AFTER @ LHC

A fixed-target programme at the LHC for heavy-ion, hadron, spin and astroparticle physics

Daniel Kikoła
AFTER@LHC Study group: http://after.in2p3.fr/after/index.php/Current_author_list

Why a fixed-target experiment at the LHC?

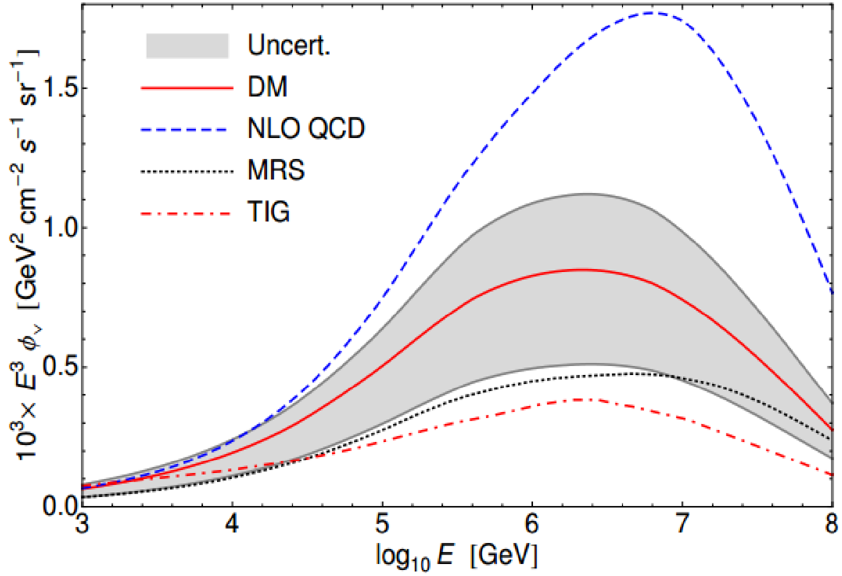
- High luminosities → access to rare probes (heavy quarks)
- High precision Heavy-Ion program between SPS and RHIC top energy
- Access to high Feynman x_F domain ($|x_F| = |p_z|/p_{z\,max} \rightarrow 1$)
- Variety of atomic mass of the target,
- Large kinematic coverage
- Polarization of the target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

Physics program

High-x frontier

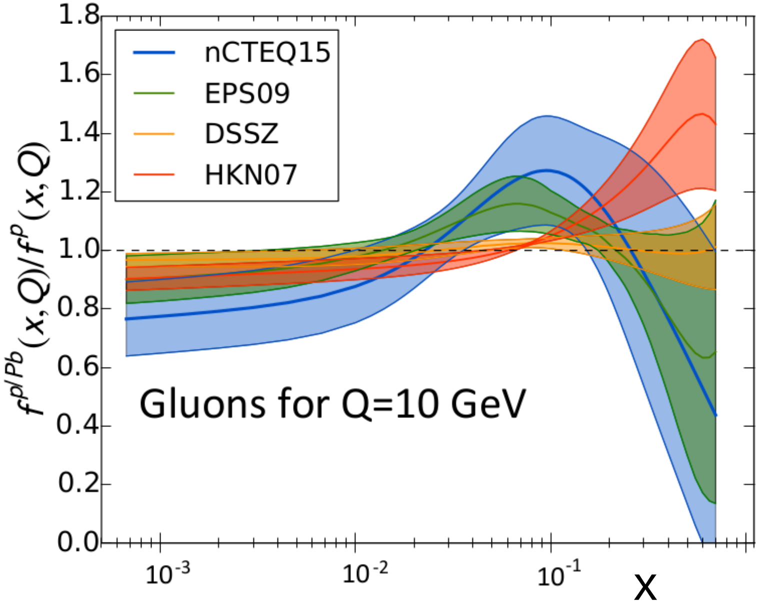
- Advance our understanding of high-x gluons, antiquark and heavy-quark content in the nucleon & nucleus
- AFTER@LHC data→ reduce uncertainties on PDFs, astrophysics calculations

Energy spectrum of neutrino flux



Phys.Rev.D78:043005,2008

Gluon nuclear PDFs



Phys. Rev. D 93, 085037 (2016)

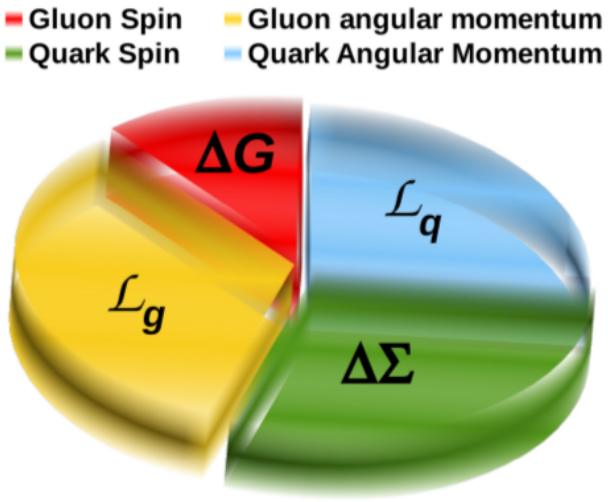
The Spin Physics Program

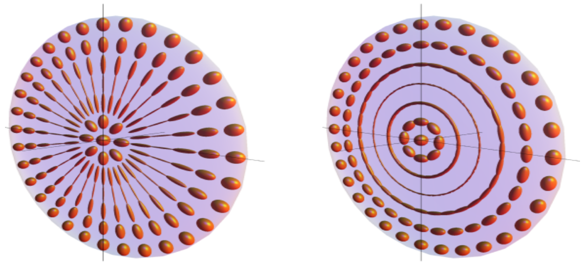
3D mapping of the parton momentum:

- Missing contribution to the proton spin: Gluon and Quark Orbital Angular Momentum L_q and L_g

  p+p↑ → (indirect) access to quark L_q, gluon L_g and gluon transverse-momentum dependent PDF

- Determination of the linearly polarized gluons in unpolarized protons





Phys. Rev. Lett. 112, 212001

Heavy-ion collisions

AFTER@LHC

Heavy-ion collisions at

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

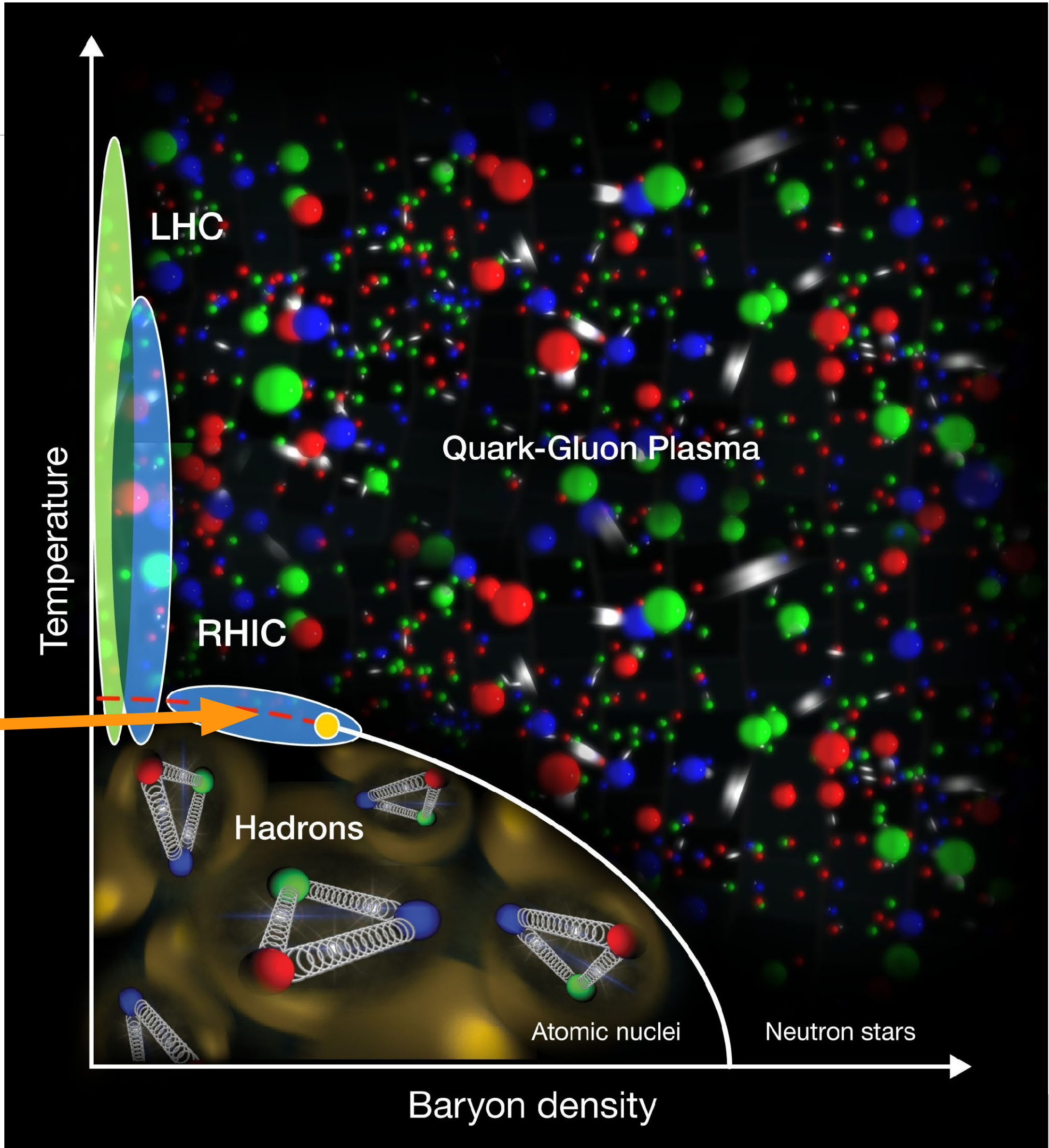
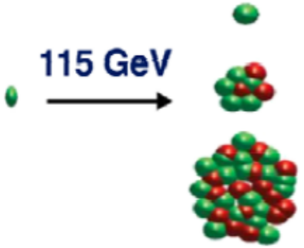


Figure courtesy of Brookhaven National Laboratory

Fixed-target collisions at LHC

Kinematics

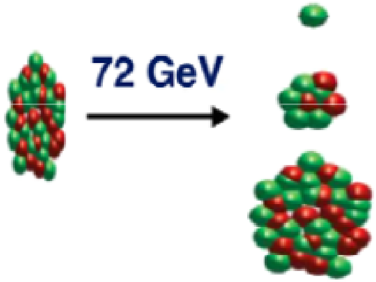
- p+p or p+A with a 7 TeV p on a fixed target



$$\sqrt{s}=\sqrt{2m_N E_p}\approx 115\,GeV$$

$$y_{CMS}=0 \rightarrow y_{Lab}=4.8$$

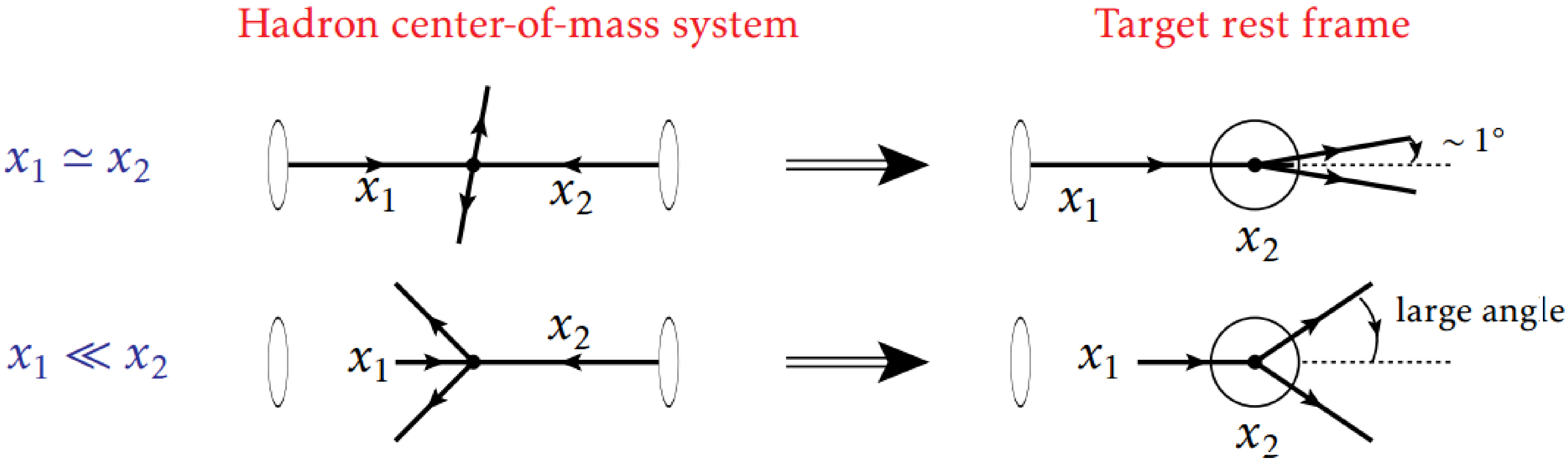
- A+A collisions with a 2.76 TeV Pb beam



