AFTER@LHC: A fixed-target programme at the LHC for heavy-ion, hadron, spin and astroparticle physics

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

Outline

- **Part 1:** The scope of a fixed-target programme at the LHC

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- **Part 4:** Flagship studies
- **Conclusions and Outlooks**

Part I

The scope of a fixed-target programme at the LHC

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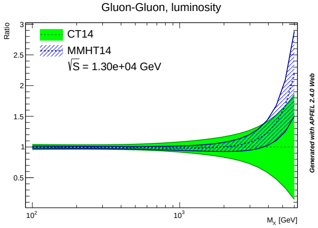

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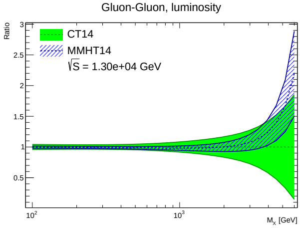

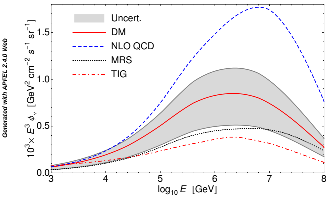

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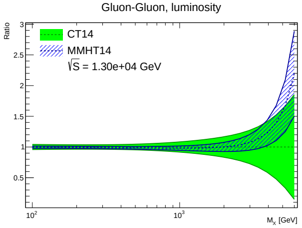

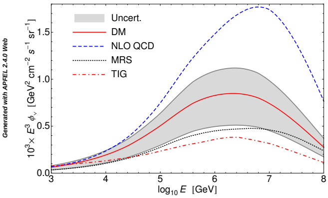

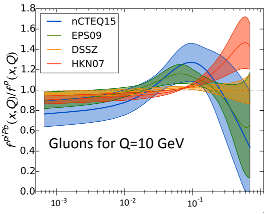

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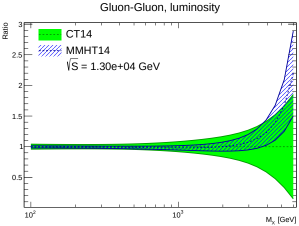
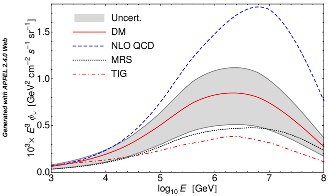
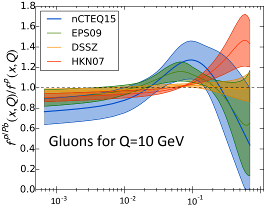
- Search and study rare proton fluctuations

  where one gluon carries most of the proton momentum







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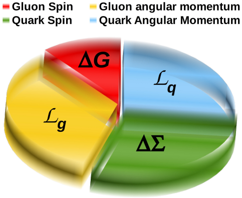

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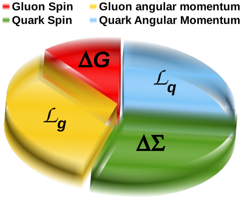

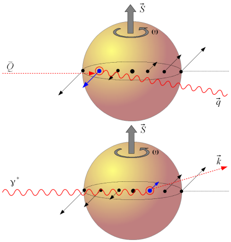

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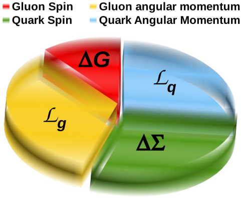
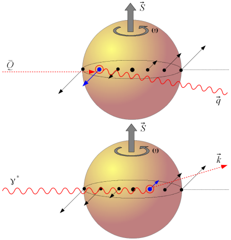
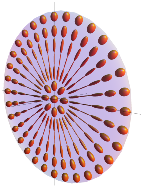
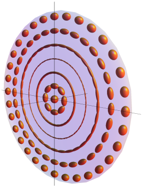
- Test of the QCD factorisation framework [beyond the DY A_N sign change]
- Determination of the linearly polarised gluons in unpolarised protons

[once measured, allows for spin physics without polarised proton, e.g. at the LHC]









Heavy-ion collisions from one colliding nucleus rest frame

Heavy-ion collisions towards large rapidities

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Heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies
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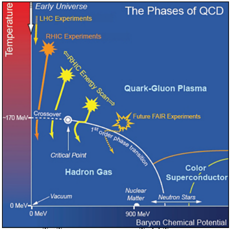

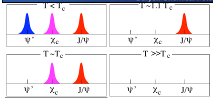

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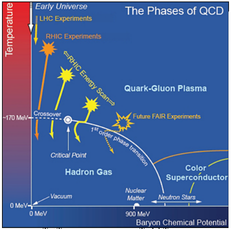

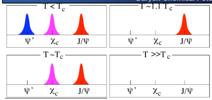

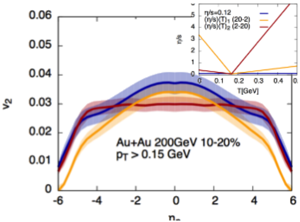

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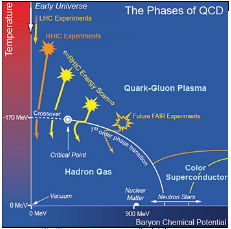

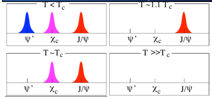

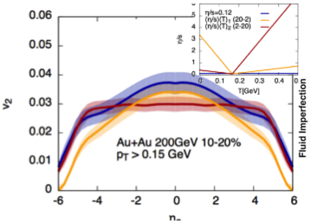

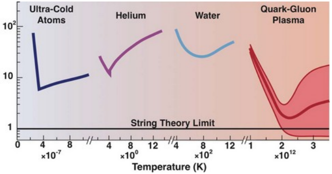

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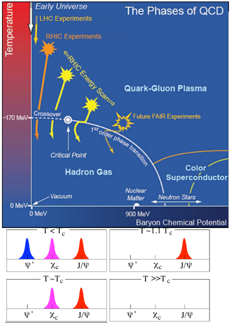
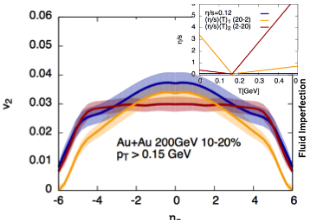
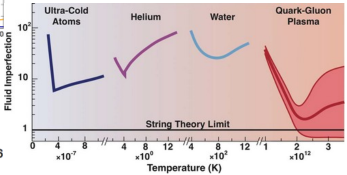
- Test the formation of azimuthal asymmetries: hydrodynamics vs. initial-state radiation
- Explore the longitudinal expansion of QGP formation
- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions







Part II

Assets, Kinematics, Possible Implementations and Luminosities

The fixed-target mode with TeV beams

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- accessing the high x frontier $\left[|x_F| \equiv \frac{|p_z|}{p_{z\,\max}} \to 1\right]$
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- polarising the target.

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- polarising the target.

This can be realised at CERN in a parasitic mode with the most energetic beams ever!

Nota: all (past) colliders with $E_p \geq 100$ GeV have had a fixed-target program (Tevatron, HERA, SPS, RHIC)

Fixed-target collisions at the LHC: main kinematical features

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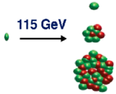
Energy range

7 TeV proton beam on a fixed target

c.m.s. energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\text{GeV}$		**Rapidity shift:**
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	$y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$



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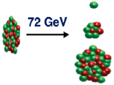

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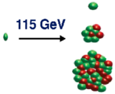

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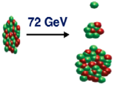

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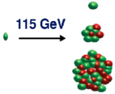

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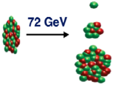

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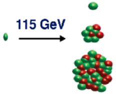

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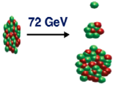

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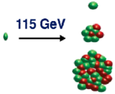

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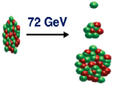

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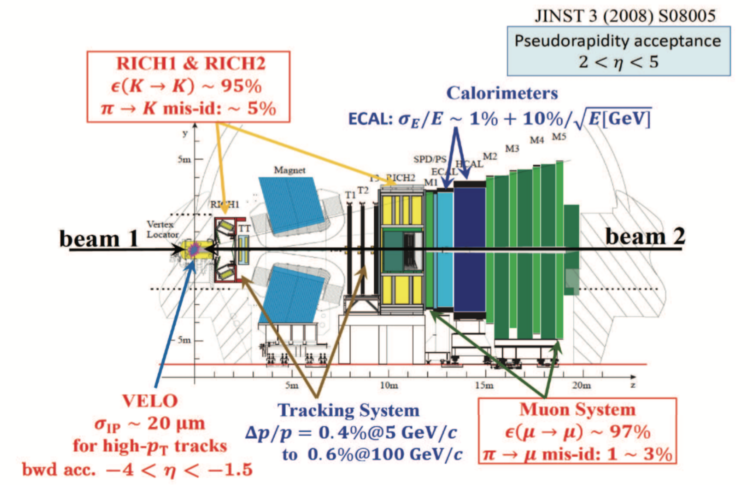
- With the reduced $\sqrt{s}$, their acceptance for physics grows and nearly covers half of the backward region for most probes [$-1 < x_F < 0$]
- Allows for backward physics up to high x_{target} ($\equiv x_2$) [uncharted for proton-nucleus; most relevant for p-p$^\uparrow$ with large $x^\uparrow$]

LHCb acceptance for various colliding modes



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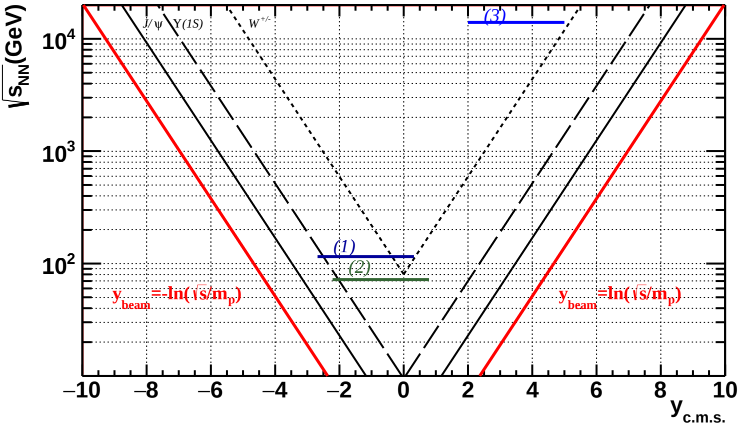
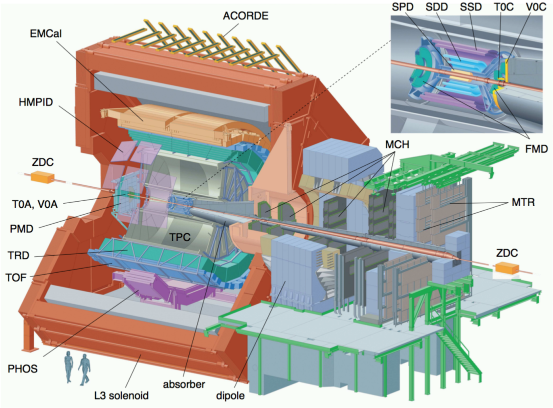


- (1) Fixed-target using p beam, E_p = 7 TeV
- (2) Fixed-target using Pb beam, E_{Pb} = 2.76 A.TeV
- (3) Collider using p beams, E_p = 7 TeV

ALICE muon acceptance for various colliding modes



- Central barrel: $-0.9 < \eta < 0.9$
- Muon spectrometer acceptance: $2.5 < \eta < 4$

