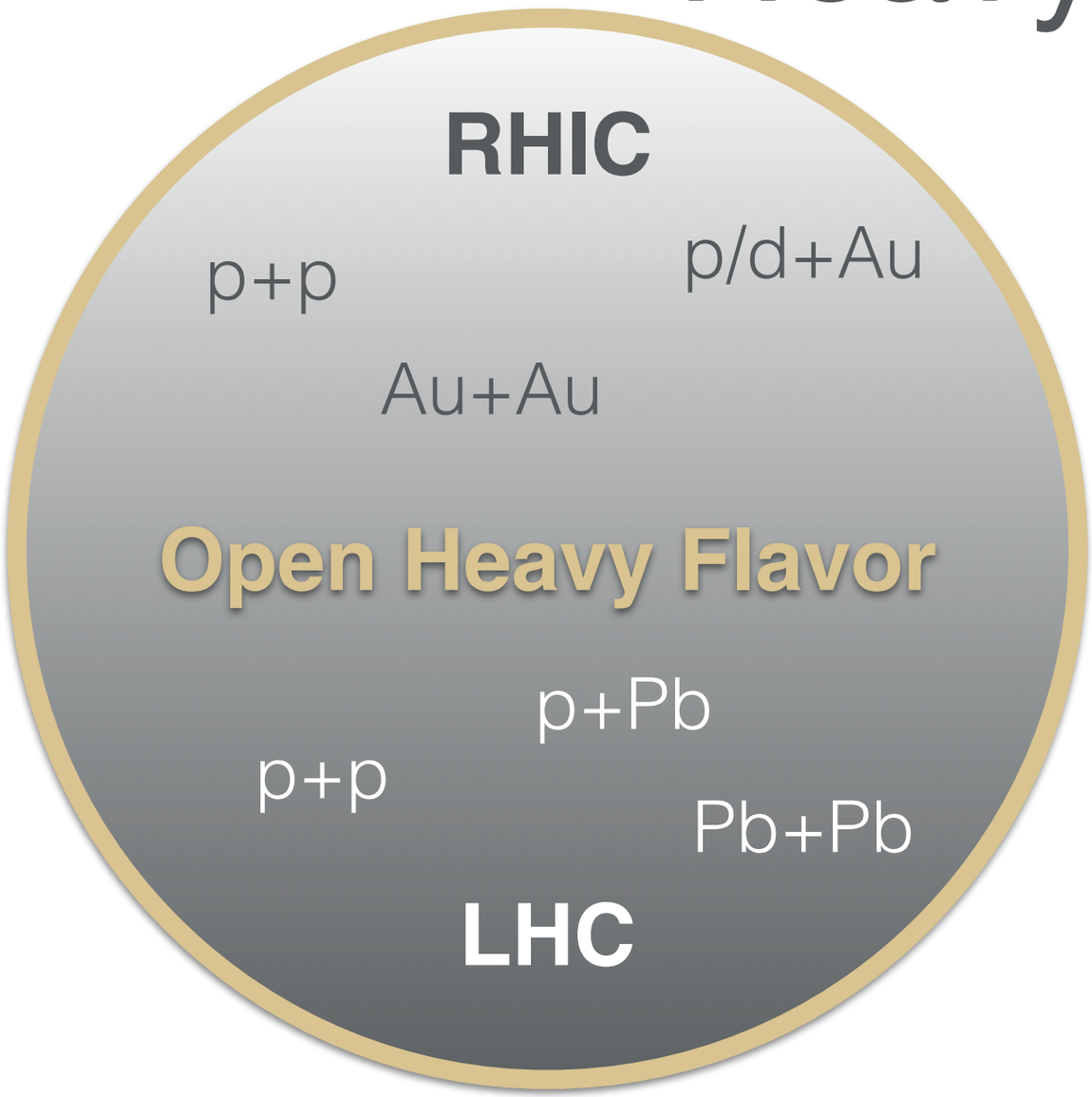
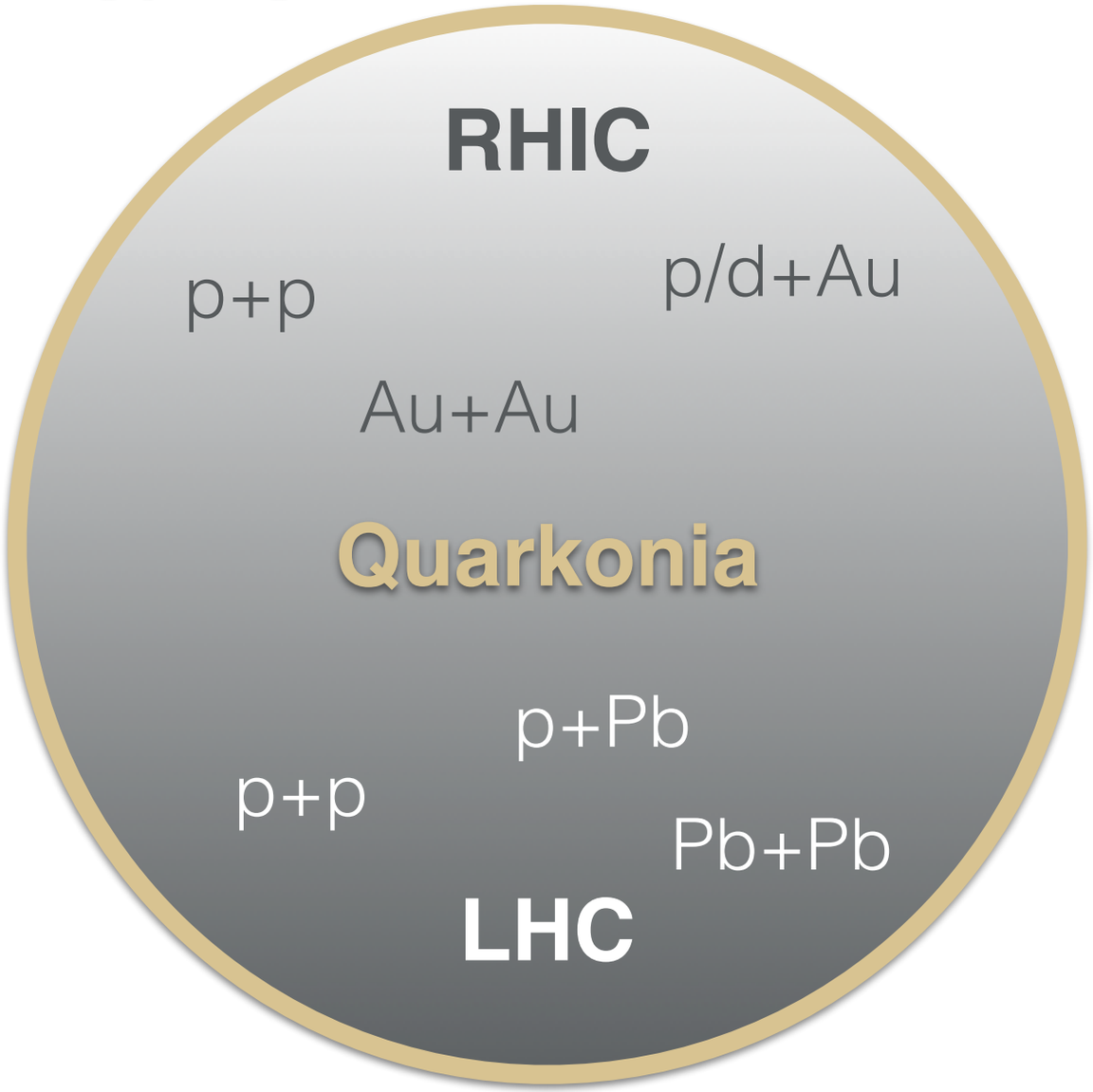
Heavy Flavor
an experimental perspective

Darren McGlinchey
University of Colorado Boulder
10 June 2016

Disclaimer

Heavy Flavor





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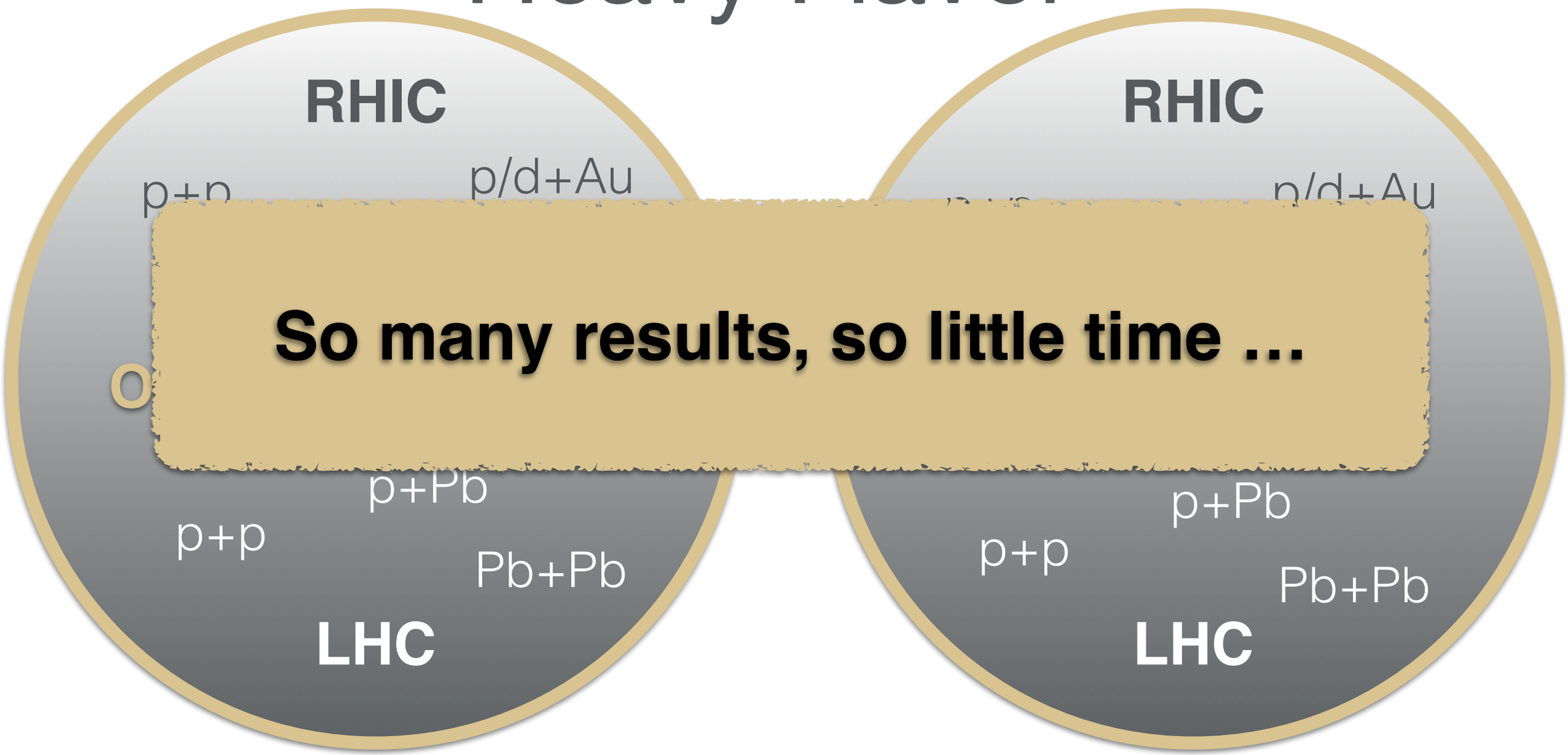
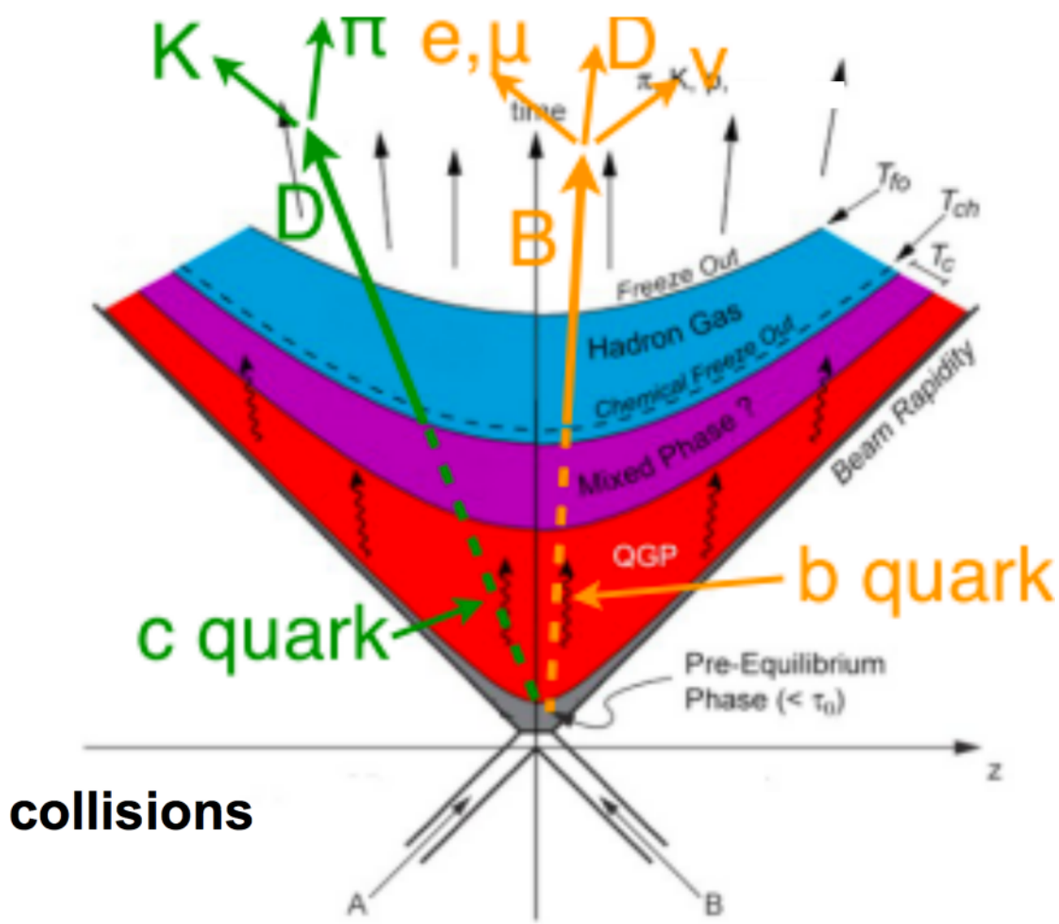


So many results, so little time …

Open Heavy Flavor



Charm & Bottom Quarks

- Produced in initial hard scatterings
- No thermal production
- Experience full medium evolution

Parton energy loss

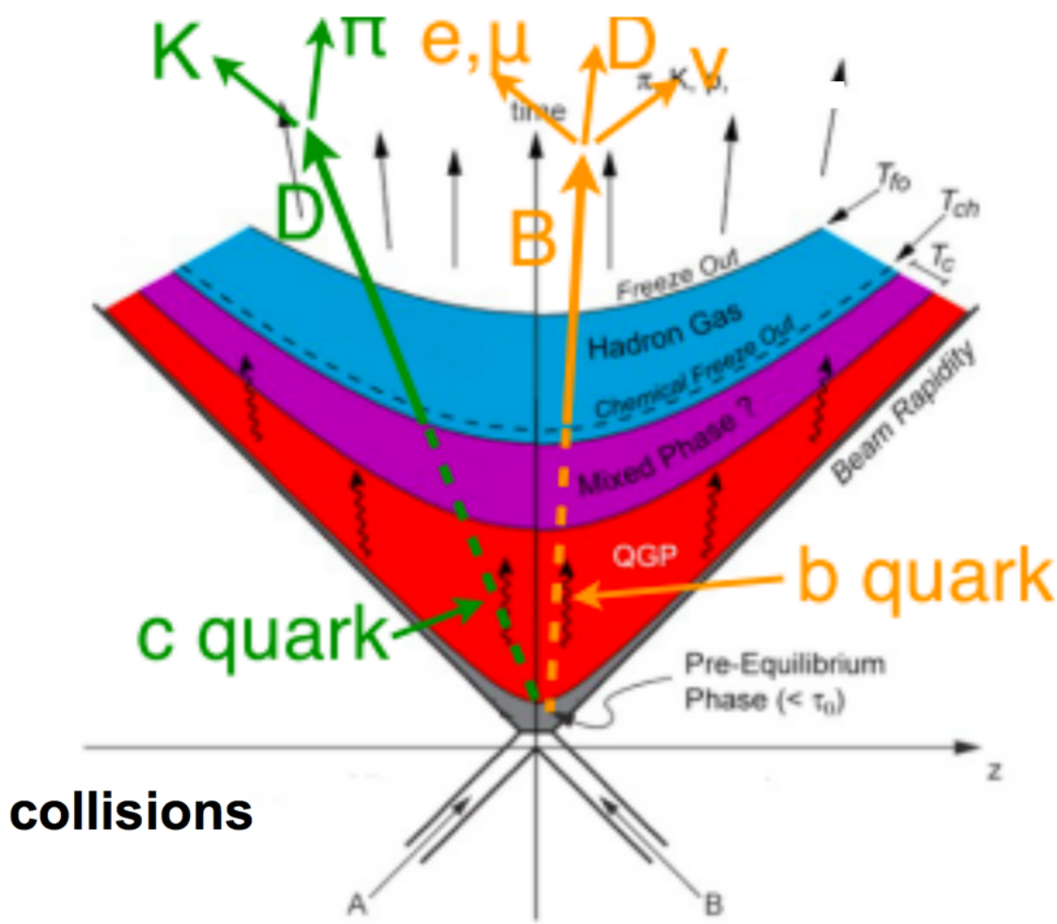
- Depends on: color charge, m_q, path length, medium density & T
- Disentangle radiative vs collisional eloss

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

$$\Big\downarrow ?$$

$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

Open Heavy Flavor



Measuring Heavy Flavor

- D meson reconstruction (charm)
- Non-prompt J/ψ (bottom)
- Electrons from semileptonic charm & bottom decays

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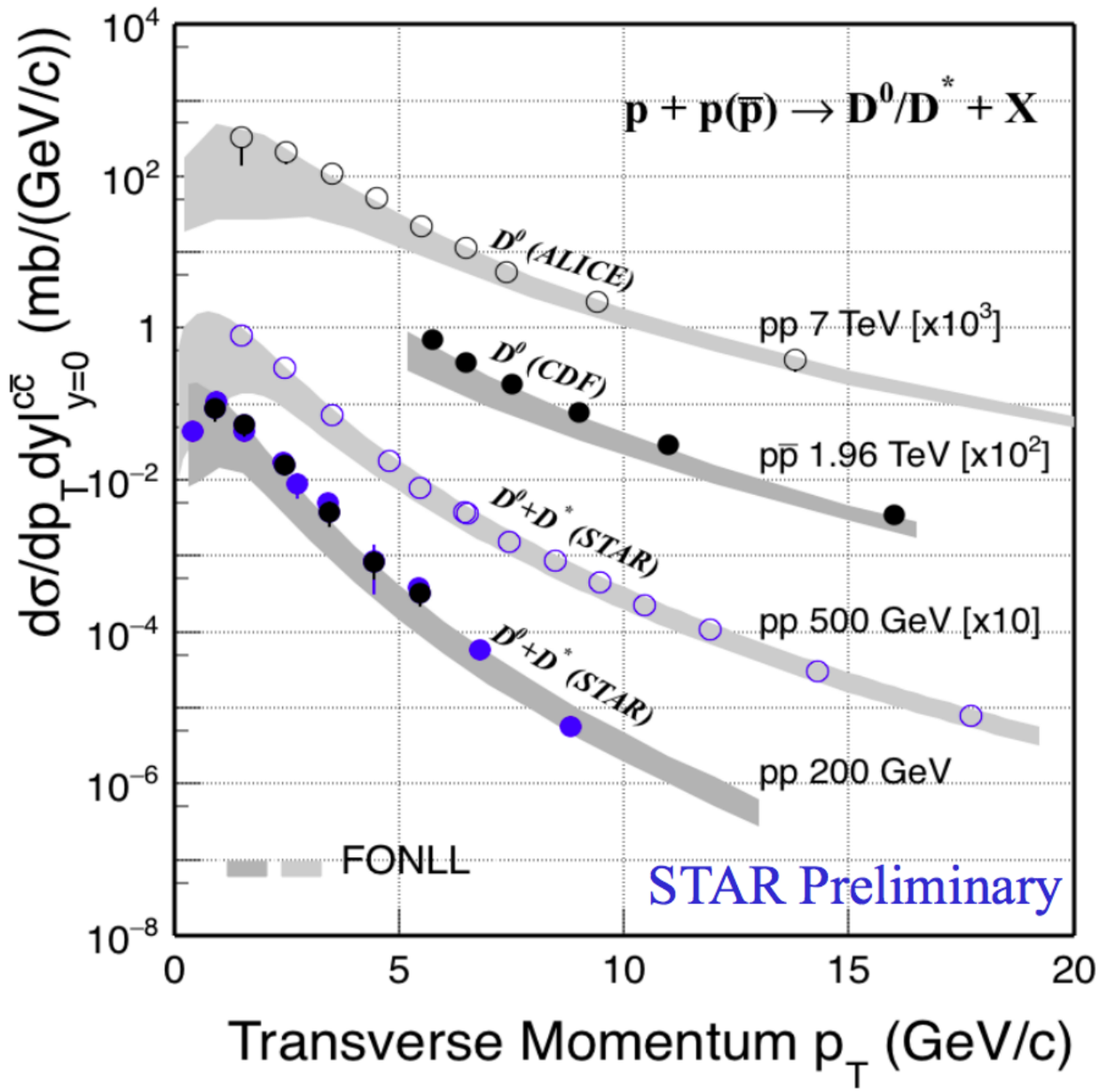
Baseline under control



D production well understood over broad energy range

STAR: PRD 86 (2012) 072013,
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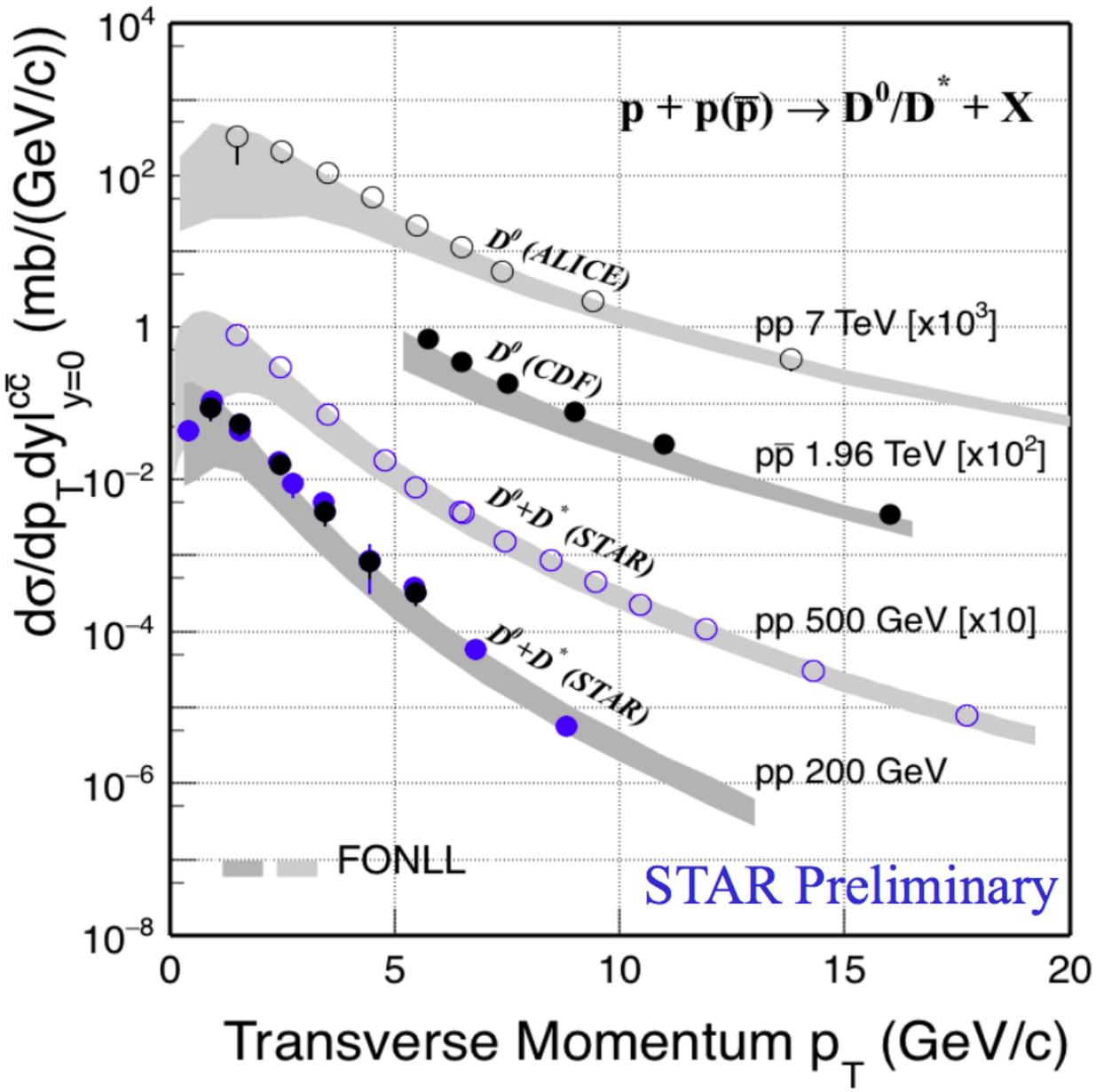
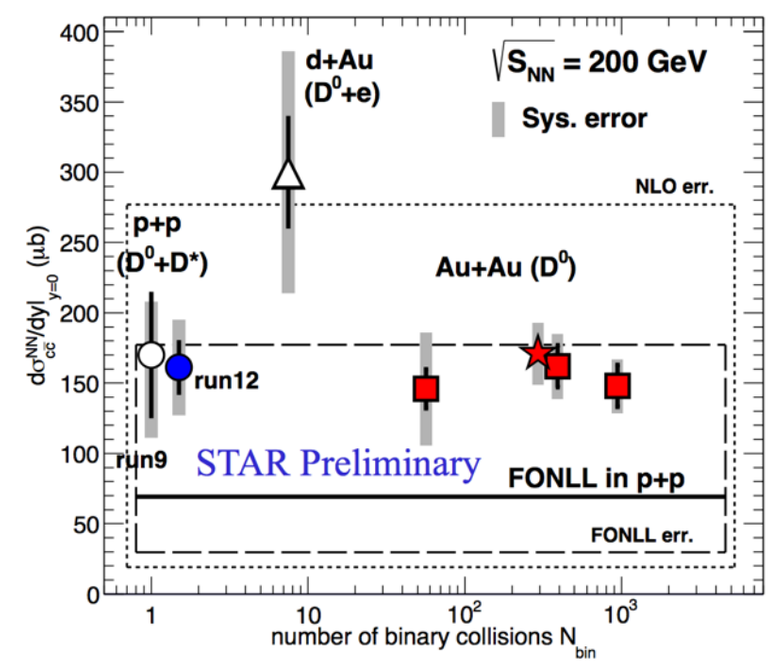


D production well understood over broad energy range

Binary scaling holds for charm at RHIC (R_{AA} good quantity)



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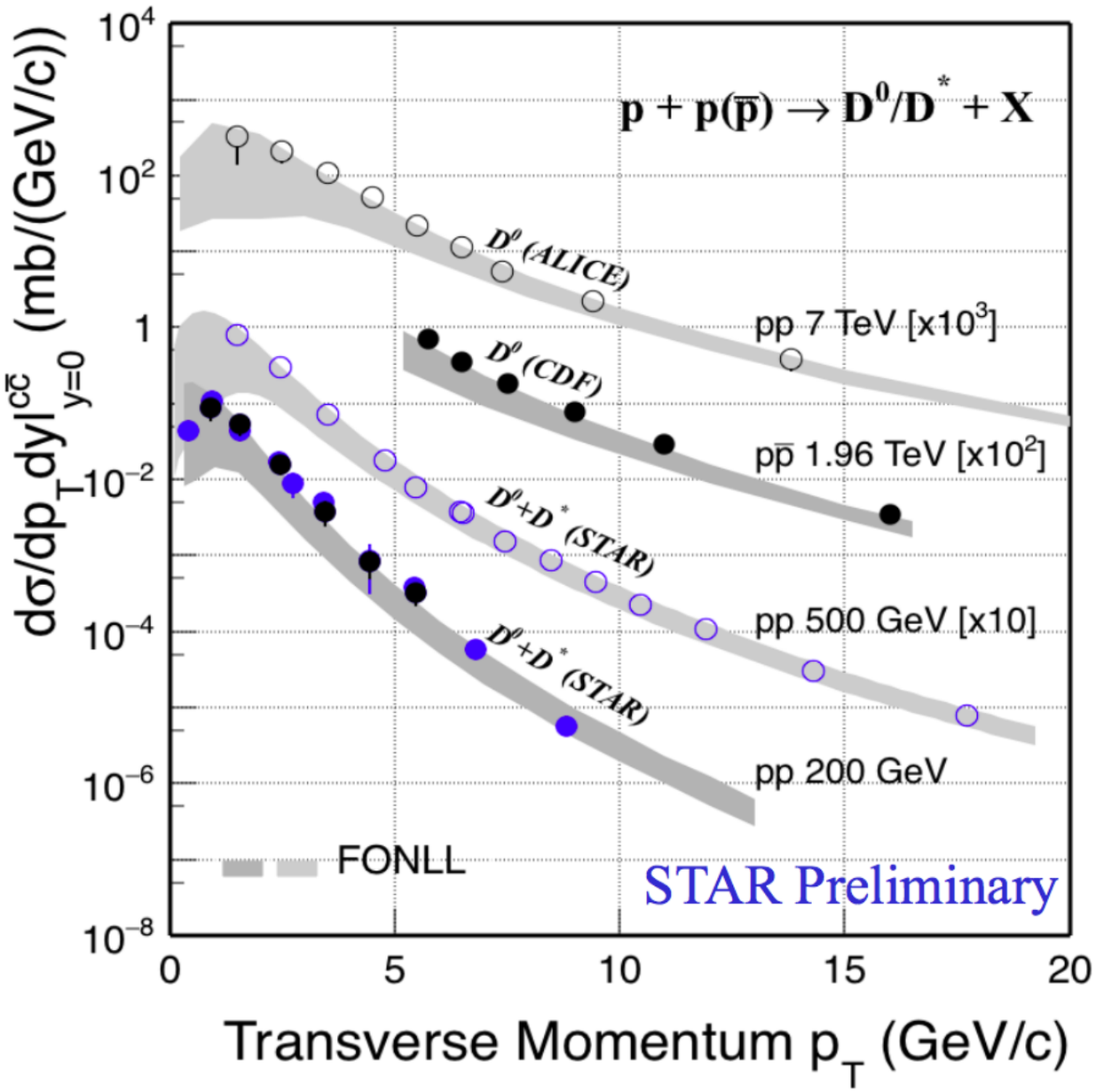

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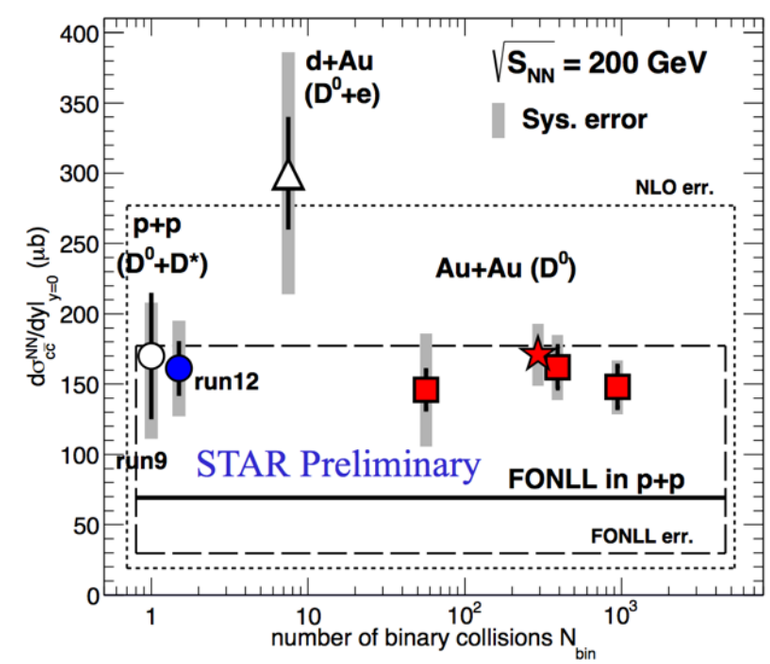
Binary scaling holds for charm at RHIC (R_{AA} good quantity)

… Not confirmed at LHC …



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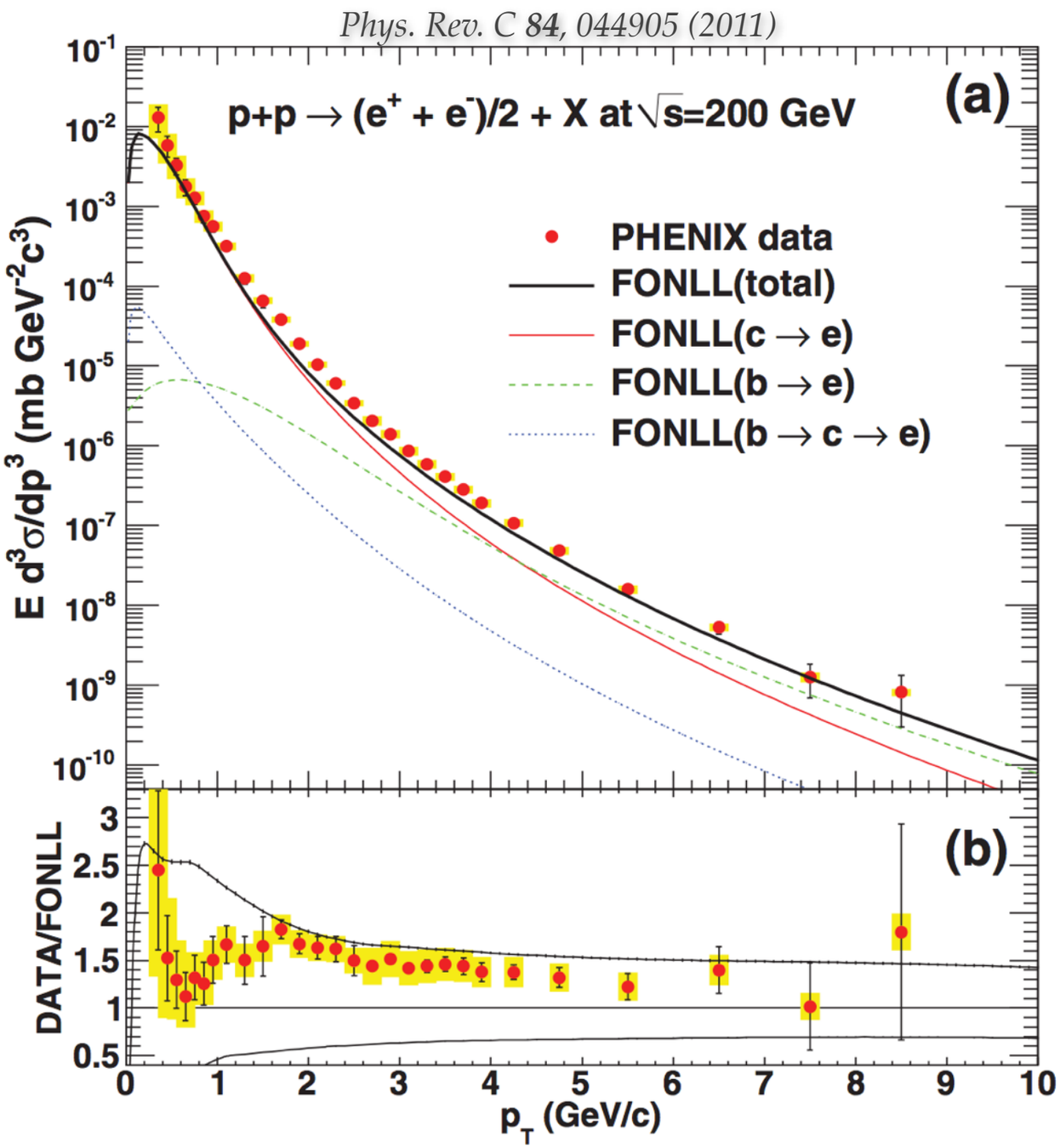
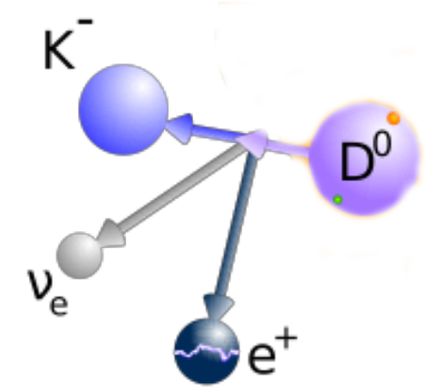
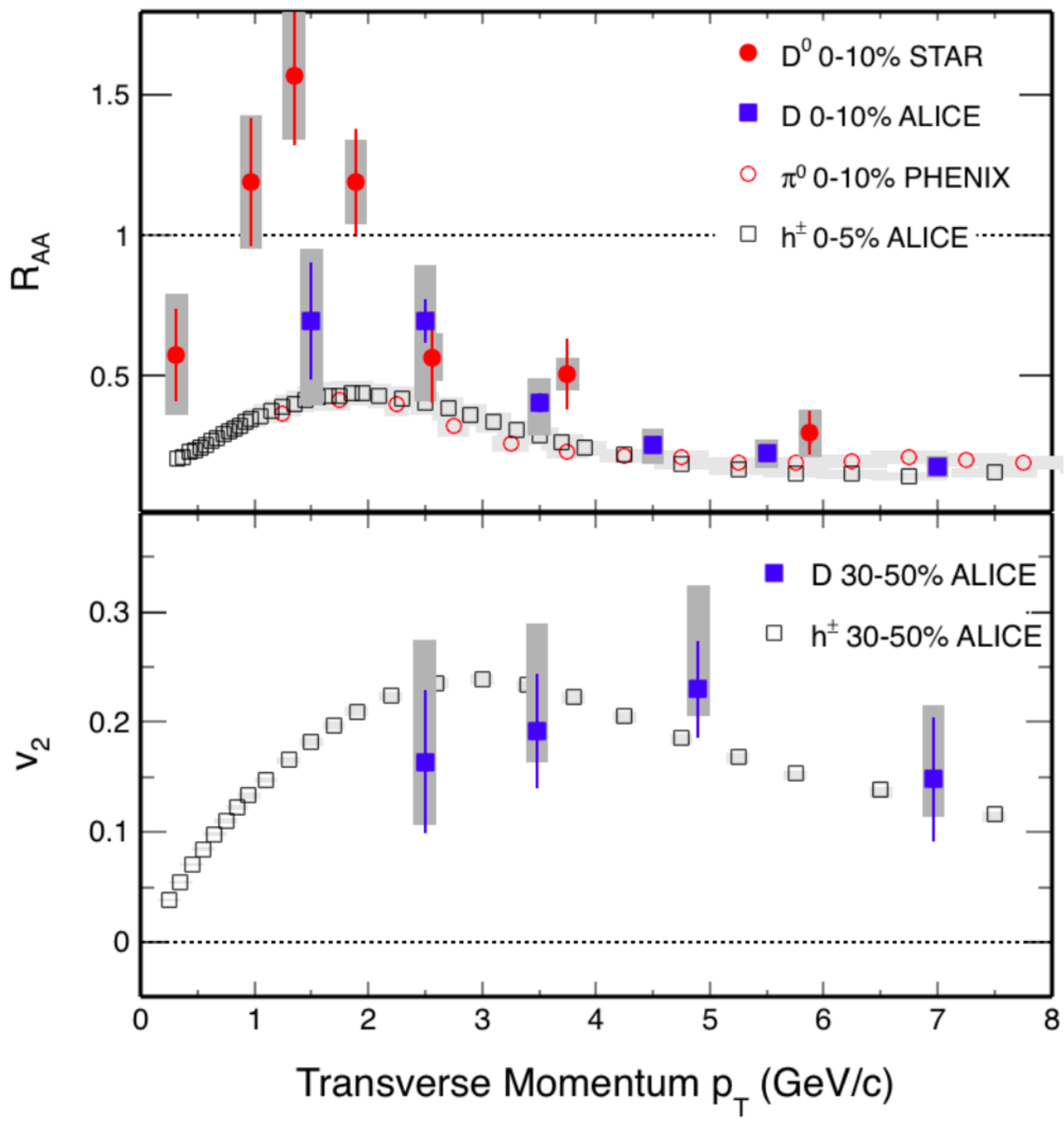




c+b → e well reproduced by FONLL as well

Expect b → e dominate for $p_T > 5$

The Story so Far — D mesons



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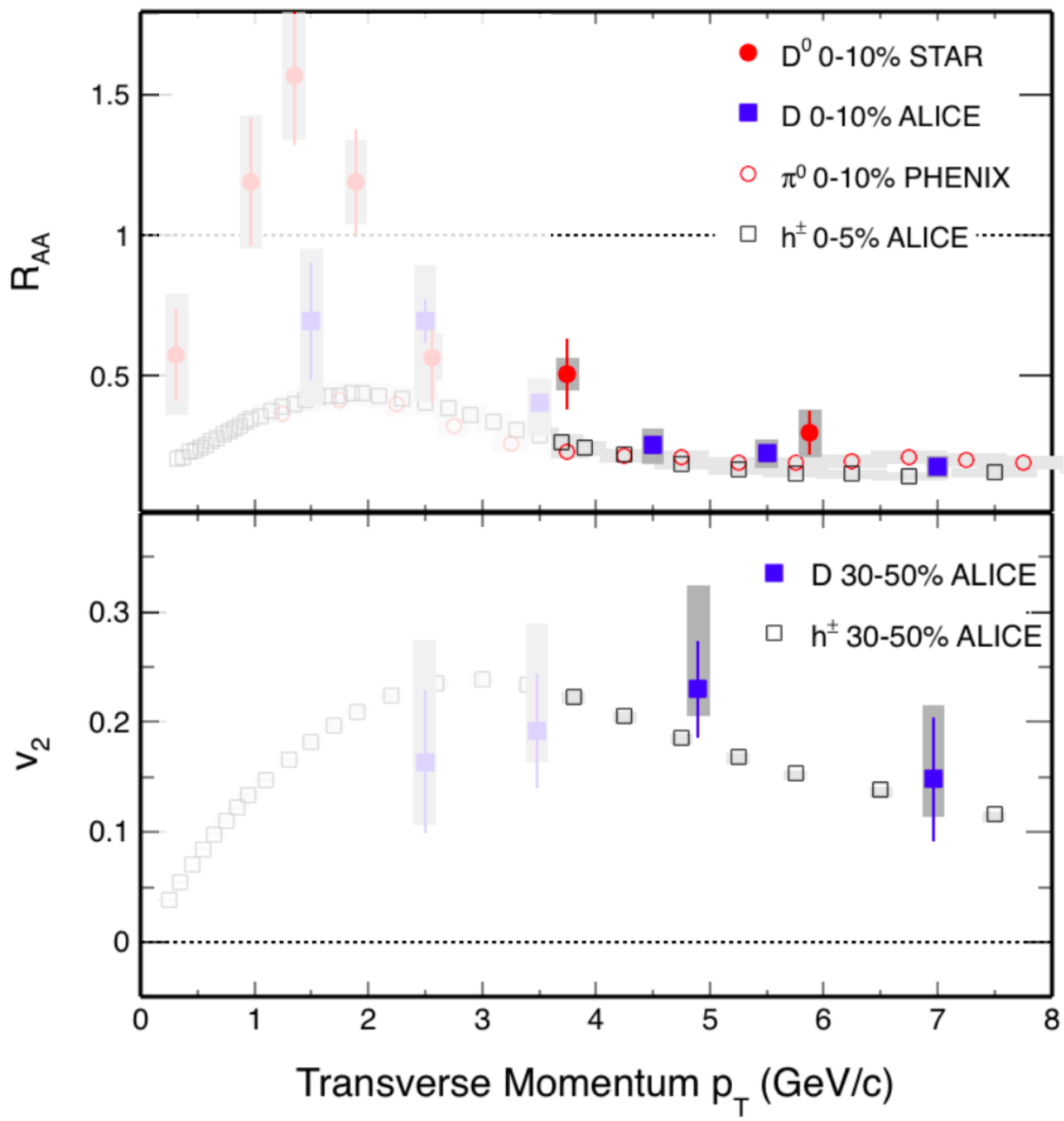

