Uttam Acharya

On behalf of PHENIX Collaboration

10th Workshop of APS Topical Group on Hadronic Physics
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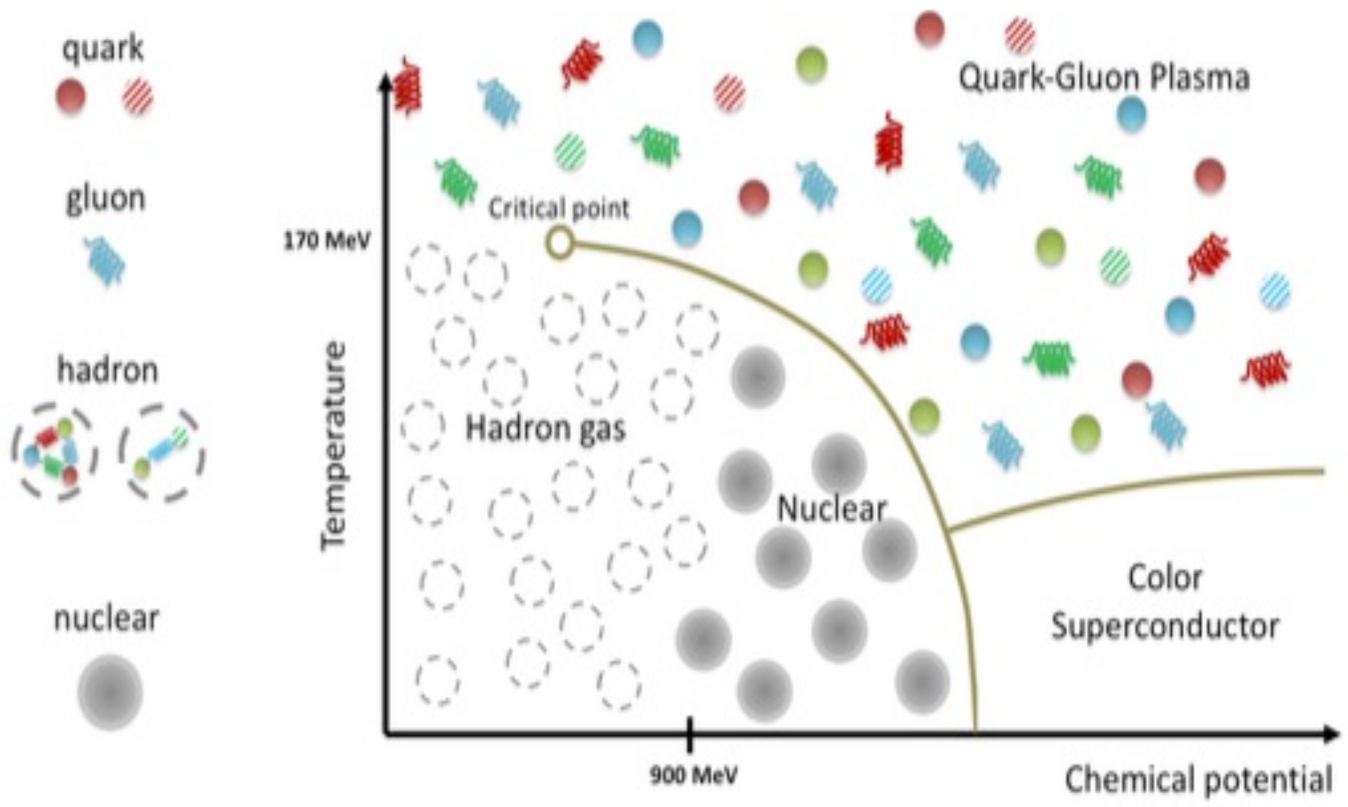
Φ-Meson production at Forward Rapidity in Au + Au collisions at 200 GeV.

Motivation: Quark Gluon Plasma

- At sufficiently high temperature, the bonding between partons weaken → hadrons deconfined and moves freely "Asymptotic freedom".



QCD Phase Diagram

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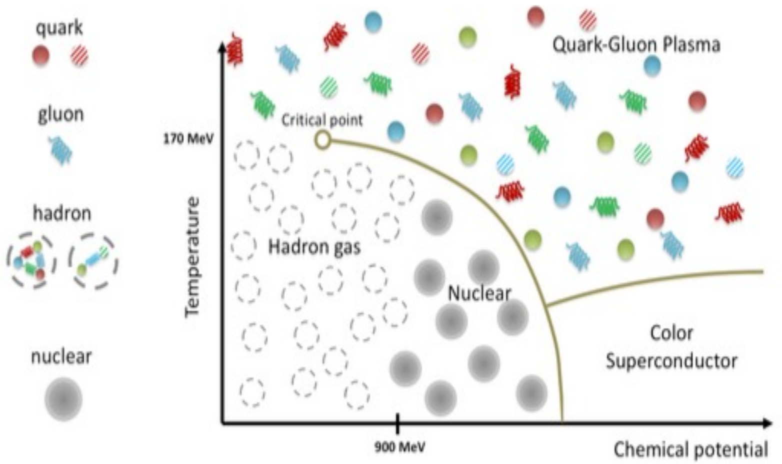
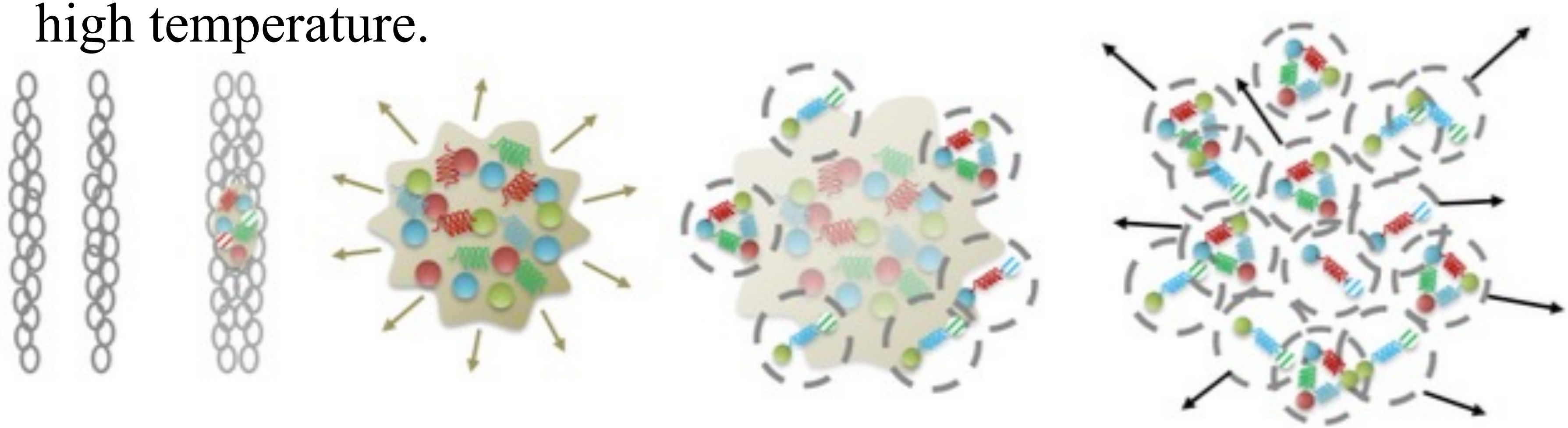


QCD Phase Diagram



Incoming nuclei | Heavy ions collide | QGP formation and Thermal expansion | Hadronization occurs as temperature decreases. | Hadronic freeze out

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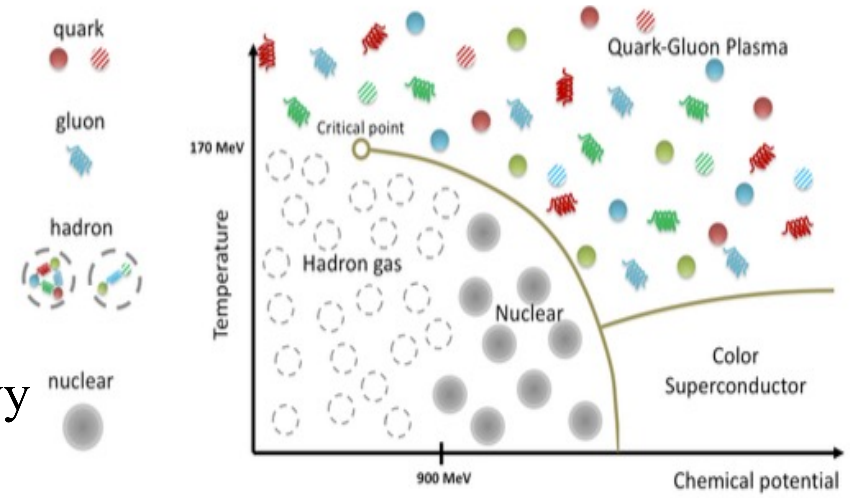
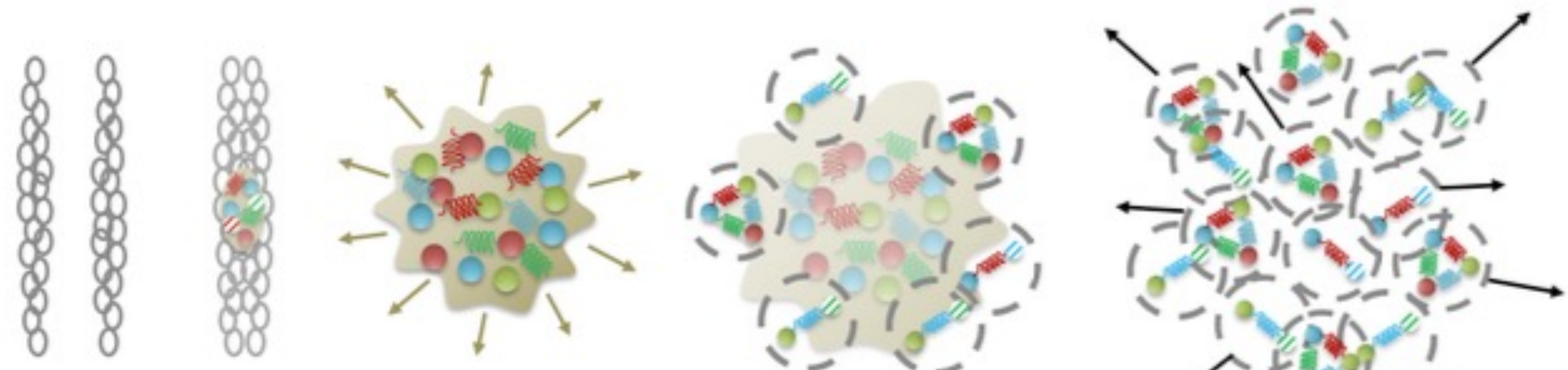
- At sufficiently high temperature, the bonding between partons weaken → hadrons deconfined and moves freely "Asymptotic freedom".
- Existed few microseconds after Big Bang:- Produced in laboratory from collision of heavy ions at sufficiently high temperature.
- In p + p collision, no QGP formation ⇒ taken as baseline for studying QGP.

