next : * Expression of Interest in 2015

* AFTER week @ CERN, 17-21 Nov. 2014

We're looking for more partners.
Join us !

webpage :
after.in2p3.fr



Joint meeting IPNO-LAL LUAS AFTER

18-20 novembre 2013
Orsay
Europe/Paris timezone

Overview
Scientific Programme
Timetable
Contribution List
Author index
Registration
Registration Form
List of registrants

The most convenient way for a fixed target experiment is, to our knowledge, to use bent-crystal beam extraction. The idea is therefore to have a crystal in the halo of the beam such that a few protons (or lead) per bunch pass through it and be deflected by a couple of degrees. Such a method also has the virtue of better collimating the beam, increasing the luminosity of the collider experiments. Tests of this technique will soon be performed by the LUAS collaboration following the recommendation of the LHCC.

During this meeting, we will discuss:

- the status of bent-crystal beam collimation and extraction
- the status of future test at the LHC

18-20 Nov. 2013

LES HOUCHES, 12-17 JAN. 2014

Probing the Strong Interaction at A Fixed Target Experiment with the LHC beams

12-17 January, 2014
Les Houches, France

Organised by:
J.P. Lansberg
J. L. Albacete
A. Rakotozafindrabe
I. Schienbein

Topics include:
Nucleon and nucleus pdf extraction in hadronic processes // Spin physics // Quark-gluon plasma physics // Nuclear matter studies in proton-nucleus collisions // Diffractive physics and ultra-peripheral collisions // Heavy-quark dynamics and spectroscopy at high x_F // Bent-crystal beam extraction // Possibility for secondary beams // Target polarization // Modern detector technologies // Event generator and detector simulation

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IPN
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CEA
GdR PH-QCD
Université Joseph Fourier
ÉCOLE DE PHYSIQUE des HOUCHES



