Measurements of J/ψ Production vs Event Multiplicity in the Forward Rapidity in p + p Collisions in the PHENIX Experiment

22nd Zimányi School Winter Workshop on Heavy Ion Physics

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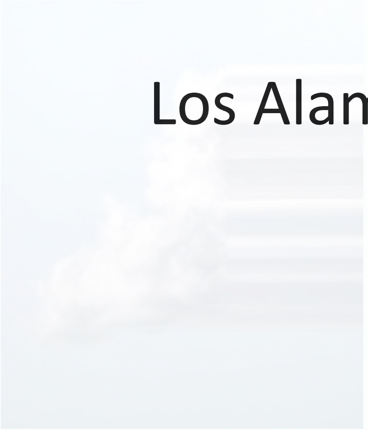
Los Alamos National Laboratory

12/05/2022


Andrea Katalin Gulyás: Error 2 (detail)


József Zimányi (1931 - 2006)

Outline

- **Physics Motivation**
- **Experimental Measurement**
- **Preliminary Results**
- **Summary**

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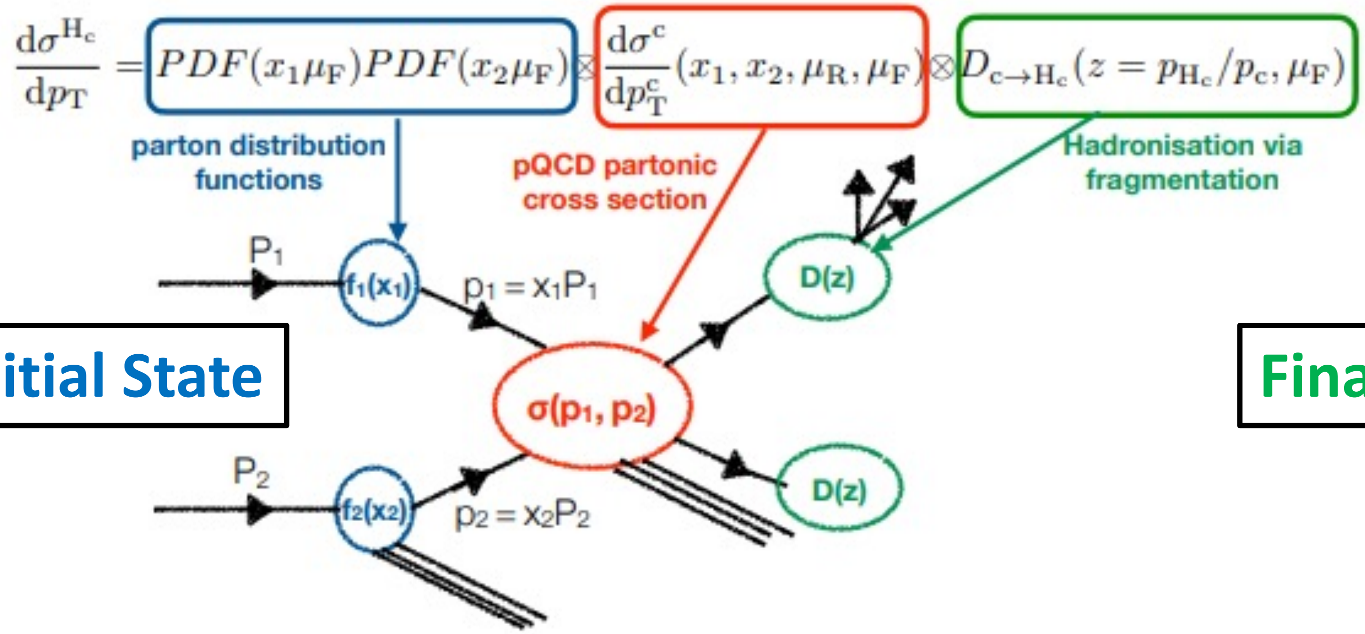
QCD Factorization Theorem

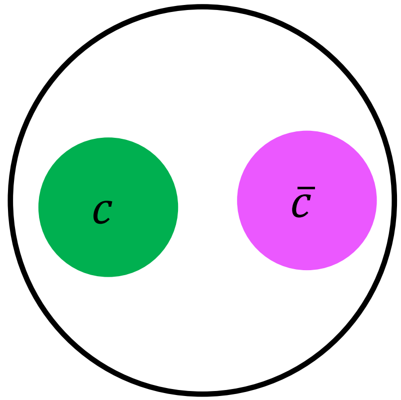


Initial State

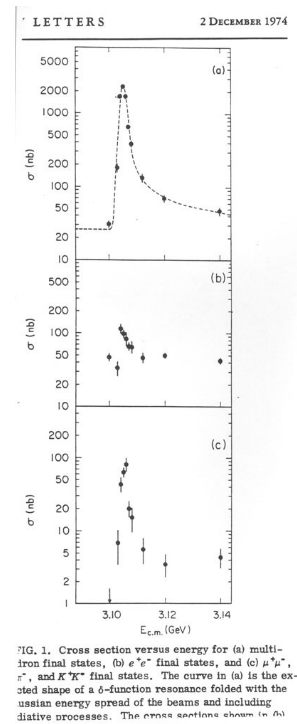
Final State

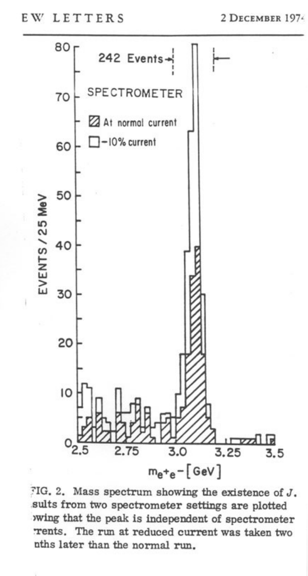
- Particle production at colliders: complex processes involving different energy scales at different stages
- **pQCD General Assumptions**
  - Hard processes: perturbatively calculable by Feynman diagrams
  - Soft processes: non-perturbative but universal from different colliders → allow to measure PDF(x) and D(z) from different experiments
  - Hard processes completely factorized from soft processes
- Describe particle production at high energy e^+e^-, ep, and pp colliders

Charmonium Production



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





Historical Background of J/ψ (1S)

- First discovered in 1974: November Revolution
- Confirmation charm quark and the quark model
- Lead to Nobel Prize in 1976

<u>Wonderful Playground to Test QCD</u>

- Large mass of charm quark: $m_c \gg \Lambda_{QCD}$
- J/ψ production intrinsically involve with two scales
  - Heavy quark production (hard scale)
  - Bound state formation (soft scale)
- Interplay between hard and soft mechanisms in both partonic and hadronic stages

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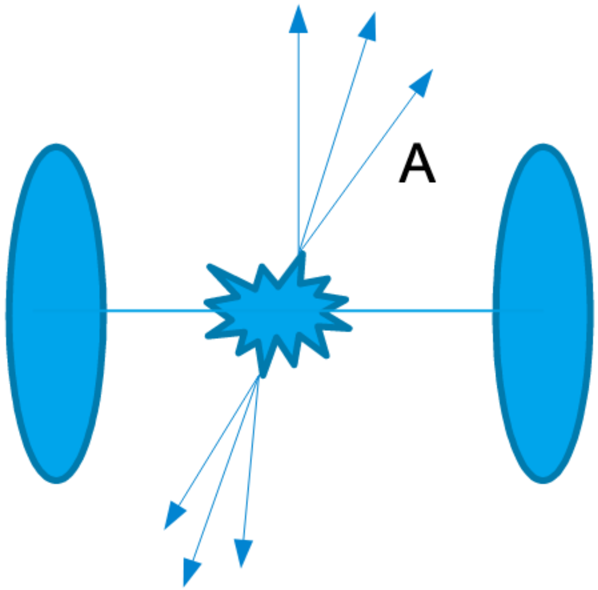
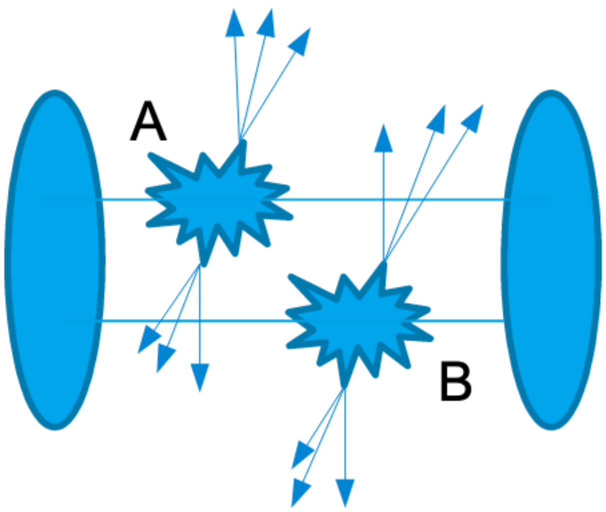
Multiple Parton Interactions (MPI)

Traditional pQCD Picture



MPI Picture

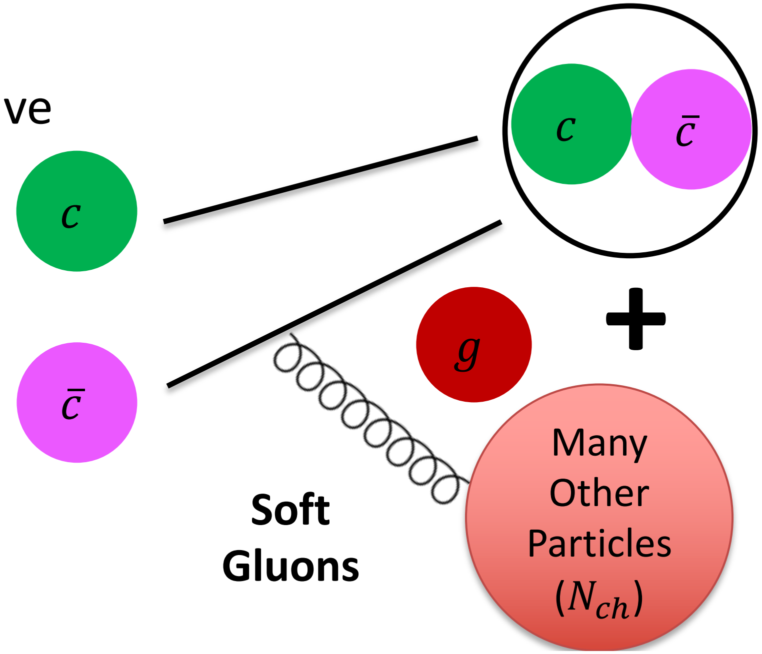


- Hadronic collider at higher energy enables the phase space for MPI
  - Allow several semi-hard scatterings near the charmonium mass
- Traditional single hard scattering picture is inaccurate
  - Typically 4 – 10 scatterings at LHC pp collisions
- MPI: influence charmonium production at high energy hadronic colliders

Final State Effects

Prior to Hadronization

- Energy loss via soft gluon emission until the relative speed between the $c\bar{c}$ pair to be non-relativistic
- A soft process and non-perturbative



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

- $c\bar{c}$ state formed color neutral J/ψ bound state
- Transversely polarized J/ψ production at RHIC

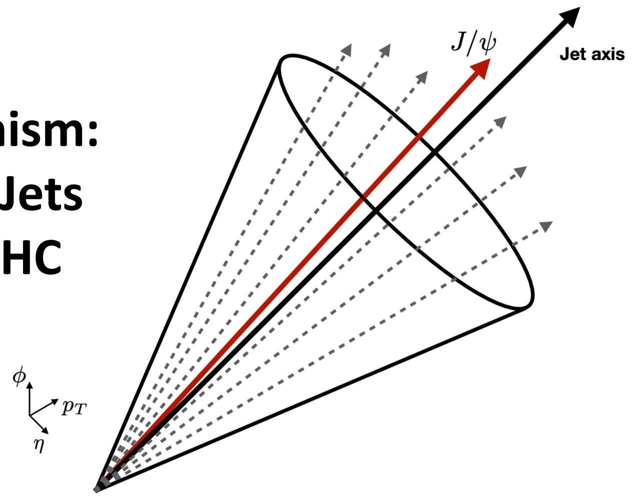
Effective Theory: Non-Relativistic QCD (NRQCD)