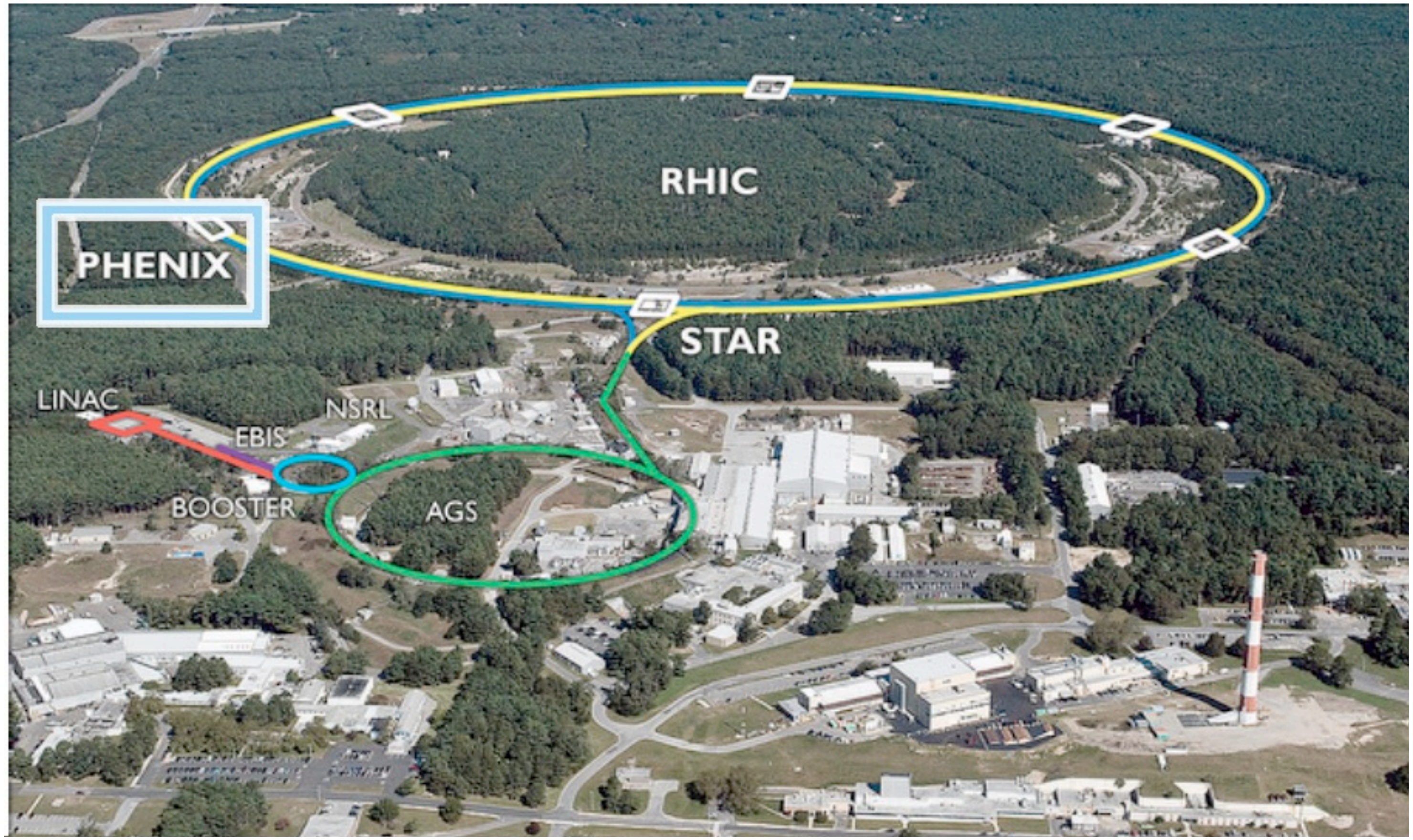


QCD Phase Diagram



Incoming nuclei | Heavy ions collide | QGP formation and Thermal expansion | Hadronization occurs as temperature decreases. | Hadronic freeze out

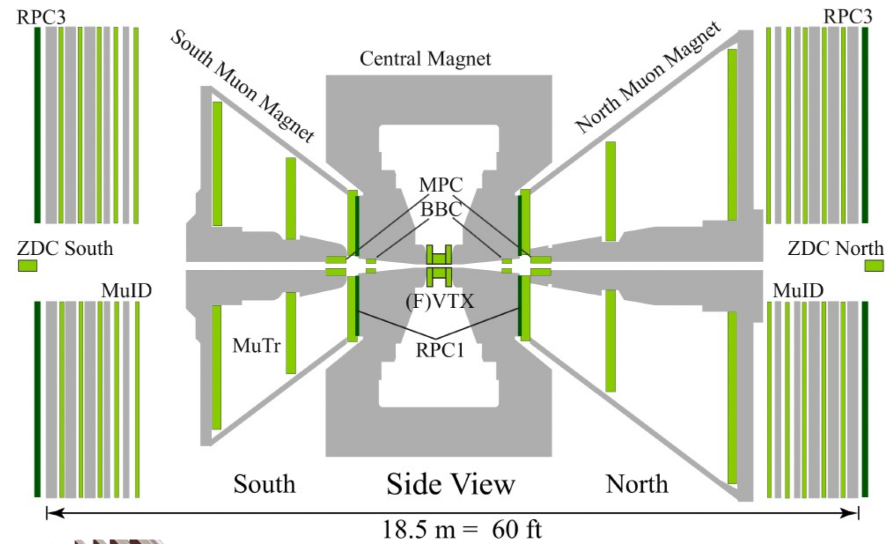
The Relativistic Heavy Ion Collider(RHIC)

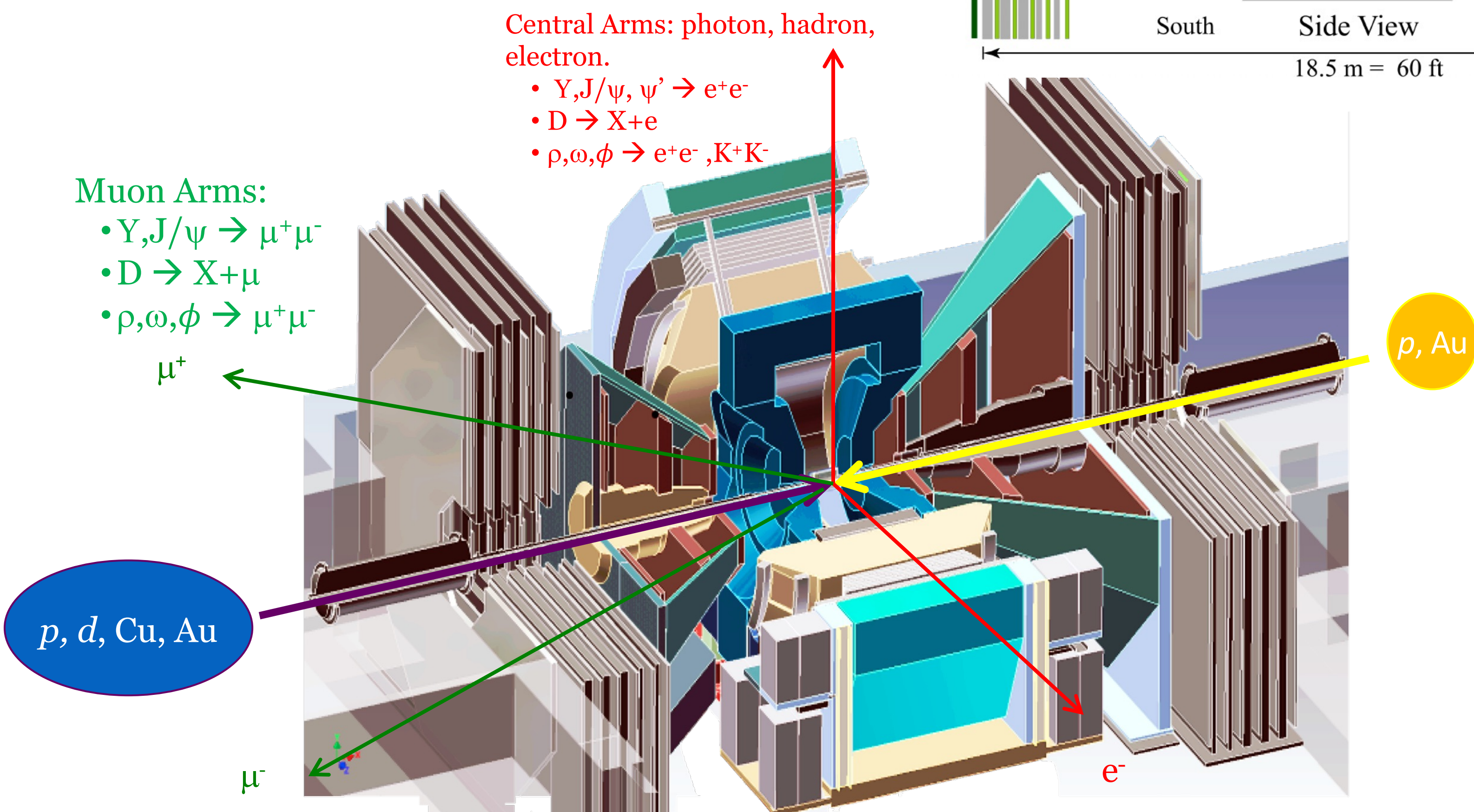


- RHIC is an extremely versatile machine, located at Brookhaven National Lab (BNL), that collides a variety of collision species at various energies.
  - Collision species:- p + p, d + Au, p + Al, p + Au, Cu + Cu, Cu + Au, U + U, Au + Au.
- First machine capable of colliding polarized protons up to 510 GeV.

The PHENIX Detector

- Large rapidity coverage: $|y|<0.35$, $1.2<|y|<2.2$.
- Detector subsystems relevant for this analysis:
  - BBCs, Magnets, Muons Spectrometers
  - Central(VTX) and forward Silicon vertex detectors (FVTX).





Φ - Meson

- $\boldsymbol{\phi}(s\bar{s})$ mass =1.019 GeV/c^2
- Excellent probe for studying QGP.
- Small cross-section for scattering with non strange hadrons: act as penetrating probe as it retain information on initial state evolution of the system.
- Compose of $s\bar{s}$ quarks: provide insight on strangeness enhancement in-medium.
- $\phi \rightarrow \mu^+\mu^-$, muon decay channel is particularly interesting because they experience no final state effect and carry important information about QGP itself.

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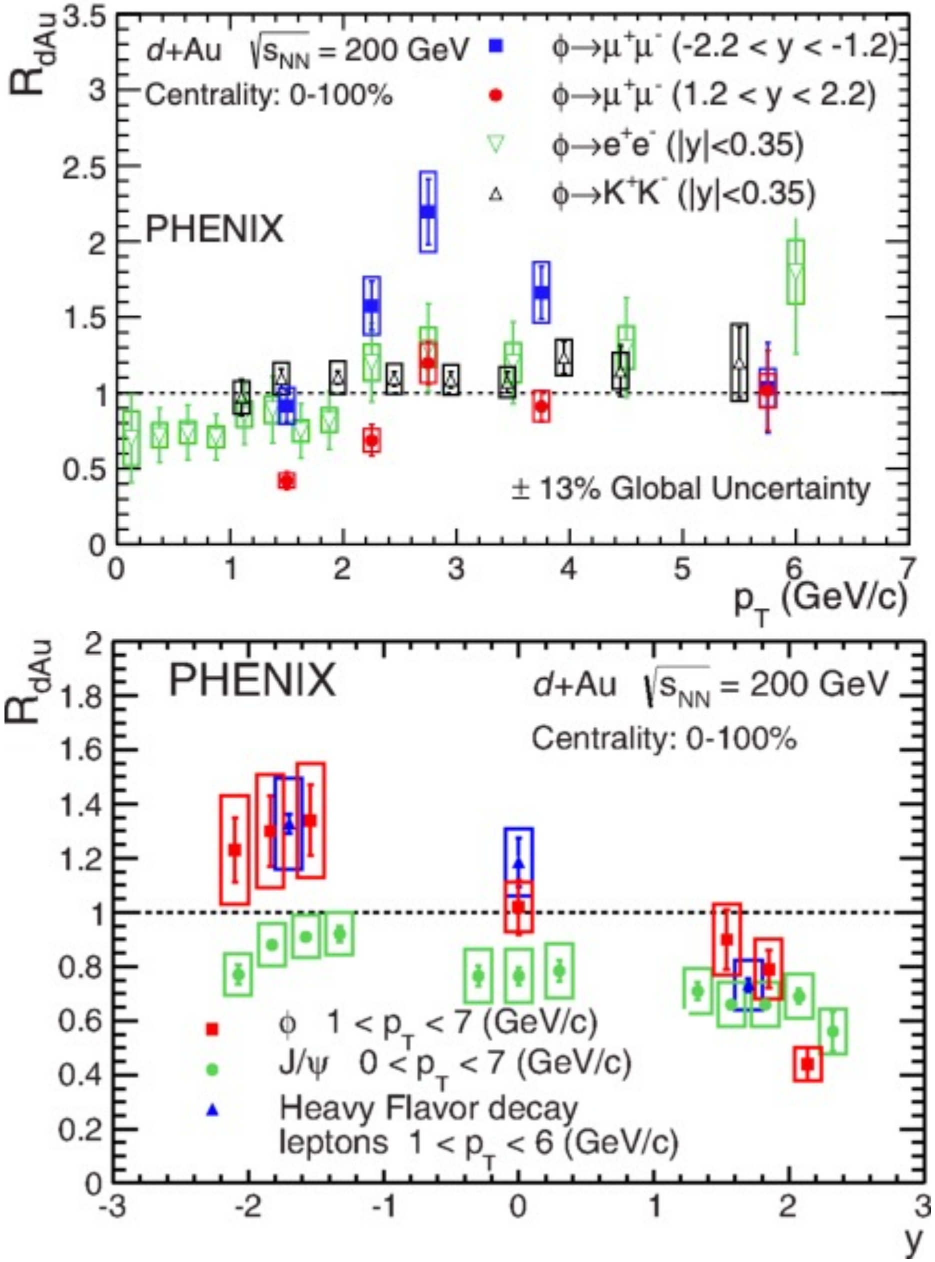
Past Measurements

Collision System	Energy ($\sqrt{s_{NN}}$)	Rapidity	Decay mode	Detector	Publications
p + p	200 GeV	1.2<|y|<2.2	$\phi \rightarrow \mu^+ \mu^-$	RHIC(PHENIX)	PRD 90, (2014)
	2.76 TeV	2.5 < y <4	$\phi \rightarrow \mu^+ \mu^-$	LHC(ALICE)	PLB, 768, 203 (2017)
d + Au	200 GeV	1.2<|y|<2.2	$\phi \rightarrow \mu^+ \mu^-$	RHIC(PHENIX)	PRC, 92 (2015) / PRC, 83 (2011)
		|y|<0.35	$\phi \rightarrow e^+ e^-$ / $\phi \rightarrow K^+ K^-$		
Cu + Cu	200 GeV	|y|<0.35	$\phi \rightarrow K^+ K^-$	RHIC(PHENIX)	PRC, 83 (2011)
Cu + Au		1.2<|y|<2.2	$\phi \rightarrow \mu^+ \mu^-$		PRC, 93 (2016)
p + Pb	5.02 TeV	2.03 < y <3.53 -4.46 < y< -2.96	$\phi \rightarrow \mu^+ \mu^-$	LHC(ALICE)	PLB, 768, 203 (2017)
Pb + Pb	2.76 TeV	2.5<y<4	$\phi \rightarrow \mu^+ \mu^-$	LHC(ALICE)	Eur. Phys. J. C 78(2018)
Au + Au	200 GeV	1.2<|y|<2.2	-	RHIC(PHENIX)	-

ϕ - Meson Production in small system.

