J/ψ production in pPb and PbPb collisions by CMS

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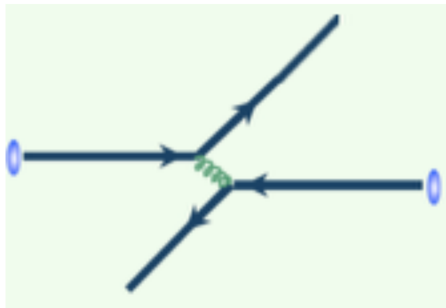
HIM 2014-12
Haeundae Grand Hotel, Busan, Korea
5th-6th December 2014

Outline

- **Introduction – collision systems**
- **J/ψ in PbPb collisions**
  - Final state effects
  - CMS detector & analysis method
  - Nuclear modification factor R_{AA}
- **J/ψ in pPb(dAu) collisions**
  - Initial state effects
  - Nuclear modification factor R_{pPb} and R_{dAu}
  - Status of J/psi analysis in pPb with CMS
- **System size study – Cu+Au collisions**
- **Summary**

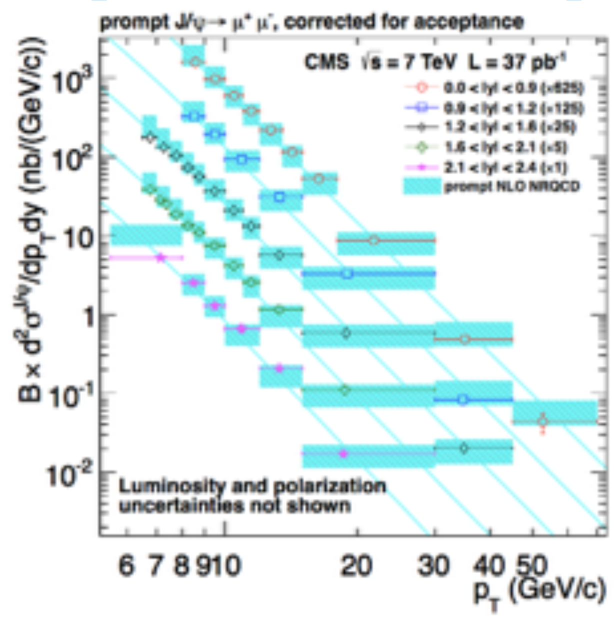
Collision systems

JHEP 02 (2012) 011 | PLB 727 (2013) 381

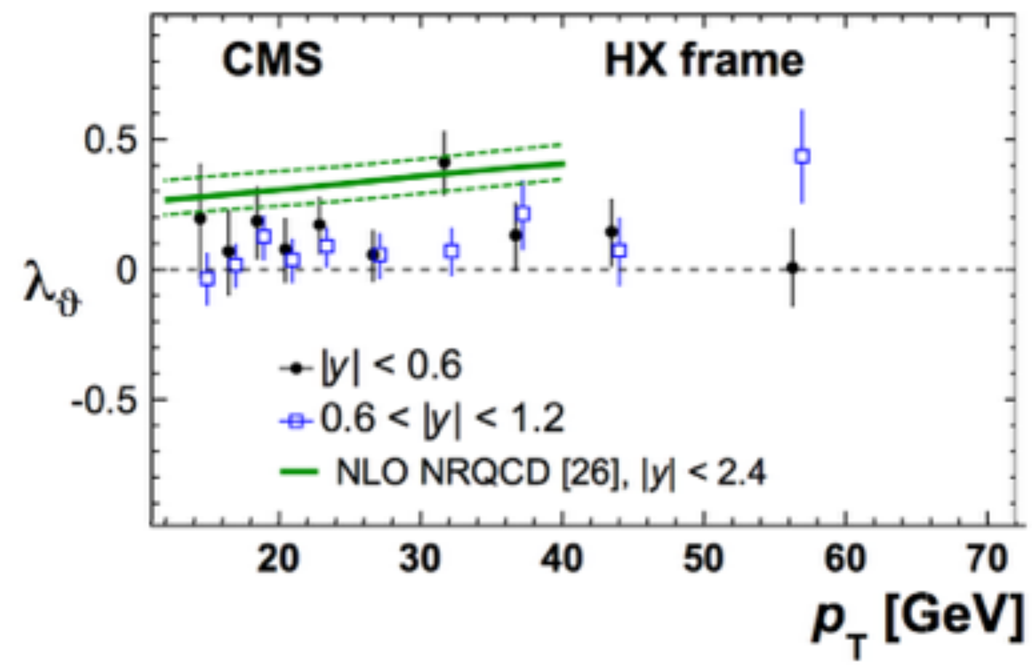


- **pp collisions**
  - No single hadro-production model describes all quarkonia data.

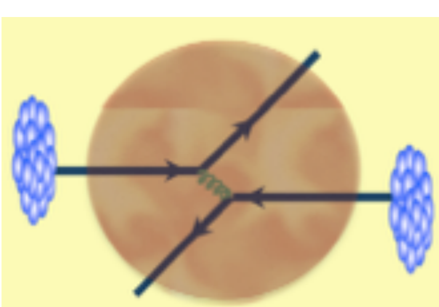
[cross section]



[polarization]



- **pPb collisions**
  - Cold Nuclear Matter effects
  - p_T broadening, Initial energy loss, absorption, nPDF, etc.



- **PbPb collisions**
  - Quark-Gluon plasma formation in central collisions (deconfined state of strongly interacting matter)
  - Sequential suppression, recombination, etc.

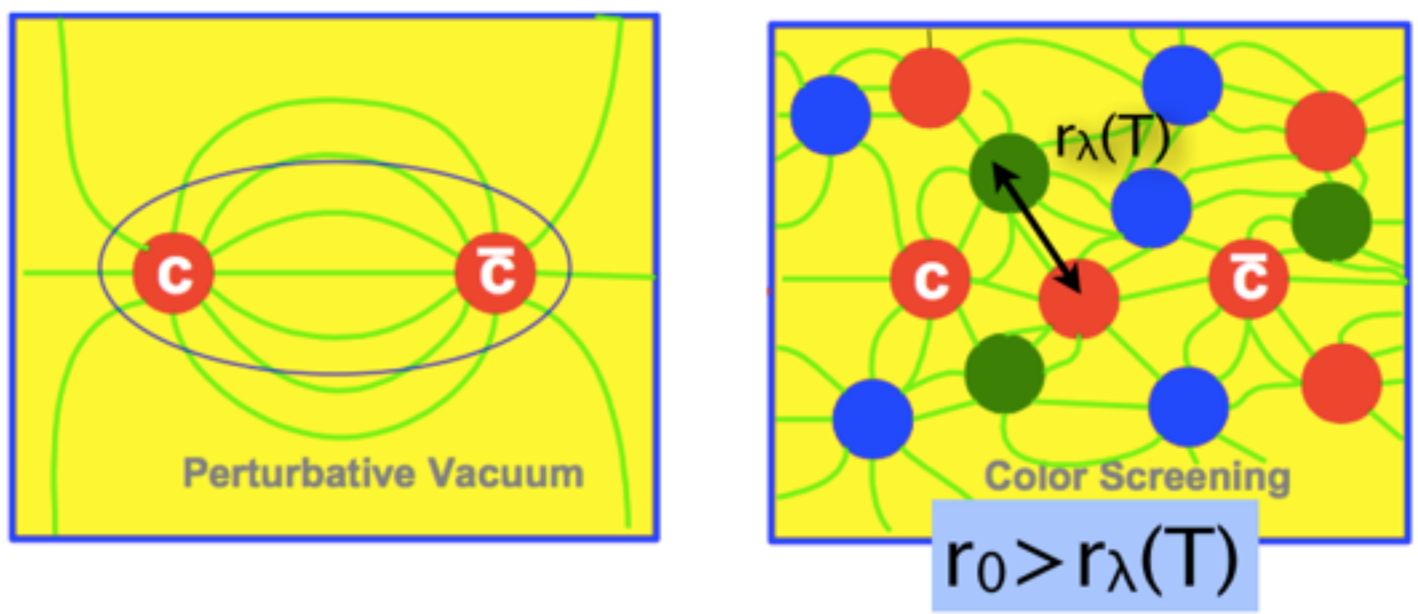
final state effects in PbPb

Quarkonia

- Bound states of heavy quark and antiquark
- Large mass requires a large momentum transfer during the early stage.
  ⇒ Powerful tool to probe QGP

Debye screening (suppression)

- Loosely bound states (with smaller binding energies) melt at lower temperature.
- Sequential melting of the quarkonia ⇒ Thermometer of QGP

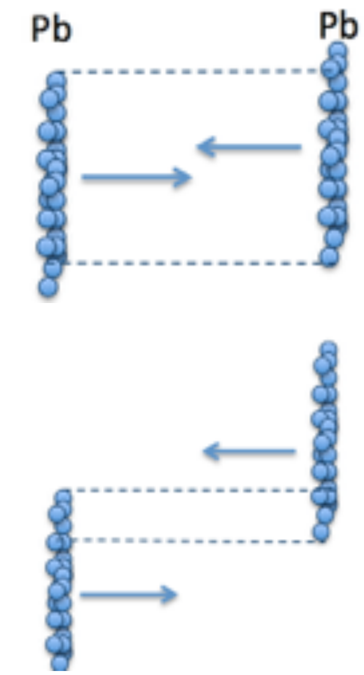


Recombination (enhancement)

- combination of quarks and antiquarks which are initially produced in “different” nucleon-nucleon collisions.

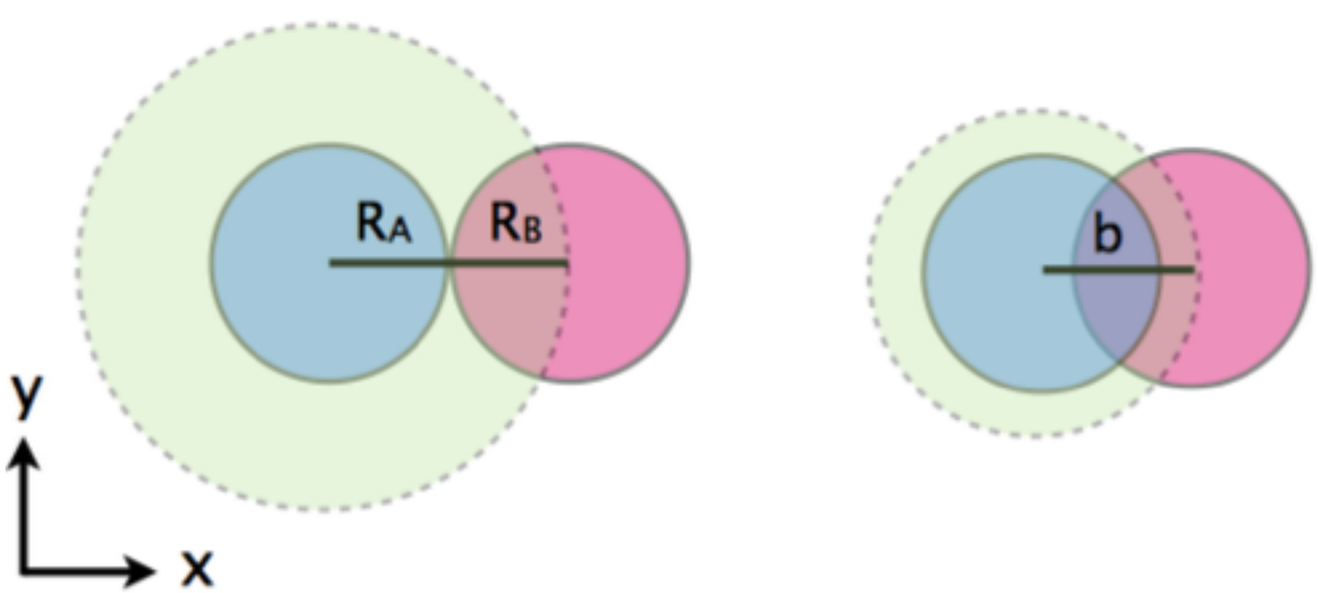
PLB 178 (1986) 416 | PLB 490 (2000) 196 | PRC 63 (2001) 054905

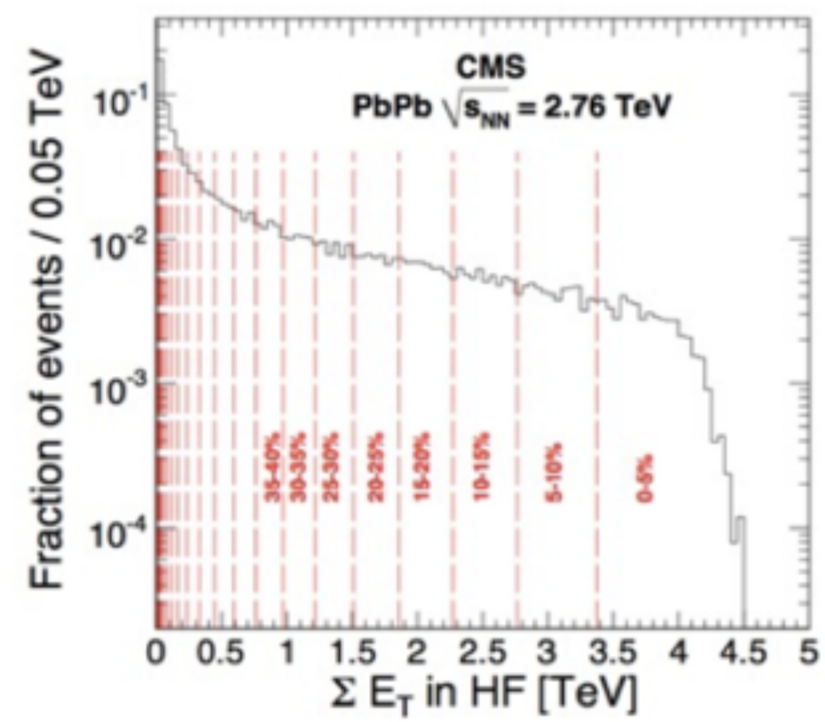
Centrality



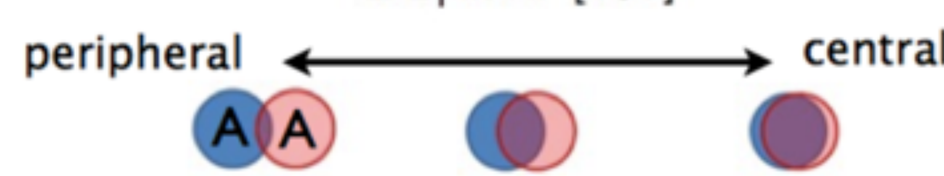
- **Centrality**
  - related to the overlap fraction of the geometrical cross sections
  - 0% is the most central, 100% is the most peripheral collisions.
  - In CMS experiment – defined by transverse energy deposit in HF

$[\sigma_{geom} \sim \pi(R_A+R_B)^2]$ $[\sigma_{reac} \sim \pi b^2]$

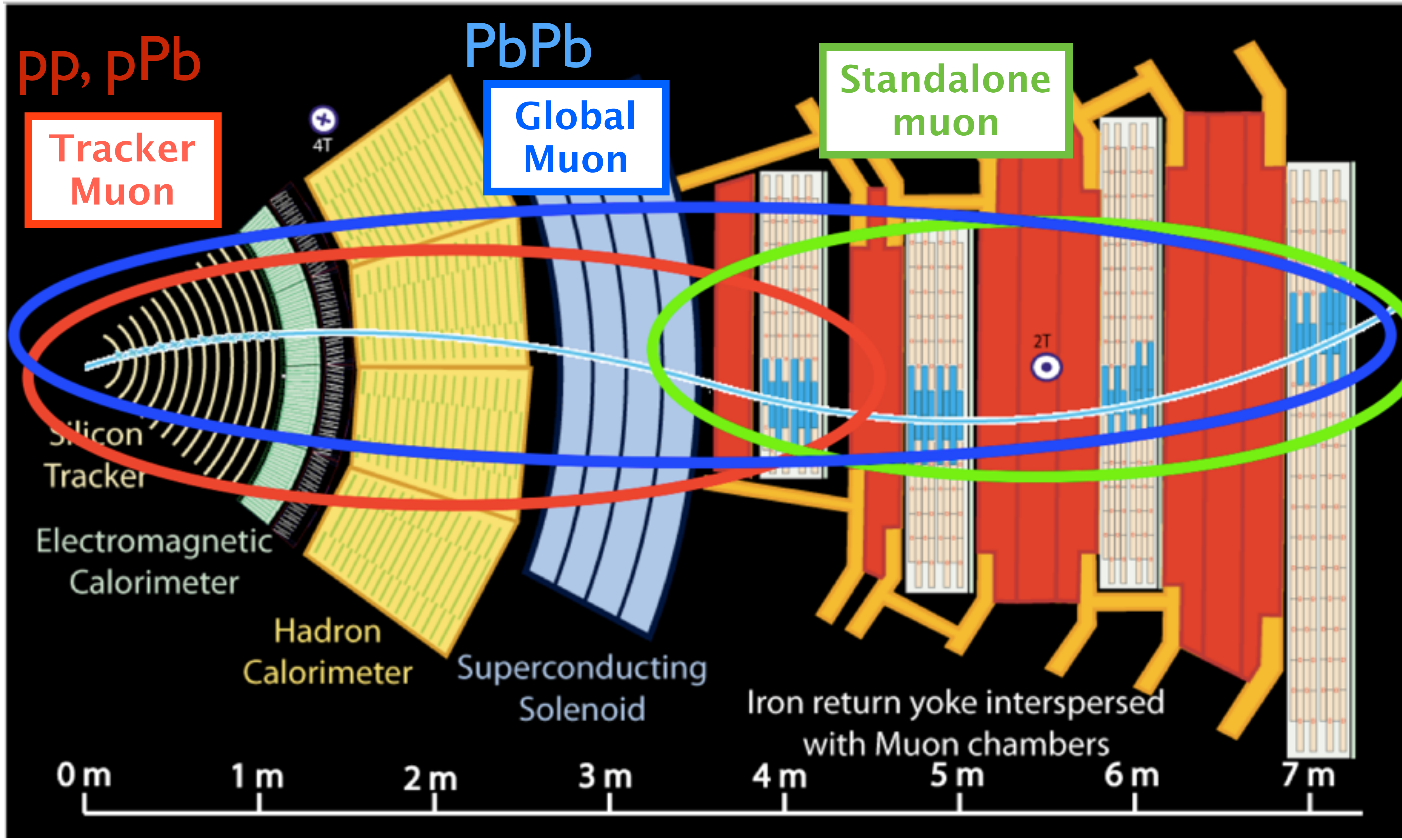




$$centrality(\%) = \frac{\sigma_{reac}}{\sigma_{geom}} \times 100$$



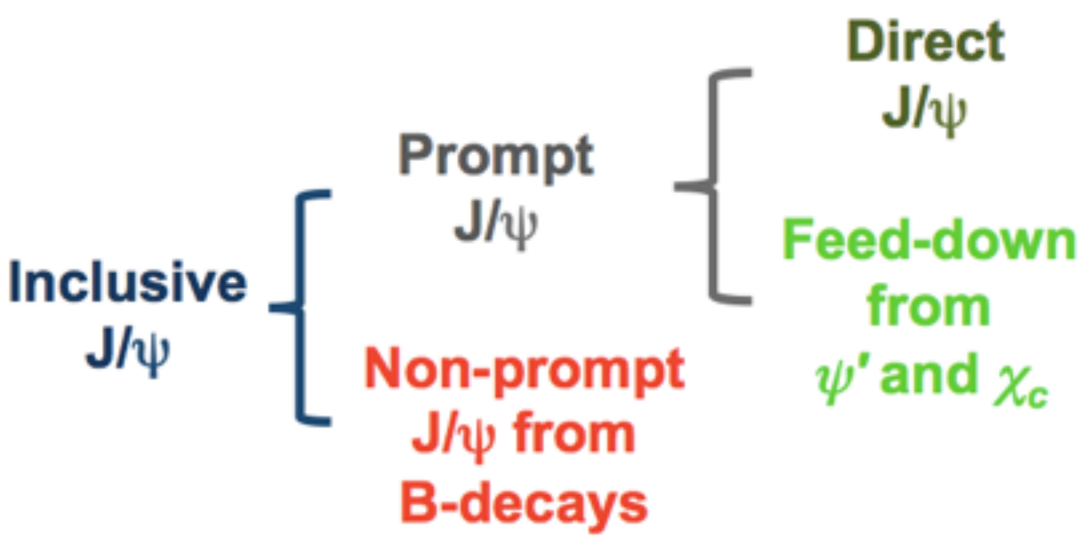
Muon Reconstruction



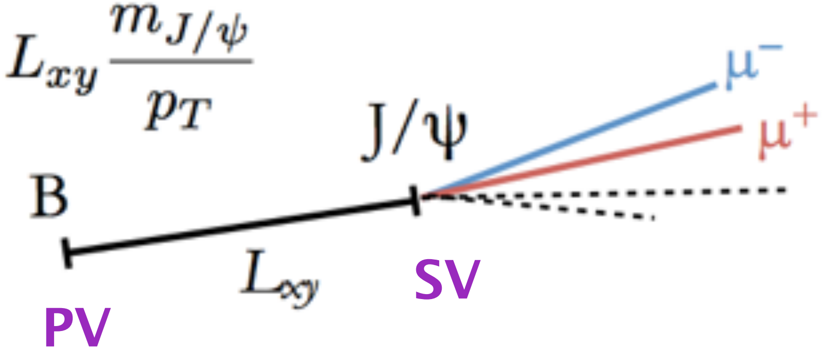
- Excellent muon Identification and triggering in the muon system
- High momentum and vertex resolution of the tracking system

Signal extraction

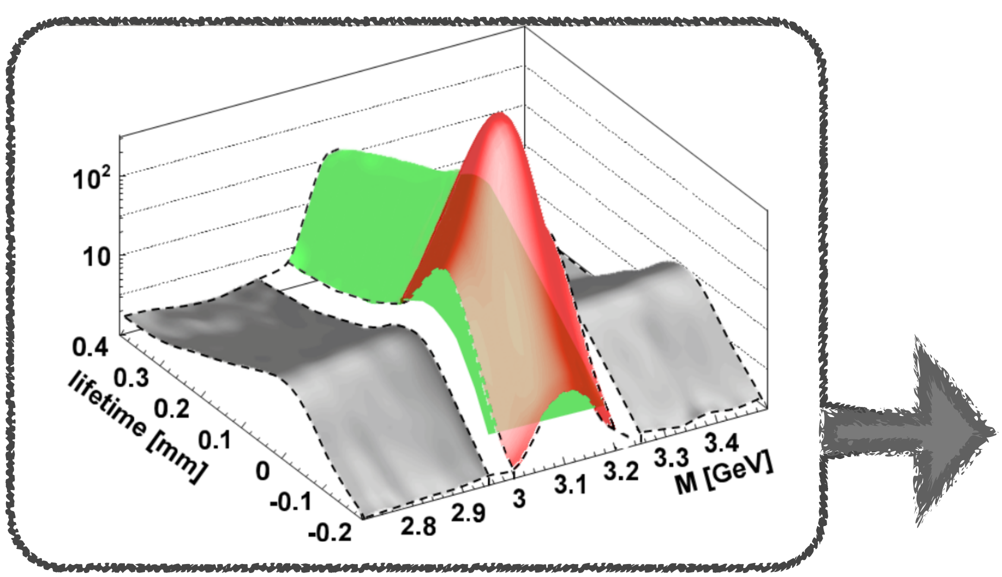
- **Separation of prompt J/ψ and non-prompt J/ψ**
  - 2-Dimensional simultaneous fit for $m_{\mu\mu}$ & $\ell_{J/\psi}$

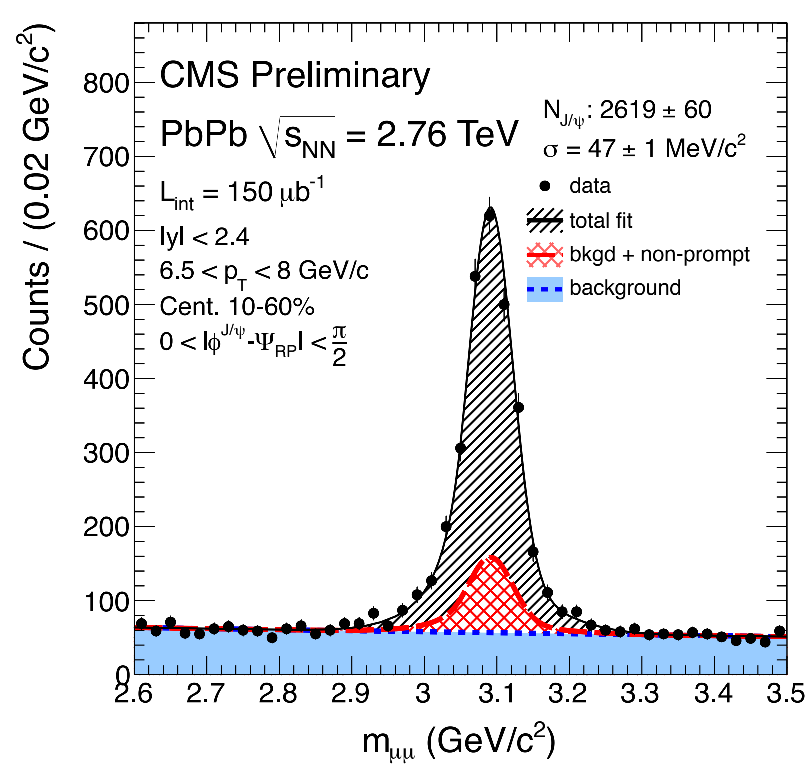


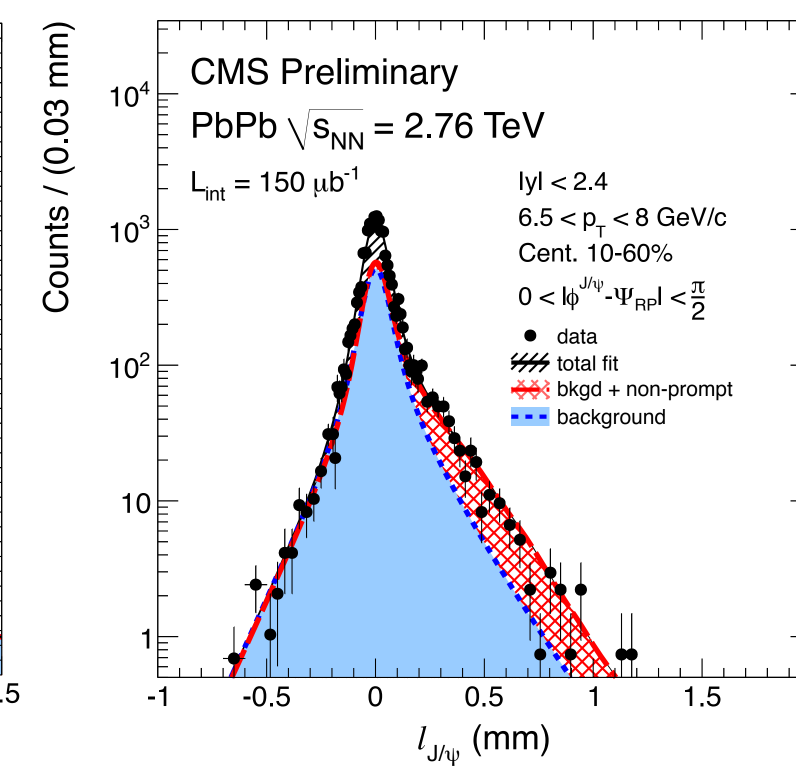
$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$



lifetime of the b hadrons ($\mathcal{O}(500)\ \mu m/c$)







