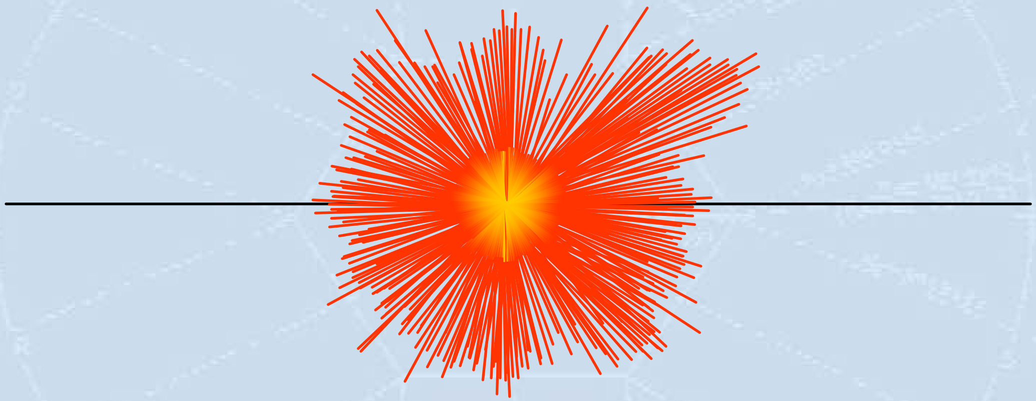
Heavy Quarks and Quarkonia: the experimental point of view



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IN2P3-CNRS et École polytechnique

Overview

- ✓ Quarkonia → dileptons
  - ✓ Why quarkonia ? Why dileptons ?
- ✓ Detecting dileptons
- ✓ Normalized to what ?
- ✓ As a function of what ?
- ✓ Compared to what ?
- ✓ What's expected ?
- ✓ Interpretations ?
- ✓ Other observables ?
- ✓ The ultimate reference ?
- ✓ *En route* for higher energies !

Today

Thursday

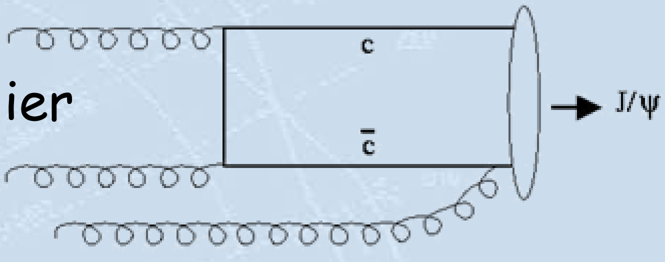
Sunday

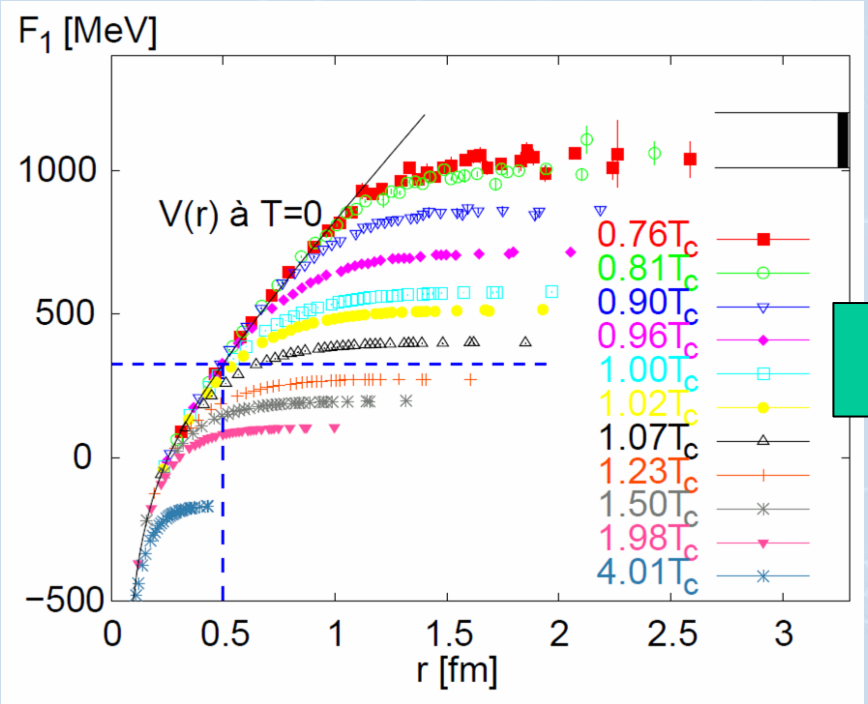
Let's start with

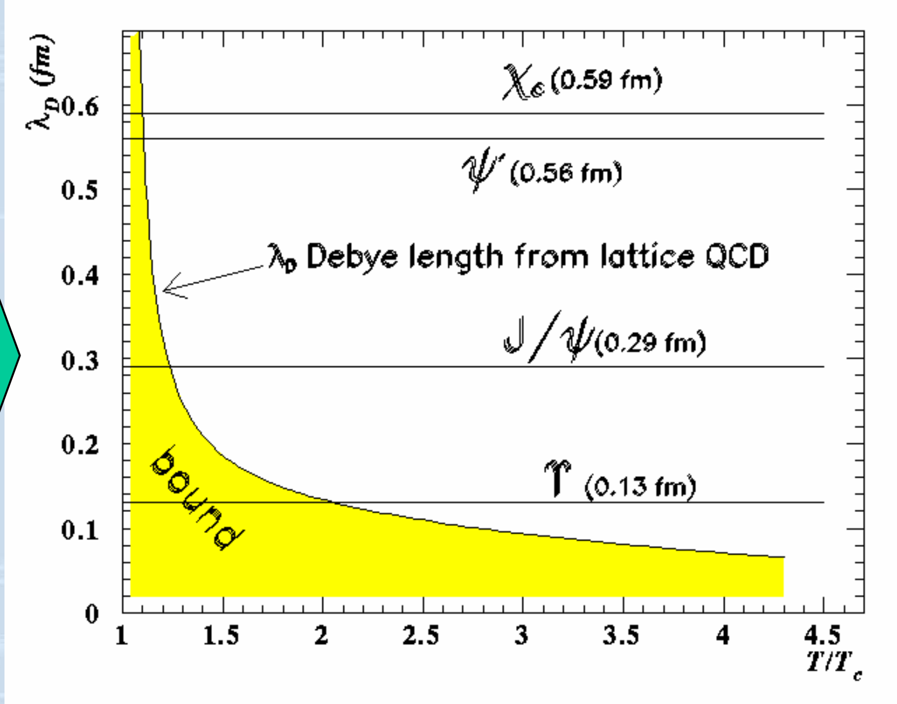
Quarkonia → dileptons

Why Quarkonia ?

- ✓ T. Matsui and H. Satz … 22 years ago (already !?)
  - ✓ c-$\bar{c}$ potential screened by surrounding color charges in a QGP
  - ✓ no c-$\bar{c}$ bound state above ~ 1.2 Tc …
  - ✓ higher excited states are dissolved earlier
  - ✓ b-$\bar{b}$ states can be dissolved at higher temperatures

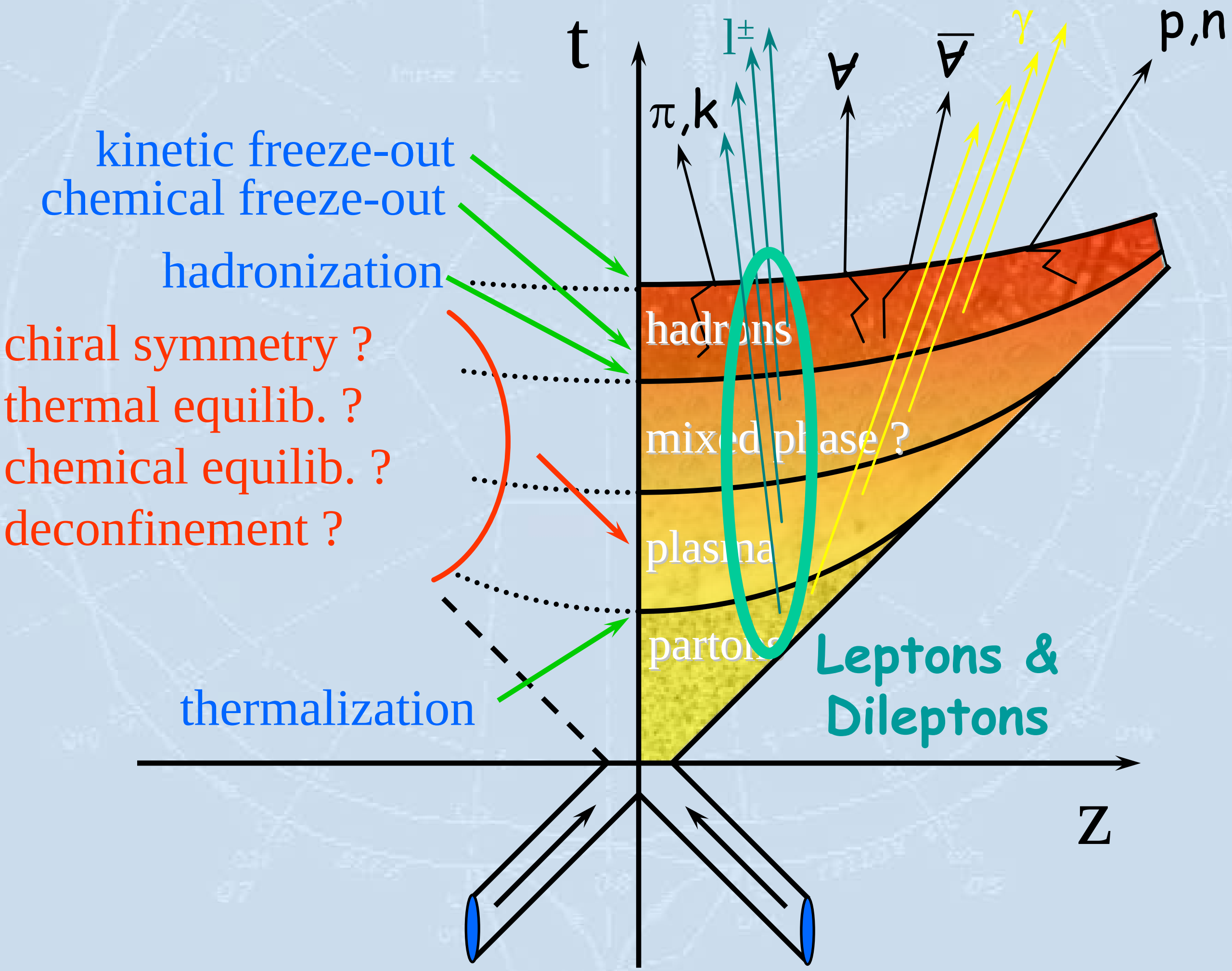






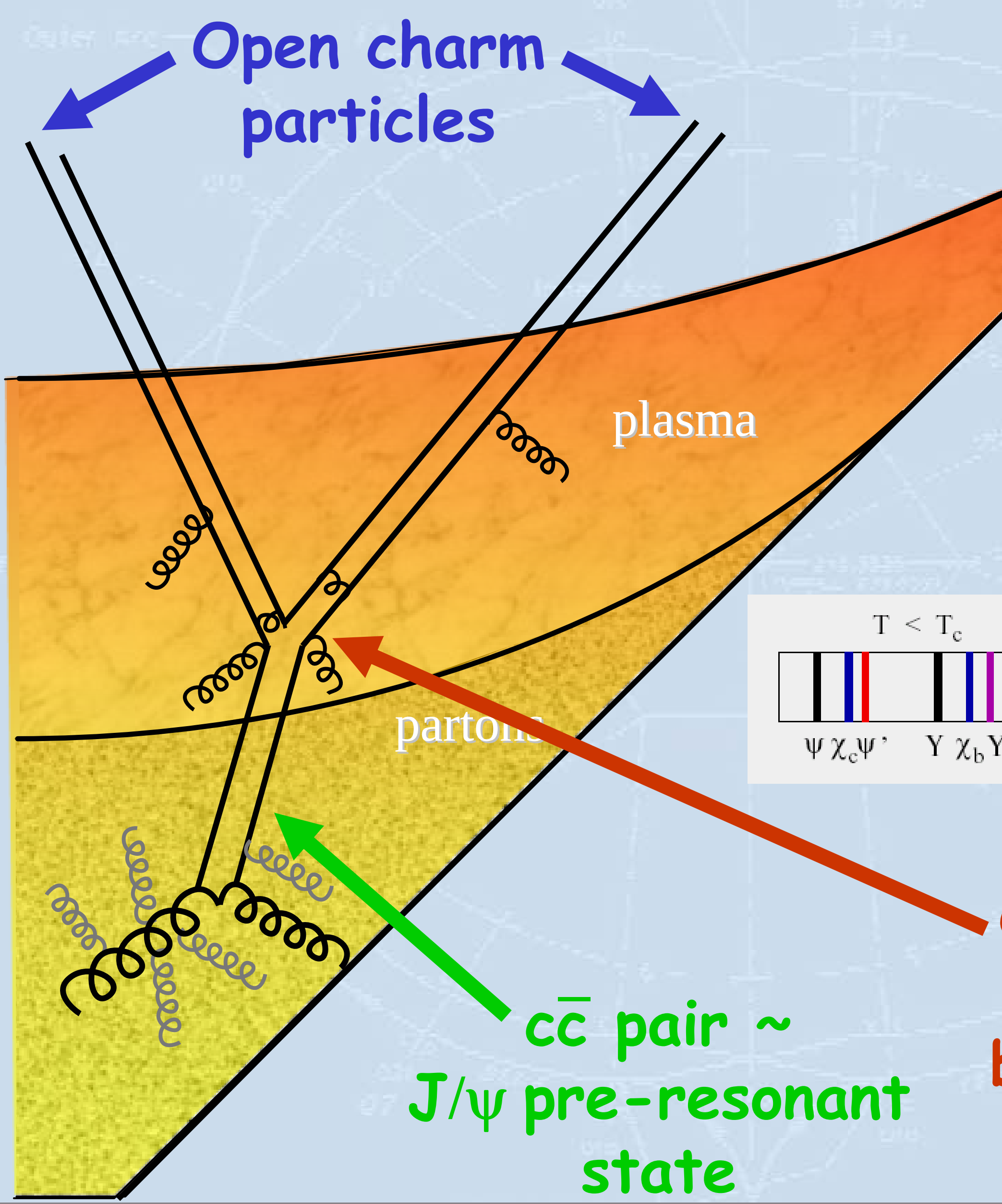
Why dileptons ?

- ✓ $J/\psi \rightarrow \mu^+\mu^-$ or e^+e^- (6%) $\Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu^+\mu^-$ or e^+e^-
- ✓ leptons ~ not affected by later stages of the collision

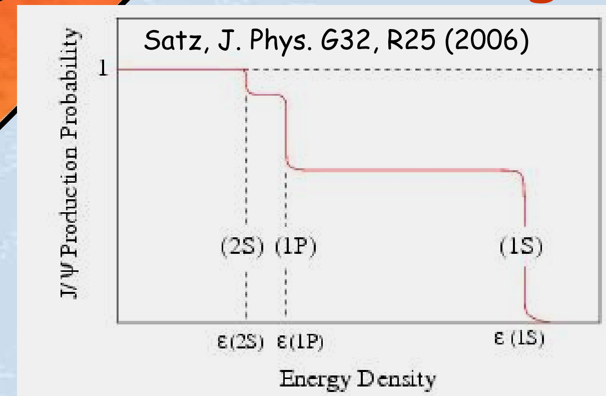


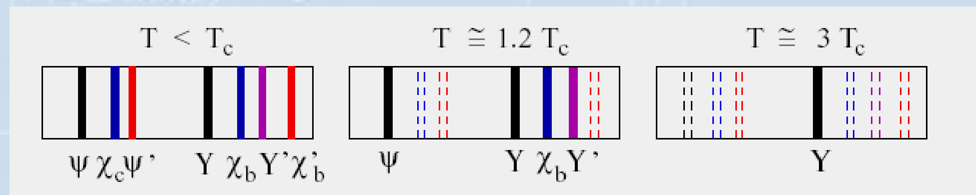
J/ψ suppression in the QGP

Open charm particles



"sequential Melting"



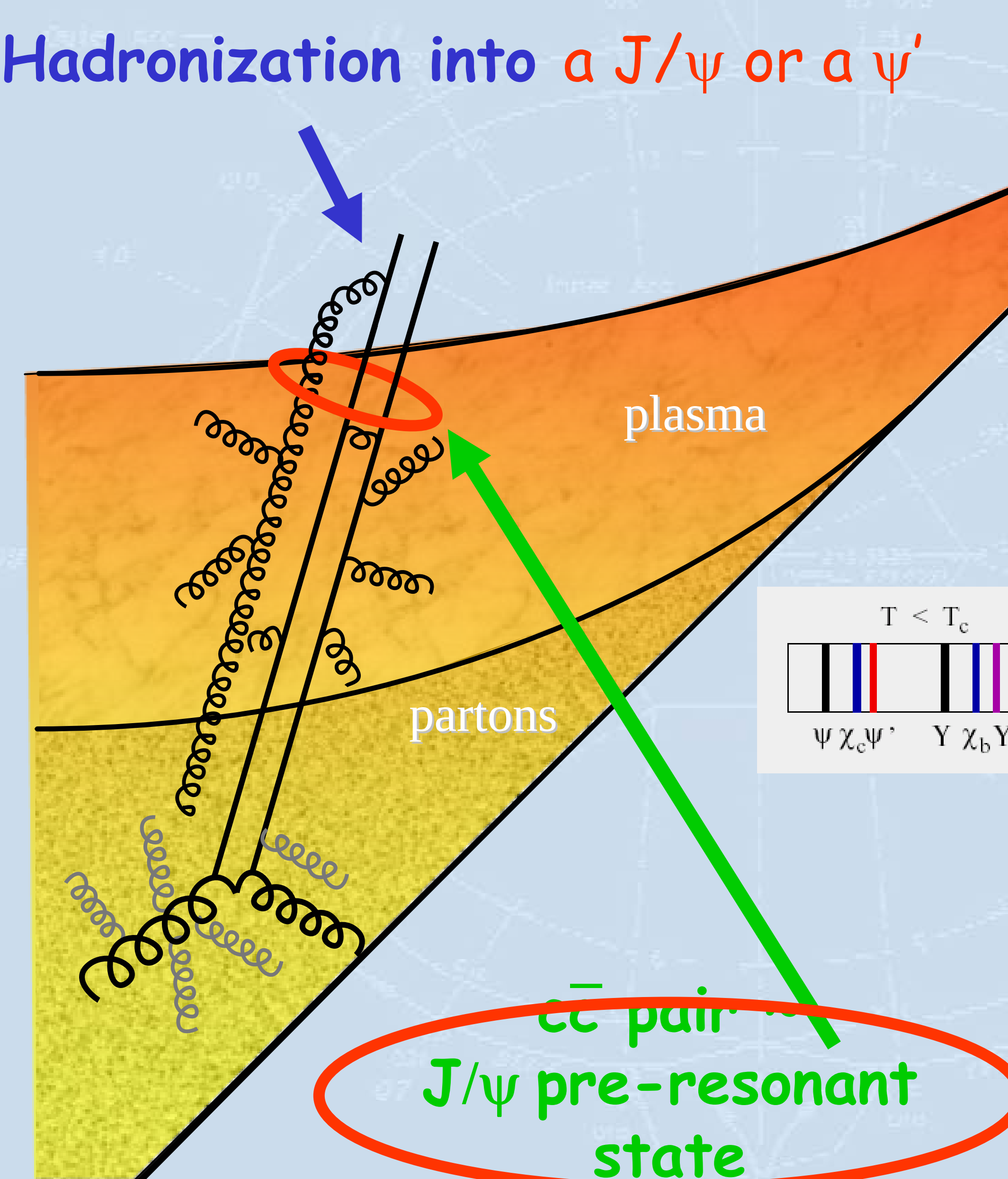


$c\bar{c}$ pair ~ J/ψ pre-resonant state

Color screening of the $c\bar{c}$ potential by the surrounding color charges

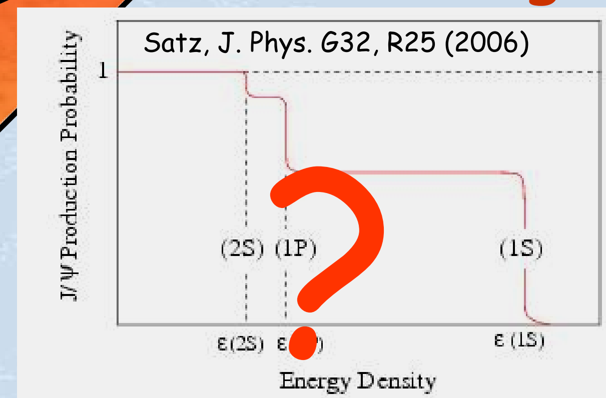
This picture might be somewhat naive ...

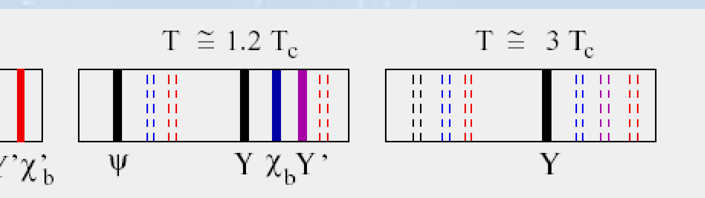
Hadronization into a J/ψ or a ψ′



$c\bar{c}$ pair → J/ψ pre-resonant state

"sequential Melting"



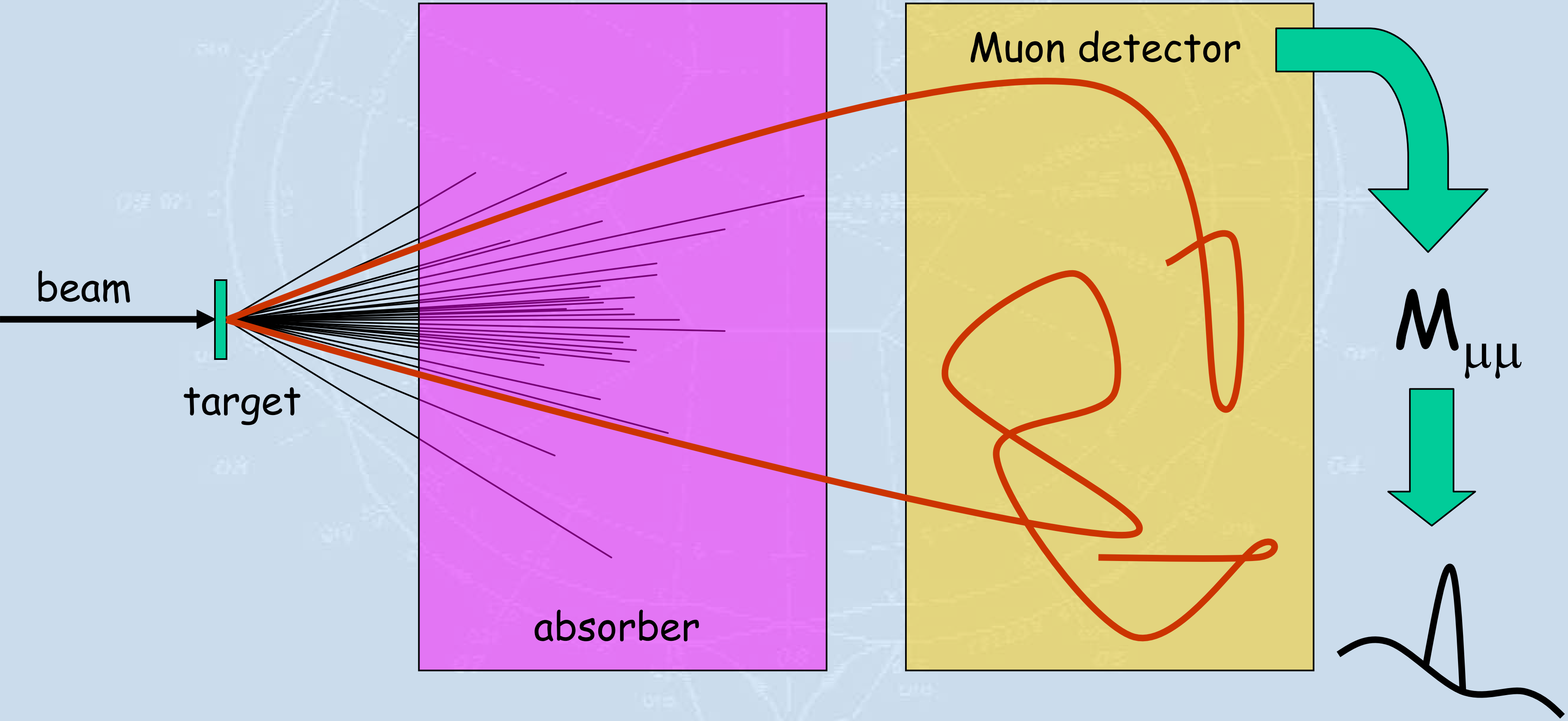


How does the « pre-resonant state » know whether it will become a J/ψ or a ψ′ ?

Muons are easily detected …

- ✓ In fixed target experiment , the central rapidity zone is boosted ;-)

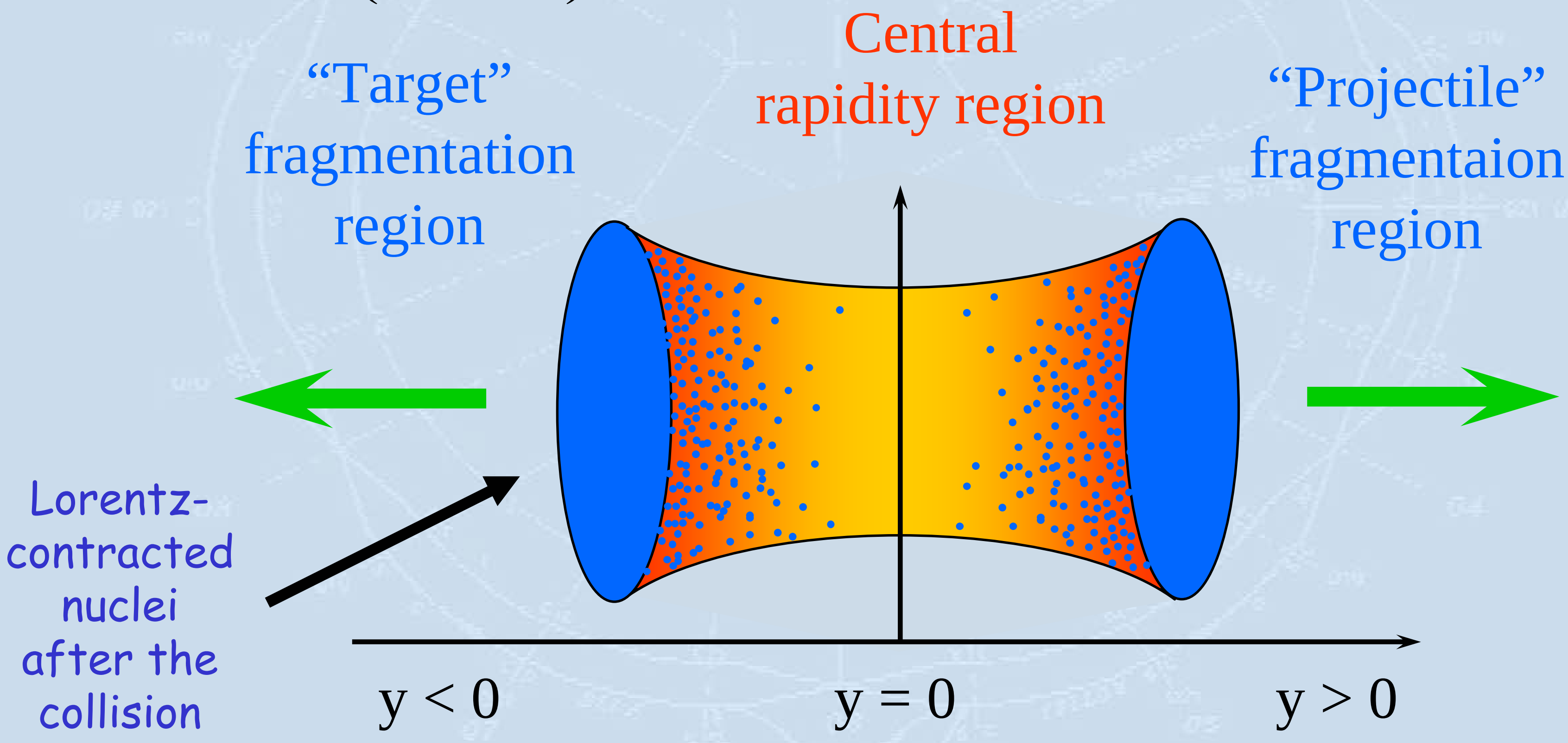
Let's absorb everything … … except muons, thanks to their high energy (due to the boost) … … with witch you do whatever you want



What is rapidity ?

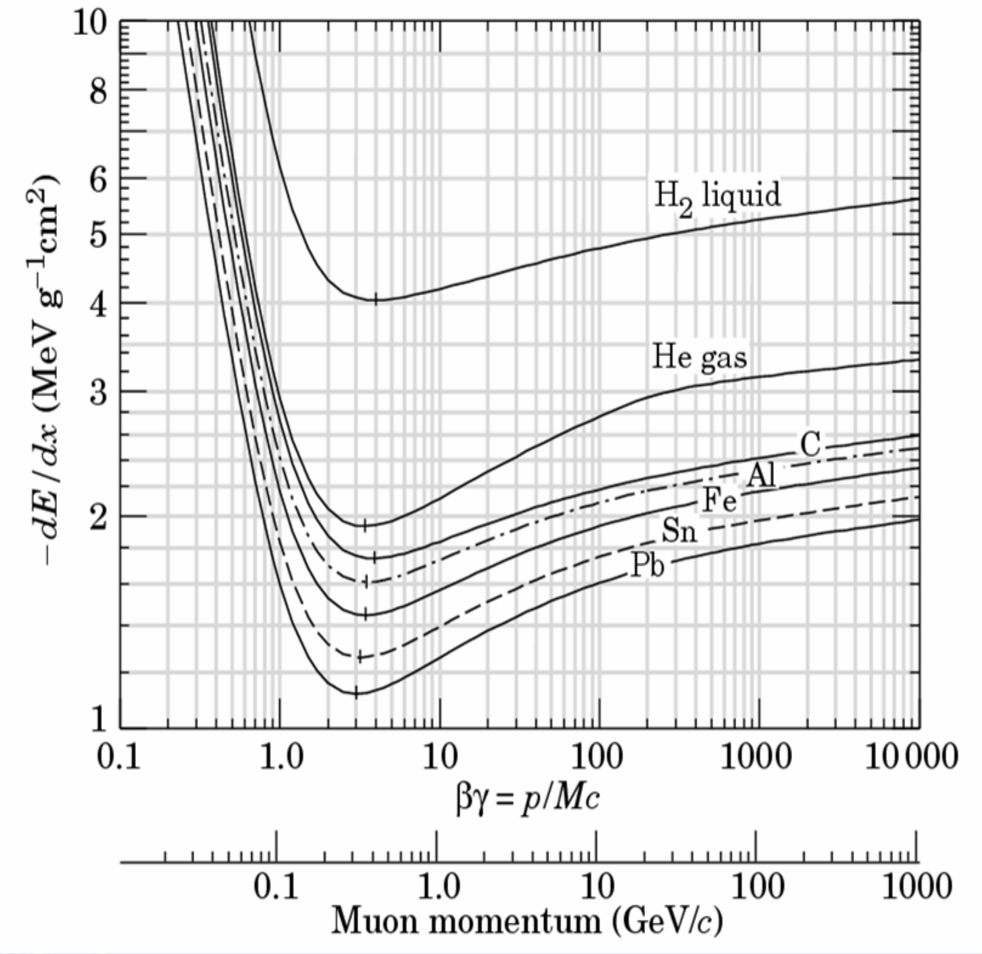
✓ Rapidity is a convenient "boost additive" velocity variable

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



Muon energy loss in matter

- ✓ Muons lose ~ 2 MeV/g/cm2 in C and Fe
  - ✓ Whereas nuclear interaction length is:
  - ✓ 86 g/cm2 = 38 cm in carbon
  - ✓ 132 g/cm2 = 16.8 cm in iron

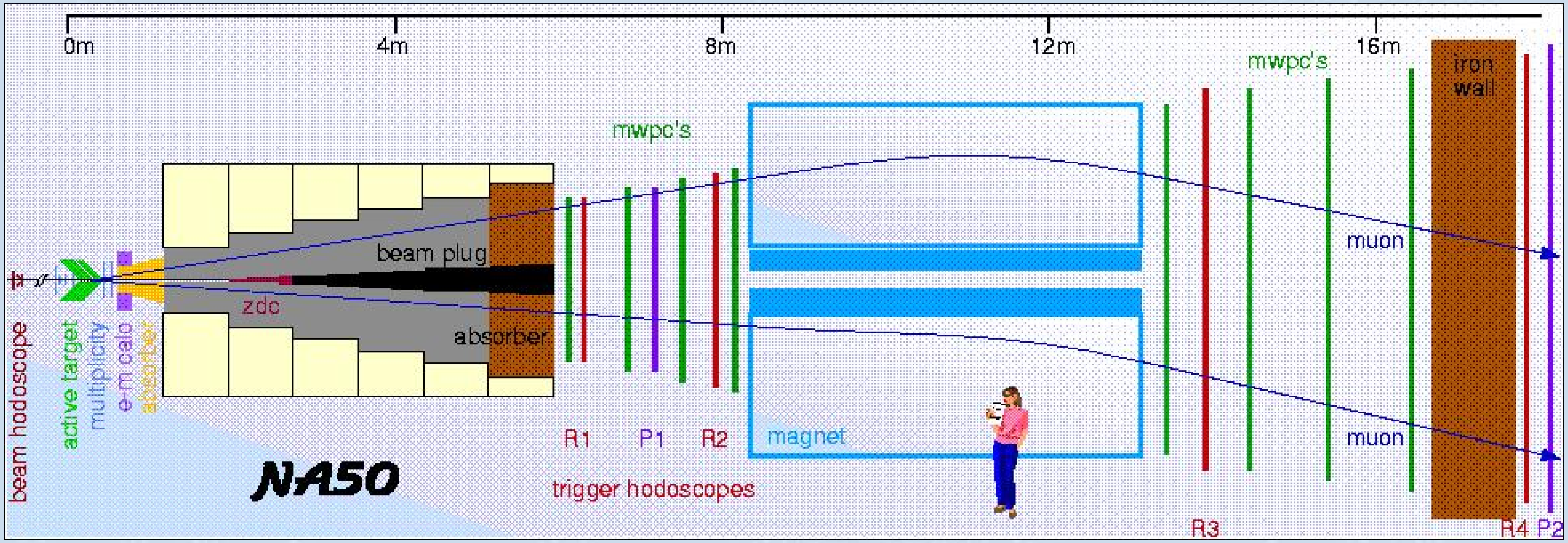


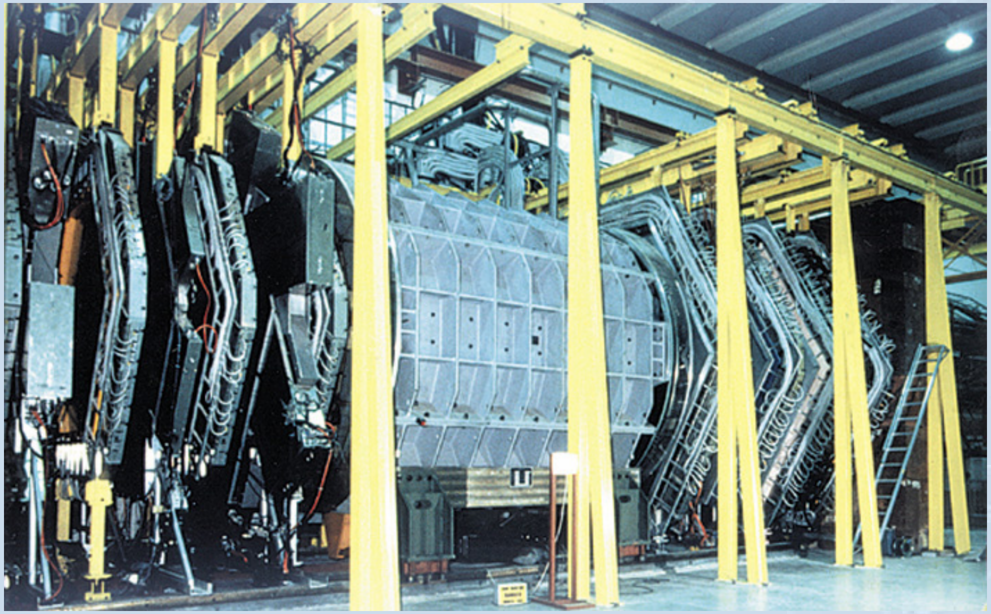
- ✓ E.g. : @ Cern SPS:

  $E\mu$ ~ 50 GeV in the lab.
  - ✓ C absorber, 5m thick
  - ✓ Muons lose ~ 2 GeV
  - ✓ π yield x $e^{-(500/38)}$

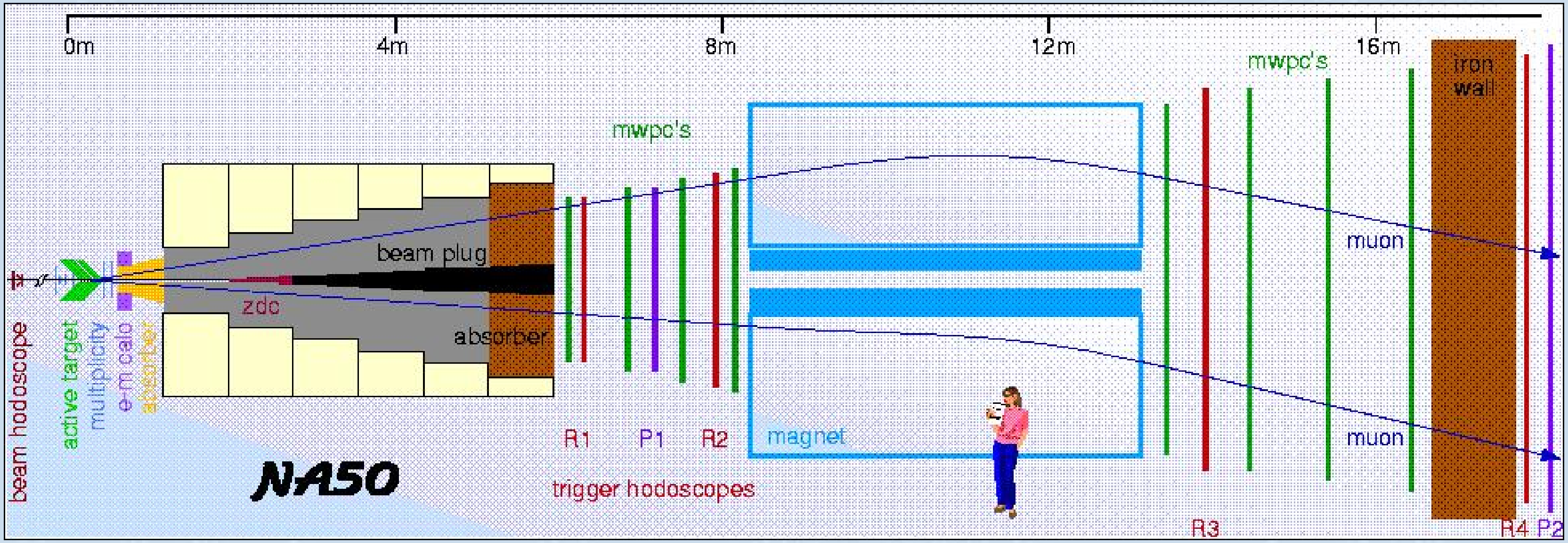
  Various absorbers
  - ✓ Fe, C, Polyethylene, etc ...

Example : NA38/50/60 @ CERN





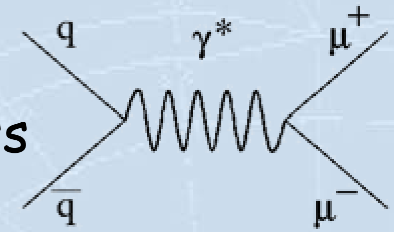
Example : NA38/50/60 @ CERN



- ✓ 5m thick absorber
- ✓ Tracking chambers
- ✓ Trigger scintillators
  - ✓ Homothetic from target region
  - ✓ Last trigger hodoscope downstream a last iron absorber
    - ✓ Filter possible remaining punch through
    - ✓ Does not degrade mass resolution

Dimuons in NA50

- « continuum » =
  - Drell-Yan process

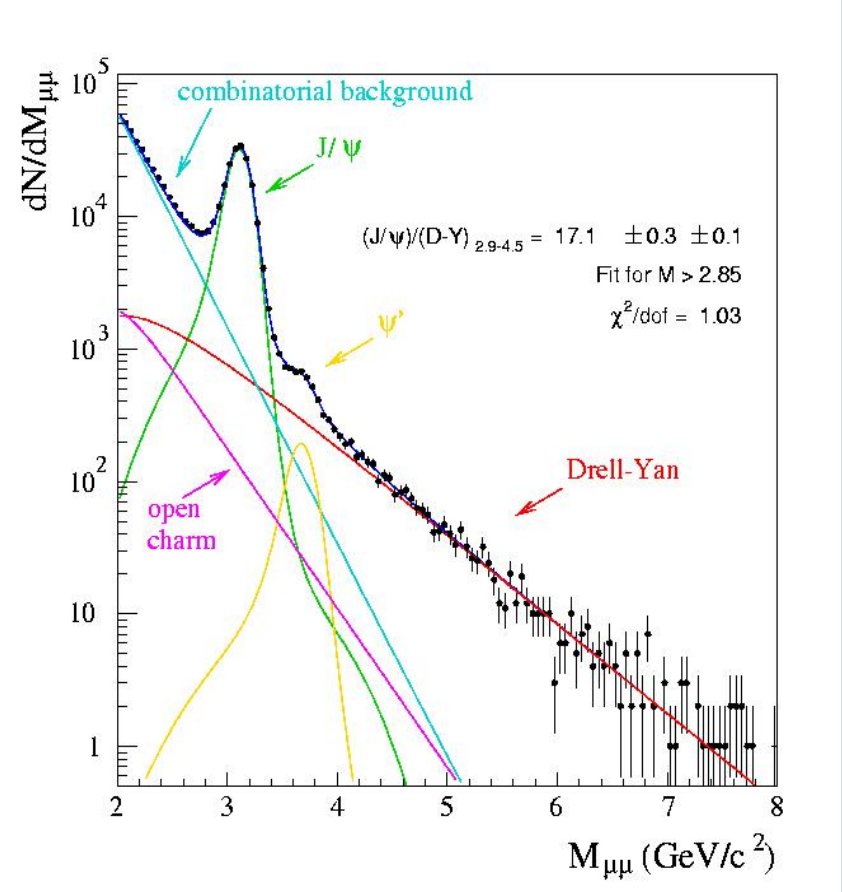


e.g. NA50 @ CERN: Pb-Pb
158 GeV on fixed target
$\sqrt{s} \approx 17$ GeV

  - + open charm (D) particles through semi-leptonic decay

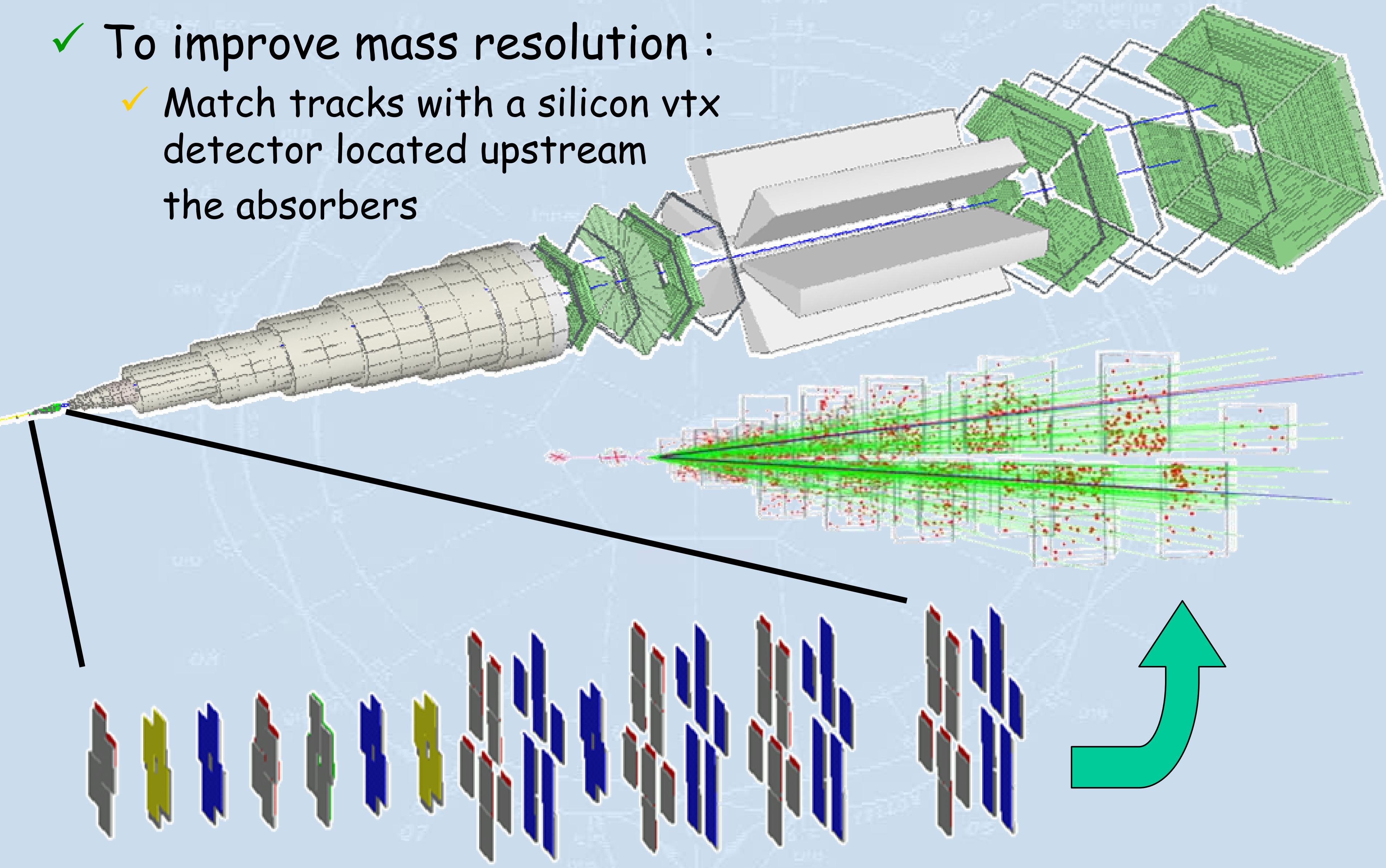
- Combinatorial background
  - Due to π and K decay
  - Contribute to « like sign » as well as to « unlike sign »
  - Measure ++, -- and +-
  - Compute background contribution as:

$$N^{+-}_{Backgnd} = 2R\sqrt{N^{++}N^{--}}$$



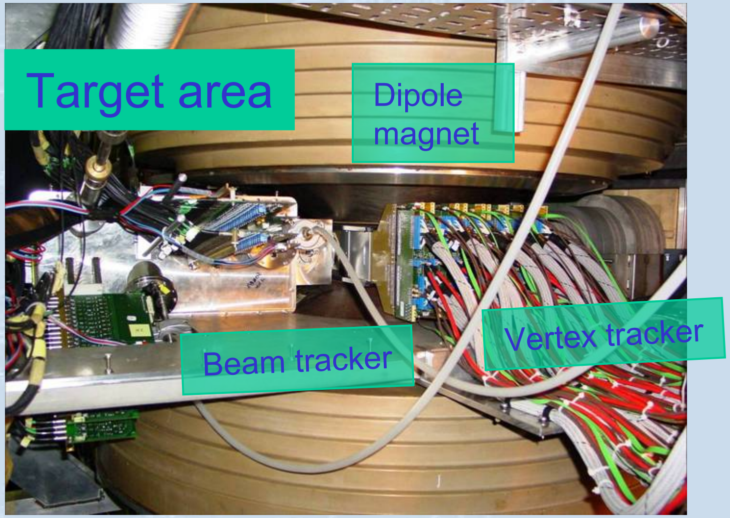
NA50 + Si vertex detector = NA60

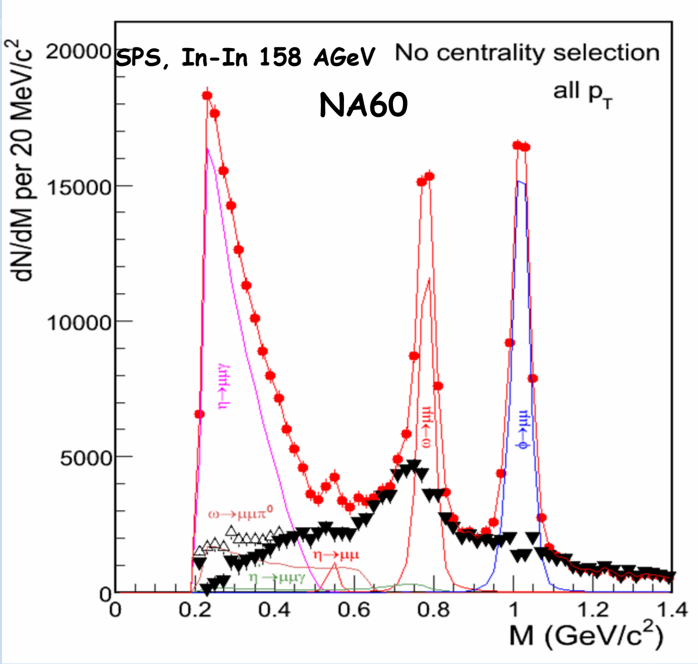
- ✓ To improve mass resolution :
  - ✓ Match tracks with a silicon vtx detector located upstream the absorbers

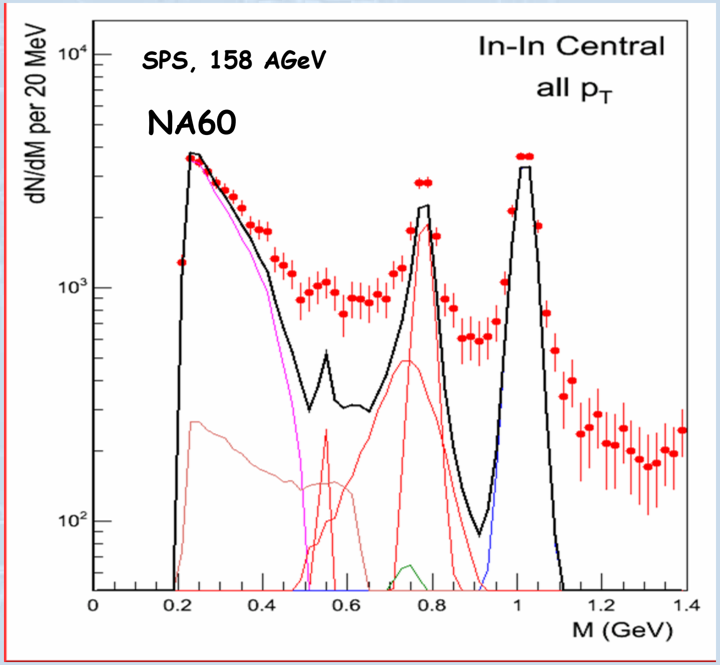


NA50 + Si vertex detector = NA60

- ✓ To improve mass resolution :
  - ✓ Match tracks with a silicon vtx detector located upstream the absorber
  - ✓ Very helpful at low masses
  - ✓ Matching ~ inefficient at high mass



