Physics opportunities at A Fixed-Target Experiment at the LHC (AFTER@LHC) and why not FCC?

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Heavy Flavor and Electromagnetic Probes in Heavy Ion Collisions

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Part I

Introduction
Generalities

- \( pp \) or \( pA \) collisions with a 7 TeV proton beam on a fixed target occur at a CM energy \( \sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV} \)
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    \( p_{z,CM} = 0, \ E_{CM}^{\gamma} = p_T \)
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  \begin{pmatrix}
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  \end{pmatrix}
  =
  \begin{pmatrix}
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  \gamma \beta & \gamma
  \end{pmatrix}
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  - $p_{z,Lab} \approx 60p_T$! [A 67 MeV $\gamma$ from a $\pi^0$ at rest in the CM can easily be detected.]
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  - Angle in the Lab. frame: \( \tan \theta = \frac{p_T}{p_{z,Lab}} = \frac{1}{\gamma \beta} \Rightarrow \theta \approx 1^\circ \).
    
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  - The entire forward CM hemisphere ($y_{CM} > 0$) within $0^\circ \leq \theta_{\text{Lab}} \leq 1^\circ$

    [$y_{CM} = 0 \Rightarrow y_{\text{Lab}} \approx 4.8$]
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  - **Good thing**: small forward detector \( \equiv \) large acceptance

  - **Bad thing**: high multiplicity \( \Rightarrow \) absorber \( \Rightarrow \) physics limitation
Backward physics?

- Let’s adopt a novel strategy and look at larger angles.
Backward physics?

Let’s adopt a **novel strategy** and look at **larger angles**

- Advantages:
  - reduced multiplicities at large(r) angles
  - **access to partons with momentum fraction** $x \to 1$ in the target
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**Diagram:**

- **Hadron center-of-mass system**
  - \( x_1 \approx x_2 \)

- **Target rest frame**
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### Diagram

**Hadron center-of-mass system**

$x_1 \simeq x_2$

$x_1 \ll x_2$

**Target rest frame**

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x_1 \approx x_2
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\[
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\]

**backward physics = large-$x_2$ physics**
First systematic access to the target-rapidity region 

\( (x_F \to -1) \)
First systematic access to the target-rapidity region $(x_F \to -1)$

**J/ψ suppression in pA collisions**

- $x_F$ systematically studied at fixed target experiments up to +1
First systematic access to the target-rapidity region

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First systematic access to the target-rapidity region ($x_F \to -1$)

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- PHENIX @ RHIC: $-0.1 < x_F < 0.1$ [could be wider with $\Upsilon$, but low stat.]
- CMS/ATLAS: $|x_F| < 5 \cdot 10^{-3}$; LHCb: $5 \cdot 10^{-3} < x_F < 4 \cdot 10^{-2}$
The target-rapidity region: the uncharted territory

First systematic access to the target-rapidity region
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$J/\psi$ suppression in $pA$ collisions

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- CMS/ATLAS: \(|x_F| < 5 \cdot 10^{-3}\); LHCb: \(5 \cdot 10^{-3} < x_F < 4 \cdot 10^{-2}\)
- If we measure \( \Upsilon(b \bar{b}) \) at \( y_{\text{cms}} \approx -2.5 \) \( \Rightarrow x_F \approx \frac{2m_{\Upsilon}}{\sqrt{s}} \sinh(y_{\text{cms}}) \approx -1 \)
The beam extraction

★ The LHC beam may be extracted using “Strong crystalline field” without any decrease in performance of the LHC!

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★ Illustration for collimation

A solid state primary collimator-scatterer

Bent-crystal as primary collimator
The beam extraction

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★ Tests will be performed on the LHC beam: LUA9 proposal approved by the LHCC
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★ Illustration for collimation

★ Tests will be performed on the LHC beam:

LUA9 proposal approved by the LHCC

★ 2 crystals and 2 goniometers already installed in the LHC beampipe
The beam extraction

- Inter-crystalline fields are huge

Ge (110), 450 GeV protons

2000 T!
The beam extraction

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Ge (110), 450 GeV protons

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

- Inter-crystalline fields are huge

![Graph showing deflection efficiency vs. deflection angle for Ge (110), 450 GeV protons.](image)

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

- Inter-crystalline fields are huge

- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:
Luminosities with proton beams

- Expected proton flux $\Phi_{beam} = 5 \times 10^8 \text{ p}^+\text{s}^{-1}$
Luminosities with proton beams

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- Instantaneous Luminosity:

$$\mathcal{L} = \Phi_{beam} \times N_{\text{target}} = N_{beam} \times (\rho \times \ell \times N_A) / A$$

[ $\ell$: target thickness (for instance 1 cm)]
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- Integrated luminosity: $\int dt L$ over $10^7$ s for $p^+$ and $10^6$ for Pb
  \[\text{[the so-called LHC years]}\]
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<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>
</tr>
</thead>
<tbody>
<tr>
<td>Sol. H$_2$</td>
<td>0.09</td>
<td>1</td>
<td>26</td>
<td>260</td>
</tr>
<tr>
<td>Liq. H$_2$</td>
<td>0.07</td>
<td>1</td>
<td>20</td>
<td>200</td>
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<tr>
<td>Liq. D$_2$</td>
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<td>Be</td>
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<td>160</td>
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</table>
1 meter-long liquid $H_2$ & $D_2$ targets can be used (see NA51, ...)

