TMDs STUDIES WITH A FIXED TARGET EXPERIMENT USING THE LHC BEAMS

AFTER

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LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

cnrs dépasser les frontières

SPIN 2014 Symposium,
19-24th october 2014
Beijing, China

P2IO Physique des 2 Infinis et des Origines

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

OUTLINE

- Why a fixed-target experiment at the LHC ?
- LHC beam extraction using a bent crystal
- Luminosities
- Physics highlights for AFTER@LHC
- TMDs studies with AFTER@LHC
- First simulations

WHY A FIXED TARGET EXPERIMENT AT THE LHC ?

- ❑ **Several advantages of the fixed-target mode wrt to the collider mode**
  - Accessing **the high Feynman x_F** domain ($x_F = p_z/p_{zmax}$)
  - Achieving **high luminosities** thanks to dense targets
  - Easier **to change the target** type (≠ atomic mass)
  - Possibility to **polarize the target**

    → Open the possibility for a spin physics program!

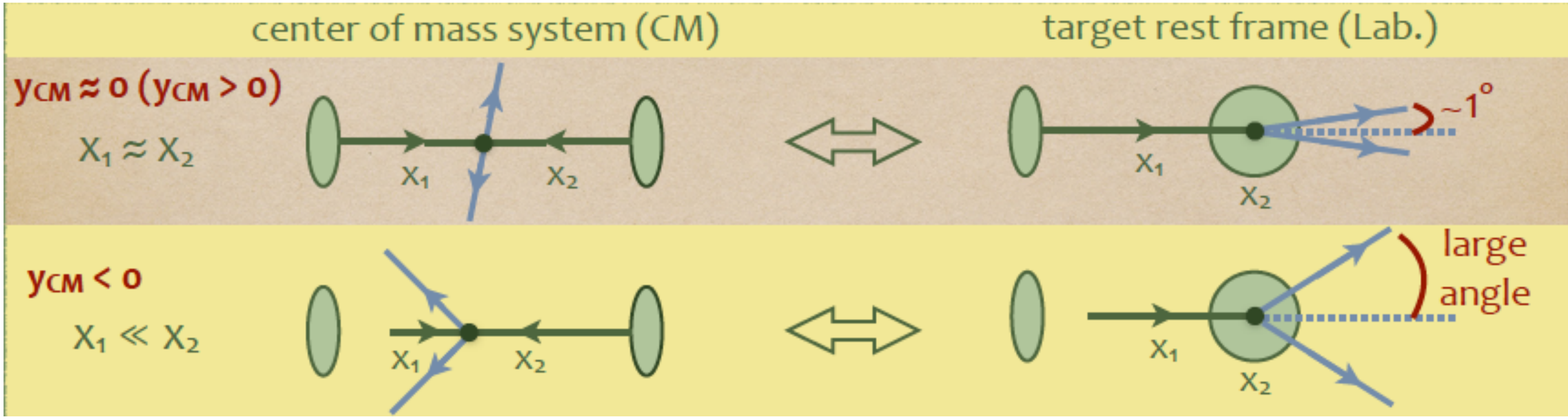
- ❑ **<u>Without affecting the LHC performances</u>**

  → Recycling of the beam loss by inserting a bent crystal in the halo (7σ) of the LHC beam
- ❑ With an outstanding luminosity, yet without pile-up
- ❑ With modern detection techniques
- ❑ Virtually no limit on particle-species studies (except top quark)

AFTER@LHC would definitely be a unique experiment

WHY A FIXED TARGET EXPERIMENT AT THE LHC ?

- Provide a novel testing ground for QCD in the high x frontier: x = [0.3-1]



- Entire CM forward hemisphere ($y_{CM} > 0$) within $0° < \theta_{lab} < 1°$ (small detector and high multiplicities → large occupancies)
- Backward physics ($y_{CM} < 0$) : larger angle in the laboratory frame (low occupancies, no constraint from beam pipe). Access to parton with momentum fraction $x_2 \rightarrow 1$ in the target

7 TeV proton beam on a fixed target

CMS energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115$ GeV	**Rapidity shift:** $y_{CM} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_p) \approx 60$	

2.76 TeV Pb beam on a fixed target

CMS energy:	$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72$ GeV	**Rapidity shift:** $y_{CM} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	

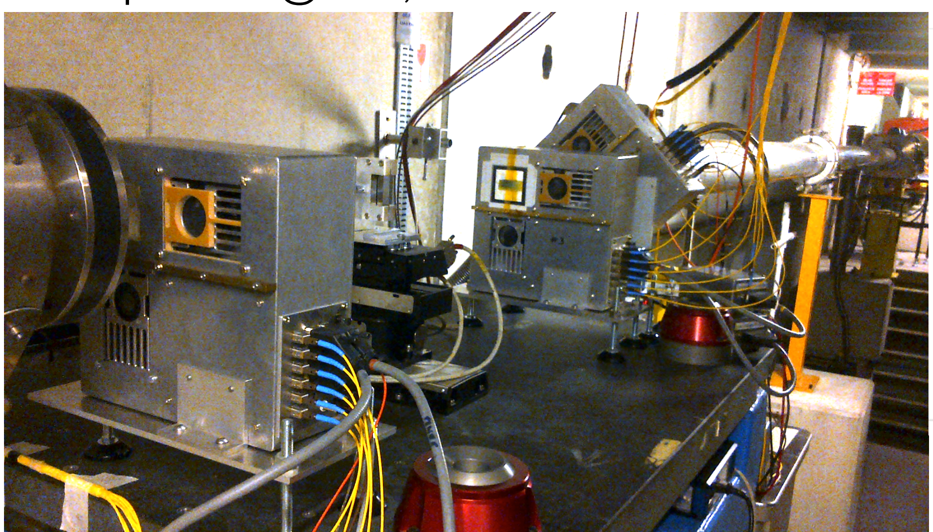
LHC BEAM EXTRACTION USING A BENT CRYSTAL

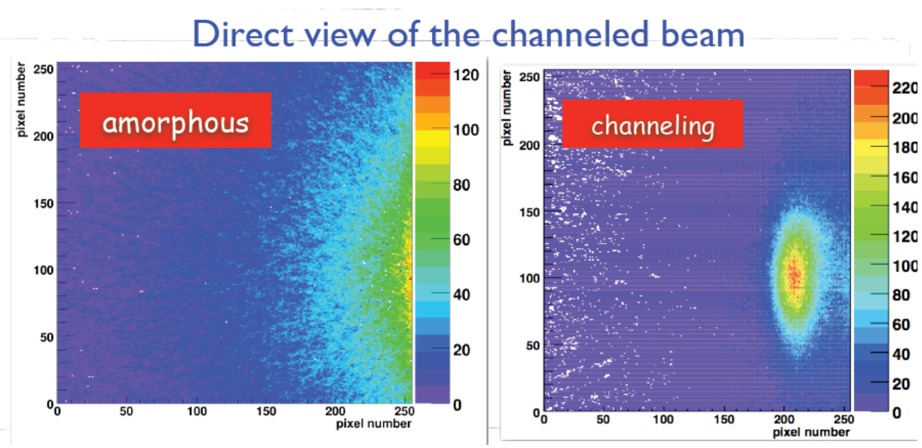
Standard collimation today

Crystal-based collimation
- UA9 (@SPS)
- LUA9 (@LHC)

To beam extraction
- CRYSBEAM (@SPS then LHC)
- AFTER@LHC

UA9 experiment @ SPS, 15/10/2014





S. Montesano, W. Scandale, Joint LUA9-AFTER meeting, Nov. 2013

LHC BEAM EXTRACTION USING A BENT CRYSTAL

Beam collimation @LHC: amorphous collimator, inefficiency of 0.2% (3.5TeV p beam)
→ Expected bent cristal inefficiency : 0.02%

UA9: test @SPS on the crystal with proton and ion beams
LUA9 (beam bending experiment using crystal): approved by LHCC
- 2 bent crystals installed in IR7 during LS1
- 2015/2016 first tests with beams

