Perspectives for ultra-peripheral collisions at LHC fixed-target energies (AFTER@LHC)

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Workshop on photon-induced collisions at the LHC

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Part I

Introduction

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- They exhibit 4 decisive features,
  - accessing the high Feynman x_F domain ($x_F \equiv \frac{p_z}{p_{z\,\max}}$)
  - achieving high luminosities with dense targets,
  - varying the atomic mass of the target almost at will,
  - polarising the target.

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- Good thing: small forward detector $\equiv$ large acceptance
- Bad thing: high multiplicity $\Rightarrow$ absorber $\Rightarrow$ physics limitation

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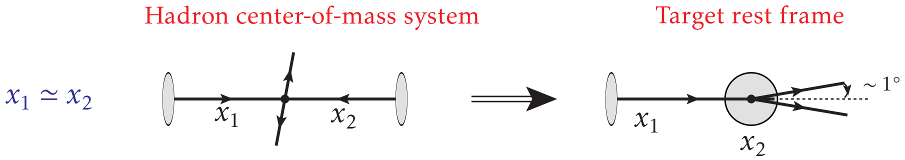

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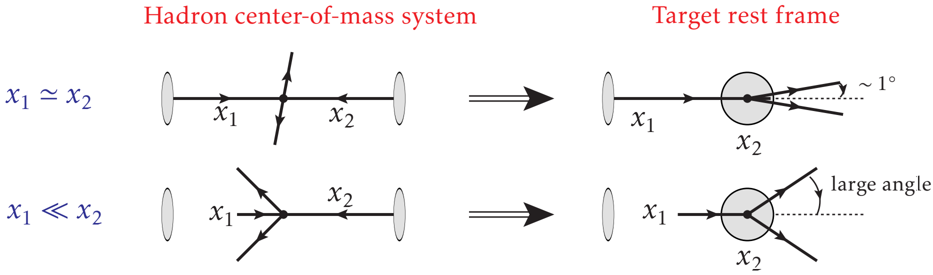

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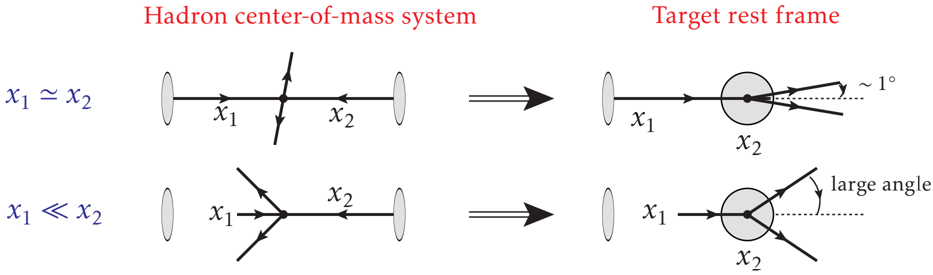

backward physics = large-x_2 physics

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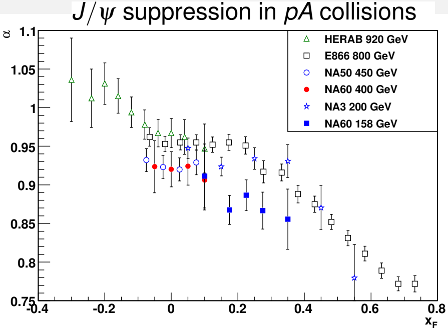

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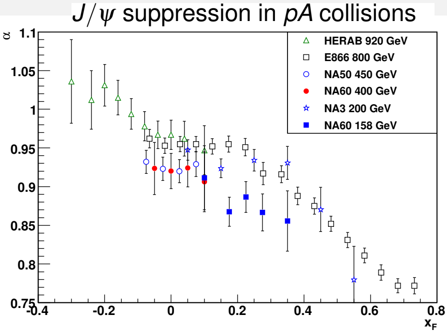

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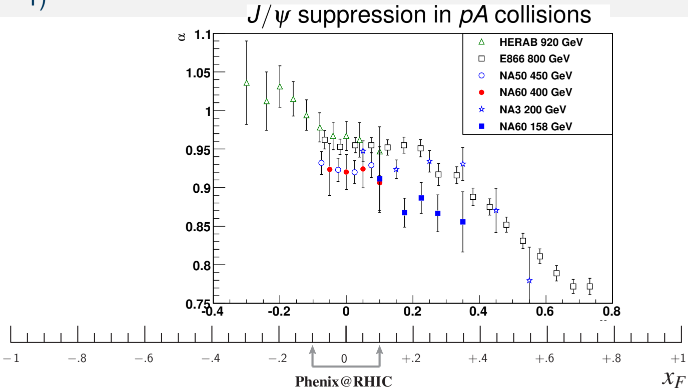

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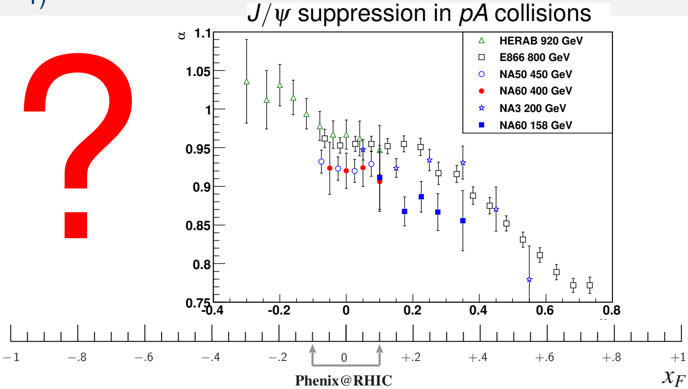

