Heavy Quarkonia Measurements with STAR

Thomas Ullrich for the STAR Collaboration

January 5, 2011

International Workshop on Heavy Quark Production in Heavy-ion Collisions

Purdue University

Office of Science
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY

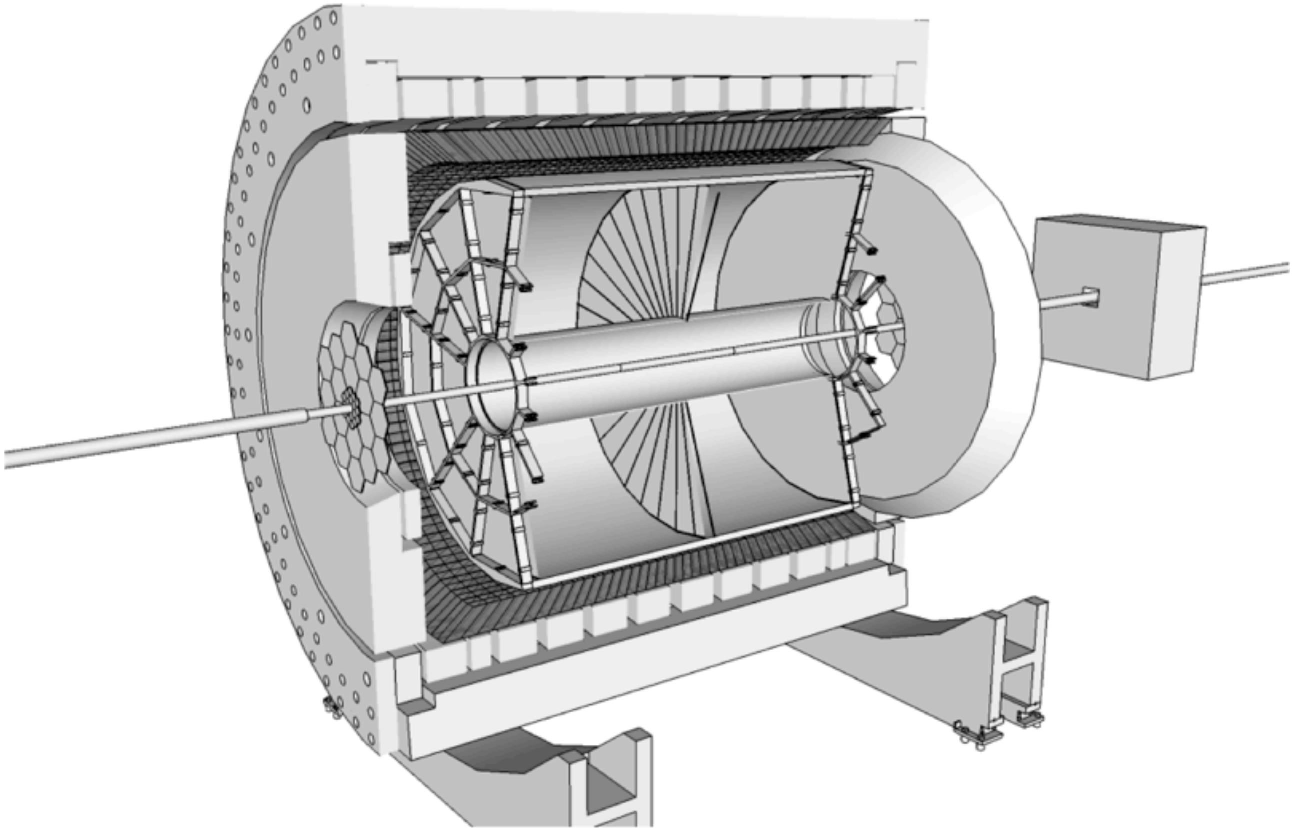
STAR Detector & Analysis Techniques

Upfront

STAR's Quarkonium Program (for now):

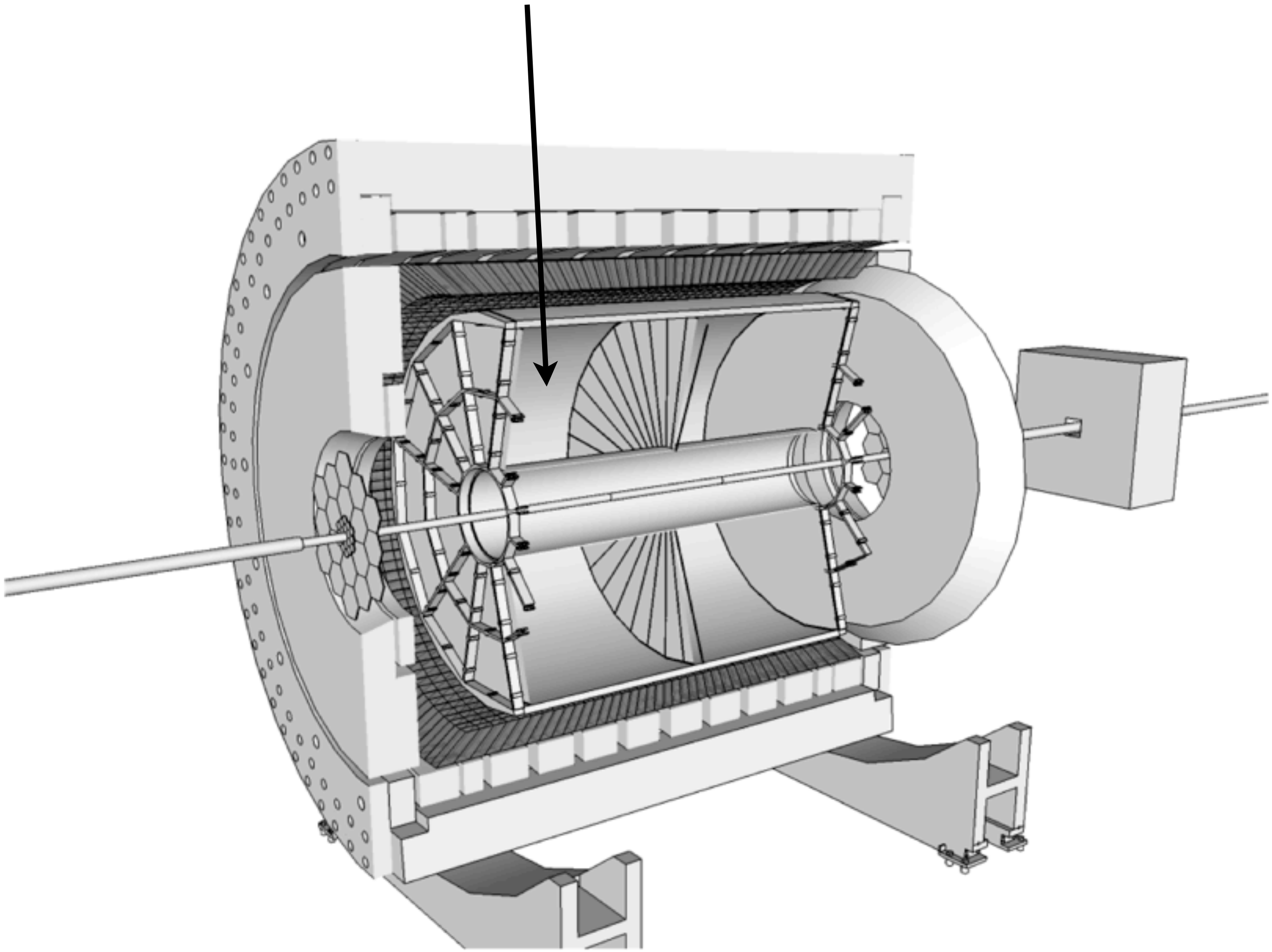
- Golden channel for Quarkonia is $\bar{Q}Q \rightarrow e^+e^-$
- Strength:
  - Υ measurements over all p_T
  - J/ψ measurements at high-p_T
  - Sampling of full luminosity (trigger)
- Current weaknesses:
  - Low S/B ratio for J/ψ at low-p_T
  - Moderate mass resolution for Υ 1,2,3 S states
    - possible but requires large statistics
  - Feed-down from B can be measured only indirectly
- Future improvements:
  - Time-of-flight provides improved e ID at low-p_T
  - Vertex detectors (direct measure of B feed-down)
  - $\mu^+\mu^-$ at mid-rapidity (MTD)

STAR detectors for onium physics ...



STAR detectors for onium physics ...

TPC: $|\eta| \leq 1$ ($|\eta| \leq 1.3$ possible), $0 < \phi \leq 2\pi$
Tracking $\Rightarrow p_T, \eta, \phi$
dE/dx $\Rightarrow$ PID (incl. electron ID)



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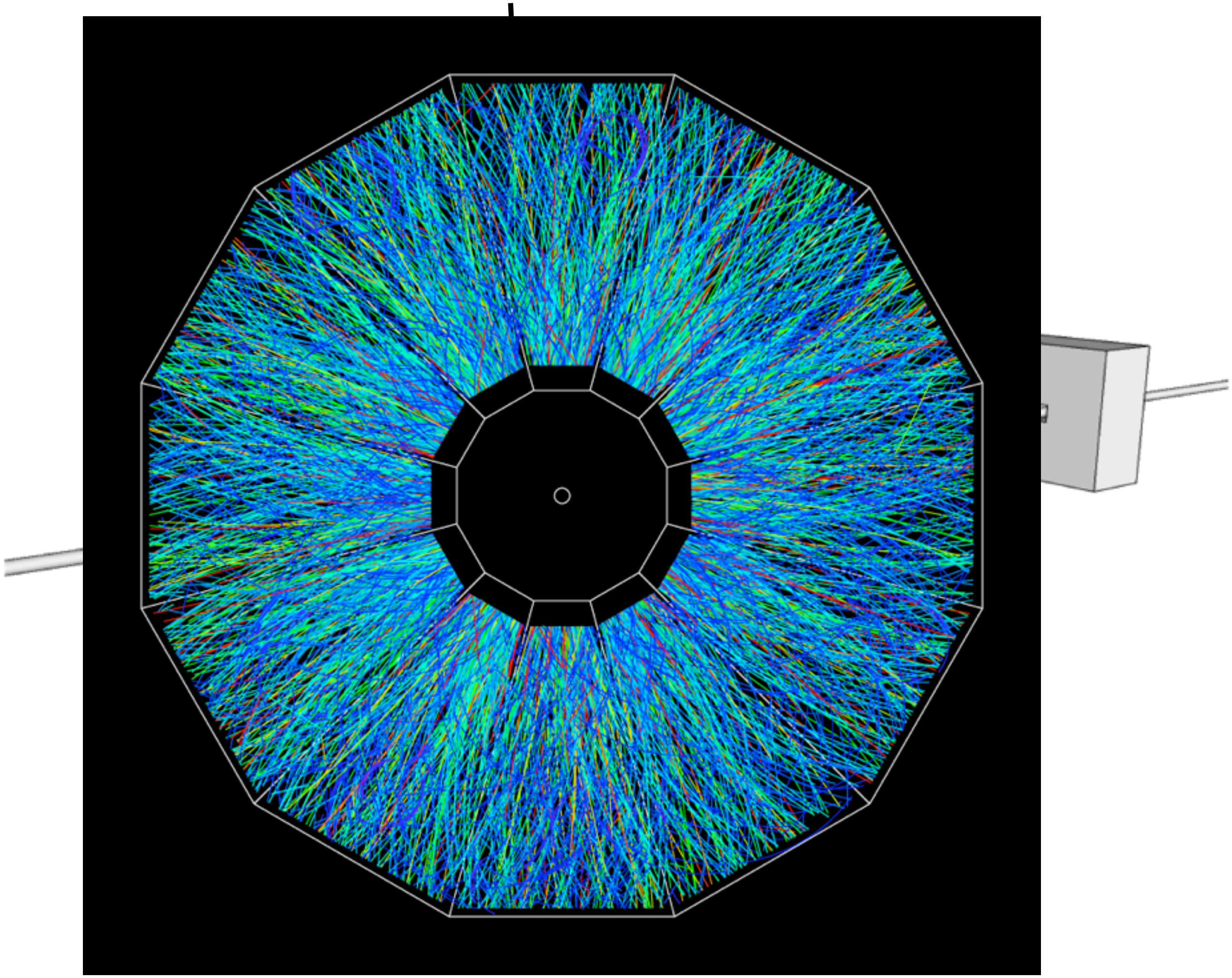

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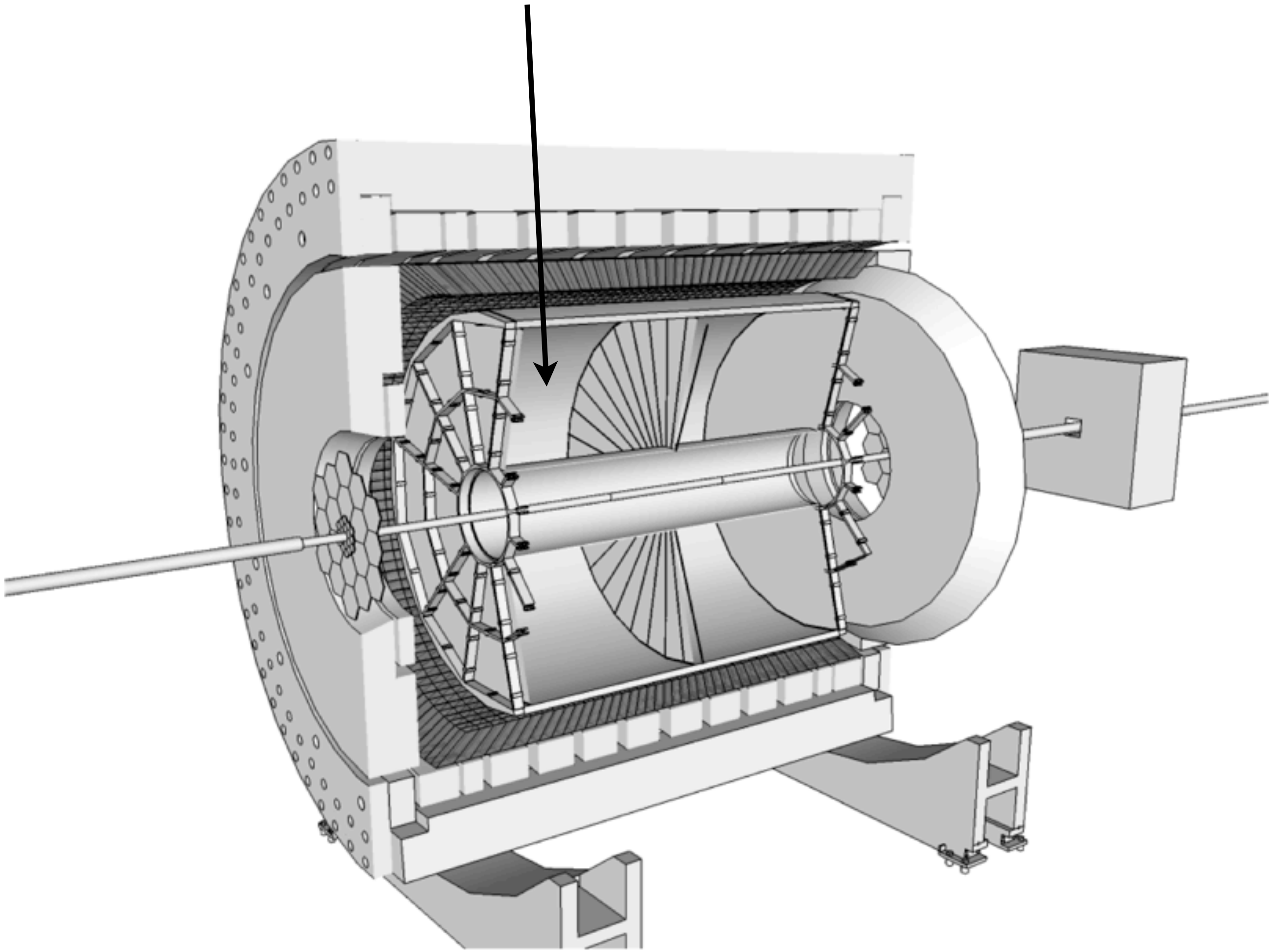