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High-p_T

- Significant suppression
- Similar suppression of light hadrons & charm
- Similar suppression at RHIC & LHC
- D meson v_2 at LHC — agrees with light hadrons

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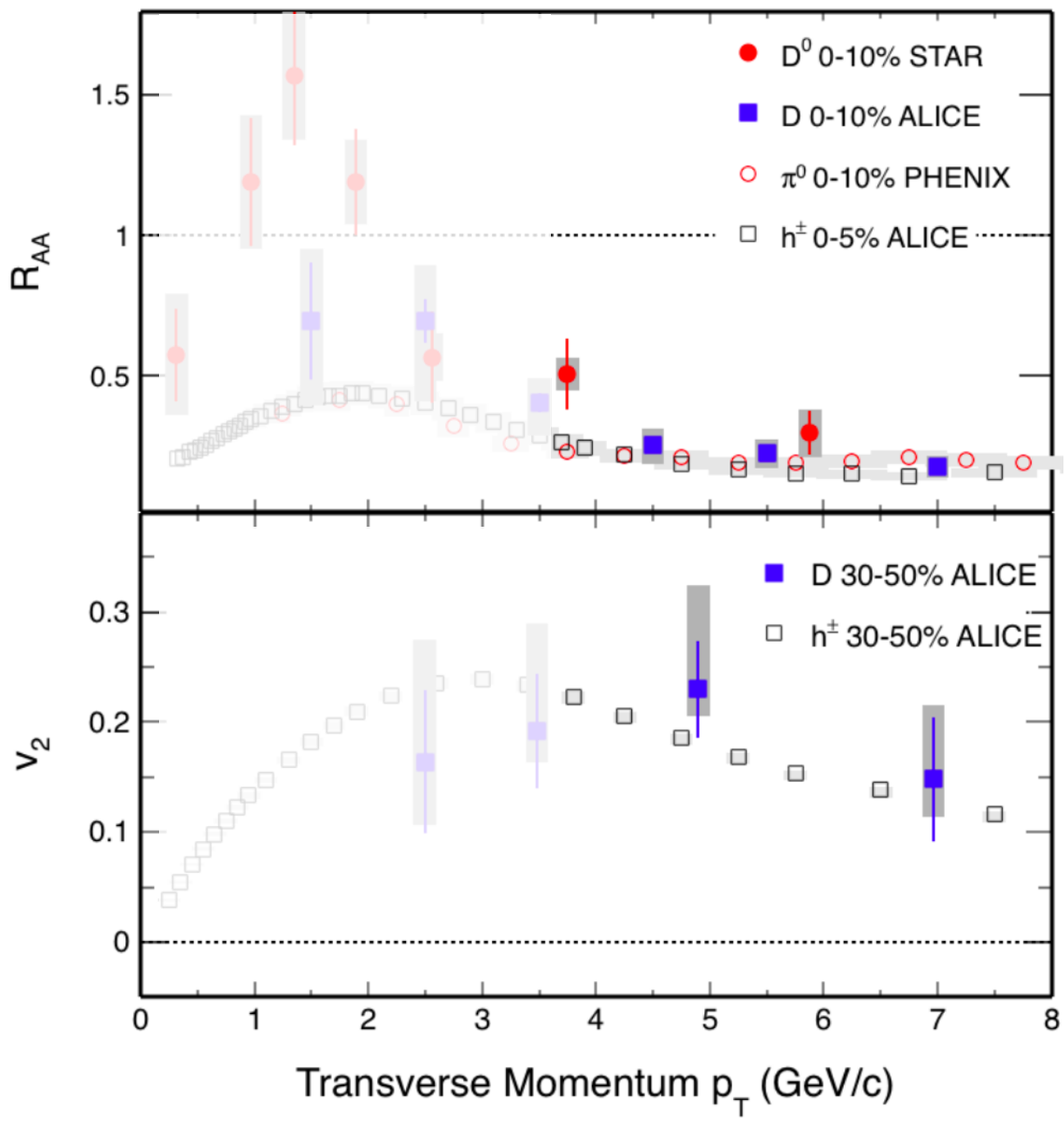

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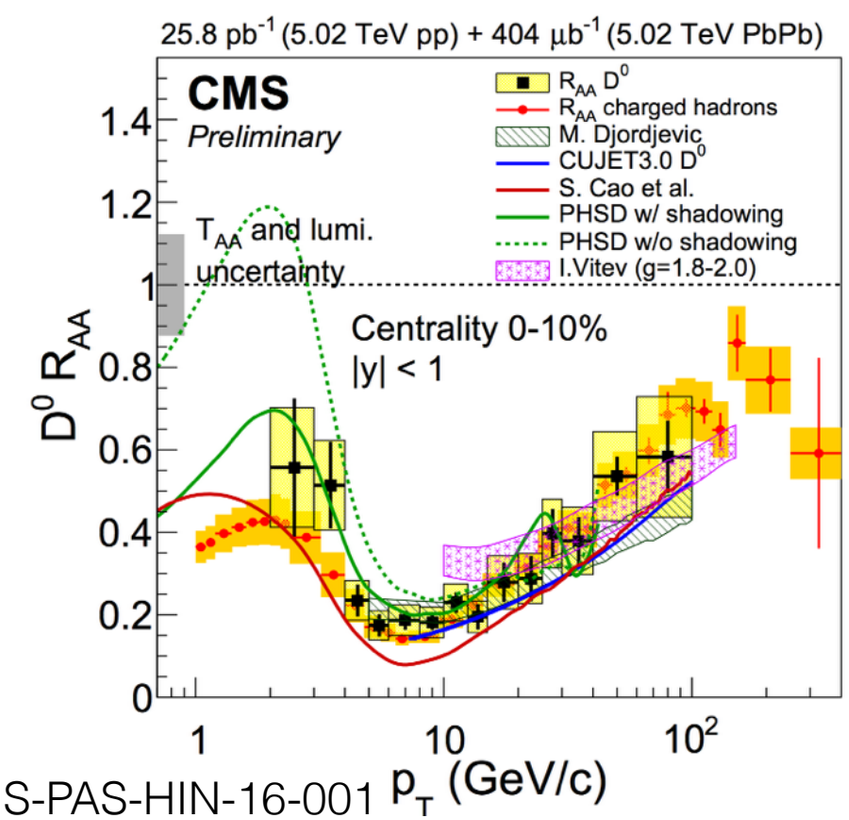

CMS-PAS-HIN-16-001

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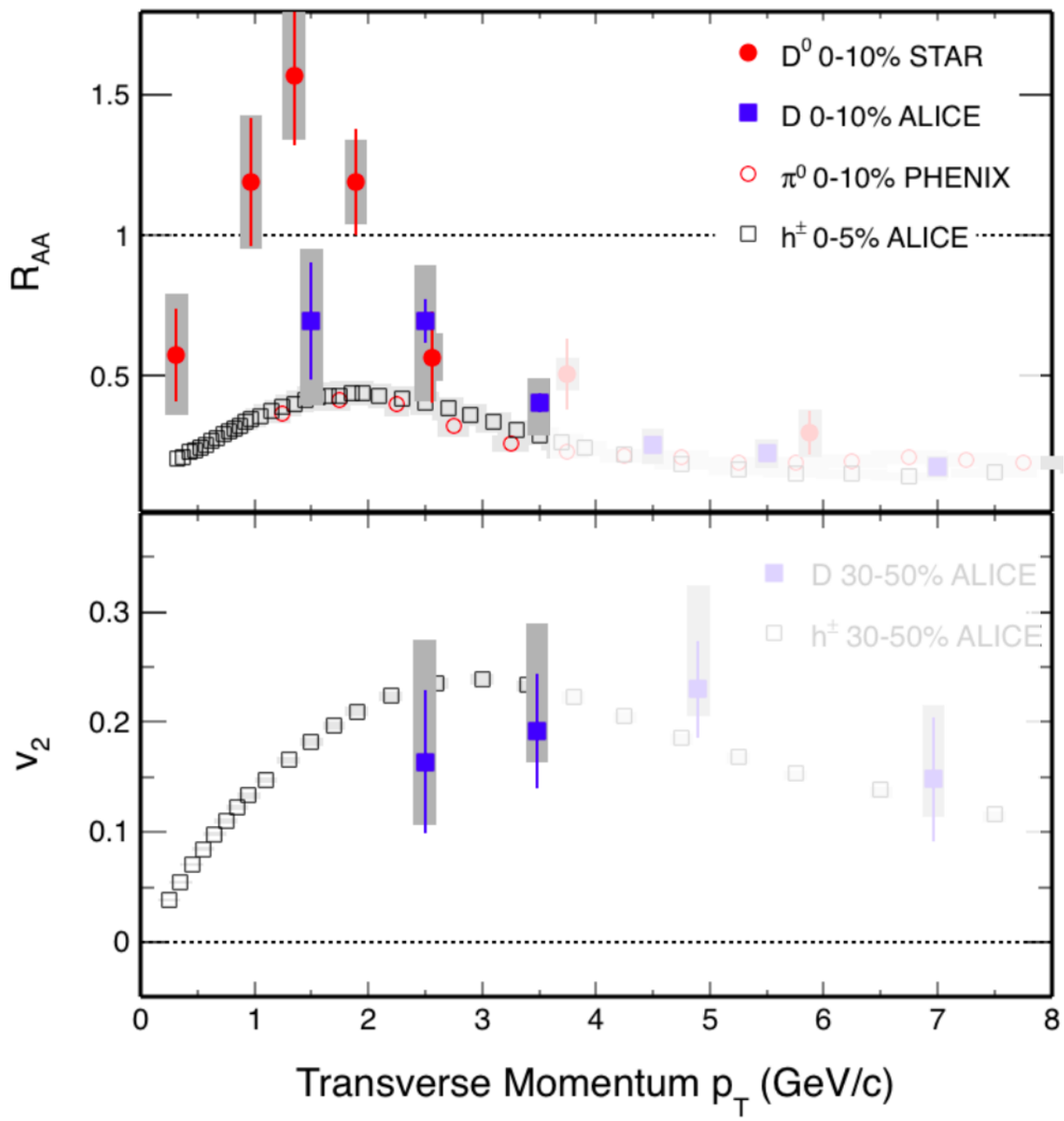

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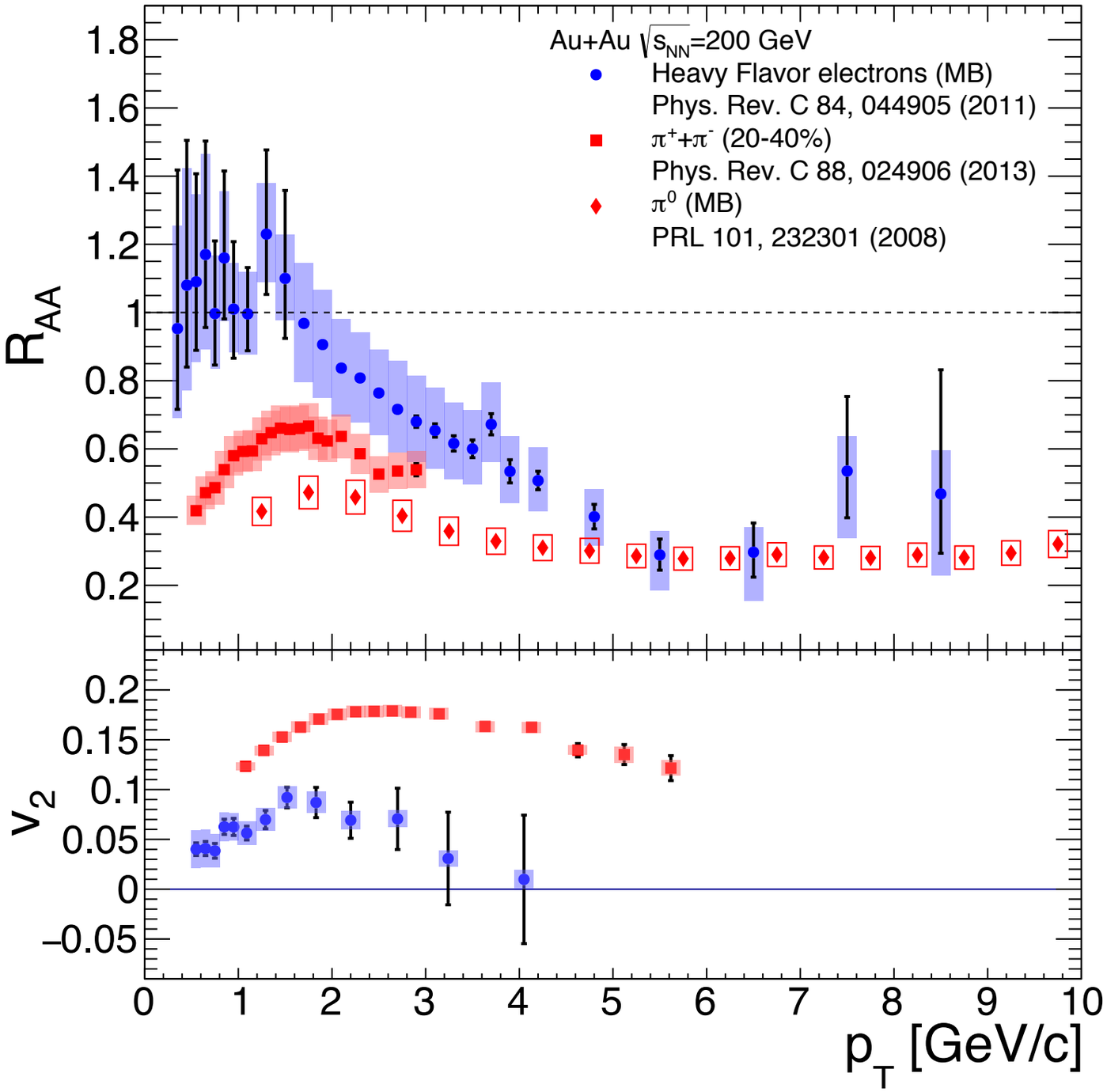
Low-p_T

- Enhancement of D R_{AA} observed at RHIC. Maybe not at LHC?
- Separation from light hadron R_{AA}

The Story so Far — HF electrons



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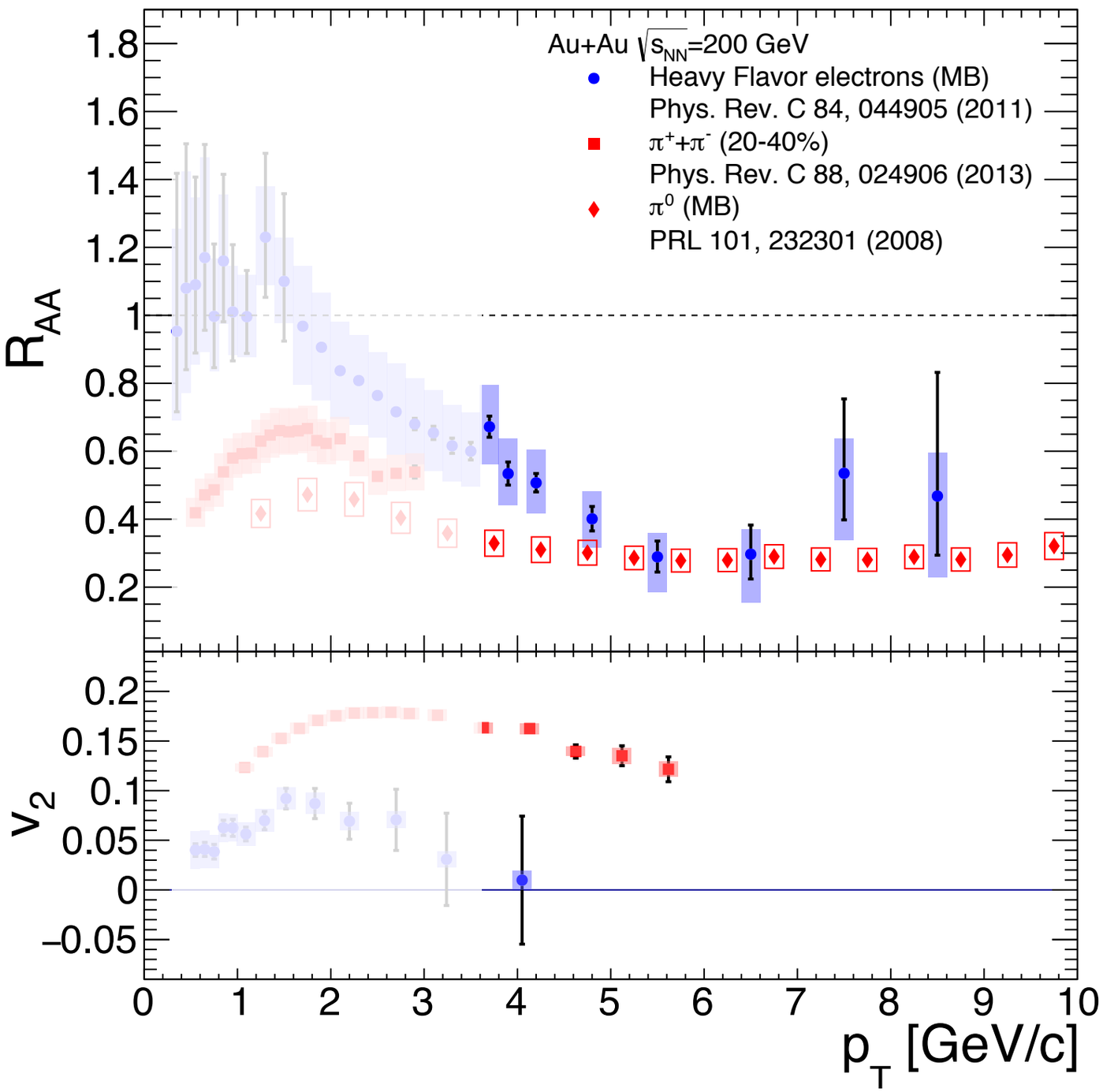

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- Significant suppression
- Similar suppression of light hadrons, charm, and bottom?

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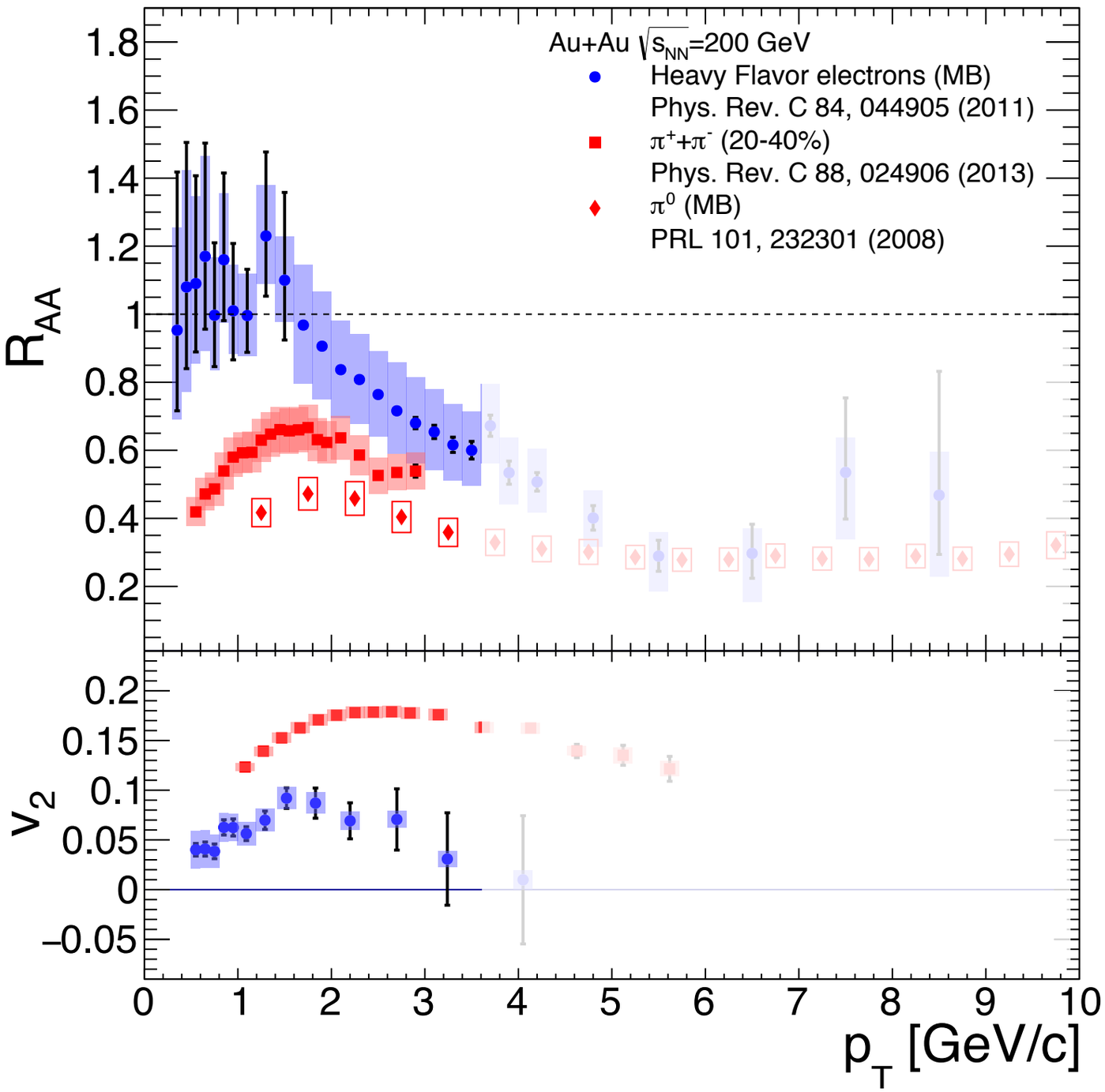


High-p_T

- Significant suppression
- Similar suppression of light hadrons, charm, and bottom?

Low-p_T

- Little suppression
- Electrons less suppressed than light hadrons.
- Significant v_2, but less than light hadrons

What about CNM Effects?

Cold Nuclear Matter

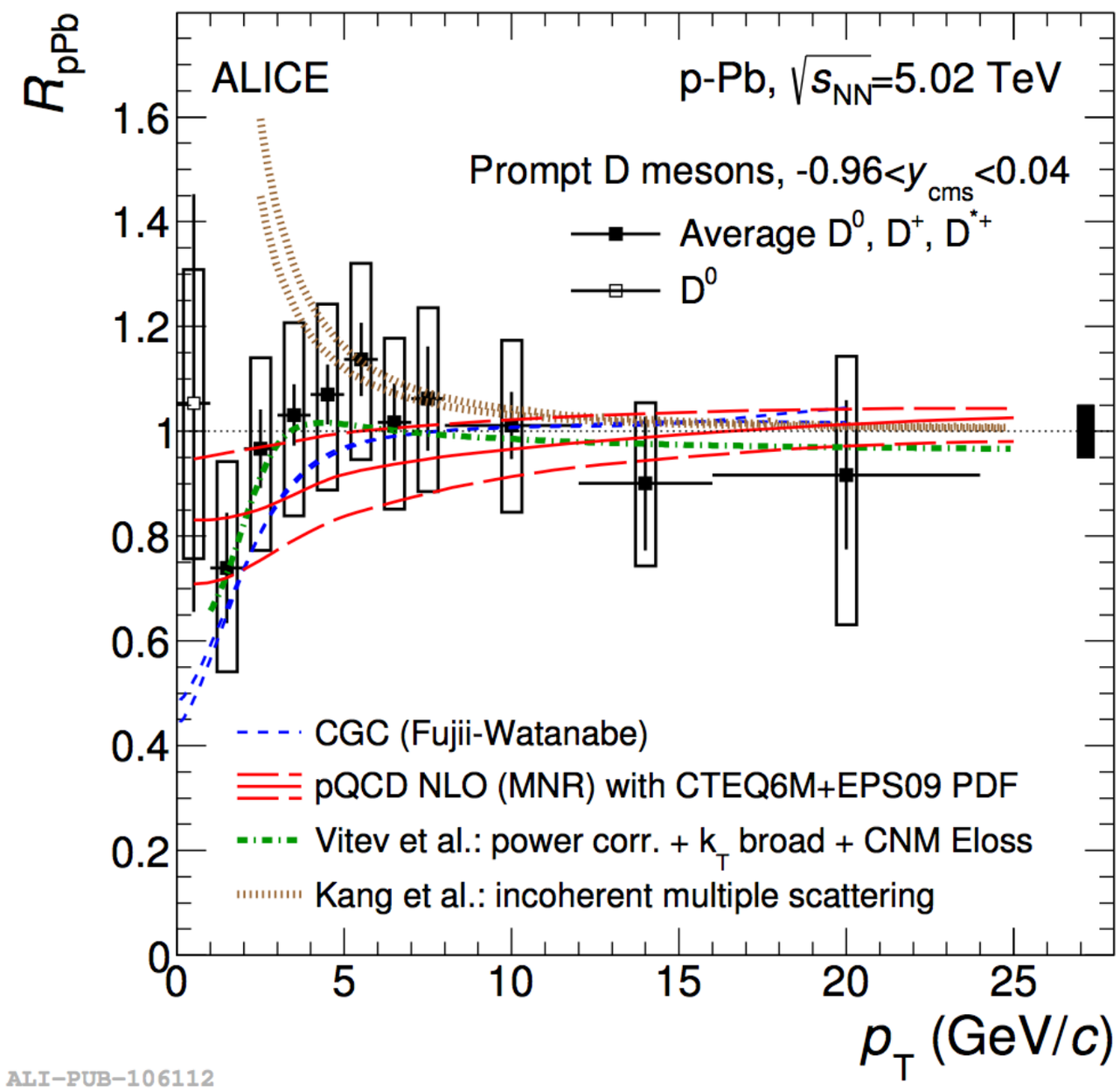
- Nuclear modified PDFs
- k_T broadening
- CNM energy loss
- CGC

LHC

- Small modification (large uncertainties)
- Consistent with CNM models

RHIC

- ???



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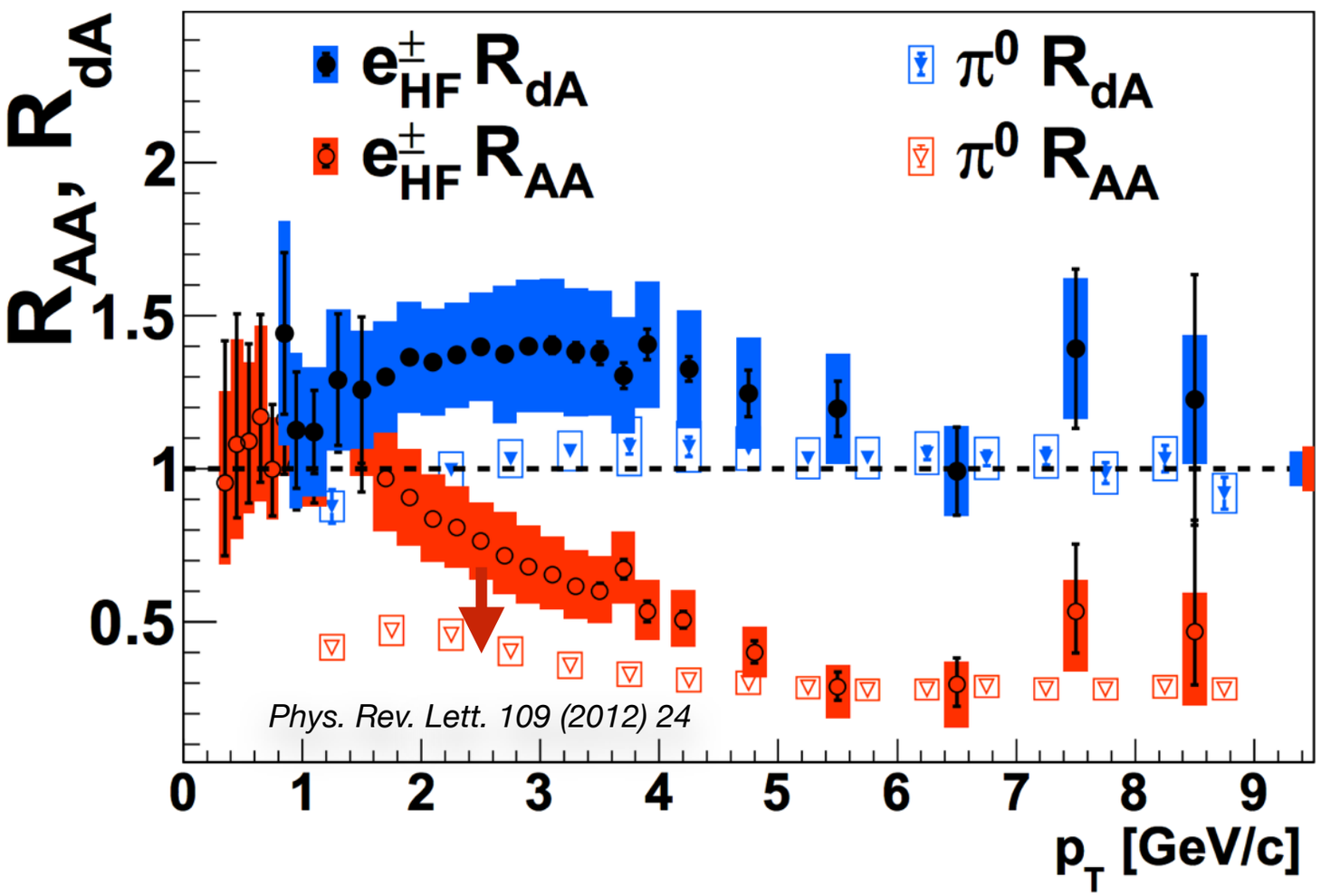

Baseline is no longer R_{AA}=1

Implies R_{AA} is more strongly suppressed for p_T < 4!

Need detailed calculations to propagate effects to Au+Au collisions!

How do we move forward at RHIC?

