

## A Fixed-Target Programme at the LHC

**J.P. Lansberg**

IPN Orsay – Paris-Sud U./Paris Saclay U. –CNRS/IN2P3

Rencontre QGP France, Etretat, July 4, 2018

AFTER@LHC Study group: [http://after.in2p3.fr/after/index.php/Current\\_author\\_list](http://after.in2p3.fr/after/index.php/Current_author_list)

# Part I

## The AFTER@LHC programme



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame .....
3.2.1. Quarkonia.....	6.5. Nuclear-matter baseline.....
3.2.2. Jets.....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions.....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions.....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY.....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter.....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon–jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame .....
3.2.1. Quarkonia .....	6.5. Nuclear-matter baseline.....
3.2.2. Jets .....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions .....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions .....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon–jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	

# The Genesis

- Submitted to arXiv on February 2012
- At the time, the bent crystal solution was the only one mentioned

Physics Reports 522 (2013) 239–255



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame .....
3.2.1. Quarkonia.....	6.5. Nuclear-matter baseline.....
3.2.2. Jets.....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions .....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions .....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon-jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	

# The Genesis

- Submitted to arXiv on February 2012
- At the time, the bent crystal solution was the only one mentioned
- All the subjects (even astroparticles) already considered

Physics Reports 522 (2013) 239–255



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame .....
3.2.1. Quarkonia.....	6.5. Nuclear-matter baseline.....
3.2.2. Jets .....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions .....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions .....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon–jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	

# The Genesis

- Submitted to arXiv on February 2012
- At the time, the bent crystal solution was the only one mentioned
- All the subjects (even astroparticles) already considered
- First real discussions about SMOG at Les Houches on January 2014 (first look at reconstructed data; first simulations of the occupancy in LHCb for HIC)

Physics Reports 522 (2013) 239–255



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame .....
3.2.1. Quarkonia.....	6.5. Nuclear-matter baseline.....
3.2.2. Jets.....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions .....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions .....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon–jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	

# The Genesis

- Submitted to arXiv on February 2012
- At the time, the bent crystal solution was the only one mentioned
- All the subjects (even astroparticles) already considered
- First real discussions about SMOG at Les Houches on January 2014 (first look at reconstructed data; first simulations of the occupancy in LHCb for HIC)
- First dedicated workshop to start to draft an EoI/review/YR August 2015, followed by a couple others with feasibility study publications as outcome

Physics Reports 522 (2013) 239–255



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame.....
3.2.1. Quarkonia.....	6.5. Nuclear-matter baseline.....
3.2.2. Jets .....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions.....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions .....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon-jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	

# The Genesis

- Submitted to arXiv on February 2012
- At the time, the bent crystal solution was the only one mentioned
- All the subjects (even astroparticles) already considered
- First real discussions about SMOG at Les Houches on January 2014 (first look at reconstructed data; first simulations of the occupancy in LHCb for HIC)
- First dedicated workshop to start to draft an EoI/review/YR August 2015, followed by a couple others with feasibility study publications as outcome
- September 2016: PBC kickoff, ...

Physics Reports 522 (2013) 239–255



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large $x$ .....	6.4. Deconfinement and the target rest frame.....
3.2.1. Quarkonia .....	6.5. Nuclear-matter baseline.....
3.2.2. Jets .....	7. $W$ and $Z$ boson production in $pp$ , $pd$ and $pA$ collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in $pA$ .....
3.3. Gluons in the deuteron and in the neutron.....	7.2. $W/Z$ production in $pp$ and $pd$ .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions.....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. $J/\psi + D$ meson production.....	8.2. Hard diffractive reactions.....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at $x_F \rightarrow$ .....
4. Spin physics.....	8.4. Very backward physics.....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon.....	9.1. $D$ and $B$ physics .....
4.4. Spin asymmetries with a final state polarization.....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower.....
5.1. Quark nPDF: Drell–Yan in $pA$ and $PbP$ .....	10. Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments.....
5.2.1. Isolated photons and photon-jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus.....	

# The Genesis

- Submitted to arXiv on February 2012
- At the time, the bent crystal solution was the only one mentioned
- All the subjects (even astroparticles) already considered
- First real discussions about SMOG at Les Houches on January 2014 (first look at reconstructed data; first simulations of the occupancy in LHCb for HIC)
- First dedicated workshop to start to draft an EoI/review/YR August 2015, followed by a couple others with feasibility study publications as outcome
- September 2016: PBC kickoff, ...
- Finally the EoI, which became a review to motivate a full FT LHC program, is out !

Physics Reports 522 (2013) 239–255



Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: [www.elsevier.com/locate/physrep](http://www.elsevier.com/locate/physrep)



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

S.J. Brodsky<sup>a</sup>, F. Fleuret<sup>b</sup>, C. Hadjidakis<sup>c</sup>, J.P. Lansberg<sup>c,\*</sup>

<sup>a</sup> SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA

<sup>b</sup> Laboratoire Leprince Ringuet, Ecole polytechnique, CNRS/IN2P3, 91128 Palaiseau, France

<sup>c</sup> IPNO, Université Paris-Sud, CNRS/IN2P3, 91406 Orsay, France

### Contents

1. Introduction.....	6. Deconfinement in heavy-ion collisions .....
2. Key numbers and features .....	6.1. Quarkonium studies .....
3. Nucleon partonic structure .....	6.2. Jet quenching .....
3.1. Drell–Yan.....	6.3. Direct photon .....
3.2. Gluons in the proton at large x.....	6.4. Deconfinement and the target rest frame.....
3.2.1. Quarkonia .....	6.5. Nuclear-matter baseline.....
3.2.2. Jets .....	7. W and Z boson production in pp, pd and pA collisions.....
3.2.3. Direct/isolated photons.....	7.1. First measurements in pA.....
3.3. Gluons in the deuteron and in the neutron.....	7.2. W/Z production in pp and pd .....
3.4. Charm and bottom in the proton.....	8. Exclusive, semi-exclusive and backward reactions .....
3.4.1. Open-charm production.....	8.1. Ultra-peripheral collisions .....
3.4.2. J/ψ + D meson production .....	8.2. Hard diffractive reactions .....
3.4.3. Heavy-quark plus photon production.....	8.3. Heavy-hadron (diffractive) production at xF → .....
4. Spin physics.....	8.4. Very backward physics .....
4.1. Transverse SSA and DY .....	8.5. Direct hadron production.....
4.2. Quarkonium and heavy-quark transverse SSA .....	9. Further potentialities of a high-energy fixed-target set-.....
4.3. Transverse SSA and photon .....	9.1. D and B physics .....
4.4. Spin asymmetries with a final state polarization .....	9.2. Secondary beams .....
5. Nuclear matter .....	9.3. Forward studies in relation with cosmic shower .....
5.1. Quark nPDF: Drell–Yan in pA and Pbp.....	Conclusions.....
5.2. Gluon nPDF.....	Acknowledgments .....
5.2.1. Isolated photons and photon–jet correlations.....	References.....
5.2.2. Precision quarkonium and heavy-flavour studies.....	
5.3. Color filtering, energy loss, Sudakov suppression and hadron break-up in the nucleus .....	

# The AFTER@LHC programme

arXiv:1807.00603v1 [hep-ex] 2 Jul 2018

## A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

C. Hadjidakis<sup>a,1</sup>, D. Kikola<sup>b,1</sup>, J.P. Lansberg<sup>a,1,\*</sup>, L. Massacrier<sup>a,1</sup>, M.G. Echevarria<sup>c,2</sup>, A. Kusina<sup>d,2</sup>,  
I. Schienbein<sup>c,2</sup>, J. Seixas<sup>f,g,2</sup>, H.S. Shao<sup>h,2</sup>, A. Signori<sup>i,2</sup>, B. Trzeciak<sup>j,2</sup>, S.J. Brodsky<sup>k</sup>, G. Cavoto<sup>l</sup>,  
C. Da Silva<sup>m</sup>, F. Donato<sup>n</sup>, E.G. Ferreira<sup>o,p</sup>, I. Hřivnáčová<sup>a</sup>, A. Klein<sup>m</sup>, A. Kurepin<sup>q</sup>, C. Lorcé<sup>r</sup>, F. Lyonnet<sup>s</sup>,  
Y. Makdisi<sup>t</sup>, S. Porteboeuf<sup>u</sup>, C. Quintans<sup>g</sup>, A. Rakotozafindrabe<sup>v</sup>, P. Robbe<sup>w</sup>, W. Scandale<sup>x</sup>,  
N. Topilskaya<sup>q</sup>, A. Uras<sup>y</sup>, J. Wagner<sup>z</sup>, N. Yamanaka<sup>a</sup>, Z. Yang<sup>aa</sup>, A. Zelenski<sup>t</sup>

### Abstract

We review the context, the motivations and the expected performances of a comprehensive and ambitious fixed-target program using the multi-TeV proton and ion LHC beams. We also provide a detailed account of the different possible technical implementations ranging from an internal wire target to a full dedicated beam line extracted with a bent crystal. The possibilities offered by the use of the ALICE and LHCb detectors in the fixed-target mode are also reviewed.

