Proposed fixed target experiment at the LHC beams.

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Institute for Nuclear Research, RAS
for AFTER@LHC study group

1. Fixed target proposal.
2. Physical motivation.
3. Experimental situation.
4. Summary.

1. Proposal of fixed target experiments at the LHC

1. **Fixed-target experiment with wire target at the LHC— energy between SPS and RHIC was proposed in 2005 and then in 2009 at CERN Workshop "New opportunities at CERN" by INR RAS.**

   A.B.Kurepin, N.S.Topilskaya, M.B.Golubeva

   Charmonium production in fixed-target experiments with SPS and LHC beams at CERN.
   Phys.Atom.Nucl.74:446-452, 2011, Yad.Fiz.74:467-473, 2011.

2. **Then proposal of experiment AFTER@LHC (A Fixed Target ExpeRiment at the LHC).**

   S.J.Brodsky, F.Fleuret, C.Hadjidakis and J.P.Lansberg

   Physics Opportunities of a Fixed-Target Experiment using the LHC Beams
   Phys. Rept. 522 (2013) 239

3. **Experiment started at LHCb with low density gas target (SMOG)**

4. **J.-P.Lansberg et al., Special issue " Advances in High Energy Physics 2015 (2015)"**

Physics at a Fixed-Target Experiment Using the LHC Beams

Study and physical ideas

The Gluon Sivers Distribution: Status and Future Prospects, D.Boer et al., ID 371396

Transverse Single-Spin Asymmetries in Proton-Proton Collisions at the AFTER@LHC Experiment in a TMD Factorization Scheme, M.Anscelmino et al., ID 475040

A Gas Target Internal to the LHC for the Study of *pp* Single-Spin Asymmetries and Heavy Ion Collisions, C.Barschel et al., ID 463141

Quarkonium Production and Proposal of the New Experiments on Fixed target at the LHC, A.B.Kurepin and N.S.Topilskaya, ID 760840

Feasibility Studies for Quarkonium Production at a Fixed-Target Experiment Using the LHC Proton and Lead Beams (AFTER@LHC), I.Massacrier et al., ID 986348

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

<http://inspirehep.net/record/1680152>

By C. Hadjidakis et al.. [arXiv:1807.00603 [hep-ex]].

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

Current study group of AFTER@LHC experiment

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2. Physical motivation
Advantages of the fixed target experiment

Four features:

- **accessing the high x,** $[x_F = |p_z| / p_{zmax} \rightarrow 1]$
- **achieving high luminosities**
- **varying the beams and atomic mass of the target**
- **possibility polarizing the target**

Three physics reasons:

- **Heavy-ion physics between SPS&RHIC energies towards large rapidities**
  (Test of factorization of the cold nuclear matter effects from p+A to A+B collisions, study of quarkonia production and suppression depending on the phase transition of matter to quark-gluon phase)
- **High –x gluon, antiquark and heavy quark content in the nucleon&nucleus**
  (Very large PDF uncertainties for x>0.5,could be crucial to characterize possible BSM discoveries)
- **Transverse dynamics and spin of quarks/gluons inside (un)polarized nucleon**
  (Possible missing contribution to the proton spin from quark/gluon orbital angular momentum)

All this can be realized at CERN without disturbing other experiments at the LHC with the beams of highest energy and luminosities

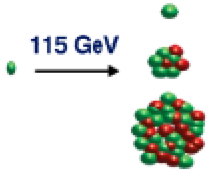
Note, that all accelerators with energy E_p > 100 GeV now have fixed target program: (Tevatron, HERA, SPS, RHIC)

Fixed target experiment at the LHC: main kinematical features

Energy range

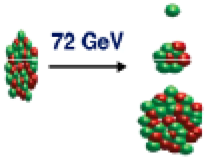
7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\mathrm{GeV}$	Rapidity shift: $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	



2.76 TeV Pb beam on a fixed target

c.m.s. energy:	$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72\,\mathrm{GeV}$	Rapidity shift: $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	

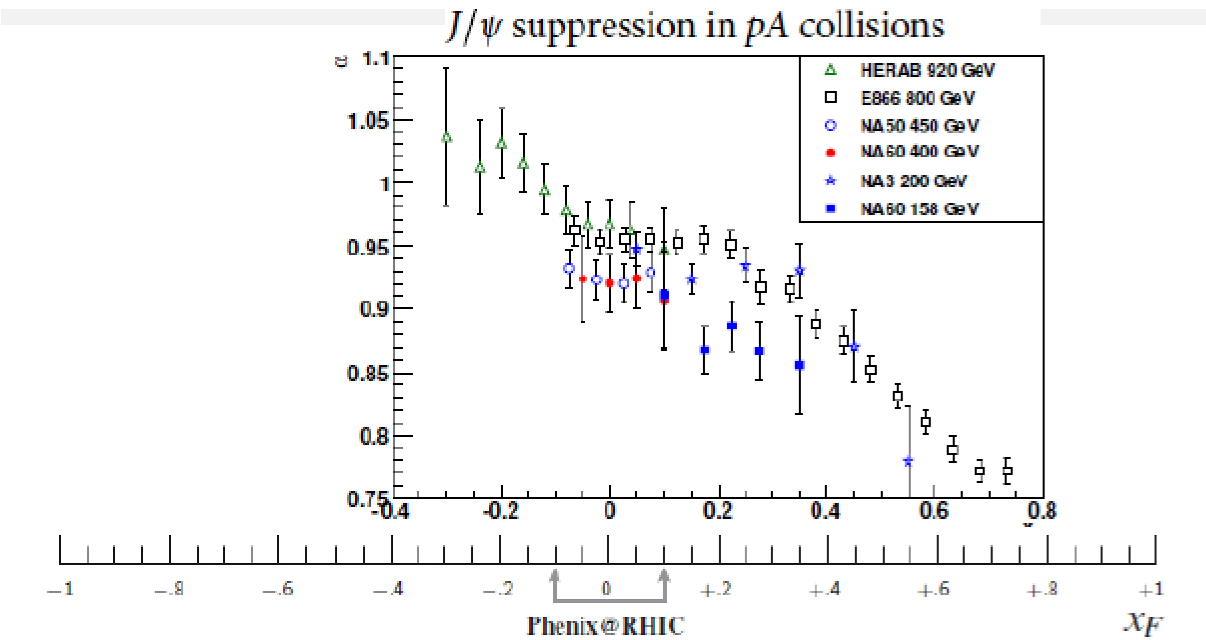


Such energies allow systematic studies of spin physics, heavy ion physics, quarkonia production and p_T spectra, associated production and W - boson production in a fixed target mode .

- **ALICE and LHCb become backward detectors (y_{cms} <0)**
- **acceptance for physics grows and for most probes covers ($-1 < x_F < 0$)**
- **allows for backward physics access to high target x (most relevant for p-p↑)**

The new target rapidity region

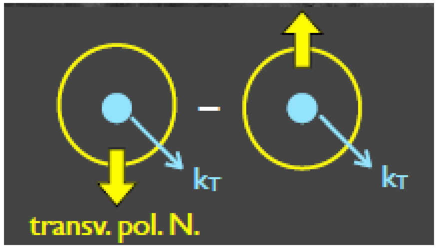
The first systematic access to the target rapidity region $x_F \rightarrow -1$



- **CMS/ATLAS : $|x_F| < 5 \cdot 10^{-3}$; LHCb, ALICE: $< 5 \cdot 10^{-3} < x_F < 4 \cdot 10^{-2}$**
- **fixed target : $x_F \approx -1$ if measure Υ at y_{cms} =-2.5**

Spin physics in AFTER@LHC

The orbital angular momentum (OAM) of the quarks and gluons



- Missing knowledge on the contribution of the orbital angular momentum (OAM) L_g and L_q to the proton spin

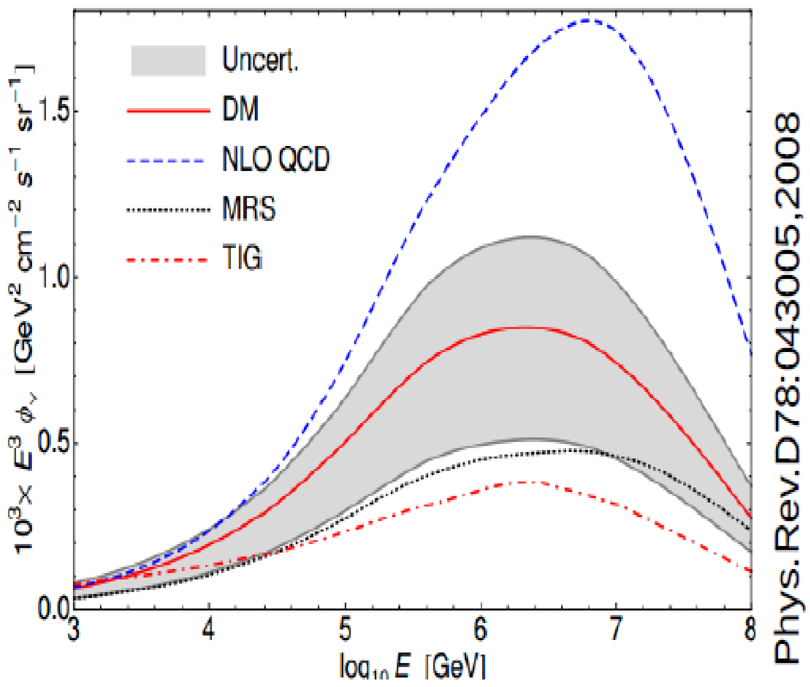
- In fixed-target experiment it is **possible to use polarized target**.
- The polarization can be longitudinal and transverse.
- Single Transverse Spin Asymmetries connected with the correlations between parton k_T and the proton spin
  → information about orbital motion of partons in the proton

- Quark/Gluon Sivers function : distortion in the distribution of an unpolarized partons with momentum fraction x and transverse momentum $k_\perp$ due to the proton transverse polarization: $f^{\perp}_{1T}(x, k_\perp^{2})$
- First sugested by D.Sivers to explain the large observed left-right single transverse spin asymmetries A_N in $p\uparrow p \to \pi X$
- Non-zero quark/gluon Sivers function → non-zero quark/gluon OAM

