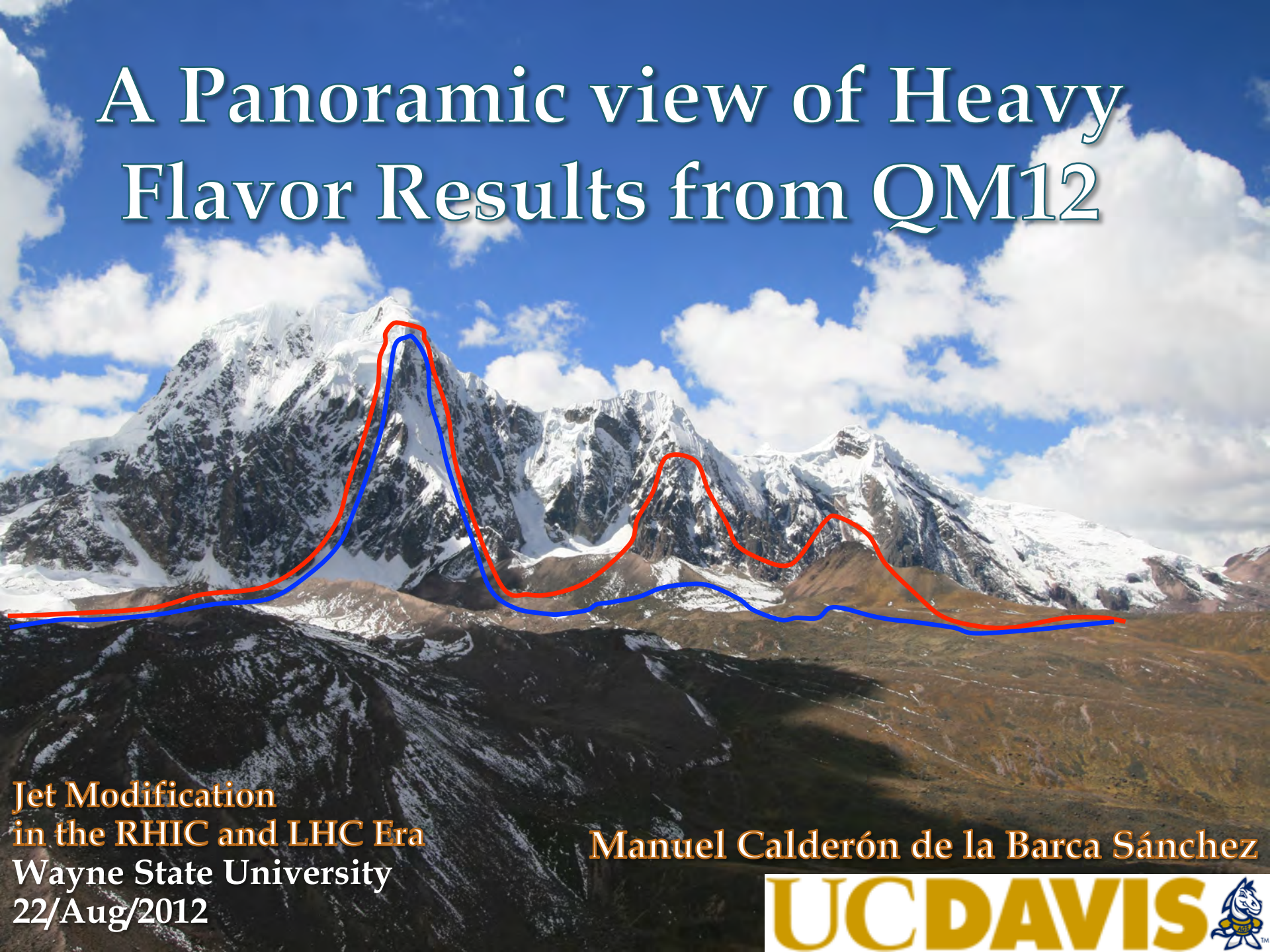
# A Panoramic view of Heavy Flavor Results from QM12



Jet Modification
in the RHIC and LHC Era
Wayne State University
22/Aug/2012

Manuel Calderón de la Barca Sánchez
UCDAVIS

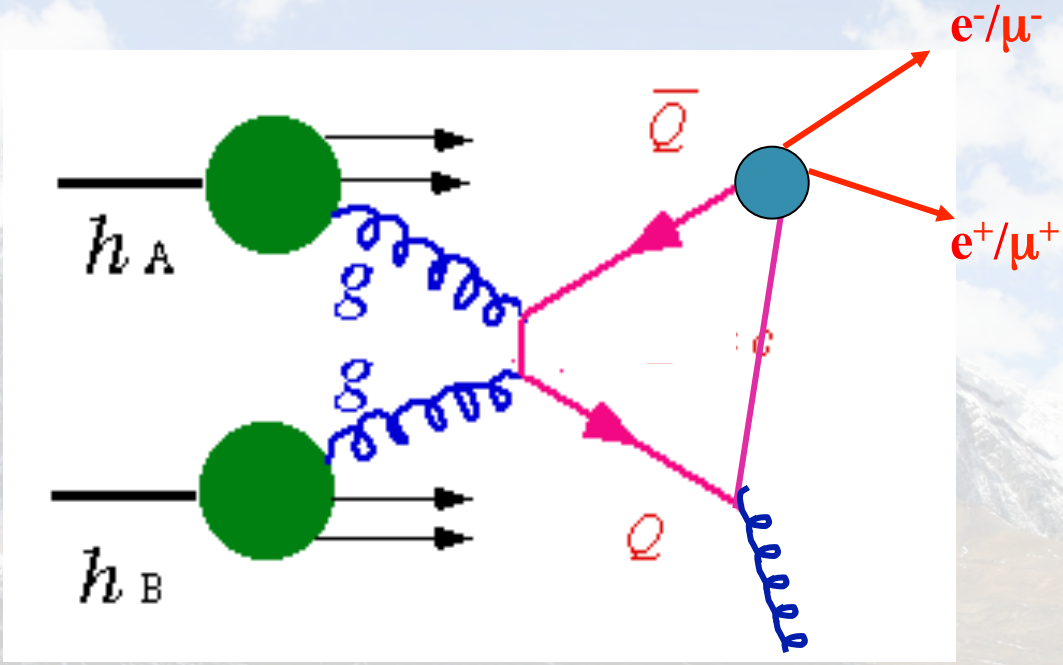
# Heavy Quarks

- Heavy Quarkonia in medium
  - J/$\psi$
  - $\Upsilon$ : A cleaner probe of the medium.
- Open Heavy Flavor
  - Non-Photonic Electrons and D meson $R_{AA}$
  - D meson $v_2$
  - The quest for Beauty
    - b fraction via electron DCA
    - Non-prompt J/$\psi$
    - b-jet reconstruction

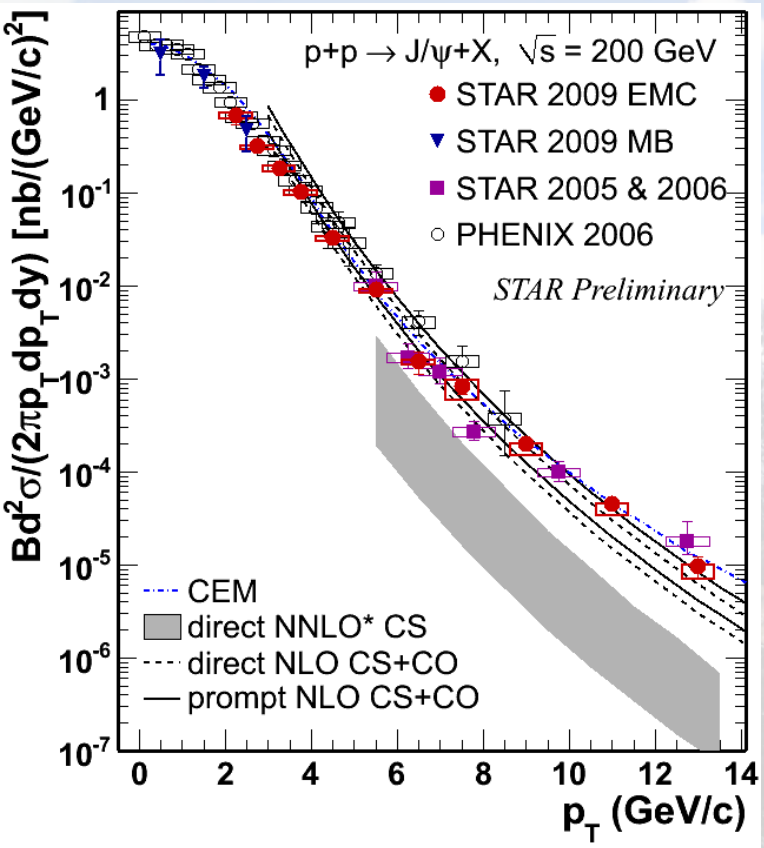


Ilya Ilyin.
WR: 233 kg lift

# Quarkonia

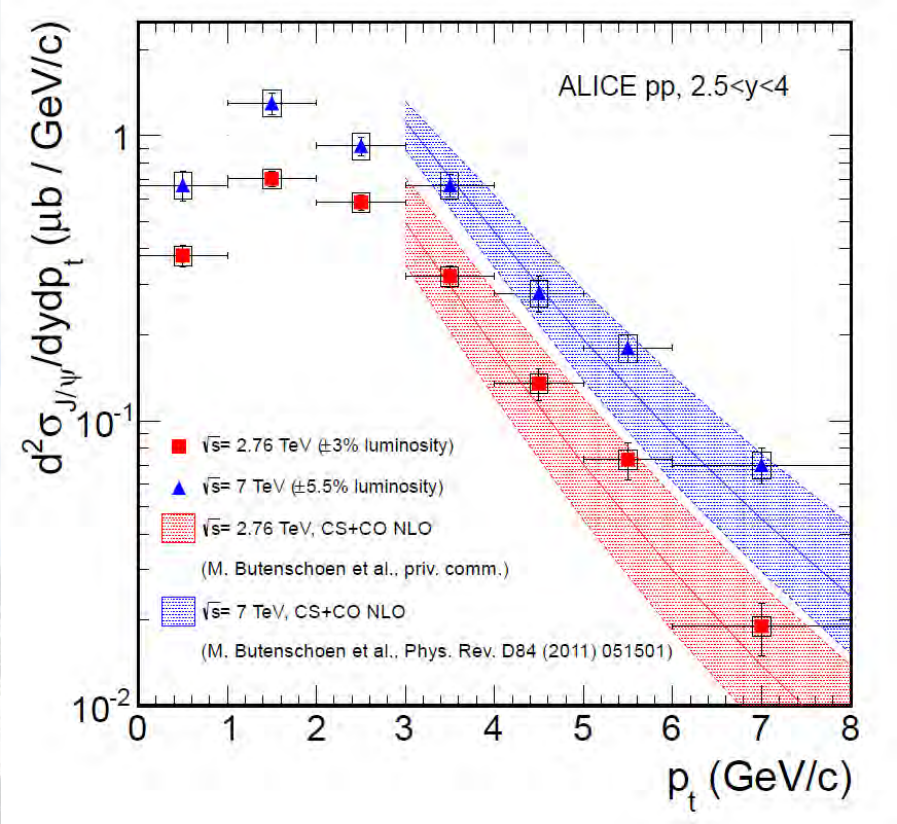


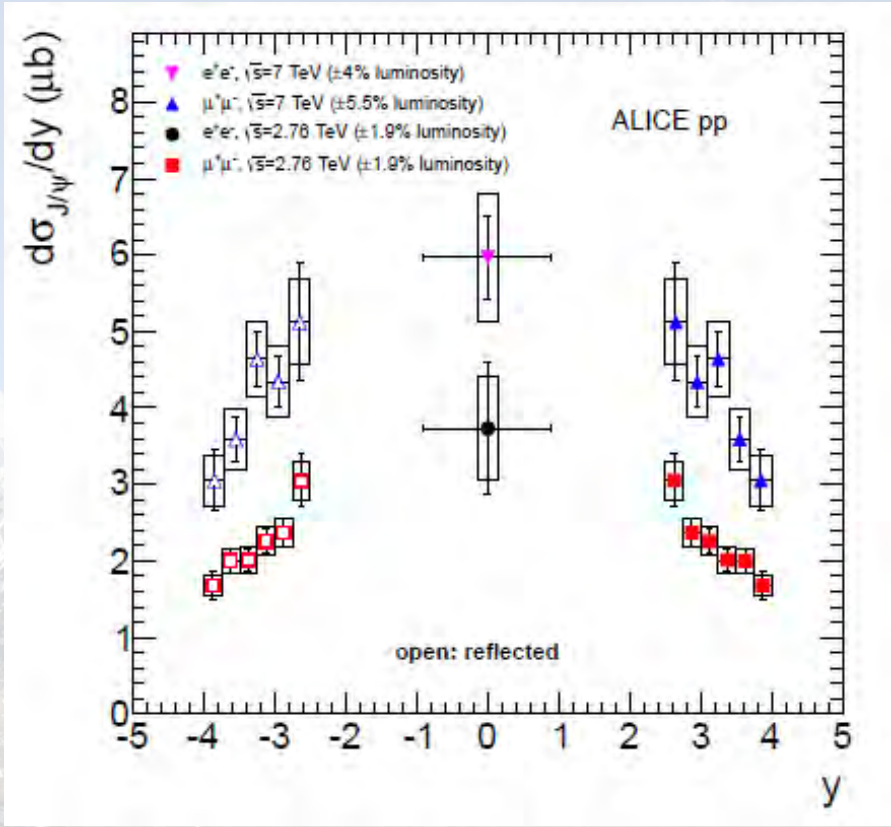
# J/Ψ Production: pp Baseline @ RHIC




- STAR & PHENIX: Consistent results
- Color Singlet + Color Octet, Color Evaporation: consistent with data.
- Color Singlet: ruled out.

# J/Ψ Production: pp Baseline @ LHC

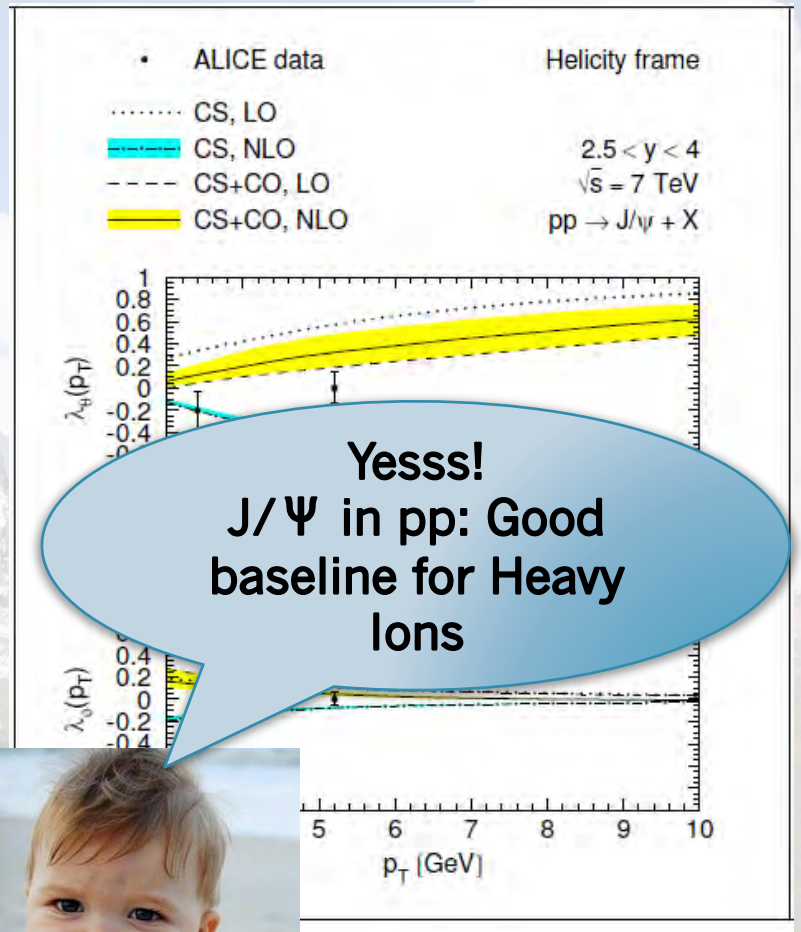


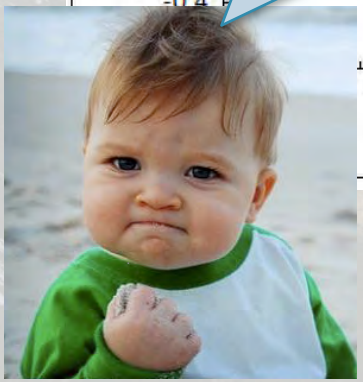




- ALICE results.
- CS + CO NLO : Consistent with ALICE data.
- Rate can be calculated in pp. What about polarization?