$$\sqrt{s}\approx 72\,GeV$$

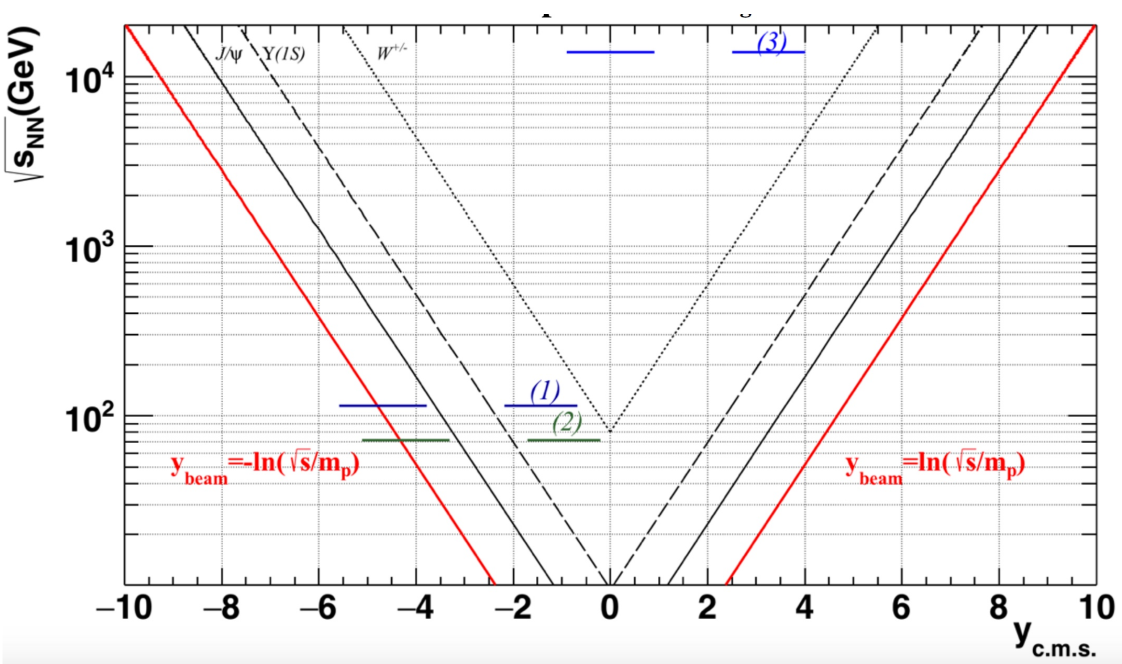
$$y_{CMS}=0 \rightarrow y_{Lab}=4.3$$

Boost effect → access to backward physics

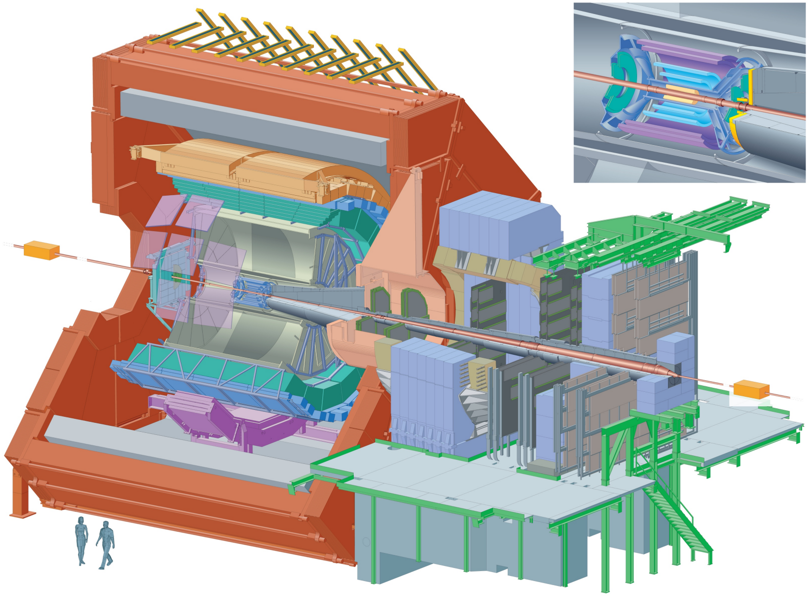


backward physics = large-x_2 physics ($x_F < 0 \rightarrow$ large x_2)

Kinematic coverage: collider vs fixed target



ALICE detector



ALICE: Muon Det.: $2.5 < \eta^{lab} < 4$,

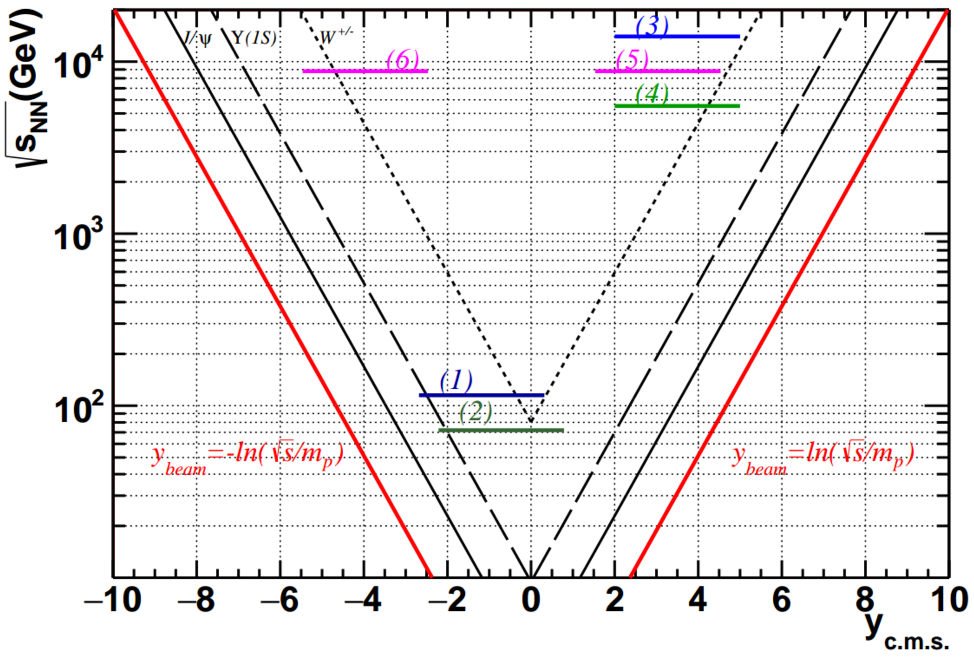
TPC: $|\eta^{lab}| < 0.9$

http://aliceinfo.cern.ch

(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV; (2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV;
(3) collider mode, $\sqrt{s}$ = 14 TeV;

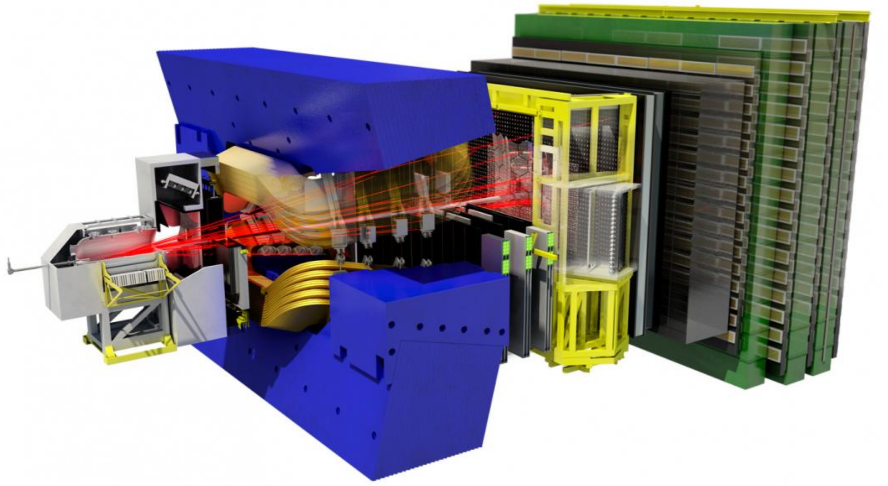
for $Z_{target} \sim 0$

Kinematic coverage: collider vs fixed target



LHCb: $2 < \eta^{lab} < 5$

LHCb detector



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

(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV; (2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV;
(3) collider mode, $\sqrt{s}$ = 14 TeV; (4) collider mode, $\sqrt{s_{NN}}$ = 5.5 TeV, (5),(6) $\sqrt{s_{NN}}$ = 8.8 TeV

How to make fixed-target collisions with the LHC beams?

- Internal (solid or gas) target + existing detector
  - gas target (unpolarized/polarized) and full LHC beam
  - beam splitting by bent-crystal + internal (solid, pol.?) target
  - internal Wire/Foil target (directly in the beam halo)

- Beam extraction by bent-crystal
  - new beam line + new experiment

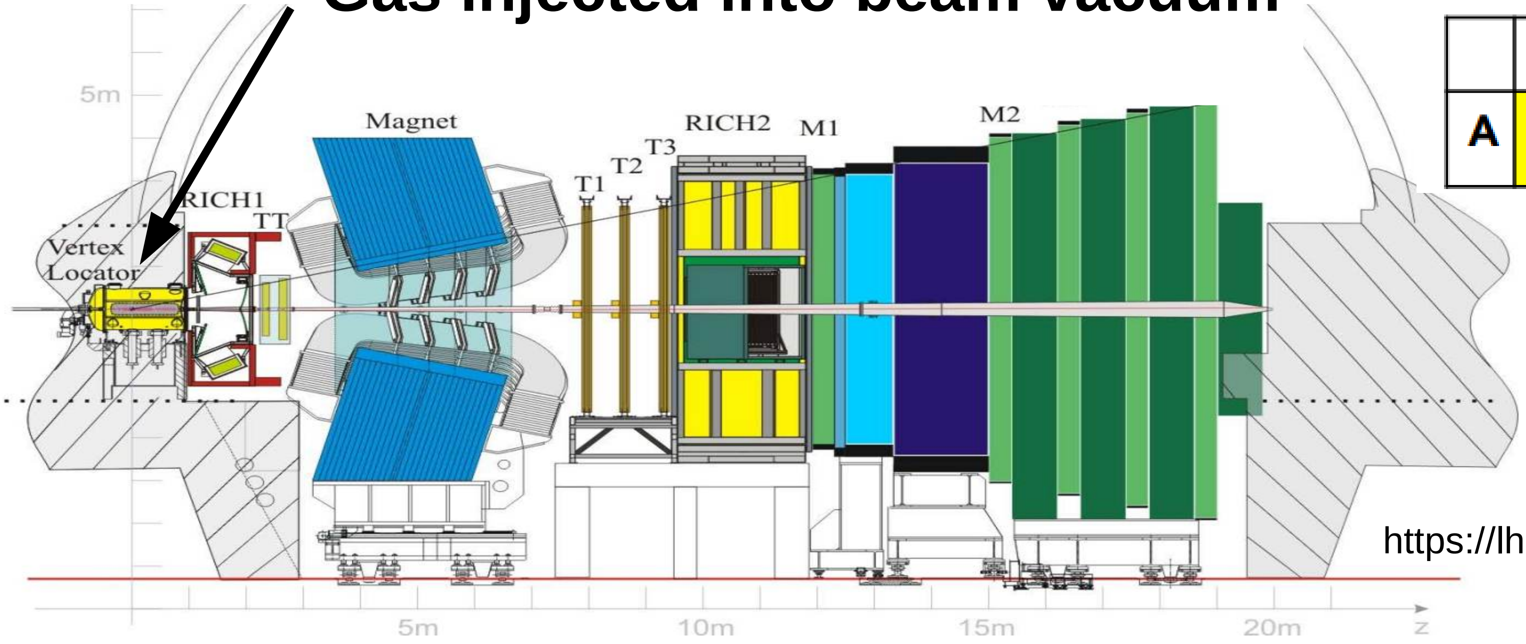
SMOG-LHCb: the demonstrator of a gas target