Proton beam extraction:
- Single or multi-pass extraction efficiency of 50%
- LHC beam loss ~ 10^9 p/s → Extracted beam : 5 x 10^8 p/s
- Extremely small emittance:
  → beam size (in the extraction direction) 950m after the extraction: 0.3mm

Ion beam extraction:
- Successfully tested at the SPS
- Should also work at the LHC

LUMINOSITIES IN pH, pA @ $\sqrt{S_{NN}}$ = 115 GeV AND Pb-A $\sqrt{S_{NN}}$ = 72 GeV

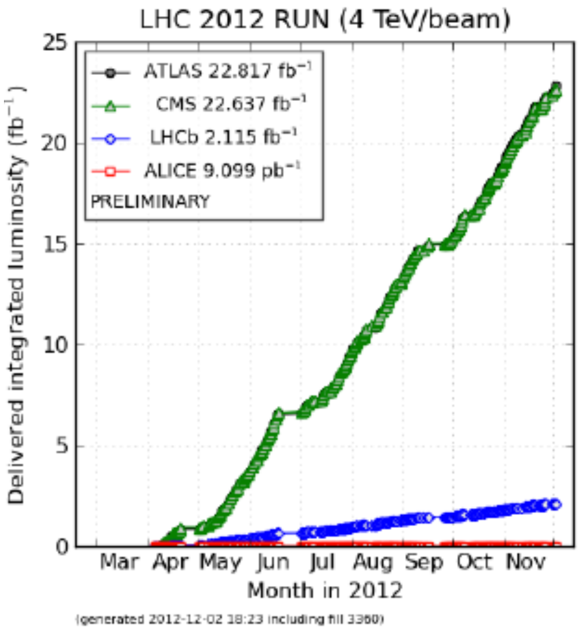
Instantaneous luminosity: $L = \phi_{\mathrm{beam}} \times N_{\mathrm{target}} = \phi_{\mathrm{beam}} \times (\rho \times l \times N_A) / A$

With l target thickness, $\phi_{beam} = 5 \times 10^8 \, p^+ s^{-1}$ (1/2 of the beam loss)

Integrated luminosity: assuming 10^7s of p beam and 10^6s of Pb beam (LHC year)

In pH and pA (115 GeV/c)

Target	ρ ($g.cm^{-3}$)	A	L ($\mu b^{-1}.s^{-1}$)	$\int L$ ($pb^{-1}.yr^{-1}$)
Liq H_2 (1m)	0.07	1	2000	20000
Liq D_2 (1m)	0.16	2	2400	24000
Be (1cm)	1.85	9	62	620
Cu (1cm)	8.96	64	42	420
W (1cm)	19.1	185	31	310
Pb (1cm)	11.35	207	16	160



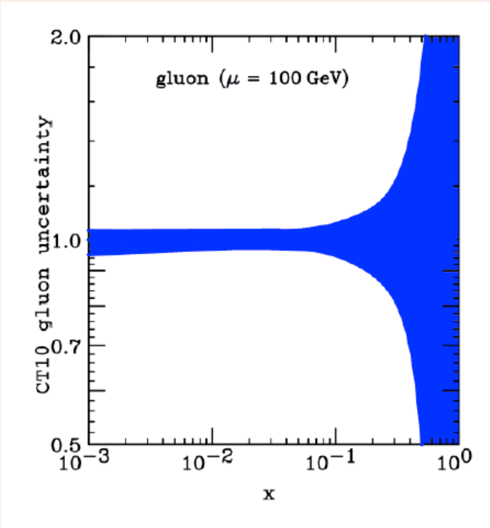
Luminosity comparable to the LHC itself (with 1m long H_2 (D_2) target)
3 orders of magnitude larger than PHENIX@RHIC
(run14pp@200GeV: 12pb^{-1}, run14dAu@200GeV: 0.15pb^{-1})

PHYSICS HIGHLIGHTS FOR AFTER@LHC

p-p and p-A @ $\sqrt{s_{NN}}$ = 115 GeV

Nucleon partonic structure

- Gluon PDF in the proton → large uncertainty at large x. DIS not ideal
- $g_n(x) = g_p(x)$?
- Experimental probes: quarkonia, isolated photons, high p_T jets
- Multiple probes essential to check factorization



Heavy quark distribution at large x in the proton

- Intrinsic charm?
- Experimental probes: open heavy flavors

Spin Physics

Gluon Sivers effect

Linearly polarized gluons: $h_1^{\perp g}$

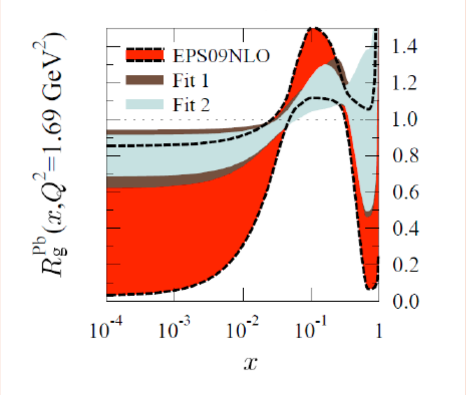
Single Spin Asymetry in HF and DY studies

W and Z bosons production near threshold?

Pb-A @ $\sqrt{s_{NN}}$ = 72 GeV

Gluon distribution in nucleus at large x

- Large uncertainty at high x
- EIC, LHeC experiments do not help much



Quark Gluon Plasma

- ϒ sequential suppression
- Quarkonium excited state suppression
- Jet-HF quenching
- Direct photons

Ultra-peripheral collisions

PHYSICS HIGHLIGHTS FOR AFTER@LHC

- More details in Physics Reports 522 (2013) 239

Physics Reports 522 (2013) 239–255

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Physics Reports

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Physics opportunities of a fixed-target experiment using LHC beams

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Contents

TMDs STUDIES IN AFTER@LHC (WITH A POLARIZED TARGET)

See also presentation by J.P. Lansberg, Gluon TMDs and Quarkonium production in unpolarised and polarised Proton-Proton collisions, on Monday 20th October, s1, 16:30

(Gluon) Sivers effects with a transversely polarized target

Gluon Sivers effect: correlation between the gluon transverse momentum k_T and the proton spin

- **The target rapidity region ($x_F < 0$) corresponds to high $x^{\uparrow}$ ($x_F \rightarrow -1$) where the k_T - spin correlation is the largest**

- Transverse single spin asymmetries studied using **gluon sensitives probes:**
  - quarkonia (J/ψ, ϒ, χ_c)
  - B & D mesons production
  - γ, γ-jet, γ-γ also J/ψ-γ

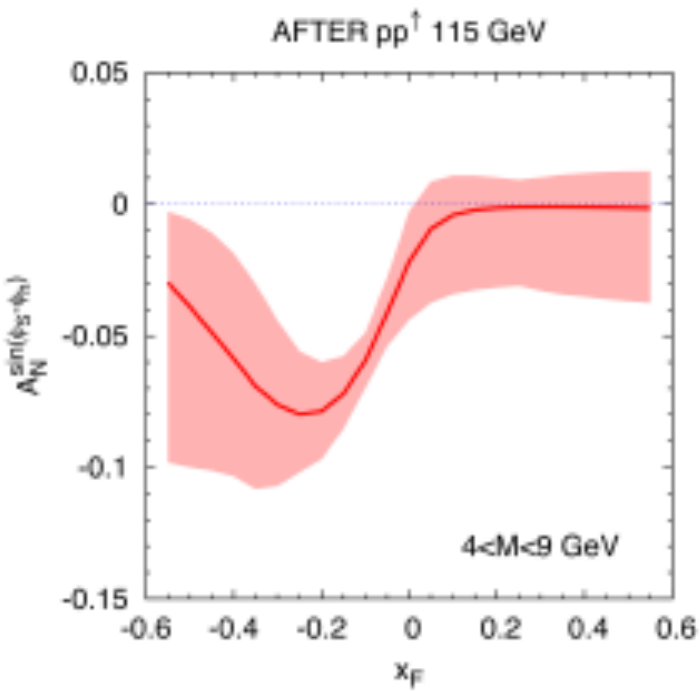
TMDs STUDIES WITH AFTER@LHC (WITH A POLARIZED TARGET)