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

Phenomenological Models

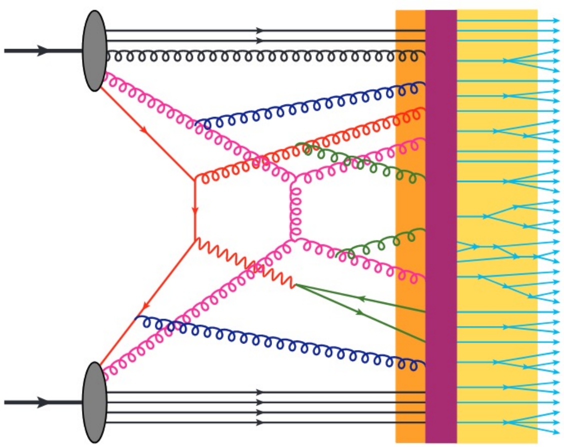
- Color Evaporation
- Lund String
- Statistical Hadronization
- Quark coalescence

Alternative mechanism: J/ψ production in Jets Observed at the LHC

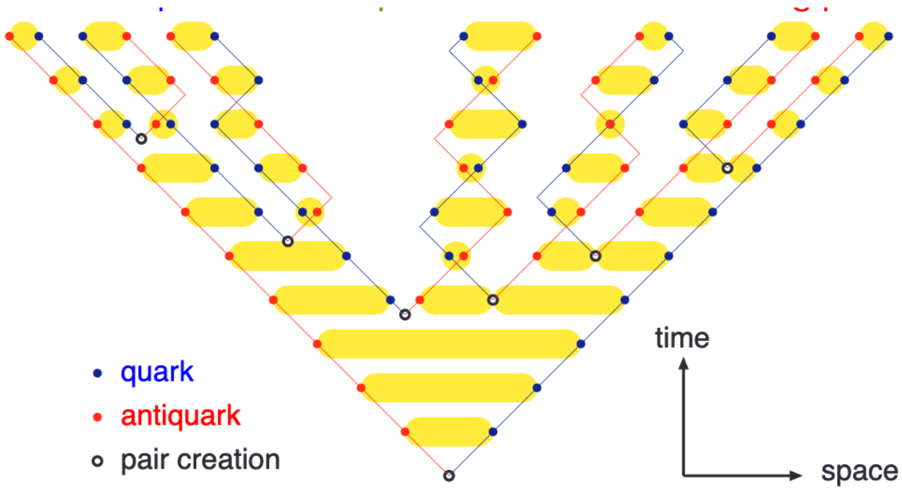


PYTHIA Event Generator

Event Structure

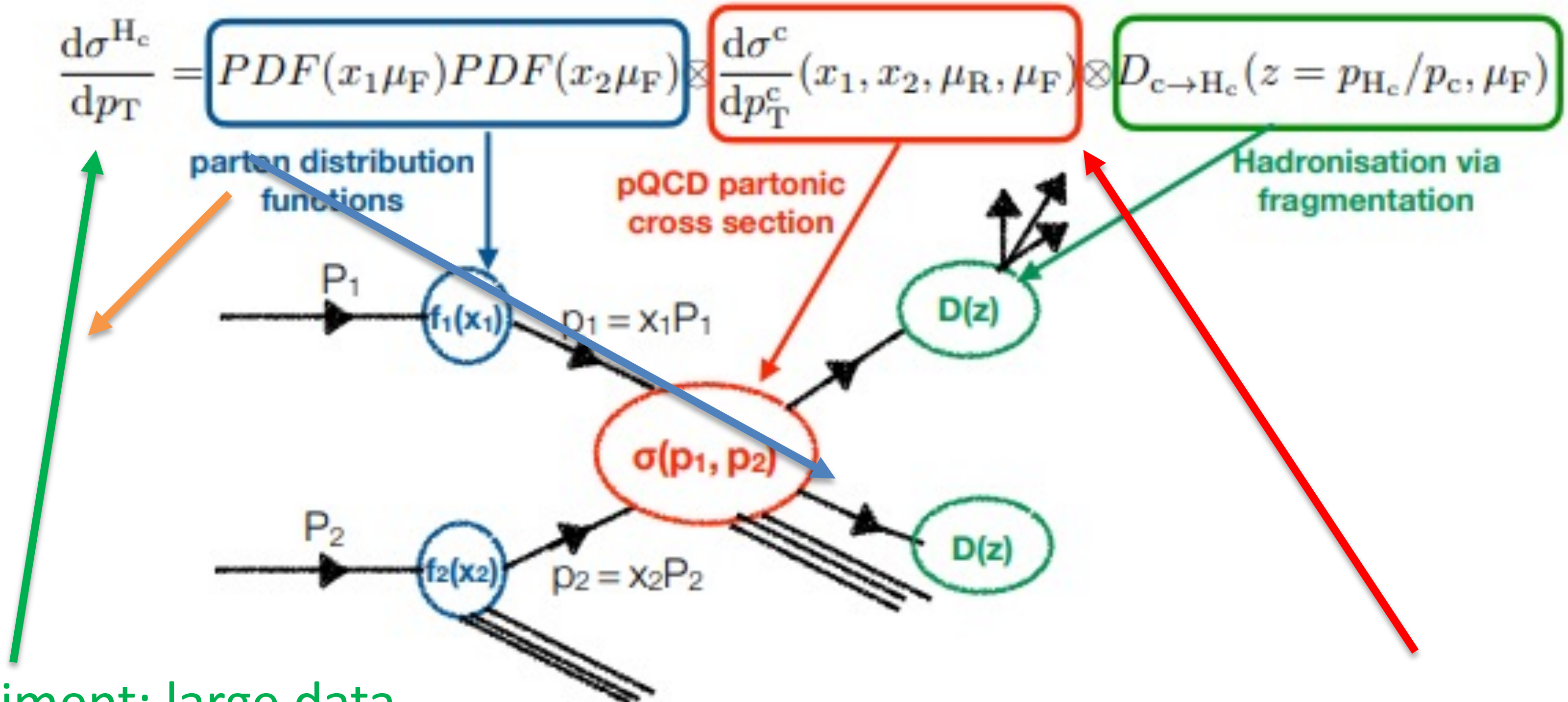


Hadronization: Lund String Model



- 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 applicable to pA and AA systems
- Tune the parameters to best fit to the data at different colliders
- Options with MPI ON and OFF
- Adjust CO and CS contributions

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

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Experimental Observables

Experimental Observables

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

Scaling Behavior in 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 $N_{J/\psi}/\langle N_{J/\psi}\rangle \propto N_{ch}/\langle N_{ch}\rangle$

Auto-correlation: 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
- Generally increase the multiplicity in J/ψ production events

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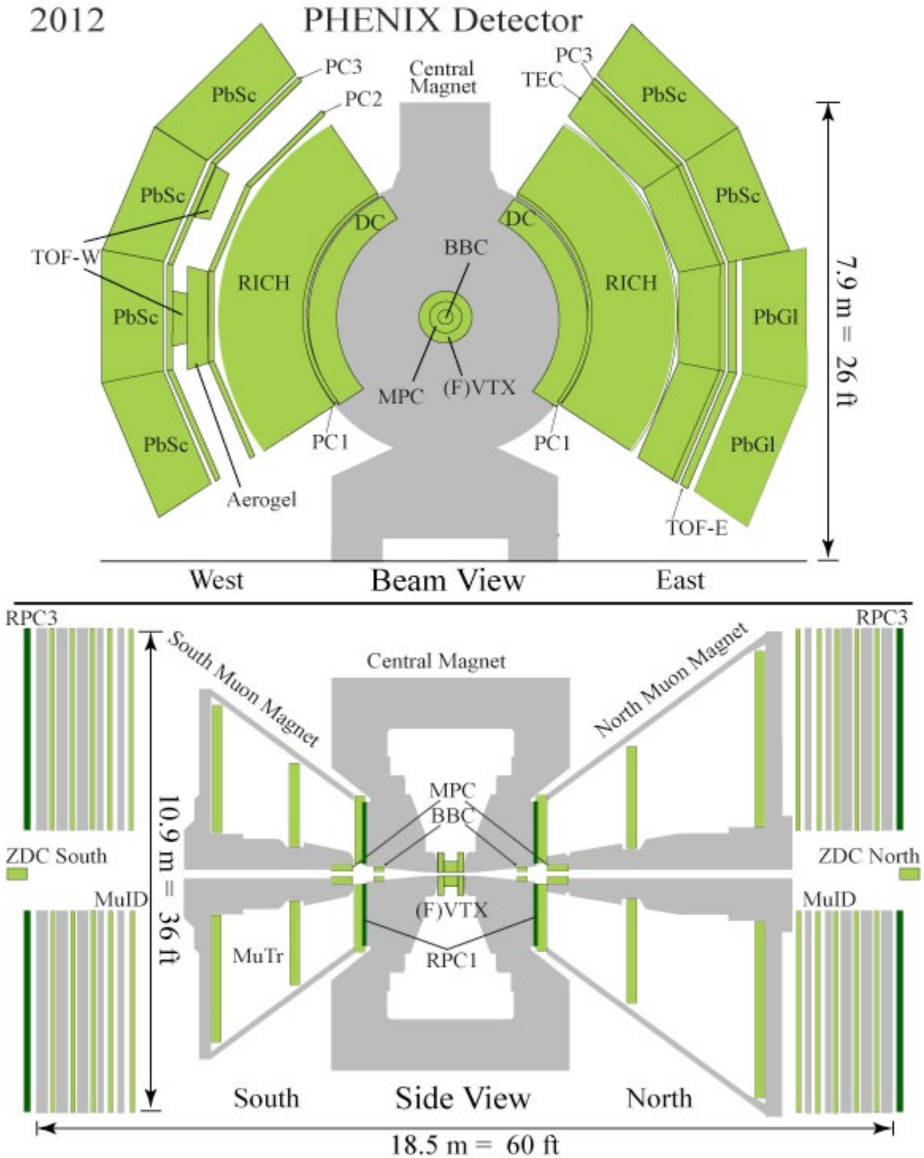
The PHENIX Detector at RHIC