Phys. Rev. C **92**, 044909 (2015)



Nuclear modification Factor:

$$R_{AB} = \frac{d^2N_{\phi}^{A+B}/dp_T dy}{d^2N_{\phi}^{p+p}/dp_T dy} \cdot \frac{1}{<N_{coll}>}$$

$< N_{coll} >$ → corresponding mean number of nucleon nucleon collision.

- An enhancement (suppression) observed at backward (forward) rapidity region in d + Au collision.
- The observed enhancement in Au going direction (backward) is a typical behavior of Cronin effect.
- The rapidity dependent R $_{dAu}$ is similar to the open heavy flavor modification.
  - indicates cold nuclear matter effects.

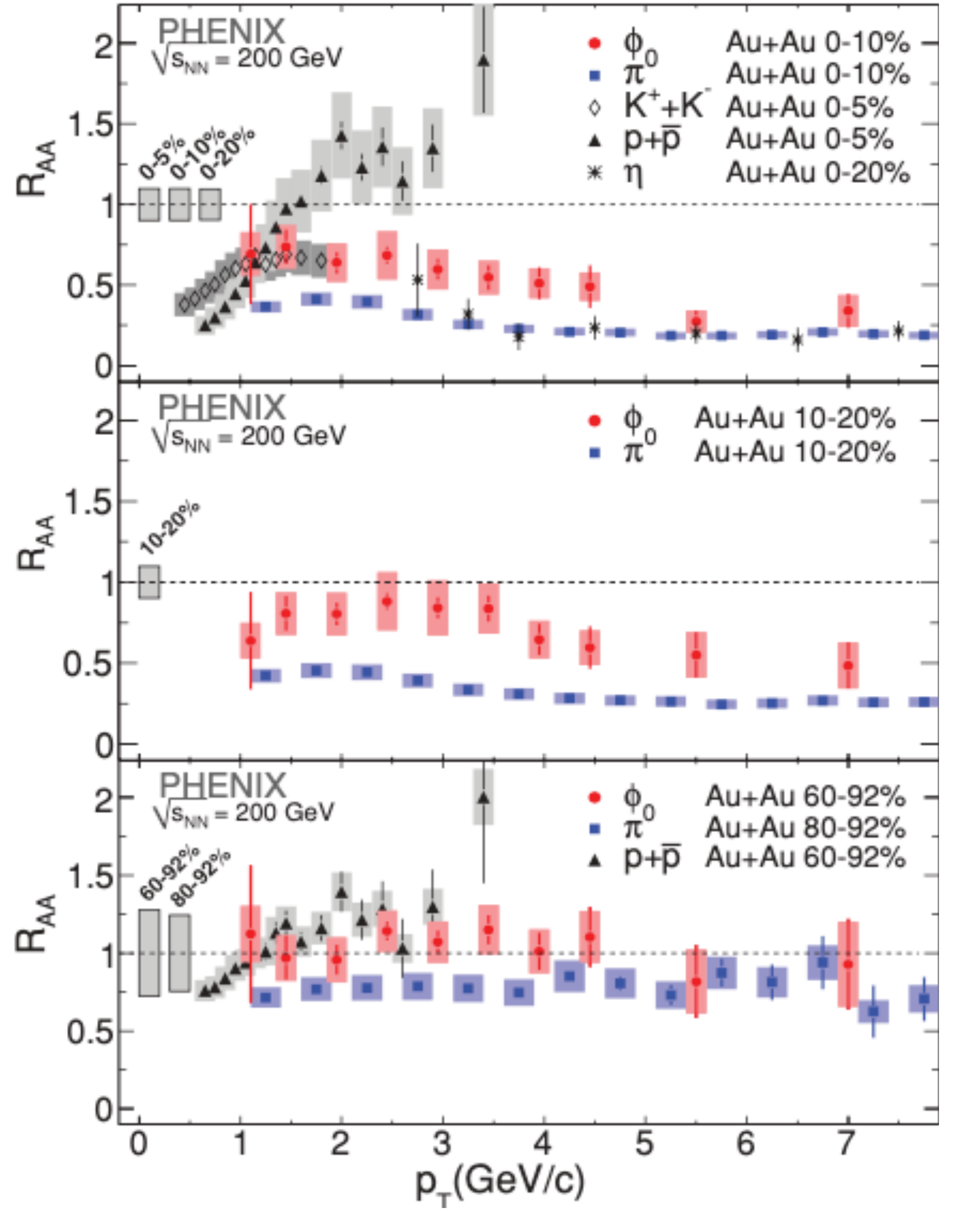
ϕ - Meson production at Mid Rapidity

- For all centralities , ϕ-meson is less suppressed than π^0 in the intermediate p_T range in Au + Au collision, whereas similar suppression in higher p_T range.

- ϕ-meson production in dense medium has centrality and energy dependence.

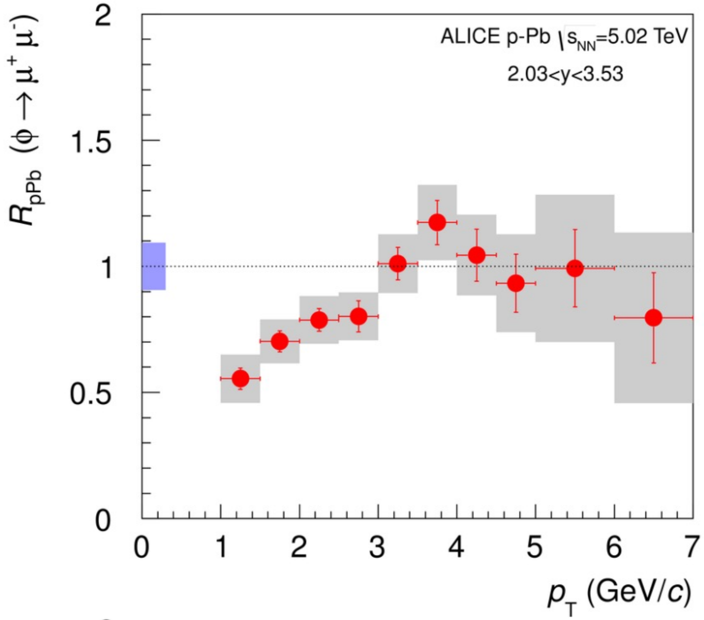
- Suppression patterns of different mesons at high p_T favors the production of mesons via jet fragmentation outside the hot and dense medium created in the collision.

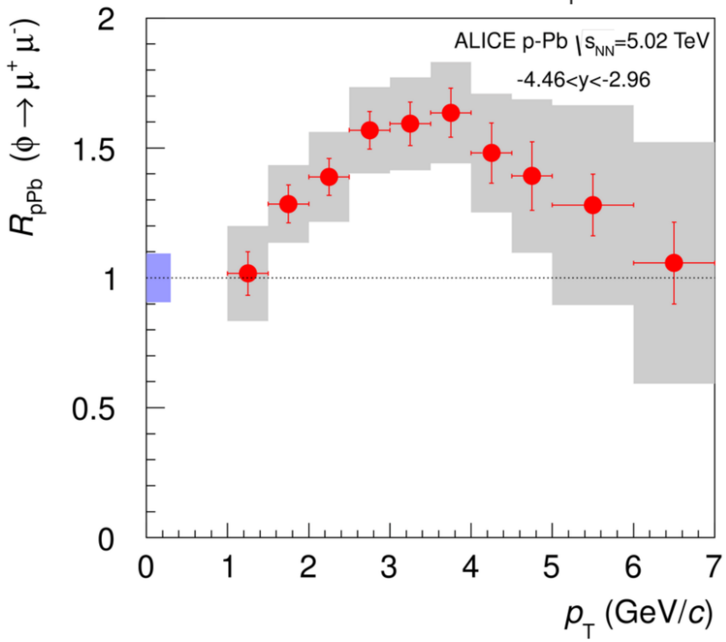
PHENIX, PRC **83**, 024909 (2011)

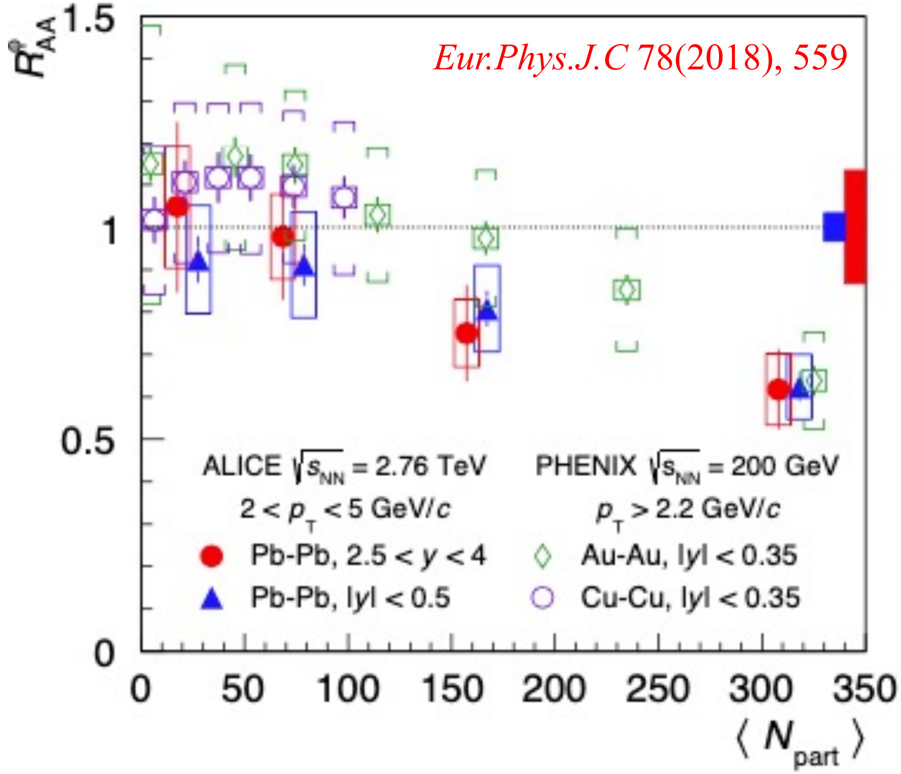


ALICE Measurement at forward rapidity

PLB, 768, 203 (2017)







- *Φ*-enhancement is observed in p + Pb collision, consistent with PHENIX *d* + Au collisions.
- Similar nuclear suppression pattern observed for ALICE in Pb+ Pb collision as observed for PHENIX in Au + Au, Cu + Cu , given the current uncertainties.

Where are we so far?

- Φ - mesons production has been observed in small p + A collision system at forward and mid rapidities in A+A collision by PHENIX.
- Observed CNM effect in small system while the enhancement in large system providing information about the bulk and the hydrodynamical evolution.
- PHENIX collected large data set from Au + Au collision in 2014 and 2016.
- The study of ϕ-mesons production at forward rapidity may provide more insight into the QGP formation and possible hot nuclear matter (HNM) effect.