(Quark) Sivers effects with a transversely polarized target

- Can be probed with the Drell-Yan process

Experiment	particles	energy (GeV)	$\sqrt{s}$ (GeV)	$x_p^{\uparrow}$	$\mathscr{L}$ ($nb^{-1}s^{-1}$)
AFTER	$p+p^{\uparrow}$	7000	115	$0.01 \div 0.9$	1
COMPASS	$\pi^{\pm}+p^{\uparrow}$	160	17.4	$0.2 \div 0.3$	2
COMPASS (low mass)	$\pi^{\pm}+p^{\uparrow}$	160	17.4	~ 0.05	2
RHIC	$p^{\uparrow}+p$	collider	500	$0.05 \div 0.1$	0.2
J–PARC	$p^{\uparrow}+p$	50	10	$0.5 \div 0.9$	1000
PANDA (low mass)	$\bar{p}+p^{\uparrow}$	15	5.5	$0.2 \div 0.4$	0.2
PAX	$p^{\uparrow}+\bar{p}$	collider	14	$0.1 \div 0.9$	0.002
NICA	$p^{\uparrow}+p$	collider	20	$0.1 \div 0.8$	0.001
RHIC Int.Target 1	$p^{\uparrow}+p$	250	22	$0.2 \div 0.5$	2
RHIC Int.Target 2	$p^{\uparrow}+p$	250	22	$0.2 \div 0.5$	60
P1027	$p^{\uparrow}+p$	120	15	$0.35 \div 0.85$	400-1000
P1039	$p+p^{\uparrow}$	120	15	$0.1 \div 0.3$	400-1000

Relevant parameters for the future proposed polarized DY experiments



Prediction for AFTER

M. Anselmo, ECT*, Feb. 2013
(Courtesy U. d'Alessio)

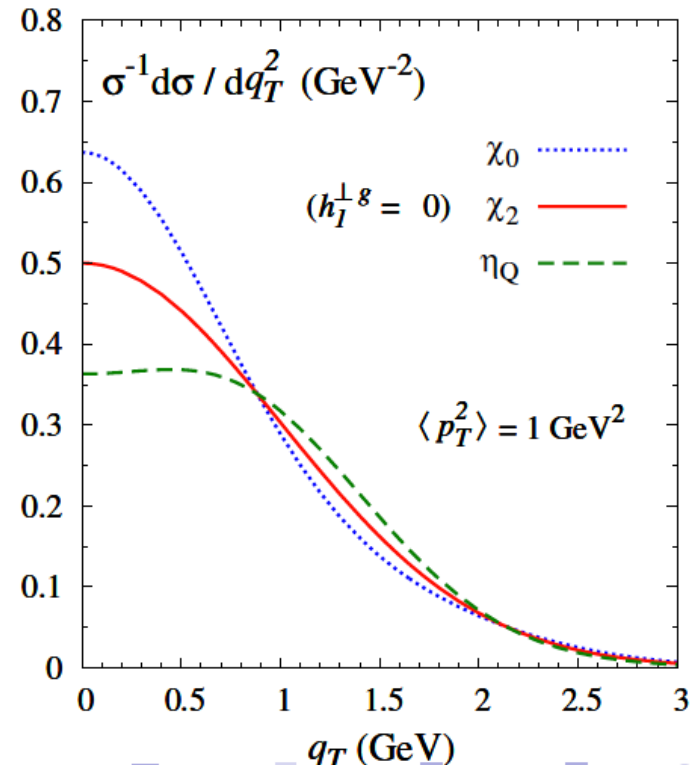
S. J. Brodsky et al., Phys. Rep. 522 (2013) 239
V. Barone et al., Prog. Part. Nucl. Phys. 65 (2010) 267

Asymmetry up to 10% predicted in DY for the target rapidity region ($x_F < 0$)

Access to the distribution of linearly polarized gluons ($h_1^{\perp g}$)

« Boers-Mulder » effect: correlation between the parton k_T and its spin
For gluons, it is encoded in $h_1^{\perp g}$

- Low-p_T C-even quarkonium production is a good probe of the gluon TMDs.
- The low-p_T spectra of scalar and pseudo-scalar quarkonium (χ_{c0}, χ_{b0}, η_c, η_b) are affected differently by the linearly polarized gluons in unpolarized nucleons
  - → Boost: better access to low-p_T C-even quarkonia
  - → Still challenging experimentally (first study of η_c in collider by LHCb for p_T > 6 GeV/c)
    LHCb 1409.3612
  - → If possible somewhere, it is at AFTER@LHC



Boer, Pisano, PRD 86 (2012) 094007

- Back-to-back J/ψ + γ is also a good probe of gluon TMDs

Den dunnen et al., PRL 112 (2014) 212001,
J. P. Lansberg, Transversity 2014

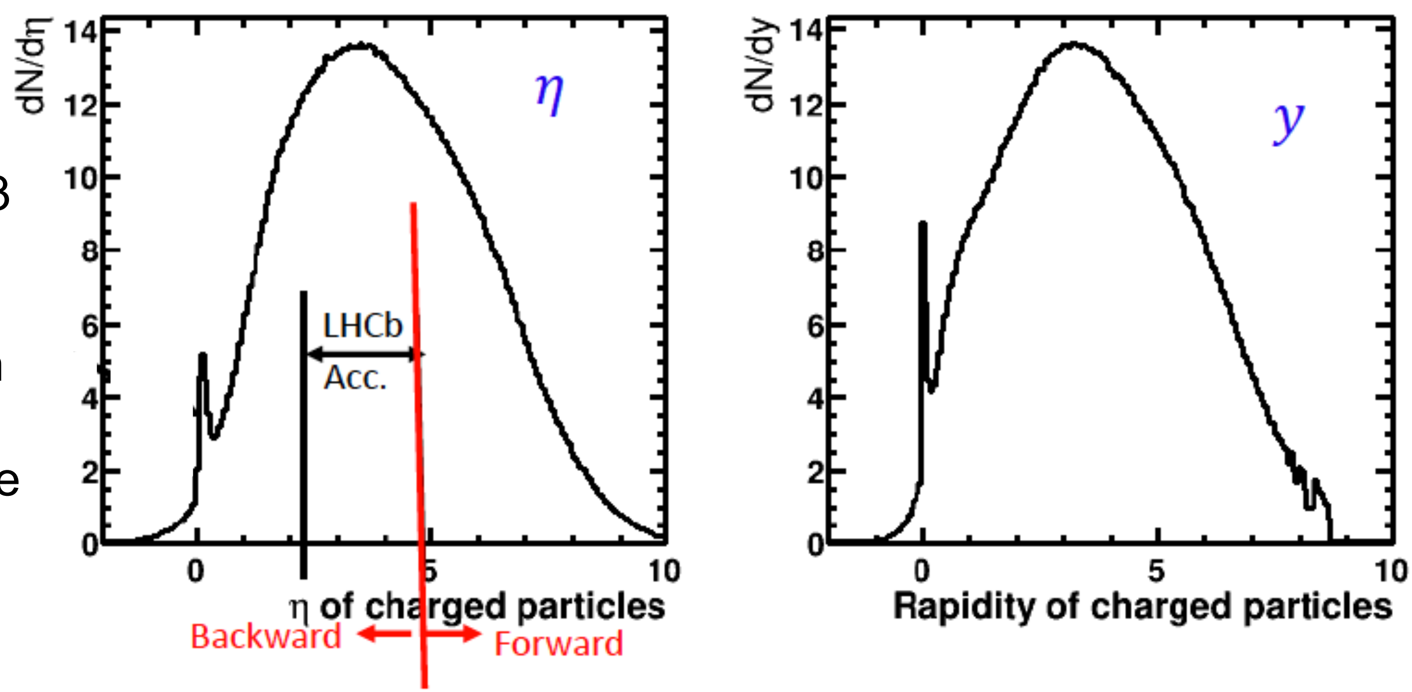
Simulations of a 7 TeV proton beam on a Pb target ($\sqrt{s_{NN}}$ = 115 GeV)

