The experimental quest for in-medium effects
Episode II

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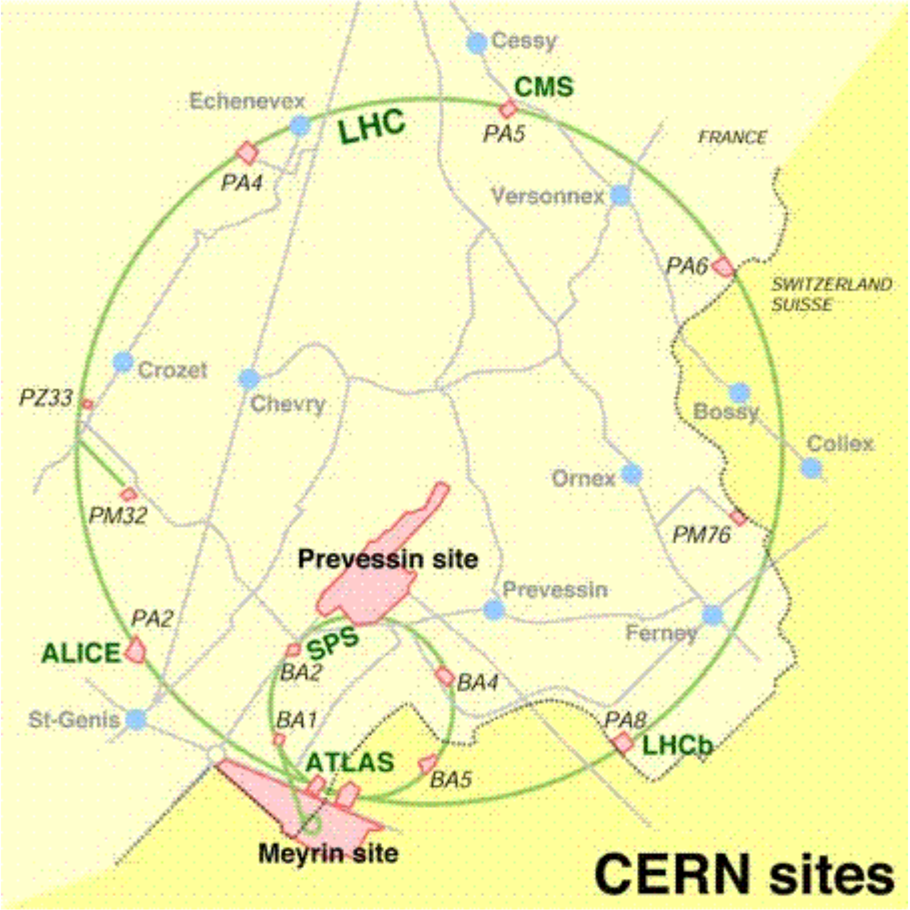
SPS at CERN

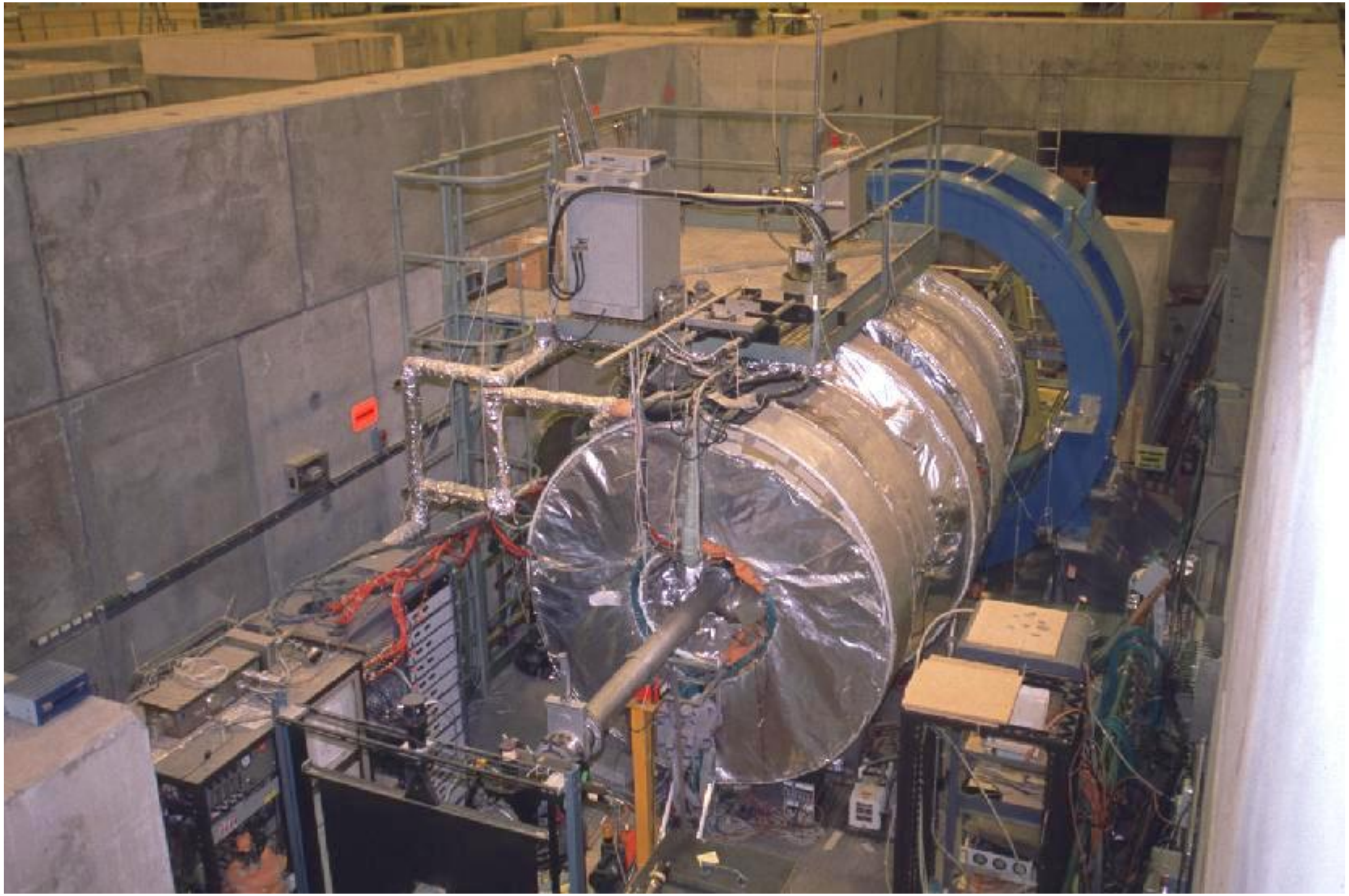
- SuperProtonSynchrotron
  - Parameters
    - ➛ circumference: 6.9 km
    - ➛ beams for fixed target experiments
      - ➛ protons up to 450 GeV/c
      - ➛ lead up to 158 GeV/c
  - Past
    - ➛ SppS proton-antiproton collider
      → discovery of vector bosons $W^{\pm}$, Z
  - Now
    - ➛ injector for LHC
  - Experiments
    - ➛ Switzerland: west area (WA)
    - ➛ France: north area (NA)
      → dileptons speak french!



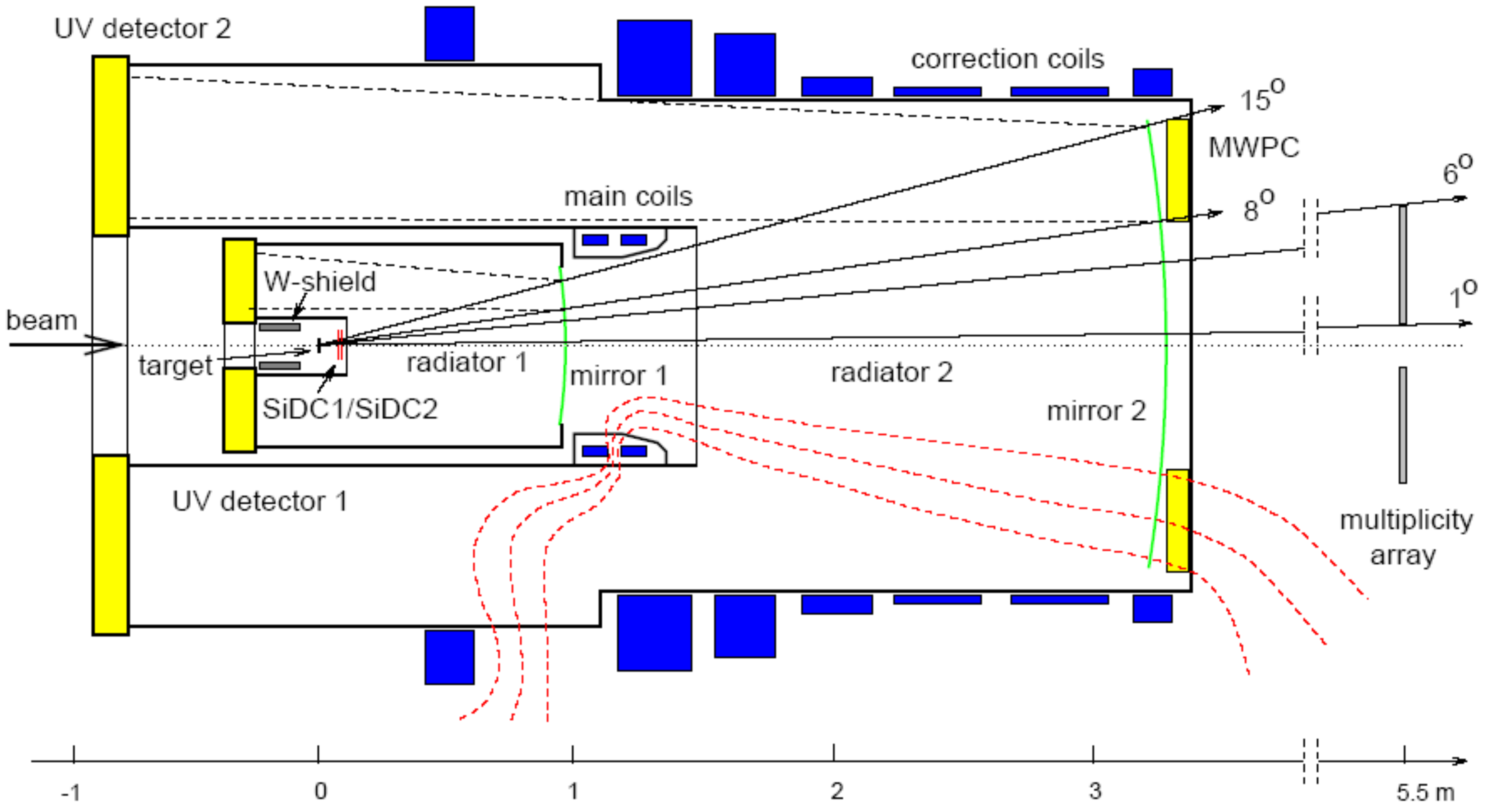
Dilepton experiments at SPS

Experiment		System	Mass range	Publications
HELIOS-1	μμ ee	p-Be (86)	low mass	Z.Phys. C68 (1995) 64
HELIOS-3	μμ	p-W,S-W (92)	low & Intermediate	E.Phys.J. C13(2000)433
CERES	ee	pBe, pAu, SAu (92/93) Pb-Au (95) Pb-Au (96)	low mass	PRL (1995) 1272 Phys.Lett. B (1998) 405 Nucl.Phys. A661 (1999) 23
CERES-2	ee	Pb-Au 40 GeV (99) Pb-Au 158 GeV (2000)	low mass	PRL 91 (2002) 42301 preliminary data 2004
NA38/ NA50	μμ	p-A, S-Cu, S-U, Pb-Pb	low (high m_T) intermediate	E.Phys.J. C13 (2000) 69 E.Phys.J. C14 (2000) 443
NA60	μμ	p-A, In-In (2002,2003) p-A (2004)	$>2m_m$	PRL 96 (2006) 162302

The CERES/NA45 experiment

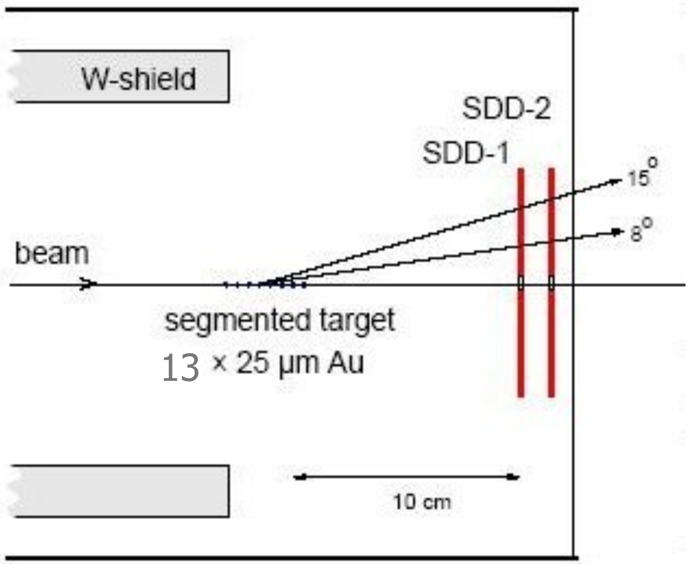


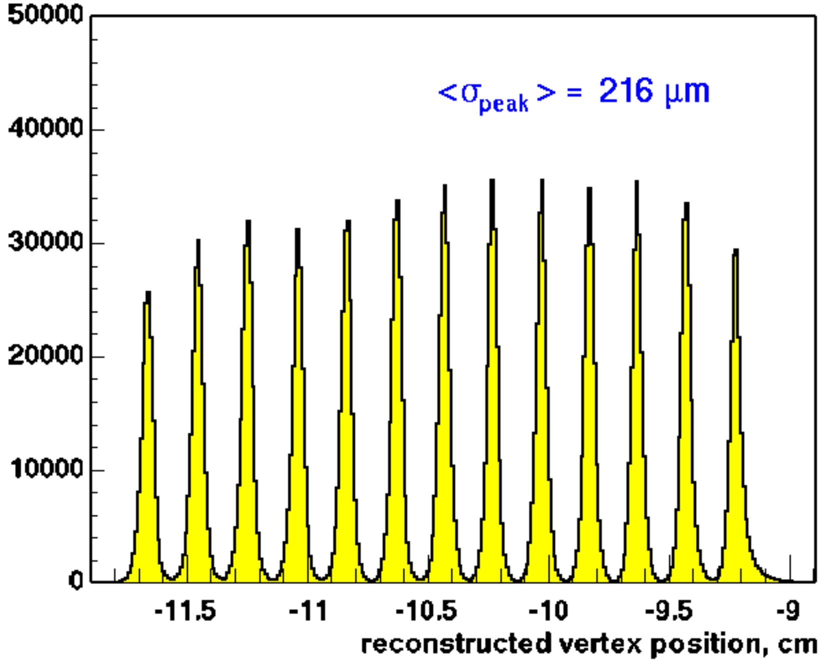
Experimental setup: CERES 1



polar angles of **8°<<14°** (2.1< η < 2.65)

Target region

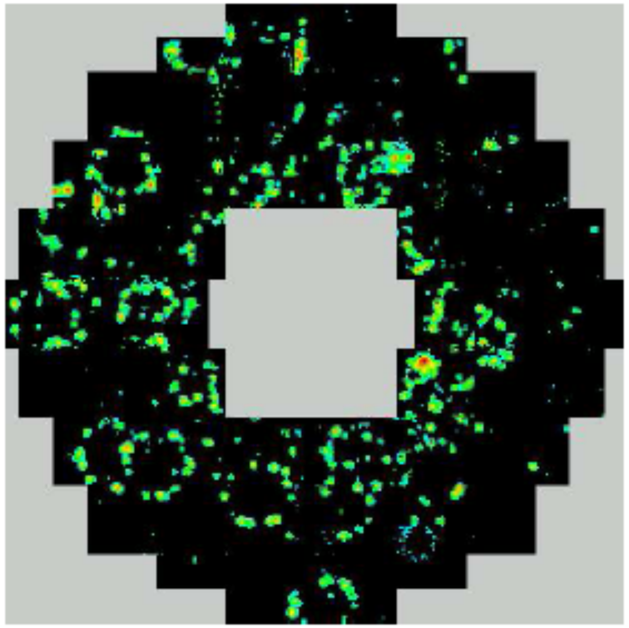




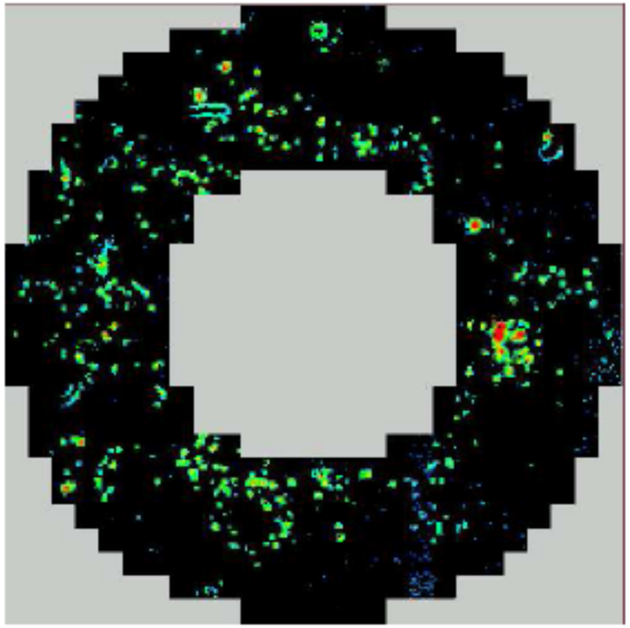
- Segmented target
  - 13 Au disks (thickness: 25 mm; diameter: 600 mm)
- Silicon drift chambers:
  - provide vertex: σ_z = 216 mm
  - powerful tool to recognize conversions at the target

Electron identification: RICH

RICH1



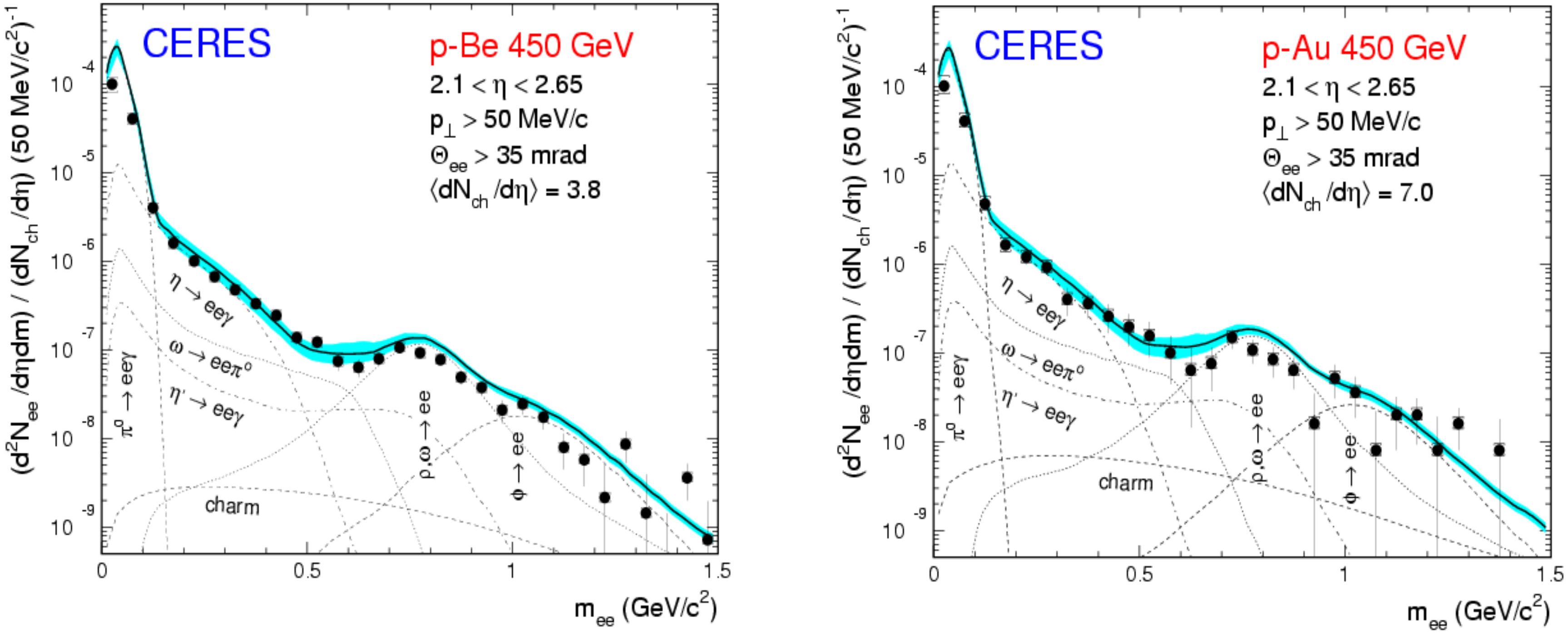
RICH2



- Main tool for electron ID
- Use the number of hits per ring (and their analog sum) to recognize single and double rings