This gives: $L_{H_2/D_2} \approx 20 \text{ fb}^{-1}$

Recycling the LHC beam loss, one gets a luminosity comparable to the LHC itself!

PHENIX lumi in their decadal plan:
- Run14pp $12 \text{ pb}^{-1}$ @ $\sqrt{s_{NN}} = 200 \text{ GeV}$
- Run14 $dAu$ $0.15 \text{ pb}^{-1}$ @ $\sqrt{s_{NN}} = 200 \text{ GeV}$

AFTER vs PHENIX@RHIC: 3 orders of magnitude larger
Luminosities with proton beams II

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(Generated 2012-12-02 18:23 including fill 3360)
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- Run14pp 12 pb$^{-1}$ @ $\sqrt{s_{NN}} = 200$ GeV
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- **Instantaneous Luminosity:**
  \[
  \mathcal{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times N_A) / A
  \]
  \[
  \Phi_{beam} = 2 \times 10^5 \text{ Pb s}^{-1}, \quad \ell = 1 \text{ cm (target thickness)}
  \]

- **Integrated luminosity**
  \[
  \int dt \mathcal{L} = \mathcal{L} \times 10^6 \text{ s for Pb}
  \]

- **Expected luminosities with** \(2 \times 10^5\) Pb s\(^{-1}\) extracted (1cm-long target)

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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\(^{-1}\)
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)  
Luminosities

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- Revolution frequency: Each bunch passes the extraction point at a rate of $3 \times 10^5 \, \text{km.s}^{-1}/27 \, \text{km} \simeq 11 \, \text{kHz}$
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- Extracted “mini” bunches:
  - the crystal sees $2808 \times 11000 \ s^{-1} \approx 3.10^7 \ bunches \ s^{-1}$
  - one extracts $5.10^8 / 3.10^7 \approx 15p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%, no pile-up!
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  - $5 \times 10^8 p^+ \times 3600 \, \text{s h}^{-1} \times 10 \, \text{h} = 1.8 \times 10^{13} p^+ \, \text{fill}^{-1}$
  - This means $1.8 \times 10^{13} / 3.2 \times 10^{14} \simeq 5.6\%$ of the $p^+$ in the beam

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- similar figures for the Pb-beam extraction

J.P. Lansberg (IPNO, Paris-Sud U.)
A Fixed-Target ExpeRiment at the LHC
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Part II

AFTER: flagship measurements
Key studies: gluons in the proton

- **Gluon distribution** at mid, high and ultra-high $x_B$ in the proton

  Not easily accessible in DIS

  ⇒ very large uncertainties

  Accessible thanks gluon sensitive probes, quarkonia
  see a recent study by D. Diakonov et al., JHEP 1302 (2013) 069

  Isolated photon
  see the recent survey by D. d'Enterria, R. Rojo, Nucl.Phys. B860 (2012) 311

  Jets ($P_T \in [20, 40] \text{ GeV}$)

  Multiple probes needed to check factorisation

  Large-$x$ gluons: important for BSM searches at the LHC
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![Gluon distribution plot](image-url)
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![Gluon distribution plot](attachment:image.png)
Gluon and heavy-quark distributions

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**Large-$x$ gluons:** important for BSM searches at the LHC
Key studies: gluons in the neutron

Gluon PDF for the neutron unknown

Gluon (μ = 100 GeV)
Key studies: gluons in the neutron

Gluon PDF for the neutron unknown

- possible experimental probes
  - heavy quarkonia
  - isolated photons
  - jets

Pioneer measurement by E866 using \( \Upsilon \rightarrow Q^2 \approx 100 \text{ GeV}^2 \)

outcome: \( g_n(x) \approx g_p(x) \)

could be extended with after using \( J/\psi, \ldots, C = +1 \) onia, ...

wider range & lower \( Q^2 \)

target yearly lumi

\( \frac{dN_{J/\psi}}{dy} \) 2.1 m Liq. H

\( \frac{dN_{\Upsilon}}{dy} \) 20 fb

\( \times 10^8 \)

\( \times 10^5 \)

\( \frac{dN_{J/\psi}}{dy} \) 2.1 m Liq. D

\( \frac{dN_{\Upsilon}}{dy} \) 24 fb

\( \times 10^8 \)

