Quarkonia Measurements with the STAR Detector (RHIC & RHIC II)

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RHIC & AGS Users' Meeting

Why Quarkonia?

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

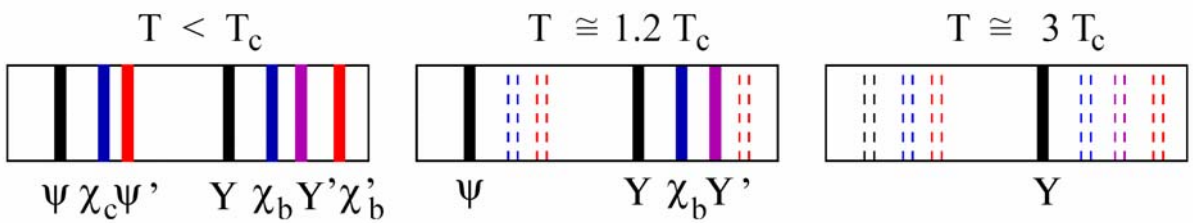
Key Idea: Melting in the plasma

- Color screening of static potential between heavy quarks:
  - J/ψ suppression: Matsui and Satz, *Phys. Lett. B* **178** (1986) 416
- Suppression of states is determined by T_C and their binding energy
- Lattice QCD: Evaluation of spectral functions ⇒ $T_{melting}$

– Sequential disappearance of states:
⇒ Color screening ⇒ Deconfinement
⇒ QCD thermometer ⇒ 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

Υ and J/ψ States in STAR

J/ψ, ψ'

- J/ψ likely to melt at RHIC
- ψ' melts at RHIC

Pros

- moderate rate
- J/ψ and ψ' can be separated

Cons

- co-mover absorption affects yield
- recombination affects yield
- trigger only in pp (still low eff.)
- moderate electron PID in J/ψ momentum range

Υ, Υ', Υ''

- Υ(1S) no melting at RHIC ⇒ standard candle (reference)
- Υ(2S) likely to melt at RHIC (analog J/ψ)
- Υ(3S) melts at RHIC (analog ψ')

Pros

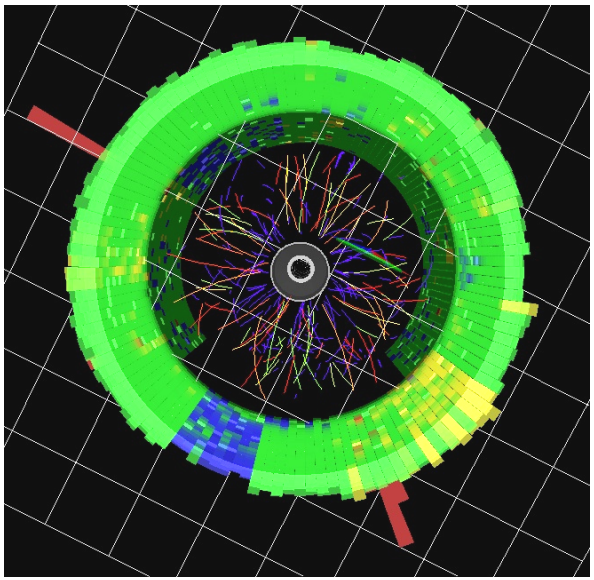
- co-mover absorption negligible
- recombination negligible at RHIC
- STAR efficient trigger and large acceptance

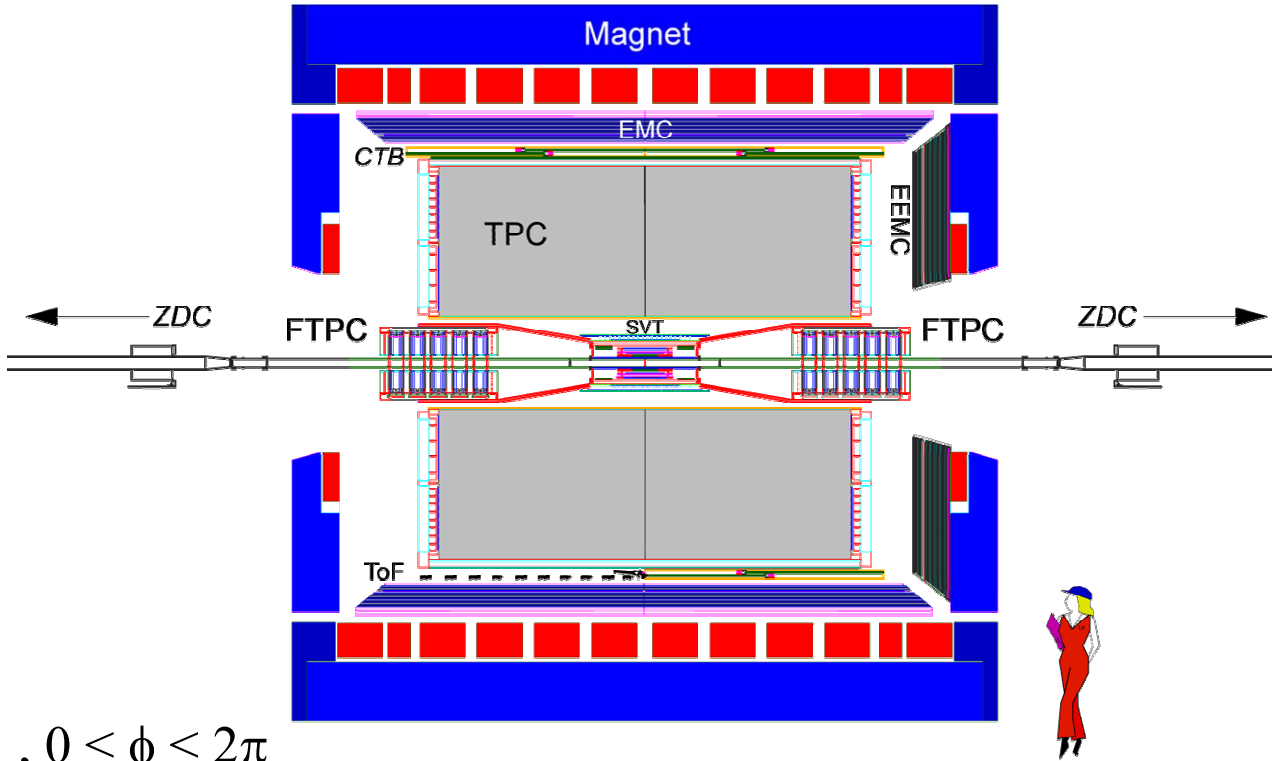
Cons

- extremely low rate
- need good resolution to separate 3 S states

⇒ STAR's strength are the Υ states

STAR Detectors Used for Quarkonia

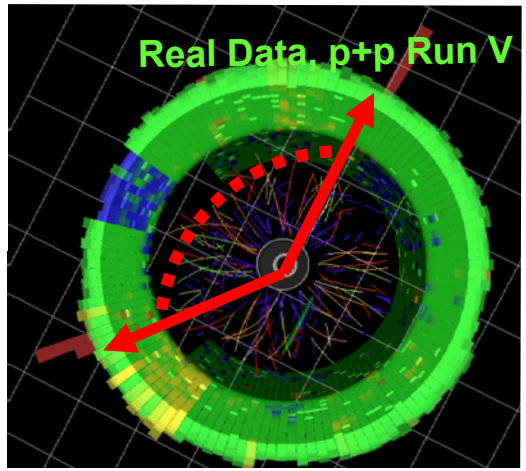


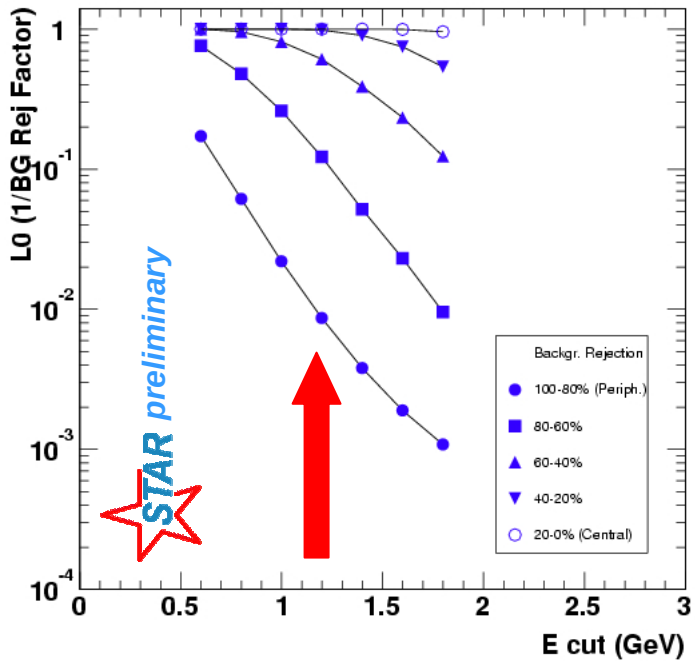


- EMC
  - Acceptance: $|\eta| < 1$, $0 < \phi < 2\pi$
  - PID with EMC detectors
    - Tower (energy) $\Rightarrow$ p/E
  - High-energy tower trigger $\Rightarrow$ enhance high-p_T sample
  - Essential for quarkonia triggers
  - Luminosity limited for Υ

