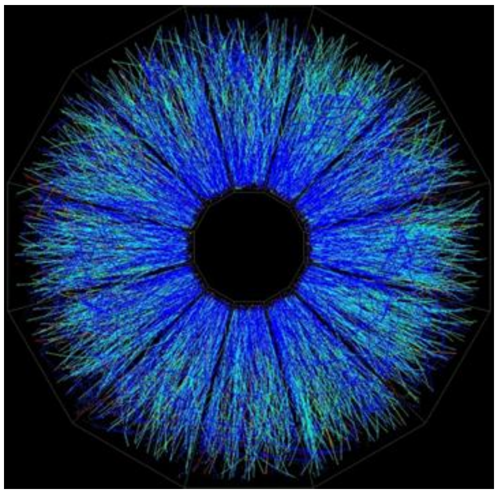
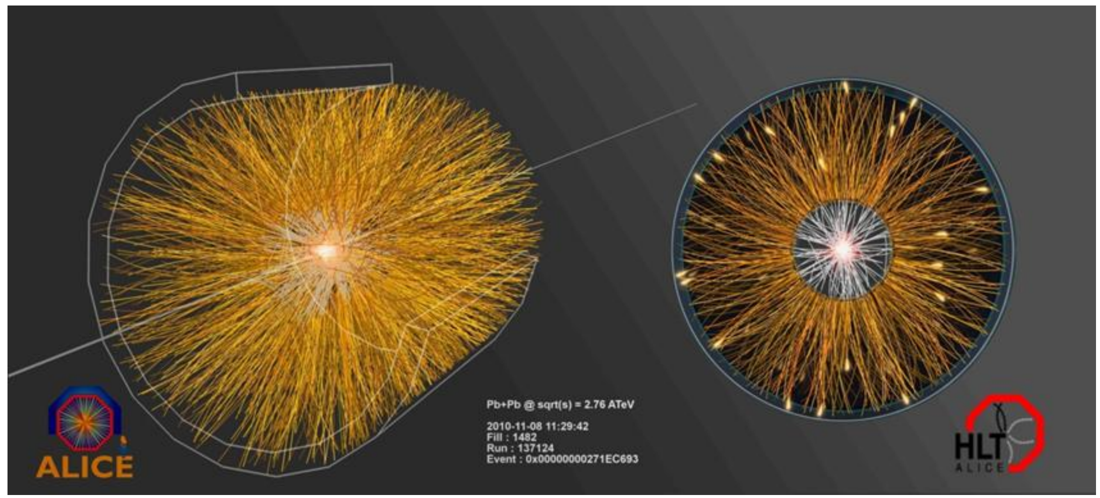
Heavy flavor measurements in heavy ion collisions





Jaroslav Bielčík

STAR+ALICE collaboration

FNSPE, Czech Technical University in Prague

Seminár FzÚ AV ČR, Prague, March 2012

Outline

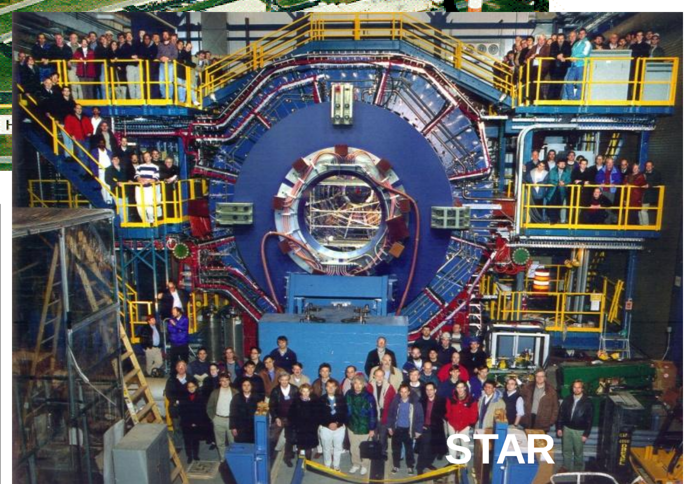
- Heavy ion collisions
- Motivation for heavy flavor physics
- STAR + ALICE detectors
- Open heavy flavor
  - Charm mesons
  - Non-photonic electrons
- Quarkonia
  - J/ψ and Υ measurements
- Summary

Relativistic Heavy Ion Collider

RHIC site in BNL on Long Island - taking data from 2000

RHIC has been exploring nuclear matter at extreme conditions over the last years

Lattice QCD predicts a phase transition from hadronic matter to a deconfined state, the **Quark-Gluon Plasma**



Colliding systems:

p↑+p↑, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U

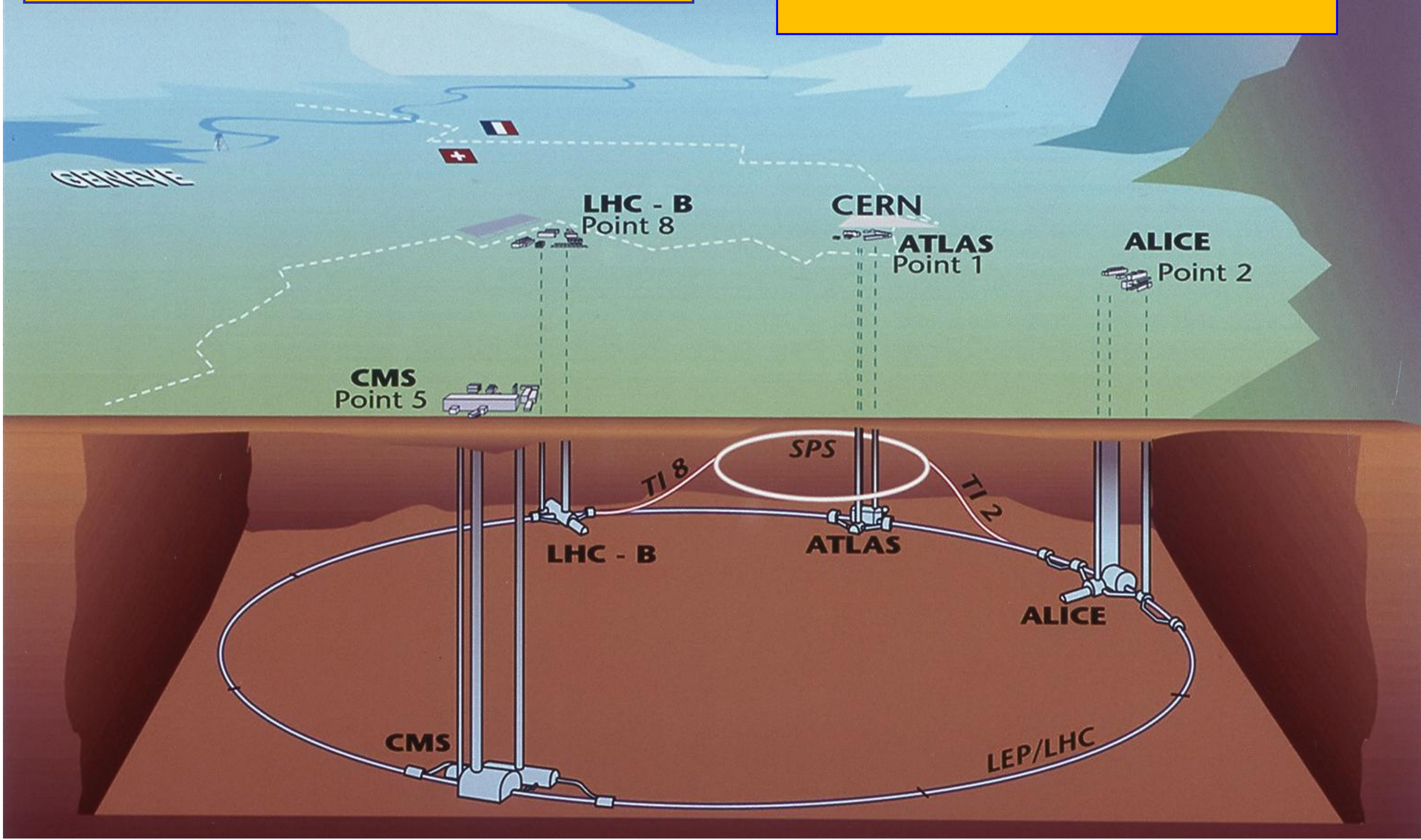
Energies

$\sqrt{s_{NN}}$ = 20, 62, 130, 200 GeV
(500 GeV)
+ 7.7, 11.5, 27, 39 GeV

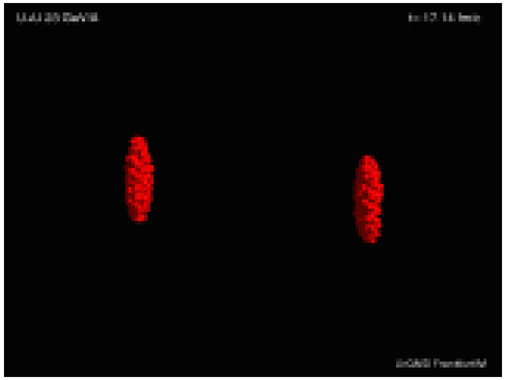
Overall view of the LHC experiments.

p+p	900 GeV, 7 TeV (14 TeV)
Pb+Pb	2.76 TeV (5.5 TeV)
p+Pb	2012?

Heavy ion experiments:
ALICE
ATLAS + CMS hardprobes



Little Big Bang in laboratory



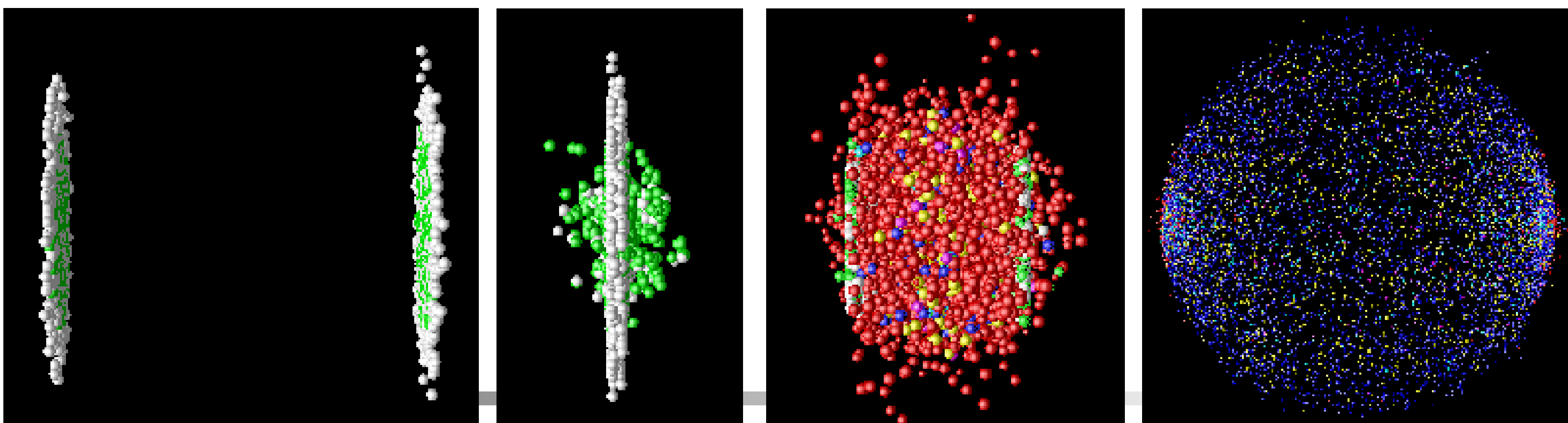
- compress large amount of energy in a very small volume
- produce a “fireball” of hot matter:

  temperature O(10^{12} K)

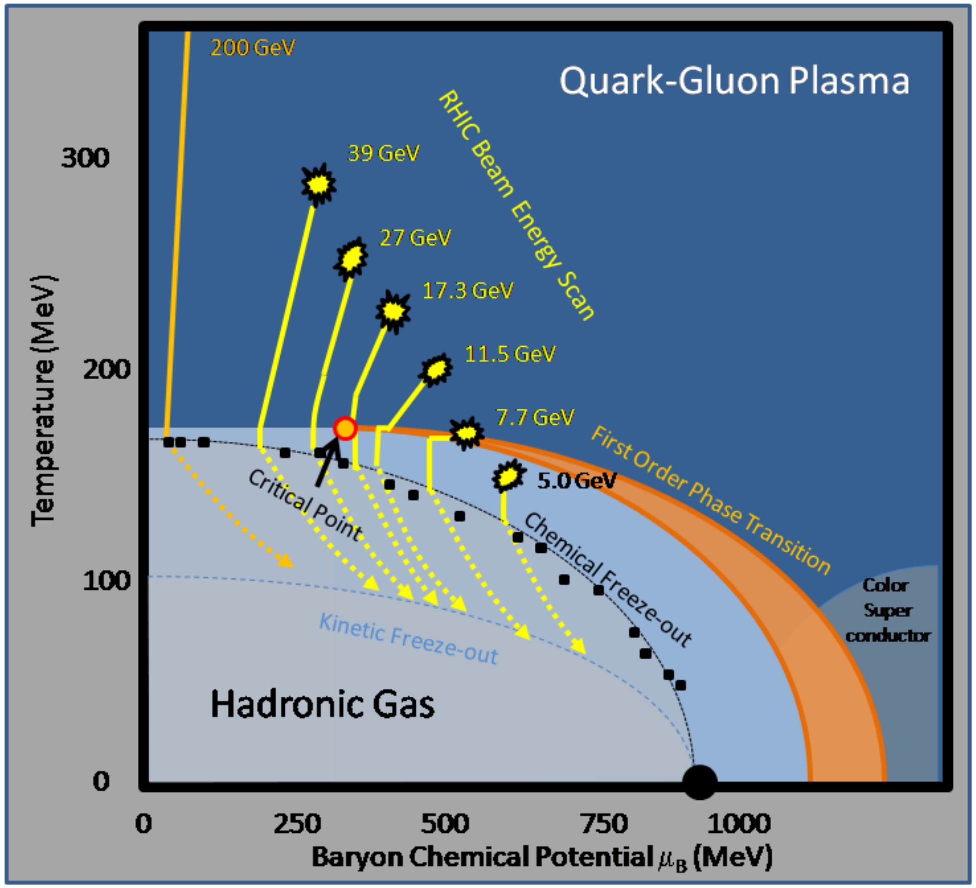
  ~ 105 x T at center of Sun

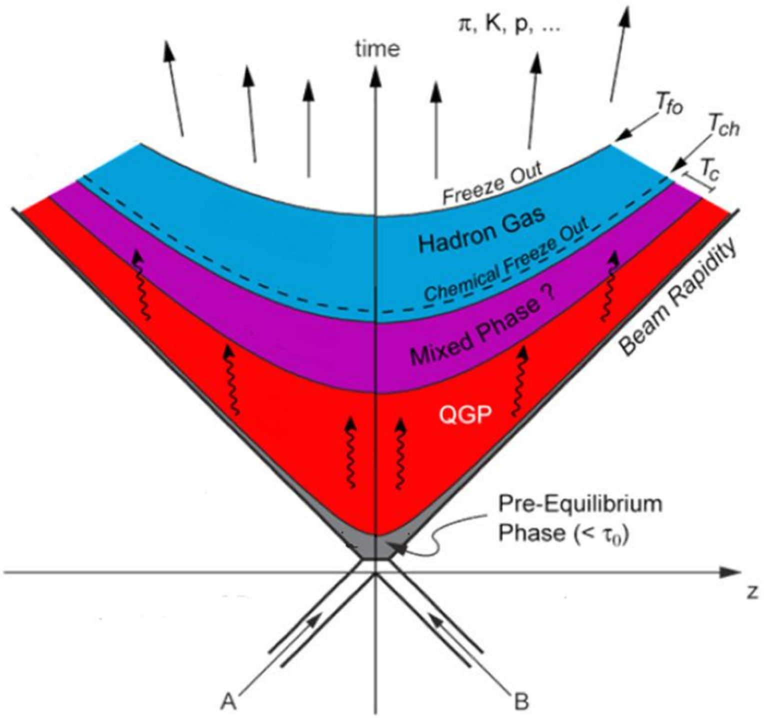
  ~ T of universe @ ~ 10 μs after Big Bang

- how does matter behave under such extreme conditions?
- study the fireball properties
- QCD predicts state of deconfined quarks and gluons **(Quark-Gluon Plasma)**

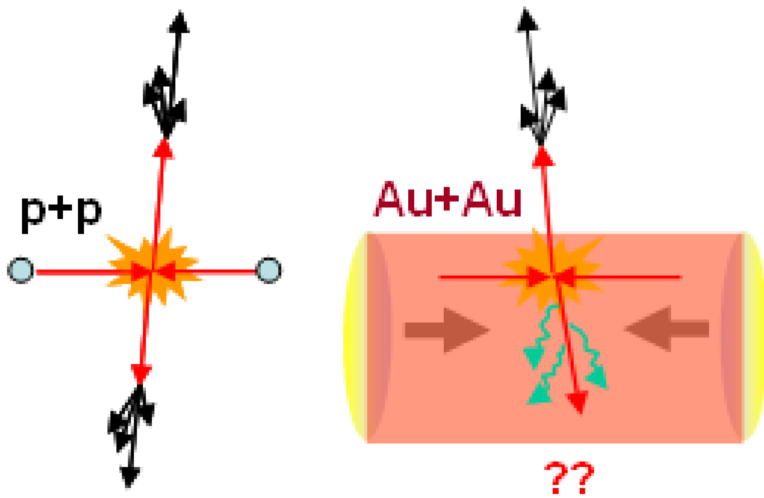


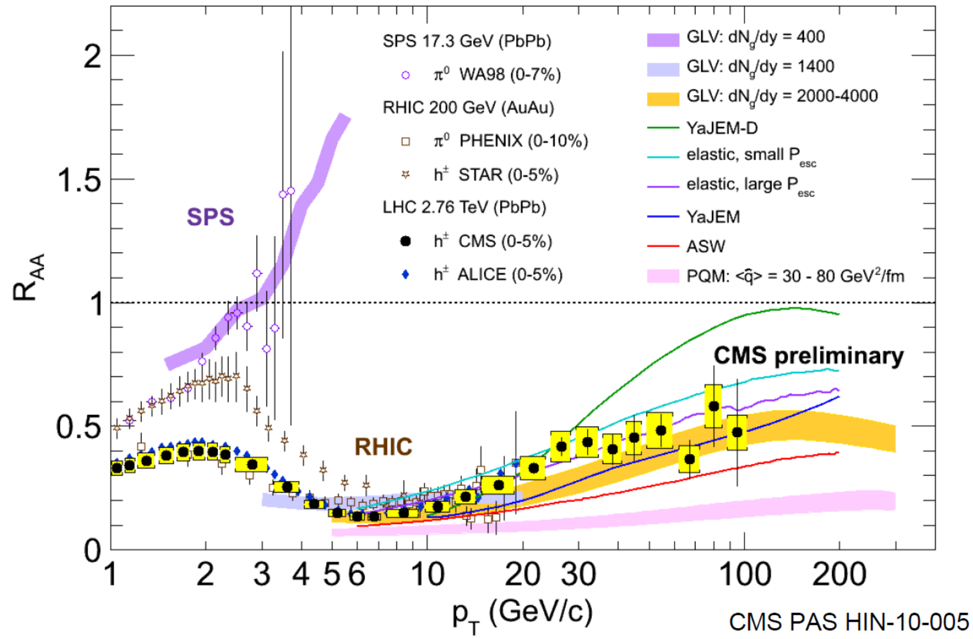
Exploring QCD phase diagram





Nuclear modification factor





- **Hard probes** - produced in hard scatterings in initial phase of collision
- Nuclear matter influences the final particle production

  e.g. production of particles at given p_T

  supresion of particle production of particular type

- **Nuclear modification factor** - quantification of nuclear effects R_{AA}

$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle Nbin \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

Heavy quarks as a probe of QGP

- p+p data:

→ baseline of heavy ion measurements.
→ test of pQCD calculations.

- Due to their large mass heavy quarks are primarily produced by gluon fusion in early stage of collision.

→ production rates calculable by pQCD.
M. Gyulassy and Z. Lin, PRC 51, 2177 (1995)

- heavy ion data:

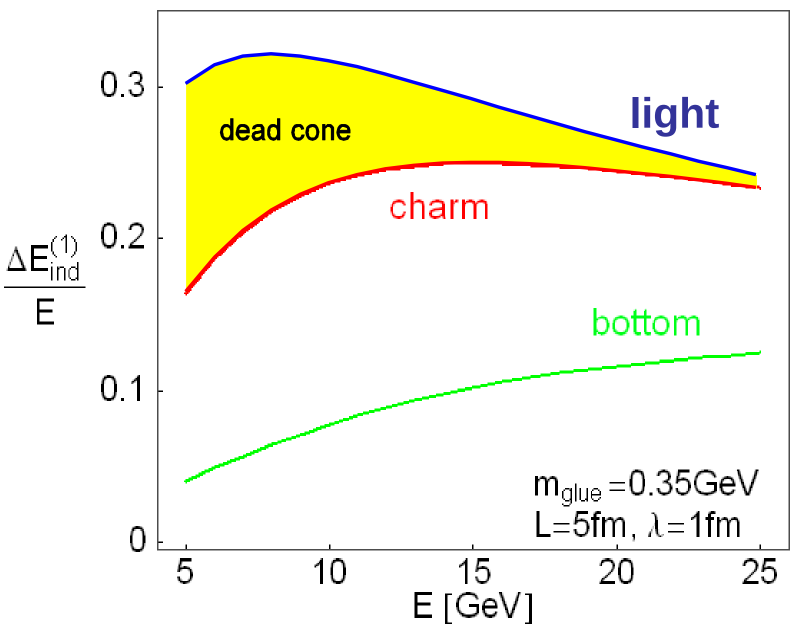
- Studying energy loss of heavy quarks.

→ independent way to extract properties of the medium.

- Studying the quarkonia suppression

→ deconfinement

ENERGY LOSS



M.Djordjevic PRL 94 (2004)

Quarkonia states in A+A

Charmonia: J/ψ, Ψ', χ_c Bottomonia: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

Key Idea: Quarkonia melt in the QG plasma due to color screening of potential between heavy quarks

- Suppression of states is determined by T_C and their binding energy
- Lattice QCD: Evaluation of spectral functions $\Rightarrow T_{melting}$

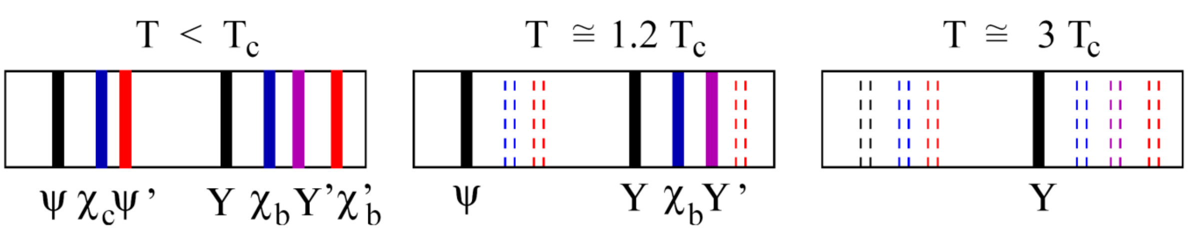
Sequential disappearance of states:

$\Rightarrow$ Color screening $\Rightarrow$ Deconfinement

$\Rightarrow$ QCD thermometer $\Rightarrow$ Properties of QGP

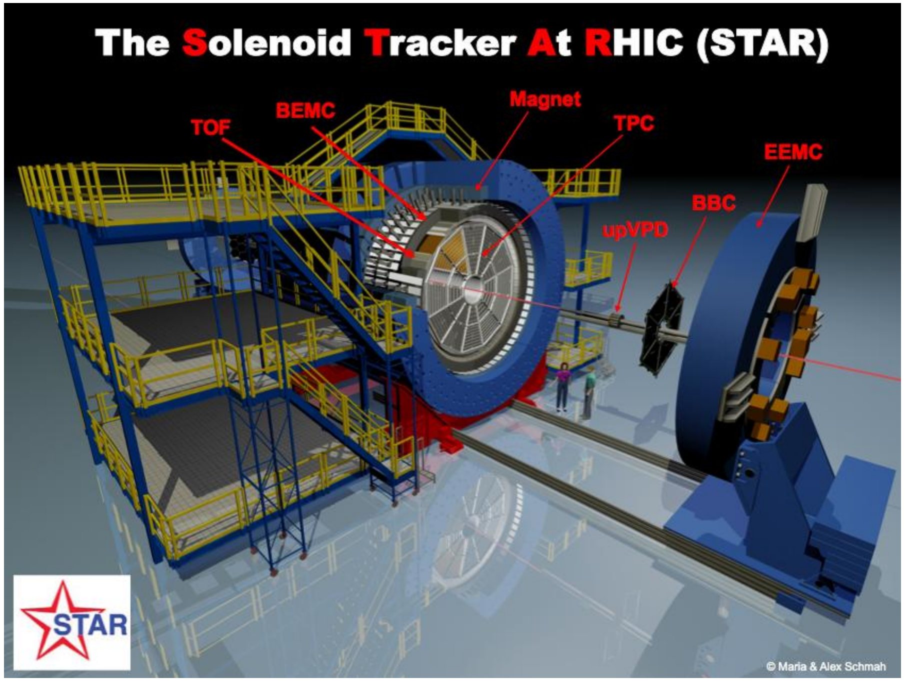
When do states really melt?