\( \times 10^6 \)
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Key studies: gluons in the neutron

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<table>
<thead>
<tr>
<th>target</th>
<th>yearly lumi</th>
<th>$\mathcal{B} \frac{dN_{J/\psi}}{dy}$</th>
<th>$\mathcal{B} \frac{dN_{\Upsilon}}{dy}$</th>
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<td>1m Liq. H$_2$</td>
<td>20 fb$^{-1}$</td>
<td>$4.0 \times 10^8$</td>
<td>$9.0 \times 10^5$</td>
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<td>1m Liq. D$_2$</td>
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<td>$9.6 \times 10^8$</td>
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- Pin down intrinsic charm, ... at last

3 sets from CTEQ6c (Pumplin et al.)
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- **Heavy-quark** distributions (at high $x_B$)
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  - **Total open charm and beauty** cross section
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Sealike

BHPS

DGLAP

requires several complementary measurements

good coverage in the target-rapidity region

high luminosity to reach large $x_B$

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![Graph showing gluon and heavy-quark distributions](image)

- **Pin** down intrinsic charm...
Key studies: gluon contribution to the proton spin

- **Gluon Sivers effect**: correlation between the gluon transverse momentum & the proton spin
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  - J.W. Qiu, et al., PRL 107 (2011) 062001
- The target-rapidity region corresponds to high $x^\uparrow$
  - Where the $k_T$-spin correlation is the largest
Key studies: gluon contribution to the proton spin

- **Gluon Sivers effect**: correlation between the gluon transverse momentum & the proton spin
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- **B & D meson production**


- the target-rapidity region corresponds to high \(x^\uparrow\)

where the \(k_T\)-spin correlation is the largest

- In general, one can carry out an extensive spin-physics program
Access to “Boer-Mulders”-like functions for gluons
Access to “Boer-Mulders”-like functions for gluons

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

Daniël Boer*

Theory Group, KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

Cristian Pisano†

Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy
Access to “Boer-Mulders”-like functions for gluons

- Low $P_T$ $C$-even quarkonium production is a good probe of the gluon “B-M” functions
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- Affect the **low** $P_T$ spectra:
  \[
  \frac{1}{\sigma} \frac{d\sigma(\eta_Q)}{dq_T^2} \propto 1 - R(q_T^2) \quad \& \quad \frac{1}{\sigma} \frac{d\sigma(\chi_0,Q)}{dq_T^2} \propto 1 + R(q_T^2)
  \]
  \[
  (R \text{ involves } f_1^g(x,k_T,\mu) \text{ and } h_{1}^{\perp g}(x,k_T,\mu))
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Access to “Boer-Mulders”-like functions for gluons II

Wilco J. den Dunnen, Jean-Philippe Lansberg, Cristian Pisano, and Marc Schlegel

1 Institute for Theoretical Physics, Universität Tübingen, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
2 IPNO, Université Paris-Sud, CNRS/IN2P3, F-91406, Orsay, France
3 Nikhef and Department of Physics and Astronomy, VU University Amsterdam, De Boelelaan 1081, NL-1081 HV Amsterdam, The Netherlands

PRL 112, 212001 (2014)

Gluon B-M can also be accessed via back-to-back $\psi$ + $\gamma$ associated production at the LHC. Also true at AFTER!

Smaller yield (14 TeV $\rightarrow$ 115 GeV) compensated by an access to lower $P_T$.

$0.01 < Q < 10$ GeV, $|Y| < 0.5$; $|\cos \theta_{CS}| < 0.45$

$d\sigma/dQ/dY/d\cos\theta_{CS} \times Br(Onium \rightarrow \mu \mu)$ (fb/GeV)

$Q_{J/\psi + \gamma}$ GeV

Direct back-to-back $J/\psi + \gamma$ at $\sqrt{s}=115$ GeV

$R = m_{\text{onium}}$, $T = \frac{m_{\text{onium}}}{2}$

$X_{\text{CS}} > 0.02$ GeV

$X_{\text{CS}} > 0.002$ GeV

$-1.5 < Y < -0.5$; $|\cos \theta_{CS}| < 0.45$

$-2.5 < Y < -1.5$; $|\cos \theta_{CS}| < 0.45$

$gg$: Color Singlet

$gg$: Color Octet

$qq$: Color Singlet

$qq$: Color Octet

At $Y \approx -2$, $x_2 \approx \frac{10}{115} \times e^2 \approx 0.65$. Yet, $g-g > q-\bar{q}$!
Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC

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SSA in heavy-flavour studies with AFTER@LHC

To give a direct access to the gluon Sivers effect, pure color-singlet final states are preferred (no color entanglement) $\eta_c$ production is an option $\left[ d\sigma\left(\sqrt{s} = 115\text{GeV}\right)\right]_{dy|y = 0} \gtrsim 1\text{nb}$, although difficult at low $P_T$ see A. Schaefer, J. Zhou, PRD (2013) for a study of SSA

First $\eta_c$ production production study at LHC ever, released this month LHCb, arXiv:1409.3612 [hep-ex]

As just discussed for the unpolarised case, $\psi^+\gamma$ may be more tractable $\psi^+\gamma$ pair, i.e. $\psi^+\ell\ell$, is another option, although with a small rate
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- $\psi + \text{DY pair, i.e. } \psi + \ell\ell$, is another option, although with a small rate.
AFTER@LHC: A dilepton observatory?