CMS-PAS HIN-12-014

JHEP 05 (2012) 063

R_{AA} vs centrality

CMS-PAS HIN-12-014

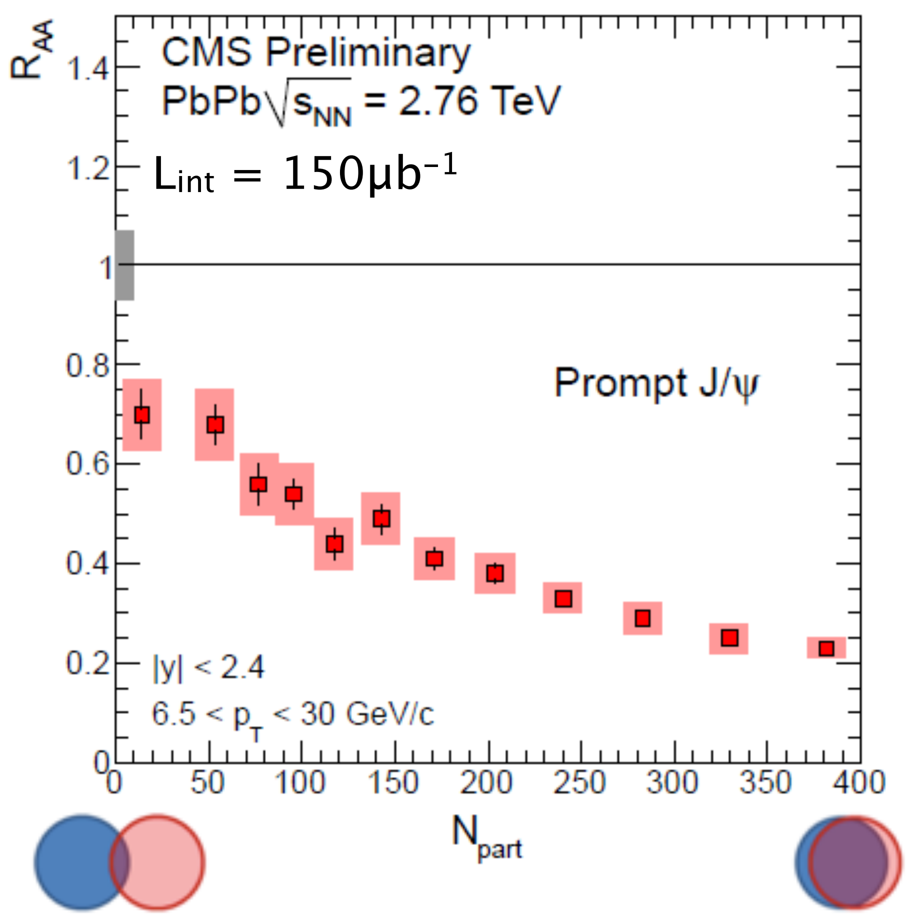
arXiv.1311.0214

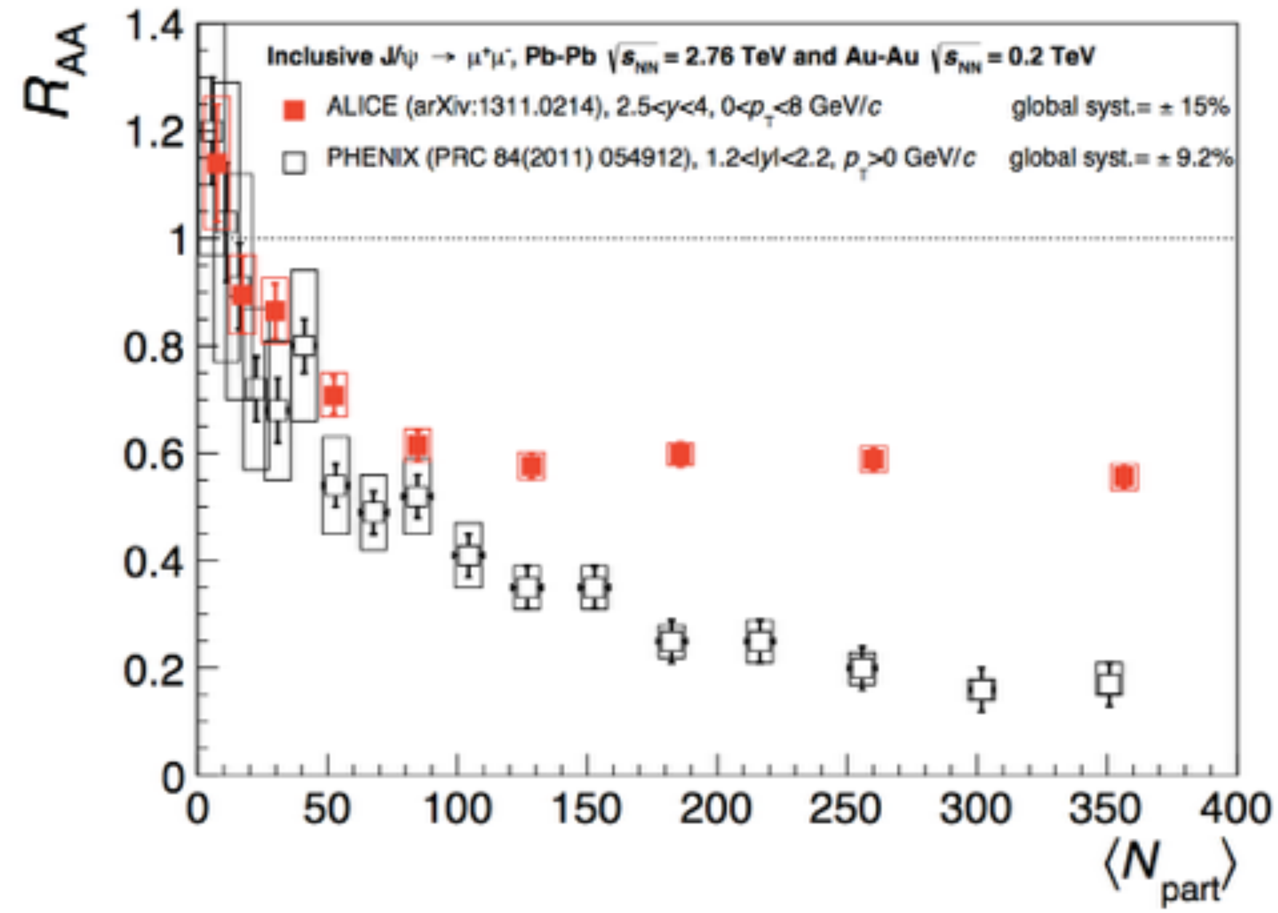
- **Nuclear modification factor**

$$R_{AA} = \frac{1}{< N_{coll} >} \frac{N_{AA}}{N_{pp}}$$

: R_{AA} =1 No modification compared to pp collisions

- **Centrality dependence**





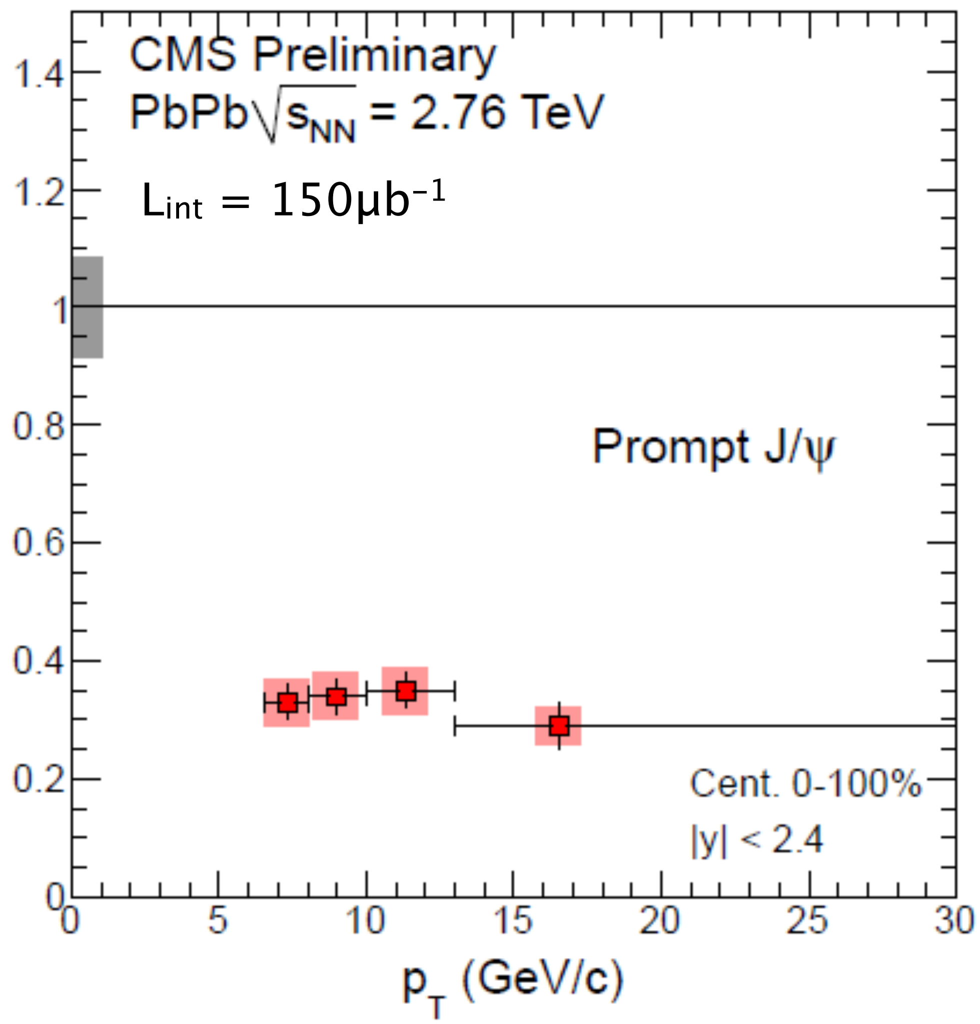
- Different kinematic ranges, different collision energies, prompt vs inclusive

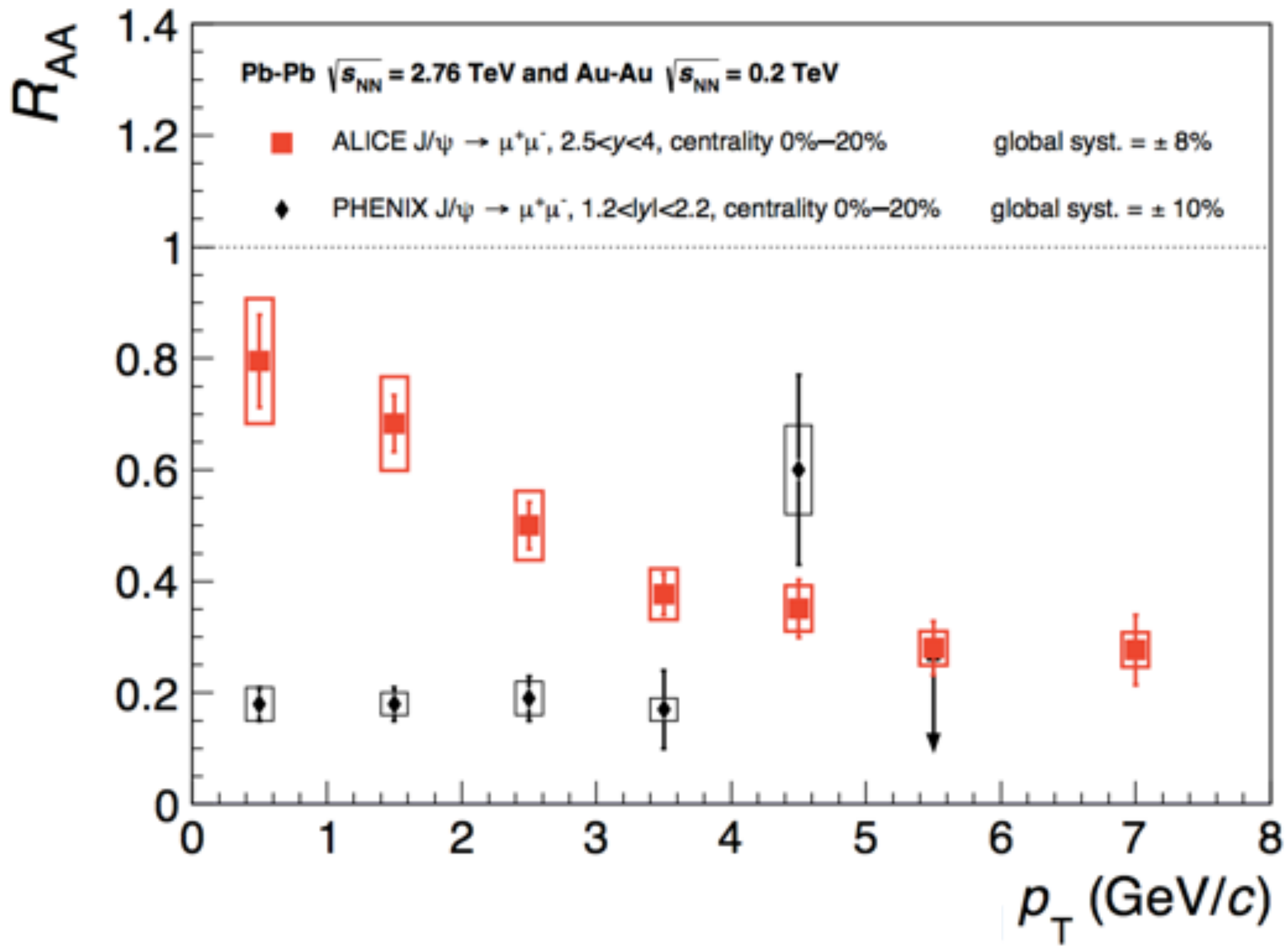
R_{AA} vs P_T

CMS-PAS HIN-12-014

arXiv.1311.0214

- **p_T dependence**





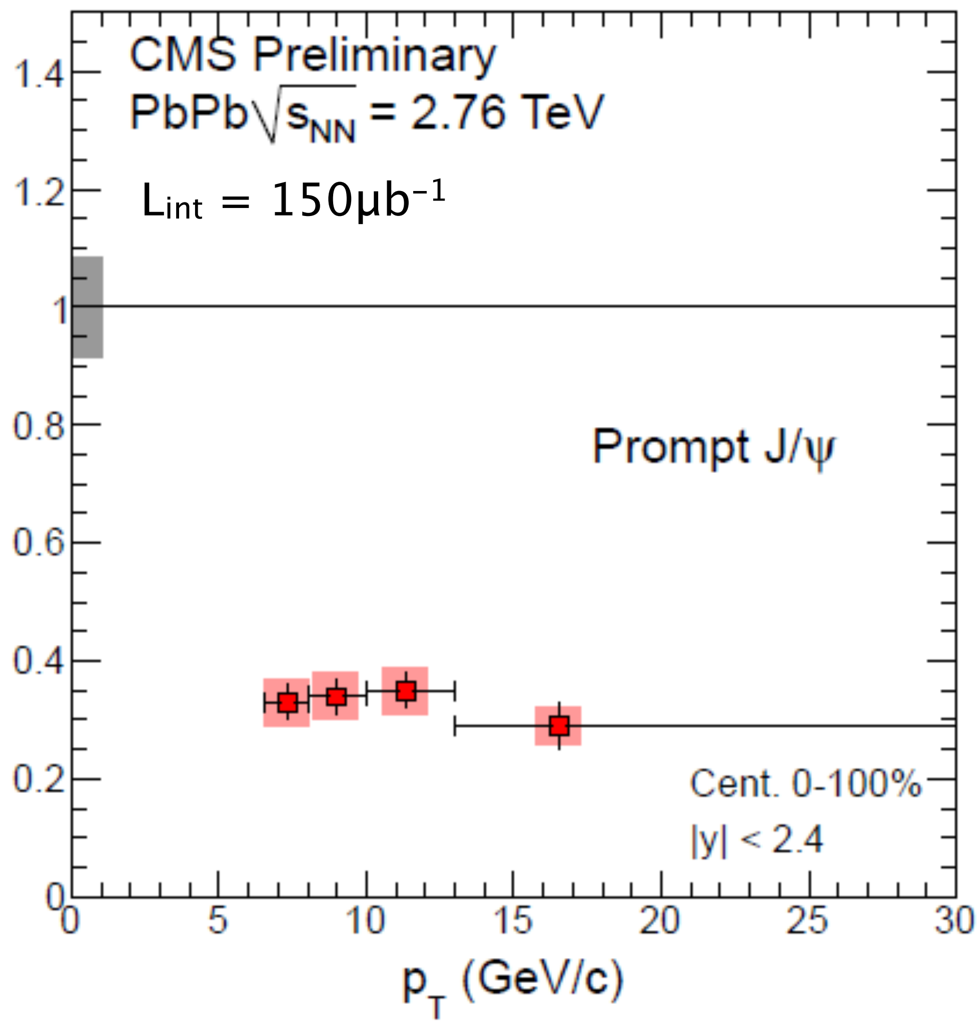
- CMS and ALICE show similar suppression in the overlapping p_T range.
- ALICE shows less suppression at low pT compared to PHENIX.

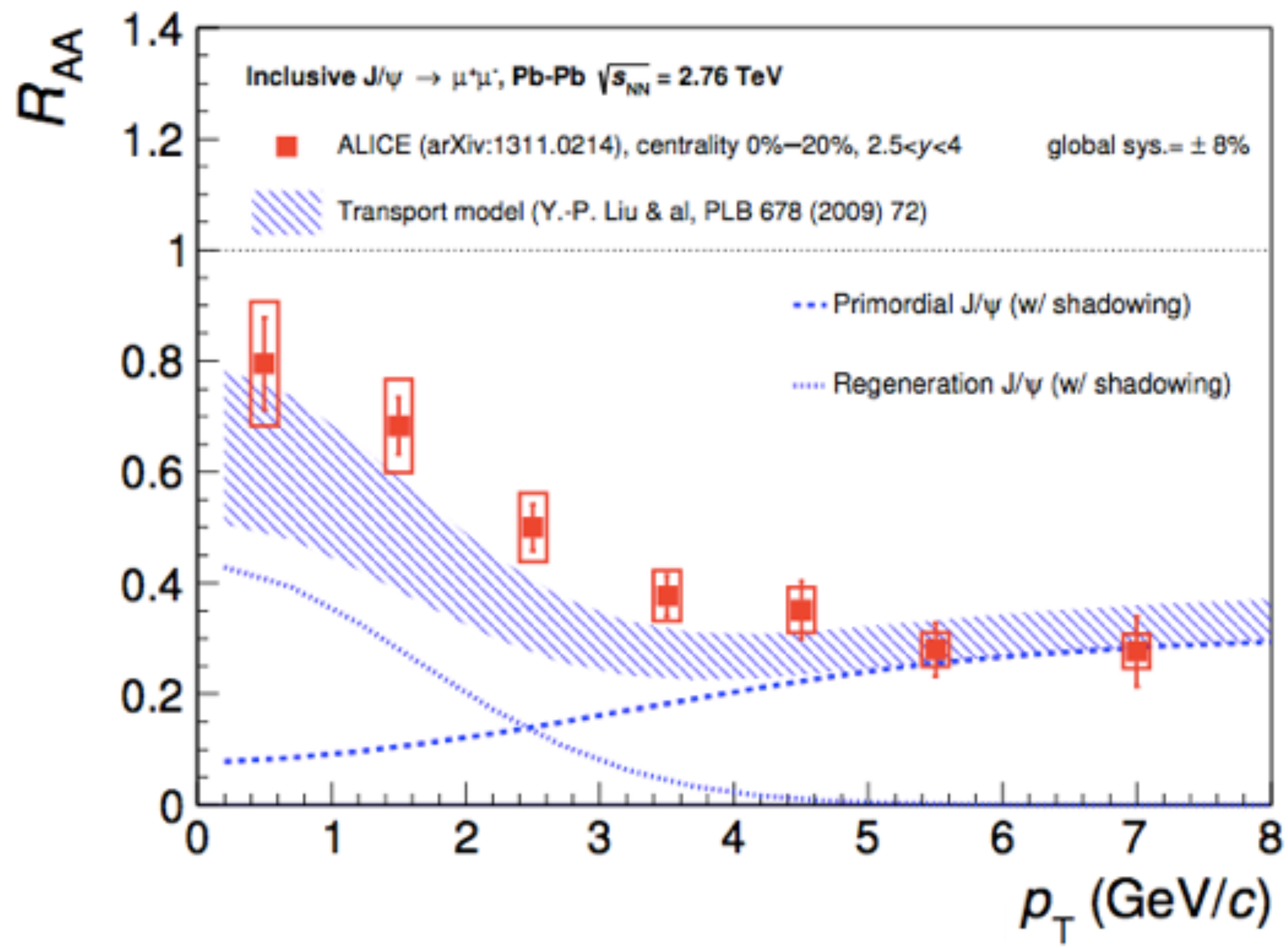
R_{AA} vs P_T

CMS-PAS HIN-12-014

arXiv.1311.0214

- **p_T dependence**





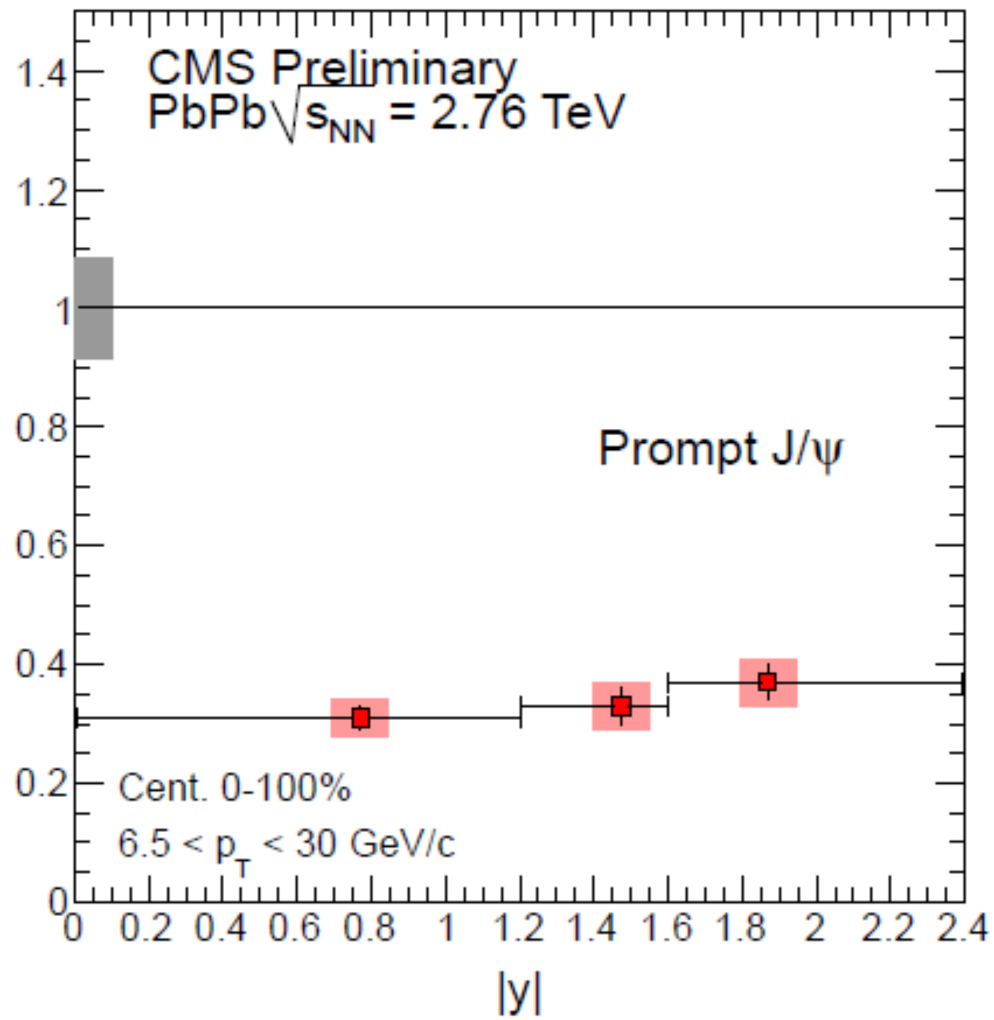
- CMS and ALICE show similar suppression in the overlapping p_T range.
- ALICE shows less suppression at low pT compared to PHENIX.
  → Recombination contribution important at low p_T?