$T_{diss}(\psi') \approx T_{diss}(\chi_c) < T_{diss}(\Upsilon(3S)) < T_{diss}(J/\psi) \approx T_{diss}(\Upsilon(2S)) < T_{diss}(\Upsilon(1S))$



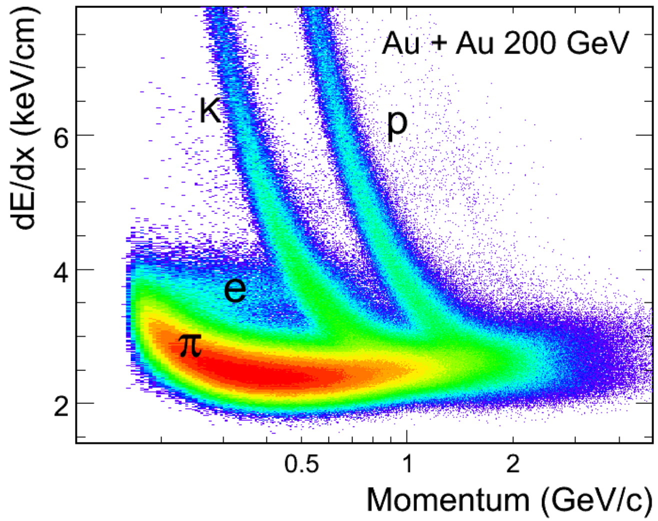
H. Satz, HP2006

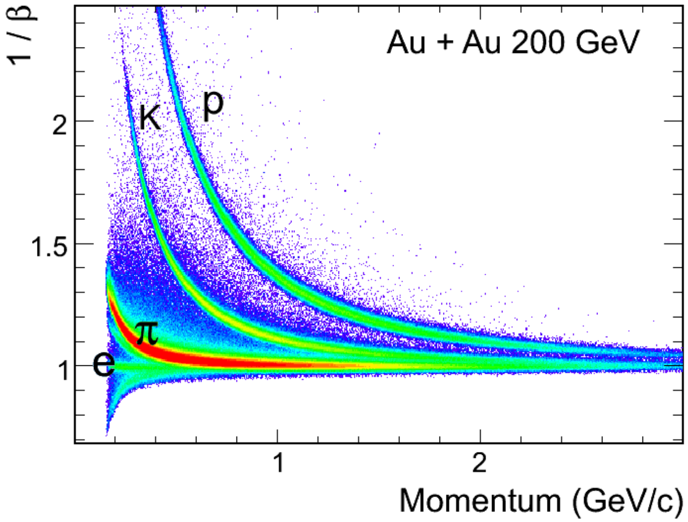
STAR detector and Particle ID



Large acceptance
$|\eta|<1, \; 0<\phi<2\pi$

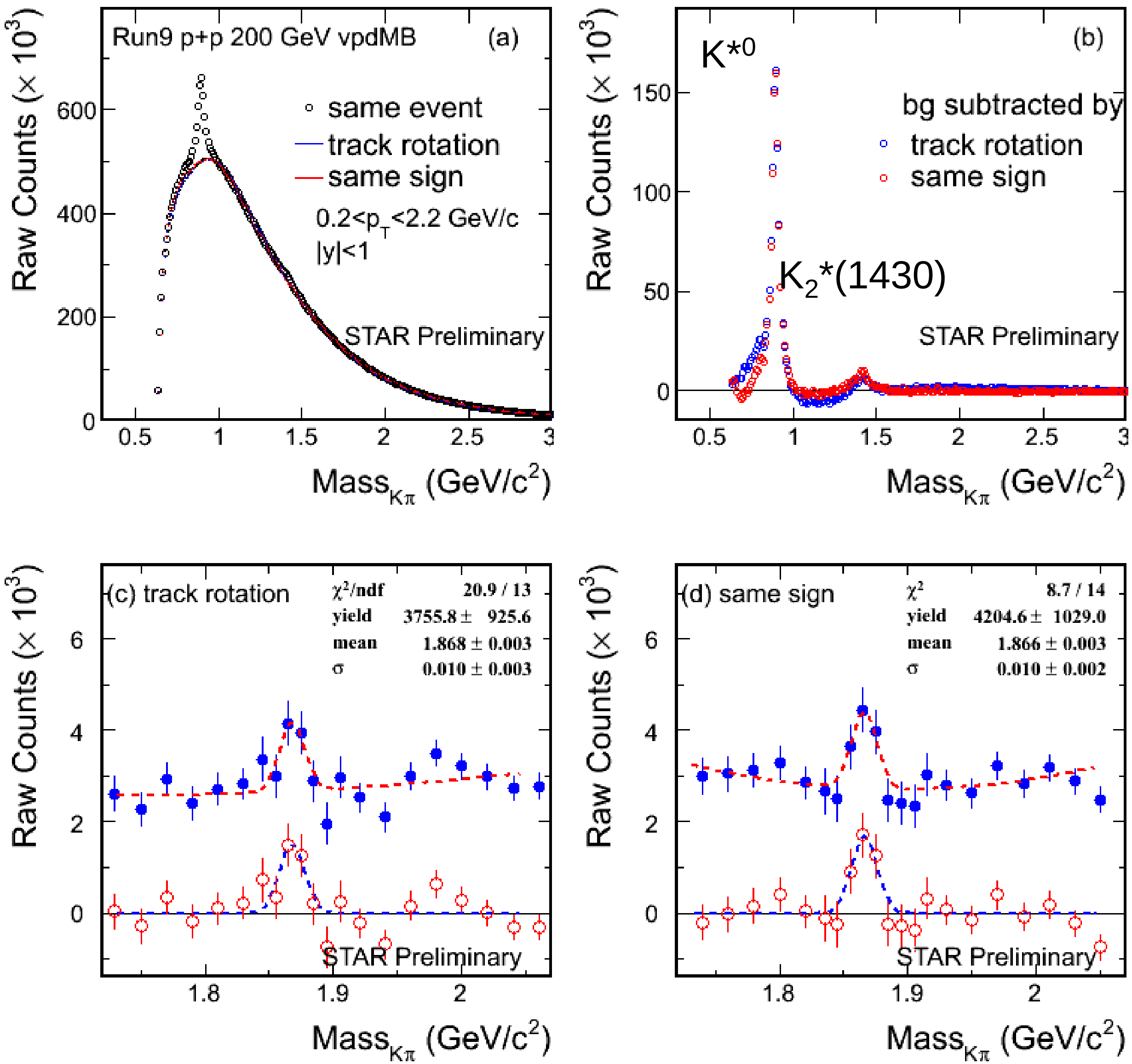
- Time Projection Chamber
  dE/dx, momentum
- Time Of Flight detector
  particle velocity $1/\beta$
- ElectroMagnetical Calorimeter
  E/p, single tower/topological Trigger





Open heavy flavor

D^0 signal in p+p 200 GeV



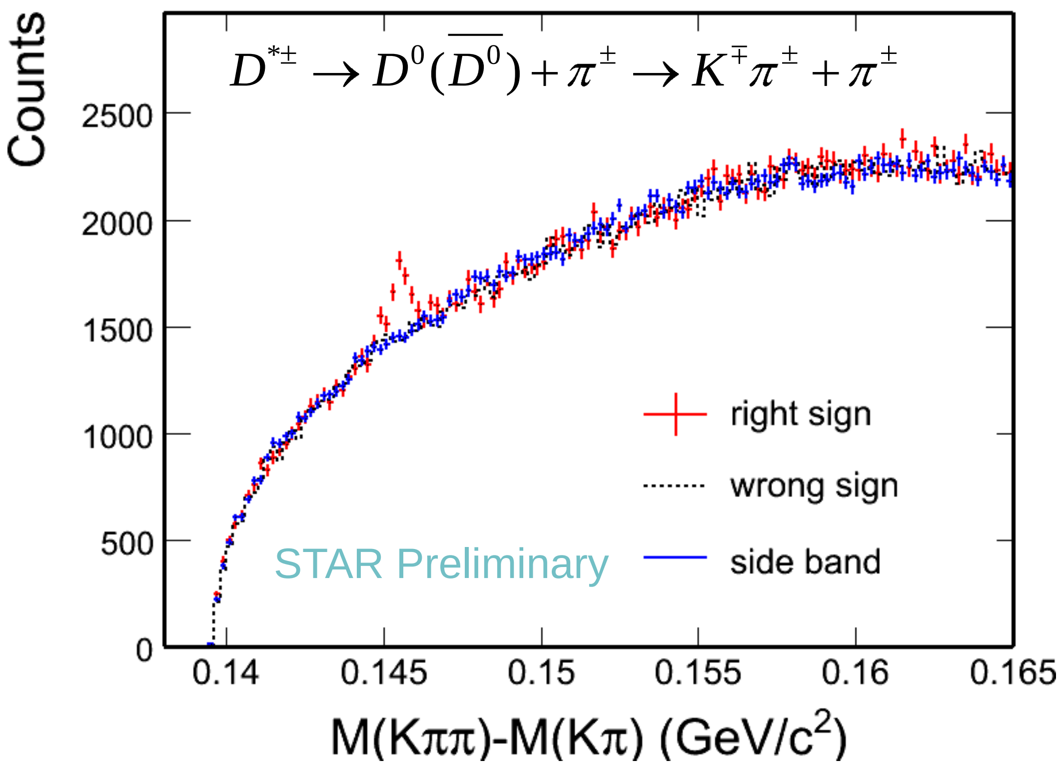
$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$

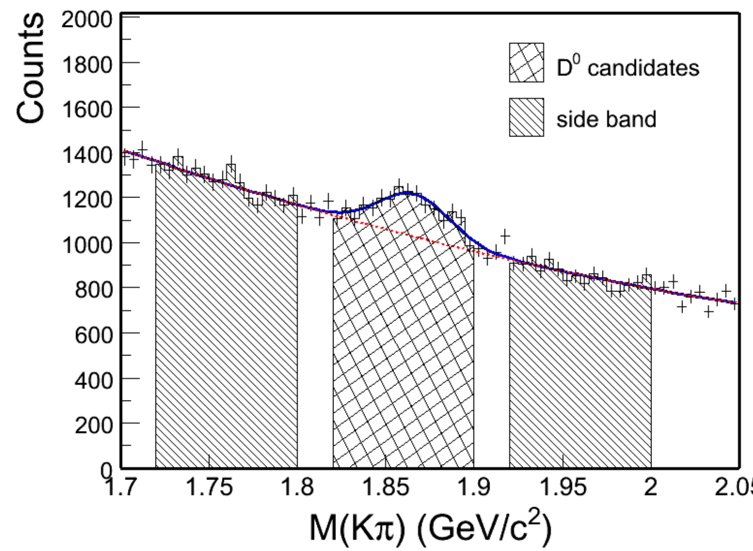
B.R. = 3.89%

- p+p 200 GeV MB 105 M
- 4-σ signal observed.
- Different methods reproduce combinatorial background.

D* signal in p+p 200 GeV

STAR QM2011





B.I.~Abelev, *et al.*, *PRD 79 (2009) 112006.*

- Minimum bias 105M events in p+p 200 GeV collisions.
- Two methods to reconstruct combinatorial background: wrong sign and side band.
- 8-σ signal observed.

Background combinations:

Wrong sign:

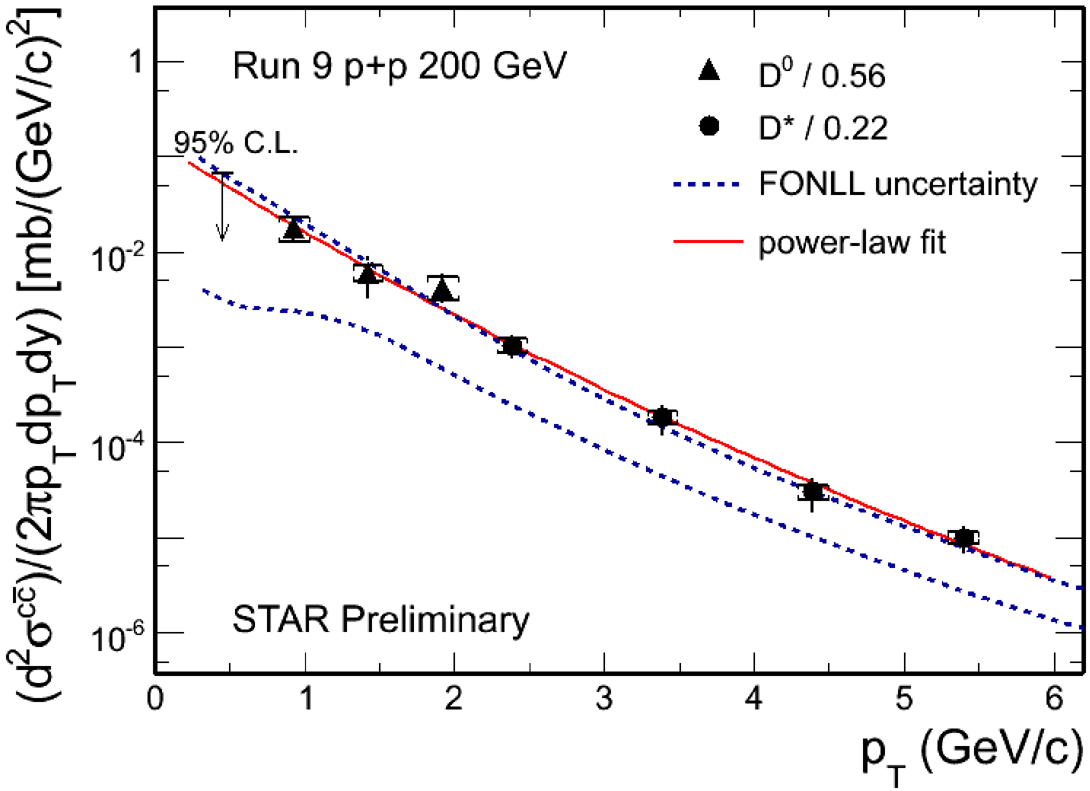
D^0 and π^-, D^0 and π^+

Side band:

1.72< M(Kπ) < 1.80 or

1.92 < M(Kπ) < 2.0 GeV/c^2

D^0 and D* p_T spectra in p+p 200 GeV



STAR QM2011

D^0 scaled by $N_{cc} / N_{D0} = 1 / 0.56$[1]

D* scaled by $N_{cc} / N_{D*} = 1 / 0.22$[1]

Consistent with FONLL[2] upper limit.

$Xsec = dN/dy|^{cc}_{y=0} \times F \times \sigma_{pp}$

$F = 4.7 \pm 0.7$ scale to full rapidity.

$\sigma_{pp}(NSD) = 30$ mb

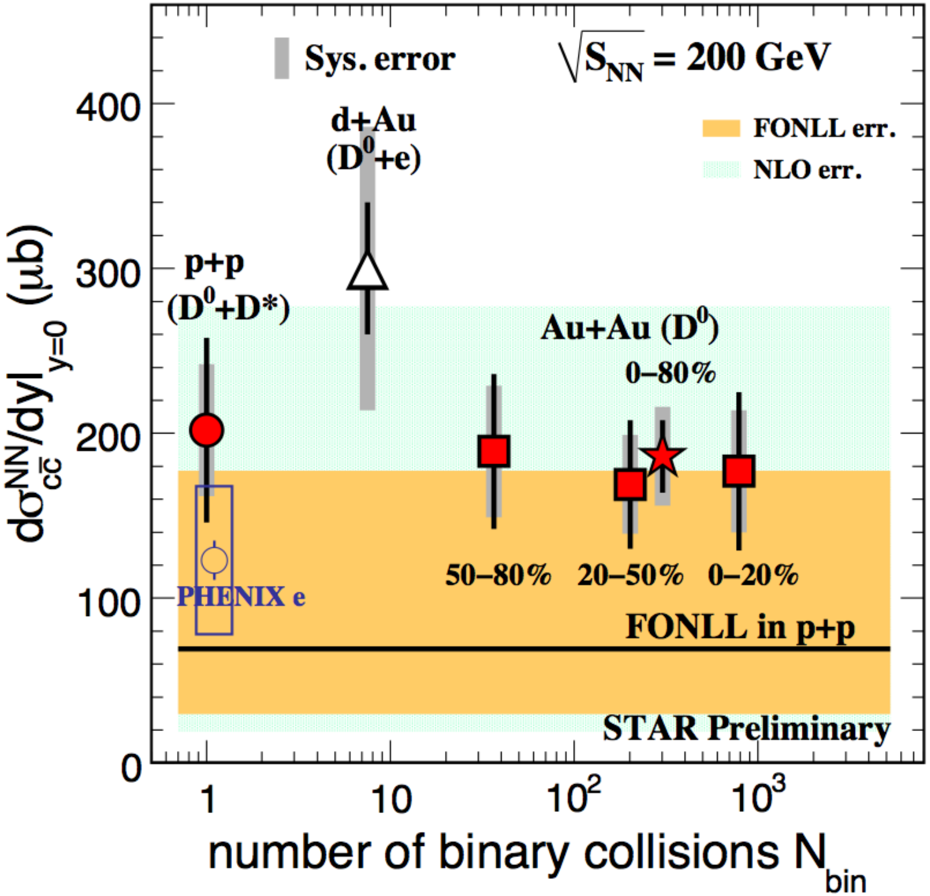
The charm cross section at mid-rapidity is:
202 ± 56 (stat.) ± 40 (sys.) ± 20 (norm.) μb

The charm total cross section is extracted as:
949 ± 263 (stat.) ± 253 (sys.) μb

[1] C. Amsler et al. (Particle Data Group), PLB 667 (2008) 1.
[2] Fixed-Order Next-to-Leading Logarithm: M. Cacciari, PRL 95 (2005) 122001.

Charm cross section vs N_{bin}

STAR QM2011



All of the measurements are consistent.

Year 2003 d+Au : D^0 + e

Year 2009 p+p : D^0 + D*

Year 2010 Au+Au: D^0

Assuming N_{D0} / N_{cc} = 0.56 does not change.

Charm cross section in Au+Au 200 GeV:

Mid-rapidity:

186 ± 22 (stat.) ± 30 (sys.) ± 18 (norm.) μb

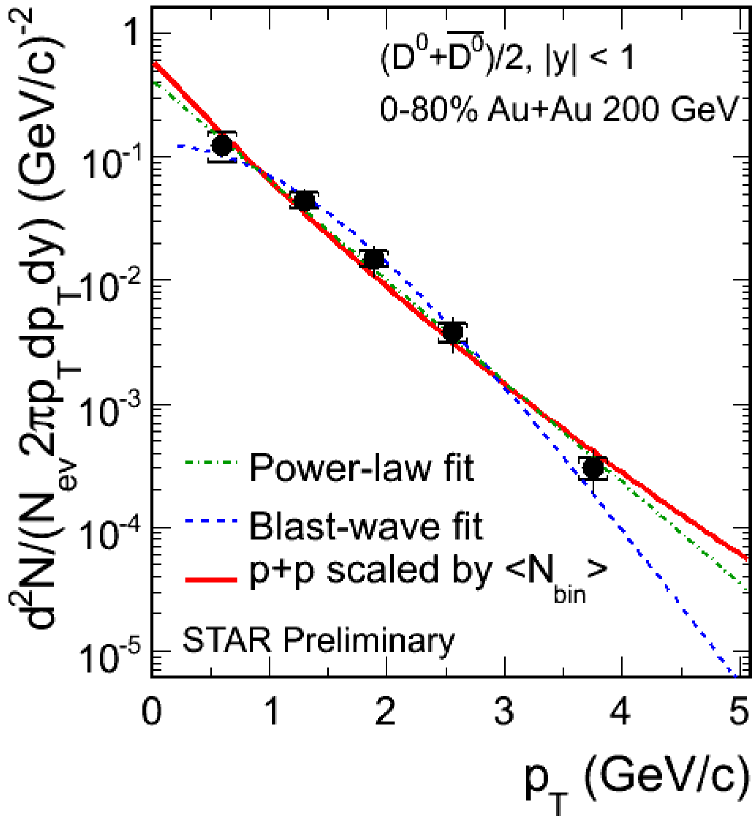
Total cross section:

876 ± 103 (stat.) ± 211 (sys.) μb

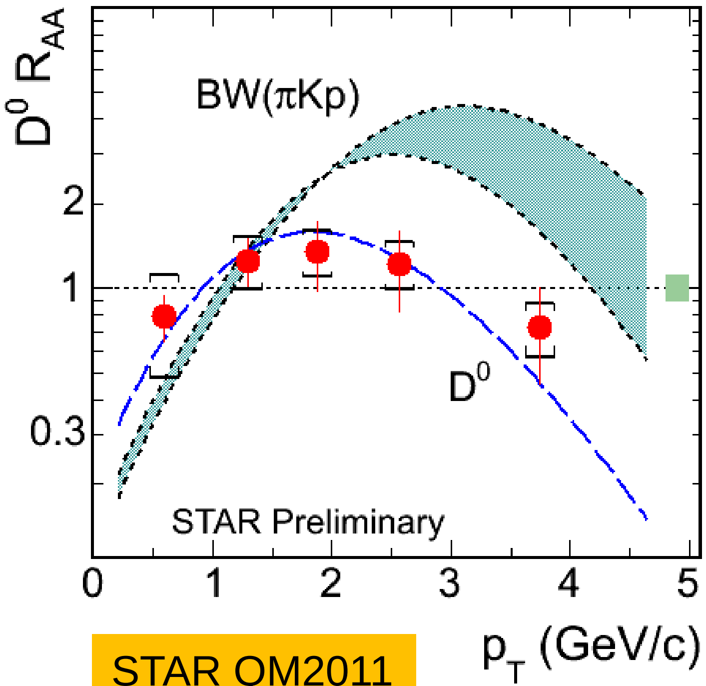
[1] STAR d+Au: J. Adams, et al., PRL 94 (2005) 62301
[2] FONLL: M. Cacciari, PRL 95 (2005) 122001.
[3] NLO: R. Vogt, Eur.Phys.J.ST 155 (2008) 213
[4] PHENIX e: A. Adare, et al., PRL 97 (2006) 252002.

Charm cross section follows number of binary collisions scaling =>
Charm quarks are mostly produced via initial hard scatterings.

D^0 R_{AA} vs p_T



BW (πKp): B. I. Abelev, et al., Phys. Rev. C 79 (2009) 34909.



STAR QM2011

- No obvious suppression at p_T < 3 GeV/c.
- Blast-wave predictions with light hadron parameters are different from data.

=> D^0 freeze out earlier than light hadrons.