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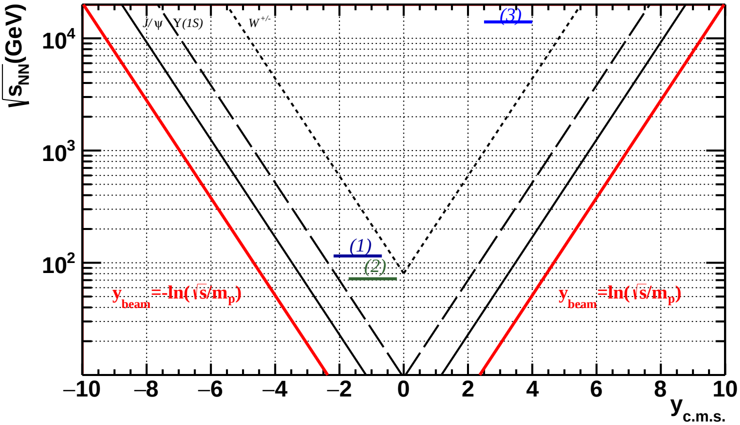

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Possible implementations

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- Internal gas target
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated by the LHCb collaboration via a luminosity monitor (SMOG)
  - uses the high LHC particle current
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  - similar fluxes as beam line
- Luminosities with an internal gas target or a crystal-based solution are similar

pp	pA	PbA
$\mathcal{O}(10\ \text{fb}^{-1}\text{yr}^{-1})$	$\mathcal{O}(0.1 - 1\ \text{fb}^{-1}\text{yr}^{-1})$	$\mathcal{O}(1 - 50\ \text{nb}^{-1}\text{yr}^{-1})$

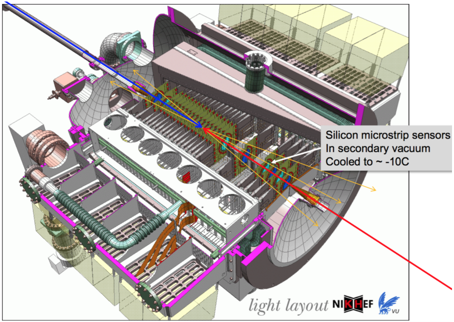
Internal gas target at the LHC

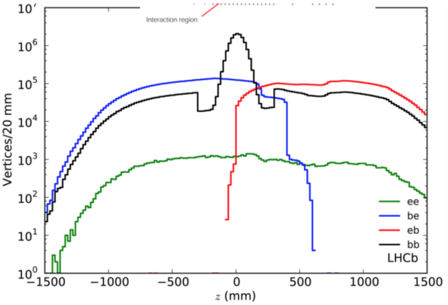
Ultra-high vacuum in the LHC but
already various places with gas injection into the beam pipe:

- beam gas ionisation monitors in LSS4: P(Ne) $< 10^{-8}$ mbar
- gas injection system near ALICE, ATLAS and CMS for beam-gas background studies
- SMOG@LHCb for beam shape imaging: P(noble gases) $< 1.5 \times 10^{-7}$ mbar
  [pure residual gas, P=10^{-9} mbar]
- beam gas vertex detector demonstrator in LSS2 for beam shape imaging for HL-LHC: P(Ne) $< 6 \times 10^{-8}$ mbar

Internal gas target at the LHC

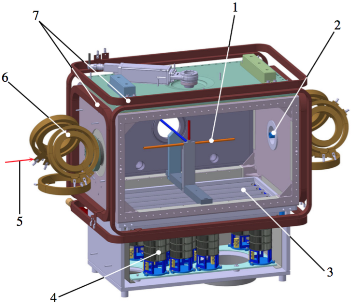
SMOG: System for Measuring Overlap with Gas

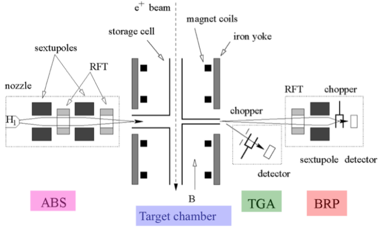




- Designed for precise luminosity determination
- Noble gas directly injected in the vessel of the Vertex Locator (VELO)
- p+(He,Ne,Ar), Pb+(Ne,Ar) tested with P ~ 1.5×10^{-7} mbar
- Pumping systems at ±20 m: limit in the gas injection (pressure and duration)
- Gas injection duration: up to one week
- Kr and Xe could be in principle injected, not tested yet
- Improvement foreseen: gauge pressure in the VELO (absolute gas density measurement), ...

A proposal for a high-density gas target at LHC





HERMES target with LHC beams: C. Barschel et al. *Adv.High Energy Phys. 2015 (2015) 463141*

- Used at DESY with electron beam for 10 years
- Injection of gas in an open-end Al storage cell (1 m x 1.4 cm): pressure in the cell higher wrt gas jet
- Polarized H, D and ^{3}He can be injected with high polarisation
- Unpolarised gas (H_2, He, Ne, Ar, Kr, Xe) can also be injected
- Dedicated pumping systems (NEG and turbo-molecular pumps) below the target chamber
- Openable storage cell in development (needed for LHC beams)
- Large instantaneous luminosity of $L_{\rm PbA} \sim 10^{28}$/cm^2/s and $L_{\rm pp} \sim 10^{33}$/cm^2/s

Internal gas targets

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HERMES(-like) system

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- ✓ Dedicated pumping system [turbo-molecular pumps]
- ✓ Pressure in the cell significantly higher [diameter ≤ 2cm in the closed position]
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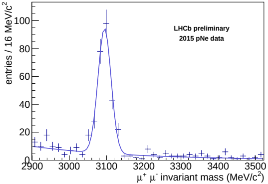

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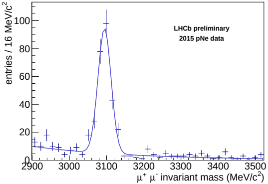

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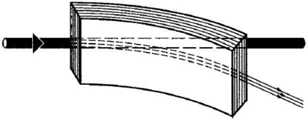
The simulations showed in Part III are based on this set-up coupled to a LHCb like detector

Bent crystal at LHC

The LHC beam may be extracted using "Strong crystalline field" without any decrease in performance of the LHC

E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131



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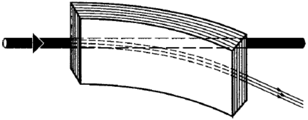
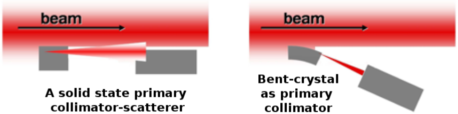


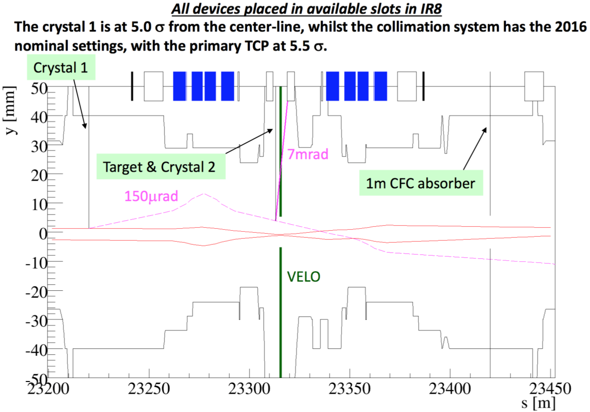
More efficient for beam collimation than usual collimator



2 crystals and 2 goniometers installed in the LHC beampipe (LUA9)

Beam splitting option

Proposed at the *Physics Beyond Collider workshop Sept.2016* (S.Redaelli, W.Scandale)



- Crystal located ~ 100 m downstream the target to deflect the beam halo
- Solid target close to the nominal interaction point
- Absorber 100 m upstream for the non-interacting beam halo

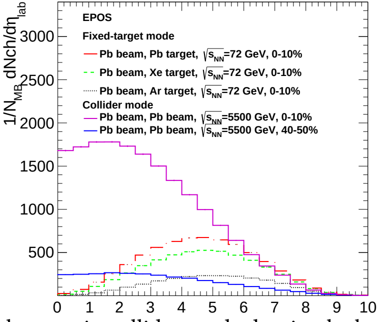
Part III

Simulation set-up

First simulation: is the boost an issue ?

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

- Using EPOS, comparison of the multiplicity vs η_{lab} in PbA in collider ($\sqrt{s}$ = 5 TeV) vs. fixed-target mode ($\sqrt{s}$ = 72 GeV)



- Multiplicities lower than the ones in collider mode despite the boost

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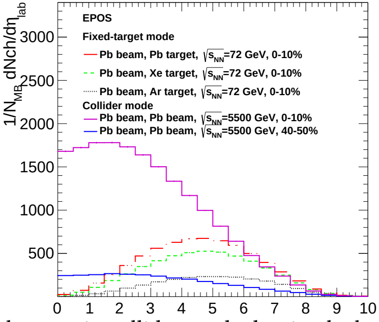


- Multiplicities lower than the ones in collider mode despite the boost
- A detector such as LHCb ($2 < \eta < 5$) has carried out pPb and Pbp analyses at 5 TeV and is currently analyzing PbAr at 72 TeV (fixed-target mode) and also PbPb (collider mode) at 5 TeV up to 40-50% event centrality

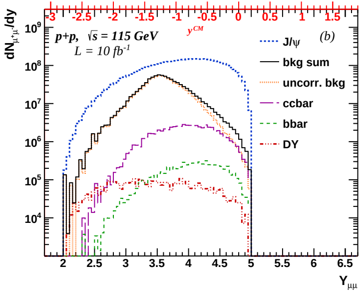
Fast simulation using LHCb reconstruction parameters

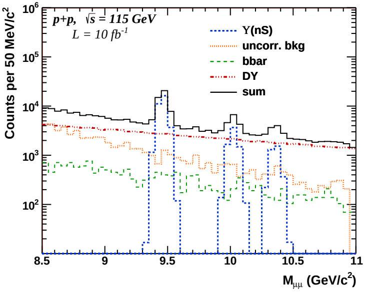
Projection for a LHCb-like detector

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

- Simulations with Pythia 8.185
- HELAC-Onia for quarkonium, $c\bar{c}$, $b\bar{b}$ and Drell-Yan signal
- Fast LHCb simulation with realistic 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 π and K decay before the calorimeters (12m), they are rejected by the tracking
  - otherwise a misidentification probability is applied following: F. Achilli et al, *JINST 8 (2013) P10020*

Drell-Yan background & signal reach

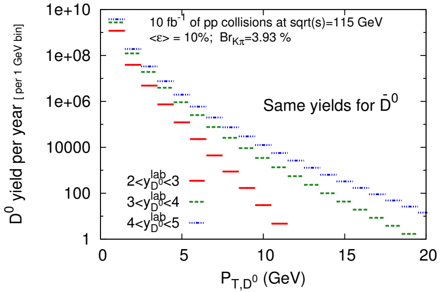




- At backward rapidities, quark-induced processes are favoured and the background get smaller
- Lower combinatorial background at large $M_{\mu\mu}$
- Charm and beauty can be removed/estimated by a cut on secondary vertex
- Uncorrelated background can be subtracted by the event-mixing or like-sign method
- $L_{pp} = 10$ fb^{-1}: 4000+ DY events in $2 < y < 3$ for $8 < M_{\mu\mu} < 9$ GeV, *i.e.* at $x_{target} \simeq 0.7$
- Statistics allow for precise measurements of A_N^{DY} at large x_{target} as discussed later

Open heavy flavour: charm

- Extremely good prospects to measure charm
  - down to zero p_T (total x-section can be measured)
  - over a wide rapidity coverage ($x_F \to -1$)
  - with high statistical precision in *pp*, *pA* and *AA* collisions



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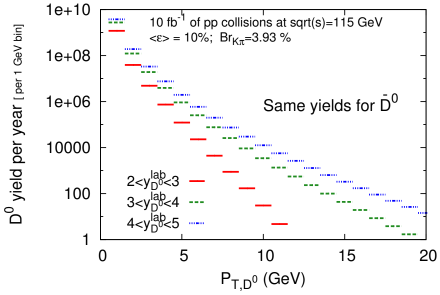

