A Fixed-Target ExpeRiment (AFTER) using the LHC beams

AFTER @ LHC

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IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

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Overview

- Beam extraction technique using bent crystal and its application at the LHC

- Expected luminosities and physics opportunities for a fixed target experiment at the LHC

- Expected yields for quarkonium production studies

Strong crystalline fields in bent crystals

Strong electric fields in the lattice nuclei of a crystal in the rest frame of the crossing particles

In a bent crystal, guidance of particles ⇔ bending strength as for a magnetic dipole
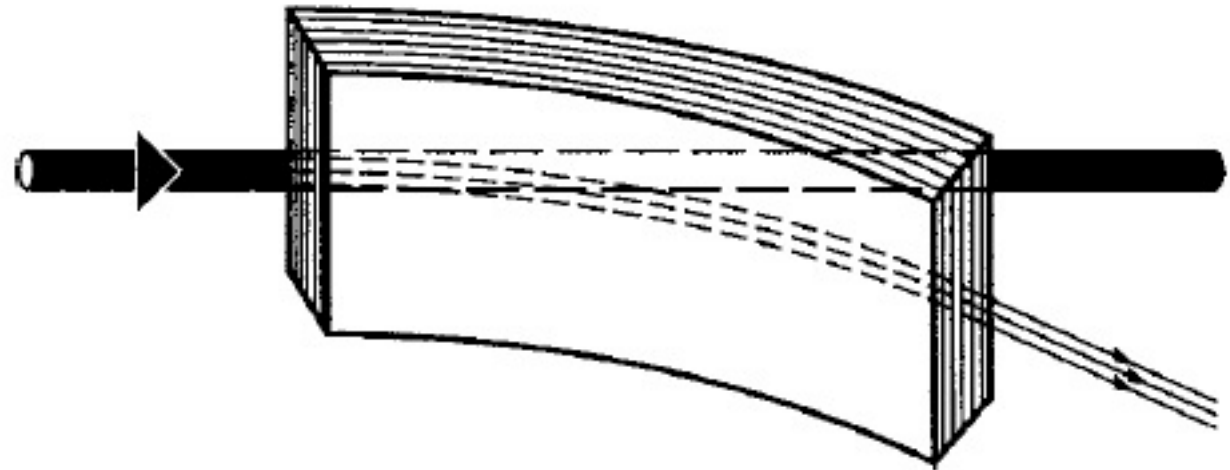
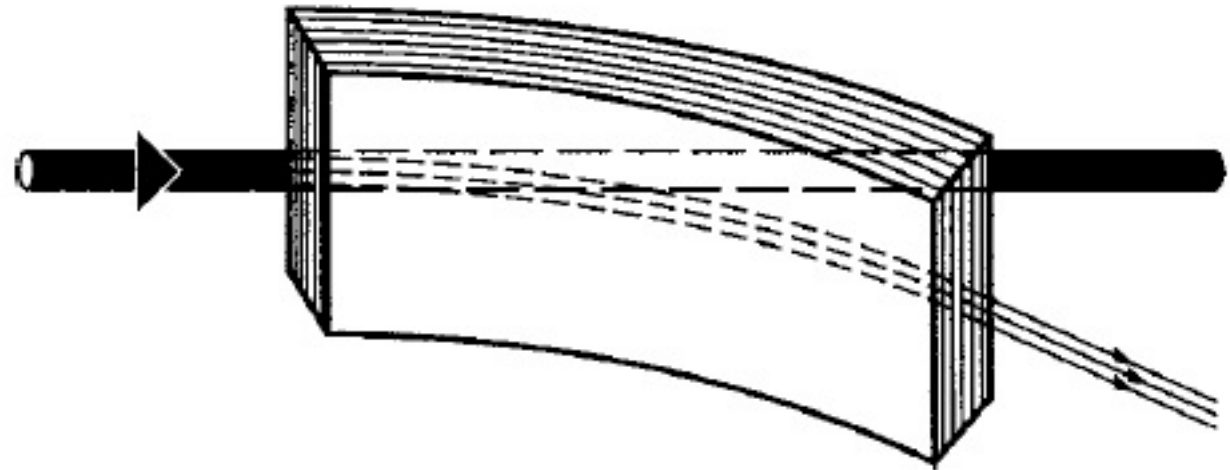Many experiments for proton beam extraction and collimation using crystals:
- RD22 @ CERN-SPS (1990-95)
- E853 @ FNAL-Tevatron (1993-97)
- INTAS @ U70 IHEP (2001-03)
- RHIC (2001-05)
- Tevatron (2005-11)
- UA9 @ SPS (2008-...)
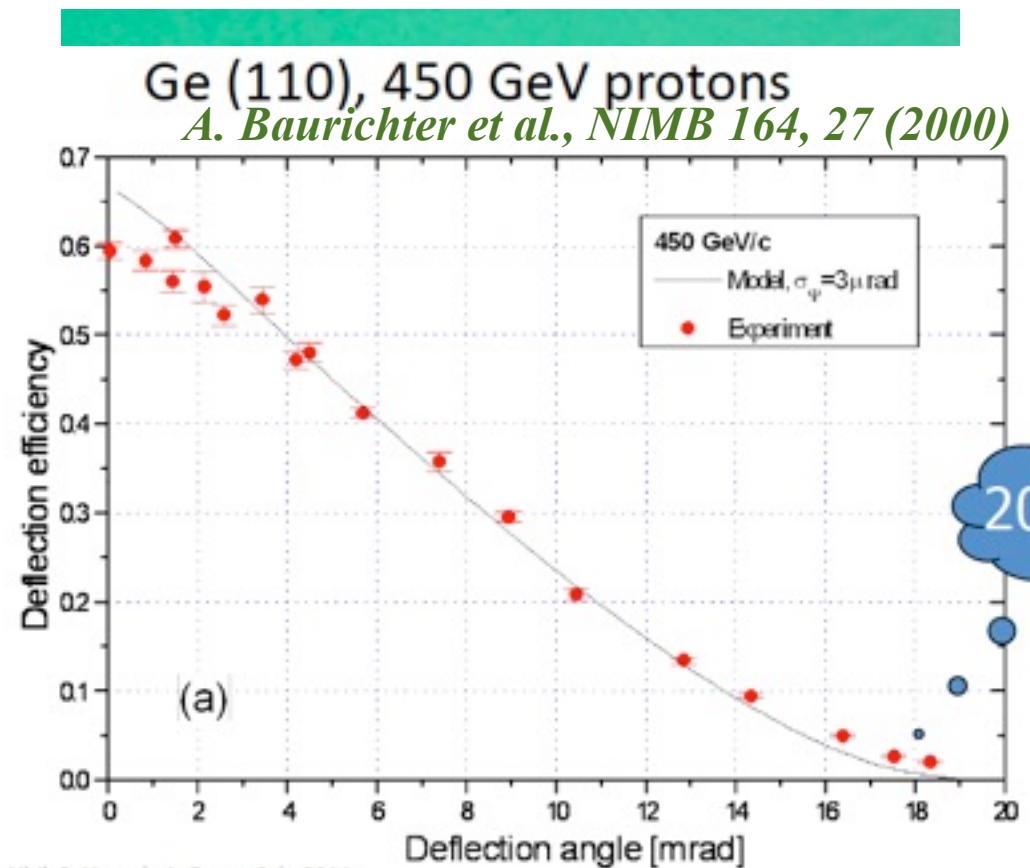- ...

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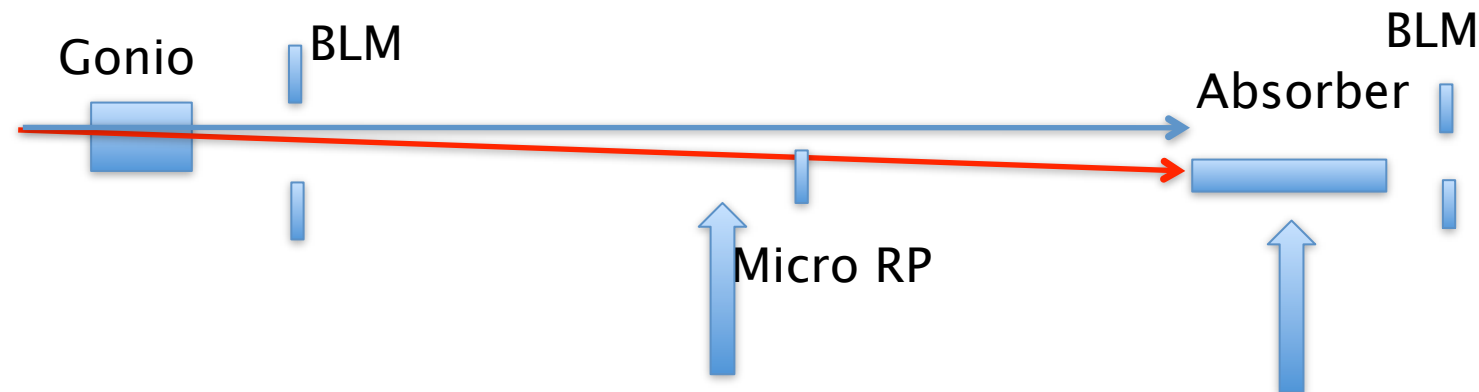- Tevatron (2005-11)
- UA9 @ SPS (2008-...)
- ...

Ge (110), 450 GeV protons

A. Baurichter et al., NIMB 164, 27 (2000)

450 GeV/c
Model, $\sigma_\varphi = 3\mu$rad
Experiment

Deflection efficiency

(a)

Deflection angle [mrad]

2000 T !

Ulrik I. Uggerhøj, Orsay, July 2011

11

Next: beam collimation experiment @ LHC

W. Scandale et al., JINST 6 T10002 (2011)

- LHC Committee approved beam bending experiments using crystals at the LHC (LUA9 Collaboration)

- Beam collimation @ LHC: amorphous collimator: inefficiency @ 3.5 TeV proton beam = 0.2% → expected bent crystal inefficiency = 0.02%

