Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

# Production of quarkonium at RHIC and in the fixed-target mode at the LHC

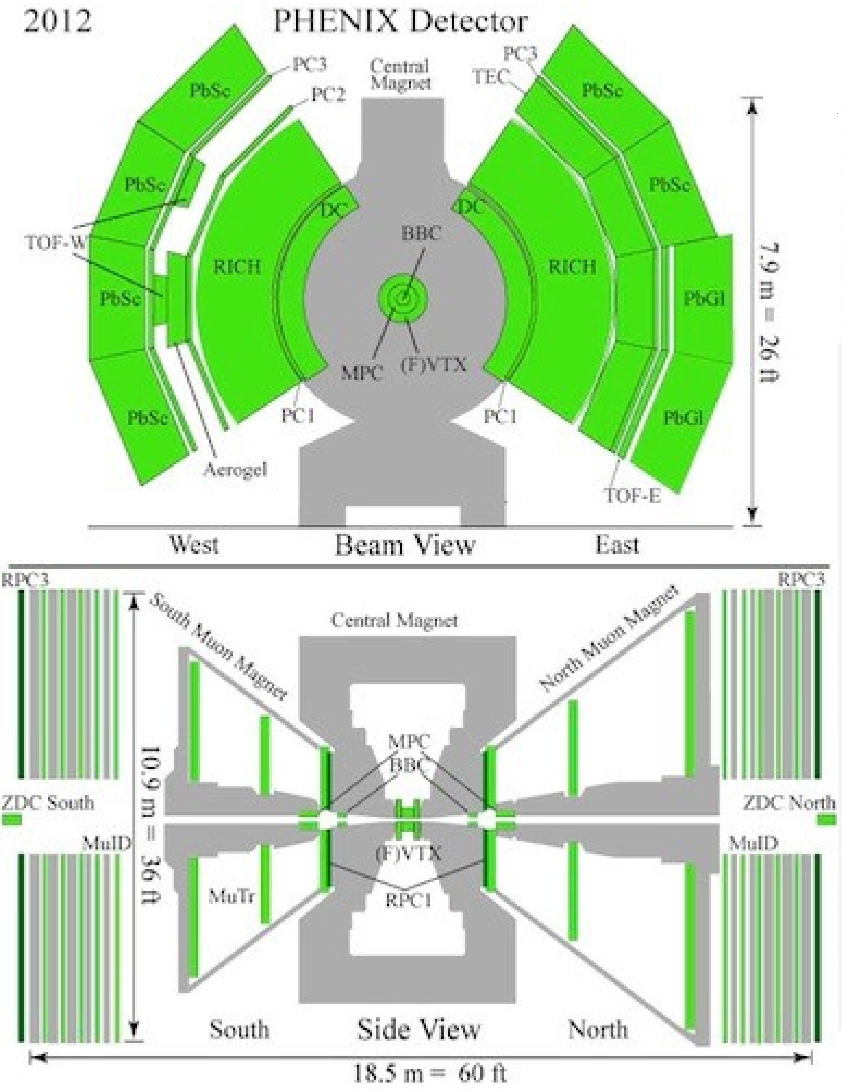
Daniel Kikoła

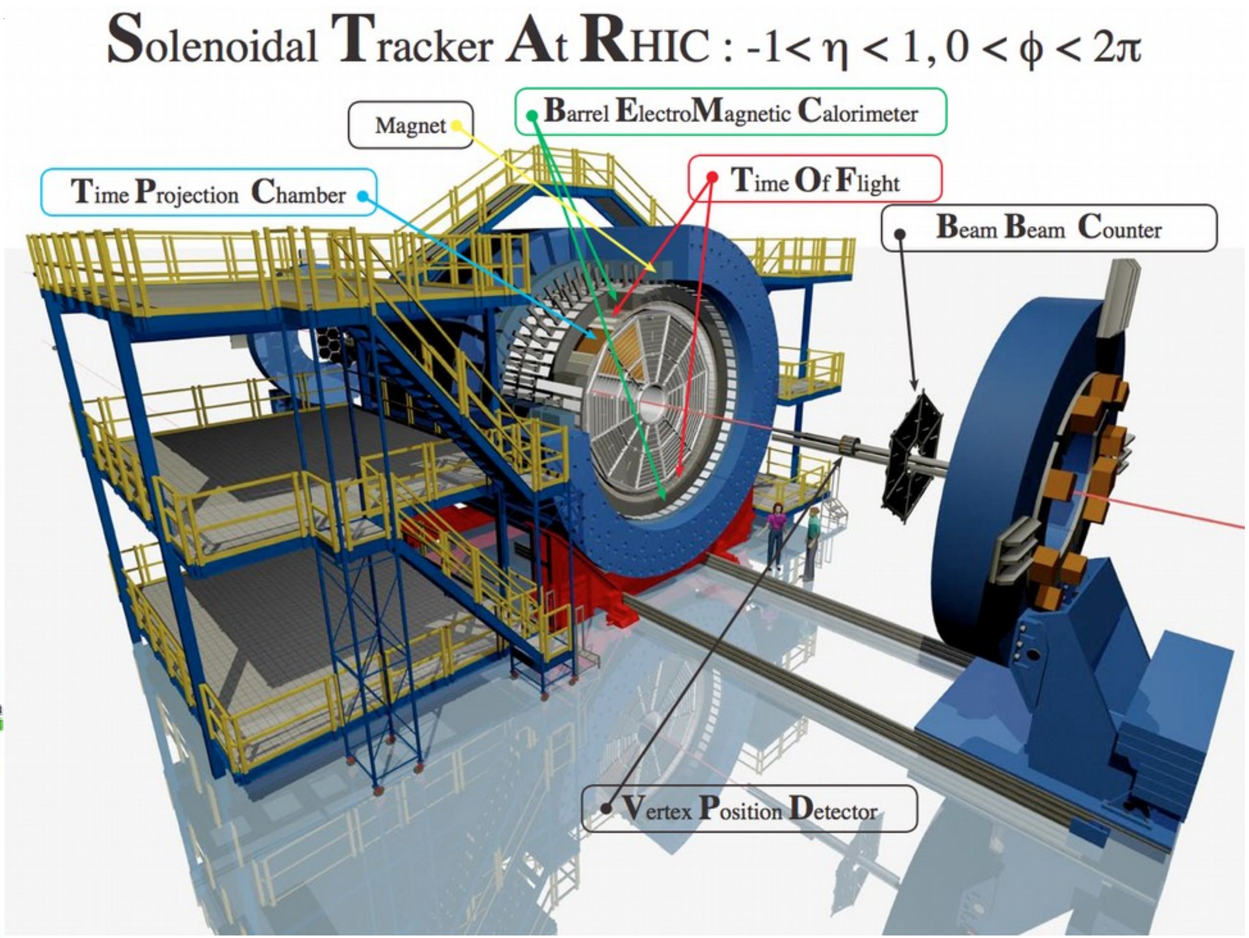
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824093

# Outline

- Recent J/ψ polarization results at RHIC
- Recent studies of old nuclear matter effects at RHIC

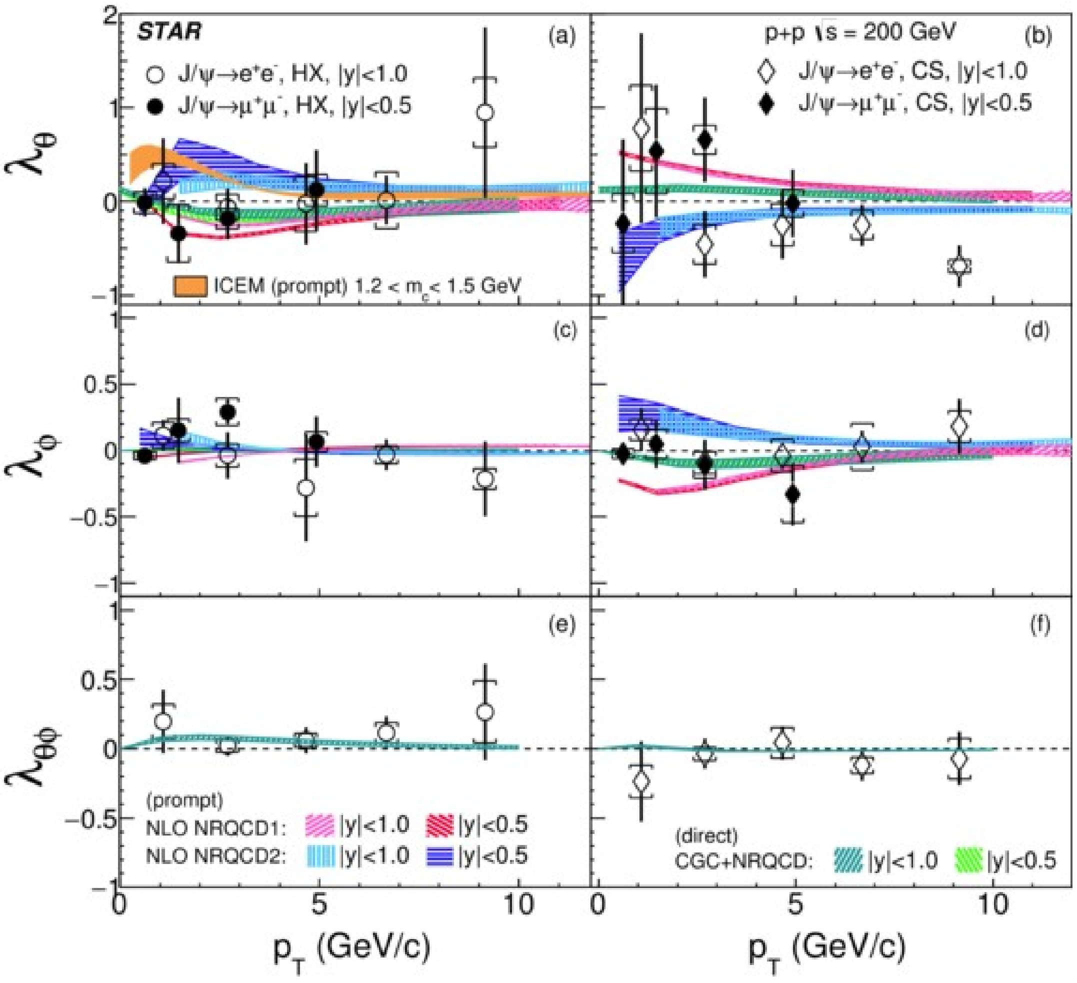
- Fixed-target collisions at the LHC
  - Why?
  - Selection of results and performance studies
  - Status



