AFTER@LHC: A Fixed Target ExpeRiment
for hadron, heavy-ion and spin physics: Status and short-range plan

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EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Outline

- ✓ Advantages of a fixed target experiment at LHC
- ✓ Internal gas target *vs* beam extraction with a bent crystal
- ✓ Expected luminosities
- ✓ Physics Highlights
- ✓ First simulations

Advantages of a fixed target experiment at LHC

✓ <u>**Advantages of a fixed-target experiment:**</u>

- **high luminosities with dense targets**
- **target versatility**
- **possibility to polarize target**
  - **spin physics program**
- **access to large Feynman $|x_F|$**

➔ With LHC beams:

7 TeV proton beam on a fixed target

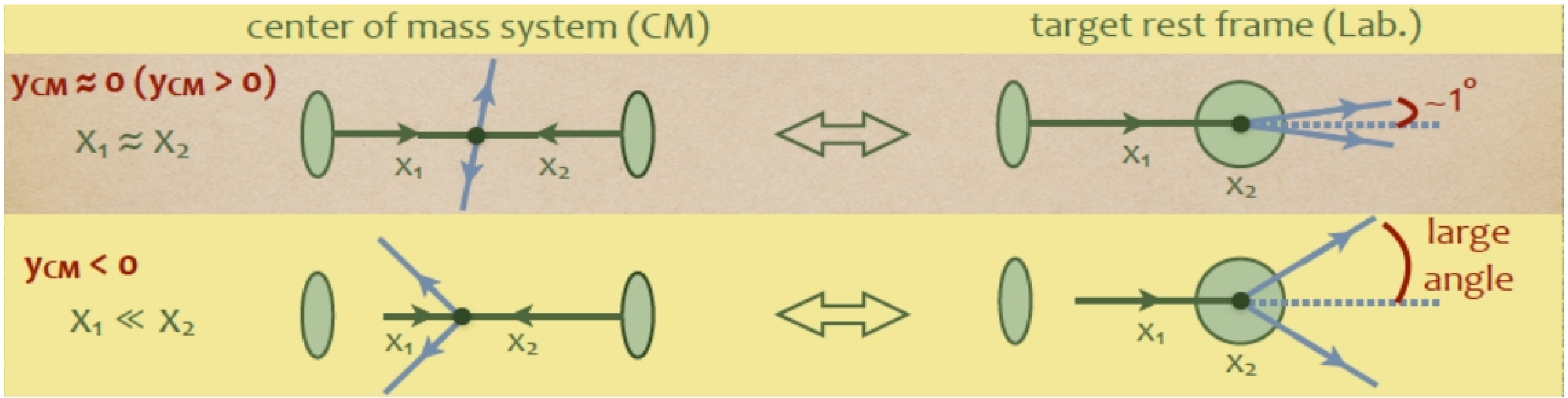
CMS energy: $\sqrt{s} = \sqrt{2m_N E_p} \approx 115 \text{ GeV}$		**Rapidity shift:** $y_{CM} = 0 \rightarrow y_{lab} = 4.8$
Boost: $\gamma = \sqrt{s} / (2m_p) \approx 60$		

2.76 TeV Pb beam on a fixed target

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

Advantages of a fixed target experiment at LHC

✓ Testing QCD at large x = (0.3,1)



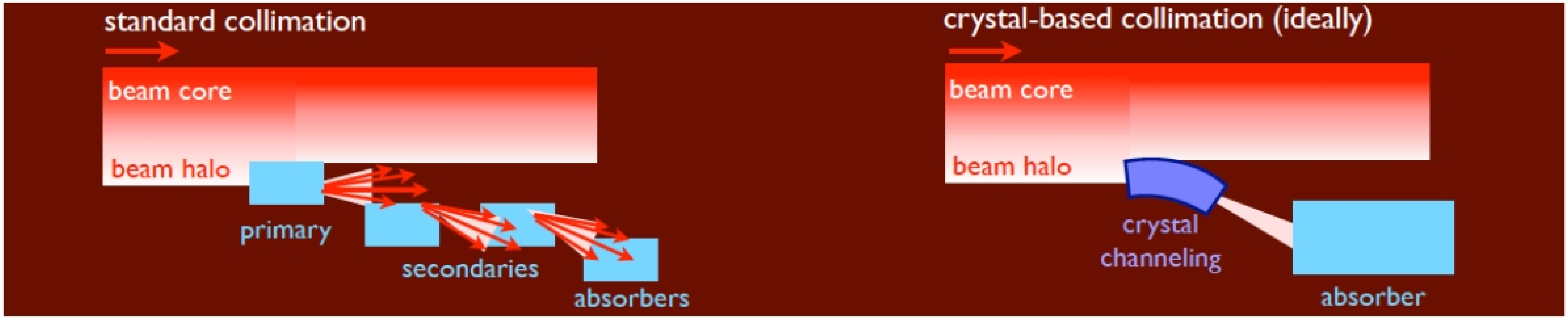
✓ Entire forward hemisphere – $y_{CM} > 0$ – within: $0° < \theta_{lab} < 1°$ - large occupancy – more challenging

✓ Backward region - $y_{CM} < 0$ – at large angles in the lab frame – low occupancy, no constrain from a beam pipe

- Backward physics accessible
- Access to partons with momentum fraction $x_2 \rightarrow 1$ in the target ($x_F \rightarrow -1$)

Beam extraction using bent crystal

✓ **Possible fixed-target mode**



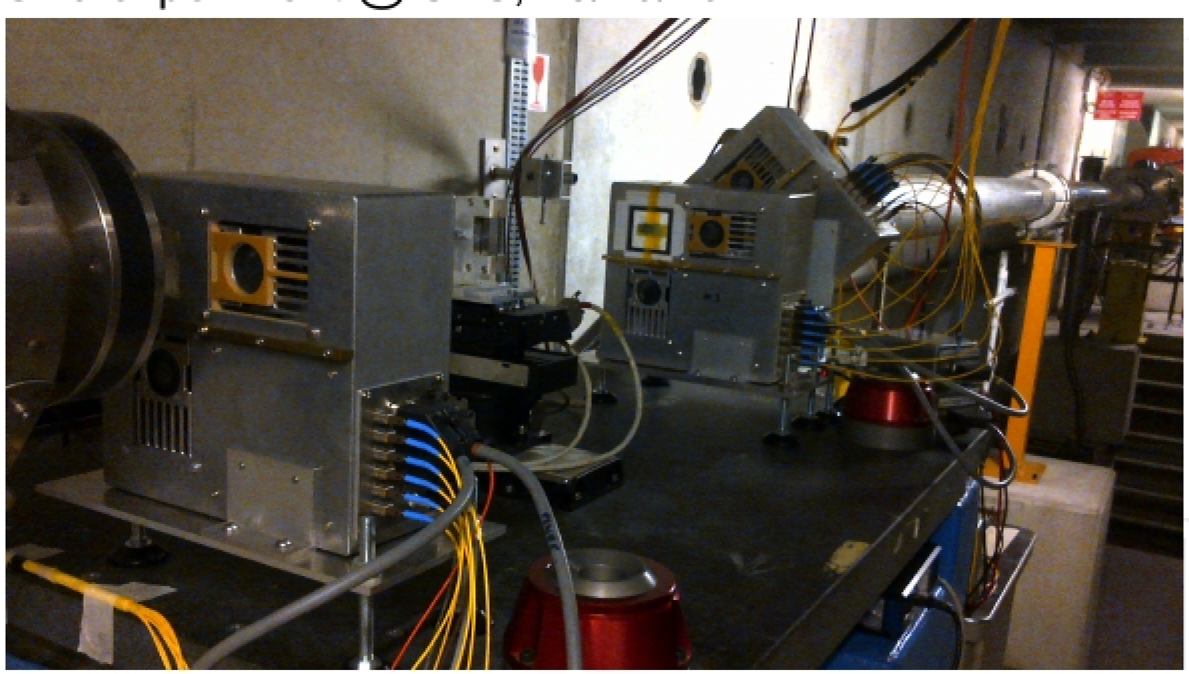
Standard collimation today

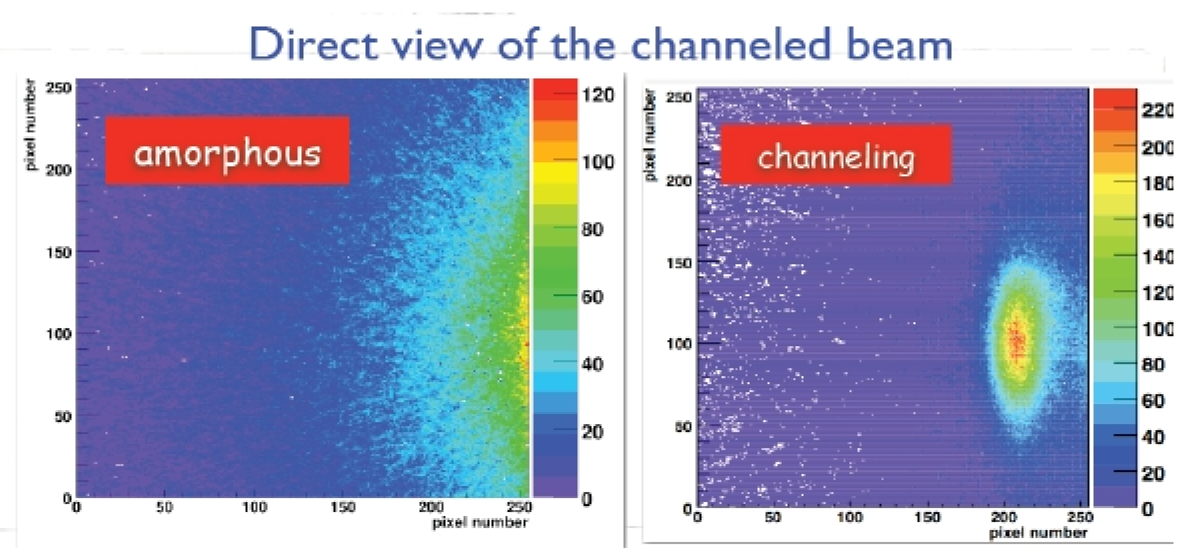
W. Scandale et al., JINST 6 T10002 (2011)