Increase precision by upgrading detectors

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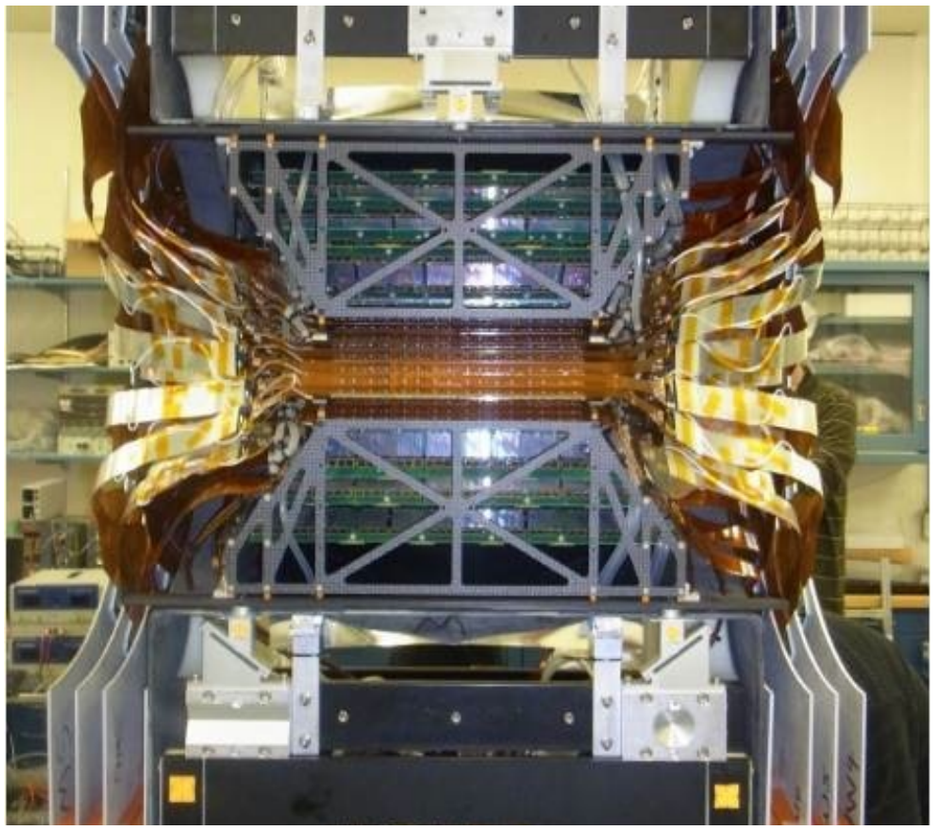

PHENIX Silicon Vertex Detectors

- Midrapidity — VTX (2011)
  - ~60 μm DCA_T resolution in Au+Au
- Forward rapidity — FVTX (2012)
  - Improved muon momentum resolution & precise tracking

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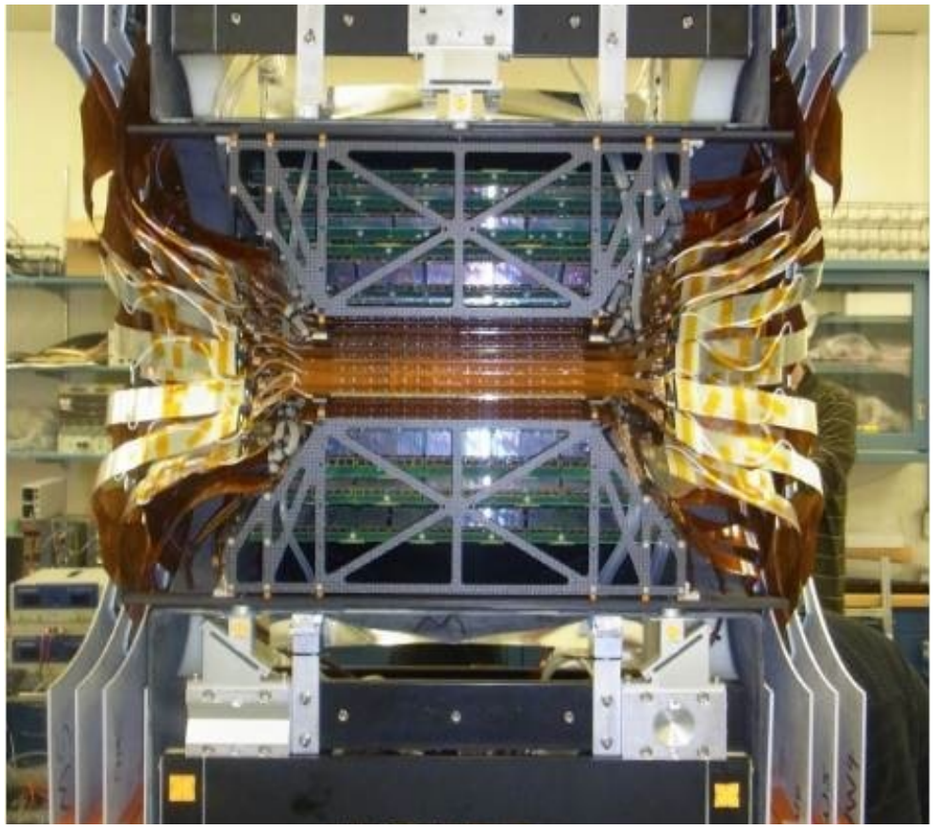

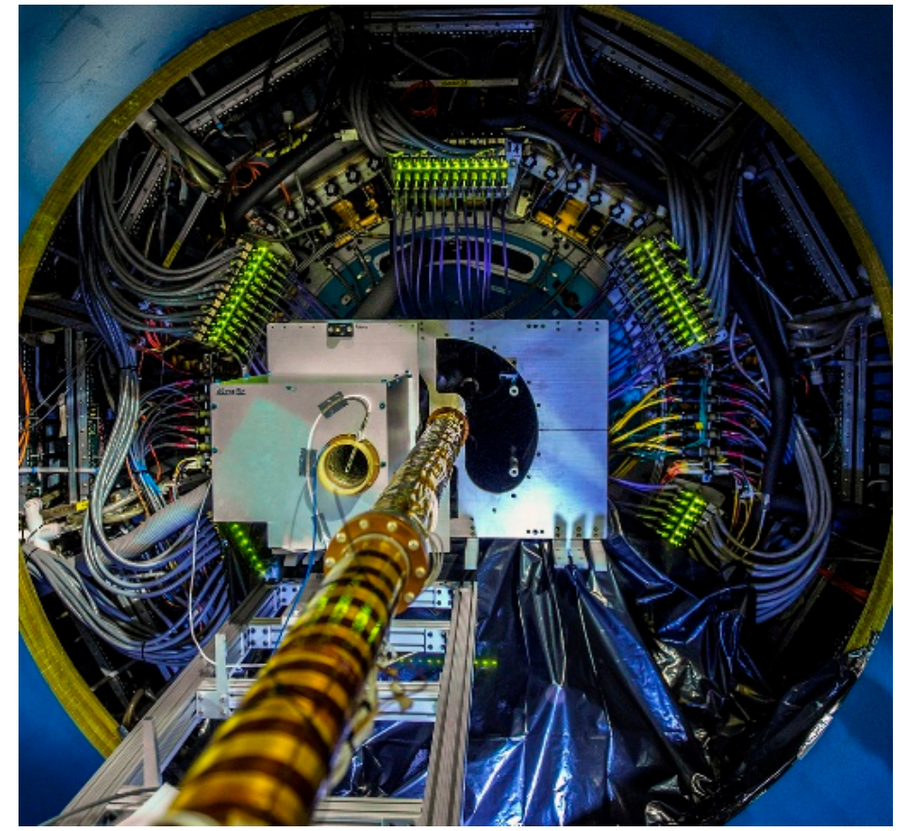

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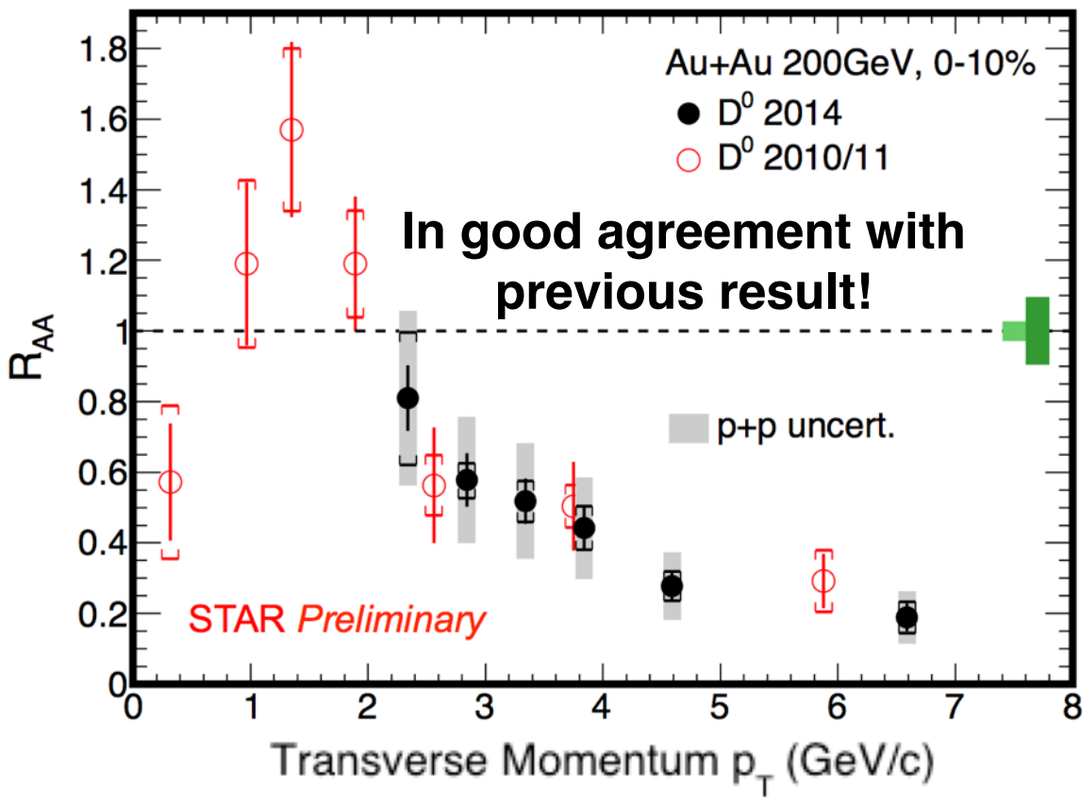
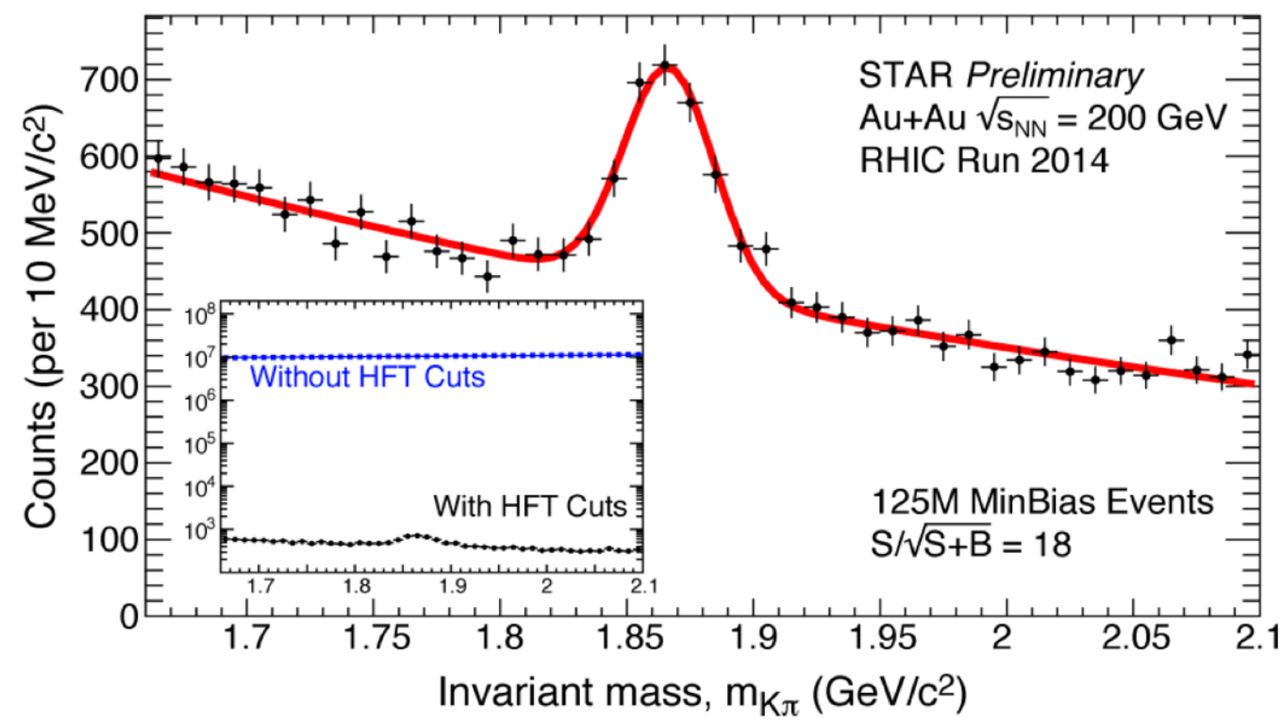
STAR Heavy Flavor Tracker (HFT)

- Midrapidity, installed 2014
- Kaon DCA_{XY} <55 μm in Au+Au

First Results from the STAR HFT

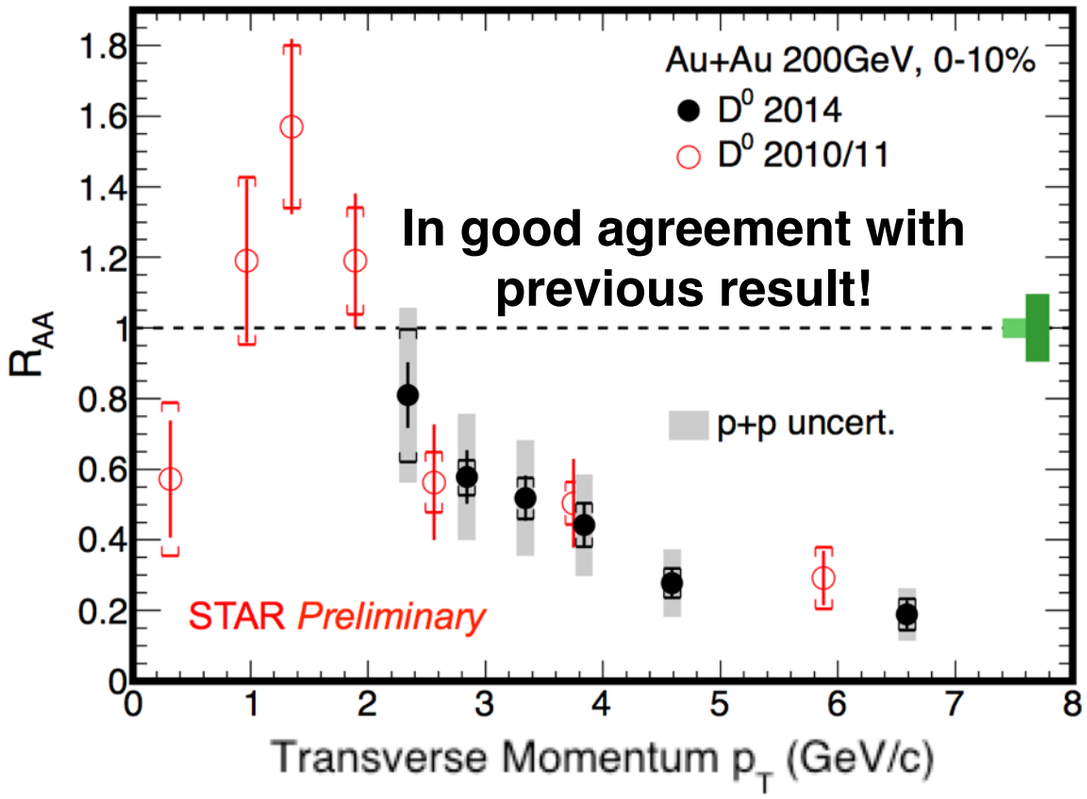


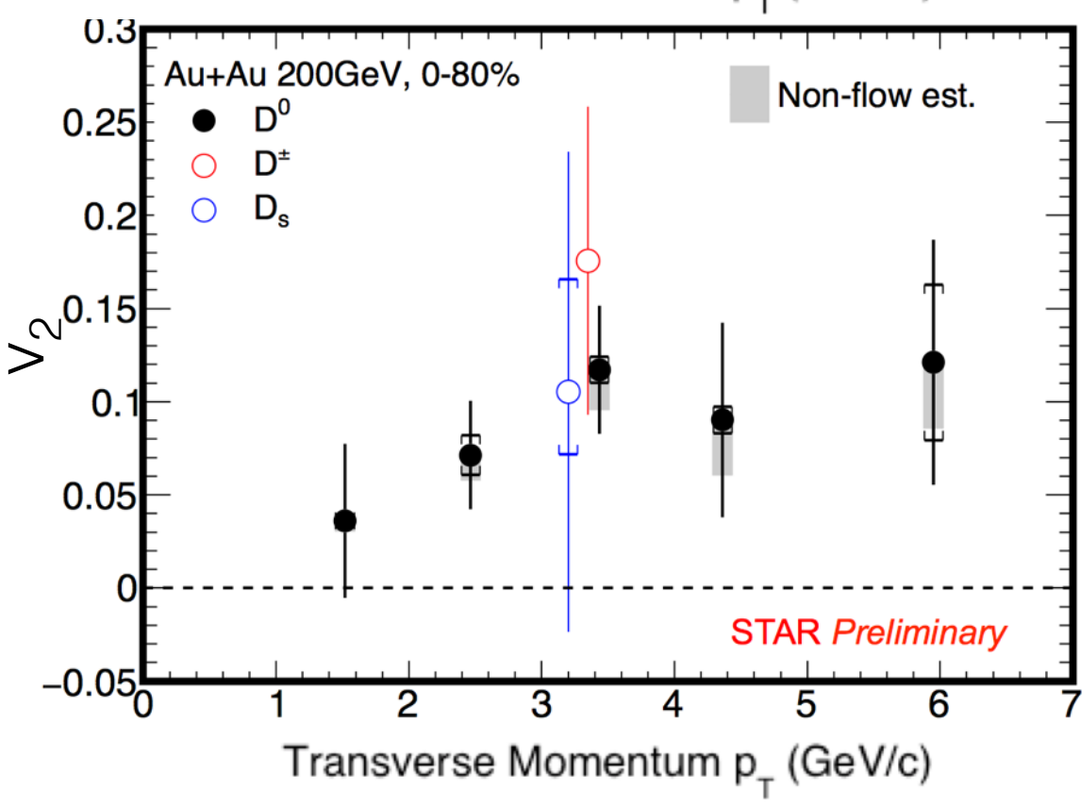
Using ~70% of the 2014 statistics



See M. Lomnitz talk from Tues HF workshop

First Results from the STAR HFT





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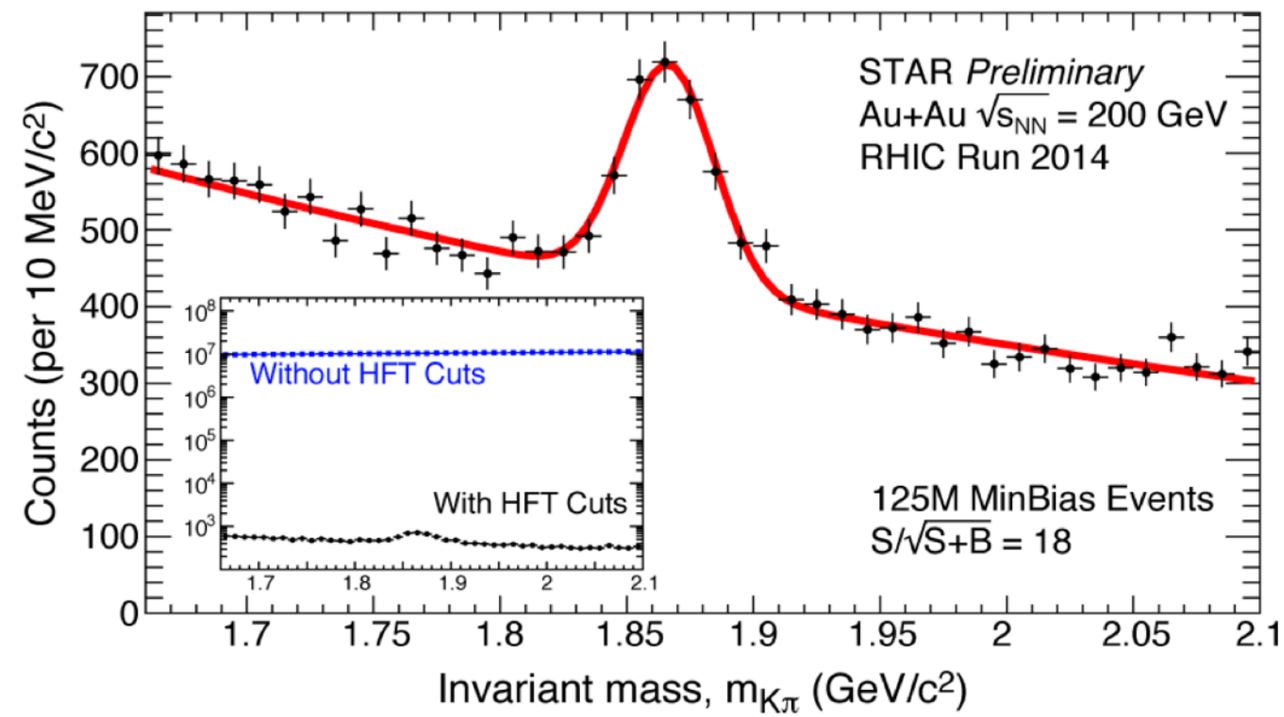

Significant v_2 for D's at RHIC

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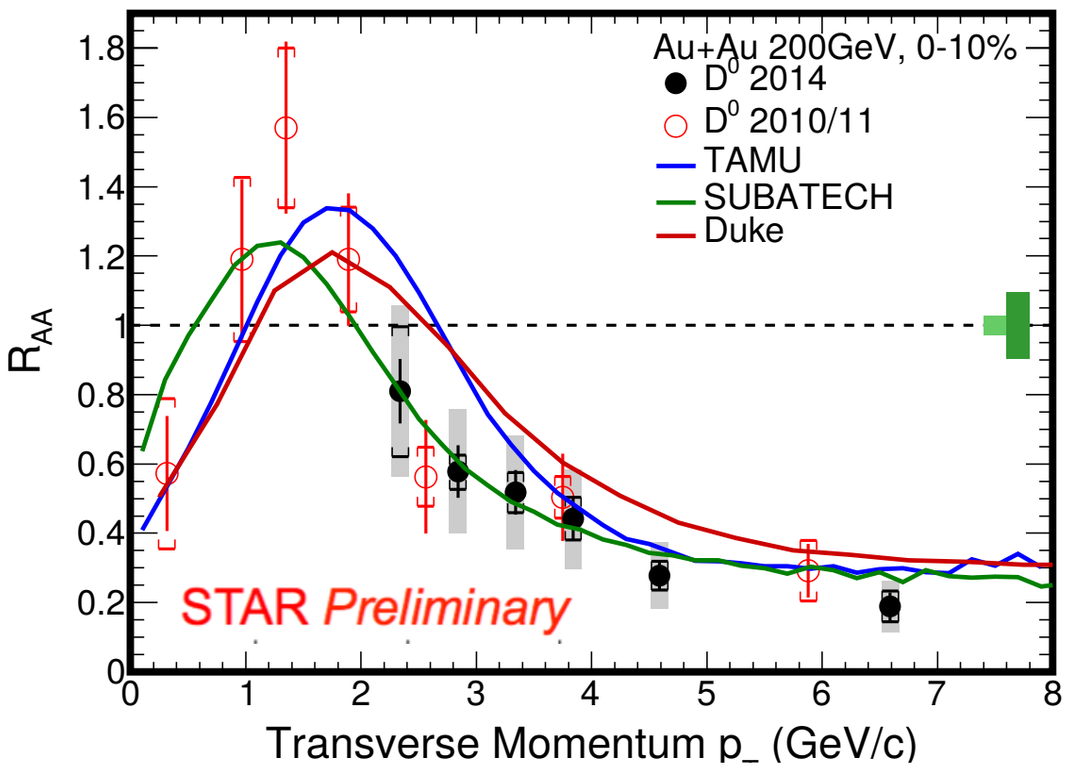

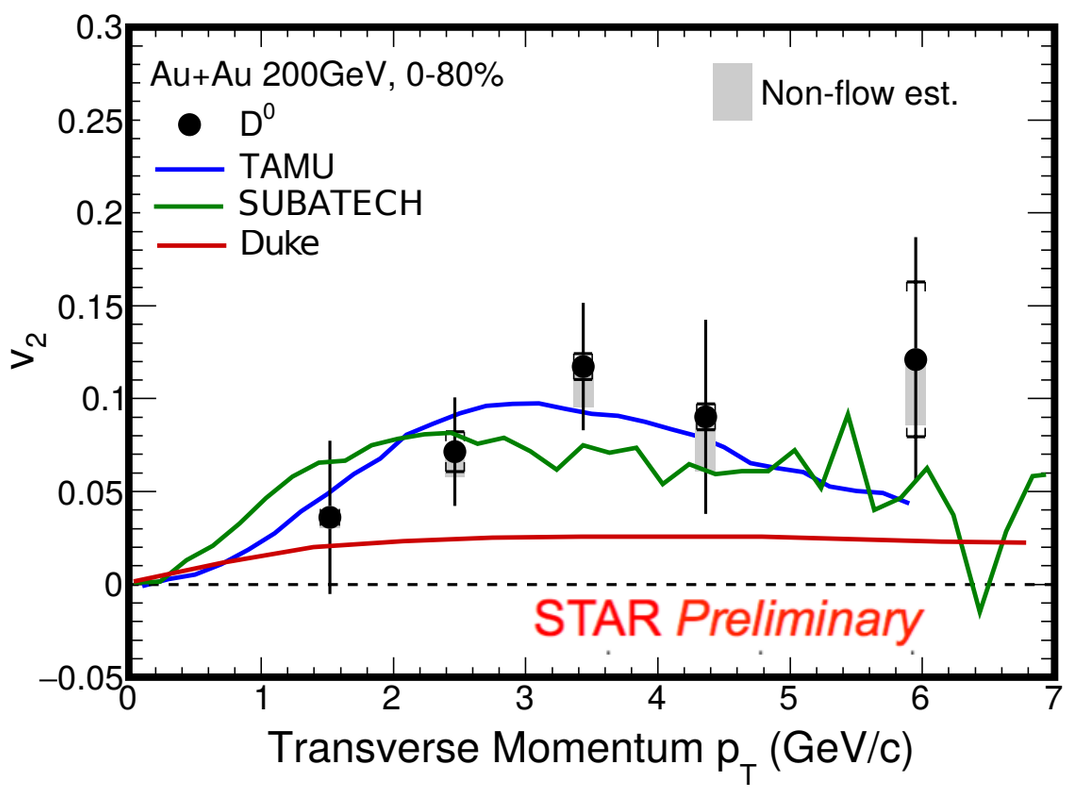

Model Comparison

- Models should describe R_{AA} + v_2 simultaneously
- Very good agreement between models & data for both v_2 and R_{AA}

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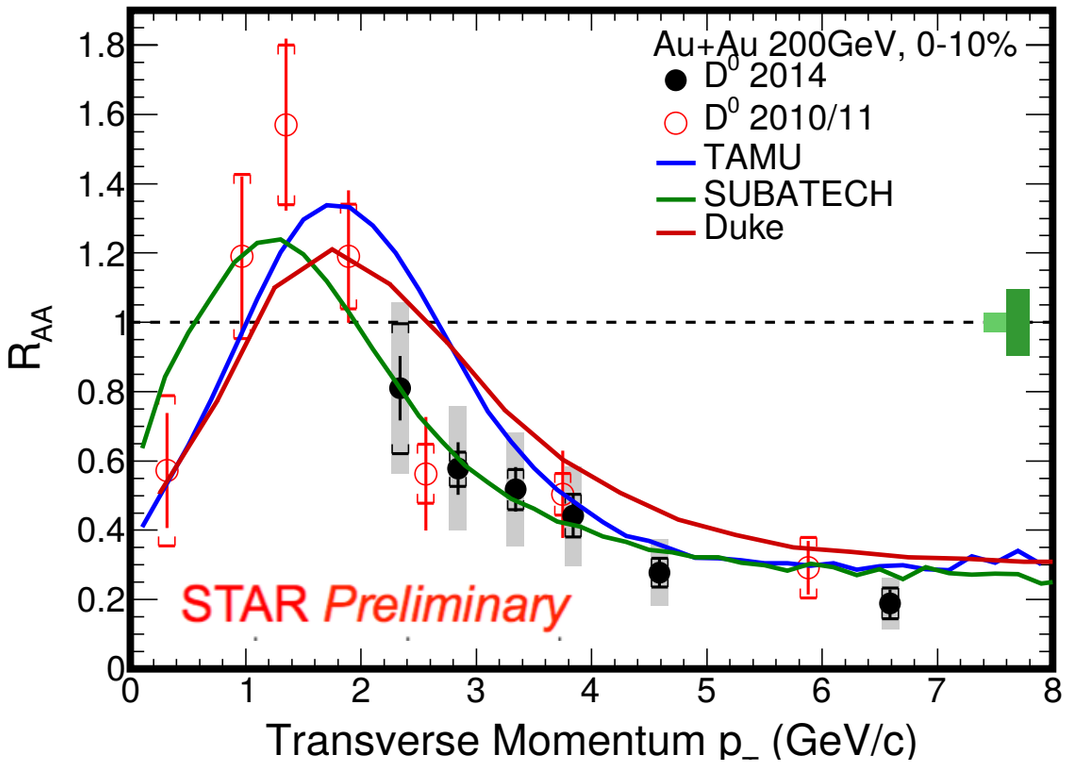
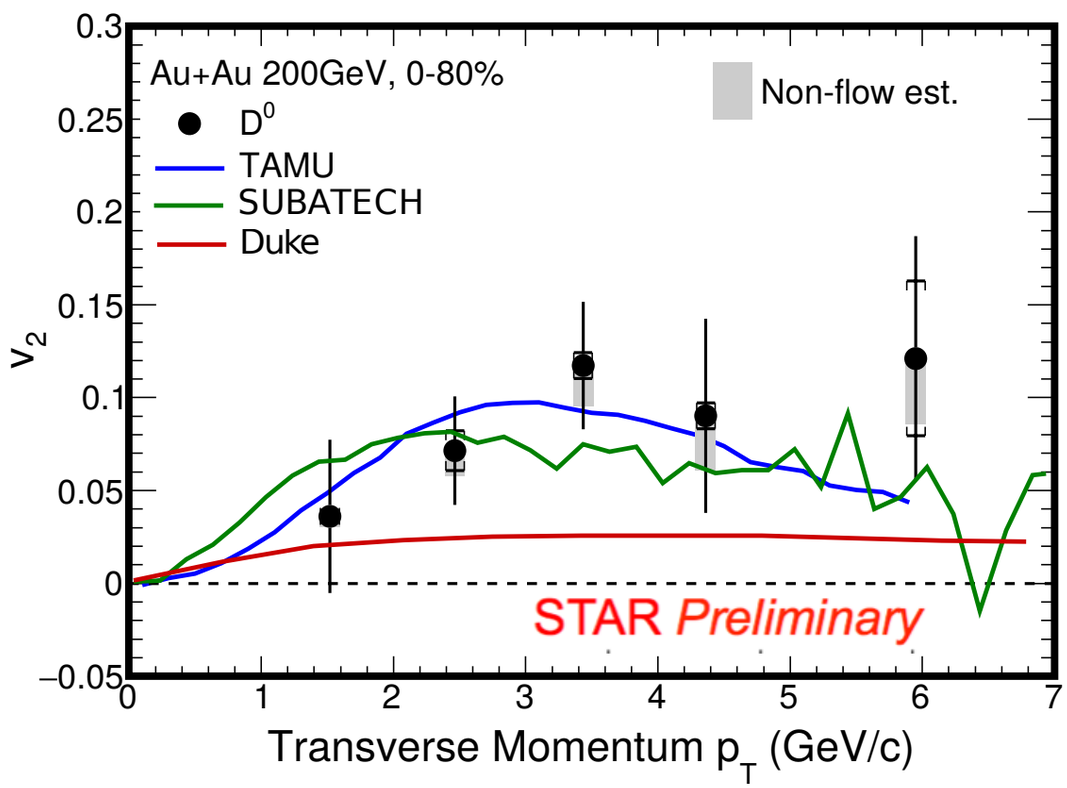
Outlook from the STAR HFT





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Expect many more results to come …

Stolen from M. Lomnitz Tuesday Talk

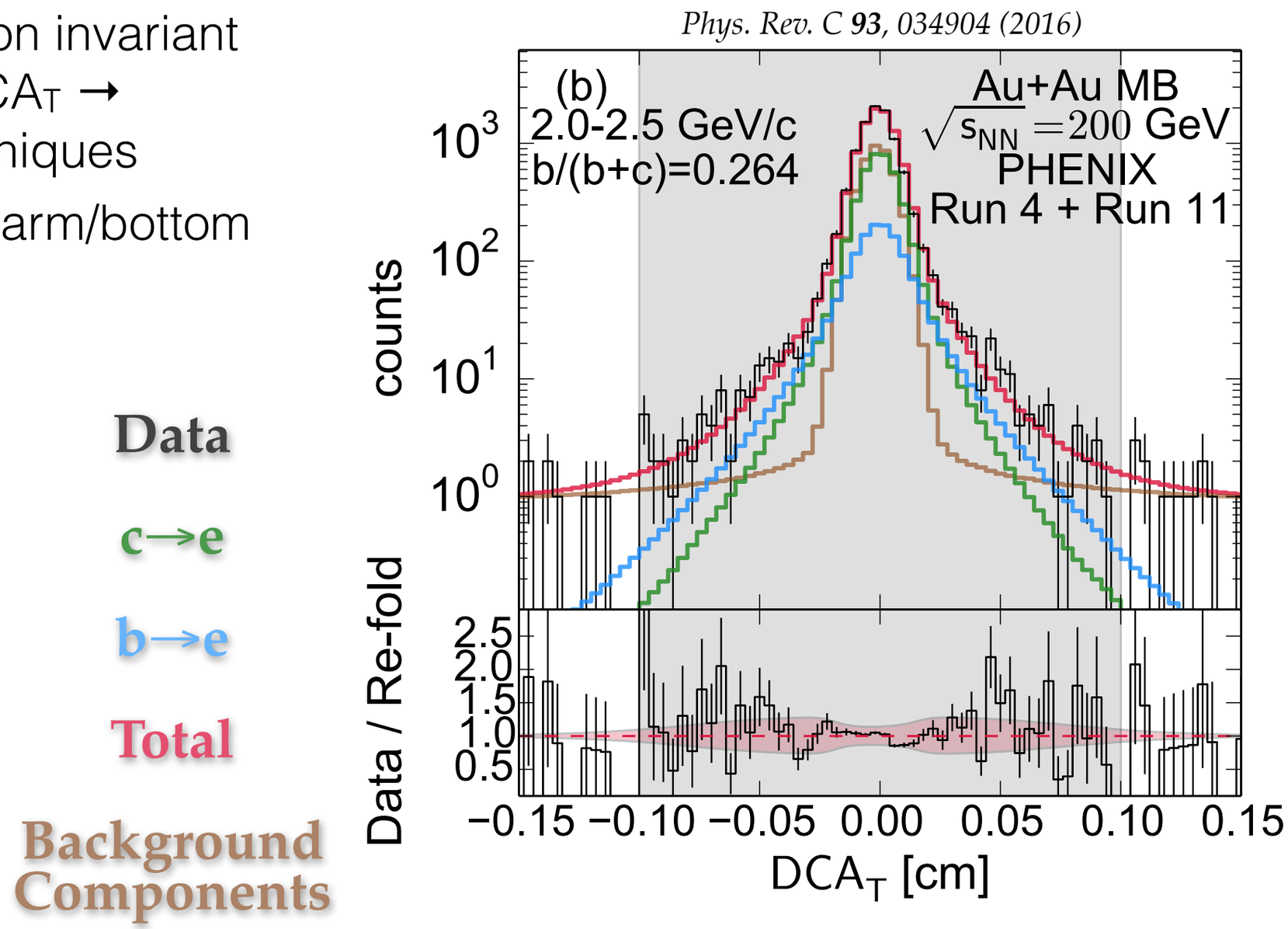
Year	System	Events(MB)
Run 14:		
	Au+Au	1.2 B
Run 15:		
	p+p	1 B
	p+Au	0.6 B
Run 16:		
	Au+Au	1.5 B *
	d+Au	~0.3 B

See M. Lomnitz talk from Tues HF workshop

First Results from the PHENIX VTX

Separating HF electrons

- Use DCA to separate electrons from charm vs. bottom hadron decays.
- 2007 heavy flavor electron invariant yield + 2011 electron DCA_T → Bayesian inference techniques
- Parameters = yield of charm/bottom hadrons
- Good fit to electron data



See T. Rinn talk from Tues HF workshop

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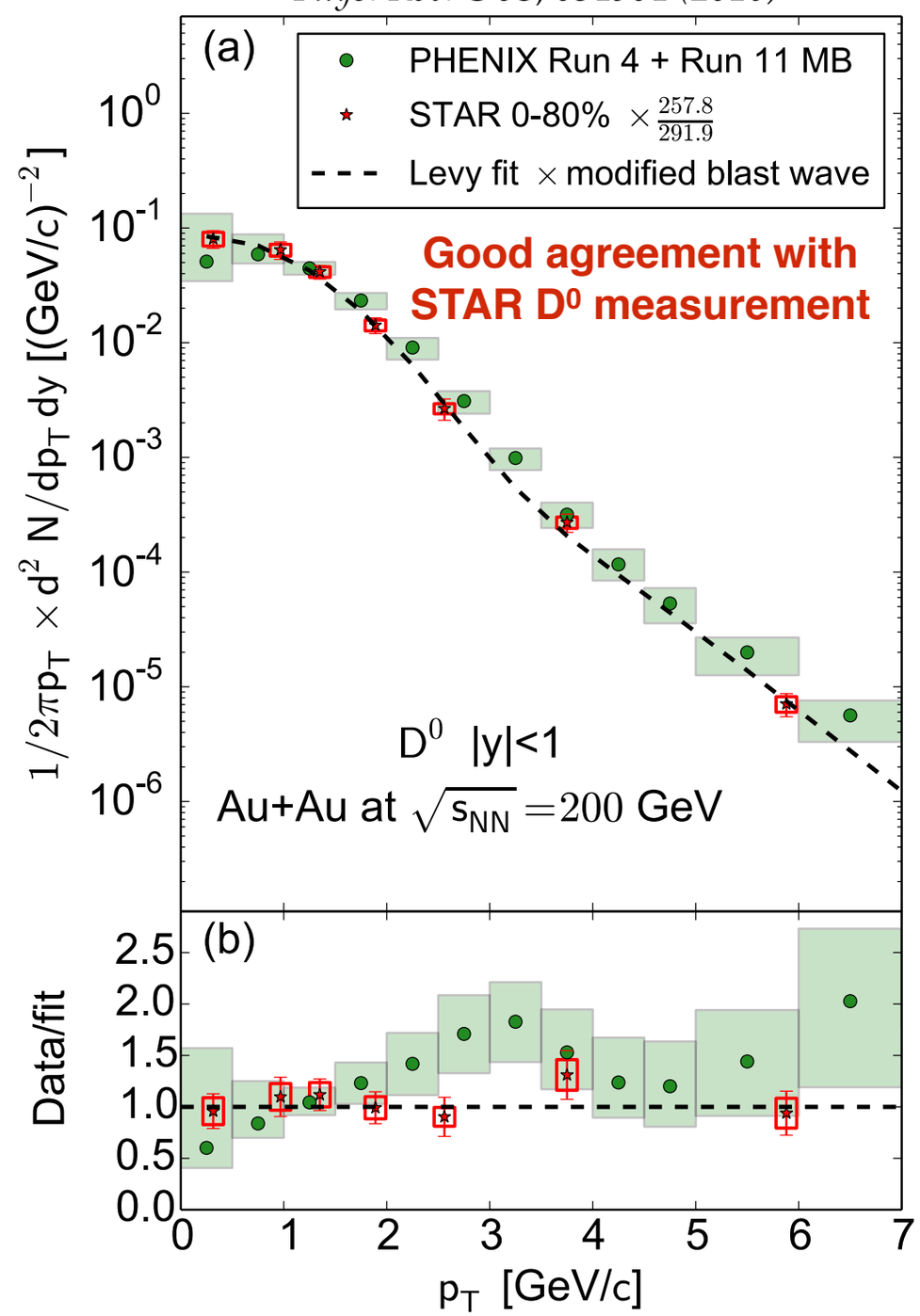
Phys. Rev. C **93**, *034904 (2016)*