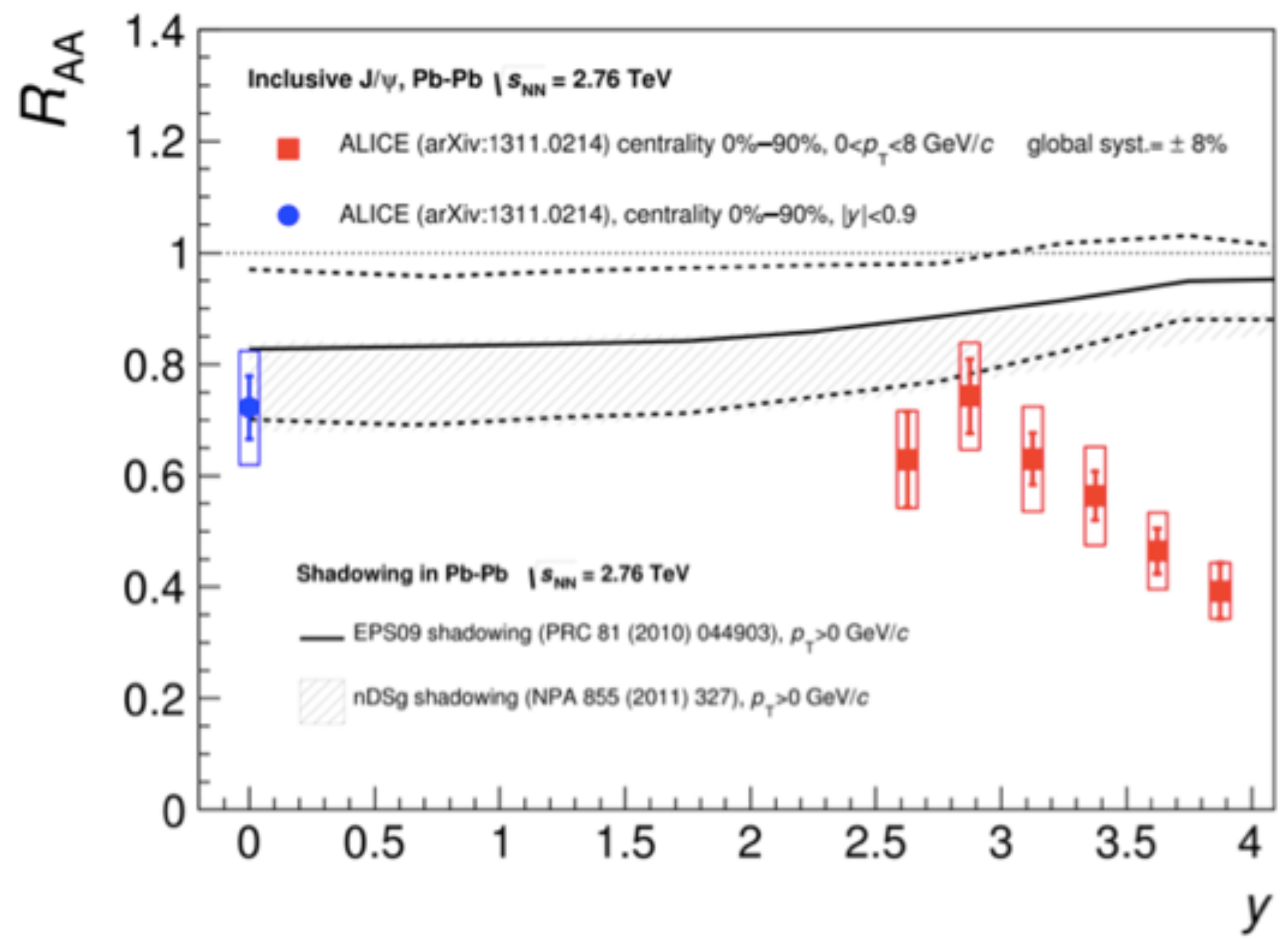
R_{AA} vs rapidity

CMS-PAS HIN-12-014

arXiv.1311.0214

- **Rapidity dependence**

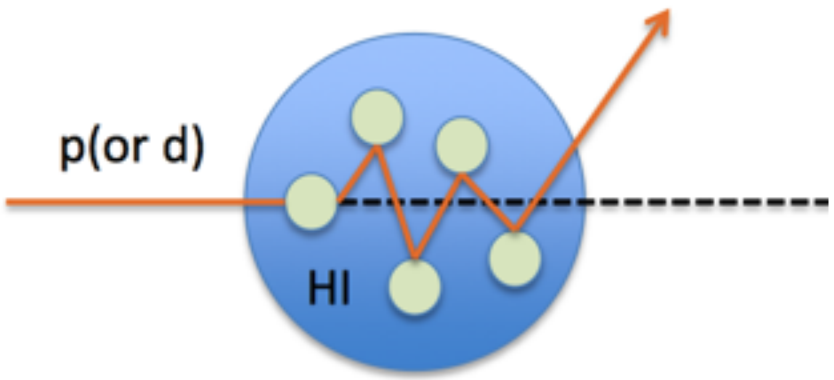




- CMS – No strong rapidity dependence
- ALICE – More suppression at forward rapidity
  – CNM models fail to describe data.

Initial state effects in pPb

p_T broadening

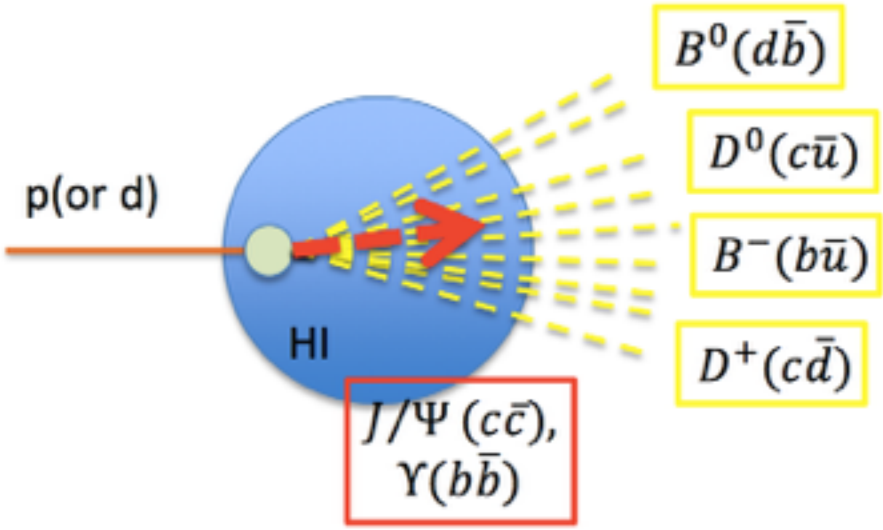


- Before the hard scattering, multiple elastic scatterings can occur.
  - → Projectile can get p_T from soft scattering.
  - → Yields decrease at low p_T, while increase at intermediate p_T.

Initial State Energy Loss

- Energy loss by soft scattering reduces the initial energy of hard scattering.
- Yields decrease at forward rapidity, while increase at mid-rapidity regions.

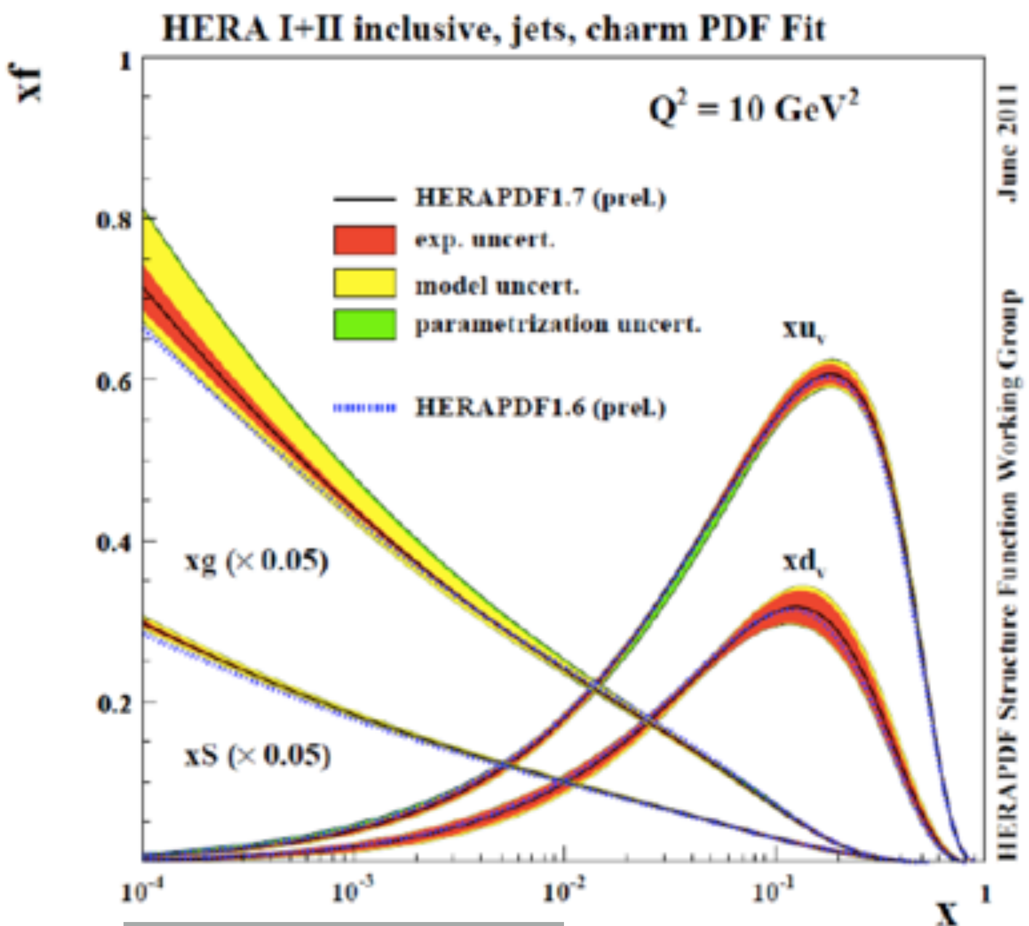
Nuclear absorption



- Right after cc_bar pairs are created, they interact with surrounding nucleons and break up.
- negligible at LHC energy (crossing time shorter than quarkonia formation time)

Parton Distribution Function in nucleon

- Q^2 : momentum transfer
- x : fraction of nucleon momentum carried by parton



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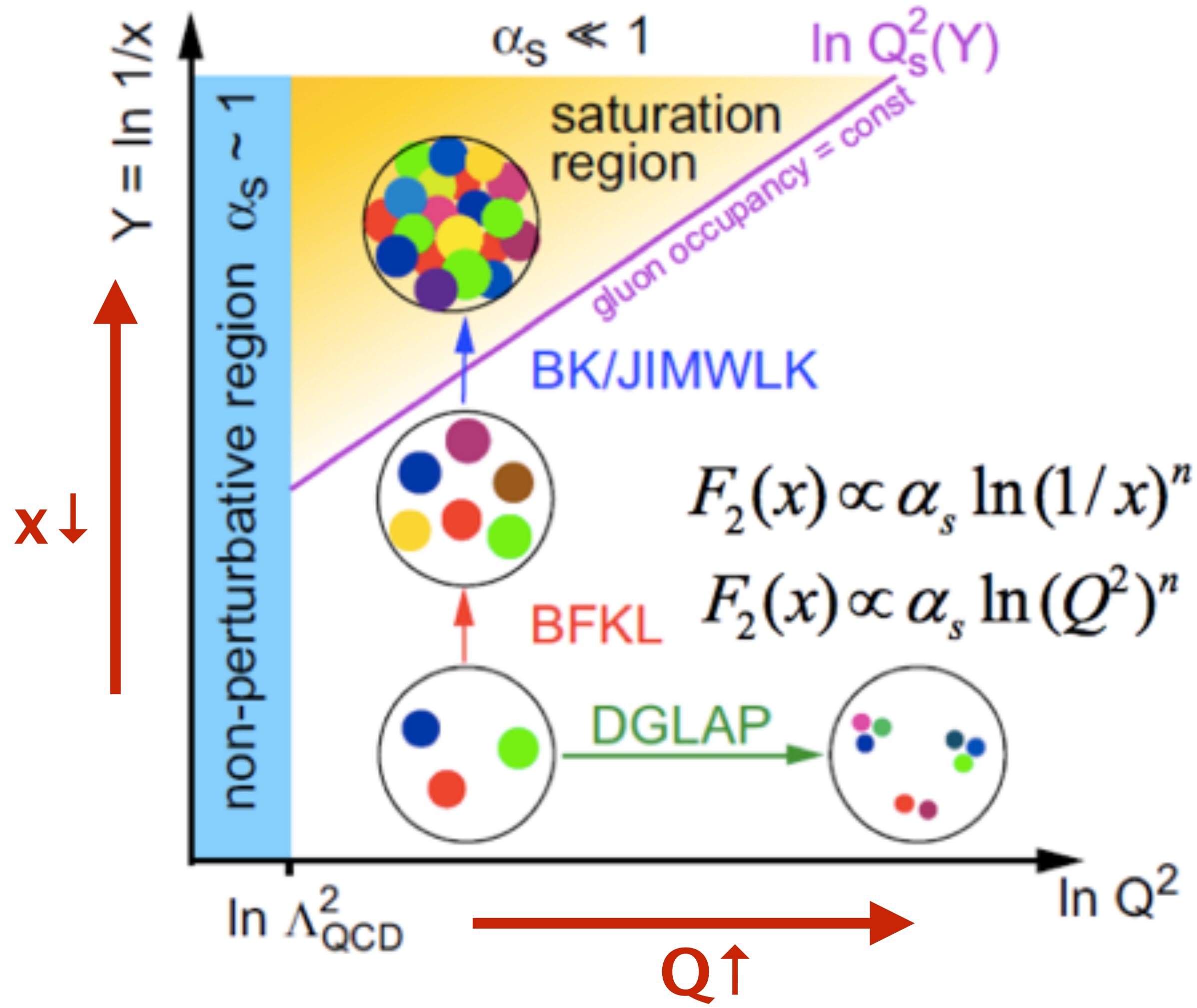


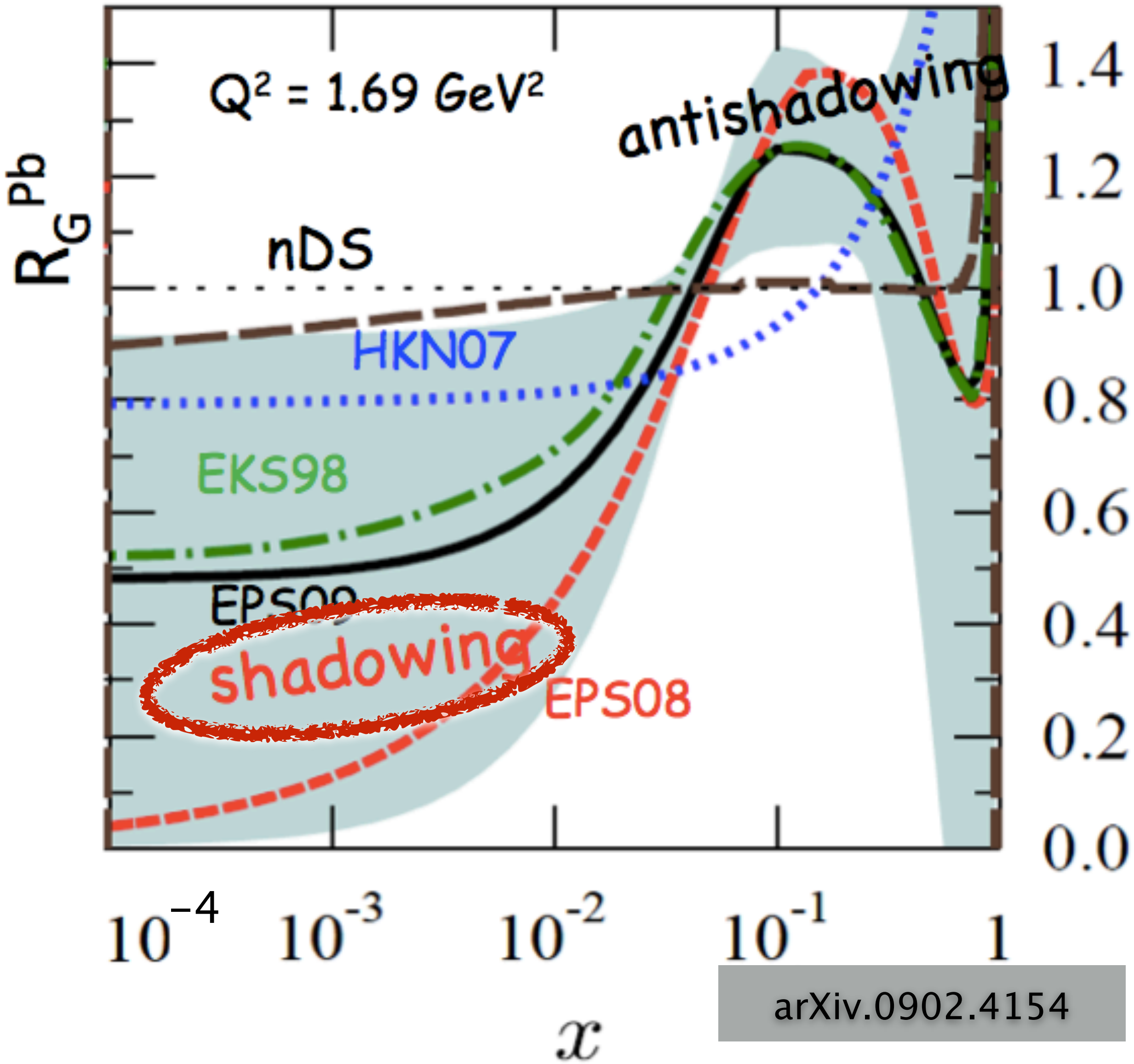
- Distributions of partons are related to the momentum fraction, **Bjorken x**.
- At low x, gluons are saturated and occupancy becomes constant.

PDF in nucleus

nuclear Parton Distribution Function

$$R_G^{Pb}(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$

- A : mass number of nucleus
- x : Bjorken x
- G_p : gluon structure function in proton
- G_A : gluon structure function in nucleus



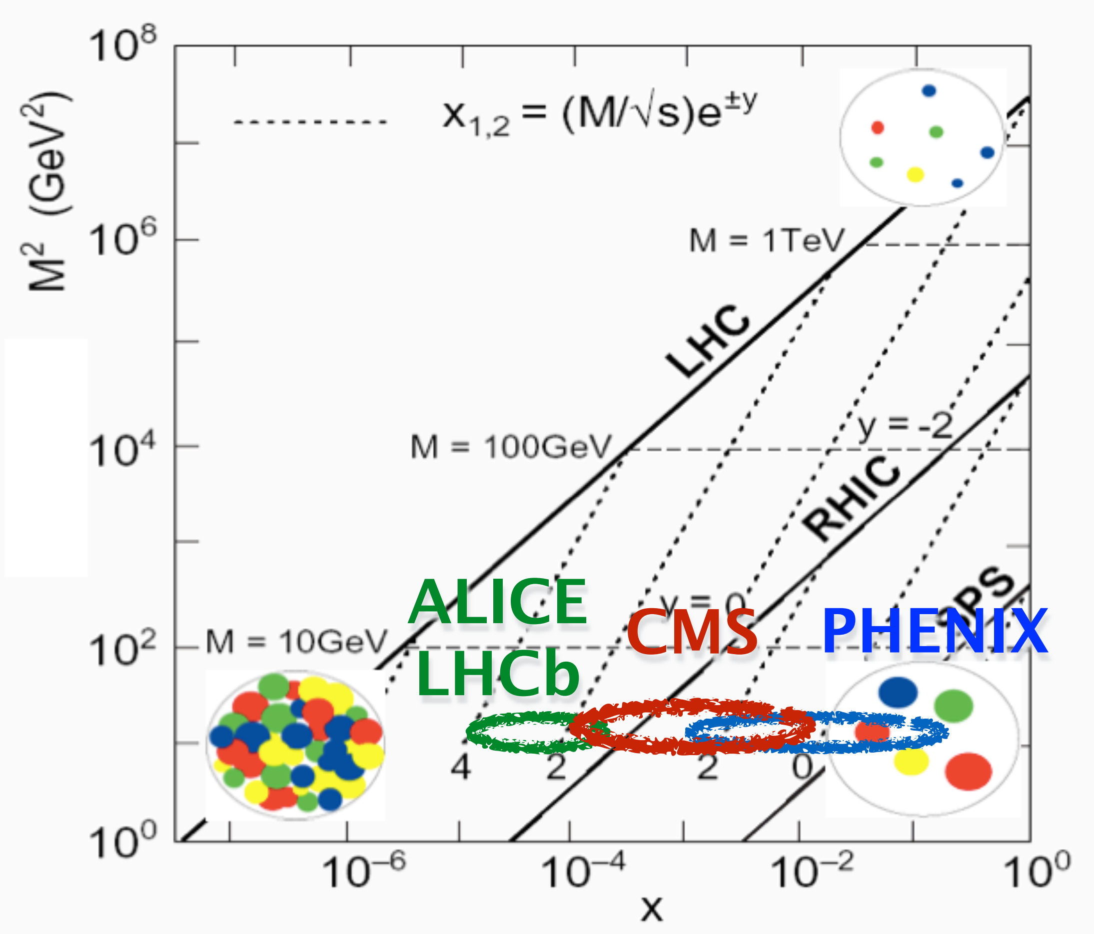
- **$R_i^{pPb} \neq 1$**
  : Parton distributions in nucleus are different from those in free nucleons.
- nPDF is different for various model predictions (especially at low x).

J/ψ in pPb with CMS

J/ψ in pPb collisions

- J/psi production measurements help in constraining nPDF of gluons, which dominate the production process.
- In case of 2→1 process, x_2(of Pb nucleus) can be approximately :

$$x_2 = \frac{Q}{\sqrt{S_{NN}}} e^{-y}$$



J/ψ with CMS at LHC

- $M = 3.09\ \mathrm{GeV}/c^2$
- $\sqrt{S_{NN}} = 5.02$ TeV
- $-2.87 < y_{CM} < 1.93$
- $0 < p_T < 30$ GeV/c

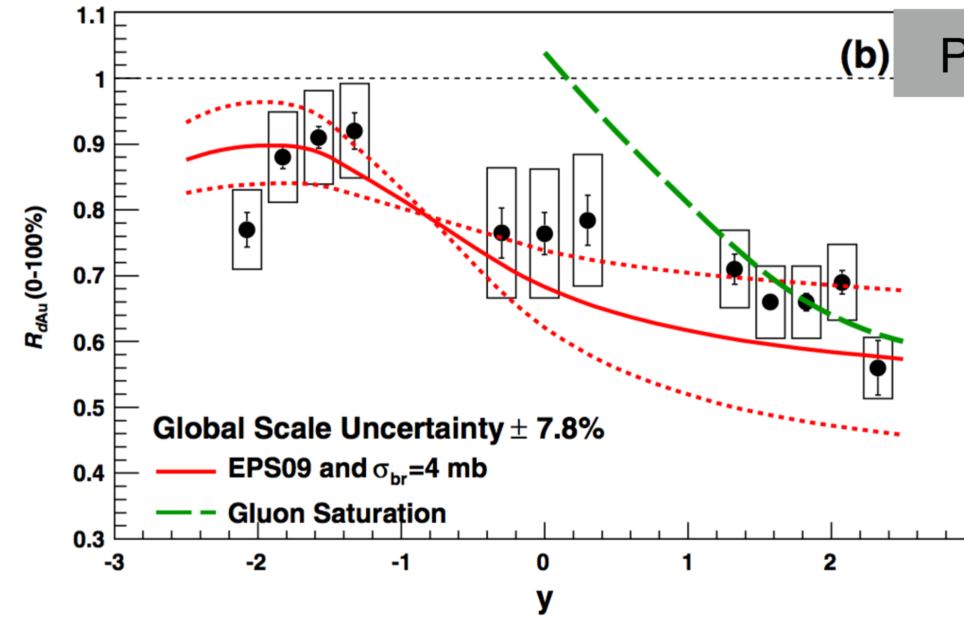
→ $10^{-4} < x_2 < 10^{-2}$

- We expect to investigate smaller x regions than RHIC
- Different kinematics range (mid-rapidity, higher p_T) with ALICE, LHCb
  → Better understanding & more constraints on nPDF models

R_{pPb} (R_{dAu}) vs rapidity

- **Nuclear modification factor**

$$R_{pA} = \frac{1}{A} \cdot \frac{\sigma_{pA}}{\sigma_{pp}}$$

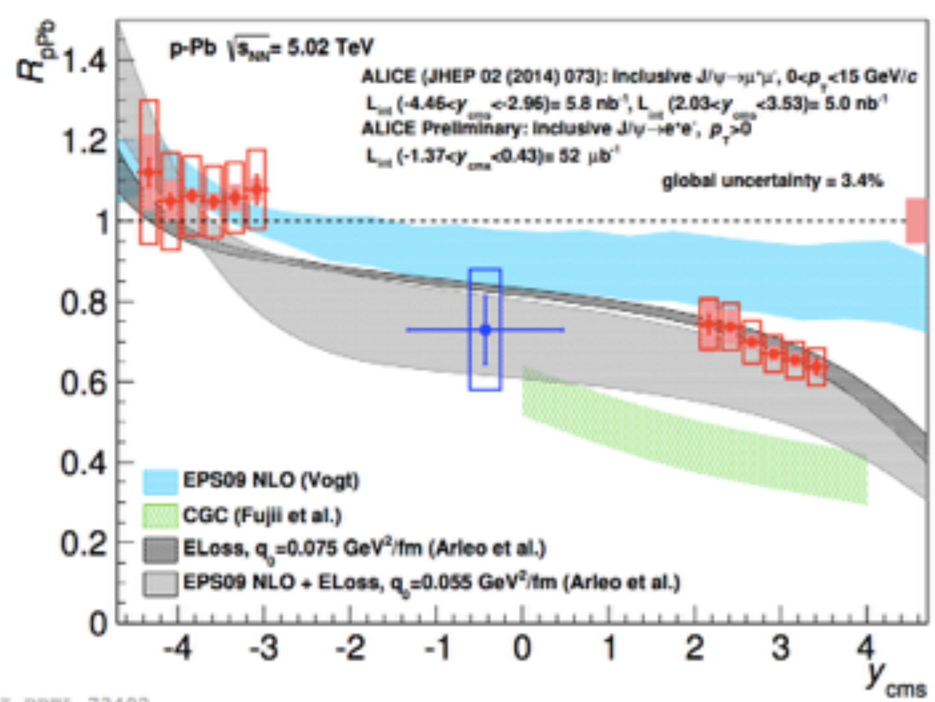


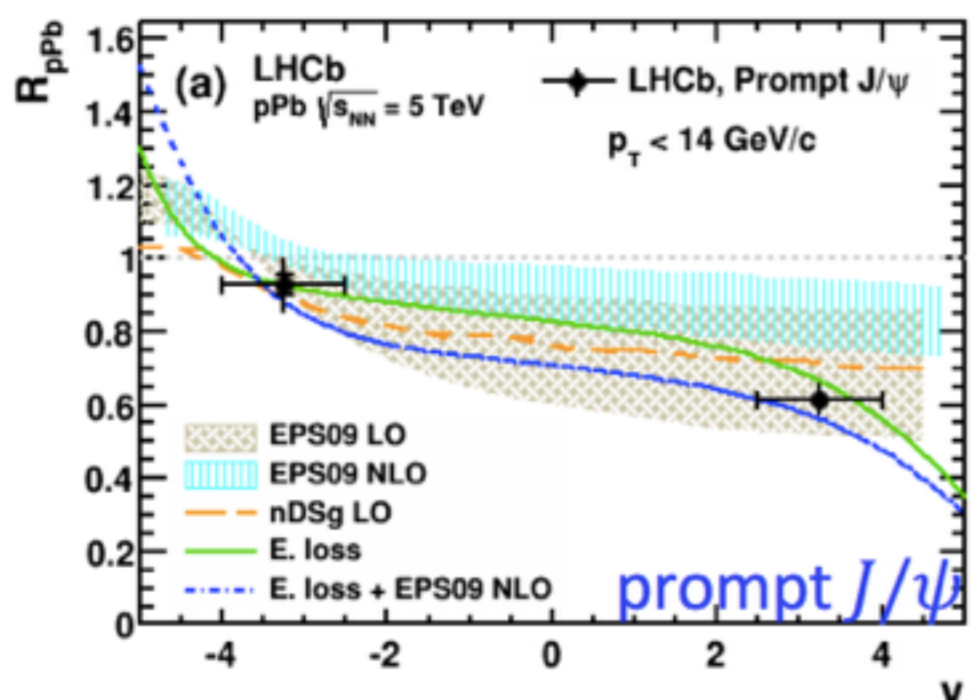
PRL 87 (2013) 034904

JHEP 02 (2013) 072

JHEP 02 (2014) 073

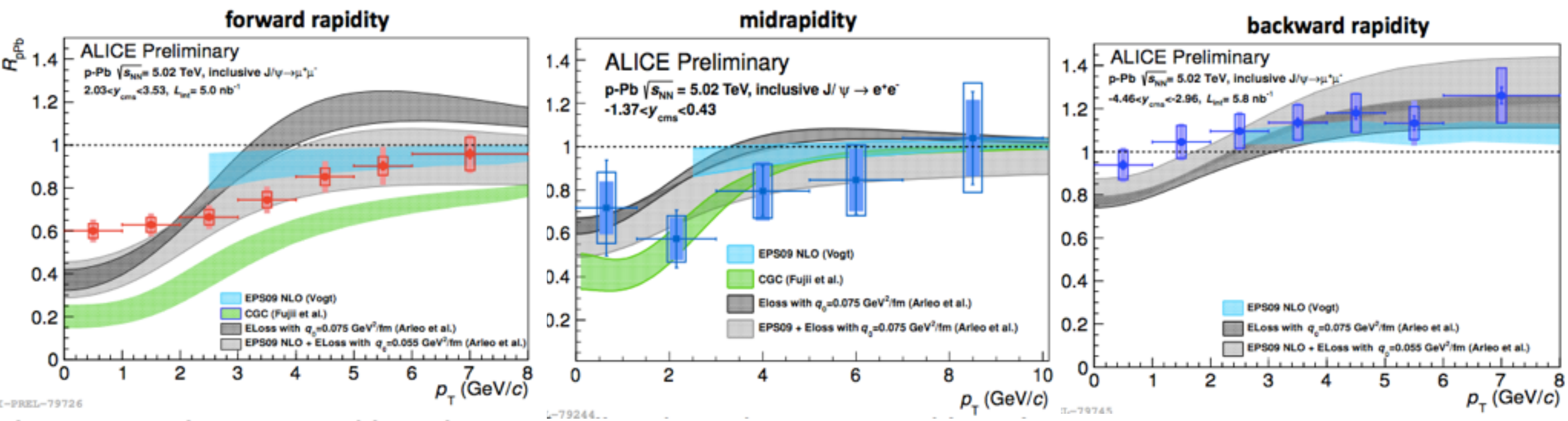
- [Shadowing + Breakup] reproduces PHENIX data.