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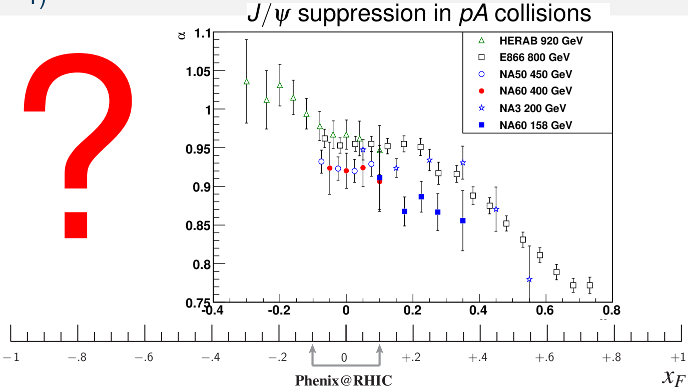

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- If we measure $\Upsilon(b\bar{b})$ at $y_{\rm cms} \simeq -2.5$ $\Rightarrow x_F \simeq \frac{2m_\Upsilon}{\sqrt{s}} \sinh(y_{\rm cms}) \simeq -1$

The beam extraction

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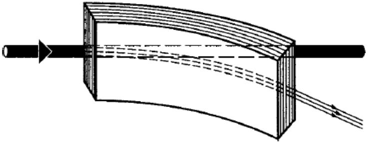

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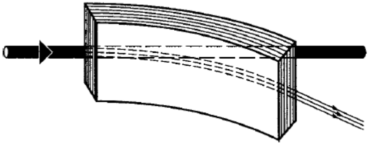

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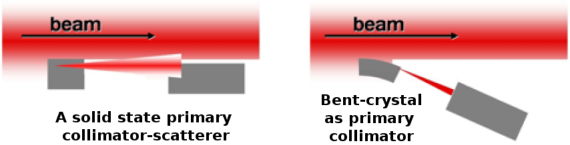

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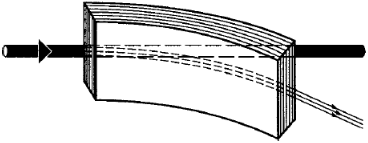

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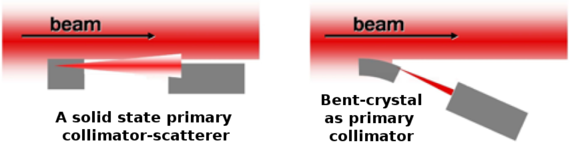

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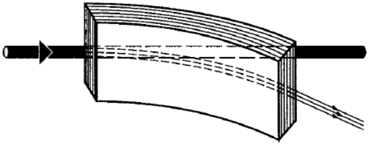

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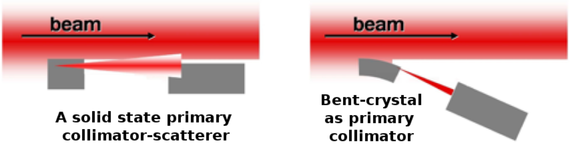

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Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (μb^{-1}.s^{-1})	$\int\mathcal{L}$ (pb^{-1}.yr^{-1})
Sol. H_2	0.09	1	**26**	**260**
Liq. H_2	0.07	1	**20**	**200**
Liq. D_2	0.16	2	**24**	**240**
Be	1.85	9	**62**	**620**
Cu	8.96	64	**42**	**420**
W	19.1	185	**31**	**310**
Pb	11.35	207	**16**	**160**

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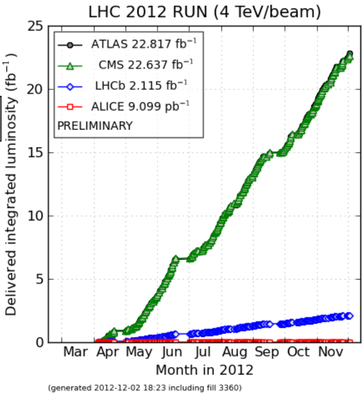

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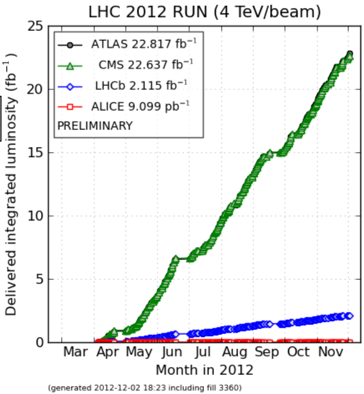

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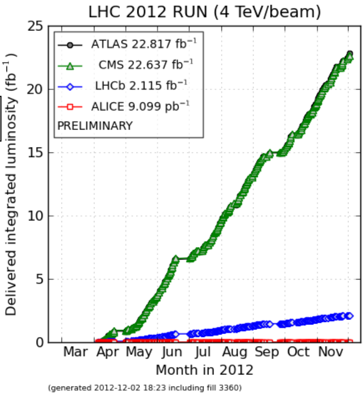

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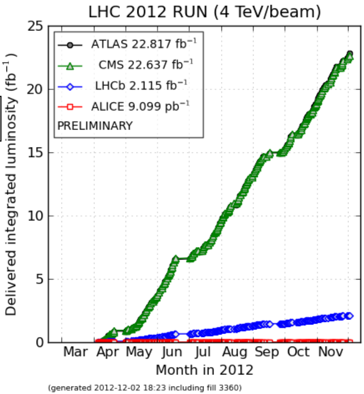
- Lumi for Pb runs in the backup slides

(roughly 10 times that planned for the LHC)



A few figures on the (extracted) proton beam

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- Extracted "mini" bunches:
  - the crystal sees 2808×11000 s^{-1} $\simeq 3.10^7$ bunches s^{-1}
  - one extracts $5.10^8/3.10^7 \simeq$ 15p^+ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%,

no pile-up !

