# Studying the nucleon structure, quarkonium production and spin effects with AFTER@LHC: Connections with COMPASS

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COMPASS beyond 2020 Workshop
March 21-22, 2016, CERN

AFTER@LHC Study group: http://after.in2p3.fr/after/index.php/Current_author_list

# Part I

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

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

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

Part II

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

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- Let us simply avoid the forward region ! How ?

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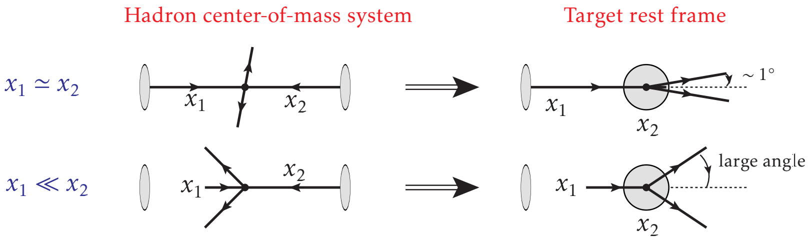

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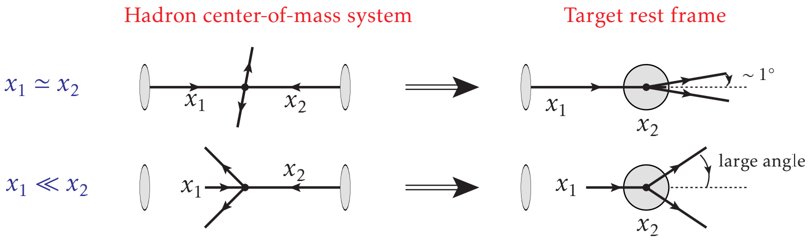


backward physics = large-$x_2$ physics

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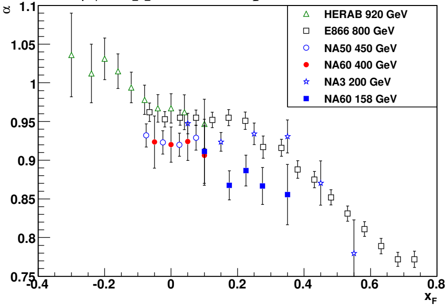


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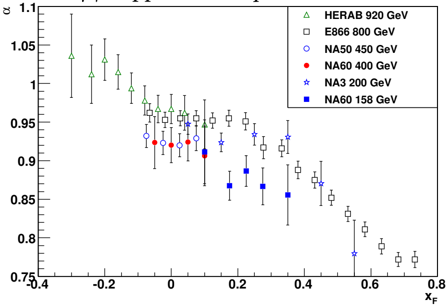


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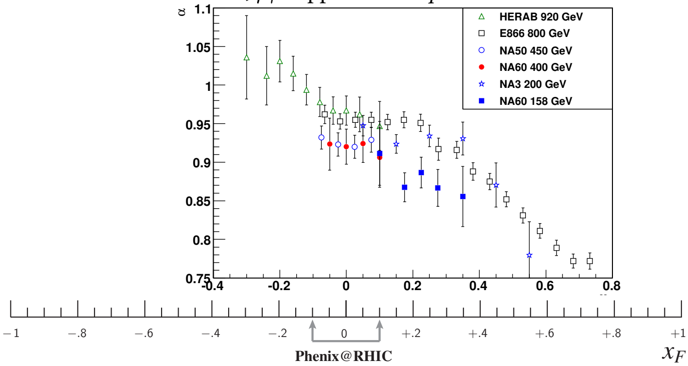


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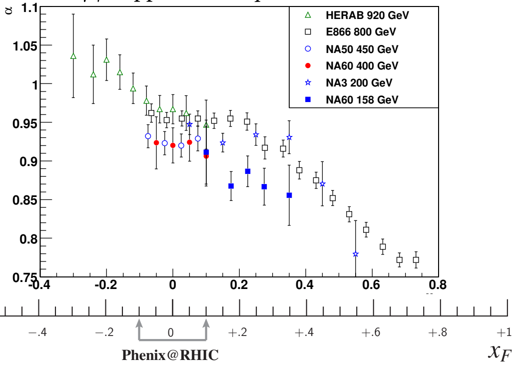


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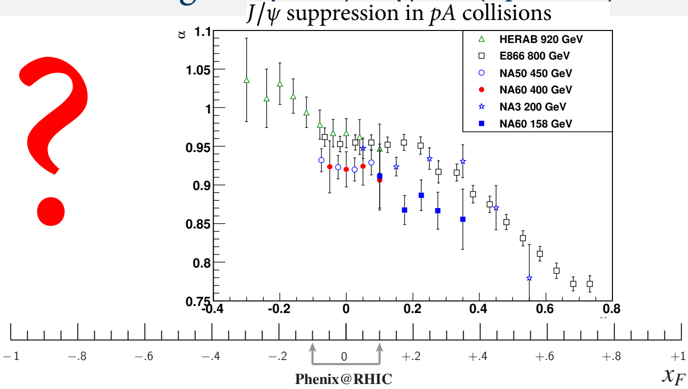


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- If we measure $\Upsilon(b\bar{b})$ at $y_{cms} \simeq -2.5 \Rightarrow x_F \simeq \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{cms}) \simeq -1$

# Part III

## Colliding the LHC beams on fixed targets: 2 options

# The extracted-beam option

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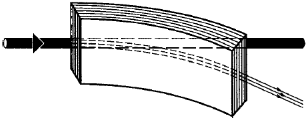

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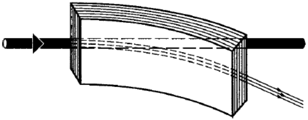

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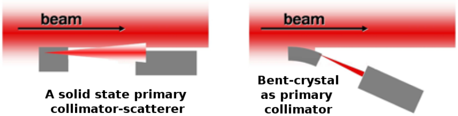

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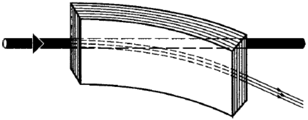

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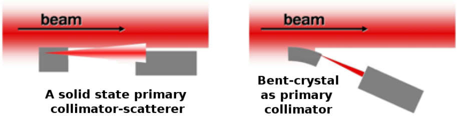


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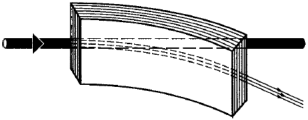

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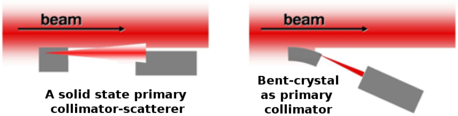


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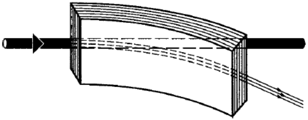

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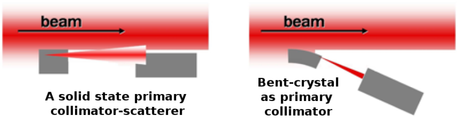


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| Target | ρ (g.cm⁻³) | A | $\mathcal{L}$ (μb⁻¹.s⁻¹) | $\int \mathcal{L}$ (fb⁻¹.yr⁻¹) |
|---|---|---|---|---|
| **1m Liq. $H_2$** | 0.07 | 1 | **2000** | **20** |
| **1m Liq. $D_2$** | 0.16 | 2 | **2400** | **24** |
| **1cm Be** | 1.85 | 9 | **62** | **.62** |
| **1cm Cu** | 8.96 | 64 | **42** | **.42** |
| **1cm W** | 19.1 | 185 | **31** | **.31** |
| **1cm Pb** | 11.35 | 207 | **16** | **.16** |

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

[ $\ell$: target thickness (for instance 1cm)]

- Integrated luminosity: $\int dt \mathcal{L}$ over $10^7$ s for $p^+$ and $10^6$ for Pb

[the so-called LHC years]

| Target | ρ (g.cm⁻³) | A | $\mathcal{L}$ (μb⁻¹.s⁻¹) | $\int \mathcal{L}$ (fb⁻¹.yr⁻¹) |
|---|---|---|---|---|
| **1m Liq. $H_2$** | 0.07 | 1 | **2000** | **20** |
| **1m Liq. $D_2$** | 0.16 | 2 | **2400** | **24** |
| **1cm Be** | 1.85 | 9 | **62** | **.62** |
| **1cm Cu** | 8.96 | 64 | **42** | **.42** |
| **1cm W** | 19.1 | 185 | **31** | **.31** |
| **1cm Pb** | 11.35 | 207 | **16** | **.16** |

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

3 orders of magnitude larger than RHIC (200 GeV)

# SMOG@LHCb: the first step towards an internal (polarised) target ?

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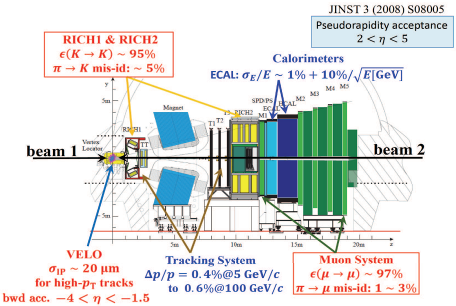
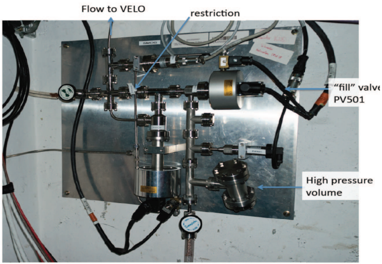



