Measurements of J/ψ production vs event multiplicity in the forward rapidity in p + p and p + Au collisions in the PHENIX experiment

Initial Stages 2023

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on behalf of the PHENIX Collaboration

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The VII-th International Conference on the **Initial Stages** of High-Energy Nuclear Collisions (IS2023), Copenhagen.

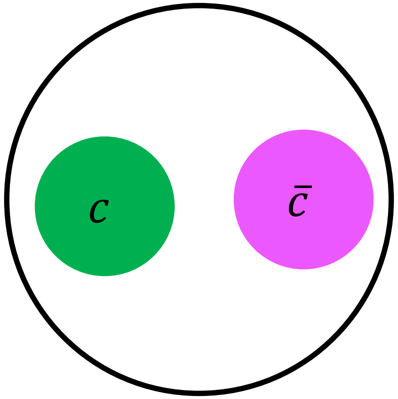
Charmonium Production for QCD Studies

Excellent Probe to Study QCD

- Large mass of charm quark: $m_c \gg \Lambda_{QCD}$
- Production cross section calculable by QCD
- Studied extensively at different colliders since discovery in 1970s

Charmonium Production Mechanism

- Multiple stage processes across many different scales: initial state, hard partonic scattering, and final state
- Hard process: first principle perturbative QCD calculations to very high precisions
- Soft processes: non-perturbative, described by the experimental data, effective theory, and phenomenological models
- Event Generator: incorporated many underlying processes and tuned the parameters with experimental data to model the event through Monte Carlo simulation



$\boldsymbol{J/\psi : J^{PC} = 1^{--}}$

Significance in Heavy-Ion Physics

- Probing nuclear parton distribution in p + A collisions
- Thermometer for the QGP in A + A collision

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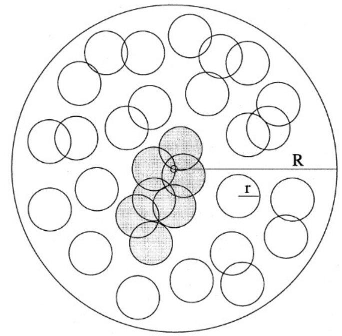
Soft Processes for J/ψ Production

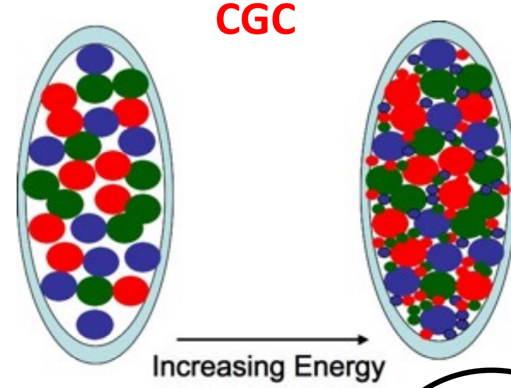
Initial State Descriptions

- Parton distribution function
- Color Glass Condensate (CGC)
- Percolation of Color Strings

Percolation



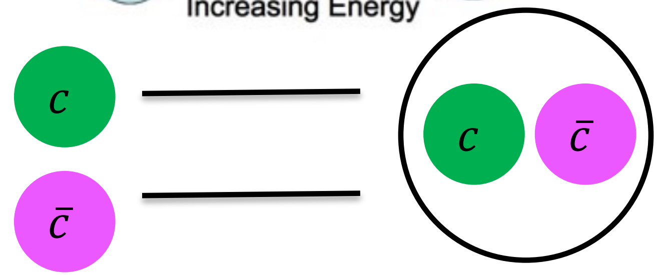
CGC



Hadronization: $c\bar{c} \rightarrow J/\psi$

- Occur after $c\bar{c}$ relative speed become non-relativistic
- Transversely polarized J/ψ production at RHIC

Color Singlet



Effective Theory: Non-Relativistic QCD (NRQCD)

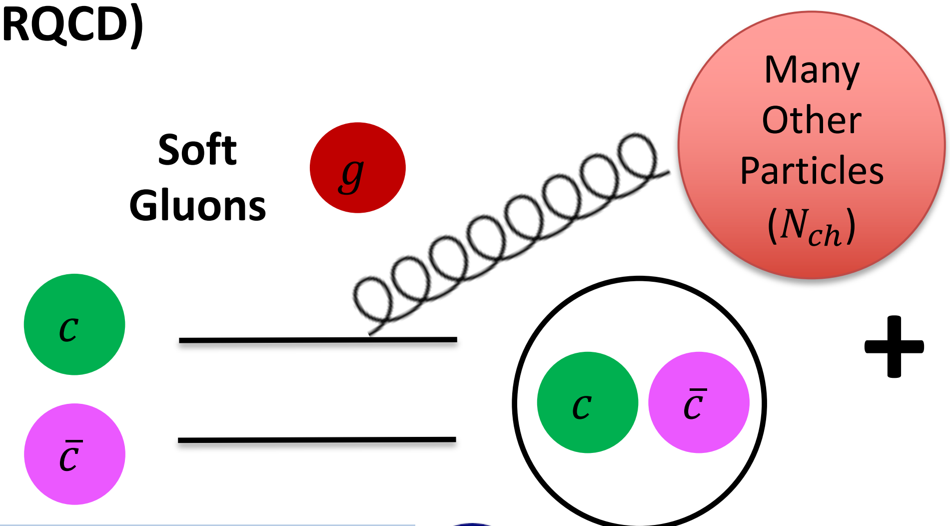
- Color Singlet (CS)
- Color Octet (CO)

Final State Comover Effect

- Modify J/ψ kinematics
- Possibly result in J/ψ break-up
- Scale with event multiplicity

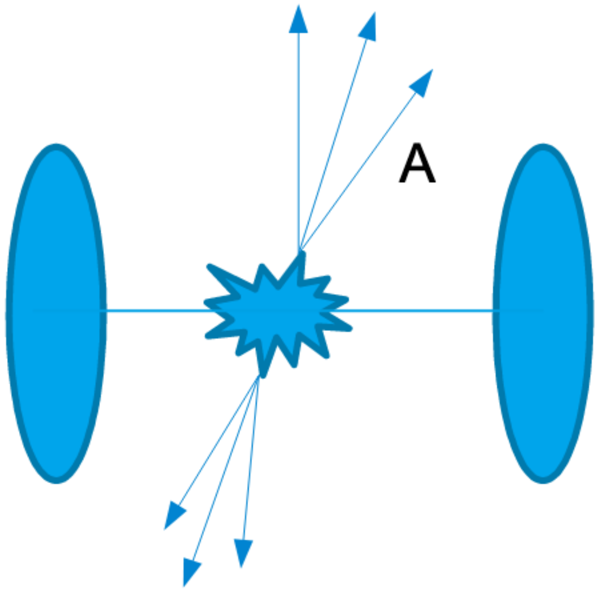
Soft Gluons

Color Octet

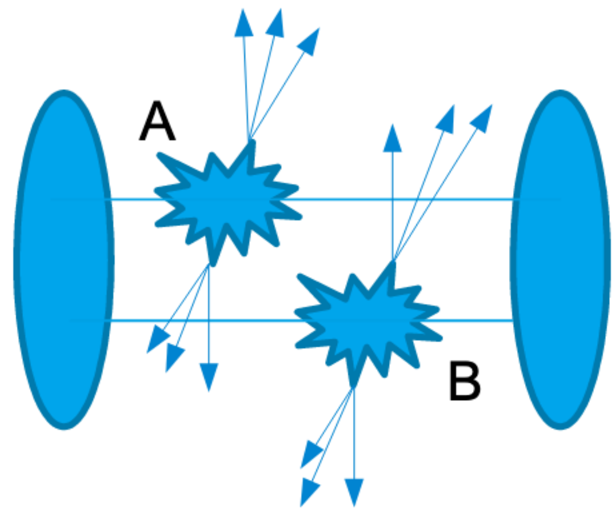


Multiparton Interactions (MPI)

Traditional pQCD Picture



Elaborated MPI Picture

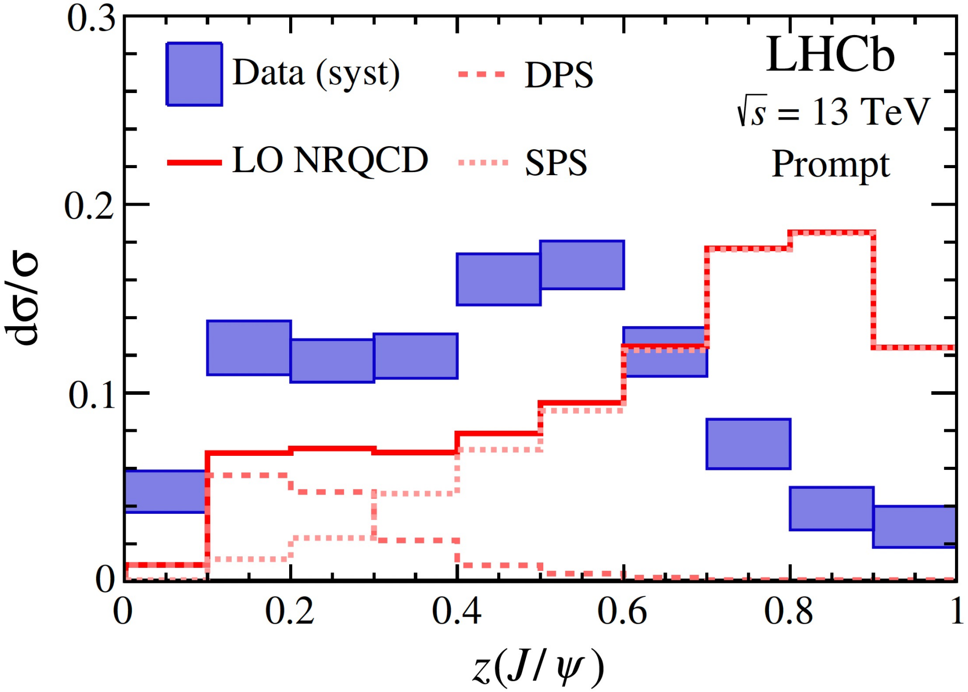


- Hadronic collider at higher energy enables the phase space for MPI
  - Allow several semi-hard scatterings near the charmonium mass
- Traditional single hard scattering picture is insufficient
  - Typically 4 – 10 scatterings at LHC pp collisions
- MPI: influence charmonium production at high energy hadronic colliders
- Enhance of J/ψ production along with color reconnection model

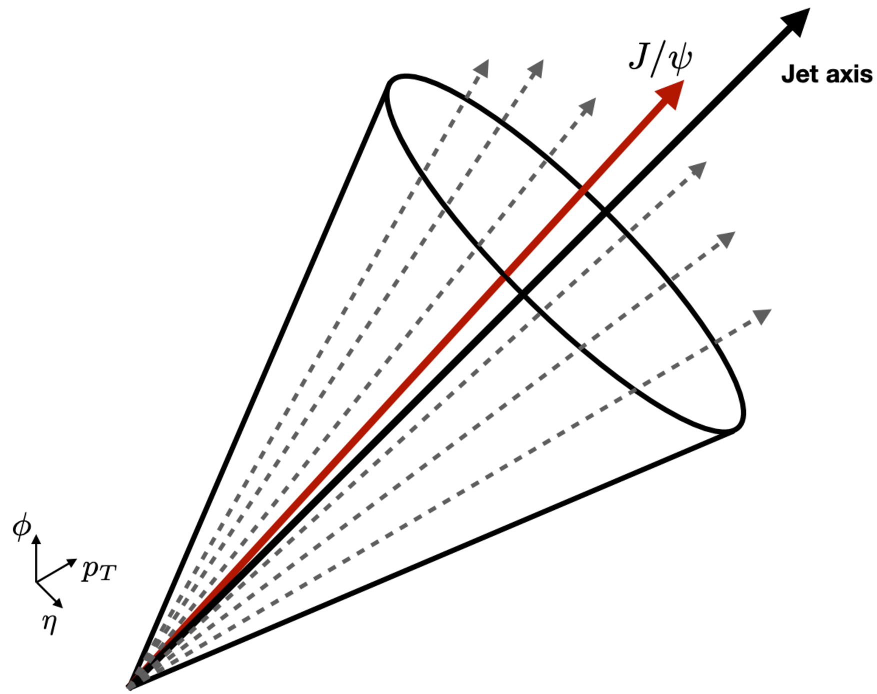
Alternative Production of J/ψ from Jets

J/ψ Production from Jets at the LHC

- Observed by the CMS experiments in both pp and AA collisions
- Unpolarized prompt J/ψ down to low p_T reported by LHCb
- Different production mechanism from NRQCD