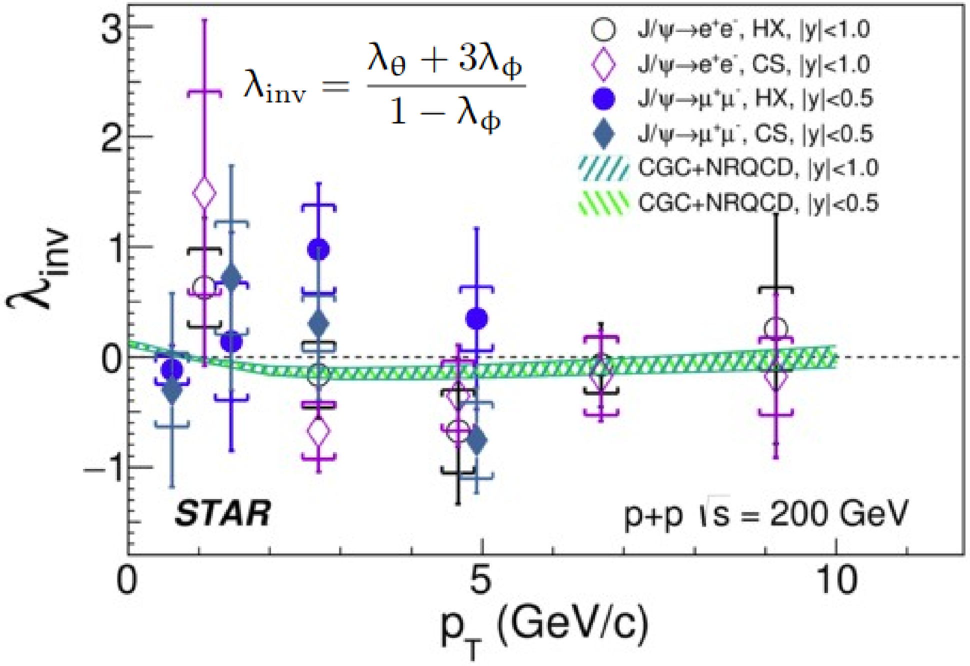

https://www.phy.ornl.gov/groups/heavy_ions/RHIC.html

# J/ψ polarization in p+p 200 GeV




$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi$$
$$+\lambda_{\theta\phi}\sin 2\theta\cos\phi),$$

p+p 200 GeV: data consistent with **no polarization** within (sizeable) uncertainties




Phys. Rev. D 102 (2020) 92009

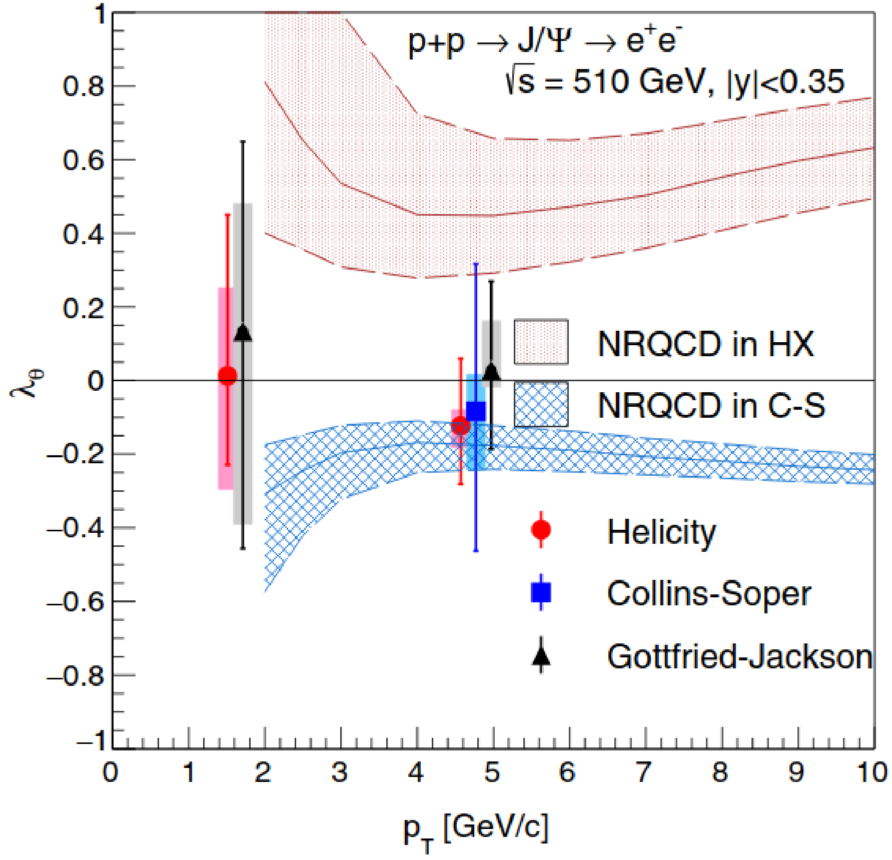



FIG. 8. $\lambda_\theta$ measured in $J/\psi$ transverse momentum bins of $0.0 < p_T < 3.0$ GeV/$c$ and $3.0 \le p_T < 10.0$ GeV/$c$ overlaid with NRQCD predictions in the helicity and Collins-Soper frames. The points for different frames are shifted for visual clarity.

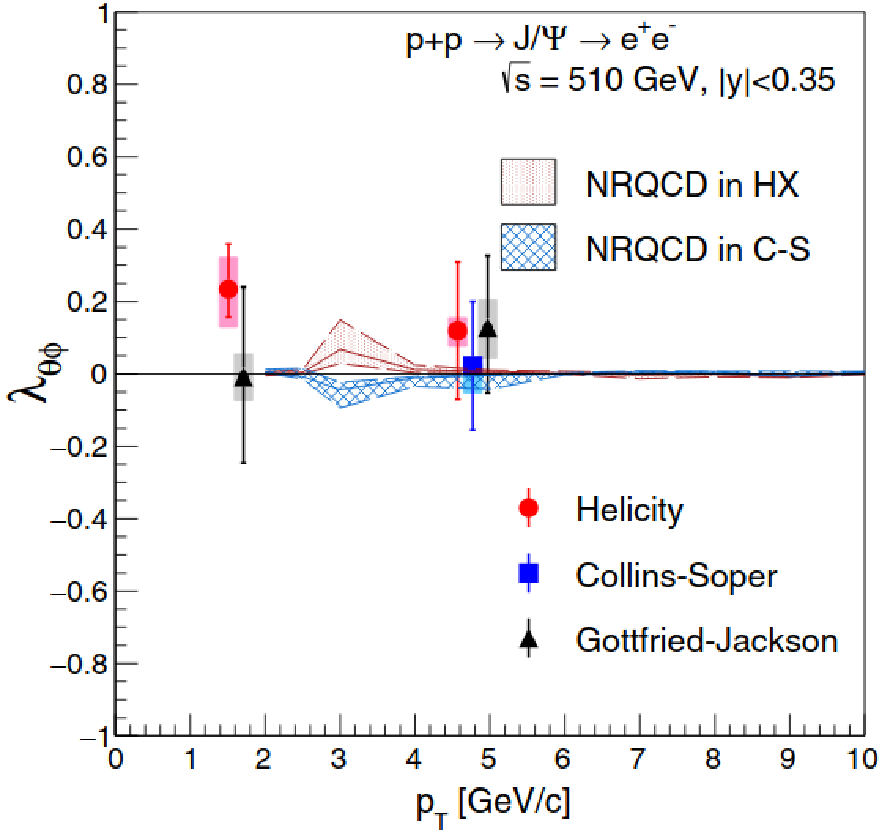
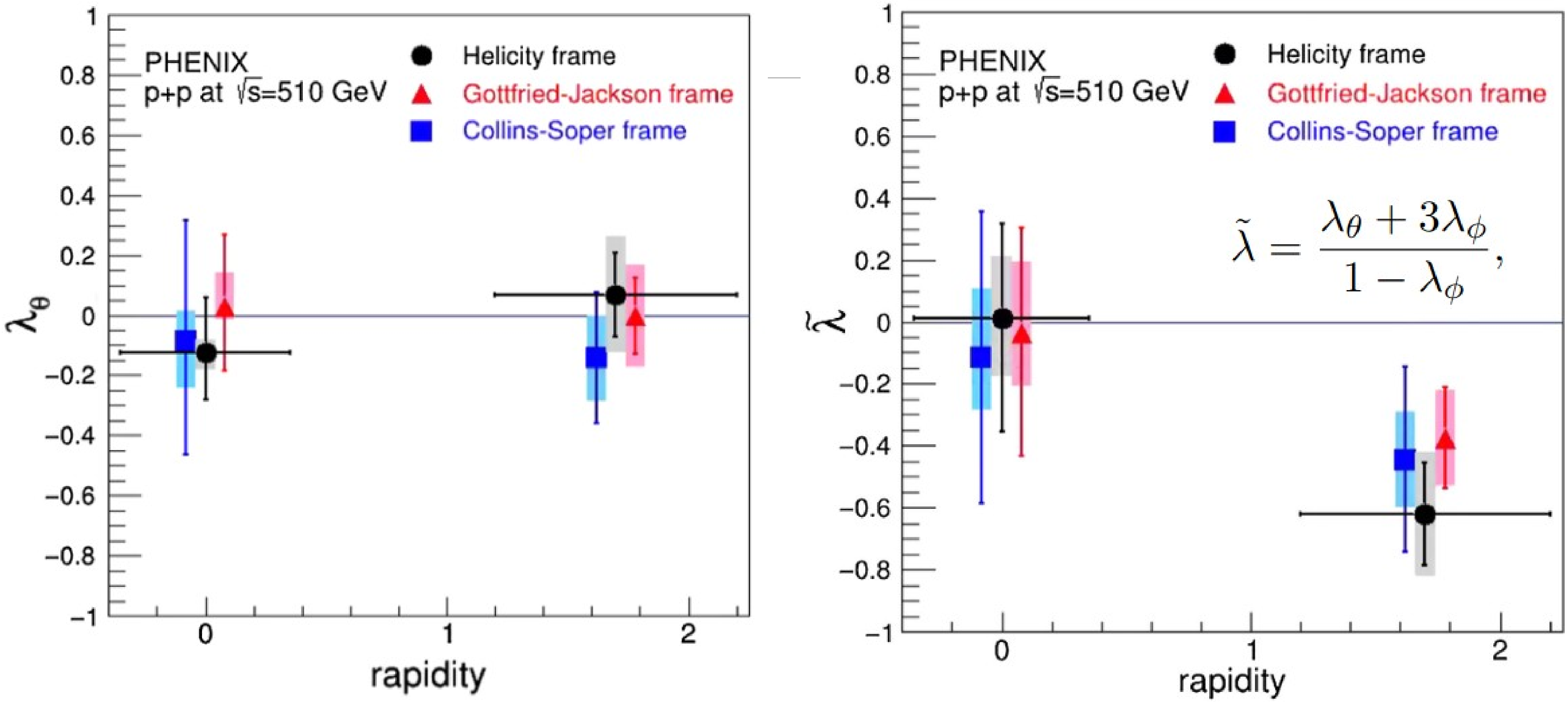



FIG. 10. Angular coefficient $\lambda_{\theta\phi}$ measured in $J/\psi$ transverse momentum bins of $0.0 < p_T < 3.0$ GeV/$c$ and $3.0 \le p_T < 10.0$ GeV/$c$ overlaid with NRQCD predictions in the helicity and Collins-Soper frames. The points for different frames are shifted for visual clarity.