- Tests at SPS in 2012 on proton and ion beams for a LHC setup

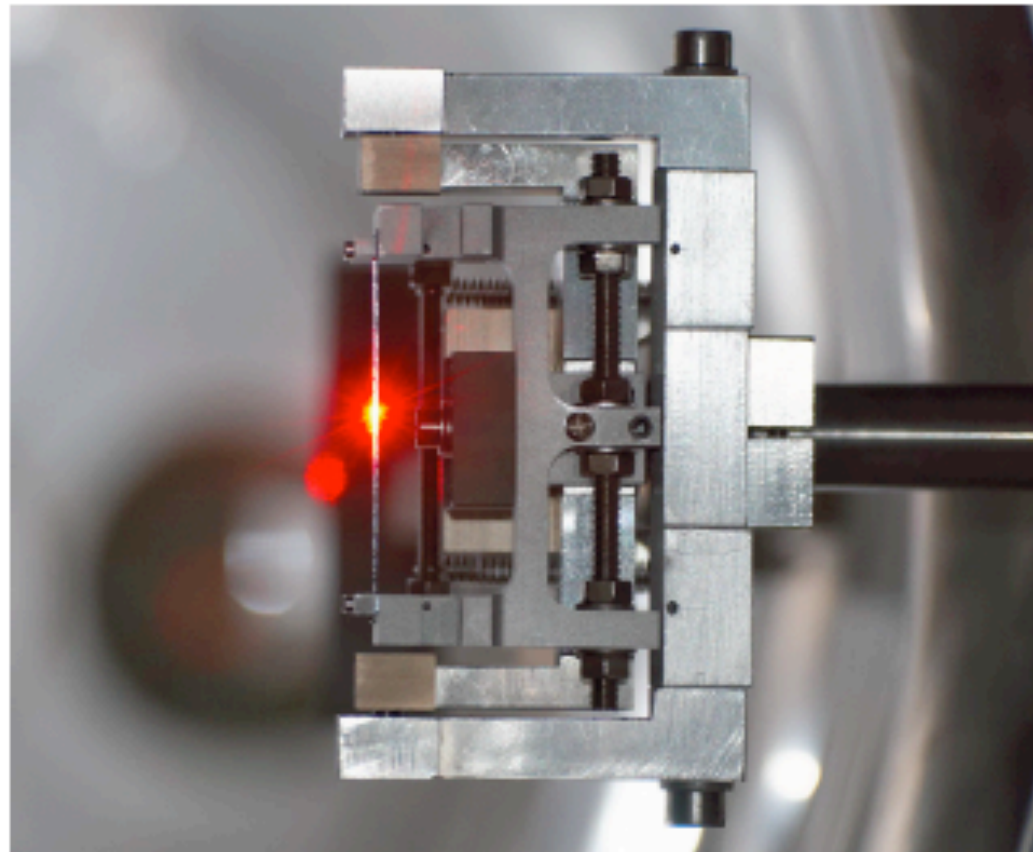- Long Shutdown 1 (2013): bent crystals in LHC beams

Next: beam

W. Scand...

Gonio

- LHC Comm...
  at the LHC

- Beam collir...
  3.5 TeV pro...
  0.02%

- Tests at SPS

- Long Shutd...

Next: beam extraction experiment at the LHC

Continuous extraction in the beam dump line

- **Proposal for the insertion of a bent crystal in the LHC beam**
- Bent, single crystal of Si or Ge - 17cm long crystal
- MKD kicker section at ~200 m from IP6
- Deflection angle = 0.257 mrad (~7 T.m equivalent magnet)
- Distance of 7 σ to the beam to intercept and deflect the beam halo
- No loss in the LHC beam

- **Proton beam extraction**
- Single- or multi pass extraction efficiency of 50%
  - $N_{beam\ loss\ LHC} \sim 10^9$ p/s → $N_{extracted\ beam} = 5\ 10^8$ p/s
- Extremely small emittance: beam size in the extraction direction) 950 m after the extraction ~ 0.3 mm

- **Ion beam extraction**
- Ions extraction tested at SPS, is expected to be also possible at LHC but needs more study
- May require bent diamonds (highly resistant to radiations)

Next: beam extraction experiment at the LHC

E. Uggerhoj and U.I Uggerhoj NIMB 234 (2005) 34

Continuous extraction in the beam dump line
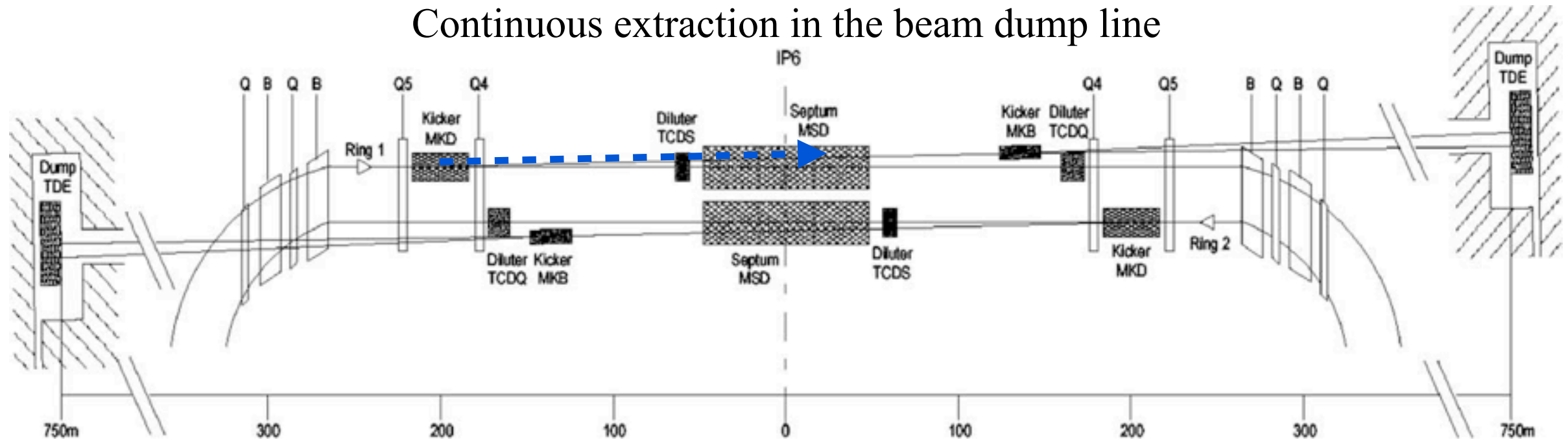
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• Proton beam extraction
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- Extre   direction

• Ion
- Ions
possible at LHC but needs more study
- May require bent diamonds (highly resistant to radiations)
P. Ballin et al, NIMB 267 (2009) 2952

• **Use LHC beams on fixed target**
- 7 TeV proton beam ($\sqrt{s}$ ~115 GeV)
  • p+H, p+A
- 2.76 TeV Pb beam ($\sqrt{s_{NN}}$ ~72 GeV)
  • Pb+A, Pb+H

Luminosities in pH and pA @ 115 GeV

- **Intensity: $N_{beam} = 5.10^8$ protons.s^{-1}**
  - Beam: 2808 bunches of 1.15×10^{11} p = 3.2×10^{14} p
  - Bunch: Each bunch passes IP at the rate: ~11 kHz
  - Instantaneous extraction: IP sees 2808 x 11000~3.10^7 bunches passing every second → extract ~16 protons in each bunch at each pass
  - Integrated extraction: Over a 10h run: extract ~5.6% of the protons stored in the beam

- **Instantaneous Luminosity**
  $$L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times N_A)/A$$
  - N_{beam}=5 x 10^8 p$^+$/s
  - e (target thickness) = 1 cm

- **Integrated luminosity**
  - 9 months running/year
  - 1 year ~ 10^7 s

Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (μb^{-1} s^{-1})	$\int \mathcal{L}$ (pb^{-1} 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

$\Rightarrow$ Large luminosity in pH(A) ranging from 0.1 and 0.6 fb^{-1} for a 1 cm thick target

$\Rightarrow$ Larger luminosity with 50 cm or 1 m H2 or D2 target (1 m $\leftrightarrow$ 20 /fb/yr = LHC in 2012)

Luminosities in PbA @ 72 GeV

- **Intensity: N_{beam} = 2.10^5 Pb.s^{-1}**

  – Beam: 592 bunches of 7x10^7 ions = 4.1x10^{10} ions

  – Bunch: Each bunch passes IP at the rate ~ 11 kHz

  – Instantaneous extraction: IP sees 592 x 11000~6.5.10^6 bunches passing every second → extract ~0.03 ions in each bunch at each pass

  – Integrated extraction: Over a 10h run: extract ~15% of the ions stored in the beam

- **Instantaneous Luminosity**

  $$L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times N_A)/A$$

  – N_{beam}=2 x 10^5 Pb/s

  – e (target thickness) = 1 cm

- **Integrated luminosity**

  – 1 months running/year

  – 1 year ~ 10^6 s

Target (1 cm thick)	ρ (g cm^{-3})	A	$\mathcal{L}$ (mb^{-1} s^{-1})	$\int \mathcal{L}$ (nb^{-1} 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

⇒ AFTER provides a large luminosity to study QGP related measurements

Polarizing the hydrogen target

- **Instantaneous Luminosity**

  $L = N_{beam} \times N_{Target} = N_{beam} \times (\rho \times e \times N_A)/A$

  - $N_{beam} = 5 \times 10^8$ p$^+$/s
  - e (target thickness) = 50 cm

$x_p^\uparrow$ range corresponds to Drell-Yan measurements

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

$\Rightarrow$ AFTER provides a competitive uminosity to study target spin related measurements
$\Rightarrow$ Complementary x_p range with other spin physics experiments

Rapidity boost in a fixed target mode

- **Very high boost:**
  - With 7 TeV beam
    $\gamma = \sqrt{s}/(2m_p) = 61.1$ and $y_{CMS} = 4.8$
  - With 2.76 TeV beam
    $\gamma = 38.3$ and $y_{CMS} = 4.3$

- $y_{lab} = y_{CM} + y_{CMS}$
    forward region: $y_{CM} > 0$
    backward region: $y_{CM} < 0$

- $\eta = -\ln \tan \theta/2$ (= y for massless particles)
  - With 7 TeV beam
    $y_{CM} = 0 \leftrightarrow \theta \sim 16$ mrad (0.9°)

projectile

x_1 x_2 target
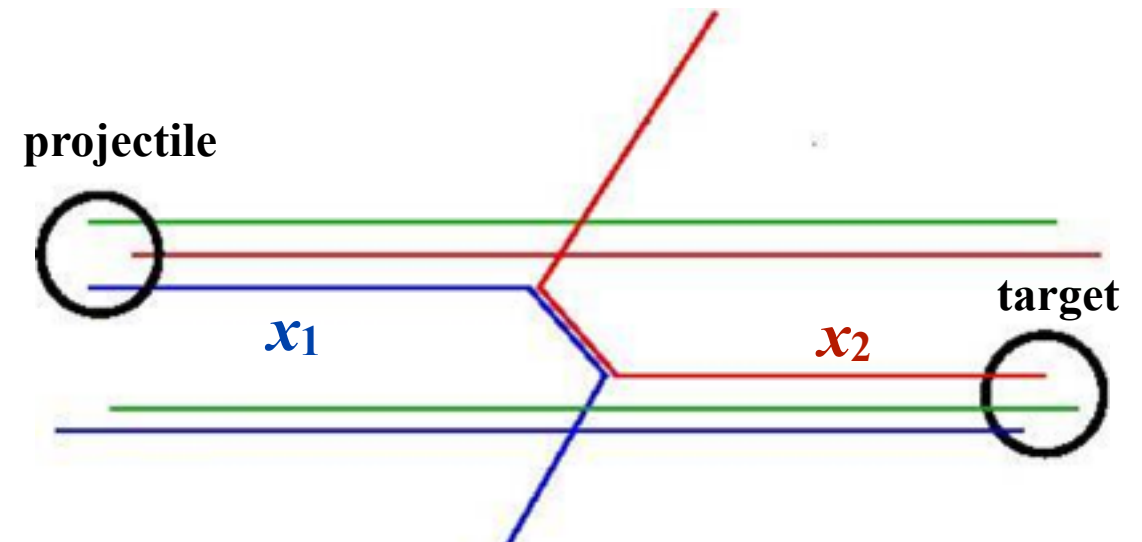
For a $2 \to 1$ process (e.g. gg→QQbar)

$$x_{1,2} = M/\sqrt{s} \; e^{\pm y_{CM}}$$

y_{CM} : QQbar CMS rapidity
M : QQbar mass

- $y_{lab} = 4.8 \leftrightarrow y_{CM} = 0 \to x_1 = x_2$
- **backward region: $y_{CM} < 0 \to x_1 < x_2$**
- $y_{lab}(J/\Psi) \sim 1.2 \to x_2 = 1$
- $y_{lab}(\Upsilon) \sim 2.4 \to x_2 = 1$

Good condition to access large target x_2 and low $x_F = x_1 - x_2 \to -1$: target-rapidity region

Physics opportunities of A Fixed-Target ExpeRiment (AFTER) @LHC

- **Idea: use LHC beams on fixed target**
  - 7 TeV proton beam ($\sqrt{s}$ ~115 GeV)
    - p+H, p+A
  - 2.76 TeV Pb beam ($\sqrt{s_{NN}}$ ~72 GeV)
    - Pb+A, Pb+H

- **High boost and luminosity giving access to**
  - QCD at large x
  - nPDF and nuclear shadowing
  - Spin physics using polarized target
  - W/Z production near threshold
  - Quark Gluon Plasma
  - Other ?