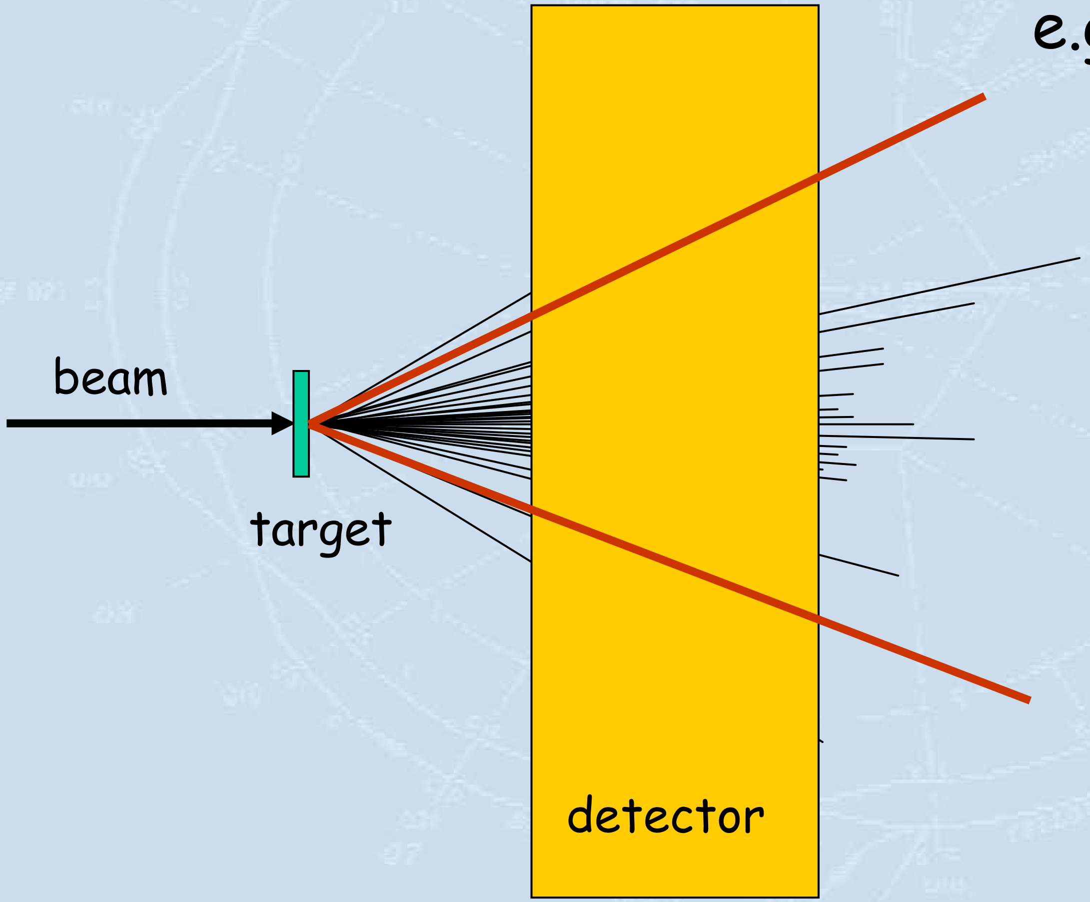




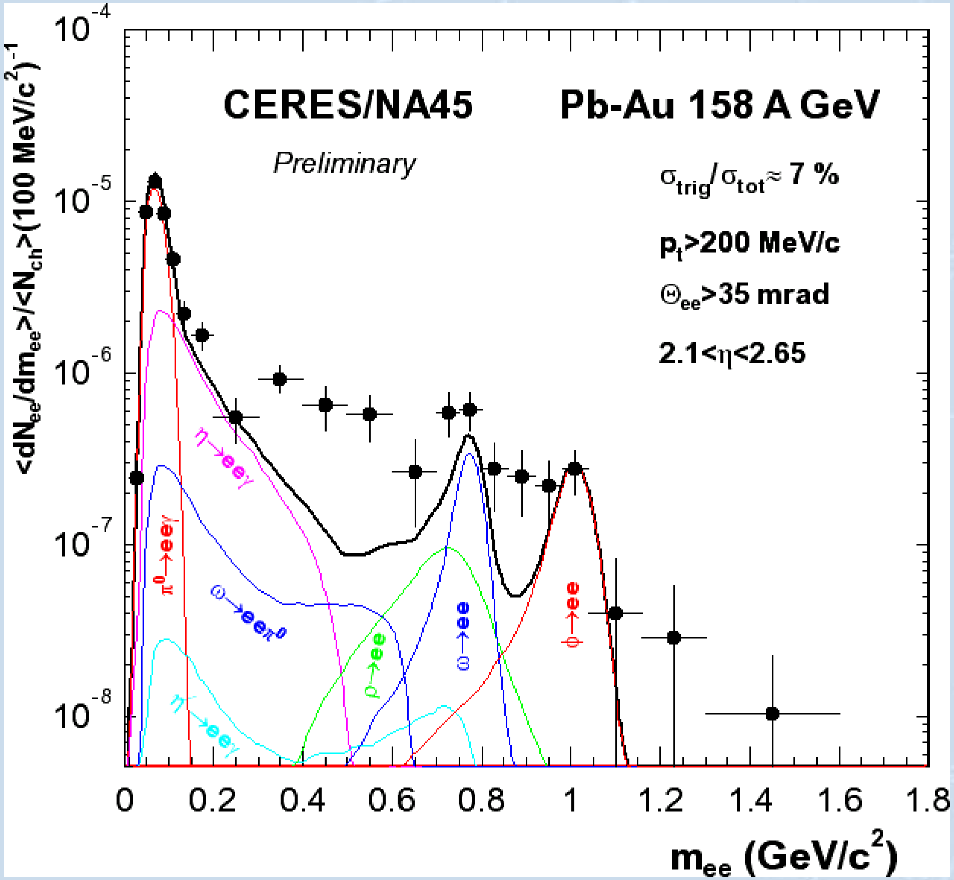
Detecting electrons is tricky

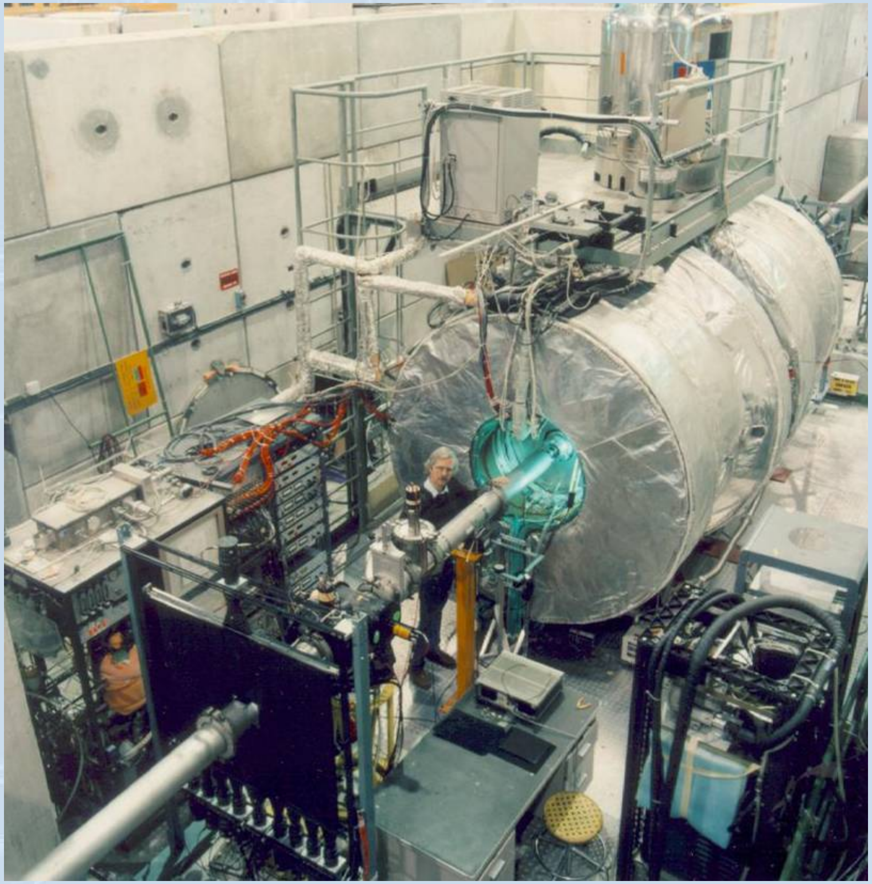
- In fixed target experiments ...
  - e.g. « hadron blind detector »

Electrons are seen whereas hadrons are not, e.g. using a Cerenkov gaseous radiator detector



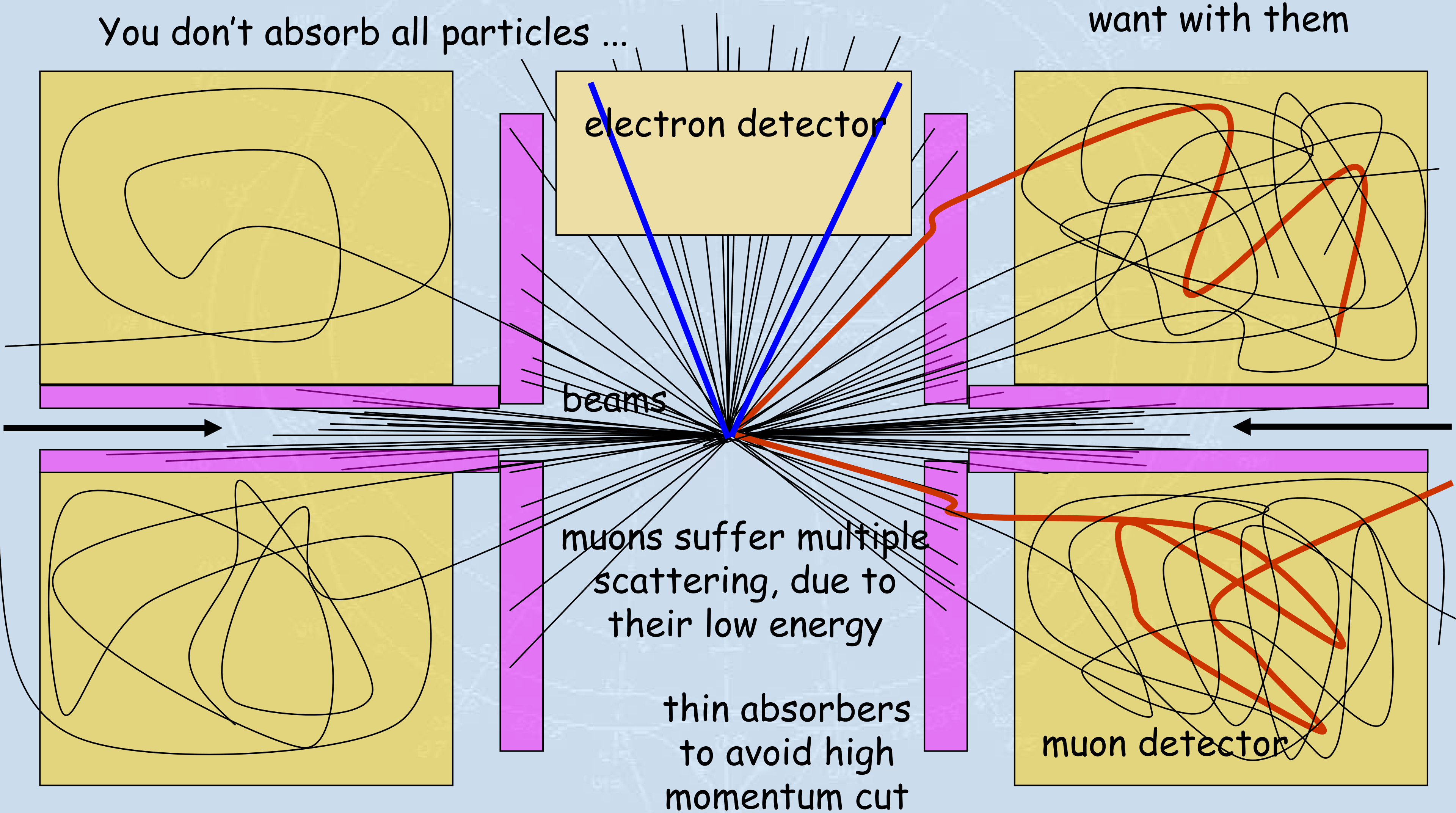
- Two Rich detectors and a magnetic field pointing to the target region, leading to azimuthal deflection of all particles ...





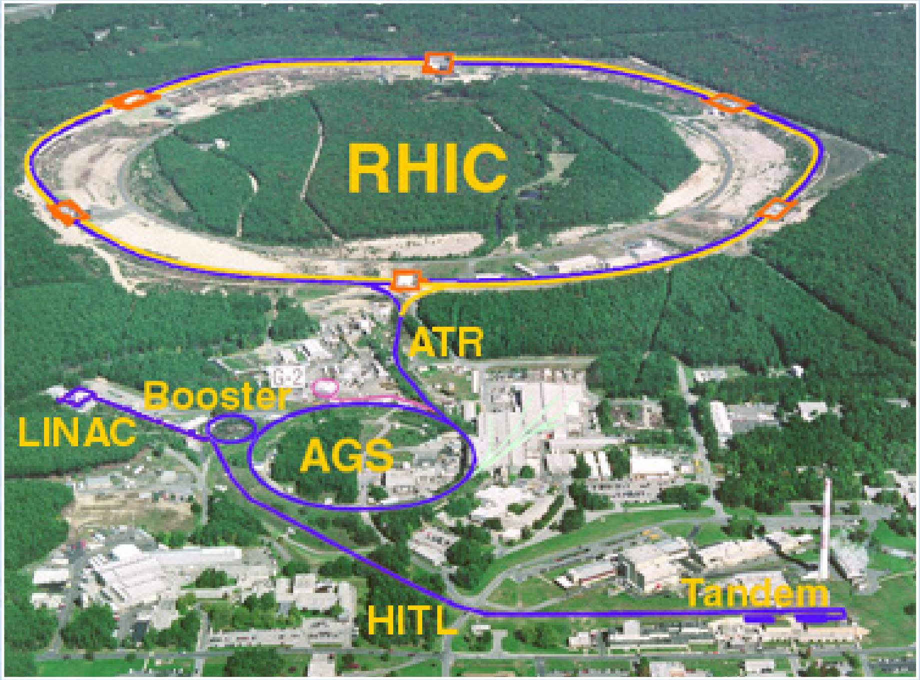
What about colliders ?

- ✓ Collider = NO BOOST ! :o(



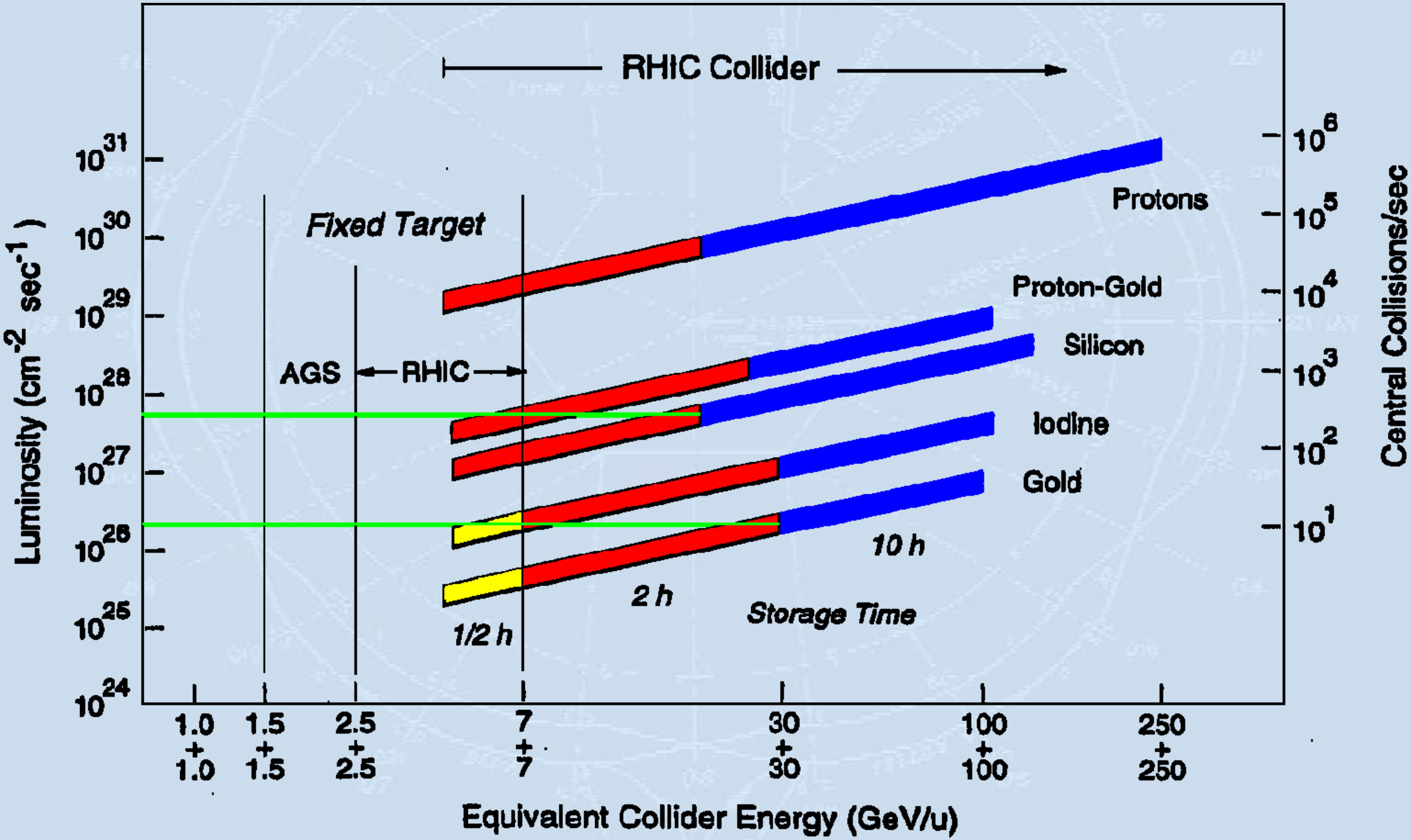
Example : PHENIX @ RHIC

- RHIC (Relativistic Heavy Ion Collider)
  - On Long Island, 100 km far from New-York
  - Dedicated to HI physics
  - 4 experiments
  - 100+100 GeV/A
  - Variable energy
  - p-p up to 500 GeV



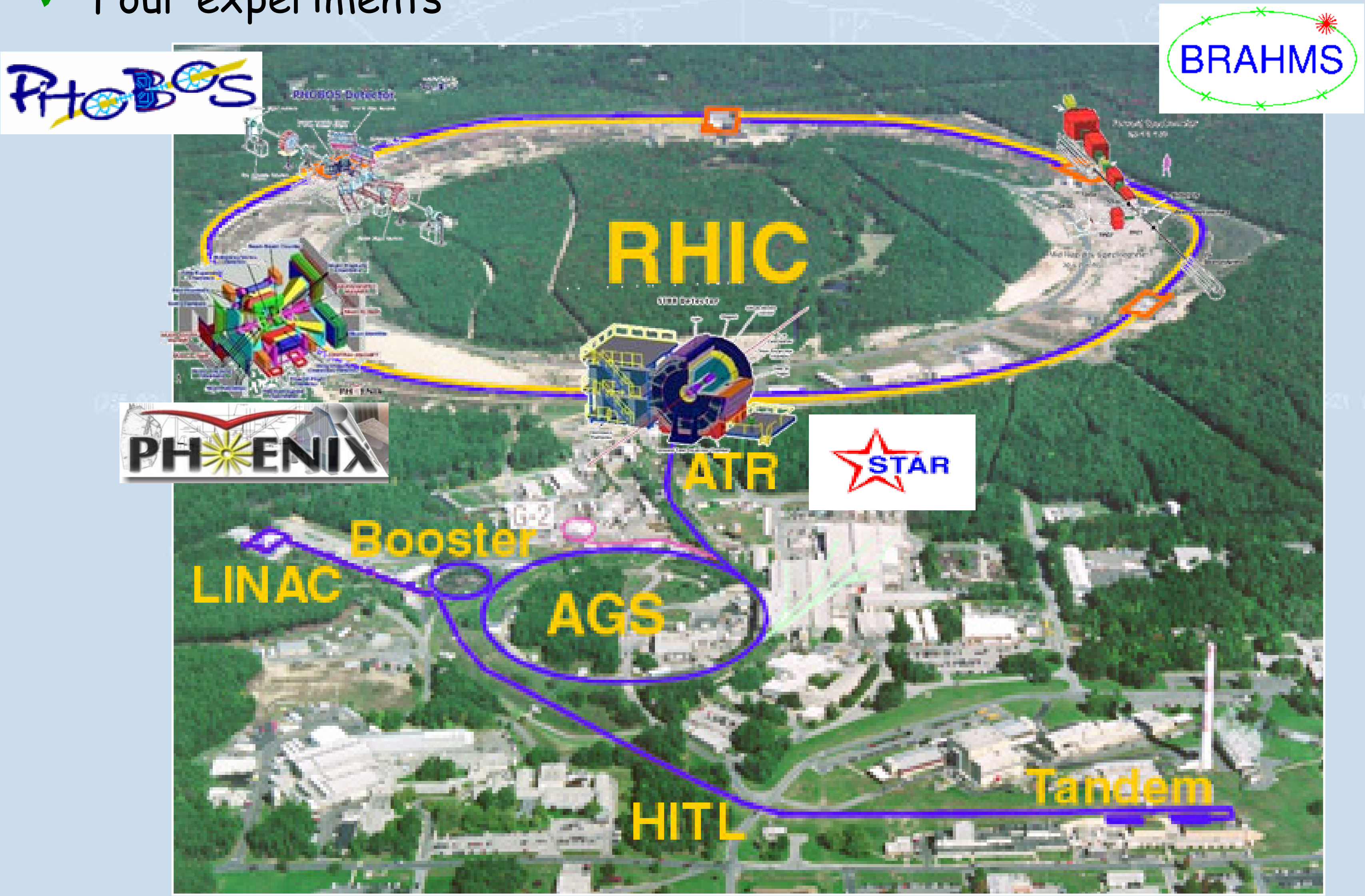
RHIC

- ✓ Vast energy range
- ✓ Different nuclei, so far: p, d, Cu and Au

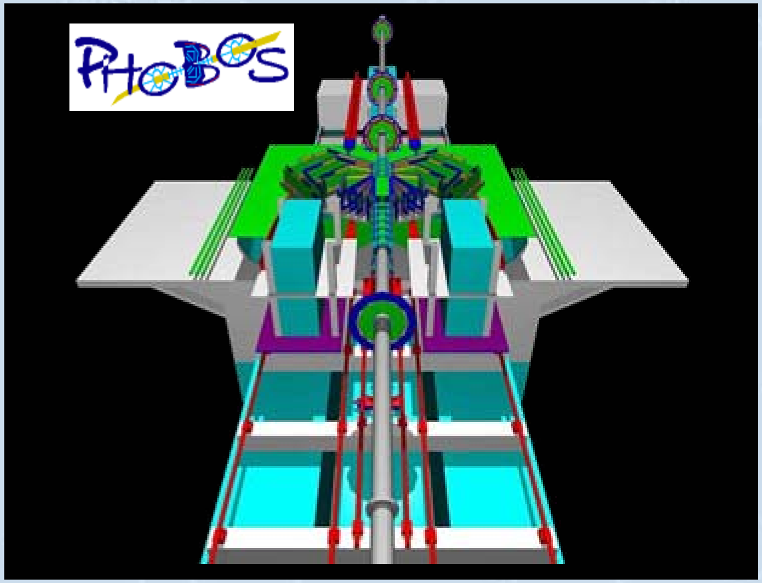


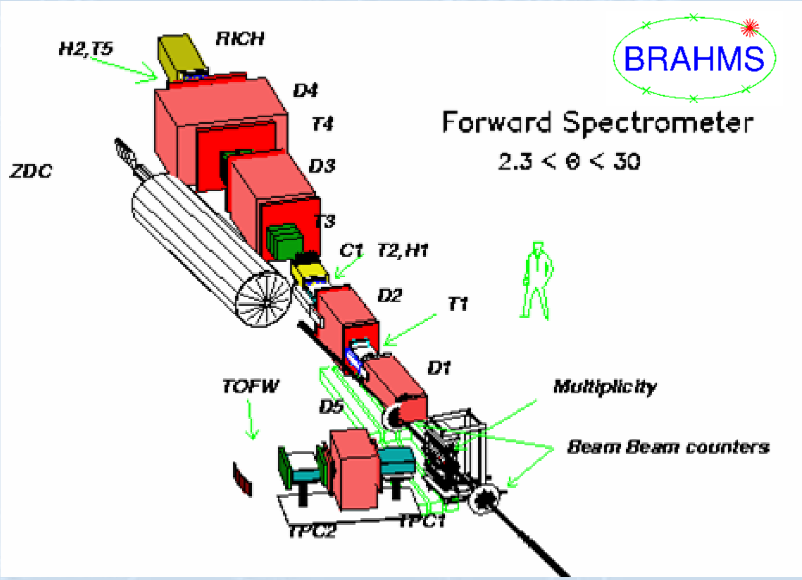
RHIC

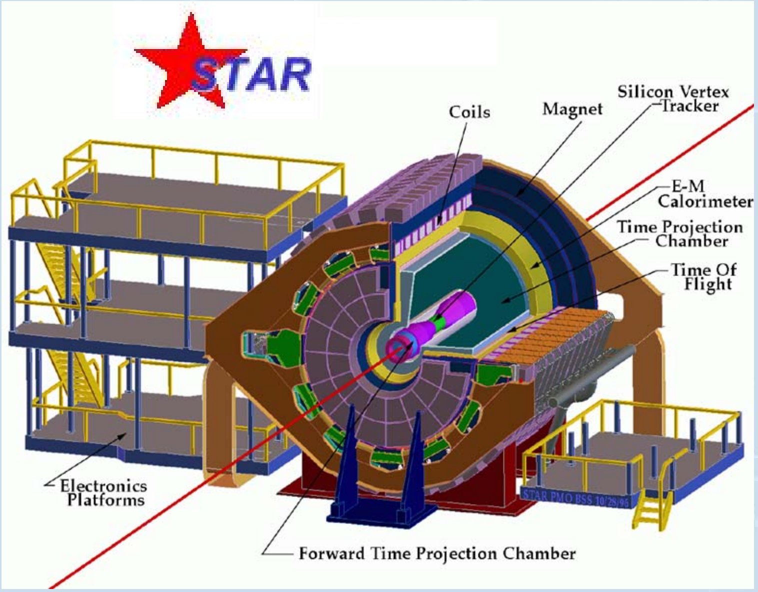
- ✓ Four experiments

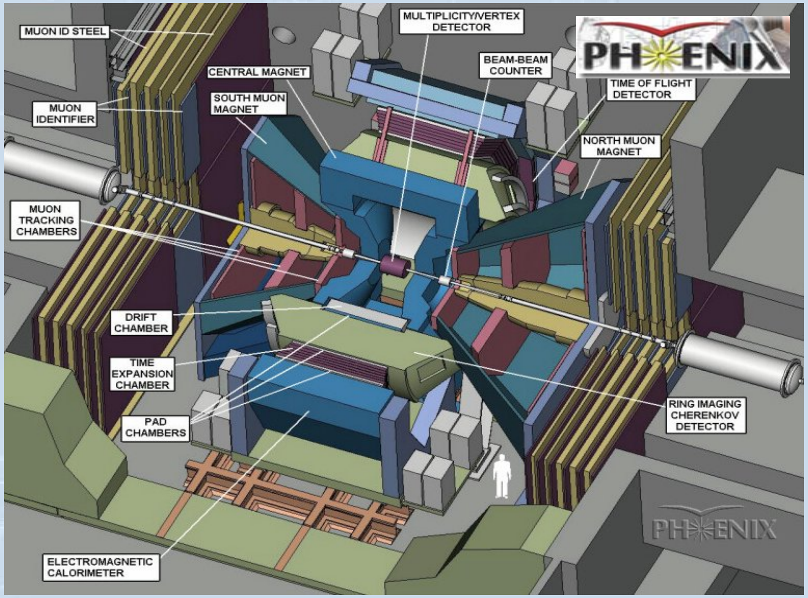


Four experiments

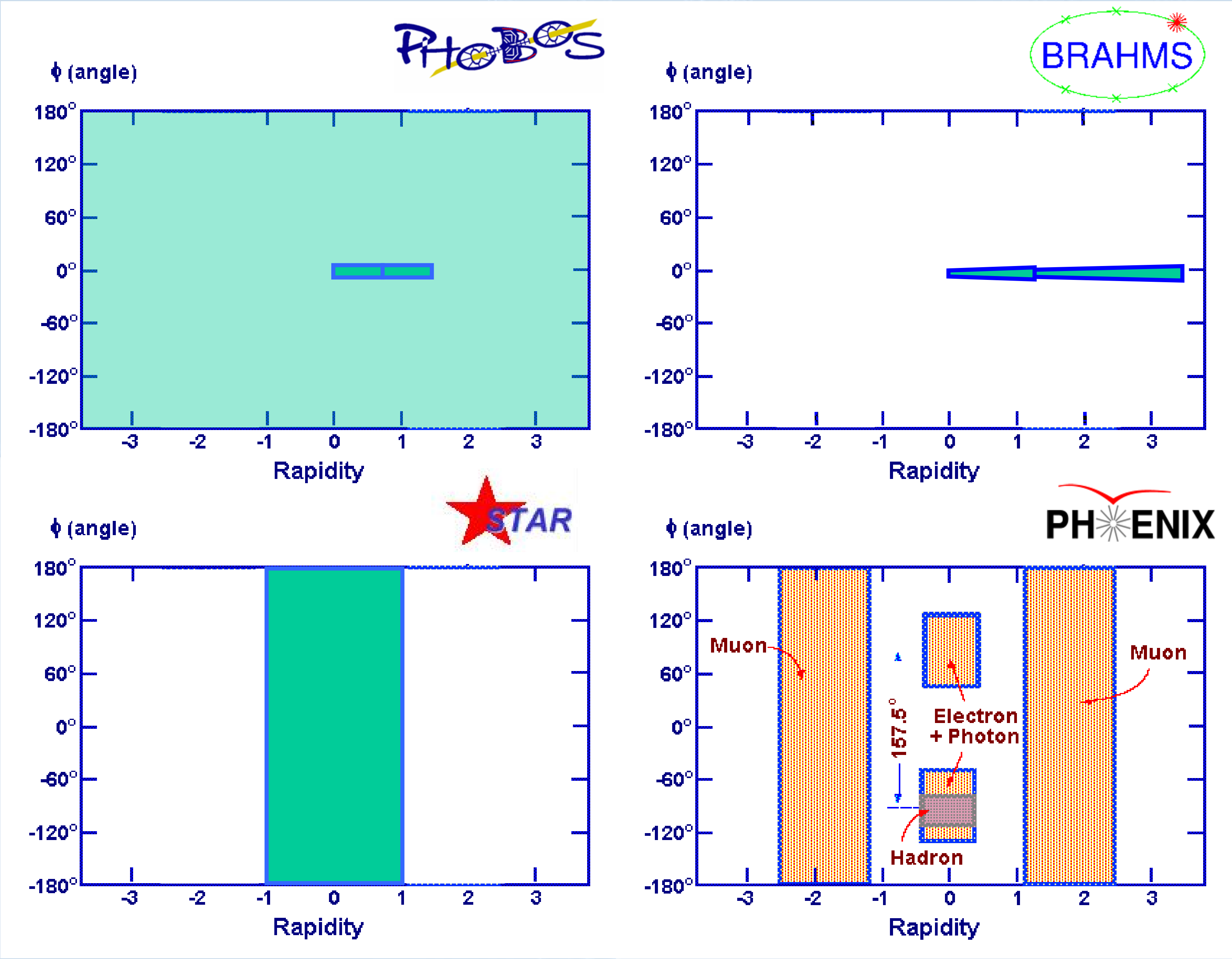




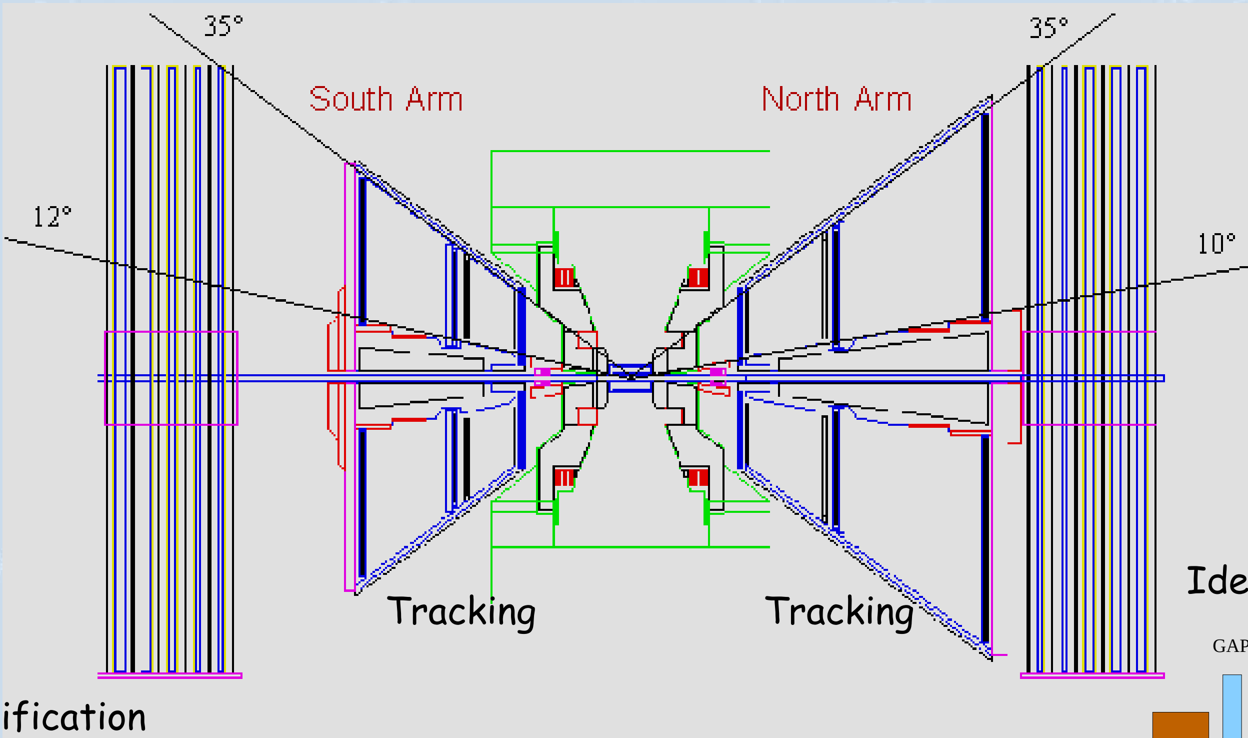




Four experiments

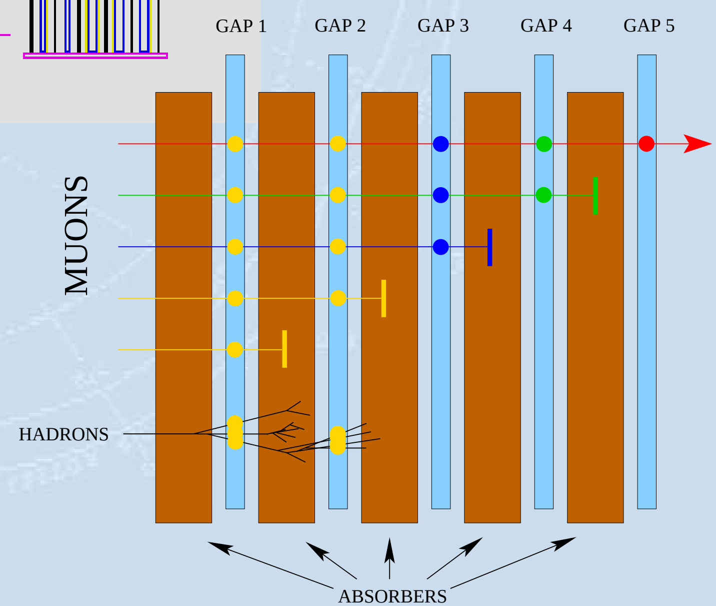


PHENIX muon arms



Identification

Identification



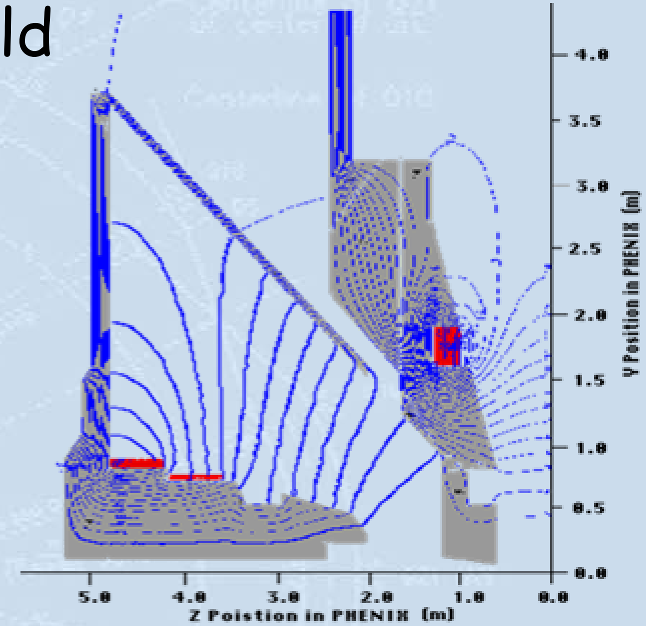
- ✓ Tracking = Cathode-strip chambers
  - ✓ (24000 channels / arm)
  - ✓ strips = 1cm σ (barycentre) = 100μm
- ✓ Identification + Trigger = Iarocci tubes
  - ✓ pitch = 0.9cm

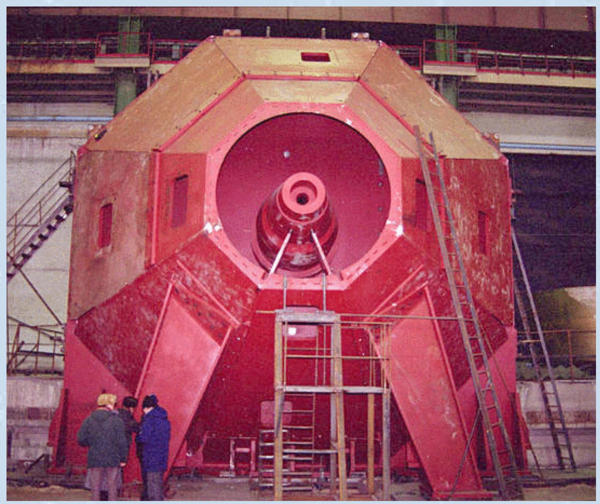
PHENIX

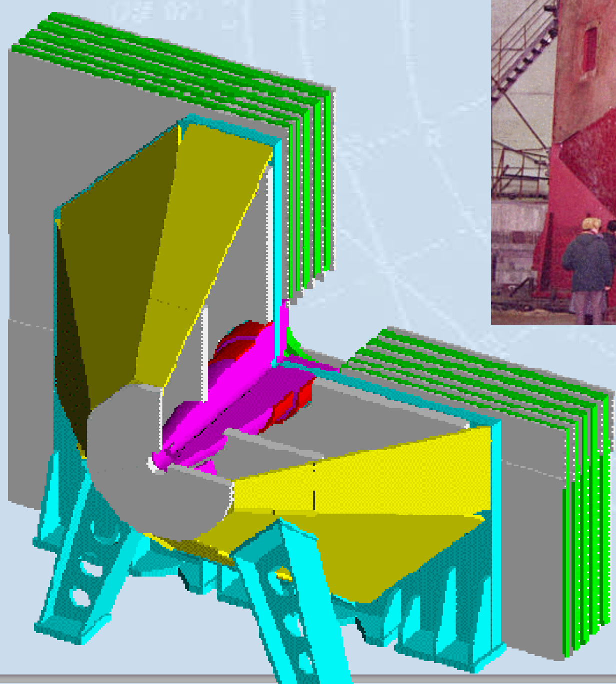
✓ The detector

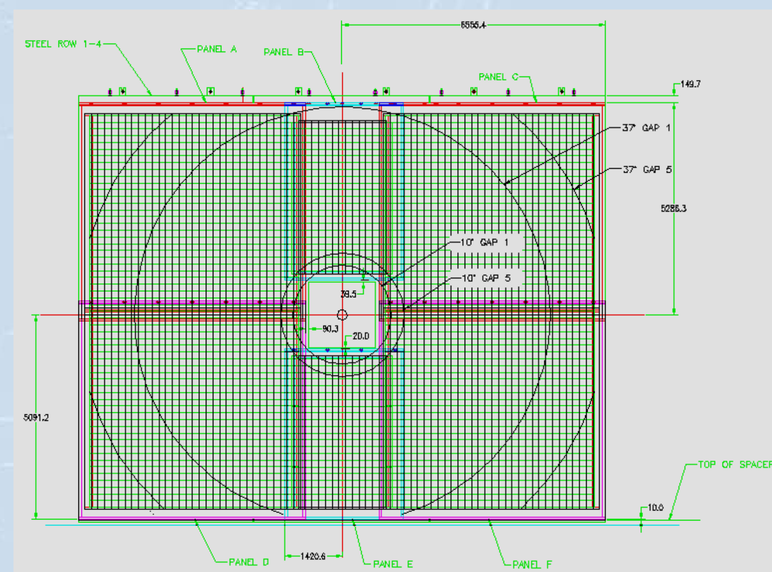
PHENIX muon arms

- ✓ « lamp shade » magnets with radial field
  - ✓ azimuthal muon bending = f(p)
  - ✓ Constant polar angle
- ✓ Identification downstream tracking
  - ✓ iron + « Iarocci » Tubes



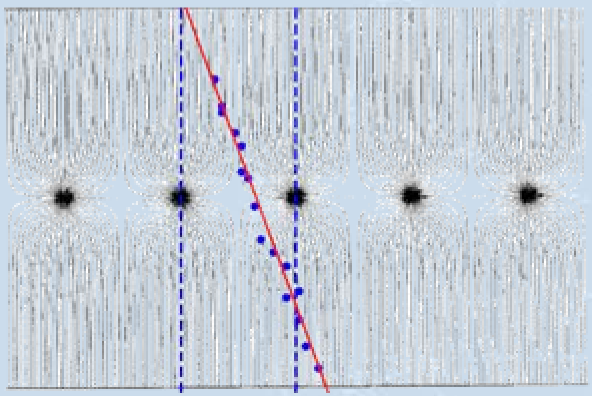


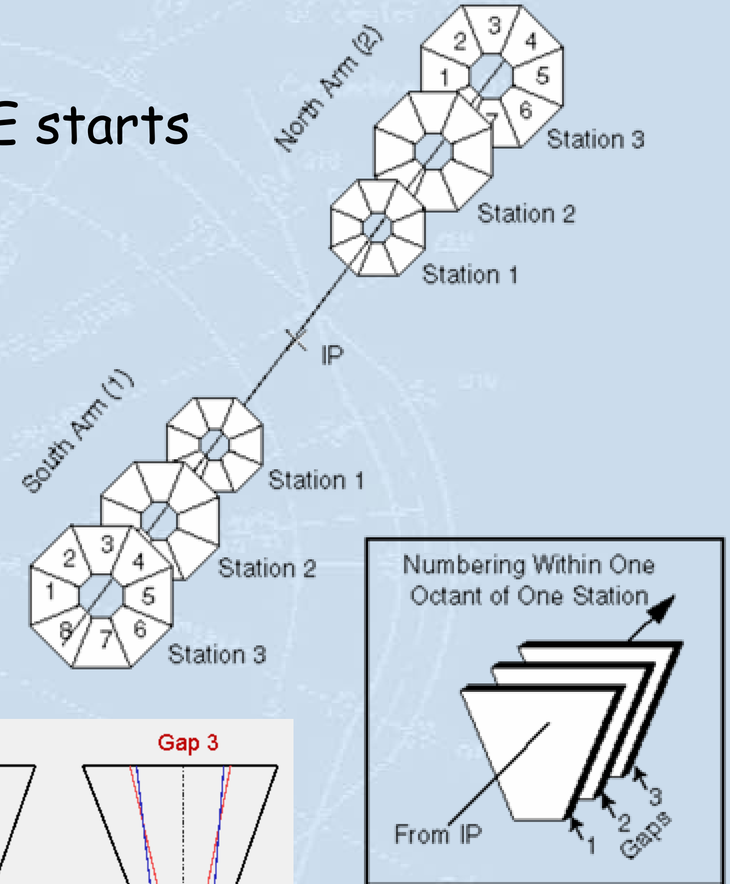


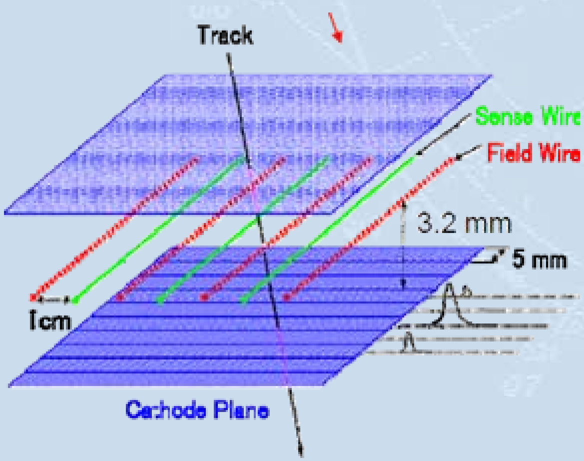


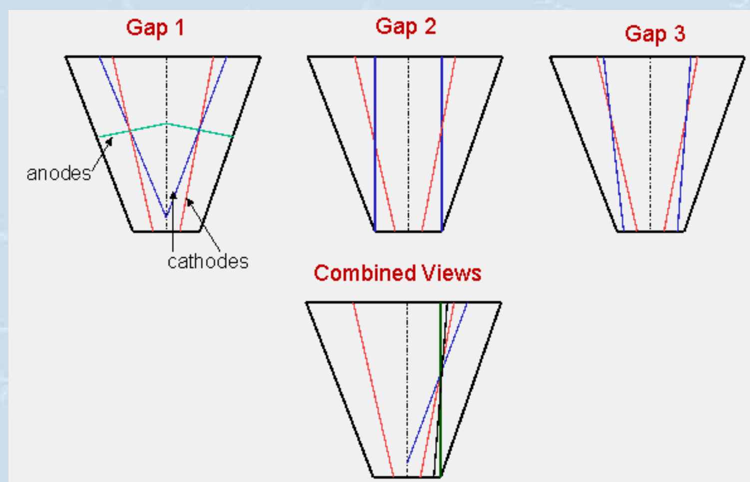
PHENIX muon arms

- Muon tracker :
  - The largest CSC in operation until ALICE starts
  - 3 stations with 6, 6 et 4 planes
    - Quasi-radial + stéréo

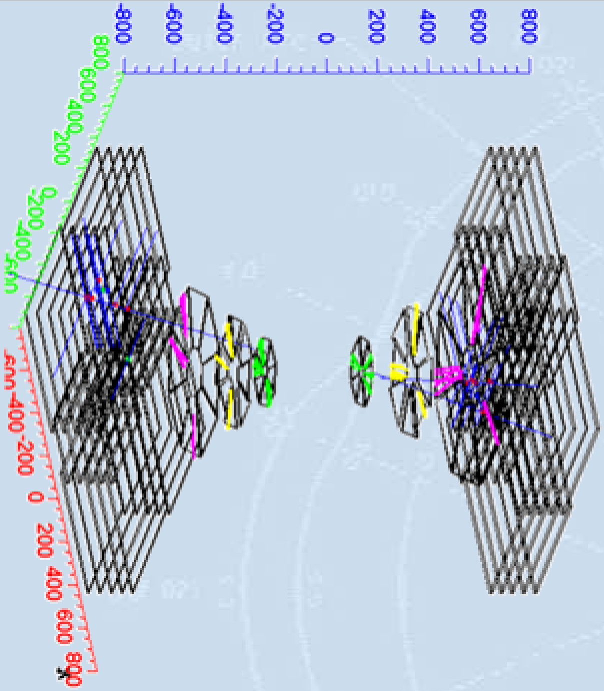


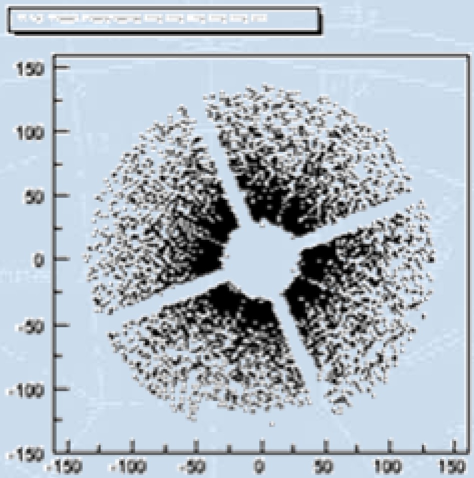




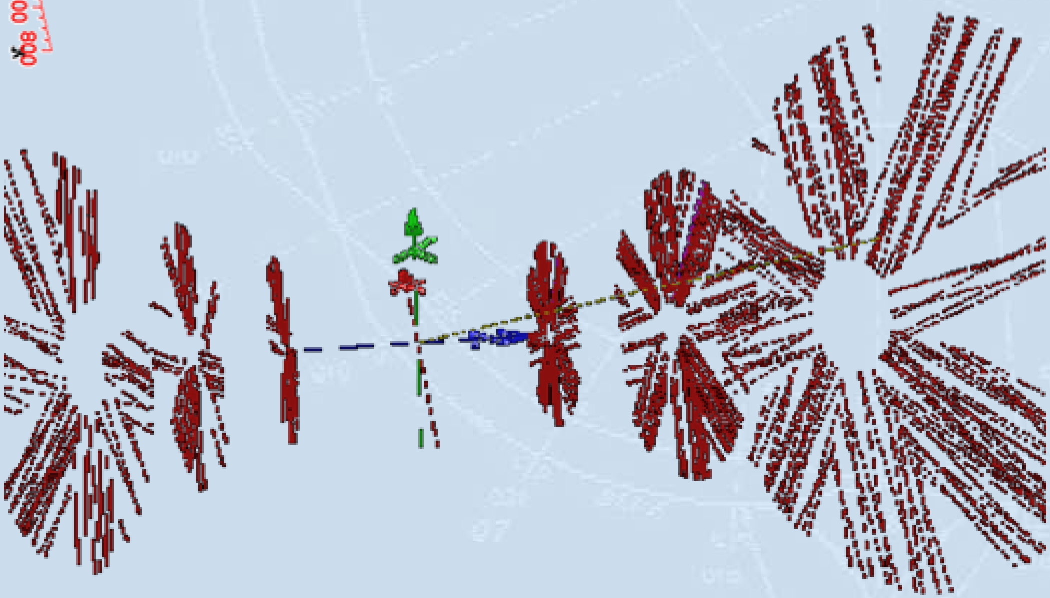


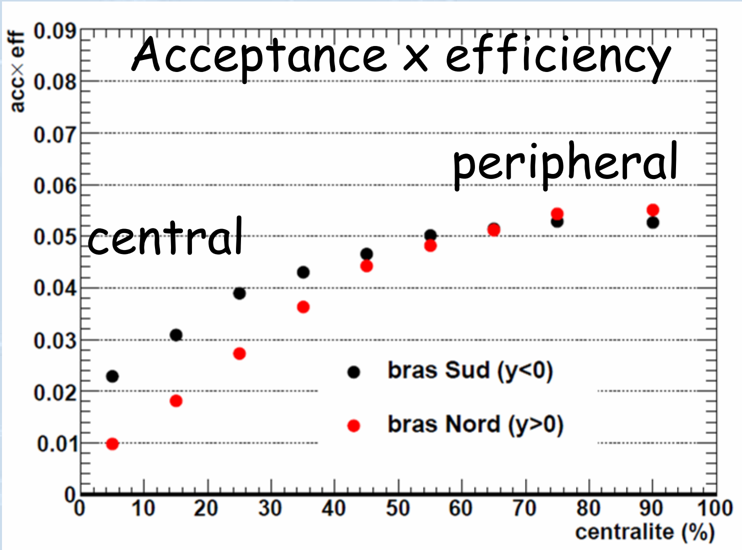
Track reconstruction



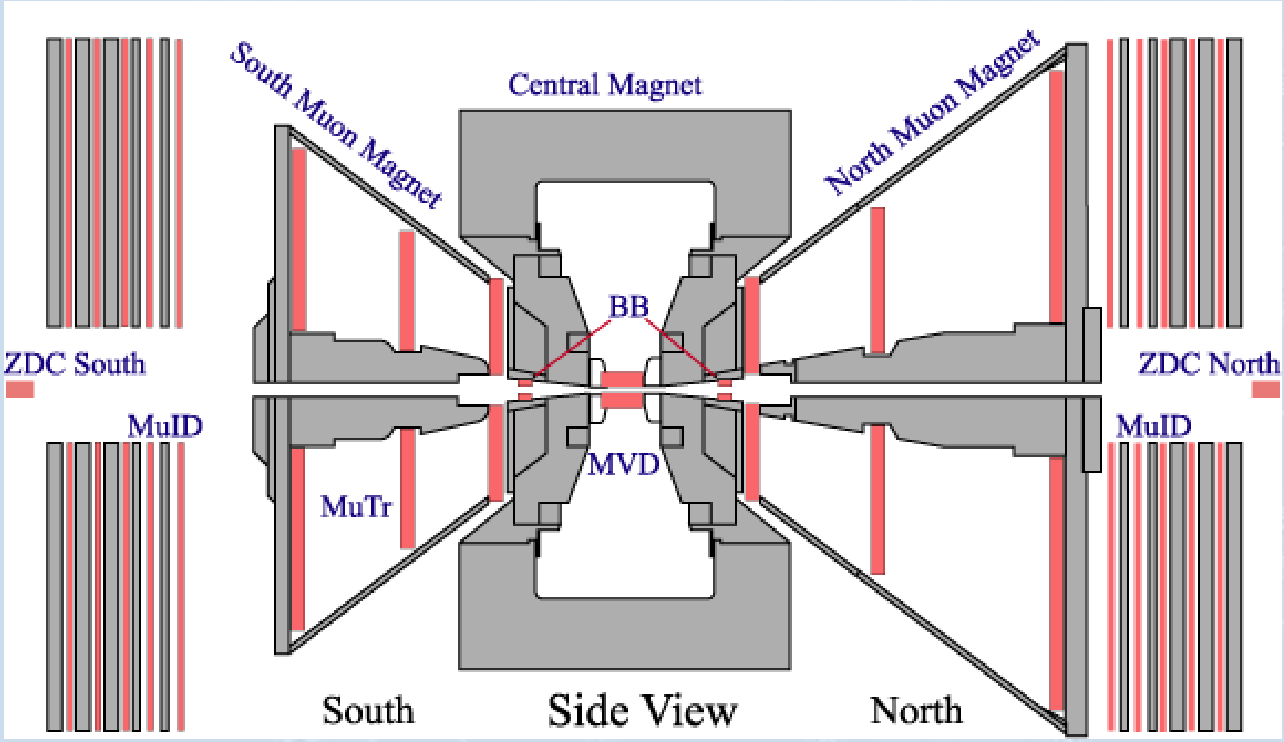


- ✓ This geometry results in a poor reconstruction efficiency at high occupancy (e.g. central Au-Au events)