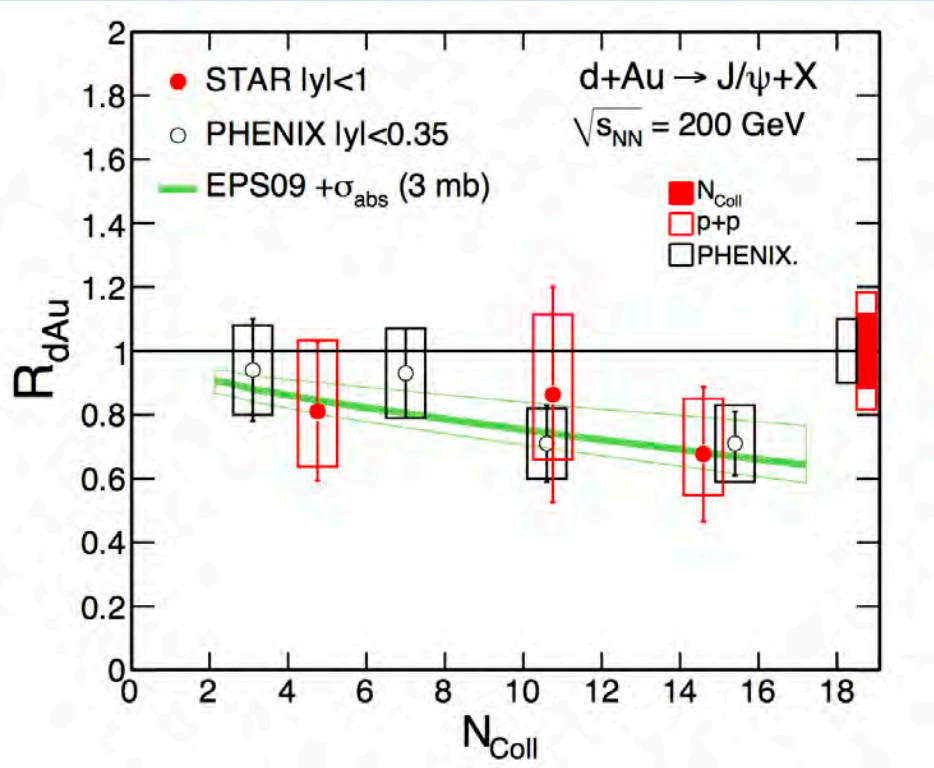
# J/Ψ Polarization

- Polarization: can help discriminate between production mechanisms.
- Longstanding puzzle from Tevatron measurements.
  - No model was consistent with data.
- Experimental result:
  - Almost no polarization.
- Theory result:
  - CS+CO at NLO: not too bad!



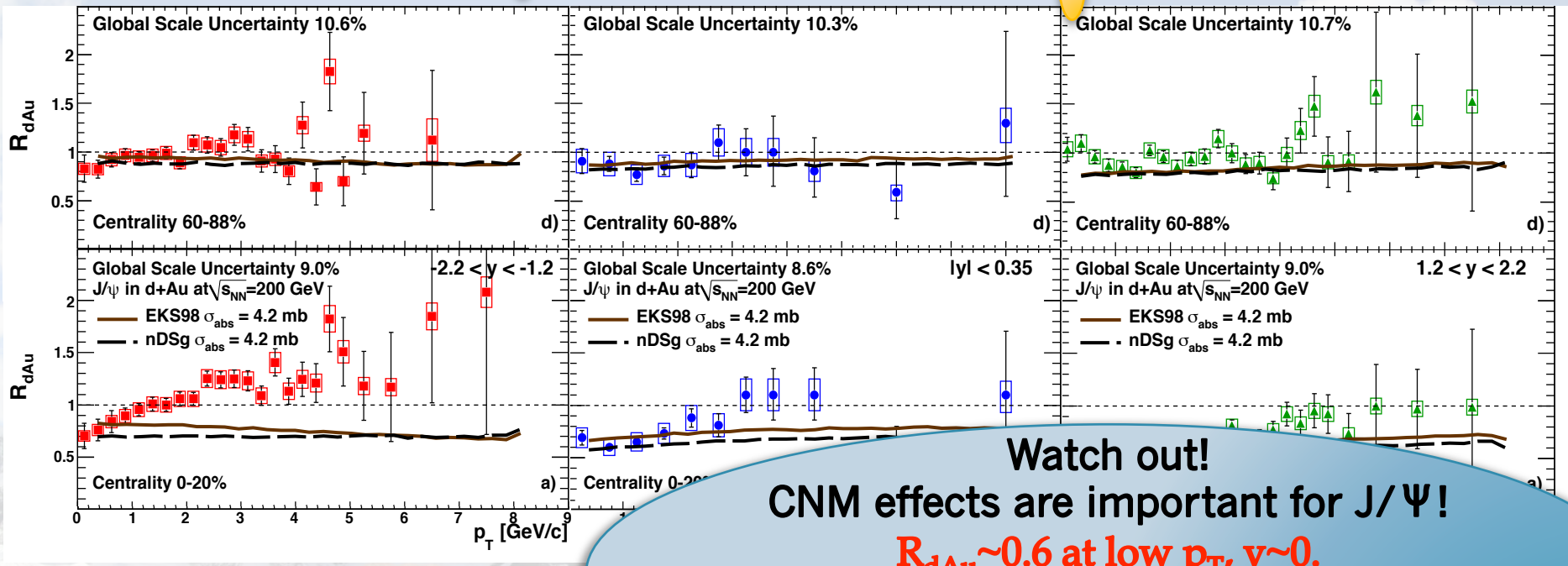



# J/Ψ in dAu: STAR & PHENIX




- STAR and PHENIX: consistent results at midrapidity.
- Is shadowing + breakup cross-section enough to describe dAu?

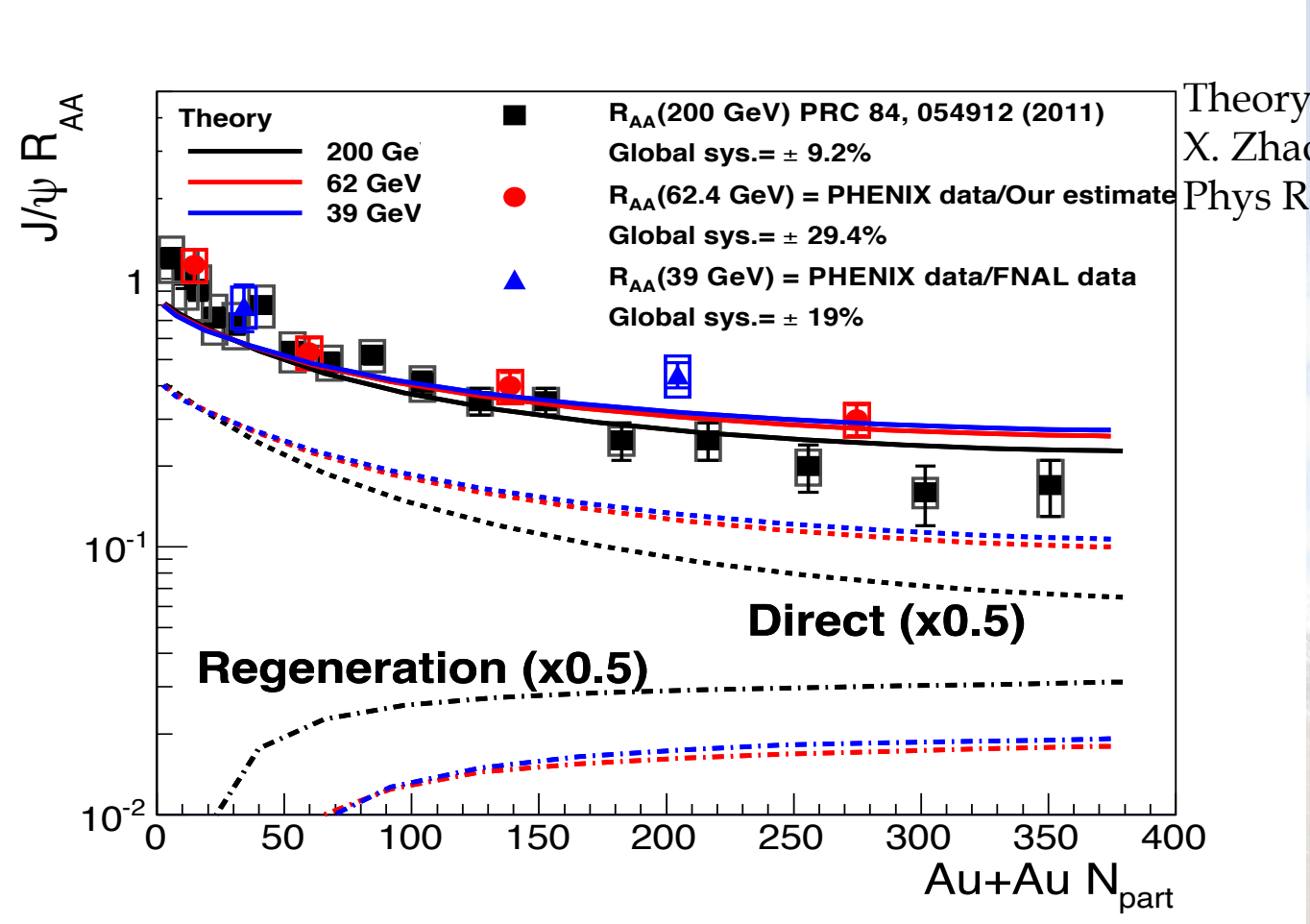
# J/Ψ in dAu: CNM effects




**Watch out!**
**CNM effects are important for J/Ψ!**
**$R_{dAu}$~0.6 at low $p_T$, y~0.**
**Backward rapidity needs more than Shadowing + $\sigma_{br}$**

- PHENIX: Study rapidity and cent
  - Dashed line: Shadowing + $\sigma_{br}$ model (no Cronin)
  - Peripheral (Top) : Weak modification. Shadowing works ok.
  - Central (bottom) : Stronger modification. Suppression in CNM. No suppression in high pT.
    - Largest enhancement at Backward rapidity high pT. Model ta. Cronin?

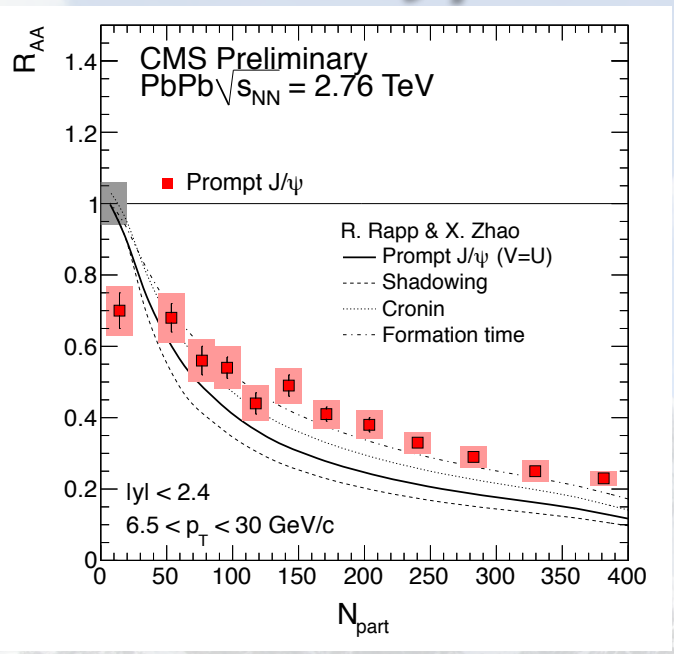
# J/Ψ in AuAu: Energy dependence

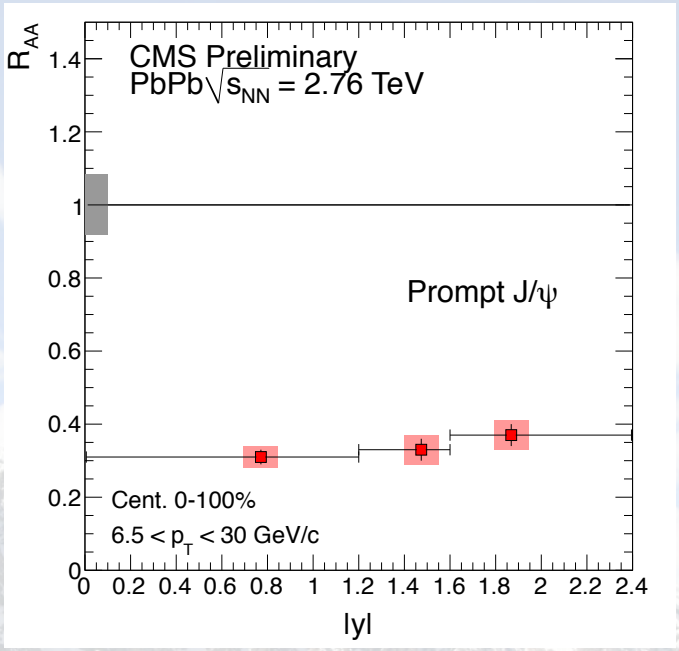


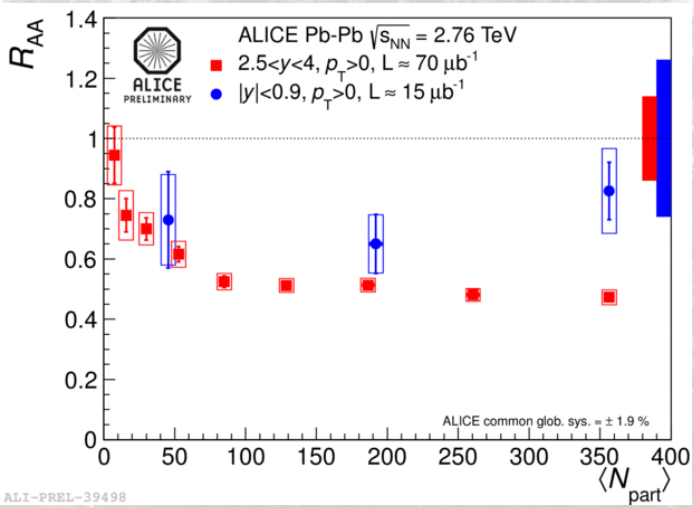

Theory:
X. Zhao, R. Rapp
Phys Rev C82 064905 (2010)

- Lower energies: suppression is similar than at 200 GeV.
- Suppression + Regeneration: surprising cancellation!
  - This is at forward rapidity: 1.2 < |y| < 2.2

# J/Ψ in PbPb at LHC

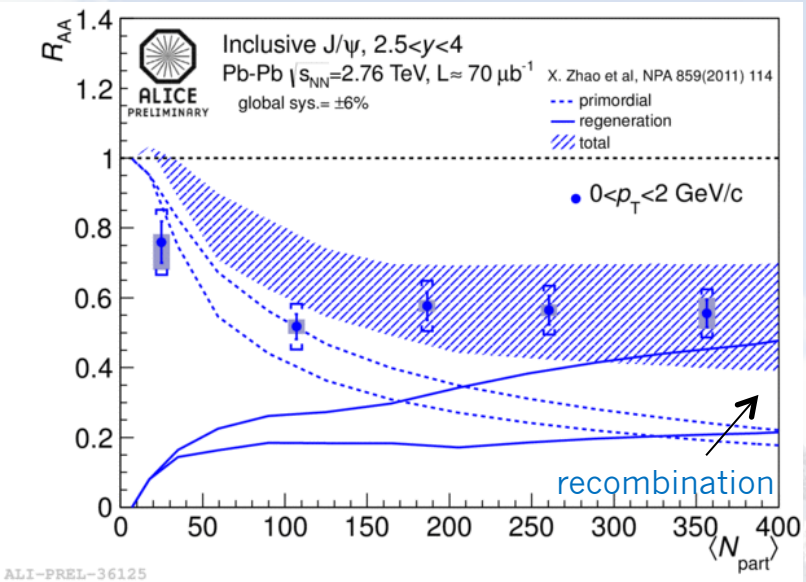


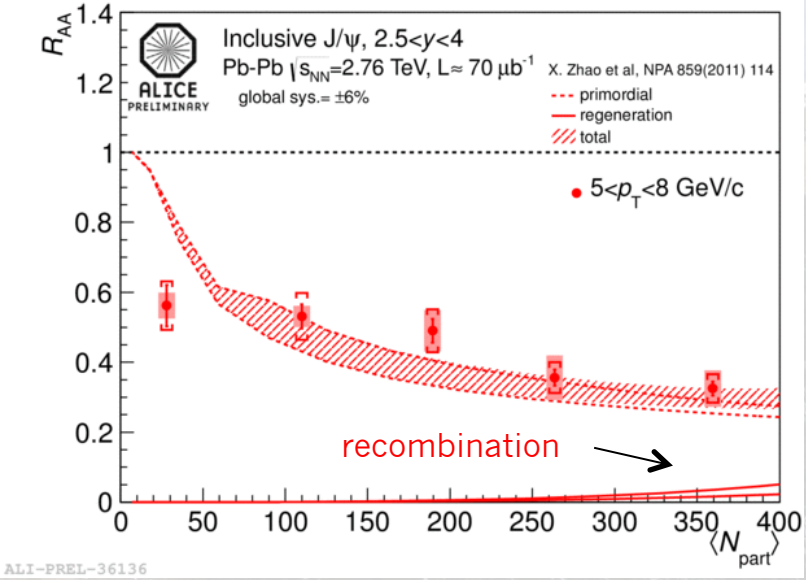




- CMS: $p_T$>6.5 GeV/c |y|<2.4
  - Increasing suppression vs. Npart
- ALICE: $p_T$>0. **|y|<0.9** and **2.5<y<4**
  - Less Suppression at low pT
    - Less suppression than at RHIC
    - Midrapidity vs. forward: errors too large to say if difference is significant
- Recombination?
  - At low $p_T$ needed to explain ALICE data.
  - Not needed at high pT to explain CMS data.

