Studying the QGP at ALICE with the ρ meson

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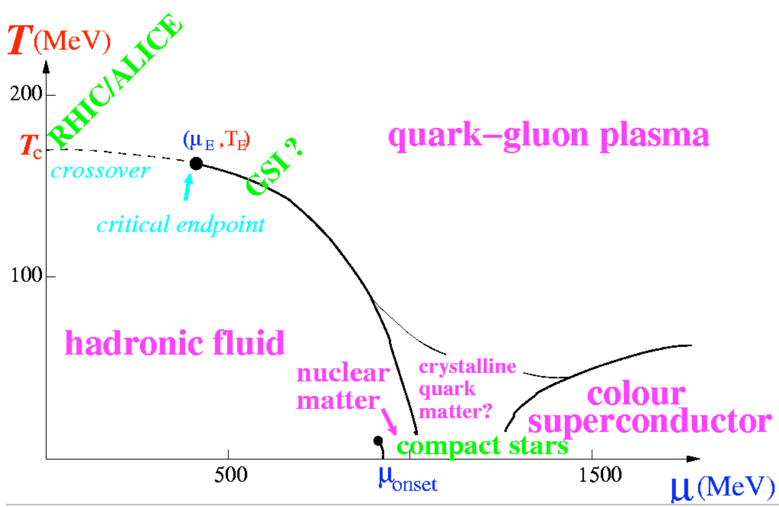
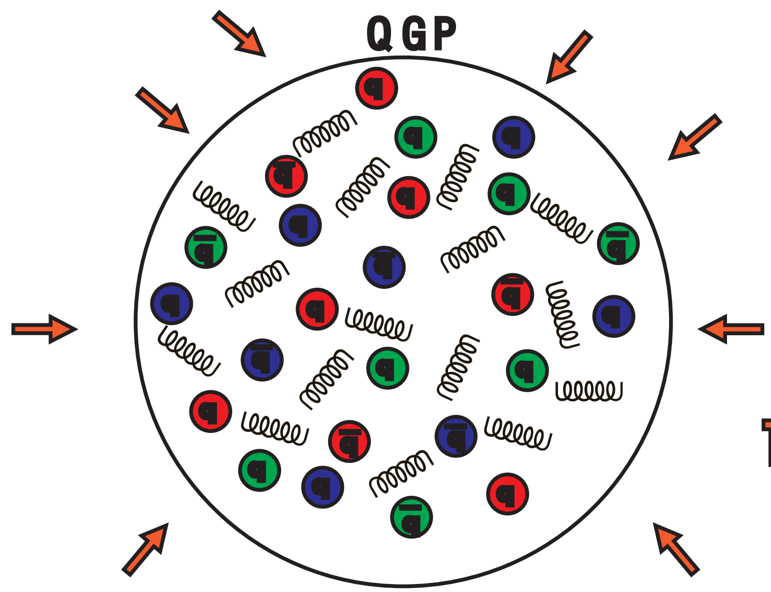
Introduction

- What is the Quark-Gluon Plasma?
- The LHC and heavy ion collisions.
- The ALICE experiment at the LHC.
  - Summary of relevant sub-detectors.
- Resonances as QGP probes.
  - Theoretical motivation - modification of resonance properties in medium.
- My analysis of the ρ in Monte Carlo Pb-Pb collisions.
- Prospects for ρ measurement in Pb-Pb at the LHC.
- Summary.

The Quark-Gluon Plasma

- Under conditions of high temperature or density, nuclear matter undergoes a phase transition to a state of deconfined quarks and gluons.
- Lattice QCD predicts this transition at a temperature of around 170 MeV.

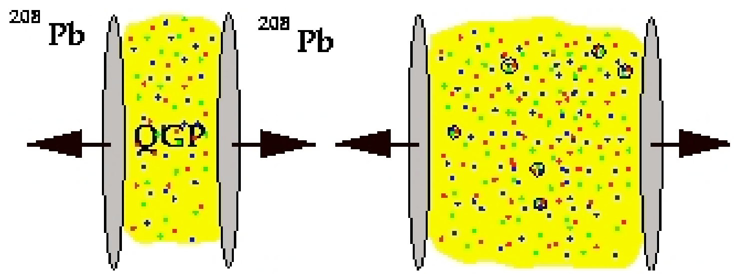




- Additional transition to a state of (partial) chiral symmetry restoration.
- Quark masses drop to their “bare” values, around 5 MeV for u and d.

Creating the QGP at the LHC

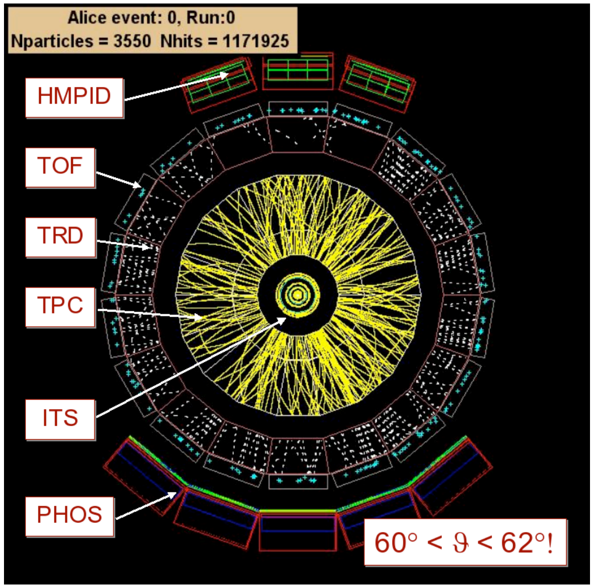
LHC will collide lead ions at 5.5 TeV per nucleon.