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  - the crystal sees 2808×11000 s^{-1} $\simeq 3.10^7$ bunches s^{-1}
  - one extracts $5.10^8/3.10^7 \simeq 15p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%,

no pile-up !

- Extraction over a 10h fill:
  - $5 \times 10^8 p^+ \times 3600$ s h^{-1} $\times 10$ h $= 1.8 \times 10^{13} p^+$ fill^{-1}
  - This means $1.8 \times 10^{13}/3.2 \times 10^{14} \simeq$ 5.6% of the p^+ in the beam

These protons are lost anyway !

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
- Number of p^+: 2808 bunches of $1.15 \times 10^{11} p^+ = 3.2 \times 10^{14} p^+$
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- similar figures for the Pb-beam extraction

A few more figures II

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  37 % no coll., 37 % 1 coll., 26 % 2 coll.
- For $\mathscr{L} = \frac{1}{10}\mathscr{L}_{max}$, $\mu = 0.1$ thus
  90.5 % no coll., 9 % 1 coll., 0.5 % 2 coll.
  (ratio 1 coll. vs. 2 coll. : better)

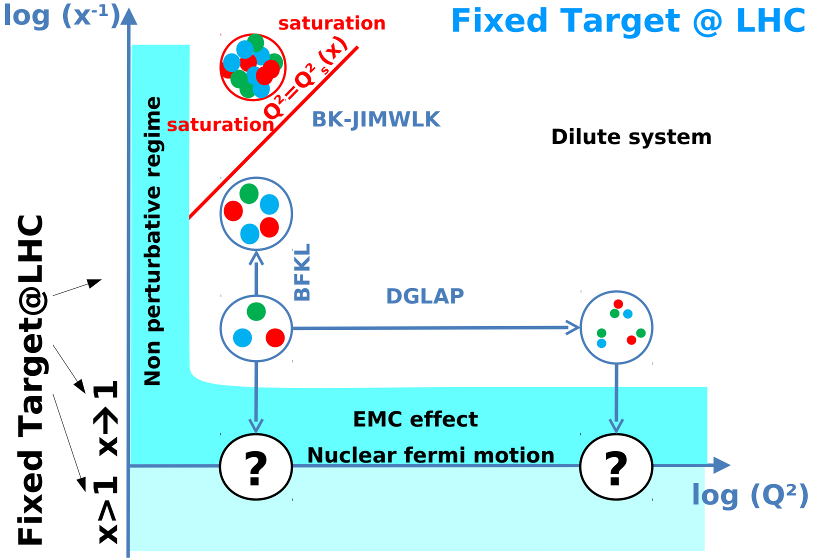
Luminosities for the Pb beam

- Instantaneous Luminosity:
  $\mathscr{L} = \Phi_{beam} \times N_{target} = N_{beam} \times (\rho \times \ell \times \mathscr{N}_A)/A$
  $\Phi_{beam} = 2 \times 10^5$ Pb s^{-1}, $\ell = 1$ cm (target thickness)
- Integrated luminosity $\int dt \mathscr{L} = \mathscr{L} \times 10^6$ s for Pb
- Expected luminosities with 2×10^5Pb s^{-1} extracted (1cm-long target)

Target	ρ (g.cm^{-3})	A	$\mathcal{L}$ (mb^{-1}.s^{-1})=$\int\mathcal{L}$ (nb^{-1}.yr^{-1})
Sol. H_2	0.09	1	**11**
Liq. H_2	0.07	1	**8**
Liq. D_2	0.16	2	**10**
Be	1.85	9	**25**
Cu	8.96	64	**17**
W	19.1	185	**13**
Pb	11.35	207	**7**

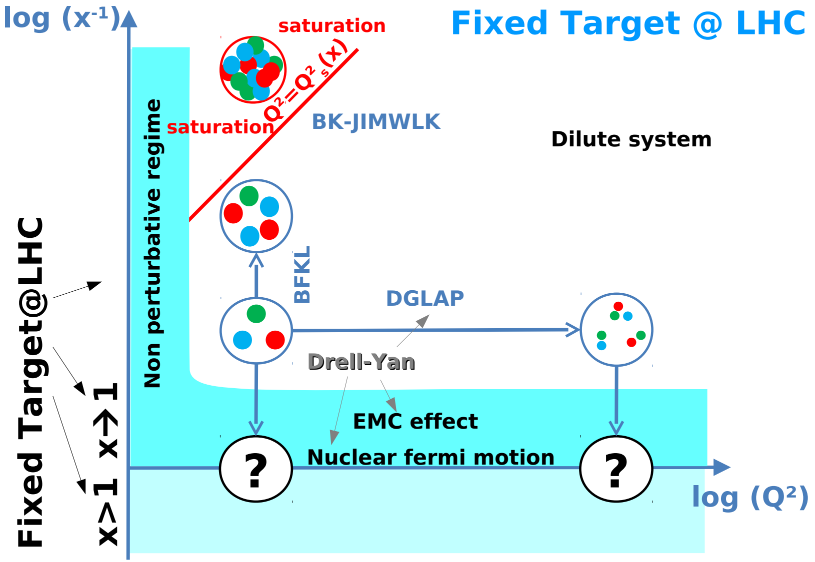
- Planned lumi for PHENIX Run15AuAu 2.8 nb^{-1} (0.13 nb^{-1} at 62 GeV)
- Nominal LHC lumi for PbPb 0.5 nb^{-1}