Lepton pairs in p+Be & p+Au collisions

- Dielectron mass spectra and expectation from a ‘cocktail’ of known sources
    - Dalitz decays of neutral mesons ($\pi^0 \rightarrow \gamma\ e^+e^-$ and η, ω, η', ϕ)
    - dielectron decays of vector mesons (ρ, ω, $\phi \rightarrow e^+e^-$)
    - semileptonic decays of particles carrying charm quarks

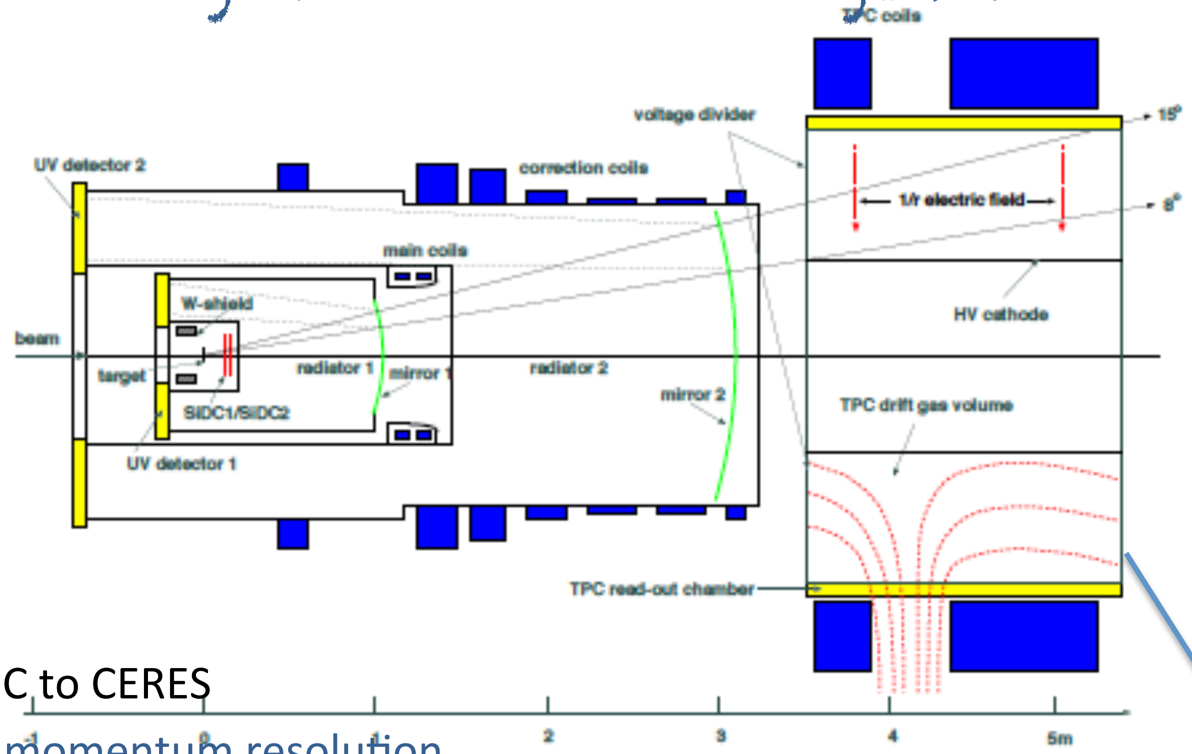


→ dielectron production in p+p and p+A collisions at SPS well understood in terms of known hadronic sources

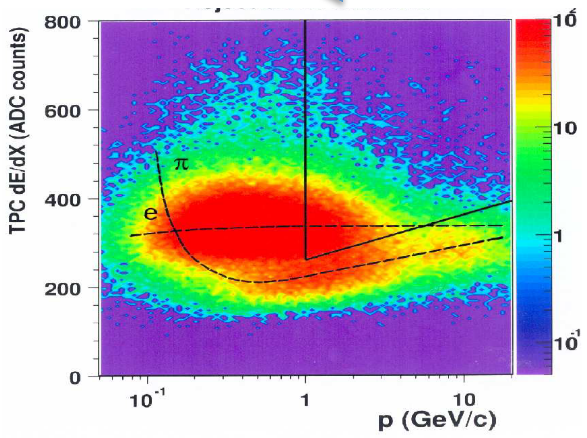
CERES 1 - CERES 2

< year 2000

> year 2000



- Adition of a TPC to CERES
  - ➛ improved momentum resolution
  - ➛ improved mass resolution
  - ➛ dE/dx → hadron identification and improved electron ID
  - ➛ inhomogeneous magnetic field → a nightmare to calibrate

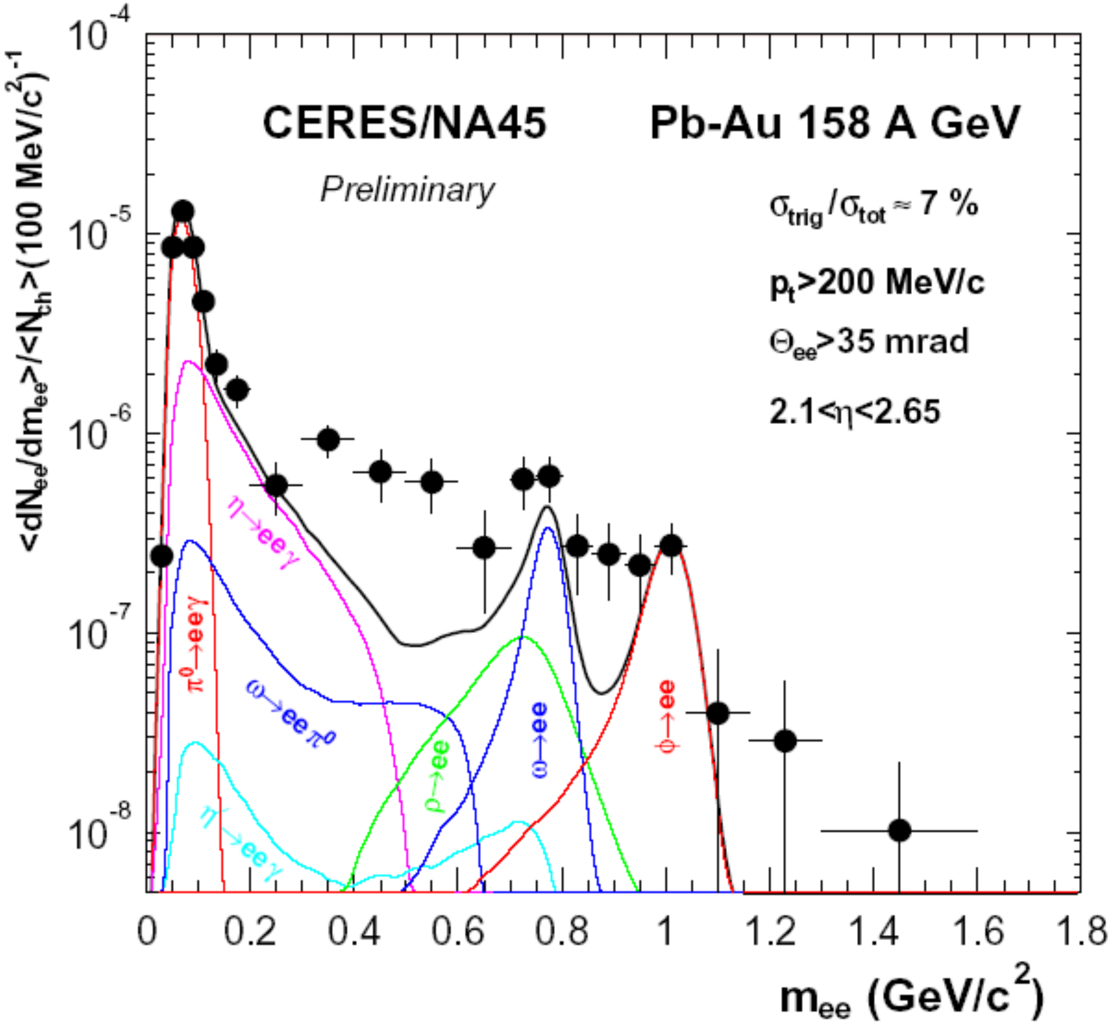


CERES data (Pb+Au 158 AGeV)

High-resolution analysis

- Large excess yield:

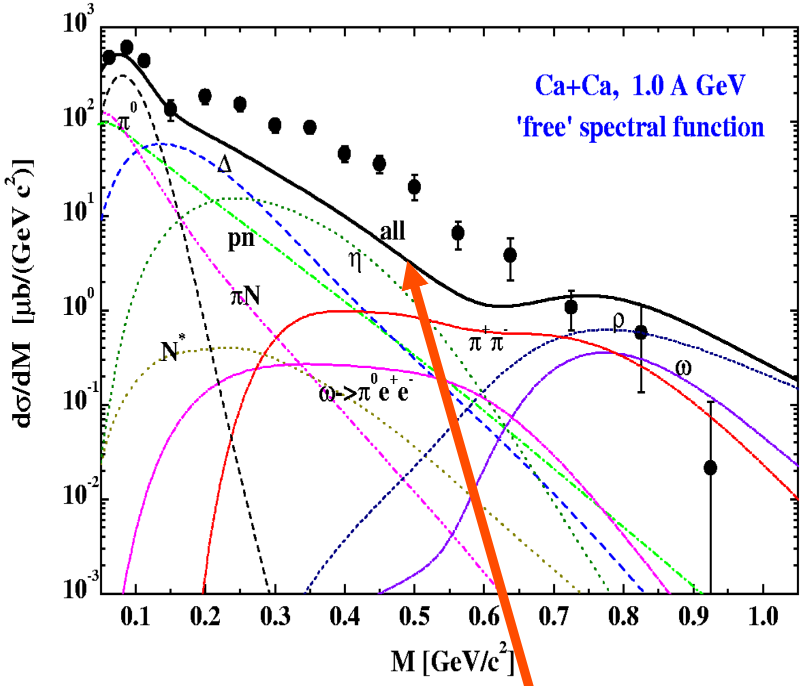
- at low masses
- also between ω and ϕ



J. Stachel, ISHIP 2006 and NPA 774 (2006) 43c

DLS: enhanced dilepton yields in A+A

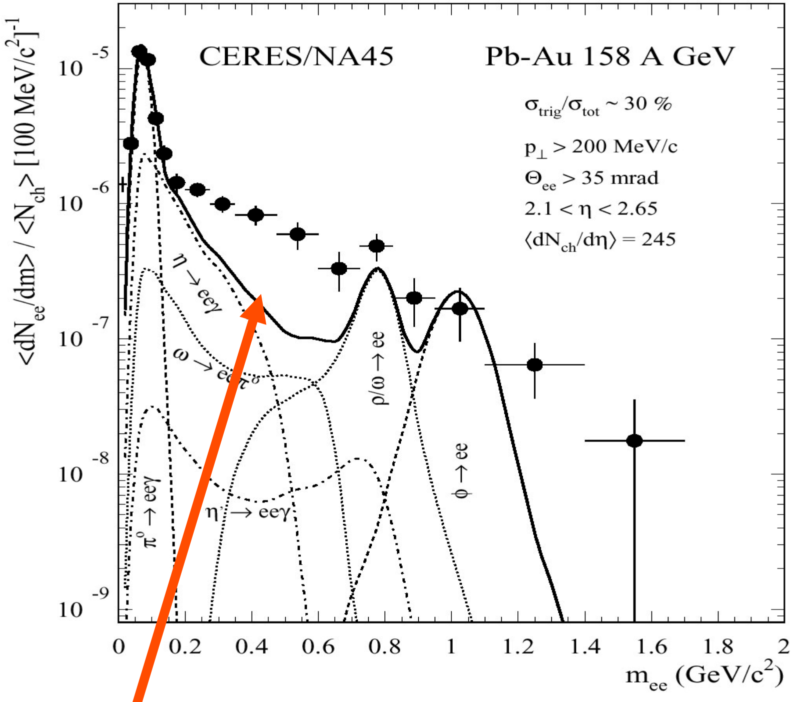
DLS at Bevalac @ 2 AGeV



Data: R.J. Porter et al.: PRL 79(97)1229

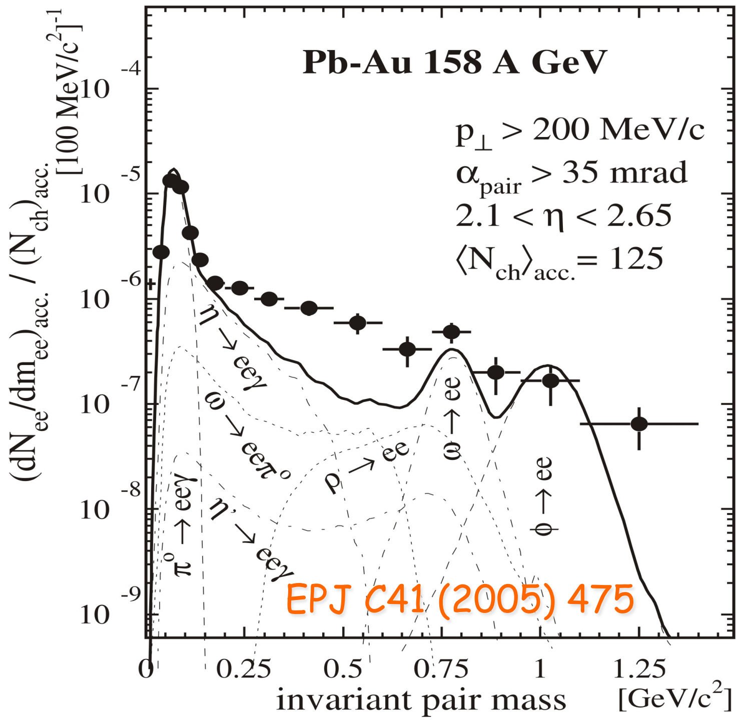
Model: E.L. Bratkovskaya et al.: NP A634(98)168, BUU, vacuum spectral function

CERES at SPS @158 AGeV

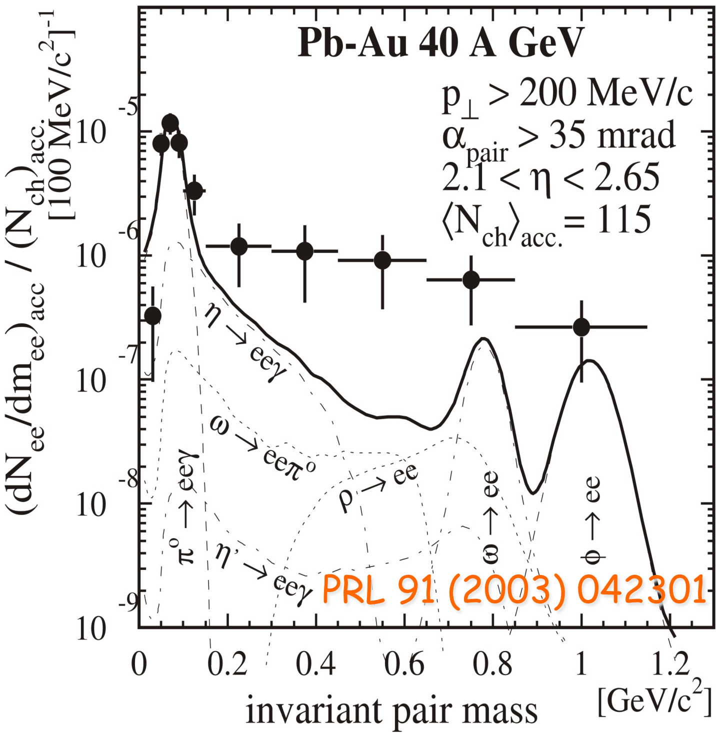


Strong dilepton enhancement over hadronic cocktails

CERES: Low-mass dilepton enhancement



EPJ C41 (2005) 475



PRL 91 (2003) 042301

- Central A-A collisions exhibit a strong enhancement of low-mass dilepton production as compared to p-A reactions (CERES, HELIOS)

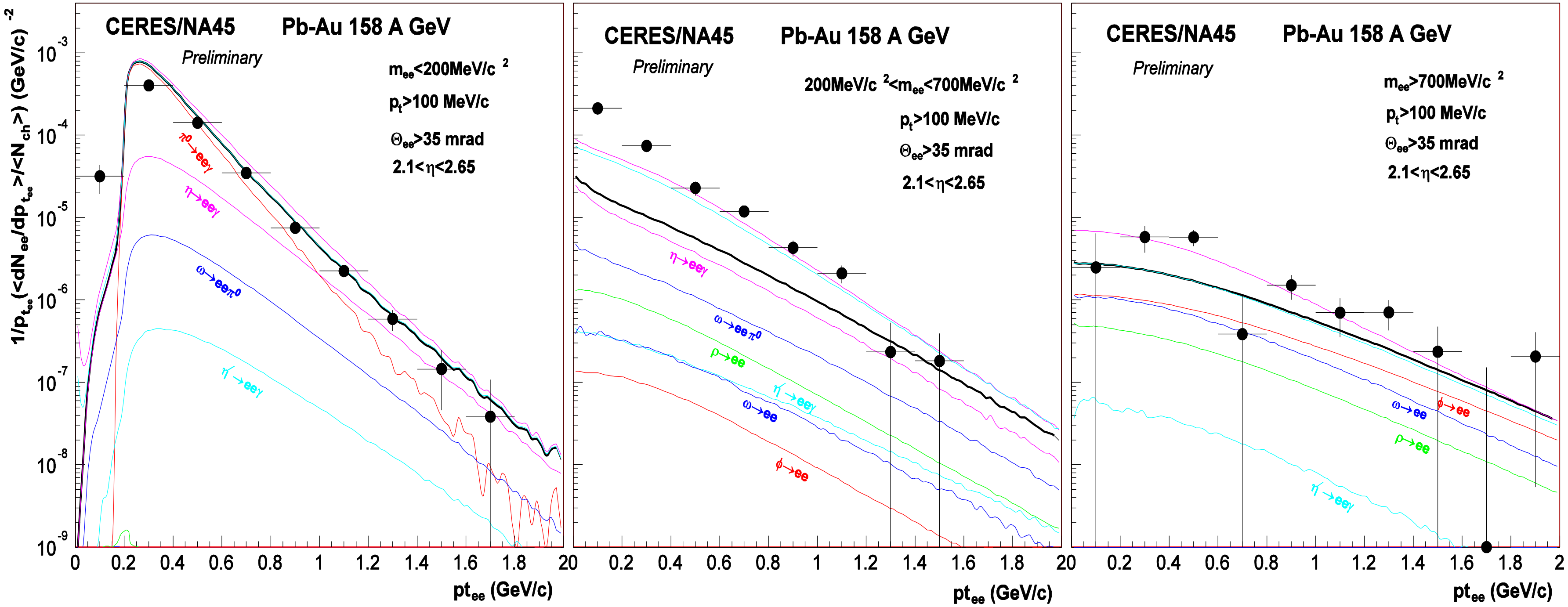
- Vacuum properties of vector mesons do not suffice to describe data, needed are:
  - pion annihilation (accounts for part only)
  - in-medium modifications of vector meson properties
  - broadening and/or mass shift of the rho meson

And what about p_T dependence?