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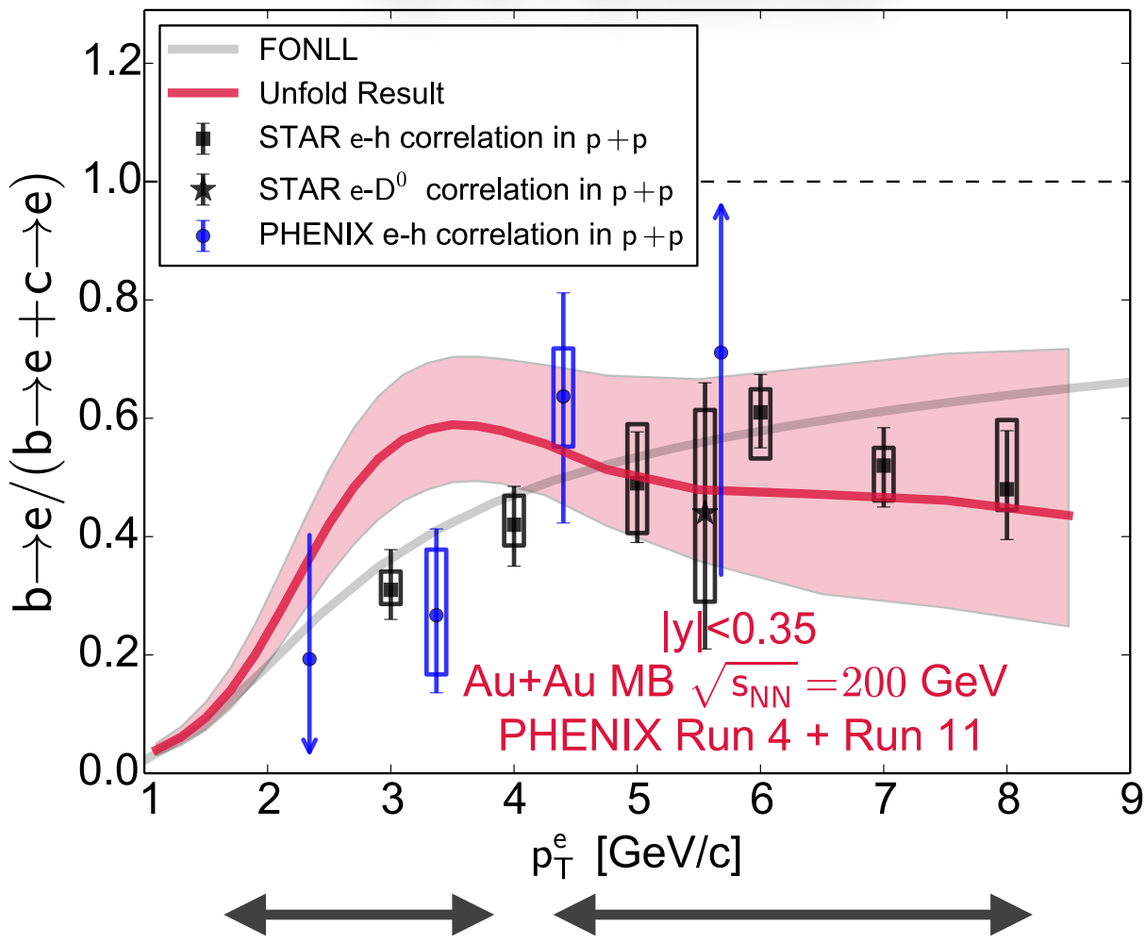
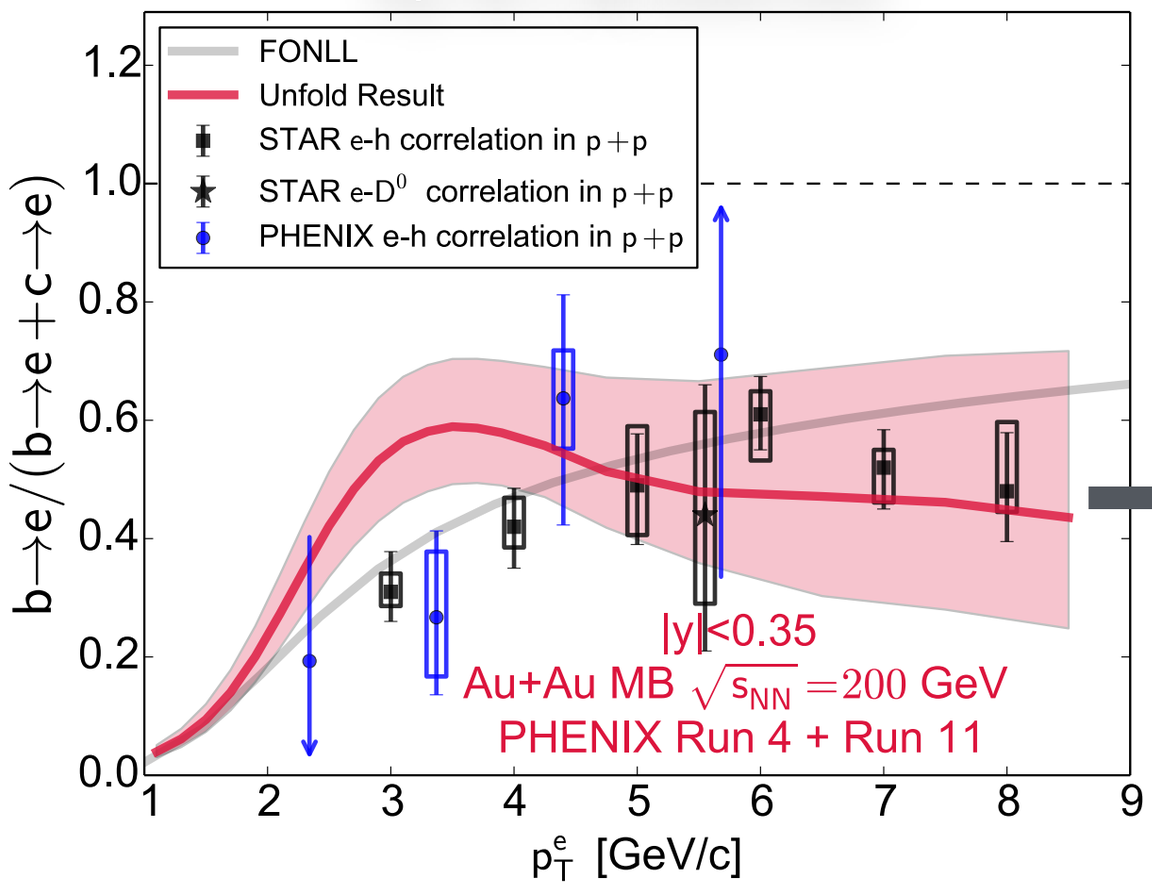


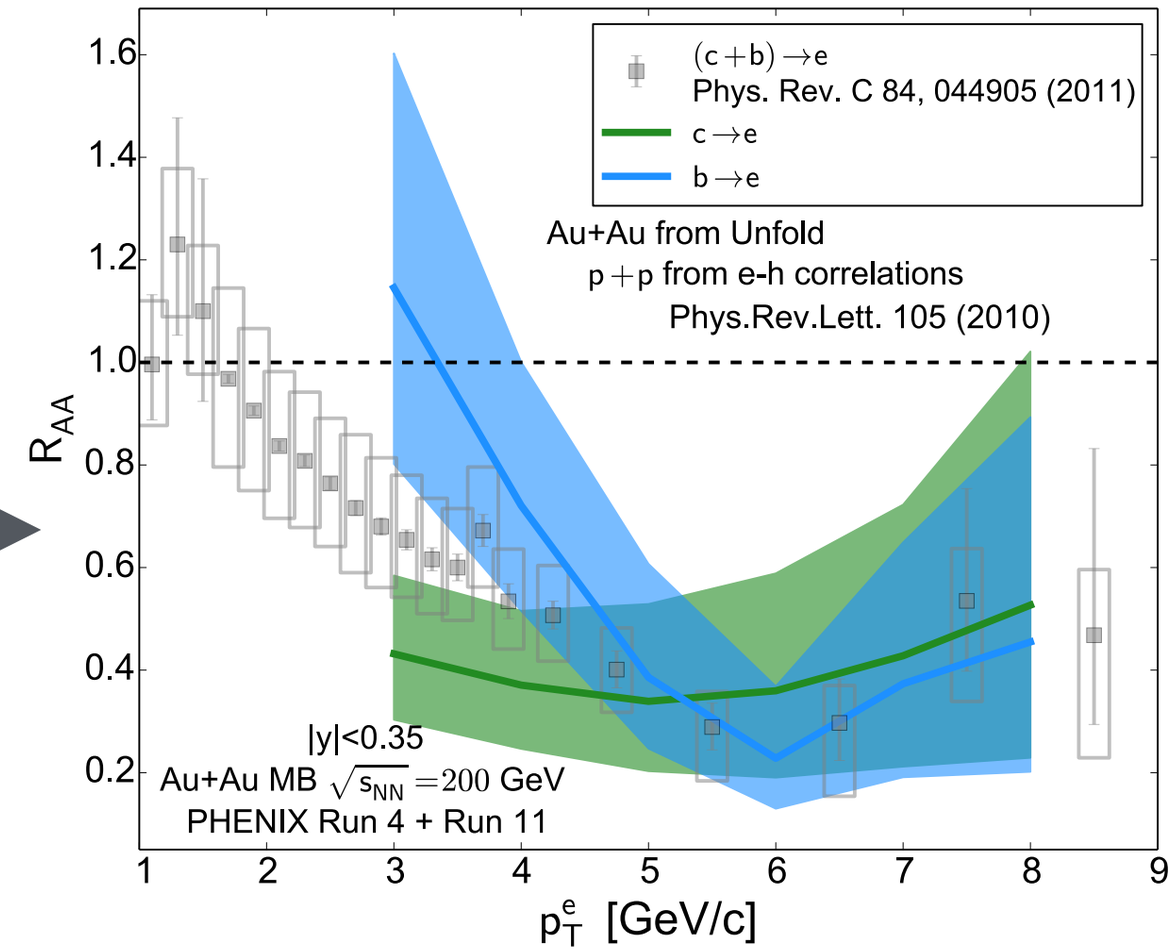
$F_{AuAu} > F_{pp}$ $F_{AuAu} \approx F_{pp}$

$$F = \frac{b \to e}{b \to e \; + \; c \to e}$$

First Results from the PHENIX VTX

Phys. Rev. C **93**, 034904 (2016)





$F_{AuAu} > F_{pp}$ $\quad$ $F_{AuAu} \approx F_{pp}$

$$F = \frac{b \to e}{b \to e \; + \; c \to e}$$

$$R_{AA}^{c\to e} = \frac{(1-F_{AuAu})}{(1-F_{pp})} R_{AA}^{HF}$$
$$R_{AA}^{b\to e} = \frac{F_{AuAu}}{F_{pp}} R_{AA}^{HF},$$

Electrons from bottom less suppressed than those from charm for $p_T < 4$ GeV/c
Similarly suppressed for $p_T > 4$ GeV/c

First Results from the PHENIX VTX

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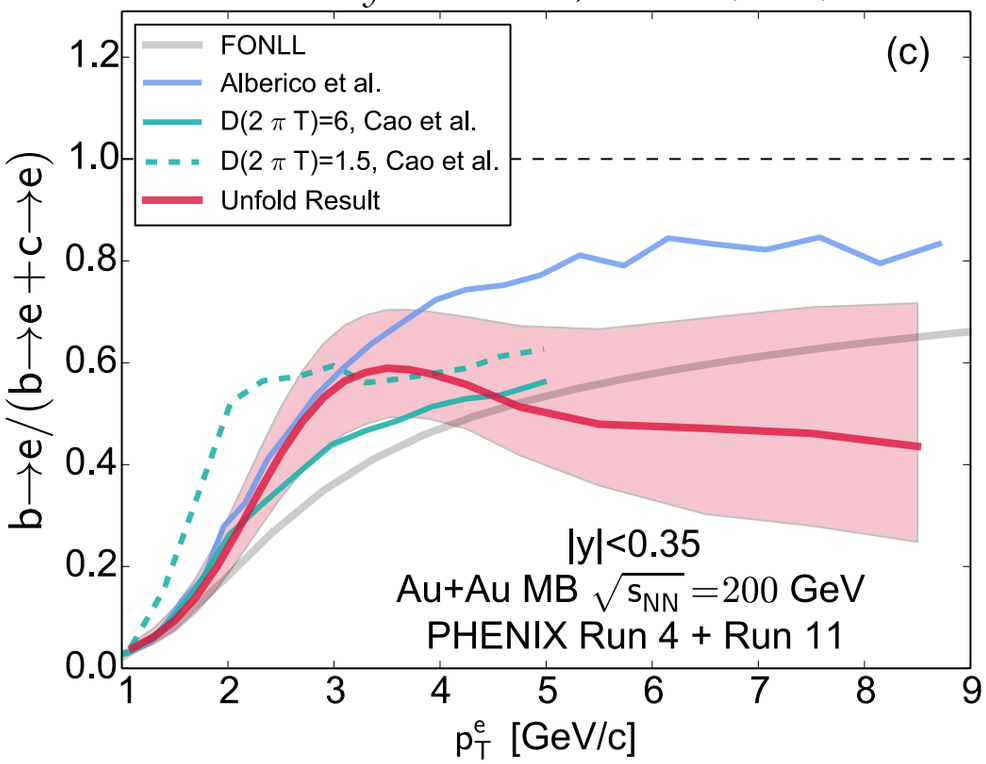
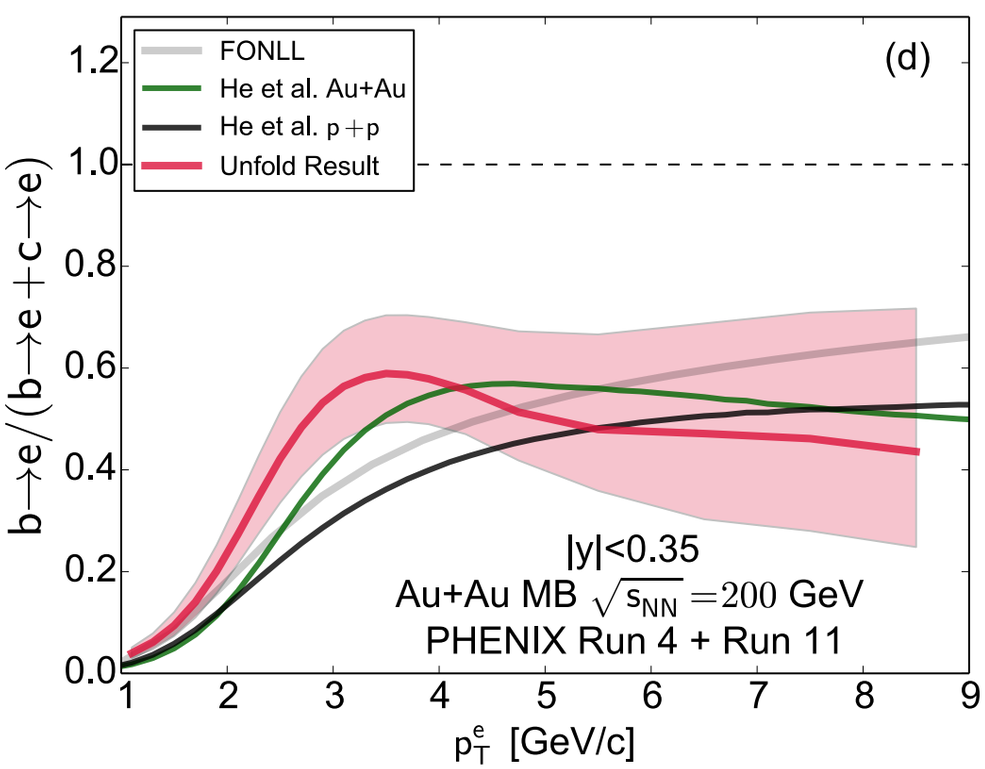
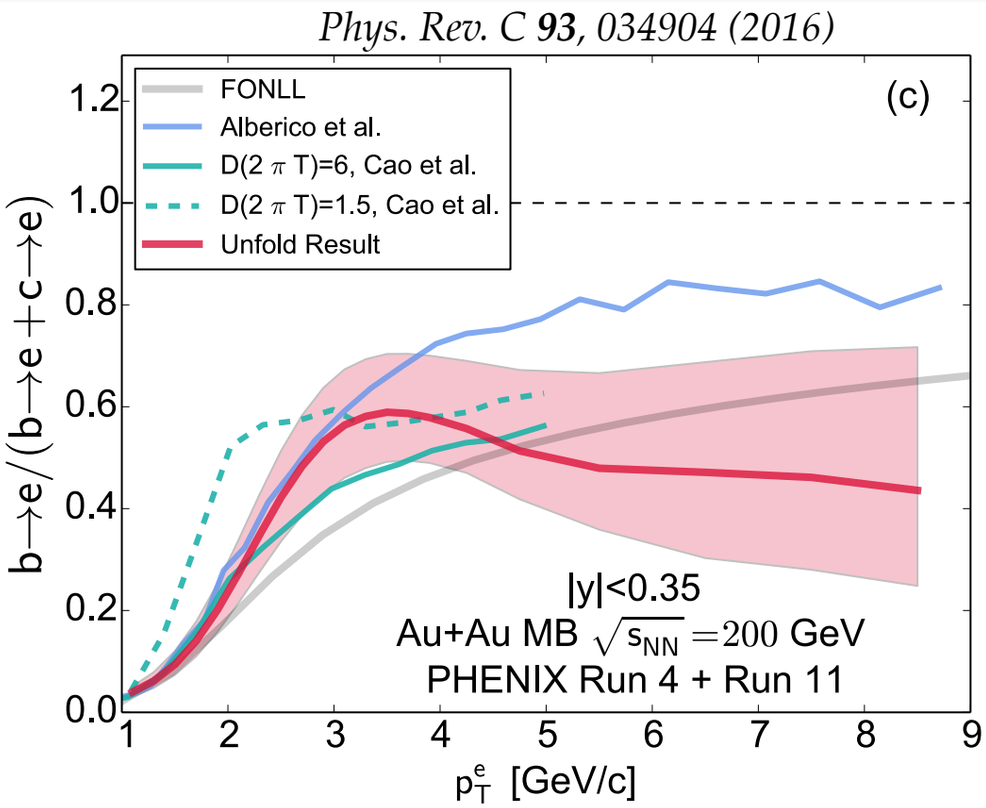


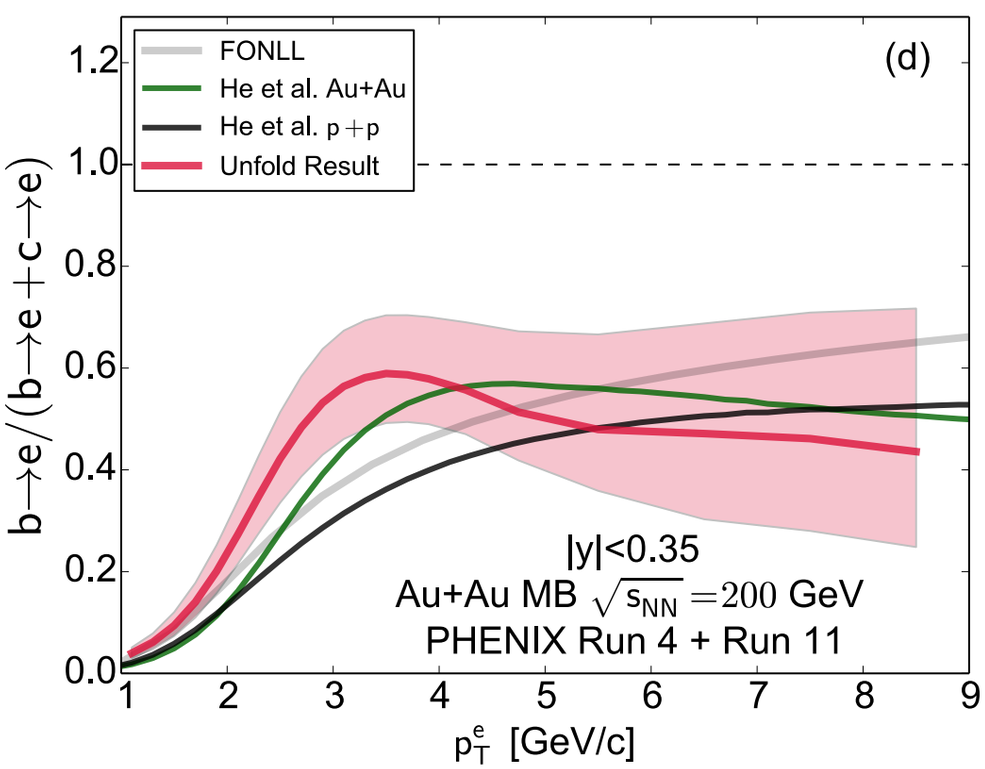


Model Comparison

- Various models incorporating collisional and/or radiative energy loss
  - *Eur. Phys. J. C 71, 1666 (2011)*
  - *J. Phys. G 40, 085103 (2013)*
  - *Phys. Lett. B 735, 445 (2014)*
- All curves were predictions!
- No smoking gun yet …

Outlook from the PHENIX VTX





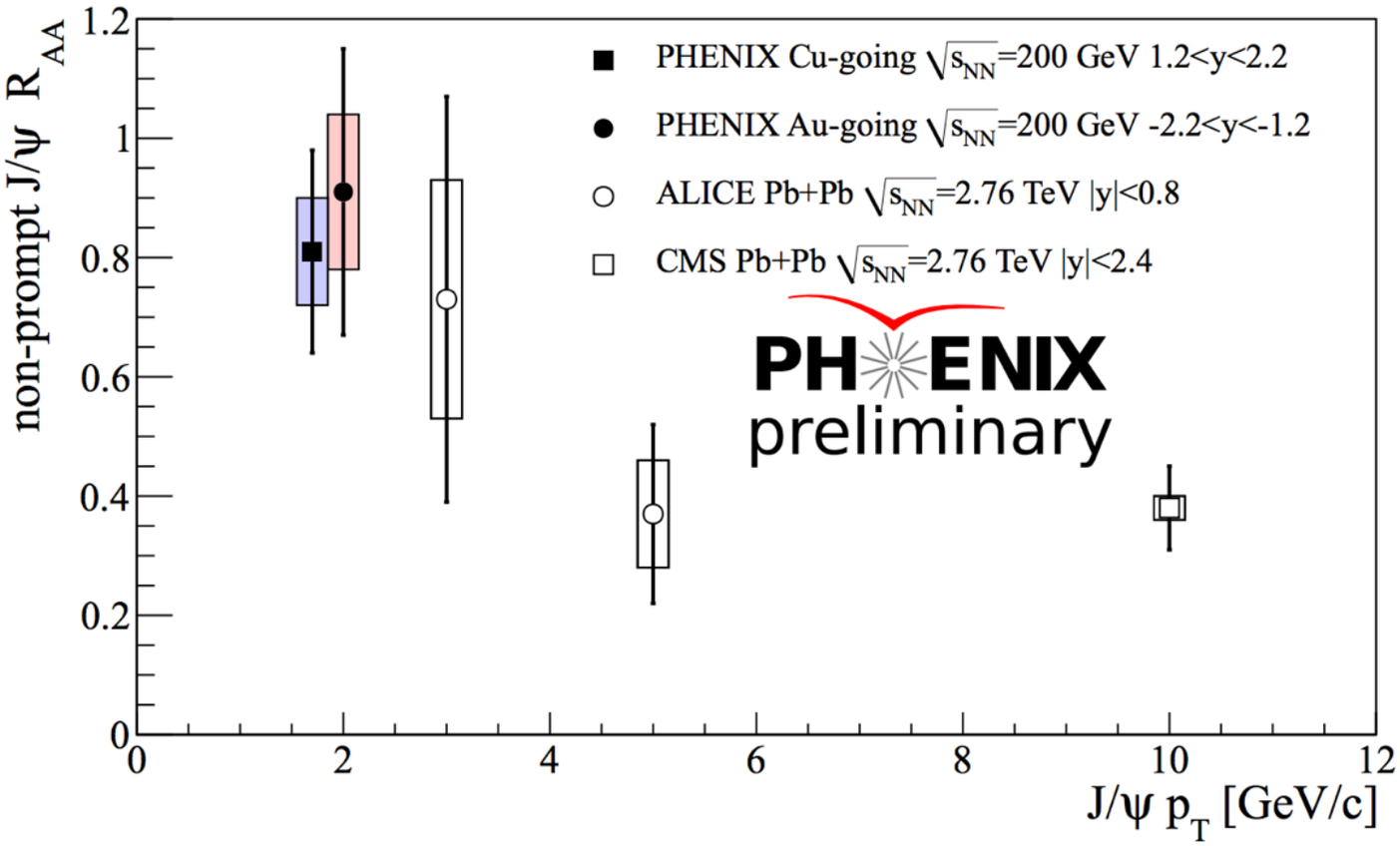
Model Comparison

- Various models incorporating collisional and/or radiative energy loss
  - *Eur. Phys. J. C 71, 1666 (2011)*
  - *J. Phys. G 40, 085103 (2013)*
  - *Phys. Lett. B 735, 445 (2014)*
- All curves were predictions!
- No smoking gun yet …

Stay Tuned …

- 2014 data set x10 better statistics than 2011
  - Decrease uncertainties
  - Increase p_T reach
  - Centrality separation
- Good 2015 p+p and p+Au data sets

First Results from the PHENIX FVTX



Non-prompt J/ψ at RHIC consistent with little to no suppression in Cu & Au-going directions

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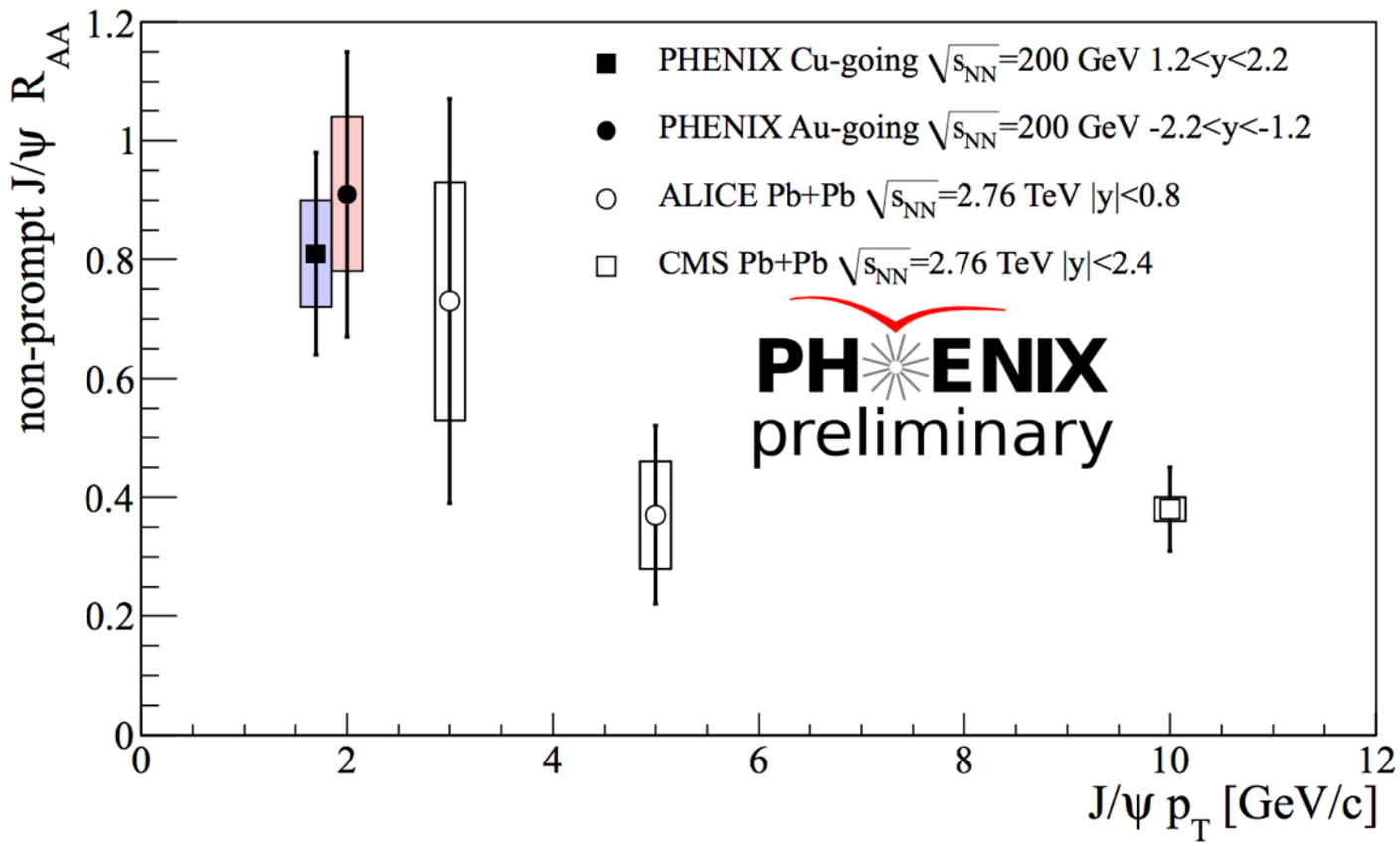
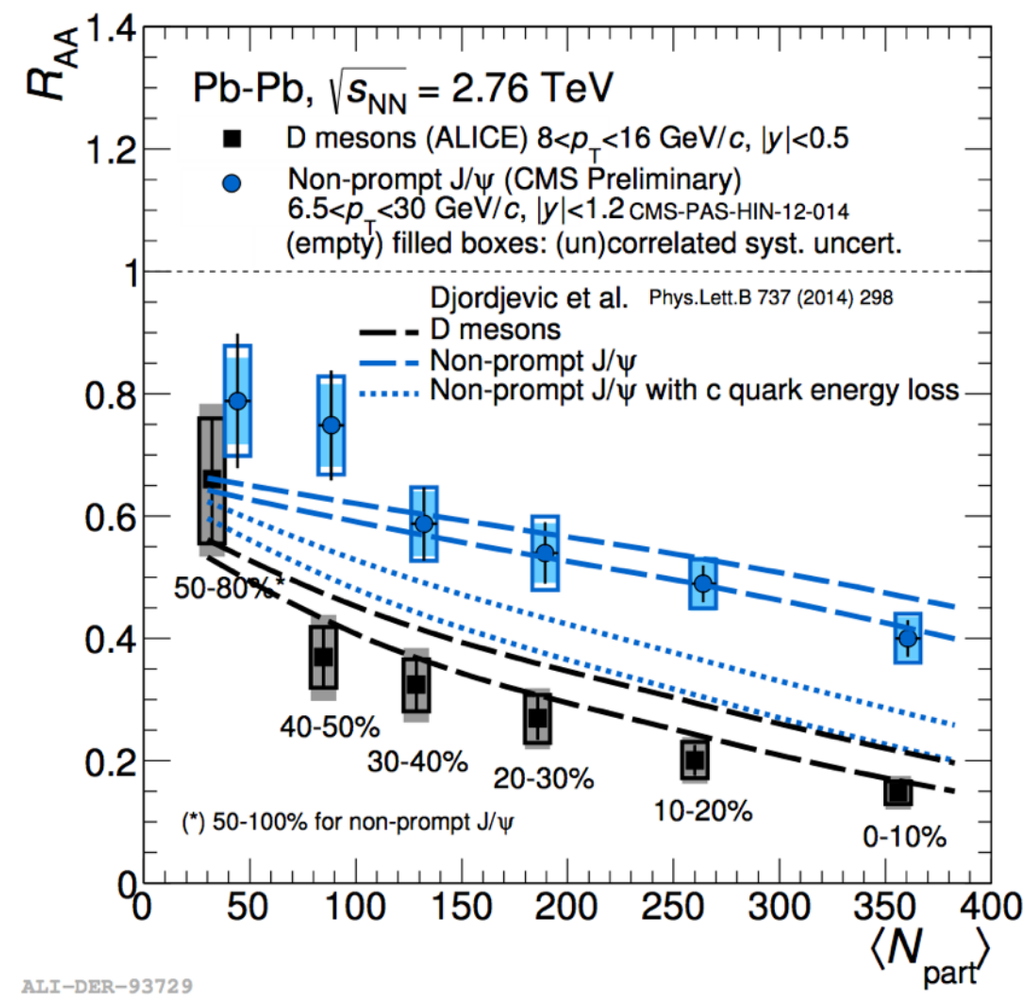
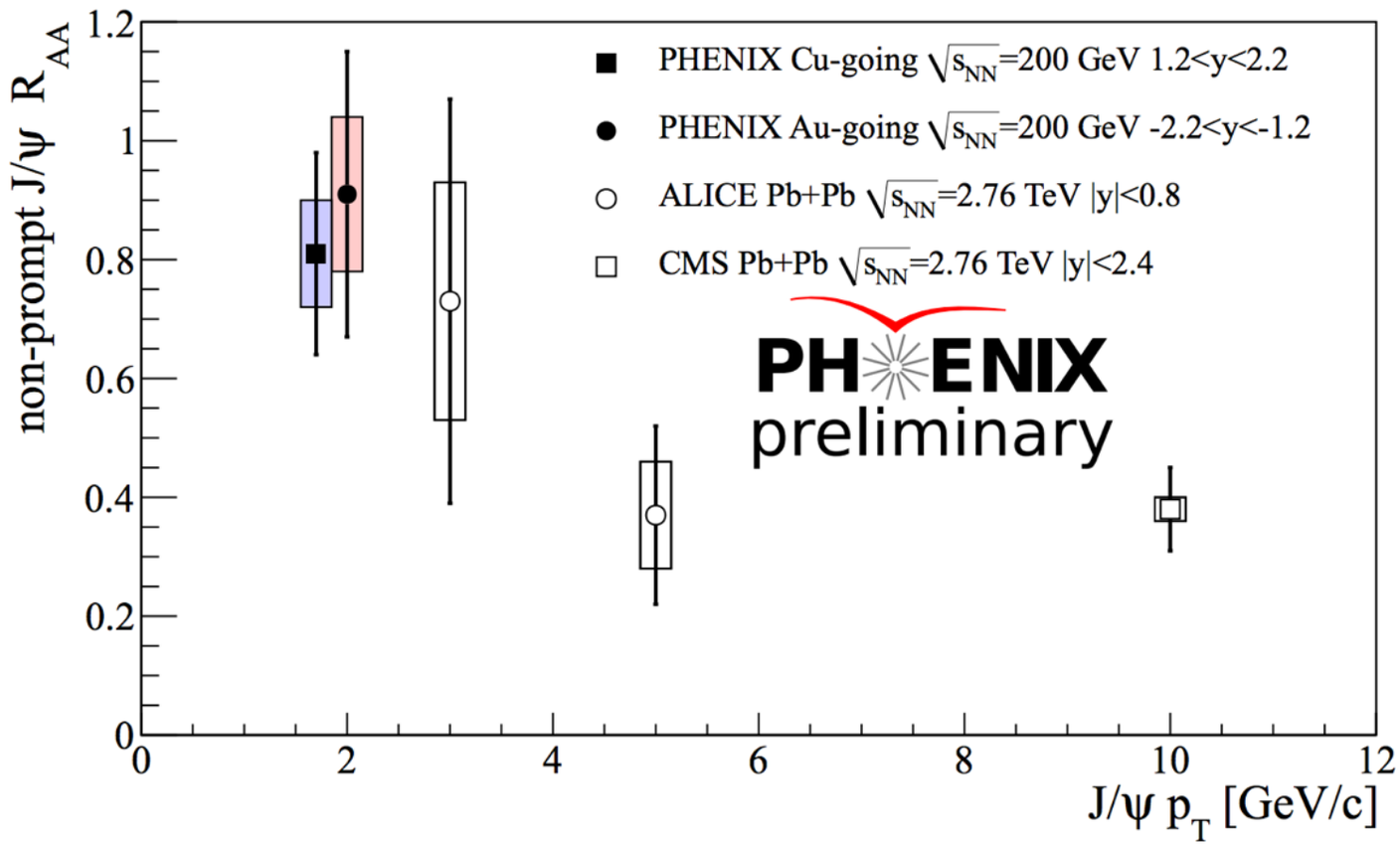


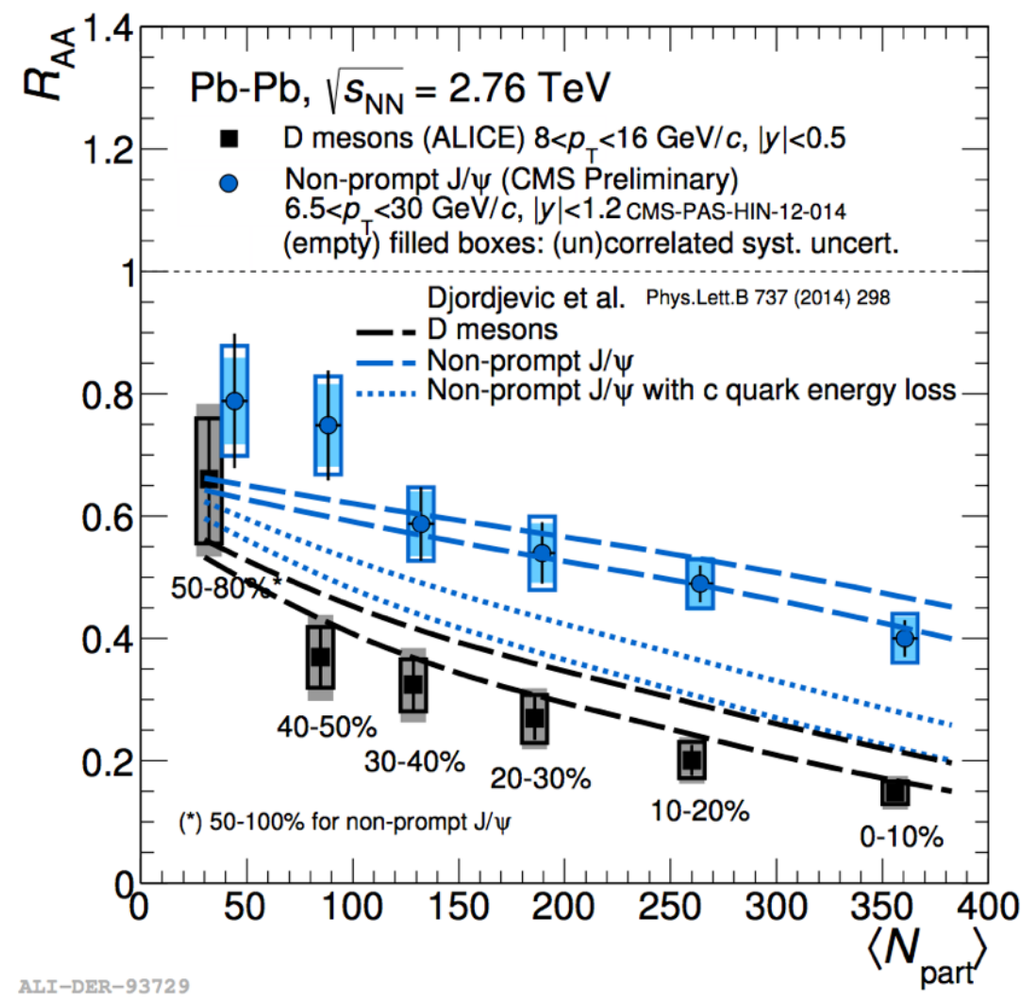


Non-prompt J/ψ at RHIC consistent with little to no suppression in Cu & Au-going directions

Clear mass ordering seen for p_T>8 at LHC

Outlook from the PHENIX FVTX



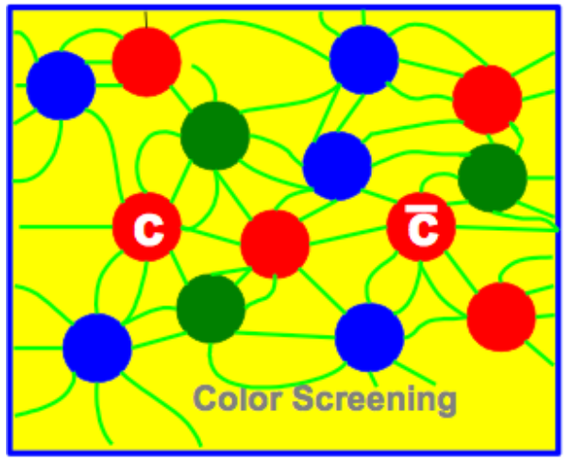


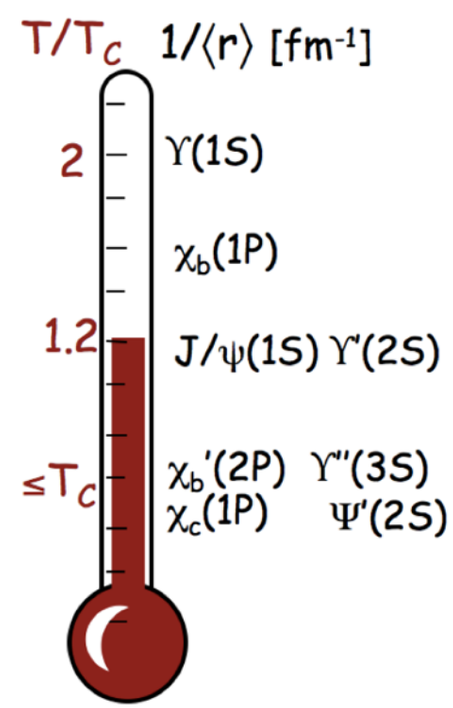
- Large 2014+2016 Au+Au data sets
  - Separated charm/bottom heavy flavor muons
- Large p+p and p+Au data sets from 2015
- Plenty more results in the works

Open Heavy Flavor Summary

- Open Heavy Flavor
  - Similar suppression of D mesons and light hadrons as well as between both RHIC & LHC
  - Significant D^0 and low-p_T HF electron v_2 → charm flow
  - Electrons from bottom similarly suppressed to those from charm for p_T>4, but less suppressed than charm for p_T<4
  - **Beginning of a new age for open heavy flavor measurements at RHIC with new VTX, FVTX, and HFT capabilities and high RHIC luminosities.**

Quarkonia



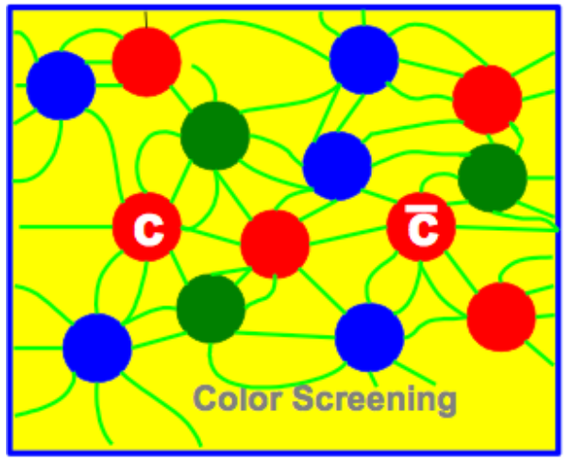


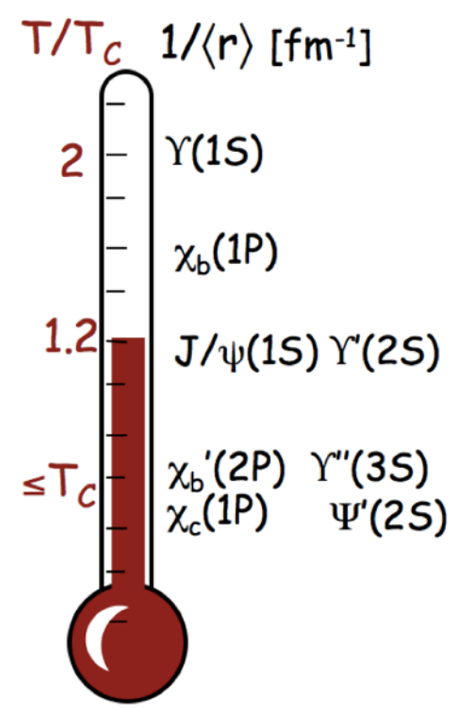
arXiv:0811.0337

Quarkonia

- Color screening in dense medium can cause disassociation of the bound state
- Should see sequential melting of the different states
- Use quarkonia as a medium thermometer!