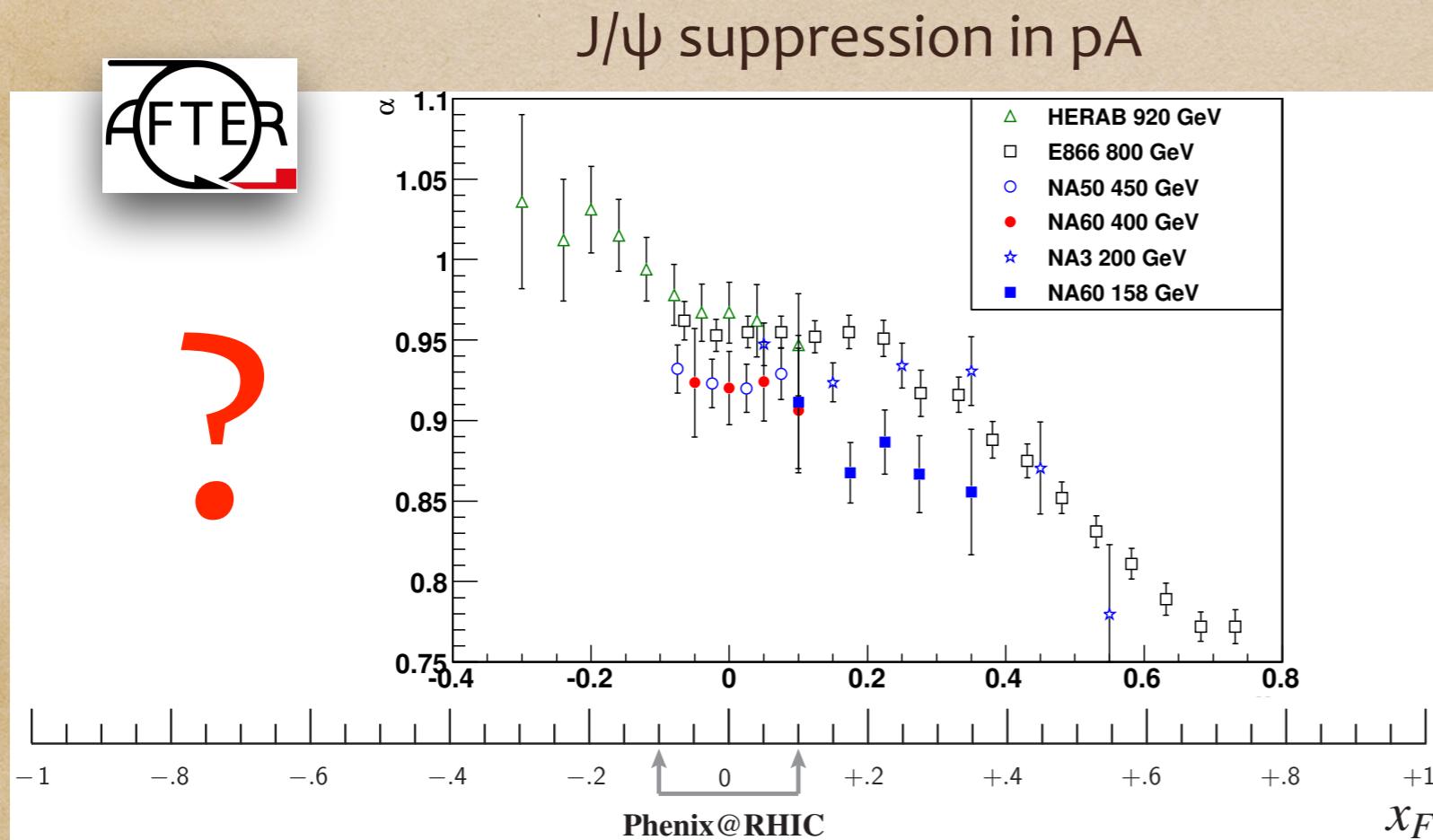
SPARE SLIDES

THE UNCHARTED NEGATIVE x_F REGION

P-A

AFTER : precision studies of the nuclear matter

✓ First systematic access to the target-rapidity region, down to $x_F \rightarrow -1$



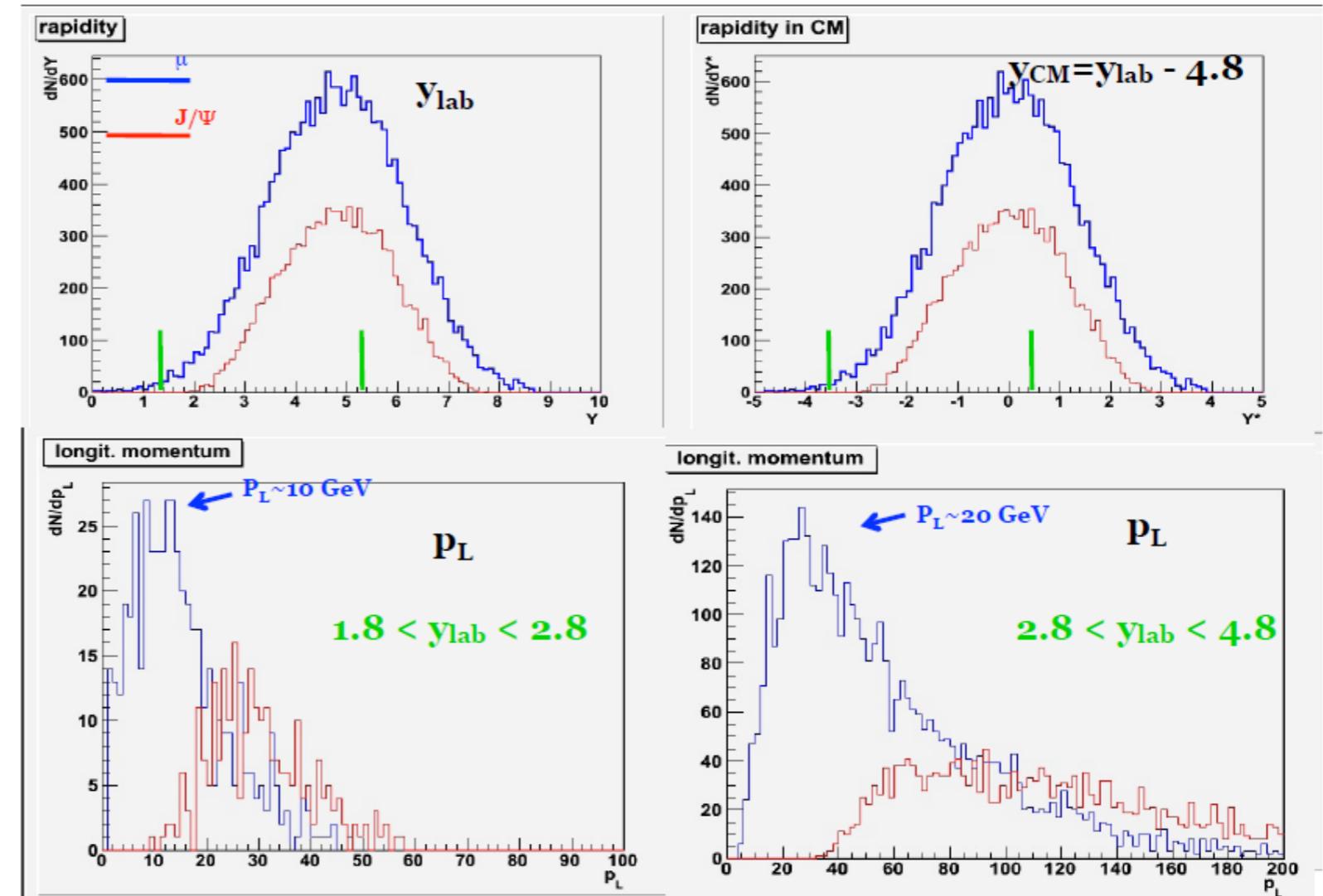
- HeraB down to $x_F = -0.3$
- PHENIX@RHIC: $|x_F| < 0.1$
(could be wider with Y, but low stat.)
- CMS/ATLAS : $|x_F| < 5.10^{-3}$
- LHCb : $5.10^{-3} < x_F < 4.10^{-2}$