- 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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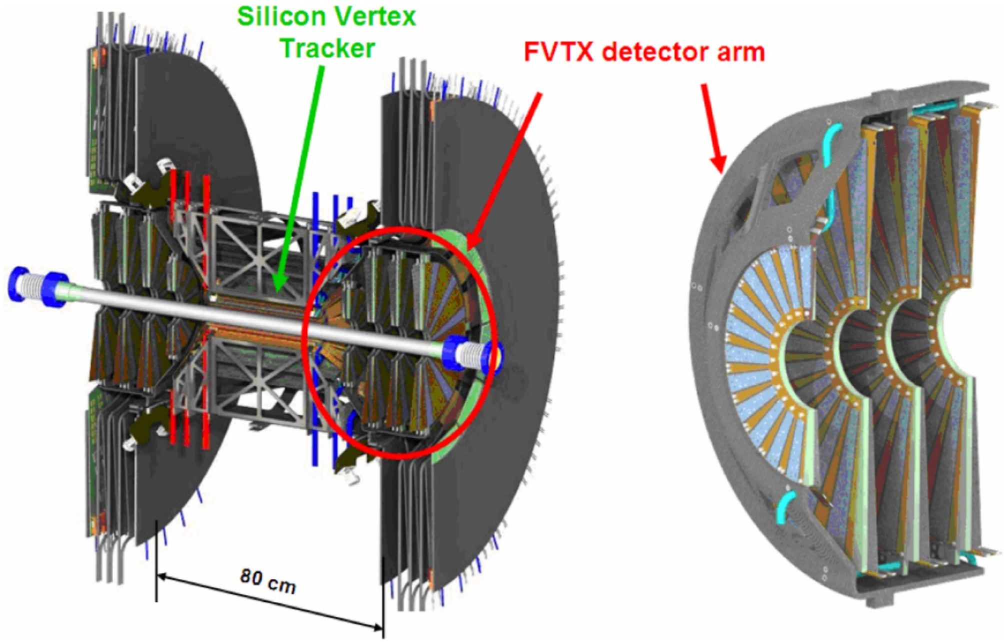
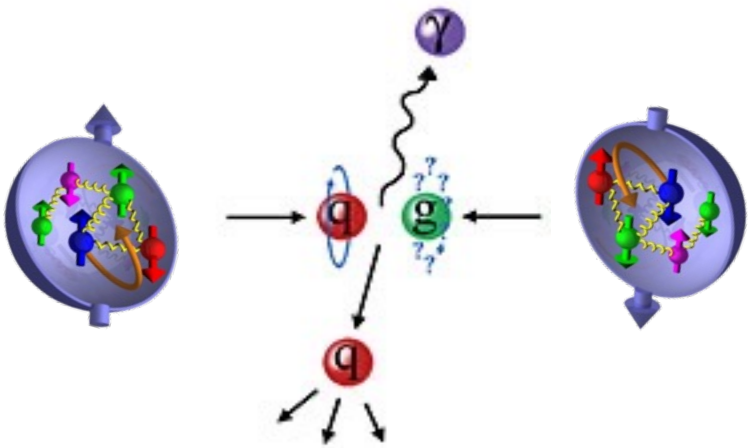
Triggers and Data Acquisition

- **MB Trigger**
  - Trigger on non-diffractive inelastic pp collision events
  - Use clock trigger with Beam-Beam Counter (BBC) and Muon Piston Calorimeters (MPC)

- **Dimuon trigger**
  - Trigger on hard scattering dimuons
  - Enrich J/ψ sample with good statistics

- PHENIX 2015 pp $\sqrt{s} = 200$ GeV data at RHIC





Data Analysis Strategies

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

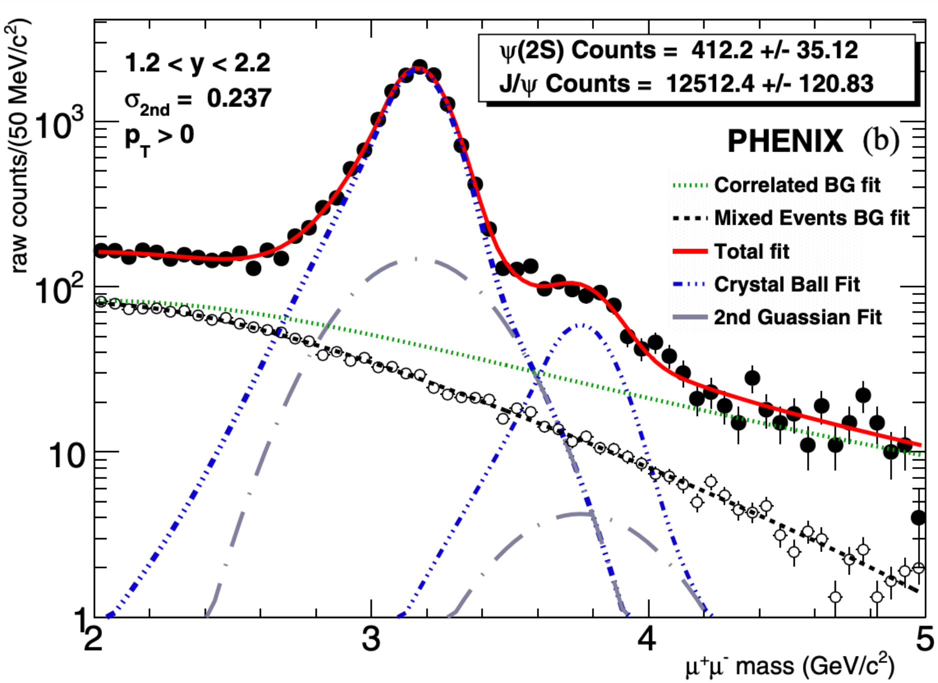
$$R(N_{ch}/\langle N_{ch}\rangle) = \frac{N_s^{J/\psi}\epsilon_{trig}^{MB}}{N_{Recorded}^{MB}\epsilon_{trig}^{J/\psi}} \Big/ \frac{N_s^{J/\psi(tot)}\langle\epsilon_{trig}^{MB}\rangle}{N_{Recorded}^{MB(tot)}\left\langle\epsilon_{trig}^{J/\psi}\right\rangle} f_{coll}$$

Definitions

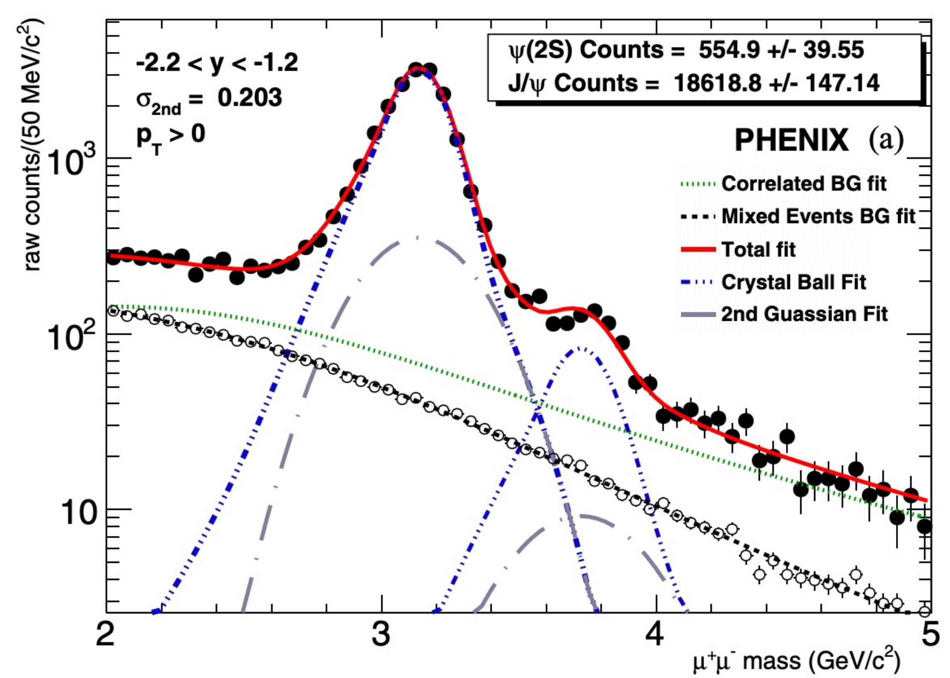
- R: normalized J/ψ yield ratio
- N_{ch}: charged particle multiplicity of the FVTX and SVX detectors
- $N_S^{J/\psi}$: J/ψ signal raw yield extracted from fits to the dimuon sample
- $N_{Recorded}^{MB}$: number of minimum biased events
- ϵ_{Trig}^{MB}: minimum biased event trigger efficiency using data 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

J/ψ Signal Extraction

FVTX North J/ψ



FVTX South J/ψ



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- Clear J/ψ and $\psi(2S)$ resonances observed at both forward and backward rapidity
- Inclusive J/ψ measurement in the range of $p_T < 5$ GeV/c and $1.2 < |y| < 2.2$ by PHENIX Forward Vertex Track North and South (FVTXN and FVTXS)

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Sources of Systematic Uncertainties

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

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

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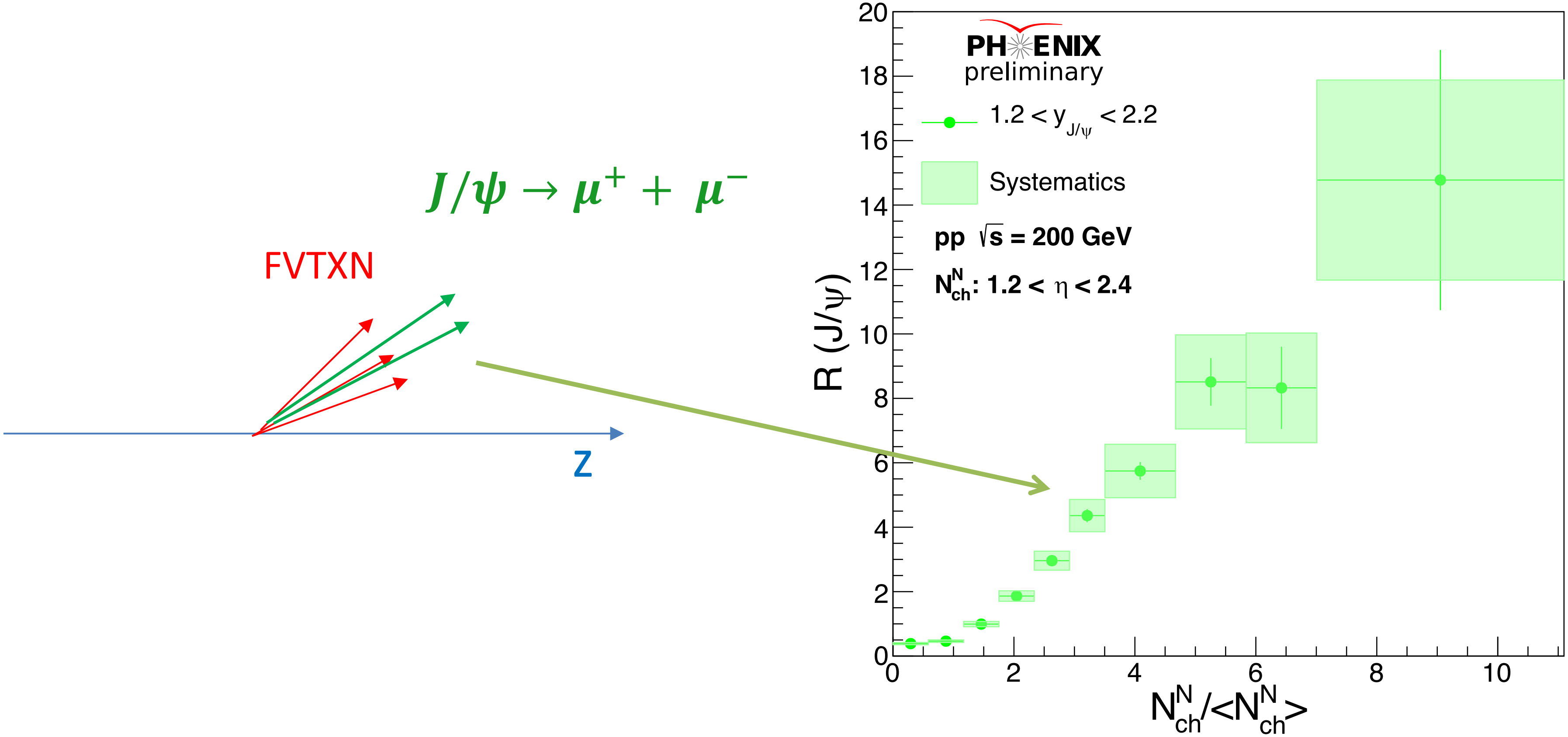
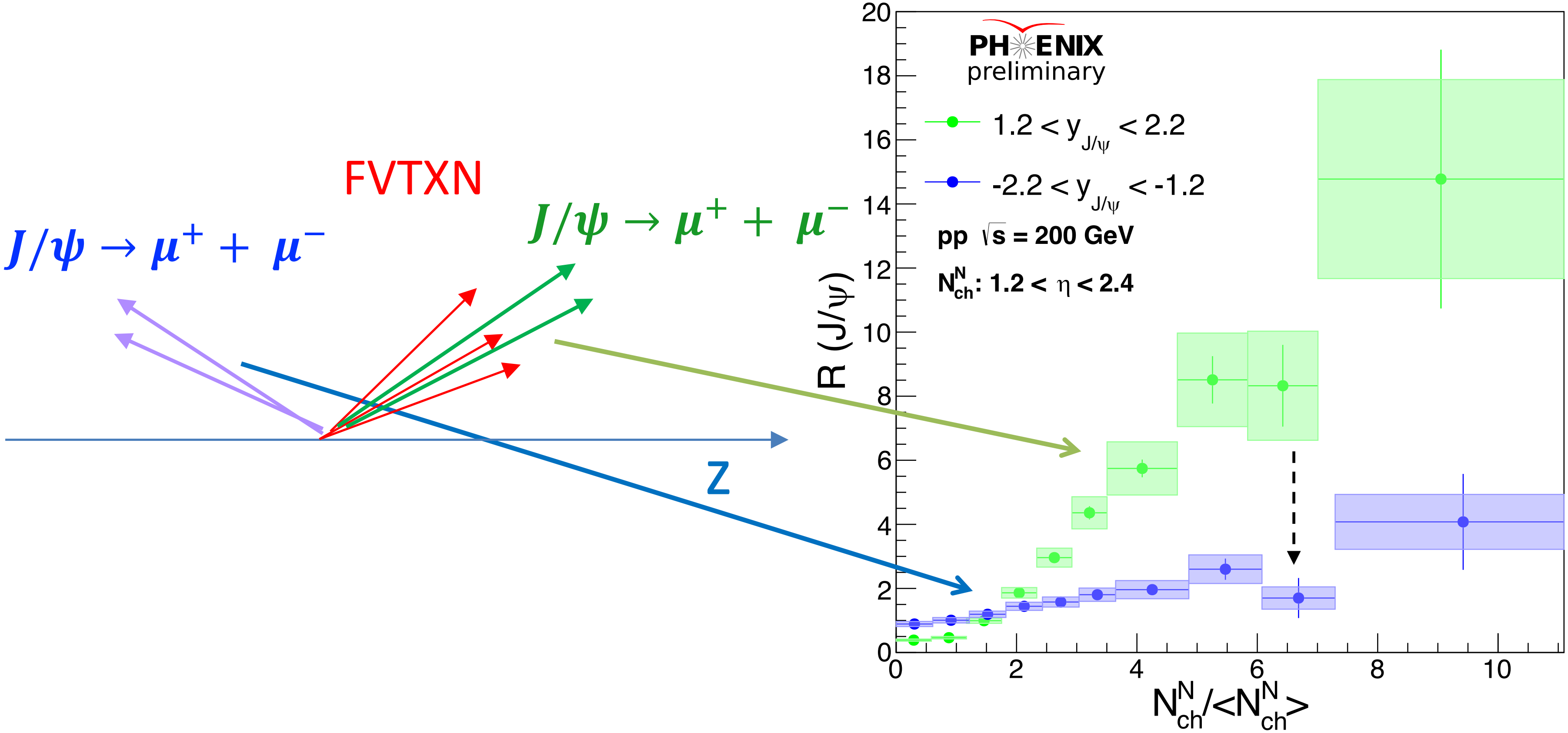
J/ψ Production in the Same Kinematic Region



