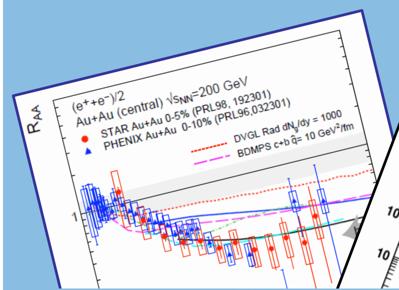
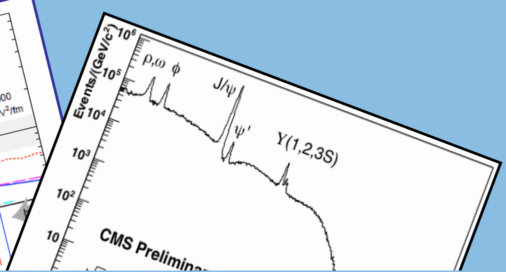
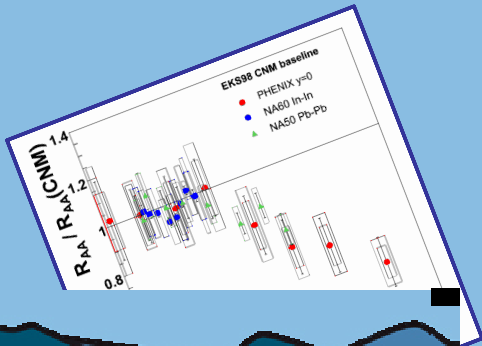
Heavy quarks and quarkonia

Roberta Arnaldi
INFN, Torino







QUARK MATTER 2011

Student Day, 22 May 2011, Annecy

Outloo

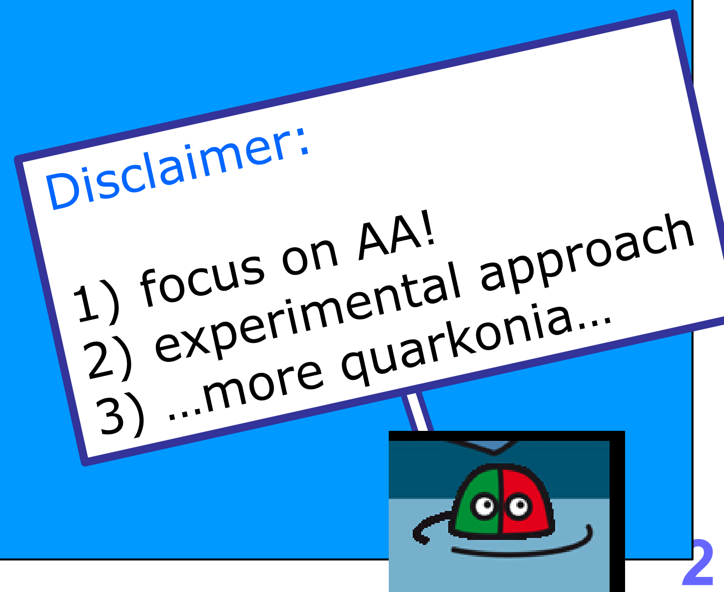
1) Quarkonia

2) Heavy Quarks

1) Theoretical expectations

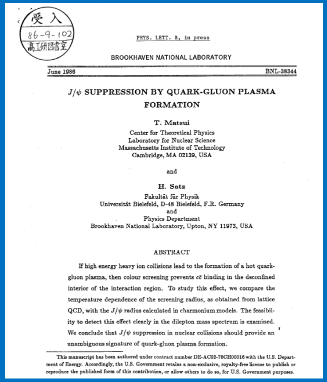
2) SPS/RHIC results

3) ...waiting for LHC results!



Quarkonium: introduction

Quarkonium suppression is considered since a long time as one of the most striking signatures for the QGP formation in AA collisions



受入 86-9-102 高工研図書室

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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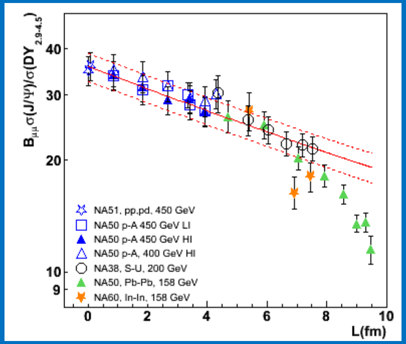
ABSTRACT

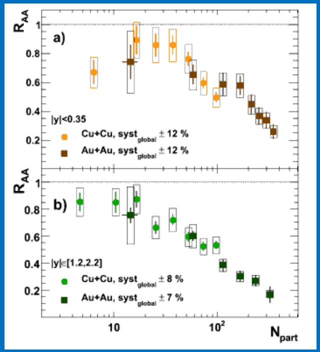
If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

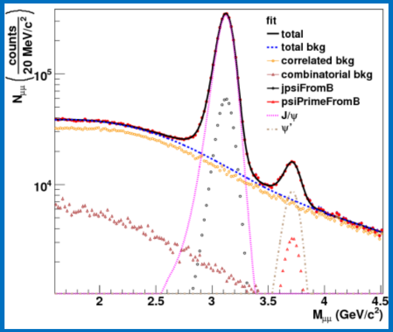
SPS



RHIC



LHC



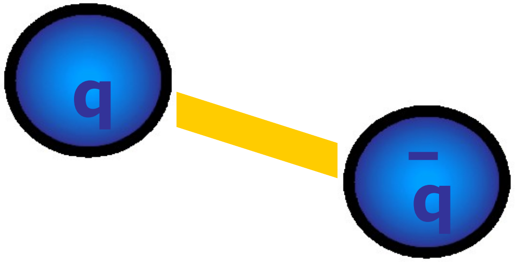
√s — 17 GeV/c — 200 GeV/c — 2.76 TeV/c →

years – 1986 — 1990 — ~2000 — 2010 →

…but, as for the other hard probes, in order to understand quarkonium behaviour in the hot matter (AA collisions), its interactions with the cold nuclear matter should be under control (pA/dAu collisions)

Quarkonium

At T=0, the binding of the q and $\bar{q}$ quarks can be expressed using the Cornell potential:



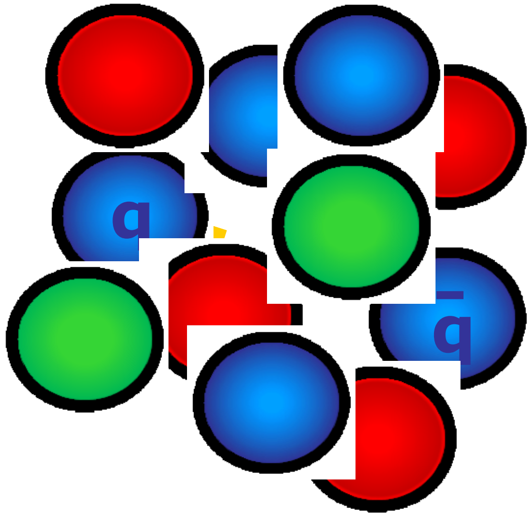
$$V(r) = -\frac{\alpha}{r} + kr$$

Coulombian contribution, induced by a g exchange between q and $\bar{q}$

Confinement term

What happens to a $q\bar{q}$ pair placed in the QGP?

The QGP consists of deconfined colour charges
→ the binding of a $q\bar{q}$ pair is subject to the effects of colour screening

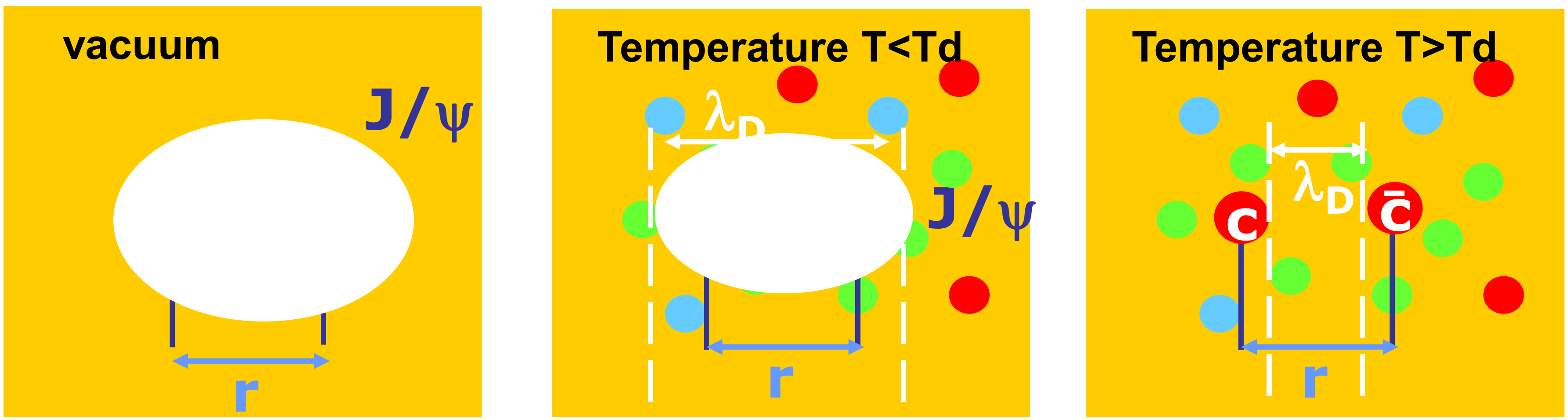


- The "confinement" contribution disappears
- The high color density induces a screening of the coulombian term of the potential

$$V(r) = -\frac{\alpha}{r} + kr \longrightarrow V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

Debye screening

The screening radius $\lambda_D(T)$ (i.e. the maximum distance which allows the formation of a bound qq pair) decreases with the temperature T

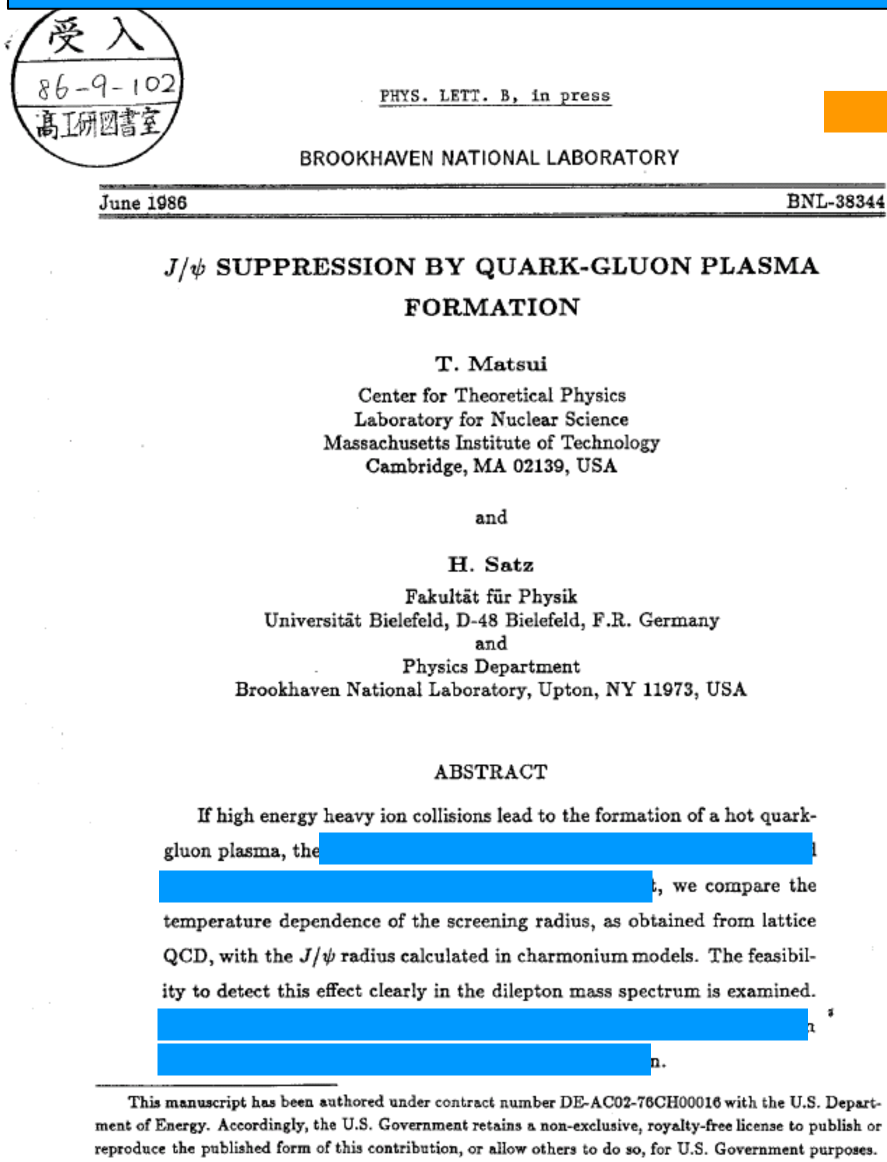


At a given T:

if resonance radius < $\lambda_D(T)$ → resonance can be formed

if resonance radius > $\lambda_D(T)$ → no resonance can be formed

Charmonium suppression



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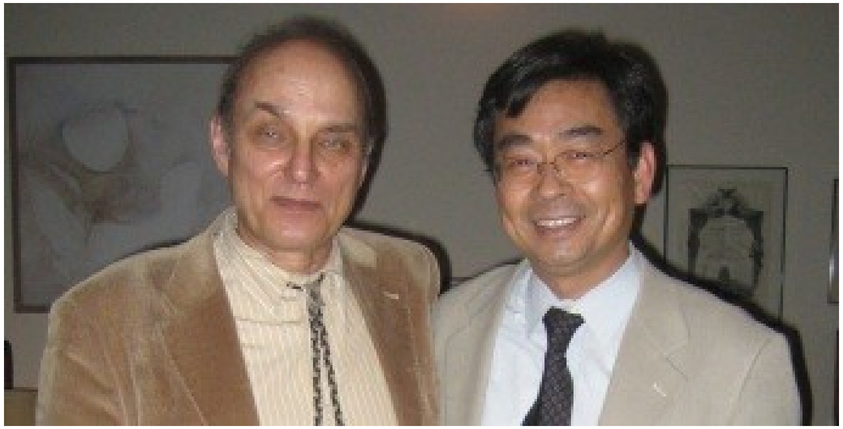
This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy.

Phys.Lett. B178 (1986) 416

This is the idea behind the suggestion (by Matsui and Satz) of the J/ψ as a signature of QGP formation (25 years ago!)



Very famous paper, cited ~ 1400 times!

Sequential screening

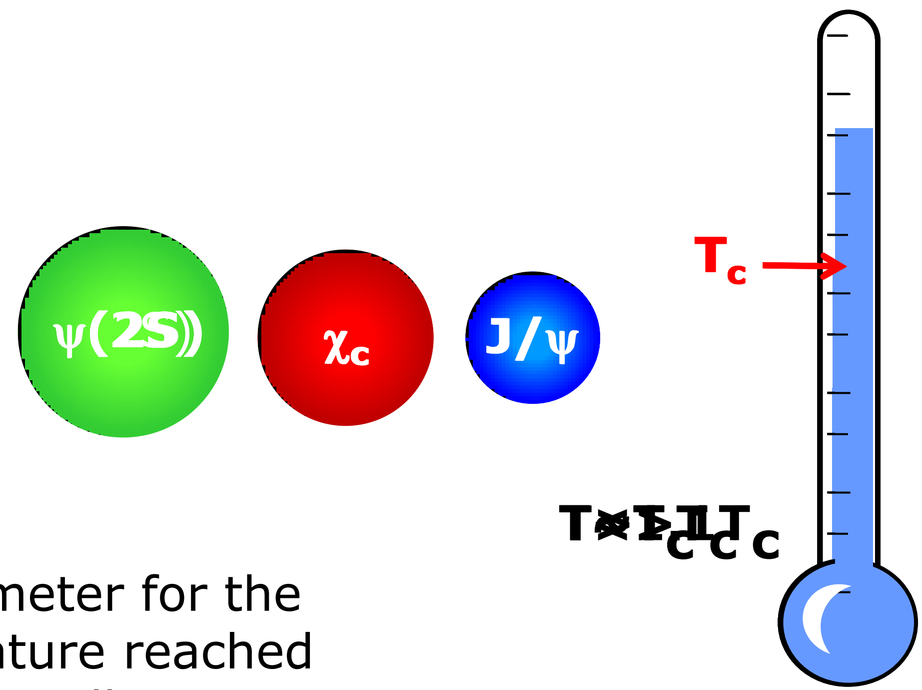
➡ The quarkonium states can be characterized by
- the binding energy
- radius

state	J/ψ	χ_c	$\psi(2S)$
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_o(fm)	0.25	0.36	0.45

state	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

➡ More bound states have smaller size

➡ Debye screening condition $r_0 > \lambda_D$ will occur at different T



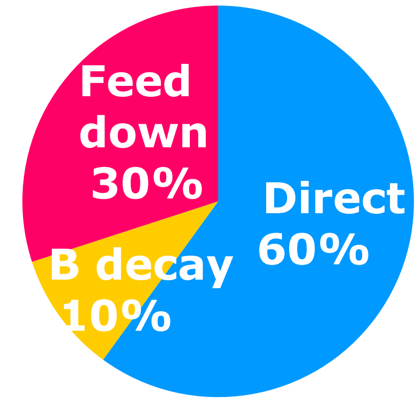
Sequential suppression of the resonances ➡ thermometer for the temperature reached in the HI collisions

Quarkonium production and decay

J/ψ production

Quarkonium production can proceed:

- directly in the interaction of the initial partons
- via the decay of heavier hadrons (feed-down)



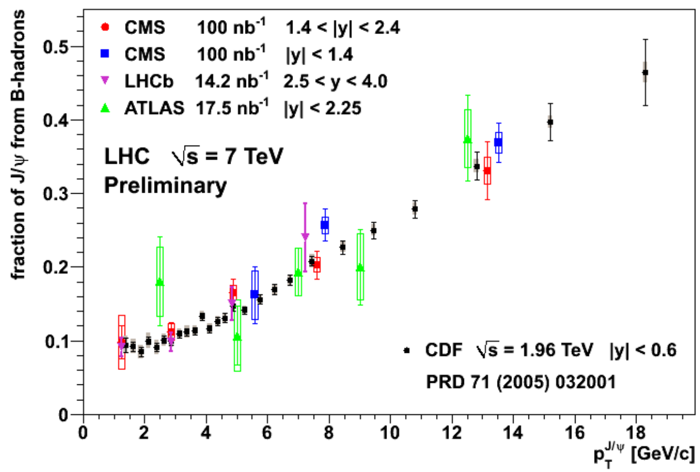
For J/ψ (LHC energies) the contributing mechanisms are:

Prompt

- Direct production
- Feed-down from higher charmonium states:
  ~ 8% from ψ(2S), ~25% from χ_c

Displaced

- B decay
  contribution is p_T dependent
  ~10% at p_T~1.5GeV/c



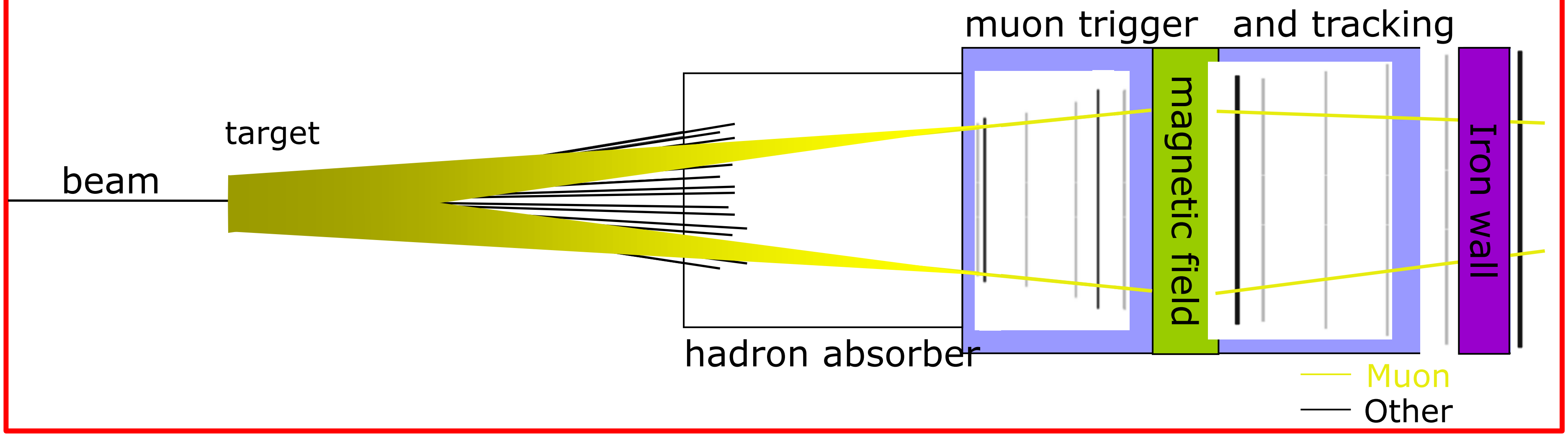
J/ψ decay

J/ψ can be studied through its decays:

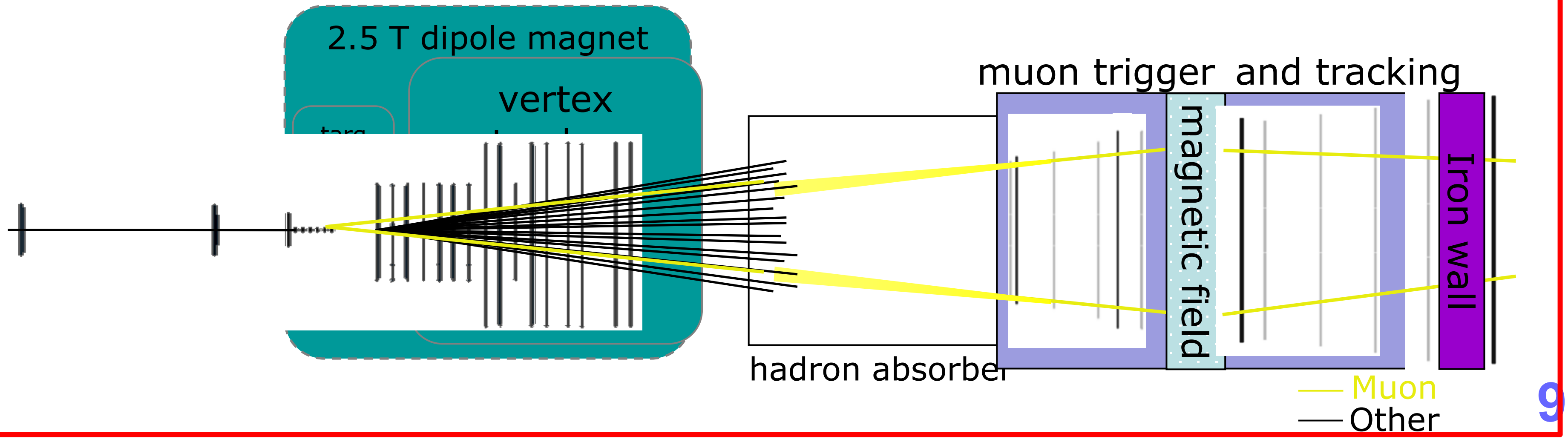
$J/\psi \rightarrow \mu^+\mu^-$ **$J/\psi \rightarrow e^+e^-$** (~6% branching ratio)

How to measure μ pairs?

