Recent PHENIX Results on Production and Hadronization of Heavy Quarks in p+p and p+Au Collisions at RHIC

33rd INTERNATIONAL WORKSHOP ON **DEEP INELASTIC SCATTERING AND RELATED SUBJECTS**

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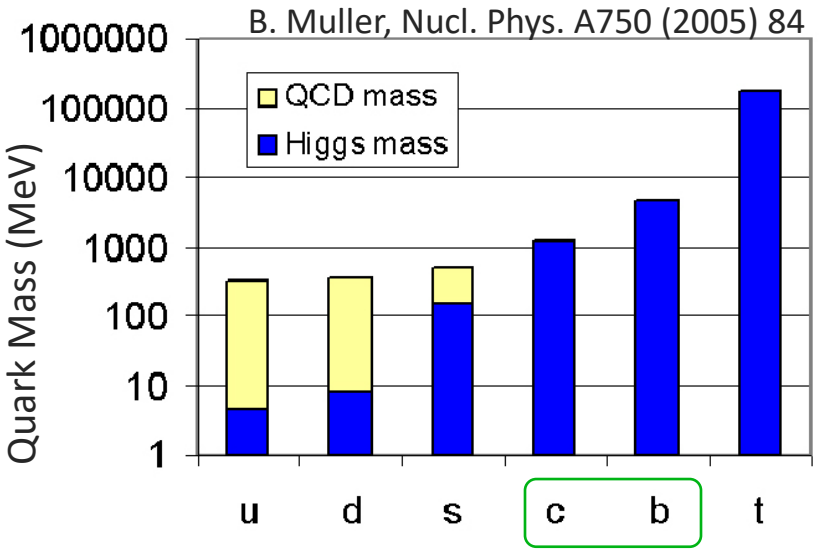
Flavor: Ideal Probe of QCD Matter

Theoretical motivation

- Symmetry breaking
  - **Higgs mass:** electroweak symmetry breaking
    → **current quark mass**
  - **QCD mass:** chiral symmetry breaking
    → **constituent quark mass**
- Charm and beauty quark masses are not affected by QCD vacuum
  → **ideal probes to study QGP**



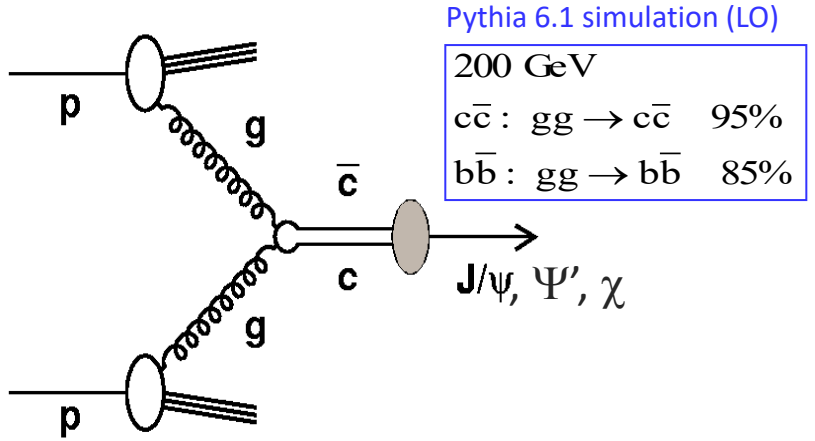
- Heavy quarks ($c\bar{c}$, $b\bar{b}$)
  - Bound states (J/ψ, Υ)

State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
Mass (GeV)	3.10	3.53	3.68	9.46	9.99	10.02	10.36	10.36
ΔE (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
Radius (fm)	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

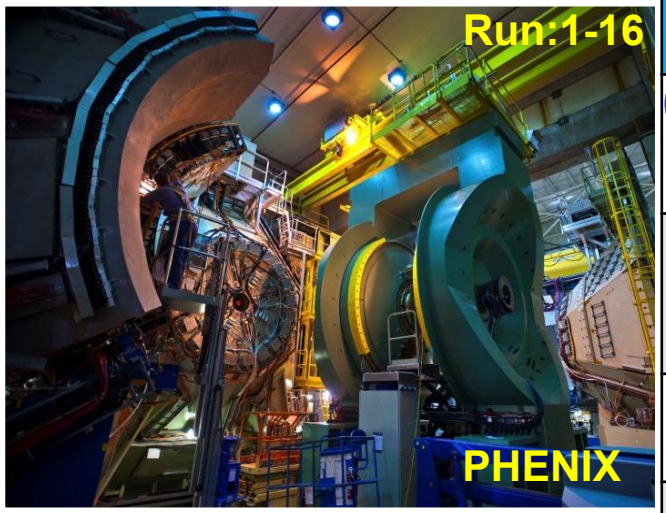
- Due to their mass ($m_Q >> T_{cri}$, Λ_{QCD})
  → **higher penetrating power**

- Gluon fusion dominates
  → **sensitive to initial state gluon distribution**

M. Gyulassy and Z. Lin, Phys. Rev. C51 (1995) 2177



PHENIX Collected and Analyzing a Golden Data from RHIC



❖ 2012 to 2016: data were taken with Central Silicon Vertex Tracker for Heavy Flavor Physics

Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity [mb^{-1}]
I (2000)	Au+Au	56	< 0.001
	Au+Au	130	20
II (2001/2002)	Au+Au	200	25.8
	Au+Au	19.6	0.4
	p+p	200	1.4×10^{-6}
III (2003)	d+Au	200	73×10^{-3}
	p+p	200	5.5×10^{-6}
IV(2004)	Au+Au	200	3.53×10^{-3}
	Au+Au	62.4	67
	p+p	200	7.1×10^{-6}
V (2005)	Cu+Cu	200	42.1×10^{-3}
	Cu+Cu	62.4	1.5×10^{-3}
	Cu+Cu	22.4	0.02×10^{-3}
	p+p	200	29.5×10^{-6}
	p+p	410	0.1×10^{-6}
VI (2006)	p+p	200	88.6×10^{-6}
	p+p	62.4	1.05×10^{-6}
VII (2007)	Au+Au	200	7.25×10^{-3}
	Au+Au	9.2	Small
VIII (2008)	d+Au	200	437×10^{-3}
	p+p	200	38.4×10^{-6}
	Au+Au	9.6	Small

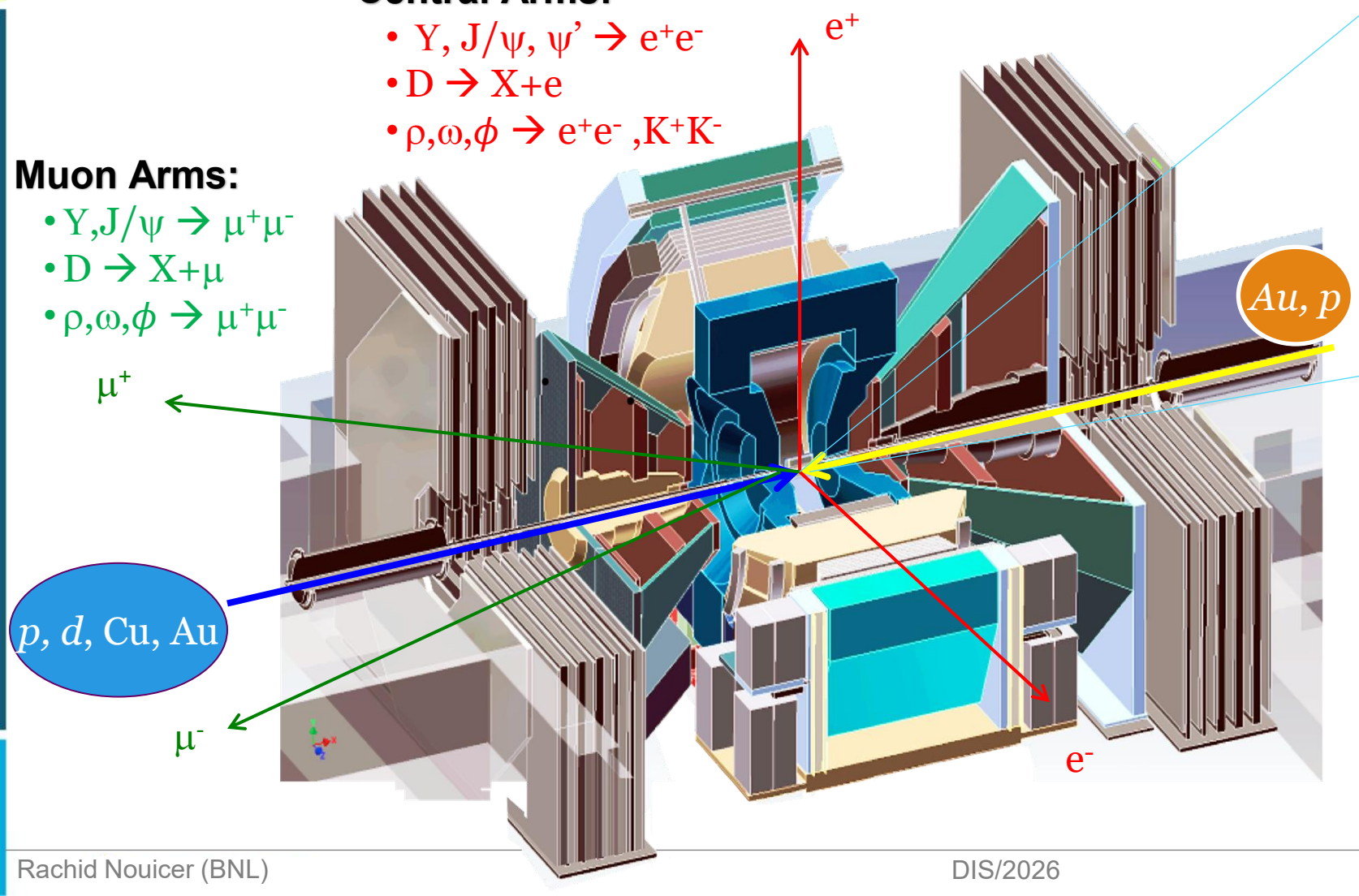
Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity [mb^{-1}]
IX (2009)	p+p	500	110×10^{-6}
	+p	200	114×10^{-6}
X (2010)	Au+Au	200	10.3×10^{-3}
	Au+Au	62.4	544
	Au+Au	39	206
	Au+Au	7.7	4.23
	Au+Au	11.5	7.8
XI (2011)	p+p	500	166×10^{-6}
	Au+Au	19.6	33.2
	Au+Au	200	9.79×10^{-3}
	Au+Au	27	63.1
XII (2012)	p+p	200	74×10^{-6}
	p+p	510	283×10^{-6}
	U+U	193	736
	Cu+Au	200	27×10^{-3}
XIII (2013)	p+p	510	1.04×10^{-9}
XIV (2014)	Au+Au	14.6	44.2
	Au+Au	200	43.9×10^{-3}
	^{3}He+Au	200	134×10^{-3}
XV (2015)	p+p	200	282×10^{-6}
	p+Au	200	1.27×10^{-6}
	p+Al	200	3.97×10^{-6}
XVI (2016)	Au+Au	200	52.2×10^{-3}
	d+Au	200	46.1×10^{-3}
	d+Au	62.4	44.0×10^{-3}
	d+Au	19.6	7.2×10^{-3}
	d+Au	39	19.5×10^{-3}

Heavy Flavor Physics Program in PHENIX

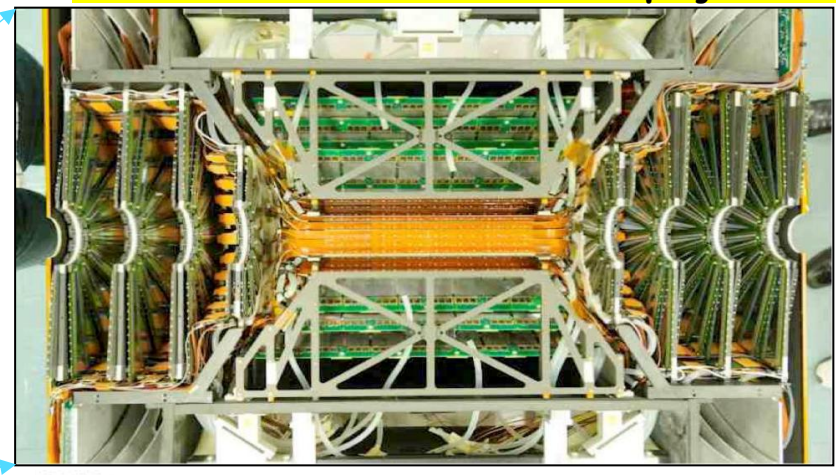
- PHENIX optimized to measure leptons: rapidity coverage: 1.2<|y|<2.2 and |y|<0.35

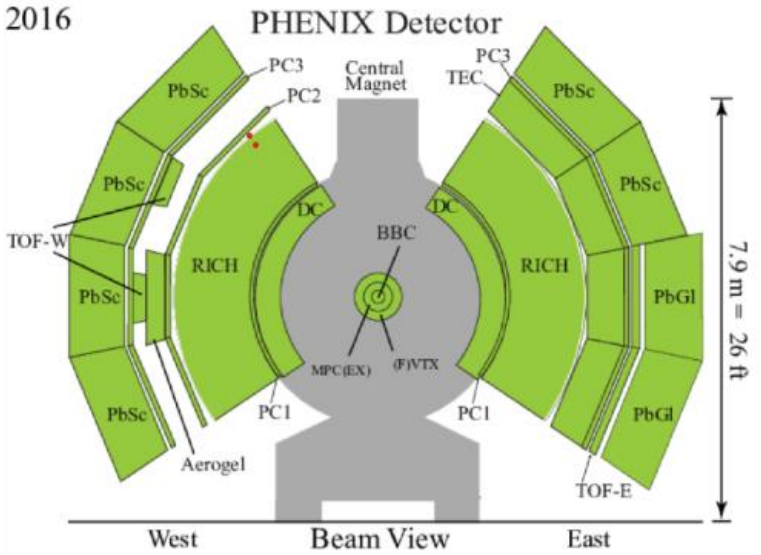
Central Arms:
- Υ, J/ψ, ψ' → e^+e^-
- D → X+e
- ρ,ω,ϕ → e^+e^- ,K^+K^-