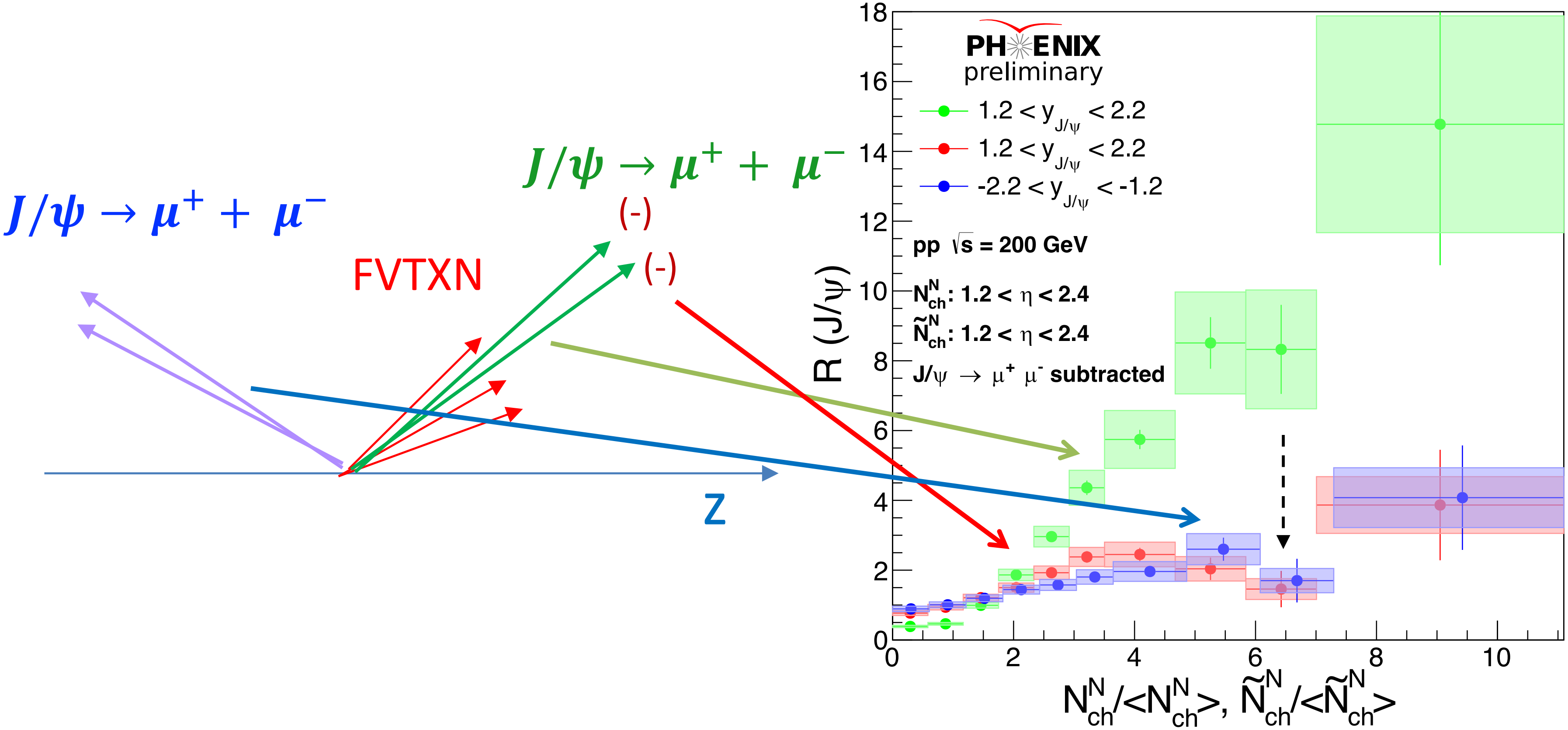
- MPI and FR contribution along with auto correlation effects
- $R(J/\psi)$ with a slope greater than 1
- Large uncertainties at very high multiplicity bins due to limited statistics

J/ψ Production in the Opposite Kinematic Region



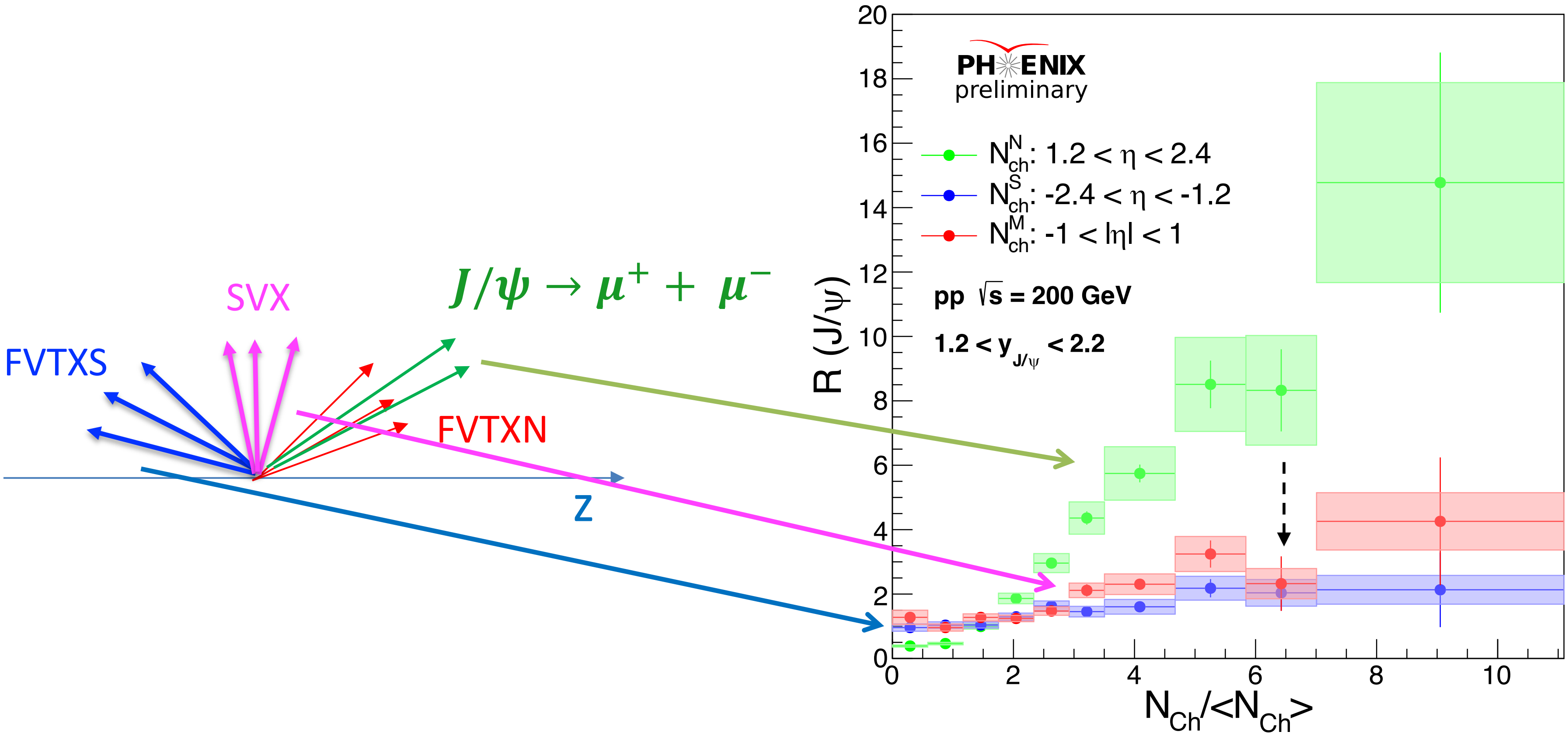
- Final state interaction significantly reduced
- $R(J/\psi)$ significantly reduced with respect to same kinematic region
- $R(J/\psi)$ with a slope greater than 1
- Large uncertainties at very high multiplicity bins due to limited statistics