SMOG: System for Measuring Overlap with Gas

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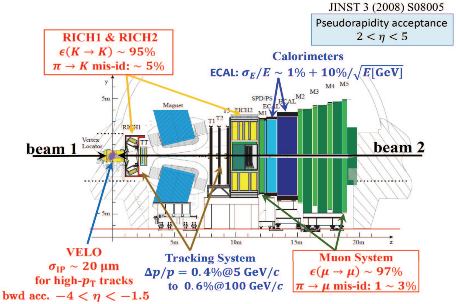


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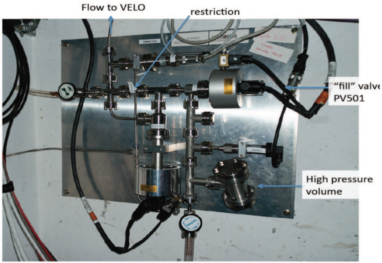


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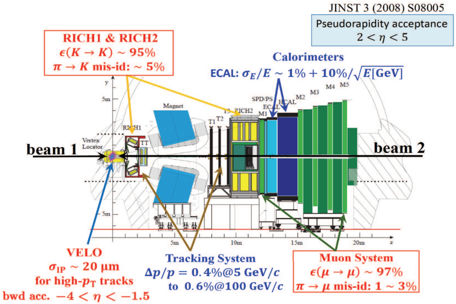


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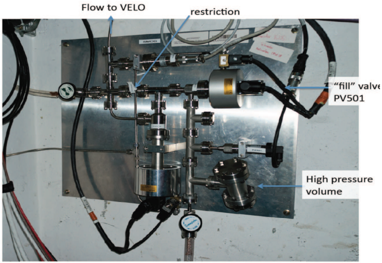


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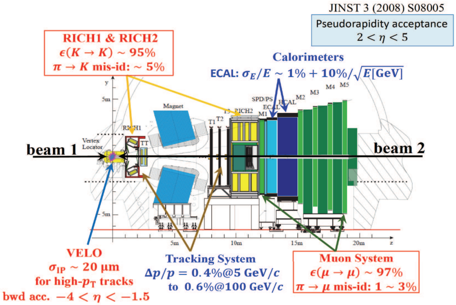


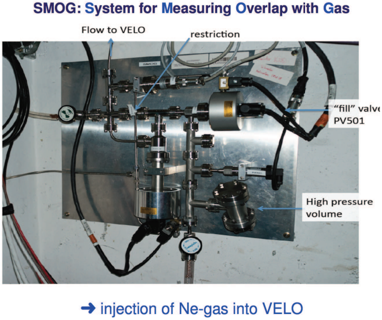


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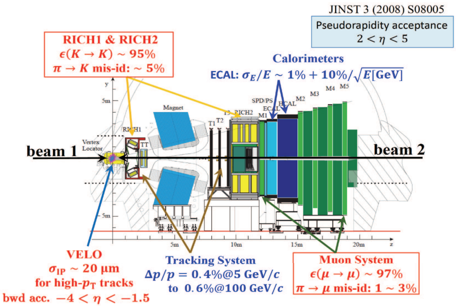


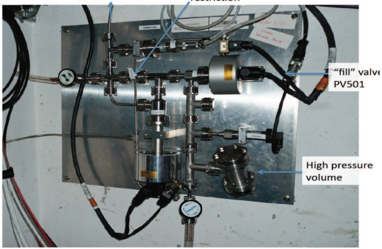


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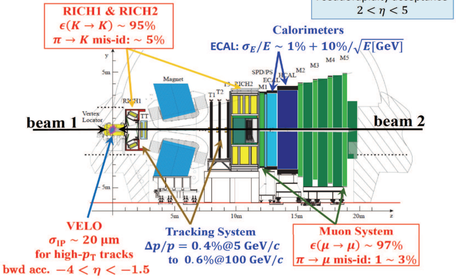
JINST 3 (2008) S08005

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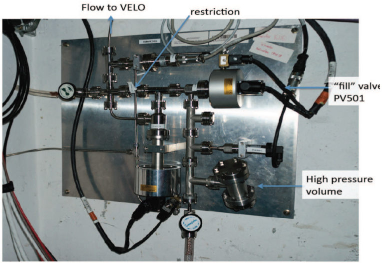


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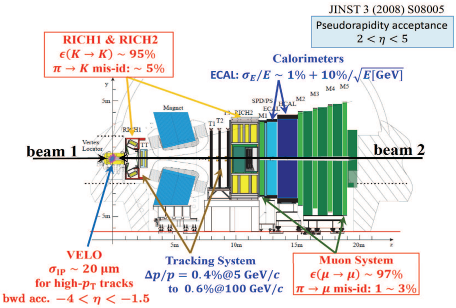


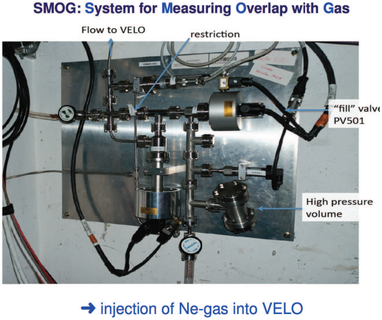


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- SMOG test : no decrease of LHC performances observed

# Luminosities with the internal-gas-target option

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**C. Barschel, P. Lenisa, A. Nass, and E. Steffens, Adv.Hi.En.Phys. (2015) 463141; See E. Steffens's talk at PSTP 2015**

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- Simply scaled up, this would give, for Pb$p$ or Pb$A$, 100 nb$^{-1}y^{-1}$.

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- A specific gas target is a competitive alternative to the beam extraction

# Luminosities with a polarised internal-gas-target option

Advances in High Energy Physics
Volume 2015, Article ID 463141, 6 pages
http://dx.doi.org/10.1155/2015/463141

## A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions

**Colin Barschel,[1] Paolo Lenisa,[2] Alexander Nass,[3] and Erhard Steffens[4]**

[1] *LHCb Collaboration, CERN, 1211 Geneva 23, Switzerland*
[2] *University of Ferrara and INFN, 44100 Ferrara, Italy*
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We discuss the application of an open storage cell as gas target for a proposed LHC fixed-target experiment AFTER@LHC. The target provides a high areal density at minimum gas input, which may be polarized $^1$H, $^2$H, or $^3$He gas or heavy inert gases in a wide mass range. For the study of single-spin asymmetries in pp interaction, luminosities of nearly $10^{33}$/cm$^2$ s can be produced with existing techniques.

[1] $T = 300K$

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Figures-of-merit Comparison : $\mathrm{FoM} = P^2 \times \{f^2, \alpha^2\} \times \theta$ **[ E. Steffens at PSTP 2015]**

$$\mathrm{FoM}^* = \phi \times \mathrm{FoM} = P^2 \times \{f^2, \alpha^2\} \times \phi \times \theta = P^2 \times f^2 \times \mathcal{L}$$

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| Target and mode | Target characteristics | FoM* |
|---|---|---|
| $NH_3$ UVa-target & extr. beam | $P = 0.85; f = 0.17; \theta = 1.5 \times 10^{23}$ cm$^{-2}$ | $1.6 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ |
| $NH_3$ COMPASS & extr. beam | $P = 0.9; f = 0.176; \theta = 2.8 \times 10^{25}$ cm$^{-2}$ | $3.5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ |
| 'HERMES' H target[1] & LHC beam | $P = 0.85; \alpha = 0.95; \theta = 2.5 \times 10^{14}$ cm$^{-2}$ | $6 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ |

[1] $T = 300K$

Part IV

# AFTER@LHC: the case of spin physics

# The quest for the orbital angular momentum of the quarks and gluons

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- Quark/Gluon Sivers function: distortion in the distribution of an unpolarised partons with momentum fraction $x$ and transverse momentum $k_\perp$ due to the proton transverse polarisation : $f_{1T}^{\perp}(x, \vec{k}_\perp^2)$

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- First suggested by D. Sivers to explain the large observed left-right single transverse spin asymmetries $A_N$ in $p^\uparrow p \to \pi X$

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- Several experiments wish to measure $A_N^{Drell-Yan}$ to extract $f_{1T}^{\perp q}(x, \vec{k}_\perp^2)$
  - COMPASS: valence quarks using a pion beam (160 GeV) on a polarised proton target
  - E1027: valence quarks using a polarised proton beam (120 GeV) on an unpolarised proton target
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➠ Some parameters of existing and proposed polarised DY experiments.

**S.J. Brodsky, F. Fleuret, C. Hadjidakis, JPL, Phys. Rep. 522 (2013) 239**
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- AFTER could be the only project able to reach $x^\uparrow = 10^{-2}$ and $x^\uparrow > 0.4$

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## Expected asymmetries

The target-rapidity region (negative $x_F$) corresponds to high $x^{\uparrow}$
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How large ?