- [Shadowing + Energy loss] describes ALICE and LHCb well.
- [CGC inspired model] in poorer agreement with data

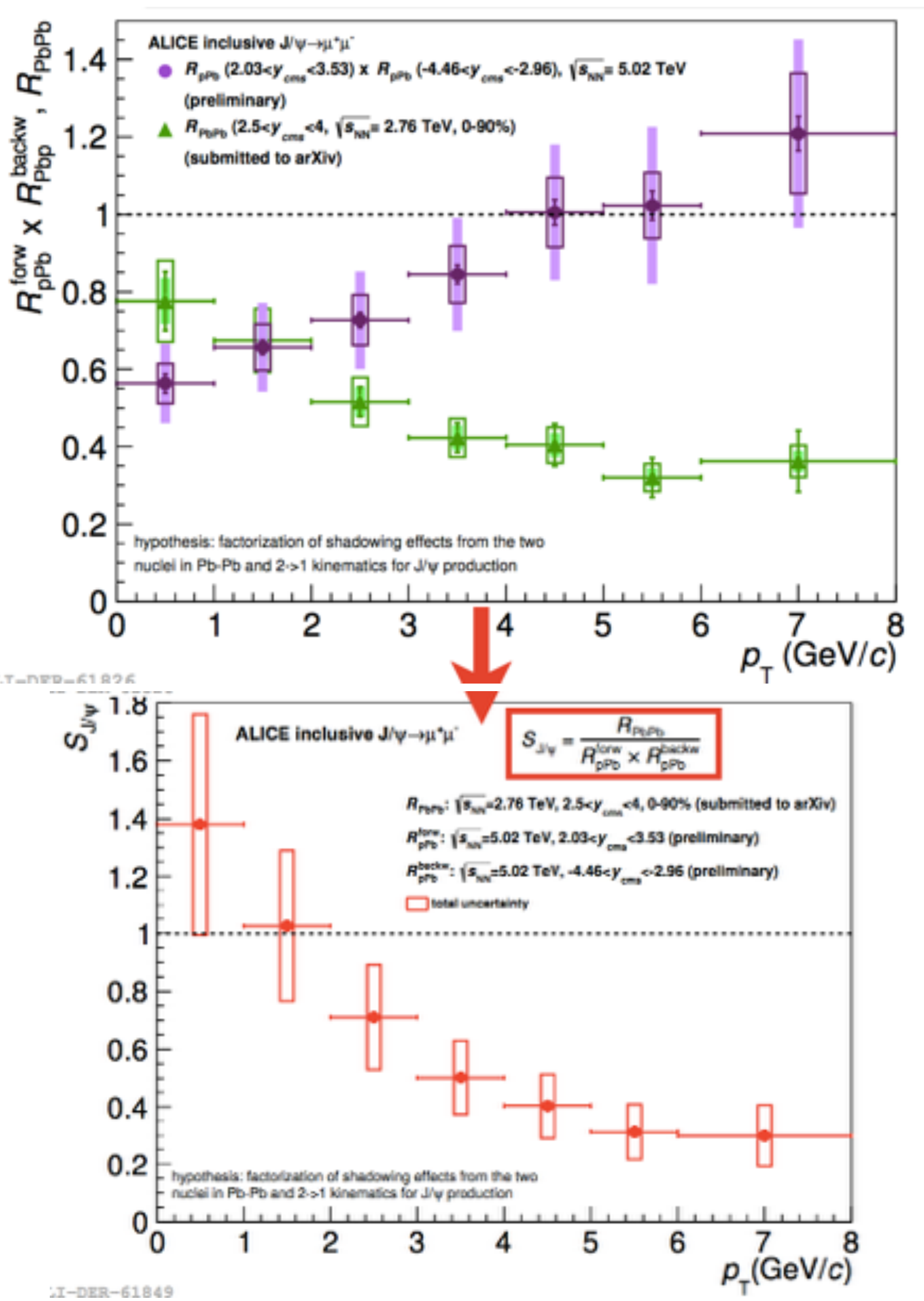
R_{pPb} (R_{dAu}) vs p_T



- Forward : R_{pPb} increases with p_T, goes to unity for p_T > 5 GeV
- Mid-rapidity & backward : small p_T dependence, compatible with unity

- EPS09 calculation is consistent with data (p_T > 2.5 GeV).
- Energy loss shows disagreement at forward rapidity and low p_T.
- CGC overestimates suppression at forward rapidity.

CNM effects in PbPb?



- $R_{pPb}^{forward}$ X $R_{pPb}^{backward}$ = R_{PbPb} ?
  - Assumption
    - Production mechanism g+g →J/ψ
    - CNM effects factorize in p-nucleus and are donimated by shadowing

- At low p_T, enhancement (recombination scenario?)
- At high p_T, strong suppression

J/ψ analysis in pPb with CMS

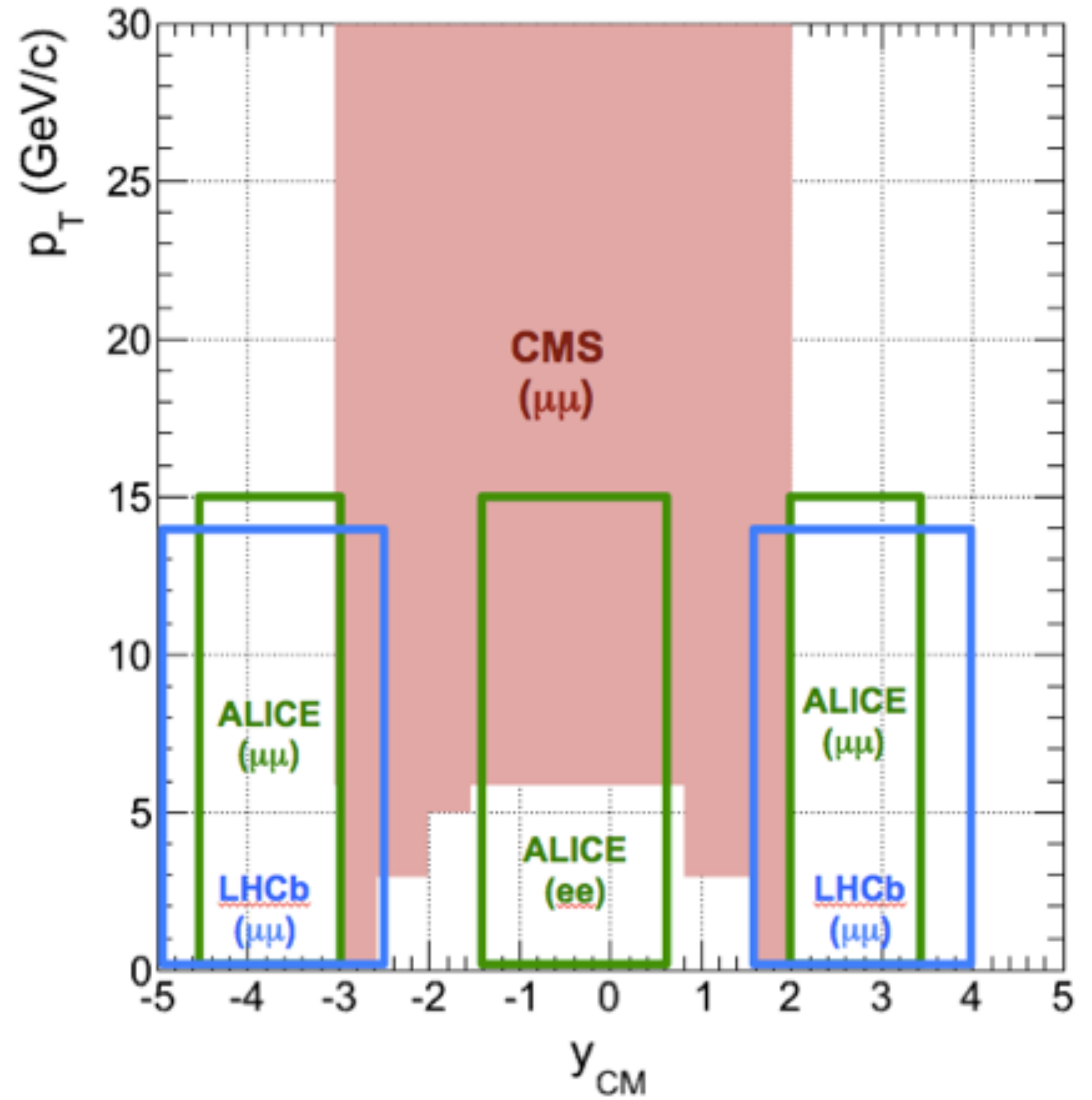
Observables

- Production cross-sections
- Forward to backward ratios R_{FB}
- Event-activity dependence

Down to p_T~0 GeV/c

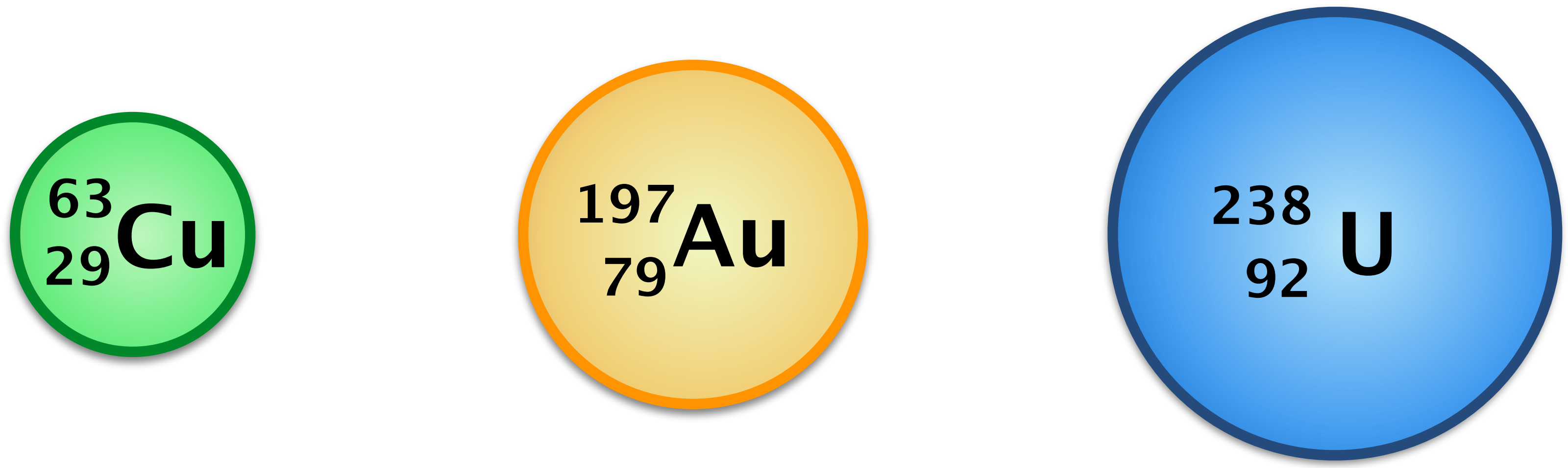
- Less background compared to PbPb collisions
- Tracker-tracker muon pairs can be used
- Basic technique is similar with PbPb analysis

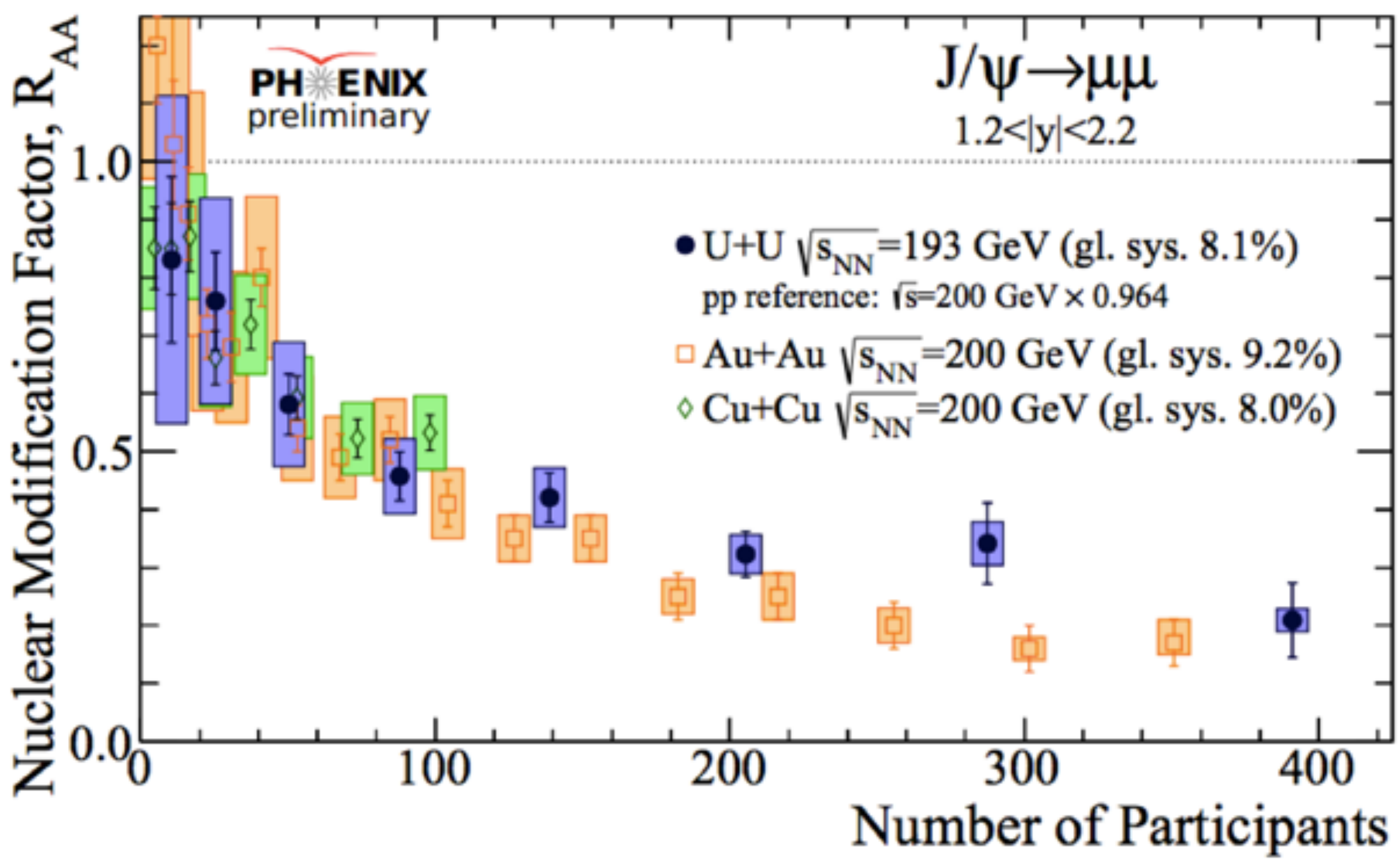
- **J/ψ Acceptance**
  - at mid-rapidity : $p_T > 6.5$ GeV/c
  - at forward rapidity : $p_T > 0$ GeV/c



System size study

- **Both initial and final state effects depend on system size.**

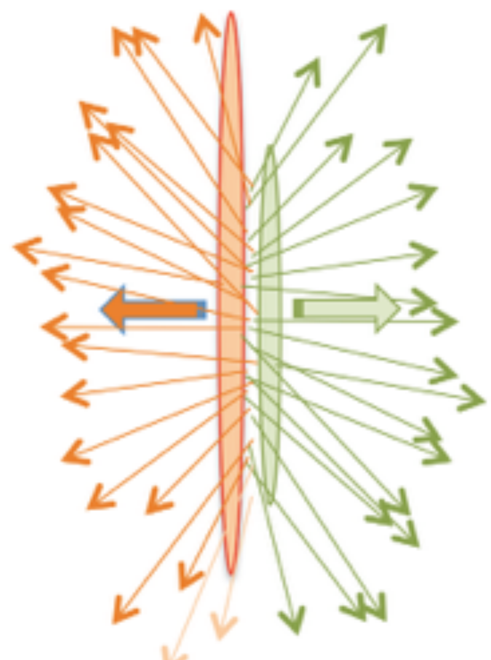




- **R_{AA} consistent with each other**

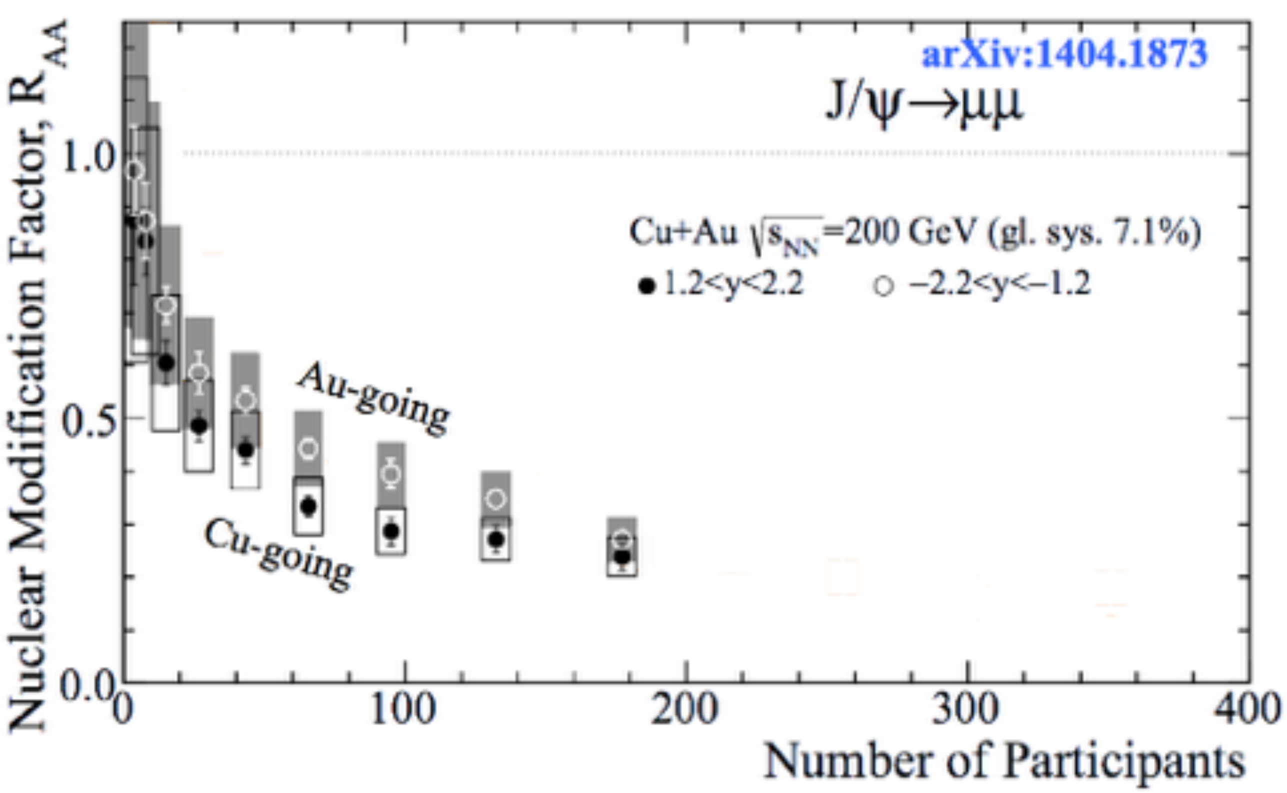
Asymmetric mass collisions

Backward (Au–going) — Cu+Au — **Forward (Cu–going)**



- **Final state effects**
  - Higher energy density
    - – more suppression
    - – (or more enhancement?)

- **Initial state effects**
  - probes small x in Au
    - – PDF more strongly modified in heavier Au compared to Cu.
  - Longer crossing time for Cu than Au
    - – energy loss depends on Au
    - – break-up depends on Cu

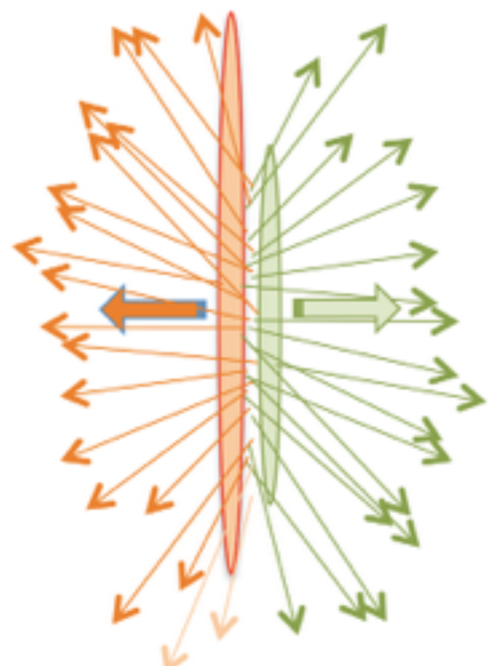


arXiv.1404.1873

- **R_{AA} is also asymmetric?**
  - Their ratio R (forward/backward) in the next slide

Asymmetric mass collisions

Backward (Au-going) — Cu+Au — **Forward (Cu-going)**



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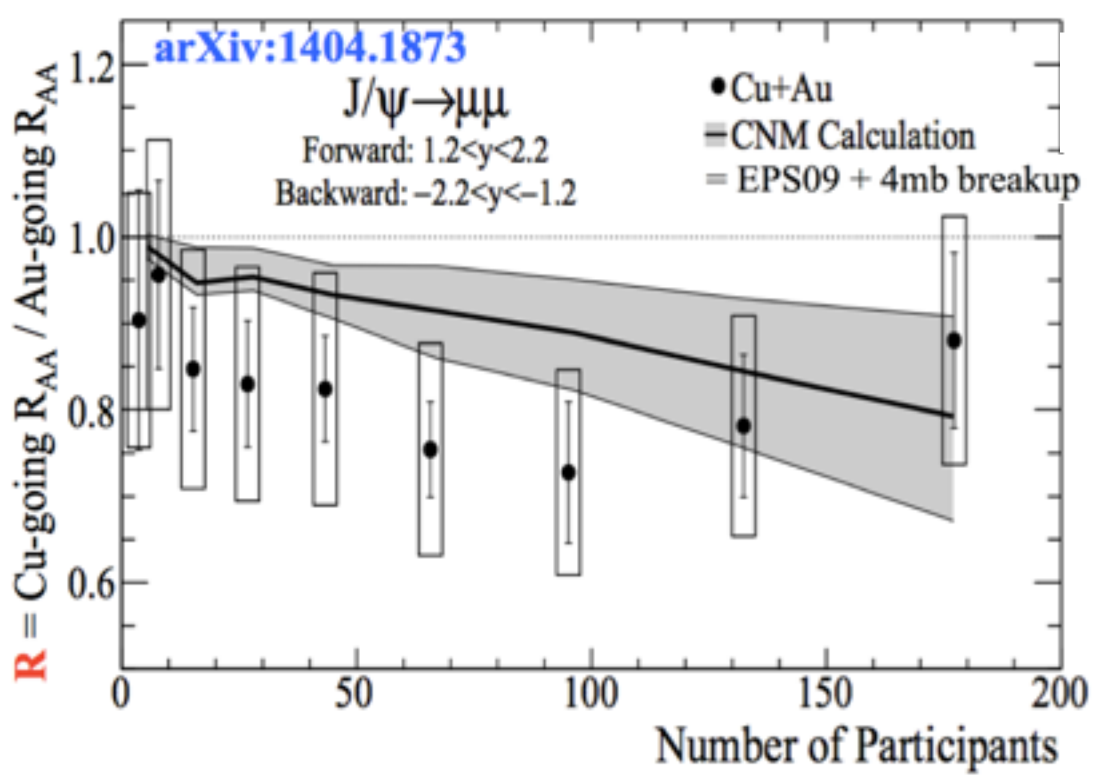


arXiv.1404.1873

- Initial state effects cause R decrease with centrality
- Final state effects would increase R with centrality.