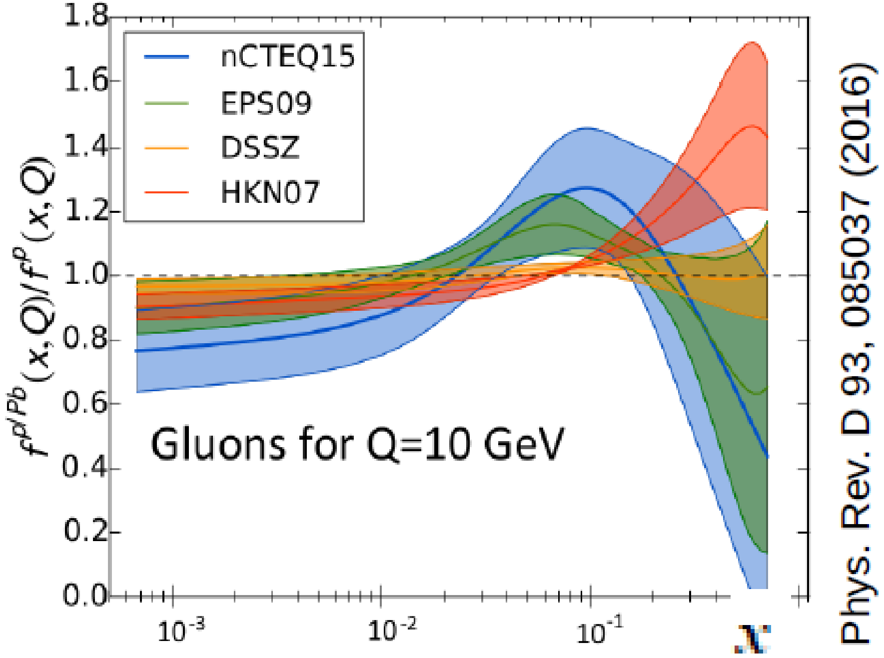
High-*x* frontier

- High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus
- Help to reduce uncertainties on PDFs, astrophysics calculations

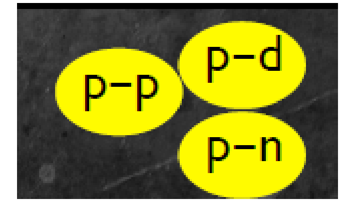
Energy spectrum of neutrino flux



Gluon nuclear PDFs



The gluon PDF



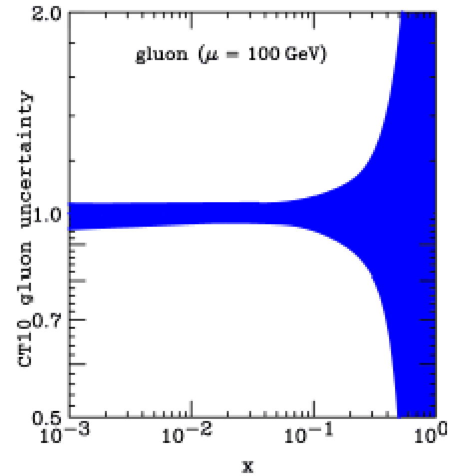
- Gluon distribution at high and ultra-high x_B in the
  - proton
  - **neutron** (via deuteron target)

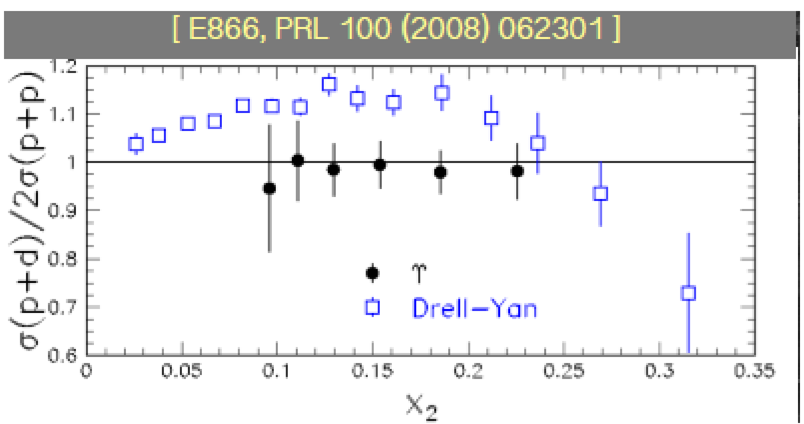
Gluon PDF for **neutron** – experimentally unknown
Gluon PDF at high x – large uncertainties for **proton**

Need high luminosity to reach high x

Experimental probes :

- heavy quarkonia (gg fusion at high energy)
- isolated photons (gq fusion)
- high p_T jets (p_T >20 GeV)



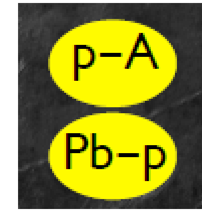


Was measured by E866 Fermilab

- using ϒ
- at Q^2~100 GeV^2 similar gluon distribution in proton and neutron

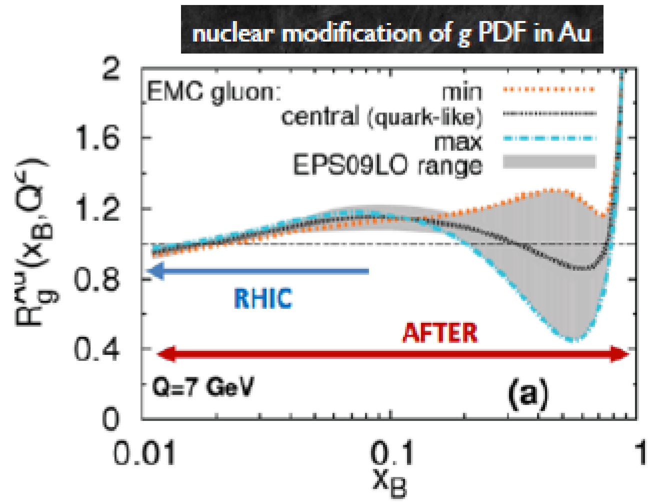
At AFTER@LHC could be extended

- using J/ψ
- to lower x and Q^2
- need high luminosity



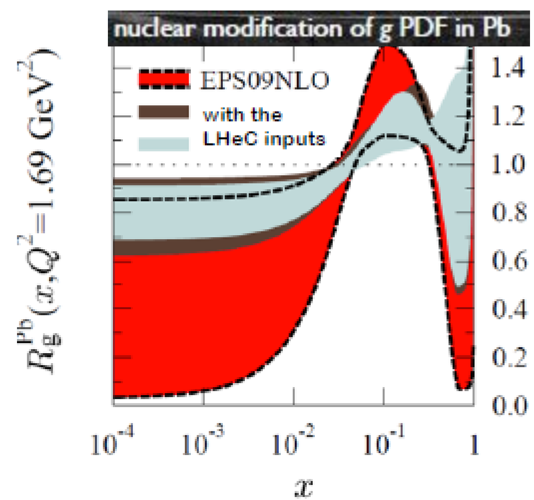
The gluon nPDF

- **A dependence** with target versatility - probing nuclear matter effects and shadowing
- **nuclear PDF** from intermediate to high x: antishadowing, EMC region, Fermi motion



Experimental probes for AFTER:

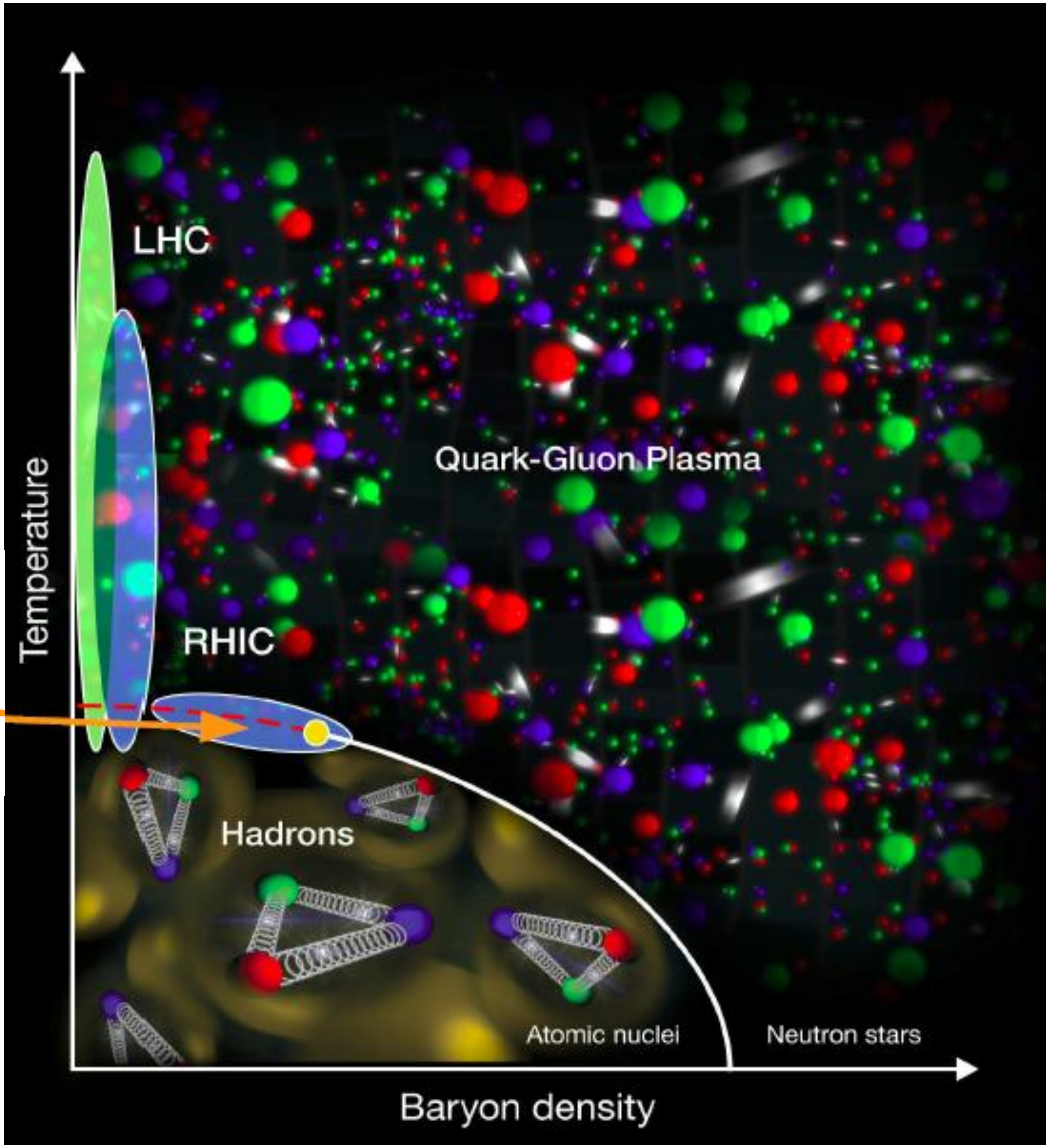
- quarkonia
- isolated photons
- high p_T jets (p_T >20 GeV) – to access target $x_F \approx 0.3$-1