STAR J/ψ Trigger

- L0 (hardware)
  - J/ψ topology trigger: two towers above $E_T \approx 1.2$ GeV
  - Separated by 60° in φ
- L2 (software)
  - Match EMC high tower to CTB slat ⇒ photon rejection
  - Tower clustering
  - Cut on $m_{ee}=\sqrt{2E_1E_2(1-\cos\theta)}$
  - Cut on cosθ
- High background contamination ~1.5 GeV/c
- Rejection ~ 100 ⇒ not sampling full luminosity
- Challenging analysis!!!
- Efficiency × acceptance ≈ 12%

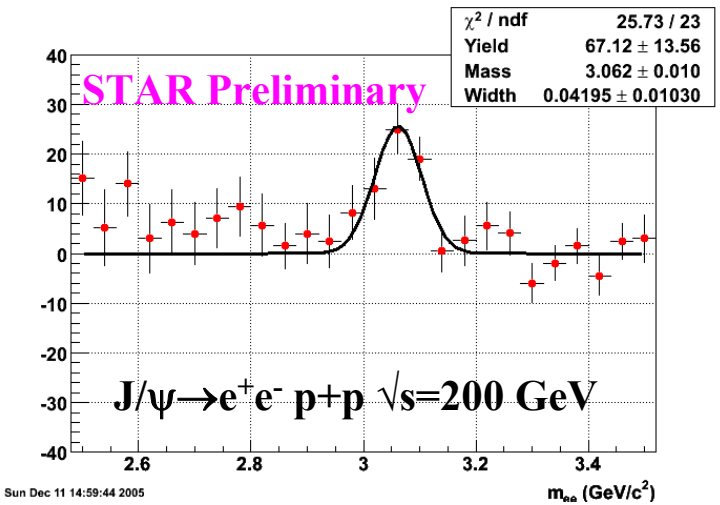


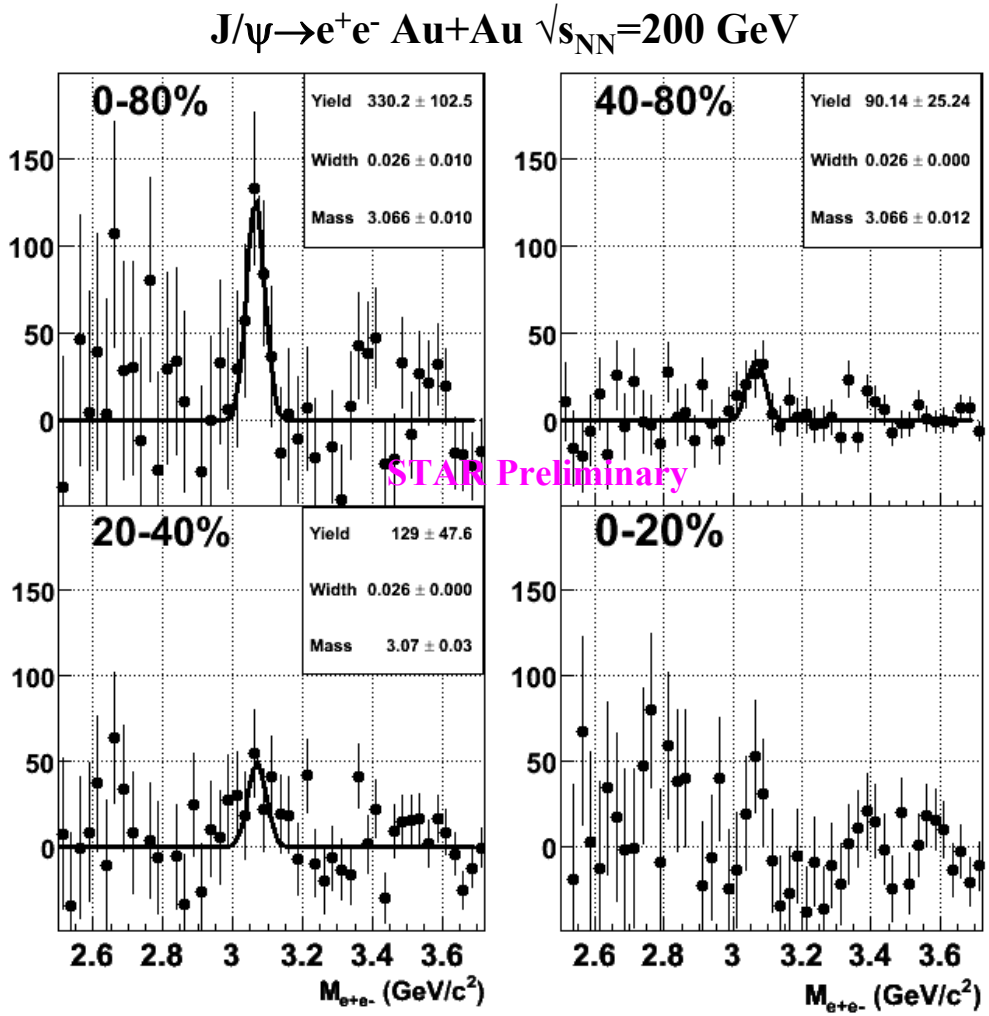


STAR J/ψ Signal

- Signal in 200 GeV p+p from 2005
  - Tested and working trigger in p+p
  - No trigger for AuAu until full ToF in 2009
- Also signal in Au+Au with TPC only
  - Large hadron contamination
  - Need full EMC

