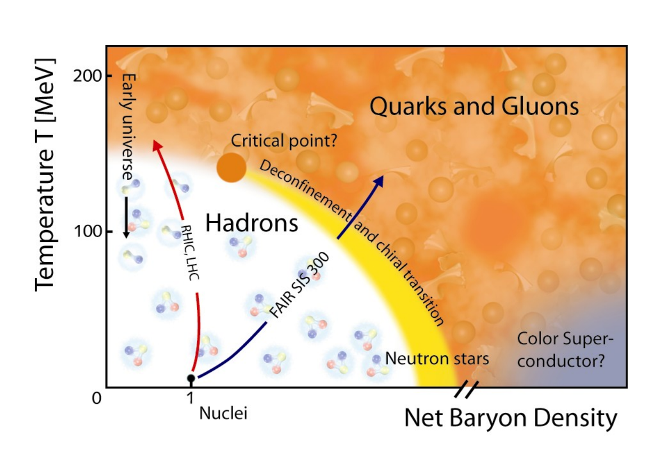
Dimuon measurements with NA60

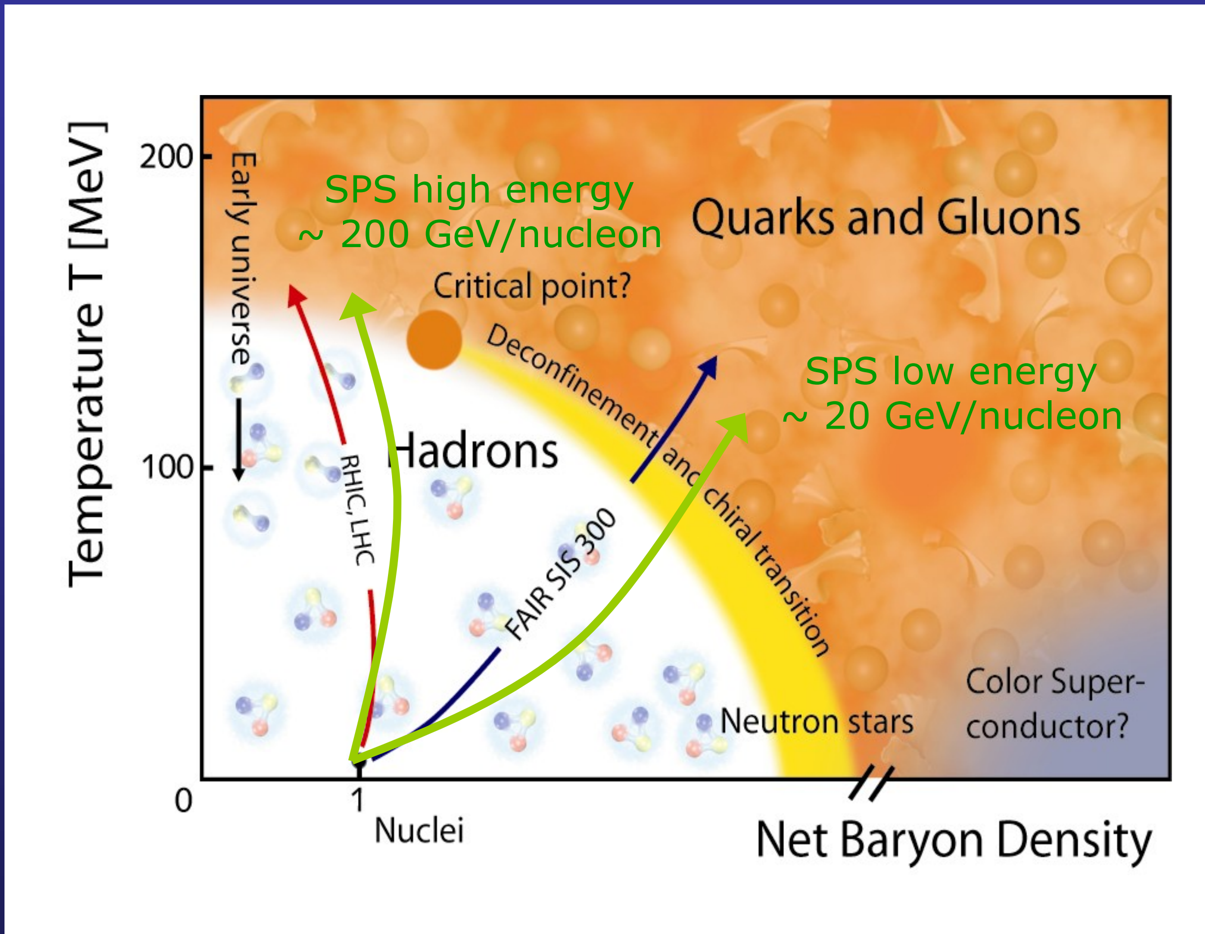
- Introduction
- NA60 physics results
  - Low-mass dimuons
  - J/ψ suppression
- Future developments



International workshop
The physics of high baryon density
Trento, May 29 – June 2, 2006

E. Scomparin – INFN Torino (Italy)
on behalf of the NA60 Collaboration

NA60 at the CERN SPS



SPS probably sitting in the region close to

- Deconfinement threshold
- Critical point

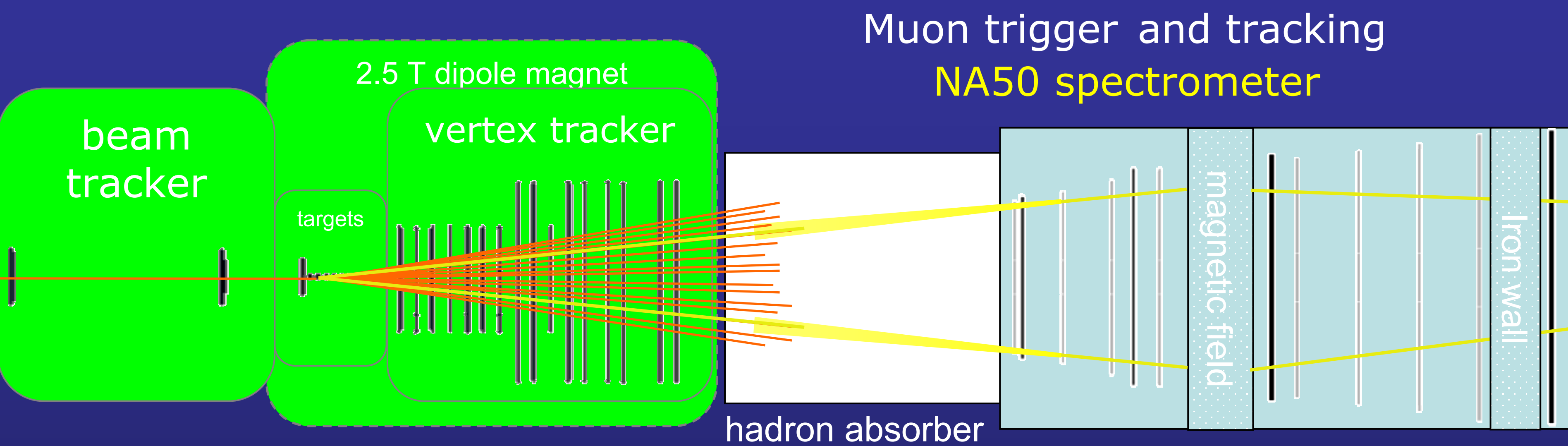
- Well positioned to study
  - Onset of deconfinement → J/ψ suppression
  - Approach to chiral symmetry restoration → in-medium modifications of vector mesons

NA60 at the CERN SPS (2)

- NA60 experiment
  - Data taking: 2003-2004
  - Second generation experiment
  - Aim: answer specific questions left open, in the leptonic sector, by the previous round of SPS experiments, finished in 2000 (and that can hardly be addressed at RHIC and LHC)
  - Designed in order to reach unprecedented accuracy in the measurement of muon pair production in HI collisions

  - Main physics topics
    - Determine the origin of the low-mass excess seen by CERES, possibly connected with chiral symmetry restoration
    - Determine the origin of the intermediate-mass excess seen by HELIOS-3, NA38 and NA50, possibly connected with thermal dilepton production
    - Investigate the origin of the J/ψ suppression, by comparing NA50 Pb-Pb results with new data obtained with lighter ions

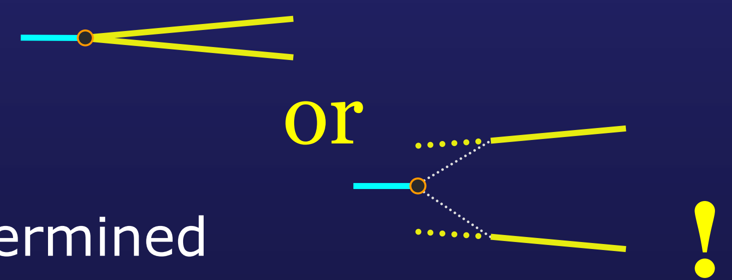
NA60: detector concept



— Muon
— Other

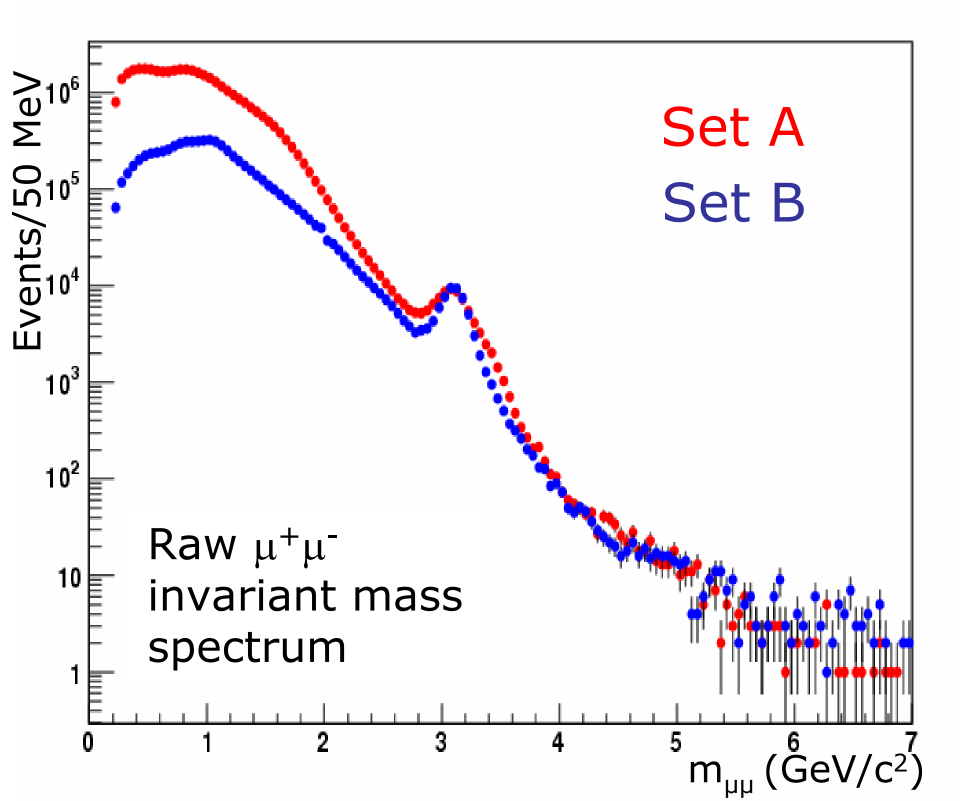
Matching in coordinate
and momentum space

- Improved dimuon mass resolution
- Origin of muons can be accurately determined



Data taking: In-In collisions

- 5-week long run in 2003 – In-In @ 158 GeV/nucleon
- ~ 4×10^{12} ions on target
- ~ 2×10^{8} dimuon triggers collected



- Two muon spectrometer settings
  - Set A (low ACM current)
    - Good acceptance at low mass
    - Used for LMR and IMR analysis
  - Set B (high ACM current)
    - Good resolution at high mass
    - Used for J/ψ suppression

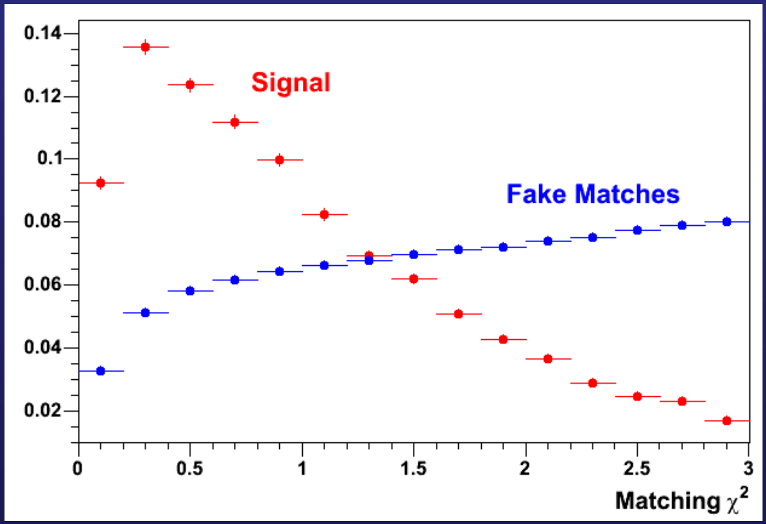
- Centrality selection: use
  - spectator energy in the ZDC
  - charged multiplicity in the vertex spectrometer

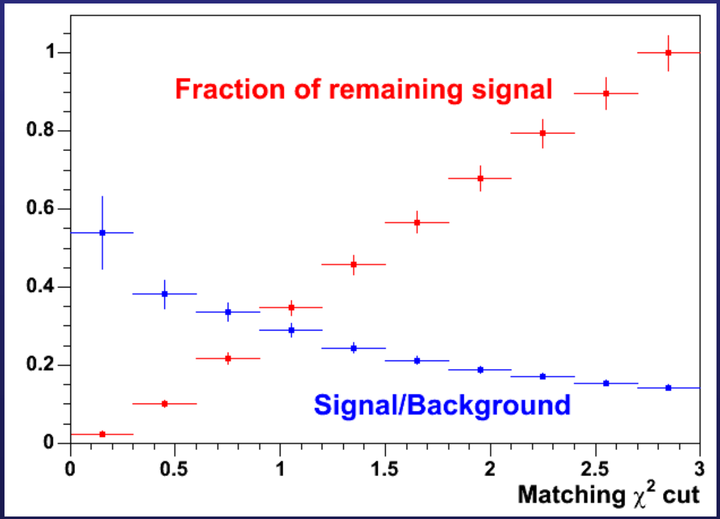
Muon matching

Muons from muon spectrometer ⟷ Vertex spectrometer tracks

Compare slopes and momenta
Define a matching χ^2
Re-fit matched tracks

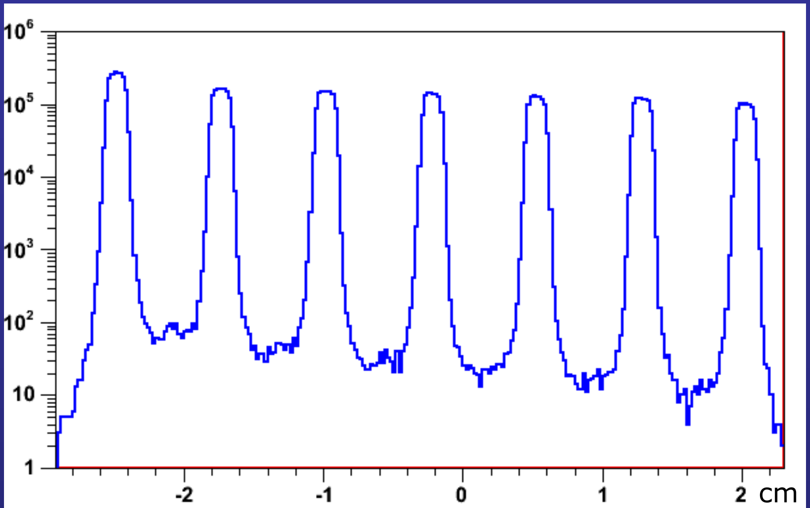
- With this procedure
  - Combinatorial background can be reduced
  - A certain level of fake matches is present (new kind of background)