- **Full LHCb simulation and standard reconstruction**
- Study the resolution at vertex, the occupancy in the pixels…
- Compare multiplicities in AFTER with LHCb pA run

- Simulations with HIJING version 1.383bs.2
- 10 000 events generated, no pile-up

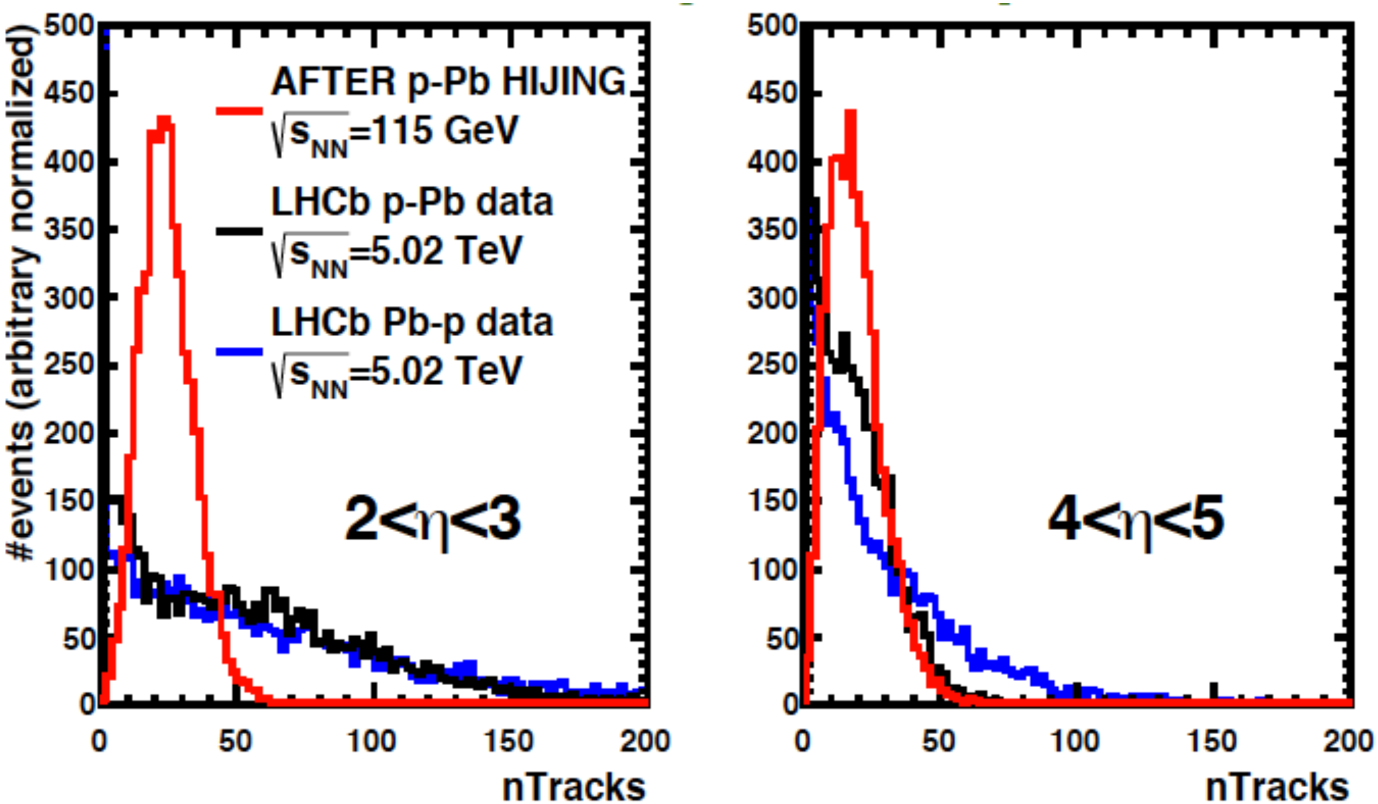
Z. Yang, AFTER workshop les Houches, January 2014

dN/dη ~ 13 Generated charged particles in LHCb acceptance



Simulations of a 7 TeV proton beam on a Pb target ($\sqrt{s_{NN}}$ = 115 GeV)

Z. Yang, AFTER workshop les Houches, January 2014



- Probability for high track multiplicity in AFTER (pPb @ 115 GeV) is lower than the one measured by LHCb (pPb/Pbp @ 5.02 TeV)

- No problem for a LHCb-like detector to cope with the multiplicity of pPb collisions at $\sqrt{s_{NN}}$ = 115 GeV in $2 < \eta < 5$

QUARKONIUM CASE

Expected quarkonium yields

In pH and pA (115 GeV)

Target	$\int\mathcal{L}$ (fb^{-1}.yr^{-1})	N(J/Ψ) yr^{-1} = $A\mathcal{L}B\sigma_\Psi$	N(Υ) yr^{-1} = $A\mathcal{L}B\sigma_\Upsilon$
1 m Liq. H_2	20	4.0 10^8	8.0 10^5
1 m Liq. D_2	24	9.6 10^8	1.9 10^6
LHC pp 14 Tev (low pT)	0.05 (ALICE) 2 LHCb	3.6 10^7 1.4 10^9	1.8 10^5 7.2 10^6
RHIC pp 200GeV	1.2 10^{-2}	4.8 10^5	1.2 10^3

Target	$\int\mathcal{L}$ (fb^{-1}.yr^{-1})	N(J/Ψ) yr^{-1} = $A\mathcal{L}B\sigma_\Psi$	N(Υ) yr^{-1} = $A\mathcal{L}B\sigma_\Upsilon$
1cm Be	0.62	1.1 10^8	2.2 10^5
1cm Cu	0.42	5.3 10^8	1.1 10^6
1cm W	0.31	1.1 10^9	2.3 10^6
1cm Pb	0.16	6.7 10^8	1.3 10^6
LHC pPb 8.8 TeV	10^{-4}	1.0 10^7	7.5 10^4
RHIC dAu 200GeV	1.5 10^{-4}	2.4 10^6	5.9 10^3
RHIC dAu 62GeV	3.8 10^{-6}	1.2 10^4	18

In PbA (72 GeV)

Target	$\int\mathcal{L}$ (nb^{-1}.yr^{-1})	N(J/Ψ) yr^{-1} = $AB\mathcal{L}B\sigma_\Psi$	N(Υ) yr^{-1} = $AB\mathcal{L}B\sigma_\Upsilon$
1 m Liq. H_2	800	3.4 10^6	6.9 10^3
1cm Be	25	9.1 10^5	1.9 10^3
1cm Cu	17	4.3 10^6	0.9 10^3
1cm W	13	9.7 10^6	1.9 10^4
1cm Pb	7	5.7 10^6	1.1 10^4
LHC PbPb 5.5 TeV	0.5	7.3 10^6	3.6 10^4
RHIC AuAu 200GeV	2.8	4.4 10^6	1.1 10^4
RHIC AuAu 62GeV	0.13	4.0 10^4	61

pp : 1000 times more statistics than at RHIC ($\sqrt{s}$ = 200 GeV) and comparable statistics to LHCb with a 1m H_2 target
pA: 100 times more statistics than at RHIC (dAu $\sqrt{s}$ = 200 GeV) with a 1cm Pb target

PbA: similar statistics as at RHIC (Au-Au $\sqrt{s_{NN}}$ = 200 GeV) and 2 orders of magnitude larger than at RHIC (Au-Au $\sqrt{s_{NN}}$ = 62 GeV) with a 1cm thick Pb target