Heavy-ion physics

Heavy-ion collisions at

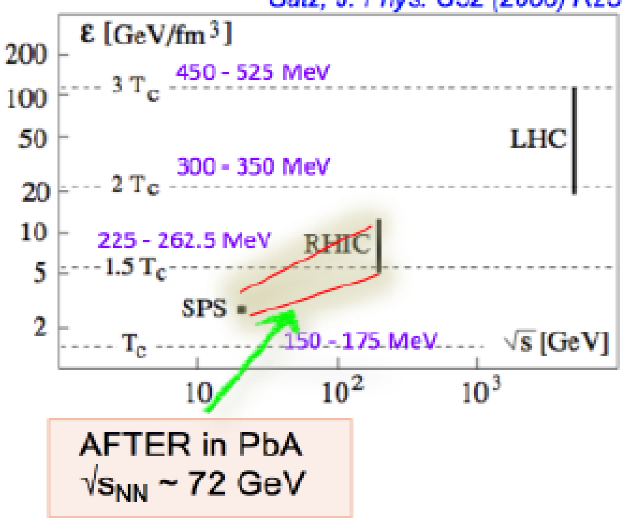
$\sqrt{s_{NN}}$ = 72 -115 GeV



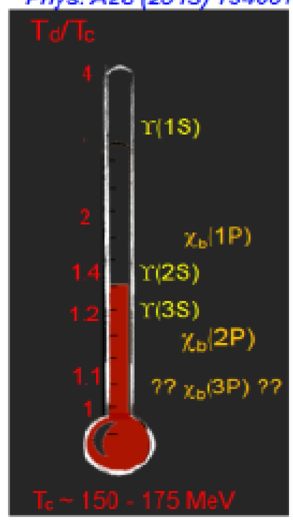
Heavy-ion collisions towards large rapidity

A complete sets of quarkonium studies between SPS and RHIC energies (calibration of quarkonium thermometer (J/ψ, ψ', χ_c, Υ, D, $J/\psi \leftarrow b$ +pairs) in new energy and kinematical ranges , contribution of recombination

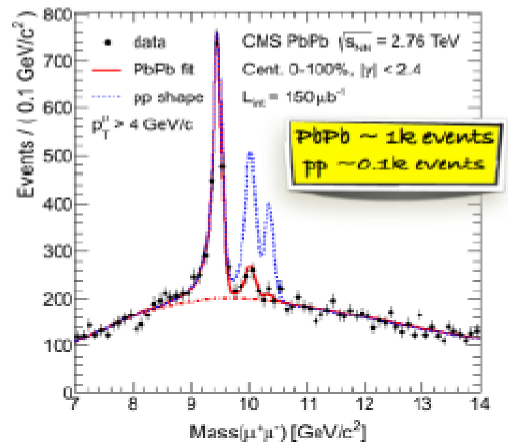
Satz, J. Phys. G32 (2006) R25



Mocsy et al, Int. J. Mod. Phys. A28 (2013) 1340012



Dissociation temperature from lattice QCD (+hydro)



Phys. Rev. Lett. 109 (2012) 222301

Factorization of cold nuclear matter effects from p+A to A+B collisions in new energy and kinematical ranges

3. Experimental situation

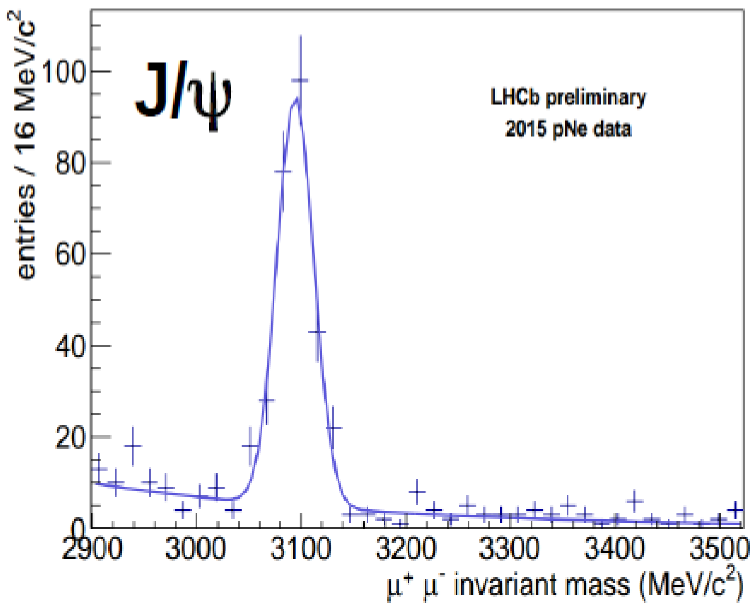
Three possibilities for internal fixed target experiment with existing detectors ALICE or LHCb:

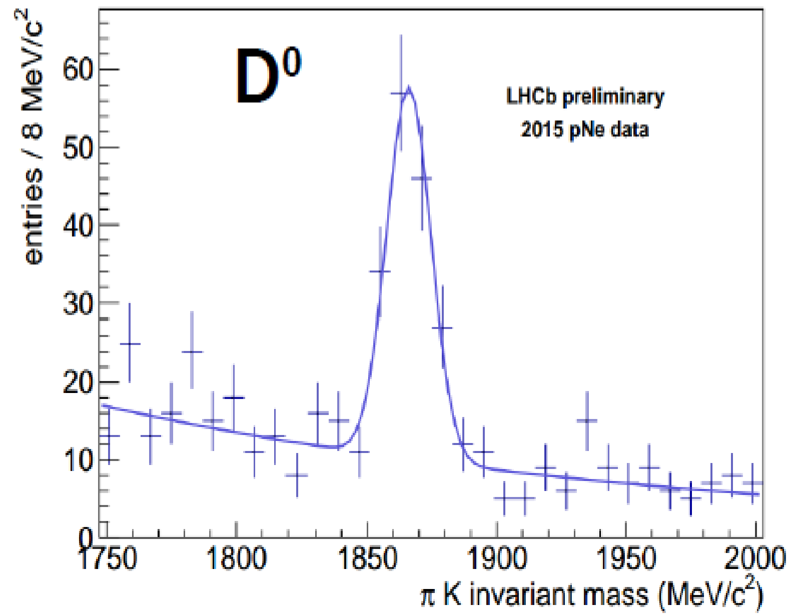
1. **To use extracted with bent crystal part of the beam and then put fixed target**
2. **To put the internal gas target (like SMOG at LHCb) or polarized gas target (HERMES-type system at HERA) and full LHC beam**
3. **To use wire or ribbon target in the beam halo (like HERA-B, STAR)**

or extraction of beam with bent crystal ---new beam line and new experimental system.

At the LHC the possible technical implementation are discussed within the Physics Beyond Collider Fixed-Target working group.
Conveners: S.Redealli and M.Ferro-Luzzi
http://pbc.web.cern.ch

SMOG - LHCb data





No distortion of the other LHC experiments

Successful p+A and A+A data taking, good resolution, low background

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

Fixed-target charmonium data (SPS, FNAL, HERA)

AA collisions
SU, PbPb, InIn

NA38
S-U 200 GeV/nucleon, $0 < y_{cm} < 1$, $\sqrt{s}$=19.4 GeV
NA50
Pb-Pb 158 GeV/nucleon, $0 < y_{cm} < 1$, $\sqrt{s}$=17.3 GeV
NA60
In-In 158 GeV/nucleon, $0 < y_{cm} < 1$, $\sqrt{s}$=17.3 GeV

pA collisions

HERA-B
p-Cu,(Ti),W 920 GeV, $-0.34 < x_F < 0.14$, $\sqrt{s}$=41.6 GeV
E866
p-Be, Fe, W 800 GeV, $-0.10 < x_F < 0.93$, $\sqrt{s}$=38.8 GeV
NA50
p-Be,Al,Cu,Ag,W,Pb 400/450 GeV, $-0.1 < x_F < 0.1$,
$\sqrt{s}$=27.4/29.1 GeV
NA51
p-p, d 450 GeV, $-0.1 < x_F < 0.1$, $\sqrt{s}$=29.1 GeV
NA3, NA38
p-p,Pt, Cu,U 200 GeV, $0 < x_F < 0.6$, $\sqrt{s}$=19.4 GeV
NA60
p-Be,Al,Cu,In,W,Pb,U 158/400 GeV, $-0.1 < x_F < 0.35$,
$\sqrt{s}$=17.3/27.4 GeV

Colliders (RHIC, LHC) data

AA collisions

RHIC CuCu, AuAu $\sqrt{s}$ =39, 62, 130 GeV, 200 GeV
UU $\sqrt{s}$ =193 GeV
LHC PbPb $\sqrt{s}$ = 2.76, 5.02 TeV (max 5.5 TeV)

pA collisions

RHIC pp, dAu $\sqrt{s}$ = 130, 200 GeV
LHC pp $\sqrt{s}$ = 2.76, 7, 8, 13 TeV (max 14TeV)
pPb $\sqrt{s}$ = 5.02 , 8.16 TeV

Fixed target experiment at LHC

AA collisions

Pb-Pb 2.75 TeV/nucleon, $\sqrt{s}$ = 72 GeV

pA collisions

p-A 7.0 TeV , $\sqrt{s}$ = 115 GeV

Quarkonium production at LHC: ALICE, ATLAS, CMS and LHCb .

