$\mu^+\mu^-$ Production in p+p and p+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV with the Muon Telescope Detector at STAR

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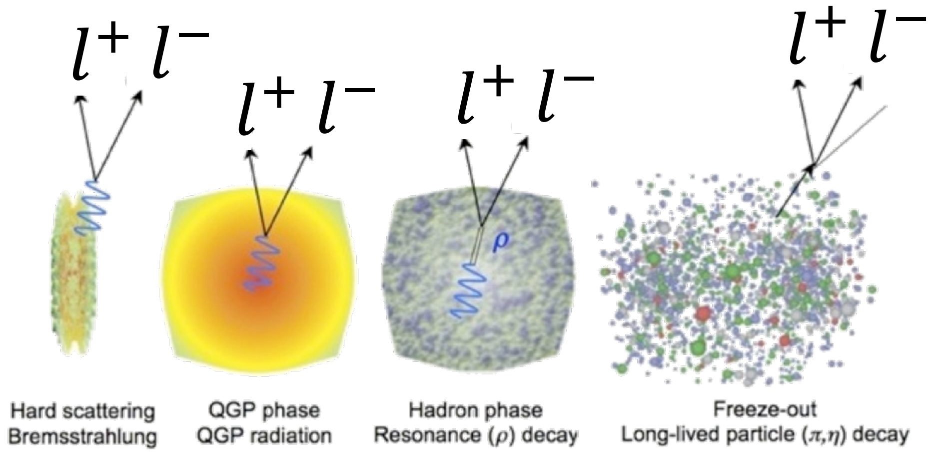
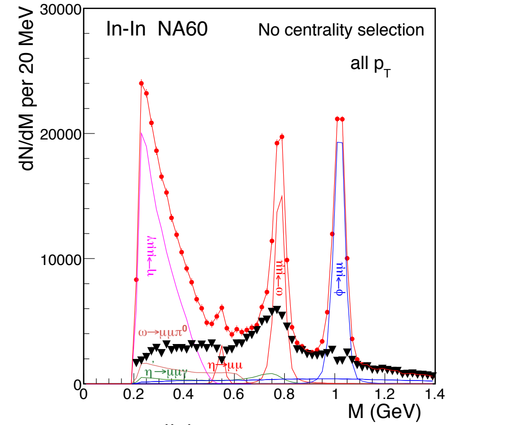
Introduction





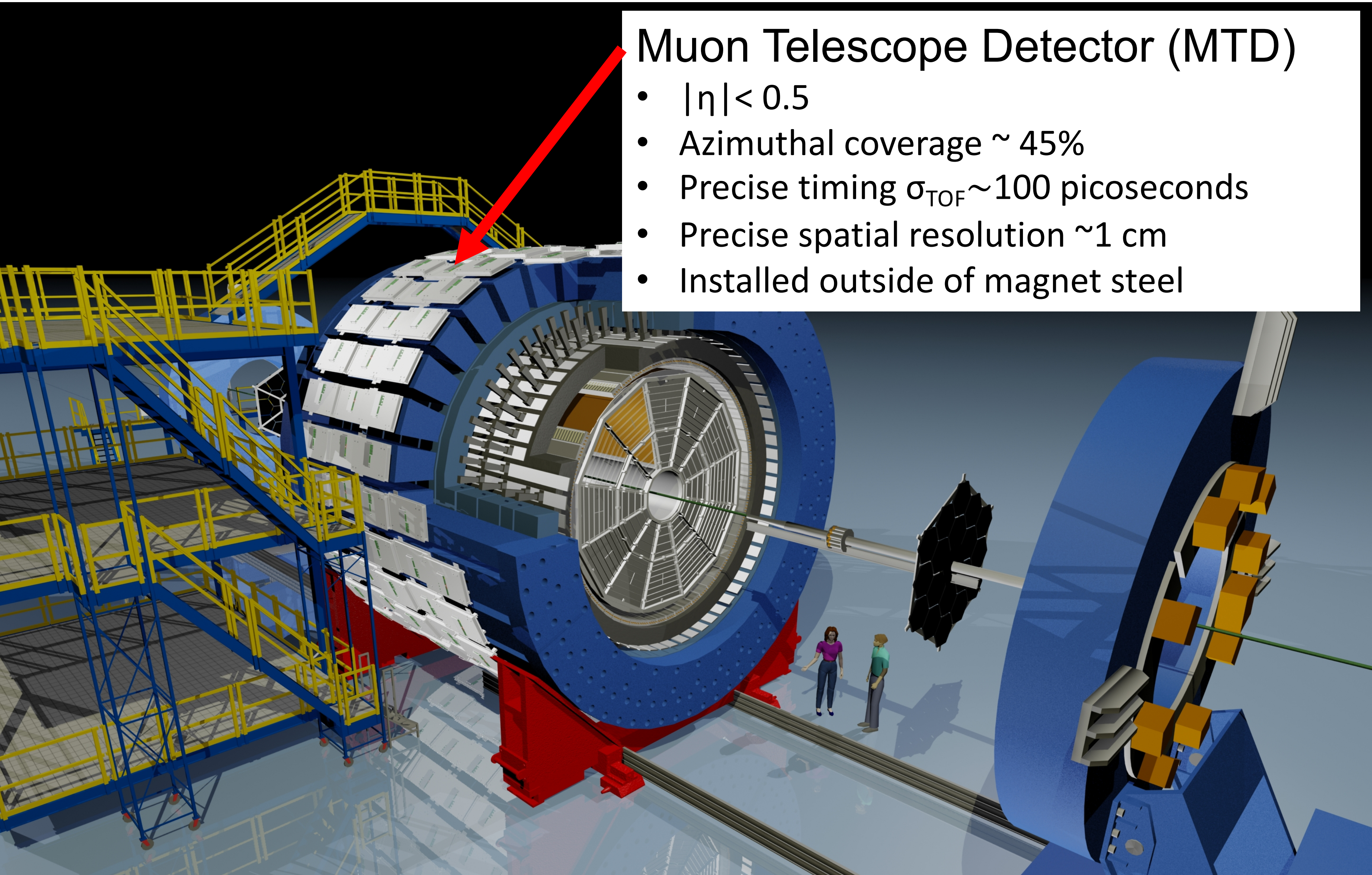
NA60 Collaboration EPJC, 2009: pp. 711–720.

- Leptons are inert to the strong force → provide a penetrating probe of medium
- NA60's dimuon measurements in In+In at $\sqrt{s_{NN}} = 17.3$ GeV demonstrated that dimuons ($\mu^+\mu^-$) are ideal for studying:
  - In-medium ρ-meson broadening – may be linked to chiral symmetry restoration
  - Thermal radiation emitted by the QGP – provides a pristine measurement of the system's early temperature

Rapp *PLB* 753 (2016): 586–90.

- Muon Telescope Detector → identify muons over a large momentum range at STAR for the first time
- In this talk:
  - Techniques developed to study $\mu^+\mu^-$ invariant mass spectra with the MTD at STAR
  - Results from p+p, p+Au and viability of measurement in Au+Au

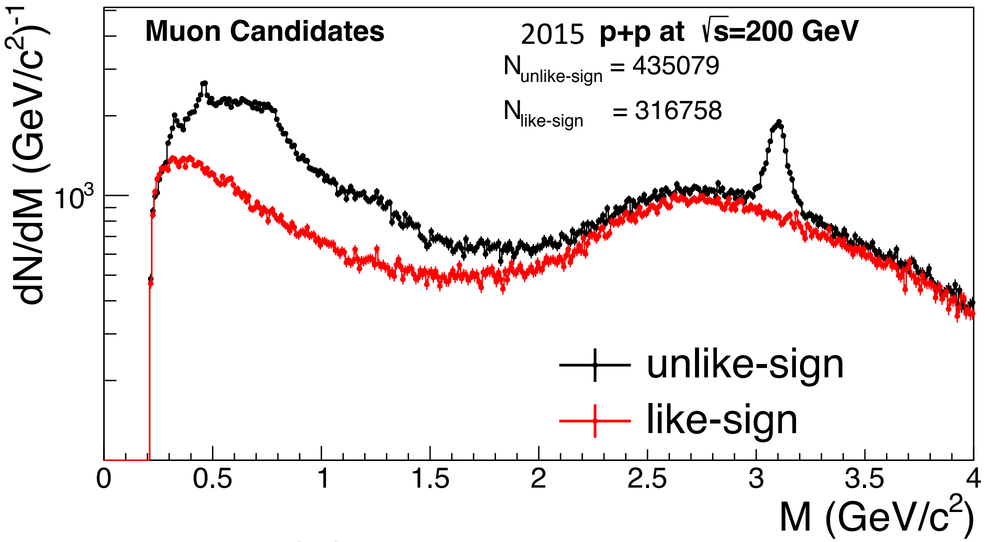
Muon Telescope Detector at STAR

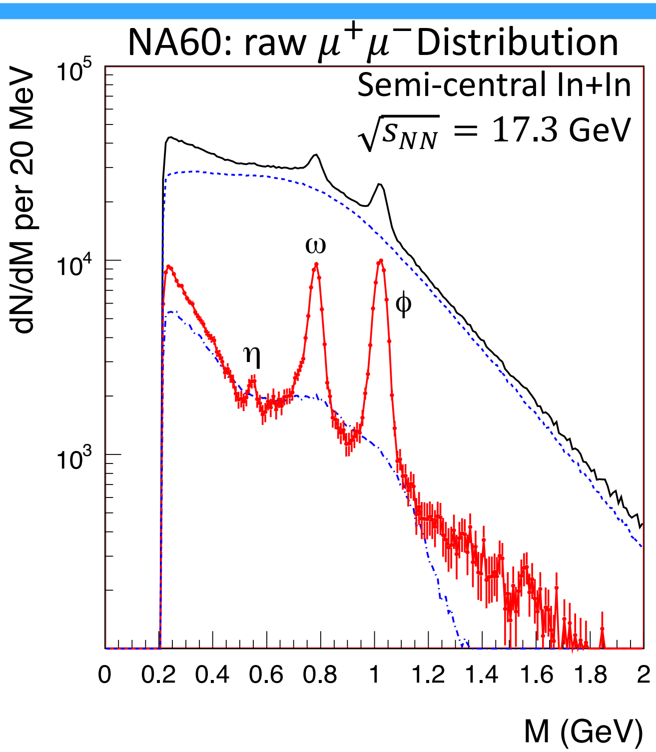


Muon Telescope Detector (MTD)