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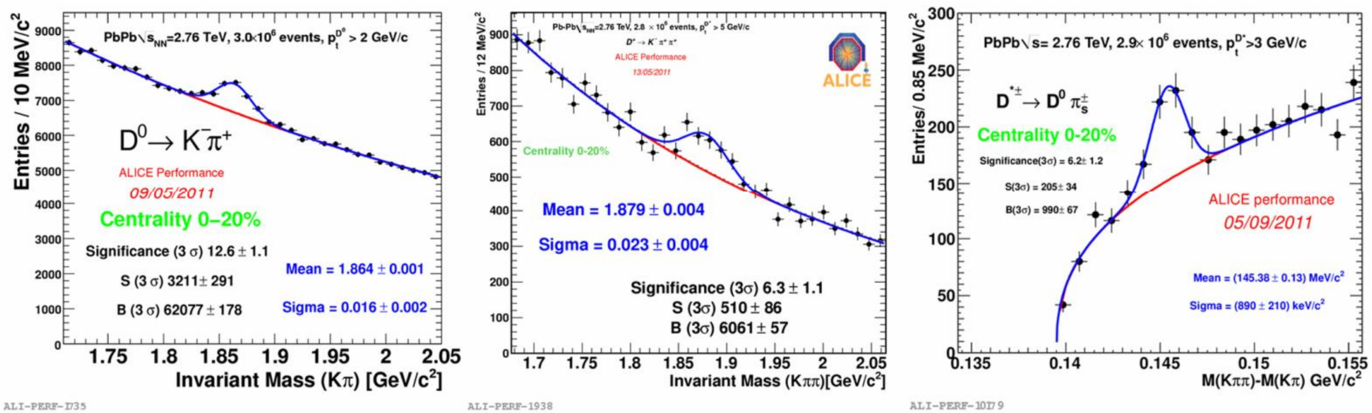
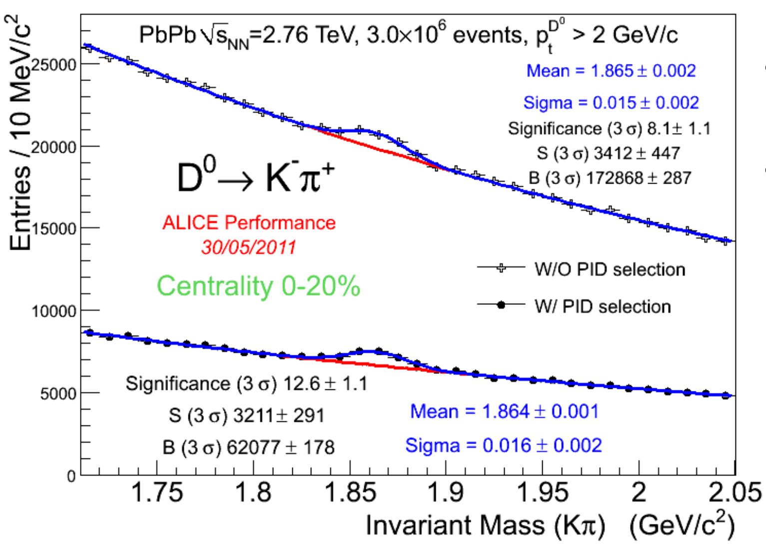
ALICE charm measurements

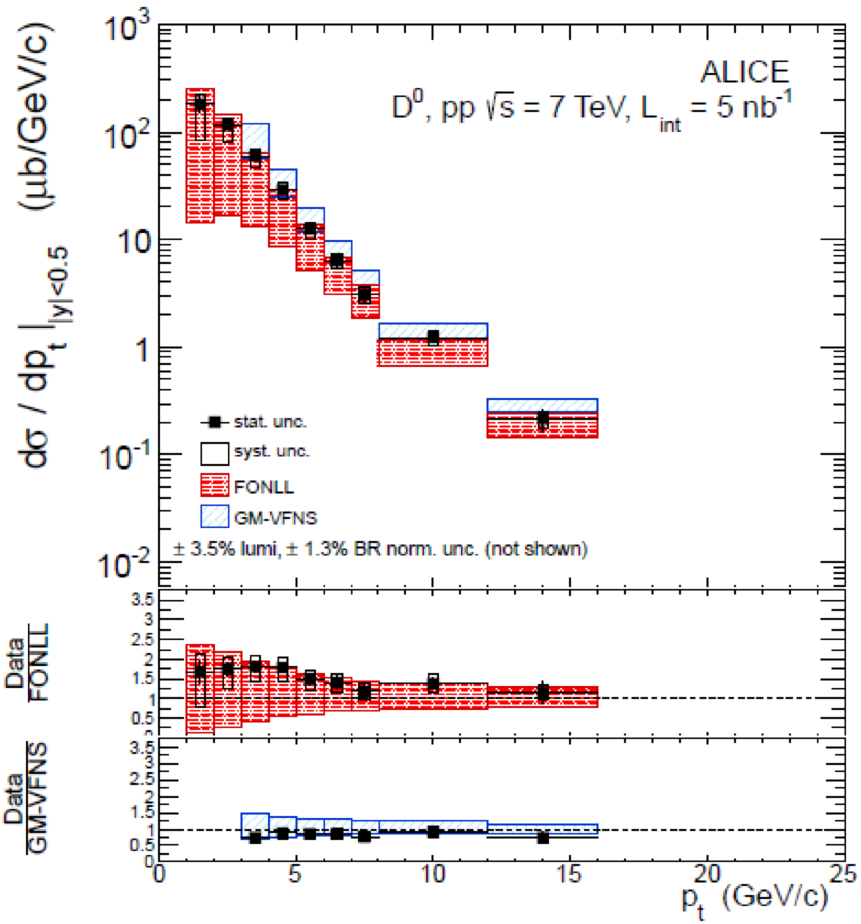
ALICE SQM2011

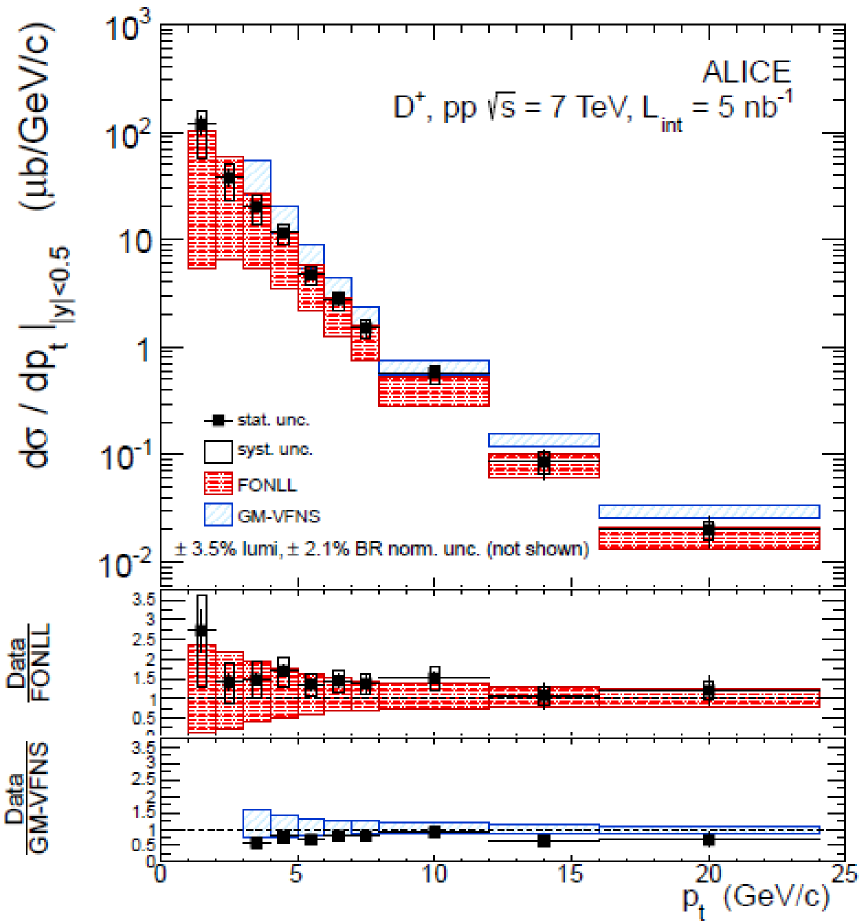




- Using secondary vertex detectors
- Excellent capability to measure wide p_T spectrum on many charm mesons + Λ_c

Comparison to pQCD

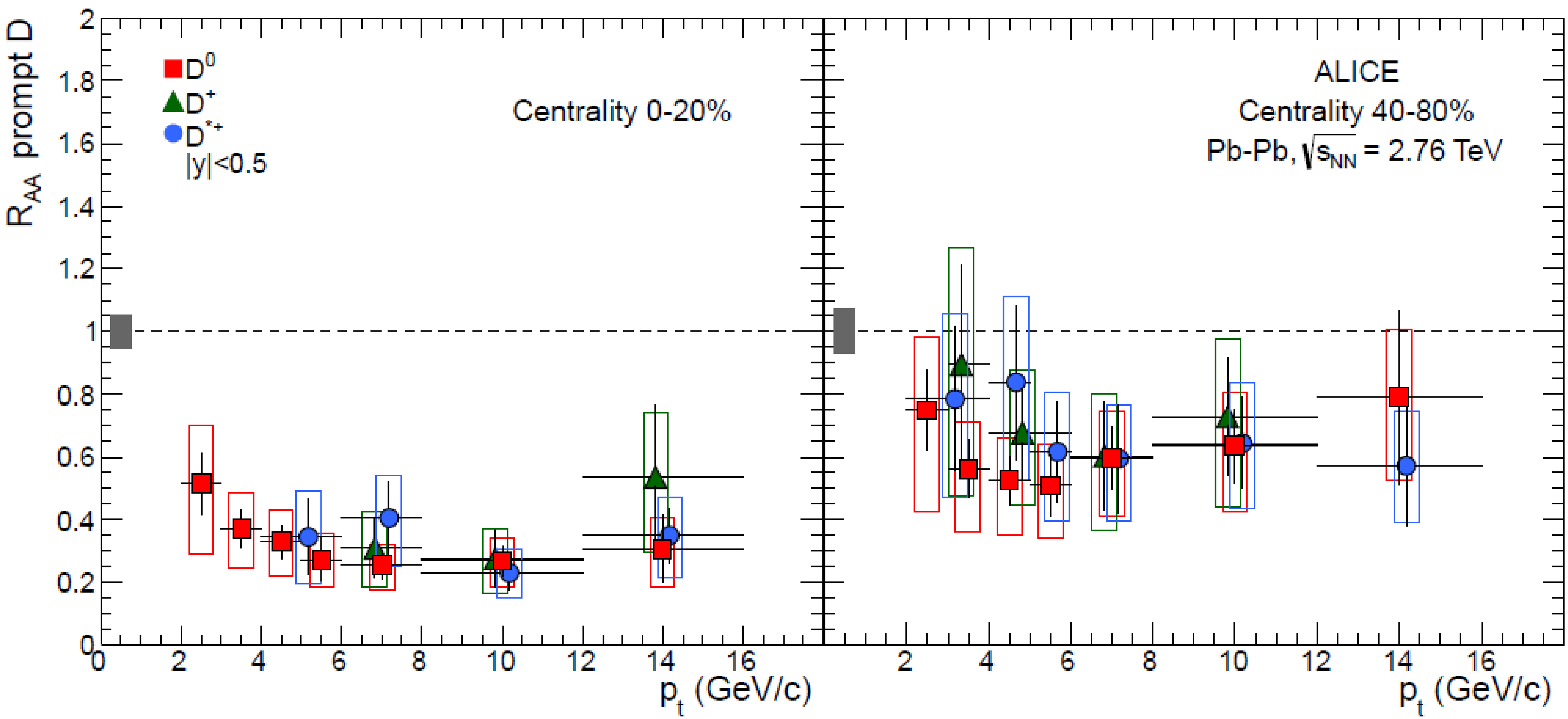




- Data compatible with pQCD prediction within uncertainties
  - As observed at lower energies, data are on the upper edge of FONLL uncertainty band

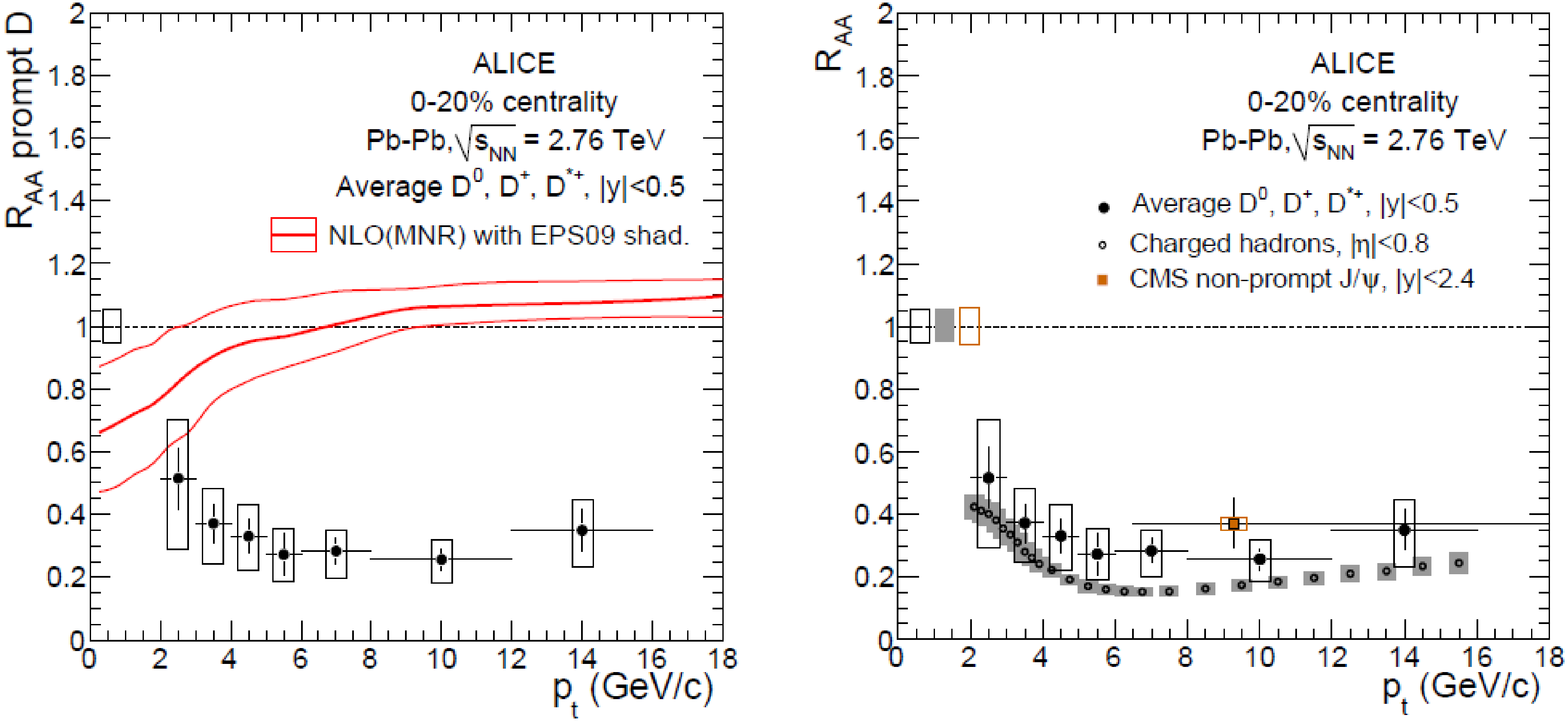
ALICE SQM2011

Prompt D meson R_{AA}



- Suppression of prompt D mesons in central (0-20%) Pb+Pb collisions by a factor 3-4 for p_T>5 GeV/c
  - Smaller suppression for peripheral events

Prompt D meson R_{AA}



- Little shadowing at high p_T → suppression is a hot matter effect
- Similar suppression for D mesons and pions
  - Hint of $R_{AA}^D > R_{AA}^\pi$ at low p_T
  - CMS measurement of displaced J/ψ (from B feeddown) indicate $R_{AA}^B > R_{AA}^D$

Measurement of non-photonic electrons

Background Dominated by Photonic Electrons from :

$$\pi^0 \rightarrow \gamma + e^+ + e^-$$

Same for All Experiments

$$\eta \rightarrow \gamma + e^+ + e^-$$

$$\gamma \rightarrow e^+ + e^-$$

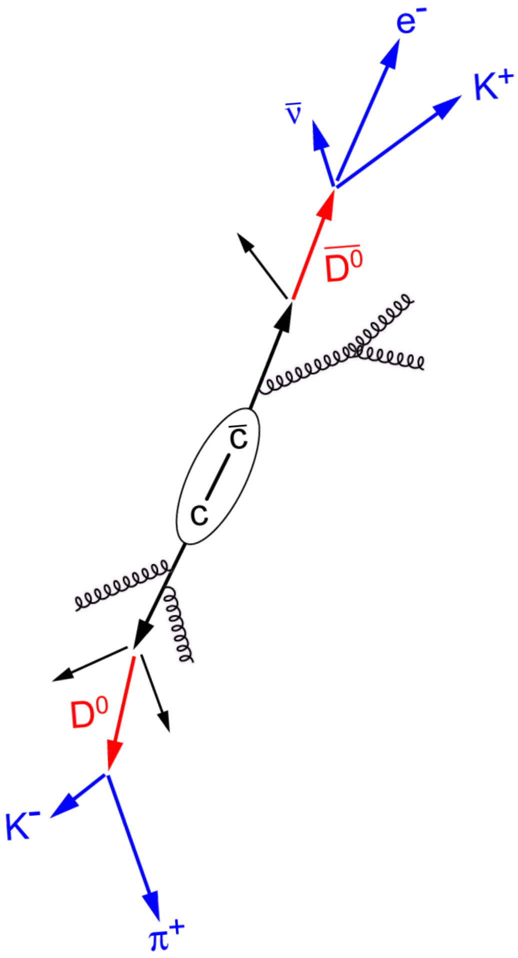
Depend on Experiment

- Mostly from $\pi^0(\eta) \rightarrow \gamma + \gamma$
- Conversion probability: 7/9* X_0

When X_0 is large, gamma conversion dominate all the background.

These background has to be properly subtracted

Still mixture of B,D origin



Non-photonic R_{AA} at RHIC

DGLV:
Djordjevic, PLB632, 81 (2006)

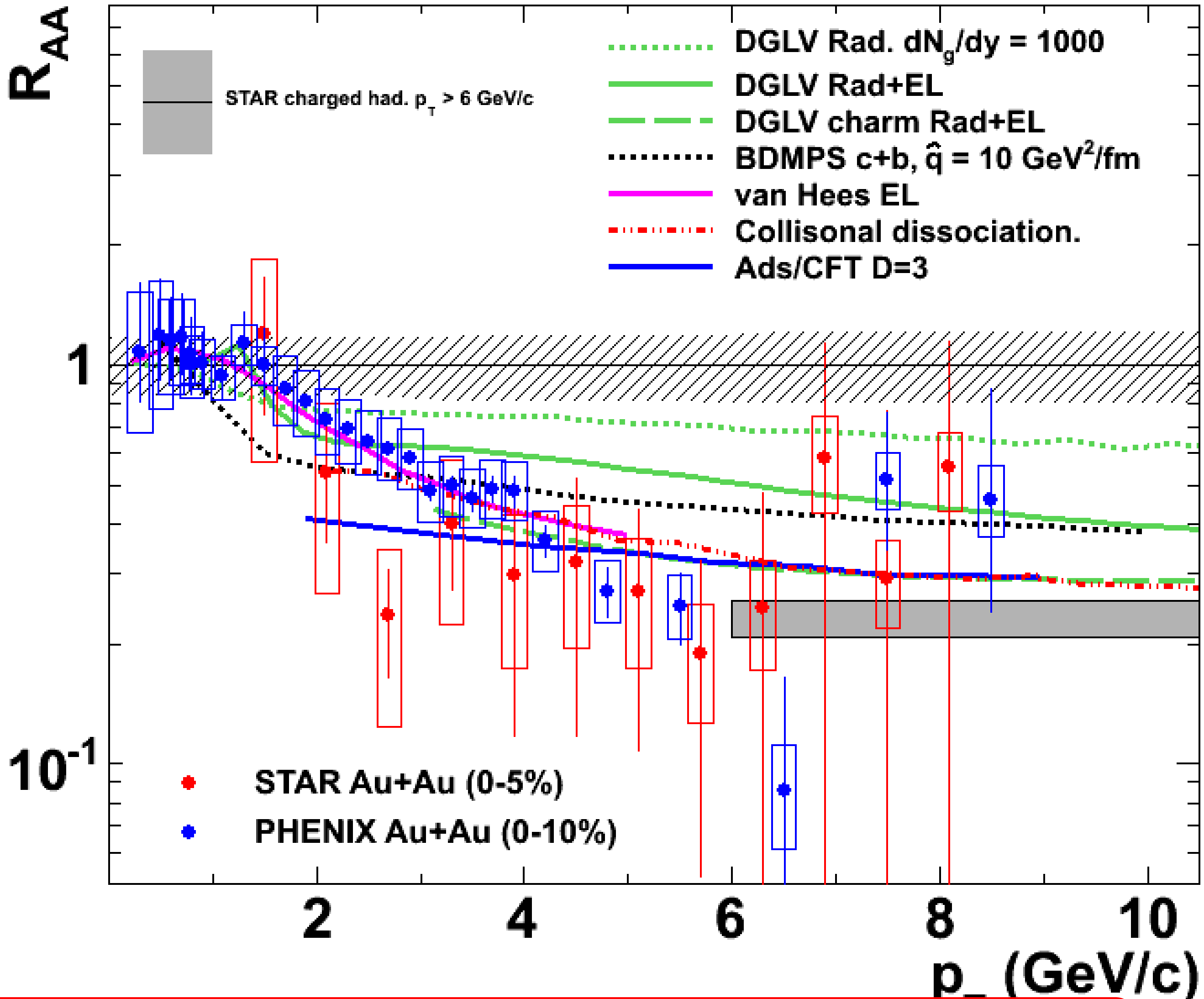
BDMPS:
Armesto, et al.,PLB637, 362 (2006)

T-Matrix:
Van Hees et al., PRL100,192301(2008).

Coll. Dissoc.
R. Sharma et al., PRC 80, 054902(2009).

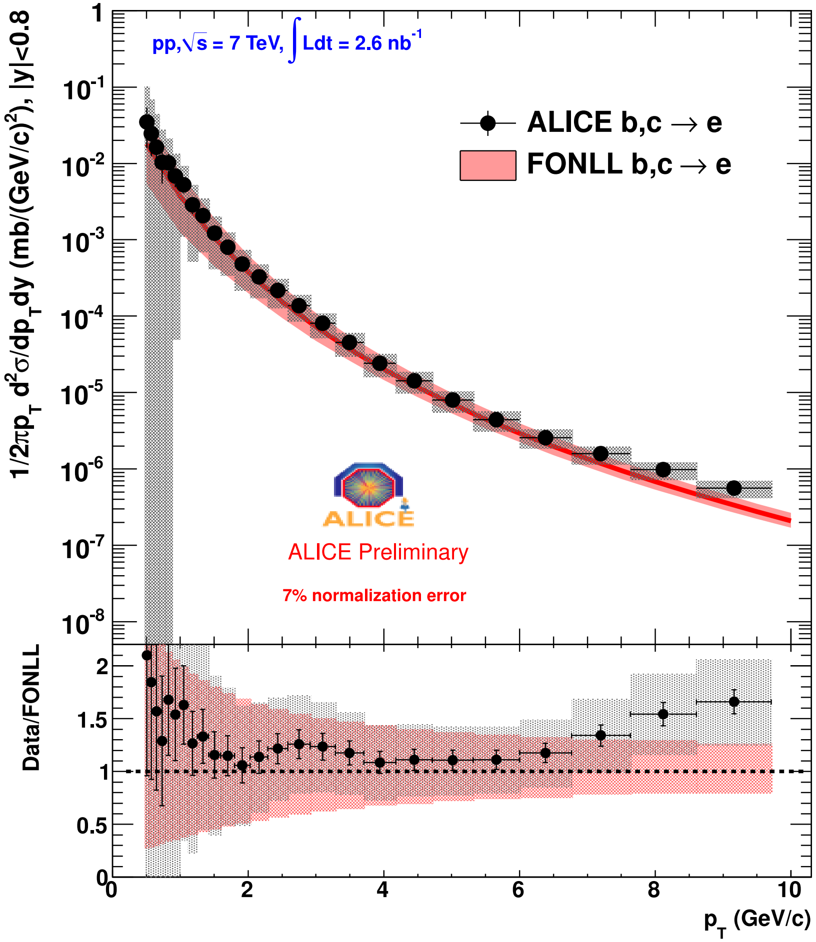
Ads/CFT:
W. Horowitz Ph.D thesis.