J/ψ Production with Dimuon Subtracted



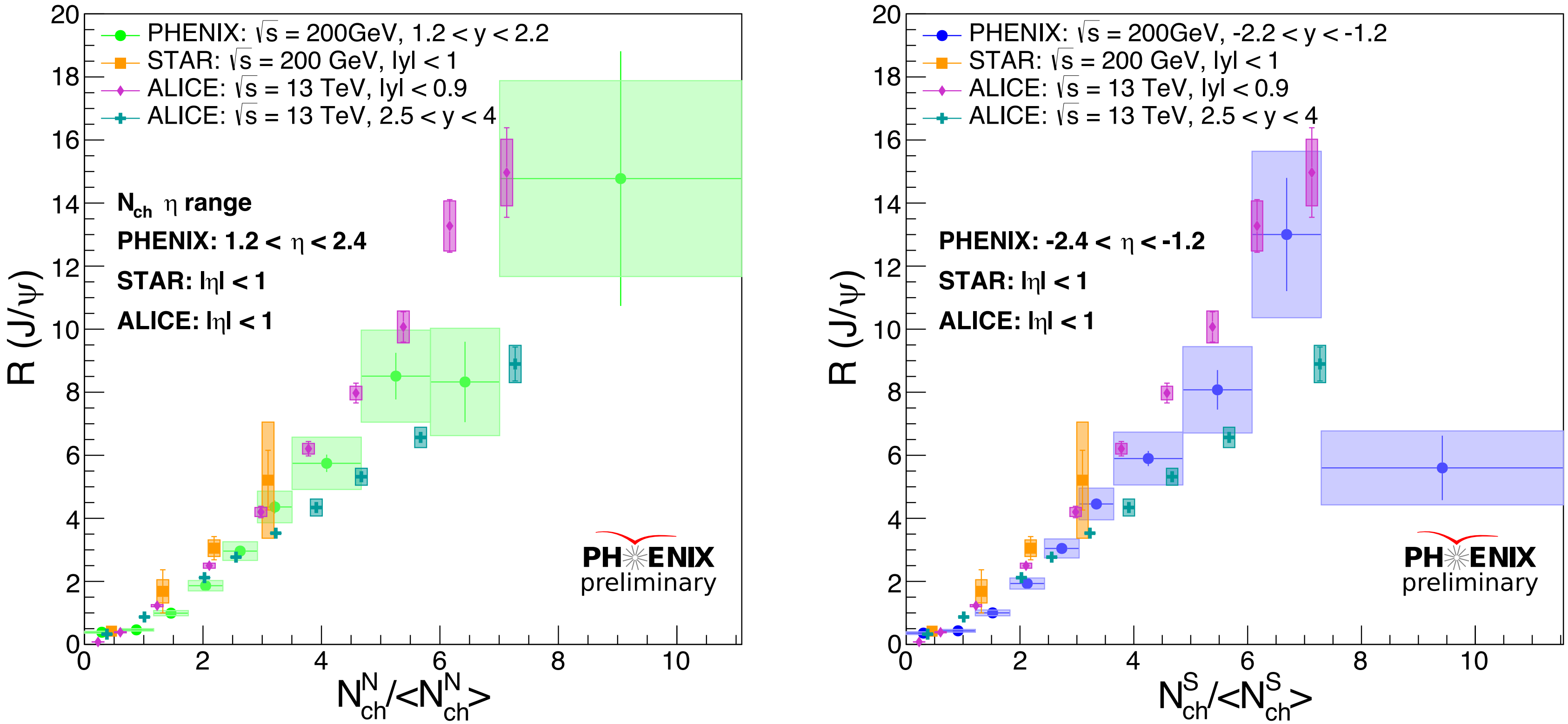
- Suppress the dimuon contribution to the charged particle multiplicity for J/ψ produced in the same kinematic region
- $R(J/\psi)$ significantly reduced and becomes fully consistent to J/ψ produced in the opposite kinematic region

Rapidity Comparison



- Reduction of auto-correlation 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



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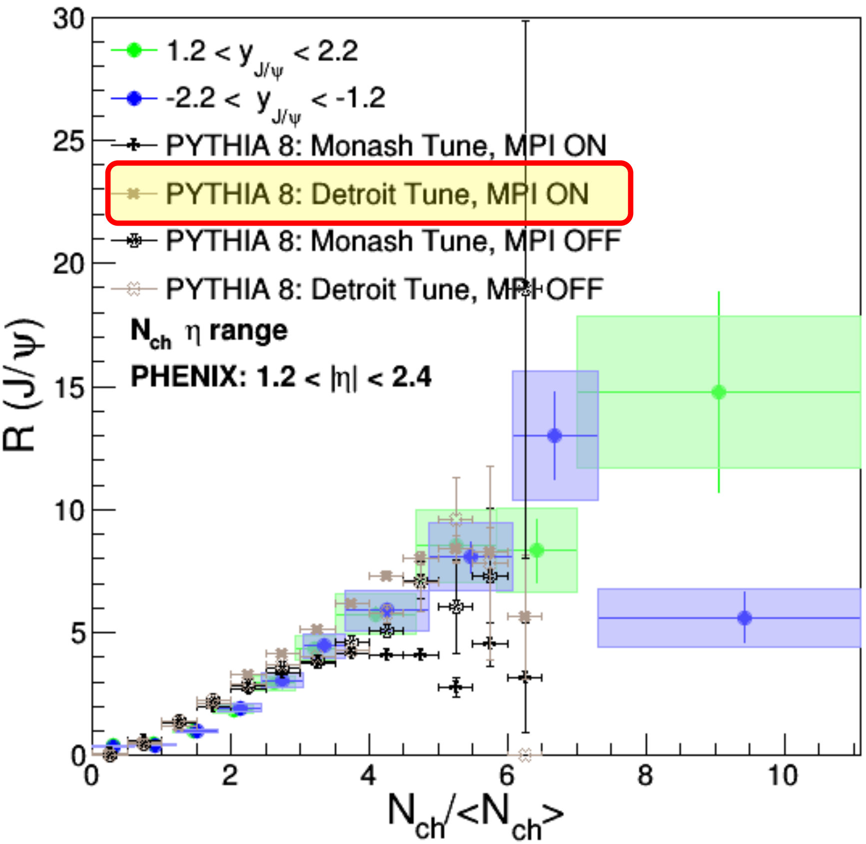
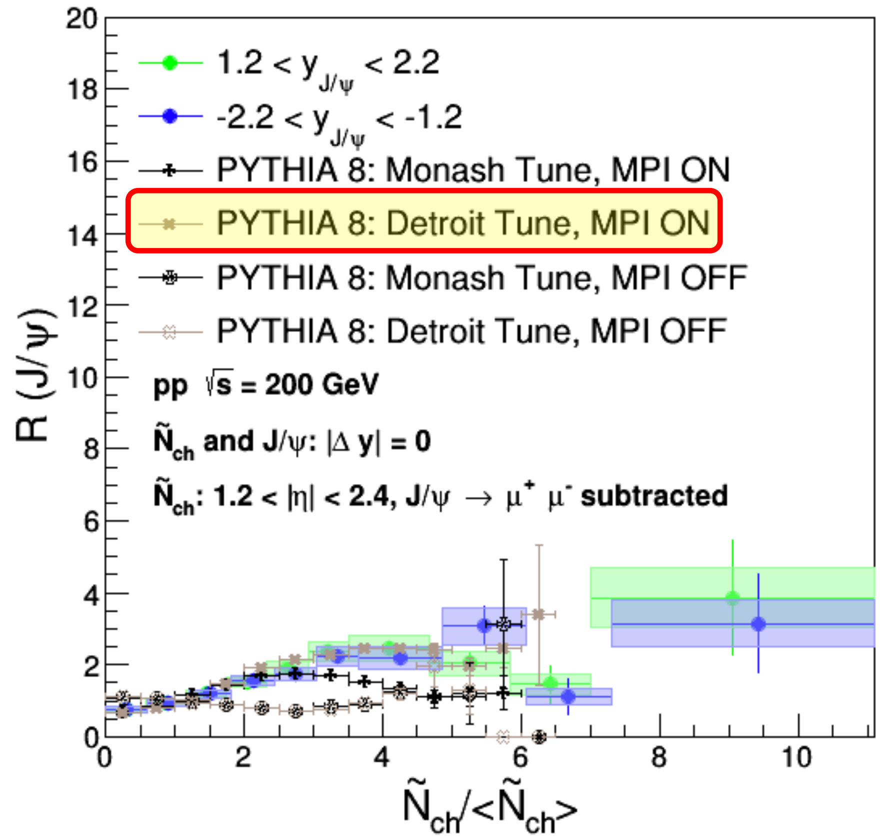
- $R(J/\psi)$ consistent in **forward** and **backward** rapidity regions
- $R(J/\psi)$ higher at mid-rapidity than forward region
  - Confirmed with **ALICE** **mid-rapidity** and **forward rapidity** measurements
  - **Data** systematically below **STAR** **mid-rapidity** as expected
- **Data** in between **ALICE** **mid-rapidity** and **forward rapidity**

Comparison to PYTHIA Simulations



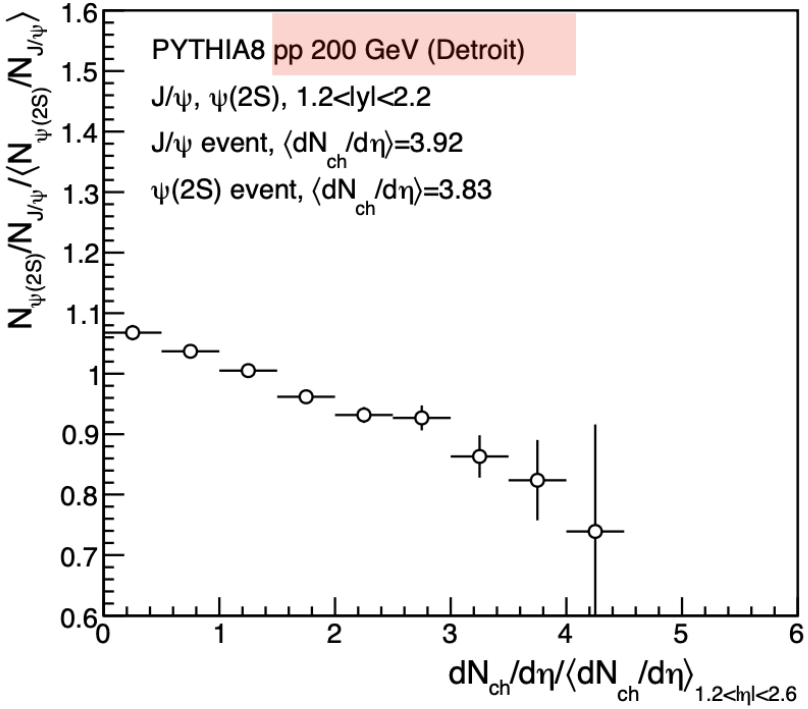


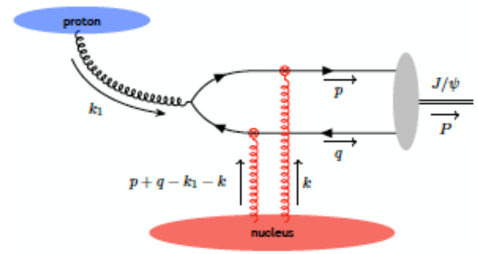
- Comparison with PYTHIA 8 Monash and Detroit Tunes with MPI ON and OFF in the generated level
- **PYTHIA 8 Detroit Tunes with MPI ON** best describes the data