NA50, PHENIX and ALICE (forward region)



NA60, LHC exp. and foreseen in PHENIX,ALICE(forward muon) upgrades



Quarkonium production in pp

J/ψ is produced in two steps that can be factorized:

- **Production of the $Q\bar{Q}$ pair → perturbative**
- **Evolution of $Q\bar{Q}$ pair into a bound state → non perturbative**

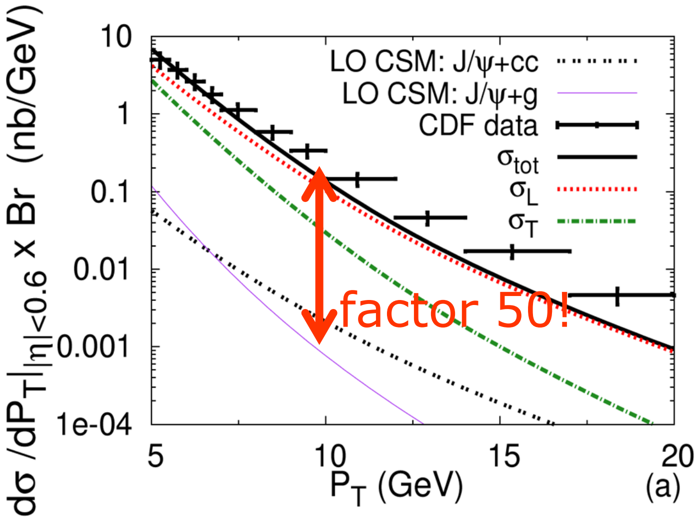
Different descriptions of this evolution are behind the various theoretical models

→ Color singlet model
→ Color evaporation model
→ NRQCD

CDF results on J/ψ direct production revealed a striking discrepancy wrt LO CSM

The agreement improves in NRQCD approach

…but situation still puzzling, because J/ψ polarization is not described!



Open questions, to be investigated at LHC!

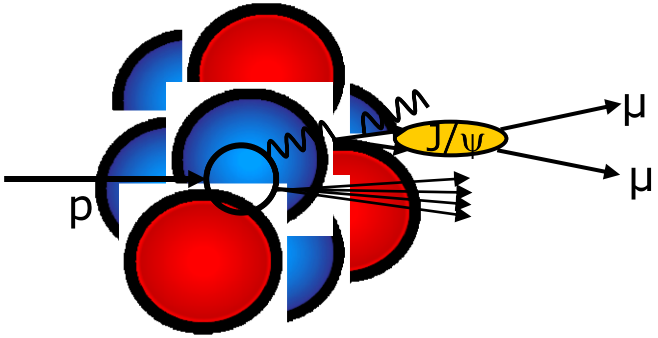
Quarkonium production in pA

To understand quarkonium behaviour in the hot medium, it's important to know its behaviour in the cold nuclear matter.
→ this information can be achieved studying pA collisions

allow the understanding the J/ψ behaviour in the cold nuclear medium
→ complicate issue, because of many competing mechanisms:

Initial state

shadowing,
parton energy loss,
intrinsic charm



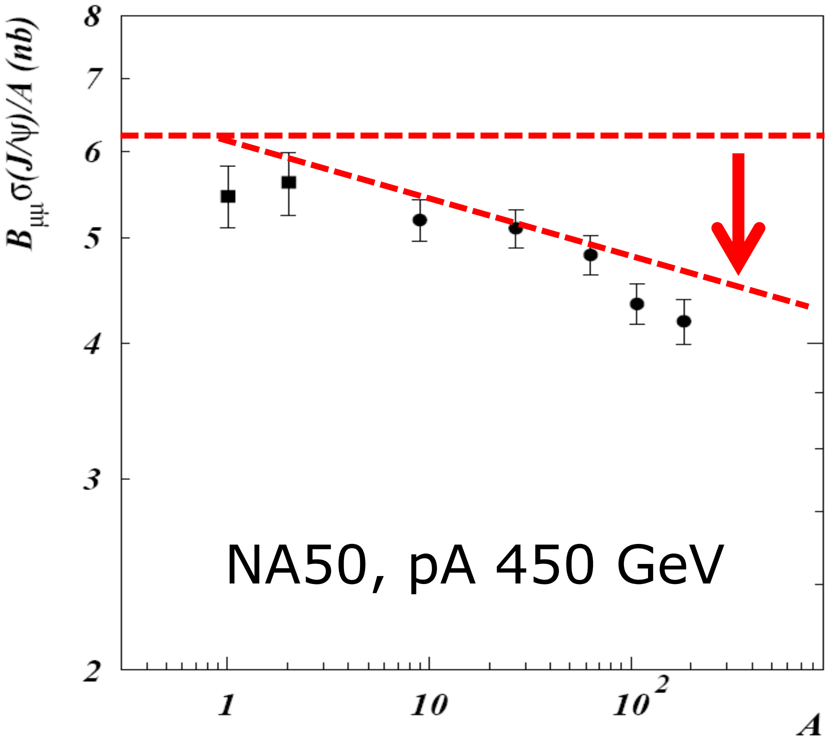
Final state

cc dissociation
in the medium,
final energy loss

provide a reference for the study of charmonia dissociation in a hot medium
→ approach followed at SPS and similarly at RHIC (with dAu data)

Cold Nuclear Matter effects

- In pA collisions, no QGP formation is expected
  - → in principle, no J/ψ suppression
  - → however a reduction of the yield per nucleon-nucleon collisions is observed
- These effects can be quantified, in pA collisions, in two ways:



$$\sigma_{pA} = \sigma_{pp} A^{\alpha}$$

α = 1 → no nuclear effects

α <1 → nuclear effects

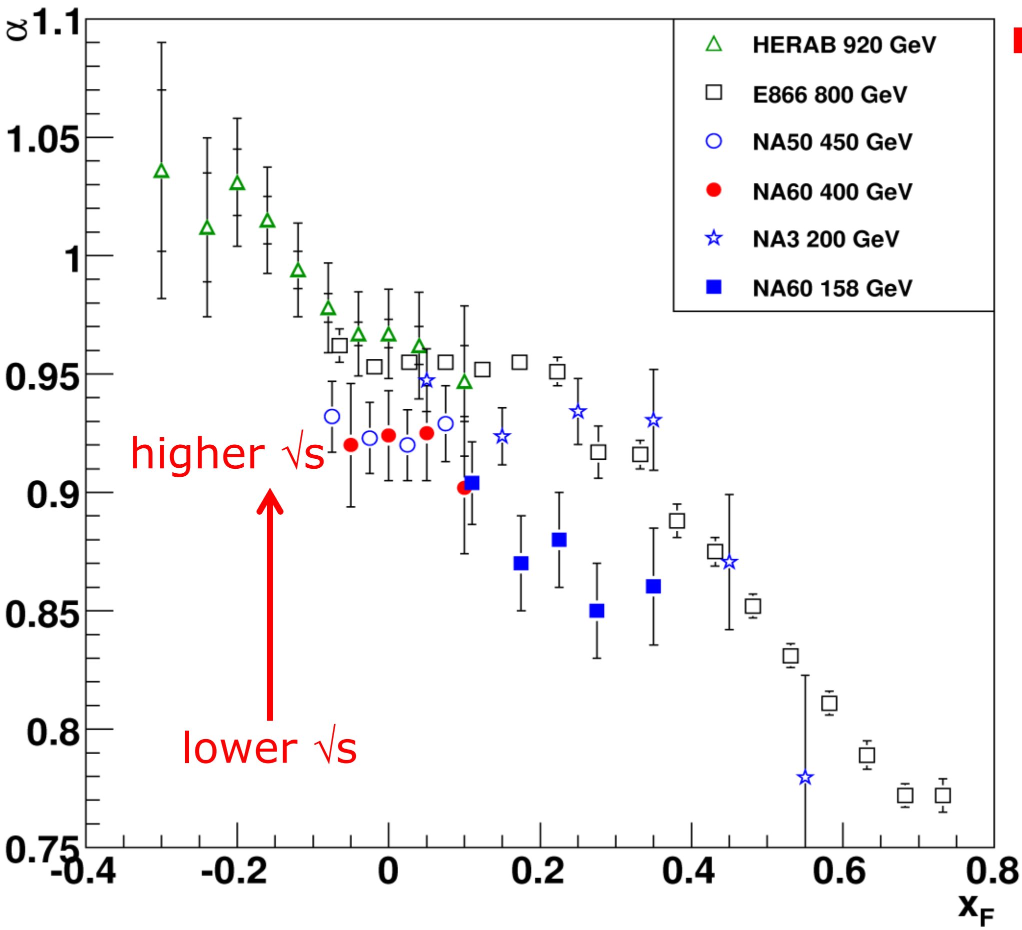
$$\sigma_{pA} \sim \sigma_{pp} A e^{-\rho L \sigma_{abs}}$$

- The larger σ_{abs}, the more important are the nuclear effects
- L is the length of nuclear matter seen by the resonance

Effective quantities which include all initial and final state effects

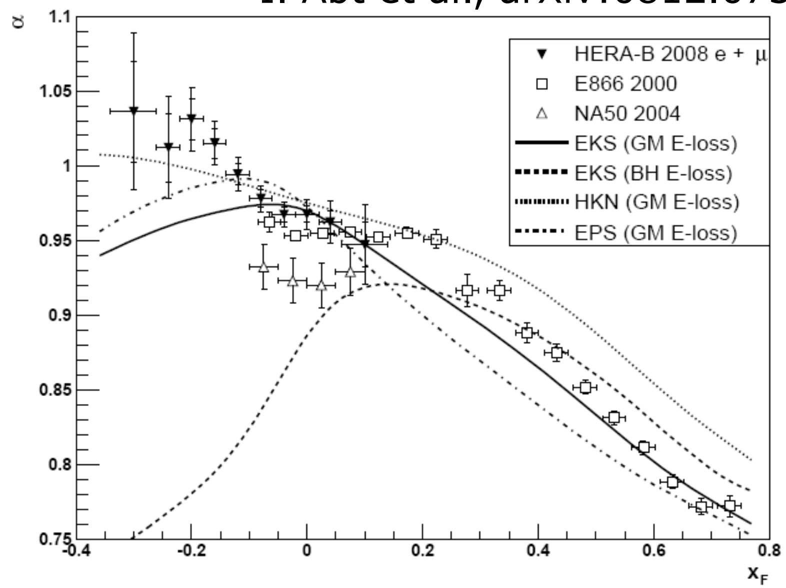
Nuclear effects vs x_F

- Collection of results from many fixed target pA experiments



- Nuclear effects show a strong variation vs the kinematic variables

I. Abt et al., arXiv:0812.0734

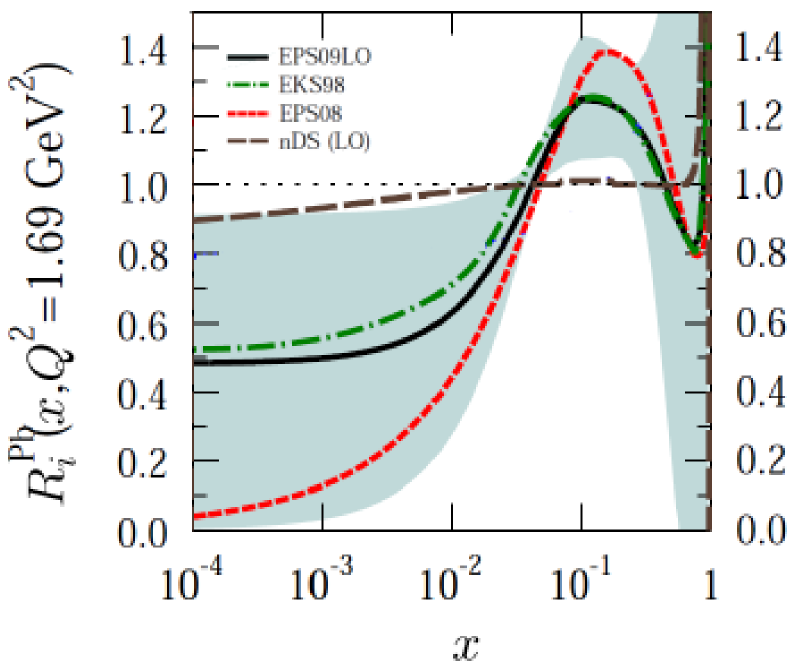


- Because of the α dependence on x_F and energy
  → the reference for the AA suppression must be obtained under the same kinematic/energy domain as the AA data

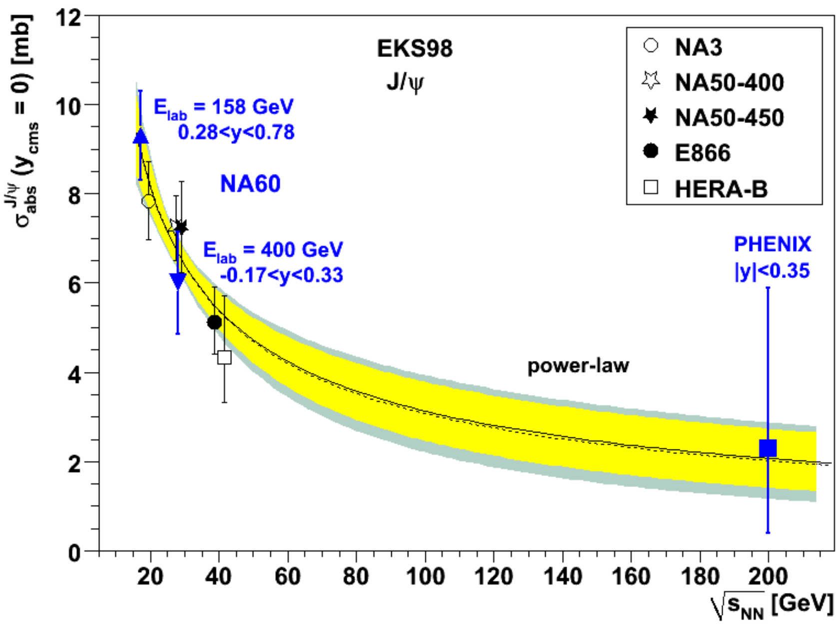
Nuclear effects

- Interpretation of results not easy
  → many competing effects affect J/ψ production/propagation in nuclei
    - anti-shadowing (with large uncertainties on gluon densities!)
    - final state absorption…
  → need to disentangle the different contributions

- Size of shadowing effects may be large → to be taken into account comparing results at different √s



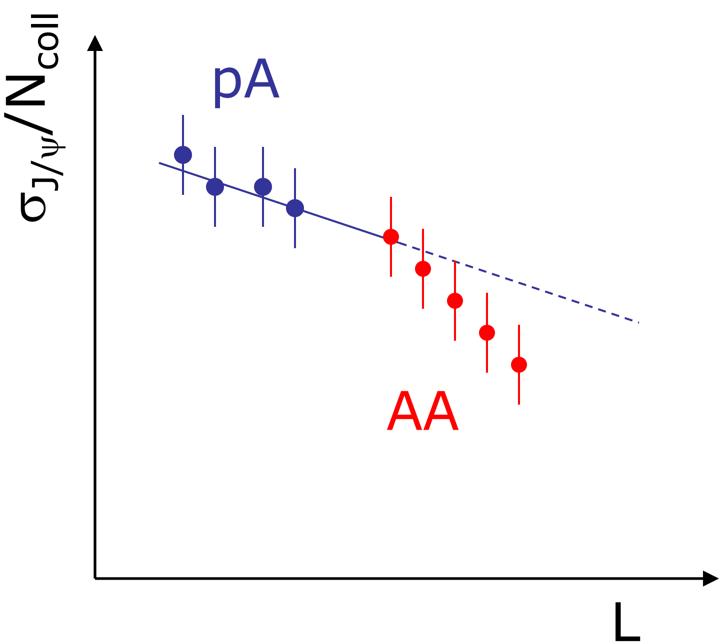
- Clear tendency towards stronger absorption at low √s

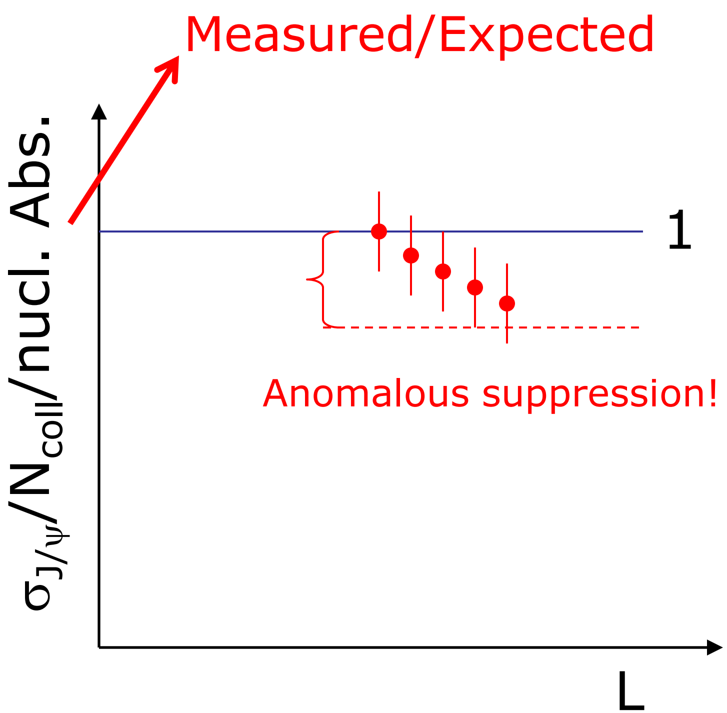


C. Lourenco, R. Vogt and H.Woehri, JHEP 0902:014,2009
F. Arleo and Vi-Nham Tram Eur.Phys.J.C55:449-461,2008, arXiv:0907.0043

Why CNM are important?

- The cold nuclear matter effects present in pA collisions are of course present also in AA and can mask genuine QGP effects





- It is very important to measure cold nuclear matter effects before any claim of an "anomalous" suppression in AA collisions

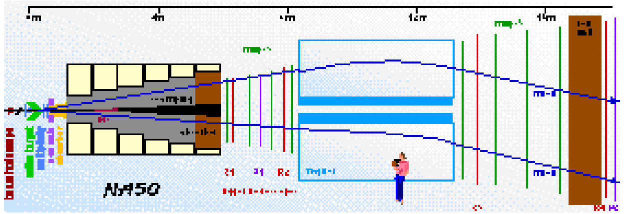
- CNM, evaluated in pA, are extrapolated to AA, in order to build a reference for the J/ψ behaviour in hadronic matter

J/ψ in AA collisions @ SPS

A long heavy-ion program has been carried out at SPS and several experiments (NA38, NA50, NA60) were focused on charmonia study

NA50

- PbPb collisions @ 158 GeV
- Number of collected J/ψ ~ 100000
- J/ψ width ~ 100 MeV/c^2



NA60

Based on the NA50 apparatus improved with a pixel vertex detector in the target region

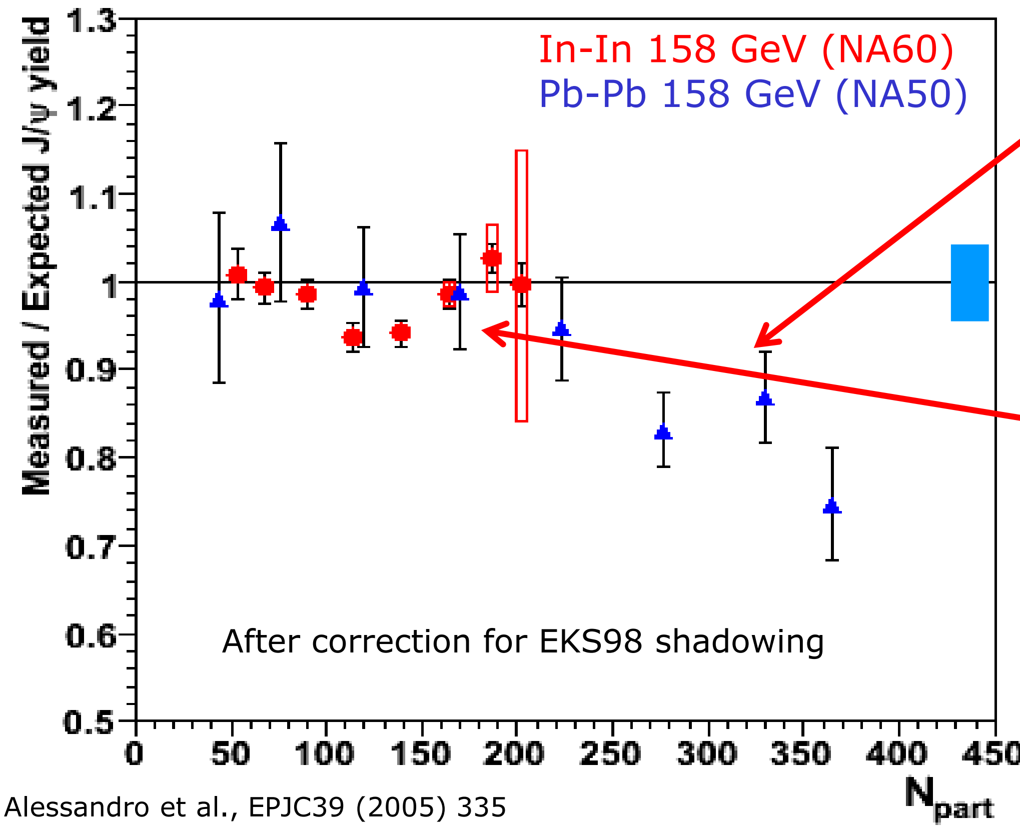
- High quality data, thanks to the improved experimental apparatus
  - ~30000 J/ψ
  - J/ψ width ~70MeV
- Lighter colliding system: InIn @ 158GeV

  to get further insight in the J/ψ suppression comparing lighter and heavier systems at the same energy

J/ψ results @ SPS

Let's compare NA50 and NA60 results. The measured J/ψ is compared to the expected yield extrapolated from pA data:

To understand anomalous suppression, the reference determination is crucial
→ reference now based on NA60 pA data @ 158GeV, the same AA energy



Anomalous suppression visible in central PbPb collisions

Agreement between PbPb and InIn in the common N_{part} region

PbPb data not precise enough to clarify the details of the pattern!