PHENIX muon arms



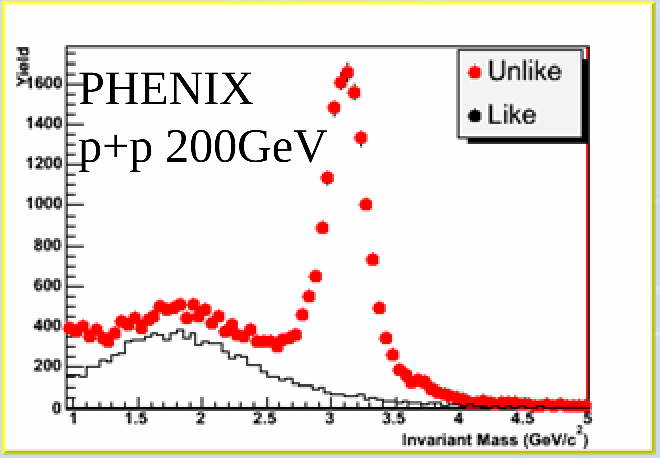
$J/\psi \rightarrow \mu^+ \mu^-$

p > 2GeV/c

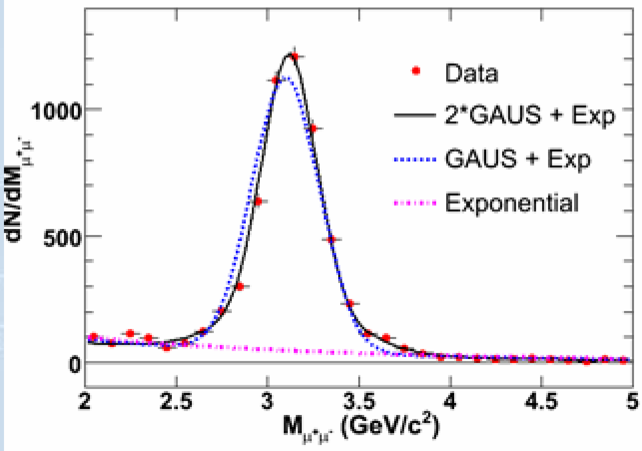
1.2 < |y| < 2.2

$\Delta\phi = 2\pi$

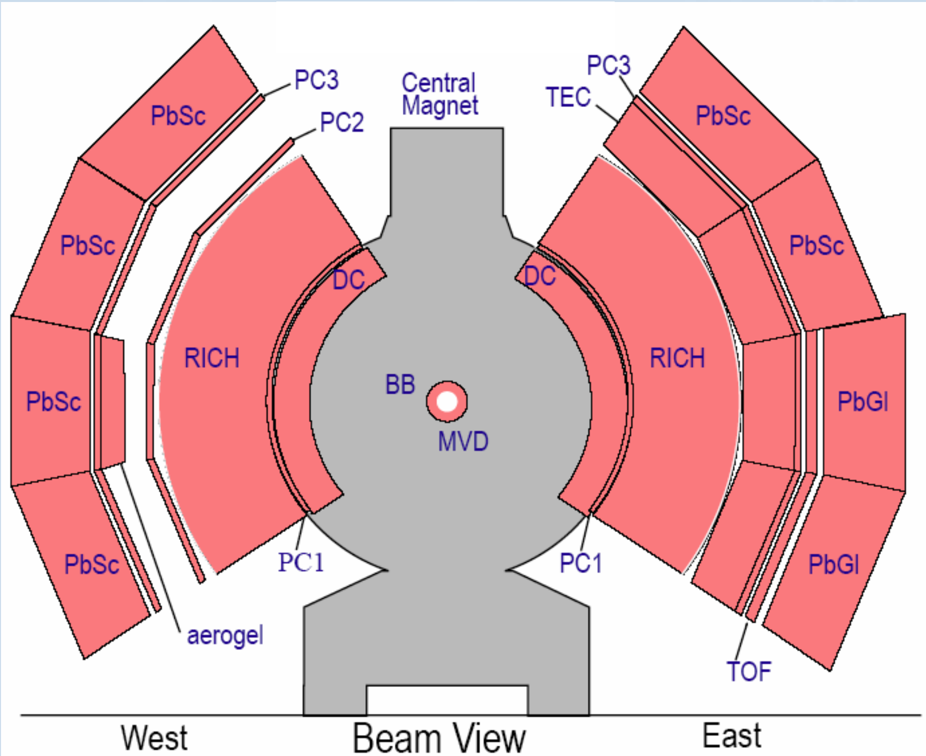
- ✓ Less absorber to lower momentum cut
  - ✓ Bad mass resolution
  - ✓ High track multiplicity
    - ✓ Low reconstruction efficiency



Event Mixing Background Subtraction



Example : electrons in PHENIX



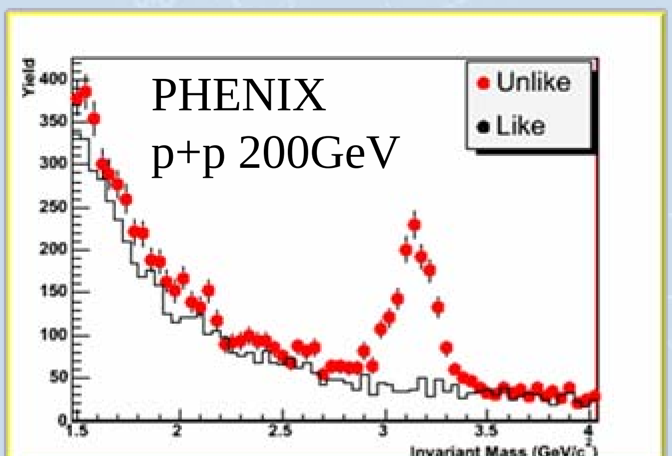
- ✓ Identification with a RICH + emcal
- ✓ Tracking with drift chambers and pad chambers

$$J/\psi \rightarrow e^+ e^-$$

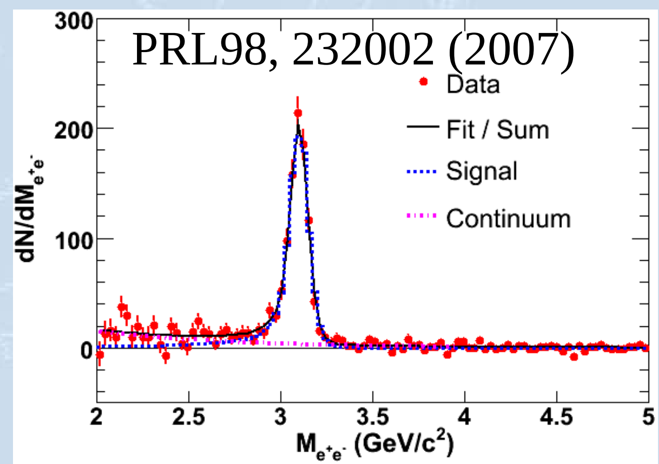
$p > 0.2 GeV/c$

$|\eta| < 0.35$

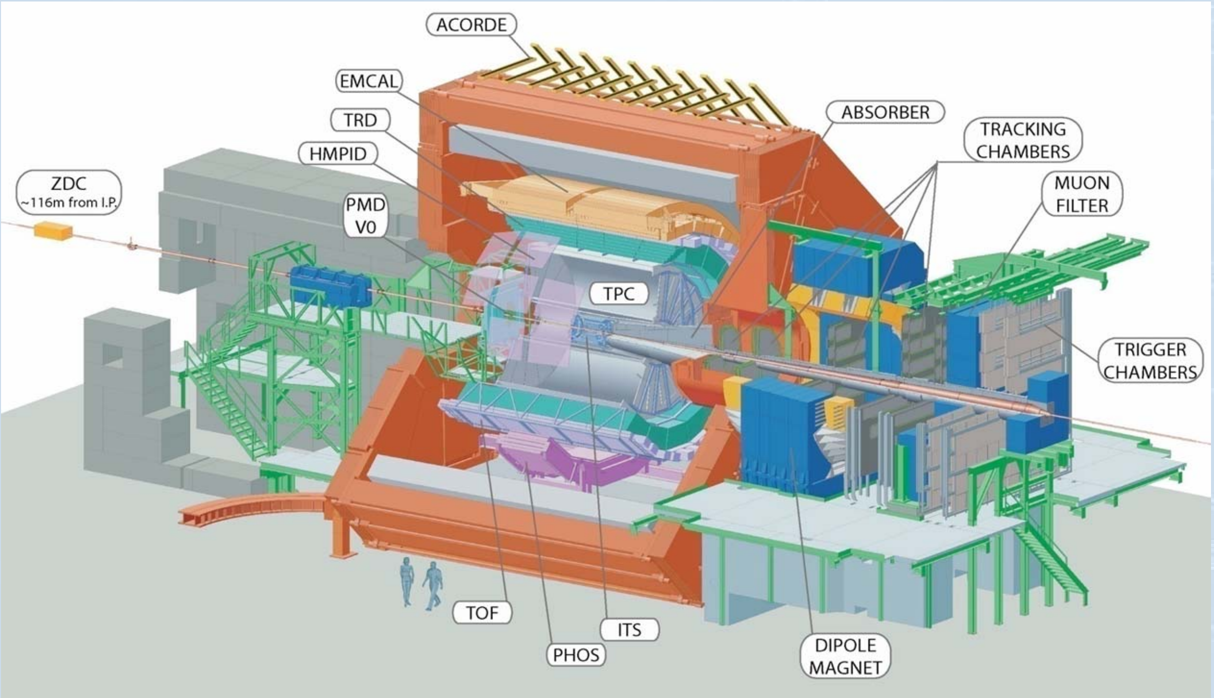
$\Delta\phi = \pi$



Like Sign Subtraction



ALICE @ LHC


ACORDE
EMCAL
TRD
HMPID
ZDC
~116m from I.P.
PMD
V0
ABSORBER
TRACKING
CHAMBERS
MUON
FILTER
TPC
TRIGGER
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ITS
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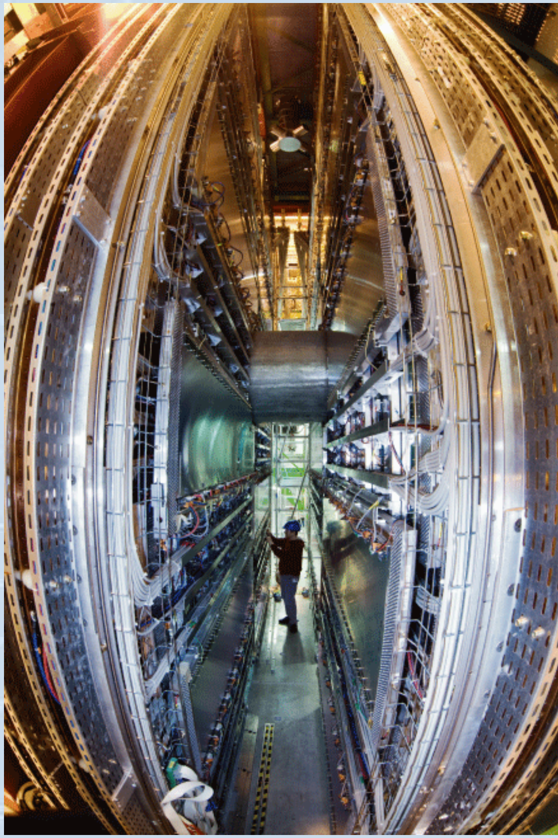
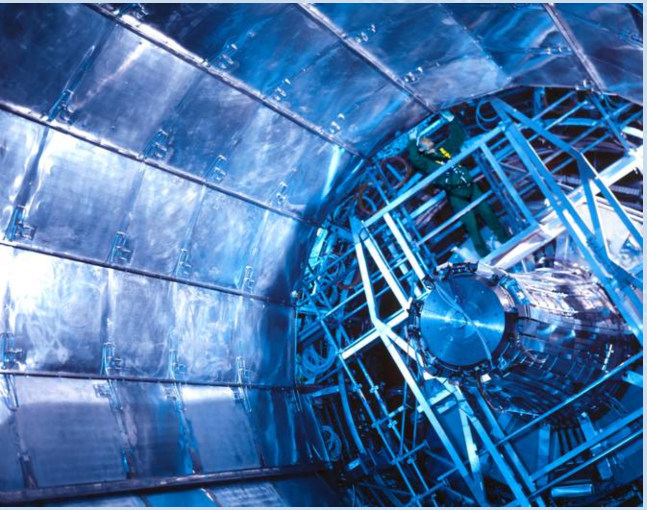
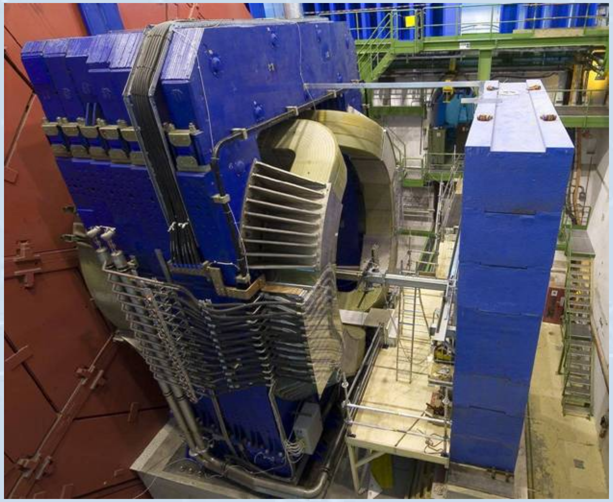
MAGNET

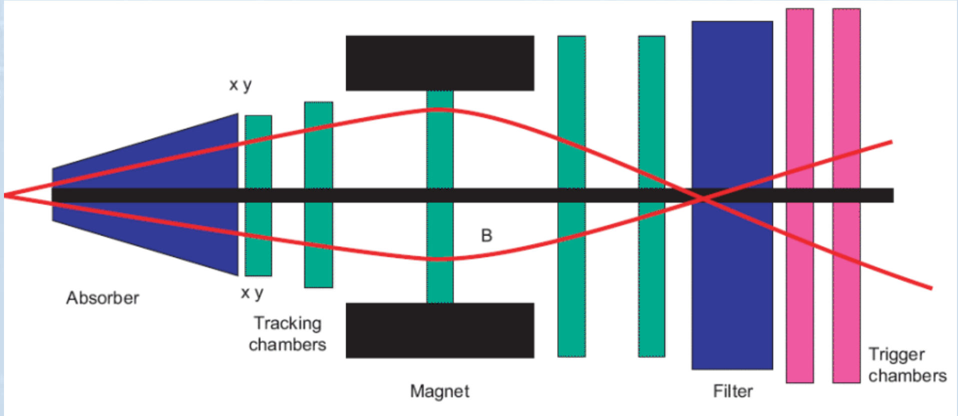


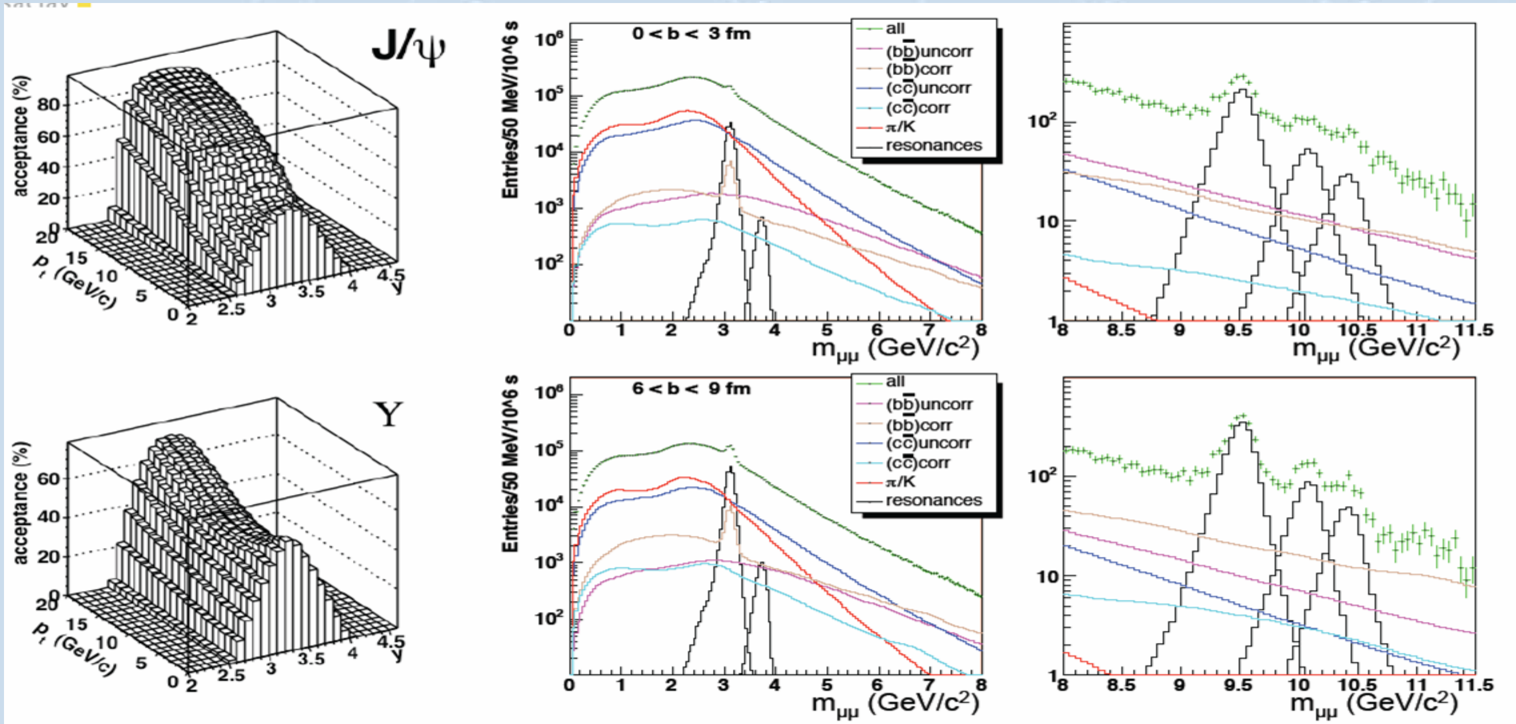




Muons in ALICE

- ✓ Higher rapidity !
  $2.5 < \eta < 4$
  - ✓ « some boost »
  - ✓ Thicker absorber
  - ✓ Less hadrons

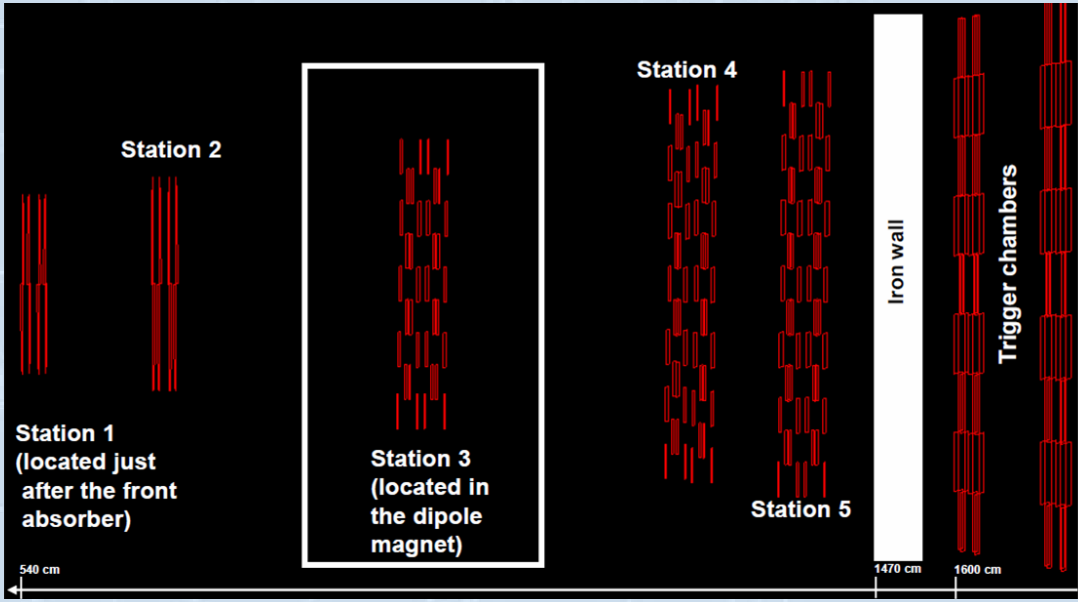


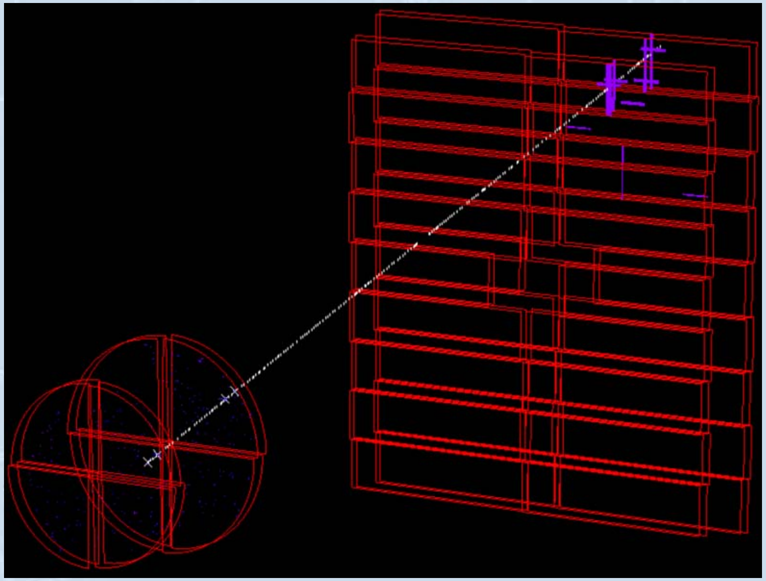


- ✓ ~ 400 k J/ψ per month
- ✓ ~ 3k Υ

ALICE muon tracking

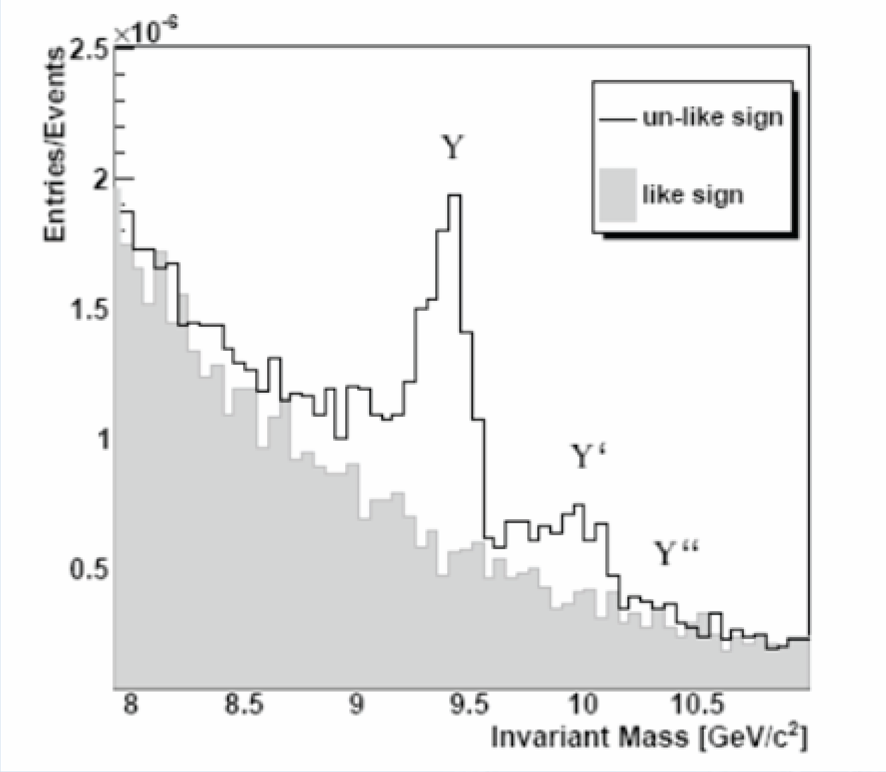
- ✓ Pad chamber geometry minimizes the occupancy
  - ✓ Better reconstruction efficiency
  - ✓ Less centrality dependant
- ✓ Better design !!
- ✓ But higher rapidity region

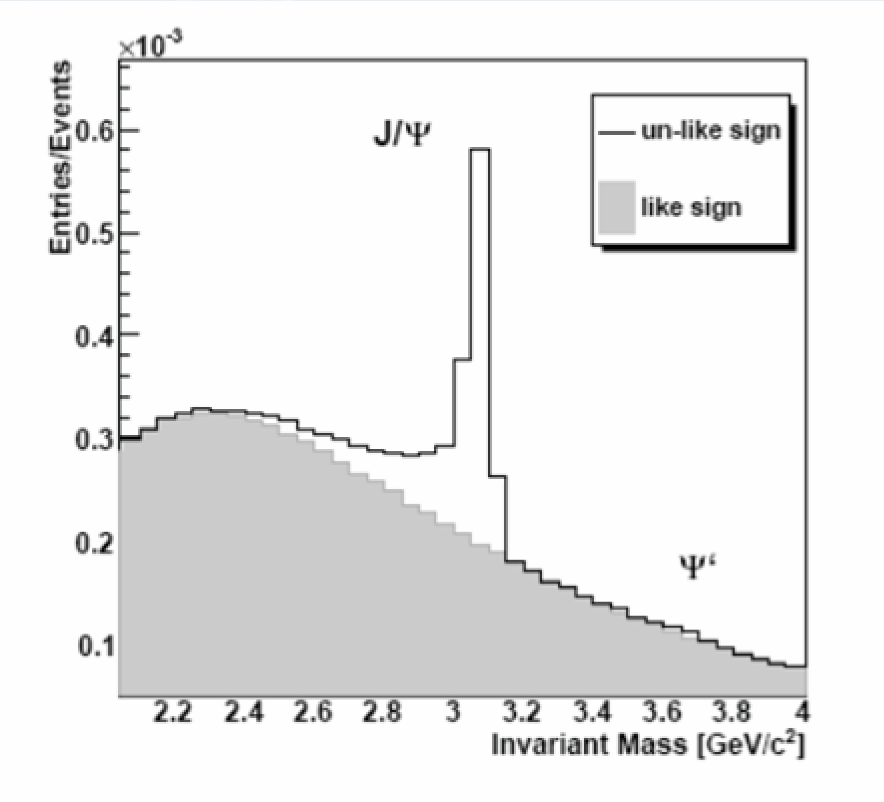




Dielectrons in ALICE

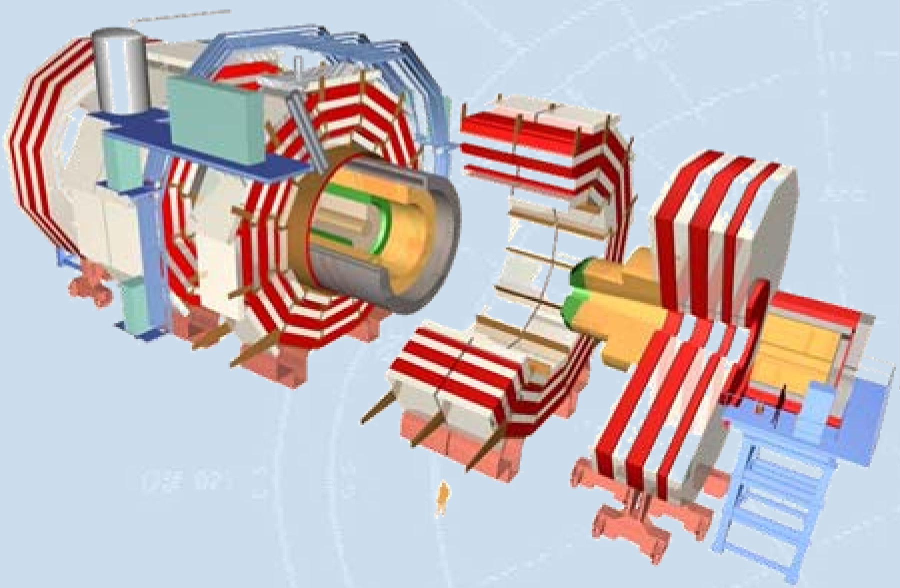
- ✓ Electron pairs : $|\eta| < 0.9$
- ✓ Tracking ITS, TPC and TRD
- ✓ Identification TRD

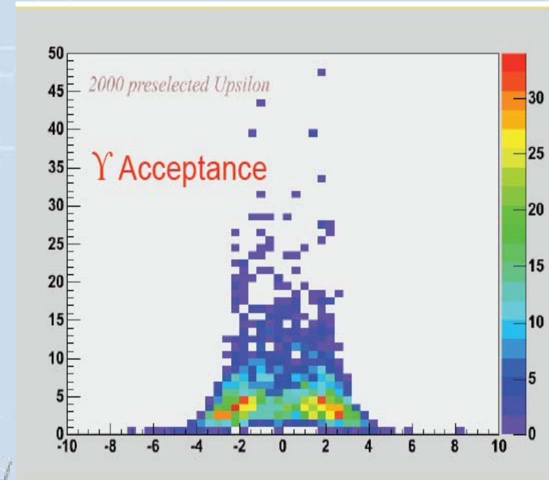


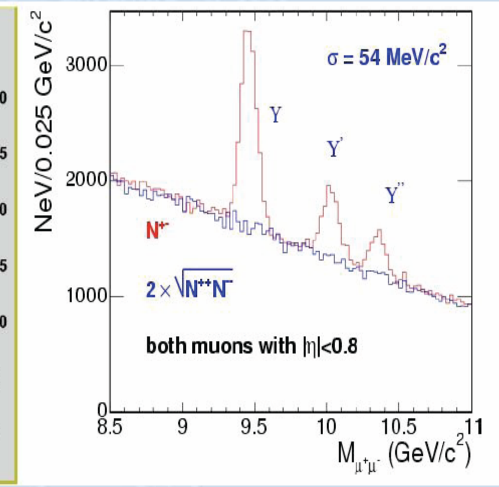


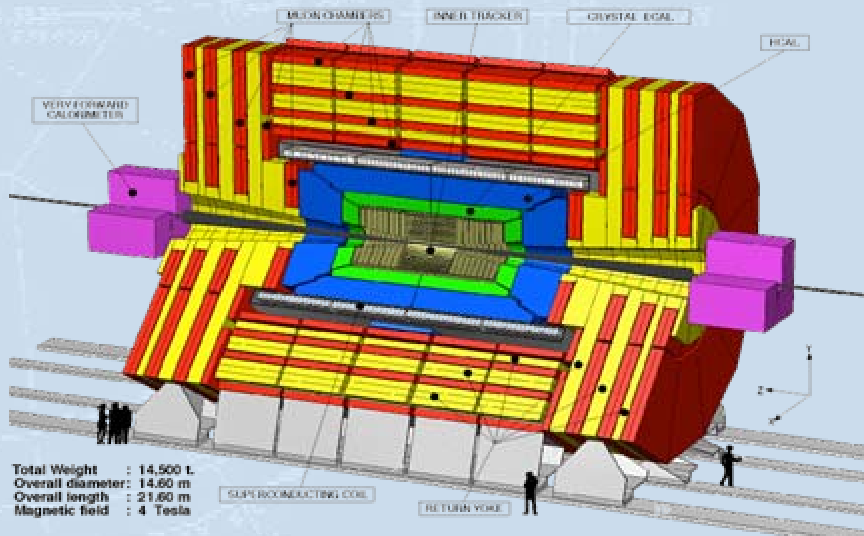
- ✓ ~ 120 k J/ψ per month
- ✓ ~ 1k Υ

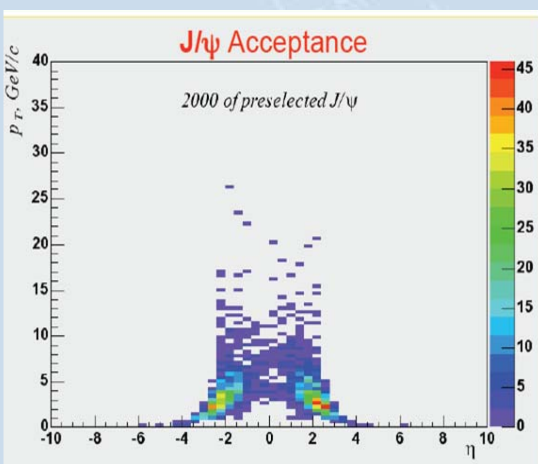
Dimuons in CMS

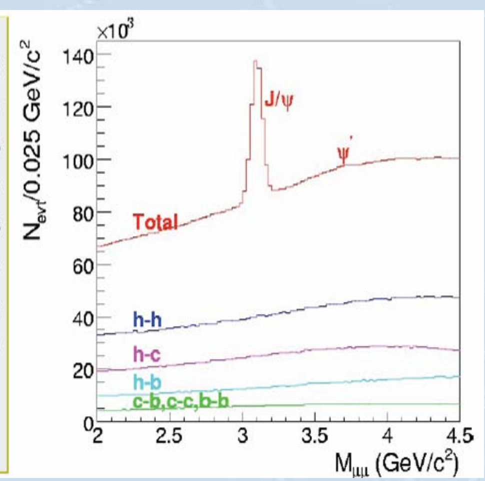










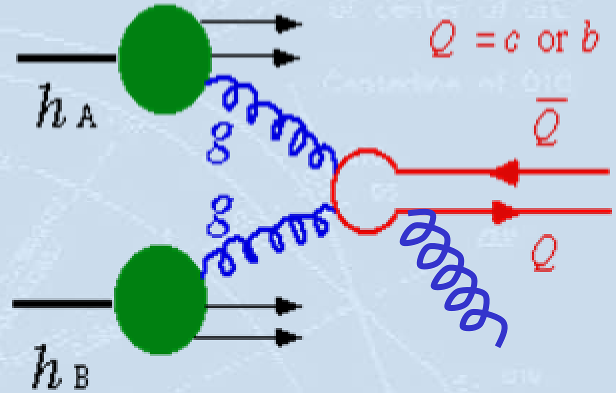


Normalization ?

We need a reference process

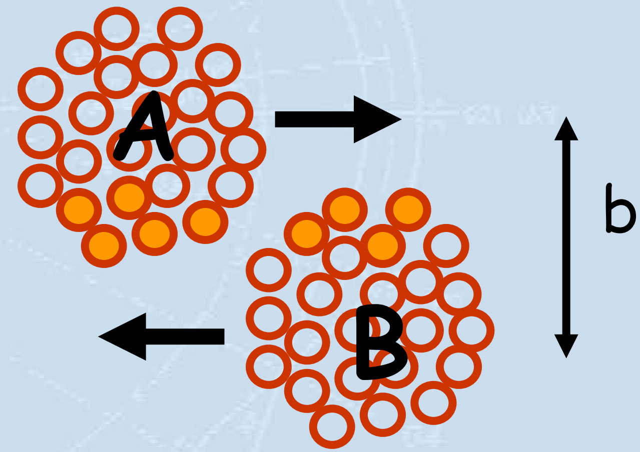
- ✓ First problem: reference process
  - ✓ J/ψ production in AB collisions must be compared to independent n-n interactions :

$$R_{AB} = \frac{dN_{J/\psi}^{AB}}{dN_{J/\psi}^{nn} \times \langle N_{coll} \rangle}$$



J/ψ or Υ

  - ✓ Where N_{COLL} = Number of BINARY COLLISIONS (e.g. 5*4)
  - ✓ Not to be confused with N_{PART} = Number of PARTICIPANTS (e.g. 5+4)

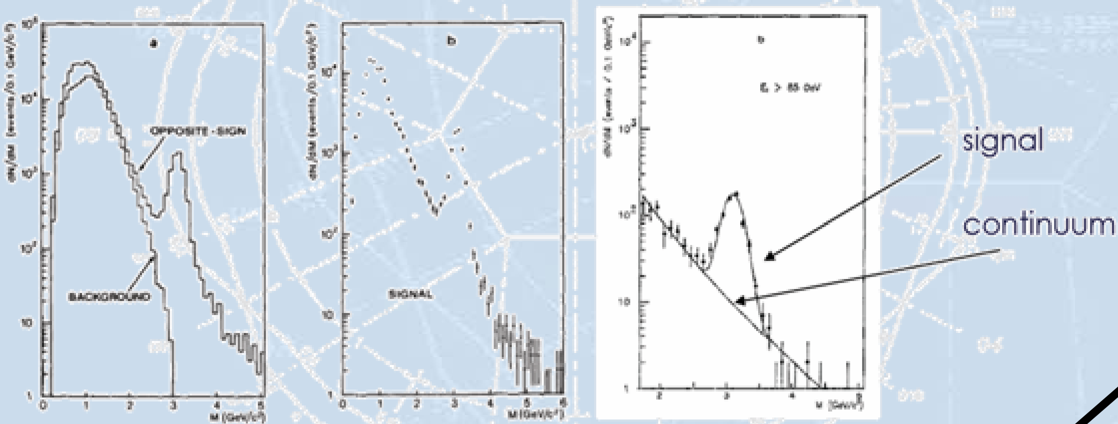


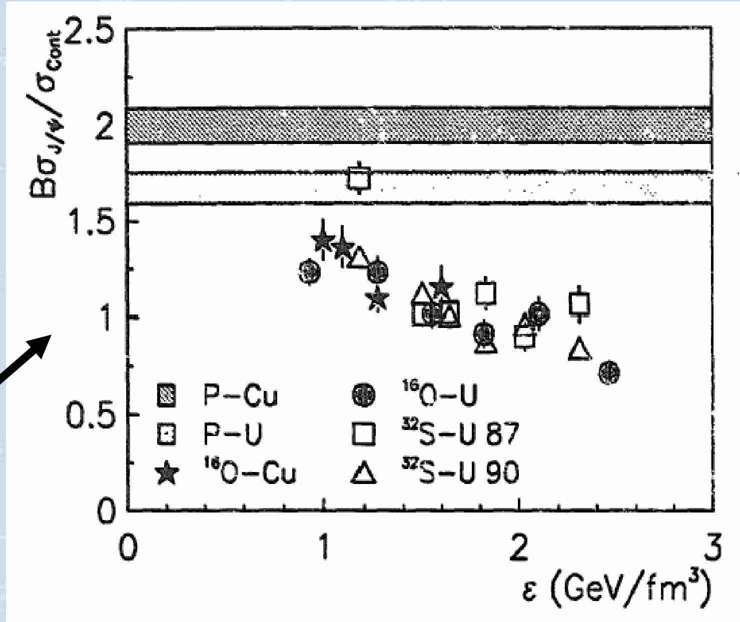
- ✓ But N_{COLL} is NOT an observable !
- ✓ ⇨ find a « hard » process

Proportional to the number N_{coll} of binary N-N collisions

In the old days ...

- « mass continuum » i.e. compute (J/ψ) / continuum [m1,m2]
- Mixture of a lot of phenomena
- Can be anything but proportional to Ncoll
  - e.g. thermal dileptons, rho melting, etc ...
- Done in NA38 but was probably wrong !
  - Na38 mass plot:

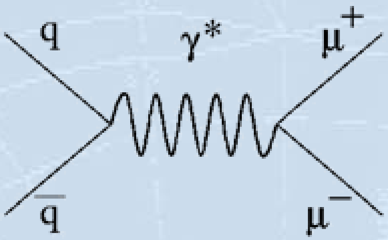




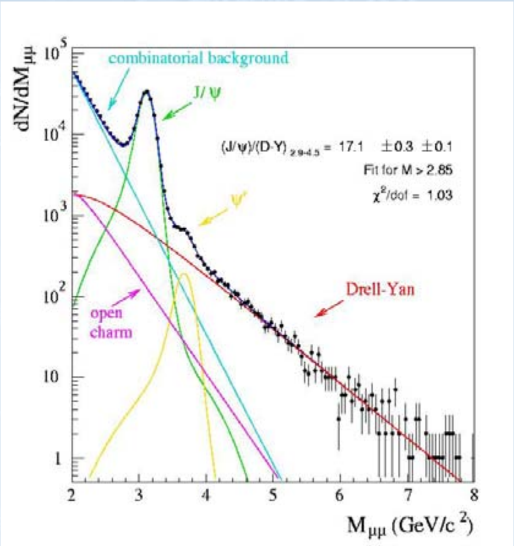
  - + we know that the suppression observed corresponds mainly to nuclear absorption ...

Not ideal but observable, at least

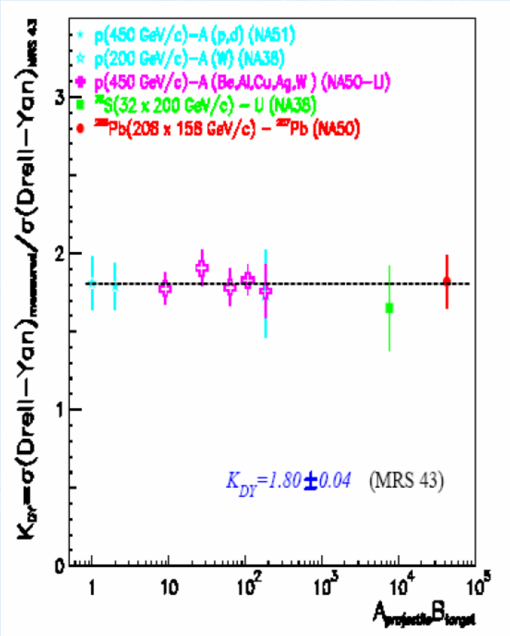
- ✓ Drell-Yan



  - ✓ i.e. compute (J/ψ) / D.Y. [m1,m2]



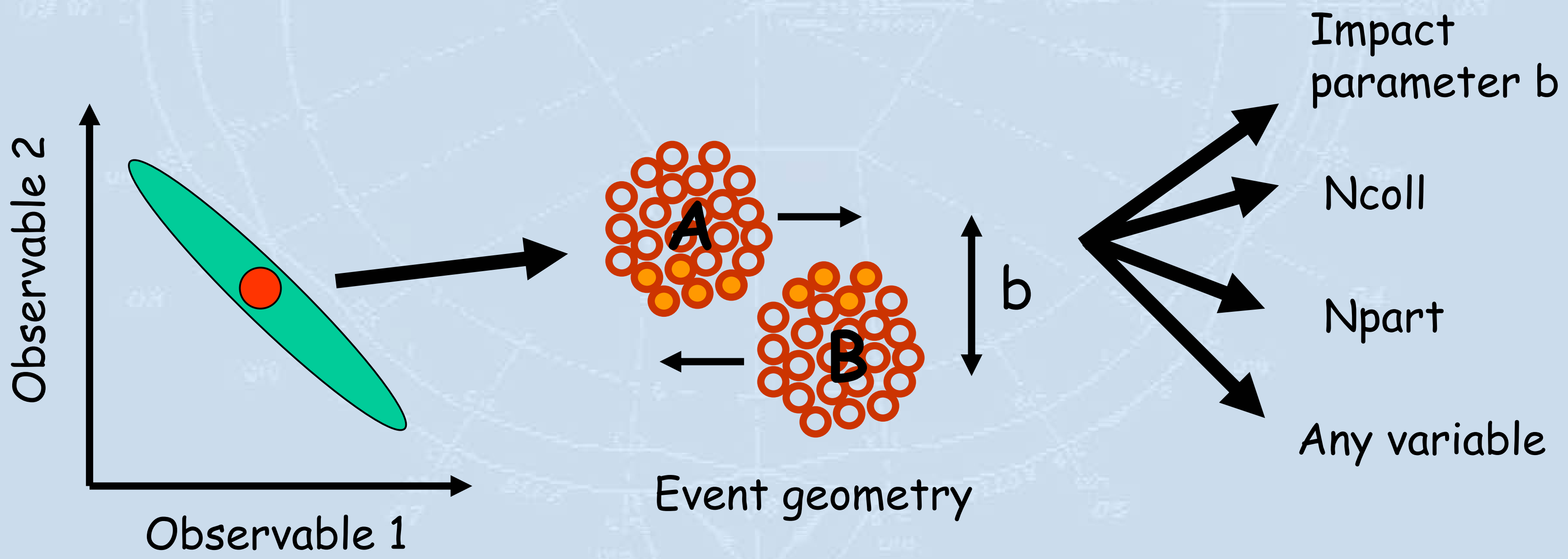
- ✓ Possible in NA50/60
  - ✓ Check prop to Ncoll integrated over b:
    - ✓ A*B scaling in AB collisions
  - ✓ Take it as reference = f(b)



- ✓ Several drawbacks:
  - ✓ Poor statistics
  - ✓ Not available at higher √s

The Glauber model

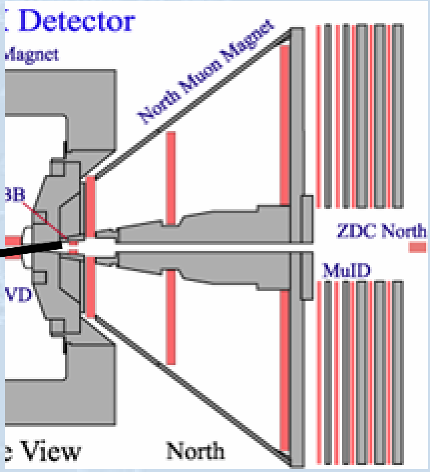
- ✓ Simple geometrical model + nuclear density
- ✓ Establishes the correspondance between one or several variables measured event by event, and the geometry of the collision
- ✓ Adjusted on the total event distributions
- ✓ Used to compute the complete geometry, event by event

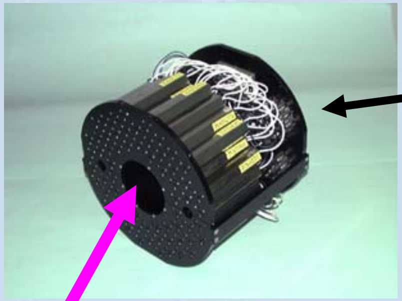


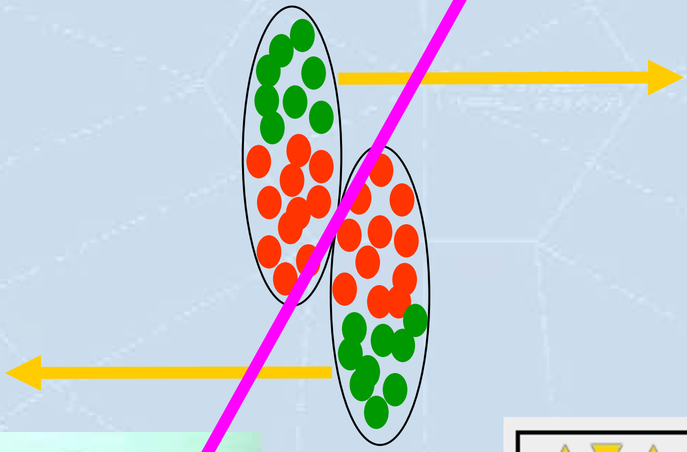
Example: PHENIX Au-Au

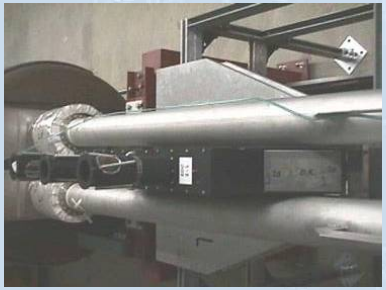
- ✓ E_{ZDC} (spectators)
  - ✓ "zero degree calorimeter"
- ✓ BBC (secondary particles)
  - ✓ "beam-beam counter"

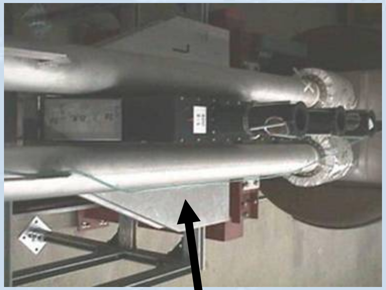
Beam-Beam counters

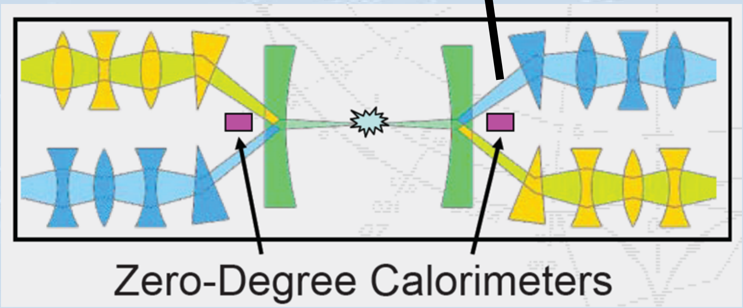






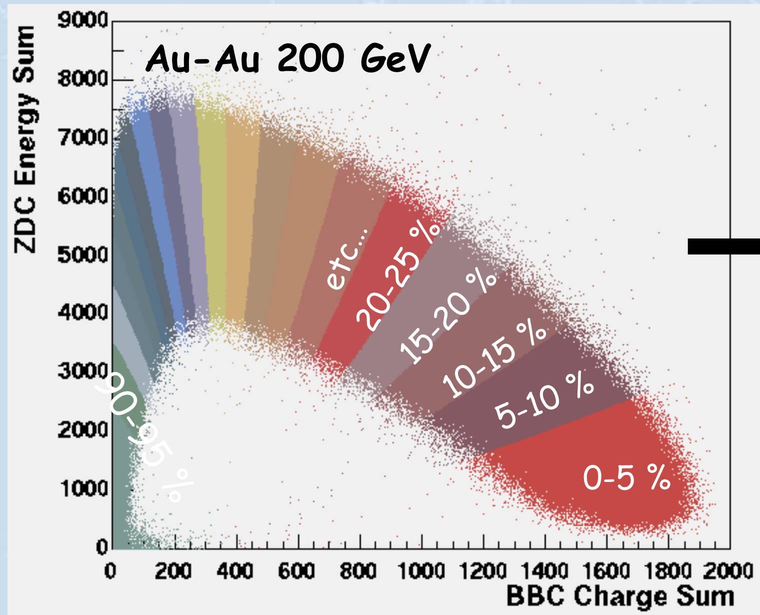




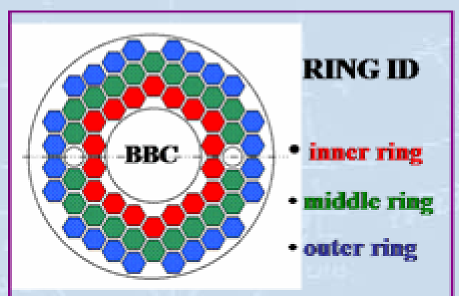


Example: PHENIX Au-Au

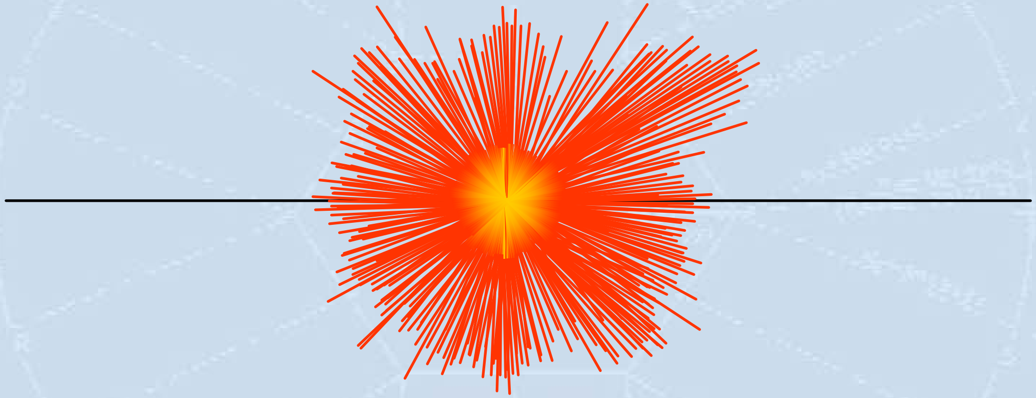
- E_{ZDC} (spectators) / BBC (secondary particles) correlation
  - "zero degree calorimeter" + "beam-beam counter"
- As % of total cross-section



→ N_{coll}



Heavy Quarks and Quarkonia: the experimental point of view



Lecture # 2

Overview

- ✓ Quarkonia → dileptons
  - ✓ Why quarkonia ? Why dileptons ?
- ✓ Detecting dileptons
- ✓ Normalized to what ?
- ✓ As a function of what ?
- ✓ Compared to what ?
- ✓ What's expected ?
- ✓ Interpretations ?
- ✓ Other observables ?
- ✓ The ultimate reference ?
- ✓ *En route* for higher energies !