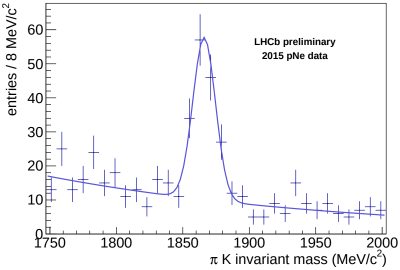

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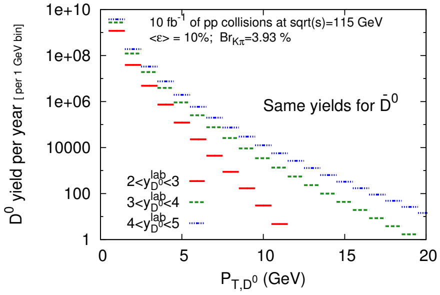
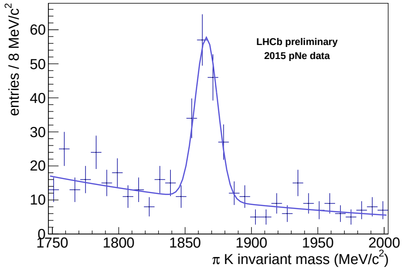
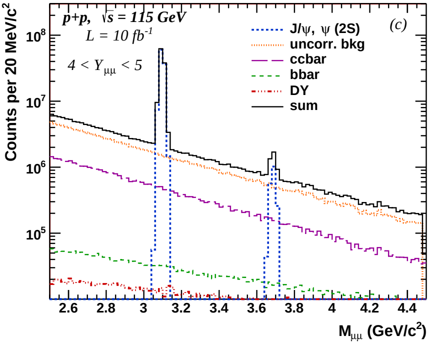
- Looking at $D \to K\pi$ gives direct access to charm – anticharm asymmetries

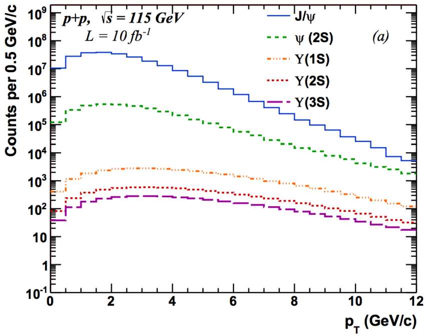




Charmonium

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

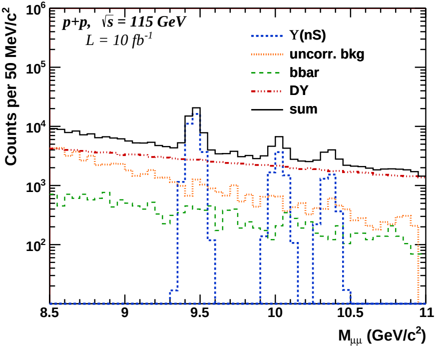


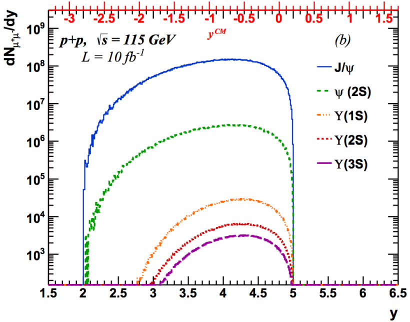


- L_{pp} = 10 fb^{-1}: up to 10^9 charmonia per year
- Measurement possible for $0 < p_T < 15$ GeV/c with high statistical precision

Bottomonium

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





- L_{pp} = 10 fb^{-1}: up to 10^6 bottomonia per year
- Dominant background is Drell-Yan
- Measurement possible for $0 < p_T < 10$ GeV/c and $3 < y_{lab} < 5$ (can reach large $x_{target} \sim 0.7$)

Part IV

A selection of projected performances

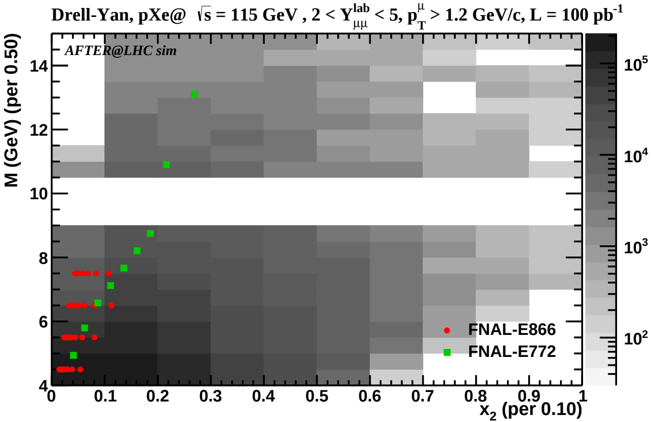
What is not covered by lack of time

- Azimuthal anisotropies [Heavy-Ion, Spin]
- Photon related observables [High-x, Spin, Heavy-Ion]
- W boson [High-x, Spin]
- Antiproton and related x-section measurements for astroparticle MC tuning [High-x]
- C-even quarkonia [High-x, Spin, Heavy-Ion]
- Associated production [Spin, Heavy-Ion]

Drell-Yan

Drell-Yan

- Unique acceptance (with a LHCb-like detector) compared to existing DY *pA* data used for nuclear PDF fit (E866 & E772 @ Fermilab).



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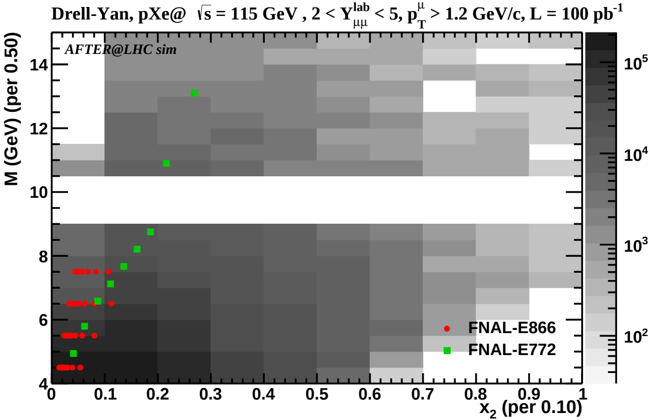

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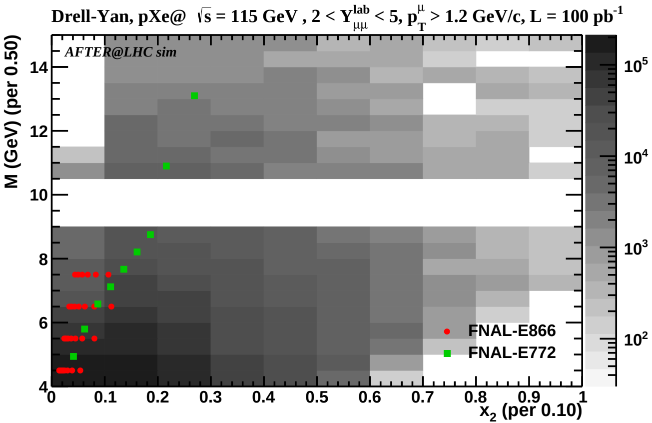

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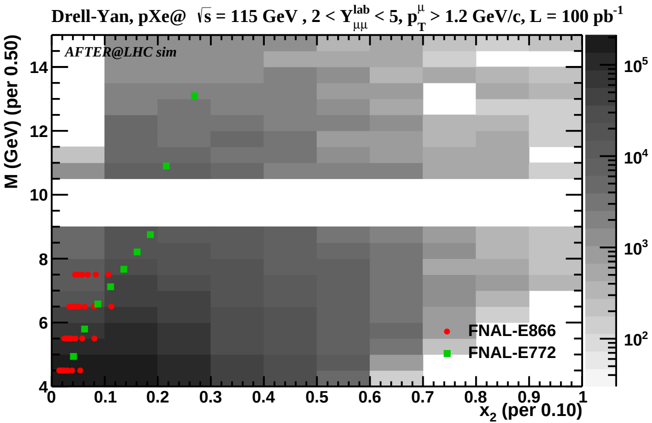

Drell-Yan performances for spin analyses [LHCb-like detector]

D. Kikola, arXiv:1702.01546

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- DY pair production on a transversely polarised target is the aim of several experiment (COMPASS, E1039, STAR, E1039)

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Experiment	particles	energy (GeV)	$\sqrt{s}$ (GeV)	$x_p^\uparrow$	$\mathcal{L}$ (nb^{-1}s^{-1})
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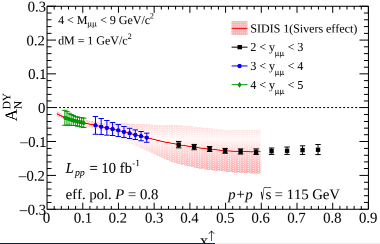

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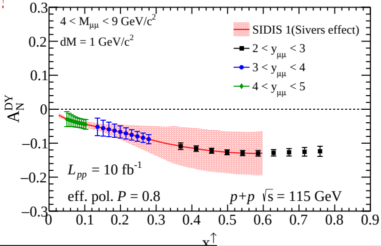

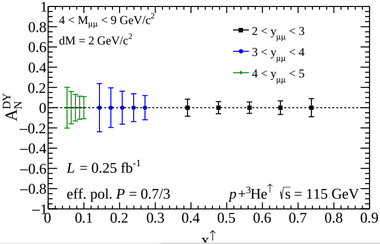

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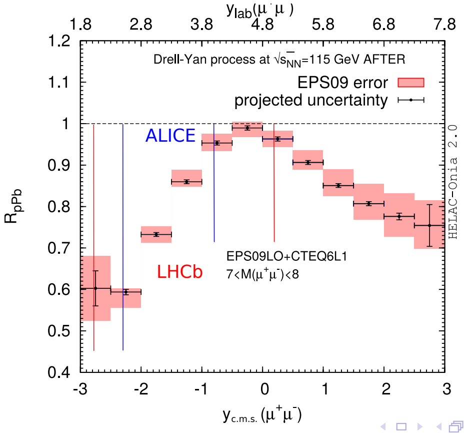

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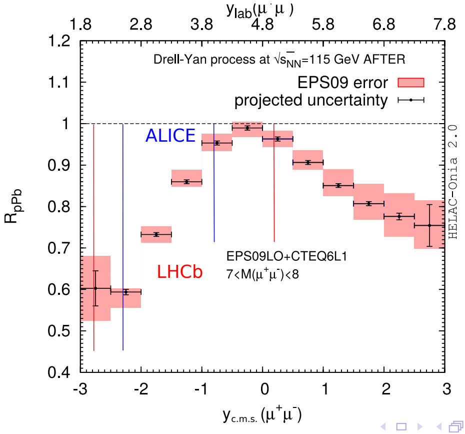
- With the muon spectrometer of ALICE and its absorber, opportunity to study DY in PbA coll.