- **This study may provide insight on the balance of hot and cold nuclear effects.**

Summary

- **J/ψ measurements in pp, pPb and PbPb collisions play a key role to understand and factorize the initial and final state effects.**

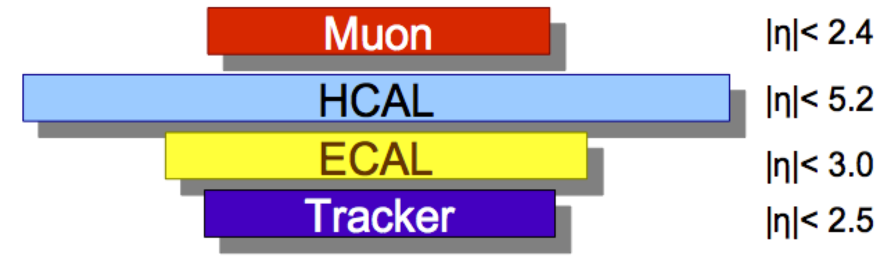
- **In PbPb, suppression has been observed and its dependence on centrality, p_T and rapidity in different kinematic ranges and beam energies need to be interpreted further.**

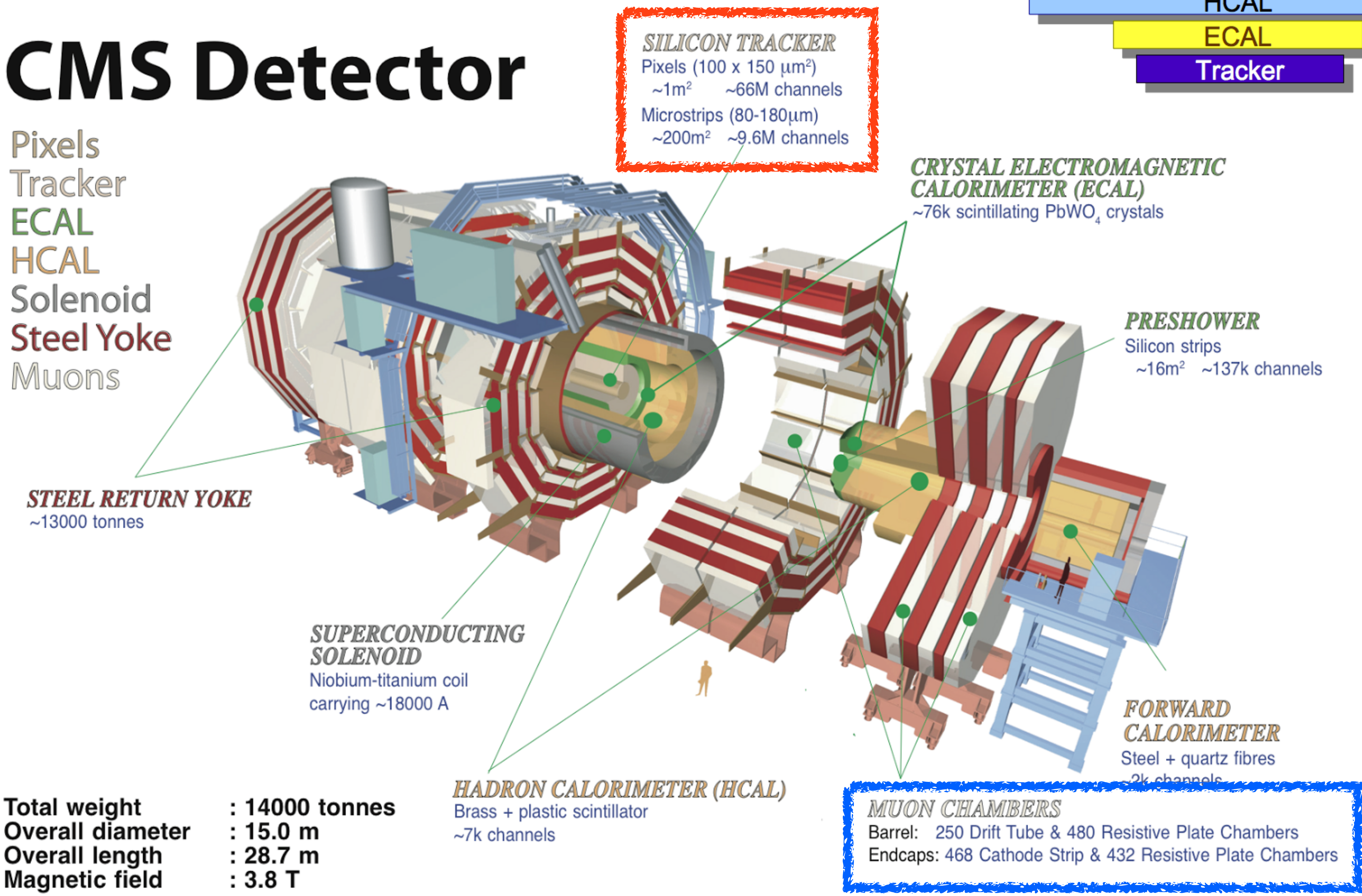
- **In pPb, data can be described by several CNM models, especially nuclear shadowing, but no single models can describe all results.**

- **System size can help to investigate the different sources of J/ψ modification in heavy ion collisions.**

BACK-UP

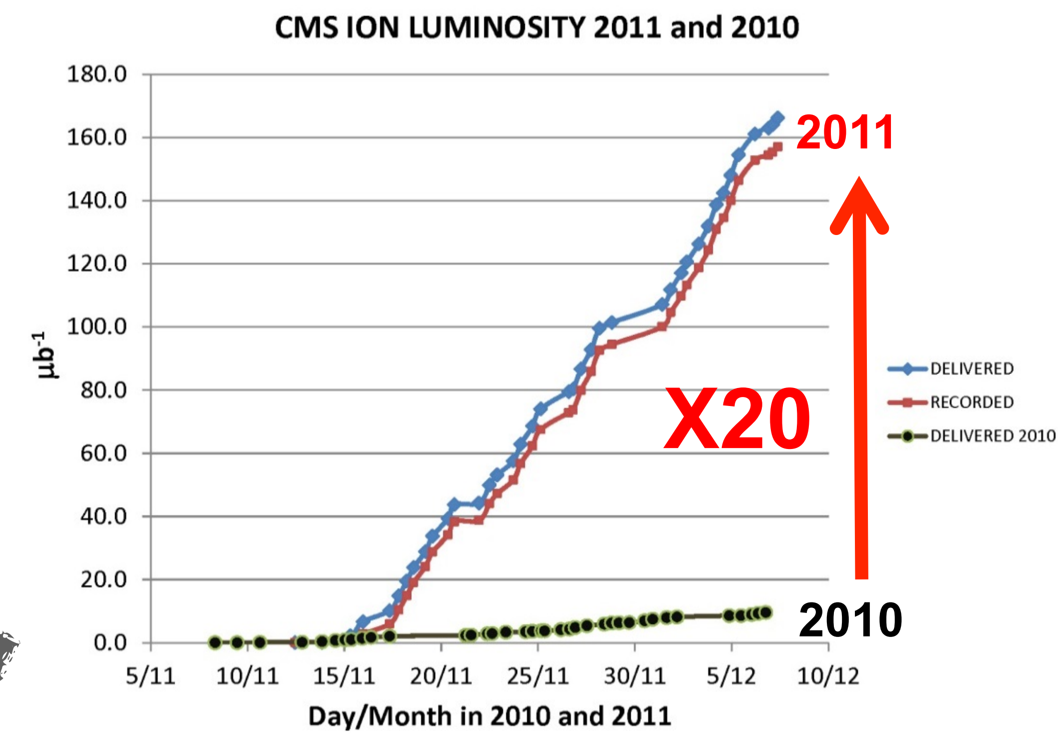
CMS detector

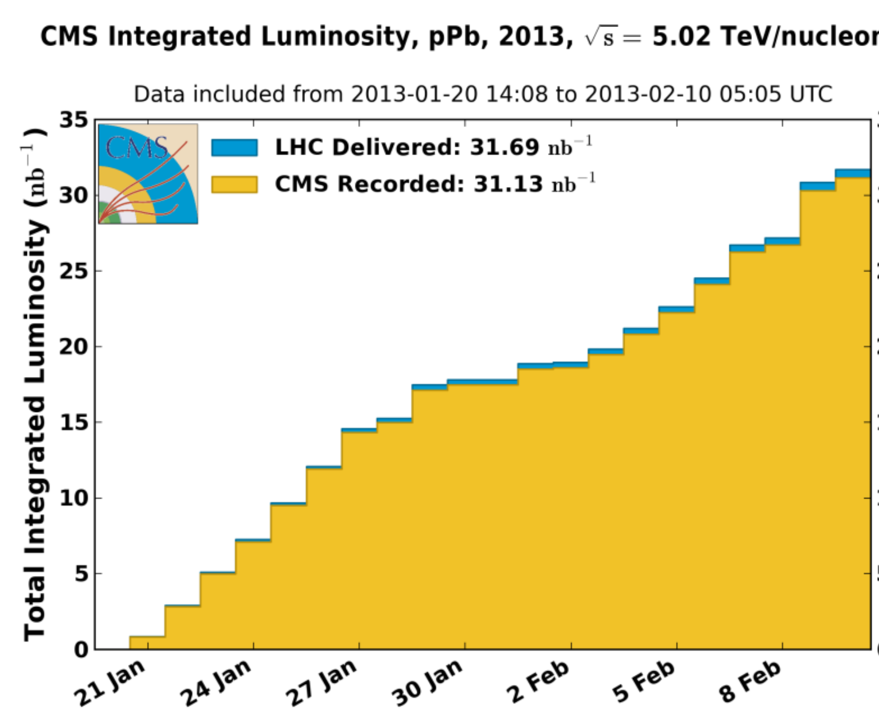




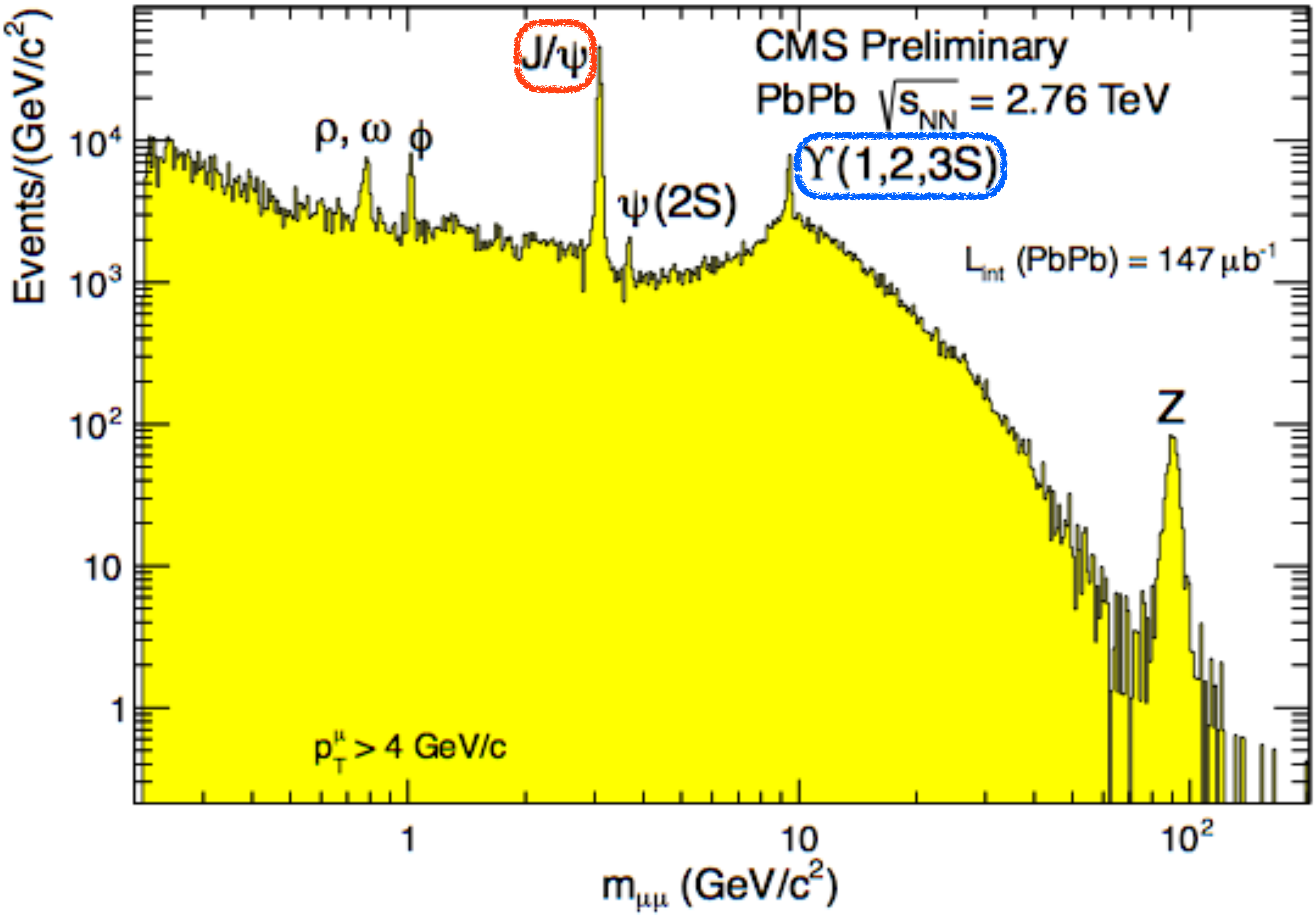
Data taking

- **1st PbPb run @ $\sqrt{S_{NN}}$ = 2.76 TeV**
  - Nov. – Dec. 2010
  - Recorded luminosity by CMS : 7.28 μb^{-1}
- **1st pp run @ $\sqrt{S_{NN}}$ = 2.76 TeV**
  - March 2011
  - Recorded luminosity by CMS : 225 nb^{-1}
- **2nd PbPb run @ $\sqrt{S_{NN}}$ = 2.76 TeV**
  - Nov. – Dec. 2011
  - Recorded luminosity by CMS : 150 μb^{-1}
- **pPb run @ $\sqrt{S_{NN}}$ = 5.02 TeV**
  - Jan. – Feb. 2013
  - Recorded luminosity by CMS : 35 nb^{-1}
- **2nd pp run @ $\sqrt{S_{NN}}$ = 2.76 TeV**
  - Feb. 2013 (3 days)
  - Recorded luminosity by CMS : 5.41 pb^{-1}

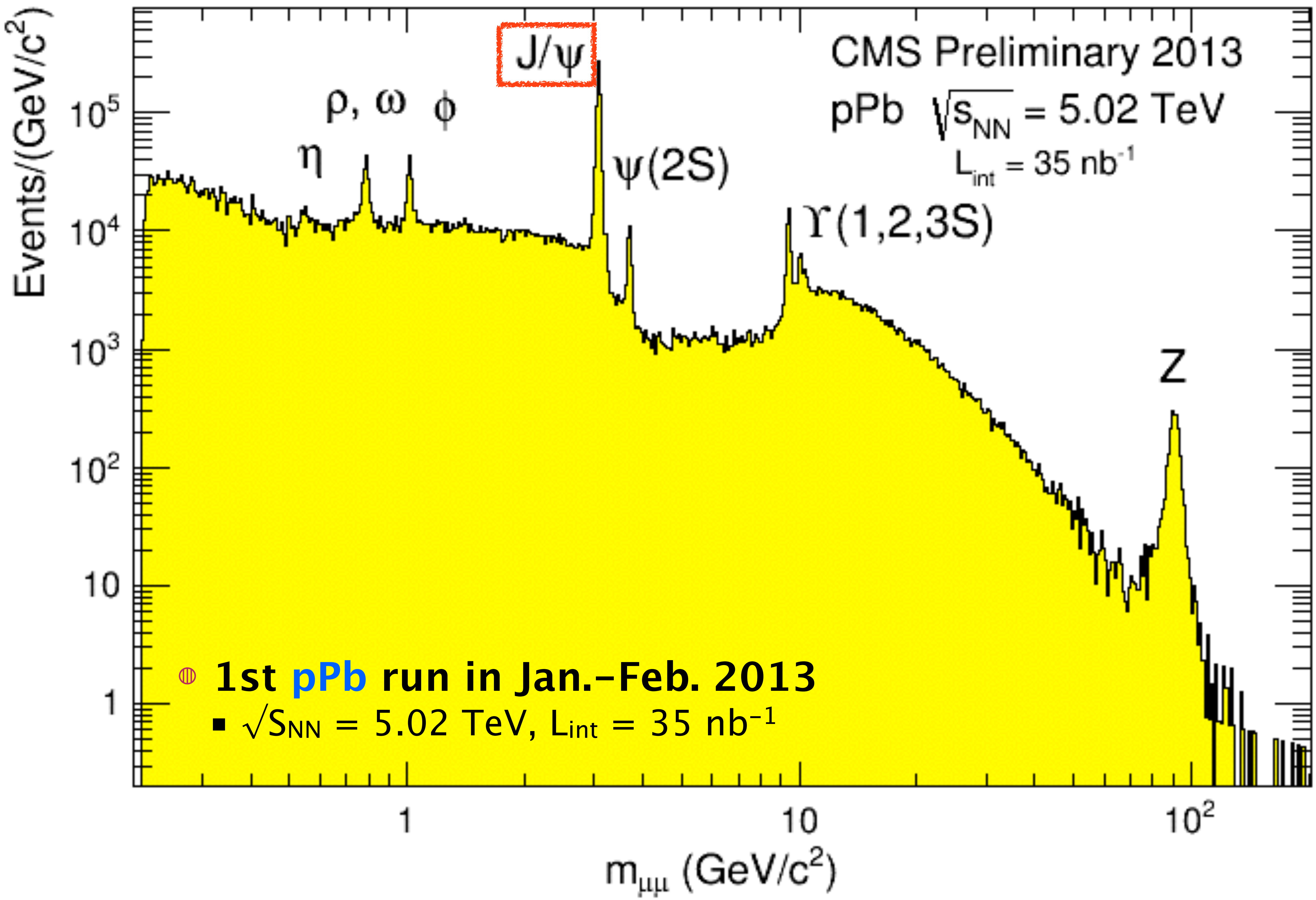




Dimuon mass plots - PbPb



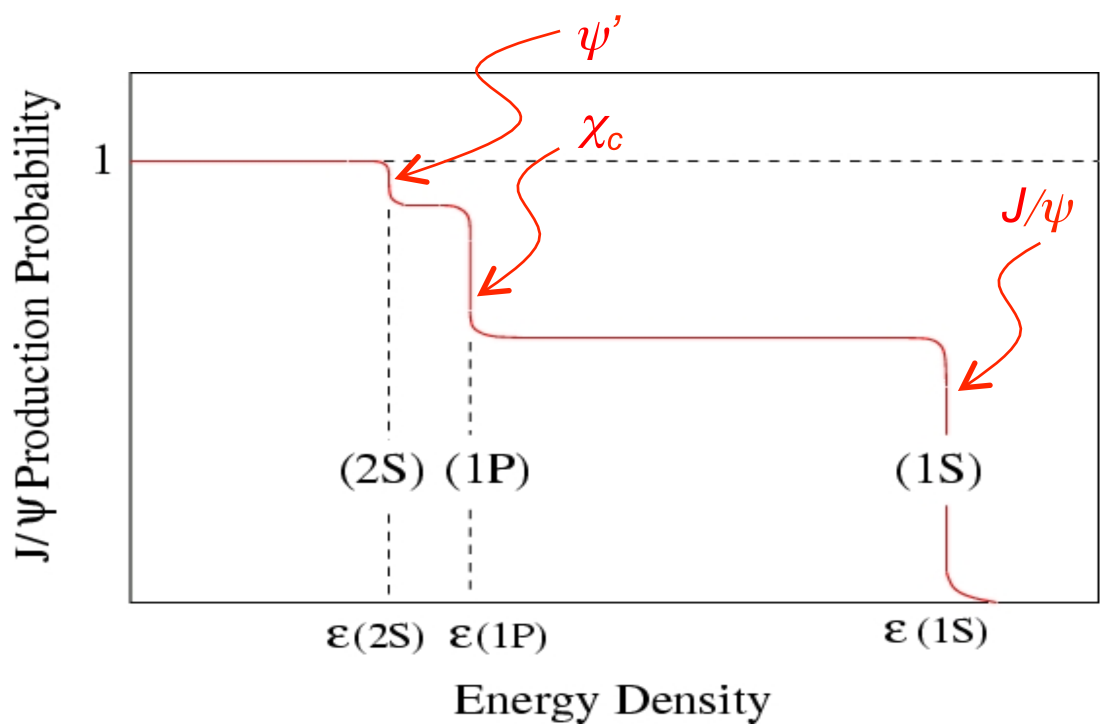
Dimuon mass plots - pPb

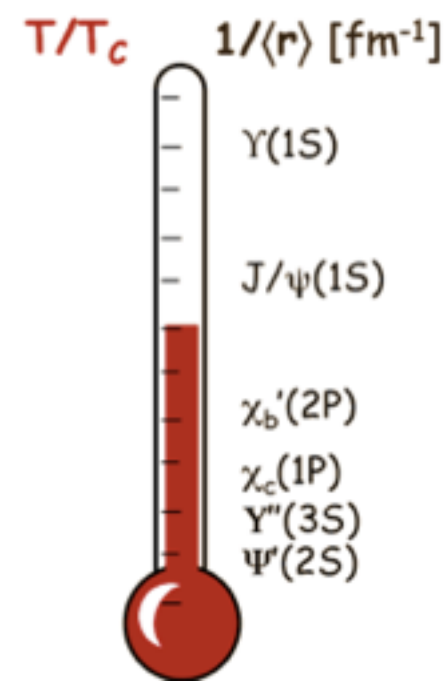


- **1st pPb run in Jan.–Feb. 2013**
  - $\sqrt{S_{NN}}$ = 5.02 TeV, L_{int} = 35 nb^{-1}

- **Debye screening**
  - The larger the binding energy, the higher the dissociation temperature T_d.
  - As temperature goes up, Debye length $r_\lambda(T)$ decreases.