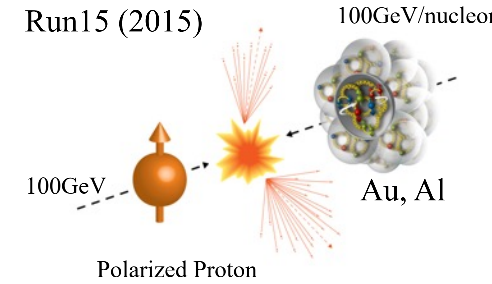
Ongoing Further Studies

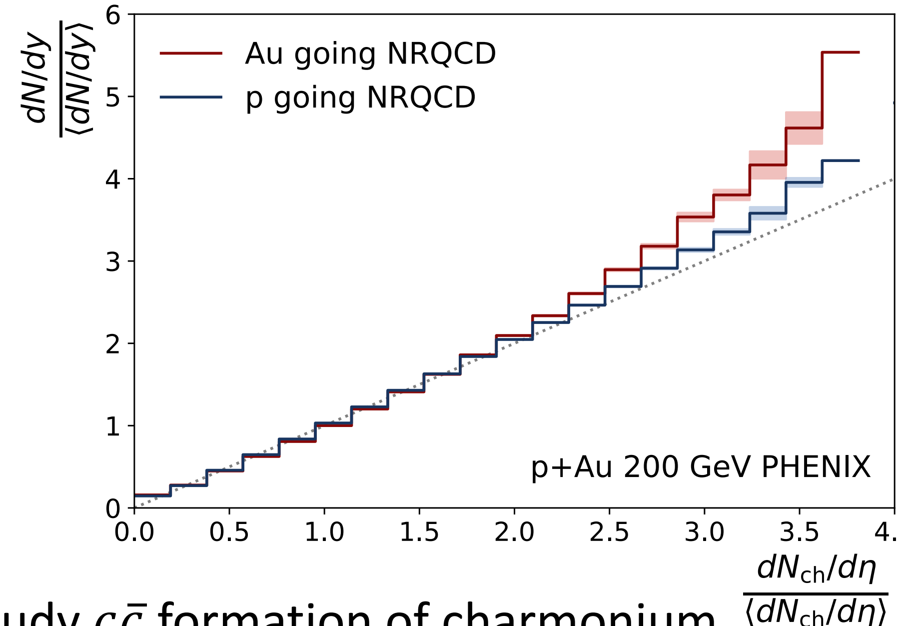
PYTHIA 8: $\psi(2S)/J/\psi$

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 conducted with decreasing trend
- $R(J/\psi)$ studies in p + Au and p + Al to probe the CGC region in nucleus
  - Theoretical calculations carried out

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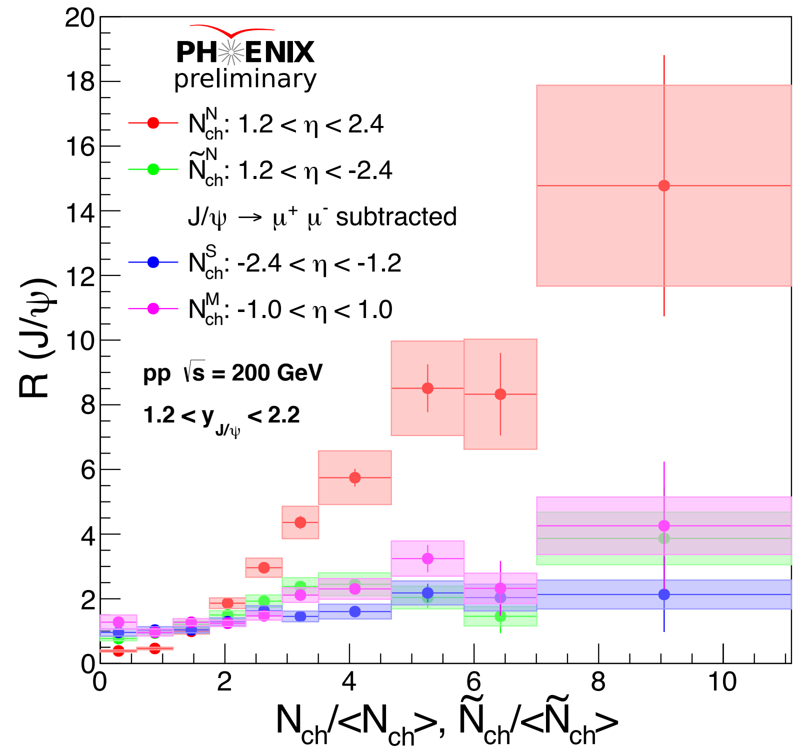
Summary

Physics Motivation

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



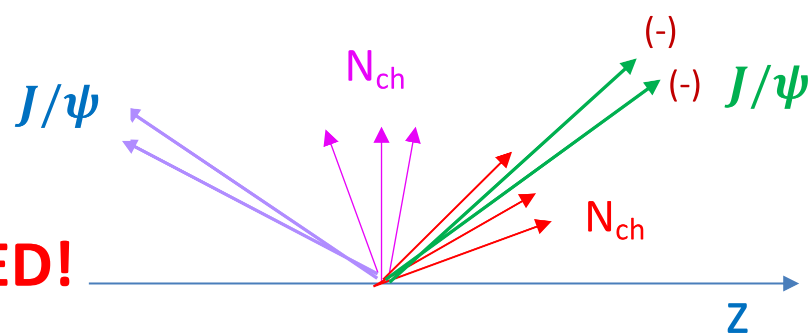
Preliminary Results

- 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

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

STAY TUNED!



Acknowledgement

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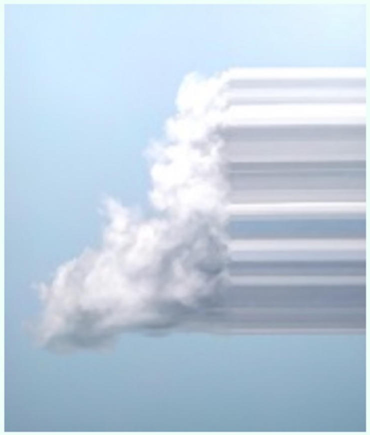

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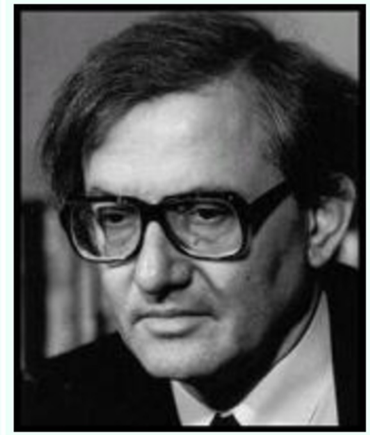
22nd ZIMÁNYI SCHOOL

WINTER WORKSHOP

ON HEAVY ION PHYSICS

December 5-9, 2022

Budapest, Hungary



József Zimányi (1931 - 2006)

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

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LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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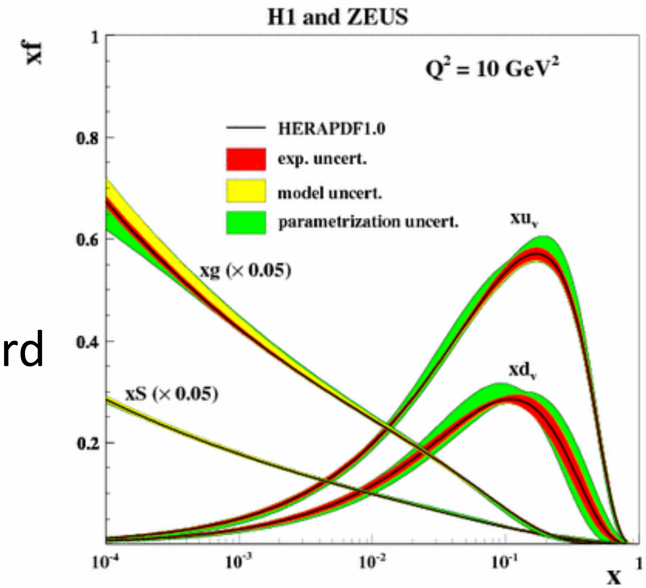
Back Up

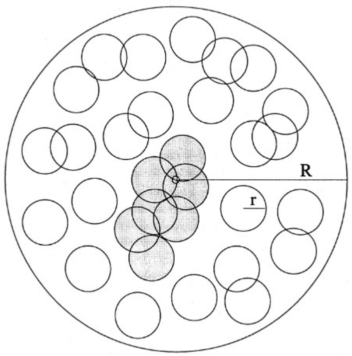
Initial State Effects

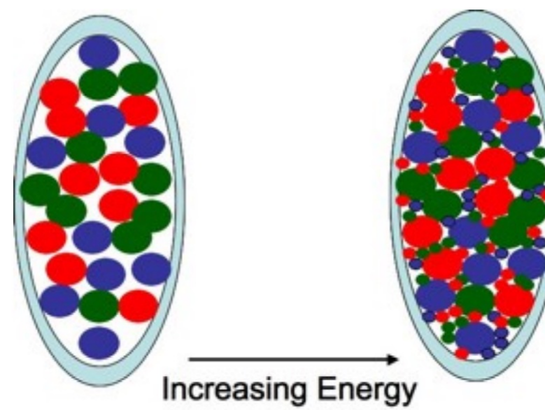
Initial Parton Dynamics in Hadrons
- Initial ion partonic structure
- Encoded in PDF and more generally GPD



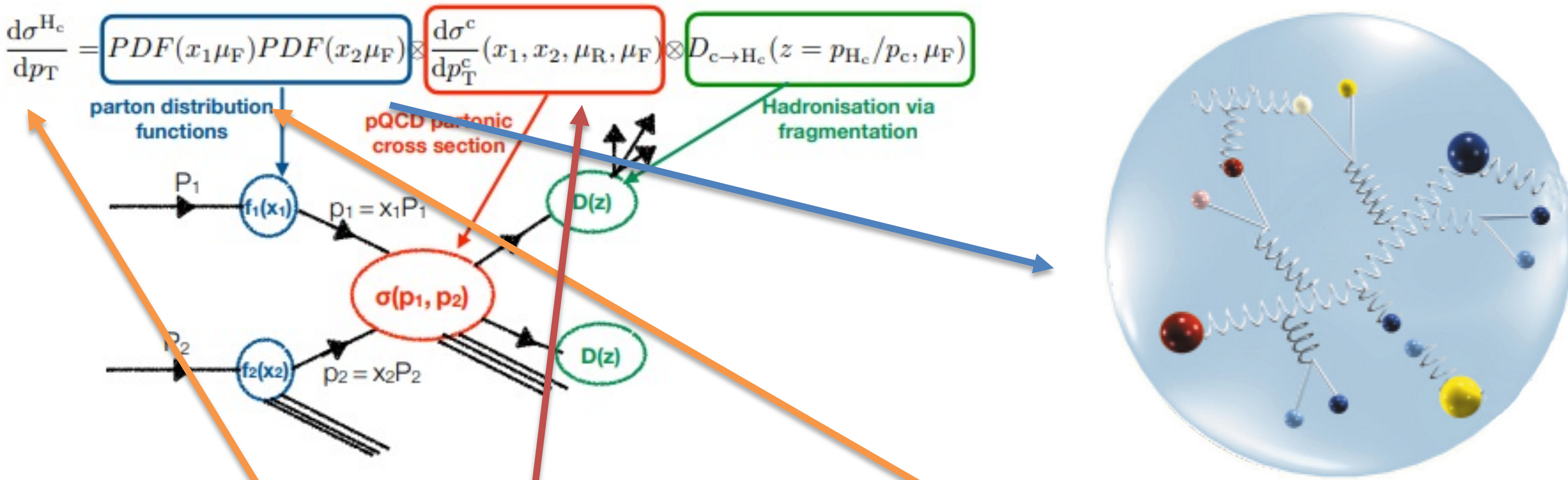
Initial State Radiation (ISR)
- Occur after partons become energetic and before hard partonic interactions
- Generally soft and non-perturbative → models to explain experimental data
- Contribute to the initial kinematics $c\bar{c}$ production