- **Multi-purpose experiment**
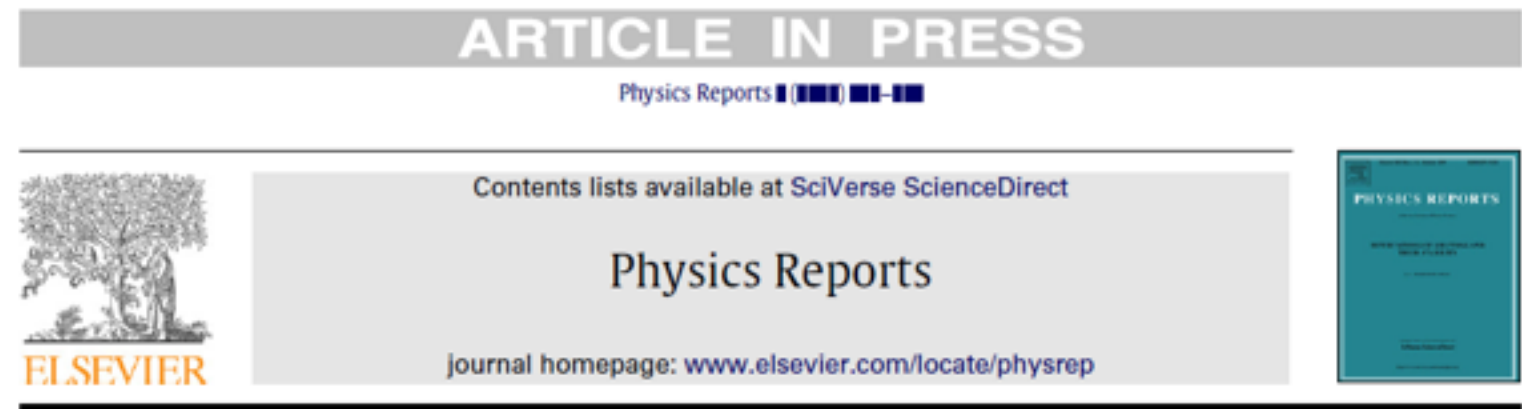
Physics opportunities of a fixed-target experiment using LHC beams

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

ABSTRACT

We outline the many physics opportunities offered by a multi-purpose fixed-target experiment using the proton and lead-ion beams of the LHC extracted by a bent crystal. In a proton run with the LHC 7 TeV beam, one can analyze pp, pd and pA collisions at center-of-mass energy $\sqrt{s_{NN}} \simeq 115$ GeV and even higher using the Fermi motion of the nucleons in a nuclear target. In a lead run with a 2.76 TeV-per-nucleon beam, $\sqrt{s_{NN}}$ is as high as 72 GeV. Bent crystals can be used to extract about 5×10^8 protons/s; the integrated luminosity over a year reaches 0.5 fb^{-1} on a typical 1 cm long target without nuclear species limitation. We emphasize that such an extraction mode does not alter the performance of the collider experiments at the LHC. By instrumenting the target-rapidity region, gluon and heavy-quark distributions of the proton and the neutron can be accessed at large x and even at x larger than unity in the nuclear case. Single diffractive physics and, for the first time, the large negative-x_F domain can be accessed. The nuclear target-species versatility provides a unique opportunity to study nuclear matter versus the features of the hot and dense matter formed in heavy-ion collisions, including the formation of the quark-gluon plasma, which can be studied in PbA collisions over the full range of target-rapidity domain with a large variety of nuclei. The polarization of hydrogen and nuclear targets allows an ambitious spin program, including measurements of the QCD lensing effects which underlie the Sivers single-spin asymmetry, the study of transversity distributions and possibly of polarized parton distributions. We also emphasize the potential offered by pA ultra-peripheral collisions where the nucleus target A is used as a coherent photon source, mimicking photoproduction processes in ep collisions. Finally, we note that W and Z bosons can be produced and detected in a fixed-target experiment and in their threshold domain for the first time, providing new ways to probe the partonic content of the proton and the nucleus.
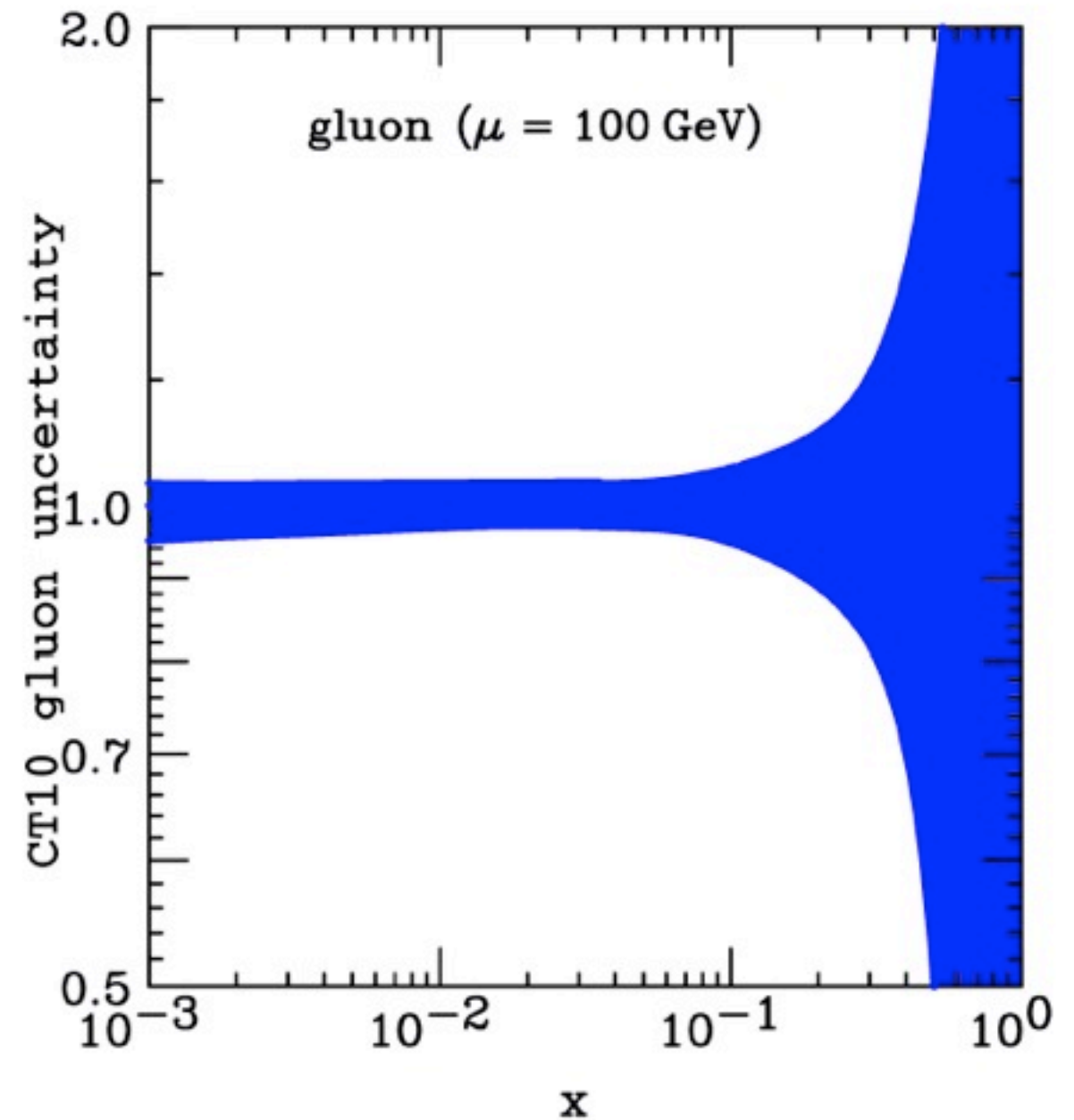
IPN
ORSAY

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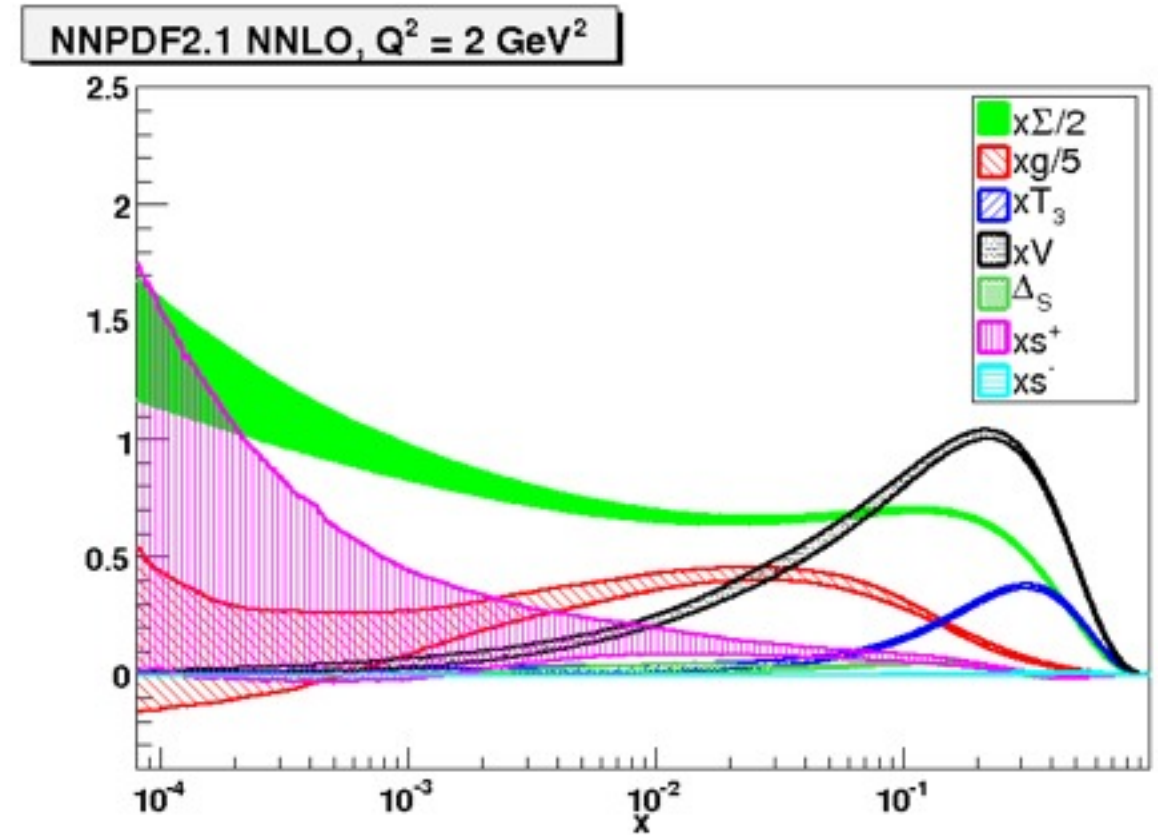
Gluon distribution function in the proton: very large uncertainty at large *x* also at large Q