PHYS. REV. D102,072008 (2020)



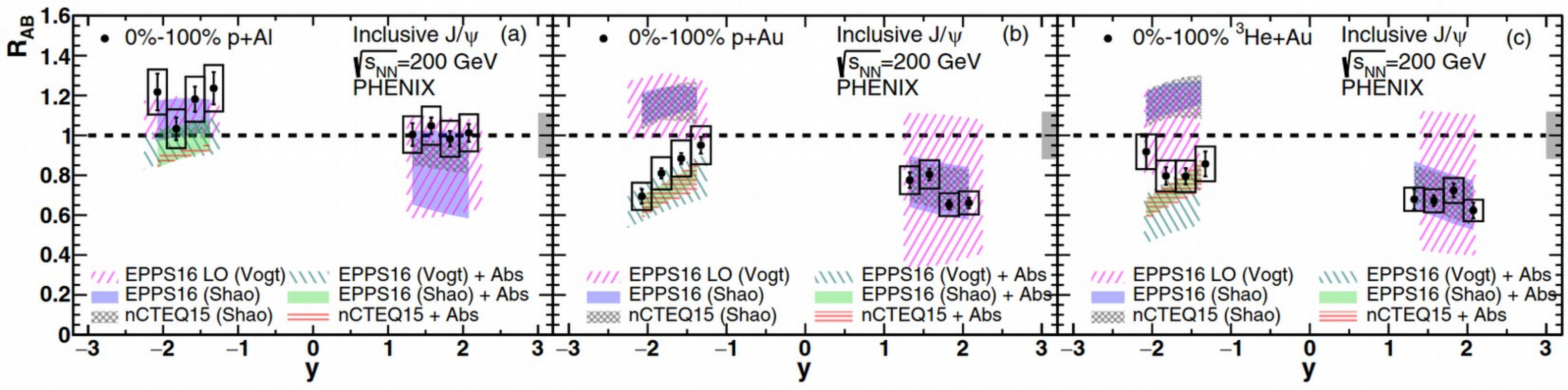

Results consistent with no polarization at mid-rapidity

A hint of negative polarization at forward rapidity

PHYS. REV. D102,072008 (2020)

# J/ψ in p+Al, p+Au, and $^3$He+Au at $\sqrt{s_{NN}}$ = 200 GeV

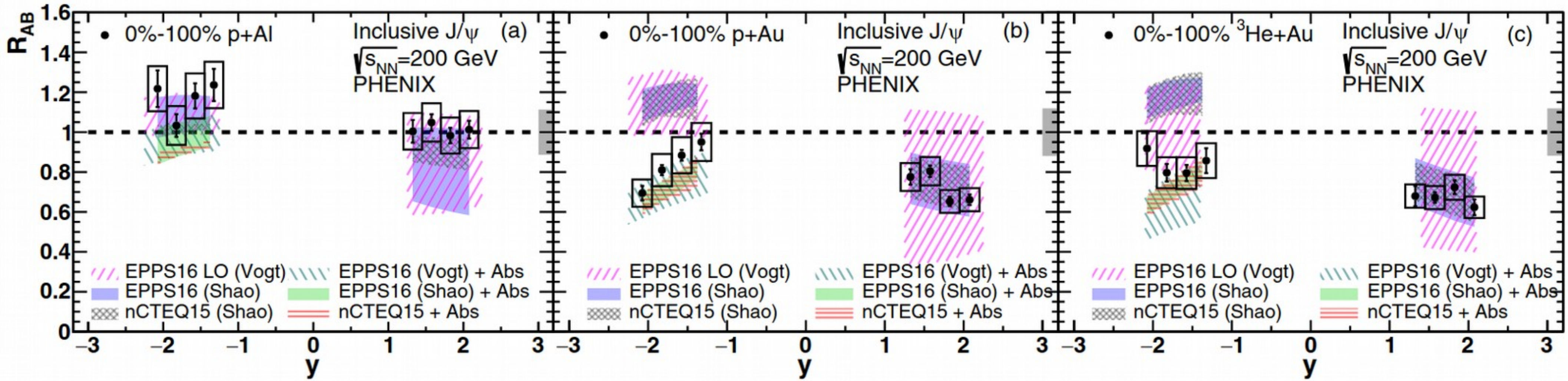
PHYSICAL REVIEW C102, 014902 (2020)

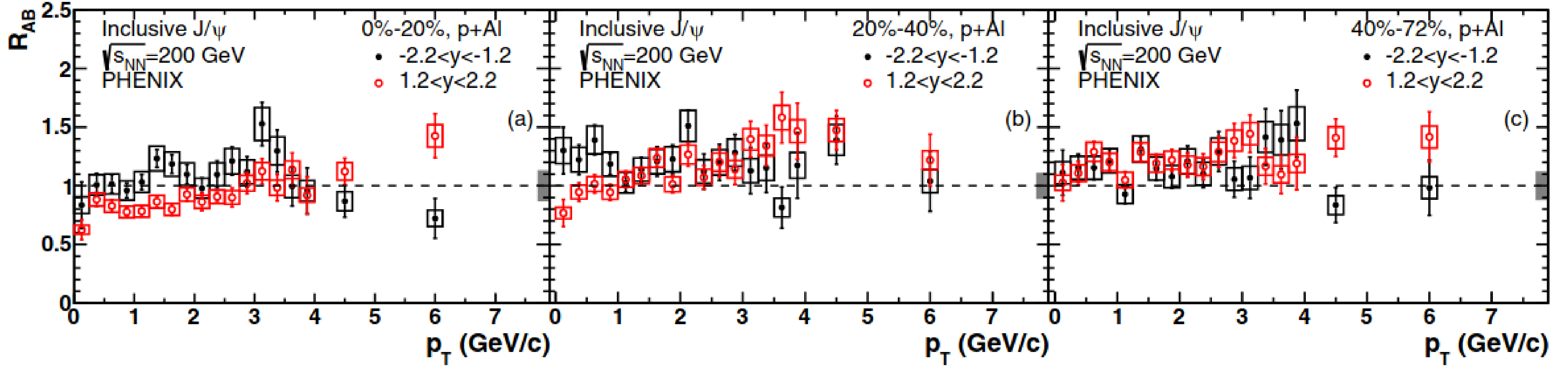



$$R_{AB} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{d^2N^{AB}/dy\,dp_T}{d^2N^{pp}/dy\,dp_T}$$

# J/ψ in p+Al, p+Au, and $^3$He+Au at $\sqrt{s_{NN}}$ = 200 GeV

PHYSICAL REVIEW C102, 014902 (2020)

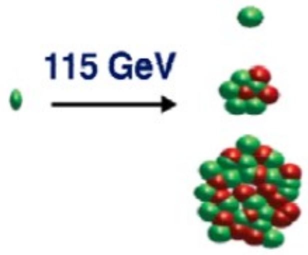


# Fixed-target collisions at LHC

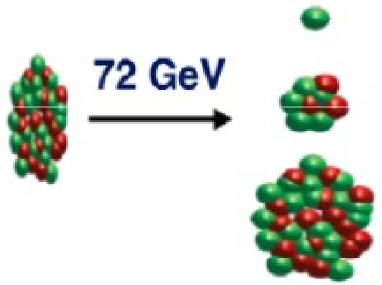
# Kinematics

- p+p or p+A with a 7 TeV p on a fixed target




$$\sqrt{s}=\sqrt{2m_N E_p}\approx 115\,GeV$$
$$y_{CMS}=0 \rightarrow y_{Lab}=4.8$$

- A+A collisions with a 2.76 TeV Pb beam




$$\sqrt{s}\approx 72\,GeV$$
$$y_{CMS}=0 \rightarrow y_{Lab}=4.3$$

backward physics = large-$x_2$ physics ( $x_F < 0 \rightarrow$ large $x_2$ )

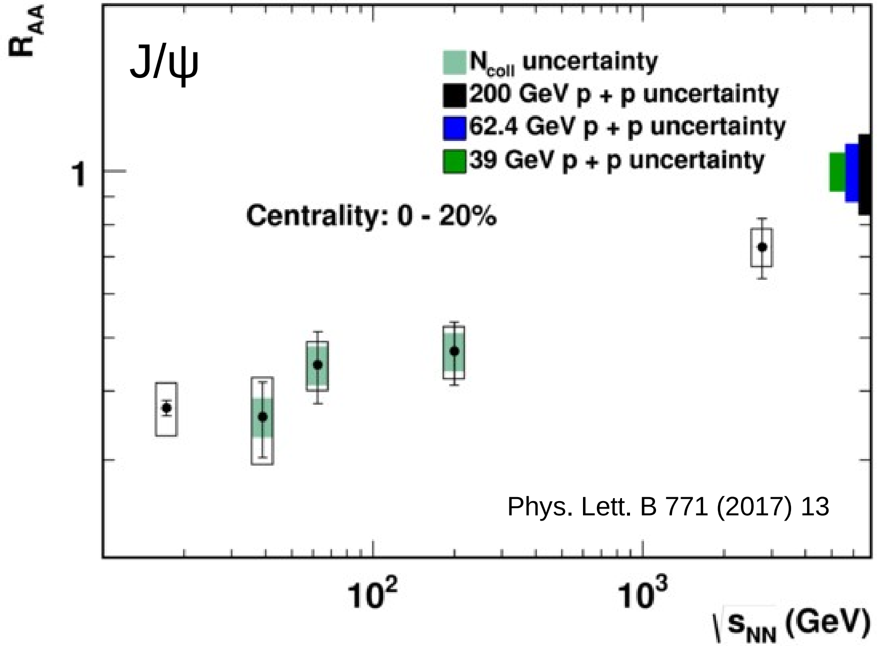
# Why a fixed-target experiment at the LHC?