$m_{ee}<0.2$ GeV/c^2

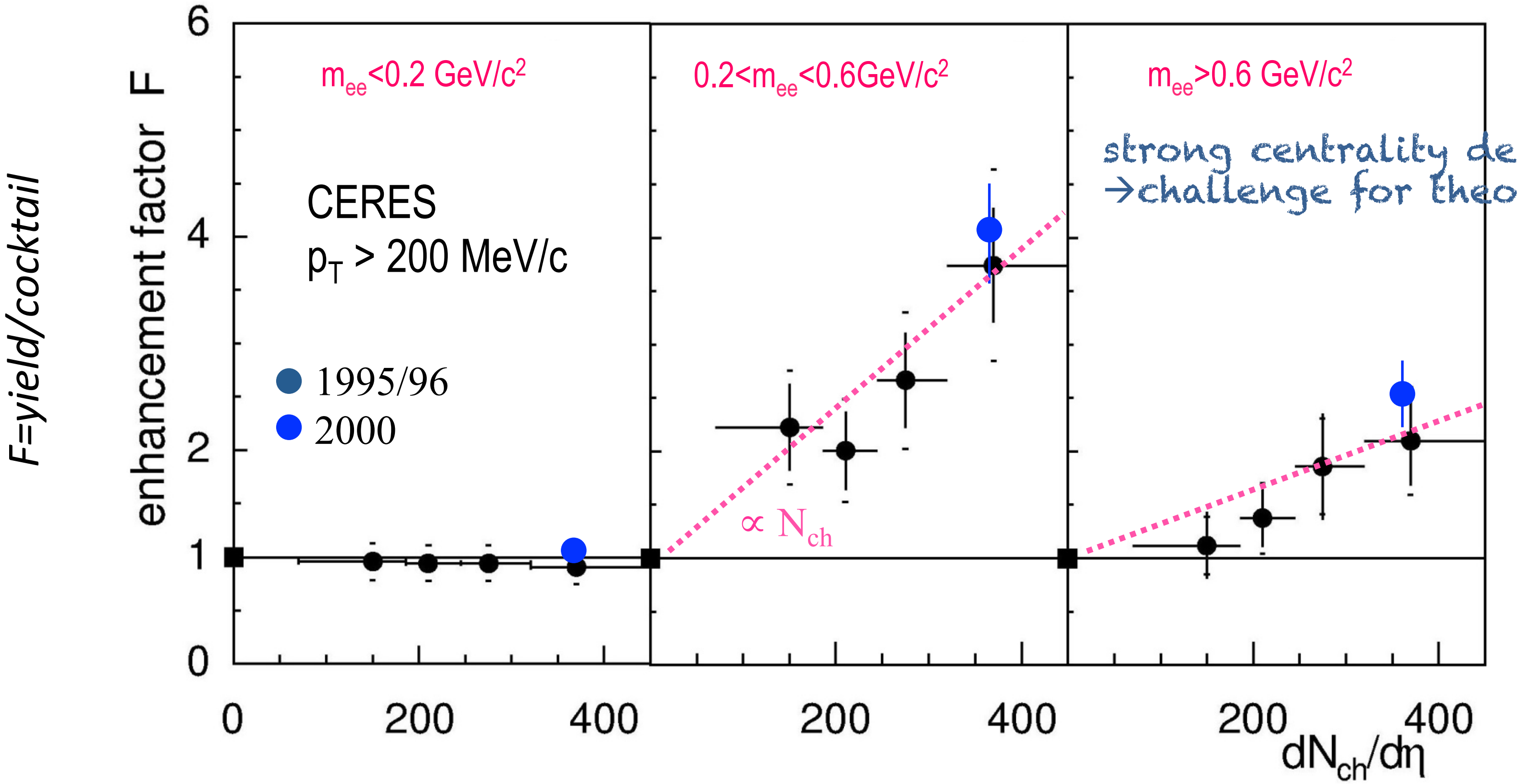
$0.2<m_{ee}<0.7$ GeV/c^2

$m_{ee}>0.7$ GeV/c^2



- low mass e^+e^- enhancement at low p_T
  - qualitatively in a agreement with ππ annihilation
  - p_T distribution has little discriminative power

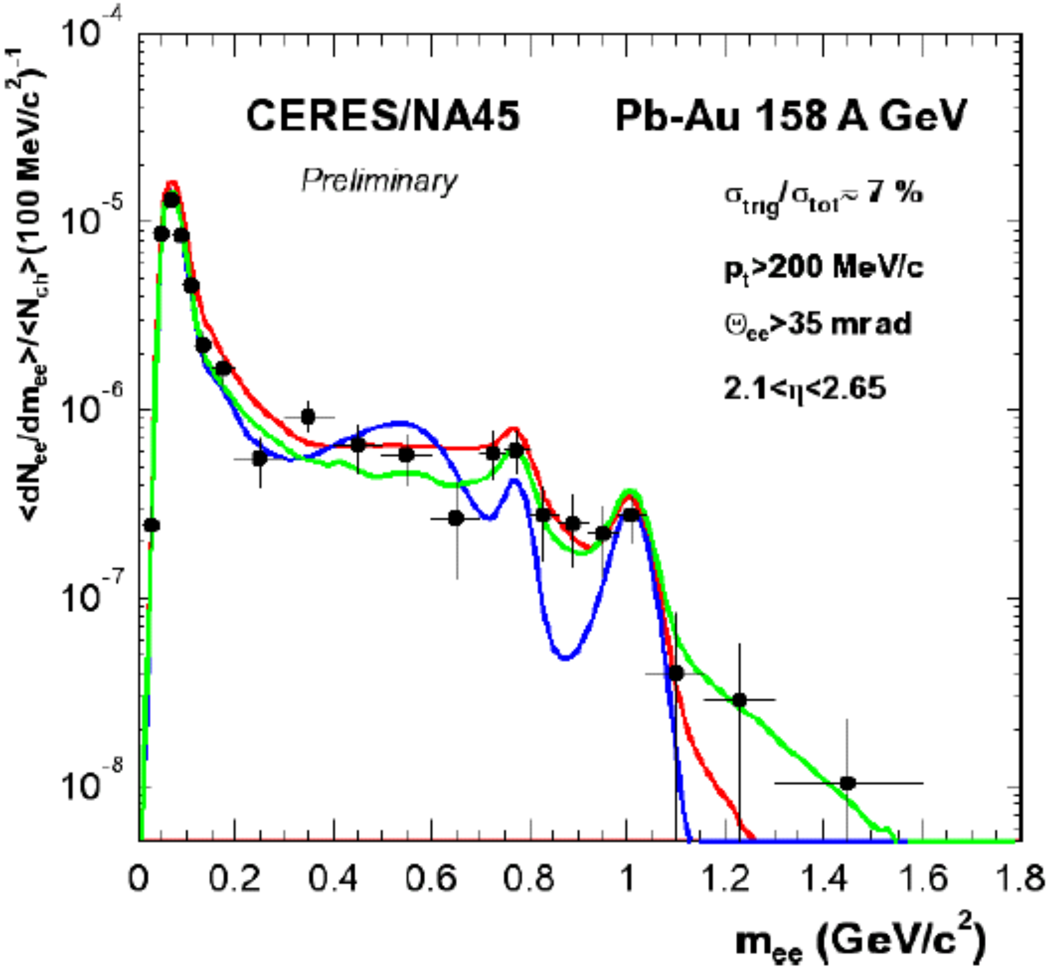
Centrality dependence of excess



strong centrality dependence
→challenge for theory !

- naïve expectation: quadratic multiplicity dependence
  - medium radiation ∝ particle density squared
- more realistic: smaller than quadratic increase
  - density profile in transverse plane
  - life time of reaction volume

CERES dat vs. theory



calculation by R.Rapp using Rapp/Wambach medium modification of rho spectral function

calculation by R.Rapp using Brown-Rho scaling

B. Kämpfer, thermal emission

...added to the cocktail.

in the 0.8 < m < 0.98 GeV region:
Brown-Rho curve: $\chi^2/n = 2.4$
the other two curves: $\chi^2/n \sim 0.3$

What did we get from CERES?

- first systematic study of e^+e^- production in elementary and HI collisions at SPS energies
    - pp and pA collisions are consistent with the expectation from known hadronic sources
    - a strong low-mass low-p_T enhancement is observed in HI

➛ consistent with in-medium modification of the ρ meson

➛ data can't distinguish between two scenarios

- dropping ρ mass as direct consequence of CSR?
- collisional broadening of ρ in dense medium

- WHAT IS NEEDED FOR PROGRESS?
    - **STATISTICS**
    - **MASS RESOLUTION**

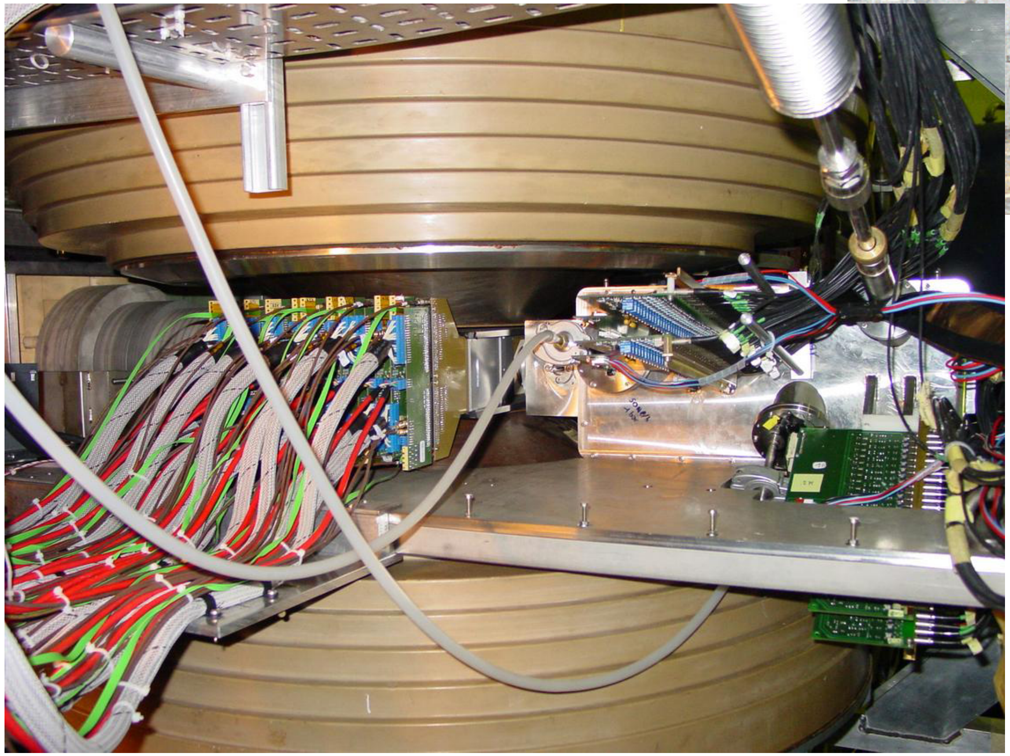
How to overcome these limitations?

- More statistics
  - run forever → not an option
  - higher interaction rate
    - ➢ higher beam intensity
    - ➢ thicker target
  - needed to tolerate this
    - ➢ extremely selective hardware trigger
    - ➢ reduced sensitivity to secondary interactions, e.g. in targe
  - can't be done with dielectrons as a probe, but dimuons are just fine!

- Better mass resolution
  - stronger magnetic field
  - detectors with better position resolution
  - → silicon tracker embedded in strong magnetic field!

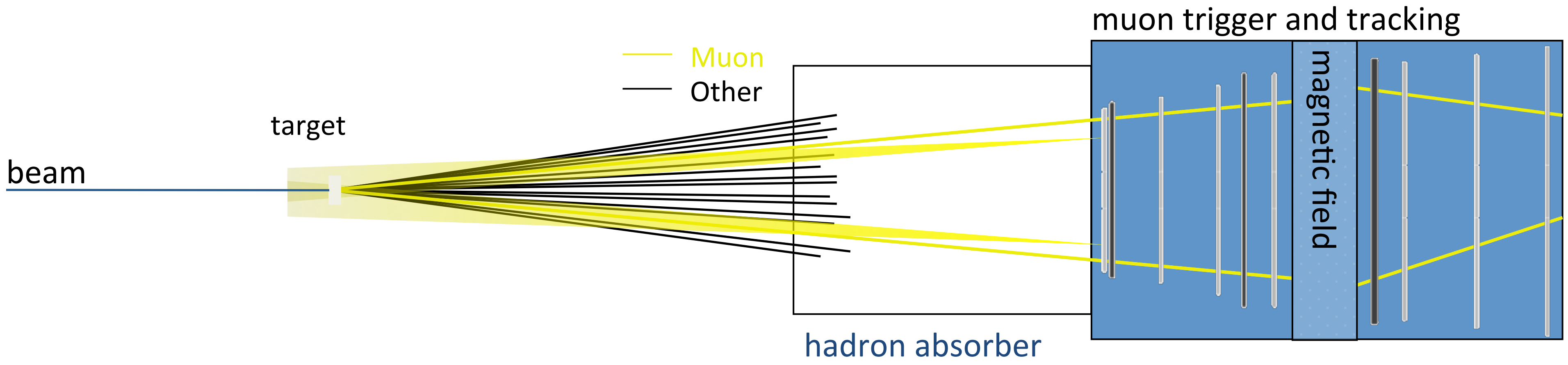
The NA60 experiment

- A huge hadron absorber and muon spectrometer (and trigger!)…



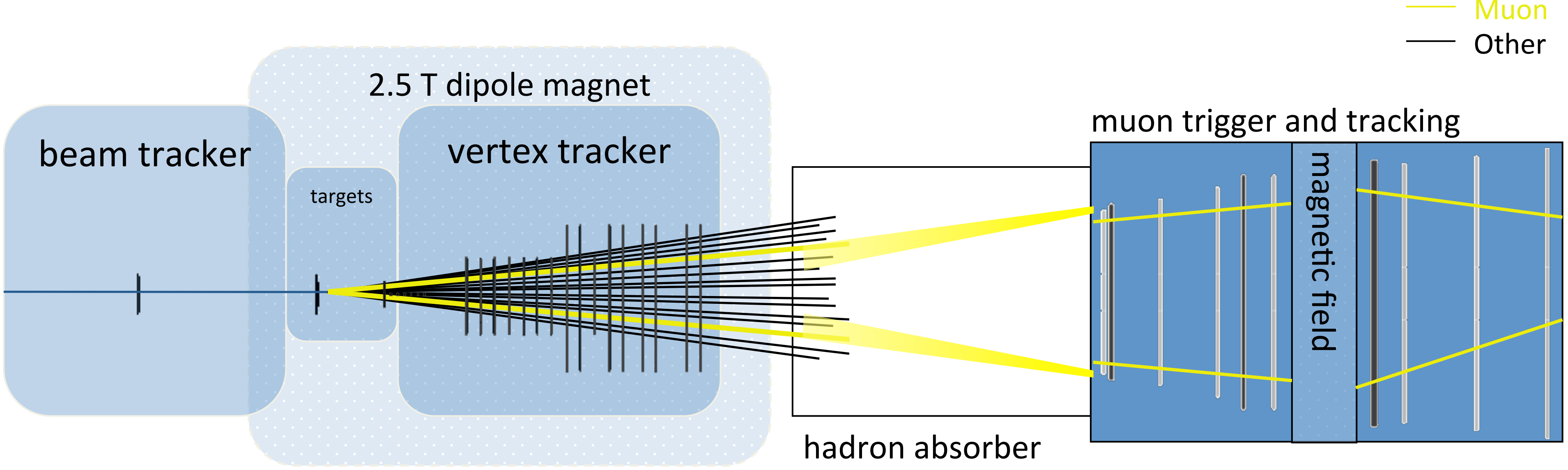
- … and a tiny, high resolution, radiation hard vertex spectrometer

Standard $\mu^+\mu^-$ detection: NA50



- thick hadron absorber to reject hadronic background
- trigger system based on fast detectors to select muon candidates (1 in 10^4 PbPb collisions at SPS energy)
- muon tracks reconstructed by a spectrometer (tracking detectors +magnetic field)
- extrapolate muon tracks back to the target taking into account multiple scattering and energy loss, but …
  - poor reconstruction of interaction vertex (σ_z ~10 cm)
  - poor mass resolution (80 MeV at the ϕ)

A step forward: the NA60 case



2.5 T dipole magnet

beam tracker

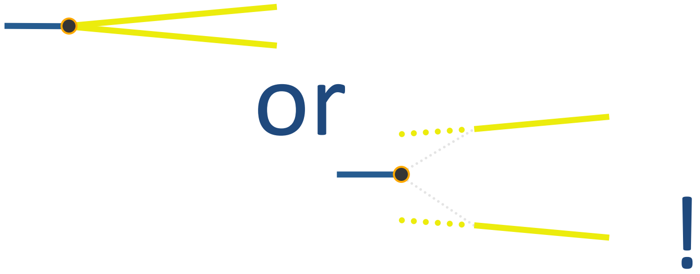
targets

vertex tracker

muon trigger and tracking

magnetic field

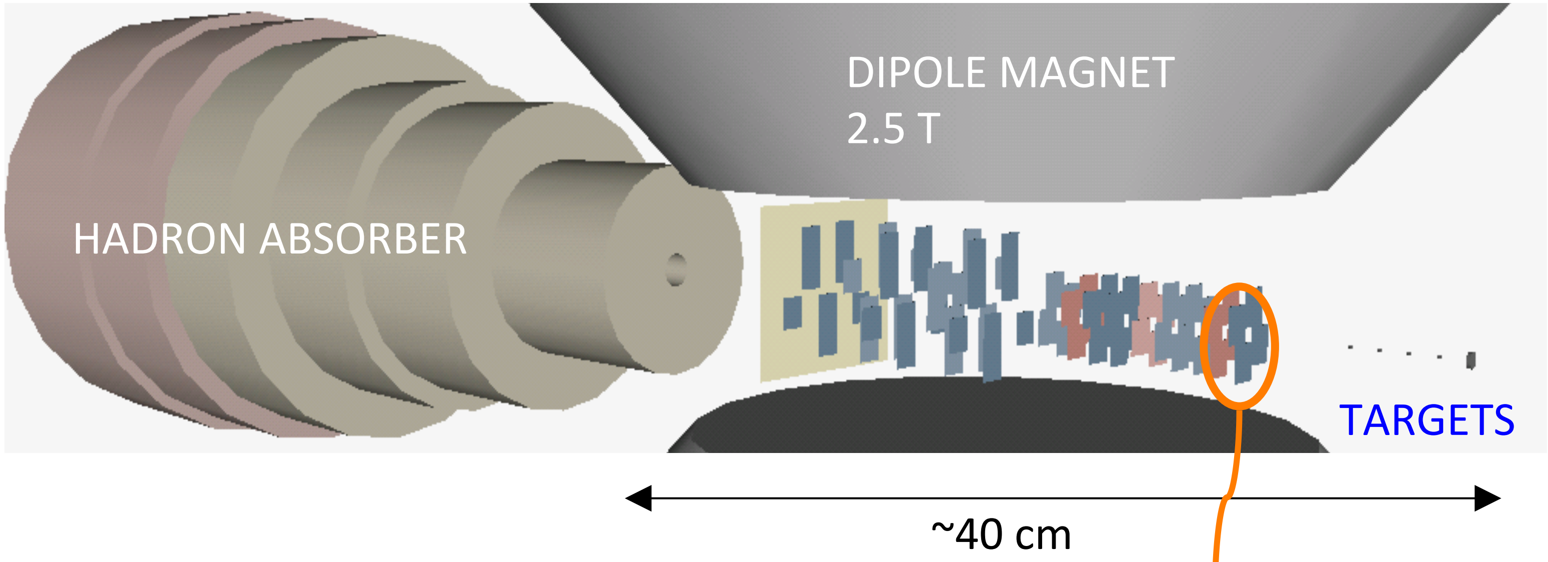
hadron absorber

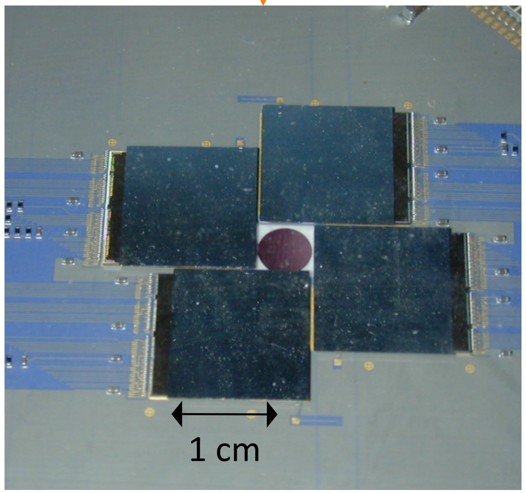


matching of muon tracks

- origin of muons can be determined accurately
- improved dimuon mass resolution

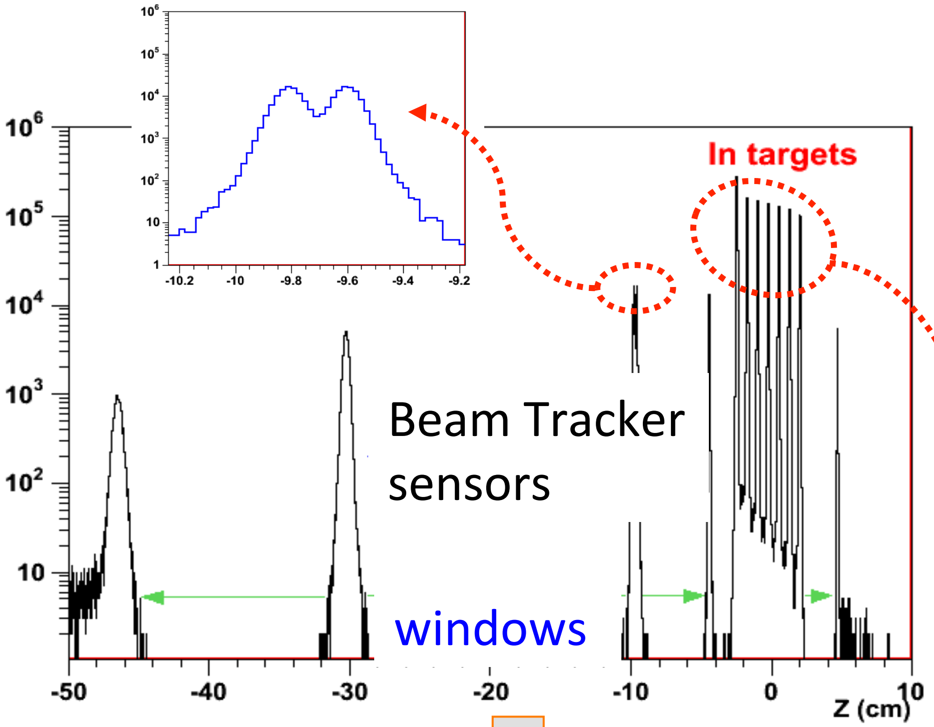
The NA60 pixel vertex spectrometer



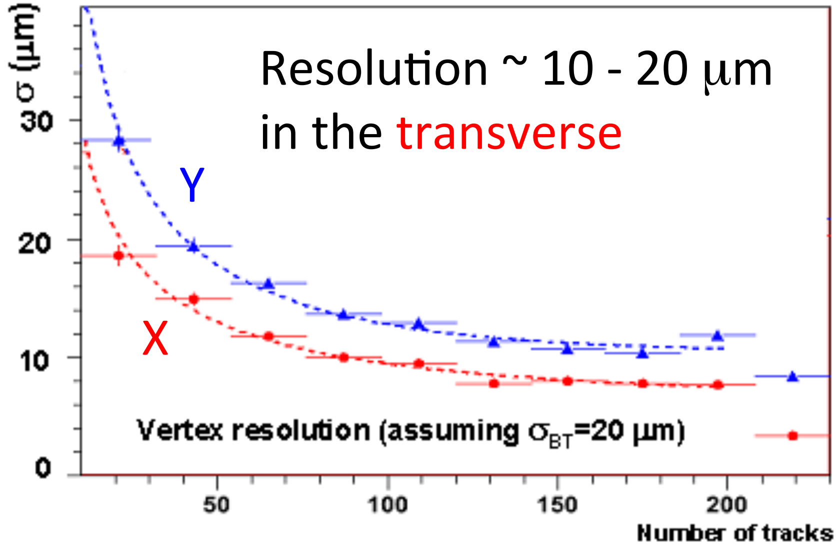


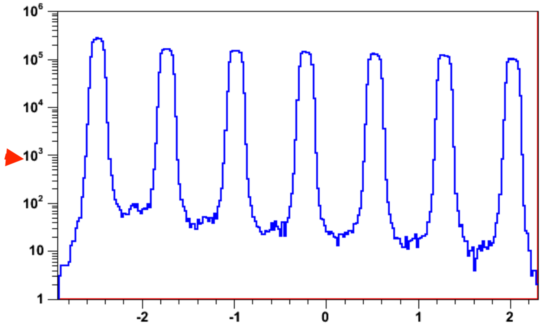
- 12 tracking points with good acceptance
  - 8 small 4-chip planes
  - 8 large 8-chip planes in 4 tracking stations
- ~3% X_0 per plane
  - 750 mm Si readout chip
  - 300 mm Si sensor
  - ceramic hybrid
- 800000 readout channels
  in 96 pixel assemblies