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

**Tianbo Liu**[1], **Bo-Qiang Ma**[1,2,a]

[1]School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[2]Center for High Energy Physics, Peking University, Beijing 100871, China

**Transverse Single-Spin Asymmetries in Proton-Proton Collisions at the AFTER@LHC Experiment in a TMD Factorisation Scheme**

**M. Anselmino,**[1,2] **U. D'Alesio,**[3,4] **and S. Melis**[1]

*[1]Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy*
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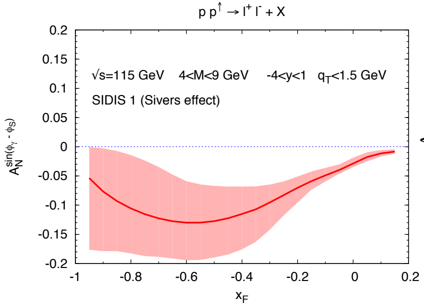


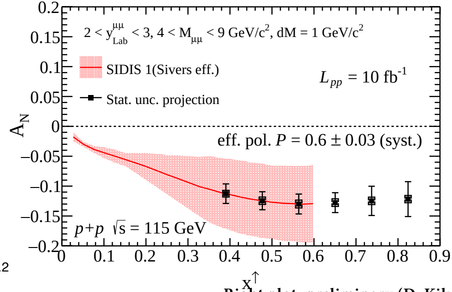


M. Anselmino, U. D'Alesio, S. Melis. Adv.Hi.En.Phys. (2015) 475040

**Right plot: preliminary (D. Kikola)**

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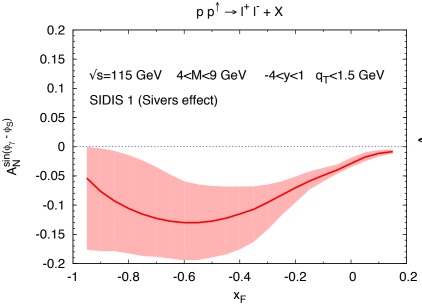


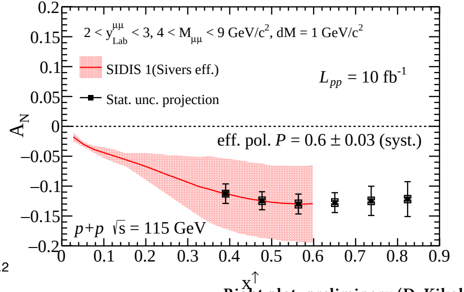


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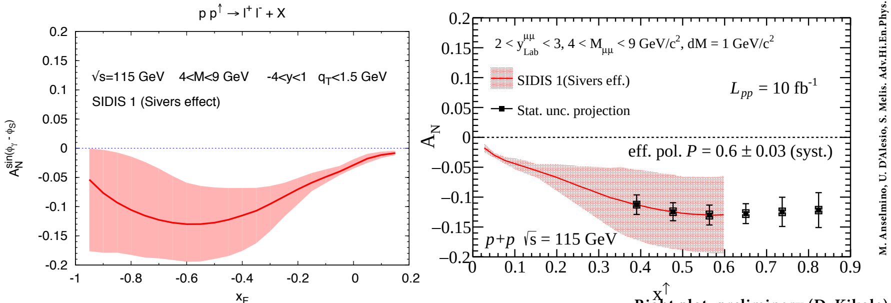


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- With 10 fb$^{-1}$, one can indeed expect up to $10^6$ DY events in $4 < M < 9$ GeV
- $W$ and $Z$ should be reachable with 10 fb$^{-1}$: $x^{\uparrow} \simeq 0.7 \div 0.8$

# The gluon OAM contribution to the proton spin

- Gluon Sivers effect essentially unconstrained

**D. Boer, C. Lorcé, C. Pisano,J. Zhou. Adv.Hi.En.Phys. (2015) ID:371396**

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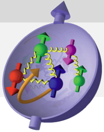

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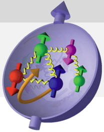

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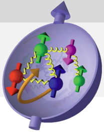

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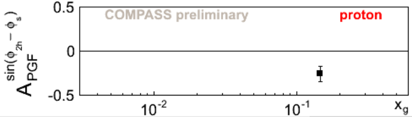
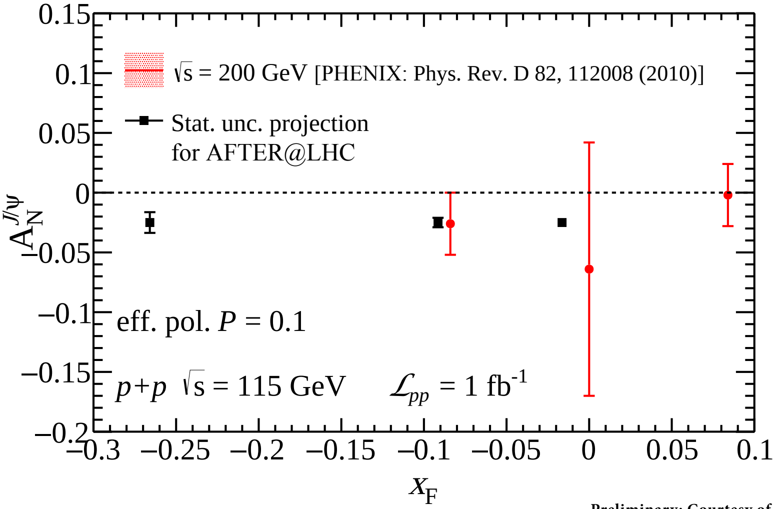
- Hint of nonzero gluon Sivers effect in $ep^\uparrow \to hh$: COMPASS JPhys. Conf.S. 678 (2016) 012055



# $J/\psi$ $A_N$ projection (vs. current PHENIX data)




**Preliminary; Courtesy of D. Kikola**

Nota: *P* was choosen to be smaller than above, otherwise the statistical uncertainties are invisible

Part V

# AFTER@LHC: the case for gluon PDF and quarkonium physics

# *pp* physics: gluons in the proton

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

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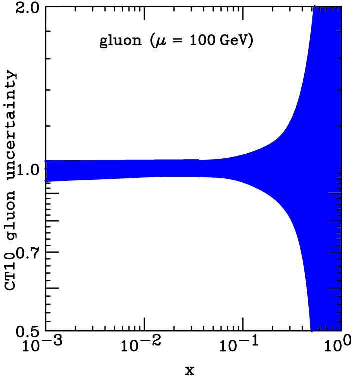

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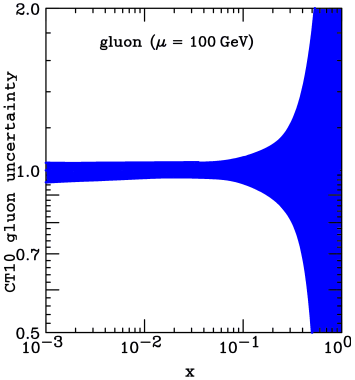


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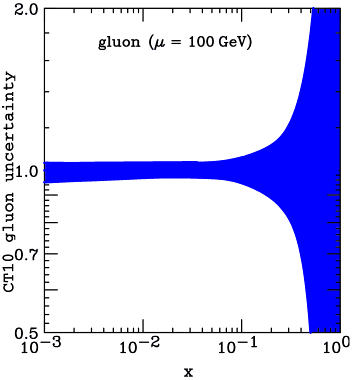


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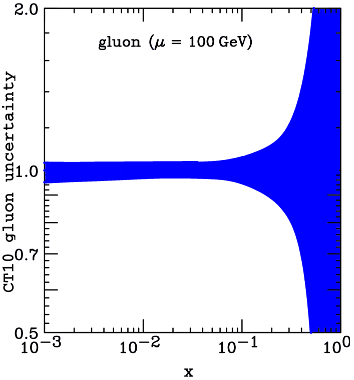


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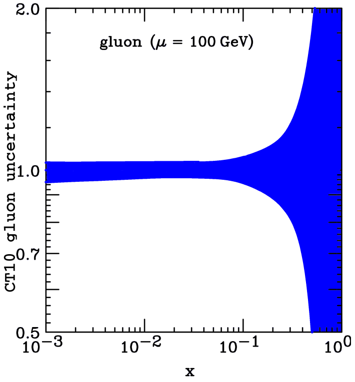


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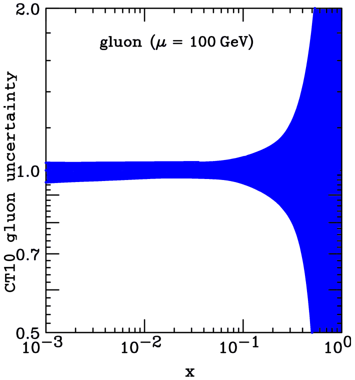


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Multiple probes needed to **check factorisation**

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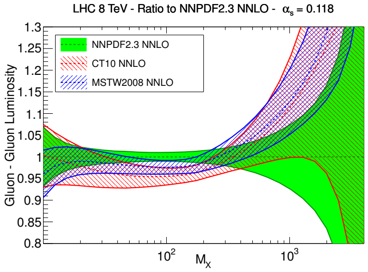


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| |
|---|
| Large-$x$ gluons: important to characterise some possible BSM findings at the LHC |

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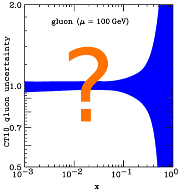


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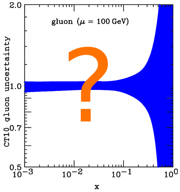


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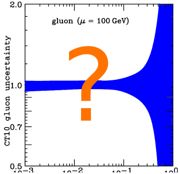


