Charmonium production in heavy ion collisions and suggestion of new experiments on fixed target.

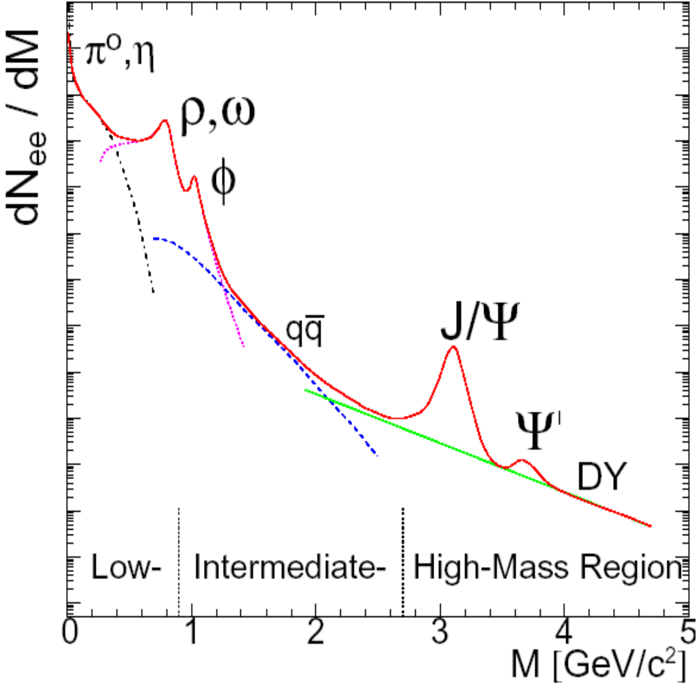
N.S. Topilskaya and A.B. Kurepin
INR RAS, Moscow

1. Physical motivaion.
2. Experimental situation.
3. Fixed target suggestion.
3. Summary.

ISHEPP XXII, Dubna, 16 September 2014.

Charmonium

- 1974 г.: discovery of J/ψ, 1986 г.: Matsui & Satz:



colour screening in deconfined matter
→ J/ψ suppression
→ possible signature of QGP formation

Experimental and theoretical investigations
→ situation is more complicated

cold nuclear matter (CNM)/initil states.

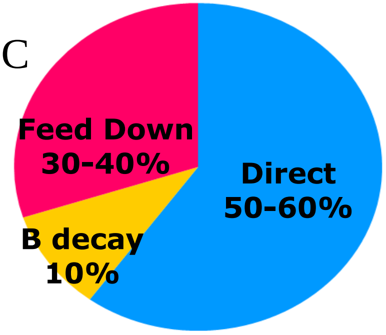
- **“normal” nuclear suppression**
- **(anti)shadowing**
- **saturation, color glass condensate**

suppression via comovers
feed down from χ_c, ψ’
sequential screening (first : χ_c, ψ’, J/ψ only well above T_c)

regeneration via statistical hadronization or charm coalescence

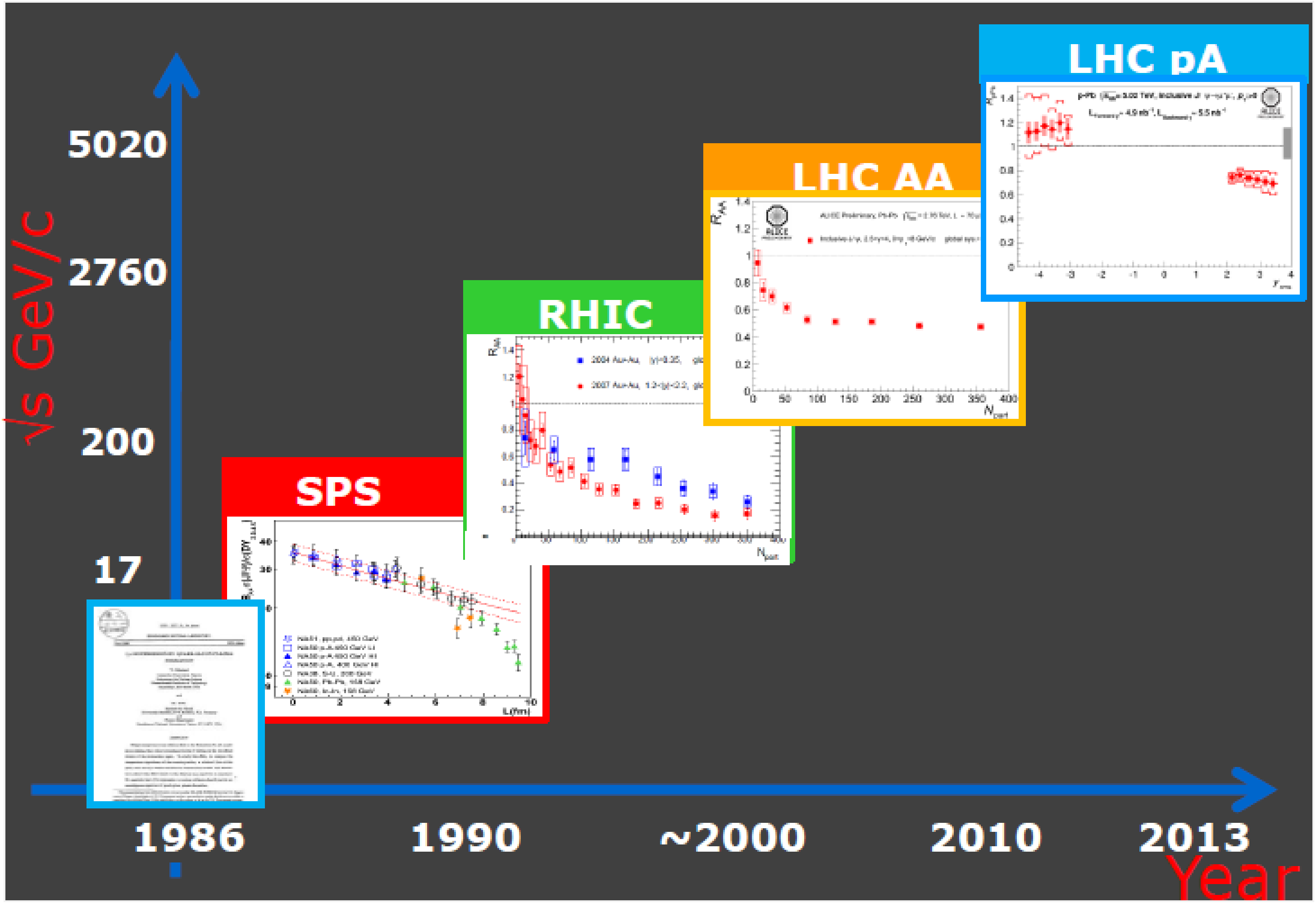
J/ψ production from *B*-hadron

CDF-LHC
Low pt



Important for “large” charm yield, i.e. RHIC and LHC

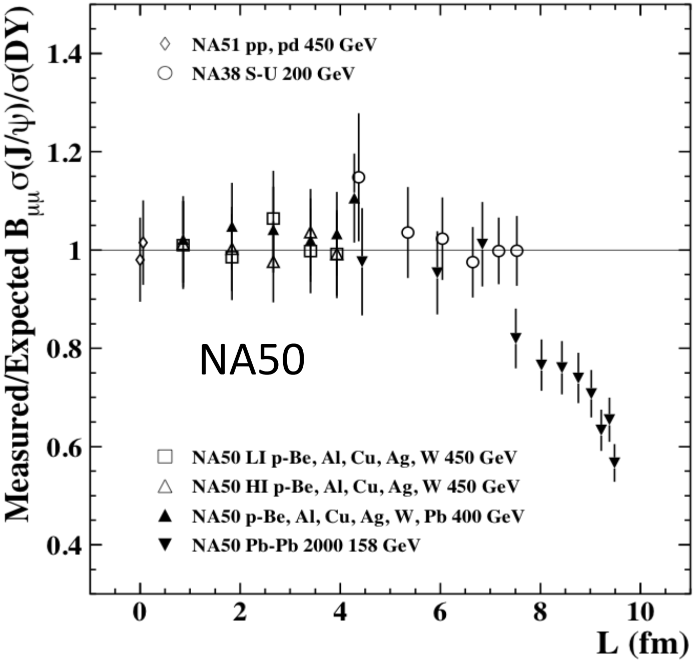
Charmonium production



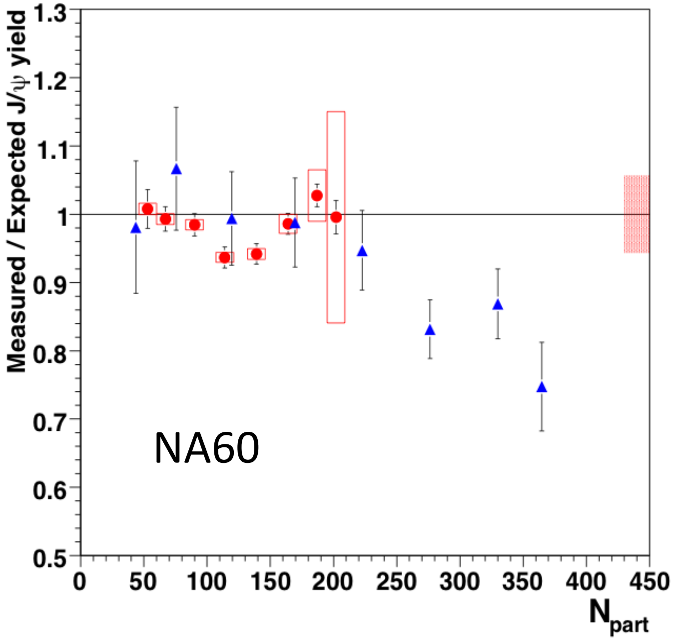
- Charmonium suppression is one of the important signal of QGP formation

J/ψ suppression at SPS

NA50



NA60



Suppression (~40%);

ψ' suppression is measured

σ_{abs} depends on energy ;

Suppression (~20-30%);

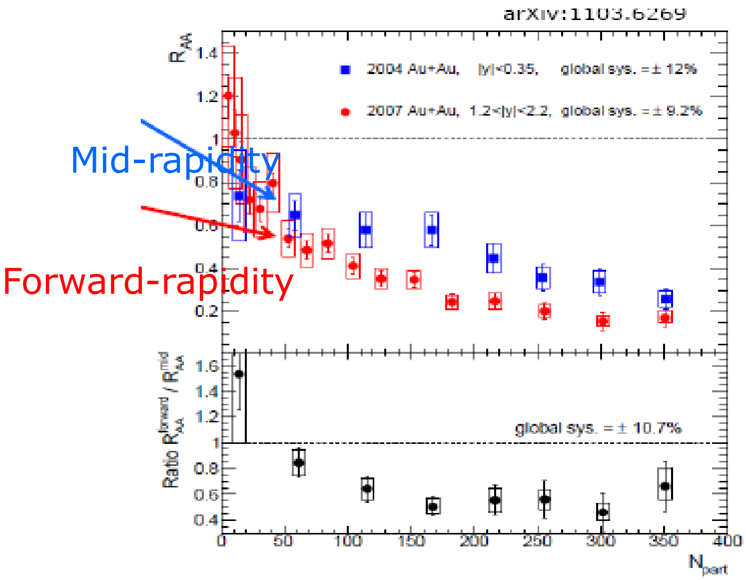
$\sigma_{abs}^{J/\psi}$ (158 GeV) = 7.6 ± 0.7 ± 0.6 mb

$\sigma_{abs}^{J/\psi}$ (400 GeV) = 4.3 ± 0.8 ± 0.6 mb

B. Alessandro et al. (NA50), EPJC39 (2005) 335

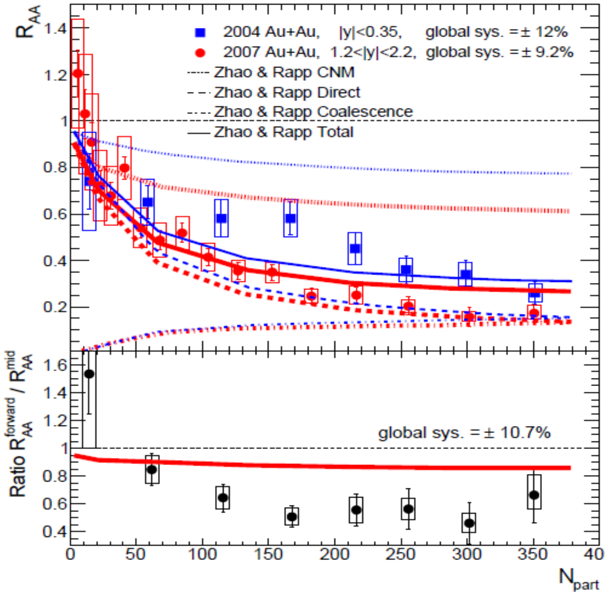
R. Arnaldi et al. (NA60), Nucl. Phys. A (2009) 345

J/ψ suppression at PHENIX, RHIC



Mid-rapidity

Forward-rapidity



Suppression (~40-80%);

Larger suppression at forward rapidity

Models could describe main features but no quantitative agreement.

Is regeneration important?