Muon Arms:
- Υ,J/ψ → $\mu^+\mu^-$
- D → X+μ
- ρ,ω,ϕ → $\mu^+\mu^-$

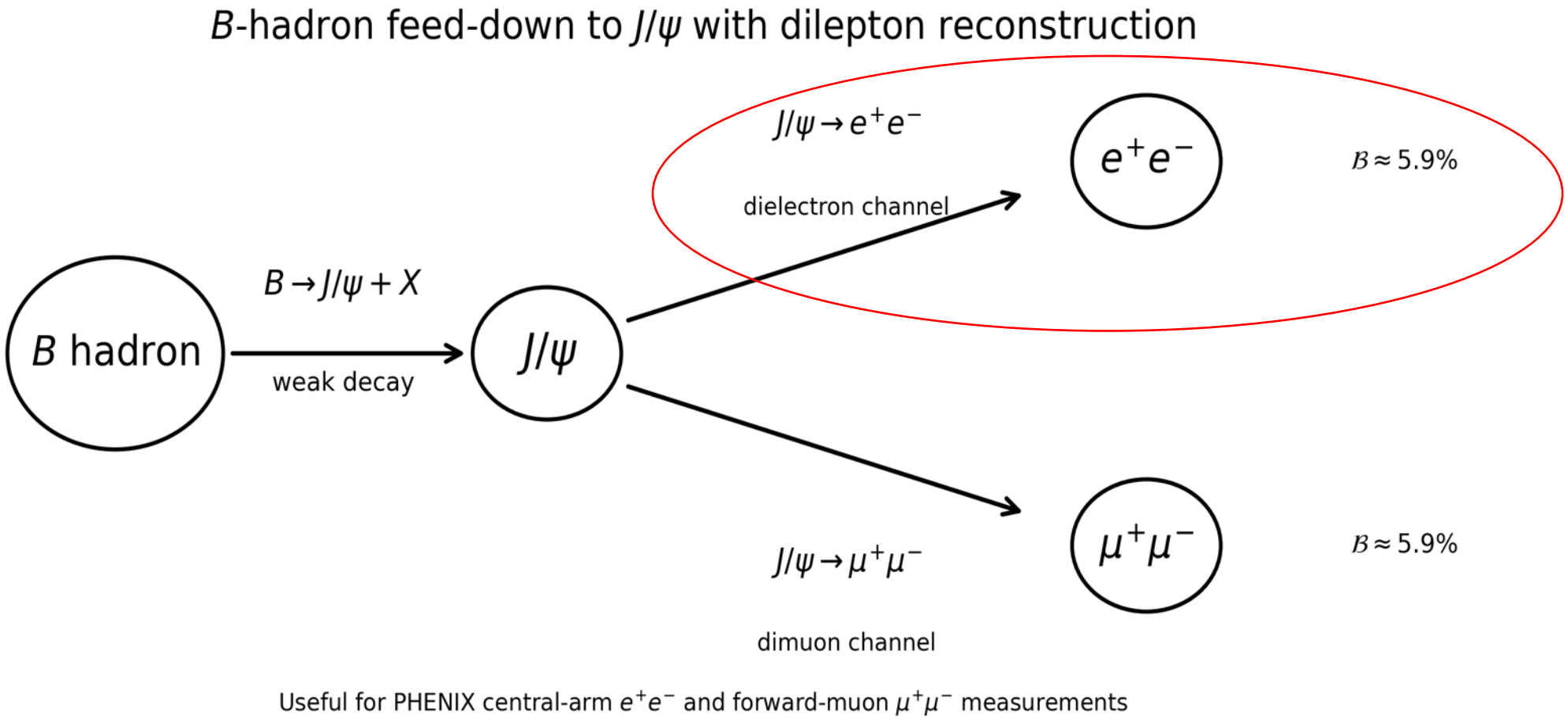


2012: upgraded with Silicon detector VTX/FVTX for HF physics



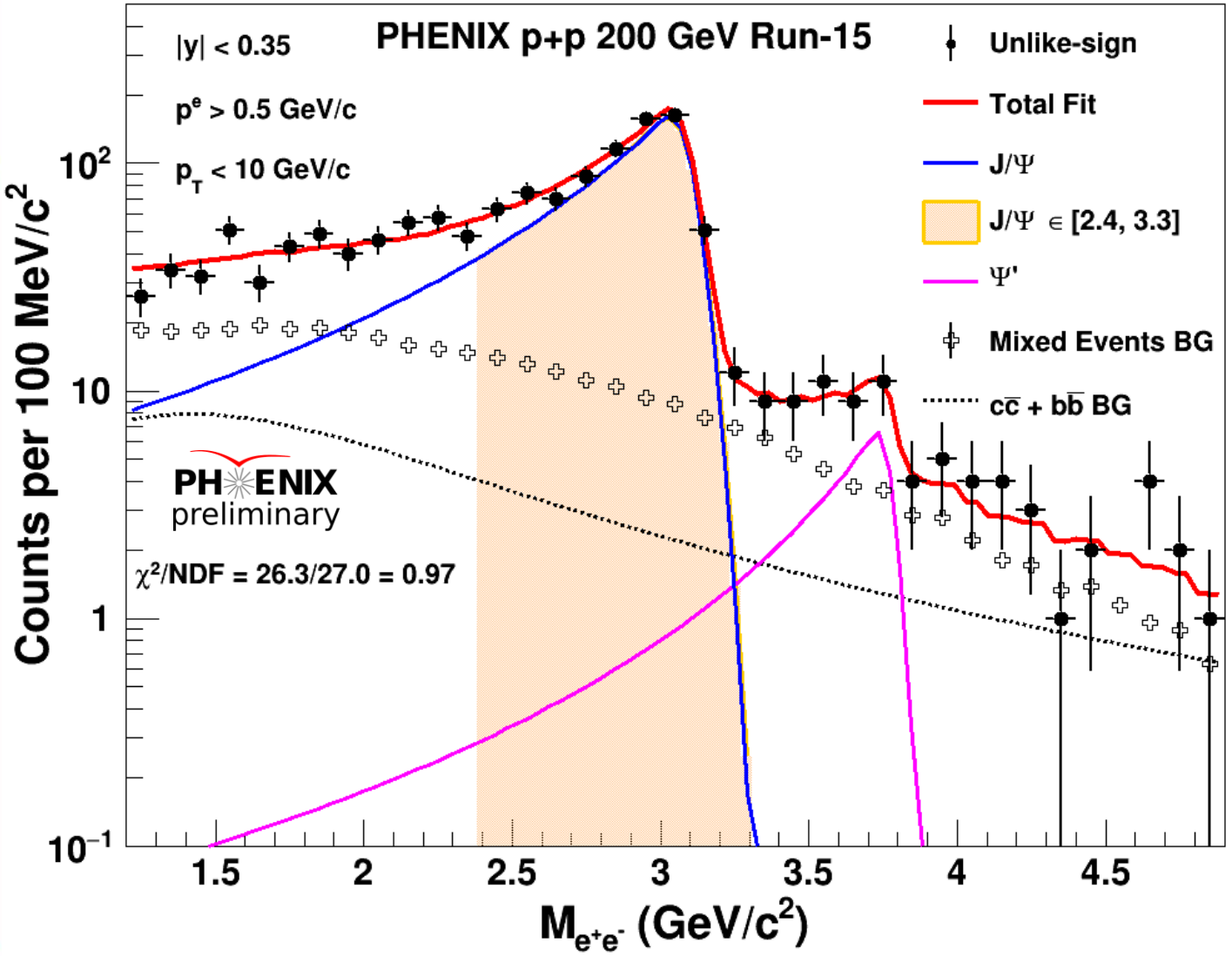


Study of B-> J/ψ Production in p+p at 200GeV

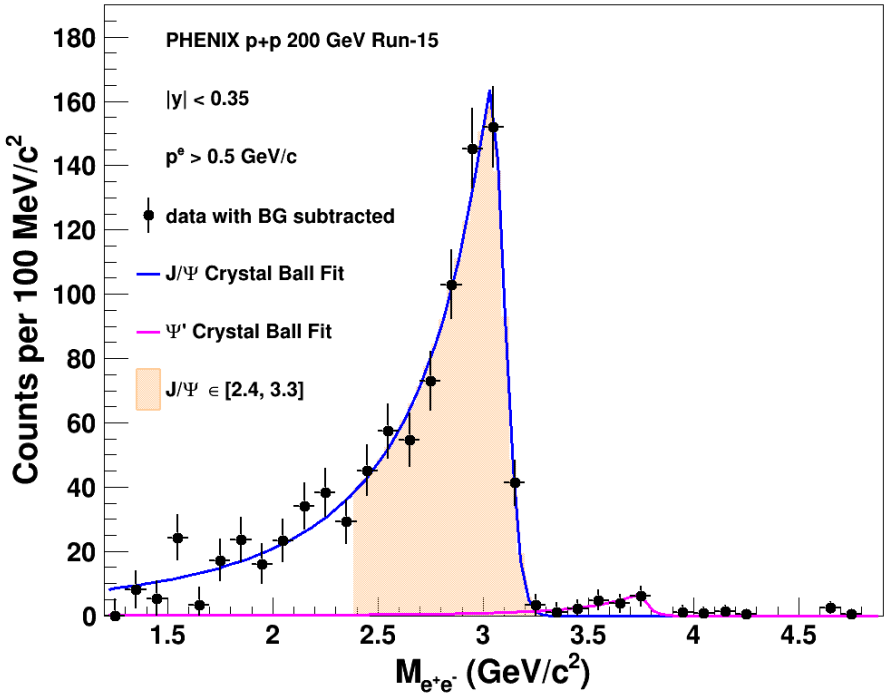


Useful for PHENIX central-arm e^+e^- and forward-muon $\mu^+\mu^-$ measurements

Analysis Method: Dielectron Invariant Mass Distribution



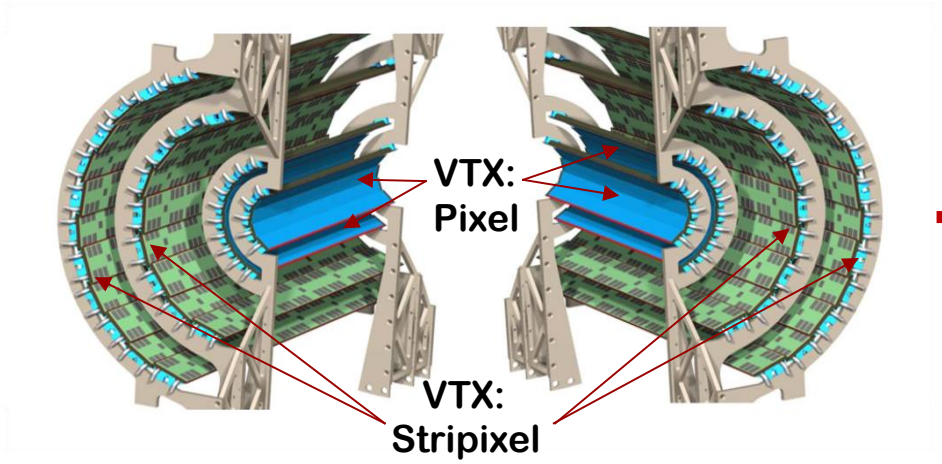
Background subtracted



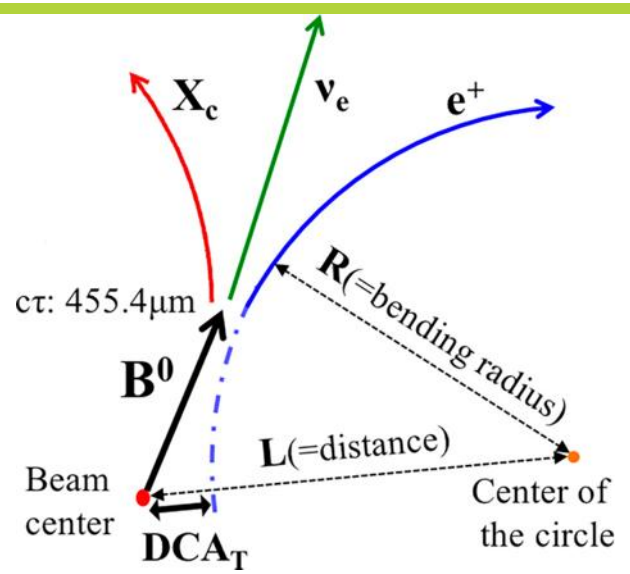
Measures the dielectron invariant mass distribution, selects inclusive J/ψ peak, and determines the raw yields of J/ψ and heavy flavor ($c\bar{c}$ + $b\bar{b}$) background in the mass region of $M_{e^+e^-}$= [2.4, 3.3] GeV/c^2