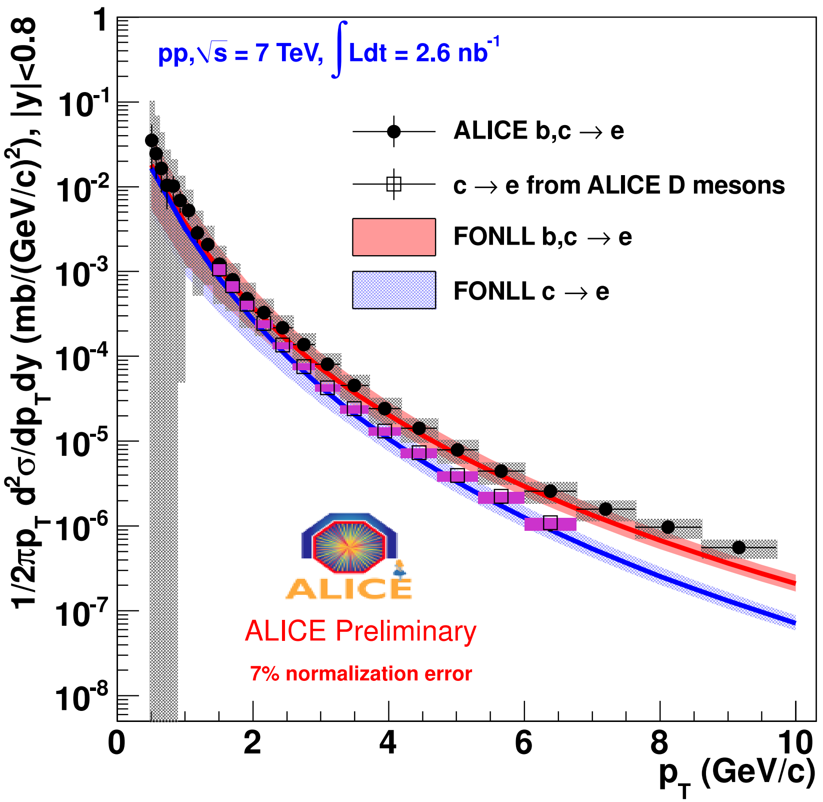
RL.+ Coll.
J. Aichelin et al., SQM11



- ❑ Models with different or similar mechanisms can or can not describe the data
  - ➢ Which one is right and what are missing?

Electrons from Heavy Flavour decays



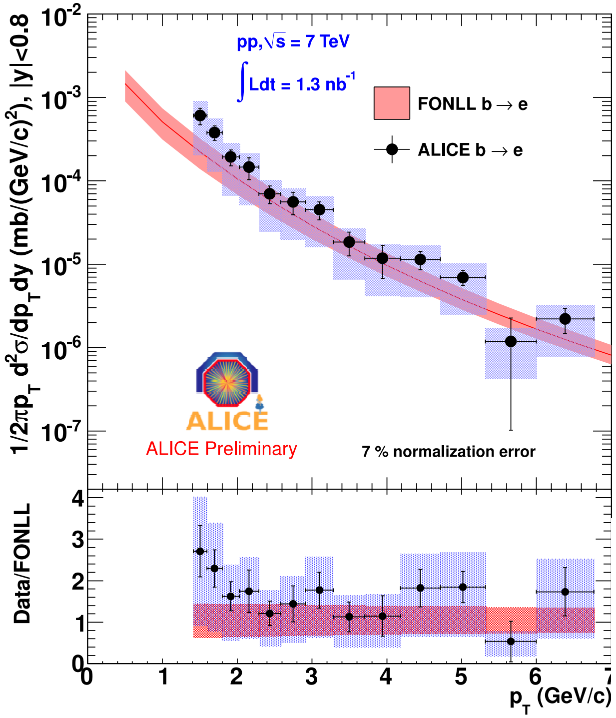


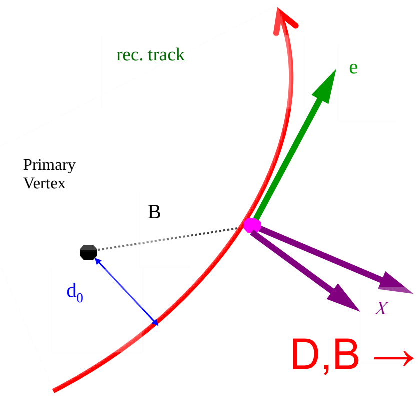
- Subtracted cocktail of electron background based on the measured π^0 spectrum + m_t-scaling + pQCD direct photons.
- Good agreement with FONLL b+c over the full p_t range
- Consistent with the prompt charm measurement from D mesons

Electrons from Beauty decays

Strategy : select electrons from displaced vertexes

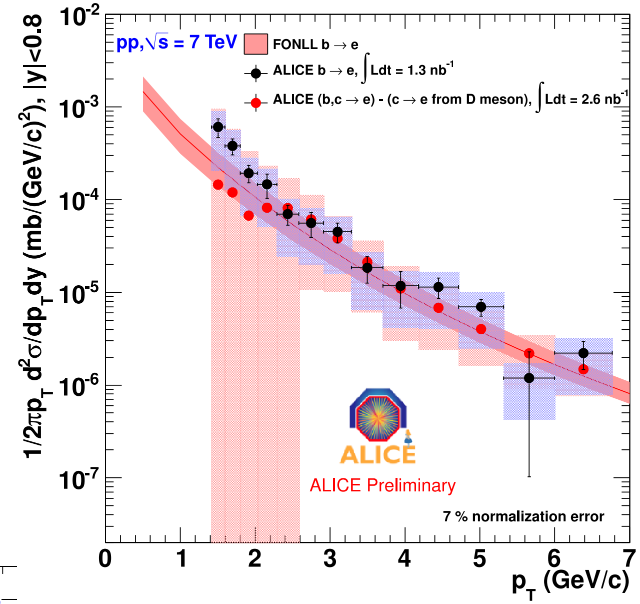
Impact parameter analysis



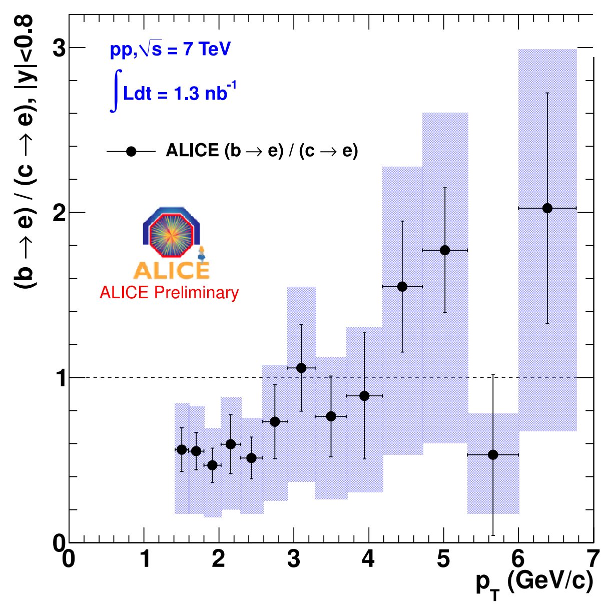


D,B → e + X

D→e+X
=
B→e+X



- Measurementof B-> e+X from1.5 to 6 GeV/c
- Good crosscheck with D,B e + X and D meson measurements
- Well described by FONLL calculations

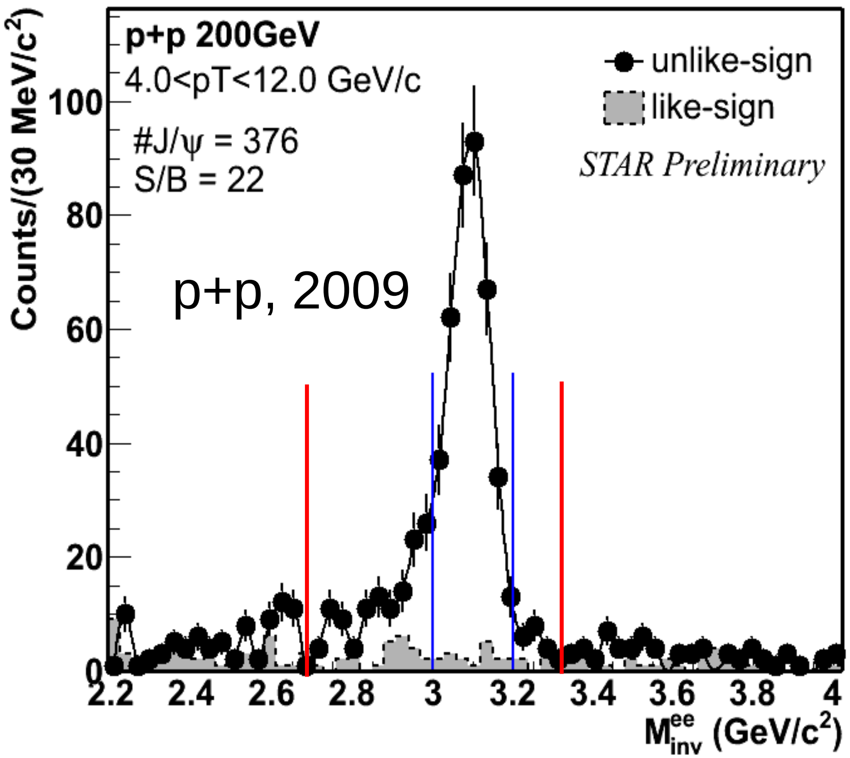


QUARKONIA

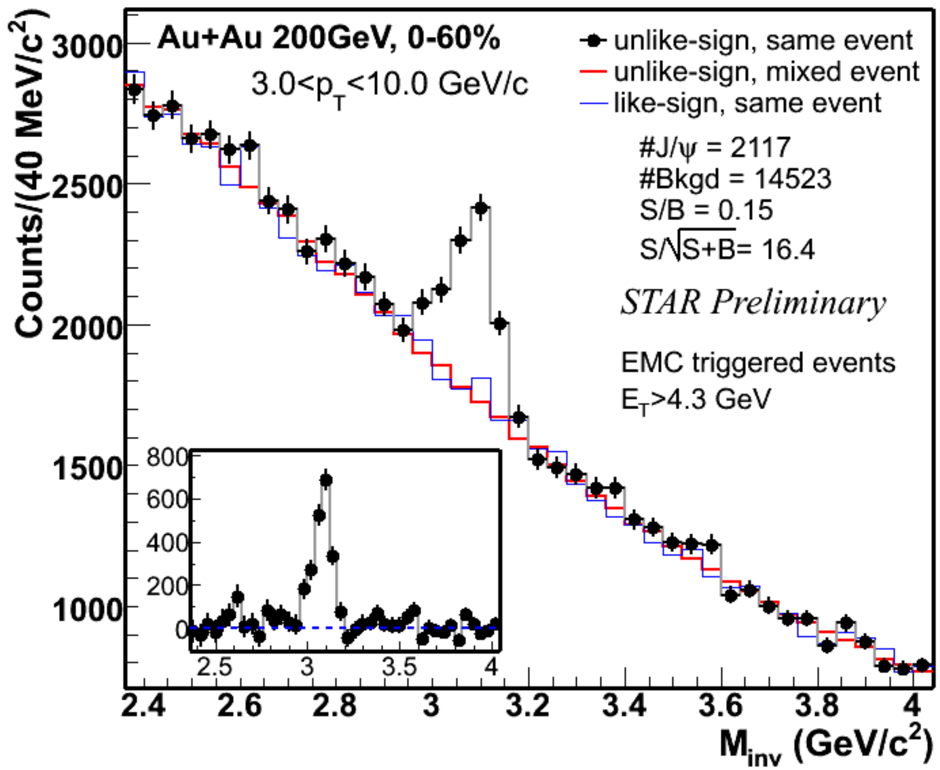
J/ψ

SQM11 LHC results

J/ψ –> e^+e^- signals



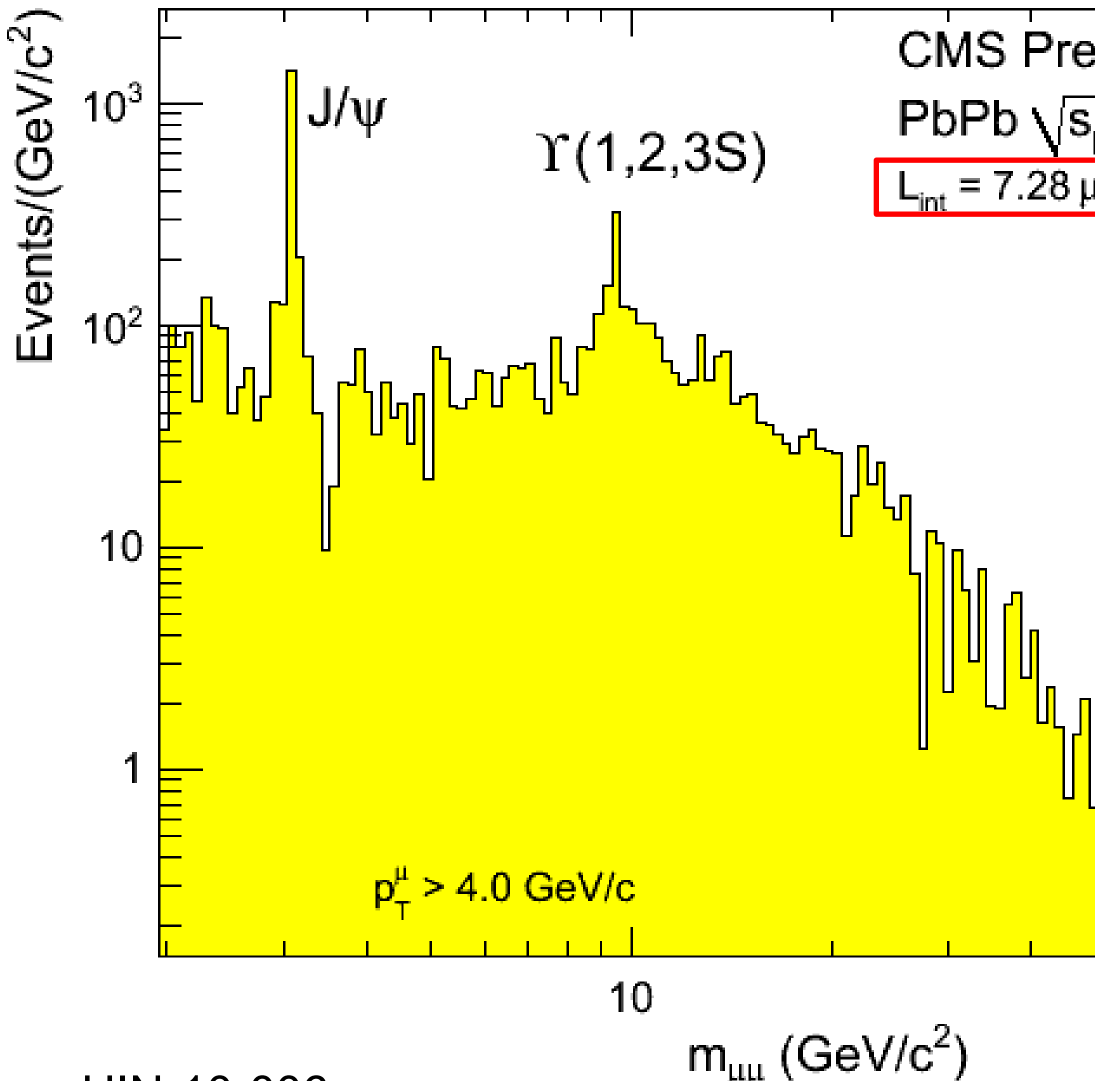
TPC+BEMC



TPC+BEMC+TOF

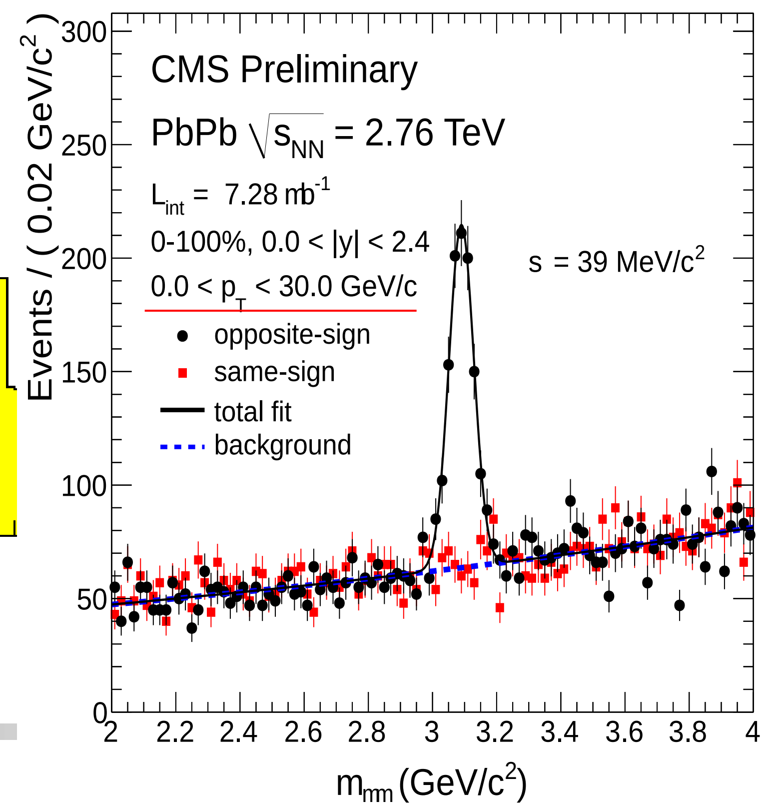
- Significantly reduced material in 2009 p+p and 2010 Au+Au collisions
- Clear signal for high-p_T in both p+p and Au+Au 200 GeV collisions

Di-muons in PbPb at 2.76 TeV



$N_{J/\psi}$=734±54

(0 < p_T < 30 GeV/c)

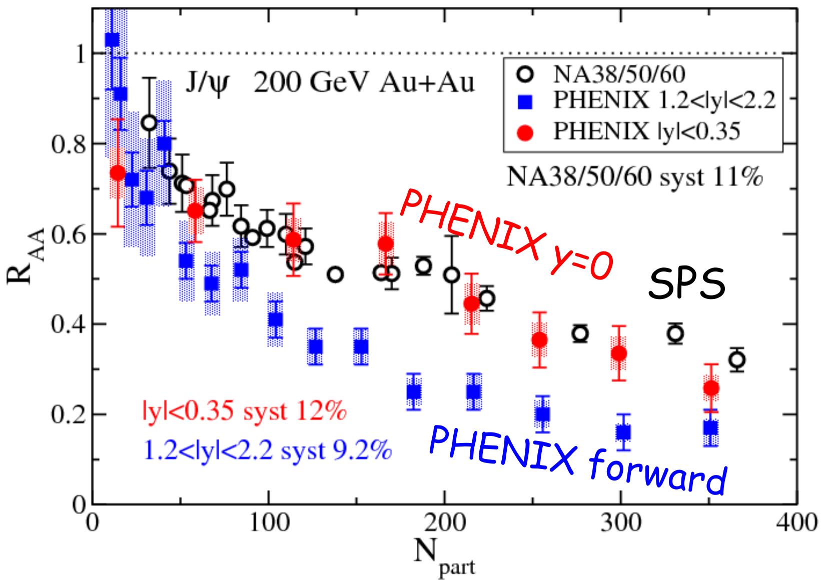


HIN-10-006

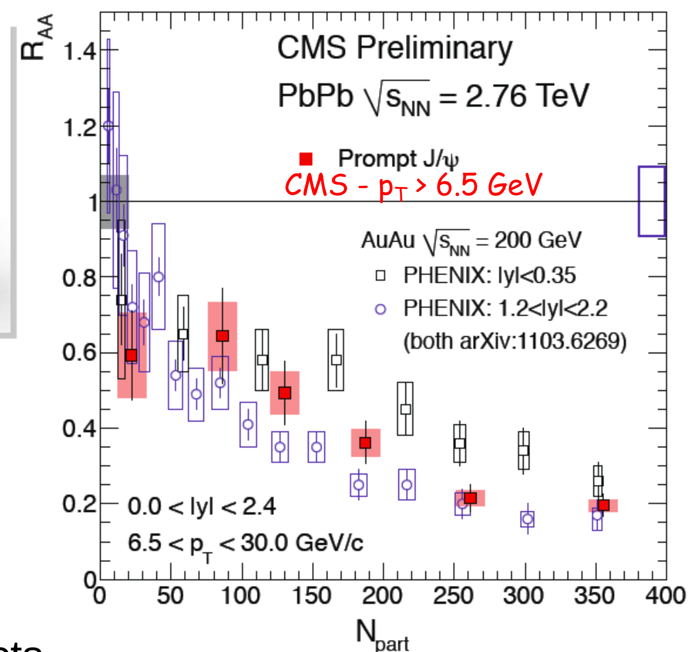
This is really impressive!