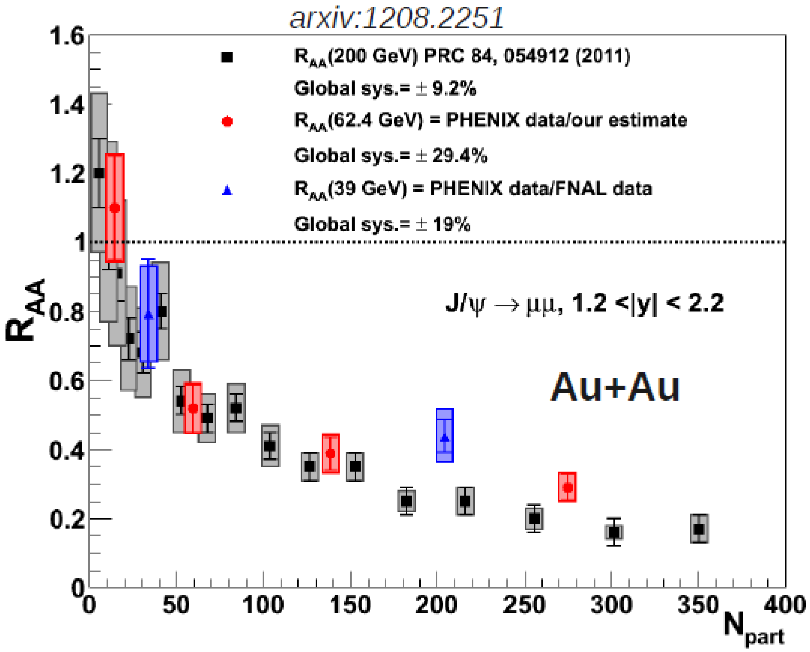
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

N-N cross section

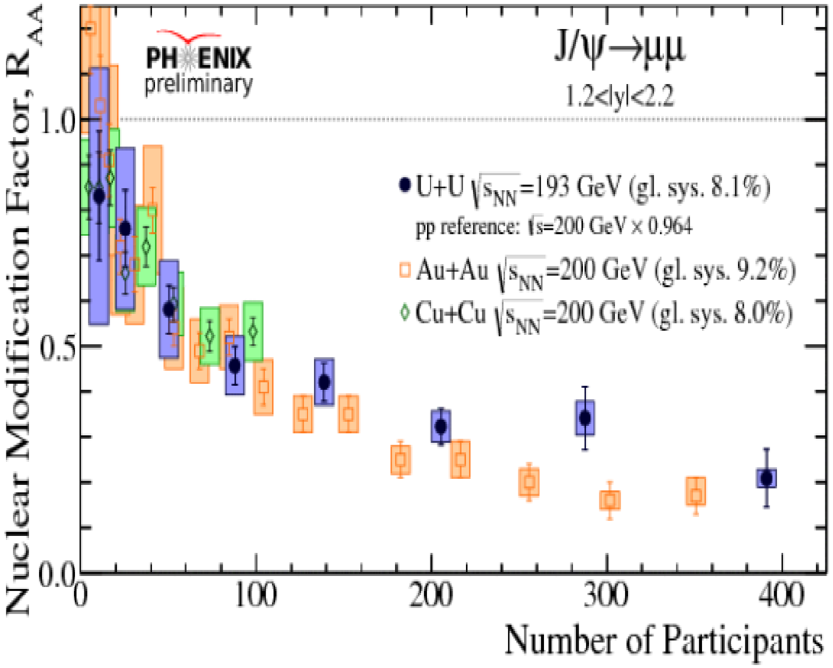
$\langle N_{binary}\rangle / \sigma_{inel}^{p+p}$

A.Adare et al. (PHENIX), PRC84 (2011) 054912

J/ψ suppression at PHENIX, RHIC(+low energy+AA)



Phys. Rev C 86 064901 (2012)



Au+Au

Cu+Cu

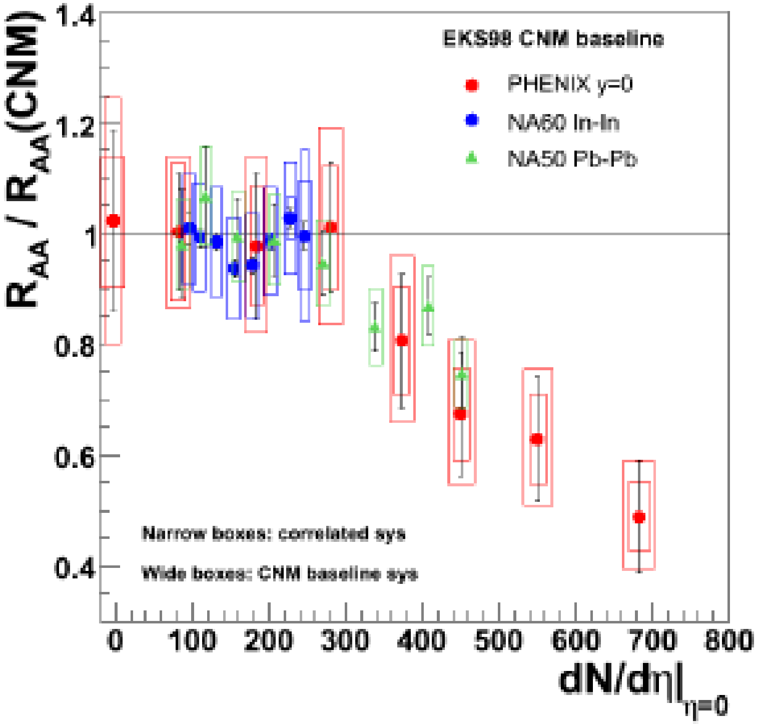
U+U

No *pp*- data at
62.4 and 39 GeV –
large systematic errors

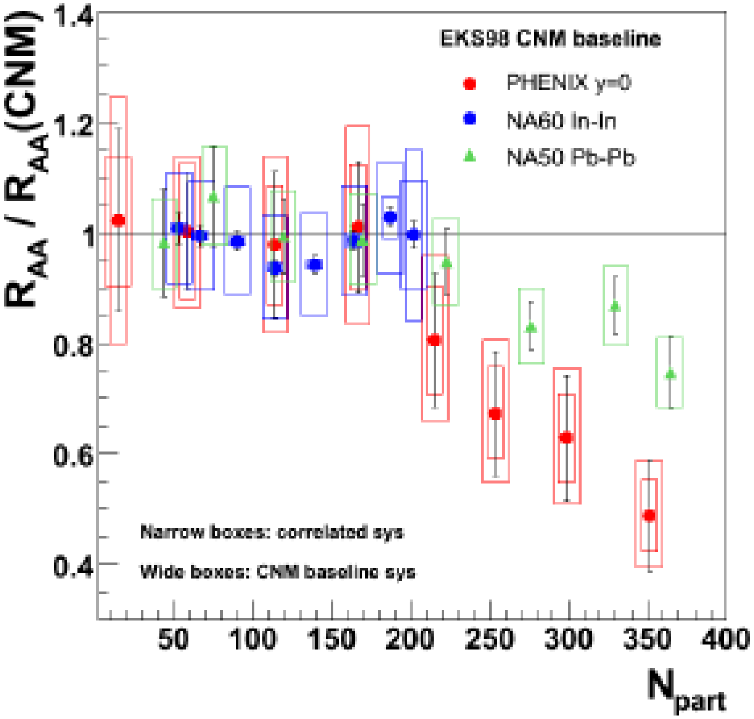
Suppression approximately the same.

Comparison of SPS and RHIC data at mid rapidity

R_{AA} as a function of multiplicity (~ε)



R_{AA} as a function of N_{part}



Which dependence to choose?

With NA60 data (σ_{abs}depends on energy) suppression of charmonium production at PHENIX larger that at NA50

N.Brambilla et al. , EPJ C71 (2011) 1534

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

At LHC energy ? Suppression or/and regeneration ?

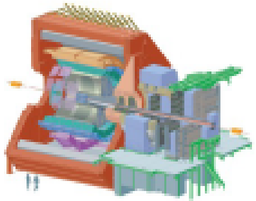
ALICE

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

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

p_T coverage down to $p_T \sim 0$

(up tp now only inclusive J/ψ results)

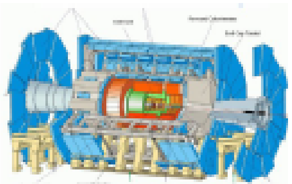


ATLAS

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

$p_{T\mu}>3$GeV,
$|\eta_\mu|<2.5$
→ p_T $J/\psi>6.5$GeV/c

(separation between B and prompt J/ψ)

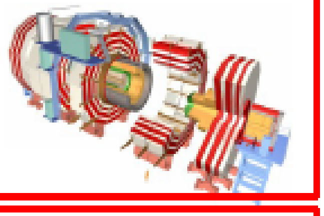


CMS

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

p_T coverage depending on the y region

(separation between B and prompt J/ψ)



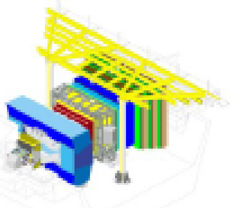
LHCb

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

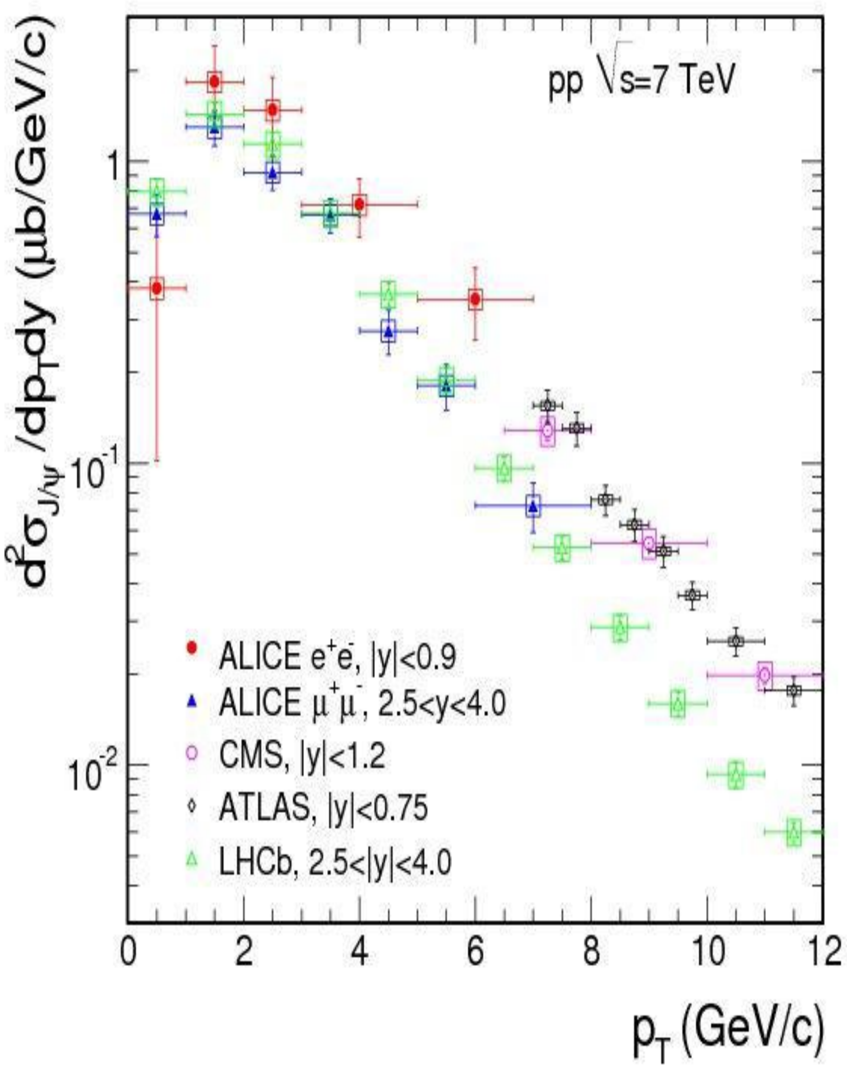
p_T coverage down to $p_T \sim 0$

(separation between B and prompt J/ψ)

(no heavy ion physics program)



Charmonium production in *pp*- collisions at LHC: ALICE, CMS, ATLAS and LHCb .



Good agreement of experimental data of ALICE, CMS and ATLAS for mid-rapidity

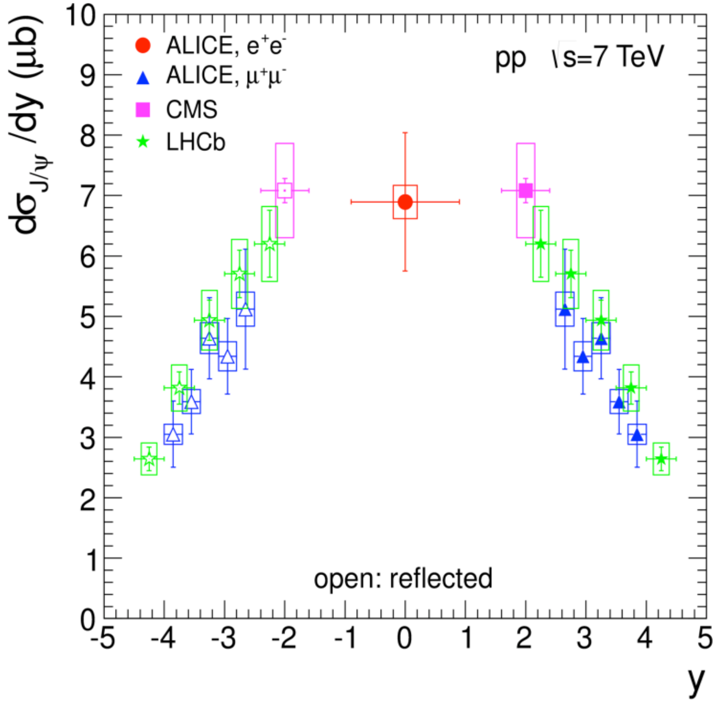
and ALICE and LHCb for forward-rapidity

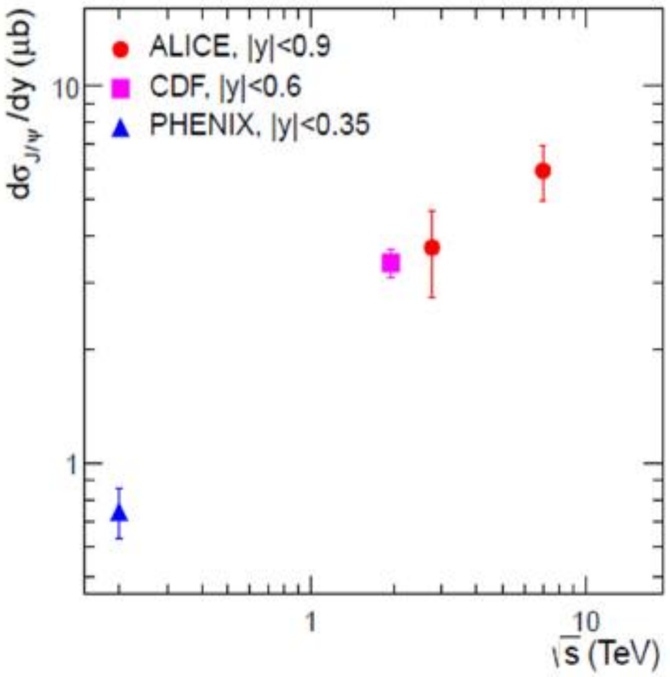
Transverse momentum distribution- dependence on rapidity range.