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345
R.A., P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

J/ψ measurements @ RHIC

PHENIX/STAR

Similar strategy as the one adopted at SPS:

AuAu @ $\sqrt{s}$=200GeV
CuCu @ $\sqrt{s}$=200GeV ← lighter system
pp @ $\sqrt{s}$=200GeV ← for reference
dAu @ $\sqrt{s}$=200GeV ← to determine cold nuclear matter effects

PHENIX $J/\psi \to e^+e^-$ $|y|<0.35$ & $J/\psi \to \mu^+\mu^-$ $|y| \in [1.2,2.2]$

STAR $J/\psi \to e^+e^-$ $|y|<1$

➡ Results based on a smaller statistics wrt SPS
- ~ 15000 J/ψ in the forward region
- ~ 1000 J/ψ at midrapidity

arXiv:1103.6269

➡ The J/ψ suppression is studied through the nuclear modification R_{AA} or the R_{CP} factors

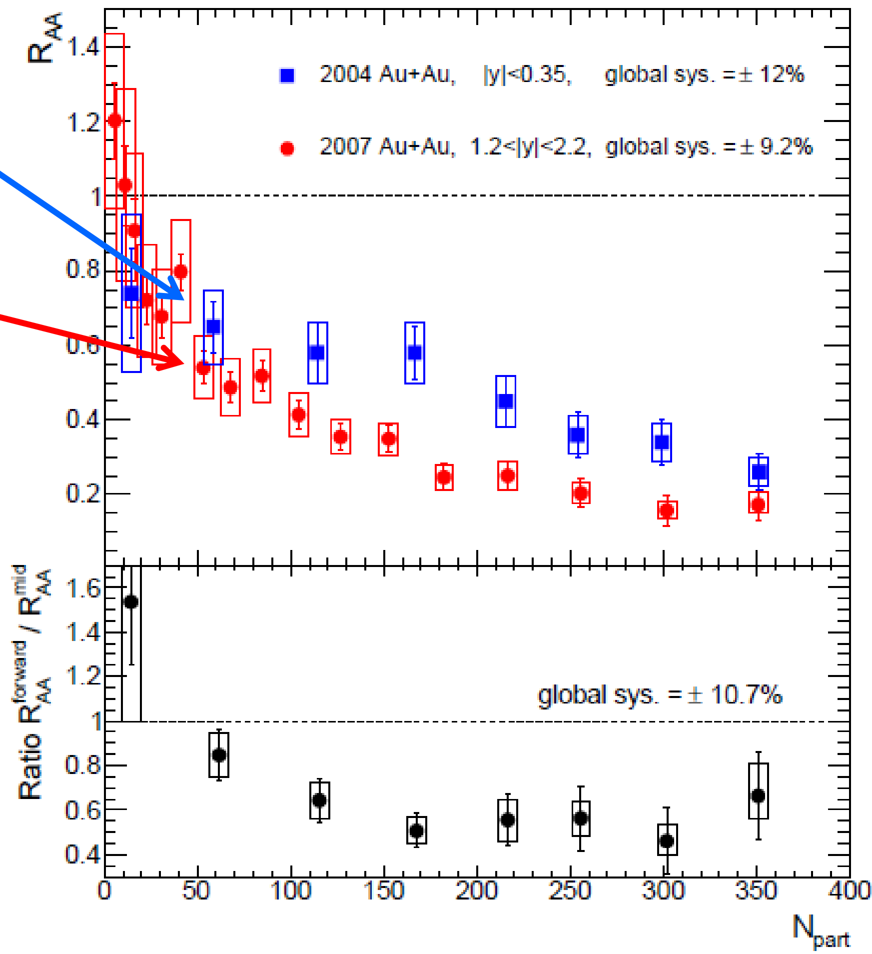
➡ Recent comparison with dAu data, in order to account for cold nuclear matter effects in AuAu

J/ψ @ RHIC: AA collisions

- Comparison of results obtained at different rapidities

Mid-rapidity

Forward-rapidity

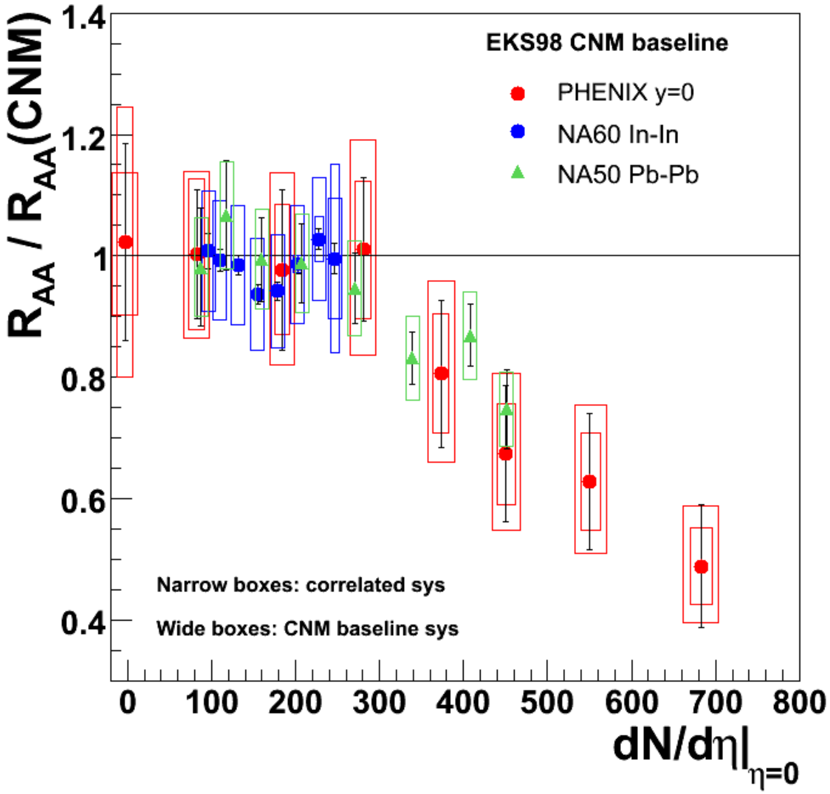


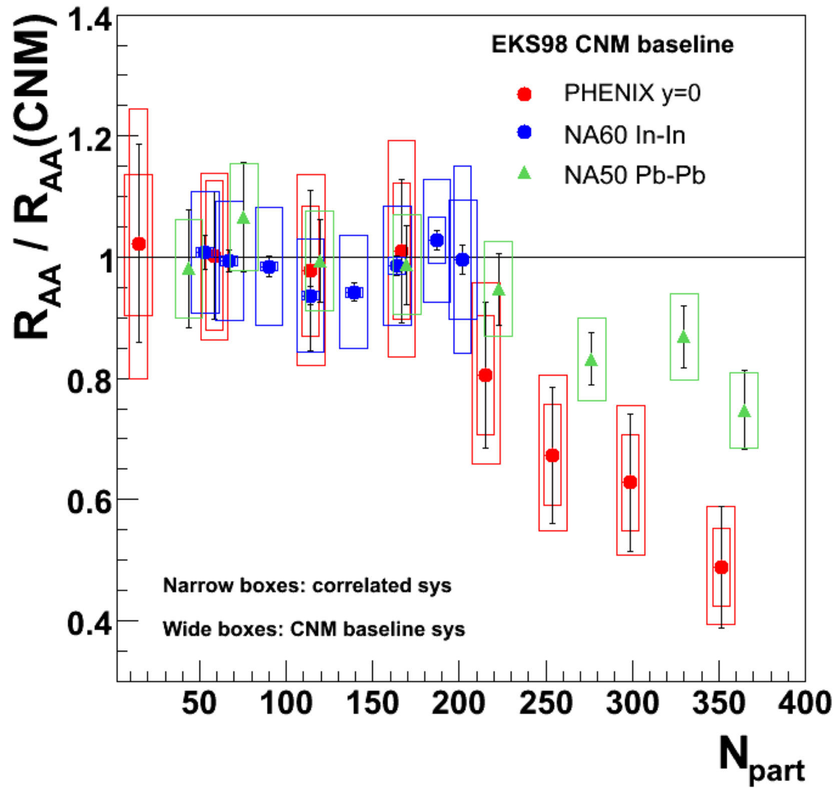
- Stronger (unexpected) suppression at forward rapidities

- No satisfactory theoretical description
- Suppression larger than CNM expectations
- Comprehensive understanding of the numerous CNM effects not yet available
  → quantitative estimate of hot matter effects still missing!

Comparison of RHIC/SPS results

Have SPS and RHIC results already provided a clear picture of J/ψ behaviour in a hot matter?



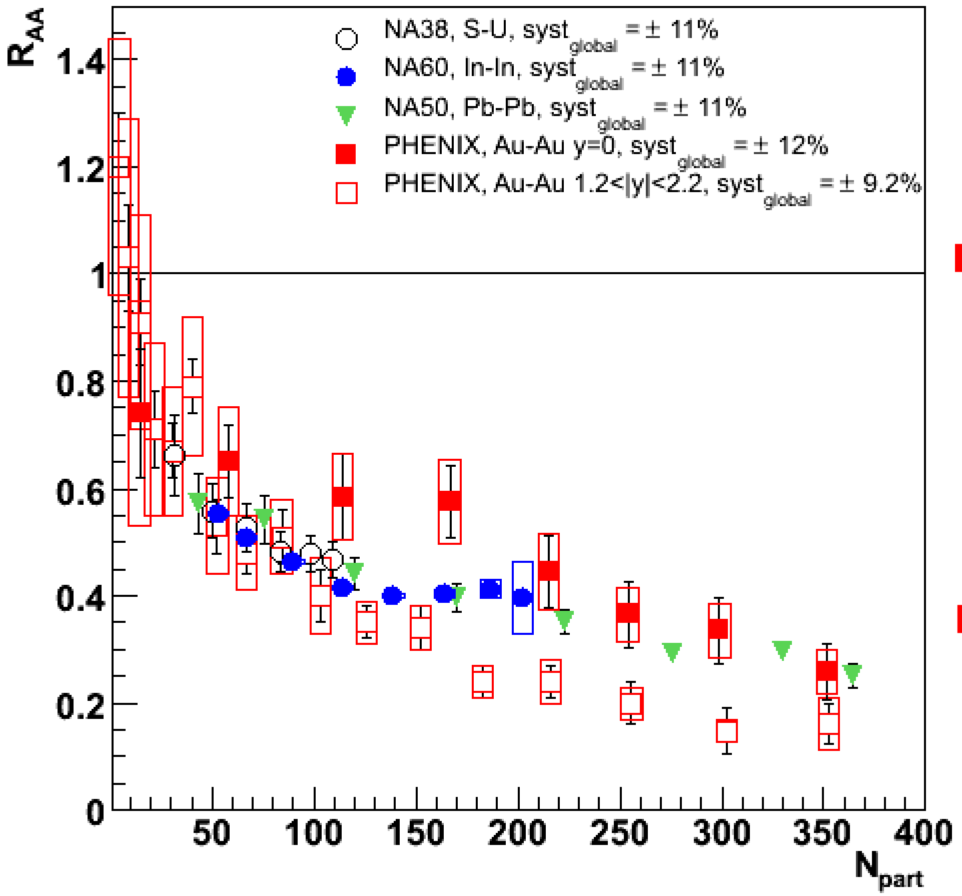


Results are shown as a function of the multiplicity of charged particles (~energy density, assuming $\tau_{SPS} \sim \tau_{RHIC}$)

Comparison done also in terms of number of participants

Comparison RHIC/SPS

- R_{AA} comparison between SPS and RHIC



CAVEAT: at SPS no pp data taking @ 158GeV → need to build the reference extrapolating pA data to A=1

- The initial estimate of the pp reference was obtained from pA data at higher energy, 450 GeV, (and rescaled to 158GeV)
  → All R_{AA} looked similar!

- …but recently the pp reference was obtained directly from NA60 pA @ 158 GeV
  → the comparison looks different!

- pp reference is crucial to correctly interpret the results!

- …picture not yet clear!

Theoretical interpretations

- Several theoretical models have been proposed to explain the similar suppression at SPS and RHIC:

  1) Only J/ψ from ψ' and χ_c decays are suppressed at SPS and RHIC
     - → same suppression is expected at SPS and RHIC
     - → reasonable if T_{diss} (J/ψ) ~ $2T_c$

  2) Also direct J/ψ are suppressed at RHIC but cc multiplicity high
     - → J/ψ regeneration ($\propto N_{cc}^2$) contributes to the J/ψ yield
     - → The 2 effects may balance: suppression similar to SPS

- Unfortunately data do not allow to clearly assess if recombination can play a role at RHIC

Recombination is measured in an indirect way:

- J/ψ elliptic flow
  → J/ψ should inherit the heavy quark flow
- J/ψ y distribution
  → should be narrower wrt pp
- J/ψ p_T distribution
  → should be softer ($\langle p_T^2 \rangle \downarrow$) wrt pp

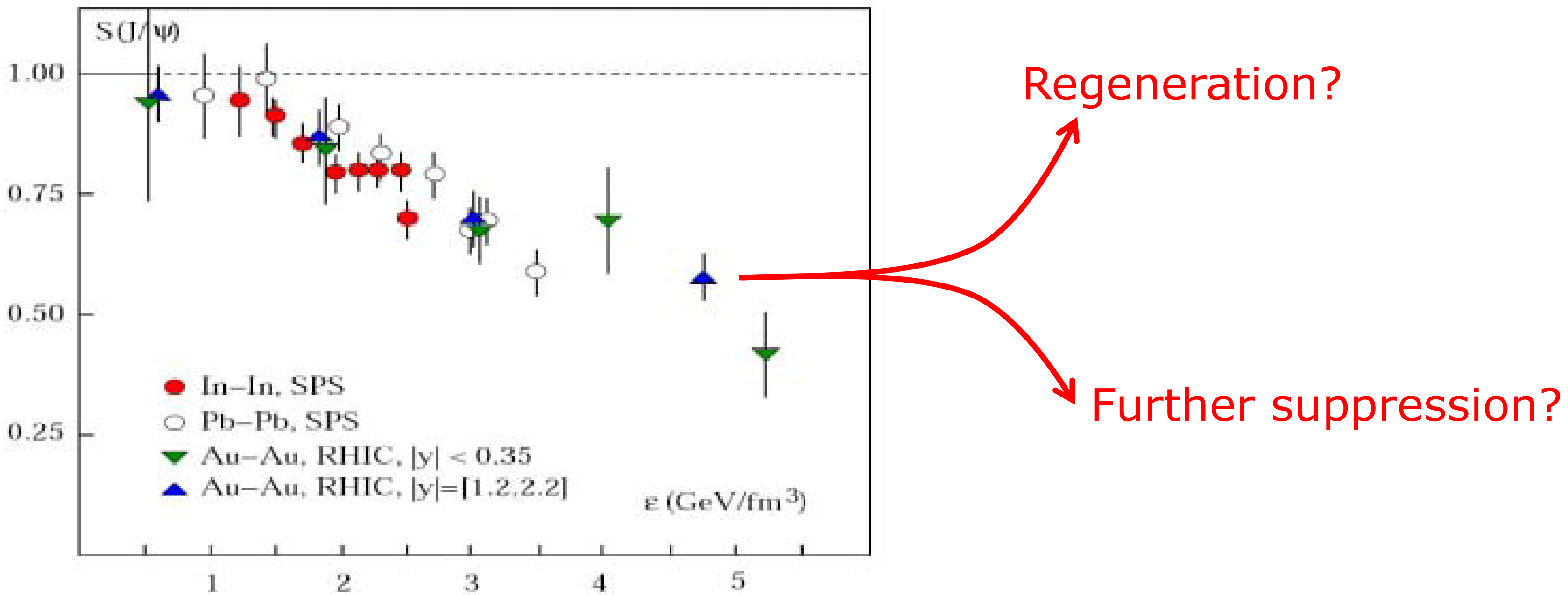
What should we expect @ LHC?

...many questions still to be answered at LHC energy!

- Role of the large charm quark multiplicity

$$\sigma c\bar{c}(LHC) = 10 \times \sigma c\bar{c}(RHIC)$$

→ **will J/ψ regeneration dominate the J/ψ picture?**



- Role of other quarkonia states (in particular bottomonium)

still (almost) unexplored in HI collisions
(<100 ϒ(1S+2S+3S) in AuAu@200GeV – STAR)

References for PbPb data

pp reference

- To quantify the J/ψ behaviour in AA, it is crucial to have a well defined reference
  → $\sigma_{J/\psi}$ in proton-proton at $\sqrt{s}$=2.76TeV as PbPb

Two possibilities:

- In March 2011 LHC has provided pp collisions at 2.76TeV
- Evaluate $\sigma_{J/\psi}$ at 2.76 TeV, relying on the 7TeV measurement and rescaling it via FONLL and CEM calculations (syst. error ~15%)

reference process

- Further insight on quarkonia in a hot matter can be obtained comparing the measured yield to a reference not affected by the medium
- at SPS, J/ψ was studied wrt Drell-Yan …but low DY rate at LHC
- several proposals: Z^0, open charm, open beauty…

Best reference should:

→ share the same production mechanism with quarkonium
→ have initial/final state effects under control

Quarkonium @ LHC

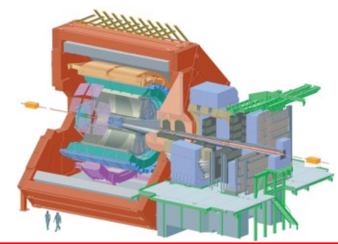
ALICE

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

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

p_T coverage down to $p_T \sim 0$

(up tp now only inclusive J/ψ results)

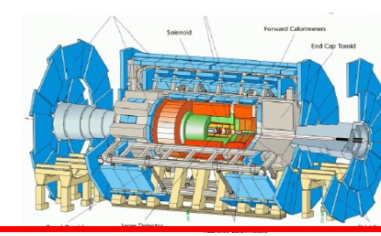


ATLAS

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

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

(separation between B and prompt J/ψ)

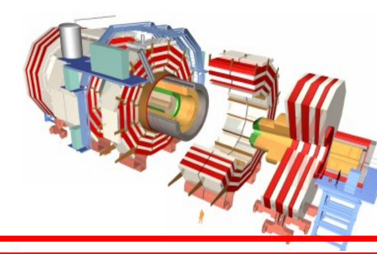


CMS

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

p_T coverage depending on the y region

(separation between B and prompt J/ψ)



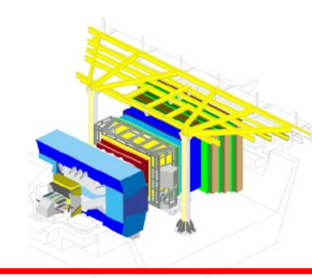
LHCb

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

p_T coverage down to $p_T \sim 0$

(separation between B and prompt J/ψ)

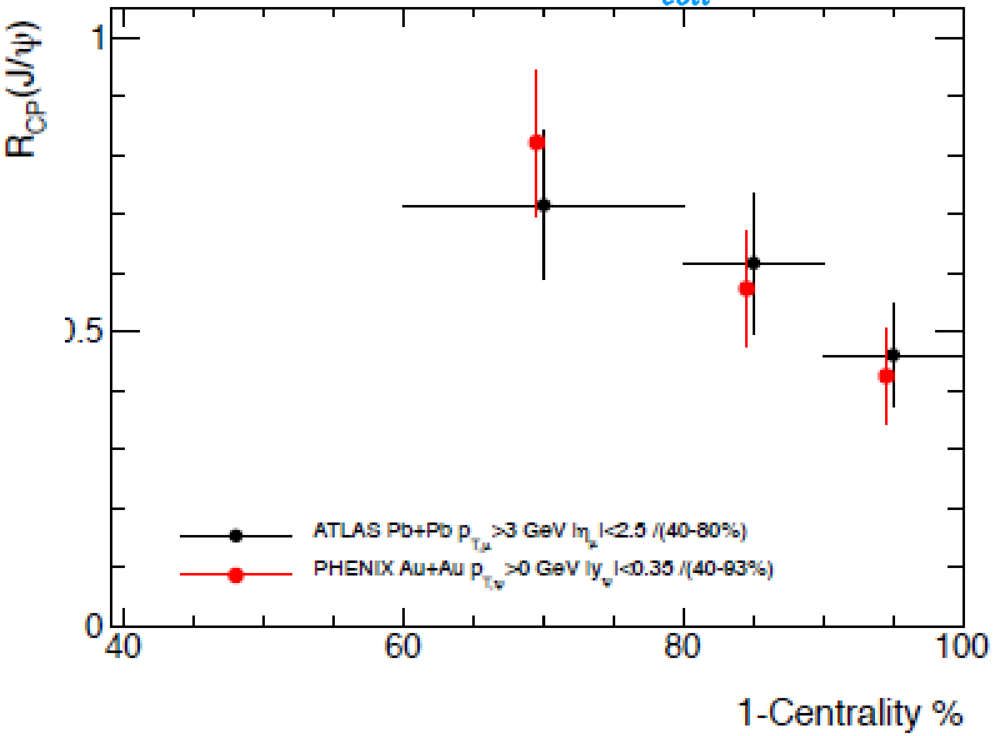
(no heavy ion physics program)



First PbPb results!

Preliminary comparison of ATLAS and PHENIX data

$$R_{CP} = \frac{dN^{central} / \langle N_{coll}^{central} \rangle}{dN^{peripheral} / \langle N_{coll}^{peripheral} \rangle}$$



P. Steinberg, LPCC HI@LHC, March 2011

Centrality dependence of J/ψ suppression seems invariant with beam energy in spite of different

- $\sqrt{s}$ (factor x14)
- initial energy density (~3)
- kinematic range (p_T>0 for PHENIX, p_T>6.5GeV ATLAS)
- no B feed-down correction (4% PHENIX, 20% ATLAS)

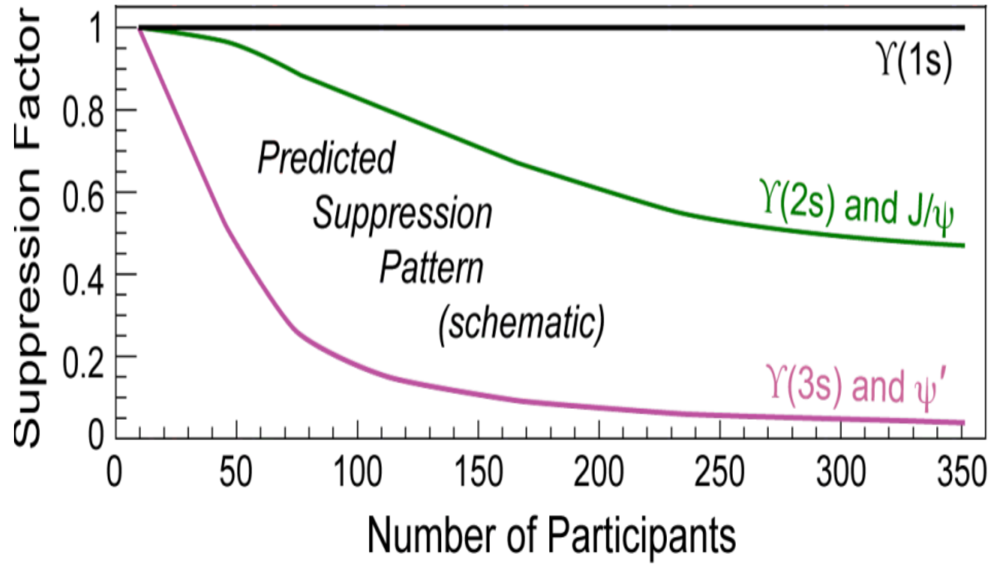
At a first glance…first LHC results do not seem to clarify all open questions…but new results expected at QM!

What about the ϒ?

Bottomonium states should be a cleaner probe, accessible at LHC

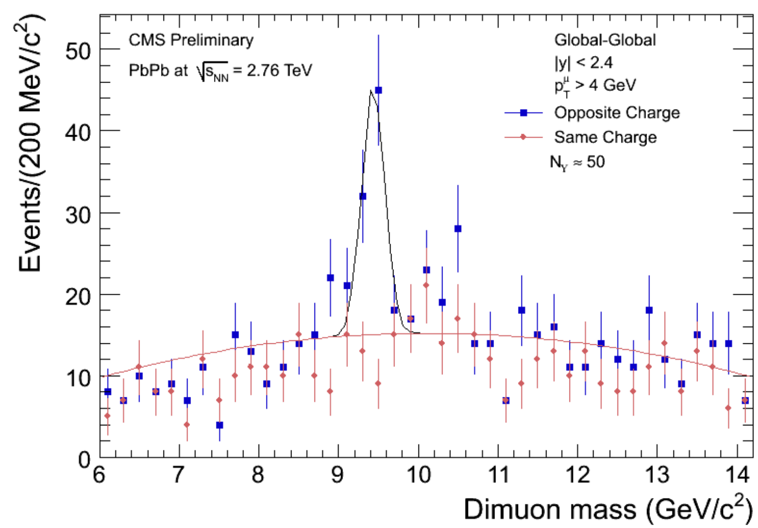
- More robust theoretical calculations
- No b hadron feed-down

…but with a lower production cross section

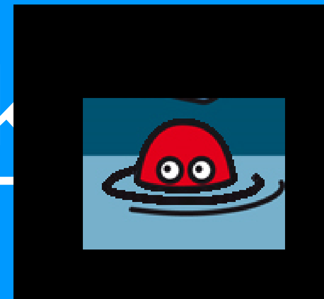


A good resolution is crucial to separate the 3 ϒ states, which have different dissociation temperatures . ϒ(1S) more easily separated (higher significance)

ϒ was hardly visible in AuAu @ 200GeV, but it has already been seen at LHC!