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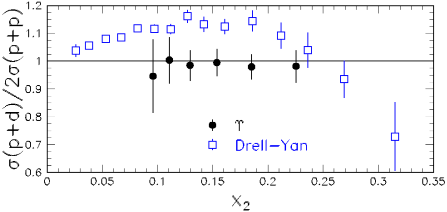


Pioneer measurement by E866

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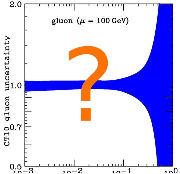


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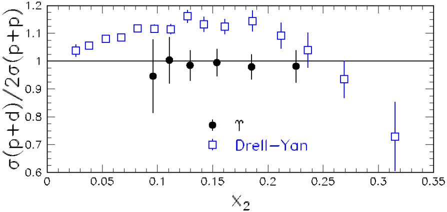


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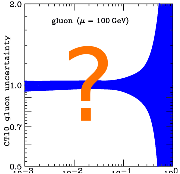


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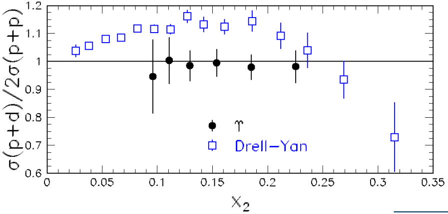


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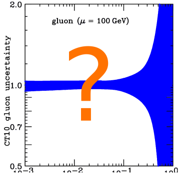


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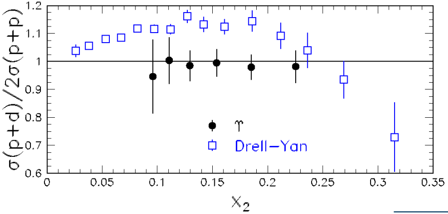


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If $g_n(x) - g_p(x)$ is too small, this measurement would anyhow be sensitive to the EMC and Fermi-motion effects in the deuteron

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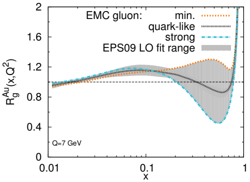

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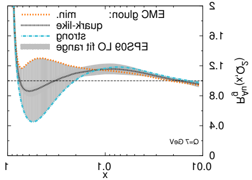

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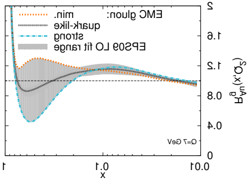


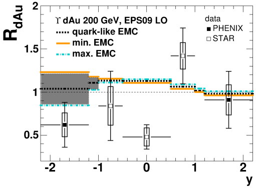

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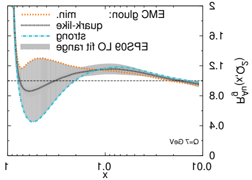

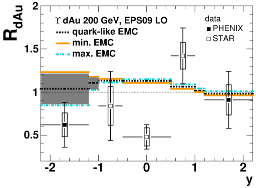


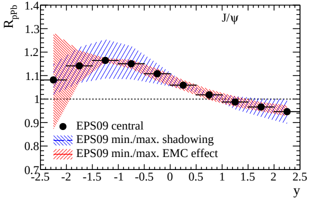

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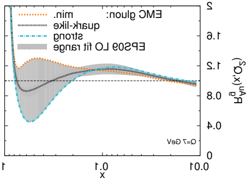

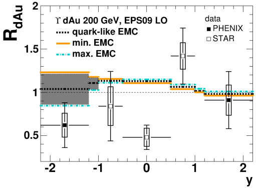


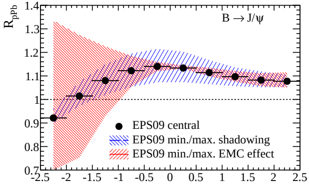


L. Massacrier*et al.*, Adv.Hi.En.Phys. (2015) 986348

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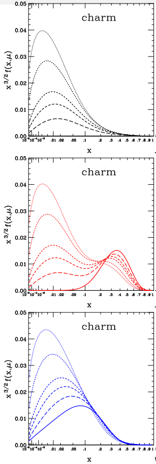


DGLAP

BHPS

Sea-like

3 sets from CTEQ6c (Pumplin *et al.*)

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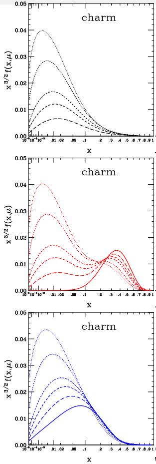


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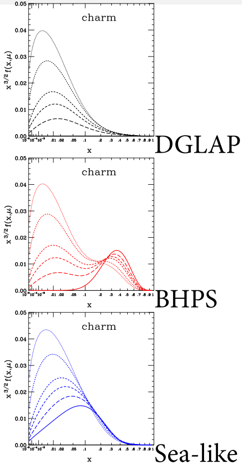


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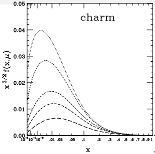

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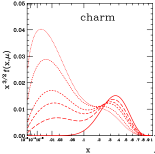

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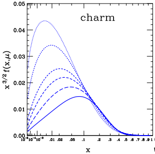

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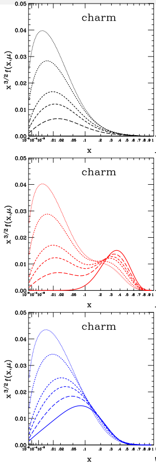


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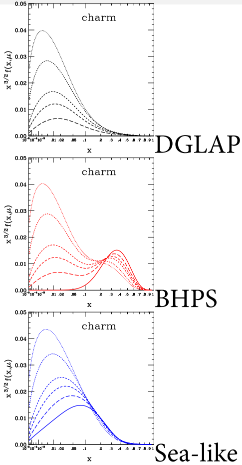


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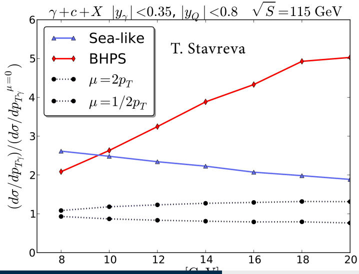


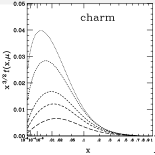


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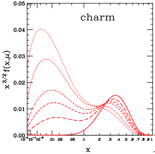


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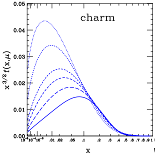


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# QCD uncertainties in PeV neutrino studies

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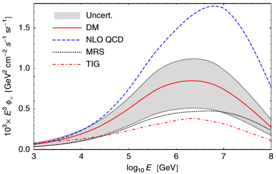


FIG. 6 (color online). Prompt muon neutrino fluxes obtained in perturbative QCD. The shaded area represents the theoretical uncertainty in the prompt neutrino flux evaluated in this paper, and the solid line in the band is our standard result. The dashed curve is the NLO perturbative QCD calculation of Ref. [14] (PRS), modified here to include fragmentation; the dotted curve is the saturation model result of Ref. [16] (MRS); and the dash-dotted curve is the LO perturbative QCD calculation of Ref. [15] (TIG).

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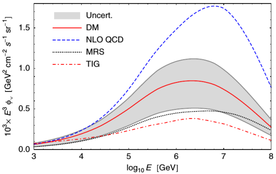


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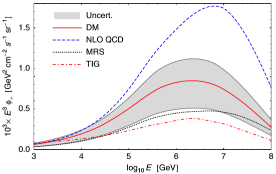


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- Charm measurements at the LHC are not of great help **F. Riehn,*et al.*, EPJ W. C. 99 (2015) 12001**

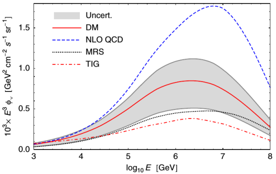


FIG. 6 (color online). Prompt muon neutrino fluxes obtained in perturbative QCD. The shaded area represents the theoretical uncertainty in the prompt neutrino flux evaluated in this paper, and the solid line in the band is our standard result. The dashed curve is the NLO perturbative QCD calculation of Ref. [14] (PRS), modified here to include fragmentation; the dotted curve is the saturation model result of Ref. [16] (MRS); and the dash-dotted curve is the LO perturbative QCD calculation of Ref. [15] (TIG).

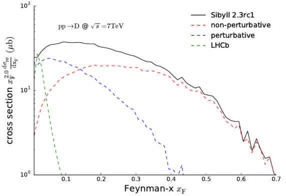


**Figure 8.** Weighted spectrum for *D*-mesons in SIBYLL at $\sqrt{s}$ = 7 TeV. The contributions from the perturbative and non-perturbative model components are shown by the blue and red lines, respectively. Note the negligible contribution to the energy spectrum from the phase space covered by the LHCb experiment ($2.5 < y < 4.5$, green line).

