Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks,
INT Program INT-17-1b, Week 5-6, May 28 – June 8

Quarkonium Measurements in p+p and Heavy-ion Collisions at RHIC

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Outline

Quarkonium measurements in p+p collisions

- J/ψ p_T spectra and feed-down
- J/ψ polarization
- J/ψ self-normalized yield vs. event activity
- ϒ

Quarkonia measurements in heavy-ion collisions

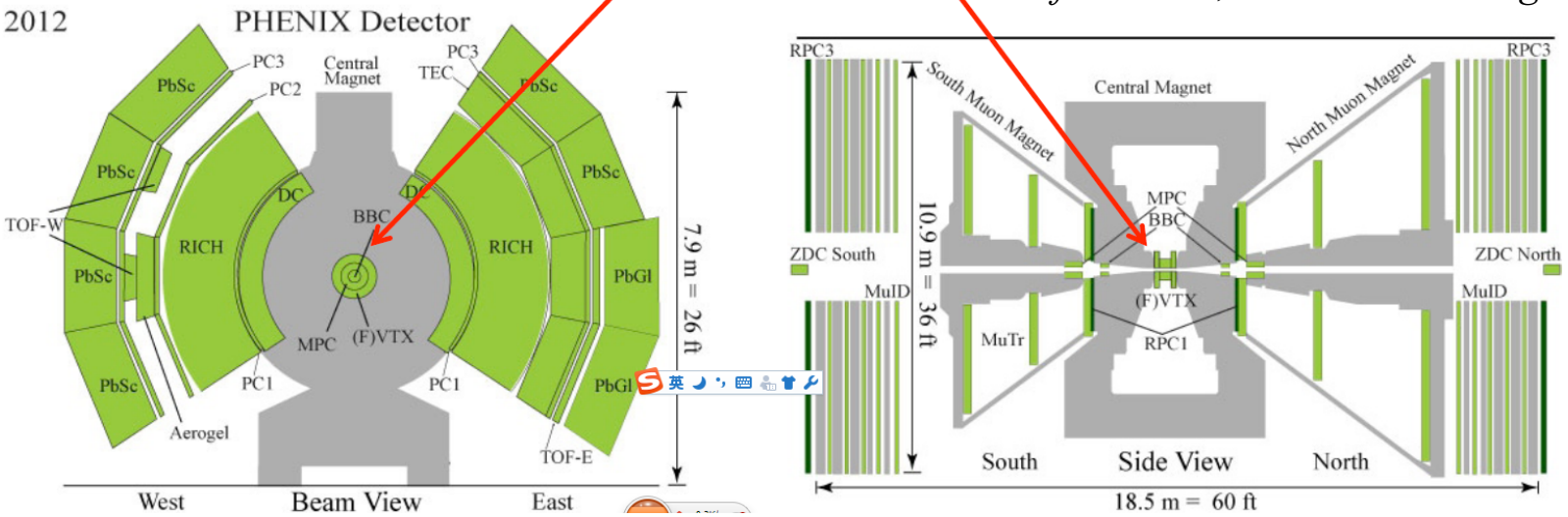
- J/ψ
- ϒ(1S) and ϒ(2S+3S)

Summary

PHENIX Detector System

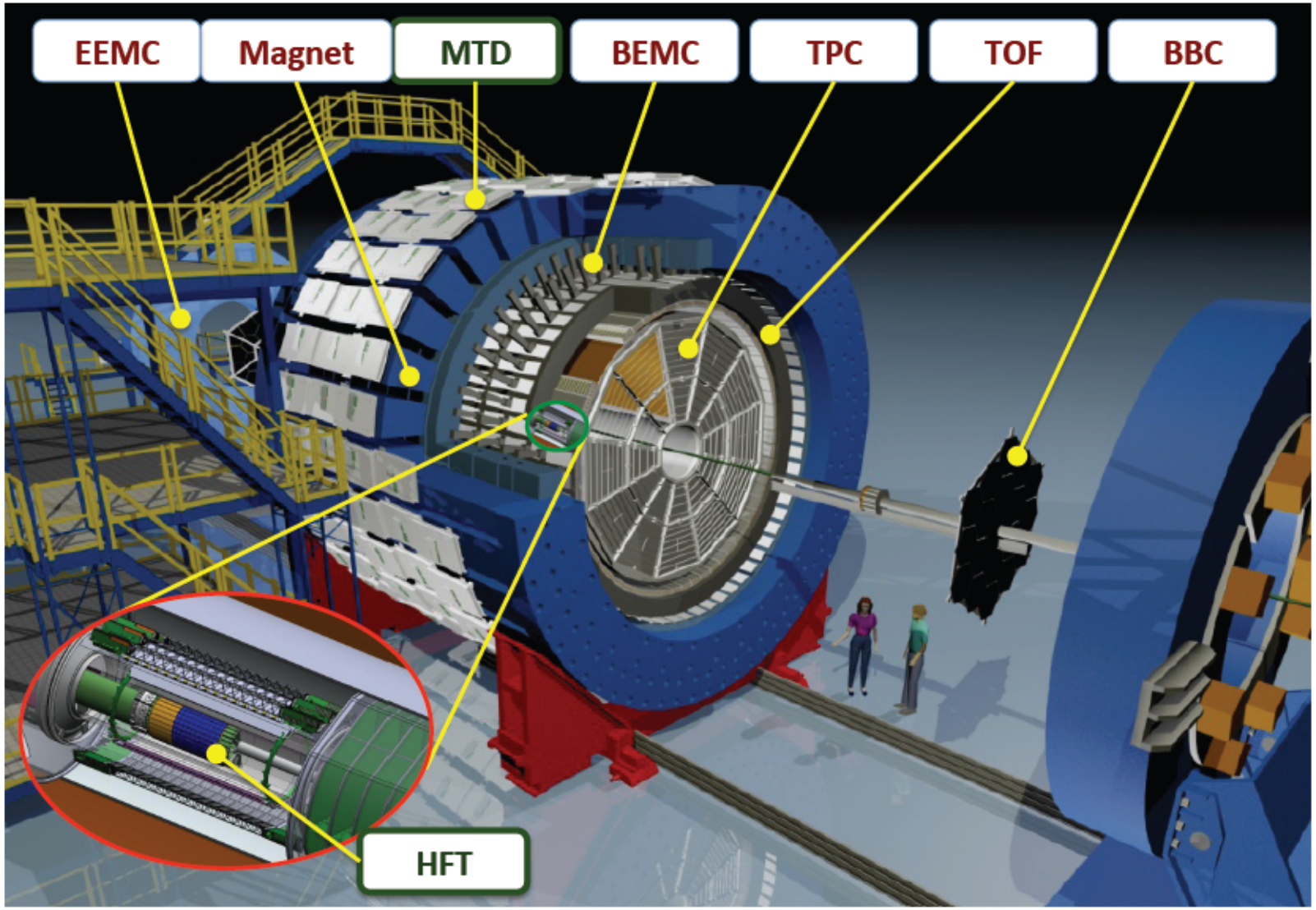
- 2009--2010: Hadron Blind Detector (HBD)
- 2011--present: Silicon Vertex Detector (VTX)
- 2012--present: - Forward Silicon Vertex Detector (FVTX)
- Decommissioned in 2016

Stefan Bathe, BNL PAC meeting

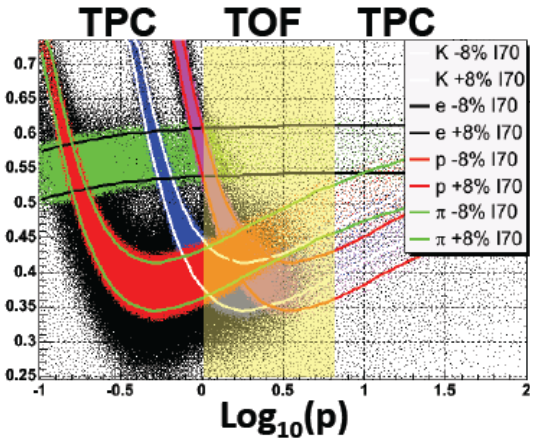


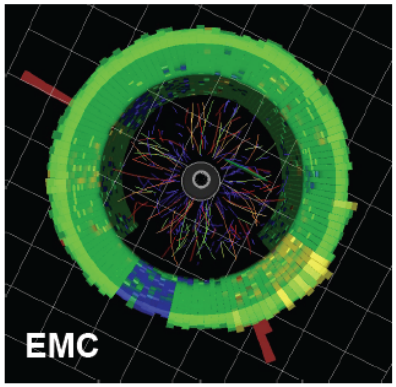
- ee at mid-rapidity (|y|<0.35) and μμ at forward rapidity (1.2<|y|<2.2)
- Switching to large acceptance ϒ measurements at mid-rapidity with sPHENIX

STAR Detector System

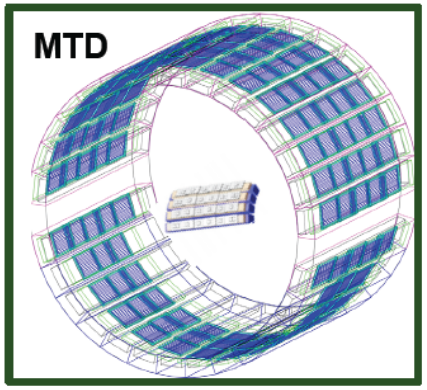


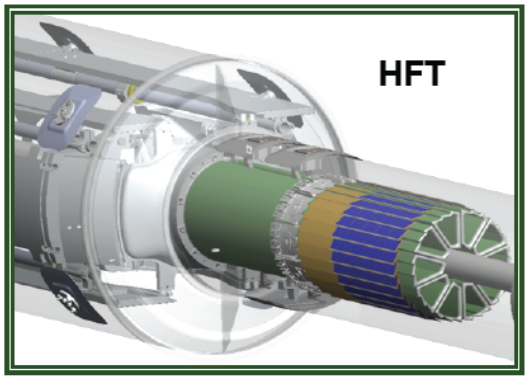
STAR Detector System





Period	Detectors at mid-y
2001-2005	TPC
2005-2009	TPC+EMC
2009	DAQ1k (TPC→TPX)
2010	TPX+EMC+TOF
2013	TPX+EMC+TOF+MTD
2014-2016	TPX+EMC+TOF+MTD+HFT
2016-	… + Forward Upgrades





STAR:

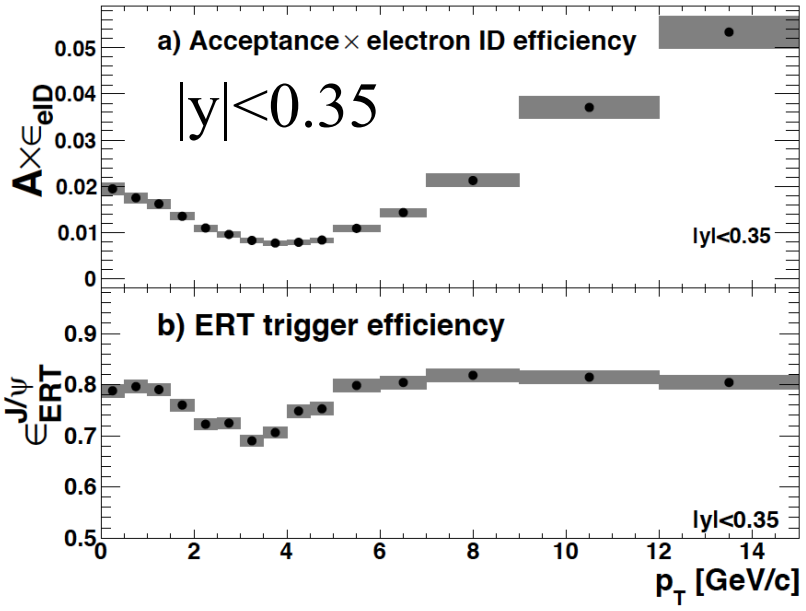
- Large acceptance, excellent PID
- Excellent mid-rapidity experiment
- Expanding into forward rapidity region

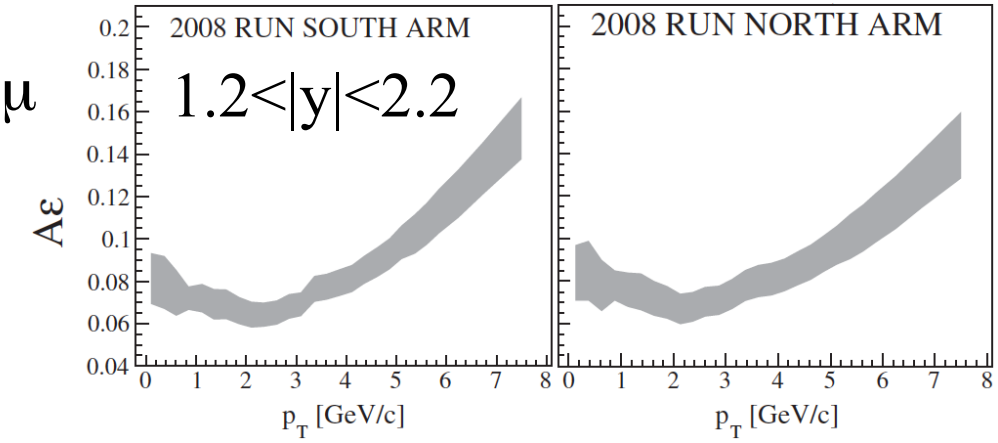
J/ψ detection efficiency at RHIC

ee

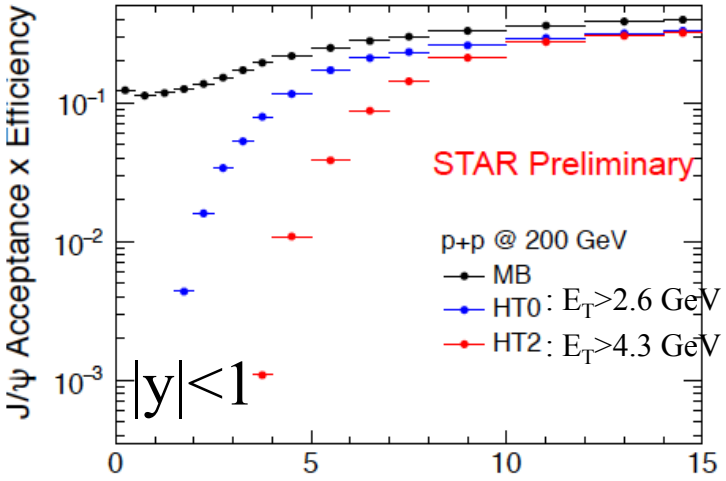
μμ

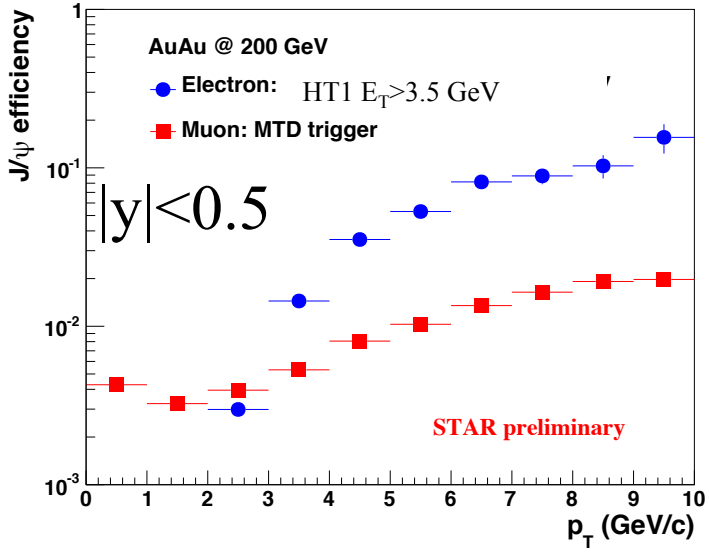
PHENIX





STAR



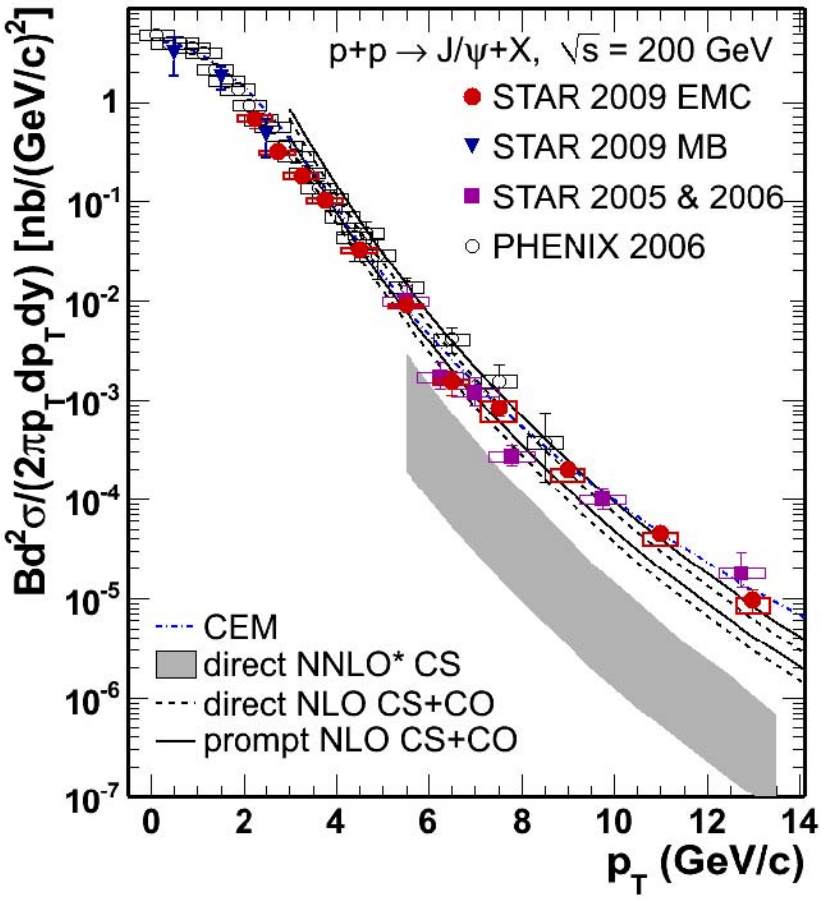


Quarkonium in p+p

Quarknoium data in p+p at RHIC

Year	√s	STAR								PHENIX			
		ee					μμ	cc	bb	ee	μμ	cc	bb
		MB	HT0	HT1	HT2	HT3							
2001										0.07	0.08	PRL 2004	
2004										~0.2	~0.2	PRL 2006	
2005	200		2.8					PRC 2009		2.6	~3	PRL 2007	
2006	200			11					PRD 2010	6.2	22	PRD 2010 PRD 2012	PRC 2015 (ee)
2009	200	77 M	1.9			23		PLB 2013 PLB 2014 PRC 2016	PLB 2014		22		PRC 2013 (μμ)
2011	500				22			**Preli.**	**Preli.**				
2012	200 500	0.4 B	1.4		24	4.4		**Preli.**			0.5	PRD 2017	
2013	500				60		28	**Preli.**			222	arXiv:1612	
2015	200	1.1 B		38	120		120	**Preli.**	**Preli.**			PRC 2017	
2017	500	1.1 B			80	300	300						

J/ψ p_T spectra in 200 GeV p+p collisions



NNLO* CSM:

pQCD calculation, for direct only

Misses high-p_T part

NRQCD:

Long-distance matrix elements from world-data fitting

Calculation at NLO available

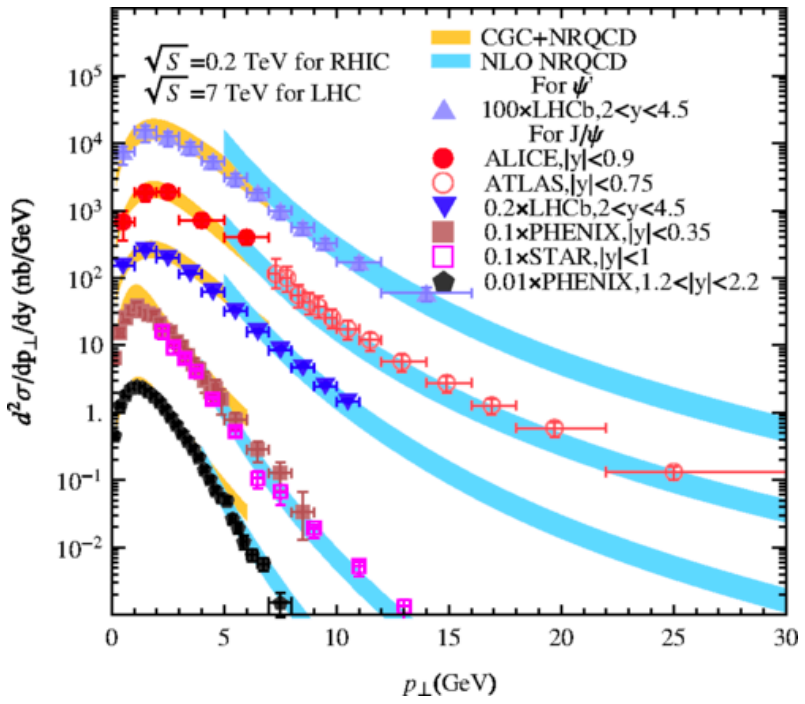
Agrees with data well at high-p_T

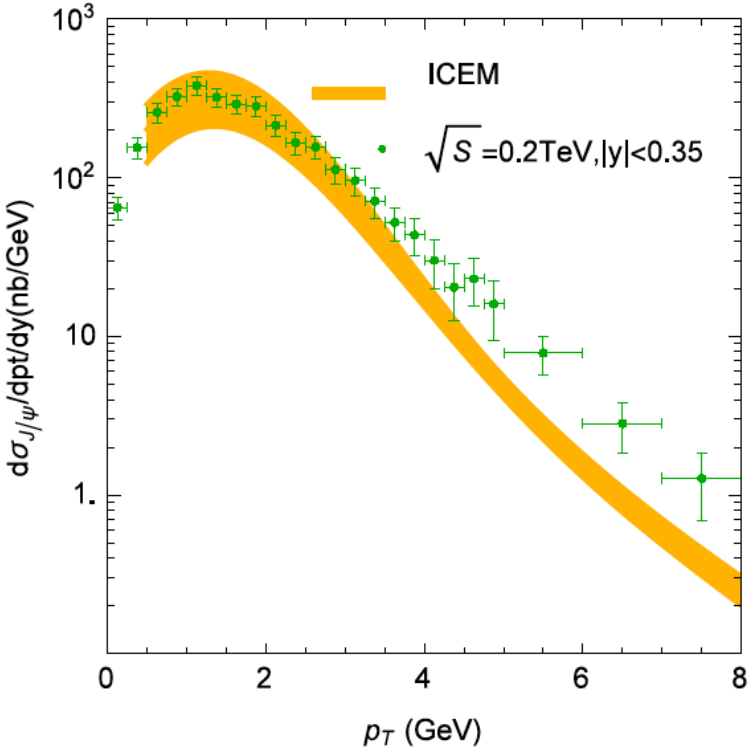
CEM:

Describes in the entire p_T

STAR : PRC80, 041902 (2009), PLB722, 55 (2013)
PHENIX: PRD85, 092004 (2012)
direct NNLO CS: P.Artoisenet et al., PRL101, 152001 (2008) and private communication
NLO CS+CO: Y.-Q.Ma, K.Wang, and K.T.Chao, PRD 84, 114001 (2011) and private communication
CEM: A.D. Frawley, T Ullrich, R. Vogt, Phys. Rept. 462, 125 (2008) and R.Vogt private communication

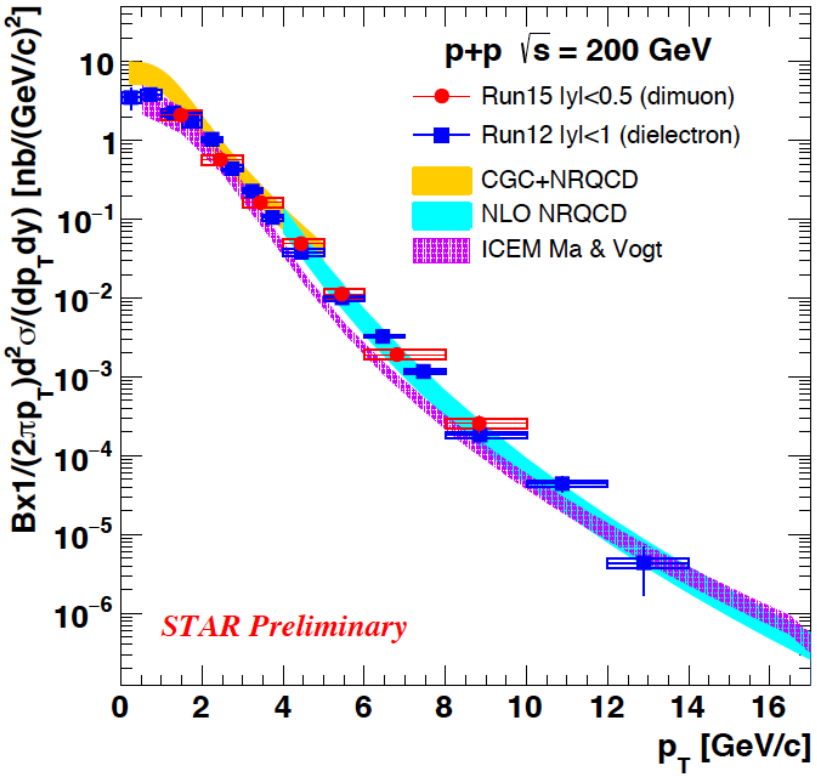
Theoretical developments

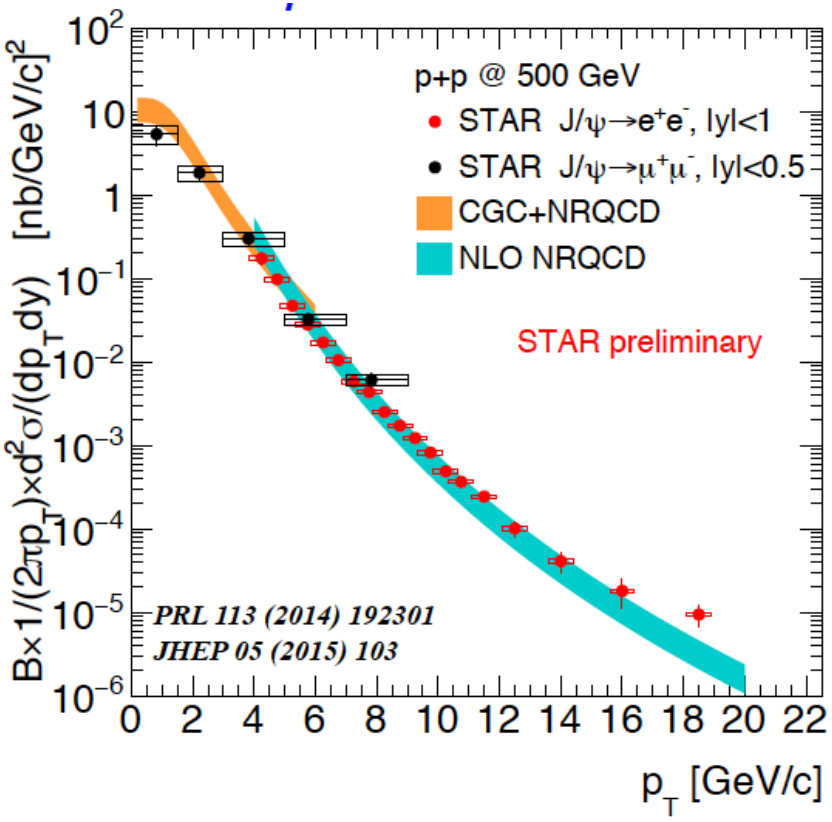




- NRQCD describes world-data at high-p_T
- CGC+NRQCD describes world-data at low- and intermediate-p_T
- ICEM describes at low-p_T, leaves room for B feed-down at high-p_T

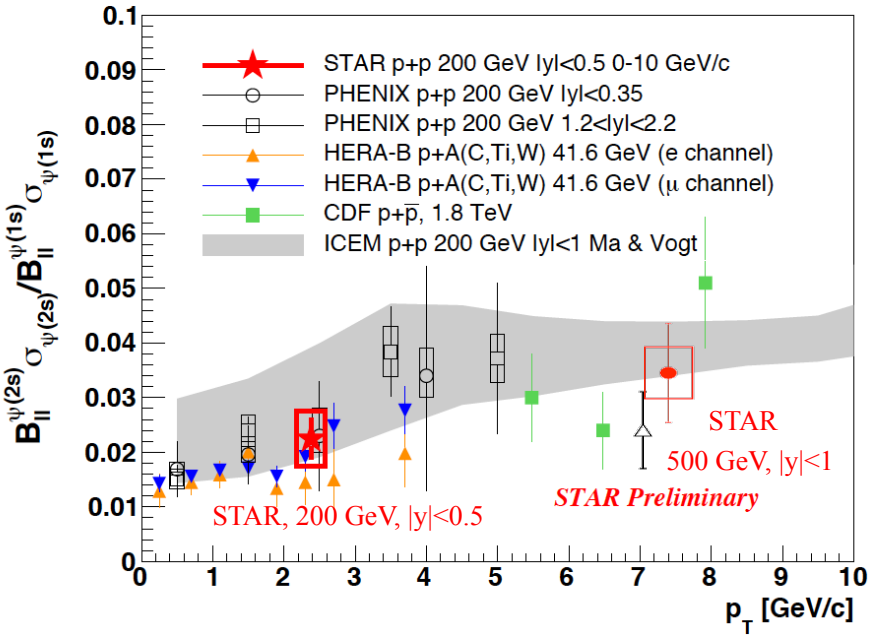
New data compared to New theory

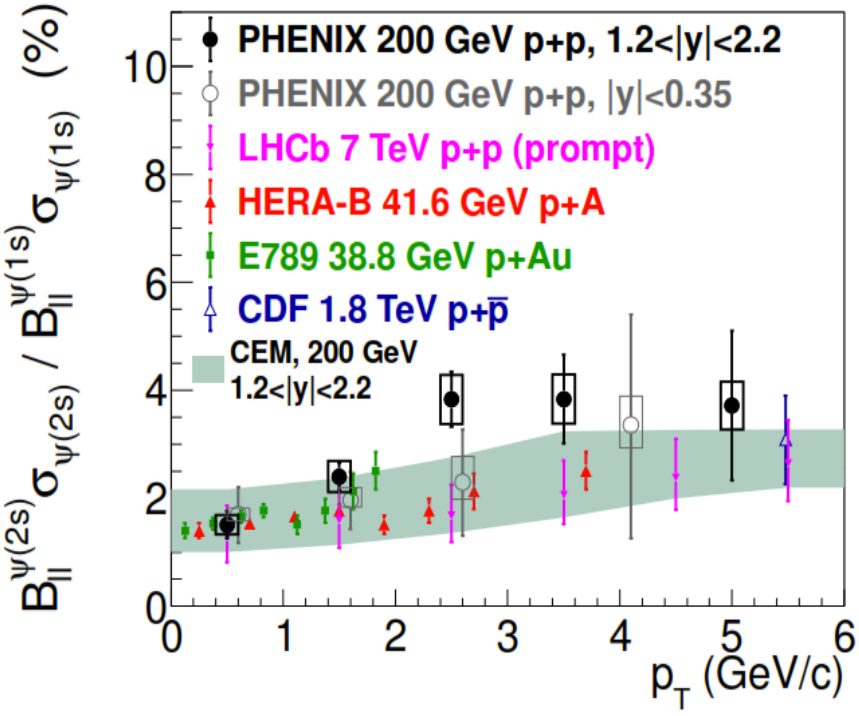




- New data at 200 GeV and 500 GeV from ee and μμ channels
- Consistent with model calculations/predictions
- Some tension for CGC+NRQCD at low-p_T

ψ(2S)/ψ(1S) ratio

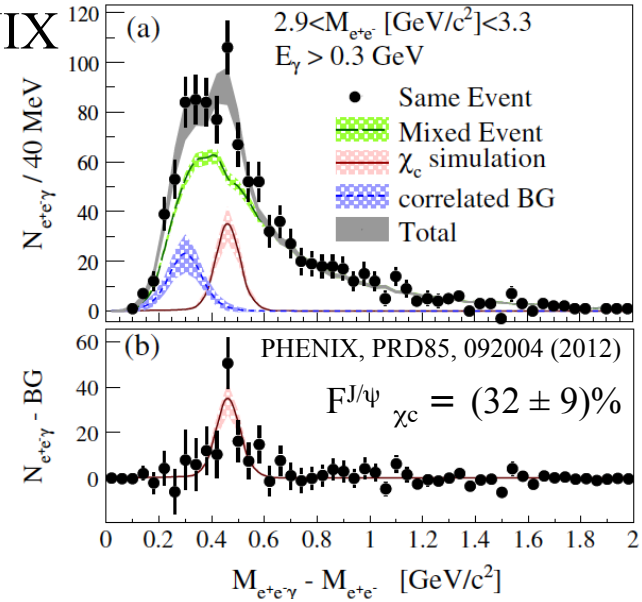


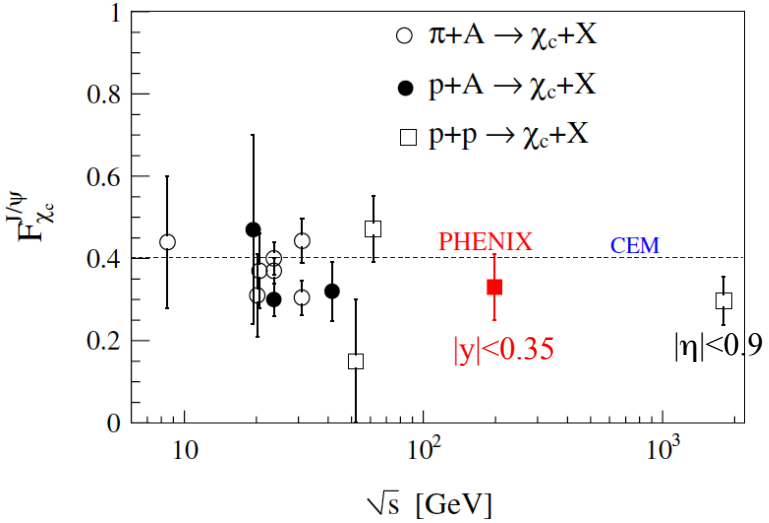


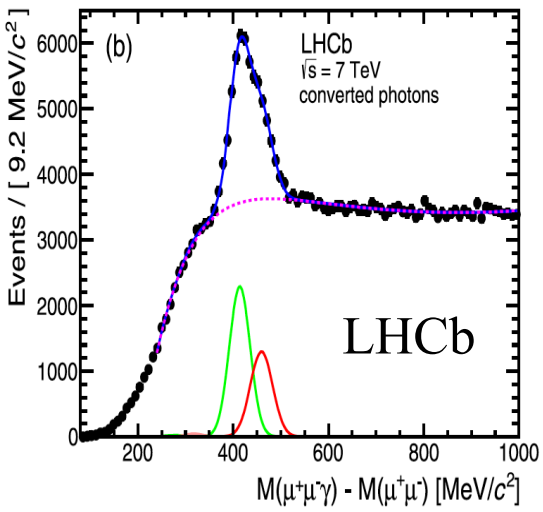
- Increasing trend vs. p_T in mid- and forward rapidity
- ICEM describes data

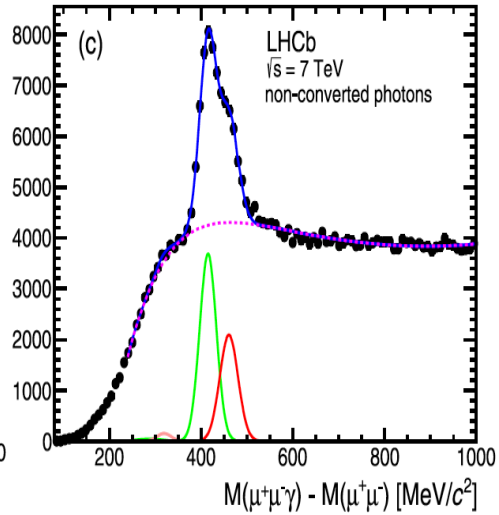
$\chi_c/\psi(1S)$ ratio

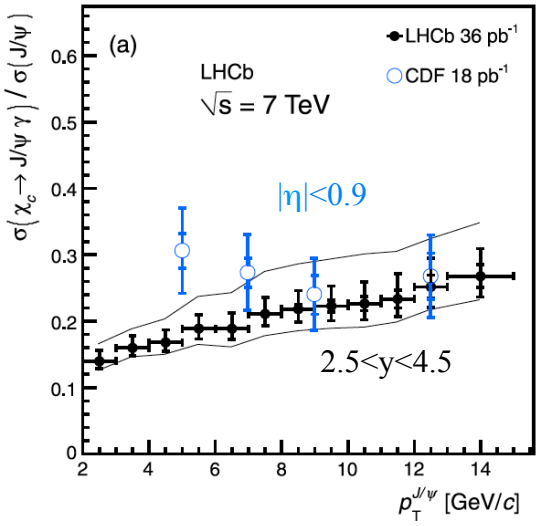
PHENIX

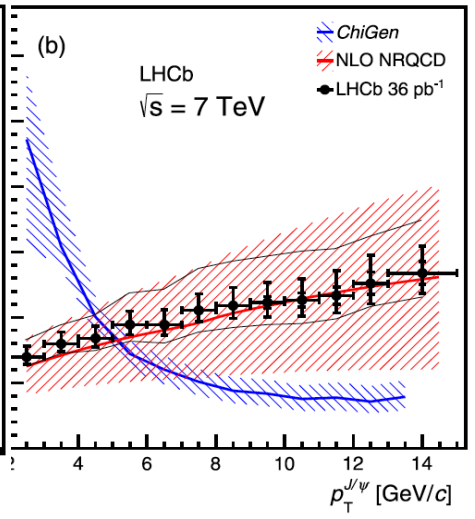








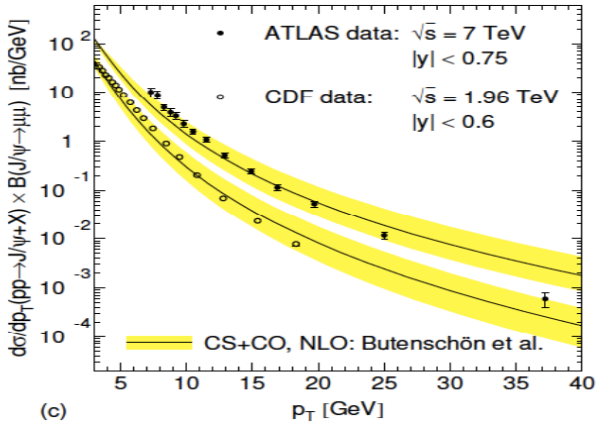


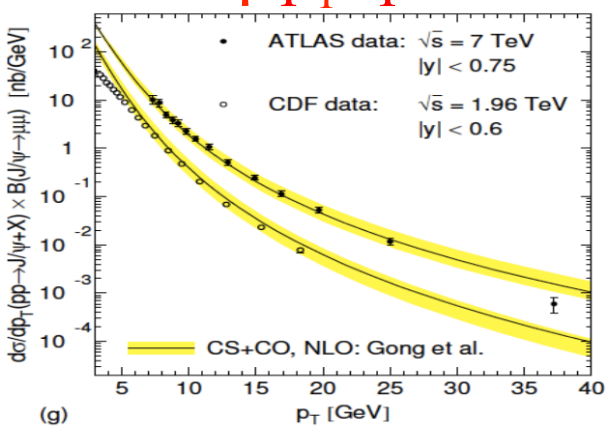


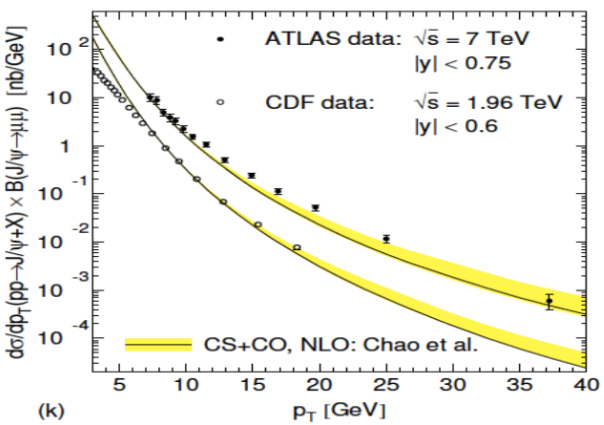
LHCb, PLB718, 431 (2012)