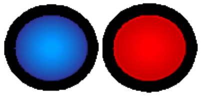
Heavy Quark



Heavy quarks

Because of their large mass (m_b~4.8 GeV, m_c~1.2 GeV), heavy quarks (charm and bottom) are produced in parton-parton collisions with large momentum transfer Q^2, at the initial stage of the reaction.

pp



the study of their production is

→ a useful test of the theory
→ it provides a baseline for AA study

AA

different interaction with the medium wrt light quarks (dead cone effect, see later)

→ powerful tool to investigate medium properties in AA collisions

Important measurement for quarkonium physics

→ Open $Q\bar{Q}$ production is a natural normalization for quarkonium
→ B decay is a not negligible source of non-prompt J/ψ

Heavy quark production

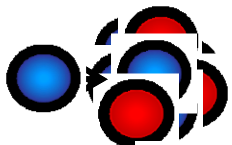
At high energies, heavy quarks are produced by hard scattering
→ their production cross section in pA or AB collisions is proportional to the number of hard scattering (number of nucleon-nucleon collisions)

→ Binary scaling

$$\sigma_{pA} = \sigma_{pp} \times A$$

$$\sigma_{AB} = \sigma_{pp} \times AB$$

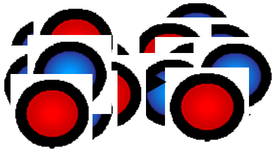
Binary scaling can be broken because of



Initial state effects → present in pA and AA collisions

- Cronin effect → inducing changes in the parton momenta
- Nuclear PDF → changes to the PDF in nuclei wrt parton ones
- Color Glass Condensate → gluon saturation at low x

Final state effects → present only in AA collisions



- Energy loss/ jet quenching

Heavy quarks radiative energy loss

- In the heavy quarks case the energy loss should be smaller wrt light hadrons:

$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$

  - Casimir factor (color-charge dependence)
    → 3 for g interactions, 4/3 for q interactions
    → heavy hadrons are mainly produced from heavy quarks jet (while light hadrons are produced from gluon jets)

  - Dead cone effect (mass dependence)
    → Gluon radiation is suppressed for angles $\vartheta < M_Q/E_Q$

- Heavy flavour en. loss should be different (smaller) than the light hadrons one

  - Summarizing

$$\begin{cases} \Delta E_{light\ h} > \Delta E_{charm} > \Delta E_{beauty} \\ R_{AA}\ (\text{light hadrons}) < R_{AA}\ (D) < R_{AA}\ (B) \end{cases}$$

Heavy flavour hadrons

- Lower mass heavy flavor decay weakly with:
  - $\tau \sim$ ps (produced in the first instants of the collisions)
  - $c\tau \sim$ hundreds μm (decay vertex displaced wrt the interaction vertex)

	Mass (MeV)	cτ (μm)
$D^+(c\bar{d})$	1869	312
$D^0(c\bar{u})$	1865	123
$D_s{}^+(c\bar{s})$	1968	147
$\Lambda_c{}^+(udc)$	2285	60
$\Xi_c{}^+(usc)$	2466	132
$\Xi_c{}^0(dsc)$	2472	34
$\Omega_c{}^0(ssc)$	2698	21

	Mass (MeV)	cτ (μm)
$B^+(u\bar{b})$	5279	501
$B^0(d\bar{b})$	5279	460
$B_s{}^0(s\bar{b})$	5370	438
$B_c{}^+(c\bar{b})$	6400	100-200
$\Lambda_b{}^0(udb)$	5624	368

- Large branching ratios to kaons:
  - $D^+ \to K^-X$ BR~28%
  - $D^+ \to K^-\pi^+\pi^+$ BR ~9%
  - $D^0 \to K^-X$ BR~50%
  - $D^0 \to K^-\pi^+$ BR ~4%
- Large semileptonic branching ratio decays ~ 10% ($e^\pm$ or $\mu^\pm$)

Heavy flavour: experimental techniques

Let's start considering the experimental techniques for the HF study, which have been adopted at RHIC:

D, B reconstruction

Reconstruct D (B) from their decay products

→ Most direct measurement, but complicate since it requires good capability in the decay vertex reconstruction.

→ In AA collisions it suffers from large combinatorial background

Non photonic electrons

Measure single leptons from heavy flavour decay (both charm and bottom have relatively large BR ~10% to single e)

→ More indirect approach, requiring an accurate knowledge of the photonic/non-photonic background sources

Muons

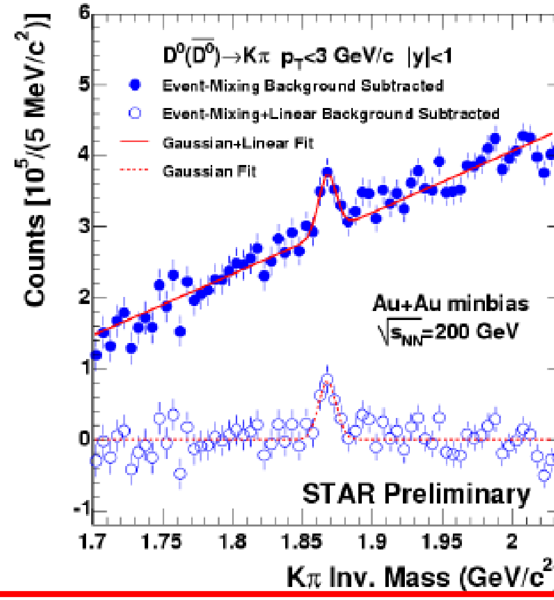
Measure DCA (distance of closest approach) to separate μ from charm from μ from π and K decay

Heavy flavour: RHIC results

D reconstruction

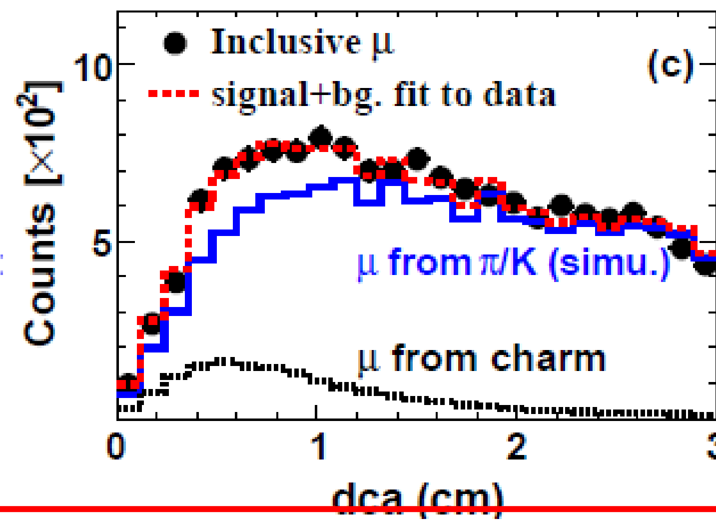
$D^0 \rightarrow K^- \pi^+$

- K, π identification from dE/dx (TPC). Measurement at p_T<2 GeV/c
- Large comb. background (especially in AA collisions) evaluated by event mixing
- Complicate measurement at RHIC because of lack of vertex detectors



D from μ

- Muons identified combining TOF+TPC
- Measurement at very low p_T 0.17<p_T<0.25 GeV/c
- DCA distribution allows to disentangle μ from charm decay from μ from π and K decay



HF: RHIC results (2)

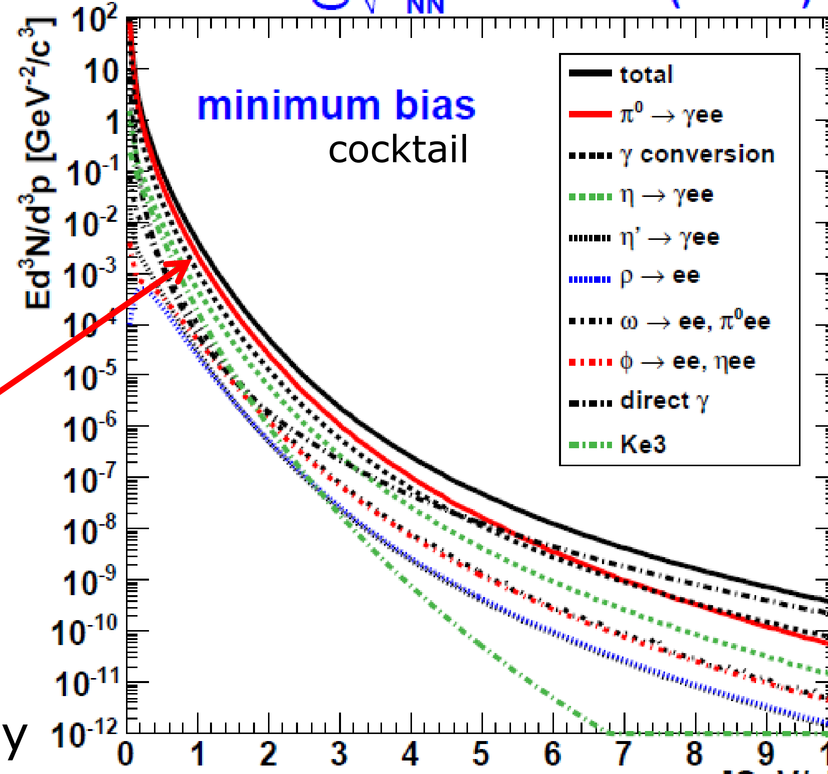
Non photonic electrons

- **Electron spectra identification**
  - → STAR: dE/dx in TPC+TOF @ low p_T, EMC @ high p_T
  - → PHENIX: combined RICH and E/p (E from EMCAL)

- **Rejection of non-heavy-flavour electrons, i.e. electrons from:**

photonic bck:
- $\gamma \rightarrow e^+e^-$ conversions
- Dalitz decay: $\pi^0(\eta) \rightarrow \gamma e^+e^-$

non-phot. bck:
- $K \rightarrow e\pi\nu$, vector mesons $e^\pm$ decay
- quarkonium, DY



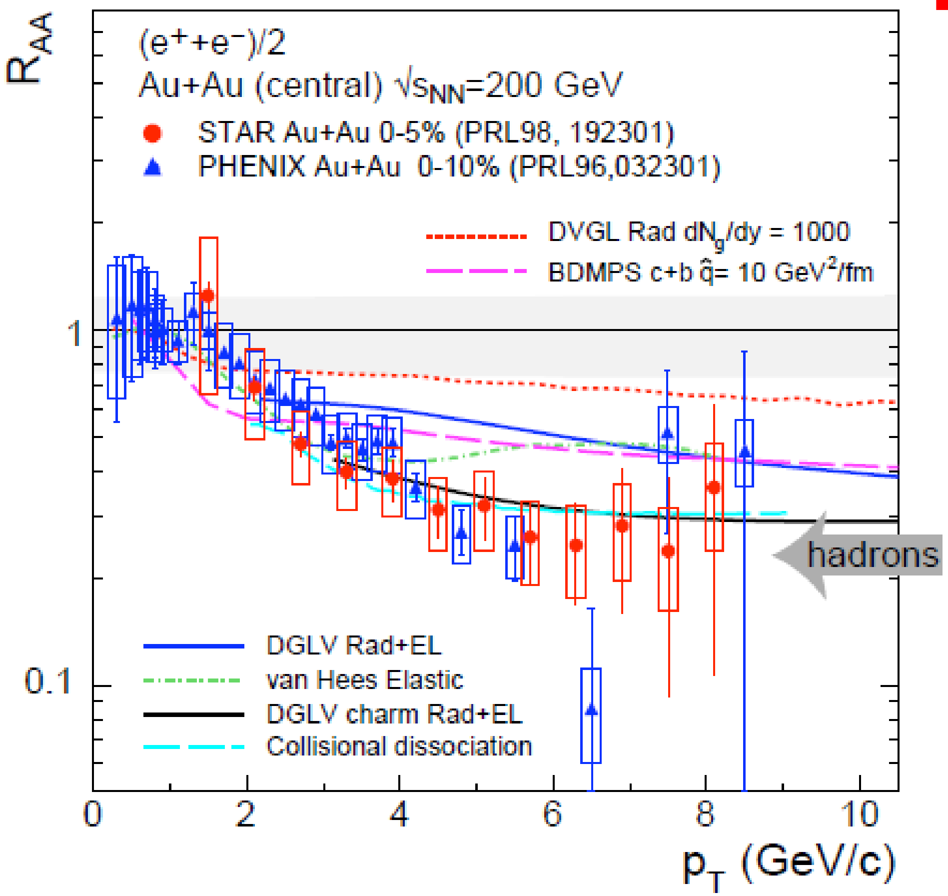
PHENIX, arXiv:1005.1627

→ STAR: full inv. mass analysis of e^+e^- and cocktail method

→ PHENIX: estimated through "cocktail method" or "converter method" and then subtracted

HF: RHIC experimental results - AA

R_{AA} from non photonic electrons

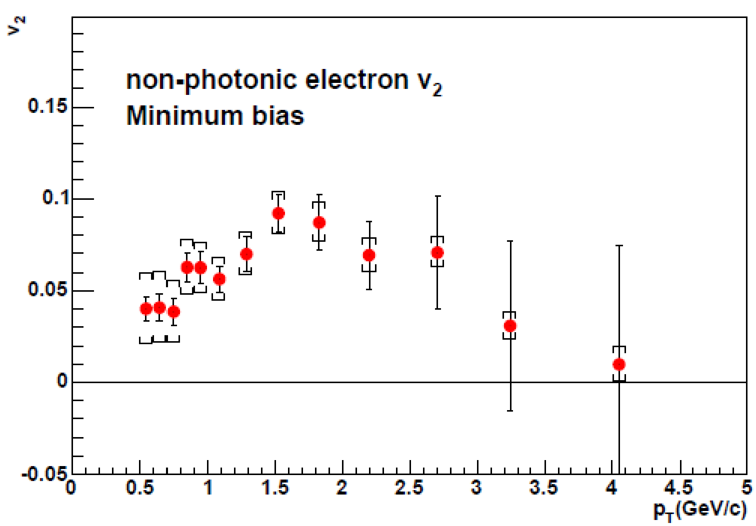


- Heavy quarks energy loss was expected to be reduced because of dead cone effect…but unexpected R_{AA} behaviour observed!

Same suppression as light hadrons!

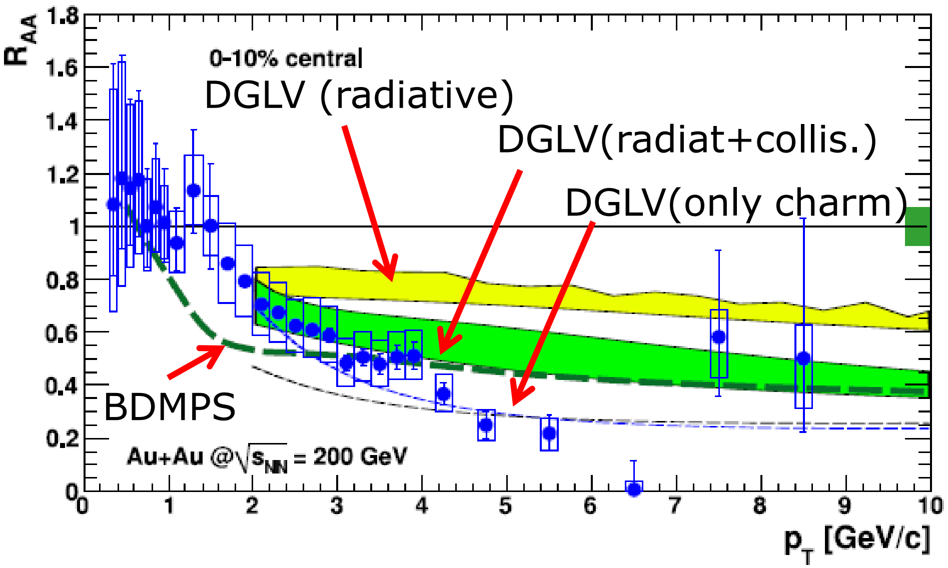
Difficult to explain theoretically

- nphe v_2 similar to the meson one

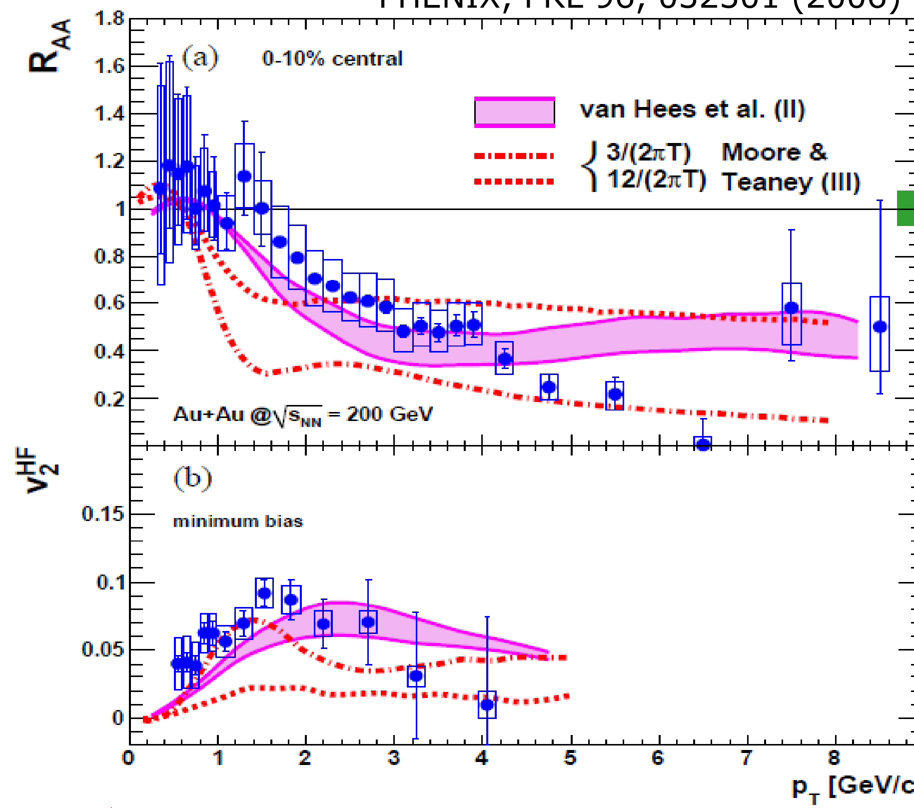


- c and b not disentangled @ RHIC because no vertex detector available → only indirect measurements

Some R_{AA} interpretations…



PHENIX, PRL 96, 032301 (2006)



- Collisional (elastic) energy loss
to be taken into account?

- Energy loss models sensitive to the B/D admixture
→ important to establish b and c contributions, since their en. loss should be different (less important for b)

- Models should describe at the same time the RAA and the v_2

- New AdS/CFT calculations also available

W. Alberico et al. arXiv:1102.6008
G.D.Moore and D. Teaney Phys. Rev zC 71, 064904

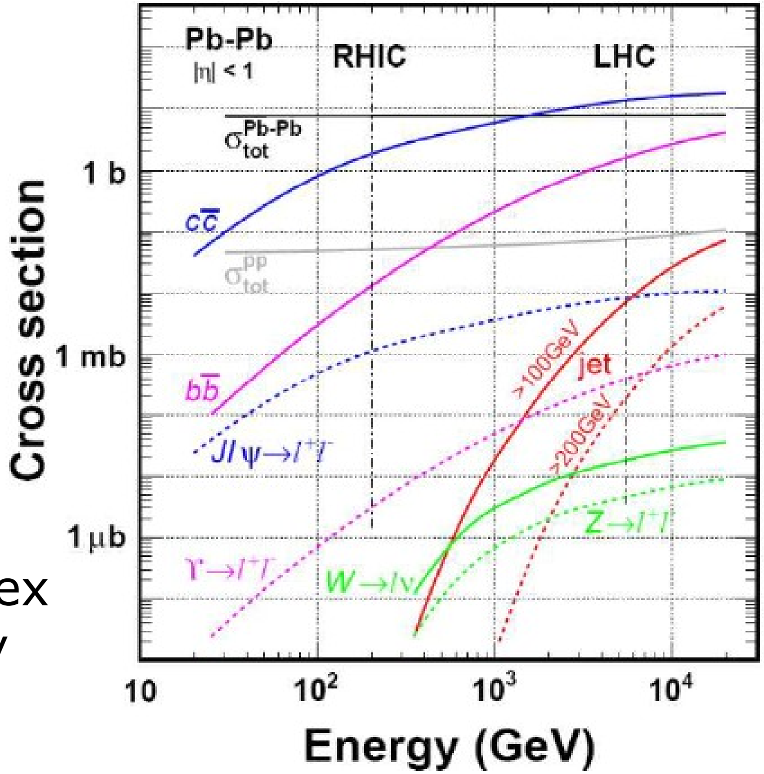
H. Van Hees et al. Phys. Rev. C 73, 034913
V. Greco et al. Phys. Lett B595 202
…and many more!

Heavy flavours @ LHC

- RHIC results limited by lack of vertex detectors and small production rate, especially for b

- Plenty of heavy quarks produced @LHC!

LHC PbPb@5.5TeV	RHIC AuAu@200GeV
σ_c (LHC)	~10 x σ_c(RHIC)
σ_b (LHC)	~100 x σ_b(RHIC)



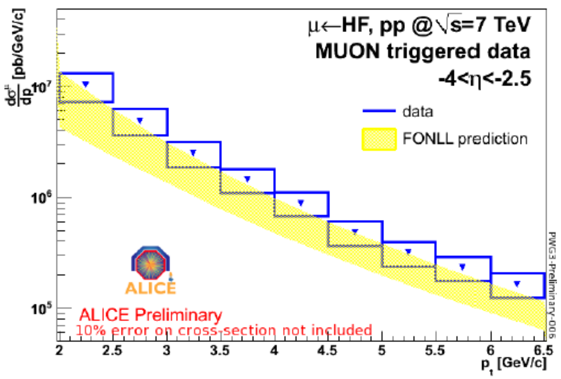
- All LHC experiments equipped with vertex detectors crucial for heavy flavour study

- D and B separation feasible at LHC!

Heavy quarks @ LHC

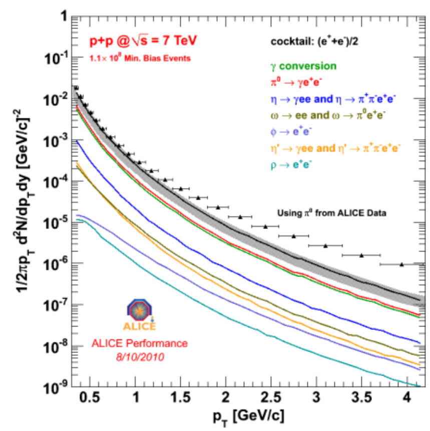
Similar analysis technique as those used at RHIC, with the improvement due to excellent displaced vertex identification
For the moment pp results are available, …waiting for PbPb results @ QM!

Muons



dσ/dp_T for D and B decay muons in $2<p_T<6.5$ GeV/c (main source of background are decay muons, removed with simulation)

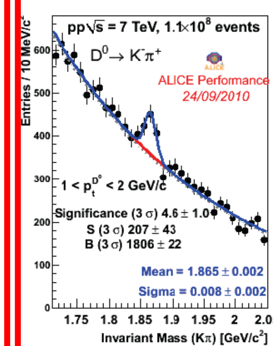
Non photonic electrons

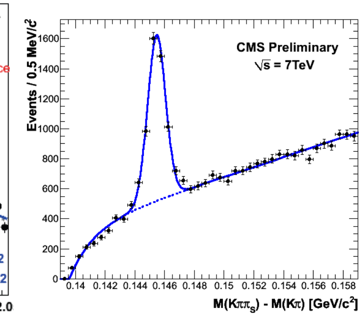


Two approaches:

- Cocktail, à la RHIC, to measure combined c+b cross sections
- Select e^- with large displacement to separate $e^\pm$ from b decay

D, B reconstruction





Selection based on displaced vertex topology.
Precise tracking and vertexing required!