# QCD uncertainties in PeV neutrino studies

- Uncertainties in atmospheric neutrino flux (background of cosmic neutrinos) dominated by those on charmed meson decays

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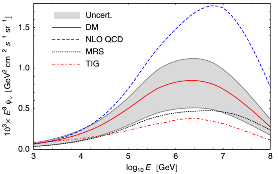


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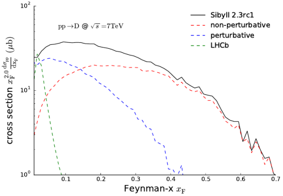


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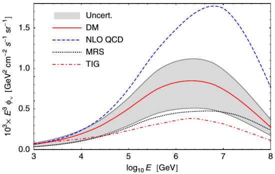


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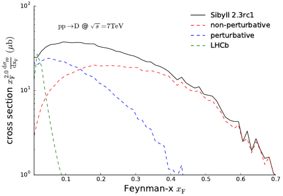


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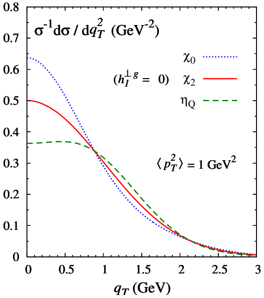

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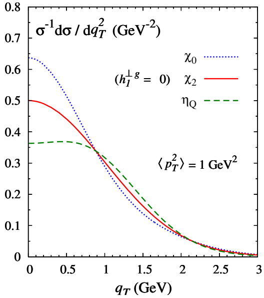

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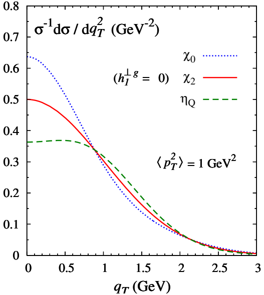

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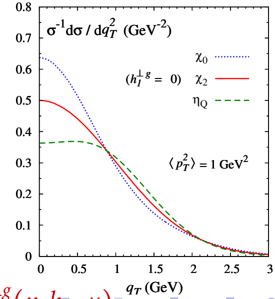

# Part VI

## Connections and synergies with COMPASS

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# Part VII

# Further readings

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## Heavy-Ion Physics

- *Gluon shadowing effects on $J/\psi$ and $\Upsilon$ production in p+Pb collisions at $\sqrt{s_{NN}} = 115$ GeV and Pb+p collisions at $\sqrt{s_{NN}} = 72$ GeV at AFTER@LHC* by R. Vogt. Adv.Hi.En.Phys. (2015) 492302.
- *Prospects for open heavy flavor measurements in heavy-ion and p+A collisions in a fixed-target experiment at the LHC* by D. Kikola. Adv.Hi.En.Phys. (2015) 783134
- *Quarkonium suppression from coherent energy loss in fixed-target experiments using LHC beams* by F. Arleo, S.PeignÃ©. [arXiv:1504.07428 [hep-ph]]. Adv.Hi.En.Phys. (2015) 961951
- *Anti-shadowing Effect on Charmonium Production at a Fixed-target Experiment Using LHC Beams* by K. Zhou, Z. Chen, P. Zhuang. Adv.High Energy Phys. 2015 (2015) 439689
- *Lepton-pair production in ultraperipheral collisions at AFTER@LHC* By J.P. Lansberg, L. Szymanowski, J. Wagner. JHEP 1509 (2015) 087
- *Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams.* By J.P. Lansberg, S.J. Brodsky, F. Fleuret, C. Hadjidakis. [arXiv:1204.5793 [hep-ph]]. Few Body Syst. 53 (2012) 11.

# Further readings

## Spin physics

- *Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment* by K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak. [arXiv:1502.04021 [hep-ph]. Adv.Hi.En.Phys. (2015) 257934.
- *Transverse single-spin asymmetries in proton-proton collisions at the AFTER@LHC experiment in a TMD factorisation scheme* by M. Anselmino, U. D'Alesio, and S. Melis. [arXiv:1504.03791 [hep-ph]]. Adv.Hi.En.Phys. (2015) 475040.
- *The gluon Sivers distribution: status and future prospects* by D. Boer, C. Lorcé, C. Pisano, and J. Zhou. [arXiv:1504.04332 [hep-ph]]. Adv.Hi.En.Phys. (2015) 371396
- *Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)* By T. Liu, B.Q. Ma. Eur.Phys.J. C72 (2012) 2037.
- *Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER* By D. Boer, C. Pisano. Phys.Rev. D86 (2012) 094007.

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## Hadron structure

- *Double-quarkonium production at a fixed-target experiment at the LHC (AFTER@LHC).*
  by J.P. Lansberg, H.S. Shao. [arXiv:1504.06531 [hep-ph]]. Nucl.Phys. B900 (2015) 273-294
- *Next-To-Leading Order Differential Cross-Sections for Jpsi, psi(2S) and Upsilon Production in Proton-Proton Collisions at a Fixed-Target Experiment using the LHC Beams (AFTER@LHC)*
  by Y. Feng, and J.X. Wang. Adv.Hi.En.Phys. (2015) 726393.
- $\eta_c$ *production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon*
  By V.P. Goncalves, W.K. Sauter. arXiv:1503.05112 [hep-ph].Phys.Rev. D91 (2015) 9, 094014.
- *A review of the intrinsic heavy quark content of the nucleon*
  by S. J. Brodsky, A. Kusina, F. Lyonnet, I. Schienbein, H. Spiesberger, and R. Vogt. Adv.Hi.En.Phys. (2015) 231547.
- *Hadronic production of* $\Xi_{cc}$ *at a fixed-target experiment at the LHC*
  By G. Chen *et al.*. Phys.Rev. D89 (2014) 074020.

# Further readings

## Feasibility study and technical ideas

- *Feasibility studies for quarkonium production at a fixed-target experiment using the LHC proton and lead beams (AFTER@LHC)* by L. Massacrier, B. Trzeciak, F. Fleuret, C. Hadjidakis, D. Kikola, J.P.Lansberg, and H.S. Shao arXiv:1504.05145 [hep-ex]. Adv.Hi.En.Phys. (2015) 986348
- *A Gas Target Internal to the LHC for the Study of pp Single-Spin Asymmetries and Heavy Ion Collisions* by C. Barschel, P. Lenisa, A. Nass, and E. Steffens. Adv.Hi.En.Phys. (2015) 463141
- *Quarkonium production and proposal of the new experiments on fixed target at LHC* by N.S. Topilskaya, and A.B. Kurepin. Adv.Hi.En.Phys. (2015) 760840

## Generalities

- *Physics Opportunities of a Fixed-Target Experiment using the LHC Beams*
  By S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. [arXiv:1202.6585 [hep-ph]]. Phys.Rept. 522 (2013) 239.

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- Free eTOC Alerts
- Publication Ethics
- Reviewers Acknowledgment
- Submit a Manuscript
- Subscription Information
- Table of Contents

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- Published Special Issues
- Special Issue Guidelines

**Physics at a Fixed-Target Experiment Using the LHC Beams**

Guest Editors: Jean-Philippe Lansberg, Gianluca Cavoto, Cynthia Hadjidakis, Jibo He, Cédric Lorcé, and Barbara Trzeciak

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## Physics opportunities of a fixed-target experiment using LHC beams

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[a] SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA
[b] Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France
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**Contents**

# Part VIII

# Conclusion and outlooks

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  - The approach to the deconfinement phase transition:
    new energy, new rapidity domain and new probes
- 2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS
  - A slow extraction with a bent crystal
  - An internal gas target inspired from SMOG@LHCb/Hermes/H-jet@RHIC, ...
- An Expression of Interest to be submitted to the LHCC is being written
  to be finished before the NuPECC LRP
- Additional contributions are always welcome !
- Strong similarities and complementarities between COMPASS pion runs and
  AFTER@LHC: Synergies useful to keep young colleagues in the field

# Part IX

## Backup slides

# First simulation: is the boost an issue ?

**B. Trzeciak, L. Massacrier *et al.*, Adv.Hi.En.Phys. (2015) 986348**

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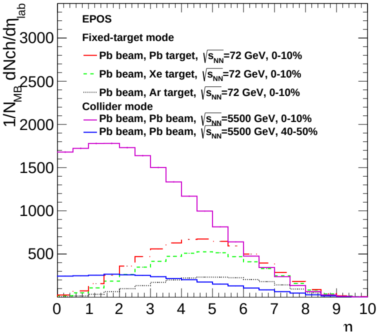

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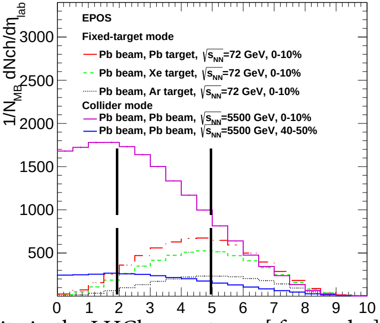


- Despite the boost, the multiplicity in the LHCb acceptance [ forward $\eta$] is lower in the fixed mode than in the collider mode (at higher $\sqrt{s}$)

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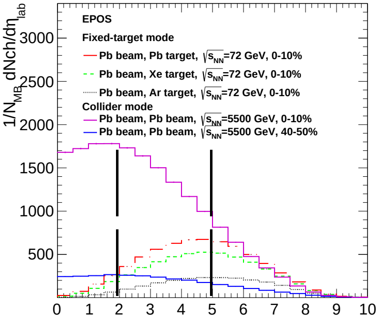



- Despite the boost, the multiplicity in the LHCb acceptance [ forward $\eta$] is lower in the fixed mode than in the collider mode (at higher $\sqrt{s}$)
- Simulation backed-up with a comparison of the number-of-track distribution between simulations at the detector level and data