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

Beam extraction using bent crystal

✓ Beam collimation @LHC: amorphous collimator, inefficiency of 0.2% (3.5 TeV p beam)

- Expected bent crystal 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^{-1} - extracted beam : ***5 x 10⁸ p⁺ s⁻¹***
- 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 (P. Ballin et al, NIMB 267 (2009) 2952)

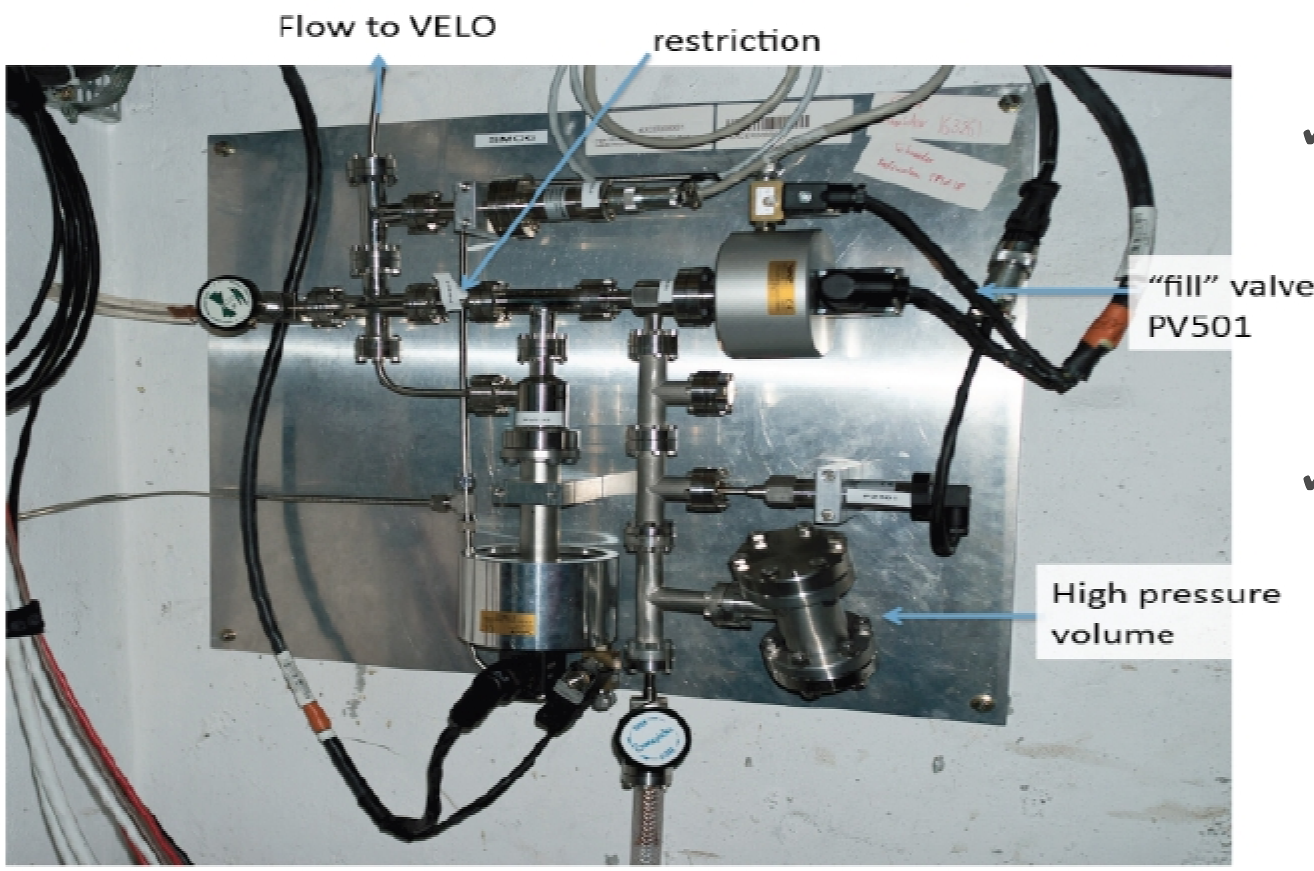
→ Deflecting the beam halo at 7σ distance to the beam

→ No loss in the LHC beam

Internal gas target: SMOG@LHC

✓ **Possible fixed-target mode**

SMOG: System for Measuring Overlap with Gas



➜ injection of Ne-gas into VELO

✓ Low density Ne-gas injected into VELO in LHCb

✓ Short pNe pilot run at $\sqrt{s_{NN}}$ = 87 GeV in 2012

LHCb-CONF-2012-034

✓ Short PbNe pilot run at $\sqrt{s_{NN}}$ = 54 GeV in 2013

More details on SMOG in the Michael Schmelling's talk, earlier today

- Noble gases favored
- As for now, target polarization is not possible with SMOG
- Internal gas target can be polarized, would be another system with respect to SMOG

Luminosities in pH and pA at $\sqrt{s_{NN}}$ = 115 GeV

With bent crystal

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

  l is a target thickness
- ✓ ϕ beam = 5×10^8 p^+ s^{-1} (50% of the beam loss)
- ✓ Integrated luminosity - LHC year – 9 months running = 10^7 s

Target	ρ ($g.cm^{-3}$)	A	L ($\mu b^{-1} s^{-1}$)	∫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

- ➢ Large luminosities comparable to LHC - with 1 m long H_2(D_z) target, 3 orders of magnitude larger that at RHIC

Luminosities in pA – bent crystal *vs* SMOG

With bent crystal

Target	ρ (g.cm^{-3})	A	L (μb^{-1}s^{-1})	∫L (pb^{-1}yr^{-1})
Be (1cm)	1.85	9	**62**	620
Cu (1cm)	8.96	64	**42**	420

SMOG
based on the pilot run

Target: Ne gas

- **Ne target density: 10^{-6} mbar**
- **L = <u>8 μb^{-1}s^{-1}</u>**

- Higher **instantaneous** luminosities using a bent crystal compare to what is expected from SMOG from the pilot run - 62 μb^{-1}s^{-1} with 1cm Be target *vs* 8 μb^{-1}s^{-1} for Ne in SMOG
- Higher Ne pressure needed in SMOG in order to reach comparable luminosity as in the bent crystal case
  - assuming *1 year of running with proton beam and P ≈ <u>10^{-5} mbar</u> one can obtain comparable luminosity as in the bent crystal case*
- Increasing the pressure is not expected to decrease the beam life time
- Tests for long runs have to be done – 1-week SMOG test proposed in LHCb for the next year

Luminosities in PbA at $\sqrt{s_{NN}}$ = 72 GeV

With bent crystal

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

  l is a target thickness
- ✓ ϕ beam = 2 $\times 10^5$ Pb s^{-1}
- ✓ Integrated luminosity - LHC year – 1 month running = 10^6 s

Target	ρ ($g.cm^{-3}$)	A	L ($mb^{-1}s^{-1}$)	∫L ($nb^{-1}yr^{-1}$)
Liq H_2 (1m)	0.07	1	800	800
Liq D_2 (1m)	0.16	2	1000	1000
Be (1cm)	1.85	9	25	620
Cu (1cm)	8.96	64	17	17
W (1cm)	19.1	185	13	13
Pb (1cm)	11.35	207	7	7

- Planned luminosity for PHENIX Run15 AuAu 2.8 nb^{-1} (0.13 nb^{-1} at 62 GeV)
- Nominal LHC luminosity for PbPb 0.5 nb^{-1}

Physics Highlights: AFTER @ LHC

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Physics opportunities of a fixed-target experiment using LHC beams