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

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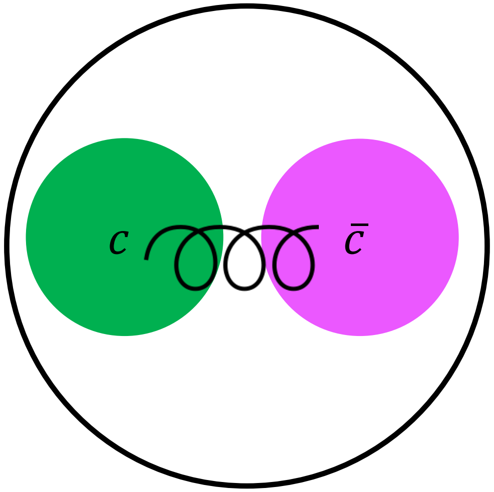
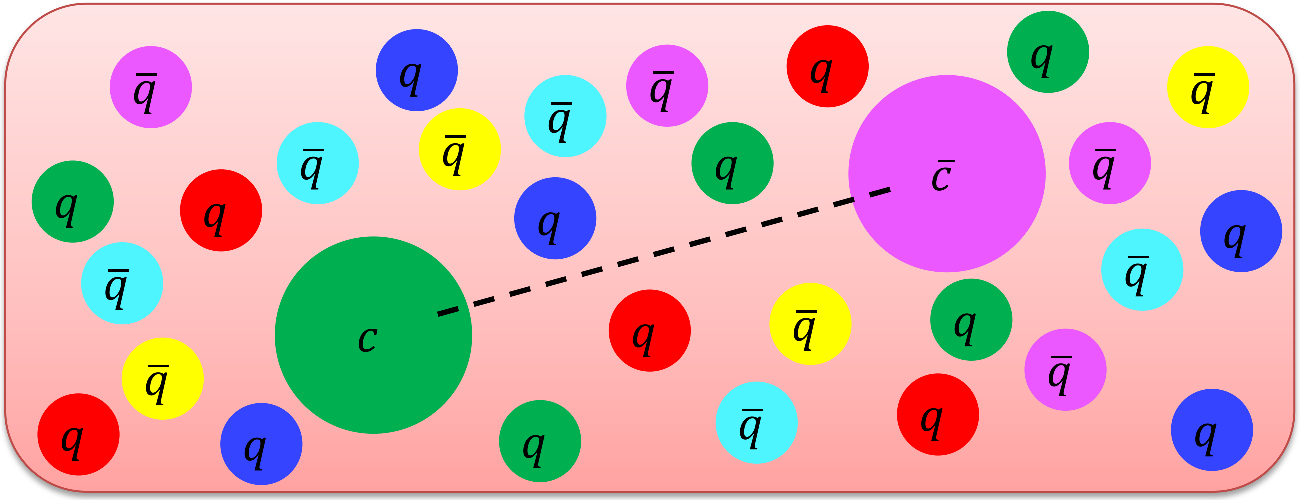
Thermometer for QGP in Heavy Ion Physics

- 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





Auto-Correlation Contributions

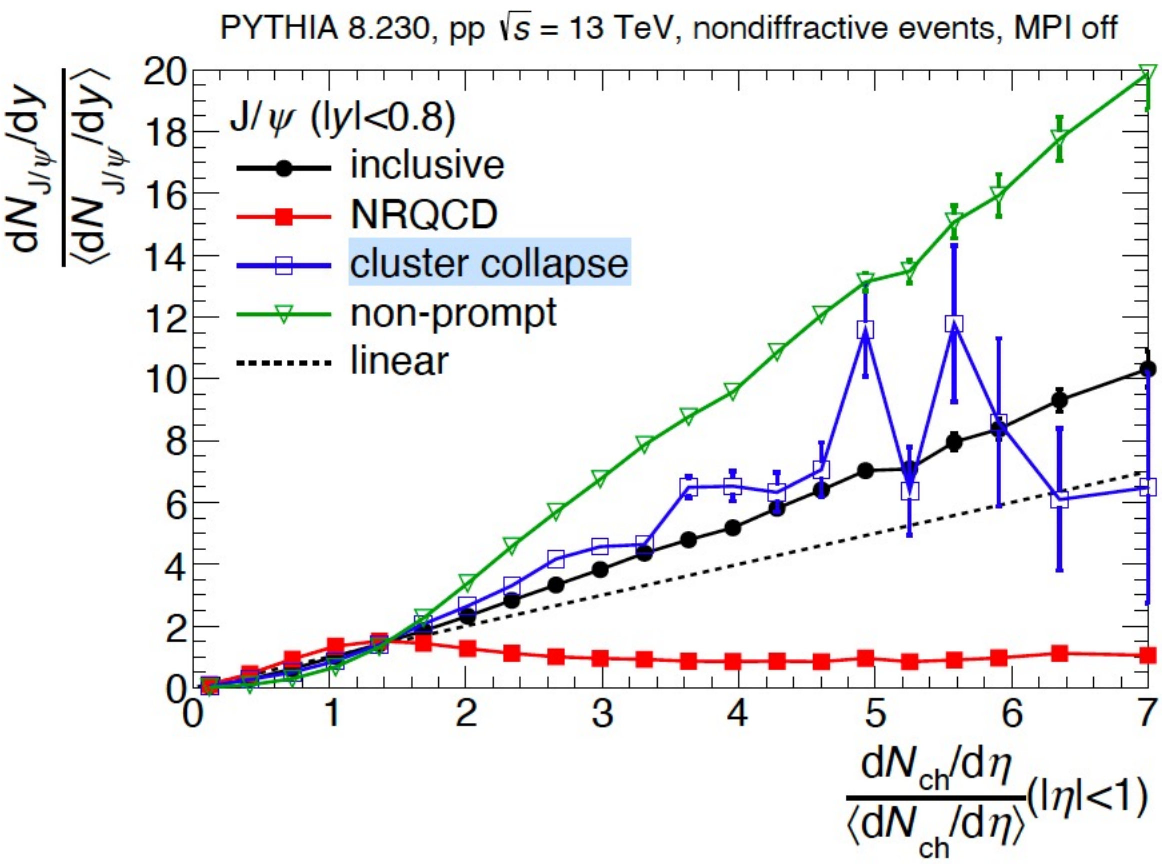


Figure 8. Mid-rapidity J/ψ production as a function of mid-rapidity multiplicity in events without MPI from PYTHIA8.

Comparison to PYTHIA 8 Simulations

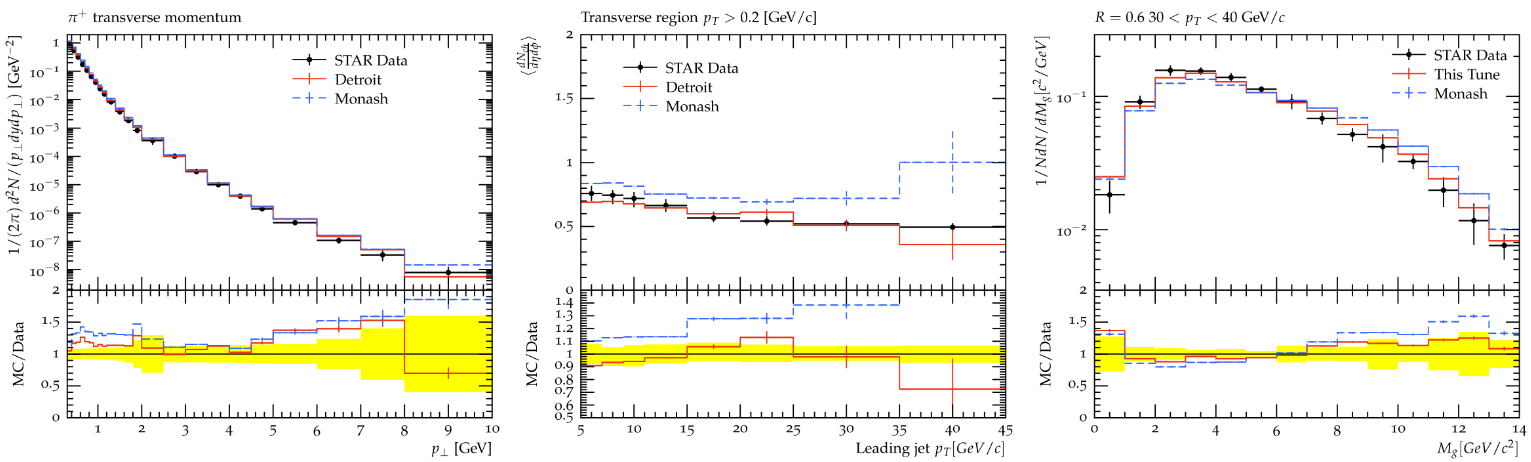
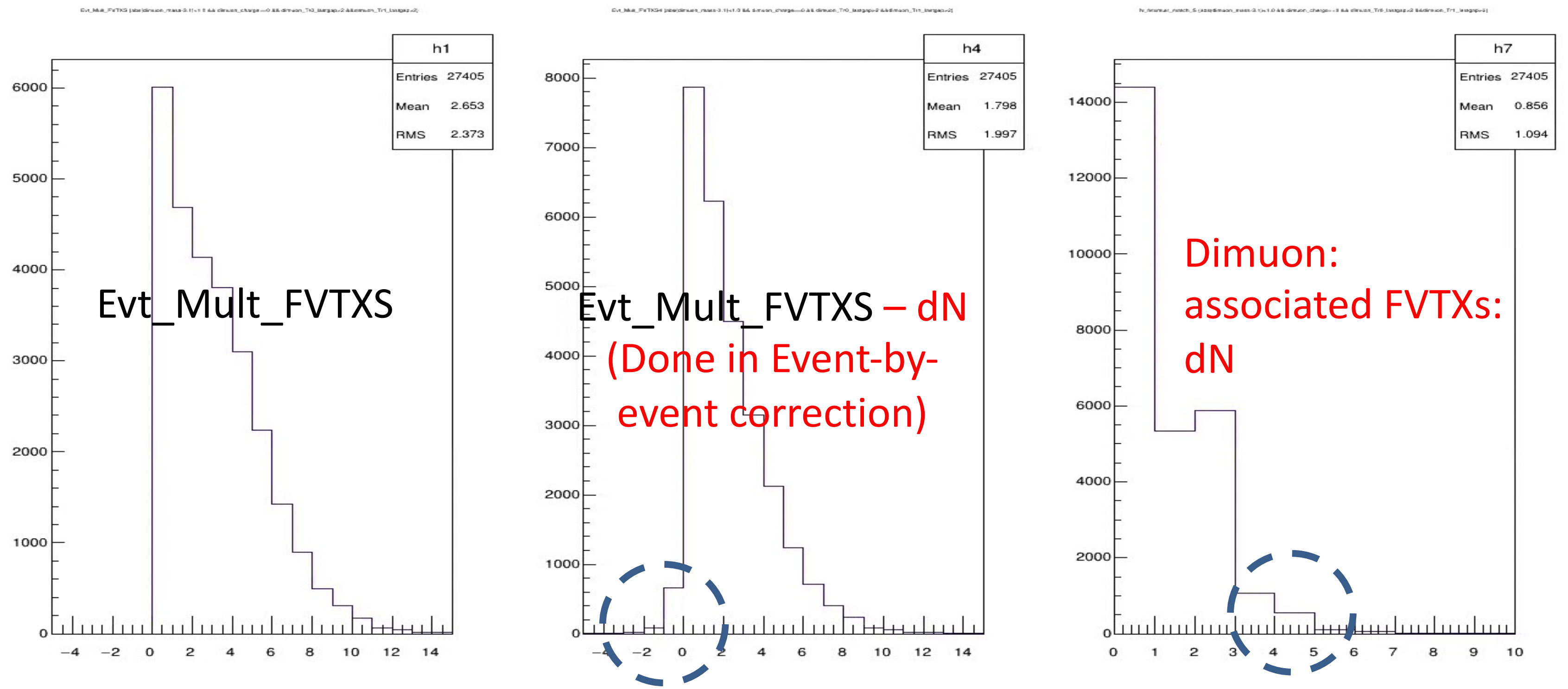