CMS: Eur. Phys. J. **C71**, 1575 (2011).
ATLAS: Nucl. Phys. **B850**, 387 (2011).
LHCb: Eur. Phys. J. **C71**, 1645 (2011).

ALICE: Phys. Lett. B704 (2011) 442

J/ψ production in *pp*-collisions and dependence on rapidity and energy



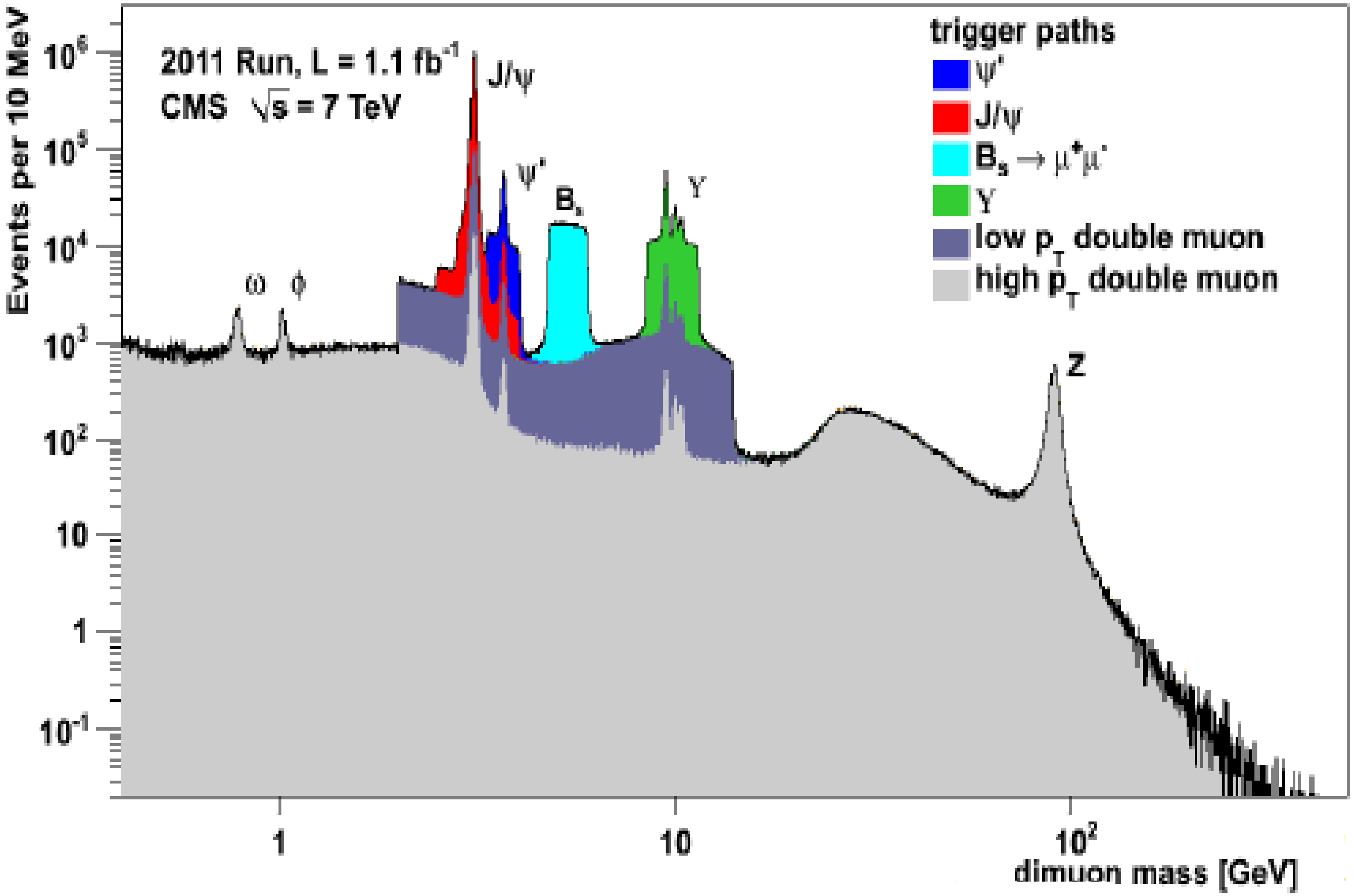


Good agreement of experimental data at ALICE and LHCb for forward-rapidity

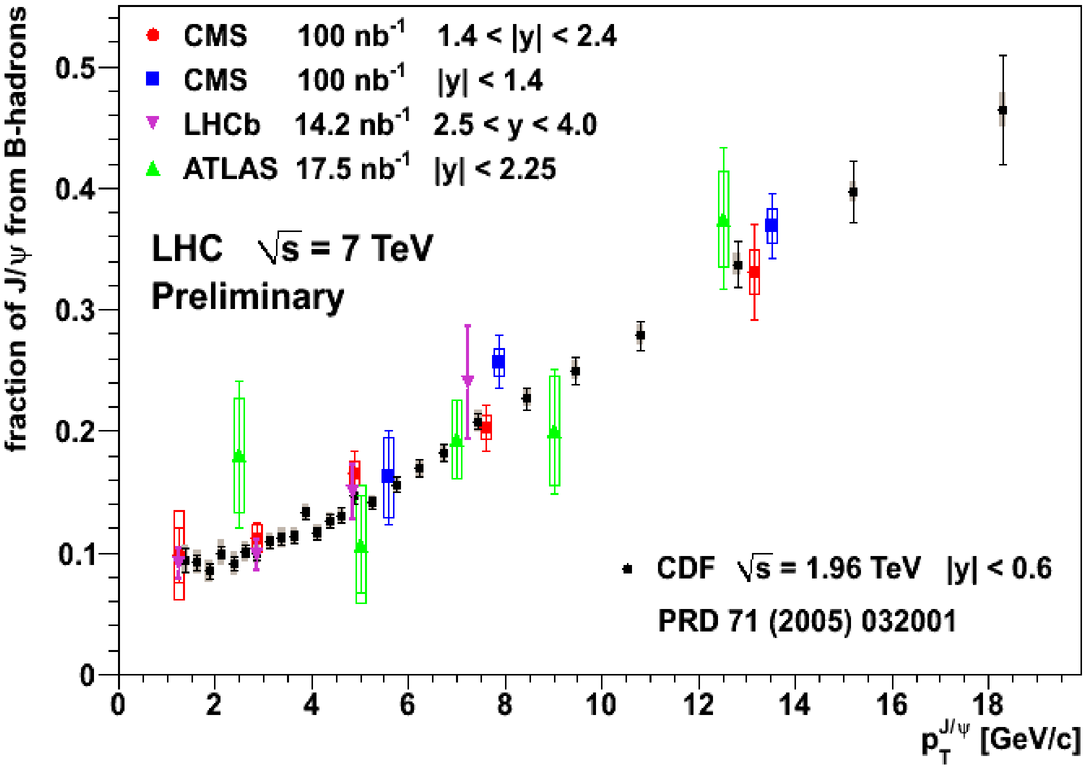
CMS: Eur. Phys. J. **C71**, 1575 (2011).
ATLAS: Nucl. Phys. **B850**, 387 (2011).
LHCb: Eur. Phys. J. **C71**, 1645 (2011).

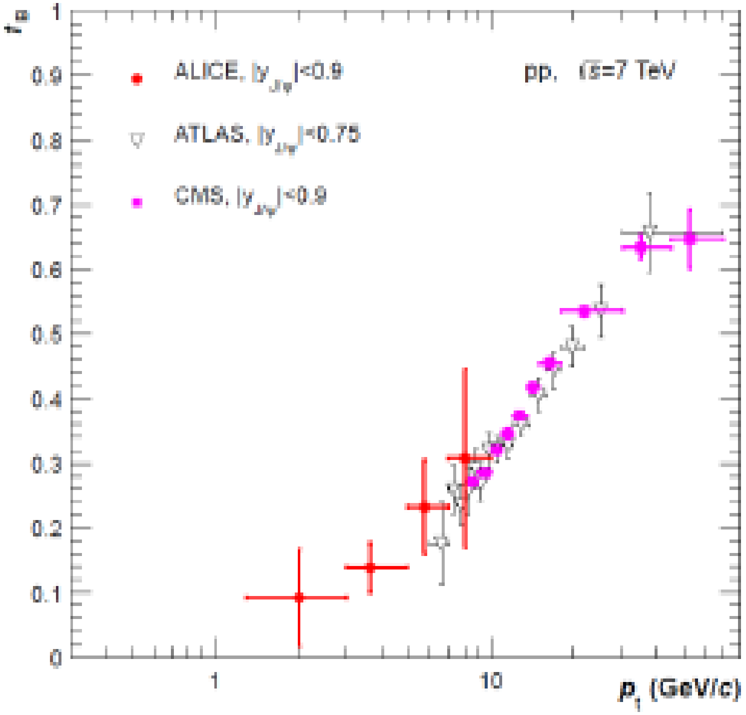
ALICE: Phys. Lett. B718 (2012) 295

Dimuons spectra at CMS in *pp* at √s = 7 TeV



B_s is now seen by CMS, ATLAS and LHCb



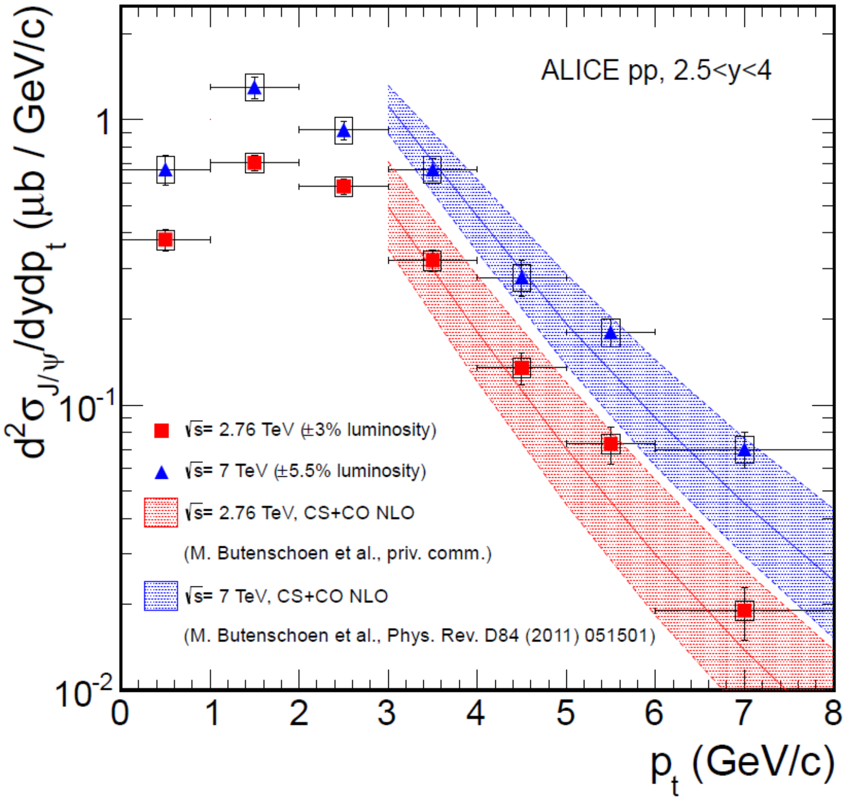


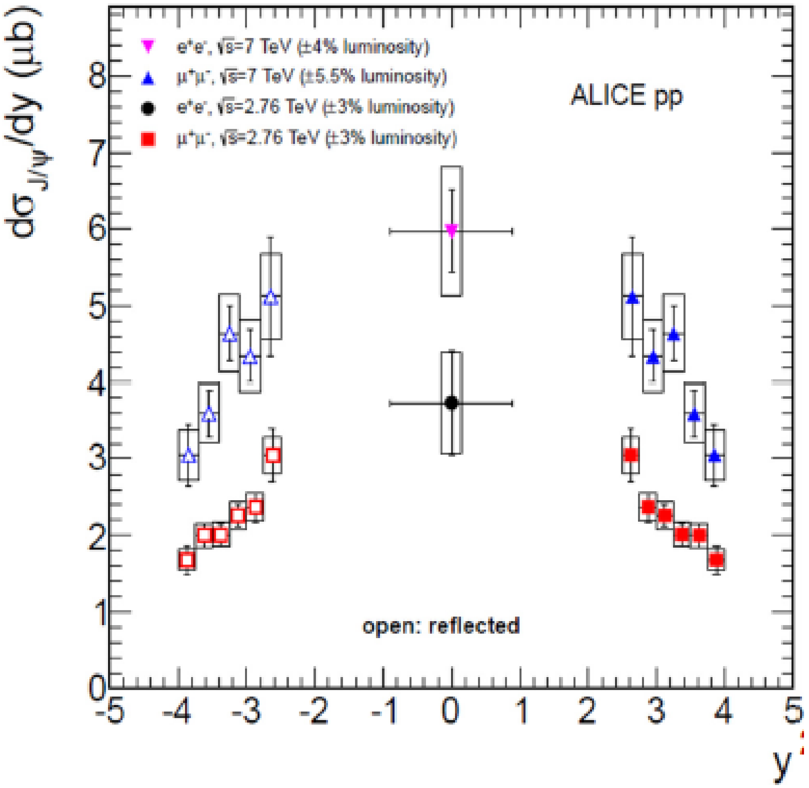
ATLAS: Nucl.Phys/B **850**, 387 (2011).
CMS: JHEP **2**, 011 (2012).
ALICE: JHEP **11**, 065 (2012).

The fraction of J/ψ from B-hadrons decay depends on pt

and consists ~10% for pt ~1.5 GeV/c.