$$z(J/\psi) = p_T(J/\psi)/p_T(jet)$$

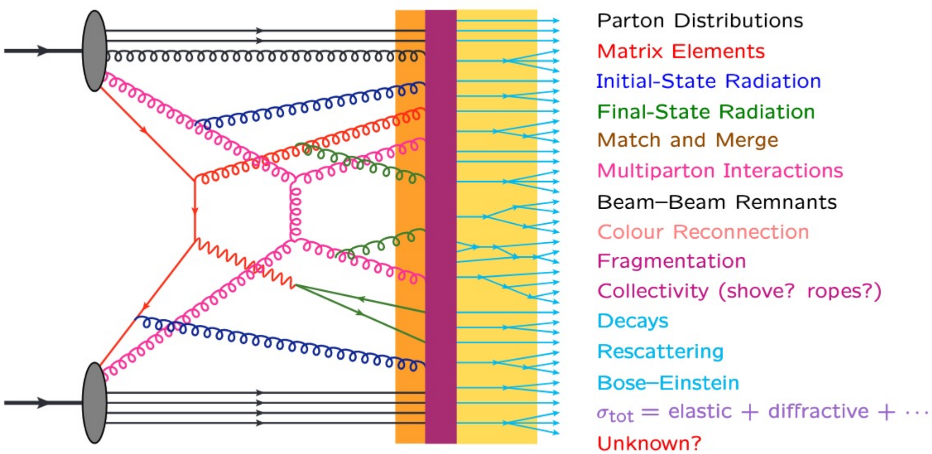


CMS: Phys. Lett. B 825 (2022) 136842

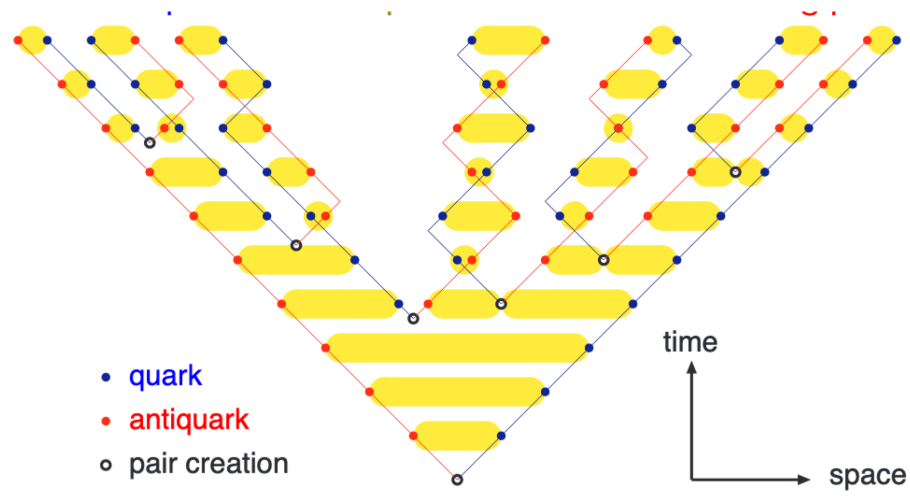
LHCb: Phys. Rev. Lett. 118, 192001

PYTHIA Event Generator

Event Structure



Hadronization: Lund String Model



- General propose MC event generator for high energy physics incorporating many physics processes across different scales
- Well describe high energy e^+e^-, ep, and pp collisions
- Recent development also applicable to pA and AA systems
- Tune the parameters to best fit to the data at different colliders
- Options to turn MPI ON and OFF
- Adjust CS and CO contribution to describe $c\bar{c} \rightarrow J/\psi$

Experimental Observables

Experimental Observables

- Goal: quantify the correlation between fully reconstructed J/ψ production and minimum biased (MB) event activity
- J/ψ self-normalized yield $R(J/\psi) = N_{J/\psi}/\langle N_{J/\psi}\rangle$ as a function of normalized charged particle multiplicity $N_{ch}/\langle N_{ch}\rangle$
  - Experimentally convenient: cancellation of luminosity and reduce systematics

Scaling Behavior Inspired by the Color String Percolation Model

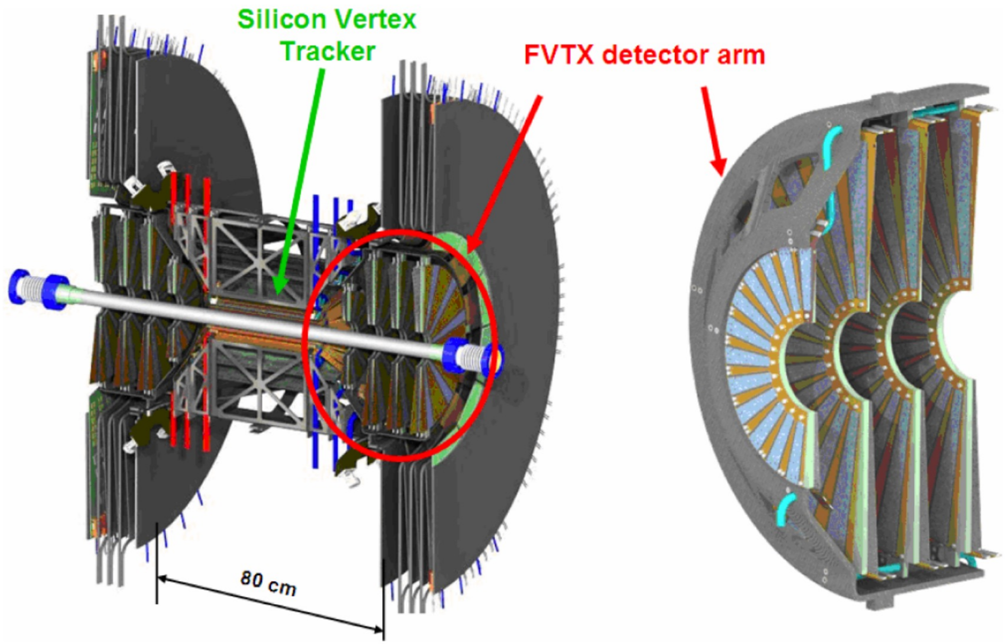
- $N_{J/\psi}$ scales as N_{coll}: partonically equivalent to the number of color strings N_s
- N_{ch} scales as N_{part}: in the partonic level proportional N_s
- Expect a linear relation $N_{J/\psi}/\langle N_{J/\psi}\rangle = N_{ch}/\langle N_{ch}\rangle$

Autocorrelation: contribution to charged particle multiplicity

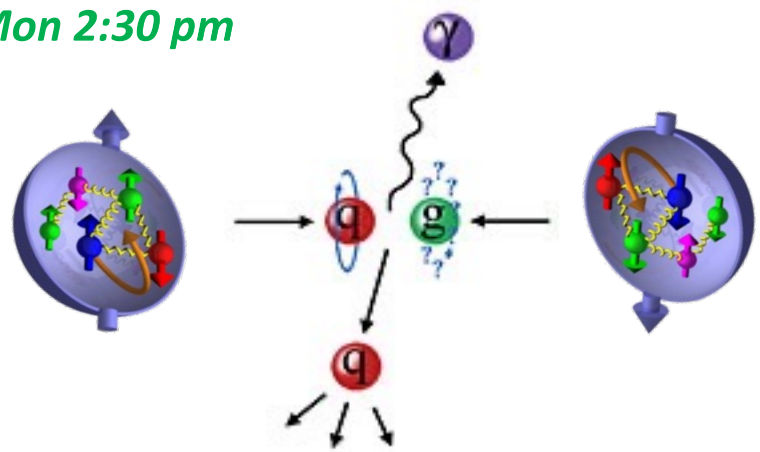
- J/ψ decay daughters
- In NRQCD, J/ψ produced as $gg \to [c\bar{c}]g$ where the extra gluon hadronization
- J/ψ cluster collapsing into hadrons
- Non-prompt J/ψ: feed down from b hadron decays
- In general increase the multiplicity in J/ψ production events

Triggers and Data Sample

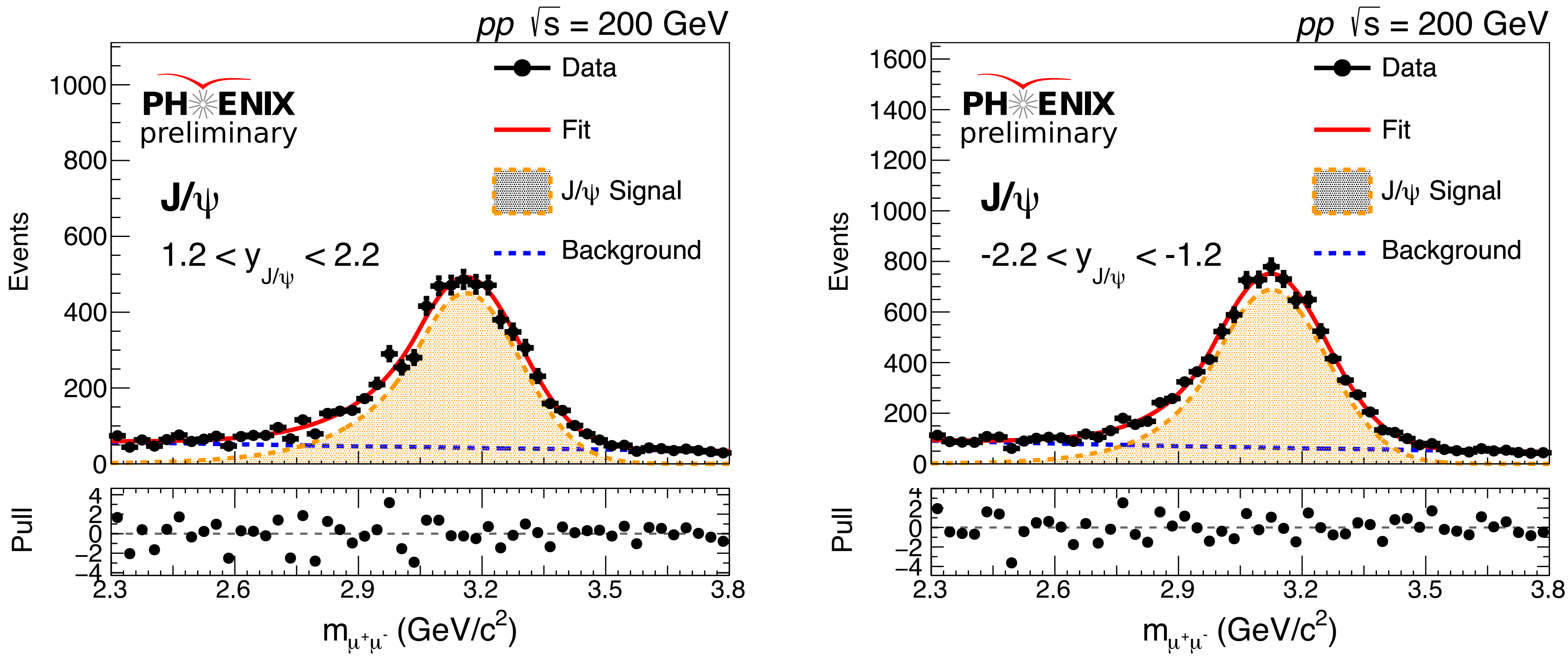
- **PHENIX 2015 $p + p$ at $\sqrt{s} = 200$ GeV data at RHIC**
  - Polarized proton beam
  - Excellent muon performance
  - Good vertexing and tracking
  - Large data sample
- **RHIC Beam Clock Trigger**
  - Used for efficiency studies
- **MB Trigger**
  - Trigger on non-diffractive inelastic pp collision events
  - Normalization for J/ψ analysis
- **Dimuon trigger**
  - Trigger on hard scattering dimuons to enrich J/ψ statistics



Axel Drees, Mon 2:30 pm



J/ψ Signal Raw Yield Extraction



- Clear J/ψ resonances observed
- A small $\psi(2S)$ signal also seen
- Good J/ψ invariant mass resolution with the peak near 3.1 GeV/c^2
- J/ψ kinematics: $\langle p_T \rangle = 1.7$ GeV/c and $1.2 < |y| < 2.2$
- Higher J/ψ yield in the backward rapidity due to the muon arm efficiency

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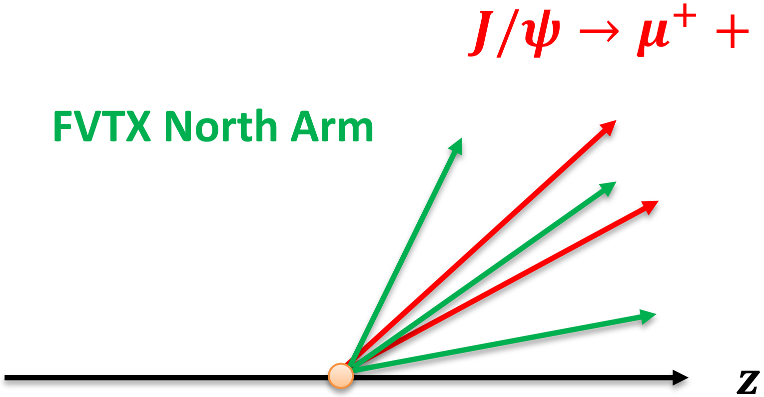
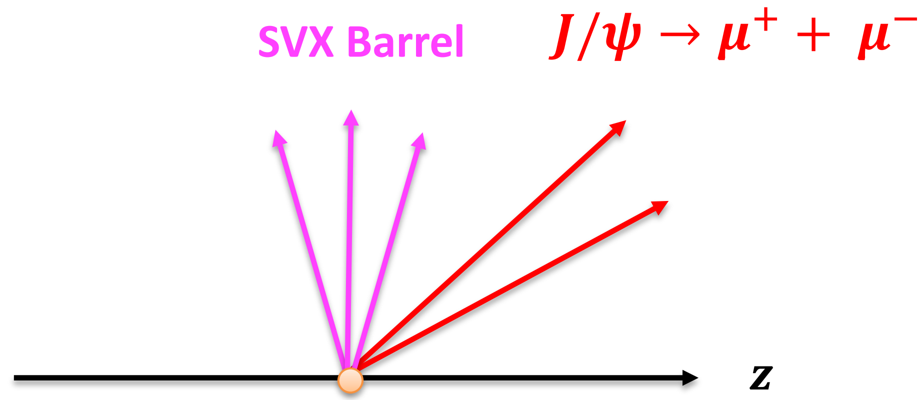
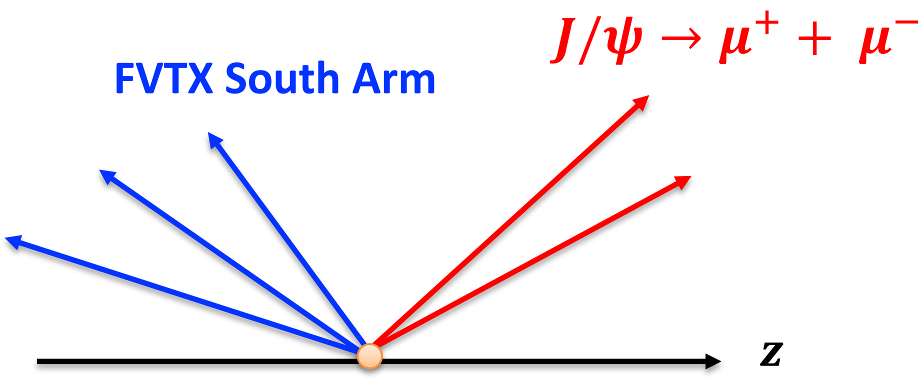
Presentation of Measurements