  [Only done once at SPS; no effect seen]



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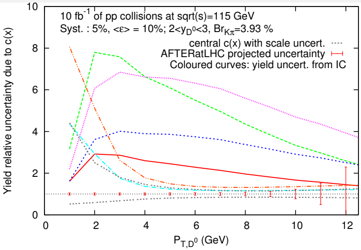

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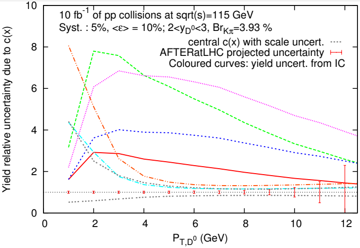

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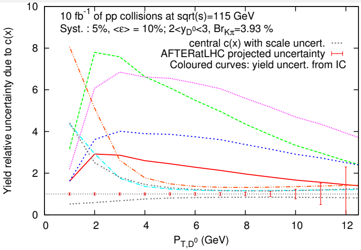

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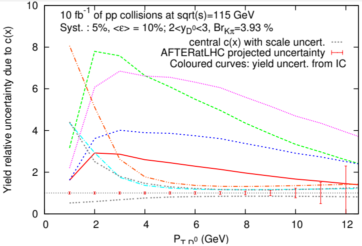

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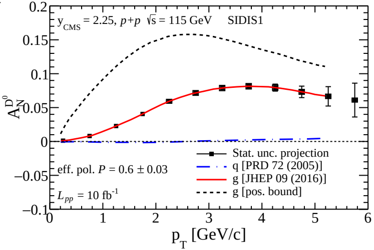

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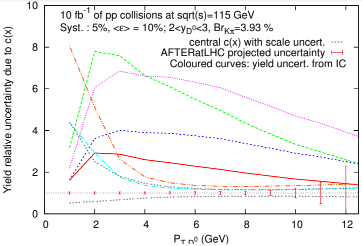

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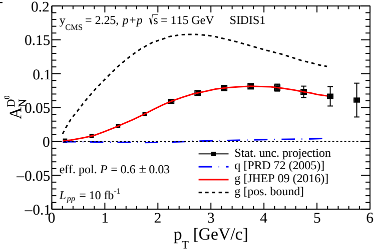

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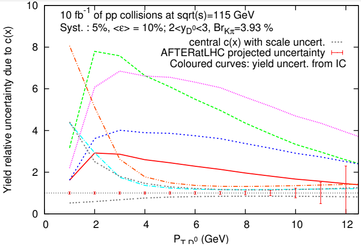

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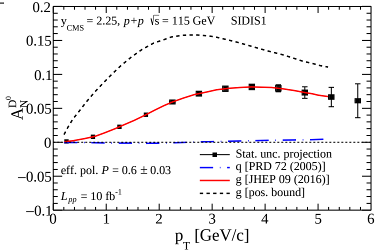

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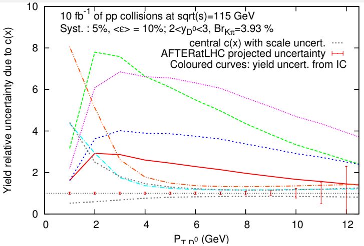

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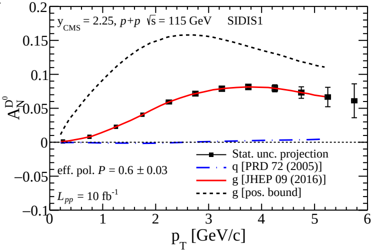

As for AA collisions, nuclear modification factors vs p_T, y, centrality as well as azimuthal anisotropies (v_2) can be of course measured [no time to cover them]

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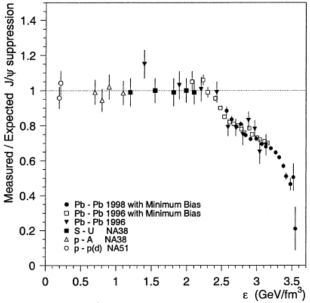

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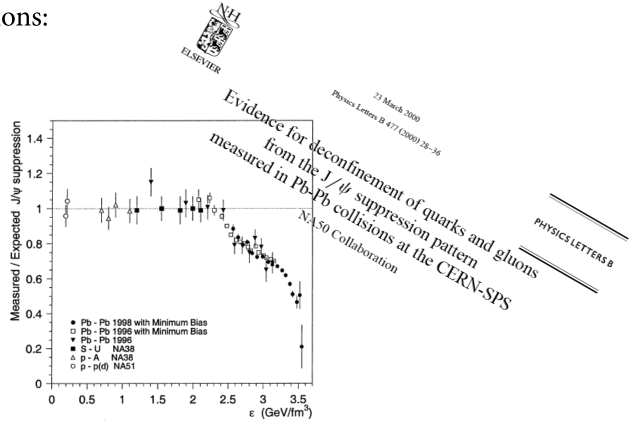

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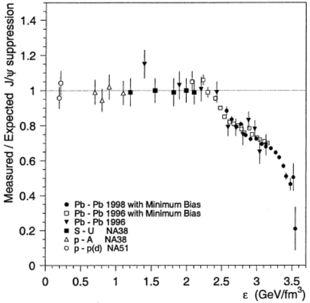

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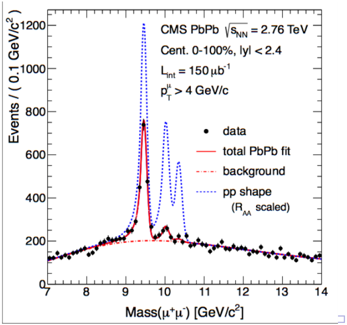

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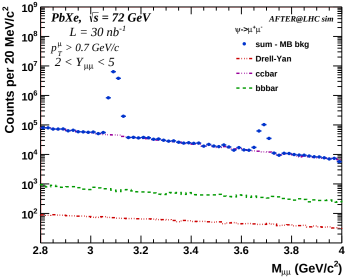

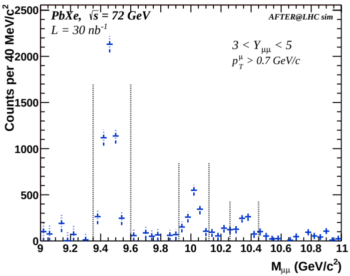

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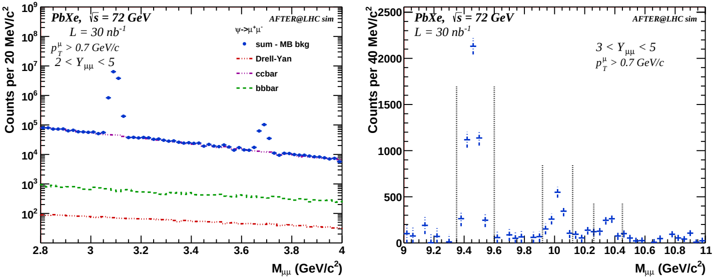
- In PbA collisions, one can repeat the celebrated $\Upsilon(nS)$ CMS analysis in a new energy domain



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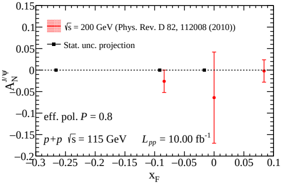

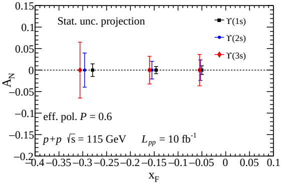

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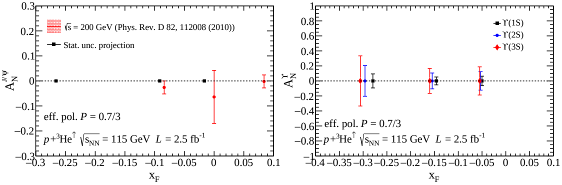

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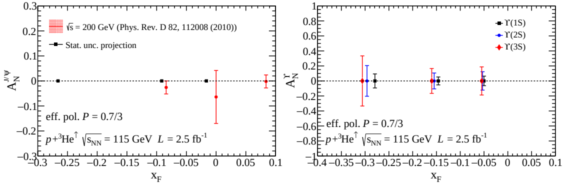

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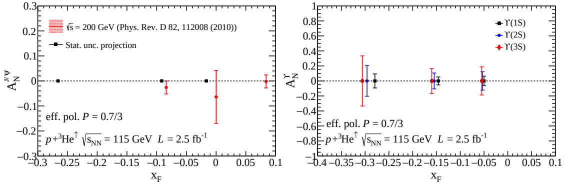

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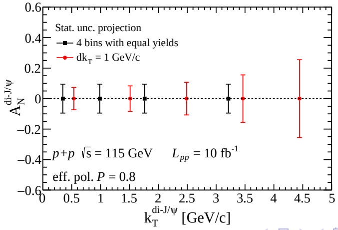

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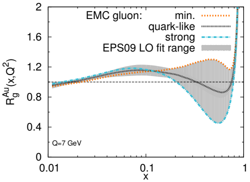

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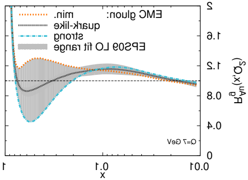

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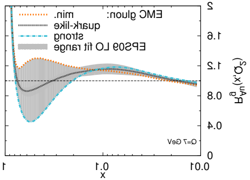

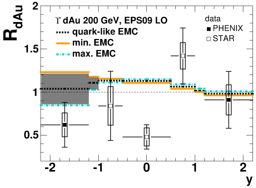

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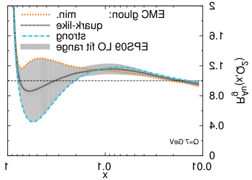

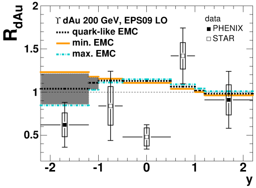

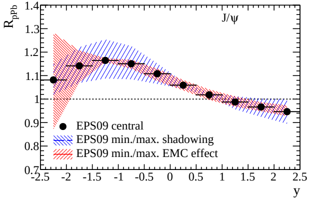

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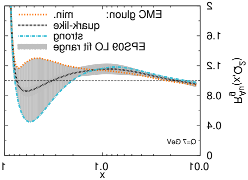

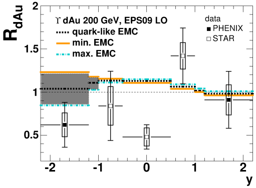

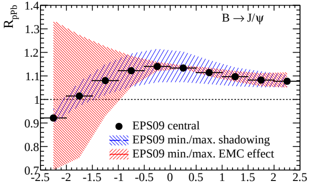

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L. Massacrieret al., Adv.Hi.En.Phys. (2015) 986348

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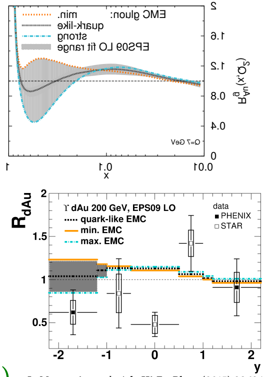

L. Massacrier*et al.*, Adv.Hi.En.Phys. (2015) 986348

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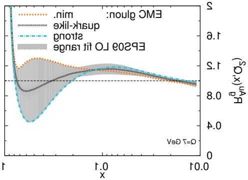

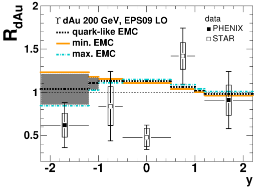

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- High stat. → quarkonium polarisation in pA and AA collisions

[→ production/suppression mechanisms]

UPC in the fixed target mode and J/ψ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner

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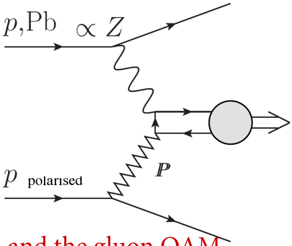

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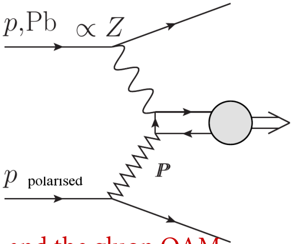

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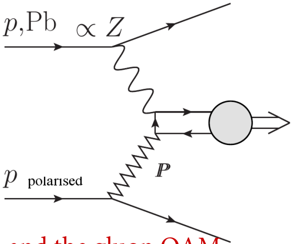

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  - 1600 dimuon events with the Pb beam [which we know for sure to be the γ emitter]
  - 340 000 dimuon events with the p beam [each p can emit; possible $\mathbb{O}\mathbb{P}$ contributions]

Part V

Conclusion and outlooks

Scientific conclusions

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  [without interfering with the other experiments]

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- In parallel, we pursuit our effort to finalise the Expression of Interest

Part VI

Backup slides

Further readings

Heavy-Ion Physics

- *Gluon shadowing effects on J/ψ and Υ 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.Peigne. [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.

Further readings

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.
- *η_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 Ξ_{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.

