The Quest For Beauty in Heavy Ion Collisions

Physics Colloquium

UC Riverside

9/May/2013

Manuel Calderón de la Barca Sanchez

NSF

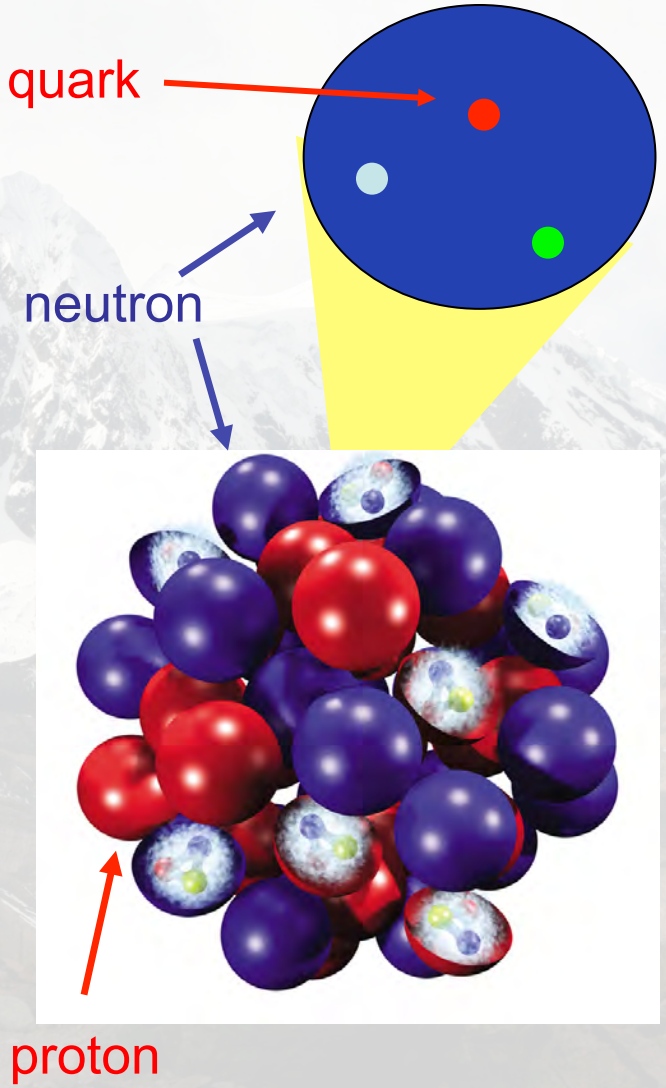
UCDAVIS

Outline

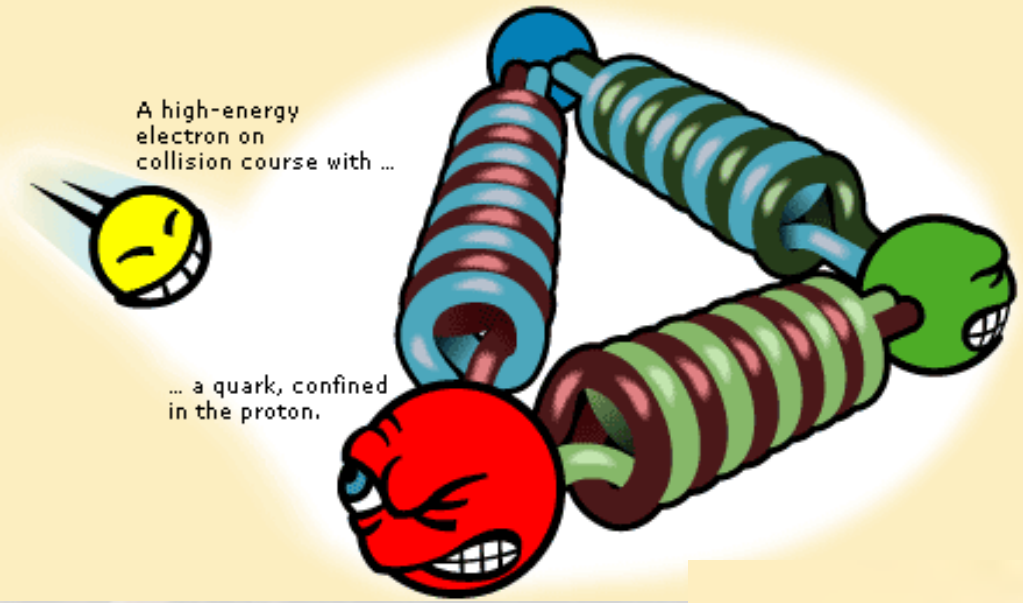
- What happens when we take the ***strongest*** force of nature, and turn up the heat?
- Quark-Gluon Plasma: **Hot QCD**
  - What has been established about matter produced in heavy ion collisions?
- Heavy Quarkonium in Heavy Ion collisions.
  - Charmonium, Bottomonium.
    - what can charm and beauty tell us about Hot QCD?
      - How **hot** does it get?
      - Is **color** deconfined?
  - Bottomonium measurements in STAR and CMS.
- Summary

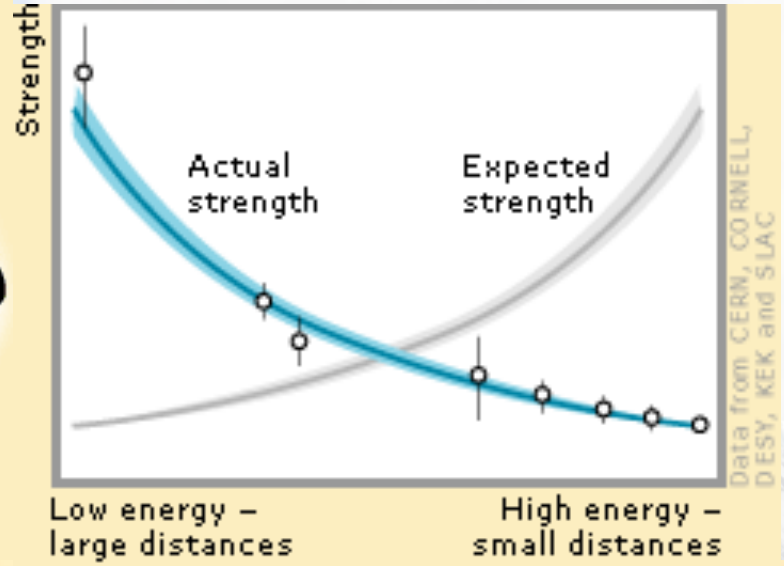
The Strong Interaction in Nuclear Physics

- Nuclei composed of:
  - protons (+ electric charge)
  - neutrons (no electric charge)
- Does not blow up!? → "nuclear force"
  - overcomes electrical repulsion
  - determines nuclear reactions (stellar burning, fusion…)
- Arises from fundamental strong force :
  - **Quantum Chromo Dynamics (QCD)**
    - Acts on color charge of **quarks**
    - **Observation: we never see a free quark!**
      - **QCD "confines" the quarks in protons and neutrons**

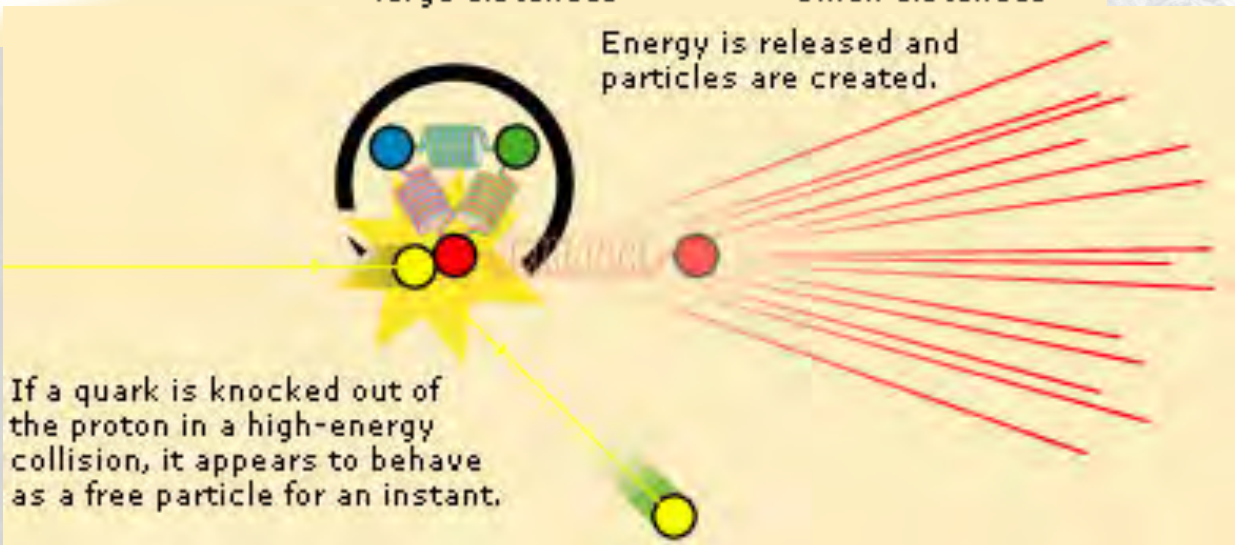


QCD and confinement: a cartoon





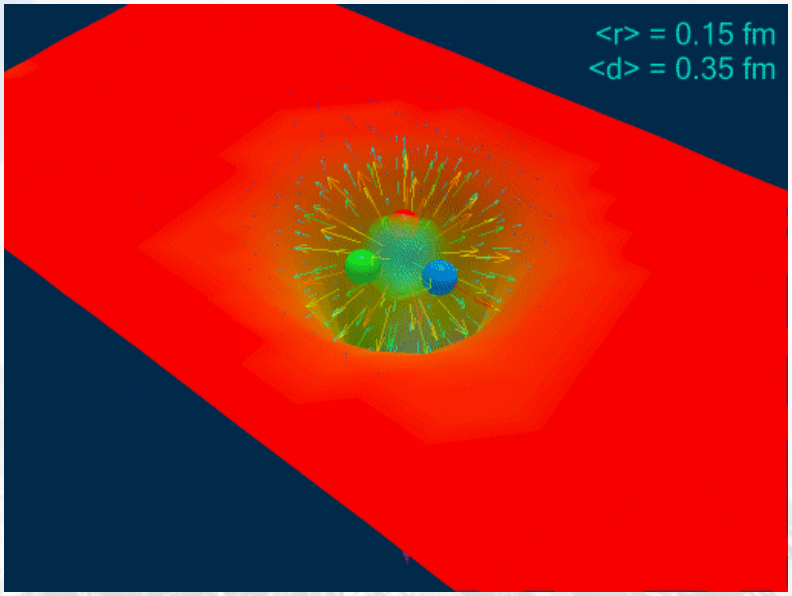
- At high energy and small distances, the strength of this force decreases!
- "Asymptotic freedom"
- Nobel Prize 2004

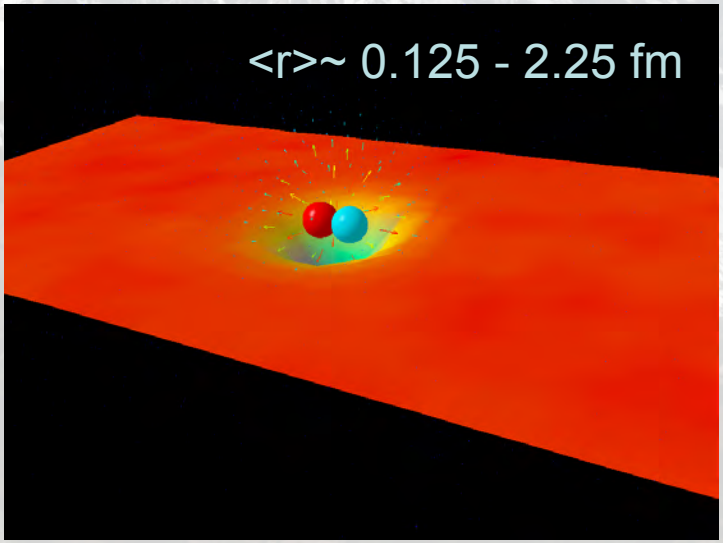


http://nobelprize.org/nobel_prizes/physics/laureates/2004/illpres/index.html

Numerical QCD: Hadrons in the Lattice

- Lattice methods: Non-pertubative, numerical solution of QCD.
  - Surface plot: reduction of vacuum action density
  - Vector field: gradient
- Flux tubes are visible: position where vacuum action is maximally expelled.
- **Linear confining potential between quarks.**
  - Energy cost of getting rid of the vacuum fluctuations of the gluon field.





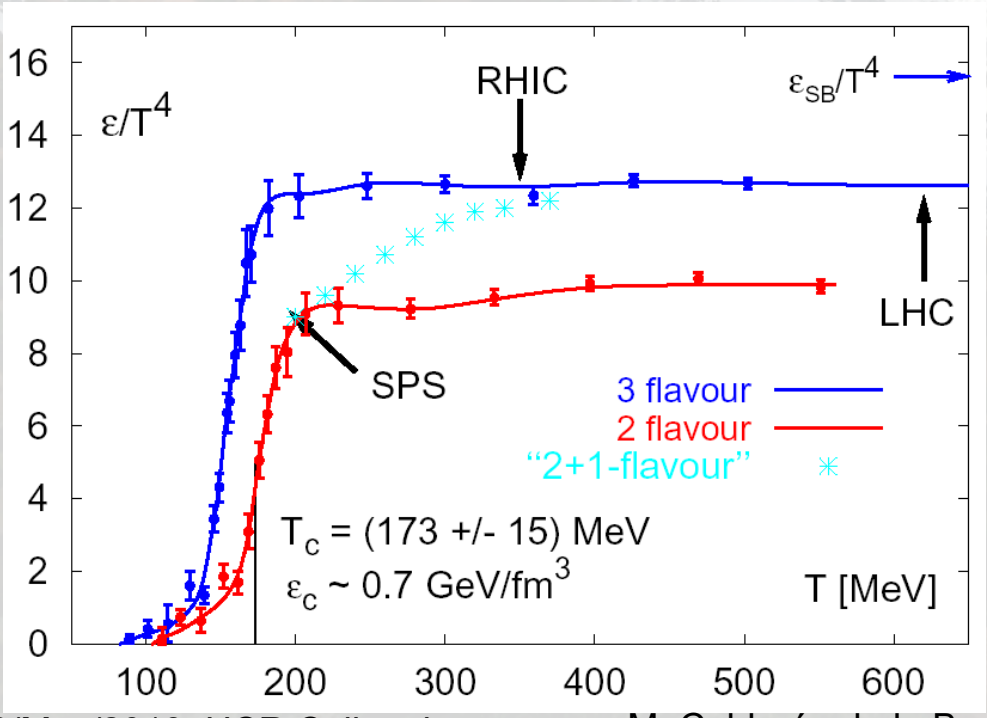
- D. Leinweber, et al., Center for Subatomic Structure. Physics Dept. U. of Adelaide, Australia. 2003.

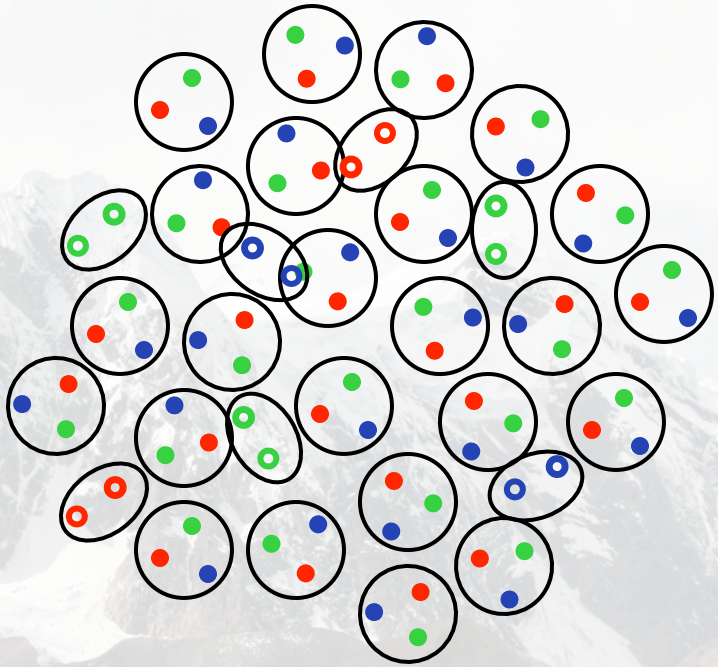
Generating a deconfined state

Melting protons and neutrons: Hot quarks and gluons in (QCD)

- heating
- compression

→ *deconfined color matter !*

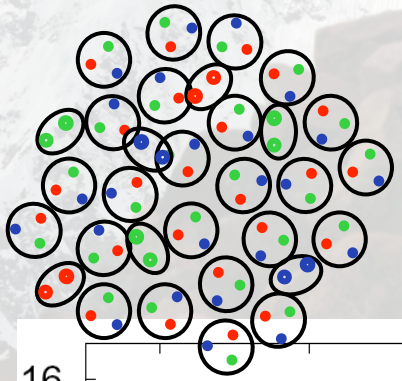




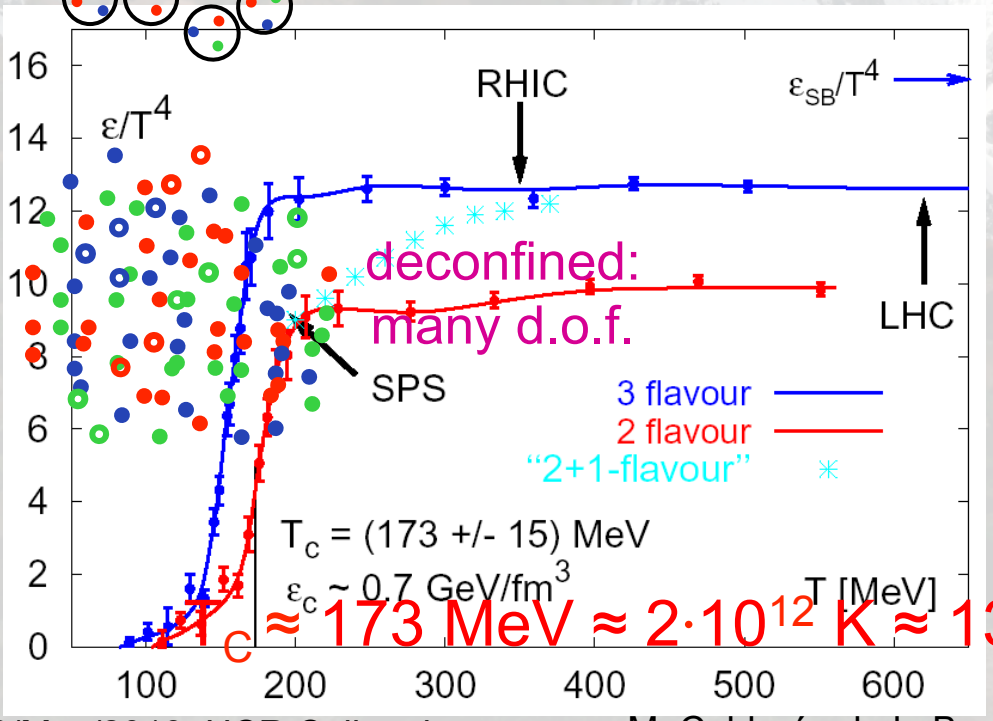
Quark Gluon Matter (deconfined)!