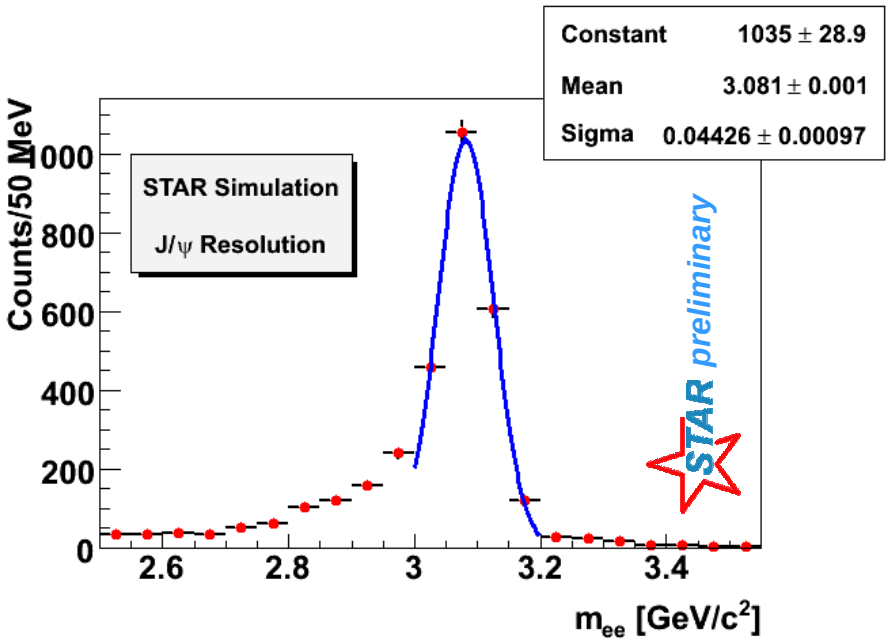
Johann Gonzalez

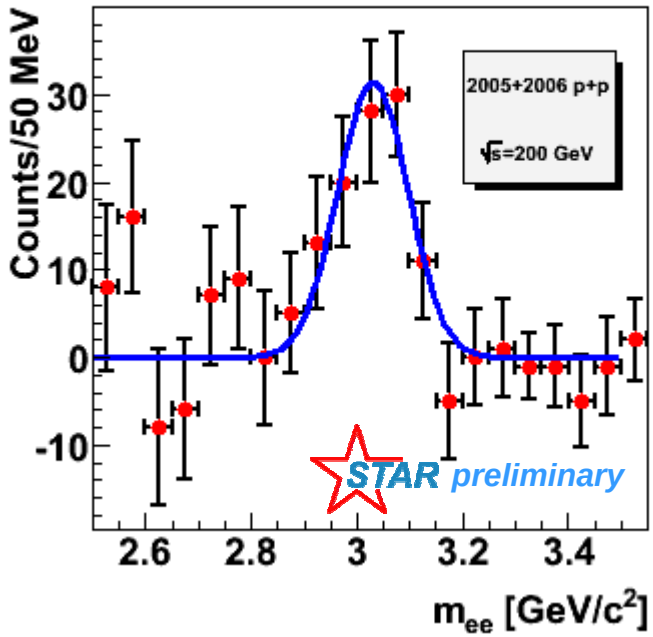




STAR J/ψ Signal

- Signal in 200 GeV p+p from 2006
- Integrated luminosity in Run 6 ~ 377 nb^{-1}

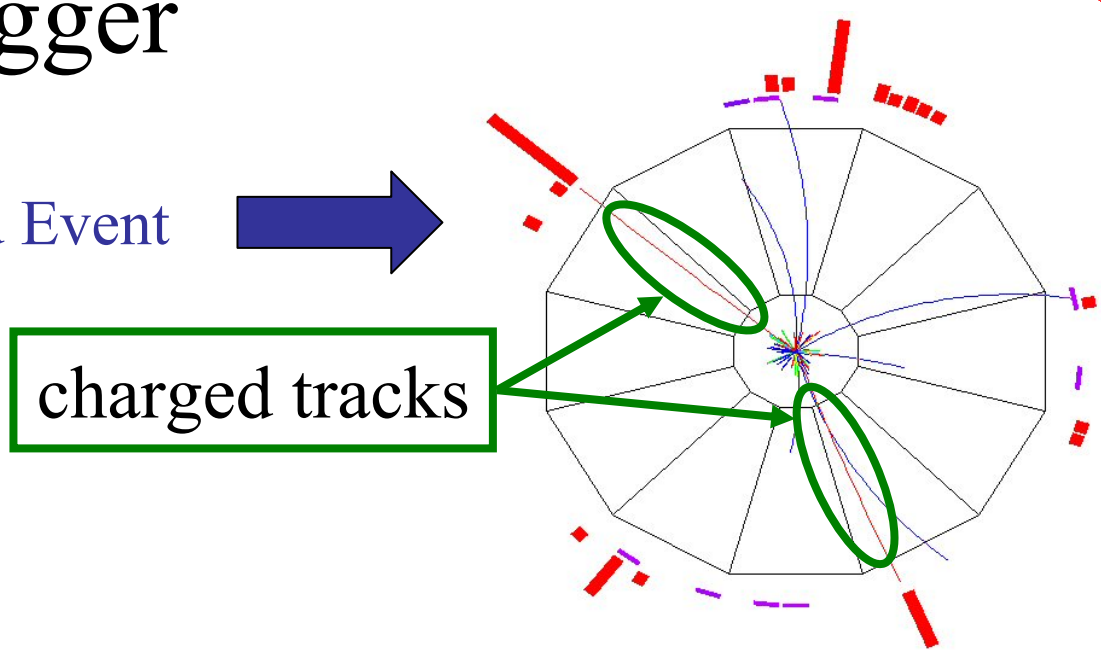




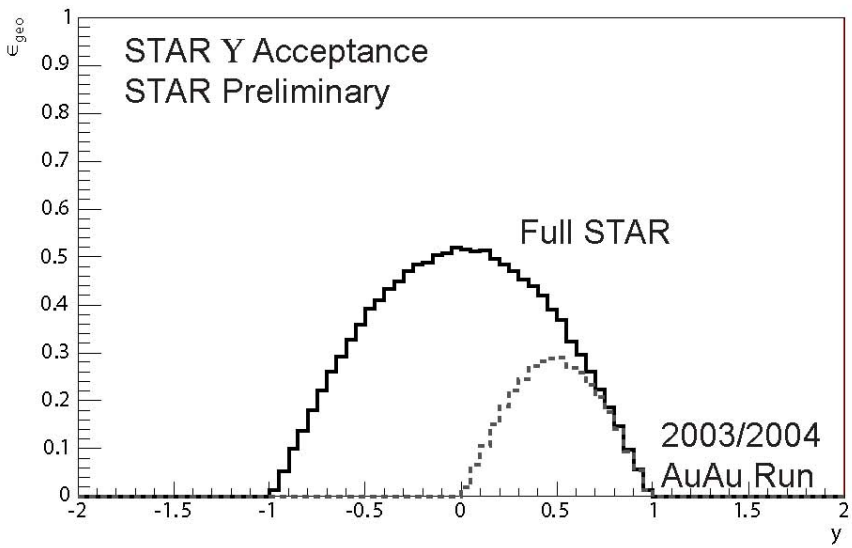
STAR ϒ Trigger

Sample ϒ-triggered Event

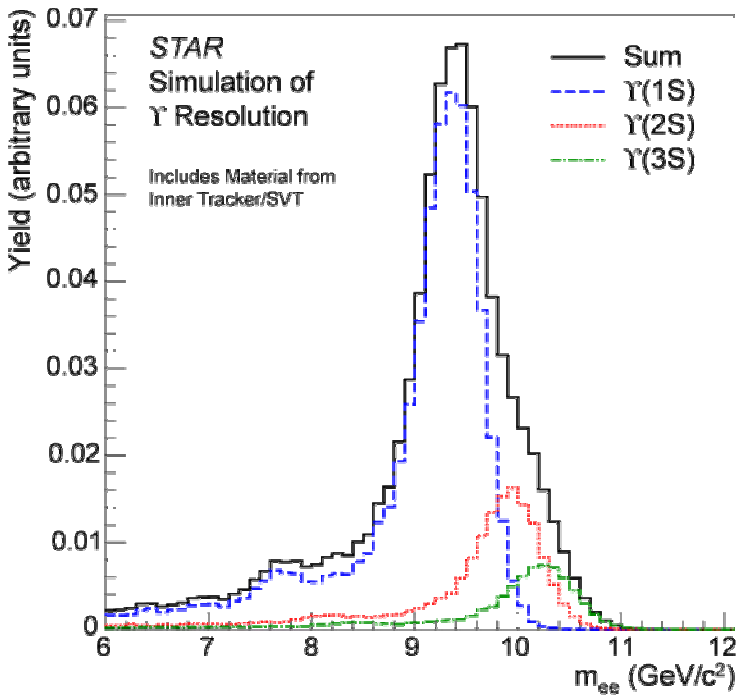
- $\Upsilon \rightarrow e^+e^-$
- $m_{ee} = 9.5\ GeV/c^2$
- $\cos\theta = -0.67$
- $E_1 = 5.6\ GeV$
- $E_2 = 3.4\ GeV$



- Similar L0+L2 triggers
  - Higher mass state ⇒ higher energy threshold
  - Pros: Easier and cleaner to trigger
  - Cons: Small yield; need large luminosity and acceptance
- Full EMC acceptance $|\eta|<1$ in Run 6
- Integrated luminosity ≈ 9 pb^{-1} in Run 6



STAR ϒ Mass Resolution



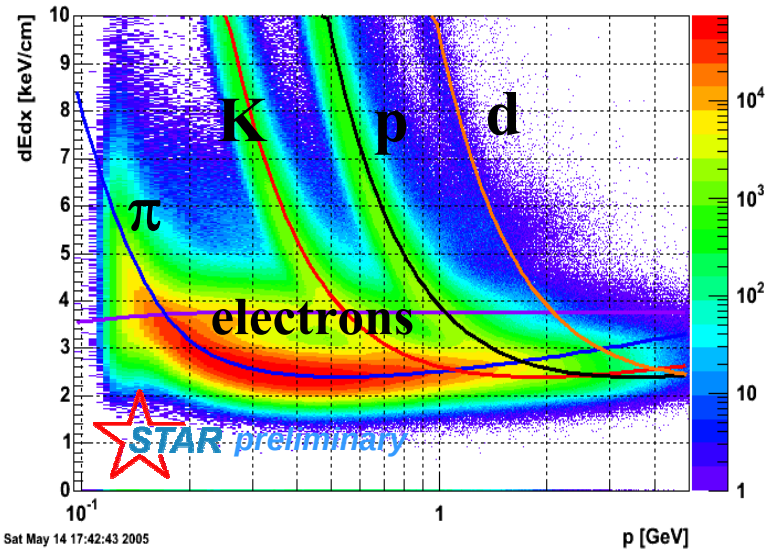
- STAR detector does not resolve individual states of the ϒ
  - Finite p resolution
  - e-bremsstrahlung
- Yield is extracted from combined ϒ+ϒ′+ϒ″ states
- FWHM ≈ 1 GeV/c^2

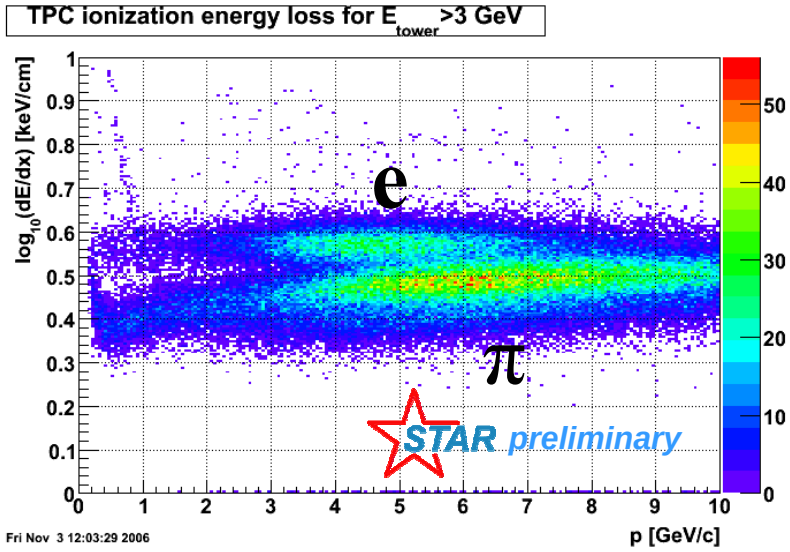
W.-M. Yao *et al.* (PDG), J. Phys. G **33**, 1 (2006);
R. Vogt *et al.*, RHIC-II Heavy Flavor White Paper

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

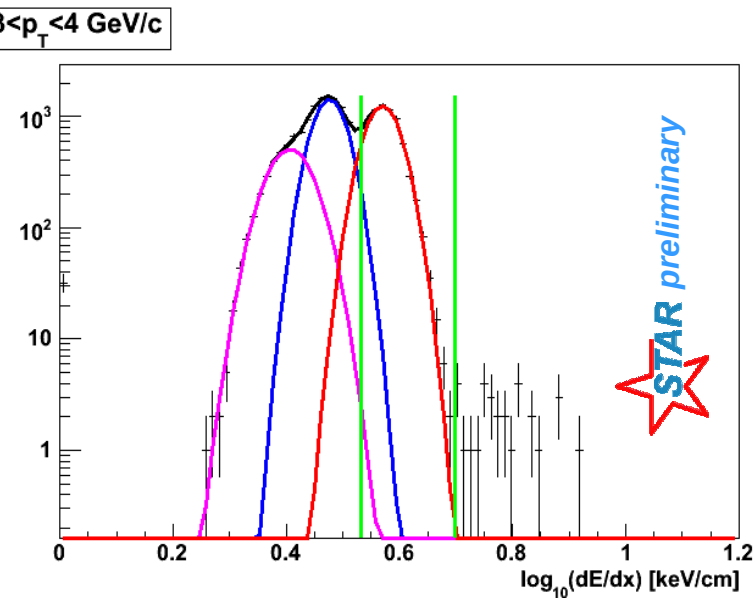
ϒ Analysis: Electron ID with TPC and EMC