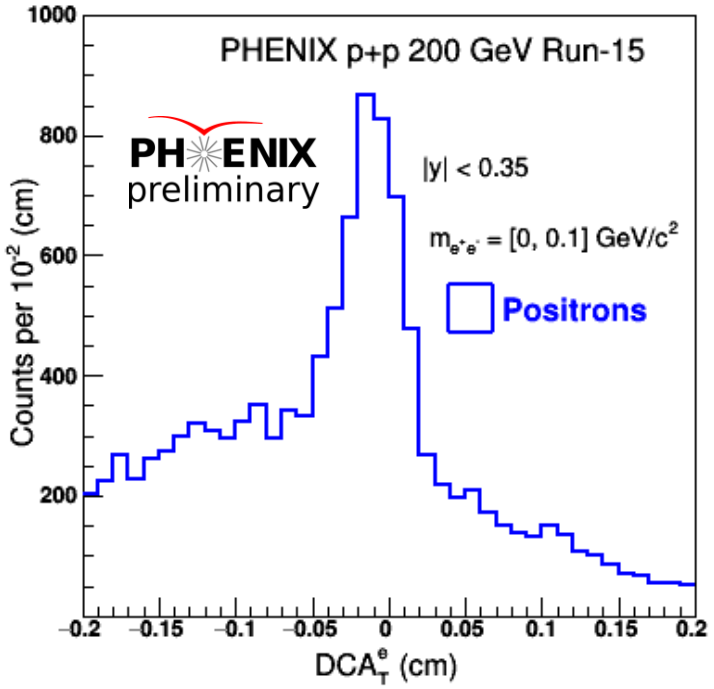
DCA_T Distributions of e+/e- from Dalitz Decay and Photon Conversion $M_{e^+e^-} < 0.1\ GeV/c^2$

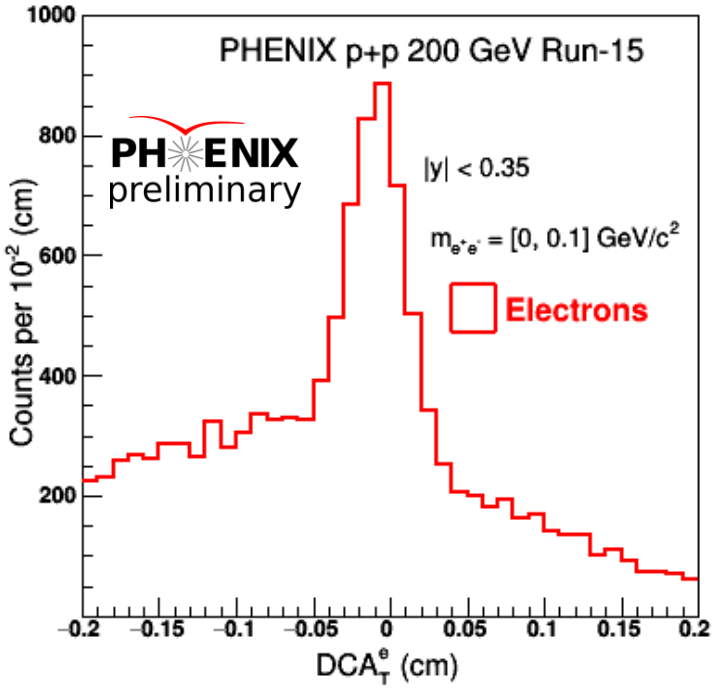
VTX: silicon VerTeX barrel tracker

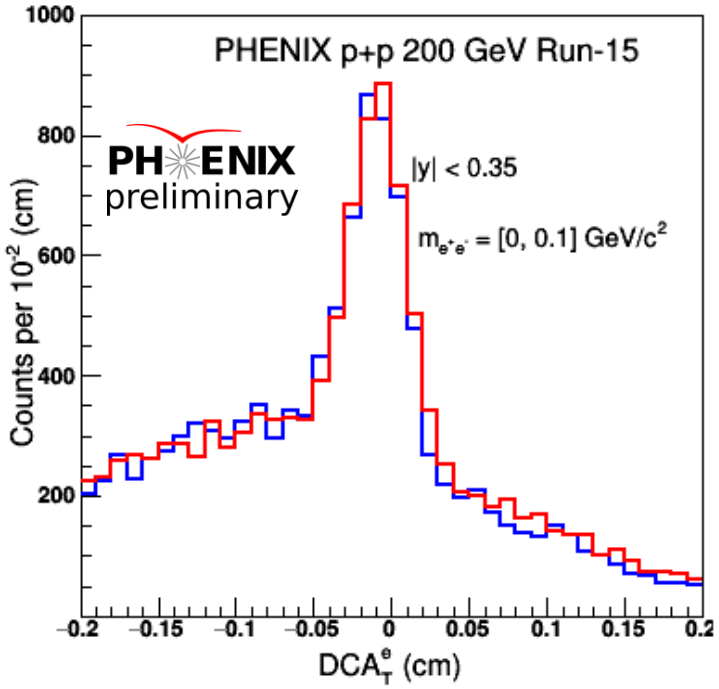


DCA









Analysis Method: Extract the Fraction of B-meson Decays to J/ψ $F_{B\to J/\psi}$

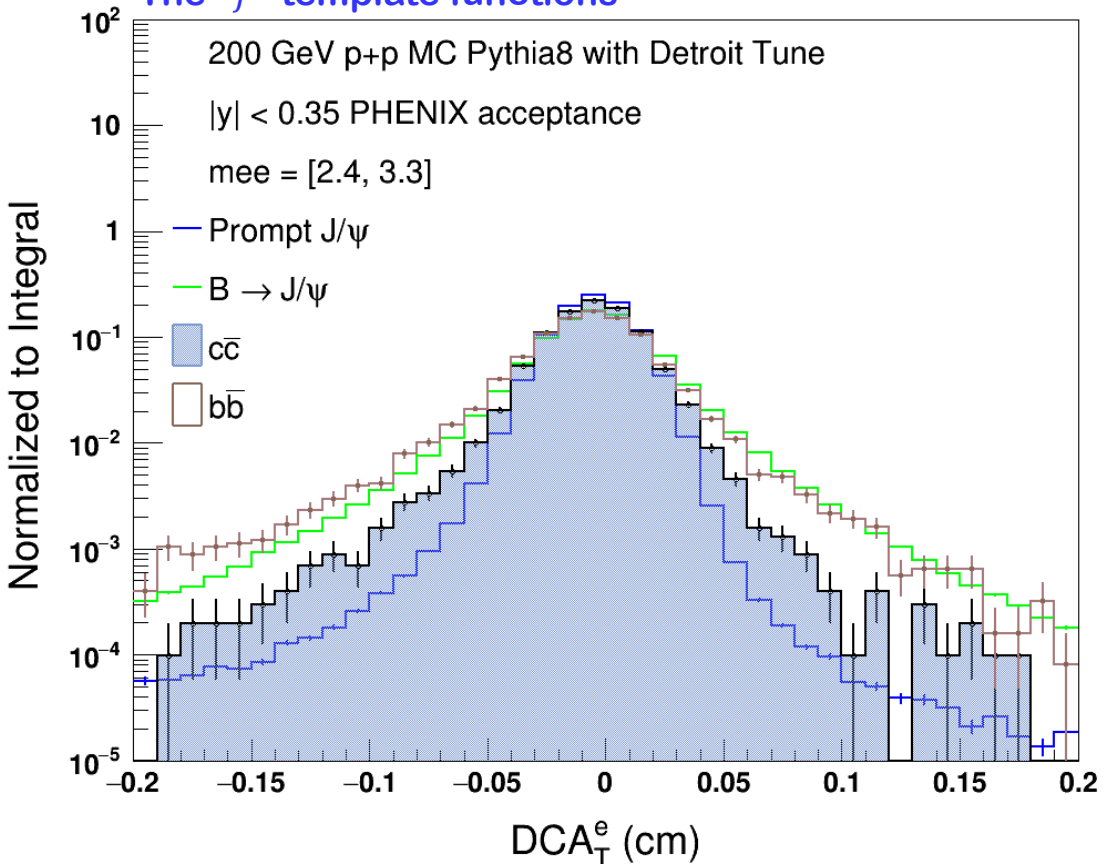
DCA Fit function

In p+p collisions at 200 GeV, $R_b = 0.3 \pm 0.1$

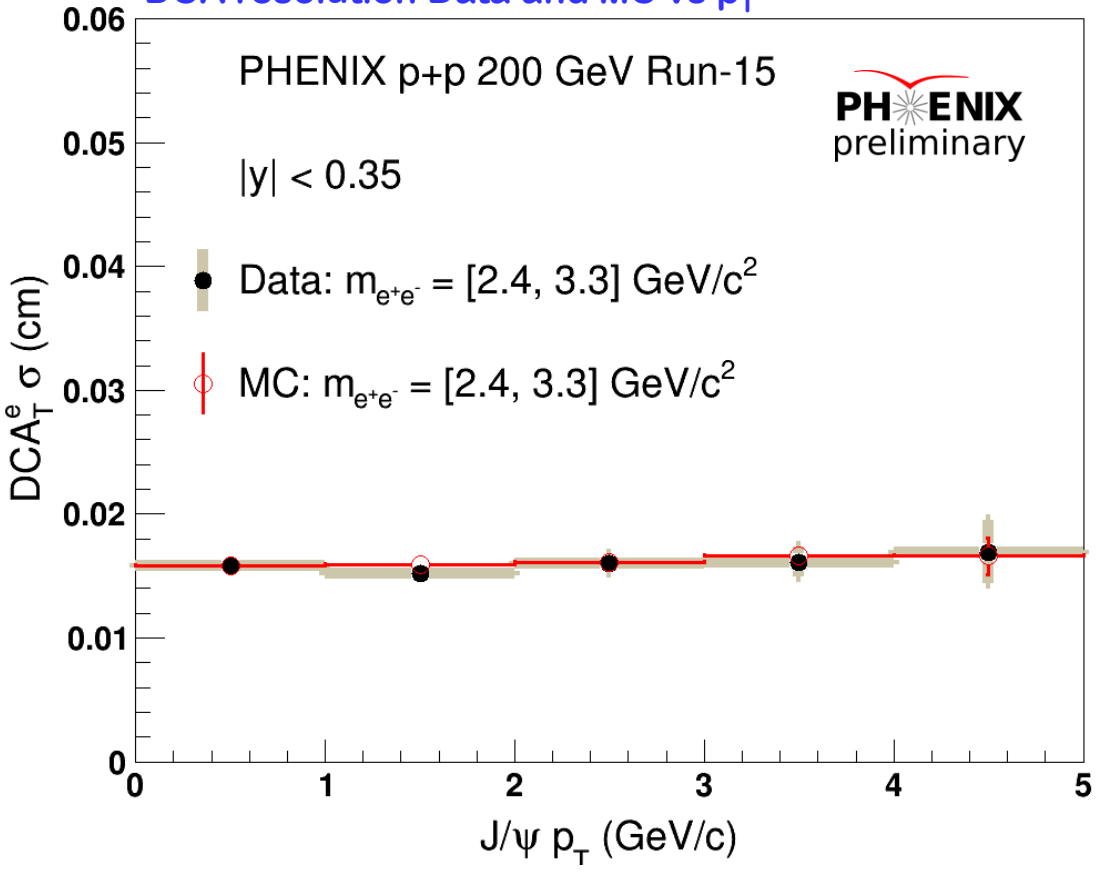
$$f_{\text{total}}(\text{DCA}_T) - f_{\text{combinatorial}}(\text{DCA}_T) = \text{Yield}_{\text{incl. } J/\psi} \times [F_{B\to J/\psi} \times f_{B\to J/\psi}(\text{DCA}_T) + (1 - F_{B\to J/\psi}) \times f_{\text{prompt } J/\psi}(\text{DCA}_T)]$$

$$+ \text{Yield}_{c\bar{c}+b\bar{b}} \times [(1 - R_b) \times f_{c\bar{c}}(\text{DCA}_T) + R_b \times f_{b\bar{b}}(\text{DCA}_T)]$$