Quarkonia





arXiv:0811.0337

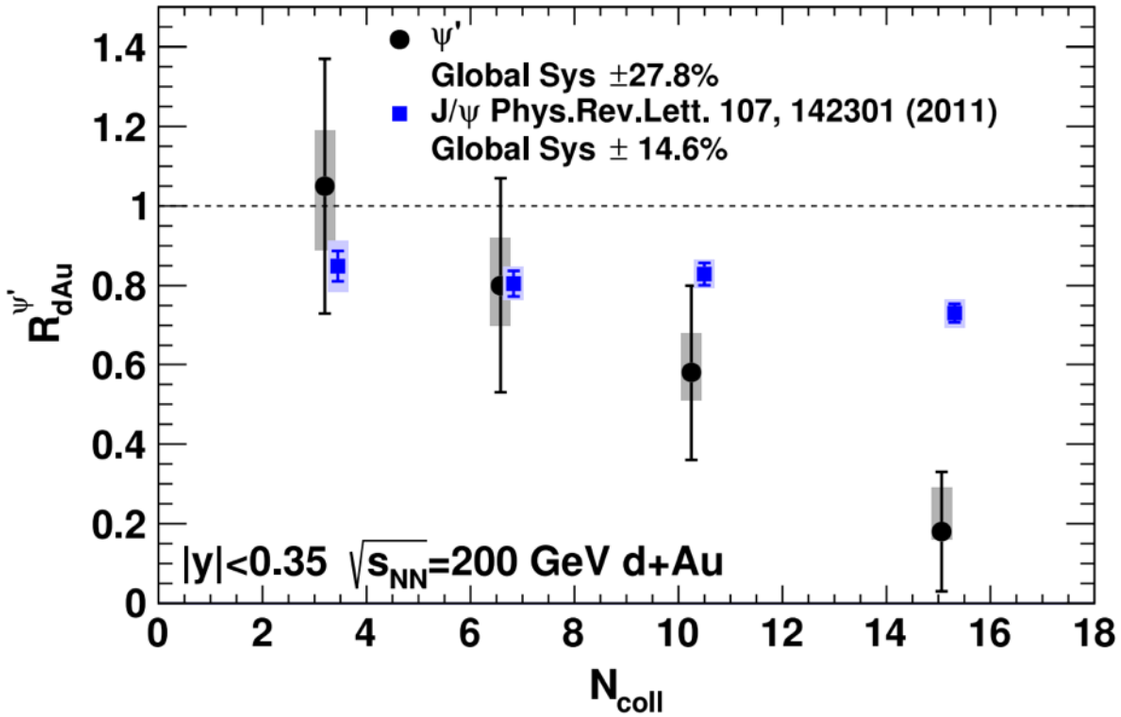
Quarkonia

- Color screening in dense medium can cause disassociation of the bound state
- Should see sequential melting of the different states
- Use quarkonia as a medium thermometer!

… Turns out it's not that simple

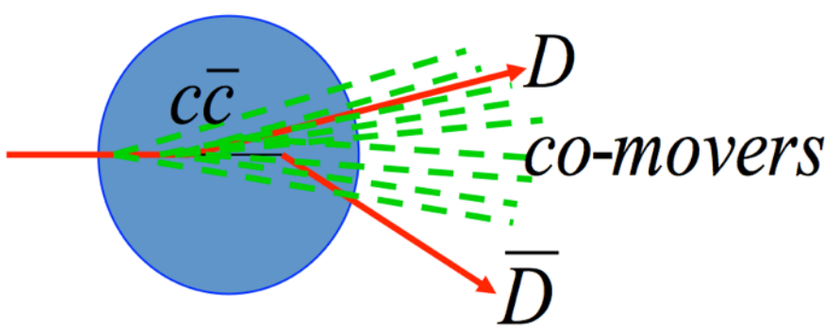
- Many effects which modify the yield other than disassociation!
  - Regeneration
  - Nuclear shadowing
  - CNM energy loss
  - Nuclear breakup
  - Breakup with co-moving hadrons

Quarkonia in p/d+A



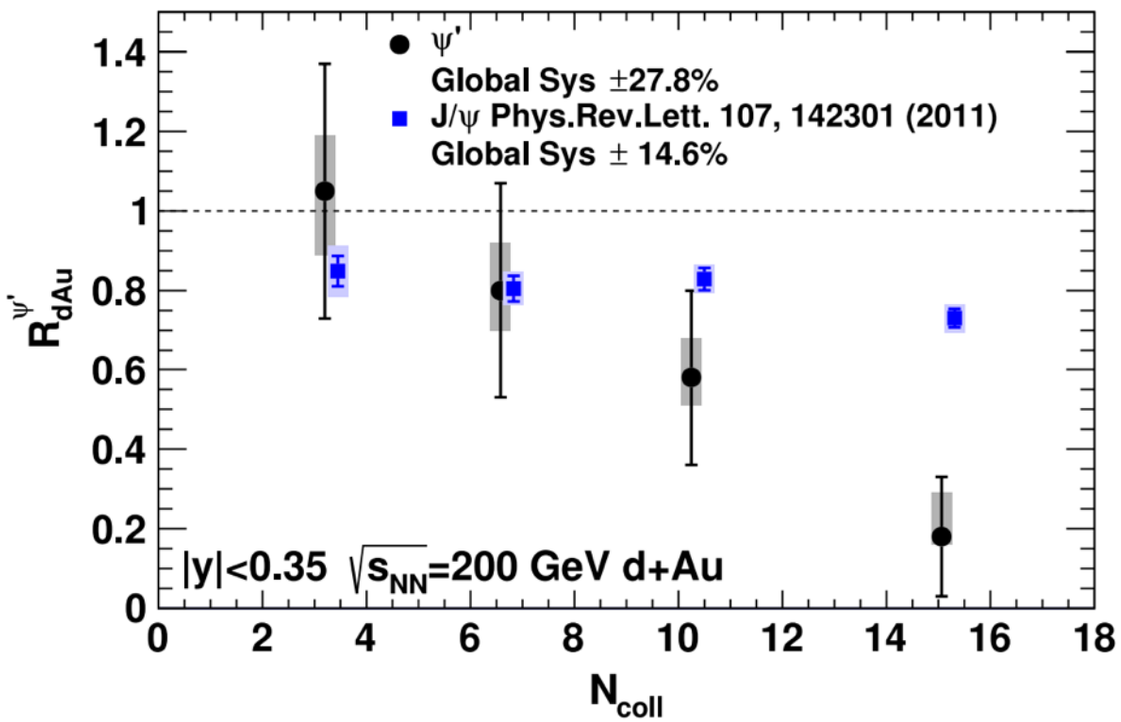
ψ' suppression > J/ψ suppression

Unexplained by nPDF's or nuclear breakup

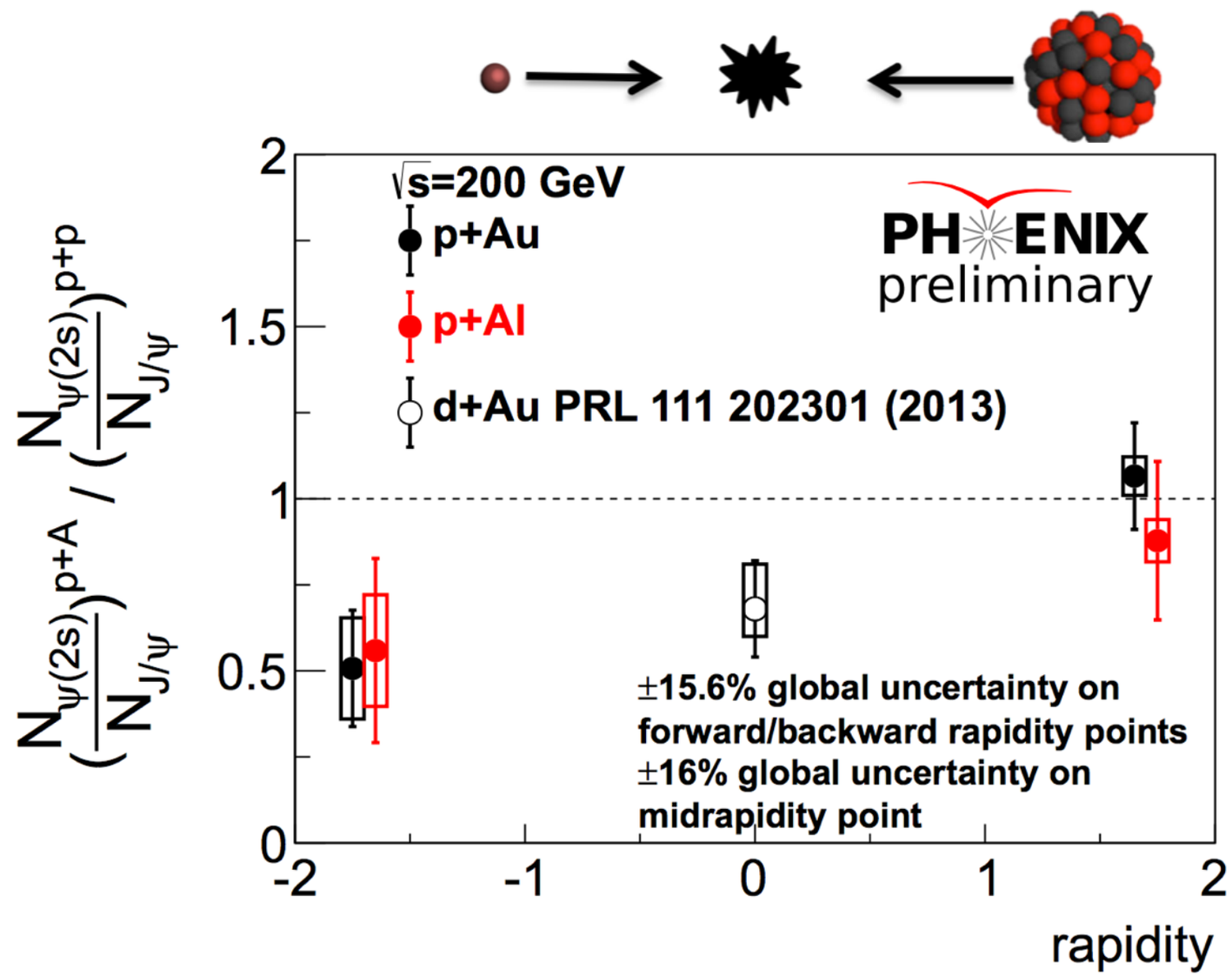


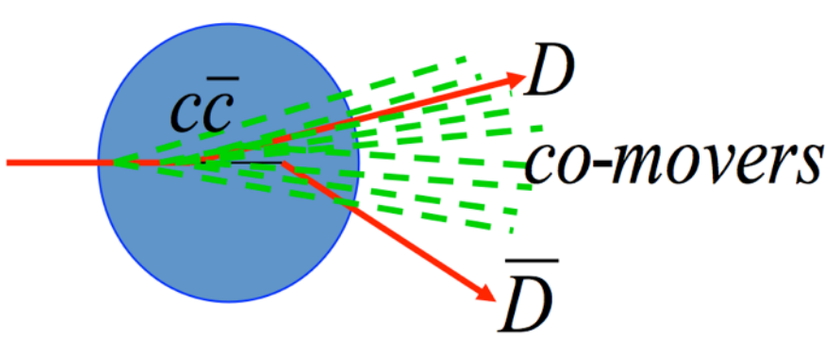
See S. Lim talk from Tues HF workshop

Quarkonia in p/d+A



New result made possible by the PHENIX FVTX





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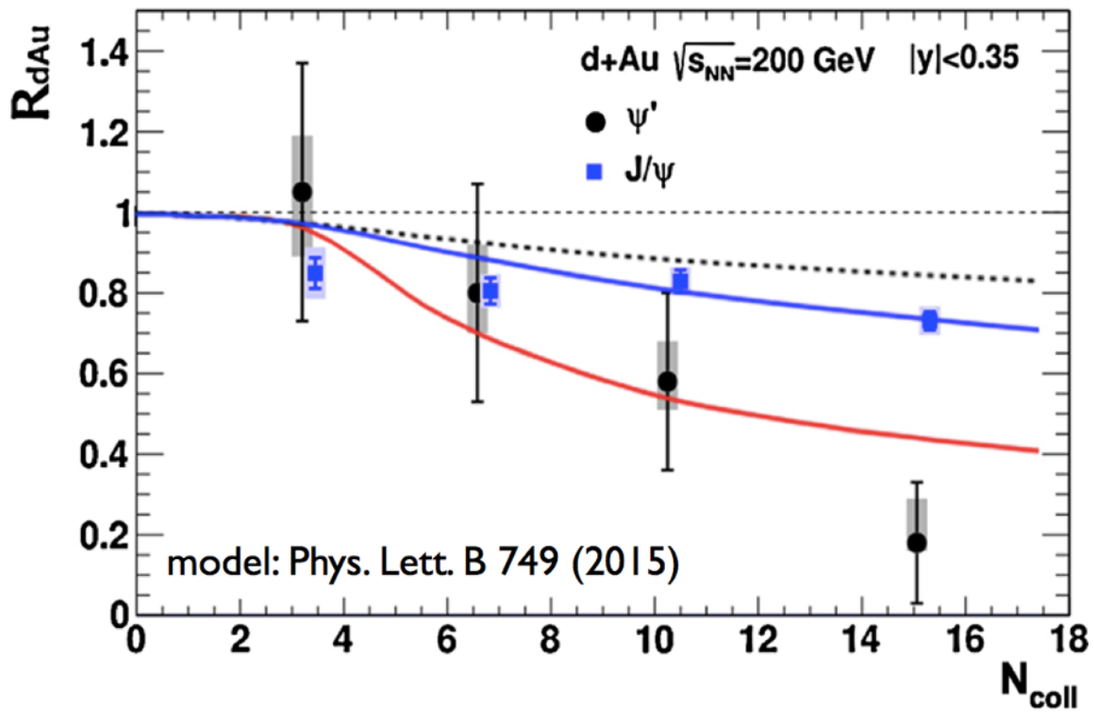

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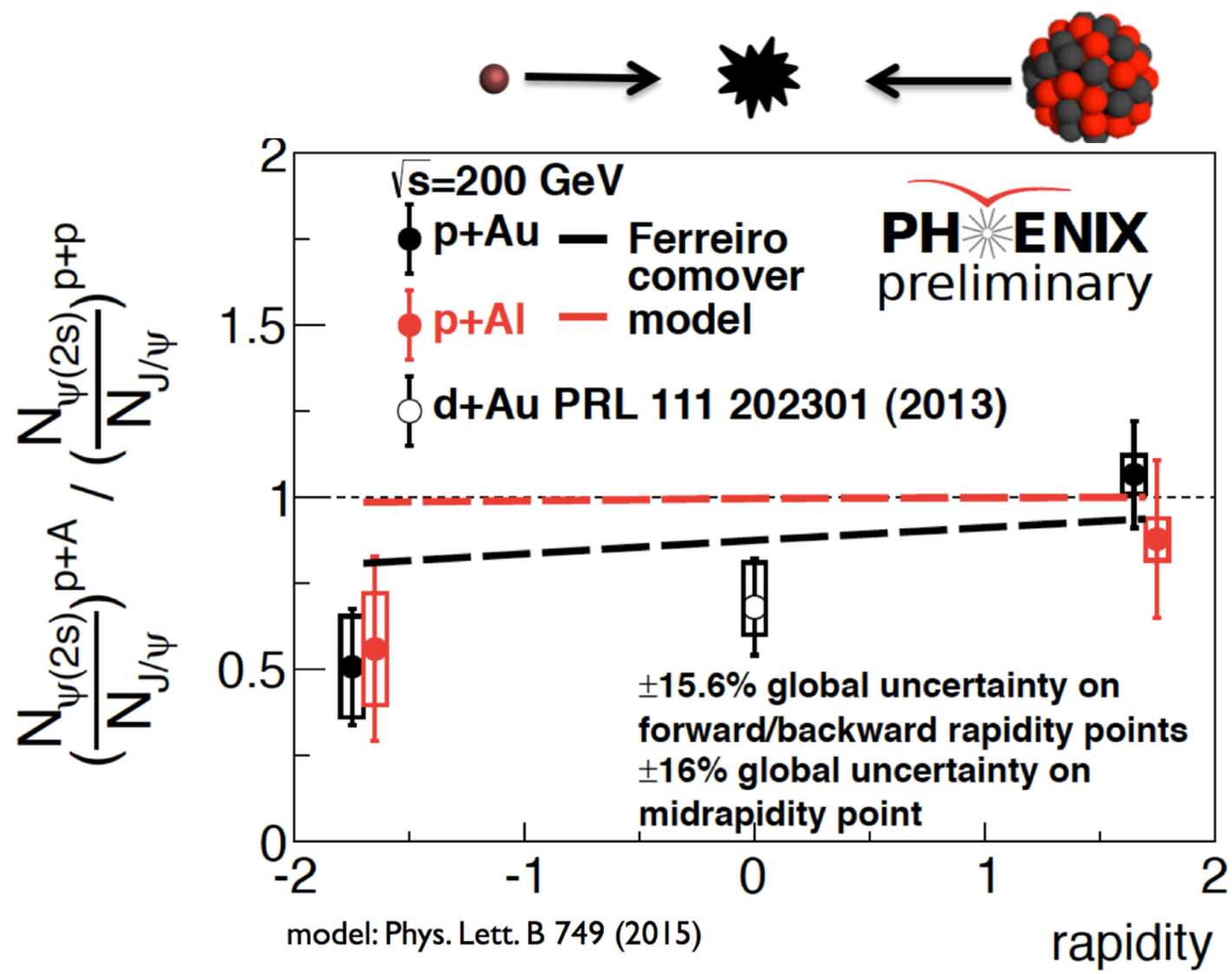
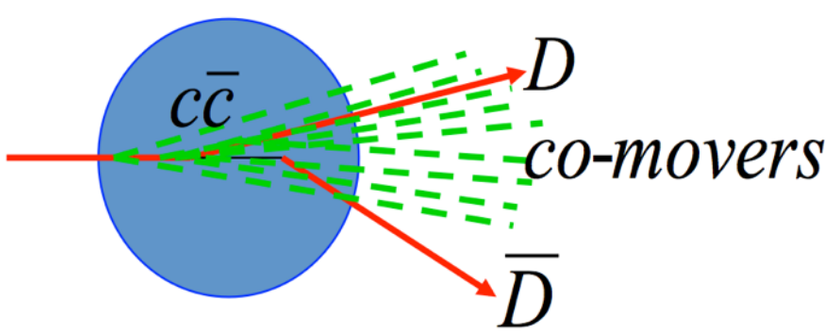


Reasonably consistent with models including interactions with co-moving hadrons



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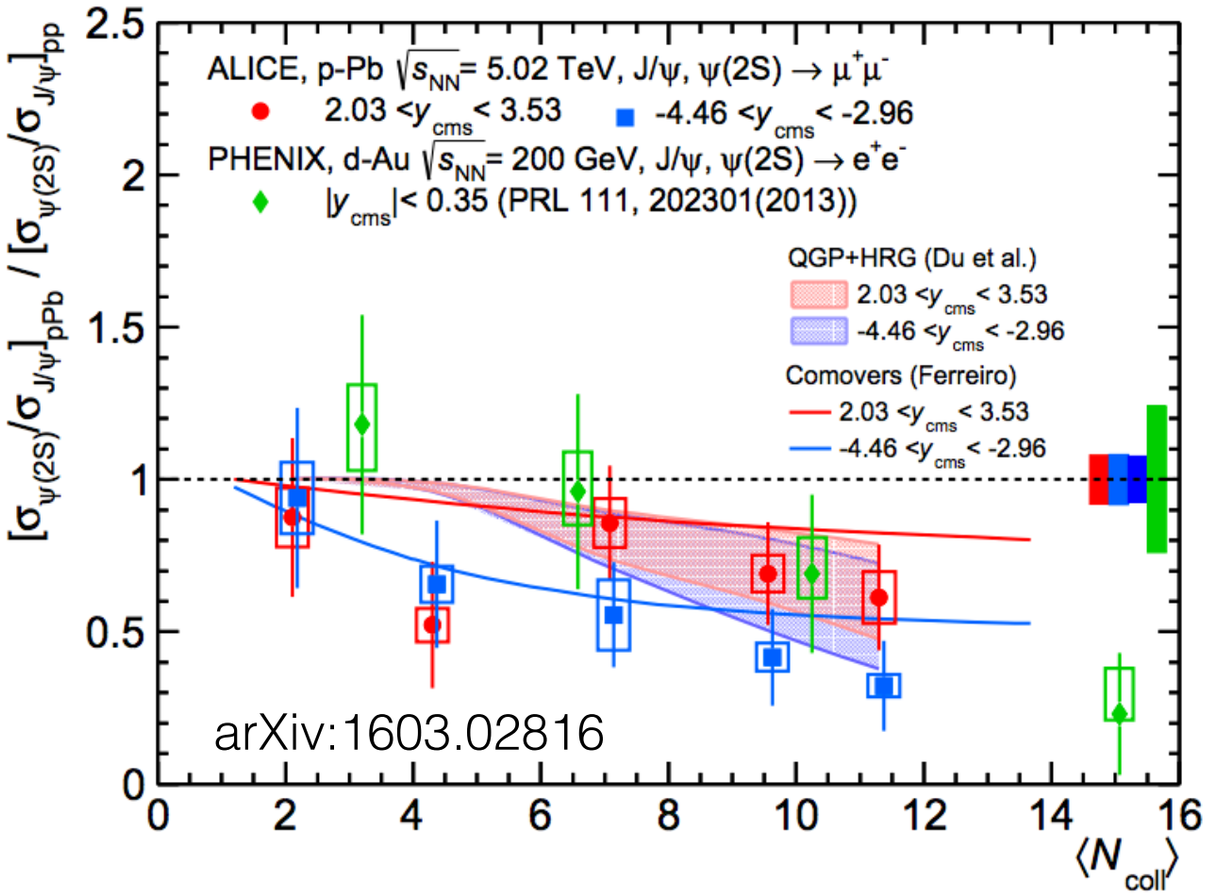

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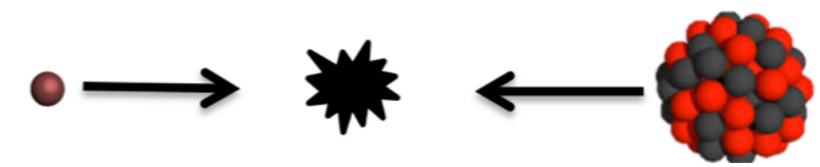

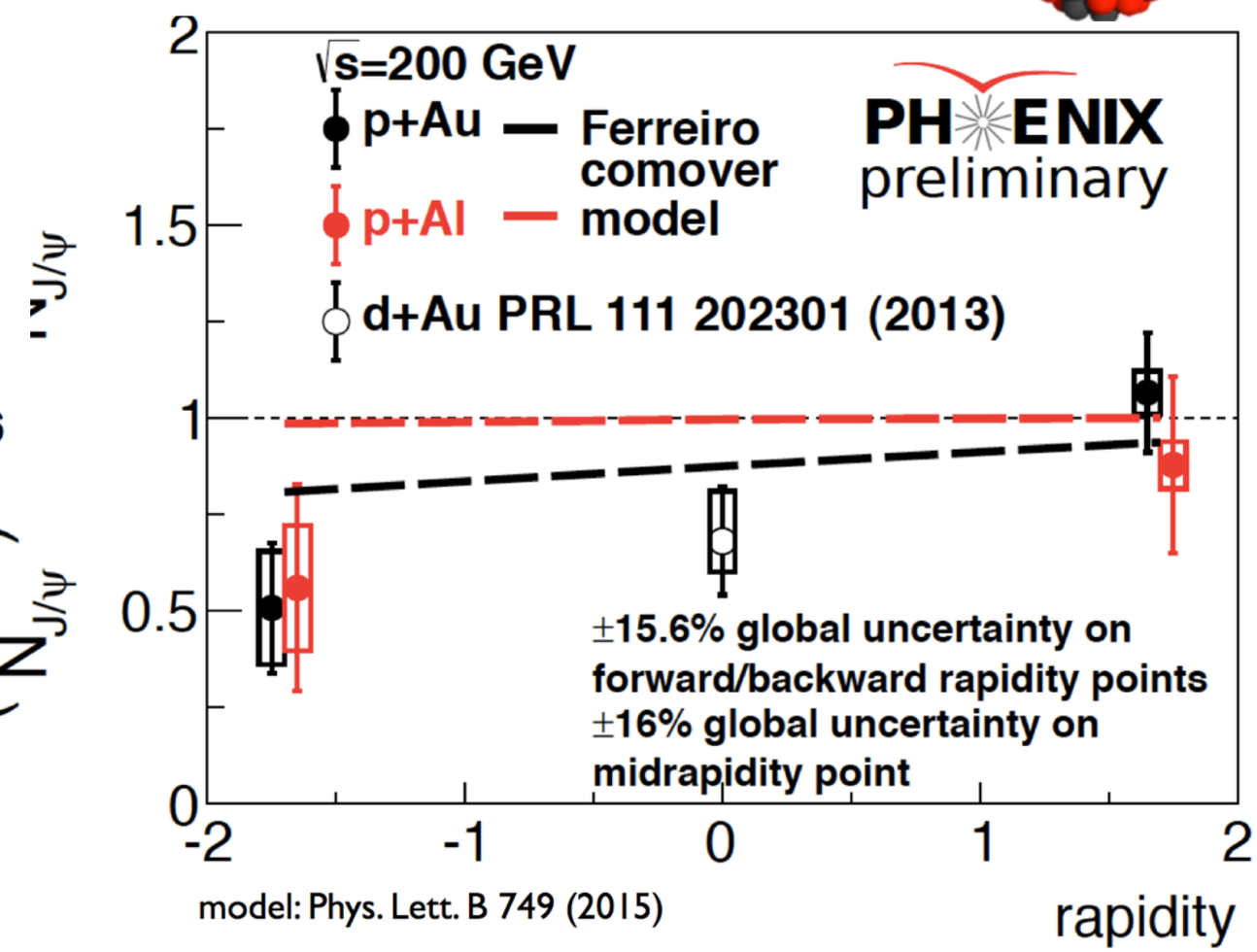

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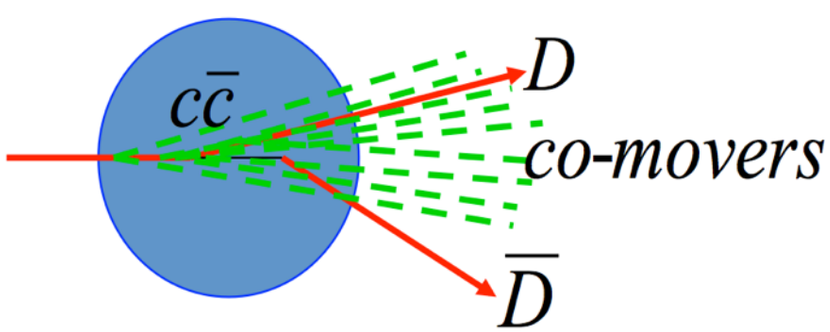
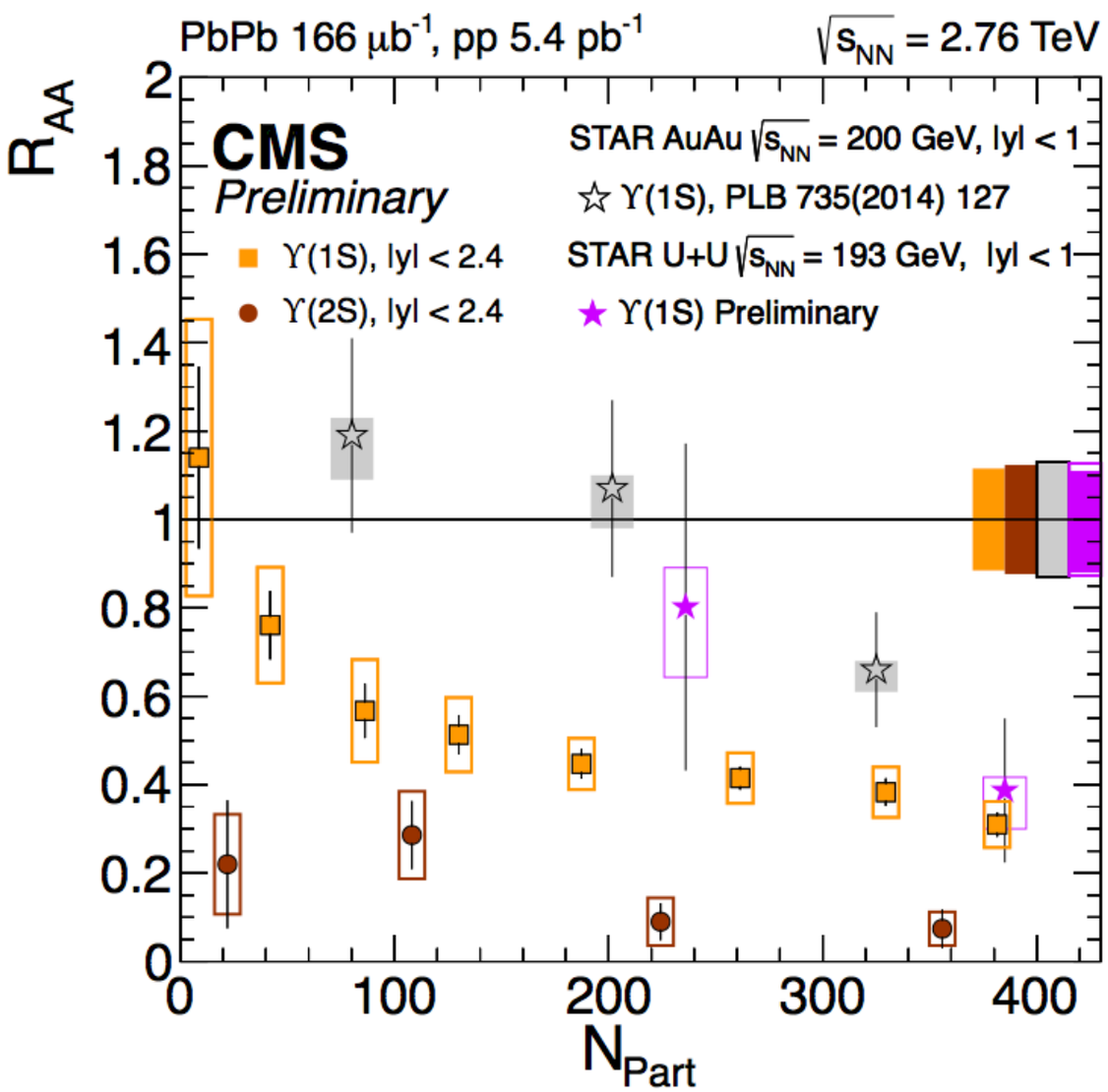


See S. Lim talk from Tues HF workshop

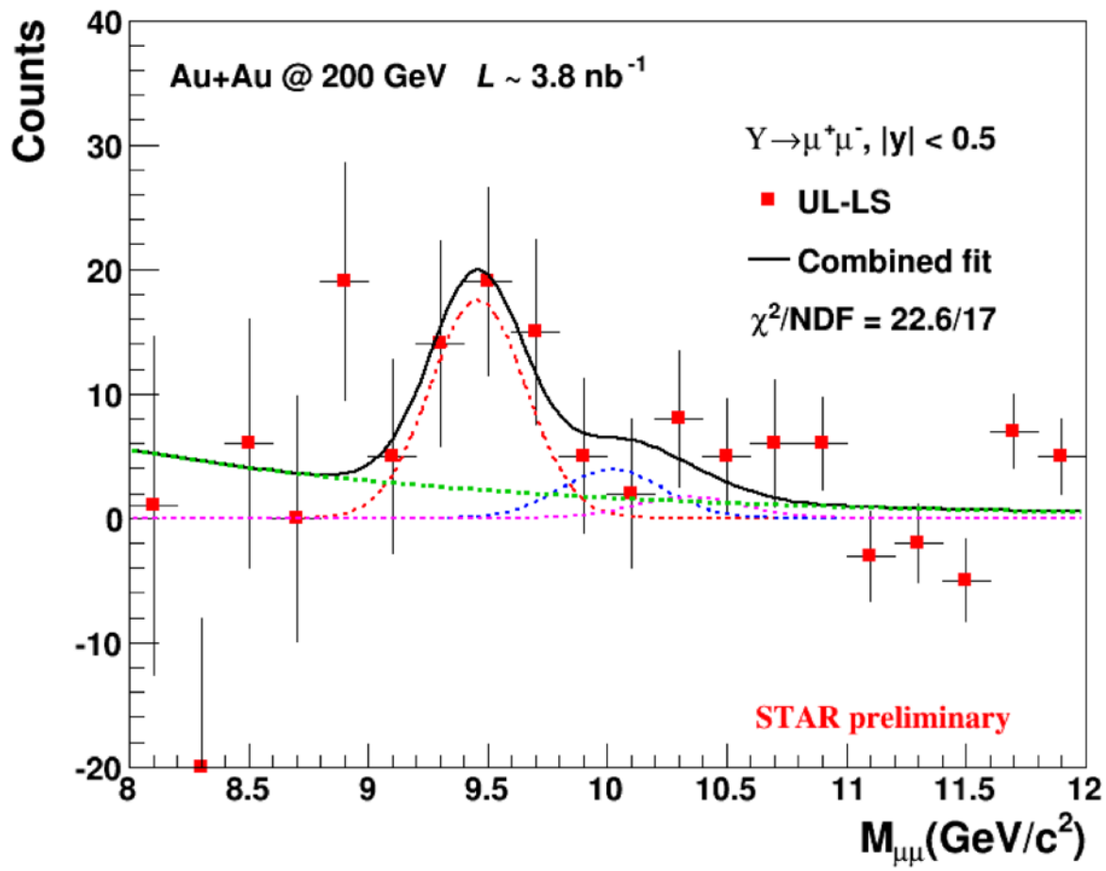
Quarkonia in A+A

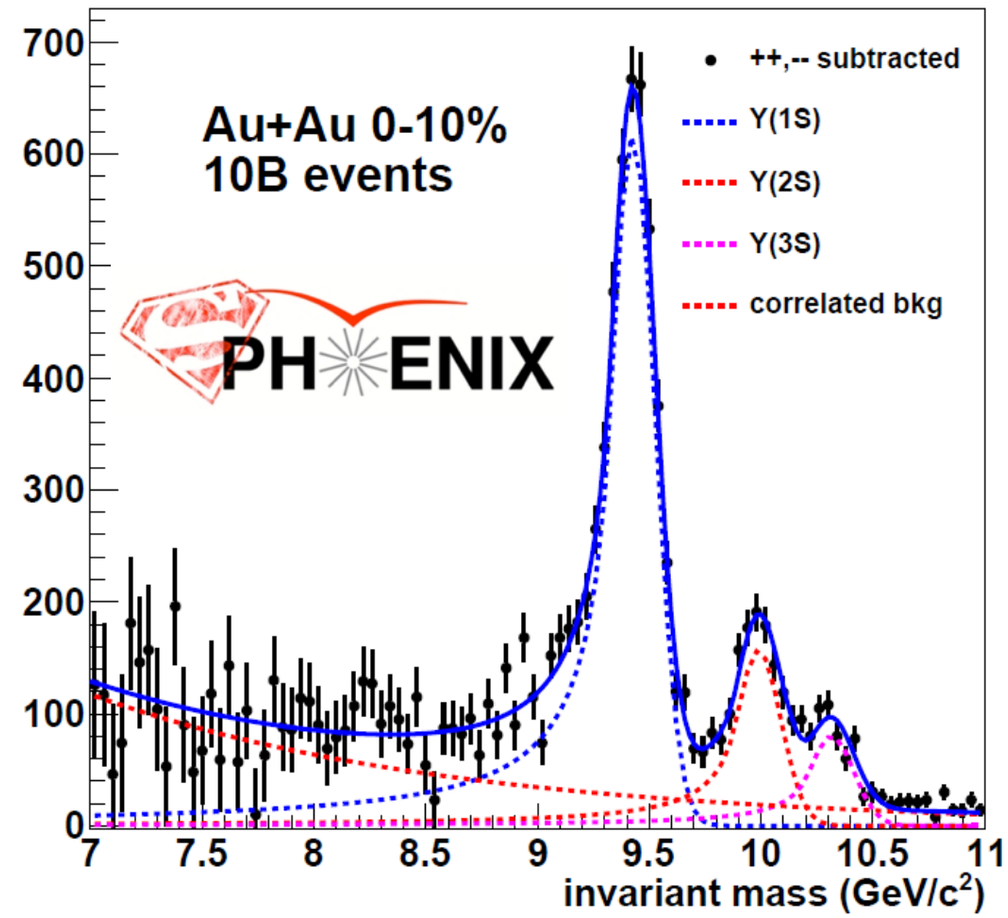


Upsilons

- Switch gears …
- 3 Upsilon states provide "ideal" probes
- CNM effects should be effectively the same
- Recombination should be negligible at RHIC
- … Not so clear at the LHC
- Y(1S) suppressed in central collisions at RHIC, consistent with suppression of excited states
  - ~30-40% expected from feed-down
- Y(1S) suppressed beyond feed-down (maybe) at the LHC
- Separated Upsilons would be ideal at RHIC