# $R_{AA}$ vs $N_{part}$ in $p_T$ bins



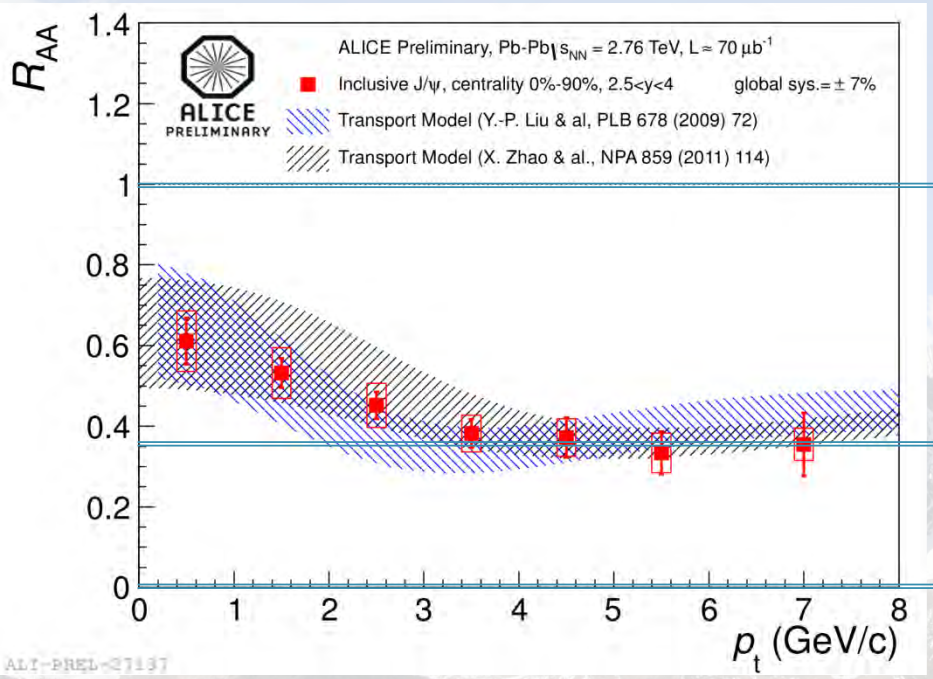



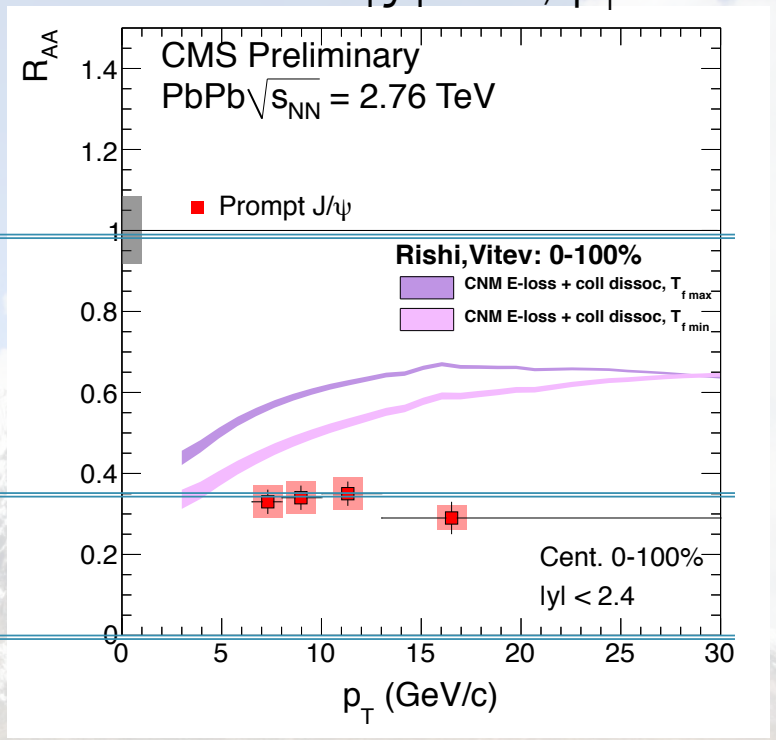

- Recombination should play a role at low $p_T$.
- Different suppression pattern for low- and high-$p_T$ J/ψ
  - Data also in forward rapidity:
    - 2.5<y<4
- Smaller $R_{AA}$ for high $p_T$ J/ψ
- Model (Zhao & Rapp):
  - ~50% of low-$p_T$ J/ψ produced via (re)combination
  - high $p_T$: contribution is negligible
  - Works well for $N_{part}$ > 100
  - Same model worked for PHENIX energy dependence of J/ψ $R_{AA}$.

# $J/\Psi$ $R_{AA}$ vs. $p_T$

ALICE: 2.5<y<4. $p_T$<8

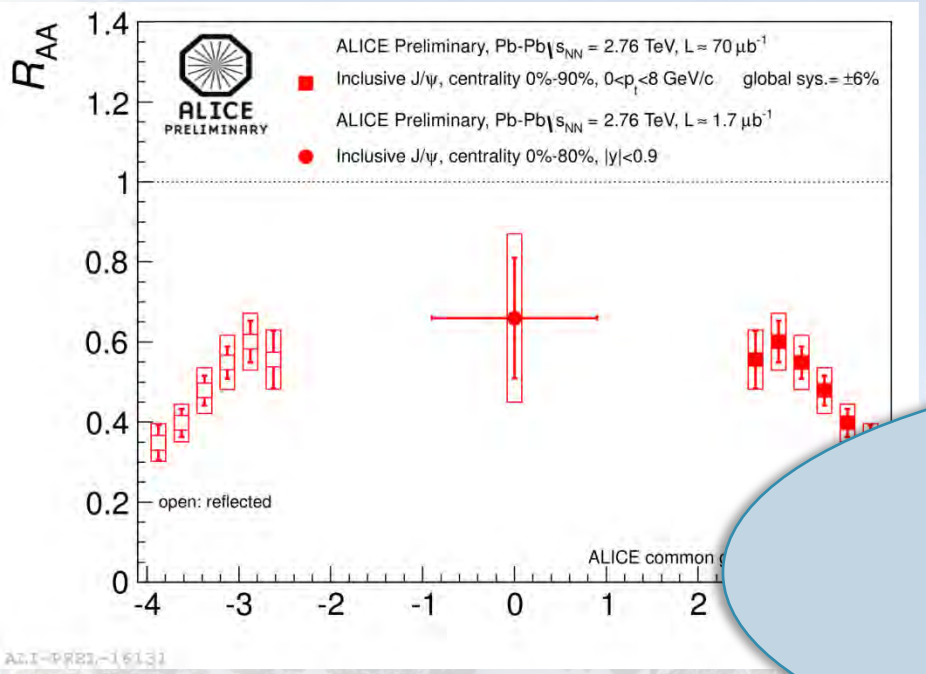
CMS: |y|<2.4, $p_T$>6.5

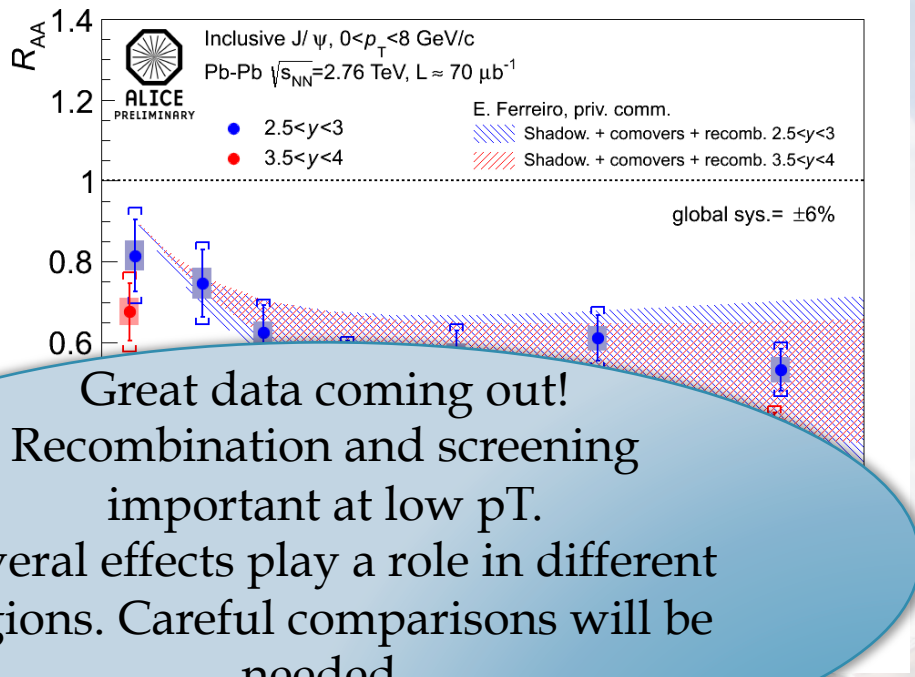



- $R_{AA}$ above $p_T$>4 GeV ~ 0.35 for both.
  - Not apples to apples: inclusive vs. prompt. Different *y*.
- $R_{AA}$ for low $p_T$ in ALICE: contributions from recombination needed at low $p_T$.
- $R_{AA}$ for high $p_T$ in CMS:
  - no recombination.
  - Model including CNM E-loss + collisional dissociation: ruled out at high $p_T$.

# J/Ψ $R_{AA}$ vs. y at LHC



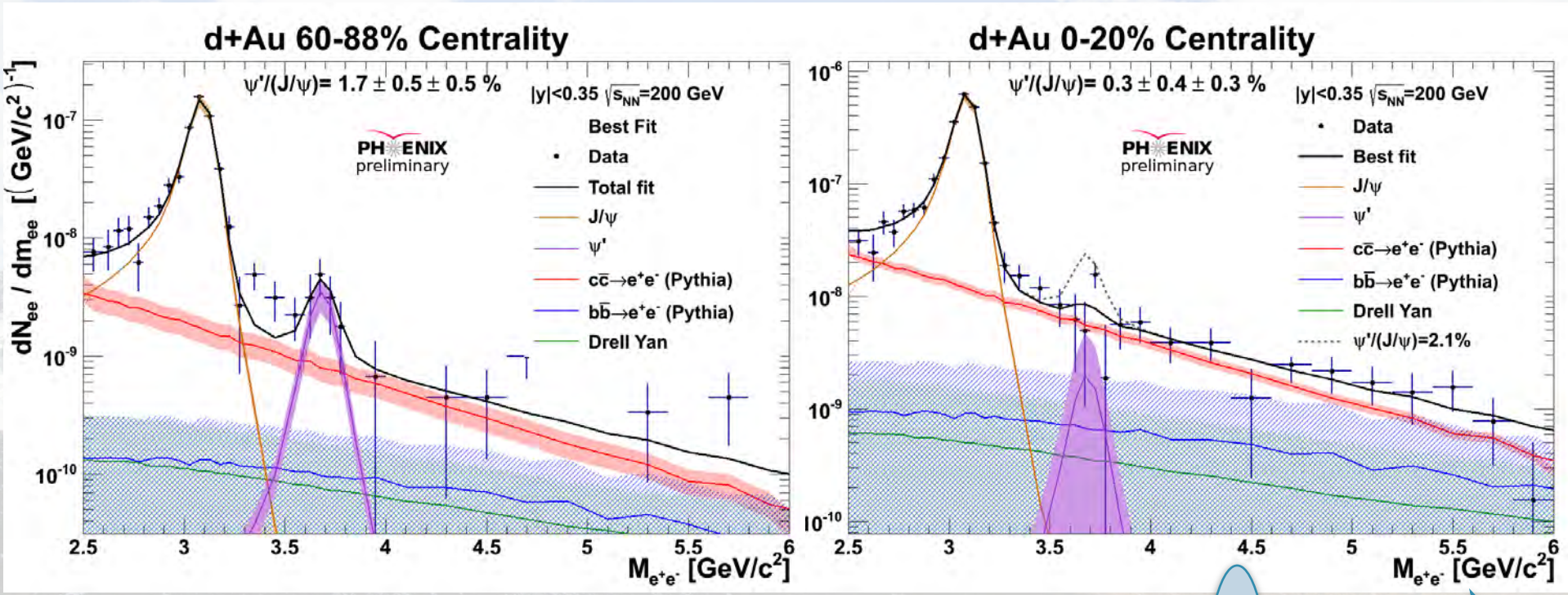




Great data coming out!
Recombination and screening important at low pT.
Several effects play a role in different regions. Careful comparisons will be needed.

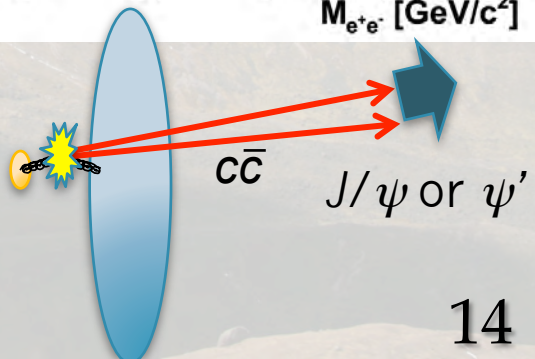
- Suppression:
  - More suppressed in central collisions.
  - More suppressed in forward rapidities.
  - Comover+regeneration+shadowing model
    - (no screening/primordial suppression)
    - predicts a weaker rapidity dependence than seen in data.

# Ψ' in dAu collisions at RHIC

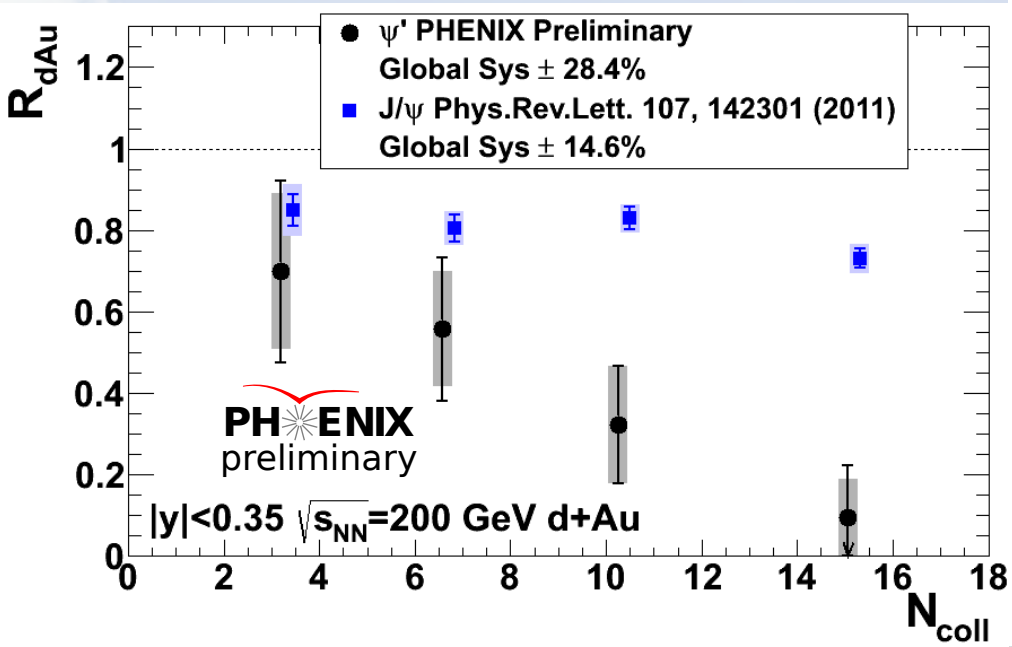
- Measure Ψ(2S) relative to Ψ(1S)
  - PHENIX : |y|<0.35, e+e- measurement

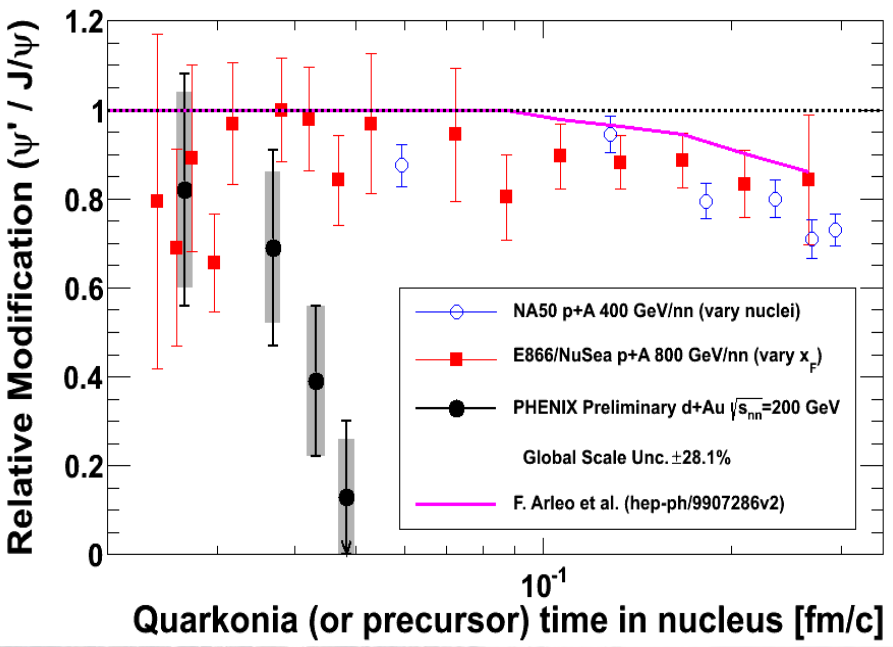



- If both charmonium states form outside the medium:
  - ψ‘/ J/ψ should be the same in dAu and pp.