The "f" template functions

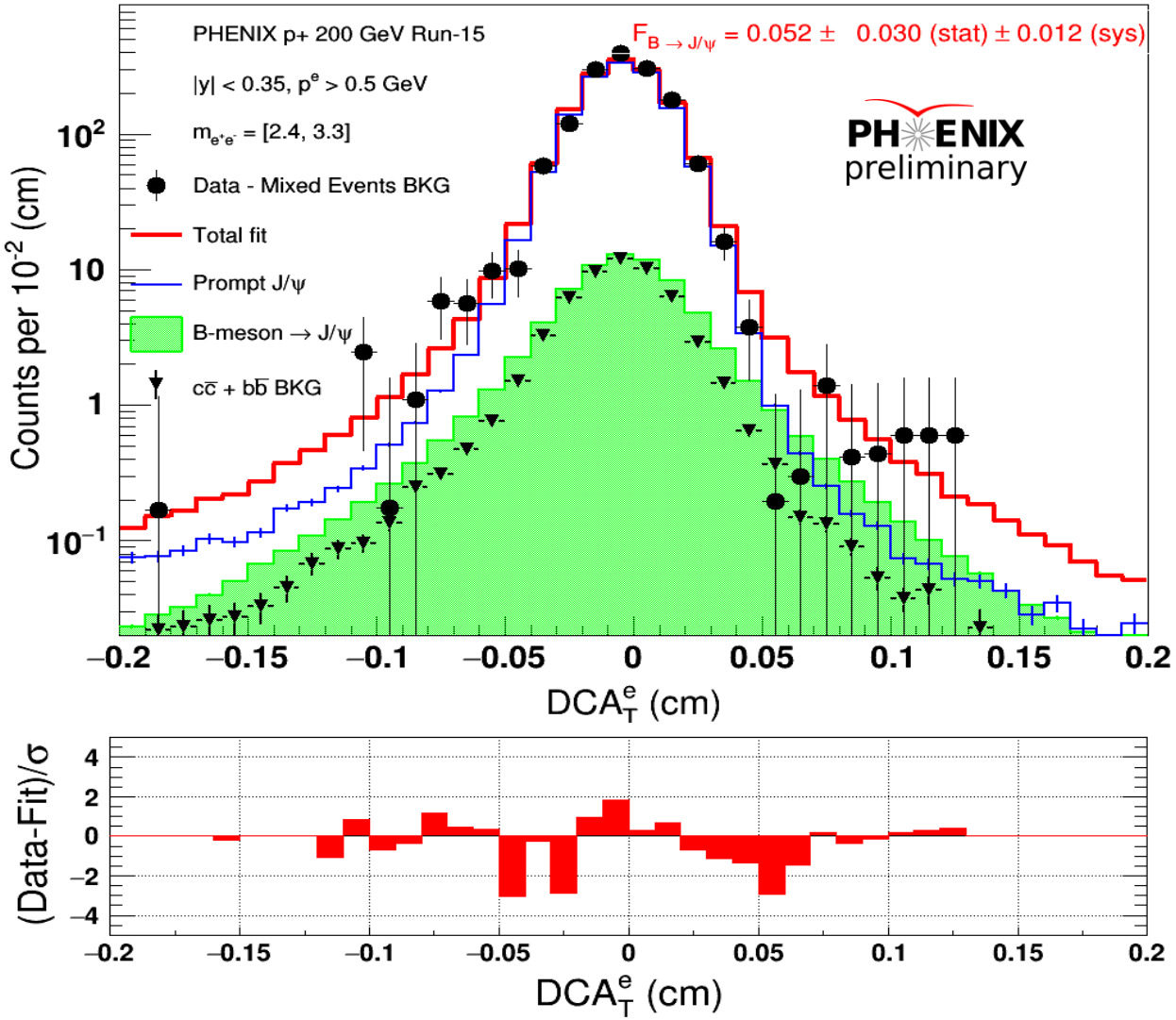


DCA resolution Data and MC vs p_T



Results: B→ J/ψ using DCA Technique

Extraction of fraction B-meson decays to J/ψ ($F_{B\to J/\psi}$)



$F_{B\to J/\psi}$ distribution for 200k fit iterations

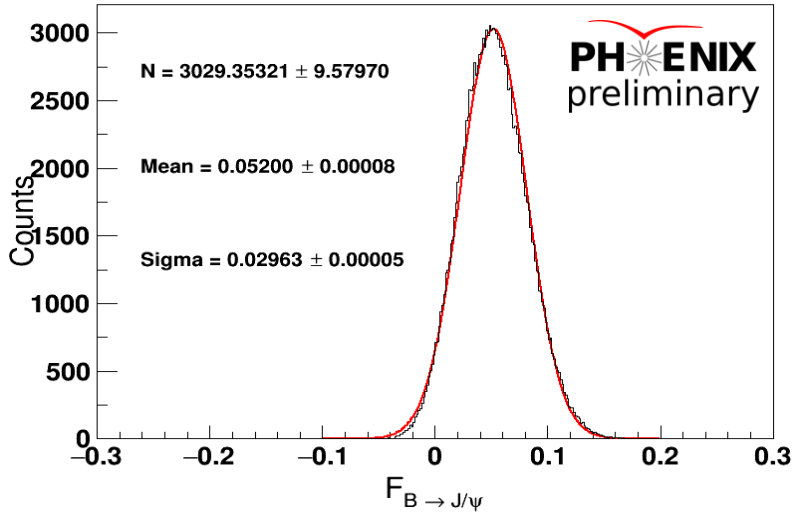


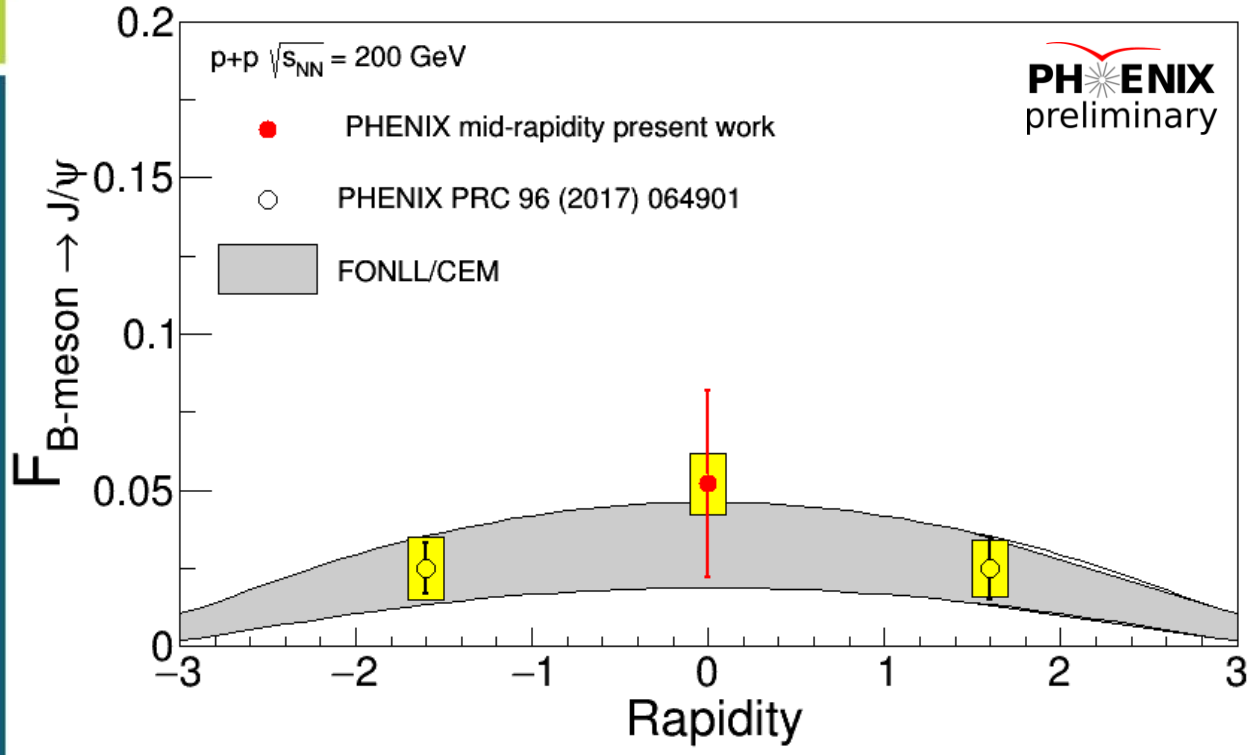
Table 2: Systematic uncertainty summary for the fraction of J/ψ from B-meson decay in the $-0.35 < y < 0.35$ rapidity regions. Values are in absolute scale.

Source	$-0.35 < y < 0.35$	Specific meaning
a	< 1%	Fit method variation
b	6.0%	Fraction of charm and bottom (R_b) variation
c	6.3%	J/ψ yield variation
d	6.7%	Collision vertex variation
e	4.6%	Mixed events background variation
Total syst uncertainty	**23.6%**	

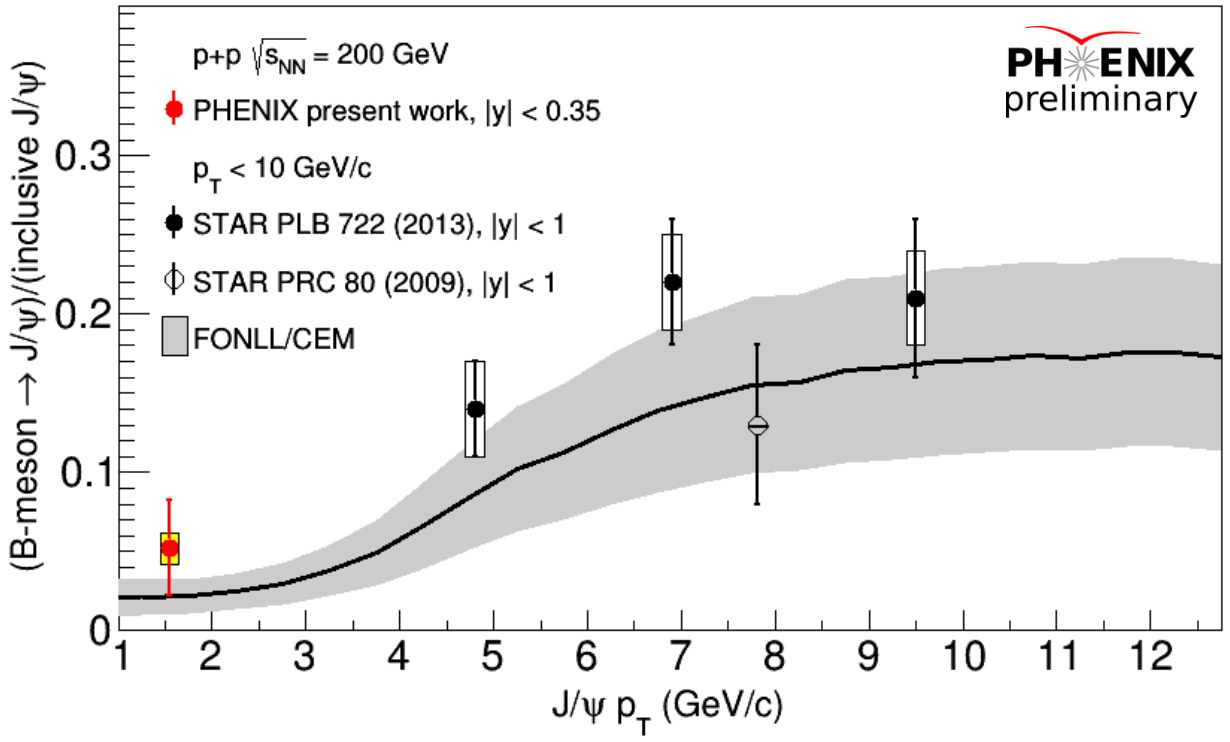
$$F_{B\to J/\psi} = 0.052 \pm 0.030\,(\text{stat}) \pm 0.012\,(\text{sys})$$

B → J/ψ Fraction in p+p at 200 GeV (RHIC)