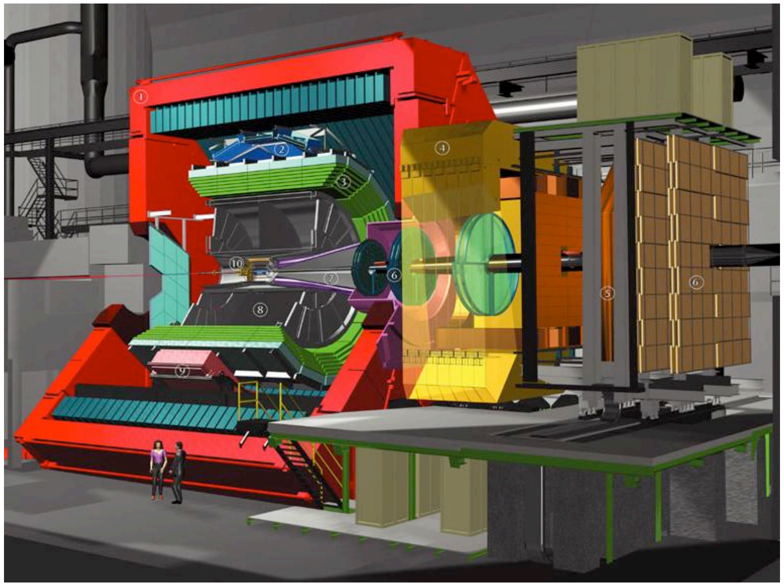


Central Collisions	RHIC	LHC
Energy (GeV)	200	5500
dN_{ch}/dY	650	3000-8000
Density (GeV/$(fm)^3$)	3.5	15-40
Plasma volume ($(fm)^3$)	7000	20000
QGP lifetime (fm/c)	1.5-40	4.0-10.0

- Aim is to create a hot, thermalised medium over a significant volume.
- LHC collision energy is 27 times the previous maximum for heavy ions.
- This will allow a large number of QGP observables to be studied.

The ALICE experiment





- Time Projection Chamber, used to track the thousands of particles produced per Pb-Pb event and for particle identification (PID) by dE/dx.
- ITS, for tracking, vertex finding and PID by dE/dx.
- TOF - tracking and hadron identification by Time of Flight.
- TRD - tracking and electron identification.

Resonances as QGP probes

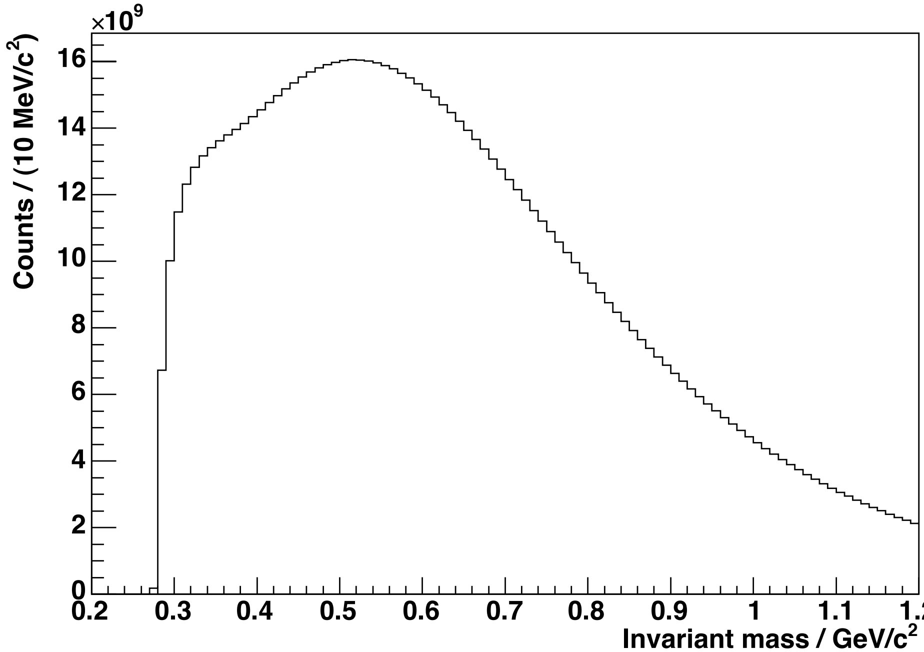
- QGP lifetime is around 10 fm/c, ρ lifetime is 1.3 fm/c.
- Reconstructed ρs may show in-medium modification of mass and width.
- Yields are useful as input to statistical models, and also to study rescattering and regeneration in the medium.
- Study of different decay channels provides different information:
  - $\rho \rightarrow \pi^+\pi^-$ (hadronic channel) - branching ratio $\sim 100\%$:
    - Decay pions will undergo rescattering in the dense medium.
    - This channel allows reconstruction of ρs on the later stages of the system.
  - $\rho \rightarrow e^+e^-$ (leptonic channel) - branching ratio $4.5 \times 10^{-3}\%$:
    - Decay particles not strongly interacting, so not rescattered.
    - ρs from all stages of the collision system reconstructible.
- Would like to study both channels.

Analysis outline

- I have analysed the $\rho \rightarrow \pi^+\pi^-$ in Pb-Pb collisions:
  - The HIJING event generator used to generate 10^6 central Pb-Pb events.
  - It was necessary to implement my own fast simulation technique to account for detector acceptance and efficiency.
    - Full simulation takes many hours per event.
    - My fast simulation uses parameterisations as a function of p_t.
    - Acceptance in pseudorapidity - constant for $-0.9 < \eta < 0.9$, zero outside.
    - Efficiency, momentum smearing and PID efficiency and contamination as a function of p_t and particle species (e, μ, π, K, p).
  - Background subtraction methods were investigated and applied.
  - Various fits were applied to the data to obtain the ρ mass, width and yield.
- Full report published in ALICE Physics Performance Report, Volume 2, section 6.2.4.

ρ meson reconstruction

- Straightforward in principle - use invariant mass reconstruction on all +/- combinations with a $\pi^+\pi^-$ hypothesis.
- But backgrounds are large - S/B is around 0.02 for pp and 10^{-5} for Pb-Pb.



- Require a technique to model and subtract the combinatorial background.

Background subtraction

- Combinatorial background is modelled by taking +/+ and -/- track combinations.
- No resonances decaying to $\pi^+\pi^+$ or $\pi^-\pi^-$.