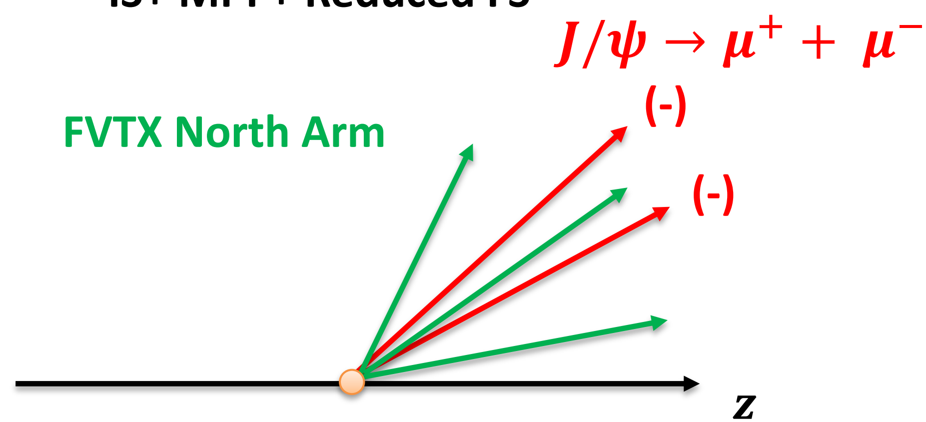
Same Muon and FVTX Arm
IS + MPI + FS



Muon Arm and SVX
IS+ MPI + Reduced FS



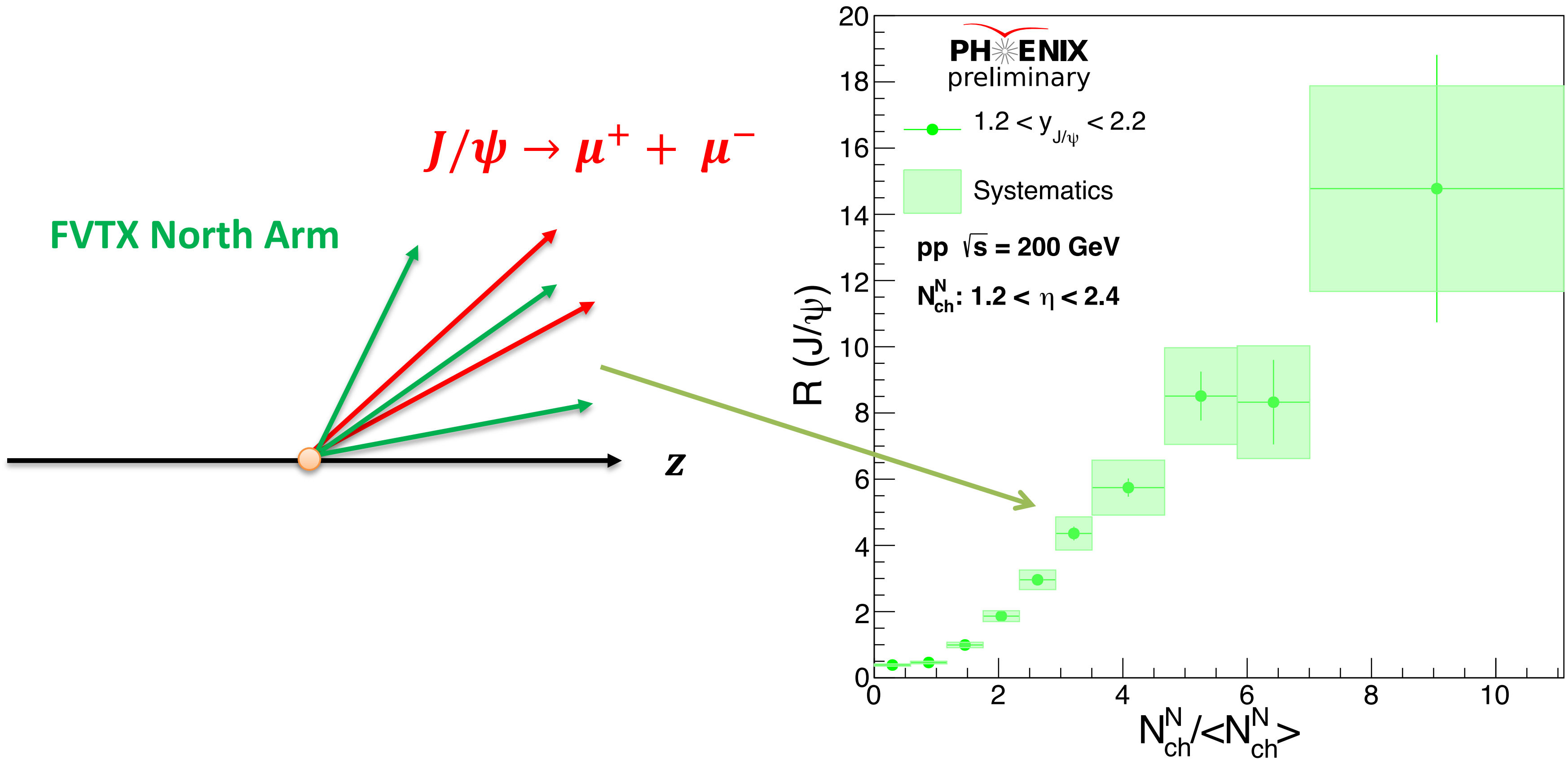
Opposite Muon and FVTX Arms
IS + MPI



Same Muon and FVTX Arm with dimuon subtracted
IS + MPI + Reduced Autocorrelation

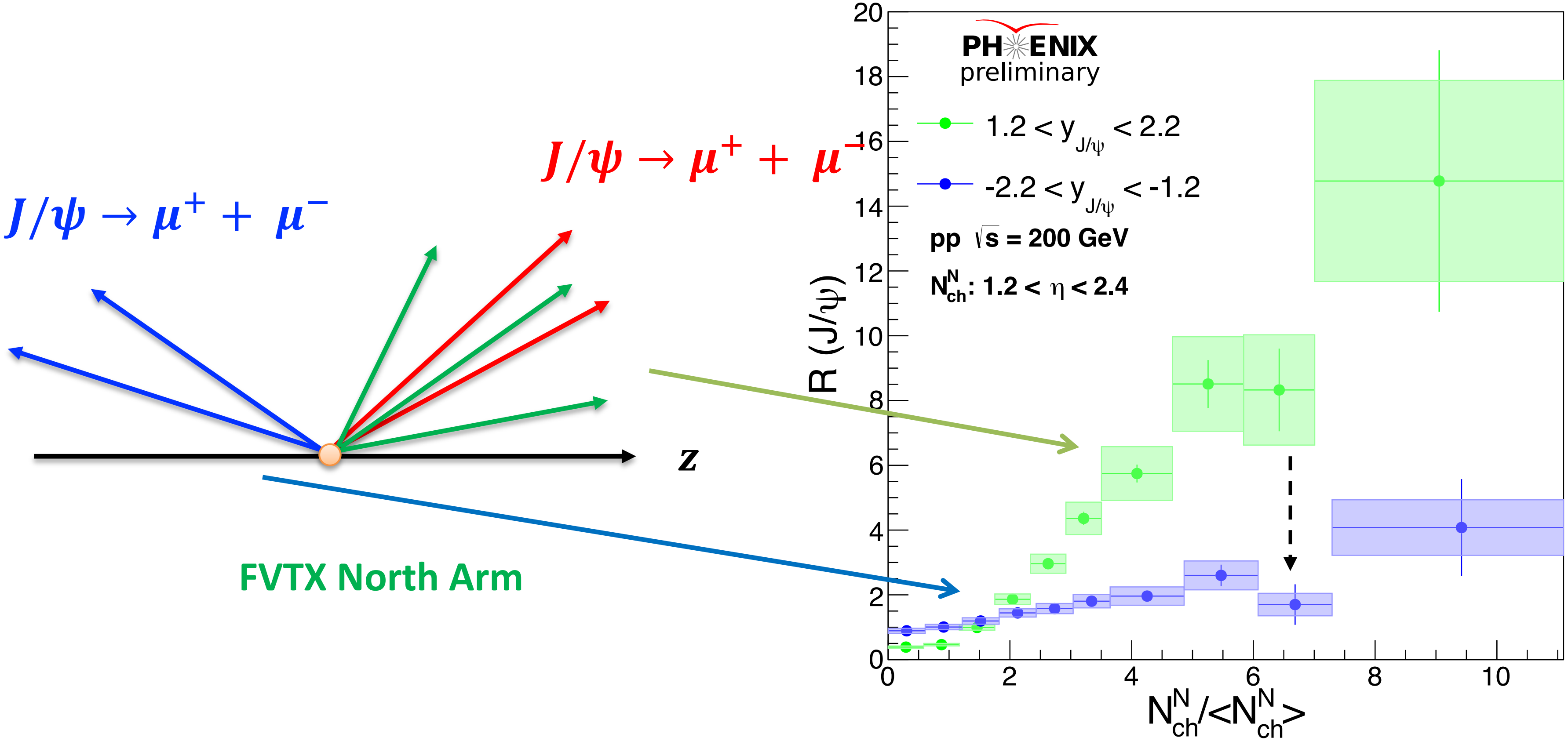
- Study different underlying physics processes with Δy between J/ψ and charged particles
- Also subtract the dimuon to reduce autocorrelation effect in our measurements

J/ψ Production in the Same Kinematic Region



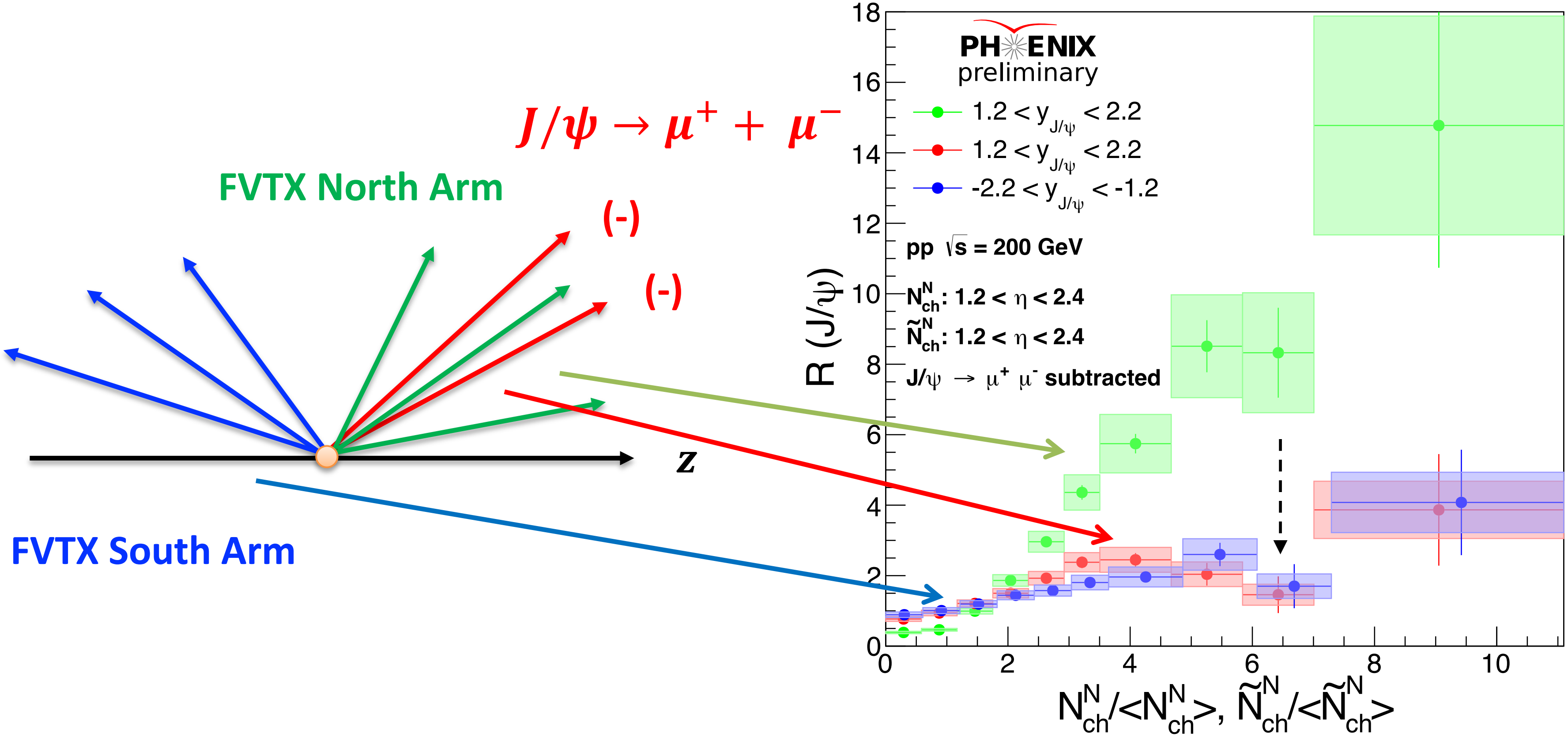
- MPI and FS contribution along with autocorrelation effects
- $R(J/\psi)$ with a slope greater than 1
  - Significant enhancement beyond linear scaling
- Broad range of measurement up to $N_{ch}/\langle N_{ch}\rangle \sim 10$