Fraction of B-meson→J/ψ versus rapidity



PHENIX and STAR results versus p_T

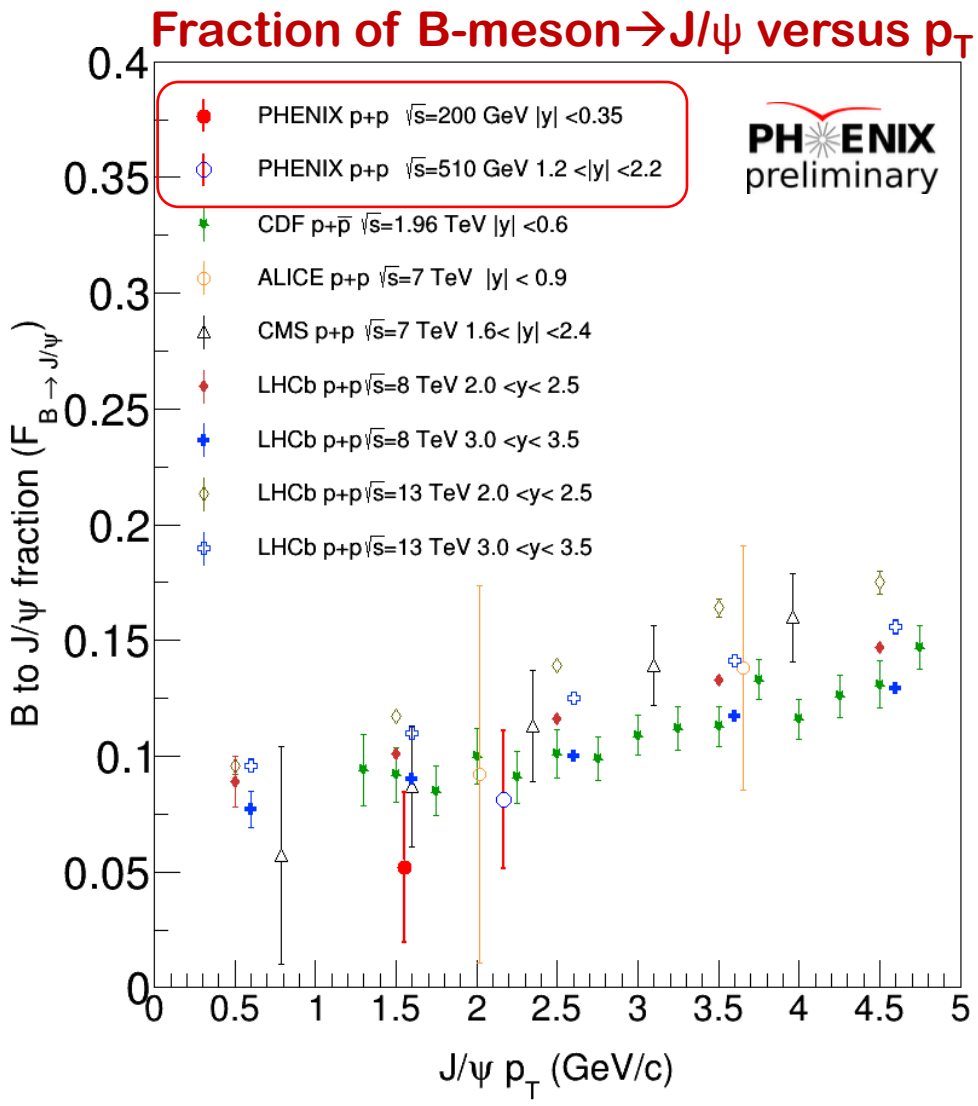


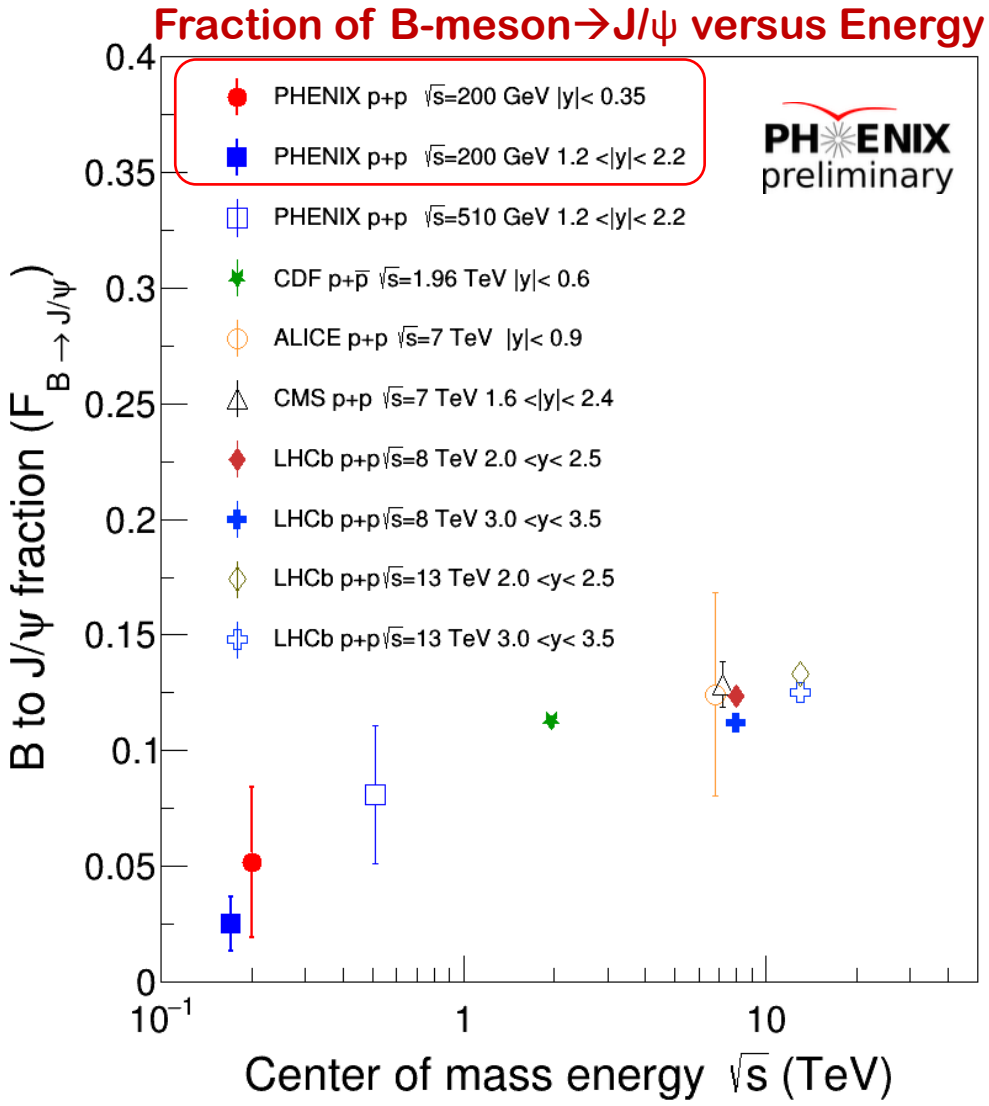
Note: STAR results used correlation method (not DCA technic)

Excellent agreement with Fixed-Order-Next-to-Leading-Logarithm plus Color-Evaporation-Model (FONLL+CEM) predictions across large rapidity range.

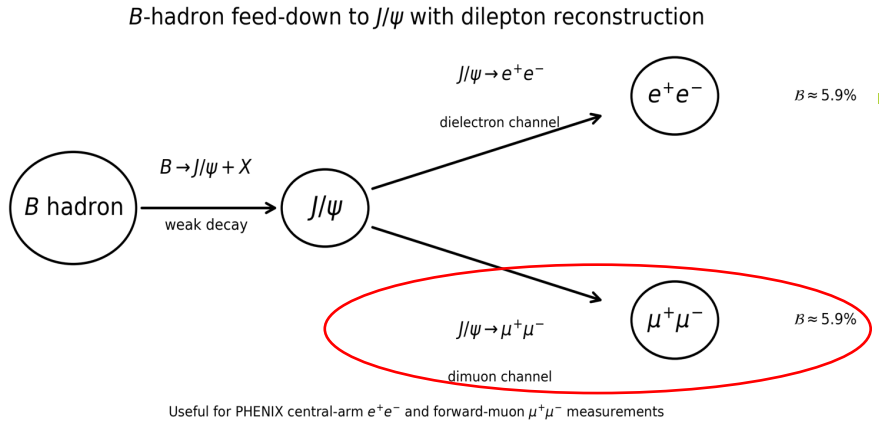
B → J/ψ Fraction: Collision Energy and p_T Dependence

- Excellent agreement with CDF/ALICE/CMS/LHCb measurements



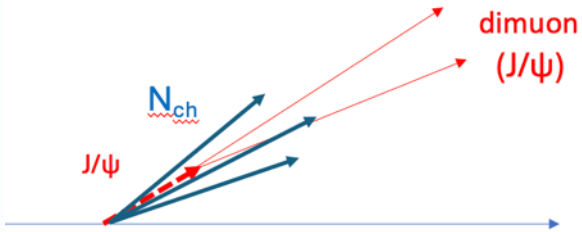


Part (2)

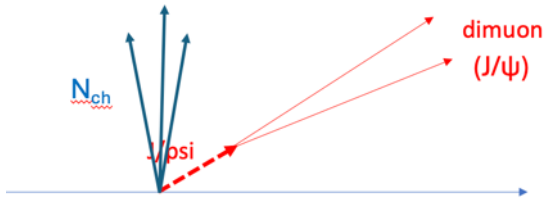


Study of J/ψ Production vs N_{ch} in p+p and p+Au at 200 GeV

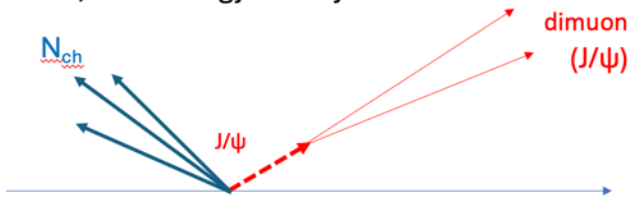
- Final State Interactions (FSI), CNM, QGP
- Local event multiplicity: N_{ch}
- Multi-Parton Interactions (MPI)
- Long-range particle correlations



J/Psi: 1.2 < |y| < 2.2

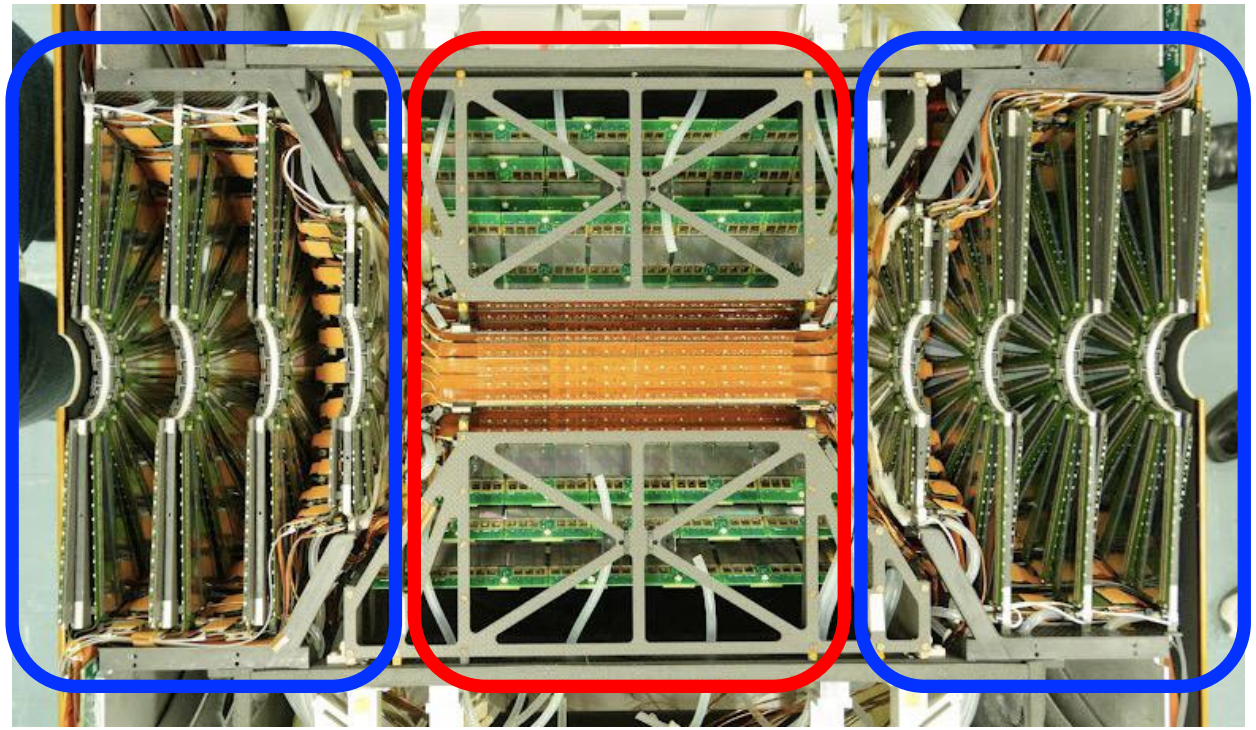


MPI, local energy density?