*To be submitted to Physics Reports*

# The AFTER@LHC HIC programme

<b>2</b>	<b>Motivations</b>	<b>5</b>
2.1	The high- $x$ frontier	5
2.2	Unraveling the nucleon spin	7
2.3	The nuclear matter in new rapidity and energy domains	10
<b>3</b>	<b>How to make fixed-target collisions at the LHC?</b>	<b>12</b>
3.1	Overview	12
3.2	Relevant LHC parameters and definitions	13
3.3	Internal gas target solutions	14
3.3.1	SMOG: a feasibility demonstrator	14
3.3.2	Gas-jet target	15
3.3.3	Storage-cell gas target	17
3.4	Internal solid target intercepting the beam halo	18
3.5	External/internal target solution with a slow beam extraction using a bent crystal	19
3.5.1	Crystal-assisted extraction of the LHC beams	19
3.5.2	Unpolarised targets	21
3.5.3	Polarised targets	21
3.6	Comparison of technologies	23
3.6.1	Qualitative comparison of the various technological solutions	23
3.6.2	Comparison of the luminosities achieved for AFTER@LHC with the various technological solutions	24
3.6.3	Comparison of the polarised-target performances for STSA measurements	26
<b>4</b>	<b>Detector requirements and expected performances</b>	<b>27</b>
4.1	Detector requirements	28
4.2	Possible implementations with existing apparatus	29
4.2.1	ALICE as a fixed-target experiment	29
4.2.2	LHCb as a fixed-target experiment	31
4.2.3	Comparison of possible implementations	34

# The AFTER@LHC HIC programme

<b>5</b>	<b>Physics Projections</b>	<b>38</b>
5.1	High- $x$ frontier for particle and astroparticle physics . . . . .	38
5.1.1	Nucleon structure . . . . .	38
5.1.2	Nuclear structure . . . . .	47
5.1.3	Astroparticle physics . . . . .	50
5.2	Spin physics . . . . .	53
5.2.1	Quark Sivers effect . . . . .	54
5.2.2	Gluon Sivers effect . . . . .	59
5.2.3	Quark-induced azimuthal asymmetries . . . . .	63
5.2.4	Gluon-induced azimuthal asymmetries . . . . .	63
5.2.5	From TMD PDFs to the partonic orbital angular momentum . . . . .	65
5.2.6	Ultrapерipheral collisions . . . . .	66
5.2.7	Accessing the strange quark helicity densities at high $x$ . . . . .	67
5.3	Heavy-ion physics . . . . .	70
5.3.1	Precise quarkonium studies in a new rapidity and energy domain . . . . .	71
5.3.2	Study of the heavy-quark energy-loss mechanism and their interaction with the surrounding nuclear matter . . . . .	75
5.3.3	Soft probes at large rapidities – a precise tool to study the bulk properties of the nuclear matter . . . . .	76
5.3.4	Looking for collectivity in small systems in a new energy domain . . . . .	78
5.3.5	Test of the factorisation of the initial-state effects in AA collisions with Drell-Yan pair production . . . . .	79
<b>6</b>	<b>Conclusions</b>	<b>82</b>

# The AFTER@LHC programme

5.3	Heavy-ion physics . . . . .	70
5.3.1	Precise quarkonium studies in a new rapidity and energy domain . . . . .	71
5.3.2	Study of the heavy-quark energy-loss mechanism and their interaction with the surrounding nuclear matter . . . . .	75
5.3.3	Soft probes at large rapidities – a precise tool to study the bulk properties of the nuclear matter . . . . .	76
5.3.4	Looking for collectivity in small systems in a new energy domain . . . . .	78
5.3.5	Test of the factorisation of the initial-state effects in AA collisions with Drell-Yan pair production . . . . .	79

# Possible implementations

# Possible implementations

- Internal **gas** target (with or without storage cell)
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
  - uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
  - Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
  - A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used

# Possible implementations

- Internal **gas** target (with or without storage cell)
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
  - uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
  - Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
  - A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used
- Internal **wire/foil** target [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]

# Possible implementations

- **Internal gas target** (with or without storage cell)
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
  - uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
  - Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
  - A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used
- **Internal wire/foil target** [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]
- **Bent crystal option: beam line vs split**
  - crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
  - the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$

# Possible implementations

- Internal **gas** target (with or without storage cell)
  - can be installed in one of the existing LHC caverns, and coupled to existing experiments
  - currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
  - uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
  - Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
  - A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used
- Internal **wire/foil** target [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]
- **Bent crystal** option: beam **line** vs **split**
  - crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
  - the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$ 
    - Beam line : provides a new facility with 7 TeV proton beam but requires civil engineering
    - Beam split : similar fluxes; less/no civil engineering; might be coupled to an existing experiment

# Possible implementations

- **Internal gas target** (with or without storage cell)
    - can be installed in one of the existing LHC caverns, and coupled to existing experiments
    - currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
    - uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
    - Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
    - A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used
  - **Internal wire/foil target** [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]
  - **Bent crystal option: beam line vs split**
    - crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
    - the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$ 
      - Beam line : provides a new facility with 7 TeV proton beam but requires civil engineering
      - Beam split : similar fluxes; less/no civil engineering; might be coupled to an existing experiment
- Luminosities with **internal gas target** or **crystal-based** solutions are not very different

# Possible implementations

- Internal **gas** target (with or without storage cell)

- can be installed in one of the existing LHC caverns, and coupled to existing experiments
- currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
- uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
- Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
- A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used

- Internal **wire/foil** target [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]

- **Bent crystal** option: beam **line** vs **split**

- crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
- the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$ 
  - Beam line : provides a new facility with 7 TeV proton beam but requires civil engineering
  - Beam split : similar fluxes; less/no civil engineering; might be coupled to an existing experiment

→ Luminosities with **internal gas target** or **crystal-based** solutions are not very different

→ The beam line option is currently a little too ambitious (this could change with FCC)

# Possible implementations

- Internal **gas** target (with or without storage cell)

- can be installed in one of the existing LHC caverns, and coupled to existing experiments
- currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
- uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
- Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
- A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used

- Internal **wire/foil** target [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]

- **Bent crystal** option: beam **line** vs **split**

- crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
- the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$ 
  - Beam line : provides a new facility with 7 TeV proton beam but requires civil engineering
  - Beam split : similar fluxes; less/no civil engineering; might be coupled to an existing experiment

→ Luminosities with **internal gas target** or **crystal-based** solutions are not very different

→ The beam line option is currently a little too ambitious (this could change with FCC)

→ The internal solid target & beam split option: **similar possibilities**; the latter is **cleaner**

# Possible implementations

- Internal **gas** target (with or without storage cell)

- can be installed in one of the existing LHC caverns, and coupled to existing experiments
- currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
- uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
- Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
- A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used

- Internal **wire/foil** target [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]

- **Bent crystal** option: beam **line** vs **split**

- crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
- the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$ 
  - Beam line : provides a new facility with 7 TeV proton beam but requires civil engineering
  - Beam split : similar fluxes; less/no civil engineering; might be coupled to an existing experiment

- Luminosities with **internal gas target** or **crystal-based** solutions are not very different
- The beam line option is currently a little too ambitious (this could change with FCC)
- The internal solid target & beam split option: **similar possibilities**; the latter is **cleaner**
- The gas target is the **best for polarised** target and **satisfactory for heavy-ion** studies

# Possible implementations

- Internal **gas** target (with or without storage cell)

- can be installed in one of the existing LHC caverns, and coupled to existing experiments
- currently validated by the LHCb collaboration with SMOG [their luminosity monitor used as a gas target]
- uses the high LHC particle current:  $p$  flux:  $3.4 \times 10^{18} \text{ s}^{-1}$  & Pb flux:  $3.6 \times 10^{14} \text{ s}^{-1}$
- Hermes storage cell proposed in LHCb (R&D needed for coating and polarisation performance)
- A system like the polarised H-jet polarimeter at RHIC-BNL (no storage cell) may also be used