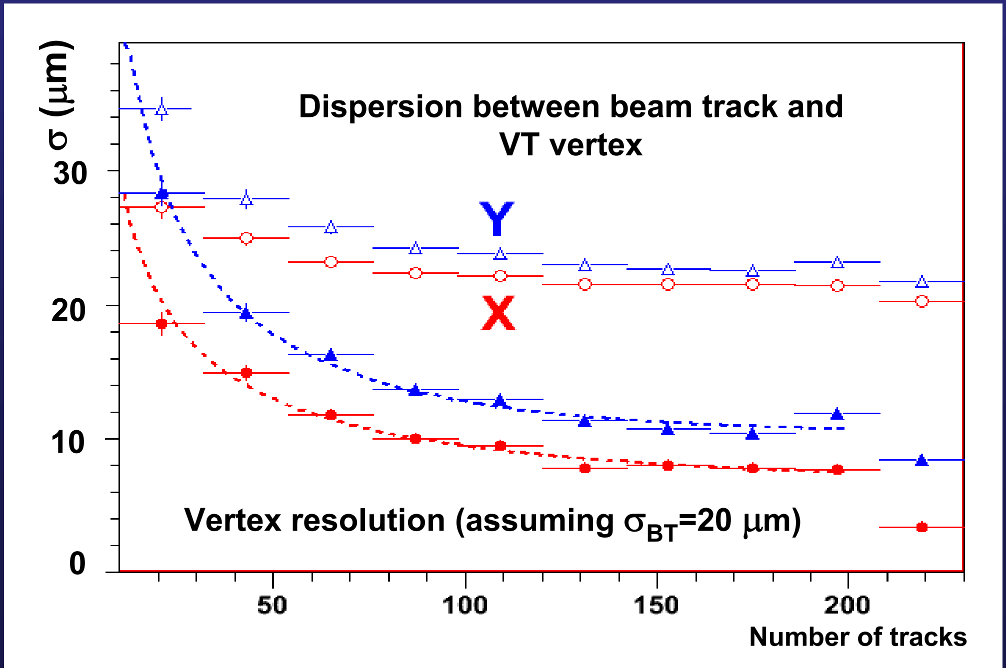
Vary the cut on the matching χ^2 ⟶ improve the signal/background ratio

Vertex resolution



$\sigma_z \sim 200\ \mu m$ along beam axis

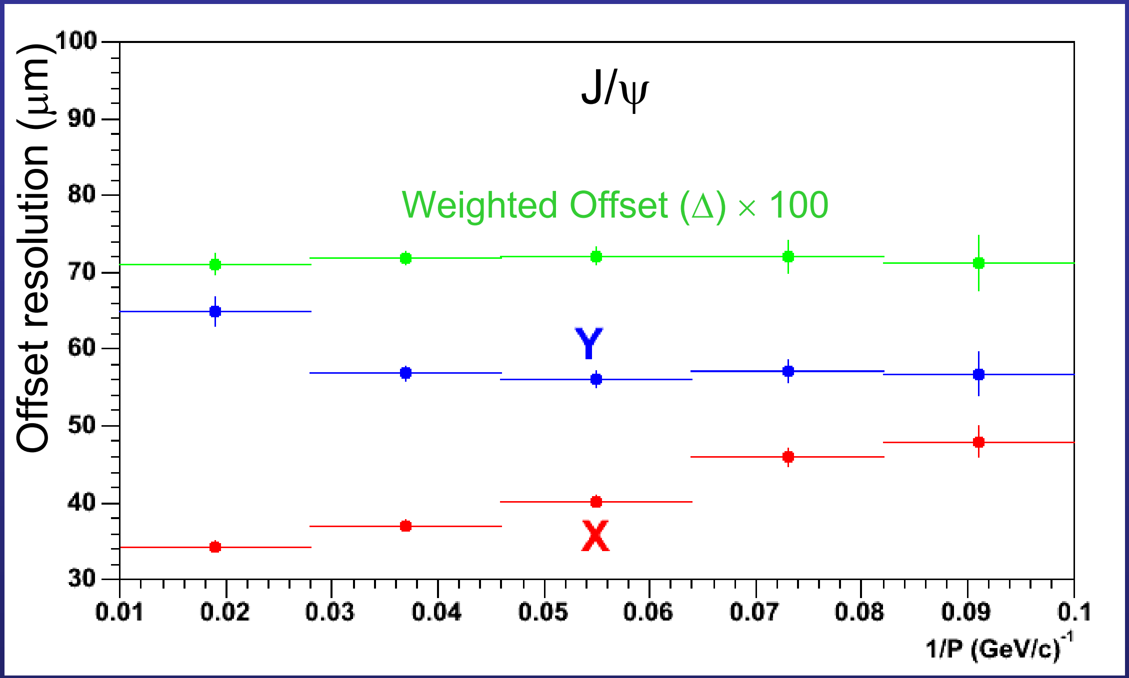
Good target ID
(down to very peripheral events)



$\sigma_x \sim \sigma_y \sim 10\text{-}\ 20\ \mu m$
in the transverse direction

(by comparing beam impact point on the target and reconstructed interaction point)

Offset resolution



Resolution of the impact parameter of the track at the vertex (offset)

40 – 50 μm

(studied using J/ψ events)

$\sigma_{vertex} \oplus \sigma_{impact} < c\tau$ $(D^+ : 312\ \mu m,\ D^o : 123\ \mu m)$

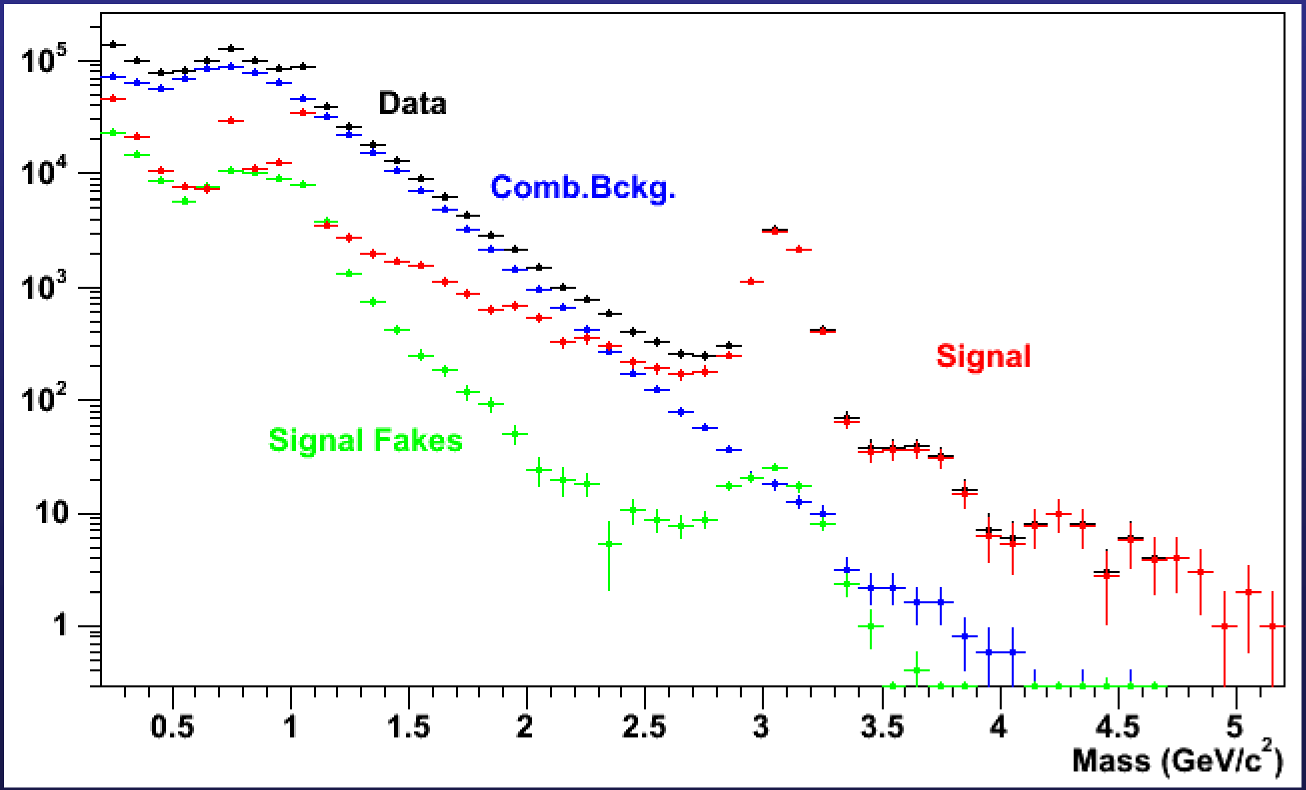
Prompt dimuons can be separated from open charm decays

- Define weighted offset Δ to eliminate momentum dependence of offset resolution (offset weighted by error matrix of the fit)

Background subtraction

- Combinatorial background
  - Dominant dimuon source for $m_{\mu\mu}<2$ GeV/c^2
  - NA60 acceptance quite asymmetric ⇒ Cannot use $N^{\pm}_{bck} = 2\sqrt{N^{++}N^{--}}$
  - Mixed event technique developed ⇒ accurate to ~ 1%

- Fake matches background also rejected with a mixed event approach
  - Less important in the intermediate mass region



1% error in the comb. background estimate

10% error on the signal

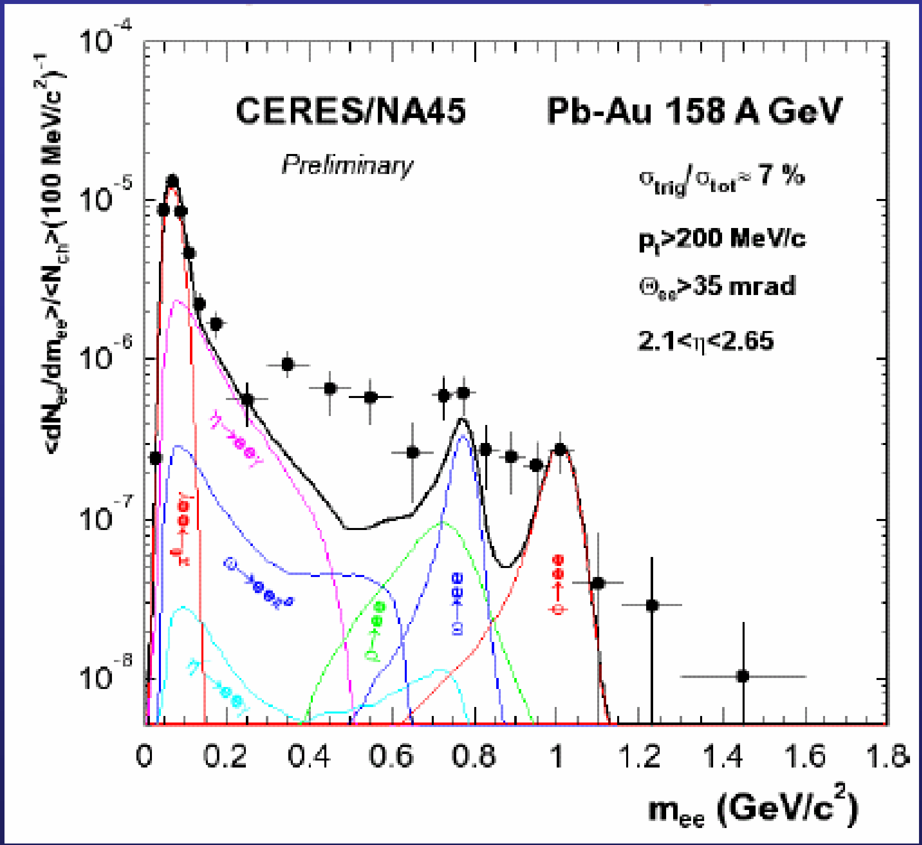
Low-mass studies

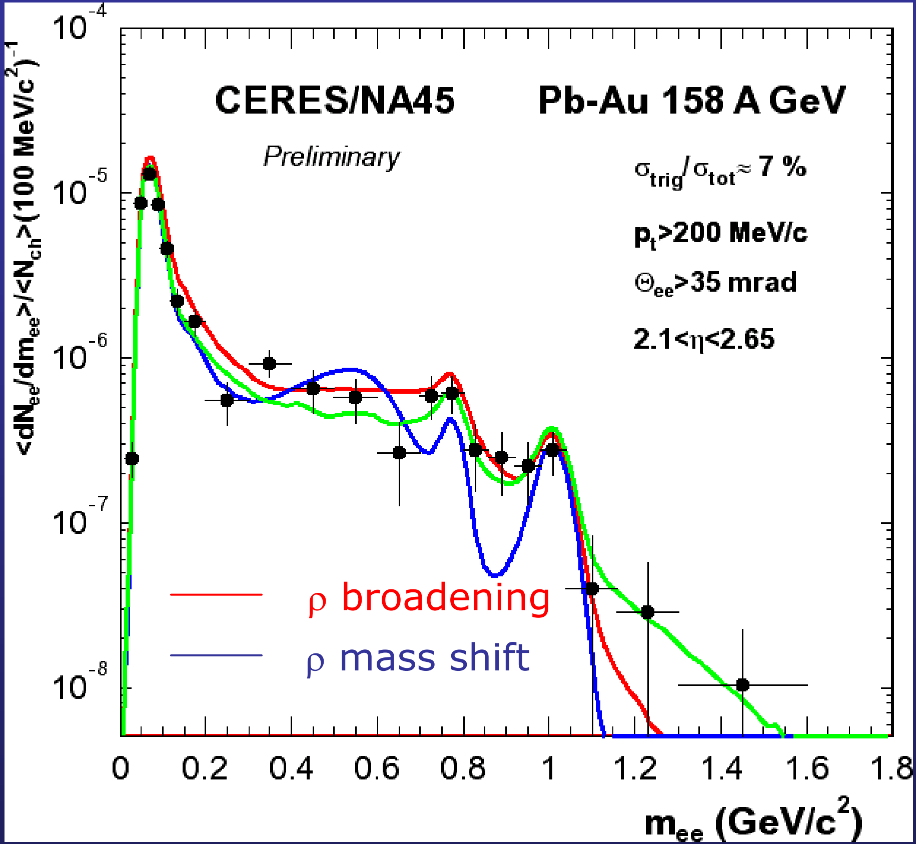
- Goal: use ρ as a probe for the restoration of chiral symmetry (Pisarski, 1982)
- Main difficulty :
  - Properties of ρ in hot and dense matter unknown (related to the mechanism of mass generation)
  - Properties of hot and dense medium unknown (general goal of the study of heavy-ion collisions)

	mass of ρ	width of ρ
Pisarski 1982	↘	↗
Leutwyler et al 1990 (π,N)	→	↗
Brown/Rho 1991 ff	↘	→
Hatsuda/Lee 1992	↘	→
Dominguez et al 1993	→	↗
Pisarski 1995	↗	↗
Rapp 1996 ff	→	↗

Many options available !