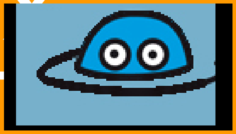
Conclusions

➡ Many questions are looking for an answer from LHC data!

the picture seems indeed quite complicate,

…but, hopefully, putting together all the pieces of the puzzle the scenario will be clarified!

Appendix



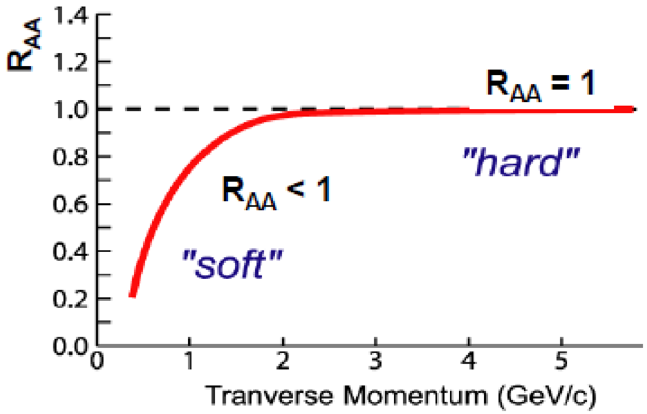
How to compare pp and AB data?

R_{AA}

$$R_{AB} = \frac{dN^P{}_{AB}}{\langle N_{Coll}\rangle \, dN^P{}_{NN}}$$

$dN^P{}_{AB}$ is the differential yield for a process P in AB collisions

$dN^P{}_{NN}$ is the differential yield for a process P in NN collisions



- If the process yield scales with the binary collisions
  → $R_{AA} = 1$
- If the binary scaling is broken:
  → $R_{AA} \neq 1$

R_{CP}

the probe behaviour in central and peripheral collisions is compared

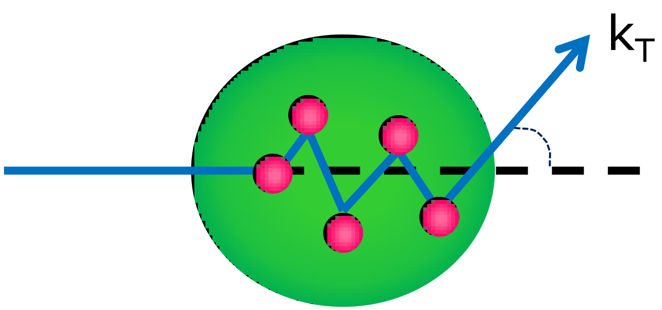
$$R_{CP} = \frac{dN^{central} / \langle N_{coll}{}^{central}\rangle}{dN^{peripheral} / \langle N_{coll}{}^{peripheral}\rangle}$$

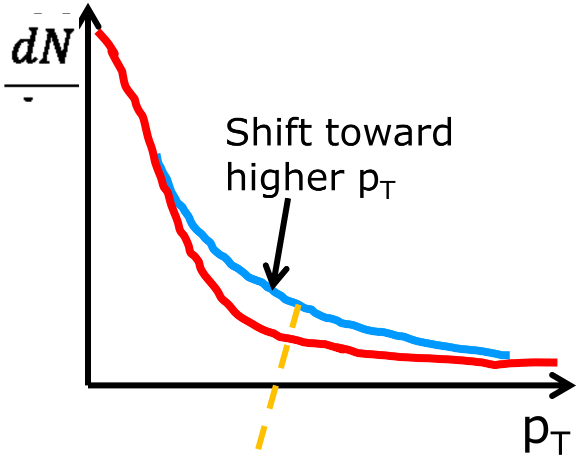
- If there is binary scaling
  → $R_{CP} = 1$
- If there are effects affecting in a different way central or peripheral collisions
  → $R_{CP} \neq 1$

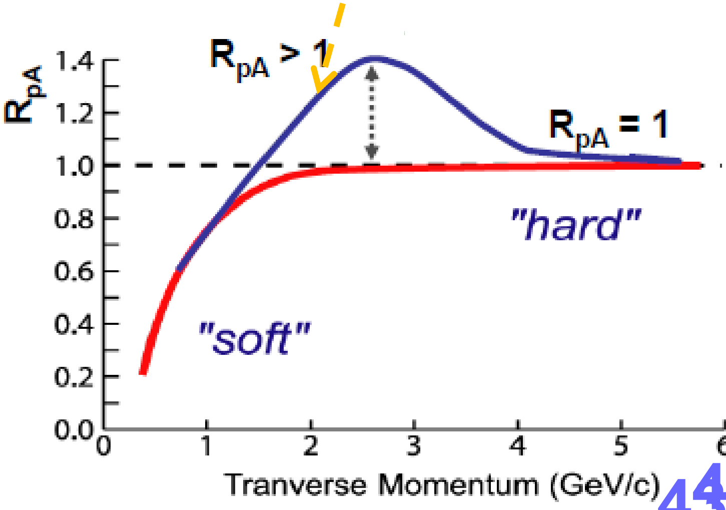
Cronin effect

Incident partons increase their transverse momentum, because of multiple scattering in their path through the nucleus A

- Projectile partons will acquire an extra transverse momentum (k_T) which will contribute to increase the transverse momentum of the produced hadron







- At very high p_T, the contribution of this extra k_T kick will become a negligible fraction of the measured p_T (~0 for $p_T \rightarrow \infty$)

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Nuclear PDFs

PDF in nuclei are strongly modified with respect to those in a free nucleon

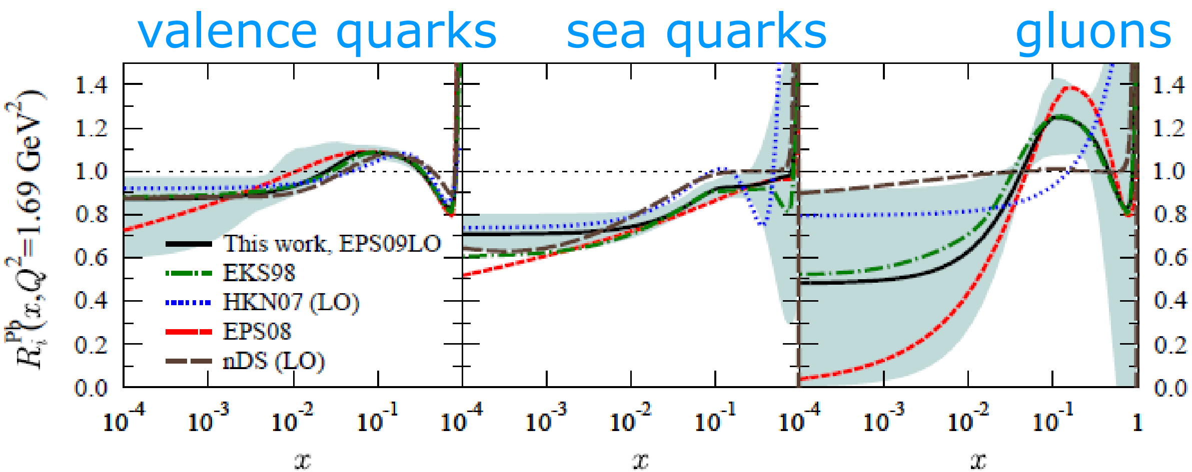
$f^A_i(x,Q^2) = R_i(A,x,Q^2) \times f^p_i(x,Q^2)$

nPDF: PDF of proton in a nucleus

free proton PDF

$R_i(A,x,Q^2) : \frac{f^A_i(x,Q^2)}{f^p_i(x,Q^2)}$

Several parameterizations to convert free nucleon pdf into the nuclear one



quark,antiquark

→ probed by DIS and Drell-Yan data
→ nuclear effects well constrained, parameterizations give similar results

gluons

→ more indirect connection between gluon densities and data
→ larger spread of results

LHC data cover an unexplored domain (small x, large Q^2)!

Energy loss

- A decrease in the parton energy implies a reduction of the momentum of the produced hadron
- A parton crossing the medium lose energy because of two mechanisms:
  - **Scattering with partons**
    → collisional energy loss
    → dominates at low energy
  - **Gluon radiation**
    → gluon bremsstrahlung
    → dominates at high energy

Radiative energy loss

$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$ (BDMPS approach)

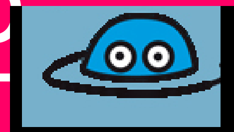
Casimir factor (C_r)
→ 3 for gg interactions
→ 4/3 for qg interactions

En. loss proportional to L^2, taking into account the probability to emit a bremsstralung gluon and the fact that radiated colored gluons interact themselves with the medium

$\hat{q}$ = transport coefficient, related to the medium characteristics and to the gluon density dN_g/dy
→ allows an indirect measurement of the medium energy density

$\hat{q}$ ~ 0.05 GeV^2/fm → cold matter
$\hat{q}$ ~ 5-15 GeV^2/fm → RHIC
$\hat{q}$ ~ 100 GeV^2/fm → LHC ?

Backup



Heavy Quarks

Heavy flavour production in pp

- Hadron production cross section in pp can be calculated in pQCD

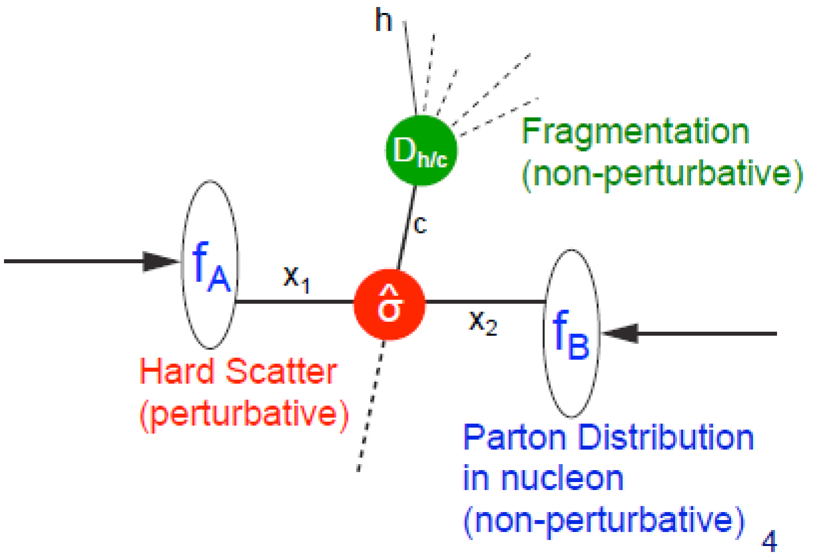
$$\sigma_{hh \to Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \to q\bar{q}} \otimes D_{q \to H}(z_q, Q^2)$$

Parton Distribution Functions
x_a, x_b → fraction of the momentum carried by the a,b partons in the hadron

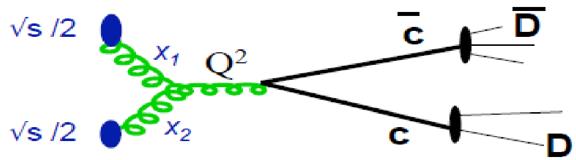
Partonic σ computed in pQCD
NLO: MNR code
Fixed order NLO: FONLL

Fragmentation of quark q into the hadron H

- Assumptions:
  - Factorization between the hard part and the non perturbative PDF and fragmentation function $D_{q \to H}(z_q, Q^2)$
  - Universal fragmentation and PDFs (e.g PDF from ep, fragmentation fz. from ee, but used in pp data)



Heavy flavour production in pp



$$\sigma_{hh \rightarrow Dx} = PDF(x_a,Q^2)PDF(x_b,Q^2) \otimes \sigma_{ab \rightarrow cc} \otimes D_{c \rightarrow D}(z_c,Q^2)$$

Partonic σ computed in pQCD

Perturbative expansion in powers of α_S

NLO: MNR code

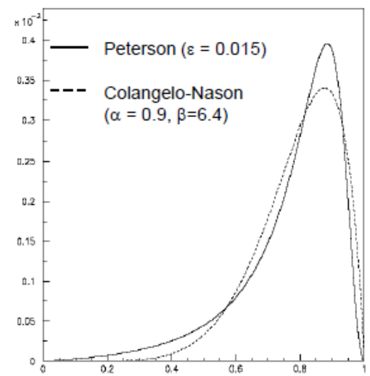
Fixed order NLO: FONLL

Parton Distribution Functions

x_a, x_b → fraction of the momentum carried by the a,b partons in the hadron

Fragmentation of quark into hadron

D and B mesons should have a large fraction z of the quark (c or b) momentum → harder fragmentation functions, peaked at z~1



Several parameterizations adopted (tuned on LEP D measurement)

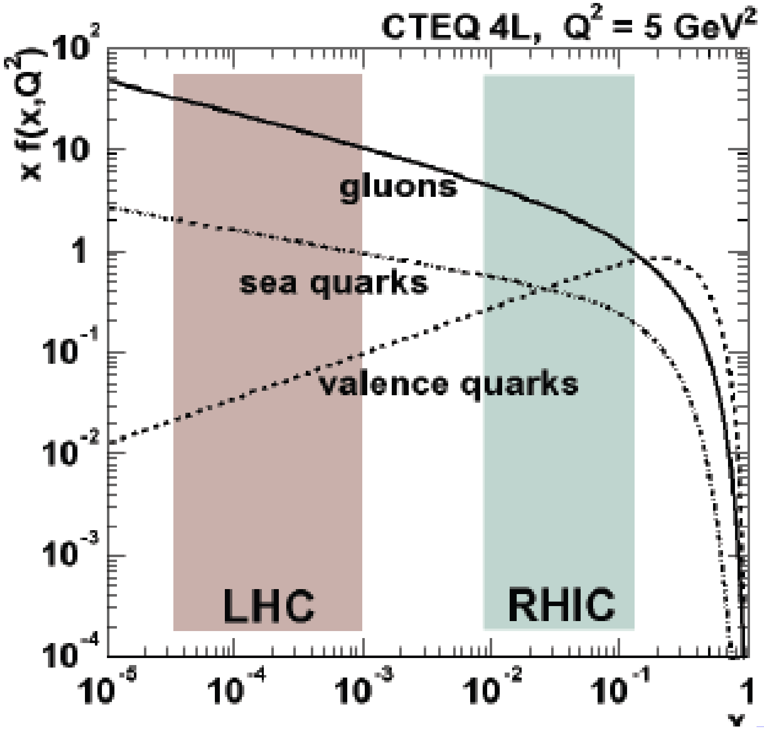
Parton Distribution Functions

PDFs: probability of finding a parton with a fraction x of the proton momentum, in a hard scattering with momentum transfer Q^2

- PDF are obtained by means of a global fit to experimental data, for one or more physical processes which can be calculated using pQCD, such as deep inelastic scattering and the Drell-Yan process

- PDFs depends on the Q^2 value

- The Q^2 evolution can be calculated in pQCD, using the DGLAP equations



Fragmentation Functions

$D_{q\rightarrow H}(z,Q^2)$ represents the probability, at a given scale Q, that a quark q originates an hadron H, with a momentum p_H which is a fraction of the quark momentum ($p_H=zp_q$)

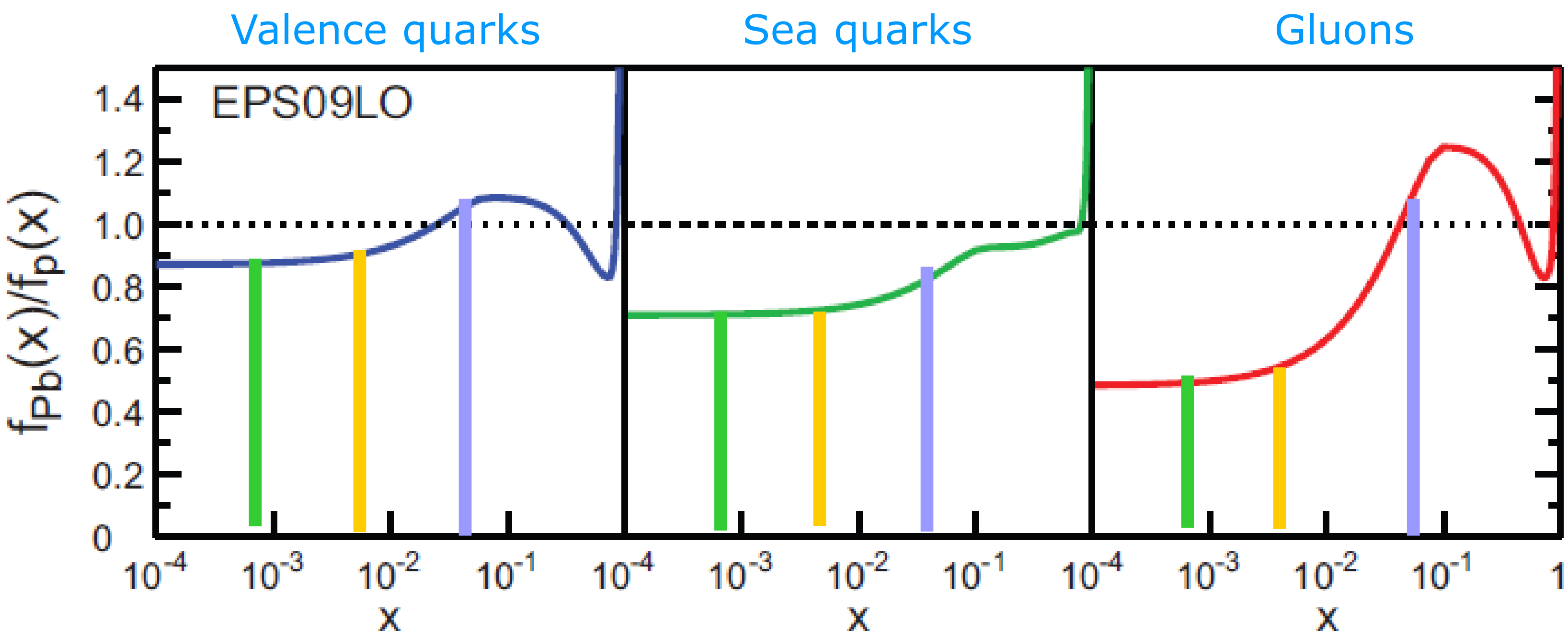
$$q, \bar{q}, g \xrightarrow{D_f^h(z,Q^2)} \pi, K, p, D, B, \gamma, \ldots$$

- Fragmentation functions are extracted from e^+e^- data. Like the PDF, they should be universal
- As for the PDF, these function depend on Q^2 → they are measured at a given Q^2_0 and their evolution is studied using the DGLAP equations

nPDF for SPS, RHIC, LHC

- A given particle probes shad/antishad. region, according to its x value
  - In a LO 2→ process: $x_1 = \frac{2m_T}{\sqrt{s}} e^{y}$; $x_2 = \frac{2m_T}{\sqrt{s}} e^{-y}$

    → the probed x region depends on y, m_T and √s



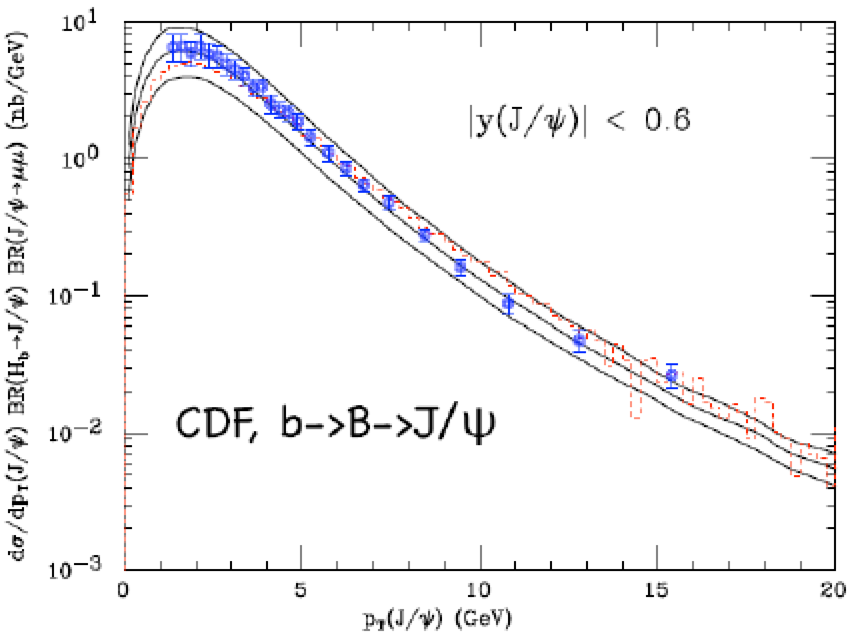
- Example (y=0):
  - J/ψ @ p_T=1GeV/c SPS(158GeV) x ~ 0.4
    RHIC(200GeV) x ~ 0.03
    LHC(7TeV) x ~ 0.001

pQCD comparison to pp data

Charm and beauty have been measured at Tevatron @ $\sqrt{s}$=1.96 TeV

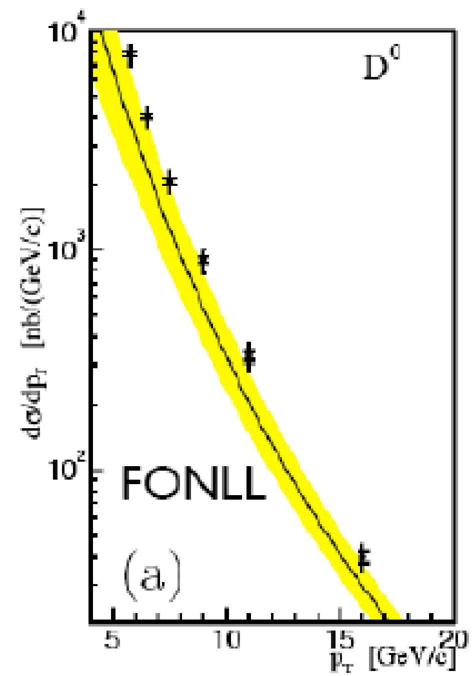
beauty

Good agreement between NLO pQCD (Fixed Order + Next To Leading Log - FONLL calculation) and experimental bottom data



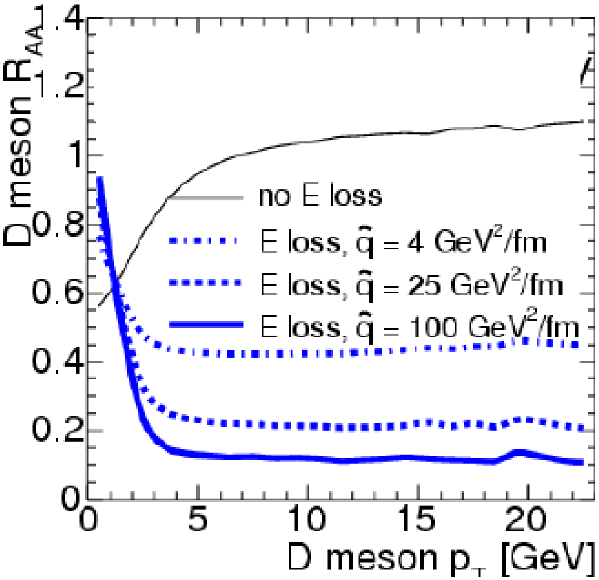
charm

Charm production σ higher than data (~50%) at high p_T, but still compatible with theoretical uncertainties