J/ψ Production in the Opposite Kinematic Region



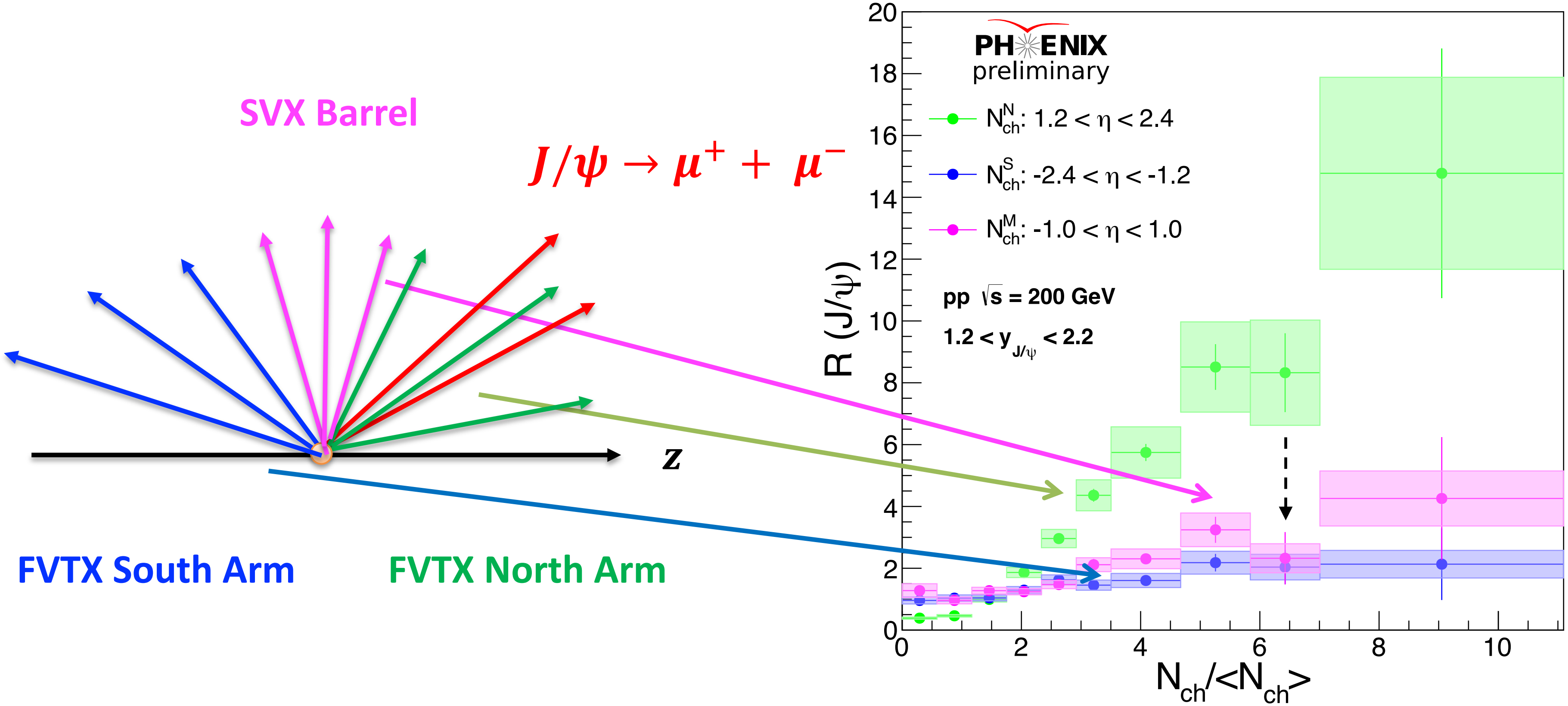
- FS significantly reduced
- $R(J/\psi)$ significantly reduced with respect to same kinematic region
- Large uncertainties at very high multiplicity bins due to limited statistics

J/ψ Production with Dimuon Subtracted



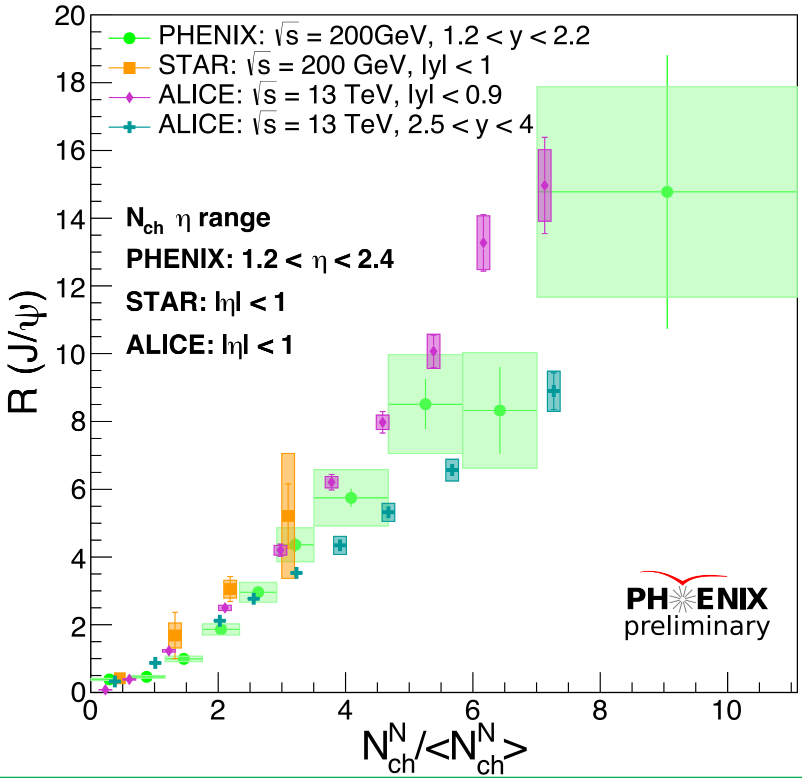
- Suppress the dimuon autocorrelation contribution to the charged particle multiplicity for J/ψ produced in the same kinematic region
- $R(J/\psi)$ significantly reduced and becomes fully consistent to J/ψ produced in the opposite kinematic region

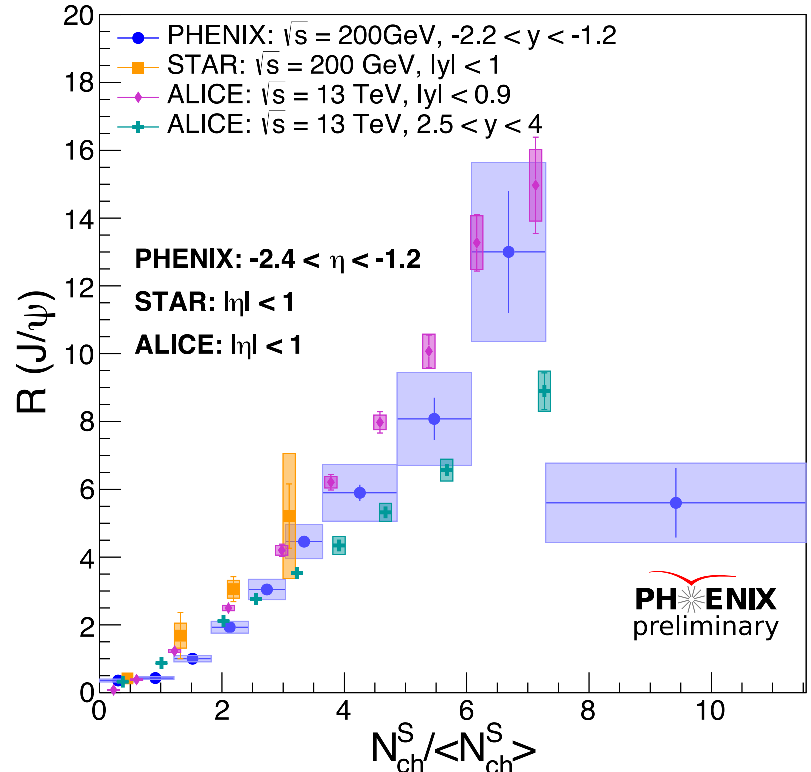
Rapidity Comparison



- Reduction of autocorrelation effect of J/ψ on particle production of the measured kinematic regions
- $R(J/\psi)$ decreases of observed as the rapidity gap of the kinematics increases

Comparison to Other Experiments



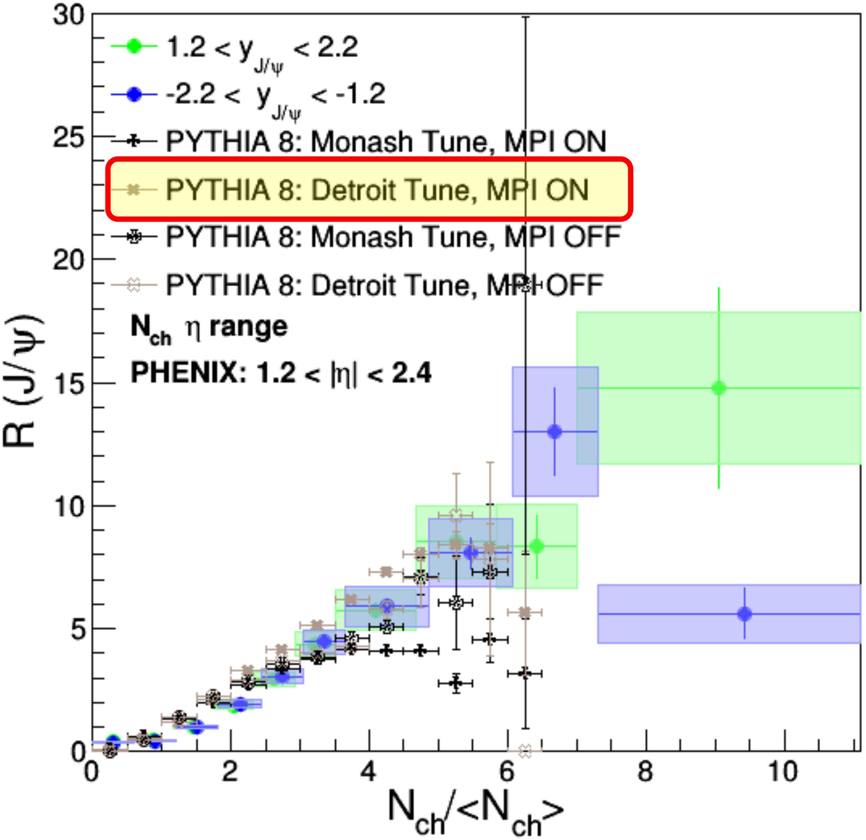


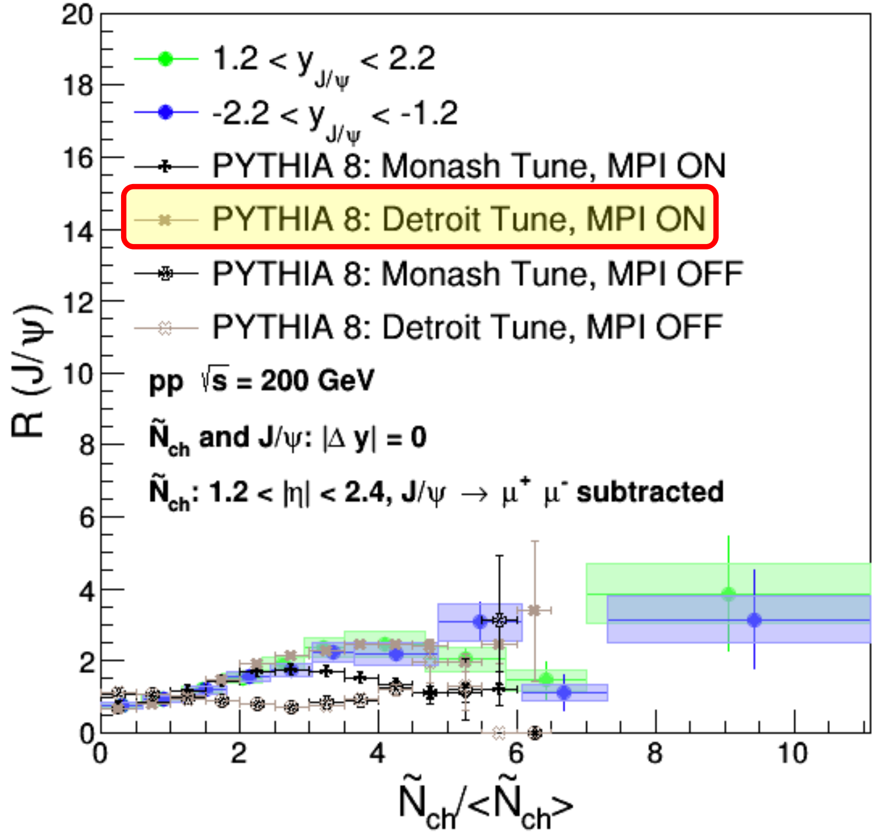
ALICE: Phys. Lett. B 498810 (2020) 135758