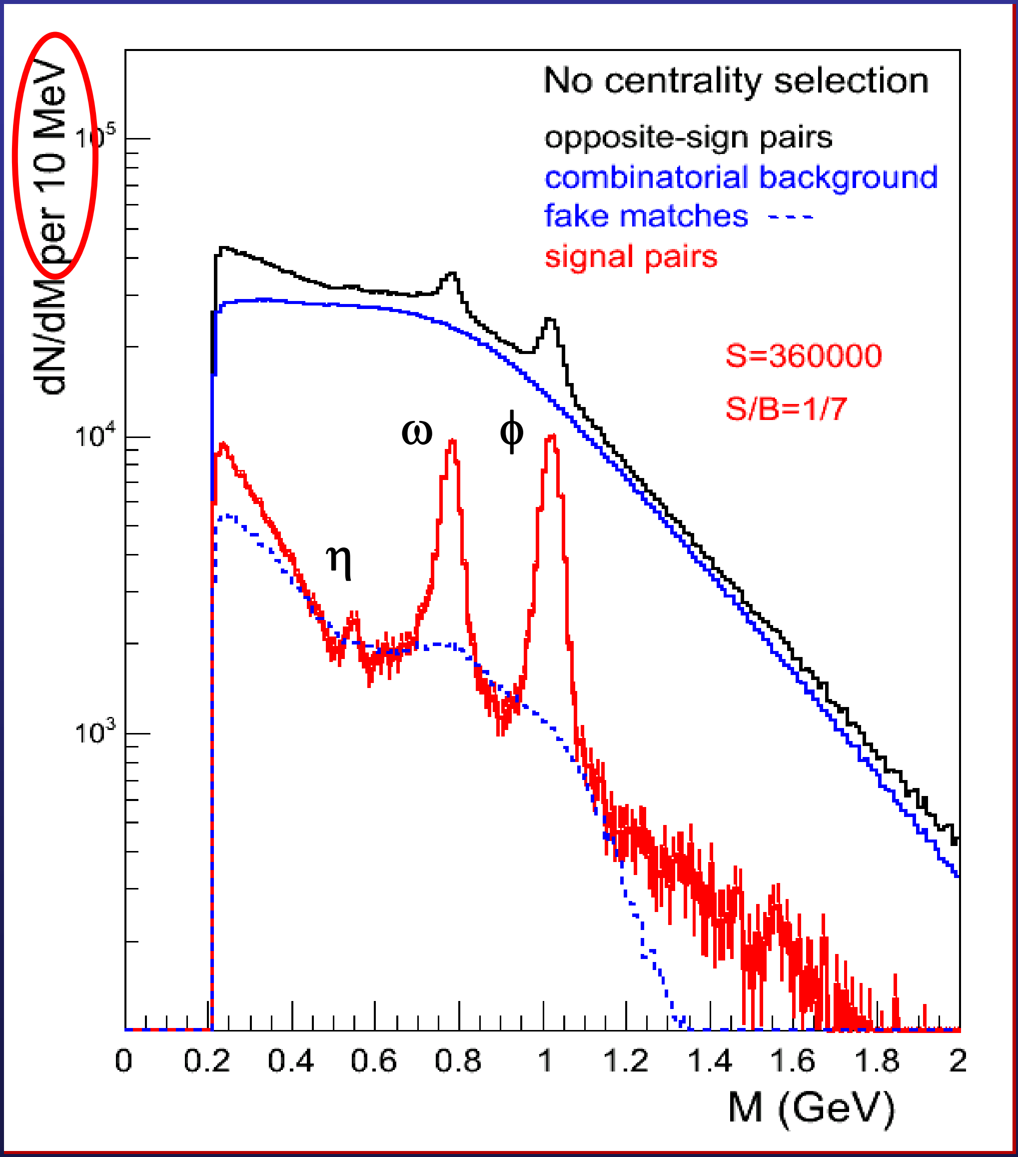
Low mass studies: previous knowledge





- Low mass excess well established by CERES (dielectrons)
- Still missing: clear discrimination between various theoretical explanations, many of them giving a reasonable description of the data

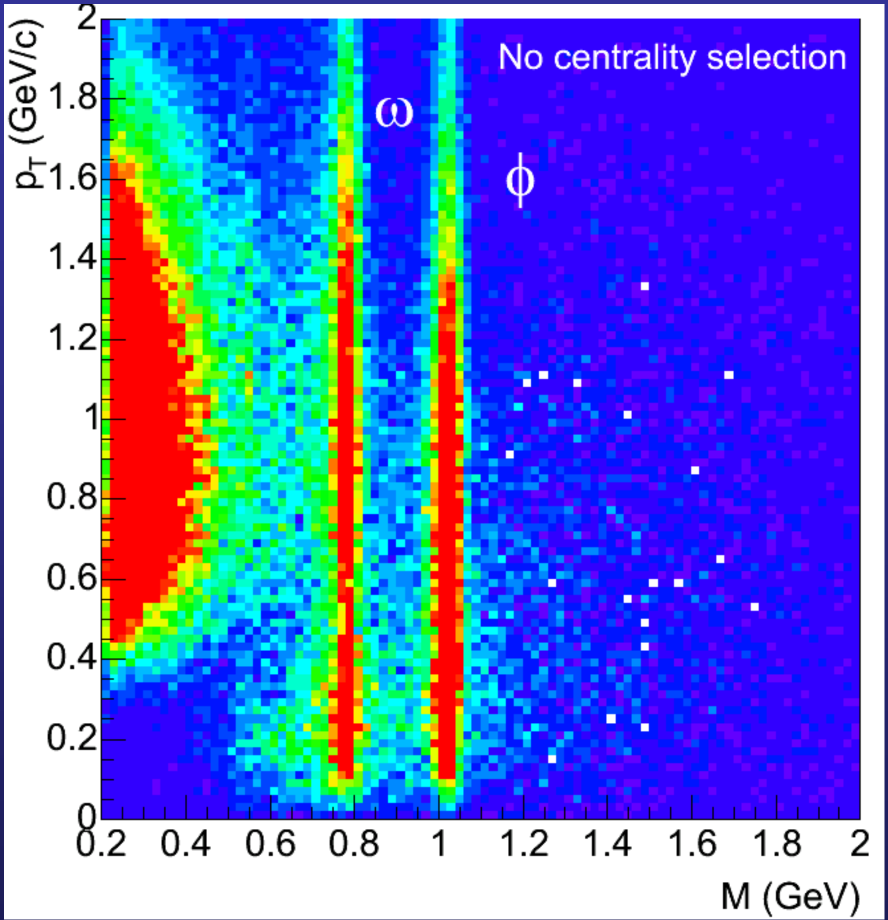
NA60 low-mass spectrum



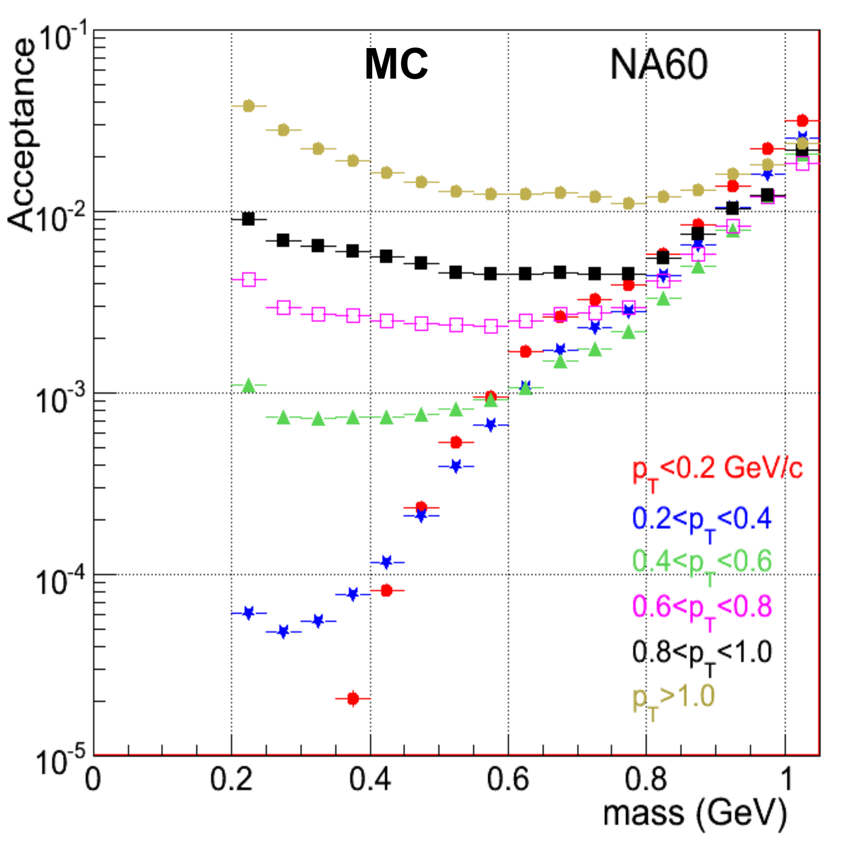
- Net data sample: 360 000 events
- Fakes / CB < 10 %
- For the first time, ω and ϕ peaks clearly visible in dilepton channel ; even $\eta \to \mu\mu$ seen
- Mass resolution: 23 MeV at the ϕ position

Progress over CERES:
statistics: factor >1000
resolution: factor 2-3

Phase space coverage in mass-p_T plane

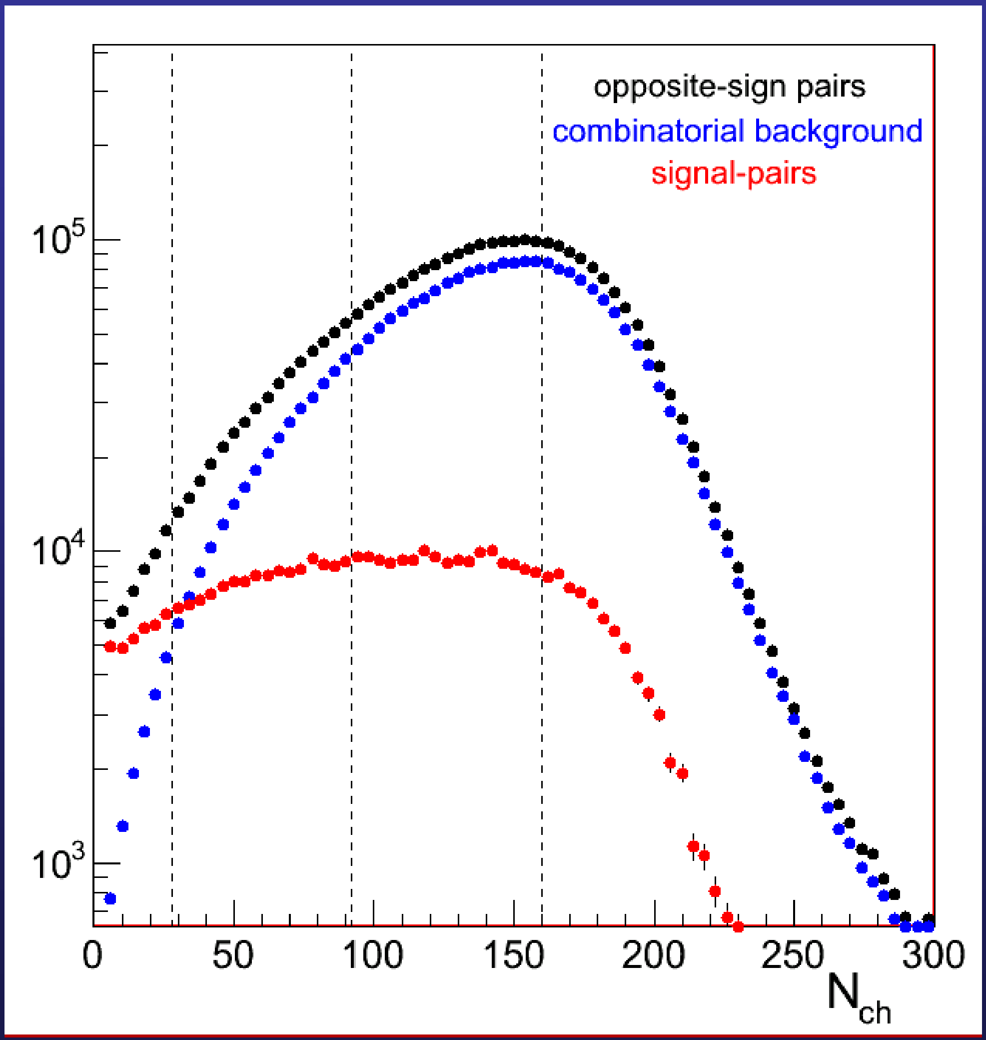


Final data after subtraction of combinatorial background and fake matches



The acceptance of NA60 extends (in contrast to NA38/NA50) all the way down to small mass and small p_T

Associated track multiplicity distribution



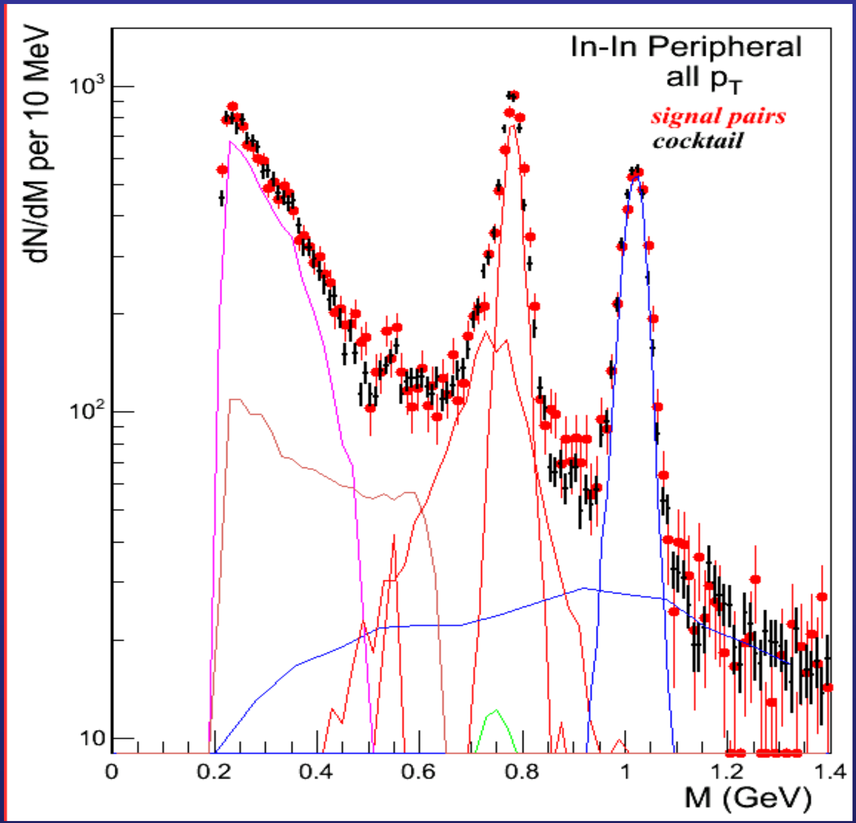
Track multiplicity from VT tracks for triggered dimuons for

opposite-sign pairs
combinatorial background
signal pairs

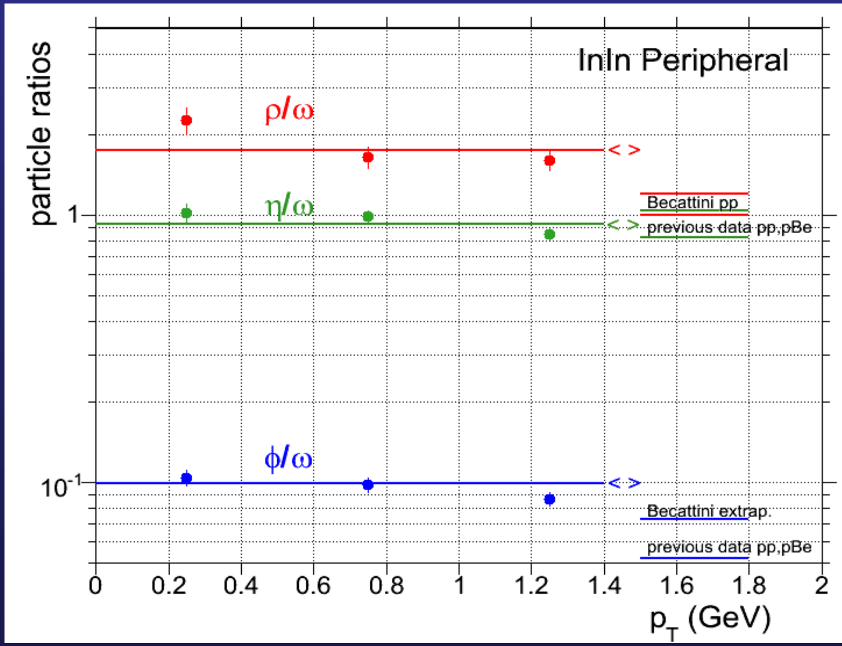
4 multiplicity windows:

Centrality bin	multiplicity	$\langle dN_{ch}/d\eta \rangle_{3.8}$
Peripheral	4–28	17
Semi-Peripheral	28–92	63
Semi-Central	92–160	133
Central	> 160	193

Low mass: peripheral collisions



- 4 centrality bins, defined through N_{ch}
- Fit independently in 3 p_T bins hadron decay cocktail and DD to the data ($m_{\mu\mu}$<1.4 GeV/c^2)
- Free parameters: η/ω, ρ/ω, ϕ/ω, DD, overall normalization



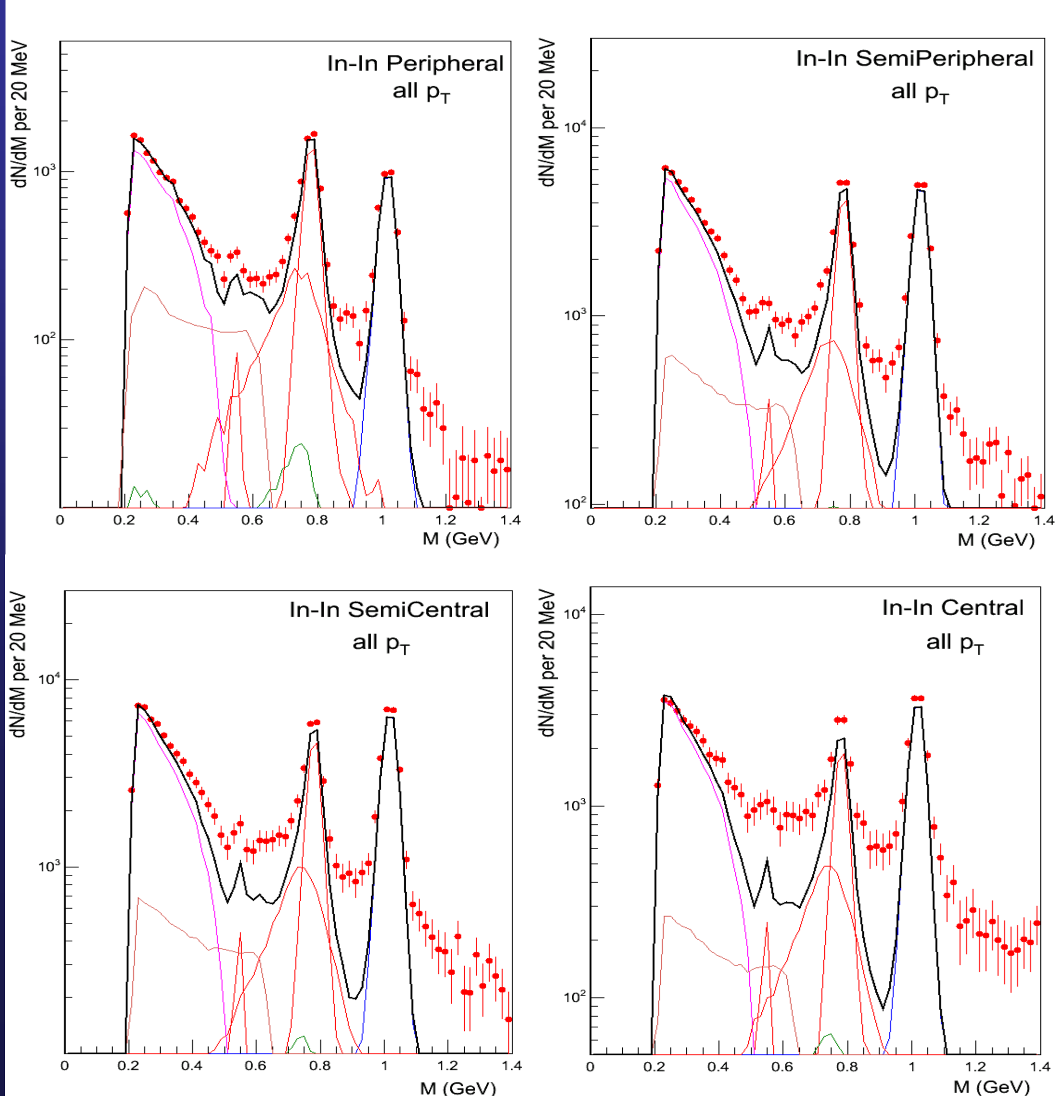
- Peripheral data well reproduced by the hadronic cocktail (for all p_T bins)
- Good fit quality down to low mass and p_T (low acceptance region well under control)

Reasonable values for the yields

Low mass: excess in central In-In collisions

• data
—— sum of cocktail sources including the ρ

See next slide for cocktail definition

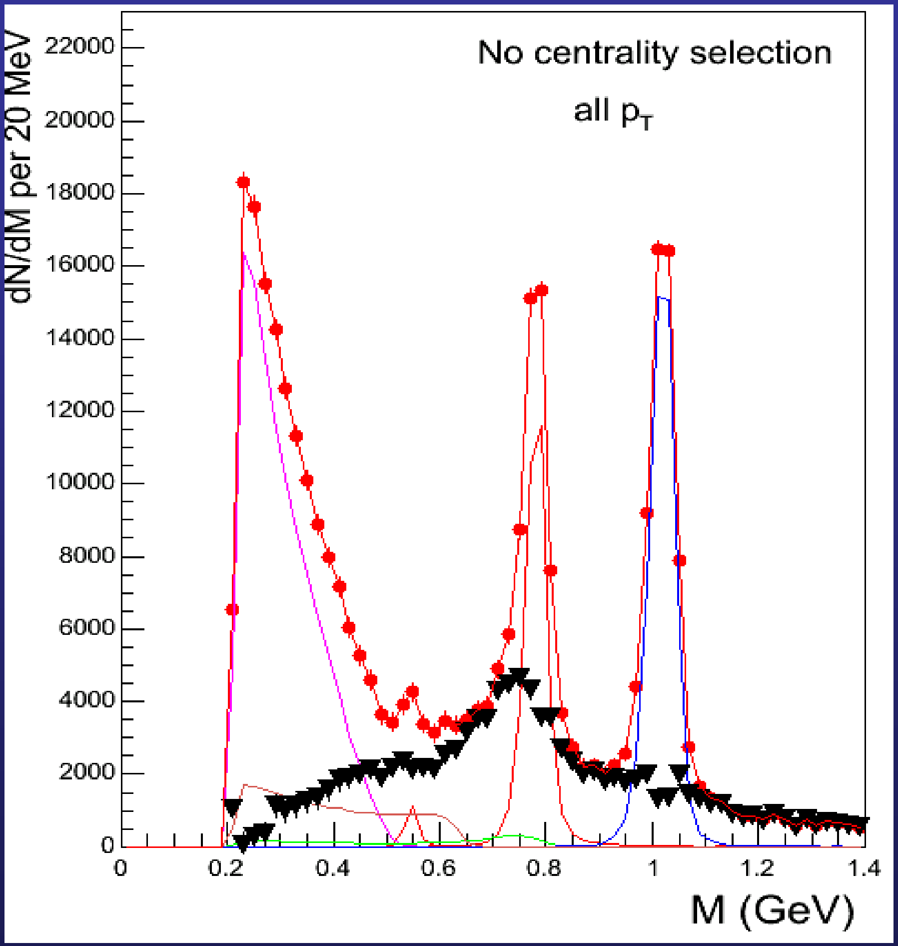


- ρ/ω fixed to 1.2

- Clear excess of data above cocktail

  ⇒ rising with centrality
  ⇒ more important at low p_T

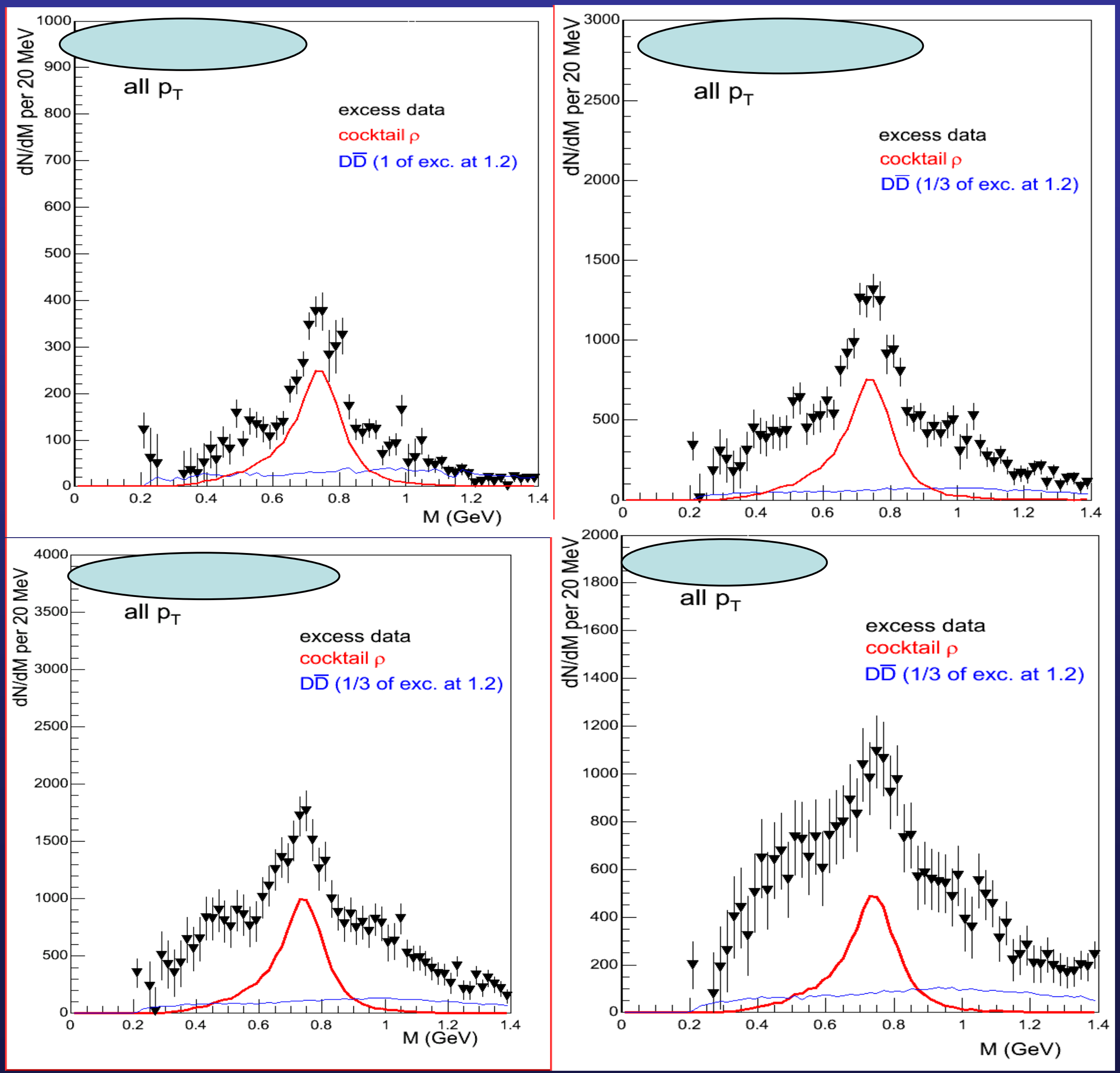
Getting the mass shape of the excess



- A simple approach is used to subtract known sources (except the ρ)
- ω and ϕ: yields fixed to get, after subtraction, a smooth underlying continuum
- η: set upper limit by "saturating" the yield in the mass region 0.2–0.3 GeV

$\Rightarrow$ leads to a lower limit for the excess at low mass

Excess spectra from difference: data - cocktail



all p_T

No cocktail ρ and no $D\bar{D}$ subtracted

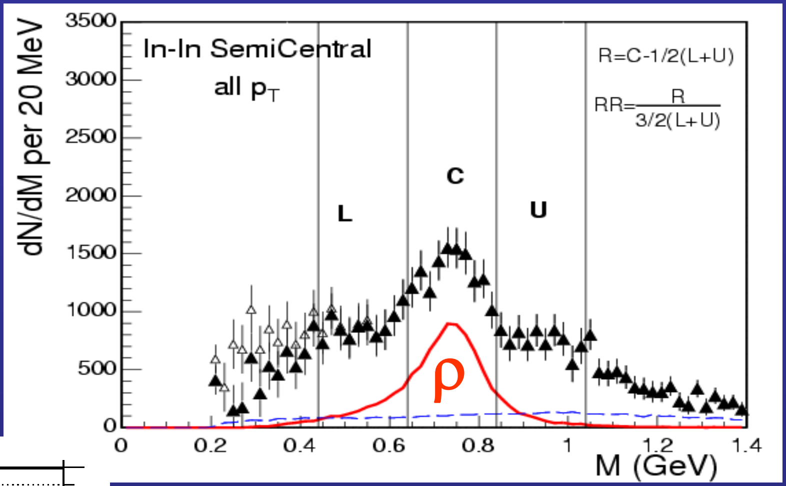
Clear excess above the cocktail ρ, centred at the nominal ρ pole and rising with centrality

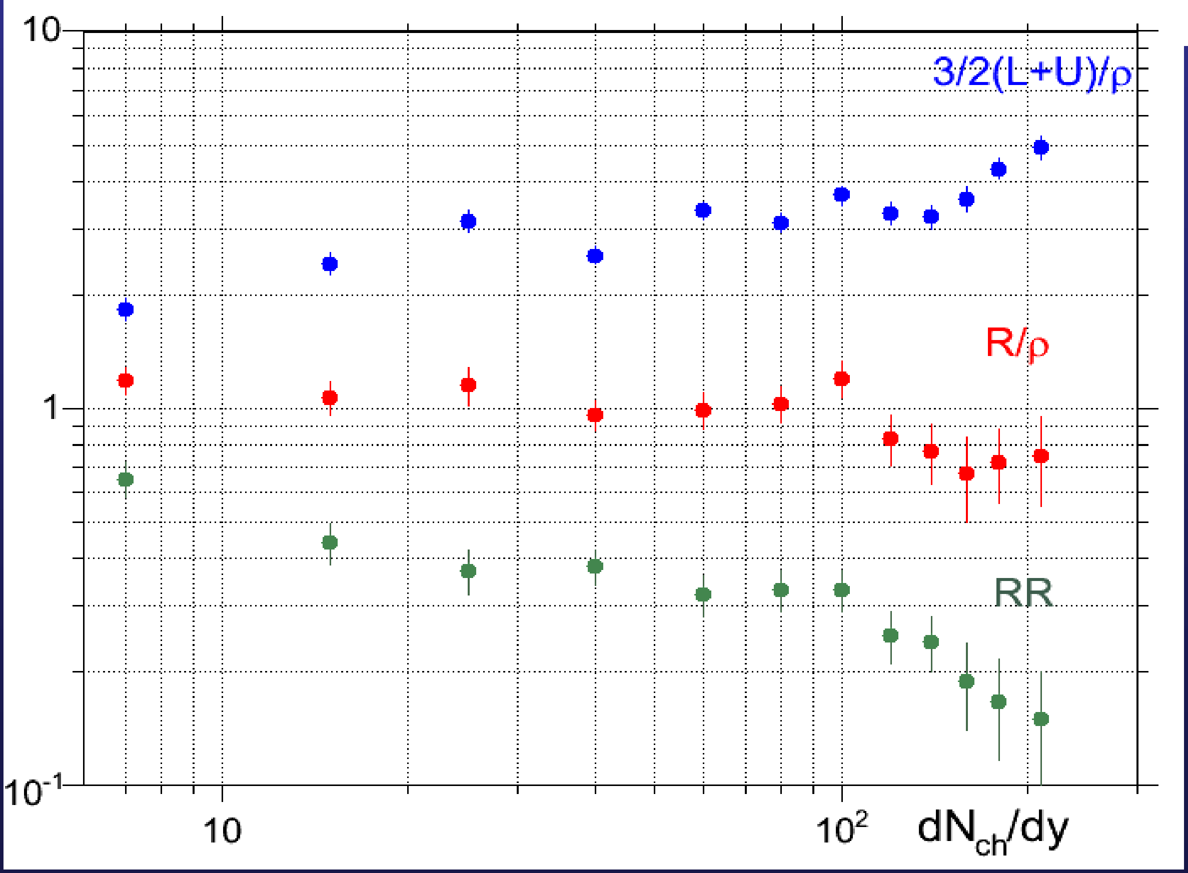
Similar behaviour in the other p_T bins

Now published !
PRL96(2006) 162302

Shape vs. centrality

nontrivial changes of all three variables at $dN_{ch}/dy>100$?