Detailed study of quarkonium production and nuclear effects

Detailed study of quarkonium states

FAST SIMULATIONS FOR QUARKONIA (pp $\sqrt{s}$ = 115 GeV) USING LHCb RECONSTRUCTION PARAMETERS

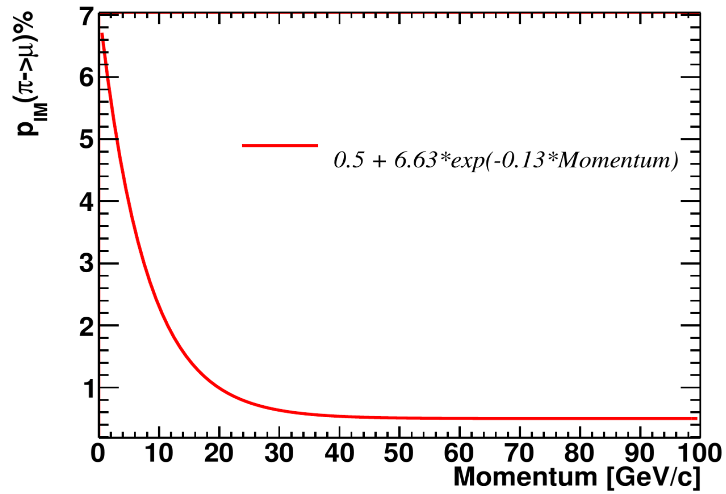
- Simulations with Pythia 8.185
- LHCb detector is NOT simulated but LHCb reconstruction parameters are introduced in the fast simulation (resolution, analysis cuts, efficiencies…)

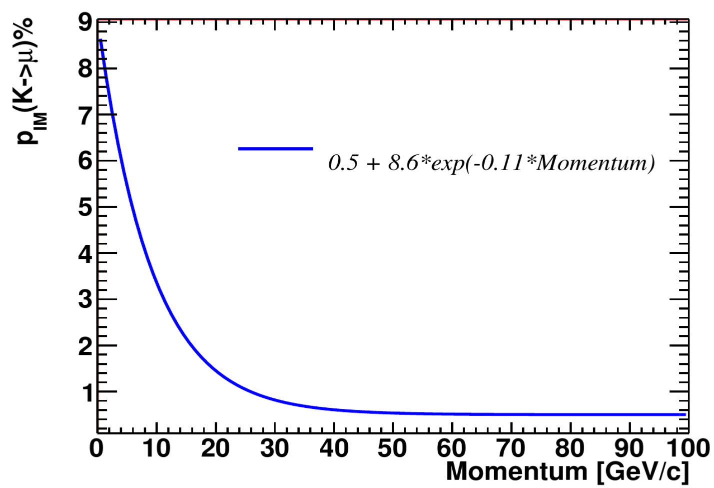
Requirements
Momentum resolution : $\Delta p/p$ = 0.5%
Muon identification efficiency: 98%

Cuts at the single muon level
$2 < \eta_\mu < 5$
$p_T^\mu > 0.7$ GeV/c

Muon misidentification
If π and K decay before the calorimeters (12m), they are rejected by the tracking
Otherwise a misidentification probability is applied

Performance of the muon identification at LHCb,
F. Achilli et al, arXiv:1306.0249

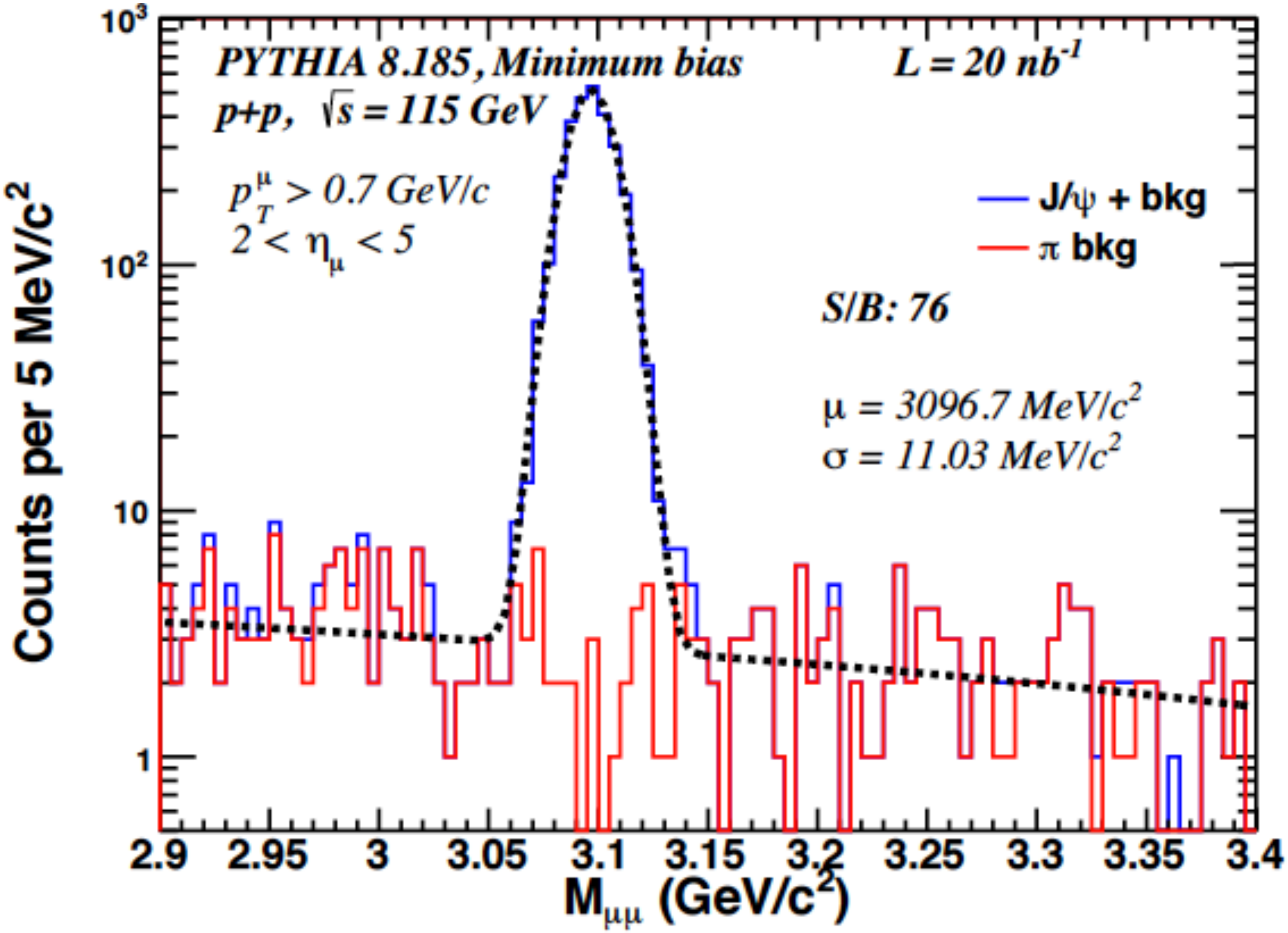




$J/\Psi \rightarrow \mu^+\mu^-$ IN MINIMUM BIAS pp COLLISIONS @ 115 GeV

- For 1m of H target and 10 seconds of data taking!