The extracted-beam option

★ The LHC beam may be extracted using "Strong crystalline field"

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E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131

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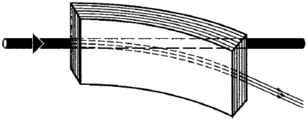

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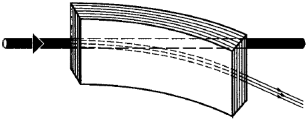

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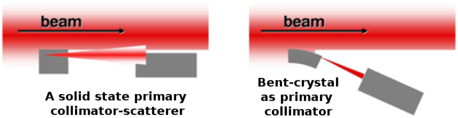

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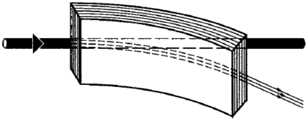

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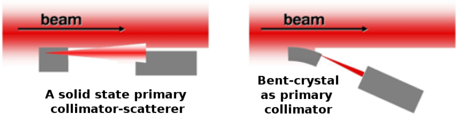

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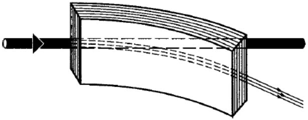

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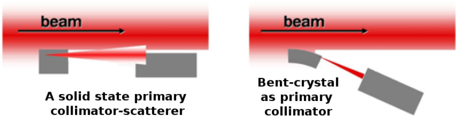

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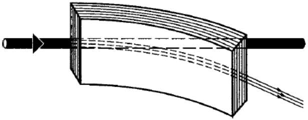

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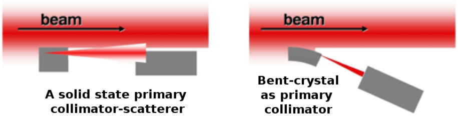

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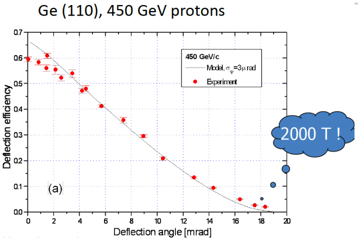
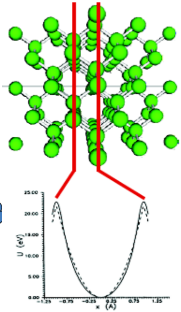
with a bent crystal (G. Cavoto - Rome)

The beam extraction with a bent crystal

- Inter-crystalline fields are huge





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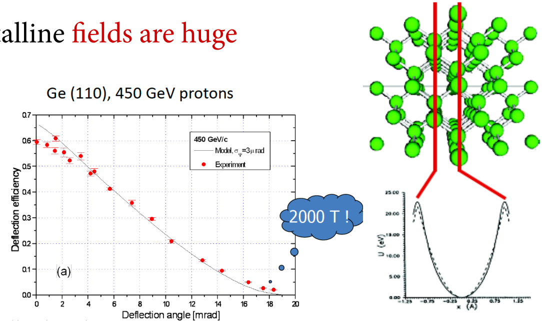

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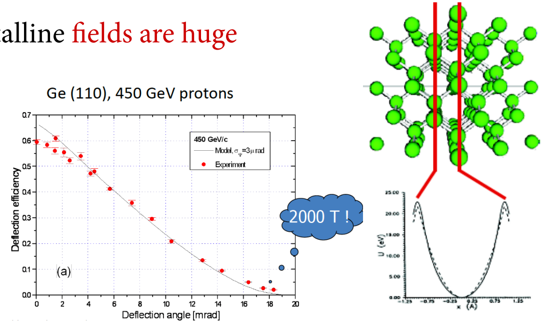

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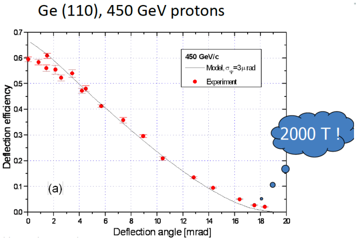

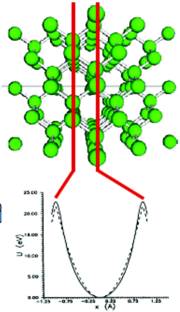

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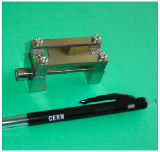
- Simple and robust way to extract the most energetic beam ever:



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- 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)

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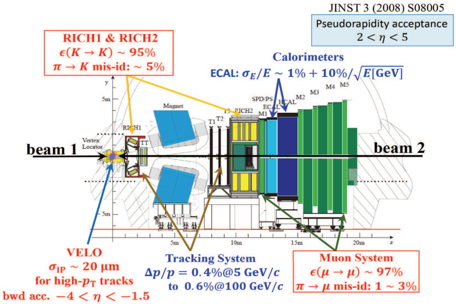
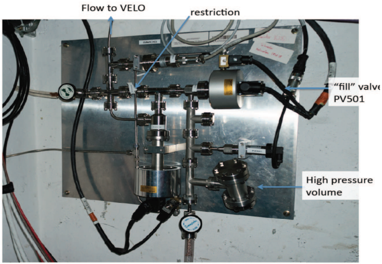


SMOG: System for Measuring Overlap with Gas



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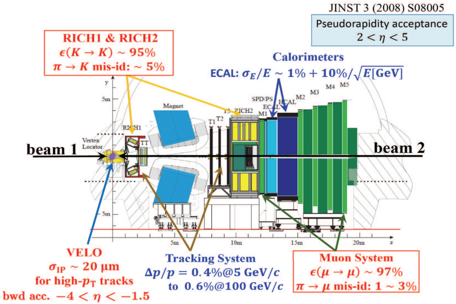

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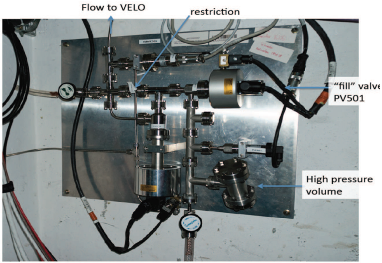

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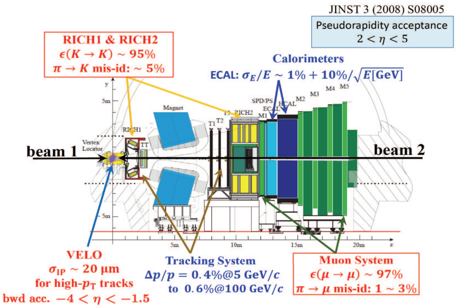

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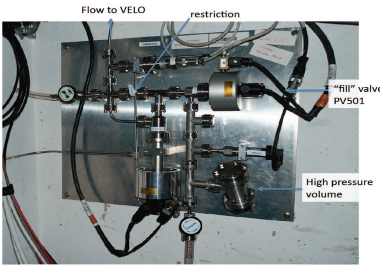

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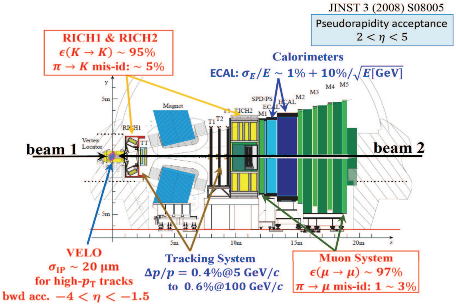

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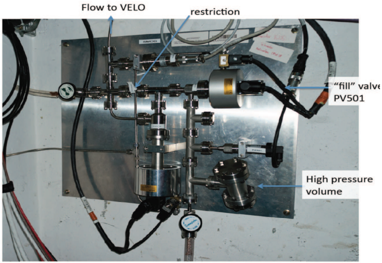

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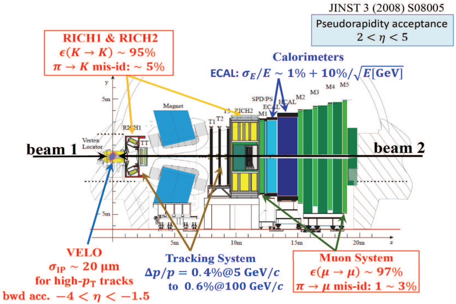

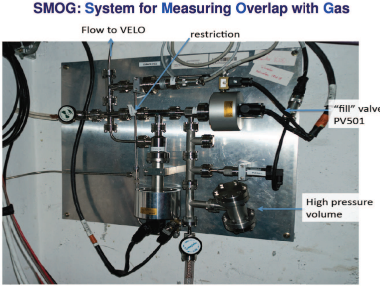

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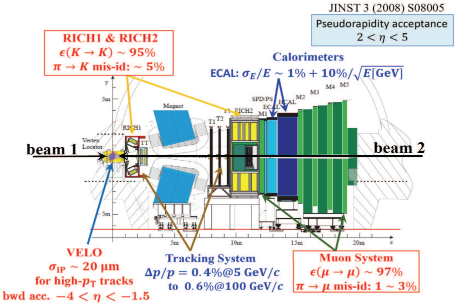

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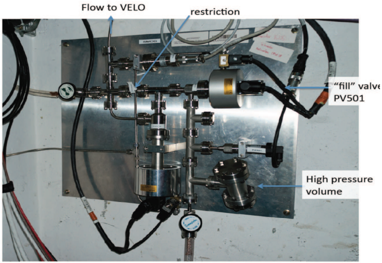

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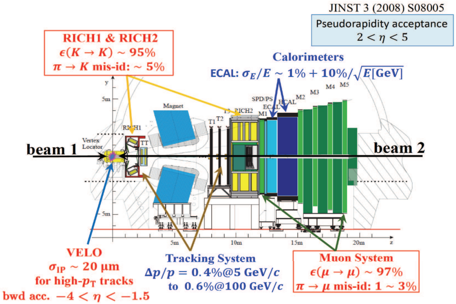

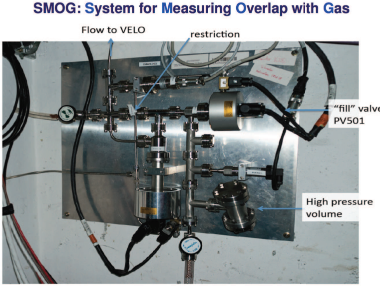

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C. Barschel, P. Lenisa, A. Nass, and E. Steffens, Adv.Hi.En.Phys. (2015) 463141; See E. Steffens's talk at PSTP 2015

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- Simply scaled up, this would give, for Pbp or PbA, 100 nb$^{-1}y^{-1}$.

$\Rightarrow$ For PbA, limitations would come first from the beam lifetime, pile-up and exp. DAQ

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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

- Simply scaled up, this would give, for Pbp or PbA, 100 nb$^{-1}y^{-1}$.

$\Rightarrow$ For PbA, limitations would come first from the beam lifetime, pile-up and exp. DAQ

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*
[3] *Institut für Kernphysik, FZJ, 52425 Jülich, Germany*
[4] *Physics Institute, Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany*

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}	1.6×10^{30} cm^{-2} s^{-1}
NH_3 COMPASS & extr. beam	$P = 0.9; f = 0.176; \theta = 2.8 \times 10^{25}$ cm^{-2}	3.5×10^{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}	6×10^{32} cm^{-2} s^{-1}

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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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- 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
  - E1039: sea quarks using an unpolarised proton beam (120 GeV) on a polarised proton target

SSA in Drell-Yan studies with AFTER@LHC

➟ Some parameters of existing and proposed polarised DY experiments.

S.J. Brodsky, F. Fleuret, C. Hadjidakis, JPL, Phys. Rep. 522 (2013) 239
V. Barone, F. Bradamante, A. Martin, Prog. Part. Nucl. Phys. 65 (2010) 267.