Expectations from Lattice QCD
Computer calculations

ε/T^4 ~ # degrees of freedom

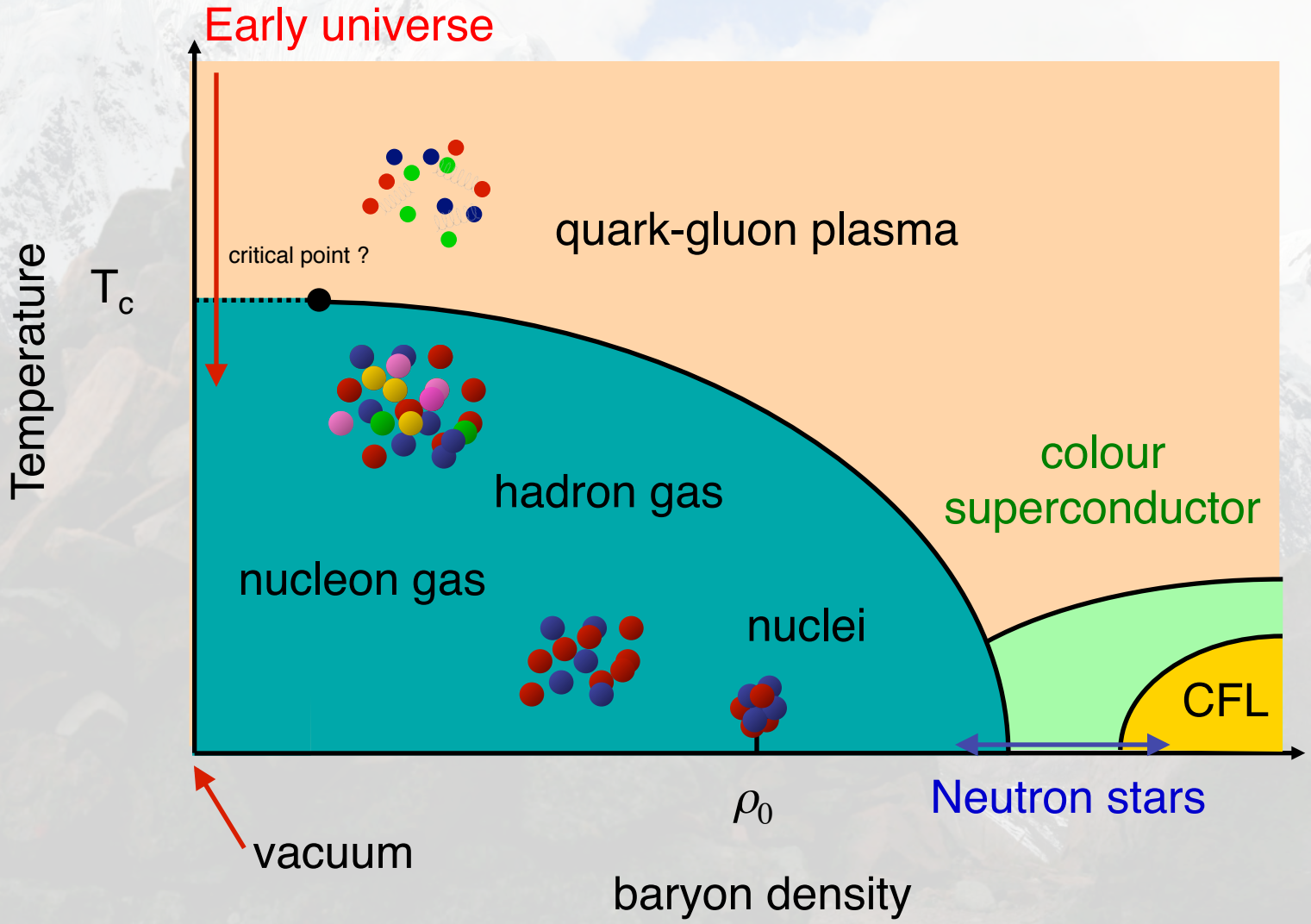


confined:
few d.o.f.

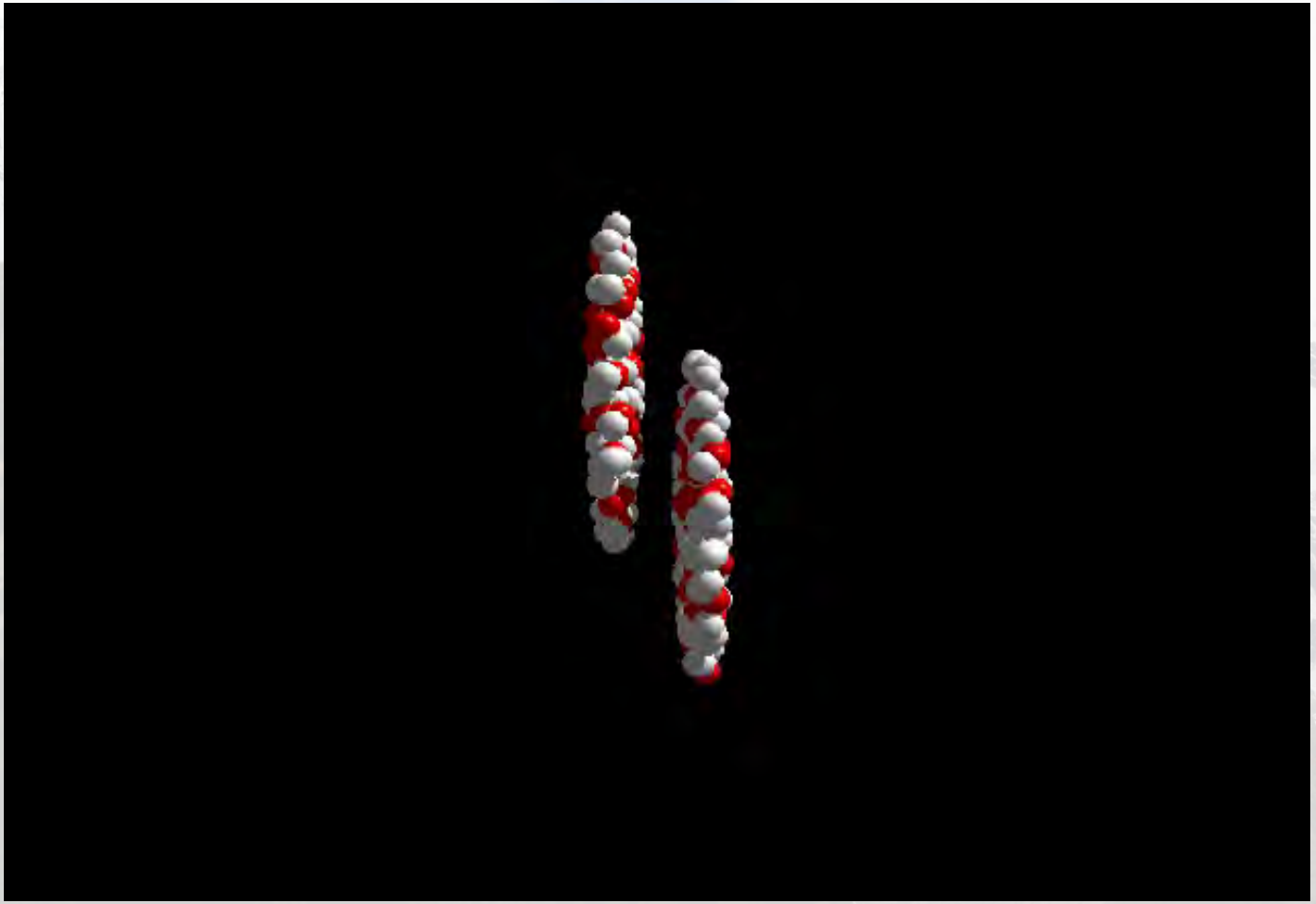


$T_c \approx 173$ MeV $\approx 2 \cdot 10^{12}$ K $\approx 130{,}000 \cdot$ T[Sun's core]

The phase diagram of QCD.



What we do: Relativistic Heavy Ion Collisions



RHIC: Key results from the 1st 5 years

- Key Goal of Heavy Ions: Produce matter in the hot phase of QCD.
  - What are its properties?
  - What are the right degrees of freedom?

- Key results and interpretation.
  - Energy density is high.
    - All estimates above critical energy density.
  - Observation of suppression of high momentum particles.
    - Matter produced is nearly opaque to passage of color-charged quarks and gluons.
  - Observation of large momentum anisotropy.
    - Generated at early times: pattern very close to collective fluid-like behavior of quarks

Sci Am May 2006. by W. Zajc.

STAR White Paper:
Nuc Phys A 757 (2005) 102

Questions we want to address

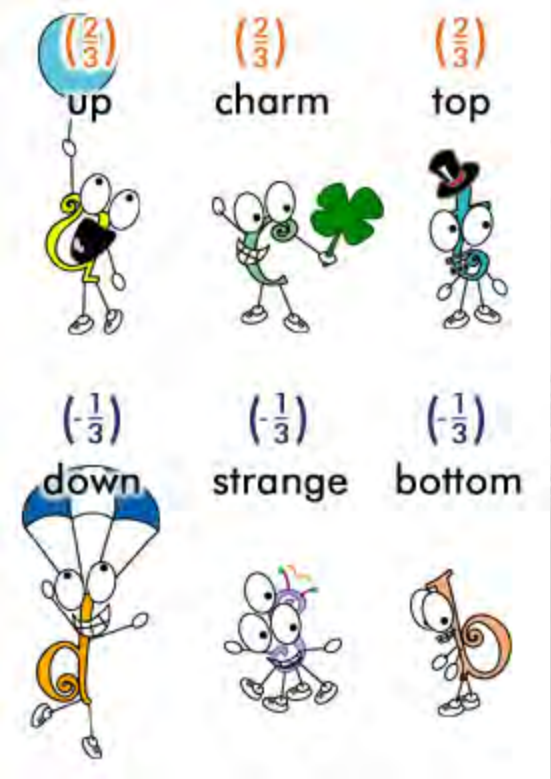
STAR White Paper:
Nuc Phys A 757 (2005) 102
(see p. 169.)

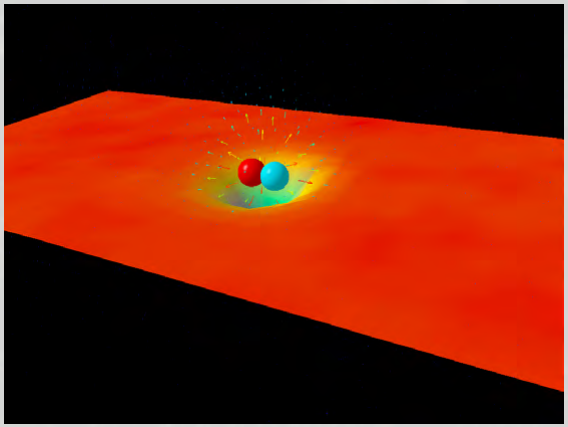
- The Heavy Ion experiments have not yet produced *direct* evidence for deconfinement.

- The measurements suggest that matter is formed at initial temperatures and energy densities at or above the critical values predicted by LQCD for a deconfinement transition.

- But they do not establish the detailed relevance of the lattice calculations to the fleeting dynamic matter produced in heavy-ion collisions

Heavy quark bound states





- Think of Schrödinger equation.
- Particles in a potential well.
- V(r) ~ kr : Linearly rising.
- Bound state of charm-anticharm: charmonium
  - J/ψ, ψ’ (ground state 1s, and excited state 2s state)
- Bottom-antibottom: bottomonium
  - ϒ’ , ϒ”, ϒ”’ (1s, 2s, 3s)

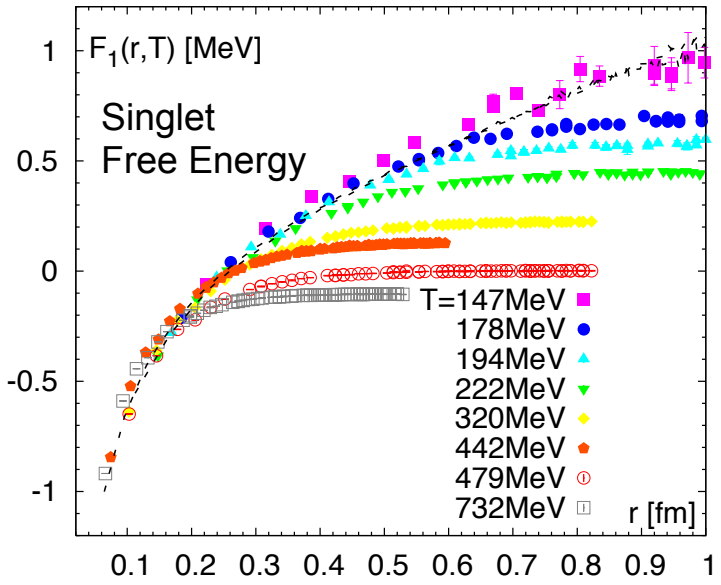
Heavy Quark Potential at High T

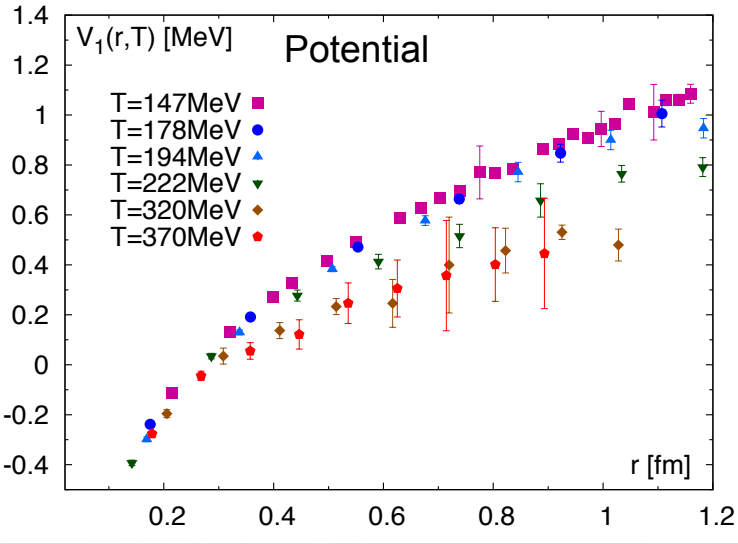
- Charmonium suppression: longstanding QGP signature
  - Original idea: High T leads to screening

$$V \sim -\frac{\alpha_{eff}}{r} \qquad T = 0$$

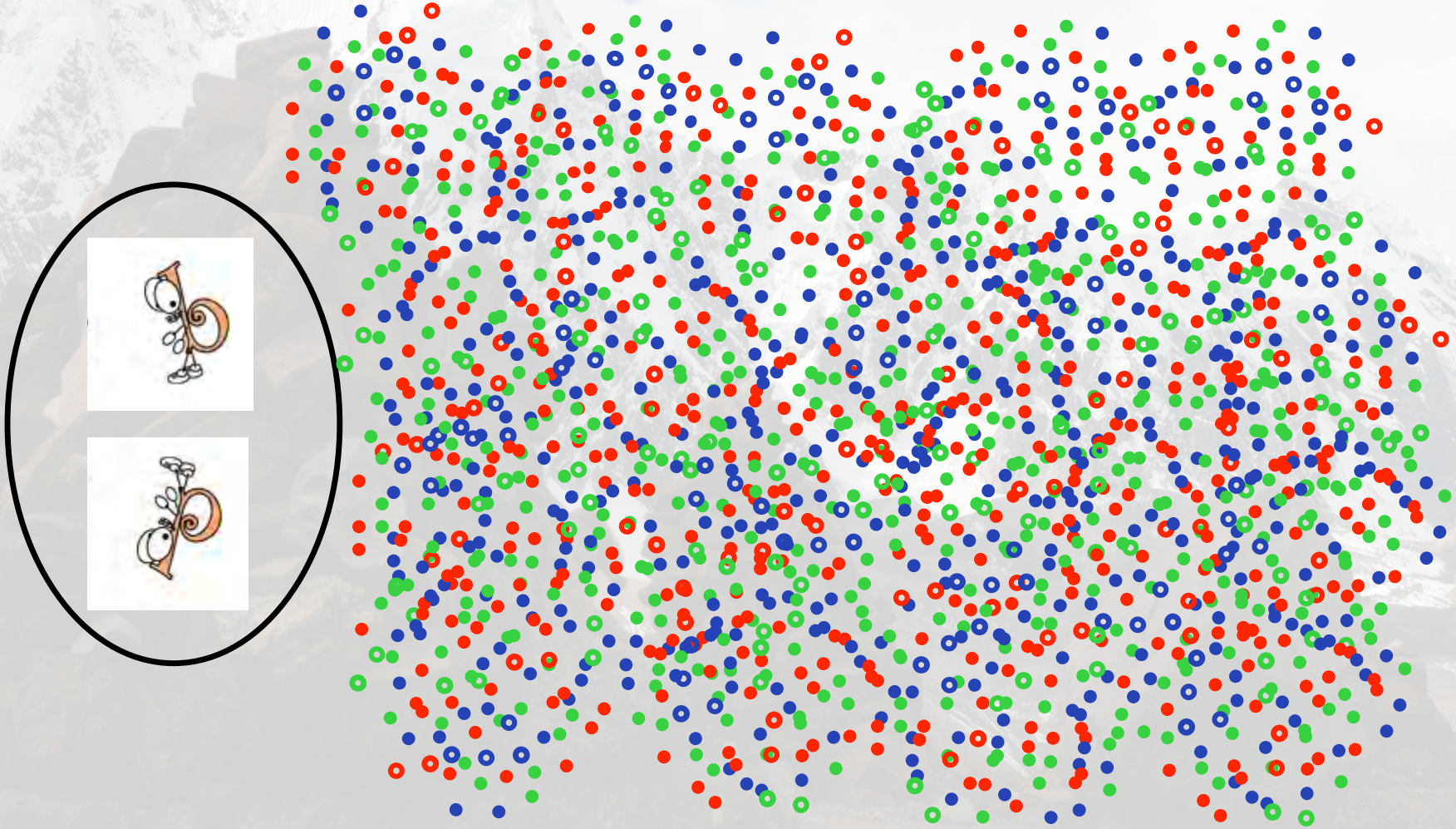
$$V \sim -\frac{\alpha_{eff}}{r} e^{-\frac{r}{r_D(T)}} \qquad T > T_C$$

  - 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
    - A. Bazavov & P. Petreczky
      - arXiv:1210.6314
    - Screening: Re V
    - Landau damping, gluodissociation: Im V
    - Both contribute to Quarkonium Suppression





Deconfinement, “screening” and suppression



Study many Quarkonia states in A+A

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

Key Idea: Quarkonia Melt in the plasma

- Color screening of static potential between heavy quarks
- Suppression of states is determined by Temp. and binding energy (or <r>)
- Excited states have larger <r>, suppressed at lower T.