Polarization measurement is needed

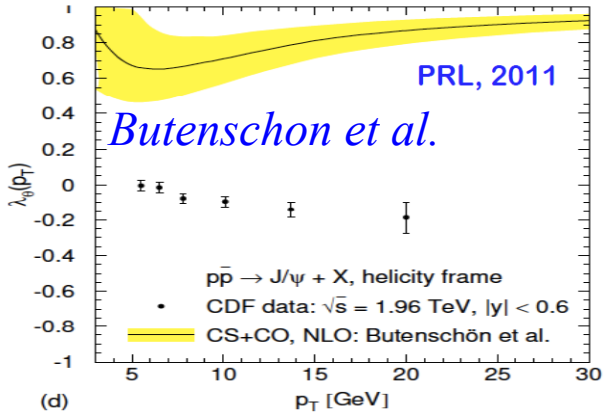
J/ψ p_T spectra

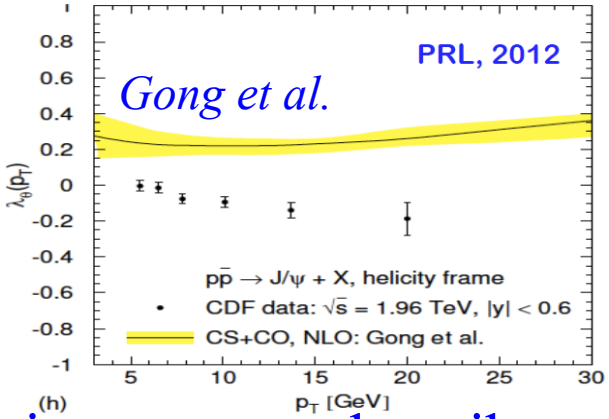


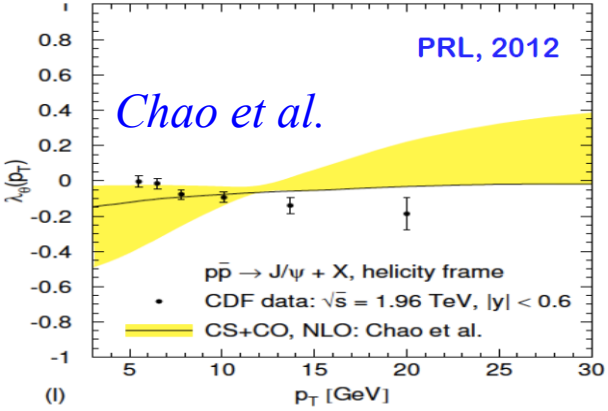




J/ψ polarization

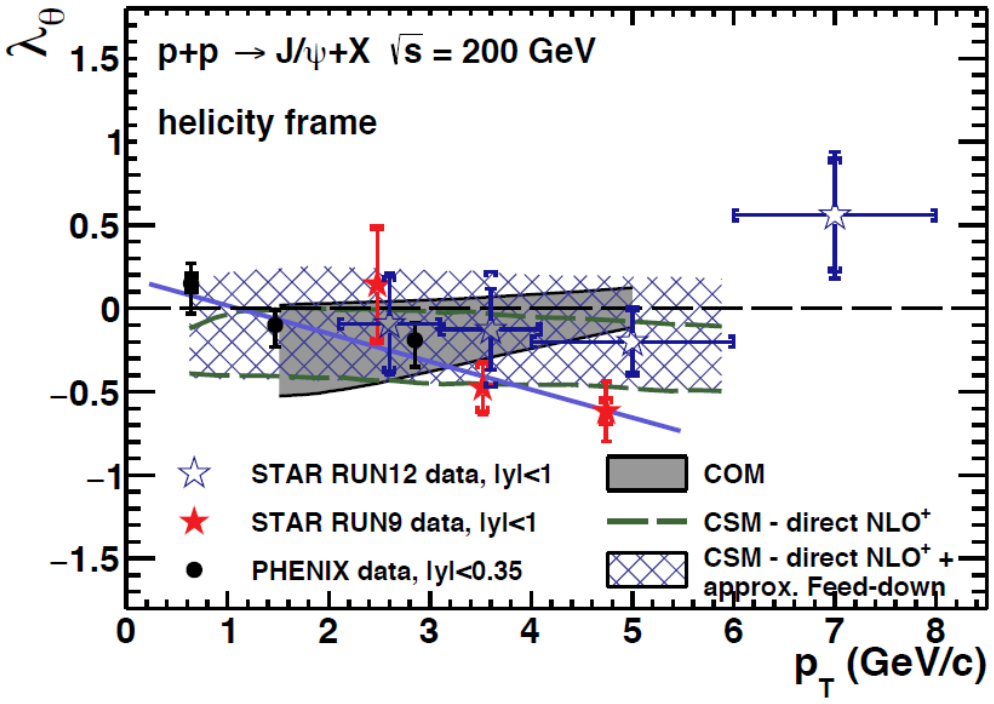






NLO NRQCD calculations cannot describe spectra and polarization measurements consistently

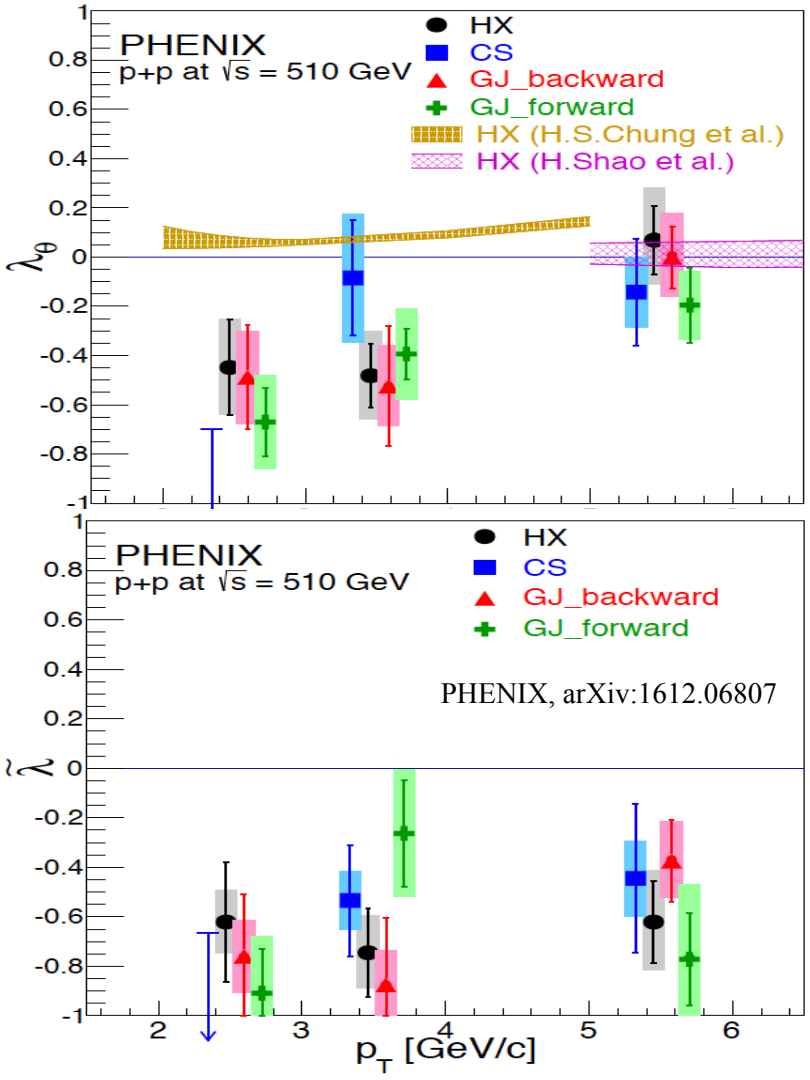
J/ψ polarization in p+p at 200 GeV

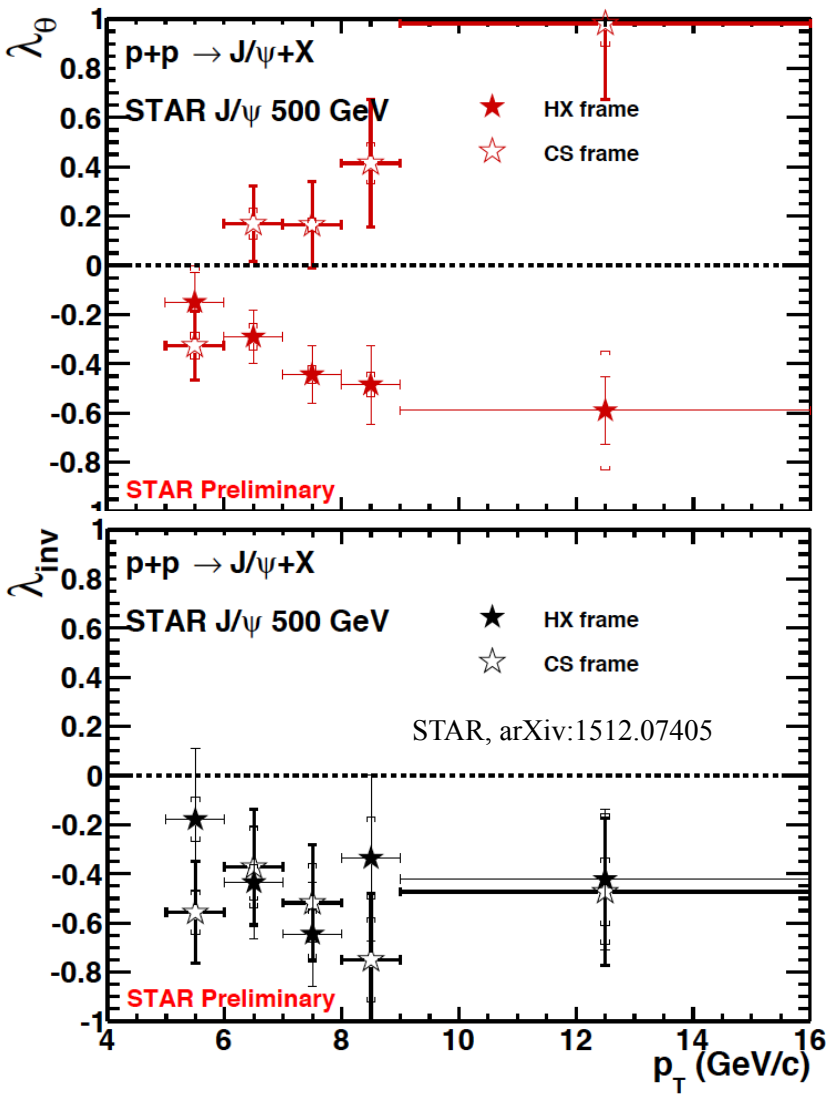


NLO NRQCD:
Phys. Rev. Lett. 108 (2012) 242004, Phys.Rev. D90 (2014) 1, 014002, Phys.Rev.Lett 112 (2014) 18, JHEP 1505 (2015) 103 and private communication

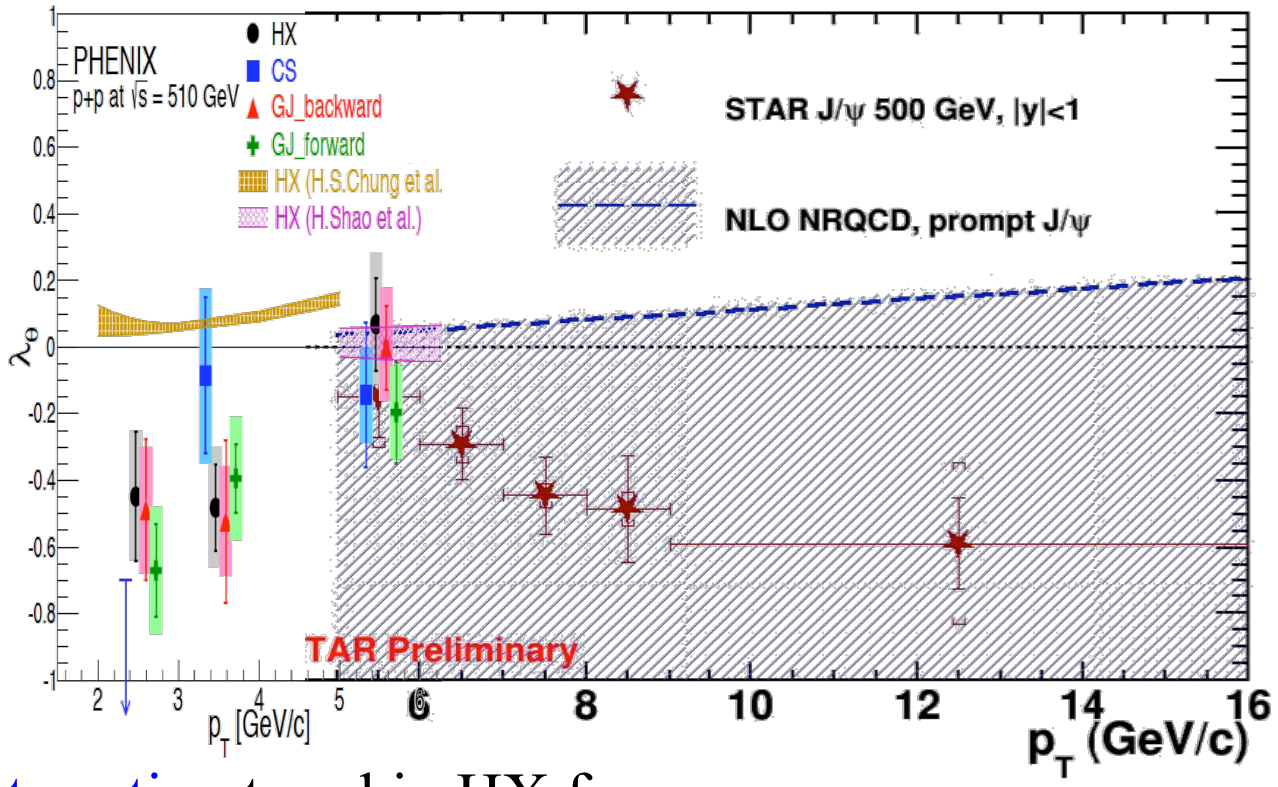
- λ_θ measured in helicity frame
- PHENIX and STAR agrees in overlapping pT range
- Consistent with longitudinal polarization at moderate p_T
- Within large uncertainties, models describe data

Polarization at 500 GeV



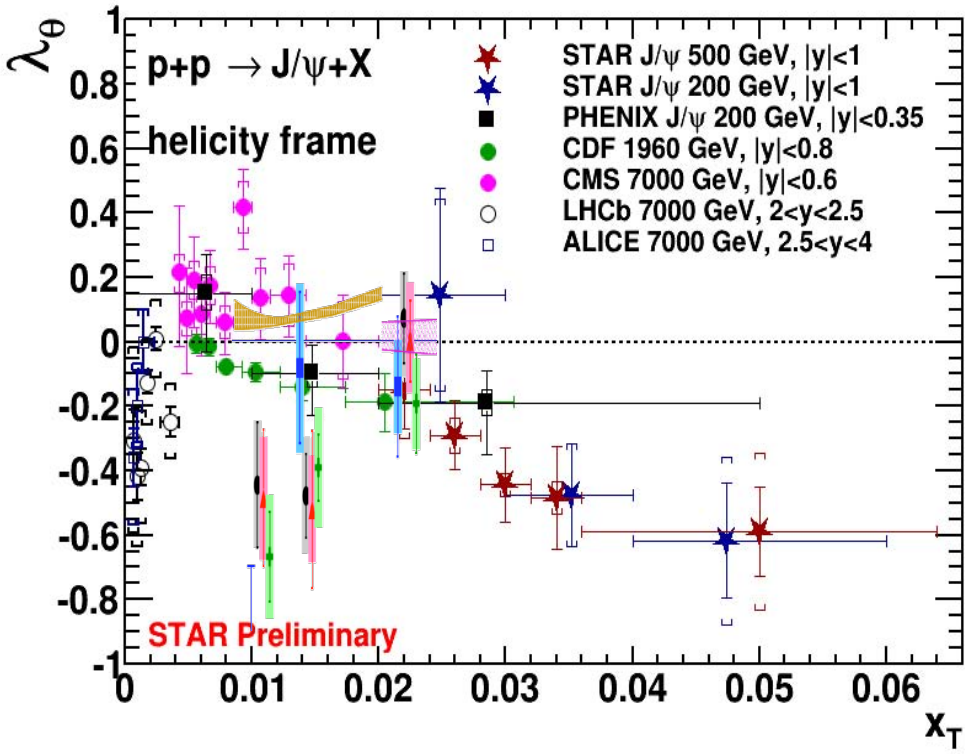


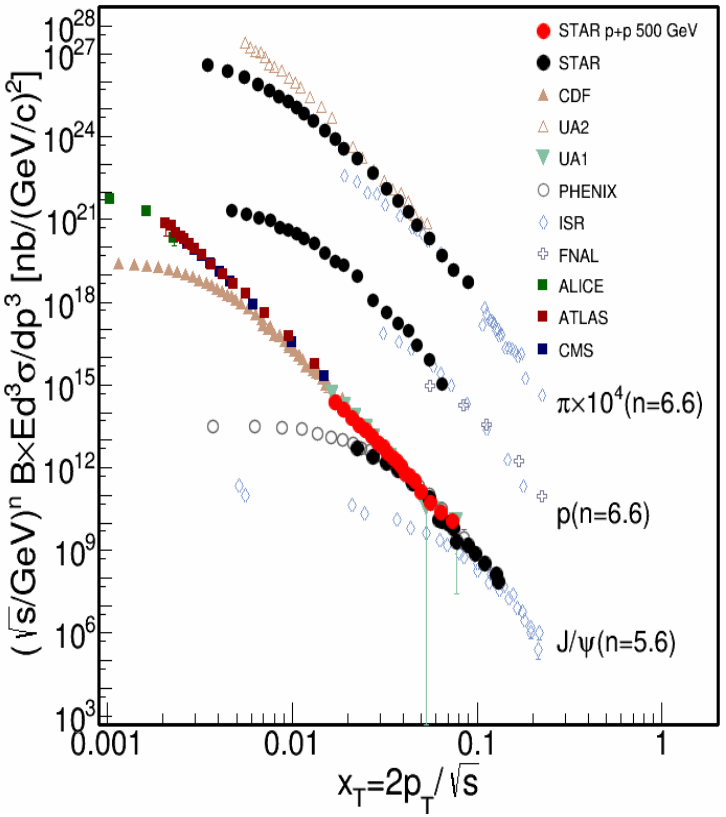
λ_θ vs. p_T in p+p at 500 GeV



- Interesting trend in HX frame
- Systematically longitudinal
- Tension between data and theoretical calculations at low-p_T
- NLO NRQCD uncertainty at high-p_T need be improved