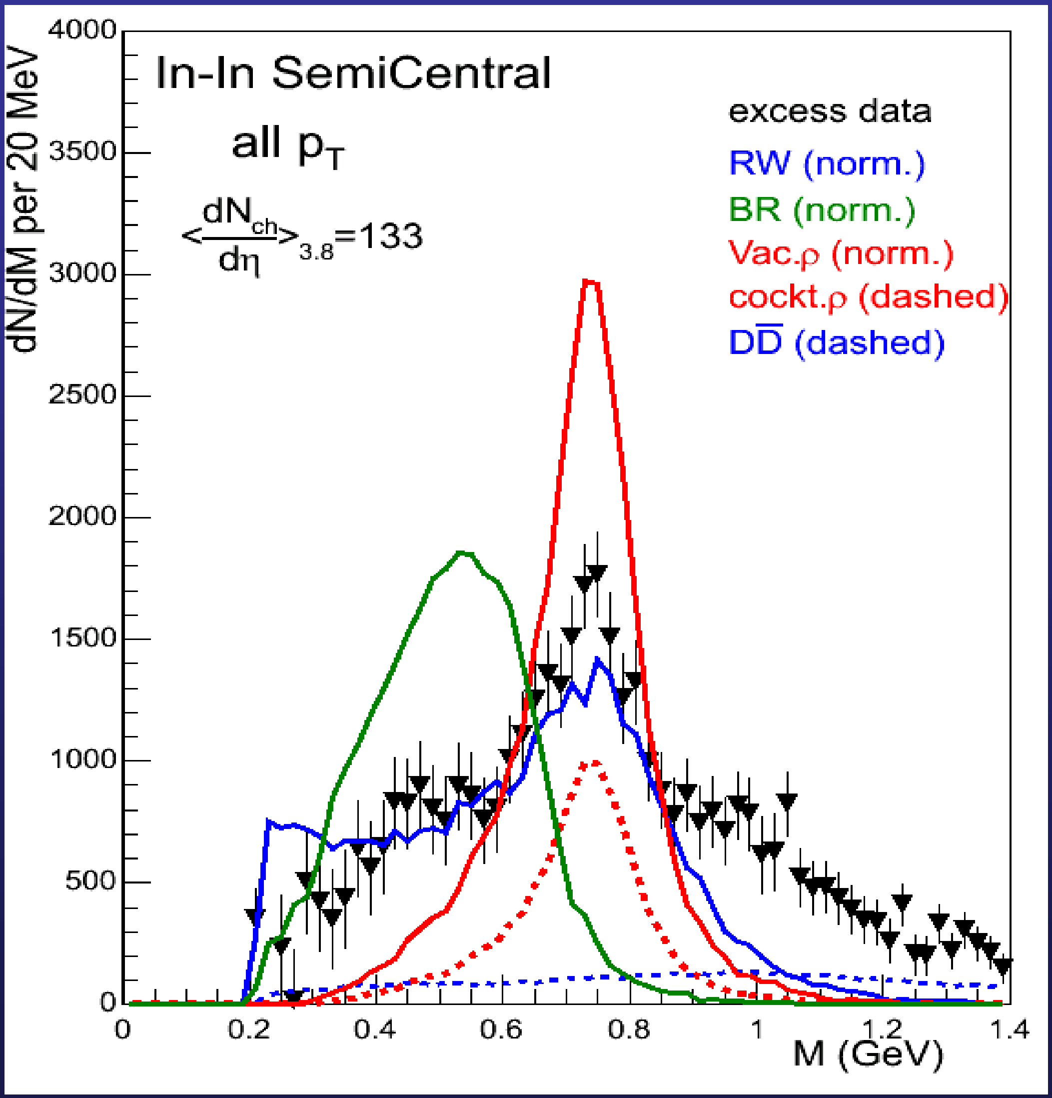


3/2(L+U) "continuum"

R=C-1/2(L+U) "peak"

RR peak/continuum

Comparison with models

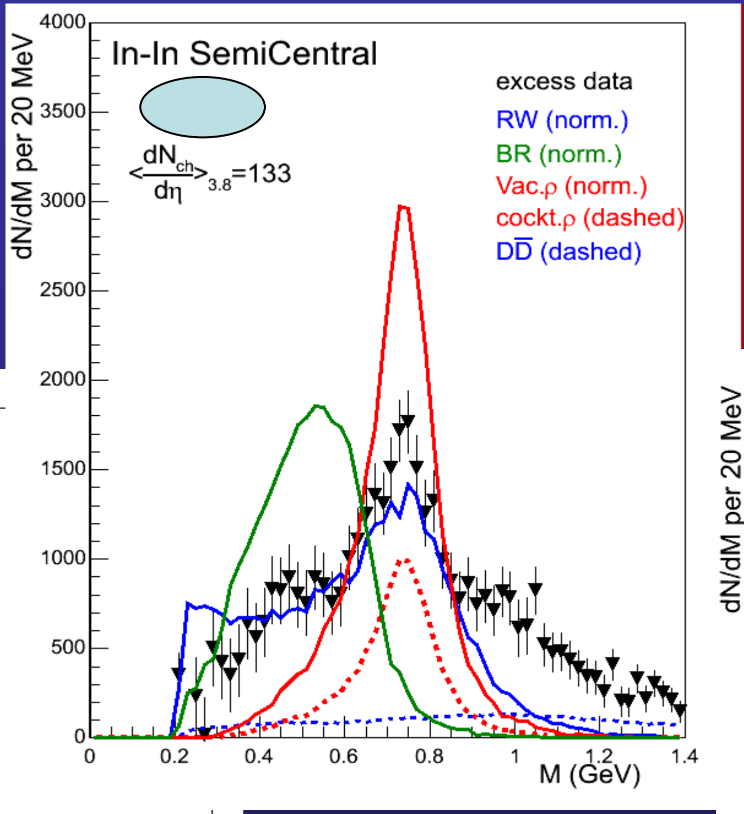


- Predictions for In-In by Rapp et al. (2003) for $\langle dN_{ch}/d\eta \rangle = 140$
- Theoretical yields folded with NA60 acceptance and normalized to data in the mass window $m_{\mu\mu} < 0.9$ GeV

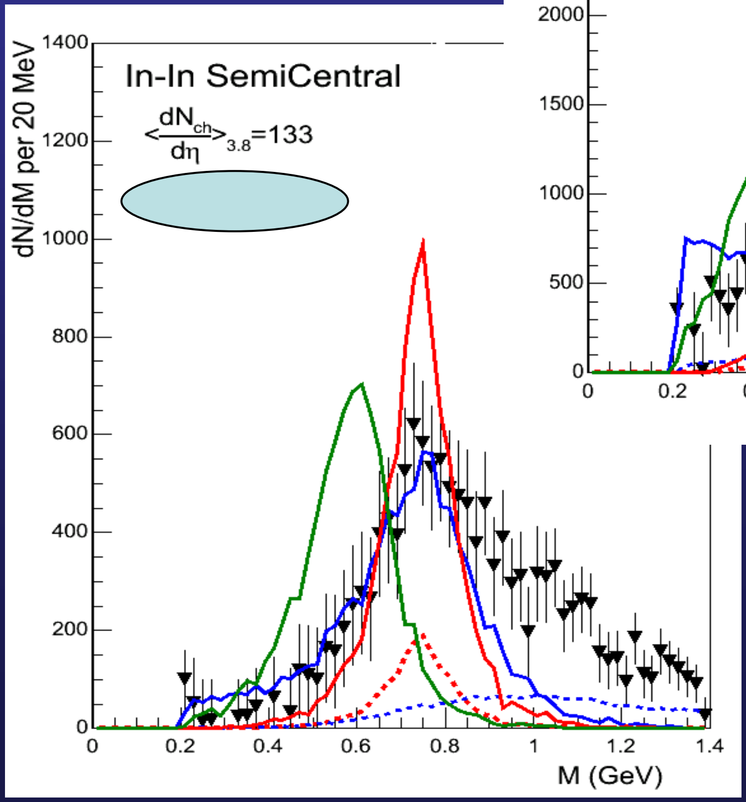
Only broadening of ρ (RW) observed,
no mass shift (BR)

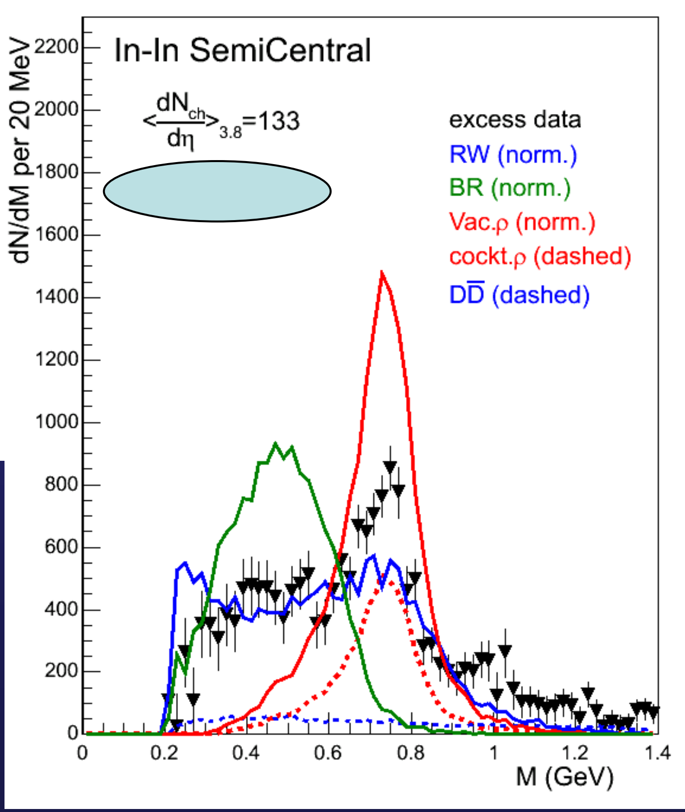
Comparison of data to RW, BR and vacuum ρ

p_T dependence



same conclusions





Recent theoretical developments

Brown and Rho, comments on BR scaling, nucl-th/0509001
Brown and Rho, formal aspects of BR scaling, nucl-th/0509002

Rapp and van Hees, parameter variations for 2π, unpublished
Rapp and van Hees, 4π, 6π … processes , hep-ph/0603084
Rapp and van Hees, 4π, 6π … processes , hep-ph/0604269

Renk and Ruppert, finite T broadening, Phys. Rev. C71 (2005)
Renk and Ruppert, finite T broadening and NA60, hep-ph/0603110
Renk, Ruppert, Müller, BR scaling and QCD Sum Rules, hep-ph/0509134
Renk, Ruppert, theoretical thoughts on NA60, hep-ph/0605130

Skokov and Toneev, BR scaling and NA60, Phys. Rev. C73 (2006)

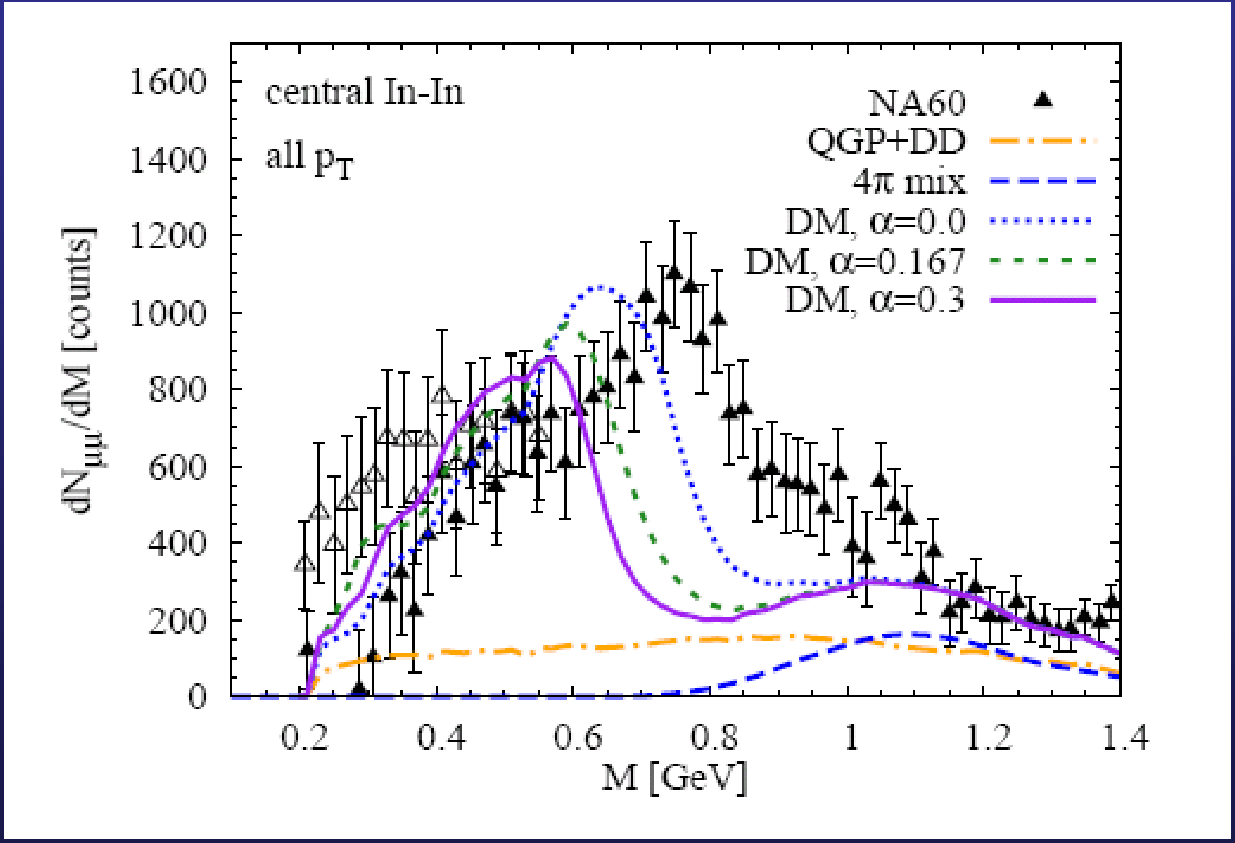
Dusling and Zahed, Chiral virial approach and NA60, nucl-th/0604071