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

![Graph showing regions probed by dilepton production as a function of $M_{\ell\ell}$ and $x$.]
AFTER@LHC: A dilepton observatory?

- Region in $x$ probed by dilepton production as function of $M_{\ell\ell}$
  - Above $c\bar{c}$: $x \in [10^{-3}, 1]$
  - Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$

Note: $x_{\text{target}} \equiv x_{\text{2}} > x_{\text{projectile}} \equiv x_{\text{1}}$

"backward" region

- sea-quark asymetries via $p$ and $d$ studies
  - at large(est) $x$: backward ("easy")
  - at small(est) $x$: forward (need to stop the (extracted) beam)

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

Interesting to check the negligible $\cos^2 \phi$ dependence in $pd$ compared to $\pi$ induced DY

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**Note:** $x_{target} (\equiv x_2) > x_{projectile} (\equiv x_1)$

“backward” region

$Z$ boson

$\Upsilon$ « family »

$J/\psi$ « family »

$\phi$

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AFTER@LHC: A dilepton observatory?

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SSA in Drell-Yan studies with AFTER@LHC

Relevant parameters for the future proposed polarized DY experiments.


<table>
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<tr>
<th>Experiment</th>
<th>particles</th>
<th>energy (GeV)</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$x_p^\uparrow$</th>
<th>$\mathcal{L}$ (nb$^{-1}$s$^{-1}$)</th>
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<tr>
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<td>115</td>
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<tr>
<td>COMPASS (low mass)</td>
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<td>17.4</td>
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<td>22</td>
<td>0.2 $\div$ 0.5</td>
<td>2</td>
</tr>
<tr>
<td>RHIC Int. Target 2</td>
<td>$p^\uparrow + p$</td>
<td>250</td>
<td>22</td>
<td>0.2 $\div$ 0.5</td>
<td>60</td>
</tr>
<tr>
<td>P1027</td>
<td>$p^\uparrow + p$</td>
<td>120</td>
<td>15</td>
<td>0.35 $\div$ 0.85</td>
<td>400-1000</td>
</tr>
<tr>
<td>P1039</td>
<td>$p + p^\uparrow$</td>
<td>120</td>
<td>15</td>
<td>0.1 $\div$ 0.3</td>
<td>400-1000</td>
</tr>
</tbody>
</table>

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 parameters for the future proposed polarized DY experiments.


<table>
<thead>
<tr>
<th>Experiment</th>
<th>p↑ + p</th>
<th>√s (GeV)</th>
<th>x↑</th>
<th>L</th>
<th>Λ (nb⁻¹ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFTER</td>
<td>p↑ + p</td>
<td>7000</td>
<td>115</td>
<td>0</td>
<td>0.10÷0.9</td>
</tr>
<tr>
<td>COMPASS</td>
<td>π± + p</td>
<td>160</td>
<td>17.4</td>
<td>0</td>
<td>∼0.05</td>
</tr>
<tr>
<td>COMPASS (low mass)</td>
<td>π± + p</td>
<td>160</td>
<td>17.4</td>
<td>0</td>
<td>∼0.05</td>
</tr>
<tr>
<td>RHIC</td>
<td>p↑ + p collider</td>
<td>500</td>
<td>0.05</td>
<td>0.1</td>
<td>0.05÷0.1</td>
</tr>
<tr>
<td>J–PARC</td>
<td>p↑ + p</td>
<td>50</td>
<td>10</td>
<td>0</td>
<td>0.5÷0.9</td>
</tr>
<tr>
<td>NICA</td>
<td>p↑ + p collider</td>
<td>20</td>
<td>0.1</td>
<td>0.8</td>
<td>0.001</td>
</tr>
<tr>
<td>RHIC Int. Target 1</td>
<td>p↑ + p</td>
<td>250</td>
<td>22</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>RHIC Int. Target 2</td>
<td>p↑ + p</td>
<td>250</td>
<td>22</td>
<td>0.2</td>
<td>60</td>
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<td>P1027</td>
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</tr>
</tbody>
</table>