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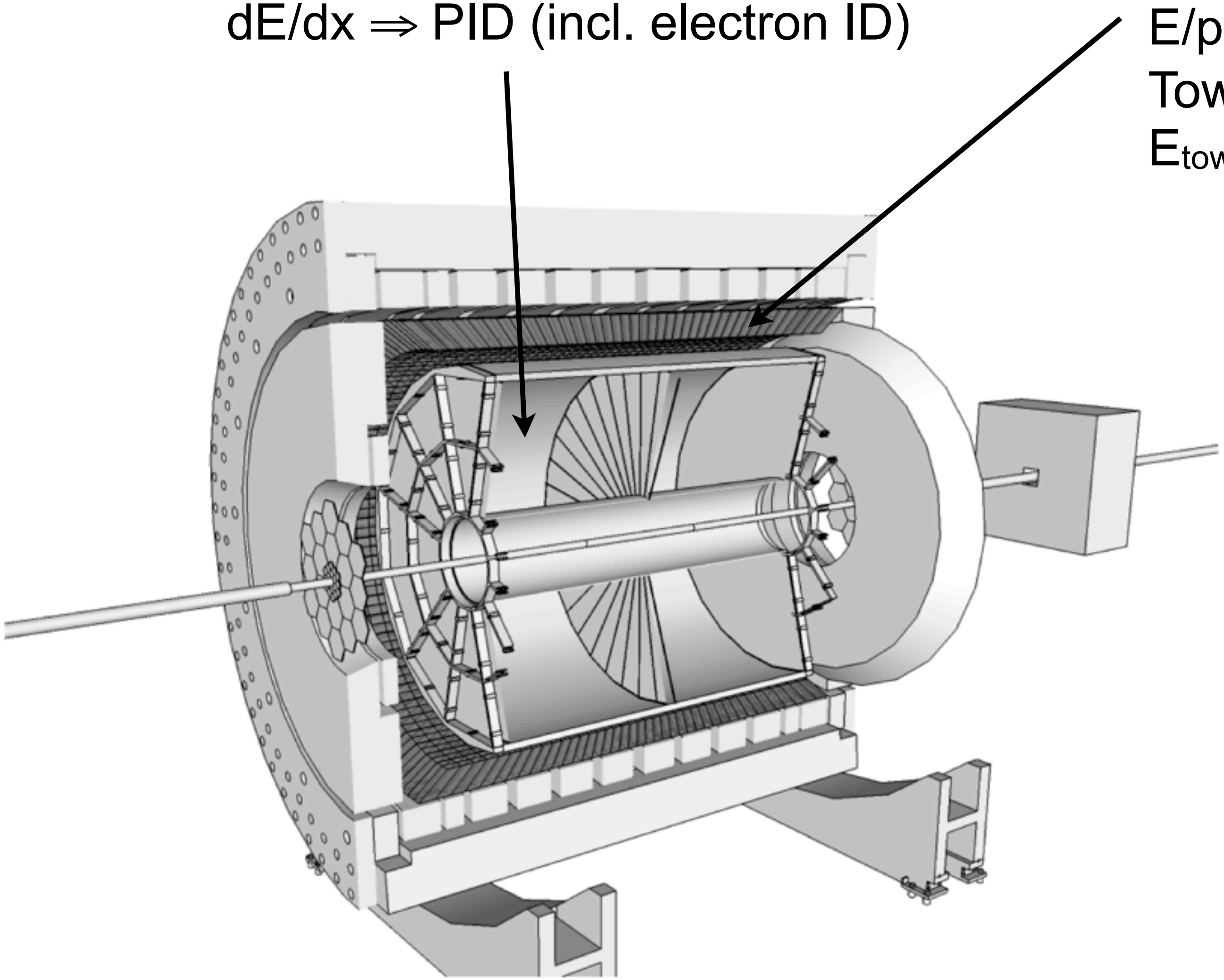
BEMC:
$|\eta|\leq 1$, $0 < \phi \leq 2\pi$
E/p $\Rightarrow$ electron ID
Tower: $\Delta\varphi\times\Delta\eta=0.05\times 0.05$
E_{tower} $\Rightarrow$ fast trigger



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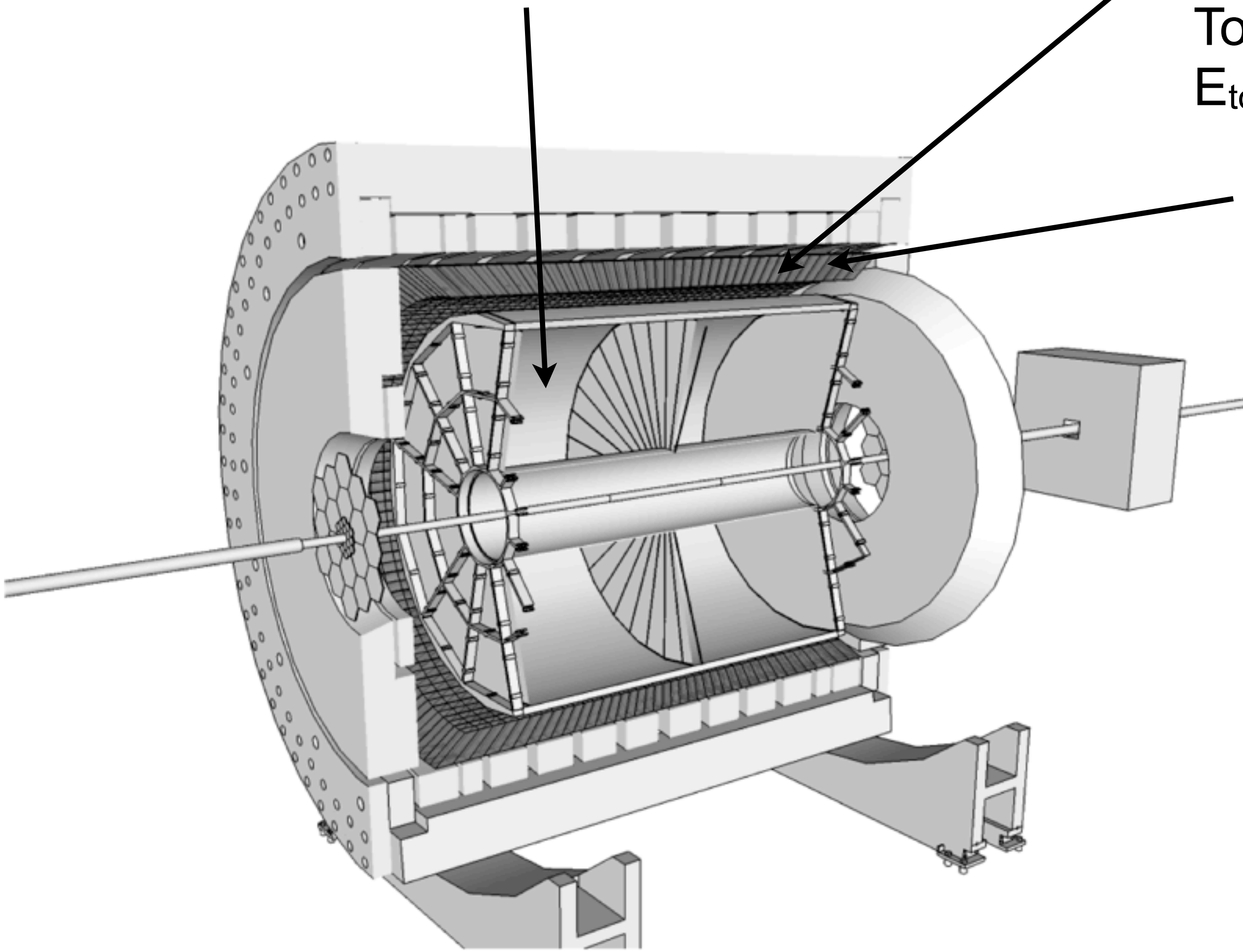
BSMD:
double layer wire PC
$\Delta\varphi \times \Delta\eta = 0.0064 \times 0.1$ rad
(0.1×0.0064) for η(φ) strips
$\Rightarrow$ spatial resolution
$\Rightarrow$ e/h separation



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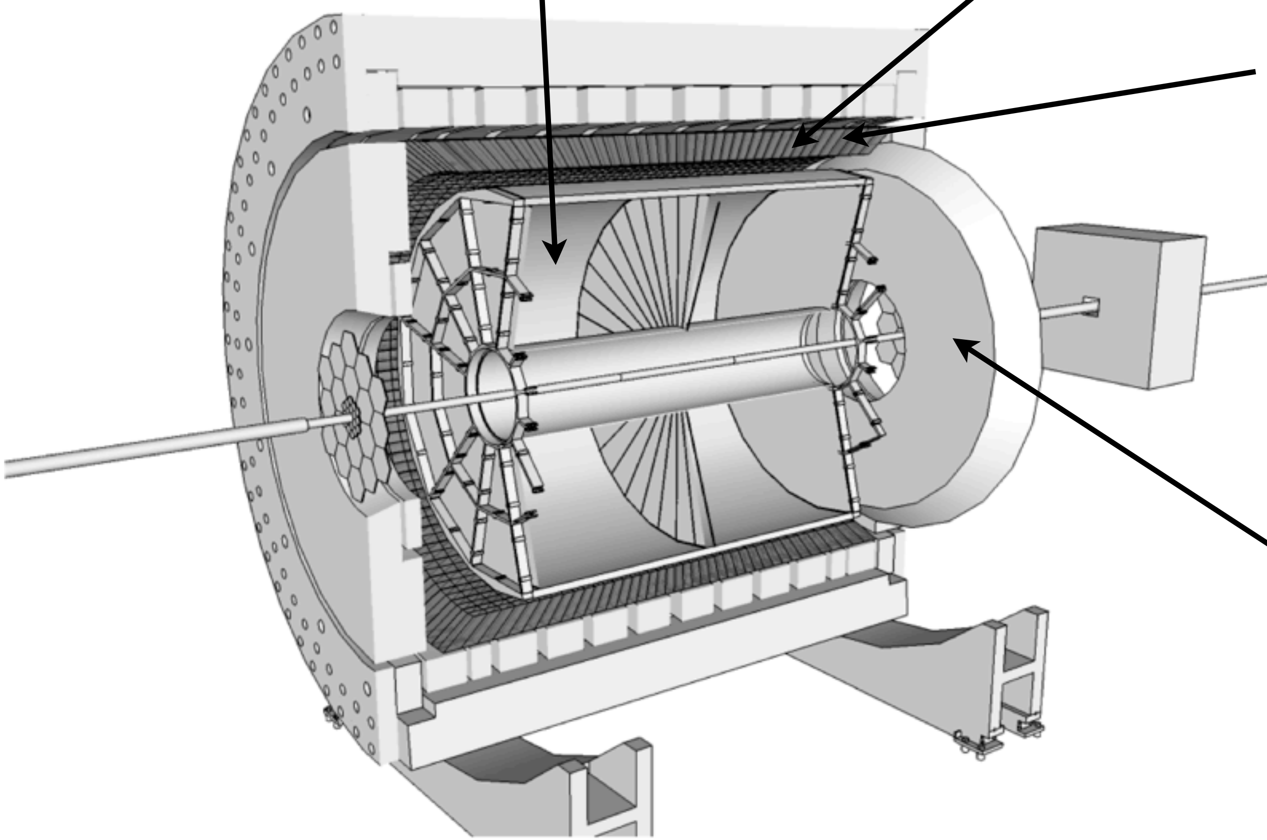


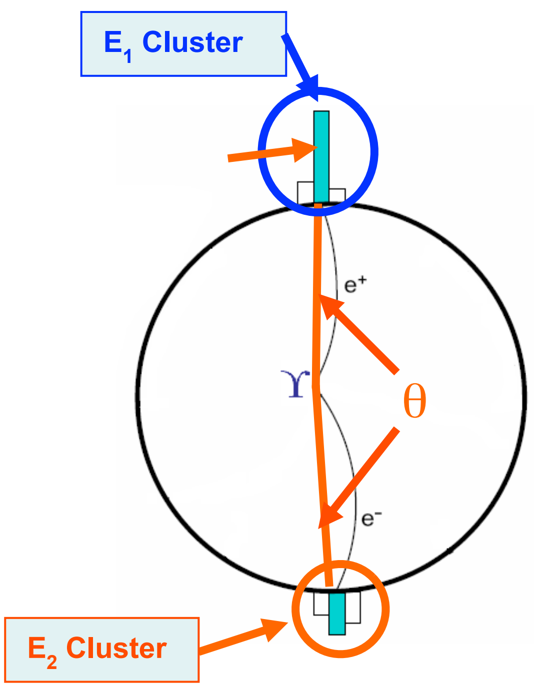
Note EEMC is a detector whose potential is not fully exploited so far:

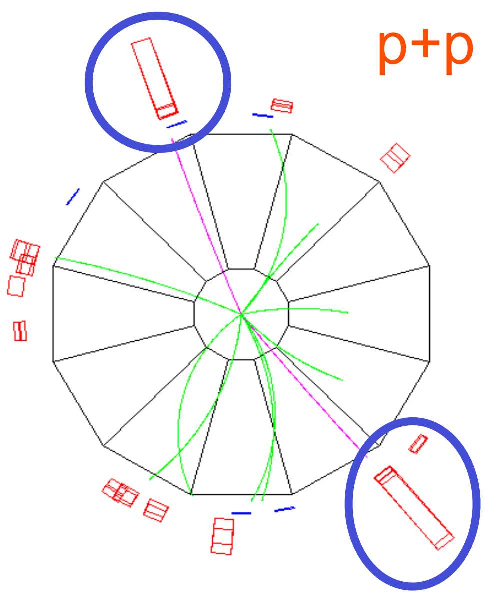
$1 < \eta \leq 2$, $0 < \phi \leq 2\pi$

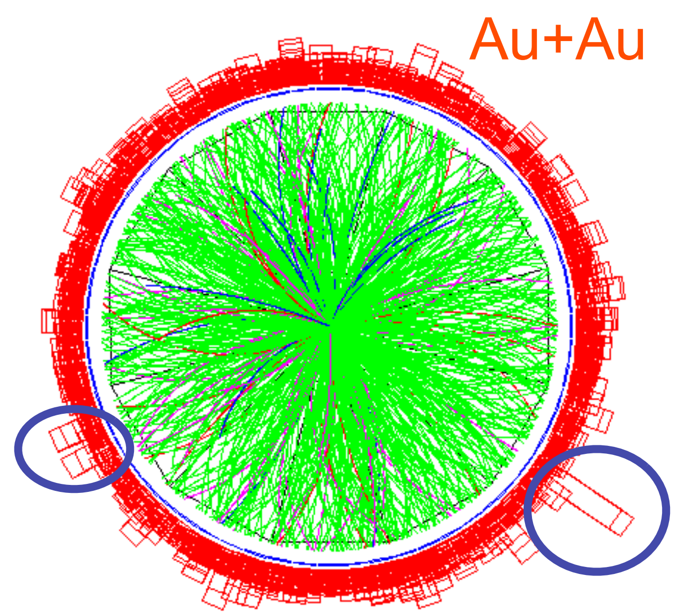
... and how they are used (trigger)

ϒ Trigger

- L0: high-tower E_T > 3.5 GeV (p+p) or 4.0 GeV (d+Au, Au+Au)
  - alternatively: trigger patch 4×4 towers (p+p only)
- L2: software algorithm building pairs from EMC towers
  - E_1, E_2, $\cos(\theta) \Rightarrow M_{inv}$
  - Rejection ~ 10^5 in p+p







Data

... and how they are used (trigger)

High-p_T J/ψ Trigger

- L0: *single* high-tower E_T > 3-4 GeV
  - alternatively: topology trigger (2 high towers separated ≥ 60°)

Low-p_T J/ψ Trigger

- not implemented - L0/L2 provide too little rejection
- use minimum bias data sets instead (⇒ low $\int L dt$)

New: Higher Level Trigger

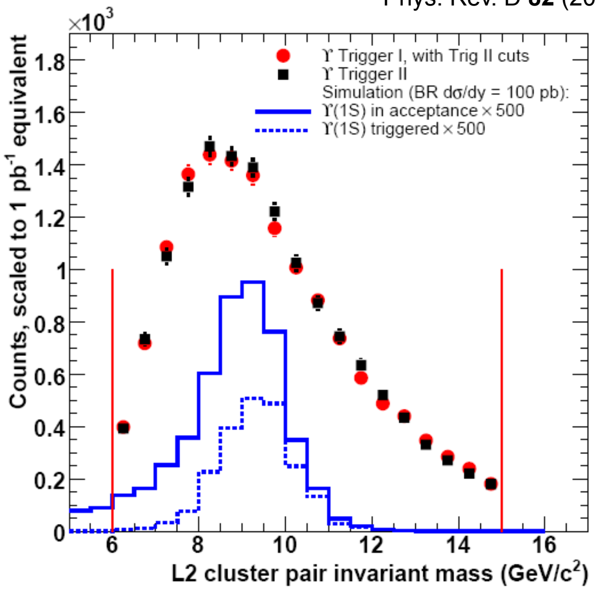
- Computer farm with fast algorithm using tracking (TPC) & calorimeter data
- Still in R&D phase but used in parallel during energy scan
- Promising results (see later)