# ψ' highly suppressed in dAu

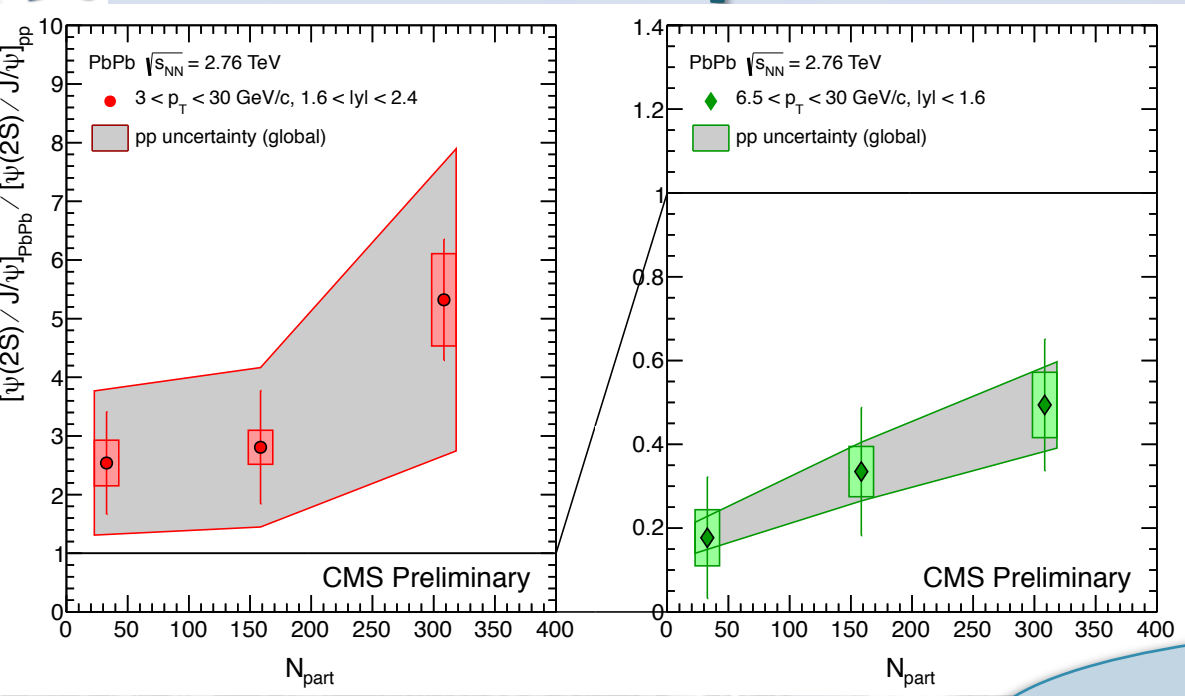


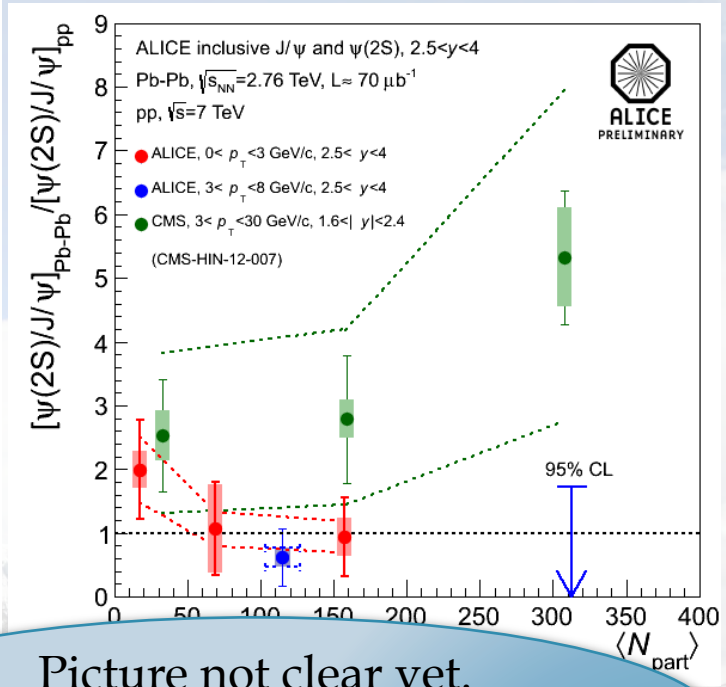




- "Relative Modification" : ψ'/ J/ψ in dAu compared to pp.
  - If only formation time matters, "Relative Modification" ~ 1.
- Expect a bit more suppression than J/ψ : Different break-up cross sections
  - r ~ 0.25 fm, r ~ 0.45 fm:
    - radius is larger by factor ~2
    - Leads to Small eff
- Relative Modificatio

**Wha..?!**
**New PHENIX data is completely at odds with formation time + $\sigma_{br}$ picture.**

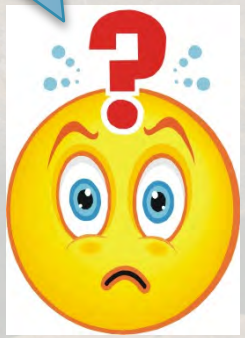
# ψ' in PbPb



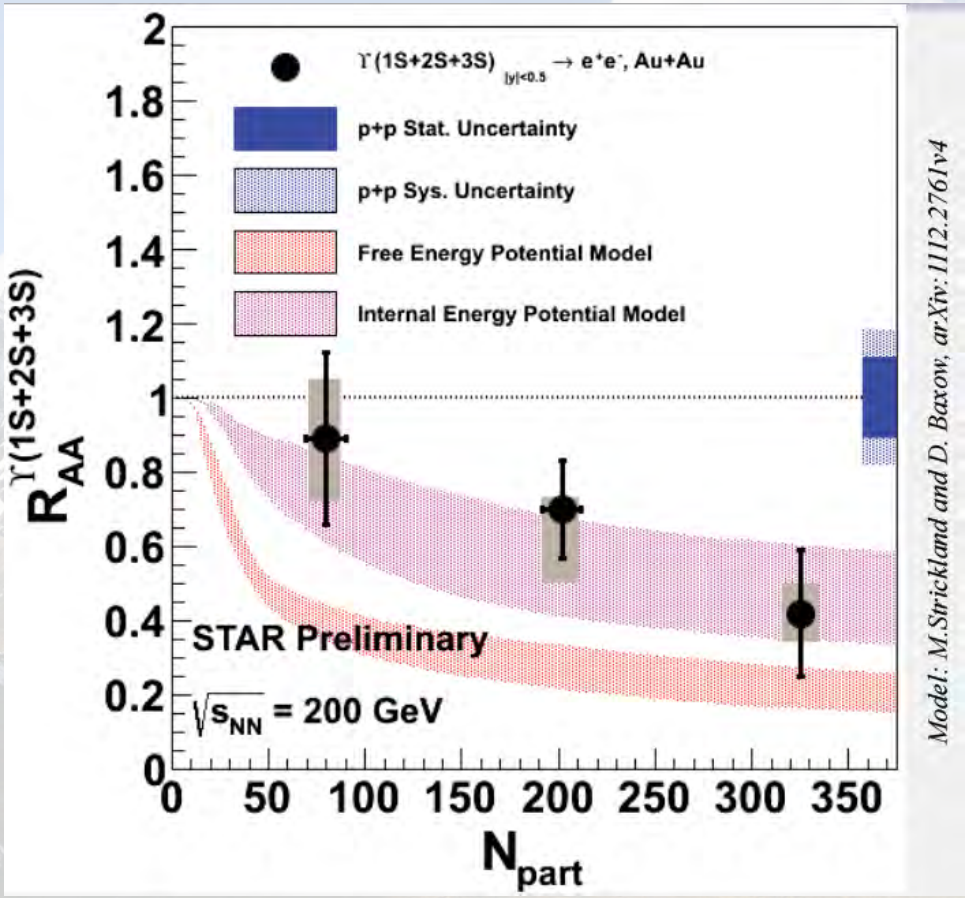

- |y|<1.6, 6.5<$p_T$<30GeV/c : ψ'/J/
- 1.6<|y|<2.4, 3<$p_T$<30 GeV/c: ψ'/J/ψ ratio **larger** th pp.
  - Large pp uncertainty. only a ~2 sigma effect.
- 2.5 < y < 4.
  - Low $p_T$ 0-3 GeV/c:ψ'/J/ψ ratio ~ **same** as in pp.
  - Intermediate $p_T$ 3-8 GeV/c: ratio ~ **same** as in pp.

Picture not clear yet. Errors still large. Need a better pp reference!

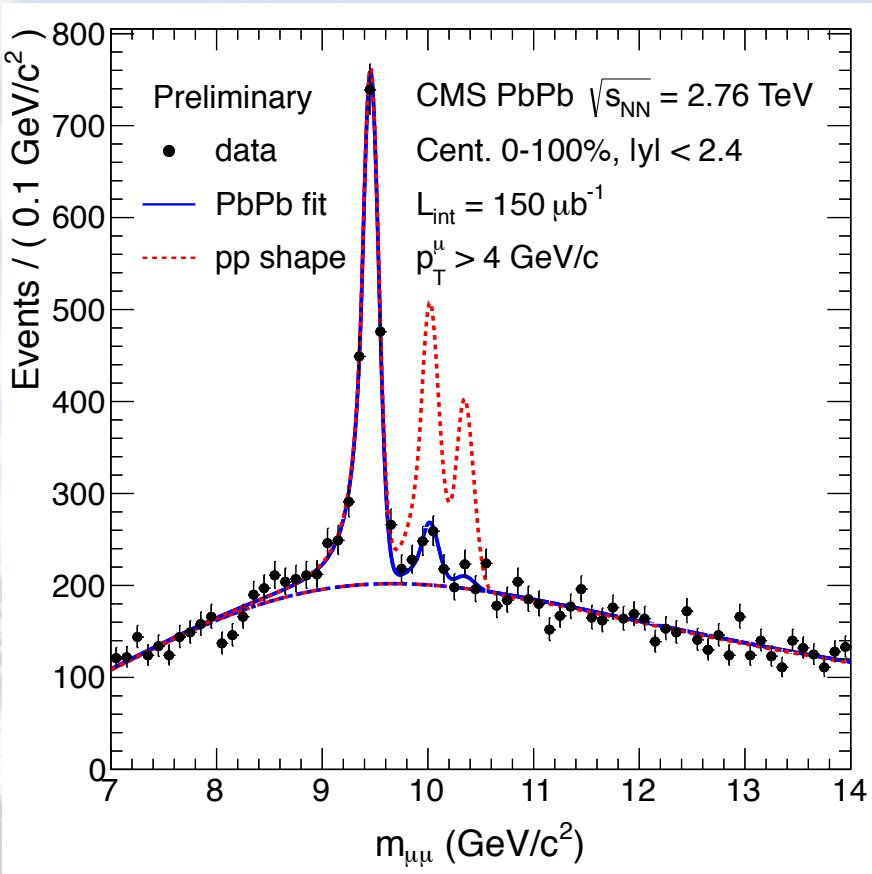


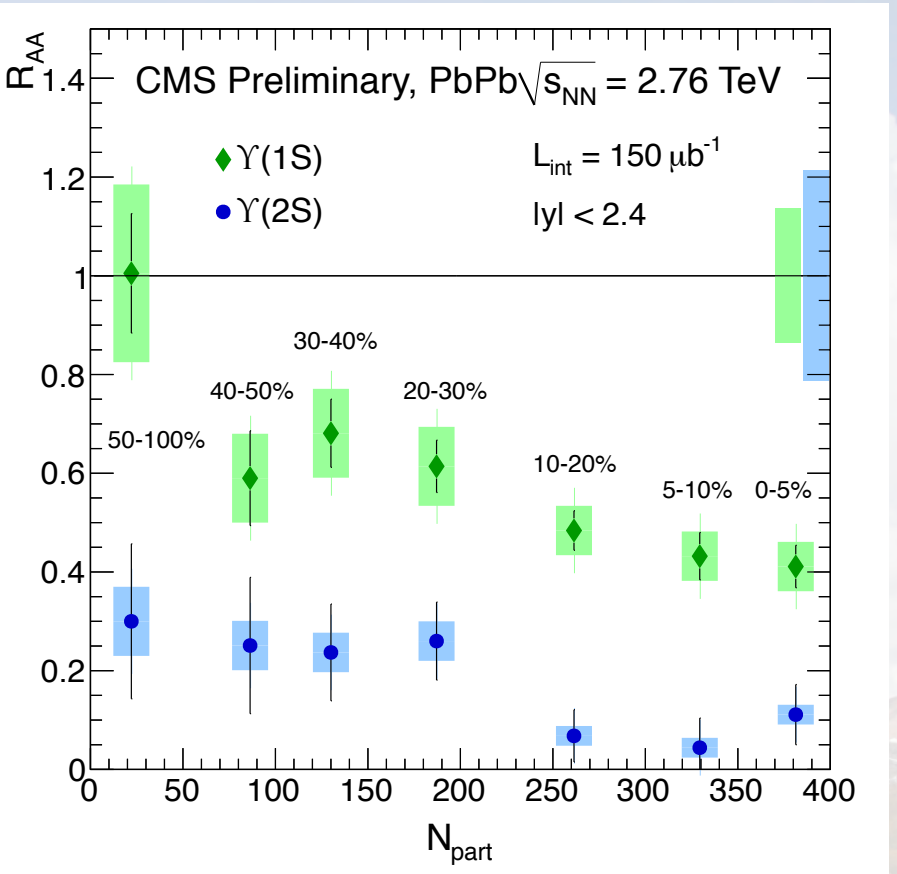
# Go Heavier! ϒ Production at RHIC

- A better probe of the medium:
- Smaller co-mover absorption
- Negligible regeneration
- Higher mass, pQCD calculations work better
- STAR:
  - Significantly improved p+p measurements w/ ~2.5x more lum.
  - Consistent with prediction from model requiring strong 2S and complete 3S suppression.



# Excited bottomonium states!

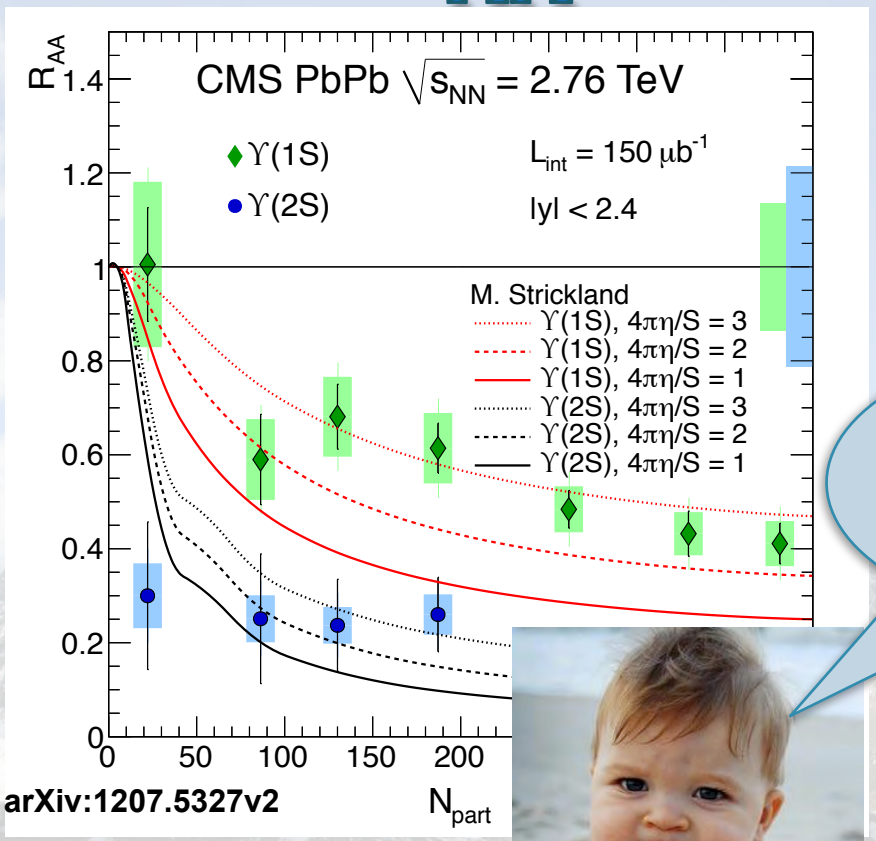


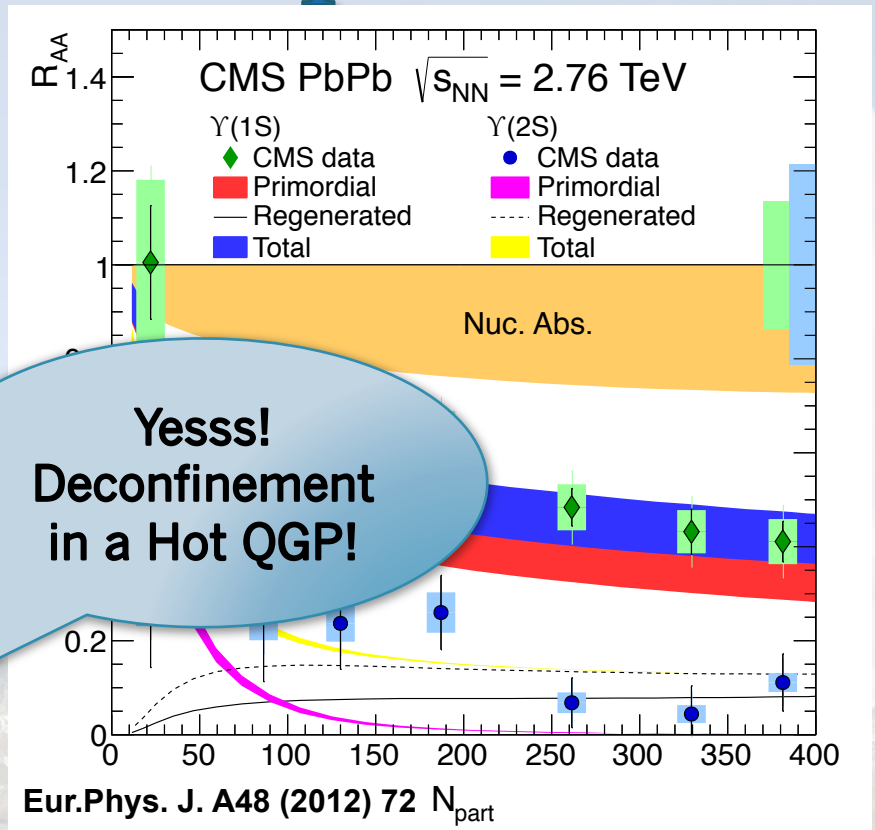




- CMS : First $R_{AA}$ measurement for Υ(2S).
- Centrality integrated:
  - Υ(1S): 0.56±0.08±0.07
  - Υ(2S): 0.12±0.04±0.02
  - Υ(3S): <0.10 at 95% CL

- $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$
- **Observation of Sequential melting**