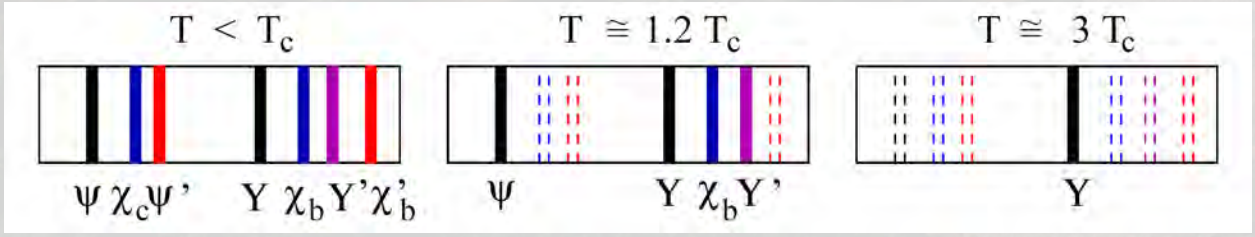
Sequential disappearance of excited quarkonia states:

$\Rightarrow$ Color screening $\Rightarrow$ Deconfinement

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

When do states melt?

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



Measuring the Temperature with Υ

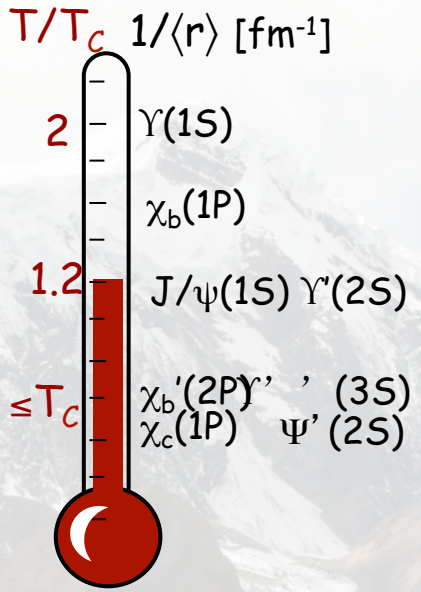
Quarkonia's suppression pattern
➔ **QGP thermometer**

Lattice QCD Calculations:

Dissociation temperatures of quarkonia states

$q\bar{q}$	J/Ψ	χ_c	ψ'	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T/T_c	1.10	0.74	0.2	2.31	1.13	1.10	0.83	0.75

hep-ph/0110406



***A .Mocsy**, 417th WE-Heraeus-Seminar,2008*

- For Υ production at RHIC and LHC
  - A cleaner probe compared to J/ψ
    - co-mover absorption → negligible
    - recombination → negligible
  - d-Au: Cold Nuclear Matter Effects
    - Shadowing / Anti-shadowing at y~0 small
    - Possible absorption / energy loss
- Challenge: low rate, rare probe
  - Large acceptance detector
  - Efficient trigger

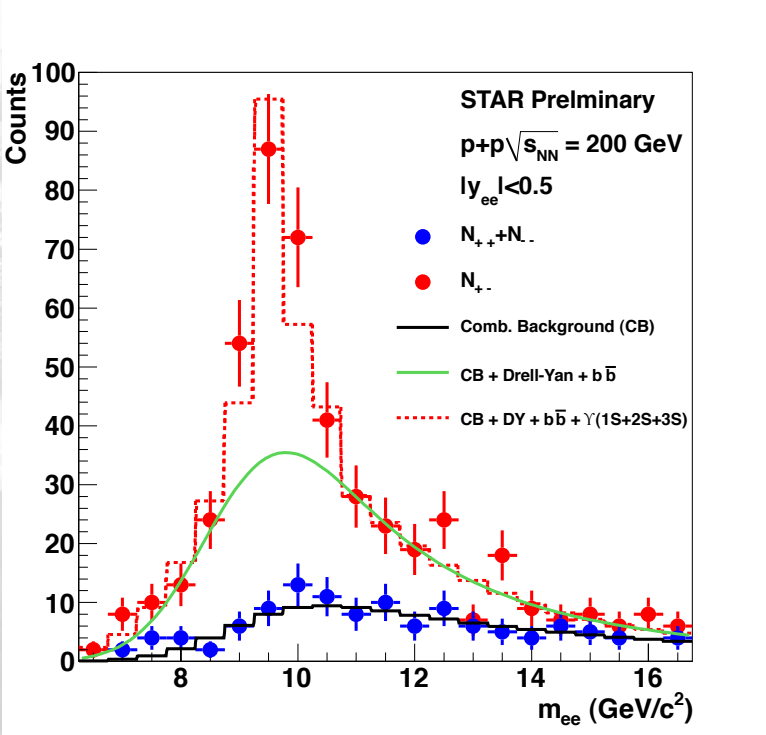
- Expectation:
  - Υ(1S) no melting
  - Υ(2S) likely to melt
  - Υ(3S) melts

How do you measure quarkonia?

- J/ψ, ϒ unstable
- Decay into e^+e^- or $\mu^+\mu^-$
- Use detectors to Identify particles (e or μ)
  - (i.e. identify the mass)
- Use spectrometers
  - measure their kinematics (p_x, p_y, p_z)
- Obtain two 4-vectors and combine them

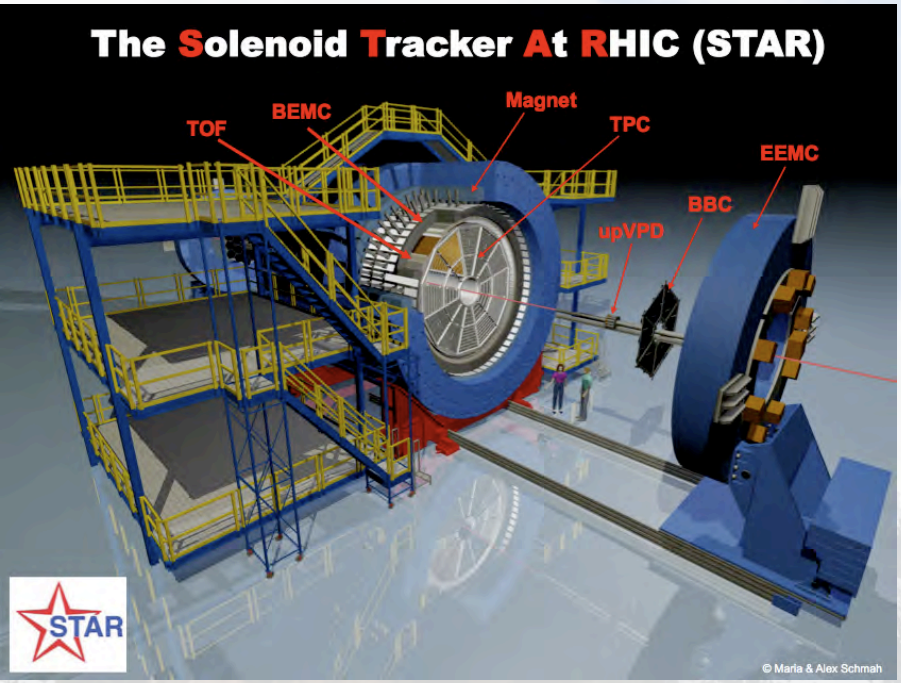
STAR ϒ → e^+ e^-

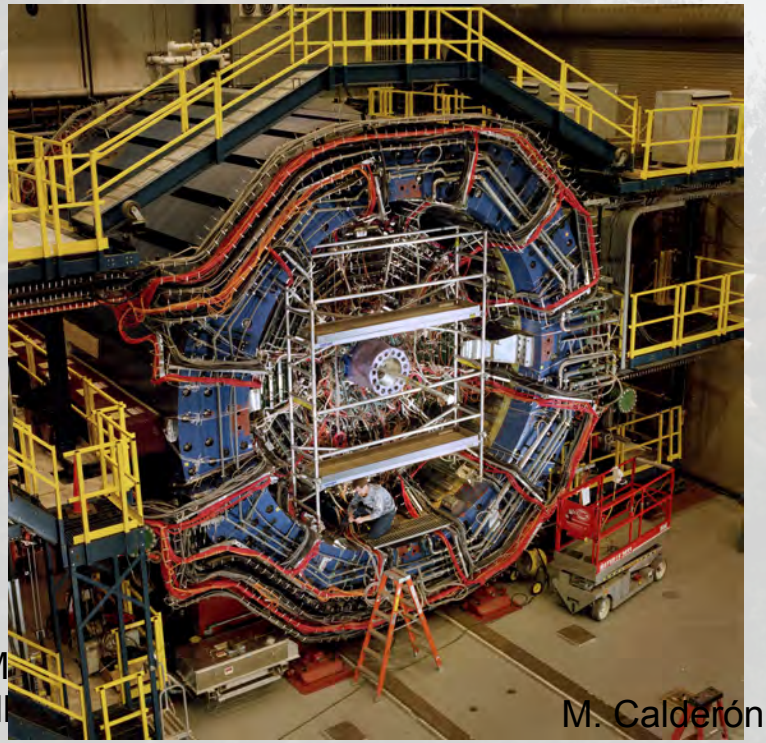
ϒ(1s+2s+3s)

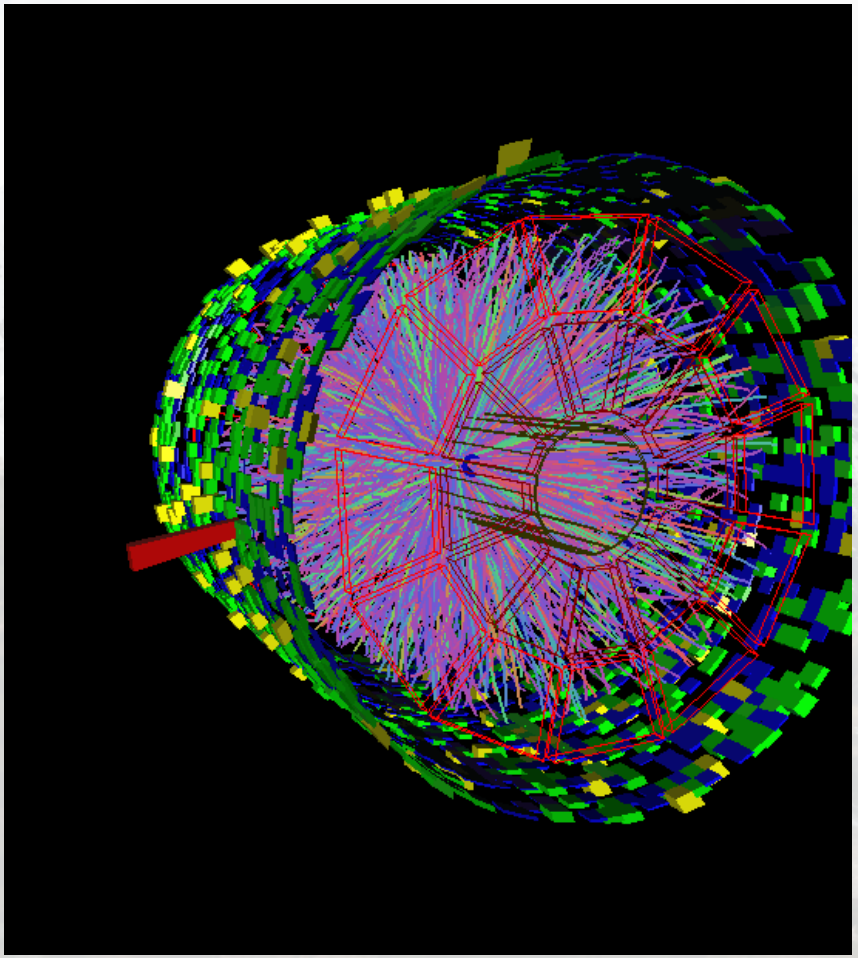


$$\left(p_1+p_2\right)^2=\left(E1+E2\right)^2-\left(\vec{p}_1^{\,2}+\vec{p}_2^{\,2}+2\vec{p}_1\bullet\vec{p}_2\right)=M^2$$

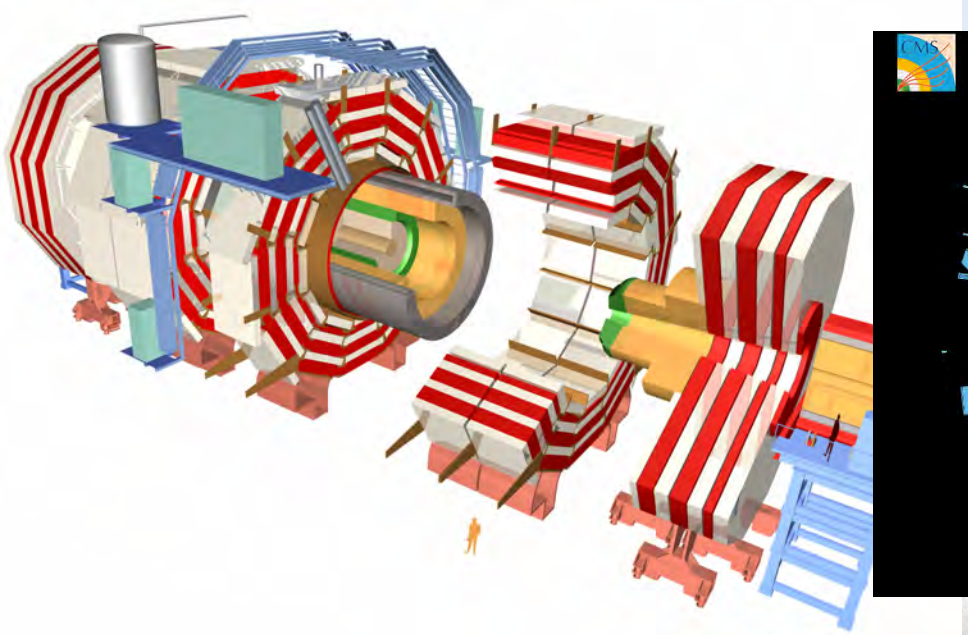
The STAR Detector

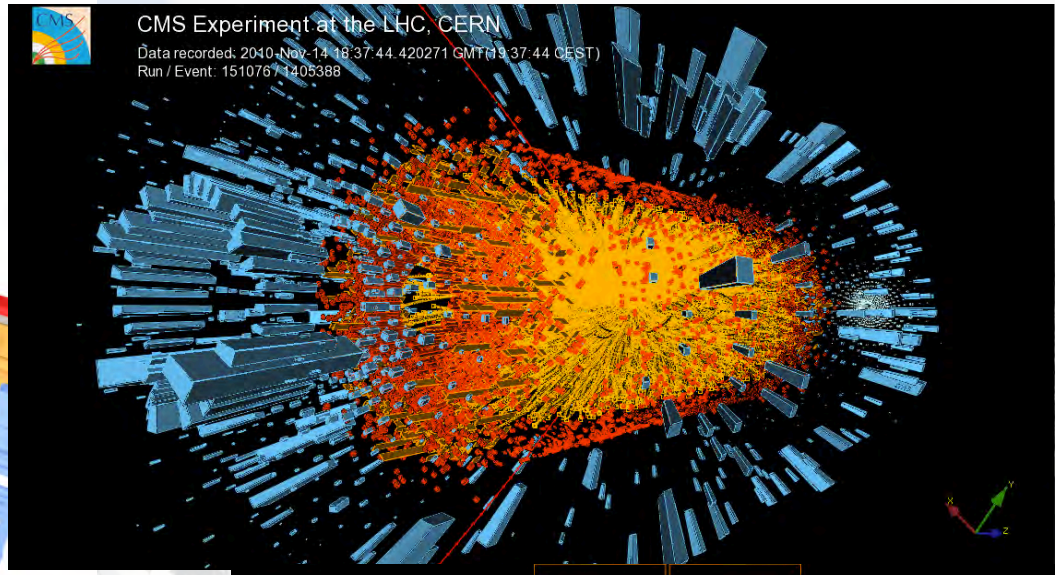


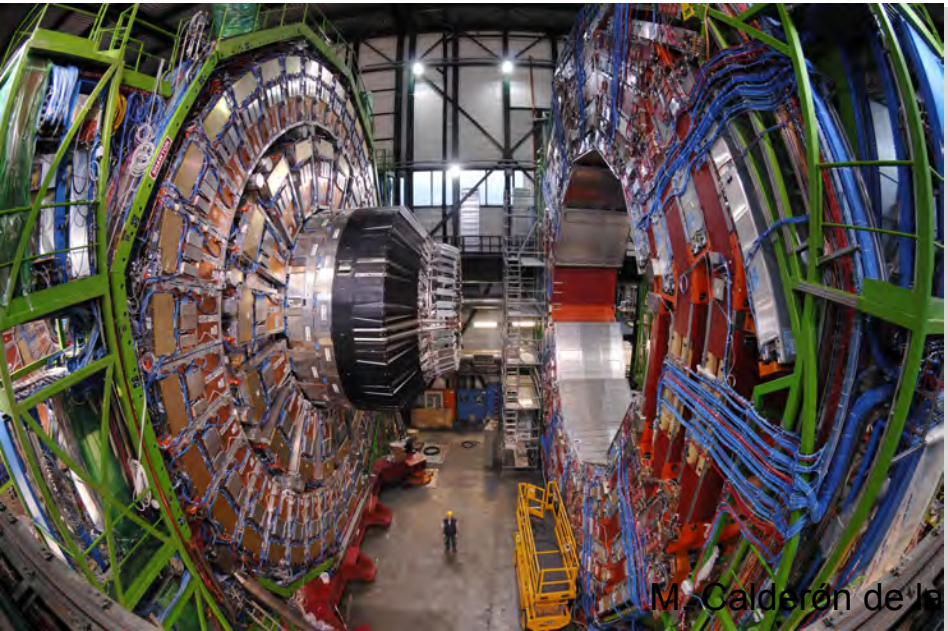


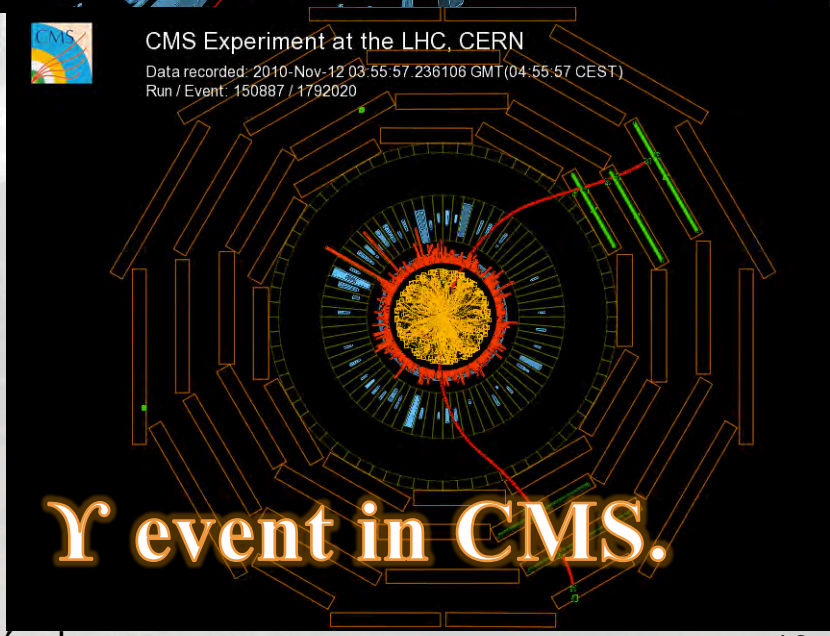


The CMS Detector





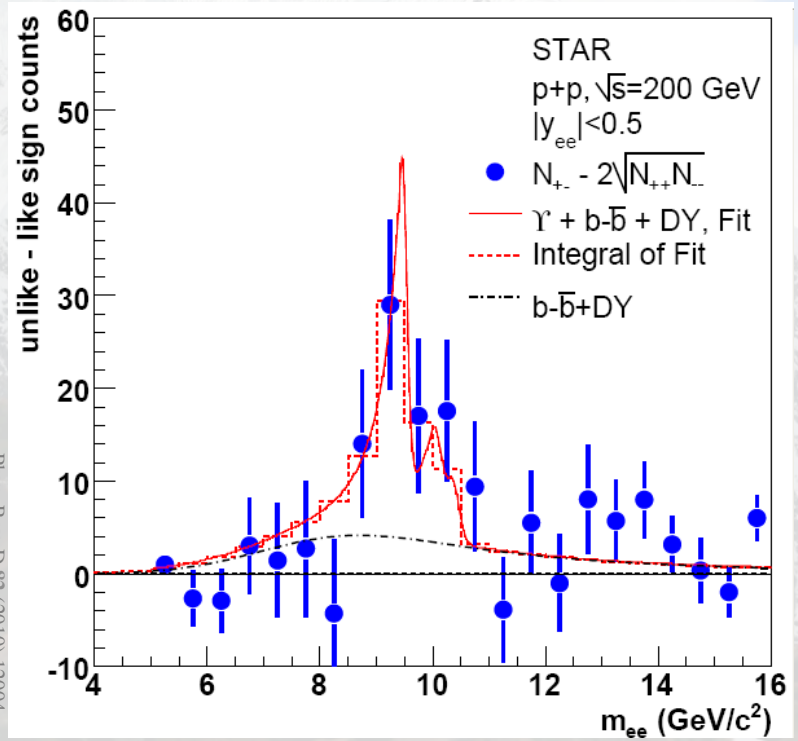




Υ event in CMS.