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

ℓ⁺ ℓ⁻ angular distribution: separation Sivers vs. Boer-Mulders effects

M. Anselmino, ECT*, Feb. 2013 (Courtesy U. d’Alessio)
pA studies: large-x gluon content of the nucleus

Gluons in nuclei
**pA studies: large-\( x \) gluon content of the nucleus**

- Large-\( x \) gluon nPDF: unknown
- Gluon EMC effect: unknown

![Graph showing EMC gluon comparison](image)
Gluons in nuclei

$pA$ studies: large-$x$ gluon content of the nucleus

- Large-$x$ gluon nPDF: unknown
- Gluon EMC effect: unknown
- Hint from $\gamma$ data at RHIC

![Graph showing EMC gluon and EPS09 LO fit range]
**pA studies: large-\(x\) gluon content of the nucleus**

- **Large-\(x\) gluon nPDF: unknown**
- **Gluon EMC effect: unknown**
- **Hint from \(\Upsilon\) data at RHIC**
- **Strongly limited in terms of statistics after 10 years of RHIC** (now 3 points from STAR):
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  - **DIS contribution expected for low \(x\) mainly projected contribution of LHeC:**
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- Hint from $\Upsilon$ data at RHIC
- Strongly limited in terms of statistics after 10 years of RHIC (now 3 points from STAR):
  - DIS contribution expected for low $x$ mainly projected contribution of LHeC:
  - AFTER allows for extensive studies of gluon sensitive probes in pA
- Unique potential for gluons at $x > 0.1$
Physics with the lead-ion beam

- Design LHC lead-beam energy: **2.76 TeV** per nucleon
Physics with the lead-ion beam

- Design LHC lead-beam energy: 2.76 TeV per nucleon
- In the fixed target mode, PbA collisions at $\sqrt{s_{NN}} \approx 72$ GeV
Physics with the lead-ion beam

- Design LHC lead-beam energy: 2.76 TeV per nucleon
- In the fixed target mode, PbA collisions at $\sqrt{s_{NN}} \simeq 72$ GeV
- Half way between BNL-RHIC (AuAu, CuCu @ 200 GeV) and CERN-SPS (PbPb @ 17.2 GeV)
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- Example of motivations:

![Graph of measured to expected J/ψ suppression](image)

Fig. 7. Measured J/ψ production yields, normalised to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. The data is shown as a function of the energy density reached in the central collision.
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![Graph showing evidence for deconfinement of quarks and gluons from the J/ψ suppression pattern measured in Pb-Pb collisions at the CERN-SPS NA50 Collaboration.](image)
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- Example of motivations: quarkonium sequential melting

![Graph showing measured J/ψ production yields normalized to the yields expected assuming that the only source of suppression is the ordinary absorption by the nuclear medium. The data is shown as a function of the energy density reached in the several collision systems.](image)
Physics with the lead-ion beam

- Design LHC lead-beam energy: 2.76 TeV per nucleon
- In the fixed target mode, PbA collisions at $\sqrt{s_{NN}} \simeq 72$ GeV
- Half way between BNL-RHIC (AuAu, CuCu @ 200 GeV) and CERN-SPS (PbPb @ 17.2 GeV)
- Example of motivations: quarkonium sequential melting
- Enough stat to perform the same study as CMS at low energy
Precision heavy-flavour studies in Heavy-Ion Collisions

- Very precise \textit{pp and pA baselines} (yields, $A$ & $y$ dependences)
Precision heavy-flavour studies in Heavy-Ion Collisions

- Very precise $pp$ and $pA$ baselines (yields, $A$ & $y$ dependences)
- Modern technologies to look for quarkonium excited states
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HERA-B PRD 79 (2009) 012001, and ref. therein
Precision heavy-flavour studies in Heavy-Ion Collisions

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- Very precise \(pp\) and \(pA\) baselines (yields, \(A\) & \(y\) dependences)
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- Energy between SPS and RHIC: QGP should be formed w/o \(c\bar{c}\) recombination
- Open heavy-flavour measurement down to \(P_T = 0\) thanks to the boost.

![Graph showing \(R_{cc}\) vs. \(\sqrt{s}\) (GeV)](HERA-B PRD 79 (2009) 012001, and ref. therein)
Physics with lead-ion beam

Precision heavy-flavour studies in Heavy-Ion Collisions

- Very precise $pp$ and $pA$ baselines (yields, $A$ & $y$ dependences)
- Modern technologies to look for quarkonium excited states
- Energy between SPS and RHIC: QGP should be formed w/o $c\bar{c}$ recombination
- Open heavy-flavour measurement down to $P_T = 0$ thanks to the boost.
- Real hope of being able to look at the quarkonium sequential suppression

HERA-B PRD 79 (2009) 012001, and ref. therein
J.P. Lansberg (IPNO, Paris-Sud U.)