Unknown for the neutron

Large uncertainty in nuclei at large *x* (LHeC will probe the low *x*)
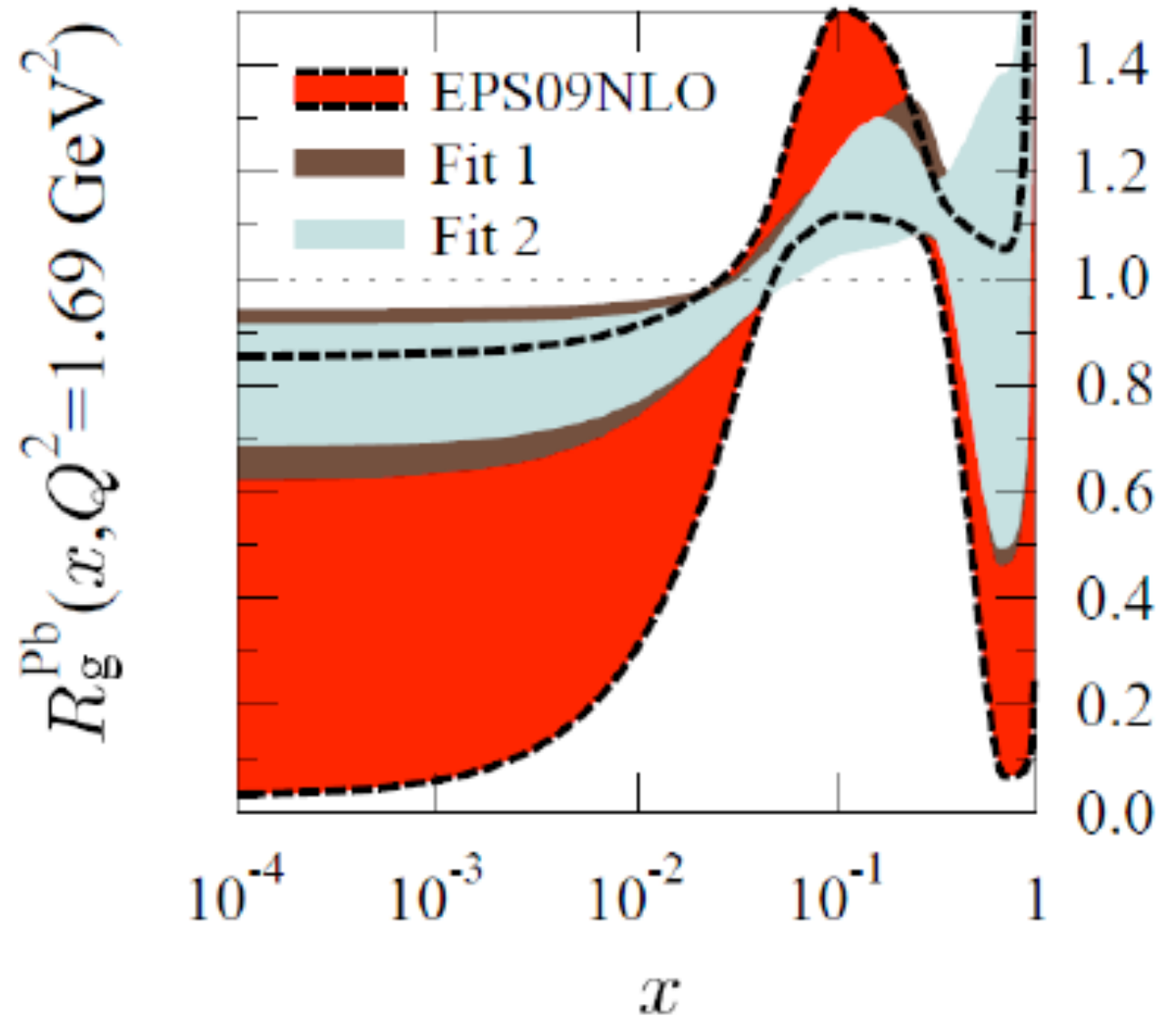
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gluon ($\mu = 100$ GeV)

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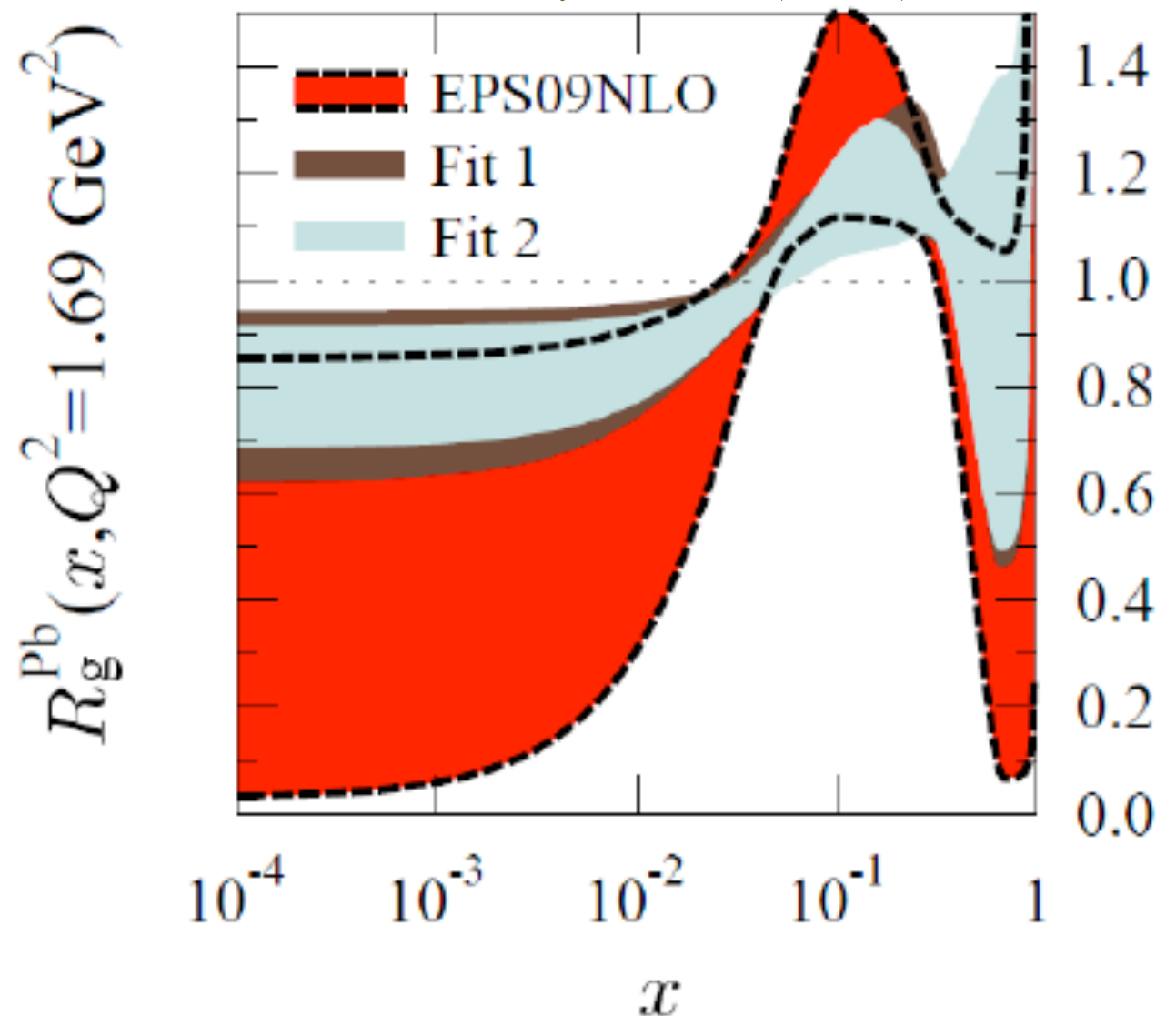Large uncertainty in nuclei at large x
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LHeC CDR J. Phys. G 39 (2012) 075001

Gluon distribution at large x

Gluon distribution function in the proton: very large uncertainty at large x also at large Q

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Large uncertainty in nuclei at large x (LHeC will probe the low x)

- **Experimental probes @ AFTER**
  – Quarkonia
  – Isolated photons
  – High p_T jets (p_T > 20 GeV/c)
    → to access target x_g = 0.3 - 1 (>1 Fermi motion in nucleus)