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



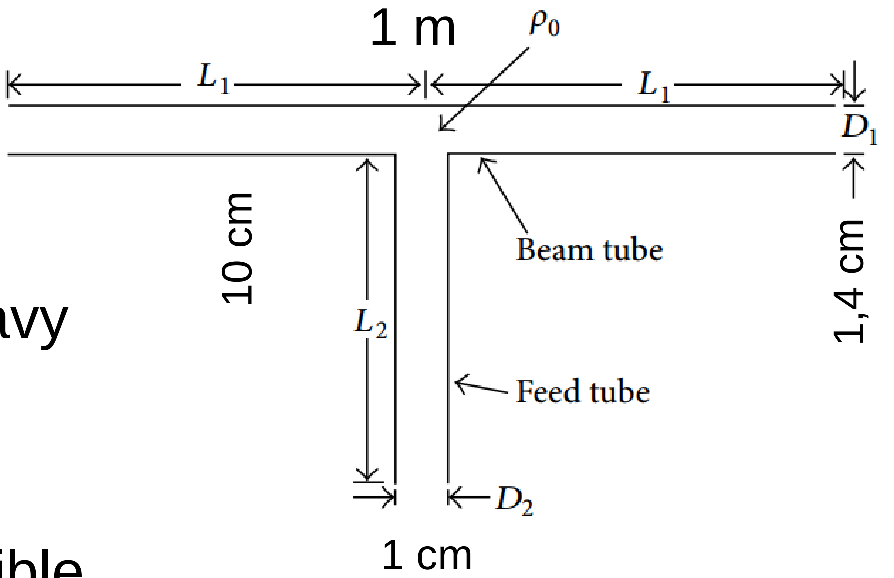
https://lhcb.web.cern.ch/lhcb

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

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

Gas target: HERMES-type system

- Dedicated pumping system
- Polarised H↑ and D↑ injected in open-end storage cell with polarisation P ~80%
- Possible polarised $^{3}He^{\uparrow}$ or unpolarised heavy gas (Kr, Xe)
- Implementation at the LHCb under study
  - what size fit the available space? possible cell coating (affects P)
- Expected L_{int} over a year (for 1 m cell):
  - p-H $\sqrt{s_{NN}}$ = 115 GeV, L_{int} ~ 10 fb^{-1}
  - Pb-H $\sqrt{s_{NN}}$ = 72 GeV, L_{int} ~ 100 nb^{-1}

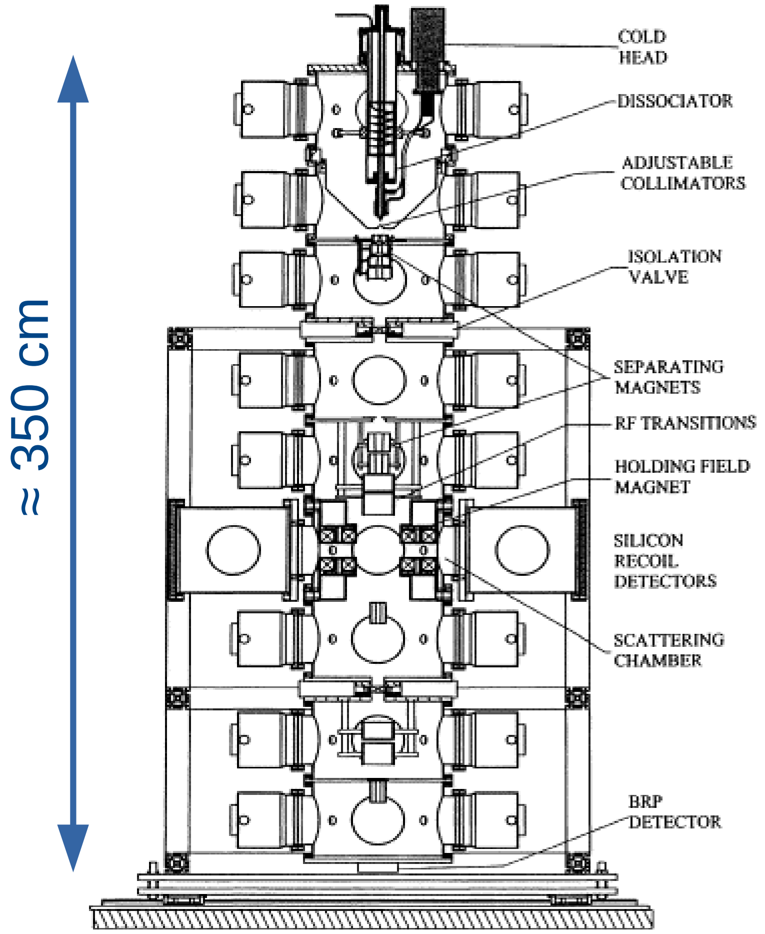


Adv. High Energy Phys 2015 (2015) 463141

E. Steffens, PoS (PSTP2015) 019

The hydrogen jet polarimeter

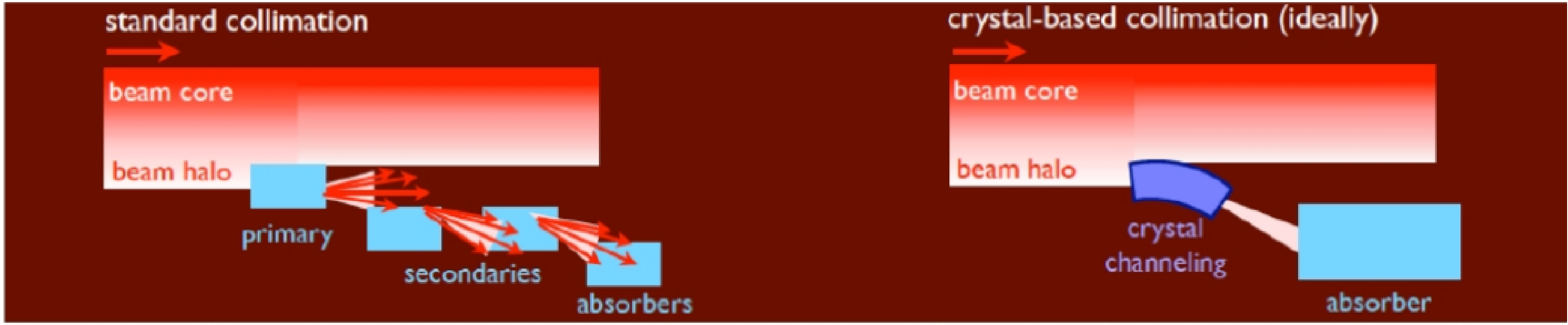
- Used to measure the proton beam polarisation at RHIC
- Compact device
- 9 vacuum chambers, 9 stages of differential pumping
- Polarised free atomic beam source (ABS)
- L_{int} (pH) ~ 50 pb^{-1} per year



NIM A 536 (2005) 248

Beam splitting by bent-crystal

Motivation: beam collimation



Standard collimation today → Crystal-based collimation
- UA9 (@SPS)
- LUA9 (@LHC)

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

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

→Deflecting the beam halo at 7σ distance to the beam, reduces beam loss

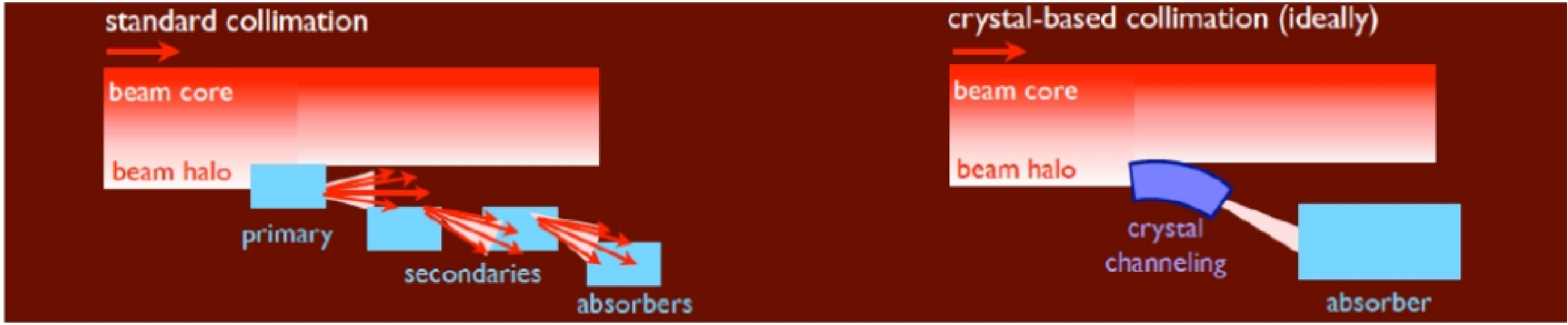
→Beam extraction: civil engineering required, new facility with 7 TeV proton beam

→Beam splitting: intermediate option, could be used with existing experiment

W. Scandale, PBC workshop 2016, https://indico.cern.ch/event/523655/contributions/2284521/

Beam splitting by bent-crystal

Motivation: beam collimation



Standard collimation today

Crystal-based collimation
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- LUA9 (@LHC)

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

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

Typical integrated luminosity over a year (for 5 mm-thick targets):
- p-C collisions at $\sqrt{s}_{NN}$ = 115 GeV, $L_{int} \sim 6\ nb^{-1}$
- Pb-W collisions at $\sqrt{s}_{NN}$ = 72 GeV, $L_{int} \sim 3\ nb^{-1}$

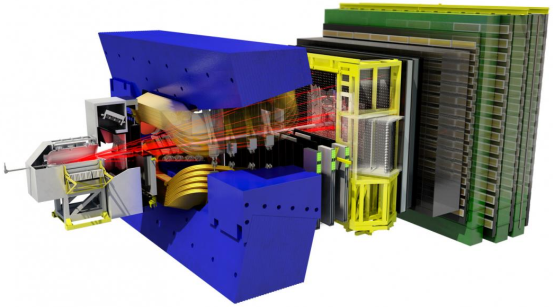
A selection of performance studies

Sensitivity studies - assumptions

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})

$2 < \eta < 5$

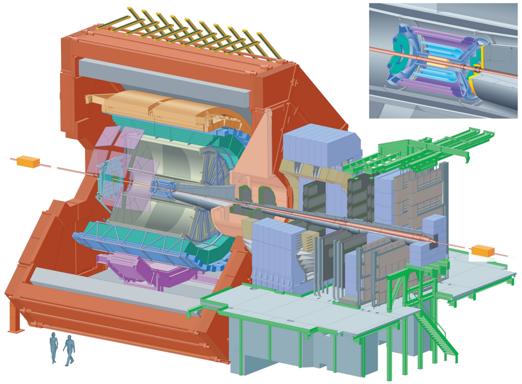


microvertexing, particle ID, μ ID

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

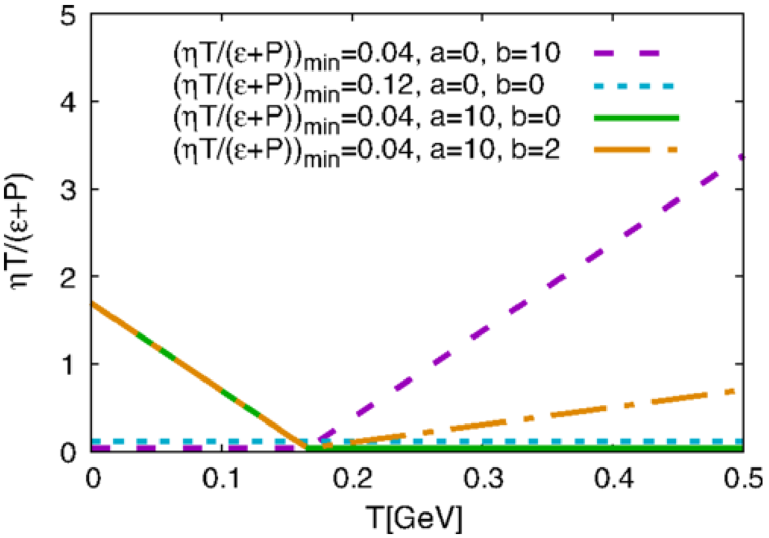
$-0.9 < \eta^{TPC} < 0.9$



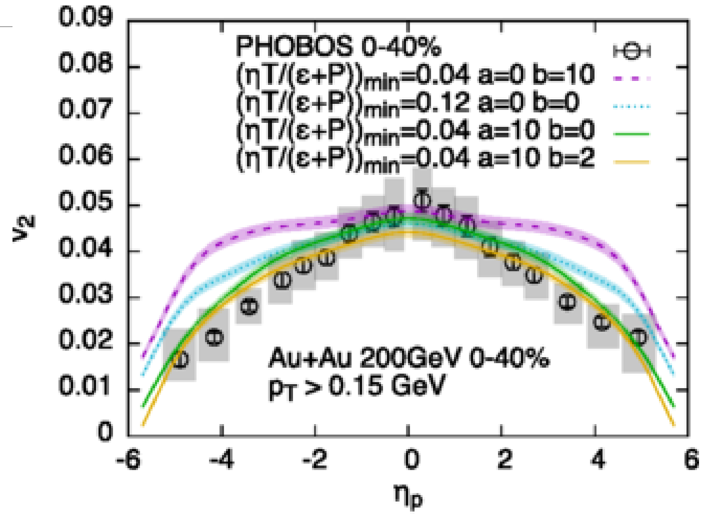
Bent crystal + internal solid target:
Z ~ 0 + ALICE-like acceptance