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Contents

Physics Highlights: AFTER @ LHC

pp and pA @ $\sqrt{s_{NN}}$ = 115 GeV

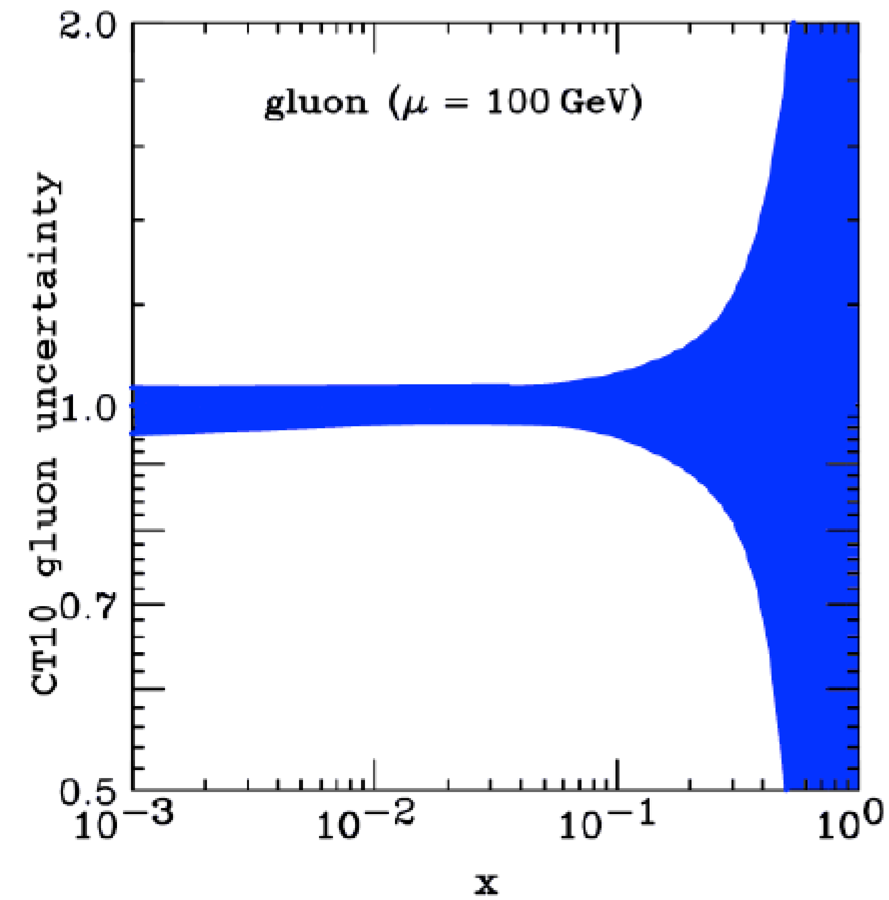
- ✓ **Nucleon partonic structure**
  - Gluon pdf in the proton – large uncertainties at high x
  - $g_p(x) = g_n(x)$?
    - ➔ Measure: quarkonia, isolated photons, high-p_T jets
    - ➔ Multiple probes to check factorization
- ✓ **Heavy-quark distribution at large x in the proton**
    - ➔ Measure: open heavy flavours
- ✓ **Spin physics**
  - Gluon Sivers effect
  - Linearly polarized gluons: $h_1^{\perp g}$
  - Single Spin Asymmetry in DY and HF studies
- ✓ **W and Z production near threshold ?**

Physics Highlights: AFTER @ LHC

pp and pA @ $\sqrt{s_{NN}}$ = 115 GeV

✓ **Understand dynamic of large-x gluon in nucleon**

- Quarkonia
- Isolated photons
- High-p_T jets (> 20 GeV/c)



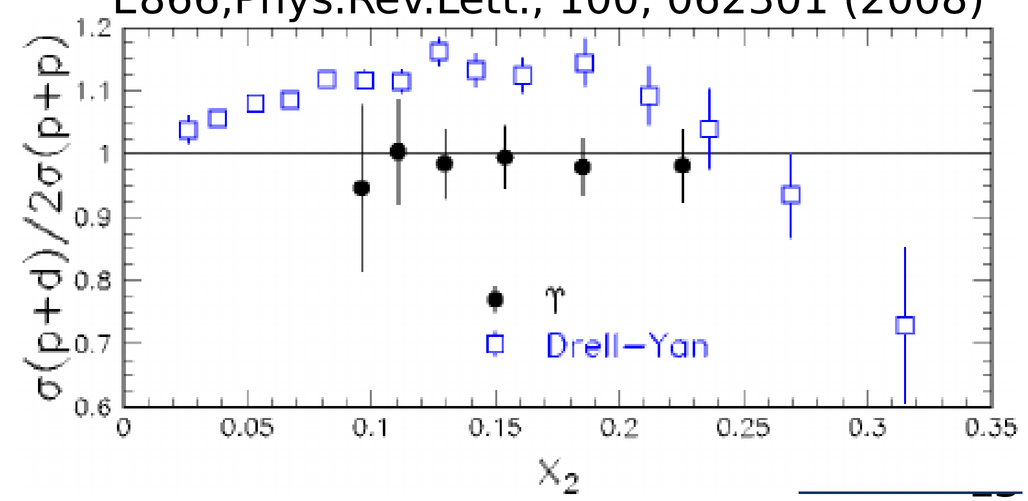
✓ Gluon distribution function in the proton: very large uncertainty at large x, also at large Q

✓ Unknown for the neutron

✓ With AFTER@LHC:

- Access to target x_g = 0.3 - 1 (>1 Fermi motion in nucleus)
- Different targets:
  - Hydrogen *pp, pd, pn*
  - Deuteron (neutron)

E866,Phys.Rev.Lett., 100, 062301 (2008)

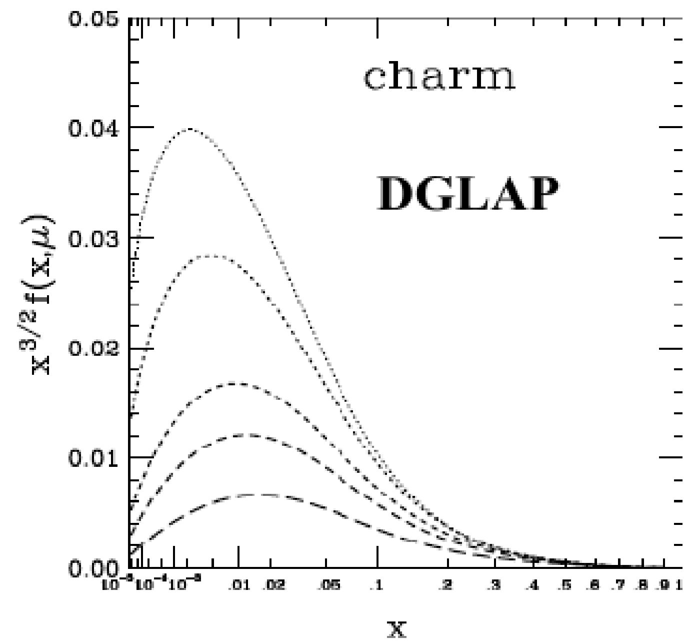


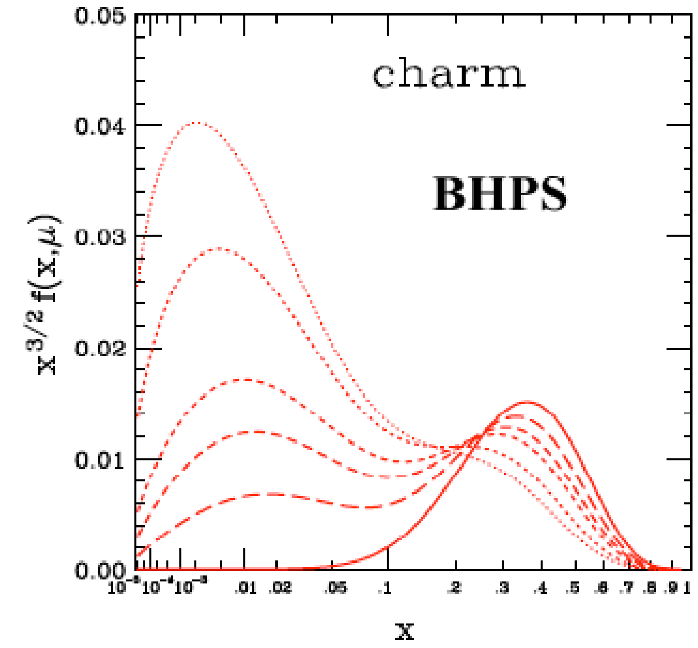
Physics Highlights: AFTER @ LHC

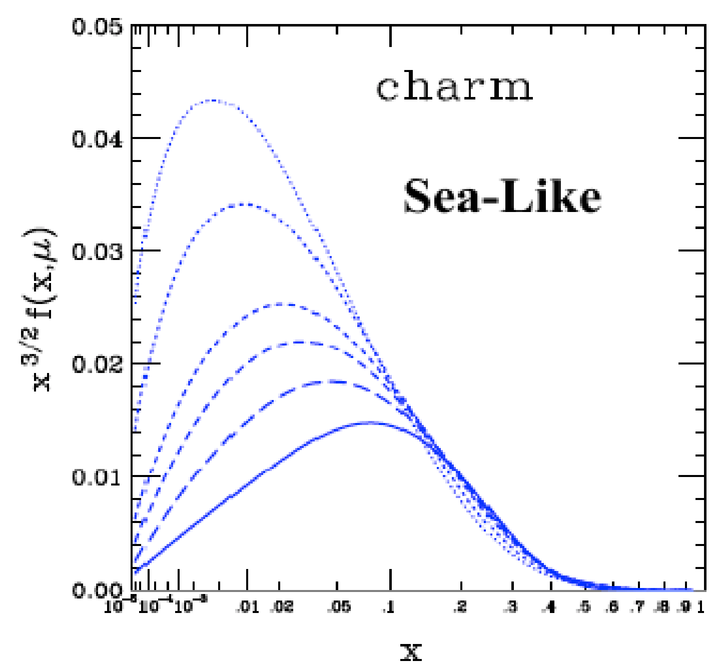
pp @ $\sqrt{s_{NN}}$ = 115 GeV

- **Heavy-quark distribution at large x**
  - ➔ Open charm
  - ➔ Open beauty

- Pin down intrinsic charm
  - Non-perturbative models of hadron structure
  - Different charm pdfs (DGLAP or models with intrinsic charm) are in agreement with DIS data
  - With AFTER@LHC
    - Good coverage in the target rapidity region
    - High luminosity to reach large x_B