Resonance	J/ψ	Ψ'	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass [GeV]	3.10	3.68	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.54	0.20
Radius [fm]	0.25	0.45	0.14	0.28	0.39





Mocsy, EPJC 61 (2009) 705

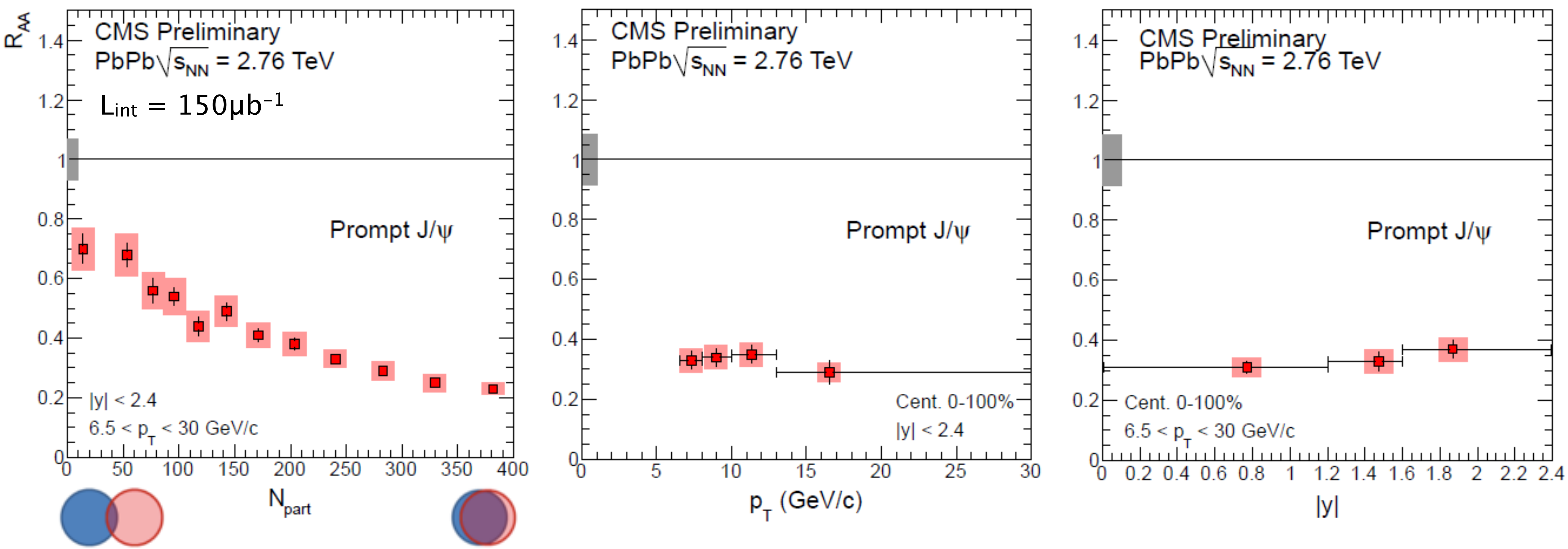
Prompt J/ψ R_{AA}

CMS-PAS HIN-12-014

- **Nuclear modification factor**

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}}{N_{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$

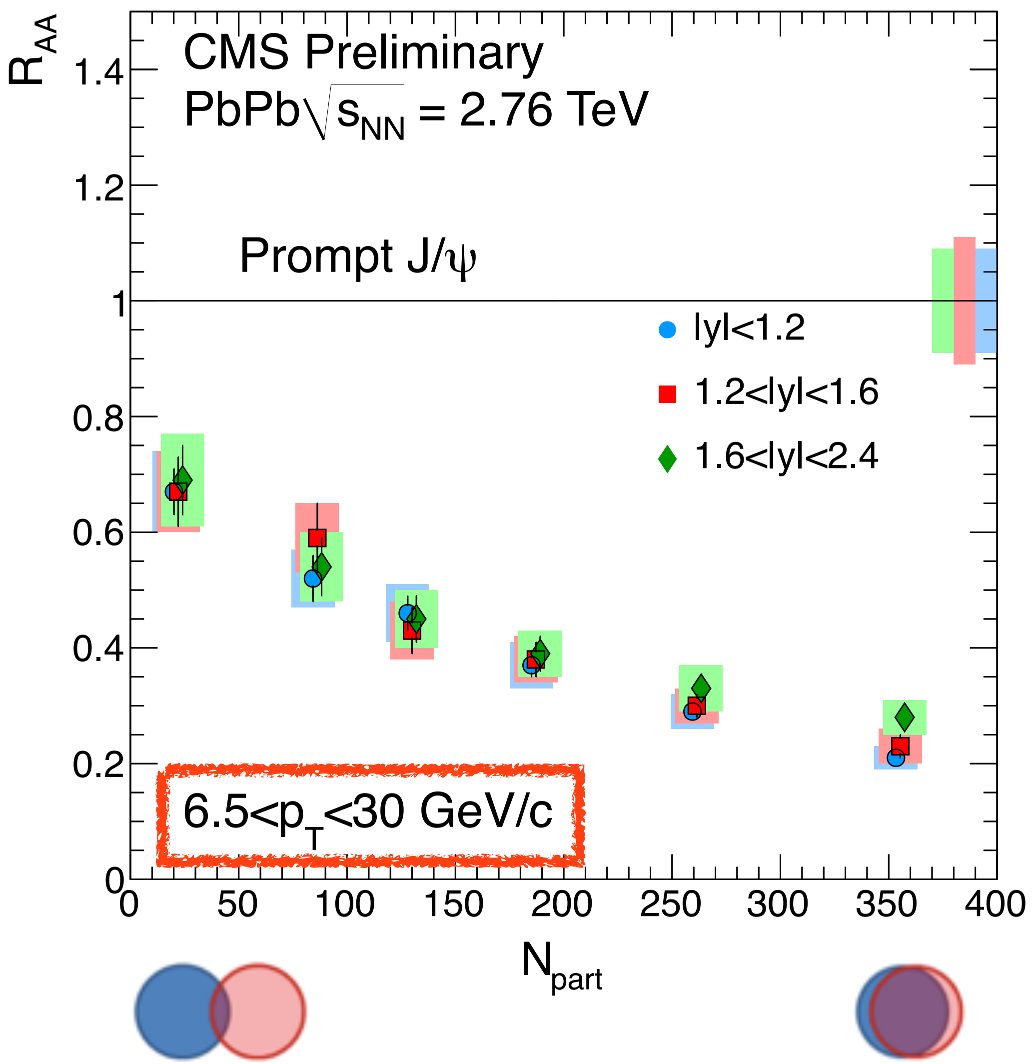
: R_{AA} =1 No modification compared to pp collisions



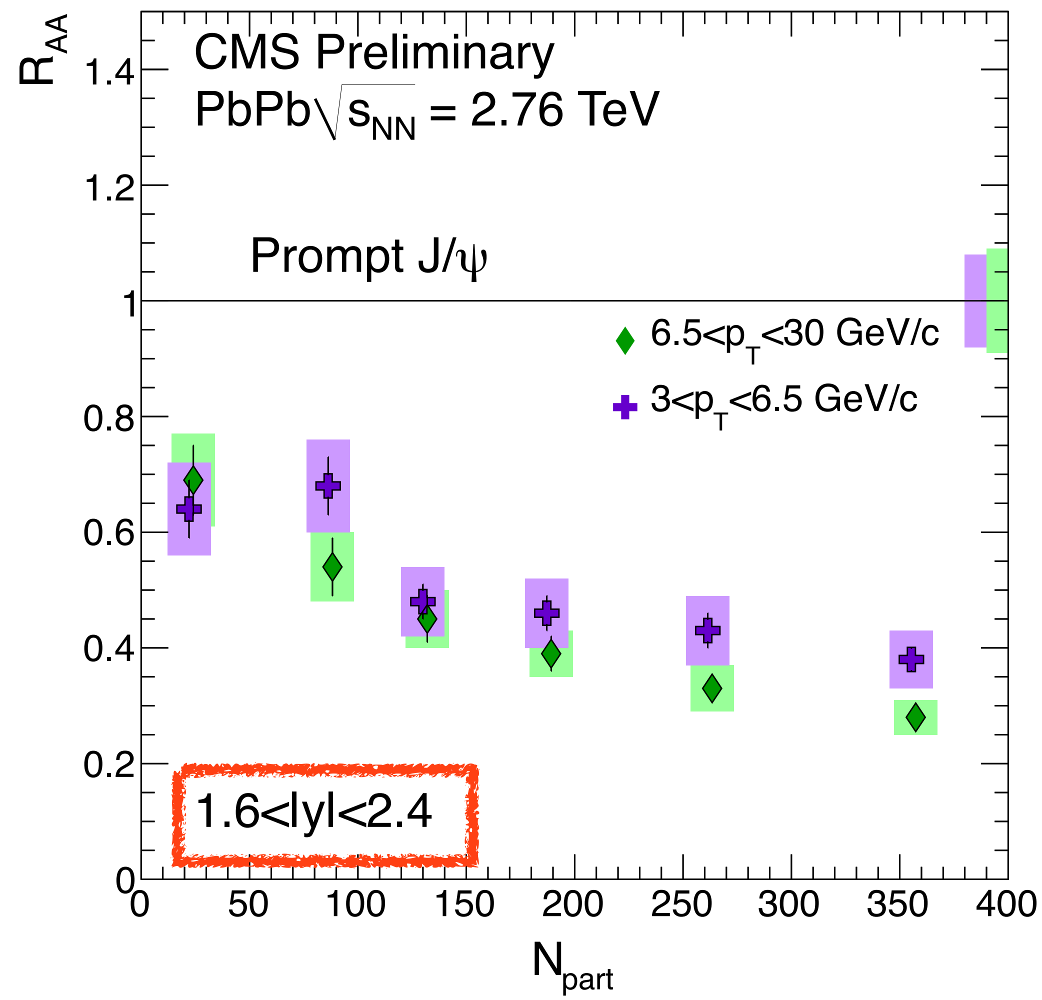
- Suppressed by factor ~5 in the most central bin
- No p_T and y dependent suppression is observed.

Prompt J/ψ R_{AA}

- **Rapidity dependence**



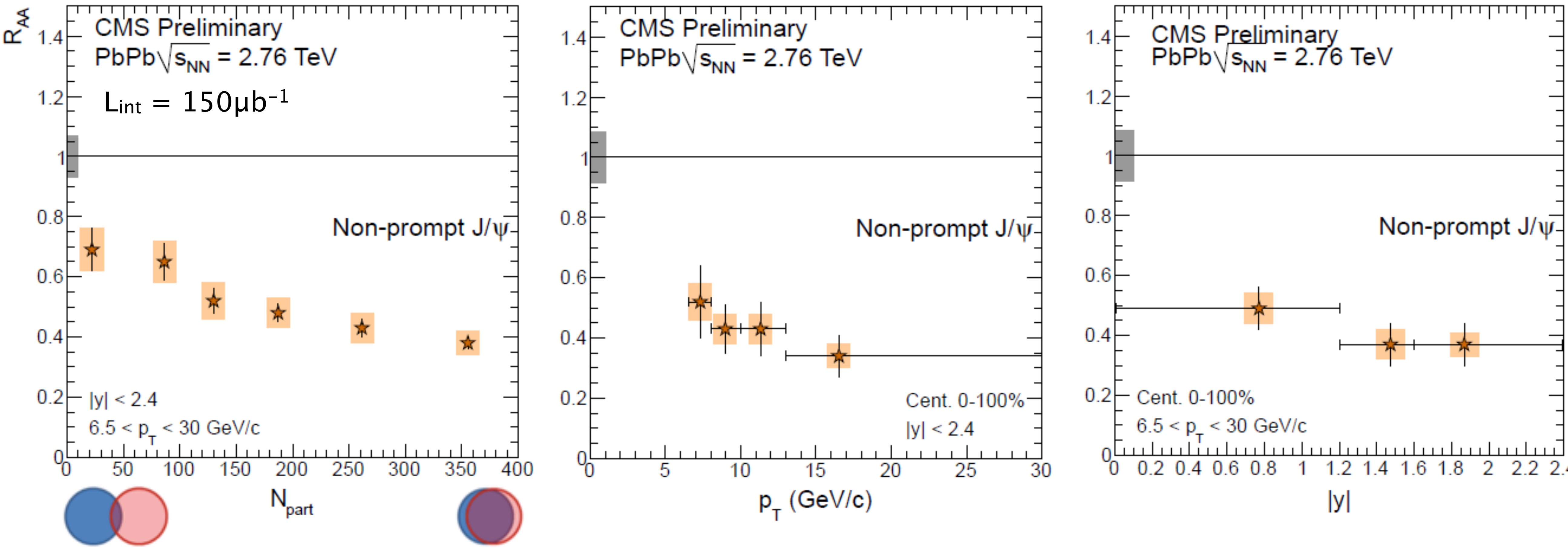
- **p_T dependence**



- Left : No strong dependence on rapidity at high p_T region
- Right : At forward rapidity region, lower p_T J/ψ is slightly less suppressed in the most central bins.

Non-prompt J/ψ R_{AA}

CMS-PAS HIN-12-014

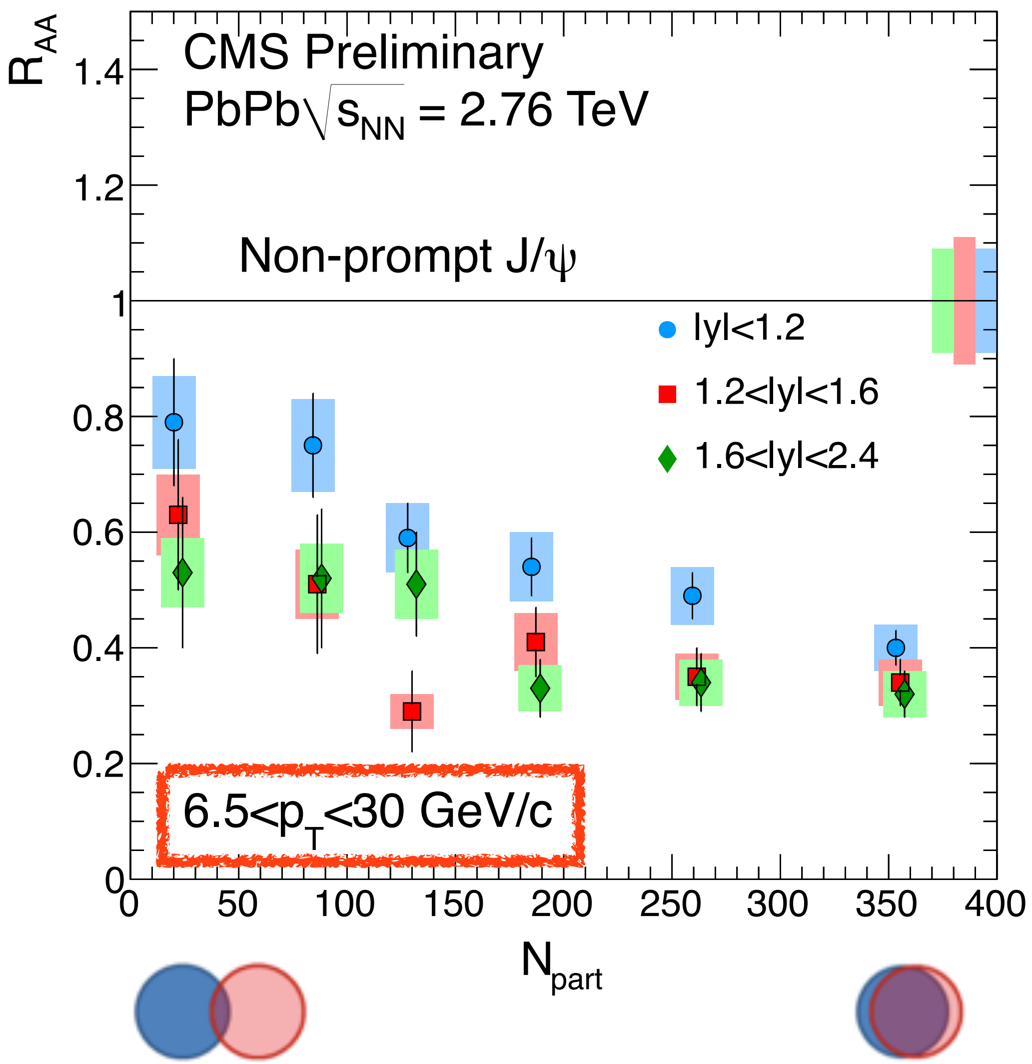


- Suppressed by factor ~3 in the most central bin
- Hints of smaller suppression at lower p_T region, mid-rapidity region

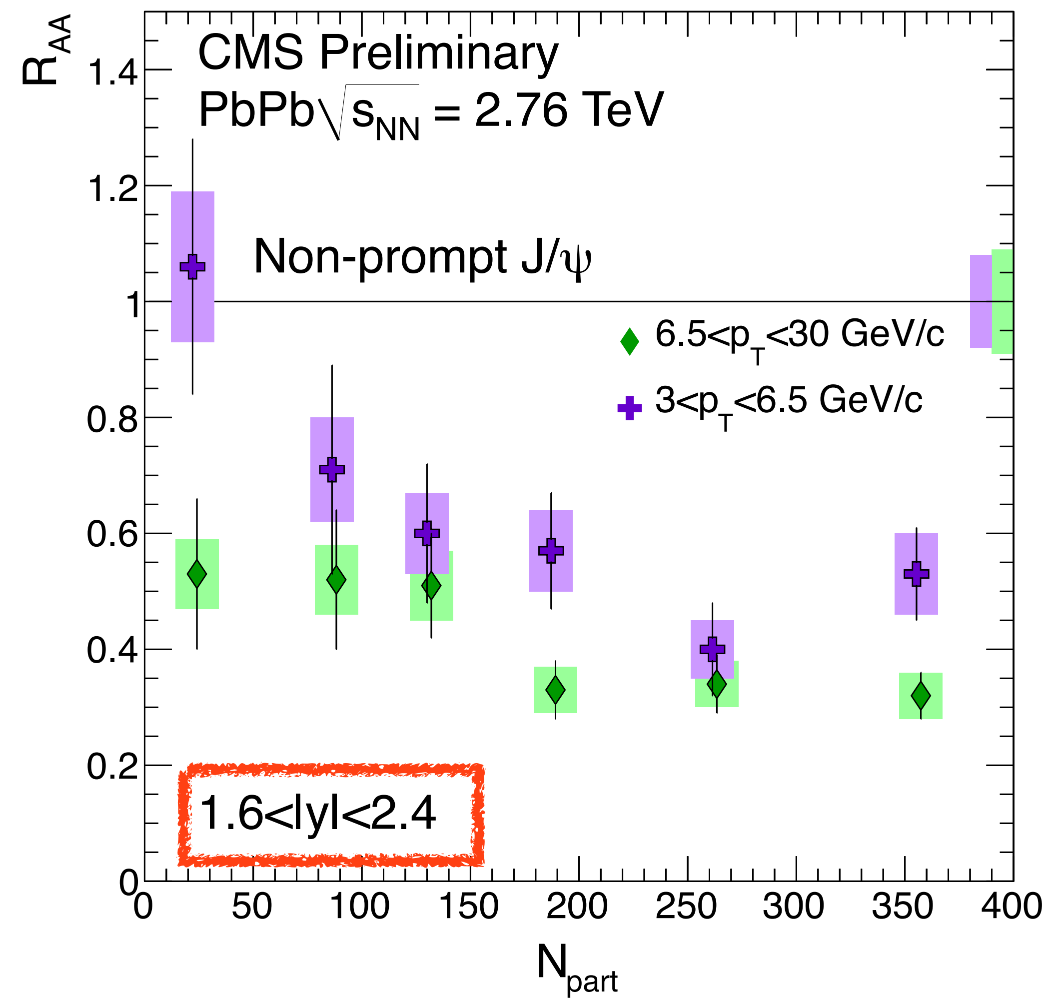
Information on the b-quark energy loss in medium

Non-prompt J/ψ R_{AA}

- **Rapidity dependence**



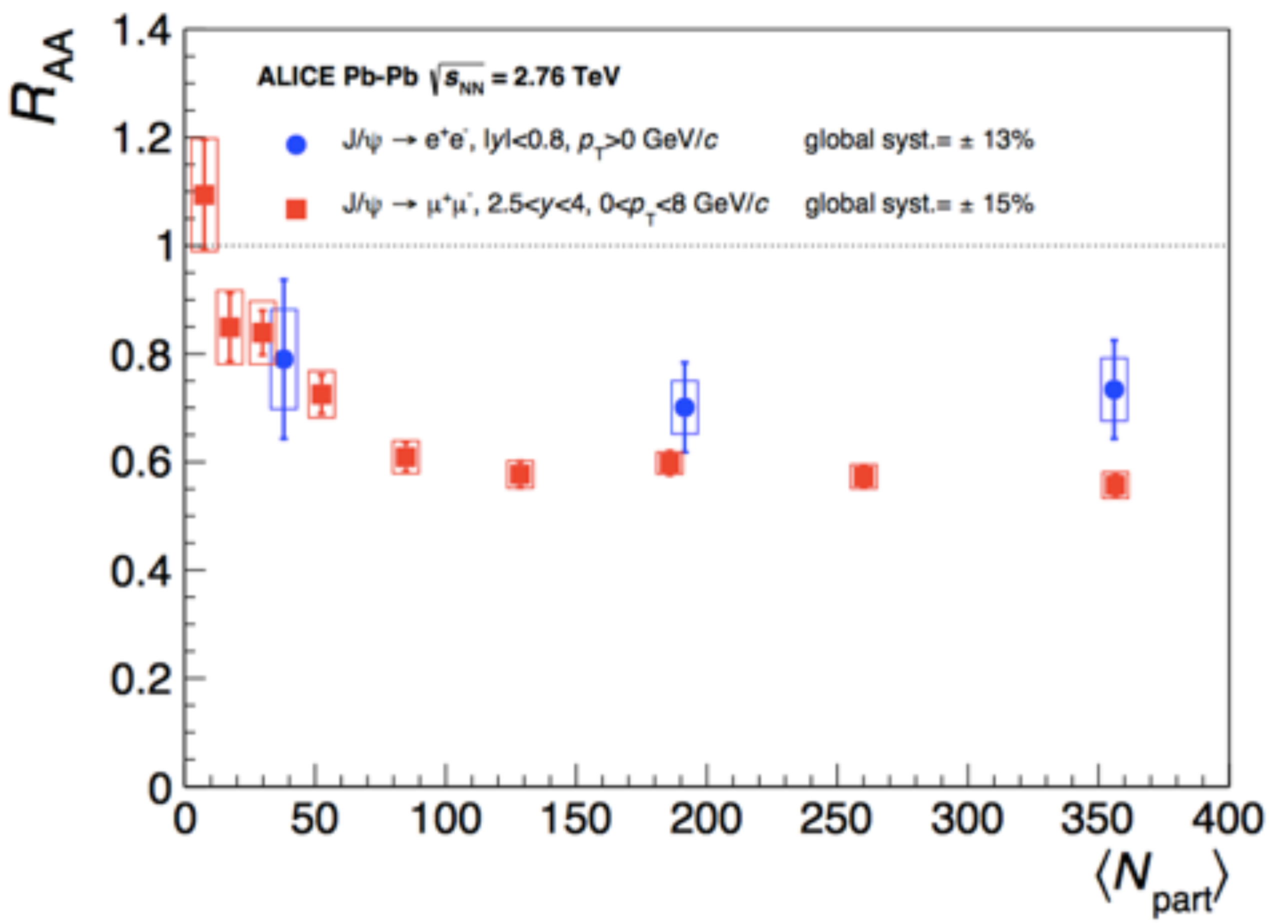
- **p_T dependence**



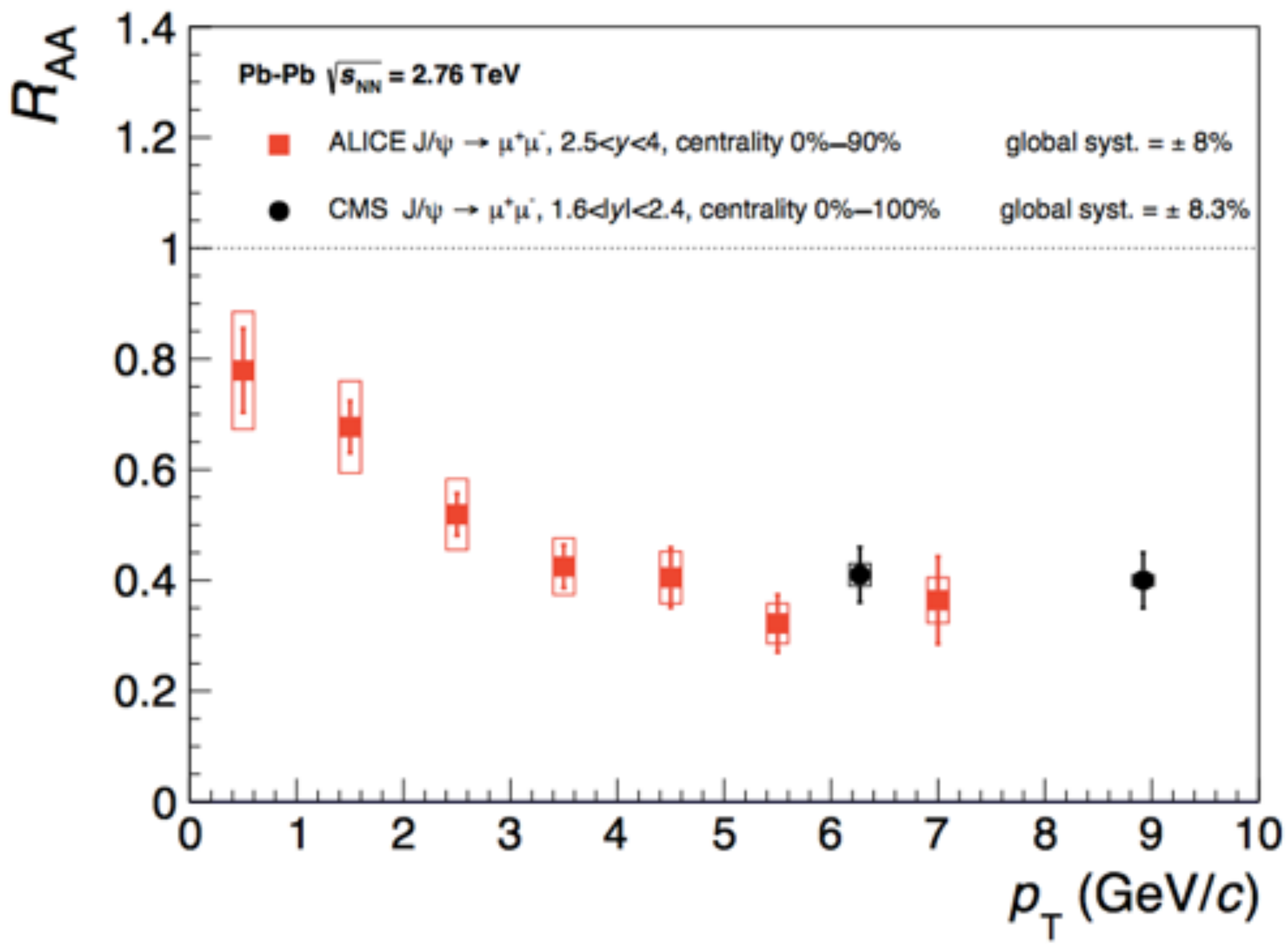
- **Left** : In all rapidity bins at high p_T region, centrality dependent suppression is shown.
- **Right** : In the forward region, lower p_T J/ψ has strong centrality dependence and less suppressed than high p_T J/ψ.