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

Pythia 6.4.21: $p(7 \text{ TeV}) + p \rightarrow J/\psi$ (isub=86)
 $J/\Psi \rightarrow \mu^+ \mu^-$

μ from J/ψ for $1.3 < y_{\text{lab}} < 5.3$
 $P_T \sim 1.7 \text{ GeV}$
 $P_L \sim 62 \text{ GeV}$

Longitudinal muon momentum
 $1.3 < y_{\text{lab}} < 3.3$
 $p_L(\text{max}) \sim 16(50) \text{ GeV}$
 $3.3 < y_{\text{lab}} < 4.3$
 $p_L(\text{max}) \sim 45(150) \text{ GeV}$
 $4.3 < y_{\text{lab}} < 5.3$
 $p_L(\text{max}) \sim 120(300) \text{ GeV}$



Luminosities using :

7 TeV proton beam
 $\text{pp, pd, pA } \sqrt{s} = 115 \text{ GeV}$

[S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239]

Target (1 cm thick)	ρ (g cm $^{-3}$)	A	\mathcal{L} ($\mu\text{b}^{-1} \text{s}^{-1}$)	$\int \mathcal{L}$ ($\text{pb}^{-1} \text{yr}^{-1}$)
solid H	0.088	1	26	260
liquid H	0.068	1	20	200
liquid D	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

Table 1: Instantaneous and yearly luminosities obtained with an extracted beam of $5 \times 10^8 \text{ p}^+/\text{s}$ with a momentum of 7 TeV for various 1cm thick targets

2.76 TeV lead beam
 $\text{Pbp, Pbd, PbA } \sqrt{s} = 72 \text{ GeV}$

Target (1 cm thick)	ρ (g cm $^{-3}$)	A	\mathcal{L} ($\text{mb}^{-1} \text{s}^{-1}$)	$\int \mathcal{L}$ ($\text{nb}^{-1} \text{yr}^{-1}$)
solid H	0.088	1	11	11
liquid H	0.068	1	8	8
liquid D	0.16	2	10	10
Be	1.85	9	25	25
Cu	8.96	64	17	17
W	19.1	185	13	13
Pb	11.35	207	7	7

Table 2: Instantaneous and yearly luminosities obtained with an extracted beam of $2 \times 10^5 \text{ Pb/s}$ with a momentum per nucleon of 2.76 TeV for various 1cm thick targets

extracted beam $N_{\text{beam}} = 5 \cdot 10^8 \text{ p}^+/\text{s}$
 9 months running / year $\Leftrightarrow 10^7 \text{ s}$

extracted beam $N_{\text{beam}} = 2 \cdot 10^5 \text{ Pb/s}$
 1 month running / year $\Leftrightarrow 10^6 \text{ s}$

Instantaneous luminosity :

$$L = N_{\text{beam}} \times N_{\text{target}} = N_{\text{beam}} \times (\rho \cdot e \cdot N_A) \text{ with } e = \text{target thickness}$$