Data summary of PHENIX Au + Au collision at 200 GeV

Year	No of Events	Integrated Luminosity
2014	19B	$7.5nb^{-1}$
2016	15B	$7nb^{-1}$

Invariant Yield and R_{AA} Extraction

- Invariant Yield extracted as function of transverse momentum (p_T) and rapidity (y).

$$\frac{B_{\phi\rightarrow\mu\mu^-}}{2\pi pT}\frac{d^2N_\phi}{dydp_T} = \frac{1}{2\pi p_T}\frac{1}{\Delta y \Delta p_T}\frac{N_\phi}{A\varepsilon_{rec}}\frac{c}{N_{Mb}}$$

- ϕ Meson is studied in the p_T and Rapidity range:
  - $2.5<p_T<6.0$
  - $1.2<|y|<2.2$

- N_ϕ is the number of the raw yield of ϕ Mesons.

- From the Simulation (GEANT4), acceptance and efficiency ($A\varepsilon_{rec}$) is calculated.

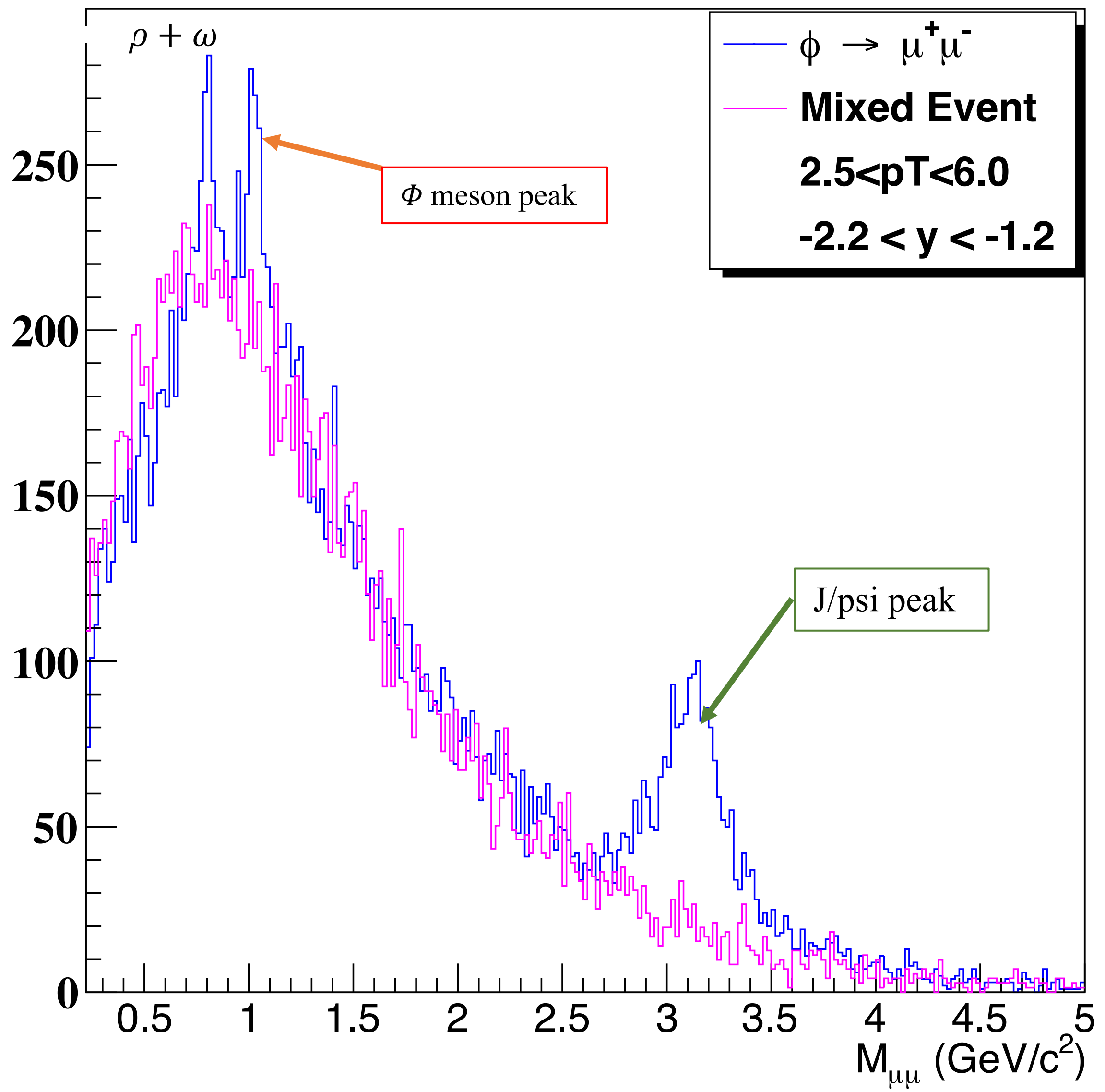
$$A\varepsilon_{rec} = \frac{No.\ of\ Reconstructed\ events}{No.\ of\ generated\ events}$$

- Nuclear modification Factor:

$$R_{AB} = \frac{d^2N_\phi^{A+B}/dp_Tdy}{d^2N_\phi^{p+p}/dp_Tdy}\cdot\frac{1}{<N_{coll}>}$$

Φ - Meson Mass Spectrum and Raw Yield (N_{ϕ})

- ϕ Meson is studied in $2.5<p_T<6.0$ & $1.2<|y|<2.2$.
- Muon candidates of opposite signs are paired together to form mass spectra.



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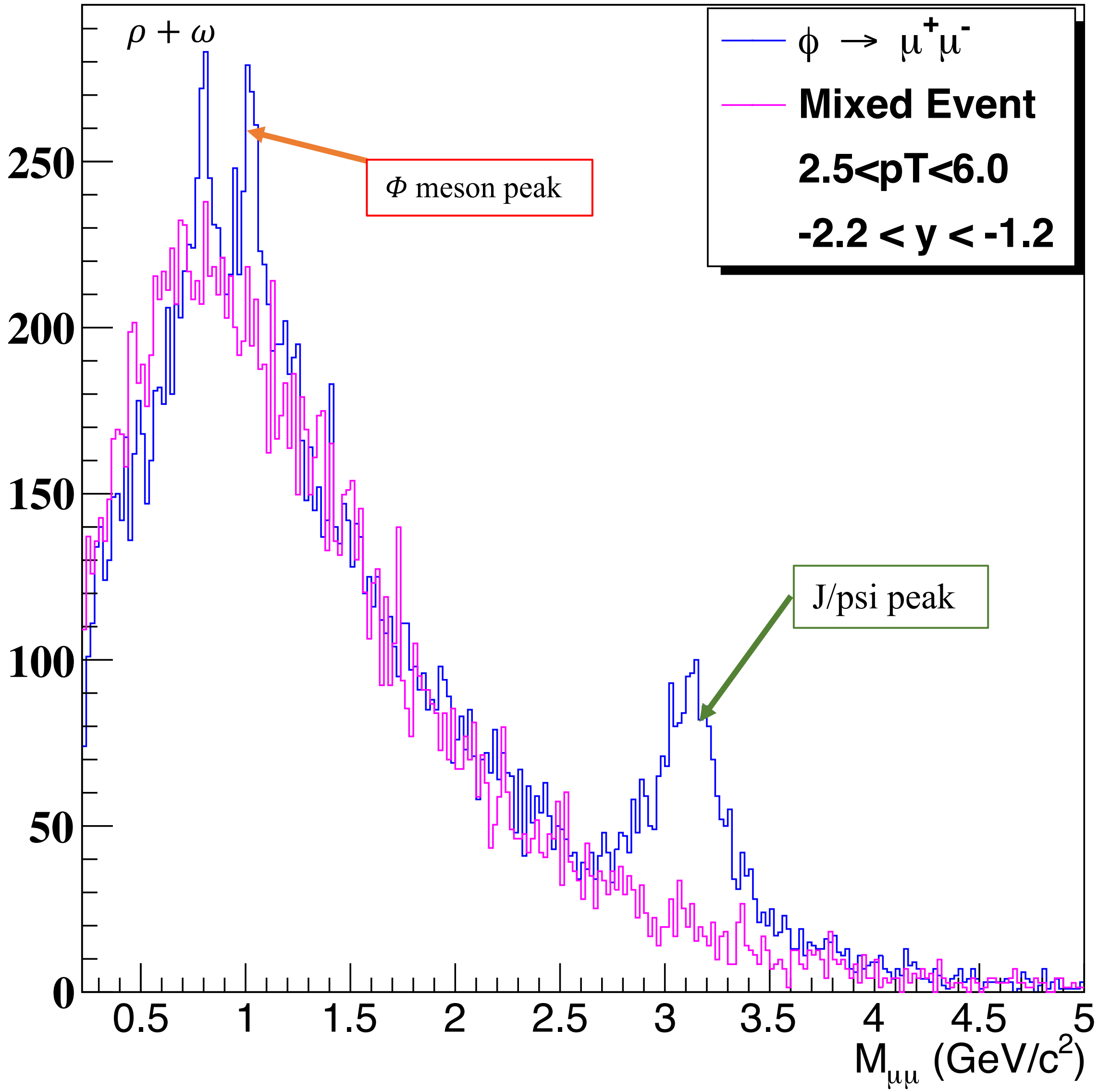
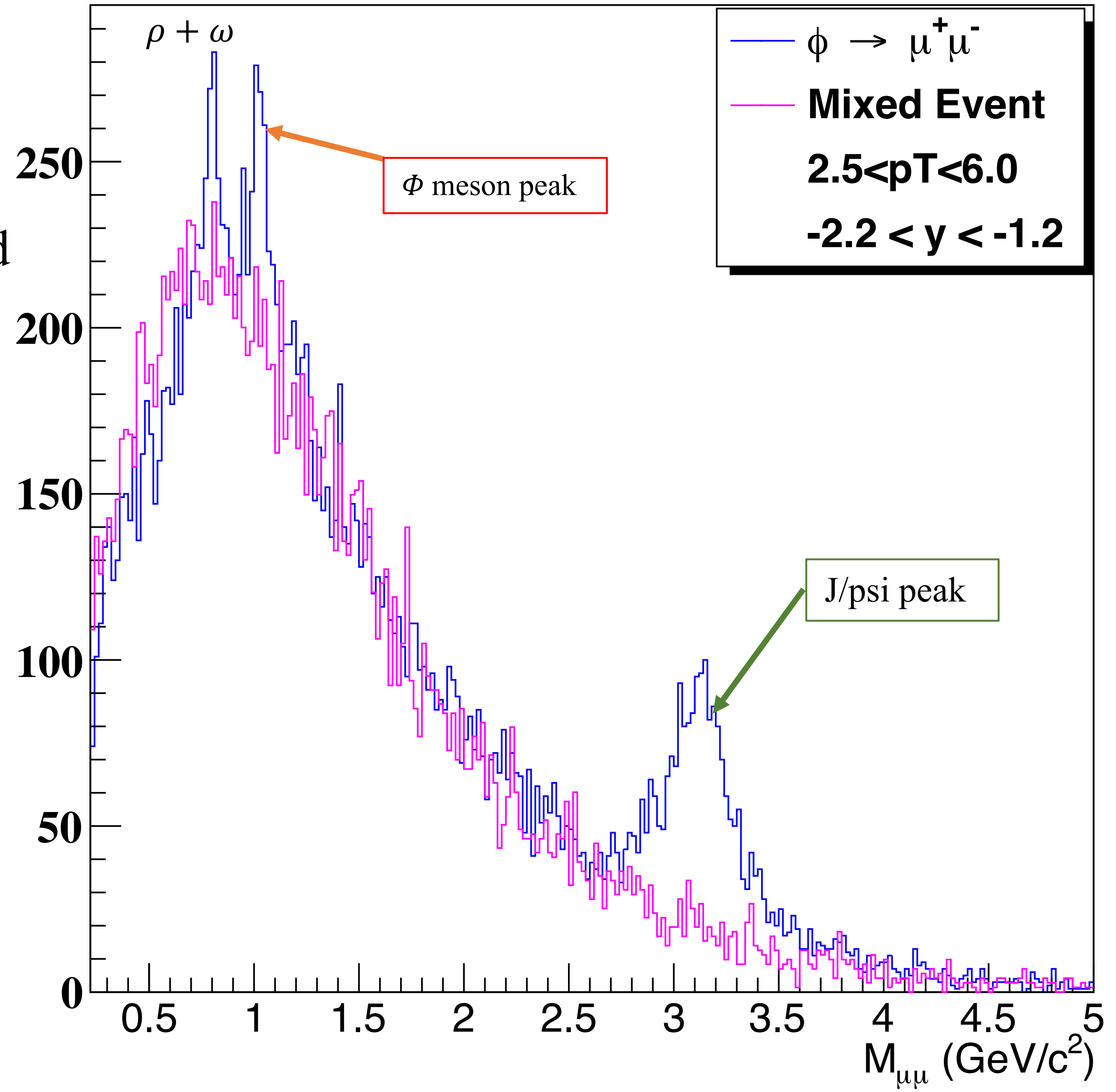
- Muon candidates of opposite signs are paired to form mass spectra.
- Required to match with FVTX: $\rho + \omega$ meson peak distinct from ϕ meson peak.



