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

Cynthia Hadjidakis

Annual meeting of the GDR PH-QCD
Orsay, December 7th 2012
Overview

• Beam extraction 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 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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Next: beam bending experiment @ LHC

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

W. Scandale et al., JINST 6 T10002 (2011)
Next: beam bending experiment @ LHC

- LHC Committee approved beam bending experiments using crystals at the LHC (UA9 Collaboration)
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- Tests at SPS in 2012 on proton and ion beams for a LHC setup
- Long Shutdown 1 (2013): bent crystals in LHC beams

Gonio

BLM

Micro RP

Absorber

W. Scandale et al., JINST 6 T10002 (2011)
Next: beam extraction experiment at the LHC

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

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 7σ to the beam to intercept and deflect the beam halo
  - No loss in the LHC beam
  - Bent crystal acts as a beam collimator

- Proton beam extraction
  - Single- or multi pass extraction efficiency of 50%
    - N_{beam loss LHC} ~ 10^9 p/s → N_{extracted beam} = 5 \times 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)

  P. Ballin et al, NIMB 267 (2009) 2952
Luminosities in pH and pA @ 115 GeV

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

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

- **Integrated luminosity**
  
  - 9 months running/year
  - 1 year $\sim 10^7$ s

<table>
<thead>
<tr>
<th>Target</th>
<th>$\rho$ (g cm$^{-3}$)</th>
<th>$A$</th>
<th>$\mathcal{L}$ (µb$^{-1}$ s$^{-1}$)</th>
<th>$\int \mathcal{L}$ (pb$^{-1}$ yr$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>solid H</td>
<td>0.088</td>
<td>1</td>
<td>26</td>
<td>260</td>
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<tr>
<td>liquid H</td>
<td>0.068</td>
<td>1</td>
<td>20</td>
<td>200</td>
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<tr>
<td>liquid D</td>
<td>0.16</td>
<td>2</td>
<td>24</td>
<td>240</td>
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<tr>
<td>Be</td>
<td>1.85</td>
<td>9</td>
<td>62</td>
<td>620</td>
</tr>
<tr>
<td>Cu</td>
<td>8.96</td>
<td>64</td>
<td>42</td>
<td>420</td>
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<tr>
<td>W</td>
<td>19.1</td>
<td>185</td>
<td>31</td>
<td>310</td>
</tr>
<tr>
<td>Pb</td>
<td>11.35</td>
<td>207</td>
<td>16</td>
<td>160</td>
</tr>
</tbody>
</table>

$\Rightarrow$ 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 20 fb$^{-1}$, i.e. the same
Luminosities in PbA @ 72 GeV

- **Intensity**: $N_{\text{beam}} = 2.10^5 \text{ Pb.s}^{-1}$
  - Beam: 592 bunches of $7 \times 10^7$ ions = $4.1 \times 10^{10}$ ions
  - Bunch: Each bunch passes IP at the rate $\sim 11 \text{ kHz}$
  - Instantaneous extraction: IP sees $592 \times 11000 \sim 6.5 \times 10^6$ bunches passing every second $\rightarrow$ extract $\sim 0.03$ ions in each bunch at each pass
  - Integrated extraction: Over a 10h run: extract $\sim 15\%$ of the ions stored in the beam

- **Instantaneous Luminosity**
  
  $$L = N_{\text{beam}} \times N_{\text{Target}} = N_{\text{beam}} \times (\rho \times e \times N_A)/A$$
  
  - $N_{\text{beam}} = 2 \times 10^5 \text{ Pb/s}$
  - $e$ (target thickness) = 1 cm

- **Integrated luminosity**
  - 1 months running/year
  - 1 year $\sim 10^6$ s

⇒ AFTER provides a good luminosity to study QGP related measurements
Polarizing the hydrogen target

- **Instantaneous Luminosity**
  
  \[ L = N_{\text{beam}} \times N_{\text{Target}} = N_{\text{beam}} \times (\rho \times e \times N_A)/A \]