Overall



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

Overall



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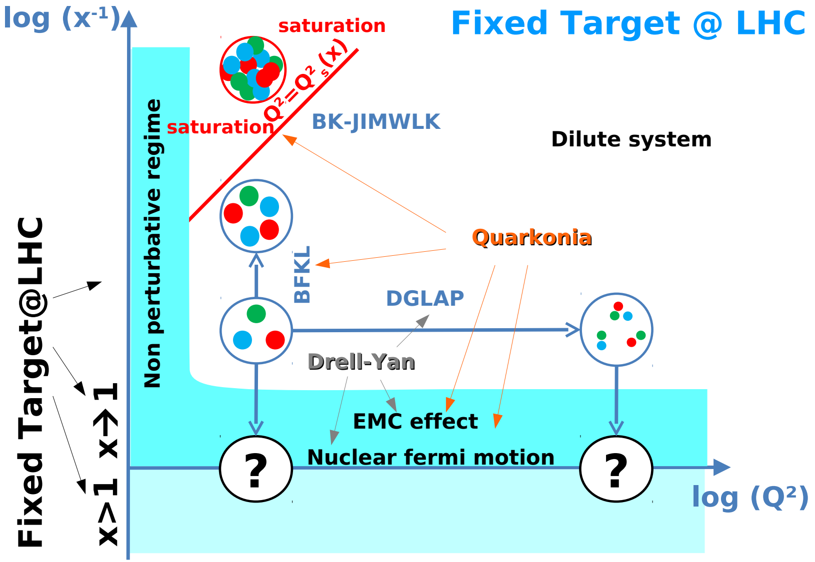

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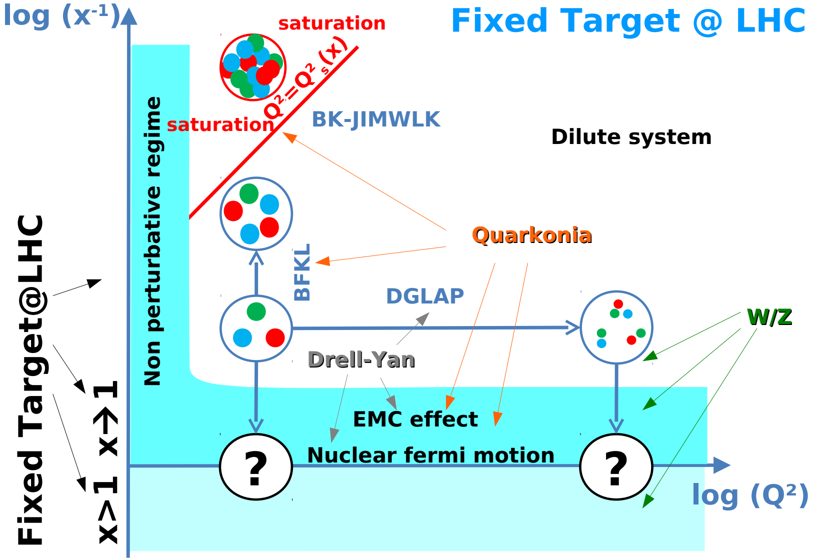
Overall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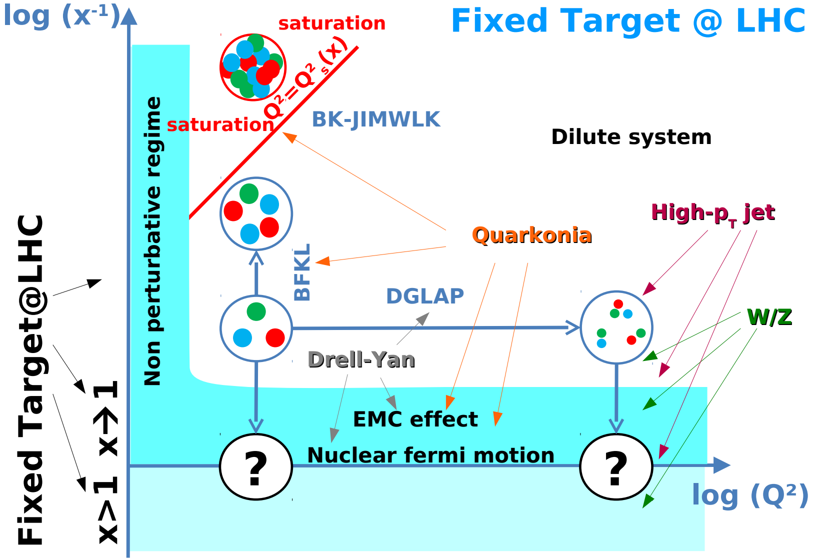
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More details in

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
[b] Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France
[c] IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

ISSN 1063-7796, Physics of Particles and Nuclei, 2014, Vol. 45, No. 1, pp. 336–337. © Pleiades Publishing, Ltd., 2014.

Spin Physics at A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)[1]

A. Rakotozafindrabe[a], M. Anselmino[b], R. Arnaldi[b], S. J. Brodsky[c], V. Chambert[d], J. P. Didelez[d], B. Genolini[d], E.G. Ferreiro[e], F. Fleuret[f], C. Hadjidakis[d], J. P. Lansberg[d], C. Lorcé[d], P. Rosier[d], I. Schienbein[g], E. Scomparin[b], and U. I. Uggerhøj[h]