Υ in p+p 200 GeV in STAR

2006

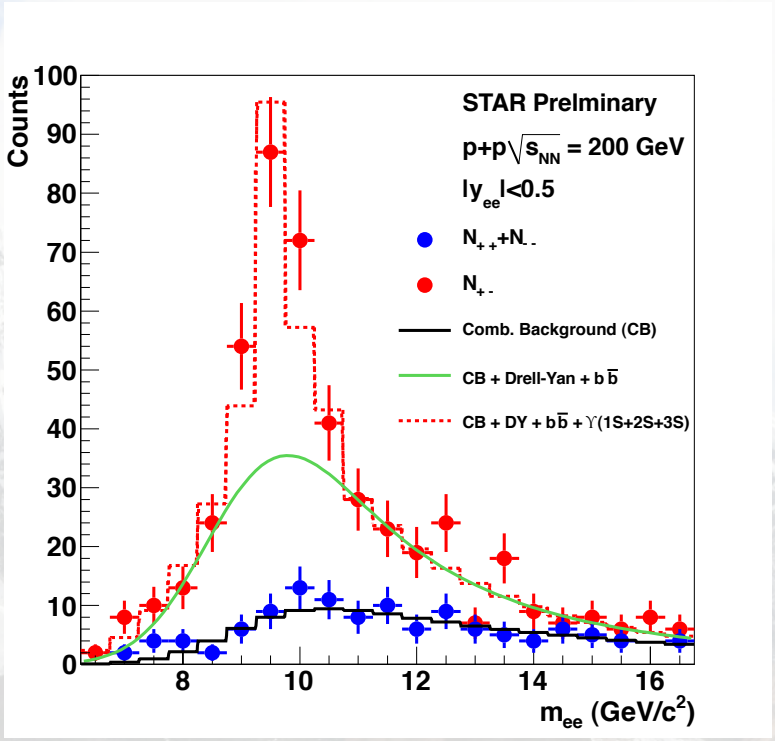


Phys. Rev. D 82 (2010) 12004

$\int \mathcal{L}\,dt = 7.9 \pm 0.6\ \text{pb}^{-1}$
$N_\Upsilon(\text{total}) = 67 \pm 22(\text{stat.})$

$$\sum_{n=1}^{3} \mathcal{B}(n\text{S}) \times \sigma(n\text{S}) = 114 \pm 38^{+23}_{-24}\ \text{pb}$$

2009

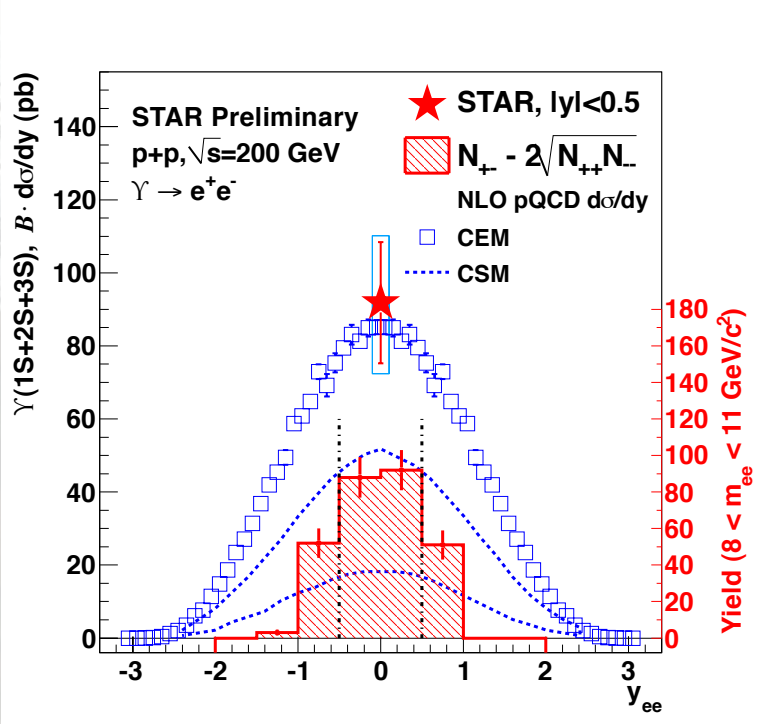


$\int \mathcal{L}\,dt = 19.7\ \text{pb}^{-1}$
$N_\Upsilon(\text{total}) = 145 \pm 26(\text{stat.})$

$$\sum_{n=1}^{3} \mathcal{B}(n\text{S}) \times \sigma(n\text{S}) = 91.8 \pm 16.6 \pm 19\ \text{pb}$$

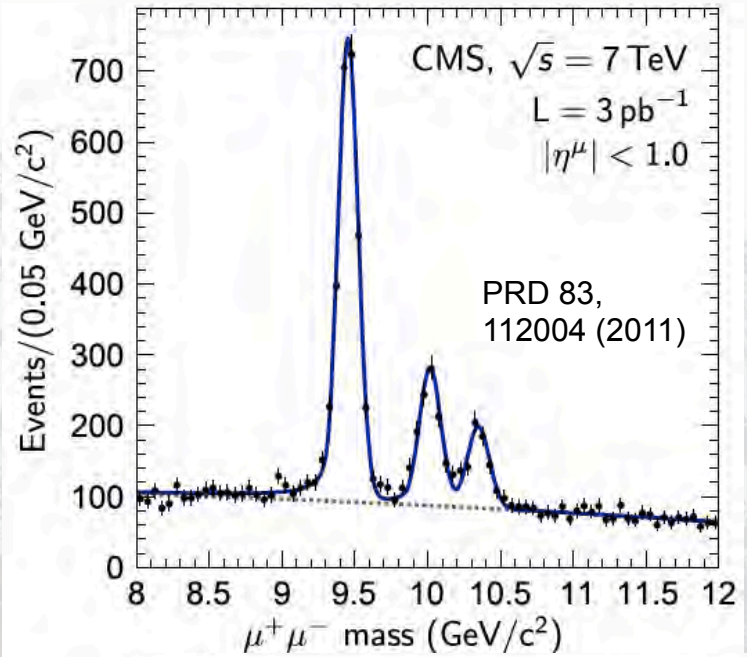
STAR Preliminary

ϒ Comparison to NLO pQCD

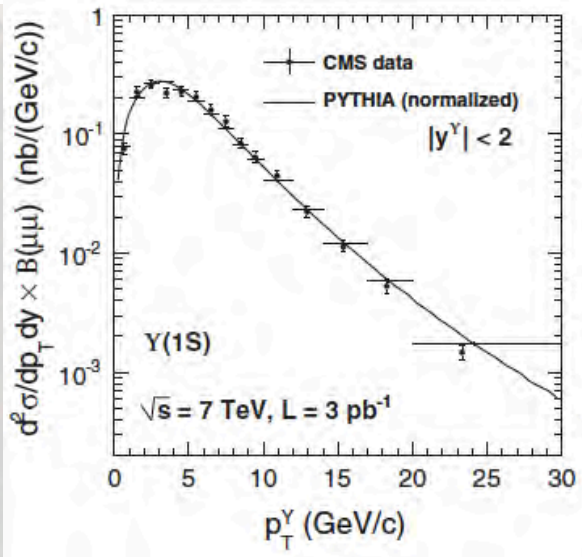


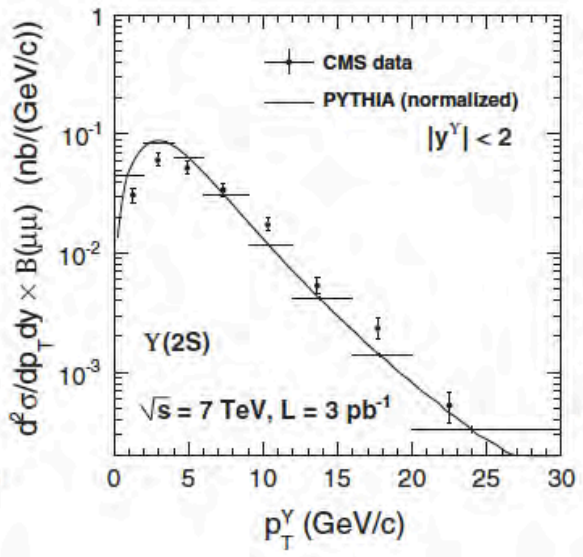
- Comparison to NLO
- STAR √s=200 GeV p+p ϒ+ϒ′+ϒ″→e^+e^- cross section consistent with pQCD Color Evaporation Model (CEM)

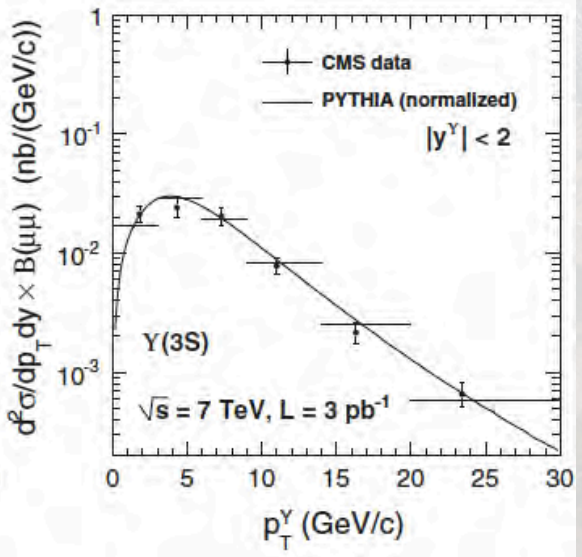
Υ in p+p 7 TeV in CMS



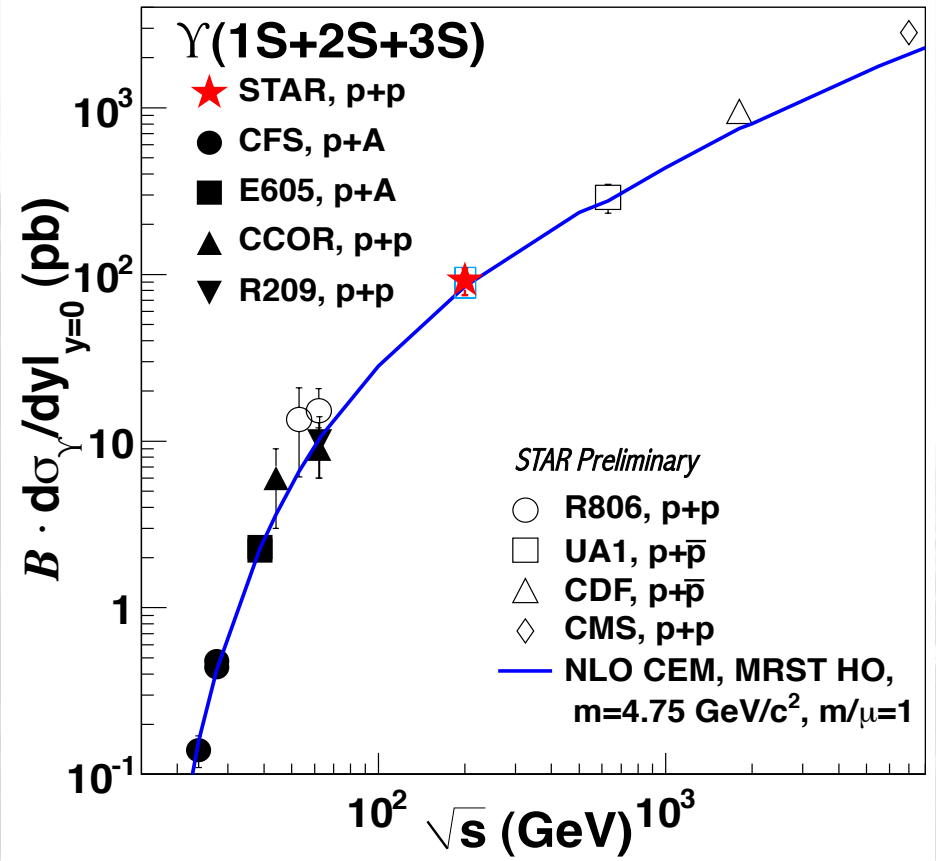
- Excellent resolution at midrapidity.
- Separation of 3 states.





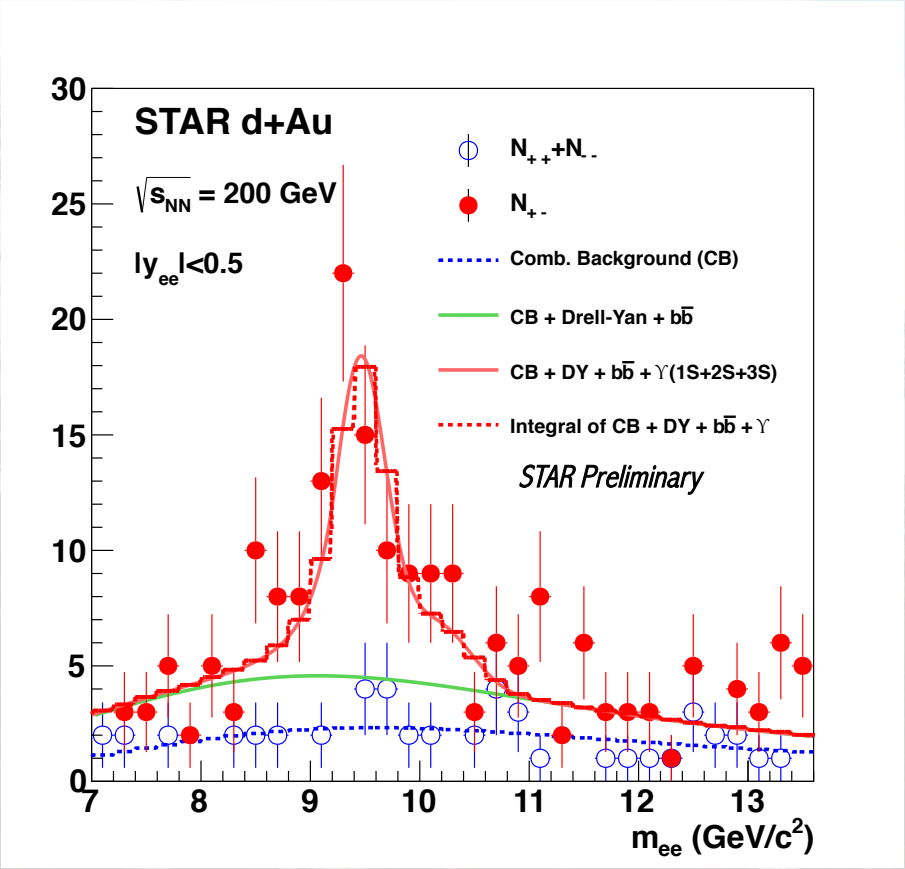


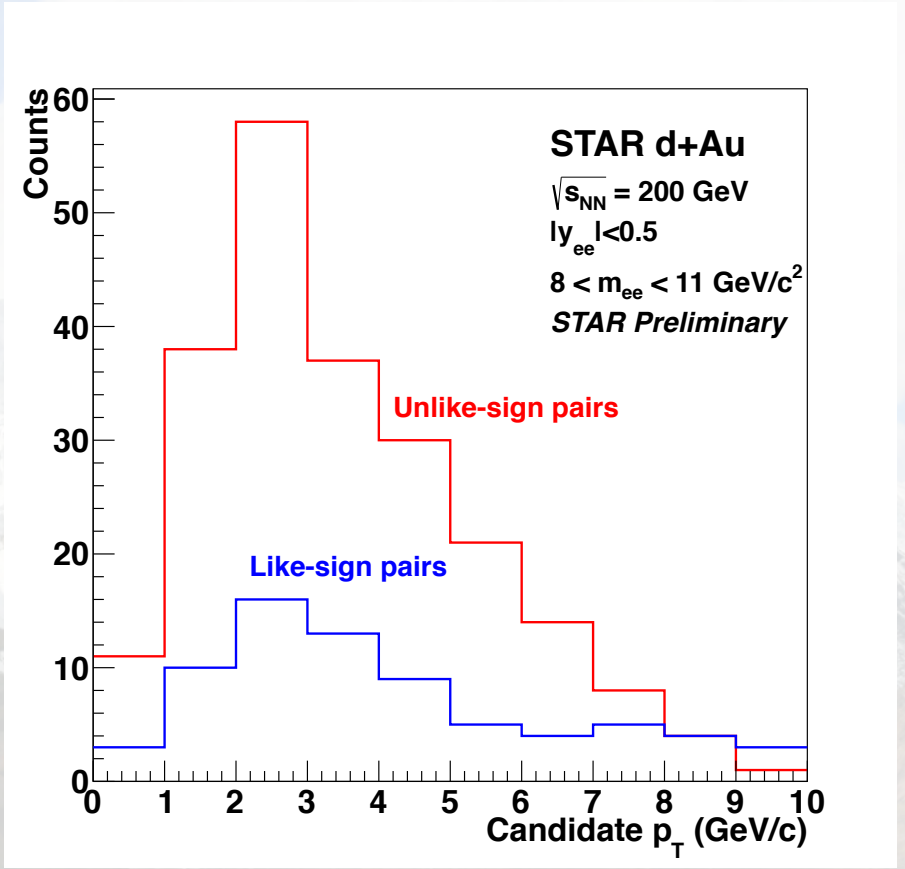
Υ vs $\sqrt{s}$, World Data



STAR $\sqrt{s}$=200 GeV and CMS $\sqrt{s}$=7 TeV p+p $\Upsilon+\Upsilon'+\Upsilon'' \rightarrow e^+e^-$ cross section consistent with pQCD and world data trend