A Fixed-Target Experiment at the LHC

Overall

Fixed Target @ LHC

log (x⁻¹)

Non perturbative regime

x > 1 \rightarrow x \rightarrow 1

EmC effect

Nuclear fermi motion

log (Q^2)

Dilute system

BKF

DGLAP

BK-JIMWLK

saturation

Q^2 = Q^2_s(x)

log (x-1)

log (Q^2)
Non perturbative regime

\[ Q^2 = Q^2_s(x) \]

\[ \log(x-1) \]

\[ \log(Q^2) \]

Fixed Target @ LHC

Dilute system

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DGLAP

BFKL

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saturation

J.P. Lansberg (IPNO, Paris-Sud U.)

A Fixed-Target Experiment at the LHC

October 2, 2014
Fixed Target @ LHC

- Non-perturbative regime
- Drell-Yan
- EMC effect
- Nuclear fermi motion

- Fixed Target @ LHC
- $x > 1 \rightarrow x \\to 1$
- $\log (x^{-1})$
- $\log (Q^2)$
Fixing Target @ LHC

- DGLAP
- BFKL
- Saturation
- Dilute system

Non-perturbative regime

1.\( \log (x^{-1}) \)

- Quarkonia
- High-\( p_T \) jet
- W/Z

\( Q^2 = Q^2_s(x) \)

J.P. Lansberg (IPNO, Paris-Sud U.)

A Fixed-Target ExpeRiment at the LHC

October 2, 2014

Page 25 of 40
Physics opportunities of a fixed-target experiment using LHC beams

S.J. Brodsky\textsuperscript{a}, F. Fleur	extsuperscript{e}, C. Hadjidakis\textsuperscript{c}, J.P. Lansberg\textsuperscript{c,*}

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Part III

First simulations
First simulation: is the boost an issue?

LHCb has successfully carried out $p$+Pb and Pb+p analyses at 5 TeV. We have compared the number-of-track distribution as function of $\eta$ measured in the collider mode by LHCb ($\sqrt{s} = 5$ TeV) vs. that expected in fixed target mode ($\sqrt{s} = 115$ TeV) using a LHCb-like detector (simulation with HIJING).

Despite the boost, the number of tracks in the LHCb acceptance ($\eta$ forward) is lower in the fixed mode than in the collider mode.

Very encouraging indication that the boost is not an issue, but really an asset.
First simulation: is the boost an issue?

- LHCb has successfully carried out \( p\text{Pb} \) and \( \text{Pb}p \) analyses at 5 TeV.
First simulation: is the boost an issue?

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![Graph showing number-of-track distribution](image)

- Despite the boost, the number of tracks in the LHCb acceptance [forward \( \eta \)] 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 $\pi$ and $K$ decay before the calorimeters (12m), they are rejected by the tracking
Else a misidentification probability is applied

Performance of the muon identification at LHCb, F. Achilli et al, arXiv:1306.0249
\( J/\Psi \rightarrow \mu^+\mu^- \) 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
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
Accessing the large $x$ glue with quarkonia:

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

Statistical relative uncertainty
Large statistics allow to access very backward region

Gluon uncertainty from MSTWPDF
- only for the gluon content of the target
- assuming
  \[ x_g = M_{J/\Psi} / \sqrt{s} \, e^{-y_{CM}} \]

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

⇒ Backward measurements allow to access large $x$ gluon pdf

Y: larger $x_g$ for same $y_{CM}$
\[ y_{CM} \sim 0 \rightarrow x_g = 0.08 \]
\[ y_{CM} \sim -2.4 \rightarrow x_g = 1 \]

Assuming that we understand the quarkonium-production mechanisms
Part IV

Special Issue in Advances in High-Energy Physics & Workshop at CERN
Fixed-target experiments (FTE) have brought essential contributions to particle and nuclear physics. They have led to particle discoveries, e.g., and evidence for the novel dynamics of quarks and gluons in heavy-ion collisions. In accessing high $x_t$ 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 $x_t$, 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, $D$, heavy flavours, jets, and $\gamma$ in $pA$ collisions can be studied with statistics previously unheard of and in the backward region, $x_t < 0$, which is uncharted. High precision QCD measurements can also obviously be carried out in $pp$ and $pd$ collisions with $^3_2H_2$ and $^2_2D_2$ 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 $\gamma$ 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 $x$
- TMDs and single-spin asymmetries
- Heavy-flavour studies in $pA$ and $AA$ collisions at FTEs
- $W$, $Z$, and $H^0$ production near threshold
- Target polarisation
- Secondary beams
- Simulation tools for high-energy physics
- Beam collimation and extraction with bent crystals
- Machine feasibility and radiological aspects
- Connection between UHECR studies and FTEs

---

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**Manuscript Due**
Friday, 20 March 2015

**First Round of Reviews**
Friday, 12 June 2015

**Publication Date**
Friday, 7 August 2015

---

Impact Factor: 2.7 (like Nucl. Phys. A, JPhysG), Open Access
Fixed-target experiments (FTE) have brought essential contributions to nuclear physics. They have led to particle discoveries (Ω, J/ψ, γ...) and for the novel dynamics of quarks and gluons in heavy-ion collisions. In high $x_t$ and in offering options for (un-)polarised proton and nuclear target, they have also led to the observation of surprising QCD phenomena. They offer advantages compared to collider experiments: access to high $x_t$, high luminosity target versatility, and polarisation.