Outlook on Quarkonia





- Using STAR MTD
- Lower brehmsstrahlung compared to dielectron channel.
- x7 more statistics with full 2014+2016 data

- sPHENIX being designed with separation of Υ states in mind
- Still exploring tracking options

See Q. Yang talk from Tues HF workshop

Summary

- Open Heavy Flavor
  - Similar suppression of D mesons and light hadrons as well as between both RHIC & LHC
  - Significant D^0 and low-p_T HF electron v_2 → charm flow
  - Electrons from bottom similarly suppressed to those from charm for $p_T>4$, but less suppressed than charm for $p_T<4$
  - **Beginning of a new age for open heavy flavor measurements at RHIC with new VTX, FVTX, and HFT capabilities and high RHIC luminosities. Stay tuned.**
- Quarkonia
  - p+A: ψ' more suppressed than J/ψ → breakup via co-moving hadrons
  - Separating Upsilon states currently included as fundamental design parameter for sPHENIX
- Many results at both RHIC and the LHC I was unable to cover
  - dileptons, J/ψ in A+A, many more LHC heavy flavor results
  - Future potential for HF jets with sPHENIX

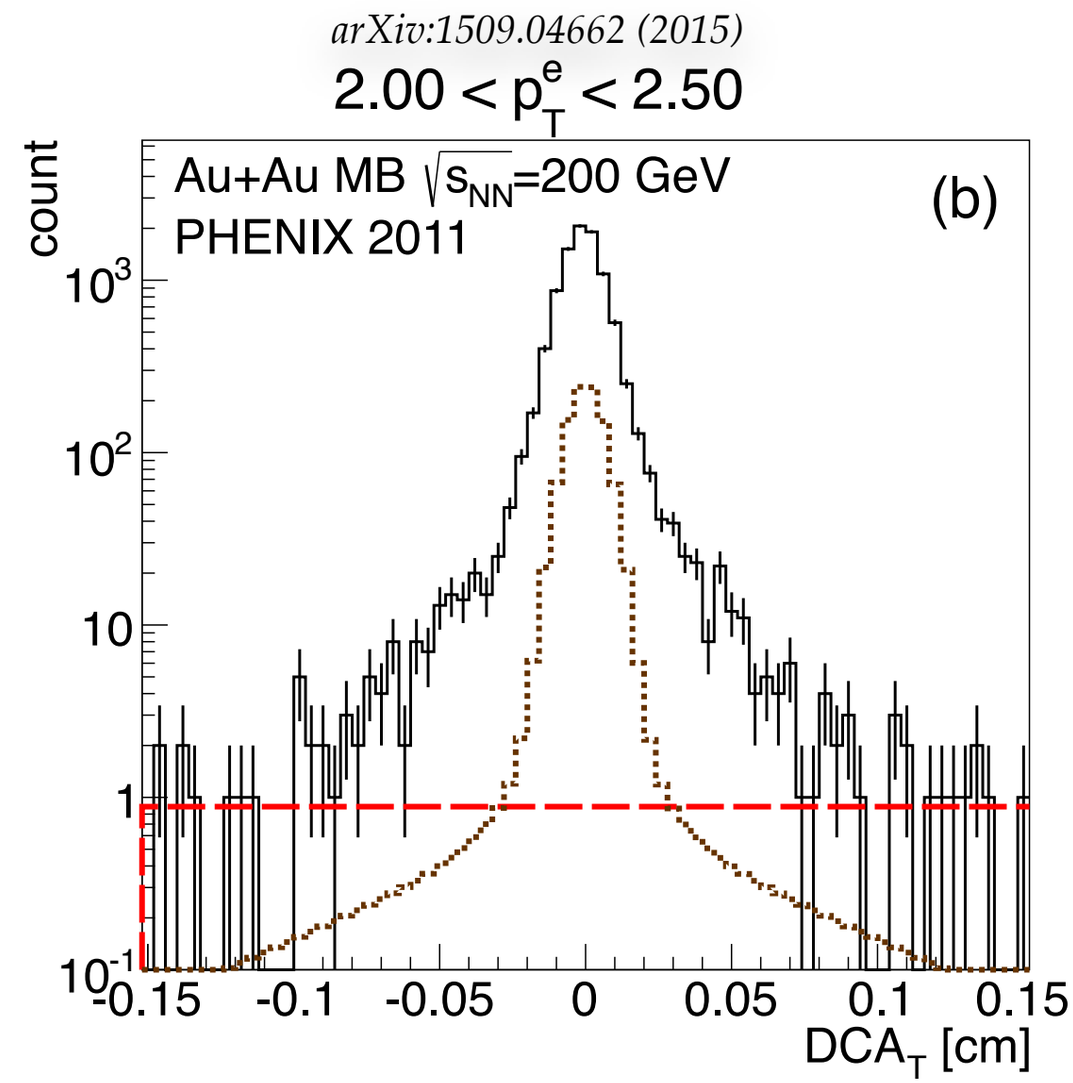
Thank you

DCA_T Data

- Measure DCA_T distribution of electrons from 2011 (Run 11) data set.
  - 5 electron p_T bins from $1.5 < p_T < 5.0$
  - no efficiency correction
- Determine normalized background contributions.

Mis-associated VTX Hits
Data Driven
Tracks with large DCA_L

Mis-identified hadron
Data Driven
RICH swap method



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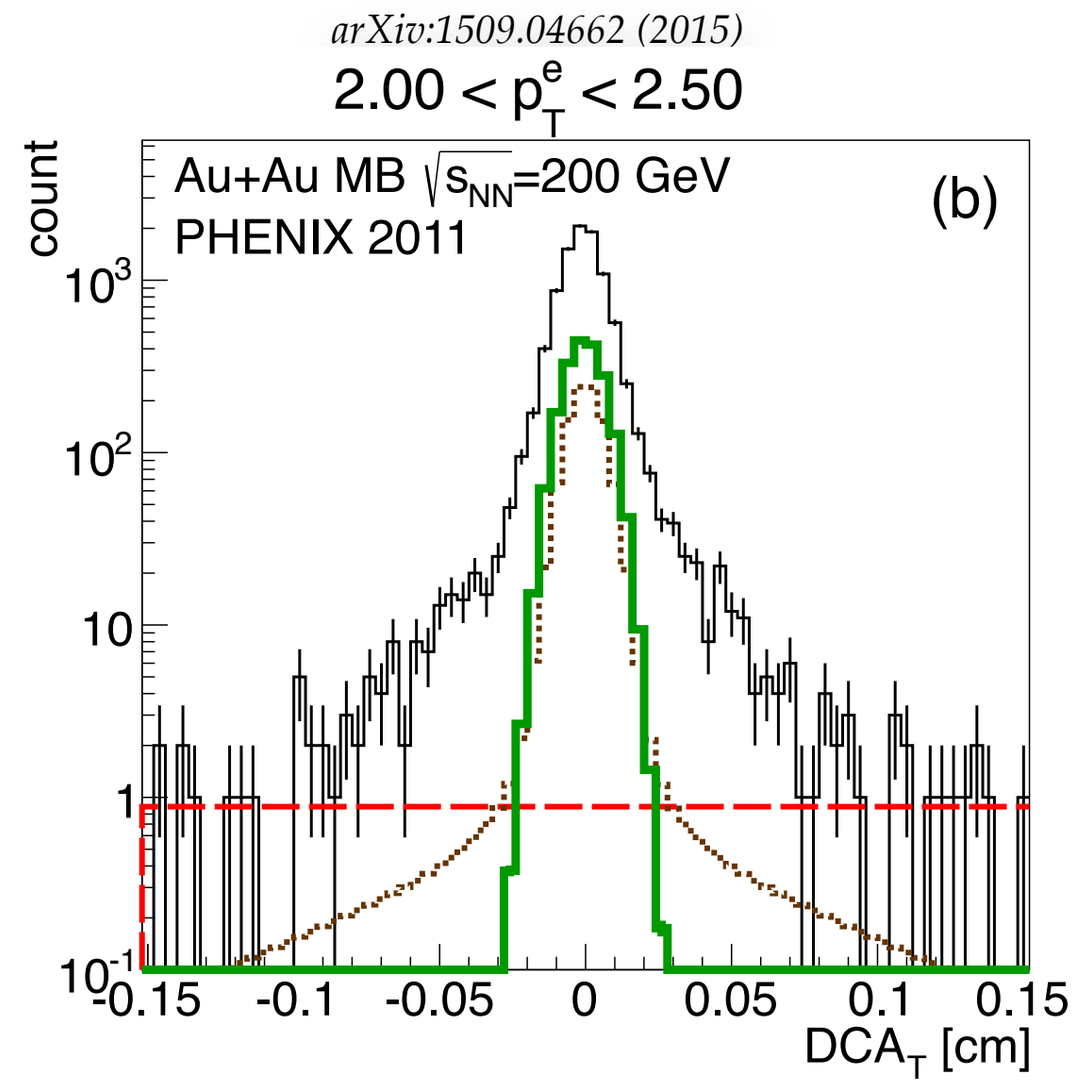

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Prompt

Dalitz ($\eta, \pi \rightarrow e^+e^-\gamma$)
Measured yield
Monte Carlo shape

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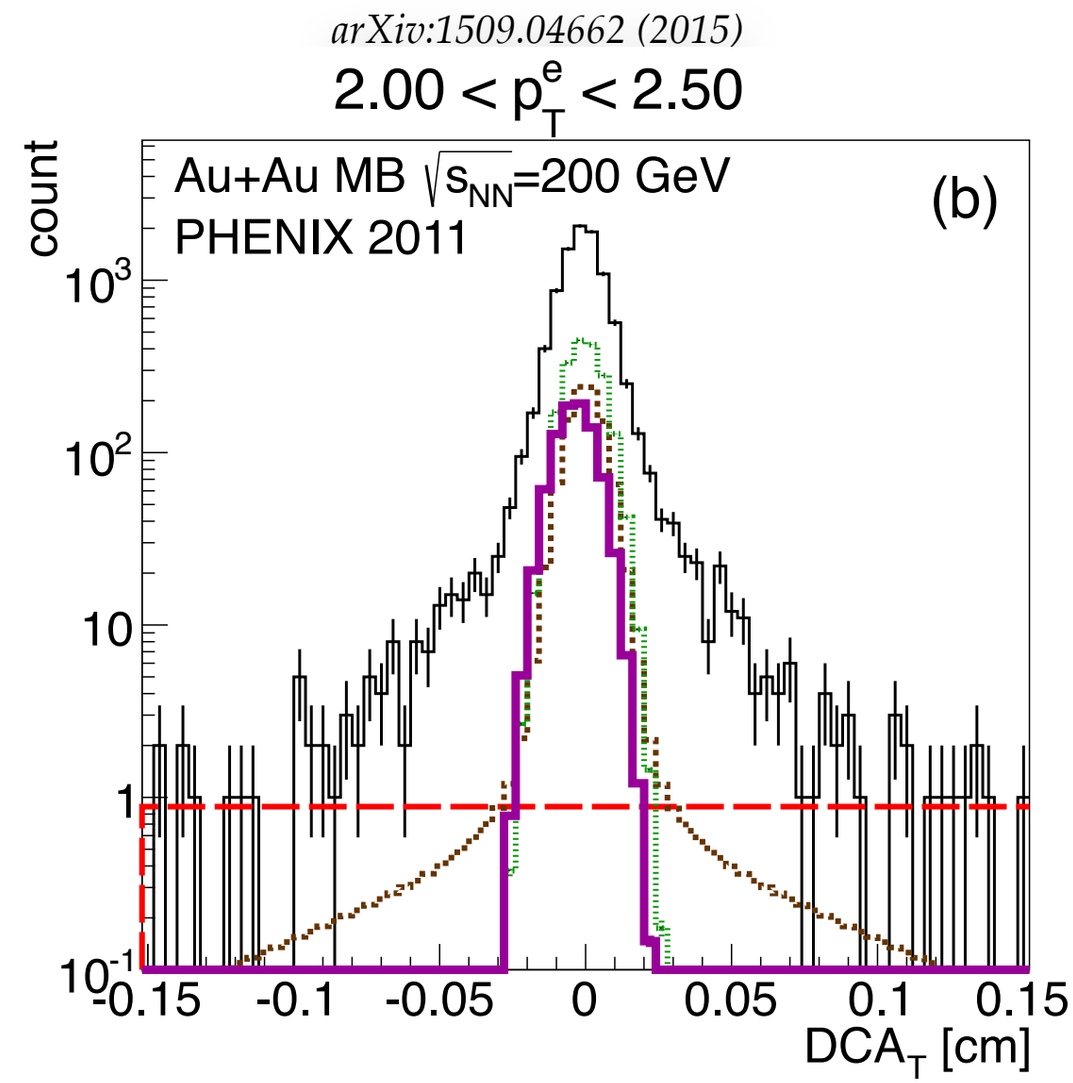

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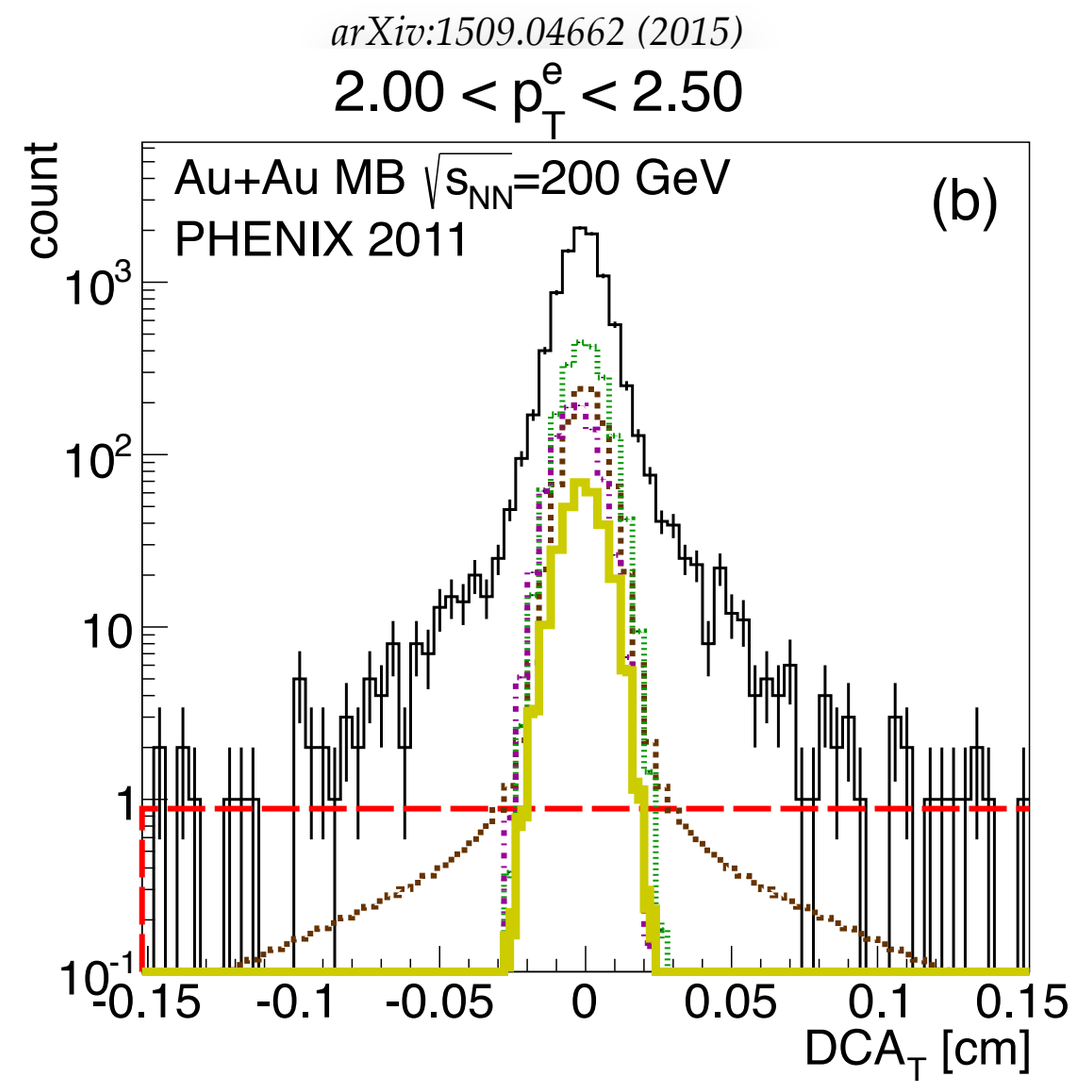

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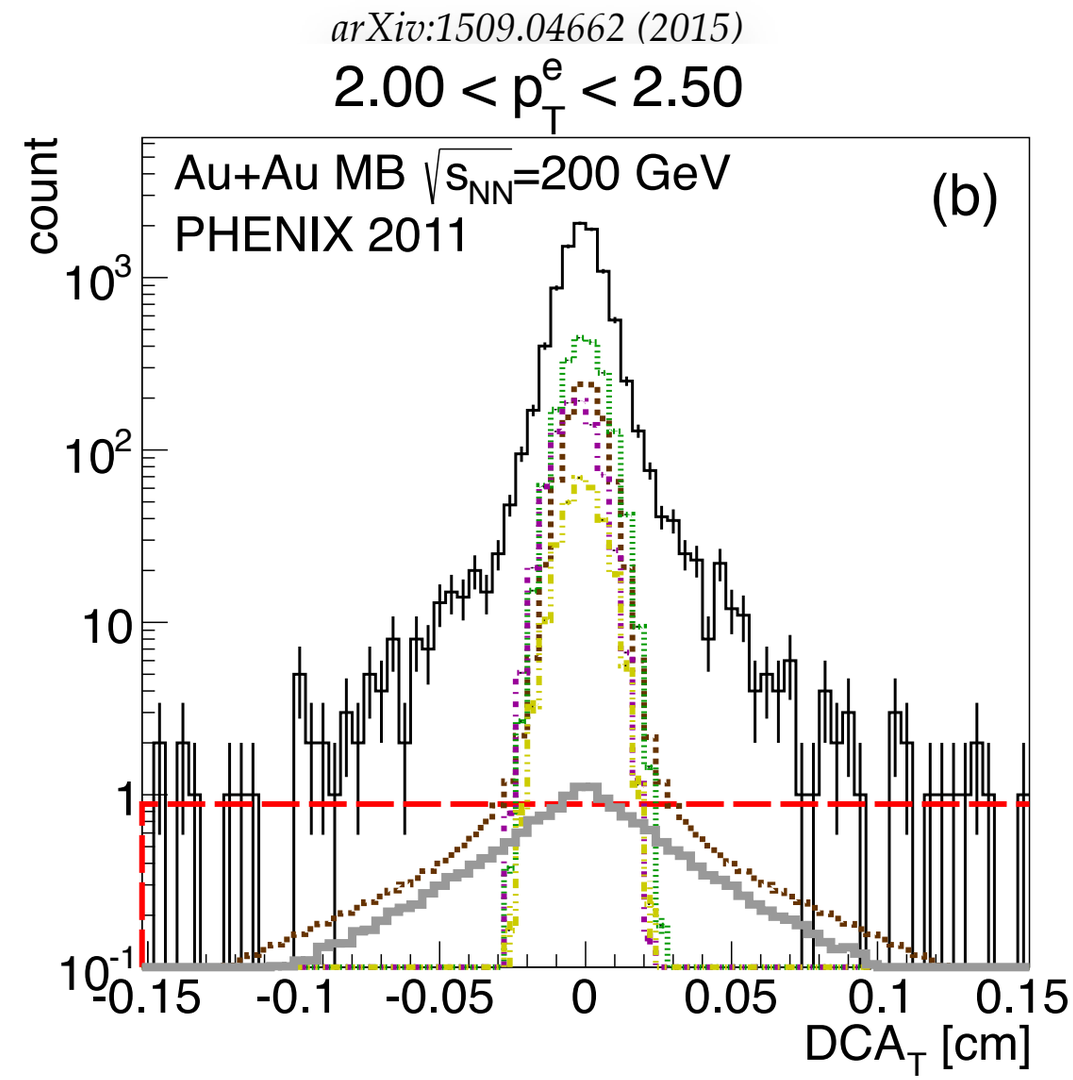

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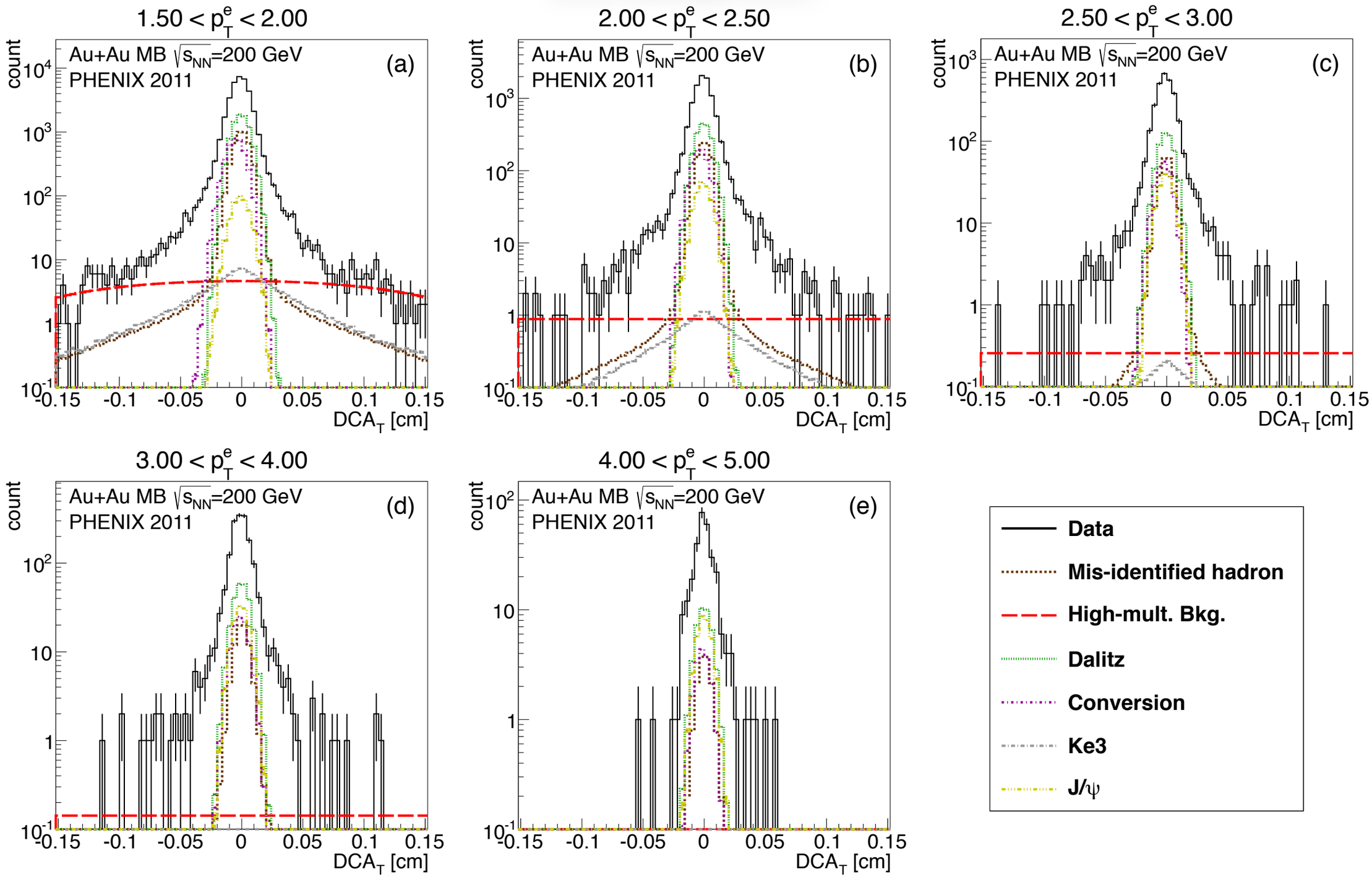
Ke3 ($K_s^0 \rightarrow e\nu\pi$)
Measured yield
Monte Carlo shape

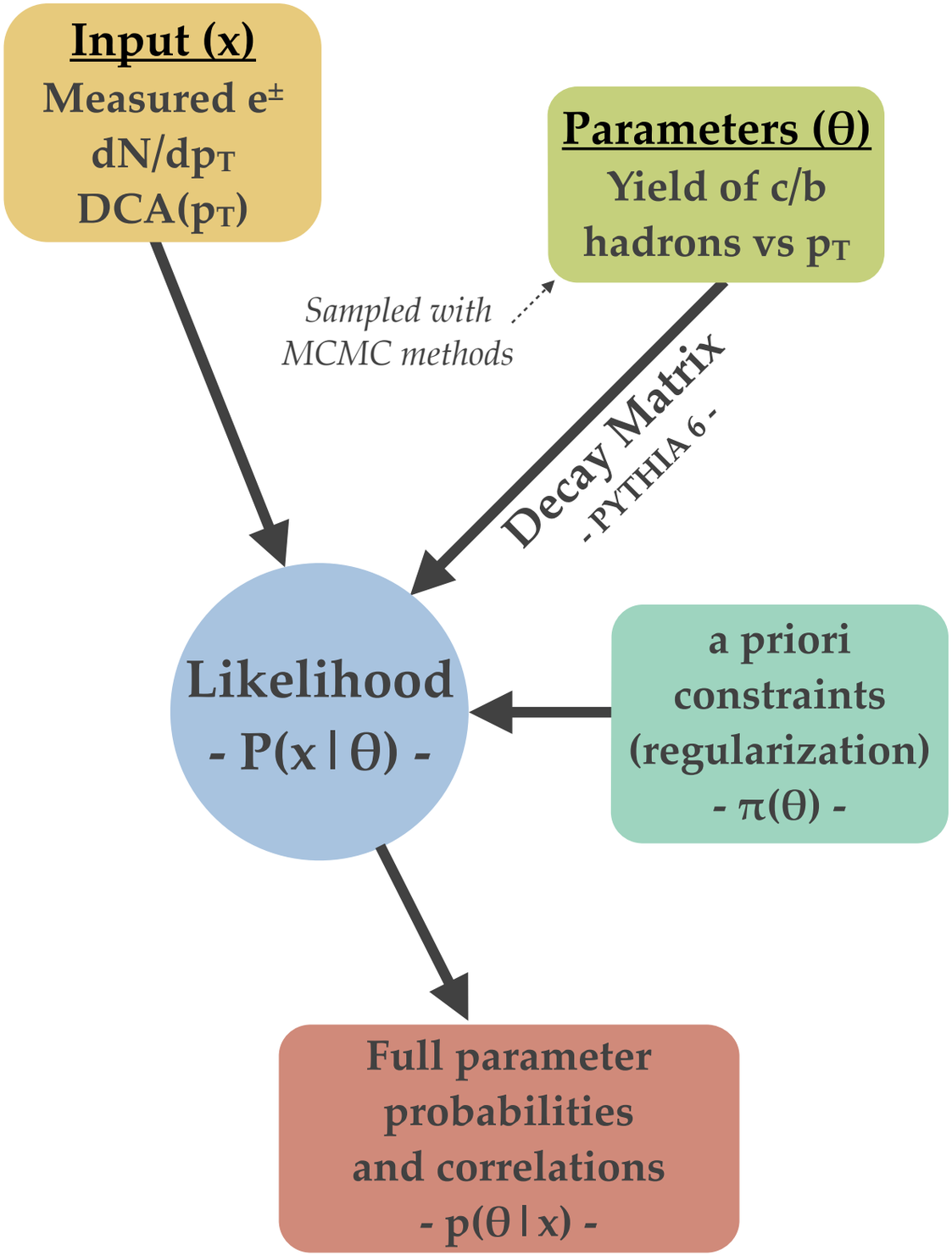
DCA_T Background Contributions

arXiv:1509.04662 (2015)



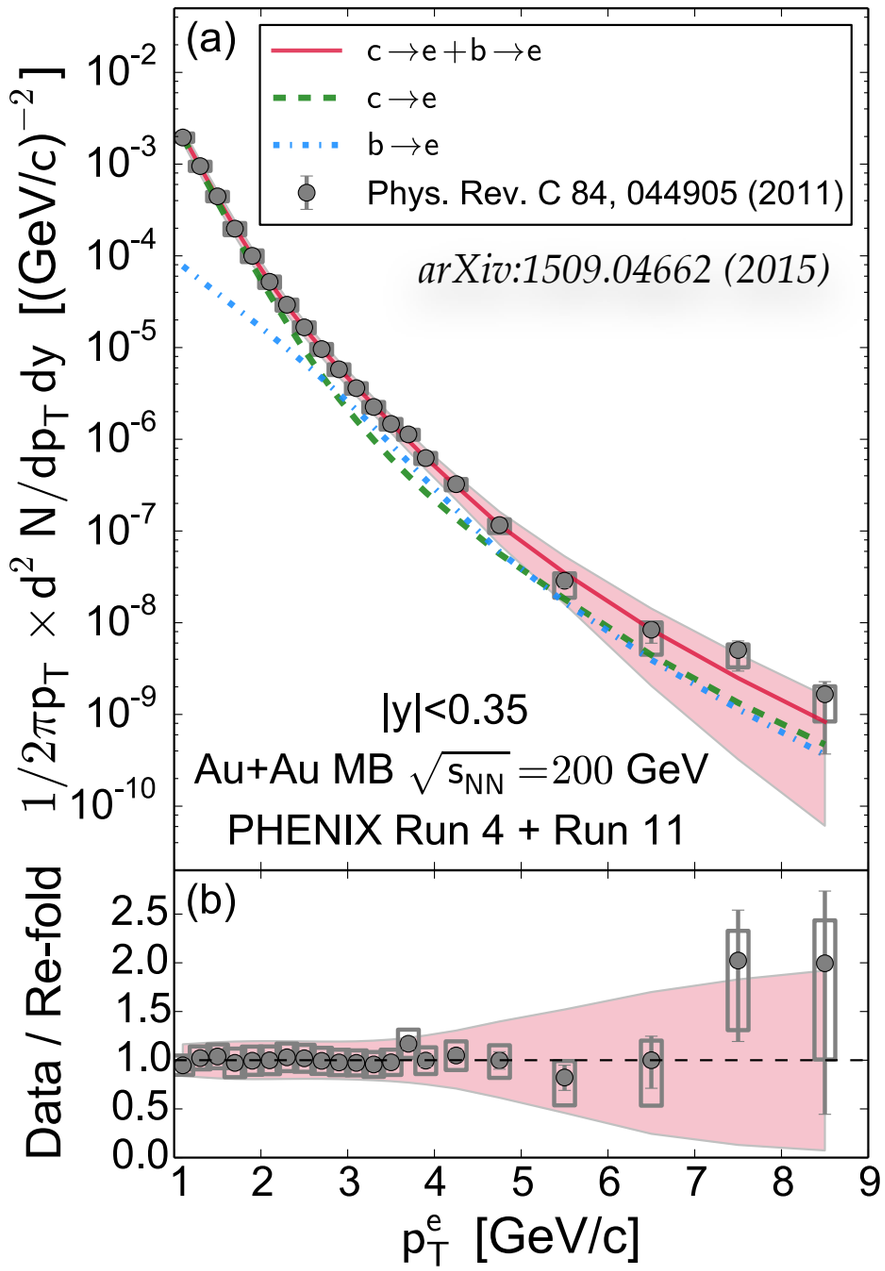
Unfolding (Bayesian Inference)

- **electron** p_T & DCA_T distributions must come from consistent physical parent **hadron** distributions
- Can't fit DCA_T independently!
- Perform simultaneous fit using Bayesian inference techniques
  - Parameters are hadron yields!



$$p(\boldsymbol{\theta}|\mathbf{x}) = \frac{P(\mathbf{x}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{P(\mathbf{x})}$$

Comparison to Data



Data

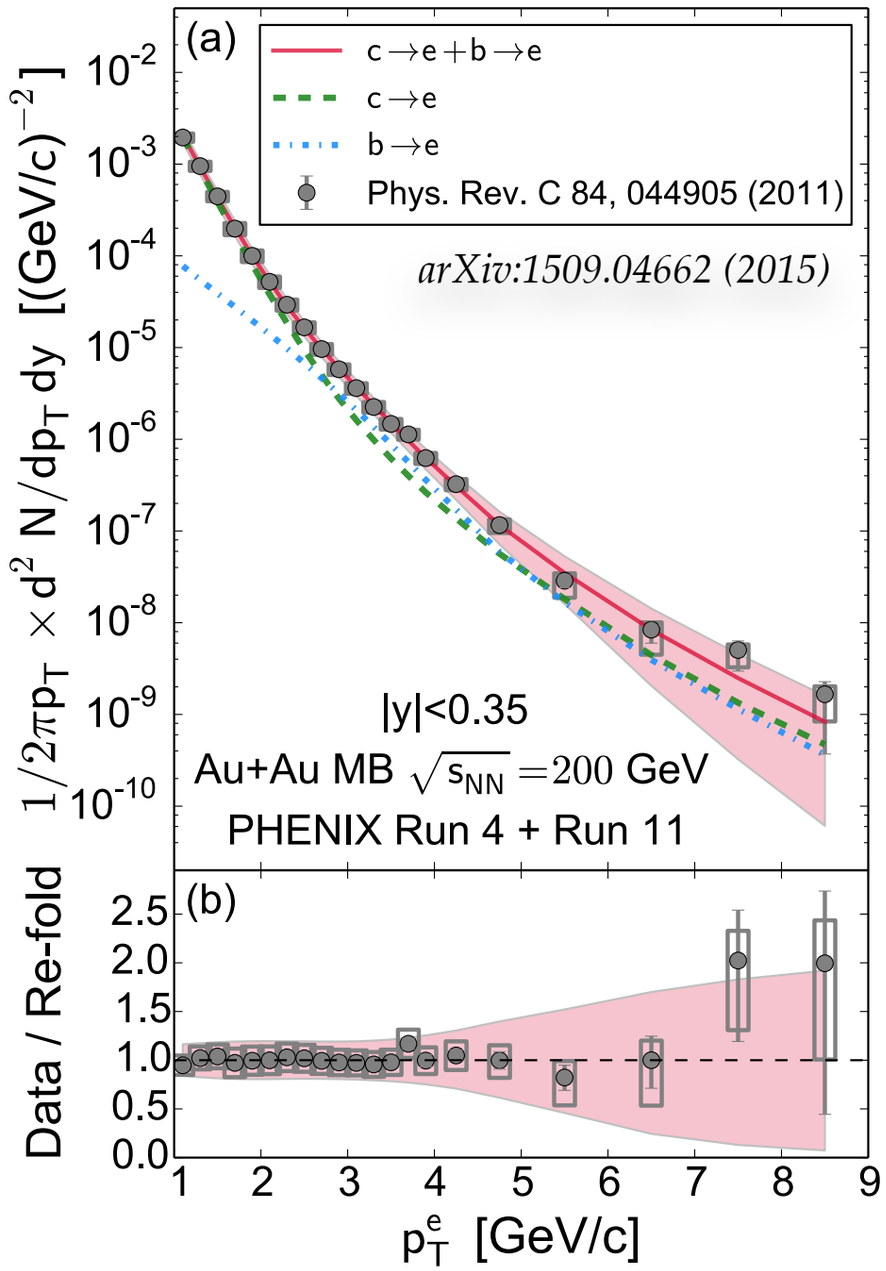
c→e

b→e

Total

Unfold gives good consistency with electron invariant yield

Comparison to Data



Data

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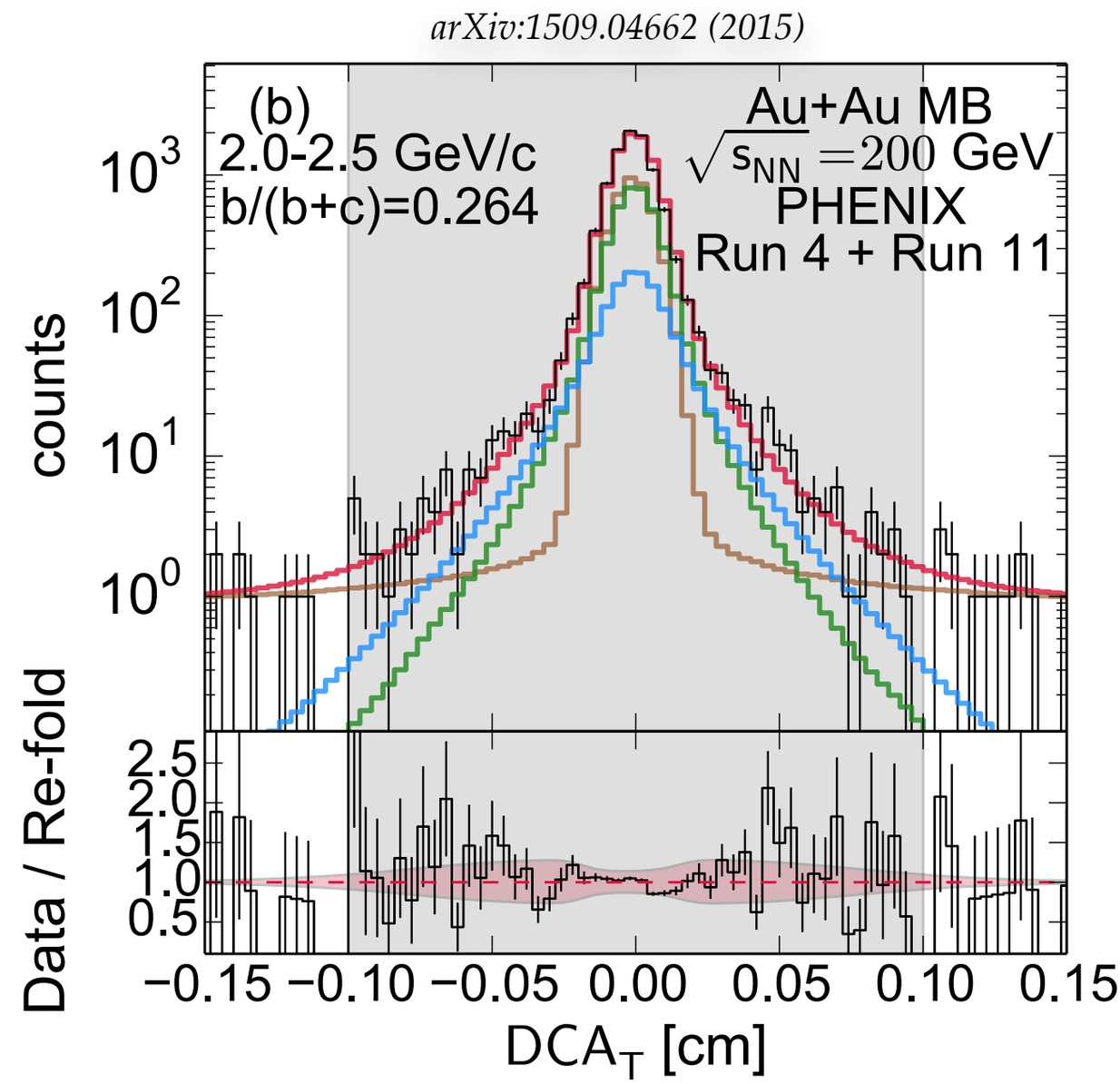
Total