Z. Yang, private comm.

# Fast simulation using LHCb reconstruction parameters

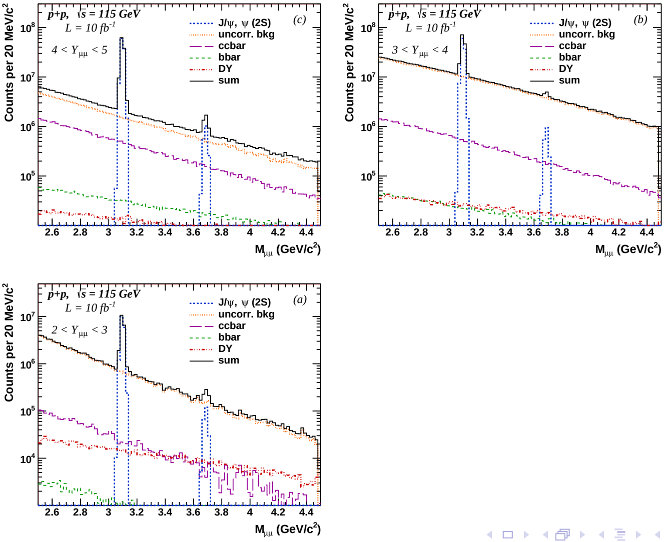
## Projection for a LHCb-like detector

L. Massacrier, B. Trzeciak, *et al.*, Adv.Hi.En.Phys. (2015) 986348

- Simulations with Pythia 8.185
- the 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
- Muon misidentification:
  - If $\pi$ and $K$ decay before the calorimeters (12m), they are rejected by the tracking
  - otherwise a misidentification probability is applied following: F. Achilli et al, arXiv:1306.0249

# Charmonium background & its rapidity dependence

**B. Trzeciak, L. Massacrier** *et al.*, **1504.05145 [hep-ex], Adv.Hi.En.Phys. (2015) 986348**



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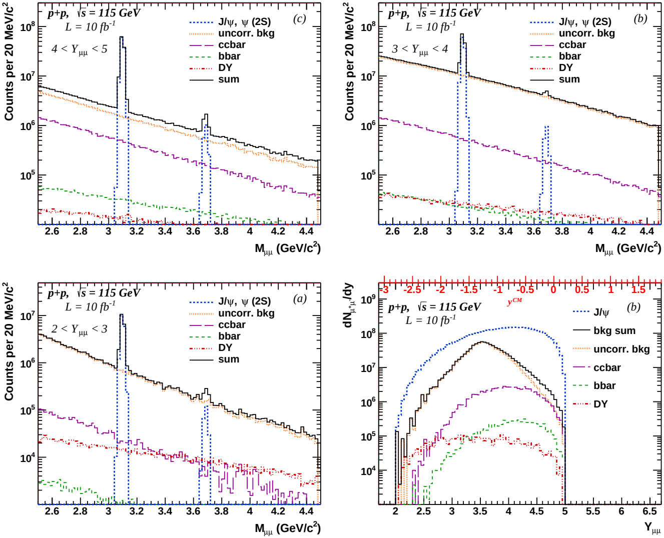

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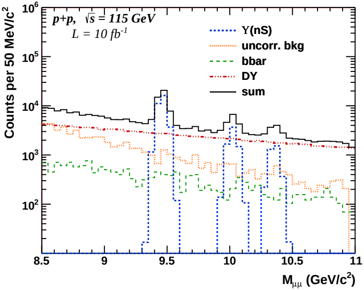


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3 peaks well resolved

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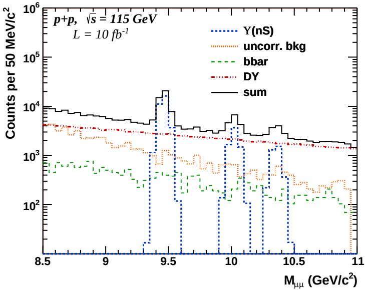


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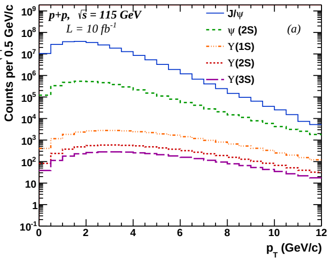
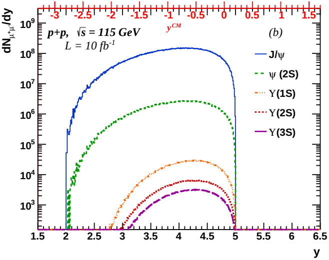
$J/\psi$: $10^4$ events at $P_T \simeq 12$ GeV

$\Upsilon$ : 200 events at $P_T \simeq 12$ GeV



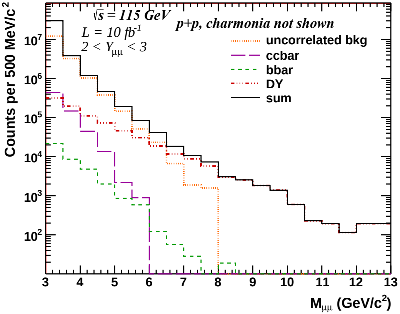




$J/\psi$: reach cut by the detector acceptance

$\Upsilon$ : 200 events at $y^{\Upsilon}_{c.m.s.} \simeq -2.1$, i.e. $x_2 \simeq 0.7$

# Drell-Yan background & signal reach

- At backward rapidities, quark-induced processes are favoured ⇒ Bkgd get smaller



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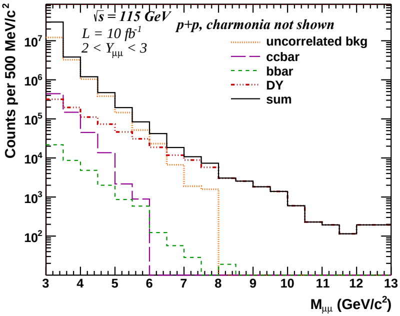


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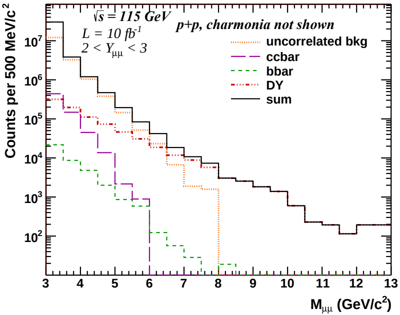


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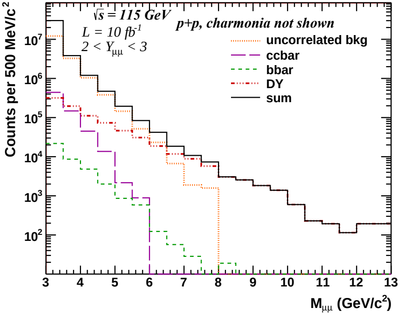


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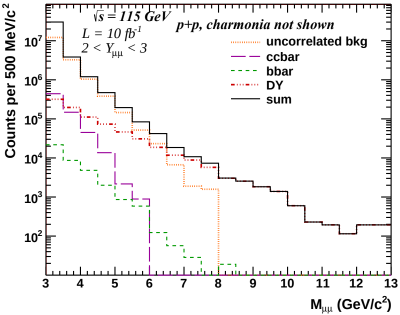


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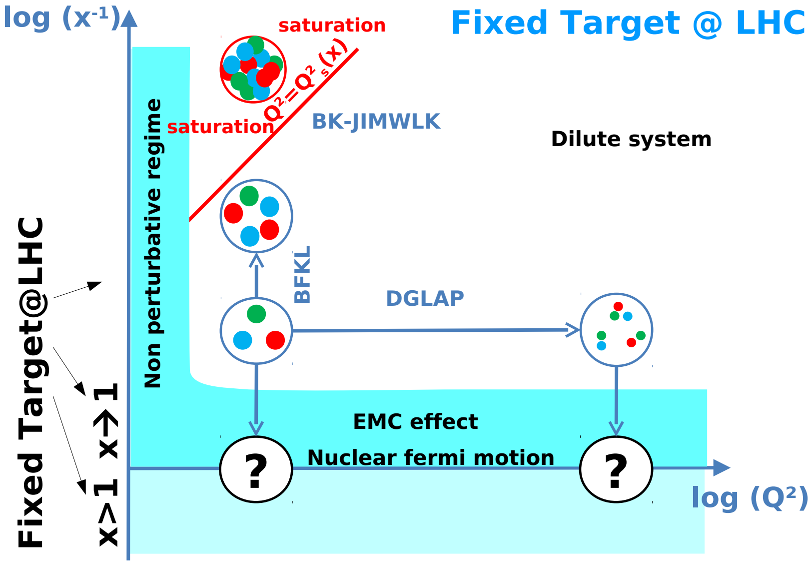
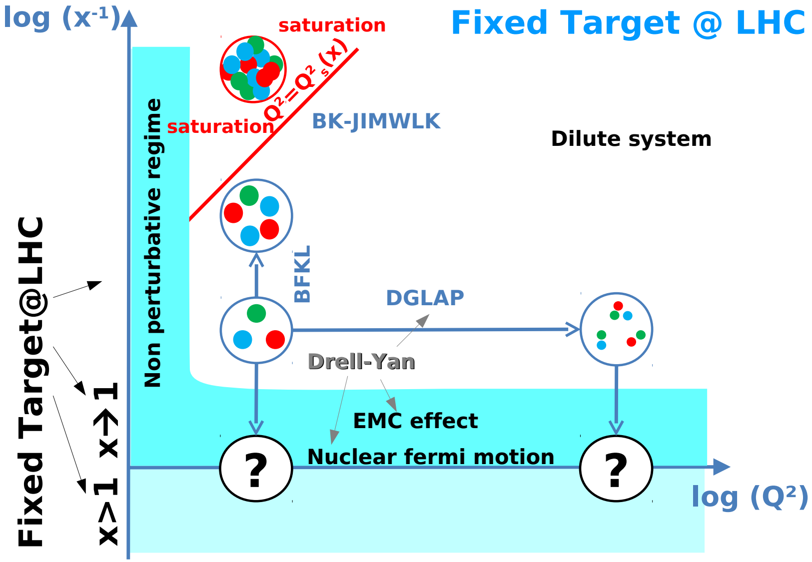
- Still 4000+ DY events left in $2 < Y < 3$ for $8 < M < 9$ GeV, *i.e.* at $x^{\uparrow} \simeq 0.7$
- Should yield to precise measurements of $A_N^{DY}$ at large $x$