B. Trzeciak, July 2014, Orsay

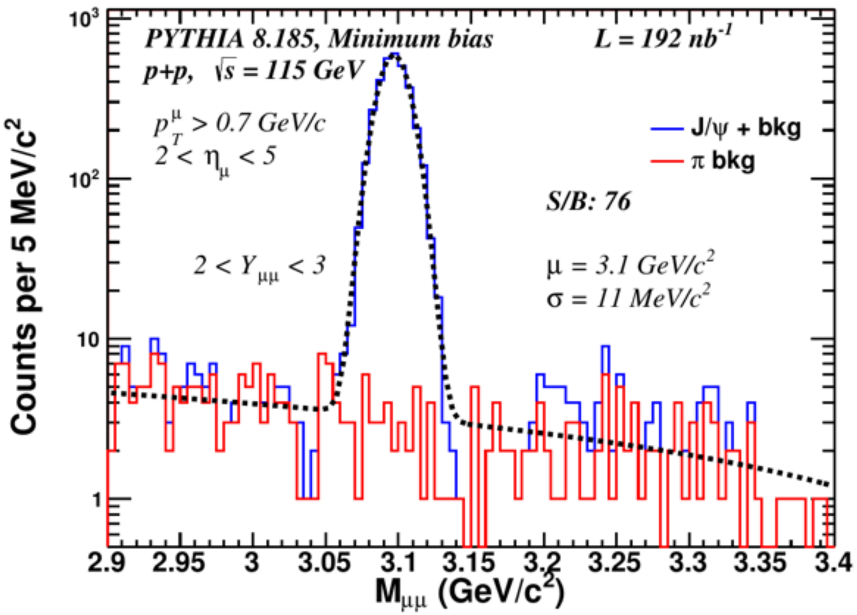


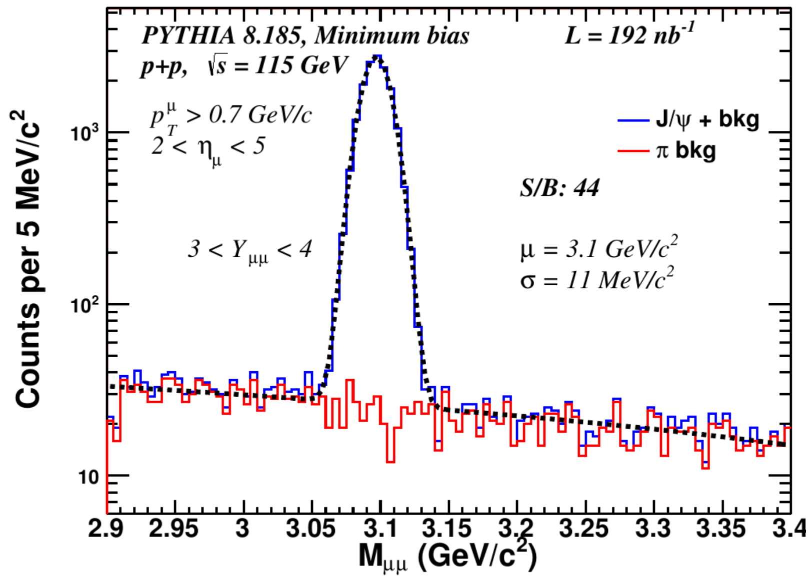
Misidentified pions is the dominant source of background

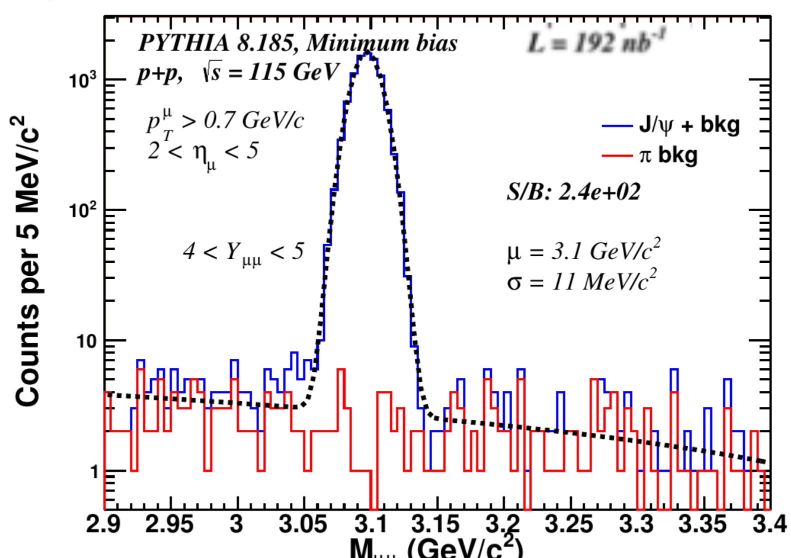
$J/\Psi \rightarrow \mu^+\mu^-$ IN MINIMUM BIAS pp COLLISIONS @ 115 GEV (BINS IN RAPIDITY)

- For 1m of H target and 1.5 minute of data taking

B. Trzeciak, July 2014, Orsay



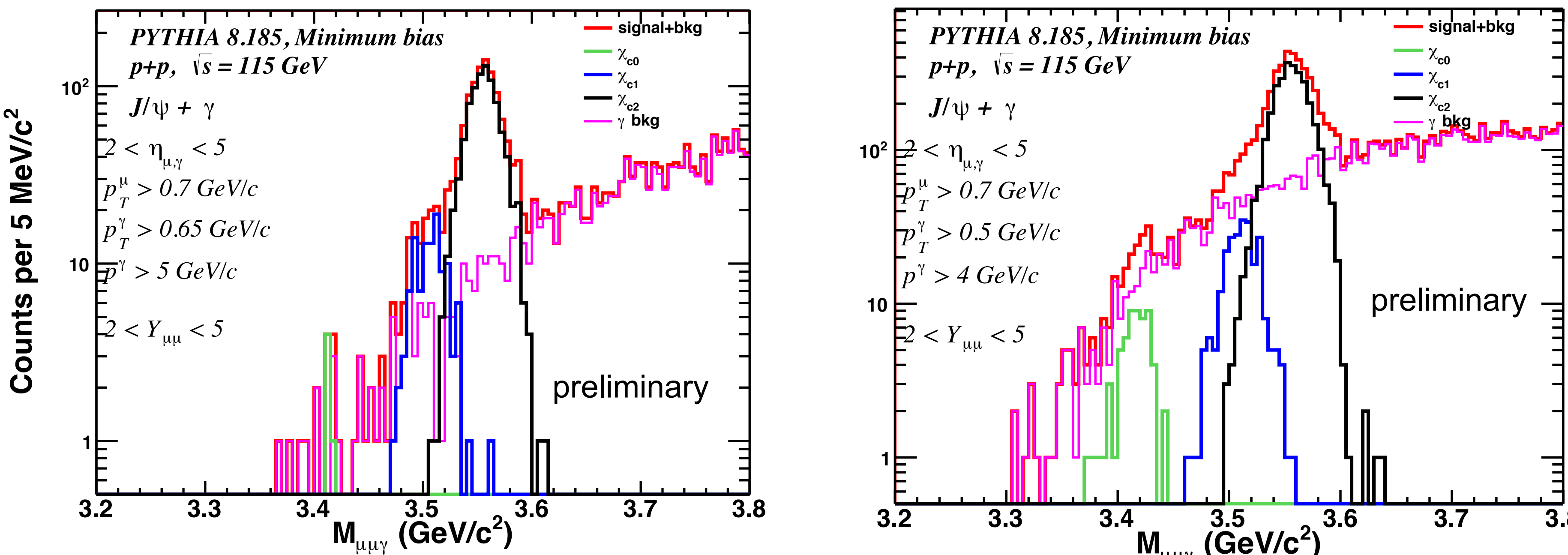




$\chi_c \rightarrow \mu^+\mu^-\gamma$ IN MINIMUM BIAS pp COLLISIONS @ 115 GEV

- Preliminary studies of the χ_c also started
- L_{int} = 192 nb^{-1}, **for 1m of H target and 1.5 minute of data taking**

B. Trzeciak, July 2014, Orsay



- Hope to be able to reach p_T of the χ_c down to 0
- χ_{c1} and χ_{c2} separation

SUMMARY

- AFTER@LHC provides a novel testing ground for QCD in the high x frontier
- High luminosities are achievable in pp, pA @ 115 GeV and PbA @ 72 GeV using dense targets and without affecting the LHC beam
- TMDs studies can be performed with/without polarizing the target thanks to e.g. low-p_T quarkonia
- First fast simulations with LHCb like setup are promising

- What's next :
  - Special issue in Advances in High Energy Physics (submission deadline in March 2015)
    Everybody is welcome to contribute
  - Expression of interest expected in 2015
  - AFTER week @ CERN, 17-21 November 2014

- The AFTER web page : after.in2p3.fr

Hindawi

Advances in High Energy Physics

Special Issue on
Physics at a Fixed-Target Experiment Using the LHC Beams

CALL FOR PAPERS

Fixed-target experiments (FTE) have brought essential contributions to particle and nuclear physics. They have led to particle discoveries (Ω, J/ψ, ...) and evidence for the novel dynamics of quarks and gluons in heavy-ion collisions. In accessing high x_F and in offering options for (un-) polarised proton and nuclear targets, they have also led to the observation of surprising QCD phenomena. They offer specific advantages compared to collider experiments: access to high x_F, high luminosities, target versatility, and polarisation.