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Workshop at CERN on November 2014

- 5 days, from Monday Nov. 17 until Friday Nov. 21, 2014
Workshop at CERN on November 2014

- 5 days, from Monday Nov. 17 until Friday Nov. 21, 2014
- Half day introductory session on Monday morning

- Preparation of the Expression of Interest to be submitted to the LHCC (aim: first semester of 2015)
- Special issue: Connexions & synergies with other projects at LHC or not (like E906,...)

Website: http://indico.cern.ch/e/AFTER-Week-1114
5 days, from Monday Nov. 17 until Friday Nov. 21, 2014
Half day introductory session on Monday morning
7 half-day sessions for 2 working groups of 10-20 people
   ((a) Physics & (b) Detector-Extraction)

Topics to be discussed
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  (aim: first semester of 2015)
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Part V

Conclusion and outlooks
Both $p$ and $Pb$ LHC beams can be extracted without disturbing the other experiments.
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- LHC long shutdown (LS2 ? in 2018) needed to install the extraction system.
- Very good complementarity with electron-ion programs (low $x$ vs. large $x$).
Outlooks

- First physics paper *Physics Reports 522 (2013) 239*
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- A 10-day exploratory workshop at ECT* Trento, February 4-13, 2013 slides at [http://indico.in2p3.fr/event/AFTER@ECTstar](http://indico.in2p3.fr/event/AFTER@ECTstar)

We are looking for more partners to:
- do first simulations (we are starting fast simulations)
- think about possible designs
- think about the optimal detector technologies
- enlarge the physics case (cosmic rays, flavour physics, ...)

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J.P. Lansberg (IPNO, Paris-Sud U.)

A Fixed-Target ExpeRiment at the LHC

October 2, 2014
Outlook

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  - think about the optimal detector technologies
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    - (cosmic rays, flavour physics, ...)
Example: \( E_P = 50 \text{ TeV} \rightarrow \sqrt{s} = \sqrt{2m_N E_P} \simeq 300 \text{ GeV} \)

One example: extensive studies of \( W \) and \( Z \) near threshold

<table>
<thead>
<tr>
<th>Beam Energy (TeV)</th>
<th>SppC-1</th>
<th>SppC-2</th>
<th>HE LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>45</td>
<td>16.5</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>193.7</td>
<td>290.6</td>
<td>175.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>6000</td>
<td>1404 (50 ns spacing)</td>
<td>10600/53000 (25 and 5 ns spacing)</td>
<td></td>
</tr>
<tr>
<td>( N_p/\text{bunch (10}^{11} )</td>
<td>1.7\cdot 10^{-3}</td>
<td>0.98\cdot 10^{-3}</td>
<td>1.3</td>
<td>1/0.2</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Proton flux</th>
<th>SppC-1</th>
<th>SppC-2</th>
<th>HE LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ } \mu b^{-1} s^{-1} )</td>
<td>7.1 \cdot 10^5</td>
<td>8.1 \cdot 10^5</td>
<td>2.5 \cdot 10^8</td>
<td>1.5 \cdot 10^9</td>
</tr>
<tr>
<td>( \int \mathcal{L}(pb^{-1} yr^{-1}) )</td>
<td>0.028/0.088/0.044</td>
<td>0.032/0.10/0.05</td>
<td>10/31/15</td>
<td>30/93/45</td>
</tr>
</tbody>
</table>

The proton flux is calculated by assuming that 5% of the beam is used within a 10 hour period. The luminosities are calculated for the case of targets that are 1 cm thick. The three values displayed represent luminosities for three different targets: liquid Helium, Beryllium and Tungsten.
Further readings

**Hadronic production of \( \Xi_{cc} \) at a fixed-target experiment at the LHC**

**Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams.**

**Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)**

**Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER**

**Ultra-relativistic heavy-ion physics with AFTER@LHC**

**Spin physics at A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)**

**Physics Opportunities of a Fixed-Target Experiment using the LHC Beams**
Part VI

Backup slides
The beam extraction: news

Goal: assess the possibility to use bent crystals as primary collimators in hadronic accelerators and colliders

Prototype crystal collimation system at SPS:
- Local beam loss reduction (5÷20x reduction for proton beam)
- Beam loss map shows average loss reduction in the entire SPS ring
- Halo extraction efficiency: 70÷80% for protons (50÷70% for Pb)
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UA9 installation in the SPS