Prompt J/ψ R_{AA}

- ALICE : μμ & ee channel



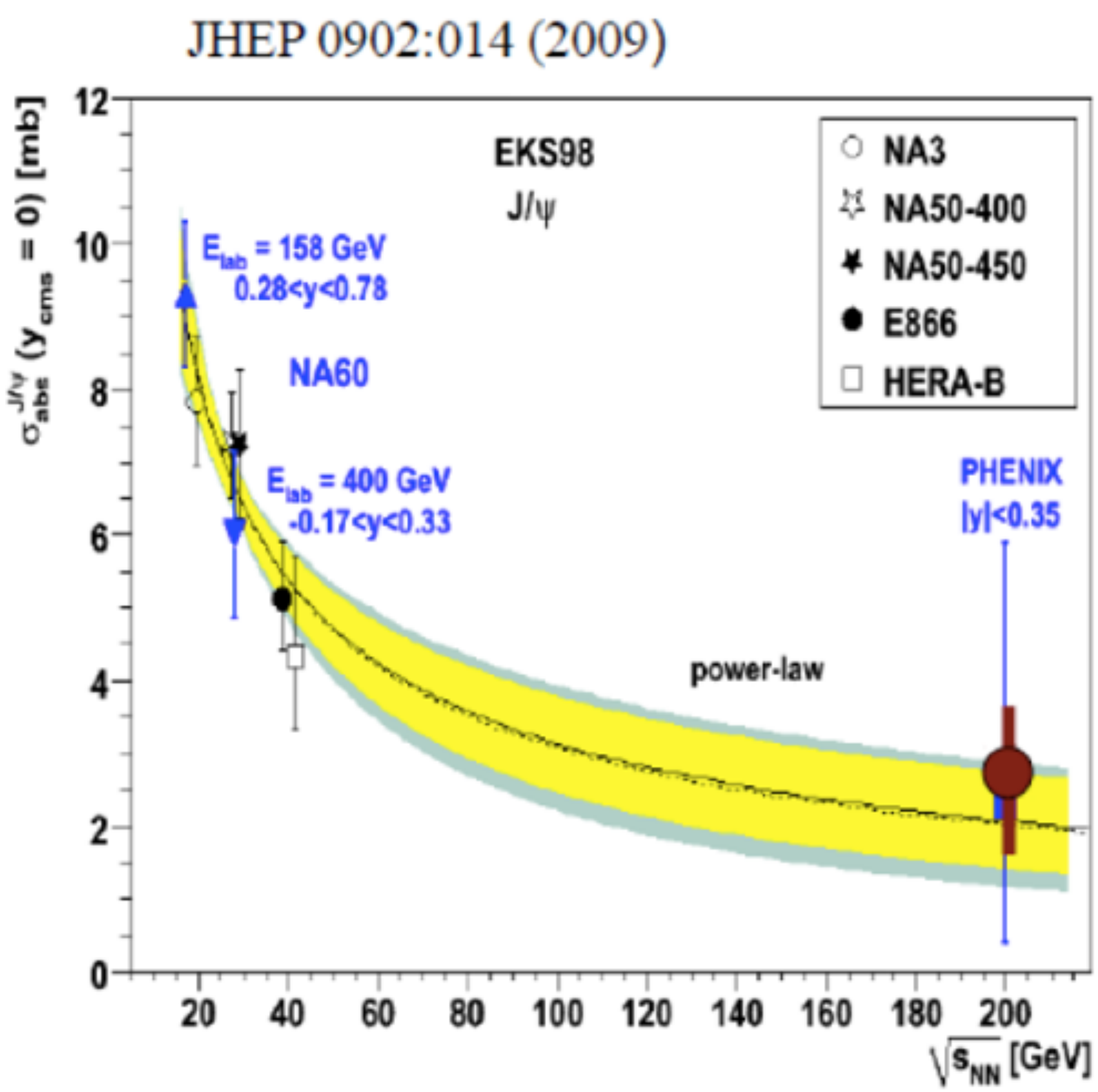
- ALICE vs CMS



ALICE : centrality 0–90%

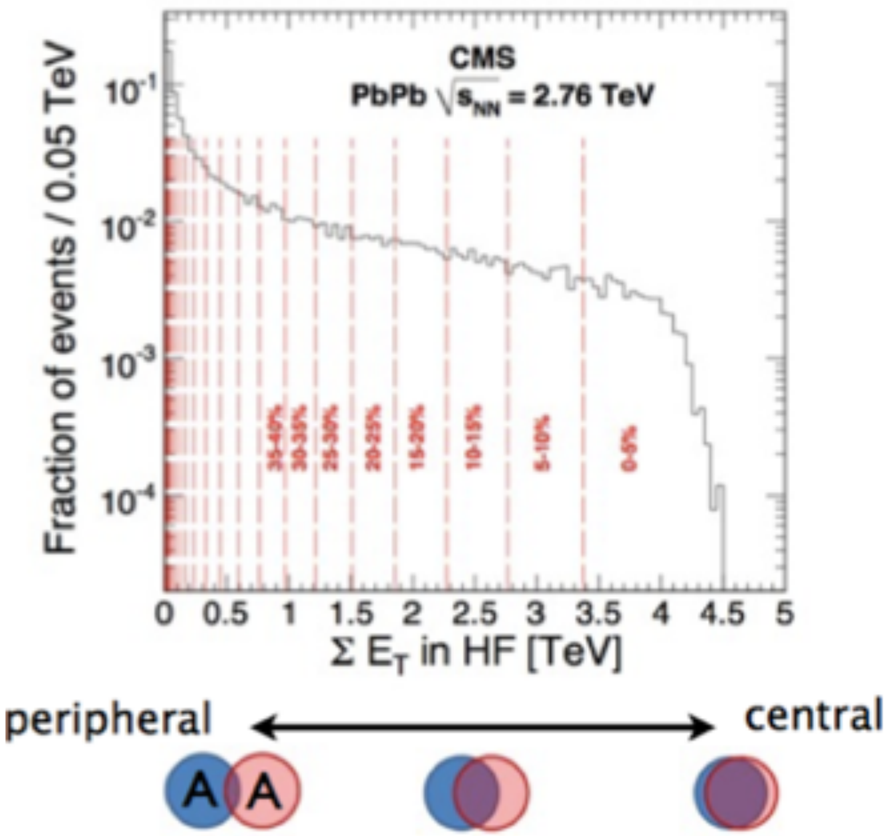
CNM effects

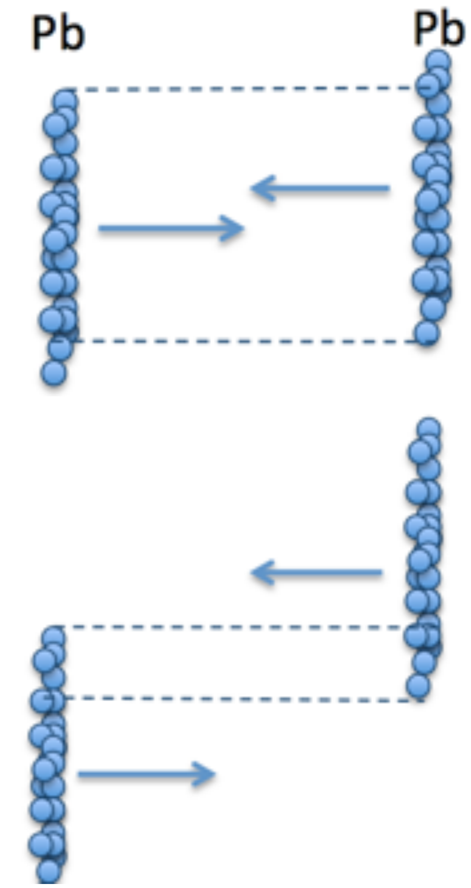
- **Nuclear absorption (break-up)**



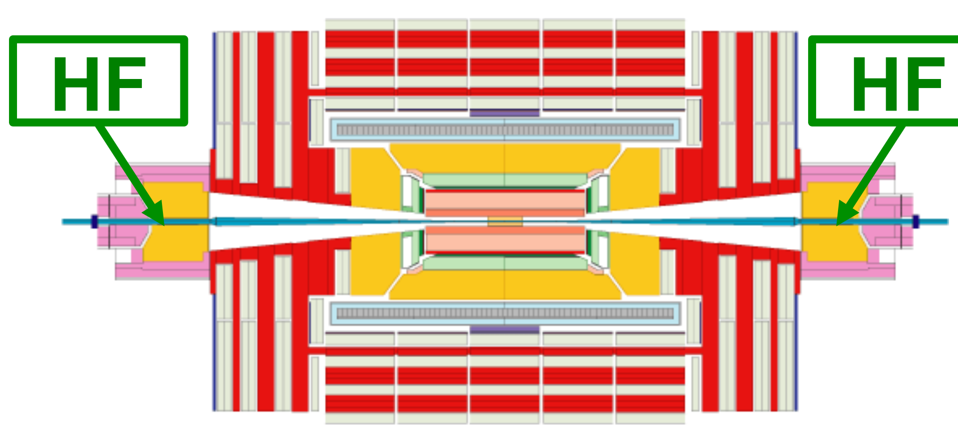
Event-activity

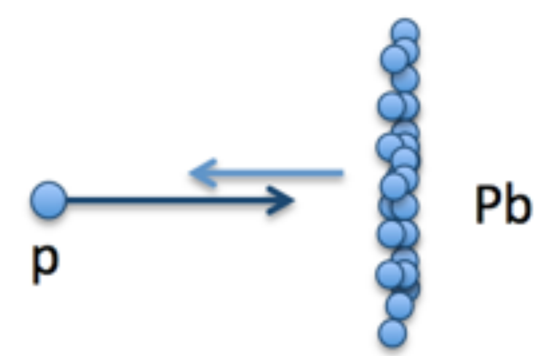
- **Centrality in PbPb**
  - related to the overlap fraction of the geometrical cross sections





- **Event-activity variables in pPb**
  - E_T^{HF} : raw transverse energy deposited in forward region HF ($4<|\eta|<5.2$)





Center of Mass Energy

E_1 = 4 TeV

E_2 = 1.58 A·TeV

Mandelstam invariant

$$S = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$m_1 \sim m_2 \sim 1\ GeV/c^2$
$m_{1,2} << E_{1,2}$

$$\Rightarrow S = (m_1^2 + \vec{p}_1^{\,2}) + (m_2^2 + \vec{p}_2^{\,2}) + 2E_1E_2 - (\vec{p}_1^{\,2} + \vec{p}_2^{\,2} + 2\vec{p}_1 \cdot \vec{p}_2)$$

$$\Rightarrow S = m_1^2 + m_2^2 + 2E_1E_2 - 2\vec{p}_1 \cdot \vec{p}_2$$

$$= -2|\vec{p}_1||\vec{p}_2|cos(180^\circ)$$

$$\sim 2E_1E_2$$

$$\Rightarrow S \simeq 4E_1E_2 \quad \Rightarrow \quad \sqrt{S} = \sqrt{4 \times 4 \times 1.58} \simeq 5.02TeV$$

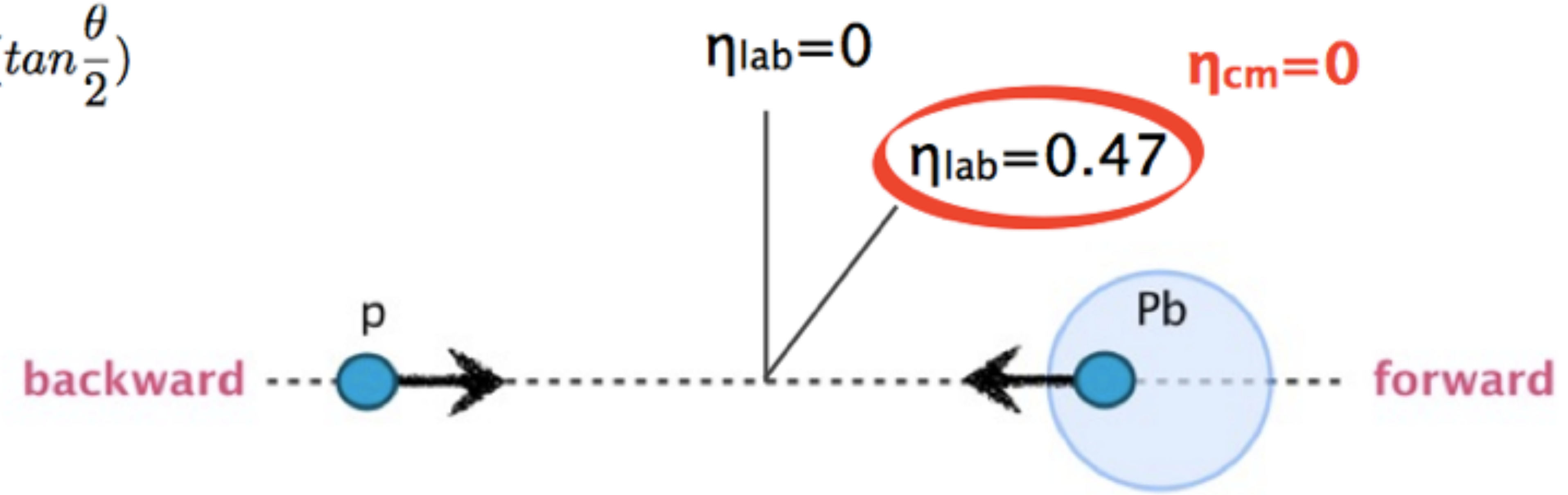
Rapidity shift

rapidity

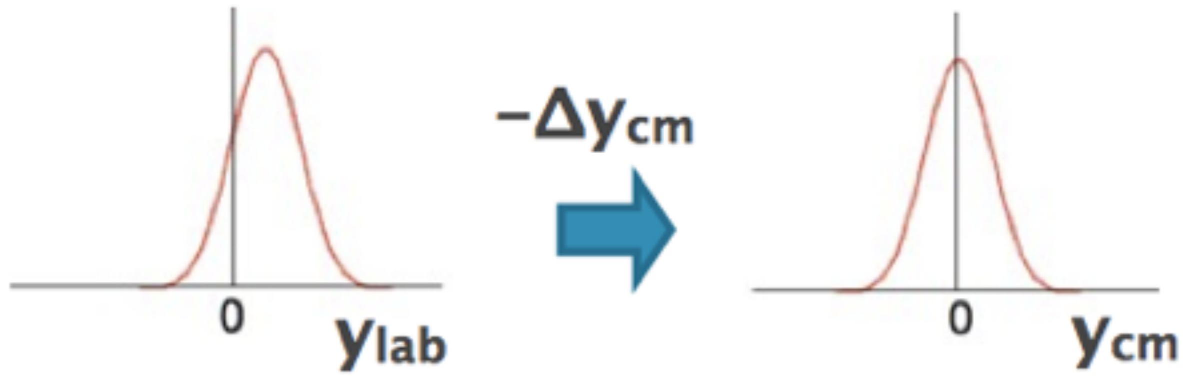
$$y = \frac{1}{2} ln(\frac{E+p_z}{E-p_z}) = \frac{1}{2} ln(\frac{1+\beta}{1-\beta})$$

$\Rightarrow \gamma = \frac{E}{mc^2}$ $\Rightarrow \beta = \sqrt{1-\frac{1}{\gamma^2}}$ $\Rightarrow$ $y_p = 9.05$, $y_{Pb} = 8.12$ $\Rightarrow \Delta y_{cm} = \frac{y_P - y_{Pb}}{2} \sim 0.47$

$$\eta = -ln(tan\frac{\theta}{2})$$



- **rapidity distribution is invariant!**

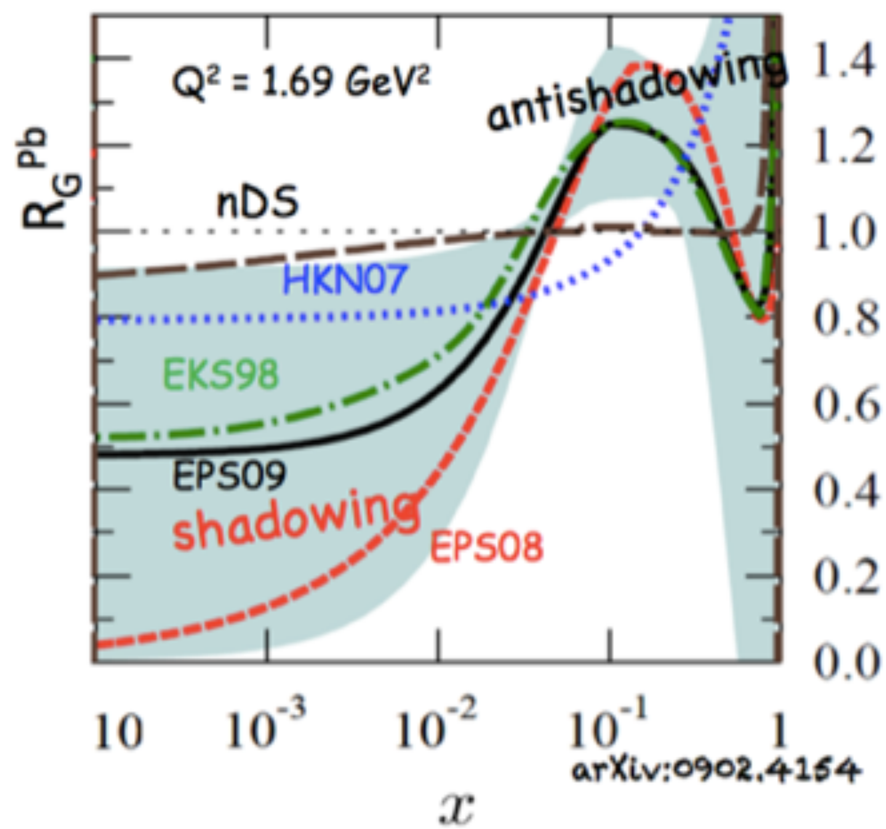


nPDF : Theoretical Models

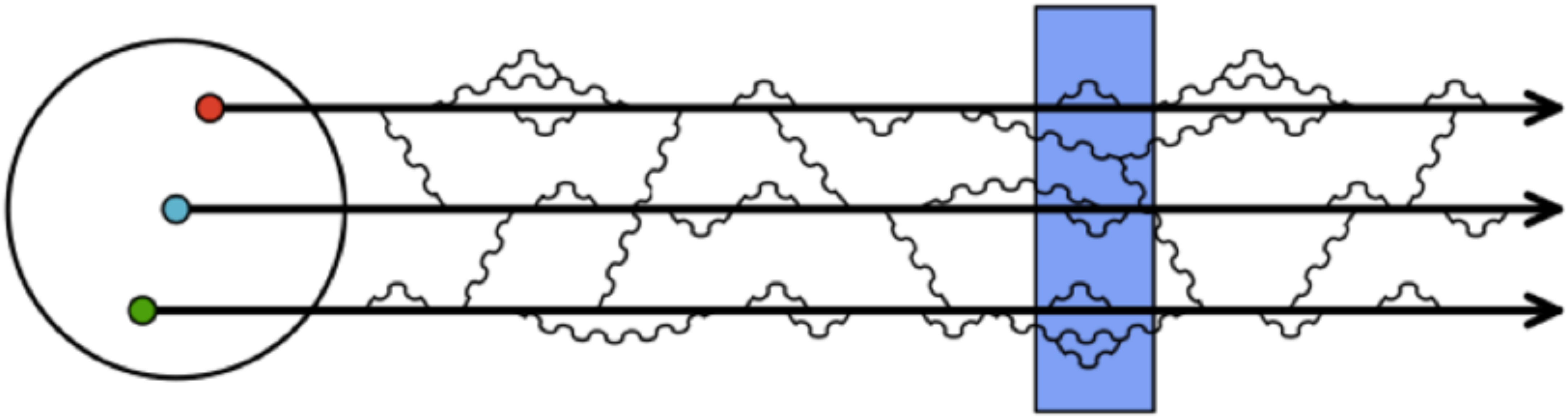
PRL 87 (2013) 034904

arXiv.0902.4154

- **Kopeliovich et. al.**
  : Shadowing – nDSg nPDFs
  : Cronin effect (parameterized from low energy data)
  : $\sigma_{break-up}$ (color dipole σ_{cc} from HERA)
- **Landberg et. al.**
  : Shadowing – EKS98, nDSg, or EPS08 nPDFs
  : effective $\sigma_{break-up}$ (0, 2.6, 4.2, 6 mb)
  : No cronin effect
  : No initial state energy loss
- **Nagle et. al.**
  : Shadowing – EPS09 nPDFs
  : $\sigma_{break-up}$ (0–20 mb)
  : Tried initial state energy loss
- **Kharzeev et. al.**
  : Shadowing – Coherent scattering / Color Glass Condensate model

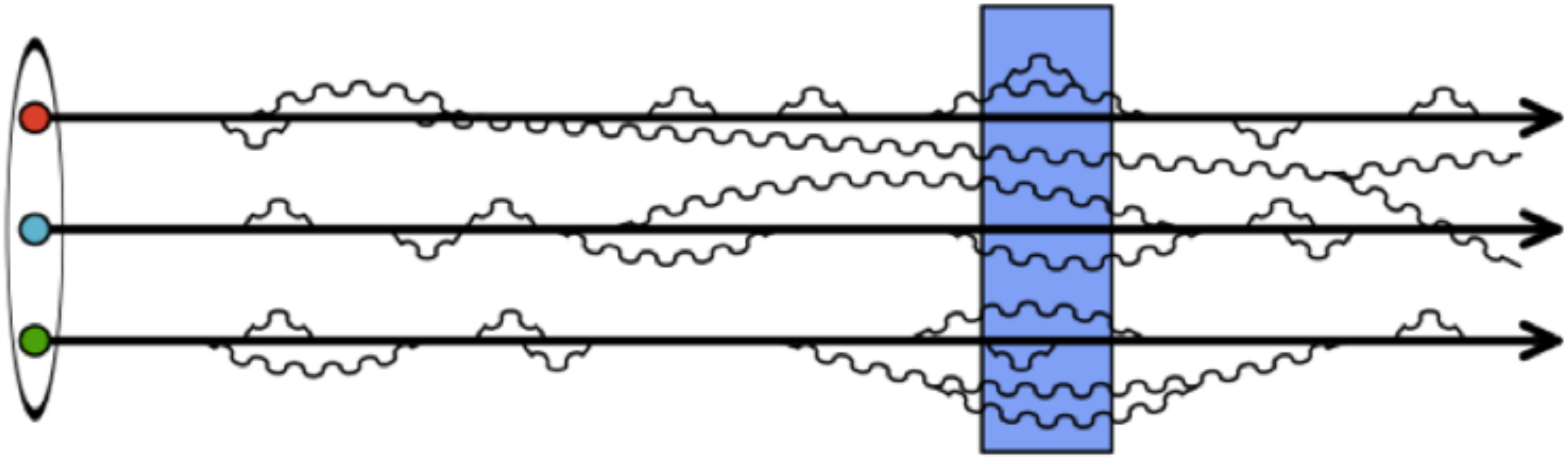


Nucleon at rest



- Very complicated non-perturbative object...
- Contains fluctuations at all space-time scales smaller than its own size
- Only the fluctuations that are longer lived than the external probe participate in the interaction process
- The only role of short lived fluctuations is to renormalize the masses and couplings
- Interactions are very complicated if the constituents of the nucleon have a non trivial dynamics over time-scales comparable to those of the probe

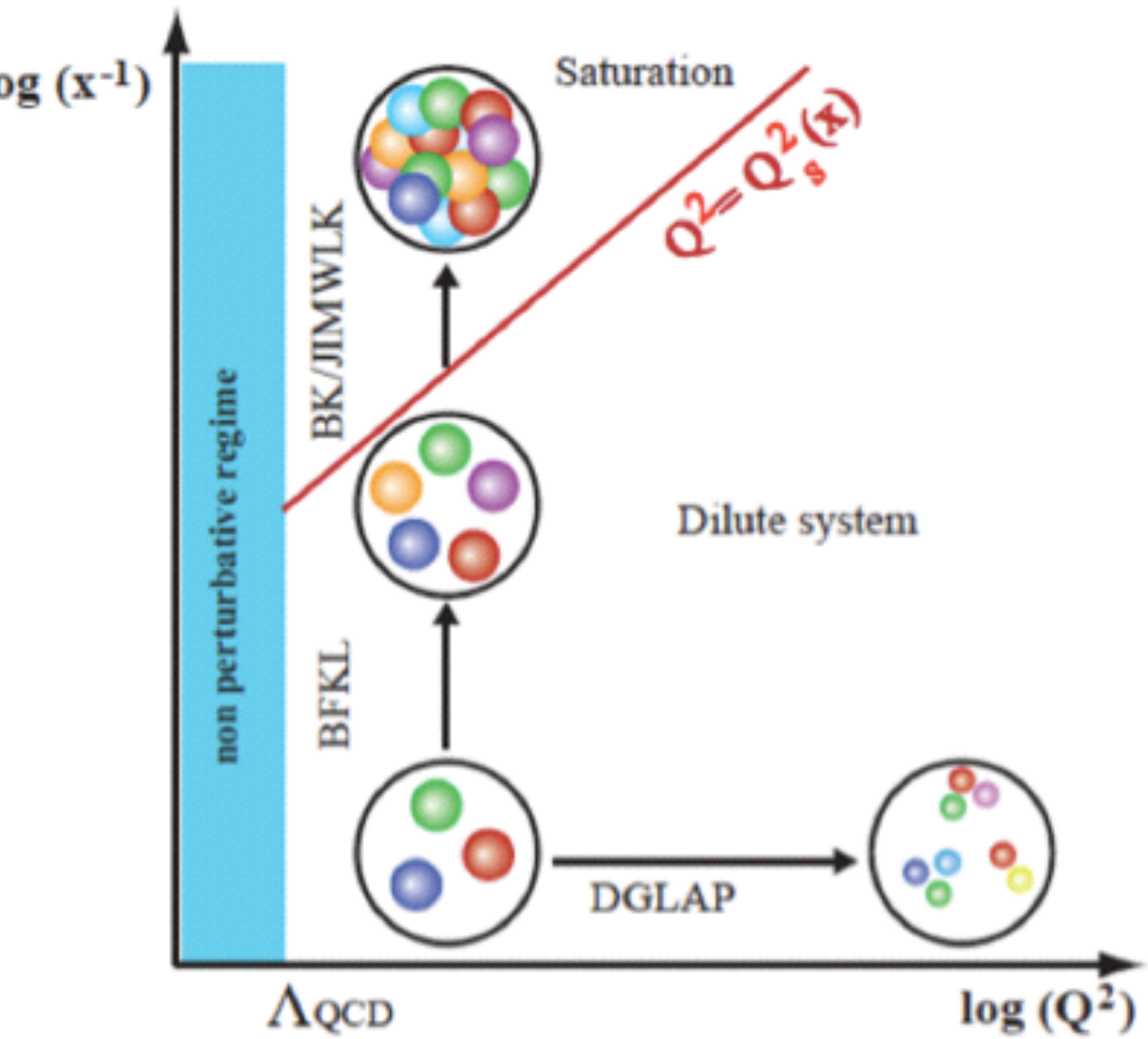
Nucleon at higher energy



- Dilation of all internal time-scales of the nucleon
- Interactions among constituents now take place over time-scales that are longer than the characteristic time-scale of the probe
  ▷ the constituents behave as if they were free
- Many fluctuations live long enough to be seen by the probe. The nucleon appears denser at high energy (it contains more gluons)
- Pre-existing fluctuations are totally frozen over the time-scale of the probe, and act as static sources of new partons