Vertexing in NA60



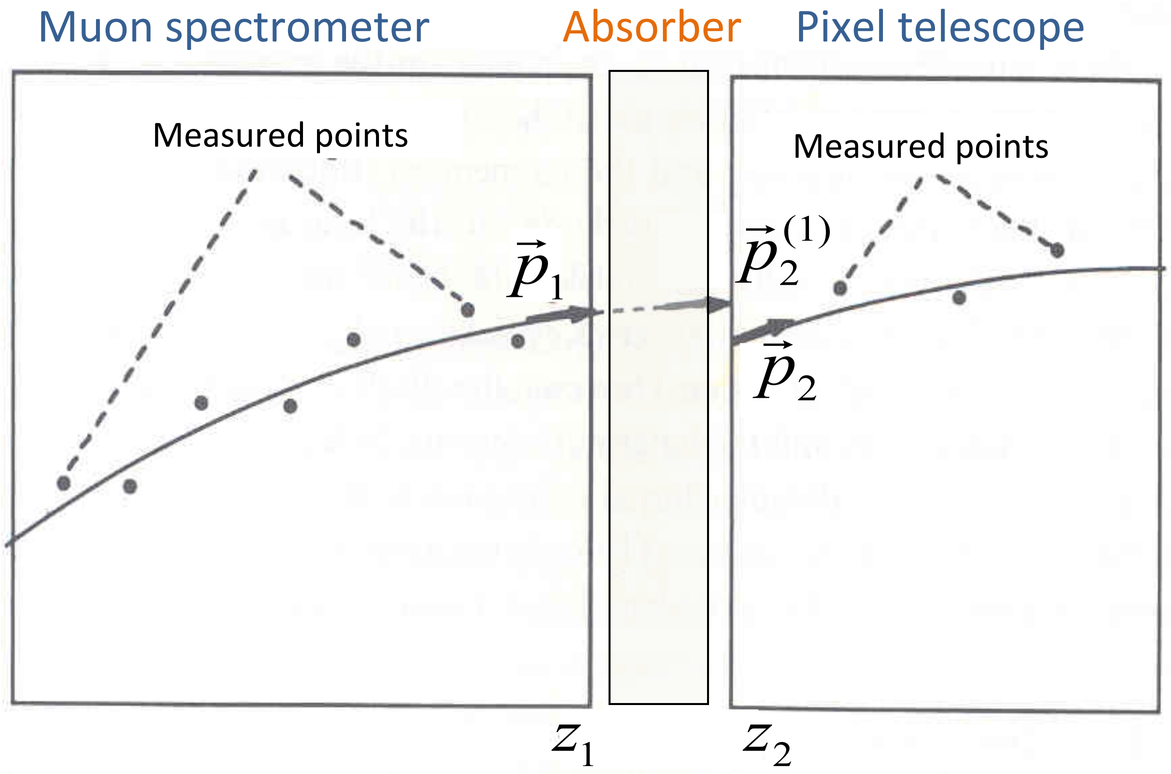
σ_z ~ 200 µm along the beam direction
Good vertex identification with ≥ 4 tracks


Resolution ~ 10 - 20 µm
in the transverse



Extremely clean target
identification (Log scale!)

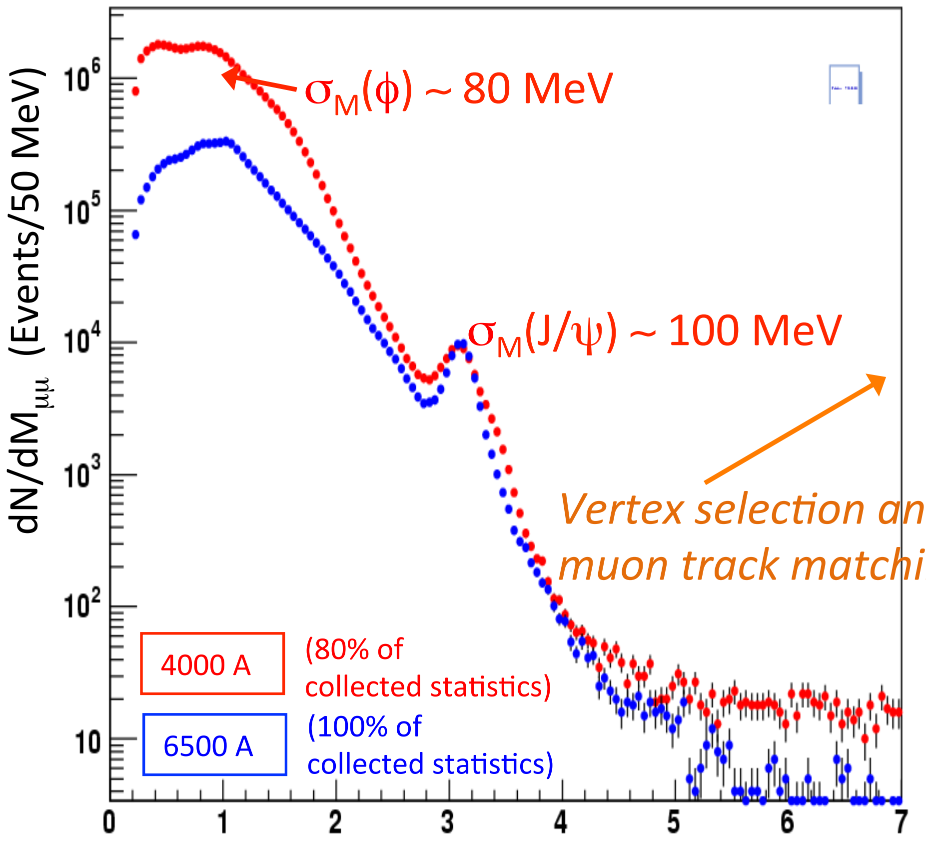
Muon track matching



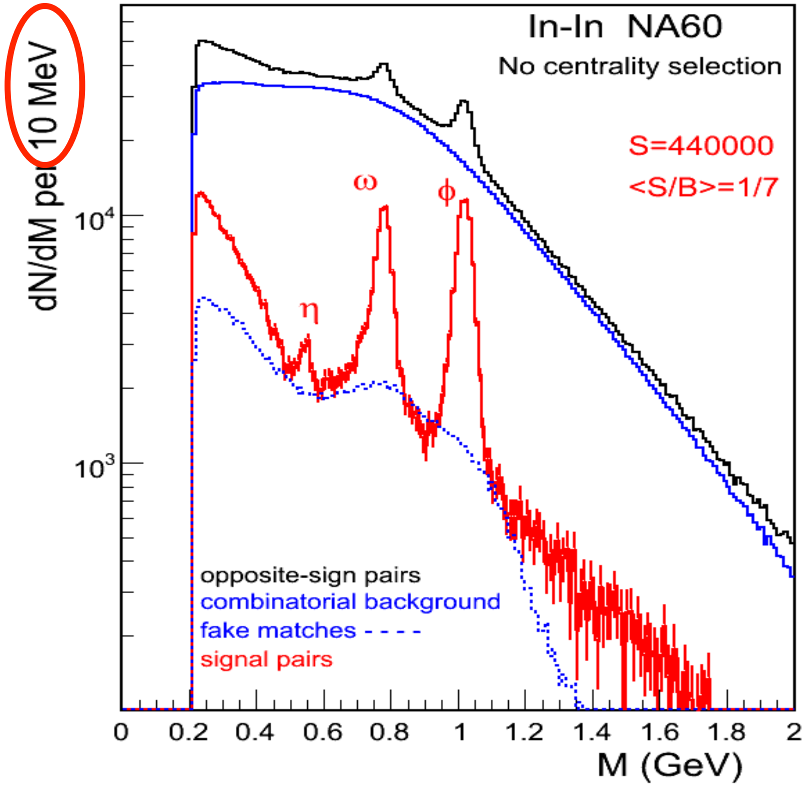
- track matching has to be done in
    - position space
    - momentum space
- to be most effective
- → the pixel telescope has to be a spectrometer!

Improvments in mass resolution

- unlike sign dimuon mass distribution before quality cuts and without muon track matching



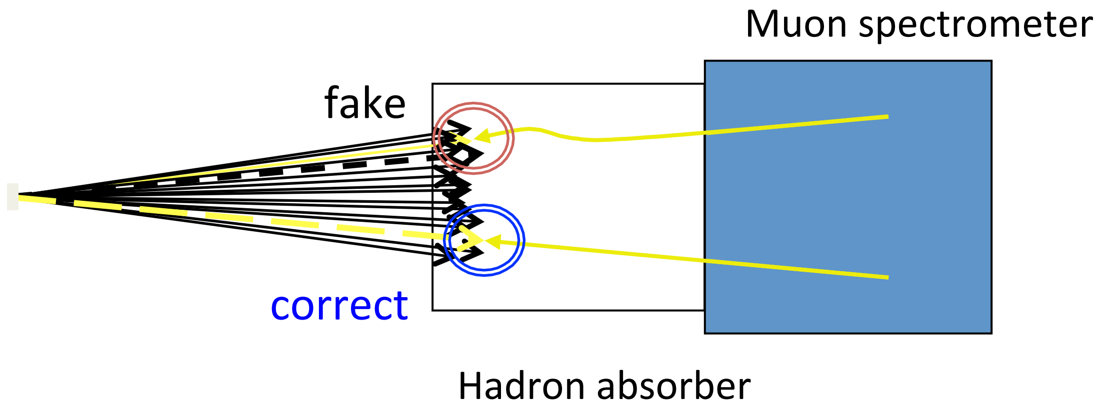
Vertex selection and muon track matching

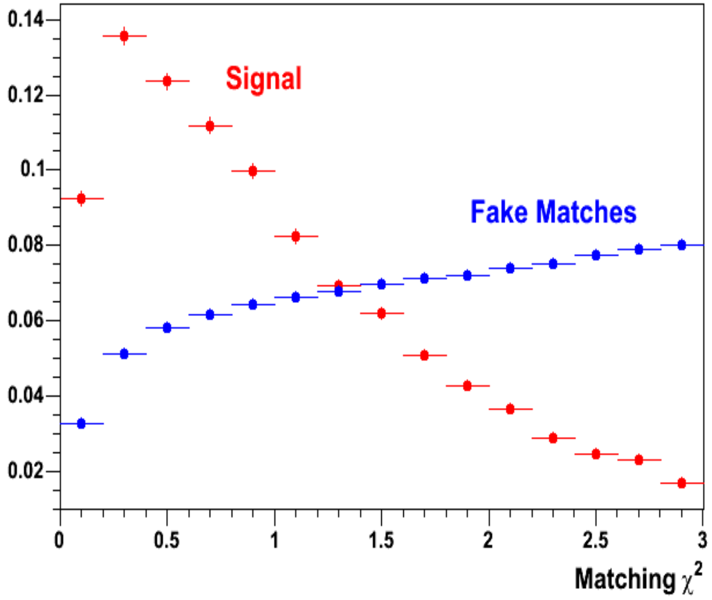


- drastic improvement in mass resolution
- still a large unphysical background

Nothing is perfect: fake matches

- fake match: μ matched to wrong track in pixel telescope
  - important in high multiplicity events

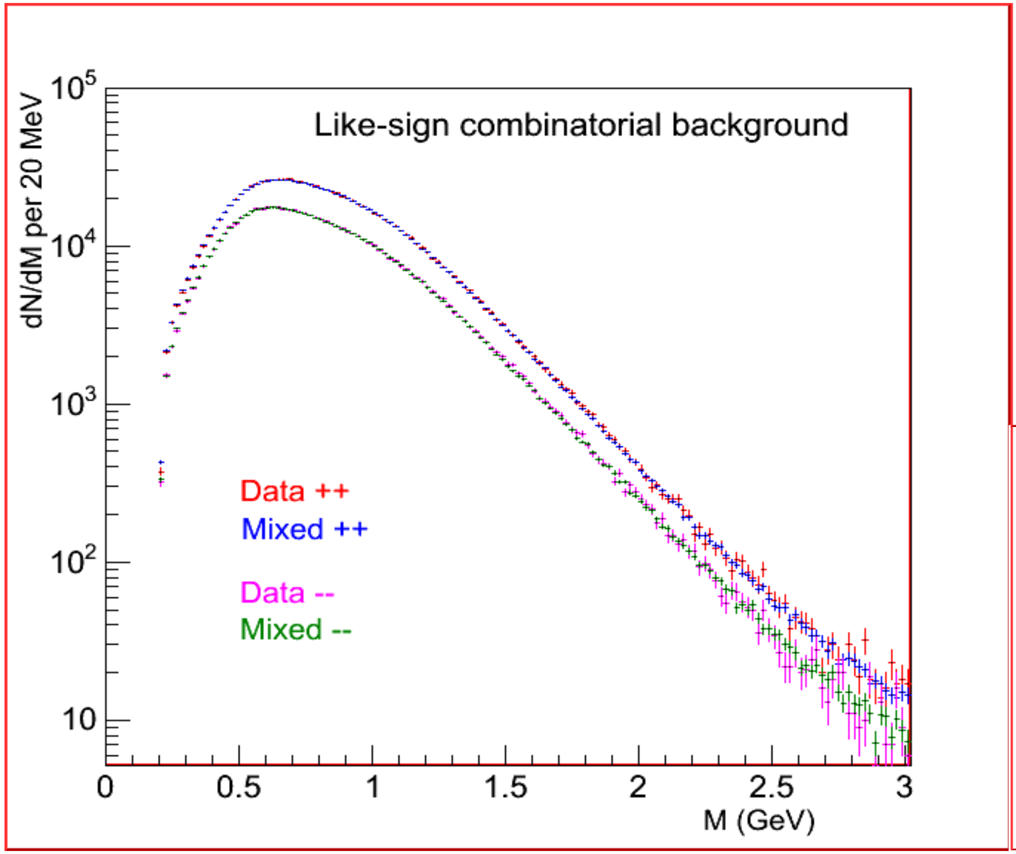


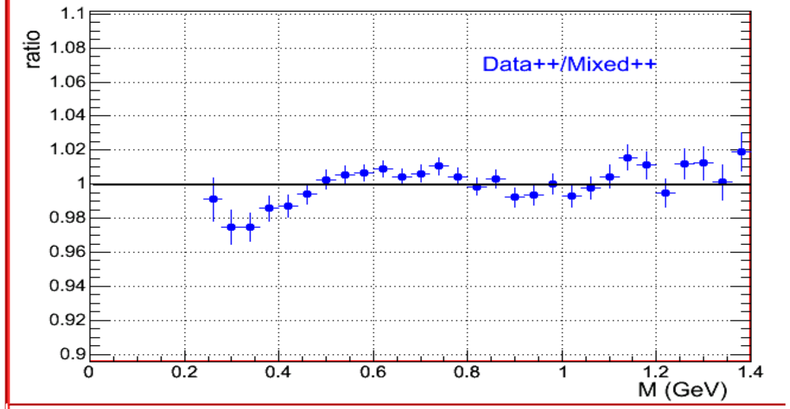


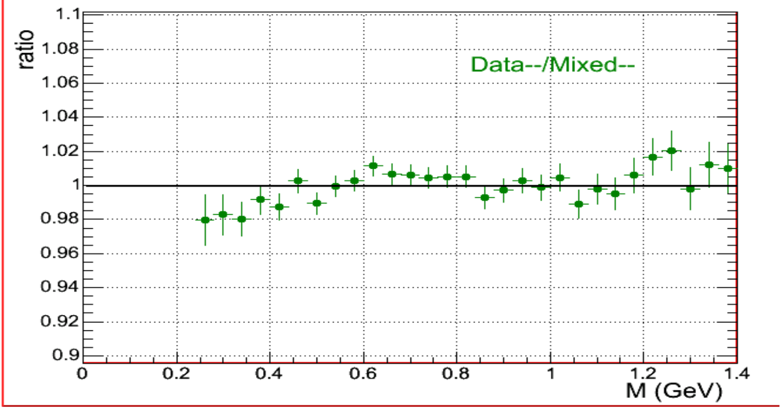
- how to deal with fake matches
  - keep track with best χ^2 (but is is right?)
  - embedding of muon tracks into other event
  - identify fake matches and determine the fraction of these relative to correct matches as function of
    - ➢ centrality
    - ➢ transverse momentum

Event-mixing: like-sign pair

- compare measured and mixed like-sign pairs





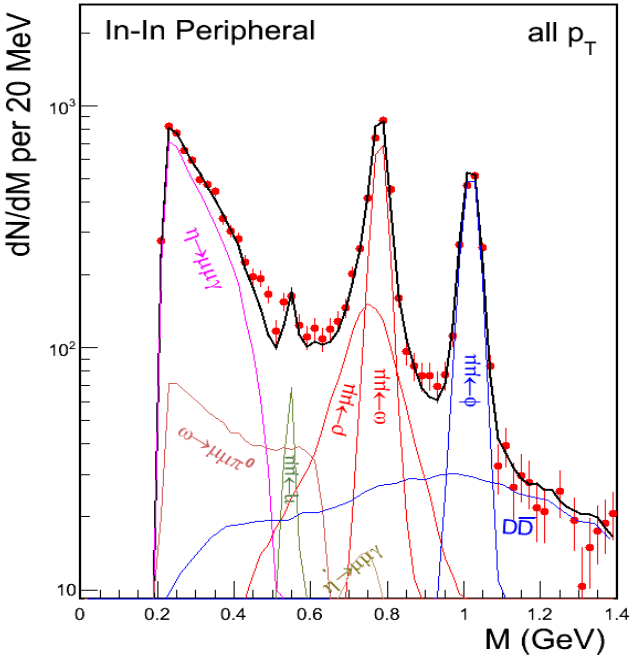


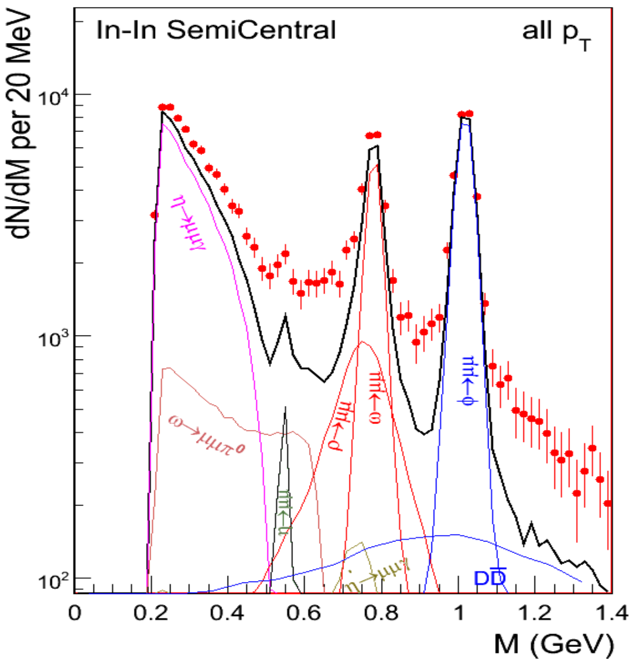
- accuracy in NA60: ~1% over the full mass range

Dimuon invariant mass from NA60

Well described by meson decay ‘cocktail’ η, η’ , ρ, ω, ϕ and DD contributions (Genesis generator developed within CERES and adapted for dimuons by NA60).