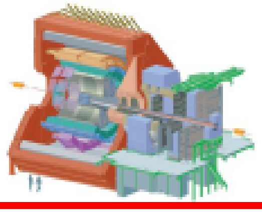
ALICE

$J/\psi \rightarrow \mu^+\mu^-$ $2.5<y<4$

$J/\psi \rightarrow e^+e^-$ $|y|<0.9$

p_T coverage down to $p_T \sim 0$

(up tp now only inclusive J/ψ results)



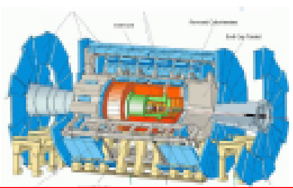
ATLAS

$J/\psi \rightarrow \mu^+\mu^-$ $|y|<2.4$

$p_{T\mu}>3$GeV, $|\eta_\mu|<2.5$

→ p_T $J/\psi>6.5$GeV/c

(separation between B and prompt J/ψ)



CMS

$J/\psi \rightarrow \mu^+\mu^-$ $|y|<2.4$

p_T coverage depending on the y region

(separation between B and prompt J/ψ)

LHCb

$J/\psi \rightarrow \mu^+\mu^-$ $2.5<y<4$

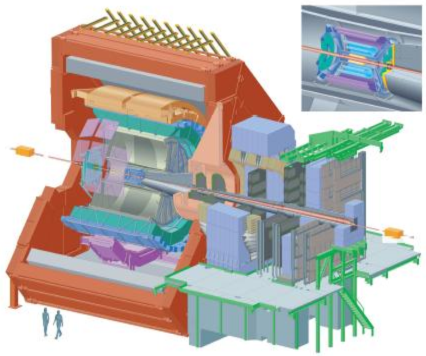
p_T coverage down to $p_T \sim 0$

(separation between B and prompt J/ψ)

(no heavy ion physics program) Now they have HI program

Rapidity shift and kinematical coverage (ALICE case)

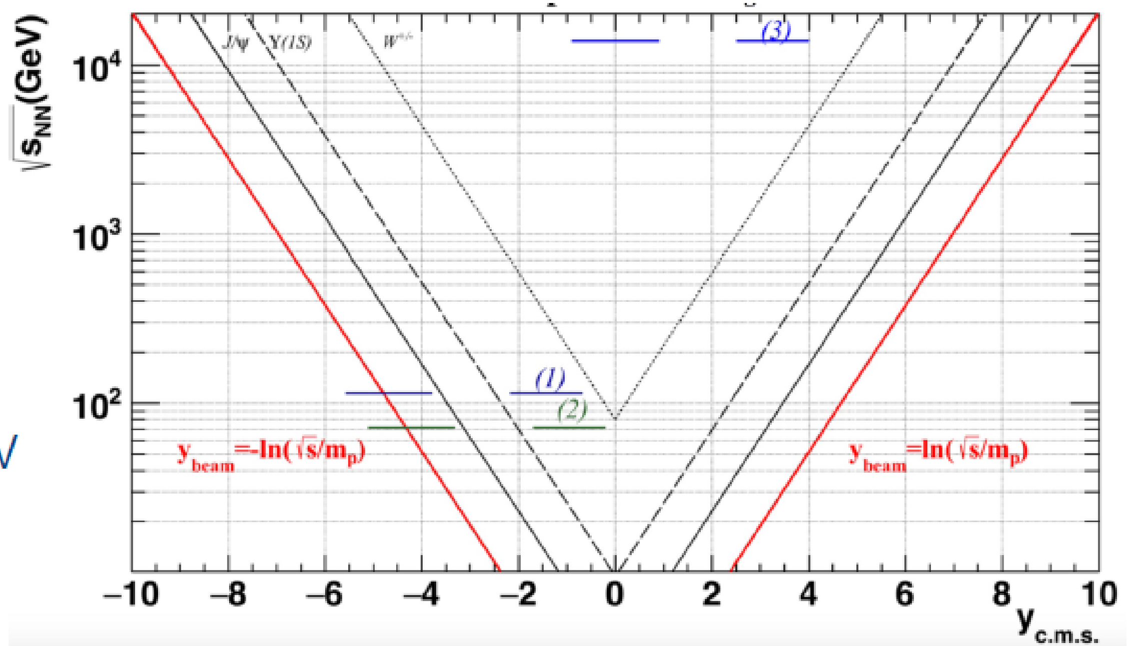
ALICE detector



(1) fixed target, $\sqrt{s_{NN}}$ = 115 GeV

(2) fixed target, $\sqrt{s_{NN}}$ = 72 GeV;

(3) collider mode, $\sqrt{s}$ = 14 TeV;



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

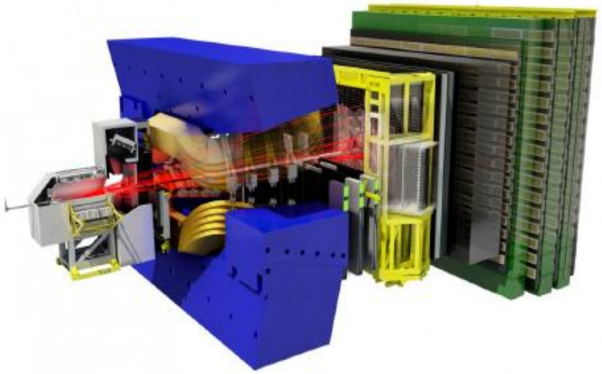
TPC: $|\eta^{lab}| < 0.9$

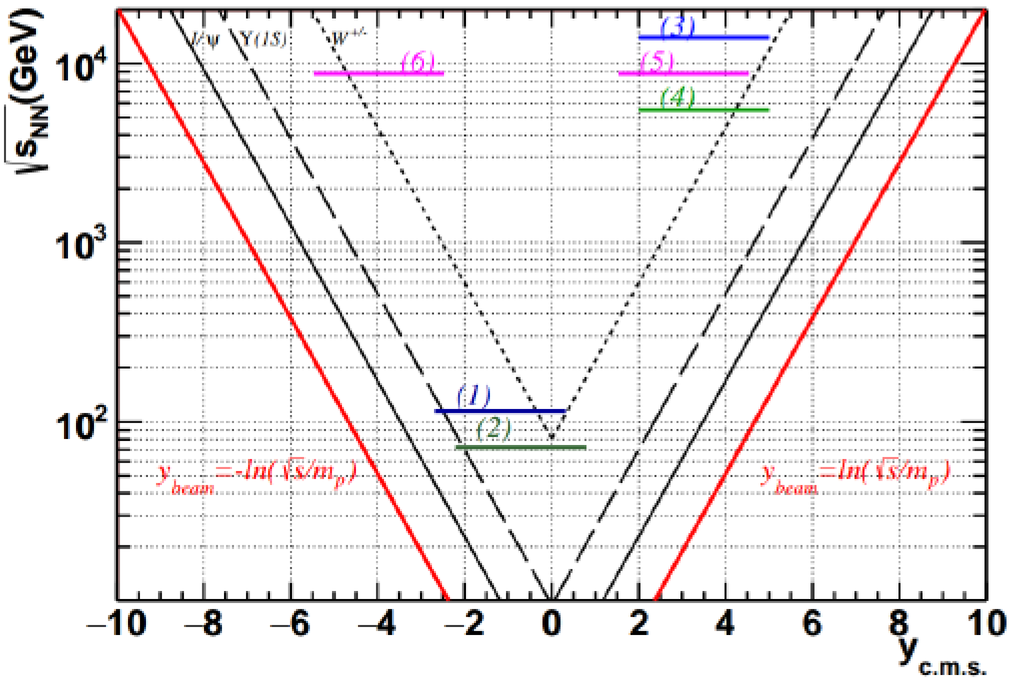
With a forward detector - access mid-to forward rapidity region (y_{cms} <0)

With mid-rapidity detector – probe very backward rapidity region

Rapidity shift and kinematical coverage (LHCb case)