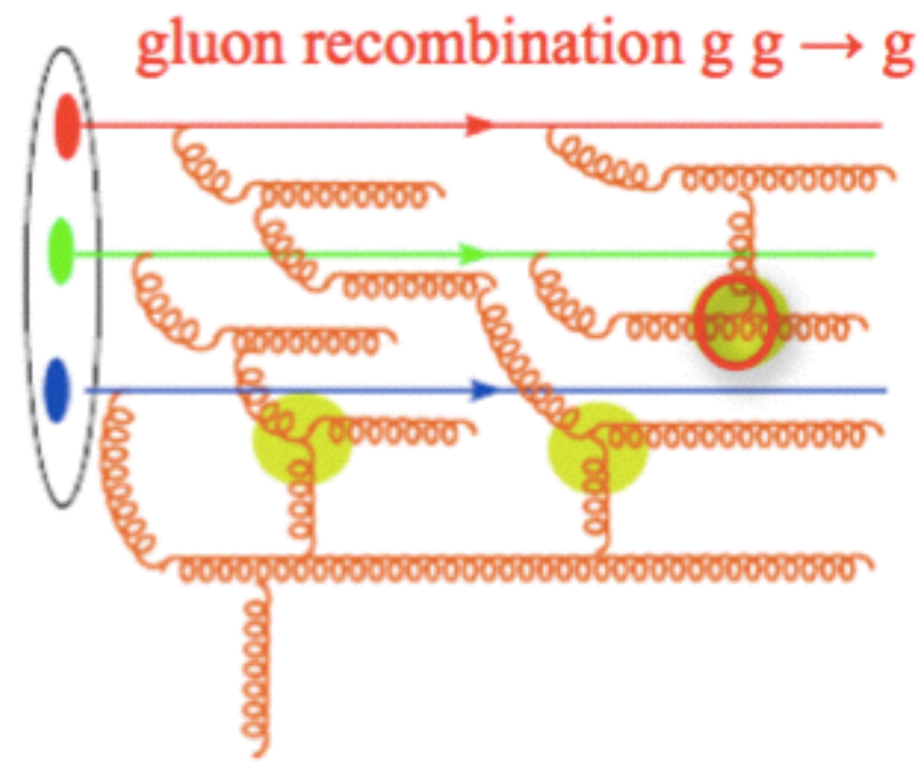
Color Glass Condensate

Nucleon structure: x and Q^2 evolution



Saturation regime at low x and Q^2

Gribov, Levin, Ryskin, Phys.Rept.100,1983
Mueller, Qiu, Nucl.Phys.B268,1986
Blaizot, Mueller, Nucl.Phys.B289,1987



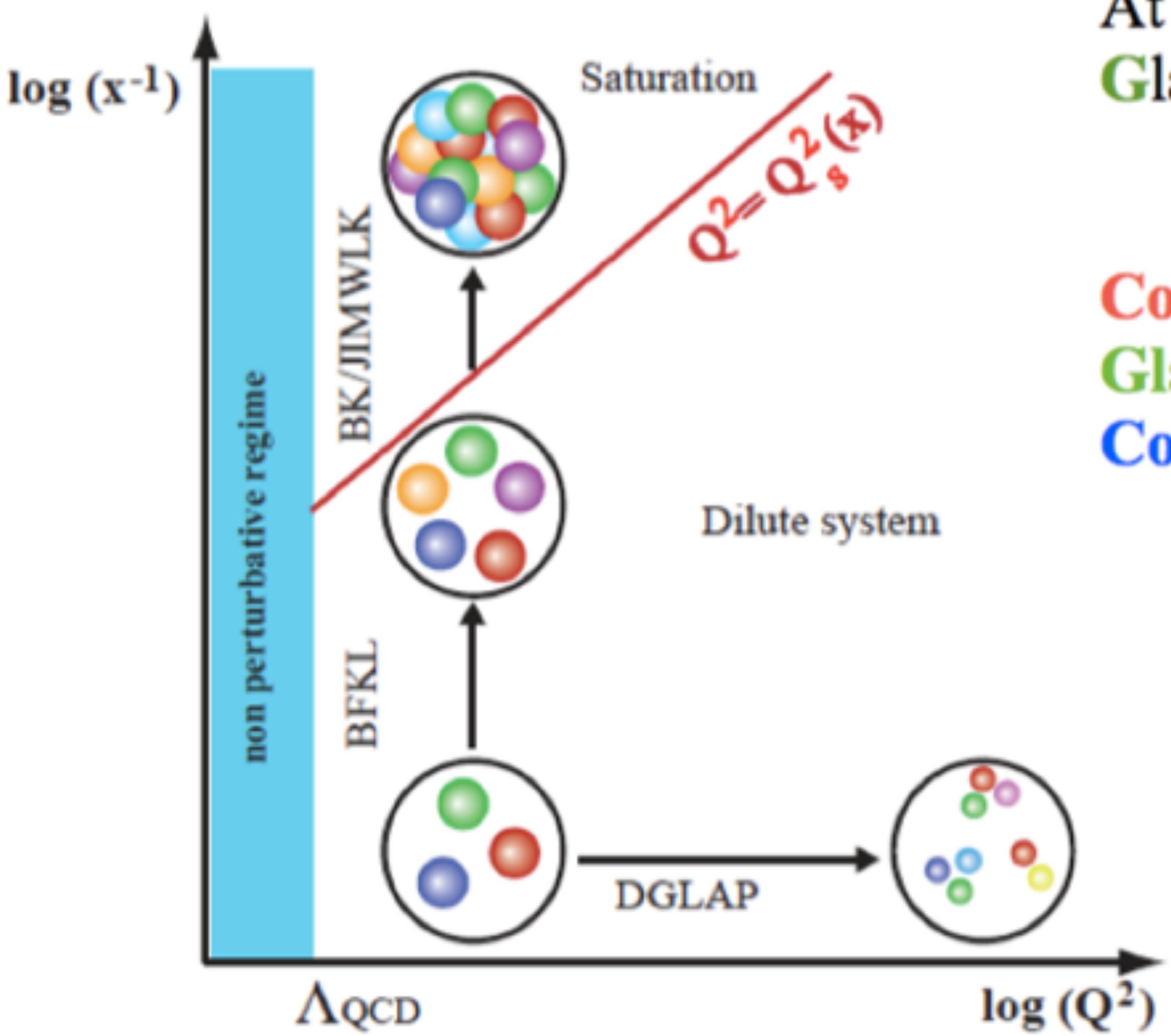
***x*-evolution**

Large-x, linear → BFKL
Balitsky, Fadin, Kuraev, Lipatov

Small-x, non linear → JIMWLK/BK
Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov, Kovner Balitsky, Kovchegov

$Q^2_s(x)$ defines the scale below which the gluon density saturates

Color Glass Condensate



At small-x, hadronic matter can be described by the Colour Glass Condensate (CGC) model

McLerran, Venugopalan, Iancu, Leonidov, Mueller, ...

Colour	gluons are coloured
Glass	fast partons as "frozen" sources of soft gluons
Condensate	high gluon occupancy

If large Q^2_s : weakly coupled QCD-based theory but not necessarily perturbative → CGC is a classical effective theory

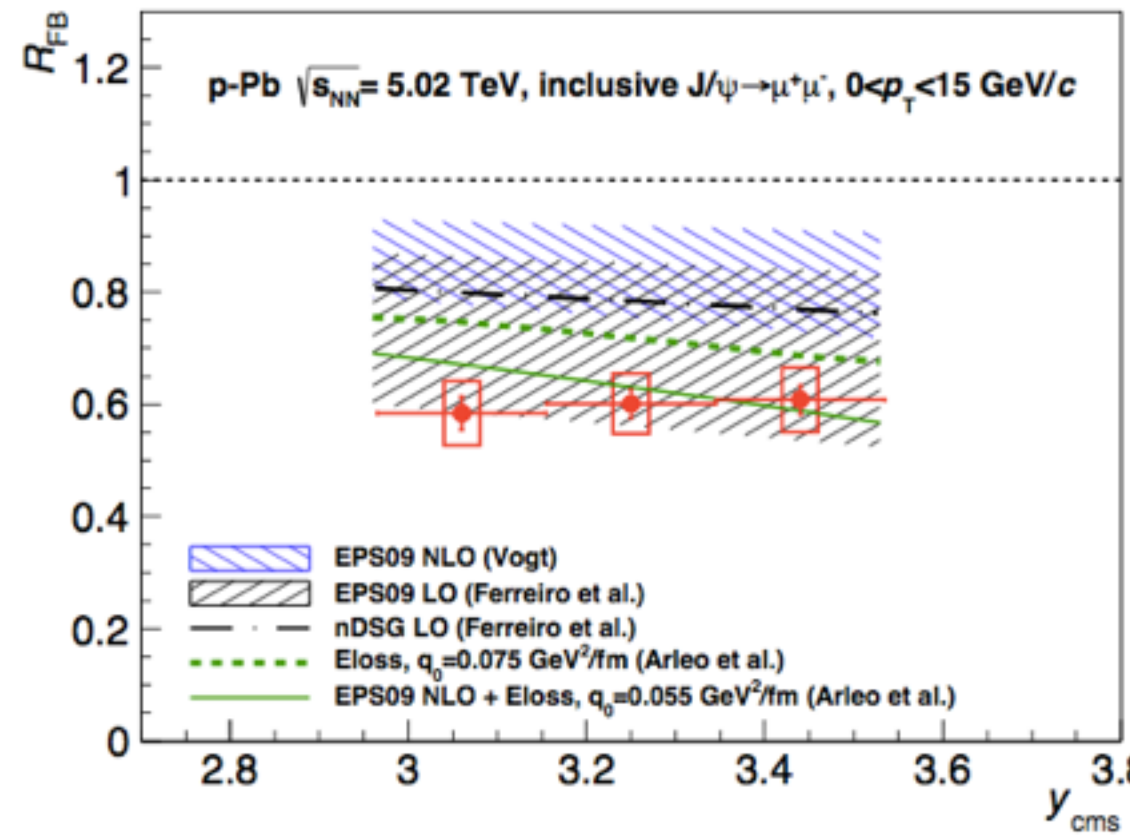
$Q^2_s \propto x^{-0.3} A^{1/3}$ → saturation for low x (high $\sqrt{s}=1/x$), large A

→ $Q^2_{s,LHC} = 3\ Q^2_{s,RHIC}$

→ $Q^2_{s,Pb} = 6\ Q^2_{s,p}$

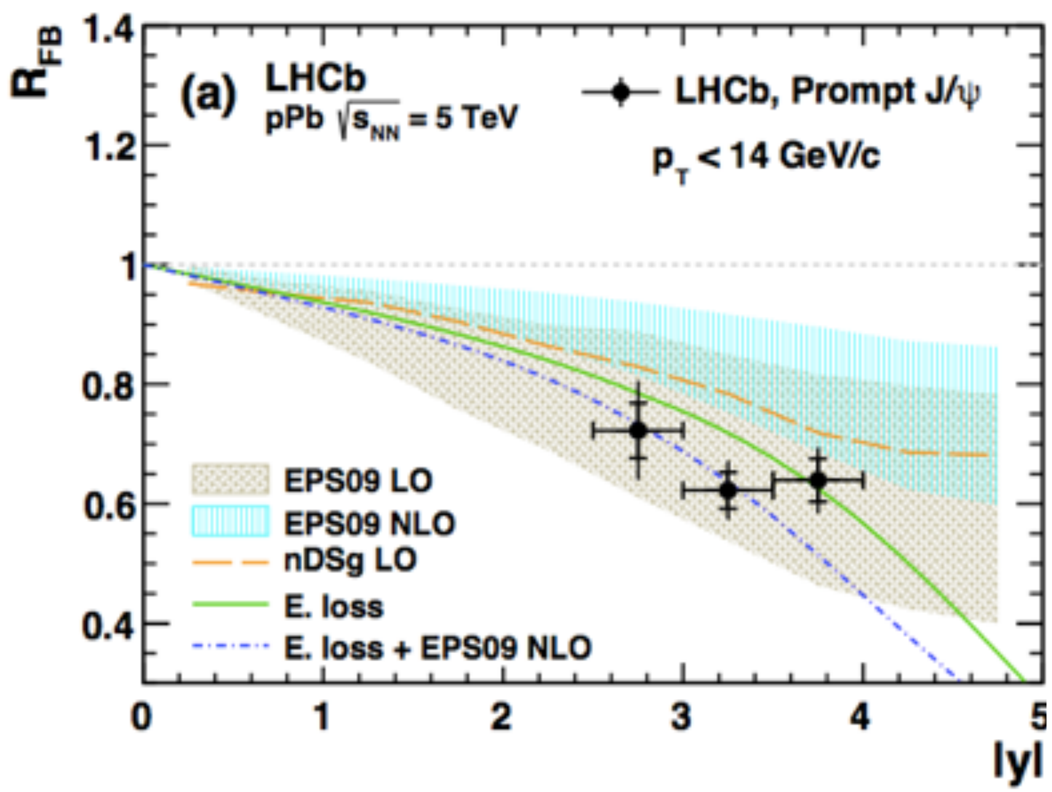
Forward-backward ratio

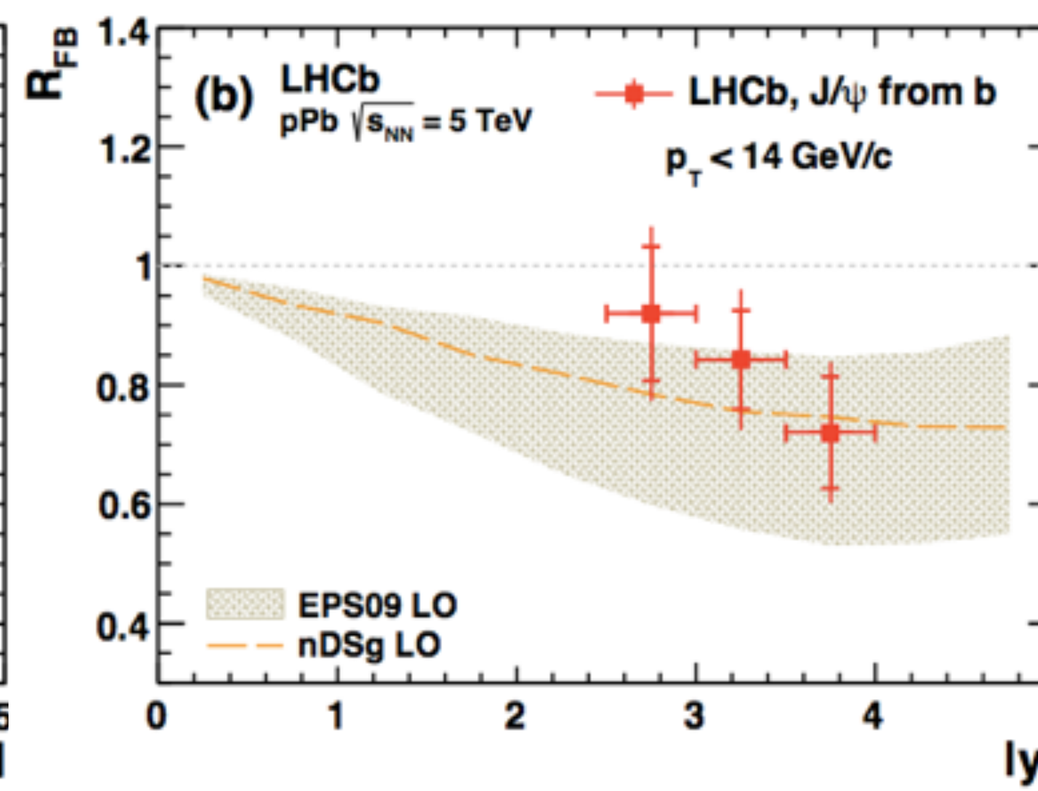
$$R_{FB} = \frac{N^{Forward}}{N^{Backward}}$$



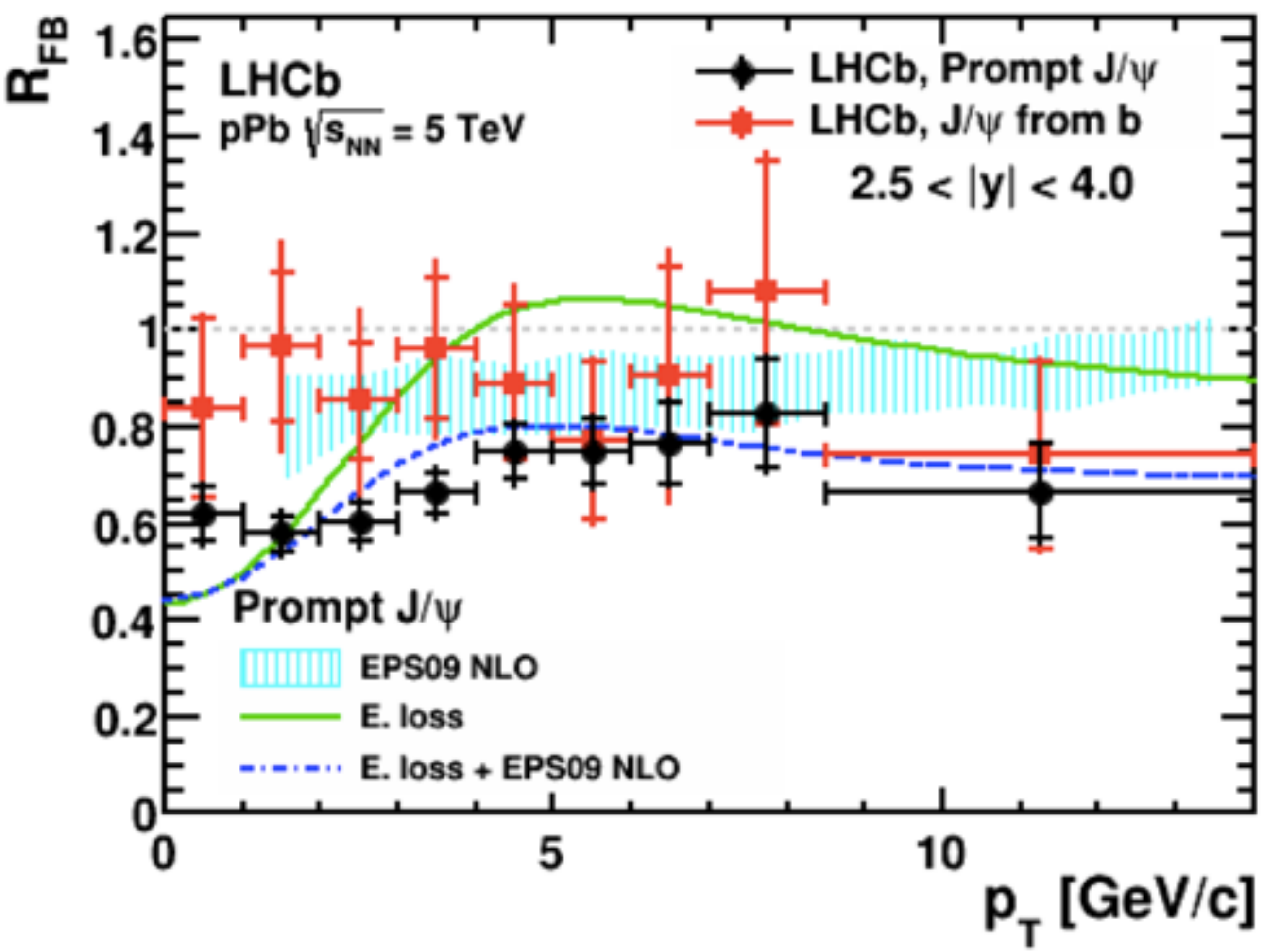
- **ALICE**
  - p_T < 15 GeV/c
  - 2.96< $|y_{CM}|$ < 3.53

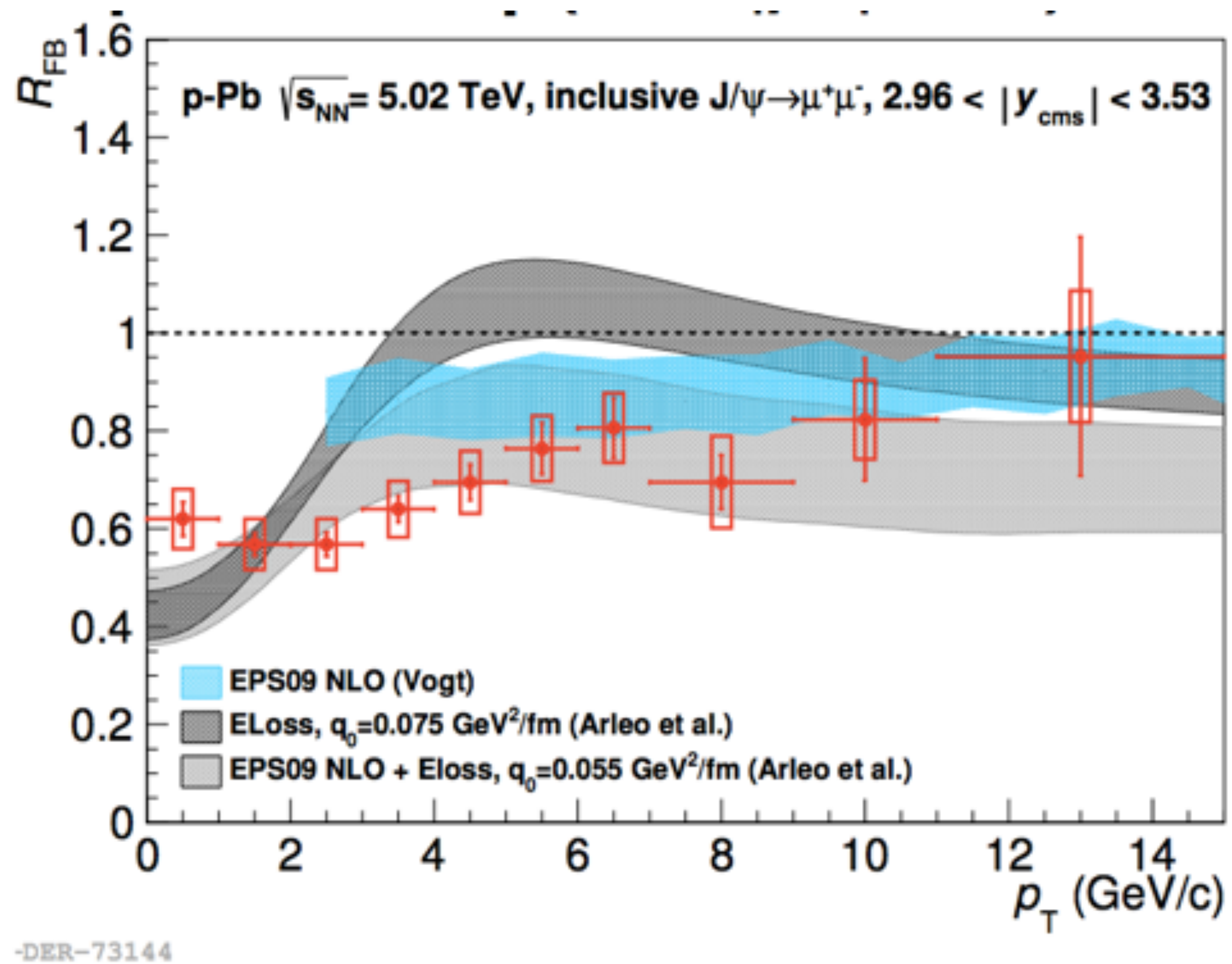
- **LHCb**
  - p_T < 14 GeV/c
  - 2< $|y_{CM}|$ < 5





Forward-backward ratio





- Shadowing + energy loss in good agreement with data
- pT dependence (suppression stronger at low p_T?)

pp inter/extrapolation (LHCb)

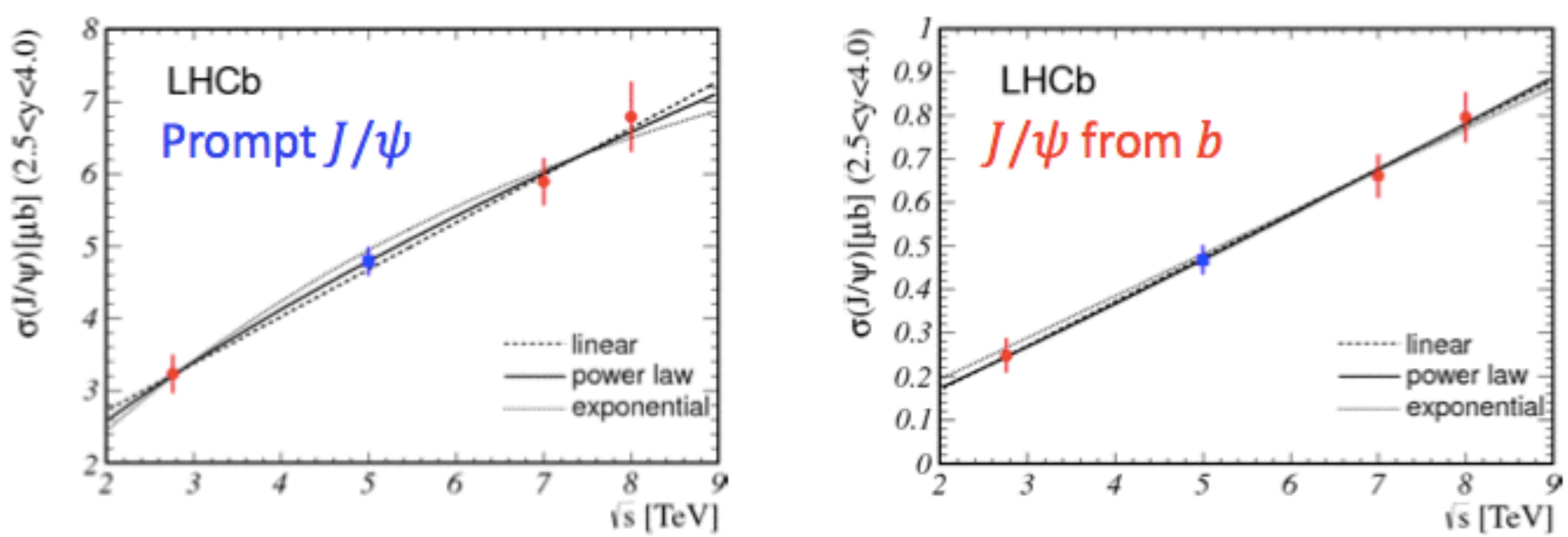
Reference cross-sections in pp at $\sqrt{s} = 5$ TeV

LHCb-CONF-2013-013

- Input to the determination of the nuclear modification factor $R_{p\mathrm{Pb}}$
- Interpolated from measurements at 2.76 TeV, 7 TeV and 8 TeV
- Three different fit functions used to interpolate

$$(\sqrt{s}/p_0)^{p_1} \longrightarrow \text{adopted as nominal}$$
$$p_0 + p_1\sqrt{s}$$
$$p_0\left(1 - e^{p_1\sqrt{s}}\right)$$

- Discrepancy between the three interpolated values taken as systematics
- Checked against functions from LO-CEM and FONLL



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pp inter/extrapolation (ALICE)

- **pp reference cross-section**: no measurement at required energy, need to interpolate. Two step procedure in both analyses.
  - Dimuon analysis [1]:
    1) $\sqrt{s}$ interpolation: performed bin-per-bin in rapidity (or p_T) using available ALICE pp results at 2.76 and 7 TeV
    2) Further rapidity extrapolation: due to rapidity shift, p-Pb y_{cms}-range lies slightly outside the pp y_{cms}-range
  - Dielectron analysis:
    1) $\sqrt{s}$ interpolation: performed using available PHENIX, CDF and ALICE results at $y \approx 0$
    2) p_T dependence: phenomenological scaling inspired by reference [2]