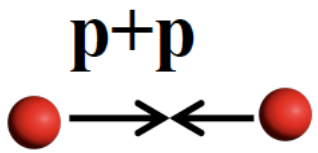


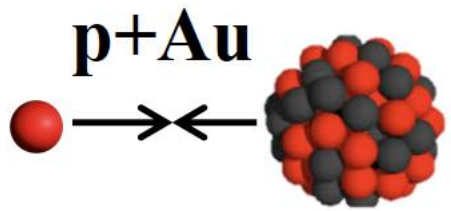
Event track multiplicity: N_{ch}

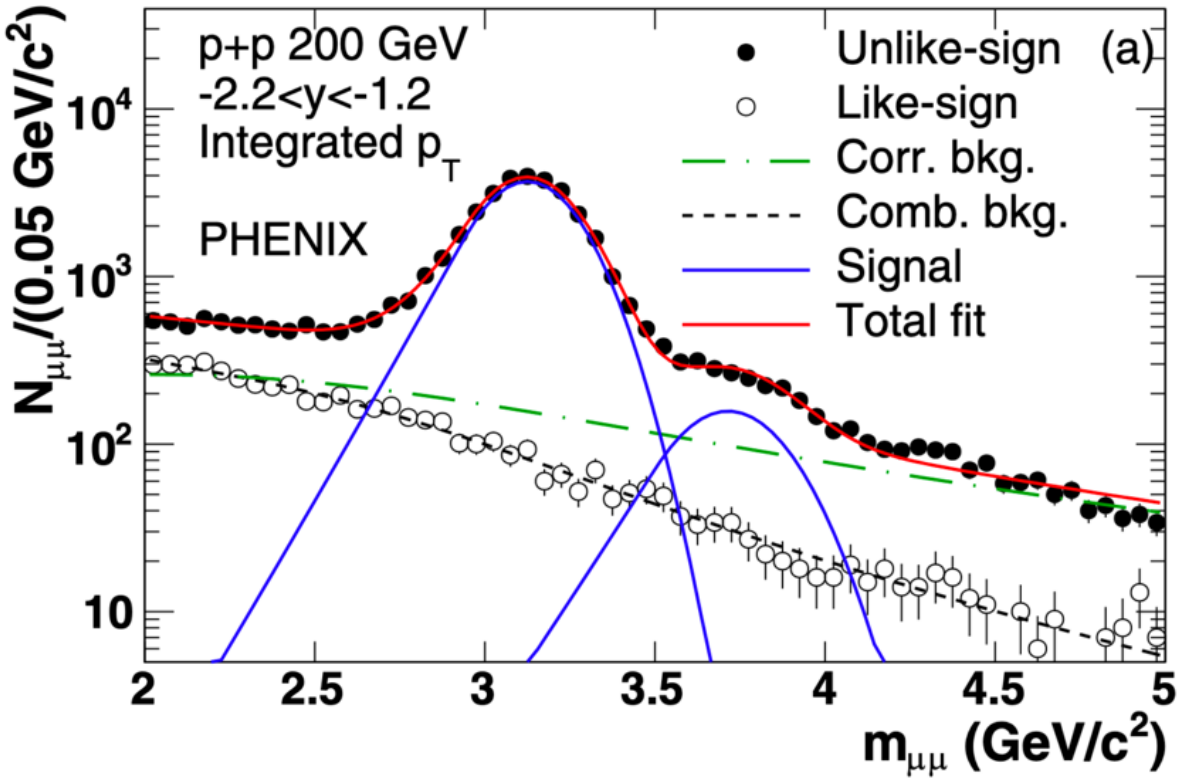
- SVX, |η| < 1
- FVTX, 1 < |η| < 3

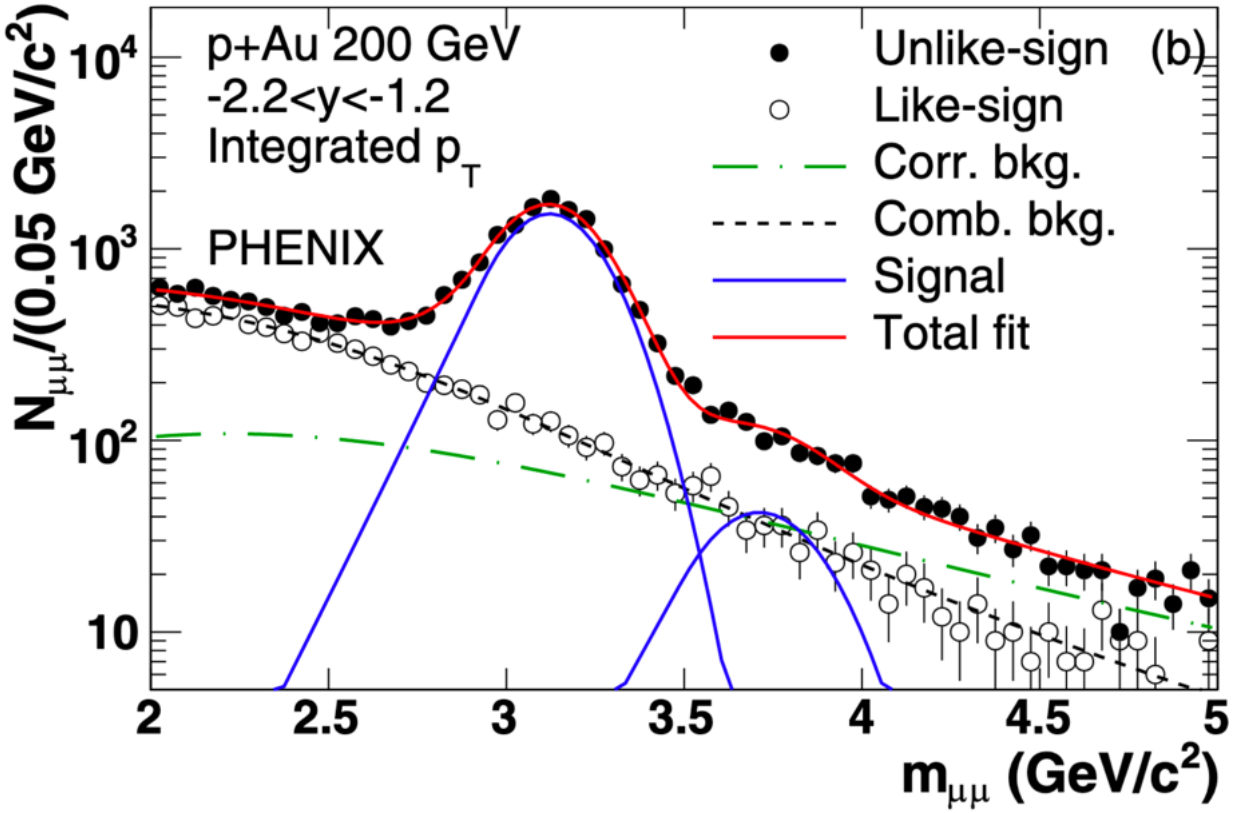


J/ψ, Psi(2S) Measurements in Dimuon Channel



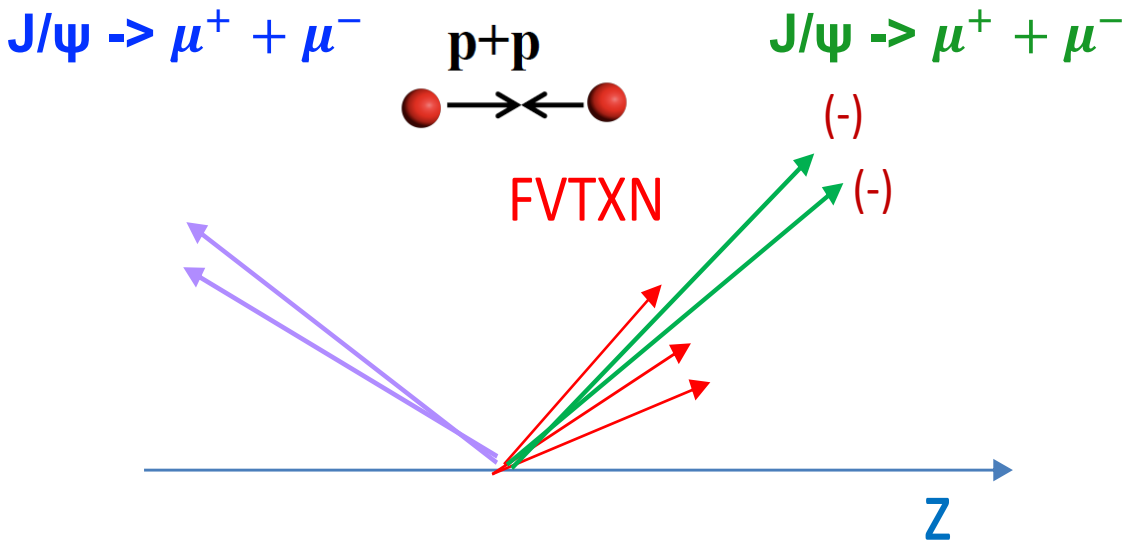




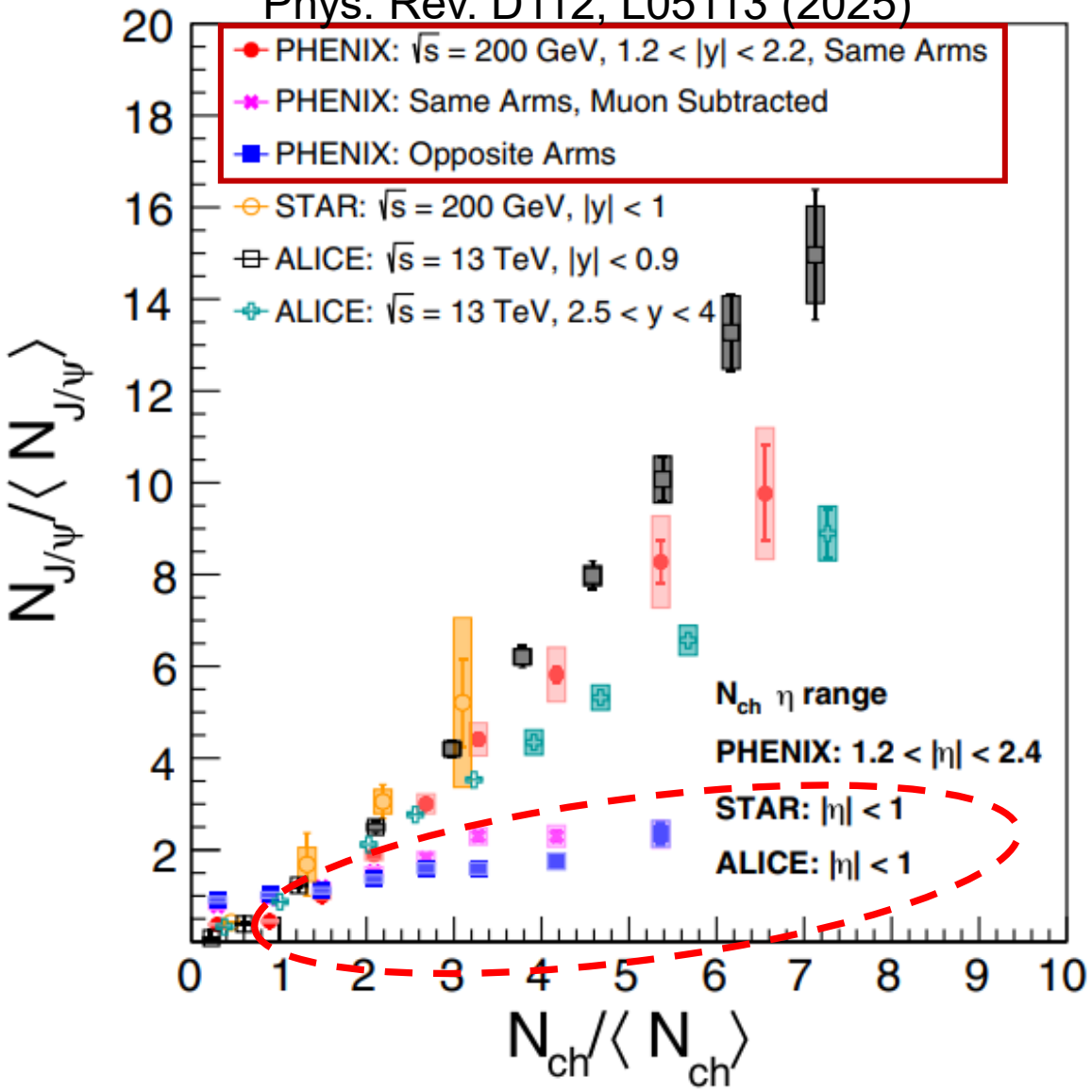


J/ψ Yield vs N_{ch} in p+p Collisions at 200 GeV

1. J/Psi yields increase vs N_{ch}
2. Similar trend as others, same-arm "inclusive" N_{ch}
3. **Apparent clear difference** in long-range <J/Psi – N_{ch}>correlations, same arm vs opposite arm
4. **Consistent** once same-arm **auto-correlation removed**
   - **Long range correlation in p+p**

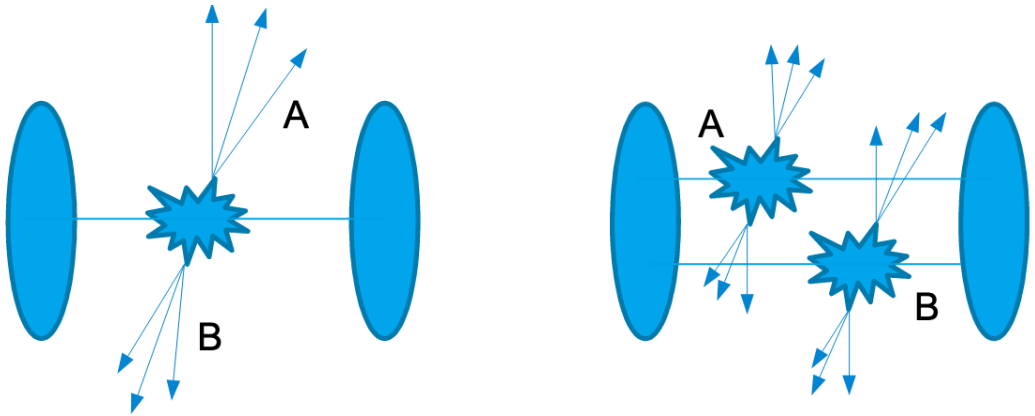


Phys. Rev. D112, L05113 (2025)



Comparison to PYTHIA8 with MPI

- **PYTHIA8 Detroit tune reasonably agrees with PHENIX data, with MPI**
  - ➢ **w/o MPI, fit failed badly**
- **Understanding of the underline event activity and correlation is important**



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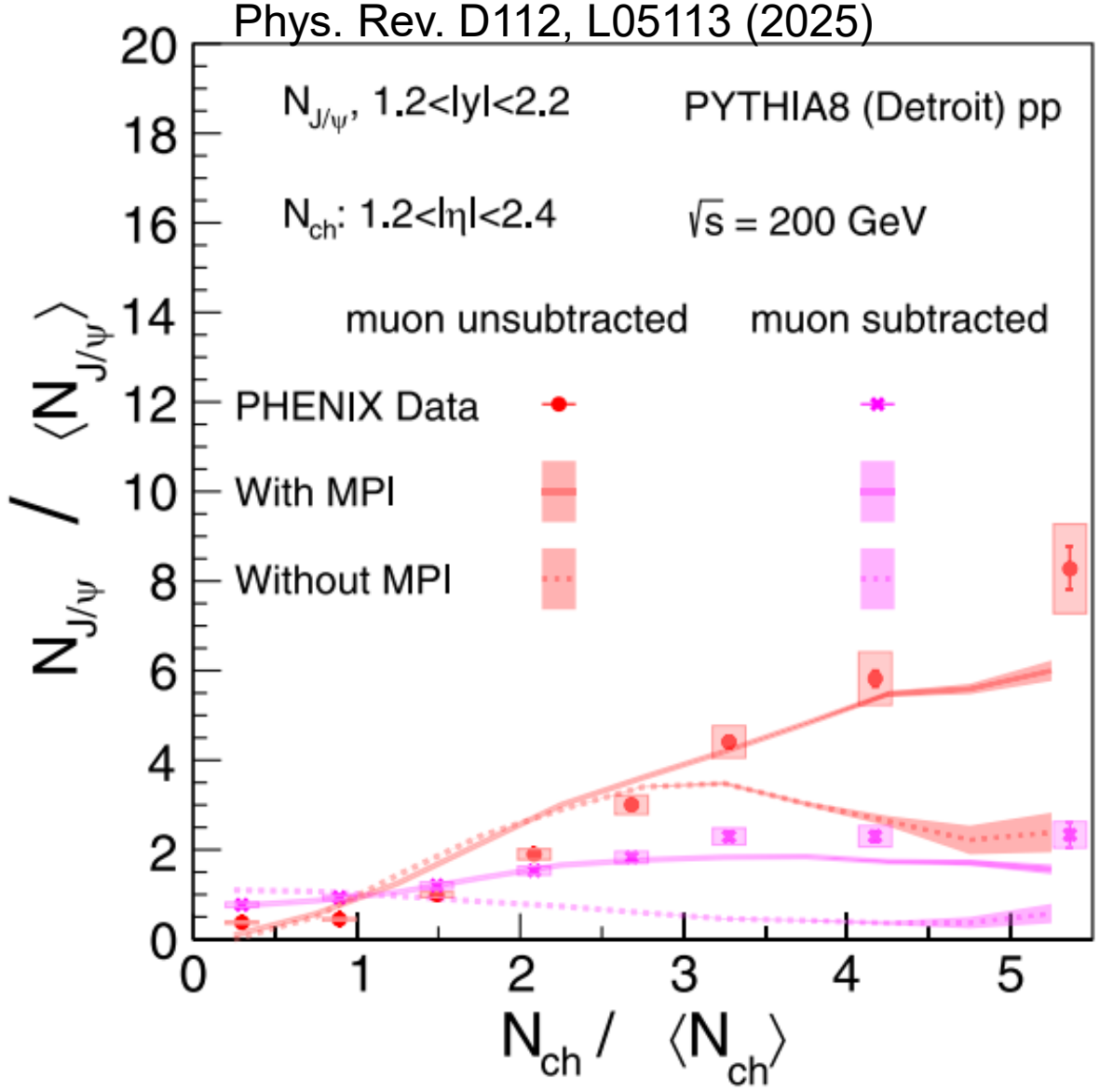