A. Knopse



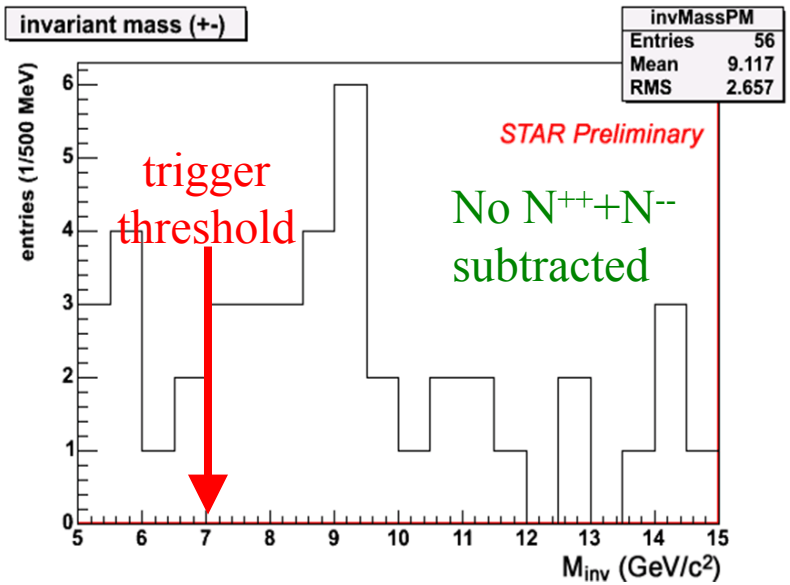


- ϒ trigger enhances electrons
- Use TPC for charged tracks selection
- Use EMC for hadron rejection
- Electrons identified by dE/dx ionization energy loss in TPC
- Select tracks with TPC, match to EMC towers above 3 GeV

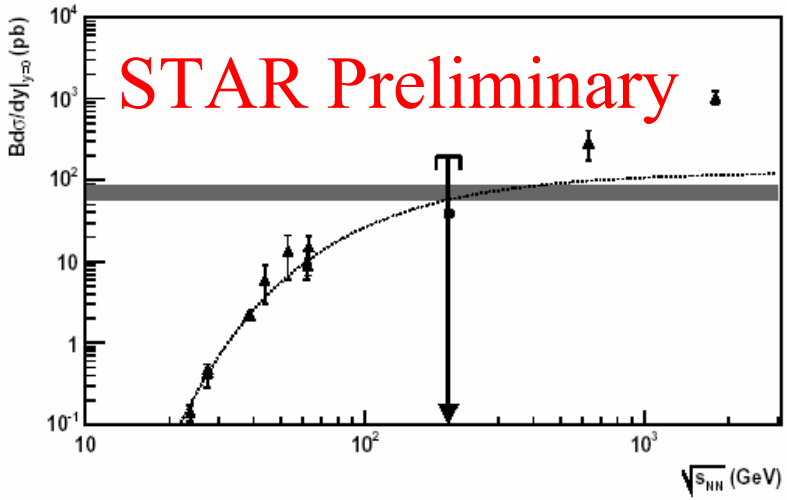


Υ in Run 4 Au+Au at $\sqrt{s_{NN}}$=200 GeV

- Cannot resolve different S states ⇒ $\Upsilon(1S+2S+3S) \rightarrow e^+e^-$
- STAR
  - Large acceptance ($|\eta| < 1$, full EMC)
  - PID for electrons (EMC, TPC)
  - Trigger
    - Very efficient > 80%
  - Luminosity limited



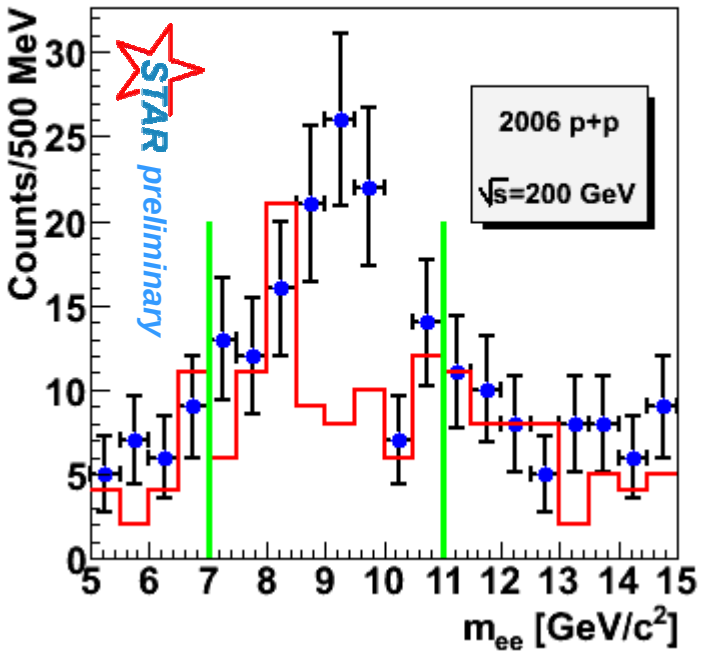
Thorsten Kollegger

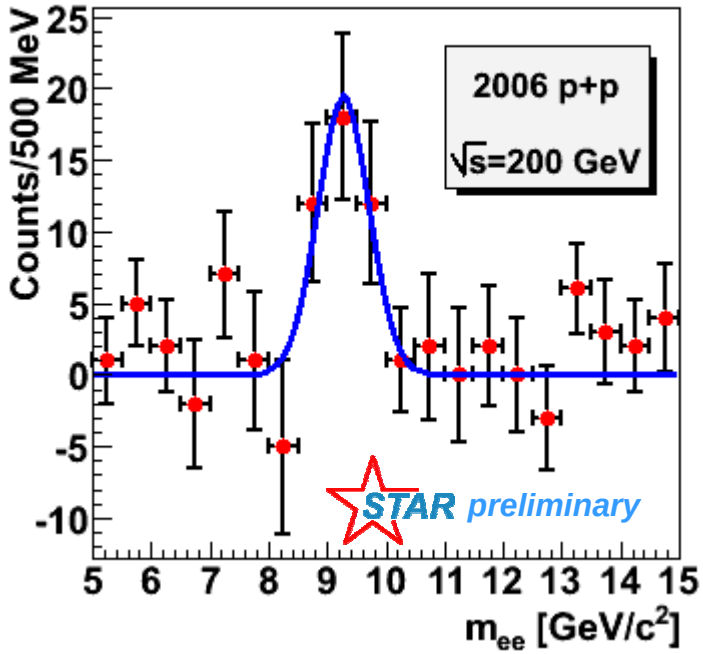


Scaling from Au+Au to elementary: α=1

- First look in 2004: ½ EMC, little statistics
- 90% C.L.: signal < 4.91
- B·dσ/dy C.L. < 7.6 μb

ϒ in Run 6 p+p at √s=200 GeV: Invariant Mass

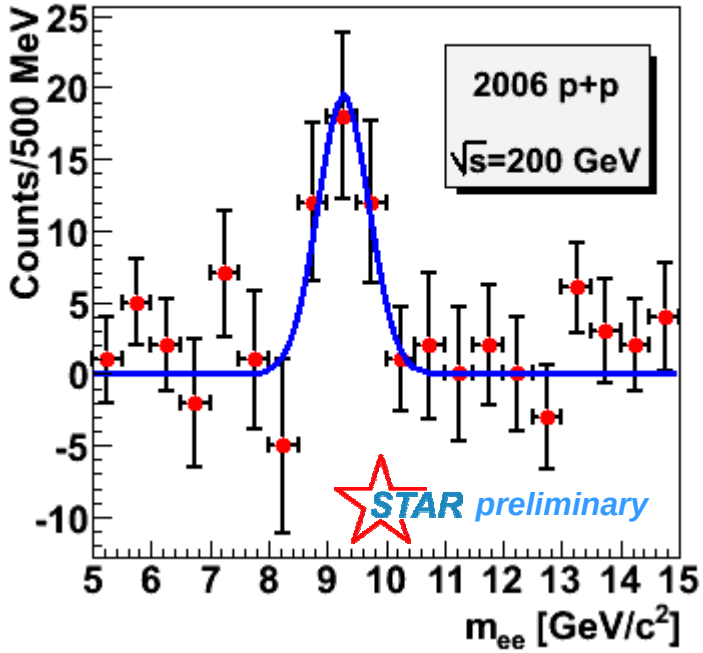




- Signal + Background ⇒ unlike-sign electron pairs
- Background ⇒ like-sign electron pairs
  - ϒ(1S+2S+3S) total yield: integrated from 7 to 11 GeV from background-subtracted m_{ee} distribution
- Peak width consistent with expected mass resolution
- Significance of signal is 3σ