- **Target versatility**
  – Hydrogen
  – Deuteron (neutron)
  – Nuclei

LHeC CDR J. Phys. G 39 (2012) 075001

Heavy-quark distribution at large *x*

Intrinsic charm motivated by non perturbative models of hadron structure

All different charm pdfs (DGLAP or intrinsic charm) in agreement with DIS data
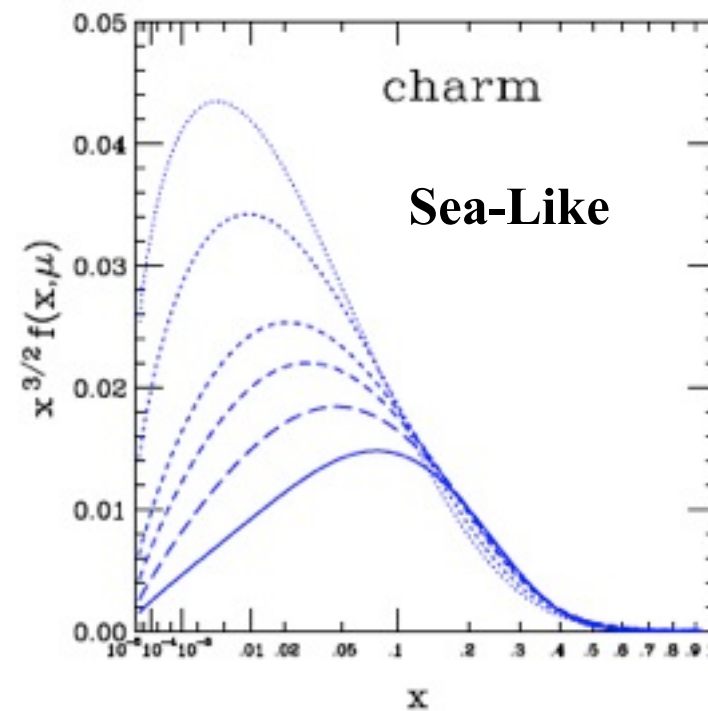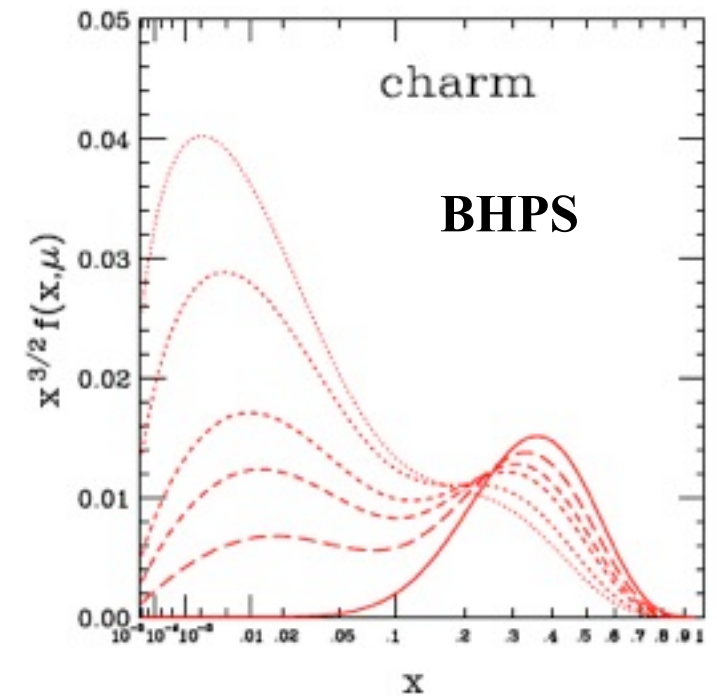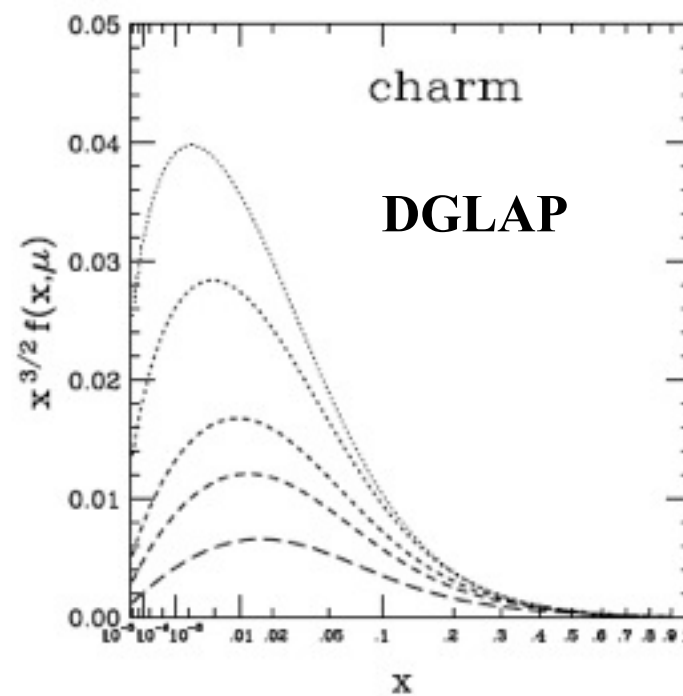
Heavy-quark distribution at large x

Pumplin et al. Phys.Rev. D75 (2007)

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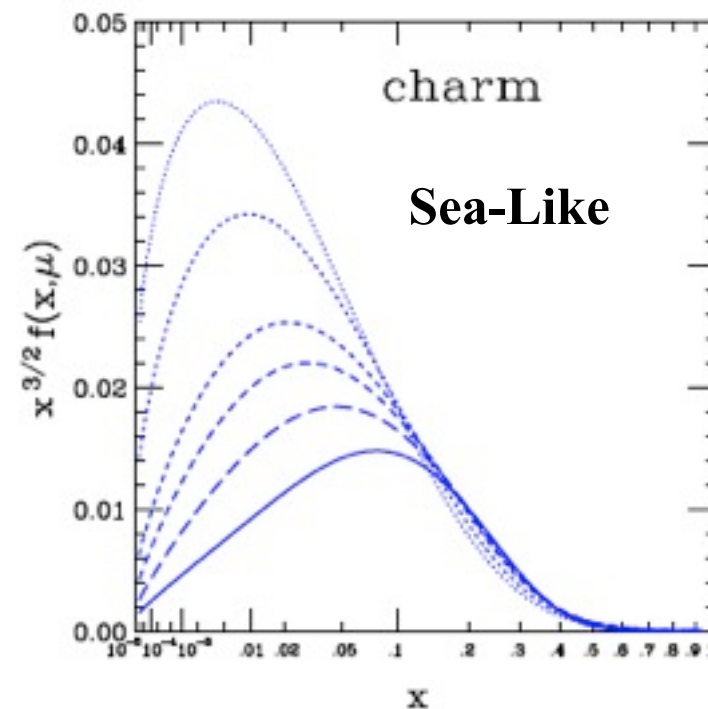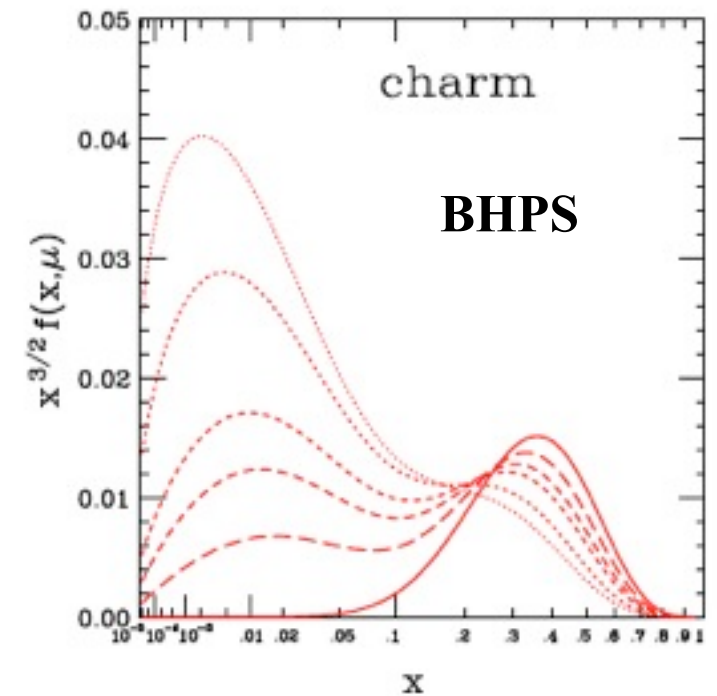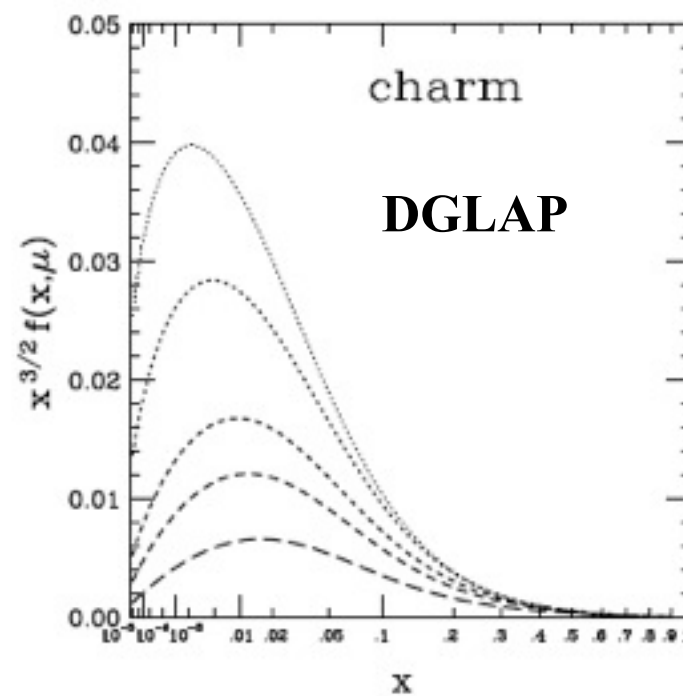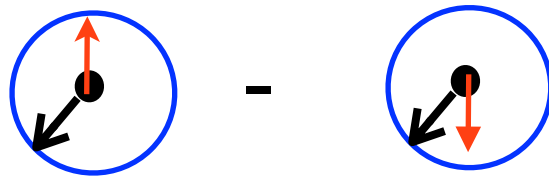
- **Experimental probes @ AFTER**
- Open charm (D meson or displaced-vertex lepton)
- Open beauty

Boer-Mulders effect

Parton distribution functions pdfs $(x, Q^2) \rightarrow$
$(x, \mathbf{k_T}, Q^2)$: 3D or Transverse Momentum Dependent
(TMD) pdfs

Boer-Mulders effect: correlation between the **parton**
$\mathbf{k_T}$ and **its spin** (in an **unpolarized nucleon**)

Boer-Mulders effect

Parton distribution functions pdfs $(x, Q^2) \rightarrow$ $(x, \mathbf{k_T}, Q^2)$: 3D or Transverse Momentum Dependent (TMD) pdfs

Boer-Mulders effect: correlation between the **parton** $\mathbf{k_T}$ and **its spin** (in an **unpolarized nucleon**)

Double-node structure of transverse-momentum distributions predicted for scalar and pseudoscalar quarkonia → give access to the Boer-Mulders TMD pdf for gluons

Boer and Pisano Phys.Rev. D86 (2012) 094007

$$1/\sigma * d\sigma / dq_T^2$$

χ_0 ....

$(h_1^{\perp g} = 0)\ \chi_2$ ———

η_Q – – –

$\langle p_T^2 \rangle = 1\ \text{GeV}^2$

q_T (GeV)