... and how they are used (reconstruction)

Phys. Rev. D **82** (2010) 12004

Example: ϒ reconstruction

- TPC: track reconstruction
  - M_{inv} peaks at ~ 2 × trigger E_T threshold
  - dominated by h^+h^- pairs



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  - track-cluster match if distance R < 0.04 in η−φ

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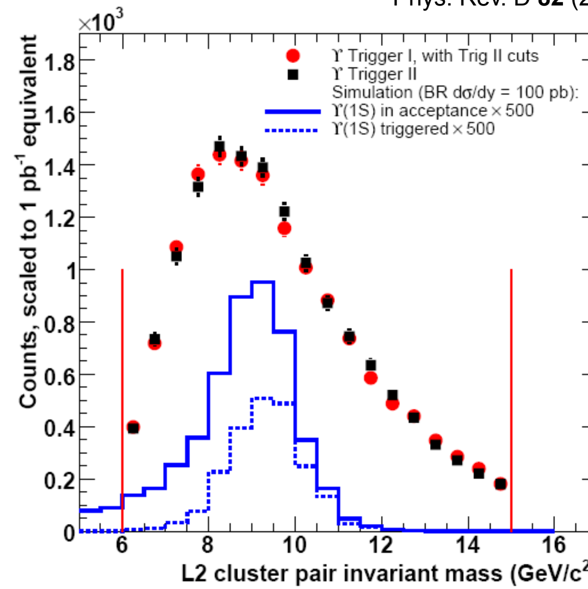

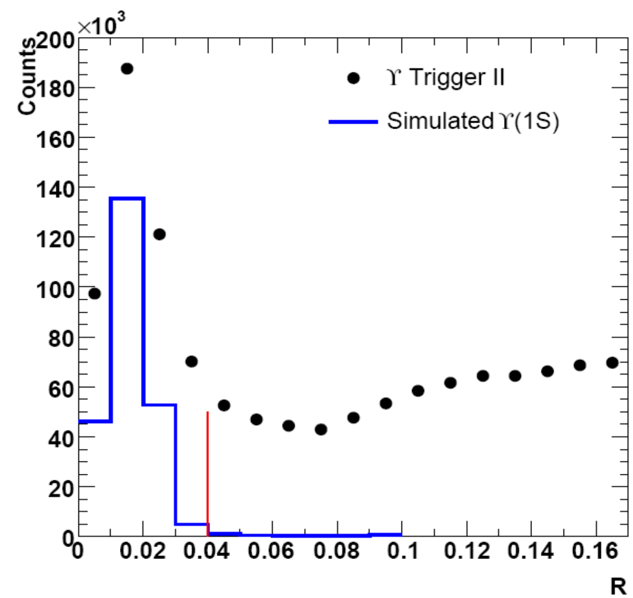

... and how they are used (reconstruction)

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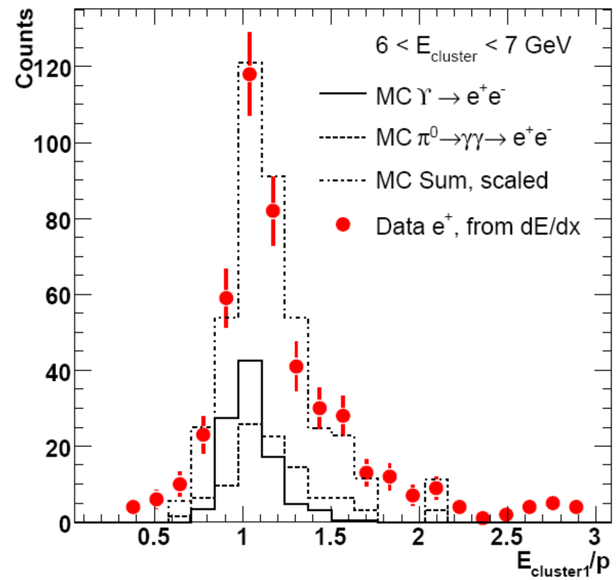
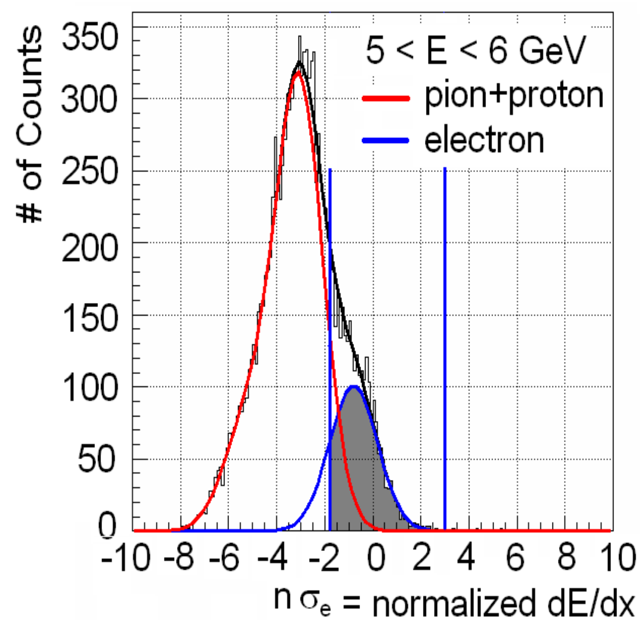
Example: Υ reconstruction

- TPC: track reconstruction
  - M_{inv} peaks at ~ 2 × trigger E_T threshold
  - dominated by h^+h^- pairs
- TPC tracks extrapolate to EMC
  - track-cluster match if distance R < 0.04 in η−φ
- Electron ID cuts
  - E/p - EMC energy vs TPC momentum
  - dE/dx in TPC: $n\sigma_e$ of matched tracks



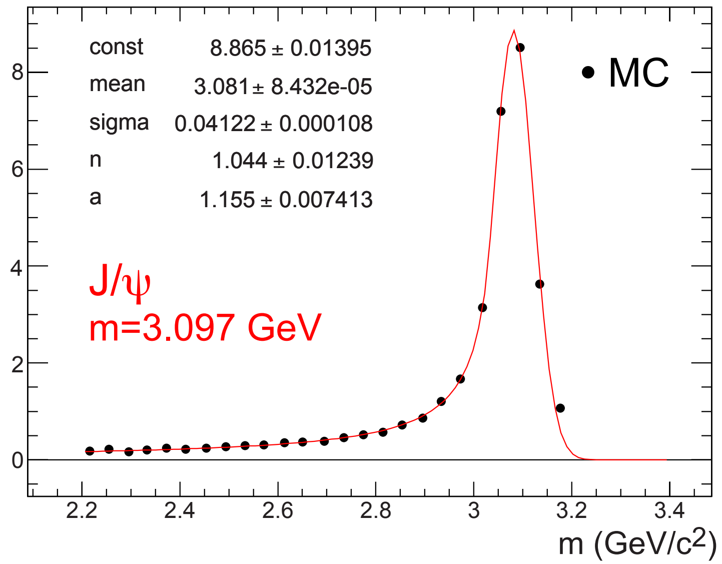


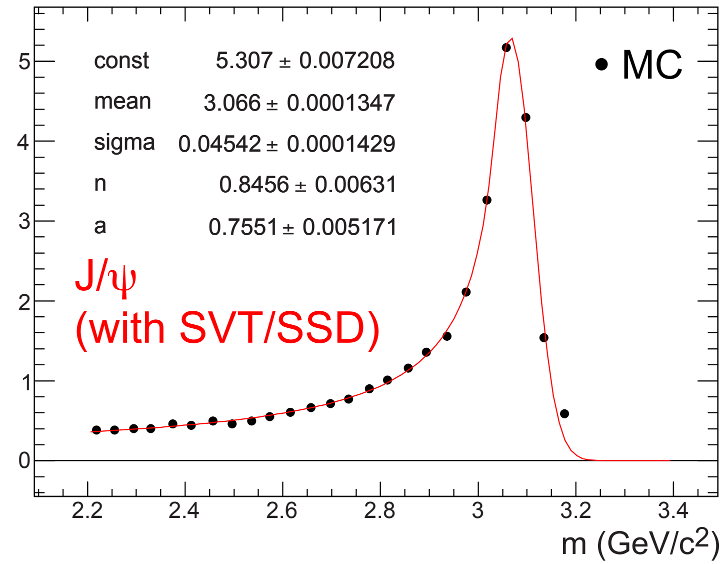
... and how they are used (reconstruction)

- Signal extraction

$$S = N_{+-} - \underbrace{2\sqrt{N_{++}N_{--}}\frac{A_{+-}}{\sqrt{A_{++}A_{--}}}}_{N_{+-}^{bck}}$$

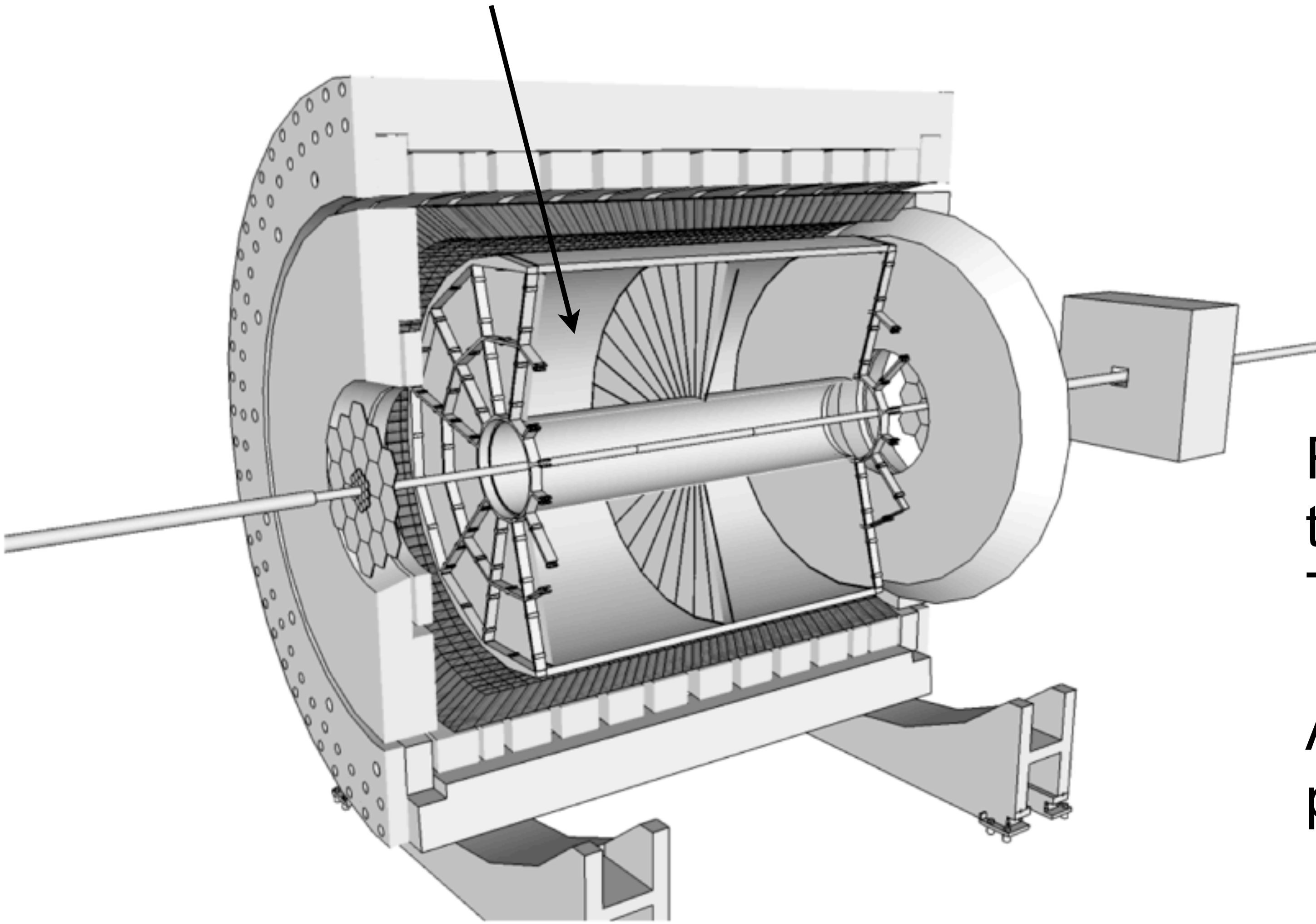
- Describing the line shape
  - Crystal ball function accommodates detector resolution and bremsstahlung: f(m; α, n, ⟨m⟩, σ)

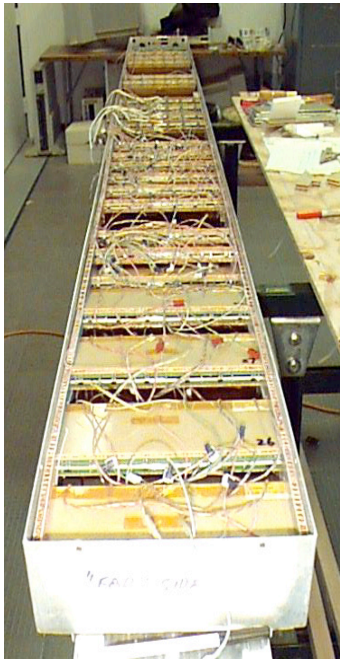




STAR's new detector ...

ToF: $|\eta| \leq 0.9$, $0 < \phi \leq 2\pi$, MRPC technology
Timing resolution < 100 ps
Improve electron ID at low-p_T