Experiment	particles	energy (GeV)	$\sqrt{s}$ (GeV)	$x_p^{\uparrow}$	$\mathcal{L}$ (nb^{-1}s^{-1})
AFTER	$p + p^{\uparrow}$	7000	115	0.01 ÷ 0.9	$\mathcal{O}(1)$
COMPASS	$\pi^{\pm} + p^{\uparrow}$	160	17.4	0.2 ÷ 0.3	2
COMPASS (low mass)	$\pi^{\pm} + p^{\uparrow}$	160	17.4	~ 0.05	2
P1039	$p + p^{\uparrow}$	120	15	0.1 ÷ 0.3	400-1000
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J–PARC	$p^{\uparrow} + p$	50	10	0.5 ÷ 0.9	1000
PANDA (low mass)	$\bar{p} + p^{\uparrow}$	15	5.5	0.2 ÷ 0.4	0.2
PAX	$p^{\uparrow} + \bar{p}$	collider	14	0.1 ÷ 0.9	0.002
NICA	$p^{\uparrow} + p$	collider	20	0.1 ÷ 0.8	0.001
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- Nota: At RHIC energy, Drell-Yan studies are very delicate
  [not yet done for unpolarised *pp* collisions]
- 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 $x^{\uparrow}$
where the k_T-spin correlation is the largest

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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
[2]INFN, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy
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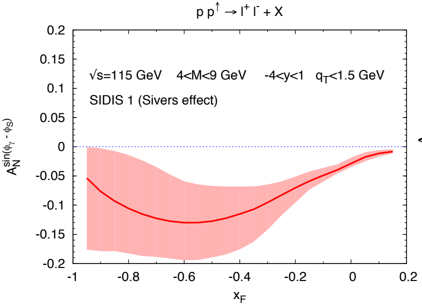

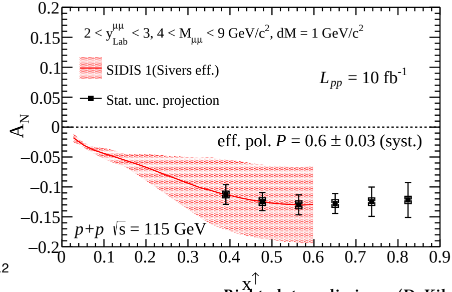

M. Anselmino, U. D'Alesio, S. Melis. Adv.Hi.En.Phys. (2015) 475040

Right plot: preliminary (D. Kikola)

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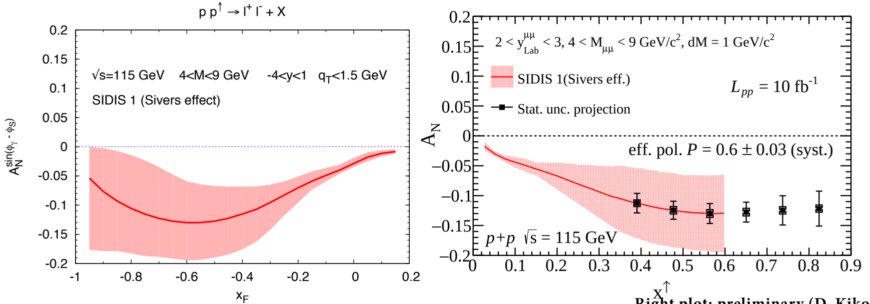

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Right plot: preliminary (D. Kikola)

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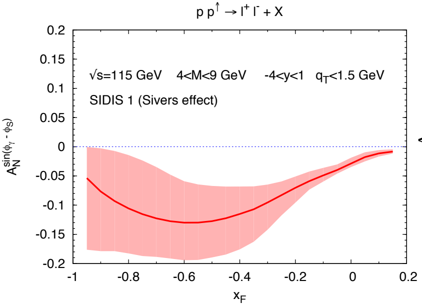

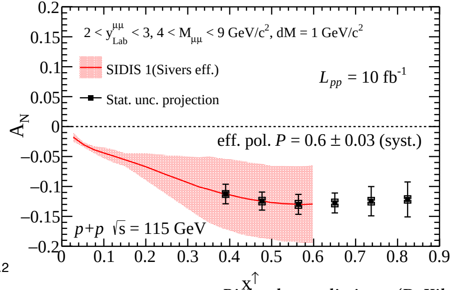

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- W and Z should be reachable with 10 fb^{-1}: $x^{\uparrow} \simeq 0.7 \div 0.8$

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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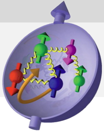

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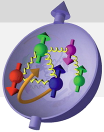

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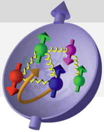

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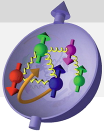

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D. Boer, C. Lorcé, C. Pisano,J. Zhou. Adv.Hi.En.Phys. (2015) ID:371396

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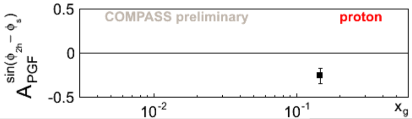
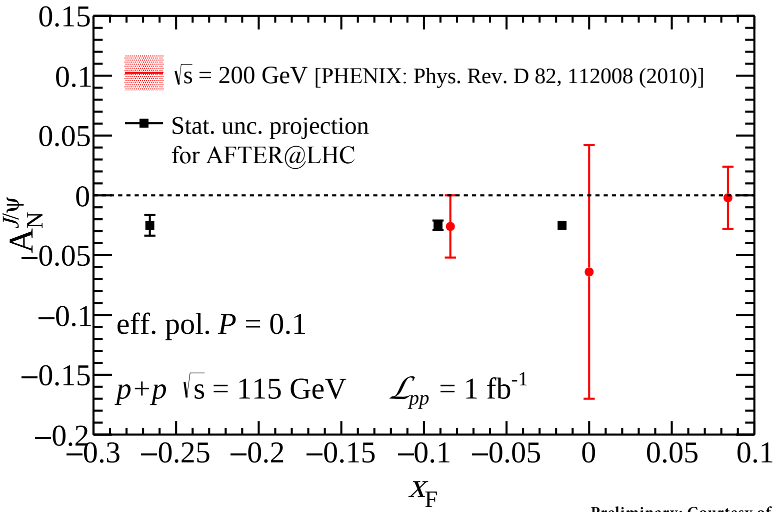
- Hint of nonzero gluon Sivers effect in $ep^{\uparrow} \rightarrow hh$: talk by A. Szabelski, yesterday



J/ψ 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

Gluons in the proton

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

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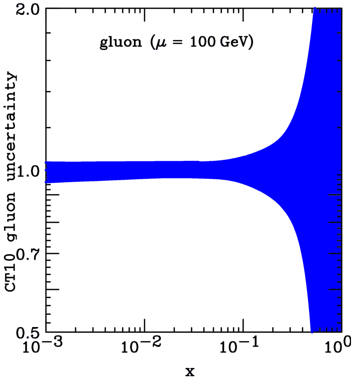

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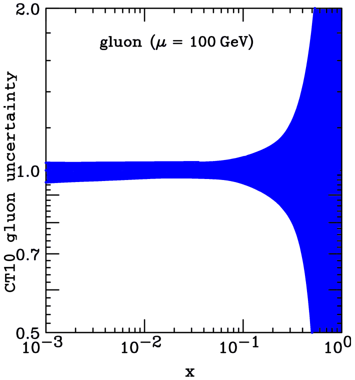

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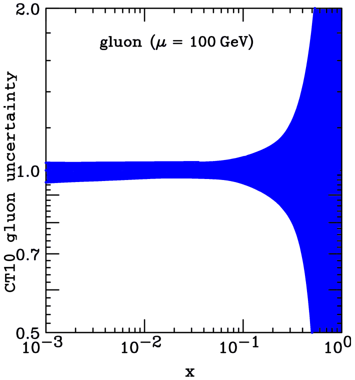

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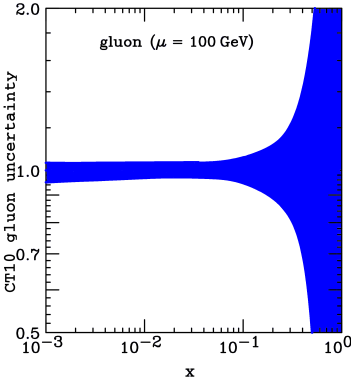

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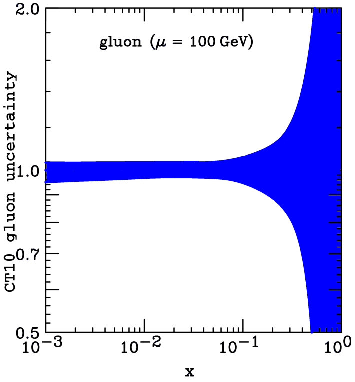

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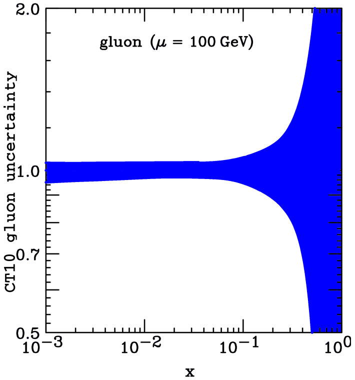

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Multiple probes needed to **check factorisation**

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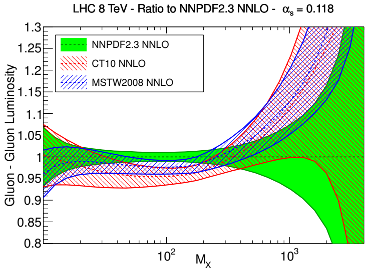

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Large-x gluons: important to characterise some possible BSM findings at the LHC

Distribution of linearly polarised gluons in unpolarised protons: $h_1^{\perp g}$

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PHYSICAL REVIEW D **86,** 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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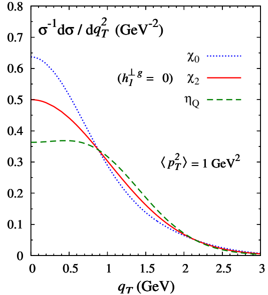

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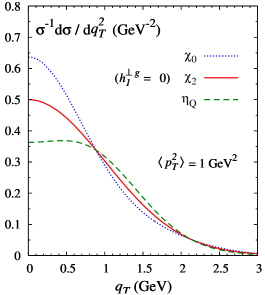

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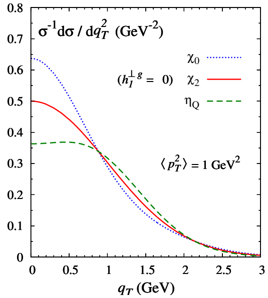

Access to $h_1^{\perp g}(x, k_T, \mu)$ II

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PRL **112,** 212001 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC

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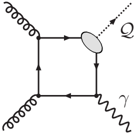

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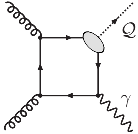

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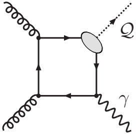

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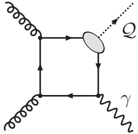

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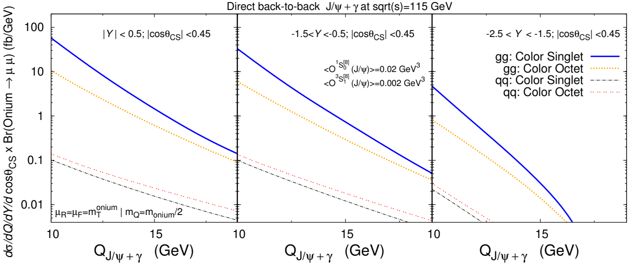

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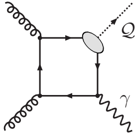

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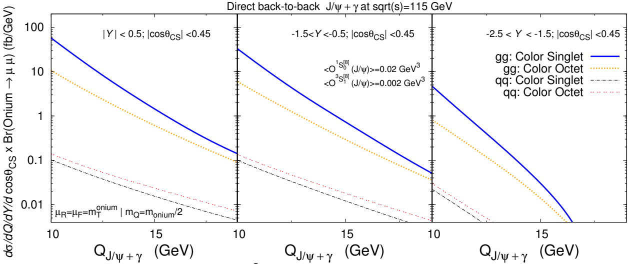