Φ - Meson Mass Spectrum and Raw Yield (N_{ϕ})

- Backgrounds:
  - Correlated backgrounds:
    - Open charm decay, open bottom decay and Drell Yan Process.
  - Uncorrelated backgrounds:
    - Random association of unrelated muon candidates (Mixed event).



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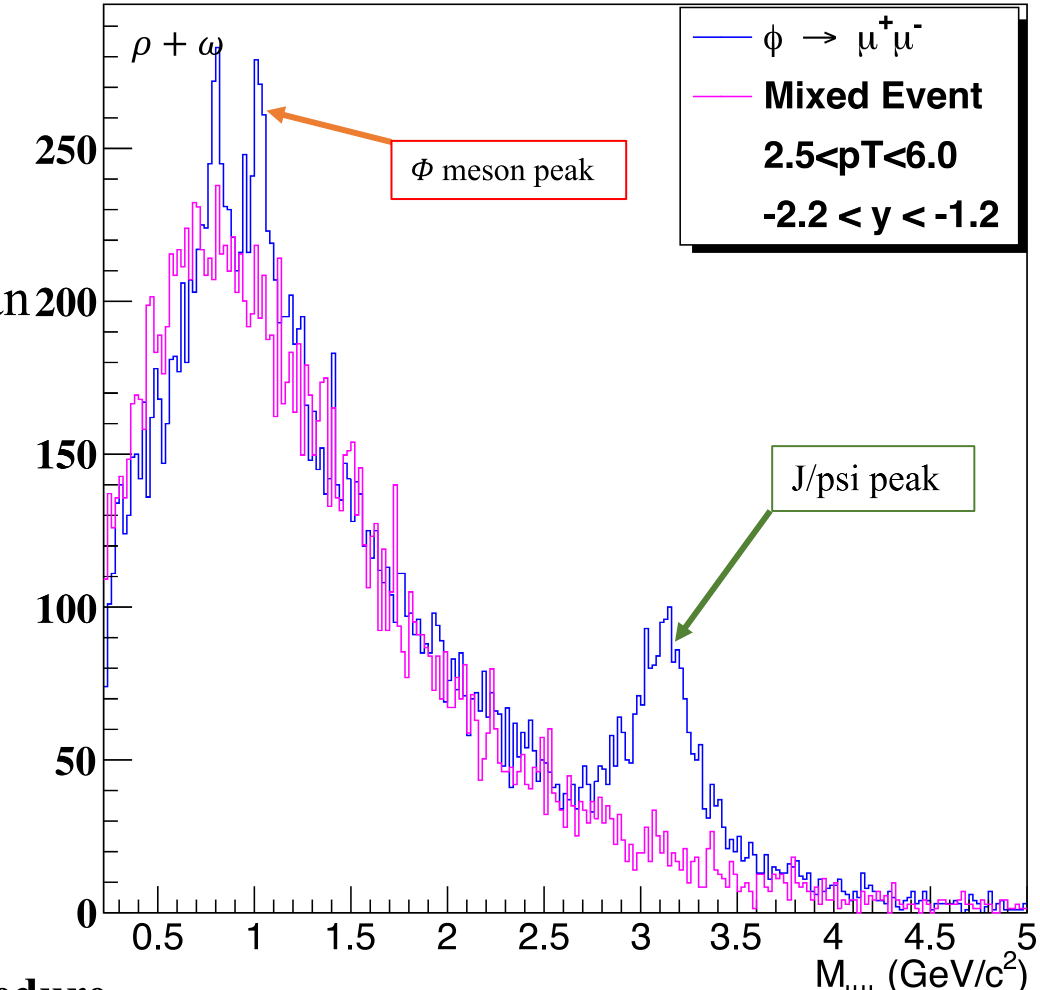
- Backgrounds:
  - Correlated backgrounds:
    - Open charm decay, open bottom decay and Drell Yan Process.
  - Uncorrelated backgrounds:
    - Random association of unrelated muon candidates (Mixed event).
- Background is subtracted to extract phi signal.

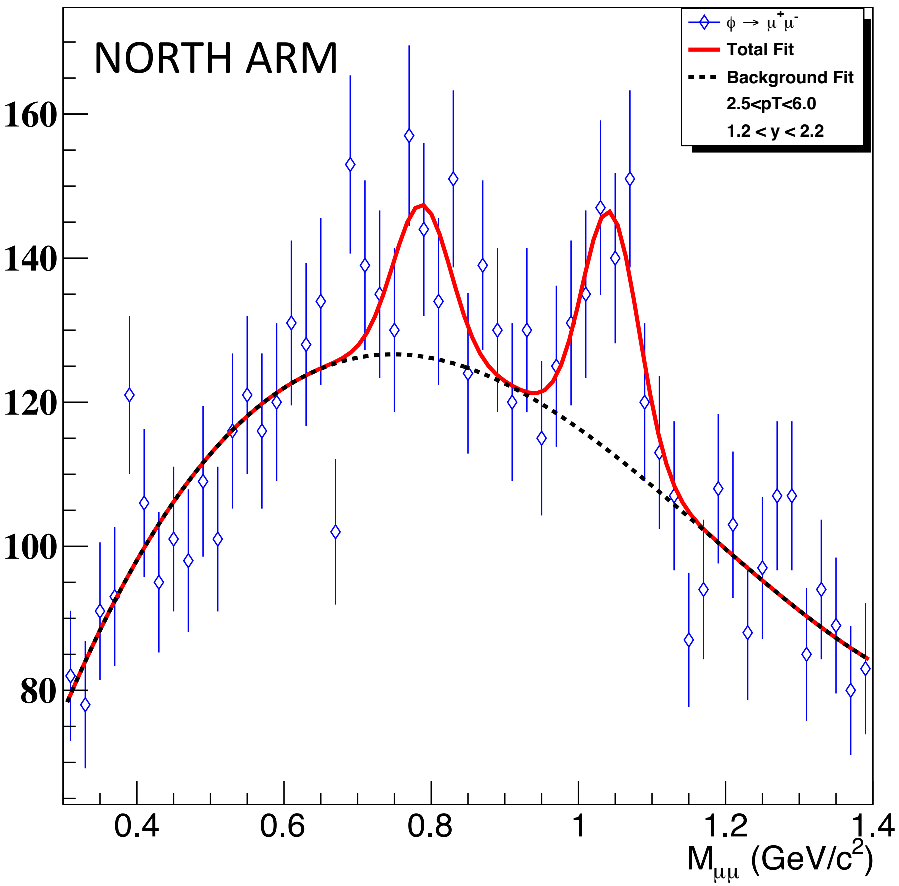


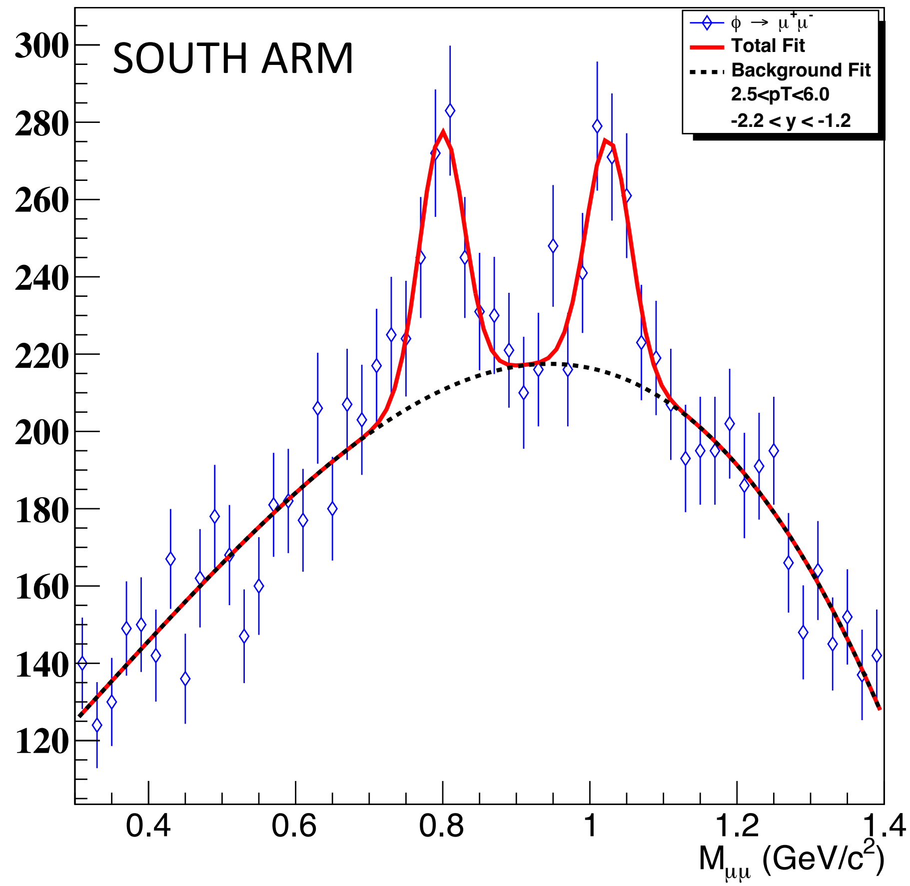
Background Normalization and Fit Procedure

$$F(x) = (1 - fG_2) * G\left(M_{\mu\mu}, M_{j/\psi}, \sigma_{G1}\right) + fG_2 * G\left(M_{\mu\mu}, M_{j/\psi} + \delta_M, \sigma_{G2}\right) + \frac{C}{(e^{-(Ax+B*x^2+\frac{x}{d})})^e}$$

$$G(M_{\mu\mu}, M, \sigma_G) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{\frac{-(M_{\mu\mu}-M)^2}{2\sigma^2}}$$