- High luminosities $\rightarrow$ access to rare probes (heavy quarks)
- High precision Heavy-Ion program between SPS and RHIC top energy
- Access to high Feynman $x_F$ domain ($|x_F| = |p_z|/p_{z\,max} \rightarrow 1$)
- Variety of atomic mass of the target,
- Large kinematic coverage
- Polarization of the target $\rightarrow$ spin physics at the LHC

# Heavy-ion collisions

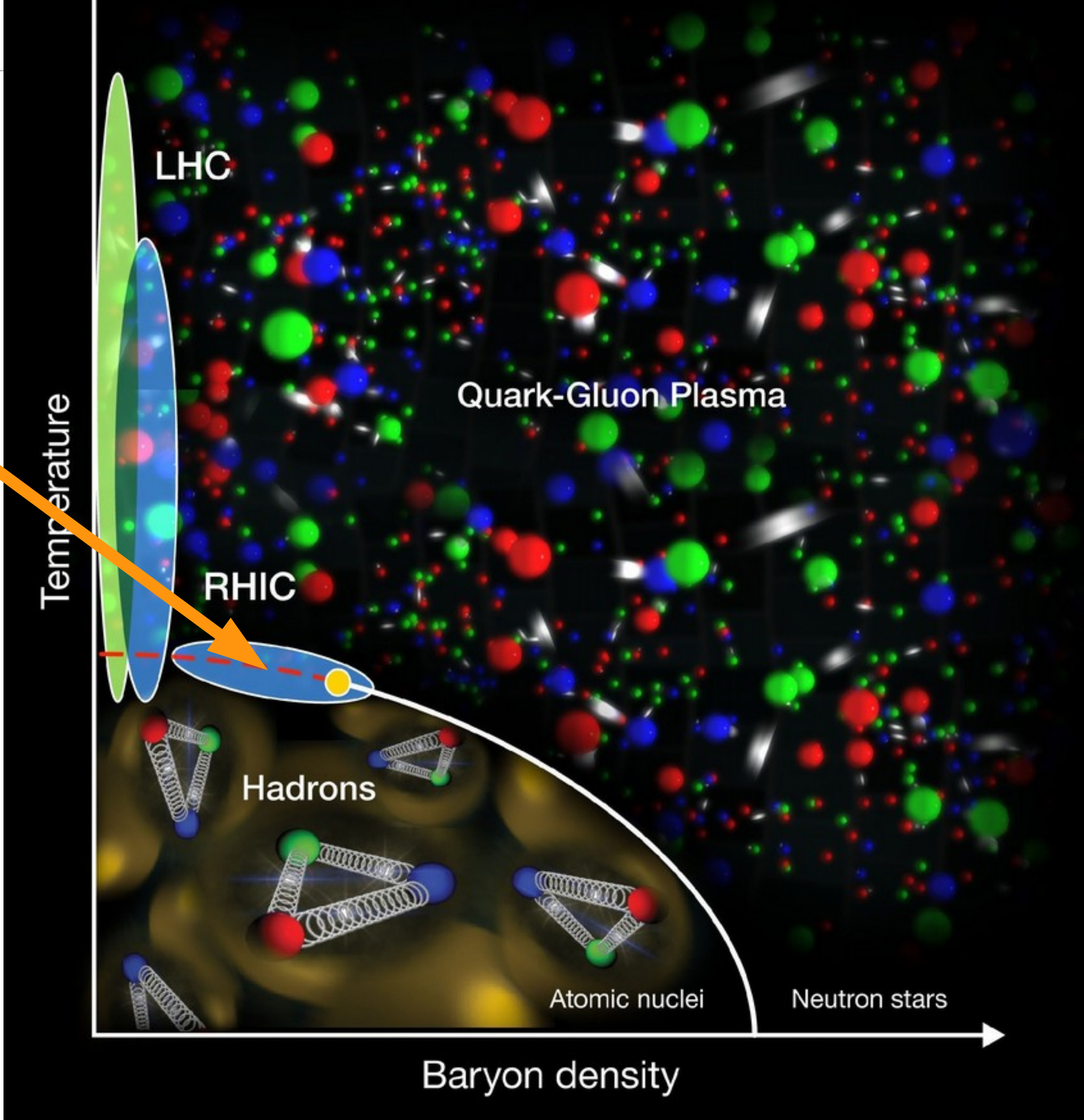
Heavy-ion collisions at

$\sqrt{s_{NN}}$ = 72 -115 GeV




Phys. Lett. B 771 (2017) 13

Figure courtesy of Brookhaven National Laboratory



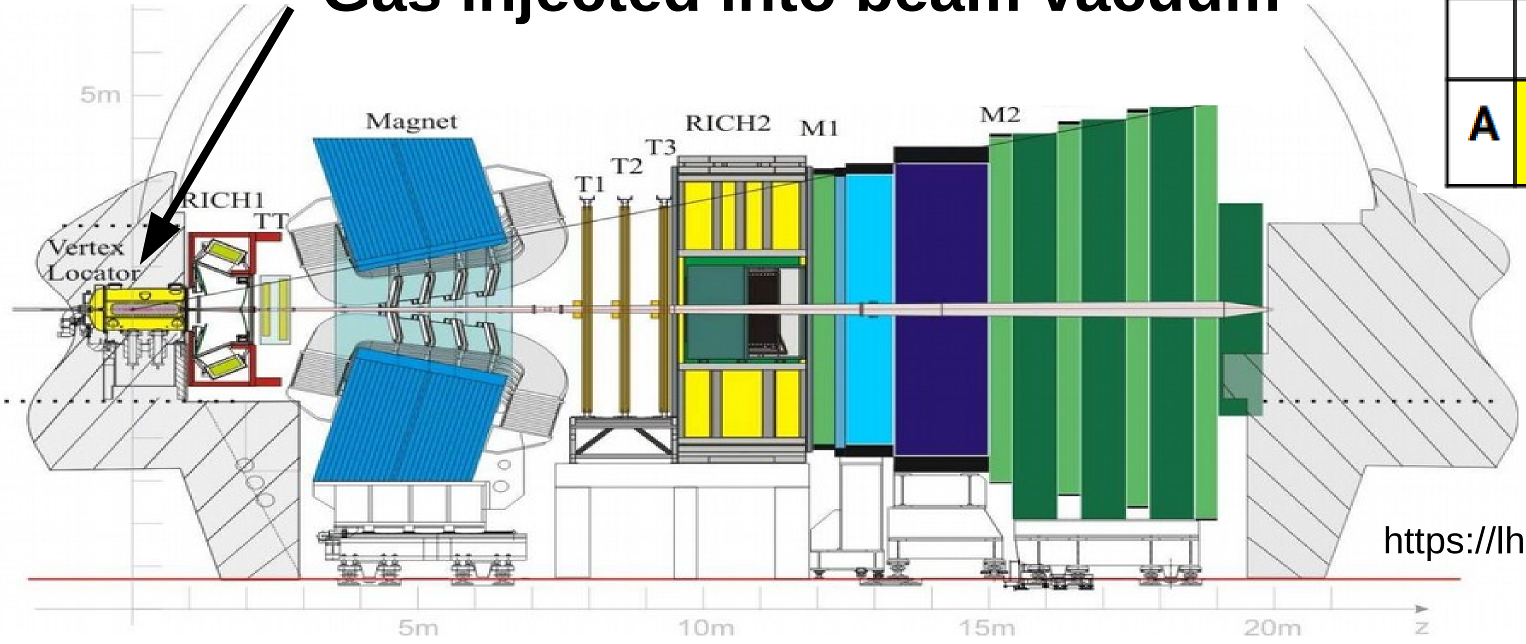
# SMOG-LHCb: the demonstrator of a gas target

System for Measuring Overlap with Gas

**Target gas: only noble gases**

| | He | Ne | Ar | Kr | Xe |
|---|---|---|---|---|---|
| A | 4 | 20 | 40 | 84 | 131 |

**Gas injected into beam vacuum**




https://lhcb.web.cern.ch/lhcb

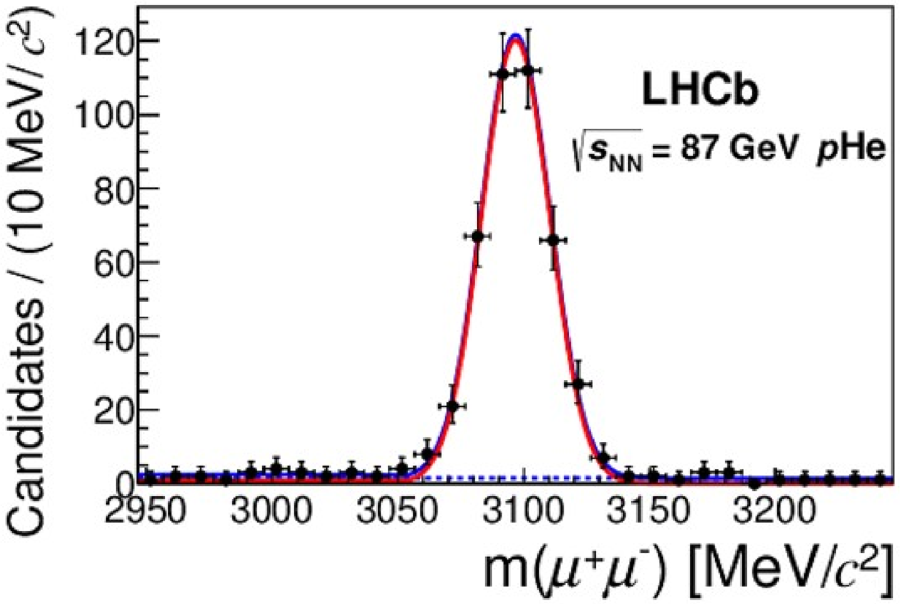
Successful p+Ne, p+Ar, p+He, Pb+Ar, Pb+Ne data taking

Limitations: Limited luminosities; no p+p baseline; no heavy nuclei yet

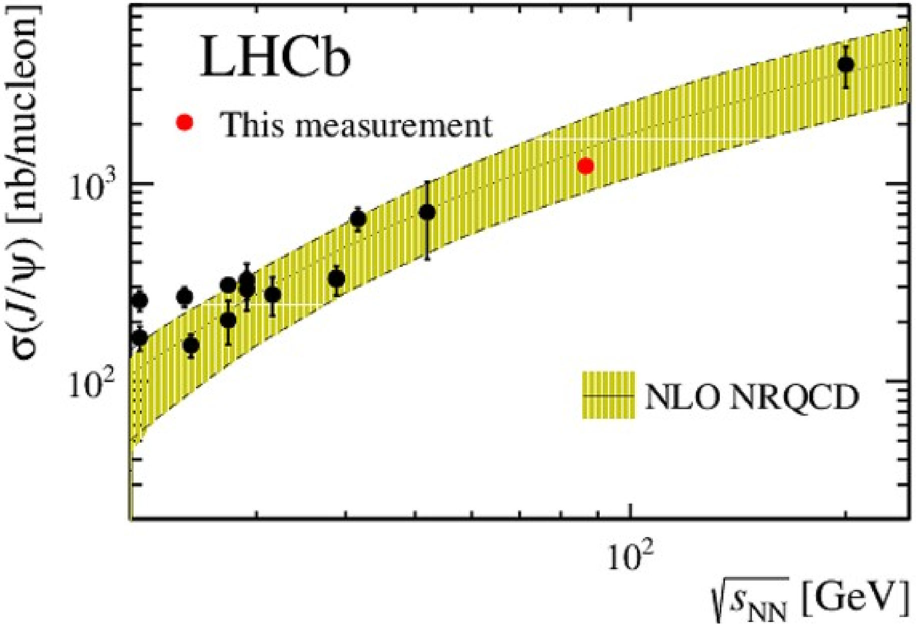
# First Measurement of Charm Production in its Fixed-Target Configuration at the LHC