At $Y \simeq -2$, $x_2 \simeq 10/115 \times e^2 \simeq 0.65$. Yet, $g - g > q - \bar{q}$! [solid vs. dashed curves] http://www.hindawi.com/journals/ahep/si/354953/

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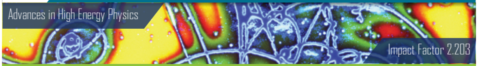

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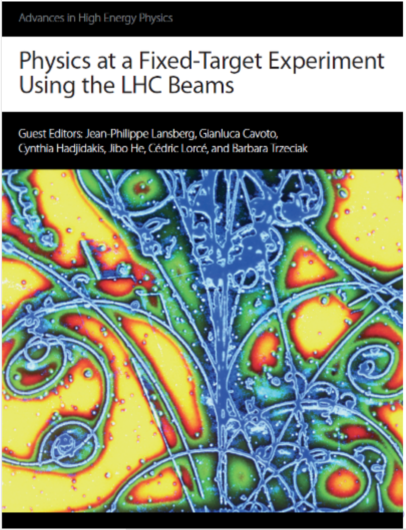
Physics at a Fixed-Target Experiment Using the LHC Beams

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



See also

Physics Reports 522 (2013) 239–255

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Physics opportunities of a fixed-target experiment using LHC beams

S.J. Brodsky [a], F. Fleuret [b], C. Hadjidakis [c], J.P. Lansberg [c,*]

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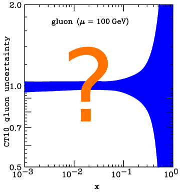

Gluon PDF for the neutron unknown

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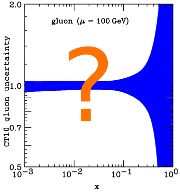

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possible experimental probes

- heavy quarkonia
- isolated photons
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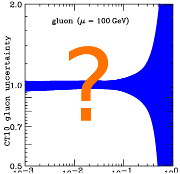

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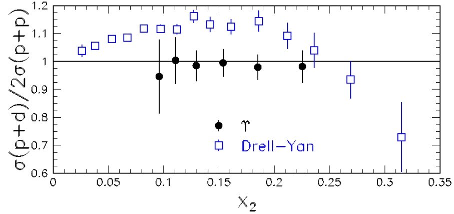
- heavy quarkonia
- isolated photons
- jets



Pioneer measurement by E866

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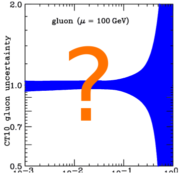
pd physics: gluons in the neutron and the deuteron



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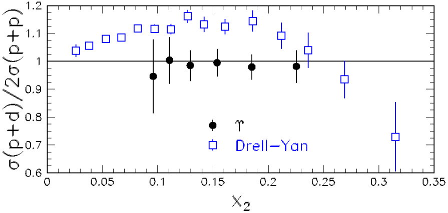

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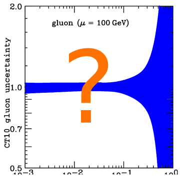

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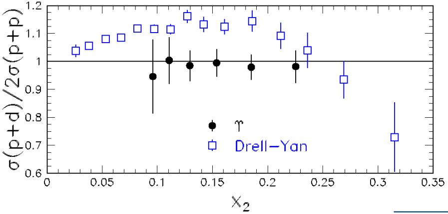

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target	yearly lumi	$\mathcal{B}\frac{dN_{J/\psi}}{dy}$	$\mathcal{B}\frac{dN_{\Upsilon}}{dy}$
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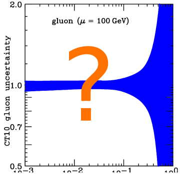

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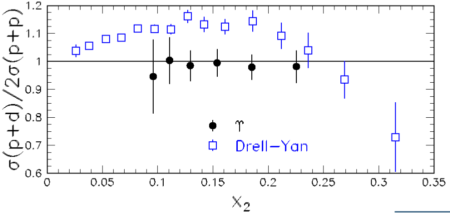

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If $g_n(x) - g_p(x)$ is too small, this measurement would anyhow be sensitive to the EMC and Fermi-motion effects in the deuteron

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

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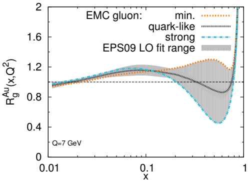

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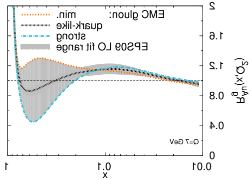

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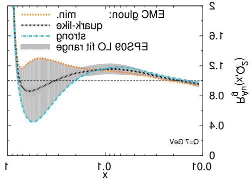

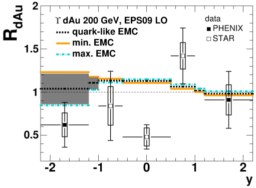

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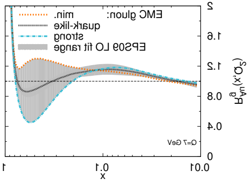

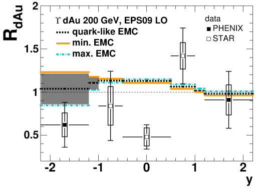

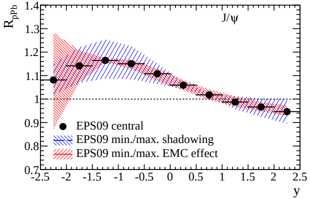

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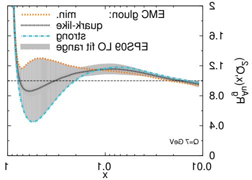

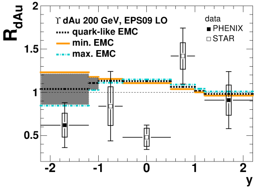

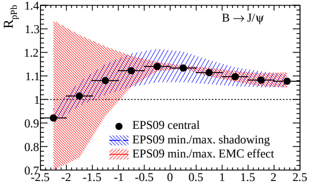

L. Massacrier*et al.*, Adv.Hi.En.Phys. (2015) 986348

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 25	$2.5 \cdot 10^{31}$ $2.5 \cdot 10^{32}$	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 T = 49.3 MeV	Cell ^{1}H, ^{2}D Cell ^{1}H	0.4	300	10^{29} $2.75 \cdot 10^{29}$	ANKE exp. PAX exp.	[4, 5] [11]
LHC CERN (proposed)	p unpol. heavy ions	7,000 $2{,}760 \cdot A$	Cell ^{1}H, ^{2}D Xe $M \approx 131$	1.0	100 ≥100	10^{33} 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 2×10^6 s (or 23 days).

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- Heavy-quark distributions (at high x_B)

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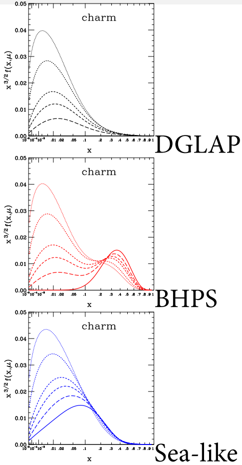

3 sets from CTEQ6c (Pumplin *et al.*)

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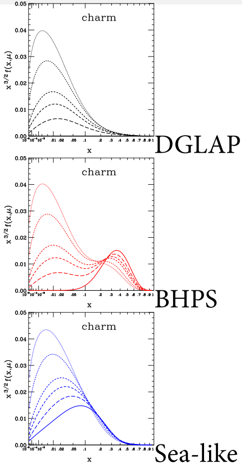

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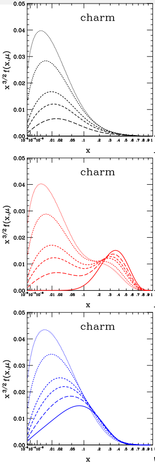

DGLAP

BHPS

Sea-like

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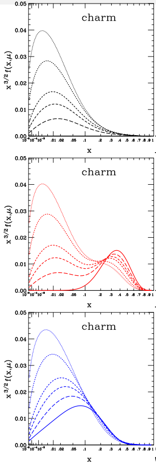

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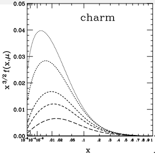

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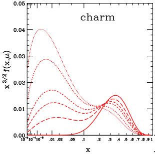

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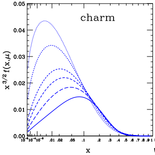

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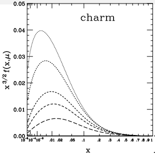

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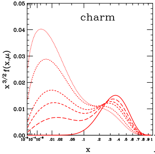

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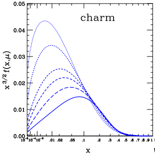

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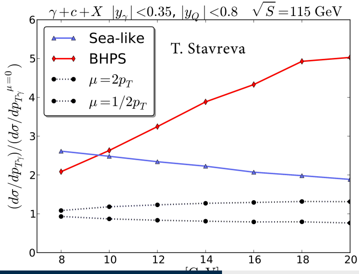

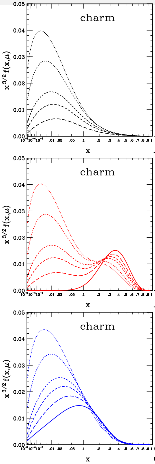

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QCD uncertainties in PeV neutrino studies

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  IceCube collab. PRL 111 (2013) 021103; Science 342 (2013) 1242856

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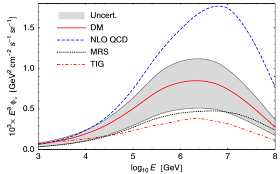

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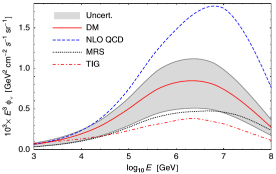

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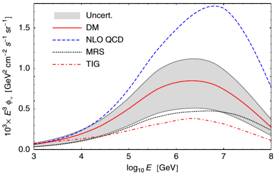

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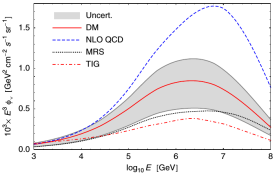

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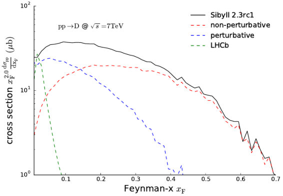

Figure 8. Weighted spectrum for *D*-mesons in SIBYLL at $\sqrt{s}$ = 7 TeV. The contributions from the perturbative and non-perturbative model components are shown by the blue and red lines, respectively. Note the negligible contribution to the energy spectrum from the phase space covered by the LHCb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

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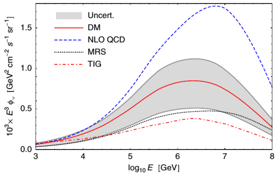
$$x_F^{collider} = \frac{2m_T}{2E_{beam}} \sinh\left(y^{lab.}\right) \;\; ; \;\; x_F^{FT} = \frac{2m_T}{\sqrt{2m_N E_{beam}}} \sinh\left(y^{lab.} - 4.8\right)$$

$$x_F^{FT}(P_T^D = 0, y^{lab.} = 2) \simeq -0.2 \;\; ; \;\; x_F^{FT}(P_T^D = 4\text{GeV}, y^{lab.} = 2) \simeq -0.6$$



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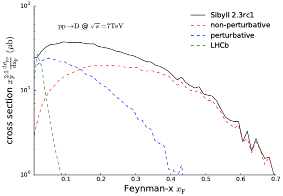

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Similar conclusion for the ALICE muon spectrometer

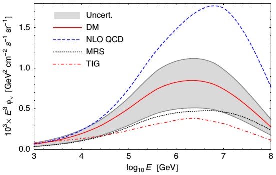


FIG. 6 (color online). Prompt muon neutrino fluxes obtained in perturbative QCD. The shaded area represents the theoretical uncertainty in the prompt neutrino flux evaluated in this paper, and the solid line in the band is our standard result. The dashed curve is the NLO perturbative QCD calculation 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).