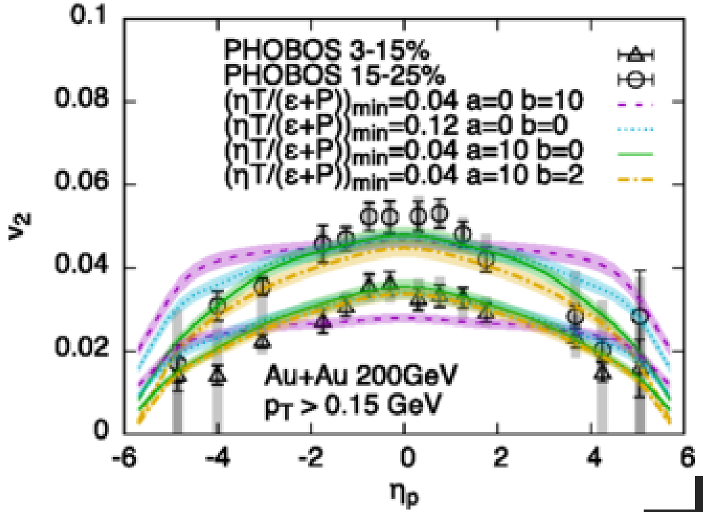
Heavy-Ion collisions

Heavy-ion collisions: toward large rapidities



The four scenarios of temperature dependent ηT/(ϵ+P),
G. Denicol et al, PRL. 116, 212301

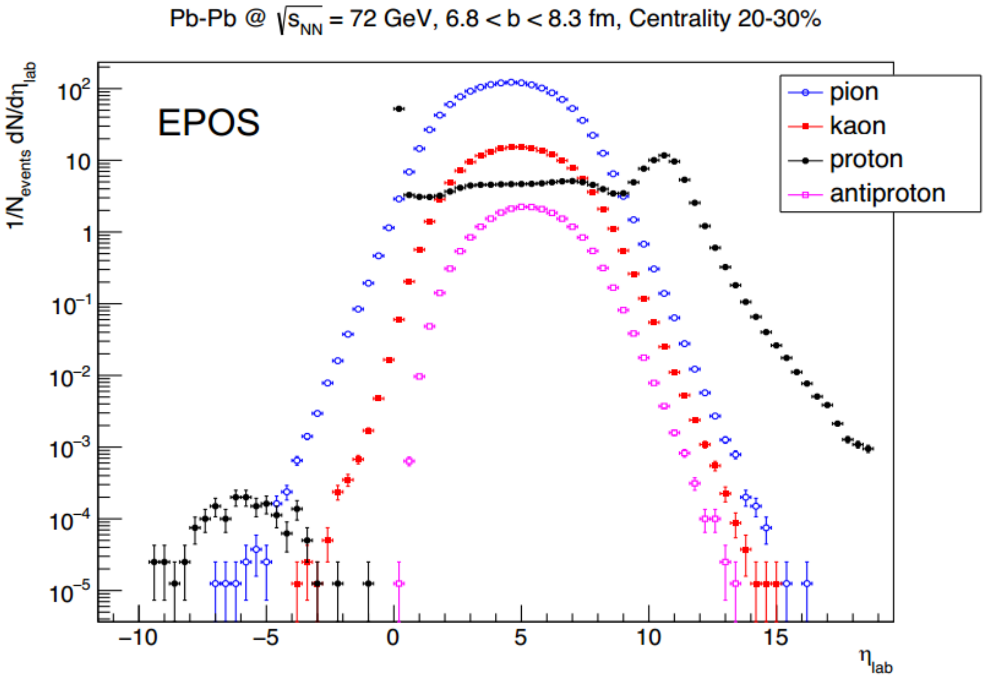


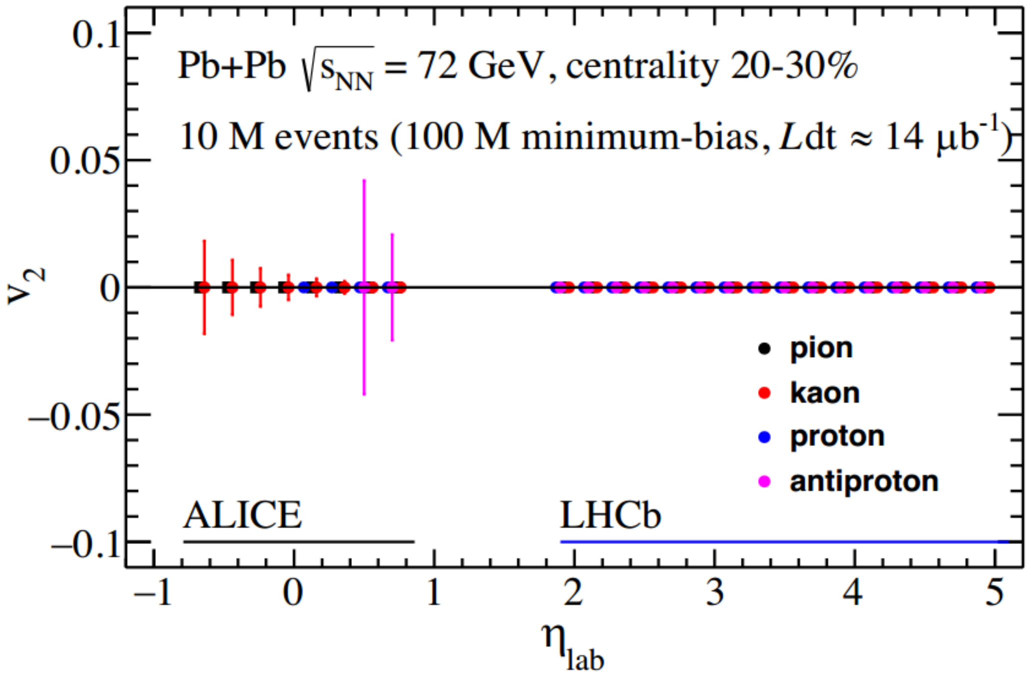


G. Denicol et al, PRL. 116, 212301

Particle yields and v_N at large rapidities → powerful tool to access the medium shear viscosity and temperature

Heavy-ion collisions: toward large rapidities

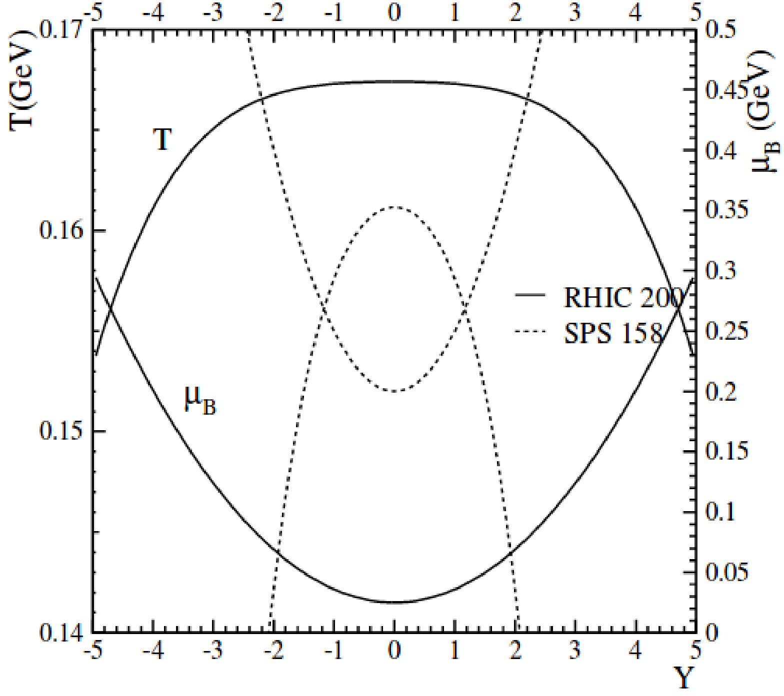




Particle yields and v_N at large rapidities → powerful tool to access the medium shear viscosity and temperature

Rapidity scan of the QCD phase diagram

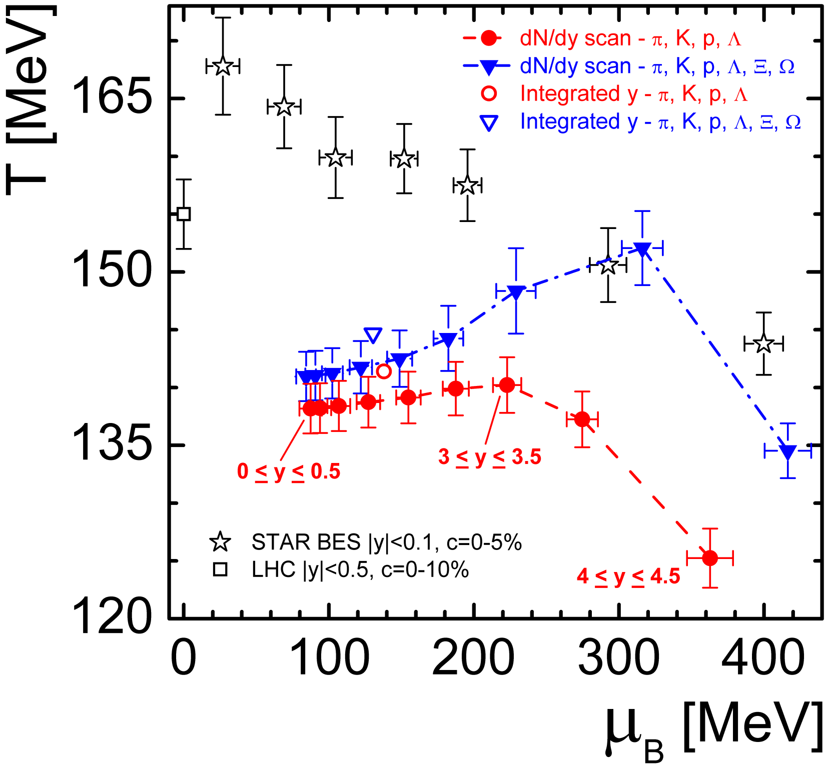
Larger rapidity → larger baryon chemical potential μ_B



F. Becattini, J. Cleymans, J.Phys.G34:S959-964,2007

AFTER@LHC: Comparable μ_B range to the RHIC Beam Energy Scan

Pb+Pb $\sqrt{s_{NN}}$ = 72 GeV, 0-10%

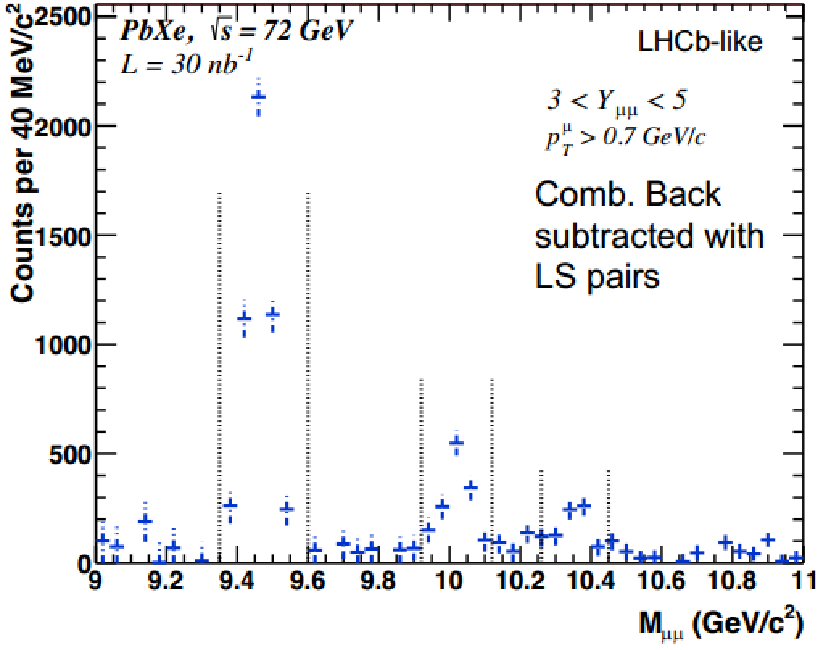


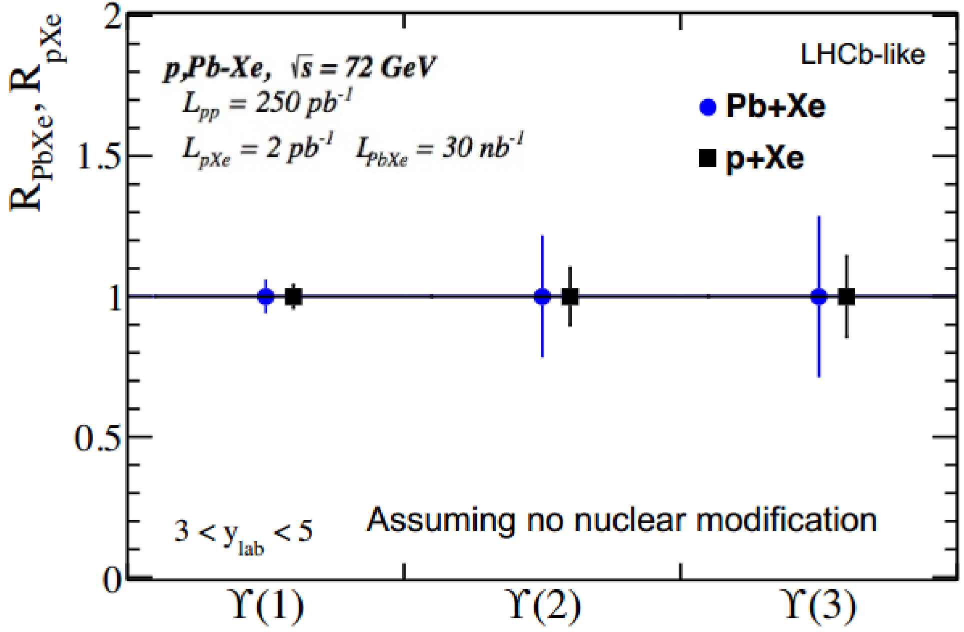
Hadron Resonance Gas model fit to UrQMD simulations, V. Begun, D. Wielanek, V. Vovchenko, D.K. (in preparation)