- Internal **wire/foil** target [used by Hera-B on the 920 GeV HERA  $p$  beam and by STAR at RHIC]

- **Bent crystal** option: beam **line** vs **split**

- crystals successfully tested at the LHC for proton and lead beam collimation [UA9 collaboration]
- the LHC beam halo is recycled on dense target: proton flux:  $5 \times 10^8 \text{ s}^{-1}$  & lead flux:  $2 \times 10^5 \text{ s}^{-1}$ 
  - Beam line : provides a new facility with 7 TeV proton beam but requires civil engineering
  - Beam split : similar fluxes; less/no civil engineering; might be coupled to an existing experiment

→ Luminosities with **internal gas target** or **crystal-based** solutions are not very different

→ The beam line option is currently a little too ambitious (this could change with FCC)

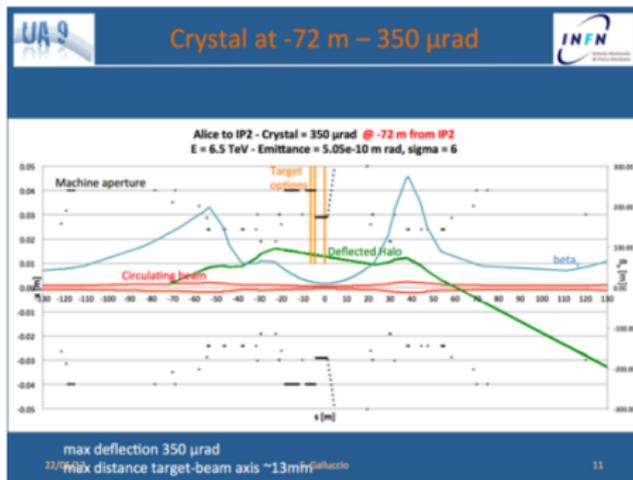
→ The internal solid target & beam split option: **similar possibilities**; the latter is **cleaner**

→ The gas target is the **best for polarised** target and **satisfactory for heavy-ion** studies

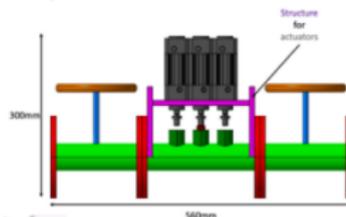
$pp$	$pA$	PbA
$\mathcal{O}(0.1 - 10 \text{ fb}^{-1}\text{yr}^{-1})$	$\mathcal{O}(0.1 - 1 \text{ fb}^{-1}\text{yr}^{-1})$	$\mathcal{O}(1 - 50 \text{ nb}^{-1}\text{yr}^{-1})$

# Solid targets

Conceptual design work for a crystal beam-splitting scenario with in-beam solid targets in ALICE started by the proponents.  
Compatibility with ALICE collider programme to be studied in detail.



Sketch of the internal solid target



- movable target with pumping system
- 2 valves on each side
- possibility to have several target types

- First study of single-crystal experiment at IP2 by F. Galluccio and W. Scandale
- Integration of a movable internal solid target with ALICE under study by K. Pressard

**My suggestion: push in ALICE for a small modification during the coming shutdown of the beampipe to allow for tests [planned in LHCb] → urgent !!!**

# Qualitative comparison

Characteristics	Internal gas target			Internal solid target with beam halo	Beam splitting	Beam extraction
	SMOG	Gas Jet	Storage Cell			
Run duration <sup>14</sup>	★	★★	★★	★	★★	★★★
Parasiticity <sup>15</sup>	★★★	★★	★★	★	★★	★★★
Integrated luminosity <sup>16</sup>	★	★★	★★	★	★★	★★★
Absolute luminosity determination <sup>17</sup>	★	★★	★★	★	★★	★★★
Target versatility <sup>18</sup>	★★	★★	★★★	★★	★★	★★★
Target polarisation <sup>19</sup>	-	★★	★★	-	- / ★ <sup>20</sup>	★
Use of existing experiment <sup>21</sup>	★★	★	★	★	★	-
Civil engineering or R&D <sup>22</sup>	★★★	★★	★★	★★	★★	★
Cost	★★★	★★	★★	★★	★★	★
Implementation time	★★★	★★	★★	★★	★★	★
High x <sup>23</sup>	★	★★	★★★	★	★ / ★★	★★★
Spin Physics <sup>24</sup>	-	★★★	★★★	-	- / ★★	★★★
Heavy-Ion <sup>25</sup>	★	★★	★★	★ / ★★	★★	★★★

Table 8: Qualitative comparison of the various technological solutions.

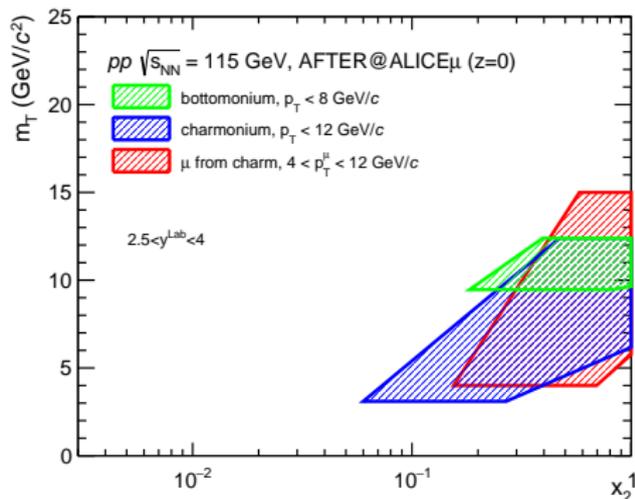
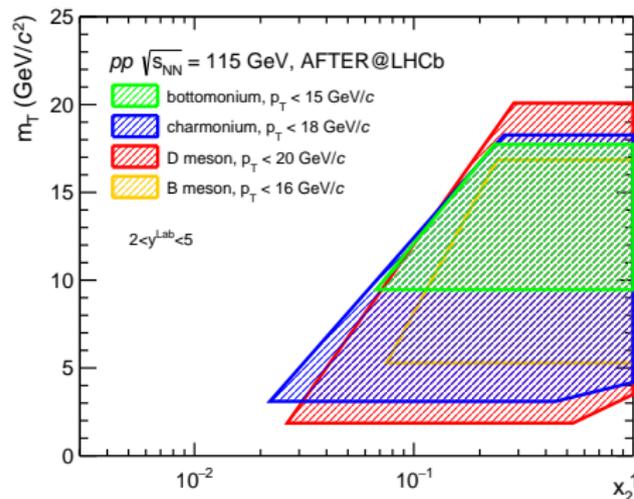
## Luminosity comparison