Bratkovskaya and Cassing, HSD and NA60, in progress

Still on Dropping Mass (DM) scenario

Modification of DM by changing the fireball parameters

$$m_\rho^* / m_\rho^0 = (1 - C\frac{\rho}{\rho_0})(1-(T/T_c^\chi)^2)^\alpha$$

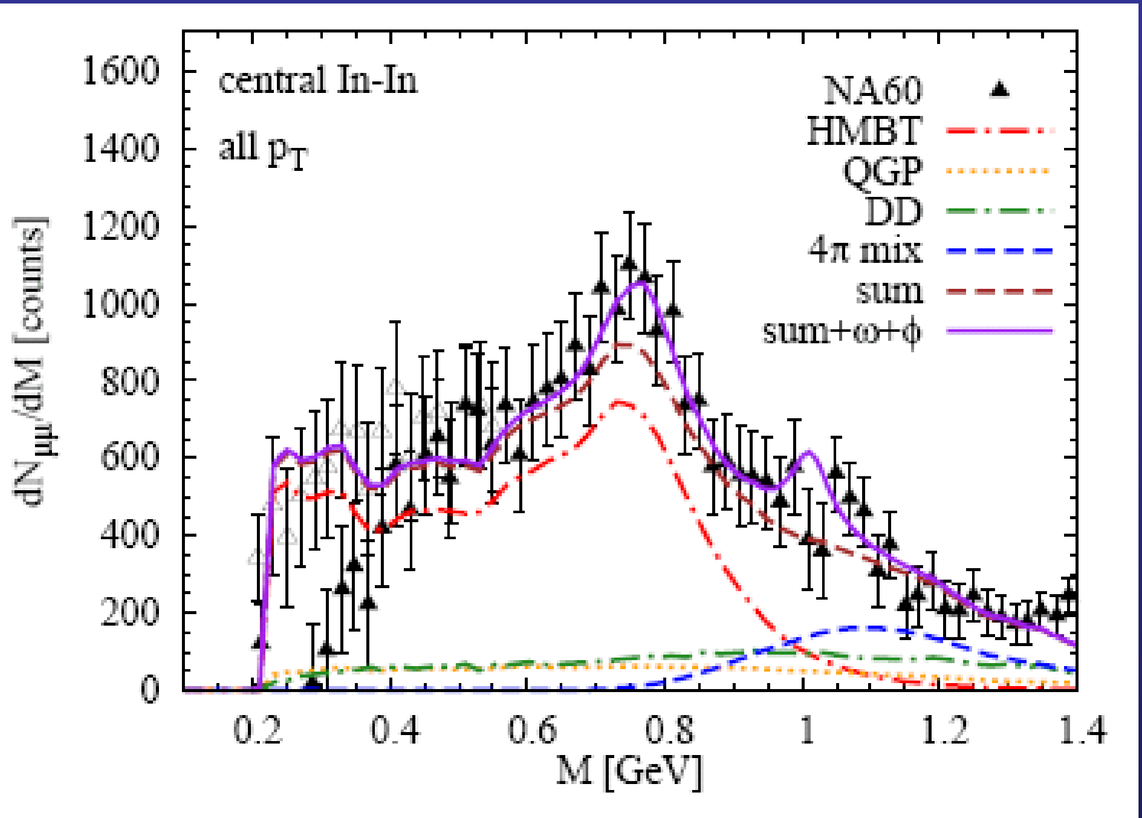


Results are shown in absolute terms and propagated through the NA60 acceptance filter

even switching out all temperature effects does not lead to agreement between DM and the data

Van Hees and Rapp, hep-ph/0604269

Comparison of data to RW(2π+4π+QGP)



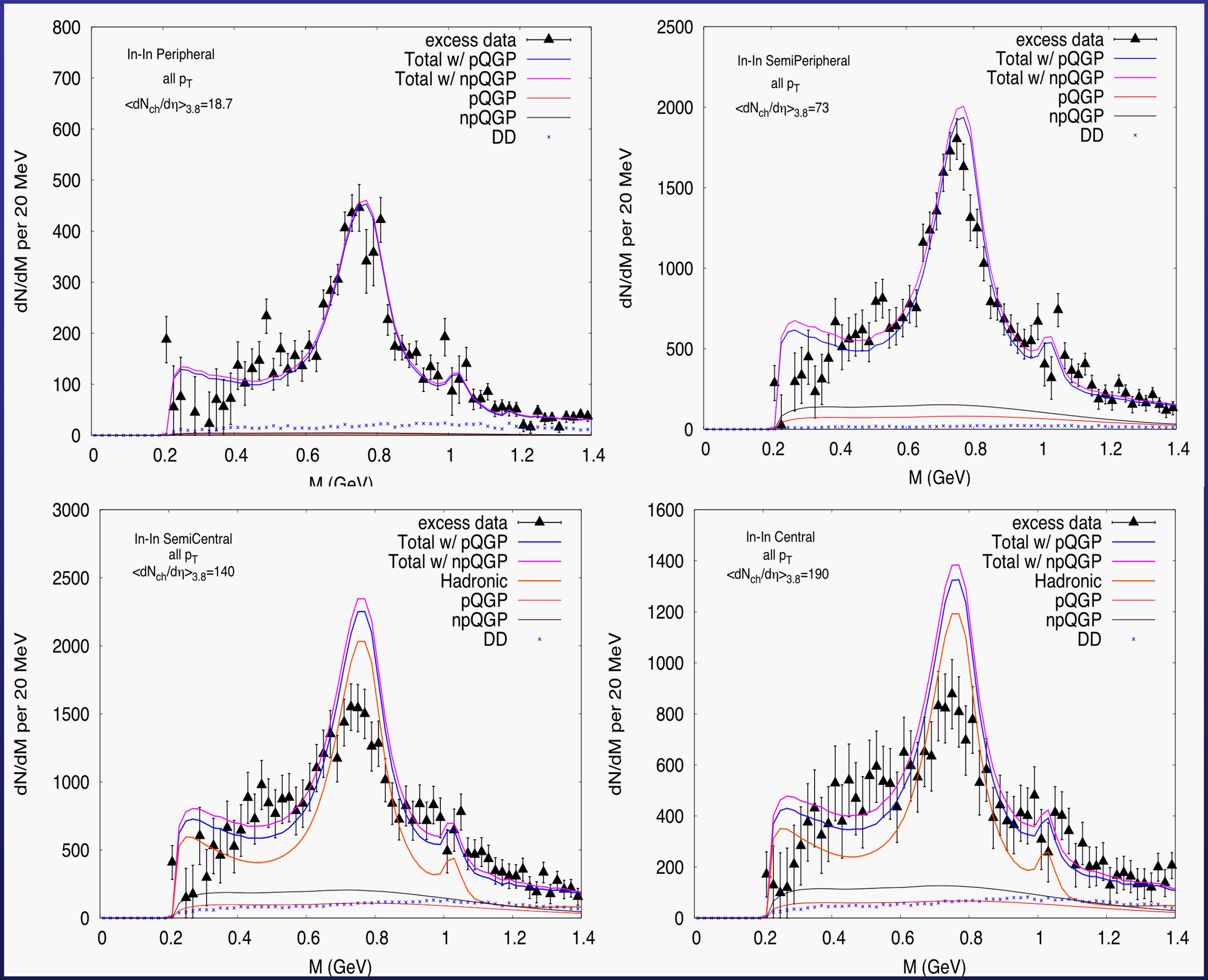
direct connection to IMR results at M>1GeV from NA60

The yield above 0.9 GeV is sensitive to the degree of vector-axialvector mixing and therefore to chiral symmetry restoration!

Whole spectrum reasonably well described, even in absolute terms (resulting from improved fireball dynamics)

Van Hees and Rapp,
hep-ph/0603084
hep-ph/0604269

Chiral Virial Approach (Dusling, Teaney and Zahed)

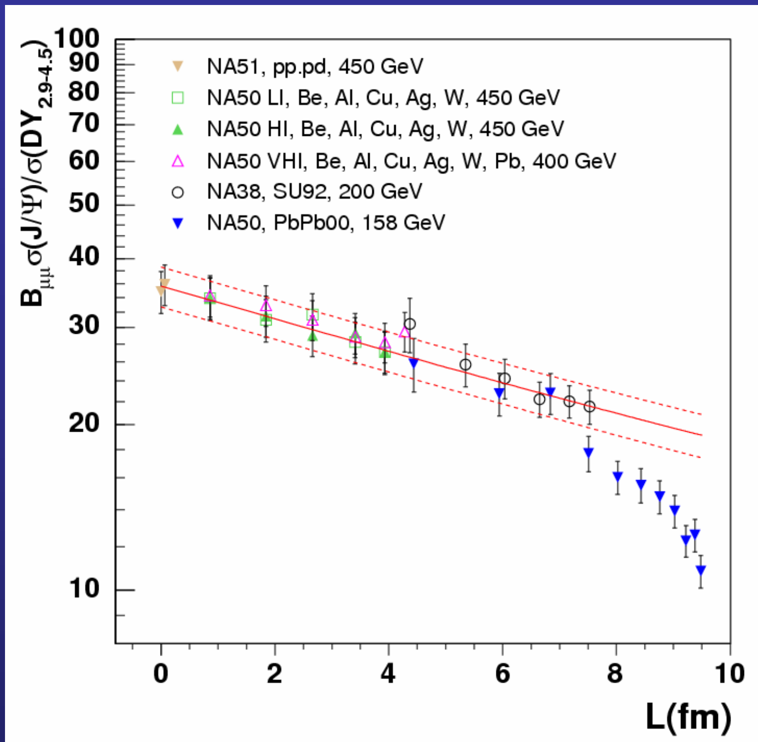


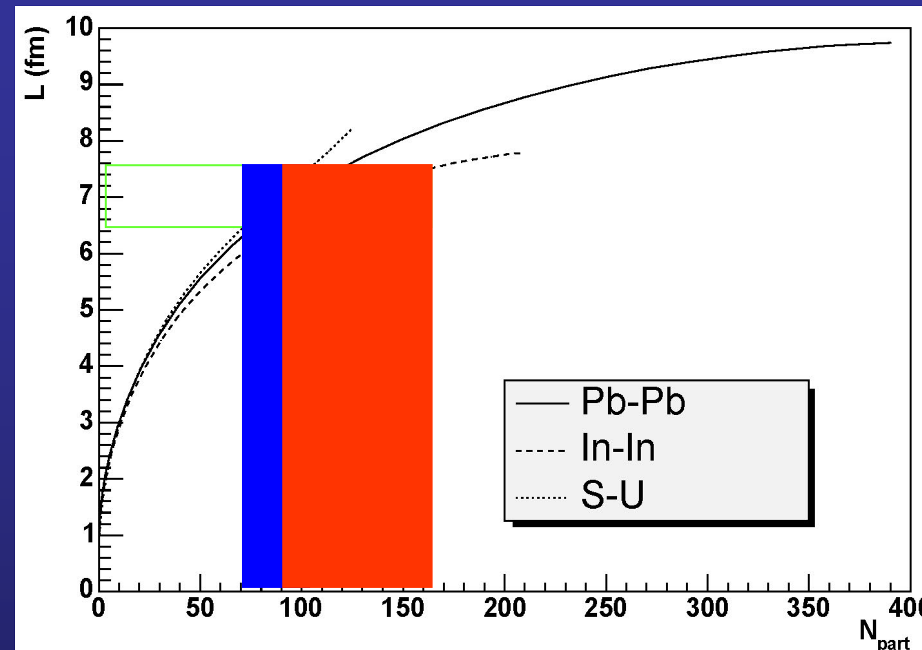
First attempt to describe the centrality dependence of the excess data

Dusling, Teaney, Zahed nucl-th/0604071

Reasonable description, but increasing overestimate of central ρ peak

J/ψ suppression





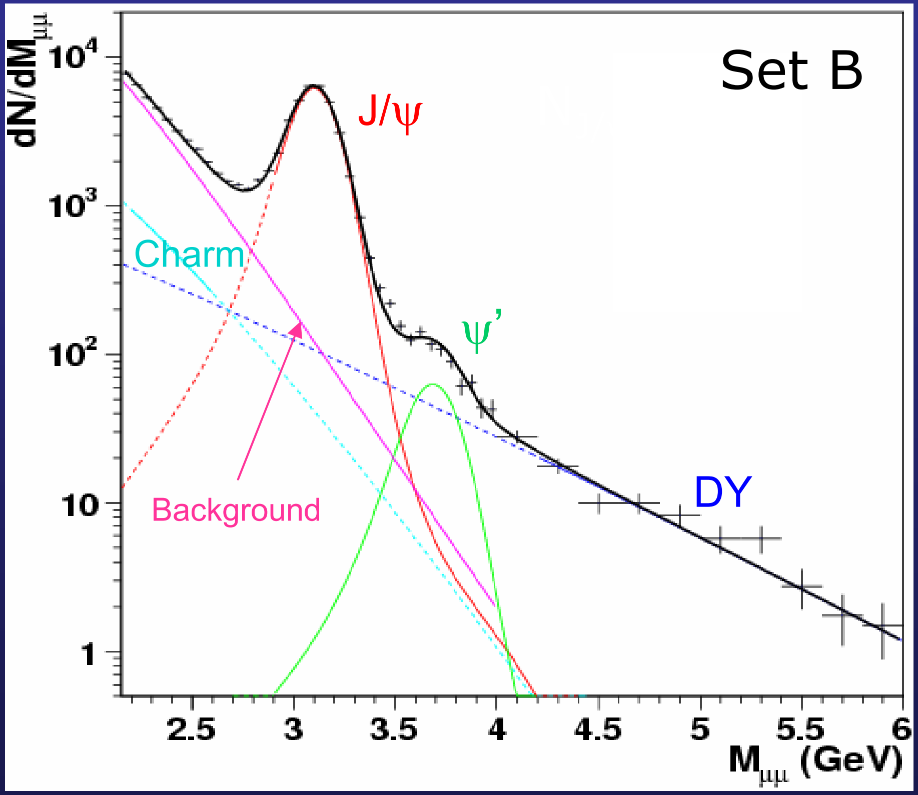
- Anomalous J/ψ suppression, discovered by NA50 in Pb-Pb collisions

NA60 proposal: is anomalous suppression present also in lighter nuclear systems ?

Can we identify a scaling variable for the suppression ?
L, N_{part}, density of participants, energy density ?