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

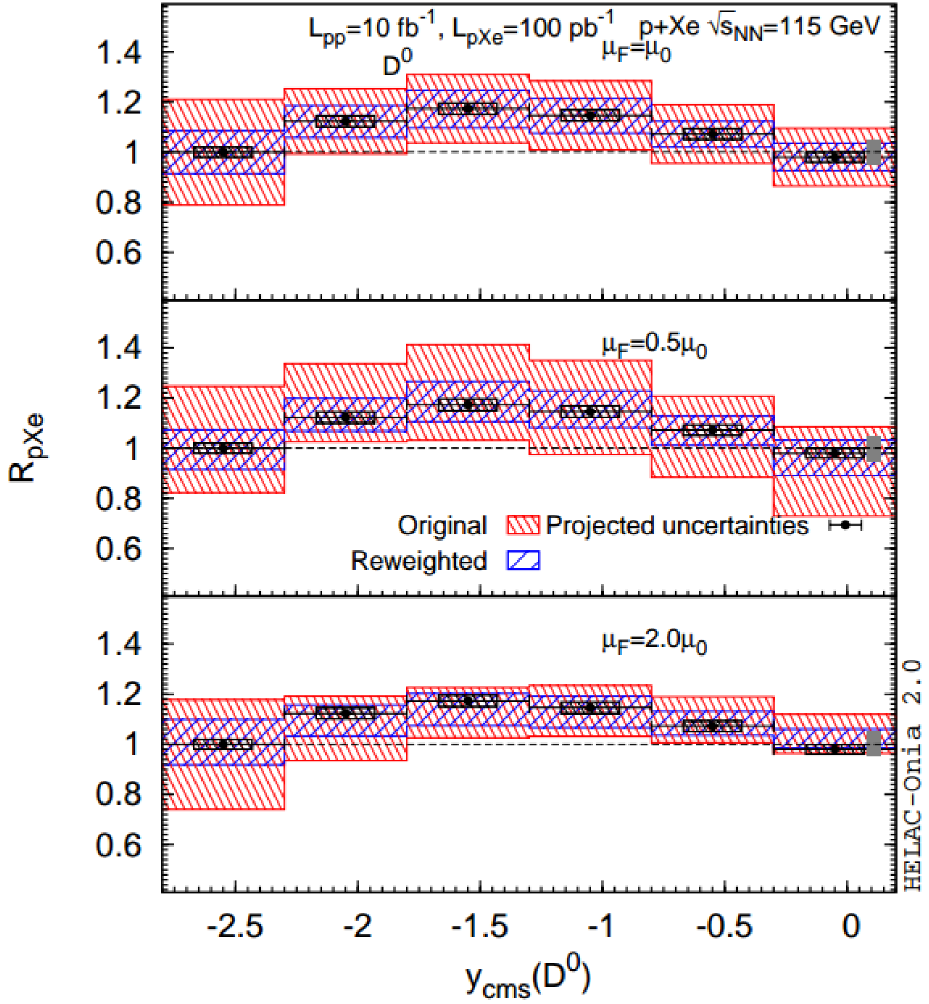
Few Body Syst. 58 (2017) no.5, 148





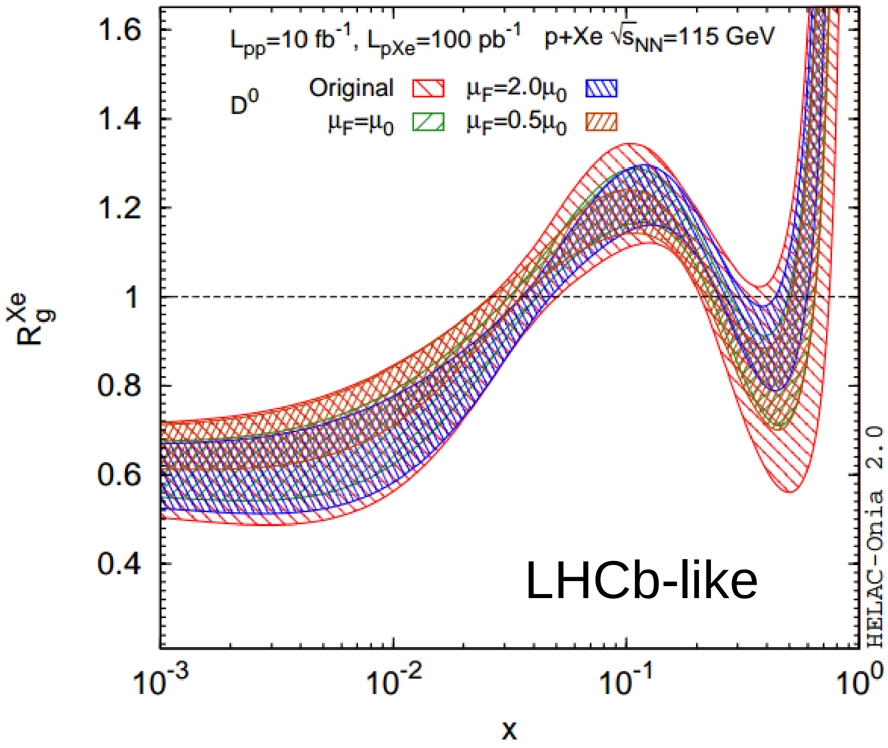
Probing the nuclear structure

Constraining gluon nPDF with heavy quarks



$$R_{pA} = \frac{dN_{pA}}{\langle N_{coll}\rangle dN_{pp}}.$$

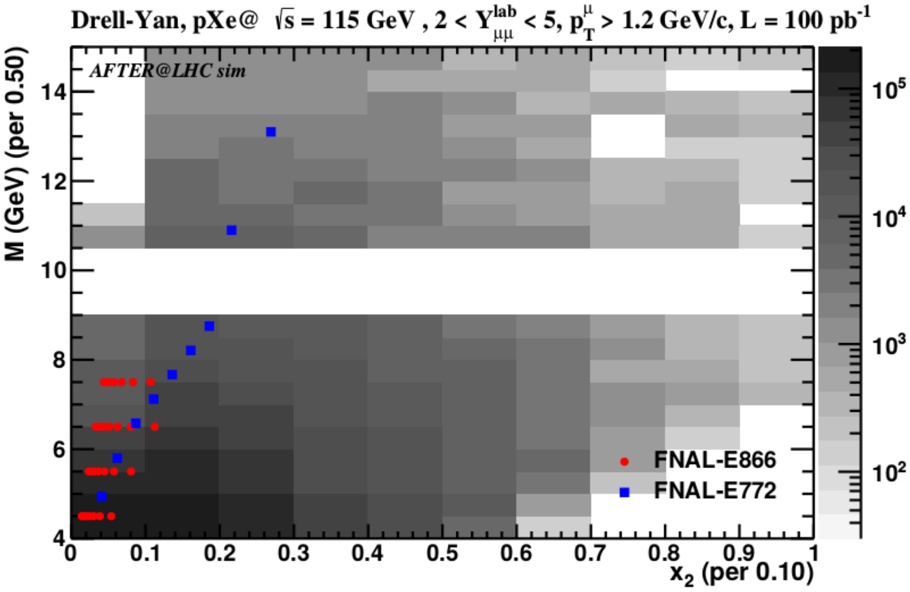
*) There are also other CNM effects in R_{pA}

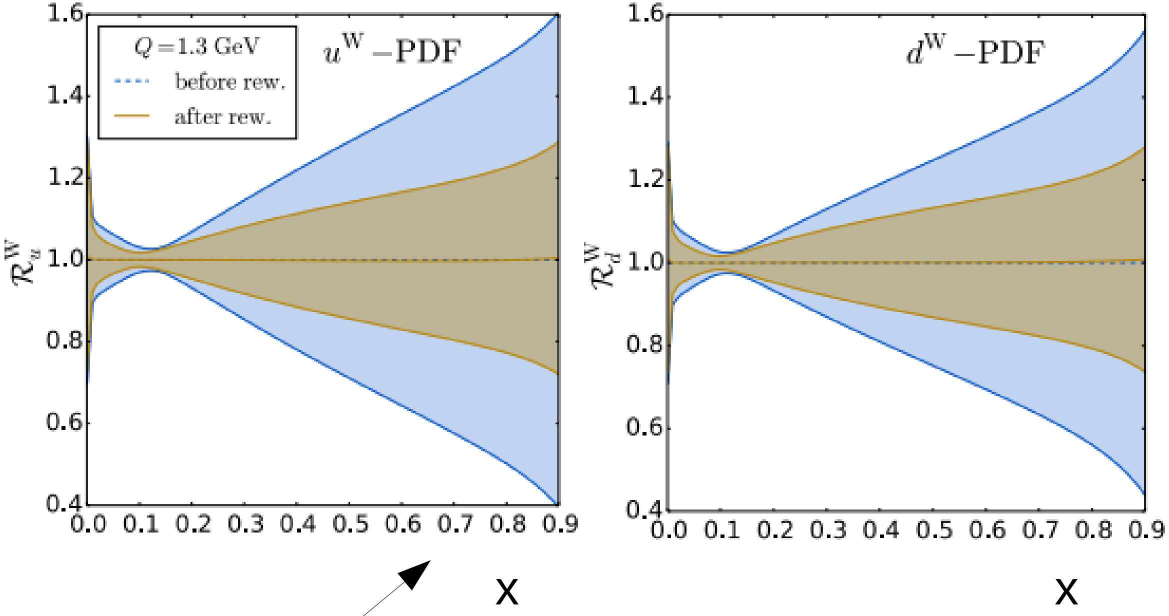


Constraining quark nPDF with Drell-Yan

Large Drell-Yan yields, wide kinematic reach ($x_2 \rightarrow 1$), various targets

LHCb-like





Few Body Syst. 58 (2017) no.4, 139

Expected improvement with AFTER@LHC data

Also: ideal test of the extrapolation of initial state effects in pA to AA

Status and summary

- Reach and unique physics program: **large-x frontier, heavy-ion collisions, spin physics program at the LHC**
- A fixed-target program at the LHC can be implemented without interfering with the other experiments
- Topic of the Physics Beyond Collider study http://pbc.web.cern.ch/ → **LHC fixed target** working group
- Ongoing feasibility studies for FT collisions with ALICE and LHCb detectors
- AFTER@LHC Study Group: http://after.in2p3.fr

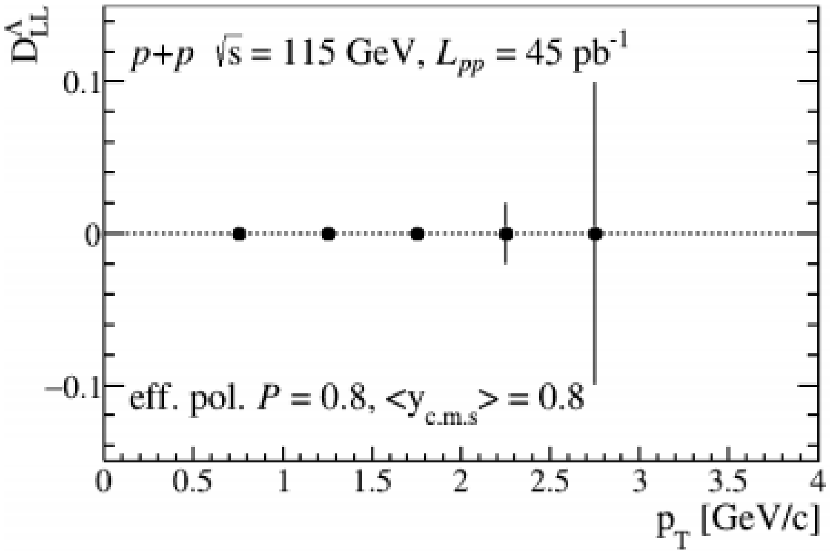
Backup

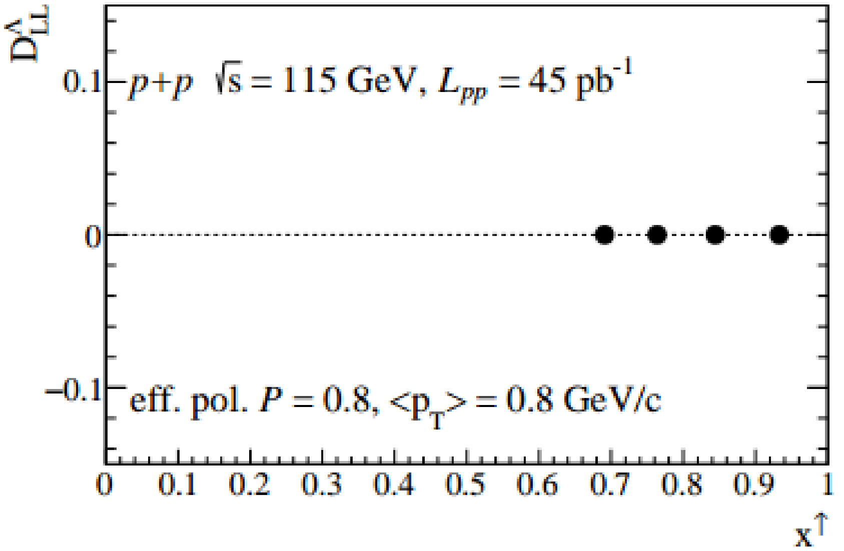
Longitudinal spin transfer D_{LL} to Λ baryons