J/ψ Yield vs N_{ch} in p+Au Collisions

Unique collision event topology:

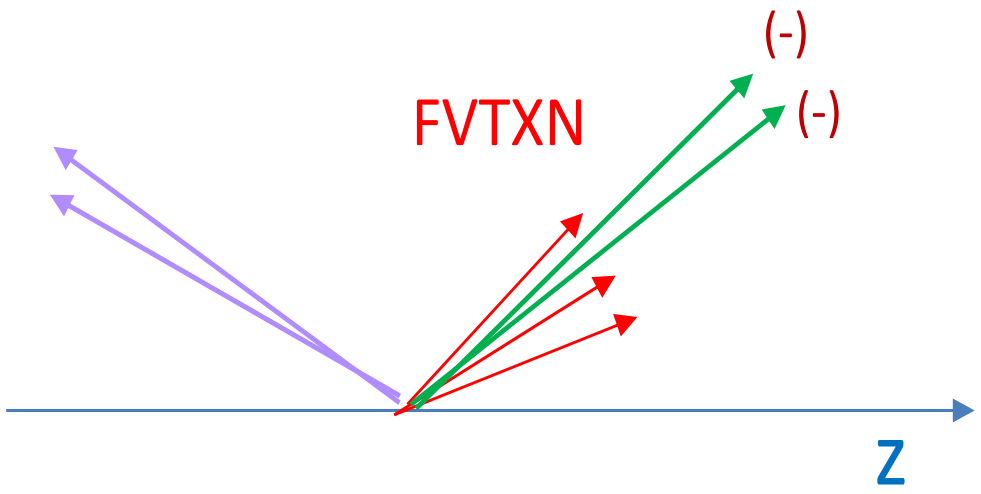
- Study correlations over wide rapidity gaps
- Small-x vs large-x in Au
- Core-corona, QGP, CNM, MPI

-2.2 < y < -1.2

J/ψ -> $\mu^+ + \mu^-$

1.2 < y < 2.2

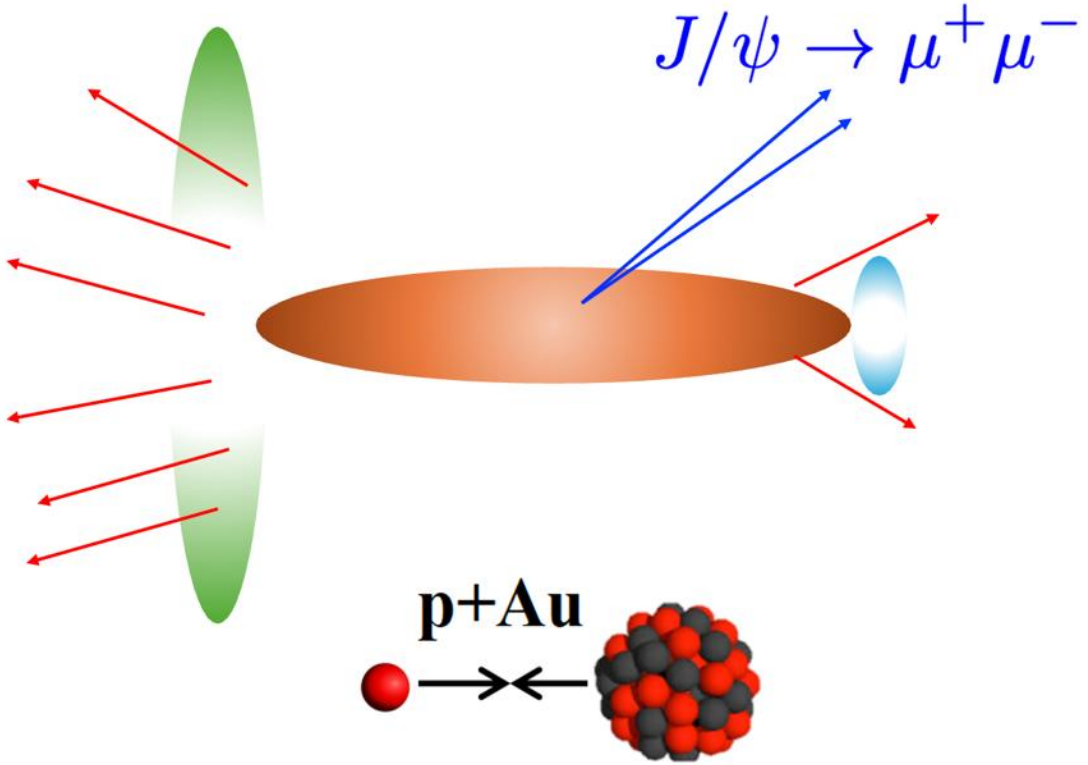
J/ψ -> $\mu^+ + \mu^-$



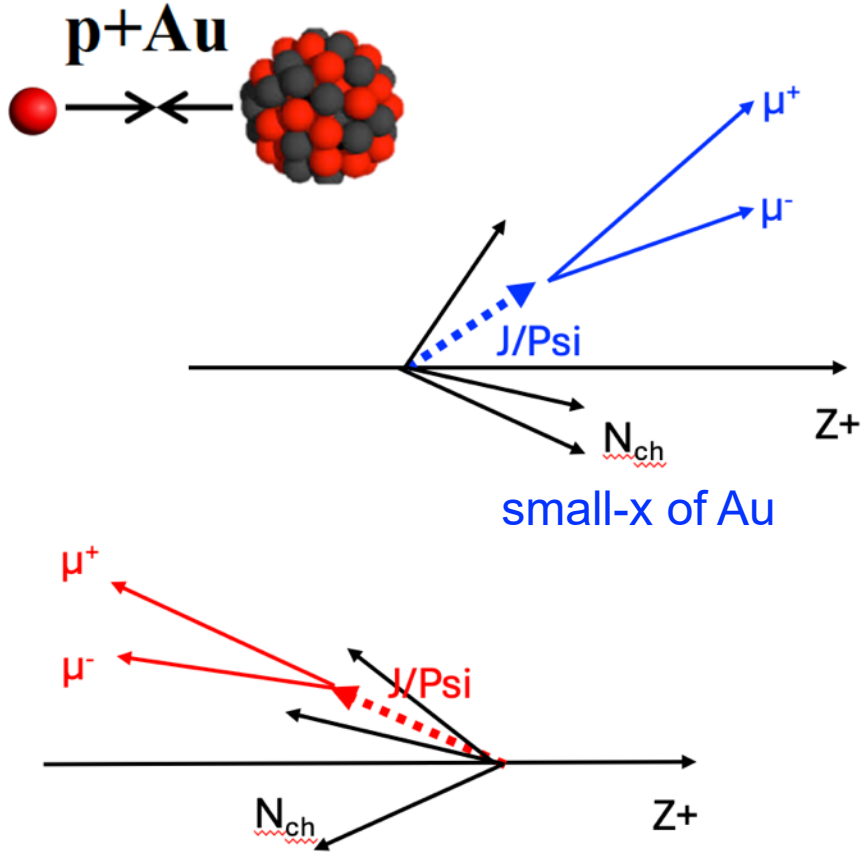
y_{beam} = 5.36 @100 GeV (LHC pp @13TeV: 9.54)