R. Aaij et al. (LHCb Collaboration)
Phys. Rev. Lett. 122, 132002

J/ψ




SMOG-LHCb data

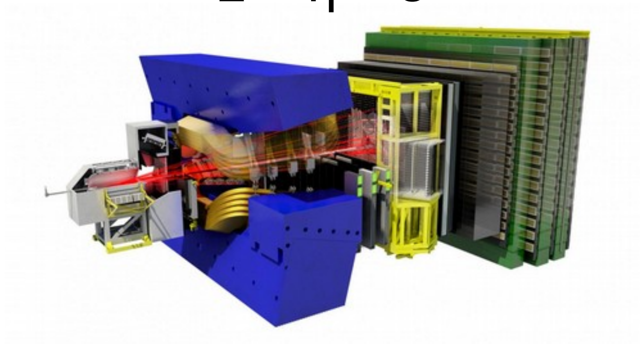


# Fixed-target collisions at the LHC: Sensitivity studies

## LHCb-like

$\sqrt{s_{NN}}$ = 115 GeV, $L_{int}$ (p-H) = 10 $fb^{-1}$ / year
$\sqrt{s_{NN}}$ = 115 GeV, $L_{int}$ (p-Xe) = 100 $pb^{-1}$ / year
$\sqrt{s_{NN}}$ = 72 GeV, $L_{int}$ (Pb-Xe) = 30 $nb^{-1}$ / year
(Ref at same energy:
$L_{int}$ (p-H) = 250 $pb^{-1}$ $L^{int}$ (p-Xe) = 2 $pb^{-1}$)

$2 < \eta < 5$

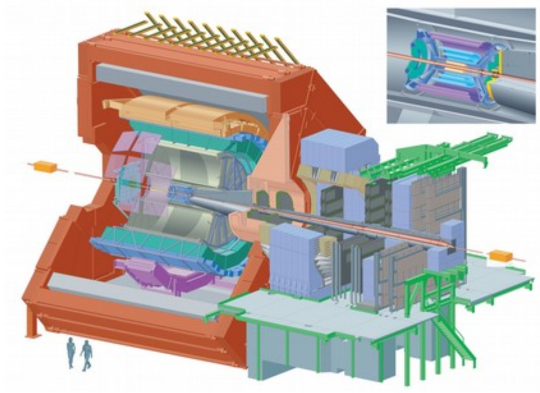


Target Z = 0, microvertexing, particle ID, $\mu$ ID

## ALICE-like

$\sqrt{s_{NN}}$ = 72 GeV, $L_{int}$ (Pb-Pb) = 1.6 $nb^{-1}$ / year
$\sqrt{s_{NN}}$ = 115 GeV, $L_{int}$ (p-H) = 45 $pb^{-1}$ / year

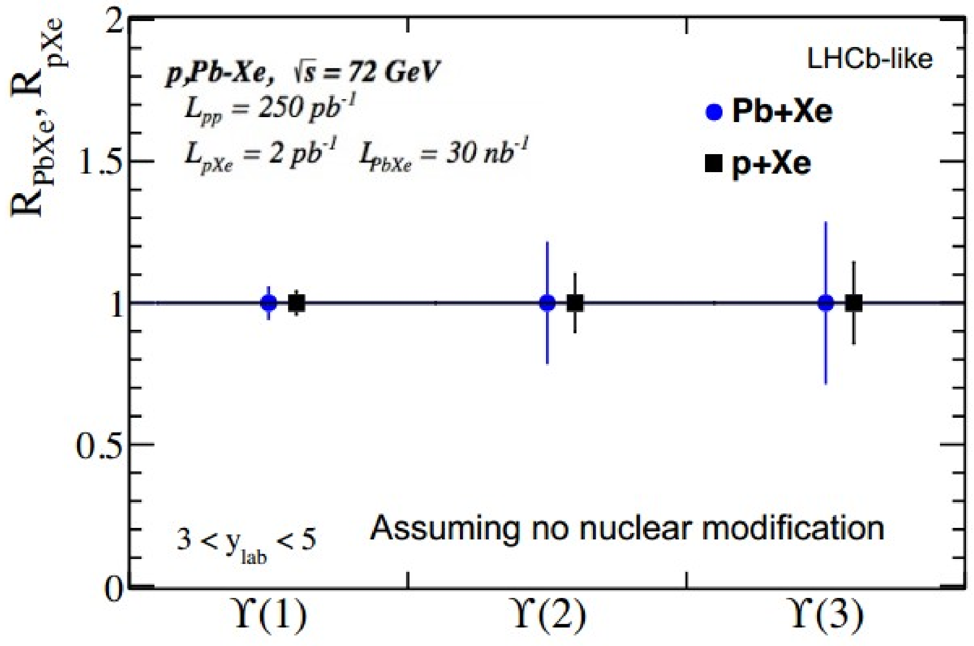
$-0.9 < \eta^{TPC} < 0.9$

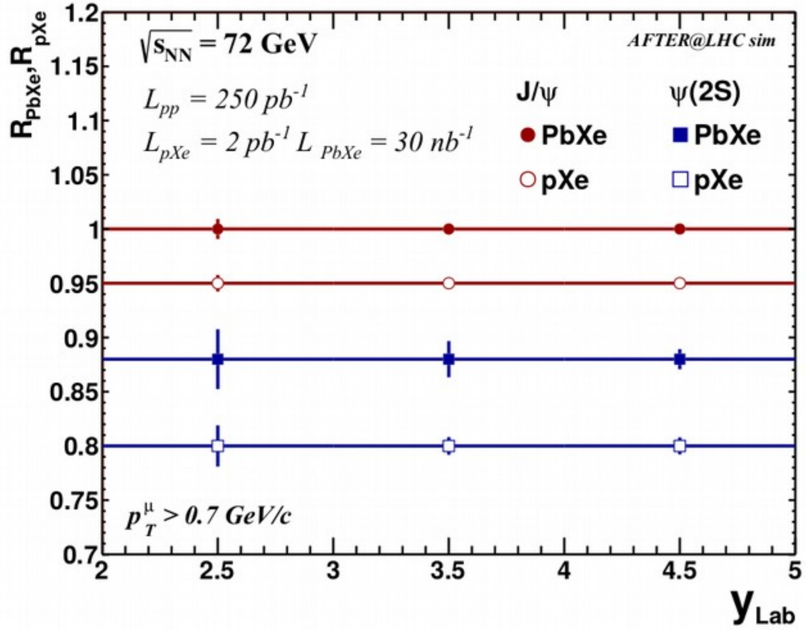


Bent crystal + internal solid target:
Z ~ 0 + ALICE-like acceptance

# Quarkonium in “cold” and “hot” mater studies

Determination of thermodynamic properties of QGP + cold nuclear matter effects with ϒ(nS) production in pp, pA, AA




LHCb-like

ArXiv:1807.00603

# Orbital angular momentum of quarks and gluons

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- **$A_N \neq 0$** → non-zero quark/gluon Sivers function → **non-zero quark/gluon OAM**

- Drell-Yan → access to $f_{1T}^{\perp q}(x, \vec{k}_{\perp}^{2})$

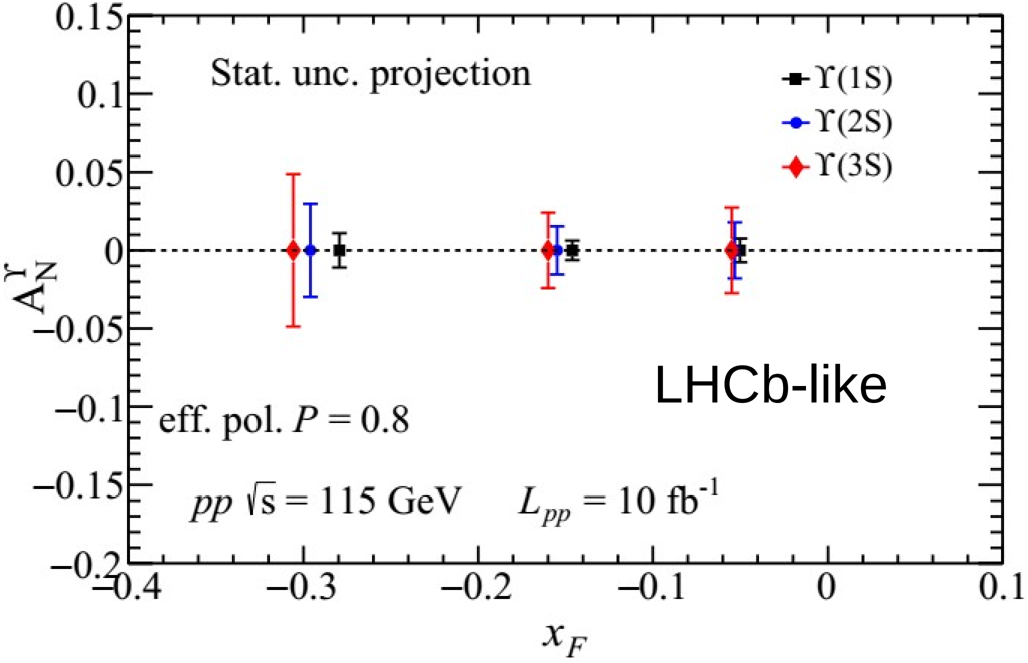
$$f_{1T}^{\perp q}(x, \vec{k}_{\perp}^{2})_{Drell-Yan} = -f_{1T}^{\perp q}(x, \vec{k}_{\perp}^{2})_{Semi-Inclusive\ DIS}$$

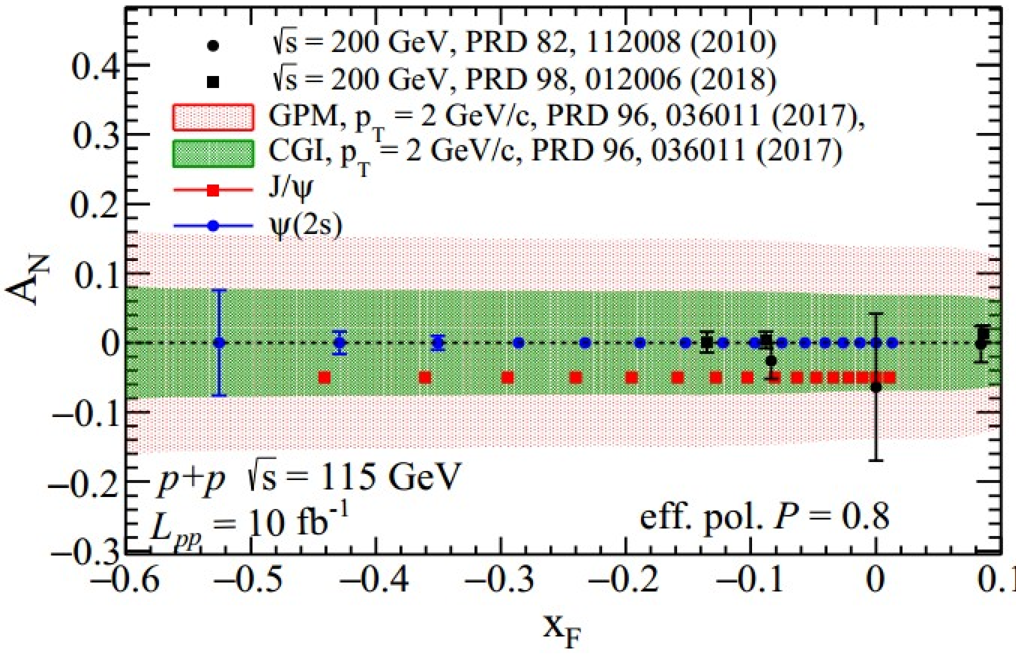
- Gluon Sivers effect → access via single spin asymmetry of open charm & quarkonia, $J/\psi$-$J/\psi$, $J/\psi+\gamma$