Target			Beam						
			p			Pb			
			$\mathcal{L}$ [cm <sup>-2</sup> s <sup>-1</sup> ]	$\Delta t$ [s]	$\int \mathcal{L}$ [nb <sup>-1</sup> ]	$\mathcal{L}$ [cm <sup>-2</sup> s <sup>-1</sup> ]	$\Delta t$ [s]	$\int \mathcal{L}$ [nb <sup>-1</sup> ]	
Internal gas target	SMOG	He, Ne, Ar	$5.8 \times 10^{29}$	$2.5 \times 10^5$	145	$7.4 \times 10^{25}$	10 <sup>6</sup>	0.074	
		Gas-Jet	H <sup>†</sup>	$4.3 \times 10^{30}$	10 <sup>7</sup>	$4.3 \times 10^4$	$5.6 \times 10^{26}$	10 <sup>6</sup>	0.56
			H <sub>2</sub>	$3.6 \times (10^{33} - 10^{34})$	10 <sup>7</sup>	$3.6 \times (10^7 - 10^8)$	$4.66 \times (10^{29} - 10^{30})$	10 <sup>6</sup>	466-4660
			D <sup>†</sup>	$4.3 \times 10^{30}$	10 <sup>7</sup>	$4.3 \times 10^4$	$5.6 \times 10^{26}$	10 <sup>6</sup>	0.56
	<sup>3</sup> He <sup>†</sup>	$3.6 \times 10^{32}$	10 <sup>7</sup>	$3.6 \times 10^6$	$4.66 \times 10^{28}$	10 <sup>6</sup>	47		
	Storage Cell	H <sup>†</sup>	$0.92 \times 10^{33}$	10 <sup>7</sup>	$9.2 \times 10^6$	$1.18 \times 10^{29}$	10 <sup>6</sup>	118	
		H <sub>2</sub>	$5.8 \times 10^{33}$	10 <sup>7</sup>	$5.8 \times 10^7$	$7.5 \times 10^{29}$	10 <sup>6</sup>	750	
		D <sup>†</sup>	$1.1 \times 10^{33}$	10 <sup>7</sup>	$1.1 \times 10^7$	$1.4 \times 10^{29}$	10 <sup>6</sup>	140	
		<sup>3</sup> He <sup>†</sup>	$3.7 \times 10^{33}$	10 <sup>7</sup>	$3.7 \times 10^7$	$4.7 \times 10^{29}$	10 <sup>6</sup>	474	
		Xe	$2.34 \times 10^{32}$	10 <sup>7</sup>	$2.34 \times 10^6$	$3.0 \times 10^{28}$	10 <sup>6</sup>	30	
Internal solid target with beam halo	Wire	C	$2.8 \times 10^{30}$	10 <sup>7</sup>	$2.8 \times 10^4$	$5.6 \times 10^{26}$	10 <sup>6</sup>	0.56	
	Target (0.5 mm)	Ti	$1.4 \times 10^{30}$	10 <sup>7</sup>	$1.4 \times 10^4$	$2.8 \times 10^{26}$	10 <sup>6</sup>	0.28	
		W	$1.6 \times 10^{30}$	10 <sup>7</sup>	$1.6 \times 10^4$	$3.1 \times 10^{26}$	10 <sup>6</sup>	0.31	
Beam splitting	E1039	NH <sub>3</sub> <sup>†</sup>	$7.2 \times 10^{31}$	10 <sup>7</sup>	$7.2 \times 10^5$	$1.4 \times 10^{28}$	10 <sup>6</sup>	14	
		ND <sub>3</sub> <sup>†</sup>	$7.2 \times 10^{31}$	10 <sup>7</sup>	$7.2 \times 10^5$	$1.4 \times 10^{28}$	10 <sup>6</sup>	14	
	Unpolarised solid target (5 mm)	C	$2.8 \times 10^{31}$	10 <sup>7</sup>	$2.8 \times 10^5$	$5.6 \times 10^{27}$	10 <sup>6</sup>	5.6	
		Ti	$1.4 \times 10^{31}$	10 <sup>7</sup>	$1.4 \times 10^5$	$2.8 \times 10^{27}$	10 <sup>6</sup>	2.8	
		W	$1.6 \times 10^{31}$	10 <sup>7</sup>	$1.6 \times 10^5$	$3.1 \times 10^{27}$	10 <sup>6</sup>	3.1	
Beam extraction	E1039	NH <sub>3</sub> <sup>†</sup>	$7.2 \times 10^{31}$	10 <sup>7</sup>	$7.2 \times 10^5$	$1.4 \times 10^{28}$	10 <sup>6</sup>	14	
		ND <sub>3</sub> <sup>†</sup>	$7.2 \times 10^{31}$	10 <sup>7</sup>	$7.2 \times 10^5$	$1.4 \times 10^{28}$	10 <sup>6</sup>	14	
	COMPASS	NH <sub>3</sub> <sup>†</sup>	$1.0 \times 10^{33}$	10 <sup>7</sup>	$1.0 \times 10^7$	$2.0 \times 10^{29}$	10 <sup>6</sup>	200	
		butanol <sup>†</sup>	$2.7 \times 10^{32}$	10 <sup>7</sup>	$2.7 \times 10^6$	$5.3 \times 10^{28}$	10 <sup>6</sup>	53	

# Part II

## Some FoM for Heavy-Ion Studies

# Kinematical coverage

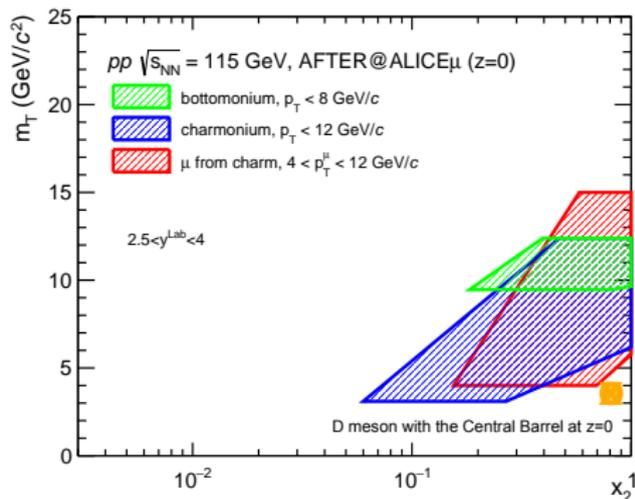
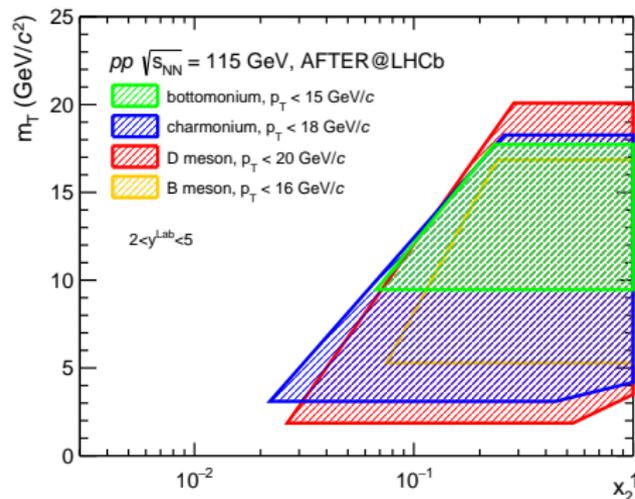


ALICE could cover  $\eta \sim 1 - 2$  for quarkonium into dileptons with one muon in the muon arm and another in the central barrel

[done for UPCs in the collider mode]

NB: The coverage depends on the target position

# Kinematical coverage

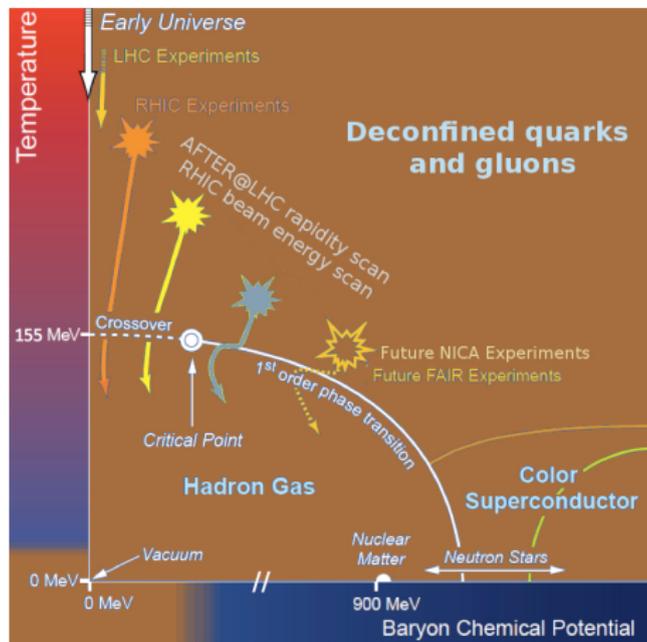


ALICE could cover  $\eta \sim 1 - 2$  for quarkonium into dileptons with one muon in the muon arm and another in the central barrel

[done for UPCs in the collider mode]

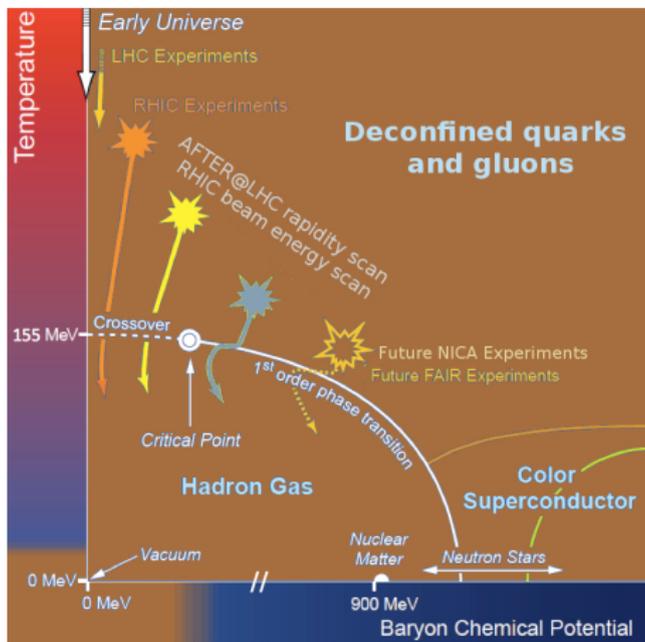
NB: The coverage depends on the target position