STAR: Phys. Lett. B 786 (2018) 87-93

- $R(J/\psi)$ higher at mid-rapidity than forward region
  - Confirmed with **ALICE** mid-rapidity and forward rapidity measurements
  - **Data** systematically below **STAR** mid-rapidity as expected
- **Data** in between **ALICE** mid-rapidity and forward rapidity, filling the rapidity gap
- Significant enhancement observed by PHENIX and ALICE at high multiplicity

Comparison to PYTHIA 8 Simulations



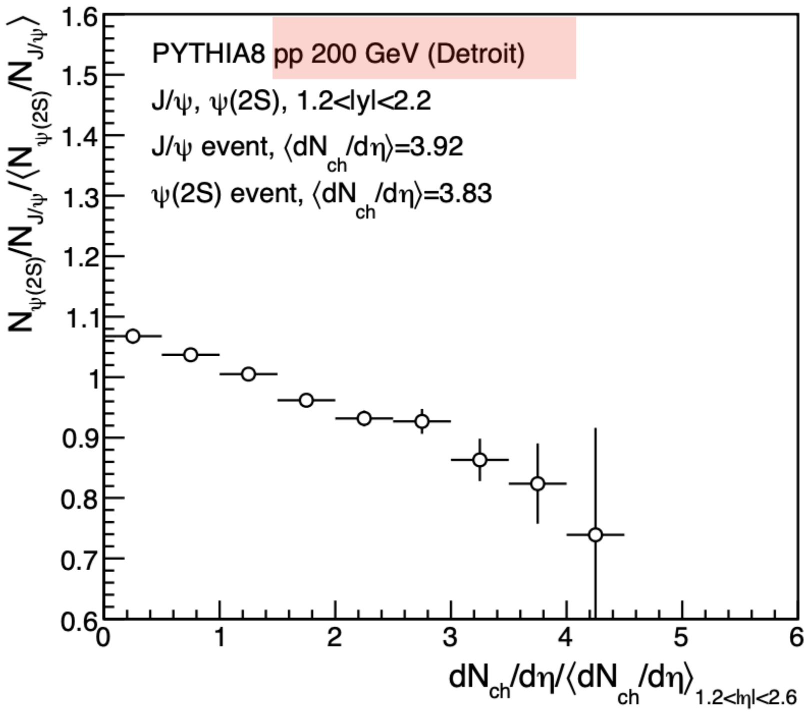


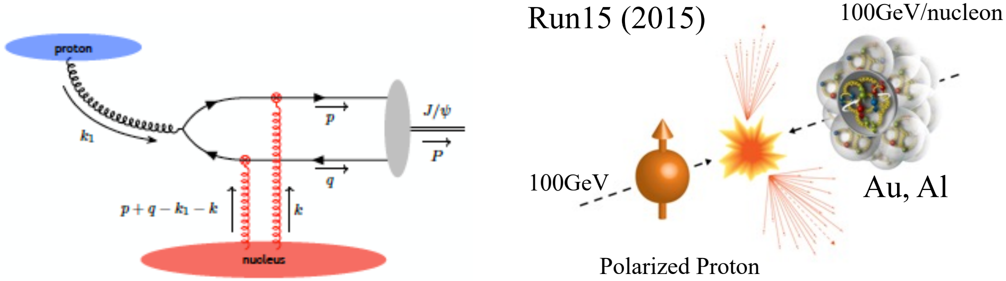
- Comparison with PYTHIA 8 Monash and Detroit Tunes with MPI ON and OFF in the generated level
- **PYTHIA 8 Detroit Tunes with MPI ON** best describes the data

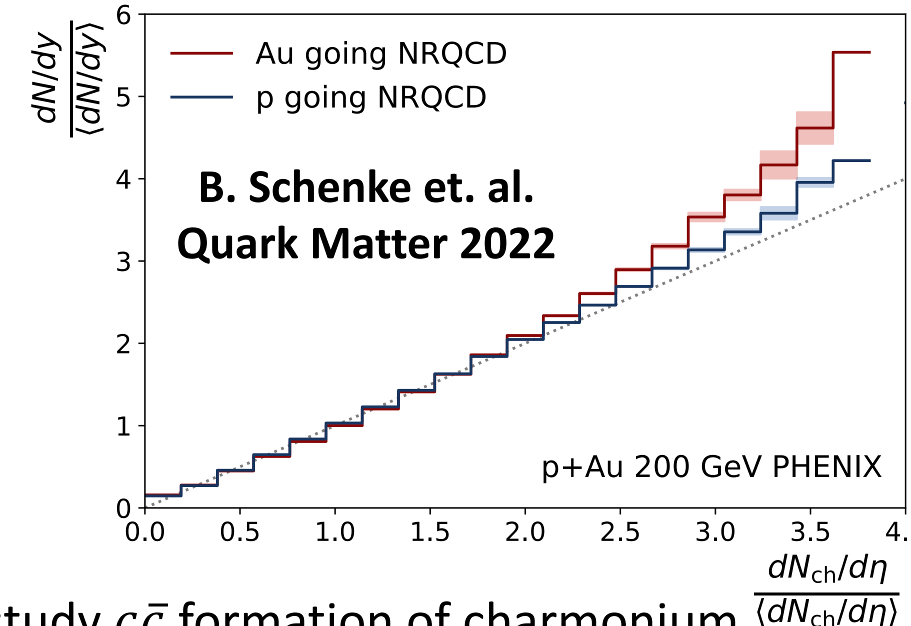
Ongoing Further Studies

PYTHIA 8: $\psi(2S)/J/\psi$

Detroit, PHENIX acceptance, pp 200 GeV





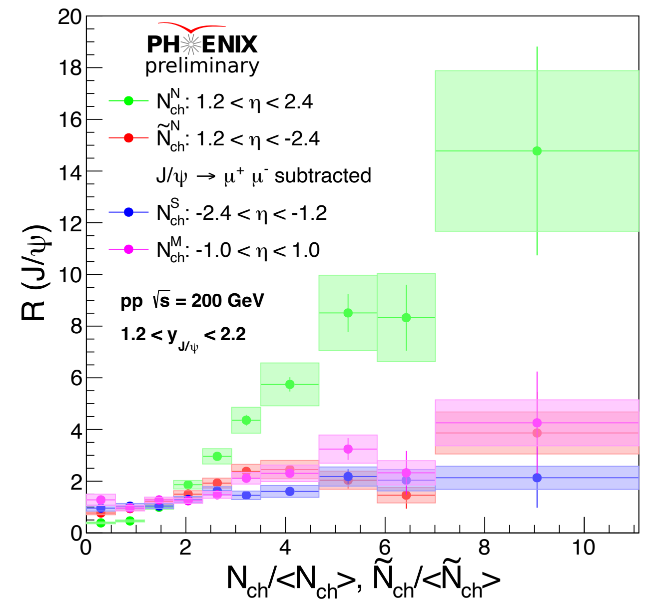


- $\psi(2S)/J/\psi$ ratio as a function of N_{ch} to study $c\bar{c}$ formation of charmonium
  - Generated level PYTHIA 8 simulation with decreasing trend
- $R(J/\psi)$ studies in p + Au and p + Al to probe the CGC region in nucleus
  - Theoretical calculations carried out

Summary

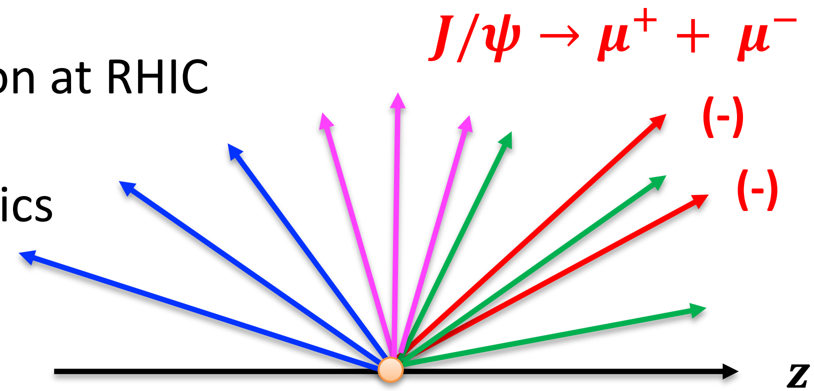
Preliminary Results

- Steep rise and beyond linearity for $R(J/\psi)$ on $N_{ch}/\langle N_{ch}\rangle$ in the same kinematic region
- $R(J/\psi)$ on $N_{ch}/\langle N_{ch}\rangle$ decreases as rapidity gap between J/ψ and charged particles increases
- After dimuon subtraction, $R(J/\psi)$ decreases and becomes consistent to opposite kinematic region



Physics Messages

- MPI effect needs to be considered
- Important for heavy-ion physics
- Possible J/ψ production from jet fragmentation at RHIC
  - Pronounced at high p_T
  - May be inconclusive due to limited statistics



Outlook

- $\psi(2S)/J/\psi$ ratio vs N_{ch} in p + p
- $R(J/\psi)$ in p + Au and p + Al to test CGC model

STAY TUNED!

Acknowledgement

- This work is supported by the United States Department of Energy Office of Science and Los Alamos National Laboratory Laboratory Directed Research & Development (LDRD)

- **Thank you very much for your attention!**

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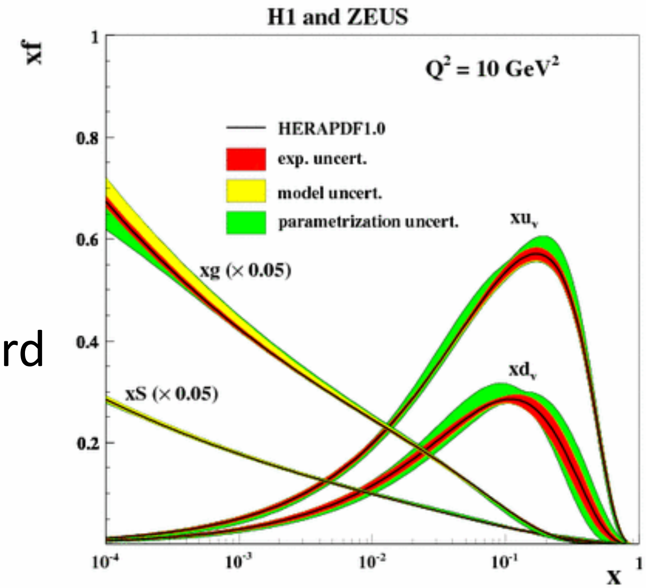
Back Up

Initial State Effects



Initial Parton Dynamics in Hadrons

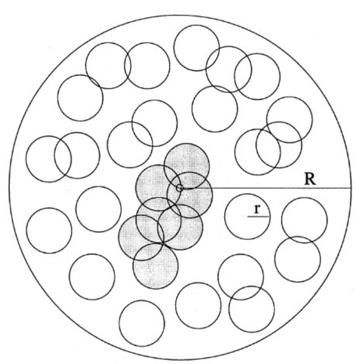
- Initial ion partonic structure
- Encoded in PDF and more generally GPD

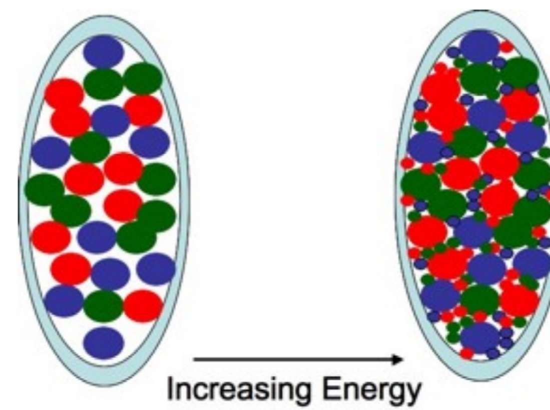
Initial State Radiation (ISR)

- Occur after partons become energetic and before hard partonic interactions
- Generally soft and non-perturbative → models to explain experimental data
- Contribute to the initial kinematics $c\bar{c}$ production