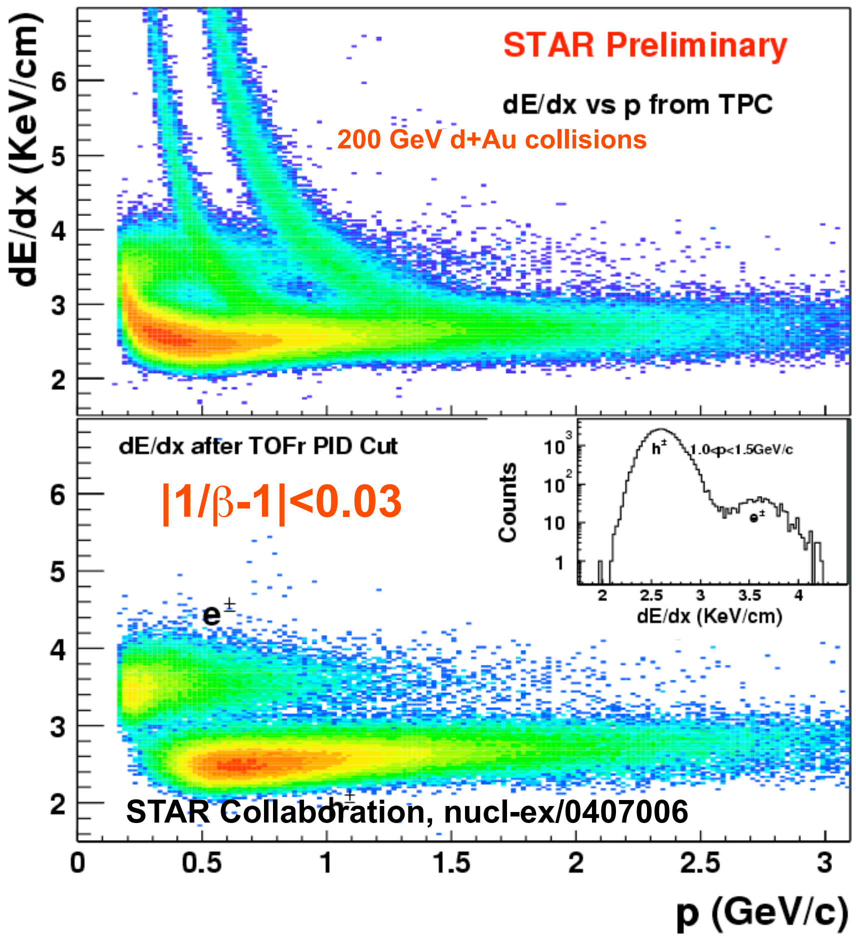


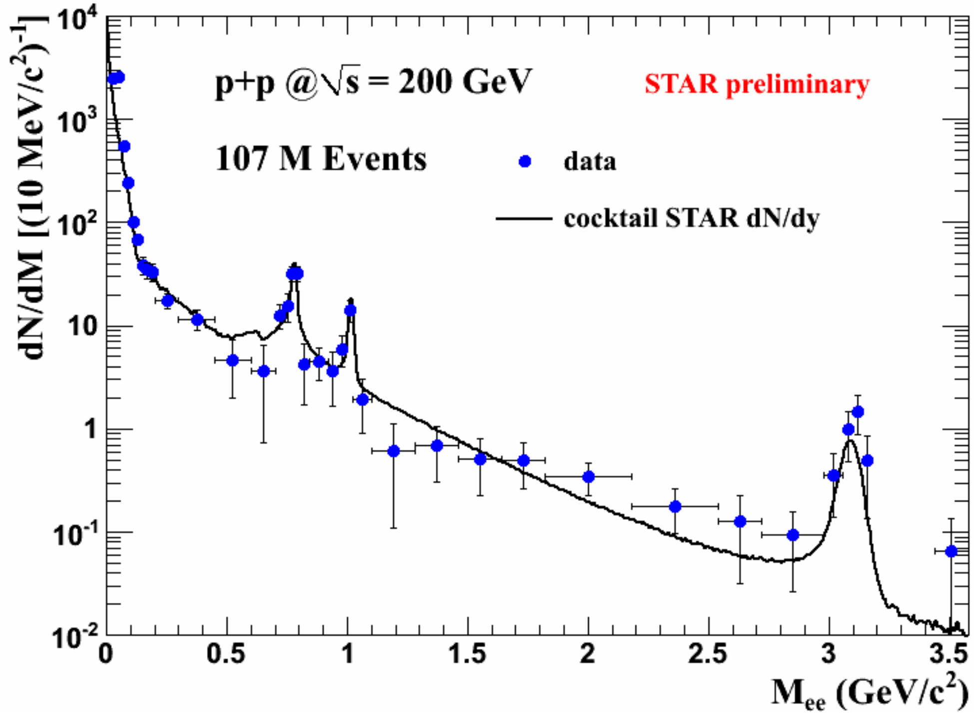


Run 10 data taken with full ToF

Analysis in progress

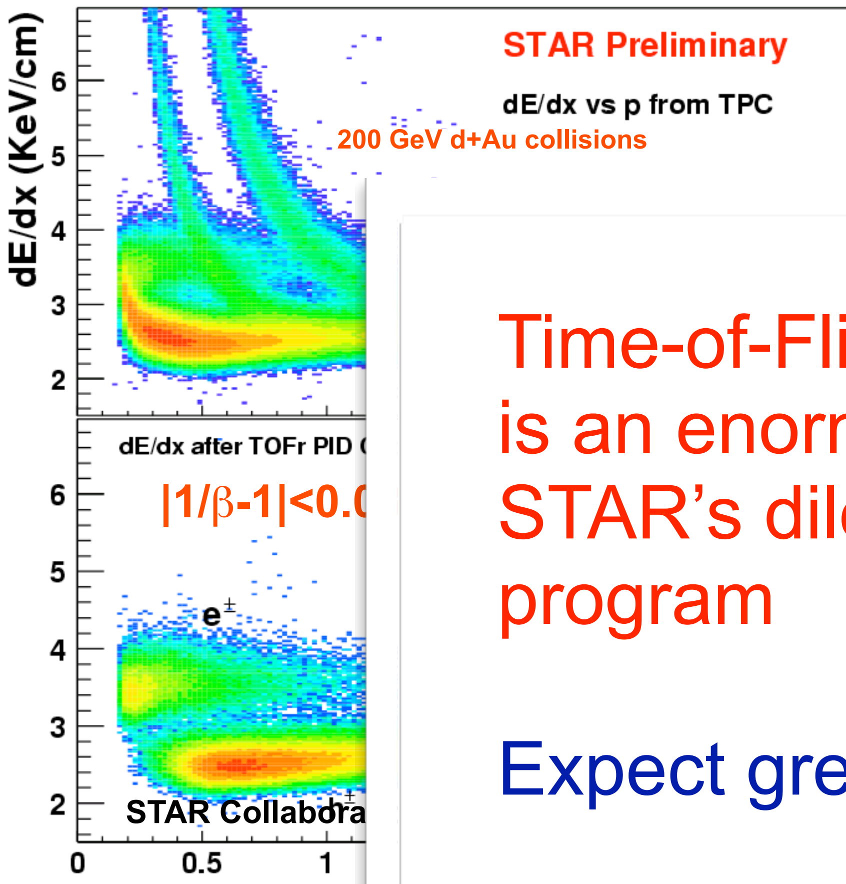
... and how they are used (ToF)

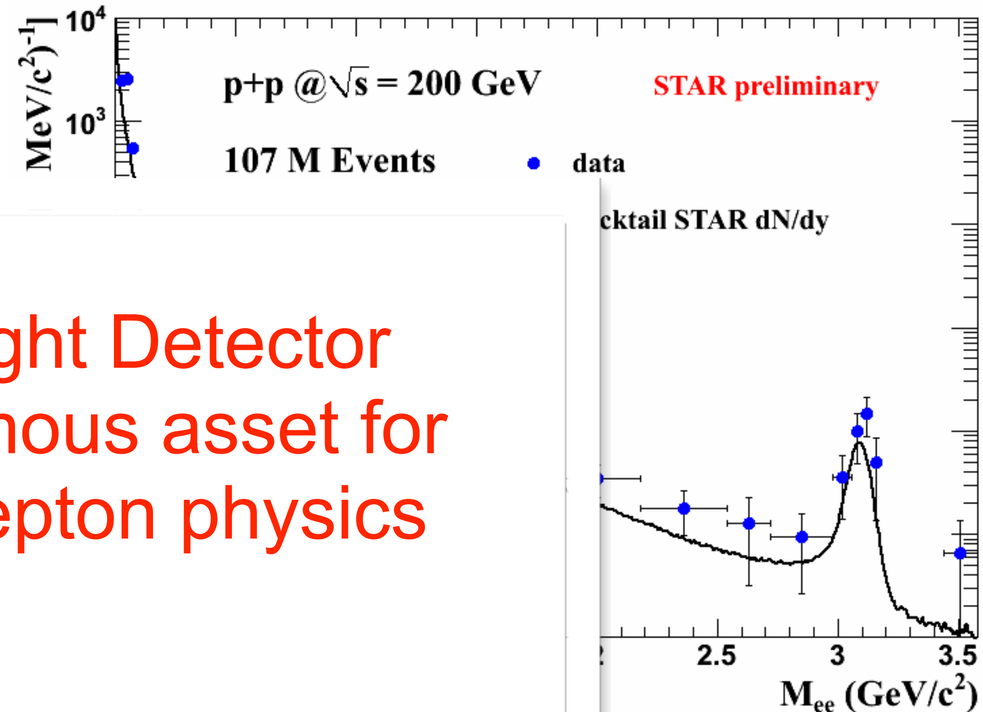




- TOF: e PID for $p_T < 3$ GeV/c
- High electron purity: 99%
- Efficiency: greater than 60% using standard cuts

... and how they are used (ToF)



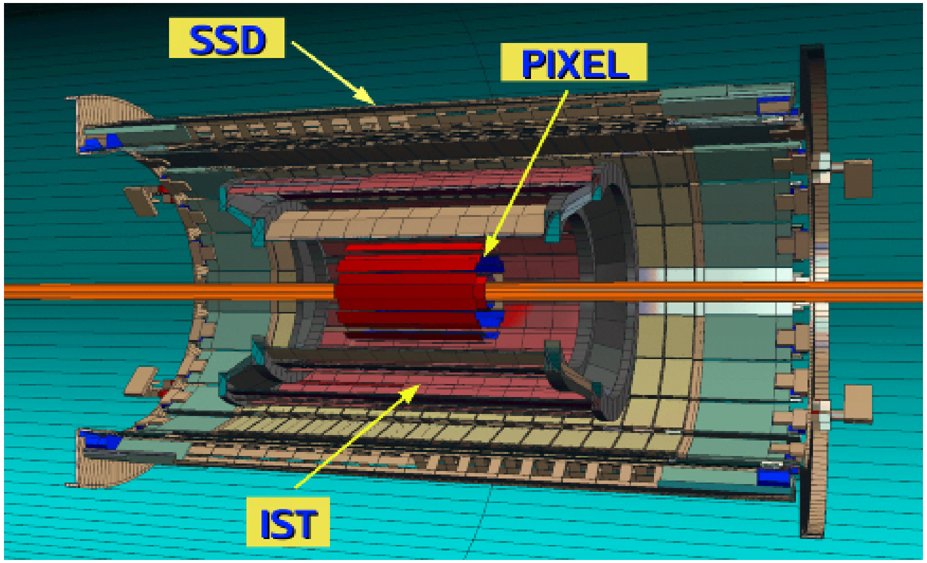


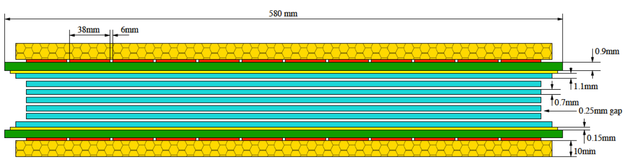
Time-of-Flight Detector is an enormous asset for STAR's dilepton physics program

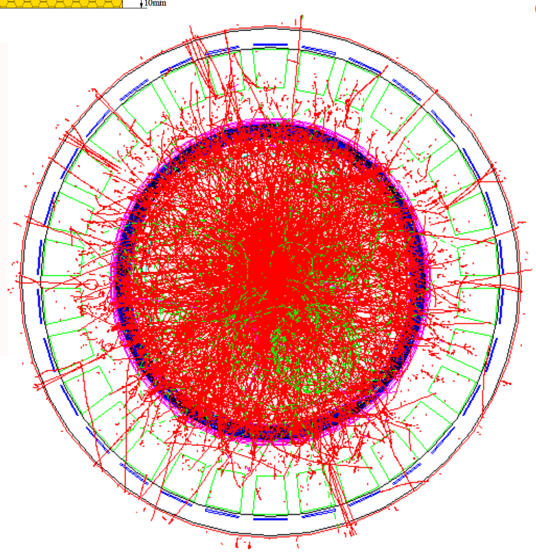
Expect great things soon!

- TOF: e PID for p_T < 3 GeV/c
- High electron purity: 99%
- Efficiency: greater than 60% using standard cuts

STAR detectors in the near future ...







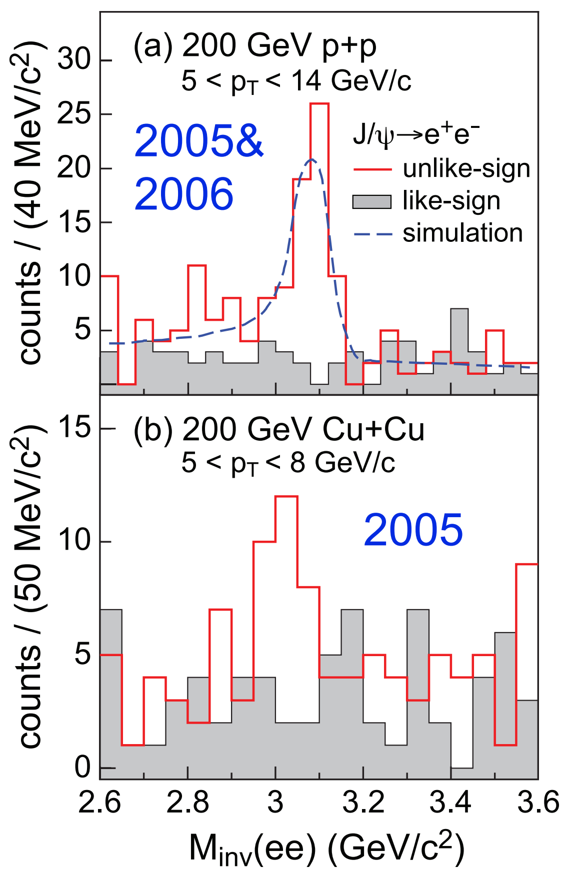
See X. Dong's talk tomorrow

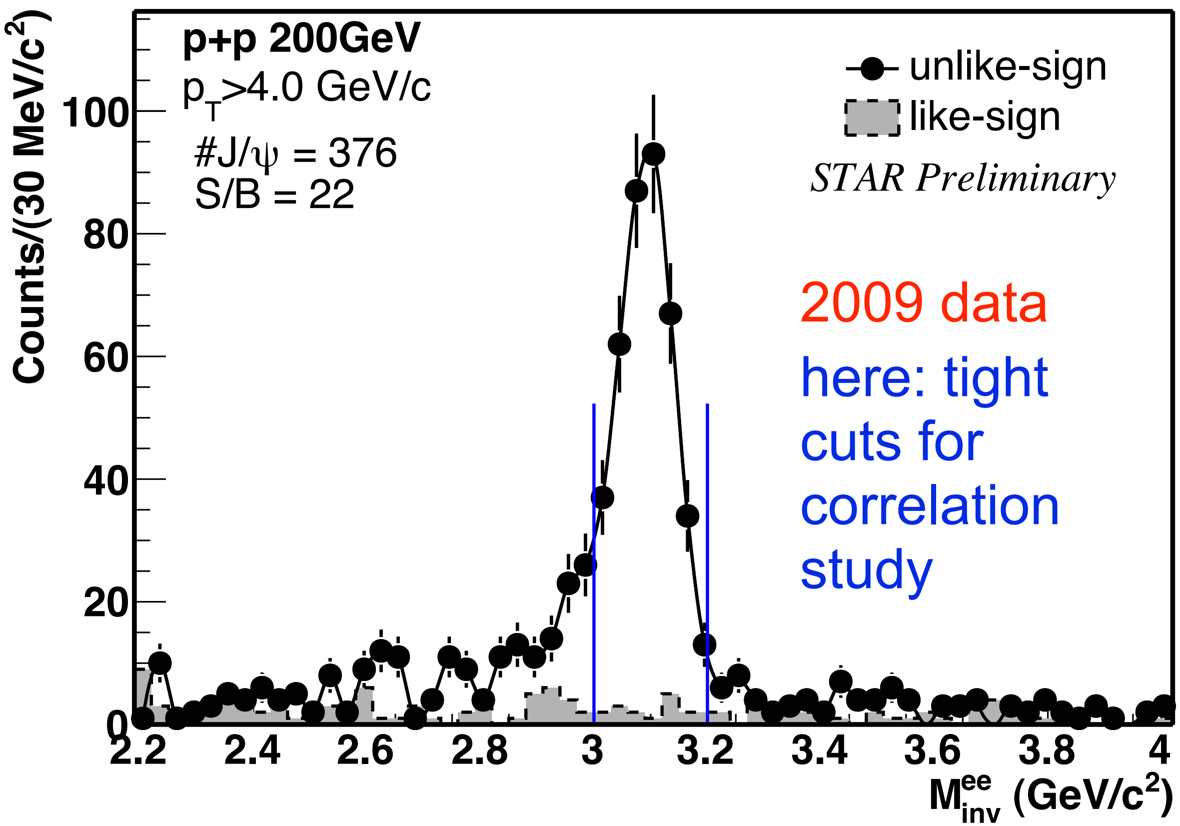
- Heavy Flavor Tracker (HFT)
  - $|\eta|\leq 1$, $0 < \phi \leq 2\pi$
  - PXL: 2 layers of thinned (50 μm) CMOS pixel detectors (2.5, 8 cm)
  - IST: layer of low mass silicon strip-pad sensors (17 cm)
  - SSD: layer of double-sided silicon strip sensors at a radius of 23 cm
  - Distinguish prompt quarkonia from B feed-down ($B \rightarrow J/\psi + X$)
- Muon Telescope Detector (MTD)
  - Acceptance: 45% at $|\eta|<0.5$
  - MRPCs covers magnet iron bars
  - 6 interaction length (yoke)
  - 117 modules, 1404 readout strips, 2808 readout channels
  - Optimal mass resolution for Υ 1,2,3 S despite increased material (HFT)