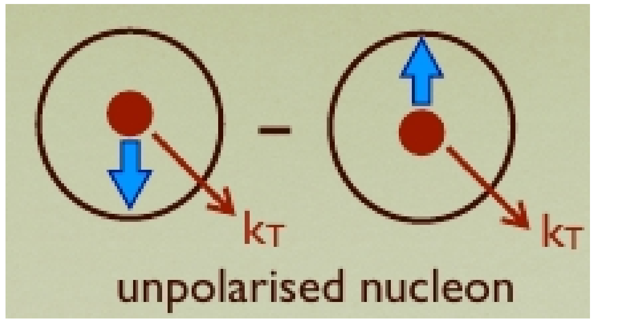
CTEQ6.5C with intrinsic charm

Pumplin et al. Phys.Rev. D75 (2007)

Physics Highlights: AFTER @ LHC

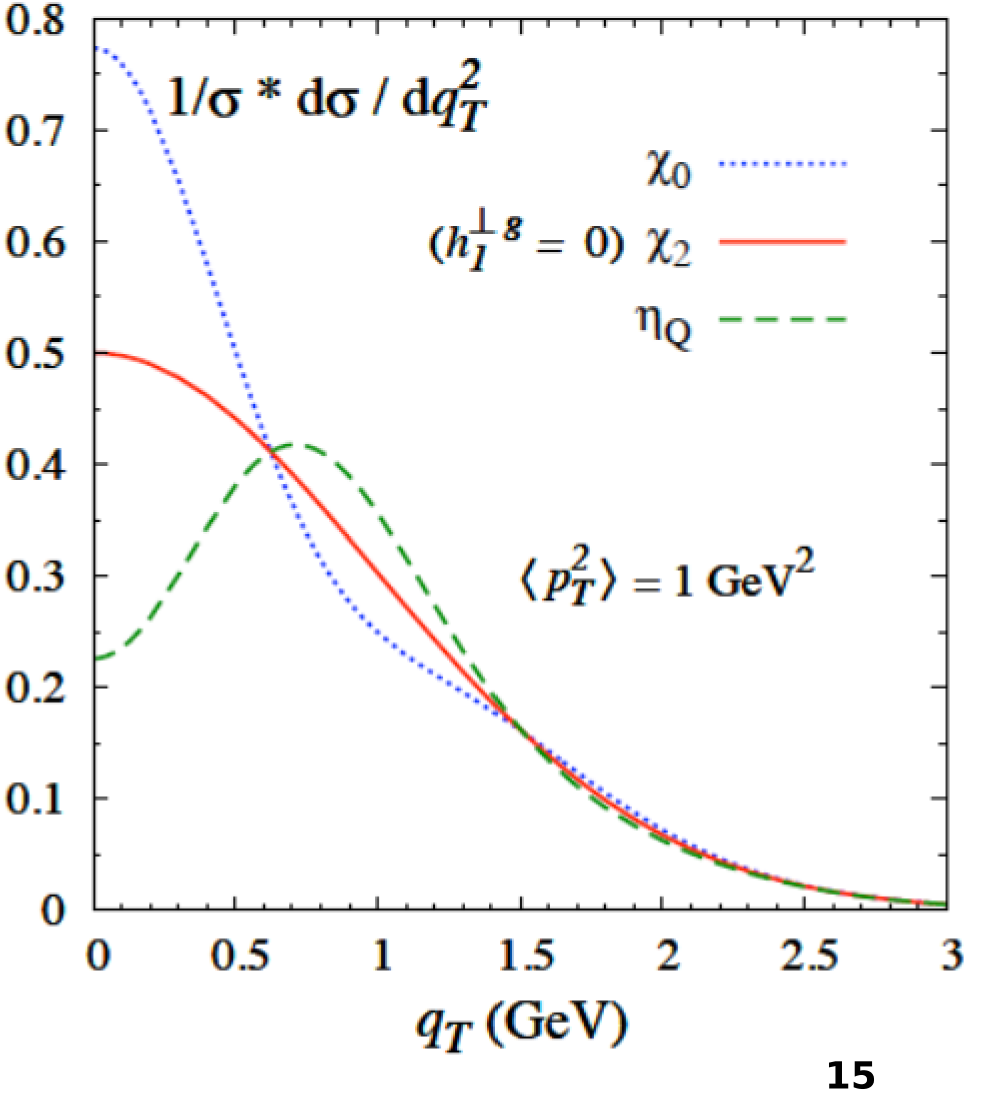
pp @ $\sqrt{s_{NN}}$ = 115 GeV

- **Linearly polarized gluons: $h_1^{\perp g}$**
  - **"Boers-Mulder" effect: correlation between the parton k_T and its spin (in unpolarized nucleon)**
  - Scalar and pseudo-scalar quarkonia – χ_{c0}, χ_{b0}, η_c, η_b



- Low-p_T C-even quarkonium production is a good probe of gluon Transverse Momentum Dependent (TMD) pdfs
- Low-p_T of scalar and pseudo-scalar quarkonia are affected differently by the linearly polarized gluons in unpolarized nucleons
- With AFTER@LHC
  - Boost – better access to the low-p_T C-even quarkonia
  - η_C (LHCb 1409.3612), (η_b), back-to-back J/ψ + γ, J/ψ + J/ψ

Boer, Pisano, PRD 86 (2012) 094007

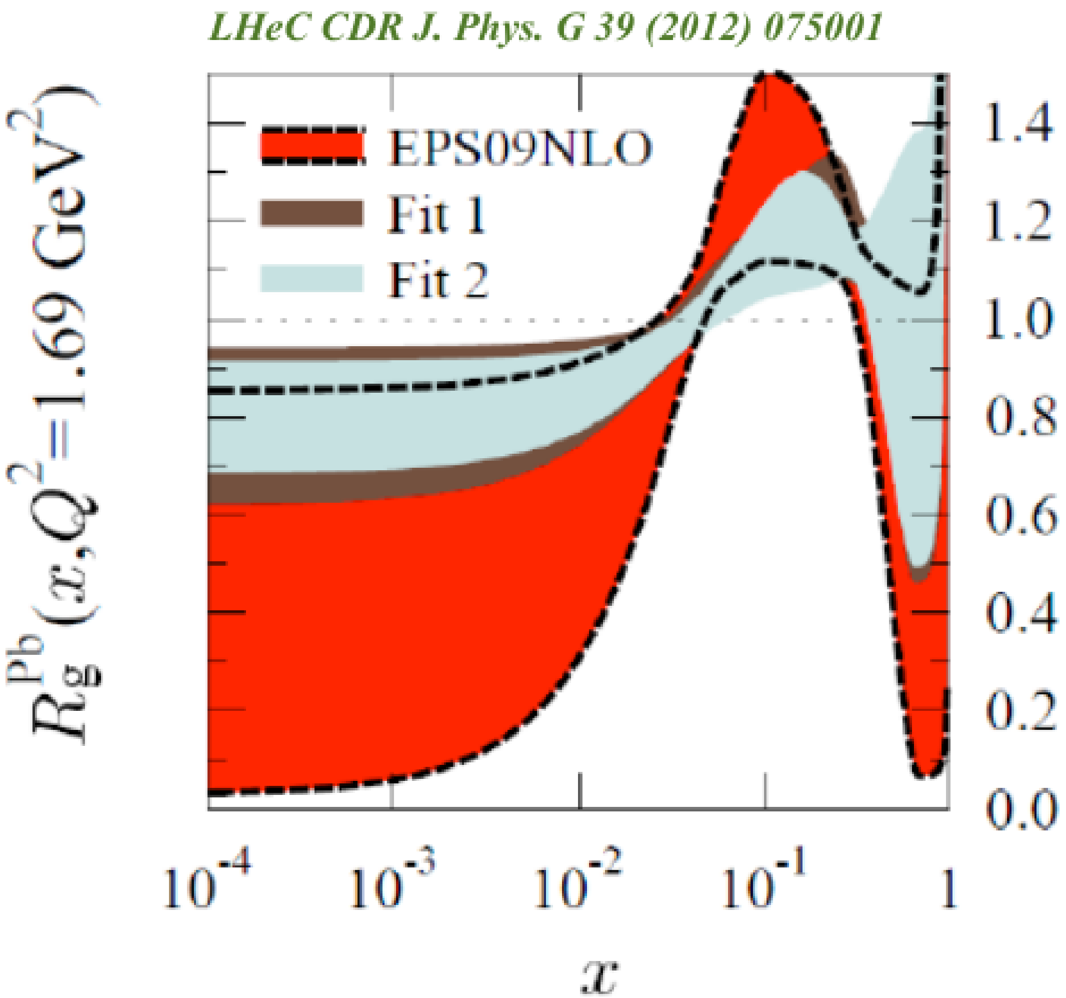


Physics Highlights: AFTER @ LHC

PbA @ $\sqrt{s_{NN}}$ = 72 GeV, pA @ $\sqrt{s_{NN}}$ = 115 GeV

✓ **Gluon distribution in nucleus at large x**

- Quarkonia
- Isolated photons
- High-p_T jets (> 20 GeV/c)