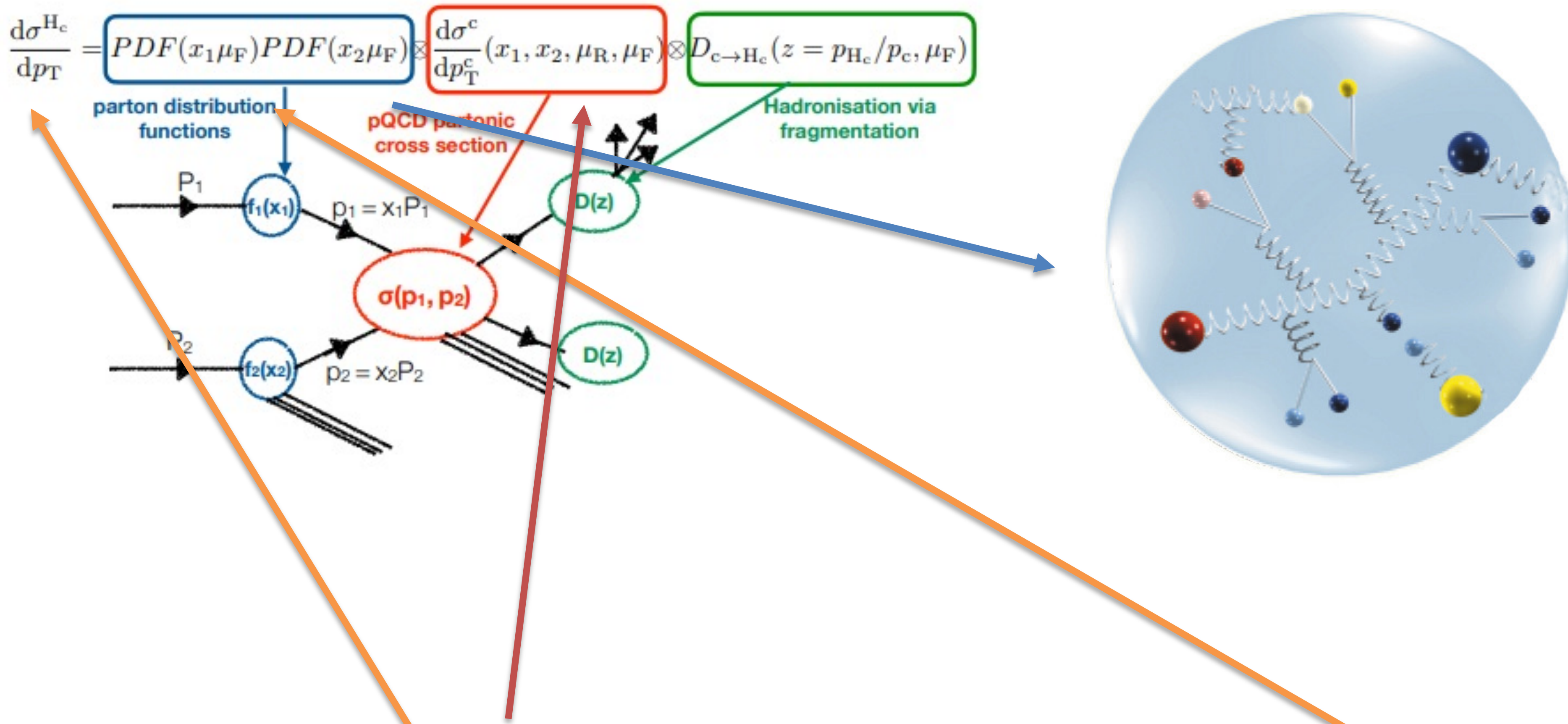
Models describing initial state in pp collisions

- Color Glass Condensate (CGC)
- Pomeron Exchange
- Higher Fock State in the Proton
- Higher Density EPOS effect
- Percolation of color strings





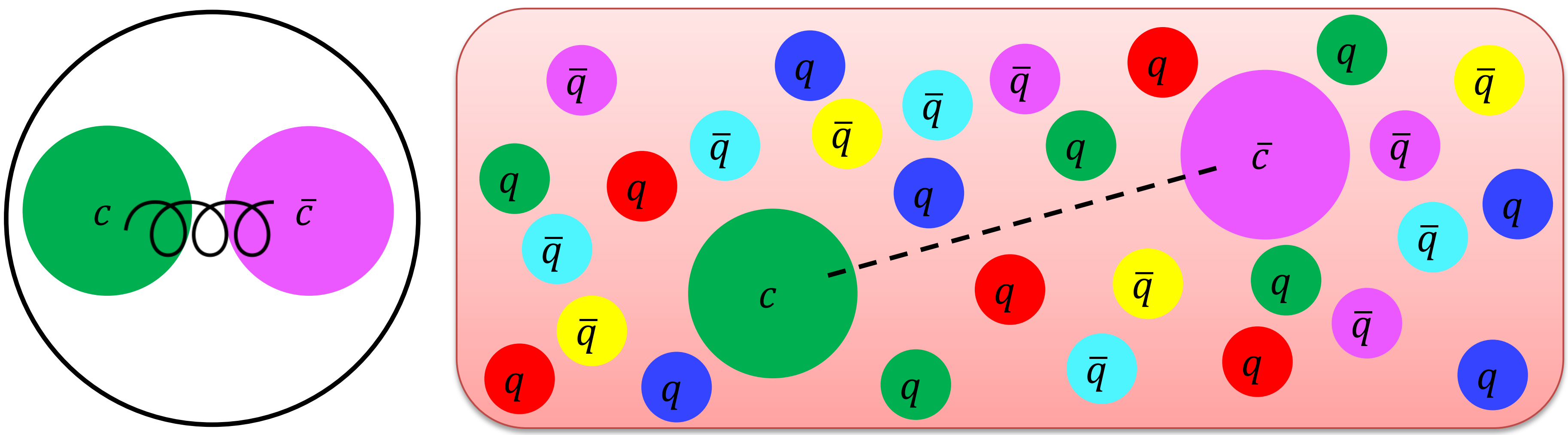
Precision Nucleon Structure



- Reformulation pQCD calculation
- Correctly use **charmonium cross section data** to precisely extract the **PDF**
- PDF describes the nucleon structure
- Benefit many studies in Nuclear Physics before EIC

Thermometer for QGP in Heavy Ion Physics

- Quark-Gluon Plasma (QGP) is one of the main topics in High Energy Nuclear Physics
- QGP is also related to cosmology as it is created in the early universe, several microseconds after the Big Bang
- Charmonium suppression in AA collisions used as a thermometer to measure the temperature of QGP via the color effect



Autocorrelation Contributions

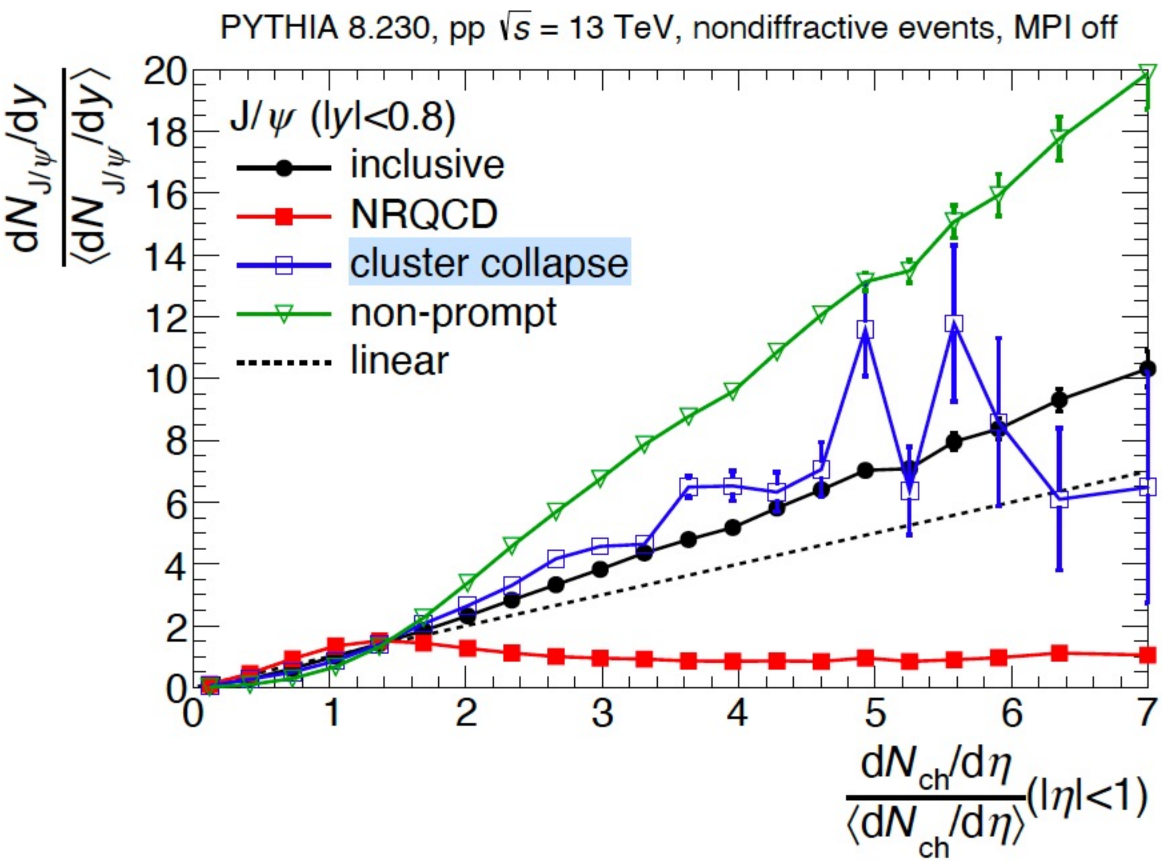
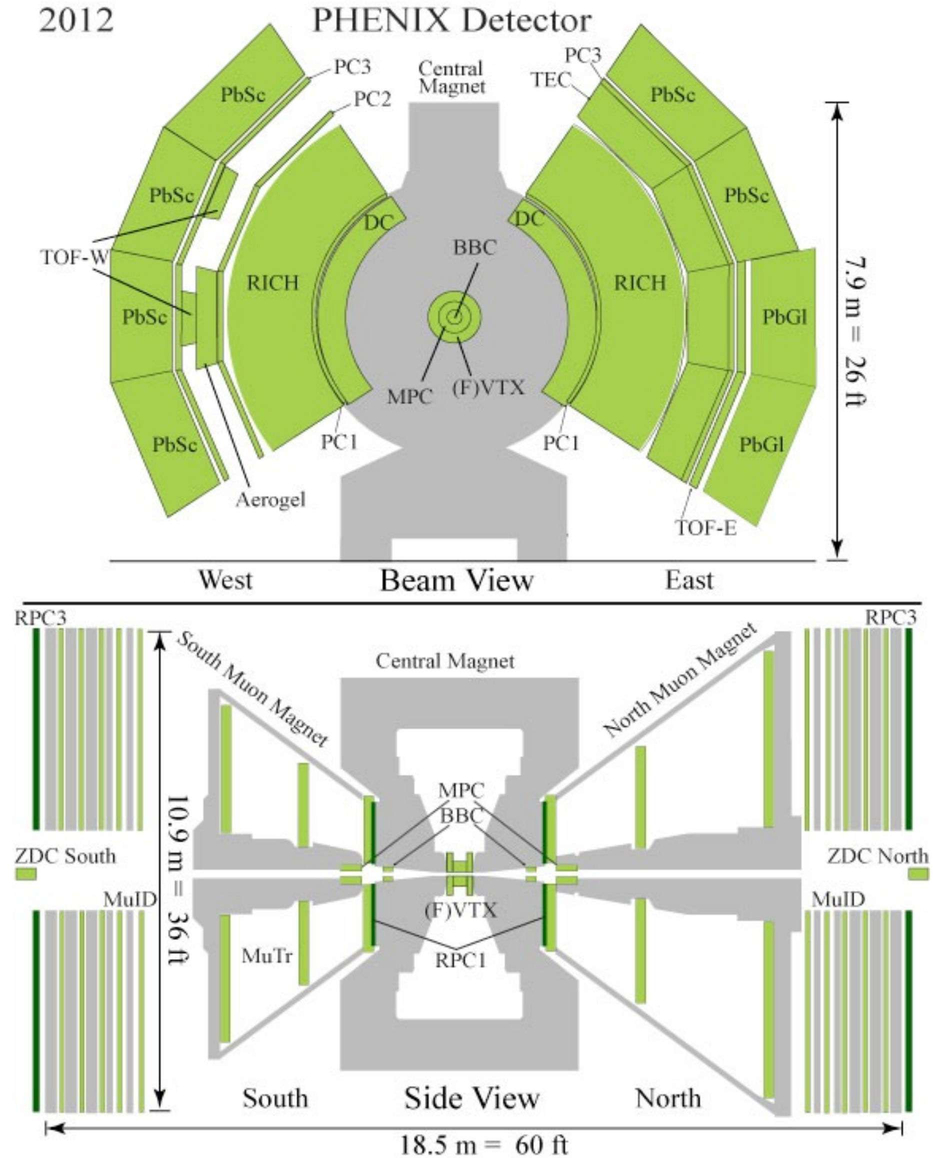


Figure 8. Mid-rapidity J/ψ production as a function of mid-rapidity multiplicity in events without MPI from PYTHIA8.