- Unique rapidity coverage with the ALICE central barrel
- Access to the strange quark polarized PDF at $x \to 1$

$$D_{LL} \equiv \frac{\sigma_{pp^+\to\Lambda^+} - \sigma_{pp^+\to\Lambda^-}}{\sigma_{pp^+\to\Lambda^+} + \sigma_{pp^+\to\Lambda^-}}$$

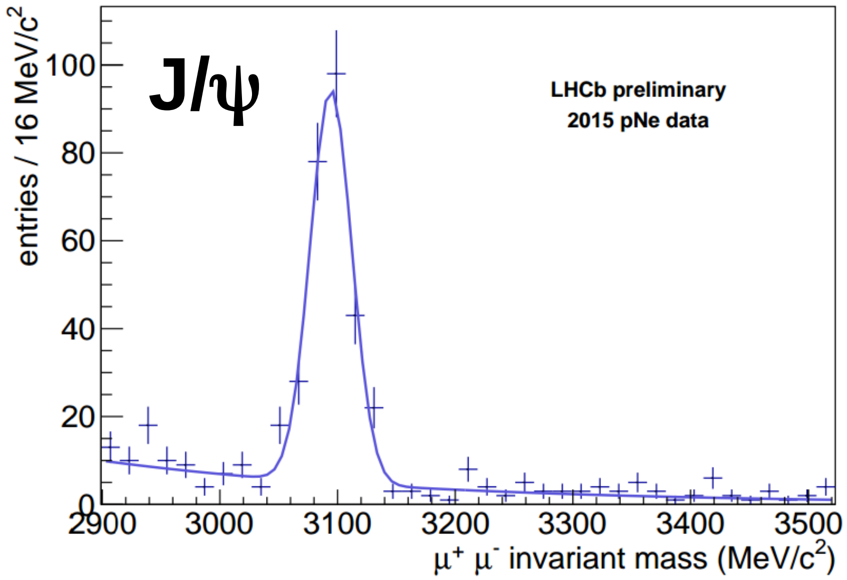
ALICE-like, $Z_{target} \sim 0$

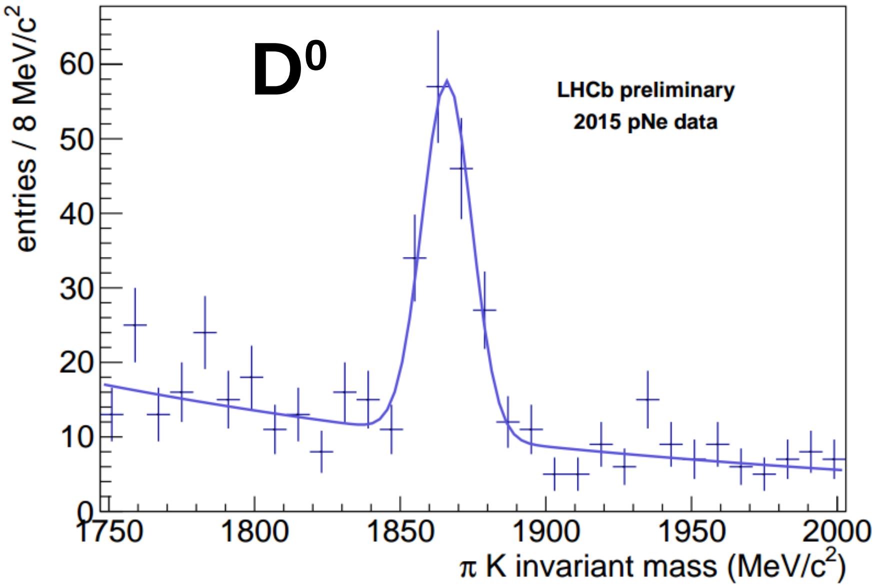




New idea for measurements with the ALICE det.

SMOG-LHCb: the perfect demonstrator



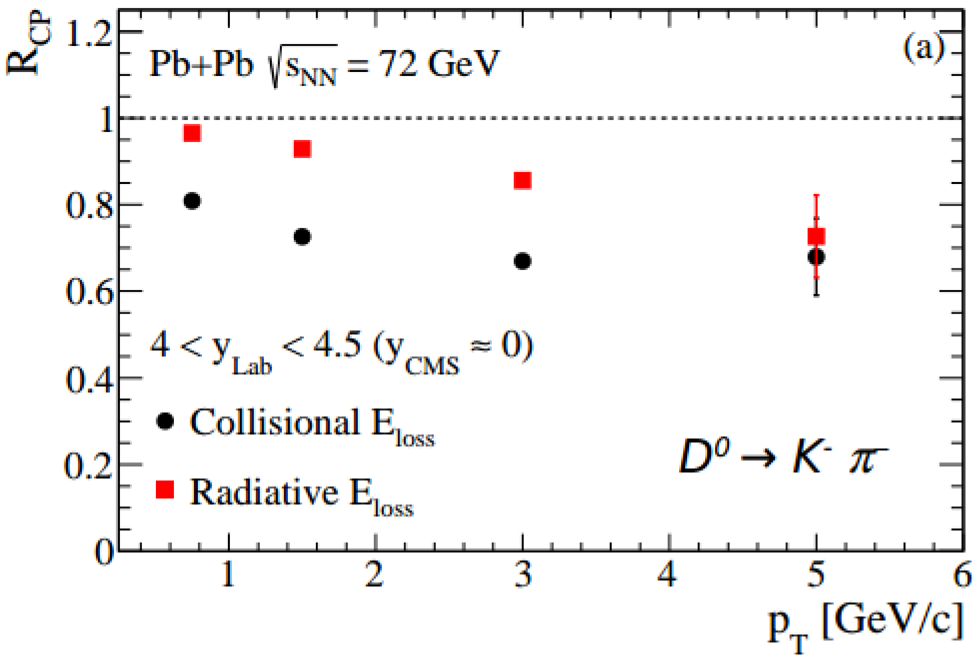


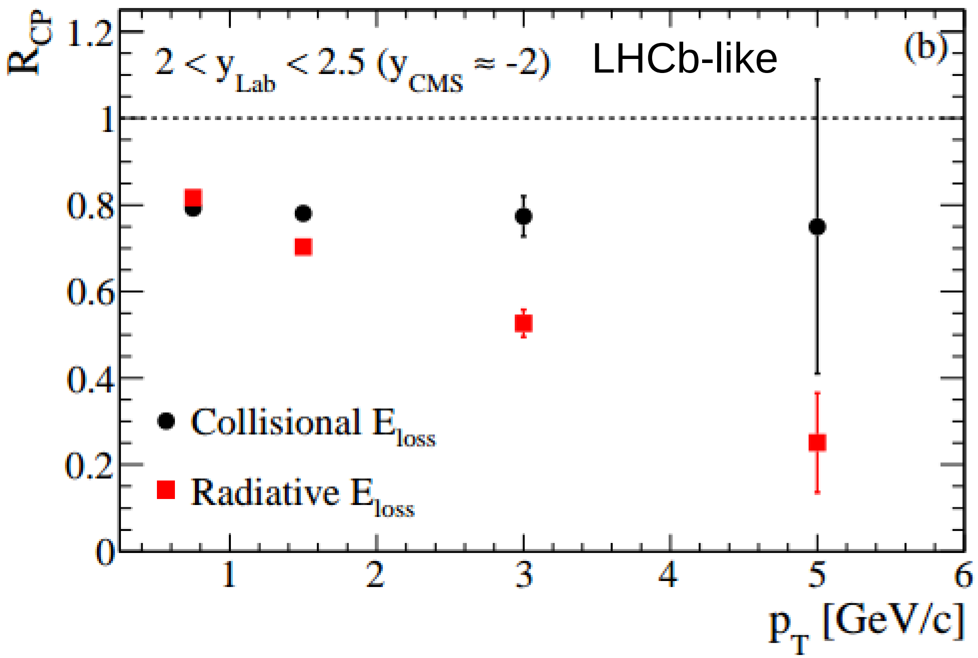
Successful p+Ne, p+Ar, p+He, Pb+Ar data taking, good resolution, low BG

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

https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

Open Heavy Flavour in Heavy Ion collisions





R_{AA} vs y and p_T → insight into charm E_{loss}

Energy loss based on: J. Aichelin, P. B. Gossiaux, and T. Gousse Journal of Physics: Conference Series, vol. 455, no. 1, Article ID 012046, 2013

Advances in High Energy Physics, Volume 2015 (2015), Article ID 783134

Available Luminosities

Technical Solution	Beam type	Target type	θ_{target} (cm^{-2})	$\mathcal{L}$ ($cm^{-2}.s^{-1}$)	$\mathcal{L}_{int}$ (pb^{-1}/year)
Gas-Jet Target	p	H↑	1.2×10^{12}	4.3×10^{30}	43
	p	H_2	10^{15} - 10^{16}	3.6×10^{33} - 3.6×10^{34}	36×10^{3} - 36×10^{4}
	Pb	H↑	1.2×10^{12}	5.6×10^{26}	0.56×10^{-3}
	Pb	H_2	10^{15} - 10^{16}	4.7×10^{29} - 4.7×10^{30}	0.47 - 4.7
Storage-Cell Target	p	H↑	2.5×10^{14}	9.2×10^{32}	9200
	p	Xe	6.4×10^{13}	2.3×10^{32}	2300
	Pb	H↑	2.5×10^{14}	1.2×10^{29}	0.120
	Pb	Xe	6.4×10^{13}	3.0×10^{28}	0.030
Bent Crystal + Solid Target	p	Pb	1.6×10^{22}	8.2×10^{30}	82
	Pb	Pb	1.6×10^{22}	1.6×10^{27}	1.6×10^{-3}

L. Massacrier et al, EPJ Web Conf. 171 (2018) 10001

FT Luminosities comparable with nominal LHC luminosities

Physics opportunities in AFTER @ LHC

Physics opportunities of a fixed-target experiment using LHC beams

Physics Reports 522 (2013) 239

Ideas for a fixed target experiment at LHC in a Special Issue in Advances in High Energy Physics:

Advances in High Energy Physics, Volume 2015 (2015)

- **Heavy-ion physics**
- **Exclusive reactions**
- **Spin physics studies**
- **Hadron structure**
- **Feasibility study and technical ideas**

SMOG-LHCb data

p+Ne pilot run at $\sqrt{s_{NN}}$ = 87 GeV (2012) ~ 30 min

Pb+Ne pilot run at $\sqrt{s_{NN}}$ = 54 GeV (2013) ~ 30min

p+Ne run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 12h

p+He run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 8h

p+Ar run at $\sqrt{s_{NN}}$ = 110 GeV (2015) ~ 3 days

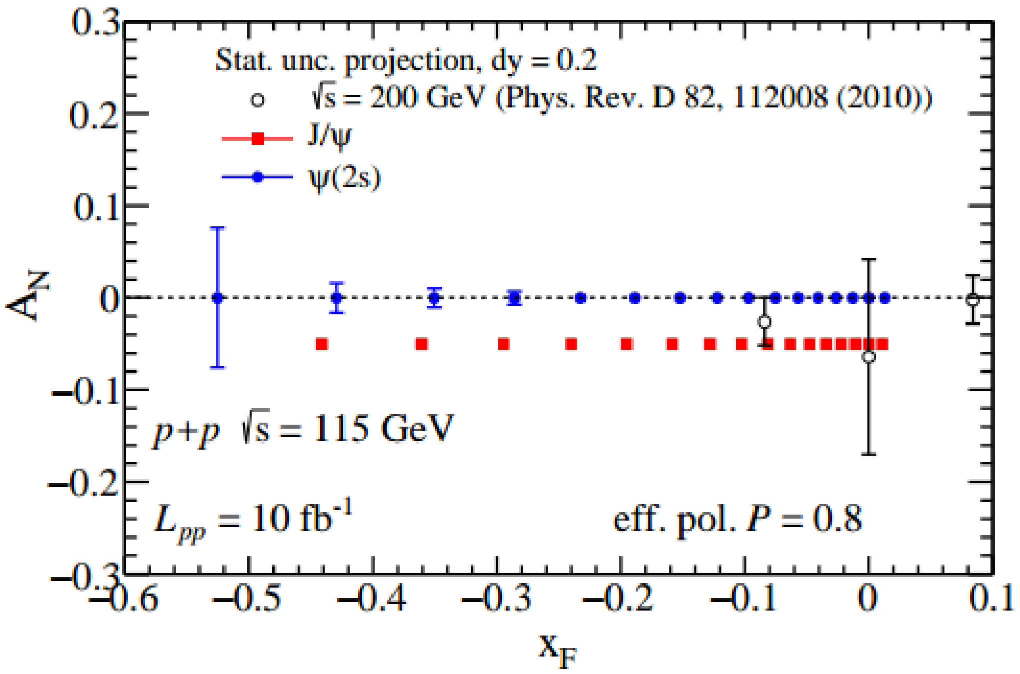
p+Ar run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ few hours