✓ Large uncertainty in nuclei at large x, unknown gluon EMC effect

✓ With AFTER@LHC:

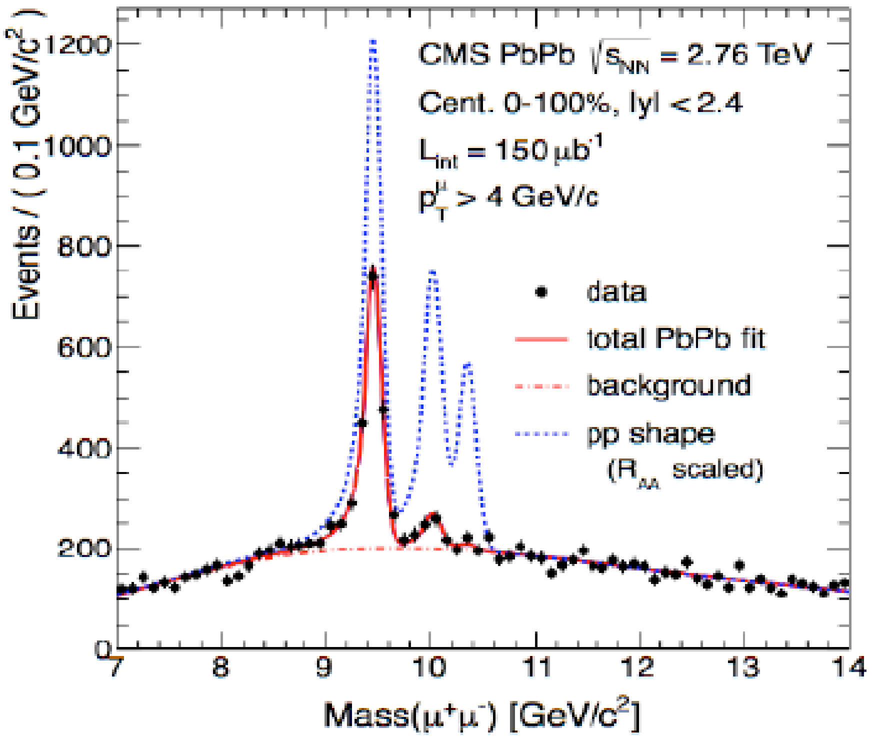
- Access to target x_g = 0.3 - 1 (>1 Fermi motion in nucleus)
- With different targets:
  - probing A dependence of shadowing and nuclear matter effects

Physics Highlights: AFTER @ LHC

PbA @ $\sqrt{s_{NN}}$ = 72 GeV

- ✓ **Gluon distribution in nucleus at large x**
  - EIC, LHeC experiments do not help much
    - ➔ Quarkonia, isolated photons, high-p_T jets

CMS, PRL 109 (2012) 222301

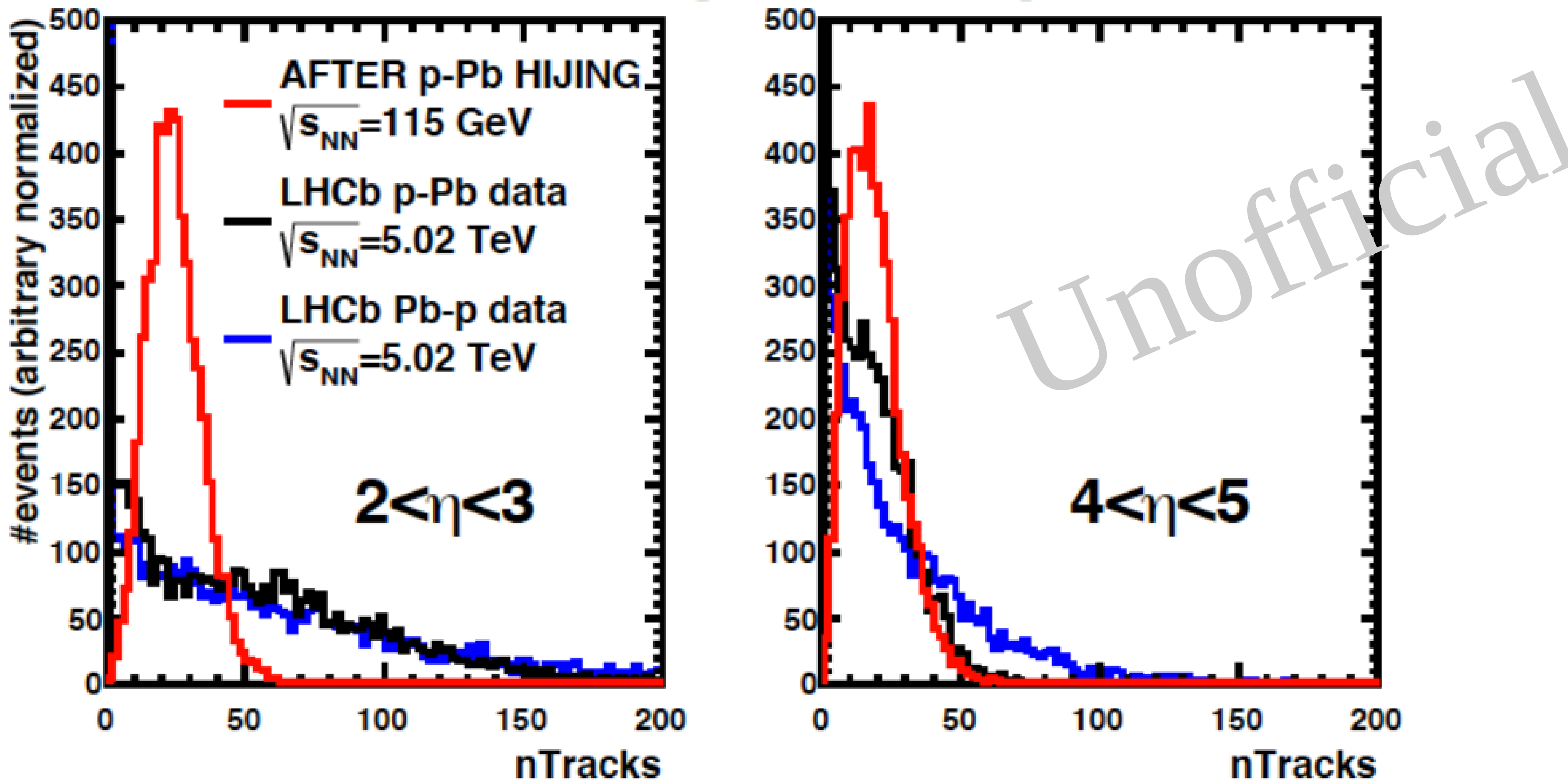


- ✓ **Quark-Gluon Plasma**
  - **Experimental probes**
    - ➔ **Quarkonia**
    - ➔ **HF jets quenching**
    - ➔ **Low mass lepton pairs**
    - ➔ **Direct photons**
      - **(Sequential ?) suppression of different quarkonia states – good resolution needed**
      - **In PbA, different nuclei, A-dependent studies**
      - ***Precise estimation of Cold Nuclear Matter effects from pA***
- ✓ **Ultra-peripheral collisions**

First simulations

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

Z. Yang, AFTER workshop les Houches, January 2014



- ✓ Probability of high track multiplicity is lower in the fixed target mode than in the collider mode, at LHCb acceptance $2 < \eta < 5$
- ✓ Boost should not be an issue – no problem for LHCb-like detector to cope with seen multiplicity

Expected quarkonium yield

pp and pA @$\sqrt{s}$ = 115 GeV

Target	$\int\mathcal{L}$ ($fb^{-1}.yr^{-1}$)	$N(J/\Psi)\ yr^{-1} = A\mathcal{L}\mathcal{B}\sigma_\Psi$	$N(\Upsilon)\ yr^{-1} = A\mathcal{L}\mathcal{B}\sigma_\Upsilon$
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	$1.2\ 10^{-2}$	$4.8\ 10^5$	$1.2\ 10^3$

pp

1 m H_2 target

- ✓ 1000 times more statistics than at RHIC (@200 GeV)
- ✓ Comparable statistics to LHC

pA

Target	A	$\int\mathcal{L}$ ($fb^{-1}.yr^{-1}$)	$N(J/\Psi)\ yr^{-1} = A\mathcal{L}\mathcal{B}\sigma_\Psi$	$N(\Upsilon)\ yr^{-1} = A\mathcal{L}\mathcal{B}\sigma_\Upsilon$
1cm Be	9	0.62	$1.1\ 10^8$	$2.2\ 10^5$
1cm Cu	64	0.42	$5.3\ 10^8$	$1.1\ 10^6$
1cm W	185	0.31	$1.1\ 10^9$	$2.3\ 10^6$
1cm Pb	207	0.16	$6.7\ 10^8$	$1.3\ 10^6$
LHC pPb 8.8 TeV	207	10^{-4}	$1.0\ 10^7$	$7.5\ 10^4$
RHIC dAu 200GeV	198	$1.5\ 10^{-4}$	$2.4\ 10^6$	$5.9\ 10^3$
RHIC dAu 62GeV	198	$3.8\ 10^{-6}$	$1.2\ 10^4$	18

1 cm Pb target

- ✓ 100 times more statistics than at RHIC (dAu@200 GeV)
- ✓ Comparable statistics to LHC