# Heavy ions: rapidity scan & quarkonium precision studies



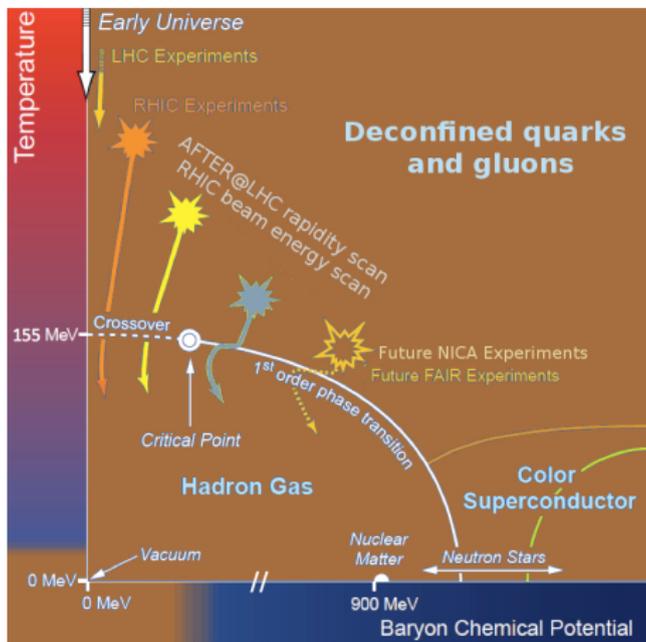
# Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain between SPS and RHIC



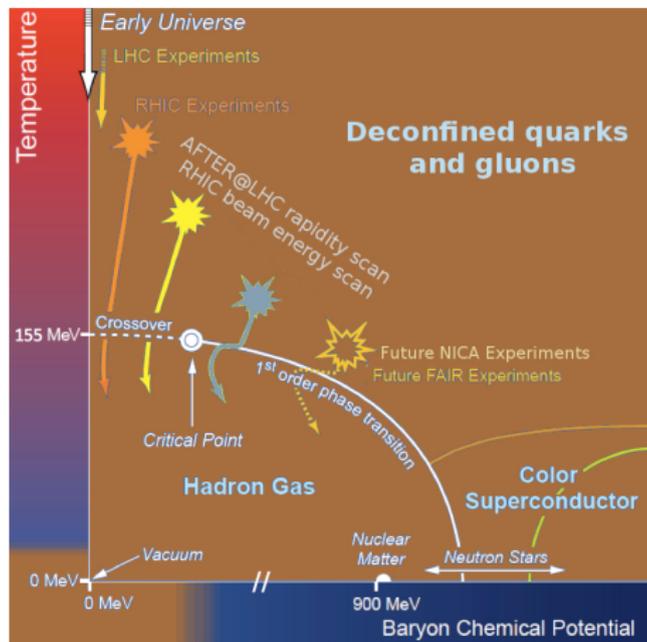
# Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain between SPS and RHIC
- Rapidity scan to scan through  $\mu_B$  &  $T$  (e.g.  $v_2(\gamma) \leftrightarrow \eta/s$ ) wit a good PID (LHCb and ALICE)



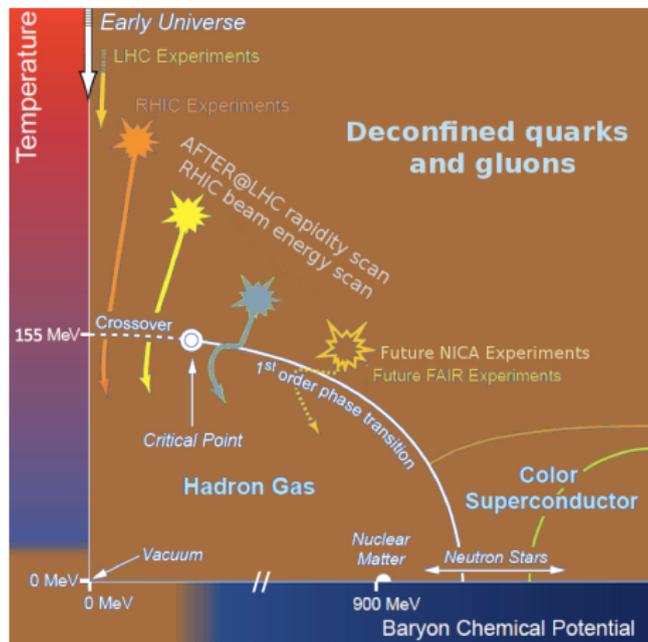
# Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain between SPS and RHIC
- Rapidity scan to scan through  $\mu_B$  &  $T$  (e.g.  $v_2(y) \leftrightarrow \eta/s$ ) wit a good PID (LHCb and ALICE)
- At backward rapidities, the background for  $\mu^+ \mu^-$  is tractable even without absorber
- Handle on **more quarkonium states** (e.g.  $\chi_{c,b}, \eta_c$ ) and on open charm and beauty



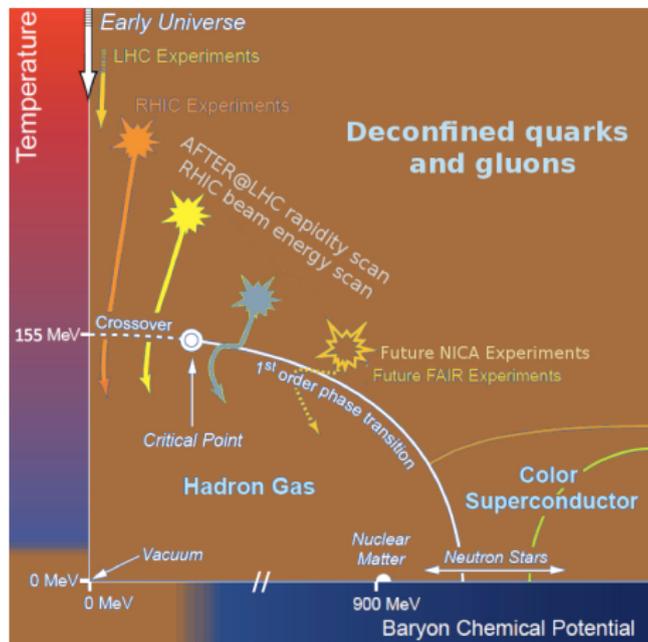
# Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain between SPS and RHIC
- Rapidity scan to scan through  $\mu_B$  &  $T$  (e.g.  $v_2(y) \leftrightarrow \eta/s$ ) with a good PID (LHCb and ALICE)
- At backward rapidities, the background for  $\mu^+ \mu^-$  is tractable even without absorber
- Handle on **more quarkonium states** (e.g.  $\chi_{c,b}, \eta_c$ ) and on open charm and beauty
- FoMs for  $\chi_{c,b}$  and  $\eta_c$  to be done in cooperation with the LHCb and ALICE collaborations with advanced simulations



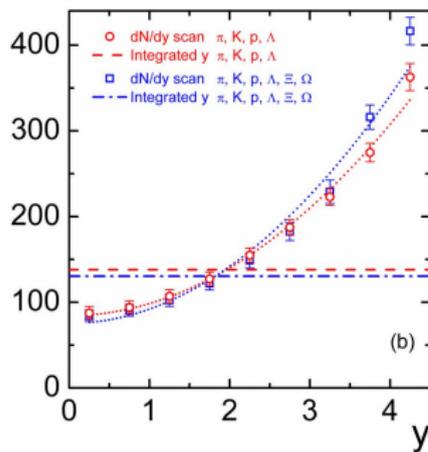
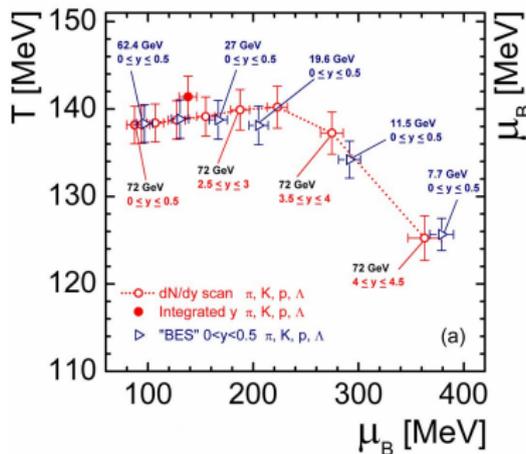
# Heavy ions: rapidity scan & quarkonium precision studies