# J/ψ and ϒ in p+p

$$A_N = \frac{1}{\mathcal{P}_{\text{eff}}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

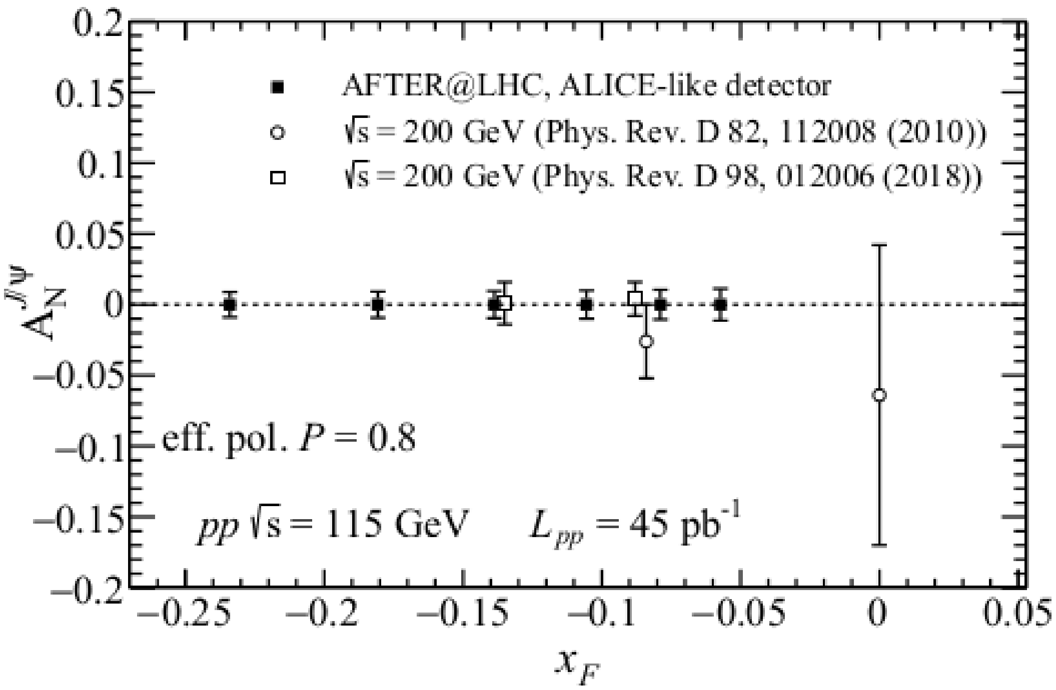
- Typically $10^9$ charmonia, $10^6$ bottomonia per year
- Unique access to C-even quarkonia ($\chi_{c,b}$, $\eta_c$ ) + associated production
- $A_N$ for all quarkonia (J/ψ, ψ', $\chi_c$ , ϒ(nS), $\chi_b$ & $\eta_c$ ) can be measured



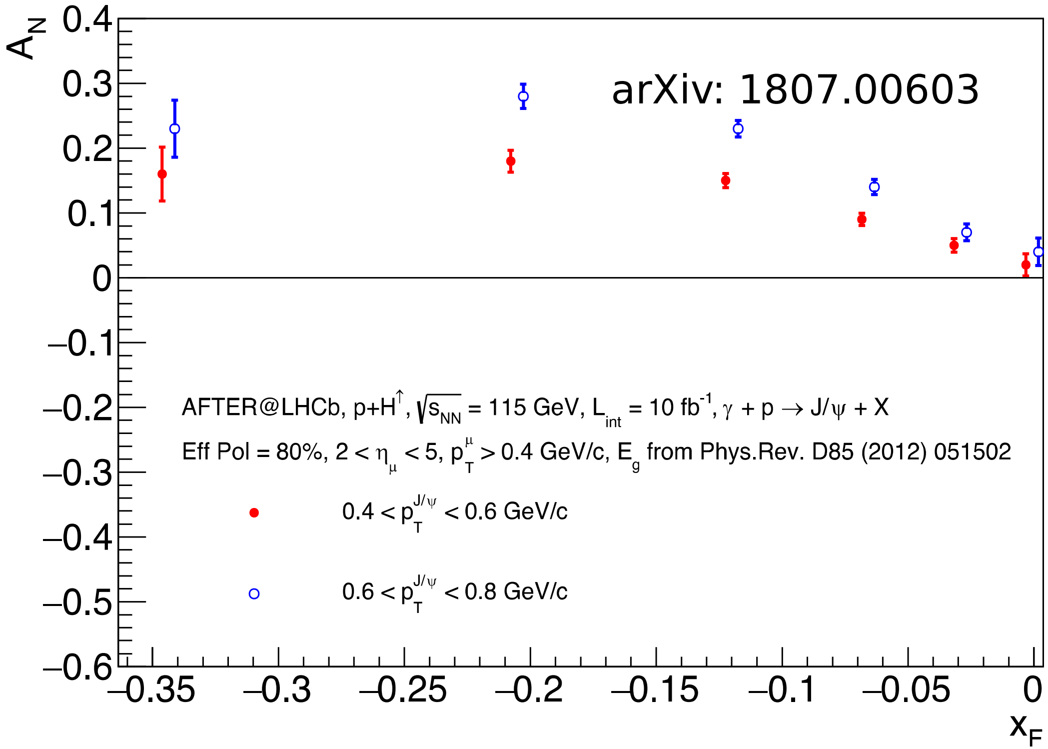



# Quarkonia $A_N$

J/ψ $A_N$ in ALICE-like detector




Photoproduced J/ψ to probe the gluon Generalized Parton Dist. Eg



# Status

# Horizon 2020 project STRONG-2020

http://www.strong-2020.eu

44 institutions from 14 EU Member States,

Budget: 10 M euro for 4 years (2019 - 2023)

JRA2-FTE@LHC: Fixed Target Experiments at the LHC

Development of novel gas-target techniques to be able to carry out the most energetic fixed-target collisions ever performed in the lab, using the LHC beams at ALICE and LHCb. Evaluation of the novel expected constraints on PDFs at high-x in the proton and nucleus, parton spin dynamics, as well as QGP properties via unique quarkonia measurements.

# New SMOG on the horizon

https://cerncourier.com/a/new-smog-on-the-horizon/

8 May 2020

## A report from the LHCb experiment

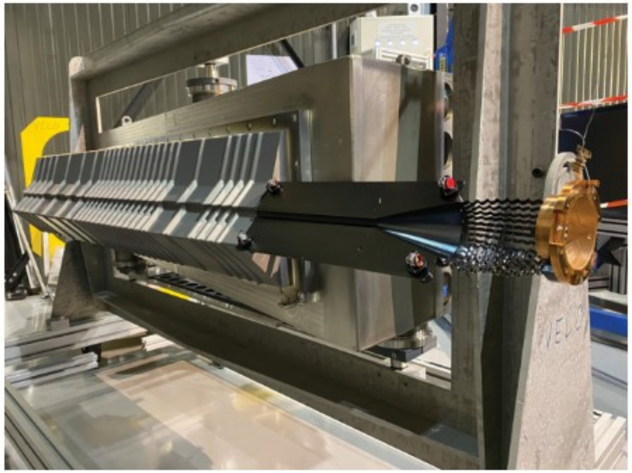
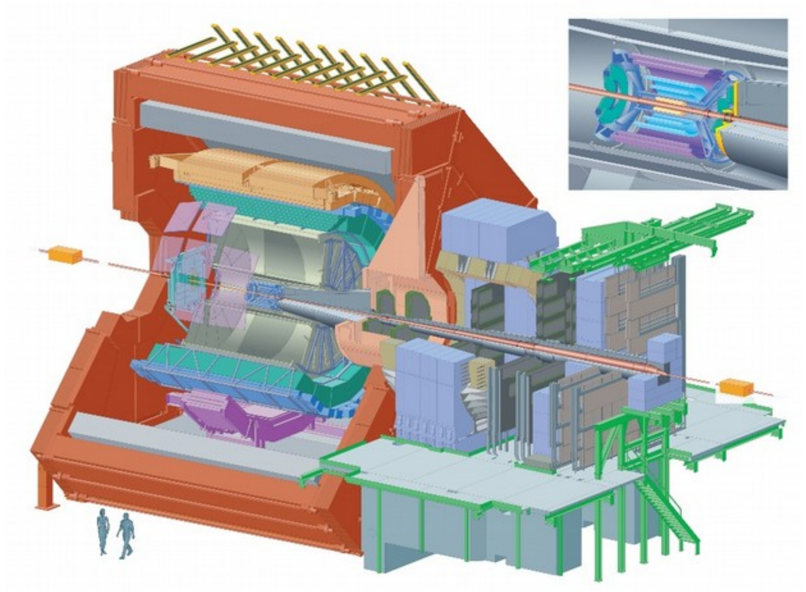


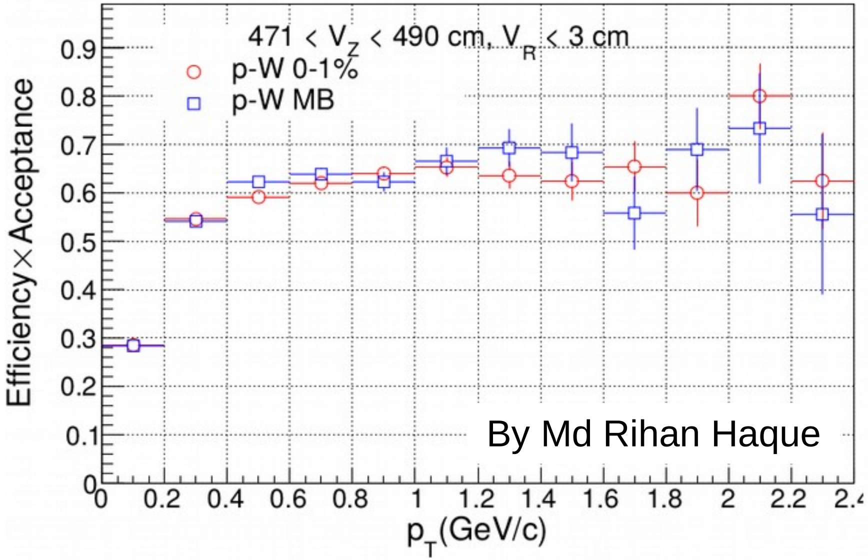

**Fig. 1.** Half of the SMOG2 storage cell (black), attached to its wake-field suppressor (black, right) and the VELO RF foil (grey, left). Credit: LHCb

LHCb will soon become the first LHC experiment able to run simultaneously with two separate interaction regions. As part of the ongoing major upgrade of the LHCb detector, the new SMOG2 fixed-target system will be installed in long shutdown 2. SMOG2 will replace the previous System for Measuring the Overlap with Gas (SMOG), which injected noble gases into the vacuum vessel of LHCb's vertex detector (VELO) at a low rate with the initial goal of calibrating luminosity measurements. The new system has several advantages, including the ability to reach effective area densities (and thus luminosities) up to two orders of magnitude higher for the same injected gas flux.