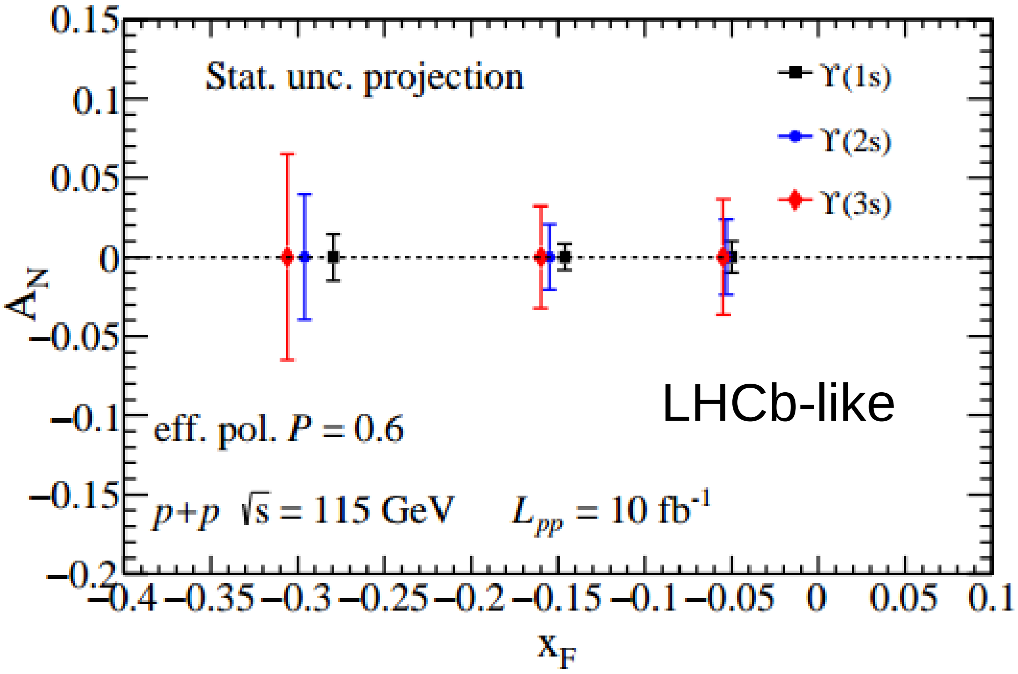
Pb+Ar run at $\sqrt{s_{NN}}$ = 69 GeV (2015) ~ 1.5 week

p+He run at $\sqrt{s_{NN}}$ = 110 GeV (2016) ~ 2 days

J/ψ and ϒ in p+p

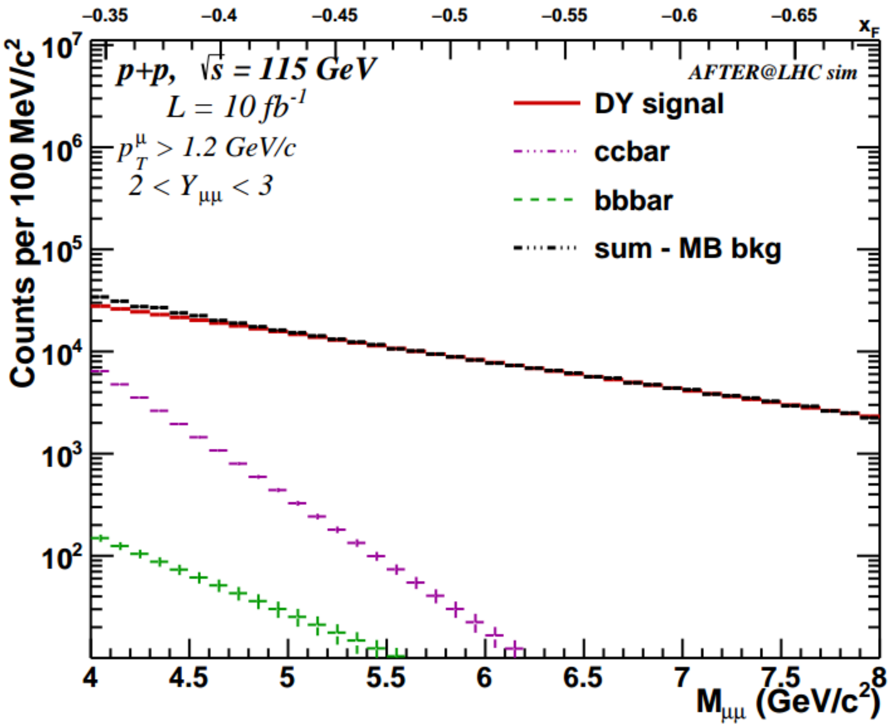
- Typically 10^9 charmonia, 10^6 bottomonia per year
- Unique access to C-even quarkonia ($\chi_{c,b}$, η_c) + associated production
- A_N for all quarkonia (J/ψ, ψ', χ_c , ϒ(nS), χ_b & η_c) can be measured

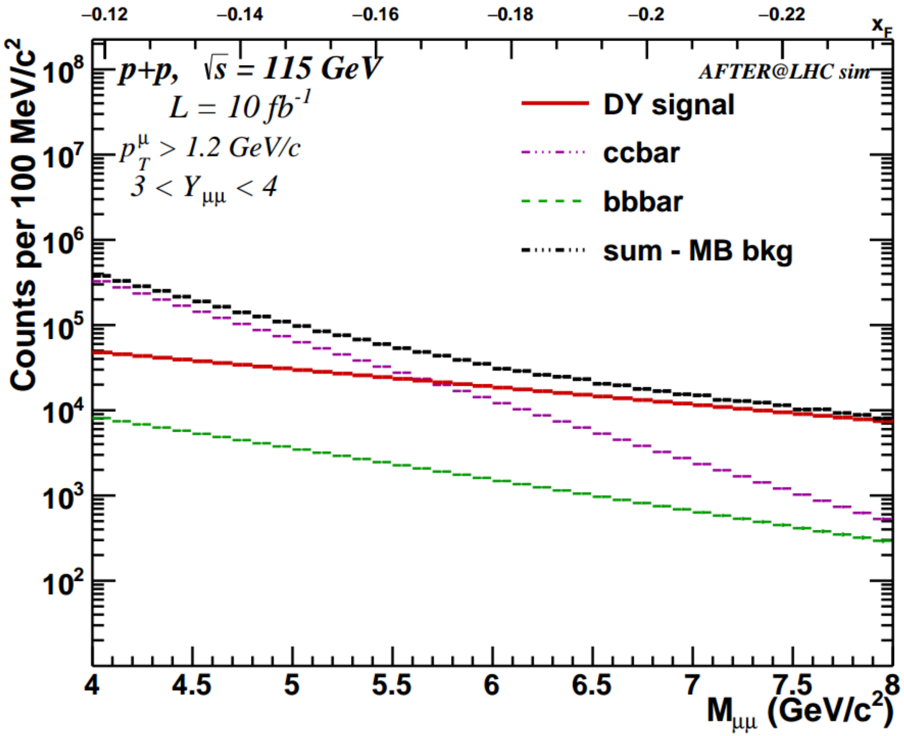




Drell-Yan production

LHCb-like



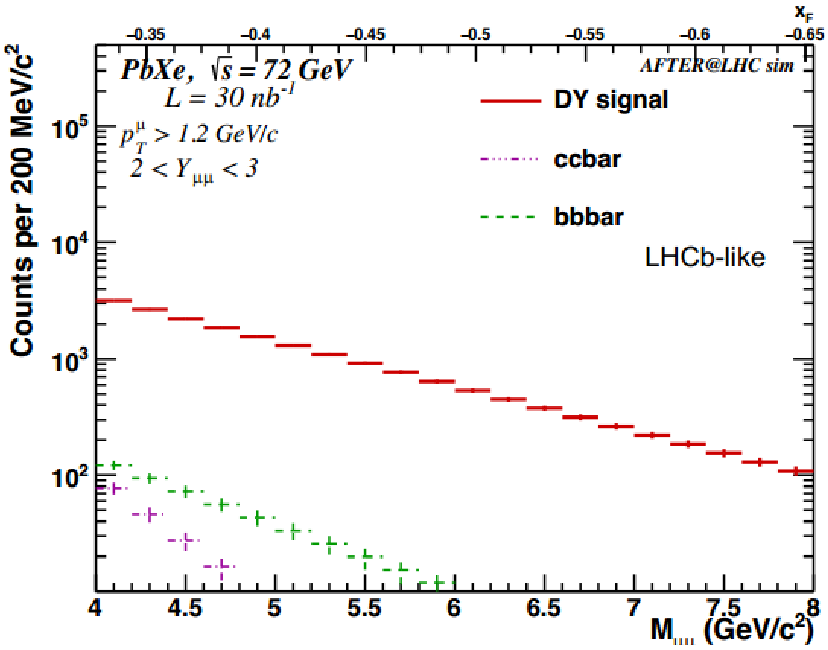


Test o factorization of initial state effects in A+A

Drell Yan:

Few Body Syst. 58 (2017) no.4, 139

- initial state production, not significant interaction with nuclear medium
- ideal test of the extrapolation of initial state effects in pA to AA



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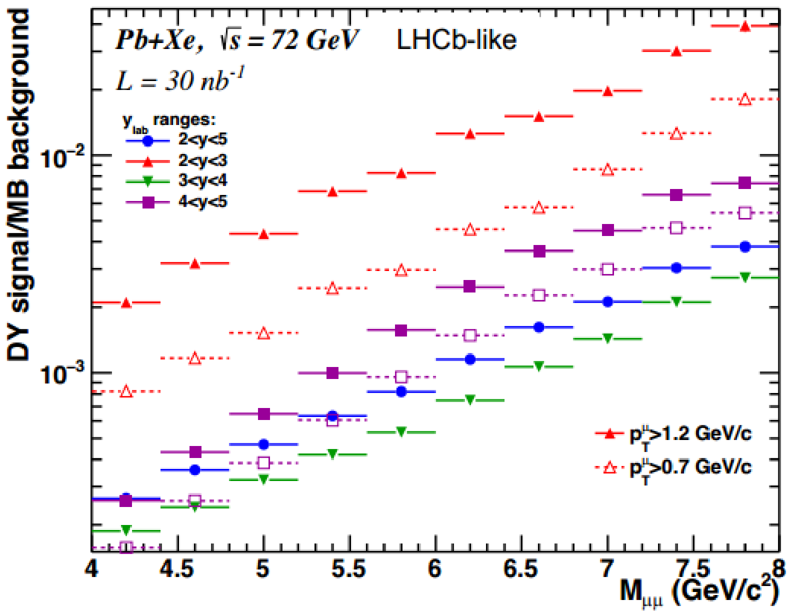
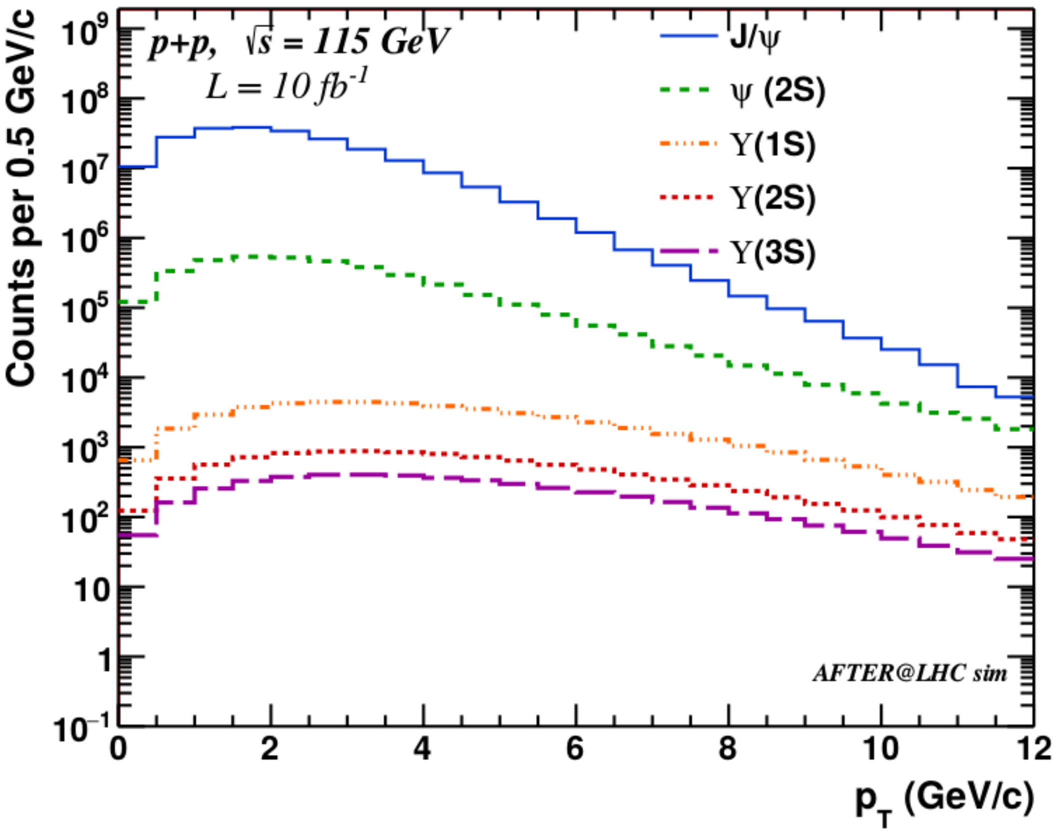