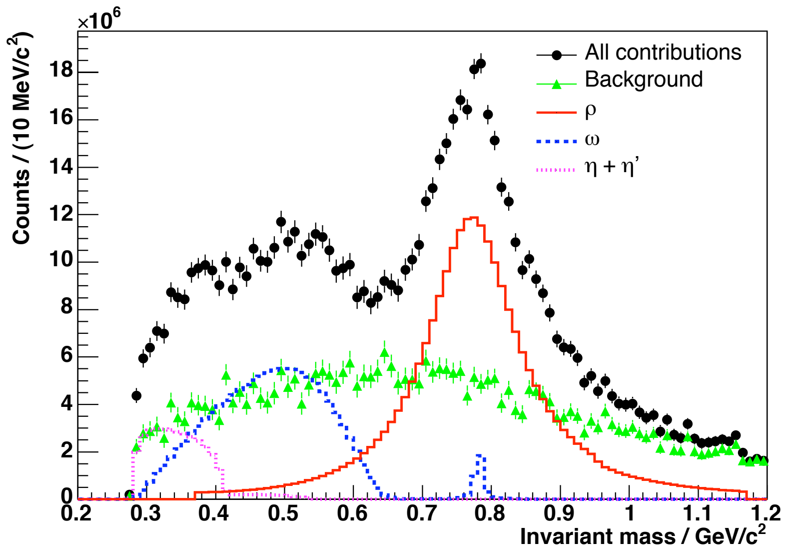
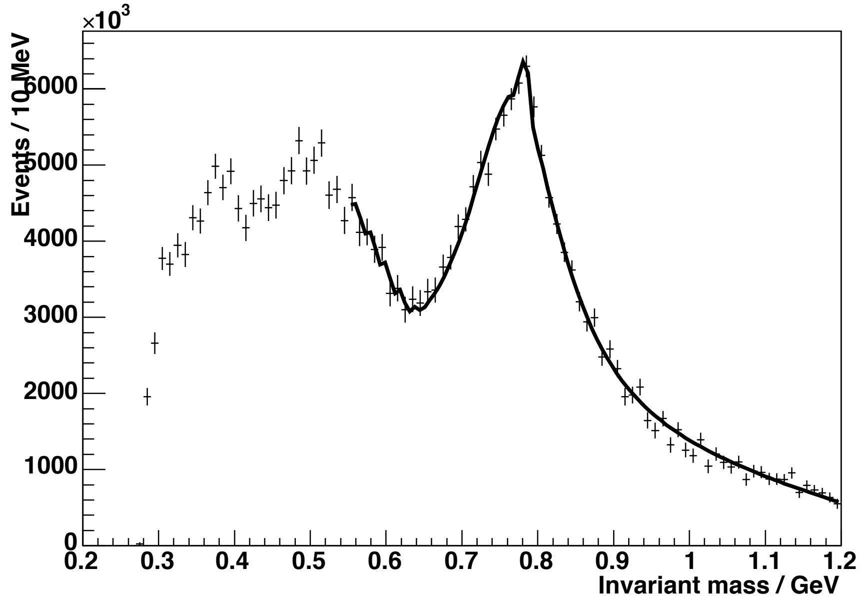


Figure 1: Invariant mass spectrum after background subtraction

- Most background (>99.9%) is removed - still have other resonances present.

ρ fitting

- The ρ is wide, and there are contributions from other resonances under the ρ peak.
- It was found that the best approach is to fit over the mass range 0.55 to 1.2 GeV.
- In this range, we have the ρ and ω on top of the residual background.
- For the fit, I use a Breit-Wigner for the ρ, the ω shape from the Monte Carlo and a straight line for the background.



Results

	Full fit	ρ without background
Mass / GeV	0.771 ± 0.001	0.774
Width / GeV	0.162 ± 0.008	0.139
Number ρs	$(2.30^{+0.69}_{-0.47}) \times 10^8$	1.97×10^8

- Yield is measured correctly.
- The fit to the ρ with no background shows an incorrect width. This is due to variation of reconstruction efficiency with track p_t, which distorts the ρ Breit-Wigner.
- Fitted mass value is within a few MeV of the correct value, so any large mass shifts should be measurable.
- These results show that changes in the ρ mass in the medium will be observable.

Summary

- At high temperature, nuclear matter is expected to undergo a phase transition to the Quark-Gluon Plasma.
- In this state, quarks and gluons are not confined to colourless objects.
- Additionally, we expect another transition - (partial) chiral symmetry restoration. Quark masses drop to their bare values.
- The ALICE experiment at the LHC will investigate all aspects of QGP physics.
- I have studied the ρ meson in heavy ion collisions:
  - Resonances may be modified by the medium.
  - Short ρ lifetime allows these modifications to be measured.
  - My results show that medium-induced mass shifts will be measurable in the $\pi^+\pi^-$ decay channel.
- The $\rho \rightarrow e^+e^-$ decay channel is also interesting, but much more difficult due to small branching ratio, extra background sources and difficulty of electron identification.

Additional slides

Introduction

- Aim is to study the ρ^0 in Pb-Pb collisions - mass, width and number produced.
- ρ lifetime ($c\tau = 1.3 fm/c$) is short compared to the lifetime of the fireball ($> 10 fm/c$), so the reconstructed ρs may show modification by the medium.
- Study of ρ in different decay channels provides different information:
  - $\rho \rightarrow \pi^+\pi^-$ hadronic channel:
    - Decay pions will undergo rescattering in the dense medium, and so the ρs which produced them will not be reconstructed.
    - Therefore, this channel provide information on the late stages of the fireball only.
    - Modification of resonance properties is expected even in the low density hadron gas near thermal freezeout.
  - $\rho \rightarrow e^+e^-$ leptonic channel:
    - Low probability for rescattering of decay electrons in medium.
    - ρs from all stages of the fireball will be reconstructible in this channel.
    - Expect much larger changes to ρ properties due to more extreme conditions, e.g. QGP.

Theoretical motivation

In the leptonic channels, ρs from all stages of the fireball will be reconstructed.

Some theoretical studies have investigated the properties of ρs in QGP conditions:

- First suggestions were changes in mass and width [a].
- Increase in ρ width is predicted by several theoretical approaches.
- However, there is no agreement on the ρ mass - a decrease [b], no change and an increase [c] have been suggested.

In the hadronic channels, only ρs from the late stages of the fireball will be reconstructed.

- Measured $\rho \rightarrow \pi^+\pi^-$ yield therefore reflects conditions at kinetic freeze-out.
- Modifications of the ρ^0 meson are expected to be small but observable under these low-density conditions

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[a] R.D. Pisarski, Phys. Lett. 110B, 155 (1982).

[b] G.E. Brown and M. Rho, Phys. Rept. 363, 85 (2002).

[c] R.D. Pisarski, Phys. Rev. D52, 3773 (1995).

Experimental results - SPS

CERES experiment:

- Measures a strong enhancement of low-mass dileptons in central A-A collisions [a], and no clear peak at the normal ρ mass.
- It has been suggested that this is due to a modified ρ.

NA60 experiment:

- Measured $\rho \rightarrow \mu^+\mu^-$ in Indium-Indium collisions with CM energy of 17.8 GeV [b].
- Evidence for broadening of ρ in In-In collisions, increasing with centrality.
- No evidence for any mass shift.

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[a] G. Agakishiev et al. (CERES), Nucl. Phys. A638, 159 (1998).