Eur.Phys.J.C 49 (2007) 235





<u>Peripheral data</u>

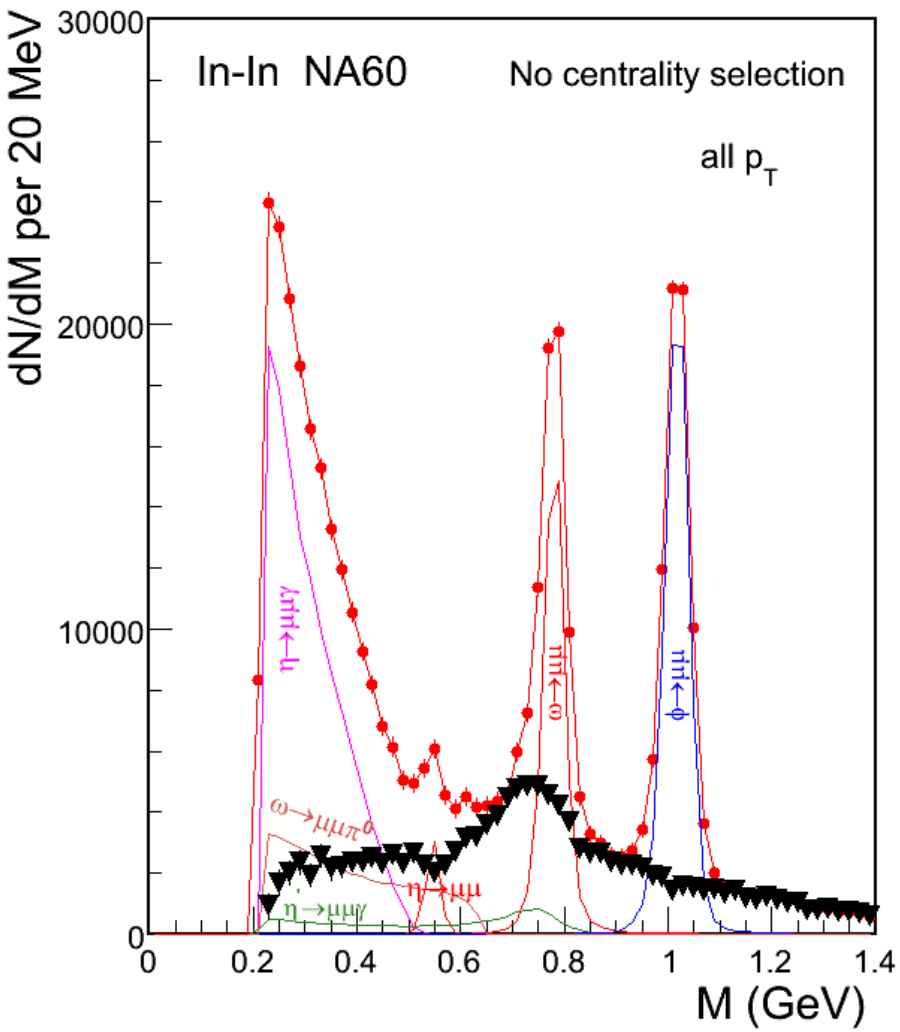
well described by meson decay ‘cocktail’ (η, η’, ρ, ω, ϕ) and DD

<u>More central data</u>

Clear excess of data above decay ‘cocktail’. But, what is the spectral shape of the excess?

Isolation of excess dimuons

Phys. Rev. Lett. 96 (2006) 162302



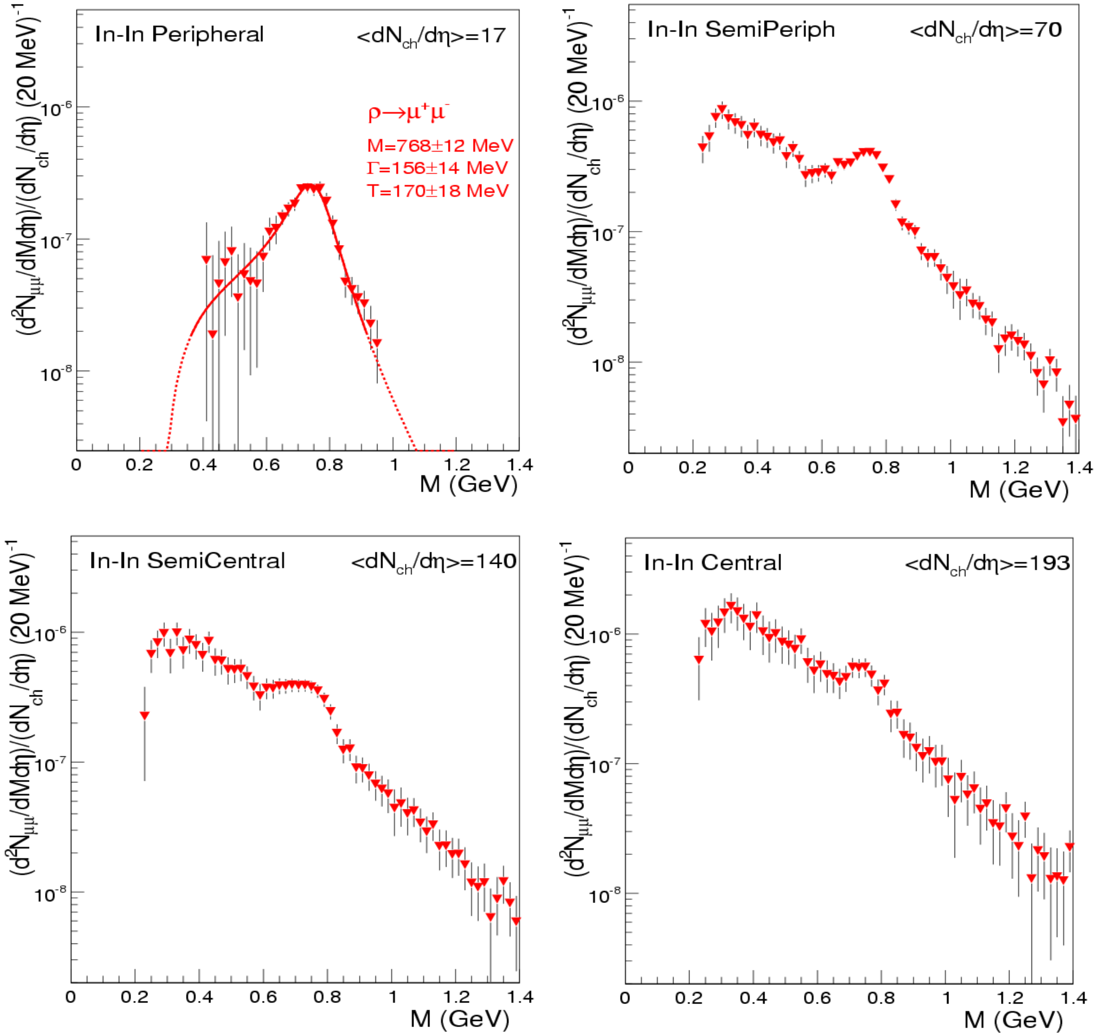
isolation of excess by subtraction of measured decay cocktail (without ρ), based solely on local criteria for the major sources η, ω and ϕ

ω and ϕ : fix yields such as to get, after subtraction, a smooth underlying continuum

η : fix yield at p_T >1 GeV profiting from the very high sensitivity of the spectral shape of the Dalitz decay to any underlying admixture from other sources; lower limit from peripheral data

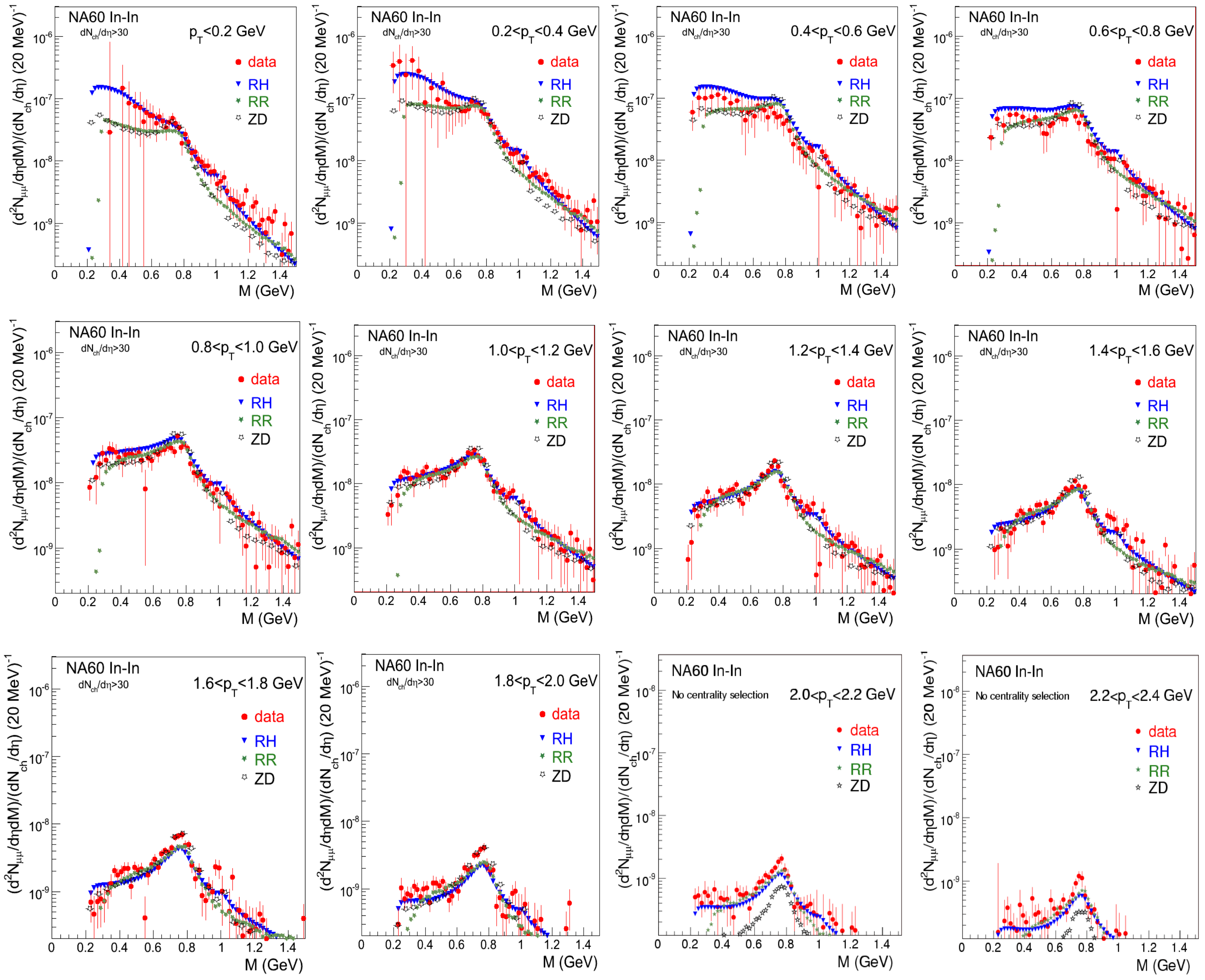
accuracy 2-3%, but results robust to mistakes even at the 10% level

Excess vs. centrality

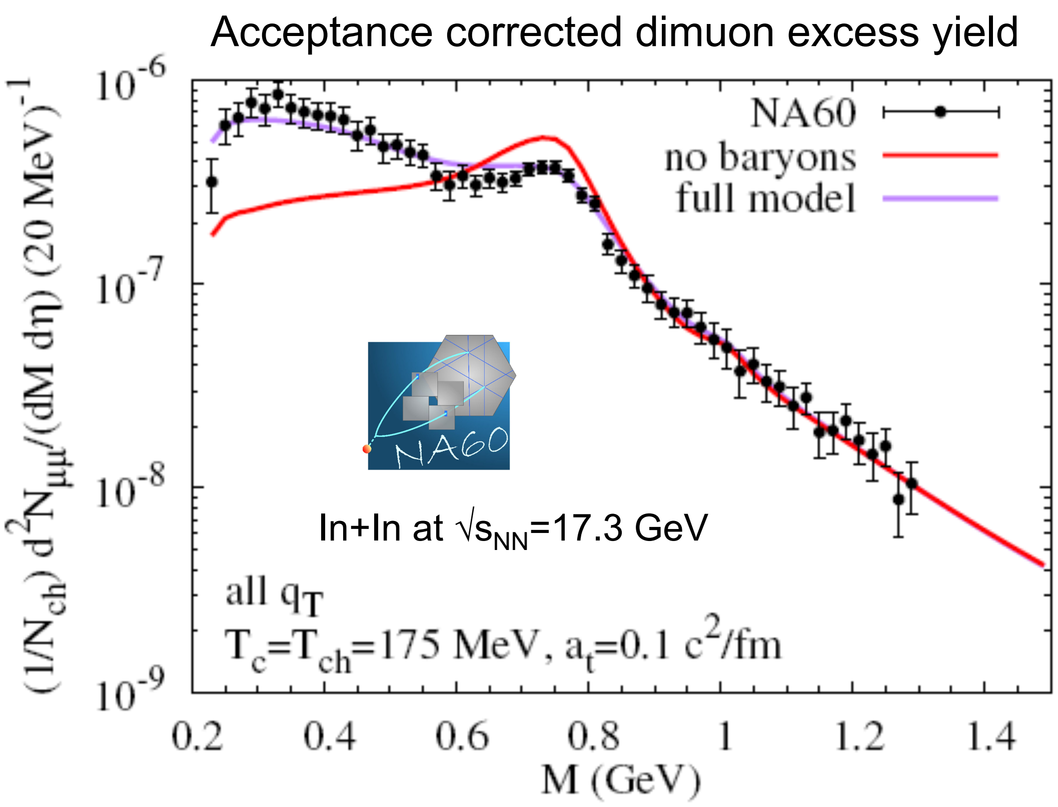


- No **cocktail** ρ and no **DD** subtracted
- **Clear excess** above the cocktail ρ**, centered at the nominal** ρ **pole** and rising with centrality

pT dependence of excess mass spectra

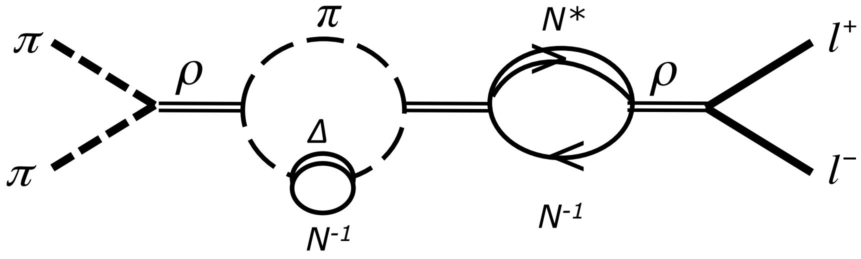


Dileptons: from SPS to SIS



In-medium ρ spectral function:

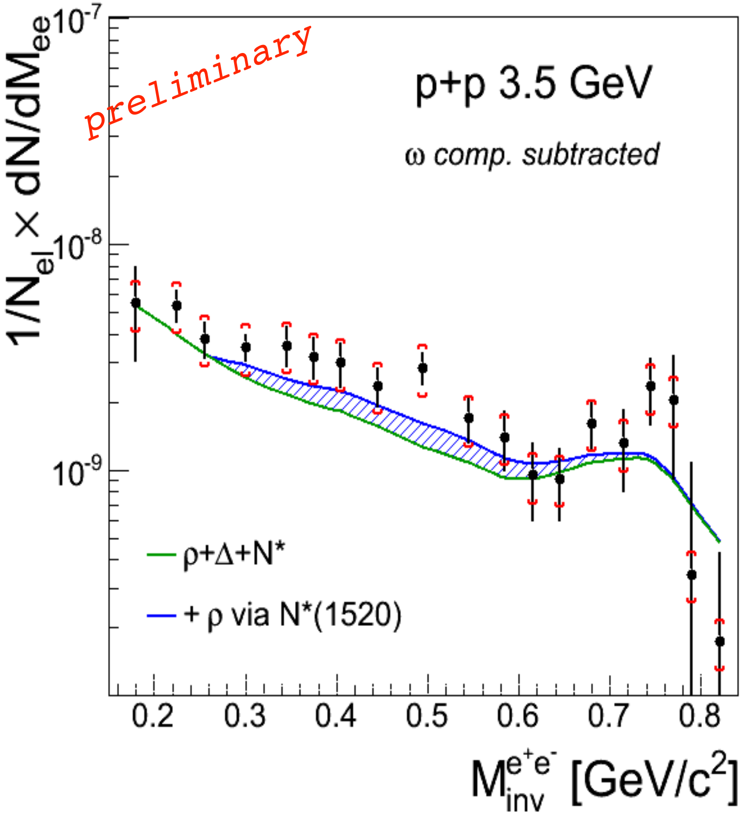
strength of dilepton yield at low masses is **due to coupling to baryons**!

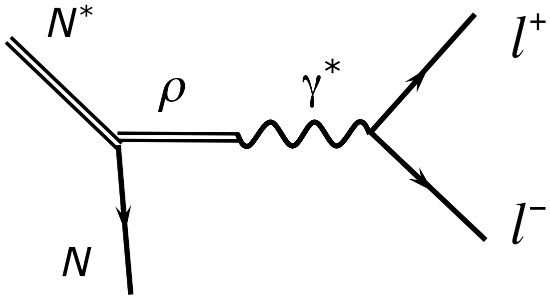


Dileptons: from SPS to SIS

Data: *in preparation, A. Dybczak*
Model: *M. Zetenyi and Gy. Wolf*
Phys. Rev. C 67, 044002 (2003).