Tuesday

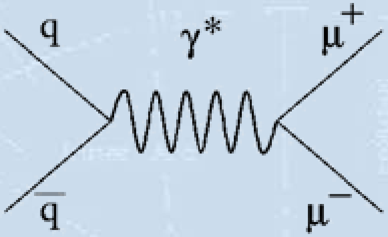
Today

Sunday

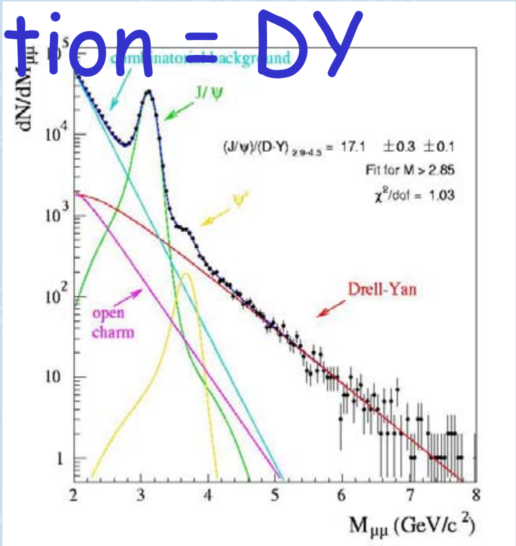
Let's start with NA50 J/ψ

Reminder : SPS : normalization = DY

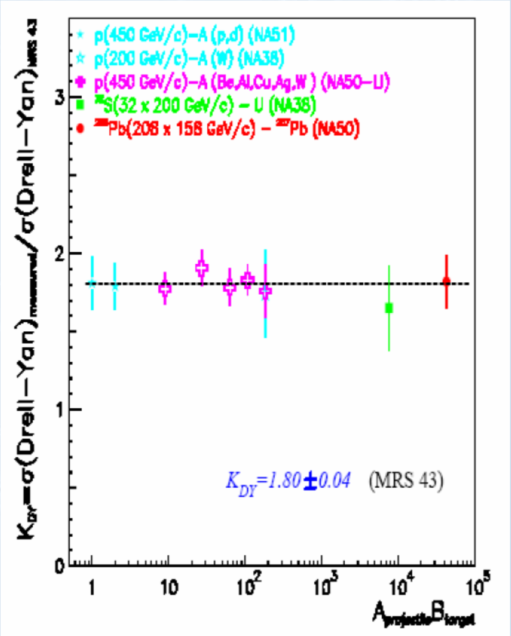
- ✓ Drell-Yan



  - ✓ i.e. compute (J/ψ) / D.Y. [m1,m2]



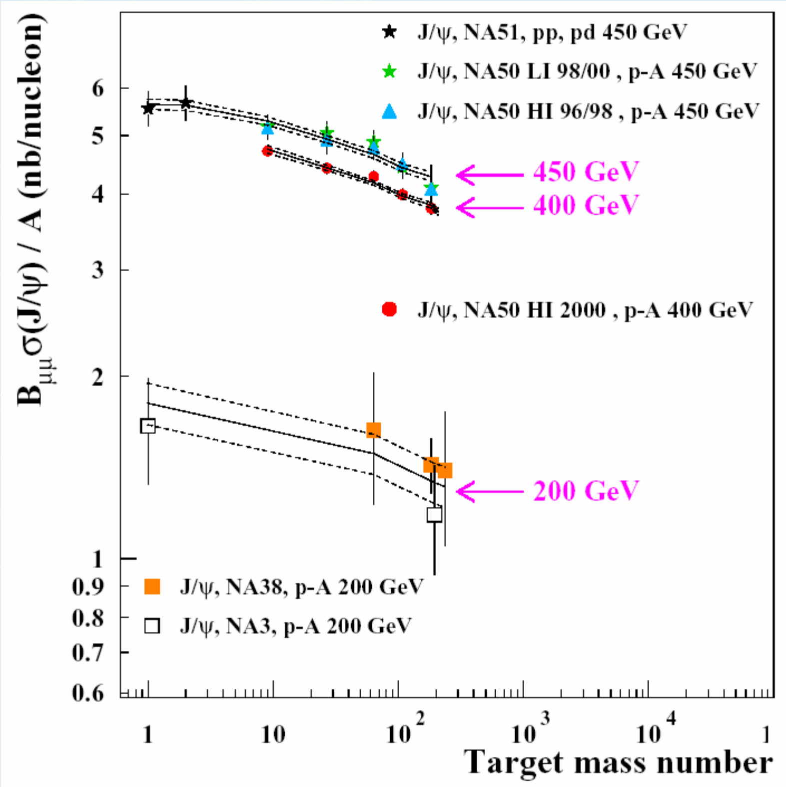
- ✓ Possible in NA50/60
  - ✓ Check prop to Ncoll integrated over b:
    - ✓ A*B scaling in AB collisions
  - ✓ Take it as reference = f(b)



- ✓ Several drawbacks:
  - ✓ Poor statistics
  - ✓ Not available at higher √s

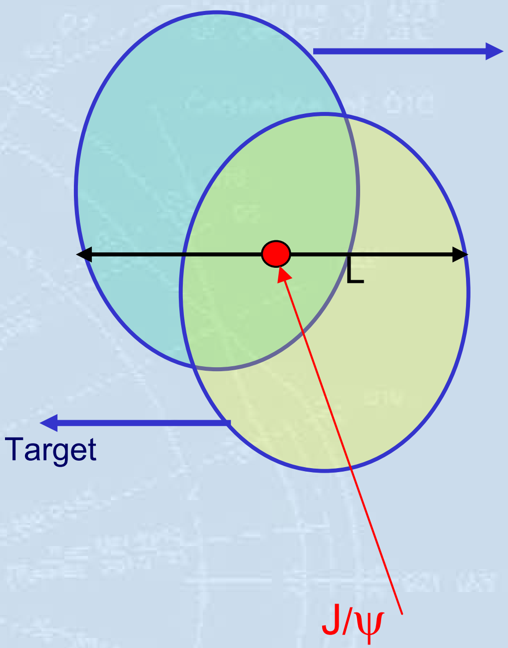
NA50 J/ψ in p-A

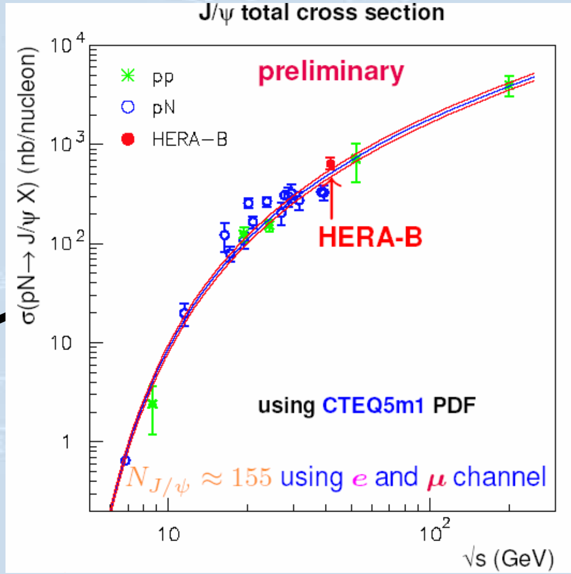
- Precise re-analysis of p-A data
  - Why all these energies ?
    - SPS = 450 GeV protons …
    - … 400 GeV to spare some energy !
    - Thus : 200 GeV ^{16}O and ^{32}S
    - … And 158 GeV ^{208}Pb
    - NA38 took 200 GeV p by means of a secondary target (huge syst)
    - NA60 obtained direct 158 GeV p
      - See later
  - No NA50 p-A data at 158 GeV !!
  - √s scaling, kinematical domain,
  - Isospin scaling, neutron halo, …
  - Are these straight lines ?
  - A^{α} means nothing !! σ_{abs} ?



σ_{abs}

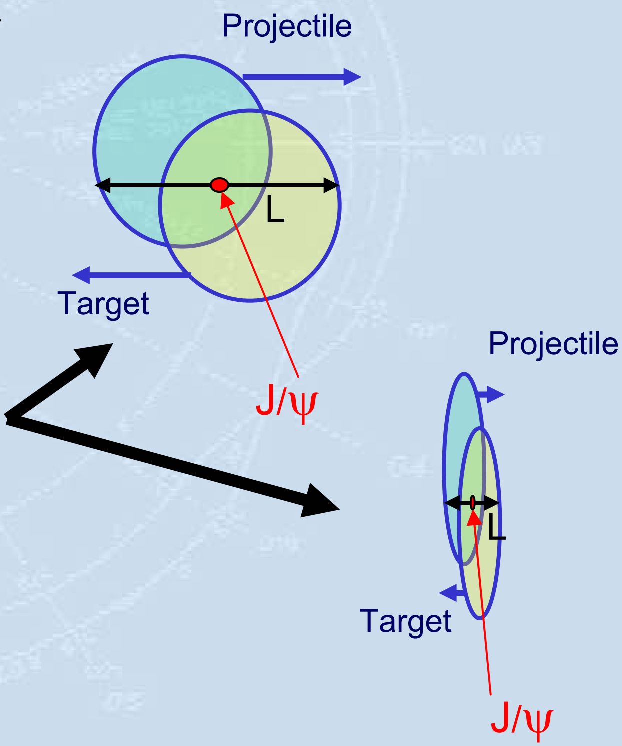
- $e^{-\langle \rho L \rangle \sigma_{abs}}$ = intuitive if J/ψ disappearance in an absorbing medium. May depend on √s
  - Can be even much more complex that that !
    - Combination of energy loss of the initial parton + J/ψ « absorption » in nuclear matter
    - Energy loss of initial gluon:
      - Modifies the effective √s
      - No reason to scale as $e^{-\langle \rho L \rangle \sigma_{abs}}$
      - Less important at RHIC ?





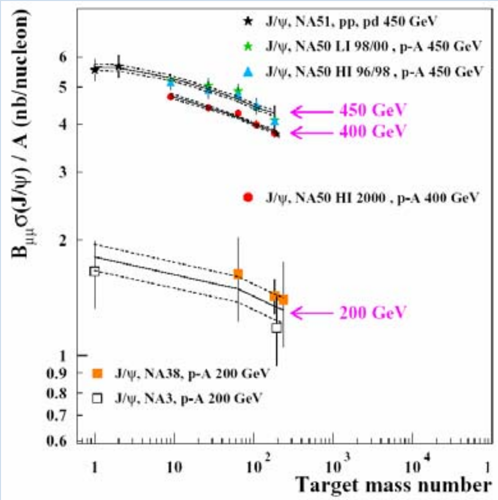
Is L lorentz-invariant ?

- It certainly doesn't look like, but YES, L is Lorentz-invariant !!
- The reason is the following : $\sigma_{p-A} = \sigma_0 A e^{\left(-\sigma_{abs} \langle \rho L \rangle\right)}$
  - $\langle \rho \mathcal{L} \rangle$ is a **NUMBER** of nucleons on the path -> γ boost :
  - $\langle \rho\gamma \; * \; \mathcal{L}/\gamma \rangle$ -> Lorentz invariant
- The « L » I quote is therefore :
  - $L = \langle \rho \mathcal{L} \rangle / \rho_0$
  - That is exactly the same in these two cases



- Indeed, $\langle \rho \mathcal{L} \rangle$ is an average weighted by Ncoll, to take into account the probability of forming a charm quark pair at each point of the transverse surface

α VS σ_{abs}

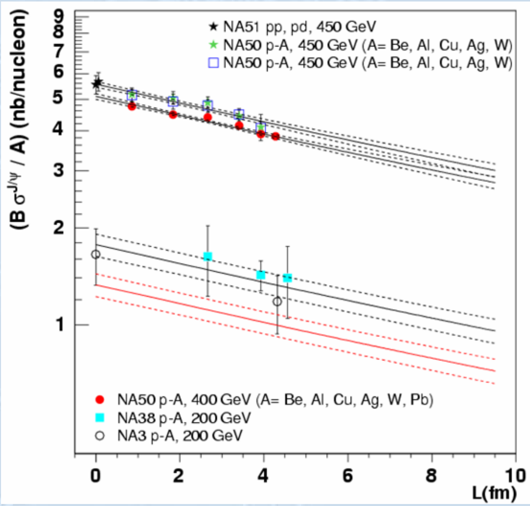


A^{α}

= straight line here

$e^{-\rho \langle L \rangle \sigma_{abs}}$

= straight line here

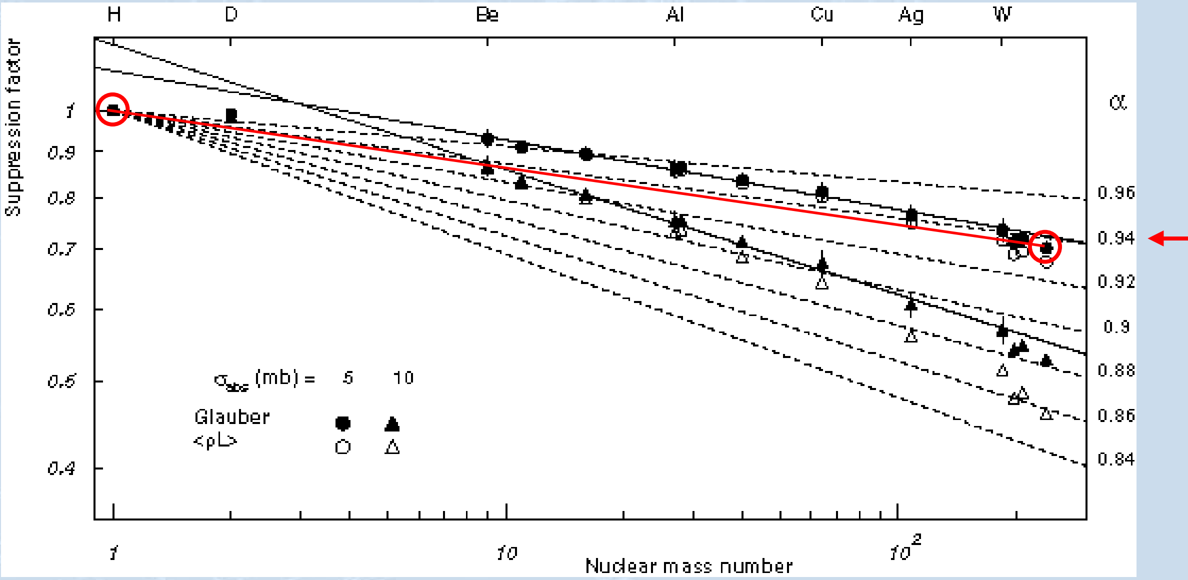


$$\sigma_{p-A} = \sigma_0 \, A^{\alpha}$$

$$\sigma_{p-A} = \sigma_0 A \exp\left(-\sigma_{abs} \langle \rho L \rangle\right)$$

$$\sigma_{p-A} = \frac{\sigma_0}{\sigma_{abs}} \int \left[1 - T_A(\vec{s})\sigma_{abs}\right]^A d\,\vec{s}$$

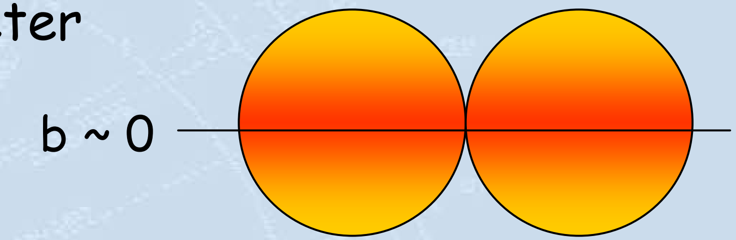
- ✓ Not equivalent !
  - ✓ Depends on which nuclei you take
  - ✓ + ρ < L > or < ρL > are only approximations



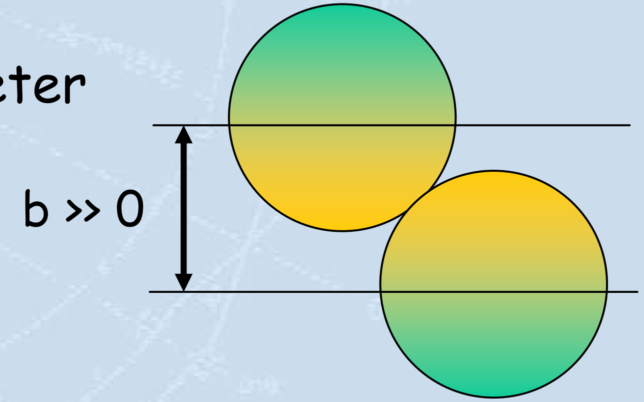
The better representation is indeed Glauber

Nuclei : centrality of the collisions

- If produced, QGP is expected to appear in the most central collisions ...
  - Central collision = small impact parameter
    - Higher energy density deposited
    - Larger volume



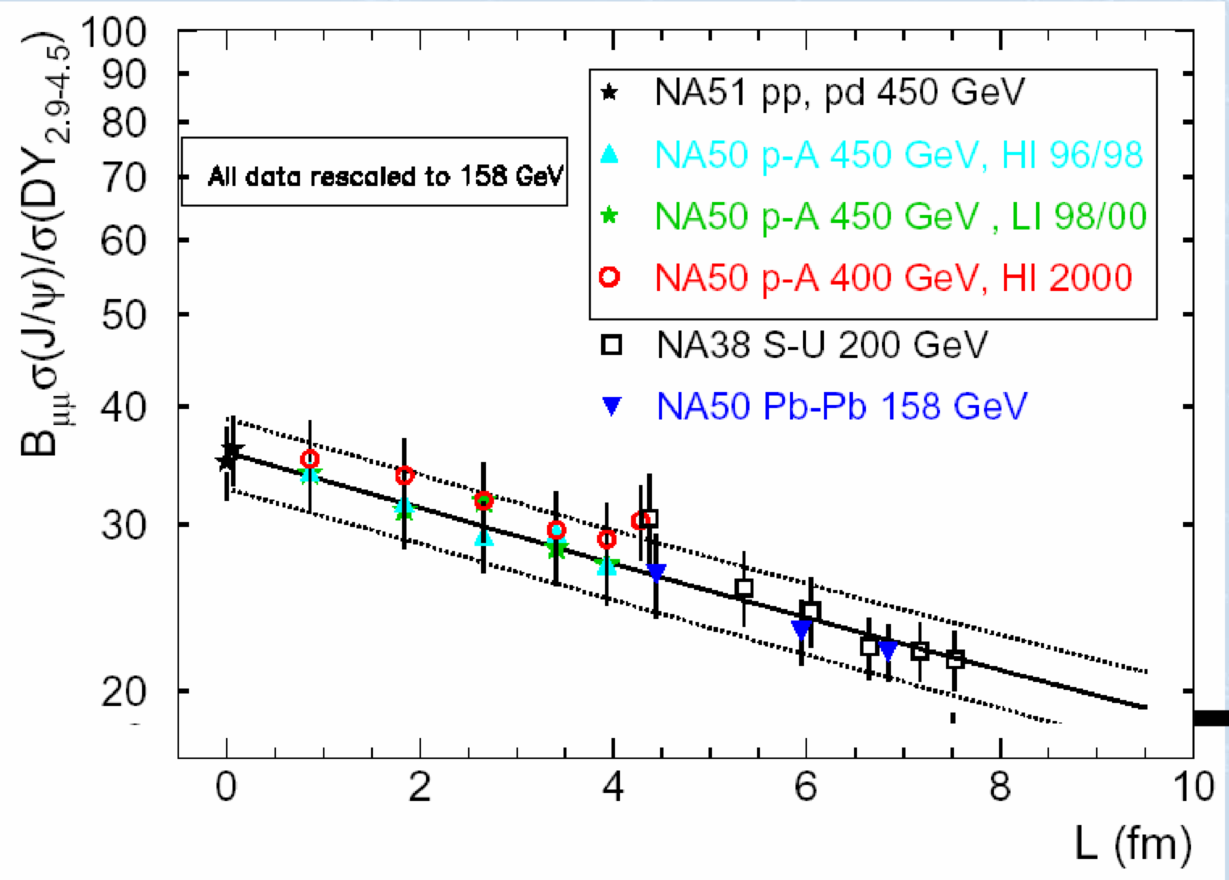
- ... and not in peripheral collisions
  - peripheral collision = large impact parameter
    - Low energy density deposited
    - Small volume



- Therefore, we have to plot all our observables as a function of a parameter that reflects the collision centrality

First choice : L -> σ_{abs}

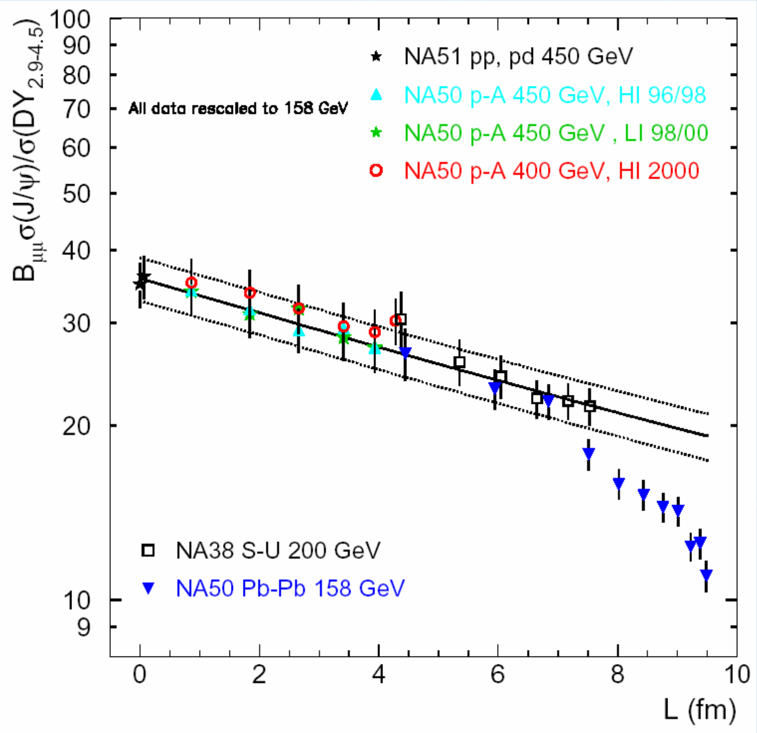
✓ $e^{-\langle\rho L\rangle \sigma_{abs}}$ representation = f(L)

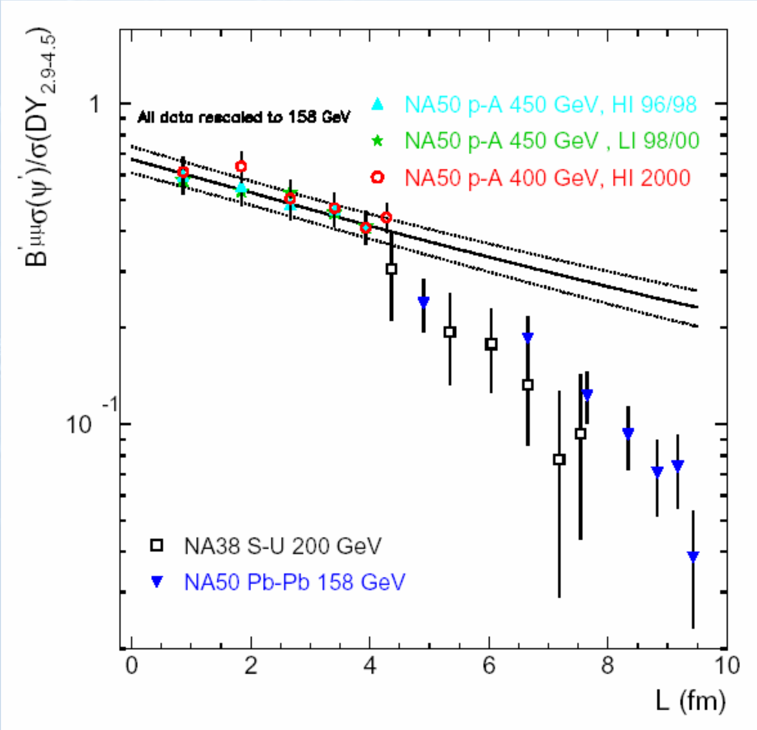


$\sigma_{abs}(J/\psi)$ =
4.18 ± 0.35 mb

NA50 J/ψ and ψ′

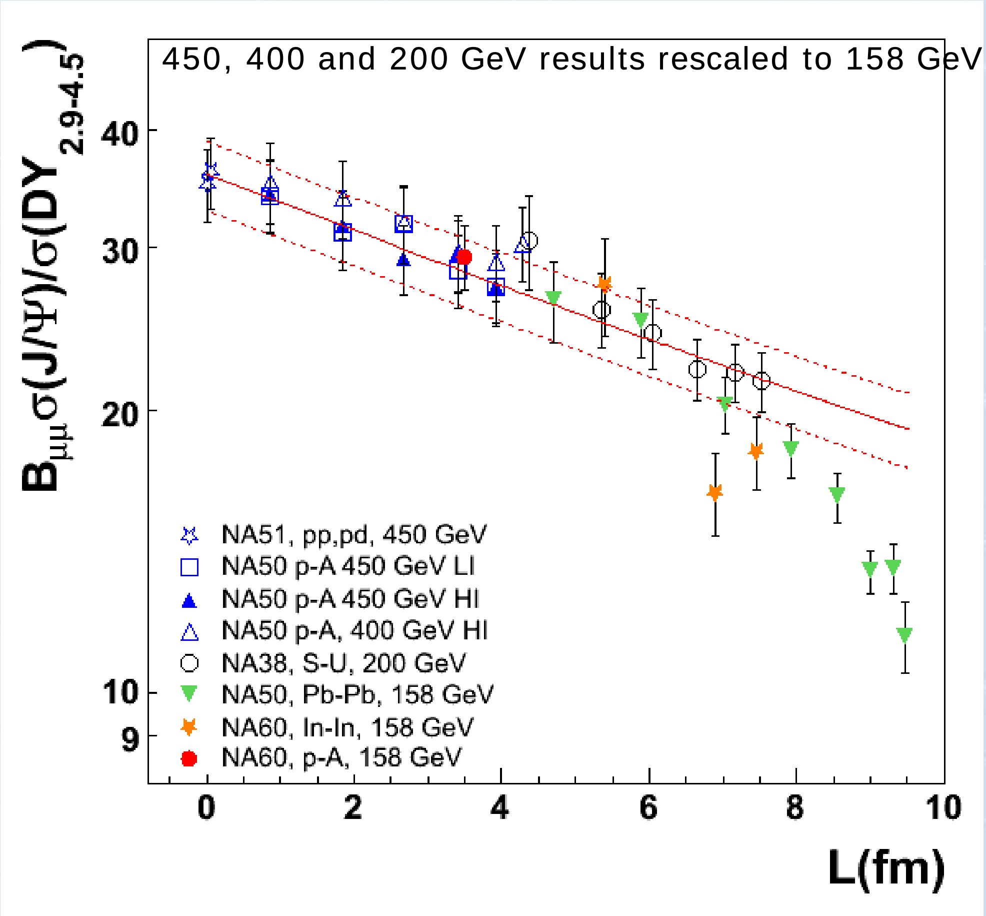
- $\sigma_{abs}(J/\psi)$ = 4.18 ± 0.35 mb
- $\sigma_{abs}(\psi')$ = 7.6 ± 1.1 mb





- « anomalous J/ψ suppression » for central Pb-Pb
- ψ′ « suppression » starts at lower L, and in S-U already

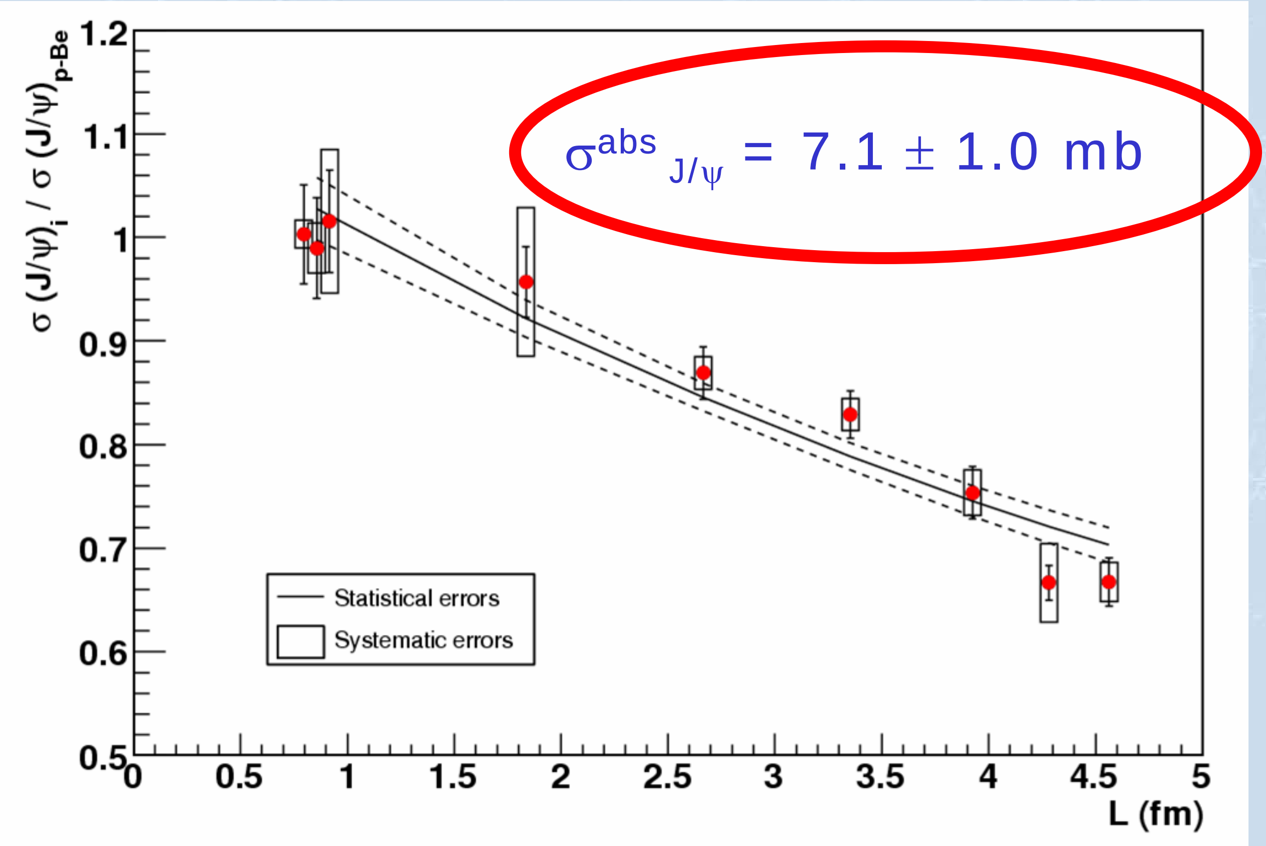
Adding NA60



- ✓ Anomalous suppression confirmed
- ✓ What about the direct 158 GeV p-A data ?

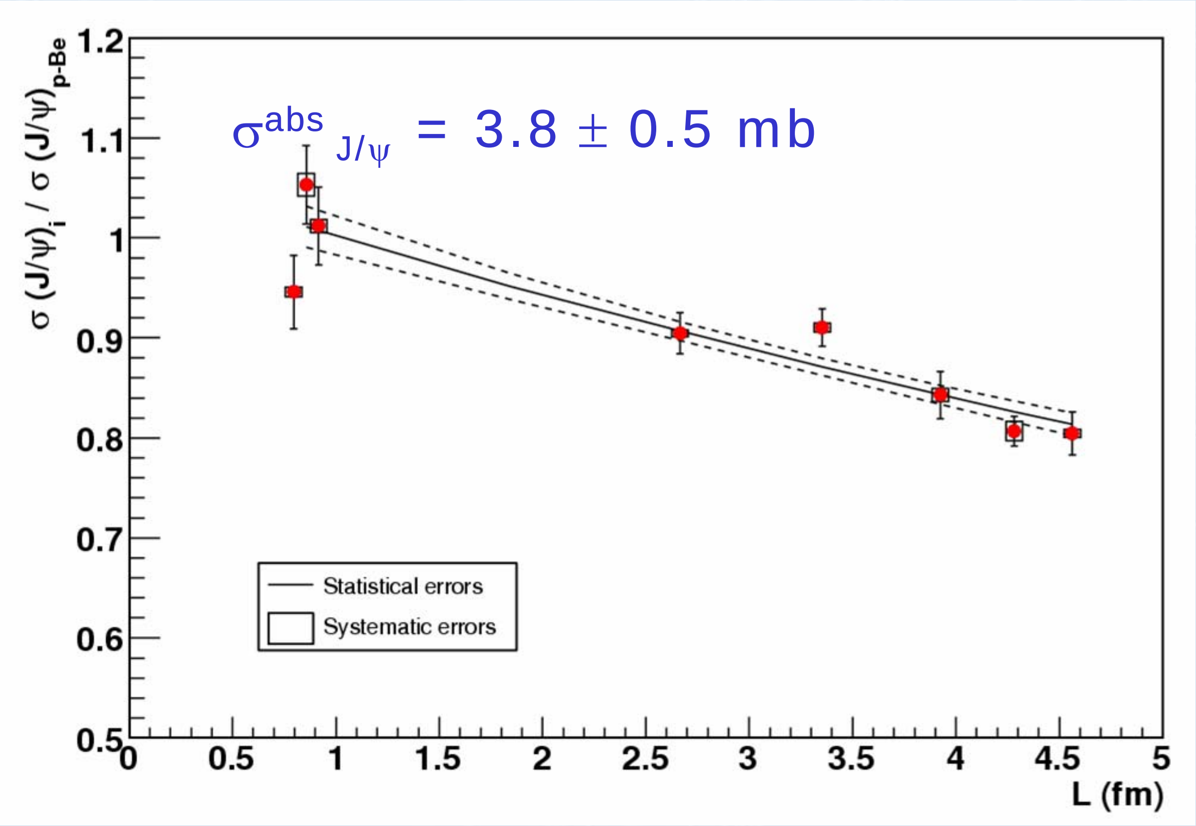
NA60 p-A @ 158 GeV / Fixed target

- ✓ J/ψ ratios for different targets / Be
- ✓ Seems incompatible with NA50 !!!!



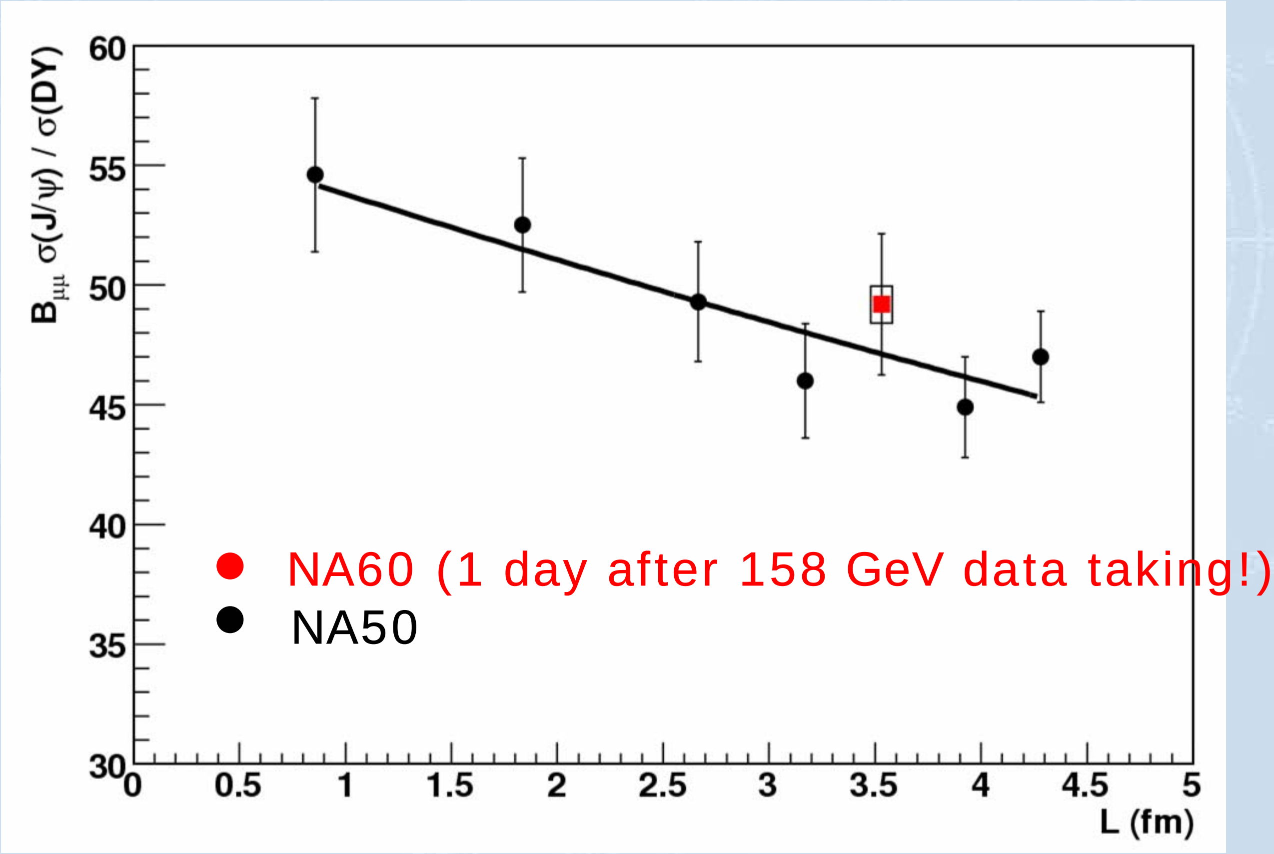
NA60 p-A @ 400 GeV / Fixed target

- ✓ Control experiment @ 400 GeV,
- ✓ J/ψ ratios for different targets / Be
- ✓ Compatible with NA50



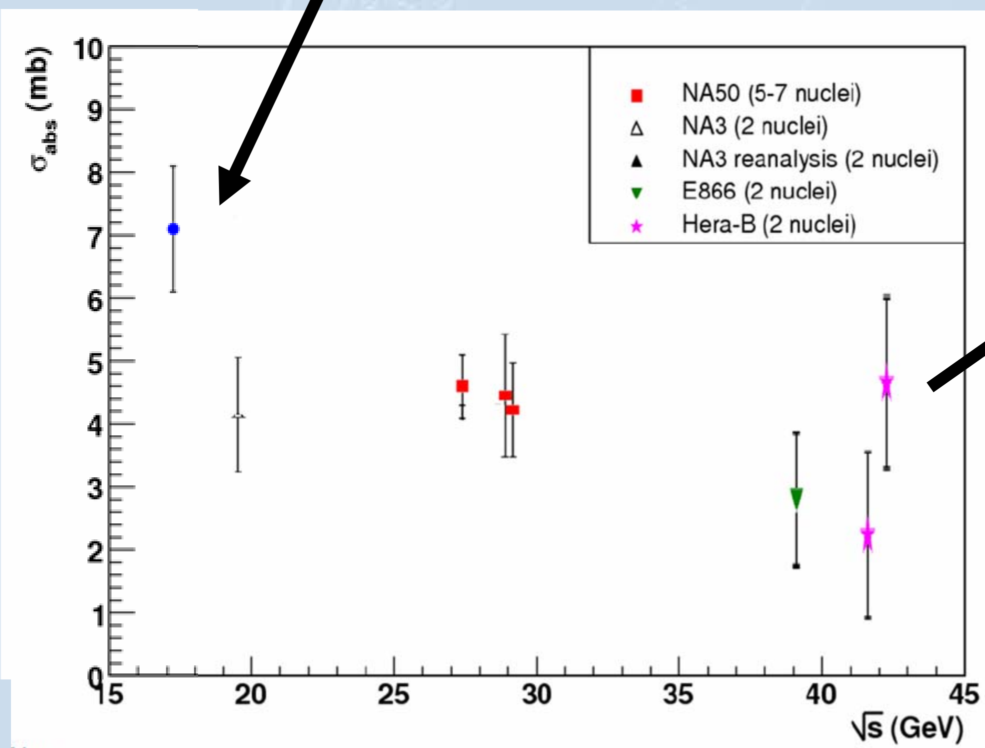
NA60 p-A @ 400 GeV / Fixed target

- Control experiment @ 400 GeV
- J/ψ / Drell-Yan, weighted average of all targets
- Compatible with NA50



The σ_{abs} puzzle

- ✓ 158 GeV $\sigma_{abs}(J/\psi)$ seems much higher
- ✓ Still debated !!!



Summary

L. Kluberg, Etretat 2008

Expt.	E	$sigma_{abs}$	selected xf	ylab
NA3	200	4.1 0.97	0.0 / 0.4	3.03 / 4.07
NA50	400	4.6 0.6	-0.10 / 0.14	2.95 / 3.95
NA50	450	4.3 0.8 / 4.4 1.0	-0.10 / 0.10	2.95 / 3.95
E866	800	2.85 1.14	-0.10 / 0.25	3.13 / 4.95
HERAB	920	2.1 1.5 / 4.75 1.5	-0.375 / 0.125	2.14 / 4.55

Weighted average: 4.12 ± 0.36 / 4.27 ± 0.36 mb

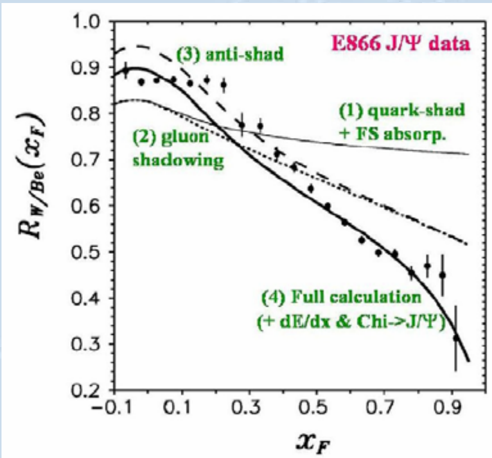
L.Kluberg 22

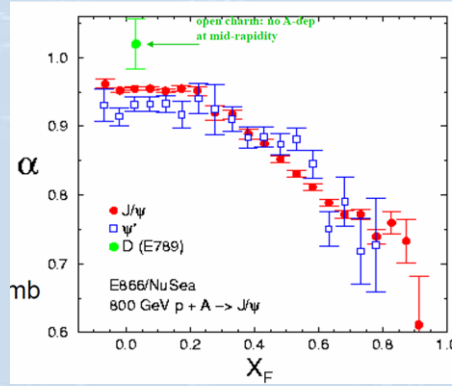
- ✓ Could this rapid change be a consequence of nucleon energy loss before charm pair production, when getting close to the threshold ?

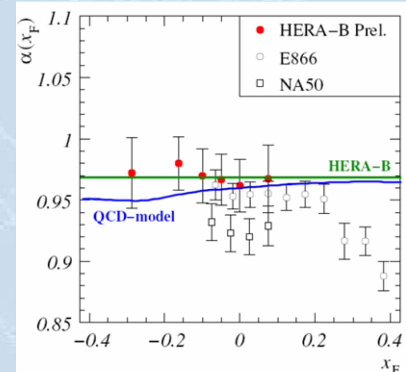
J/ψ suppression due to energy loss ?

- Energy loss of initial gluon:
  - Depends on X_f
  - Less important at RHIC

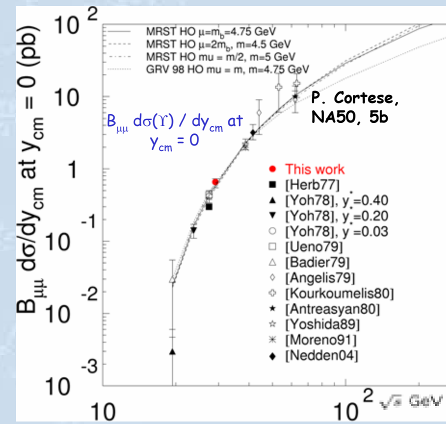
M. Leitch, E866, Eur.Phys.J.A (2004) 19, S01, 129
Curve from Kopeliovich et al., Nucl. Phys. A696 (2001) 669

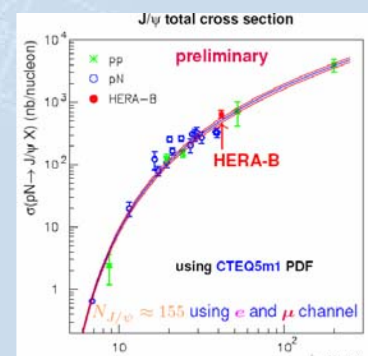




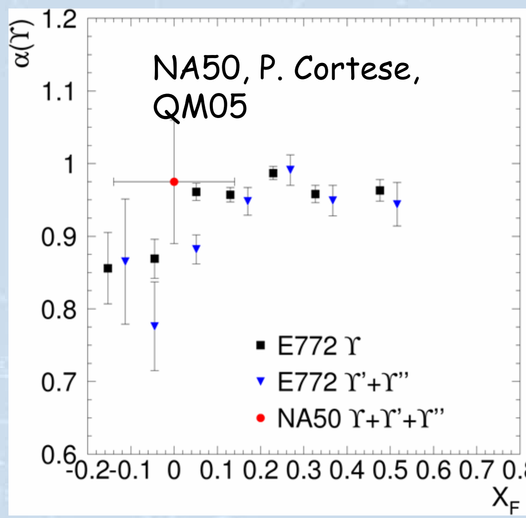


- Doesn't seem to play a role at NA50 X_f, otherwise would be seen on the ϒ





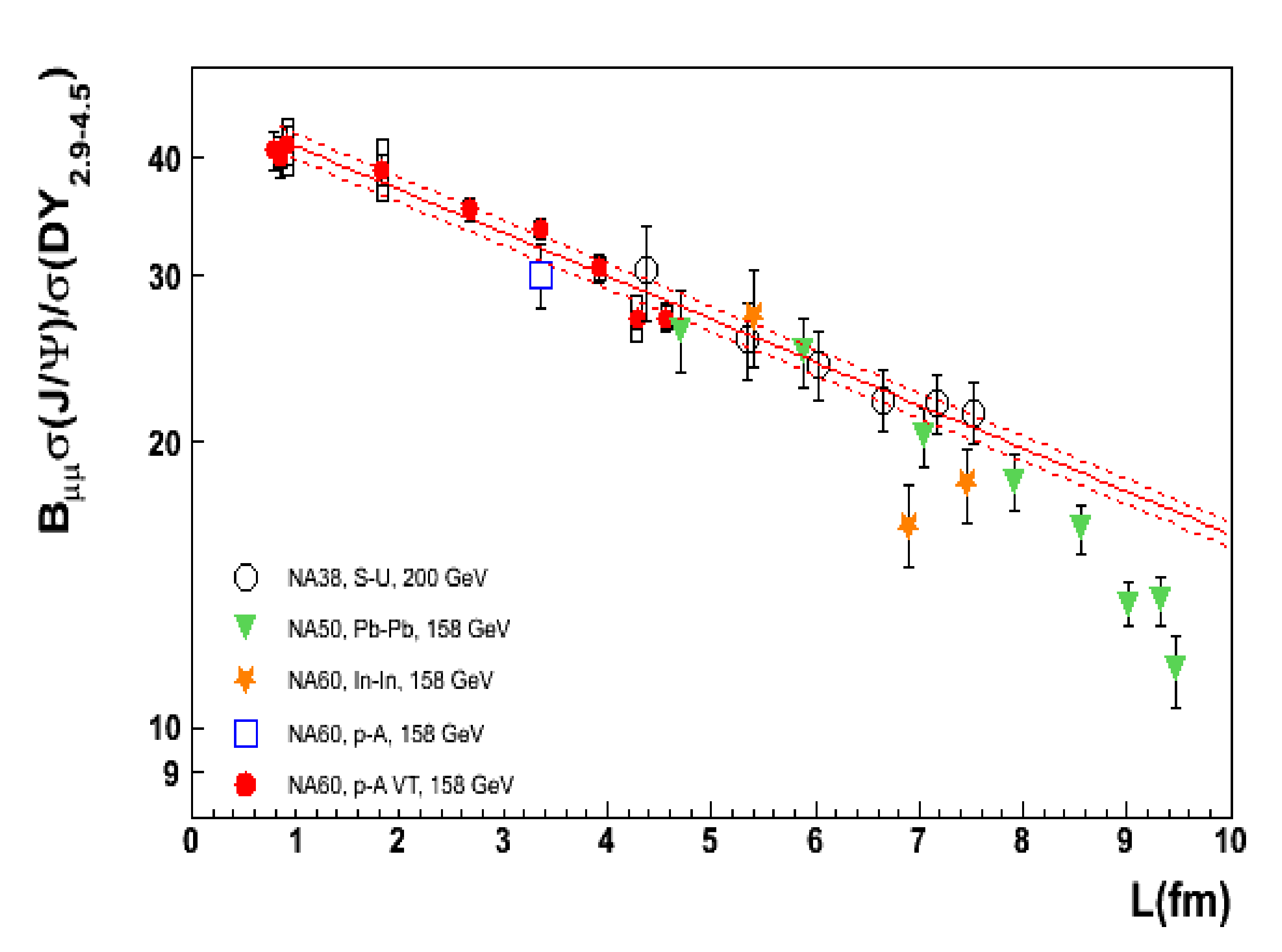
Seems to me that ϒ @ √s = 30 GeV is closer to the threshold than J/ψ @ √s =17.3 GeV



But it may not be that simple ...