Boer-Mulders effect

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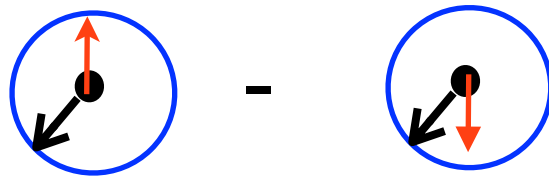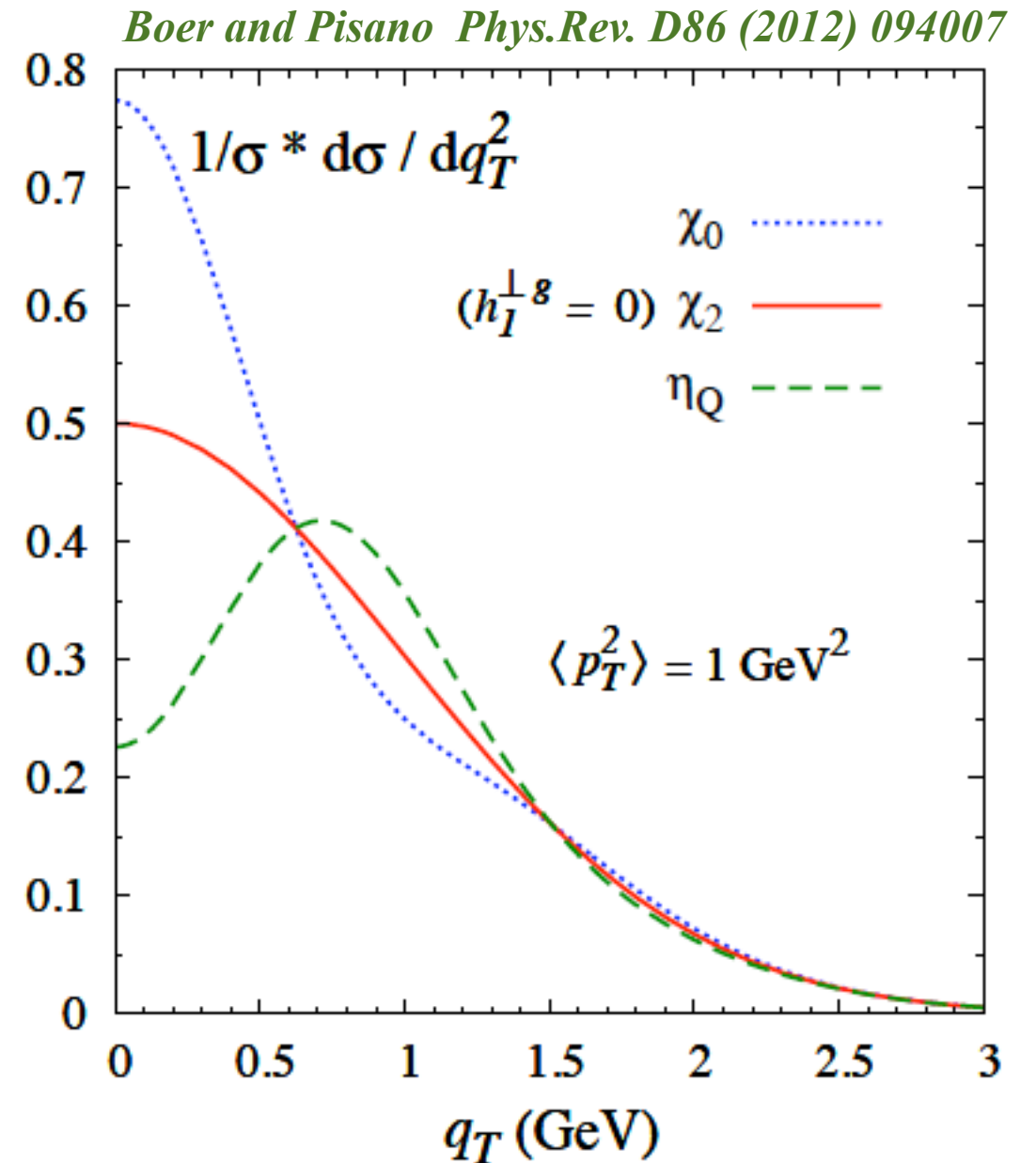
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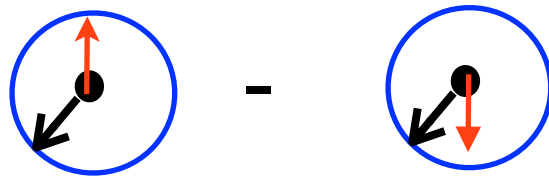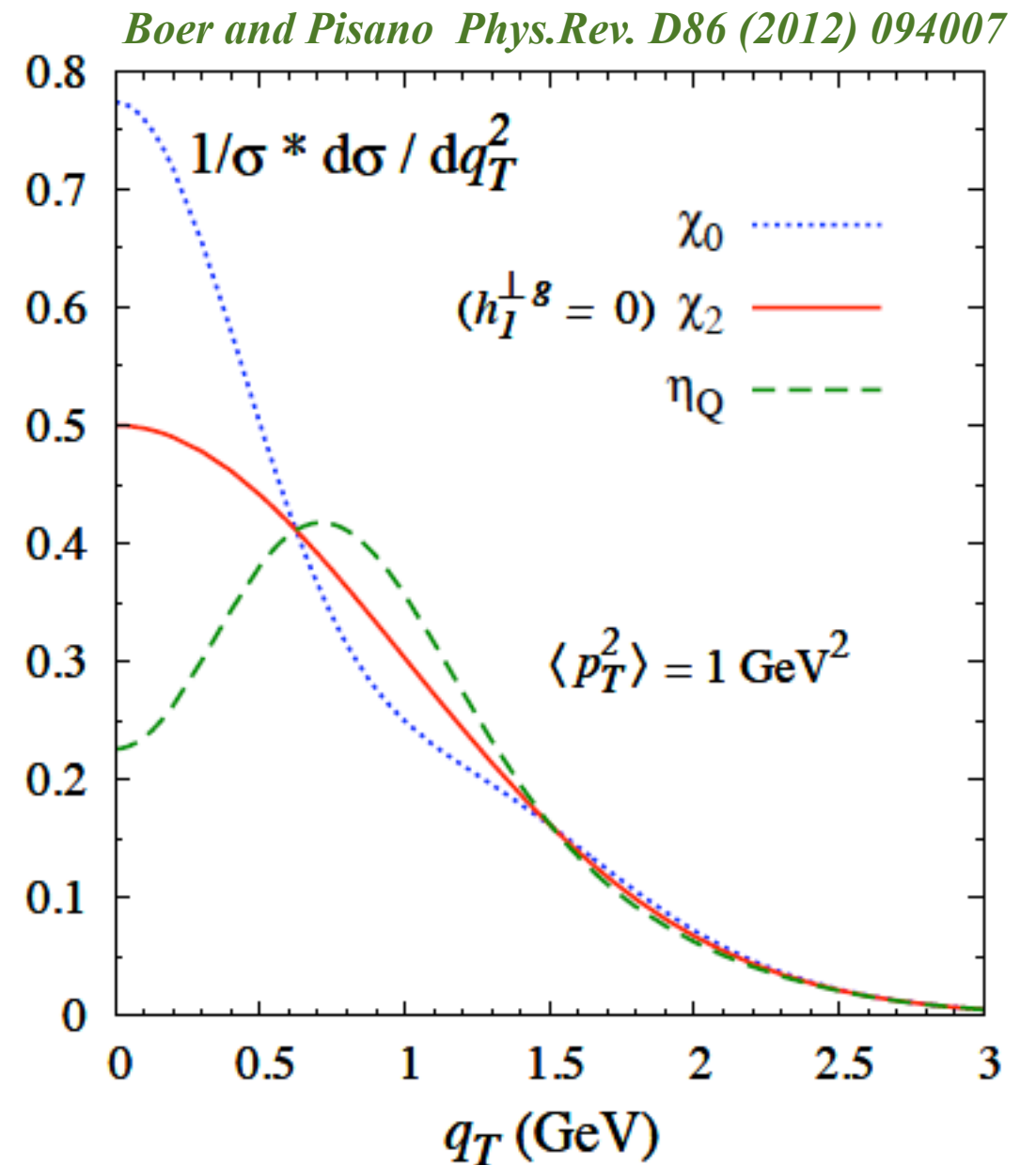
Double-node structure of transverse-momentum distributions predicted for scalar and pseudoscalar quarkonia → give access to the Boer-Mulders TMD pdf for gluons

- **Experimental probes @ AFTER**
- scalar and pseudoscalar quarkonia: χ_{c0}, χ_{b0}, η_c, η_b (PID and modern calorimetry)

Boer and Pisano Phys.Rev. D86 (2012) 094007

$$\frac{1}{\sigma} * d\sigma / dq_T^2$$

χ_0

$(h_1^{\perp g} = 0) \, \chi_2$

η_Q

$\langle p_T^2 \rangle = 1 \text{ GeV}^2$

q_T (GeV)

Sivers effect with a transversaly polarized target

Polarizing the target: measuring asymmetry to access the 3D
or Transverse Momentum Dependent (TMD) pdfs.

Sivers effect in a **transversaly polarized nucleon**:
correlation between the **parton k_T** and the **proton spin**

Sivers effect with a transversaly polarized target

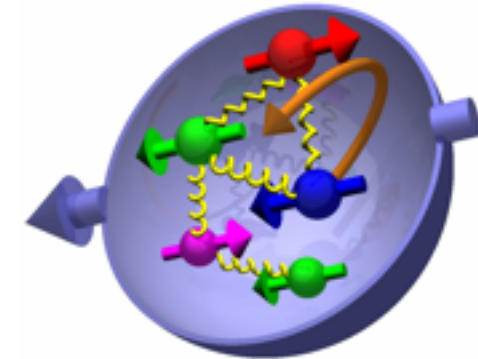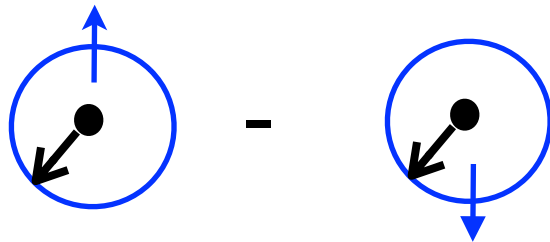Polarizing the target: measuring asymmetry to access the 3D or Transverse Momentum Dependent (TMD) pdfs.

Sivers effect in a **transversaly polarized nucleon**: correlation between the **parton k_T** and the **proton spin**

T. Liu and B.Q. Ma Eur.Phys.J. C72 (2012) 2037

$\sqrt{s} = 115$ GeV
$Q = 5$ GeV

Fig. 29 The $\sin(2\phi - \phi_S)$ azimuthal asymmetry $A_{TU}^{\sin(2\phi - \phi_S)}$ depending on x_F of target proton polarized pp Drell–Yan process at $Q = 5$ GeV.
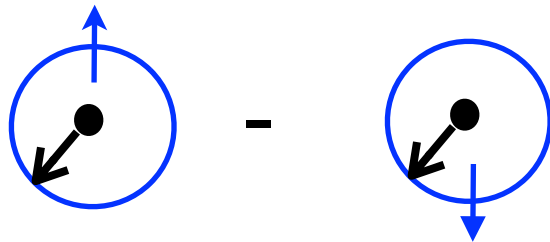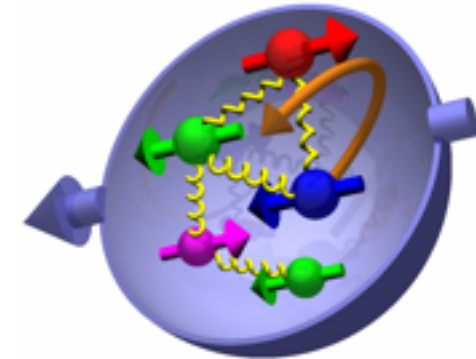
- **Experimental probes @ AFTER**
  - Drell-Yan → quark Sivers effect
  - Quarkonia, Open Charm and Beauty (B and D mesons), isolated γ and γ-jet → gluon Sivers effect

- **Large asymmetries (~20%) predicted in Drell-Yan** for the target-rapidity region ($x_F = x_{beam} - x_{target} < 0$) where the k_T spin correlation is the largest

W, Z production in the threshold region...

With high luminosity fixed-target experiment, W and Z production accessible

Unique opportunity to study the W and Z production near threshold @ AFTER

Very large x partons in the nucleon/nucleus target probed

Large NLO and NNLO corrections: QCD laboratory near threshold at large scale

If W'/Z' exists, similar threshold corrections than W and Z

But also: very forward (backward) physics:
  semi-diffractive physics
  ultra-peripheral collisions in pp, pA and PbA →**Lech Szymanowski (Timelike Compton Scattering)**
  ...