Φ-Meson Raw Yield as a function of Rapidity

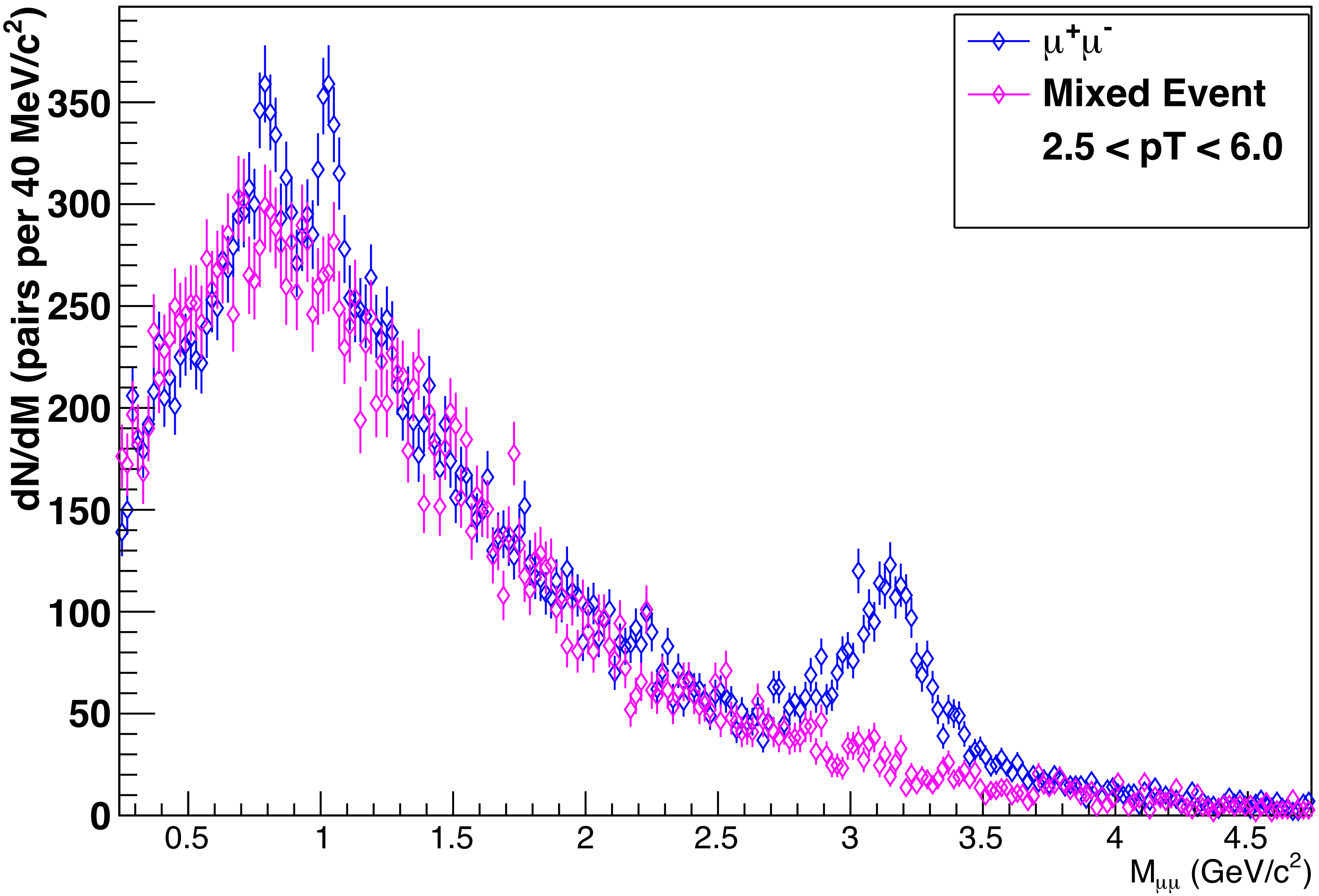




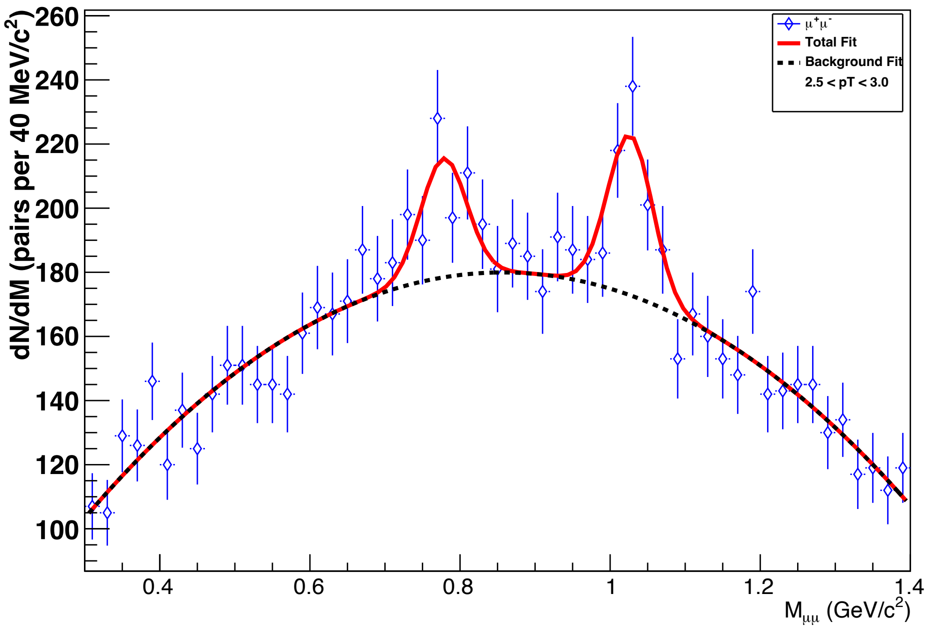
- For both arm, invariant yield is calculated.
- Symmetric Collision:- invariant yield should be consistent for both arms.

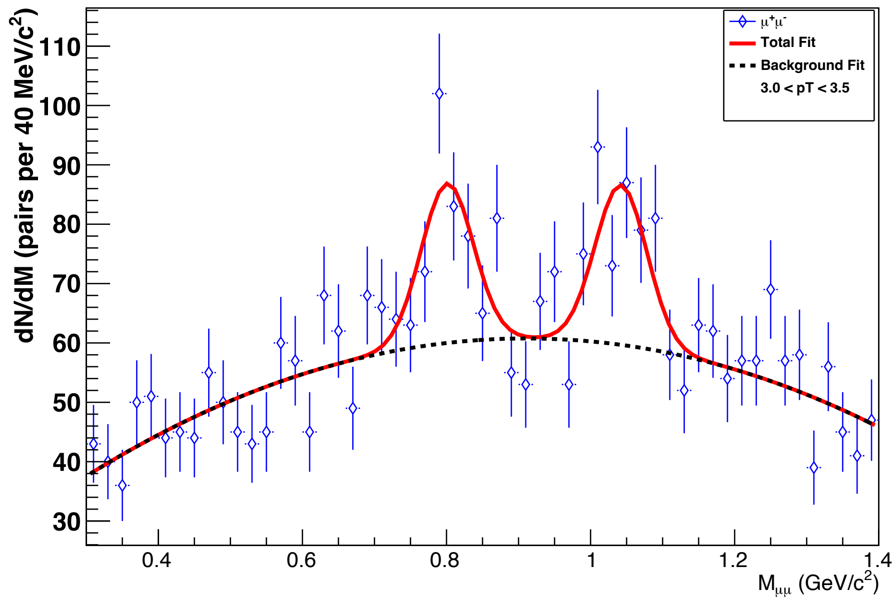
Φ - Raw Yield ($2.5<p_T(GeV/c)<6.0$ & $1.2<|y|<2.2$)

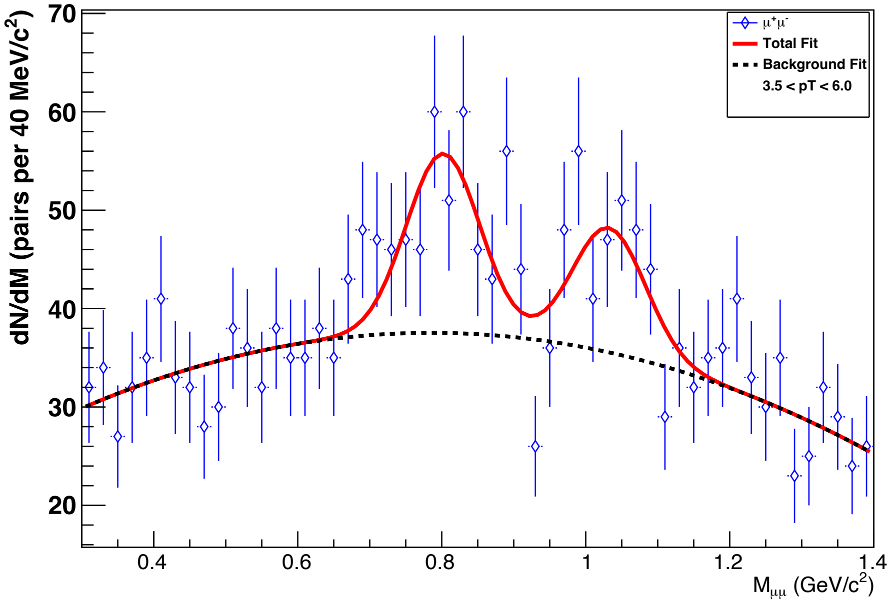
- Summed North and South arm spectra.



Φ-Meson Yield Extraction as a function of p_T







- Invariant yield in different p_T bins.
- p_T bins= {2.5, 3.0, 3.5, 6.0}

Summary & Outlook

- Φ-mesons are good probe for studying QGP, less interactive with the medium allowing to understand initial state of QGP formation.
- PHENIX observed Φ - meson suppression at forward rapidity and enhancement at backward rapidity.
- Studying Φ-mesons production at forward rapidity in Au + Au collision $\sqrt{s_{NN}}$ = 200 GeV
  - ➢ Ongoing analysis of the Au + Au data obtained in 2014 in the PHENIX muon arms.
  - ➢ Invariant Yield and Nuclear Modification Factor (R_{AA}).

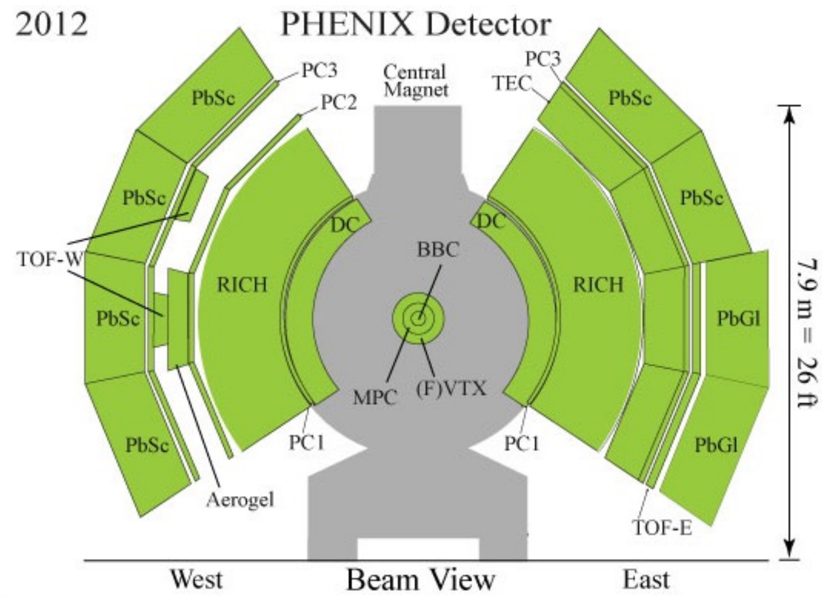
THANK YOU

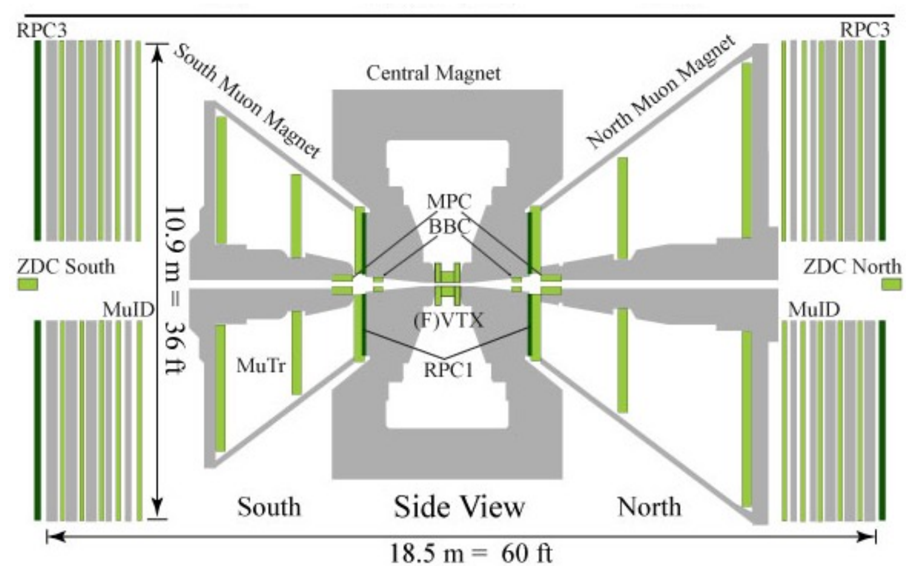
I want to acknowledge The Gordon and Betty Moore Foundation and APS for the financial support to present this work at GHP20230 workshop.

BACK UP

PHENIX DETECTOR

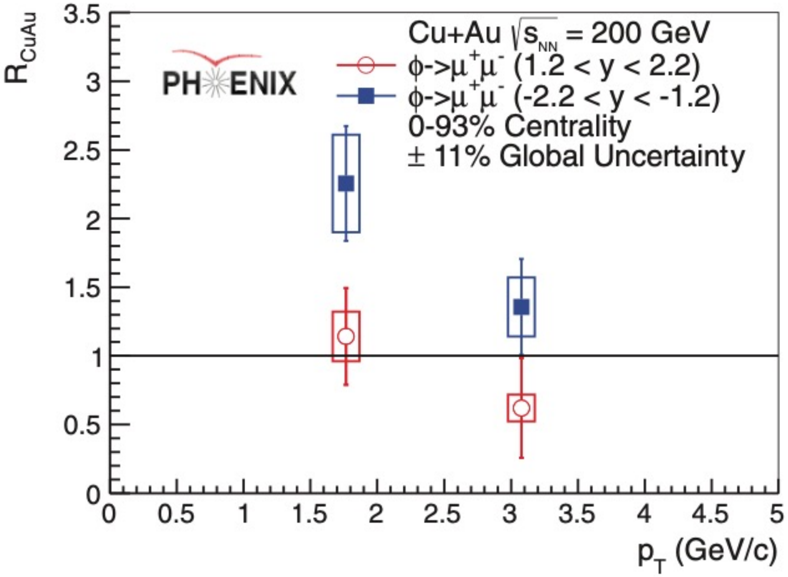
- Comprises of four spectrometers.
- Central Spectrometer:
  - o Electromagnetic calorimetry (EMCal), Pad Chamber (PC) Drift Chamber (DC).
- Muon Spectrometers.
  - o BBC
  - o FVTX
  - o Muon Trackers (MuTr):
    - o three stations of cathode strip chambers in radial magnetic field.
  - o Muon Identifiers (MuID):
    - o Five alternating steel absorbers and Iarocci tubes.