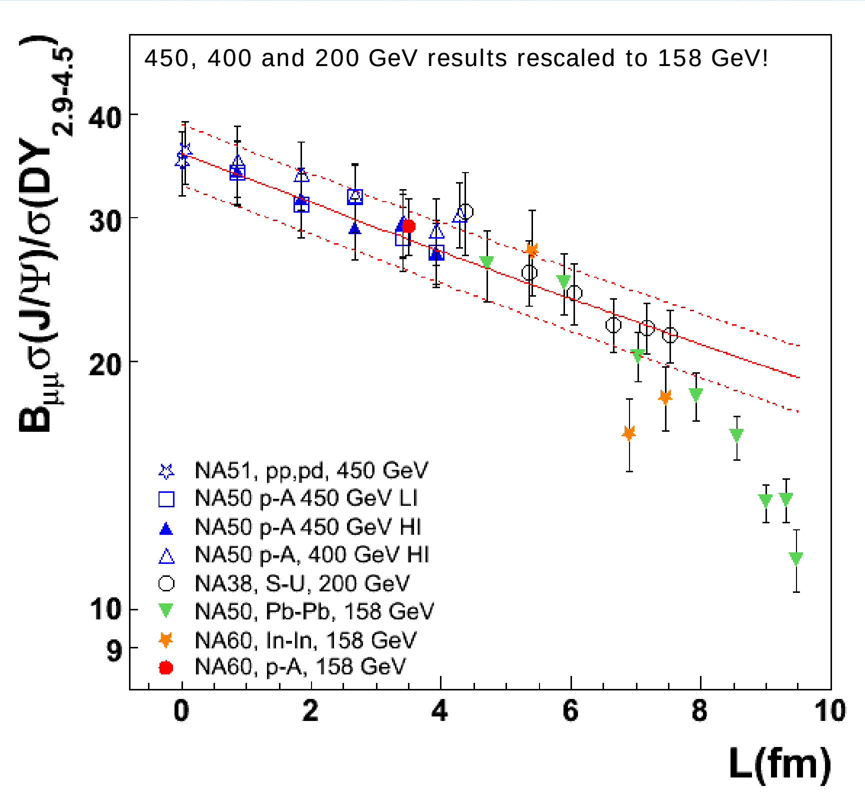
The σ_{abs} puzzle

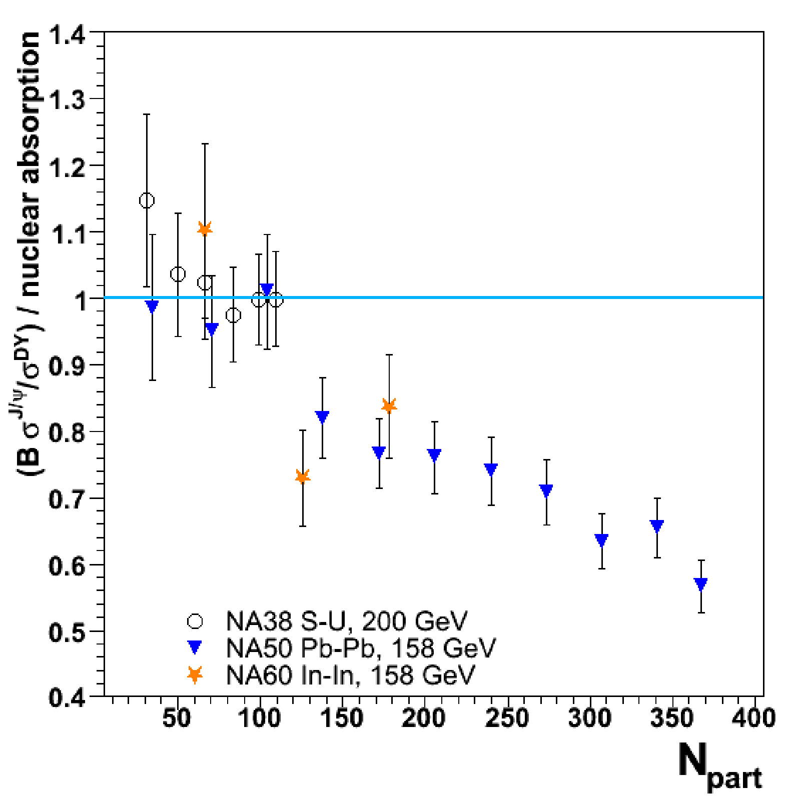
✓ Changes things ! The « anomalous suppression » is lower



Let's forget the puzzle for the moment !

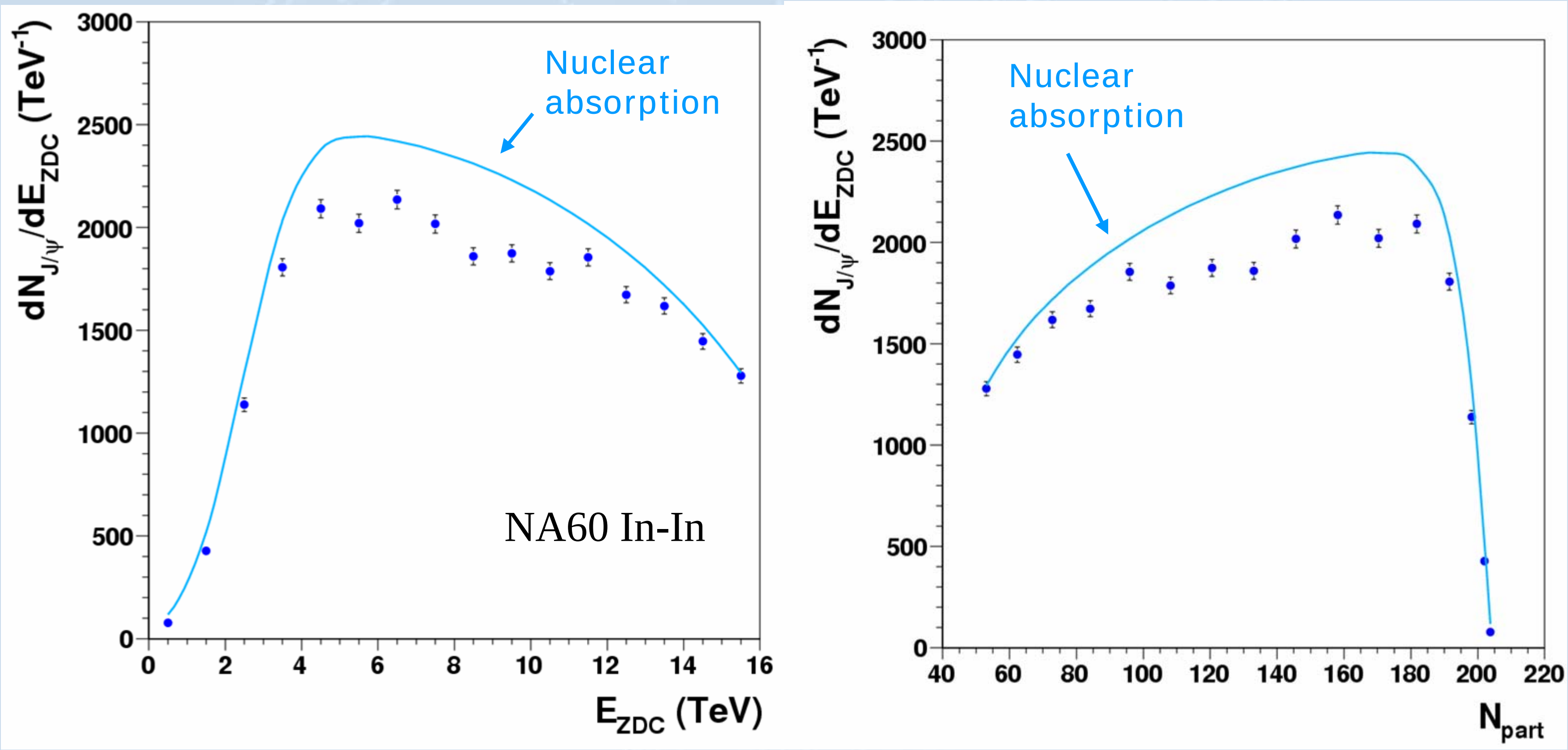
- Let's play with the plots !
  - Everything wrt « normal absorption » -> horizontal line @ 1
  - Focus on ion-ion collisions -> remove the protons
  - Change the horizontal « centrality » variable to cover the ion range





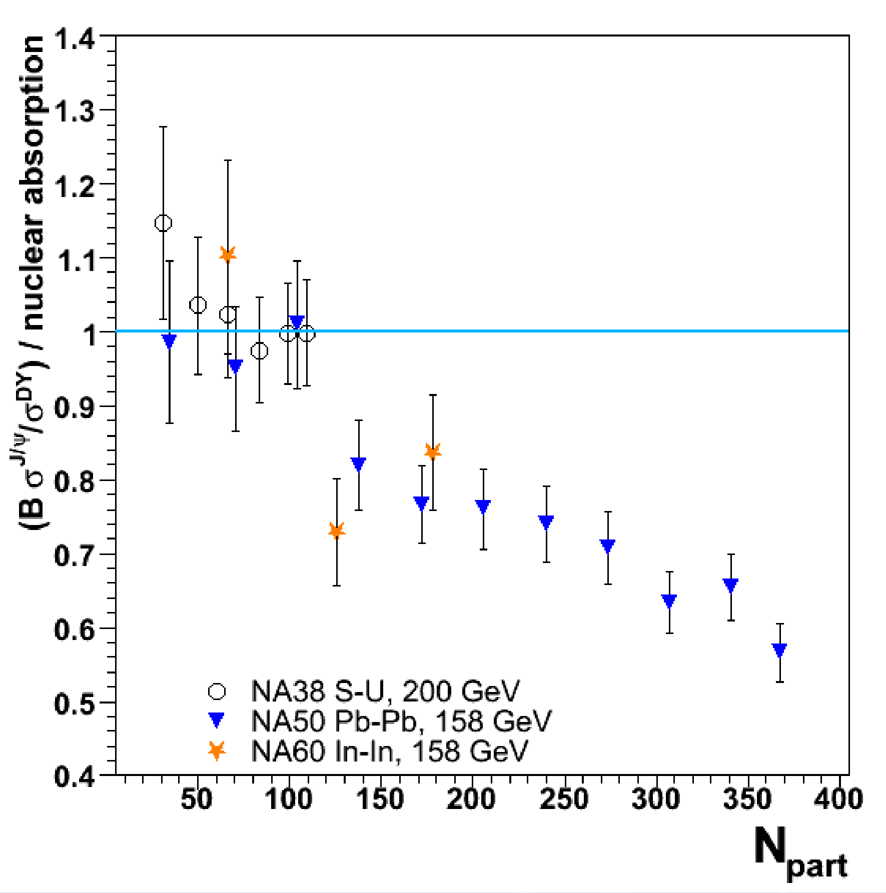
Let's play with the plots !

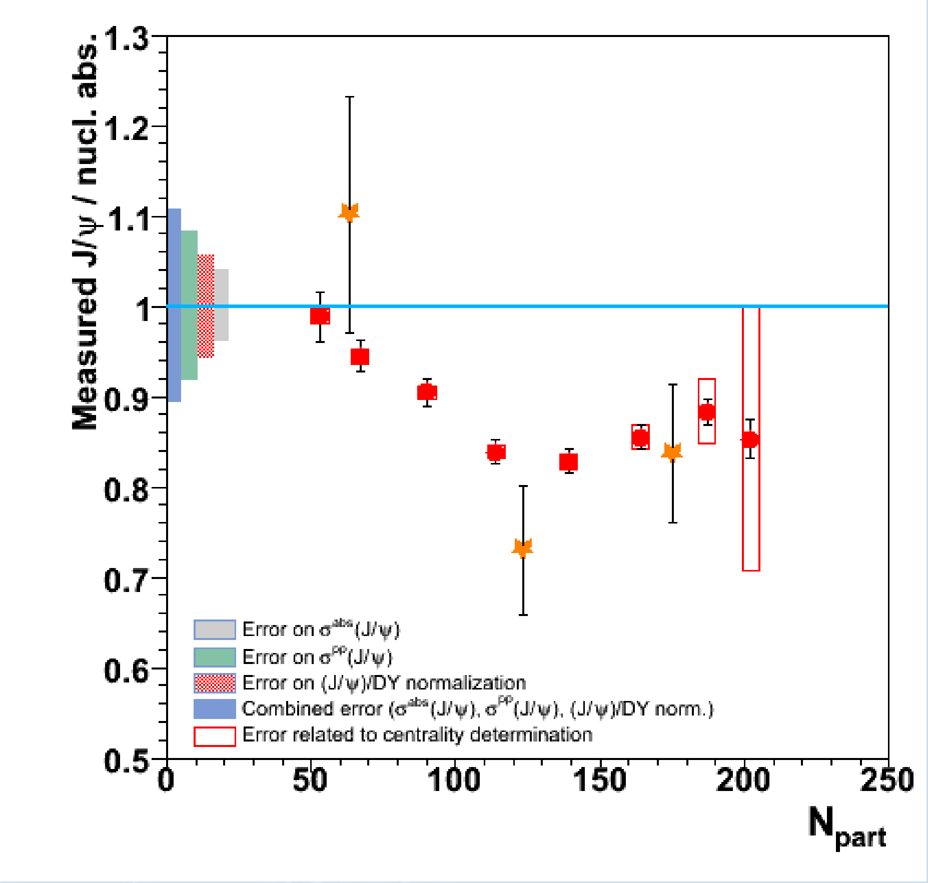
- Still some information to add !
  - Drell Yan poor statistics prevents from having many centrality bins
  - Replace it by a geometrical variable deduced from measurement + Glauber



Let's play with the plots !

✓ Hocus pocus, you've got more points !





✓ You bypass the DY statistics limitation, becomming model dependent

Let's take a break !

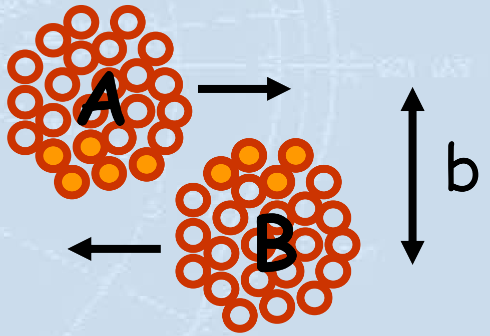
What about the centrality variable ?

No universal relevant variable ...

- What is the best relevant variable ?
  - J/ψ normalized, as a function of what ?

- Depends on what you want to demonstrate !
  - Number of participants : N_{part}
    - Or density of participants (/ $S_\perp$)
  - Number of binary collisions : N_{coll}
  - Impact parameter : b
  - « Maiani Variable » : $\ell = 2R - b$???

Pure geometry



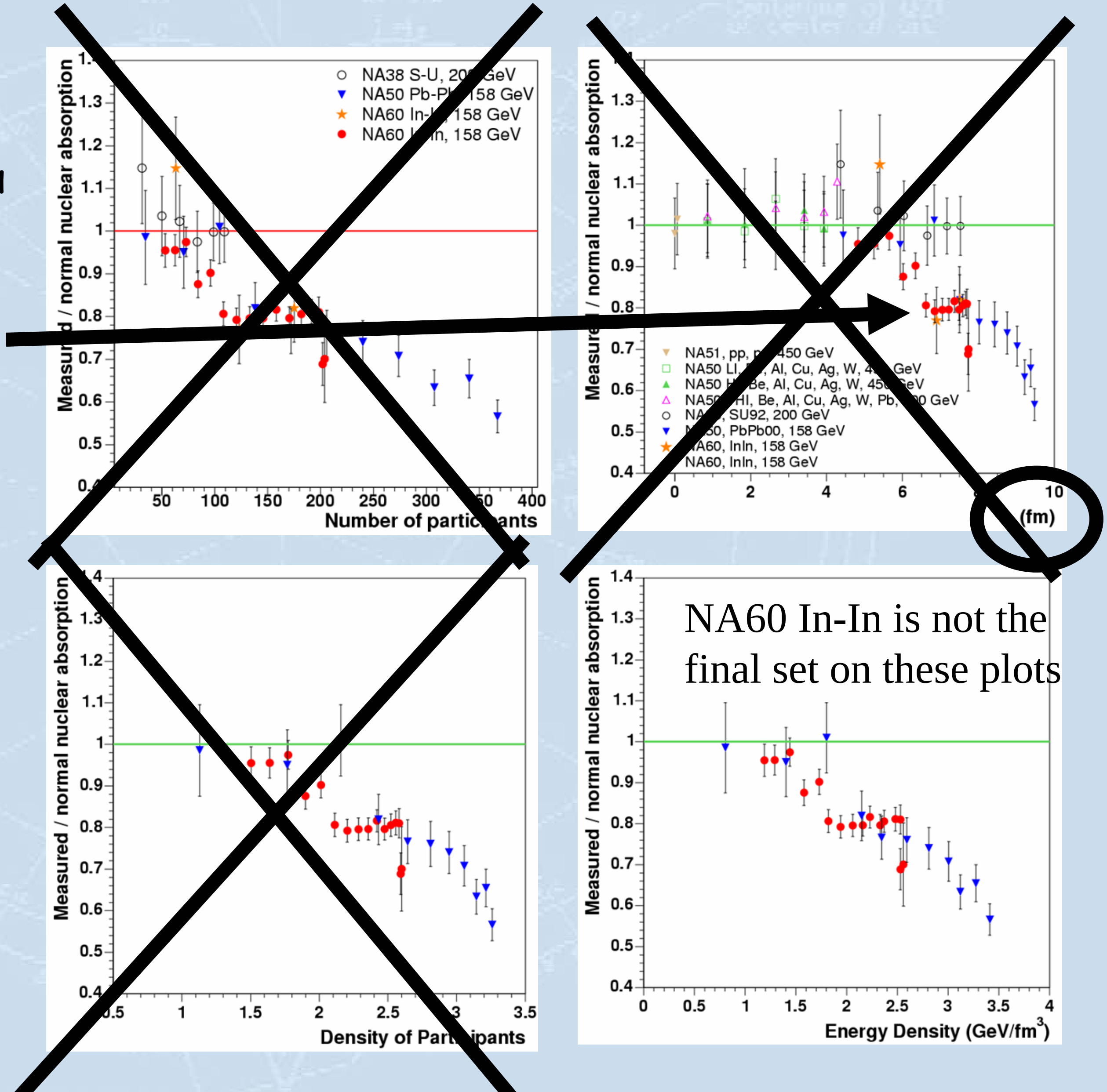
  - Energy density : $$\varepsilon = \left.\frac{dE_T}{dy}\right]_{y=0} \frac{1}{S_\perp \tau}$$

Thermodynamics

  - Secondary particle multiplicity : N_{ch}
    - Or entropy density (/ $S_\perp$)

What is the relevant variable ?

- ✓ There is NO unique universal variable
  - ✓ Depends on what you want to show
  - ✓ e.g. : anomalous suppression is NOT an absorption by nuclear matter
- ✓ More tricky if you need to compare different √s !!!
  - ✓ e.g. ε allows comparisons
  - ✓ N_{part} or L don't
    - ✓ pure geometry



Quiz

- To illustrate how you can « guide » the audience's mind by choosing your « variables »

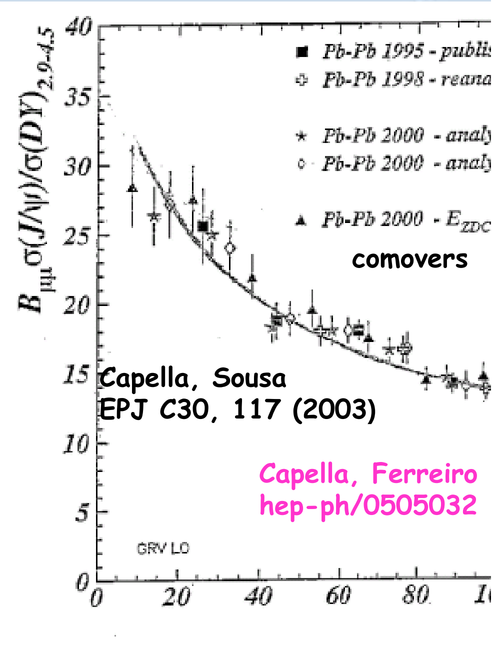
- « we're small ... »
- « ... known only since the XXth century »
- « you've never seen one of us alone ... »
- « ... but most of the time the 3 of us »
- « belonging to the same family ... »
- « ... and tightly bound together »
- « usually represented in 3 colors, red, green, blue »

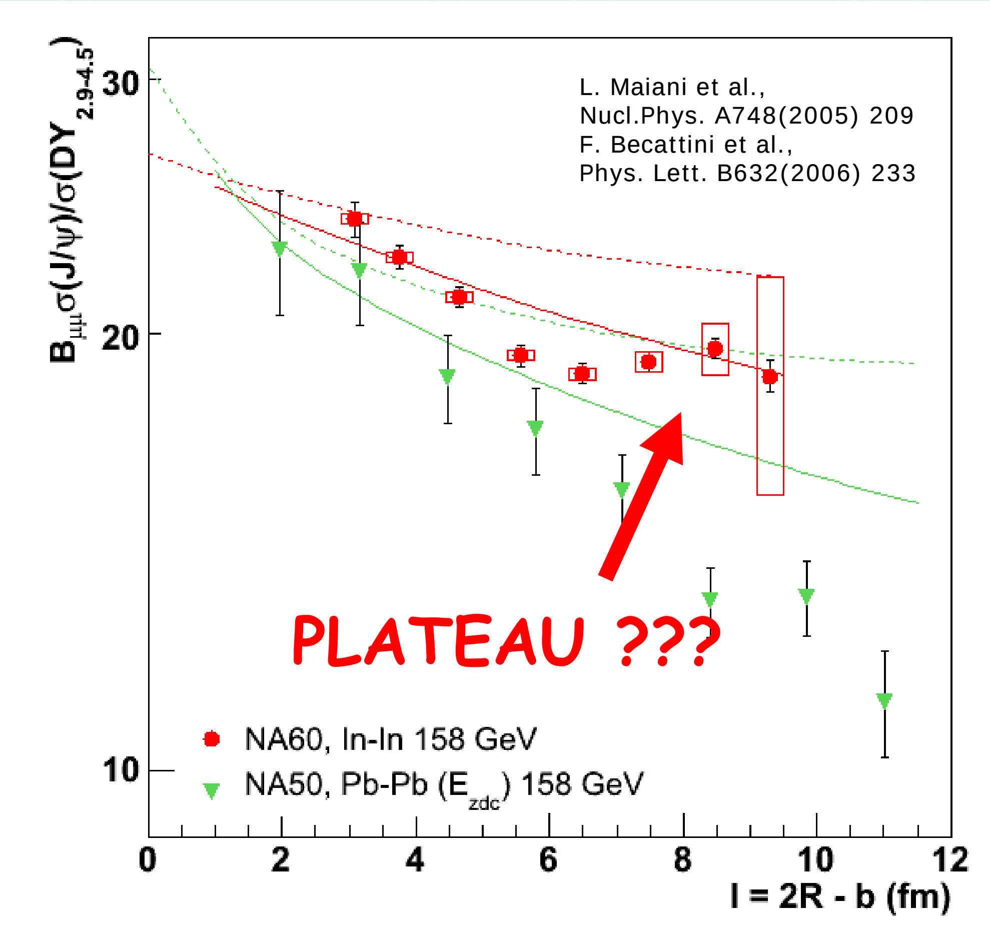
- WE ARE .... ?

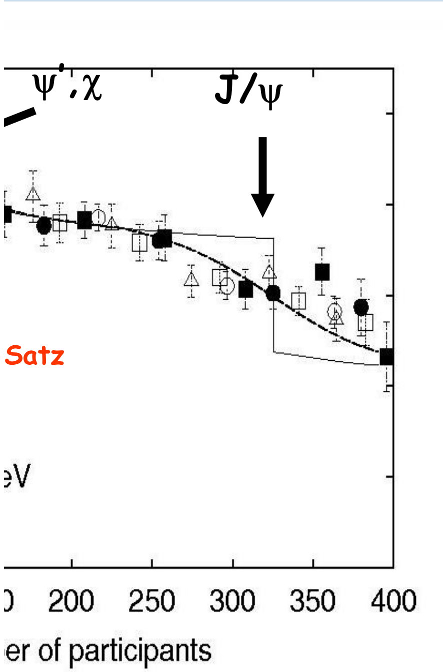
Huey, Dewey and Louie
of course !

Now let’s go back to work !

Interpretation of J/ψ suppression @ SPS







Suppression by hadr... comovers (σ_{co} = 0.65 ... tuned for Pb-Pb colli...

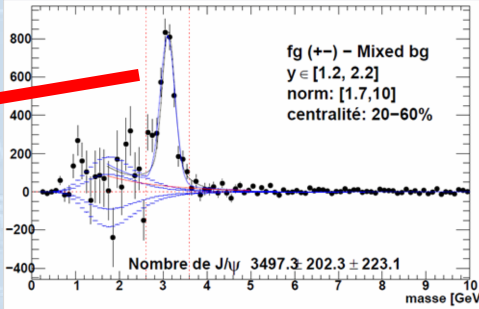
...lation, with ... of suppression ... $_{art}$~140

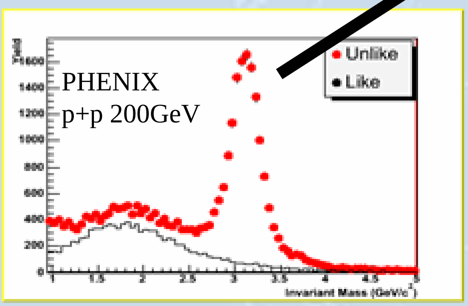
- Amplitude of the suppression almost correct
- detailed shape description not satisfactory
- IF plateau => incompatible with any continuous effect
    - e.g. nuclear absorption + hadron gas

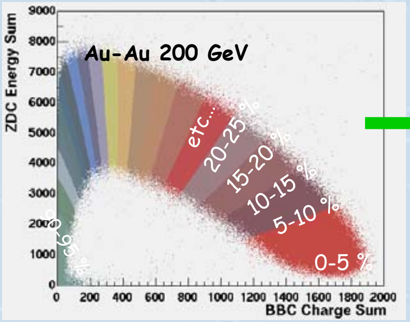
RHIC data !

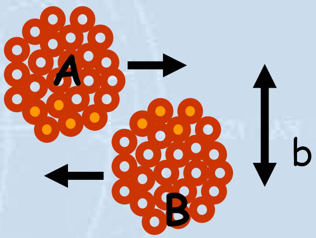
Nuclear modification factor

$$R_{AA} = \frac{dN_{J/\psi}^{AA}}{dN_{J/\psi}^{PP} \times \langle N_{coll} \rangle}$$



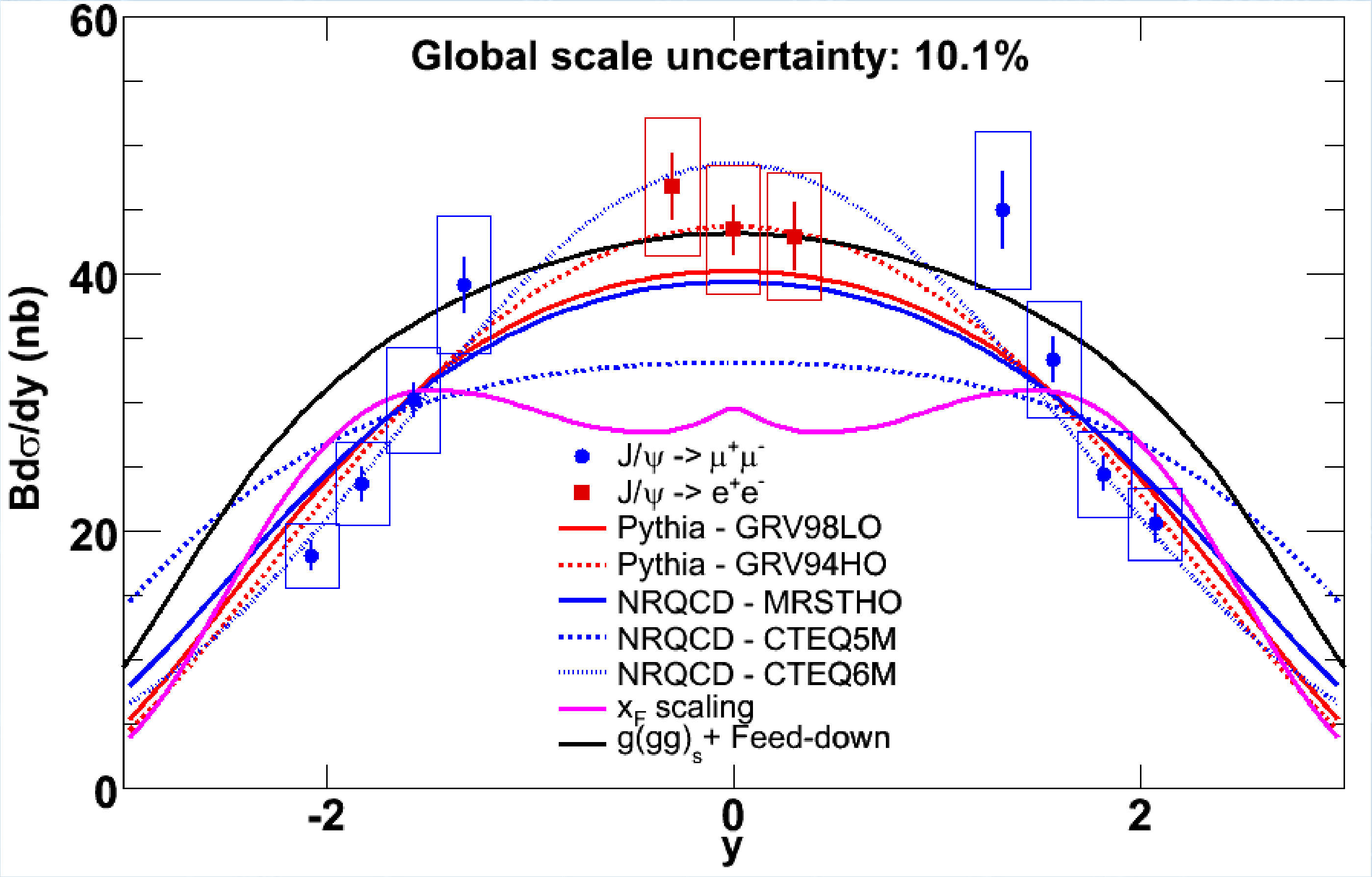






- ✓ J/ψ production in Nucleus-Nucleus / p-p
  - ✓ p-p ~ n-n since gluon fusion
- ✓ Taking into account the number of binary collisions (Glauber) corresponding to the centrality sample -> exp error
- ✓ As a function of WHAT ?

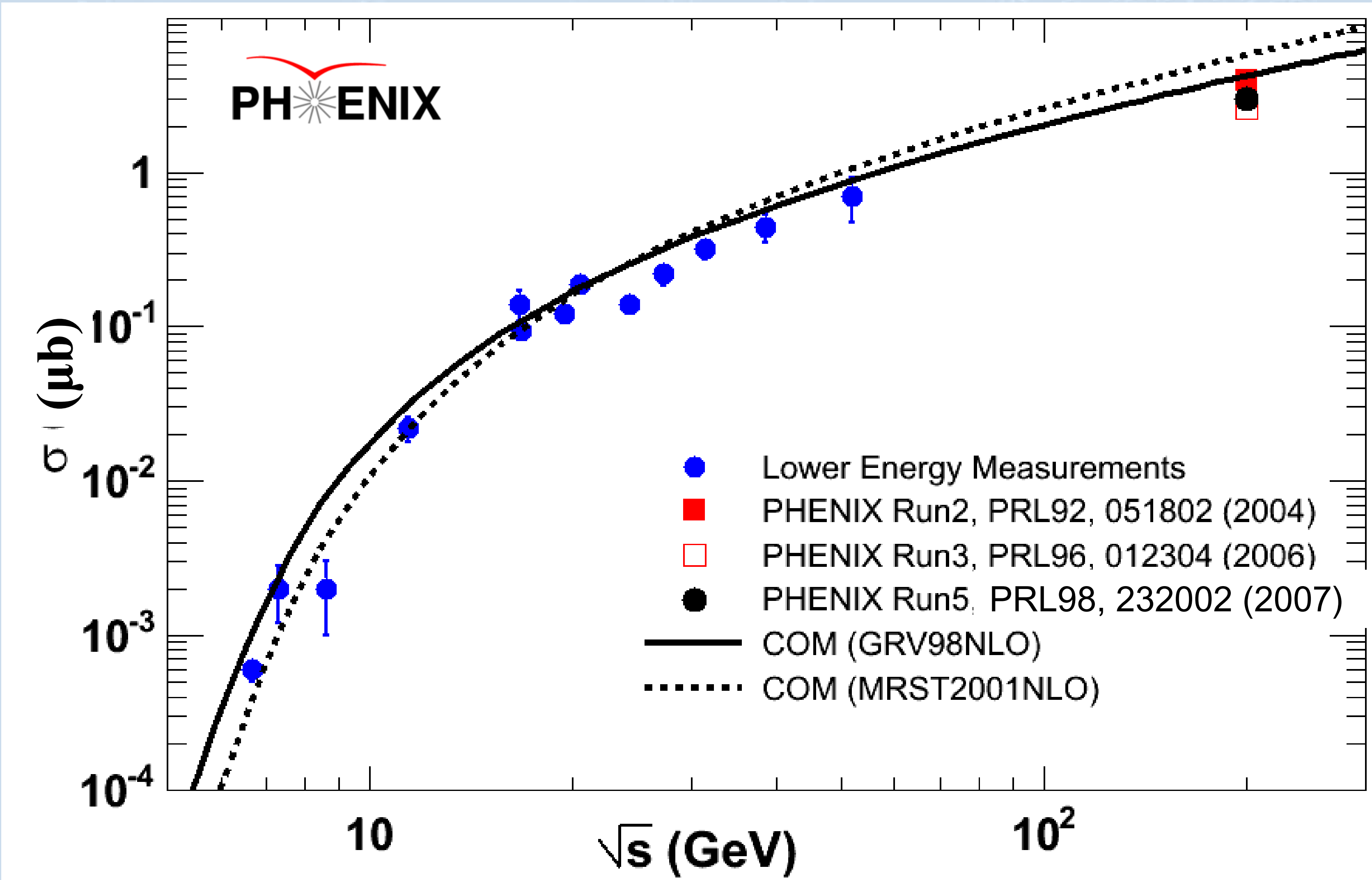
p+p -> J/ψ cross section vs rapidity



- ✓ Comparison with theoretical predictions could allow differentiation among the available J/ψ production mechanisms
- ✓ Main features of the data: steepness of the slope at forward rapidity and slight flattening observed at mid-rapidity

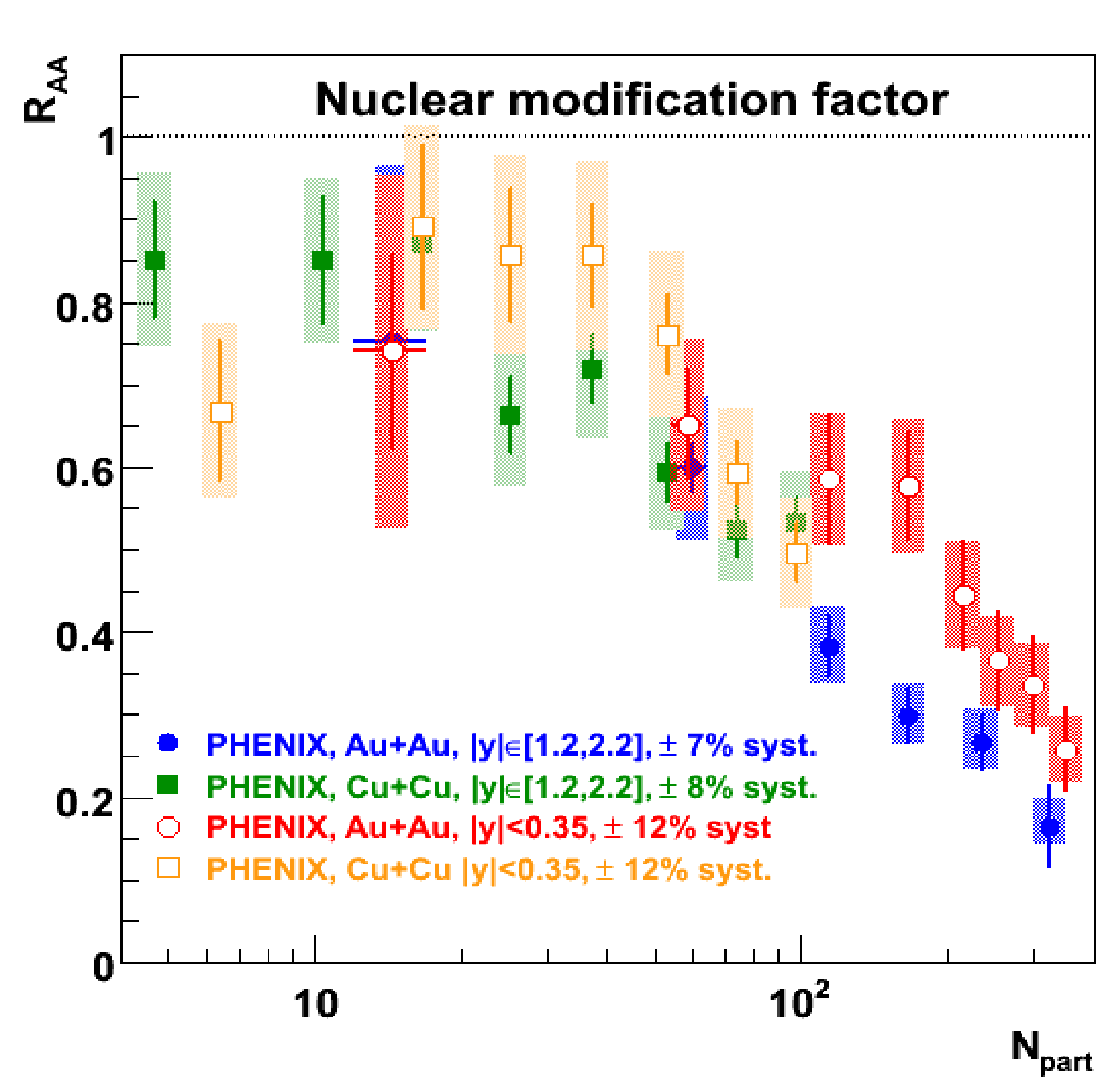
$$B_{ll}^{*}\ \sigma_{pp}(J/\psi\ )=178\pm3\pm\ 53\ \pm\ 18\ \text{nb}$$

p+p -> J/ψ cross-section



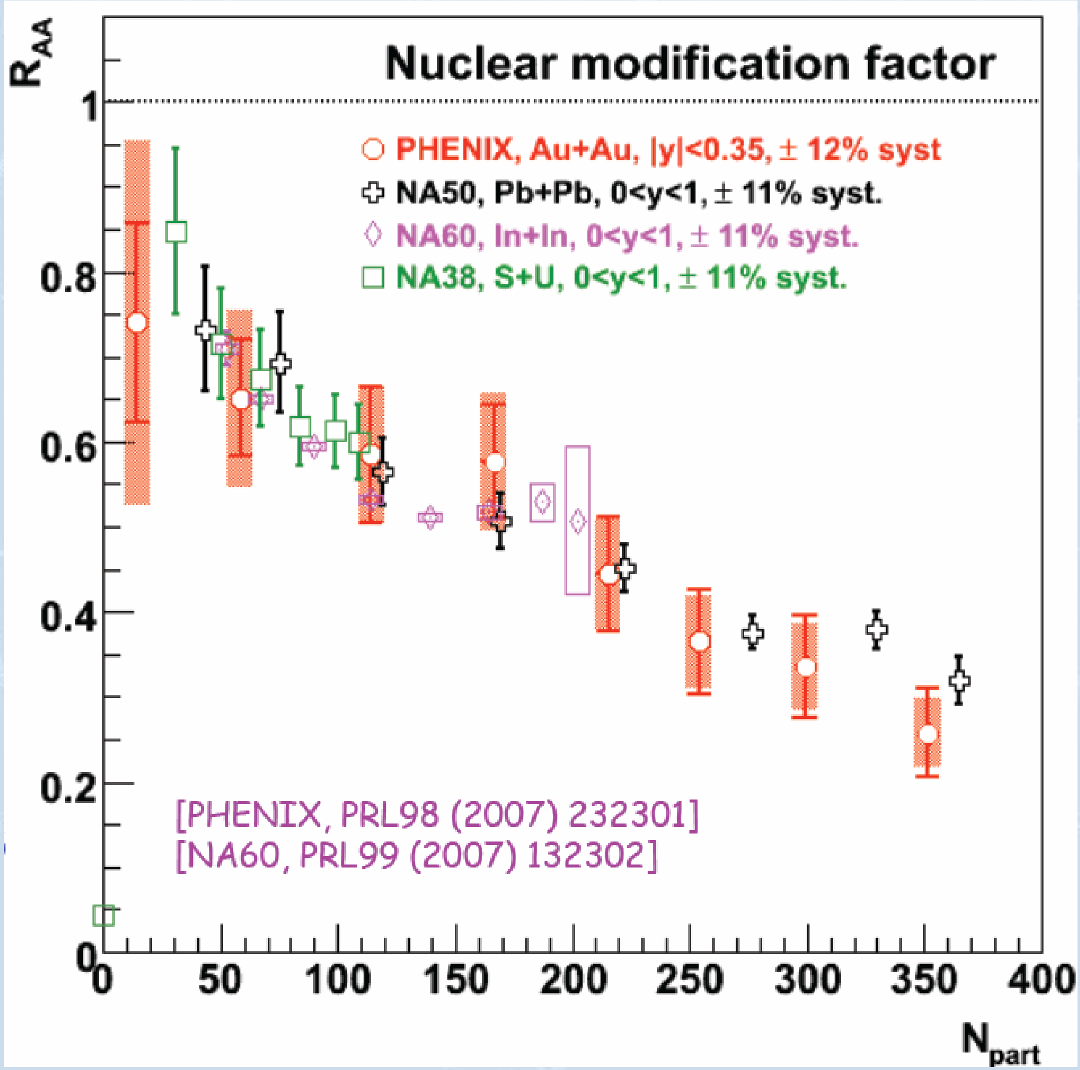
Consistent with trend of world's data and with the COM but unable to differentiate between PDF's

J/ψ suppression @ RHIC



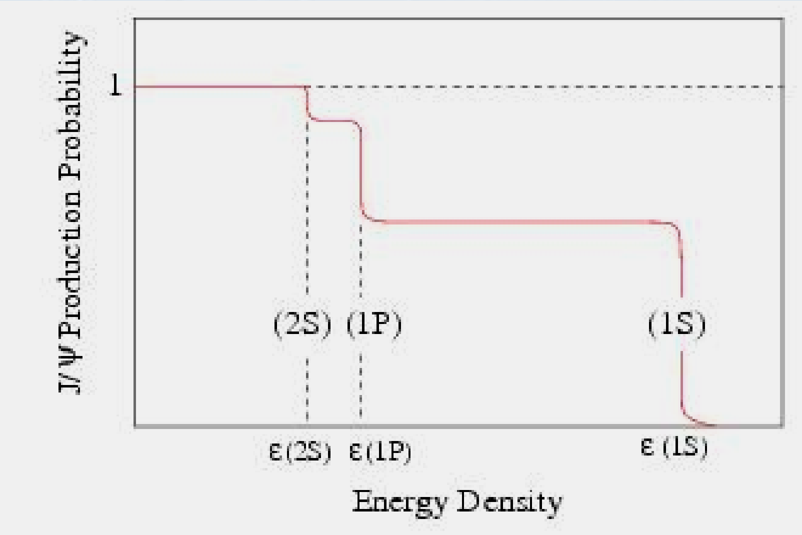
First surprise !

✓ PHENIX points lie almost exactly on top of SPS ones !!!



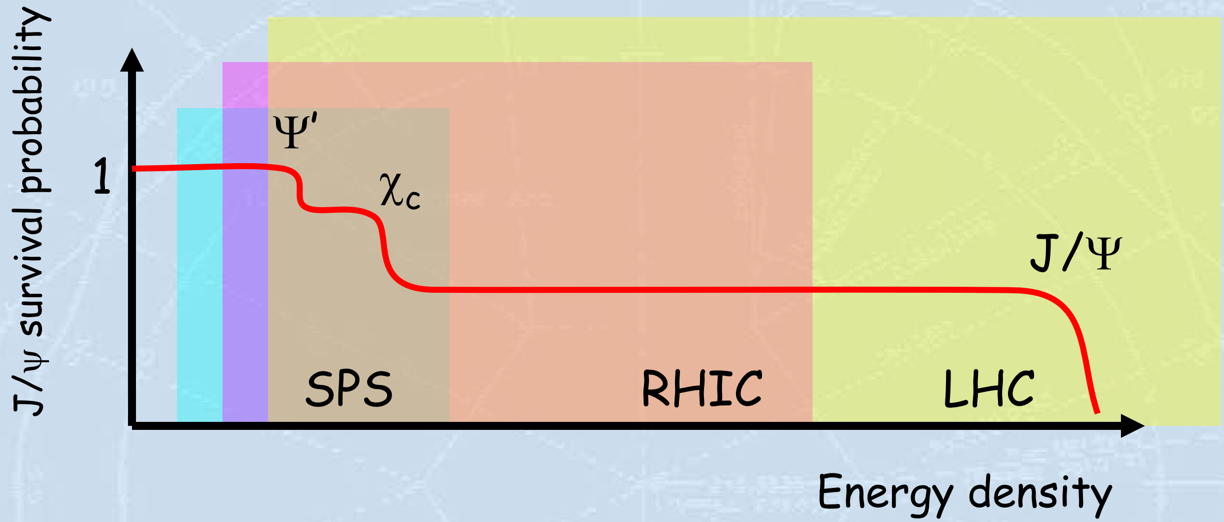
How comes ?

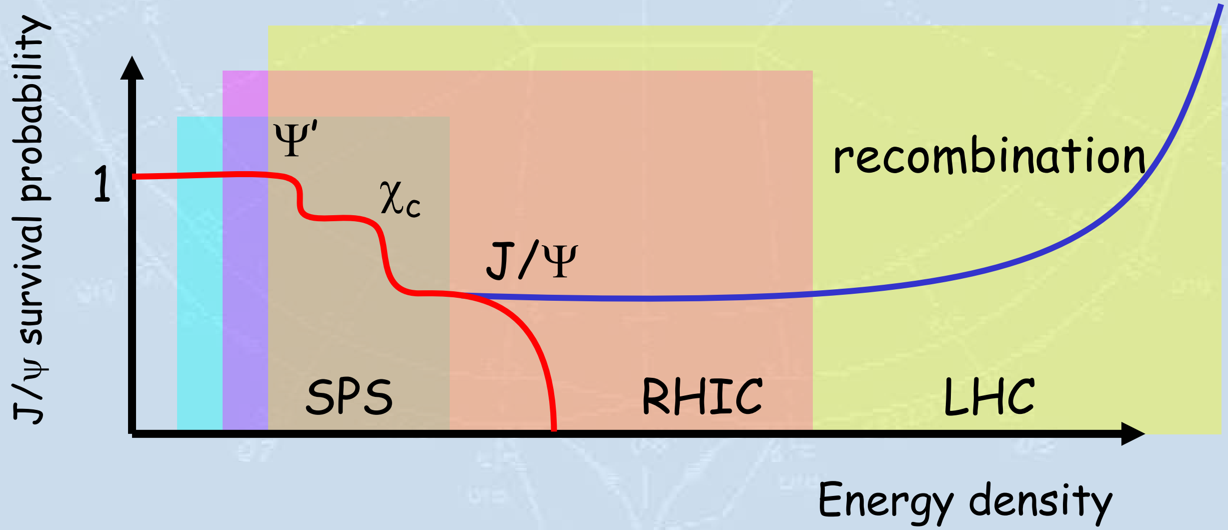
- Several models possible:
  - Sequential dissociation



  - Suppression compensated by charm quark recombination
  - I won't show you ANY ... For the moment ... Because ...

So, RHIC would lie in the desert ?





But ... Wait !

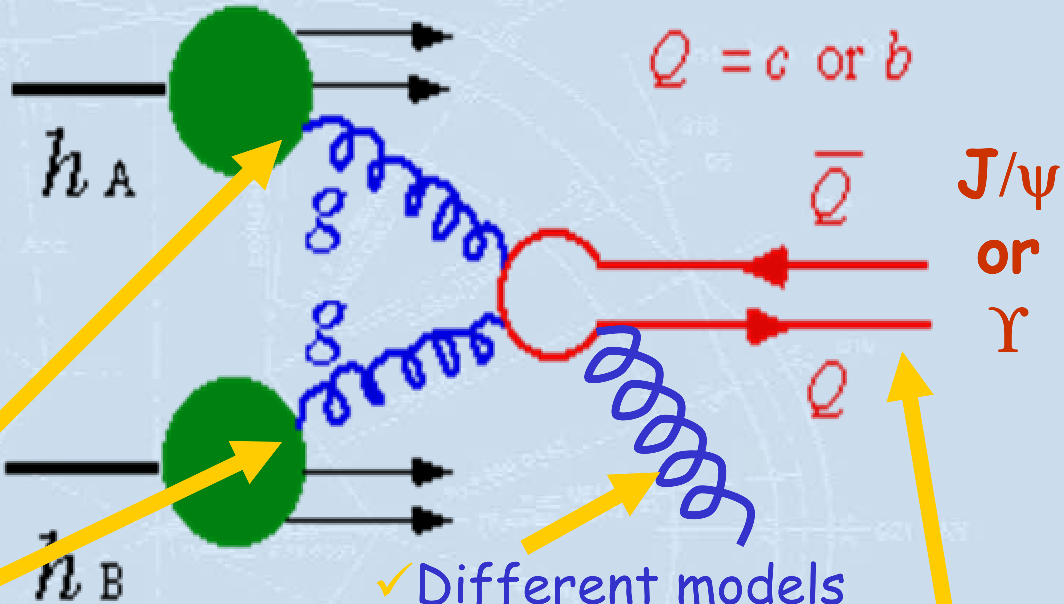
Nobody claimed that the EXPECTED (i.e. normal) suppression would be the same @ $\sqrt{s}$ = 17 GeV and 200 GeV !

What do we expect at RHIC

???