[b] S. Damjanovic for the NA60 collaboration, proceedings of QM 2005. (nucl-ex/0510044)

NA60 results

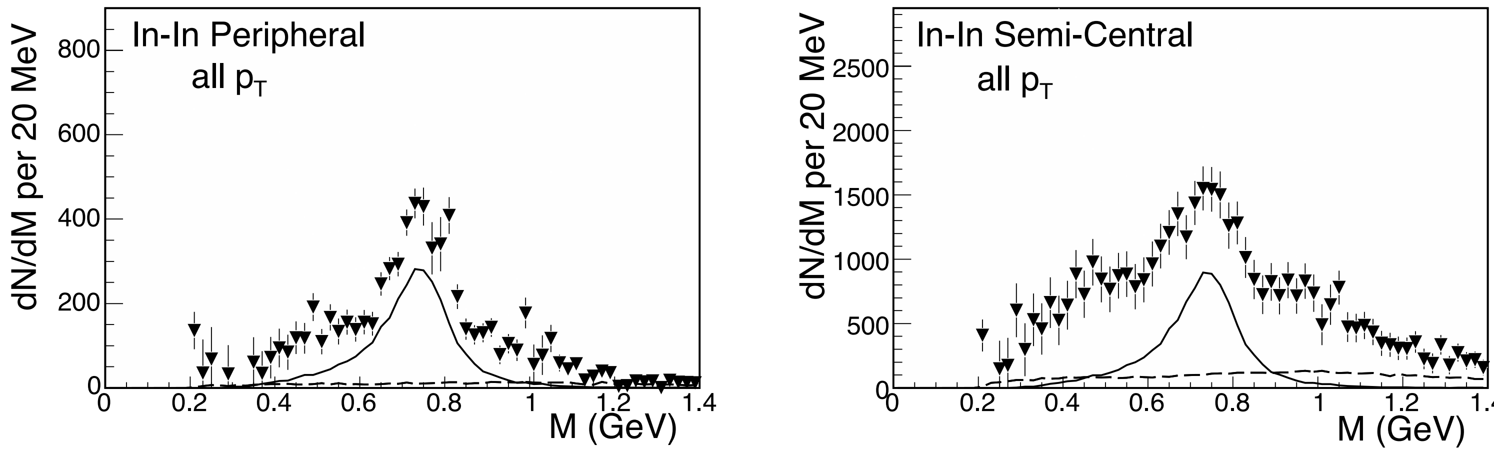


Figure 2: $\mu^+\mu^-$ spectrum for peripheral (left) and central (right) collisions

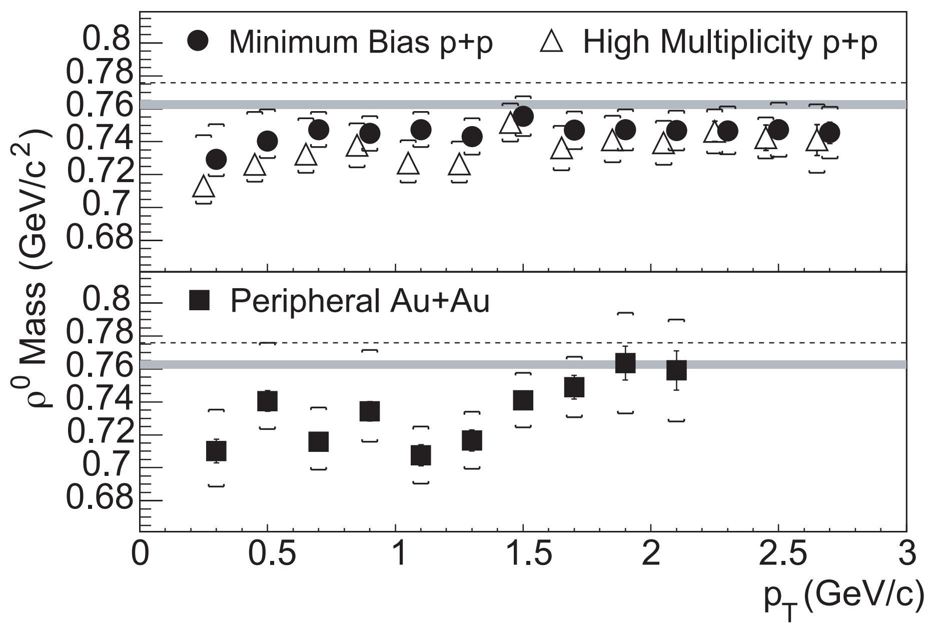
Broadening of ρ is visible when going from peripheral In-In collisions when to more central collisions. [a]

[a] S. Damjanovic for the NA60 collaboration, proceedings of QM 2005. (nucl-ex/0510044)

Experimental results - RHIC

STAR experiment:

- Measured $\rho \rightarrow \pi^+\pi^-$ in peripheral Au-Au collisions with CM energy 200 GeV [a]
- Possible -70 MeV mass shift in peripheral Au-Au, compared with -40 MeV in pp.
- Shift increases with multiplicity and decreases with p_t.



[a] J. Adams et al, Phys.Rev.Lett.92:092301 (2004), nucl-ex/0307023.

Analysis outline

This analysis was done for the $\rho \rightarrow \pi^+\pi^-$ decay channel, and consists of several parts:

- HIJING is used to generate 10^6 central Pb-Pb events.
- A fast simulation technique was developed to model the effects of the apparatus on the ability to reconstruct the ρ, and to do so at a practical speed.
- A background subtraction method was used to remove most of the combinatorial background, which is very large due to the high multiplicity.
- A suitable fitting function was used to fit the ρ, the remaining background and the ω, which complicates the $\pi^+\pi^-$ invariant mass spectrum.
- Signal-to-Background values and signal significances ($\frac{S}{\sqrt{S+B}}$) were found for several p_t sub-regions.
- The ability of the fitting method to work in cases where the ρ signal is reduced was investigated.

Fast Simulation Method

Fast simulation used to simulate the response of the apparatus:

- Geometric acceptance is described by assuming a flat acceptance function for $-0.9 < \eta < 0.9$ and zero elsewhere.
- Reconstruction efficiency is modelled by a function of p_t and particle species, obtained from the detailed simulation.
- PID efficiency is handled by using the detailed simulation to make a table of probabilities of successful identification (according to pre-specified conditions) as a function of p_t.
- Momentum resolution is handled by using the detailed simulation to make a table of "errors" in p_x, p_y and p_z as a function of p_t.
- Secondary tracks are not considered, as they form a small fraction of the total tracks - less than 10% with loose cuts, and much better with stricter cuts.
- When applying the fast simulation to the output from HIJING, the reconstruction efficiency, PID efficiency and momentum resolution are taken into account.