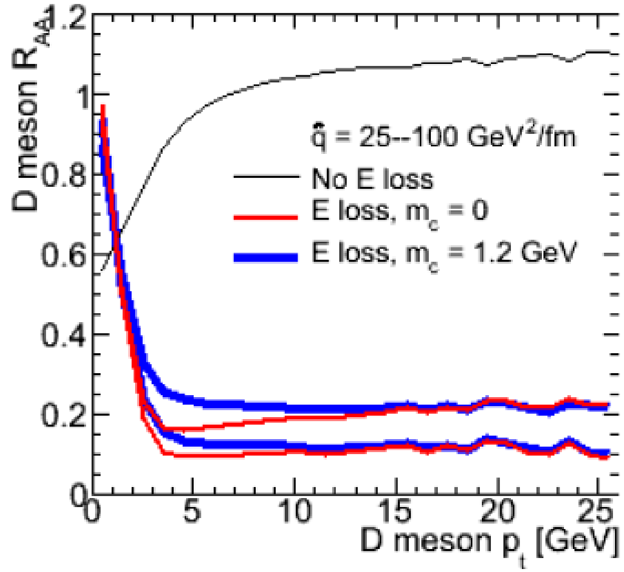


b,c radiative energy loss

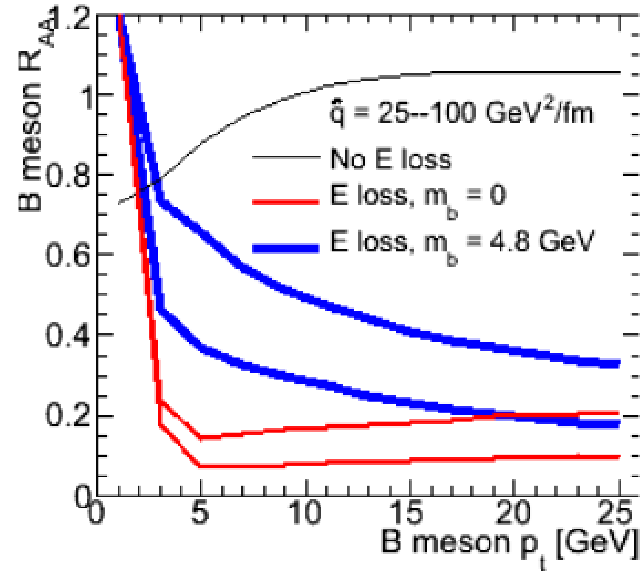
$\hat{q}$ dependence



Charm mass dependence



Beauty mass dependence



Increasing $\hat{q}$

$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$

→ En. loss increases
→ R_{AA} decreases

Increasing m_c

$\vartheta < M_Q/E_Q$

→ En. loss decreases (dead cone effect)
→ R_{AA} increases

Increasing m_b

→ En. loss decreases (dead cone effect)
→ R_{AA} increases
→ Larger effect with respect to charm, because $m_b > m_c$

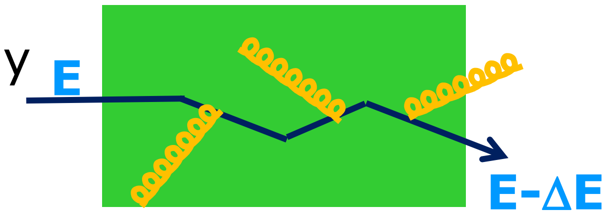
Summarizing

$\Delta E_{\text{light h}} > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}}$

R_{AA} (light hadrons) < R_{AA} (D) < R_{AA} (B)

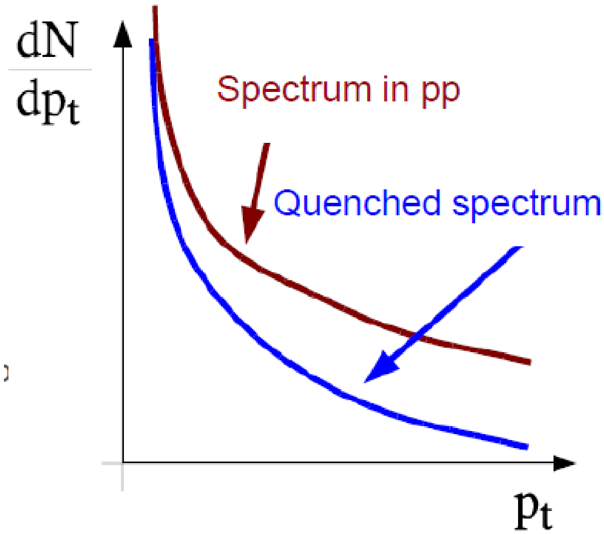
Energy loss

- A parton crossing the medium can lose energy because of two different mechanisms:
  - Scattering with partons → collisional energy loss → dominates at low energy
  - Gluon radiation → gluon bremsstrahlung → dominates at high energy



- The reduction in the parton energy translates to a reduction in the average momentum of the produced hadron, i.e. to a reduction of the yield at high p_T wrt pp collisions

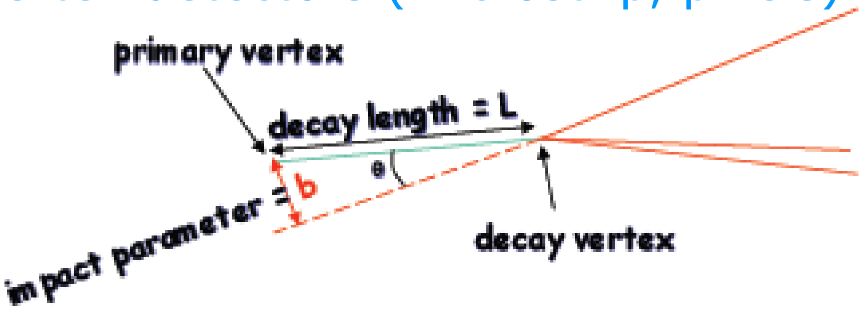
- Because of the power-law shape of the p_T spectrum for p_T>3GeV/c, a modest reduction in the parton energy produces a significant decrease in the hadron yield



Heavy flavour: experimental tools

Several tools needed experimentally to study heavy flavors:

- silicon vertex detectors (microstrip, pixels)



Tracks from heavy flavour decay are displaced by $c\tau \sim 100\mu m$ wrt the primary vertex → Typical apparatus have impact parameter resolution of ~70(20)μm @ p_T~1(20)GeV/c
→Available in LHC experiments and foreseen in RHIC upgrade

- $e^{\pm}$, $\mu^{\pm}$ identification

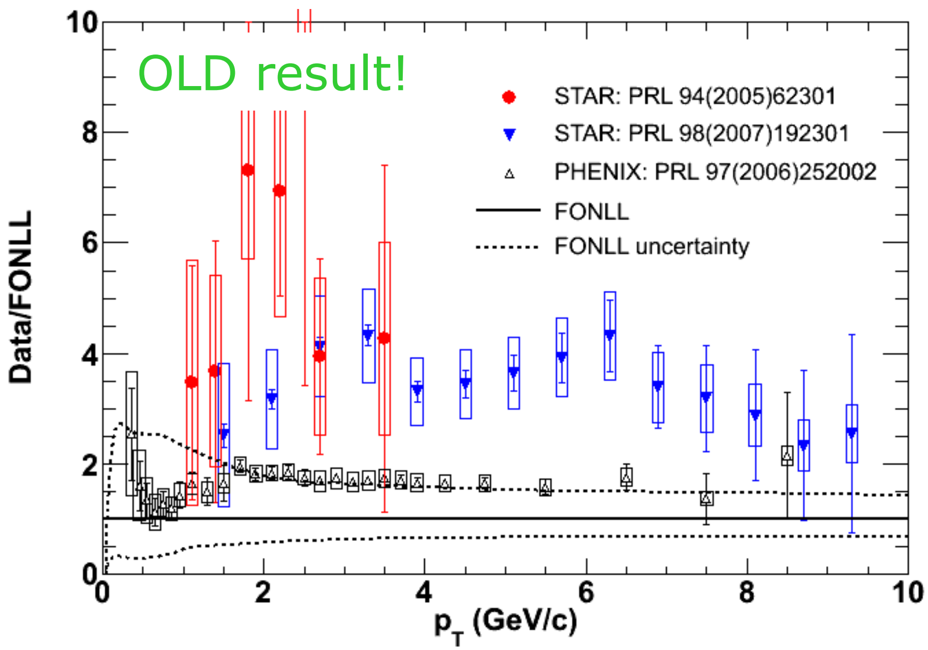
PHENIX →RICH, em. calorimeter
STAR → TPC, em calorimeter, TOF
ALICE → Muon Spectr., TPC, TOF, TRD, EMCal

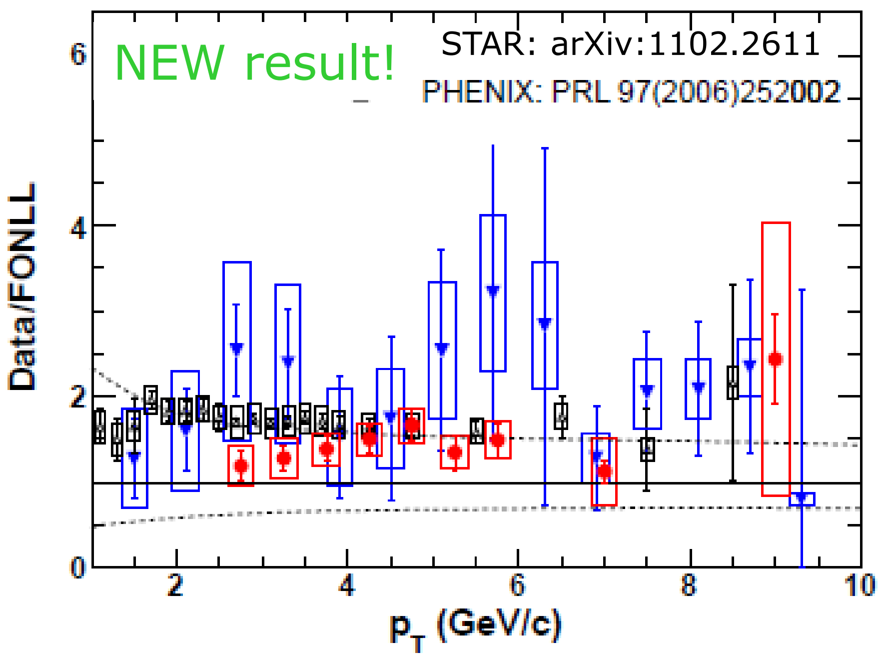
- charged kaon identification

STAR → TPC
ALICE → TPC, TOF

HF: RHIC experimental results - pp

- Long standing discrepancy between PHENIX and STAR non photonic electron results (pp, AA) in the
  - p_T differential distributions
  - integrated cross sections

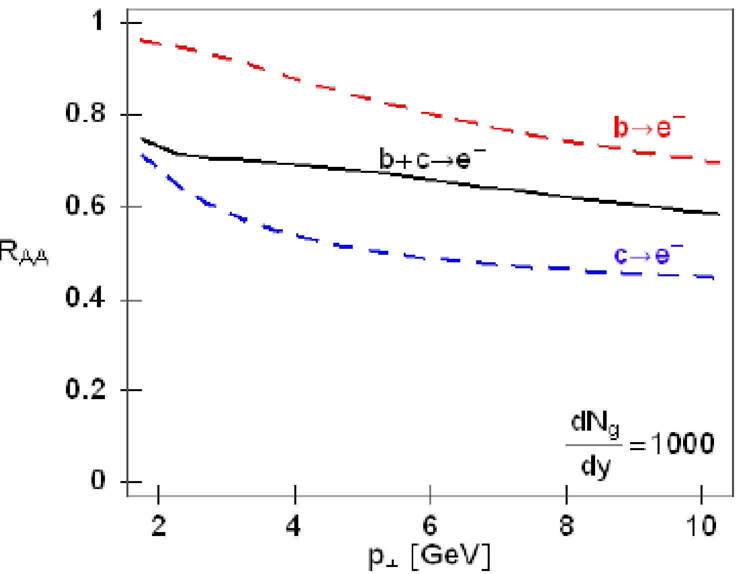




- Re-analysis of STAR pp data (affected by an error in the evaluation of the background level) improves the agreement with PHENIX results
- Comparison with FONLL estimates → results are in agreement within the theoretical uncertainties of the calculation

Role of bottom

- Bottom en. loss should be smaller than the charm one

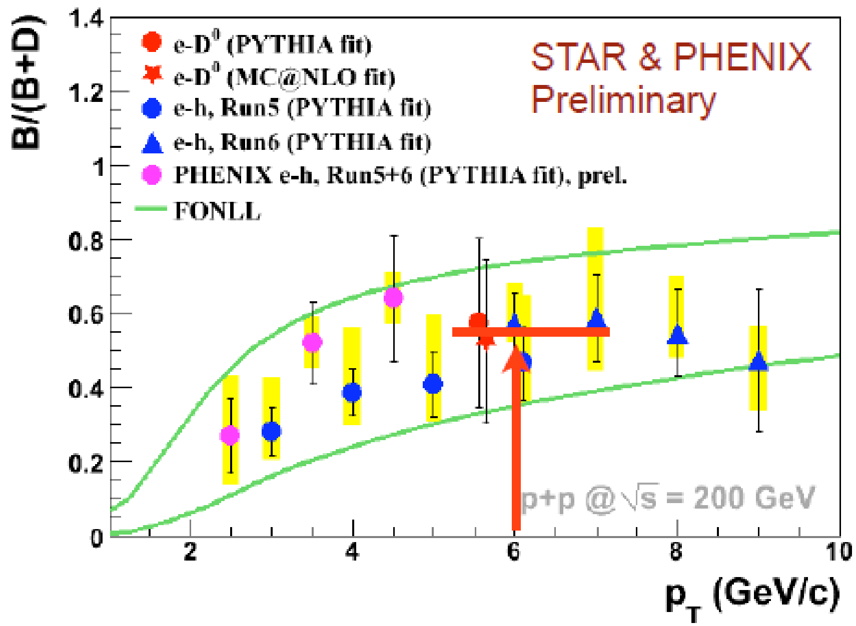


$\Delta E_g > \Delta E_{charm} > \Delta E_{beauty}$

- Results are sensitive to the charm/beauty contributions
- Not easy to disentangle c and b @ RHIC because no vertex detector are available

More indirect measurements:

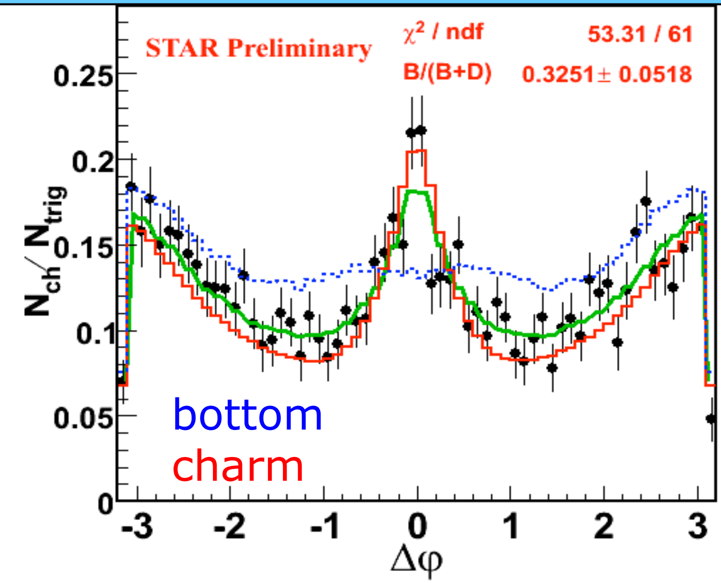
- c identification from charge correlation of K and e from D decay (PHENIX)
- small azimuthal angular correlation of e-h pairs from c or b decays (STAR)
- eD^0 correlations (STAR)



- bottom contribution ~ 55% (for p_T>6GeV/c)

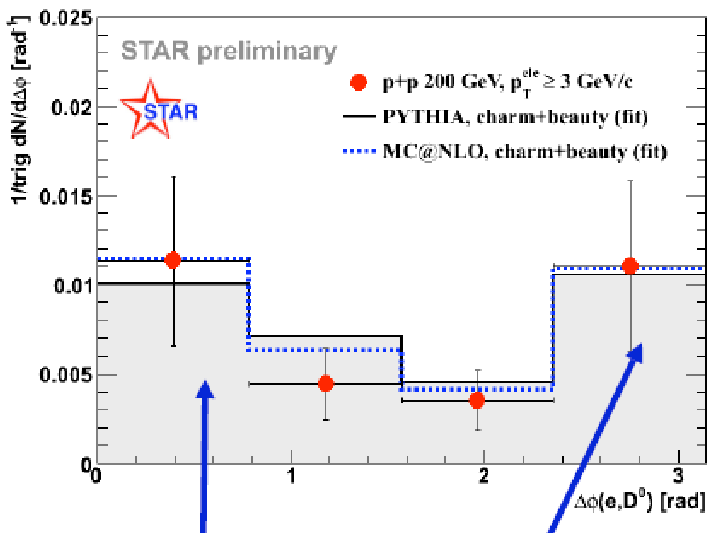
How to distinguish c and b?

- small azimuthal angular correlation of e-h pairs from c or b decays (STAR)



- c identification from charge correlation of K and e from D decay (PHENIX)

eK pairs from B are mostly like sign
eK pairs from D are opposite sign



essentially from B decay only

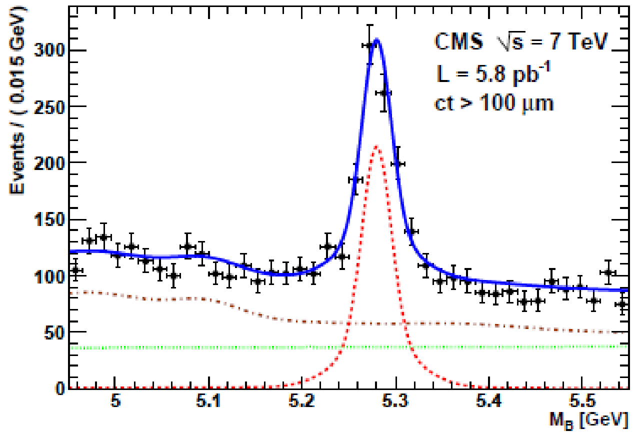
~75% from charm
~25% from beauty

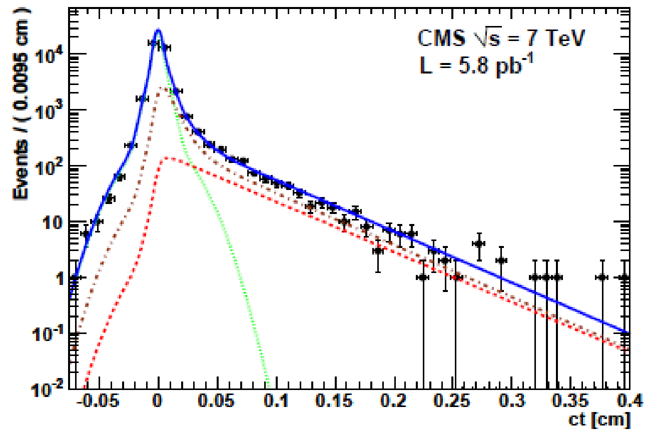
- eD^0 correlations (STAR)

B cross section

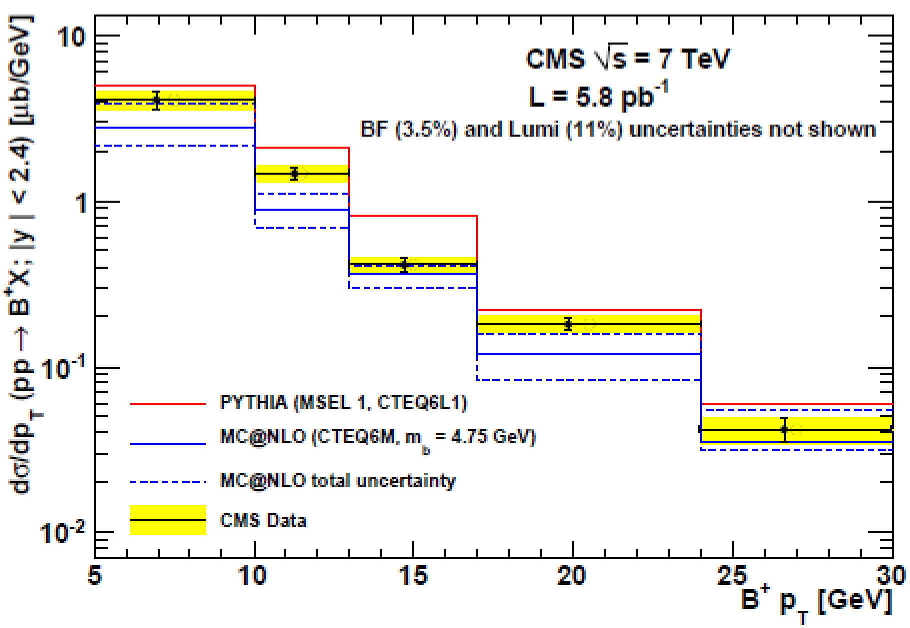
- B accessible at LHC!