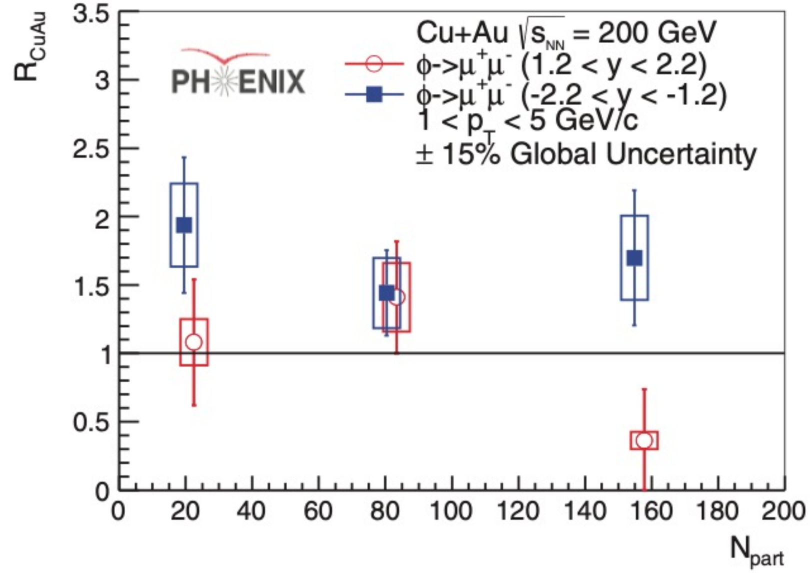


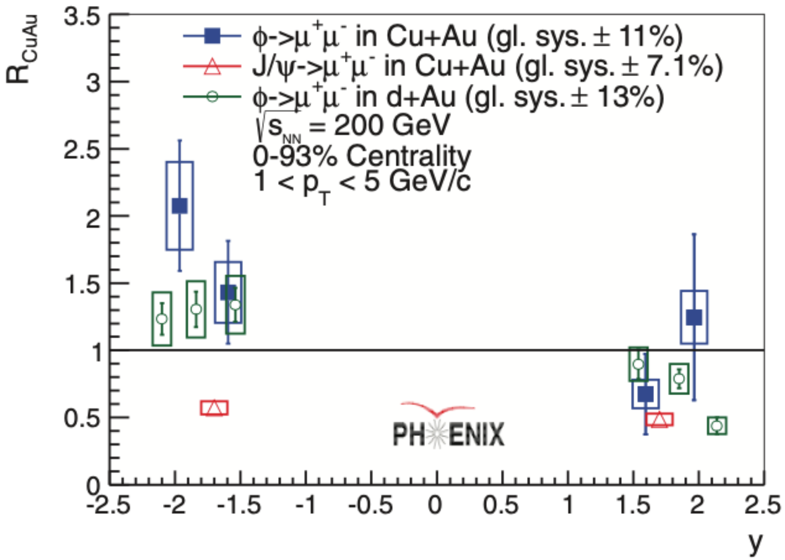


ϕ - Meson production at Forward Rapidity

PHENIX, PRC, 93 (2016)

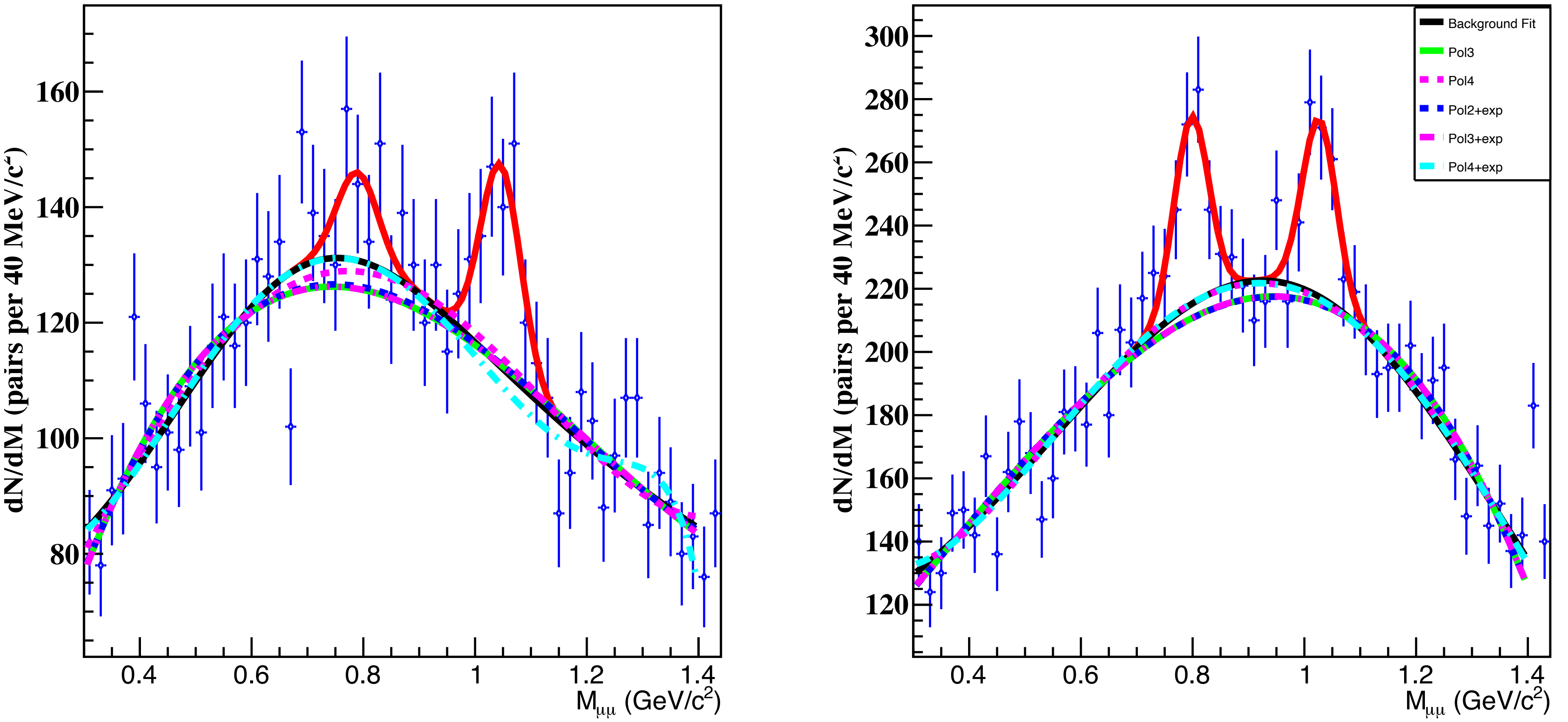




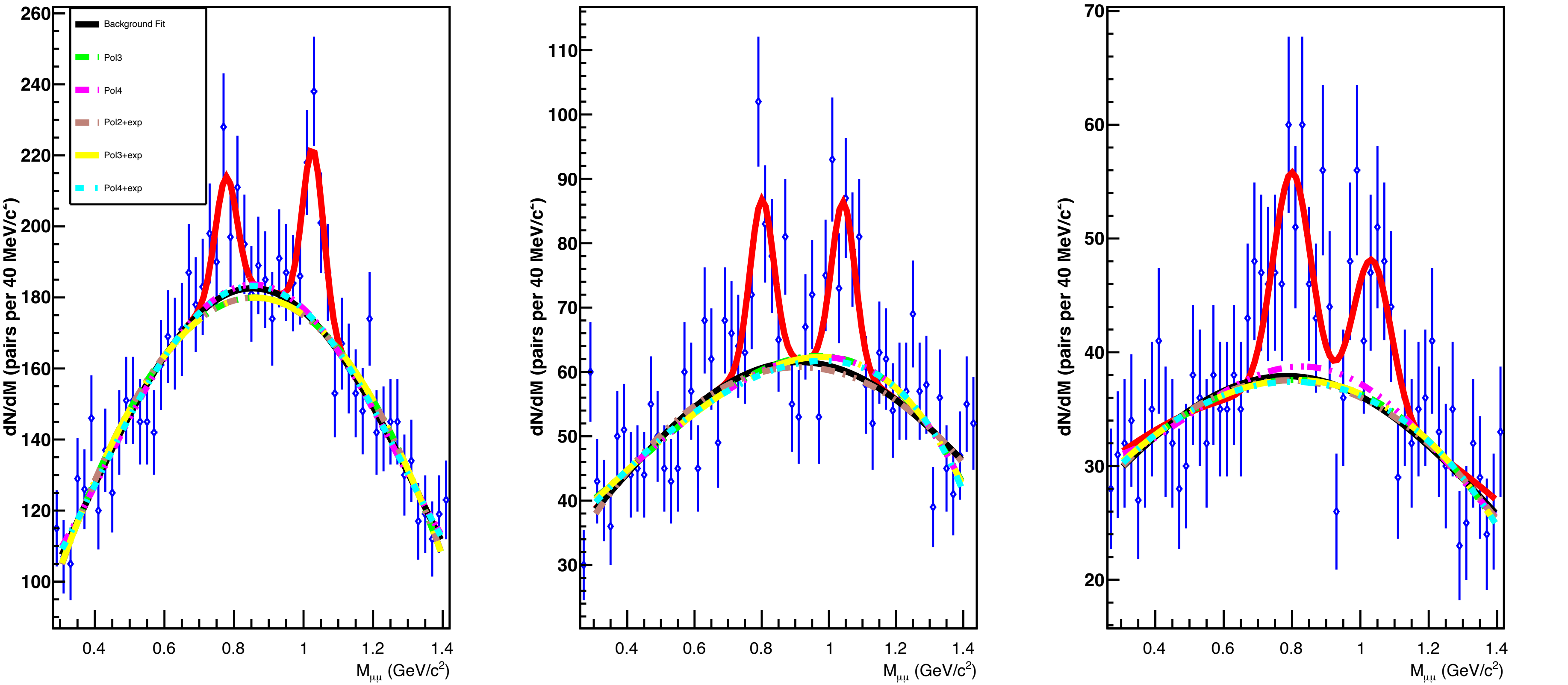


- ❑ ϕ enhancement in Au going direction and most pronounced in most central collision and at low momentum.
  - Similar trend to PHENIX in d +Au collision at same energy and rapidity as well as ALICE measurement in p +Pb collision (CNM effect).
- ❑ Expected substantial contribution from HNM effect too.