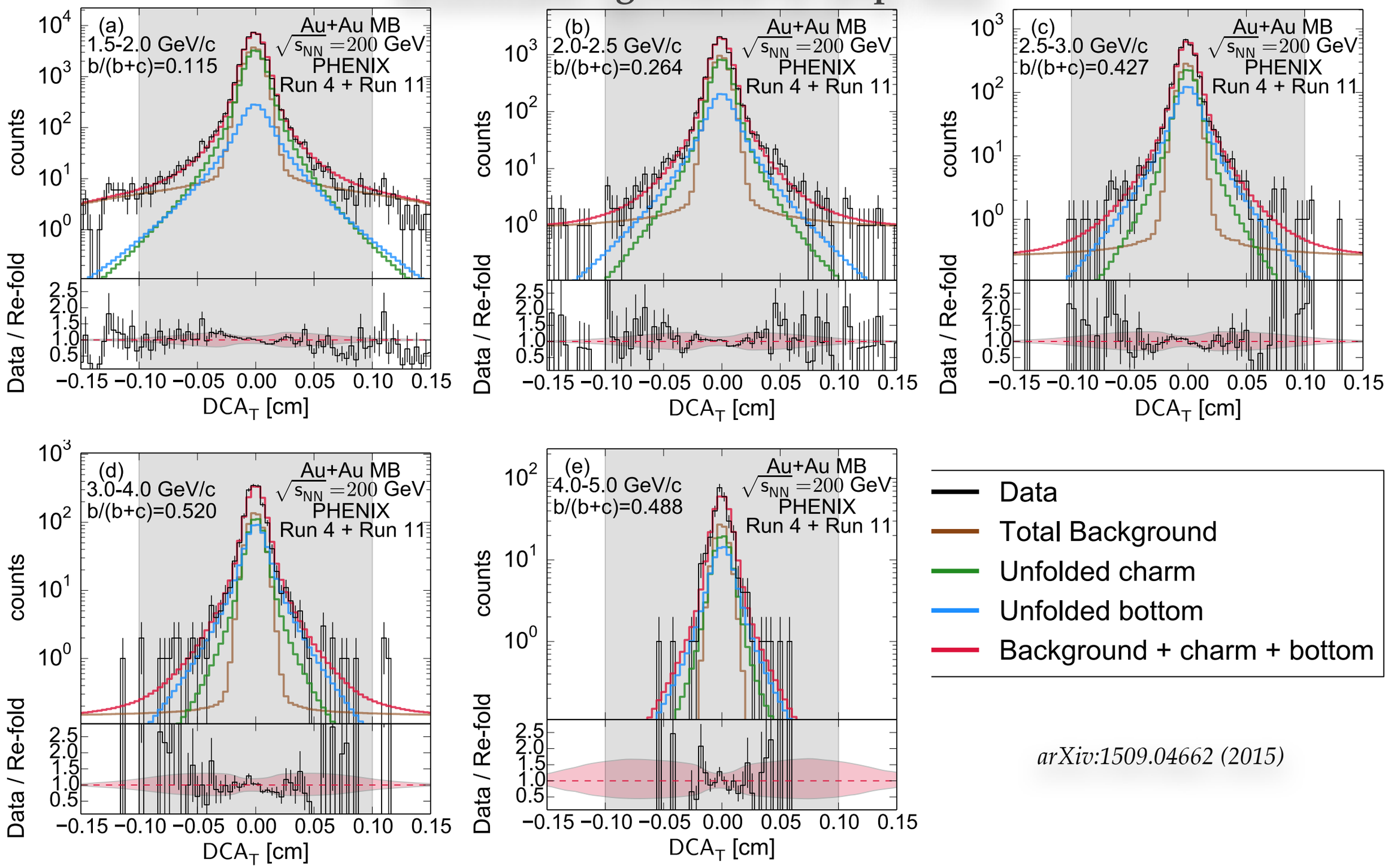
Background Components



Unfold gives good consistency with electron invariant yield and DCA_T data

Comparison to Data

Reasonable agreement in all p_T bins



arXiv:1509.04662 (2015)

Unfolding Advantages

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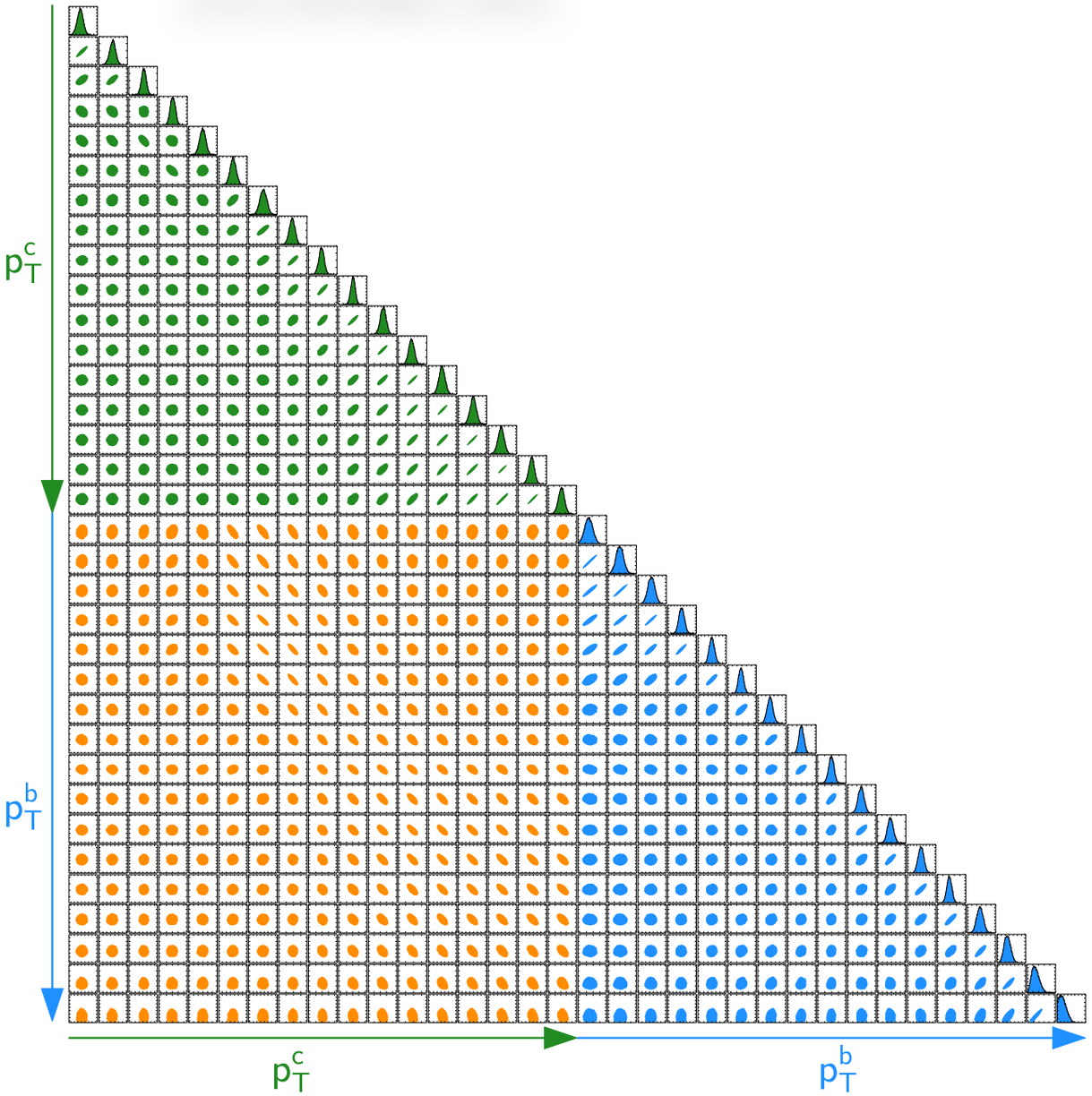

Invariant yield of **charm** and **bottom** hadrons vs p_T

*Includes **correlations** between **charm** and **bottom***

Unfolding Advantages

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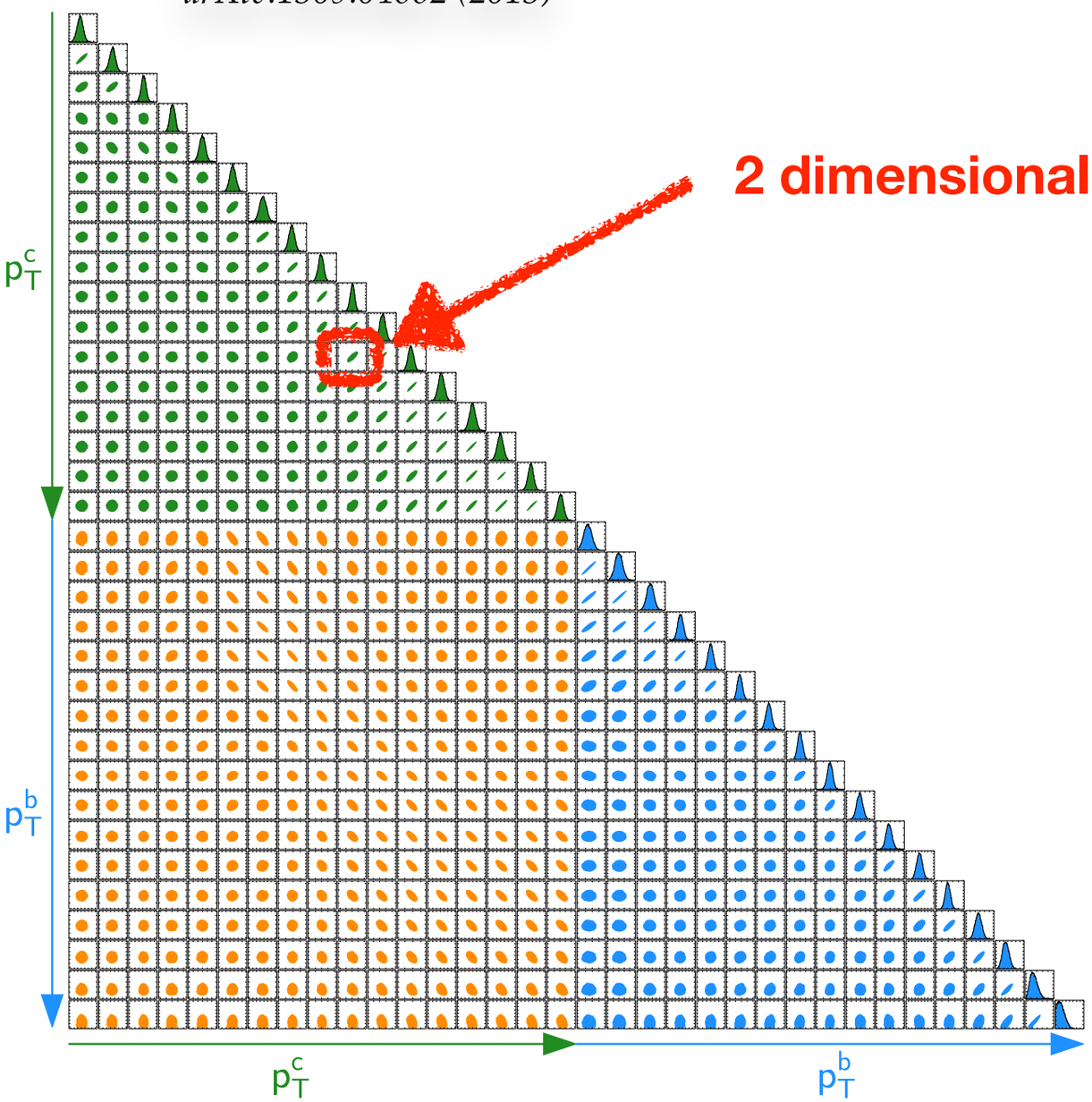

2 dimensional correlations between hadron p_T bins

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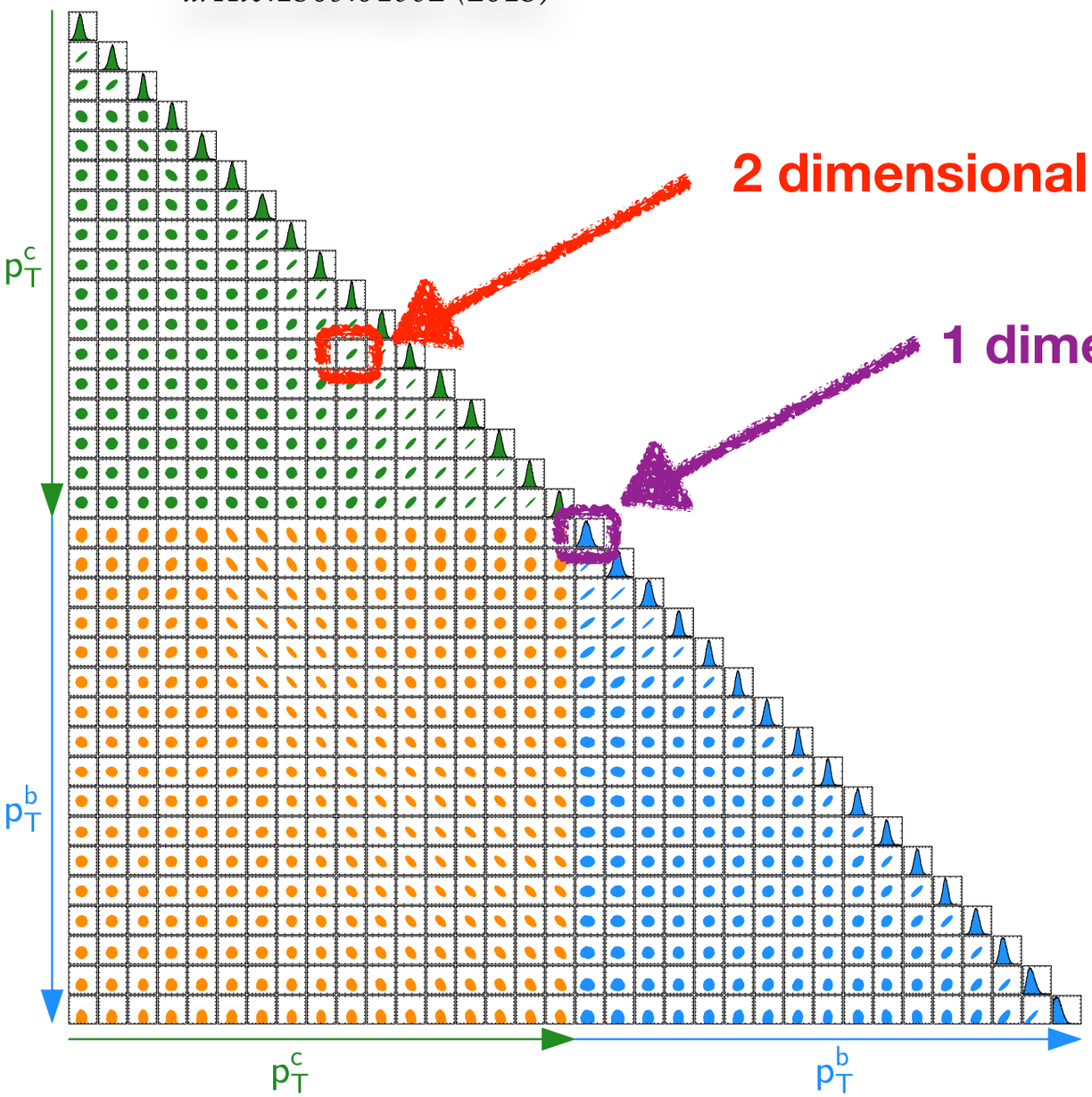

2 dimensional correlations between hadron p_T bins

1 dimensional probability for yield in given hadron p_T bin

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Unfolding Advantages

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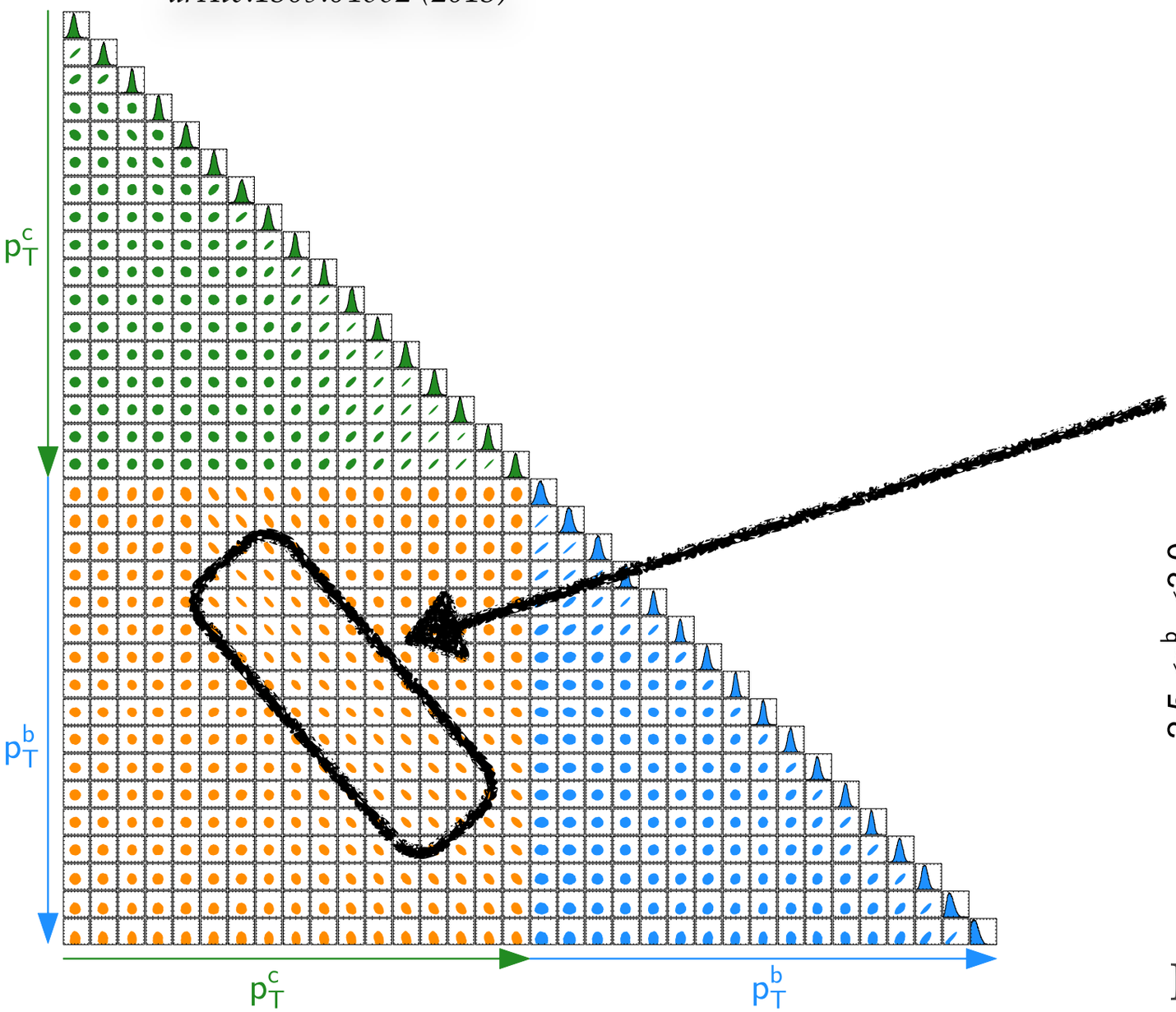
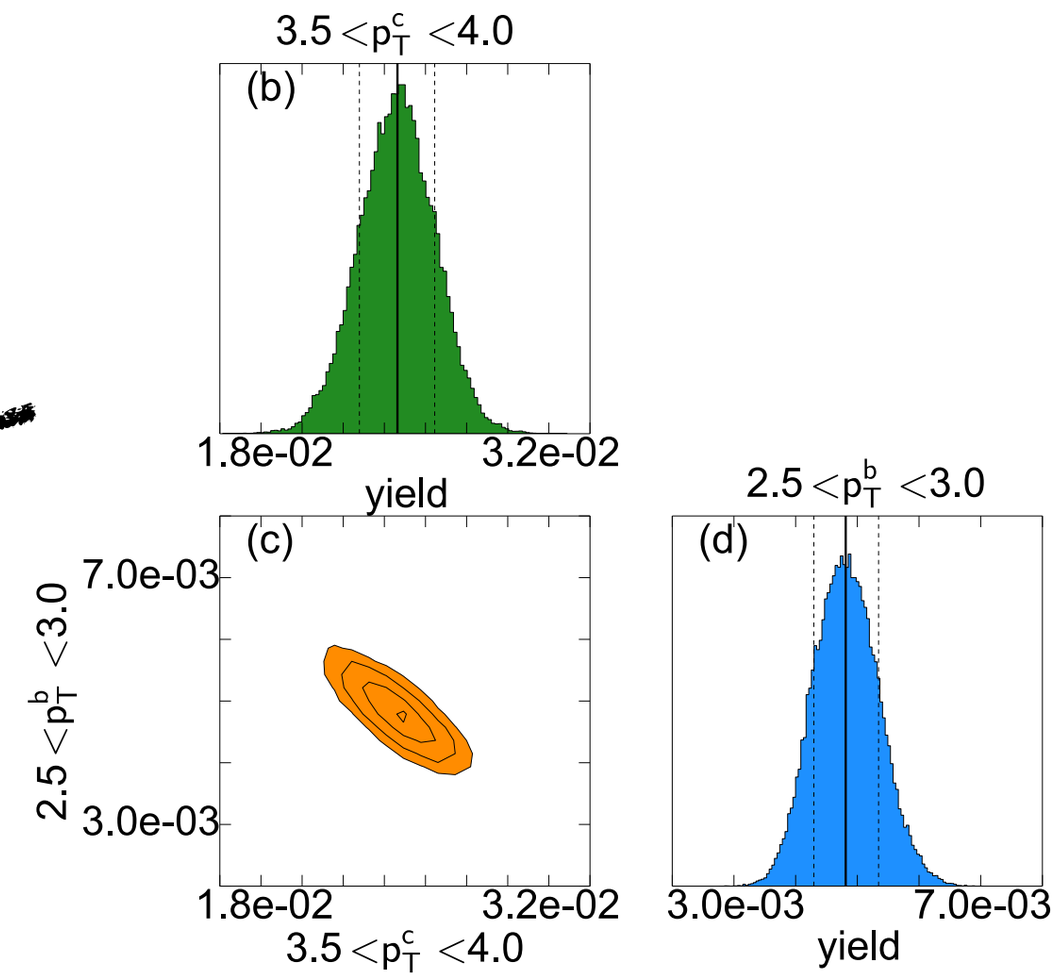


Example correlation



Negative slope means anti-correlation between bins — Trade off between charm & bottom

Unfolded Hadron Yields

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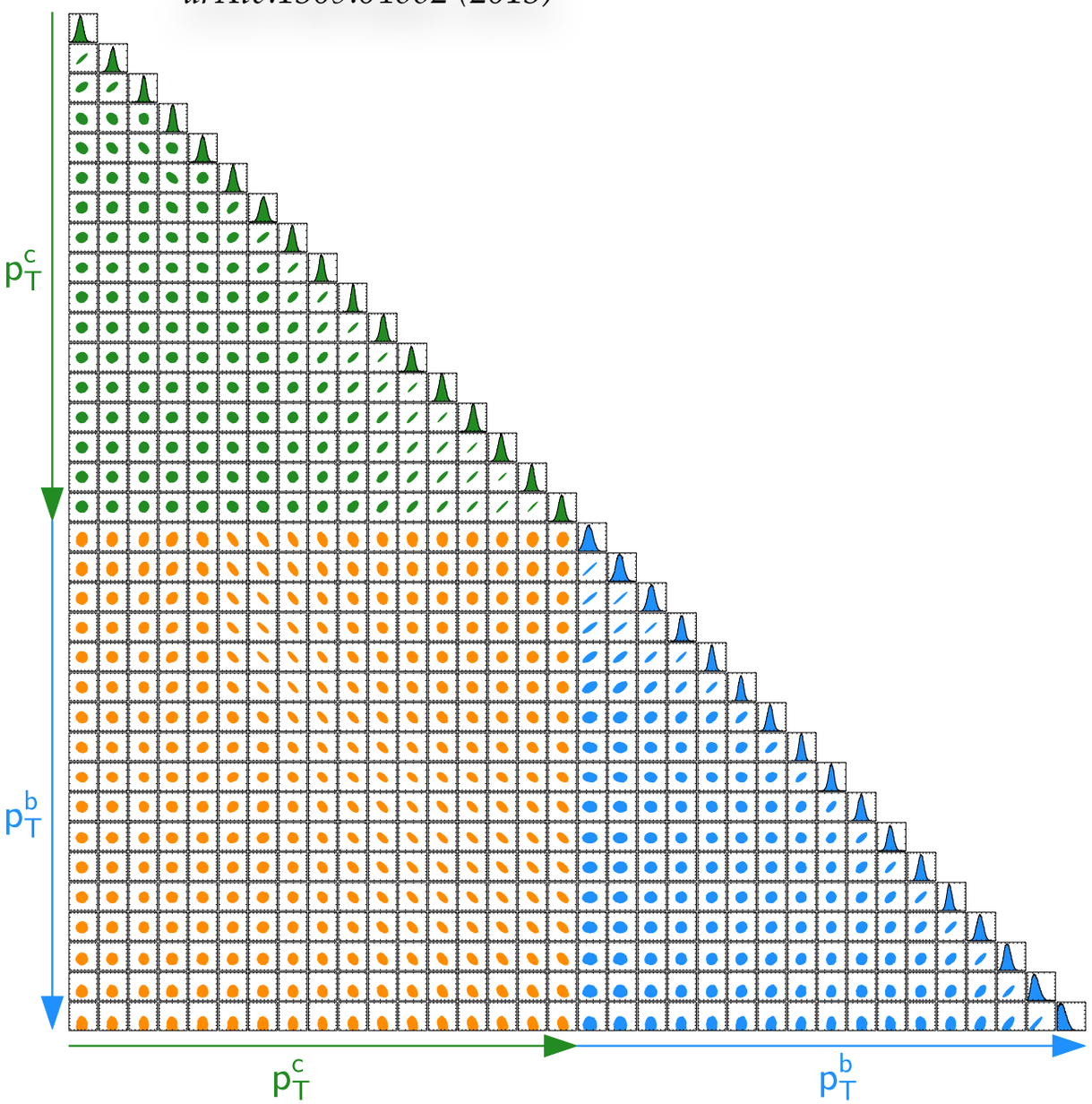

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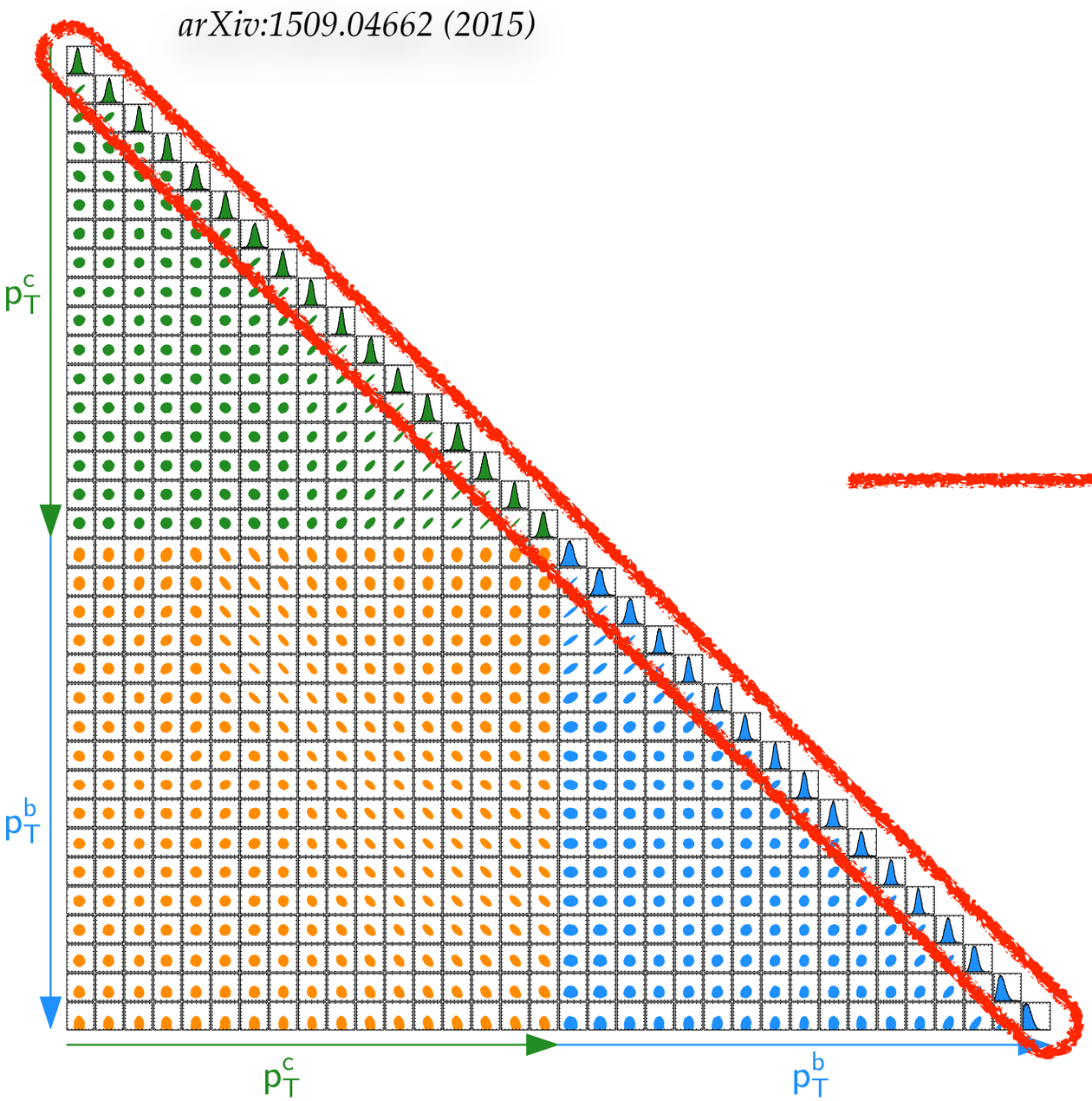
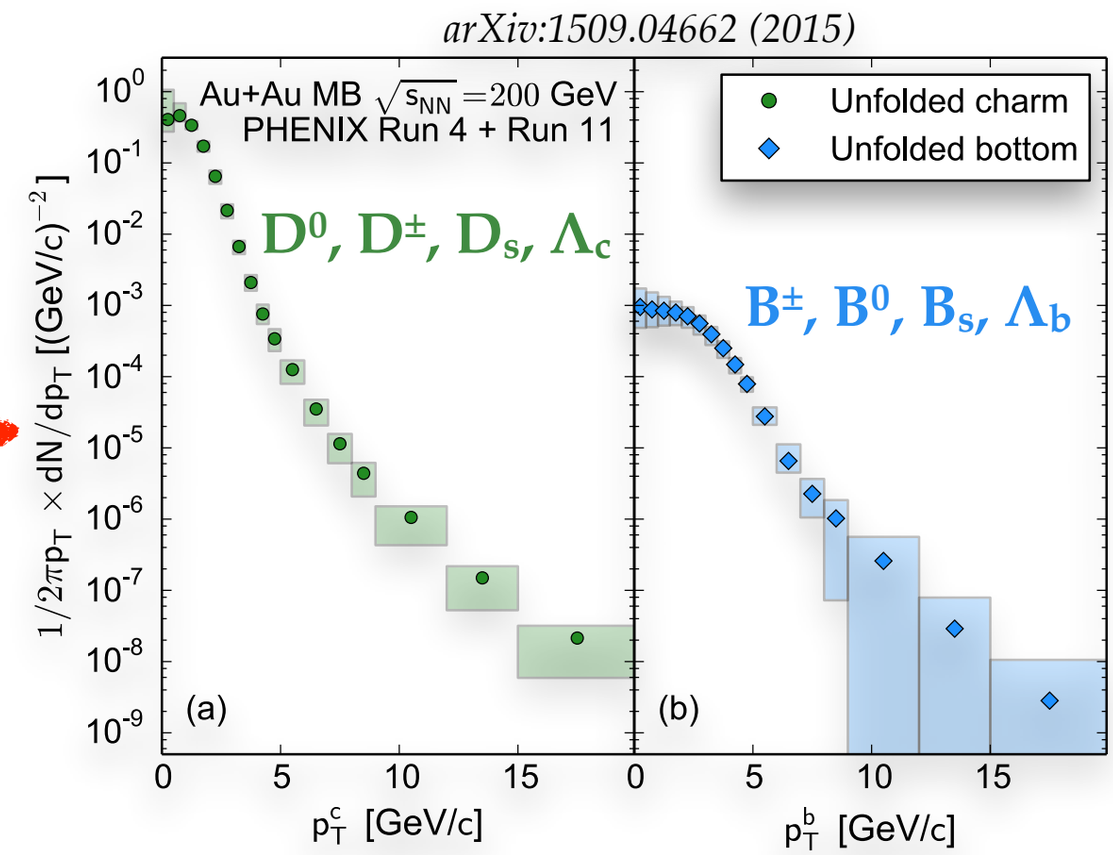
Unfolded Hadron Yields



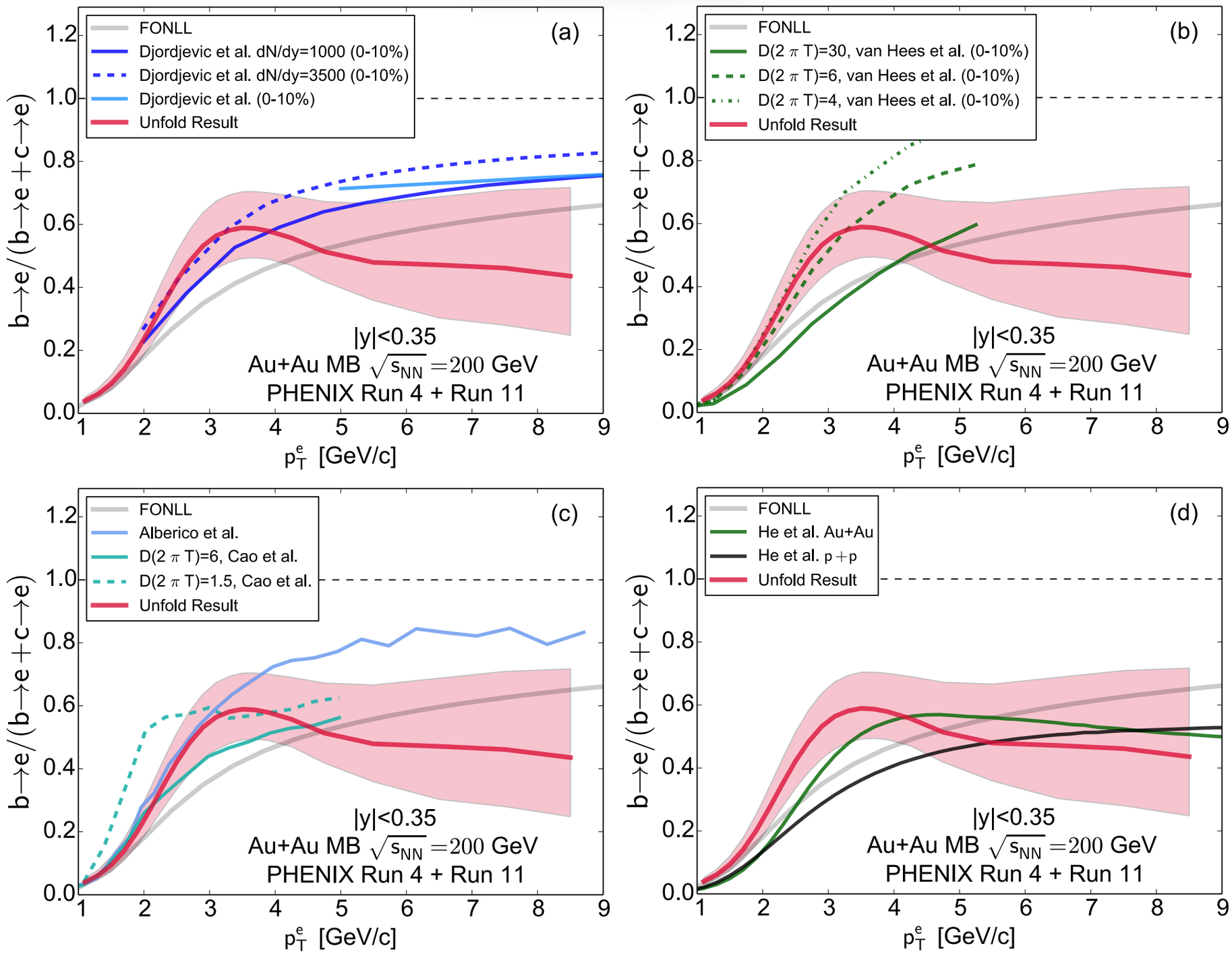


Invariant yield of **charm** and **bottom** hadrons vs p_T

*Includes **correlations** between **charm** and **bottom***

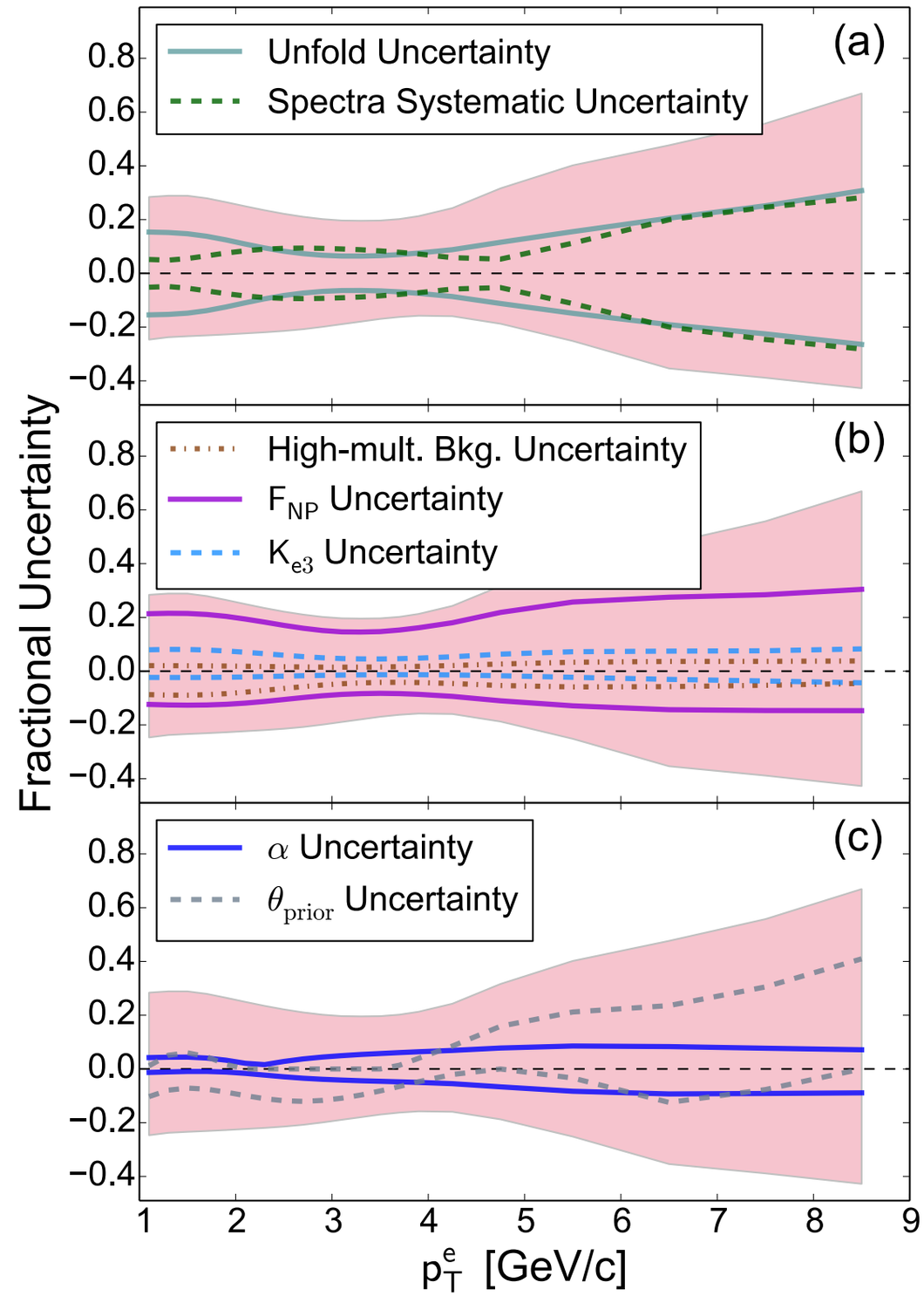
Model Comparisons

arXiv:1509.04662 (2015)