J/ψ suppression in In-In

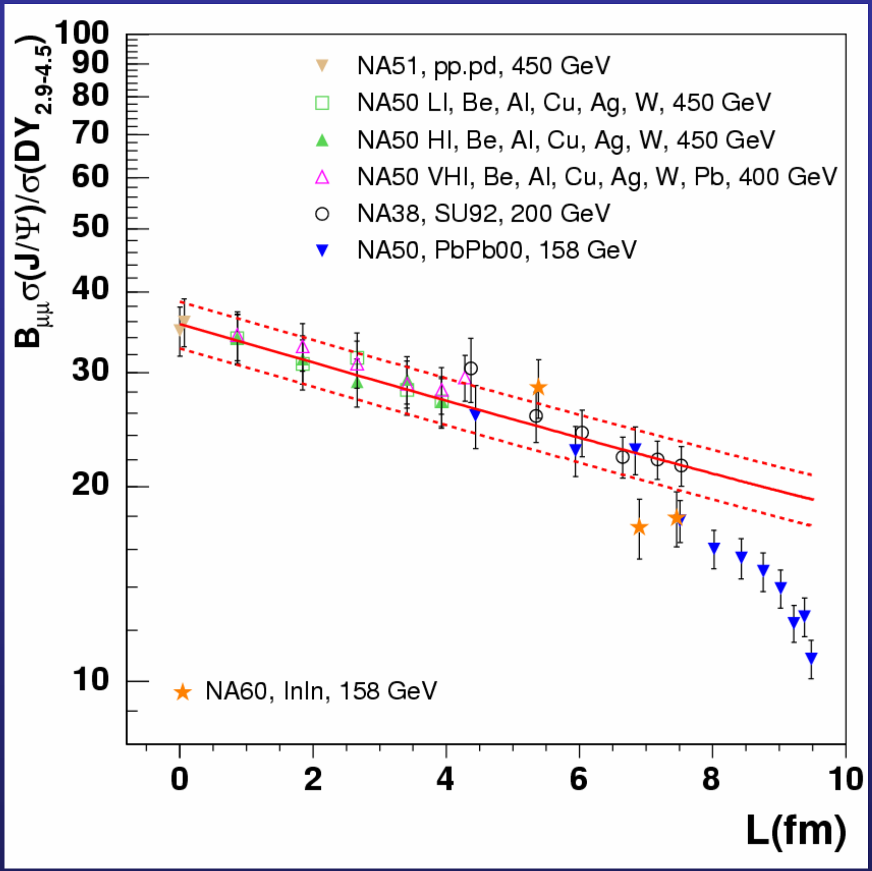
- At SPS energies, the reference process commonly used to quantify J/ψ suppression versus centrality is Drell-Yan
  - → Drell-Yan production scales with the number of binary N-N collisions
  - → No sizeable final state effects (shadowing or absorption)

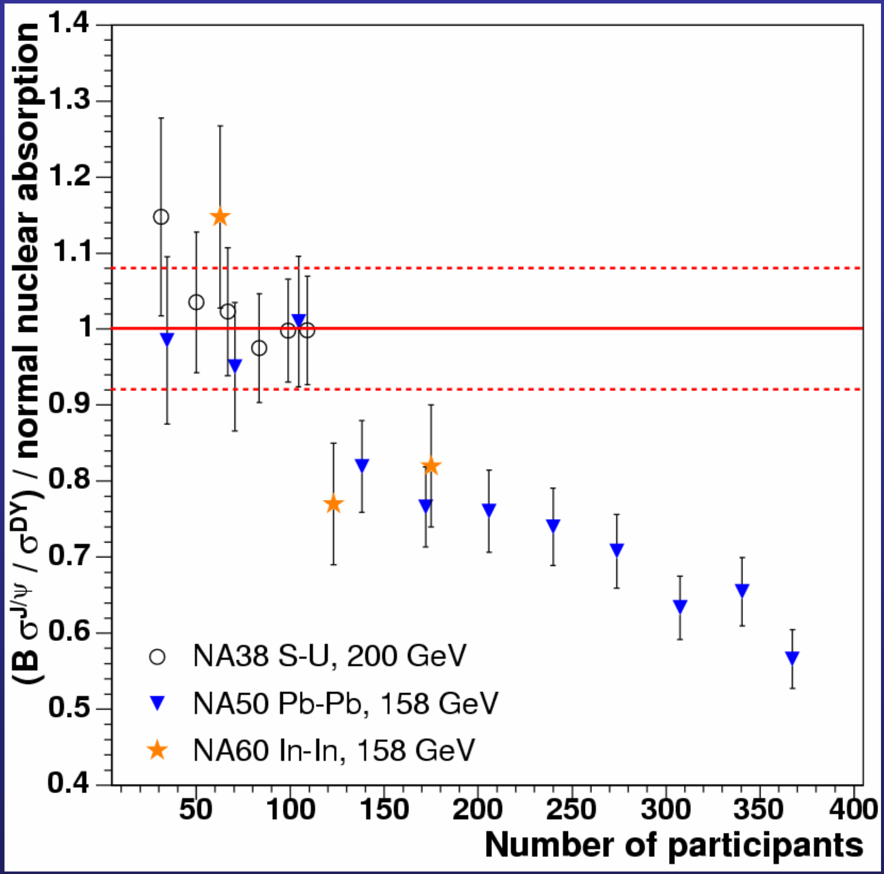


- Drawback
  Drell-Yan statistics ($m_{\mu\mu}$ > 4 GeV/c^2) marginal in NA60 (~300)

Investigate other possible normalizations in order to exploit the considerable J/ψ statistics ($>4\times10^4$)

J/ψ suppression, "standard" analysis





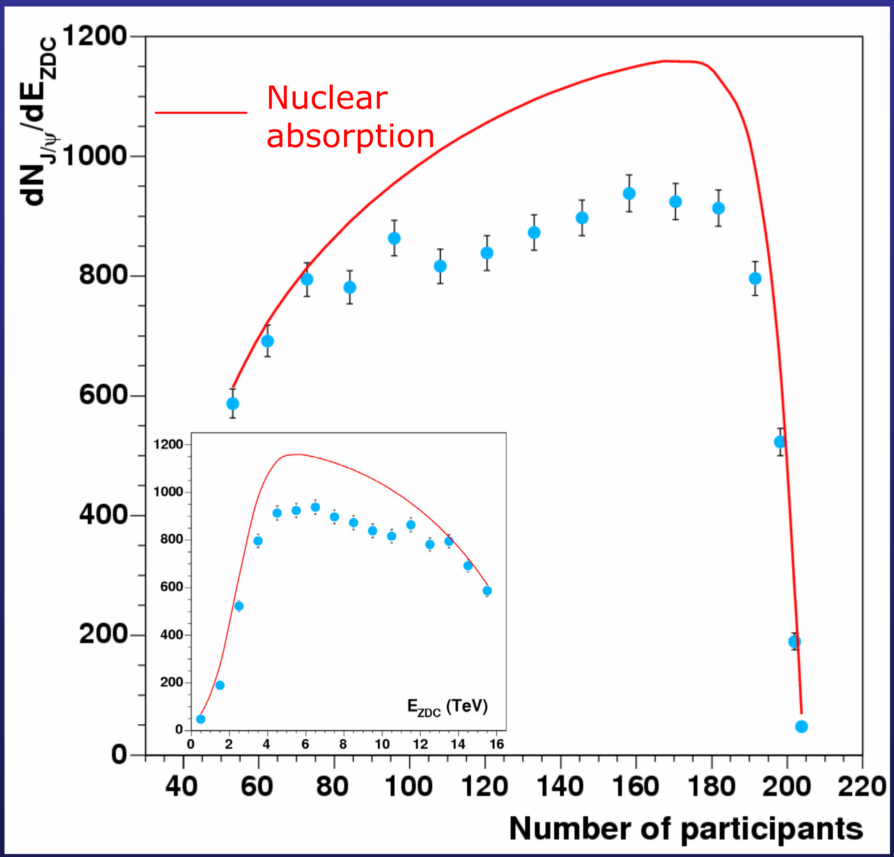
- 3 centrality bins, defined through E_{ZDC}
- J/ψ nuclear absorption → $\sigma^{J/\psi}_{abs}$ = 4.18 ± 0.35 mb (from NA50 @ 450 GeV)
- ~ 8% uncertainty on the rescaling to 158 GeV

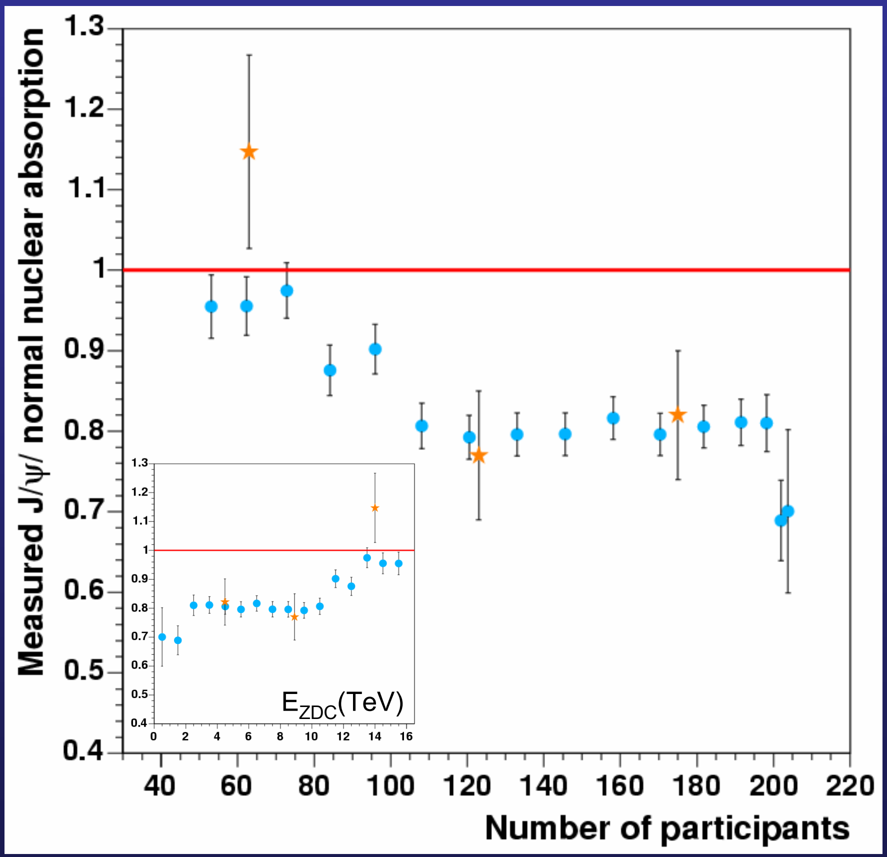
Anomalous J/ψ suppression is present in In-In collisions

A finer centrality binning is needed to sharpen the picture

Direct J/ψ sample

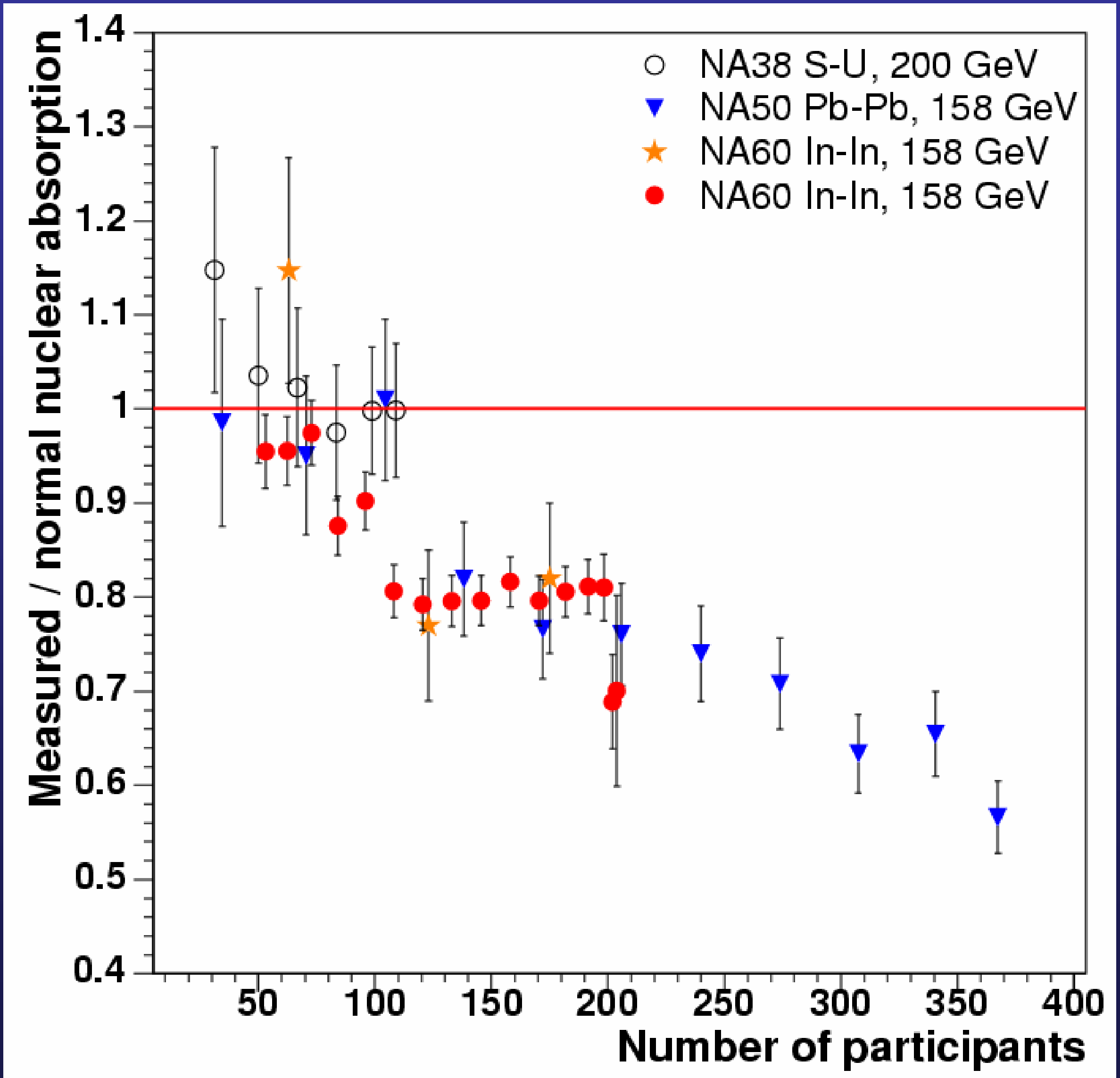
- To overcome the problem of DY statistics, directly compare the measured J/ψ centrality distribution with the distribution expected in case of pure nuclear absorption