# $\Upsilon$ $R_{AA}$ model comparison



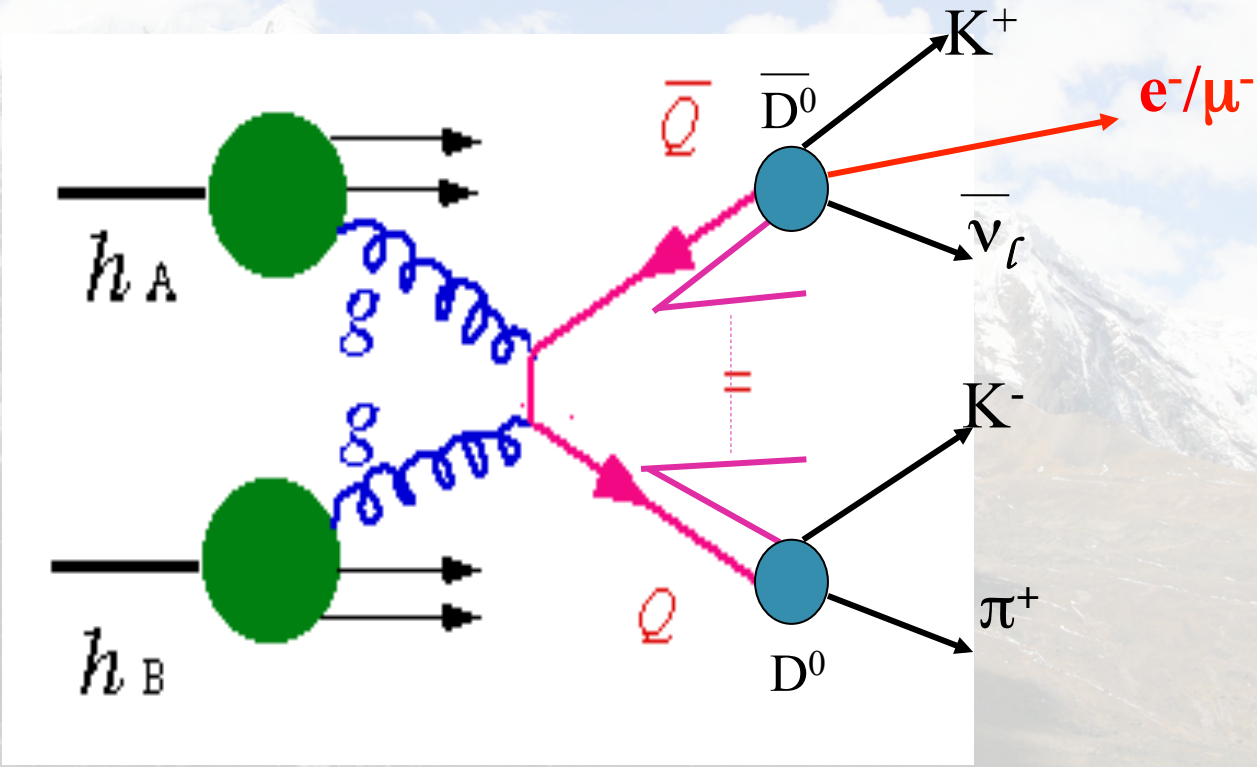




- Both models:
  - Connections to Lattice Q… …nt)
    - Potential Models or Spectral functions.
  - Dynamical evolution (hydro or kinetic theory).
  - Include feed-down contributions.

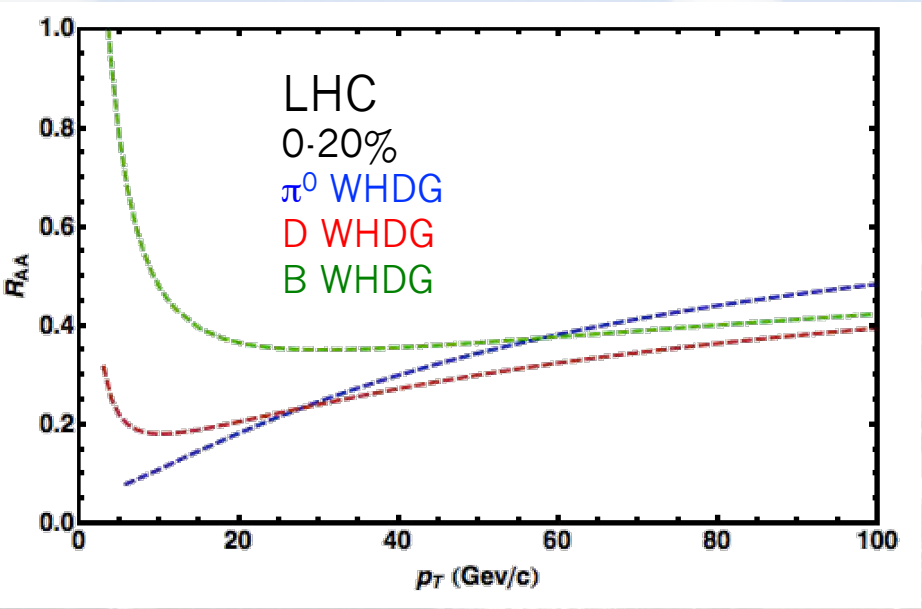
- High Temperatures!
  - M. Strickland: 494 < T < 520 MeV.
  - Emerick, Zhao & Rapp: T ≈ 600 MeV
- Regeneration is small for 1S.
- Nuclear Absorption is not: need pPb and dAu.

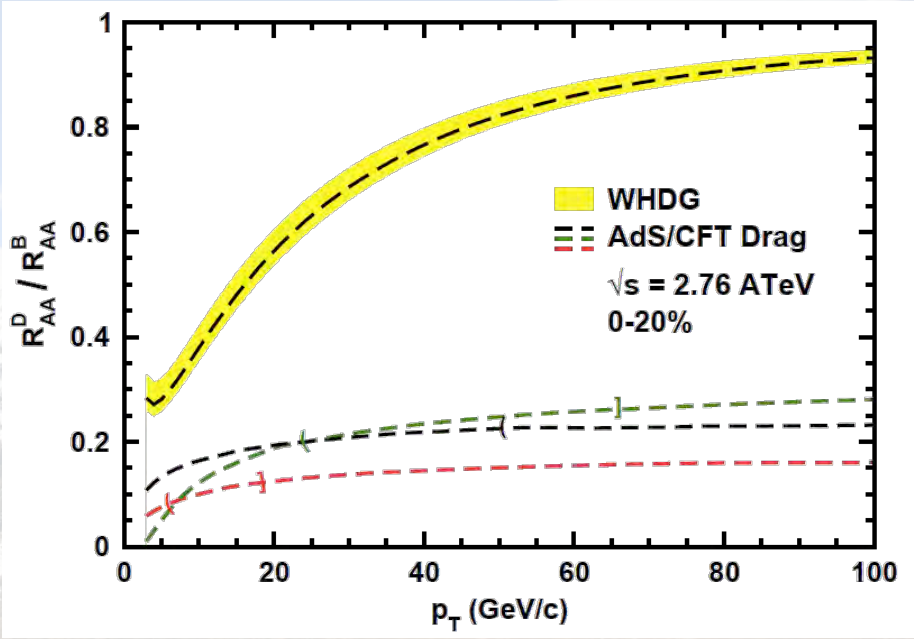
# Open Heavy Flavor



# Heavy Quark Energy Loss

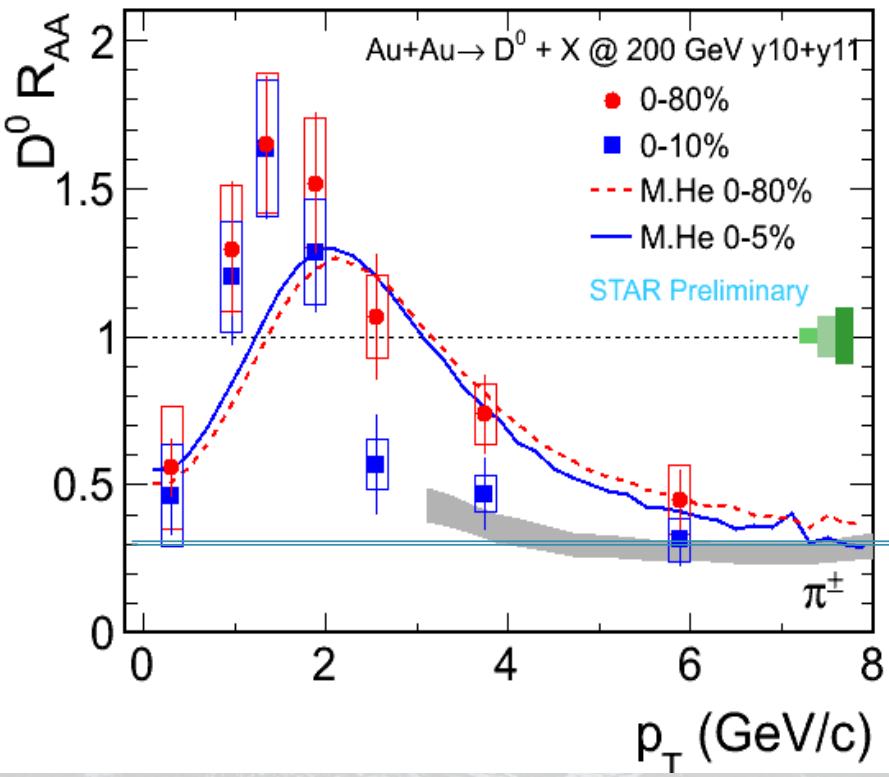
- Energy loss expectation from pQCD and AdS/CFT.

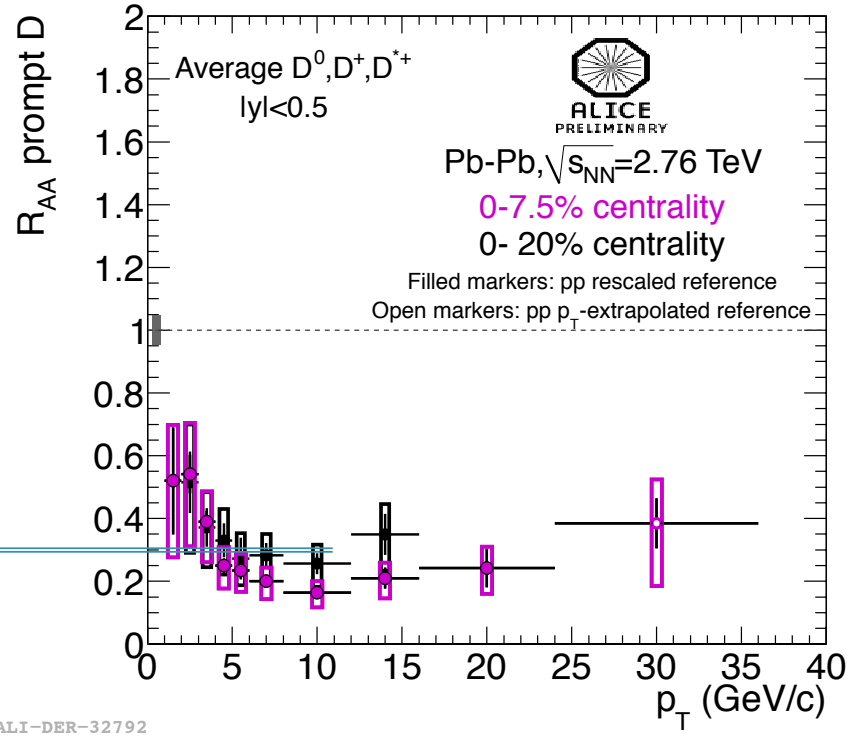



- Heavy quarks lose less energy than light quarks.
  - W. Horowitz: Ok at low $p_T$, but at high $p_T$ this can change.
- Very high $p_T$: mass effect should be less important.
  - B approaches D. Both approach light quark.
  - Not so in AdS/CFT, though corrections needed at high $p_T$.

# $D^0$ $R_{AA}$ : STAR and ALICE

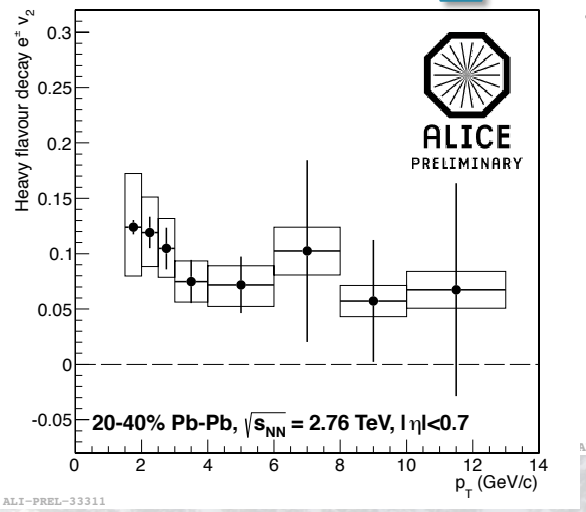


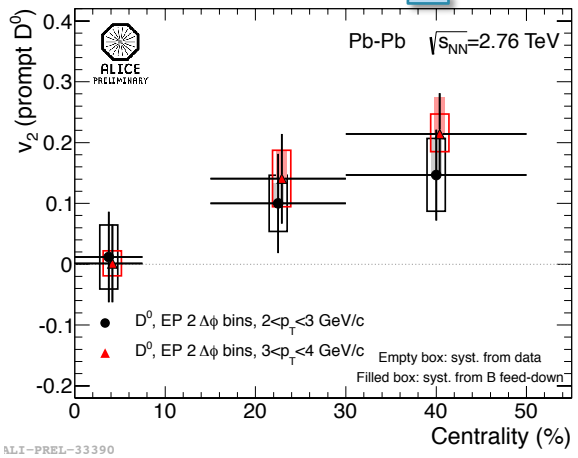

- STAR: Enhancement at low pt, suppression for $p_T$>4.
- ALICE: Hints of a minimum $R_{AA} \approx 0.2$ around 10 GeV/c.
- Both: more suppressed in central collisions, as expected.
- If there is charm energy loss, does it show a path length dependence?