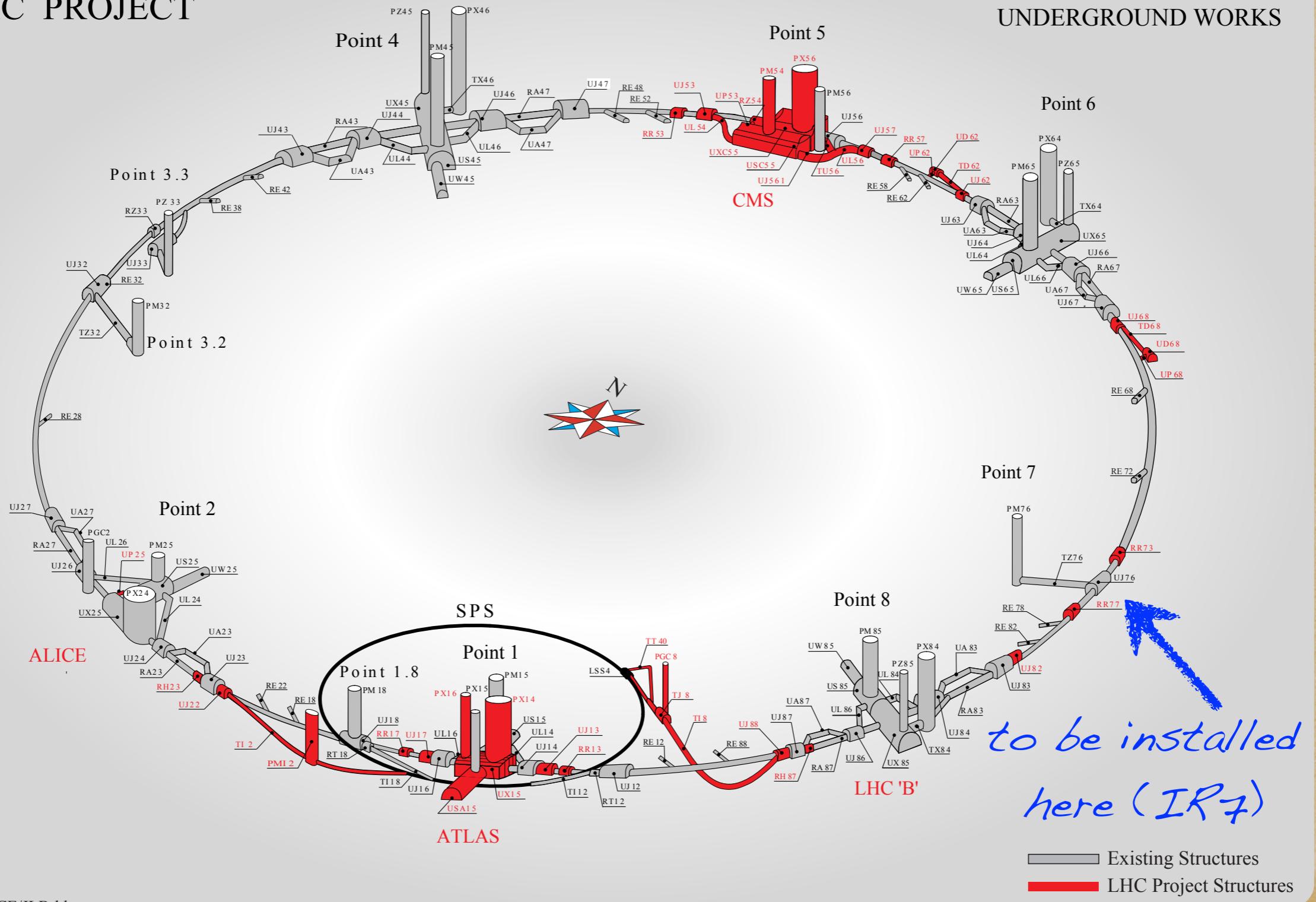
Planned luminosity for PHENIX :

- @ 200 GeV run14pp 12 pb^{-1} , run14dAu 0.15 pb^{-1}
- @ 200 GeV run15AuAu 2.8 pb^{-1} (0.13 nb^{-1} @ 62 GeV)