World data comparison

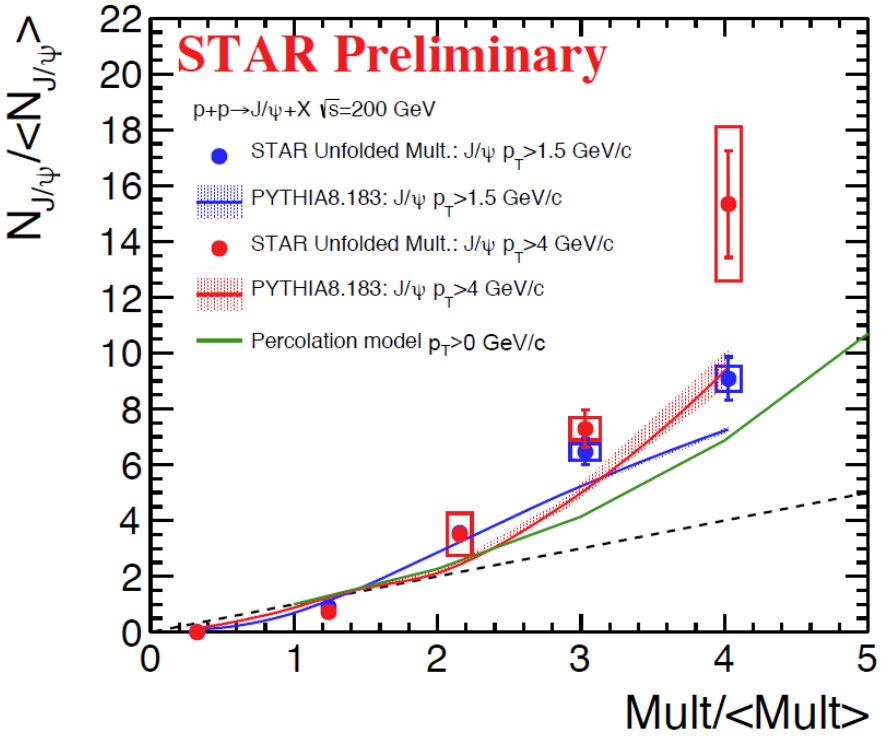




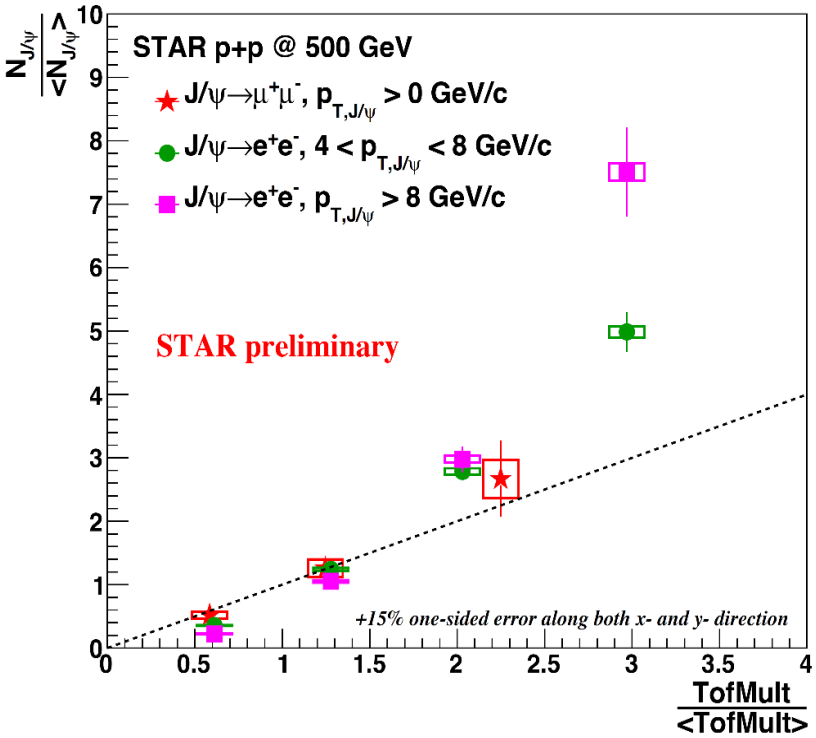
- High-p_T data (approximately) follows x_T scaling
- Similar as spectra
- Low-p_T?

J/ψ production vs. event activity

200 GeV p+p

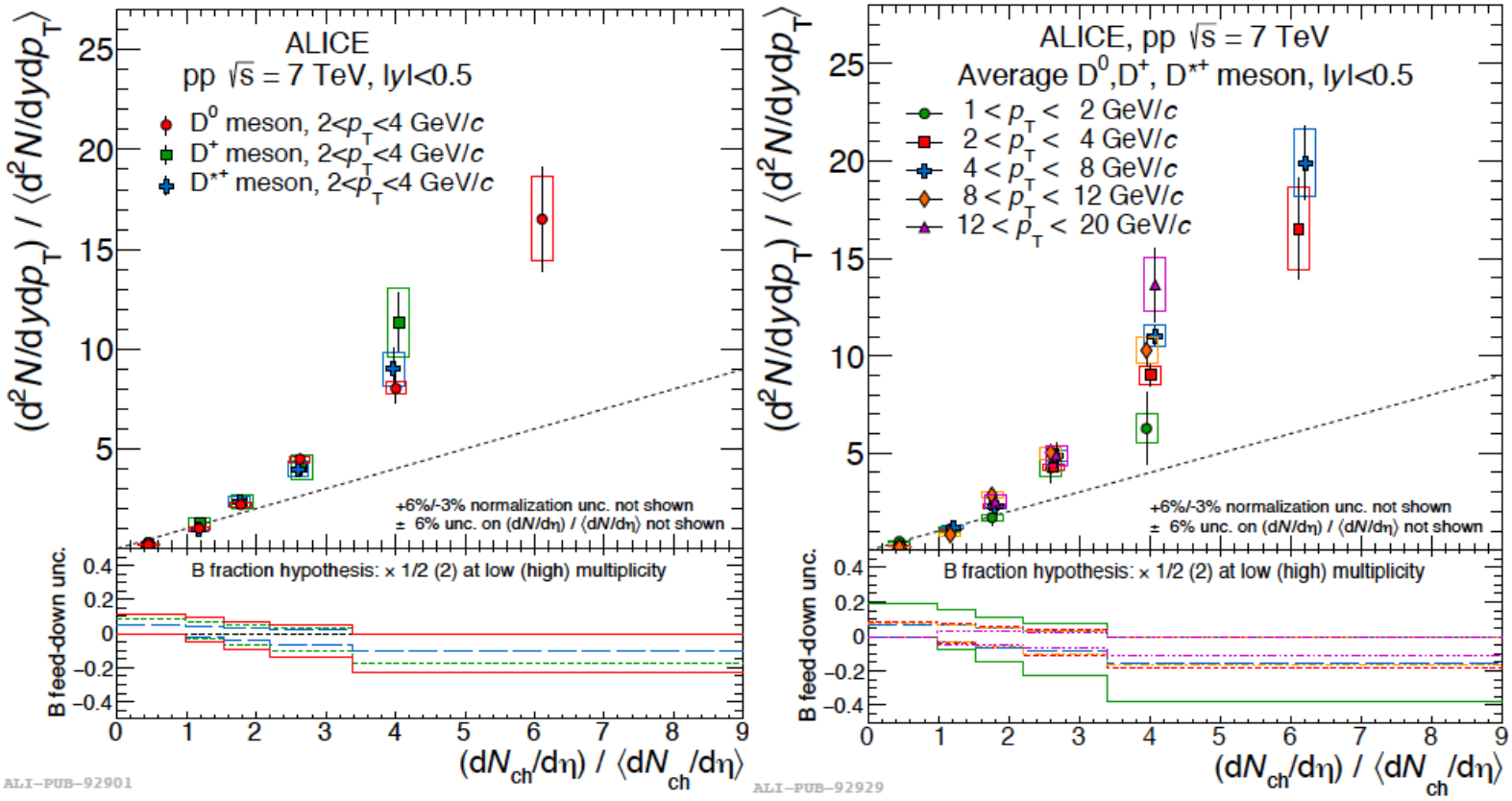


500 GeV p+p



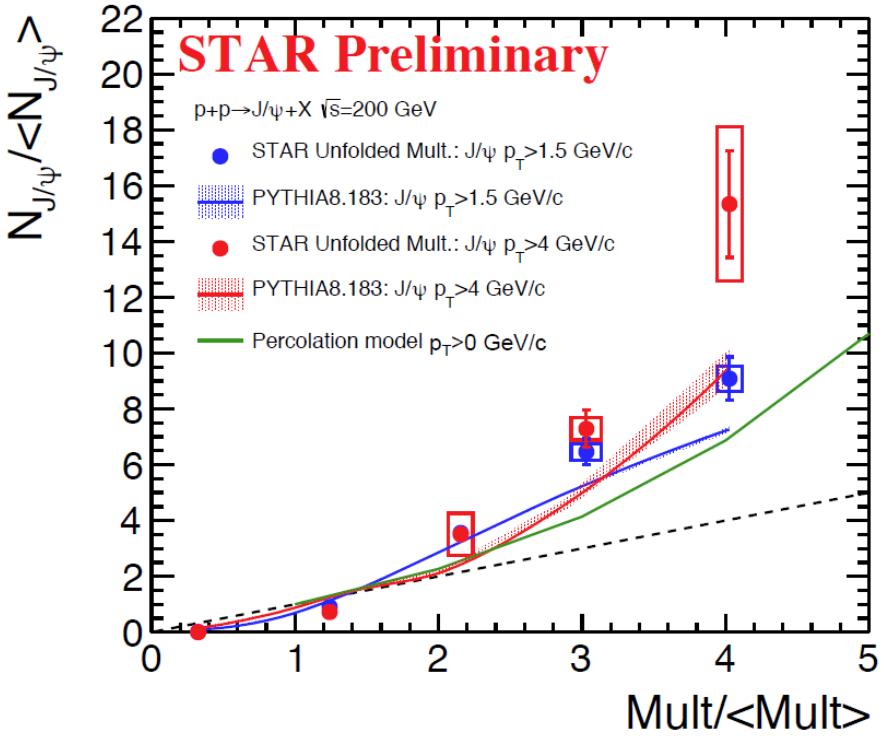
- Stronger-than-linear growth for J/ψ at both energies
- Different trends for low and high-p_T

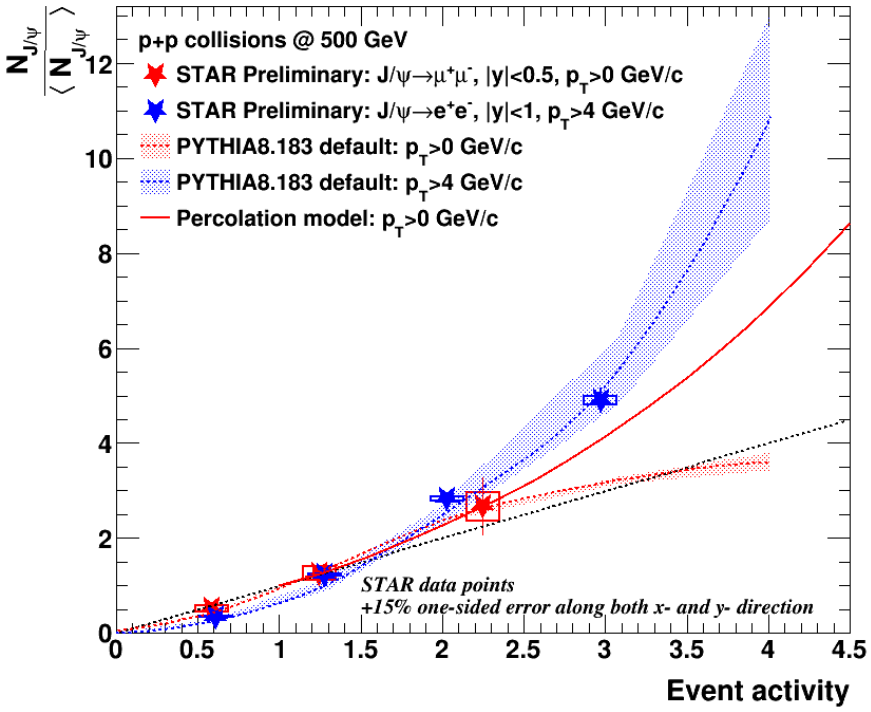
D-mesons production at LHC



”independent of p_T within uncertainties.”

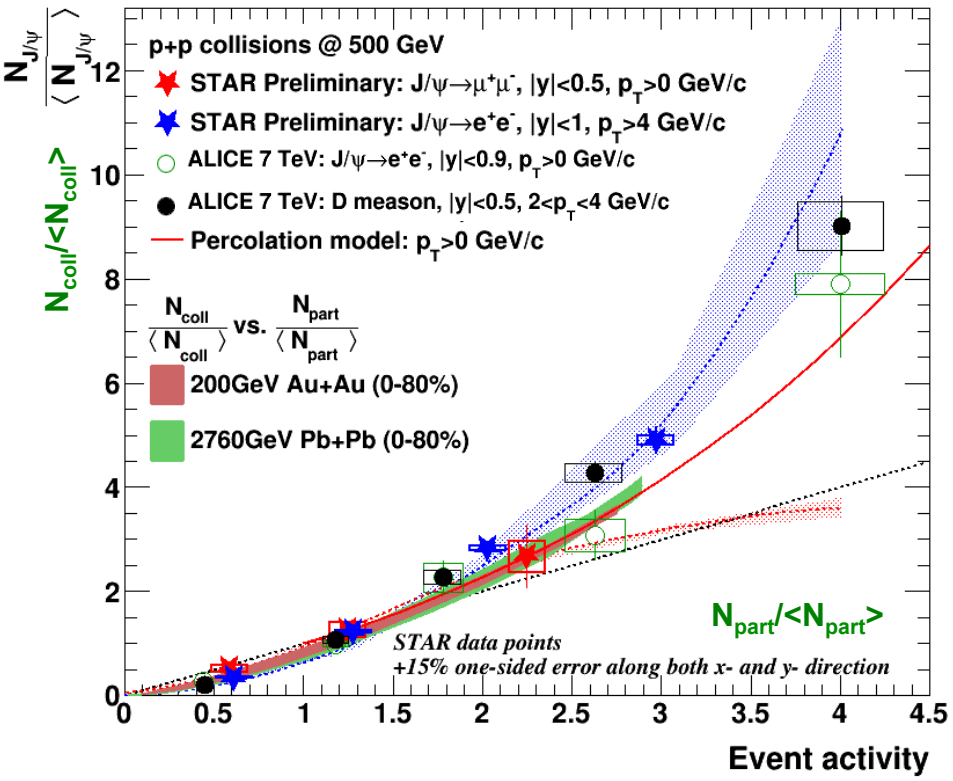
Compared to model





- Both PYTHIA8 and percolation model reproduce trend qualitatively
- Pushing to higher multiplicity bin for 500GeV data

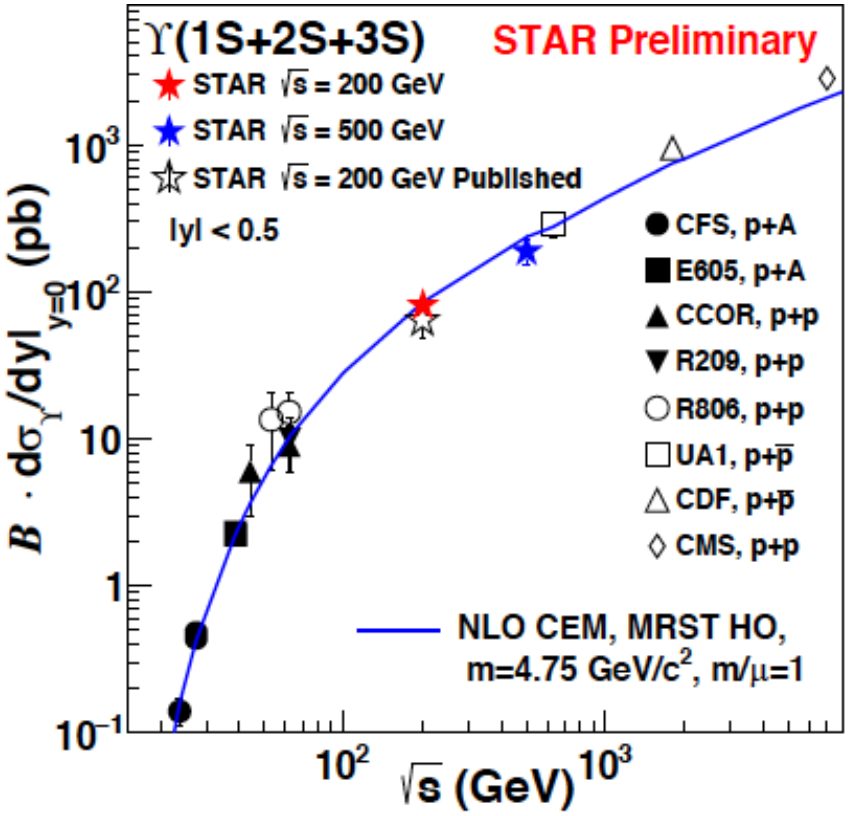
Compare to model

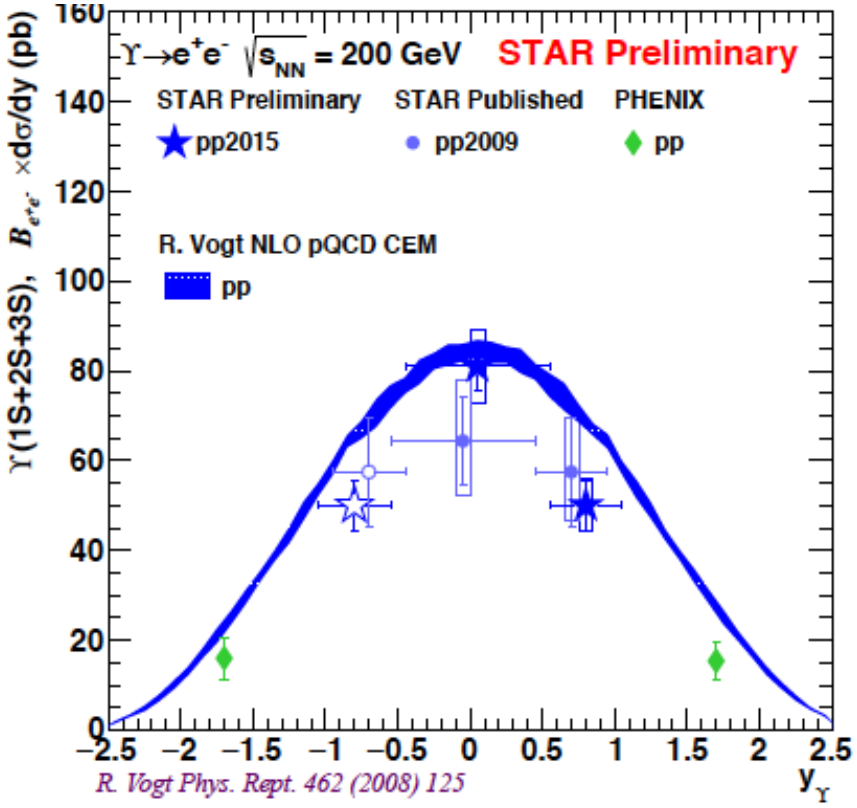


N_{coll} vs. N_{part} in heavy-ion collisions has similar trend

What a coincidence?!