J/ψ production in ALICE in *pp*-collisions at 2.76 TeV and dependence on pt and rapidity





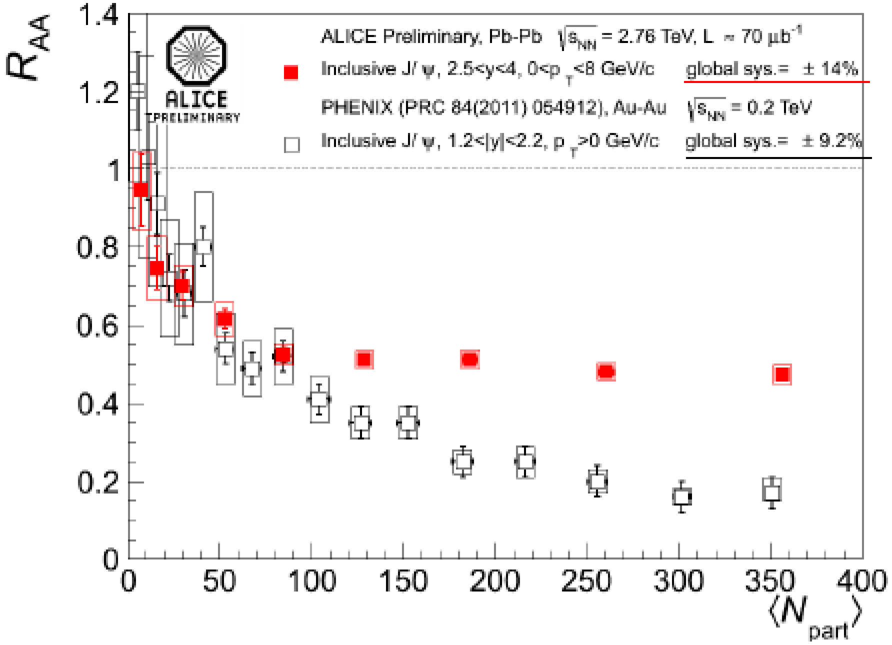
Results in agreement with NLO NRQCD calculations.

pp data at 2.76 TeV – reference for PbPb at 2.76 TeV.

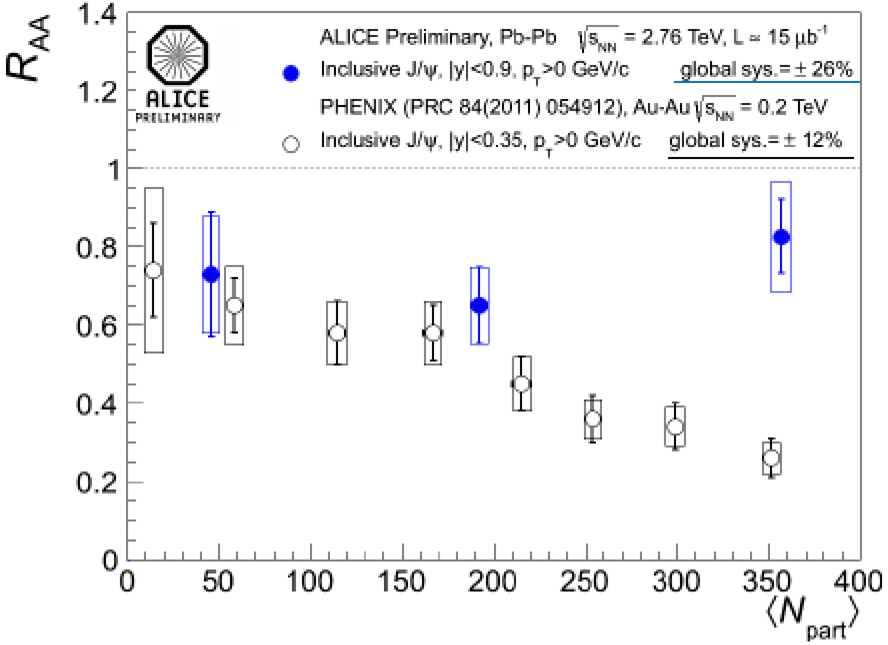
ALICE: Phys. Lett. B718 (2012) 295

R_{AA} vs number of participant for different rapidity regions. Comparison of ALICE and PHENIX data.

Forward rapidity



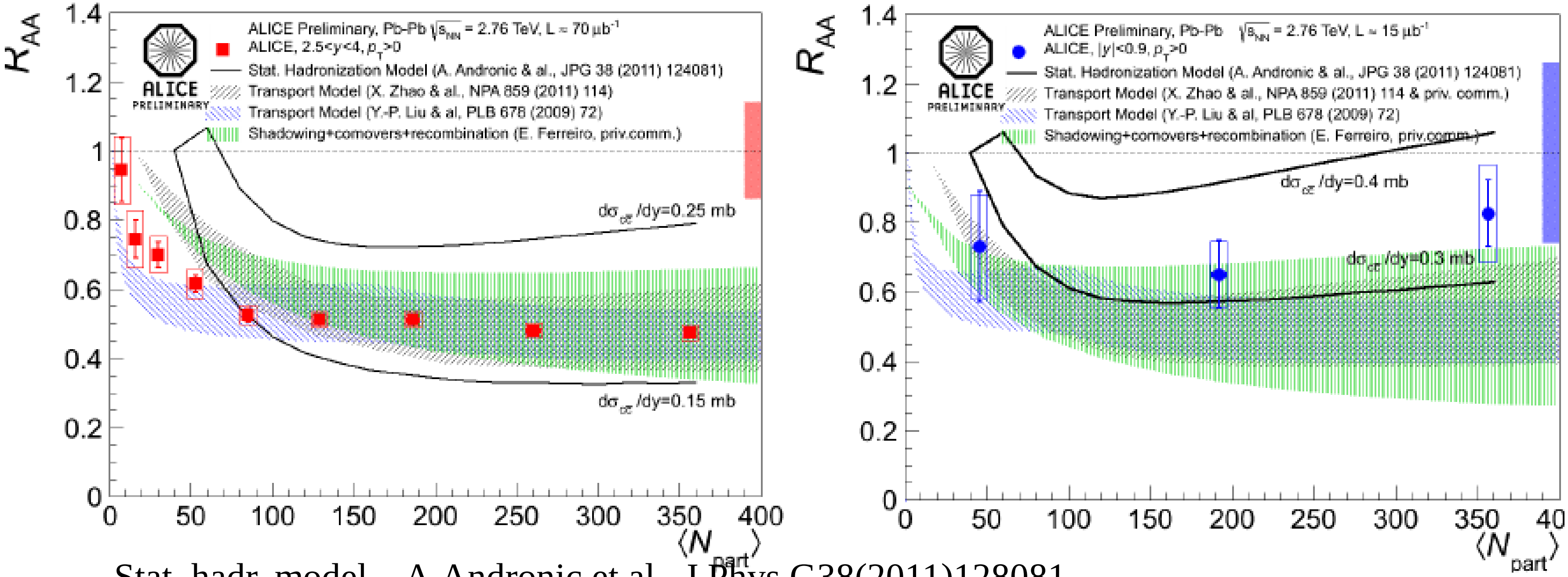
Mid- rapidity



Smaller suppression with respect to RHIC, compatible with J/ψ regeneration model

ALICE arXiv:1311.0214

Comparison with the statistical hadronization model and transport models.

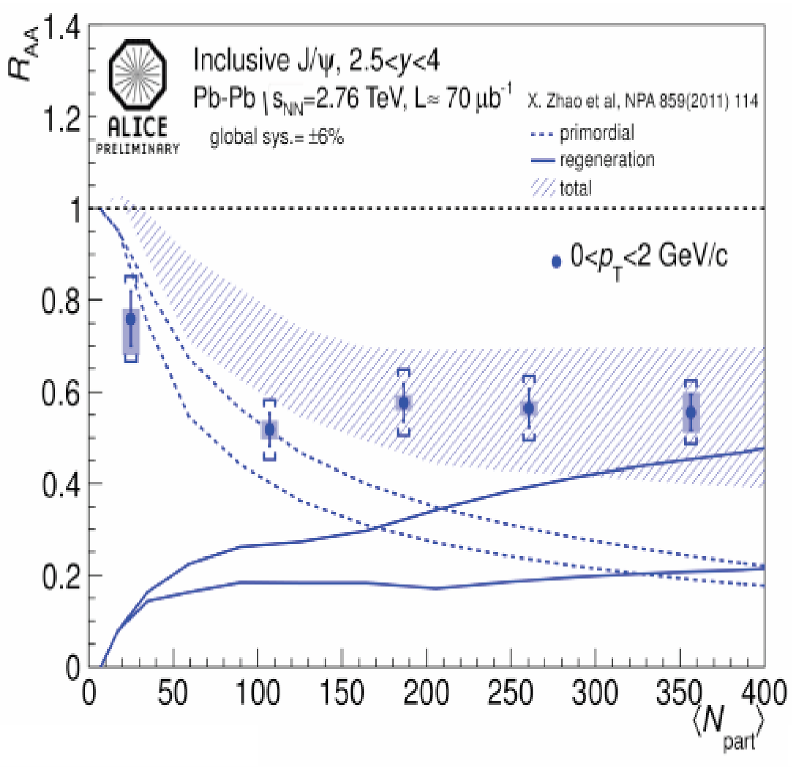


Stat. hadr. model – A.Andronic et al., J.Phys.G38(2011)128081
Transport models- X.Zhao and R.Rapp, N.Phys.A859(2011)114,
Y.Liu et al.,P.Lett.B678(2009)72
Shadowing+comovers+recomb.- Capella et al., E.Phys.G C58(2008)437 and
E.Ferreiro,priv.comm.

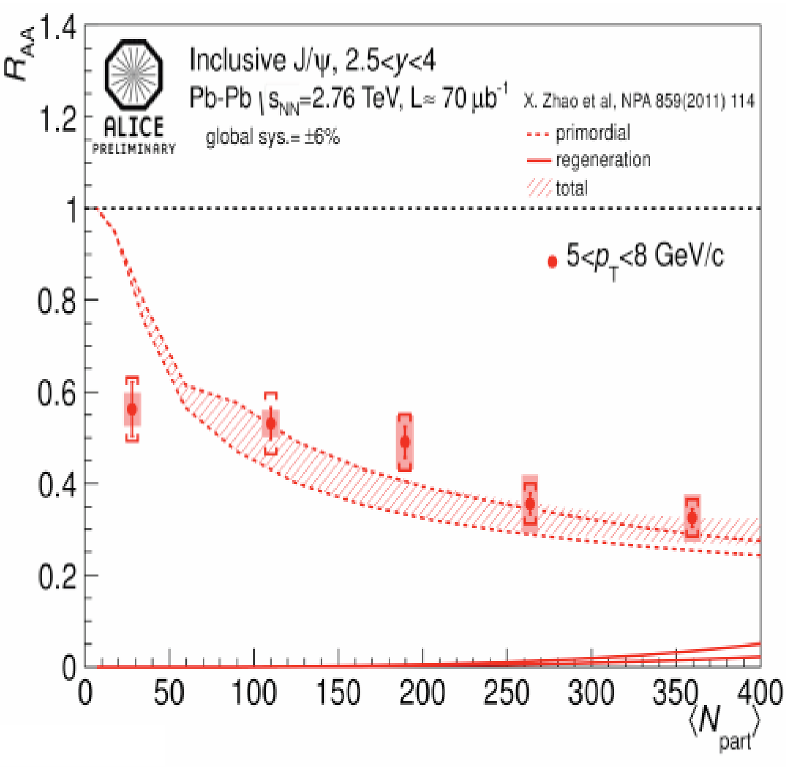
Models with all J/ψ produced at hadronization or models including large fraction (>50% in central collisions) of J/ψ produced from recombination can describe results.

ALICE arXiv:1311.0214

R_{AA} ALICE for forward rapidity vs centrality for different ranges of transverse momentum. Comparison with models of X.Zhao and Y.P.Liu



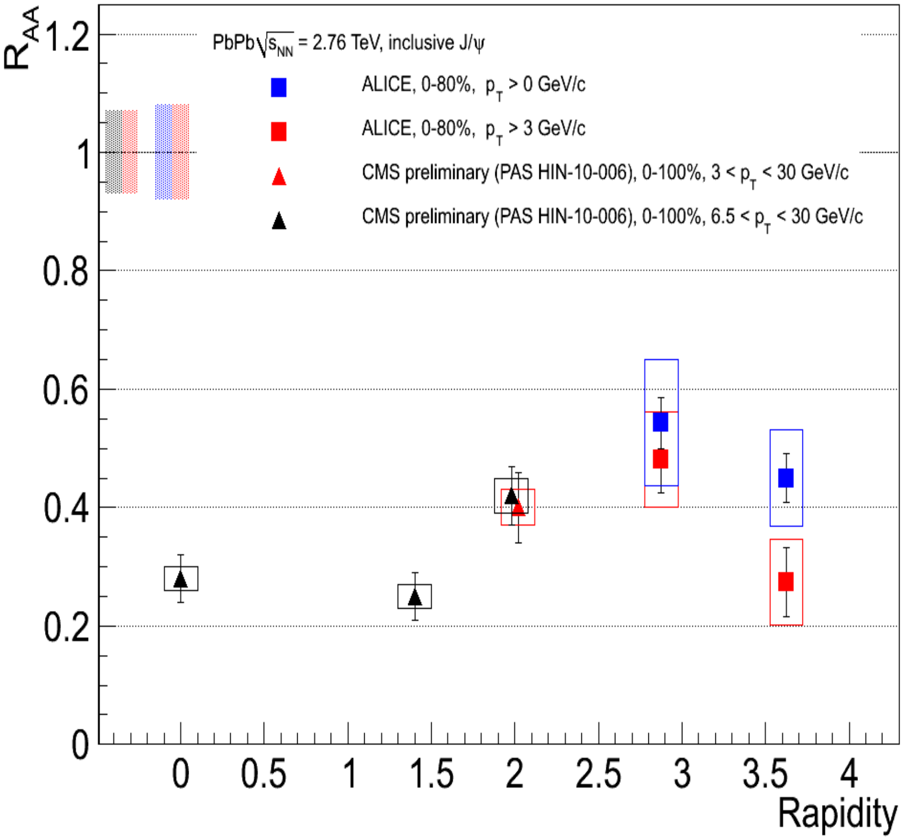
At low transverse momentum ~50% J/ψ are produced with regeneration.



At high transverse momentum contribution of regeneration is negligible.