Quarkonia Suppression Similarity in √s

PHENIX arXiv:1103.6269



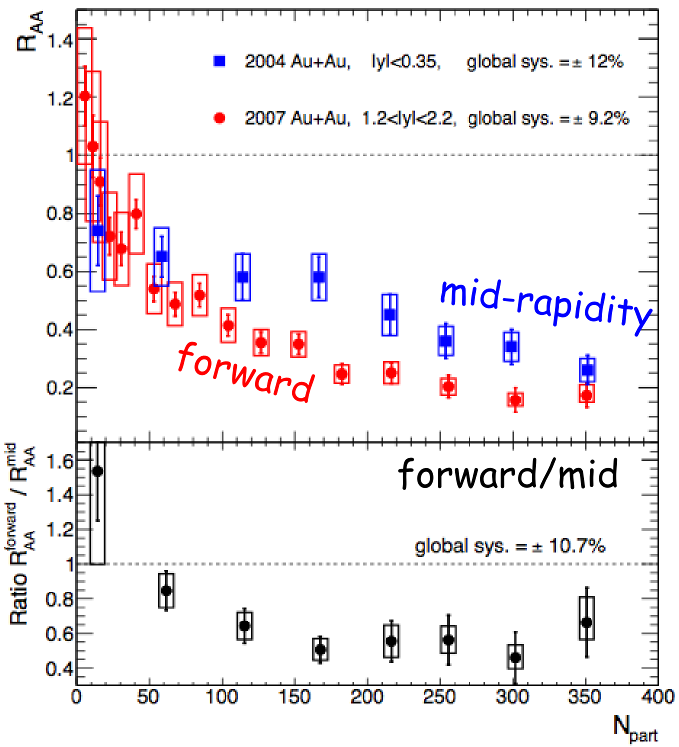
Overall suppression of J/ψ is nearly identical between RHIC, SPS, & LHC

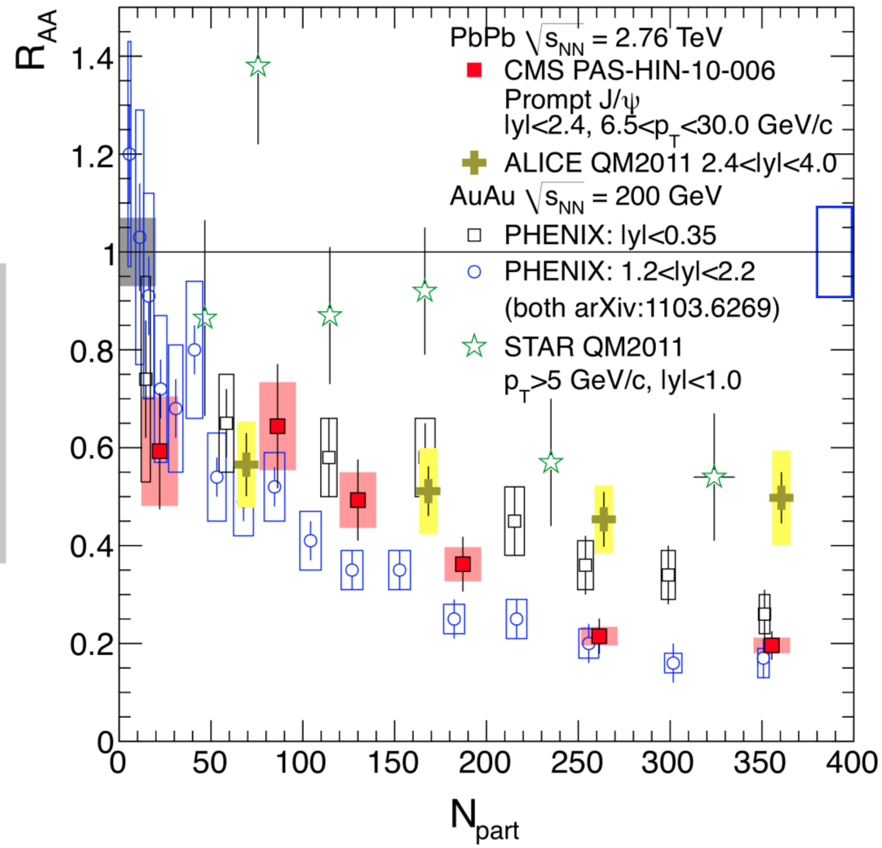


- different conditions - similar suppression
- how to get full control on cold nuclear matter effects

Quarkonia Suppression Levels Differ in Details

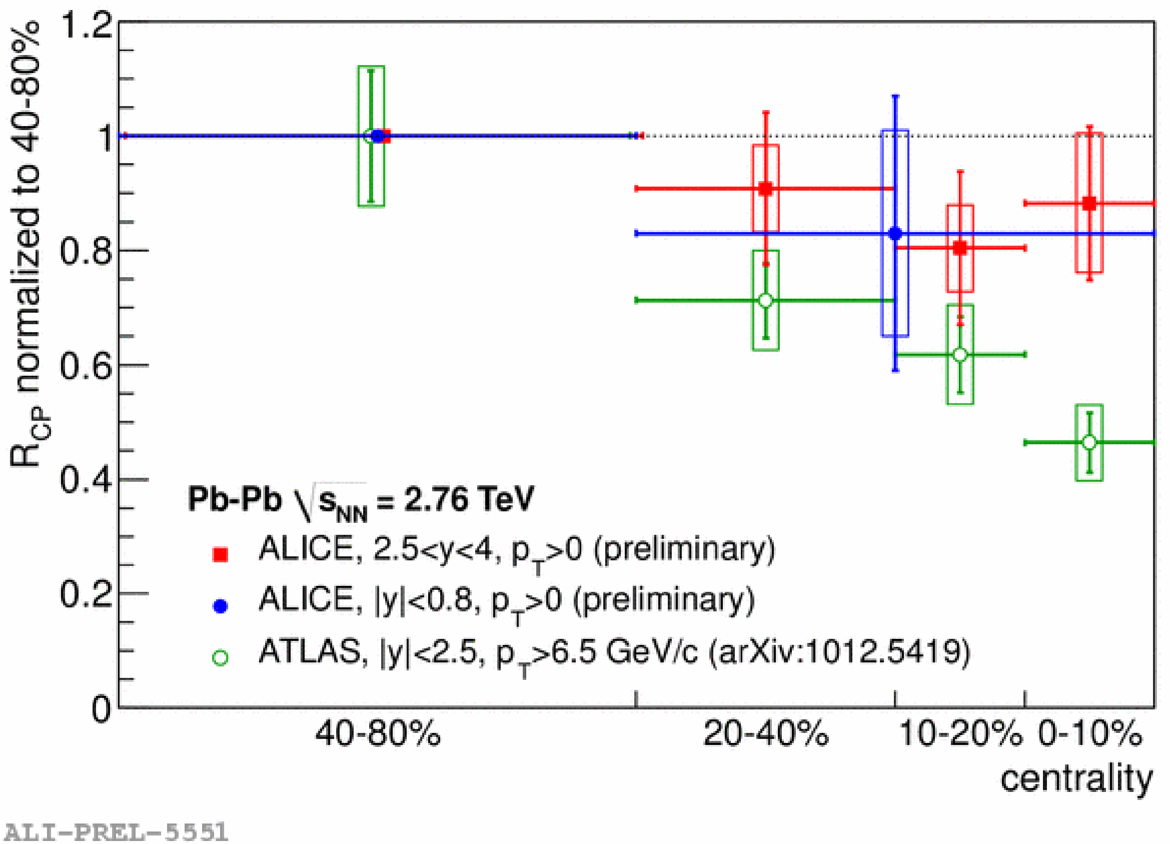
PHENIX arXiv:1103.6269





Forward-rapidity is suppressed more than Mid-rapidity

J/Ψ R_{CP}: ALICE vs ATLAS



- *Less suppression in ALICE than in ATLAS*

– ATLAS:

- |y|<2.5
- 80% of J/ψ have p_T>6.5 GeV/c
- error in the 40-80% bin not propagated

⇨ ALICE:

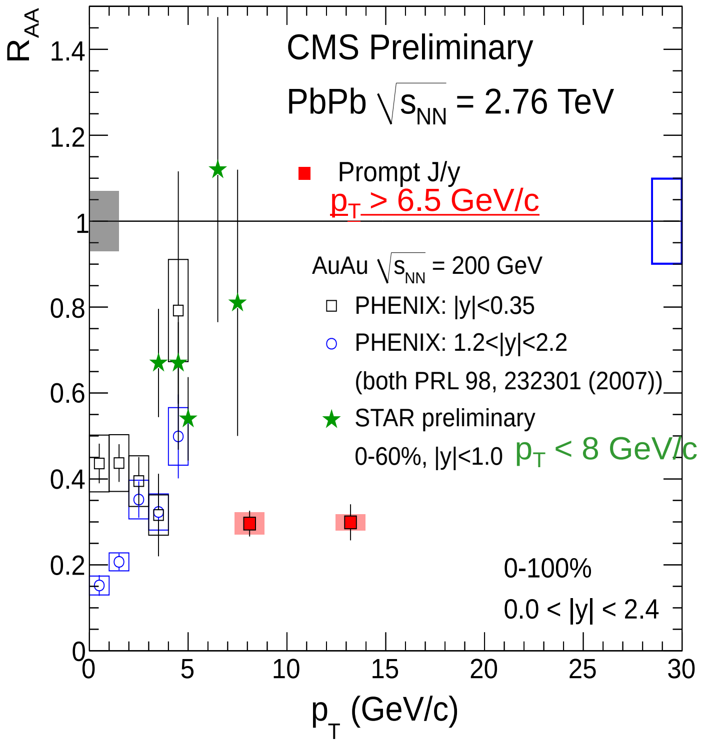
✓ ***$\mu^+\mu^-$ in 2.5<y<4.0***

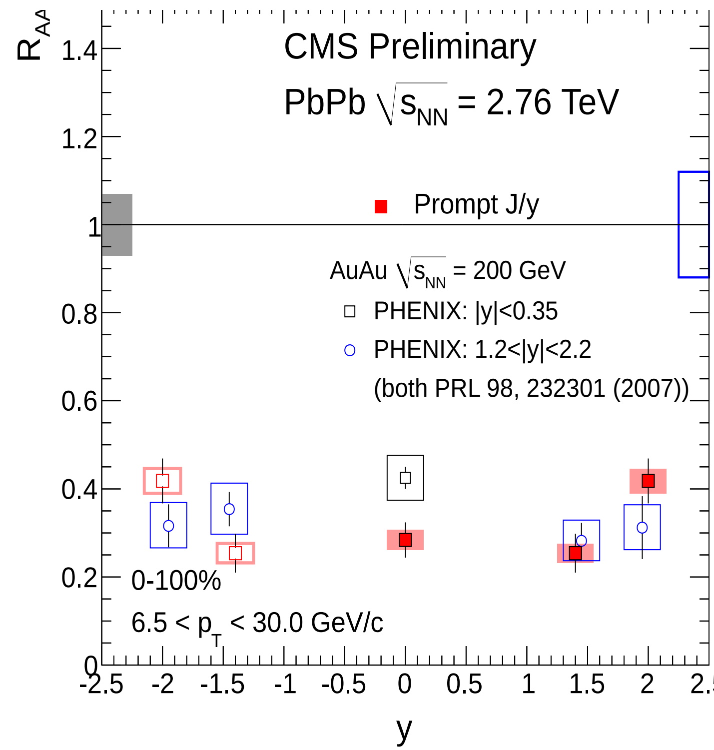
✓ ***e^+e^- in |y|<0.8***

✓ ***p_T>0 GeV/c***

Nuclear Modification of J/ψ

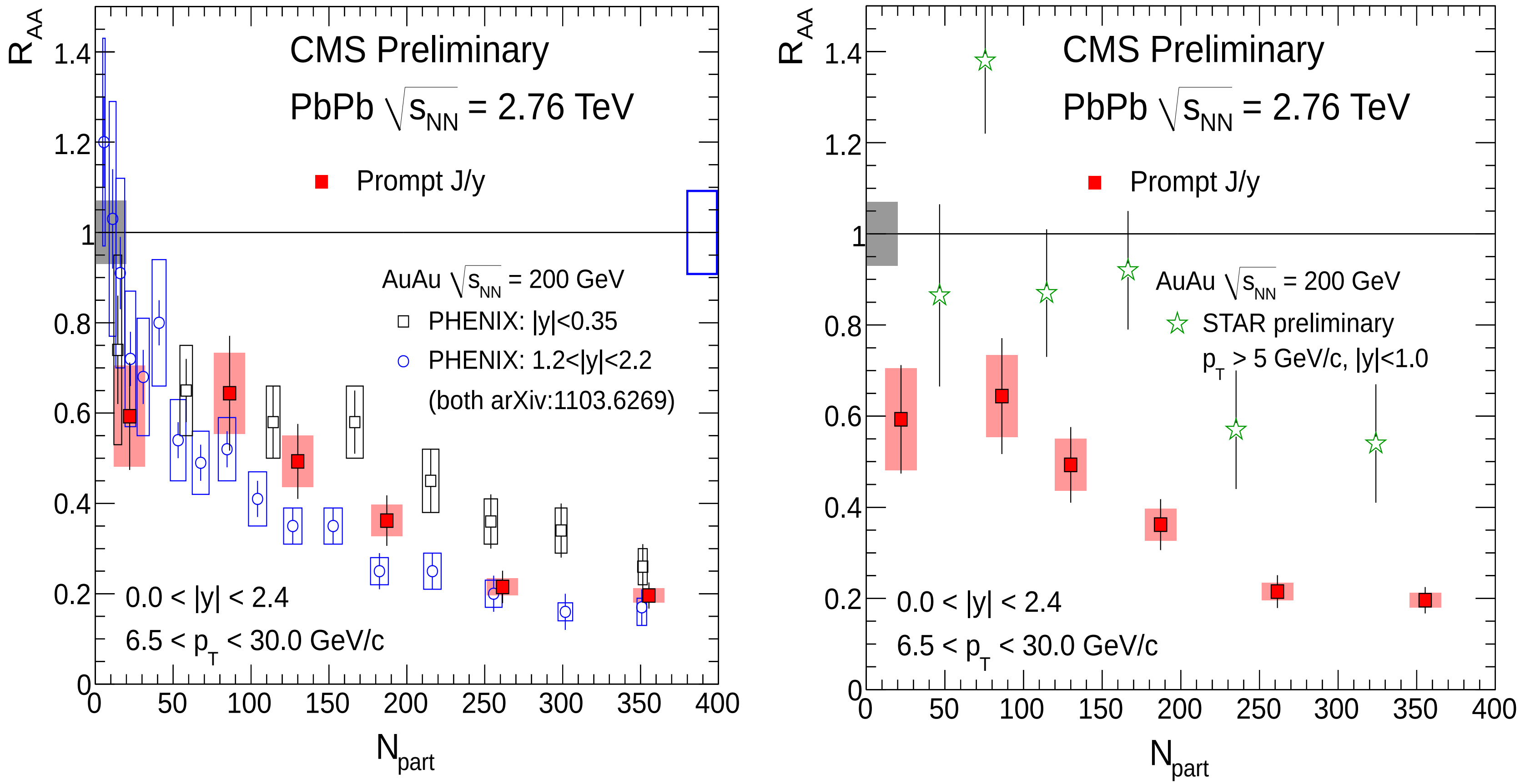
HIN-10-006





- Factor 3 suppression for p_T > 6.5 GeV/c at y=0
- Trend to less suppression at forward rapidity
- ALICE: $R_{AA}(p_T^{J/\psi} > 0$ GeV/c, $2.5 < y < 4.0) = 0.49 \pm 0.03 \pm 0.11$ (QM11)
  CMS: $R_{AA}(p_T^{J/\psi} > 3$ GeV/c, $1.6 < y < 2.4) = 0.39 \pm 0.06 \pm 0.03$

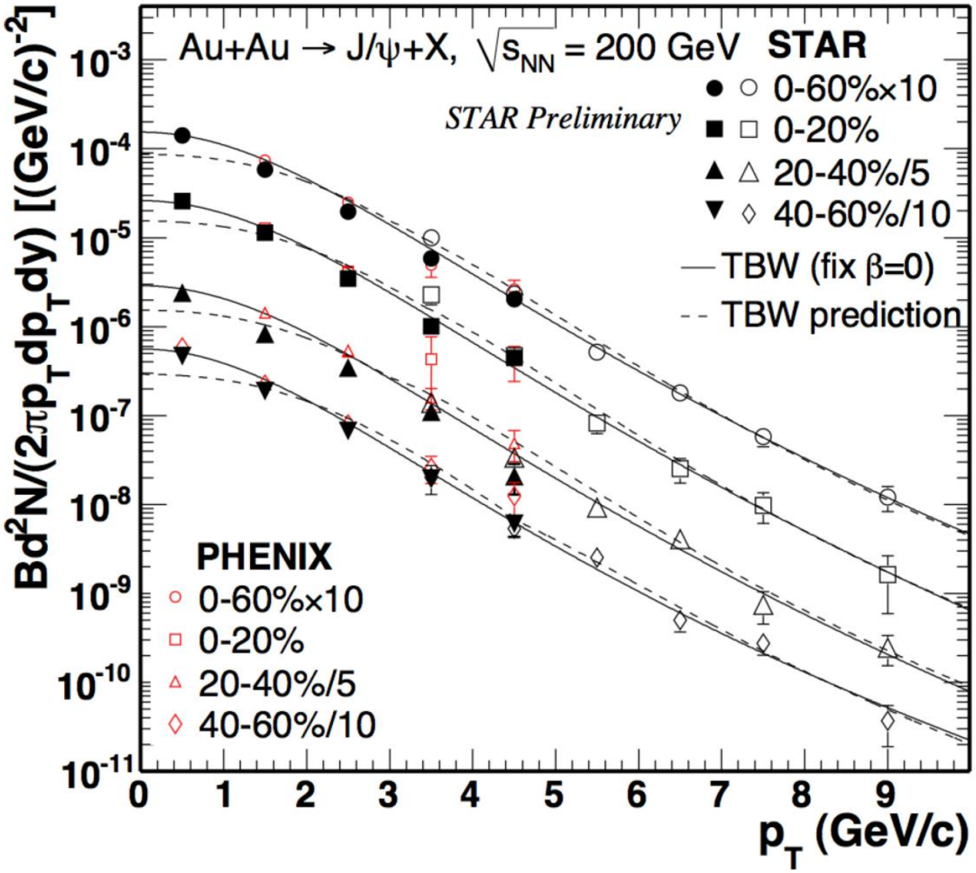
R_{AA} of Prompt J/ψ vs. Centrality



- CMS $R_{AA}^{J/\psi}$ ~ PHENIX low-p_T $R_{AA}^{J/\psi}$
- CMS $R_{AA}^{J/\psi}$ < STAR $R_{AA}^{J/\psi}$ at intermediate p_T range
- Need more systematic comparison in the same p_T range

J/ψ spectra in 200GeV Au+Au collisions

STAR EPS 2011



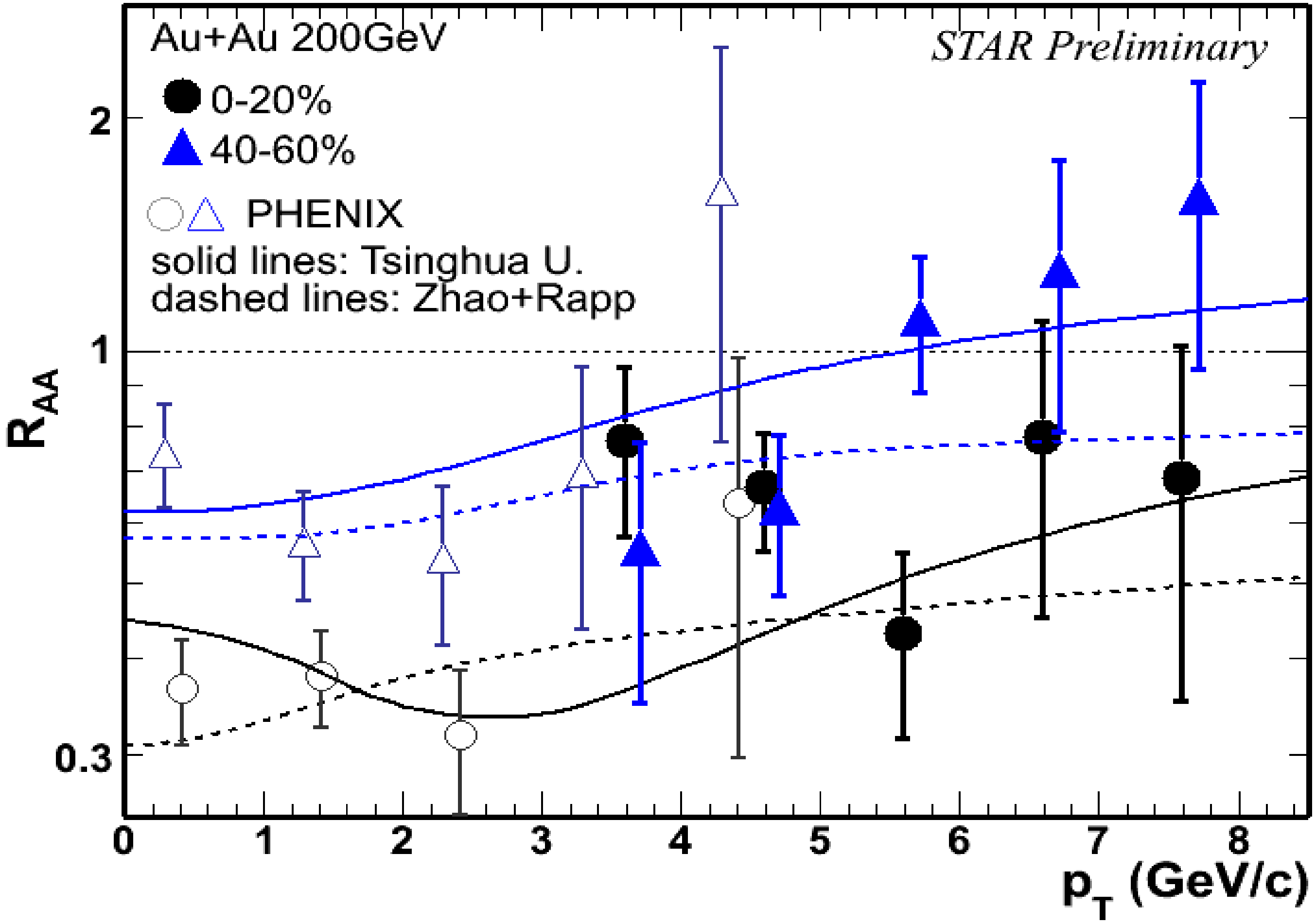
- Good consistency between STAR and PHENIX.
- Significantly extends the p_T range to 10 GeV/c.
- J/ψ spectra significantly softer than the prediction from light hadrons.
  Regeneration at low p_T?

Phys. Rev. Lett. 98, 232301 (2007)

Tsallis Blast-Wave model: ZBT *et al*., arXiv:1101.1912; JPG 37, 085104 (2010)

R_{AA} vs. p_T

STAR QM2011



STAR CuCu: PRC80, 014922(R)
PHENIX: PRL98, 232301

Yunpeng Liu, Zhen Qu, Nu Xu and Pengfei Zhuang, PLB 678:72 (2009) and private comminication

Xingbo Zhao and Ralf Rapp, PRC 82,064905(2010) and private communication

- Increase from low p_T to high p_T.
- Consistent with unity at high p_T in (semi-) peripheral collisions.
- More suppression in central than in peripheral even at high p_T.