Upsilon in p+p collisions

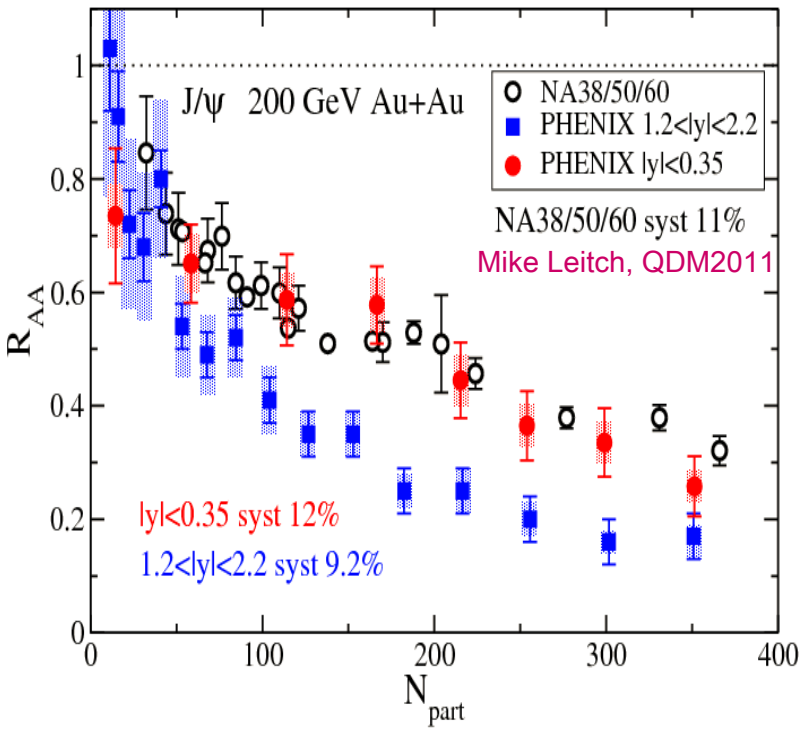


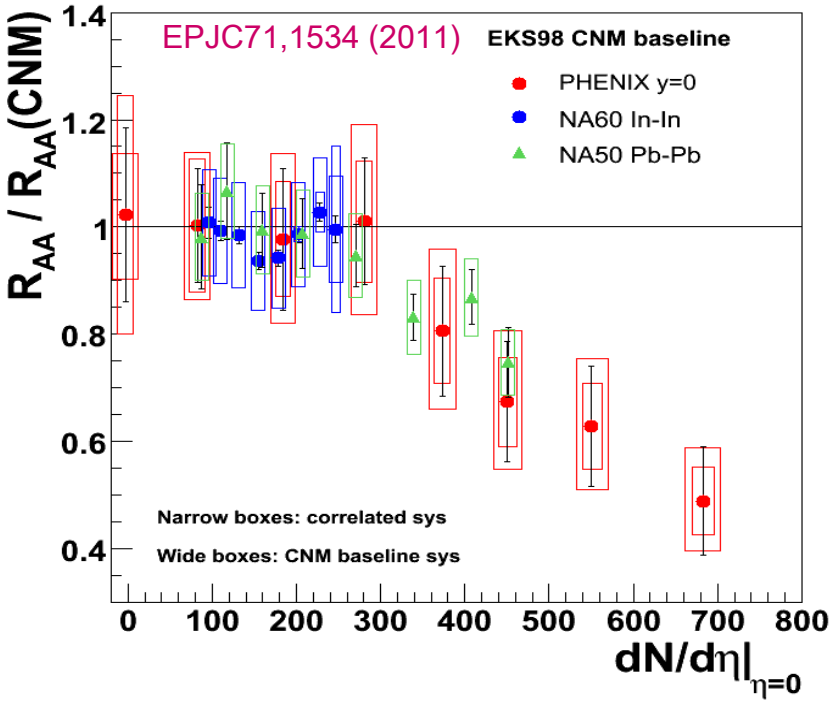


- Upsilon cross-section at 200 and 500 GeV follow world trend
- Rapidity distribution in 200 GeV seems narrower than CEM
- New data provides better baseline for p+A and A+A

J/ψ in A+A

J/ψ suppression at RHIC





Similar anomalous suppression

Mid-rapidity:

Similar suppression as SPS

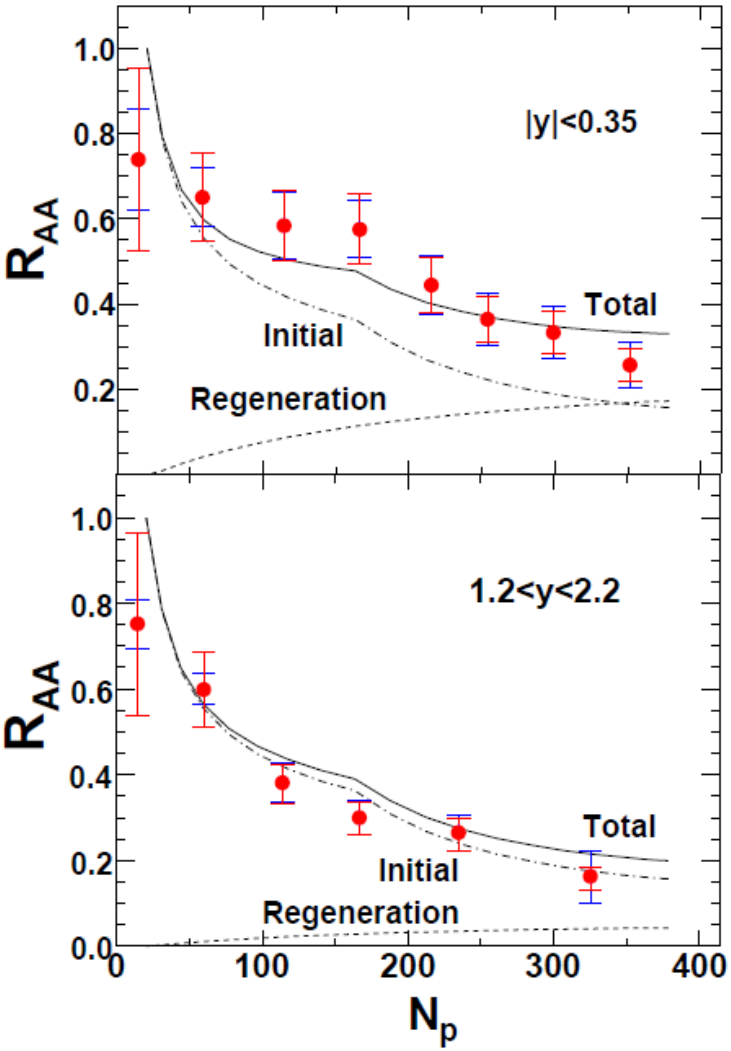
Forward rapidity:

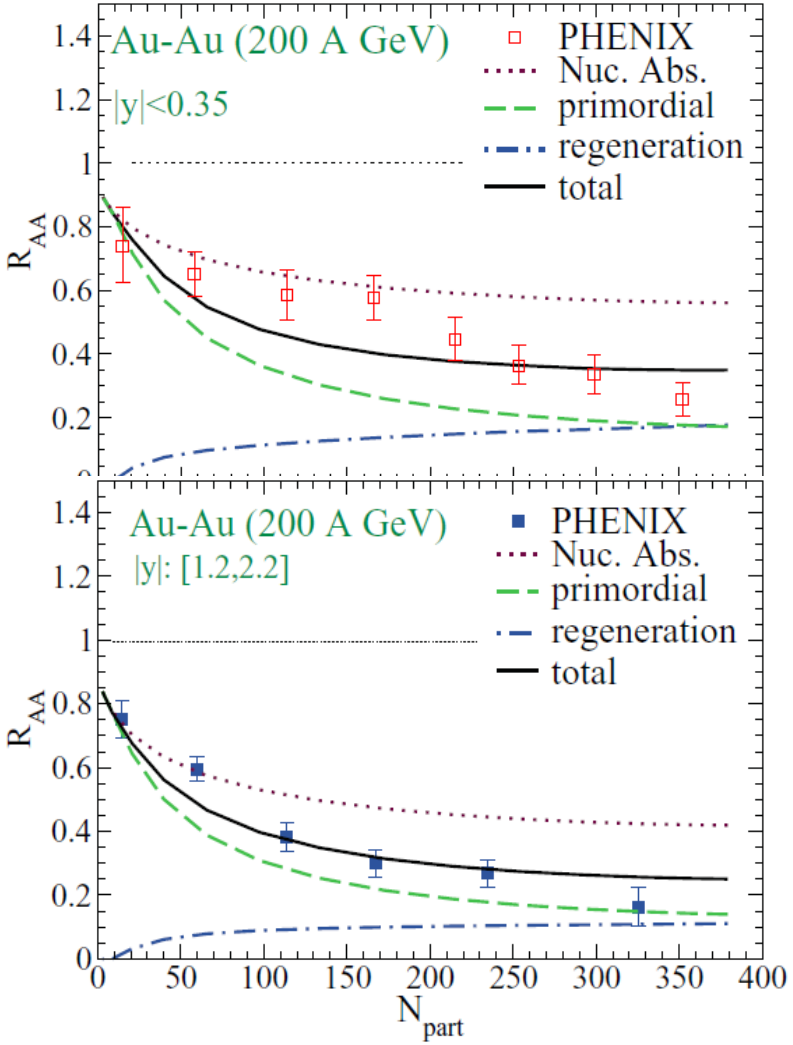
More suppression than in mid-rapidity

Two Puzzles!!

Melting+(Re)combination

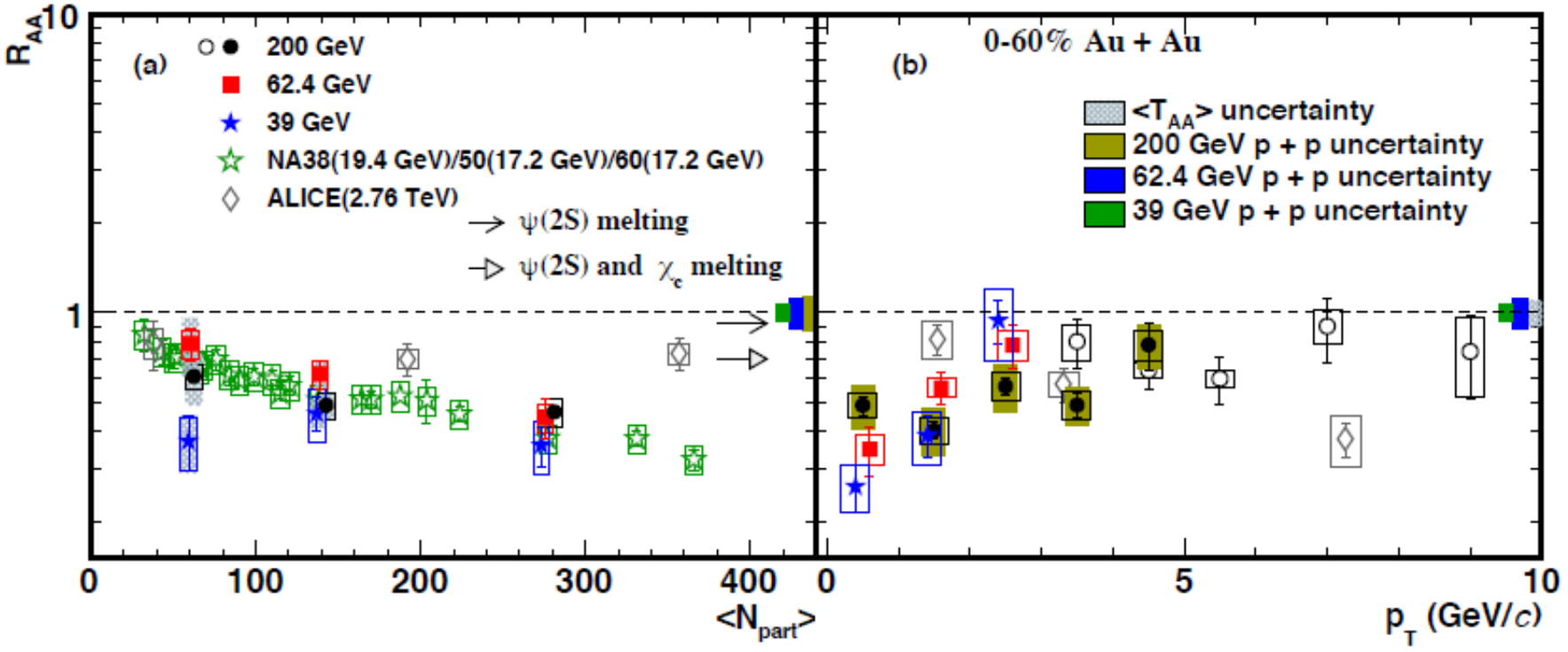
Z. Qu, Y. Liu, N. Xu, P. Zhuang, NPA830, 335c (2009) X. Zhao, R. Rapp, PRC82, 064905 (2010)





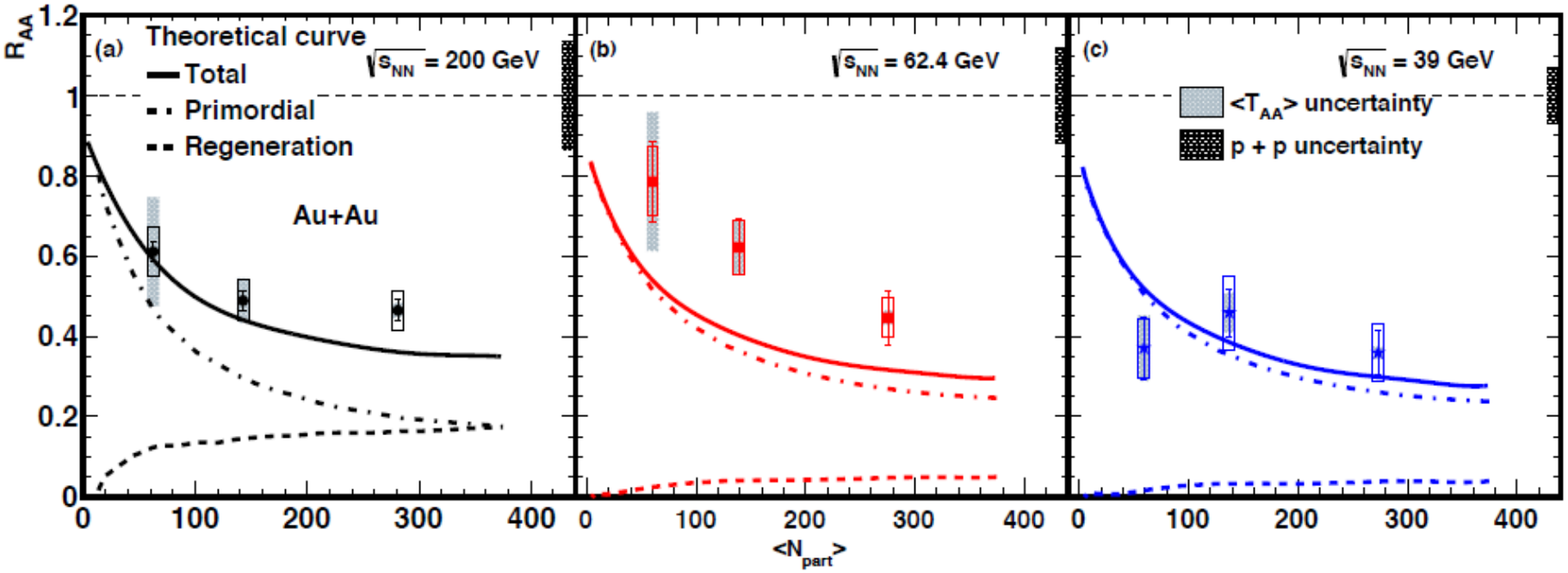
Beam energy scan at RHIC

STAR, PLB771, 13 (2017)



- No significant beam energy dependence at 17-200 GeV

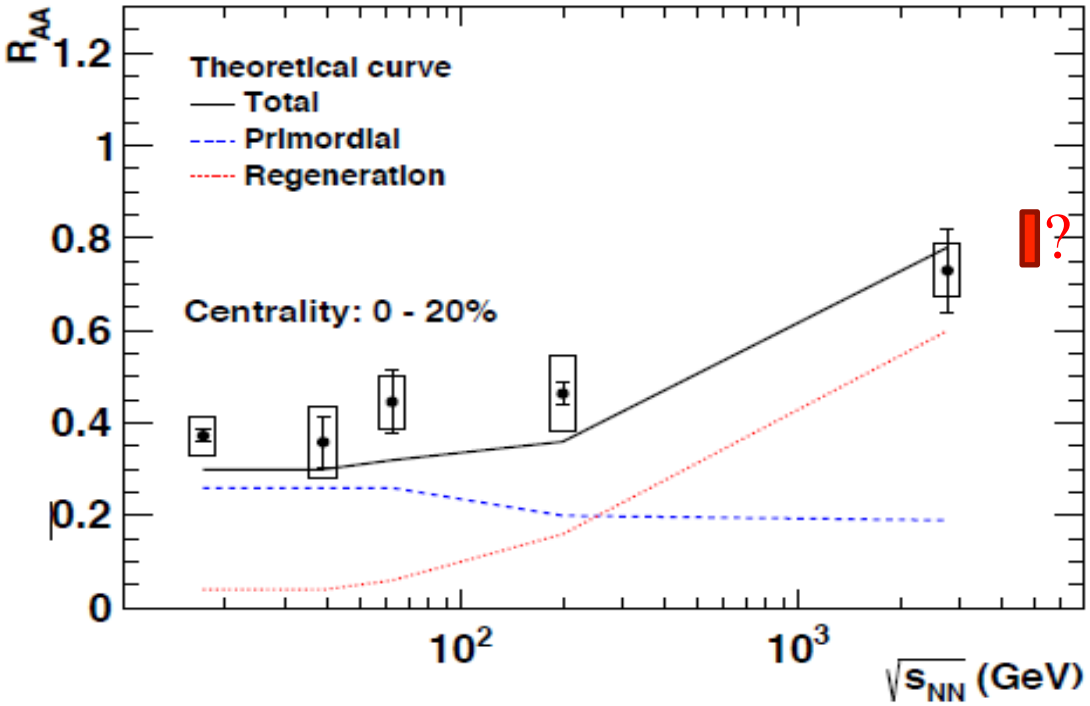
Centrality dependence in 39-200 GeV



- Centrality dependence systematically described by transport model calculations
  - Suppression from melting increases with beam energy
  - (Re)combination contribution increases with beam energy