The PHENIX Detector at RHIC

- PHENIX: international collaboration on high energy nuclear physics at RHIC
- Large datasets acquisition with dedicated triggers
- Excellent muon reconstruction and identification capabilities
- Good vertexing and tracking performance for heavy flavor physics studies



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Comparison to PYTHIA 8 Simulations

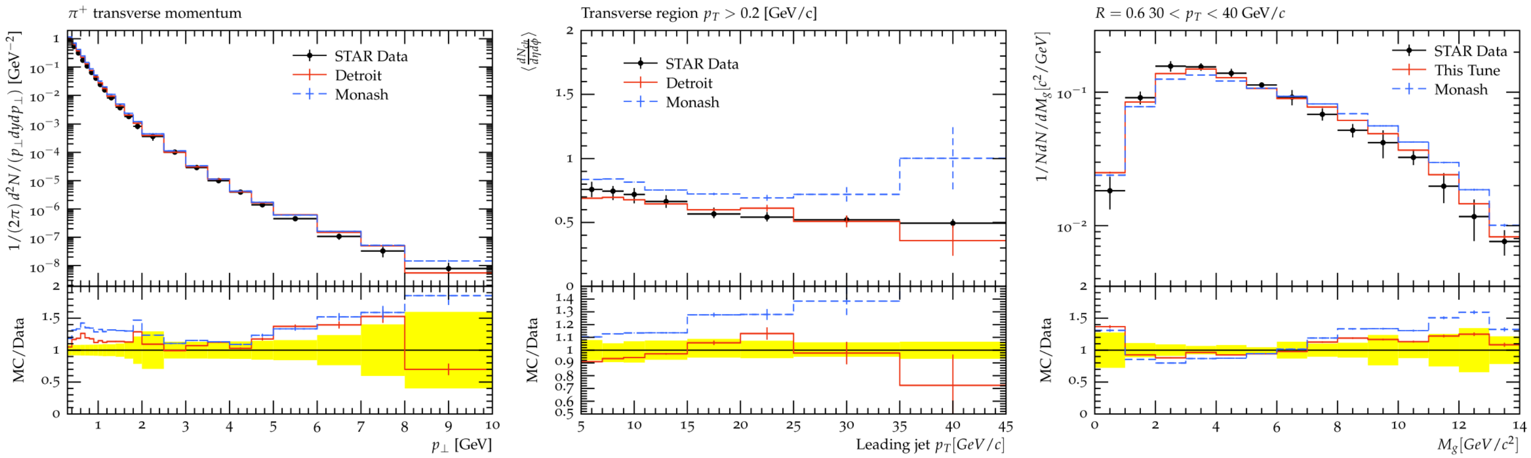
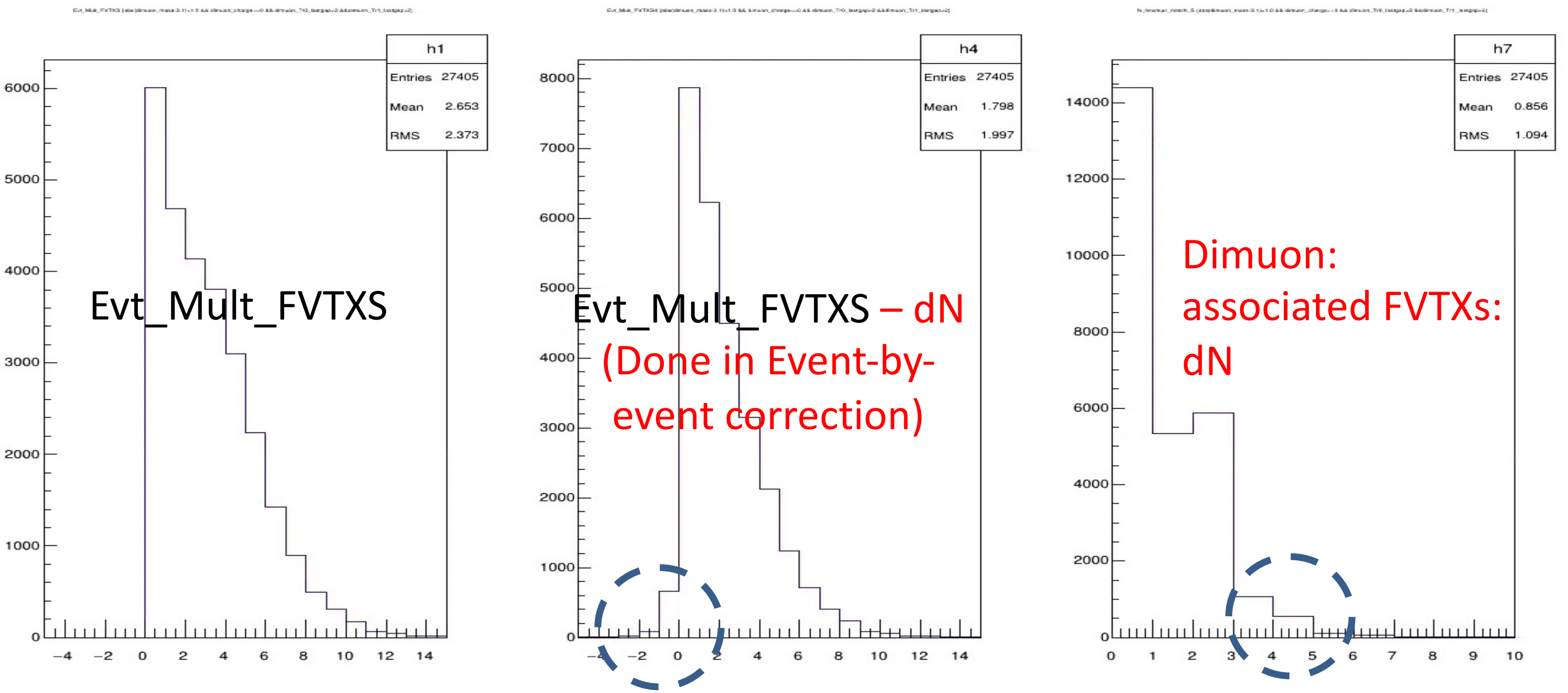


FIG. 3. Comparison of the default (blue dashed) and Detroit PYTHIA8 tunes (red solid) with mid-rapidity π^+ cross sections as a function of p_T (left) [24], UE multiplicity as a function of leading jet p_T (middle) [15], and the SoftDrop groomed jet mass (right) [27] in $p+p$ collisions at $\sqrt{s} = 200$ GeV measured by the STAR experiment. The bottom panels in each figure show the ratios of the Monte Carlo predictions with respect to the data and the yellow shaded region shows the data uncertainties.

- Detroit Tune:
- Describe RHIC charged particle $dN/d\eta$ data reasonably well
-

Muon-FVTX Matching Correction on the Same Arm

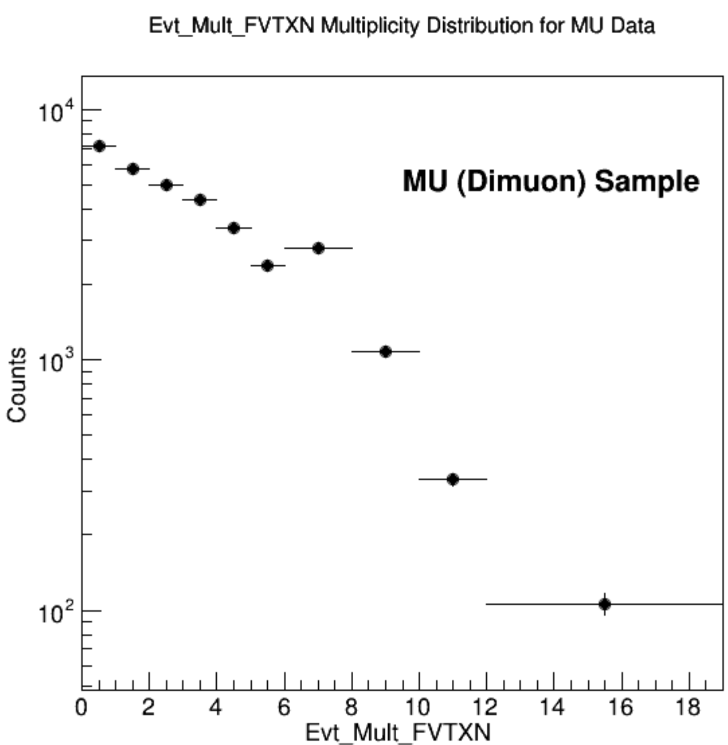


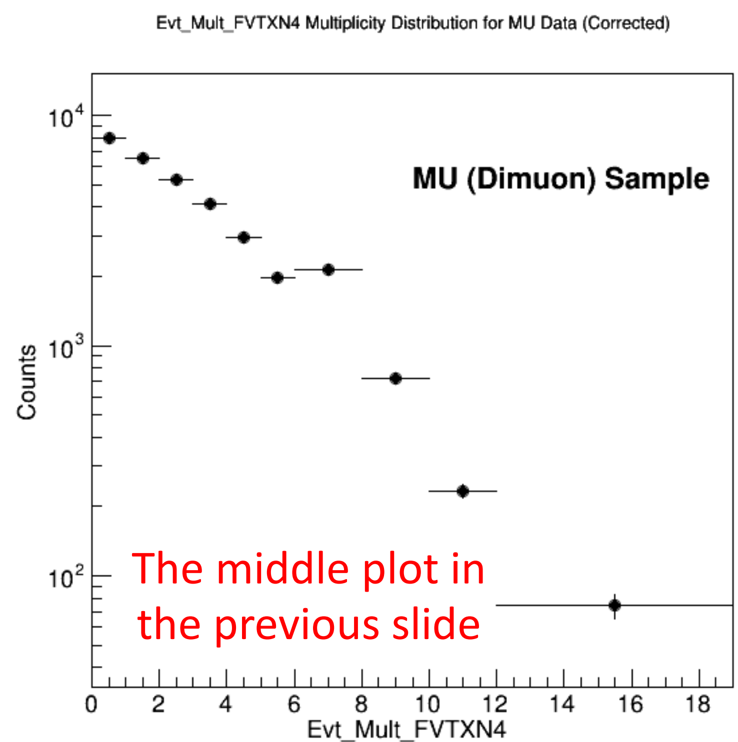
- dimuon_mass > 2 GeV
- Tr0(1)_chi2_fvtxmutr < 3, good matching between MuTr track and FVTX tracklet
- Tr0(1)_nhits_fvtx >= 2, FVTX tracklet has at least 2 hits
- Tr0(1)_lastgap >= 3, must be a good muon candidate

- Remove FVTX tracklets if from the muons in the Evt_Mult_FVTX counting
- Small fraction of over-subtraction - if more than 1 pair of dimuons

Modification on the FVTX Tracklet Multiplicity

- There is an about p = 70% of probability that a muon matched to an FVTX tracklet
- For the same arm, the average contribution of two muons from the J/ψ is given by the binominal distribution:
  $<\Delta N> = Np = 2 \times 0.7 = 1.4$
- We need to apply this correction to dimuon sample of North J/ψ on FVTXN and South J/ψ on FVTXS by recalculation the multiplicity (FVTXN/S -> FVTXN/S4)





Data-Driven Determination of Efficiency

MB trigger efficiency:

$$\epsilon_{trig}^{MB} = \frac{CLK\ \&\ FVTX\ \&\ BBCLL1}{CLK\ \&\ FVTX}$$

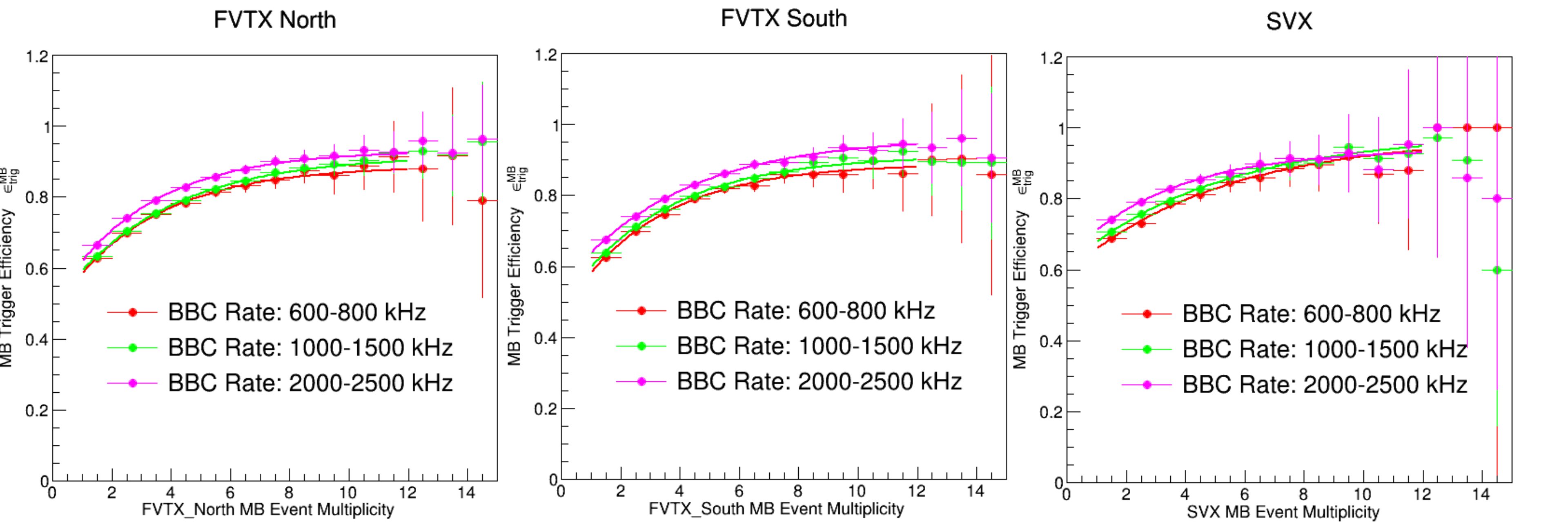
- The clock trigger data sample is used to determined MB trigger efficiency