$B^+ \rightarrow J/\psi\ K^+$
$\hookrightarrow \mu^+\mu^-$





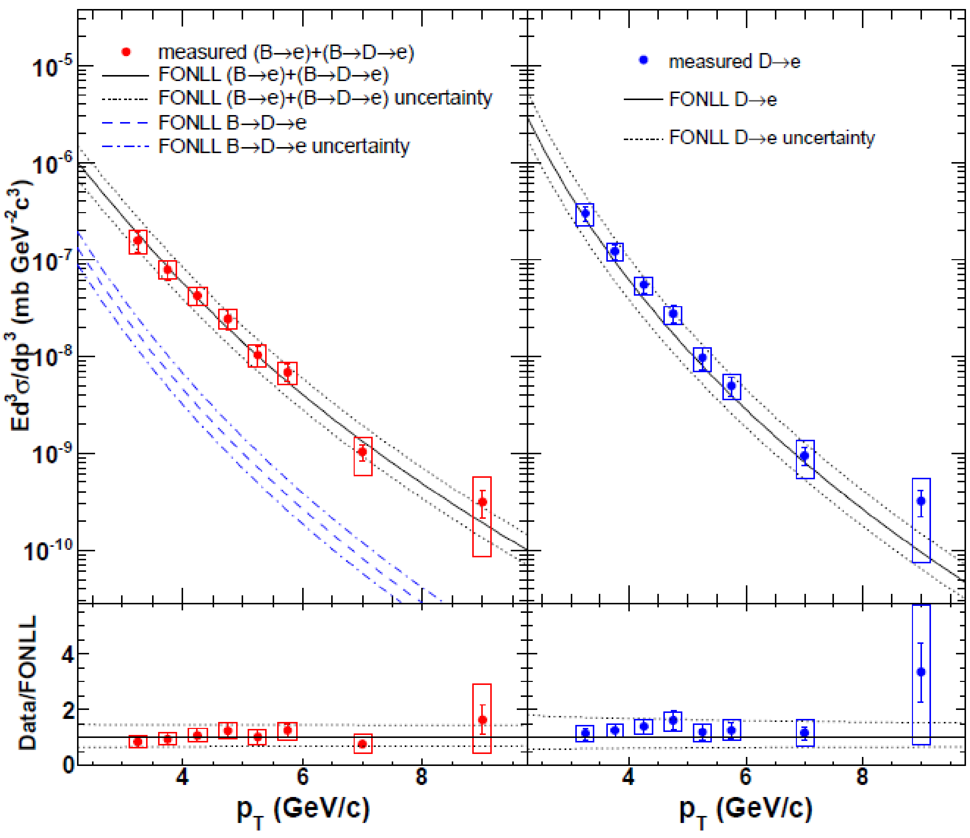
CMS: arXiv:1101.0131



- B detected using invariant mass spectrum and secondary vertex identification
- Reasonable shape agreement with NLO MC, but normalization of data 1.5 higher

FONLL predictions

STAR arXiv:1102.2611



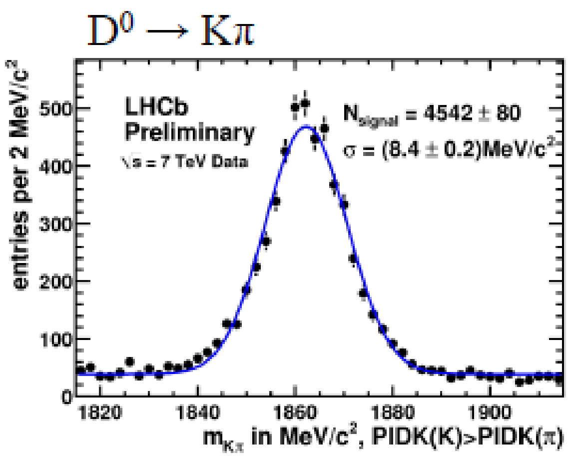
- pp @ √s=200GeV
- as already observed @ Tevatron, good agreement between b cross section and FONLL, (very) small discrepancy between c and FONLL

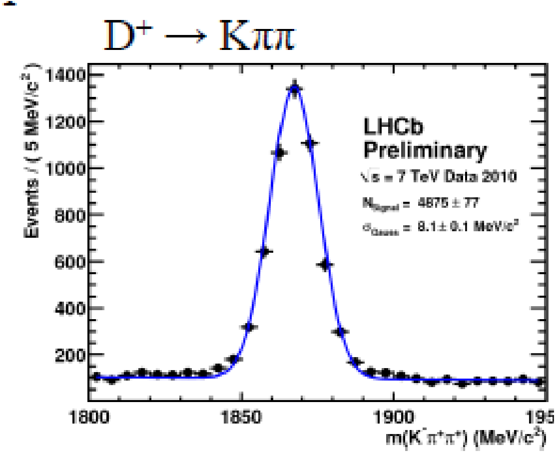
- σ_{FONLL} (bottom) = 1.87 +0.99 -0.67 μb
  σ_{data} (bottom) = 1.34 – 1.83 μb (according to PYTHIA tuning)
- σ_{FONLL} (charm) = 256 +400 -146 μb
  σ_{data} (charm) = 551+57 -195 μb

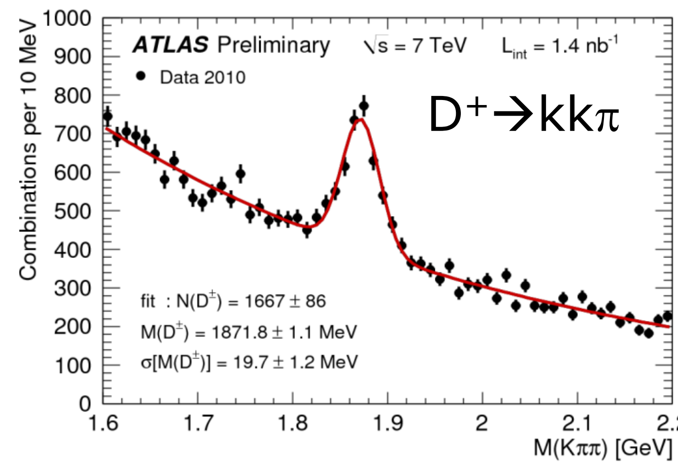
PHENIX arXiv:1005.1627

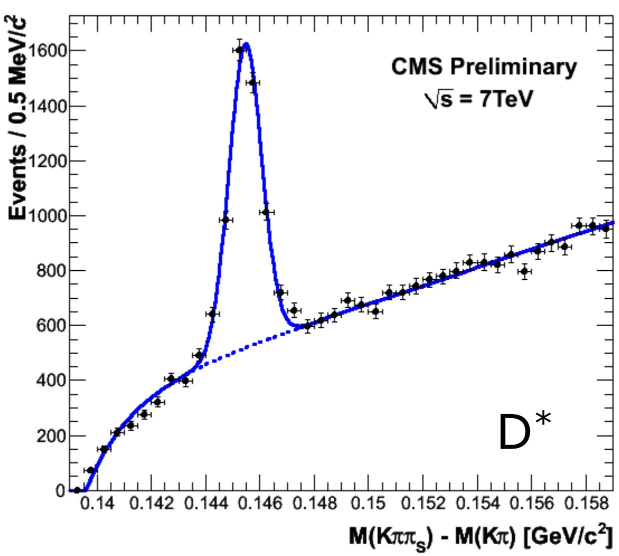
…more heavy quarks results…

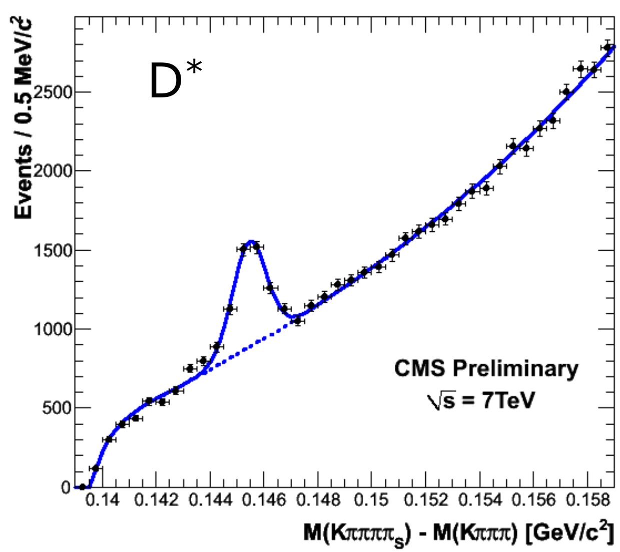
- Similar approaches adopted in the other LHC experiments

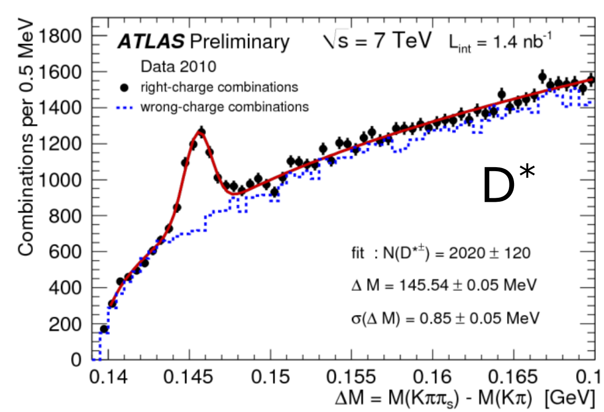












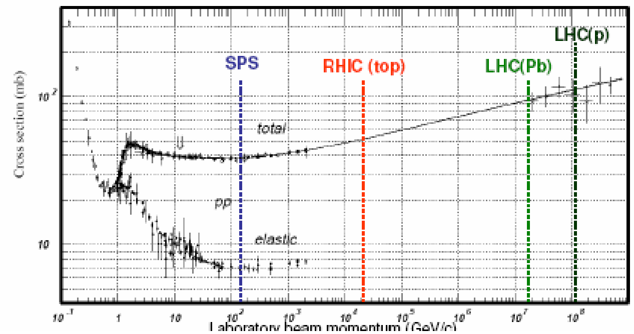
Glauber model

Geometrical model to describe the collision between two nuclei with impact parameter b

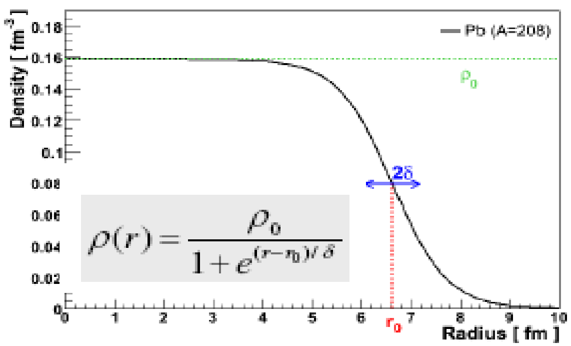
Assumptions: Nucleus-nucleus collisions are described as a superposition of independent nucleon-nucleon collisions

Ingredients:

- the nucleon-nucleon inelastic cross-section (~30mb at SPS)



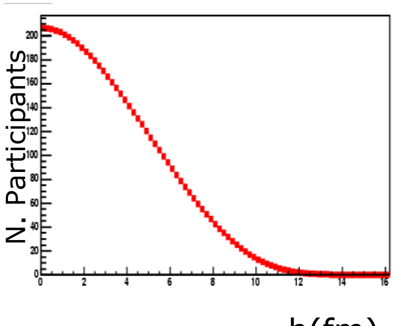
- the nuclear profile densities e.g a Wood-Saxon distribution



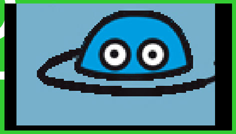
Output:

Allow to obtain several information as a function of the impact parameter b:

- num. of participant nucleons
- number of collisions
- overlap region
- …



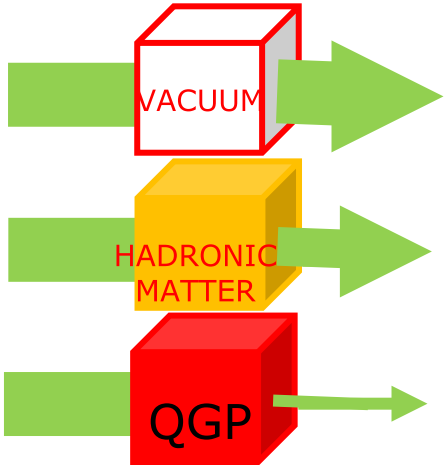
Backup



Quarkonia

Find a good probe…and calibrate it

How to study the medium created in HI collisions?



➡ Using a probe produced early in the collision evolution so that it is there before the matter to be probed

- Well understood in pp collisions
- Slightly affected by hadronic matter
- Strongly affected by the deconfined medium

How to calibrate the probe?

➡ Using, as a reference, another probe not affected by the hot matter
→ photons, Drell-Yan dimuons

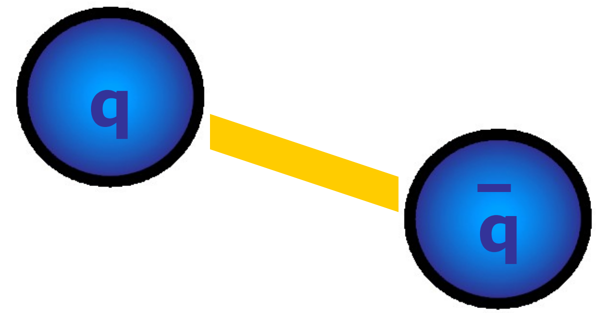
➡ Using "trivial" collision systems, to understand how the probe behaves in absence of "new physics"
→ pp, pA, light ions collisions
→ comparison of peripheral vs. central collisions

Which probes?

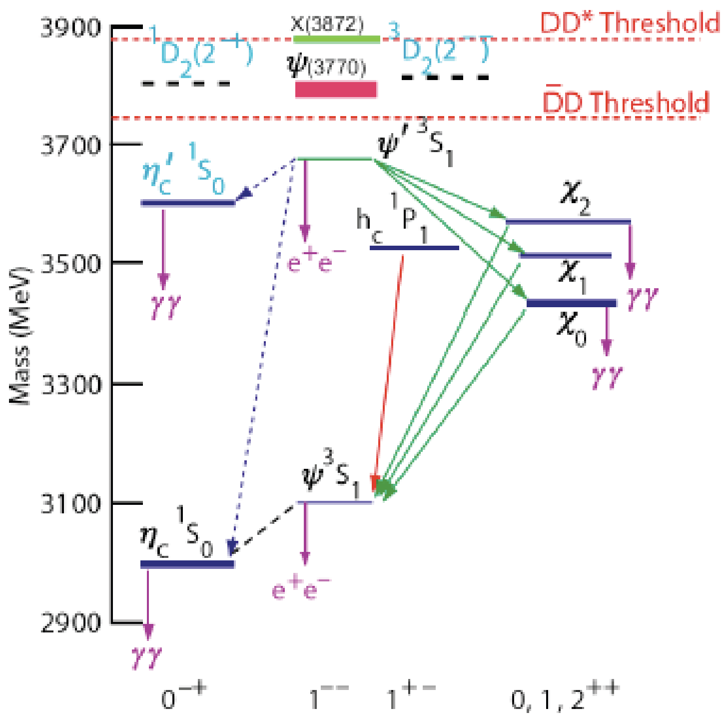
"hard probes" ➡
- high p_T hadrons, jets
- open heavy flavors (charm and beauty)
- quarkonia (J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$)

What is quarkonium?

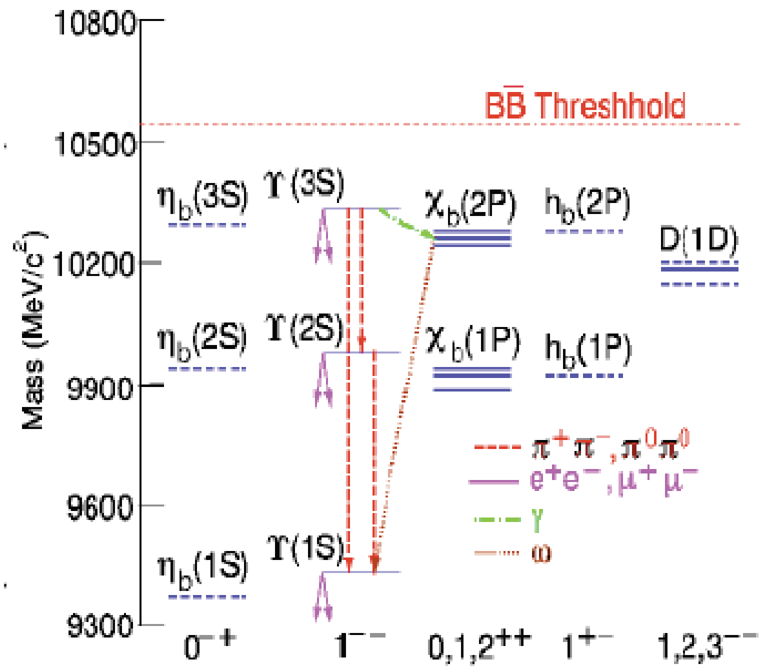
- Quarkonium is a bound state of q and $\bar{q}$ with $m_{q\bar{q}} < 2m_D(m_B)$
  - According to the quantum numbers, several quarkonium states exists



Charmonium ($c\bar{c}$) family



Bottomonium ($b\bar{b}$) family



Models for quarkonium production in pp

Color Singlet Model

Proposed soon after the J/ψ discovery

$Q\bar{Q}$ pair is produced in a color singlet state, with the same quantum numbers of the final quarkonium

Unable to describe Tevatron data.
However, recently NLO and NNLO corrections have been included to improve the agreement

Color Evaporation M.

$Q\bar{Q}$ pair evolves in quarkonium if $m_{Q\bar{Q}} < m_D$ independently of its color and spin

Probability to evolve into a certain quarkonium state depends by a constant F which is energy and process independent

Works rather well, but no detail on the hadronization of the qq pair towards the bound state

NRQCD

Inclusive quarkonium production cross section is a sum of short distance coeff. and long distance matrix elements:

$$\hat{\sigma}(ij \to J/\psi) = \sum_n C^{ij}_{\bar{Q}Q[n]} \langle O_n^{J/\psi} \rangle$$

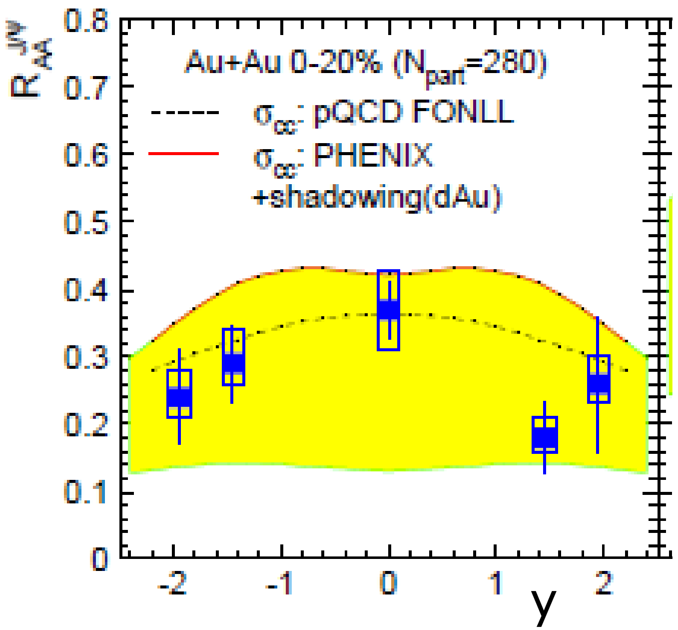
This approach includes CSM and CEM as special cases

Charmonium can be produced also through the creation of a $c\bar{c}$ color octet state

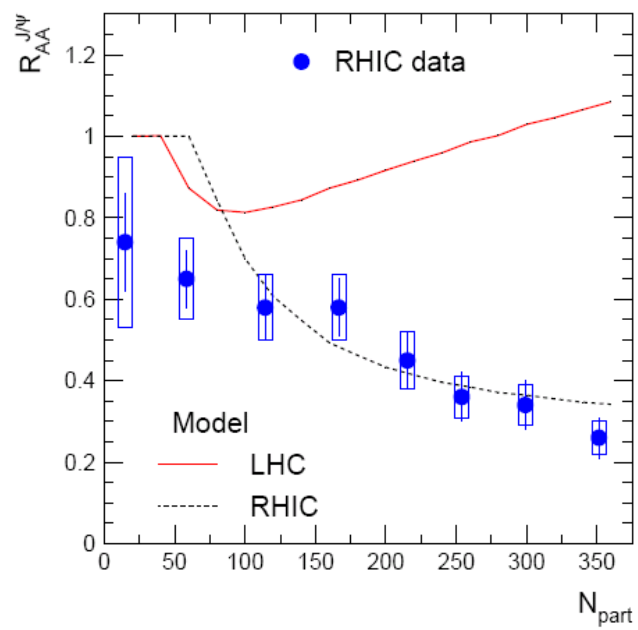
Statistical hadronization

J/ψ production by statistical hadronization of charm quarks
(Andronic, BraunMunzinger, Redlich and Stachel, PLB 659 (2008) 149)

- charm quarks produced in primary hard collisions
- survive and thermalize in QGP
- charmed hadrons formed at chemical freeze-out (statistical laws)
- no J/ψ survival in QGP



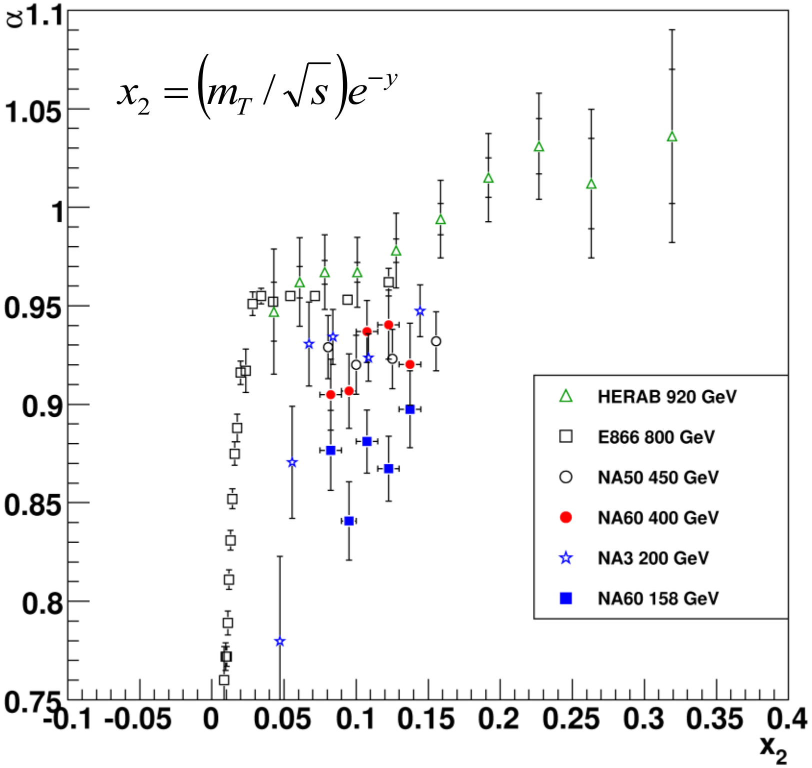
A. Andronic et al. arXiv:0805.4781



Good agreement between data and model

Recombination should be tested on LHC data!

x_2 scaling



Shadowing effects (in the 2→1 approach) and final state absorption

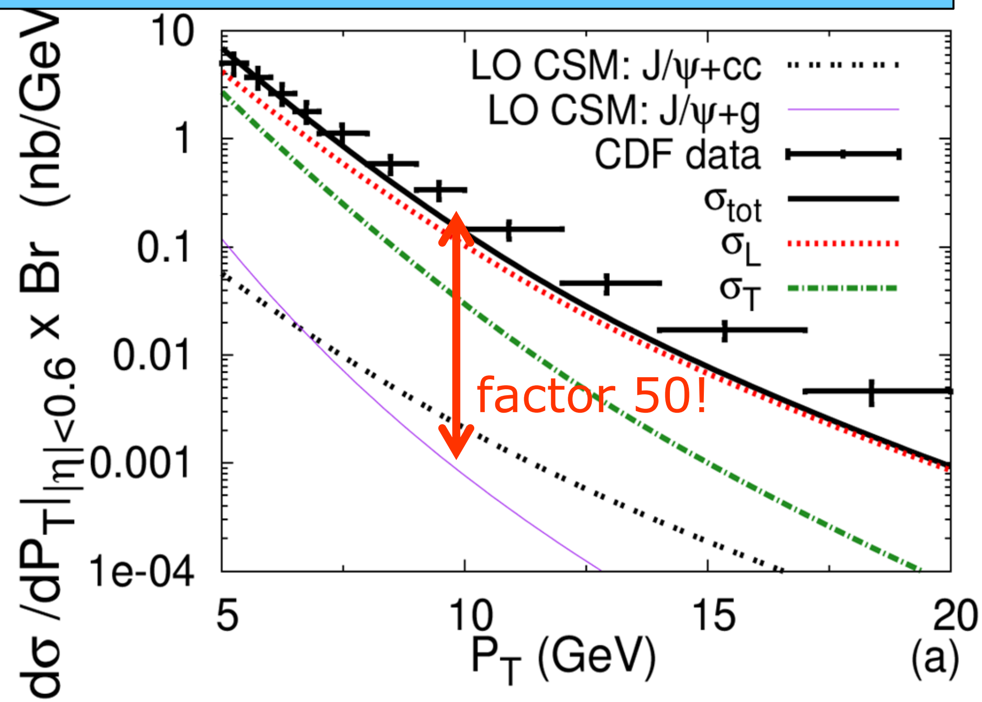
$\sqrt{s_{J/\psi N}} \sim m_{J/\psi} \sqrt{\frac{1+x_2}{x_2}}$ scale with x_2

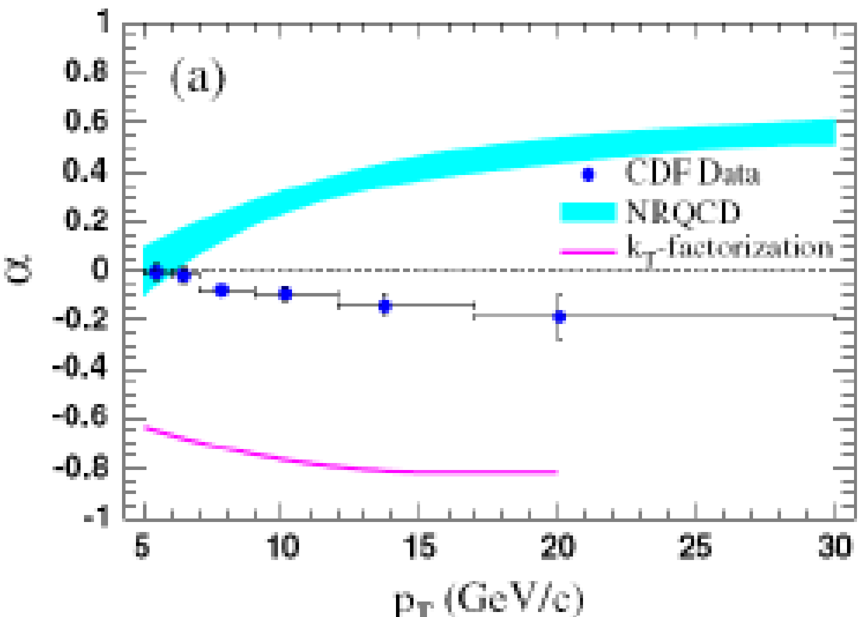
if parton shadowing and final state absorption were the only relevant mechanisms

→ α should not depend on √s at constant x_2

Production models and CDF results

- The first CDF results on J/ψ direct production revealed a striking discrepancy wrt LO CSM
- The agreement improves in NRQCD approach
- …but situation still puzzling, because polarization is not described!