Υ in Run 6 p+p at √s=200 GeV: Cross Section

$$B_{ee} \times \left(\frac{d\sigma}{dy} \right)_{y=0} = \frac{N_{\Upsilon}}{dy \times \varepsilon_{\Upsilon} \times \int \mathcal{L} dt}$$



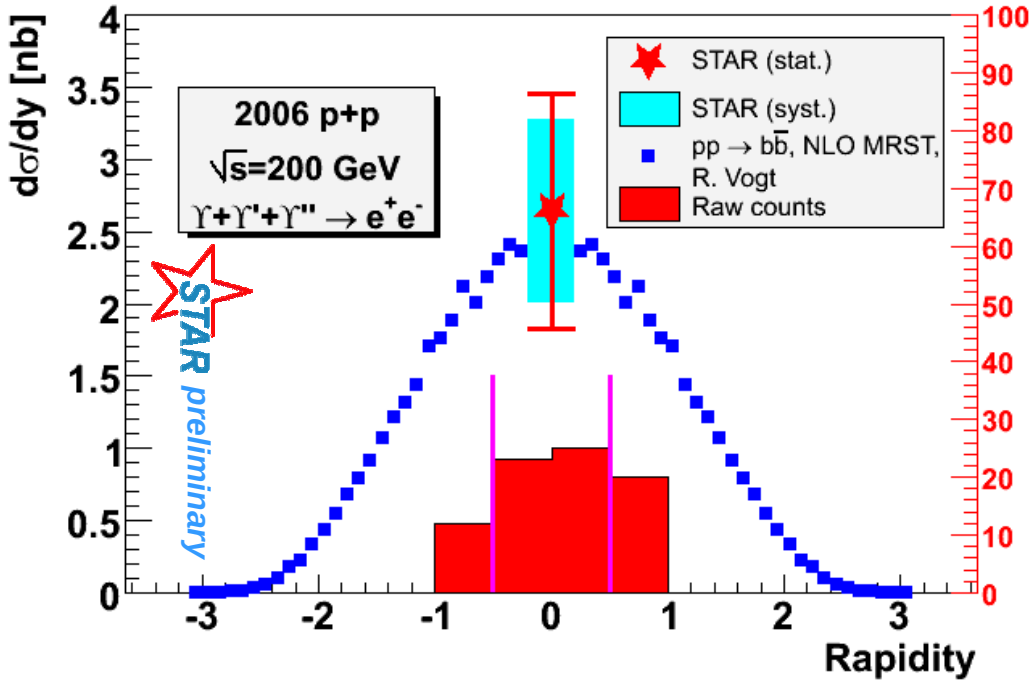
$\varepsilon_{\Upsilon} = \varepsilon_{geo} \times \varepsilon_{L0} \times \varepsilon_{L2} \times \varepsilon^2(e) \times \varepsilon_{mass}$

ε_{geo}	0.263±0.019
ε_{L0}	0.928±0.049
ε_{L2}	0.855±0.048
$\varepsilon^2(e)$	0.47±0.07
ε_{mass}	0.96±0.04
ε_{Υ}	**0.094±0.018**

- ε_{geo} is geometrical acceptance
- ε_{L0} is efficiency of L0 trigger
- ε_{L2} is efficiency of L2 trigger
- $\varepsilon(e)$ is efficiency of e reco
- ε_{mass} is efficiency of mass cut

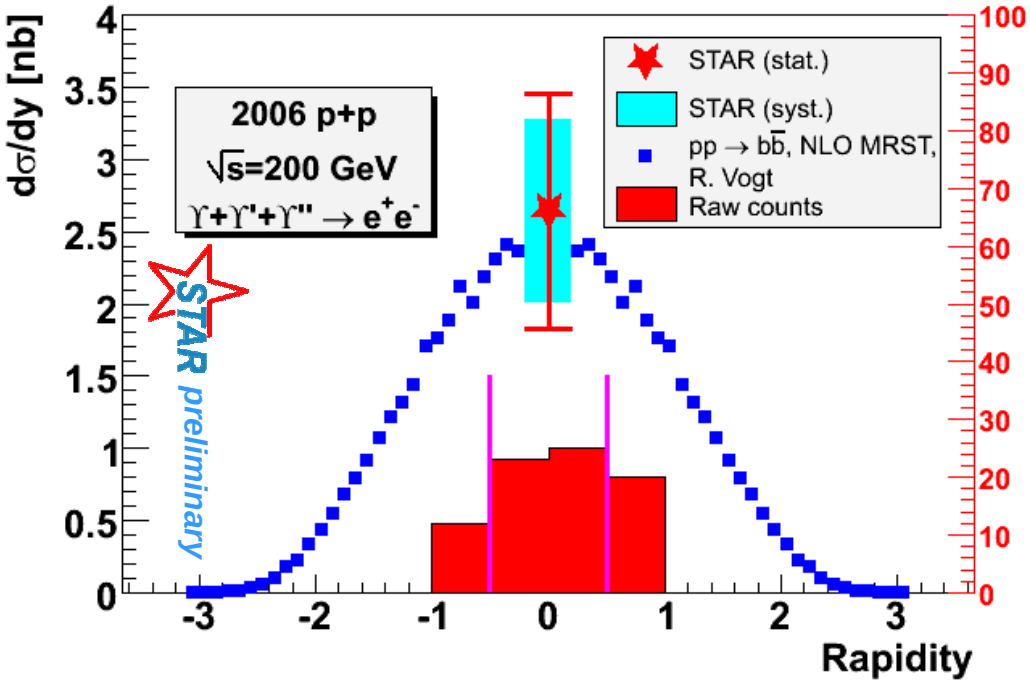
STAR Run 6 ϒ Cross Section in p+p at Midrapidity at √s=200 GeV

N_Υ	48±15(stat.)
ε_Υ	0.094±0.018
$\int \mathcal{L} dt$	(5.6±0.8) pb^{-1}
dy	1.0

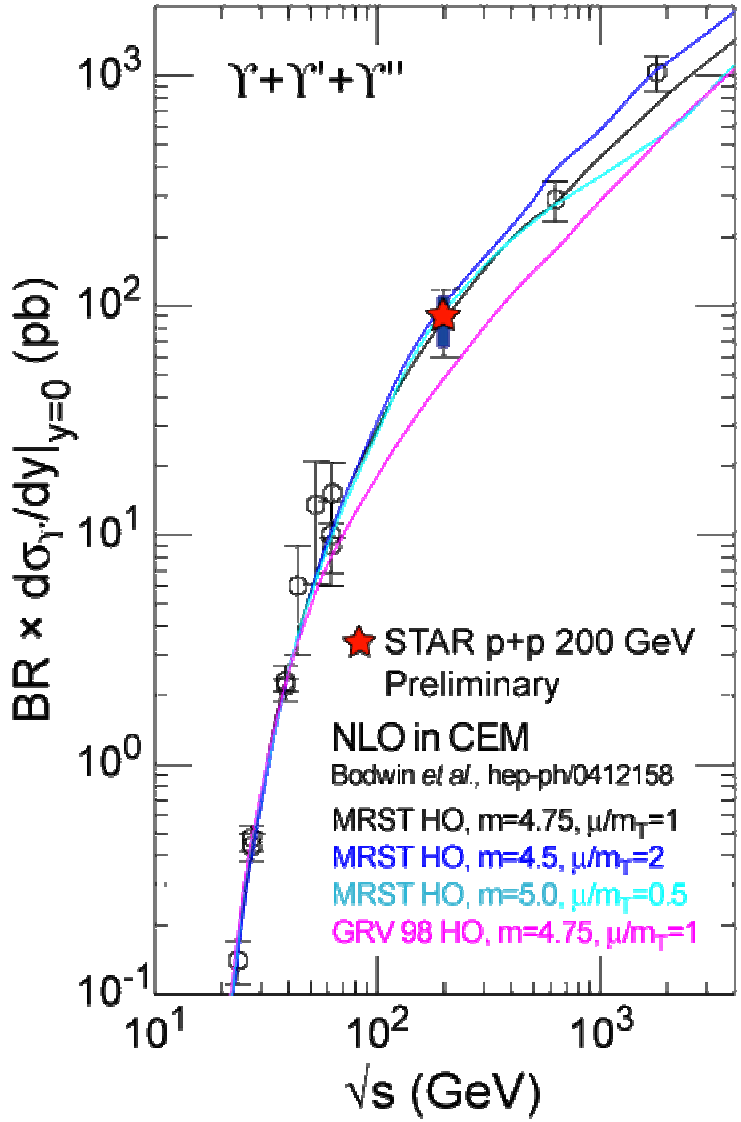


$$B_{ee} \times \left(\frac{d\sigma}{dy} \right)_{y=0}^{Y+Y'+Y''} = 91 \pm 28\,(stat.) \pm 22\,(syst.)\,pb$$