Υ in d+Au 200 GeV





Signal has ~8σ significance

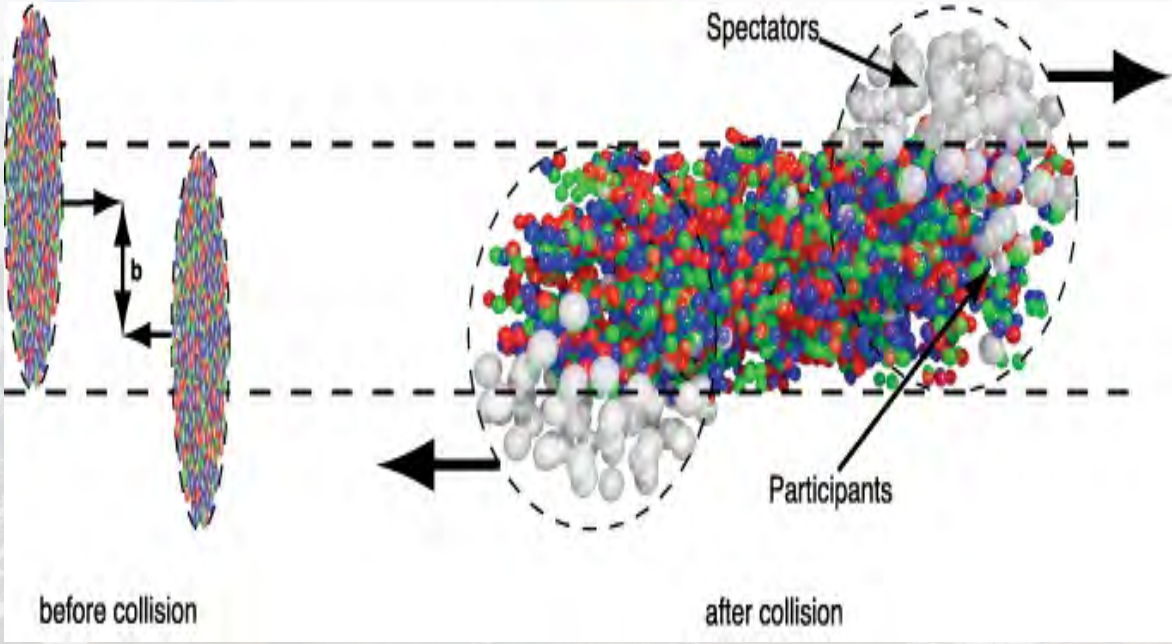
p_T reaches ~8 GeV/c

$\int L\,dt = 32.6\ nb^{-1}$

$N_\Upsilon = 79 \pm 17\ (stat.) \pm 13\ (syst.)$

Centrality in Heavy Ion Collisions

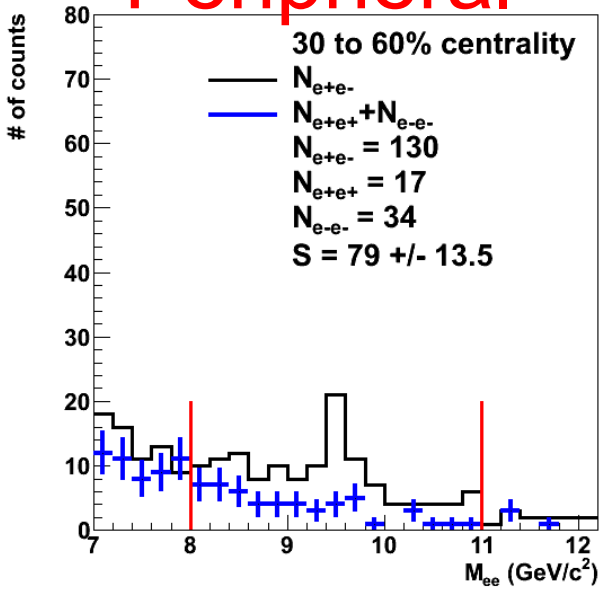
- "Centrality": a useful knob in our experiments
  - Collisions can be
    - Peripheral: barely touching, or
    - Central: "head-on"
      - Many "Participants"

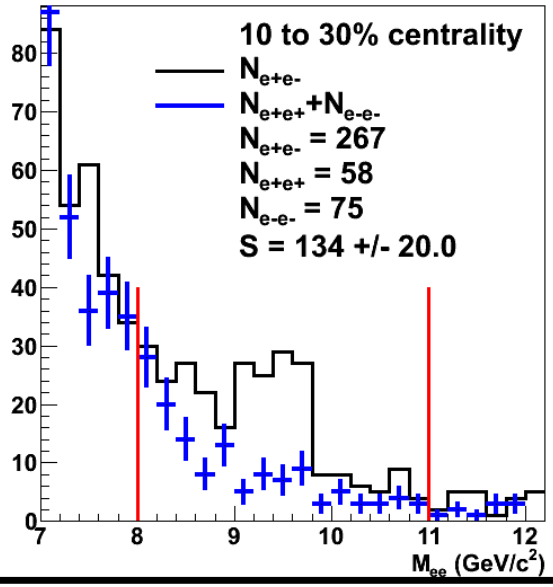


- Expectation:
  - Peripheral collisions: Do not produce hot matter.
  - Central collisions: Produce Hot QCD

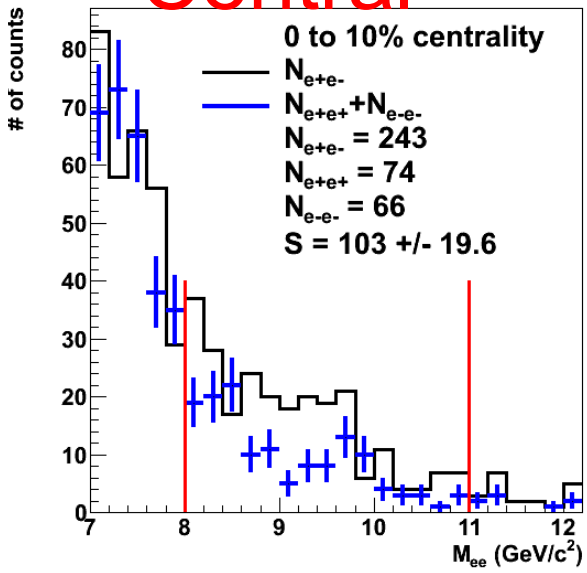
Υ: From Grazing to Head-On Collisions, STAR

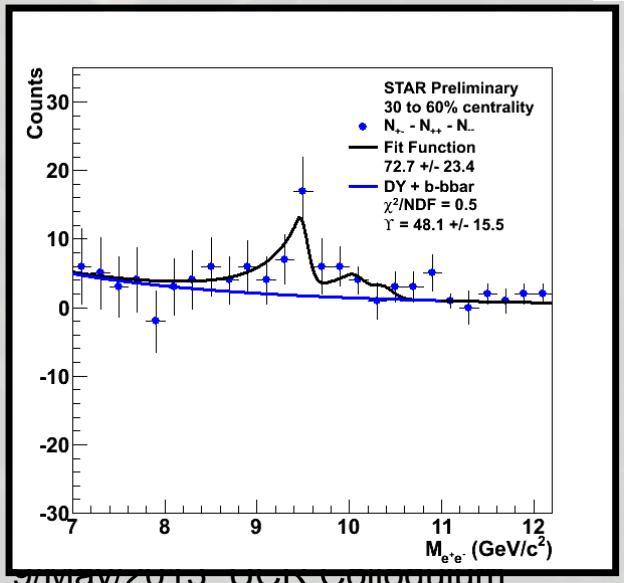
Peripheral

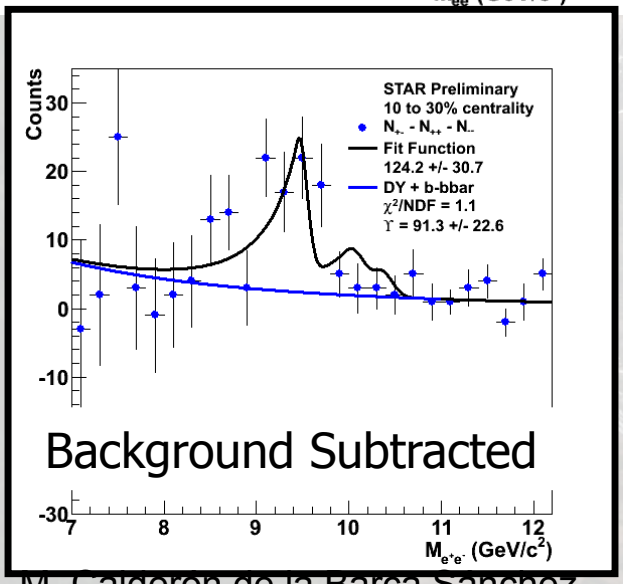


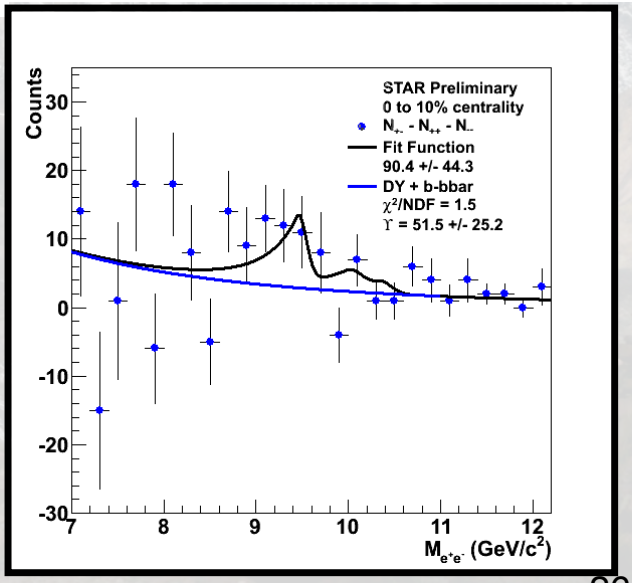


Central







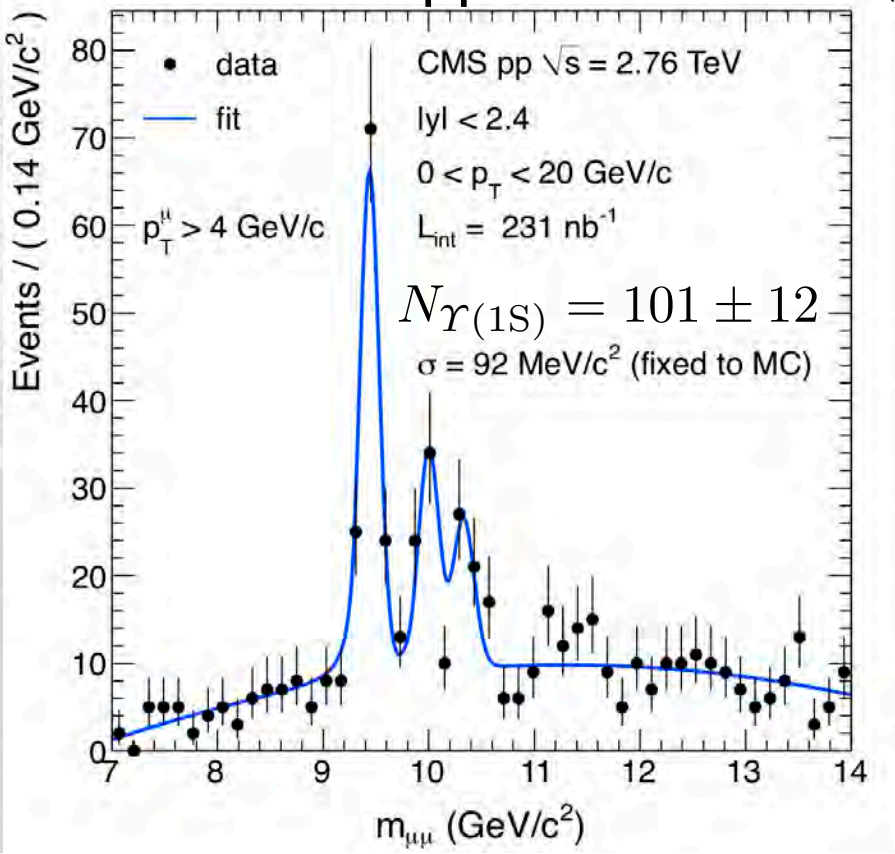


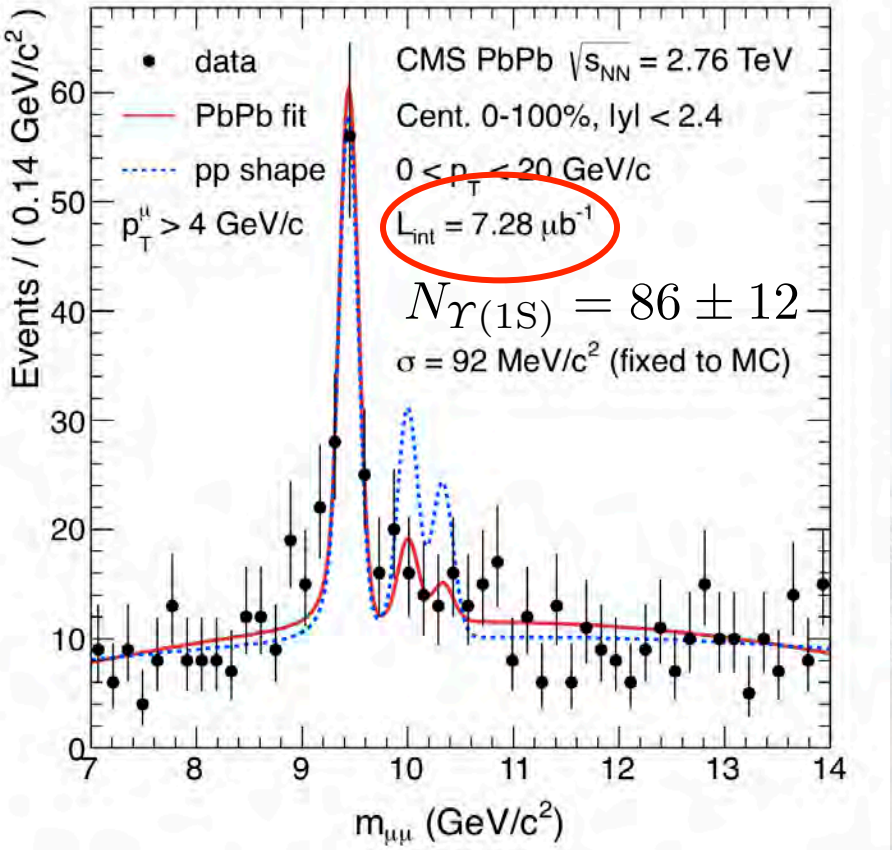
Bottomonia at 2.76 TeV: 2010 data, CMS

pp

PRL 107 (2011) 052302

PbPb





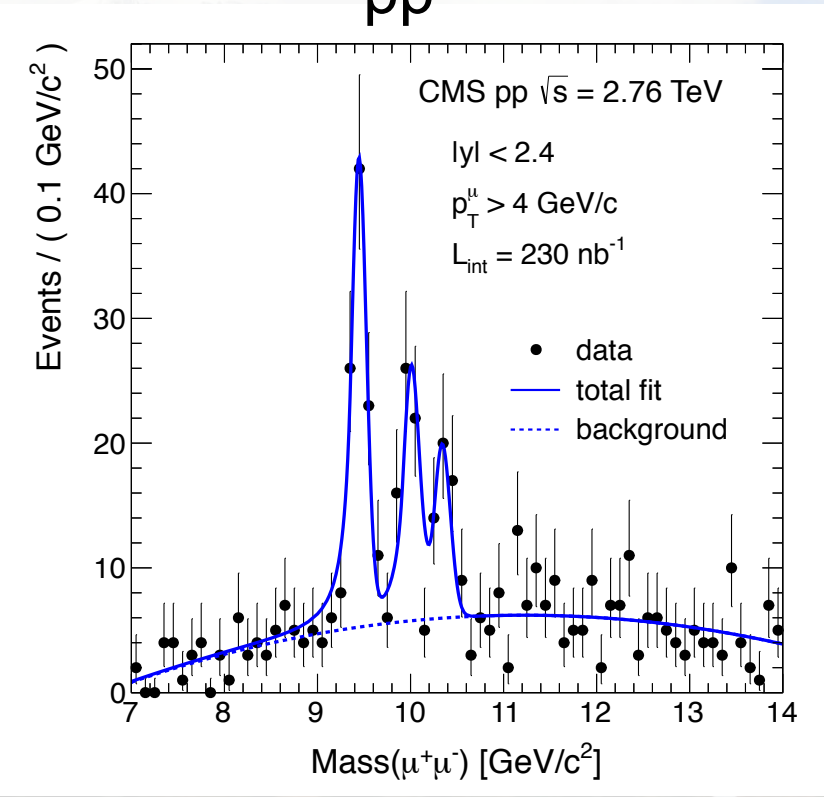
$N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