Exclusive analysis: pp → ppe^+e^-



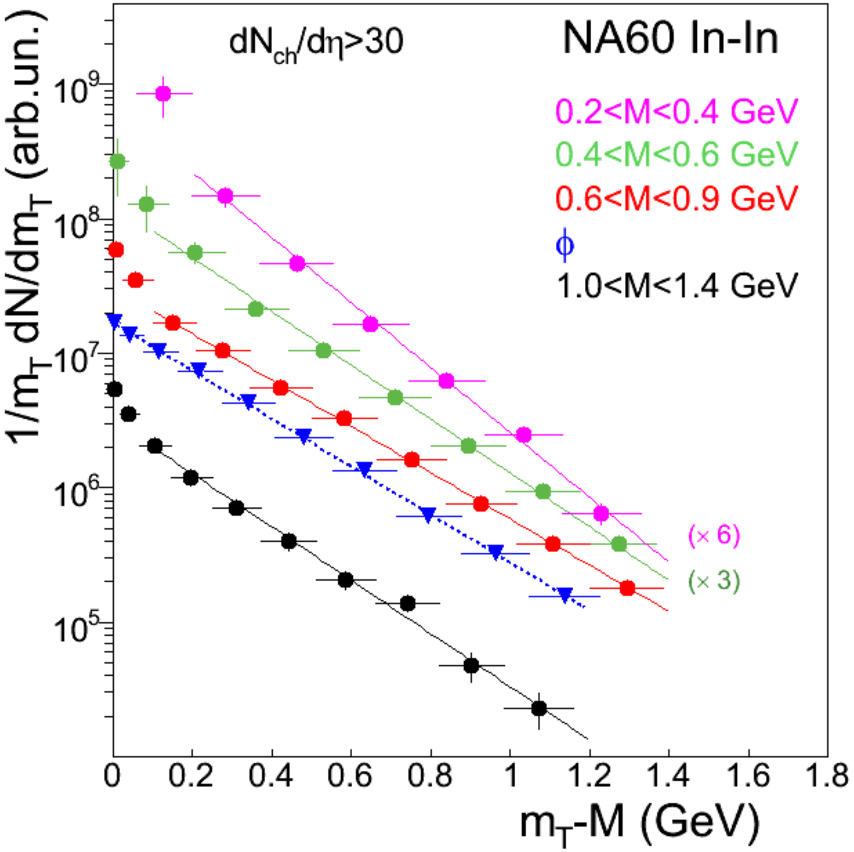


- Dalitz decays of baryonic resonances - dominant source at low beam energies.
- Relative contribution reconstructed from the hadronic channels

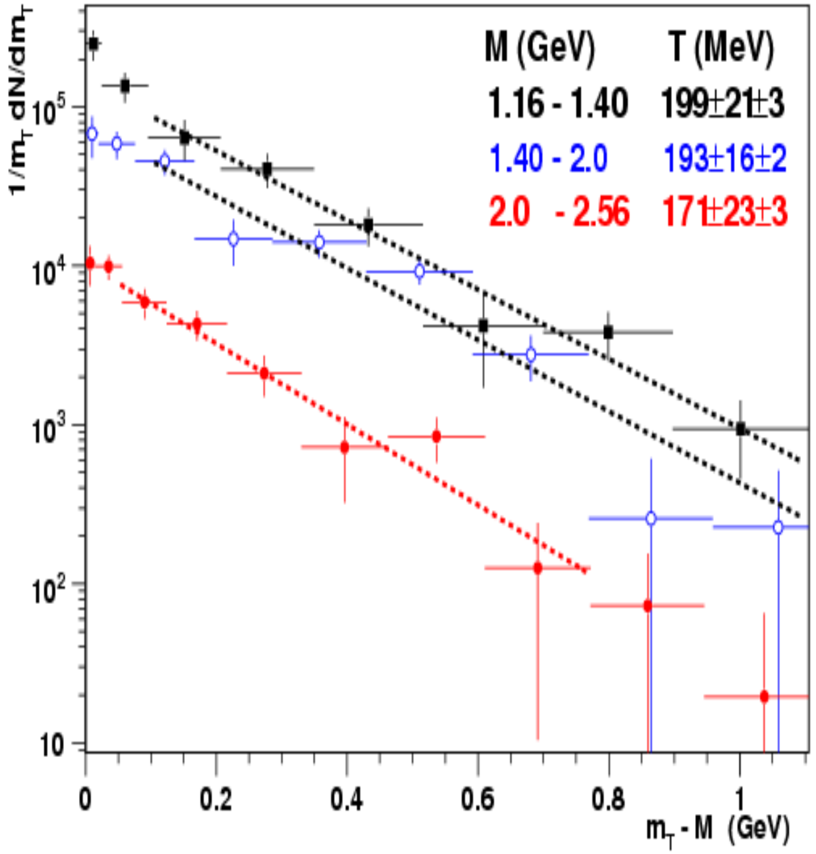
What can we learn from dilepton m_T?

variation with mass are obvious

Phys. Rev. Lett. 100 (2008) 022302



Eur. Phys. J. C 59 (2009) 607



Interpretation of effective slope parameter

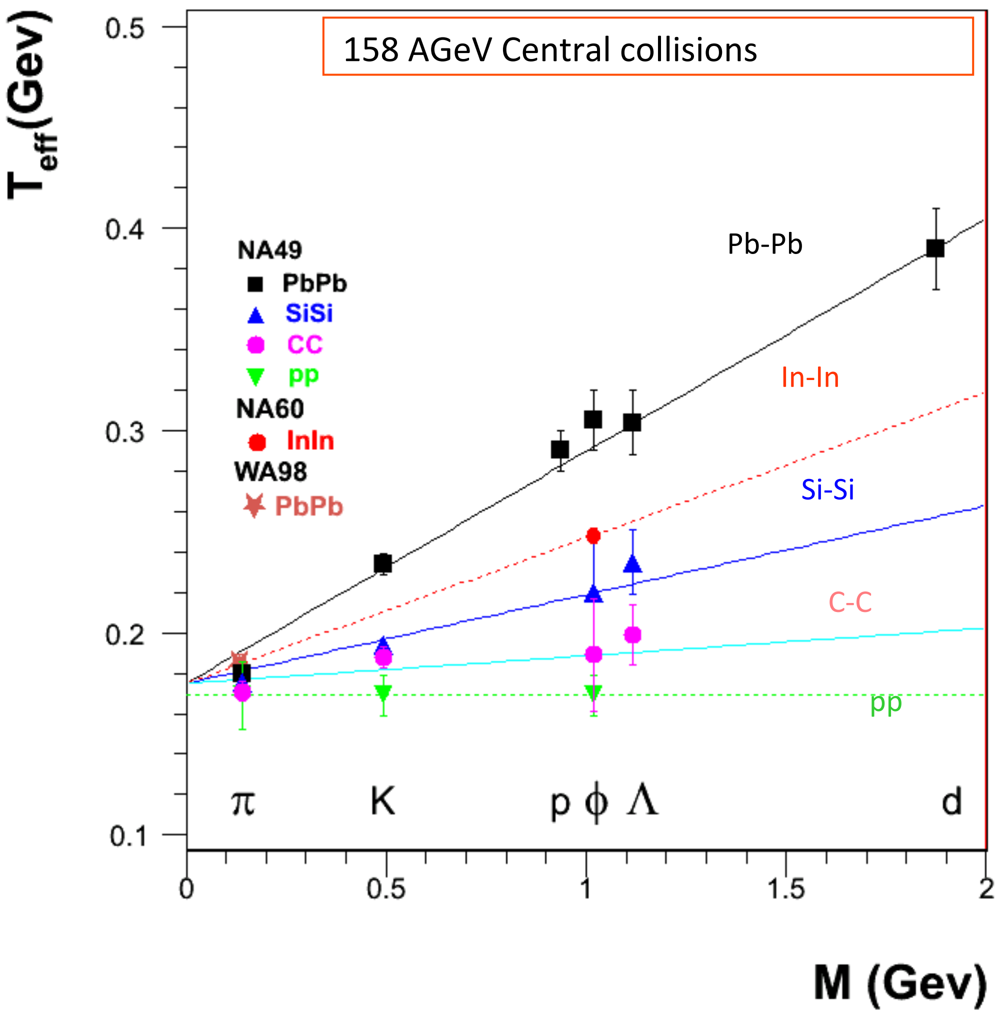
- interpretation of T_{eff} from fitting to $\exp(-m_T/T_{eff})$
  - static source: T_{eff} interpreted as the source temperature
  - radially expanding source:
    - ➛ T_{eff} reflects temperature and flow velocity
    - ➛ T_{eff} dependens on the m_T range
    - ➛ large p_T limit: $T_{eff} = T_f \sqrt{\frac{1+v_T}{1-v_T}} \quad p_T >> m$ common to all hadrons
    - ➛ low p_T limit: $T_{eff} \approx T_f + \frac{1}{2} m \langle v_T \rangle^2 \quad p_T << m$ mass ordering of hadrons
- final spectra: space-time history $T_i \rightarrow T_{fo}$ & emission time
  - hadrons
    - ➛ interact strongly
    - ➛ freeze out at different times depending on cross section with pions
    - ➛ $T_{eff} \rightarrow$ temperature and flow velocity at thermal freeze out
  - dileptons
    - ➛ do not interact strongly
    - ➛ decouple from medium after emission
    - ➛ $T_{eff} \rightarrow$ temperature and velocity evolution averaged over emission time

Mass ordering of hadronic slopes

- separation of thermal and collective motion
- reminder
    - blast wave fit to all hadrons simultaneously
- simplest approach

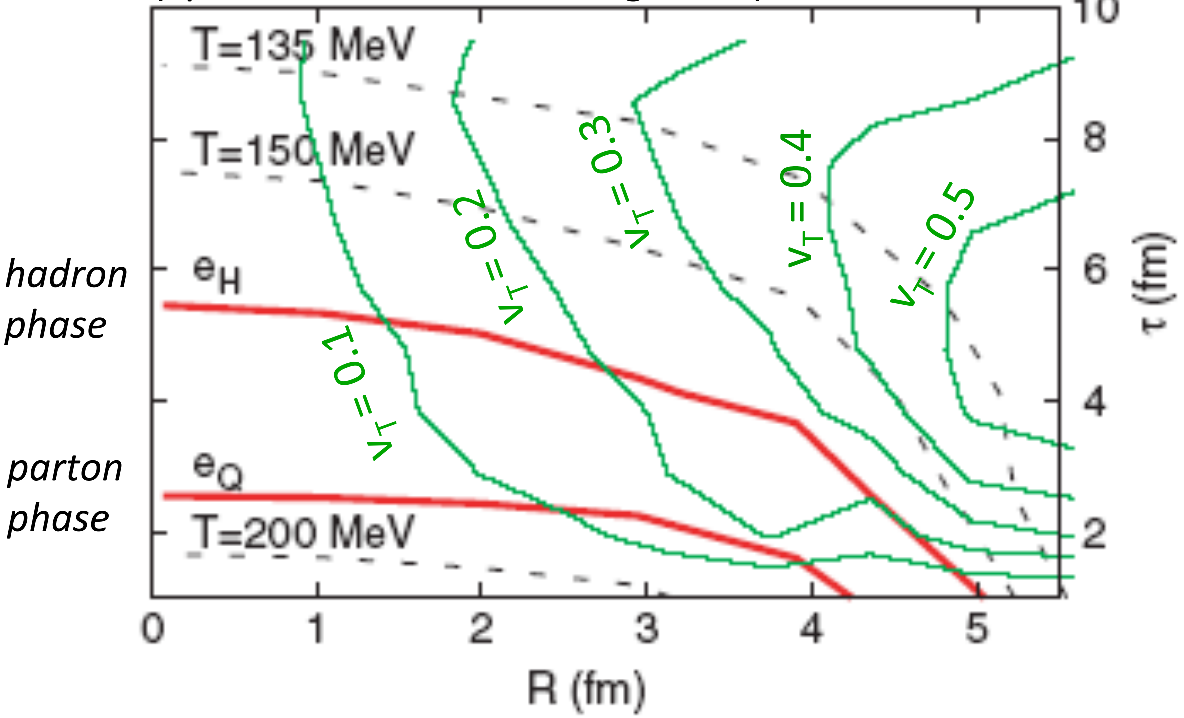
$$T_{eff} \approx T_f + \frac{1}{2} m \left\langle \mathrm{v}_T \right\rangle^2 \quad p_T << m$$

    - slope of $<T_{eff}>$ vs. m is related to radial expansion
    - baseline is related to thermal motion
- works (at least qualitatively) at SPS



Example of hydrodynamic evolution

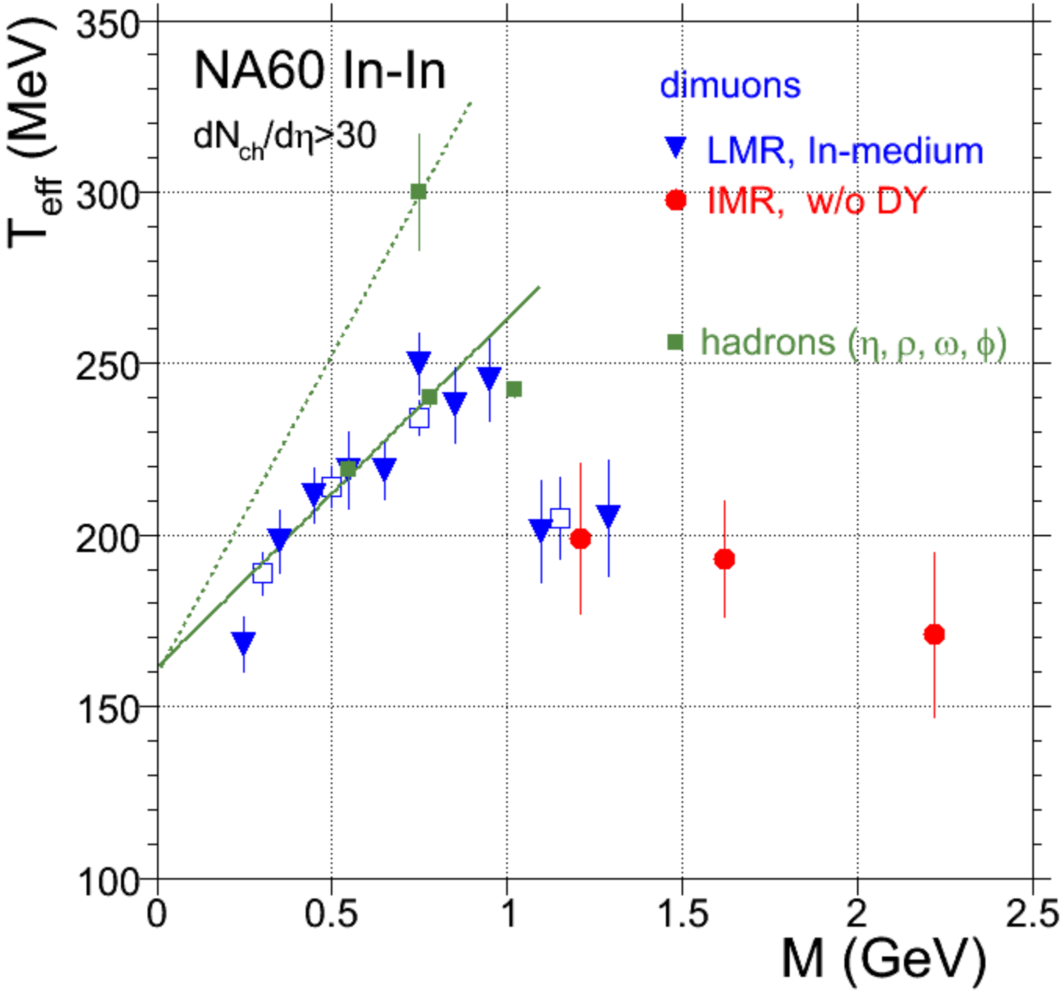
(specific for In-In: Dusling et al.)



- Monotonic decrease of T from
  - early times to late times
  - medium center to edge
- monotonic increase of v_T from
  - early times to late times
  - medium center to edge

- Dileptons may allow to disentangle emission times
  - early emission (parton phase)
    - ➛ large T, small v_T
  - late emission (hadron phase)
    - ➛ small T, large v_T

Dilepton T_{eff} systematics



Eur.Phys.J. C (2009), in press, nucl-ex/0812.3053

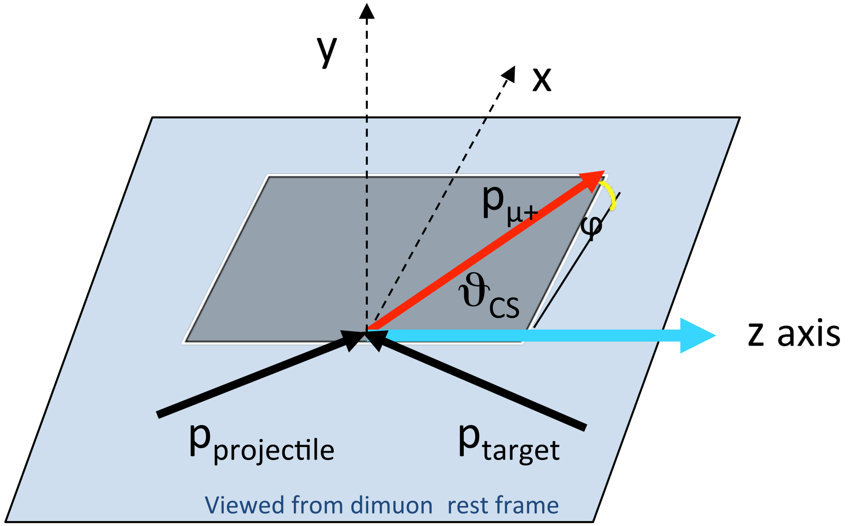
- Hadrons (η, ω, ρ, ϕ)
  - T_{eff} depends on mass
  - T_{eff} smaller for ϕ, decouples early
  - T_{eff} large for ρ, decouples late
- Low mass excess
  - clear flow effect visible
  - follows trend set by hadrons
  - possible late emission
- Intermediate mass excess
  - no mass dependence
  - indication for early emission

Angular distributions

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta\, d\phi} = \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

λ, μ, ν : structure functions related to helicity structure functions and the spin density matrix elements of the virtual photon

Choice of reference frame: Collins-Soper (CS)



In rest frame of virtual photon:

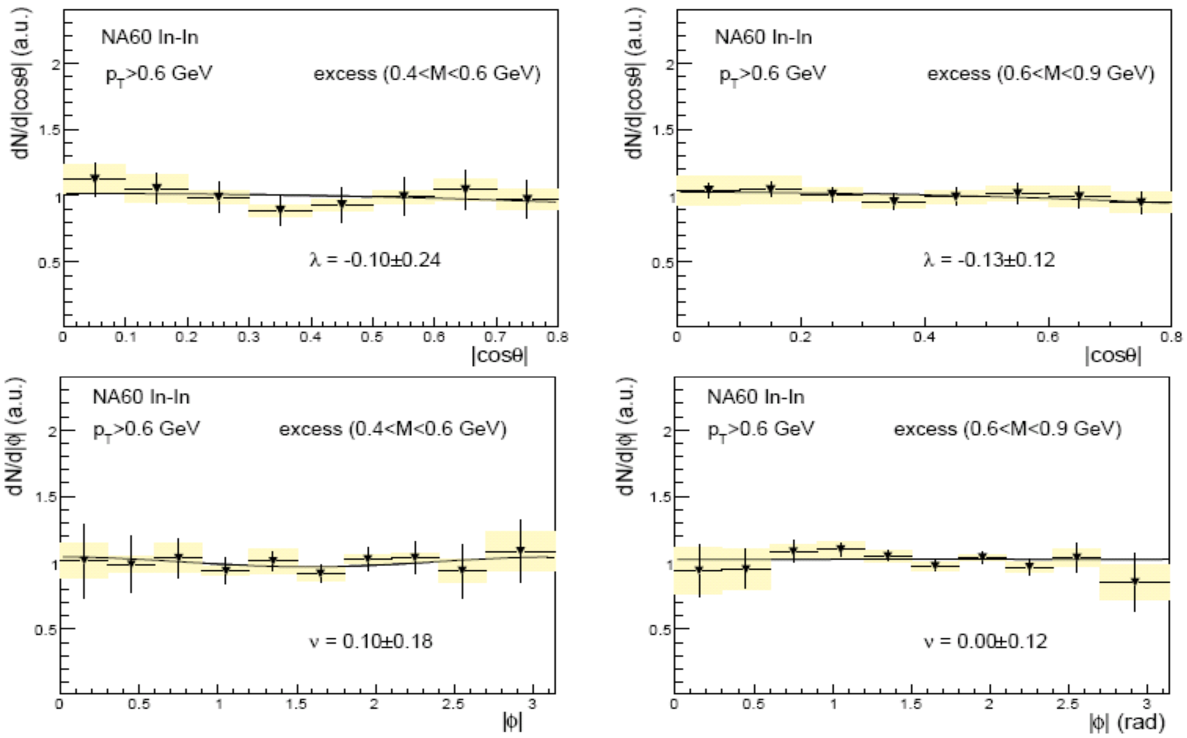
ϑ : angle between the positive muon $\mathbf{p}_{\mu+}$ and the z-axis.

z axis : bisector between $\mathbf{p}_{proj}$ and $-\mathbf{p}_{target}$

Expectation: completely random orientation of annihilating particles (pions or quarks) in 3 dimensions would lead to $\lambda, \mu, \nu = 0$

Polarisation of dileptons

PRL, nucl-ex/0812.3100



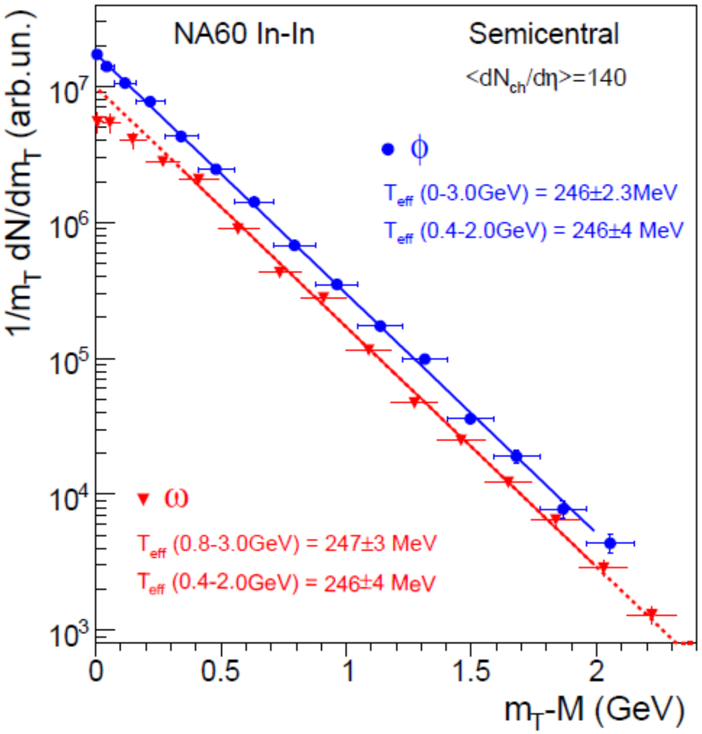
NA60 also measured the polarization for $m \leq m_\phi$

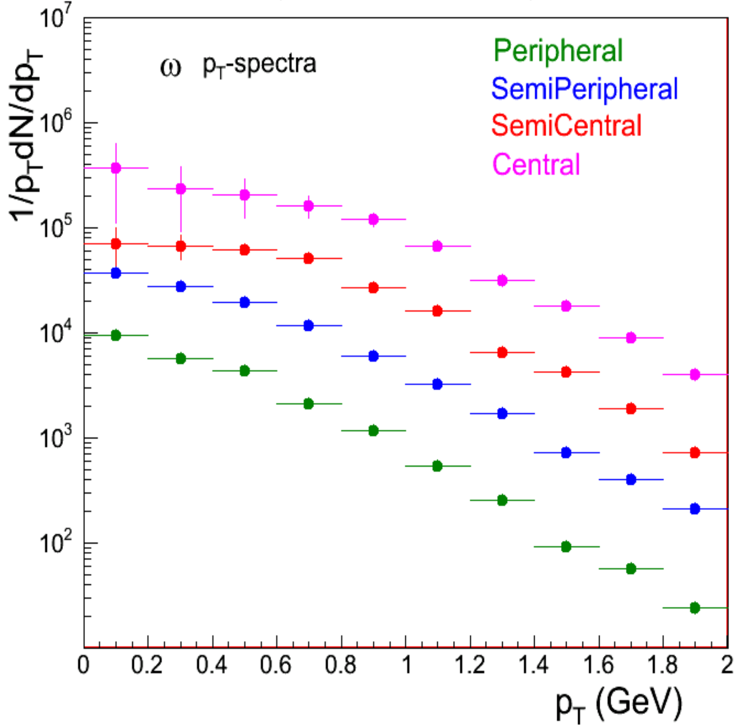
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

Lack of any polarization in excess (and in hadrons) supports emission from thermalized source.