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

  \( x_p \uparrow \) range corresponds to Drell-Yan measurements

- AFTER provides a **good luminosity** to study target spin related measurements

- Complementary \( x_p \) range with other spin physics experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>particles</th>
<th>energy (GeV)</th>
<th>( \sqrt{s} ) (GeV)</th>
<th>( x_p \uparrow )</th>
<th>( L ) (nb(^{-1})s(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>AFTER</td>
<td>( p+p \uparrow )</td>
<td>7000</td>
<td>115</td>
<td>0.01 ( \div ) 0.9</td>
<td>1</td>
</tr>
<tr>
<td>COMPASS</td>
<td>( \pi^+ + p \uparrow )</td>
<td>160</td>
<td>17.4</td>
<td>0.2 ( \div ) 0.3</td>
<td>2</td>
</tr>
<tr>
<td>COMPASS</td>
<td>( \pi^+ + p \uparrow )</td>
<td>160</td>
<td>17.4</td>
<td>~ 0.05</td>
<td>2</td>
</tr>
<tr>
<td>RHIC</td>
<td>( p \uparrow + p )</td>
<td>collider</td>
<td>500</td>
<td>0.05 ( \div ) 0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>J-PARC</td>
<td>( p \uparrow + p )</td>
<td>50</td>
<td>10</td>
<td>0.5 ( \div ) 0.9</td>
<td>1000</td>
</tr>
<tr>
<td>PANDA</td>
<td>( \bar{p} + p \uparrow )</td>
<td>15</td>
<td>5.5</td>
<td>0.2 ( \div ) 0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>PAX</td>
<td>( p \uparrow + \bar{p} )</td>
<td>collider</td>
<td>14</td>
<td>0.1 ( \div ) 0.9</td>
<td>0.002</td>
</tr>
<tr>
<td>NICA</td>
<td>( p \uparrow + p )</td>
<td>collider</td>
<td>20</td>
<td>0.1 ( \div ) 0.8</td>
<td>0.001</td>
</tr>
<tr>
<td>RHIC</td>
<td>( p \uparrow + p )</td>
<td>250</td>
<td>22</td>
<td>0.2 ( \div ) 0.5</td>
<td>2</td>
</tr>
<tr>
<td>Int.Target 1</td>
<td>( p \uparrow + p )</td>
<td>250</td>
<td>22</td>
<td>0.2 ( \div ) 0.5</td>
<td>60</td>
</tr>
</tbody>
</table>
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
    \[ y_{CM} = 0 \iff \theta \sim 16 \text{ mrad (0.9°)} \]
    \[ y_{CM} = 0.5 \iff \theta \sim 10 \text{ mrad} \]
  - With 2.76 TeV beam
    \[ y_{CM} = 0.5 \iff \theta \sim 16 \text{ mrad} \]
    \[ y_{CM} = 1 \iff \theta \sim 10 \text{ mrad} \]

For a 2 \( \rightarrow \) 1 process (e.g. \( gg \rightarrow QQ\text{bar} \))
\[ x_2 = M/\sqrt{s} \ e^{-y_{CM}} \]
\( y_{CM} \): QQ\text{bar} CMS rapidity
\( M \): QQ\text{bar} mass

- \( y_{CM} = 0 \rightarrow x_1 = x_2 \)
- **backward region:** \( y_{CM} < 0 \rightarrow x_1 < x_2 \)
- \( y_{lab}(J/\Psi) \sim 1.2 \rightarrow x_2 = 1 \)
- \( y_{lab}(Y) \sim 2.4 \rightarrow x_2 = 1 \)

Good condition to access large target \( x_2 \) and low \( x_F=x_1-x_2\rightarrow-1 \): target-rapidity region
Physics opportunities of A Fixed-Target ExpeRiment (AFTER) @LHC

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

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 $x$)
Gluon distribution at large $x$