# Do c quarks show ΔE(L)?

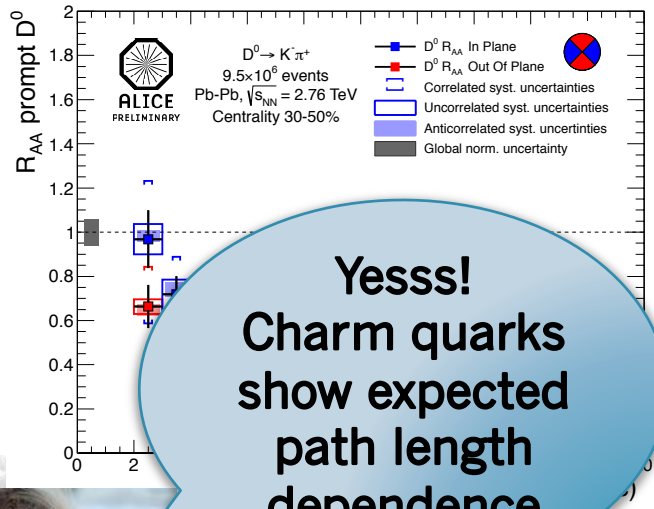
## HF $e^-$ $v_2$



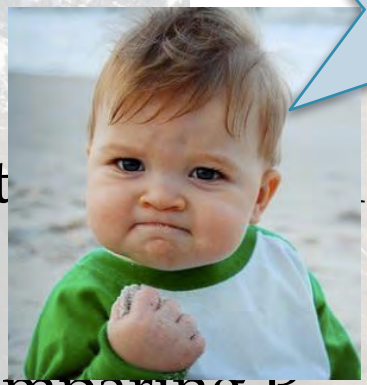

## $D^0$ $v_2$




## $D^0$ $R_{AA}$ In,Out plane

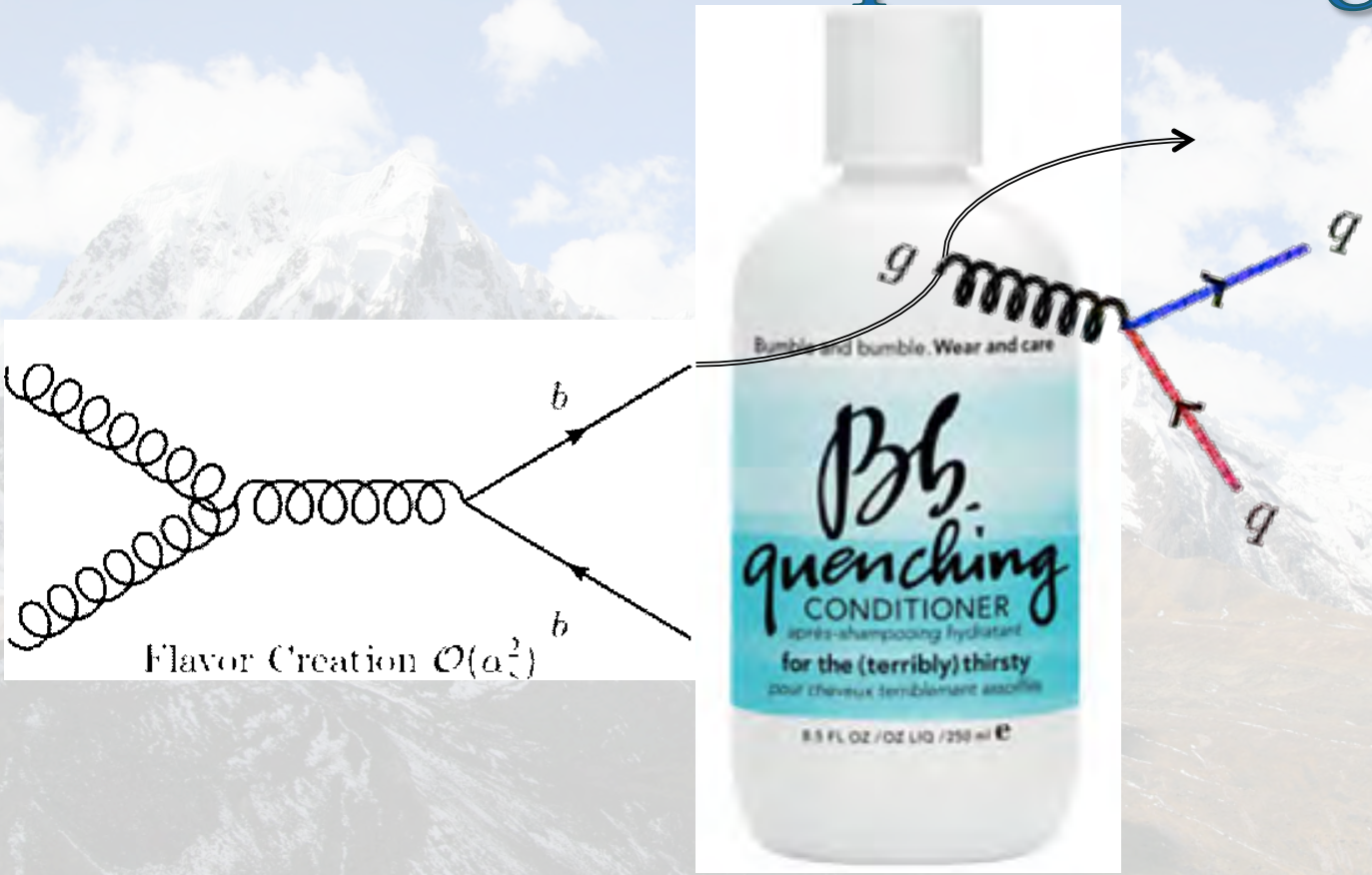



**Yesss! Charm quarks show expected path length dependence**



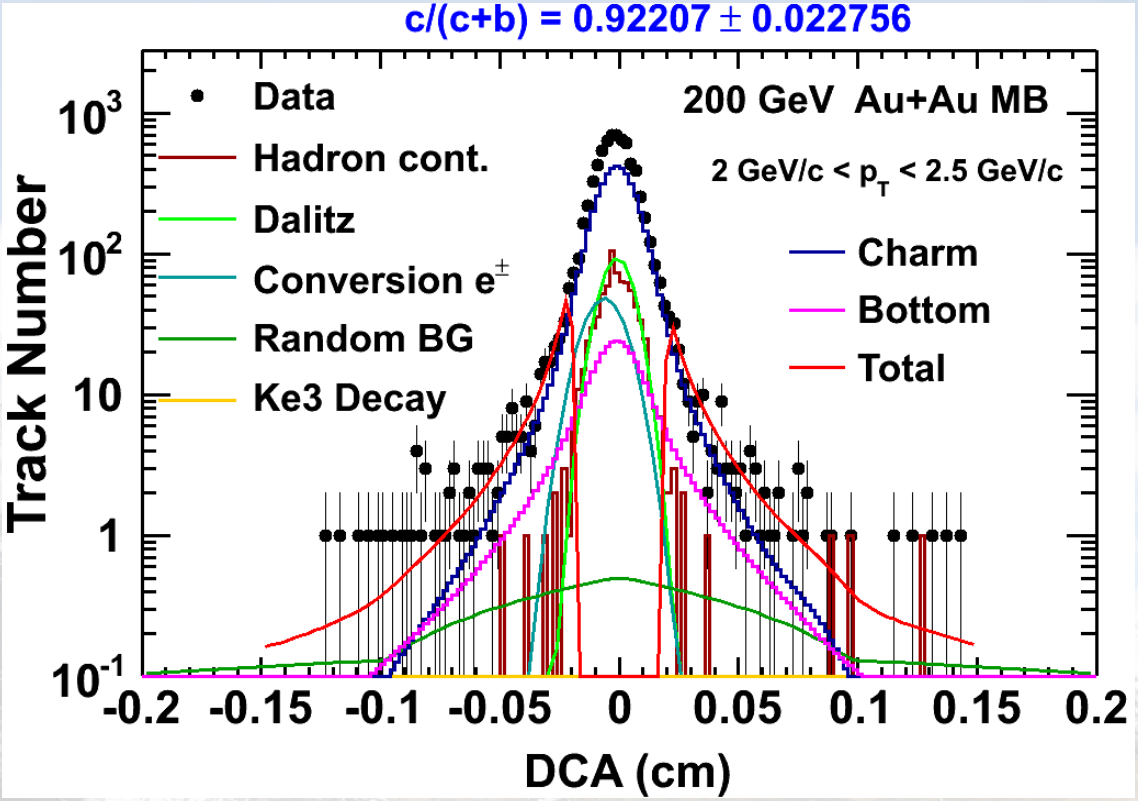
- Path length dependence is qualit…stent with expectation from energy loss.
- Would like to see calculations comparing $R_{AA}$ and $v_2$ of charm together.

# What about b quenching?




- Amazing what you can buy nowadays:
  - Bb quenching, and "hydration" in a bottle…

# PHENIX : b fraction via DCA

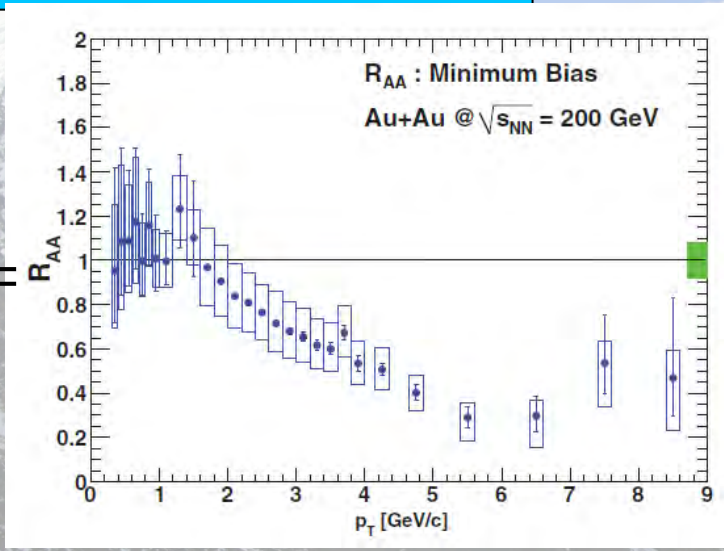



- Based on template fits to dca distributions.
- Charm and Bottom templates have same fragmentation fractions as in pp.
  - If these change in AuAu, the template shape can change.
    - cτ for D0 : 137 fm/c, for D+: 347 fm/c.

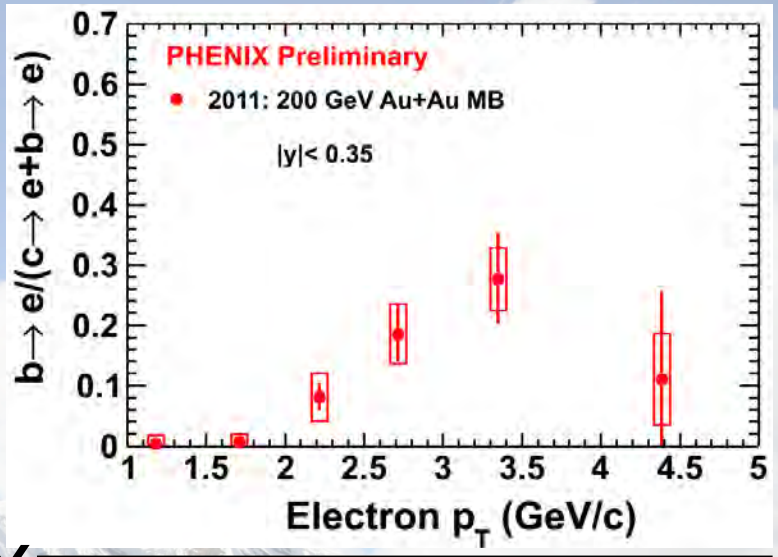
# $R_{AA}$ of Bottom Extraction

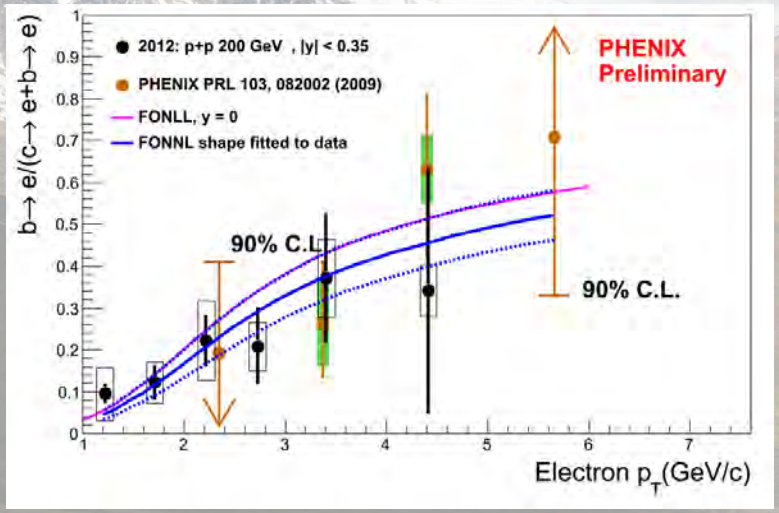
$$R_{AA}^{b\to e} = R_{AA}^{b+c\to e} \frac{\left(\frac{b\to e}{b+c\to e}\right)^{AA}}{\left(\frac{b\to e}{b+c\to e}\right)^{pp}}$$

$R_{AA}$ (b→e) =



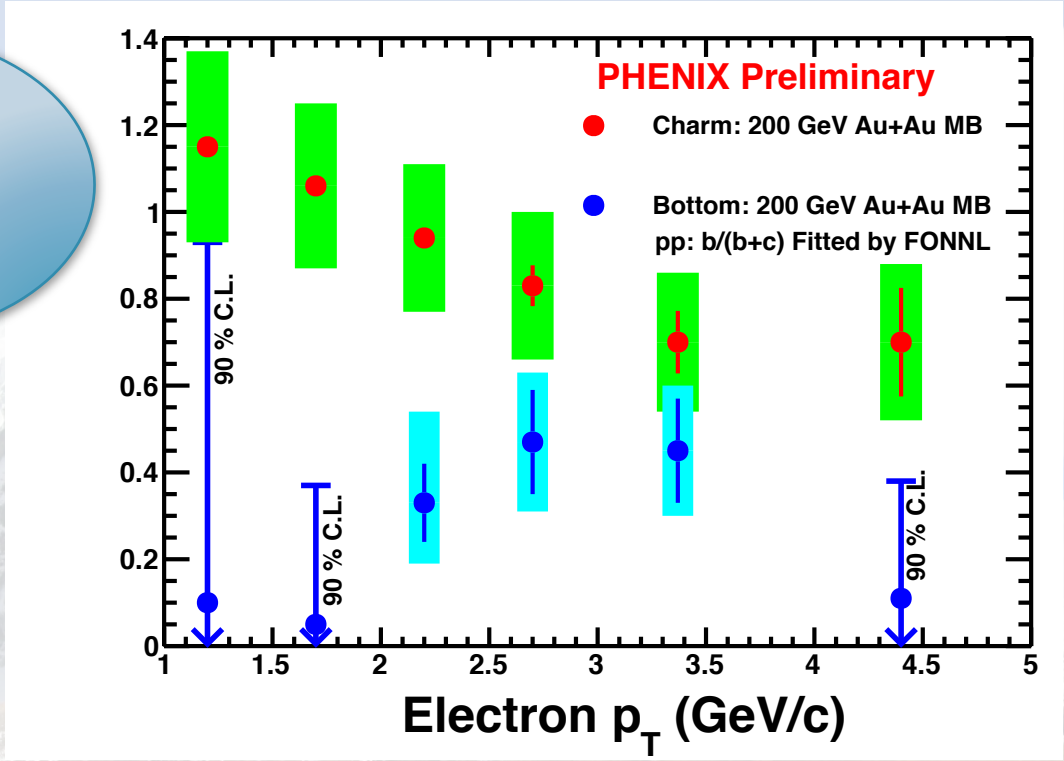

X



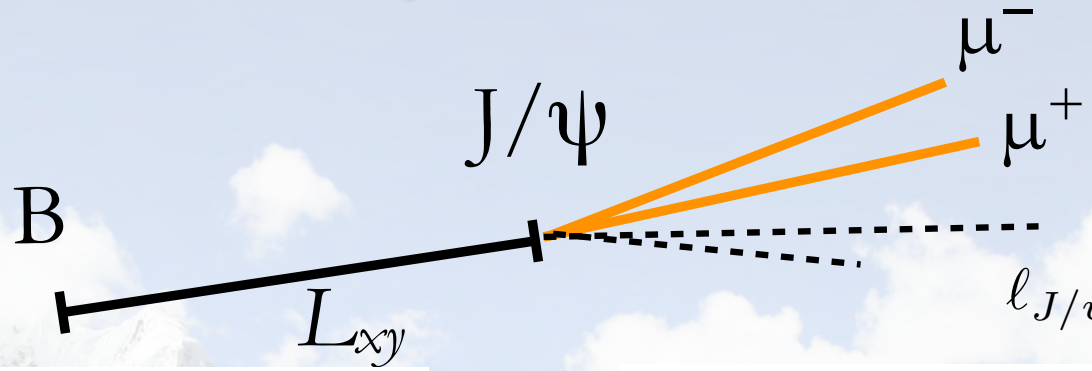

$$R_{AA}^{c\to e} = R_{AA}^{b+c\to e} \frac{1-\left(\frac{b\to e}{b+c\to e}\right)^{AA}}{1-\left(\frac{b\to e}{b+c\to e}\right)^{pp}}$$

# Bottom Measurement in PHENIX

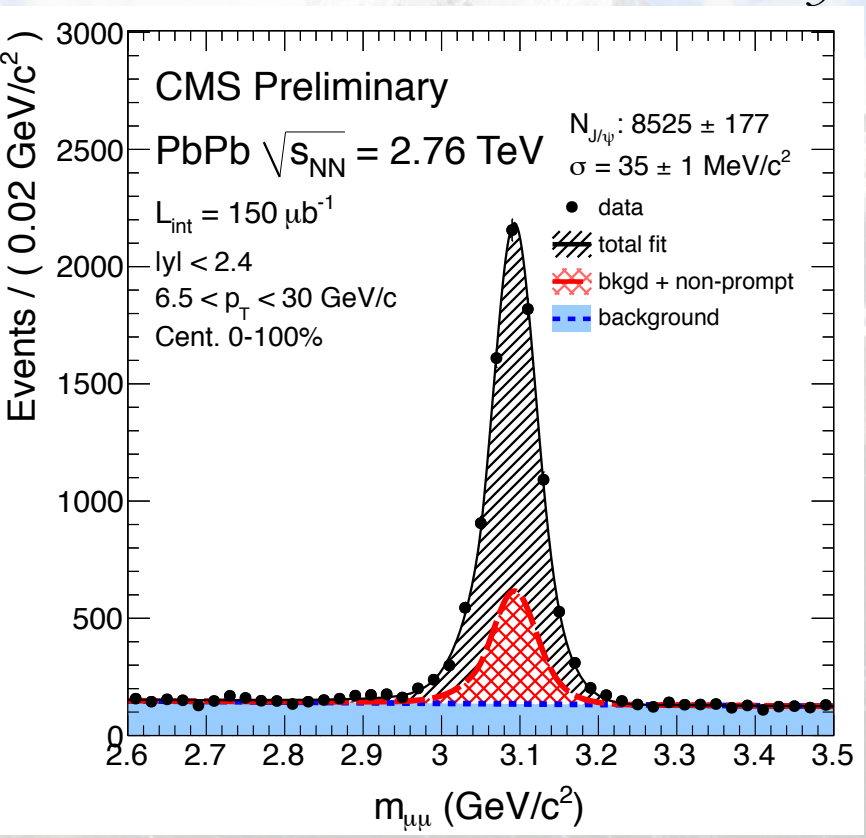



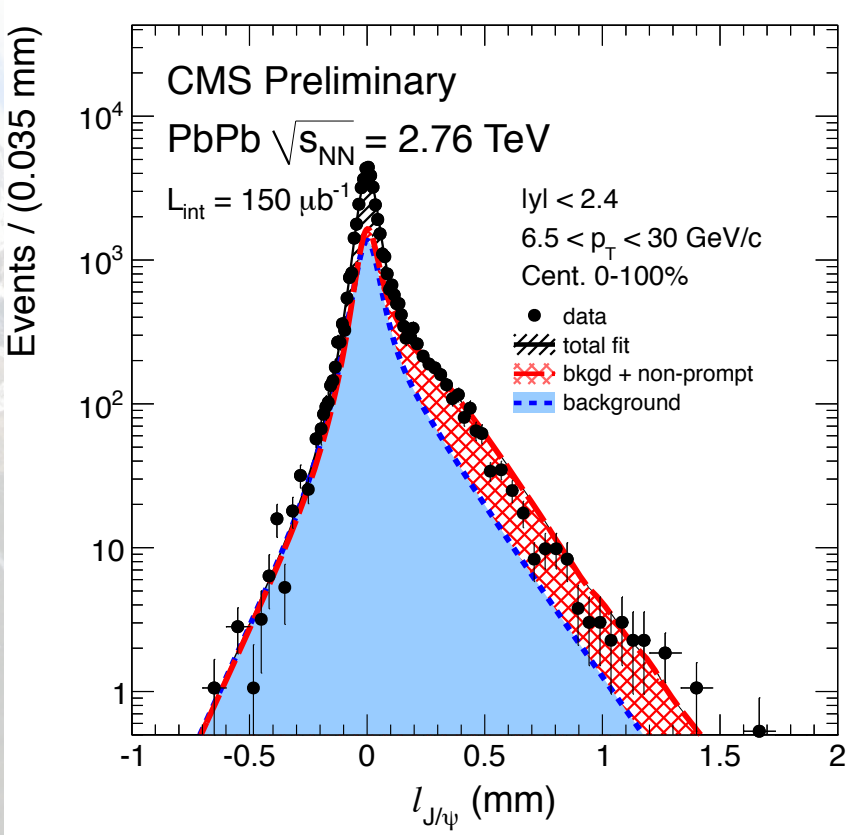

- Non-Photonic Electrons from b-quarks: more suppressed than those from c-quarks !!
- Very surprising result.
- Verification via non-prompt J/Ψ (with VTX) in PHENIX would be very useful.