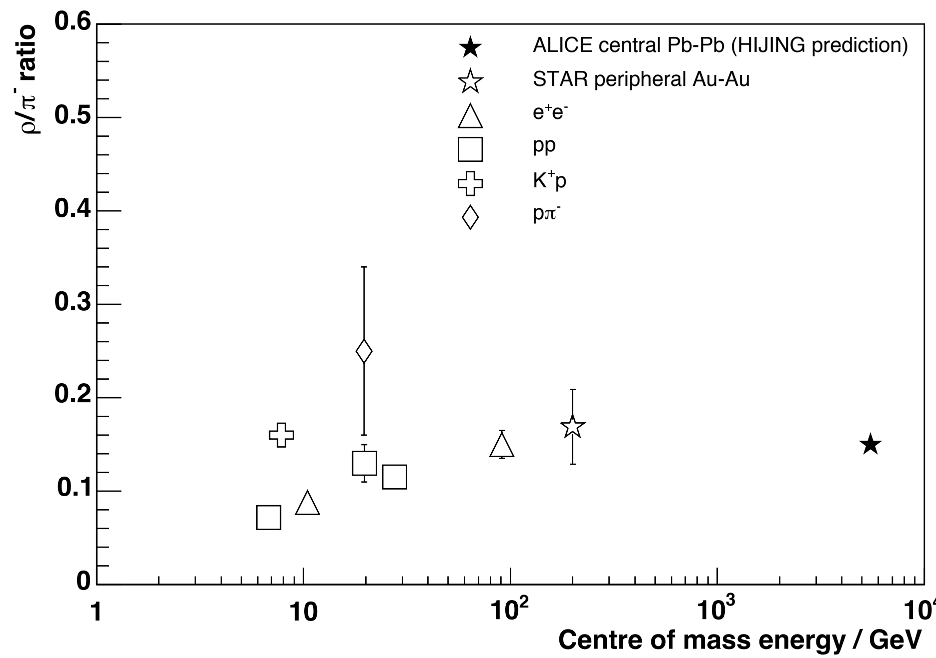
Fast simulation performance

Fast simulation characteristics:

- Performance:
  - 1 Million PYTHIA pp events can be generated, simulated and processed for resonances in about 100 CPU-hours, rather than about 30,000 CPU-hours for detailed simulation.
  - Huge improvement for Pb-Pb - fast simulation time is small compared to HIJING's generation time. Overall factor of approximately 100 improvement in speed.
- Accuracy:
  - Number of found resonances in fast simulation is within 5% of the number found in the detailed simulation.
  - Number of background resonances is within 10% of the detailed simulation.
  - Fast simulation signal significance is within 5% of the detailed simulation.
  - Expect that these errors are small compared to errors in physics predictions.

HIJING physics predictions

As a test of HIJING's predictions, we compare the ρ/π ratio predicted by HIJING to that from previous experiments:



Previous experiments - The ρ/π ratio is roughly constant over large changes in energy. HIJING's predictions are consistent with this.

$\pi^+\pi^-$ invariant mass spectrum

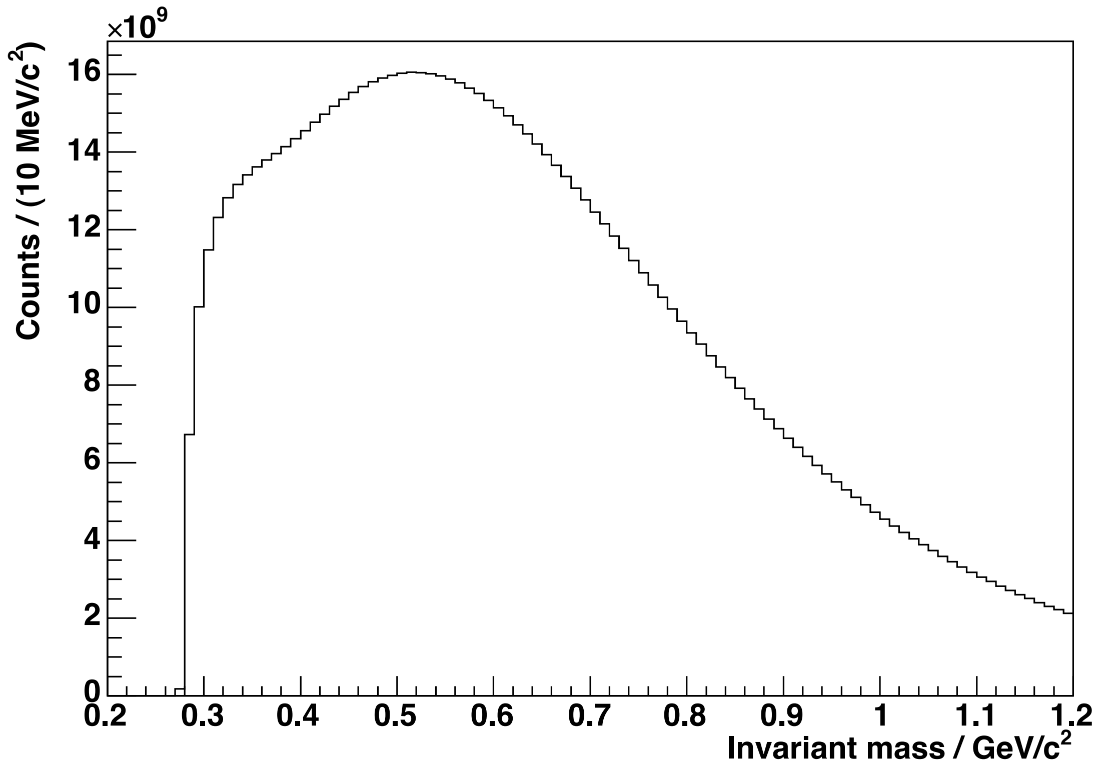


Figure 3: $\pi^+\pi^-$ spectrum for 10^6 central events.

Background subtraction

Combinatorial background is proportional to N^2_{tracks}.

Therefore, in central Pb-Pb collisions, where N_{tracks} is large, background is very large.

Signal-to-Background for ρ is 10^{-4}.