J/ψ Results

High-p_T J/ψ production

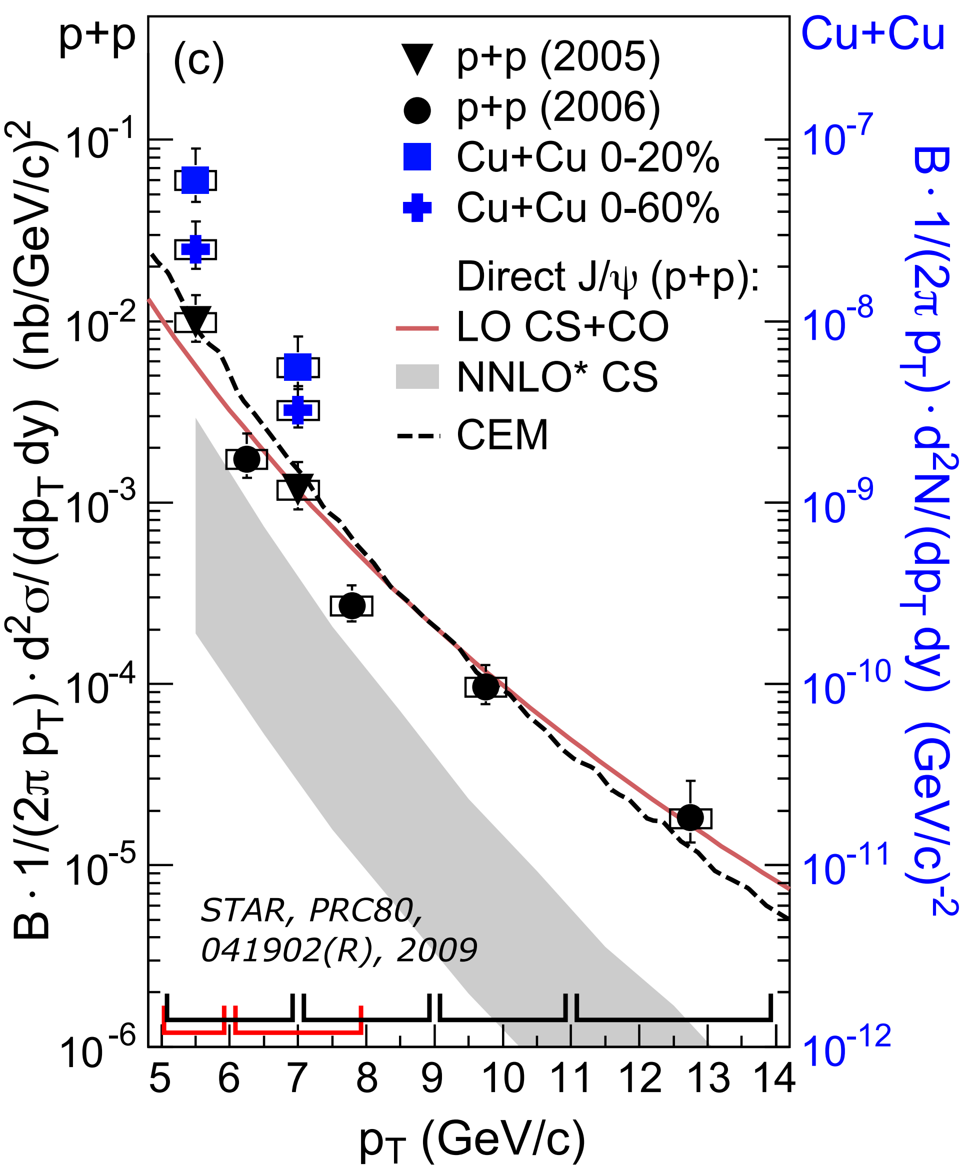
STAR, PRC80, 041902(R), 2009





- Steady improvements due to higher *L* & improved trigger
- SVT/SSD detectors taken out before run 2008
  - 7-10 times less X/X_0
- Spectra for 2009 data soon

High-p_T J/ψ: p+p spectra

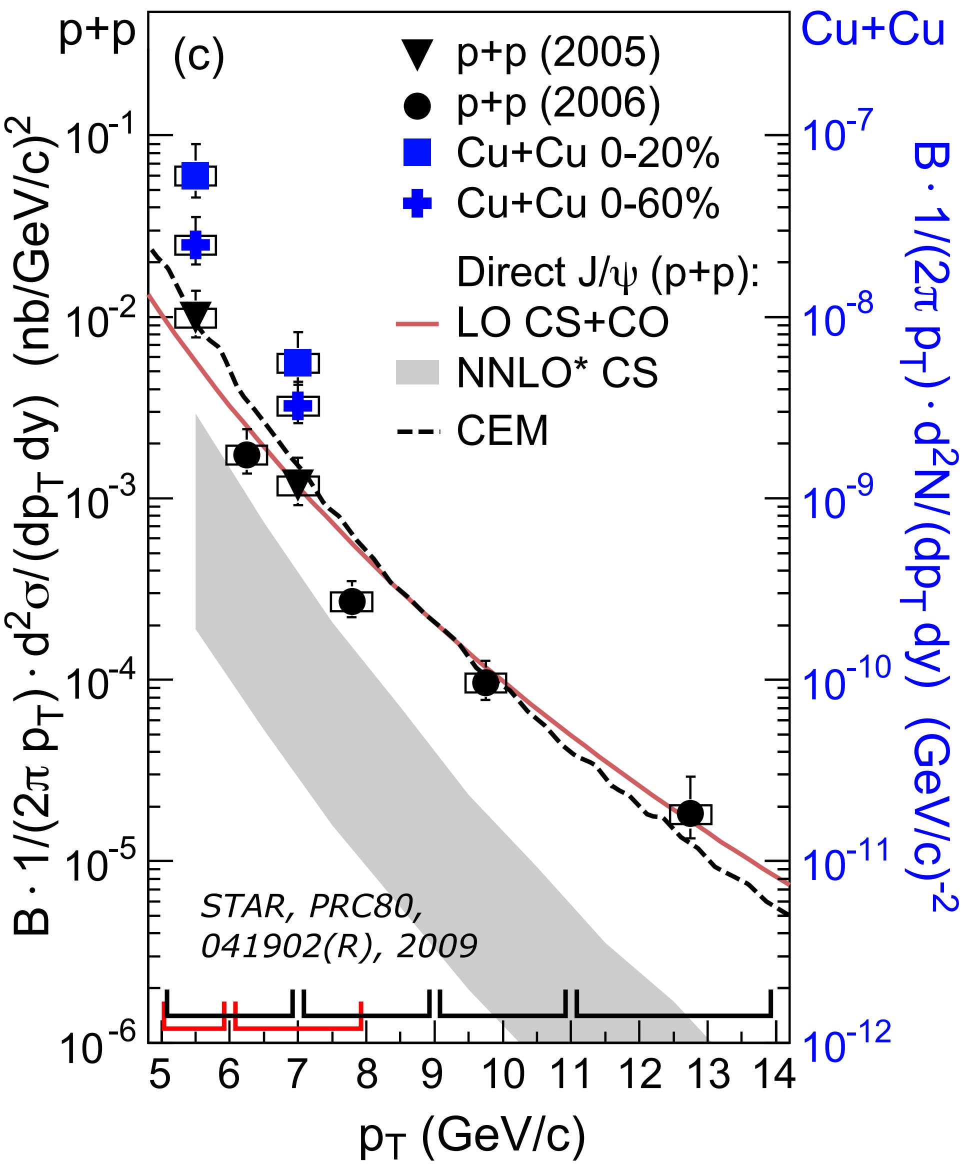


CEM:

M.~Bedjidian et al., hep-ph/0311048; R. Vogt private communication.

- MRST
- Curve includes feed-down from χ_c + ψ'
- Leaves no (little) room for B feed-down
- varying m_R, m_μ, k_T can heal this

High-p_T J/ψ: p+p spectra

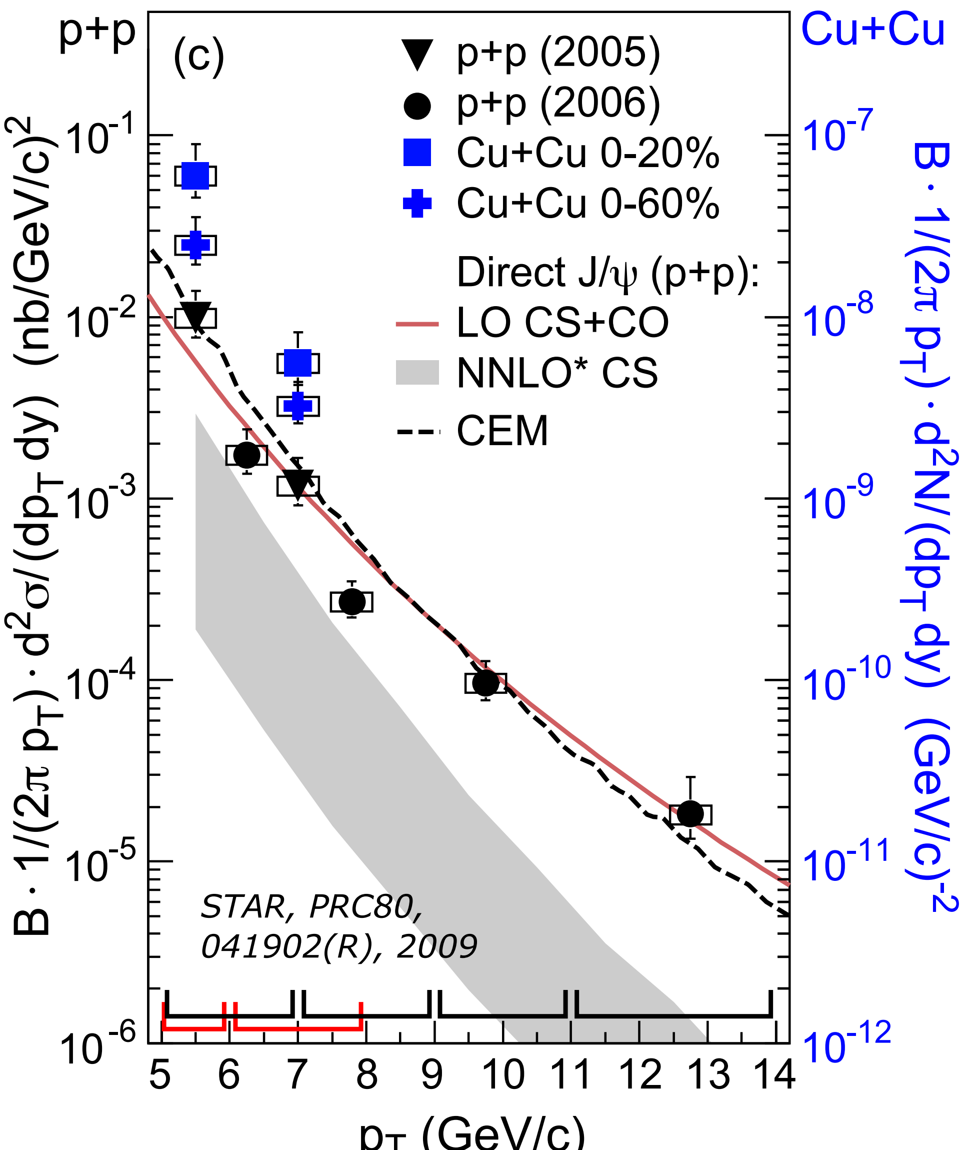


NNLO* CS:

P. Artoisenet et al., PRL 101, 152001, J.P. Lansberg private communications.

- Only CS contributions, but go to higher orders, partially with loops, partially with just tree-level higher order diagrams.
- Curve **does** not include feed-down from χ_c + ψ' (ψ' available)
- χ_c might be large because of high x_T range of STAR data
- Leaves room for substantial feed-down
- Still too low at p_T > 10 GeV/c
  - CO needed?

High-p_T J/ψ: p+p spectra

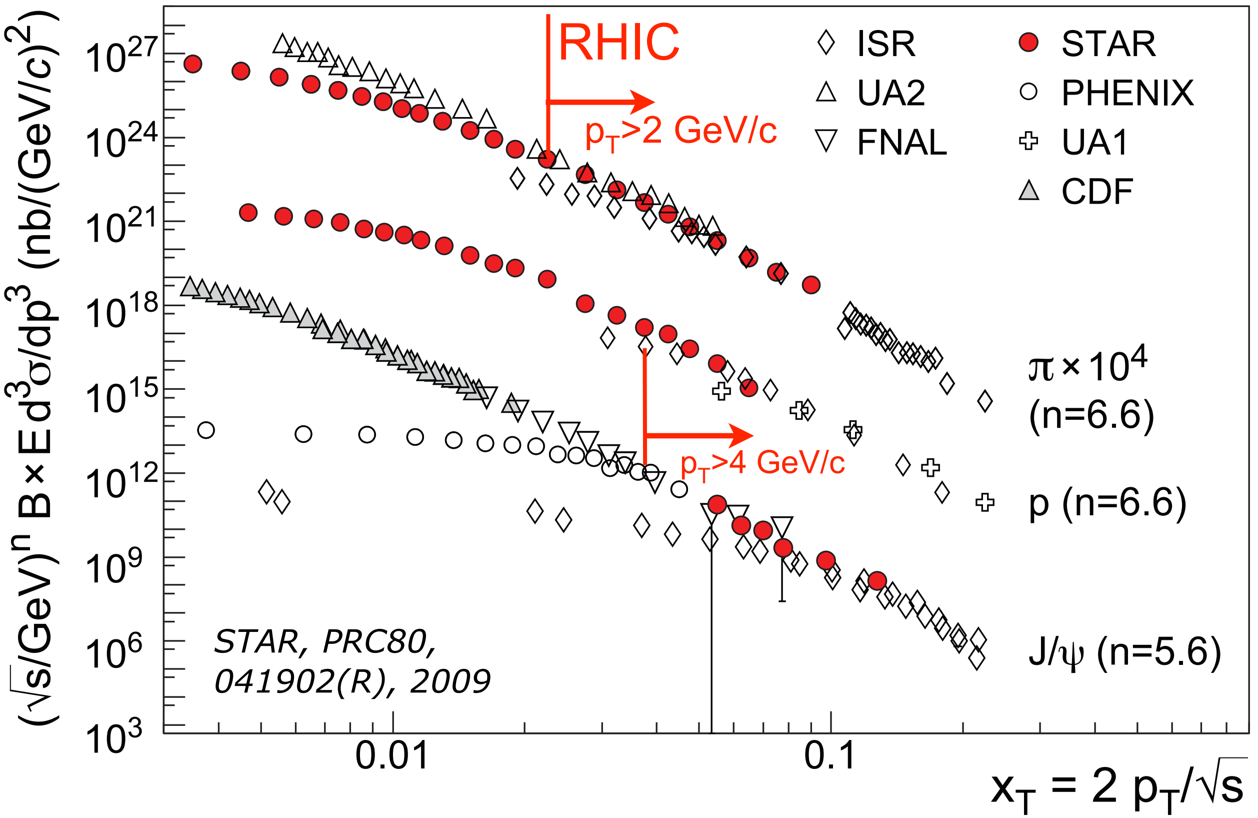


CO+CS in NRQCD:

G. Nayak, et al., PRD68, 034003 and private communications

- LO calculations
- direct J/ψ (singlet and octet)
- CO dominating
- color octet matrix elements from P. Cho, A. Leibovich, PRD 53:6203,1996
- Curve **does** not include feed-down from χ_c + ψ' (χ_c available)
- Leaves little to no room for feed-down

J/ψ in p+p: x_T Dependence



$$E\frac{d^3\sigma}{dp^3} = g(x_T)/s^{n/2}$$

In parton model:

n is related to number of point-like constituents taking active role in interaction

n=8: diquark scattering

n=4: QED-like scattering

$x_q \approx x_g \approx x_T$

- π and *p* at p_T>2 GeV/c: n=6.6±0.1 (PLB 637, 161(2006))
- J/ψ at high p_T: n=5.6±0.2 (the power parameter close to CS+CO prediction)
- low & high-p_T J/ψ production dominated by different processes?

Assessing feed-down from B mesons

So far at RHIC no Si-Det. to tag B decays. Need alternative!