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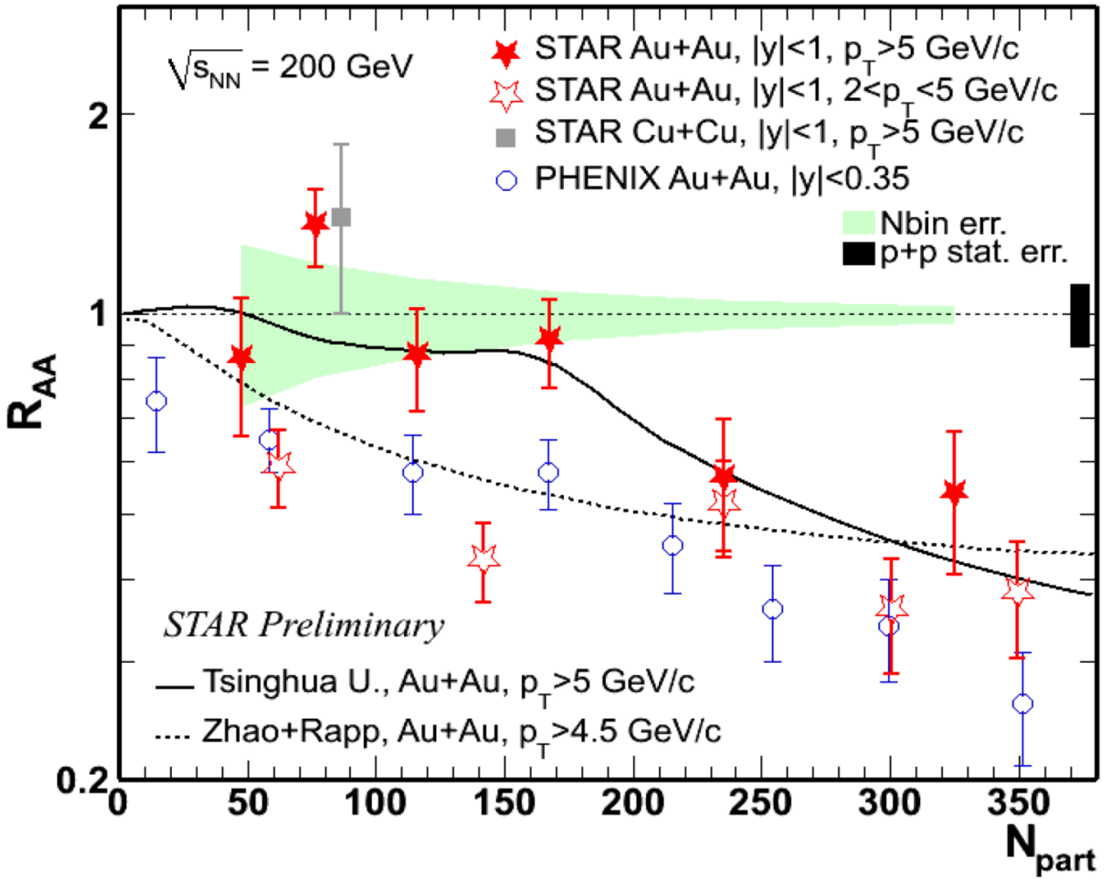
STAR EPS 2011

R_{AA} vs. Npart

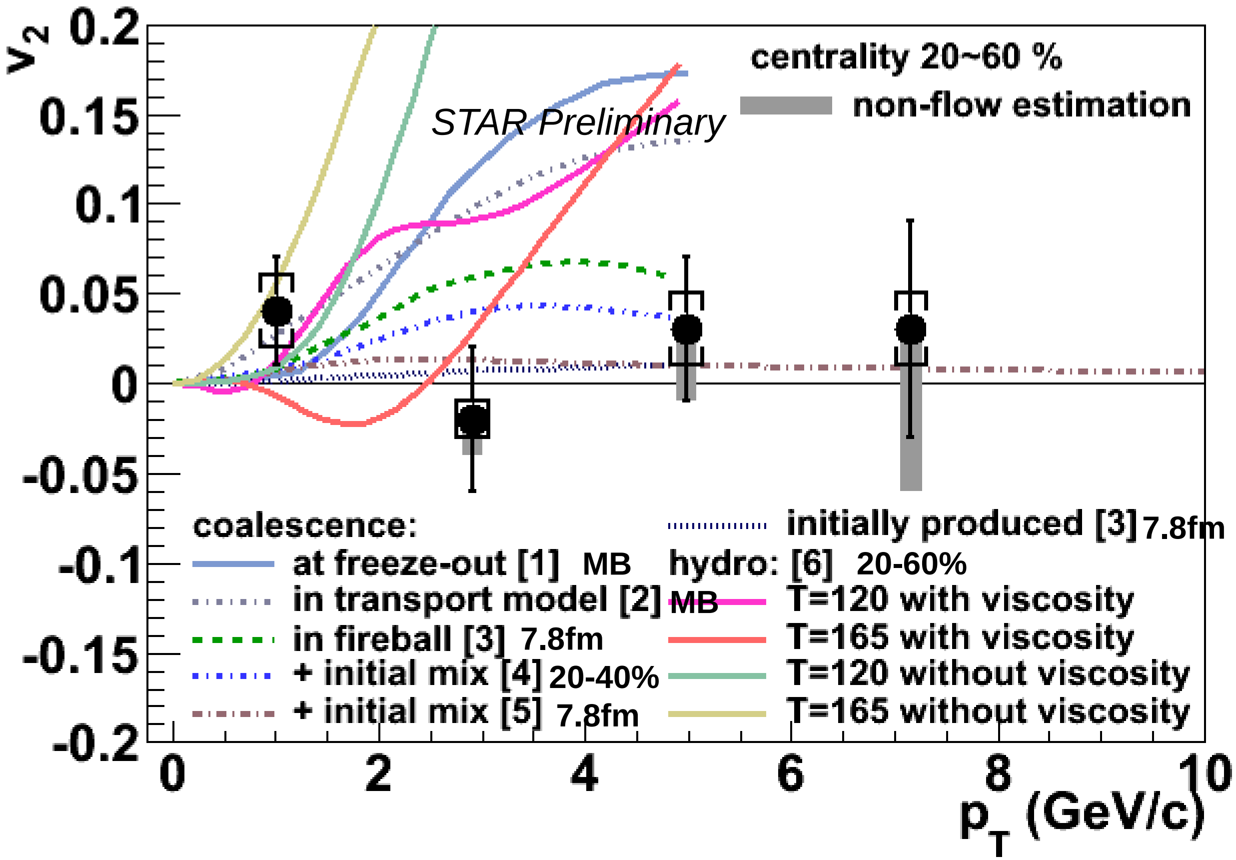


Y. Liu, et al., PLB 678:72 (2009)
X. Zhao and R.Rapp, PRC 82, 064905(2010)

- Systematically higher at high p_T in all centralities.
- Suppression in central collisions at high p_T.

J/ψ elliptic flow v_2

STAR QM2011



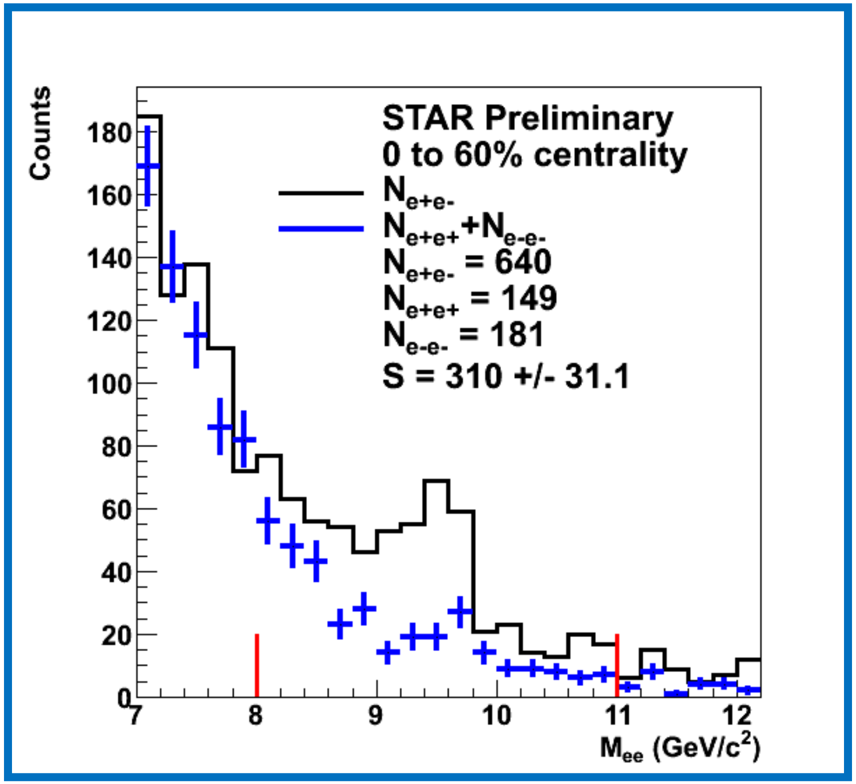
- Consistent with zero, first hadron that does not flow
- Disfavor coalescence from thermalized charm quarks at high p_T.

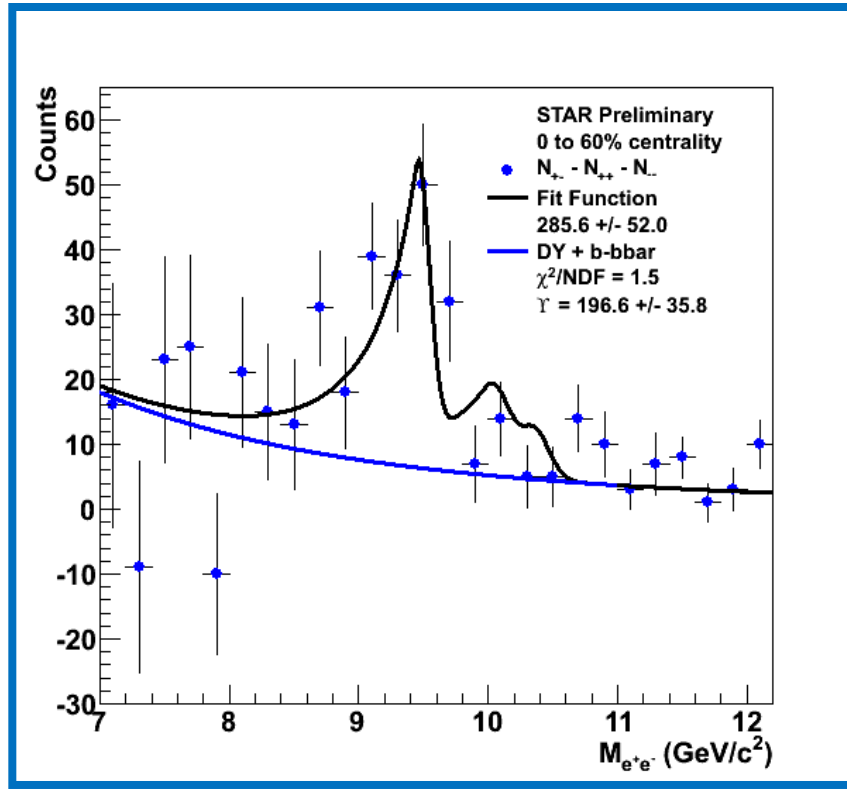
[1] V. Greco, C.M. Ko, R. Rapp, PLB 595, 202.
[2] L. Ravagli, R. Rapp, PLB 655, 126.
[3] L. Yan, P. Zhuang, N. Xu, PRL 97, 232301.
[4] X. Zhao, R. Rapp, 24th WWND, 2008.
[5] Y. Liu, N. Xu, P. Zhuang, Nucl. Phy. A, 834, 317.
[6] U. Heinz, C. Shen, priviate communication.

QUARKONIA

$\Upsilon \rightarrow e^+e^-$

ϒ Signal in Au+Au 200 GeV





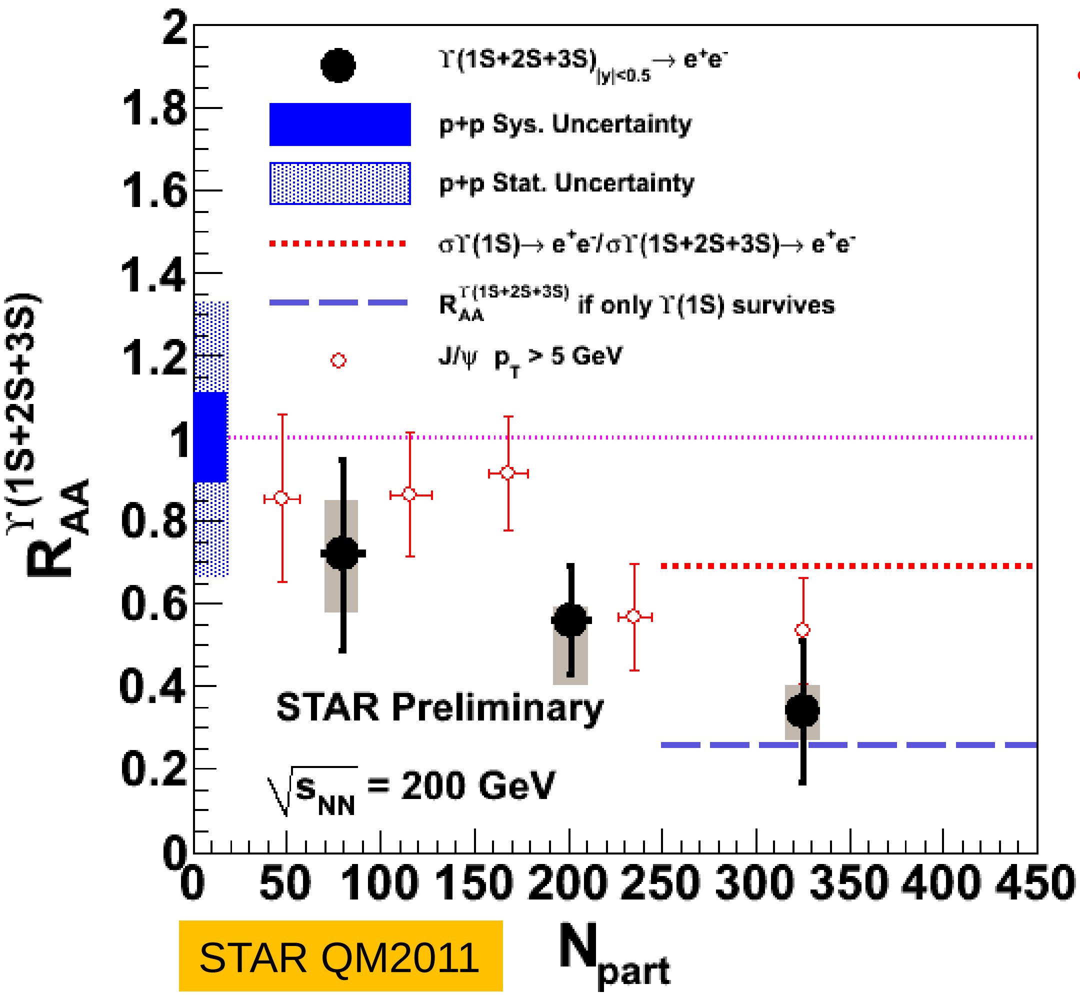
STAR QM2011

Raw yield of $\Upsilon \rightarrow e^+e^-$ with $|y|<0.5$ = 196.6 ±35.8 = N_{+-} - N_{--} - N_{++} - $\int$DY+b$\bar{b}$

$$\text{Drell-Yan}+b\bar{b} = \frac{A}{(1+\frac{m}{m_0})^n}$$

n = 4.59, m_0 = 2.7

Υ(1S+2S+3S) R_{AA}



STAR QM2011

- **Suppression** of Υ(1S+2S+3S) in central Au+Au **observed.**

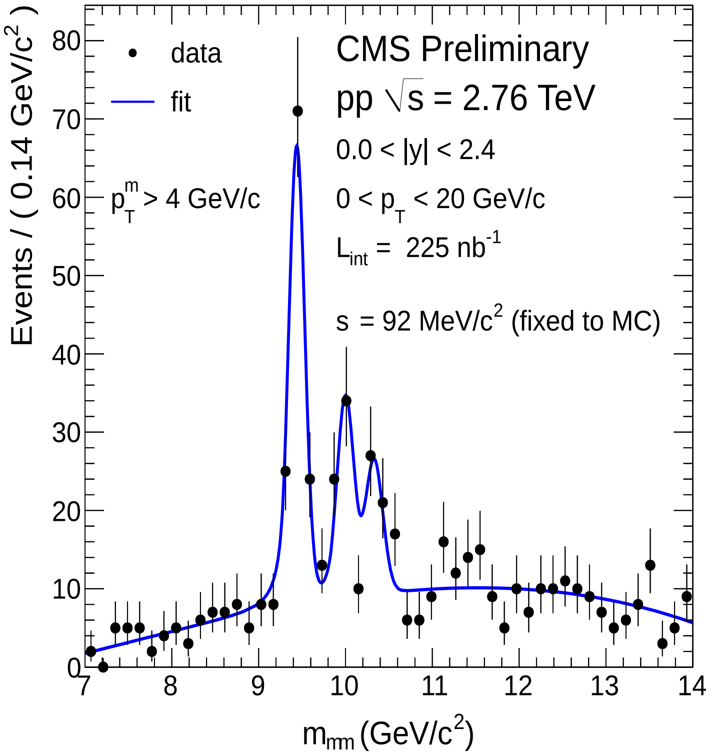
R_{AA} (0-60%) = 0.56±0.11(stat)+0.02/-0.14(sys)

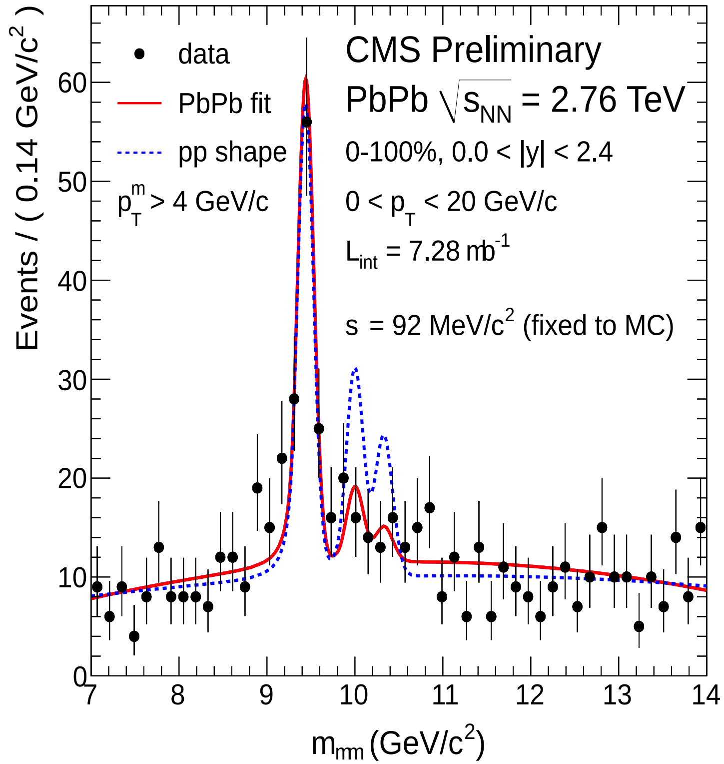
R_{AA} (0-10%)=0.34±0.17(stat)+0.06/-0.07(sys)

Data from Run 2009 and Run 2011

will reduce the uncertainty by factor of ~2.

ϒ(2S+3S) vs. ϒ(1S) in PbPb



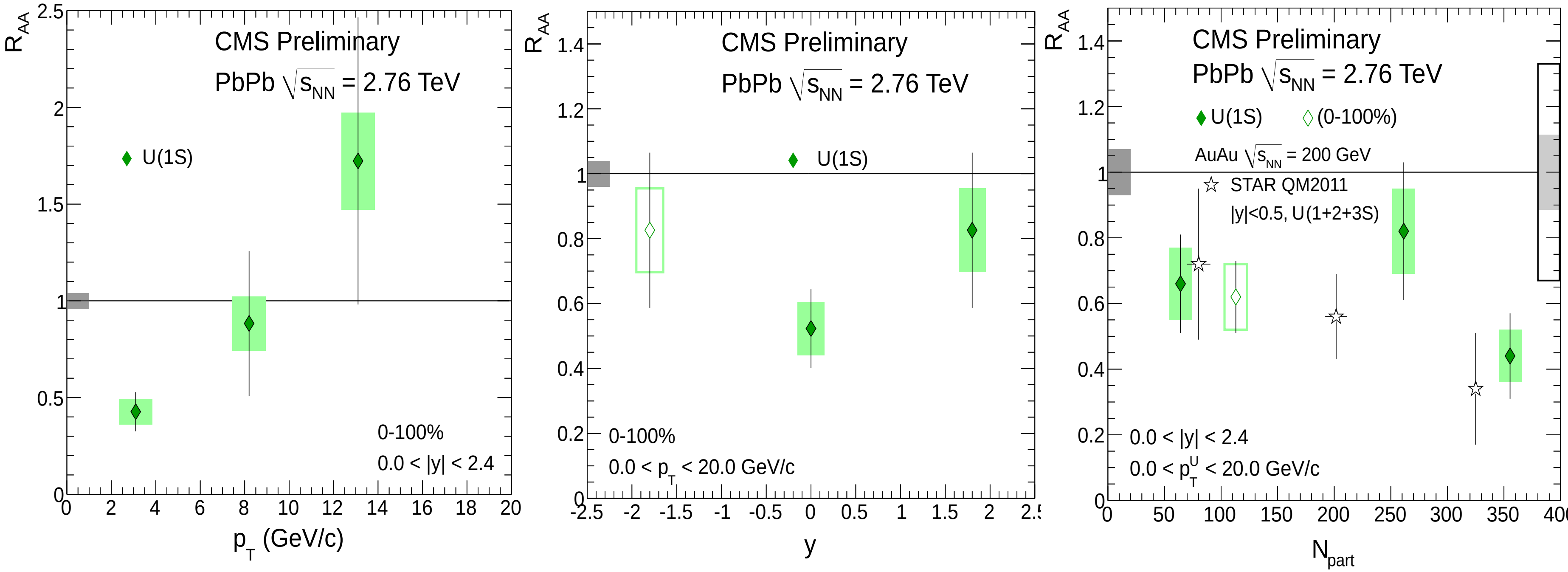


PRL 107, 052302 (2011)

- Fraction of excited states ϒ(2S+3S) relative to ϒ(1S)
  - Core Gaussian with power-law tail of EM final state radiation
  - Resolutions and efficiencies fixed by MC
  - Peak separation fixed to the PDG values
  - Background as a second-order polynomial

ϒ(1S) in PbPb at 2.76 TeV

HIN-10-006



- Needs more statistics: with the current statistics,
  - No obvious suppression at high p_T
  - No obvious rapidity dependence
- CMS ϒ(1S) R_{AA}(0-100%) = 0.62±0.11±0.10
- STAR ϒ(1S+2S+3S) R_{AA}(0-60%) = $0.56 \pm 0.11^{+0.02}_{-0.10}$ (QM11)

Summary

- Heavy flavor is an important tool to understand medium properties.
- Results are interesting and challenging.

charm measurement

- Possibility to extract charm production cross section.
- FONLL QCD describes the data rather well.
- Hint of diferent suppresion of charm mesons and hadrons at ALICE.

J/ψ

- Puzzeling situation SPS x RHIC x LHC mid x forward
- Less suppression at high-p_T in STAR
- Flow consistent with zero

Υ

- Signal observed in Au+Au collisions as well Pb+Pb
- Suppression of Υ(1S+2S+3S) in central Au+Au observed.
- Suppression of Υ(1S) in CMS

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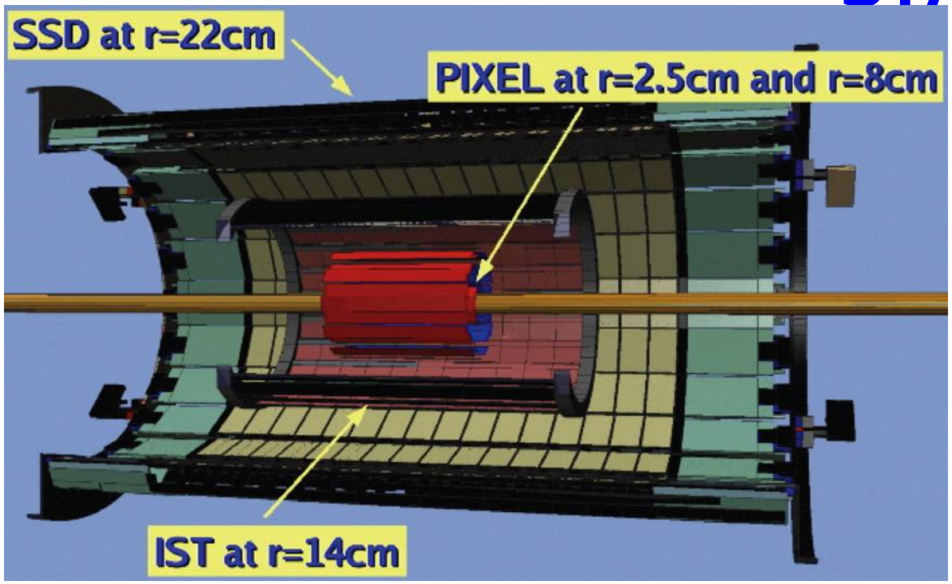
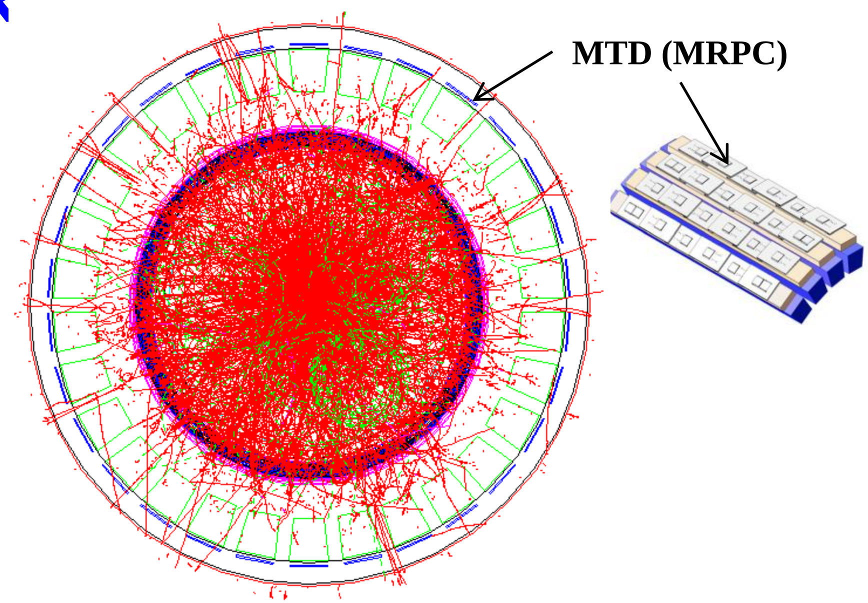
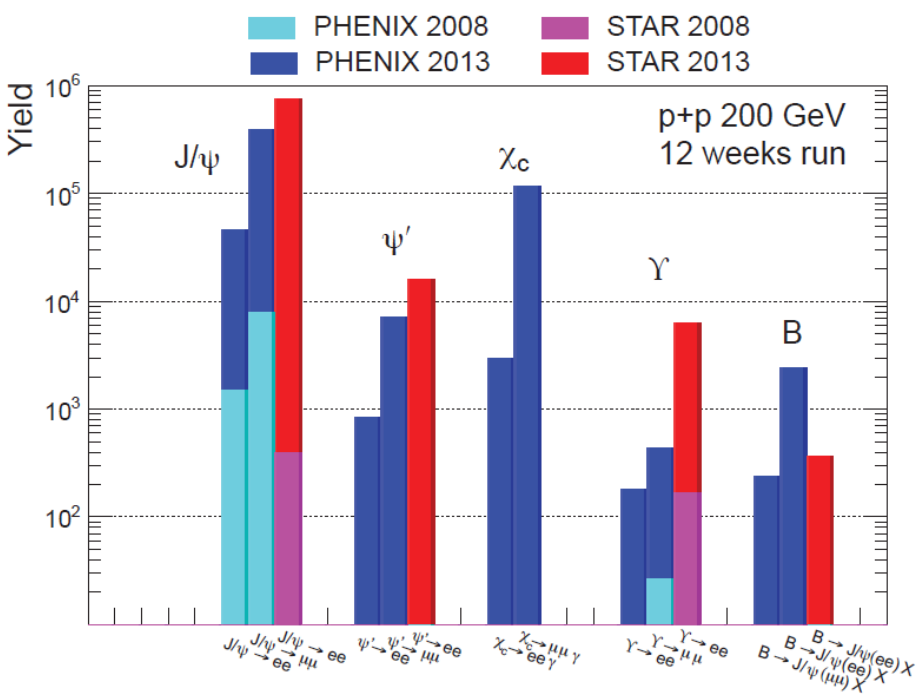
Politováníhodný je člověk, který s nejušlechtilejšími ze všech nástrojů, vědou a uměním, neusiluje o nic vyššího a k vyššímu nesměřuje než námezdná síla s nástrojem nejnižším! Protože v říši naprosté svobody v sobě nosí duši otroka!