Fortunately, most of this can be removed using the like-sign technique:

- An invariant mass spectrum is calculated using pairs of tracks of the same sign, and a second histogram is filled.
- This histogram will not contain contributions from resonance decays, but should reproduce the combinatorial background (approximately).
- This histogram is then subtracted from the unlike-sign histogram.

The result is shown on next slide.

Subtraction results

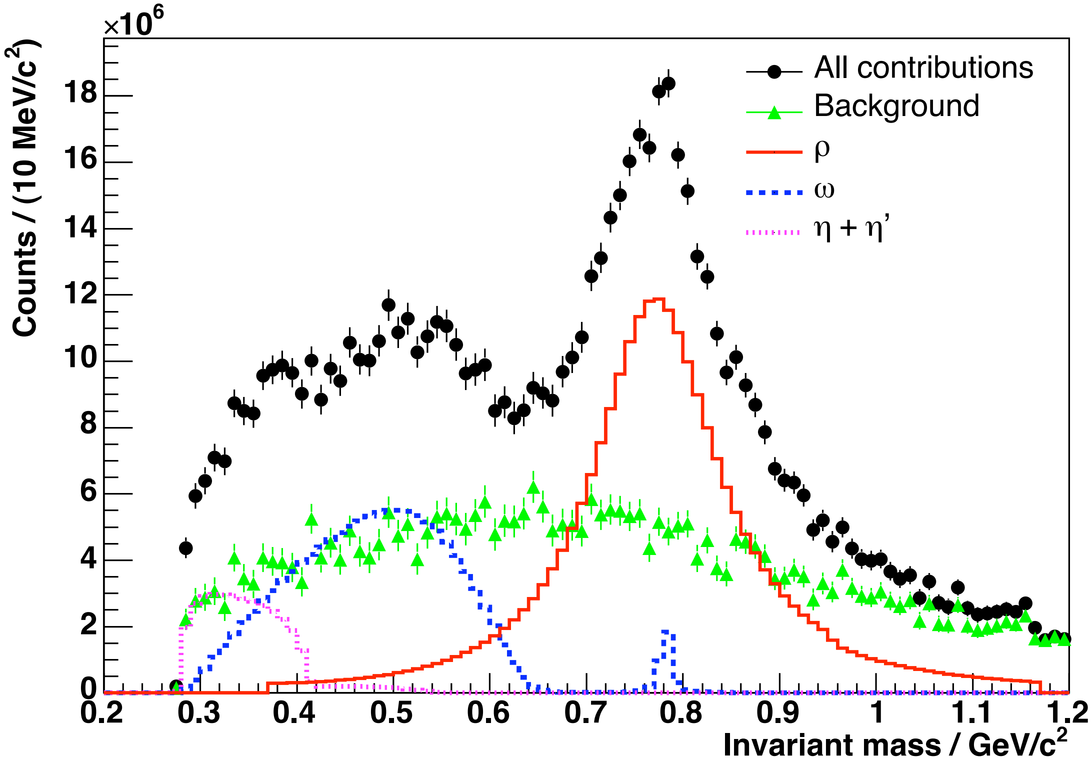
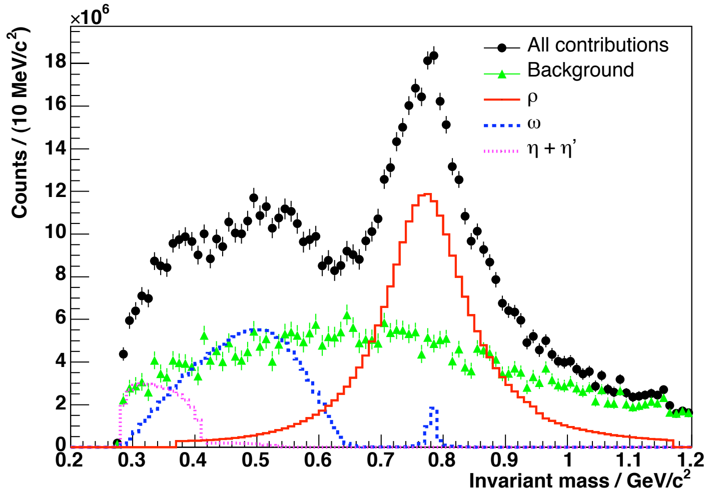


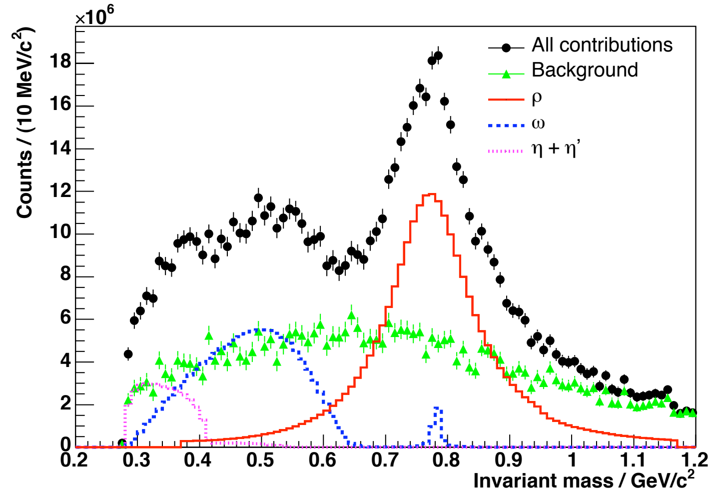
Figure 4: $\pi^+\pi^-$ spectrum for 10^6 central events after like-sign background subtraction, showing individual contributions. Black dots show the results of the like-sign subtraction.

Contributions to $\pi^+\pi^-$ spectrum



- The ρ mass peak, following a Breit-Wigner distribution. (red)
- Remaining combinatorial background after the like-sign subtraction. (green)
- $\omega \longrightarrow \pi^+\pi^-\pi^0$, with the charged pion pairs forming a wide bump. (blue)
- $\omega \longrightarrow \pi^+\pi^-$, forming a small peak at 0.782 GeV. (blue)

Contributions to $\pi^+\pi^-$ spectrum



- $\eta \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-\eta$ decays, behaving like the three-body ω decay above. (purple)
- Additionally, $K^{0*} \to K\pi$ appears as a large peak underneath the ρ. As this caused problems for the fit, the PID was used to remove it. Remaining K^{0*} contribution is negligible, and not shown.

Fitting procedure

The fit has three components:

- A non-relativistic Breit-Wigner function to fit the ρ.
- A straight line to describe the combinatorial background.
- A shape for the ω derived from the Monte Carlo simulation, with the size as a free parameter.