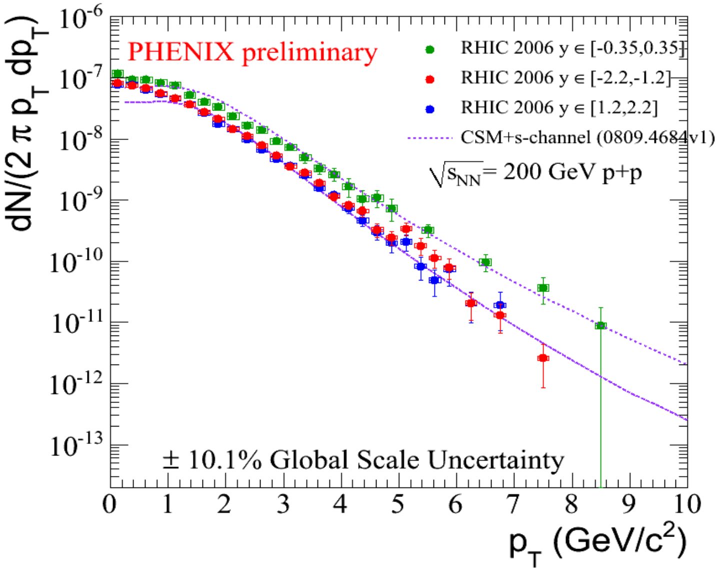
- Recently many step forwards (i.e. NLO and NNLO corrections…)
- Open questions, to be investigated at LHC!

J/ψ @ RHIC: p-p and d-Au

pp collisions

pp results should help to

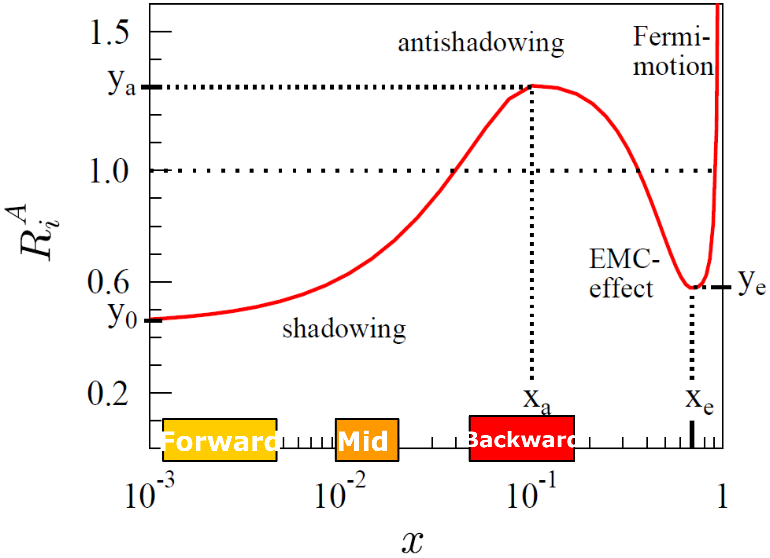
- understand the J/ψ production mechanism
- provide a reference for AA collisions (R_{AA})



dAu collisions

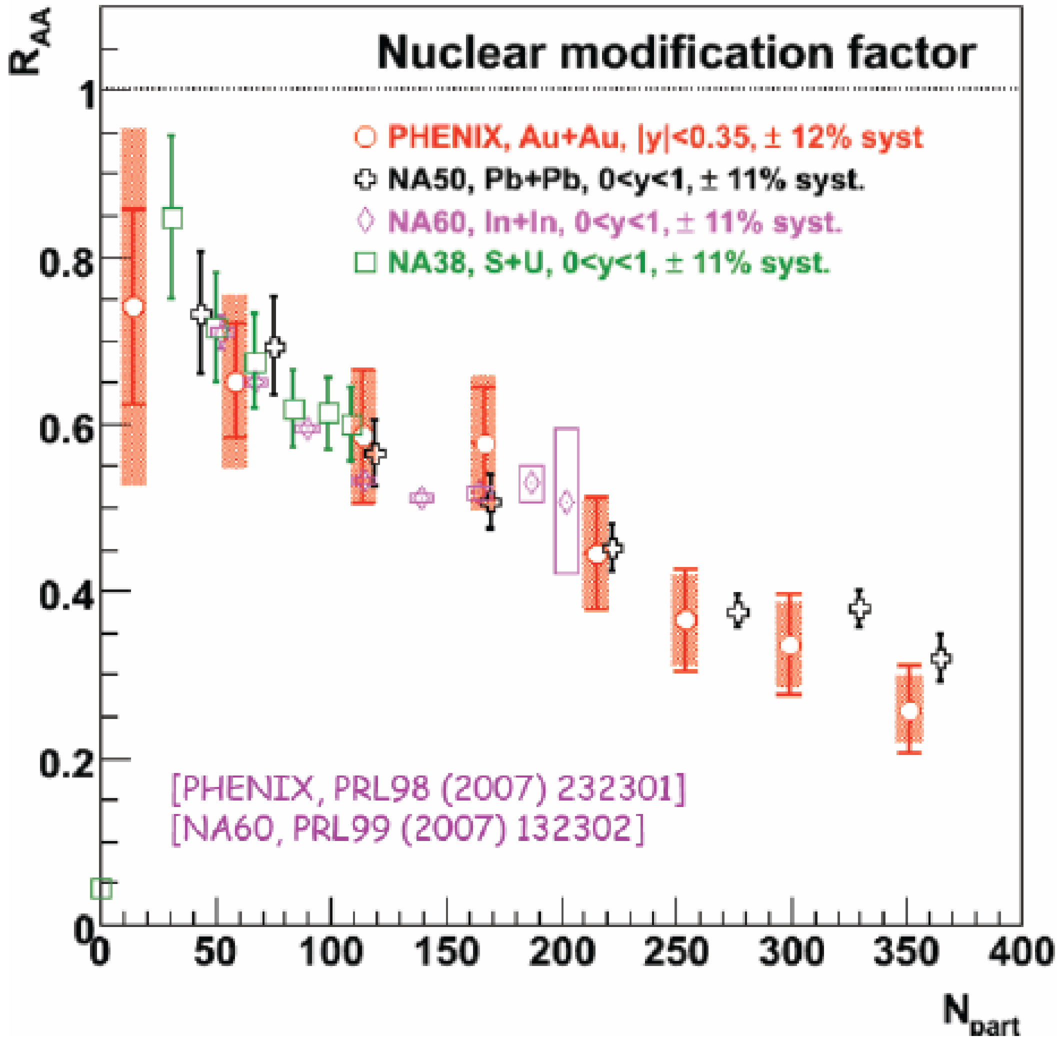
In a similar way as at SPS, CNM effects are obtained from dAu data

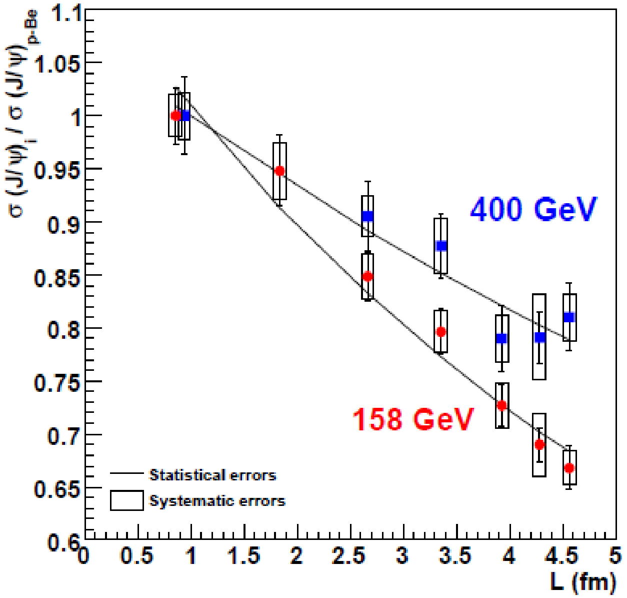
RHIC data exploit different x_2 regions corresponding to
→ shadowing (forward and midrapidity)
→ anti-shadowing (backward rapidity)



Comparison with SPS results (2)

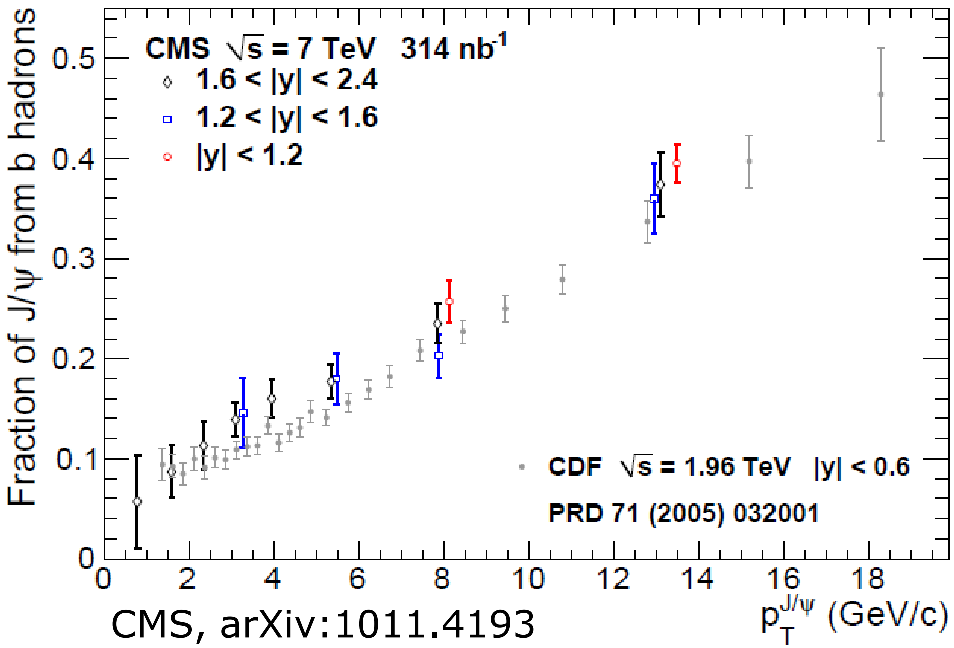
Good agreement between the SPS and RHIC R_{AA}





What about J/ψ from B?

- J/ψ from B can complicate even more the picture



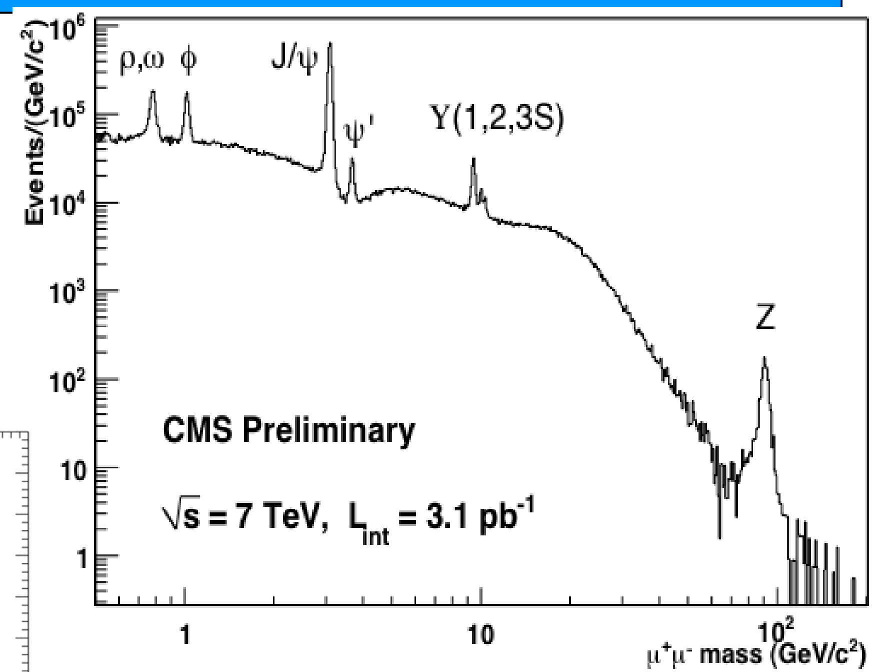
CMS, arXiv:1011.4193

- 7 TeV pp results show that the fraction of J/ψ from b hadrons does not strongly depend on energy
  → we can assume the same trend at 2.76 TeV

- Fraction of J/ψ coming from B do not suffer suppression in the medium
  - …but if B is strongly quenched by the medium, the fraction of J/ψ from b hadrons (vs p_T) will change

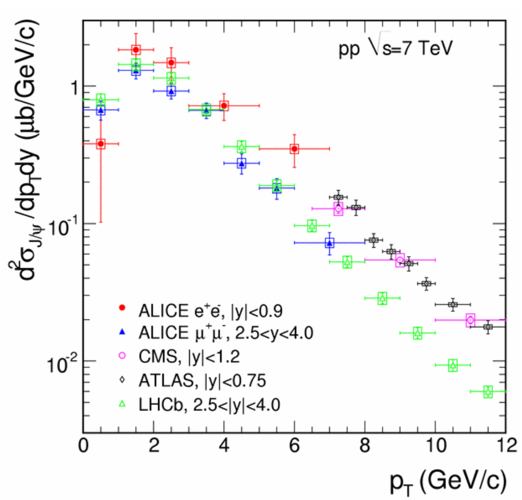
- More hints from ATLAS and CMS which will be able to separate prompt J/ψ from those from B decay also in PbPb (?)

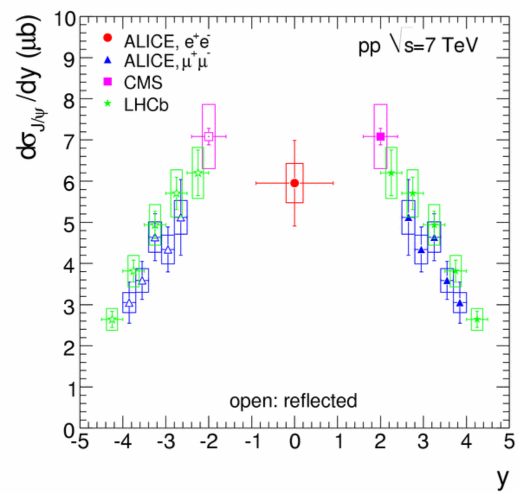
Quarkonium LHC results in pp



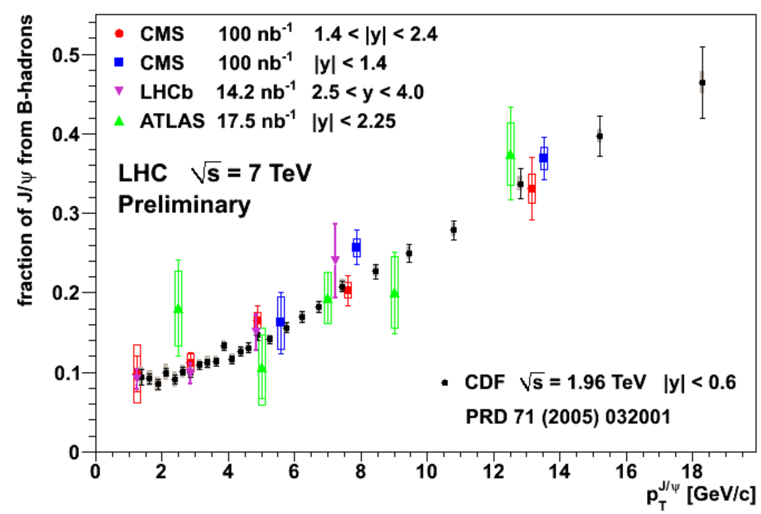
- New results presented by the 4 experiments

- Differential distributions (y, p_T)



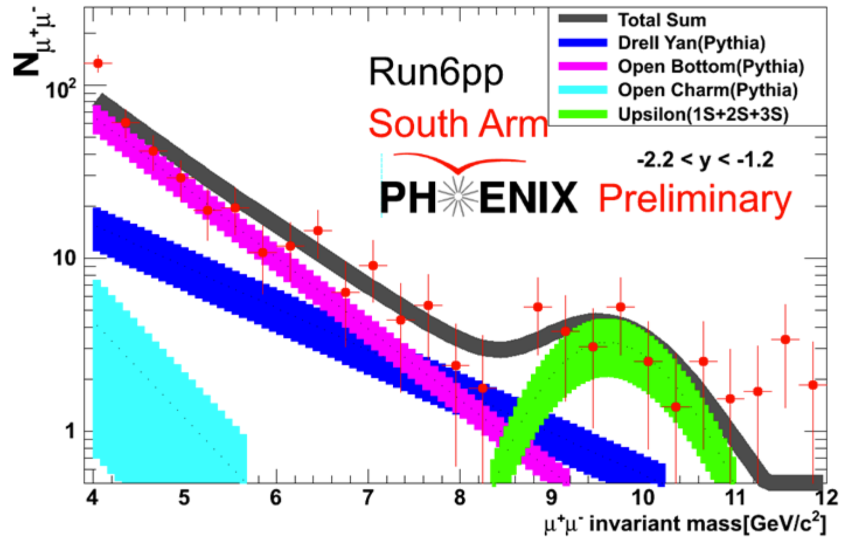


- Fraction of J/ψ from B

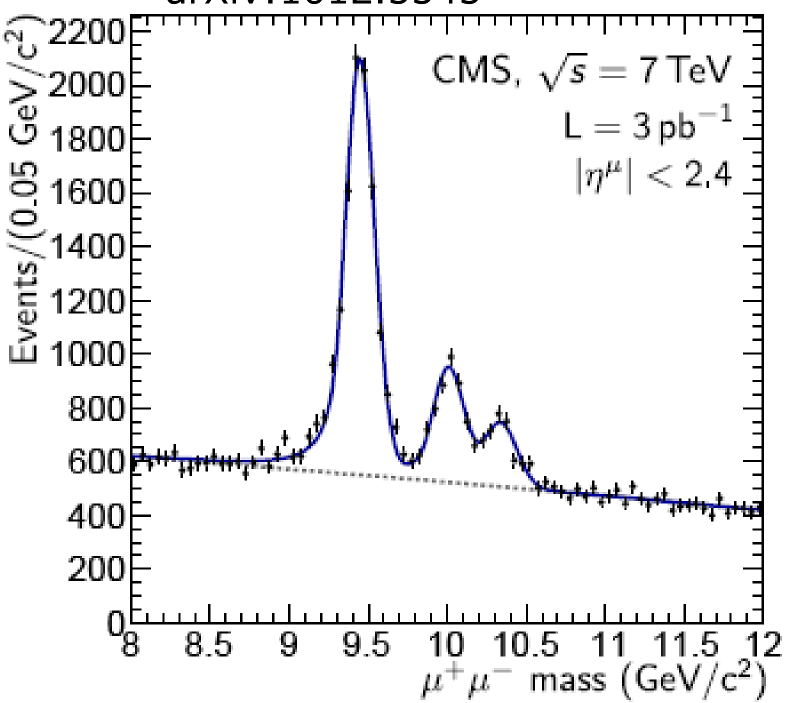


Υ results in pp @ LHC

- Υ hardly seen at RHIC, while now at LHC the Υ family is fully accessible



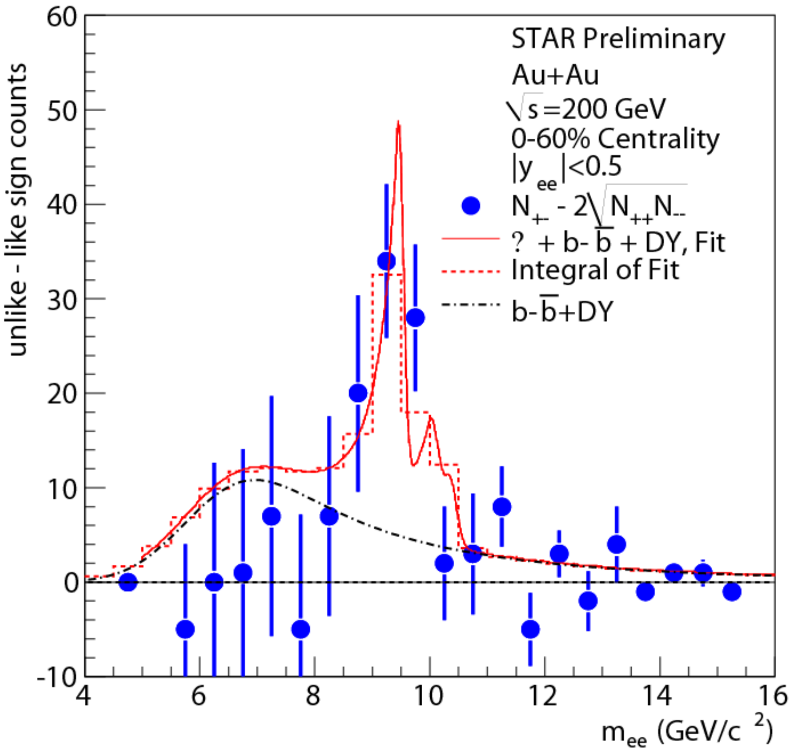
arXiv:1012.5545

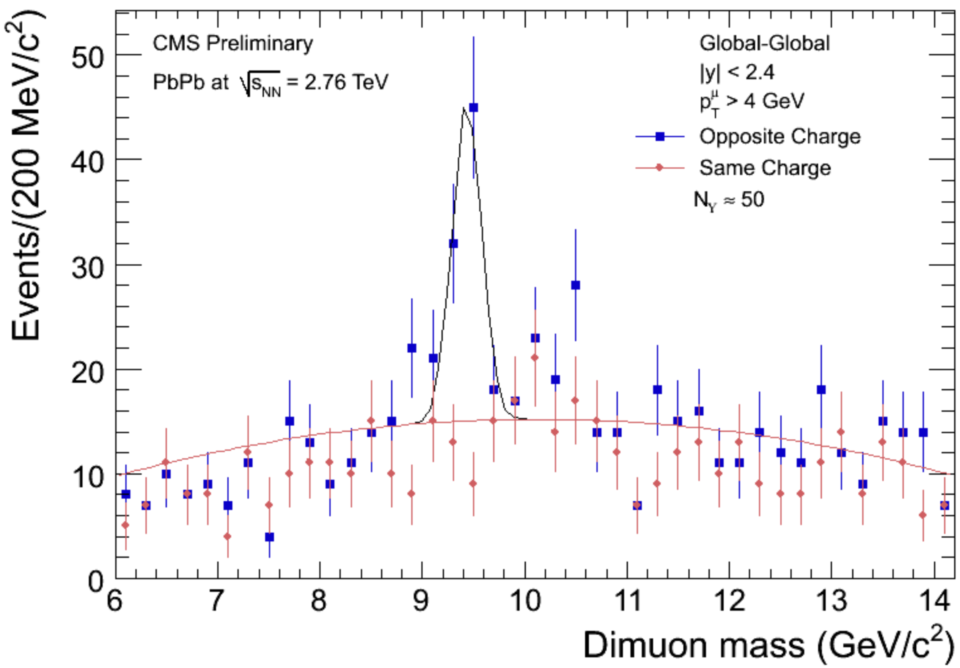


- Extremely important measurement:

→ More robust theory calculation (due to heavy bottom quark and absence of b-hadron feed-down)

Υ results in AA





Υ yield determined by:

Υ(8.5<m<11 GeV/c^2)=64±16(stat)±25(sys)