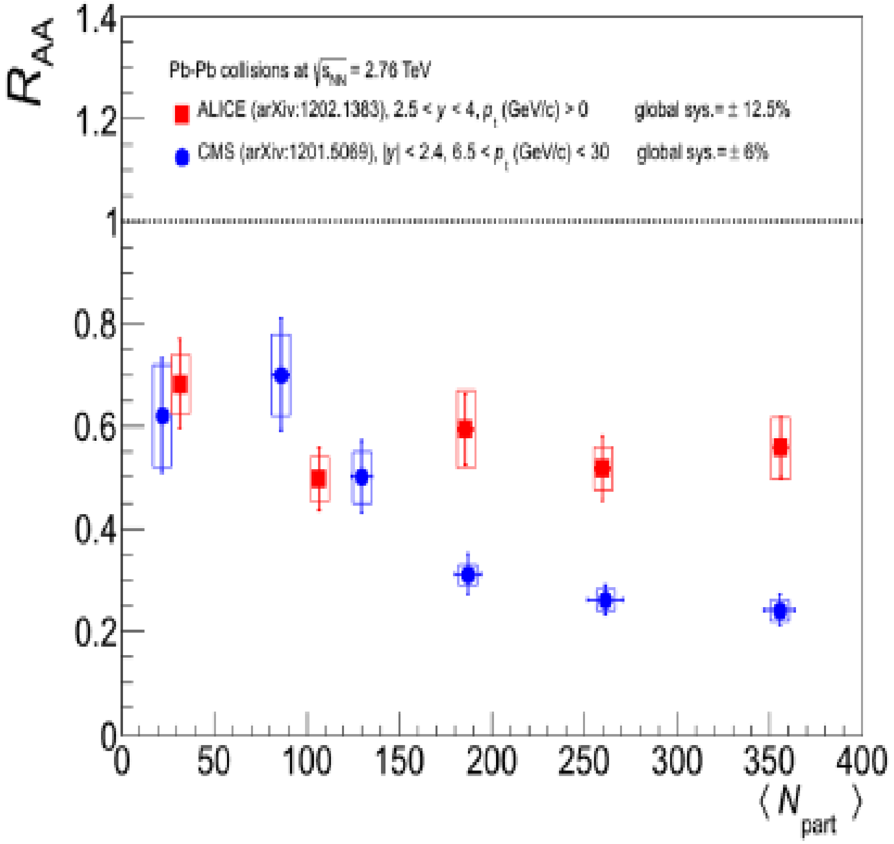
X.Zhao and R.Rapp, Nucl. Phys. A859(2011) 114
Y.Liu, Z. Qiu, N. Xu and P. Zhuang, Phys. Lett. B678(2009) 72

R_{AA} vs rapidity and comparison of ALICE and CMS data



At large rapidity suppression is higher for $p_T > 3$ GeV/c

S. Chatrchyan (CMS) ,JHEP 05(2012) 063

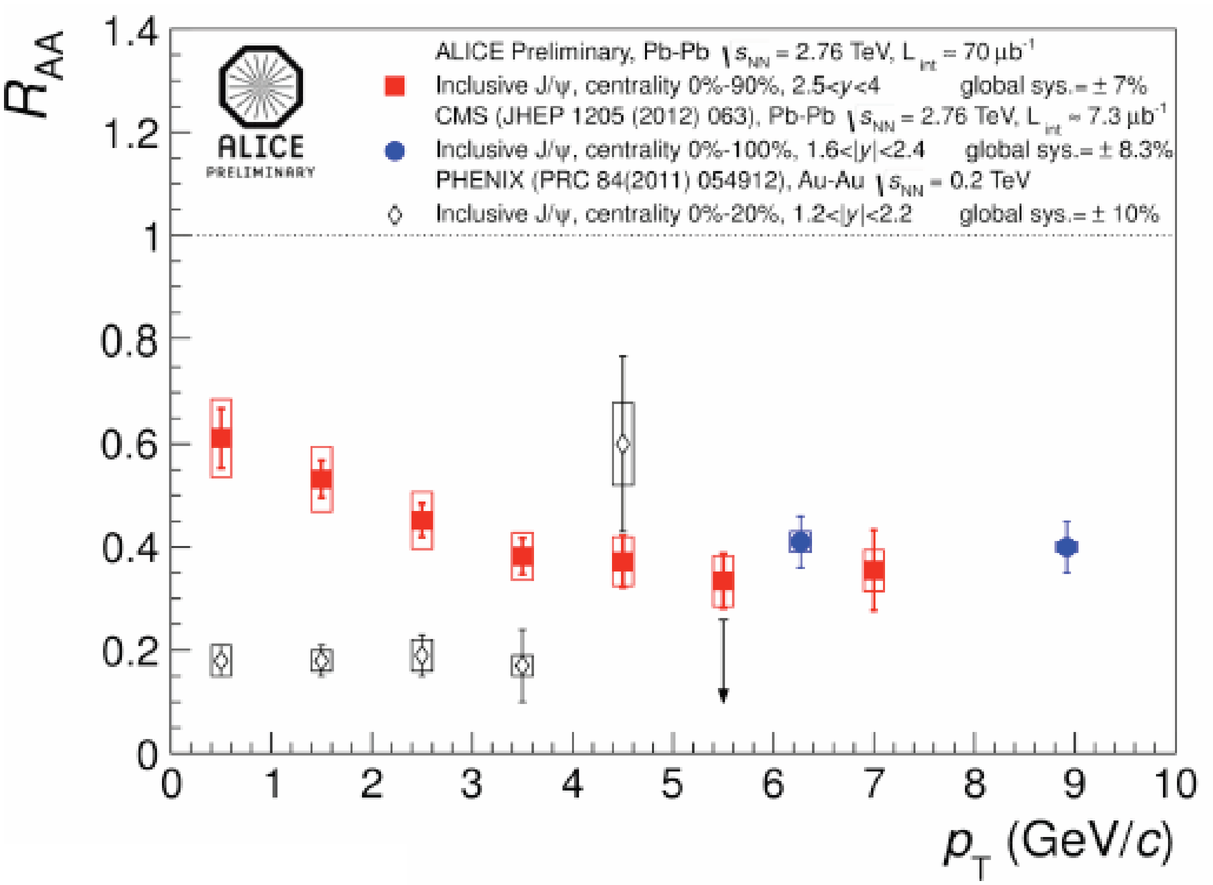


Suppression at ALICE for $2.5<y<4$ lower, than at CMS for $|y|<2.4$ and $p_T > 6.5$ GeV/c.

arXiv:1202.1383

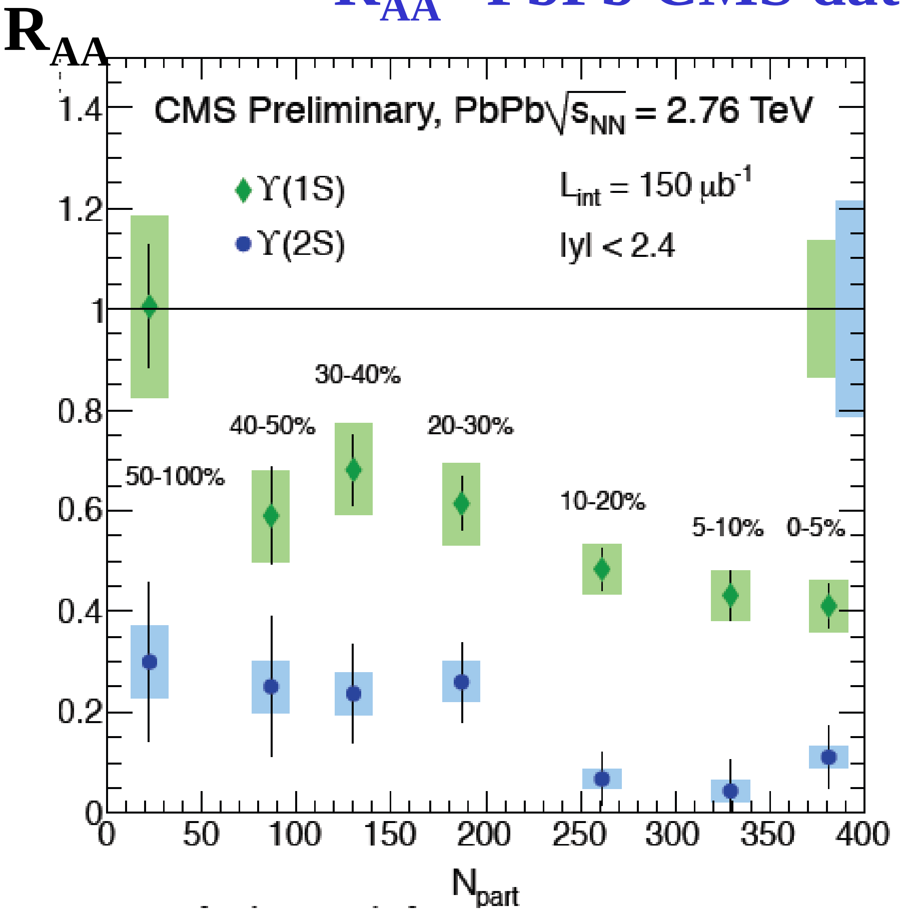
Cold nuclear effects in p-Pb collisions need to be evaluated

R_{AA} for forward rapidity vs transverse momentum. Comparison ALICE, CMS and PHENIX data.



At LHC suppression is stronger for higher transverse momentum. At low transverse momentum suppression is lower than at RHIC.

R_{AA} PbPb CMS data for bottomonium

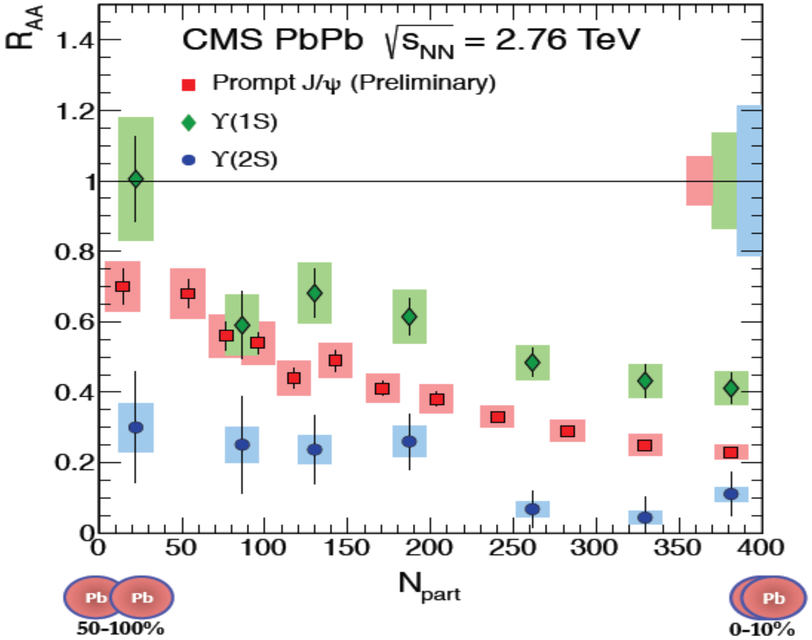


For all centrality

- Υ(1S): 0.56±0.08±0.07
- Υ(2S): 0.12±0.04±0.02
- Υ(3S): <0.10 at 95% CL

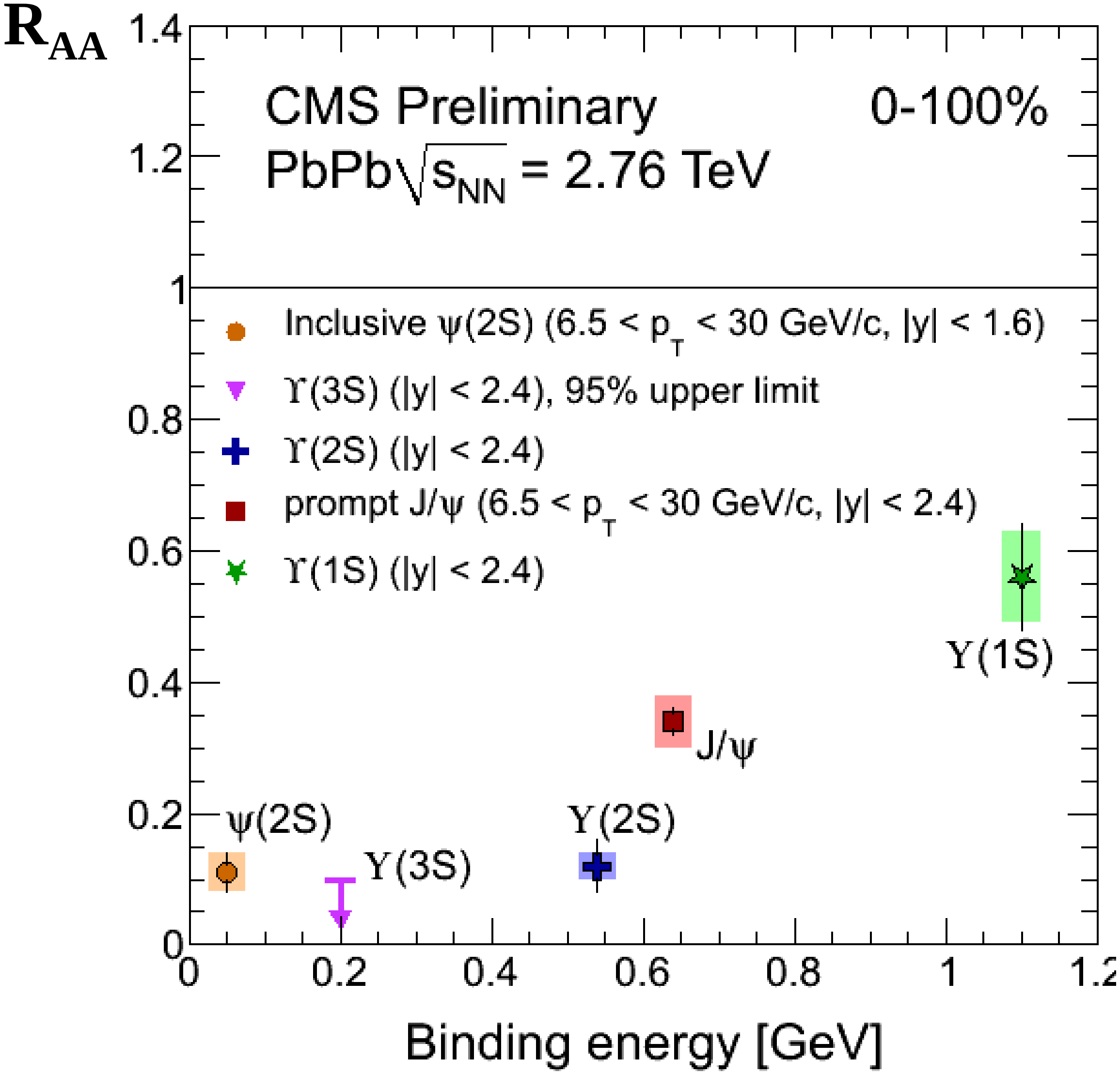
$$R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$$