Few-Body Syst (2012) 53:11–25
DOI 10.1007/s00601-012-0445-8

J. P. Lansberg · S. J. Brodsky · F. Fleuret · C. Hadjidakis

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

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SciVerse ScienceDirect

NUCLEAR PHYSICS A

Nuclear Physics A 904–905 (2013) 957c–960c

www.elsevier.com/locate/nuclphysa

Ultra-relativistic heavy-ion physics with AFTER@LHC

A. Rakotozafindrabe[a], R. Arnaldi[b], S.J. Brodsky[c], V. Chambert[d], J.P. Didelez[d], B. Genolini[d], E.G. Ferreiro[e], F. Fleuret[f], C. Hadjidakis[d], J.P. Lansberg[d], P. Rosier[d], I. Schienbein[g], E. Scomparin[b], U.I. Uggerhøj[h]

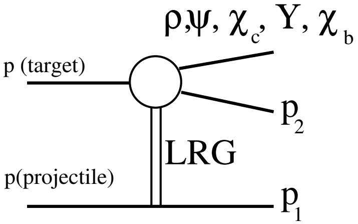
Part II

Exclusive reactions and Ultra-peripheral collisions with AFTER

Very forward (backward) physics ($x_F \to \pm 1$)

- Diffractive quarkonia production from intrisic charm

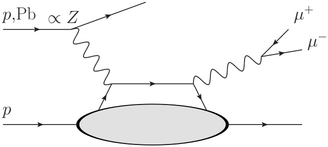
similar to Higgs production (**S. J. Brodsky** *et al.* **Phys. Rev. D 73, 113005 (2006)**)



Ultra-Peripheral Collisions

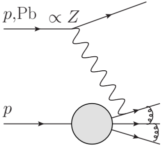
- $\sqrt{s_{\gamma p}}$ up to 60 GeV
- inverse DVCS (GPDs)

  (**B. Pire** *et al.* **Phys. Rev. D 79 (2009) 014010)**

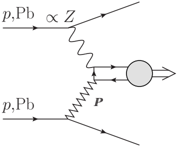


- proton dissociation (DAs)

  (**L. Frankfurt and M. Strikman, hep-ph/0210087)**
  (**D. Y. Ivanov** *et al.* **Phys. Lett. B 666 (2008) 245)**



- vector meson photoproduction



UPC in the fixed target mode

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- $\gamma_{\rm lab}^{\rm beam} \simeq 7000$ ($E_p = 7000$ GeV)
- $E_\gamma^{\rm max} \simeq \gamma_{\rm lab}^{\rm beam} \times 30$ MeV ($1/(R_{\rm Pb} + R_p) \simeq 30$ MeV)

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System	target thickness (cm)	$\sqrt{s_{NN}}$ (GeV)	$\mathcal{L}_{AB}$ [a] (pb^{-1}yr^{-1})	$E_A^{\rm lab}$ (GeV)	$E_B^{\rm lab}$ (GeV)	$\gamma^{\rm c.m.s.}$ $(\frac{\sqrt{s_{NN}}}{2m_N})$	$\gamma^{\rm A\leftrightarrow B}$ $(\frac{s_{NN}}{2m_N^2})$	$\frac{\hbar c}{R_A+R_B}$ (MeV)	$E_{\gamma\ \rm max}^{\rm A/B\ rest}$ (GeV)	$\sqrt{s_{\gamma N}^{\rm max}}$ (GeV)	$E_{\gamma\ \rm max}^{\rm c.m.s.}$ (GeV)	$\sqrt{s_{\gamma\gamma}^{\rm max}}$ (GeV)
AFTER												
pp	100	115	2.0×10^4	7000	m_N	61.2	7450	140	1050	44	8.5	17
pPb	1	115	1.6×10^2	7000	m_N	61.2	7450	26	190	19	1.6	3.2
pd	100	115	2.4×10^4	7000	m_N	61.2	7450	70	520	31	4.3	8.5
PbPb	1	72	$7. \times 10^{-3}$	2760	m_N	38.3	2940	14	40	9	0.5	1.0
Pbp	100	72	1.1	2760	m_N	38.3	2940	26	76	12	1.6	3.2
Arp	100	77	1.1	3150	m_N	40.9	3350	41	140	16	2.5	5.0
Op	100	81	1.1	3500	m_N	43.1	3720	52	190	19	3.2	6.3
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pp	N/A	200	1.2×10^1	100	100	106.4	22600	140	3150	77	15	30
AuAu	N/A	200	2.8×10^{-3}	100	100	106.4	22600	14	320	24	1.5	3.0
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InIn	.	17	.	160	m_N	9.22	170	17	2.9	2.5	0.15	0.31
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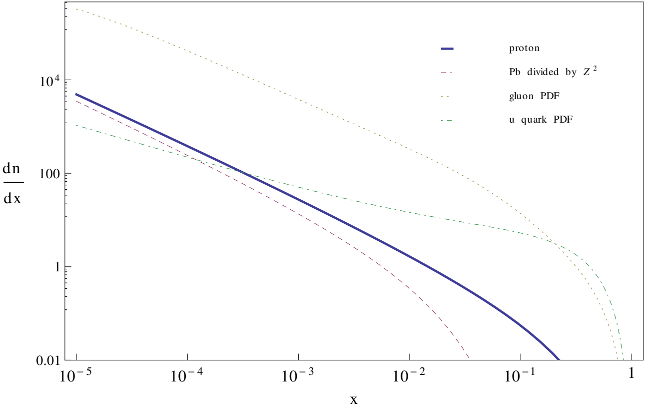
Attempt at CERN-SPS: “In-In Ultra Peripheral Collisions in NA60” by P. Ramalhete (PhD), 2009

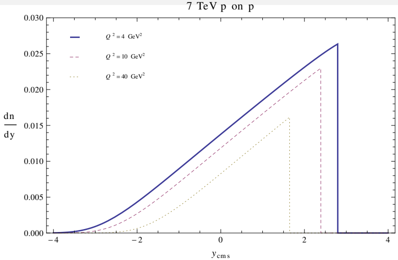
A closer look at the photon flux (as fct of the final-state kin.)