These were fitted in the mass region 0.55 to 1.20 GeV, for two reasons:

- For m < 0.55 GeV, the background cannot be described by a straight line.
- For m < 0.55 GeV, η and η' are also present.

Additionally, the fitted function was normalised so the area under it was the same as that for the histogram. This increased the reliability of the fits and the errors.

Fit results

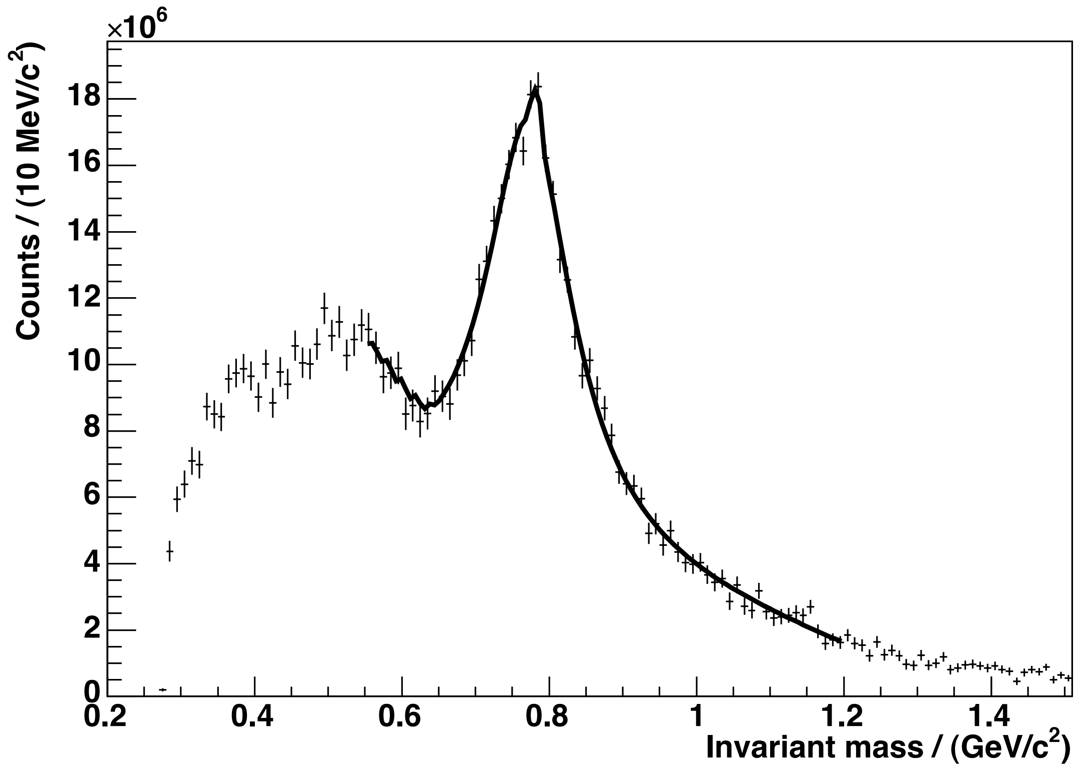


Figure 5: Fit to background-subtracted $\pi^+\pi^-$ spectrum

Fit results continued

	Full fit	Fixed width fit	ρ without background
Mass / GeV	0.771 ± 0.001	0.772 ± 0.001	0.774
Width / GeV	0.162 ± 0.008	0.139 (fixed)	0.139
Number ρs	$(2.30^{+0.69}_{-0.47}) \times 10^8$	$(2.02 \pm 0.10) \times 10^8$	1.97×10^8

- Yield is measured correctly. Fixing the width improves the yield measurement.
- The fit to the ρ with no background shows an incorrect width. This is due to variation of reconstruction efficiency with track p_t, which distorts the ρ Breit-Wigner.
- Fitted mass value is within a few MeV of the correct value, so any large mass shifts should be measurable.

Distortion of ρ shape

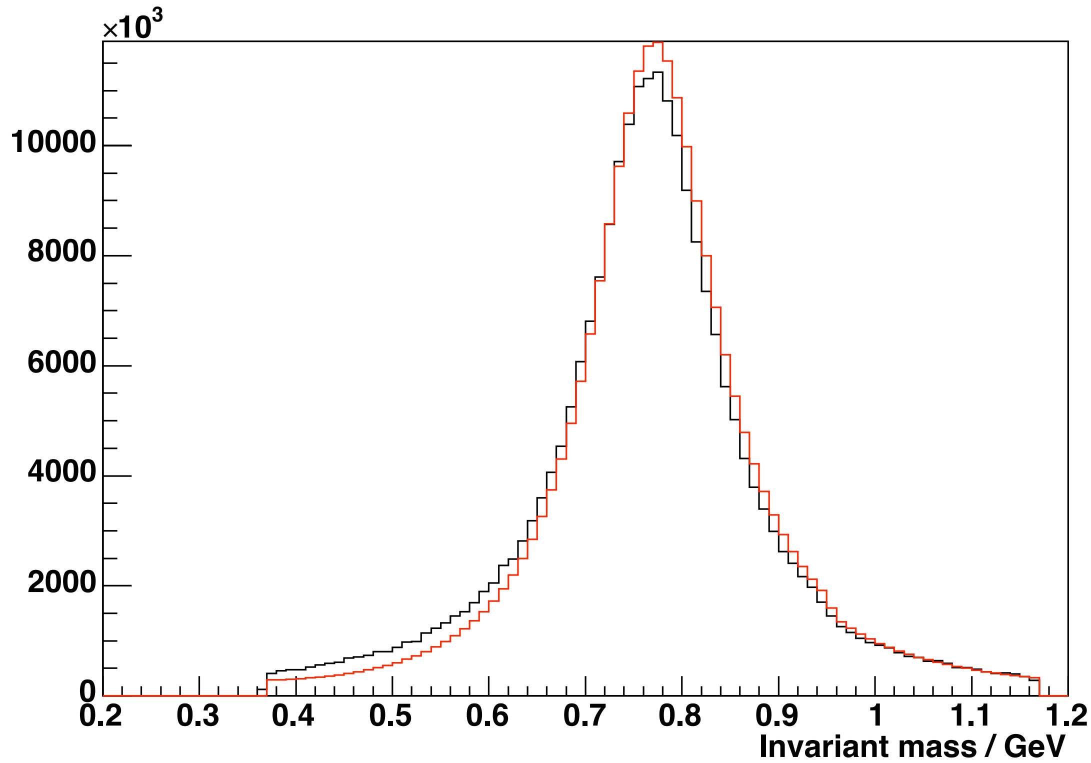


Figure 6: Comparison of generated (black) and reconstructed (red) ρ shapes for all p_t. Distortion of shape is clearly visible.