Φ-Meson Raw Yield as a function of Rapidity



Φ-Meson Raw Yield as a function of p_T



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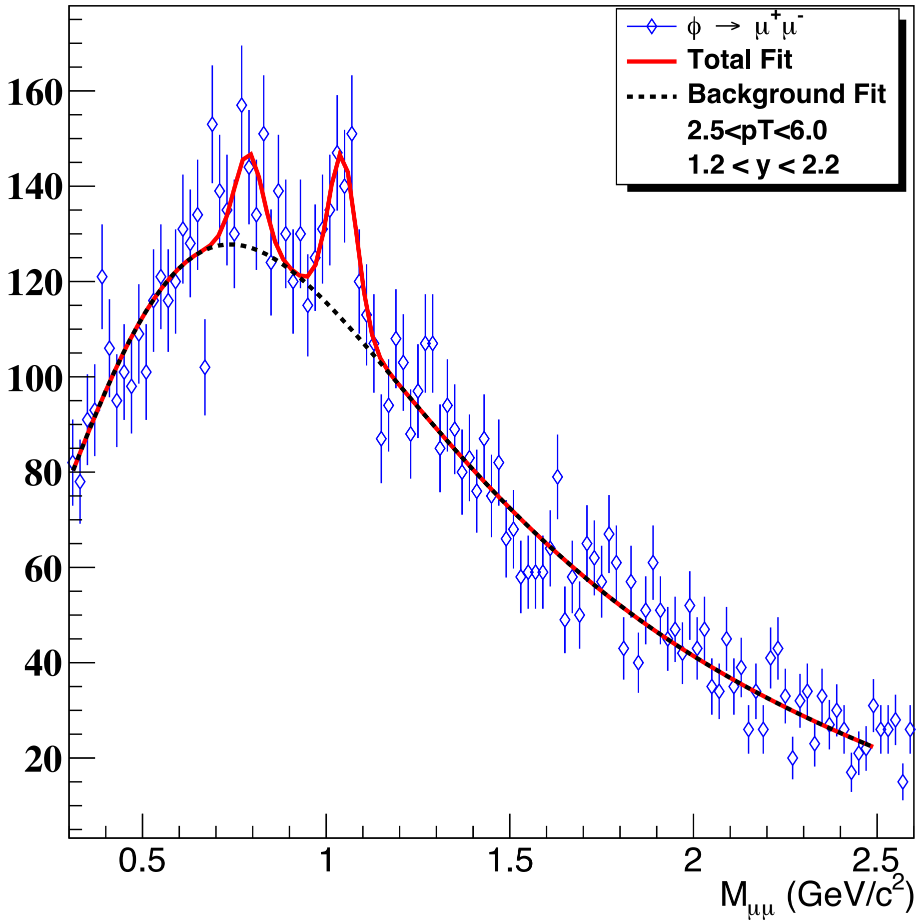
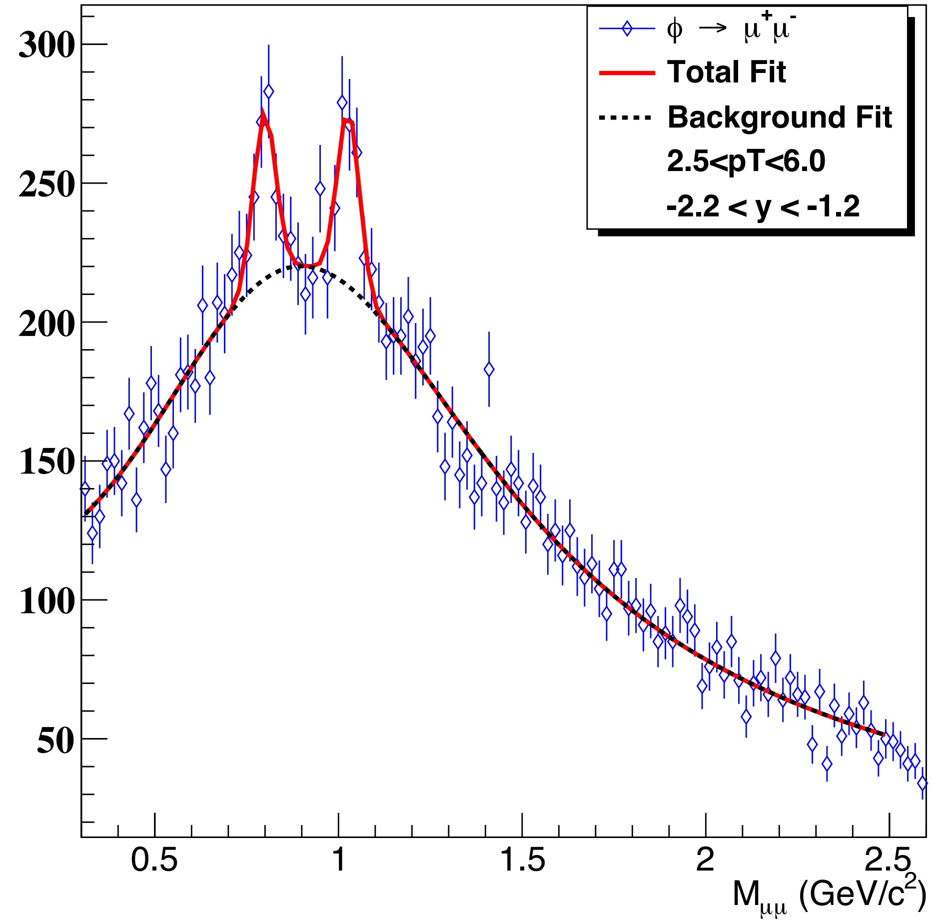
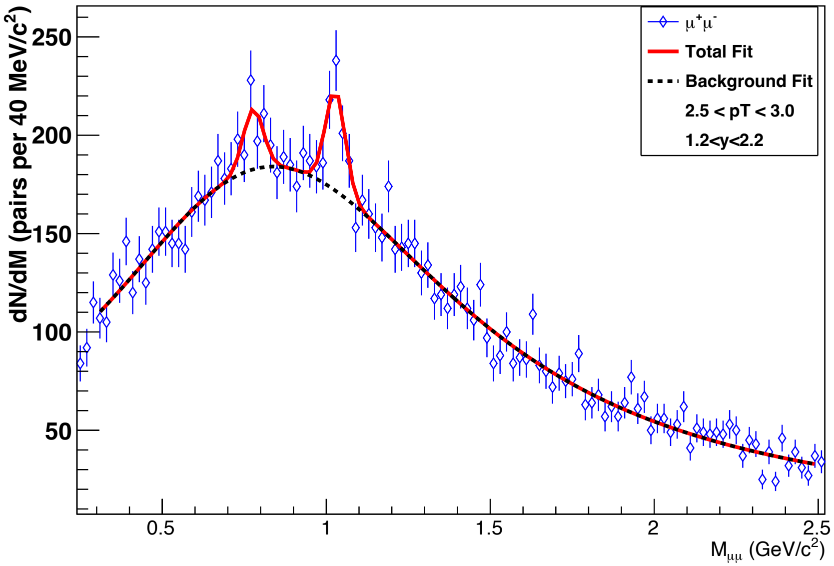
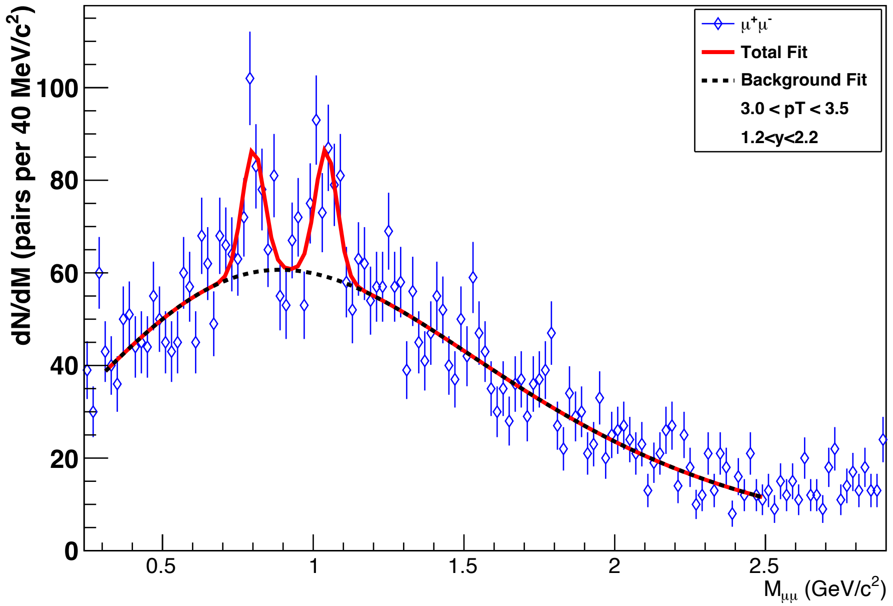
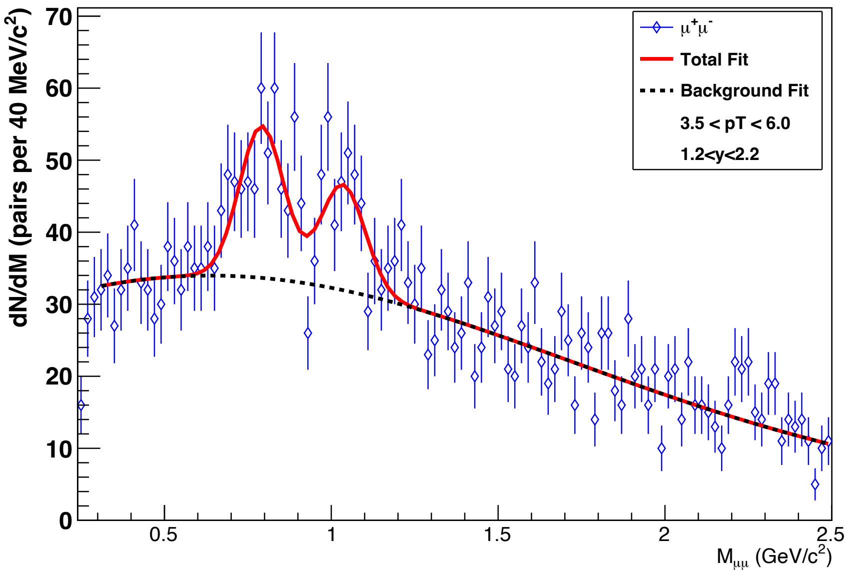




Φ-Meson Yield Extraction as a function of pT



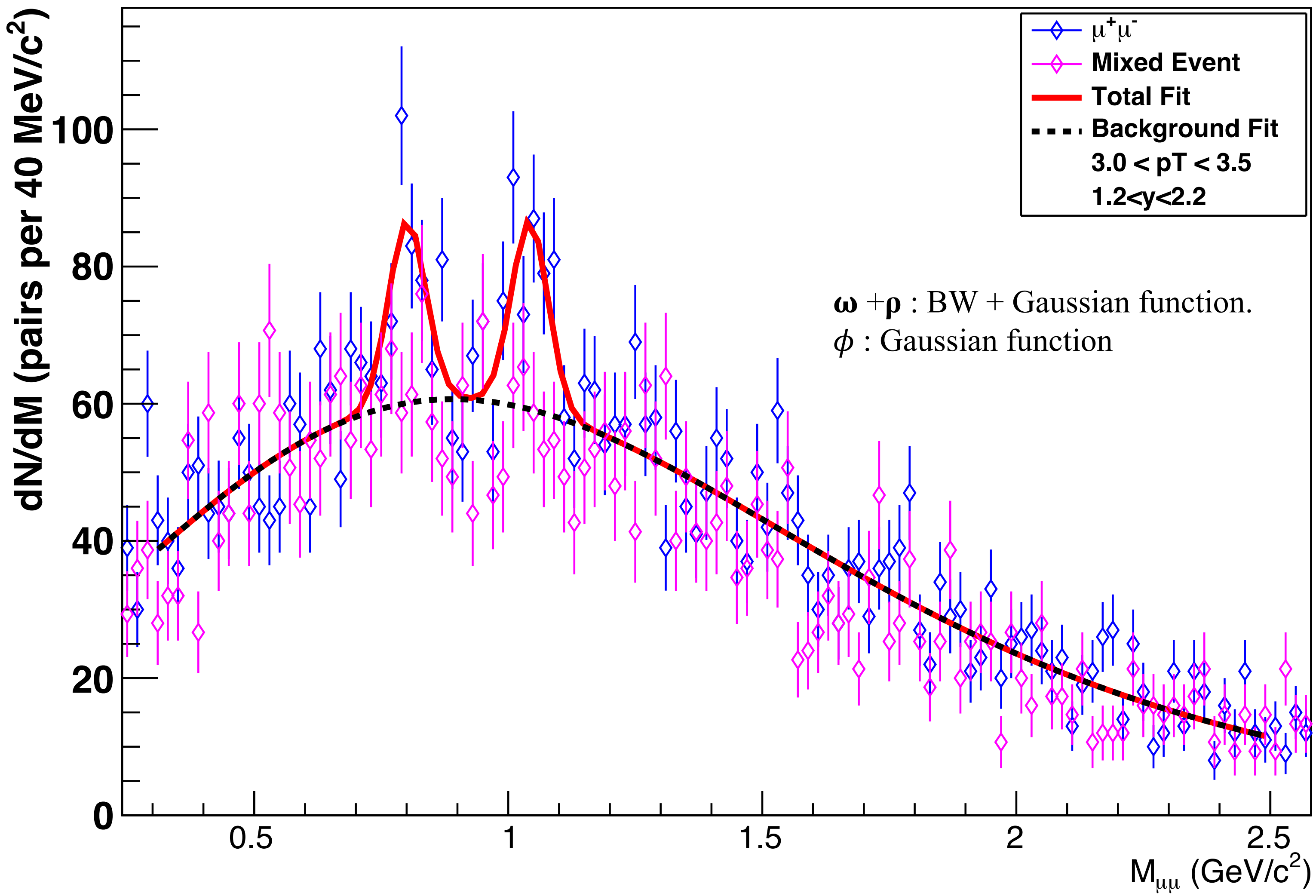




- Invariant yield in different pT bins.
- p_T bins= {2.5, 3.0, 3.5, 6.0}

Φ-Meson Yield Extraction

- Summed North and South arm spectra.
- pT bins : {2.5, 3.0, 3.5, 6.0}



Φ-Meson Raw Yield as a function of rapidity

With mixed event background