- $|\eta| < 0.5$
- Azimuthal coverage ~ 45%
- Precise timing σ_{TOF}~100 picoseconds
- Precise spatial resolution ~1 cm
- Installed outside of magnet steel

Raw $M_{\mu\mu}$ Distribution from Muon Candidates





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Muon Candidates:

- **Basic tracking cuts**
- **Match to MTD hit**
- **Satisfy Dimuon Trigger condition**

Raw $M_{\mu\mu}$ Distribution:

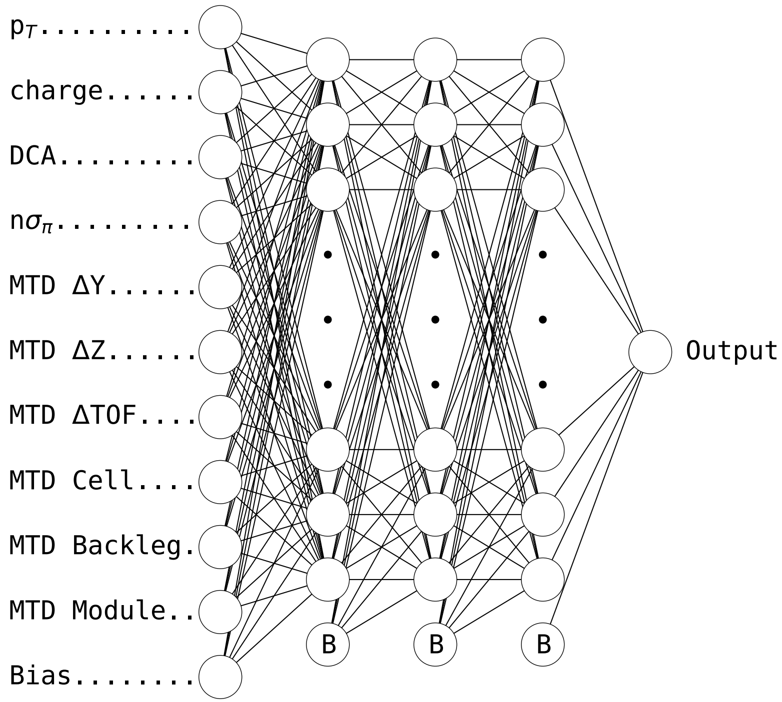
- Clear J/ψ Peak
- No clear evidence of ω or ϕ in lower mass region

-> Need for additional muon identification in order to study low + intermediate mass region

NA60's setup included

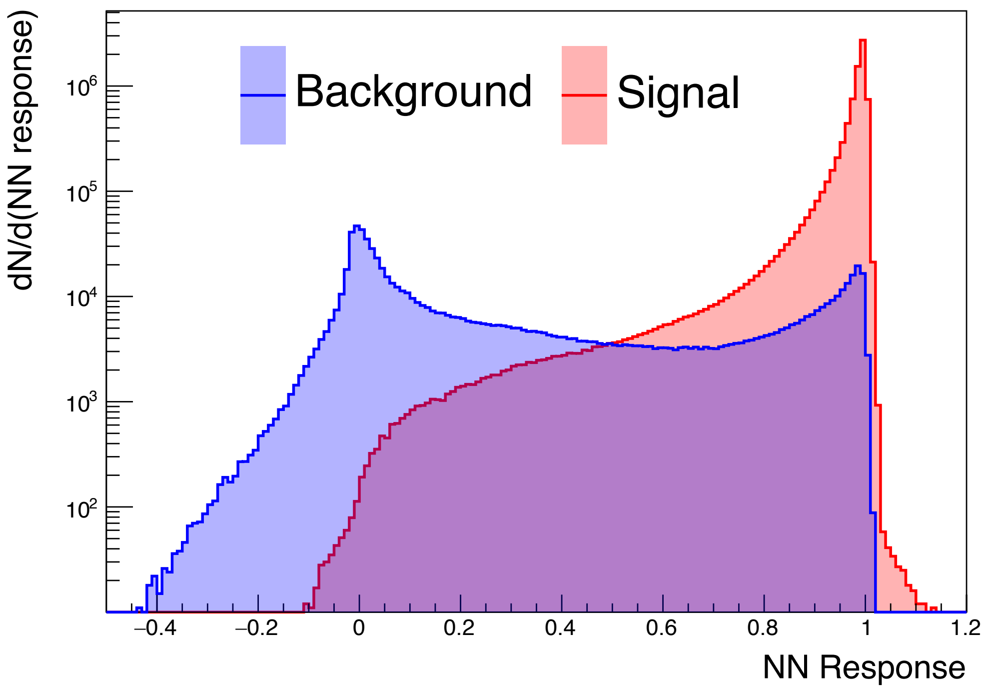
- A silicon vertex tracker
- Muon spectrometer with several layers

Muon ID with Deep Neural Networks



- Identify muons using a Deep Neural network (DNN) classifier
- Architecture optimized using grid-search through hyperparameter space
- DNN: 5% better than BDT, 10% better than shallow neural networks

Output is an optimal discriminator between Signal and Background

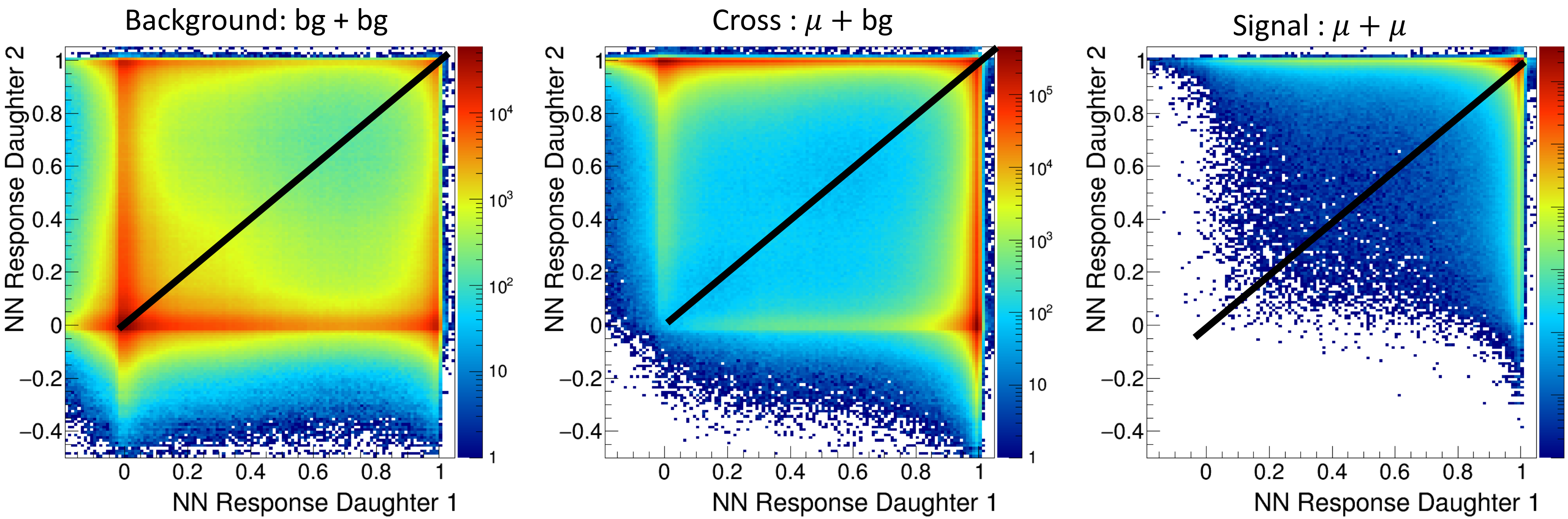


Background is a combination of:

$\pi^{\pm}, K^{\pm}, p/\bar{p}$

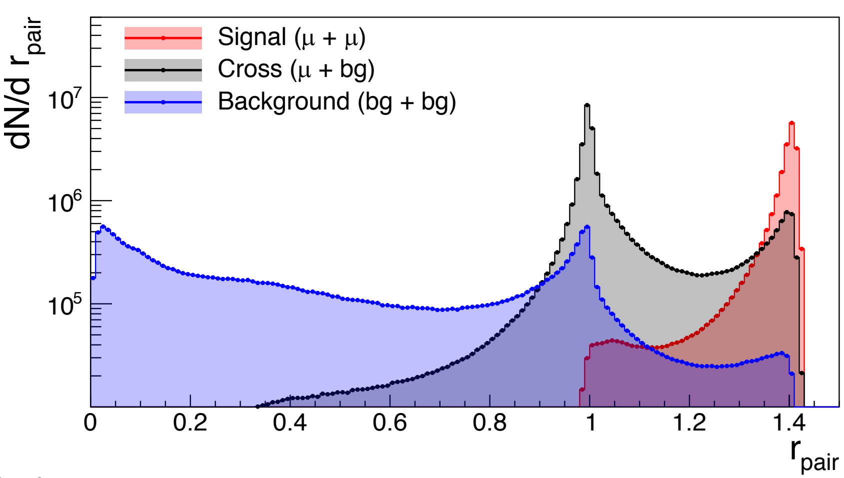
Signal: $\mu^{\pm}$

Signal Pair Selection

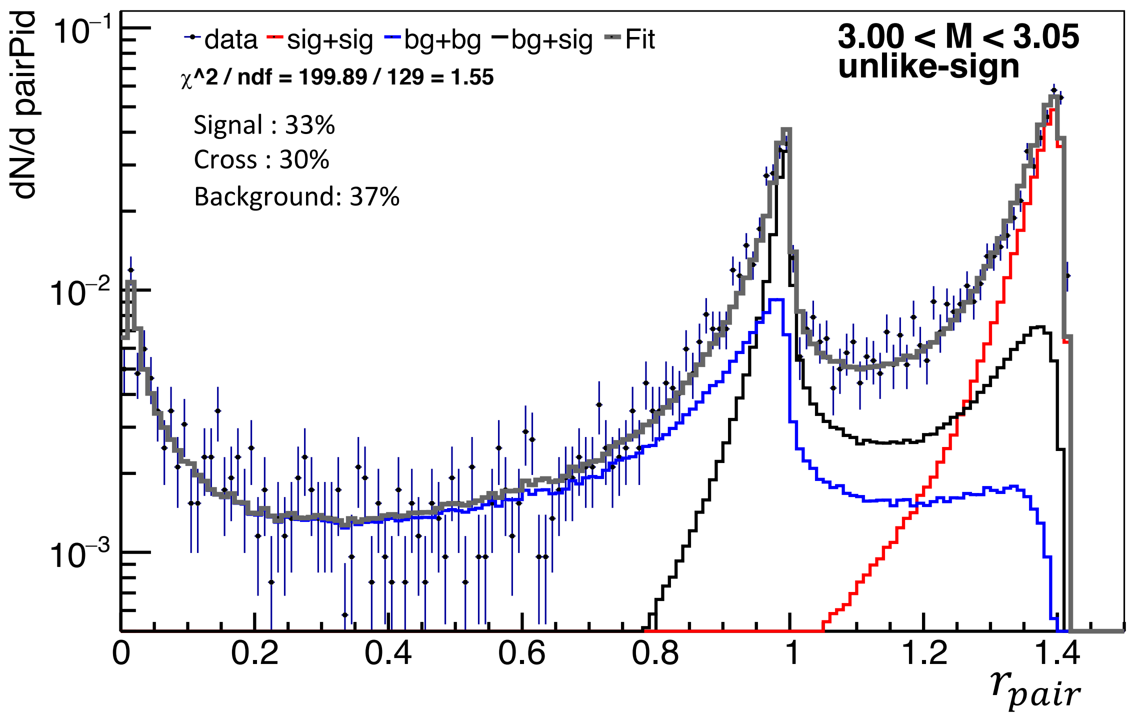


Select pairs using the projection:

$$r_{pair} = \sqrt{r_1^{NN} + r_2^{NN}}$$



Background Estimation Technique



Yield of background, cross-pairs, and signal can be extracted via template fit.

r_{pair} templates are built as function of the daughter track kinematics:

$$T^{pair}_{signal}(p_{T,1}, \eta_1, \phi_1, p_{T,1}, \eta_2, \phi_2)$$
$$= \left(T^{single-track}_{signal}(p_{T,1}, \eta_1, \phi_1) \otimes T^{single-track}_{signal}(p_{T,2}, \eta_2, \phi_2)\right)$$

Maximum likelihood is fit used to extract yield of each component

Background Estimation Technique

Like-sign ($FG_{\pm\pm}$) cannot describe backgrounds from hadron punch-through and secondary muons

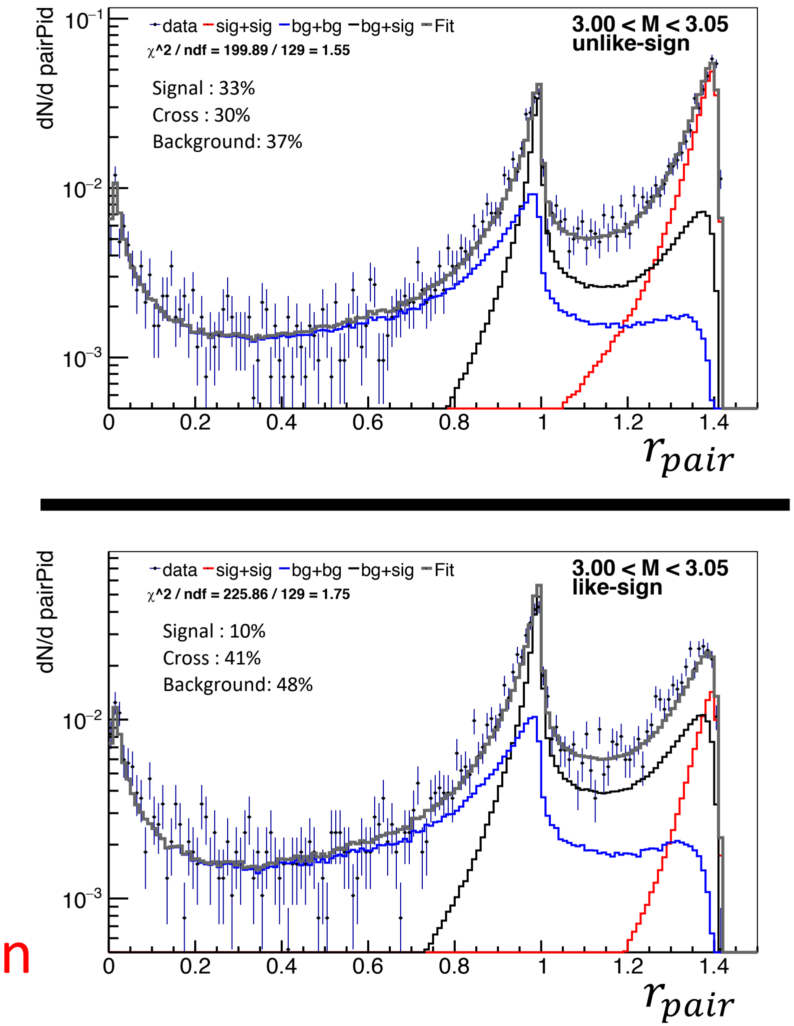
Instead, estimate background by template fitting the r_{pair} distribution in data

Express background as ratio w.r.t like-sign:

$$R(r_{pair}; M) = \frac{FG_{+-}(r_{pair}; M)}{FG_{\pm\pm}(r_{pair}; M)}$$

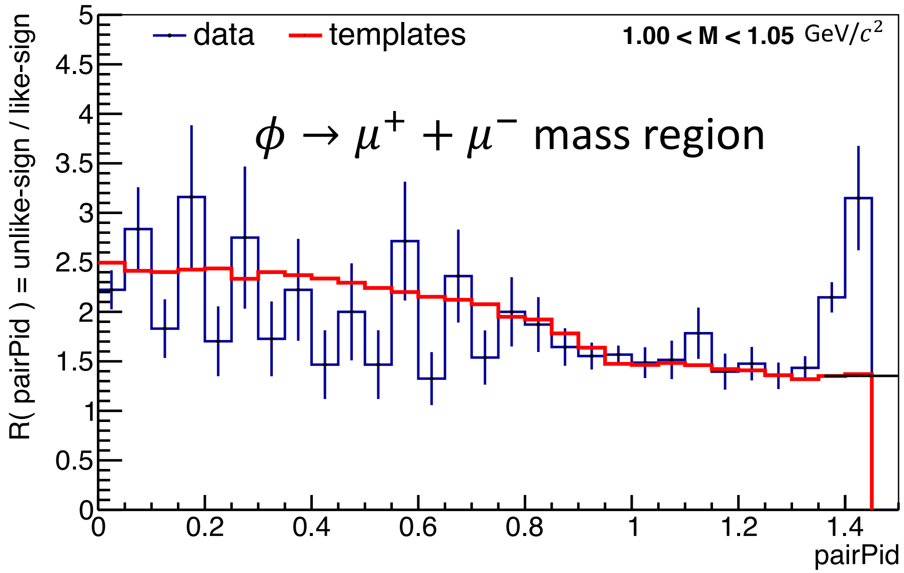
FG_{+-} : Foreground $\mu^+\mu^-$

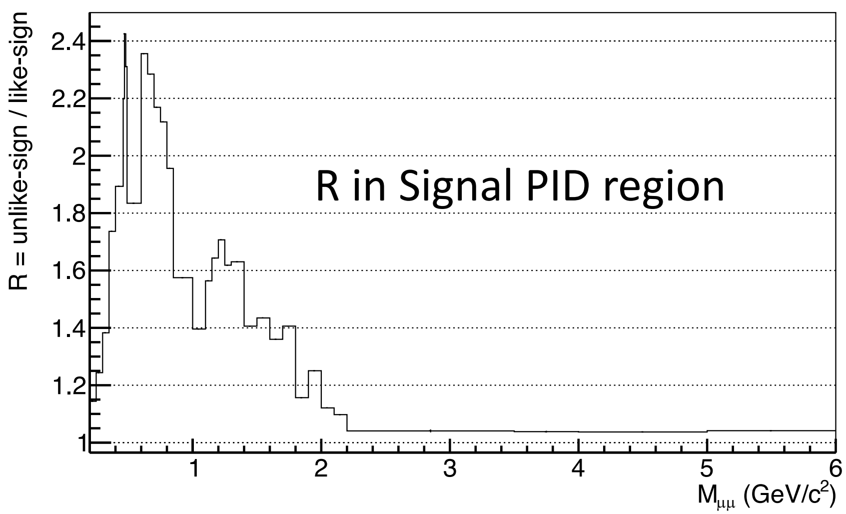
$FG_{\pm\pm}$: Foreground $\mu^+\mu^+ + \mu^-\mu^-$