LHCb detector

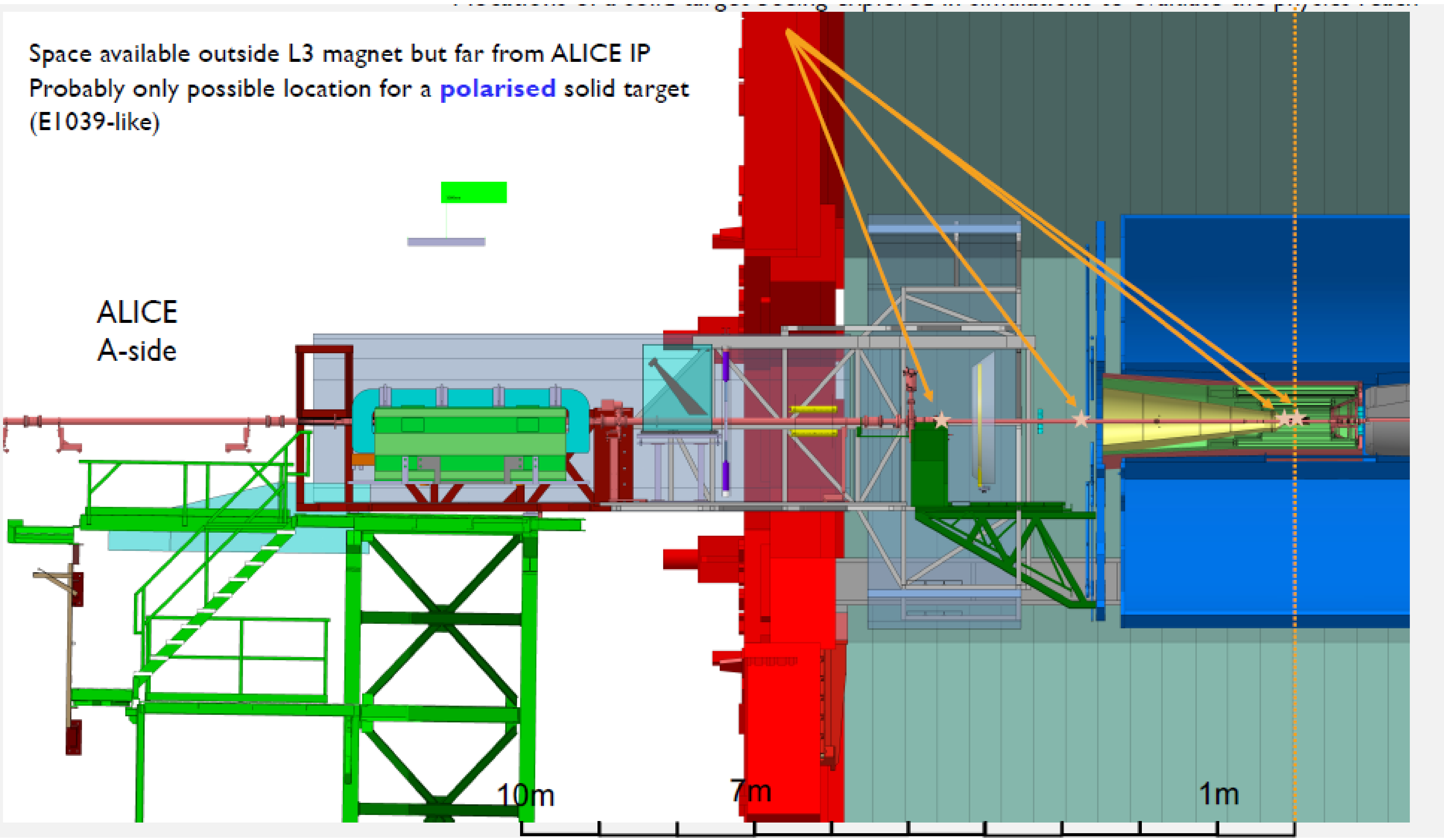




LHCb: $2 < \eta^{lab} < 5$

(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

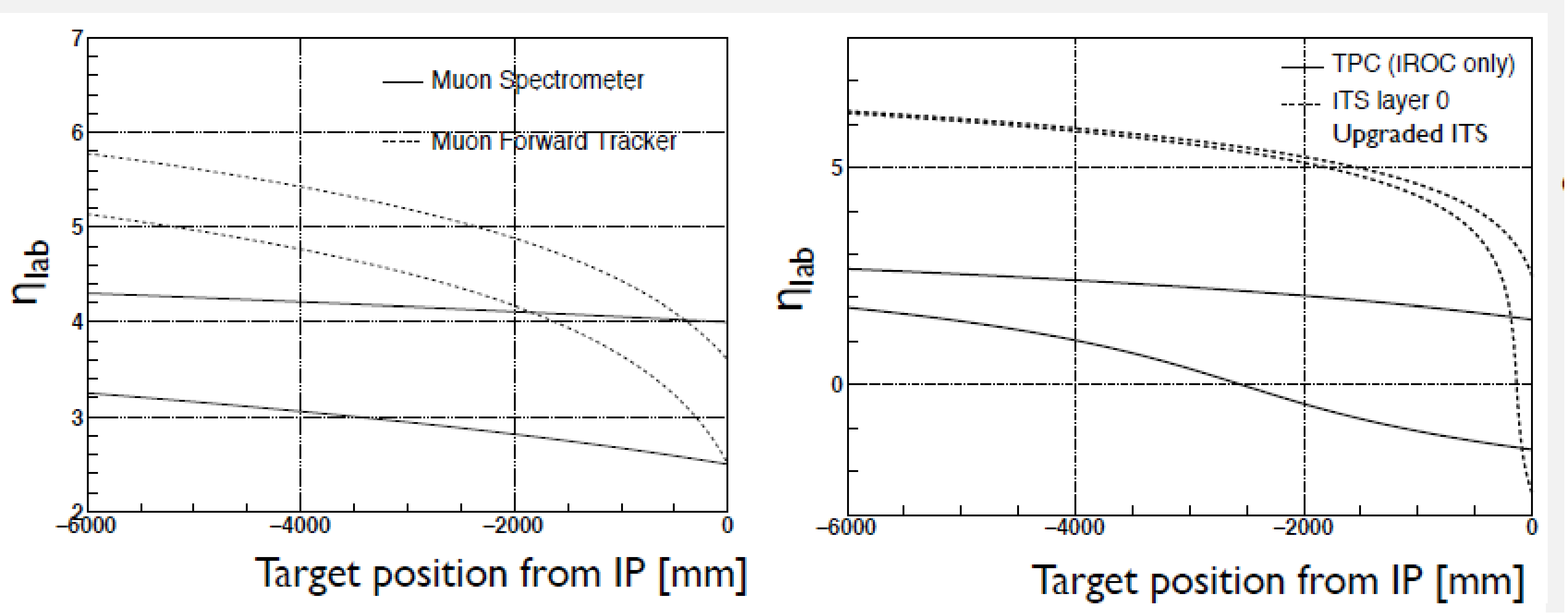
Possible target locations in ALICE



4 locations were simulated (L.Massacrier et al.)

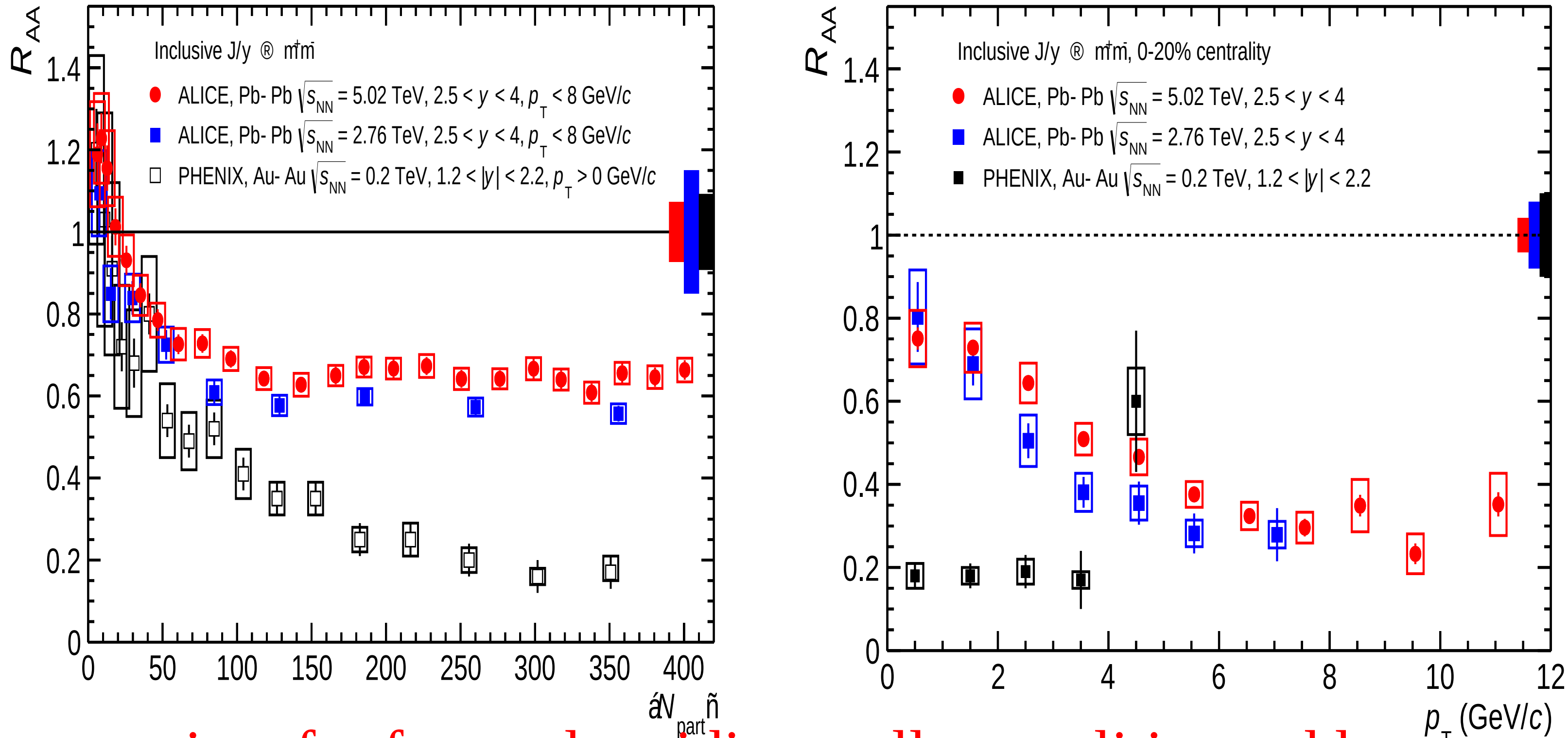
z = 4700, 2750, 135, 0 mm

ALICE acceptance versus z(target)



In target position z<<0 new vertex detector needed **(L.Massacrier)**

R_{AA} in J/ψ production vs number of participant and pt. Comparison of ALICE and PHENIX data.



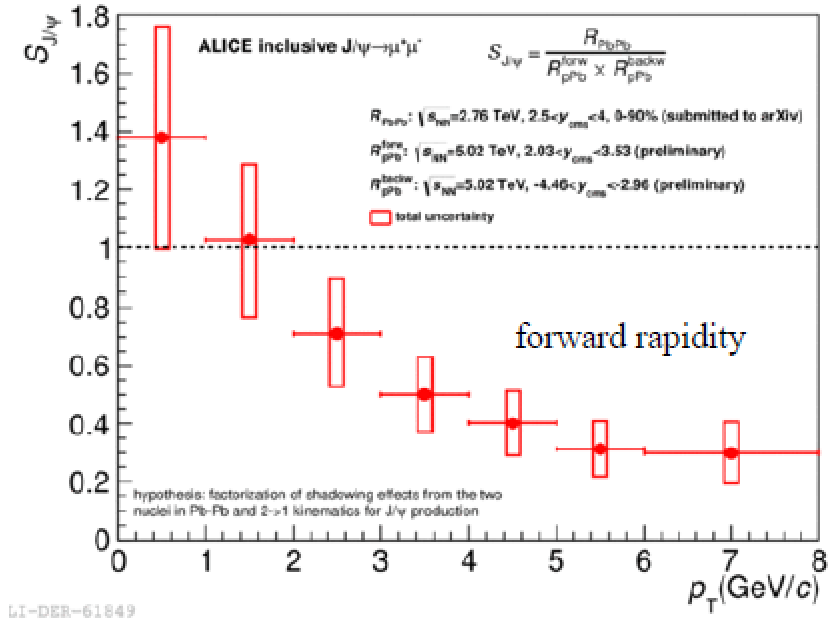
Suppression for forward rapidity at all centralities and low pt at ALICE lower than at PHENIX.