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- **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

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 $x$

Intrinsic charm motivated by non-perturbative models of hadron structure

All different charm PDFs (DGLAP or intrinsic charm) in agreement with DIS data

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


![Graphs showing charm distribution for DGLAP, BHPS, and Sea-Like models.](image-url)
Boer-Mulders effect

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

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

Double-node structure of transverse-momentum distributions predicted for scalar and pseudoscalar quarkonia \(\rightarrow\) give access to the Boer-Mulders TMD pdf for gluons
Boer-Mulders effect

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- **Experimental probes @ AFTER**
  - scalar and pseudoscalar quarkonia: \(\chi_c^0, \chi_b^0, \eta_c, \eta_b\) (PID and modern calorimetry)
Sivers effect with a transversaly polarized target

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

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

scheme to describe Sivers effect
Sivers effect with a transversely polarized target

Sivers effect in a transversely polarized nucleon: correlation between the parton $k_T$ and the proton spin

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

- **Experimental probes @ AFTER**
  - Drell-Yan $\rightarrow$ quark Sivers effect
  - Quarkonia, Open Charm and Beauty (B and D mesons), isolated $\gamma$ and $\gamma$-jet $\rightarrow$ 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

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

$Q = 5 \text{ GeV}$

Fig. 29 The $\sin(2\phi - \phi_5)$ azimuthal asymmetry $A_{TU}^{\sin(2\phi - \phi_5)}$ depending on $x_F$ of target proton polarized $pp$ Drell–Yan process at $Q = 5 \text{ GeV}$. 

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

...
Quark Gluon Plasma

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

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

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

PHENIX Collaboration arXiv 1208:2251
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Cold Nuclear Matter (i.e not Hot from QGP) measured in pA

- **Experimental probes @ AFTER $\sqrt{s} = 72 \text{ 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

PHENIX Collaboration arXiv 1208:2251
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: χ_{c2}, χ_{b2}, η_c, η_b, 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

<table>
<thead>
<tr>
<th>Target</th>
<th>∫dτdL</th>
<th>B_{ττ} dN_{J/Ψ} / dy</th>
<th>B_{ττ} dN_{ττ} / dy</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cm solid H</td>
<td>2.6</td>
<td>5.2 10^7</td>
<td>1.0 10^5</td>
</tr>
<tr>
<td>10 cm liquid H</td>
<td>2</td>
<td>4.0 10^7</td>
<td>8.0 10^4</td>
</tr>
<tr>
<td>10 cm liquid D</td>
<td>2.4</td>
<td>9.6 10^7</td>
<td>1.9 10^5</td>
</tr>
<tr>
<td>1 cm Be</td>
<td>0.62</td>
<td>1.1 10^8</td>
<td>2.2 10^5</td>
</tr>
<tr>
<td>1 cm Cu</td>
<td>0.42</td>
<td>5.3 10^8</td>
<td>1.1 10^6</td>
</tr>
<tr>
<td>1 cm W</td>
<td>0.31</td>
<td>1.1 10^9</td>
<td>2.3 10^6</td>
</tr>
<tr>
<td>1 cm Pb</td>
<td>0.16</td>
<td>6.7 10^8</td>
<td>1.3 10^6</td>
</tr>
</tbody>
</table>

Luminosity per year in fb⁻¹
Earlier studies with ALICE as a fixed target experiment

**Proposition**
Using ALICE as a fixed target experiment


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**Geometrical Acceptance @ 115 GeV**
Simulation @ 115 GeV for $J/\psi \rightarrow \mu^+\mu^-$ with $\mu$ detected in the muon arm of ALICE (2.5 < $\eta$ < 4)
A geometrical Acceptance of 8% for $J/\psi$ (4 $\pi$) $\rightarrow \mu^+\mu^-$ (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