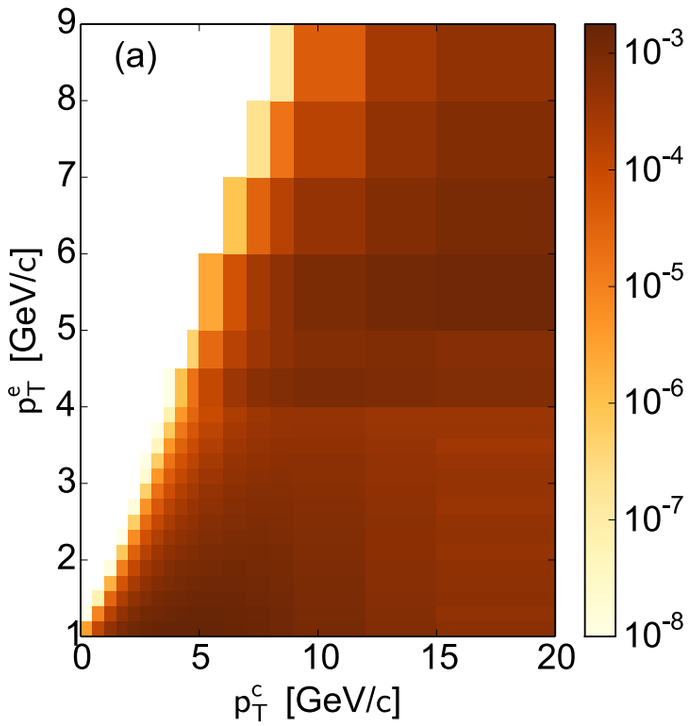


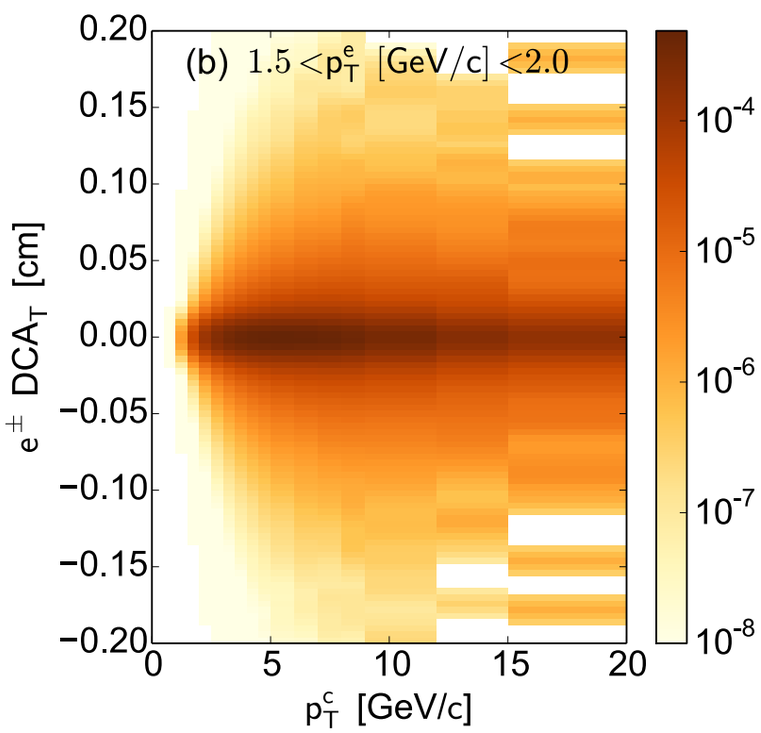
Systematic Uncertainties

- **Unfold Uncertainty** — due to statistical uncertainties on the data
- **Spectra Systematic Uncertainty** — vary HF invariant yield within systematic uncertainties
- **High-mult. Bkg. Uncertainty** — vary the normalization on the "Random" background component
- **F_{NP} Uncertainty** — vary the normalization of the photonics components
- **K_{e3} Uncertainty** — vary the normalization of the K_{e3} component
- **α Uncertainty** — vary the strength of the regularization constraint in the unfolding
- **θ_{prior} Uncertainty** — vary the shape of the hadron pT distribution used in the regularization



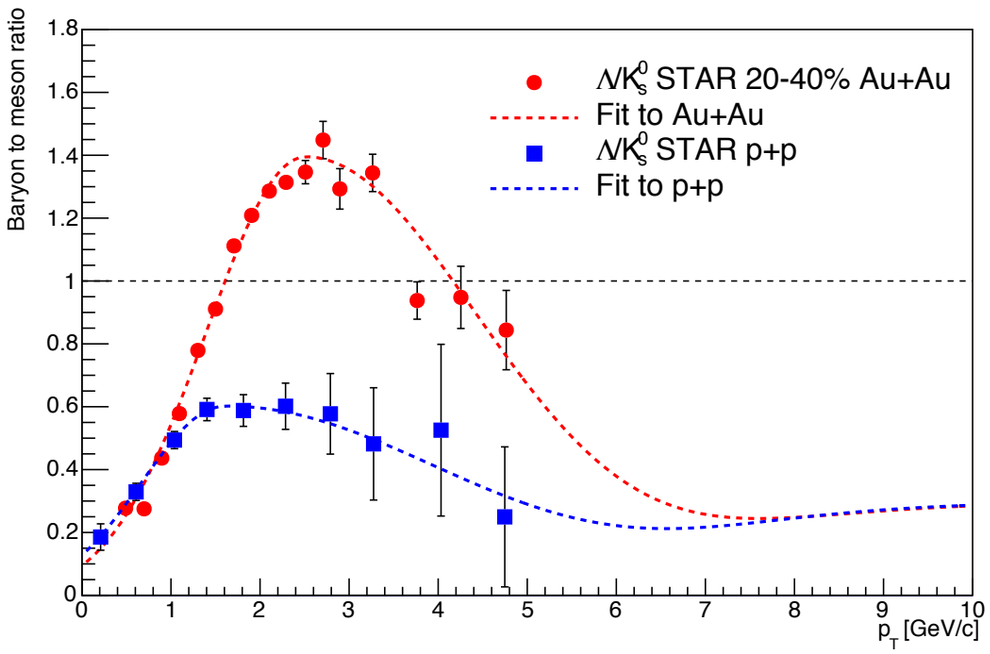
Decay Probabilities

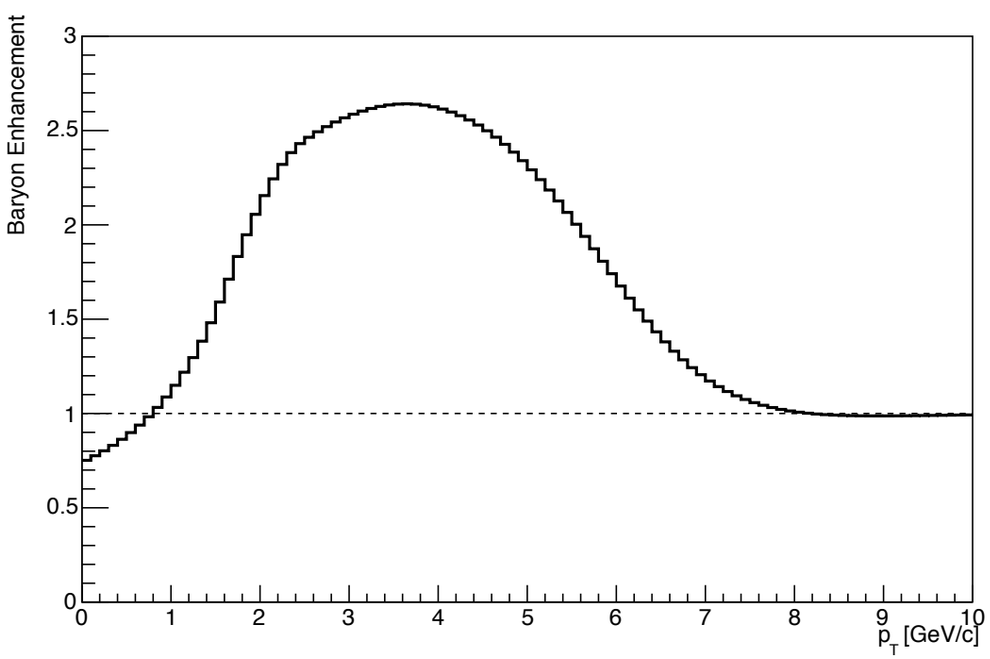




- Decay matrices obtained from PYTHIA 6
  - Forced HF (MSEL=4,5)
  - charm := D^0, $D^{\pm}$, D_s, Λ_c
  - bottom := $B^{\pm}$, B^0, B_s, Λ_b (includes $B \rightarrow D \rightarrow e$)
  - Ratios of hadrons taken from PYTHIA (baryon enhancement tested)
  - Assumes dN/dy shape from PYTHIA

Testing Possible Baryon Enhancement I

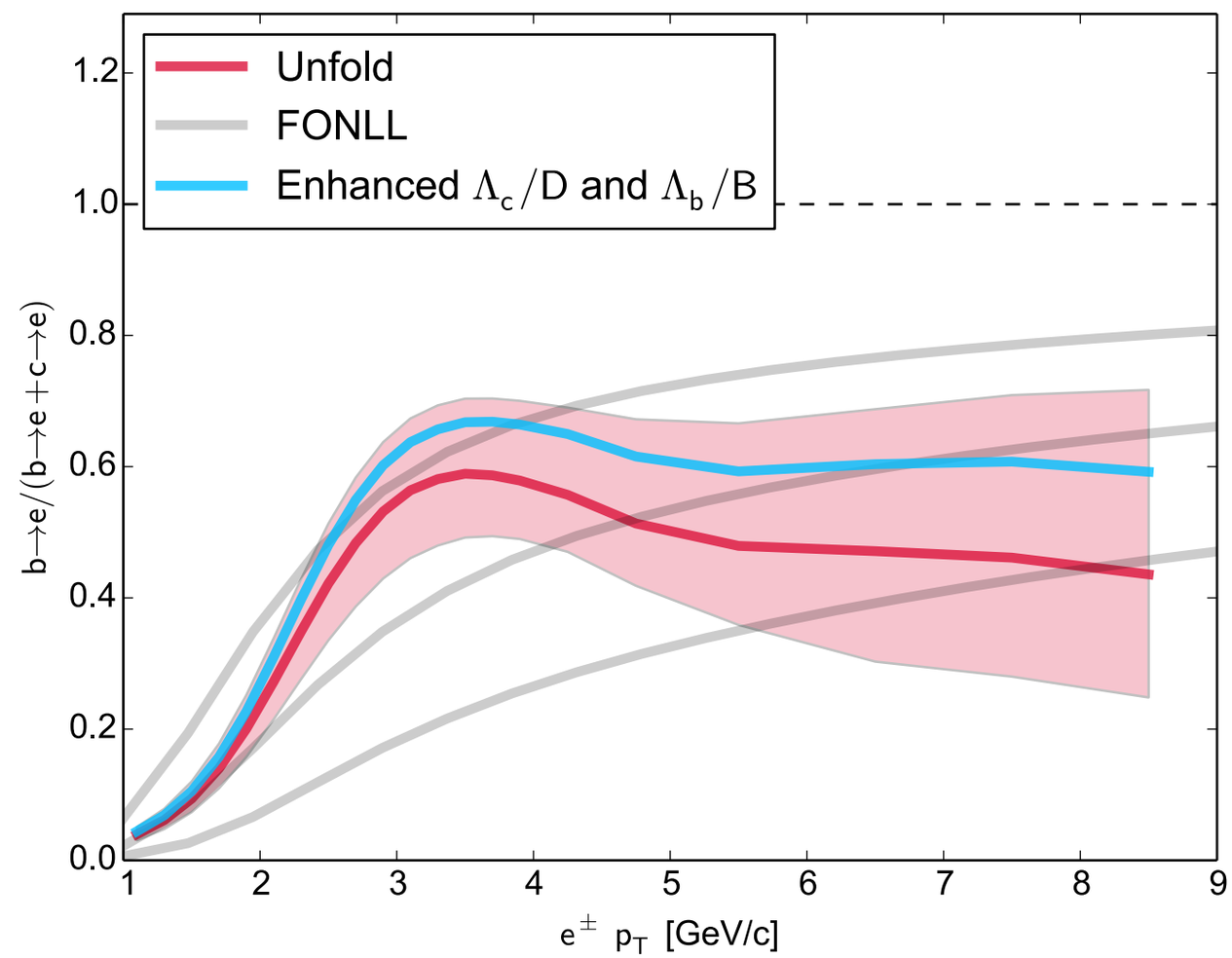




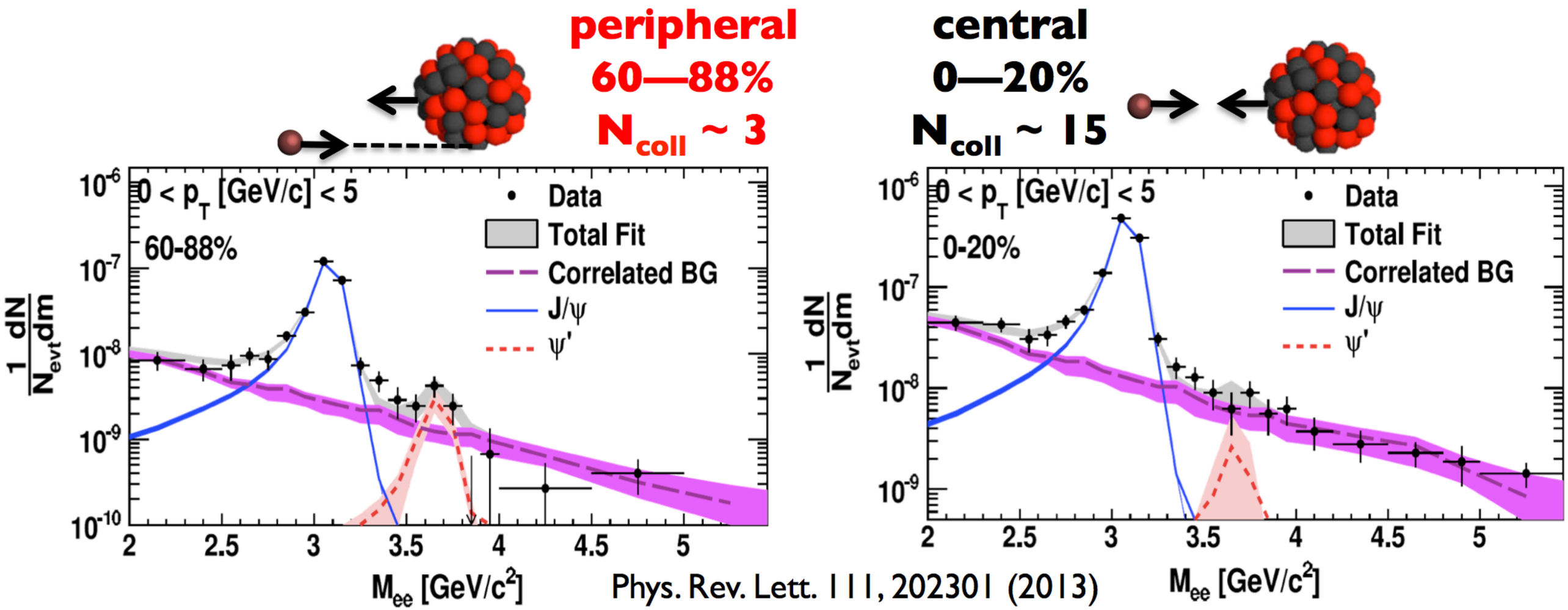
- Follow P. Sorensen and X. Dong — *Phys Rev C 74, 024902 (2006)*
- Take the Λ/K_s ratio measured in STAR 20-40% Au+Au at 200 GeV. *(arXiv:nucl-ex/0601042)*
- Take the Λ/K_s ratio measured by STAR in p+p at 200 GeV. *(arXiv:nucl-ex/0601042)*
- Fit both components to parametrize over p_T.
- Fix asymptotic value to 0.3 in both Au +Au and p+p
- Use the ratio of the fits to enhance the Λ_c and Λ_b contributions in the decay matrices.

Testing Possible Baryon Enhancement II

- Including above enhancement causes an increase in the bottom electron fraction.
- Within systematic uncertainties of the measurement.
- Not included as an additional uncertainty.



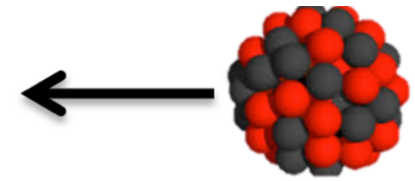
Psi(2S) at Midrapidity



Phys. Rev. Lett. 111, 202301 (2013)

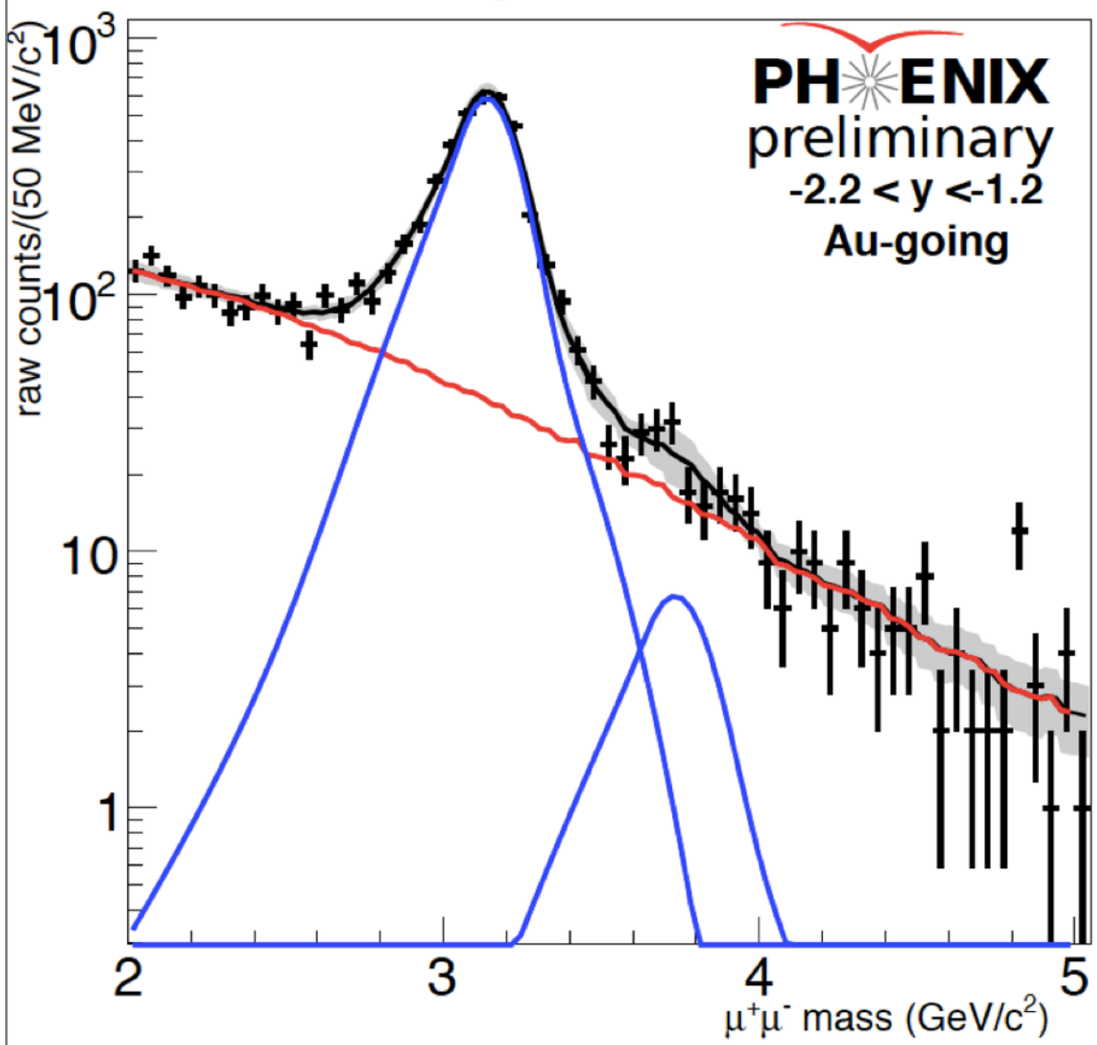
Psi(2S) in Forward/Backward rapidity

Backward
Au-going direction

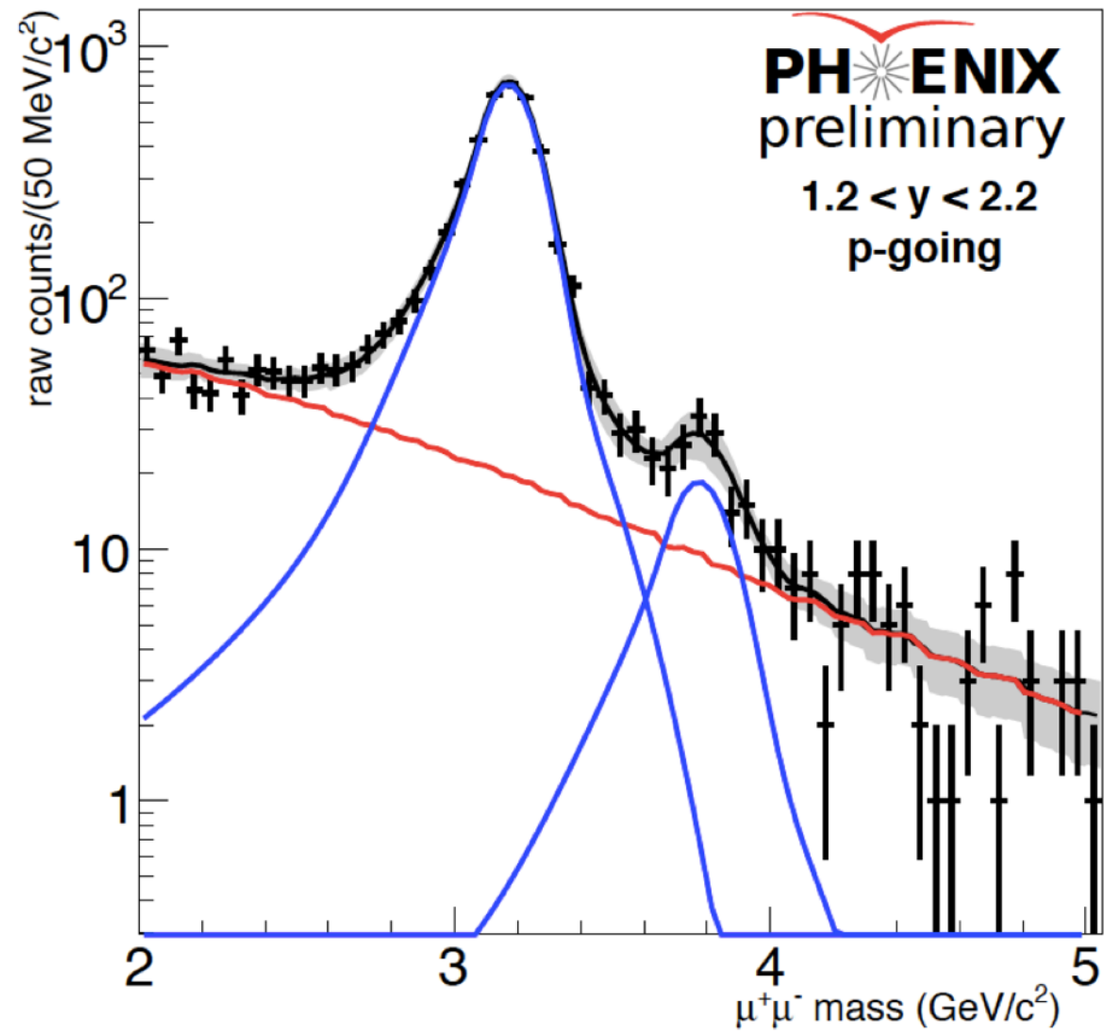


Forward
p-going direction

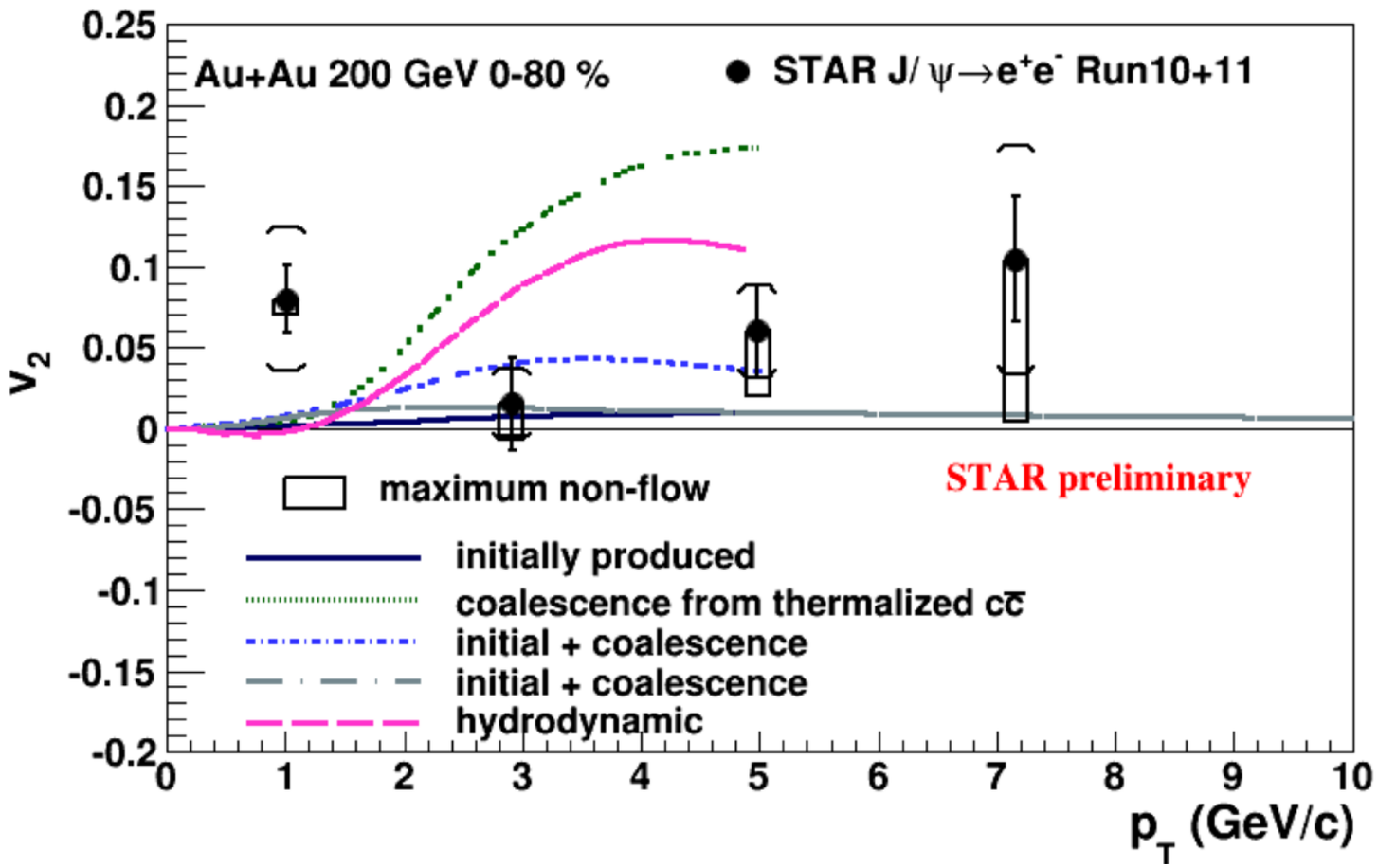
Run-15 p+Au $\sqrt{s}$ = 200 GeV

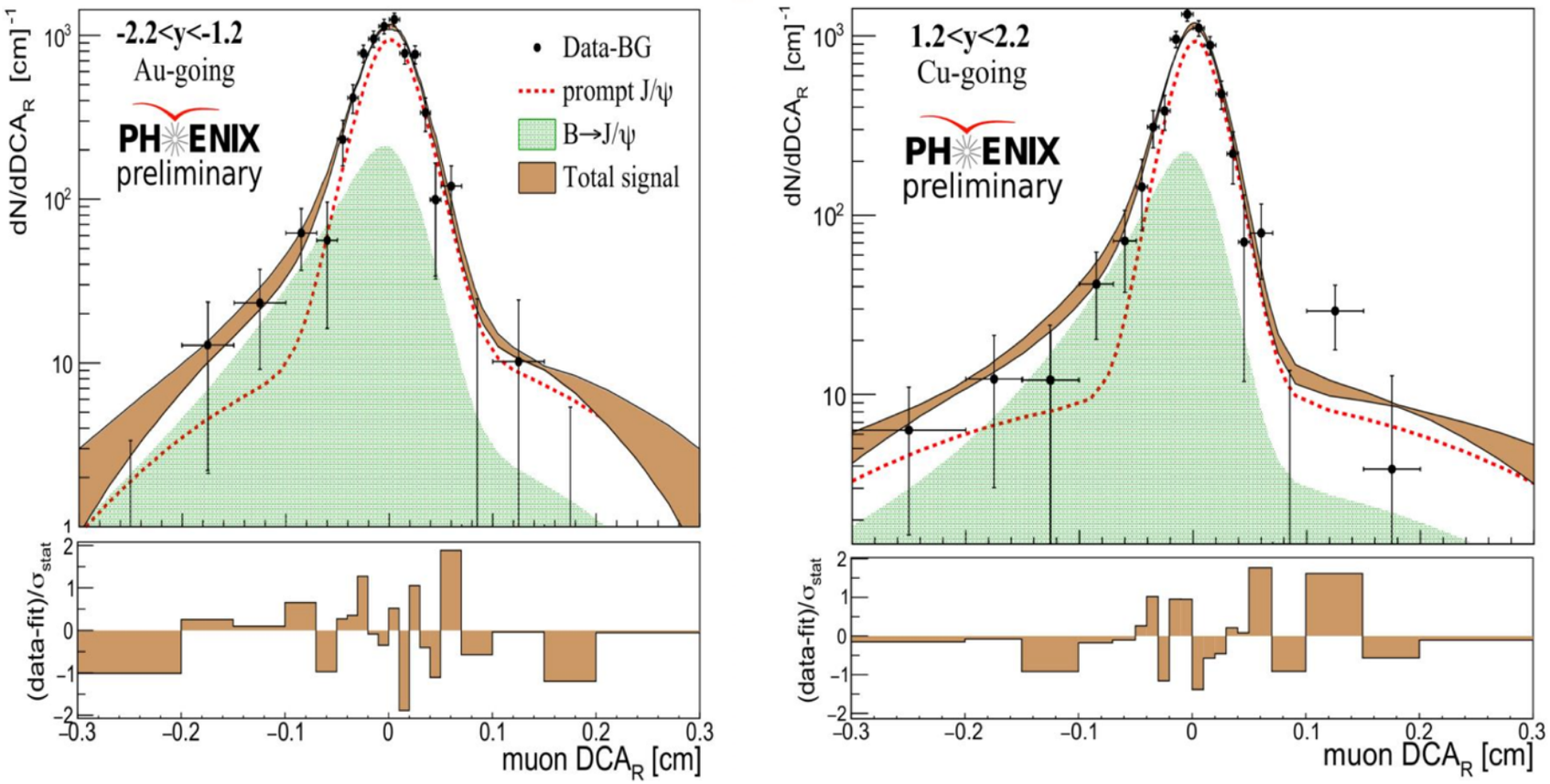
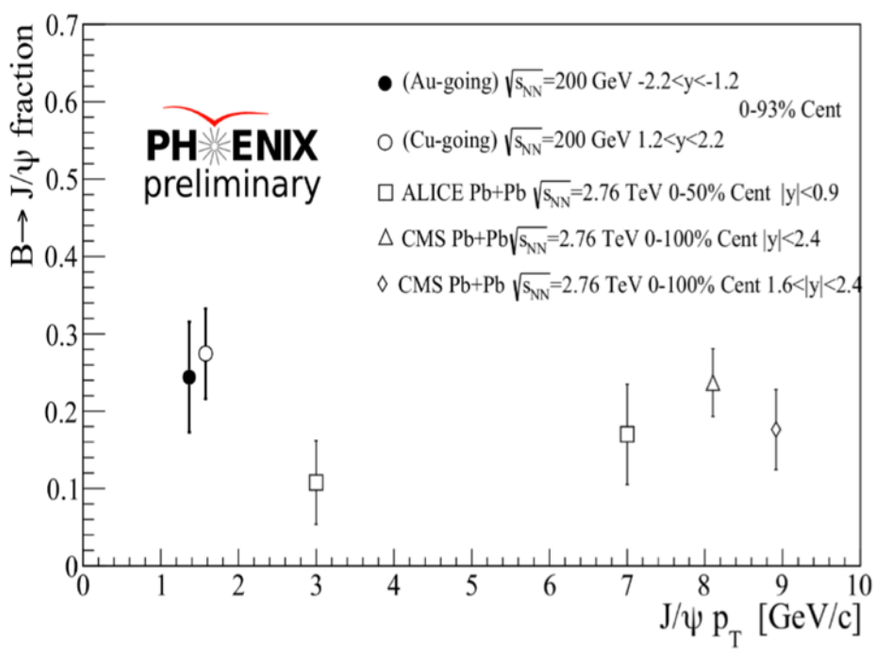
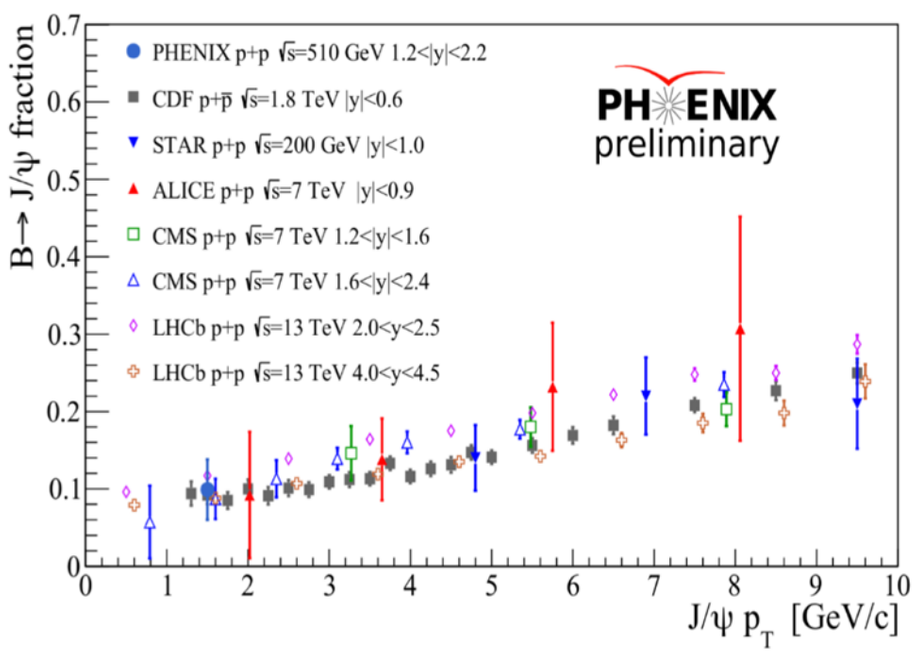


Run-15 p+Au $\sqrt{s}$ = 200 GeV



J/ψ v2


Au+Au 200 GeV 0-80 %
STAR J/ψ→e+e- Run10+11
STAR preliminary
maximum non-flow
initially produced
coalescence from thermalized cc̄
initial + coalescence
initial + coalescence
hydrodynamic
v2
pT (GeV/c)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
1
2
3
4
5
6
7
8
9
10

Non-prompt J/ψ

DCA_R Distributions for clarity are shown BG subtracted