Beam energy dependence

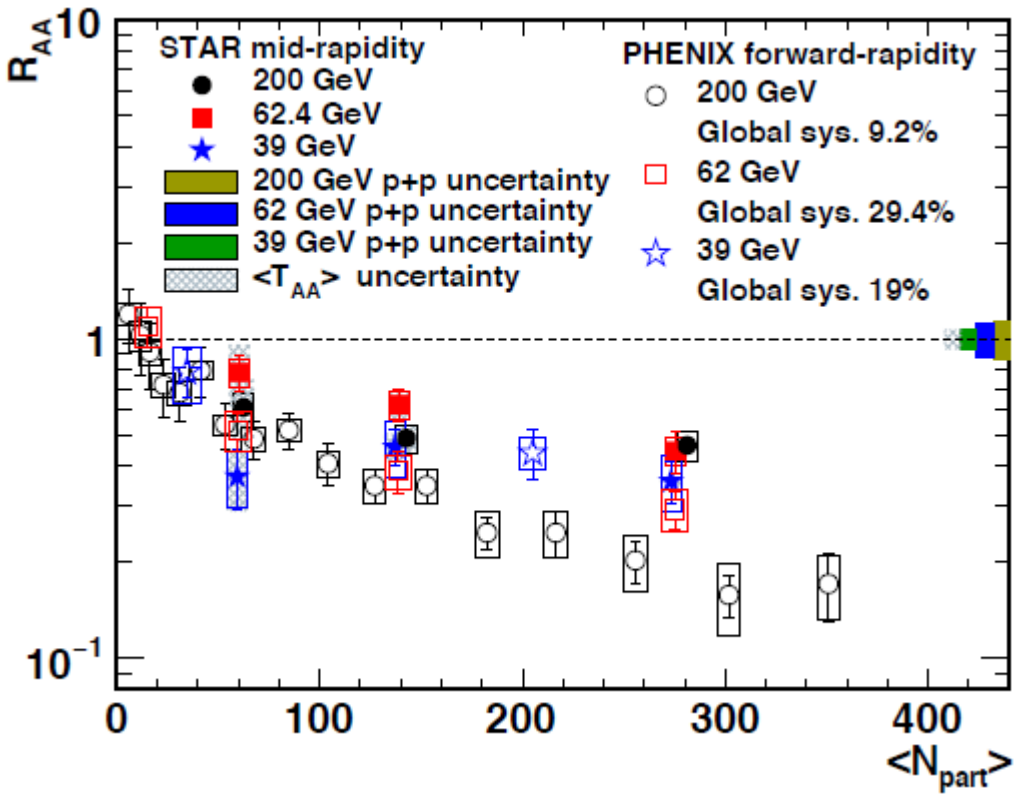
STAR, PLB771, 13 (2017)



- SPS→RHIC: Gradually increase
- RHIC→LHC: Significantly increase
- Consistently described by transport model

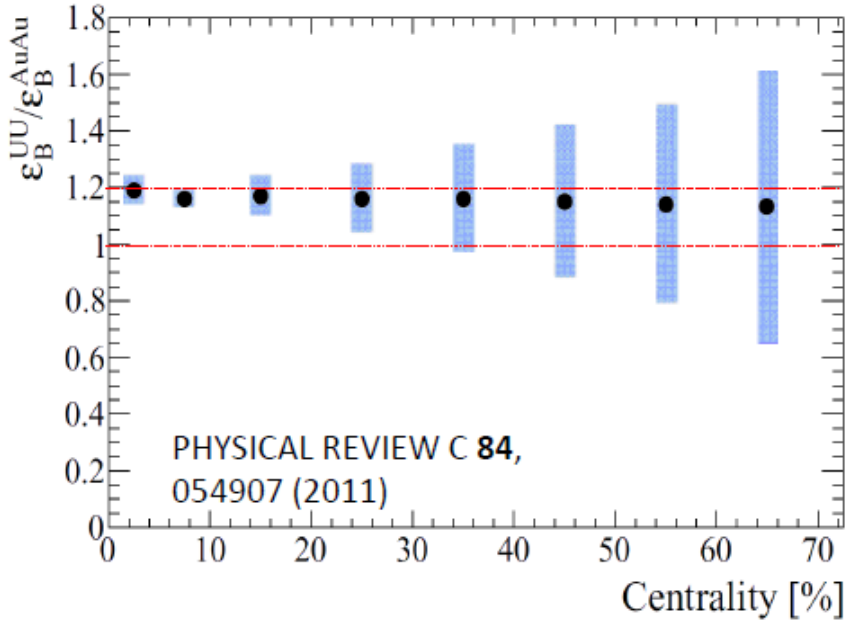
  Interplay of different effects

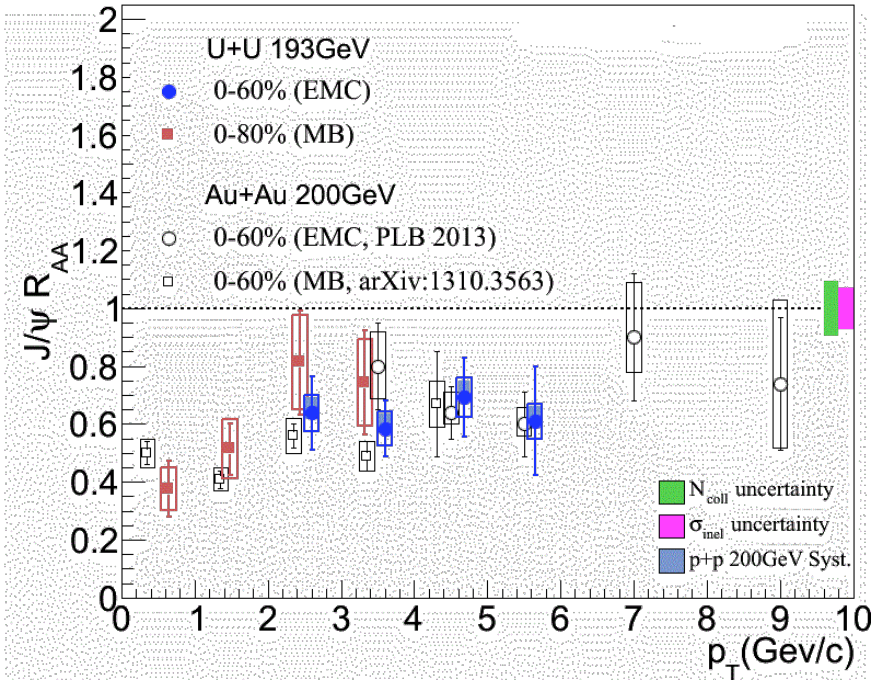
Mid-rapidity vs. forward rapidity



- Difference between forward and mid-rapidity in central collisions decreases with decreasing energy

U+U vs. Au+Au at 200 GeV

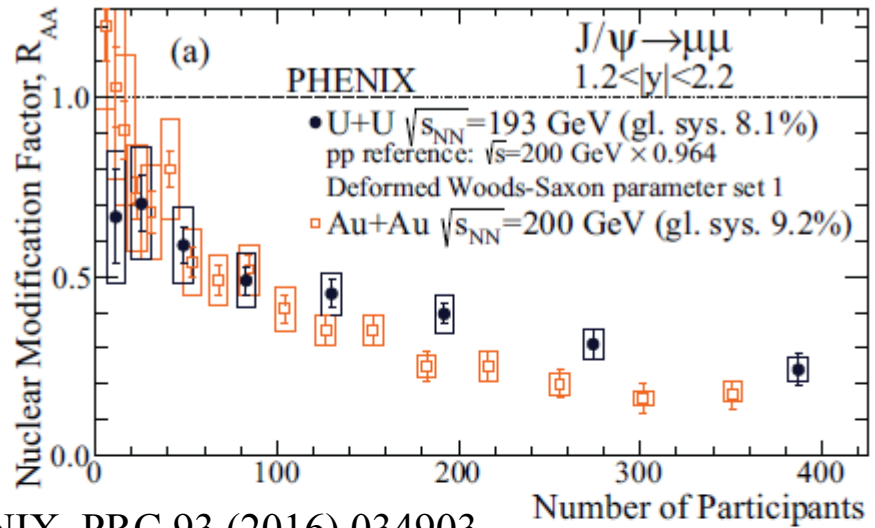




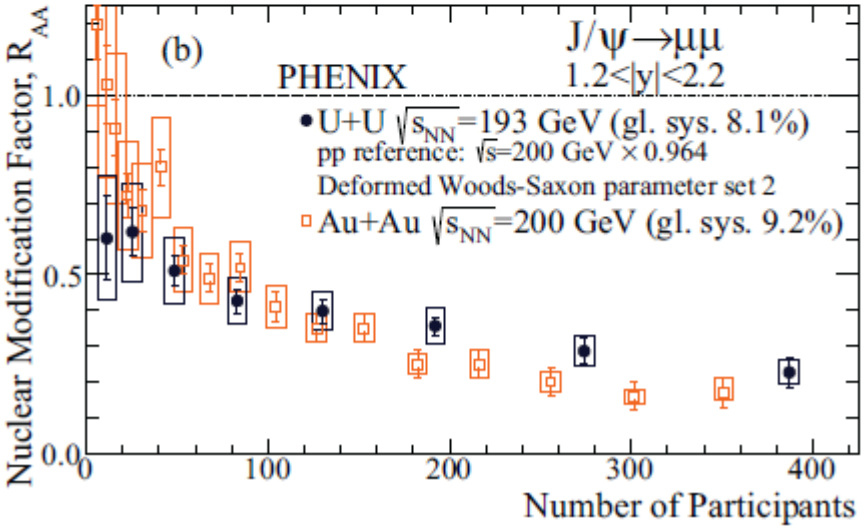
Baseline: J/ψ measurements in p+p 200 GeV.

Similar suppression pattern as in Au+Au 200 GeV at mid-rapidity

System size dependence

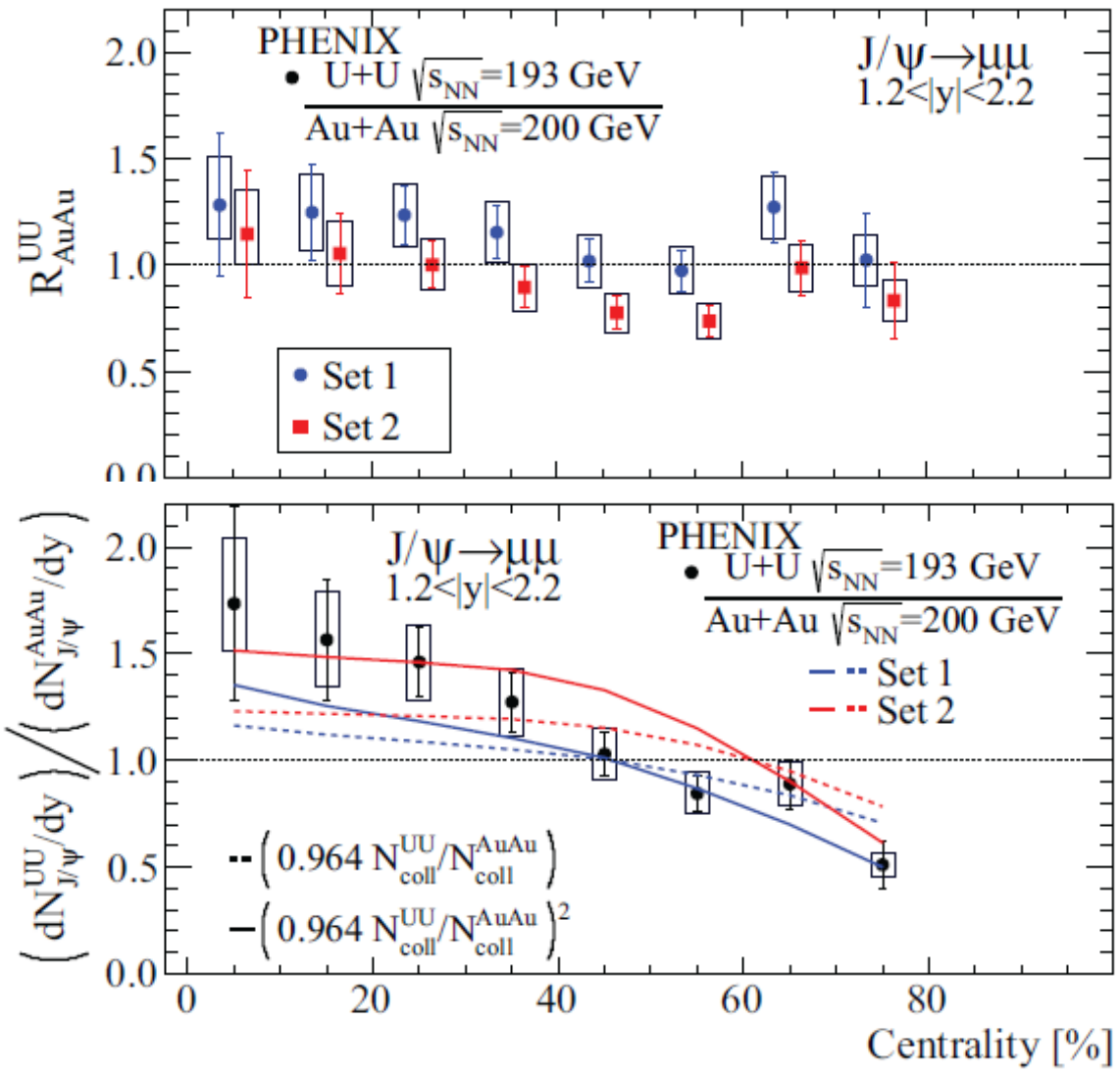


PHENIX, PRC 93 (2016) 034903



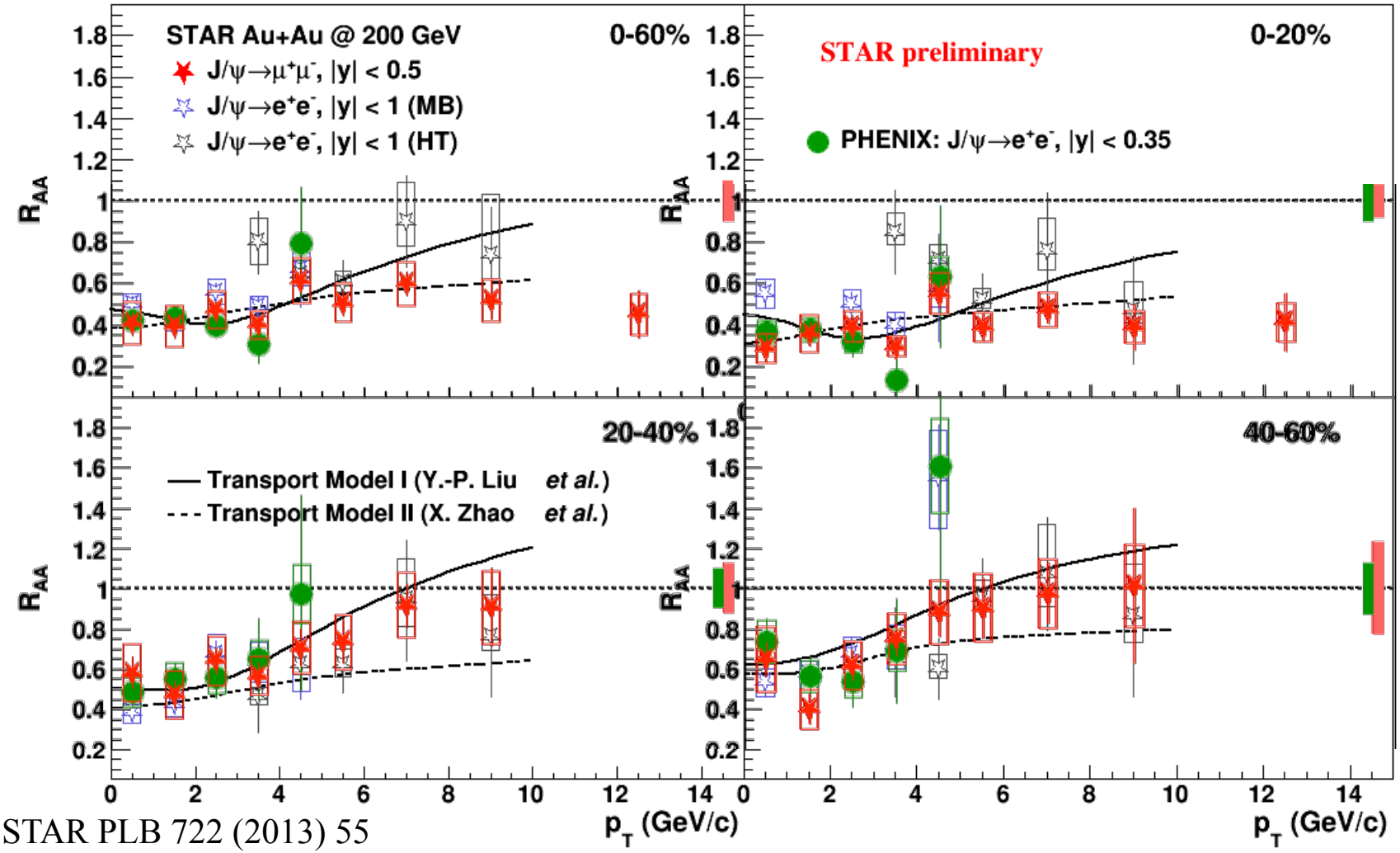
- Similar suppression at forward rapidity
- Even less suppression in U+U in central collisions
- Sign of (re)combination?

Ratio of U+U/Au+Au



- Increasing trend towards central collisions
- Decreasing trend towards peripheral
- Slightly favor N^2_{coll}

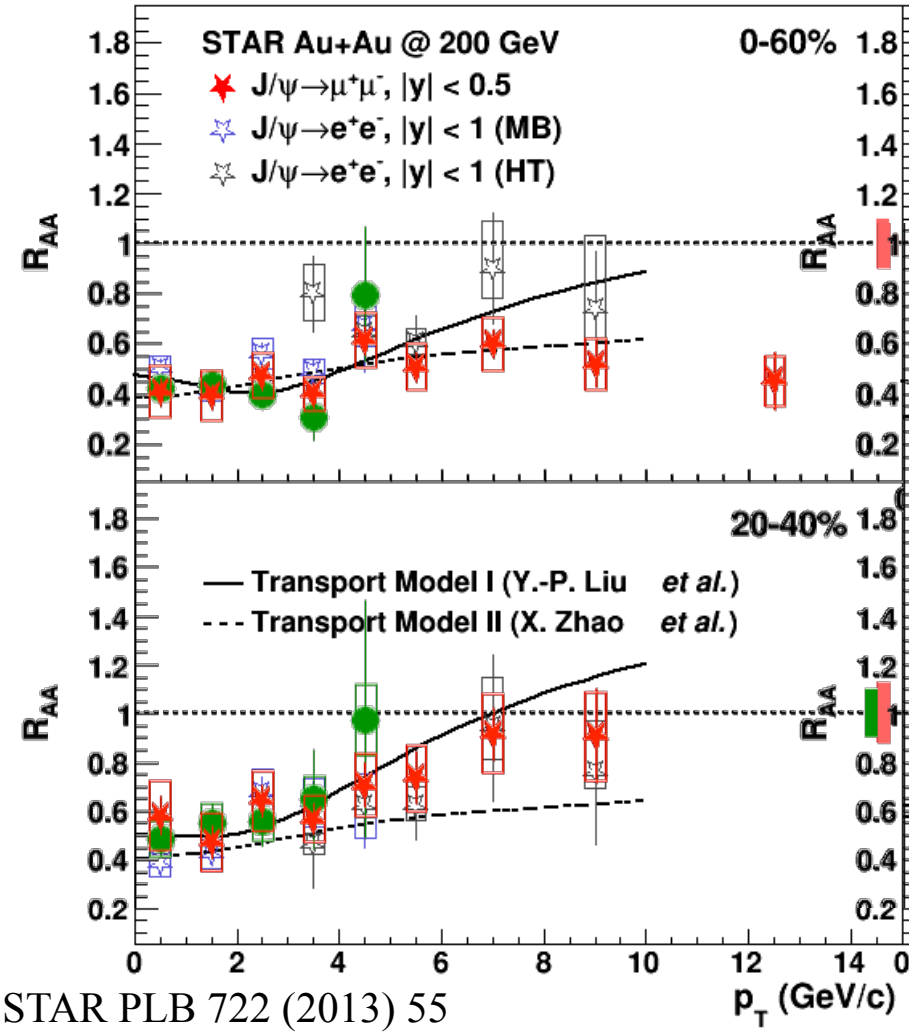
p_T dependence in Au+Au at 200 GeV



STAR PLB 722 (2013) 55
STAR PRC 90 (2014) 024906
PHENIX PRL 98 (2007) 232301

Data consistent with each other

p_T dependence in Au+Au at 200 GeV

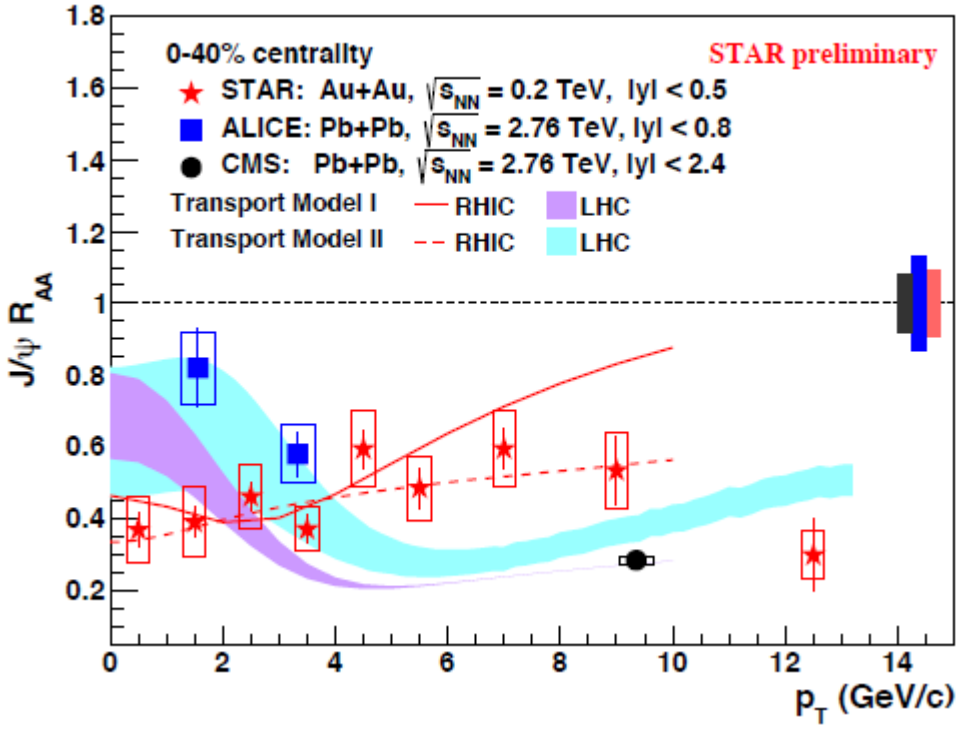


STAR PLB 722 (2013) 55
STAR PRC 90 (2014) 024906
PHENIX PRL 98 (2007) 232301

- Increasing trend from low to high p_T
- Described by transport models
- Although there is tension between models