**Statistical relative uncertainty**

Large statistics allow to access very backward region

**Gluon uncertainty from MSTWPDF**

- only for the gluon content of the target
- assuming

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

**$J/\Psi$**

$$y_{CM} \sim 0 \quad \rightarrow \quad x_g = 0.03$$

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

$\Rightarrow$ Precise measurements in the target-rapidity region allow to access large $x$ gluon content of the target

$\Rightarrow$ Next: estimate the yield for $\eta_{b,c}$ and $\chi_{b,c}$ (cleaner theoretically)
Conclusion

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

• 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
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), C. Hadjidakis (IPN), J.P. Lansberg (IPN), C. Lorcé (IPN), A. Rakotozafindrabe (CEA), P. Rosier (IPN), I. Schienbein (LPSC), E. Scomparin (Torino), U.I. Uggerhøj (Aarhus)

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.’
A tentative design for AFTER

- **Tentative design** $1.3 < \eta < 5.3$
  - With 7 TeV beam: $-3.5 < y_{CM} < 0.5$
  - With 2.76 TeV beam: $-3 < y_{CM} < 1$
  - $\theta_{min} = 10$ mrad

- **Multi-purpose detector**
  - Vertex
  - Tracking (+ dipole magnet)
  - RICH
  - Calorimetry
  - Muons

- **High boost** → forward and as compact as possible detector

- **Technology**
  - Vertex, tracker: pixel detectors
  - Ultra-granular EMCal: Tungsten/Si (Calice - ILC)
  - Muons: Magnetize Fe (Minos)
  - ...
**Multiplicity**

A highly granular detector is needed

Charged particles per unit of rapidity: $(x \times 1.5 = \text{charged+neutral})$

- $p+p$ @ 115 GeV $\sim 2$
- $d+Au$ @ 200 GeV : max $\sim 11$
- $Au+Au$ @ 62.4 GeV : max $\sim 450$

<table>
<thead>
<tr>
<th>$R_{\text{min}}$ (cm)</th>
<th>$R_{\text{max}}$ (cm)</th>
<th>Surface (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td>1.5</td>
<td>300</td>
</tr>
<tr>
<td>Calo</td>
<td>10</td>
<td>4700</td>
</tr>
</tbody>
</table>

Vertex $\sim 450$ part.

- $1\% \sim \frac{450}{300 \times \left( \frac{1}{0.8 \times 0.8 \text{ mm}^2} \right)} \sim 14\%$
- $0.1\% \sim \frac{450}{300 \times \left( \frac{1}{0.25 \times 0.25 \text{ mm}^2} \right)} \sim 3.7\%$

Calo $\sim 700$ part.

- $\frac{700}{4700 \times \left( \frac{1}{0.5 \times 0.5 \text{ cm}^2} \right)} \sim 3.7\%$
Inclusive pp cross-sections

\[ \text{B} \text{ll } \frac{d\sigma}{dy}\big|_{y=0} @ 115 \text{ GeV} \]
\[ \text{J/}\psi = 20 \text{ nb} \]
\[ \Upsilon = 40 \text{ pb} \]

Inclusive pp cross-sections

\[ \text{B} \text{ll } \frac{d\sigma}{dy}\big|_{y=0} @ 72 \text{ GeV} \]
\[ \text{J/}\psi = 10 \text{ nb} \]
\[ \Upsilon = 15 \text{ pb} \]
Target schedule: LHC plan

- **ALICE, ATLAS, CMS, LHCb** upgrade LHC
- **LS1**: 2008-09
- **LS2**: 2013
- **LS3**: 2016

**Upgrade**
- ALICE, LHC
- ATLAS, CMS
- LHCb

**Major upgrades**
- ALICE
- LHC

**AFTER**
- LHeC (CERN)

**Timeline**
- 2008-09
- 2013
- 2016
- 2018
- 2022

Cynthia Hadjidakis  Orsay  December 7th 2012
J/Ψ in pp @ 115 GeV

\[ \text{Pythia: } p (7 \text{ TeV}) + p \rightarrow J/Ψ \]
\[ J/Ψ \rightarrow \mu^+ \mu^- \]