STAR Υ *vs.* theory and world data



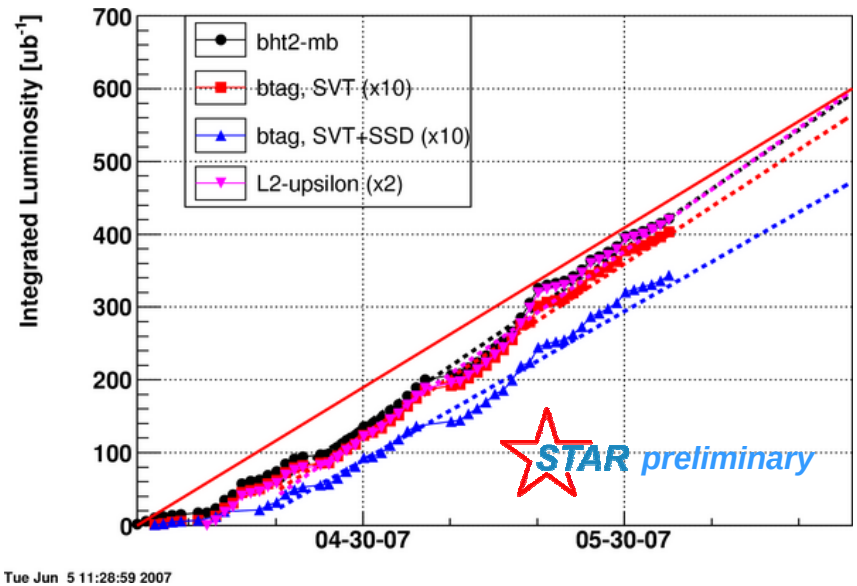
$$B_{ee} \times \left(\frac{d\sigma}{dy}\right)_{y=0}^{\Upsilon+\Upsilon'+\Upsilon''} = 91 \pm 28(\text{stat.}) \pm 22(\text{syst.})\ \text{pb}$$



STAR 2006 √s=200 GeV p+p Υ+Υ′+Υ″→e^+e^- cross section consistent with pQCD and world data

Run 7 Au+Au at $\sqrt{s_{NN}}$=200 GeV Υ Trigger Integrated Luminosity

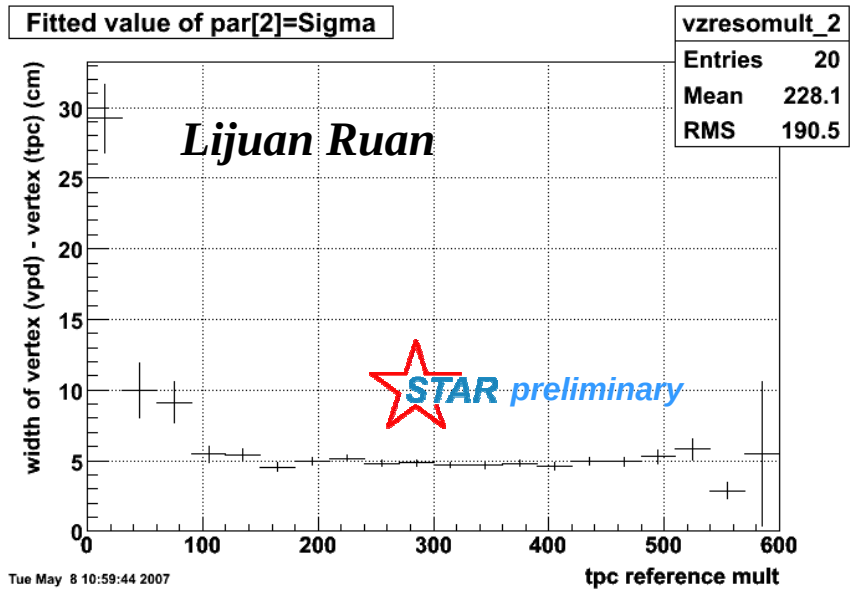
James Dunlop

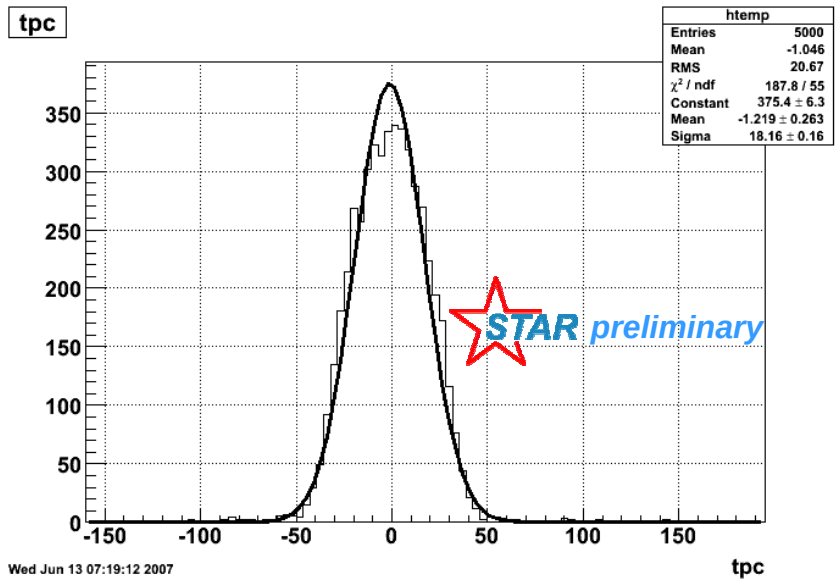


- Goal ~ 300 μb^{-1} for Run 7
- L2-upsilon integrated luminosity ~ 210 μb^{-1} per 6/5/2007
- ~37 Υ expected at y=0 for $|y|<0.5$ or ~70 Υ for $|y|<1$. Assume:
  - S/B=48/83 $\Rightarrow$ significance 3.3σ from 2006 p+p at $\sqrt{s}$=200 GeV
  - Binary scaling and nuclear effects $\Rightarrow \sigma_{AB}=\sigma_{pp}(AB)^{\alpha}$

Vertex Position Detector in Run 7

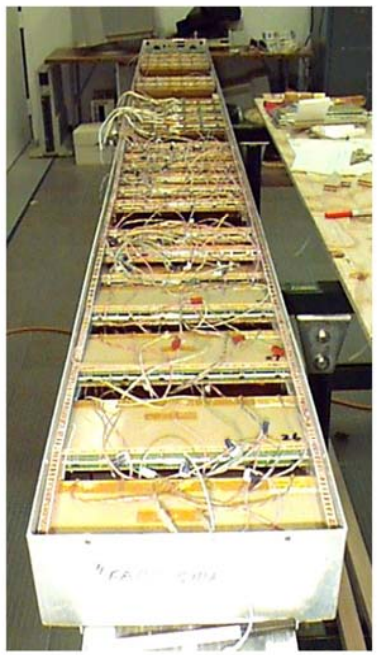
- First time ϒ trigger uses VPD
- Mostly to reduce rate
- Helps restrict ϒ to low material region
- Vertex resolution ~ 5 cm in central collisions
- Offline TPC vertex σ ~ 18 cm

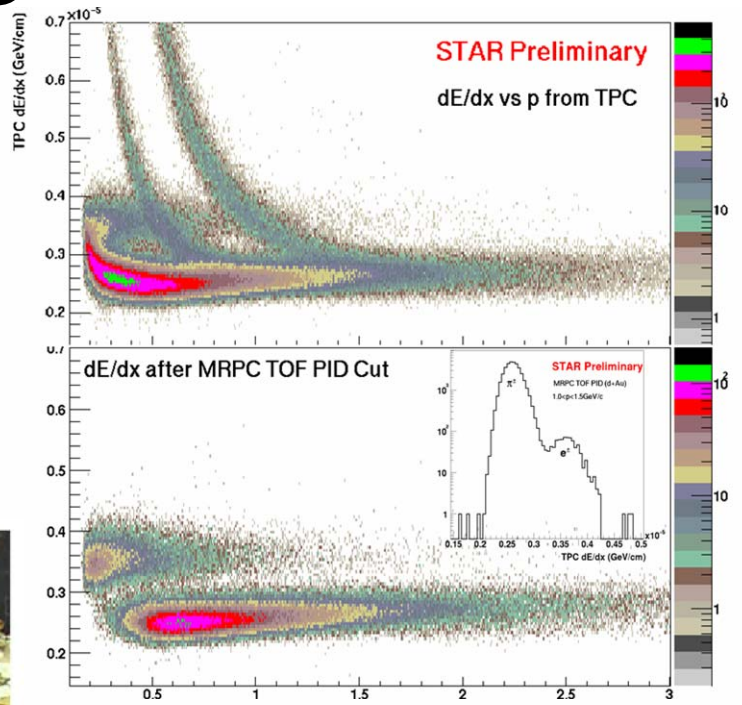


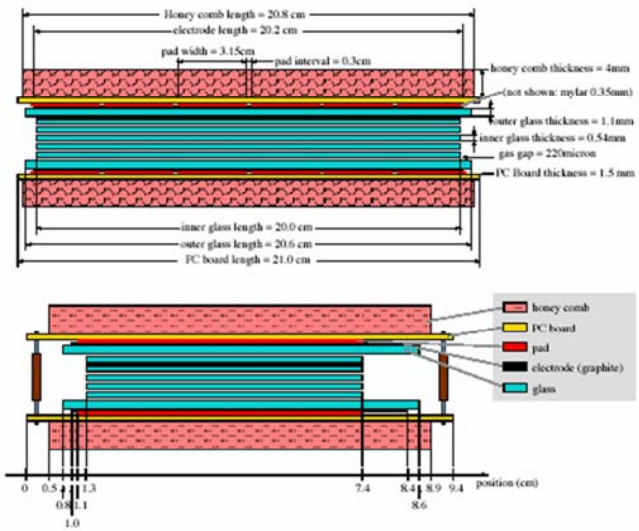


Full Barrel Time-of-Flight Detector

- **Parameter:**
  - State-of-the-art Multi-Gap Resistive Plate Chamber
  - $-0.9<\eta<0.9$, $0<\phi<2\pi$
  - 6 gap, 3×6 cm^2 pad, 23,000 channels
  - Most important USA-China collaborative effort to date in HEP detector research
- **Status:**
  - Run 8 ~ 11 trays
  - Run 9 ~ 65 trays (half detector)
  - Run 10 ~ 120 trays (full detector)
- **Impact on Heavy Flavor:**
  - Excellent Electron ID (J/ψ range $0.2<p<4$ GeV/c)
  - J/ψ trigger in Au+Au
  - Low-p_T μ ID (0.2 GeV/c)