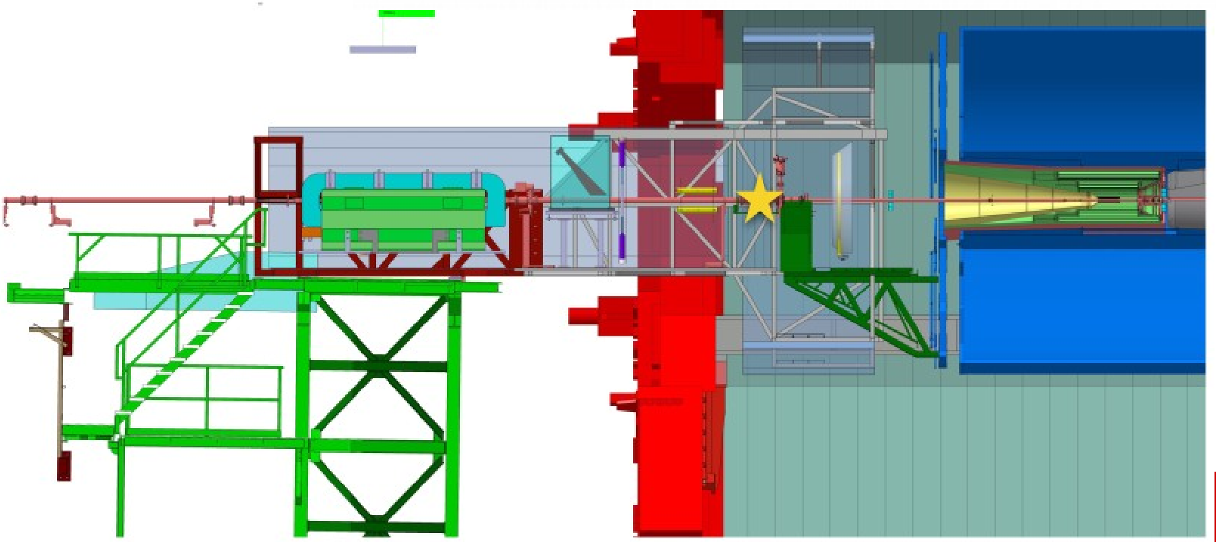
# ALICE Fixed Target study group



Simulation studies, charged hadrons




By Md Rihan Haque



Possible target integration at z ≈ -4.8 m from the nominal interaction point

# Summary

**Quarkonium at RHIC**

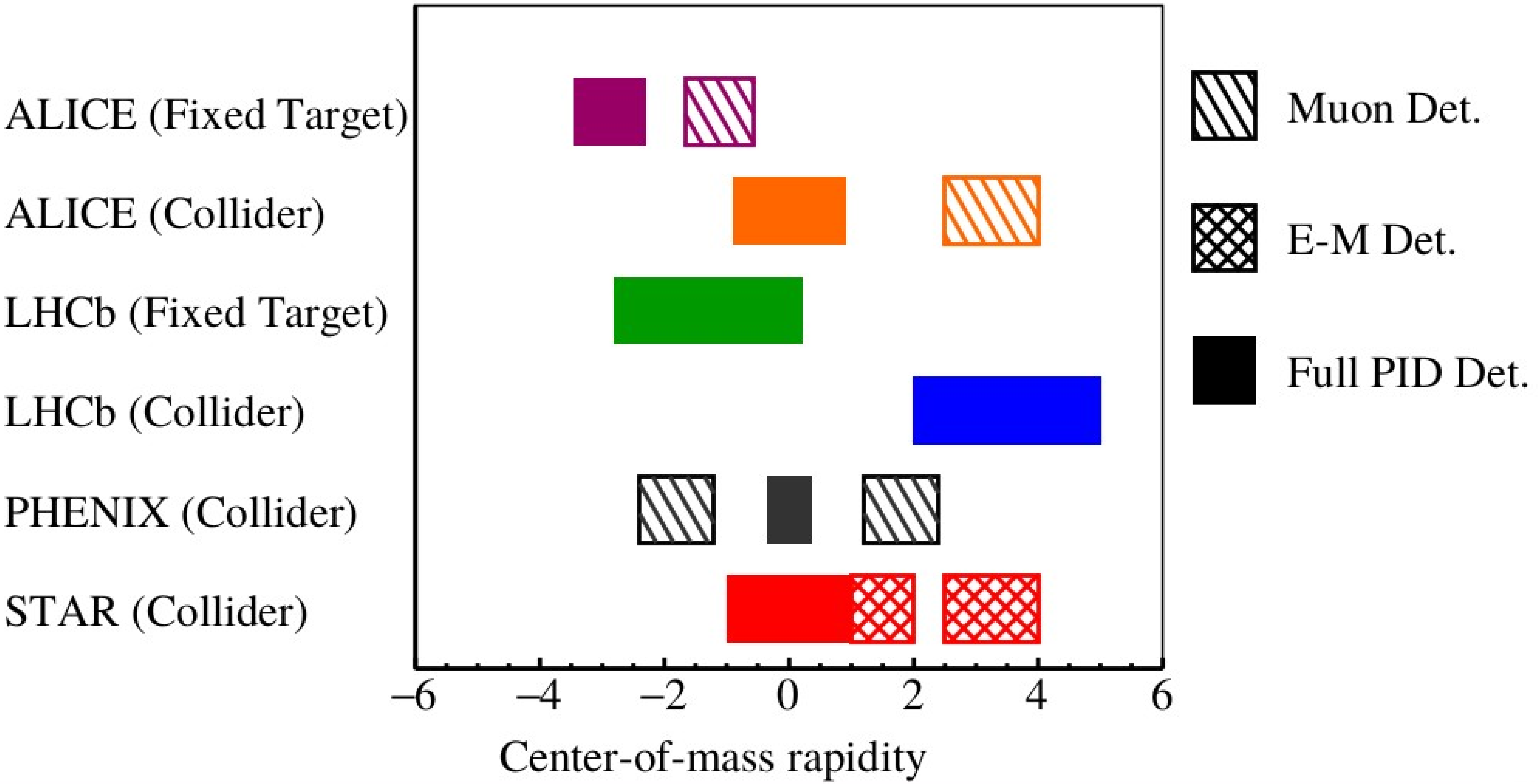
- New results on polarization and nuclear effects available
- New data taken within Beam Energy Scan II and high luminosity pp 500 GeV run in 2017

**Fixed target collisions at the LHC**

- Topic of the Physics Beyond Collider study http://pbc.web.cern.ch/ → **LHC fixed target** working group
- Ongoing technical and performance studies within the **Horizon 2020 grant STRONG-2020**

# Backup

# ALICE Fixed Target for $Z_{target}$ = -4.7 m vs other experiments



# SMOG data samples

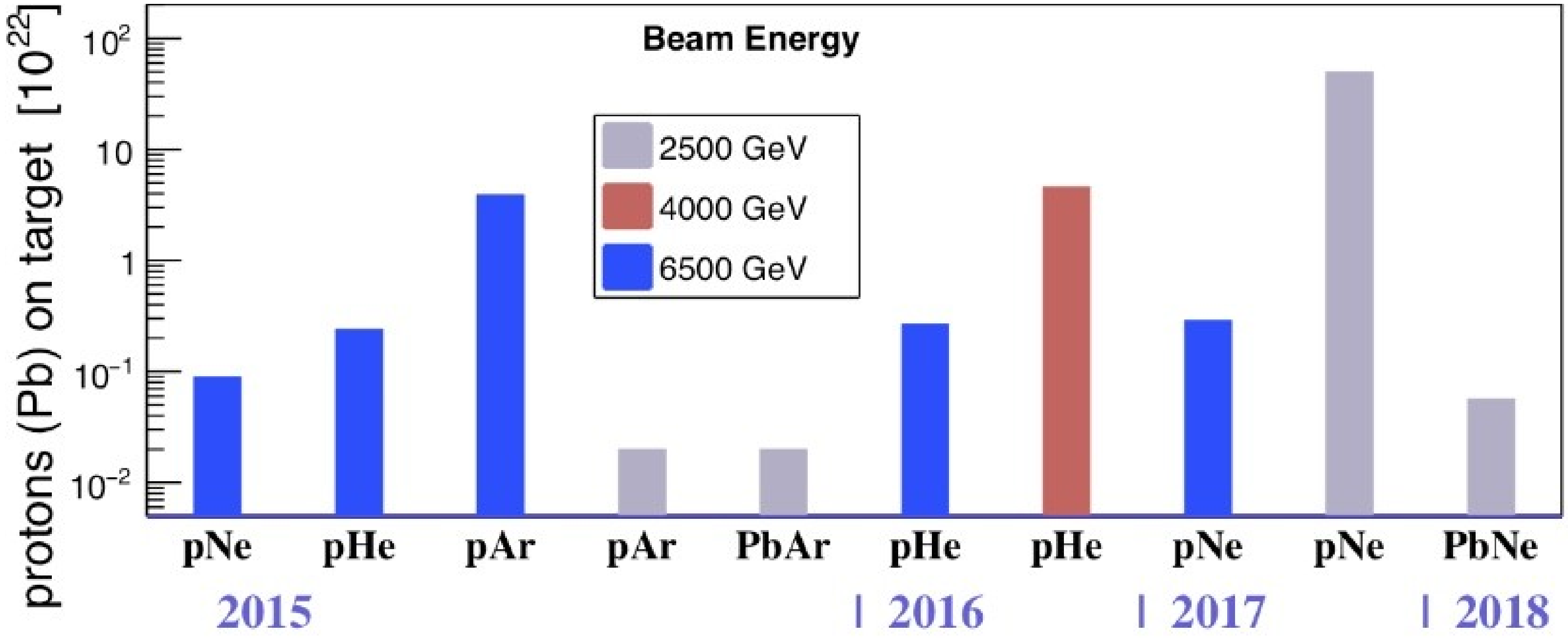
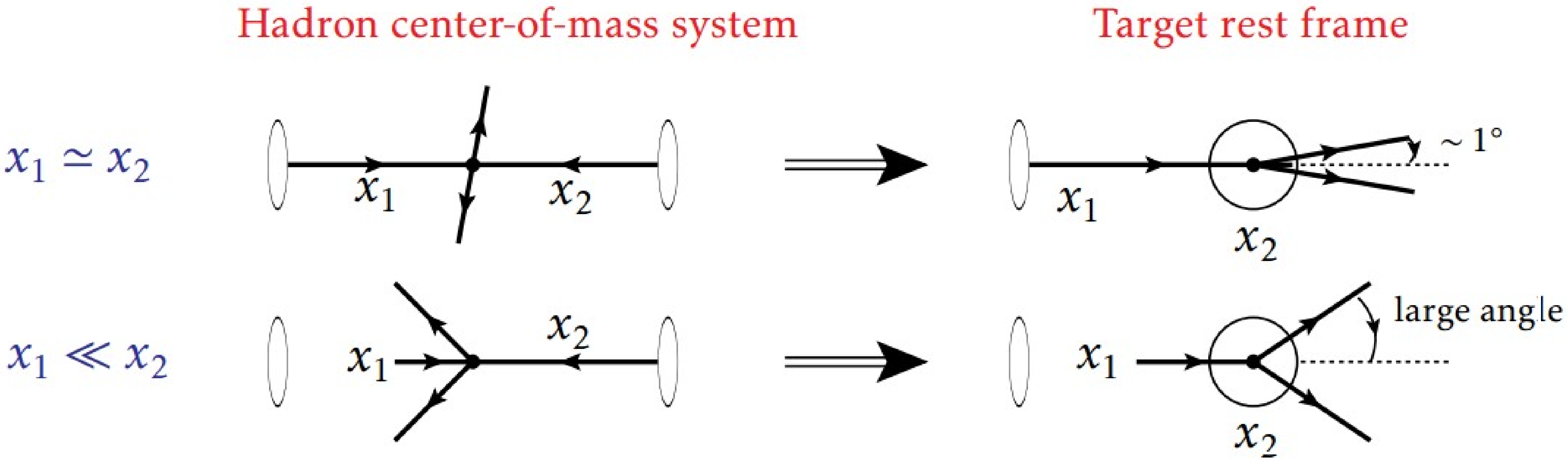