Evidence for ω in-medium effects?

Eur.Phys.J. C (2009), in press, nucl-ex/0812.3053



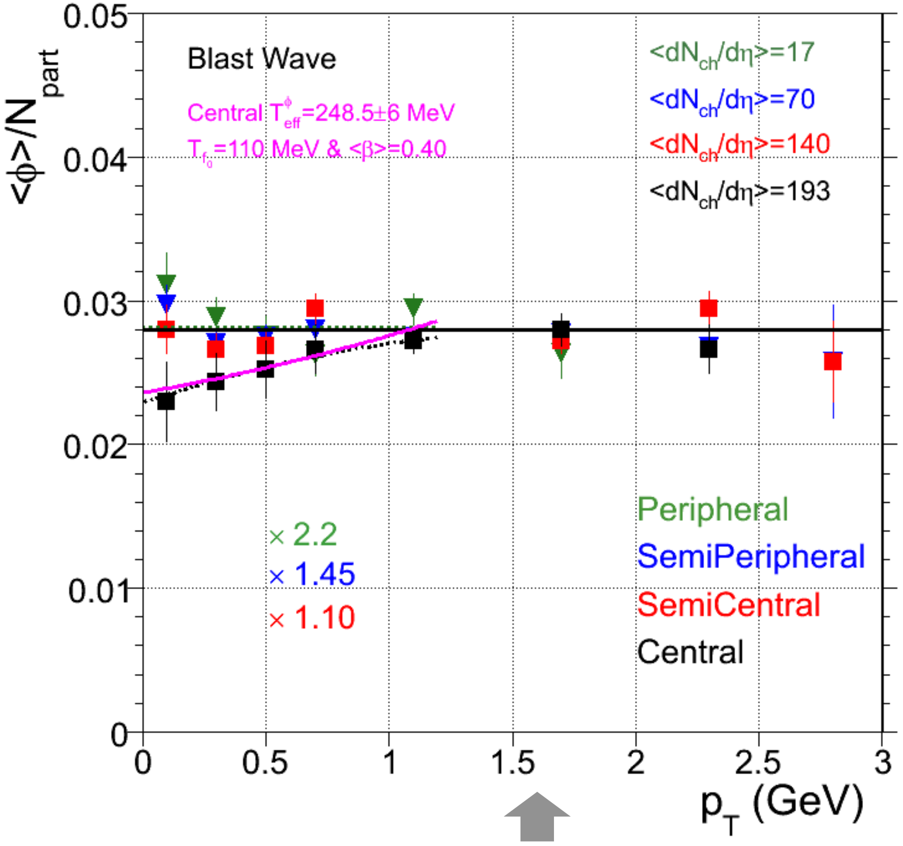


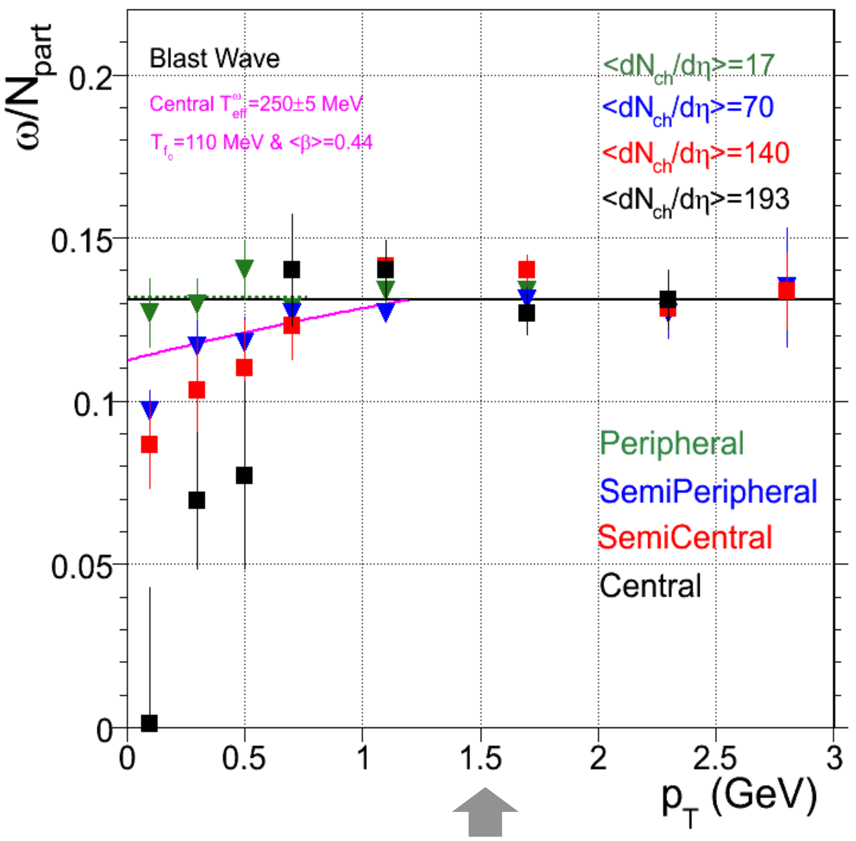
- Flattening of the p_T distributions at low p_T, developing very fast with centrality
  → **Low-pT ω's have more chances to decay inside the fireball ?**
- **Disappearance** of yield out of narrow ω peak in nominal pole position

ω yield suppression

Eur.Phys.J. C (2009), in press nucl-ex/0812.3053

Account for difference in flow effects using the results of the Blast Wave





Reference line: ϕ/N_{part} = 0.0284 f.ph.s. (central coll.)

Consistent with radial flow effects

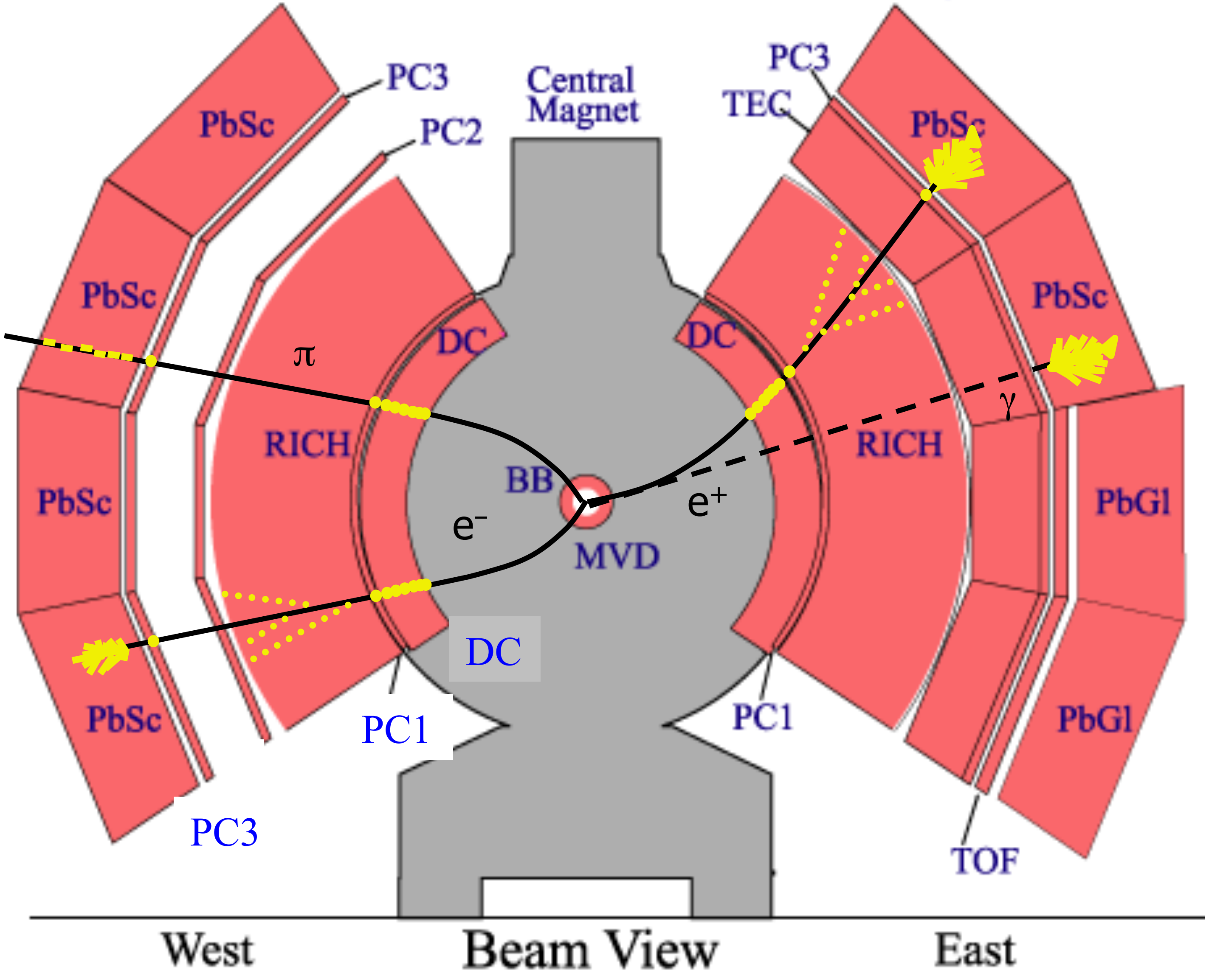
Reference line: ω/N_{part} = 0.131 f.ph.s.

Strong centrality-dependent suppression at p_T<0.8 GeV/c , beyond flow effects

What did we learned from NA60?

- high statistics & high precision dimuon spectra
- decomposition of mass spectra into “sources”
- gives access to in-medium r spectral function
- data consistent with broadening of the ρ
- data do not require mass shift of the ρ
- large prompt component at intermediate masses
- dimuon m_T spectra promise to separate time scales
  - low mass dimuons shows clear flow contribution indicating late emission
  - intermediate mass dimuons show no flow contribution hinting toward early emission

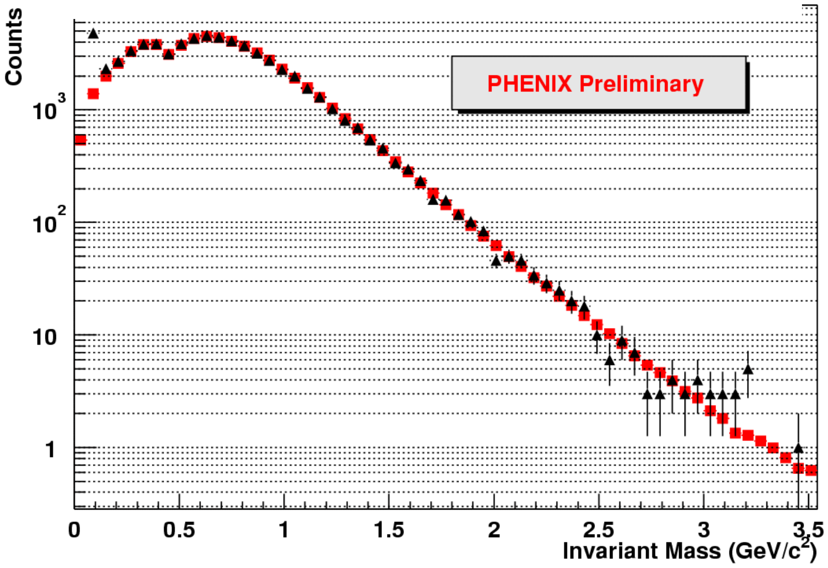
PHENIX electron ID



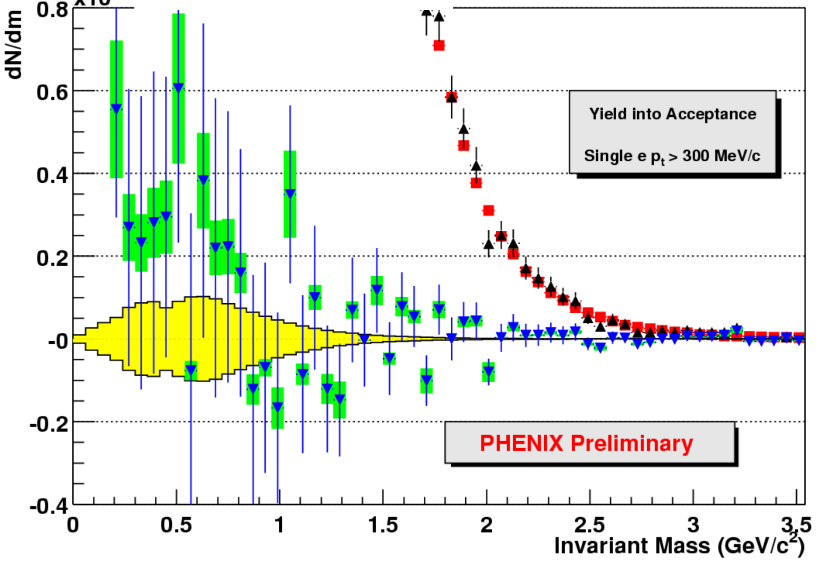
PHENIX measures dileptons

- first attempt from 2002 Au-Au Run
  - S/B ~ 1/500 (!) for minimum bias events
  - not enough statistics

Real and Mixed e^+e^- Distribution



Real - Mixed

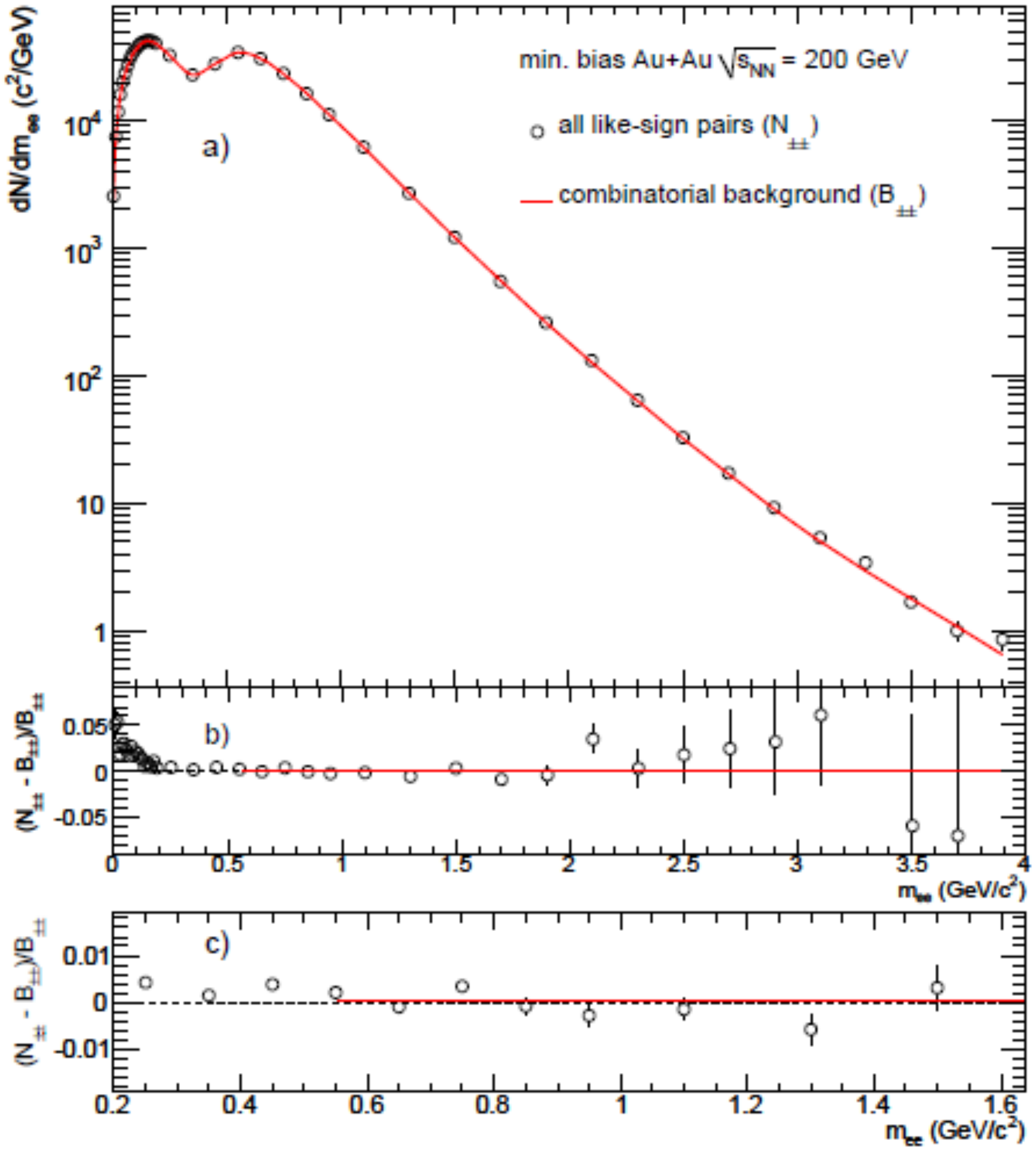


- Au-Au data taken in 2004
  - ~ 100x statistics
  - photon conversions reduced by factor 2-3
  - expect background reduction by ~ 2

- The signal is obtained by subtracting the combinatorial background (estimated by the like-sign pair yield or a mixed event technique) from the total unlike sign yield: S = U – B

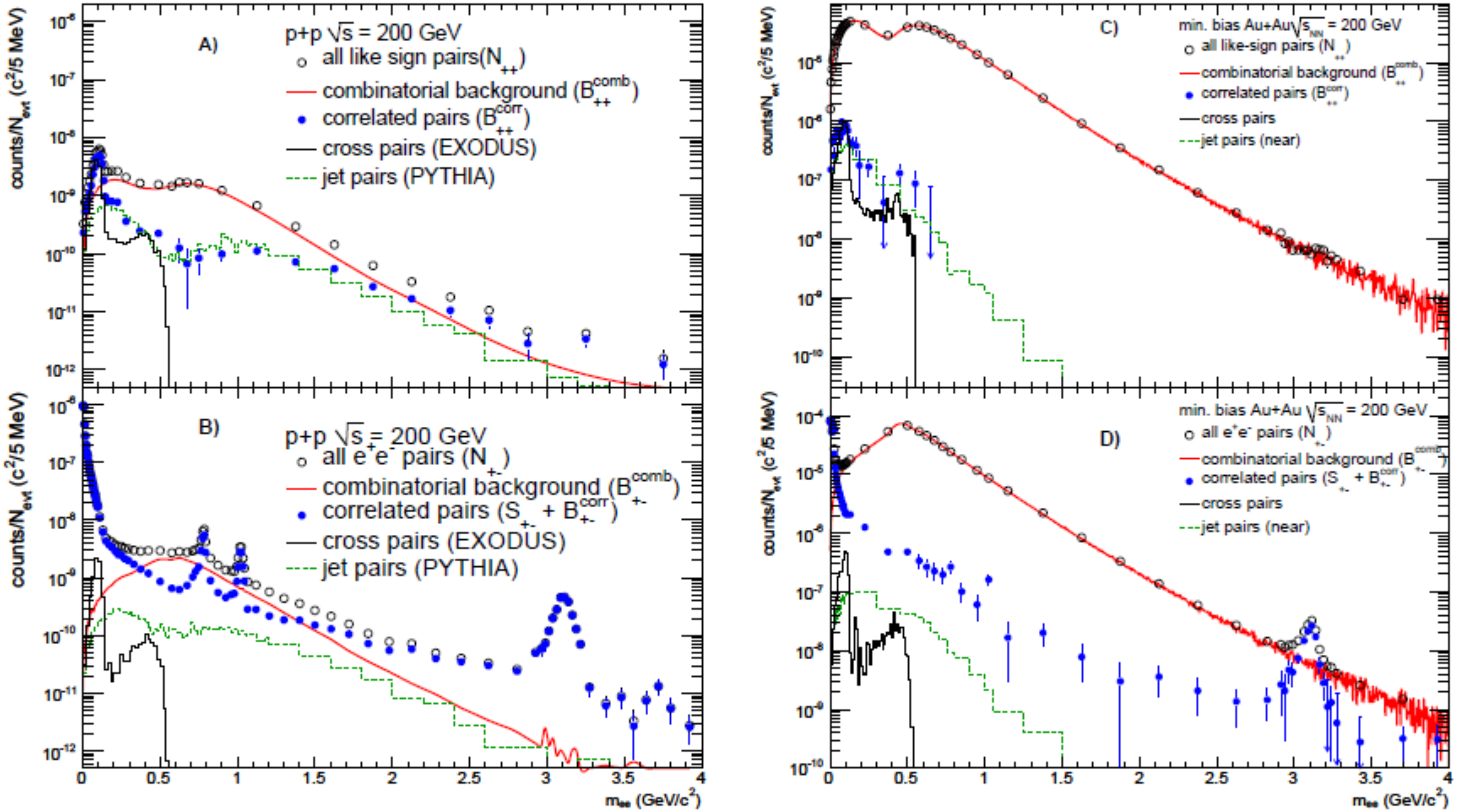
- A signal S = 10^4 pairs measured with a S/B = 1/250 has the same relative statistical error as 20 pairs measured in free background conditions.