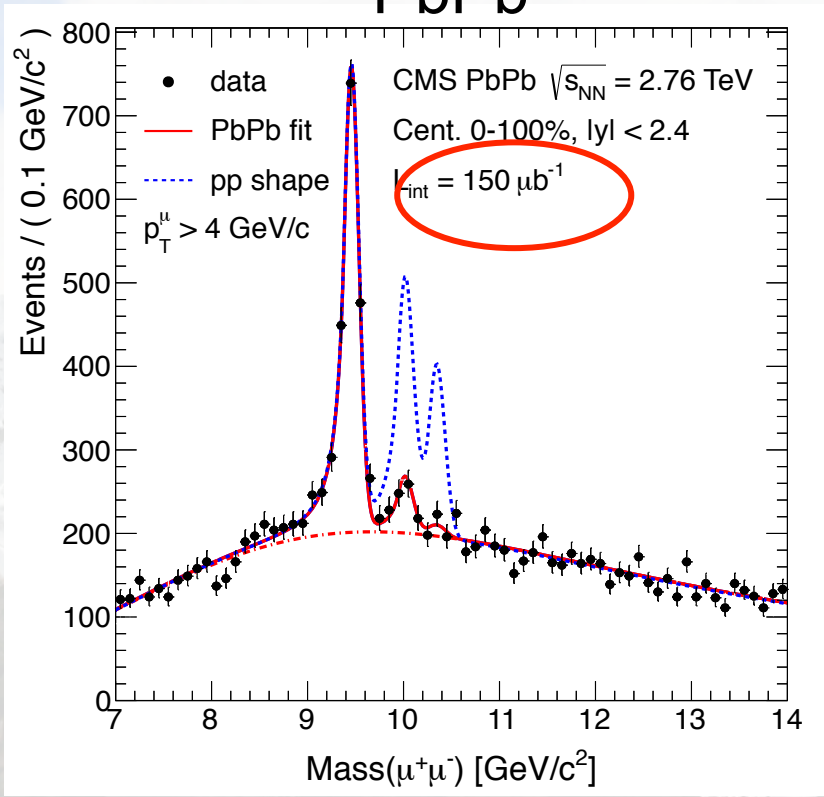
$$\frac{N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{PbPb}}{N_{\Upsilon(2S+3S)}/N_{\Upsilon(1S)}|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

Bottomonia: 2011 data

pp



PbPb



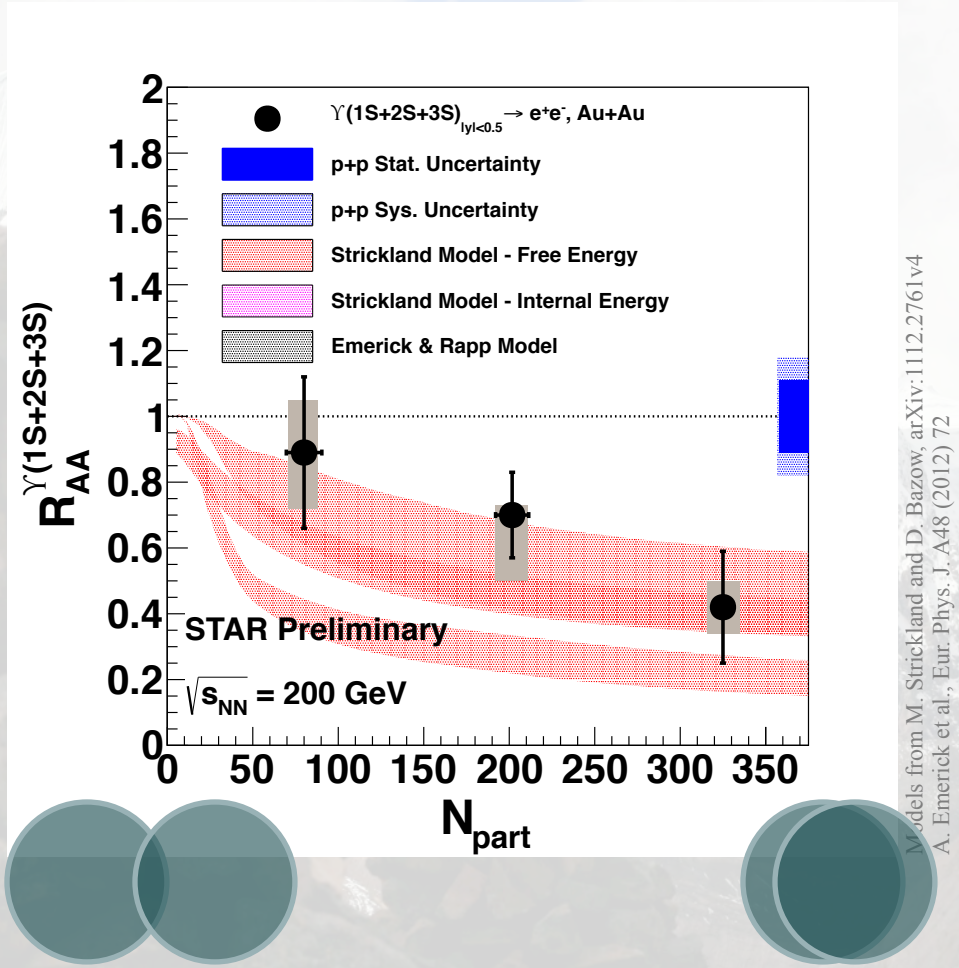
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

PRL 109, 222301 (2012)

- Clear separation of all 3 states
- Raw single ratios. Note: not corrected for acceptance and efficiency
- Can compare PbPb to pp directly: double ratio, acceptance & effic. cancel

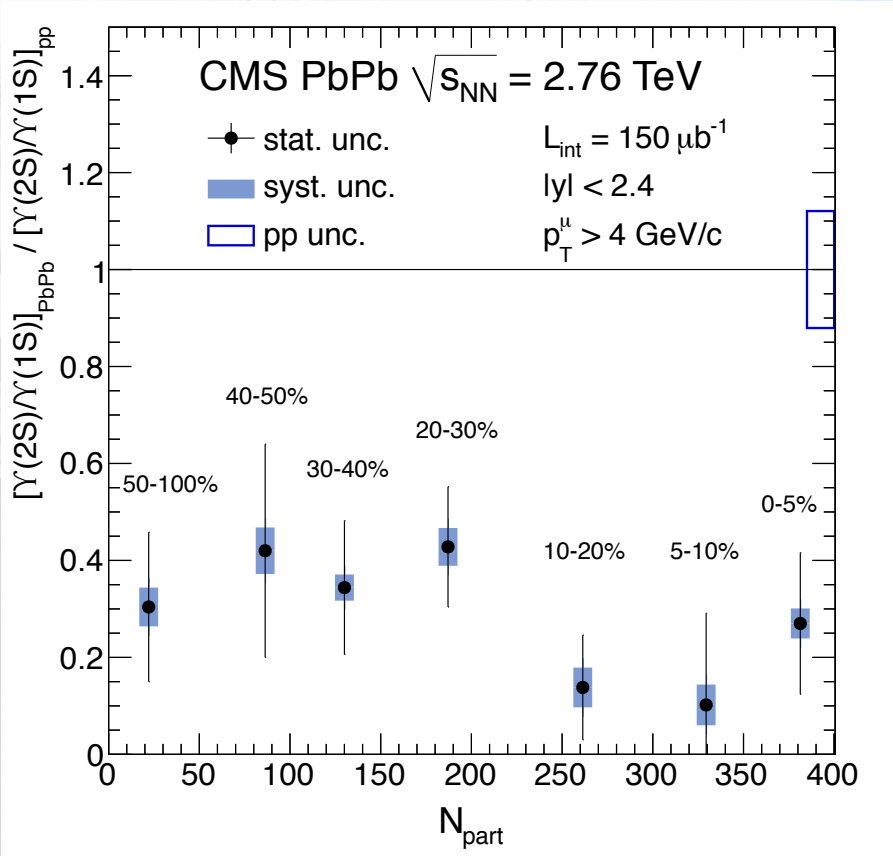
Compare to pp Reference: Υ Suppression!



Models from M. Strickland and D. Bazow, arXiv:1112.2761v4
A. Emerick et al., Eur. Phys. J. A48 (2012) 72

- Hint of stronger suppression for more central collisions.

Υ(2S)/Υ(1S) Double Ratio, CMS



PRL 109, 222301 (2012)

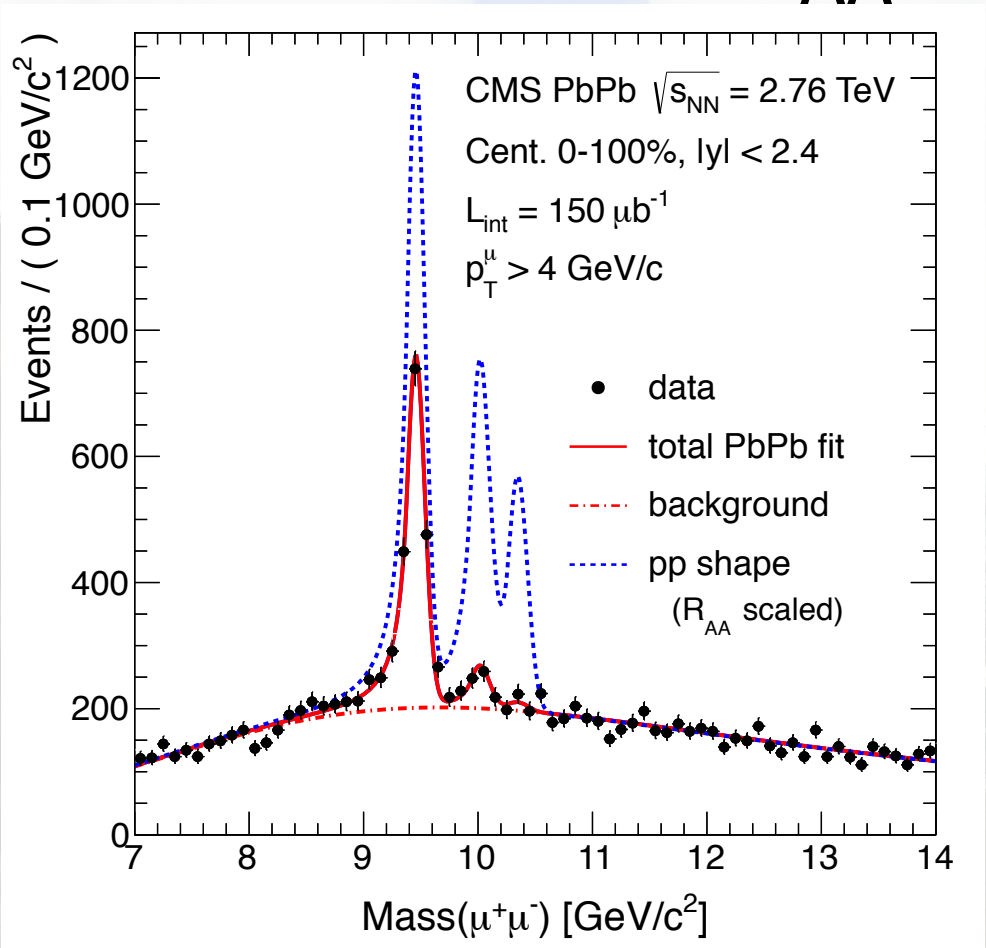
- Separated Υ(2S) and Υ(3S)

$$\frac{N_{\Upsilon(2S)} / N_{\Upsilon(1S)}\big|_{PbPb}}{N_{\Upsilon(2S)} / N_{\Upsilon(1S)}\big|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

$$\frac{N_{\Upsilon(3S)} / N_{\Upsilon(1S)}\big|_{PbPb}}{N_{\Upsilon(3S)} / N_{\Upsilon(1S)}\big|_{pp}} < 0.1 \ (95\% \ \text{C.L.})$$

- Measured Υ(2S) double ratio vs. centrality
  - no strong centrality dependence

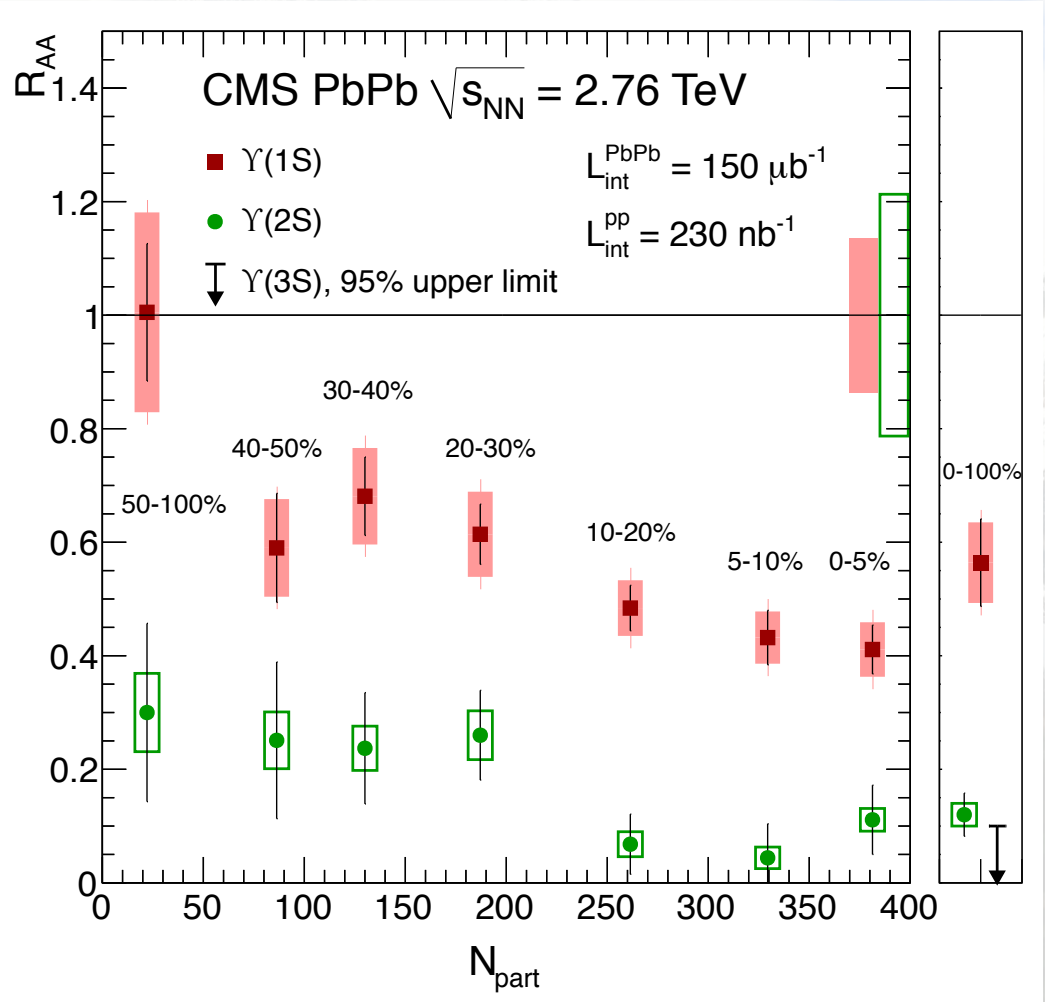
Υ R_{AA} Graphically



- Scaling pp Shape by T_{AA} : illustrate R_{AA} graphically.
  - Suppression seen for all 3 states.

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

- 2011 150 /μb
  - $\Upsilon(1S)$ R_{AA}, 7 centrality bins
  - First results on $\Upsilon(2S)$ R_{AA}
    - Clear suppression of $\Upsilon(2S)$
  - $\Upsilon(1S)$ suppression
    - Consistent with excited state suppression only
    - ~50% feed down
  - Centrality integrated



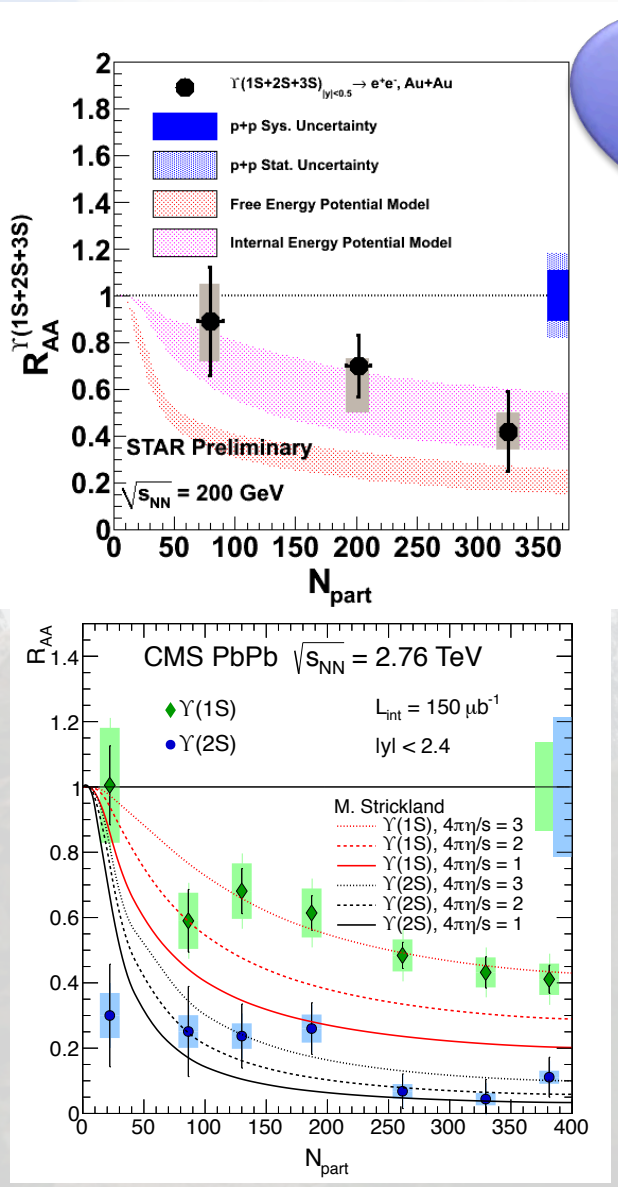
PRL 109, 222301 (2012)

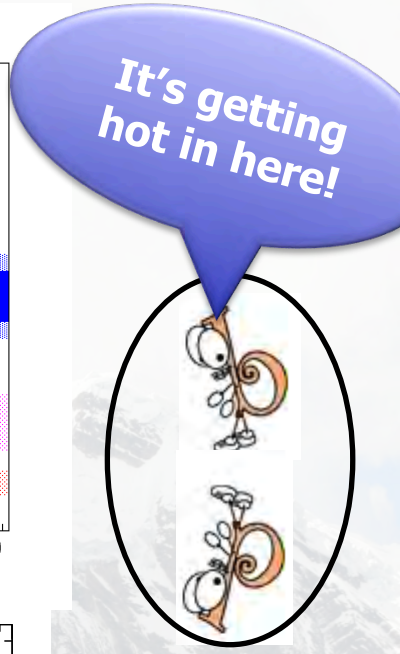
$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08\ (\text{stat.}) \pm 0.07\ (\text{syst.})$$
$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04\ (\text{stat.}) \pm 0.02\ (\text{syst.})$$
$$R_{AA}(\Upsilon(3S)) < 0.1\ (\text{at } 95\%\ \text{C.L.})$$

- **Observation of sequential suppression of Υ in order of their binding energy**