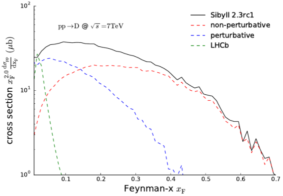
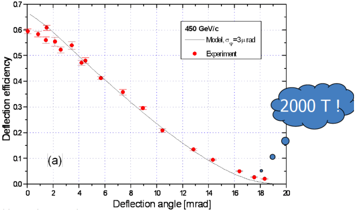


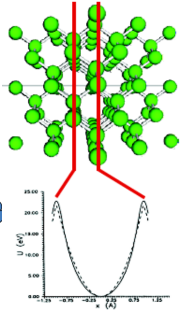
Figure 8. Weighted spectrum for *D*-mesons in SIBYLL at $\sqrt{s}$ = 7 TeV. The contributions from the perturbative and non-perturbative model components are shown by the blue and red lines, respectively. Note the negligible contribution to the energy spectrum from the phase space covered by the LHCb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

The beam extraction with a bent crystal

- Inter-crystalline fields are huge

Ge (110), 450 GeV protons





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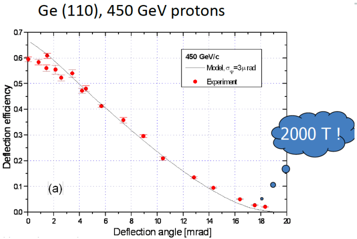

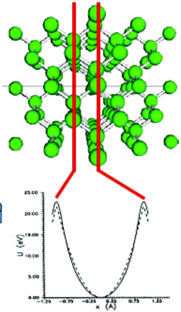

- The channeling efficiency is high for a deflection of a few mrad

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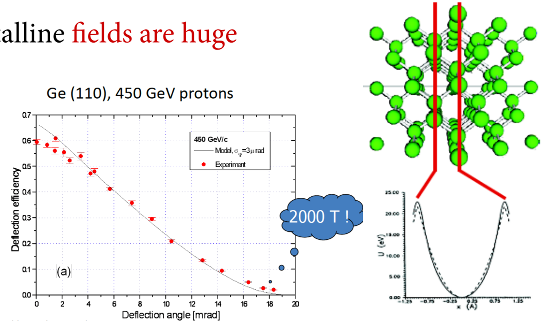

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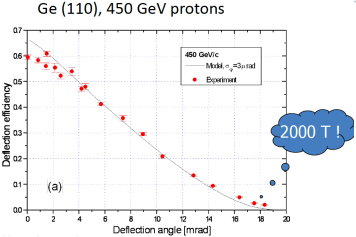
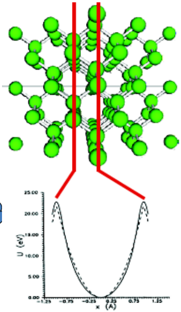
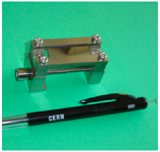




- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:

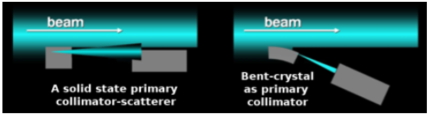


The beam extraction: news

[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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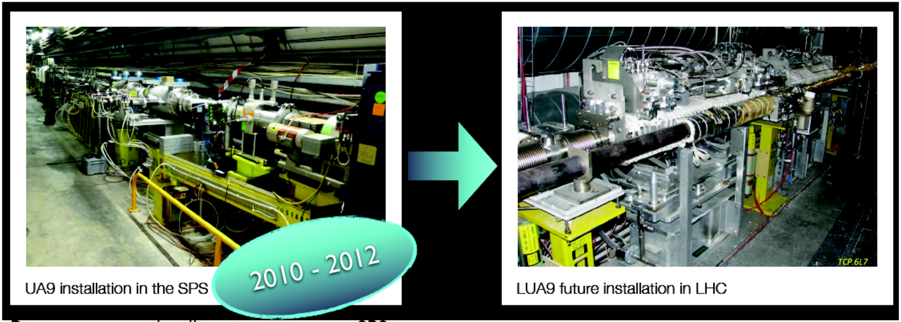

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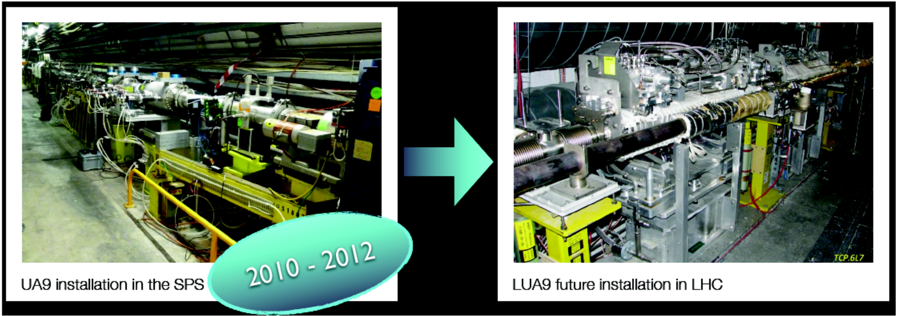

UA9 installation in the SPS

LUA9 future installation in LHC

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

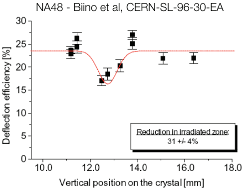
- 2 crystals

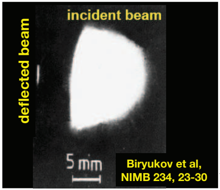
Long term plan is ambitious : propose a collimation system based on bent crystals for the upgrade of the current LHC collimation system

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

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

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These protons are lost anyway !

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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 $B^0 \to J/\psi + K^0_s$, $B^0 \to \pi^+\pi^-$. 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} $B\bar{B}$ 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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- 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:

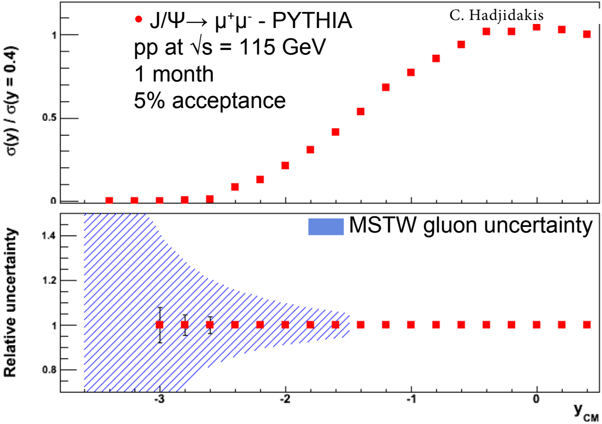
PYTHIA simulation
σ(y) / σ(y=0.4)
statistics for one month
5% acceptance considered

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

Generalities

- pp or pA collisions with a 7 TeV p^+ on a fixed target occur at a CM energy

$$\boxed{\sqrt{s} = \sqrt{2 m_N E_p} \simeq 115 \text{ GeV}}$$

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- Let us simply avoid the forward region ! How ?

Boost effect: LHCb becomes a backward detector

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- The pseudo-rapidity coverage of LHCb, $2 \leq \eta \leq 5$, approximately translates to a rapidity coverage in the *CM* of roughly $-2.8 \leq y_{CM} \leq 0.2$
- ALICE muon arm: $2.5 \leq \eta \leq 4 \Rightarrow -2.3 \leq y_{CM} \leq -0.8$

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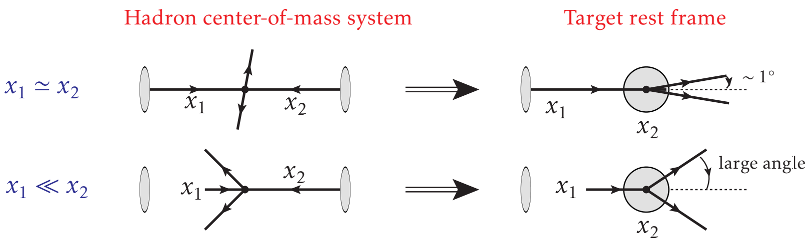

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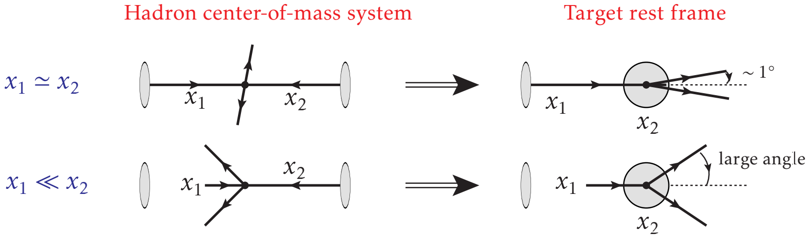

backward physics = large-x_2 physics

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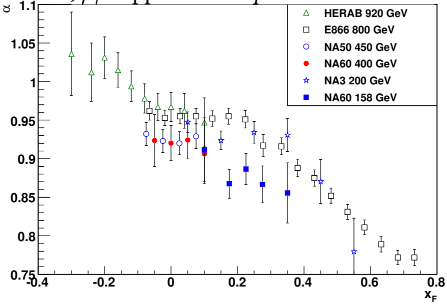

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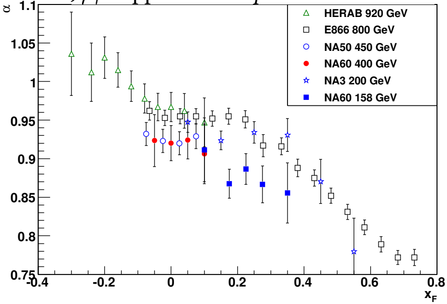

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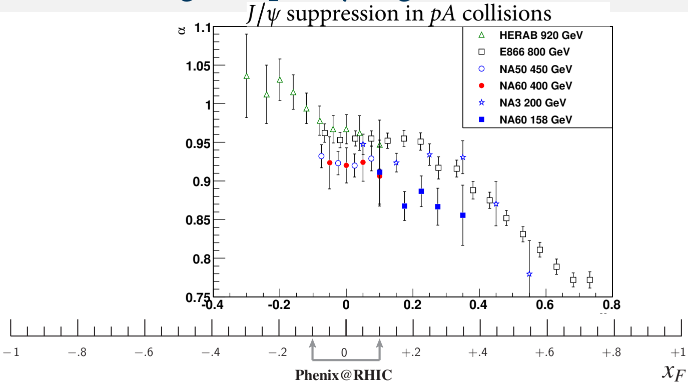

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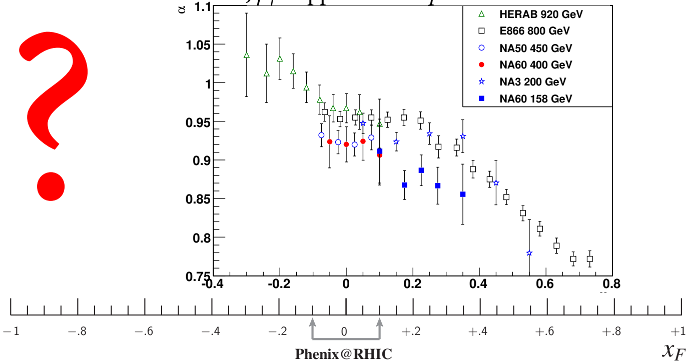

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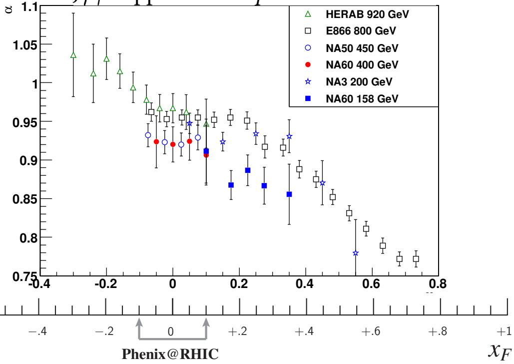

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