FIG. 3. Comparison of the default (blue dashed) and Detroit PYTHIA8 tunes (red solid) with mid-rapidity π^+ cross sections as a function of p_T (left) [24], UE multiplicity as a function of leading jet p_T (middle) [15], and the SoftDrop groomed jet mass (right) [27] in $p+p$ collisions at $\sqrt{s} = 200$ 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

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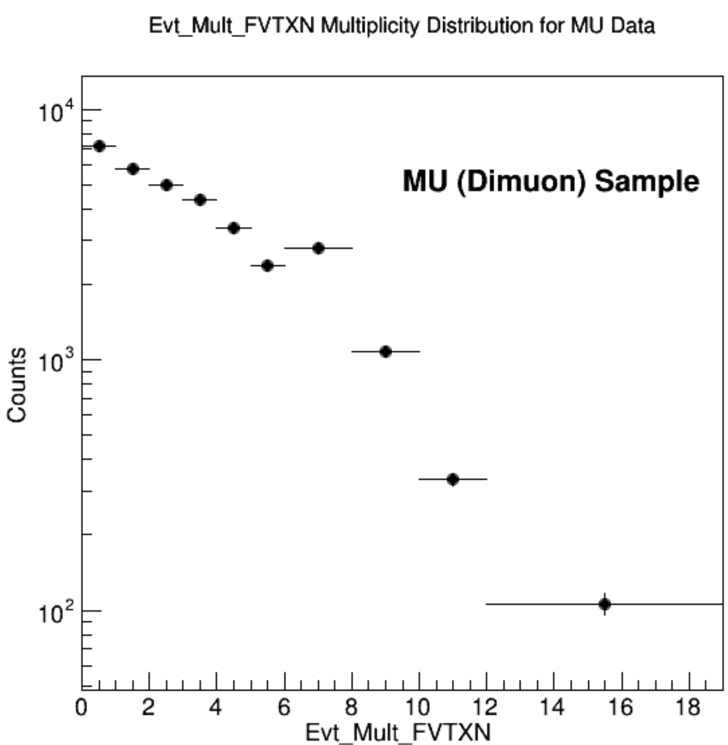
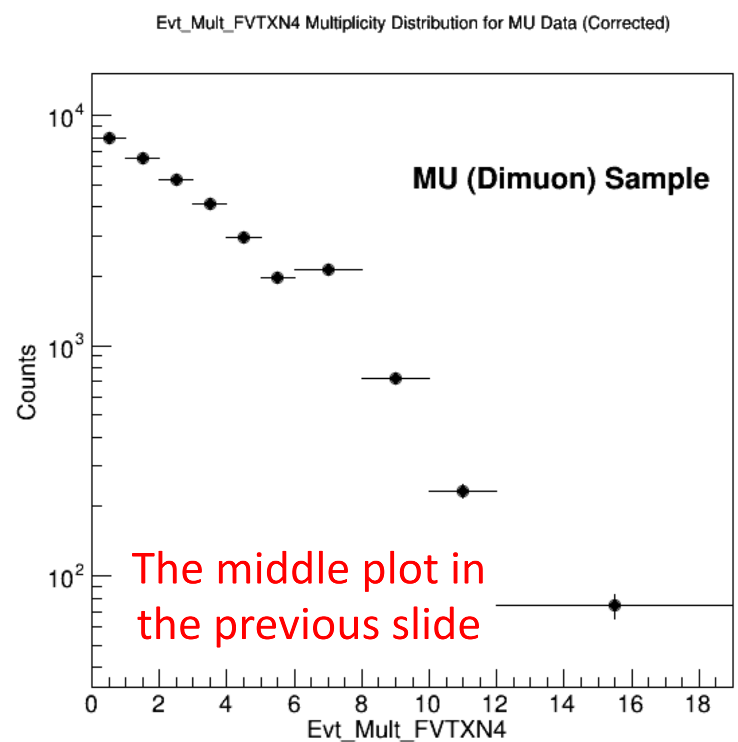
Modification on the FVTX Tracklet Multiplicity

- 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)





PHENIX

Los Alamos NATIONAL LABORATORY

Data-Driven Determination of Efficiency

MB trigger efficiency:

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

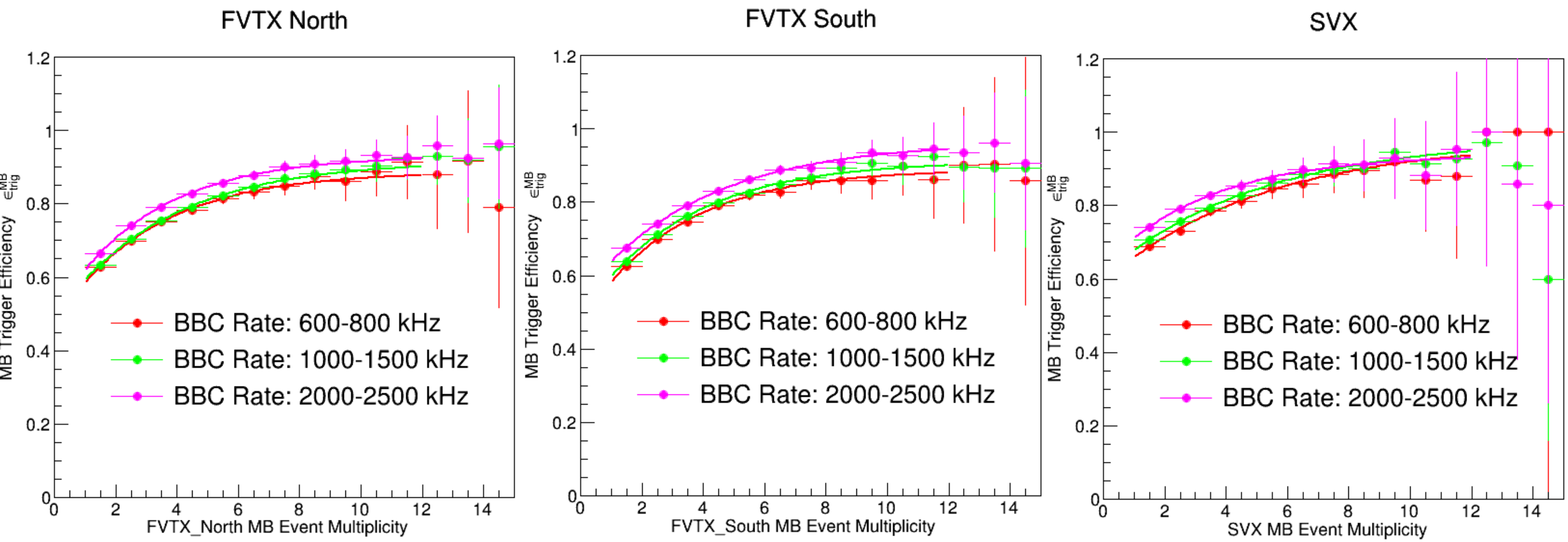
- The clock trigger data sample is used to determined MB trigger efficiency

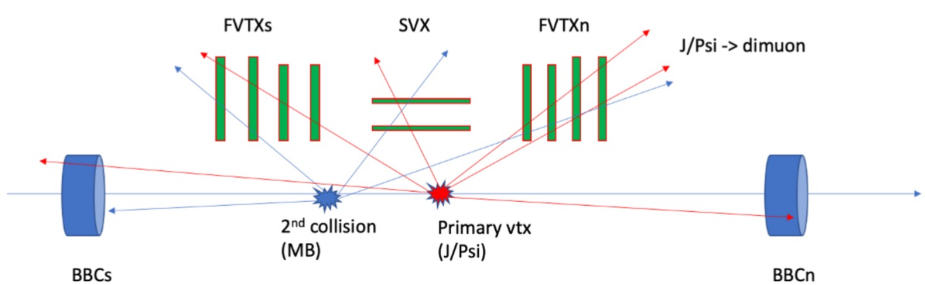
J/ψ trigger efficiency:

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

- 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

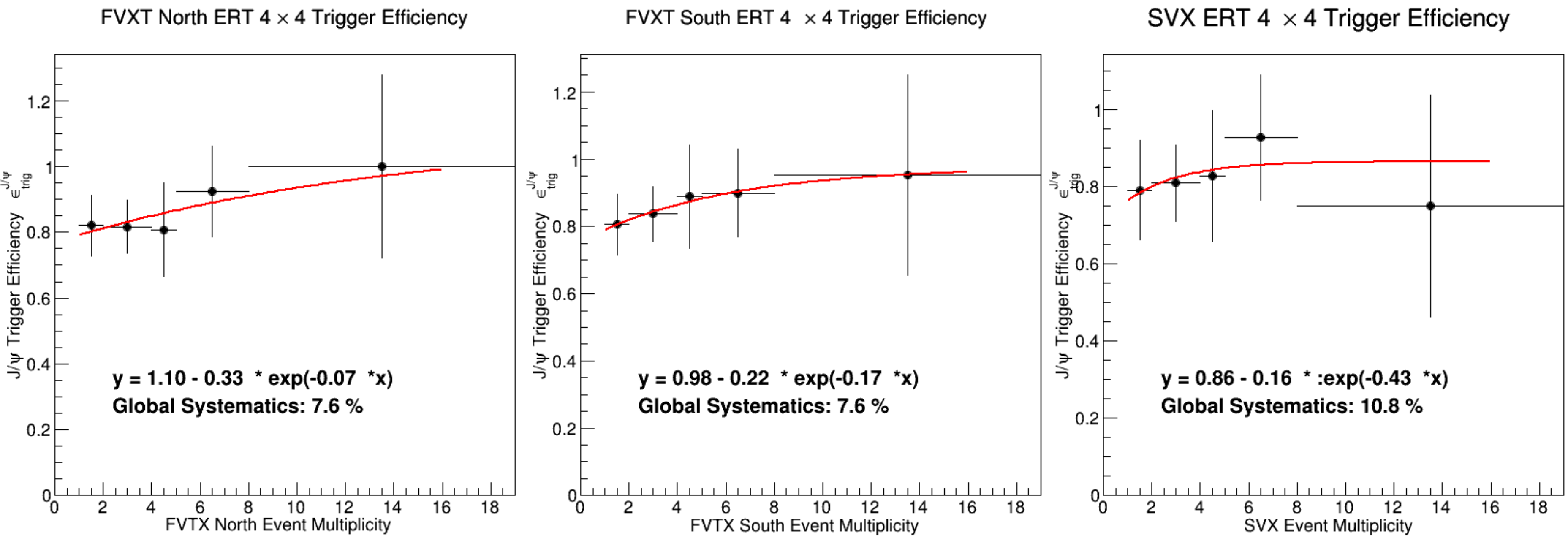
MB Trigger Efficiency Studies

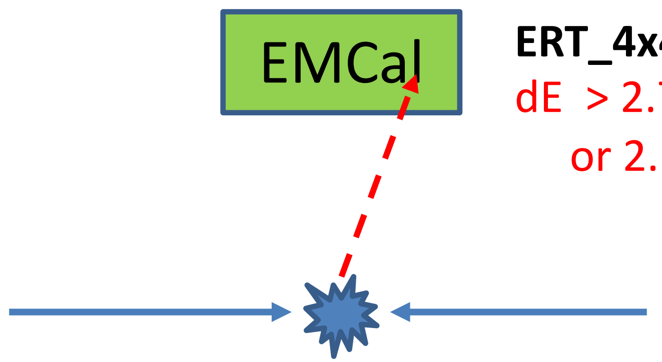




- We obtain the MB trigger efficiency for 3 BBC rate classes: 600 – 800 kHz, 1000 – 1500 kHz, and 2000 – 2500 kHz
- We fit them with functions and evaluate it by the bin center to obtain the efficiency

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