Υ R_{AA} Comparison to models I

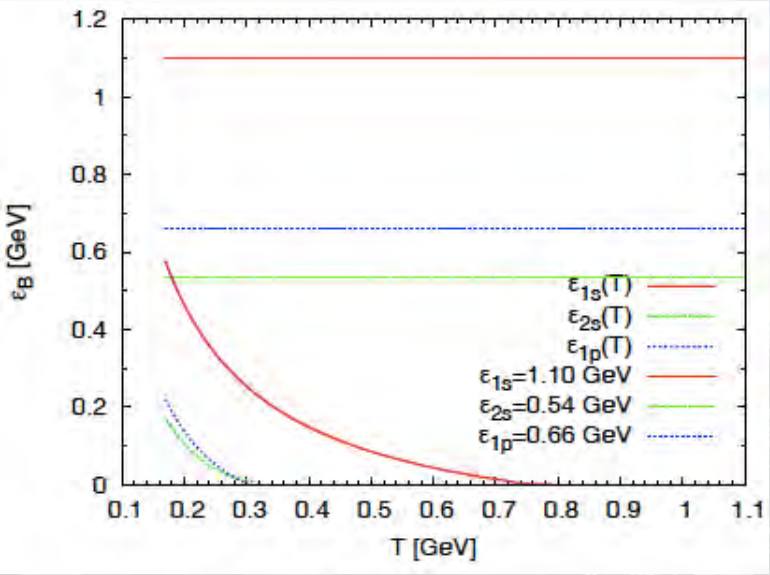
- Incorporating lattice-based potentials, including real and imaginary parts
  - A: Free energy
    - Disfavored.
  - B: Internal energy
    - Consistent with data vs. N_{part}
- Includes sequential melting and feed-down contributions
  - ~50% feed-down from χ_b.
- Dynamical expansion, variations in initial conditions (T_0, η/S)
  - Data indicate:
    - $428 < T_0 < 442$ MeV at RHIC
    - $552 < T_0 < 580$ MeV at LHC
    - for $3 > 4\pi\eta/S > 1$

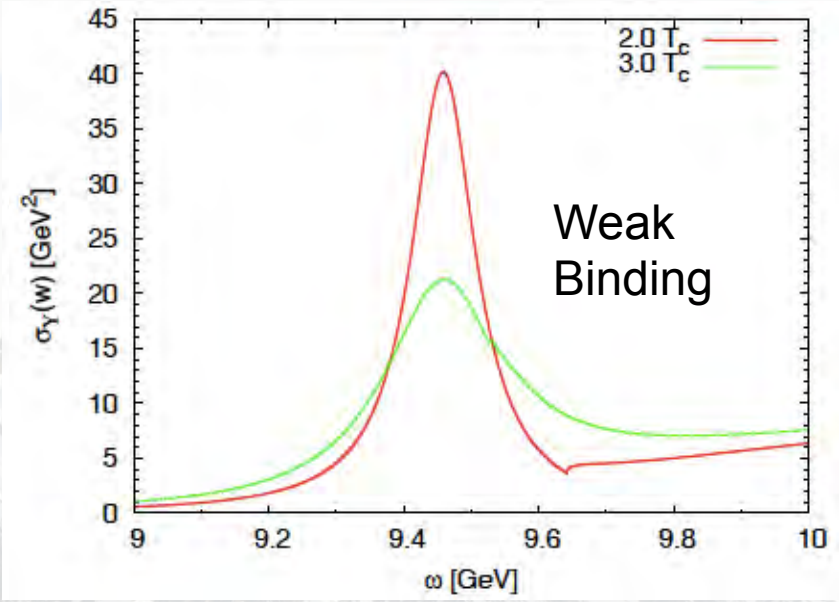




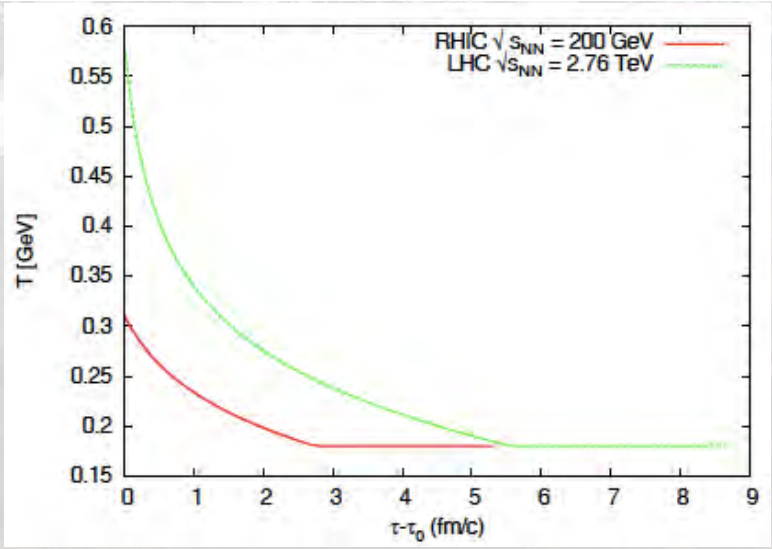
M. Strickland, D. Bazow
Nucl.Phys. A879 (2012) 25

Υ R_{AA} Comparison to models II

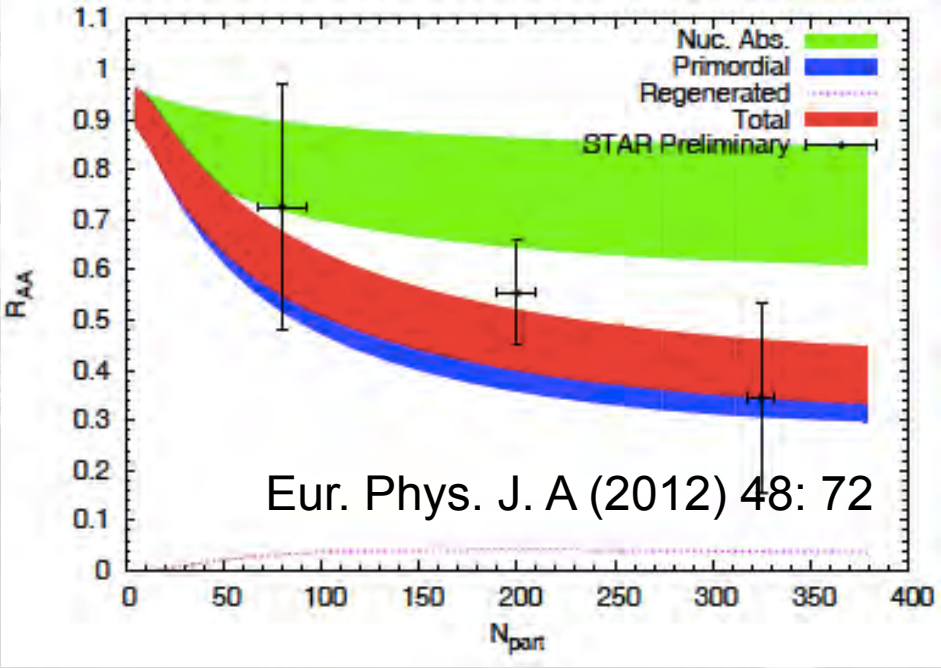


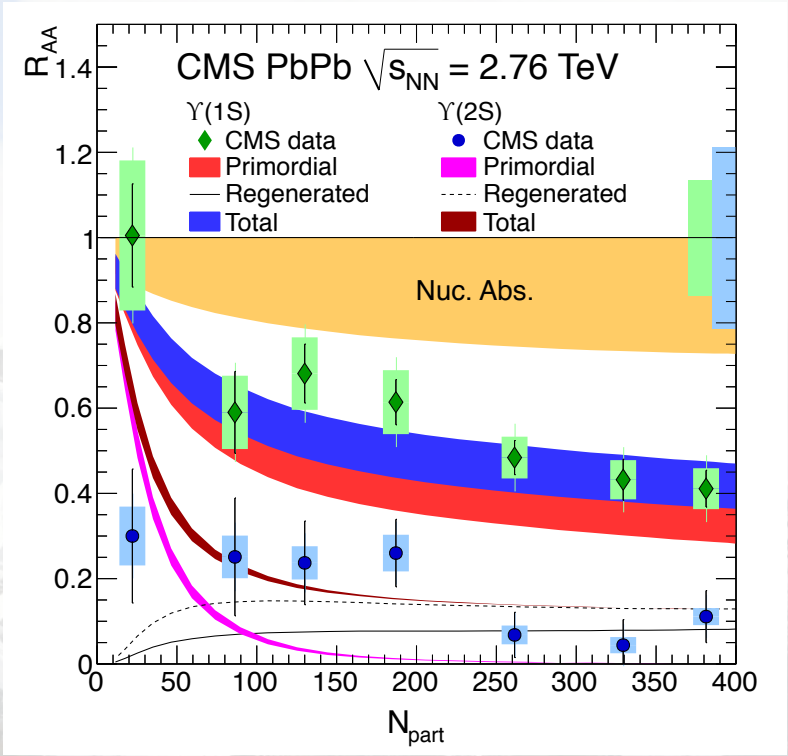


- Weak vs. Strong Binding
  - Narrower spectral functions for "Strong" case
  - Ratios of correlators compared to Lattice: favor "Strong" binding case
- Kinetic Theory Model
  - Rate Equation: dissociation + regeneration
  - Fireball model: T evolution. $T_0 \sim 300$ MeV



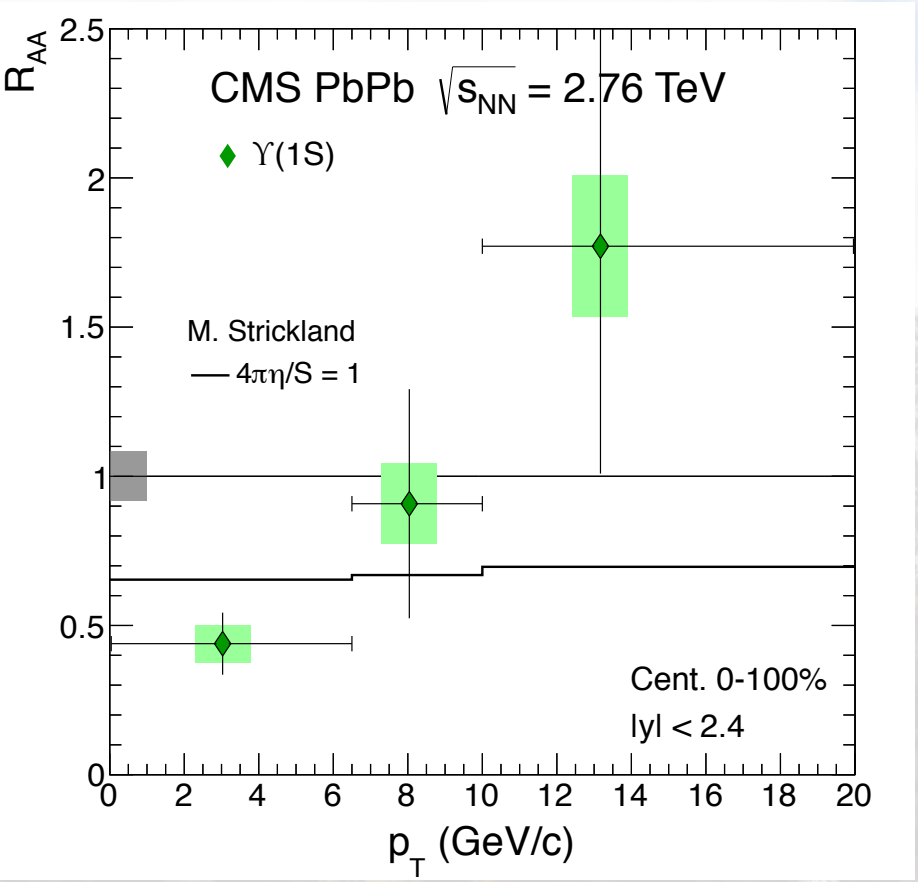
Υ R_{AA} Comparison to models II

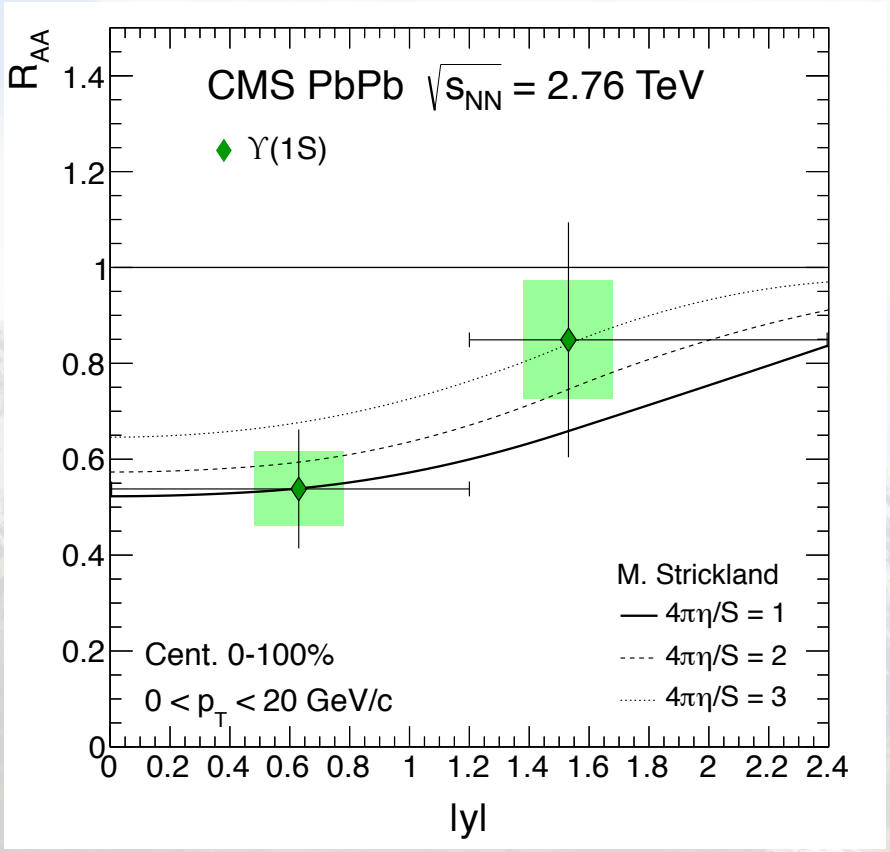




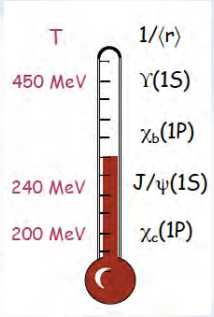
- Comparison to data for "Strong" binding:
  - Mostly consistent with data
  - Little regeneration: Final result ~ Primordial suppression
  - Large uncertainty in nuclear absorption. Need dAu, pPb.

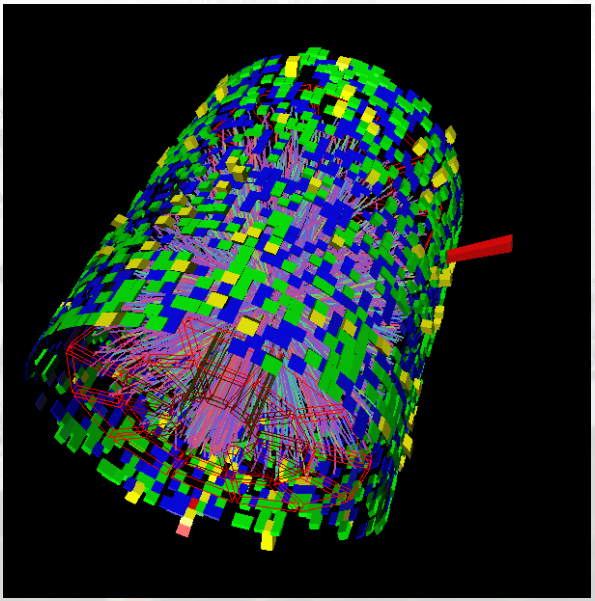
Υ R_{AA} p_T and y dependence

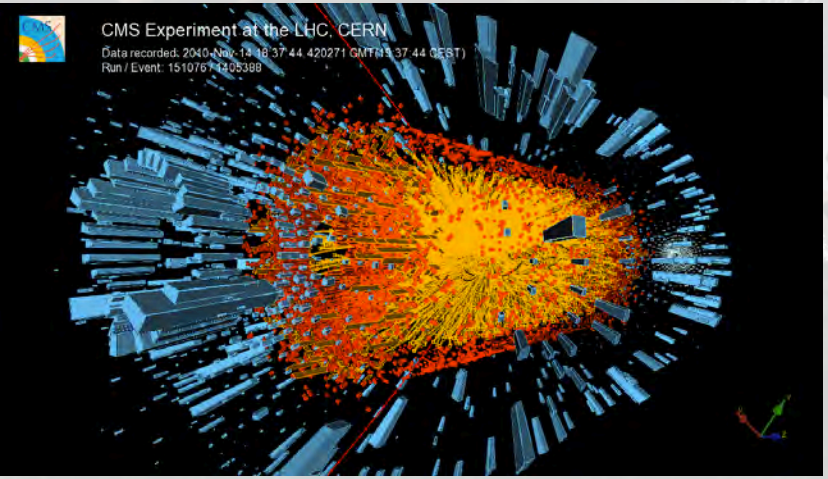




- Indications that suppression is largest at low p_T. and mid rapidity.
  - Need more statistics for firmer conclusions.



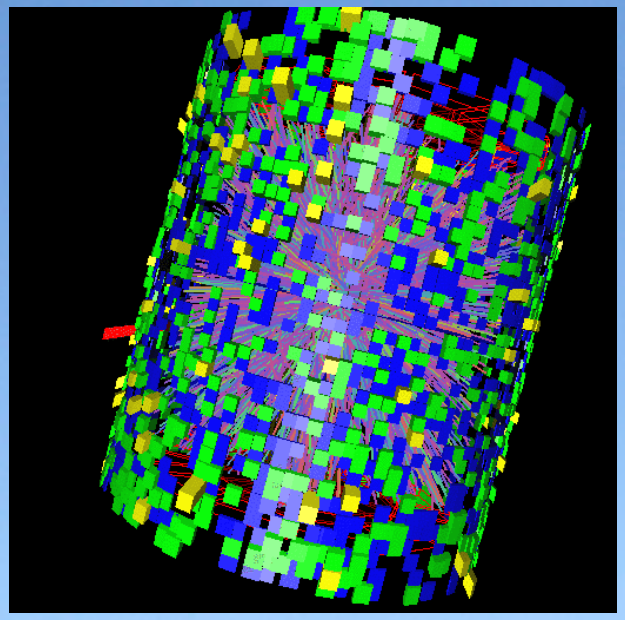




The bottom line...

- Heavy-ion collisions: turning up the heat on the strong force
- STAR and CMS have reached the bottom:
  - Υ suppression seen by both experiments.
  - R_{AA} consistent with suppression of feed down from excited states only (~50%)
  - CMS: First measurement of $\Upsilon(2S)$ suppression
  - $R_{AA}(\Upsilon(3S)) < 0.09$ (95% C.L.)
  - Cold nuclear matter:
    - coming soon!
  - Pinning down the medium properties.
- Our quest for beauty is bearing fruit!

Thank you!