Different behavior between RHIC and LHC data .

Models with all J/ψ produced at hadronization or models including large fraction (>50% in central collisions) of J/ψ produced from recombinations can describe ALICE results.

R_{AA} (PbPb) for forward rapidity vs transverse momentum without shadowing and CNM effects

$$R^{Shad}_{PbPb} = R_{pPb}(y \geq 0) \times R_{pPb}(y \leq 0) \Rightarrow S_{J/\Psi} = R_{PbPb} / R^{Shad}_{PbPb}$$



At low transverse momentum J/ψ are produced with indication on enhancement in agreement with regeneration model. At high transverse momentum strong suppression is seen – QGP formation?

Final state effects

No theoretical model that could reproduce all data of quarkonium production.

Fixed target experiment at the LHC for quarkonium production at the energy range between SPS and RHIC in p-A and A-A collisions with planning proton beam at T=7 TeV ($\sqrt{s}$ = 114.6 GeV) and Pb beam at 2.75 TeV ($\sqrt{s}$ = 71.8 GeV) with high statistics is possibility to clarify the mechanism of quarkonium (J/ψ, ψ(2S), ϒ(1S,2S,3S) and χ_c) production, to investigate the contribution of recombination .

proton and lead beams, different targets, possible scan of the energy

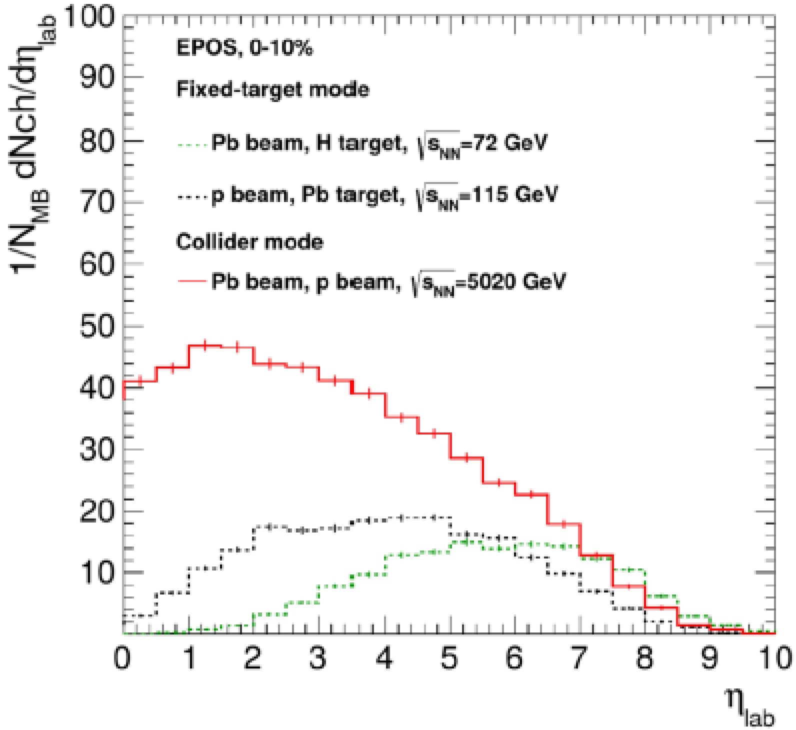
Luminosities for 500 μm target length

LHC beam	Target species	Density ρ [g cm^{-3}]	M [g mol^{-1}]	Thickness ℓ [μm]	θ_{target} [cm^{-2}]	beam flux [s^{-1}]	$\mathcal{L}$ [cm^{-2}s^{-1}]
p	C	2.25	12	500	$5.6 \cdot 10^{21}$	5×10^{8}	$2.8 \cdot 10^{30}$
p	Ti	4.43	48	500	$2.8 \cdot 10^{21}$	5×10^{8}	$1.4 \cdot 10^{30}$
p	W	19.25	184	500	$3.1 \cdot 10^{21}$	5×10^{8}	$1.6 \cdot 10^{30}$
Pb	C	2.25	12	500	$5.6 \cdot 10^{21}$	10^{5}	$5.6 \cdot 10^{26}$
Pb	Ti	4.43	48	500	$2.8 \cdot 10^{21}$	10^{5}	$2.8 \cdot 10^{26}$
Pb	W	19.25	184	500	$3.1 \cdot 10^{21}$	10^{5}	$3.2 \cdot 10^{26}$

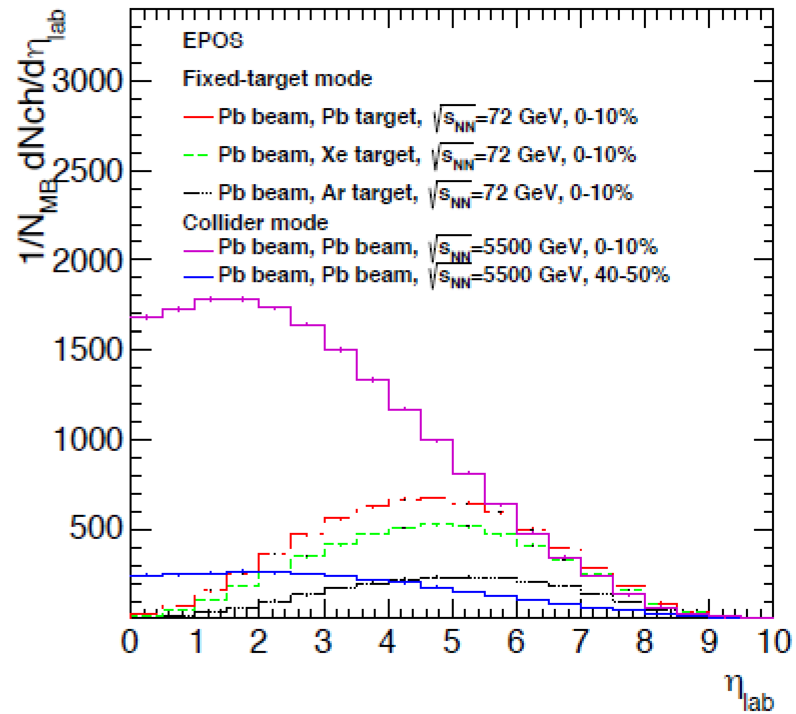
Typical luminosities integrated over a month (10^6 s): L_{PbW} (72 GeV) = 0.3/nb

Charge particle multiplicities

p+A



Pb+A

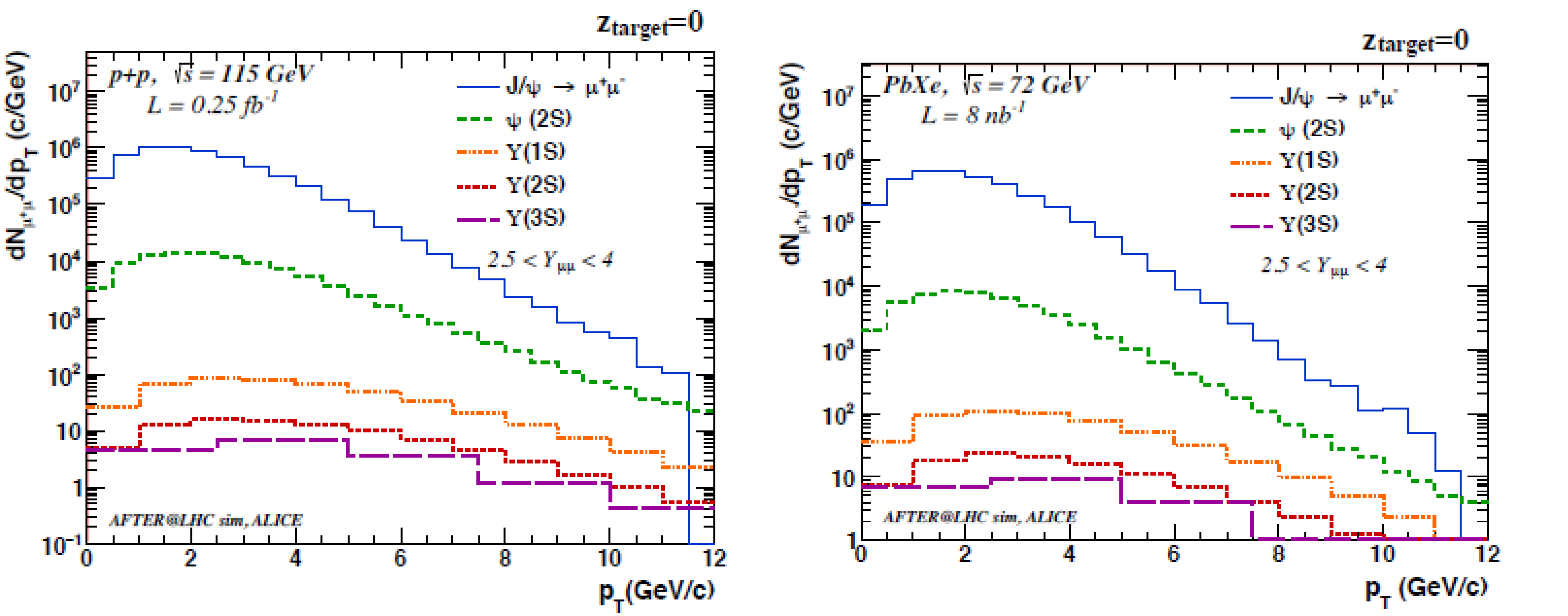


- Charge particle multiplicities for all fixed target modes: p+Pb at 115 GeV and Pb +H at 72 GeV (left) and Pb+Pb, Pb+Xe, Pb+Ar at 72 Gev (right)
- Multiplicities smaller than reached in collider mode for η_{lab} <6
- ALICE would be possible to use such multiplicities

Large yields expected for charmonia

L. Massacrier et al., Adv.Hi.En.Phys. (2015) 986348

Quarkonium production in ALICE muon spectrometer



L. Massacrier et al., Adv.Hi.En.Phys. (2015) 986348

- Luminosity corresponds to ½ year of p-H2 and 1 year of PbXe data -taking
- Probe high-x gluon in the target in particularly with ϒ(1S) within acceptance