Figure 1: Dedicated SMOG runs collected since 2015. Beam-gas collisions have been recorded using different gas types (He, Ar, Ne) and beam energies.

https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

# Boost effect → access to backward physics

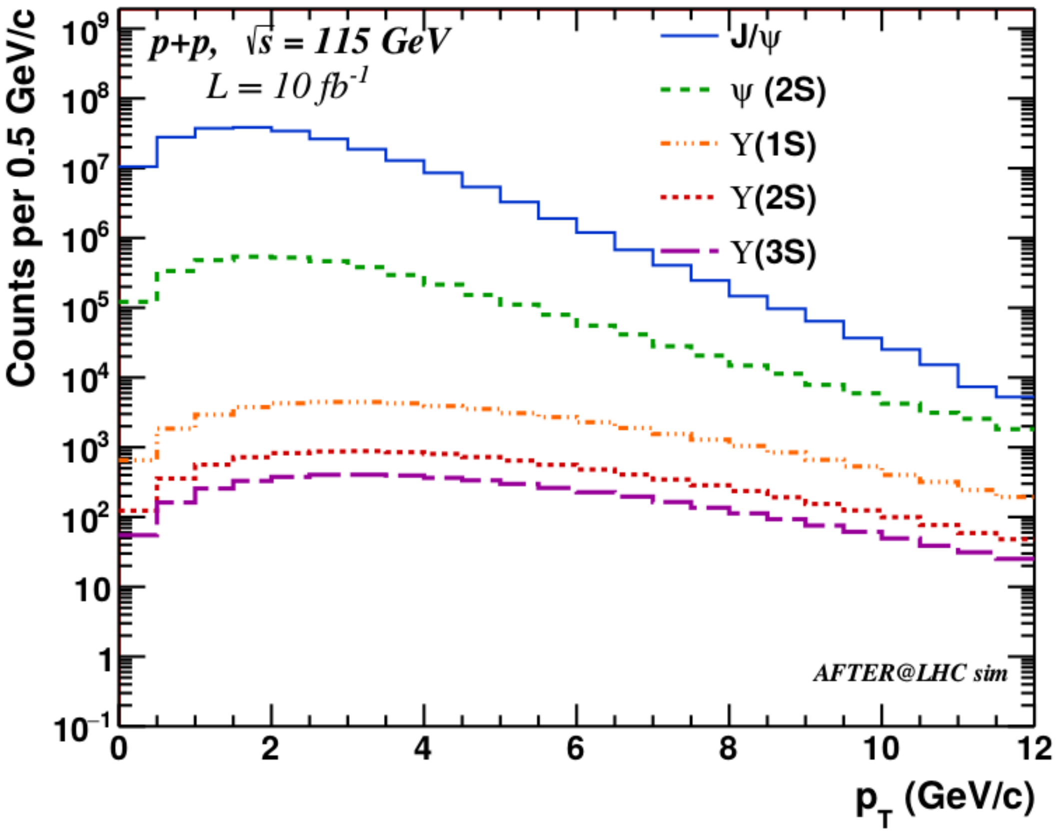



backward physics = large-$x_2$ physics ( $x_F < 0$ → large $x_2$ )

# J/ψ and ϒ yields

Typically $10^9$ charmonia, $10^6$ bottomonia per year

LHCb-like




Adv. High Energy Phys. 2015 (2015) 986348

# Extensive review, many details,
# Submitted to Physics Reports

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

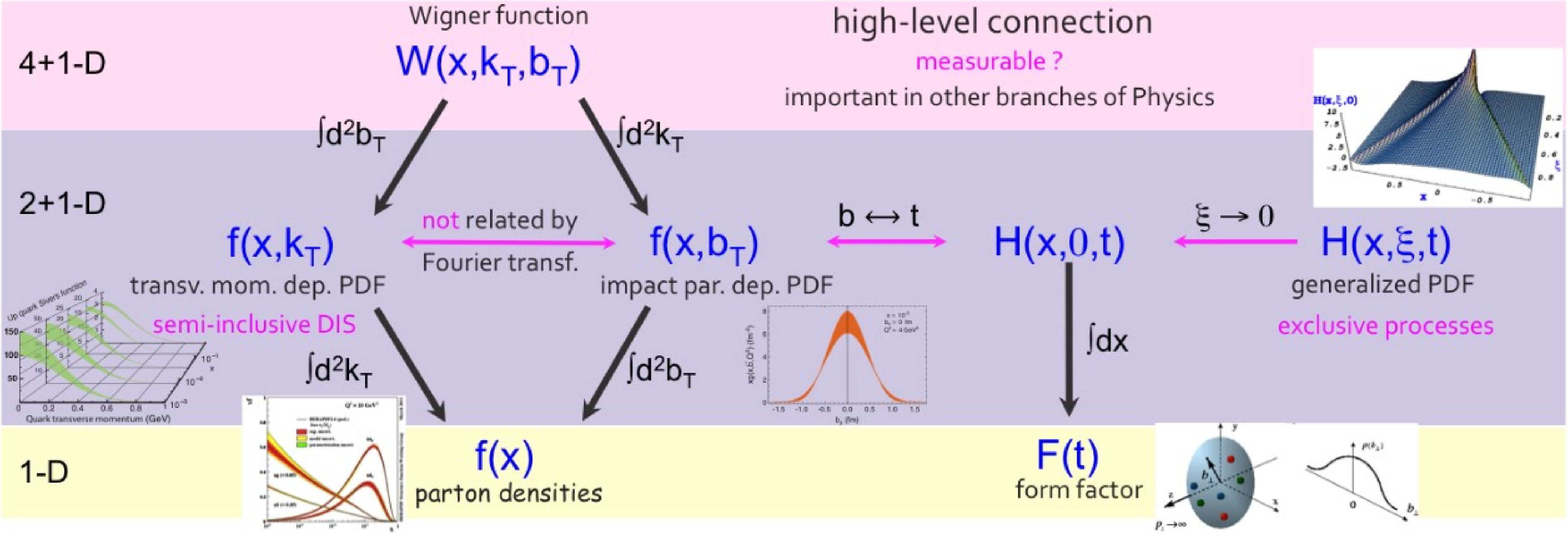
C. Hadjidakis (Orsay, IPN), D. Kikoła (Warsaw U. of Tech.), J.P. Lansberg, L. Massacrier (Orsay, IPN), M.G. Echevarria (INFN, Pavia), A. Kusina (Cracow, INP), I. Schienbein (LPSC, Grenoble), J. Seixas (Lisbon, IST & LIP, Lisbon), H.S. Shao (Paris, LPTHE), A. Signori (Jefferson Lab), B. Trzeciak (Utrecht U.), S.J. Brodsky (SLAC), G. Cavoto (INFN, Rome & Rome U.), C. Da Silva (Los Alamos), F. Donato (Turin U. & INFN, Turin), E.G. Ferreiro (Santiago de Compostela U. & Santiago de Compostela U., IGFAE & Ecole Polytechnique), I. Hřivnáčová (Orsay, IPN), A. Klein (Los Alamos), A. Kurepin (Moscow, INR), C. Lorcé (Ecole Polytechnique, CPHT), F. Lyonnet (Southern Methodist U.), Y. Makdisi (BNL, C-A Dept.), S. Porteboeuf (Clermont-Ferrand U.), C. Quintans (LIP, Lisbon), A. Rakotozafindrabe (IRFU, Saclay, DPHN), P. Robbe (Orsay, LAL), W. Scandale (CERN), N. Topilskaya (Moscow, INR), A. Uras (Lyon, IPN), J. Wagner (NCBJ, Warsaw), N. Yamanaka (Orsay, IPN), Z. Yang (Tsinghua U., Beijing), A. Zelenski (BNL, C-A Dept.) Hide

Jul 2, 2018 - 102 pages

(2018-08-20)
IFJPAN-IV-2018-11, JLAB-THY-18-2756, SLAC-PUB-17291
e-Print: arXiv:1807.00603 [hep-ex] | PDF

# AFTER@LHC *Review*

- General motivations and physics cases
- Comprehensive review of implementation options for a Fixed Target program the LHC
- Detector requirements and expected performances
- Physics Projections
  - **High-x frontier for particle and astroparticle physics**
  - **Spin physics**
  - **Heavy-ion physics**




The full spatial ($b_T$) and transverse momentum ($k_T$) dependent structure of partons in the nucleon as a function of the longitudinal momentum fraction of the partons is encoded in the Wigner function $W(x,k_T,b_T)$, which currently is not accessible in experiments

Arxiv:1501.01220