Method 1

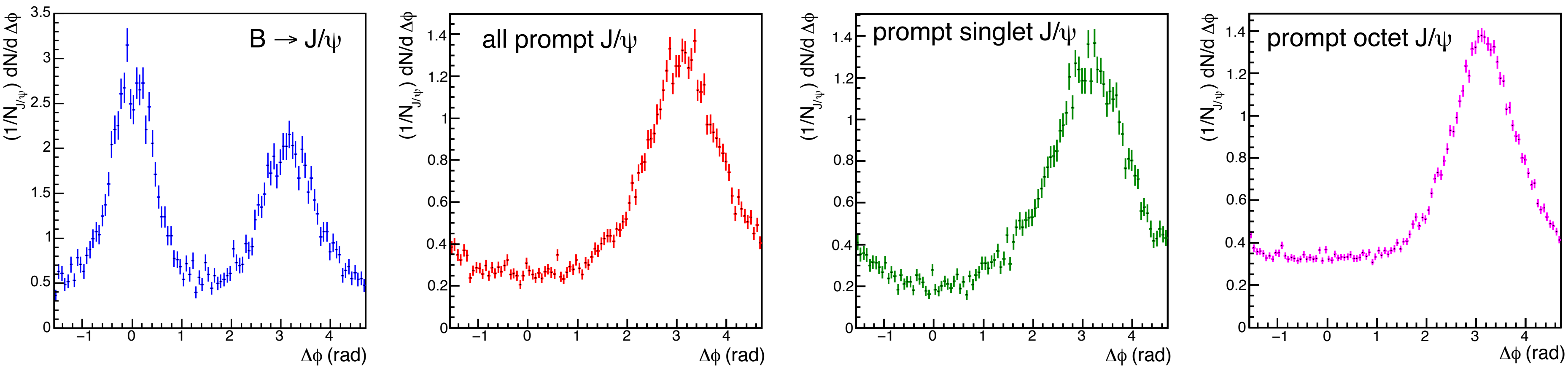
- Comparing measured J/ψ spectra with NLO b calculations + b FF + $B \rightarrow J/\psi + X$ decay kinematic
- Considerable uncertainties in absolute normalization from NLO calculations (m_μ, m_R, M_b, PDF) and ψ', χ_c feeddown

Method 2

- Use $J/\psi - h$ correlations ($d\phi$)
  - Interpretation is model dependent (here PYTHIA)
    - B fragmentation is hard and rather well known
  - Good S/B with STAR at high-p_T makes this possible

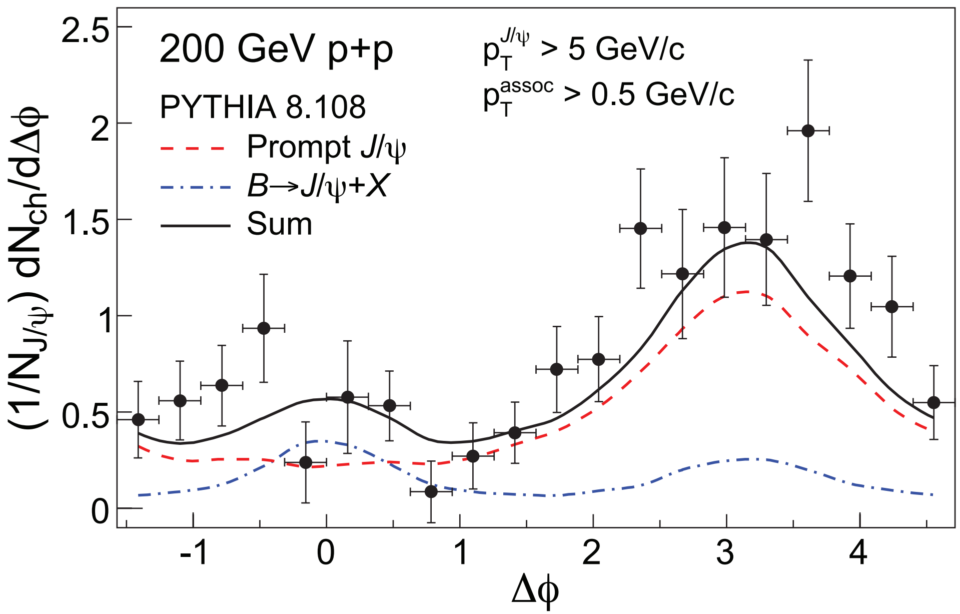
High-p_T J/ψ-h Correlations: PYTHIA/LO

- PYTHIA 8 with STAR HF-tune v1.1
- J/ψ tuned to describe measured RHIC spectra with emphasis on low-p_T (PHENIX) where B feed-down is smallest
- B tuned with parameters m_μ, m_R, M_b, ..., from latest calculations (M. Cacciari et al.)



- p_T(J/ψ) > 5 GeV/c, p_T(h) > 0.5 GeV/c
- soft processes added to mock up underlying event (minor effect)
- little difference between CO/S: confirm studies at LHC by Bargiotti & Vagnoni (LHCb-2007-042) and Kraan (arXiv:0807.3123)
- Pronounced near-side for B feed-down (moderate recoil in away-side)

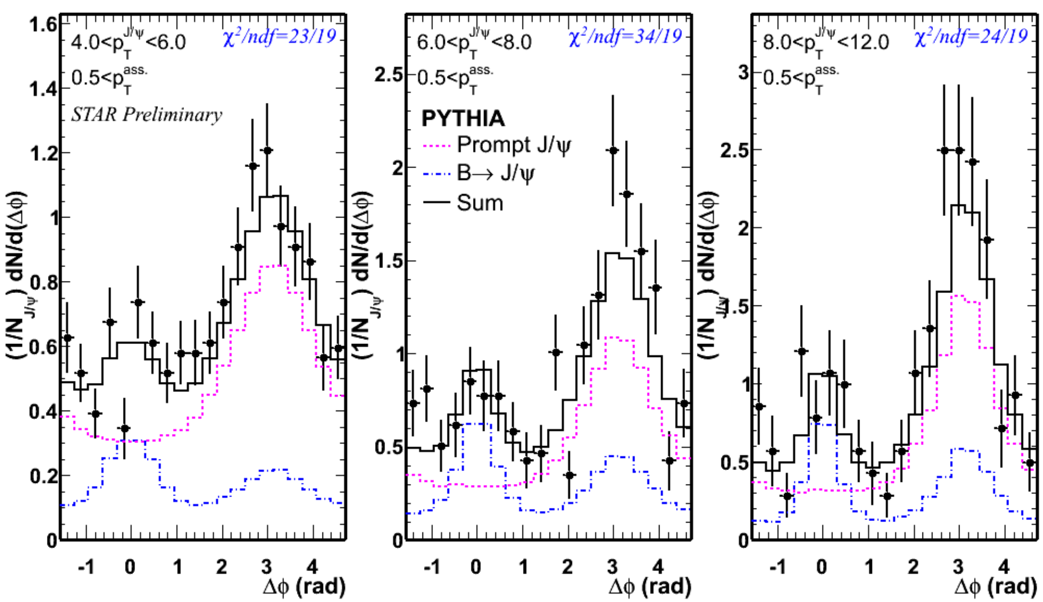
Constraining bottom contribution



Previous result:

- No significant near side J/ψ-hadron azimuthal angle correlation
- Correlation show low B contribution (13 ± 5) %

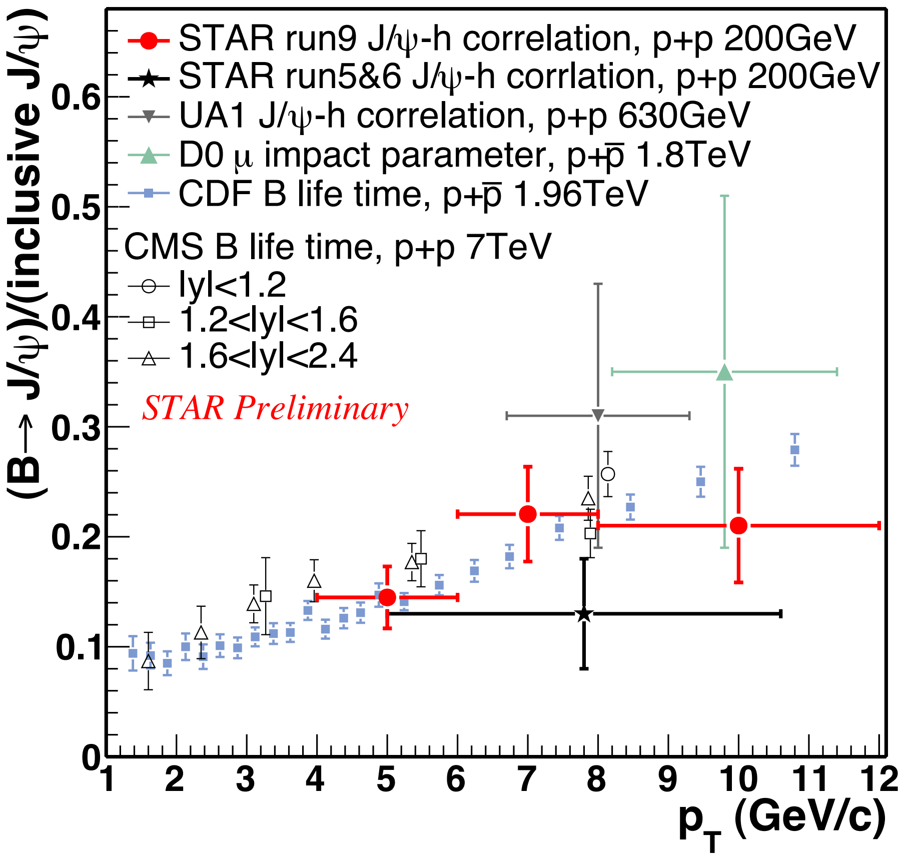
STAR, PRC80, 041902(R), 2009

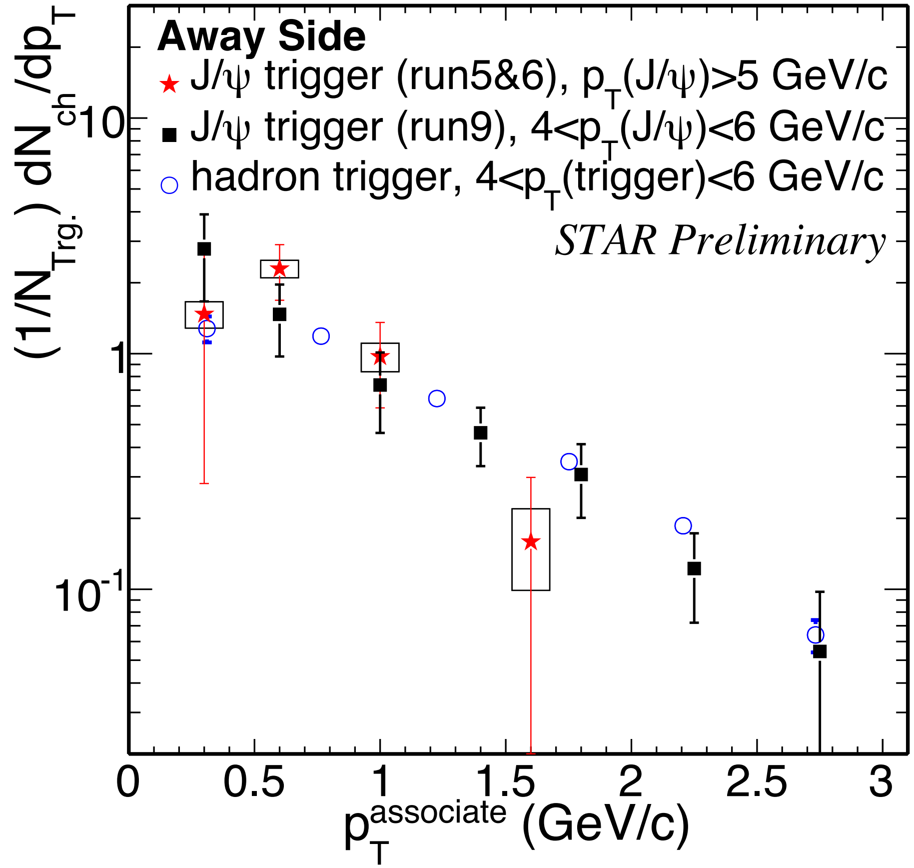


Run 9:

- Higher statistics
- Divide into 3 p_T bins

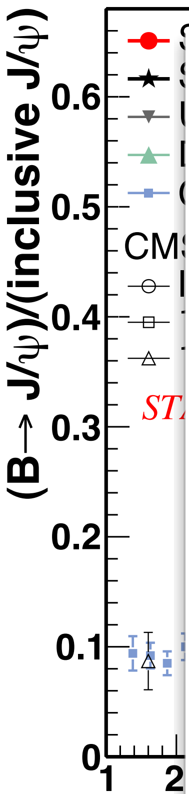
Latest results on B feed-down

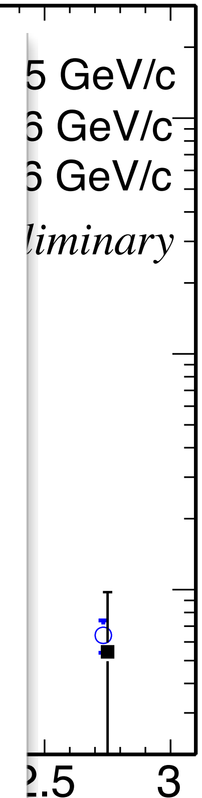




- New results consistent with previous results
- No significant beam energy dependence! Why?
- Away side: Consistent with h-h correlation (gluon/light quark fragmentation?)

Latest results on B feed-down





J/ψ-h correlations are a powerful tool to study B feed-down.

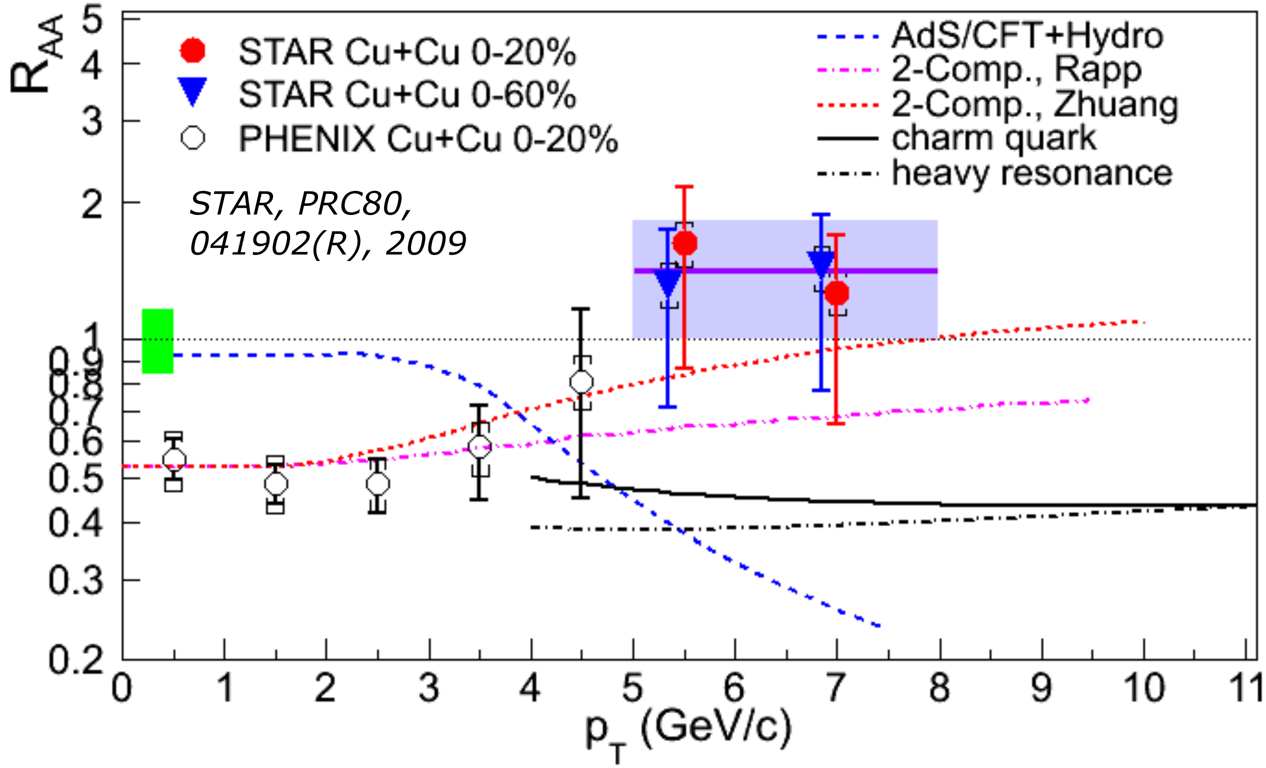
There's one assumption:
NLO effects are negligible

This has not been demonstrated yet.