Estimate of the yield from all background sources in the signal region

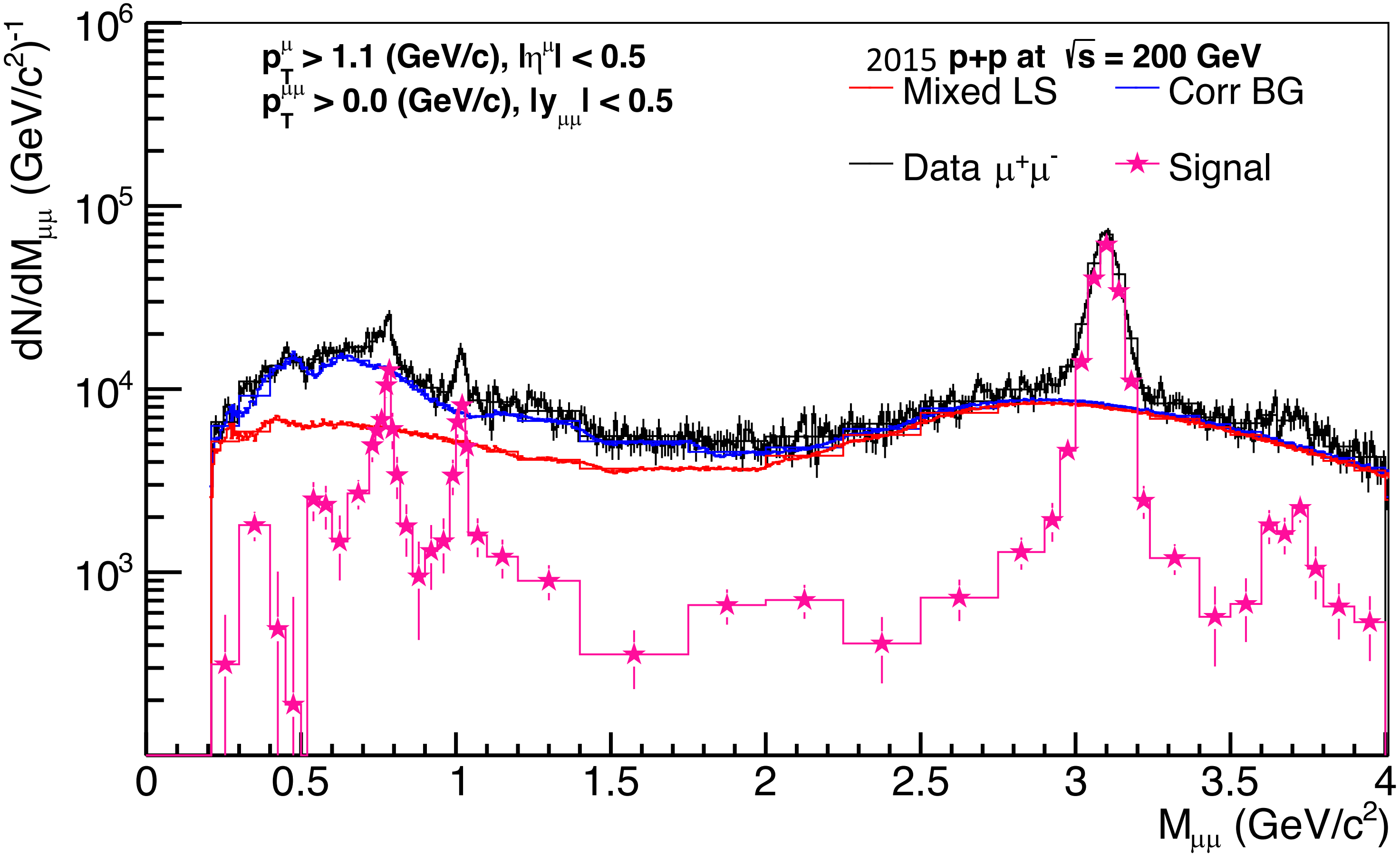
Background Estimation Technique





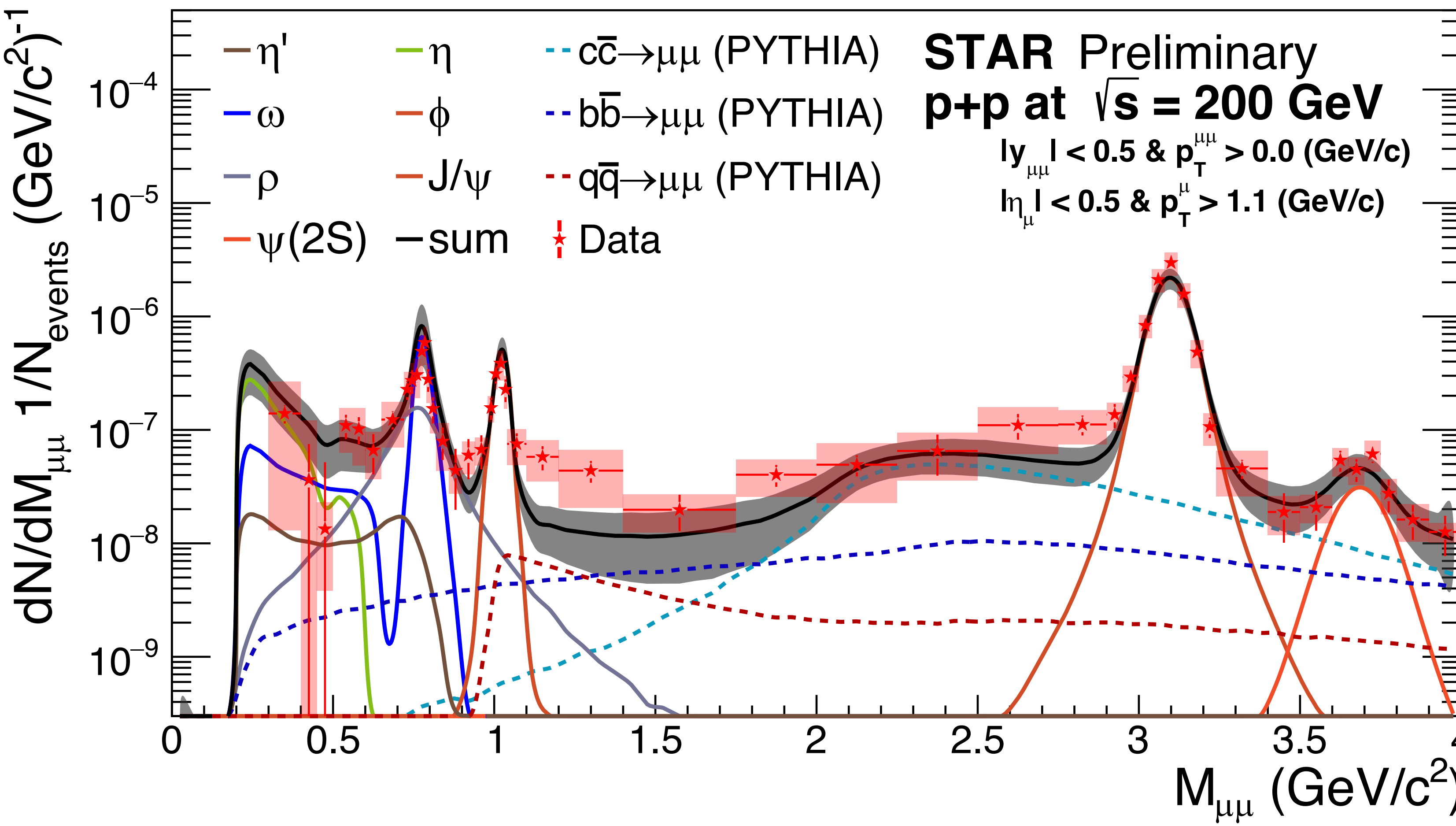
- Provides a description of correlated background in the signal region for each mass bin w.r.t like-sign distribution
- Correlated backgrounds are found predominately at invariant mass < 2.2 GeV/c^2

Raw Signal in p+p Collisions



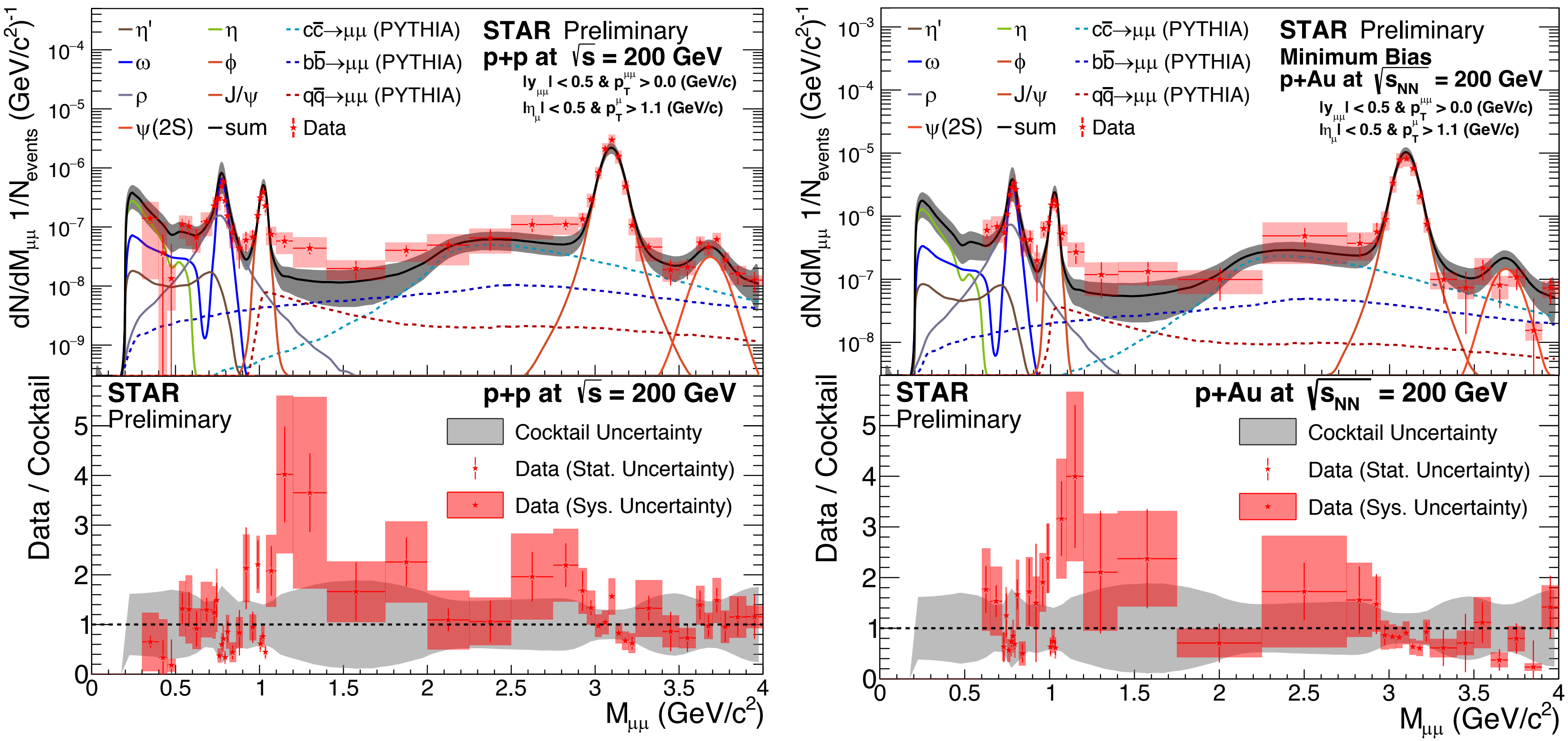
Raw dimuon invariant mass spectra in p+p collisions at $\sqrt{s}$ = 200 GeV for STAR MTD acceptance