# B→J/ψ in CMS

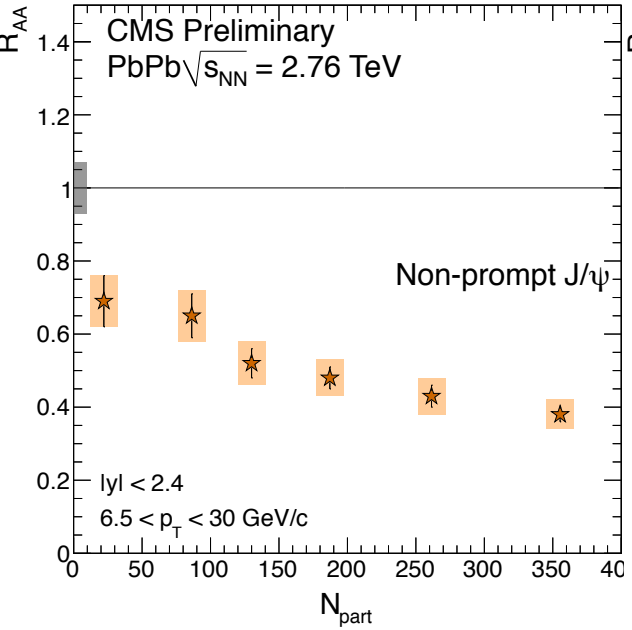


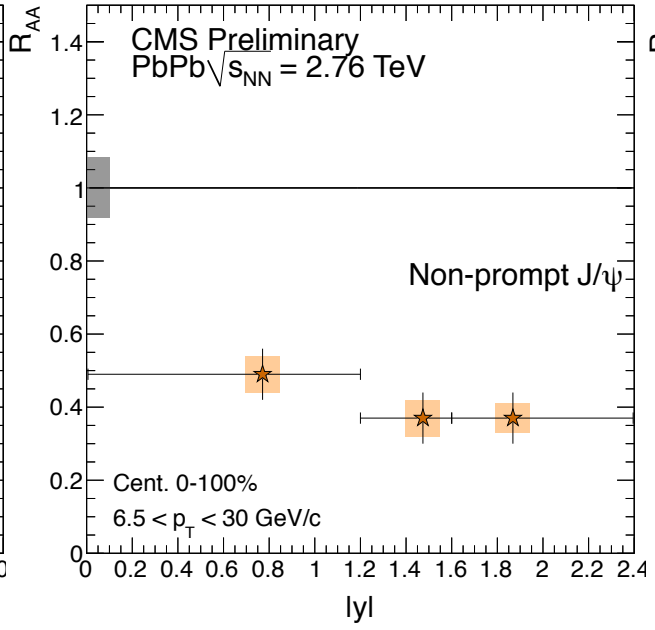

$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

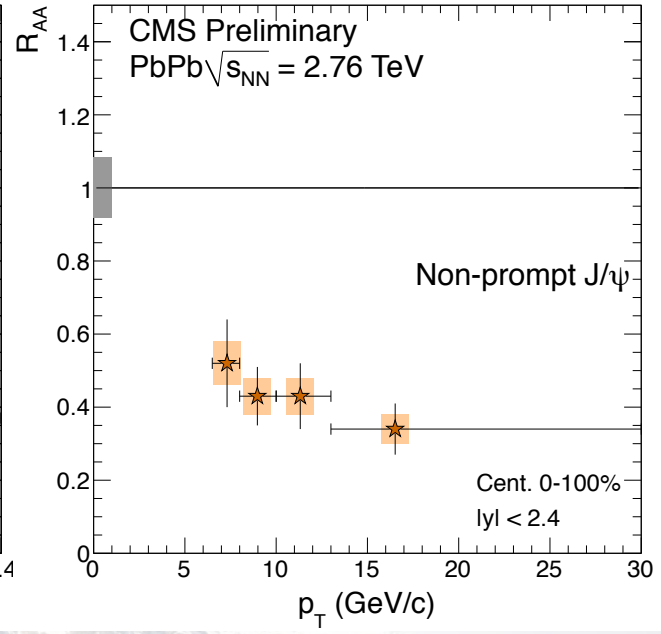


# Non-prompt J/ψ: Npart, y, $p_T$

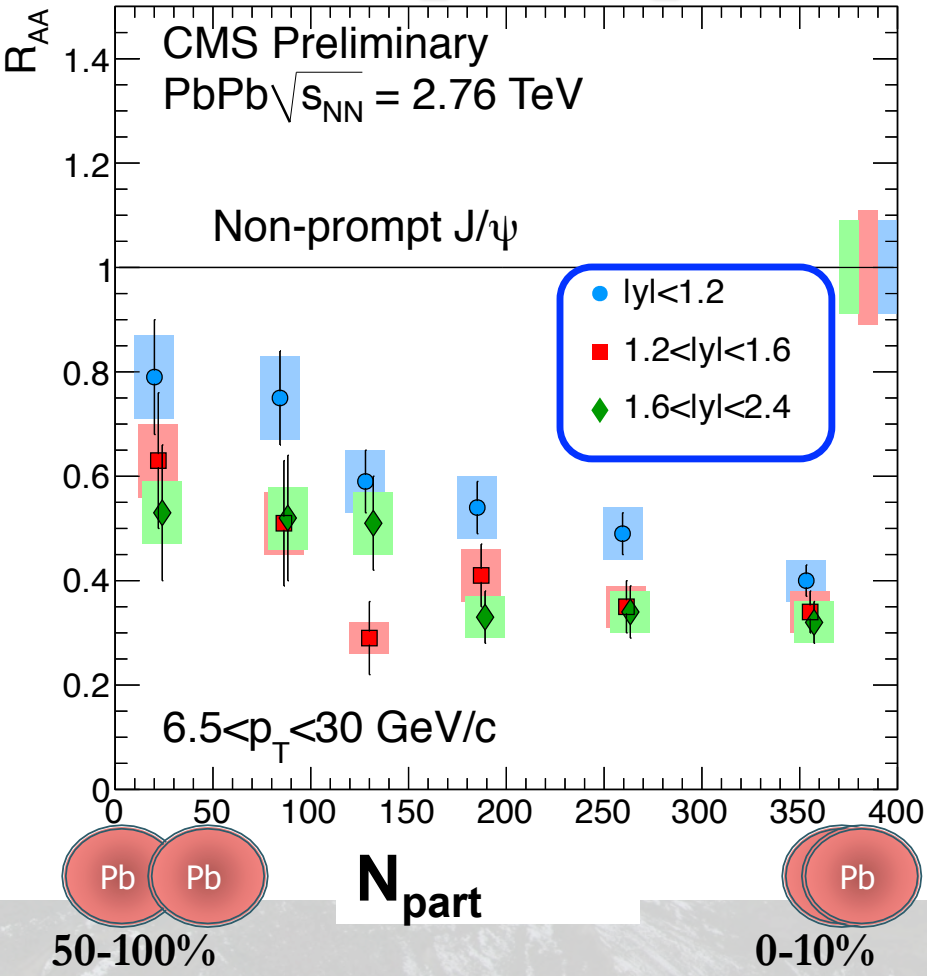


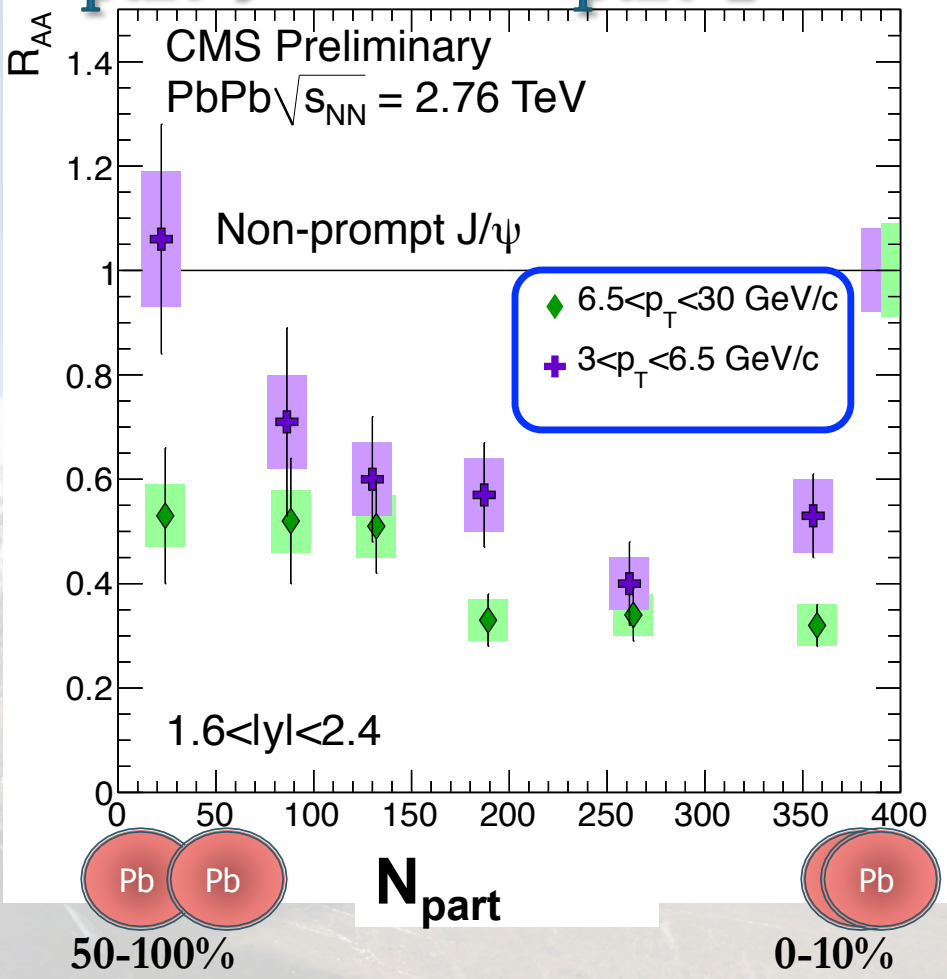




- Centrality ($p_T$, y integrated): slow decrease of $R_{AA}$
  - 50-100%: factor ~1.4
  - 0-5%: factor ~2.5
- y ($p_T$, centrality integrated): hints of less suppression at mid-rapidity
- $p_T$(y, centrality integrated): hints of increasing suppression

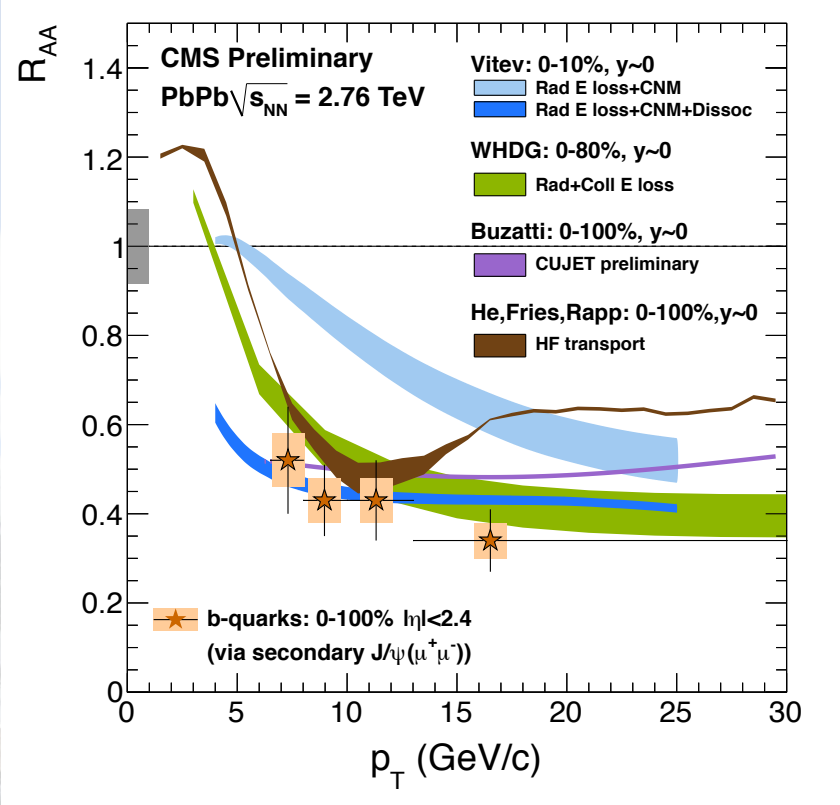
# Non-prompt J/ψ: $N_{part}$-y and $N_{part}$-pT

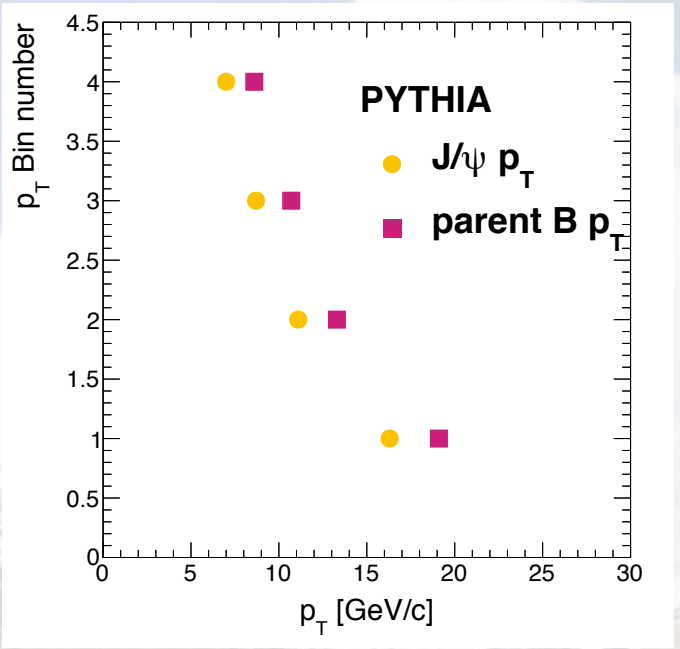



- $6.5 < p_T < 30$ GeV/c: hint of more suppression at forward y
- **$1.6 < |y| < 2.4$:** hint of less suppression for lower $p_T$

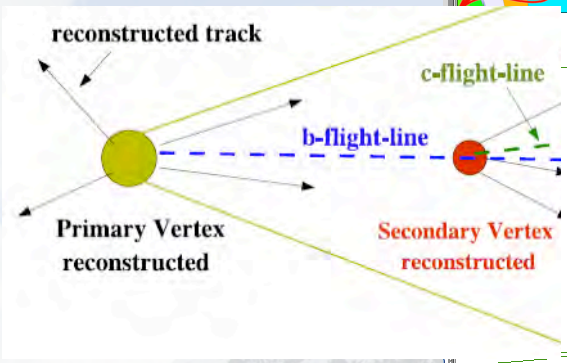
# B→J/ψ : comparison to models



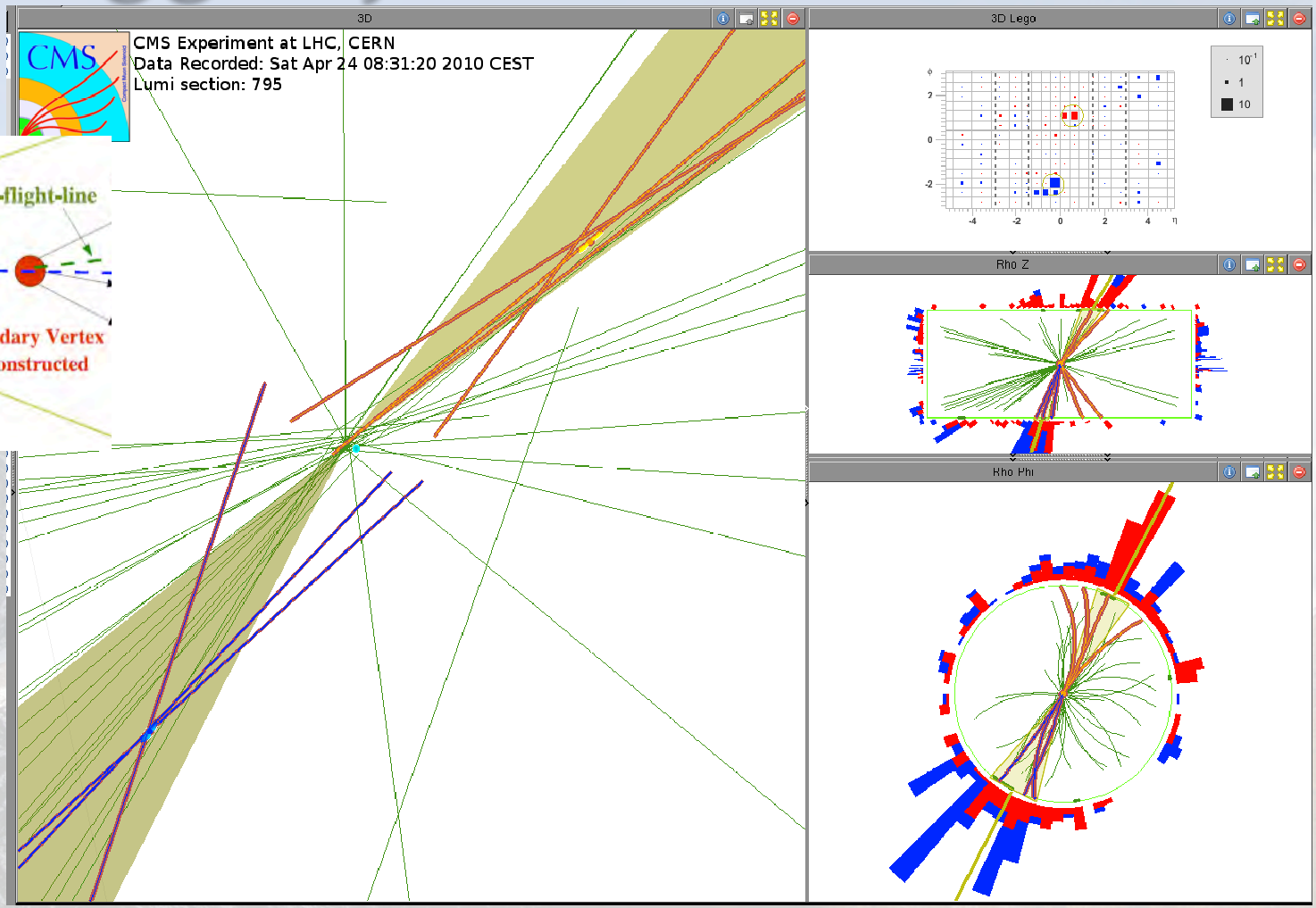




- Radiative Energy loss: not enough to describe data.
- Adding Collisional E-loss or Dissociation in QGP: better agreement.
- Even better if we did comparisons using parent B $p_T$.
- Energy loss: seems to work here for b-quarks!