- Energy domain between SPS and RHIC
- Rapidity scan to scan through  $\mu_B$  &  $T$  (e.g.  $v_2(y) \leftrightarrow \eta/s$ ) with a good PID (LHCb and ALICE)
- At backward rapidities, the background for  $\mu^+ \mu^-$  is tractable even without absorber
- Handle on **more quarkonium states** (e.g.  $\chi_{c,b}, \eta_c$ ) and on open charm and beauty
- FoMs for  $\chi_{c,b}$  and  $\eta_c$  to be done in cooperation with the LHCb and ALICE collaborations with advanced simulations

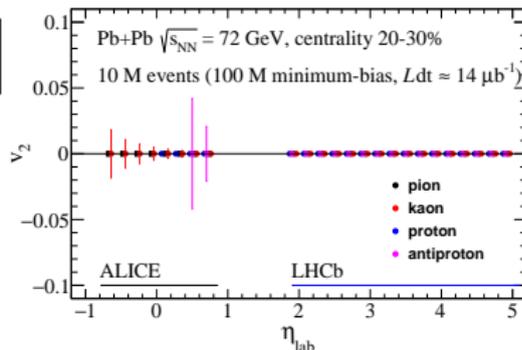
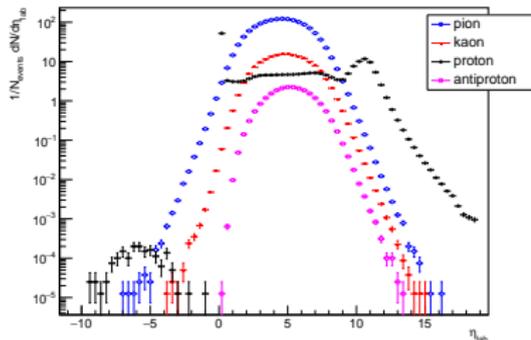


Even with 1 billion  $J/\psi$ 's, the *direct*  $J/\psi$  yield will remain unprecise by 30 % !

# Rapidity scan



Pb-Pb @  $\sqrt{s_{NN}} = 72$  GeV,  $6.8 < b < 8.3$  fm, Centrality 20-30%



# Quarkonium Projections: heavy-ion collisions

B.Trzeciak *et al.* *Few-Body Syst* (2017) 58:148

# Quarkonium Projections: heavy-ion collisions

B.Trzeciak *et al.* *Few-Body Syst* (2017) 58:148

- Like for nPDF studies, multiple quarkonium studies are needed to study the QGP formation at a new energy range between SPS and RHIC

# Quarkonium Projections: heavy-ion collisions

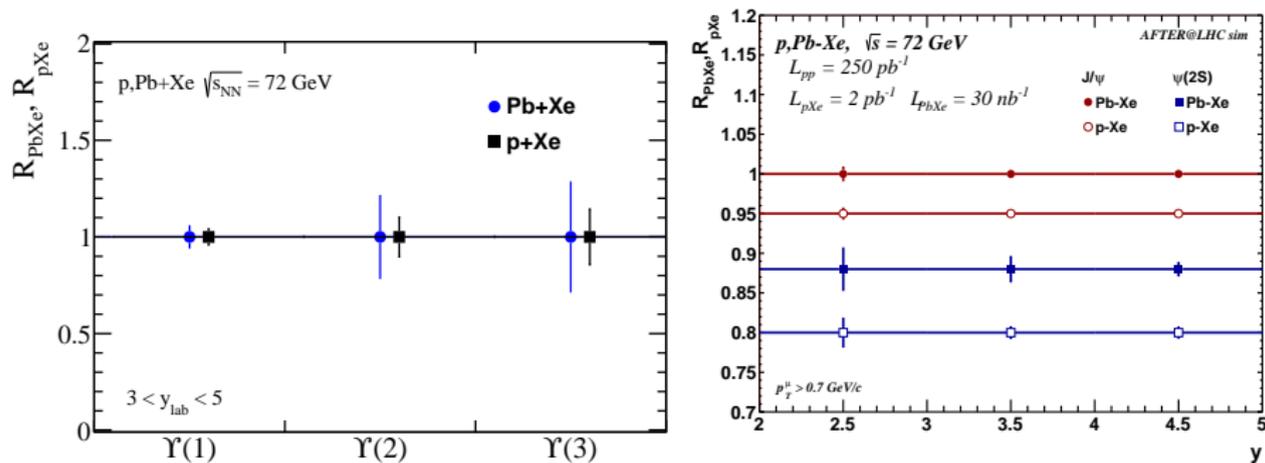
B.Trzeciak *et al.* *Few-Body Syst* (2017) 58:148

- Like for nPDF studies, multiple quarkonium studies are needed to study the QGP formation at a new energy range between SPS and RHIC
- Clear need for a reliable baseline with  $pA$  systems

# Quarkonium Projections: heavy-ion collisions

B.Trzeciak *et al.* *Few-Body Syst* (2017) 58:148

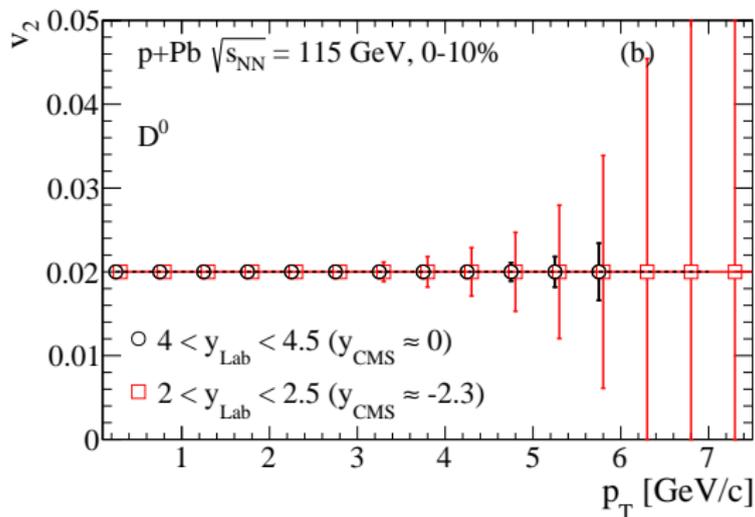
- Like for nPDF studies, multiple quarkonium studies are needed to study the QGP formation at a new energy range between SPS and RHIC
- Clear need for a reliable baseline with  $pA$  systems
- Statistical-uncertainty projections (accounting for background subtraction)



## Part III

# Some FoM for Cold Nuclear Matter Studies

# First look at small systems or new look at Cold Nuclear Matter effects



For  $pp$  collisions, multiplicity studies will be done soon !

# High- $x$ frontier

# High- $x$ frontier

- EMC gluon effect totally unknown

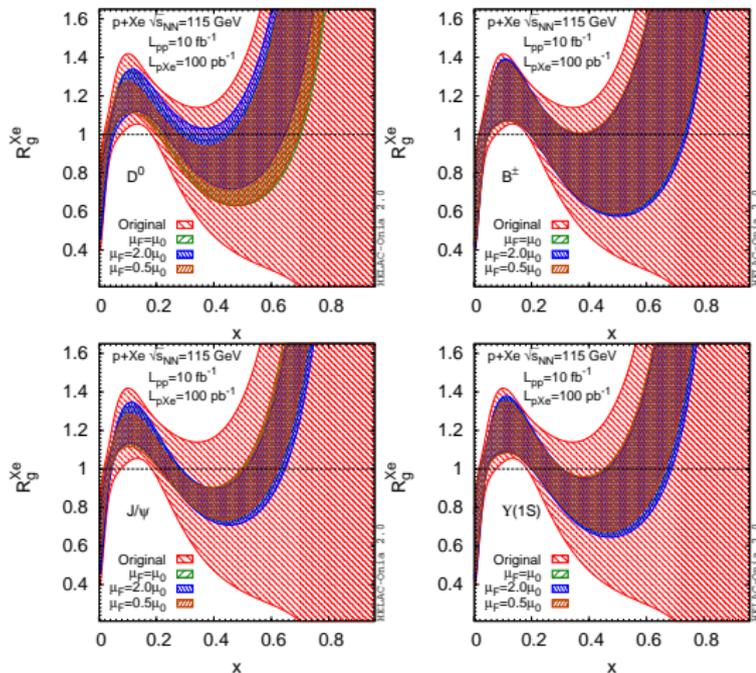
# High- $x$ frontier

- EMC gluon effect totally unknown
- This is the realm of the FT LHC experiments

# High- $x$ frontier

- EMC gluon effect totally unknown
- This is the realm of the FT LHC experiments
- First projections are extremely promising