First $\mu^+\mu^-$ Invariant Mass Spectra from STAR



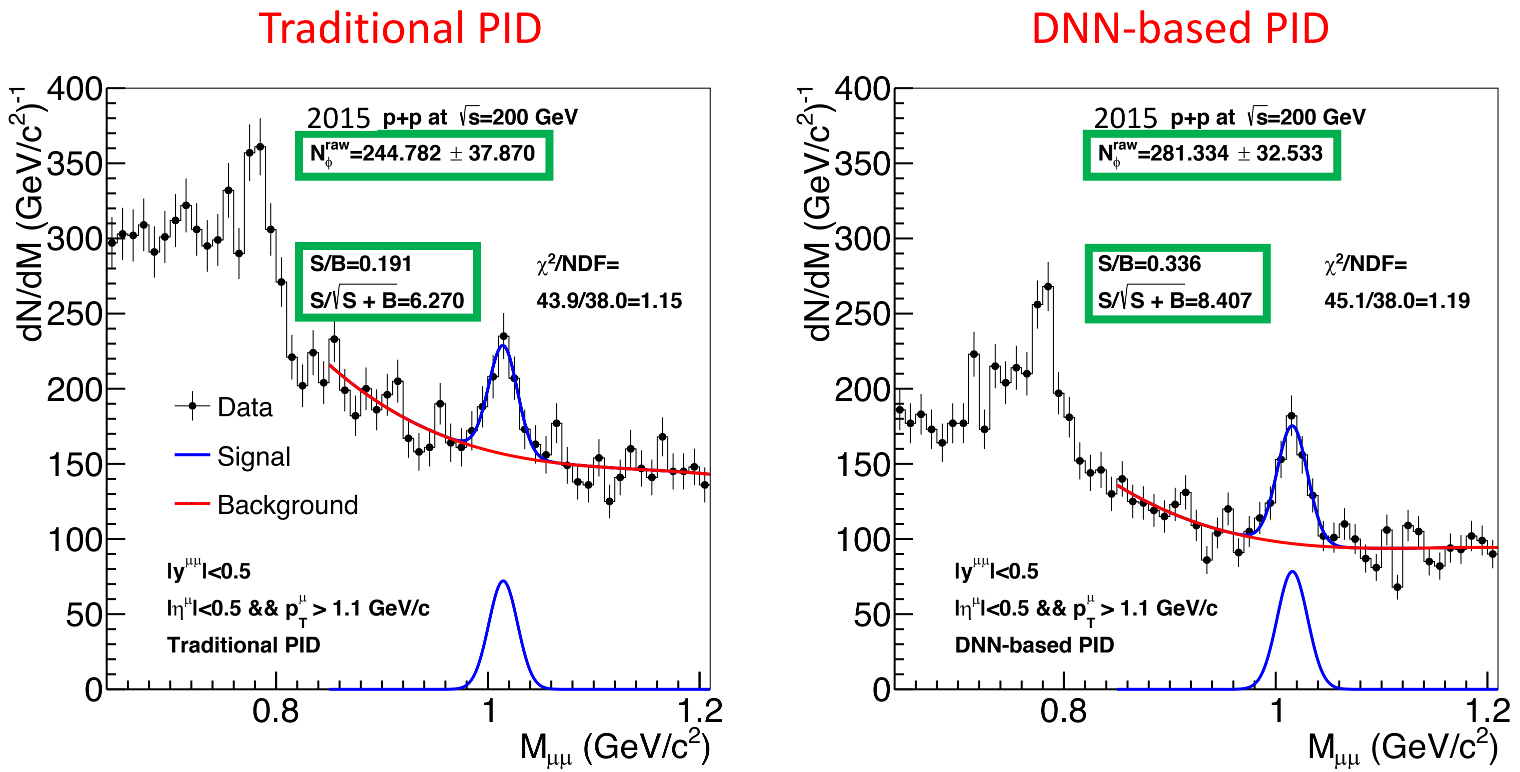
Efficiency corrected $\mu^+\mu^-$ invariant mass spectrum in the MTD acceptance compared with hadronic cocktail contributions

$\mu^+\mu^-$ Spectra in p+p and p+Au Collisions



- First STAR measurement of the $\mu^+\mu^-$ invariant mass spectra
- Clear ω, ϕ, and J/ψ visible in p+p and p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

Measurement of $\phi \rightarrow \mu^+\mu^-$ Spectra

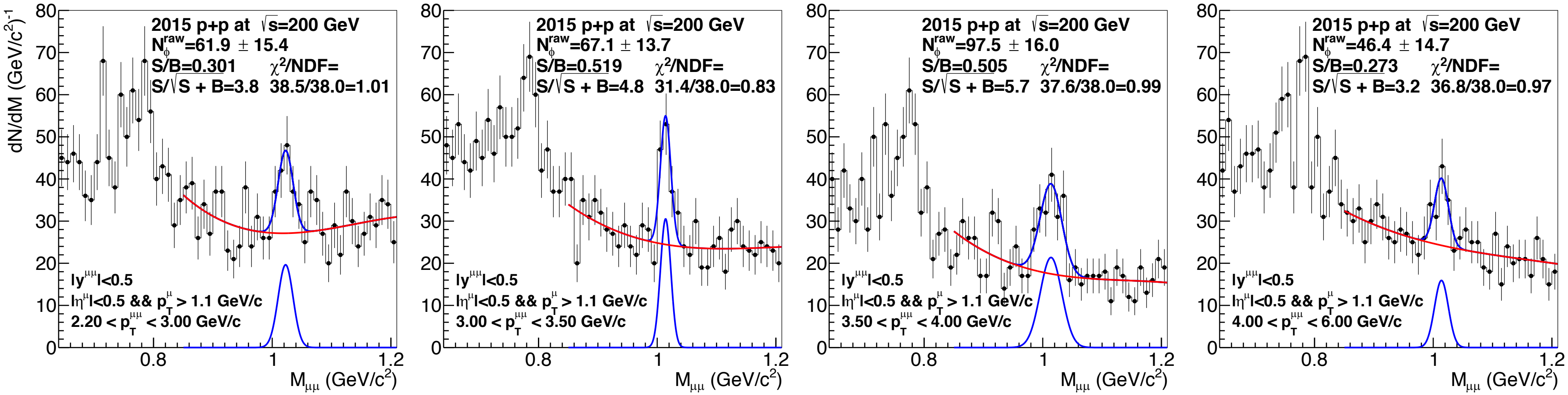


DNN PID simultaneously provides higher significance, signal-to-background ratio and signal efficiency

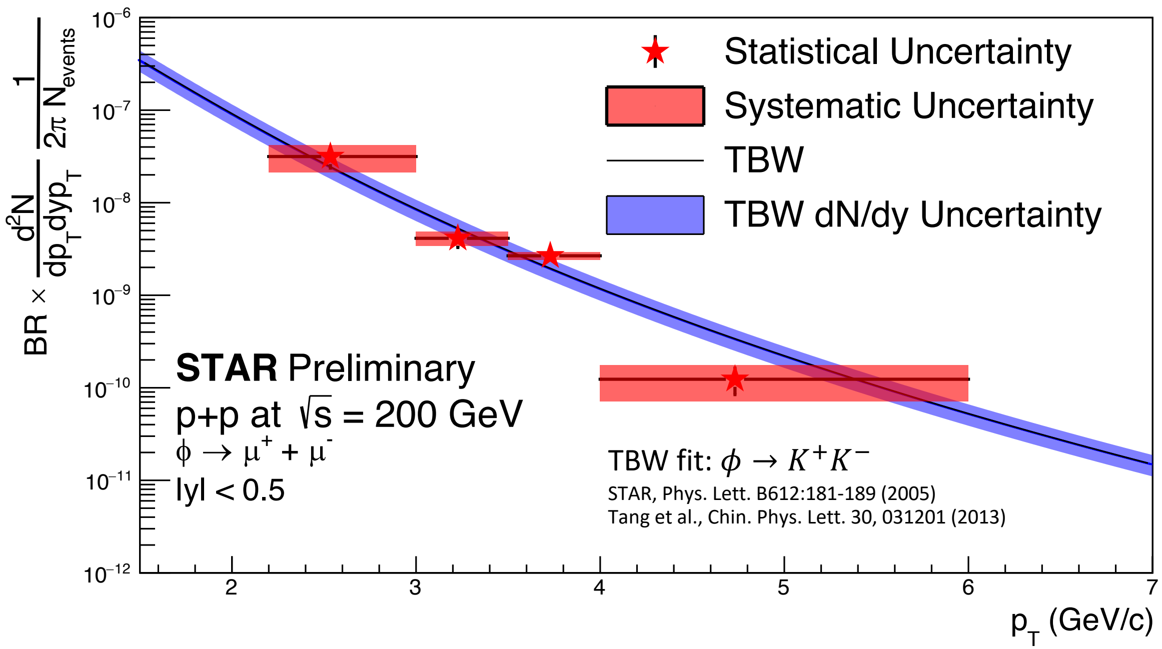
Allows the $\phi \rightarrow \mu^+\mu^-$ spectra to be extracted in p+p collisions in four transverse momentum bins