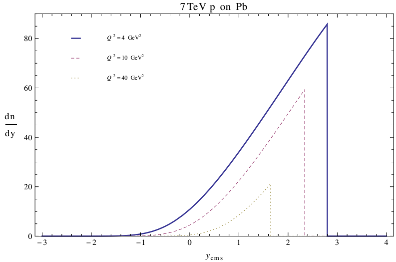


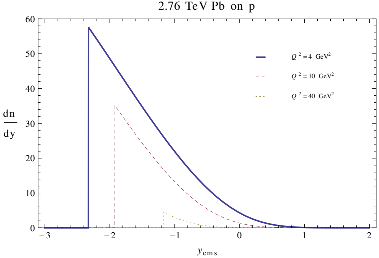
- For $\gamma\gamma$ collisions, the photon flux is simply maximum for $y_{cms} = 0$
- For γp, it is much less trivial
- It is instructive to analyse the photon flux as function of y of the produced particle

A closer look at the photon flux (as fct of the final-state kin.)

Let's look at the photoproduction of a dilepton, $\gamma p \to \ell^+ \ell^- p$, at small t and fixed dilepton mass (Q);
the dilepton rapidity depends on the incident photon energy:
$\frac{d\sigma^{hh}}{dy} = \frac{dn}{dy}\, d\sigma^{\gamma h}(s^{\gamma\, h}(k_\gamma(y)))$
$\Rightarrow$ let's look at the γ flux as a function of y







$y_{\rm Lab} = y_{\rm cms} + 4.8(4.3)$ for 7 TeV (2.76 TeV) beam

$\Rightarrow$ *Pb*p is preferred with an acceptance $y_{\rm Lab} \in [2:5]$

Timelike Compton Scattering vs. Bethe Heitler pair production

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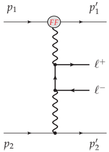
  [Should coincide with EPA $\otimes \gamma\gamma \to \ell^+\ell^-$]



$$\frac{d\sigma_{BH}^{\gamma p}}{dQ^2\, dt\, d(\cos\theta)\, d\varphi} \approx \frac{\alpha_{em}^3}{2\pi s^2} \frac{1}{-t} \frac{1+\cos^2\theta}{\sin^2\theta} \times \left[\left(F_1^2 - \frac{t}{4M^2} F_2^2 \right) \frac{2}{\tau^2} \frac{\Delta_T^2}{-t} + (F_1 + F_2)^2 \right]$$

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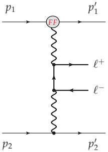

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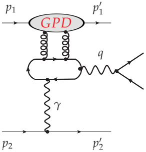
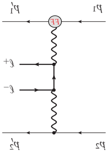




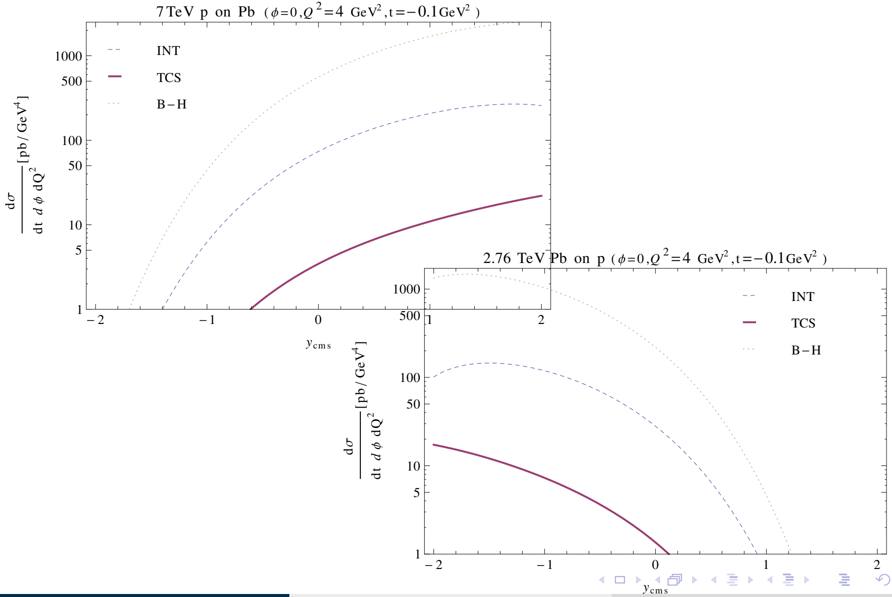
- Interference with Timelike Compton Scattering

$$\frac{d\sigma^{\gamma p}_{INT}}{dQ^2\, dt\, d(\cos\theta)\, d\varphi} \approx$$

$$-\frac{\alpha^3_{em}}{4\pi s^2}\, \frac{\sqrt{t_0 - t}}{-tQ}\, \frac{\sqrt{1-\eta^2}}{\eta} \left(\cos\varphi\, \frac{1+\cos^2\theta}{\sin\theta} \right) \mathrm{Re} \left[F_1 \mathscr{H} - \eta(F_1 + F_2)\, \tilde{\mathscr{H}} - \frac{t}{4M^2}\, F_2\, \mathscr{E} \right]$$

where $\{\mathscr{H}, \tilde{\mathscr{H}}, \mathscr{E}\}(\eta, t) = \int_{-1}^{1} dx\, T(x,\eta)\, \{H, \tilde{H}, E\}(x, \eta, t)$

First results for $\sigma^{p\mathrm{Pb}}$ and $\sigma^{\mathrm{Pb}p}$



One exotic illustration of the potentialities with UPC

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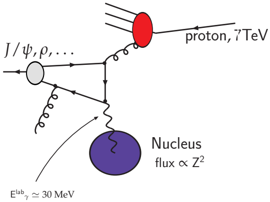
Inelastic photoproduction of J/ψ via UPC