Comparison of J/ψ and bottomonium



arXiv: 1208.2826

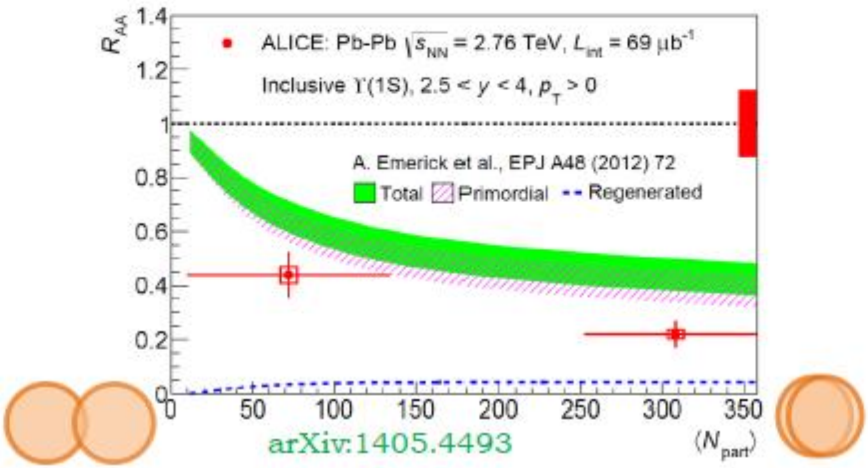
R_{AA} CMS data

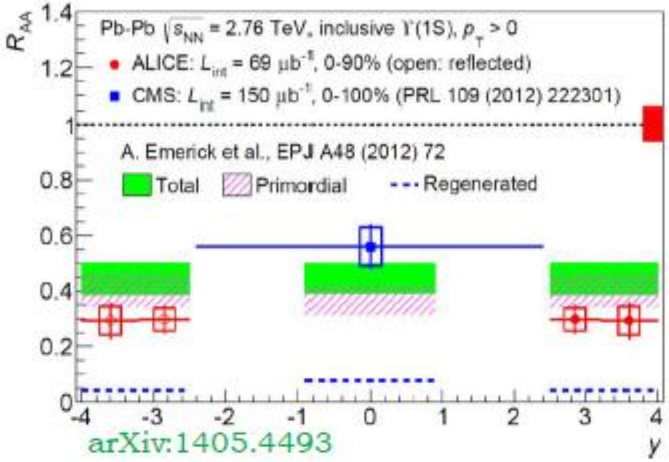


arXiv: 1208.2826
CMS-PAS HIN-12-007
CMS-PAS HIN-12-014

Less suppression for states with higher binding energy.

R_{AA} ALICE PbPb data for bottomonium



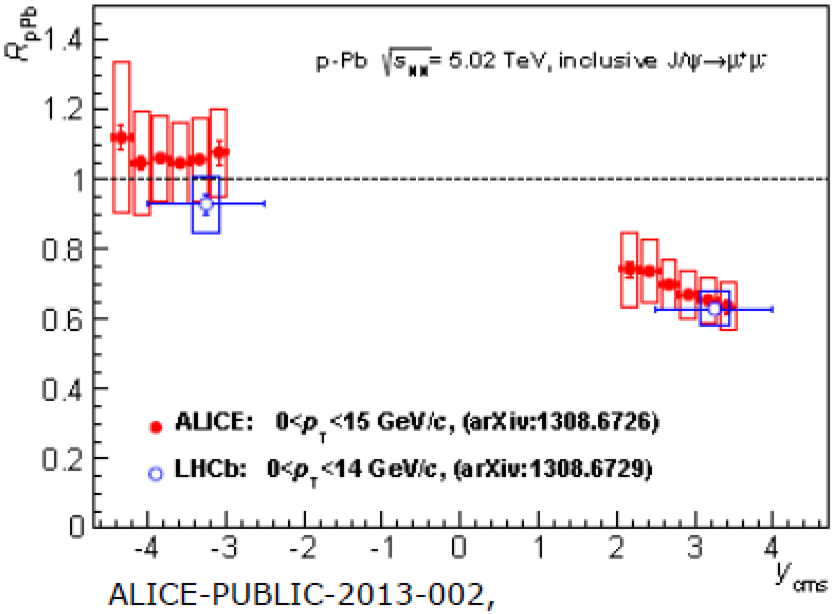


Suppression of Y(1S) grows with centrality.

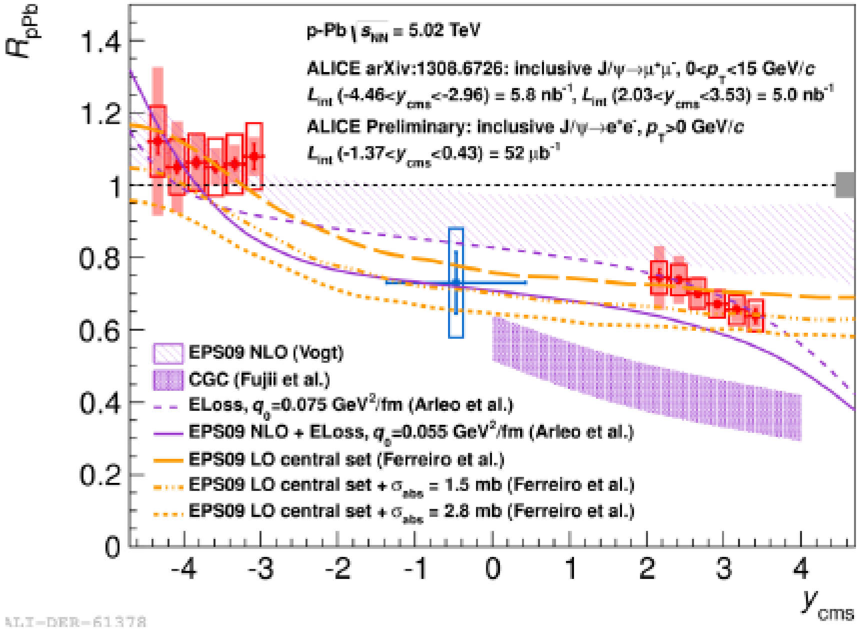
Larger suppression compared to measured by CMS at mid-rapidity.

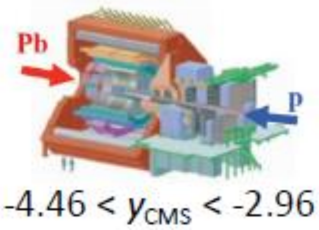
Theoretical transport model (suppression and regeneration plus CNM effects) underestimates the observed suppression both for centrality and rapidity dependences.

CNM: J/ψ suppression at LHC in pPb and Pbp vs y



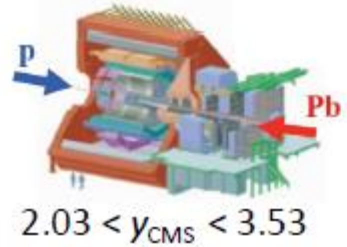
ALICE-PUBLIC-2013-002,
LHCb-CONF-2013-013





Backward

Forward



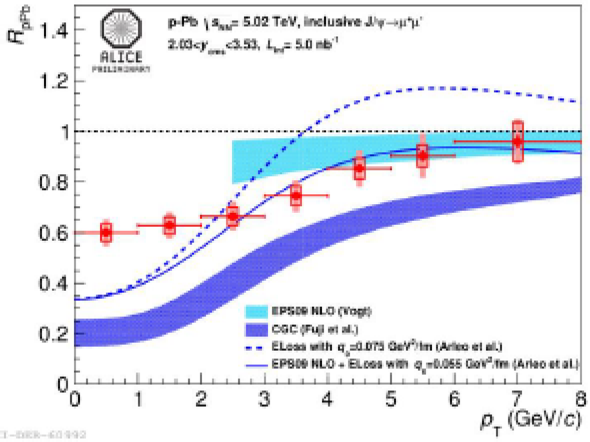
Very good agreement between ALICE and LHCb results.

Theoretical models: agreement with shadowing EPS09 NLO (R.Vogt) and LO (E.Ferreiro) results and Eloss (F.Arleo et al.) calculations.

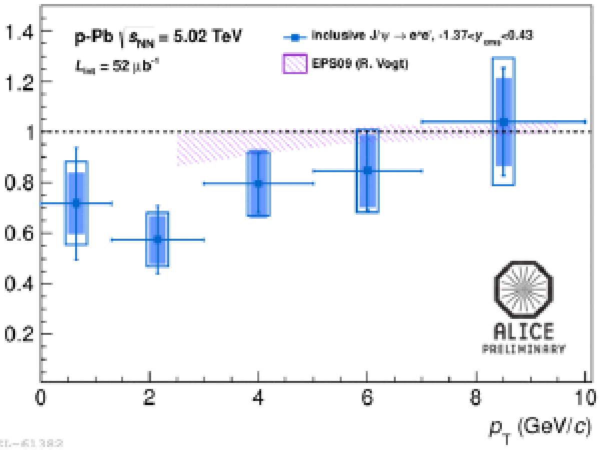
CGC (H.Fujii et al.) could not describe the data.

CNM: J/ψ suppression at LHC in pPb and Pbp vs pt

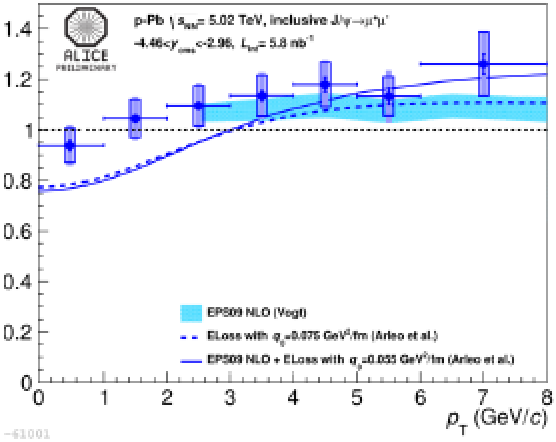
Forward rapidity



Mid-rapidity



Backward rapidity

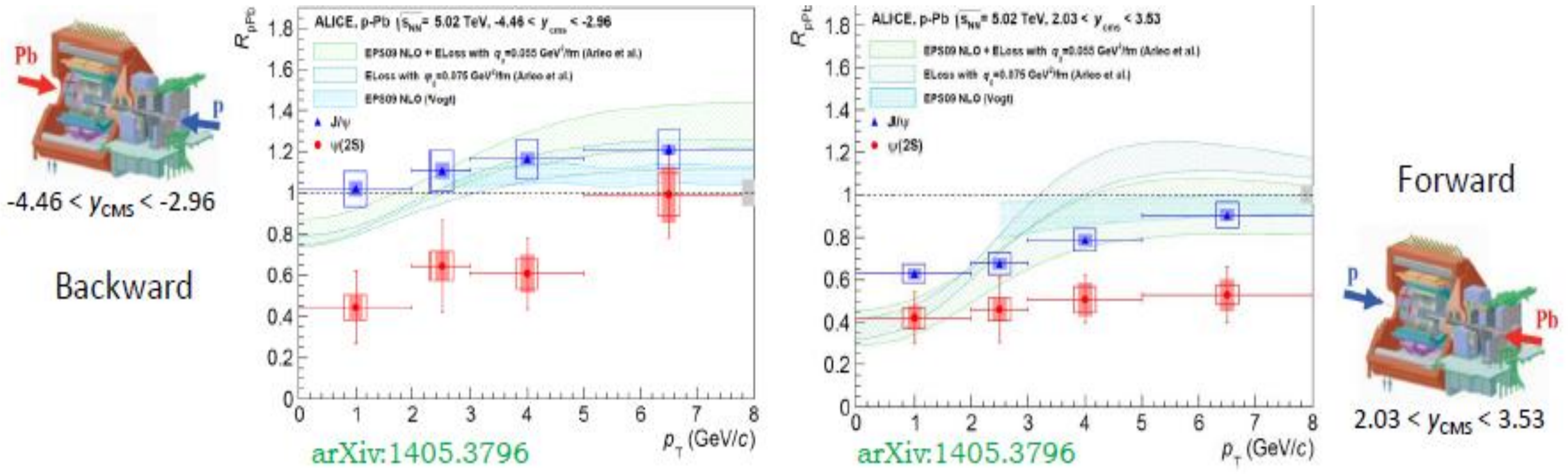


Theoretical models: agreement with shadowing EPS09 NLO (R.Vogt) and LO (E.Ferreiro) results

and Eloss (F.Arleo) calculations.

CGC (H.Fujii et al.) could not describe the data.

R_{pPb} ALICE data for J/ψ and ψ(2S) vs pt



arXiv:1405.3796

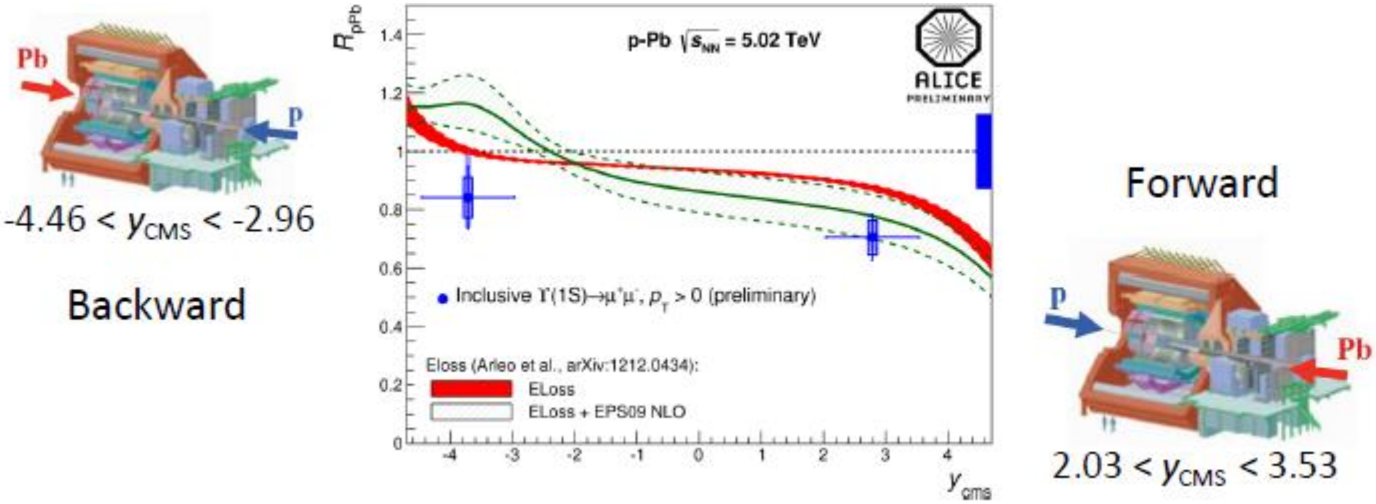
arXiv:1405.3796

Suppression for ψ(2S) is systematically higher than for J/ψ, but has the same behavior.