4. Conclusions

Three physics reasons for fixed target program at the LHC

(without disturbing the other experiment):

- **Heavy-ion physics between SPS&RHIC energies towards large rapidity**

  (the approach to the phase transition point)
- **High –x gluon, antiquark and heavy quark content in the nucleon&nucleus**

  (new probes and connection to astrophysics)
- **Transverse dynamics and spin of quarks/gluons inside (un)polarized nucleon**

  (knowledge on the contribution of the orbital angular moment to the proton spin)

The measurement in energy range for fixed target experiment between SPS and RHIC with high statistics gives important additional information for quarkonium (J/ψ, $\psi(2S)$, $\Upsilon(1S,2S,3S)$ and χ_c) production.

proton and lead beams, different targets, possible scan of energy

- **The possible technical implementation are discussed at the LHC:**

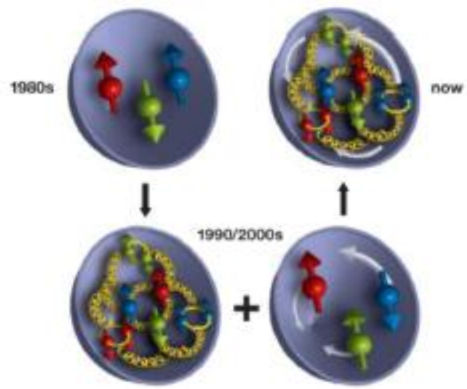
  internal gas target, beam extraction with bent crystal or internal wire target

- **The Expression of Interest is preparing to be sent to the CERN LHCC**

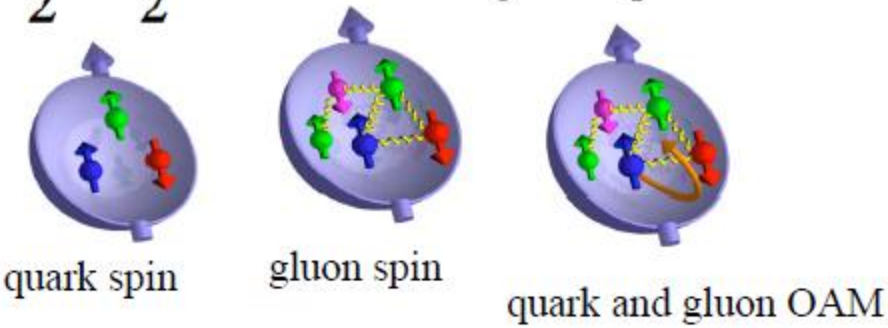
Backup

Spin physics in AFTER@LHC

- Unraveling the spin of the nucleon



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q$$



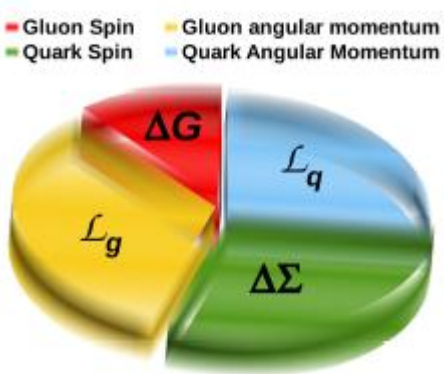
- Possible missing contribution to the proton spin: Orbital Angular Momentum $\mathcal{L}_{g;q}$:

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q}$$

[First hint by COMPASS that $\mathcal{L}_g \neq 0$]

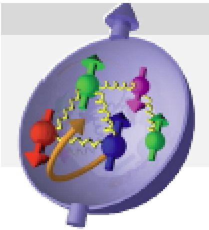
- Test of the QCD factorisation framework

[beyond the DY A_N sign change]



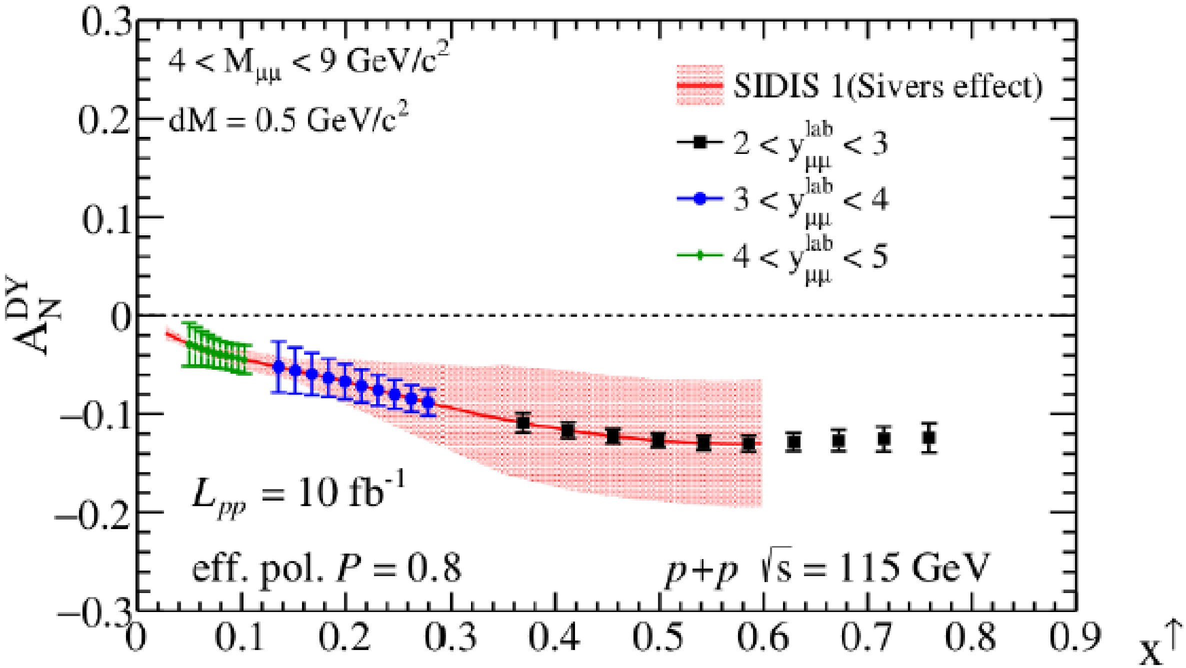
The quarks orbital angular momentum (OAM) .

Single spin asymmetry (STSA) in Drell-Yan studies with AFTER@LHC. **Expected asymmetries.**



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

Experimental goal: to measure asymmetries on the order of 5-10 % at $x_F < 0$

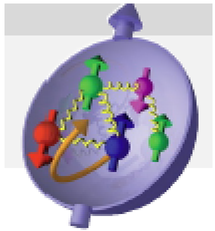


Transverse Single-Spin Asymmetries in Proton-Proton Collisions…
M.Anscelmino et al., Adv. High Energy Physics **2015** (2015) ID 475040

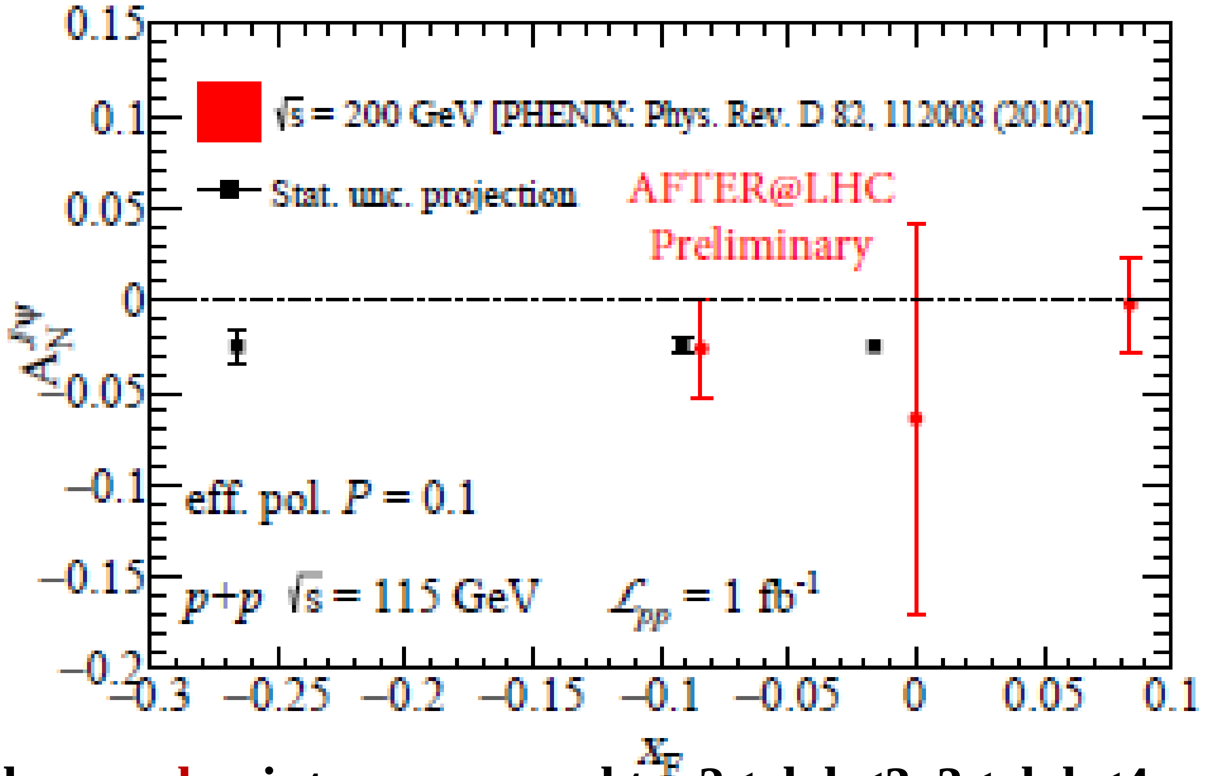
Points – calculated AFTER@LHC values.