Measurement of $\phi \rightarrow \mu^+\mu^-$ Spectra

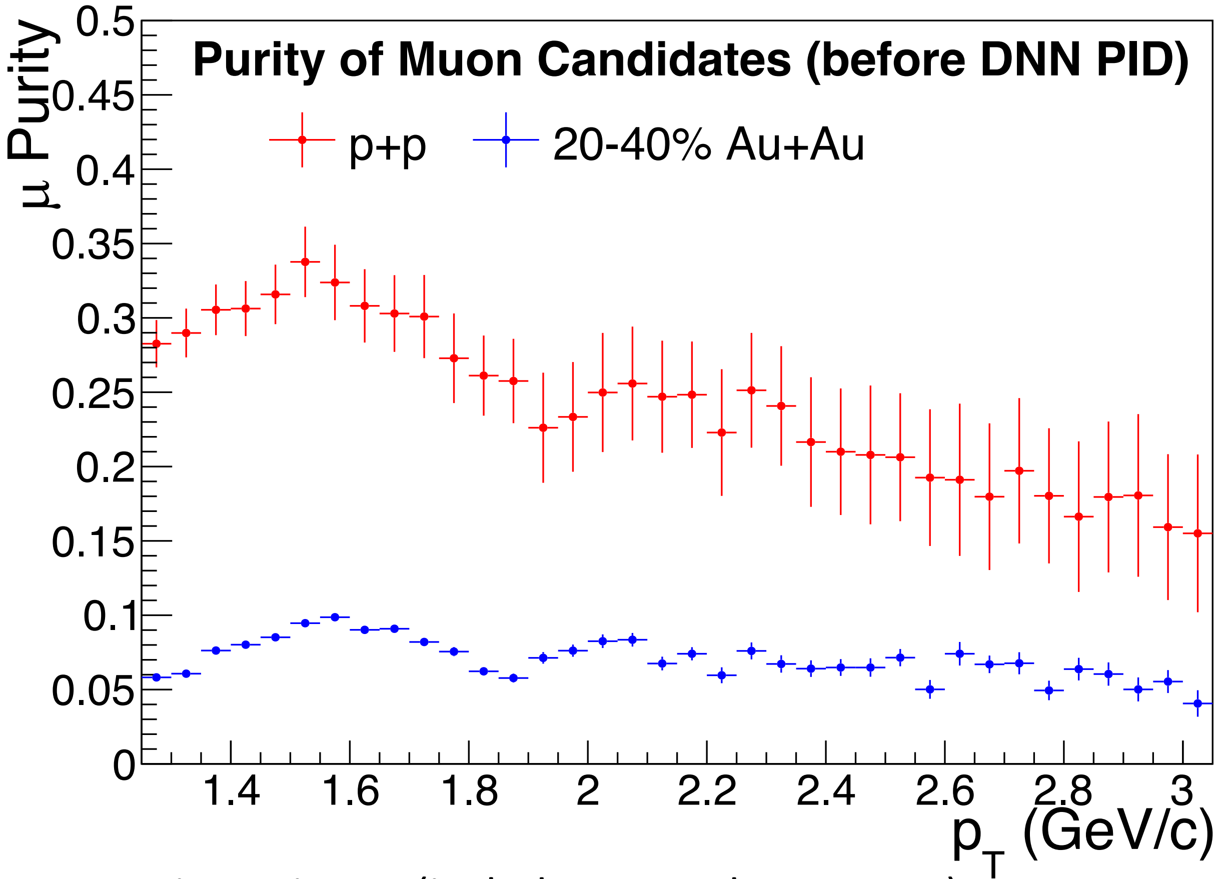
STAR



- First STAR measurement of the $\phi \rightarrow \mu^+\mu^-$ spectra
- Spectra is consistent with past measurement via $\phi \rightarrow K^+K^-$ channel



$\mu^+\mu^-$ Measurements in Au+Au



Muon purity estimate (includes secondary muons)

Even with DNN-based PID, the purity of MTD muons in Au+Au collisions is very low -> makes $\mu^+\mu^-$ measurements in Au+Au challenging

Summary

- First measurement of the $\mu^+\mu^-$ invariant mass spectra over a large range by STAR
- Measurement of the $\mu^+\mu^-$ invariant mass spectra in p+Au collisions
- Measurement of the $\phi \rightarrow \mu^+\mu^-$ channel for the first time by STAR
- Many new techniques developed to cope with low purity/statistics -> may benefit future dilepton analyses
- Low muon purity in Au+Au collisions makes $\mu^+\mu^-$ measurements very challenging

Outlook

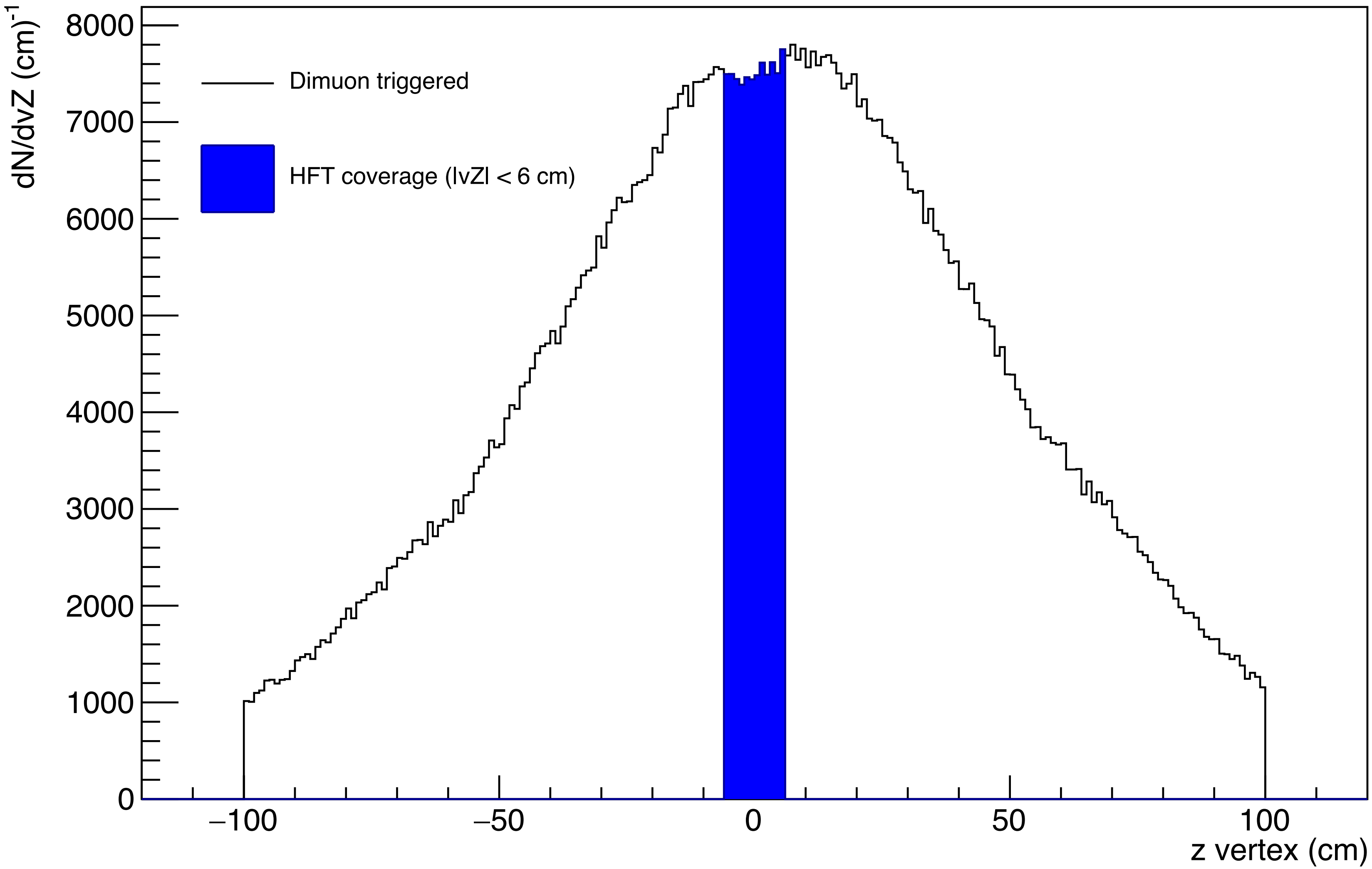
New datasets that are ideal for low mass and continuum e^+e^- measurements at STAR!

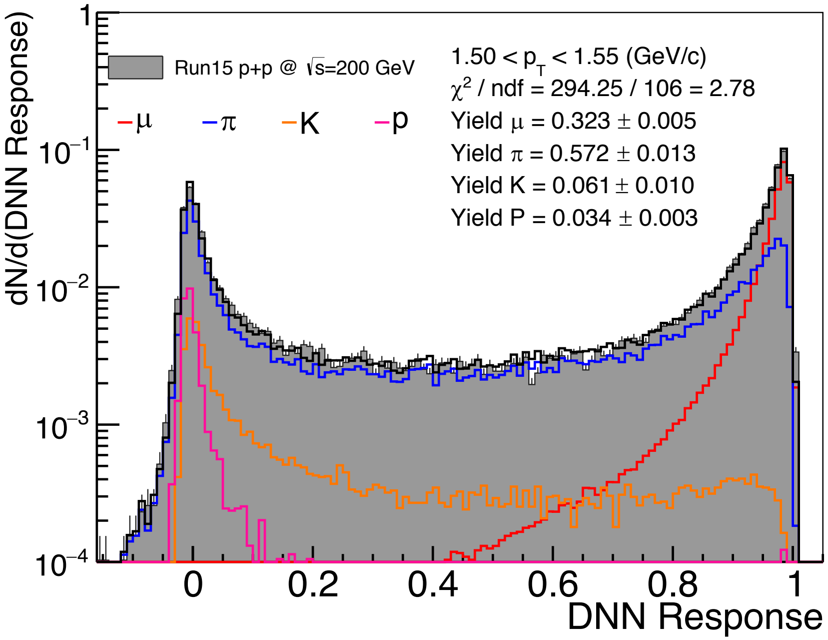
- Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV
  - ~1.5B triggered minimum bias events
- Au+Au collisions at $\sqrt{s_{NN}} = 54$ GeV
  - ~1.3B triggered minimum bias events
- Isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{NN}}$ = 200 GeV
  - ~3B triggered minimum bias events for each species!
- BES Phase II: several more datasets with $\sqrt{s_{NN}} \leq 19.6$ GeV

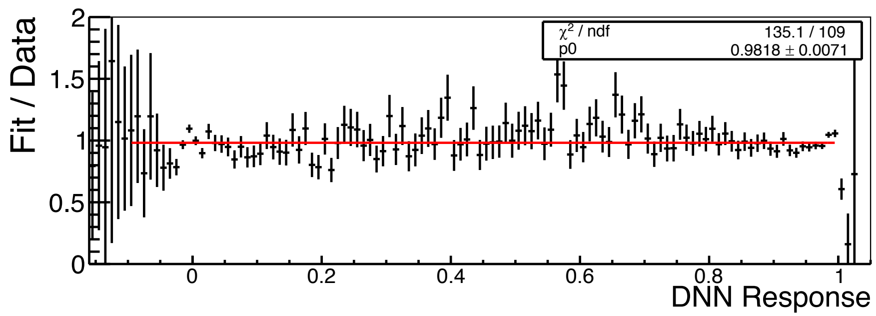
➢ STAR setup for these datasets was ideal for dielectron measurements

Expect exciting new dielectron measurements from these datasets

Thank you ☺


dN/dvZ (cm)-1
8000
7000
6000
5000
4000
3000
2000
1000
0
Dimuon triggered
HFT coverage (|vZ| < 6 cm)
−100
−50
0
50
100
z vertex (cm)