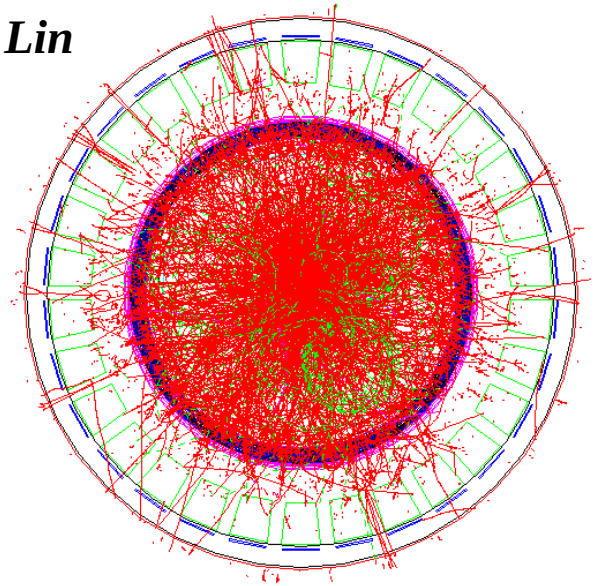




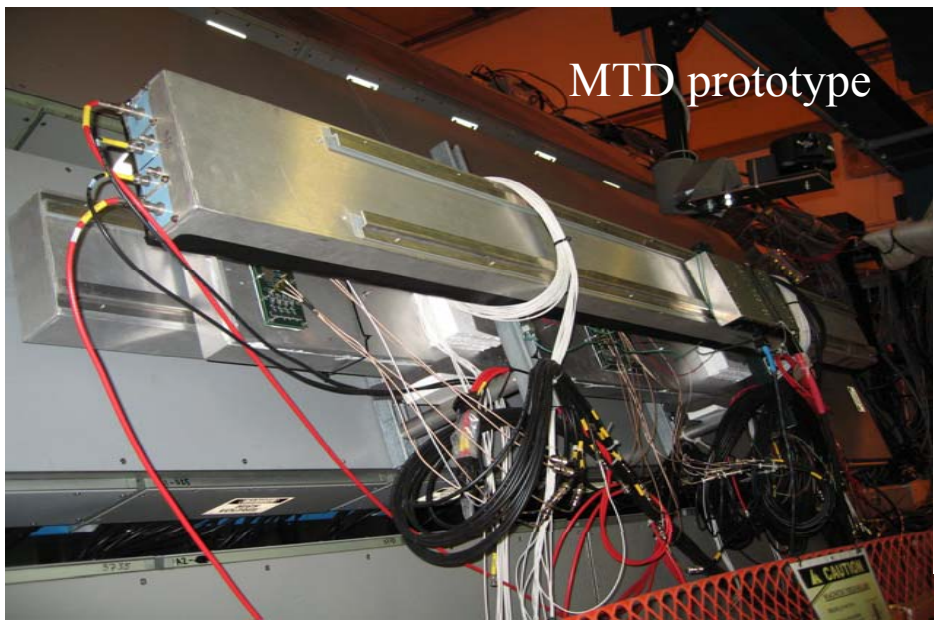


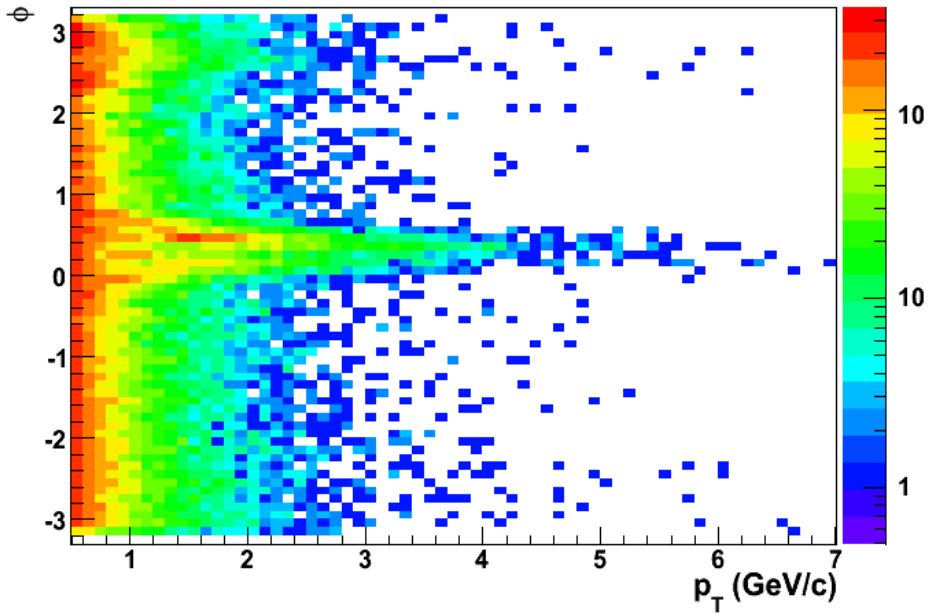
The Muon Telescope Detector

Guoji Lin



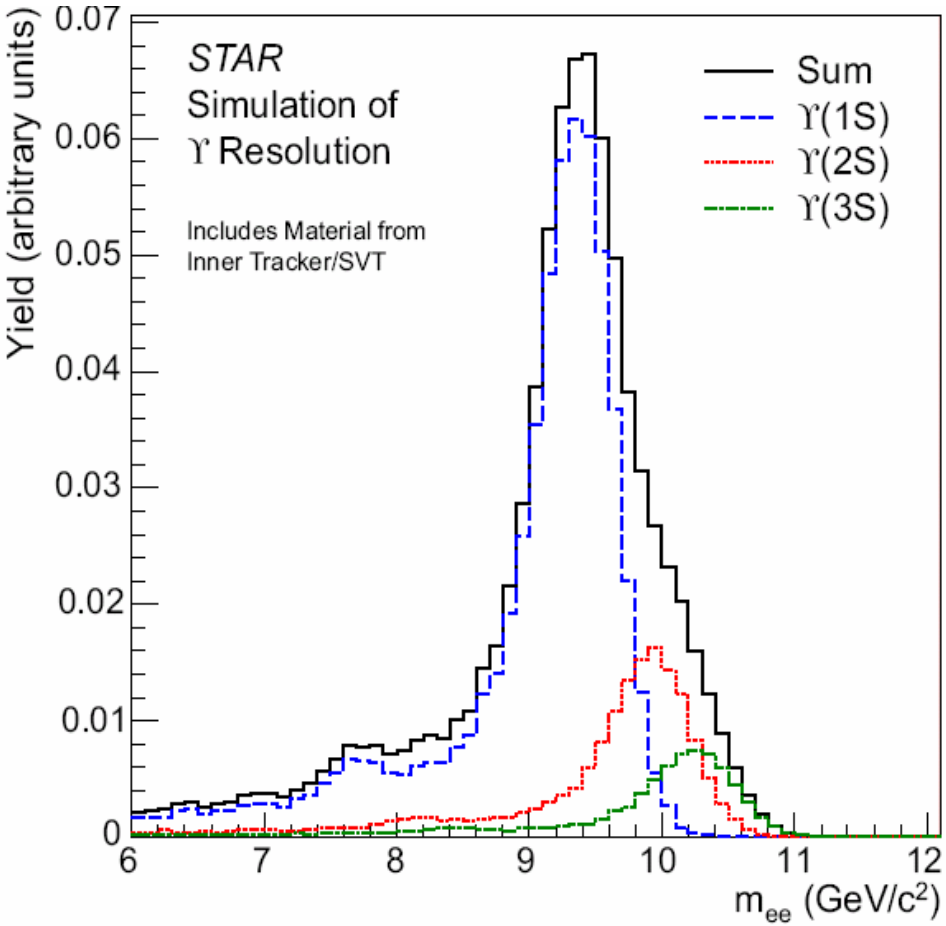
- Muons penetrate iron bars; other particles are stopped
- Timing resolution ~60 ps
- Background rejection >100
- No γ conversion
- Suppressed Dalitz decays
- Online trigger possible in Au+Au central collisions
- Enhancement of high-p_T particles