The LHC 7 TeV protons on targets release a c.m.s. energy close to 115 GeV (72 GeV with Pb), in a range never explored so far, significantly higher than that at SPS and not far from RHIC. The production of quarkonia, DY, heavy flavours, jets, and γ in *pA* collisions can be studied with statistics previously unheard of and in the backward region, $x_F < 0$, which is uncharted. High precision QCD measurements can also obviously be carried out in *pp* and *pd* collisions with H_2 and D_2 targets. With the 50 TeV protons of the future circular collider (FCC), the c.m.s. energy could reach 300 GeV for original studies of W and Z boson, and perhaps H^0, production in *pp* and *pA* collisions.

With the LHC Pb beam, one can study the quark-gluon plasma (QGP) from the viewpoint of the nucleus rest frame after its formation. Thanks to modern technologies, studies of, for instance, direct γ and quarkonium *P*-waves production in heavy-ion collisions can be envisioned.

Polarising the target allows one to study single-spin correlations including the Sivers effect, hence, the correlation between the parton k_T and the nucleon spin.

We intend to publish a special issue on the physics at such a FTE using the LHC or FCC beams. The editors welcome original research articles and review articles from both theorists and experimentalists.

Potential topics include, but are not limited to:

- Heavy-quark and gluon content at large *x*
- TMDs and single-spin asymmetries
- Heavy-flavour studies in *pA* and *AA* collisions at FTEs
- W, Z, and H^0 production near threshold
- Target polarisation
- Secondary beams
- Simulation tools for high-energy physics
- Beam collimation and extraction with bent crystals
- Machine feasibility and radiological aspects
- Connection between UHECR studies and FTEs

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Manuscript Due
Friday, 20 March 2015

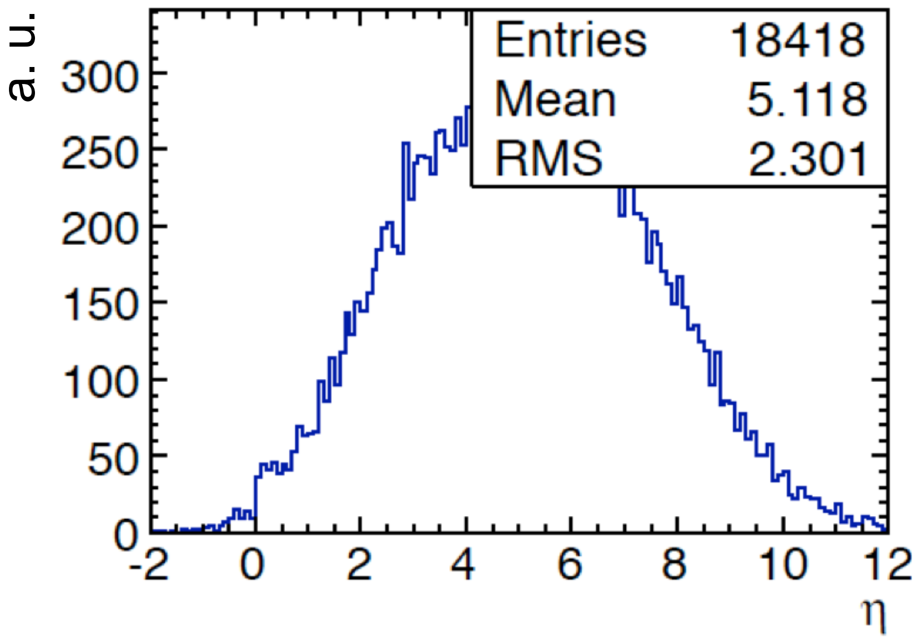
First Round of Reviews
Friday, 12 June 2015