From protons to nuclei

- ✓ "Onia" production
  - ✓ Leading order at low x = "gluon fusion"

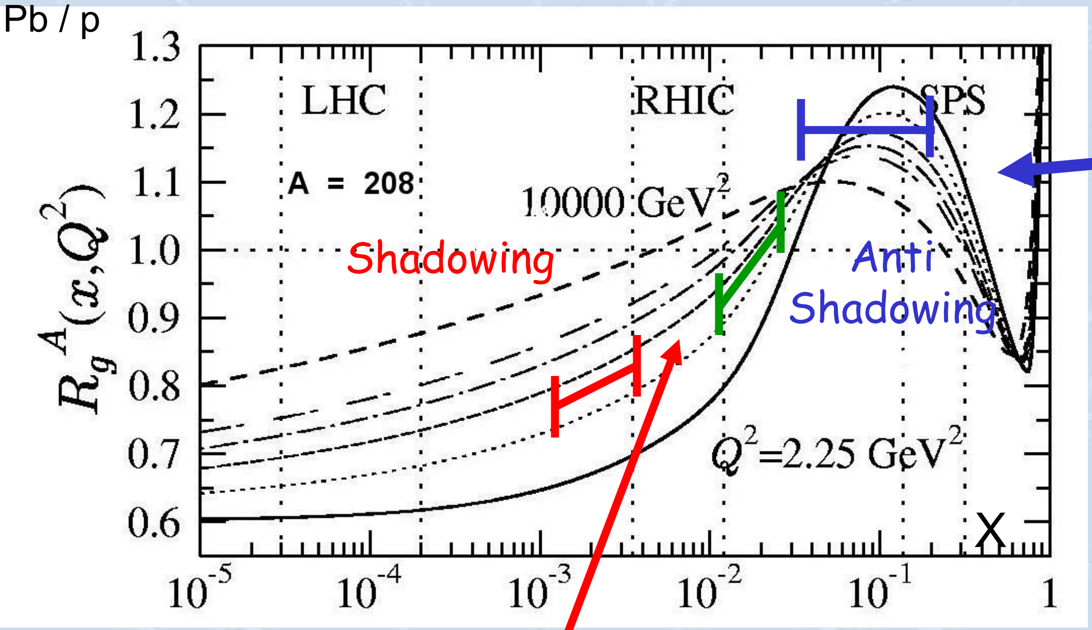


- ✓ Sensitive to:
  - ✓ Initial state
    - ✓ Parton distribution functions (PDF)
    - ✓ Parton energy loss in the initial state ?
    - ✓ p_T broadening
    - ✓ Polarization ?
  - ✓ Different models
    - ✓ CEM, CSM, COM
  - ✓ Final state
    - ✓ Nuclear absorption
    - ✓ In-medium dissociation
    - ✓ In-medium recombination
    - ✓ Thermal enhancement ?
    - ✓ Flow ?

+ feed-down (e.g. B or χ_c -> J/ψ)

@ SPS …

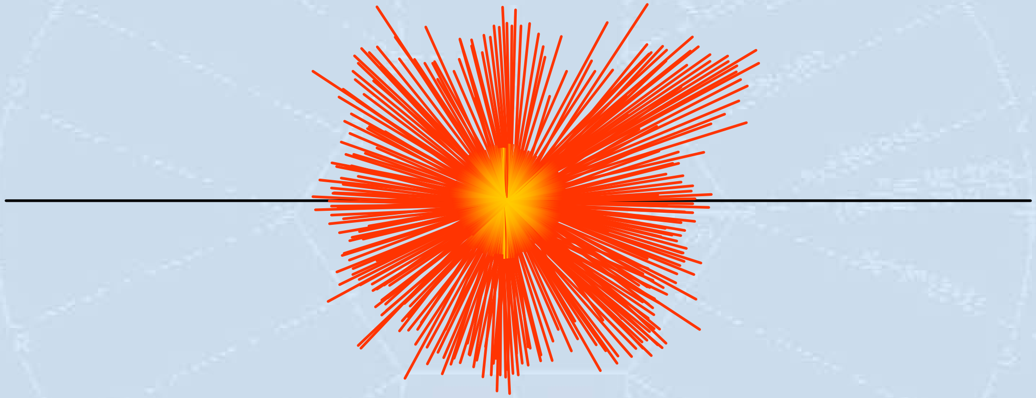
- The normal nuclear absorption has been extensively studied
  - We're left we a puzzle, though, remember ? … AND @ RHIC ???
- The pdf influence had been neglected, because it's supposed to be in the « antishadowing »



Q² ~ 9 could correspond to a ~10% effect @ SPS

- Possibly leading to a J/ψ enhancement, but by no means to a suppression … BUT @ RHIC … !

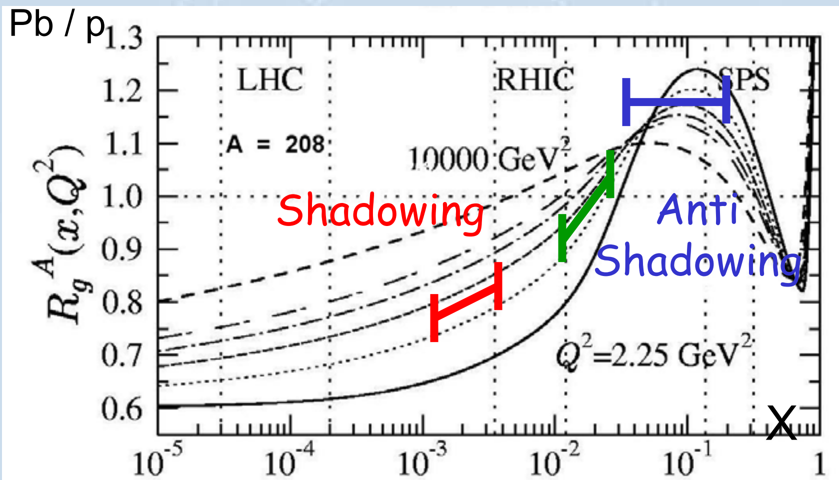
Heavy Quarks and Quarkonia: the experimental point of view



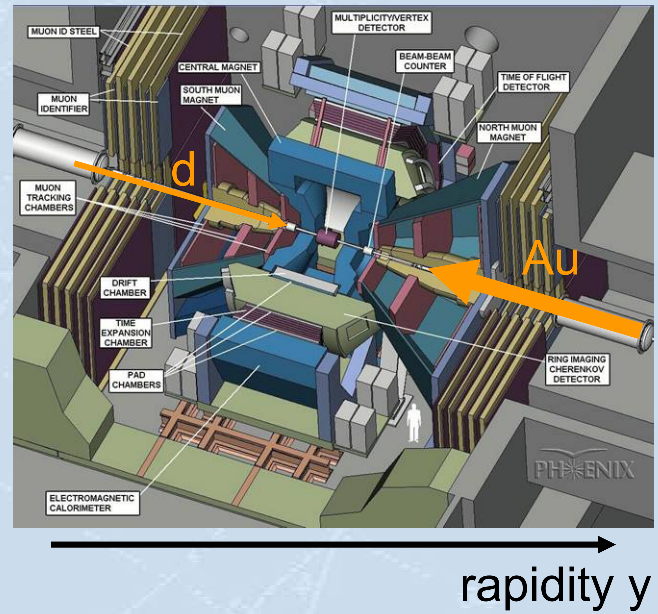
Lecture # 3

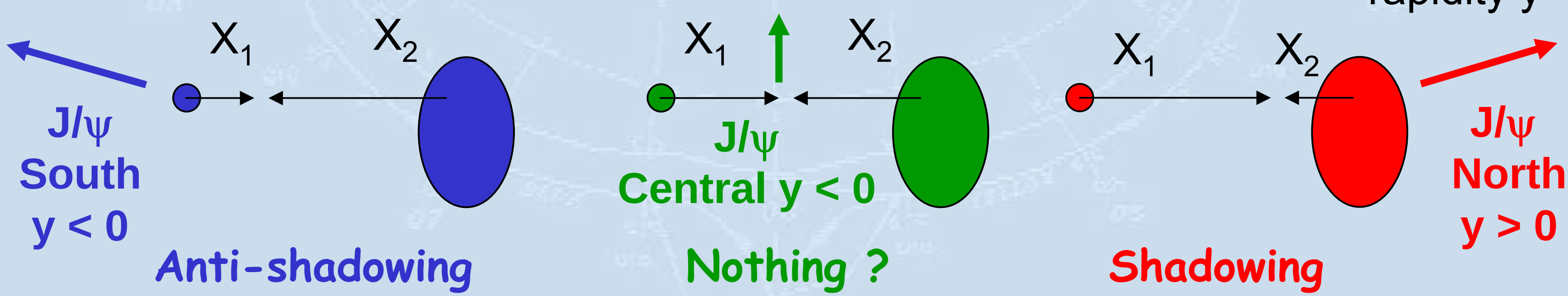
Shadowing: d+Au

- ✓ probe the « cold » nuclear effects
  - ✓ Parton distribution functions are modified in nuclei
  - ✓ e.g. in d+Au collisions :



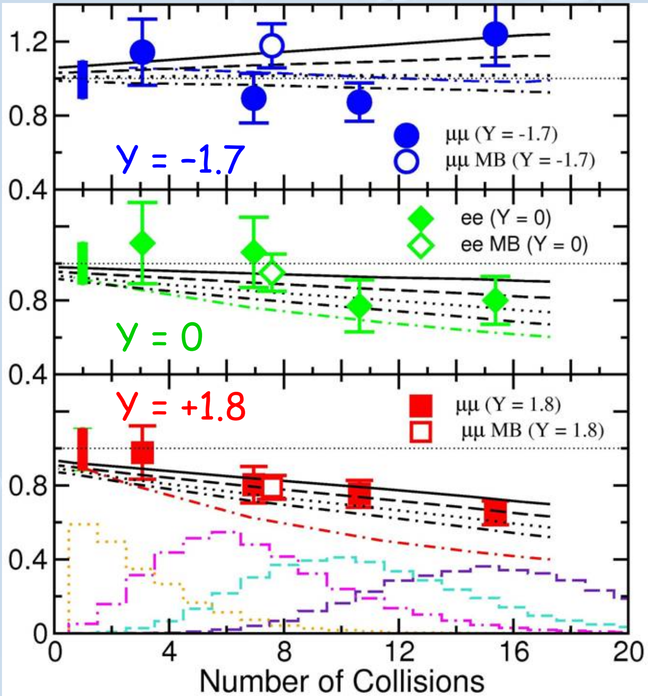
PHENIX

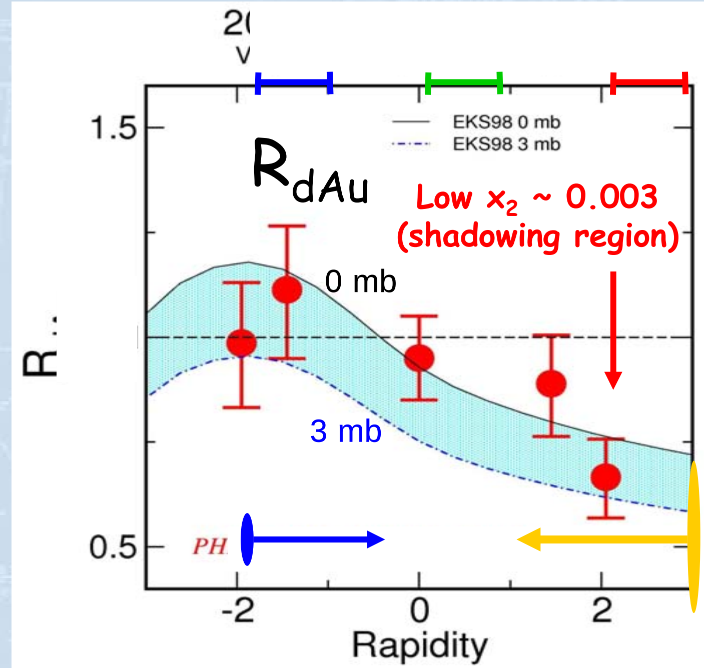


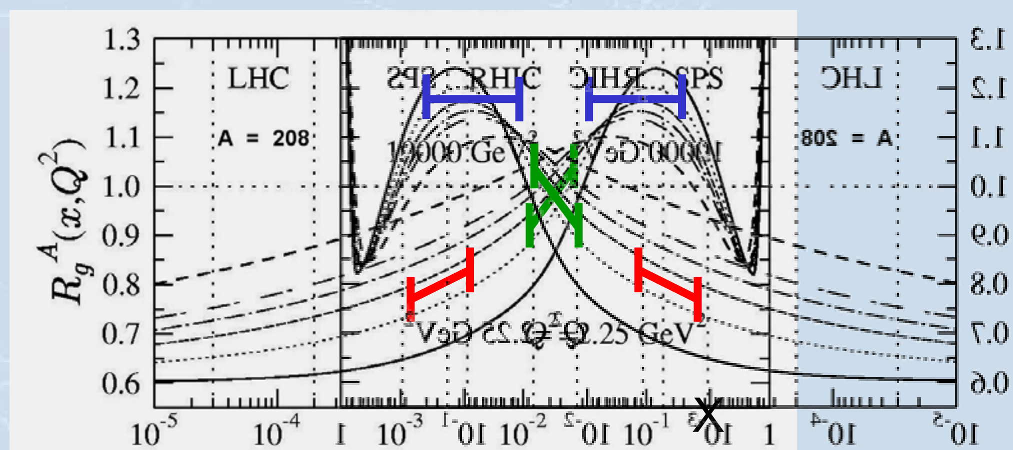


Cold nuclear matter (CNM) effects : d+Au

- ✓ PHENIX d+Au @ 200 GeV



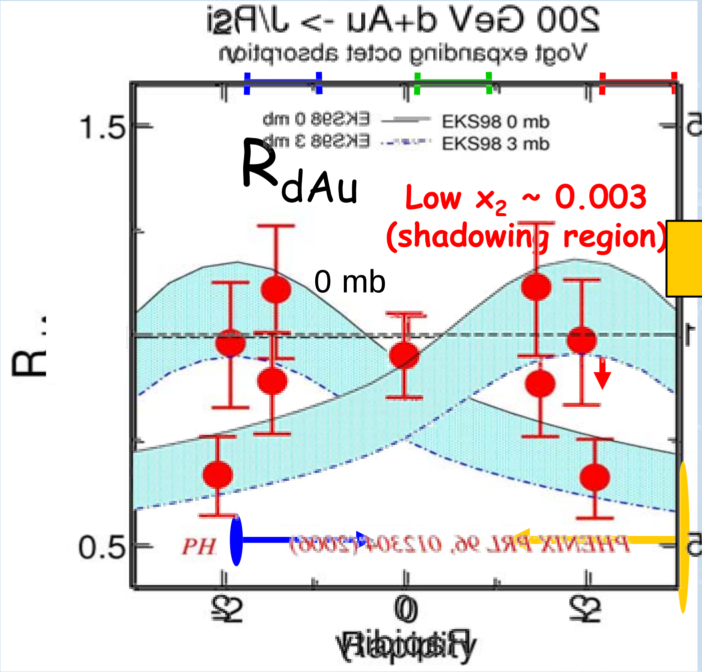


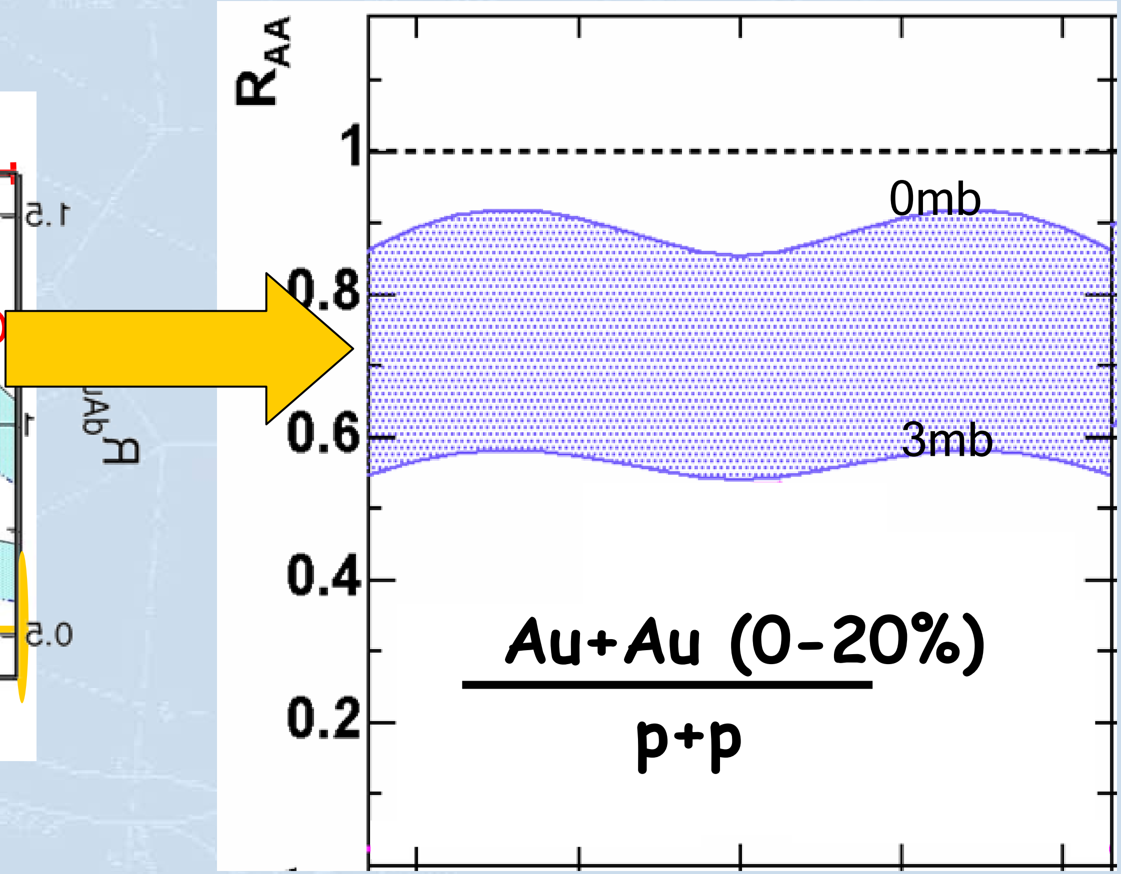


- ✓ (anti)shadowing visible
- ✓ σ_{abs} smaller than @ SPS ?
  - ✓ ~1-2 mb au lieu de 4.18 mb
- ✓ Cantrality dependent ?
- ✓ Au+Au = * mirror distribution

Shadowing in Au+Au :

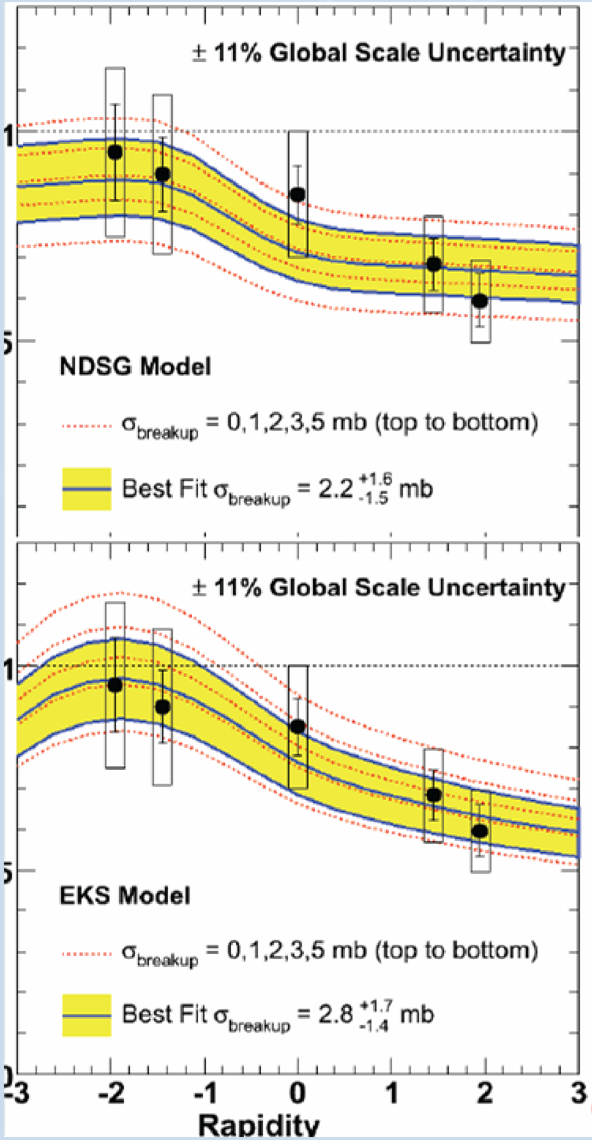
- ✓ It's then possible to deduce CNM in Au+Au from d+Au
  - ✓ Detailed model-dependant way = absorption + shadowing
  - ✓ Fully data-driven way

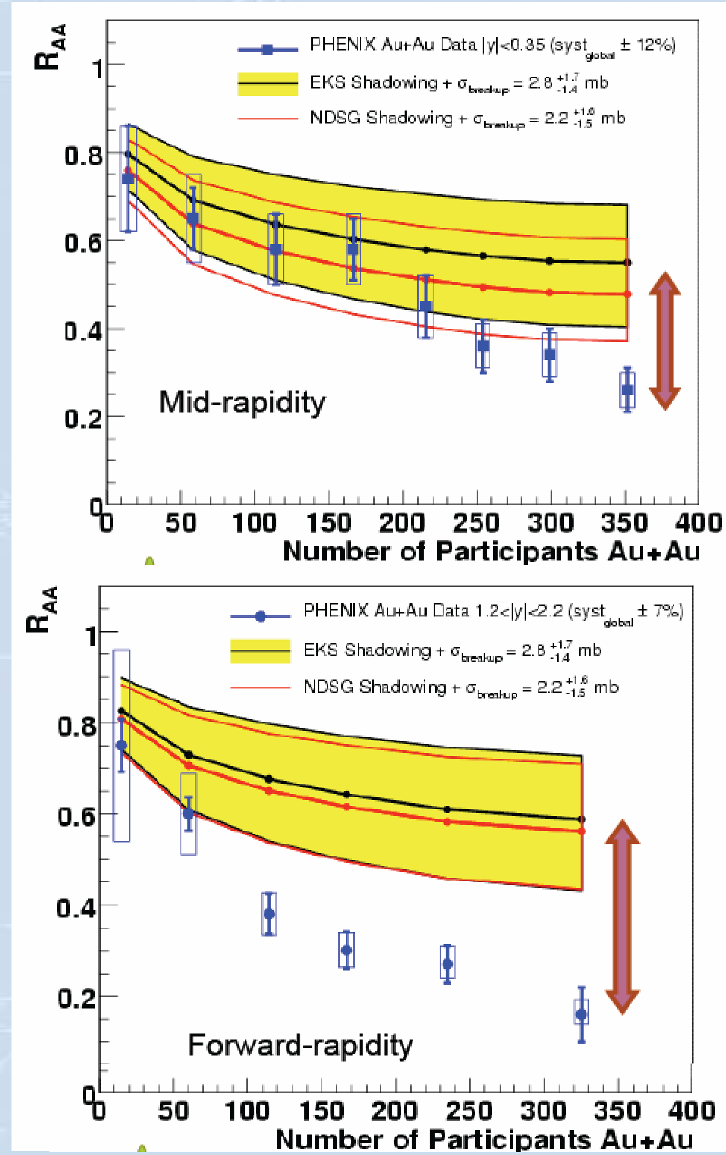




The model-dependant way

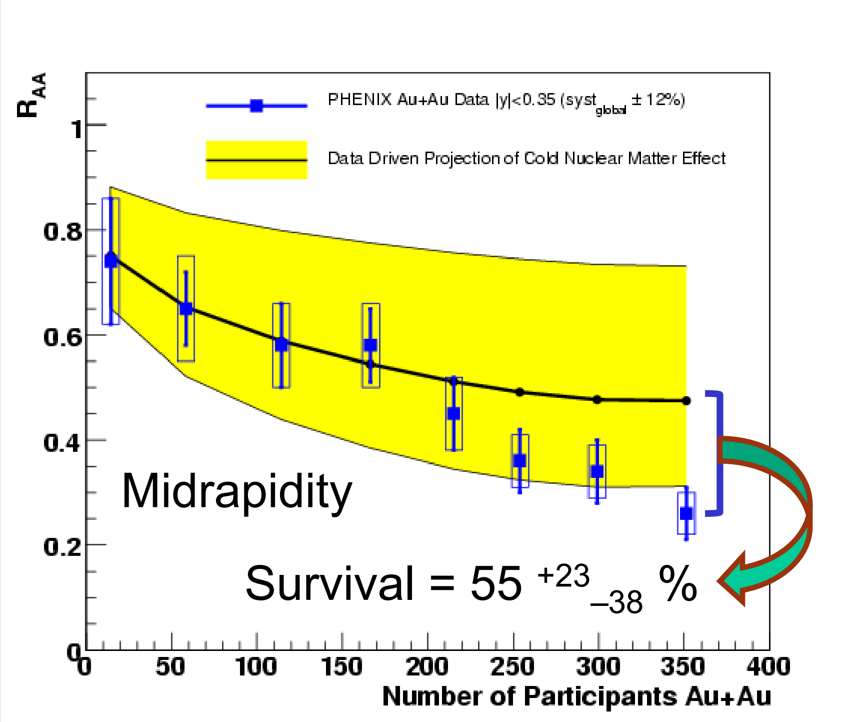
- ✓ Shadowing + nuclear absorption

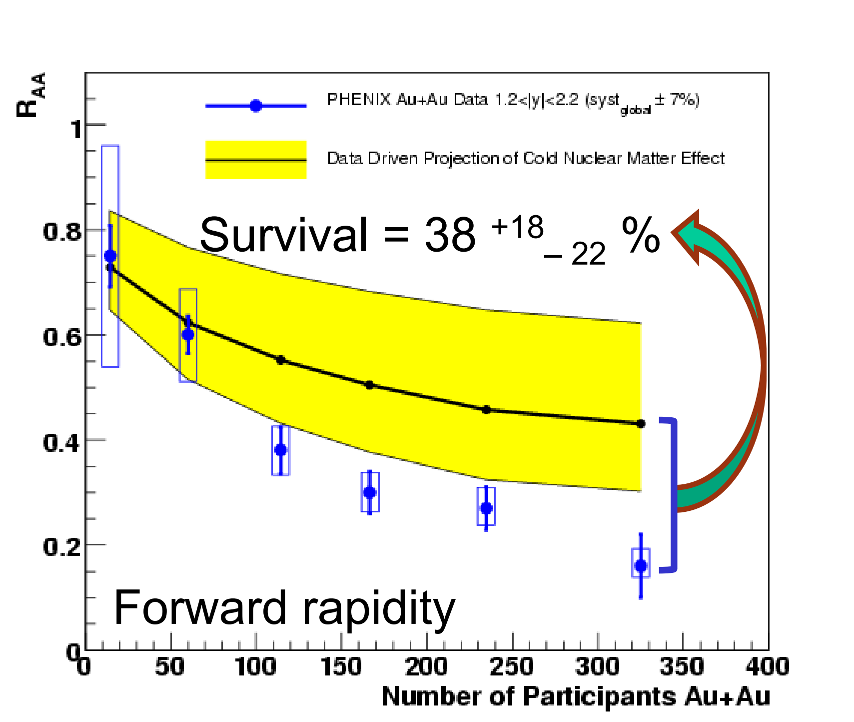




The data driven way …

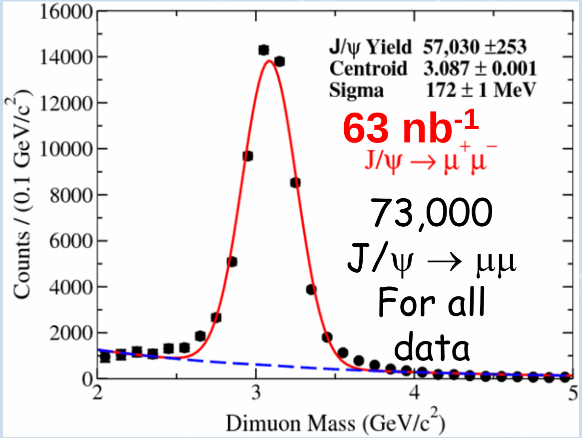
- More model independent…
- Glauber data-driven calculation using R_{dA}(y,centrality)
  - $R_{AA}(y,b) = \Sigma_i R_{dA}(-y,b^i_1) \times R_{dA}(+y,b^i_2)$
  - No shadowing scheme nor absorption scheme
  - Mid and forward rapidities not correlated
  - Less model dependent but larger uncertainties
- No d+Cu, so no Cu+Cu
- Some anomalous suppression left ! (at least for 1.2<|y|<2.2)



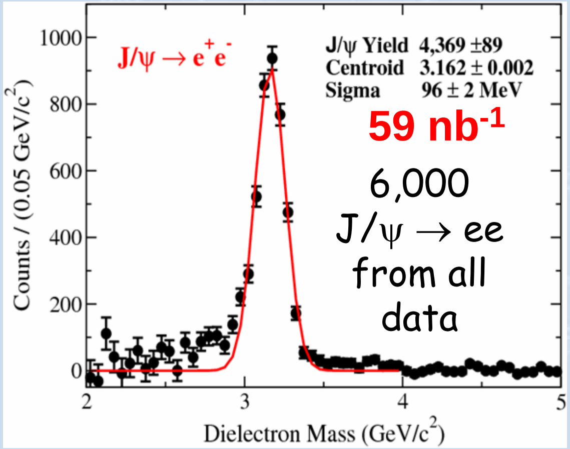


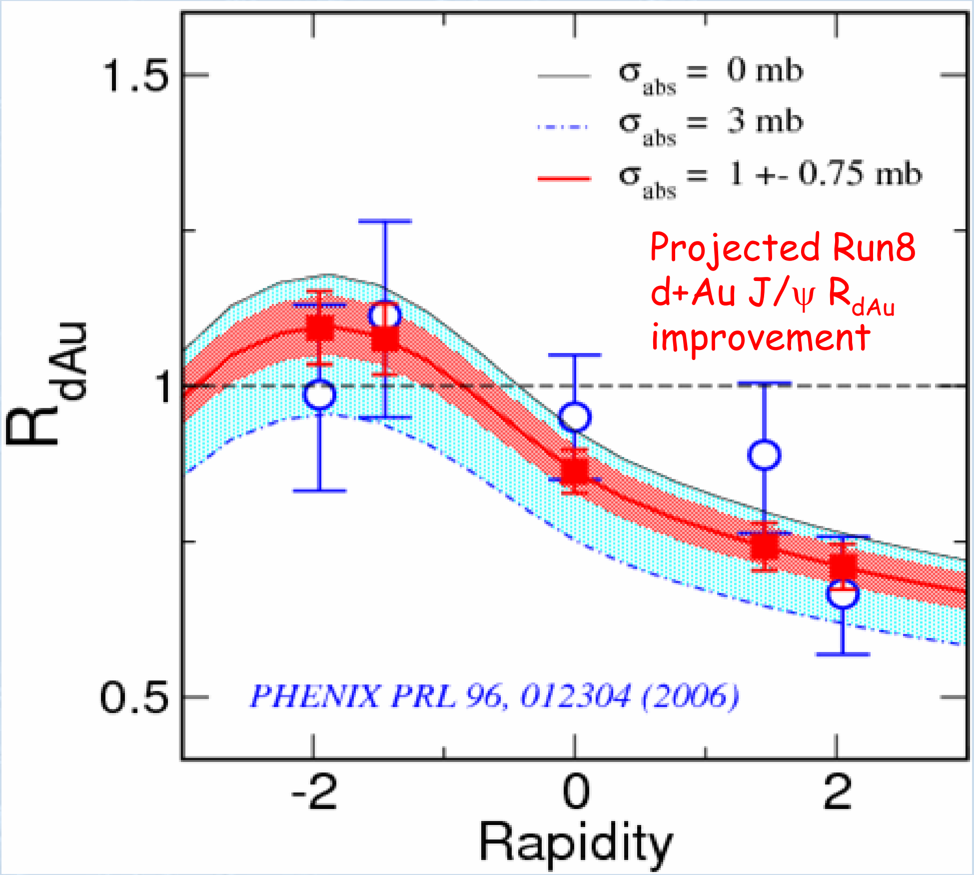
More d+Au statistics to come !!

- ✓ New PHENIX d+Au from very high luminosity run
  - ✓ 30x the previously available statistics ($80nb^{-1}$)
  - ✓ Will bring a much stronger constraint on CNM



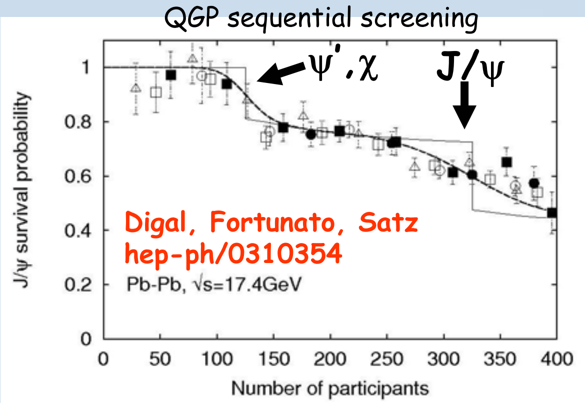
200 GeV d+Au

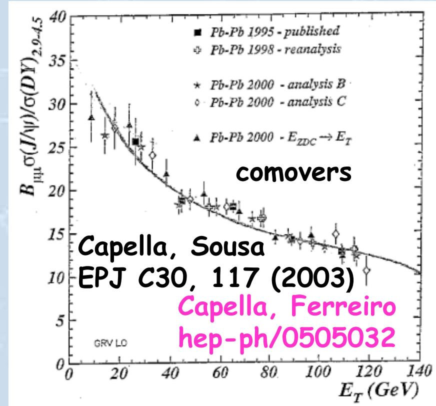


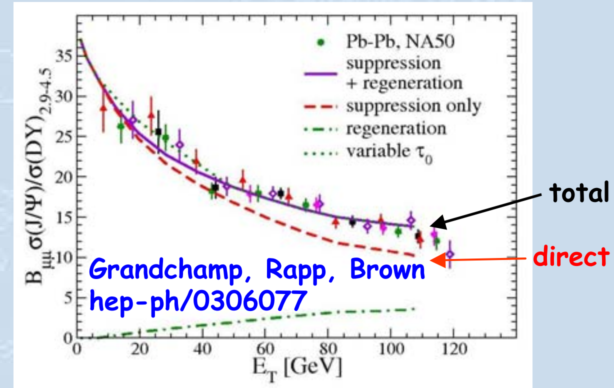


NOW, I can show you some models

Models without recombination



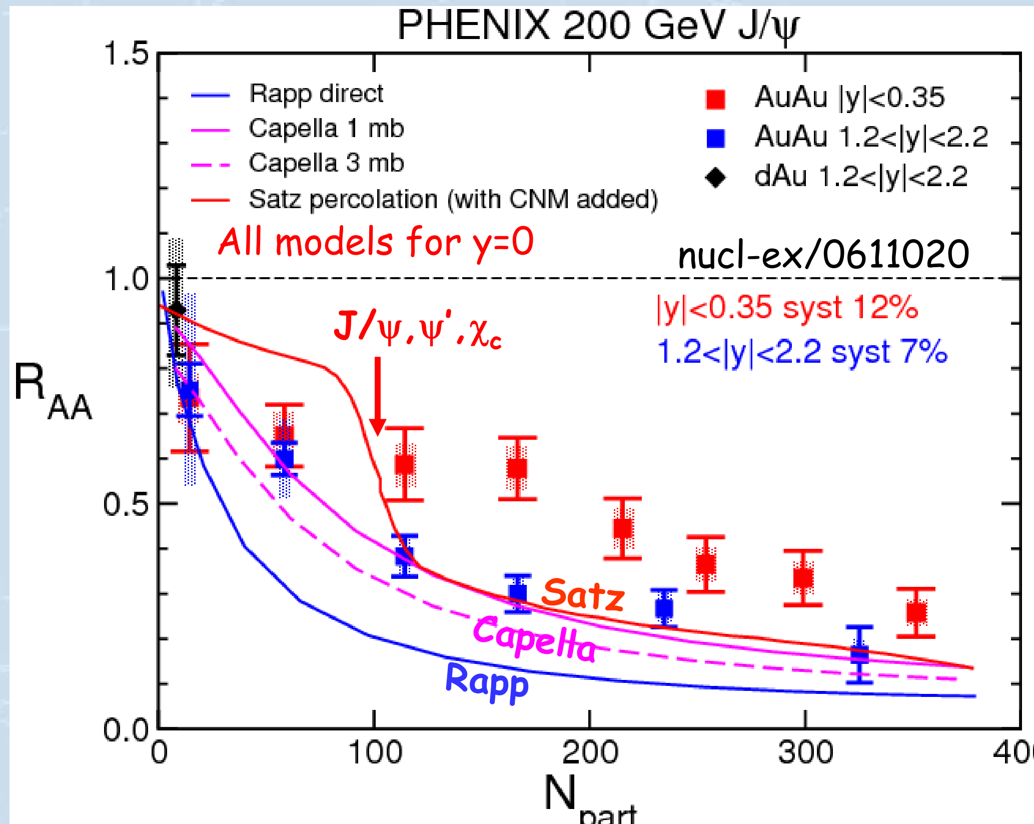




That ~ reproduce NA50 data ($\sqrt{s} \approx$ 17-19 GeV)

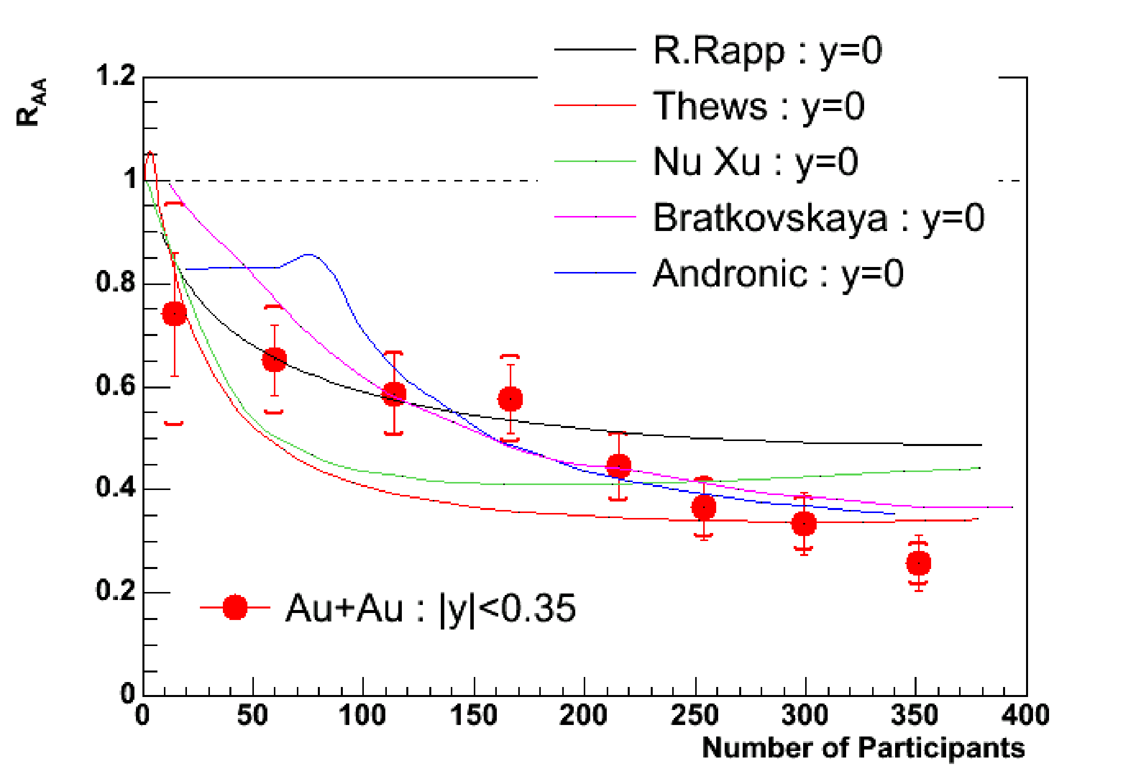
- Satz – screening in QGP (percolation) with CNM (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption + shadowing
- Rapp – direct suppression in QGP with CNM

ALL UNDERESTIMATE the suppression at mid-rapidity !



Models with recombination

- ✓ Many (even more) models with suppression + recombination



ALL MODELS
@ MID-RAPIDITY

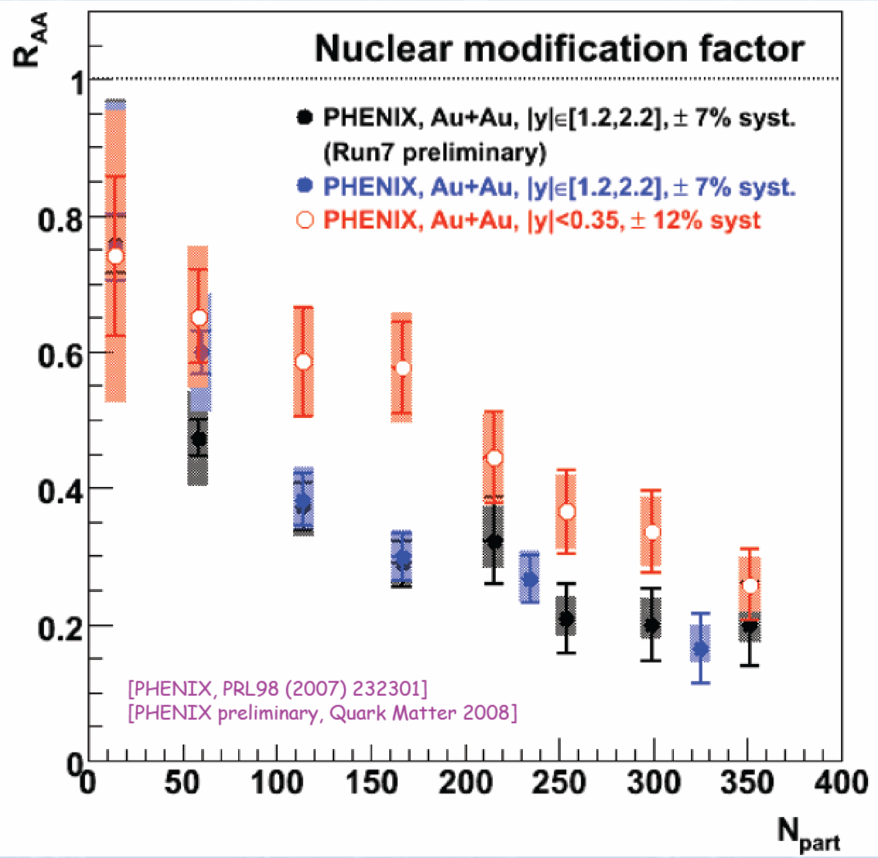
- R. Rapp *et al.* (for y=0)
  - PRL 92, 212301 (2004)
- Thews (for y=0)
  - Eur. Phys. J C43, 97 (2005)
- Nu Xu *et al.* (for y=0)
  - nucl-th/0608010
- Bratkovskaya *et al.* (for y=0)
  - PRC 69, 054903 (2004)
- A. Andronic *et al.* (for y=0)
  - nucl-th/0611023

- Better agreement BUT :
- Very dependent on the (poorly known) charm distribution !

The only way (?) to explain the ...

Second surprise !

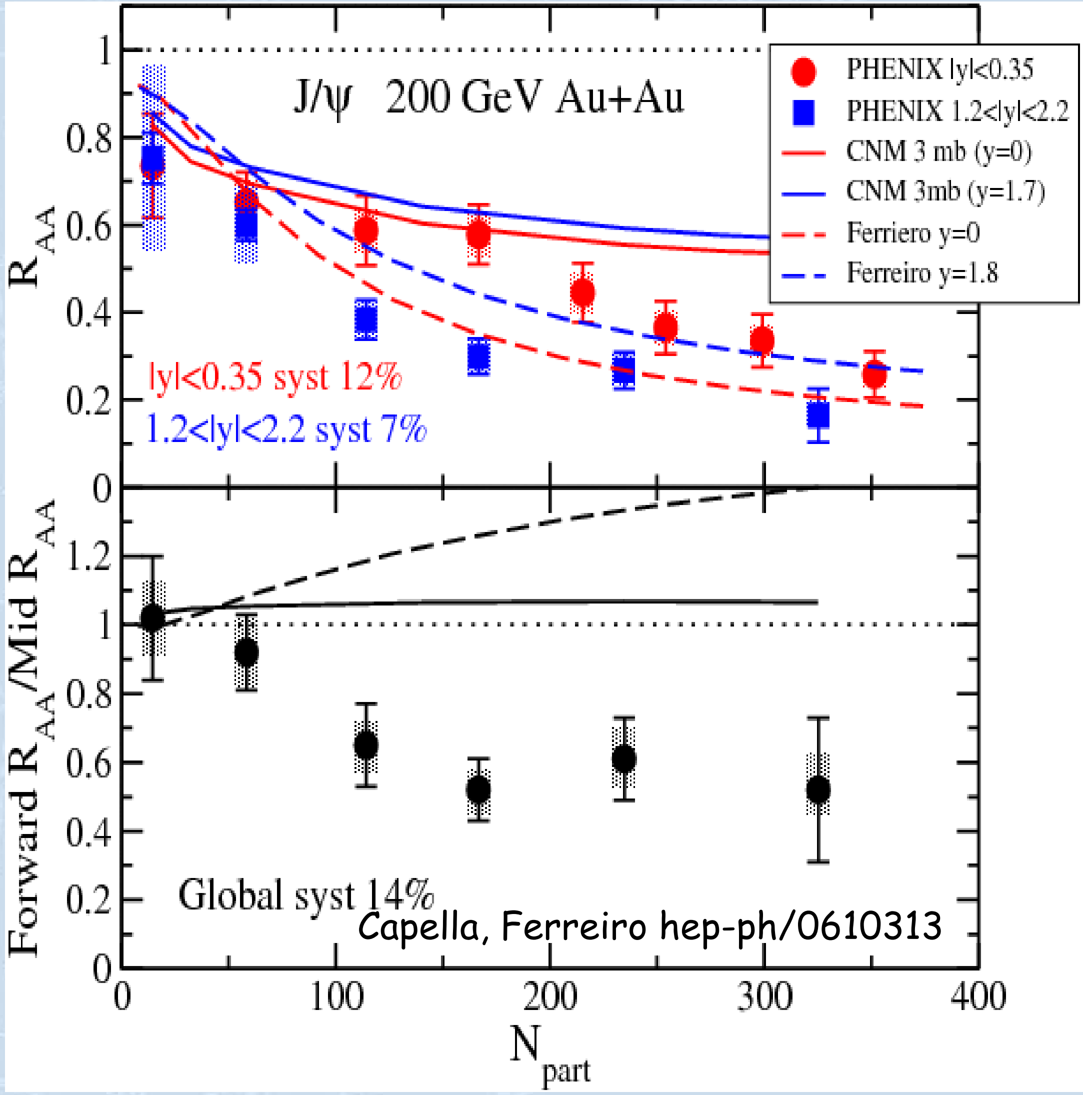
✓ The suppression is larger at forward rapidities !



✓ ... Unlike ANY deconfinement-based or density-based suppression alone would predict !

“Density-based” models

- ✓ all predict more suppression for central rapidity
  - ✓ E.g. because the comover density is higher in the central region
- ✓ Doesn’t seem to be observed that way ...



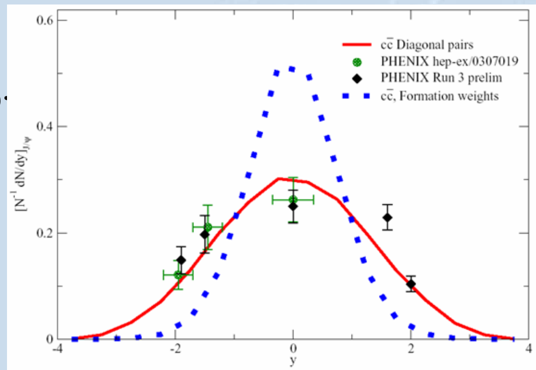
Capella, Ferreiro hep-ph/0610313

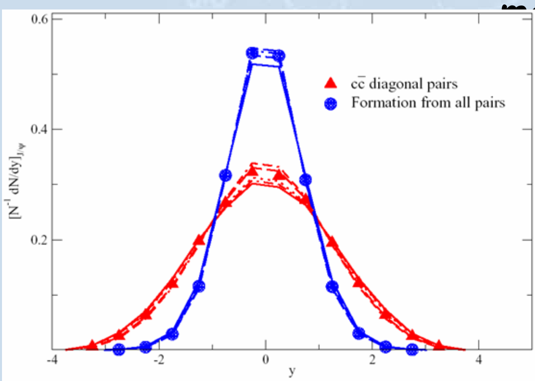
Recombination & rapidity distributions

- ✓ Rapidity distribution of recombined J/ψ is supposed to be peaked at y=0 (e.g. R.L. Thews & al., nucl-th/0505055)
  - ✓ True IF charm distribution ~ J/ψ in p+p !

p

), adjust $\langle k_T^2 \rangle$

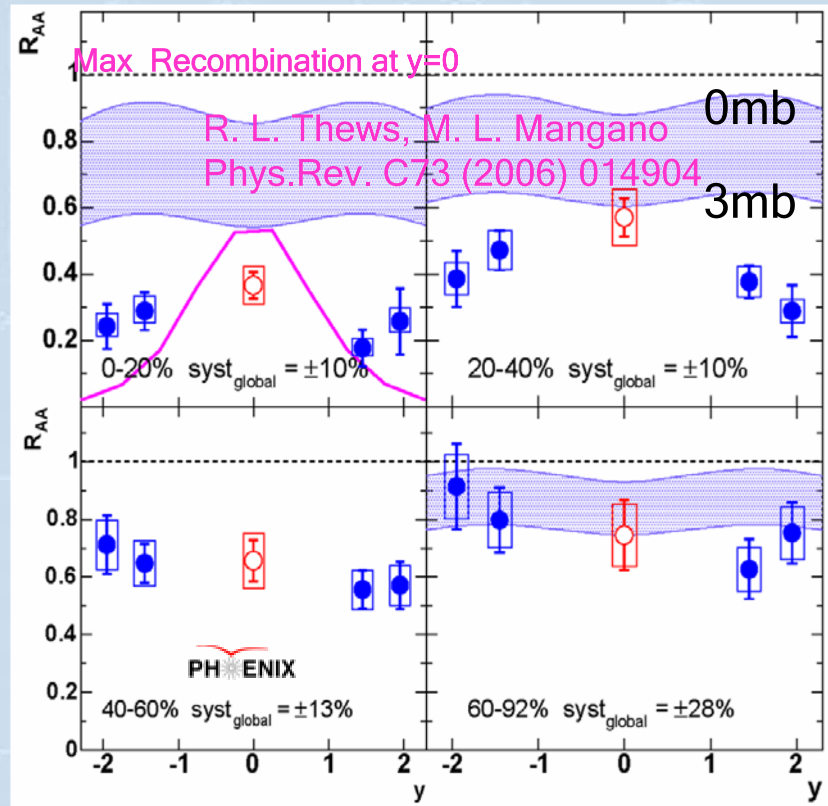




mainly

diagonal »

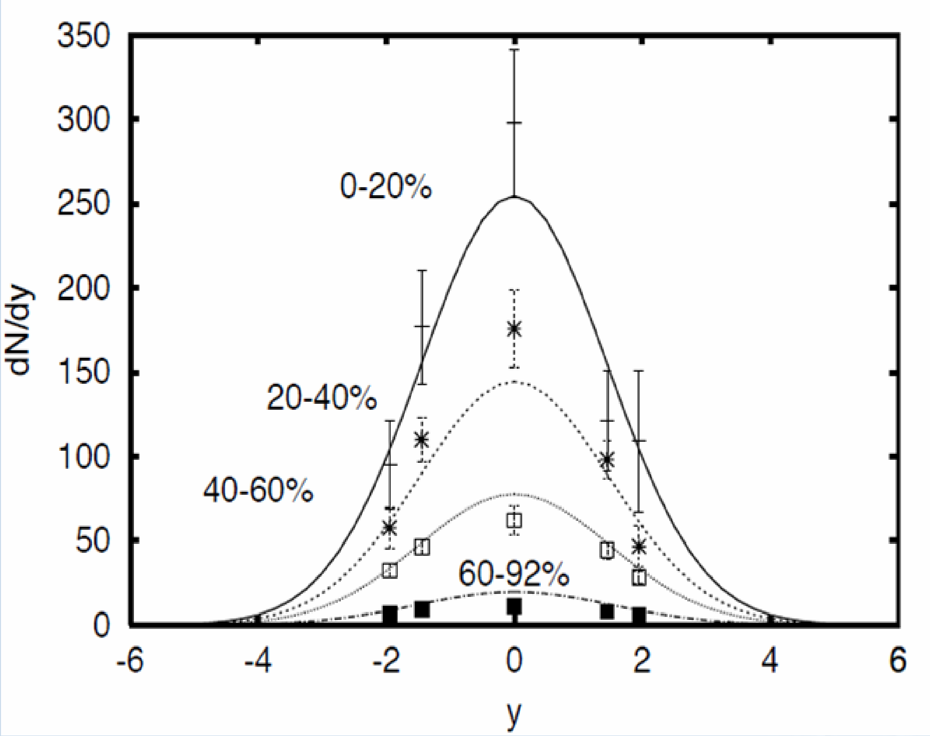
al »

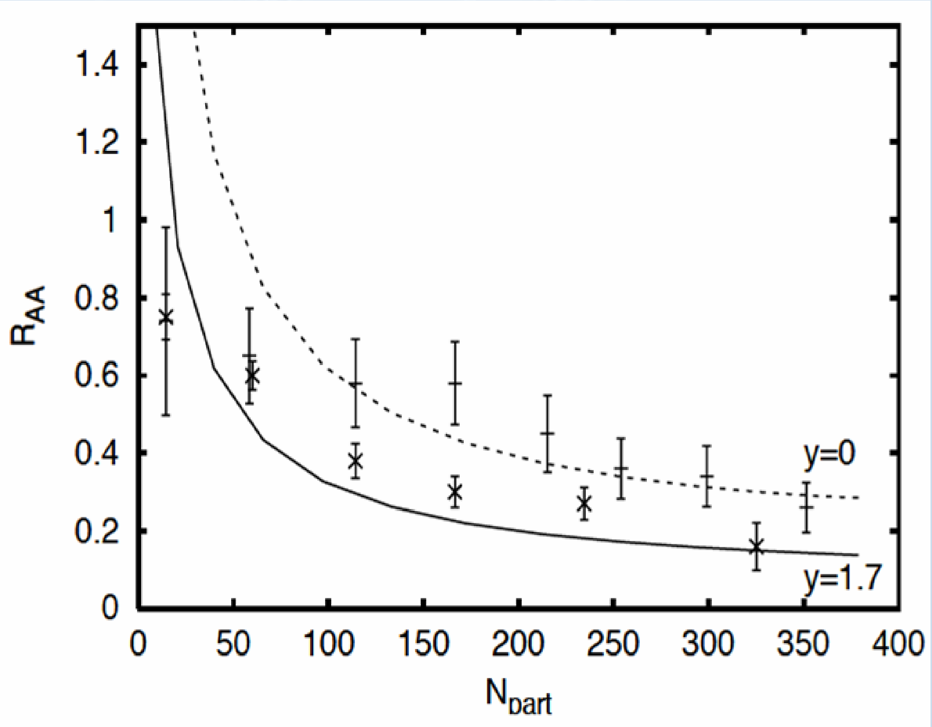


More recombination at y=0 -> OK
BUT shape not well reproduced

Gluon saturation ?