Friedrich Schiller 1789

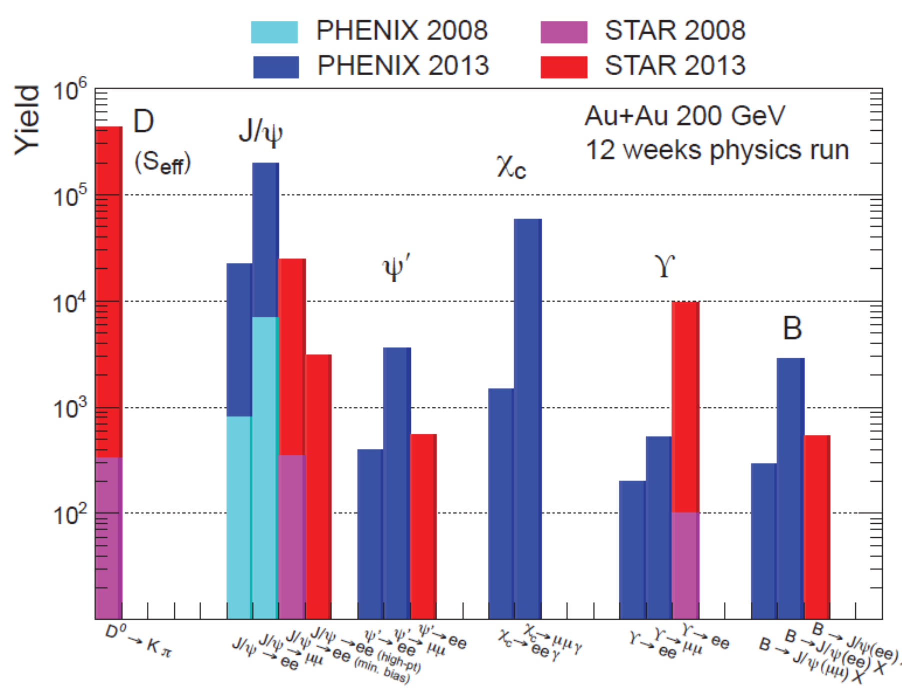
Future of Heavy Flavor Measurement at STAR





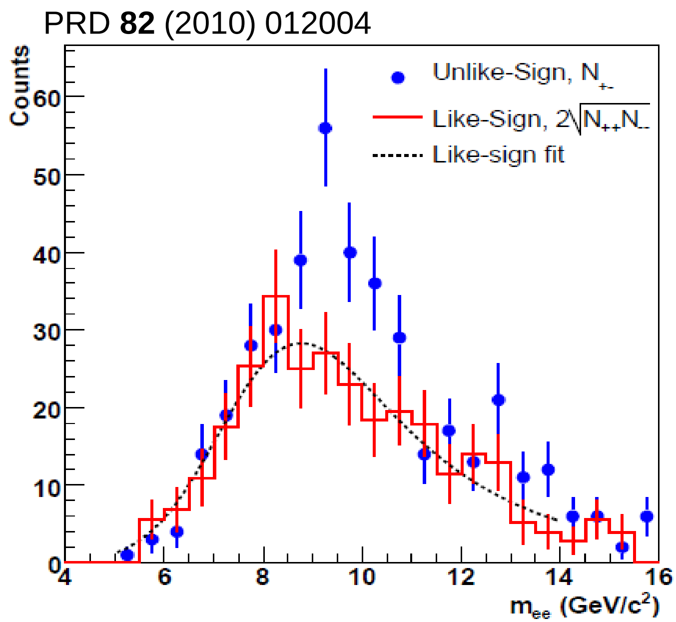


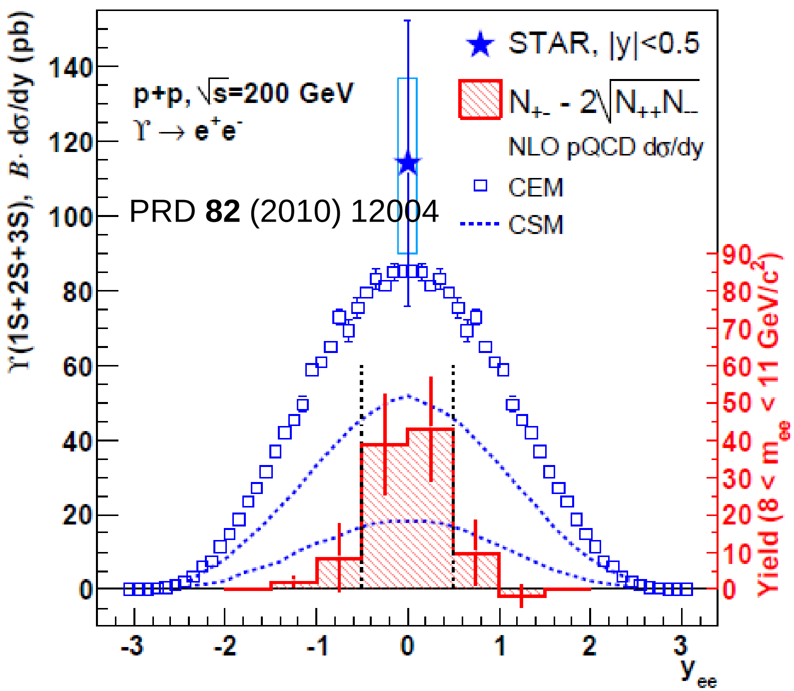
Source: Phys. Rept. 462: 125-175, 2008

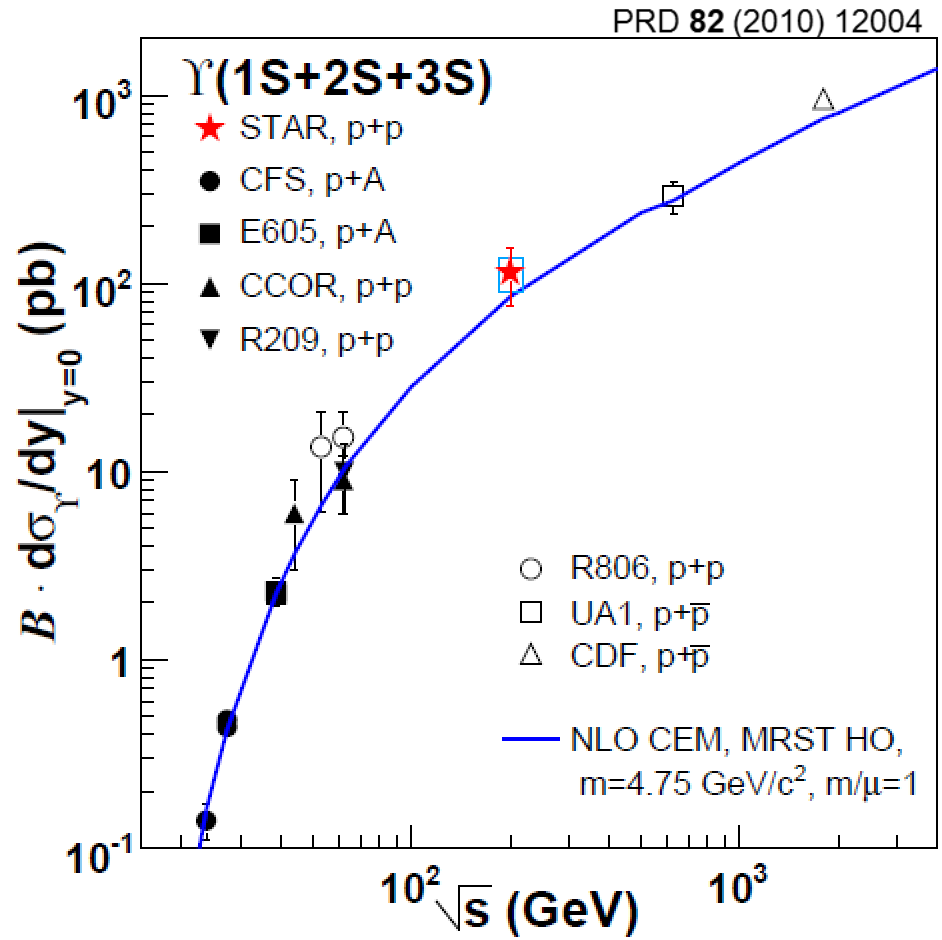


Source: Phys. Rept. 462: 125-175, 2008

Upsilon in p+p 200GeV

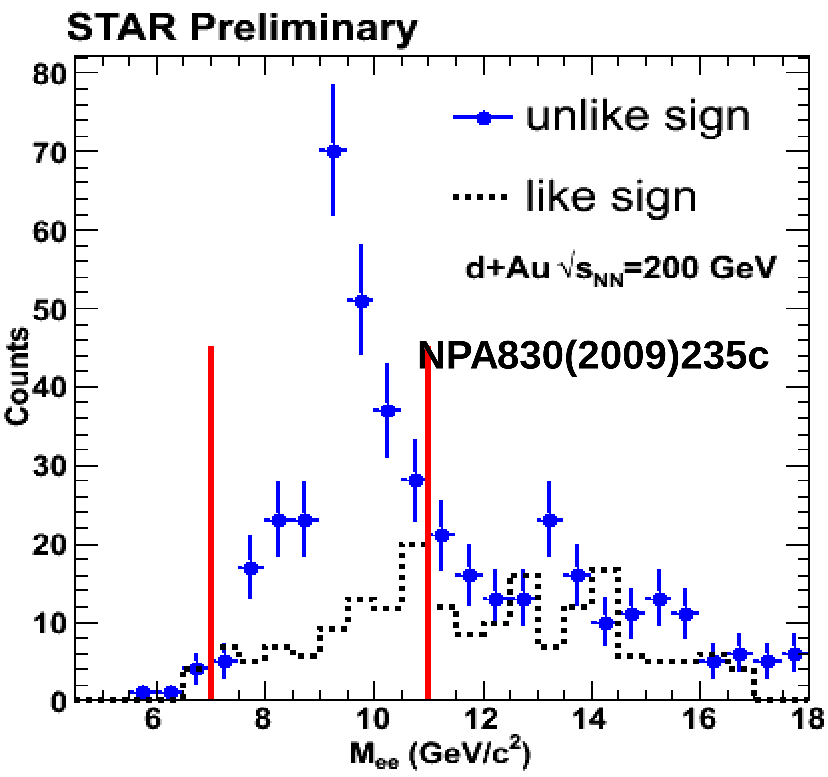


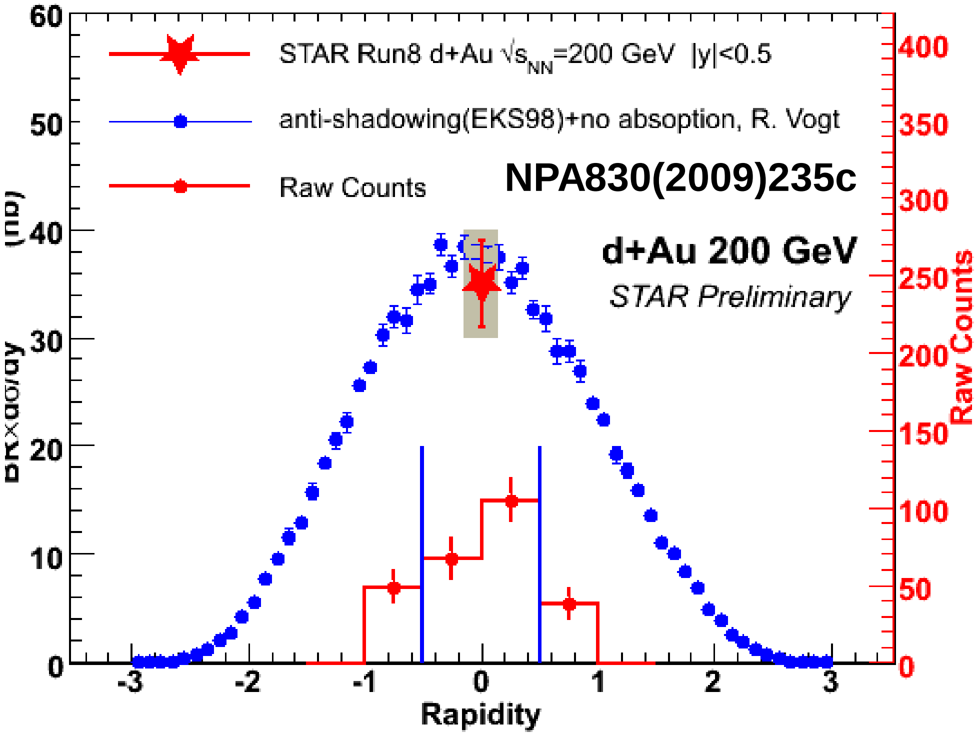




$$B_{ee}\frac{d\sigma}{dy}\bigg|_{y=0} = 114 \pm 38(stat)^{+23}_{-24}(sys) \quad \text{pb}$$

Upsilon in d+Au 200GeV



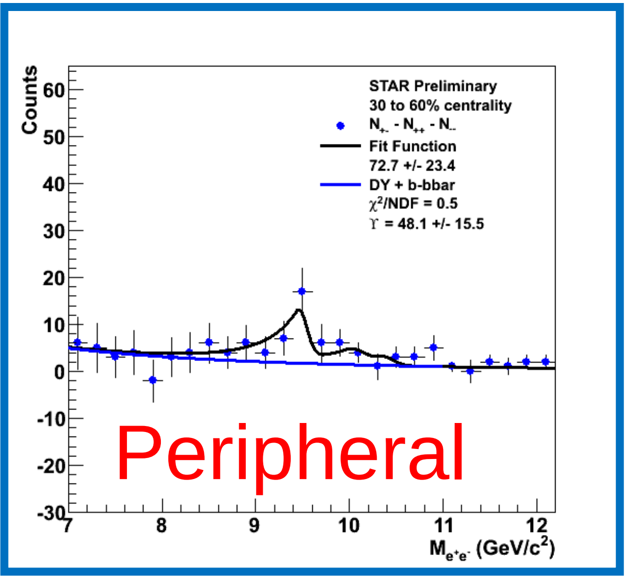


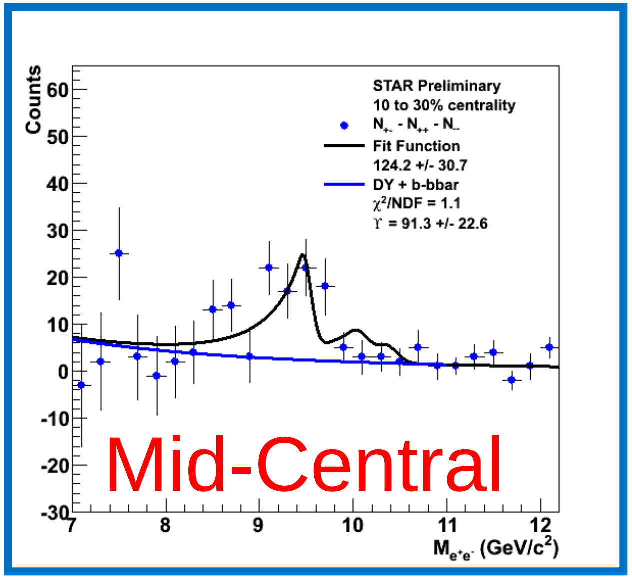
$$B_{ee} \left.\frac{d\sigma}{dy}\right|_{y=0} = 35 \pm 4(stat) \pm 5(sys) \text{ nb}$$

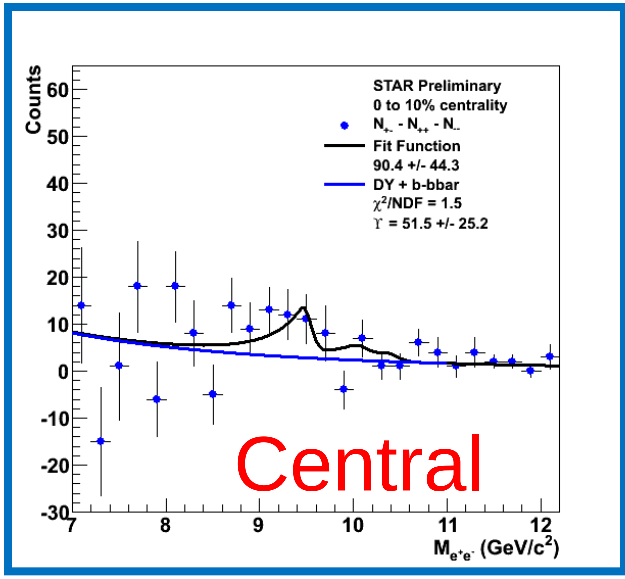
$$R_{dAu} = 0.8 \pm 0.3(stat) \pm 0.2(sys)$$

- Consistent with N_{bin} scaling of cross-section p+p - d+Au 200GeV

ϒ Yield by centrality

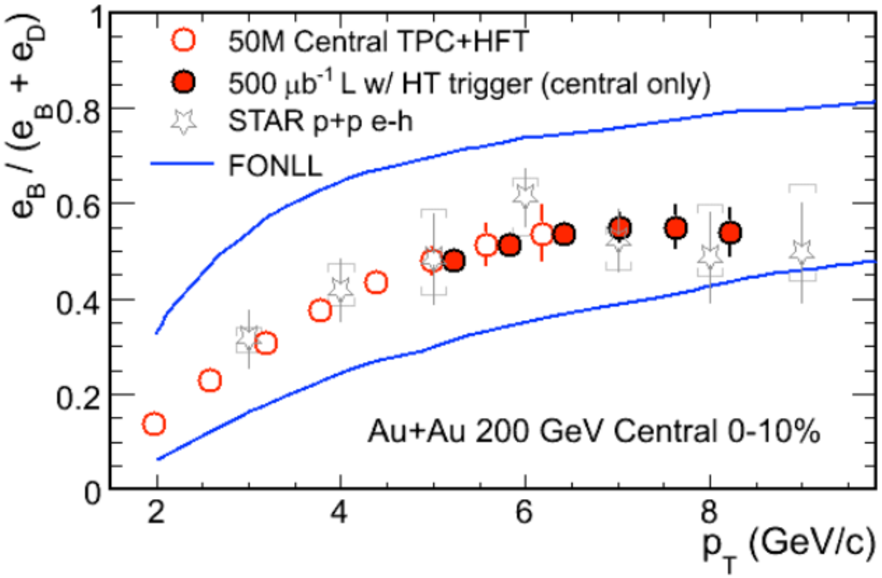


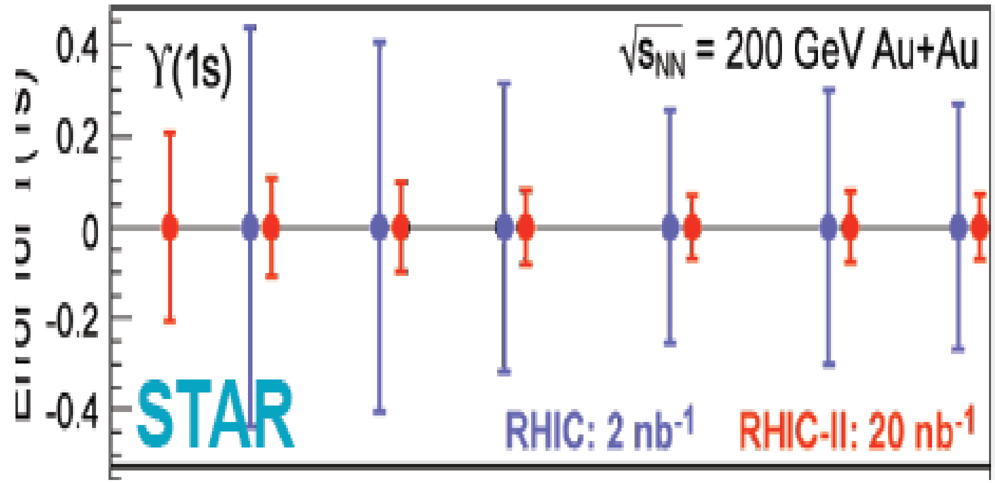


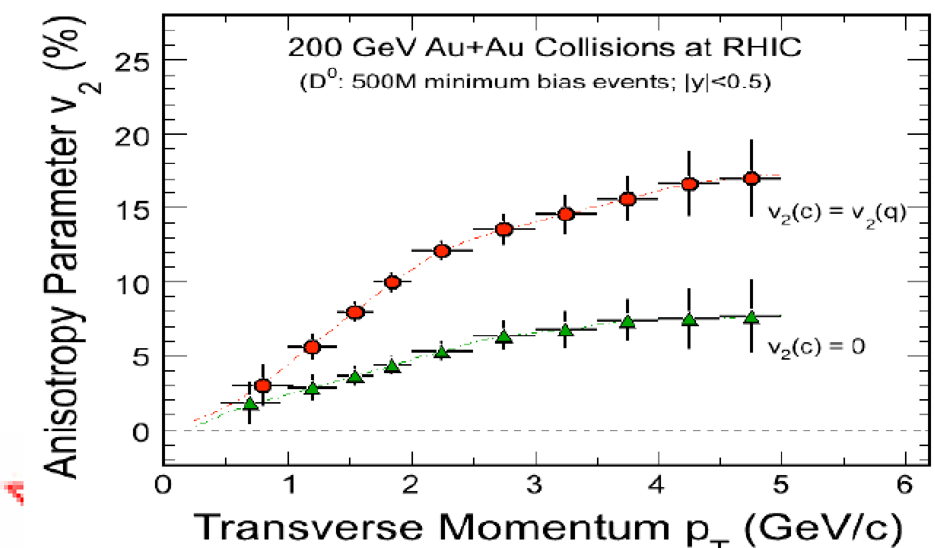


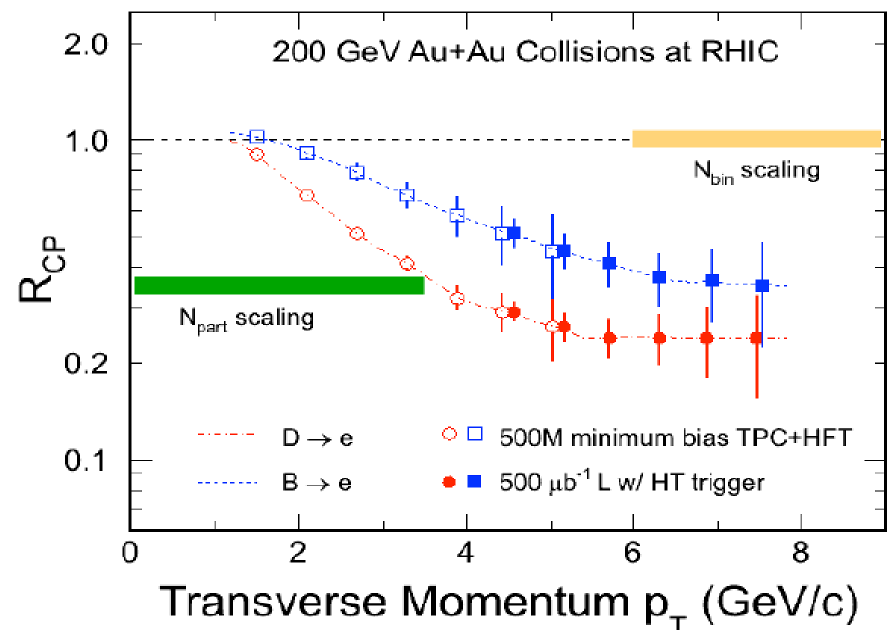
- System uncertainties
  - p+p luminosity and bbc trigger efficiency
  - ϒ Line-shape
  - Drell-Yan and bb background