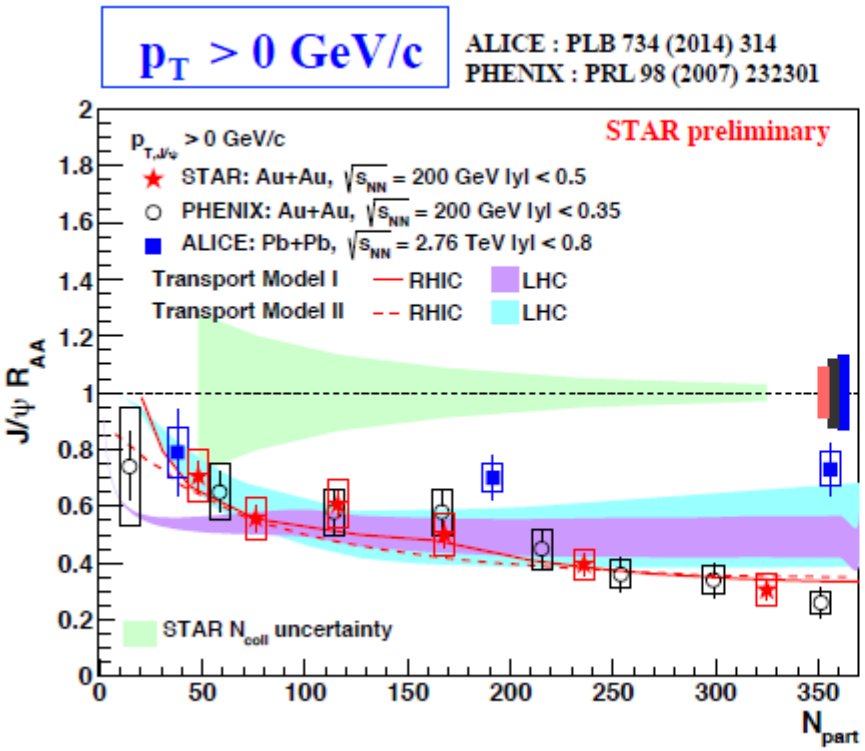
- Low-p_T: CNM + Melting vs. (Re)combination
  High-p_T: Melting dominant
- Significantly suppression at high p_T in central collisions

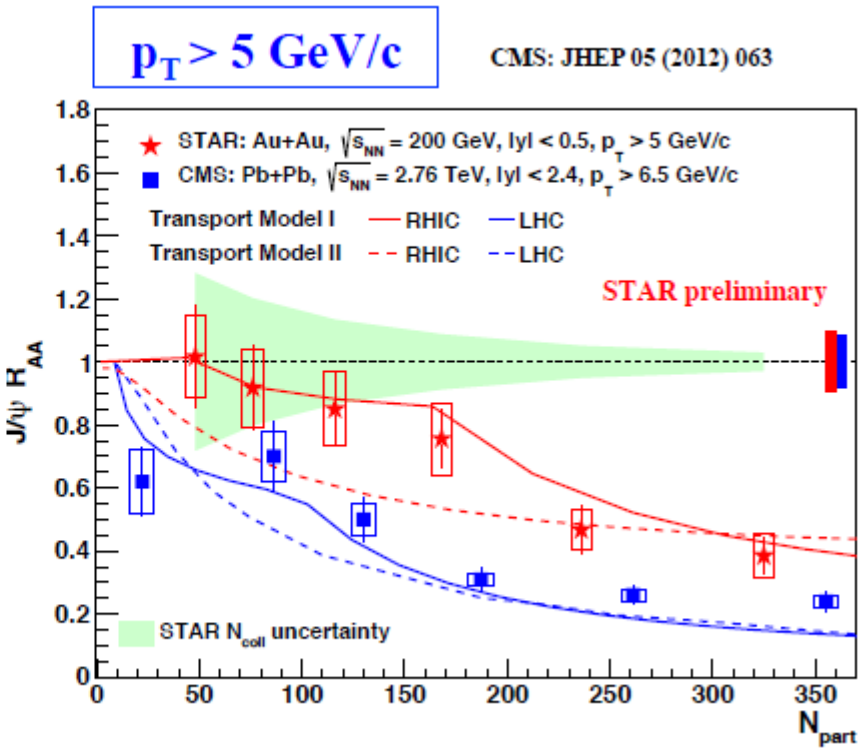
RHIC vs. LHC



- Completely different p_T dependence
  - Less suppression at LHC in low-p_T
  - More suppression at LHC in high-p_T

Centrality dependence





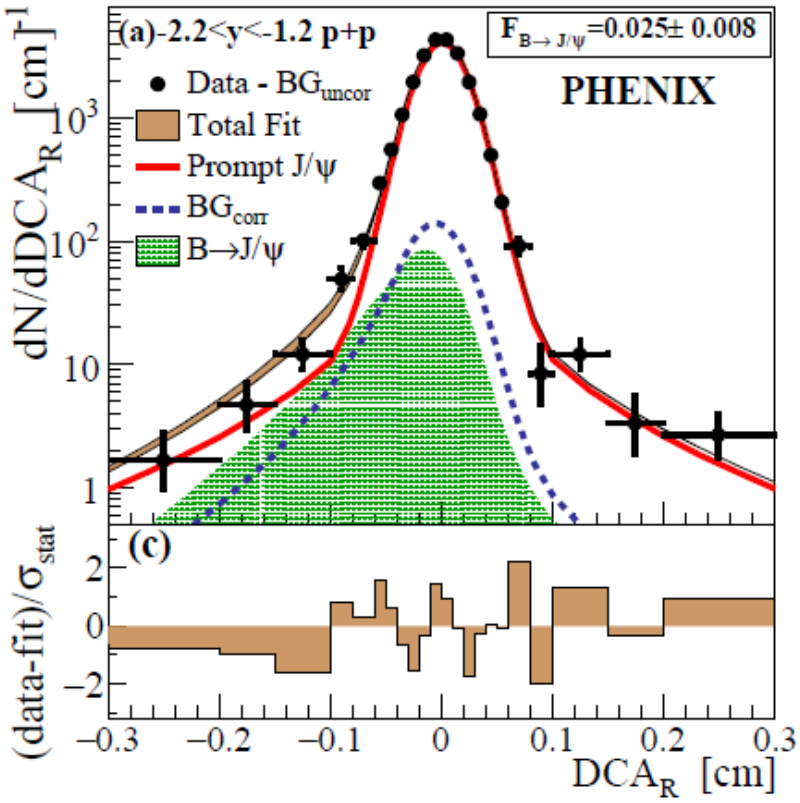
Low-p_T: SPS ~ RHIC < LHC < 1

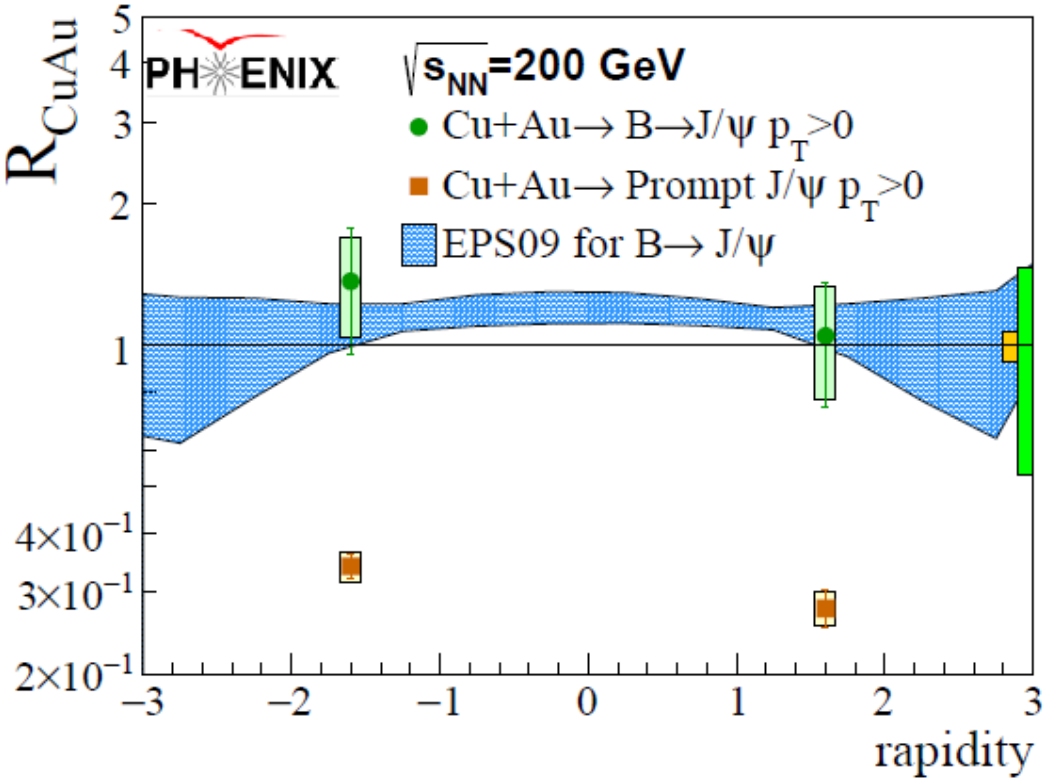
→QGP effect: (Re)combination

High-p_T: RHIC > LHC

→QGP effect: Melting

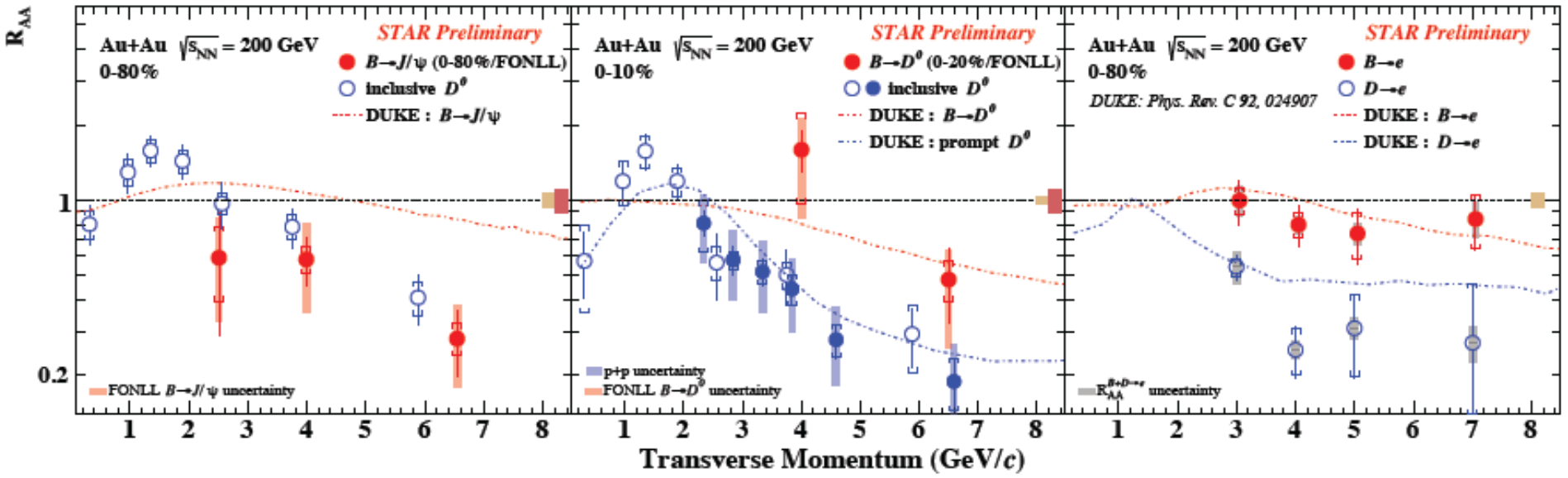
Prompt J/ψ suppression in Cu+Au





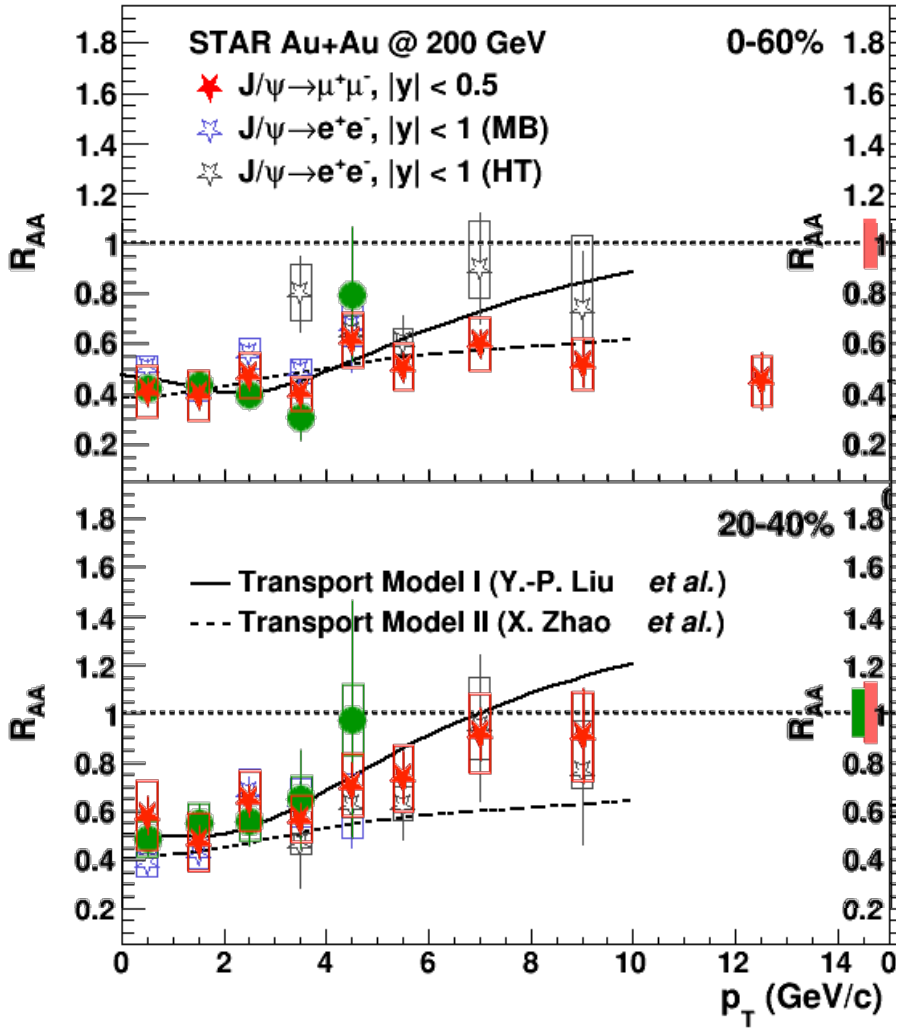
- Significant suppression of low-p_T prompt J/ψ in Cu+Au
- B→J/ψ consistent with no suppression and EPS09 shadowing

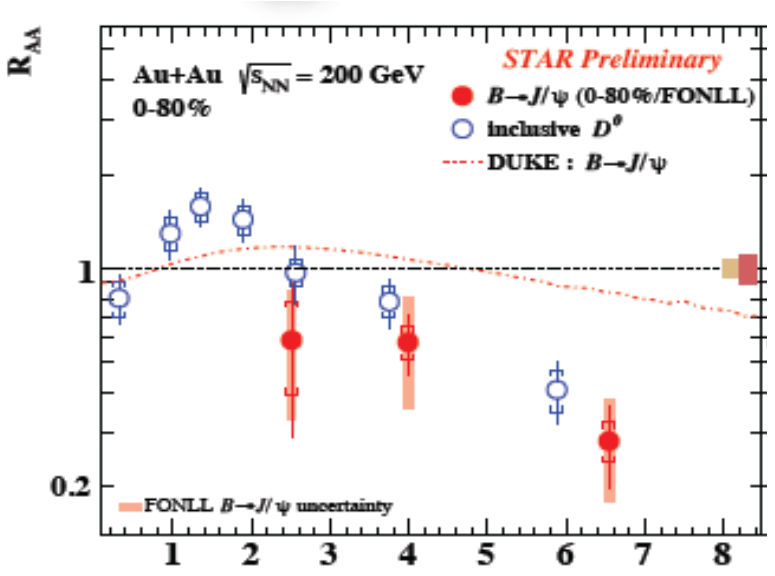
B suppression in Au+Au at 200 GeV



- Strong suppression of B→J/ψ and B→D^0

Inclusive vs. Non-prompt





p_T>2 GeV/c:

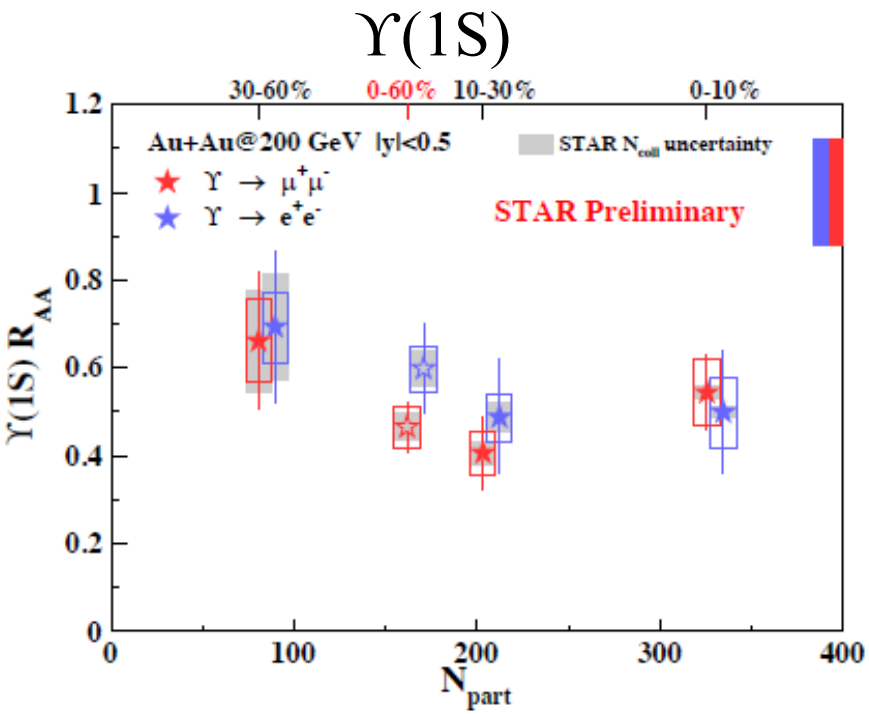
Inclusive ~ Non-prompt

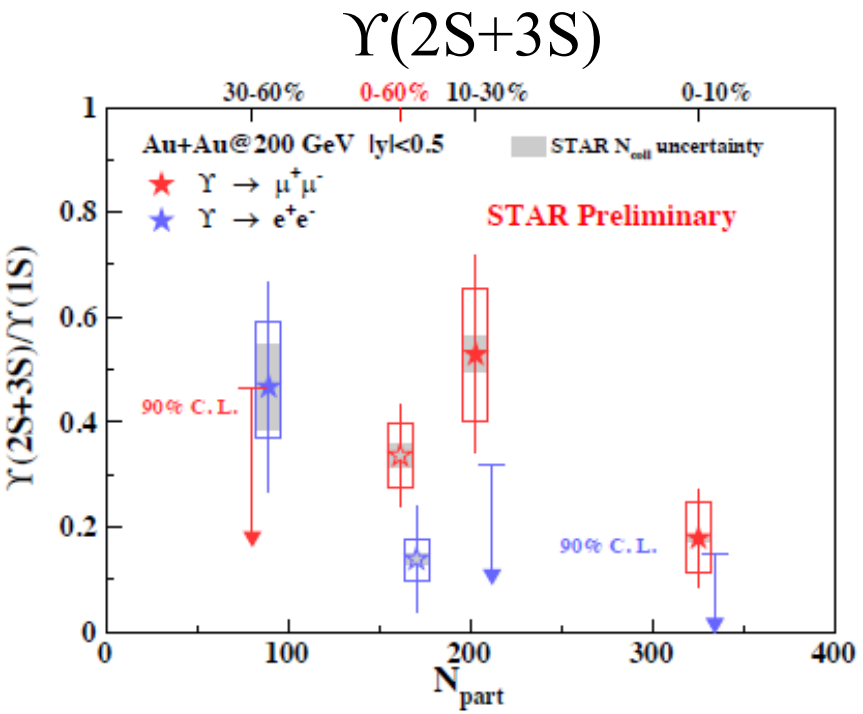
Suppression of prompt J/ψ from intermediate to high p_T

Υ Results

Upsilon in Au+Au at 200 GeV

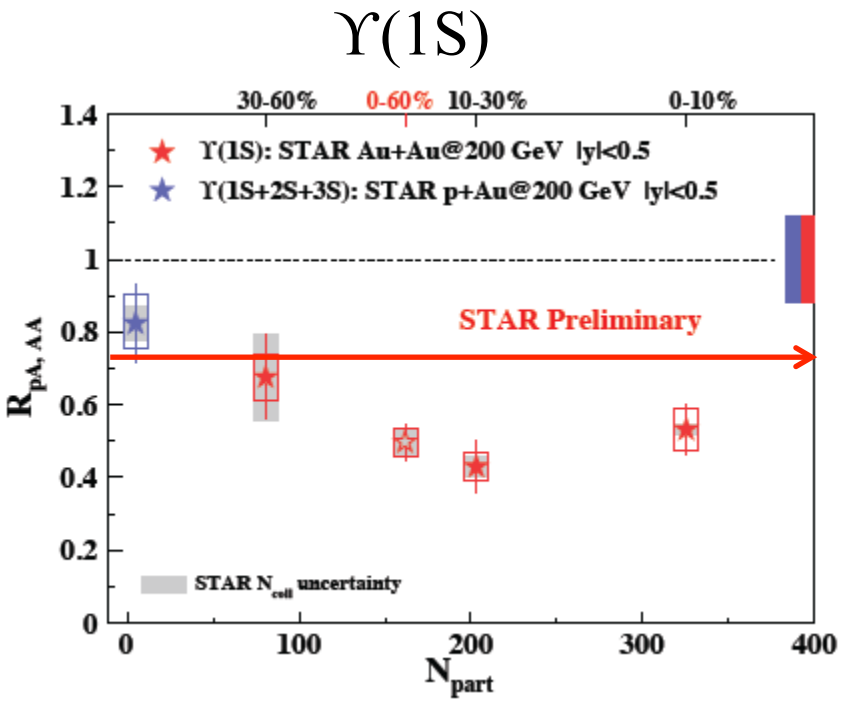
Upsilon: cleaner probe

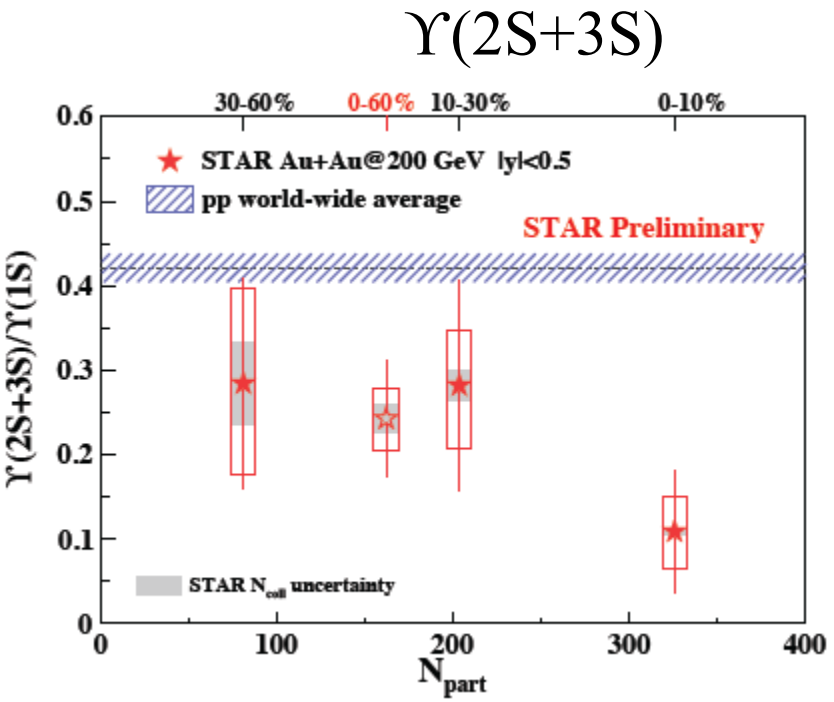




- Di-muon channel: 2014 data
- Di-electron channel: 2011 data
- Consistent with each other

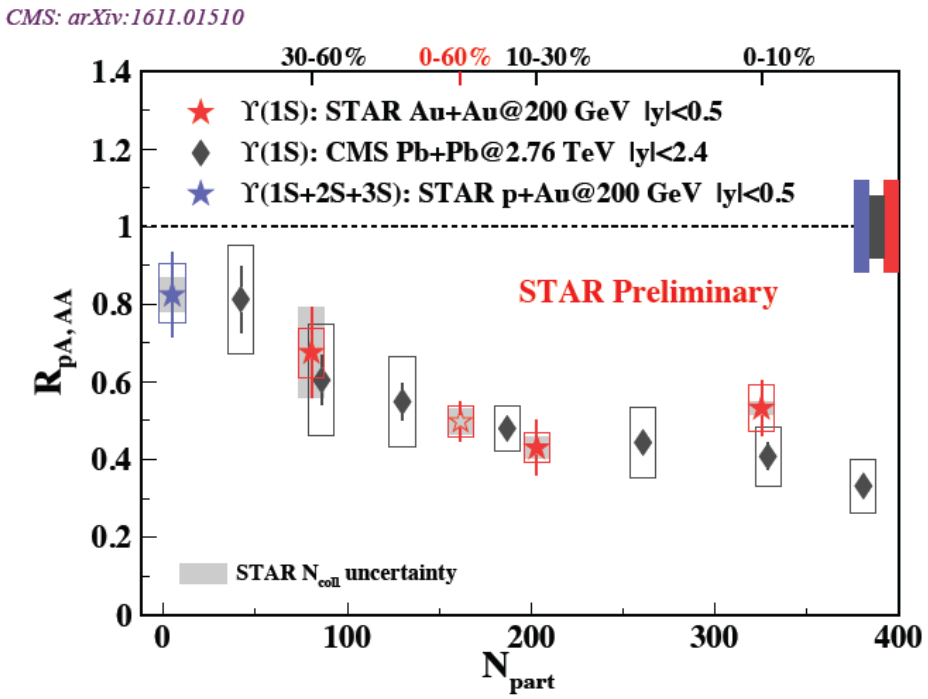
Combined results

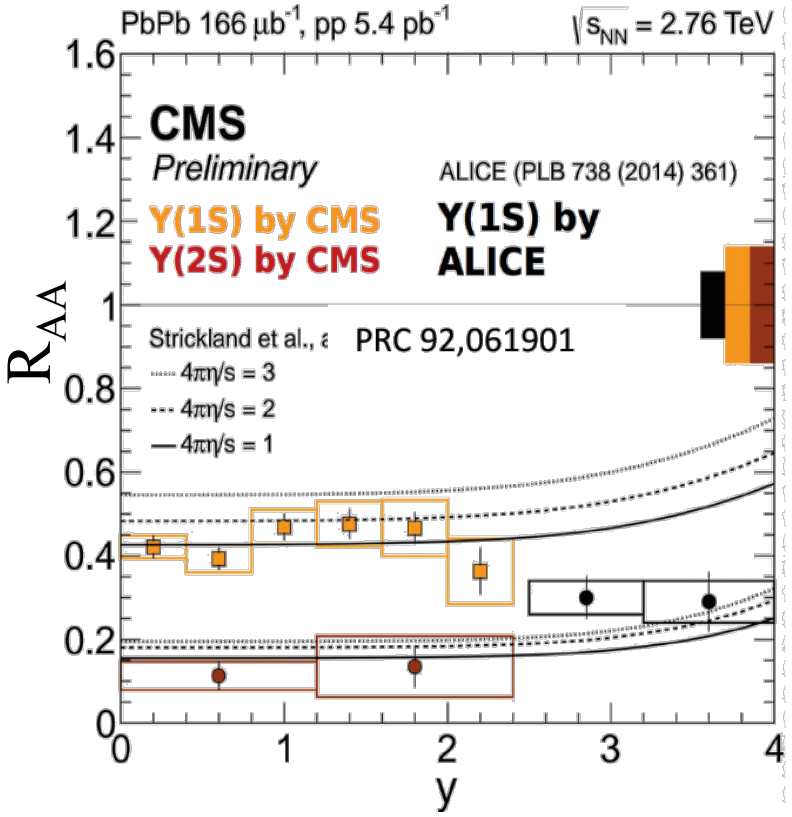




- Υ(1S) :
  - More suppression towards central collisions
  - Direct Υ(1S) could be suppressed in (semi-)central collisions
- Υ(2S+3S) : more suppressed than Υ(1S) →Sequential suppression

RHIC vs. LHC

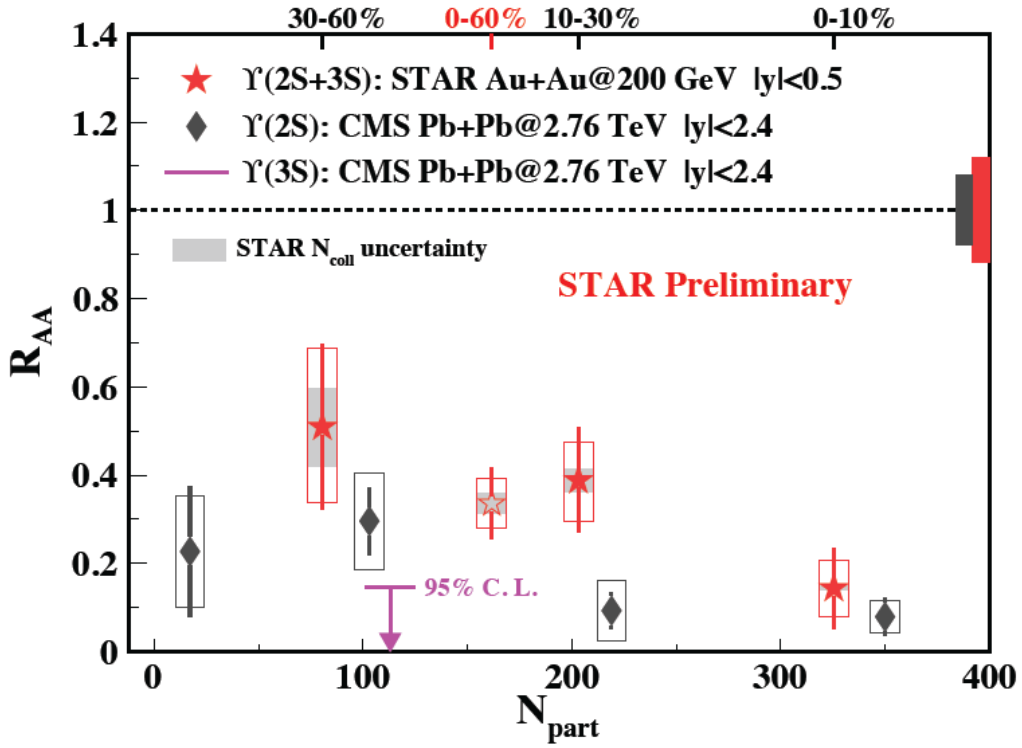




- Similar at RHIC and LHC
- Stronger suppression at forward rapidity at LHC
- Similar situation as J/ψ from SPS to RHIC

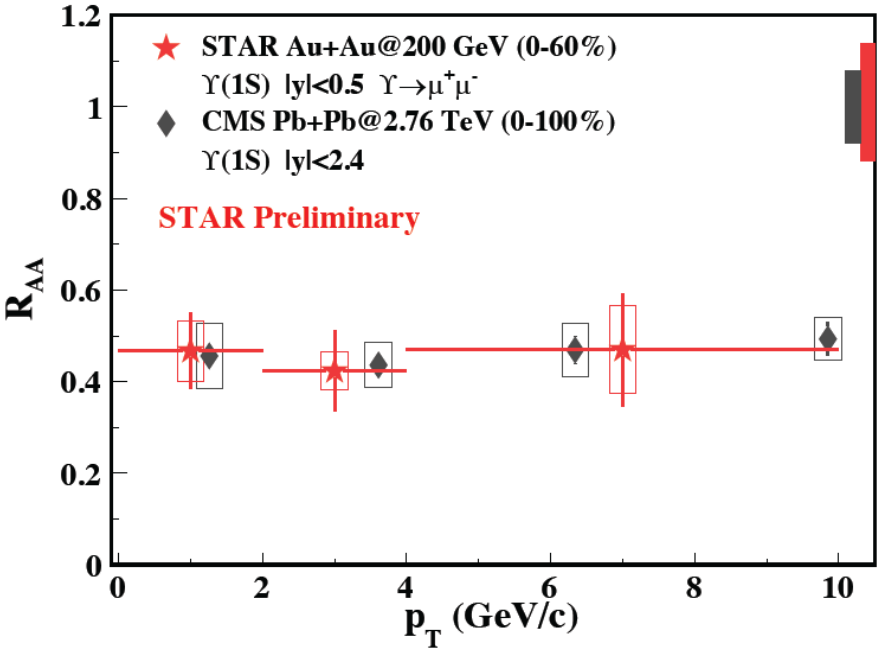
RHIC vs. LHC

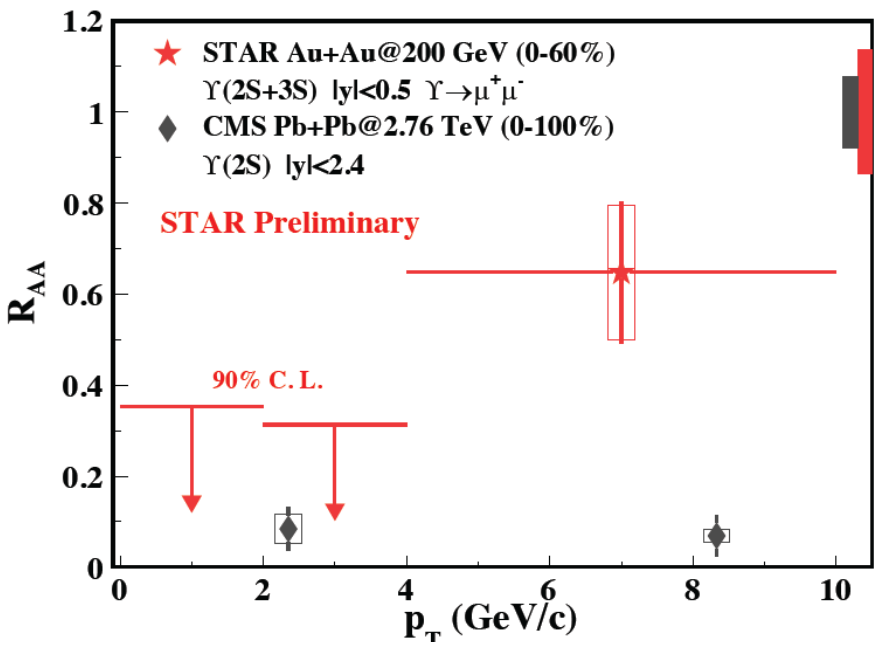
CMS: arXiv:1611.01510



- Significantly suppressed at both RHIC and LHC
- Hints of less suppression at RHIC than at LHC

p_T dependence





Υ(1S):

- No obvious dependence
- Similar to LHC

Υ(2S+3S):

- Hint of increasing trend
- Less suppression at high-p_T

Summary (p+p)

- J/ψ p_T spectrum at 200 and 500 GeV can be described by
  - CGC+NRQCD at low p_T and NLO NRQCD at high-p_T
  - ICEM at low p_T, leaves room for B feed-down

- J/ψ polarization consistent with longitudinal polarization
  - Tension between data and NRQCD at low-p_T at 500 GeV

- J/y self-normalized yield exhibits stronger-than-linear increase
  - Trend depends on p_T at RHIC, no p_T dependence at LHC?
- Upsilon:
  - Total cross-section consistent with world data and CEM
  - Rapidity distribution seems narrower than CEM

Summary (A+A)

- J/ψ has been studied extensively at RHIC
  - p_T, centrality, rapidity, collision energy and system size dependence can be systematically *described* by transport models including both melting and (re)combination effects

- Upsilon:
  - Direct ϒ(1S) may be suppressed at RHIC
  - Excited states suppressed more, sequential melting
  - ϒ(1S) energy and rapidity dependence issue?

- STAR has 2x Au+Au data on tape; Ru+Ru and Zr+Zr next year
- New ideas? New observables?