- ✓ D.Kharzeev, E. Levin, M. Nardi & K. Tuchin
  - ✓ Gluon saturation
  - ✓ Narrowing of y distributions correctly reproduced
  - ✓ Y=0 wrt forward trend OK





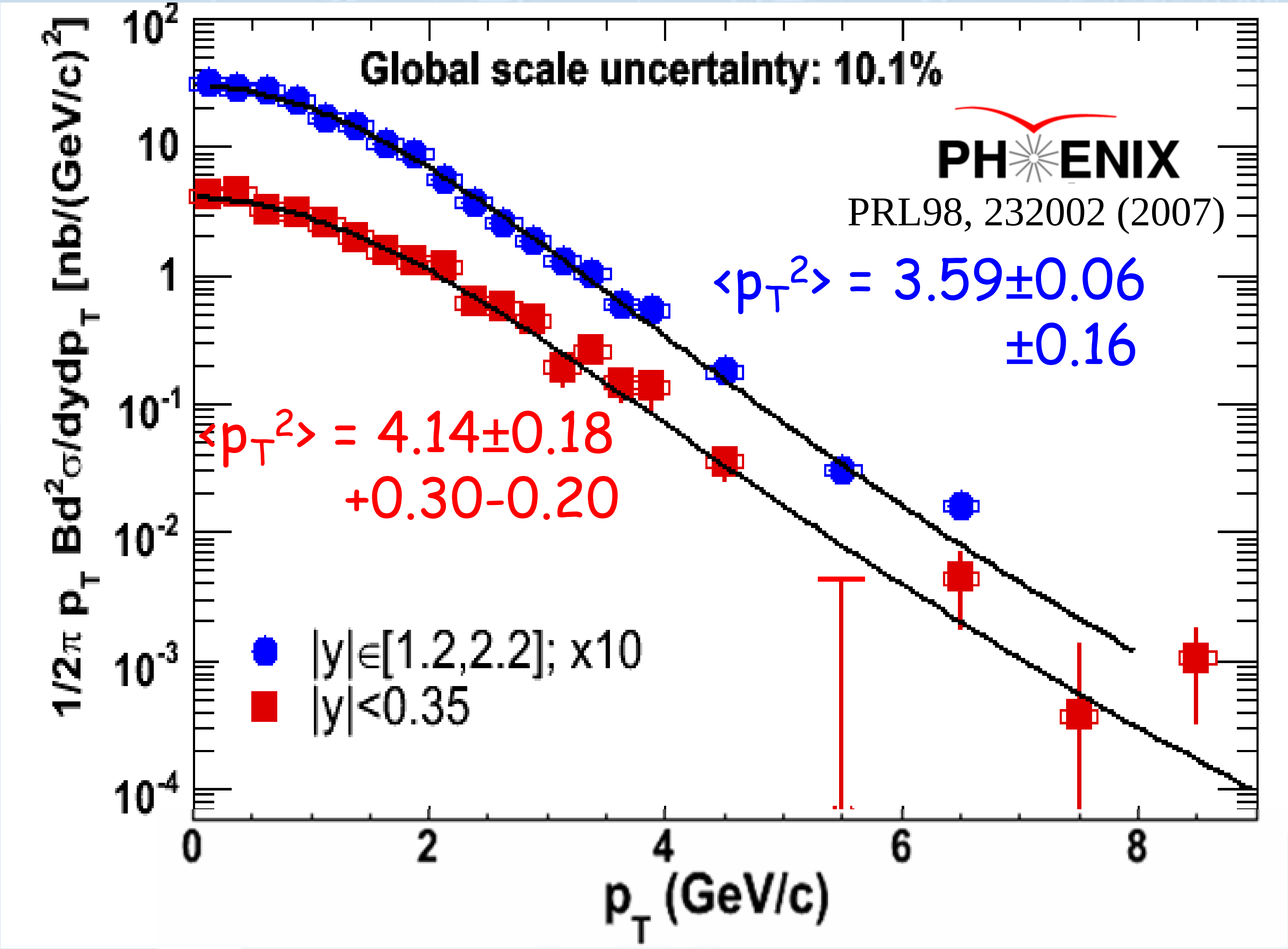
The moral on rapidity ...

Keep in mind that models should reproduce ALL the available data (at once) ...

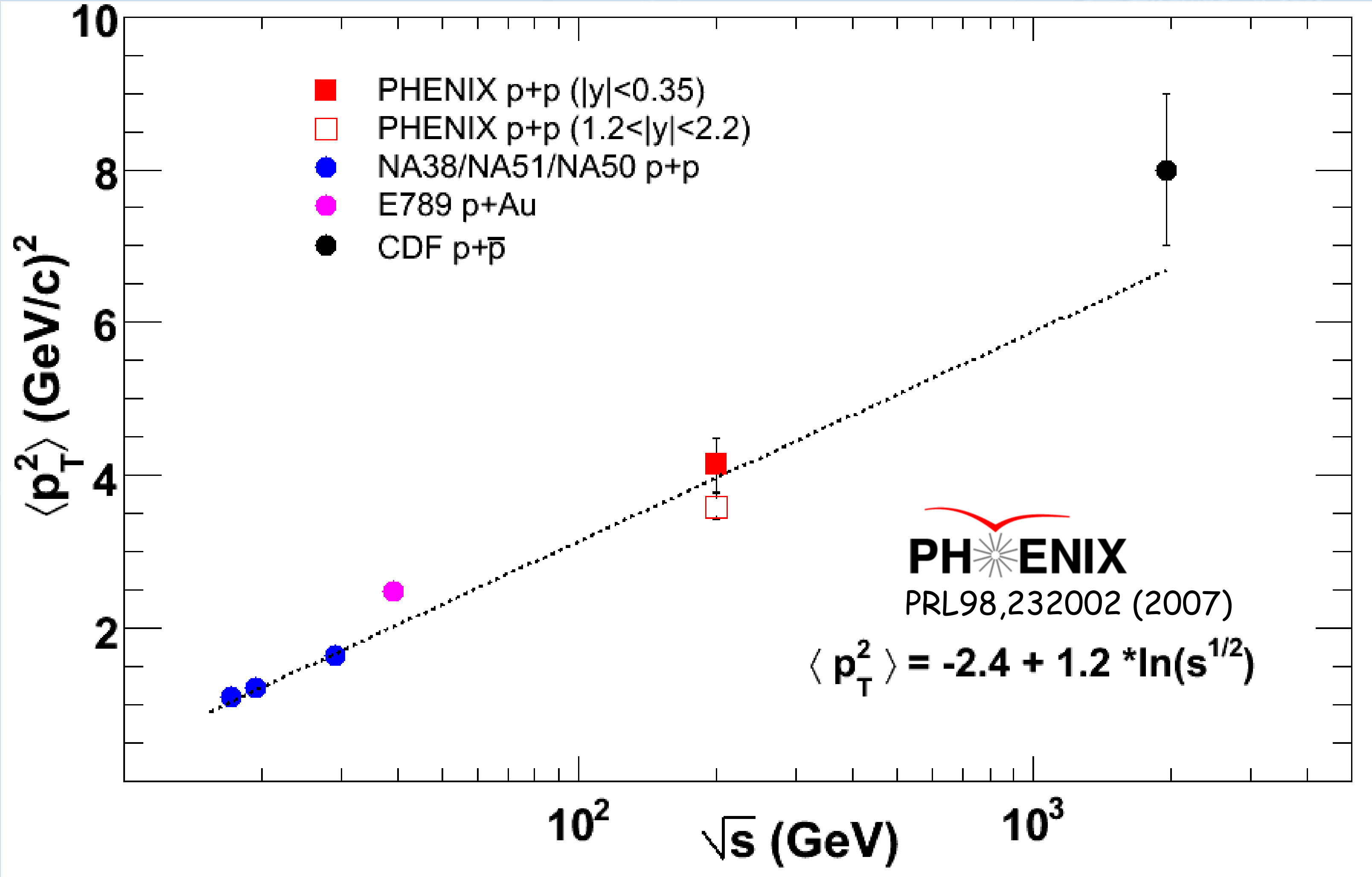
Do not neglect one particular aspect of the data, we need all the pieces of the puzzle

Transverse momentum distributions

p+p @ RHIC, √s = 200 GeV



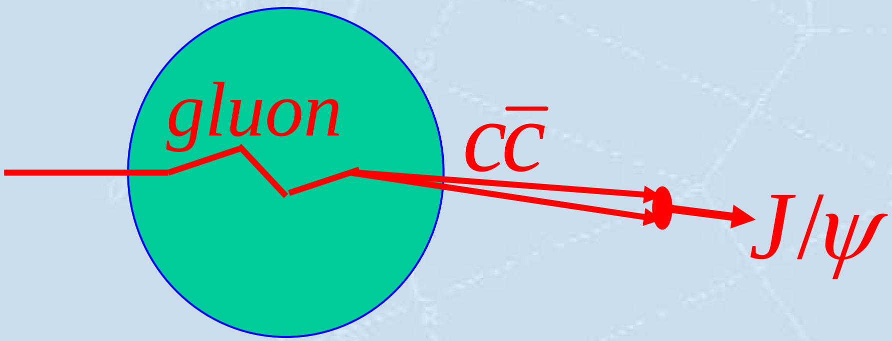
$\langle p_T^2 \rangle$ vs collision energy

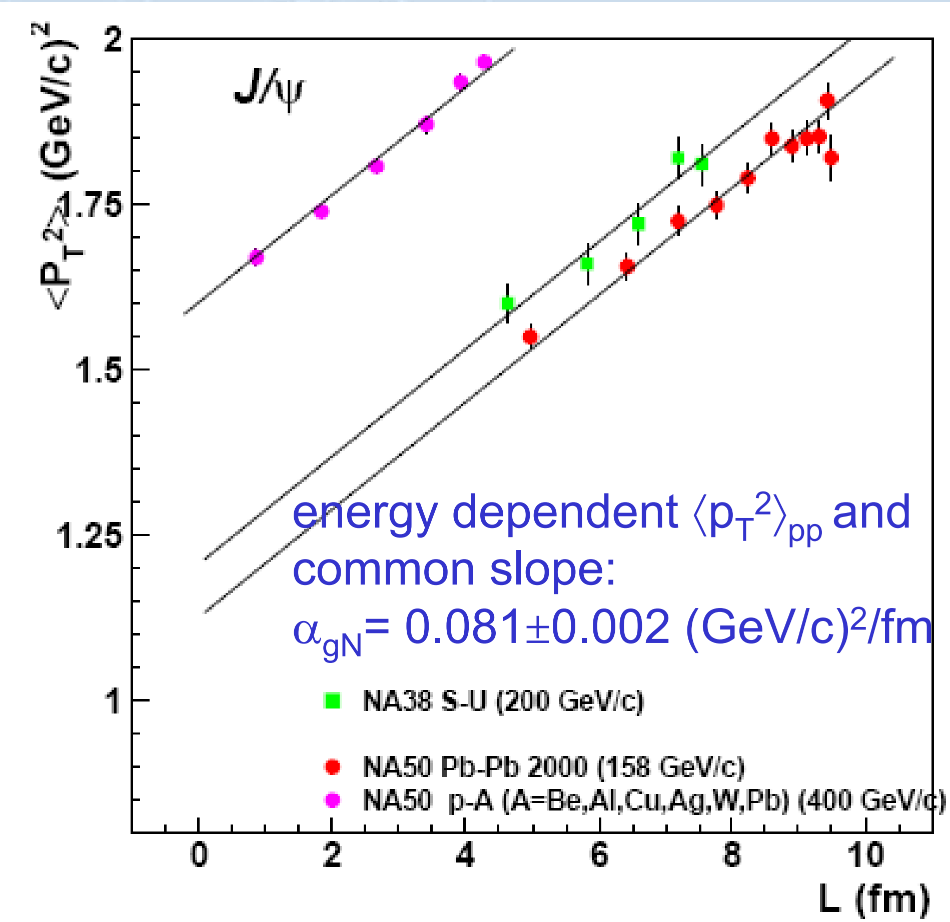


PHENIX $\langle p_T^2 \rangle$ measurements compared to measurements at other collision energies show a ~ linear dependence on $\ln(\sqrt{s})$

$\langle p_T^2 \rangle$ vs centrality

- pT broadening due to multiple diffusion on nucleons ("Cronin effect")





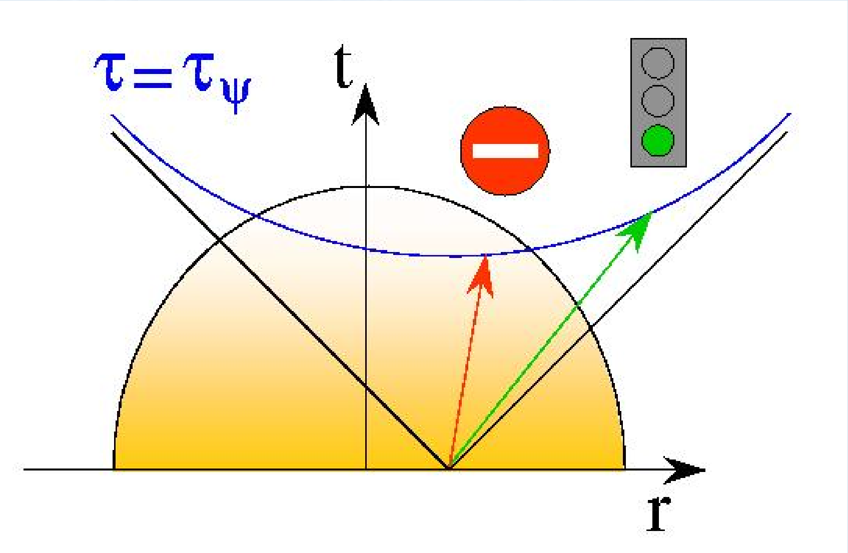
- In this case, $\langle pT^2 \rangle$ proportional to L
  - SPS data compatible with this scenario ...
  - ... with one unique slope

$$\langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \alpha_{gN} \cdot L$$

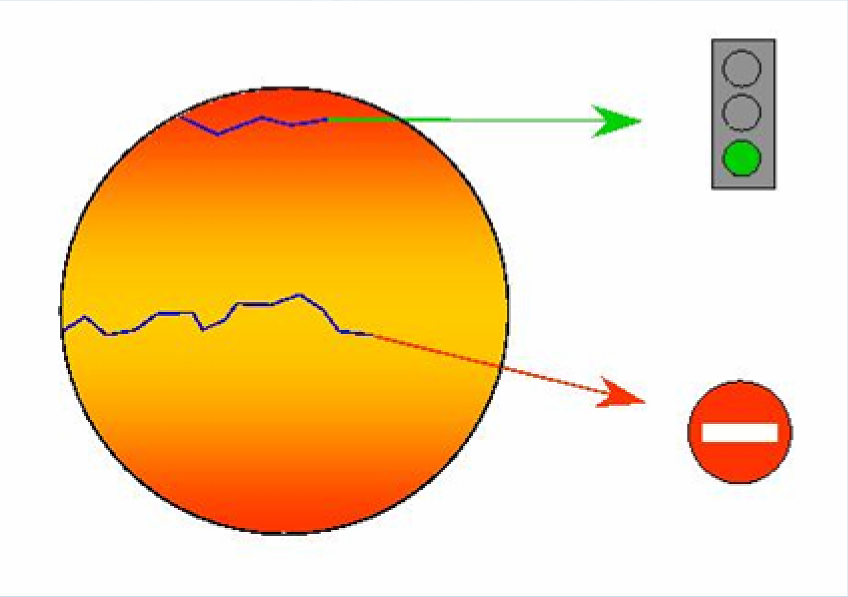
What about $\langle p_T^2 \rangle$ in QGP ?

- Two different effects ... going in opposite directions !

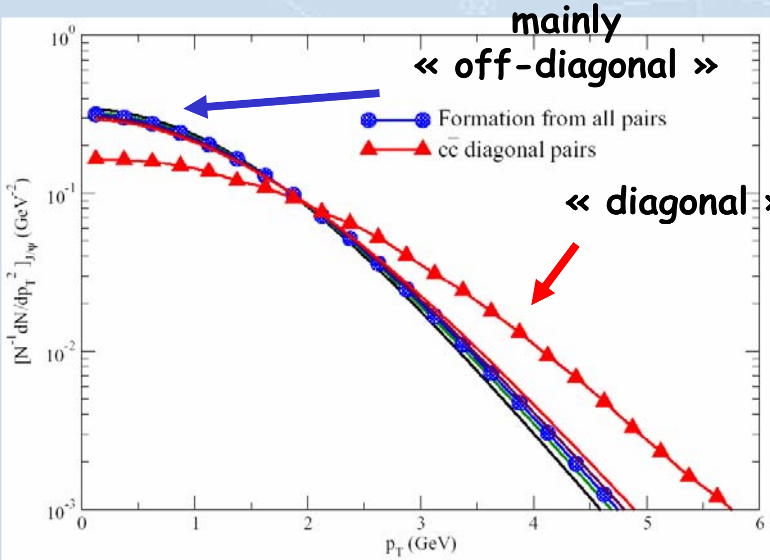
  - High p_T J/ψ escape the plasma, thus being formed outside
  - -> suppression by QGP mainly at low p_T

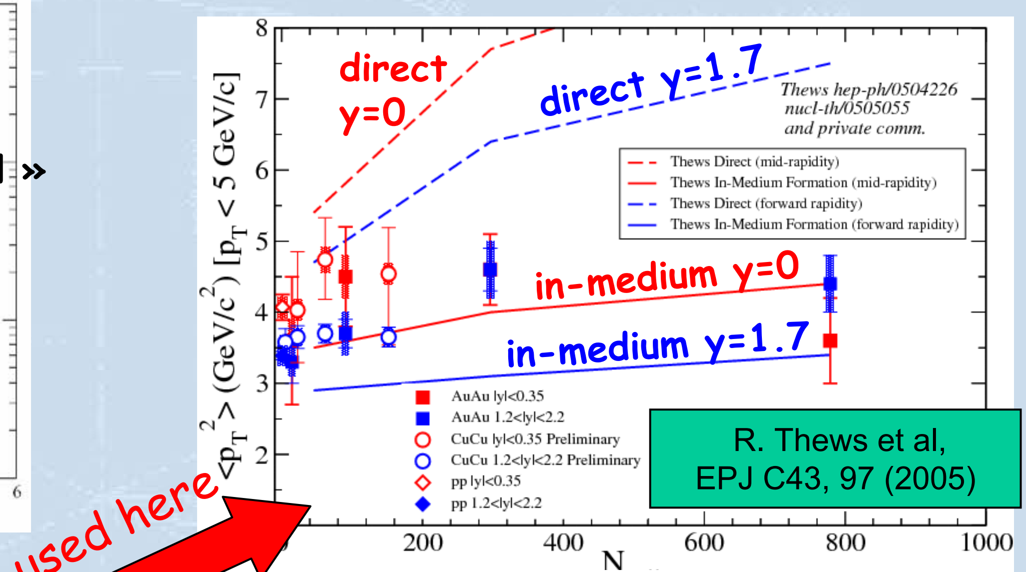


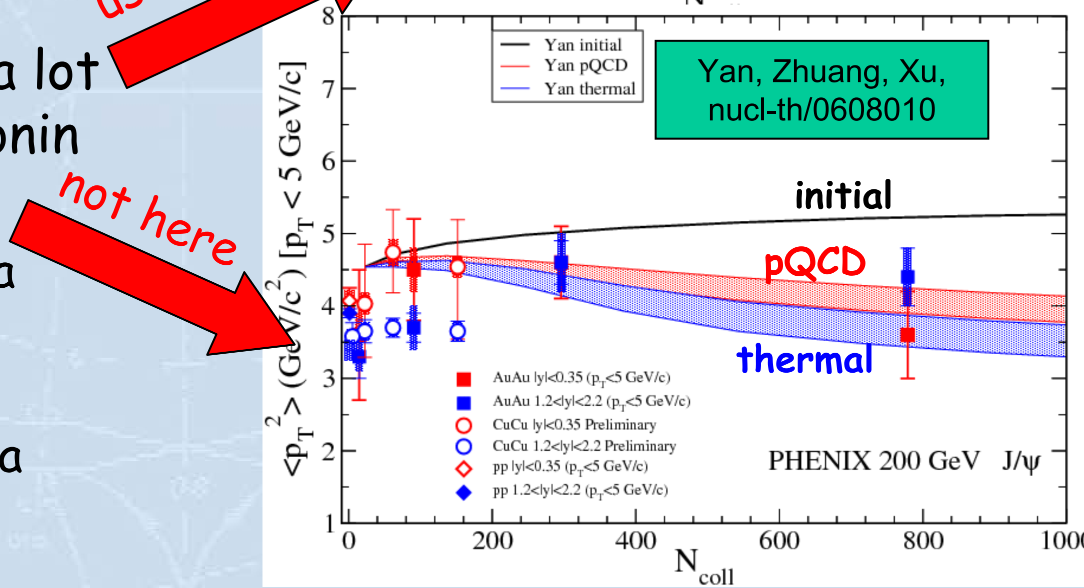
  - J/ψ suppressed in the center of the volume, where the Cronin effect is the highest
  - Surviving J/ψ's from the « corona » have a lower p_T



$\langle p_T^2 \rangle$ for recombination ?



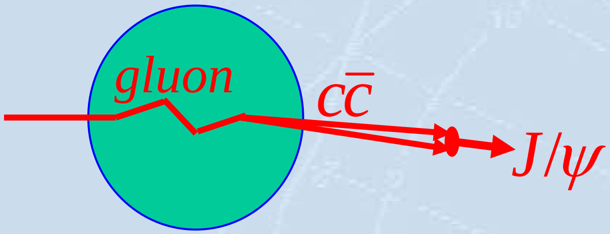




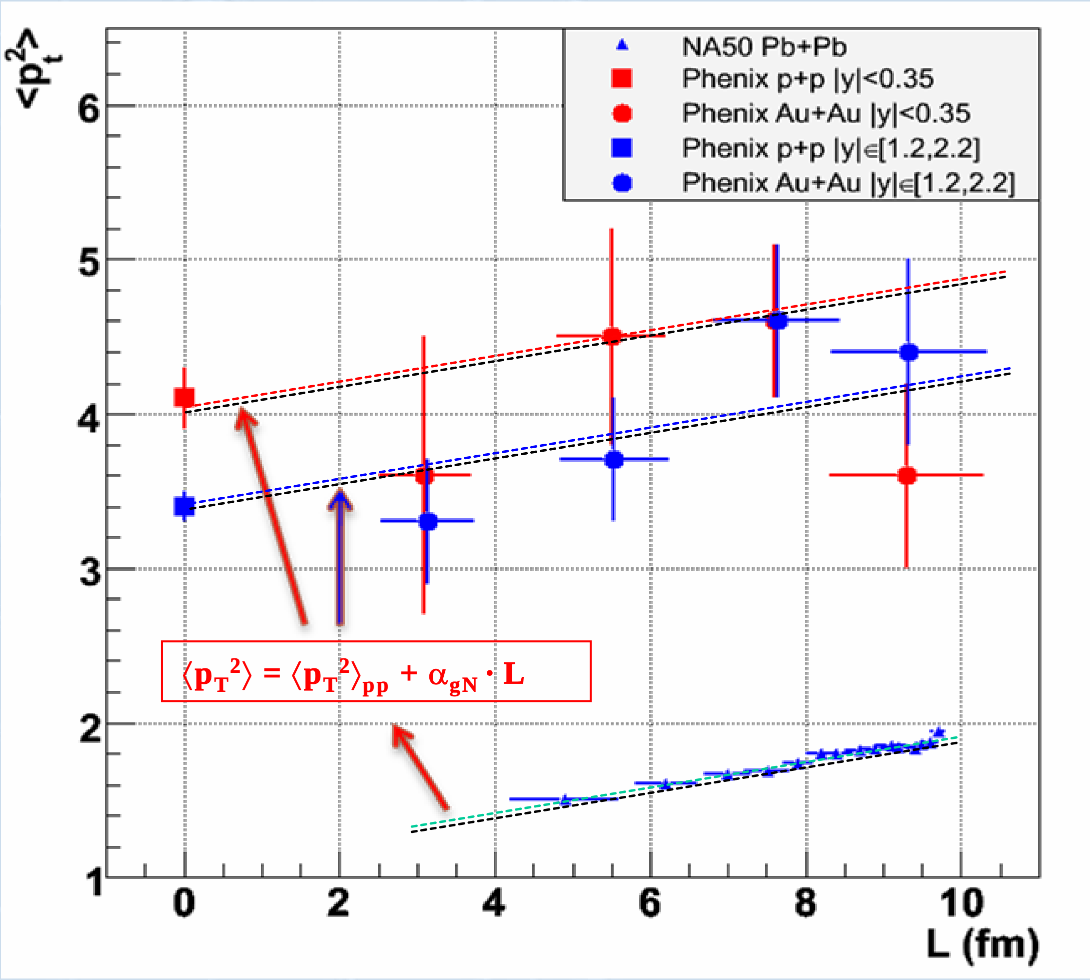
- ✓ Initial production depends a lot on initial p_T broadening (Cronin effect)
  - ✓ Earlier (run3) dAu/pp data showed clear broadening @y~1.7
  - ✓ Not clear with run5 pp data

$\langle p_T^2 \rangle$ vs centrality

- pT broadening due to multiple diffusion on nucleons ("Cronin effect")



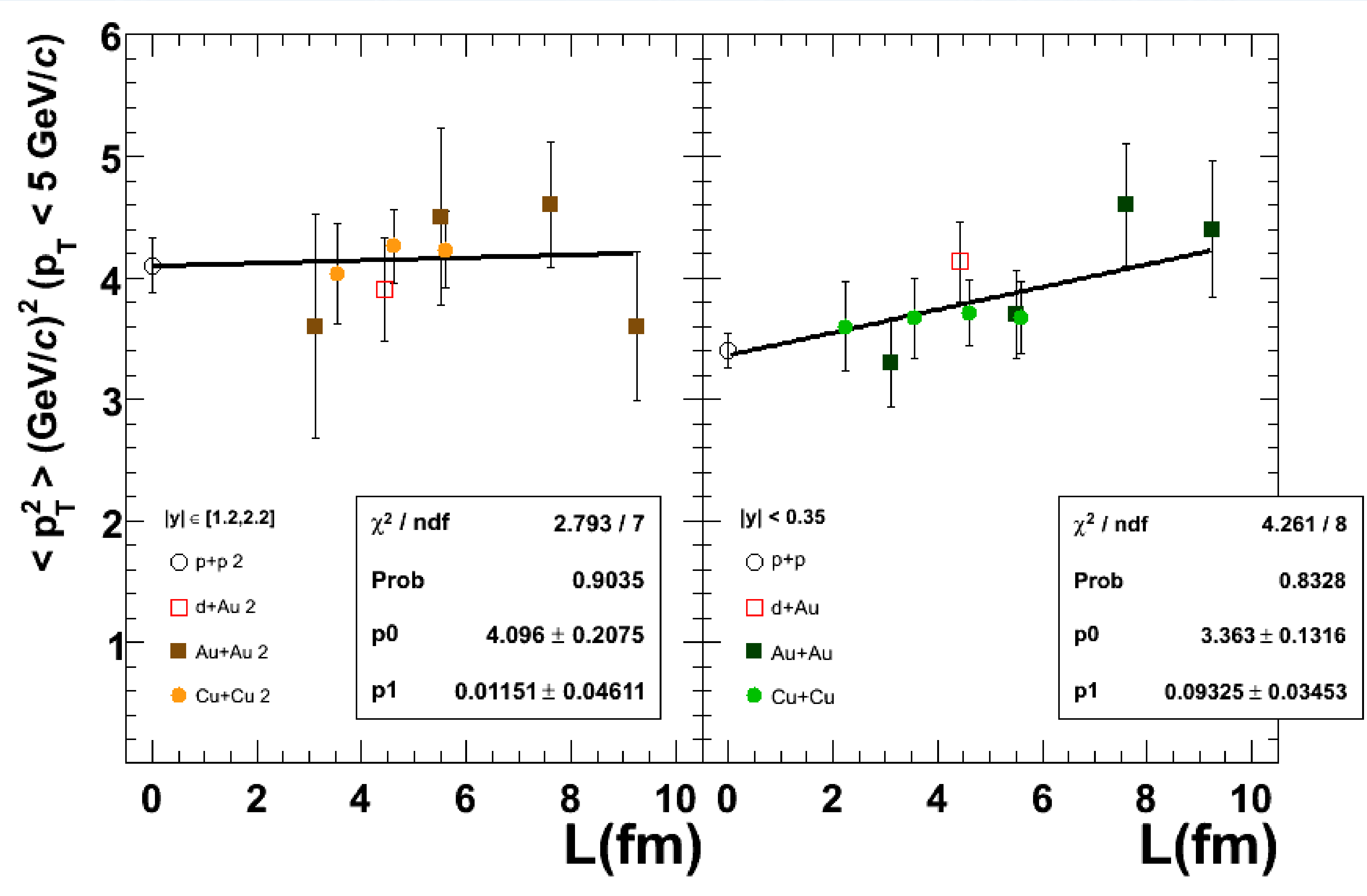
- In this case, $\langle pT^2 \rangle$ proportional to L
  - Data compatible with this scenario
  - Compatible with one single slope from SPS to RHIC



- Flattening (e.g. due to recombination) cannot be ruled out ...

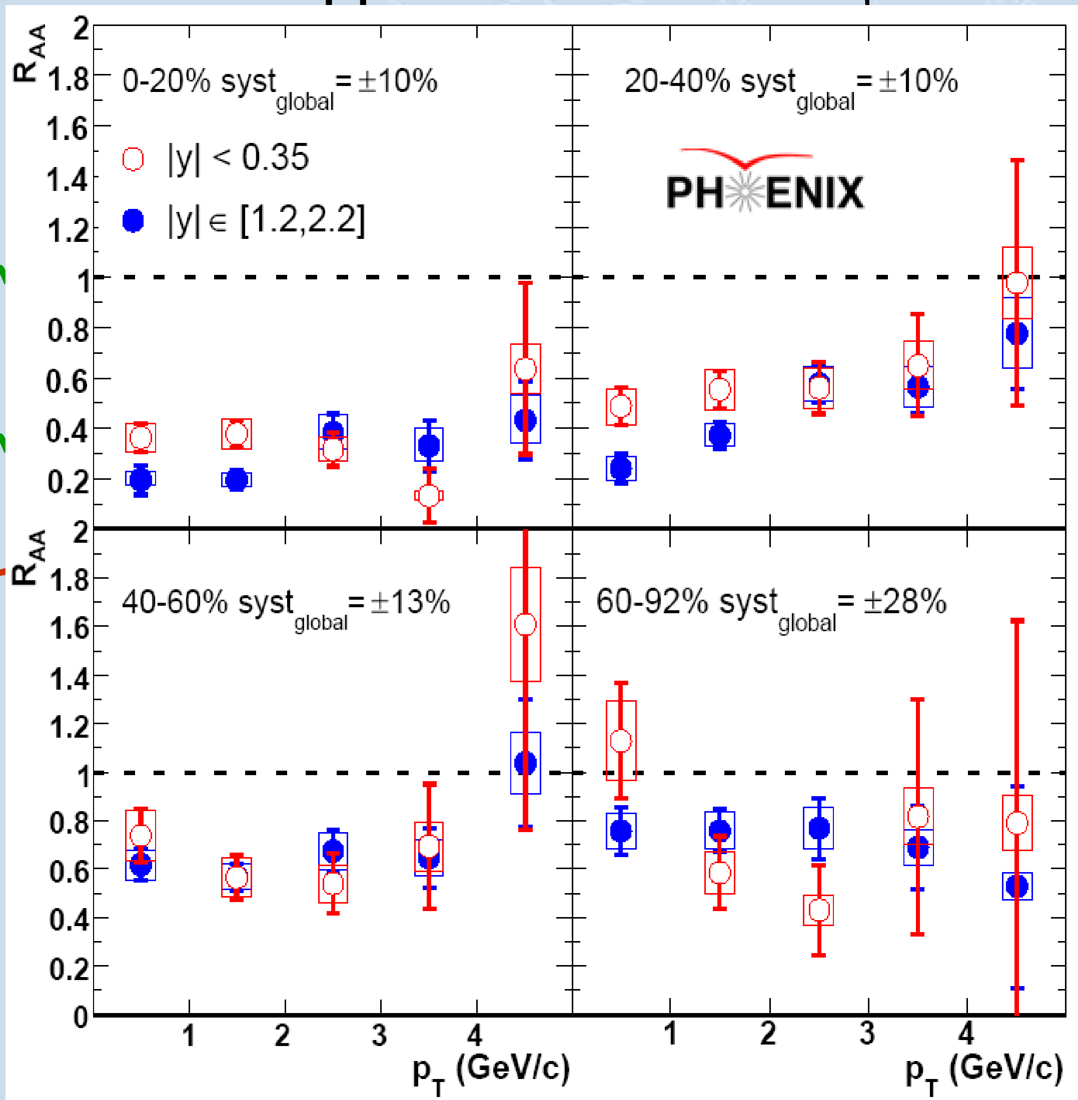
$$\langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \alpha_{gN} \cdot L$$

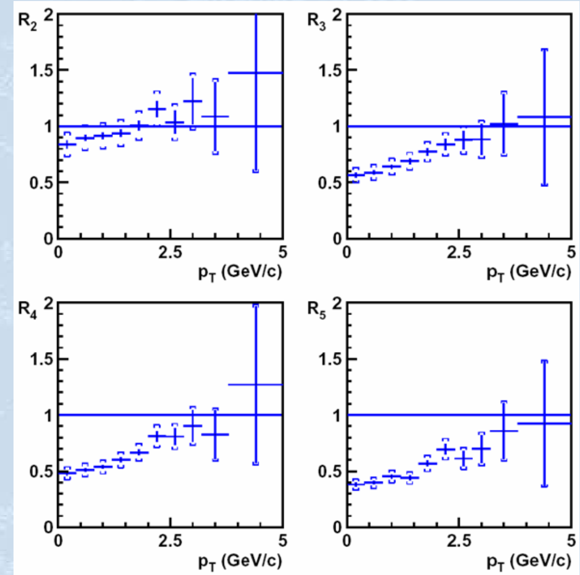
Phenix $\langle p_T^2 \rangle$



PT distributions ? Back to SPS

✓ NA50 suppression at low P_T ...





g

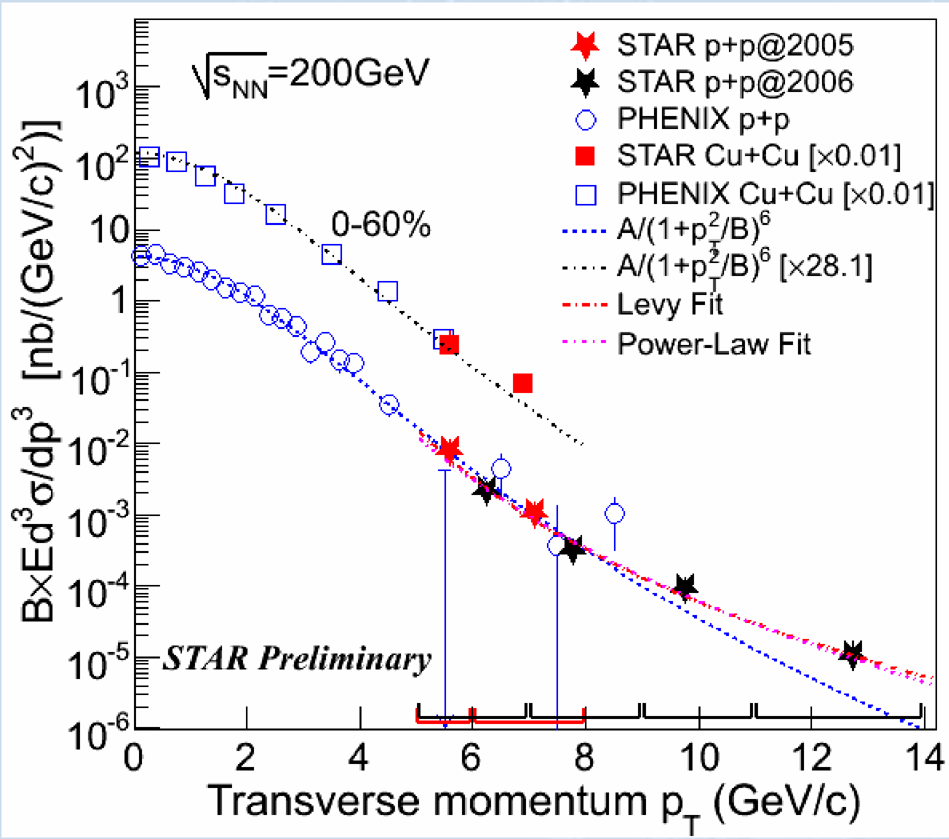
d

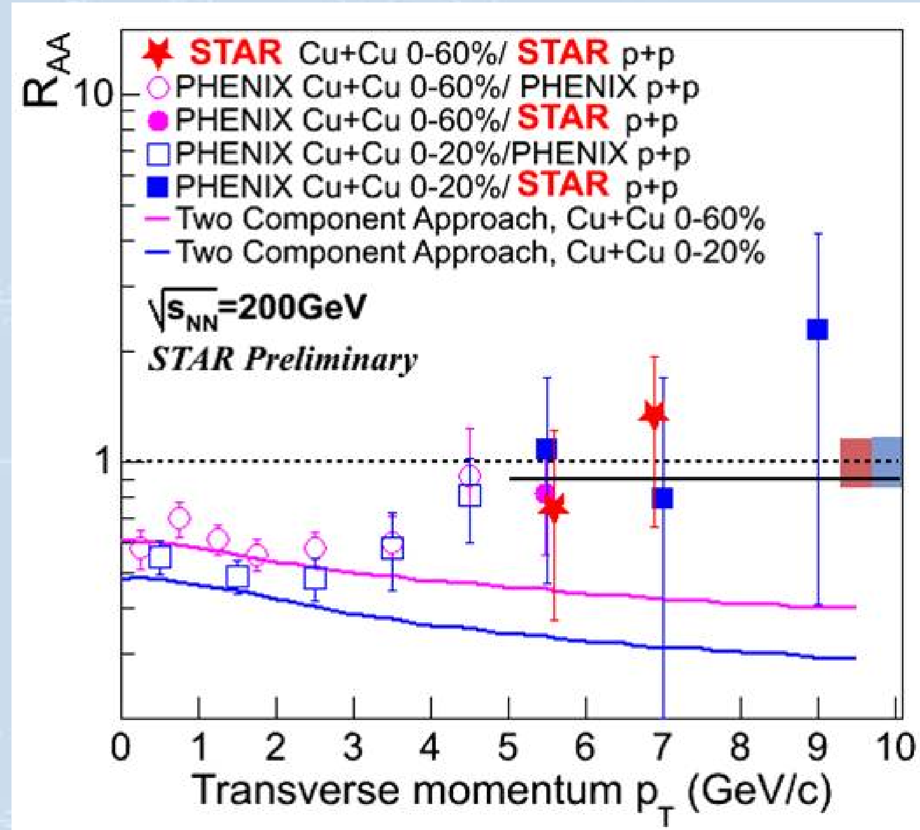
gh P_T pairs can escape

At RHIC, $\langle P_T^2 \rangle$ much higher than at sps, but plasma longer lived. What is the net result for J/ψ ?

STAR J/ψ at high p_T !!!

✓ STAR High p_T J/ψ in p+p and Cu+Cu points allow to measure $R_{CuCu}(p_T)$ up to 9 GeV/c !!!

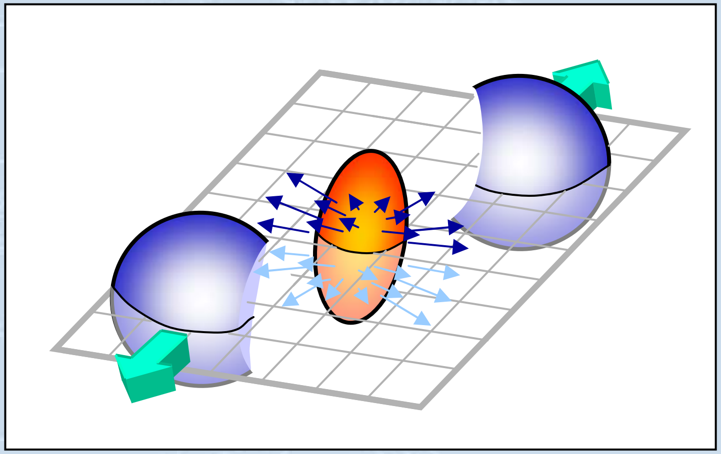




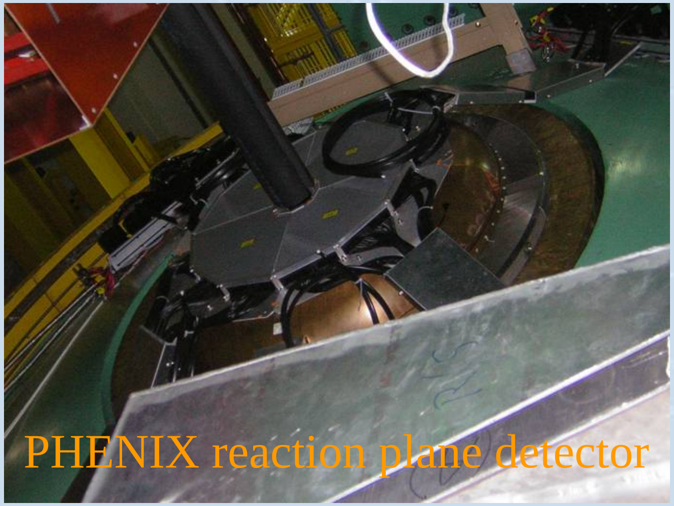
Possible test of recombination : V_2

- ✓ An elliptic flow is observed for heavy quark production @ RHIC

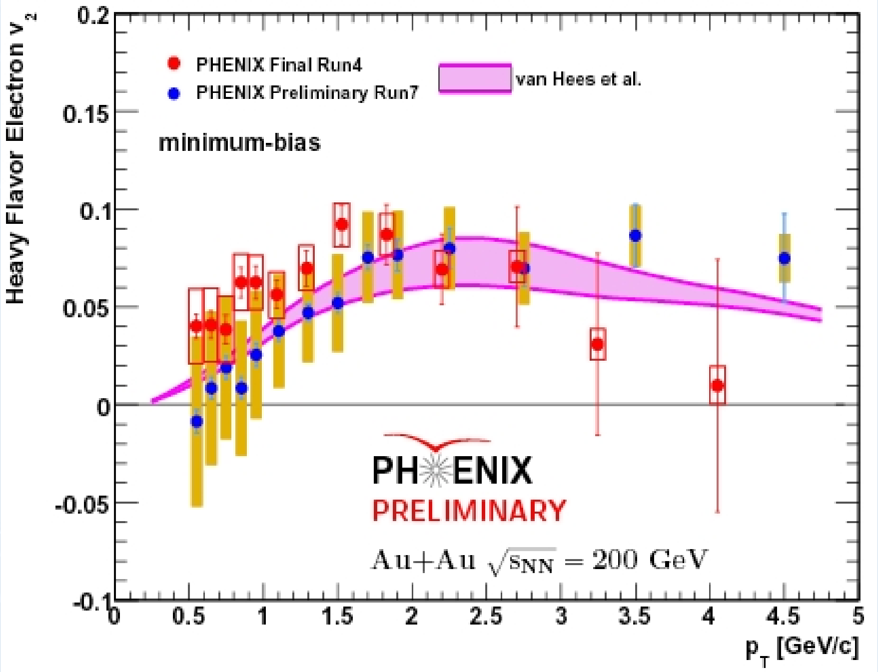
$$\frac{dN}{d(\phi - \Phi_{RP})} = A\left(1 + 2v_2 \cos\left(2(\phi - \Phi_{RP})\right) + \cdots\right)$$



- ✓ Recombined J/ψ's should inherit this flow !

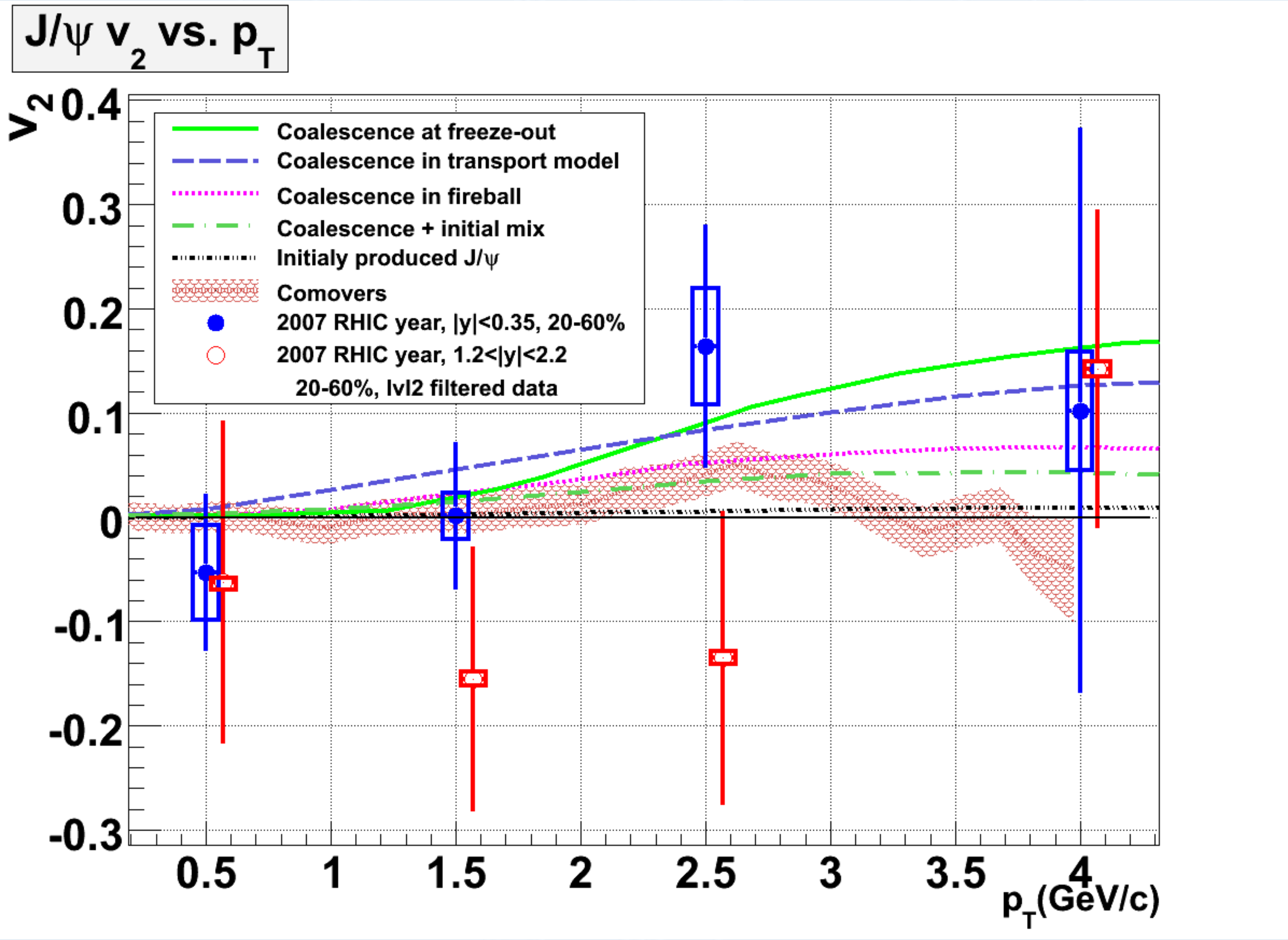


PHENIX reaction plane detector



J/ψ flow in Au+Au @ RHIC ?