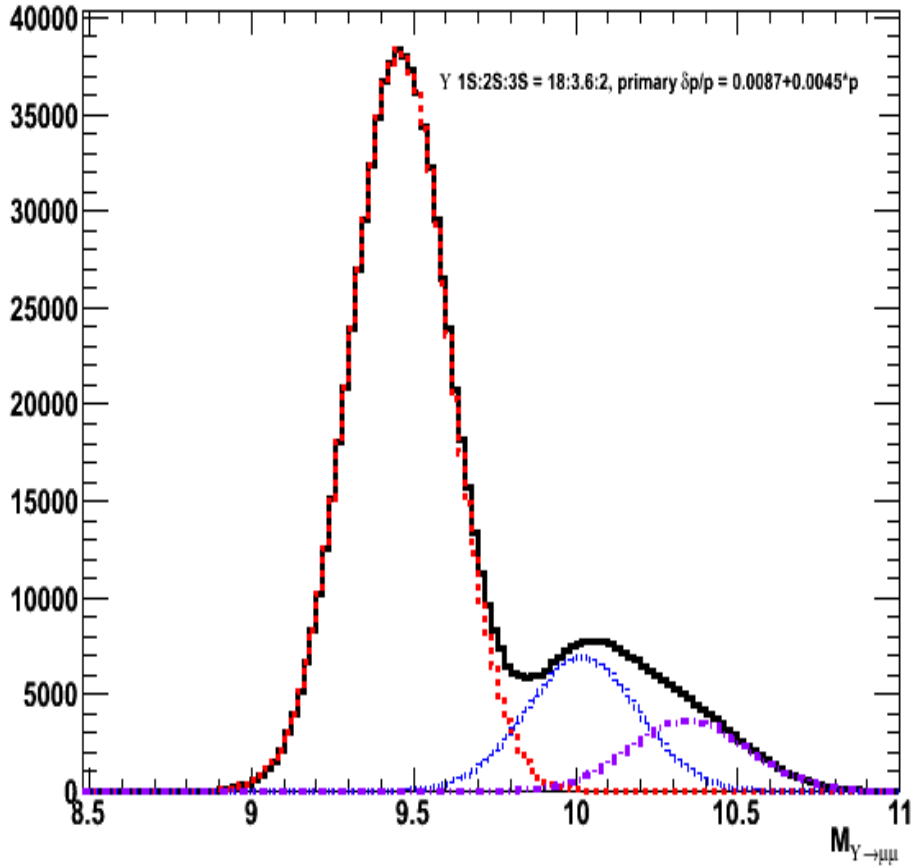
Separation of ϒ States

Manuel Calderon



- $\Upsilon \rightarrow e^+e^-$
- Resolution degraded by electron bremsstrahlung

Guoji Lin

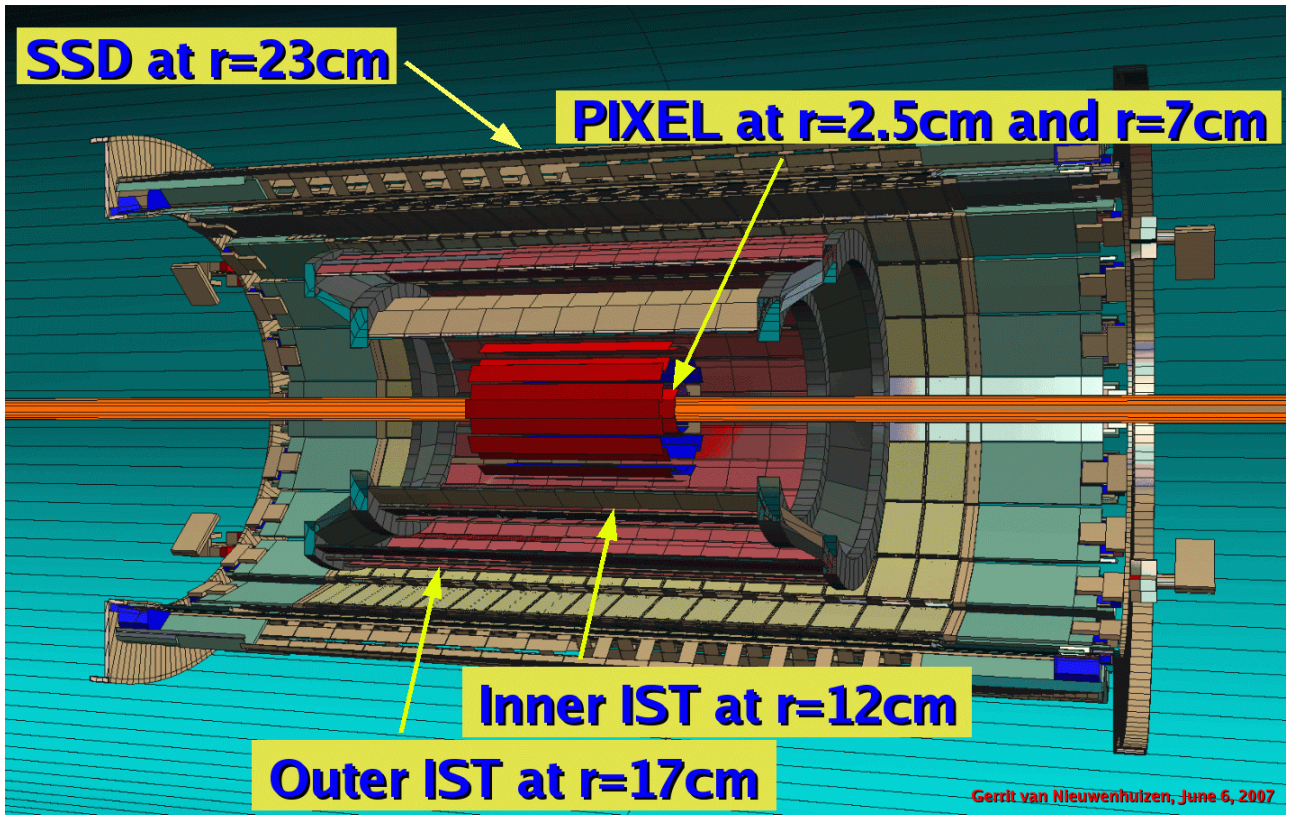


- $\Upsilon \rightarrow \mu^+\mu^-$
- Able to resolve different S states

Inner Tracking Detectors

F. Videbaek

- Relies on TPC-SSD-IST-PIXEL tracking for graded point matching and resolution
- Essential for direct D^0 topological reconstruction
- Distinction between $B \rightarrow J/\psi$ and prompt J/ψ



RHIC-I & RHIC-II STAR Projections

- 12 weeks of running
- Heavy Flavor Tracking with vertex ±10 cm

RHIC weekly luminosity

Species	RHIC-I (current)	RHIC-I (projected)	RHIC-II (projected)
p+p	0.9 pb^{-1}	26 pb^{-1}	33 pb^{-1}
Au+Au	160 μb^{-1}	327 μb^{-1}	2,500 μb^{-1}

STAR Quarkonia Yields

Species	Signal $\|\eta\|<1$	RHIC-I	RHIC-II
p+p	$J/\psi \rightarrow e^+e^-$	1,260,000	1,600,000
	$\Psi' \rightarrow e^+e^-$	23,000	29,000
	$\Upsilon \rightarrow e^+e^-$	6,600	8,300
Au+Au	$J/\psi \rightarrow e^+e^-$	16,000	220,000
	$\Psi' \rightarrow e^+e^-$	300	4,000
	$\Upsilon \rightarrow e^+e^-$	830	11,200

http://rhicii-science.bnl.gov/heavy/

Medium term upgrades:

- Replacement of CTB with ToF
- New TPC FEE
- DAQ-1000
- Heavy Flavor Tracking

Summary and Outlook

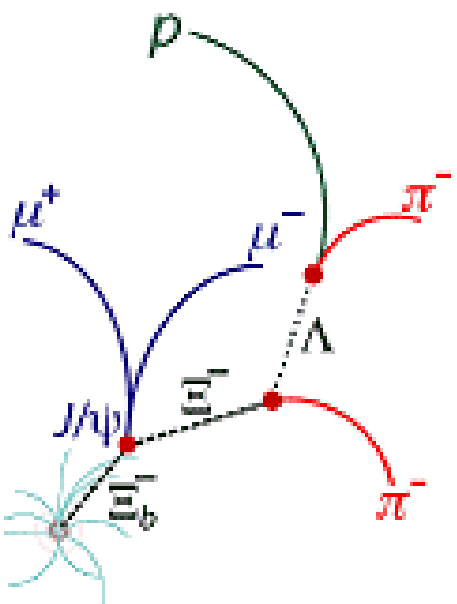
- Full EMC + trigger $\Rightarrow$ quarkonium program in STAR
- Run 6: first midrapidity measurement of $\Upsilon+\Upsilon'+\Upsilon'' \rightarrow e^+e^-$ cross section at RHIC in p+p collisions at $\sqrt{s}$=200 GeV
  - $B_{ee} \times (d\sigma/dy)_{y=0} = 91 \pm 28(stat.) \pm 22(syst.)$ pb
  - STAR Υ in p+p measurement is consistent with pQCD and world data
- Run 7: expect Υ cross section at midrapidity in Au+Au collisions at $\sqrt{s}$=200 GeV (37-70 Υ raw yield) and better J/ψ measurement from minimum bias dataset
- Near term STAR detector upgrades (ToF, MTD, HFT) and RHIC & RHIC II luminosity improvements will significantly benefit the STAR quarkonium program by opening up other decay channels ($\mu^+\mu^-$) and making feed-down discrimination possible

Extra Slides

Fermilab physicists discover "triple-scoop" baryon

http://www.fnal.gov/pub/presspass/press_releases/Dzero_baryon.html

arXiv:0706.1690v2 [hep-ex]



Three-quark particle contains one quark from each family.

Batavia, Ill. - Physicists of the DZero experiment at the Department of Energy's Fermi National Accelerator Laboratory have discovered a new heavy particle, the Ξ_b (pronounced "zigh sub b") baryon, with a mass of 5.774±0.019 GeV/c^2, approximately six times the proton mass. The newly discovered electrically charged Ξ_b baryon, also known as the "cascade b," is made of a down, a strange and a bottom quark. It is the first observed baryon formed of quarks from all three families of matter. Its discovery and the measurement of its mass provide new understanding of how the strong nuclear force acts upon the quarks, the basic building blocks of matter…