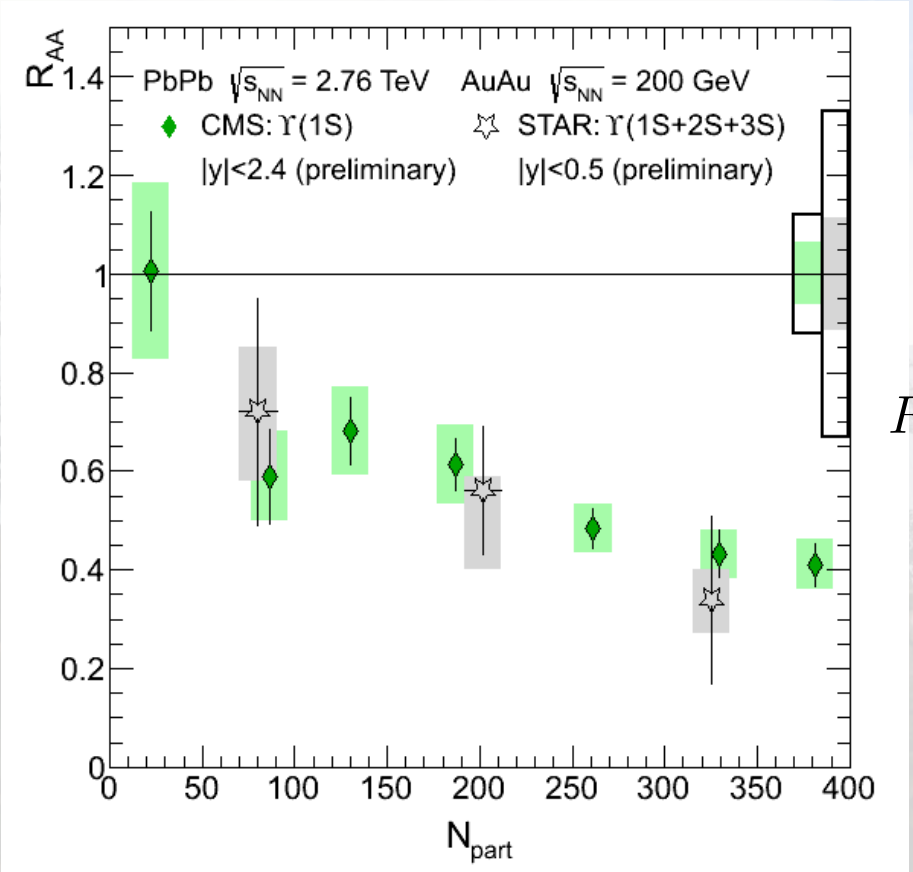


Rocky mountain national park.

Ypsilon Peak Chapin Peak Chiquita Peak

Backup Material

Comparison: RHIC and LHC



- STAR measured R_{AA} of Υ(1S+2S+3S) combined
  - arXiv:1109.3891
  - min. bias value:

$$R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$$

- CMS: separate R_{AA} for Υ(1S) and Υ(2S)
  - can calculate min. bias R_{AA} of Υ(1S+2S+3S):

$$R_{AA}(\Upsilon(1S+2S+3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}}$$

$$= 0.53 \times \frac{1+0.19}{1+0.97} \approx 0.32$$

CMS Preliminary, arXiv:1208.2826

Quenching of away-side Jets

Experiment:

Shoot a *controlled probe* through the matter and *see what happens*.

What probe?

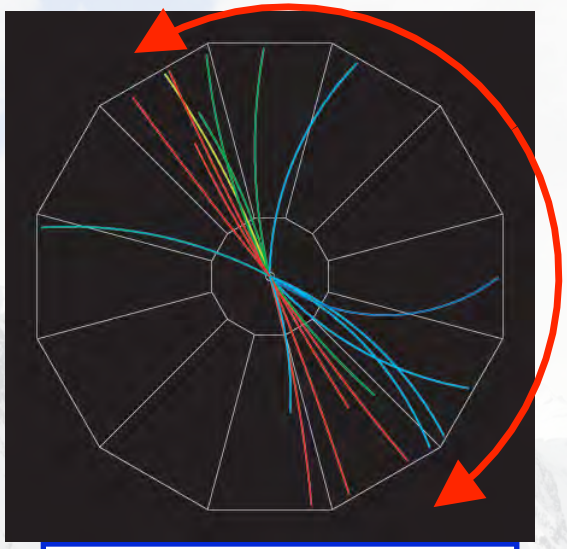
Particle jets measured in proton +proton collisions

- Property: Jets come in pairs and are **180° apart.**

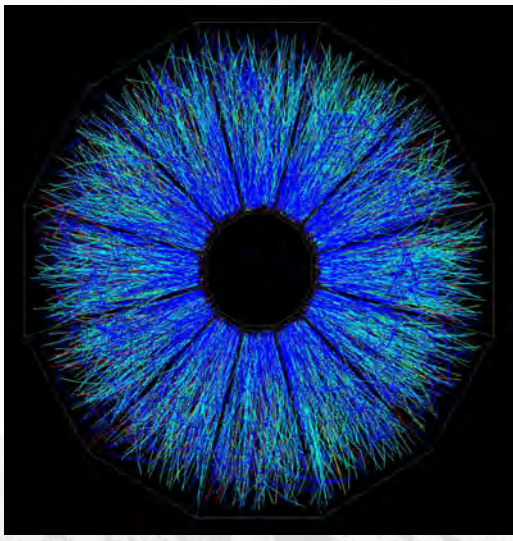
What Happens?

=> Away Side Jet is absorbed in the Quark Soup!

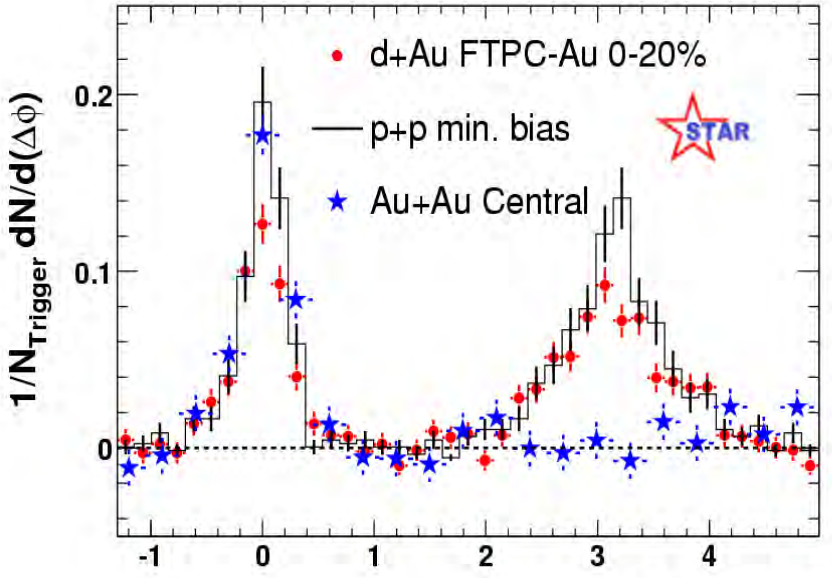
Quark Soup produced at RHIC is the *densest* matter produced in the lab!



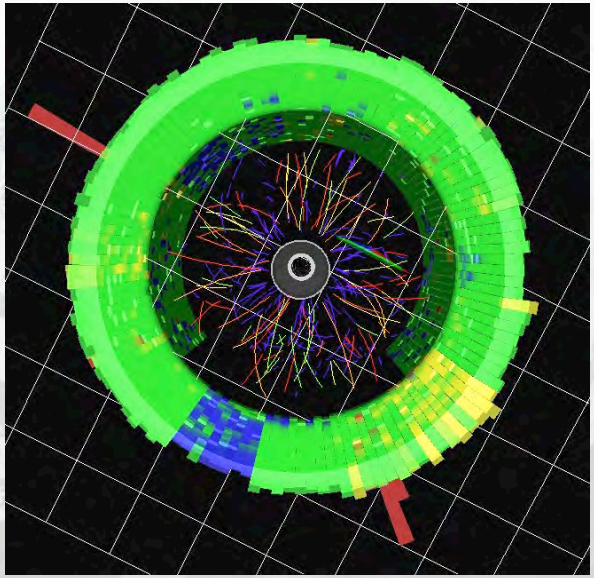
$4.0 < p_T^{trig} < 6.0$ GeV/c

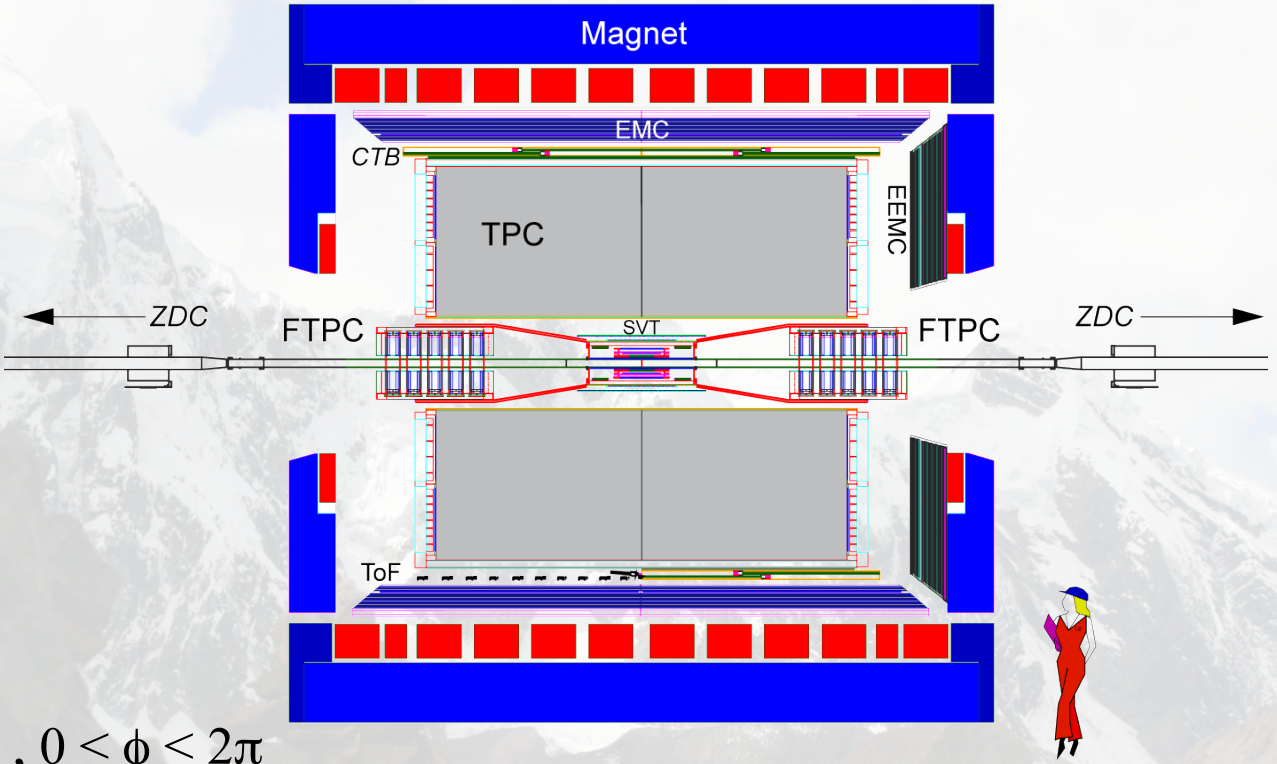


$2.0 < p_T^{assoc} < p_T(trig)$ GeV/c



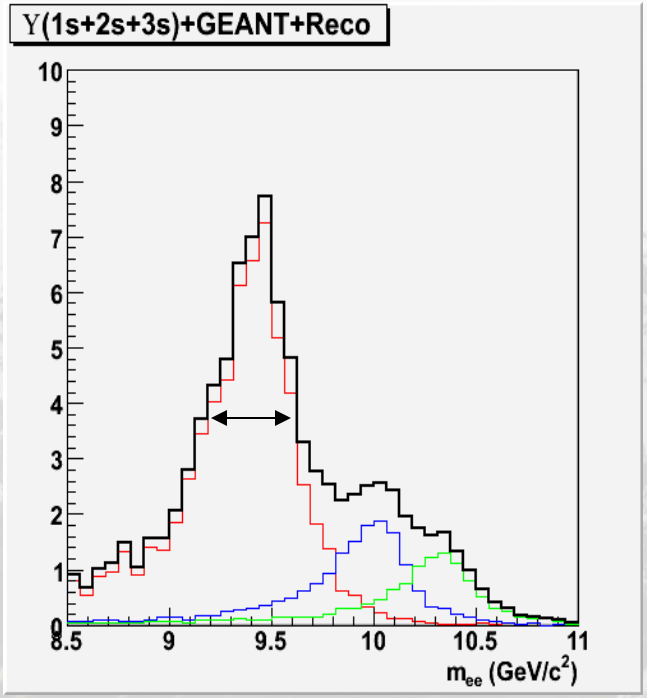
STAR Detectors Used for Υ Analysis





- EMC
  - Acceptance: $|\eta| < 1$, $0 < \phi < 2\pi$
  - PID : EMC Tower (energy) $\Rightarrow$ p/E
  - High-energy tower trigger $\Rightarrow$ enhance high-p_T sample
  - Essential for quarkonia triggers
  - Luminosity limited for Υ
- TPC
  - Tracking and dE/dx PID for electrons & positrons

ϒ Mass Resolution and expected σ

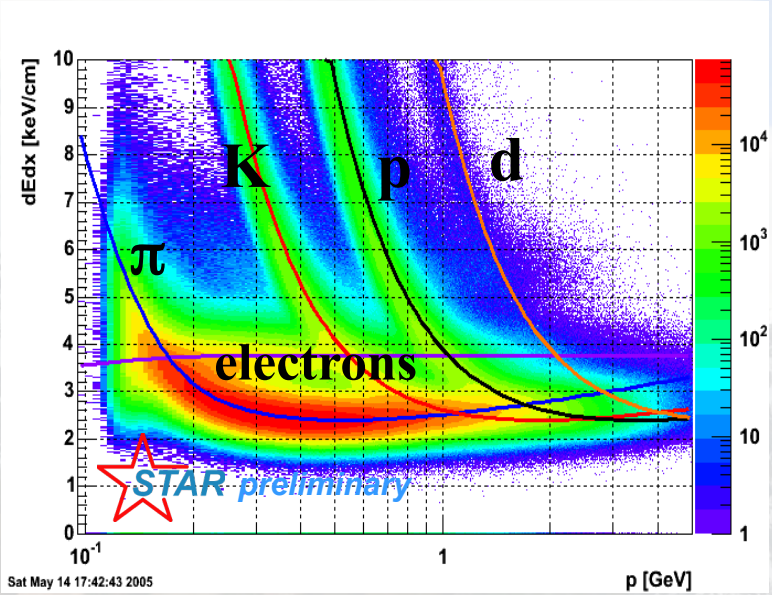


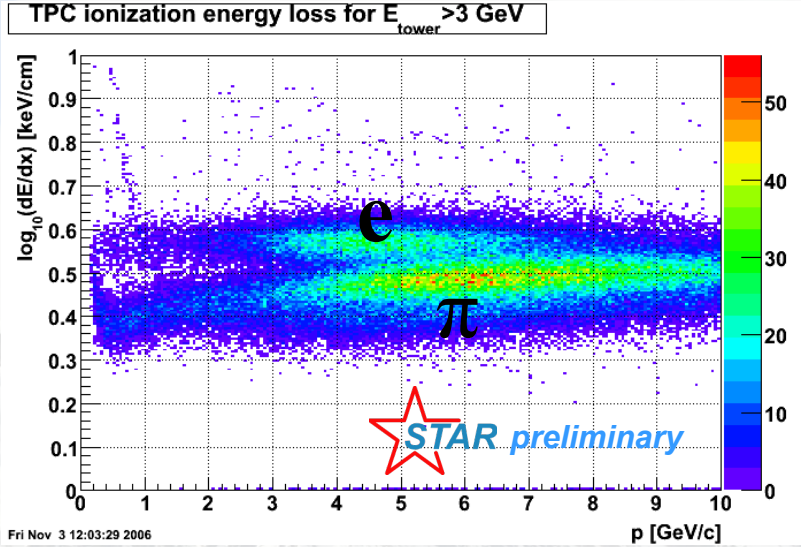
- STAR detector does not resolve individual states of the ϒ
  - Finite *p* resolution (B=0.5 T)
  - e-bremsstrahlung
- Yield is extracted from combined ϒ+ϒ′+ϒ″ states
- FWHM ≈ 0.4 GeV/c^2

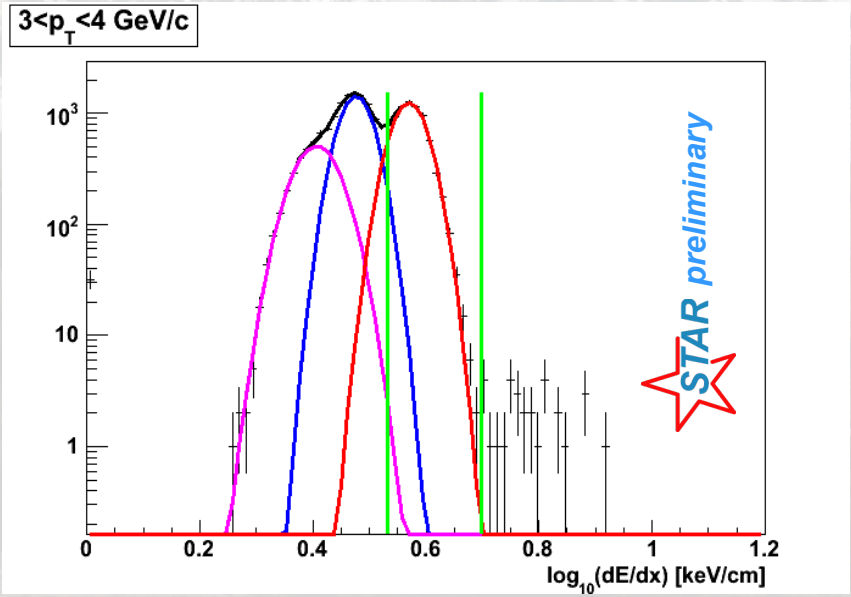
W.-M. Yao *et al*. (PDG), J. Phys. G **33**, 1 (2006);
R. Vogt *et al*., RHIC-II Heavy Flavor White Paper

State	Mass [GeV/c^2]	B_{ee} [%]	$(d\sigma/dy)_{y=0}$	$B_{ee}\times(d\sigma/dy)_{y=0}$
ϒ	9.46030	2.38	2.6 nb	62 pb
ϒ′	10.02326	1.91	0.87 nb	17 pb
ϒ″	10.3552	2.18	0.53 nb	12 pb
ϒ+ϒ′+ϒ″				91 pb

ϒ Analysis: Electron Id with TPC and EMC







- ϒ trigger enhances electrons
- Use TPC for charged tracks selection
- Use EMC for hadron rejection
- Electrons identified by dE/dx ionization energy loss in TPC
- Select tracks with TPC, match to EMC towers consistent with trigger