Distortion of ρ shape continued

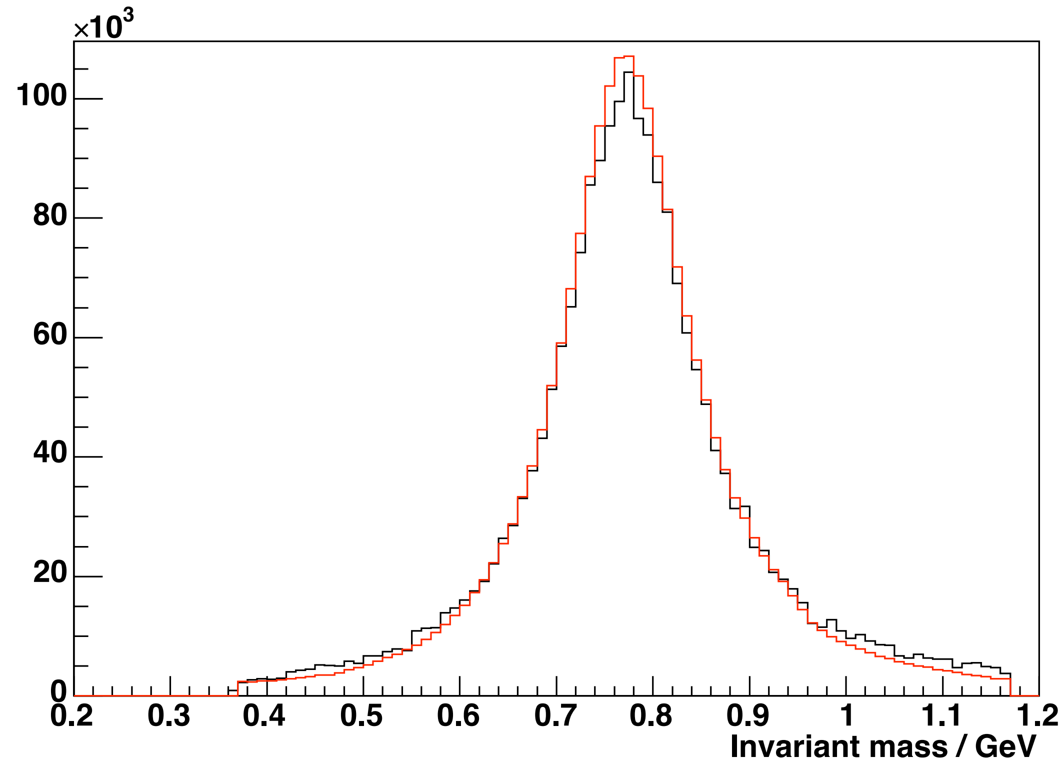


Figure 7: Comparison of generated (black) and reconstructed (red) ρ shapes for p_t from 1 to 2 GeV. Distortion of shape is smaller than for the full p_t case.

Signal significance as a function of p_t

Table 1: Significance and S/B values for ρ in various p_t regions for 10^6 HIJING central Pb-Pb events.

p_t range	Signal	Background	S/B	Significance
All	1.97×10^8	2.65×10^{12}	7.43×10^{-5}	121
Below 1 GeV	1.78×10^8	2.40×10^{12}	7.42×10^{-5}	115
1-2 GeV	1.71×10^7	2.42×10^{11}	7.06×10^{-5}	34.8
2-4 GeV	2.15×10^6	9.30×10^9	2.31×10^{-4}	22.3
Above 4 GeV	2.16×10^5	2.14×10^8	1.0×10^{-3}	14.8

- These results show that, with our expected number of events, it will be feasible to measure the ρ in p_t sub-ranges, even at quite high p_t.
- Improved use of PID may improve the high p_t results further.

Signal significances - no PID

The particle identification is not available at high p_t.

p_t range	Signal	Background	S/B	Significance
4-6 GeV	63958	1.17×10^8	5.47×10^{-4}	19.4
6-8 GeV	14383	1.28×10^7	1.12×10^{-3}	13.2
8-10 GeV	3898	2.01×10^6	1.94×10^{-3}	9.0

This table shows significances without using PID.

Therefore, some other method of dealing with the $K^{0*} \rightarrow K\pi$ contribution is required.

Effects of reduced signal

The fit was redone with the ρ contribution reduced, but the background remaining the same:

ρ fraction	Fitted mass / GeV	Fitted N_ρ	Correct N_ρ
50%	0.771 ± 0.002	$10.8 \pm 0.8 \times 10^7$	9.85×10^7
25%	0.769 ± 0.004	$6.13^{+0.65}_{-0.57} \times 10^7$	4.92×10^7
10%	0.765 ± 0.007	$1.03 \pm 0.16 \times 10^6$	1.97×10^7

- The yield can still be measured with the signal size reduced by a factor of at least 4, albeit with larger errors.
- Quoted errors in these cases seem small - is there some unconsidered systematic error?
- These results support the previous claim that measurement in p_t sub-ranges should be feasible.

Conclusions

- The ρ properties should be measurable in central Pb-Pb collisions.
  - The yield can be measured to reasonable accuracy (10%).
  - The mass can be measured to within a few MeV.
  - Reliable width measurement is difficult, due to distortions of the ρ shape by the detector and by the remaining background, if the straight line does not correctly model it.
- However, there may be effects not described in the Monte Carlo which complicate matters:
  - At STAR, the signal can be reconstructed in peripheral collisions.
  - However, there are additional correlations in central collisions which are not understood [a].
- The ρ should still be measurable even if the signal is lower than expected by a factor of four.
- The ρ should be measurable in p_t sub-ranges.

[a] P. Fachini, personal communication

$\rho \longrightarrow e^+e^-$ possibilities

The obvious next stage is to study the leptonic channel, which has quite different problems:

- Very different sources of background to hadronic channel - misidentified hadrons, gamma conversions, other meson decays etc. which must be correctly described.
- Much stronger requirement for PID to separate electrons from the much more abundant pions.

Therefore, we have extra requirements:

- Need a parameterisation of electron reconstruction and PID efficiency as a function of p_t - is this available?
- Are all sources of background included in HIJING and the detector simulation?