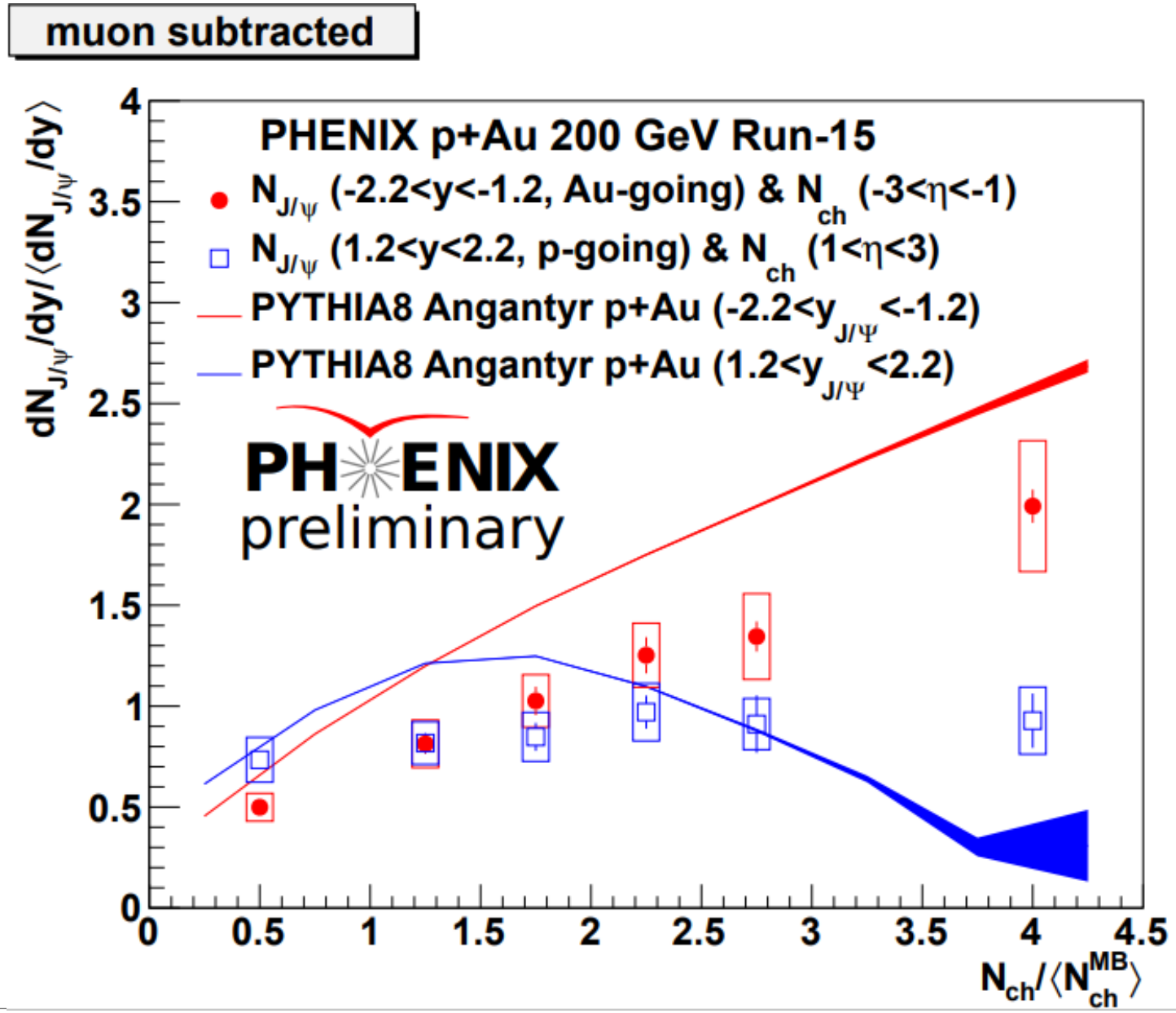
large-x of Au

small-x of Au

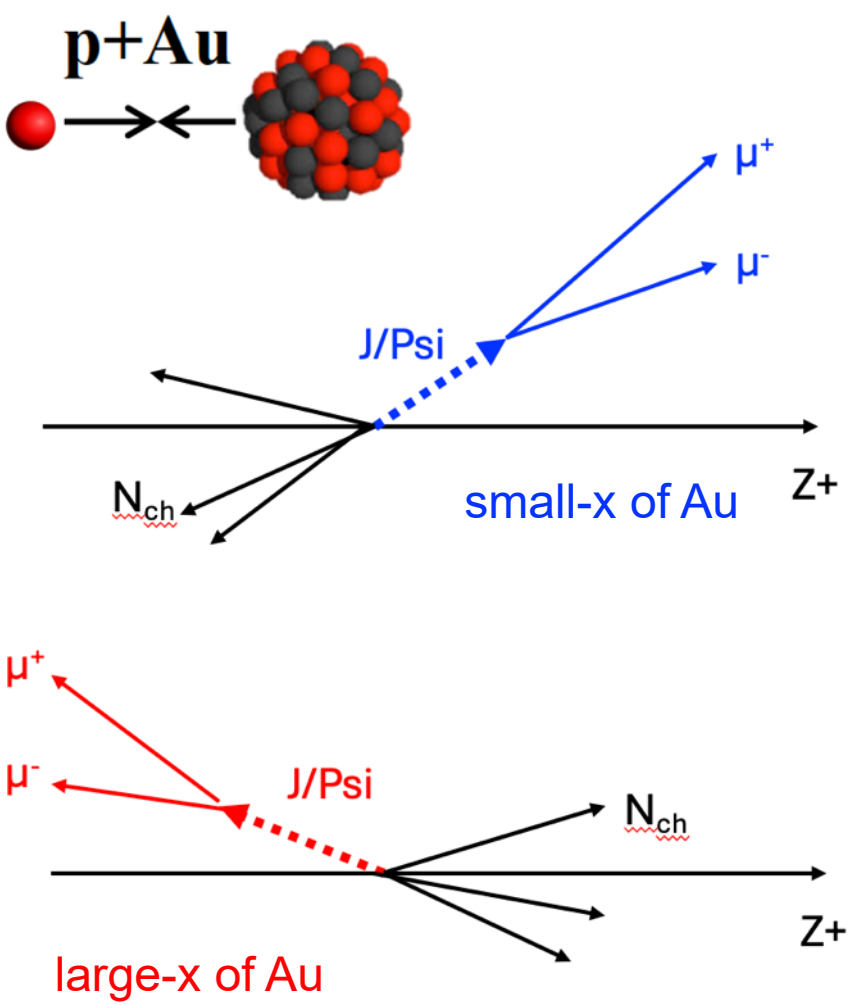


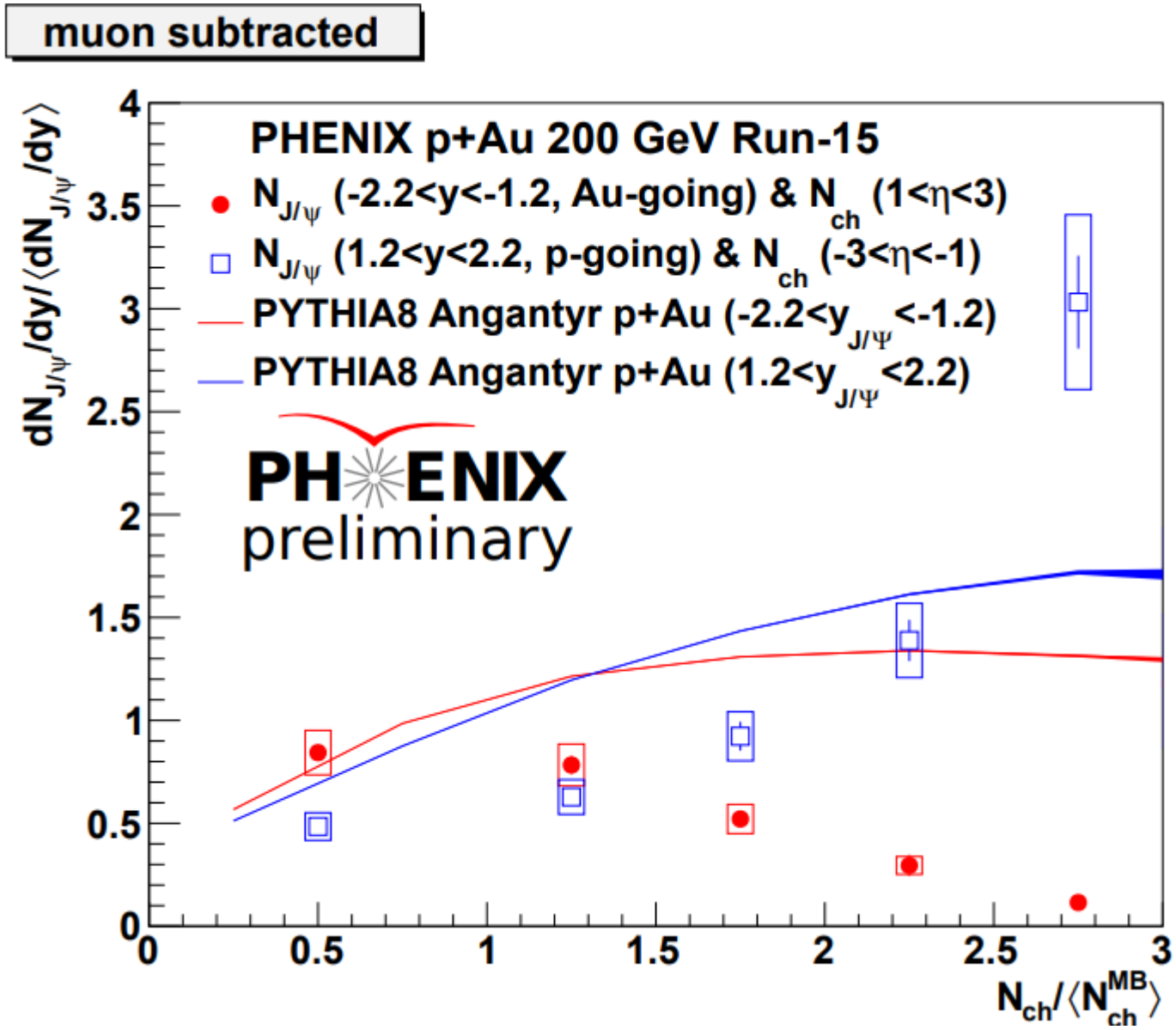
J/ψ and N_{ch} Correlation: Same Arm





J/ψ and N_{ch} Correlation: Opposite Arm



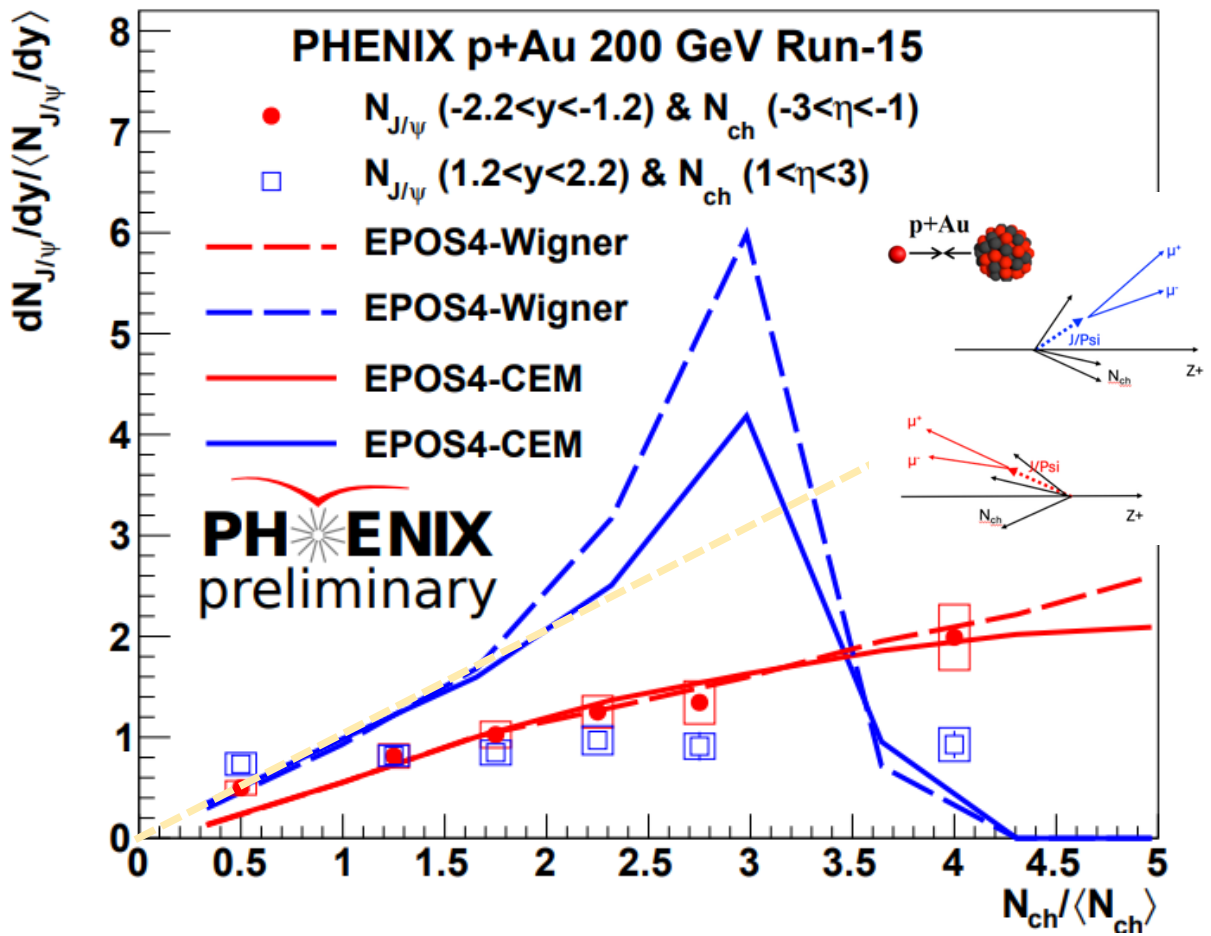


EPOS-4 and PHENIX Data

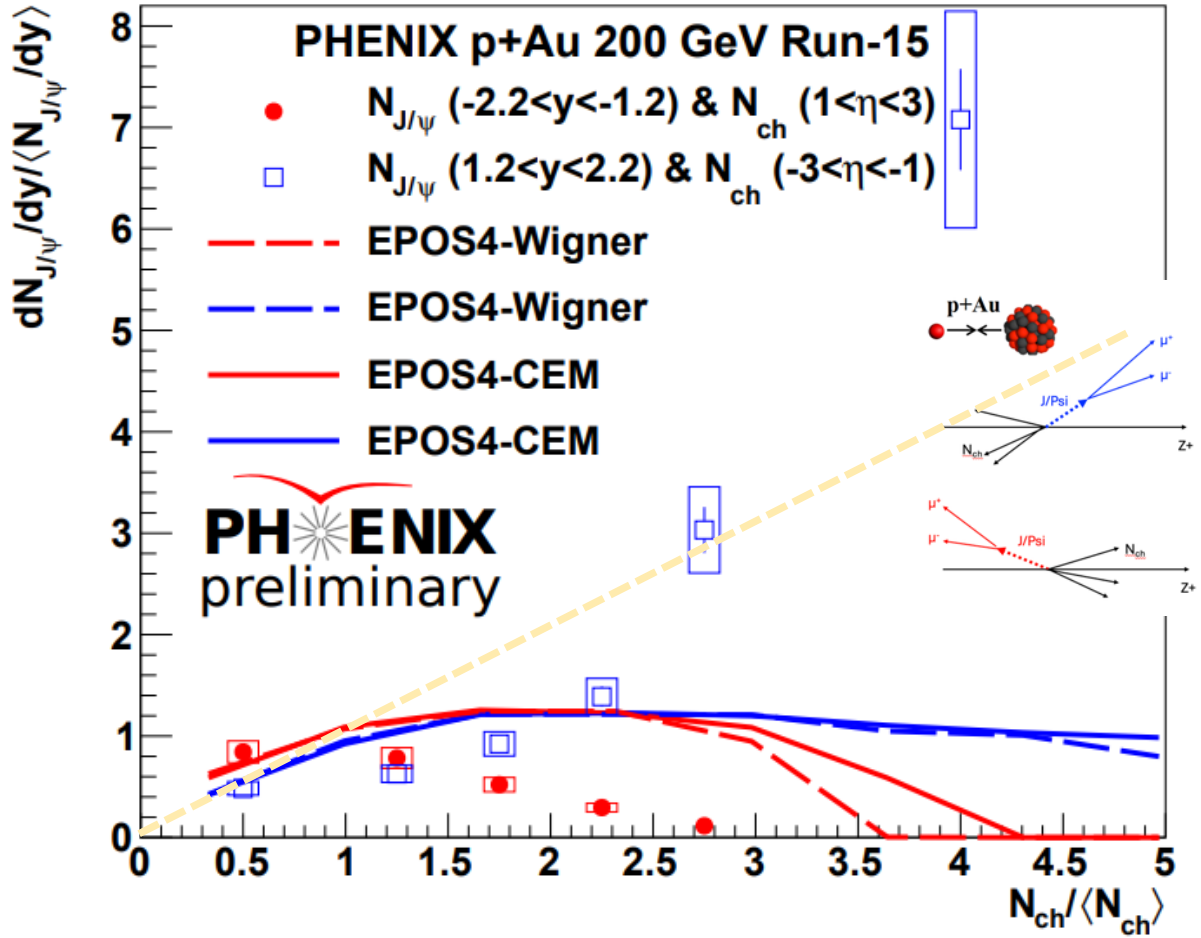
- Excellent agreement with "same-arm" data in Au-going direction
- Failed p-going direction

- Challenging for "opposite -arm" data in both Au-going direction and p-going direction

muon subtracted



muon subtracted



Summary & Outlook

Few bullets to remember

- pp@200 GeV: fraction of B-meson decays in J/ψ yields over large rapidity range has been measured, and excellent agreement with FONLL+CEM predictions
  - next step: measure B-meson→J/ψ for different p_T bins

- The present results in p+p collisions serve as a crucial baseline for the future measurements of B-meson→J/ψ in more complex environments like in small-collision systems p+Al, p+Au, d+Au, He+Au, and in the large collision system Au+Au at RHIC.

- Inclusive J/Psi yields vs event multiplicity in p+p and p+Au
  - pp results consistent with other observations at RHIC and LHC
  - Novel effects observed in p+Au in large rapidity gap correlation

- Additional studies needed to understand the physics of p+Au collisions
  - Event geometry, short and long range correlation, results versus centrality in pAu