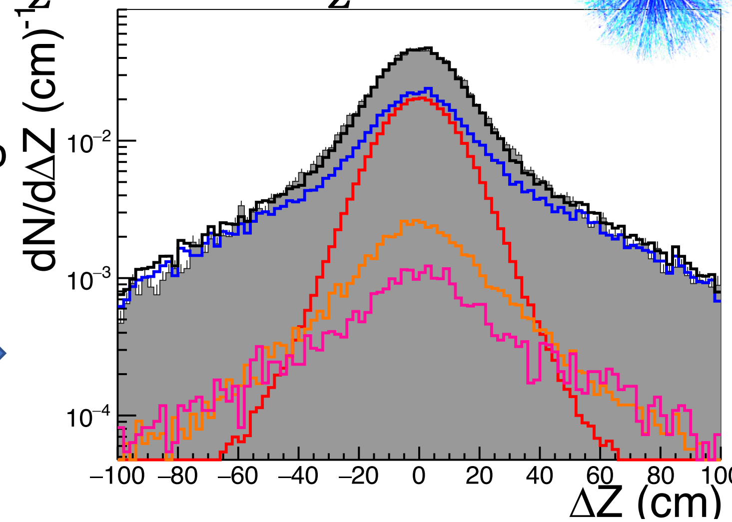




Example: MTD ΔZ

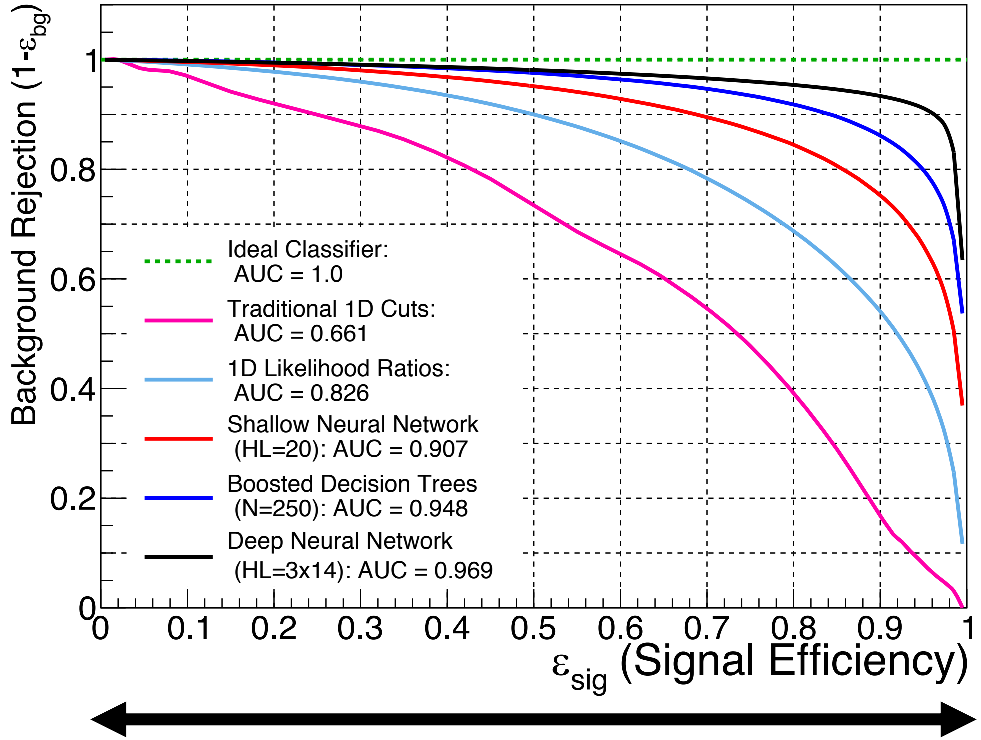
$$\Delta Z = z^{projected} - z^{measured}$$

Project DNN fit back onto input variables



1. Apply DNN to muon candidate tracks in data (grey)
2. Generate signal and background templates by evaluating DNN on MC tracks
3. Template fit the data distribution (grey) to extract the yields of μ, π, K, and p.

Muon Identification



Tighter Cut

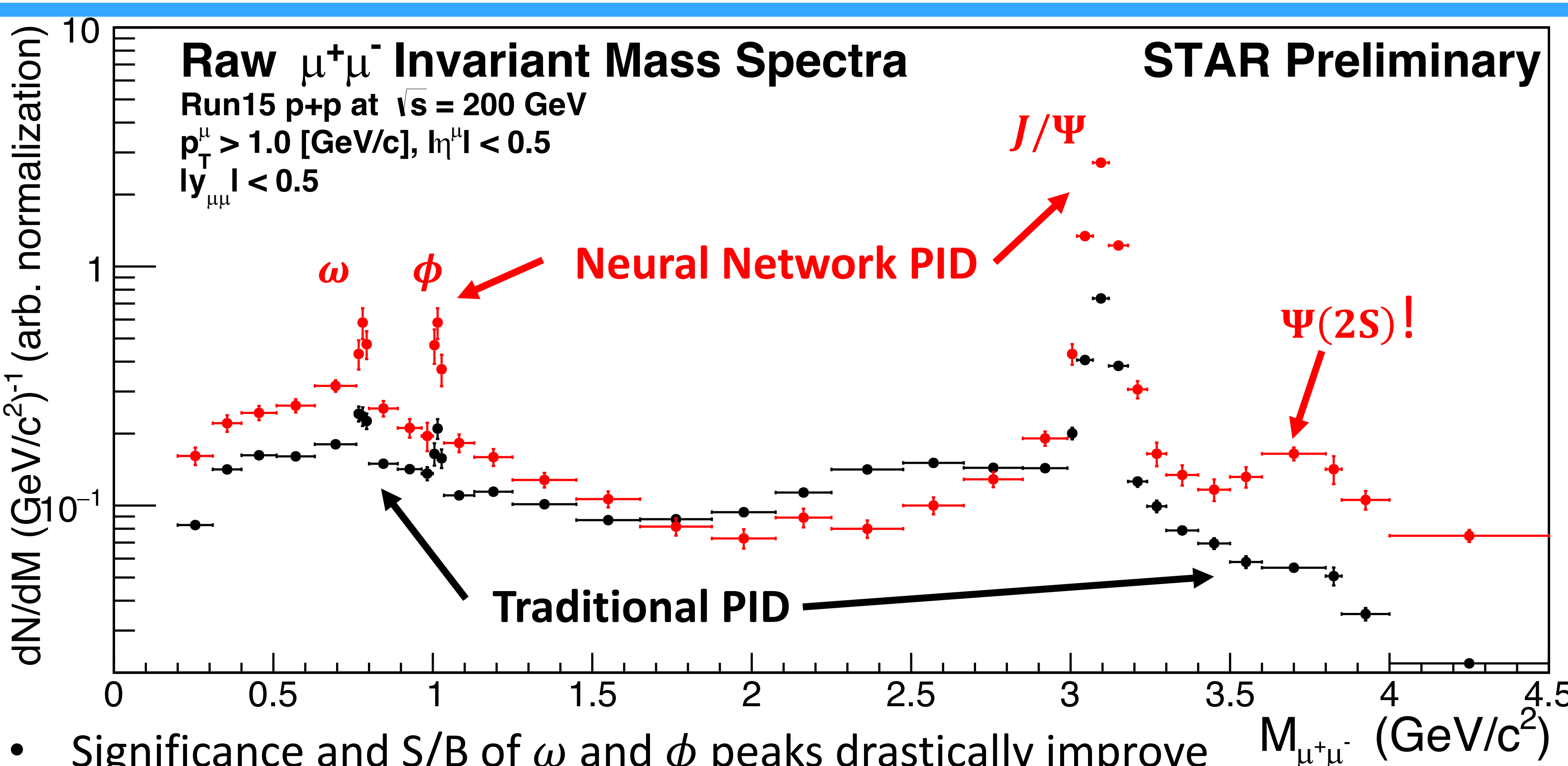
Looser Cut

Comparison of:

- Traditional cuts
- Likelihood Ratios
- Boosted Decision Trees
- Shallow ANN
- Deep ANN

DNN vastly out-performs traditional PID techniques in Monte Carlo simulations

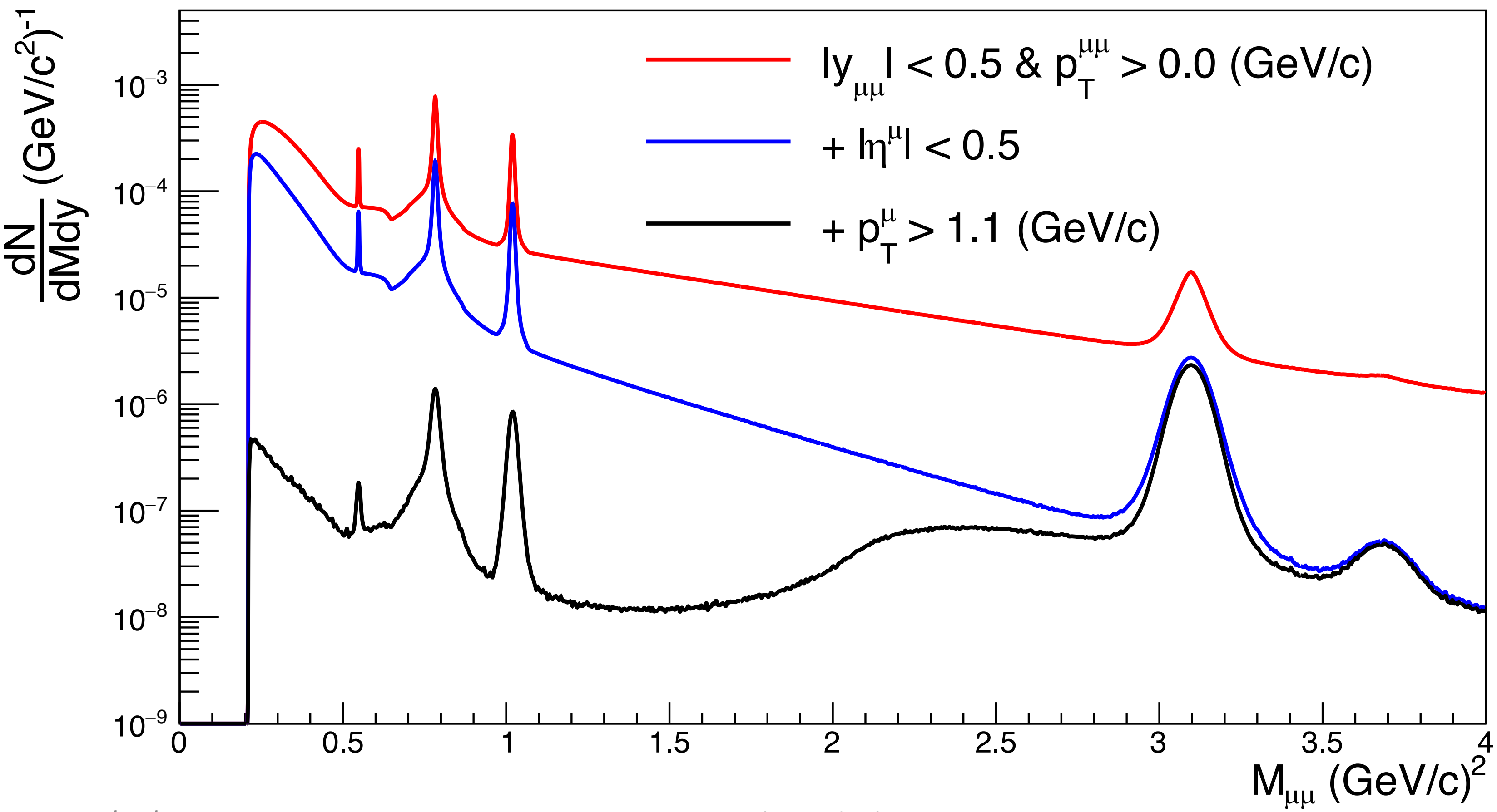
AUC = Area under curve, higher is better