- No NLO calculations for J/ψ-h exist
- Neither CDF nor CMS have conducted a study comparing B-tagged J/ψ and J/ψ-h (they could)
- Needs to be done to ultimately establish the validity of this approach

- Nev
- No
- Aw... quark fragmentation?)

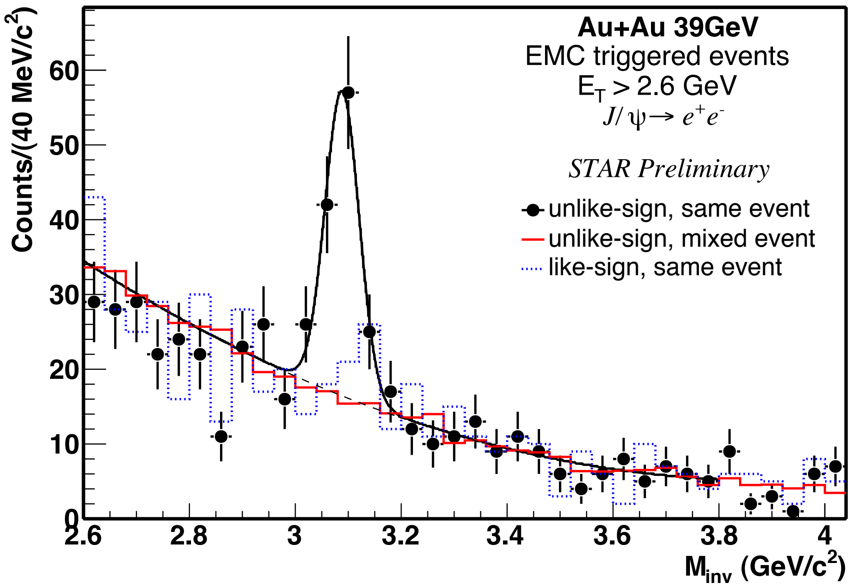
High-p_T J/ψ: R_{AA}

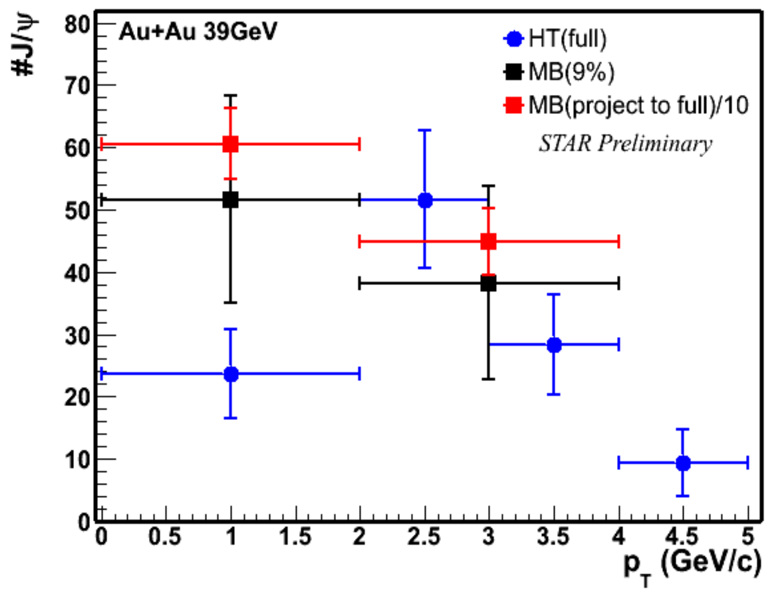


STAR Cu+Cu 0-20%: $R_{AA}(p_T>5) = 1.4 \pm 0.4 \pm 0.2$

- The only hadron measured to be not suppressed ?
- Contrast to open charm. CS vs. CO? Formation Time?
- 2-component models describes the overall “trend”

A look into the (near) future





- Beam energy scan: 39 GeV Au+Au
  - Expect ~1000 (13σ) J/ψ from full MB data
  - Able to cover p_T range 0-5 GeV/c
  - Reference data available from Fermi Lab Experiments and ISR
- 200 GeV p+p
  - J/ψ polarization study in progress
- 200 GeV Au+Au
  - J/ψ v_2 in progress

ϒ Results

Some thoughts ...

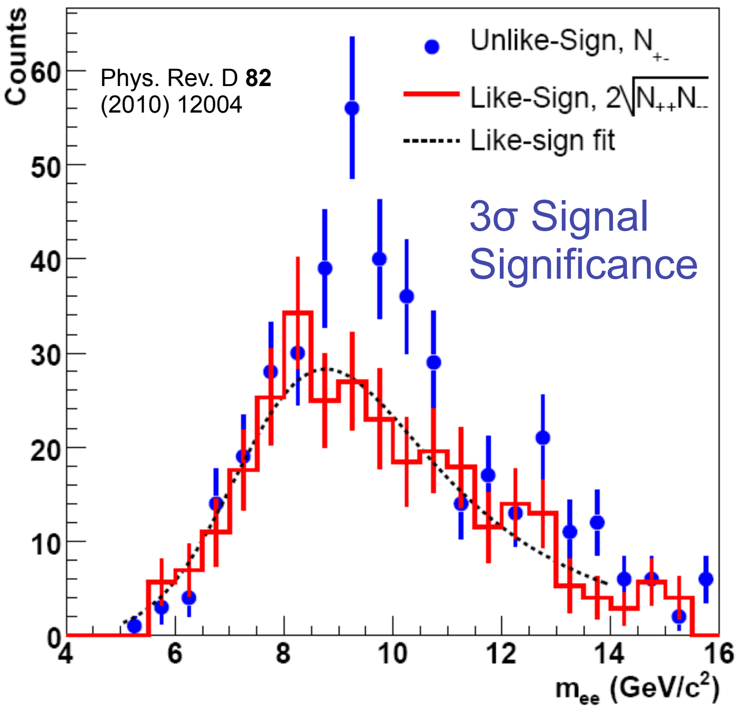
Reality check: What have we learnt about medium from J/ψ?

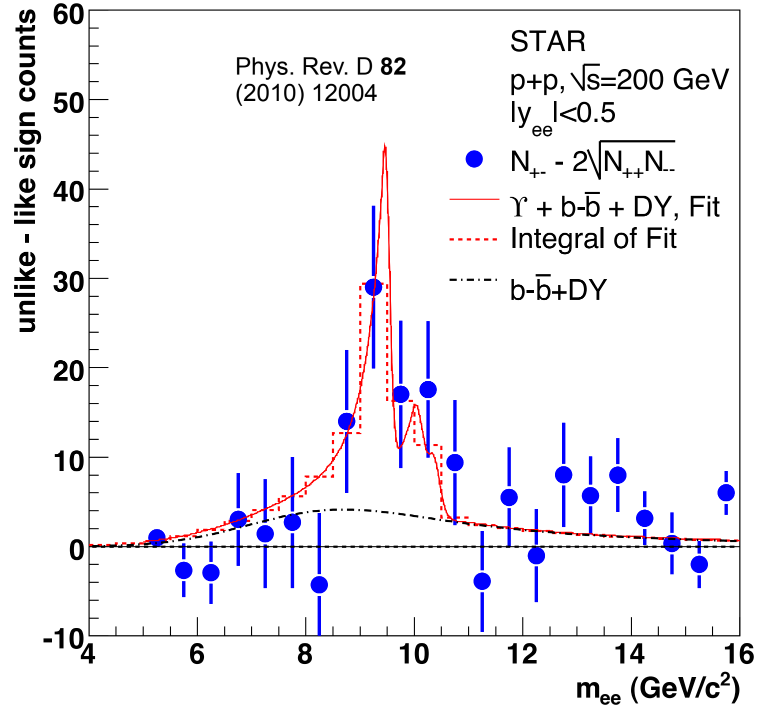
- IMHO: not much when compared to flow, spectra & high-p_T
- Studies need to go on (augmented by LHC results)
- Interpretation difficult
  - production mechanism?
  - feed-down from B and χ_c states?
  - recombination?
  - energy loss (see open heavy flavor)?
  - life and formation time effects?
  - co-mover absorption?

Study of ϒ states avoid many of these difficulties

- Ratios: ϒ(2S)/ϒ(1S) and ϒ(3S)/ϒ(1S) are powerful tools
- No recombination (dN/dy too small), no co-mover-absorption (σ too small), less E-loss ($m_b \gg m_c$), feed-down only from χ_b states
- Caveat: Experimentally difficult but possible given enough L

Υ in p+p 200 GeV





$L = 7.9 \pm 0.6\ \mathrm{pb}^{-1}$

$N_{\Upsilon}(8<m<11) = S - DY\text{-}bb = 61 \pm 20(\text{stat.})$

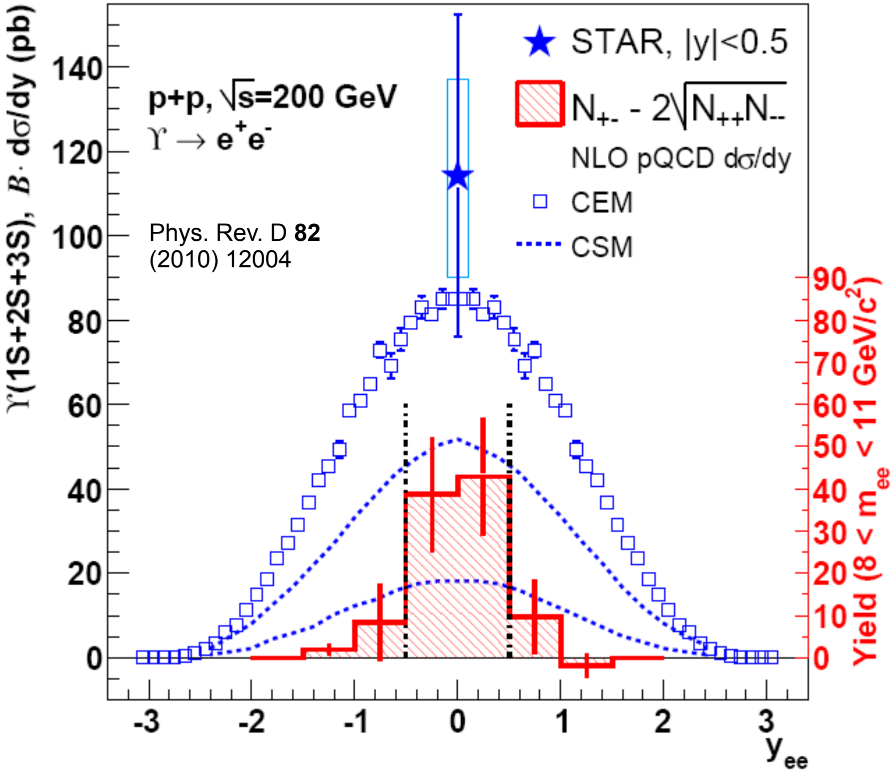
$N_{\Upsilon}(\text{total}) = 67 \pm 22(\text{stat.})$

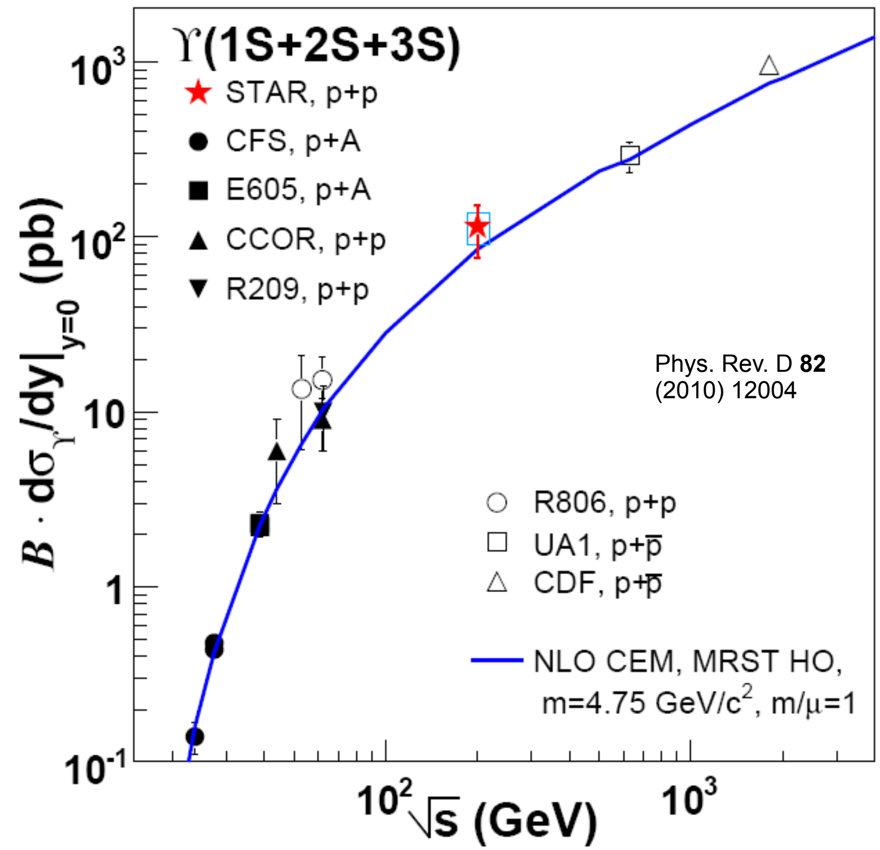
$$\sum_{n=1}^{3} \mathcal{B}(nS) \times \sigma(nS) = \frac{N}{\Delta y \times \epsilon \times \mathcal{L}}$$

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

$$\left(\sigma_{DY} + \sigma_{b\bar{b}}\right)_{|y|<0.5,\, 8<m_{ee}<11\,\mathrm{GeV/c^2}} = 38 \pm 24\ \mathrm{pb}$$

STAR ϒ vs. theory and world data

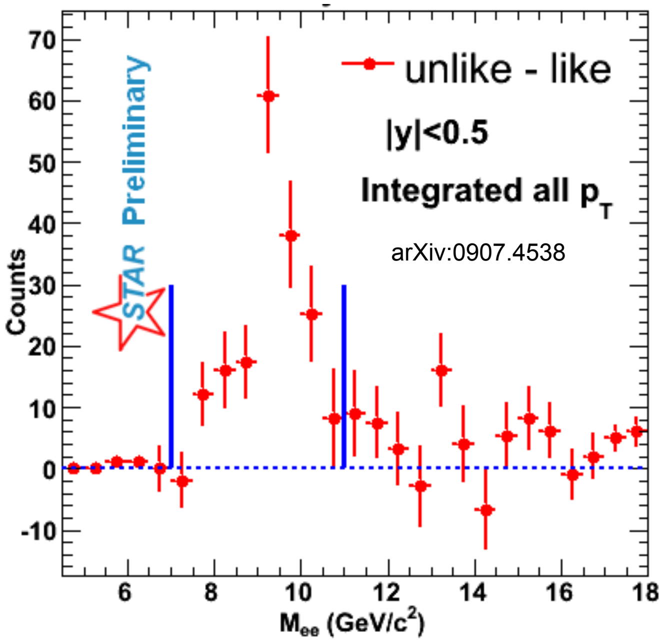




$$\sum_{n=1}^{3} \mathcal{B}(nS) \times \sigma(nS) = 114 \pm 38 \; ^{+23}_{-24} \text{ pb}$$

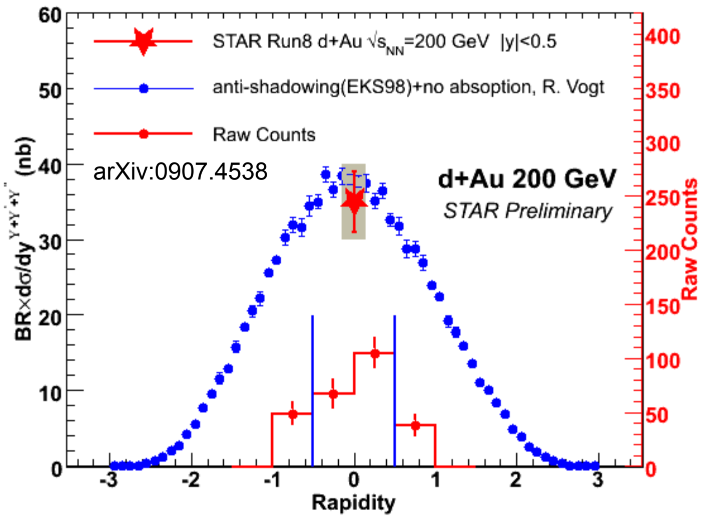
STAR 2006 √s=200 GeV p+p ϒ+ϒ′+ϒ″→ e⁺e⁻ cross section consistent with pQCD and world data trend

Υ in d+Au 200 GeV



Υ(1S+2S+3S) + DY + $b\bar{b}$:
raw yield (7<m<11) = 172 ± 2(stat.)