Detailed study of quarkonium production and nuclear effects

Expected quarkonium yield

PbA@$\sqrt{s_{NN}}$ = 72 GeV

PbA

Target	A.B	$\int\mathcal{L}$ (nb^{-1}.yr^{-1})	N(J/Ψ) yr^{-1} = AB$\mathcal{L}\mathcal{B}\sigma_\Psi$	N(Υ) yr^{-1} =AB$\mathcal{L}\mathcal{B}\sigma_\Upsilon$
1 m Liq. H_2	207.1	800	3.4 10^6	6.9 10^3
1cm Be	207.9	25	9.1 10^5	1.9 10^3
1cm Cu	207.64	17	4.3 10^6	0.9 10^3
1cm W	207.185	13	9.7 10^6	1.9 10^4
1cm Pb	207.207	7	5.7 10^6	1.1 10^4
LHC PbPb 5.5 TeV	207.207	0.5	7.3 10^6	3.6 10^4
RHIC AuAu 200GeV	198.198	2.8	4.4 10^6	1.1 10^4
RHIC AuAu 62GeV	198.198	0.13	4.0 10^4	61

1 cm Pb target

- ✓ Similar statistics than at RHIC @200 GeV
- ✓ 2 order of magnitude larger that at RHIC @62 GeV

Detailed study of quarkonium states

Quarkonia fast simulations, pp at $\sqrt{s}$ = 115 GeV

- PYTHIA 8.185
- Fast simulations with LHCb reconstruction parameters

✓ ***<u>Requirements:</u>***

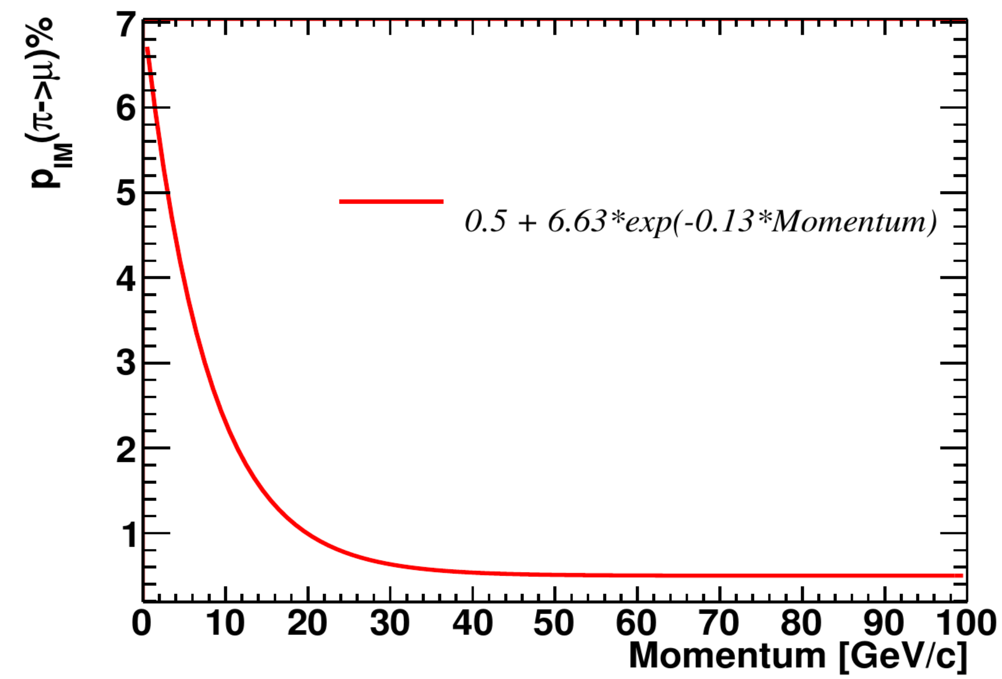
- Momentum resolution: $\Delta p/p = 0.5\%$
- μ identification efficiency: 98%

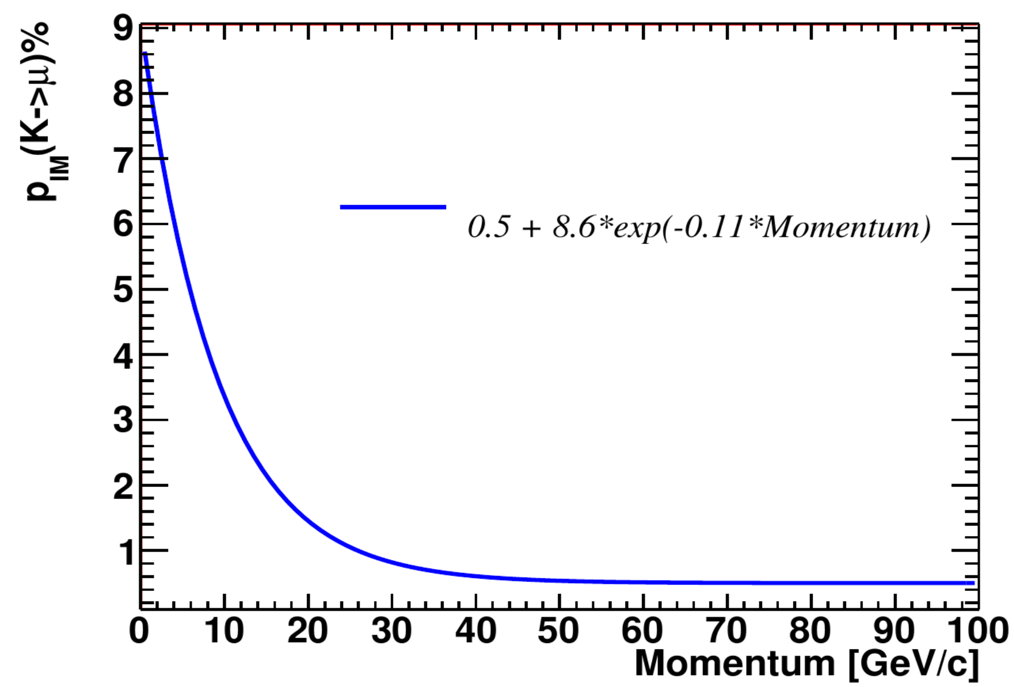
✓ ***<u>Single μ cuts:</u>***

- $2 < \eta_\mu < 5$
- $p_T^\mu > 0.7$ GeV/c

✓ ***<u>μ misidentification (with π or K):</u>***

- If π/K decays before 12m (LHCb calorimeter) it is rejected by tracking
- If decays after 12m misidentification probability is applied – see plots