[NB: initial nPDF uncertainties for  $x > 0.1$  are underestimated; simply no data exist there]



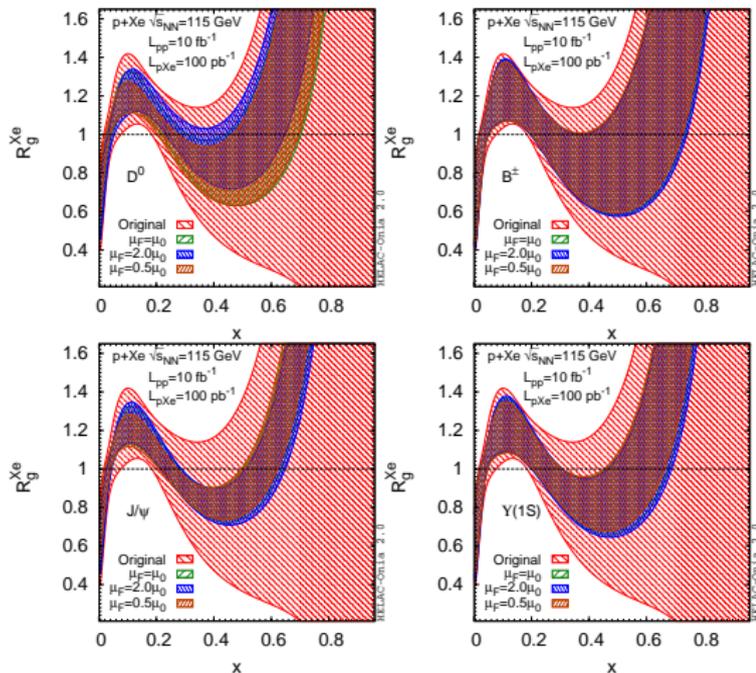
# High- $x$ frontier

- EMC gluon effect totally unknown
- This is the realm of the FT LHC experiments
- First projections are extremely promising

[NB: initial nPDF uncertainties for  $x > 0.1$  are underestimated; simply no data exist there]

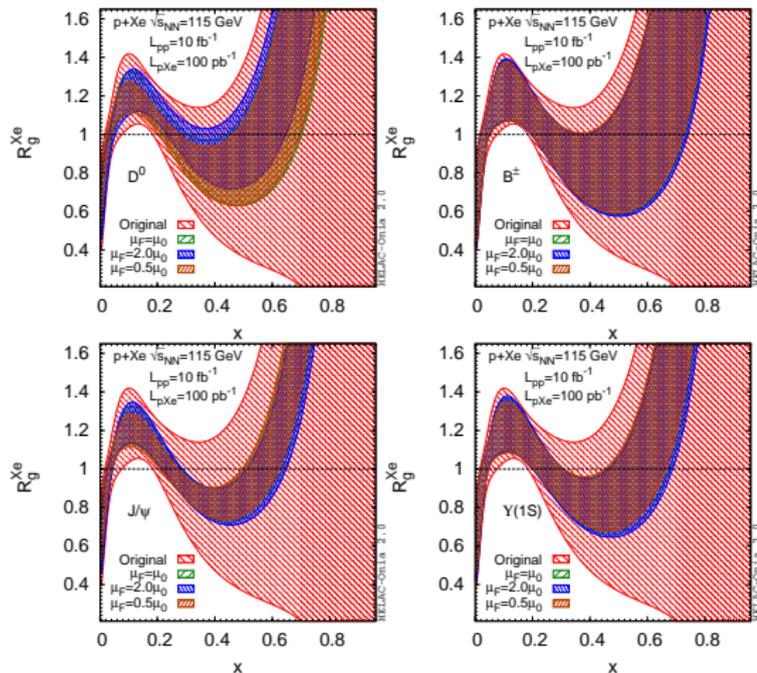
- Similar studies for the proton PDFs are yet to be done along the lines of the studies carried out for low- $x$  gluon at the LHC

396; R. Gauld, J. Rojo PRL 118 (2017) 072001



# High- $x$ frontier

- EMC gluon effect totally unknown
- This is the realm of the FT LHC experiments
- First projections are extremely promising  
[NB: initial nPDF uncertainties for  $x > 0.1$  are underestimated; simply no data exist there]
- Similar studies for the proton PDFs are yet to be done along the lines of the studies carried out for low- $x$  gluon at the LHC PROSA Coll. Eur.Phys.J. C75 (2015) 396; R. Gauld, J. Rojo PRL 118 (2017) 072001
- Contrary to nPDF studies bearing on nuclear modification factors, one needs ways to reduce the systematical theory uncertainties



Reward: unique constraints on gluon PDFs at high  $x$  and low scales

# Ultra-Peripheral Collisions in the FT mode and $J/\psi$ production

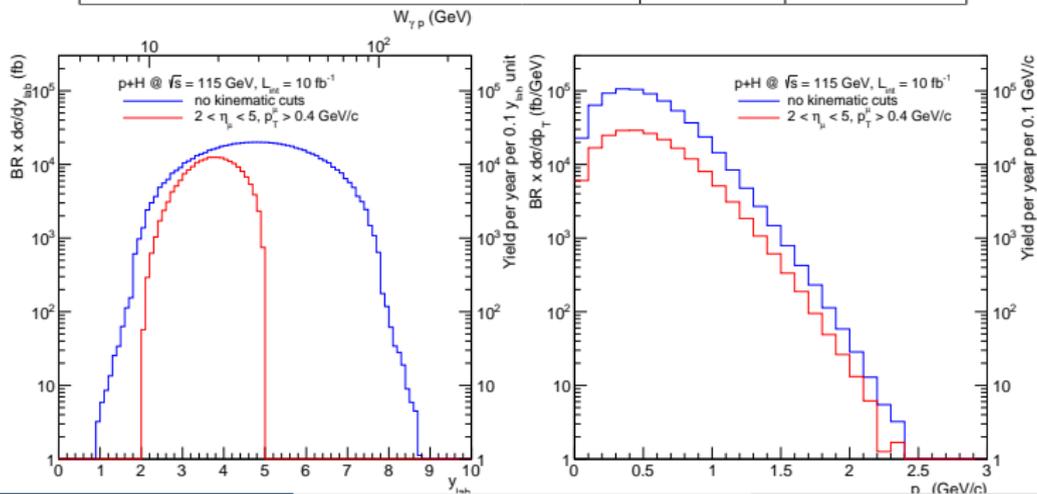
JPL, L. Massacrier, L. Szymanowski, J. Wagner, arXiv:1709.09044 & in progress

	$pH$	$PbH$
Photon-emitter	proton	Lead
$\sigma_{J/\psi}^{tot}$ (pb)	$1.18 \times 10^3$	$276.77 \times 10^3$
$\sigma_{J/\psi \rightarrow l^+ l^-}$ (pb)	70.10	$16.50 \times 10^3$
$\sigma_{J/\psi \rightarrow l^+ l^-}$ (with LHCb $\eta_\mu$ cut) (pb)	20.65	$9.81 \times 10^3$
$\sigma_{J/\psi \rightarrow l^+ l^-}$ (with LHCb $\eta_\mu$ and $p_T^\mu$ cut) (pb)	20.64	$9.81 \times 10^3$
# events	200 000	1000

# Ultra-Peripheral Collisions in the FT mode and $J/\psi$ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner, arXiv:1709.09044 & in progress