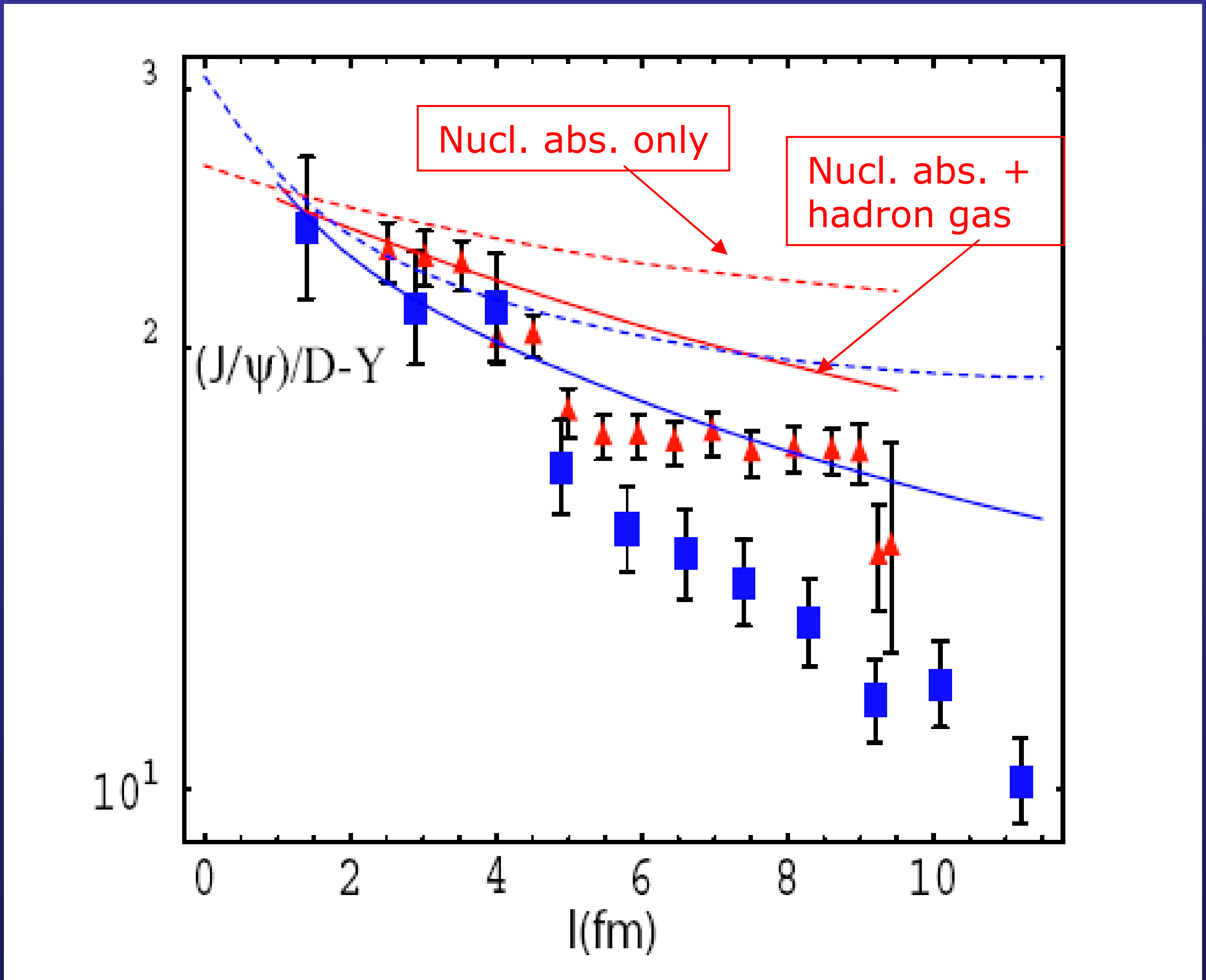
- Onset of anomalous suppression around N_{part} = 90
- Saturation at large N_{part}

Comparison with previous results



The J/ψ suppression patterns are in fair agreement when plotted against N_{part}

Comparison with models



Maximum hadronic absorption (Hagedorn gas) not enough to reproduce In-In and Pb-Pb

Mechanisms at the parton level must be invoked

Becattini, Maiani et al., Phys. Lett. B632(2006) 233

Next steps

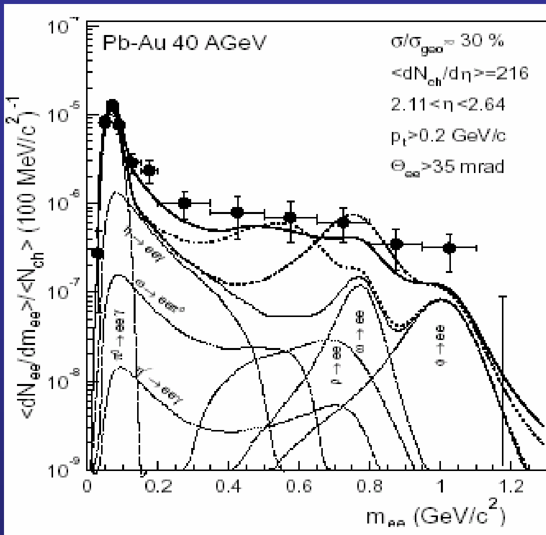
- First NA60 physics paper published a few weeks ago !
  "First Measurement of the ρ Spectral Function in
  High-Energy Nuclear Collisions", Phys. Rev. Lett. 96(2006) 162302

- All In-In results presented here obtained with a first, preliminary, reconstruction of In-In data
- Second, final reconstruction, now available
  (much better alignment, better quality results !)
- Final In-In results will be showed at the summer conferences

- Work on p-A data going on, but a considerable effort is still needed
- Results at 158 GeV/c (important as a reference for J/ψ studies) probably available at QM2006
- High intensity p-A data at 400 GeV taken in challenging conditions
  - Very high beam intensity (10^9 p/s)
    - High pile-up levels
    - Silicon-strip detector analysis (used only for p-A data taking) much more delicate with respect to pixel (used in In-In)

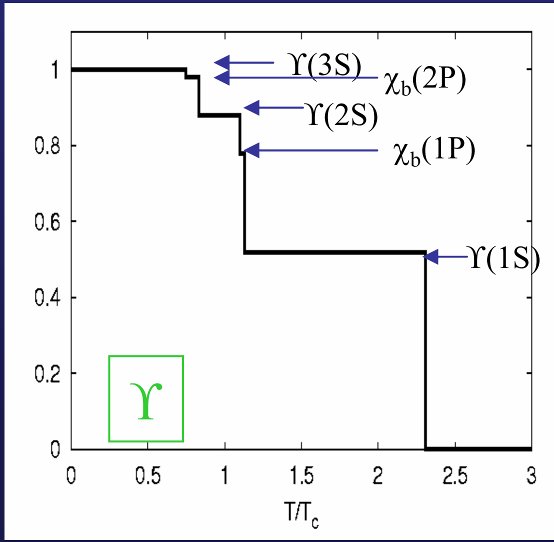
Medium term perspectives

- Dimuon production in <u>Pb-Pb collisions</u> at 158 GeV/nucleon
- Highest *energy densities* available at the SPS
  (Never studied with the accuracy allowed by a vertex tracker)



- (Low-mass) dimuon production in Pb-Pb collisions at <u>lower energies</u> (~50 GeV/nucleon)
- Highest *baryon densities* in HI collisions at SPS

- Upgrade of CERN machines
- SPS+ concept presently under discussion
  → ~1 TeV protons (and ~0.4 TeV/nucleon ions) from ~2014



- Study J/ψ and ϒ suppression vs. √s
  (not possible at present SPS energies)

Medium term perspectives

CERN SPS and PS Committee

Fixed-Target Physics at CERN beyond 2005
Summary and Conclusions of an Evaluation by the SPSC
(Villars meeting 22-28 September 2004)

February 2005

3.4 Heavy Ion Physics

Recent developments confirm that heavy ion beams at CERN SPS energies and luminosity remain ideal tools to observe the features of the phase transition between the confined and the deconfined states of hadronic matter, known as the Quark-Gluon Plasma (QGP).

Experimental technique has continued to improve. Steady developments in radiation hard detectors have resulted in more refined measurements. In particular, recent results from NA60 show the improvements that can be made using a pixel vertex telescope. The *p*A and In-In data from NA60 may provide answers to a set of open questions raised by the interpretation of previous experimental results. Important measurements include open charm production, ρ mass shift, and dilepton production (interpreted as evidence for thermal radiation from QGP). Pb-Pb data would extend such measurements to the highest possible energy densities at the SPS.

The opportunity to pursue a heavy ion physics program at the CERN SPS, within the framework and constraints imposed by the LHC, should be preserved. Once the LHC has been commissioned with ions, an SPS programme aimed at the identification of the critical point, as well as at the study of its properties, is likely to be of substantial significance.

Data taking with Pb projectiles at various energies

↓

Technically possible after LHC startup

↓

Interesting from the physics point of view

POFPA working group

- CERN POFPA working group (J. Ellis et al.) , Physics Opportunities for Future Proton Accelerator (http://pofpa.web.cern.ch/pofpa)
  - Mandate : Assess the likely physics objectives of LHC upgrades and non-collider experiments

5.3 – Heavy-ion physics

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A critical point in the quark-hadron phase diagram is thought to be accessible to fixed-target heavy-ion experiments at the SPS, but its signatures are uncertain. It is expected that data would be needed over a range of energies, with good luminosity. The possible step-wise suppression of J/ψ production would be one objective, as well as charm production studies. In order to establish a baseline for nuclear absorption, studies of both proton-ion and light-ion collisions would be desirable.

This programme could be addressed using an NA60-like dimuon spectrometer. Other research topics would include studies of low-mass lepton pairs (in the ρ region, to understand better the possible effects of chiral-symmetry restoration), the observed enhancement of intermediate-mass dimuon production (which is thought to be thermal, rather than due to charm production) and the search for fluctuations in particle yields in narrow ranges of effective temperature and baryon chemical potential (which could be a signal for the critical point of the QCD phase transition). A possible scenario would include runs in the period from 2010 to 2013, including Pb-Pb, Cu-Cu and Pb-Be collisions. If the SPS+ were to become available, runs with Pb-Pb or U-U at the highest possible beam energy would also be interesting.

Conclusions

- The NA60 experiments is providing to the HI community physics results of a very good quality

- Low-mass region
  - Pion annihilation seems to be a major contribution to the lepton pair excess in heavy-ion collisions at SPS energies
  - no significant mass shift of the intermediate ρ
  - only broadening of the intermediate ρ

- Intermediate-mass region
  - The IMR excess is prompt and increases more than linearly with N_{part}

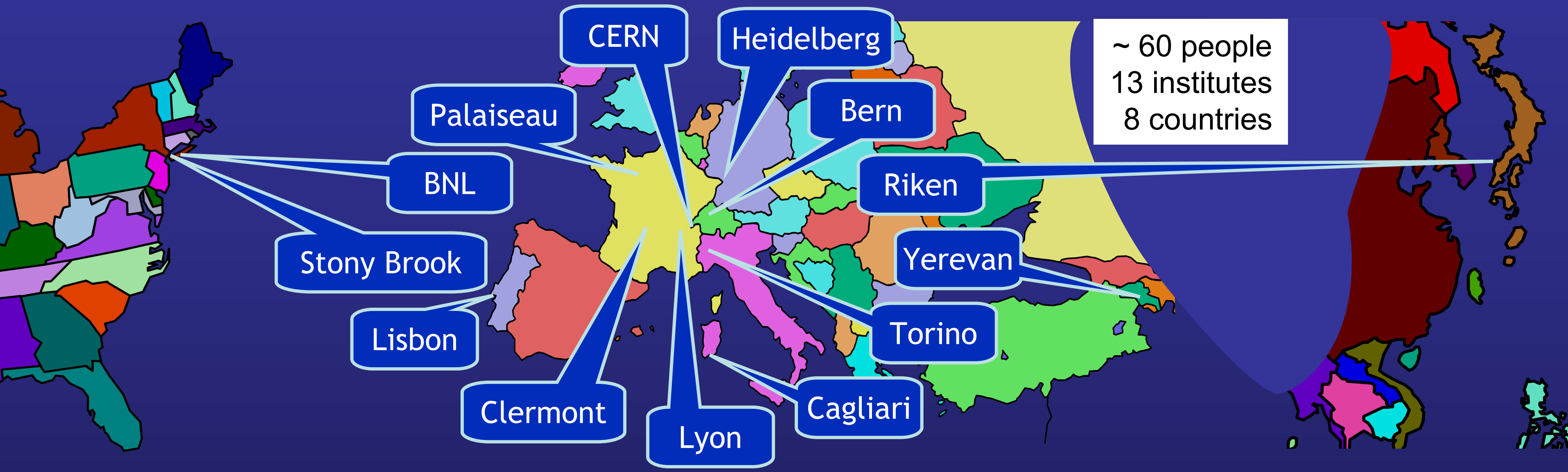
- J /ψ suppression
  - Anomalous J/ψ suppression present also in In-In
  - Centrality dependent, with an onset around N_{part}=90

- Theoretical work on NA60 data very promising
  - Connection with chiral symmetry restoration for low-mass results
  - Coherent interpretation of SPS vs RHIC for charmonia suppression

- Possibility of future runs at SPS is being investigated
  - Collaboration must be strengthened

The NA60 experiment

http://cern.ch/na60



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Systematics

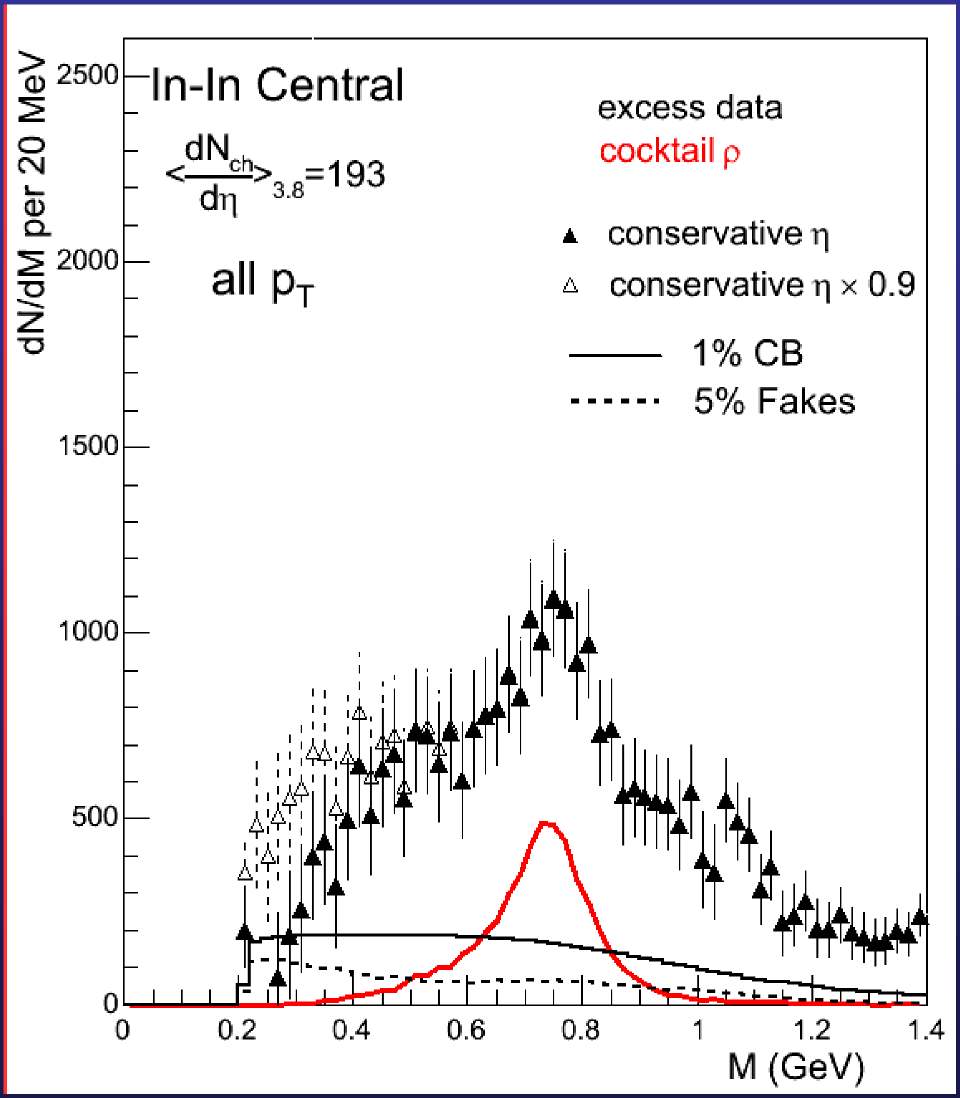

Illustration of sensitivity

- to correct subtraction of combinatorial background and fake matches;
- to variation of the η yield

Systematic errors of continuum
0.4<M<0.6 and 0.8<M<1GeV
~25%

Combinatorial Background

CB (uncorrelated muon pairs coming from p and K decays) is estimated with an Event Mixing technique

Take muons from different events and calculate their invariant mass. Takes account of charge asymmetry, correlations between the two muons (induced by magnetic field sextant subdivision: detector geometry), trigger conditions

Apparatus triggers both opposite sign ($\mu^+\mu^-$) and like sign ($\mu^+\mu^+$,$\mu^-\mu^-$) pairs.

Quality of CB is assessed comparing LS spectra.

Accuracy ~1% over several orders of magnitude!