Quark Gluon Plasma

In nucleus-nucleus collisions at high ultra-relativistic energy → Quark Gluon Plasma (QGP) formation

RHIC energy scan shows suppression of particles at $\sqrt{s_{NN}}$ = 39, 62, 200 GeV (π^0, J/Ψ, ...) but low statistics for $\sqrt{s_{NN}}$ < 200 GeV and scarse / no pp and pA reference

Cold Nuclear Matter (i.e not Hot from QGP) measured in pA
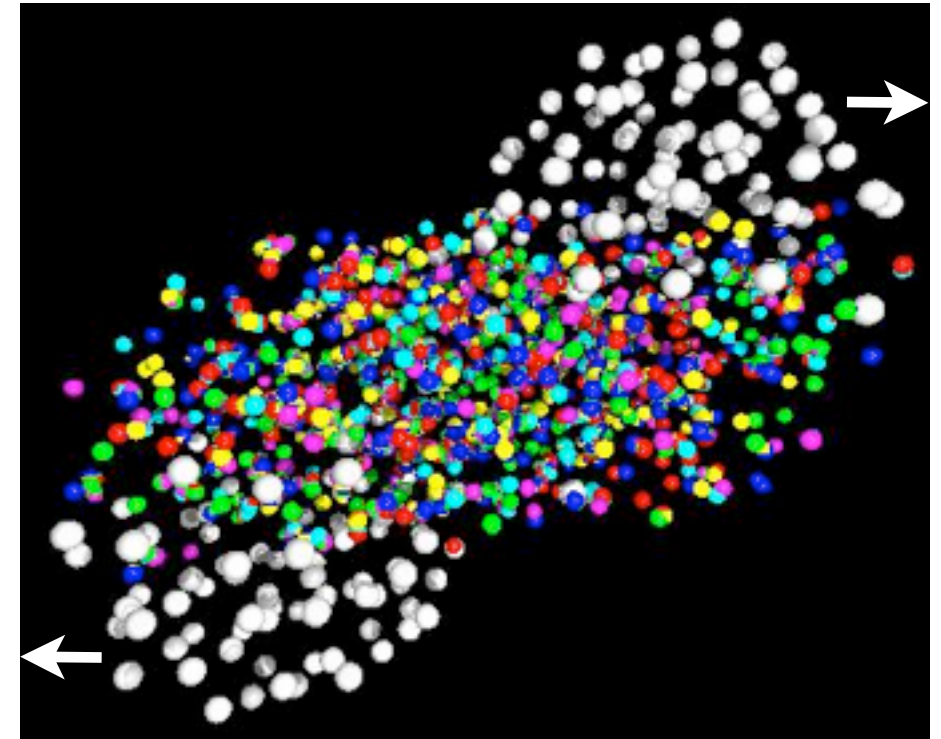

PHENIX Collaboration arXiv 1208:2251

Quark Gluon Plasma
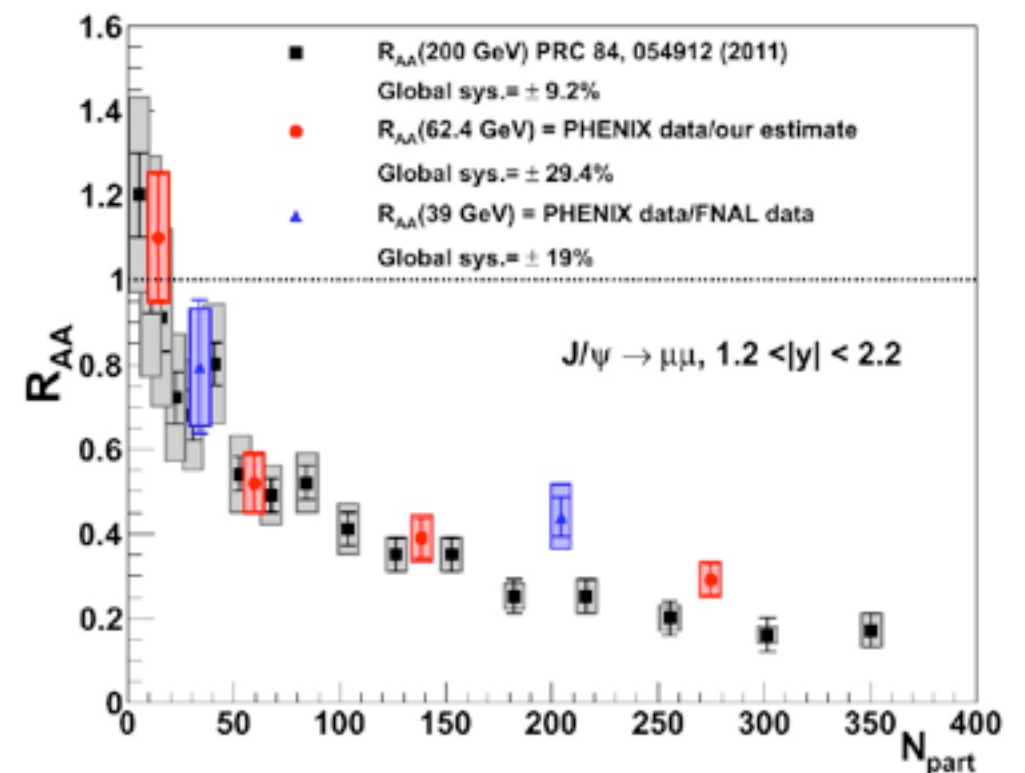
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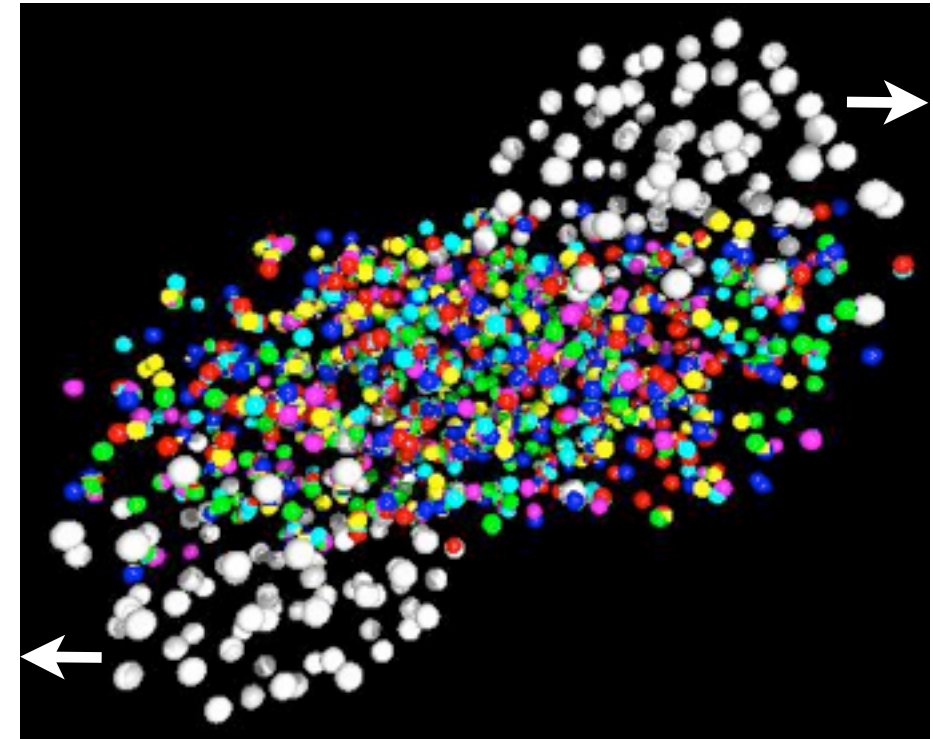*PHENIX Collaboration arXiv 1208:2251*

- **Experimental probes @ AFTER $\sqrt{s}$ = 72 GeV**
- Quarkonia
- Jets
- Low mass lepton pairs
- ...

- **Target versatility**
- In PbA, different nuclei: A-dependent studies
- In pA, precise estimate of Cold Nuclear effect with pA collisions
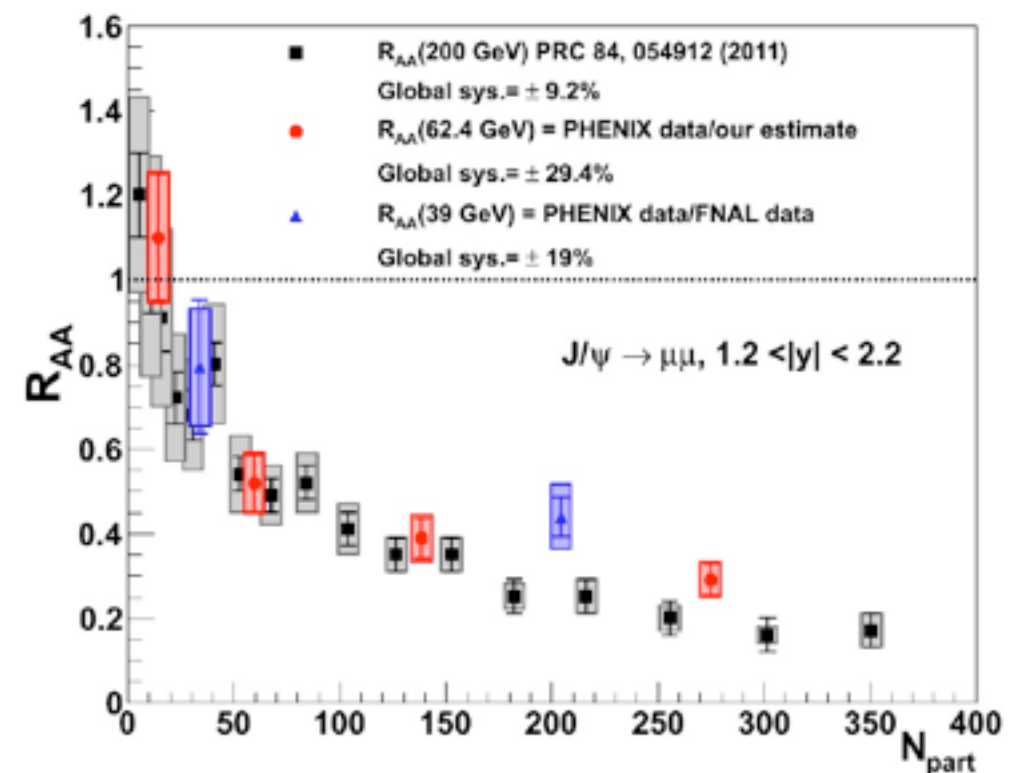
Quarkonium yields in pH and pA @ 115 GeV

In pp

⇒ RHIC @ 200 GeV x 100 with 10 cm thick H target

⇒ Comparable to LHCb if 1m H target

⇒ Detailed studies of quarkonium production (p_T, y, polarization, different quarkonium states, new observables: J/Ψ pair, J/Ψ+D, J/Ψ +γ, ...)

In pA

⇒ RHIC @ 200 GeV x 100 with 1 cm Pb target

⇒ Detailed studies of cold nuclear matter effect in pA (p_T, y, A, ...)