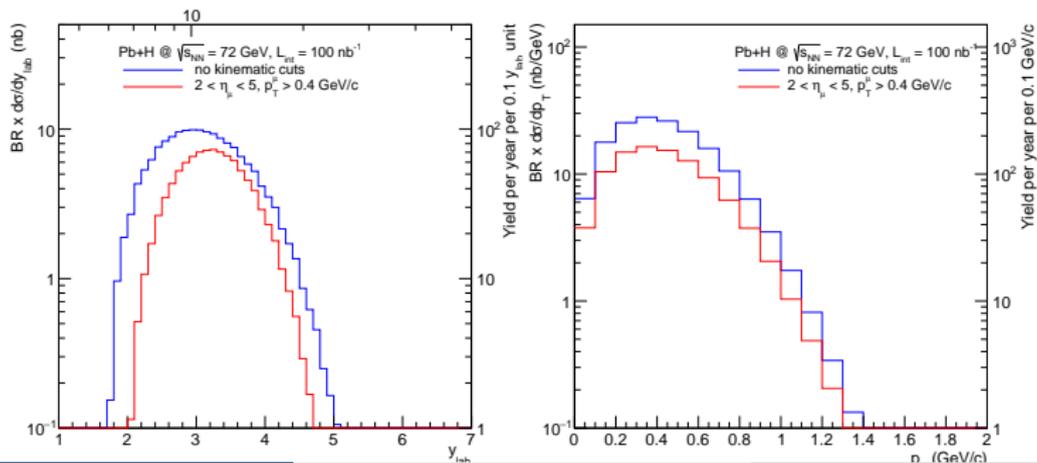
	<i>pH</i>	<i>PbH</i>
Photon-emitter	proton	Lead
$\sigma_{J/\psi}^{tot}$ (pb)	$1.18 \times 10^3$	$276.77 \times 10^3$
$\sigma_{J/\psi \rightarrow l^+l^-}$ (pb)	70.10	$16.50 \times 10^3$
$\sigma_{J/\psi \rightarrow l^+l^-}$ (with LHCb $\eta_\mu$ cut) (pb)	20.65	$9.81 \times 10^3$
$\sigma_{J/\psi \rightarrow l^+l^-}$ (with LHCb $\eta_\mu$ and $p_T^\mu$ cut) (pb)	20.64	$9.81 \times 10^3$
# events	200 000	1000



# Ultra-Peripheral Collisions in the FT mode and $J/\psi$ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner, arXiv:1709.09044 & in progress

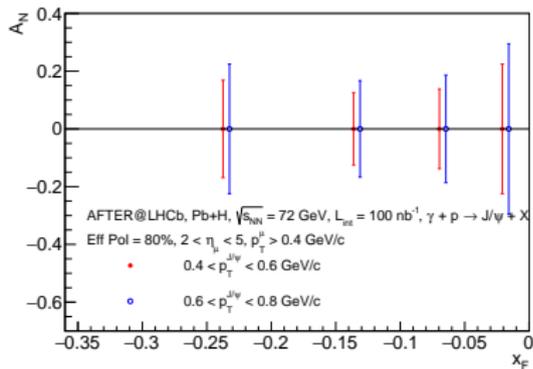
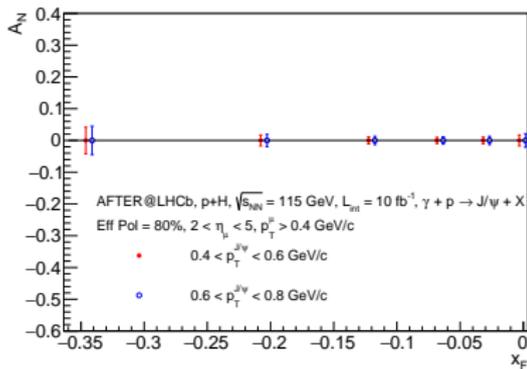
	$pH$	$PbH$
Photon-emitter	proton	Lead
$\sigma_{J/\psi}^{tot}$ (pb)	$1.18 \times 10^3$	$276.77 \times 10^3$
$\sigma_{J/\psi \rightarrow l+l-}$ (pb)	70.10	$16.50 \times 10^3$
$\sigma_{J/\psi \rightarrow l+l-}$ (with LHCb $\eta_\mu$ cut) (pb)	20.65	$9.81 \times 10^3$
$\sigma_{J/\psi \rightarrow l+l-}$ (with LHCb $\eta_\mu$ and $p_T^\mu$ cut) (pb)	20.64	$9.81 \times 10^3$
# events	200 000	1000



# Ultra-Peripheral Collisions in the FT mode and $J/\psi$ production

JPL, L. Massacrier, L. Szymanowski, J. Wagner, arXiv:1709.09044 & in progress

	$pH$	$PbH$
Photon-emitter	proton	Lead
$\sigma_{J/\psi}^{tot}$ (pb)	$1.18 \times 10^3$	$276.77 \times 10^3$
$\sigma_{J/\psi \rightarrow l+l-}$ (pb)	70.10	$16.50 \times 10^3$
$\sigma_{J/\psi \rightarrow l+l-}$ (with LHCb $\eta_\mu$ cut) (pb)	20.65	$9.81 \times 10^3$
$\sigma_{J/\psi \rightarrow l+l-}$ (with LHCb $\eta_\mu$ and $p_T^\mu$ cut) (pb)	20.64	$9.81 \times 10^3$
# events	200 000	1000



$A_N^{\gamma p^1 \rightarrow J/\psi p} \propto \sqrt{t_0 - t} \text{Im}(\mathcal{E}_g^* \mathcal{H}_g) \rightarrow$  access to the **GPD  $E_g$**  and the **gluon OAM**

# Part IV

## Conclusion

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. *Phys.Rept.* 522 (2013) 239

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles
- **The nucleon spin and the transverse dynamics of the partons**

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles
- **The nucleon spin and the transverse dynamics of the partons**
- **The approach to the deconfinement phase transition:**  
new energy, new rapidity domain and new probes

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles
- **The nucleon spin and the transverse dynamics of the partons**
- **The approach to the deconfinement phase transition:**  
new energy, new rapidity domain and new probes
- **2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS**

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles
- **The nucleon spin and the transverse dynamics of the partons**
- **The approach to the deconfinement phase transition:**  
new energy, new rapidity domain and new probes
- **2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS**
- A slow extraction with a **bent crystal**
- An internal **gas target** inspired from SMOG@LHCb/Hermes/H-Jet, ...

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles
- **The nucleon spin and the transverse dynamics of the partons**
- **The approach to the deconfinement phase transition:**  
new energy, new rapidity domain and new probes
- **2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS**
- A slow extraction with a **bent crystal**
- An internal **gas target** inspired from SMOG@LHCb/Hermes/H-Jet, ...
- Based on fast simulations, the AFTER@LHC study group has made FoMs  
for **LHCb and ALICE** in the FT mode  
which **clearly support a full physics program**

# Conclusions

- **THREE MAIN THEMES PUSH FOR A FIXED-TARGET PROGRAM AT THE LHC**

S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. Phys.Rept. 522 (2013) 239

- **The high  $x$  frontier:** new probes of the confinement  
and connections with astroparticles
- **The nucleon spin and the transverse dynamics of the partons**
- **The approach to the deconfinement phase transition:**  
new energy, new rapidity domain and new probes
- **2 WAYS TOWARDS FIXED-TARGET COLLISIONS WITH THE LHC BEAMS**
  - A slow extraction with a **bent crystal**
  - An internal **gas target** inspired from SMOG@LHCb/Hermes/H-Jet, ...
- Based on fast simulations, the AFTER@LHC study group has made FoMs for **LHCb and ALICE** in the FT mode  
which **clearly support a full physics program**
- Our review is now out and will feed in the European Strategy via the Physics Beyond Collider WG

# Part V

## Backup slides

# Further readings

## Heavy-Ion Physics

- *Gluon shadowing effects on  $J/\psi$  and  $\Upsilon$  production in  $p+Pb$  collisions at  $\sqrt{s_{NN}} = 115$  GeV and  $Pb+p$  collisions at  $\sqrt{s_{NN}} = 72$  GeV at AFTER@LHC* by R. Vogt. Adv.Hi.En.Phys. (2015) 492302.
- *Prospects for open heavy flavor measurements in heavy-ion and  $p+A$  collisions in a fixed-target experiment at the LHC* by D. Kikola. Adv.Hi.En.Phys. (2015) 783134
- *Quarkonium suppression from coherent energy loss in fixed-target experiments using LHC beams* by F. Arleo, S.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.
- *$\eta_c$  production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon*  
By V.P. Goncalves, W.K. Sauter. arXiv:1503.05112 [hep-ph].Phys.Rev. D91 (2015) 9, 094014.
- *A review of the intrinsic heavy quark content of the nucleon*  
by S. J. Brodsky, A. Kusina, F. Lyonnet, I. Schienbein, H. Spiesberger, and R. Vogt. Adv.Hi.En.Phys. (2015) 231547.
- *Hadronic production of  $\Xi_{cc}$  at a fixed-target experiment at the LHC*  
By G. Chen *et al.*. Phys.Rev. D89 (2014) 074020.

# Further readings

## Feasibility study and technical ideas

- *Feasibility Studies for Single Transverse-Spin Asymmetry Measurements at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC)* by Daniel Kikola et al. [arXiv:1702.01546 [hep-ex]]. *Few Body Syst.* 58 (2017) 139.
- *Heavy-ion Physics at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC): Feasibility Studies for Quarkonium and Drell-Yan Production* by B. Trzeciak et al. [arXiv:1703.03726 [nucl-ex]] *Few Body Syst.* 58 (2017) 148
- *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.