Theoretical models predict almost the same suppression for both resonances.

Initial state effects alone could nor describe ψ(2S) data – final state effects should be taken into account.

R_{pPb} ALICE data for inclusive γ(1s) vs y



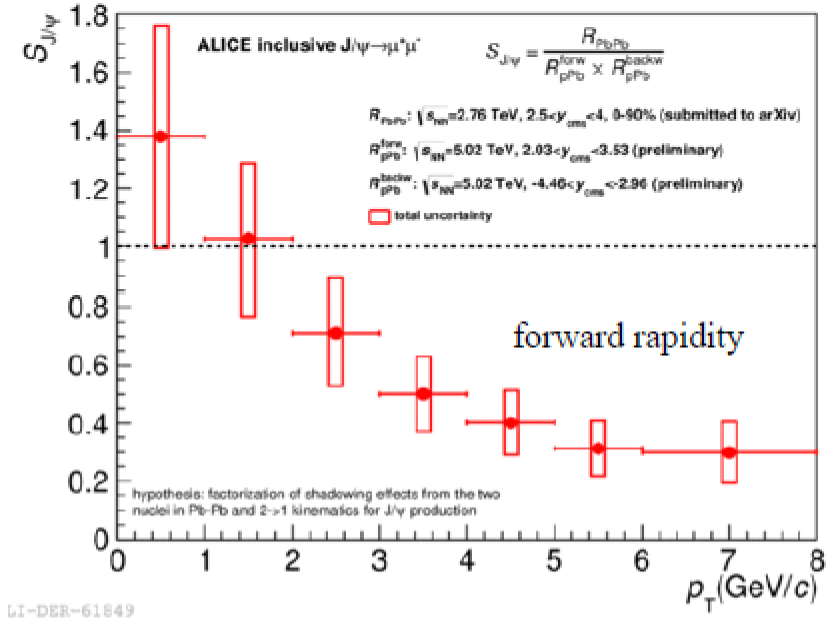
Only energy loss plus shadowing can describe the data at forward rapidity but these models underestimate the suppression at backward rapidity.

R_{AA} (PbPb) for forward rapidity vs transverse momentum without shadowing effect

factorization of shadowing effects in p-Pb and Pb-Pb:

$$R^{shad}_{PbPb} = R_{pPb} \times R_{Pbp}$$

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



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?

Conclusions

- Quarkonium production is a useful probe for the QGP formation and for testing pQCD models in pp-scattering.
- **J/ψ, $\psi(2S)$ and $\Upsilon(1S)$** differential cross sections in **pp**-scattering could be described by NLO NRQCD models.
- For **pPb** suppression+ shadowing+energy loss models reproduce **J/ψ,** but fail to describe additional suppression of **$\psi(2S)$** and underestimate the observed **$\Upsilon(1S)$** suppression at forward rapidity.
- Evidence for additional **J/ψ** production from regeneration at low pt in **PbPb** collisions.

Our suggestion to measure charmonium production at LHC with fixed targets for lower energy with high statistic to clarify the mechanism of production.

As it was already used for the experiment on collider with a fixed target at HERA-B K.Ehret, Nucl. Instr. Meth. A 446 (2000) 190, the target in the form of thin ribbon could be placed around the main orbit of LHC. The life time of the beam is determined by the beam-beam and beam-gas interactions. Therefore after some time the particles will leave the main orbit and interact with the target ribbon. So for fixed target measurements only halo of the beam will be used. Therefore no deterioration of the main beam will be introduced. The experiments at different interaction points will not feel any presence of the fixed target.

Fixed-target 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)

AA collisions

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

pA collisions

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

Fixed-target (at LHC) — energy between SPS and RHIC

was suggested in 2005 and then in 2009 at CERN Workshop "New opportunities at CERN". A.B.Kurepin, N.S.Topilskaya, M.B.Golubeva

Phys.Atom.Nucl.74:446-452, 2011.

AA collisions

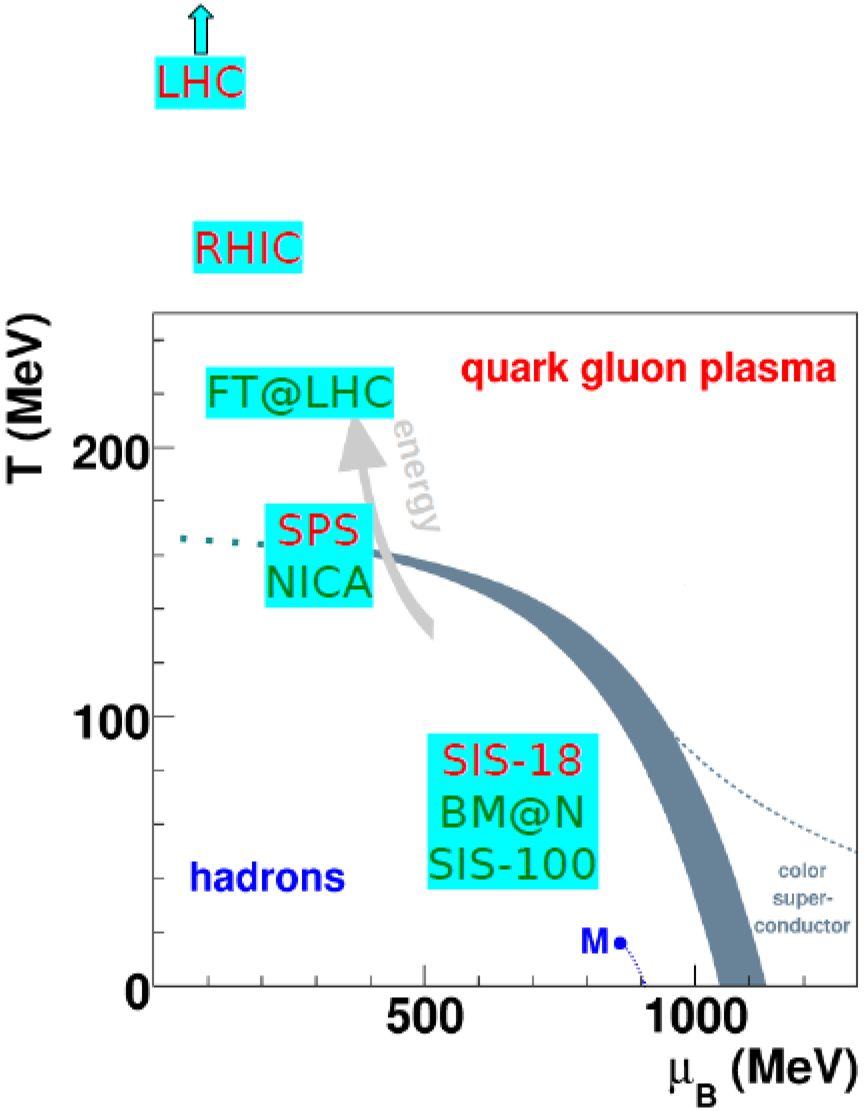
Pb-Pb 2750 GeV/nucleon, $\sqrt{s}$ = 71.8 GeV

pA collisions

p-A 7000 GeV , $\sqrt{s}$ = 114.6 GeV
(5000 GeV, $\sqrt{s}$ = 96.9 GeV)

Existing and future experiments in heavy ion collisions

energy (GeV)	accelerator/exps accelerator/exps
~2	SIS-18/HADES BM@N SIS-100/HADES-CBM
~10	SPS/NA61 SPS/NA61+/CHIC NICA/MPD/AFTER RHIC/BES II
~100	RHIC/STAR,PHENIX FT@LHC
~1000	LHC/ALICE,ATLAS,CMS

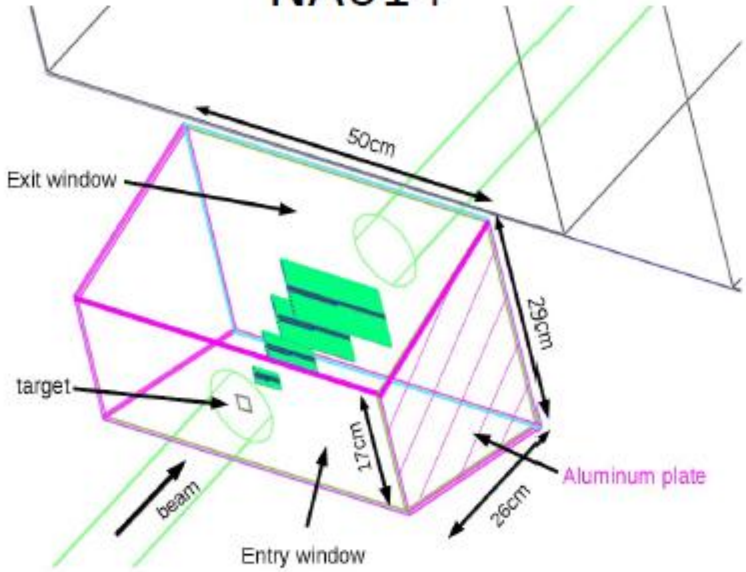


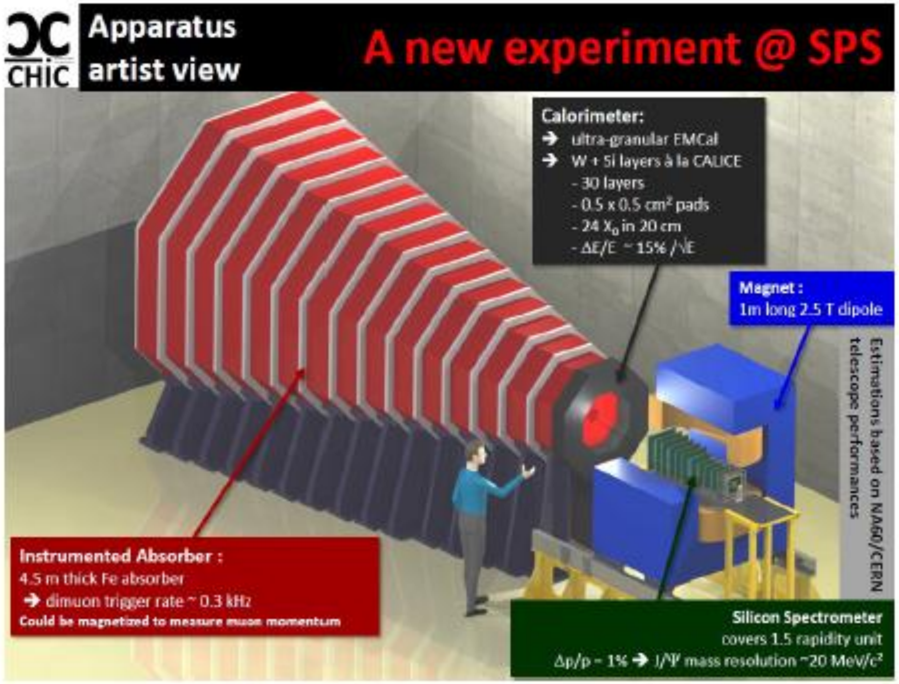
SPS, CERN, Geneva (~2017-...)

Experiments: NA61+ (open charm), CHIC (charmonia), NA60+

Energy: up to 158*A* GeV, Beams: from p to Pb

NA61+





Apparatus artist view

A new experiment @ SPS

Calorimeter:
- → ultra-granular EMCal
- → W + Si layers à la CALICE
  - 30 layers
  - 0.5×0.5 cm² pads
  - 24 X_0 in 20 cm
  - $\Delta E/E \sim 15\% / \sqrt{E}$

Magnet :
1m long 2.5 T dipole

Instrumented Absorber :
4.5 m thick Fe absorber
→ dimuon trigger rate ~ 0.3 kHz
Could be magnetized to measure muon momentum

Silicon Spectrometer
covers 1.5 rapidity unit
$\Delta p/p \sim 1\% \rightarrow J/\Psi$ mass resolution ~20 MeV/c²

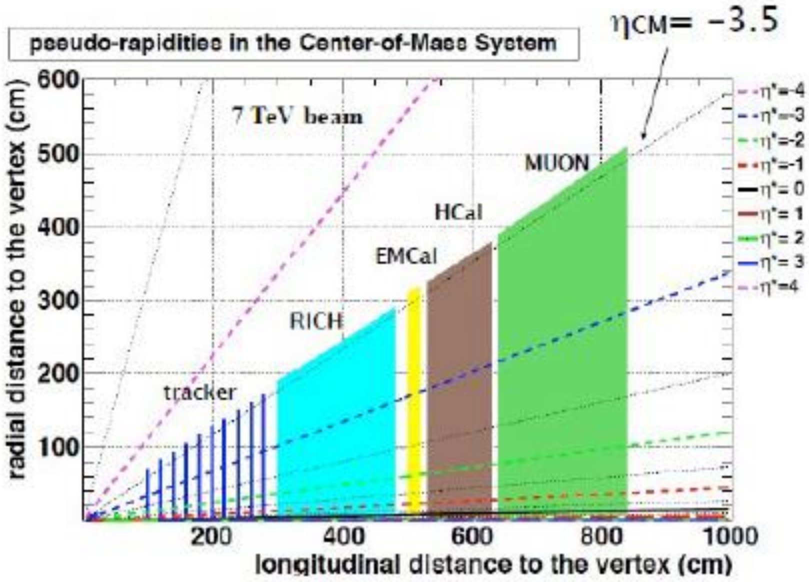
FT@LHC, CERN, Geneva (~20??-...)

Experiments: AFTER (quarkonia), ...