# Overall



log (x⁻¹)
saturation
Fixed Target @ LHC
Q²=Q²s(x)
saturation
BK-JIMWLK
Dilute system
Non perturbative regime
Fixed Target@LHC
x>1
x→1
BFKL
DGLAP
EMC effect
Nuclear fermi motion
?
?
log (Q²)

# Overall



log (x-1)
saturation
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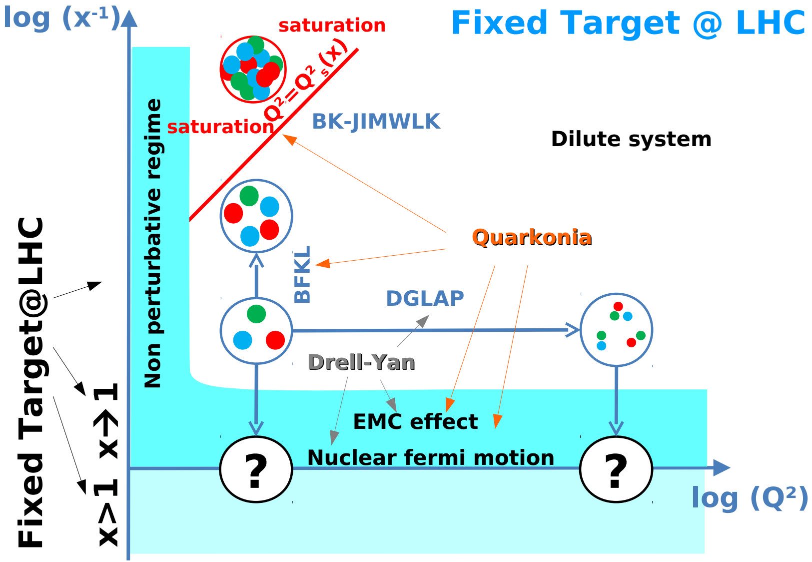
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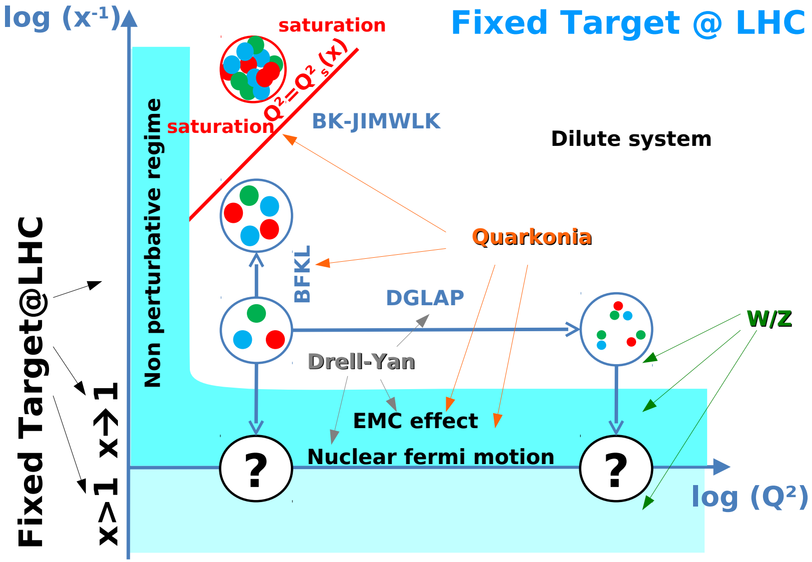
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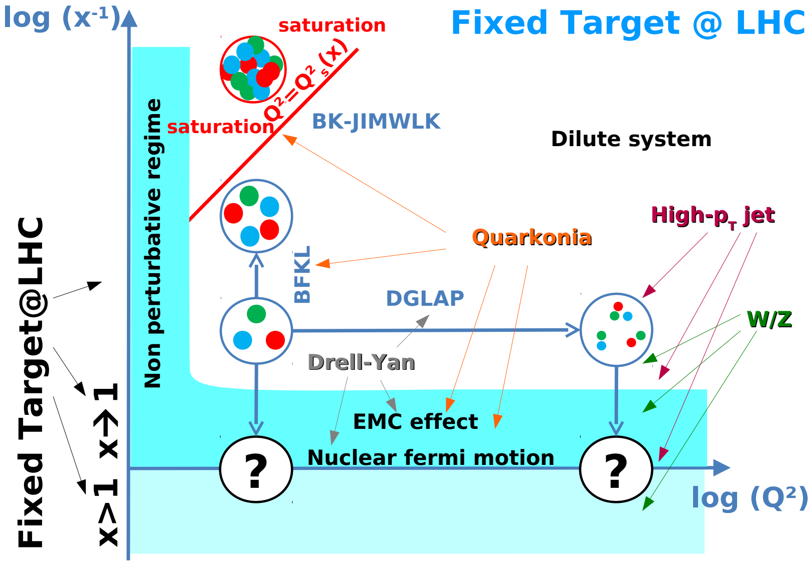

log (x⁻¹)
saturation
Fixed Target @ LHC
$Q^2=Q^2_s(x)$
saturation
BK-JIMWLK
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Non perturbative regime
High-$p_T$ jet
Quarkonia
Fixed Target@LHC
BFKL
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W/Z
Drell-Yan
x→1
EMC effect
x>1
?
Nuclear fermi motion
?
log (Q²)

# Gas target

**C. Barschel, P. Lenisa, A. Nass, and E. Steffens, Adv.Hi.En.Phys. (2015) 463141**

TABLE 1: Comparison of gas targets in storage rings with a hypothetical target for the proposed AFTER@LHC initiative [1, 2].The target gas $^1$H, $^2$D, or $^3$He is assumed to be spin polarized.

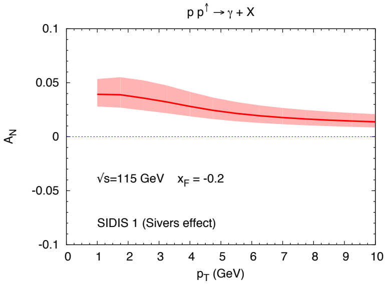
| Storage ring | Particle | $E_{max}$ [GeV] | Target type | $L$ [m] | $T$ [K] | $L_{max}$ [1/cm$^2$ s] | Remarks | Reference |
|---|---|---|---|---|---|---|---|---|
| HERA-e DESY (term. 2007) | $e^\pm$ pol. | 27.6 | Cell $^1$H, $^2$D, $^3$He | 0.4 | 100<br>25 | $2.5 \cdot 10^{31}$<br>$2.5 \cdot 10^{32}$ | HERMES exp. 1995–2007 | [9] |
| RHIC-p BNL | p pol. | 250 | Jet | — | — | $1.7 \cdot 10^{30}$ | Absolute p polarimeter | [10] |
| COSY FZ Jülich | p, d pol. | 3.77<br>$T$ = 49.3 MeV | Cell $^1$H, $^2$D<br>Cell $^1$H | 0.4 | 300 | $10^{29}$<br>$2.75 \cdot 10^{29}$ | ANKE exp.<br>PAX exp. | [4, 5]<br>[11] |
| LHC CERN (proposed) | p unpol.<br>heavy ions | 7,000<br>$2{,}760 \cdot A$ | Cell<br>$^1$H, $^2$D<br>Xe<br>$M \approx 131$ | 1.0 | 100<br>≥100 | $10^{33}$<br>$10^{27}$–$10^{28}$ | Based on techn. of HERMES target | this paper |

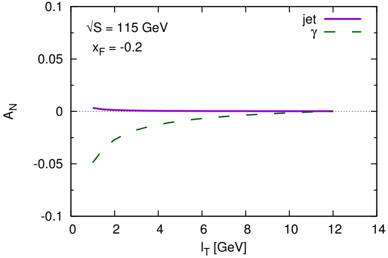
→ beam lifetime with $\mathcal{L}_{pp} = 10^{33}\text{cm}^{-2}\text{s}^{-1} = 10\ \text{nb}^{-1}\text{s}^{-1}$ of $2 \times 10^6$ s (or 23 days).