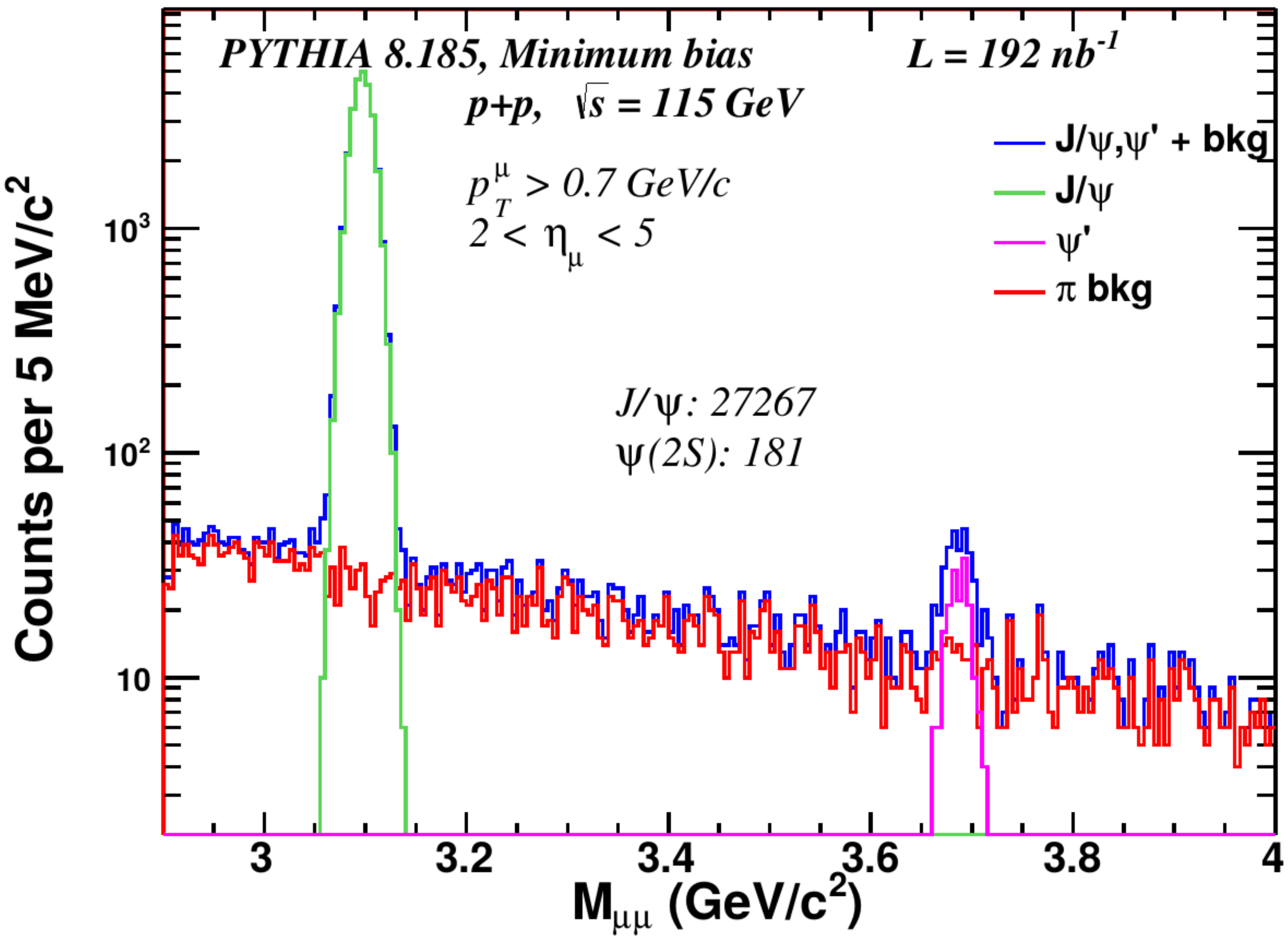


F. Achilli et al, arXiv:1306.0249

ψ signal simulation with full background

$J/\psi \,/\, \psi' \rightarrow \mu^{+}\mu^{-}$

- $\int L = 192\ nb^{-1}$, **1.5 minute of data taking with 1m H_2 target**

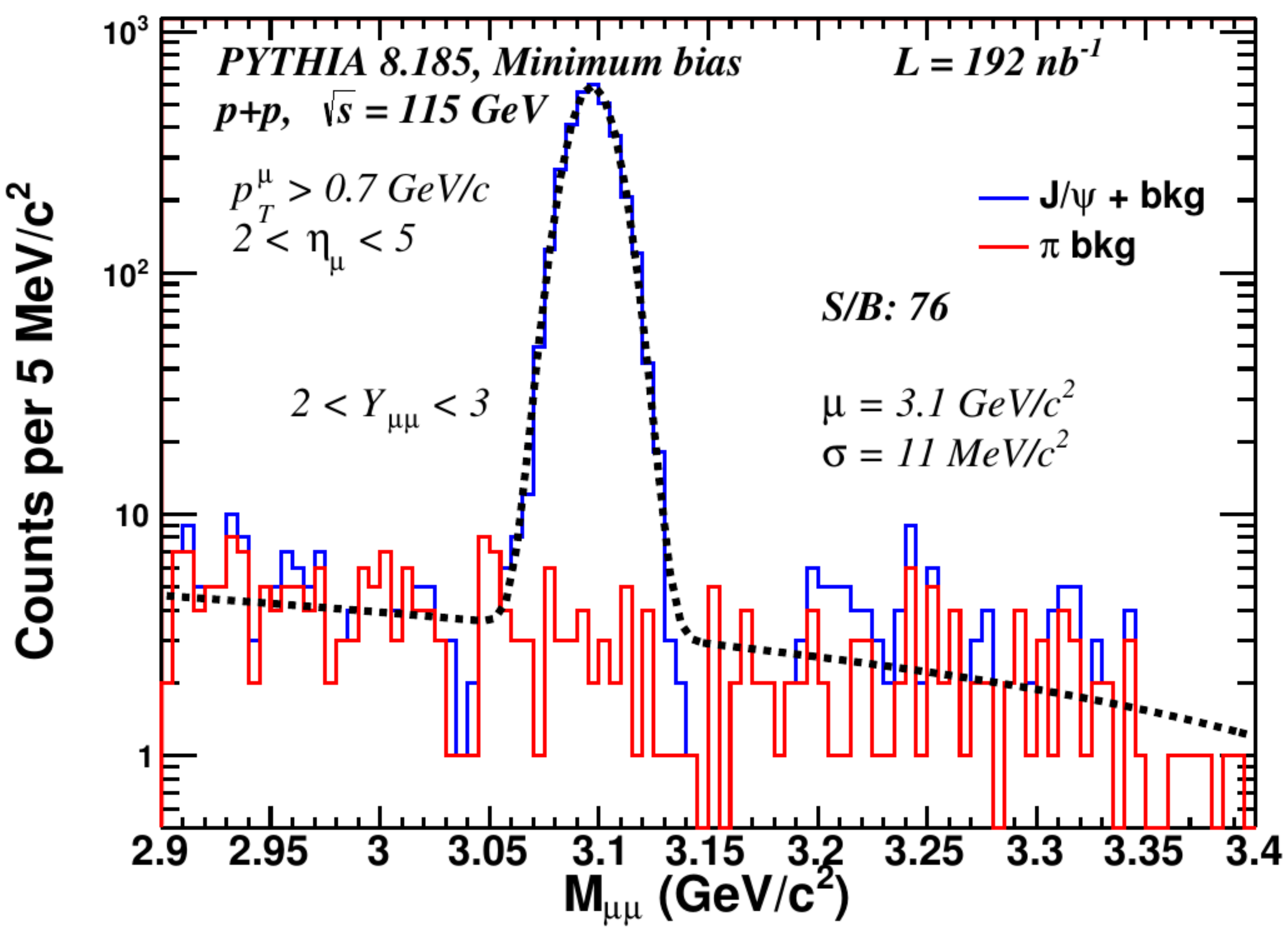


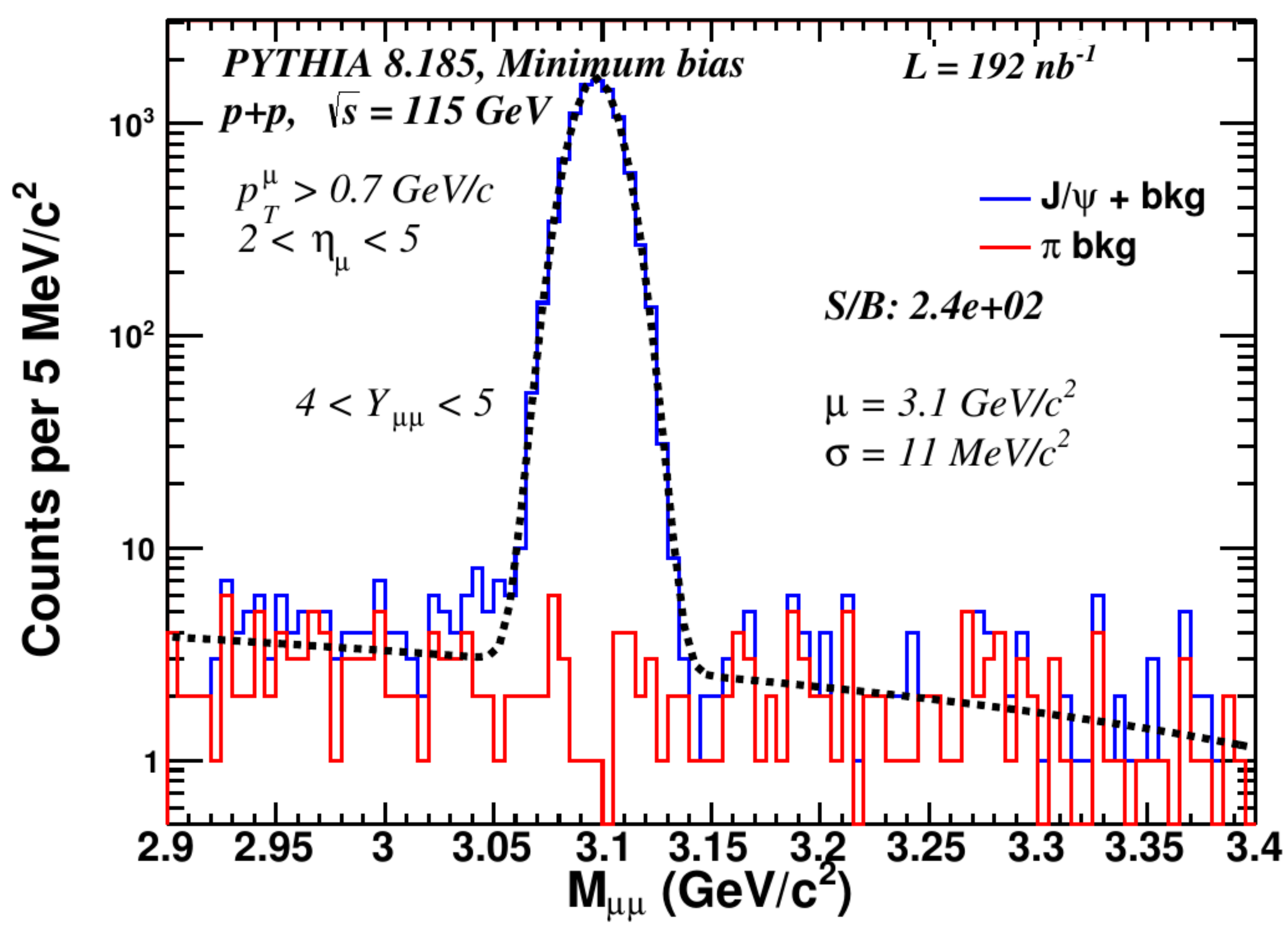
➔Dominant source of background is from misidentified π