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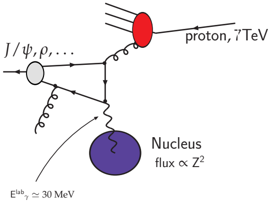

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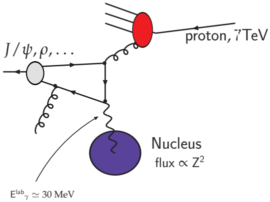

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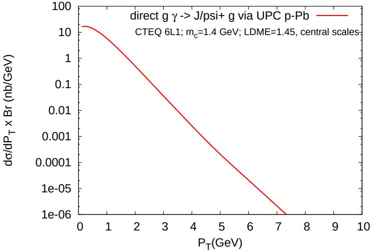

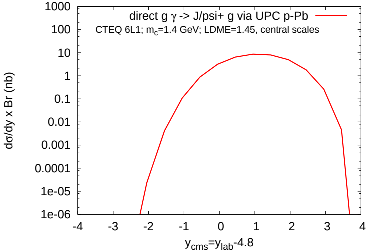

Disclaimer: these numbers suppose a dedicated trigger and are preliminary

Part III

Conclusion and outlooks

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- A 10-day exploratory workshop at ECT* Trento, February 4-13, 2013 slides at `http://indico.in2p3.fr/event/AFTER@ECTstar`
- Workshop in Les Houches on 12-17 January 2014
  `http://indico.in2p3.fr/event/AFTER@LesHouches`
  and 3-day workshop in Orsay with LUA9 on November 18-20, 2013
  `http://indico.in2p3.fr/event/LUA9-AFTER-1113`
- We are looking for more partners to
  - do first simulations (we are starting fast simulations)
  - think about possible designs
  - think about the optimal detector technologies
  - enlarge the physics case
    (cosmic rays, flavour physics, ...)

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  Webpage: **`http://after.in2p3.fr`**

Further readings

- *Hadronic production of Ξ_{cc} at a fixed-target experiment at the LHC*
  By G. Chen *et al.*. [arXiv:1401.6269 [hep-ph]]. Phys.Rev. D89 (2014) 074020.
- *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.
- *Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)*
  By T. Liu, B.Q. Ma. [arXiv:1203.5579 [hep-ph]]. Eur.Phys.J. C72 (2012) 2037.
- *Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER*
  By D. Boer, C. Pisano. [arXiv:1208.3642 [hep-ph]]. Phys.Rev. D86 (2012) 094007.
- *Ultra-relativistic heavy-ion physics with AFTER@LHC*
  By A. Rakotozafindrabe, *et al.* . [arXiv:1211.1294 [nucl-ex]]. Nucl.Phys. A904-905 (2013) 957c.
- *Spin physics at A Fixed-Target ExpeRiment at the LHC (AFTER@LHC)*
  By A. Rakotozafindrabe, *et al.* .[arXiv:1301.5739 [hep-ex]]. Phys.Part.Nucl. 45 (2014) 336.
- *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.

Part IV

Backup slides

UPC with atoms ?

Should we care about electron screening in process at the GeV scale ?

. . . . . in some experimental situations one of the colliding partners can be a neutral atom. Then the screening effect should, in principle, be taken into account. Recently the screening effects in free electron–positron pair production were studied in Refs. [7;9]. The conclusions made by these authors are quite opposite. Bertulani and Baur [7] claimed that for collisions with neutral target atoms the screening effect is very important for lower energies of the projectile nuclei and decreases in importance for higher energies. They had also found that when the screening is present the cross section for free electron–positron pair production will always be smaller by at least a factor of 1.5–2 also for very high projectile energies ($\gamma \leq 10^5$, γ is the Lorentz factor for the projectile). In contrast, Wu et al. [9] have concluded that the screening effect becomes more important when the projectile energy increases. They have found that the screening effect becomes of considerable importance only at extremely high collision energies. For example, it follows from their calculations that in $Au^{79+} + Au^0$ collisions the screening reduces the cross section for free pair production by modest 4.5 percent at a collision energy of $E = 200$ GeV/nucleon and by 31.4 percent at a collision energy of $E = 200$ TeV/nucleon.

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15 May 2000
Physics Letters A 269 (2000) 325–332
PHYSICS LETTERS A
www.elsevier.nl/locate/pla

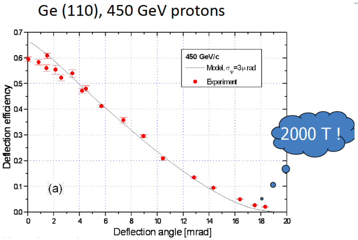
Screening effects in electron–positron pair production with capture in ultrarelativistic collisions

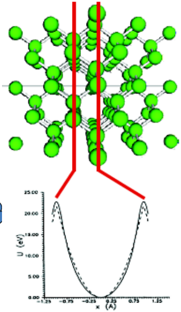
A.B. Voitkiv [1], N. Grün *, W. Scheid

Our calculations show considerably larger screening effects in the bound–free pair production than it was found in [9] for free pair production. For example, Wu et al. [9] obtained in their perturbative calculations that in collisions of 200 GeV/nucleon Au^{79+} projectiles with Au target the screening effect reduces the cross section for free pair production just by 4.5 percent. Our calculations for the bound–free pair production in the same collision system show that the screening reduces the bound–free pair production by about 16 percent. The reason for such a considerable increase of the screening effect for the bound–free pair production compared to the case of the free pair production can be attributed to the fact that the process of free pair production involves larger momentum transfers because both positron and electron are in continuum states.