STAR with HFT

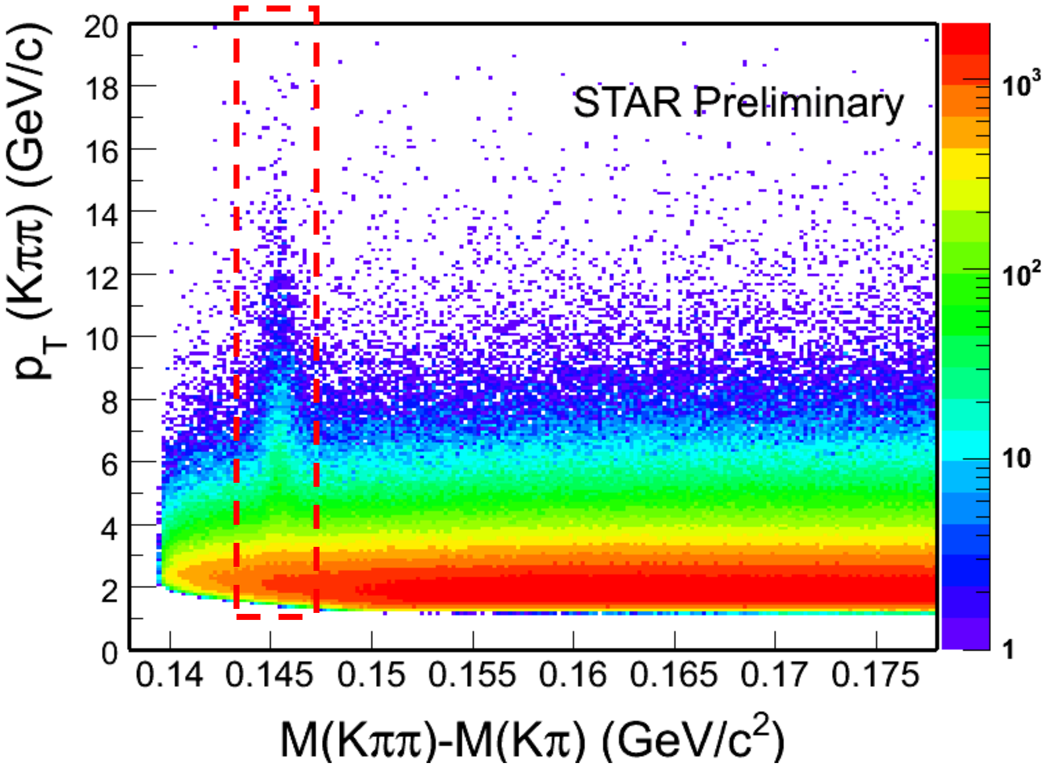


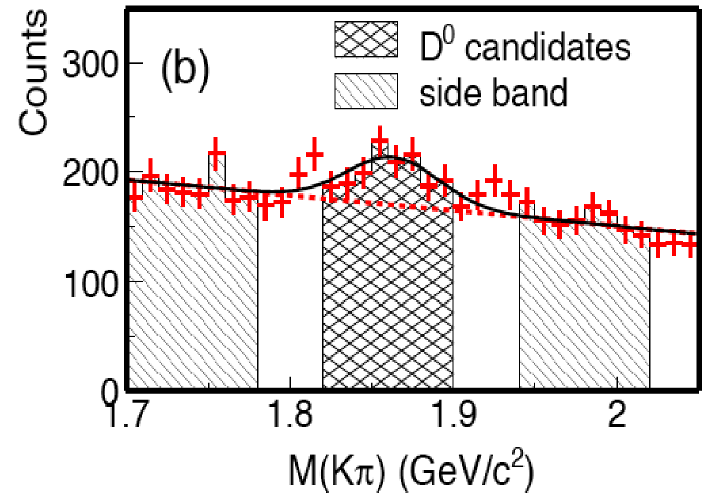






D* reconstruction





<u>Background combinations:</u>
Wrong sign:
D0 and π^-, D0bar and π^+
Side band:
1.72< M(Kπ) < 1.80 or
1.92 < M(Kπ) < 2.0 GeV/c^2

All triggers included.
More than 4σ signal at low p_T and very significant at high p_T - mostly from EMC-based high neutral energy triggers.

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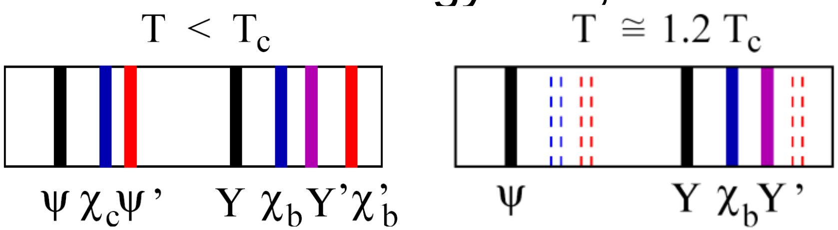
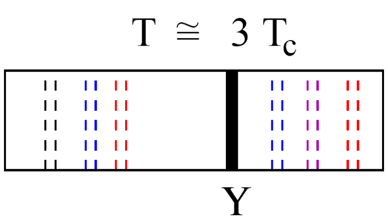
Charmonia in nuclear matter

- Production mechanism is not clear
- Observed J/ψ is a mixture of direct production + feeddown
  - All J/ψ ~ 0.6 J/ψ (Direct) + ~0.3 χ_c + ~0.1ψ'
- Suppression and enhancement in the "cold" nuclear medium
  - Nuclear Absorption, Gluon shadowing, initial state energy loss, Cronin effect and gluon saturation



H. Satz, Nucl. Phys. A (783):249-260(2007)



- Hot/dense medium effect
  - J/ψ, Υ dissociation, i.e. suppression
  - Recombination from uncorrelated charm pairs

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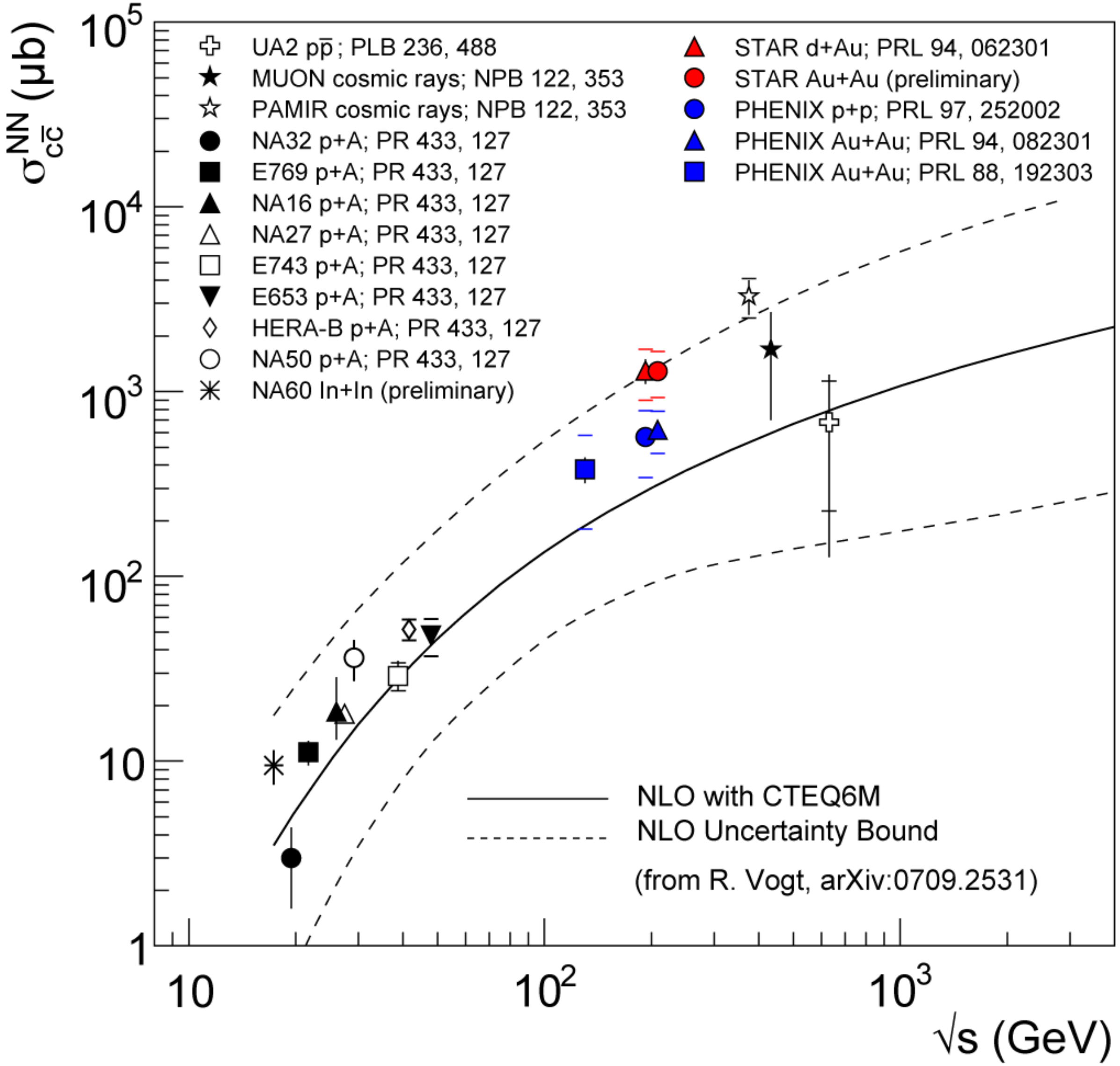
σ_{CC}: comparison with other measurements



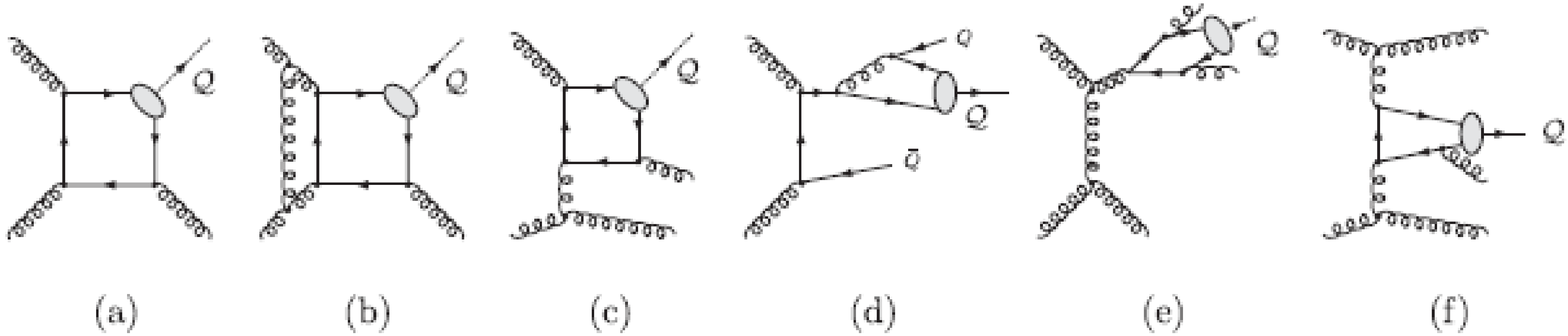
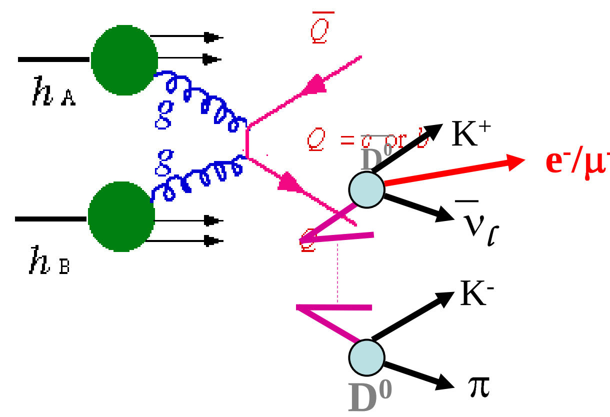
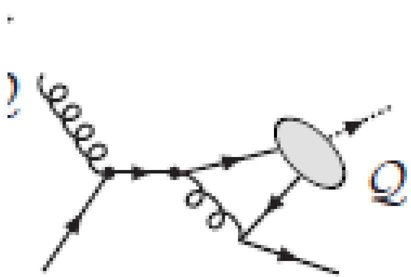
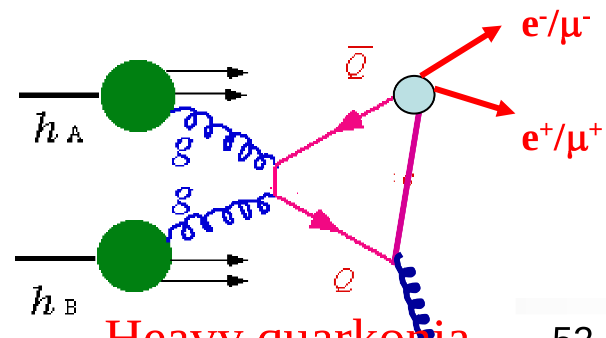


FIG. 1. Representative diagrams contributing to Υ hadroproduction at orders α_S^3 (a), α_S^4 (b,c,d), α_S^5 (e,f). See discussions in the text.



Open heavy flavor





Heavy quarkonia

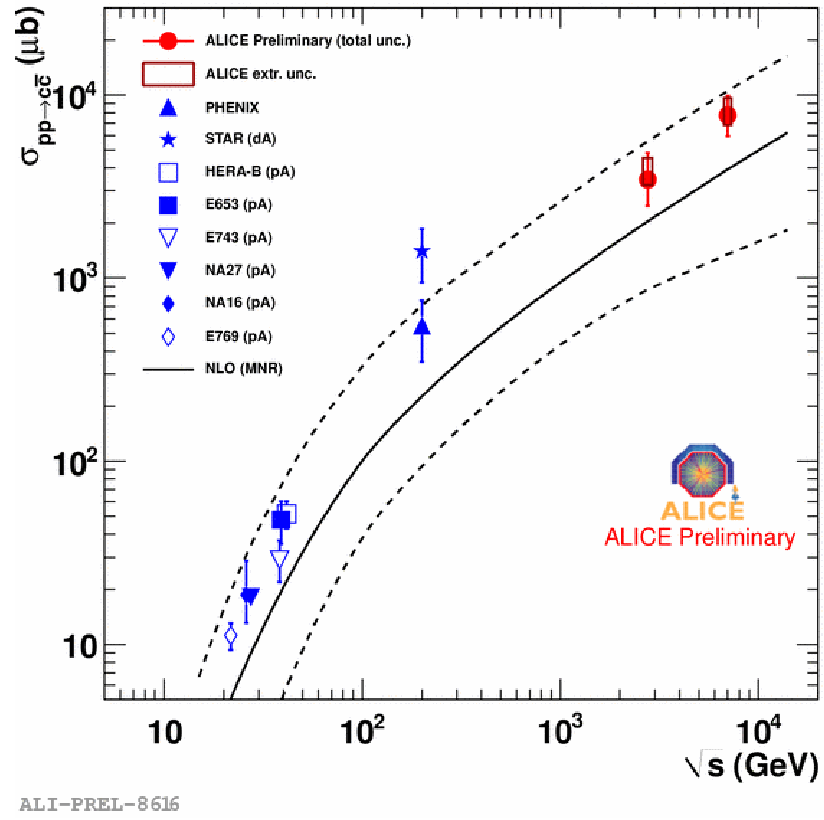
What can we learn at the LHC

- Higher c and b cross sections:
  - More abundant heavy flavour production
  - Better precision (reduced errors)

$$\sigma^{c\bar{c}}_{LHC} \approx 10 \cdot \sigma^{c\bar{c}}_{RHIC}$$

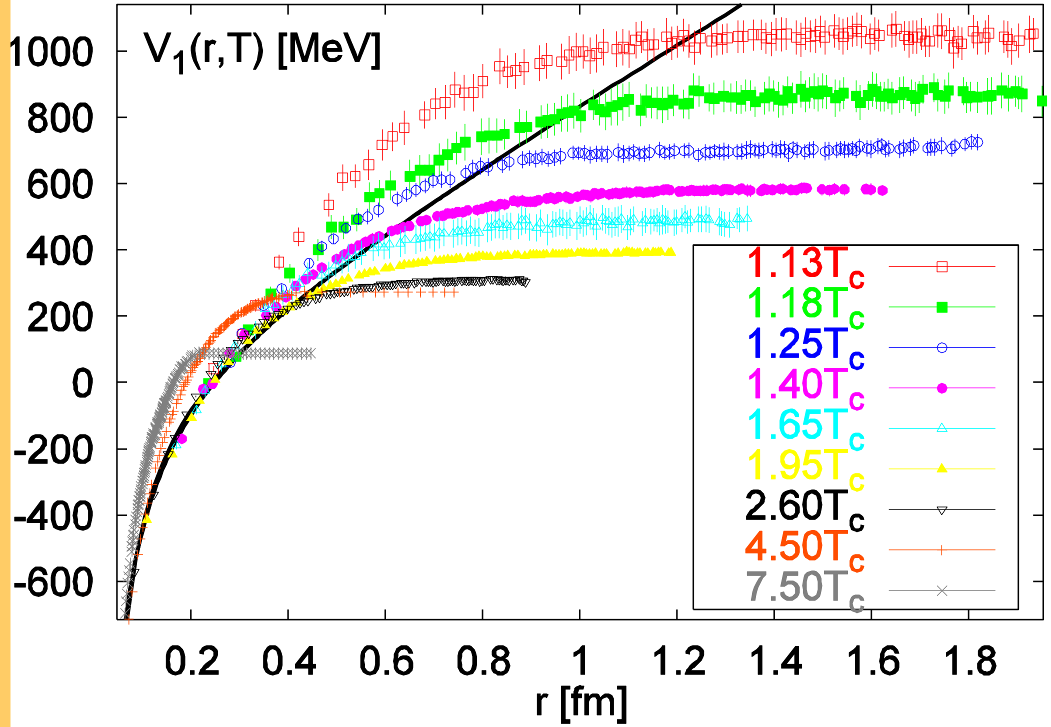
$$\sigma^{b\bar{b}}_{LHC} \approx 100 \cdot {}^{b\bar{b}}_{RHIC}$$

- High precision vertex detectors
  - Background removal
  - Separate c and b



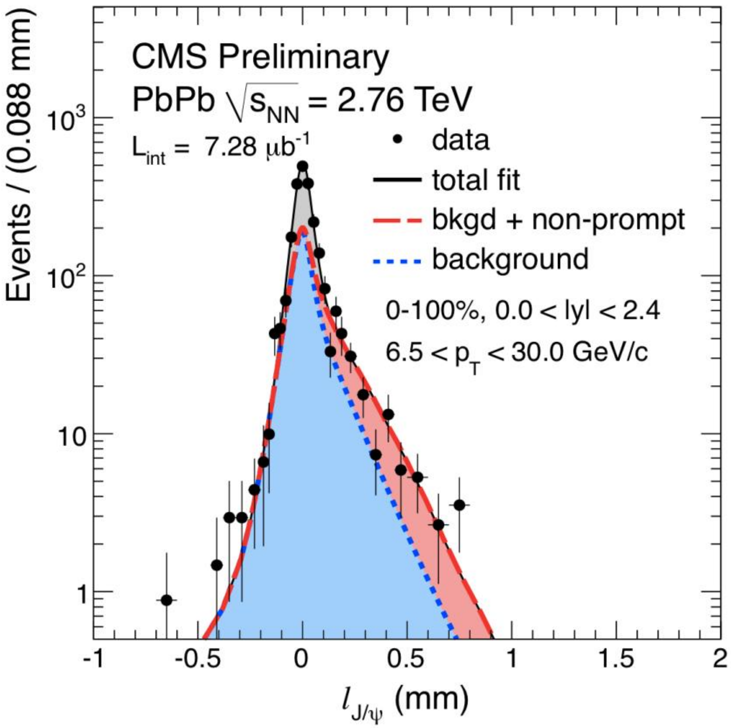
High T: the potential between the quarks is modified.

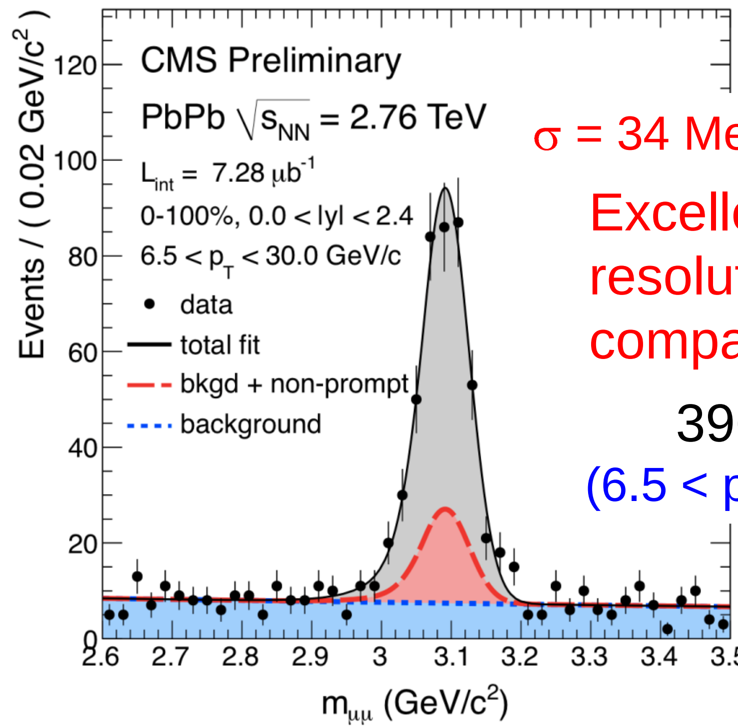
- Charmonium suppression: longstanding QGP signature
  - Original idea: High T leads to Debye screening
  - Screening prevents heavy quark bound states from forming!
  - **J/ψ suppression**:
    - Matsui and Satz, *Phys. Lett. B* **178** (1986) 416
  - lattice calculations confirm screening effects
    - **Nucl.Phys.Proc.Suppl.129: 560-562,2004**



O. Kaczmarek, et al., Nucl.Phys.Proc.Suppl.129:560-562,2004

J/ψ in Pb+Pb at 2.76 TeV





HIN-10-006

σ = 34 MeV

Excellent mass resolution of ~1%, comparable to pp

396±24 J/ψ

($6.5 < p_T < 30$ GeV/c)

First time that the prompt and non-prompt J/ψ's are separated in heavy-ion collisions

- 90±13 [B → J/ψ] events for $p_T^{J/\psi} > 6.5$ GeV/c

STAR