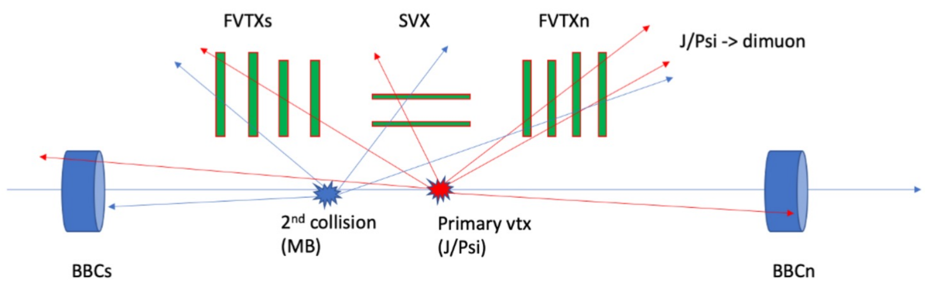
J/ψ trigger efficiency:

$$\epsilon_{trig}^{J/\psi} = \frac{ERT\ \&\ SVX\ \&\ BBCLL1}{ERT\ \&\ SVX}$$

- The ERT triggered data sample is used to determined MB trigger efficiency
- There might be correlation between ϵ_{trig}^{MB} and $\epsilon_{trig}^{J/\psi}$ but at this stage we just treat them uncorrelated
- Both of ϵ_{trig}^{MB} and $\epsilon_{trig}^{J/\psi}$ have multiplicity dependence. They converge to unity as multiplicity increases

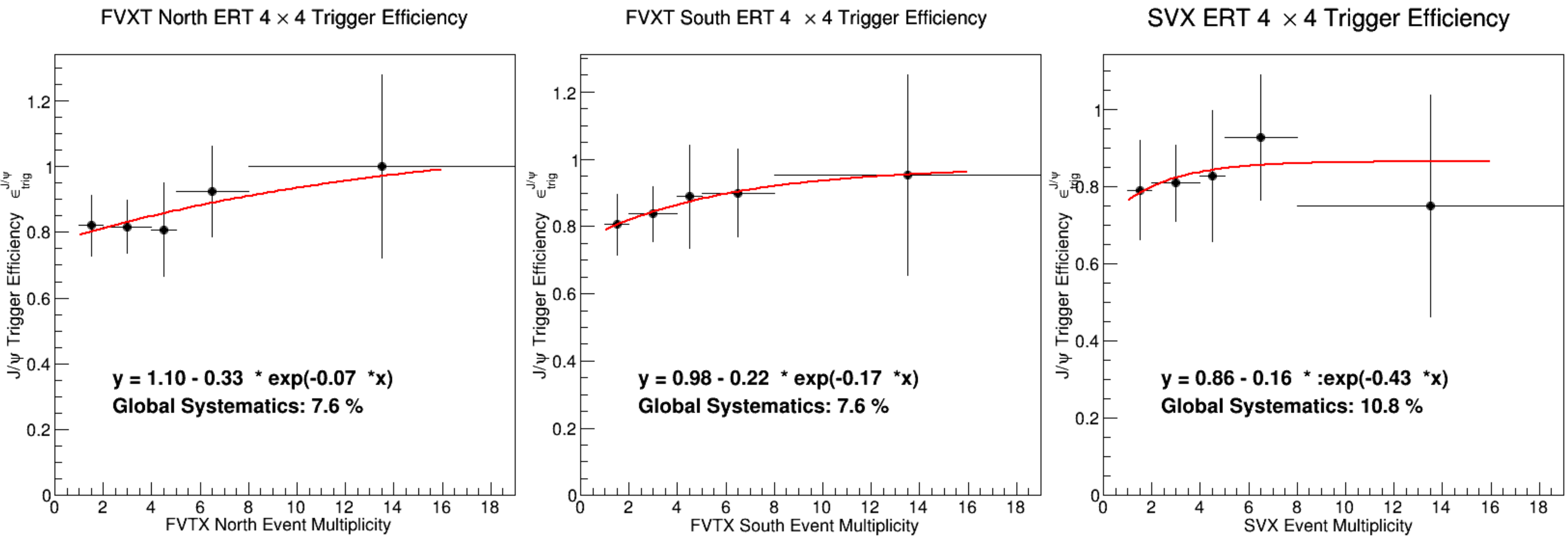
MB Trigger Efficiency Studies

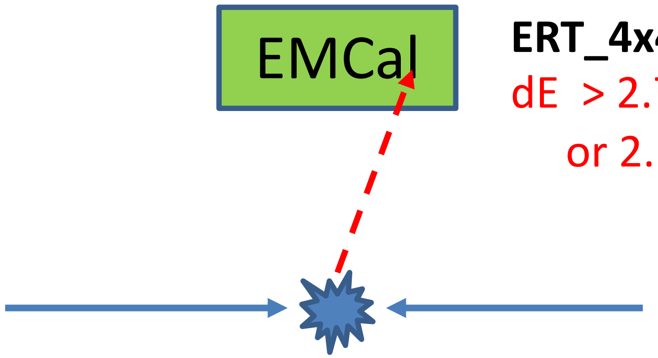




- We obtain the MB trigger efficiency for 3 BBC rate classes: 600 – 800 kHz, 1000 – 1500 kHz, and 2000 – 2500 kHz
- We fit them with functions and evaluate it by the bin center to obtain the efficiency

J/ψ Trigger Efficiency Studies

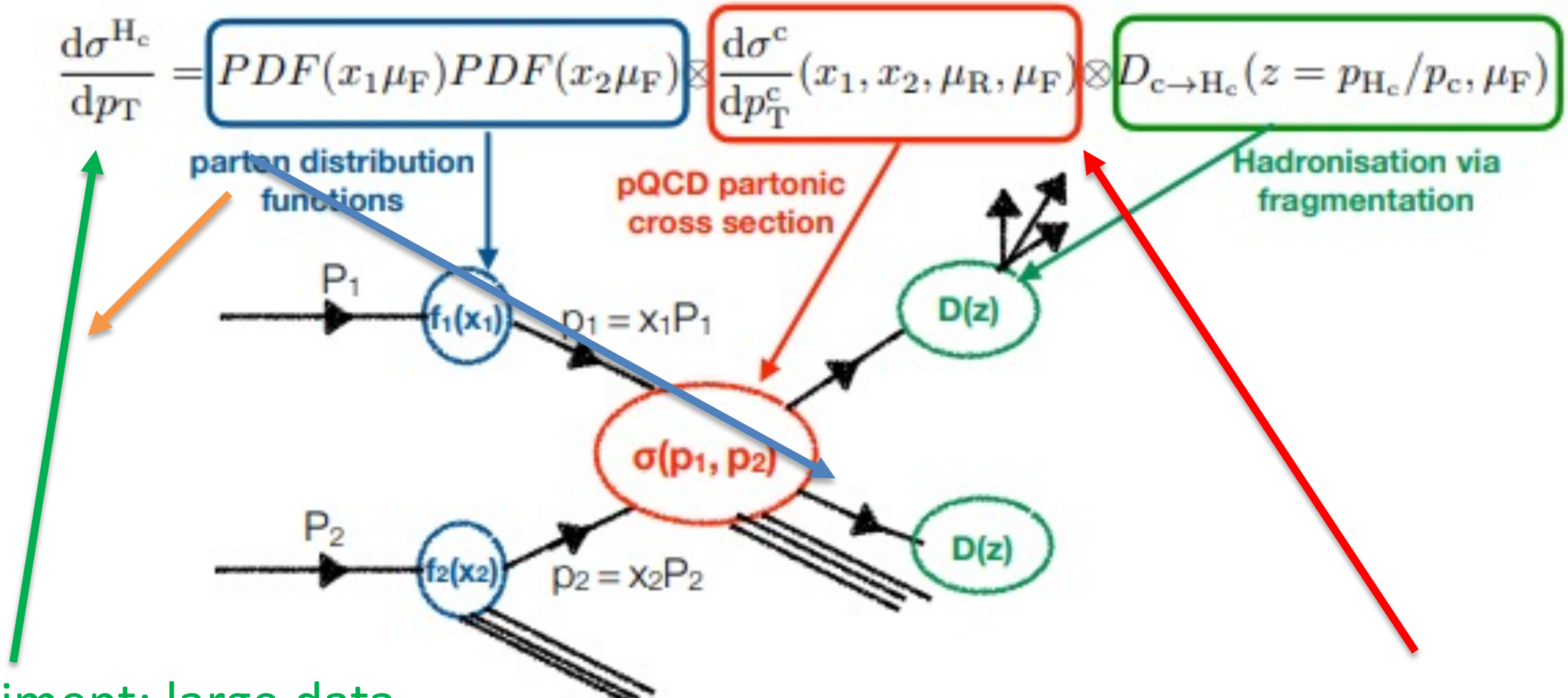




ERT_4x4b:
dE > 2.7GeV/PbSc
or 2.1GeV/PbGl

- Like the MB trigger efficiency, we fit the J/ψ with functions and evaluate it by the bin center to obtain the efficiency

Toward the Era of High Precision QCD



Experiment: large data collection with novel analysis techniques to improve the measurements and constrain PDF(x) and D(z)

Comparison

Theory: high precision N^3LO pQCD calculations with advanced computing

- Better understand J/ψ production mechanism → also beneficial measure the temperature of quark-gluon plasma produced in AA collisions

Data Analysis Strategies

Goal: measure J/ψ normalized yield vs normalized charged particle multiplicity

$$R(N_{ch}/\langle N_{ch}\rangle) = \frac{N_S^{J/\psi}\epsilon_{trig}^{MB}}{N_{Recorded}^{MB}\epsilon_{trig}^{J/\psi}} \Big/ \frac{N_S^{J/\psi(tot)}\langle\epsilon_{trig}^{MB}\rangle}{N_{Recorded}^{MB(tot)}\left\langle\epsilon_{trig}^{J/\psi}\right\rangle} f_{coll}$$

Definitions

- R: normalized J/ψ yield ratio
- N_{ch}: charged particle multiplicity of the FVTX and SVX detectors
- $N_S^{J/\psi}$: J/ψ signal raw yield extracted from fits to the dimuon sample
- $N_{Recorded}^{MB}$: number of minimum biased events
- ϵ_{Trig}^{MB}: minimum biased event trigger efficiency using data drive method on the PHENIX clock triggered data sample the BBC rate
- $\epsilon_{Trig}^{J/\psi}$: dimuon event trigger efficiency from investigation EMCAL/RICH samples of with minimum tower energy cuts
- f_{Coll}: multiple collision correction factor obtained from the ratio of multiplicity distribution of 0.5% double collisions with 99.5% single collision to the data

Sources of Systematic Uncertainties

$$\boldsymbol{R(N_{ch}/\langle N_{ch}\rangle) = \frac{N_s^{J/\psi}\epsilon_{trig}^{MB}}{N_{Recorded}^{MB}\epsilon_{trig}^{J/\psi}} \Big/ \frac{N_s^{J/\psi(tot)}\langle\epsilon_{trig}^{MB}\rangle}{N_{Recorded}^{MB(tot)}\left\langle\epsilon_{trig}^{J/\psi}\right\rangle} f_{coll}}$$

The following sources of systematic uncertainties are included

- ϵ_{Trig}^{MB}
- $\epsilon_{Trig}^{J/\psi}$
- f_{Coll} (largest source of systematic uncertainties)
- J/ψ reconstruction efficiency $\epsilon_{Reco}^{J/\psi}$

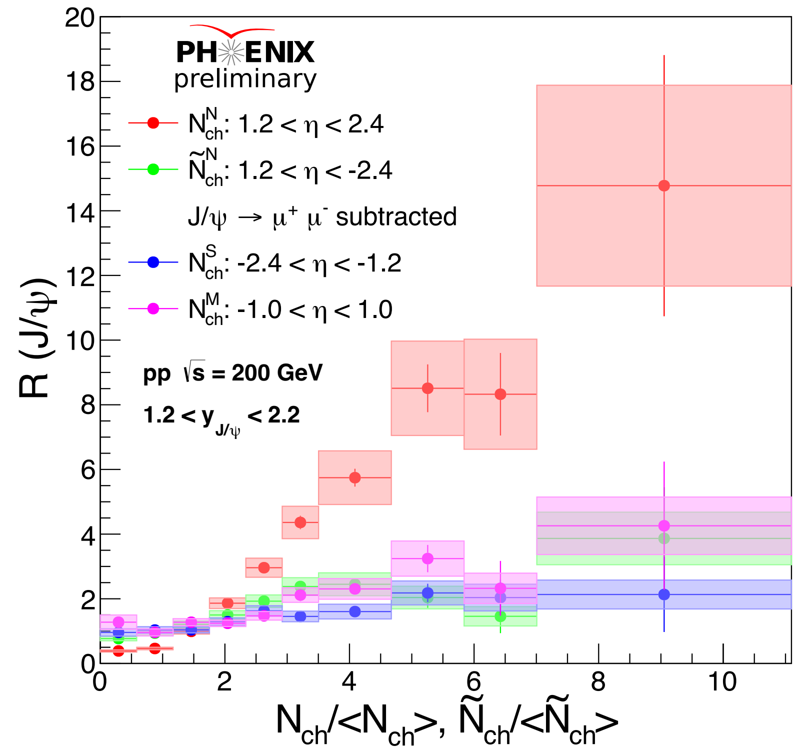
The following sources of systematic uncertainties are cancelled

- J/ψ fit model for signal extraction
- Luminosity
- Acceptance efficiency

Summary

Physics Motivation

- J/ψ as excellent probe to test QCD
- Broader impacts on heavy-ion physics
- Study J/ψ production with PHENIX at RHIC to understand IS, MPI, and FS effects



Preliminary Results

- Strong dependence of $R(J/\psi)$ on $N_{ch}/\langle N_{ch}\rangle$ in the same kinematic region
- Dependence of $R(J/\psi)$ on $N_{ch}/\langle N_{ch}\rangle$ reduces as rapidity gap increases
- After dimuon subtraction, $R(J/\psi)$ decreases and becomes fully consistent to opposite kinematic region

Outlook

STAY TUNED!

- $\psi(2S)/J/\psi$ ratio vs N_{ch} in p + p
- $R(J/\psi)$ in p + Au and p + Al