Nominal LHC luminosity PbPb 0.5 nb^{-1}

LUA9 @ LHC

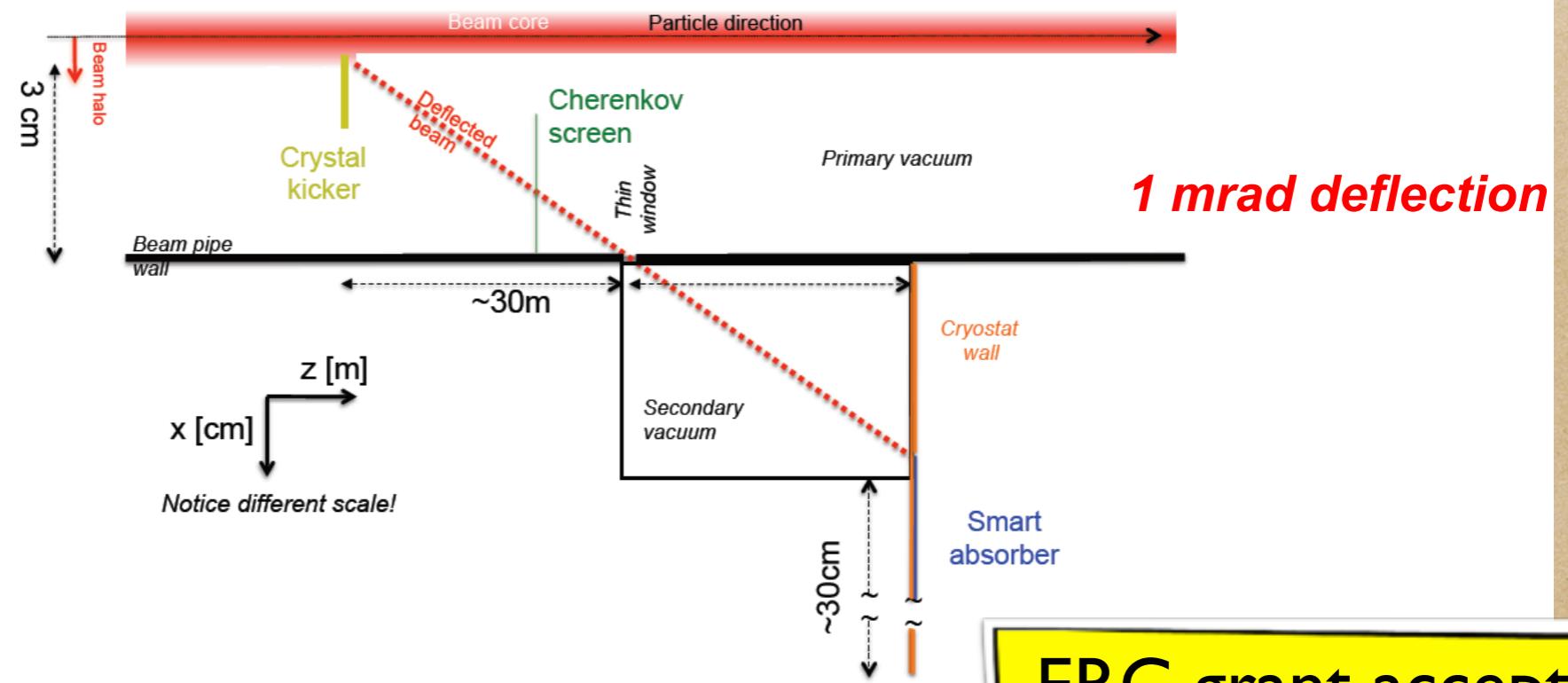
LHC PROJECT



UNDERGROUND WORKS

UA9 2.0: CRYSBEM

- A possible setup to extract a hadron beam
(not for for collimation but sharing the same difficulties)
- Meant to work at high luminosity (high current)



CRYstal channeling to extract a high energy hadron **BEam** from an **Accelerator Machine**

ERC grant accepted
in Nov 2013

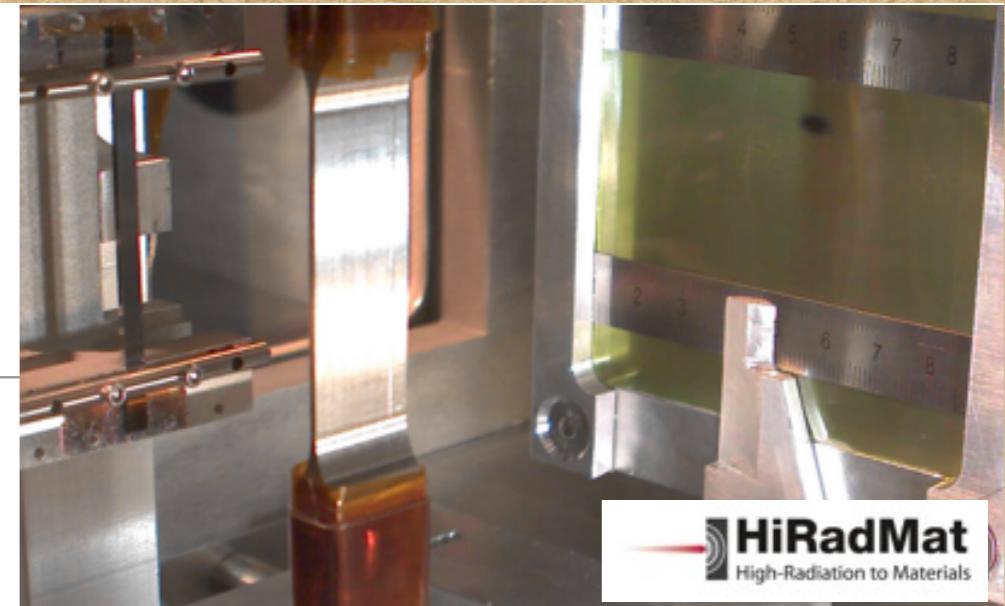
[G. Cavoto, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013]