# b-Tagged jets with CMS

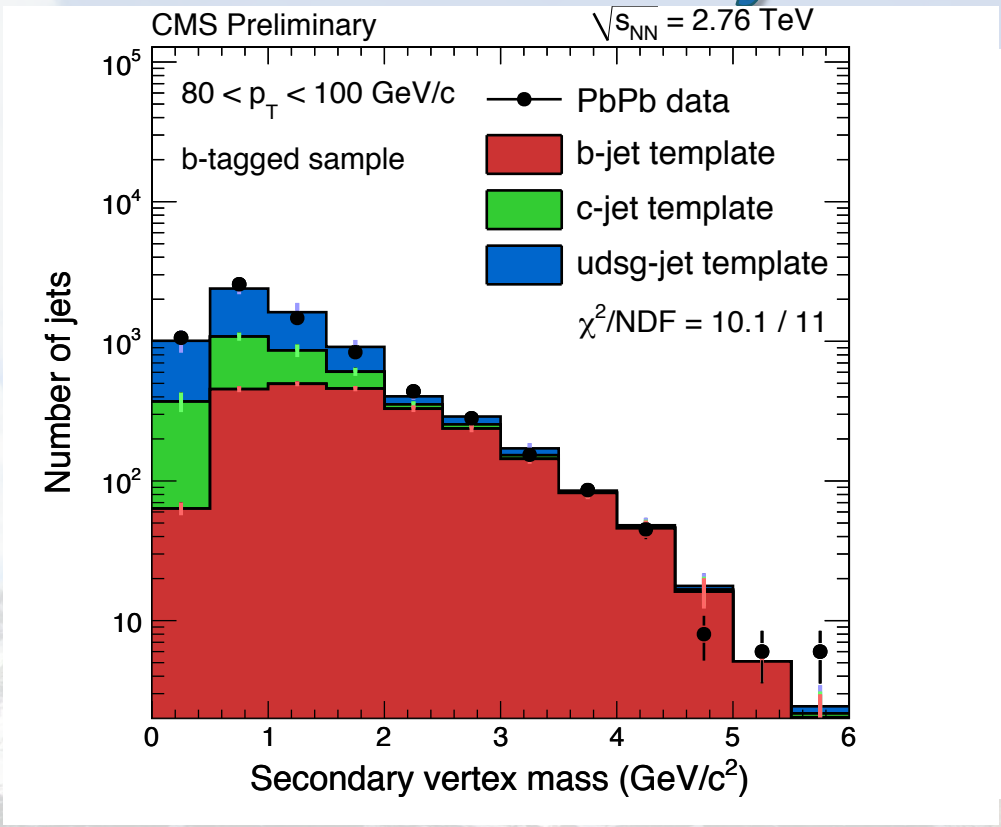


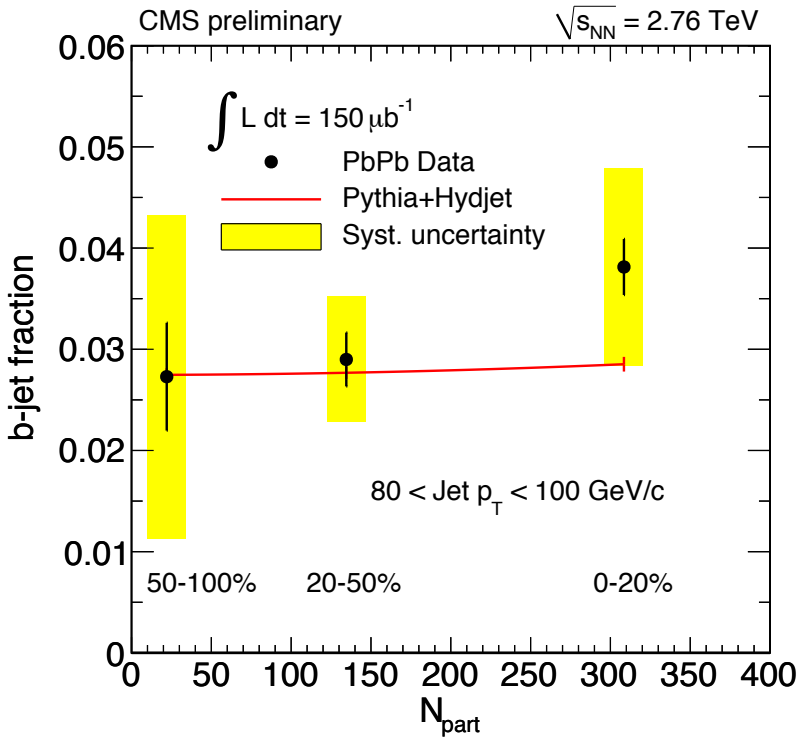

Vertex resolution:
50-100 μm.
B cτ: ~500 μm




- Very good resolution for displaced vertices.
- Above: pp event with 2 b-tagged jets.

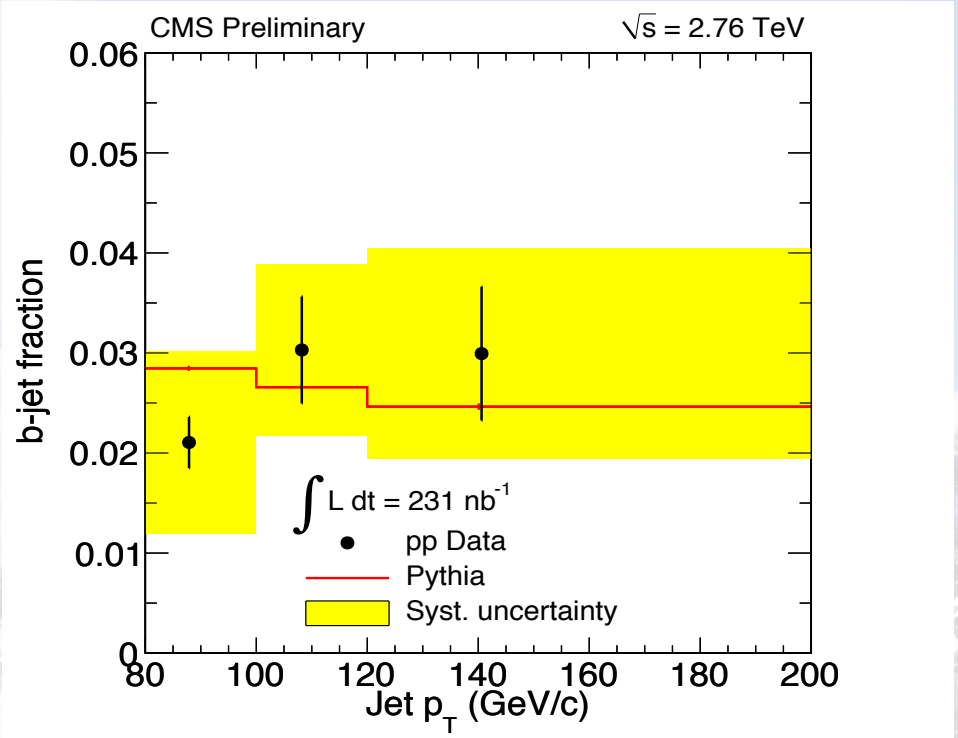
# Secondary mass distribution

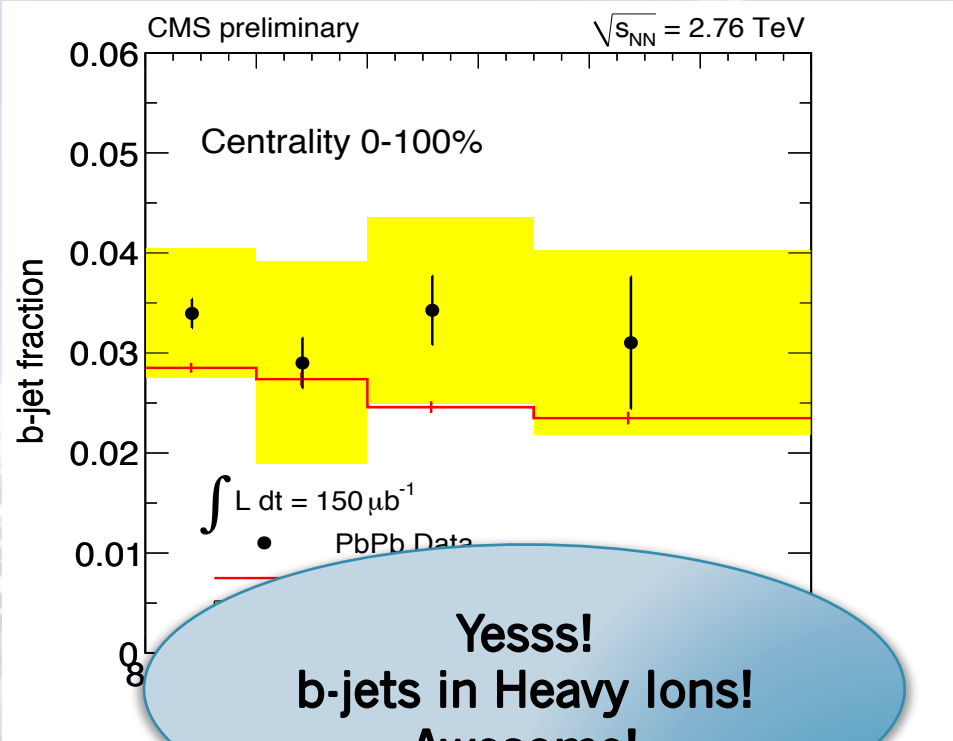



- Procedure:
  - Secondary vertex mass: higher for b-jets than for lighter quark jets.
  - Use Pythia to obtain templates for b, c and light quark jets.
  - Fit distribution to templates. Calculate efficiency and purity.
- Obtain b-jet fraction in pp and in PbPb.

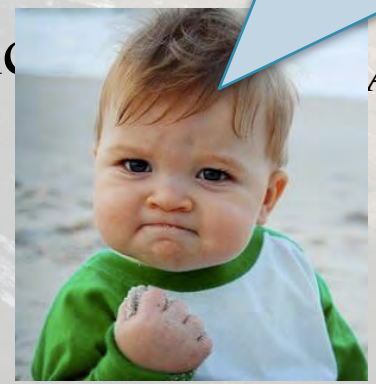
# b-jet Fraction vs. pT



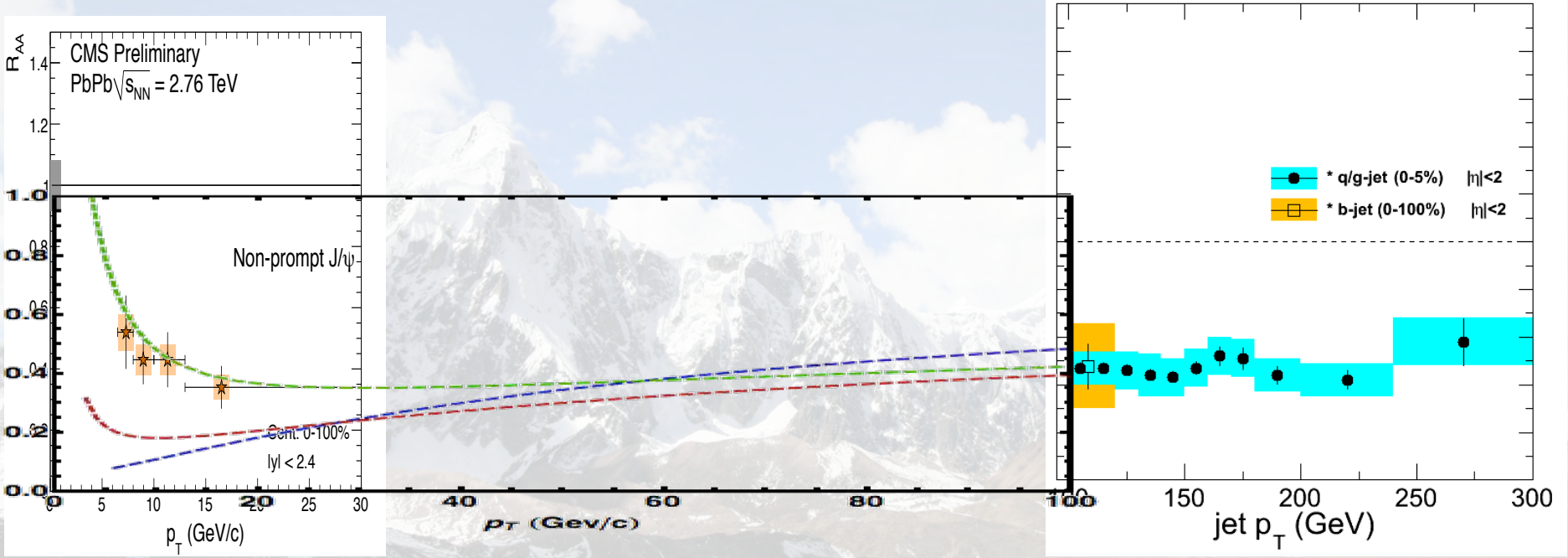

Yesss!
b-jets in Heavy Ions!
Awesome!

$$\text{b-jet } R_{AA} = \underbrace{\frac{PbPb\ b\text{-jet fraction}}{pp\ b\text{-jet fraction}}}_{\text{This measurement}} \cdot \text{Inc} \qquad AA$$



- First measurement of b-jet $R_{AA}$.

# b-jet $R_{AA}$ at high pT

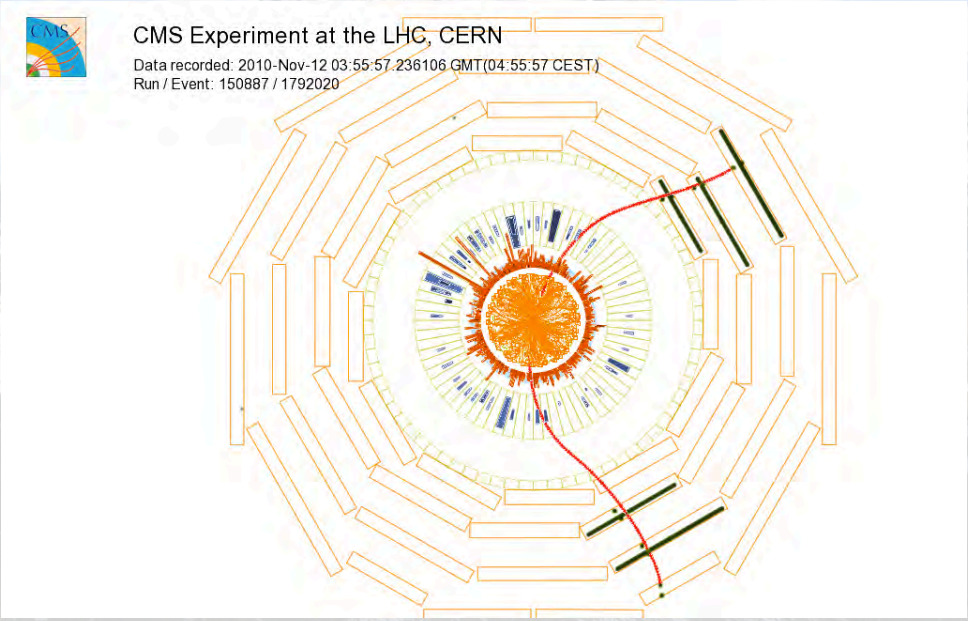



- b-jet RAA : same magnitude as inclusive jet $R_{AA}$ at 100 GeV/c.
  - beauty in the hot QGP at LHC.
  - Consistent with expectations from QCD-based energy loss (not AdS/CFT)
    - Which makes the PHENIX b result all the more puzzling...

# Summary

- Charmonium:
  - Regeneration plays an important role from 39 GeV up to 2.76 TeV.
  - Caution: cold nuclear matter effects are important.
    - Suppression at low pT. Rapidity dependence needs physics beyond shadowing + nuclear absorption.
  - **Ψ′ from PHENIX in dAu: surprising suppression!**
- Bottomonium:
  - STAR and CMS: Upsilon suppression in AuAu and PbPb.
    - Suppression expected to be dominated by Hot matter effects.
    - ϒ $R_{AA}$: Consistent with dynamical models of sequential suppression of bottomonium in a hot (T~500-600 MeV) deconfined QGP.
- Open charm
  - Observed suppression by STAR, PHENIX, and ALICE.
    - Via electrons and now via direct $D^0$ reconstruction.
  - ALICE: Suppression shows expected dependence with path length
- Bare bottom:
  - PHENIX: Measure fraction of electrons from b-quarks
    - **Surprising suppression of b!** Not expected from pQCD + dead cone effect.
      - Would like to see a confirmation with an independent measurement, e.g. B→J/ Ψ
  - CMS: Measure Non-Prompt J/ Ψ and first measurement of b-jets.
    - Consistent with pQCD energy loss.

# Thank you


CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-12 03:55:57.236106 GMT(04:55:57 CEST)
Run / Event: 150887 / 1792020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