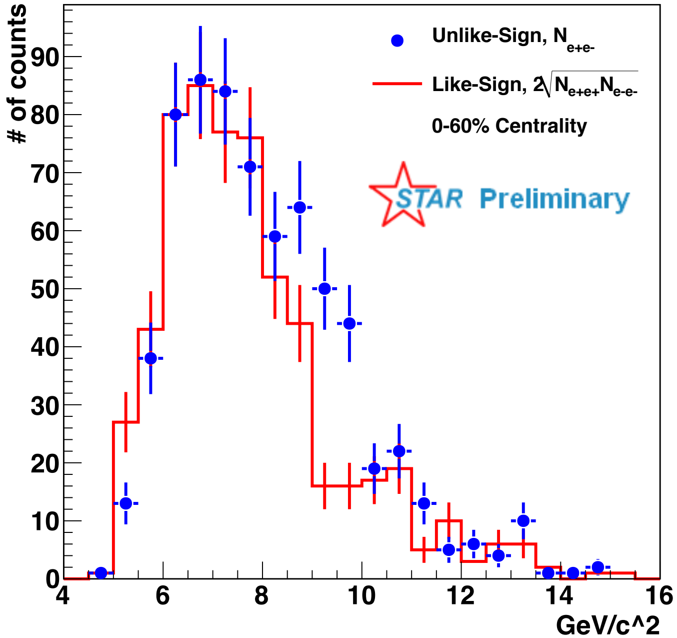
Strong signal (8σ)

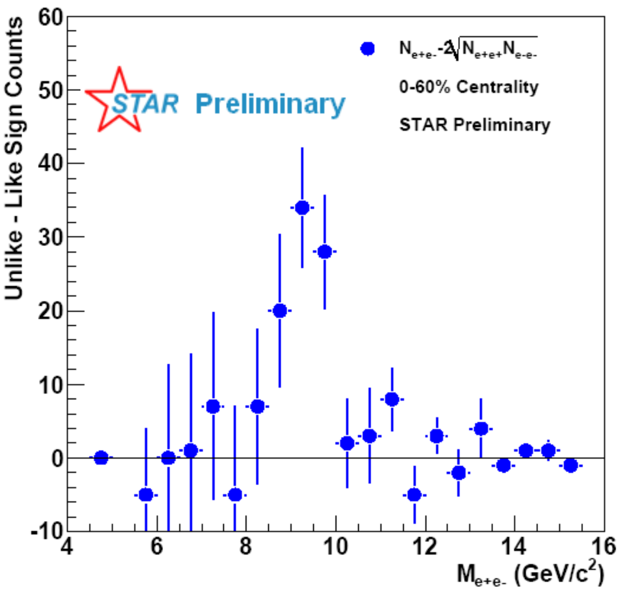


$$R_{dA} = 0.78 \pm 0.28(stat) \pm 0.20(sys)$$

Consistent with N_{bin} scaling

Υ in Au+Au 200 GeV





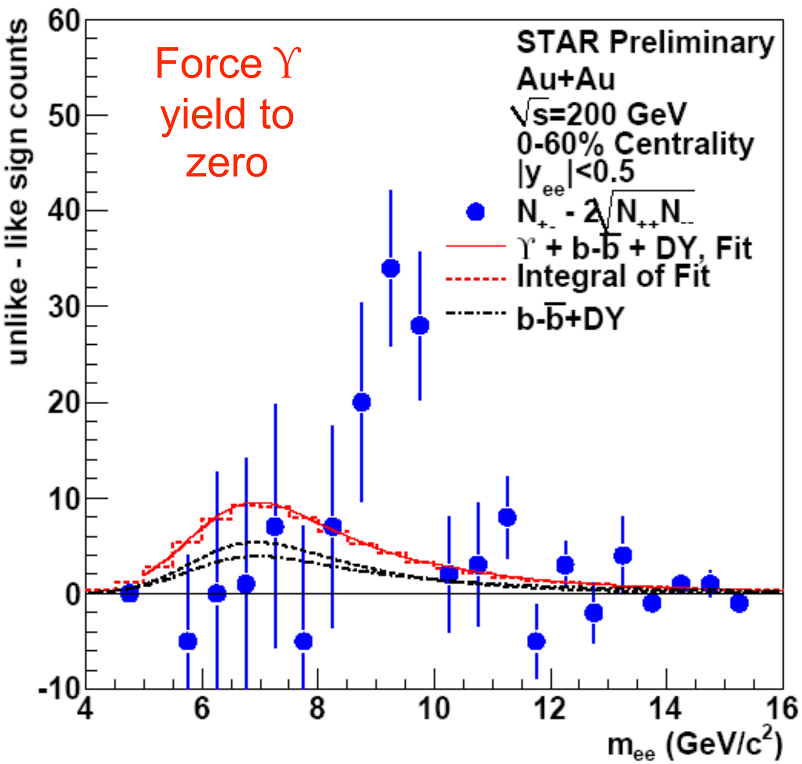
Year 2007
8<m<11 GeV/c^2
Includes: Υ, Drell-Yan, $b\bar{b}$

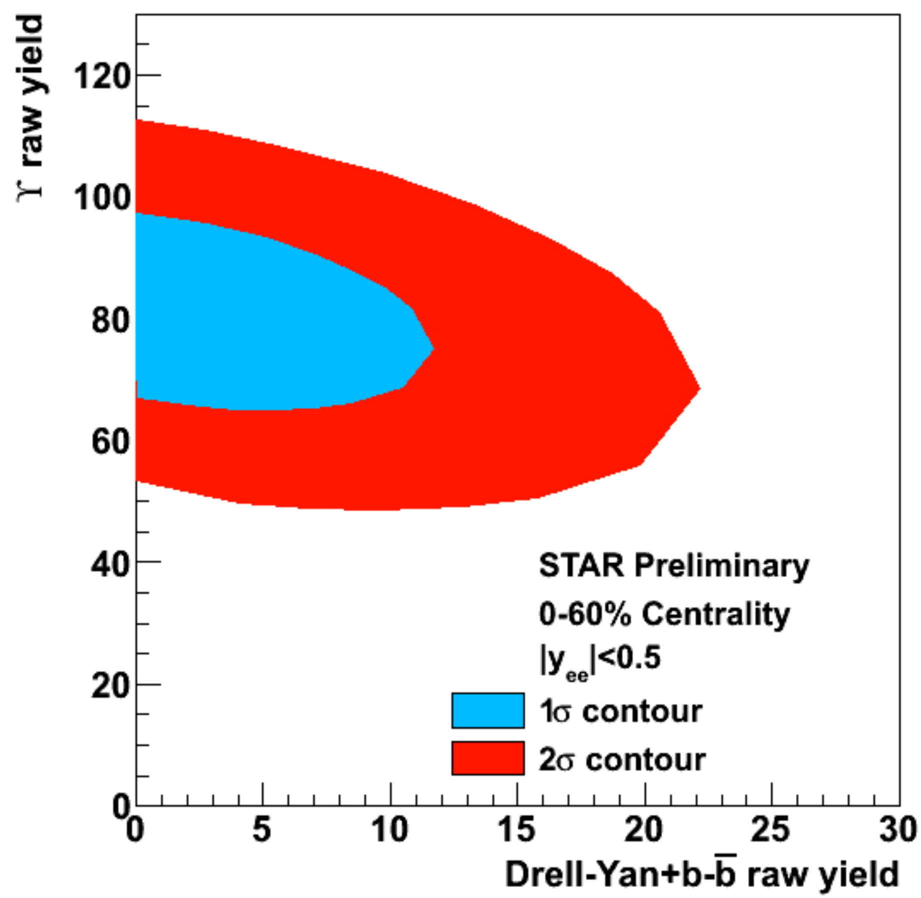
0-60%
4.6σ significance
95 Signal counts
1.11×10^9 events

0-10%
3.5σ significance
47 Signal counts
1.78×10^8 events

Υ Yield Extraction 0-60% Centrality

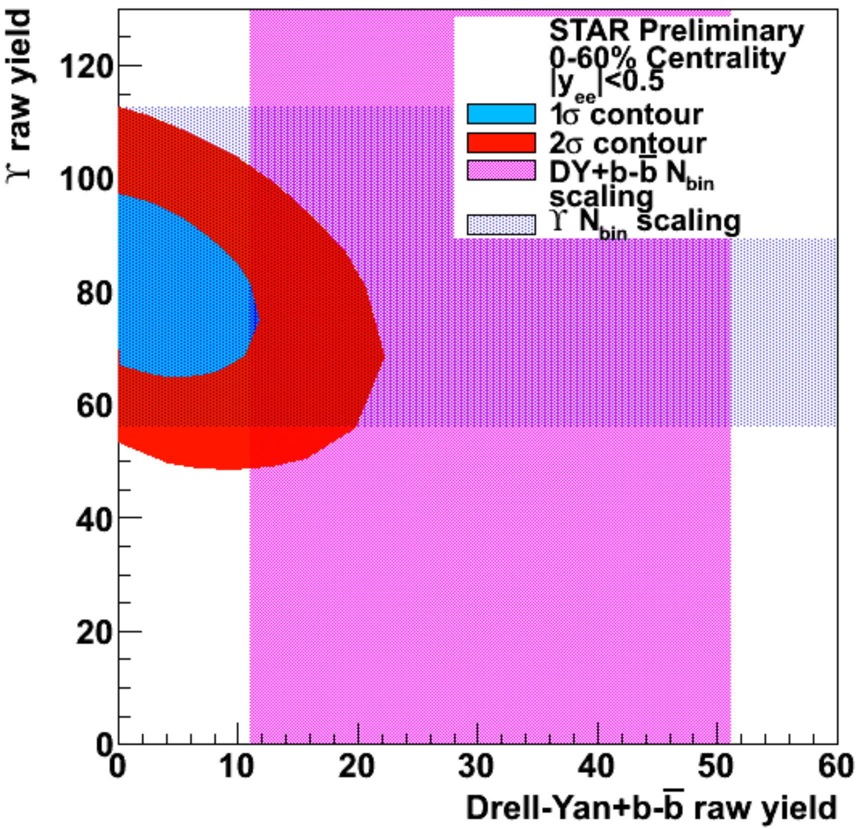
How solid is the signal in Υ(1S+2S+3S) in 0-60% centrality?





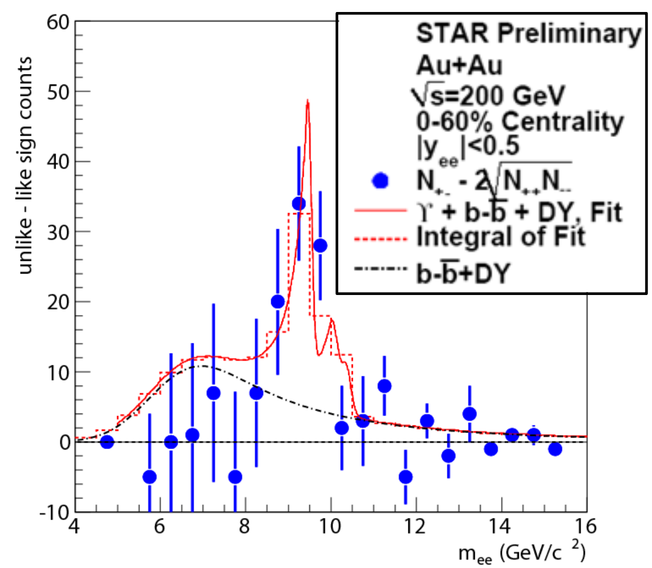
Raw yield of 0 is many sigma away from minimum χ^2

ϒ Yield Extraction 0-60% Centrality



Scaling p+p results for ϒ and DY + $b\bar{b}$ gives us colored rectangles

R_{AA}ϒ(1S+2S+3S) + DY+ $b\bar{b}$ of 1 would be at the center of the intersection between the two rectangles



ϒ yield determined by:

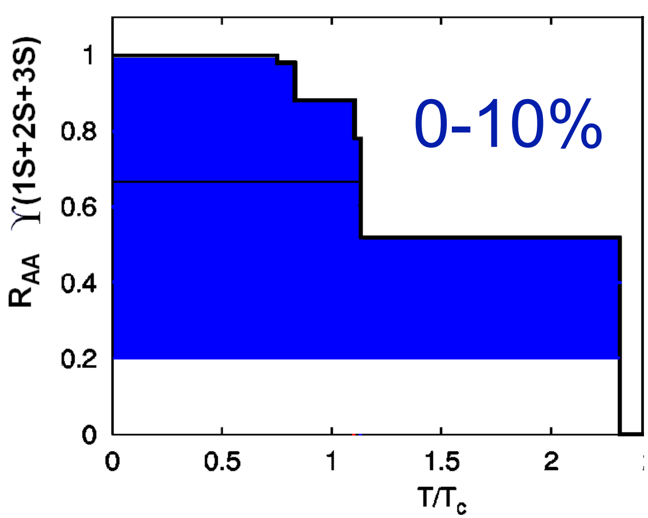
ϒ(8.5<m<11 GeV/c^2) = $N_{+-} - 2\sqrt{N_{++}N_{--}}$ - ∫DY + $b\bar{b}$ = 64±16(stat)±25(sys)

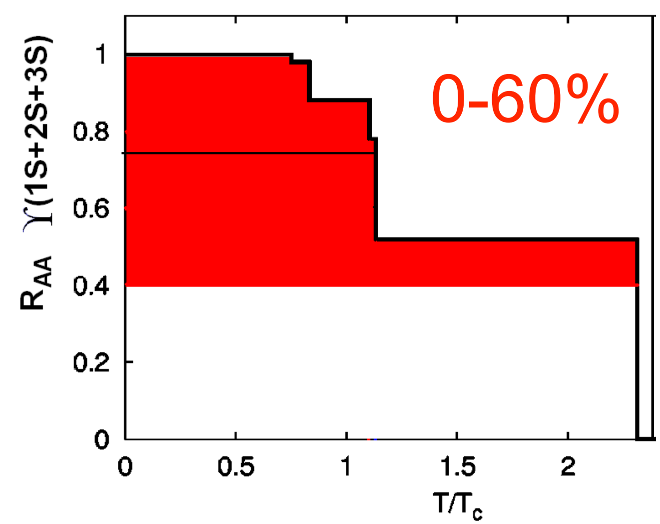
Υ R_{AA} and comparison with predictions

- 0-60%= 0.78±0.32(stat) ± 0.22(sys,Au+Au) ±0.09(sys,p+p)
- 0-10%= 0.63±0.44(stat) ± 0.29(sys,Au+Au) ±0.07(sys,p+p)

$q\bar{q}$	T/T_c
$\Upsilon(1S)$	2.31
$\chi_b(1P)$	1.13
$\Upsilon(2S)$	1.10
$\chi_b(2P)$	0.83
$\Upsilon(3S)$	0.75

S. Digal, P. Petreczky, and H. Satz, PRD 64, 094015 (2001)





No constraints from data yet: need considerably more statistics

Summary

STAR's quarkonium program is in full swing

- J/ψ
  - focus on high-p_T
  - spectra in 200 GeV p+p measured
  - R_{AA} (Cu+Cu) at high-p_T consistent with unity
  - B feed-down in p+p through J/ψ-h correlations
  - RHIC energy scan: due to good S/B solid signal at 39 GeV
- ϒ
  - first cross-section measured in p+p
    - consistent with pQCD calculations
  - d+Au: R_{dAu} = 0.78 ± 28(stat) ± 20(sys)
  - Au+Au:
    - 0-60%= 0.78±0.32(stat) ± 0.22(sys,Au+Au) ±0.09(sys,p+p)
    - 0-10%= 0.63±0.44(stat) ± 0.29(sys,Au+Au) ±0.07(sys,p+p)
  - More statistics needed but we are well on our way