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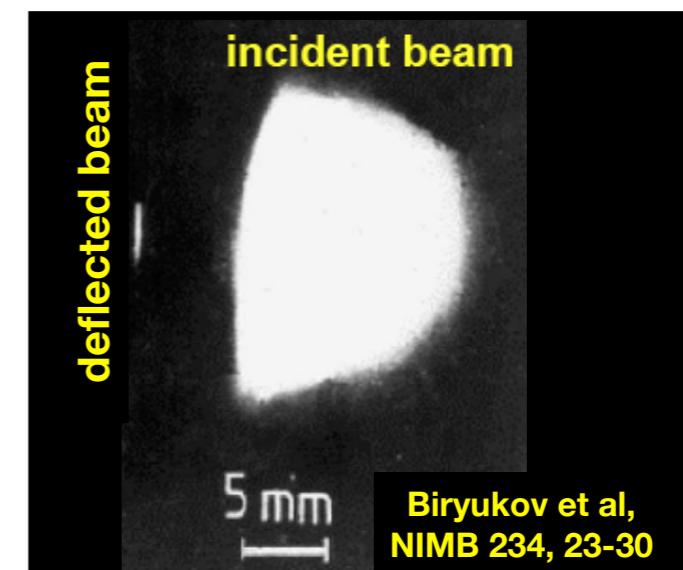
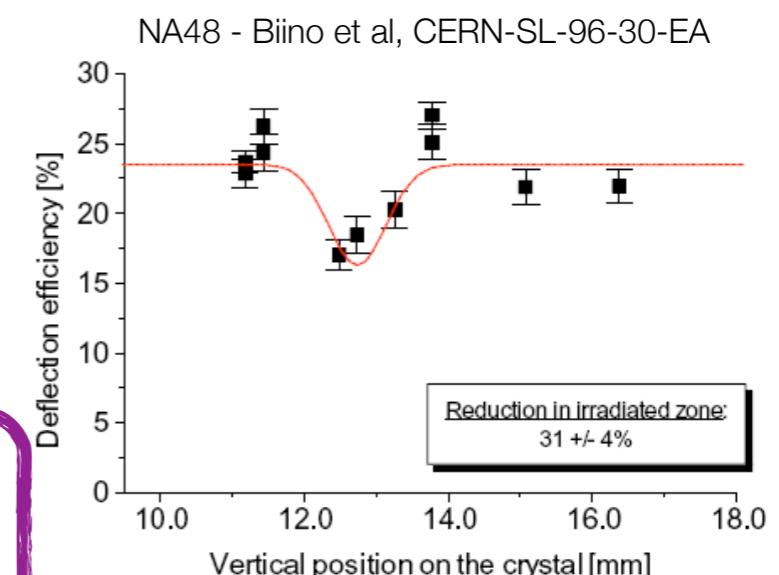
CRYSBEM could be ready for LS2

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 5×10^{12} protons every 14.4 s, one year irradiation, **2.4×10^{20} protons/cm²** in total,
 - equivalent to several years of operation for a primary collimator in LHC
 - $10 \times 50 \times 0.9$ mm³ silicon crystal, 0.8 x 0.3 mm² area irradiated, **channeling efficiency reduced by 30%**.
- **HRMT16-UA9CRY** (HiRadMat facility, November 2012):
 - 440 GeV protons, up to 288 bunches **in 7.2 μ s**, 1.1×10^{11} protons per bunch (**3×10^{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



HiRadMat
High-Radiation to Materials



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