Energy: up to 2.76*A* TeV, Beams: from p to Pb

A tentative design for AFTER

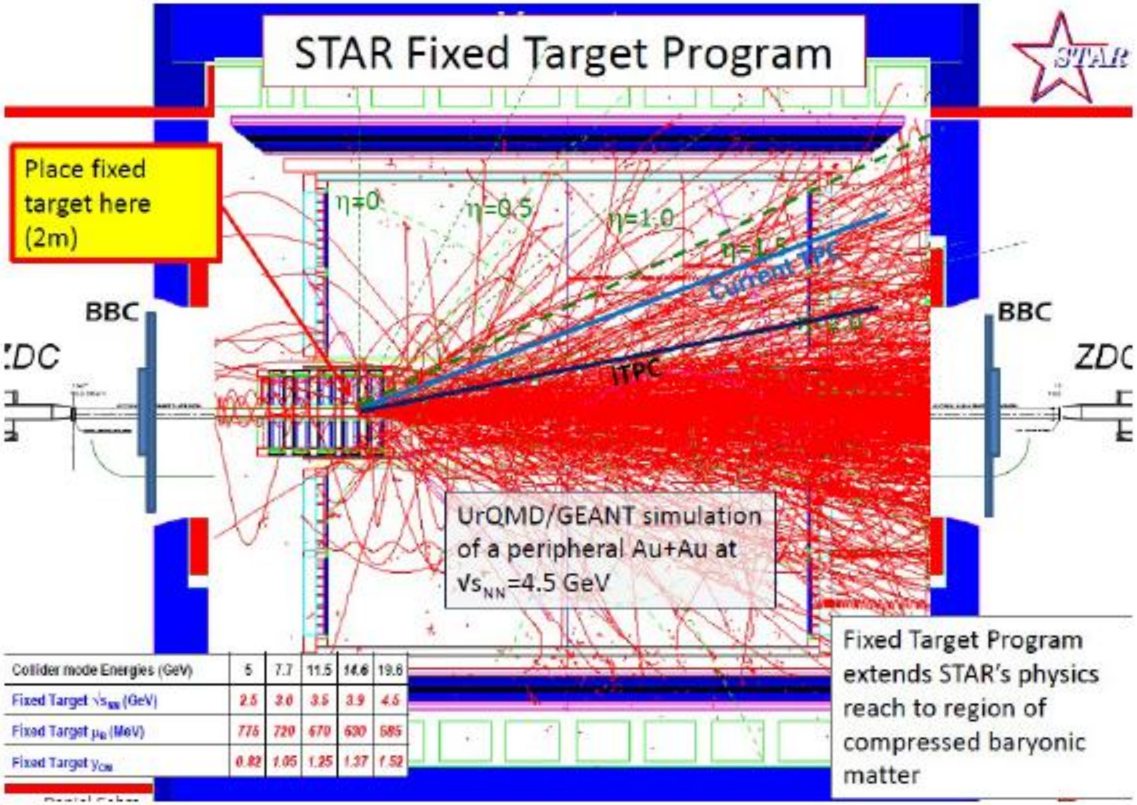
- **Tentative design** $1.3 < y_{lab} < 5.3$
  - With 7 TeV beam : $-3.5 < y_{CM} < 0.5$
  - With 2.76 TeV beam: $-3 < y_{CM} < 1$
  - $\theta_{min} = 10$ mrad
- **Multi-purpose detector**
  - Vertex
  - Tracking (+ dipole magnet)
  - RICH
  - Calorimetry
  - Muons
- **High boost** → forward and as compact as possible detector



BES-II, RHIC, Brookheaven (~2017-2018?)

Experiments: STAR+, PHENIX+

Energy: 3-20 GeV *(N+N c.m.s. energy)* Beams: from p to Au



STAR Fixed Target Program

Place fixed target here (2m)

UrQMD/GEANT simulation of a peripheral Au+Au at $\sqrt{s_{NN}}$=4.5 GeV

Fixed Target Program extends STAR's physics reach to region of compressed baryonic matter

Collider mode Energies (GeV)	5	7.7	11.5	14.6	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	2.5	3.0	3.5	3.9	4.5
Fixed Target μ_B (MeV)	775	720	670	630	585
Fixed Target y_{CM}	0.82	1.05	1.25	1.37	1.52

Luminosity, cross sections($x_F>0$) , counting rates for fixed target experiment at LHC by dimuon spectrometer of ALICE

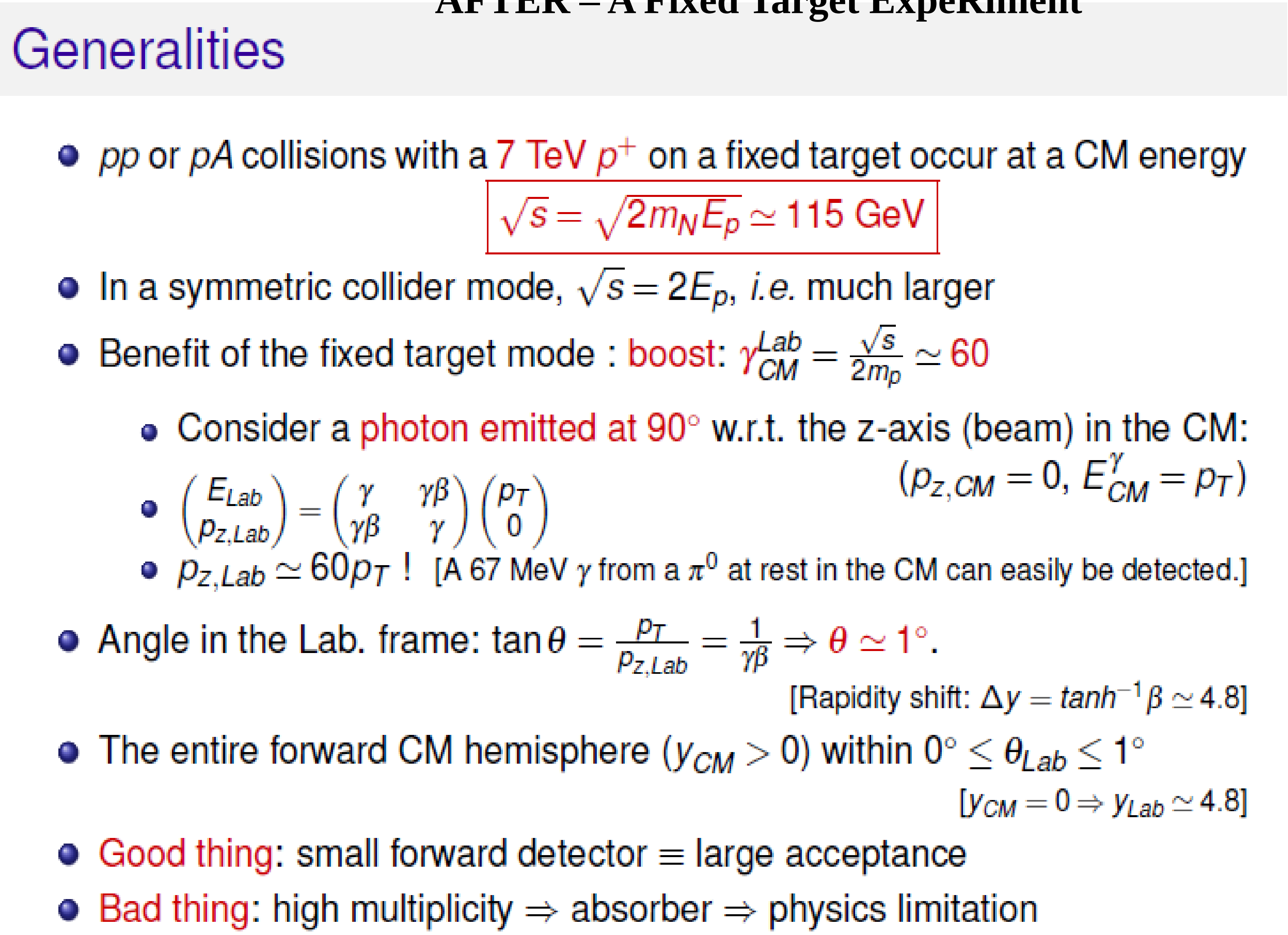
System	$\sqrt{s}$ (TeV)	σ_{nn} (μb)	$\sigma_{pA}=\sigma_{nn}\cdot A^{0.92}$ (μb)	I (%)	$I\cdot B\cdot\sigma_{pA}$ (μb)	L ($cm^{-2}s^{-1}$)	Rate ($hour^{-1}$)
pp	14	54.1	54.1	4.71	0.150	$3\cdot10^{30}$	1620
pp_{RHIC}	0.200	2.7	2.7	3.59	0.0057	$1\cdot10^{31}$	205
pPb_{fixed}	0.1146	0.65	88.2	5.98	0.310	$3\cdot10^{30}$(*)	3360
pPb_{fixed}	0.0718	0.55	74.6	7.97	0.349	$3\cdot10^{30}$(*)	3780
pPb_{NA50}	0.0274	0.19	25.8	14.0	0.212	$7\cdot10^{29}$	535
$PbPb_{fixed}$	0.0718	0.55	11970	7.97	47.9	$1.7\cdot10^{27}$(**)	292

(*) pPb_{fixed}, 500 μ wire, $3.1\cdot10^9$ protons/s

(**) $PbPb_{fixed}$, 500 μ wire, $1.4\cdot10^6$ ions/s

1. The integrated geometrical acceptances for charmonium measurement by dimuon spectrometer of ALICE are
   5.76% for $\sqrt{s}=5.5$ TeV Pb-Pb and
   4.71% for $\sqrt{s}=14$ TeV pp collisions.
2. For fixed target charmonium measurement in $2.5<y<4$ range the geometrical acceptances are of the same order and even larger: 7.97% for $\sqrt{s}=71.8$ GeV Pb-Pb
   and 5.98% for $\sqrt{s}=114.6$ GeV pA at $z=+50$ cm.
   The acceptances are compatible with the acceptances from other experiments.
3. The measurement in energy range for fixed target experiment between SPS and RHIC with high statistics gives important additional information for charmonium production.

AFTER – A Fixed Target ExpeRiment



Generalities

- pp or pA collisions with a 7 TeV p^+ on a fixed target occur at a CM energy

$$\boxed{\sqrt{s} = \sqrt{2m_N E_p} \simeq 115\ \mathrm{GeV}}$$

- In a symmetric collider mode, $\sqrt{s} = 2E_p$, *i.e.* much larger
- Benefit of the fixed target mode : boost: $\gamma^{Lab}_{CM} = \frac{\sqrt{s}}{2m_p} \simeq 60$
  - Consider a photon emitted at 90° w.r.t. the z-axis (beam) in the CM: $(p_{z,CM} = 0,\ E^{\gamma}_{CM} = p_T)$
  - $\begin{pmatrix} E_{Lab} \\ p_{z,Lab} \end{pmatrix} = \begin{pmatrix} \gamma & \gamma\beta \\ \gamma\beta & \gamma \end{pmatrix} \begin{pmatrix} p_T \\ 0 \end{pmatrix}$
  - $p_{z,Lab} \simeq 60 p_T$! [A 67 MeV γ from a π^0 at rest in the CM can easily be detected.]
- Angle in the Lab. frame: $\tan\theta = \frac{p_T}{p_{z,Lab}} = \frac{1}{\gamma\beta} \Rightarrow \theta \simeq 1^\circ$.

[Rapidity shift: $\Delta y = tanh^{-1}\beta \simeq 4.8$]

- The entire forward CM hemisphere ($y_{CM} > 0$) within $0^\circ \leq \theta_{Lab} \leq 1^\circ$

[$y_{CM} = 0 \Rightarrow y_{Lab} \simeq 4.8$]

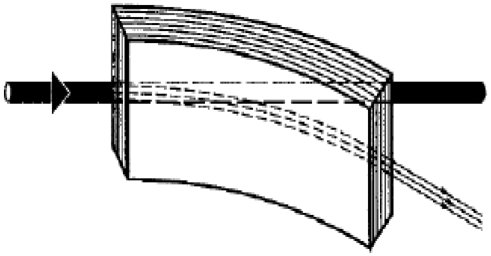
- Good thing: small forward detector ≡ large acceptance
- Bad thing: high multiplicity ⇒ absorber ⇒ physics limitation

The beam extraction

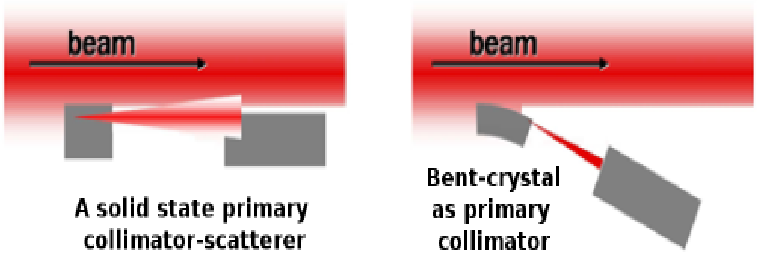
- ★ The LHC beam may be extracted using “Strong crystalline field”

  without any decrease in performance of the LHC !

  E. Uggerhøj, U.I Uggerhøj, NIM B 234 (2005) 31, Rev. Mod. Phys. 77 (2005) 1131



- ★ Illustration for collimation



- ★ Tests will be performed on the LHC beam:

  LUA9 proposal approved by the LHCC

Comparison with AFTER

AFTER has advantages:

- 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 1 meter-long 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, LHCb?)
- Possibility to measure charmonium production with rather high statistics on different targets in pA and PbA.

  First step to AFTER?

Backup

Now (*) from experimental ALICE 2011 year pp data we got $1.2 \cdot 10^{11}$ protons per bunch, 1380 bunches and life time 14.5 hours. We get particle loss of $1.1 \cdot 10^{13}$ p/hour ($3.1 \cdot 10^{9}$ p/s) and luminosity about $5 \cdot 10^{30}$ cm^{-2} s^{-1} for 500 micron lead ribbon

Mean luminosity ~ $3 \cdot 10^{30}$ cm^{-2} s^{-1} (3 μb^{-1} s^{-1}).

$\int Ldt$ = 30 pb^{-1} yr^{-1}). Yr (p)= 10^{7} s.

For PbPb (**) we got $1 \cdot 10^{8}$ protons per bunch, 358 bunches and life time 6.5 hours. We get particle loss of $5.1 \cdot 10^{9}$ Pb/hour ($1.4 \cdot 10^{6}$ Pb/s) and luminosity about $2.4 \cdot 10^{27}$ cm^{-2} s^{-1} for 500 micron lead ribbon. Mean L ~$1.7 \cdot 10^{27}$ cm^{-2} s^{-1} (1.7 mb^{-1} s^{-1}).

$\int Ldt$ = 1.7 nb^{-1} yr^{-1}. Yr (Pb) = 10^{6} s.