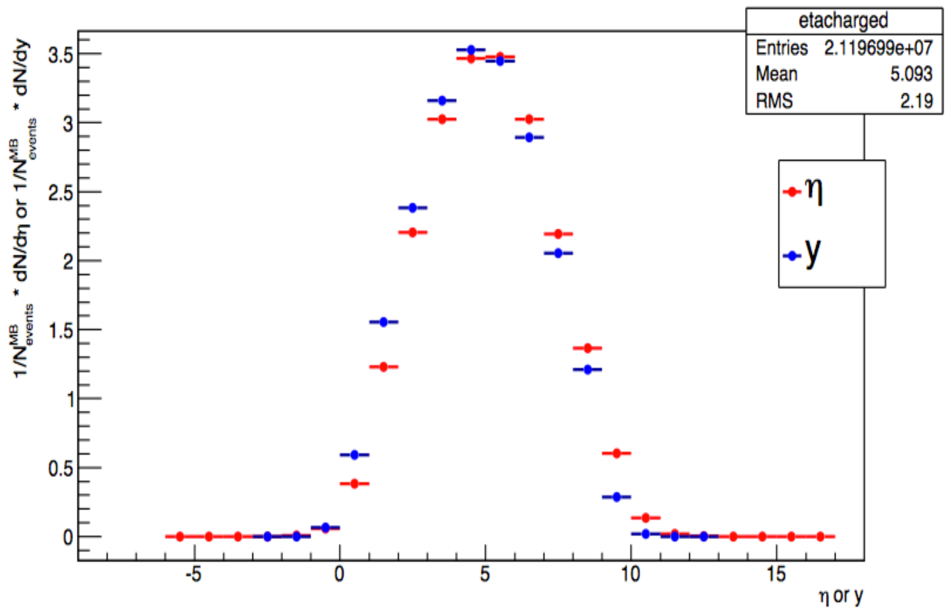
Publication Date
Friday, 7 August 2015

BACK UP

NUMBER OF CHARGED PARTICLES IN MB pp @ √S = 115 GEV

AFTER workshop les Houches, January 2014
AFTER simulation group





EPOS 1.6.5
Number of generated events: 1000

$dN_{ch}/d\eta \,|_{\eta = 0} \sim 3$

PYTHIA 8.170
Number of generated events: 10^6

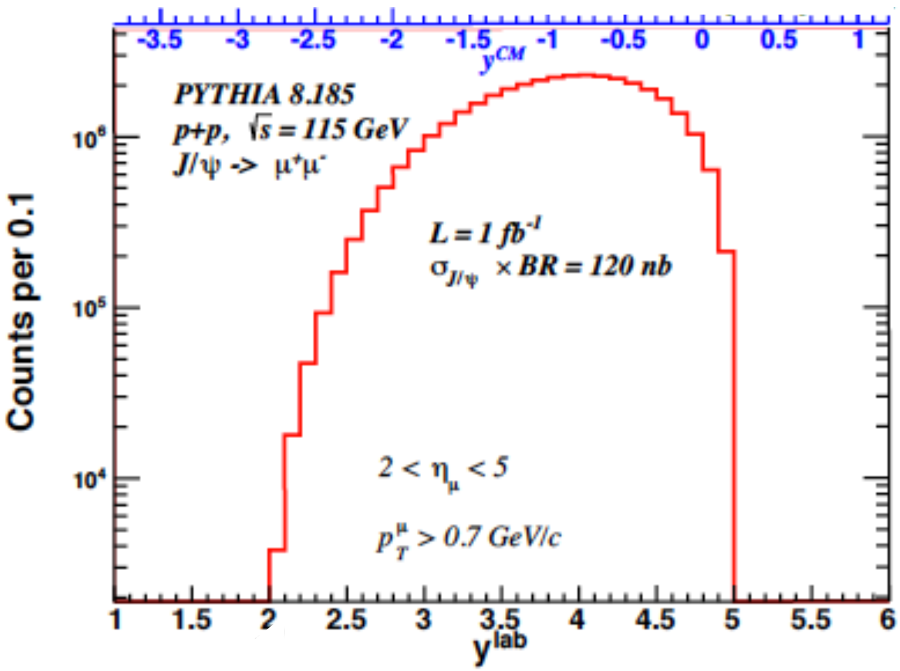
$dN_{ch}/d\eta \,|_{\eta = 0} \sim 3.5$

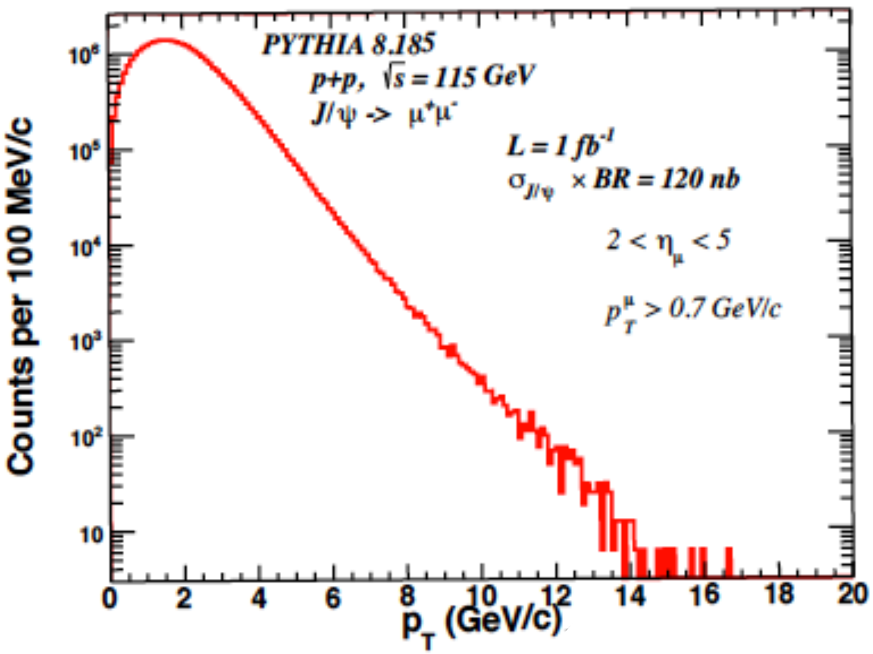
Rapidity shift: $\Delta y = \tan^{-1}\beta \approx 4.8$
$y_{CM} = 0 \rightarrow y_{lab} \approx 4.8$

J/Ψ →μ⁺μ⁻ IN MB pp @ 115 GEV (Y_{LAB} AND P_T REACH)

- For 1m of H target and 2 weeks of data taking

B. Trzeciak, July 2014, Orsay





Large statistics allow one:

- To reach large p_T
- Large y_{lab} acceptance $2 < y_{lab} < 5$

ACCESSING THE LARGE x GLUON PDF

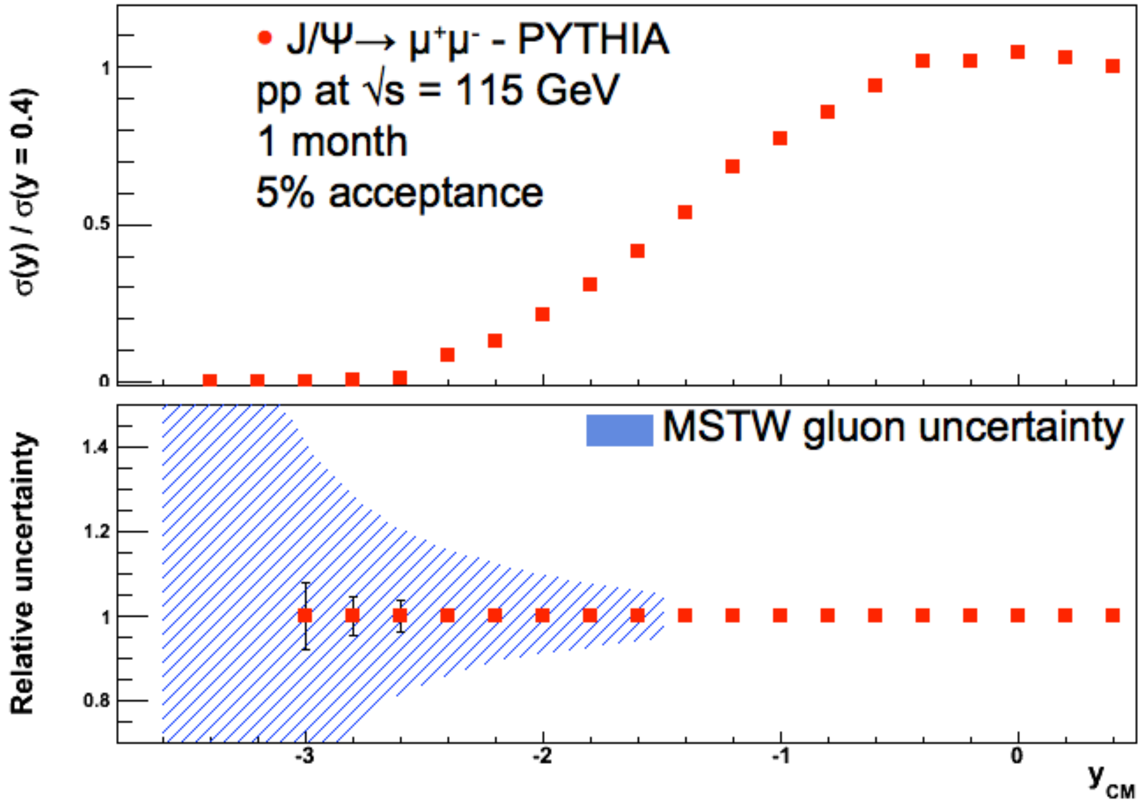
PYTHIA simulation
$\sigma(y) / \sigma(y=0.4)$
statistics for one month
5% acceptance considered

Statistical relative uncertainty
Large statistics allow to access very backward region

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

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

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

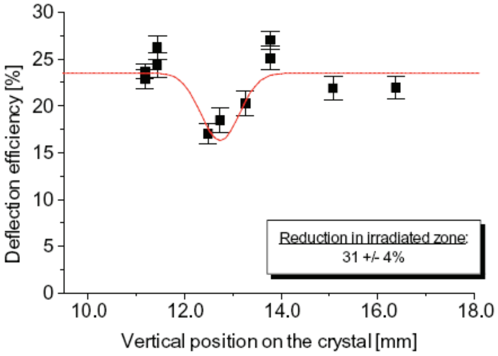


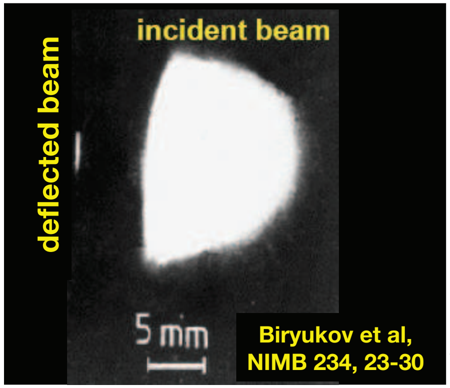
⇒ Backward measurements allow to access large x gluon pdf

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

NA48 - Biino et al, CERN-SL-96-30-EA





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