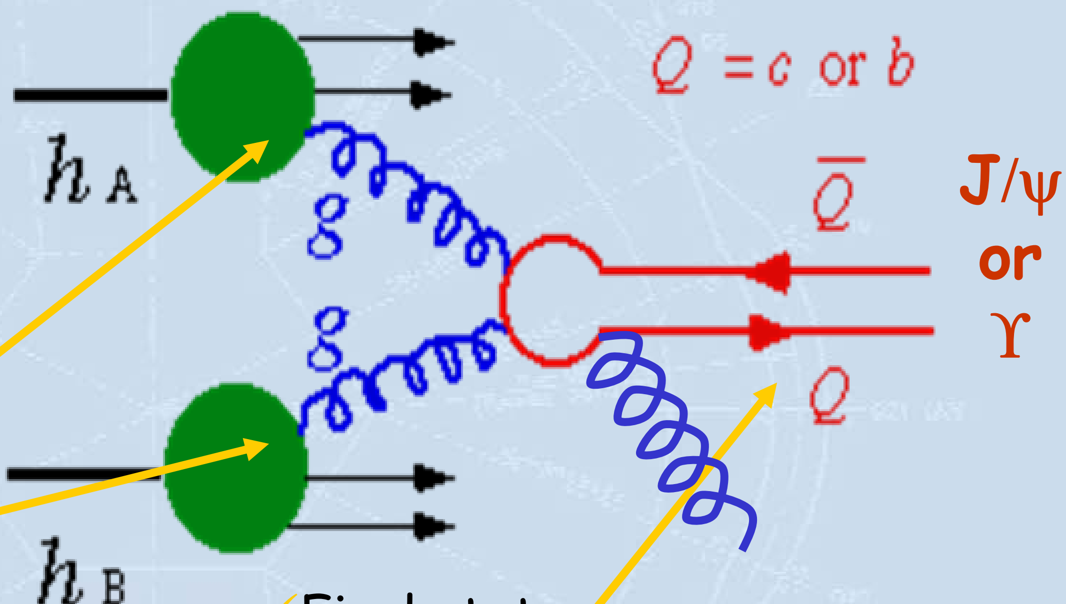
✓ We obviously lack statistics !



The ultimate reference ?

Heavy quarkonium production

- "Onia" production
  - Leading order at low x = "gluon fusion"

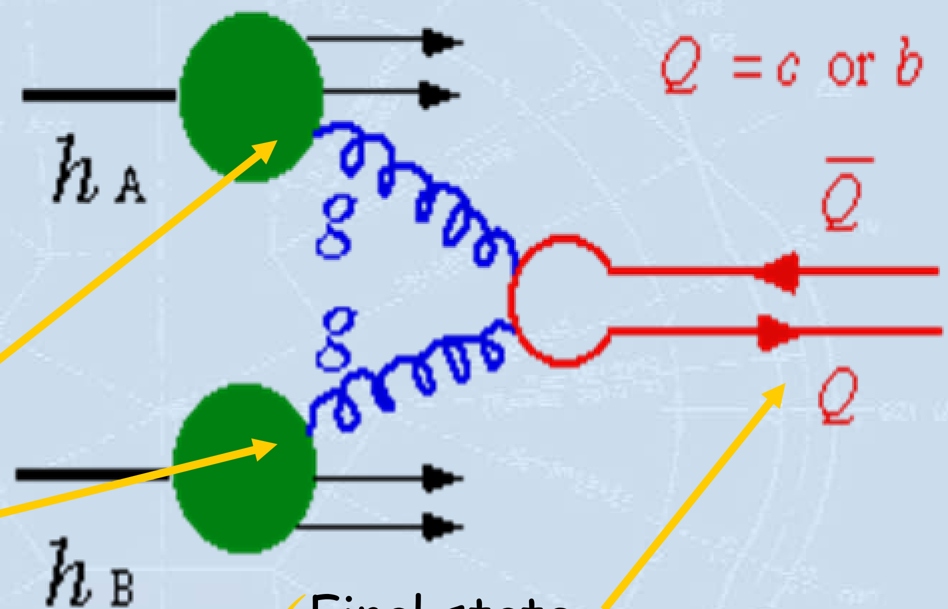


- Sensitive to:
  - Initial state
    - Parton distribution functions
    - p_T broadening
    - Parton energy loss in the initial state ?
    - Polarization ?
  - Final state
    - Parton energy loss in the hot & dense medium ?
    - In-medium dissociation
    - In-medium recombination
    - Flow ?
    - Thermal enhancement ?

\+ feed-down (e.g. B or χ_c-> J/ψ)

Open heavy flavor production

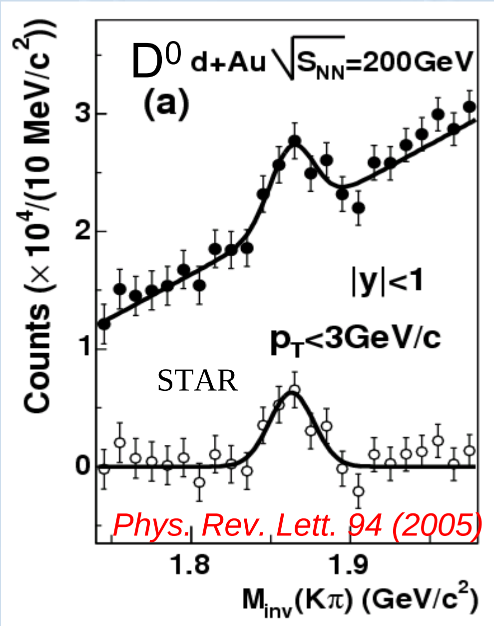
- ✓ Open charm (or beauty) production
  - ✓ Leading order at low x = "gluon fusion"

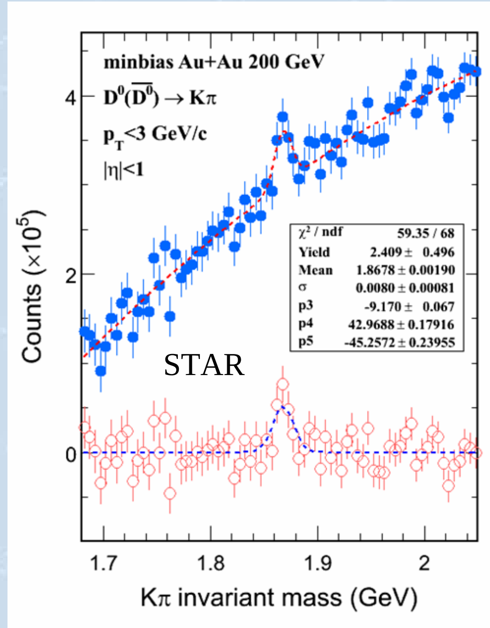


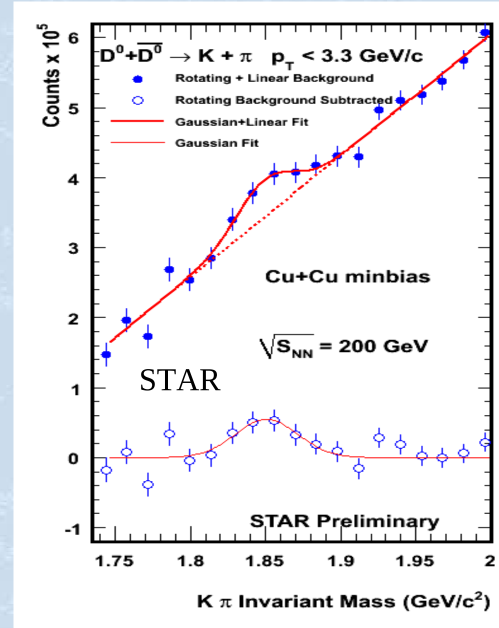
- ✓ Sensitive to:
  - ✓ Initial state
    - ✓ Parton distribution functions
    - ~~✓ p_T broadening~~
    - ~~✓ Parton energy loss in the initial state ?~~
    - ~~✓ Polarization ?~~
  - ✓ Final state
    - ✓ Parton energy loss in the hot & dense medium ?
    - ~~✓ In medium dissociation~~
    - ~~✓ In medium recombination~~
    - ✓ Flow ?
    - ✓ Thermal enhancement ?

~~+ feed-down (e.g. B or χ_c -> J/ψ)~~

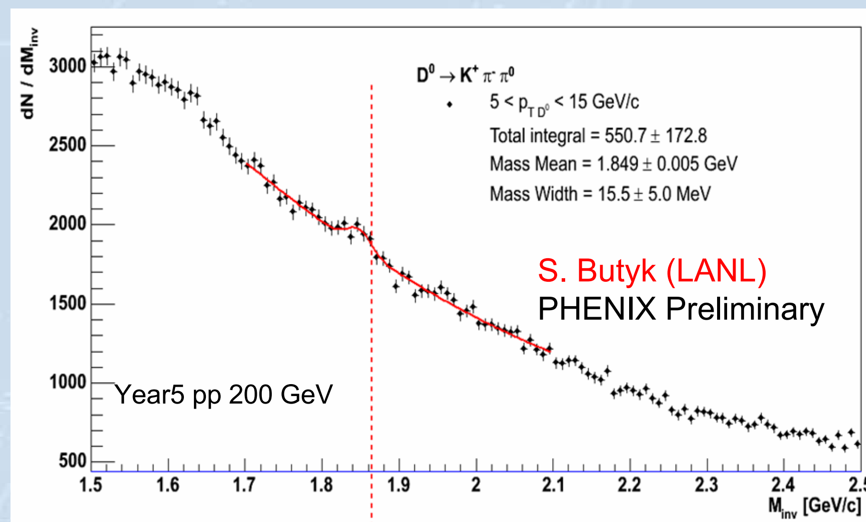
D^0 reconstruction in STAR





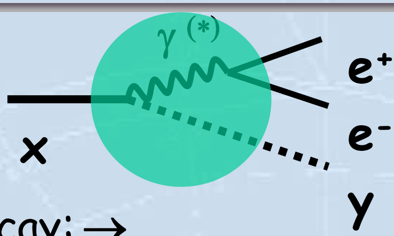


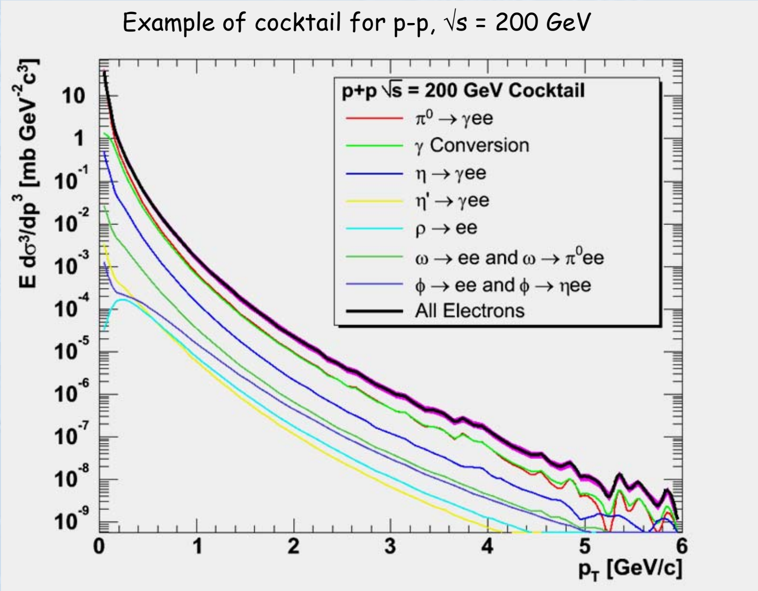
- ✓ Direct reconstruction of D^0 mesons in STAR for d+Au, Cu+Cu and Au+Au
- ✓ PHENIX for p+p
- ✓ Poor statistics !



open charm -> e : example (PHENIX)

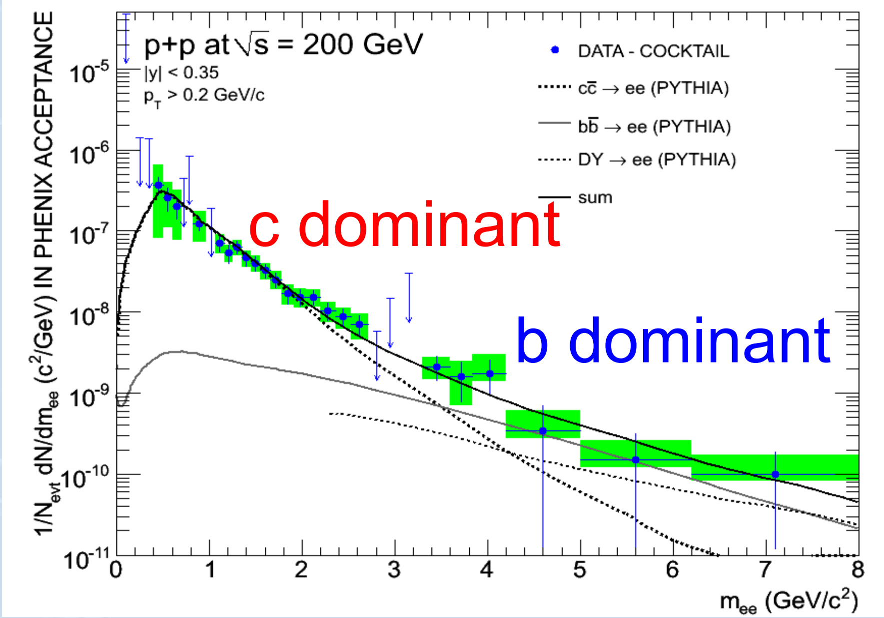
- ✓ "Photonic" electrons
  - ✓ γ conversion
  - ✓ π^0 and η/η' Dalitz decay: $\rightarrow \gamma ee$
  - ✓ light vector meson decay:
    - ✓ $\omega, \varphi \rightarrow (\pi^0,\eta)ee$



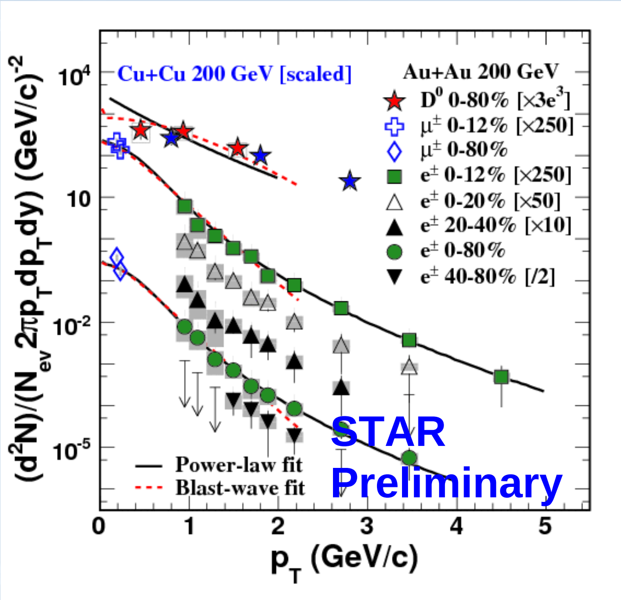


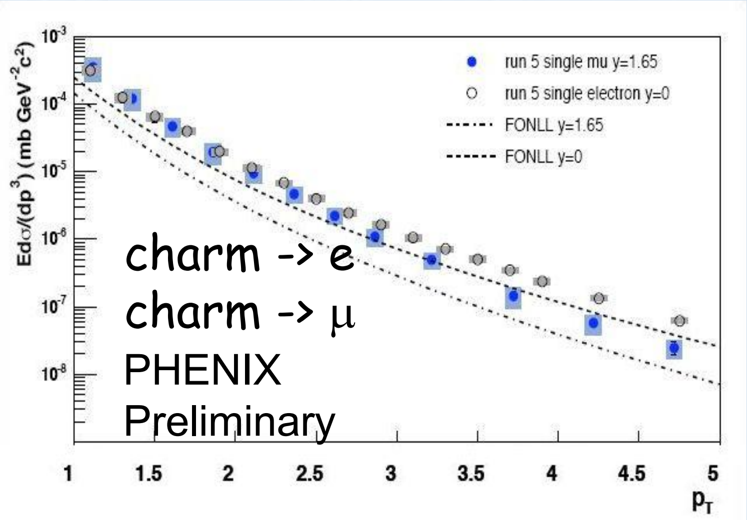
- ✓ NON-photonic electrons = ALL – PHOTONIC
  - ✓ K decay
  - ✓ $\rho, \omega, \varphi \rightarrow ee$
  - ✓ $c \rightarrow e$ (dominant)
  - ✓ $b \rightarrow e$

- ✓ Subtract background by:
  - ✓ Cocktail method
  - ✓ Converter method
  - ✓ Direct measurement of γ e coincidences + event mixing

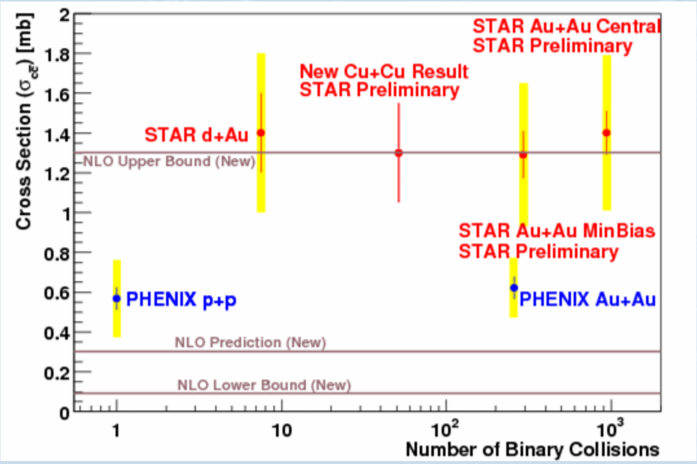


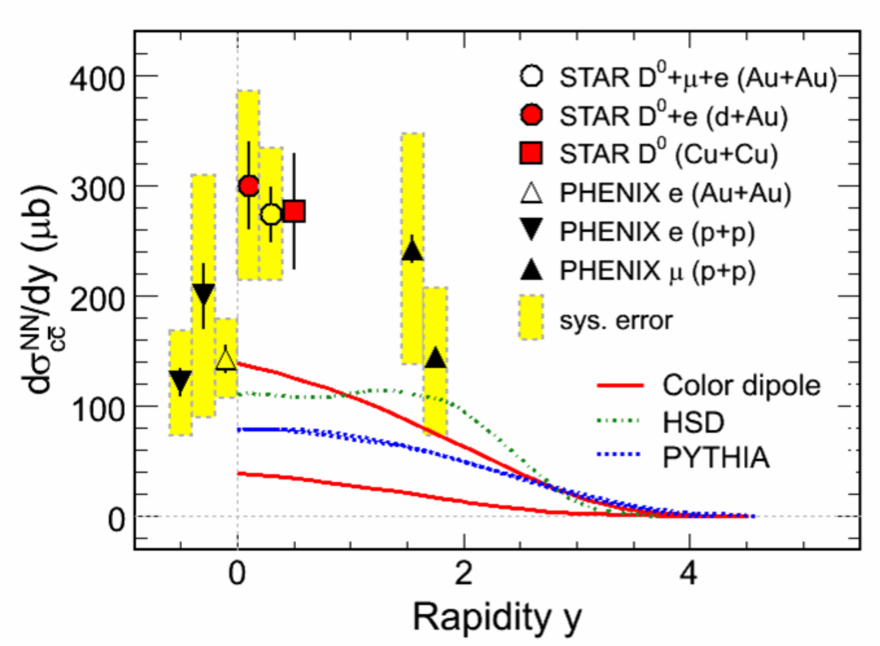
Open charm @ RHIC





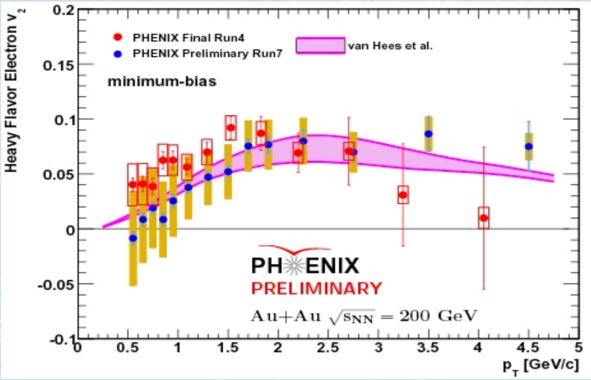
- ✓ STAR / PHENIX
  - ✓ Factor of 2 in the σ … ???





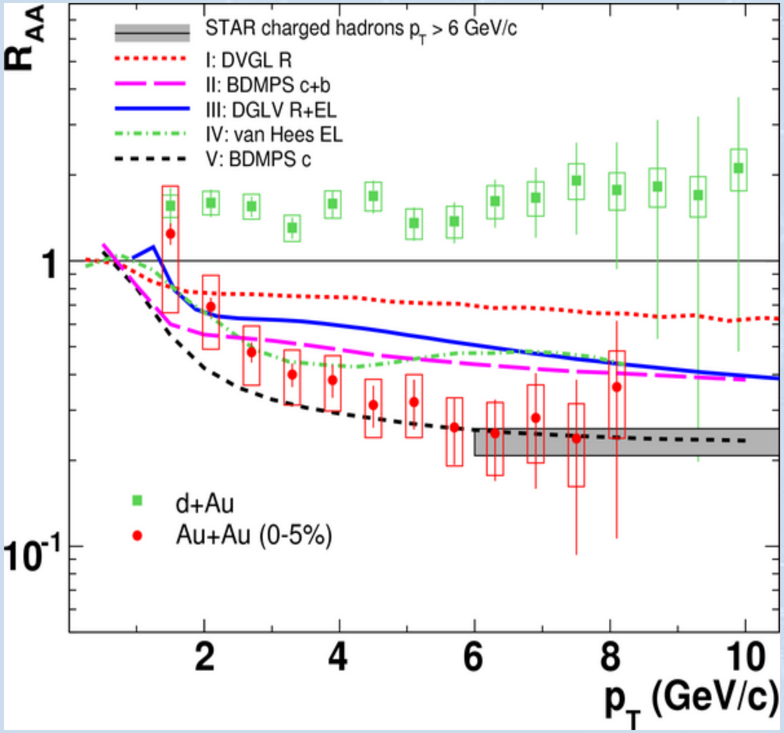
Heavy flavor energy loss

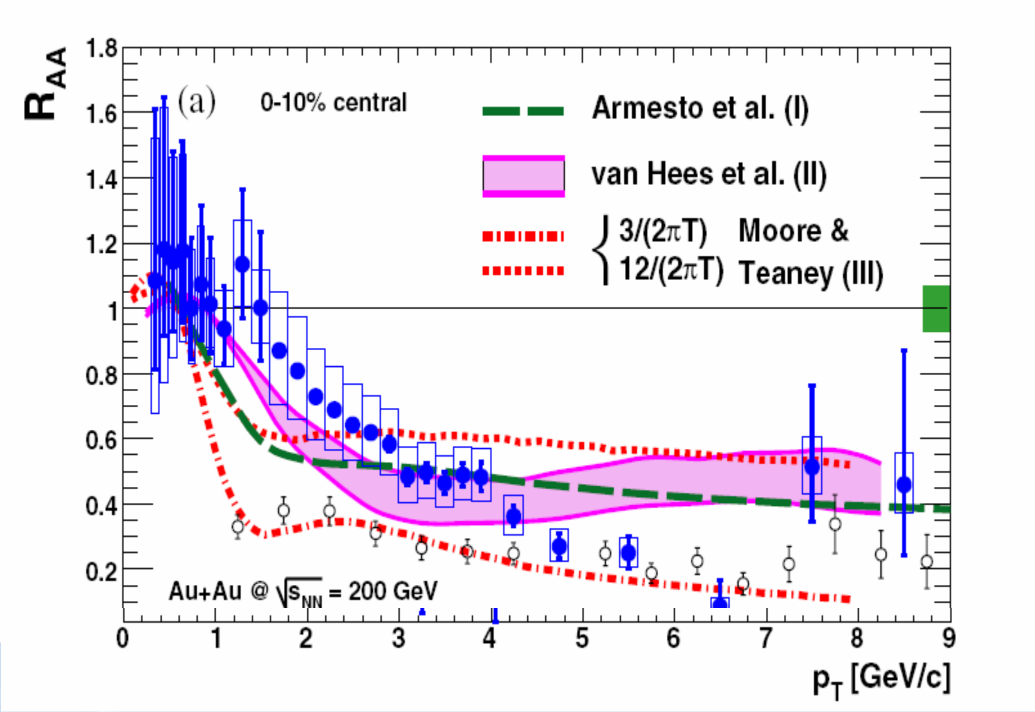
- Heavy quark « quenching » !
  - in addition to the elliptic flow already mentioned
- Is open charm still the better reference for J/y suppression studies ?



PHENIX *PRL, 98, 172301 (2007)*

STAR *PRL, 98, 192301 (2007)*

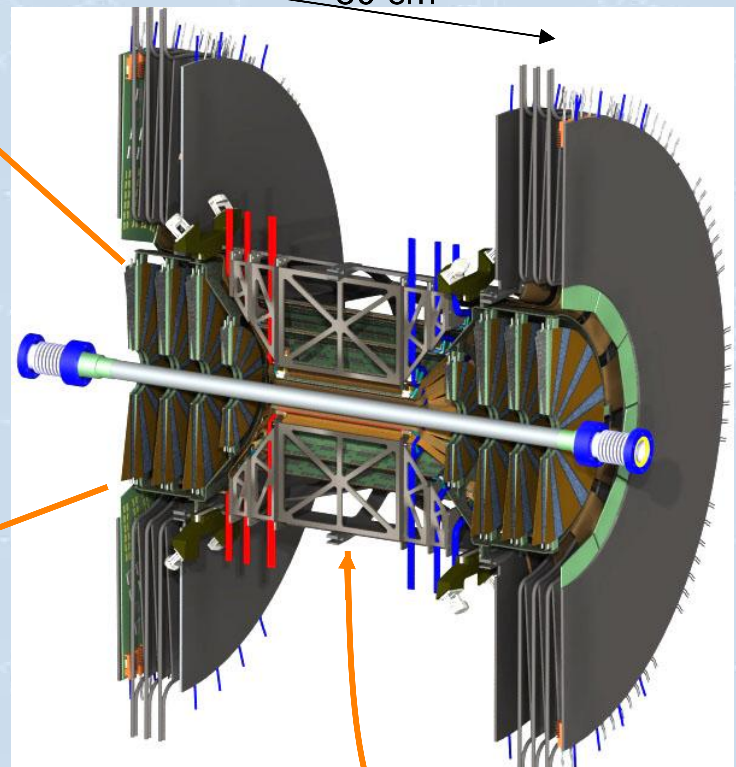


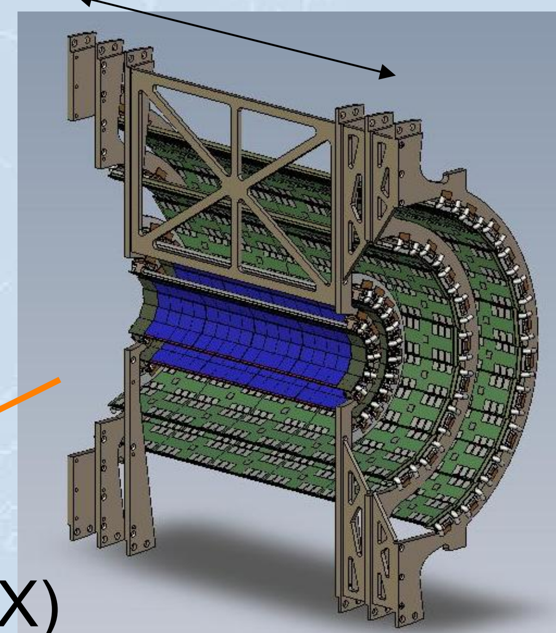


Vertex detectors needed !

- ✓ E.g. : PHENIX « VTX » to be installed in 2010 / 2011

Forward vertex detectors (FVTX)



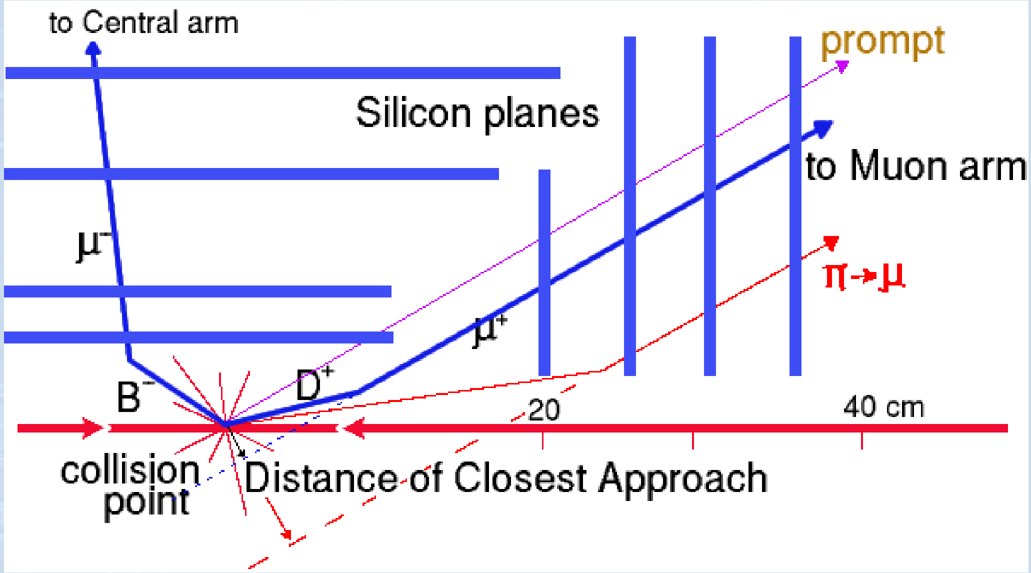


Barrel vertex detector (VTX)

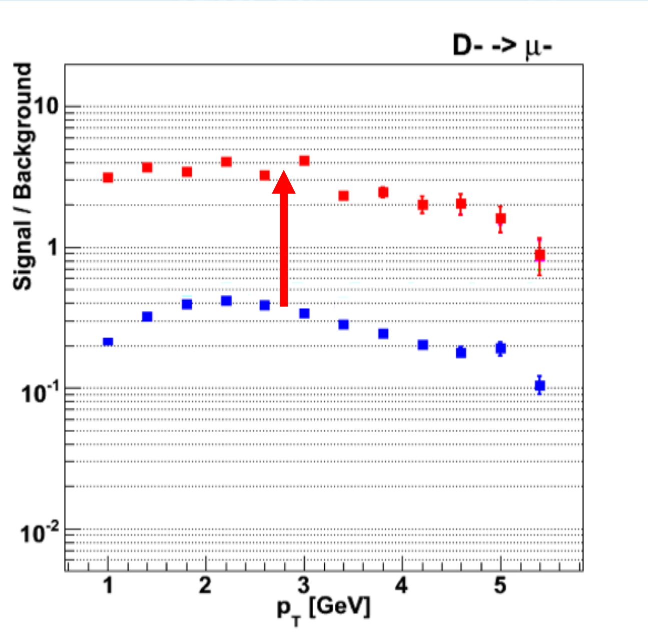
PHENIX « VTX »

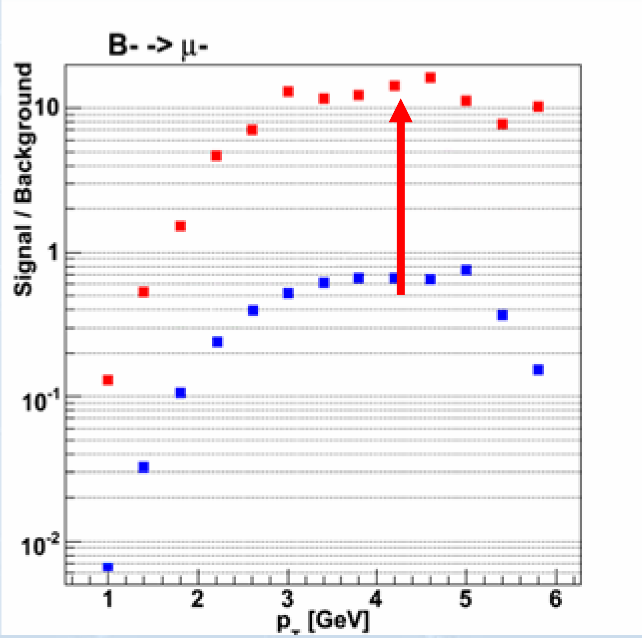
- ✓ Mean π,K ->μ,e decay distance is large
- ✓ D, B mesons travel some distance before semileptonic decay to muons or electrons
- ✓ Prompt μ,e have 0 DCA
- ✓ By measuring the DCA to the primary vertex, one can separate D, B decays from prompt leptons and from long-lived decays from π, K

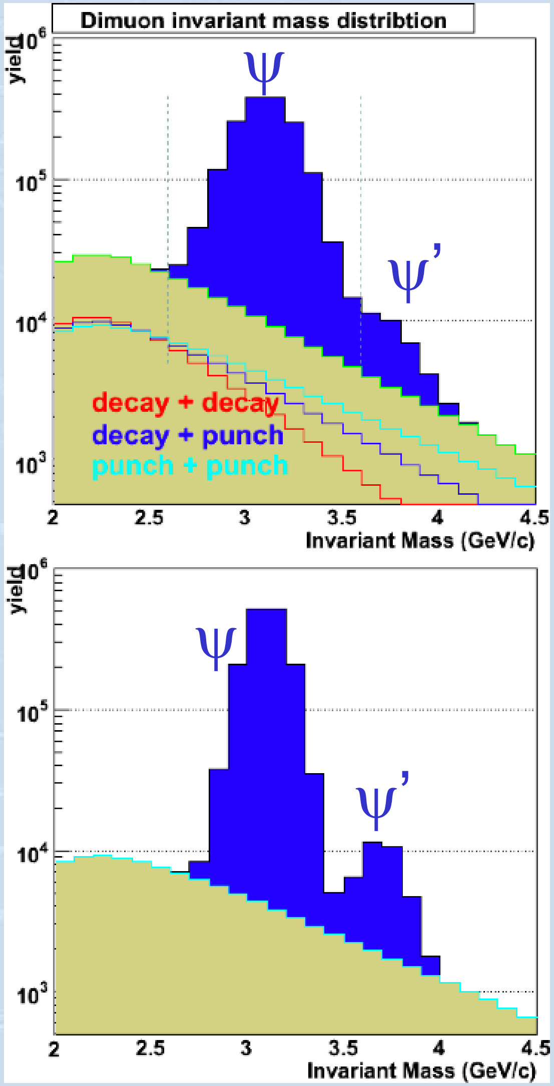
DCA resolution < 50 um for the central barrel
< 100 um for the forward det.
Occupancy < 10%
Large solid angle coverage
$|\Delta\eta| < 1.2$ - barrel, standalone
$|\Delta\eta| < 0.35$ - barrel, matches central arms
$1.2 < |\Delta\eta| < 2.4$ - covers most of the muon arms
match tracks with central & muon arms



PHENIX « VTX »





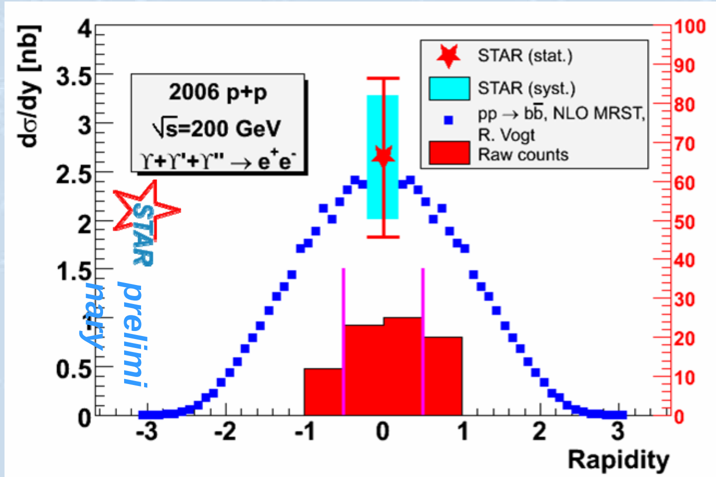


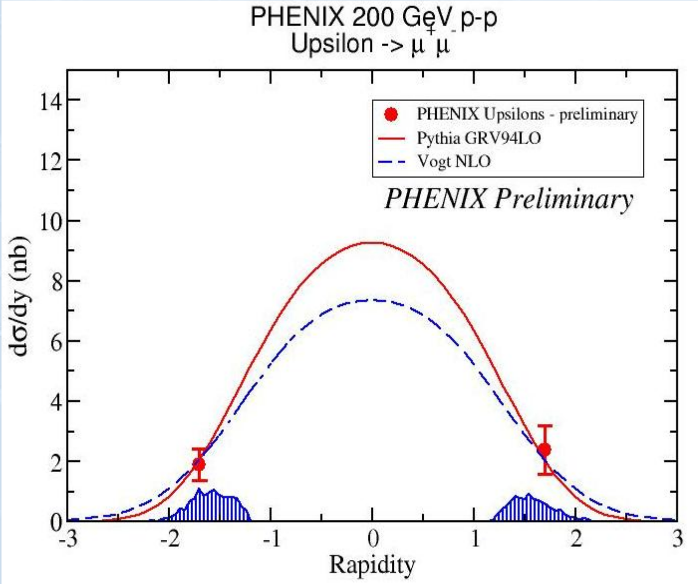
- ✓ Using DCA cuts, plus χ^2 and isolation cuts -> improvement of S/B ratio by a factor of 10 for D and B detection
- ✓ Improvement of mass resolution and S/B ratio in the charmonium -> dilepton channel

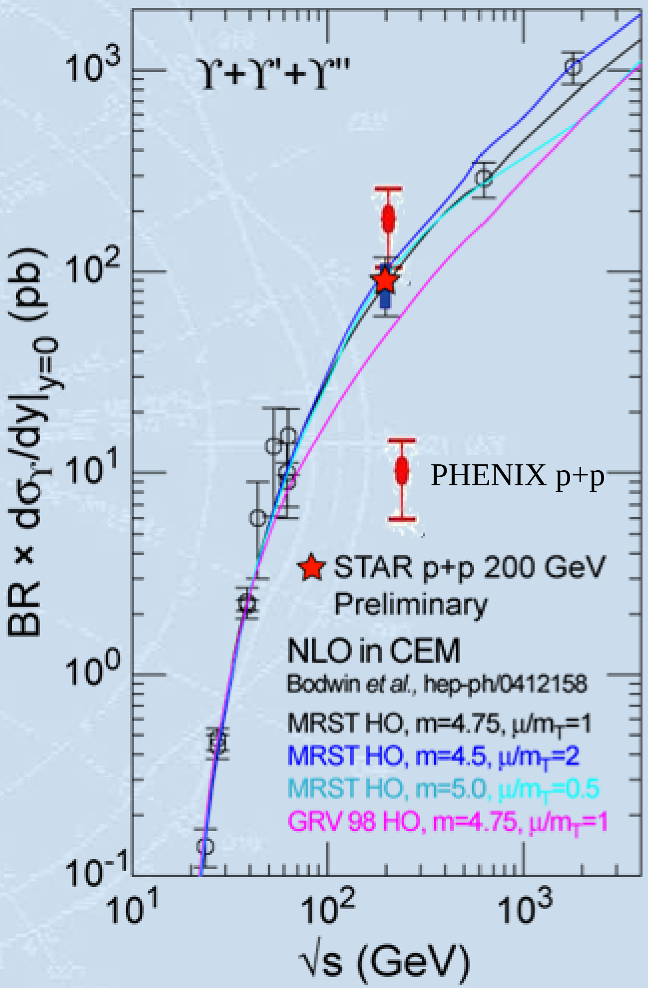
En route for higher energies !

- ✓ First Υ @ RHIC
  - ✓ Complementary y regions
- ✓ Would be interesting to see them in Au+Au !
- ✓ Would be very useful for LHC !
  - ✓ Too low luminosity
  - ✓ Too much background

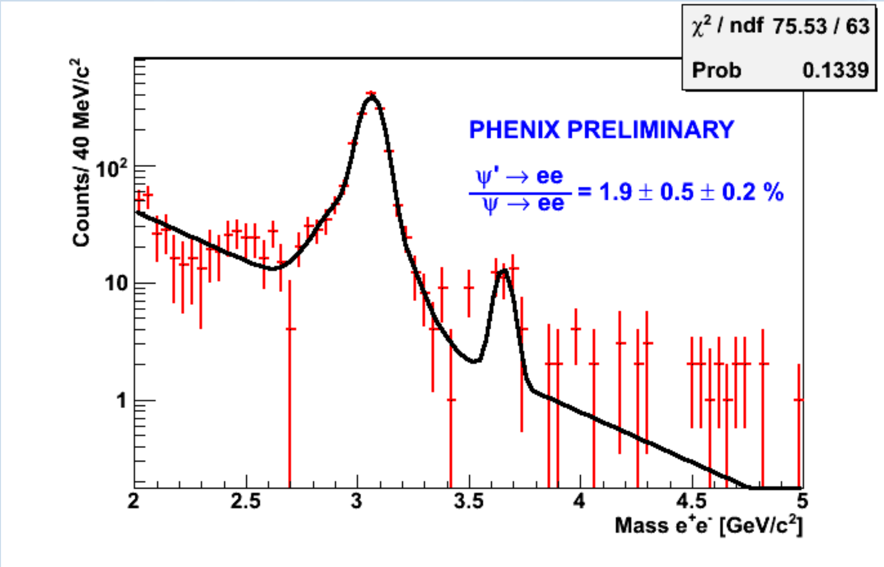
STAR & PHENIX Υ , p+p 200 GeV

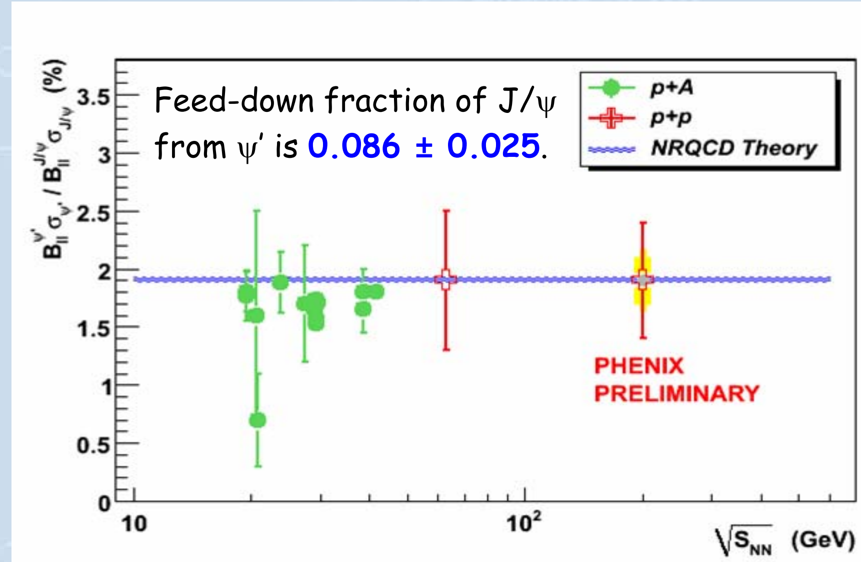


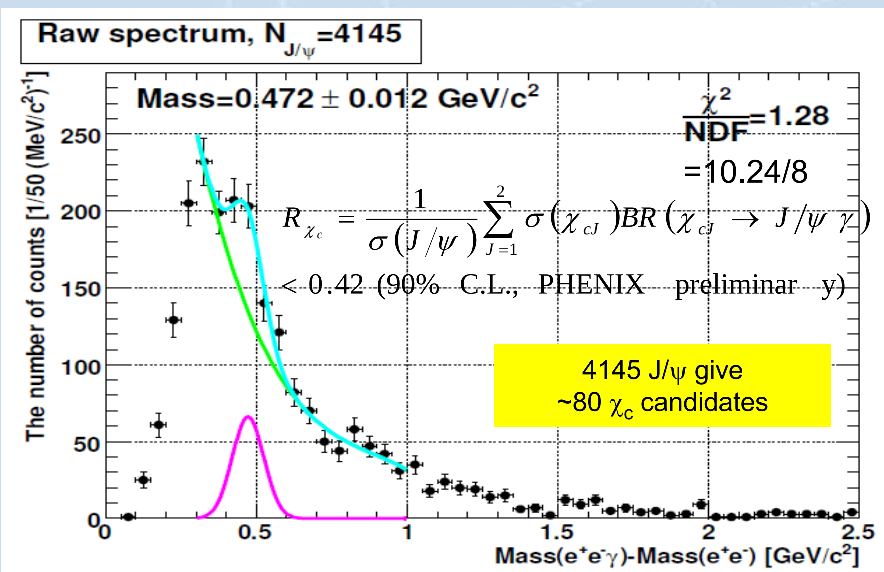


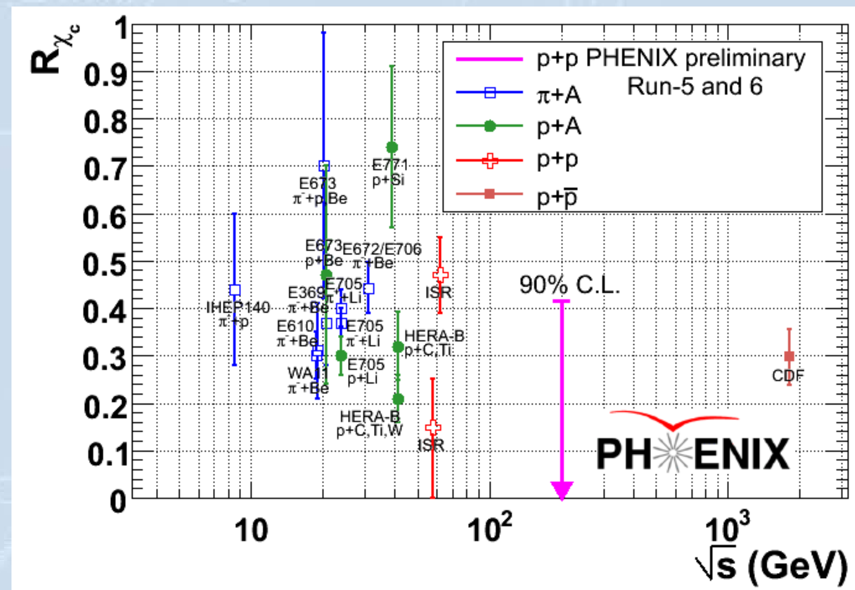


Feed down to J/ψ production (PHENIX p+p)



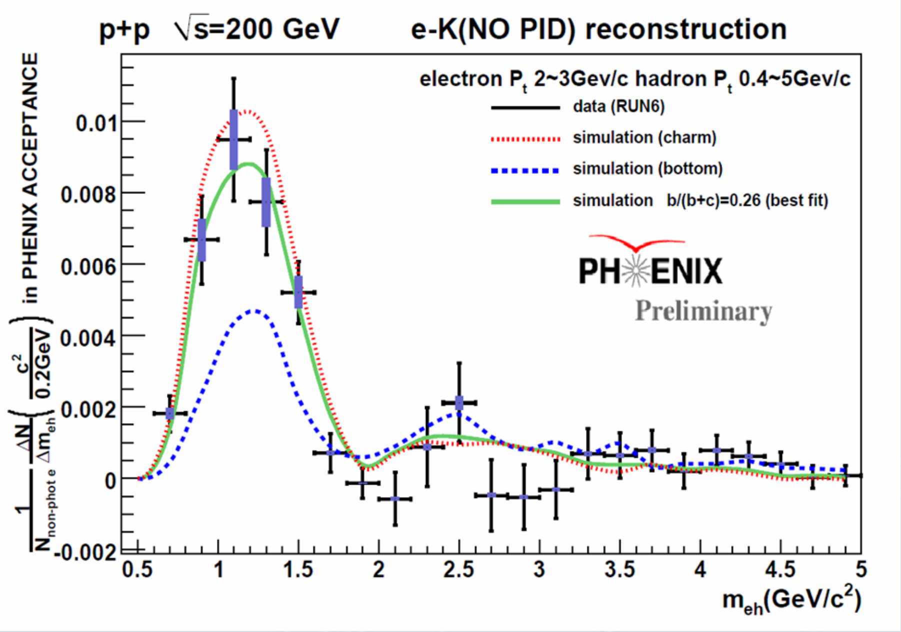


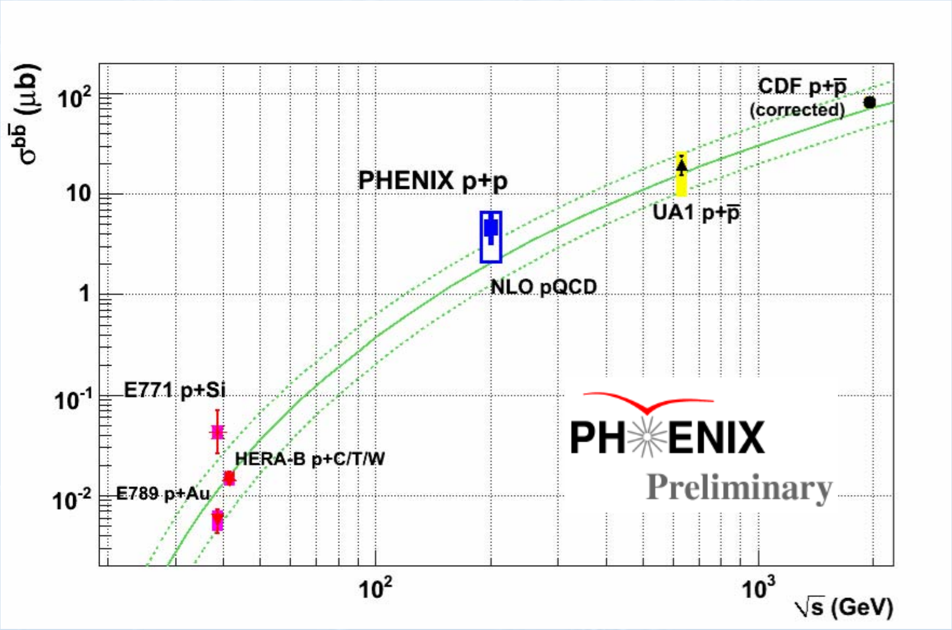




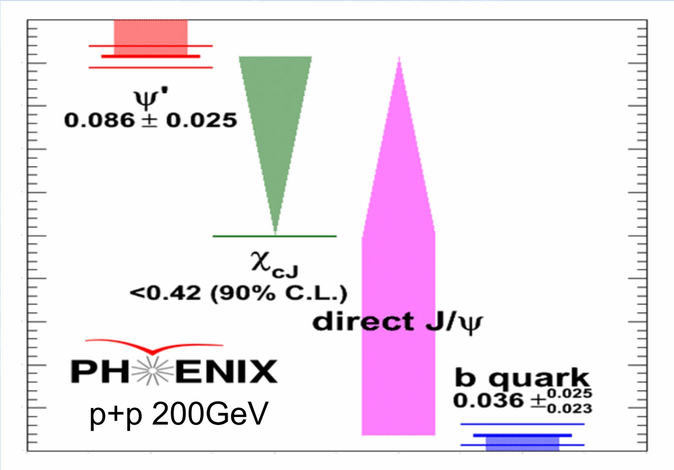
Contribution from b decay

• Feed-down fraction of J/ψ from b and b-bar quarks is **0.036 +0.025-0.023**.





- ✓ In p+p collisions at √s=200GeV, J/ψ is produced via
  - ✓ $\chi_{cJ} \rightarrow J/\psi+\gamma$ decays : <42% (90% C.L.)
  - ✓ $\psi' \rightarrow J/\psi+X$ decays : 8.6 ± 2.5%
  - ✓ b quark → J/ψ+X decays : $3.6^{+2.5}_{-2.3}$%
  - ✓ Direct J/ψ production : the rest



Conclusion

- RHIC data show a J/ψ suppression beyond CNM effects
  - ~ compatible with SPS data @ y=0
  - Stronger suppression @ forward rapidity
- ~ rules out « suppression-only » scenarios
  - Comovers alone, sequential melting alone, J/ψ suppression in QGP alone
- Regeneration ?
  - Strongly depends on charm distributions … poorly known !
  - Up to now, the only way to cope with less suppression @ y=0
  - Could account for pT behavior ?
    - Cronin effect not well known
- Need more pieces of the puzzle !
  - Better control of CNM effects (d+Au: more statistics to come soon !)
  - Open heavy flavor with vertex upgrades
  - Other resonances (ψ', χ_c, Υ) start to be investigated at RHIC