J/ψ signal simulation with full background, y bins

$J/\psi \rightarrow \mu^{+} \mu^{-}$

- $\int L = 192\ nb^{-1}$, **1.5 minute of data taking with 1m H_2 target**



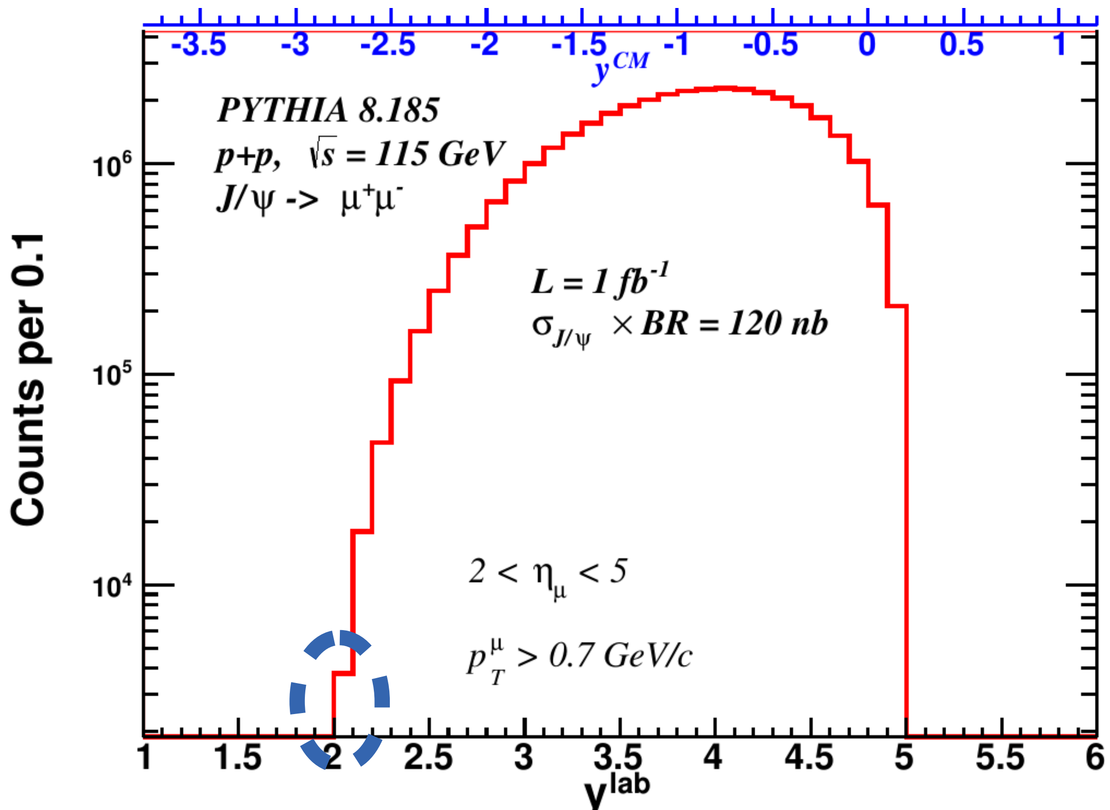


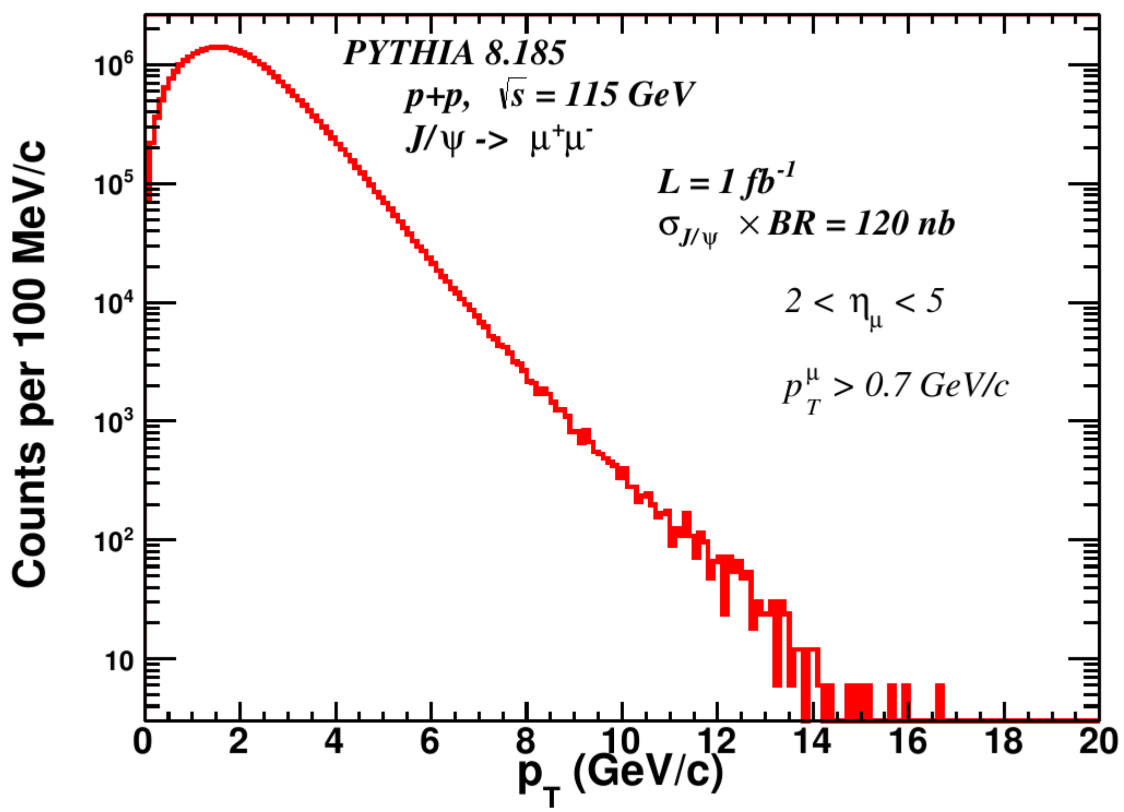
- Excellent J/ψ signal with high signal to background ratio
- Most background is combinatorial (μ not coming from J/ψ decay)

J/ψ acceptance and p_T reach

$J/\psi \rightarrow \mu^+ \mu^-$

- $\int L = 1\ fb^{-1}$, **2 weeks of data taking with 1m H_2 target**





<u>J/ψ y range:</u>

- $2 < y_{lab} < 5$
- $-2.8 < y_{CMS} < 0.2$

- J/ψ rapidity range limited only by cuts on μ ($2 < \eta_\mu < 5$)
- With larger acceptance detector even wider J/ψ rapidity range

- $p_T = 15$ GeV/c for J/ψ easily reachable with a year of data taking (20 fb^{-1})
- This corresponds to $x_T = 0.25$
- Equivalent p_T reach to RHIC @500 GeV
- The same p_T reach expected for pA

Summary

- Many physics opportunities with a fixed target experiment using LHC p and Pb beams
- Novel testing ground for QCD in the high-x frontier with AFTER@LHC
- Extensive spin program with a polarized target
- Using dense targets high luminosities can be achieved
- Target versatility: hydrogen, deuteron, nucleus – nuclear effects and QGP
- First fast simulations performed

Outlook

- Special issue in Advances in High Energy Physics - submission deadline March 20, 2015
  - ***<u>Everybody is welcome to contribute</u>***
- Expression of interest expected in 2015
- Development of the fast simulation framework

Advances in High Energy Physics

Hindawi

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

after.in2p3.fr

Thank you !

BACKUP

Physics Highlights: AFTER @ LHC

pp and pA @$\sqrt{s_{NN}}$ = 115 GeV

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

L. Massacrier – SPIN 2014 Conference

Physics Highlights: AFTER @ LHC

pp and pA @$\sqrt{s_{NN}}$ = 115 GeV

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

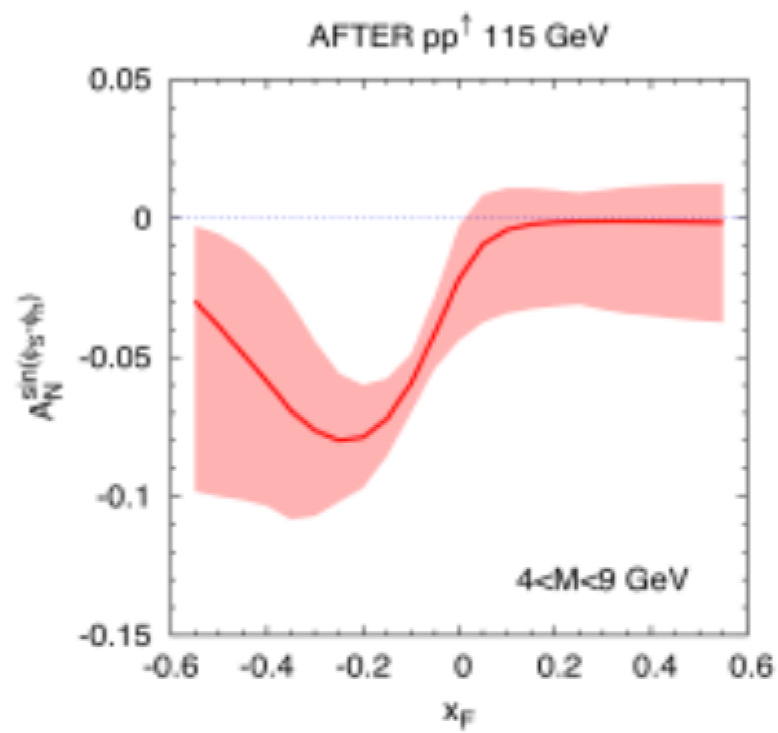
(Quark) Sivers effects with a transversely polarized target

- Can be probed with the Drell-Yan

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

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



Prediction for AFTER

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

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