# Further studies of the Sivers effect

- $A_N^\gamma$ is predicted to have an opposite sign between the Generalised Parton Model (GPM) and the Collinear-Twist 3 (CT3) approach

**GPM: M. Anselmino, U. D'Alesio, S. Melis. Adv.Hi.En.Phys. (2015) 475040**
**CT3: K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak. Adv.Hi.En.Phys. (2015) 257934.**



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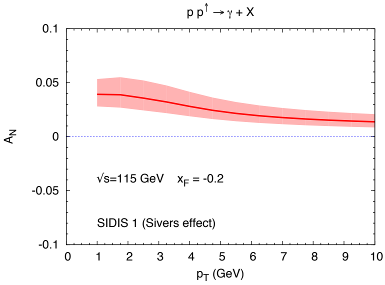
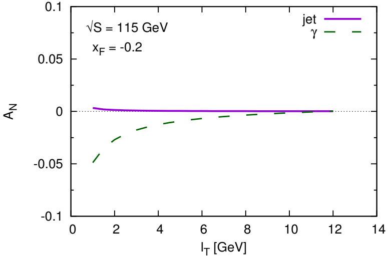
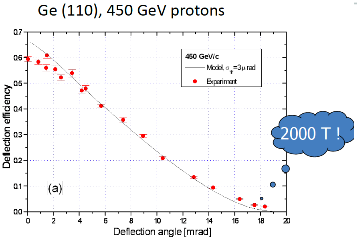


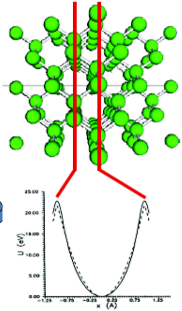




- $A_N^\pi$: sign mismatch issue with $f_{1T}^{\perp,q}(x,\vec{k}_\perp^2)$ extracted from SIDIS
  - $A_N^{jet}$: complementary since no "contamination" (fragmentation Collins effect)
  - $A_N^\pi$ should be measured at larger $p_T$

# The beam extraction with a bent crystal

- Inter-crystalline fields are huge



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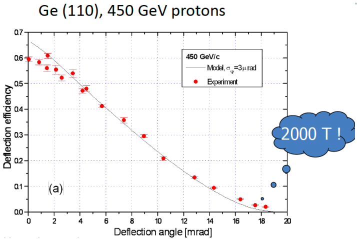


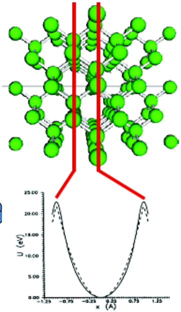


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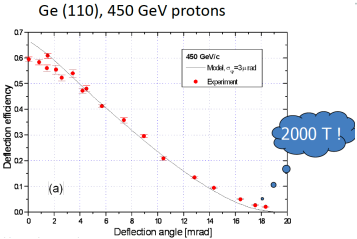


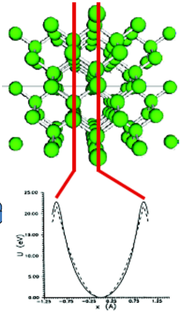

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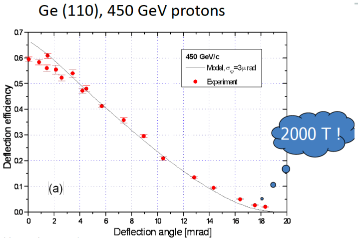
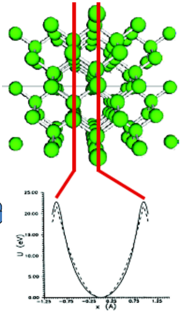
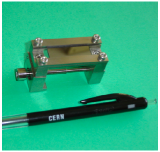



- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:

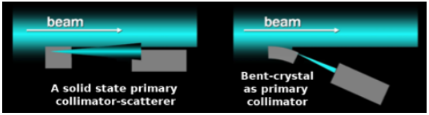


# The beam extraction: news

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

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

UA9 installation in the SPS




Prototype crystal collimation system at SPS :

- local beam loss reduction (5÷20x reduction for proton beam)
- beam loss map show average loss reduction in the entire SPS ring
- halo extraction efficiency 70÷80% for protons (50÷70% for Pb)

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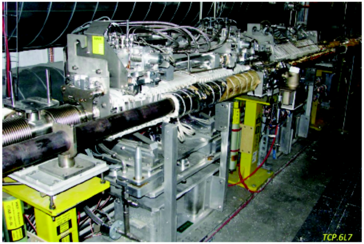


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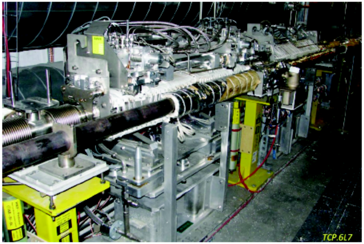


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Towards an installation in the LHC : propose and install during LS1 a min. number of devices

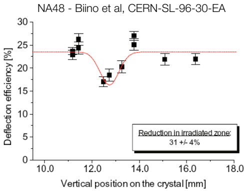
- 2 crystals

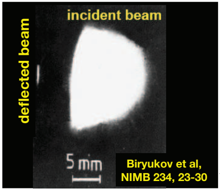
Long term plan is ambitious : propose a collimation system based on bent crystals for the upgrade of the current LHC collimation system

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

# Crystal resistance to irradiation


- **IHEP U-70** (Biryukov et al, NIMB 234, 23-30):
  - 70 GeV protons, 50 ms spills of **$10^{14}$ protons every 9.6 s**, several minutes irradiation
  - equivalent to 2 nominal LHC bunches for 500 turns every 10 s
  - 5 mm silicon crystal, **channeling efficiency unchanged**
- **SPS North Area - NA48** (Biino et al, CERN-SL-96-30-EA):
  - 450 GeV protons, 2.4 s spill of 5 x $10^{12}$ protons every 14.4 s, one year irradiation, **2.4 x $10^{20}$ protons/cm$^2$** in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - 10 x 50 x 0.9 mm$^3$ silicon crystal, 0.8 x 0.3 mm$^2$ area irradiated, **channeling efficiency reduced by 30%**.
- **HRMT16-UA9CRY** (HiRadMat facility, November 2012):
  - 440 GeV protons, up to 288 bunches **in 7.2 μs**, 1.1 x $10^{11}$ protons per bunch (**3 x $10^{13}$ protons** in total)
  - energy deposition comparable to an asynchronous beam dump in LHC
  - 3 mm long silicon crystal, **no damage to the crystal after accurate visual inspection**, more tests planned to assess possible crystal lattice damage
    - **accurate FLUKA simulation of energy deposition** and residual dose




30

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

# A few figures on the (extracted) proton beam

- Beam loss: $10^9\ p^+ s^{-1}$
- Extracted intensity: $5 \times 10^8\ p^+ s^{-1}$ (1/2 the beam loss)

**E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31**

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- similar figures for the Pb-beam extraction

# LHB

## Our idea is not completely new

Nuclear Instruments and Methods in Physics Research A 333 (1993) 125–135
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

### LHB, a fixed target experiment at LHC to measure CP violation in B mesons

Flavio Costantini

*University of Pisa and INFN, Italy*

A fixed target experiment at LHC to measure CP violation in B mesons is presented. A description of the proposed apparatus is given together with its sensitivity on the CP violation asymmetry measurement for the two benchmark decay channels $B^0 \to J/\psi + K_s^0$, $B^0 \to \pi^+\pi^-$. The possibility of obtaining an extracted LHC beam hinges on channeling in a bent silicon crystal. Recent results on beam extraction efficiencies measured at CERN SPS based on this technique are presented.

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This paper presents a fixed target experiment to measure CP violation in the B system based on the possibility of extracting the 8 TeV LHC proton beam using a bent silicon crystal [4]. A 10% extraction efficiency of the LHC beam halo will give an extracted beam intensity of about $10^8$ protons/s allowing the production of as many as $10^{10}$ $B\overline{B}$ pairs per year, i.e. about two orders of magnitude more than what could be produced by an $e^+e^-$ asymmetric B factory with $10^{34}$ $cm^{-2}s^{-1}$ luminosity [5].

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- $10^{20}$ particles/cm$^2$ : one year of operation for realistic conditions
- After a year, one simply moves the crystal by less than one mm ...

# Accessing the large *x* glue with quarkonia:

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

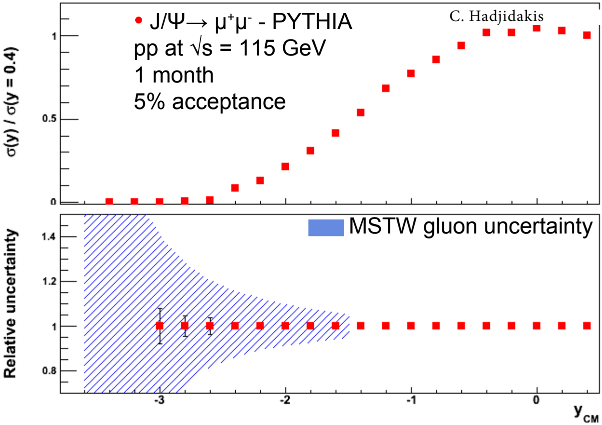
Statistical relative uncertainty
Large statistics allow to access very backward region

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

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

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

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




⇒ Backward measurements allow to access large x gluon pdf

Assuming that we understand the quarkonium-production mechanisms