J/Ψ for \( 1.3 < y < 5.3 \)
\( \mu \rightarrow P_T \sim 1.7 \text{ GeV} \)
\( \mu \rightarrow P_L \sim 62 \text{ GeV} \)

\( 1.3 < y < 3.3 \) \( P_L(\text{max}) \sim 16 (50) \text{ GeV} \)
\( 3.3 < y < 4.3 \) \( P_L \sim 45 (150) \text{ GeV} \)
\( 4.3 < y < 5.3 \) \( P_L \sim 120 (300) \text{ GeV} \)

\( 1.8 < y_{\text{lab}} < 2.8 \)
\( P_L \sim 10 \text{ GeV} \)

\( 2.8 < y_{\text{lab}} < 4.8 \)
\( P_L \sim 20 \text{ GeV} \)
Drell-Yan continuum

\[ \mathcal{M} \times \mathcal{X}_\text{target} = \mathcal{X}_\text{beam} \]

Kinematical limit for Drell-Yan at 7 TeV on fixed target

- Backward region
- Forward region

\[ x_B \text{ kinematical limit} \]

\[ M \text{ (GeV)}^{10^2} \]

- \( \Upsilon \)
- \( J/\psi \)
Drell-Yan measurements in pp

Fig. 17 The $\sin(2\phi - \phi_5)$ azimuthal asymmetry $A_{TU}^{\sin(2\phi - \phi_5)}$ depending on $Q$ of target proton polarized $pp$ Drell–Yan process with both $\gamma^*$ or $Z$ taken into account and allowed rapidity integrated in the cut $[-4.8, -2]$. The same cut of rapidity is chosen in Figs. 18-22. as Figs. 18–40.

Fig. 29 The $\sin(2\phi - \phi_5)$ azimuthal asymmetry $A_{TU}^{\sin(2\phi - \phi_5)}$ depending on $x_F$ of target proton polarized $pp$ Drell–Yan process at $Q = 5$ GeV.

T. Liu and B.Q. Ma arXiv:1203.5579
Drell-Yan measurements in pD

Fig. 7 The $\cos 2\phi$ azimuthal asymmetry depending on $Q$ of unpolarized $pd$ Drell–Yan process with both $\gamma^*$ and $Z$ taken into account.

Fig. 8 The $\cos 2\phi$ azimuthal asymmetry depending on $x_F$ of unpolarized $pd$ Drell–Yan process at $Q = 2$ GeV.

Fig. 9 The $\cos 2\phi$ azimuthal asymmetry depending on $x_F$ of unpolarized $pd$ Drell–Yan process at $Q = 5$ GeV.

Fig. 10 The $\cos 2\phi$ azimuthal asymmetry depending on $q_T$ of unpolarized $pd$ process in $Z$ resonance region.
Quarkonium yields in PbA @ 72 GeV

PbA
⇒ Same statistics than RHIC @ 200 GeV and LHC and 2 orders of magnitude larger than RHIC @ 62 GeV
⇒ Detailed studies possible for quarkonium states (ψ’, χc, A dependence, ...)

<table>
<thead>
<tr>
<th>Target</th>
<th>∫ dtL</th>
<th>B_{ee} dN_{J/ψ}/dy</th>
<th>B_{ee} dN_{X}/dy</th>
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<td>10 cm solid H</td>
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<tr>
<td>10 cm liquid D</td>
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<td>1 cm Be</td>
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<td>1 cm Cu</td>
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<td>1 cm W</td>
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<tr>
<td>1 cm Pb</td>
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<td>1.1 × 10^4</td>
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<td>dAu RHIC (200 GeV)</td>
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<tr>
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<td>pPb LHC (8.8 TeV)</td>
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<td>PbPb LHC (5.5 TeV)</td>
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Luminosity per year in fb⁻¹