LHCb-like

J/ψ and Υ yields

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

LHCb-like



Adv. High Energy Phys. 2015 (2015) 986348

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

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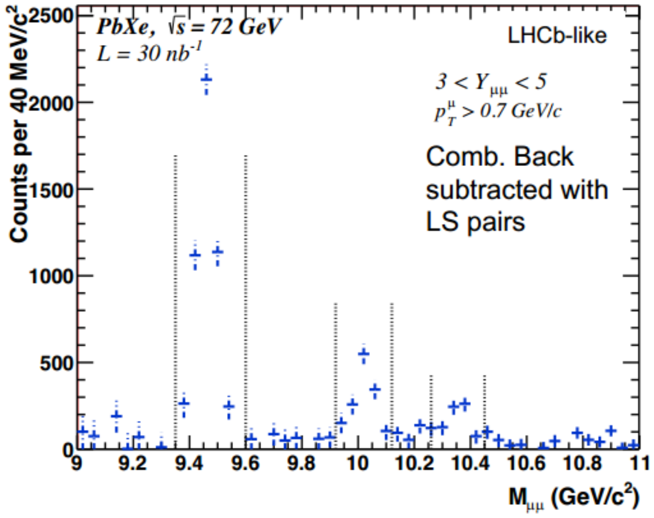
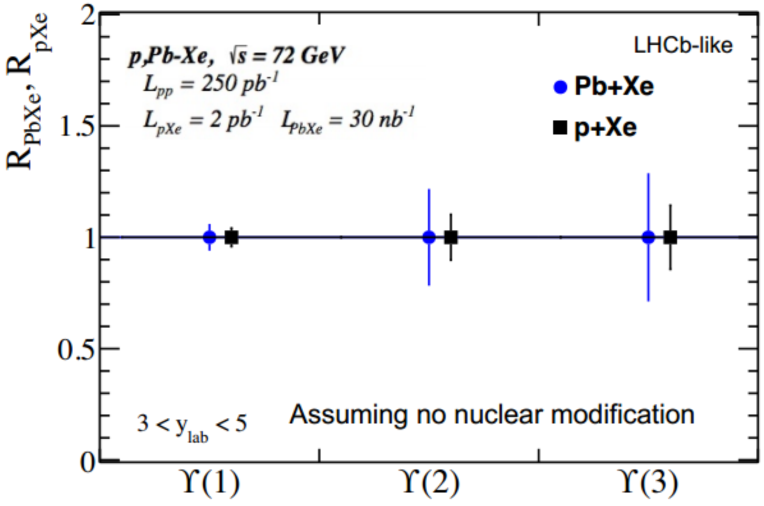
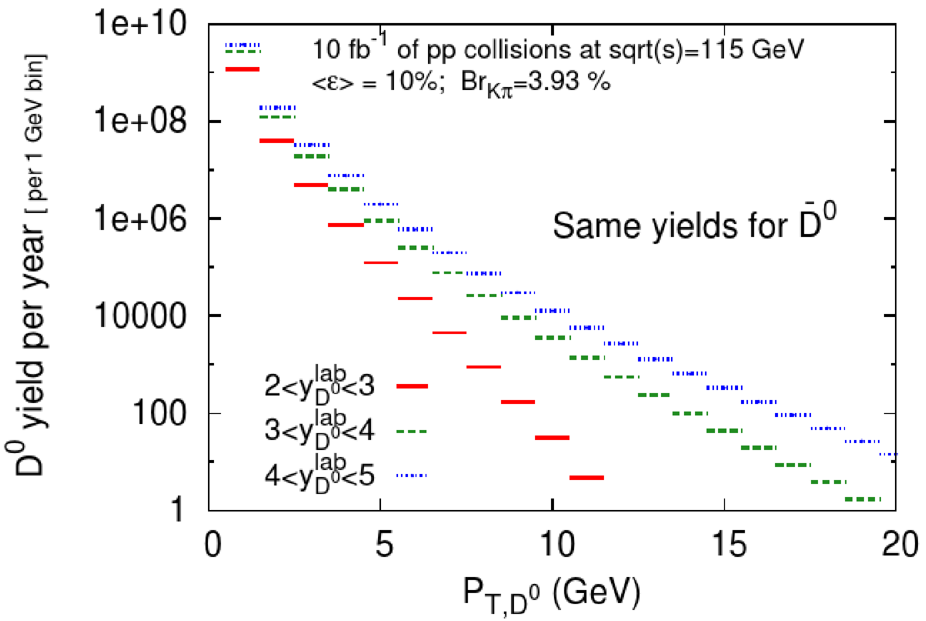




Yields		signal	S/B
$\Upsilon(1S)$	pp	1.33×10^3	29.0
	pXe	1.39×10^3	7.8
	PbXe	4.33×10^3	1.8×10^{-1}
$\Upsilon(2S)$	pp	2.92×10^2	8.2
	pXe	3.06×10^2	2.2
	PbXe	9.56×10^2	5.0×10^{-2}
$\Upsilon(3S)$	pp	1.37×10^2	10.3
	pXe	1.44×10^2	2.8
	PbXe	4.49×10^2	6.2×10^{-2}

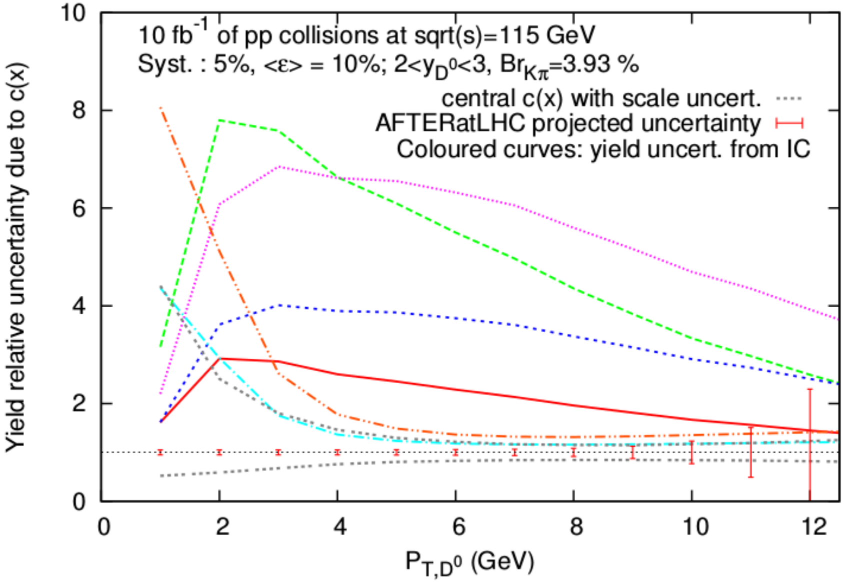
LHCb-like

Open Heavy Flavour simulations



$$D^0 \rightarrow K^- \pi^+$$

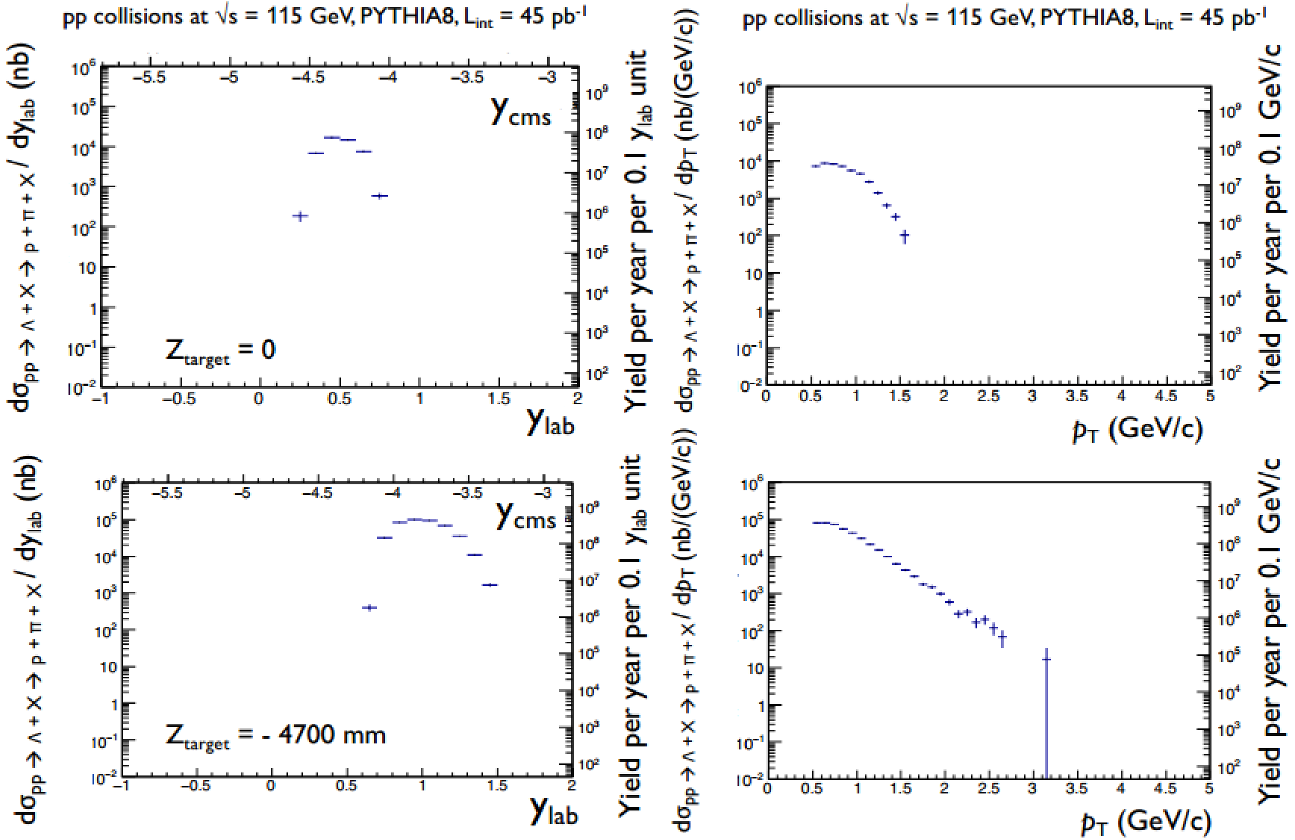
- Huge yields
- Charm measured down to 0 p_T
- Measure the intrinsic charm in proton



STRANGENESS SIMULATED PERFORMANCE

ALICE

- Strangeness in the central barrel (Λ production)



- Pythia8 minbias simulation, pp collisions, $\sqrt{s}$ = 115 GeV
- L_{int} = 45 pb^{-1} with polarised H (1 year of data taking)
  Additional factor 10 if unpolarised H_2
- 10 x 10^6 events generated
- PID &Tracking inefficiencies + decay product geometrical acceptance not accounted for
- Pseudo-rapidity of the Λ within TPC (IROC only) + TOF coverage
- $p_T(\Lambda)$ > 0.5 GeV/c

Very large yields of Λ produced in the central barrel acceptance (to be converted into an uncertainty on D_{LL})

*caveat the tracking performances of the TPC and effect of material budget for large negative Z has still to be studied

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L. Massacrier, Physics Beyond Colliders annual workshop, CERN, 2017, https://indico.cern.ch/event/644287/contributions/2724478/