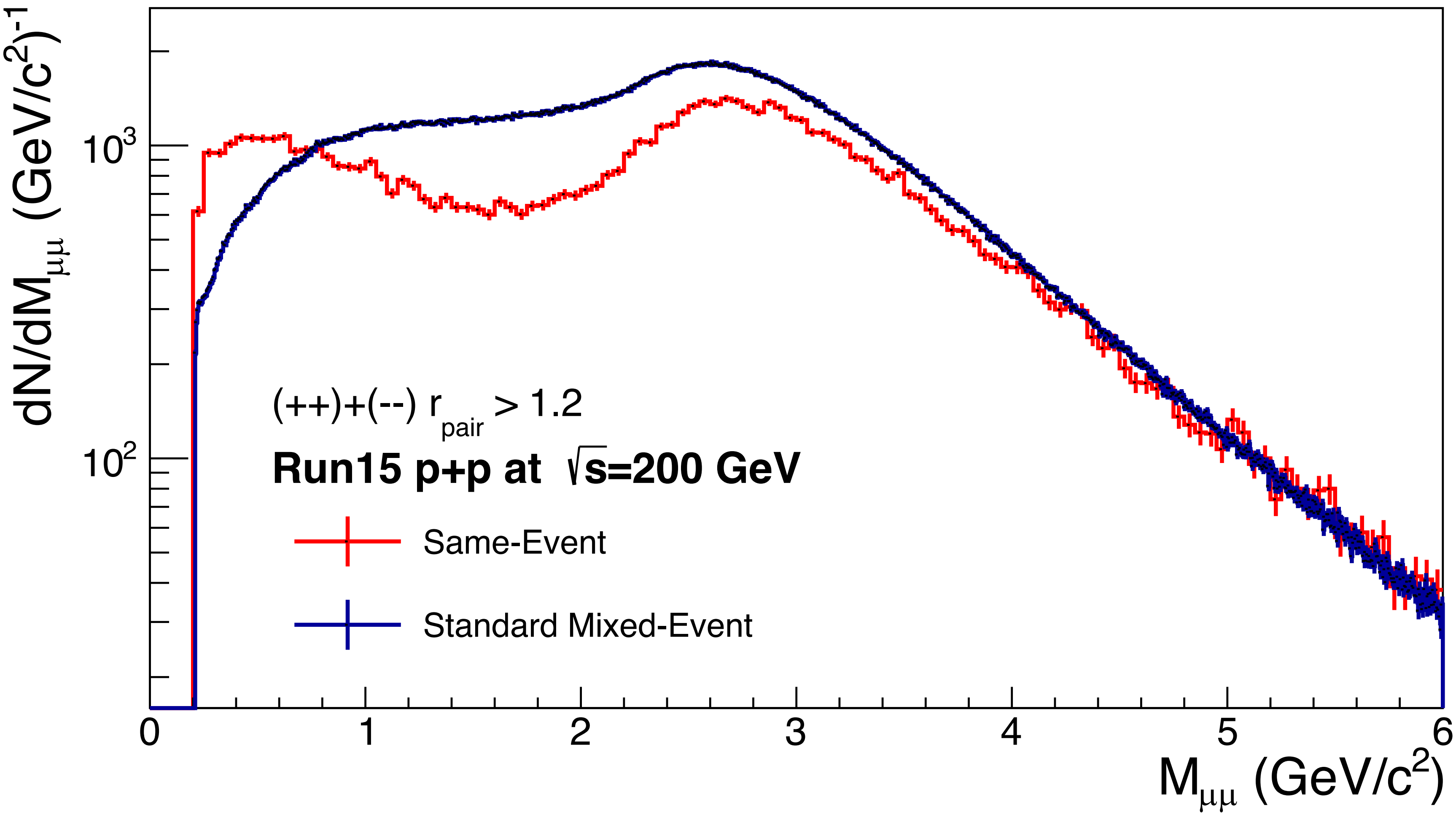


- Significance and S/B of ω and ϕ peaks drastically improve
- Measurement of $\Psi(2S)$ possible with neural net PID

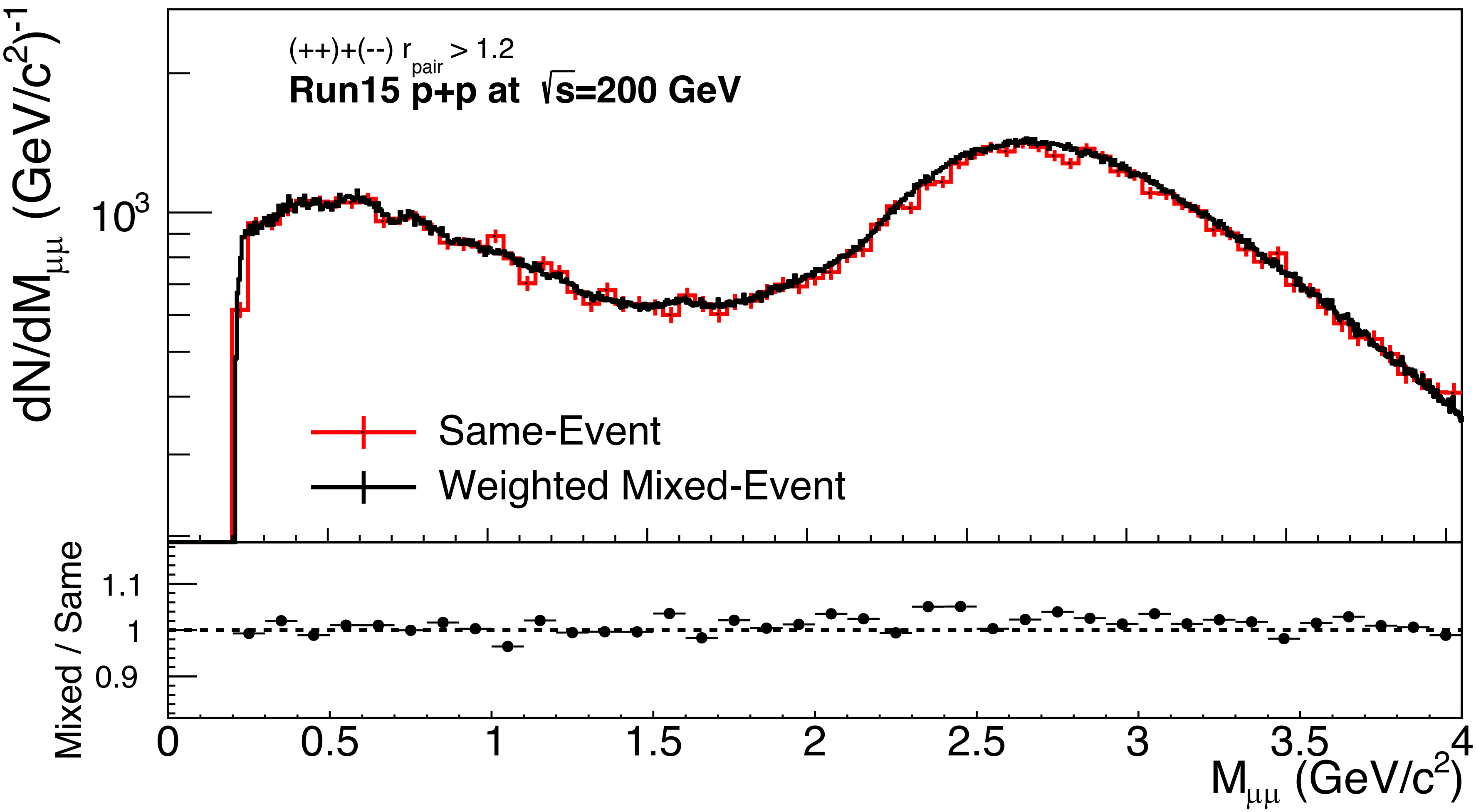
→ Neural network clearly out-performs traditional identification techniques

MTD Acceptance Affect on Cocktail





dN/dM$_{\mu\mu}$ (GeV/c^2)$^{-1}$
10^3
10^2
(++)+(--) r_{pair} > 1.2
Run15 p+p at $\sqrt{s}$=200 GeV
Same-Event
Standard Mixed-Event
0
1
2
3
4
5
6
M$_{\mu\mu}$ (GeV/c^2)



(++)+(--) r pair > 1.2
Run15 p+p at √s=200 GeV
Same-Event
Weighted Mixed-Event
dN/dMμμ (GeV/c²)⁻¹
10³
Mixed / Same
1.1
1
0.9
0
0.5
1
1.5
2
2.5
3
3.5
4
Mμμ (GeV/c²)