The gluon orbital angular momentum (OAM) contribution to the proton spin in J/ψ production

Single transverse spin asymmetry (STSA) for J/ψ production



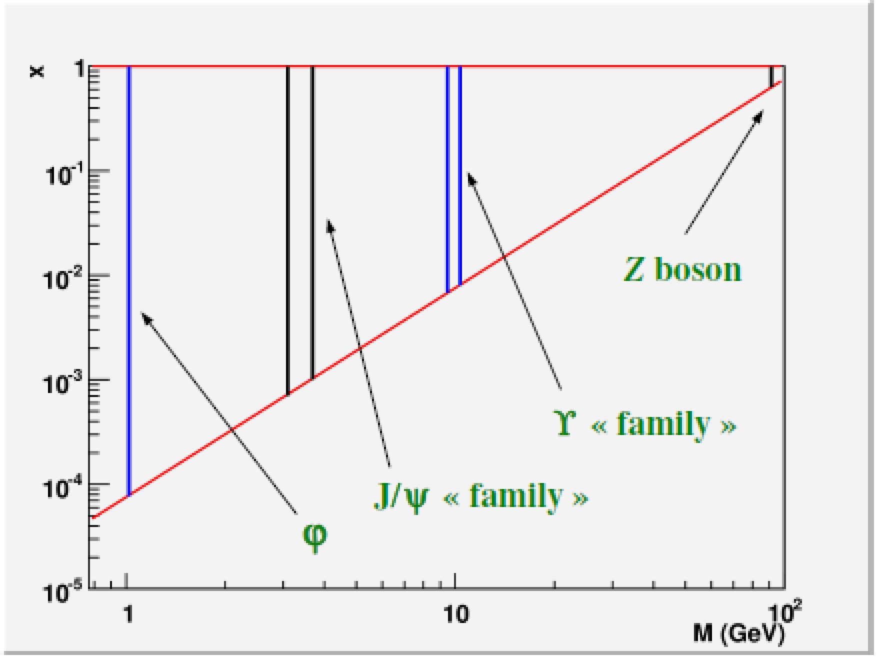
- It can be measured via A_N of gluon sensitive probes [as opposed to DY for quarks]



The three red points correspond to 2<ylab<3, 3<ylab<4 and 4<ylab<5 PHENIX data, with average central value $A_N(J/\psi)$ =-0.025.
Black points – calculated AFTER@LHC values.

The dilepton study

➟ Region in x probed by dilepton production as function of $M_{\ell\ell}$
→ Above $c\bar{c}$: $x \in [10^{-3}, 1]$
→ Above $b\bar{b}$: $x \in [9 \times 10^{-3}, 1]$



Note: $x_{target}(\equiv x_2) > x_{projectile}(\equiv x_1)$
"backward" region

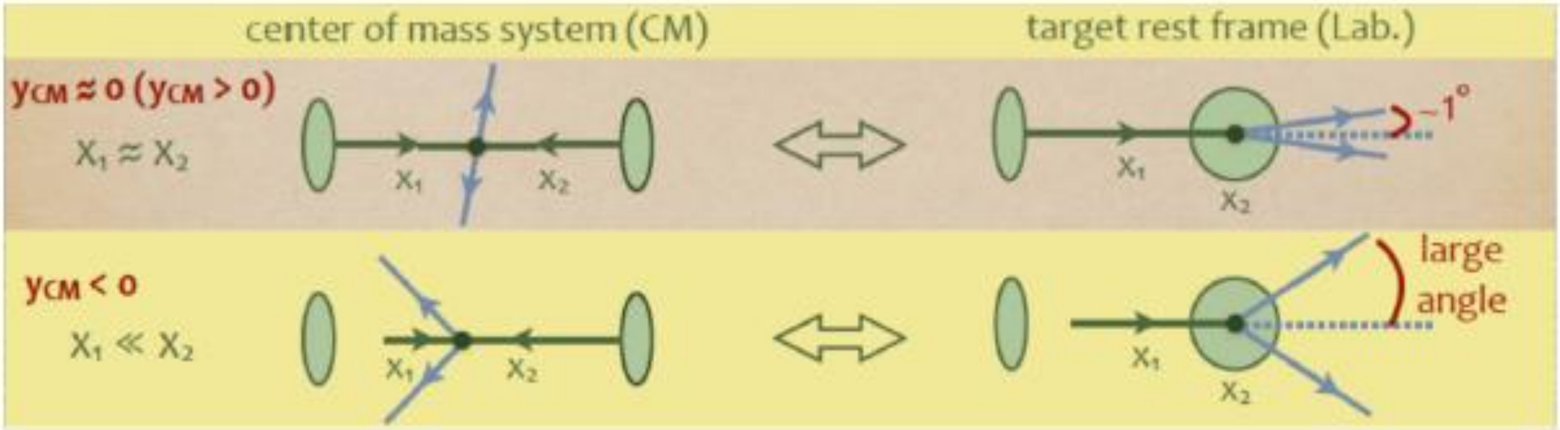
→ sea-quark asymetries
via p and d studies

- at large(est) x: backward ("easy")

- at small(est) x: forward (need to stop the (extracted) beam)

➟ To do: to look at the rates to see how competitive this will be

Fixed target experiment at the LHC: main kinematical features



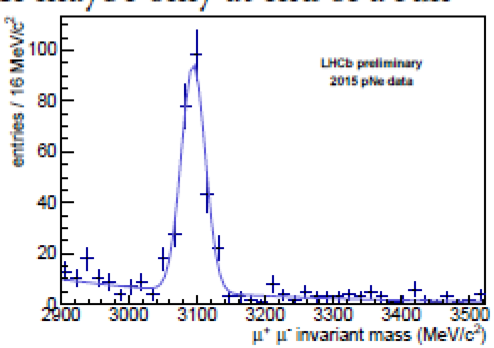
- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Large angle gives access to large parton momentum fraction (x_2) of the target

- LHCb and the ALICE muon arm become backward detectors [$y_{c.m.s.} < 0$]
- With the reduced $\sqrt{s}$, their acceptance for physics grows and nearly covers half of the backward region for most probes [$-1 < x_F < 0$]
- Allows for backward physics up to high x_{target} ($\equiv x_2$) [uncharted for proton-nucleus; most relevant for p-p$^{\uparrow}$ with large $x^{\uparrow}$]

Internal gas targets

SMOG(-like) system

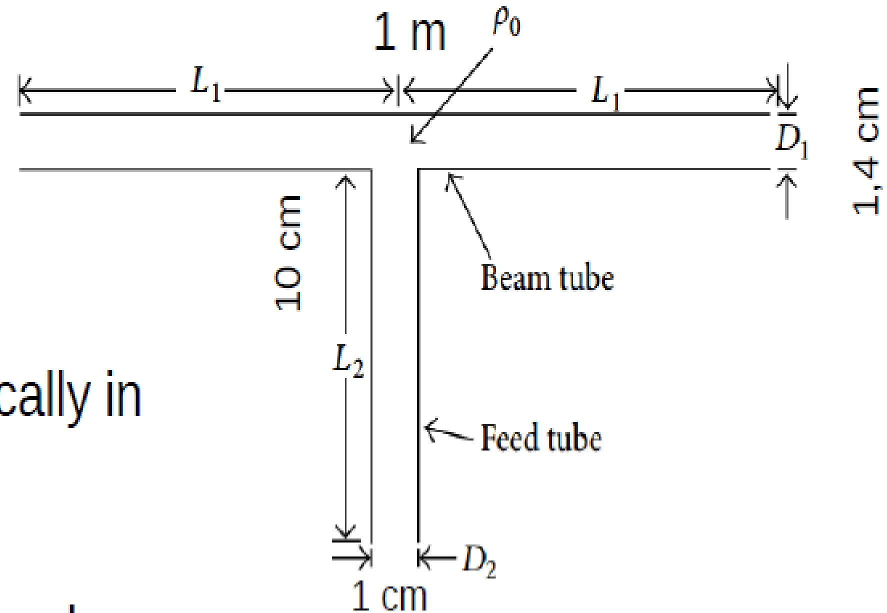
- SMOG: System for Measuring Overlap with Gas
- Designed for precise luminosity determination
- Noble gas directly injected in the VELO
- ✓ p(He,Ne,Ar), Pb(Ne,Ar) tested : completely parasitic [up to one week, so far]
- ✓ New pressure monitoring to be installed
- ✓ Could be coupled to ALICE: ideal demonstrator
- ✗ No specific pumping system: limit in the gas inject [pressure and duration]
- ✗ No possibility to use polarised gases
- ✗ Gas flows in the beampipe; pressure profile not optimised
- ✗ Kr and Xe maybe only at end of a run



HERMES(-like) system

- Injection of gas in an open-end storage cell
- Used e.g. at DESY for 10 years
- ✓ Dedicated pumping system [turbo-molecular pumps]
- ✓ Pressure in the cell significantly higher [diameter $\leq$ 2cm in the closed position]
- ✓ Polarised H and D can be injected ballistically with high polarisation
- ✓ Polarised ^{3}He or unpolarised heavy gas (Kr, Xe) can also be injected
- ✗ Not compatible with an injection inside ALICE; only upstream
- ✗ May need complementary vertexing capabilities

Polarized target: HERMES-type system



Adv. High Energy Phys. 2015 (2015) 463141

E. Steffens, PoS (PSTP2015) 019

- Dedicated pumping system
- Polarised H and D injected ballistically in open-end storage cell with high polarisation ~80%
- Possible polarised ^{3}He or unpolarised heavy gas (Kr, Xe)
- Typical integrated luminosity over a year:
  - p-H at $\sqrt{s_{NN}}$ = 115 GeV, L_{int} ~ 10 fb^{-1}
  - Pb-H at $\sqrt{s_{NN}}$ = 72 GeV, L_{int} ~ 100 nb^{-1}

Experiment AFTER

AFTER :

- Offers a wide physical program.
- Possibility to use different targets with high thickness – higher luminosity (20 times more for 1 cm target vs 500 μm)
- Possibility to use liquid H_2 and D_2 targets:

extremely high luminosity ~20 fb^{-1} yr^{-1} -compatible to LHC.

But – high cost.

Fixed target experiment with the target in the form of thin ribbon:

- Only after beam tuning with the aid of rotation system-put in the working position
- Used only halo of the beam (and may be used as extra collimator)
- May be placed at existing experimental installation (for example, ALICE and/or LHCb)
- Possibility to measure charmonium production with rather high statistics on different targets in pA and PbA.

First step ?