The beam extraction

- Inter-crystalline fields are huge





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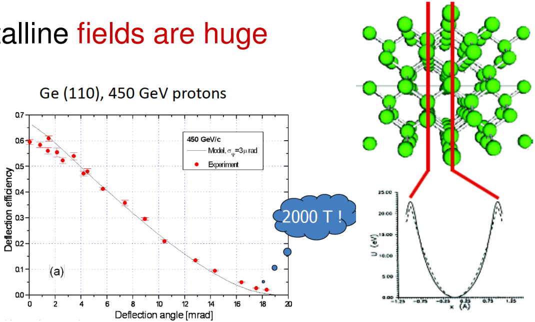

- The channeling efficiency is high for a deflection of a few mrad

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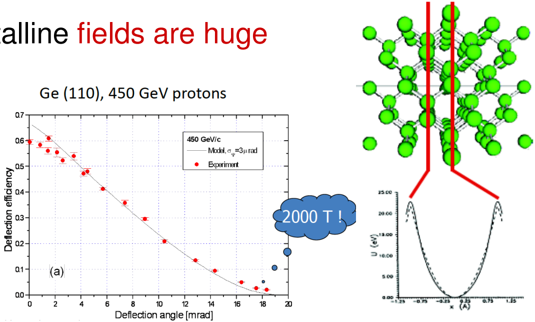

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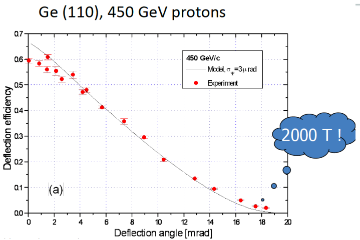
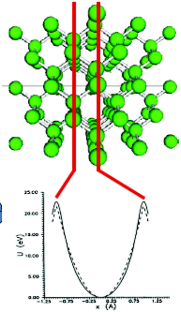
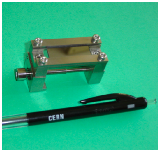




- The channeling efficiency is high for a deflection of a few mrad
- One can extract a significant part of the beam loss ($10^9 p^+ s^{-1}$)
- Simple and robust way to extract the most energetic beam ever:



Beam extraction

- **Beam extraction @ LHC**

… there are extremely promising possibilities to extract 7 TeV protons from the circulating beam by means of a bent crystal.

… The idea is to put a bent, single crystal of either Si or Ge (W would perform slightly better but needs substantial improvements in crystal quality) at a distance of $\simeq 7\sigma$ to the beam where it can intercept and deflect part of the beam halo by an angle similar to the one the foreseen dump kicking system will apply to the circulating beam.

… ions with the same momentum per charge as protons are deflected in a crystal with similar efficiencies

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Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39
NIM B
Beam Interactions with Materials & Atoms
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Strong crystalline fields – a possibility for extraction from the LHC

E. Uggerhøj, U.I. Uggerhøj *
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Received 9 September 2004; received in revised form 6 January 2005
Available online 24 February 2005

If the crystal is positioned at the kicking section, the whole dump system can be used for slow extraction of parts of the beam halo, the particles that are anyway lost subsequently at collimators.

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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- Extracted "mini" bunches:
  - the crystal sees $2808 \times 11000\ \mathrm{s}^{-1} \simeq 3.10^7$ bunches s^{-1}
  - one extracts $5.10^8/3.10^7 \simeq 15 p^+$ from each bunch at each pass
  - Provided that the probability of interaction with the target is below 5%,

no pile-up !

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- Extraction over a 10h fill:
  - $5 \times 10^8 p^+ \times 3600\ \mathrm{s\ h}^{-1} \times 10\ \mathrm{h} = 1.8 \times 10^{13} p^+\ \mathrm{fill}^{-1}$
  - This means $1.8 \times 10^{13}/3.2 \times 10^{14} \simeq$ 5.6% of the p^+ in the beam

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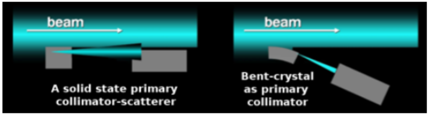
- similar figures for the Pb-beam extraction

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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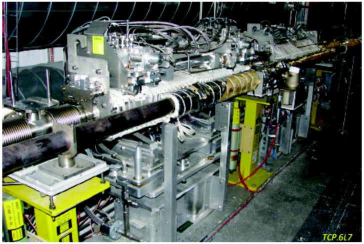

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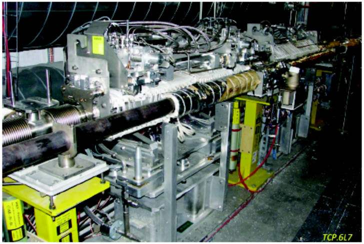

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Towards an installation in the LHC : propose and install during LS1 a min. number of devices

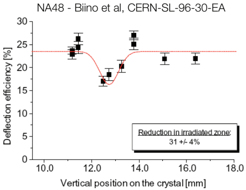
- 2 crystals

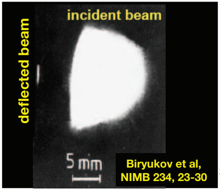
Long term plan is ambitious : propose a collimation system based on bent crystals for the upgrade of the current LHC collimation system

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 5×10^{12} protons every 14.4 s, one year irradiation, **2.4×10^{20} protons/cm^2** in total,
  - equivalent to several year of operation for a primary collimator in LHC
  - $10 \times 50 \times 0.9$ mm^3 silicon crystal, 0.8×0.3 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**, 1.1×10^{11} protons per bunch (**3×10^{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





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