LUA9 future installation in LHC

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*S. Montesano, Physics at AFTER using LHC beams, ECT* Trento, Feb. 2013*
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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
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 $5 \times 10^{12}$ protons every 14.4 s, one year irradiation, $2.4 \times 10^{20}$ protons/cm$^2$ in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - $10 \times 50 \times 0.9$ mm$^3$ silicon crystal, $0.8 \times 0.3$ 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, $1.1 \times 10^{11}$ protons per bunch ($3 \times 10^{13}$ 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
AFTER, among other things, a quarkonium observatory in *pp*

Interpolating the world data set:

<table>
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<tr>
<th>Target</th>
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Need for a quarkonium observatory

- Many **hopes** were put in **quarkonium studies** to extract **gluon PDF**

- **Production puzzle** → quarkonium not used anymore in global fits

With systematic studies, one would restore its status as gluon probe

J.P. Lansberg (IPNO, Paris-Sud U.)
Need for a quarkonium observatory

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- but also pp collisions in gg-fusion process
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- and the good detectability of a dimuon pair
Backup slides

Need for a quarkonium observatory

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**Structure-function analysis and $\psi$, jet, $W$, and $Z$ production:**
* Determining the gluon distribution

A. D. Martin
*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 $\mu N$ and $\nu N$ 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 $xG(x) \approx 1/\sqrt{x}$ at small $x$. $J/\psi$ 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 $\sigma_W$ and $\sigma_Z$ 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.
Need for a quarkonium observatory

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Production puzzle $\rightarrow$ quarkonium not used anymore in global fits
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Production puzzle $\rightarrow$ quarkonium not used anymore in global fits

With systematic studies, one would restore its status as gluon probe.
AFTER: also a quarkonium observatory in $pA$

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

- The **target versatility** of a fixed-target experiment is undisputable.

  - A wide rapidity coverage is needed for:
    - Precise analysis of gluon nuclear PDF: $y \leftrightarrow x^2$
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  - Strong need for cross checks from various measurements
  - The backward kinematics is very useful for large-x target studies

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Is there an EMC effect for gluon? (Reminder: EMC region $0.3 < x < 0.7$)

One should be careful with factorization breaking effects:

This calls for multiple measurements to (in)validate factorization.
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J.P. Lansberg (IPNO, Paris-Sud U.)

A Fixed-Target Experiment at the LHC

October 2, 2014  47 / 40
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AFTER: also an heavy-flavour observatory in PbA

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

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- Yields similar to those of RHIC at 200 GeV, 100 times those of RHIC at 62 GeV
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- Yields **similar** to those of RHIC at 200 GeV,
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AFTER: also an heavy-flavour observatory in \( \text{PbA} \)

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The same picture also holds for open heavy flavour
What for?

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

– $J/\psi$ data in $pA$ collisions

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

Our idea is not completely new

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 \( B^0 \rightarrow J/\psi + K^0_s \), \( B^0 \rightarrow \pi^+ \pi^- \). 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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1. Introduction

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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- After a year, one simply moves the crystal by less than one mm ...
Further key studies?

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*(Multiply) heavy baryons:*

- $\Lambda_b \rightarrow \Lambda J/\psi$
- $d\sigma(b)/dy|_{y=0} \gtrsim 100$ nb

$N(b)/\text{year} \simeq 2 \times 10^6 \times 20 = 4 \times 10^9$

$B(\Lambda_b \rightarrow \Lambda J/\psi \Lambda) = 5.8 \pm 0.8 \times 10^{-5}$

$(B(J/\psi \rightarrow \mu\mu) = 6\%)$

$15,000 \Lambda_b \rightarrow J/\psi \Lambda \rightarrow \mu^+ \mu^- \Lambda$ events: enough to perform a polarisation measurement (see e.g. LHCb arXiv:1302.5578 [hep-ex])

$\Xi_{cc}, \Omega^{++}(ccc)$ cross sections in the central region are being calculated with the MC generator GENXICC


They should also be calculated for $xF_{-1}$ where IQ could dominate.
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Isolated-$\gamma$ in $p(7$ TeV$)$-$p$(rest): $\sqrt{s} \sim 115$ GeV

- p-p photon kinematics at fixed-target LHC (central rapidities):
  To access $x > 0.3$ one needs isolated-$\gamma$ at: $p_T = x_T \sqrt{s}/2 > 20$ GeV/c

- JETPHOX NLO
  pQCD calculations:
  
  p-p at $\sqrt{s}=115$ GeV  
  $|y|<0.5$, $p_T > 20$ GeV/c  
  Isolation: $R = 0.4$, $E_T^{\text{had}} < 5$ GeV  
  
  $\mathcal{L}$ (10 cm $H_2$-target) $\sim 2 \times 10^3$ pb$^{-1}$/year

PDF: CT10 52 eigenval. (90% CL)  
Scales: $\mu_r = p_T$  
FF = BFG-II  
$\times$-section uncertainties(*) of $\pm 150\%$  

(*) (68%CL)/(90% CL) $\sim 1.65$