Also very promising in PbA

| Target	$\int dt\,\mathcal{L}$	$\mathcal{B}_{\ell\ell}\frac{dN_{J/\psi}}{dy}\big|_{y=0}$	$\mathcal{B}_{\ell\ell}\frac{dN_{\Upsilon}}{dy}\big|_{y=0}$
10 cm solid H	2.6	$5.2\ 10^7$	$1.0\ 10^5$
10 cm liquid H	2	$4.0\ 10^7$	$8.0\ 10^4$
10 cm liquid D	2.4	$9.6\ 10^7$	$1.9\ 10^5$
1 cm Be	0.62	$1.1\ 10^8$	$2.2\ 10^5$
1 cm Cu	0.42	$5.3\ 10^8$	$1.1\ 10^6$
1 cm W	0.31	$1.1\ 10^9$	$2.3\ 10^6$
1 cm Pb	0.16	$6.7\ 10^8$	$1.3\ 10^6$
pp low P_T LHC (14 TeV)	0.05	$3.6\ 10^7$	$1.8\ 10^5$
pp low P_T LHC (14 TeV)	2	$1.4\ 10^9$	$7.2\ 10^6$
pPb LHC (8.8 TeV)	10^{-4}	$1.0\ 10^7$	$7.5\ 10^4$
pp RHIC (200 GeV)	$1.2\ 10^{-2}$	$4.8\ 10^5$	$1.2\ 10^3$
dAu RHIC (200 GeV)	$1.5\ 10^{-4}$	$2.4\ 10^6$	$5.9\ 10^3$
dAu RHIC (62 GeV)	$3.8\ 10^{-6}$	$1.2\ 10^4$	$1.8\ 10^1$

Luminosity per year in fb^{-1}

Earlier studies with ALICE as a fixed target experiment

Proposition

Using ALICE as a fixed target experiment

Kurepin et al. Phys.Atom.Nucl. 74 (2011)
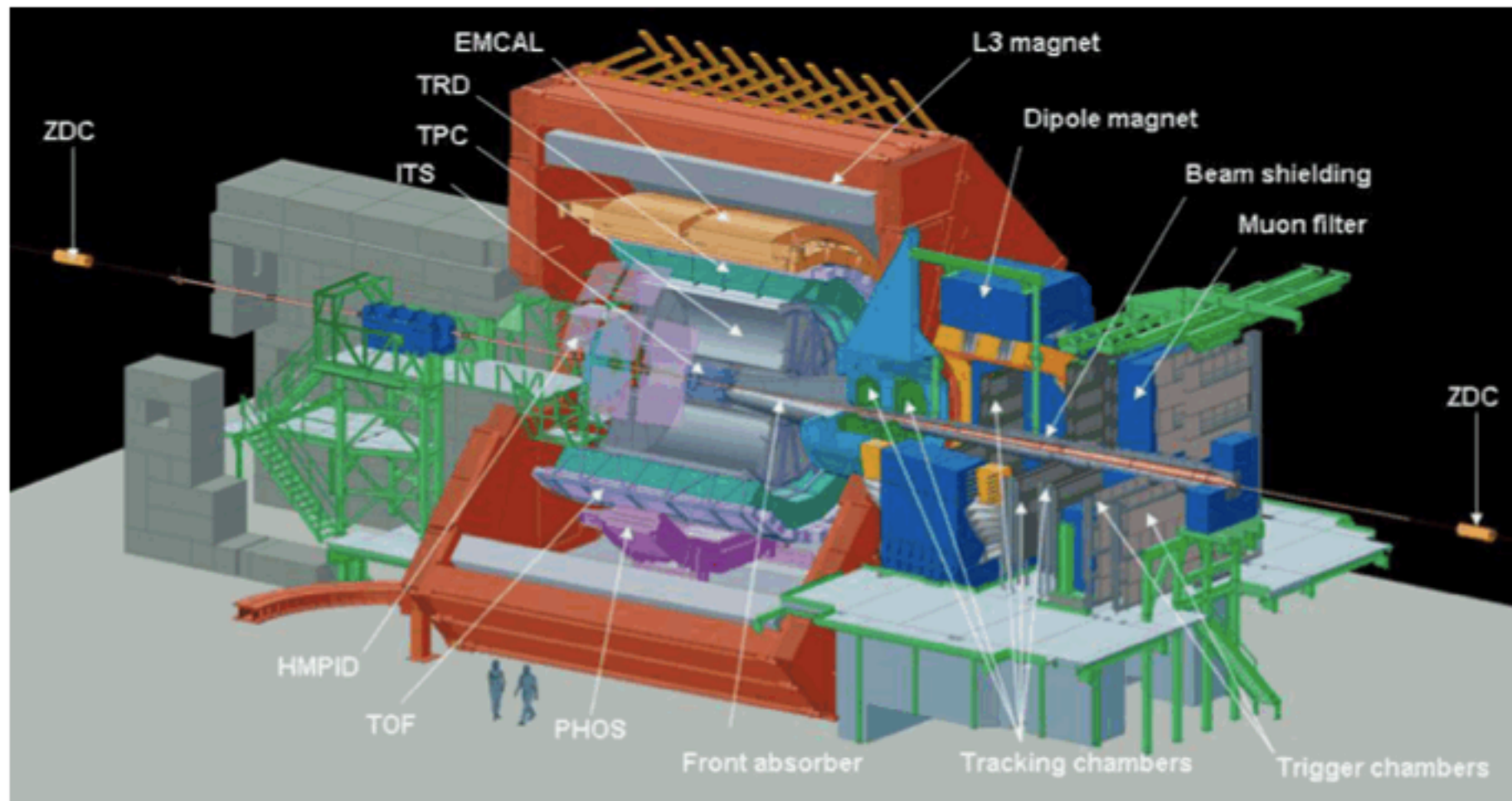
Geometrical Acceptance @ 115 GeV

Simulation @ 115 GeV for J/ψ → $\mu^+\mu^-$ with μ detected in the muon arm of ALICE (2.5< η < 4)

A geometrical Acceptance of 8% for J/ψ (4 π) → $\mu^+\mu^-$ (2.5< y < 4) is estimated

Accessing the large *x* gluon in the target

PYTHIA simulation

$\sigma(y) / \sigma(y=0.4)$

statistics for one month

5% acceptance considered

-3.5 < y$_{CM}$ < 0.5 ↔ 1.3 < y < 5.3

Statistical relative uncertainty
Large statistics allow to access very backward region

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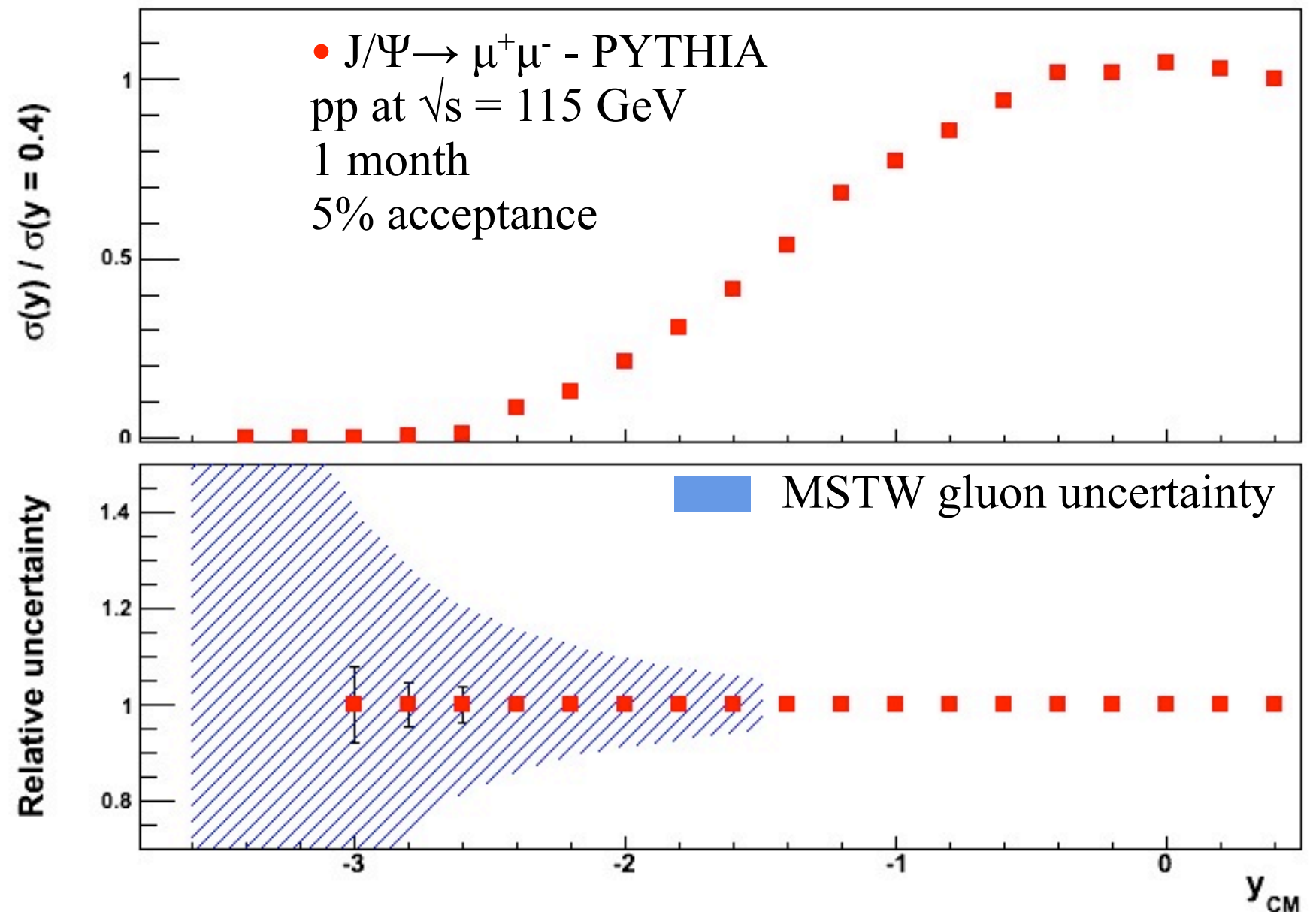- assuming

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

J/Ψ

y$_{CM}$ ~ 0 → x$_g$ = 0.03

y$_{CM}$ ~ -3.6 → x$_g$ = 1

- J/Ψ → µ$^+$µ$^-$ - PYTHIA
  pp at √s = 115 GeV
  1 month
  5% acceptance

MSTW gluon uncertainty

⇒ Precise measurements in the target-rapidity region allow to access large *x* gluon content of the target

⇒ Next: estimate the yield for η$_{c,b}$ and χ$_{c,b}$ (cleaner theoretically)

Conclusion

- LHC proton and lead beams continuous extraction with bent crystal offers many physics opportunities

- High boost and large luminosities provide access to large and very large parton x measurements for quarks and gluons: QCD laboratory at large x

- Fixed-target mode allows for target versatility: hydrogen, deuteron, nucleus (nuclear effect and QGP), polarized target (spin physics)

- AFTER designed as a multi-purpose experiment

http://after.in2p3.fr

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Looking for partners!

ECT* 'exploratory' workshop: "Physics at a fixed target experiment using the LHC beams"

- # February 4 - February 13, 2013

'This is an exploratory workshop which aims at studying in detail the opportunity and feasibility of fixed-target experiments using the LHC beam.'