- The ***systematic uncertainty*** in S is dominated by the systematic uncertainty in B. Even if the event mixing technique is mastered to a fantastic precision of ±0.25%, the resulting systematic uncertainty in S is >50% (assuming again S/B=1/250). Even in an infinite statistics measurement the systematic uncertainty will be huge.



- Shape determined with event mixing
  - Excellent agreements for like-sign pairs
- Normalization of mixed pairs
  - Small correlated background at low masses
  - normalize B_{++} and B_{--} to N_{++} and N_{--} for m_{ee} > 0.7 GeV/c^2
  - Normalize mixed B_{+-} pairs to $N_{+-} = 2\sqrt{N_{++}N_{--}}$
  - Subtract correlated background
- Systematic uncertainties
  - statistics of N_{++} and N_{--} : 0.12%
  - different pair cuts in like and unlike sign: 0.2 %

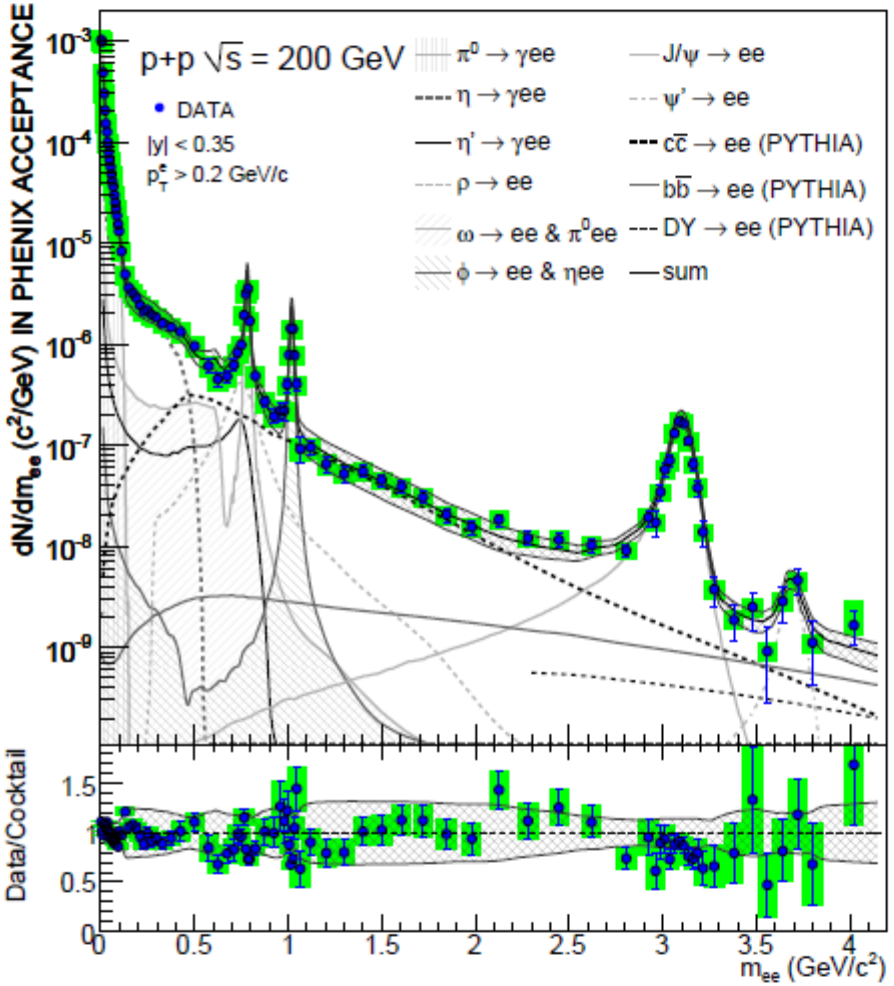
p+p **Au+Au**



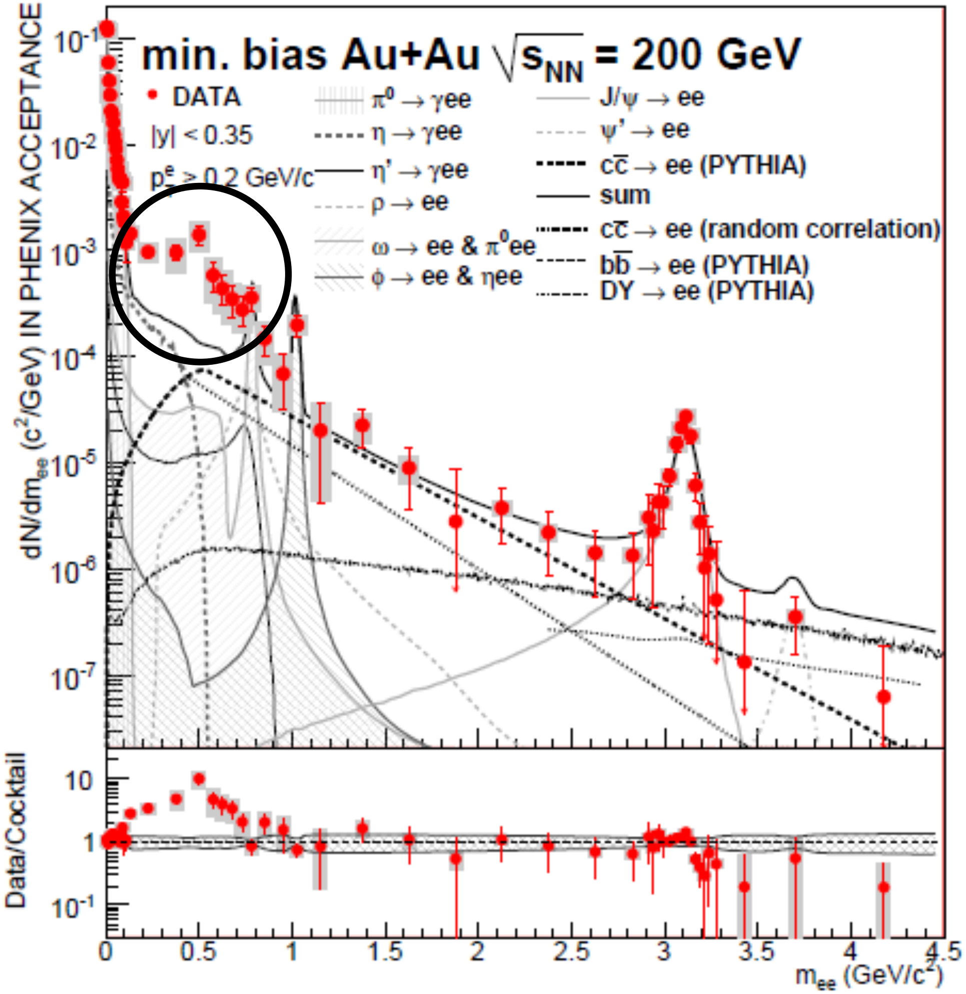
A)
$p+p\ \sqrt{s} = 200$ GeV
all like sign pairs(N_{++})
combinatorial background (B^{comb}_{++})
correlated pairs (B^{corr}_{++})
cross pairs (EXODUS)
jet pairs (PYTHIA)
B)
$p+p\ \sqrt{s} = 200$ GeV
all e^+e^- pairs (N_{+-})
combinatorial background (B^{comb}_{+-})
correlated pairs ($S_{+-} + B^{corr}_{+-}$)
cross pairs (EXODUS)
jet pairs (PYTHIA)
C)
min. bias Au+Au $\sqrt{s_{NN}} = 200$ GeV
all like-sign pairs (N_{++})
combinatorial background (B^{comb}_{++})
correlated pairs (B^{corr}_{++})
cross pairs
jet pairs (near)
D)
min. bias Au+Au $\sqrt{s_{NN}} = 200$ GeV
all e^+e^- pairs (N_{+-})
combinatorial background (B^{comb}_{+-})
correlated pairs ($S_{+-} + B^{corr}_{+-}$)
cross pairs
jet pairs (near)
counts/N_{evt} (c^2/5 MeV)
m_{ee} (GeV/c^2)
0
0.5
1
1.5
2
2.5
3
3.5
4
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-5}

Cocktail comparison

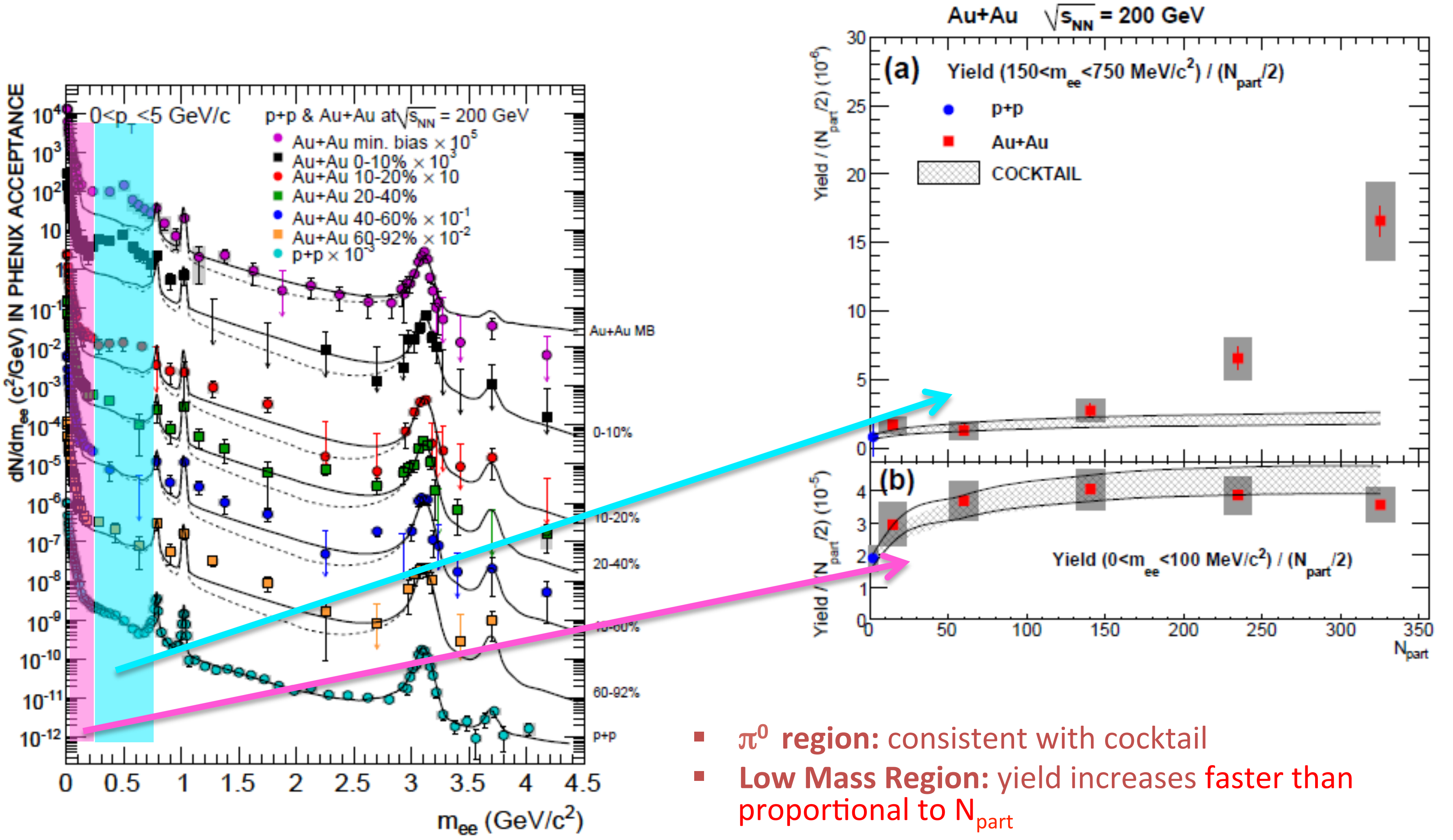
PLB 670,313(2009) arXiv:0912.0244



arXiv:0912.0244



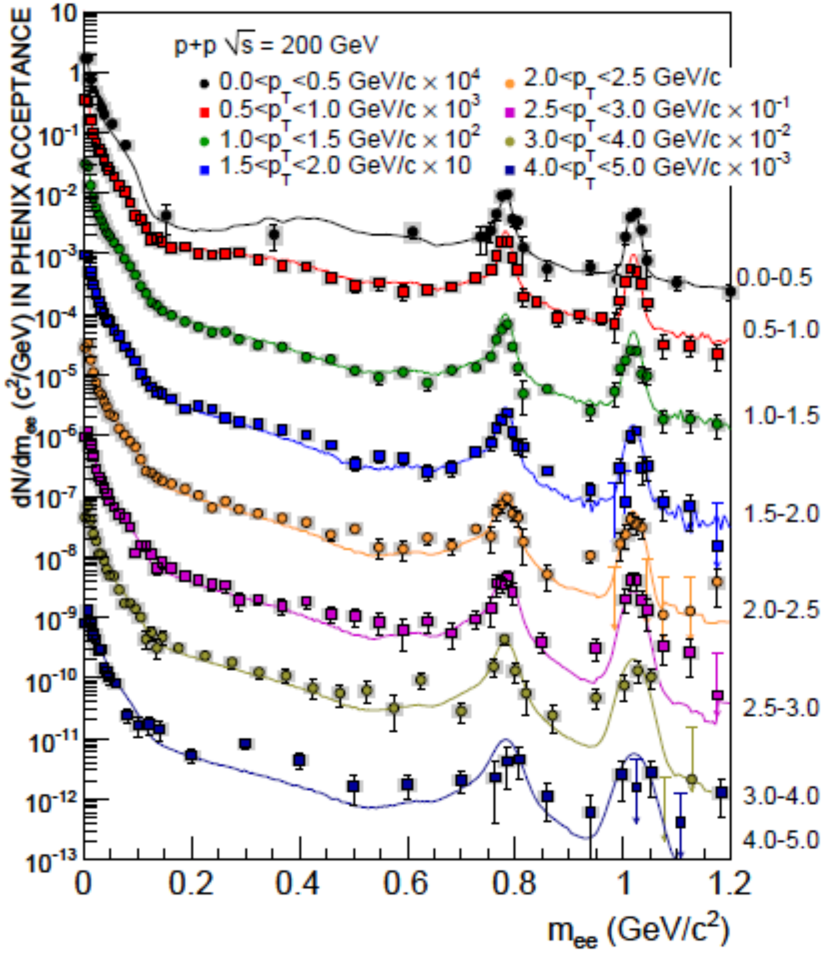
Centrality dependence

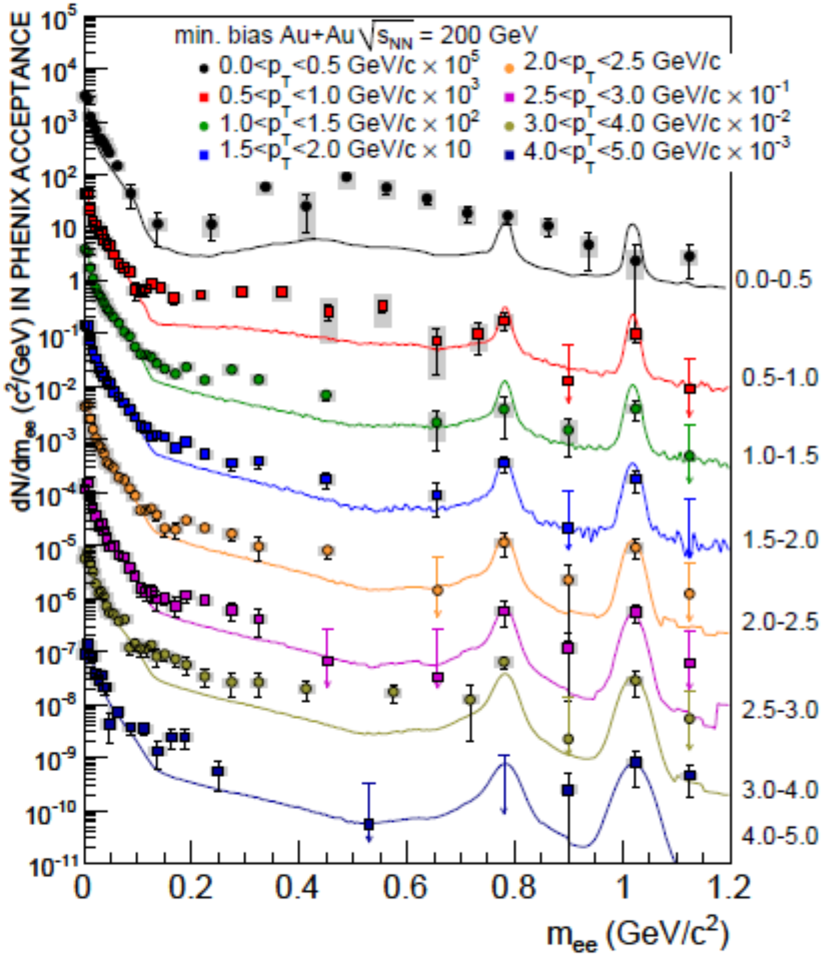


- **π^0 region:** consistent with cocktail
- **Low Mass Region:** yield increases faster than proportional to N_{part}

- → enhancement from binary annihilation ($\pi\pi$ or qq) ?

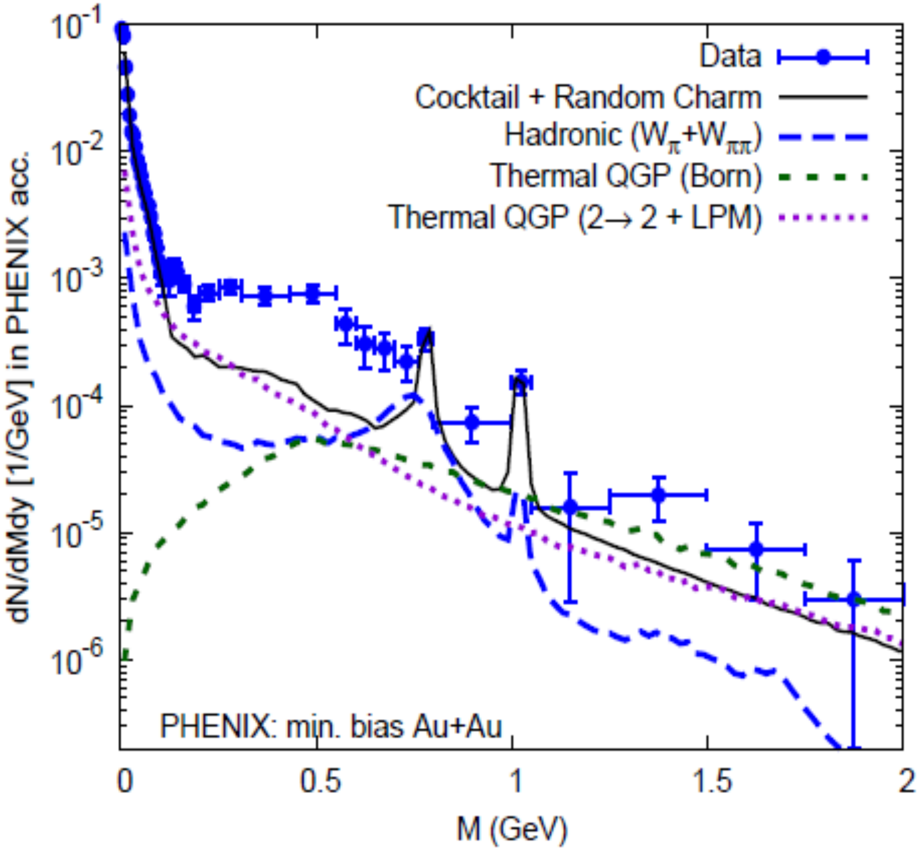
Momentum dependence



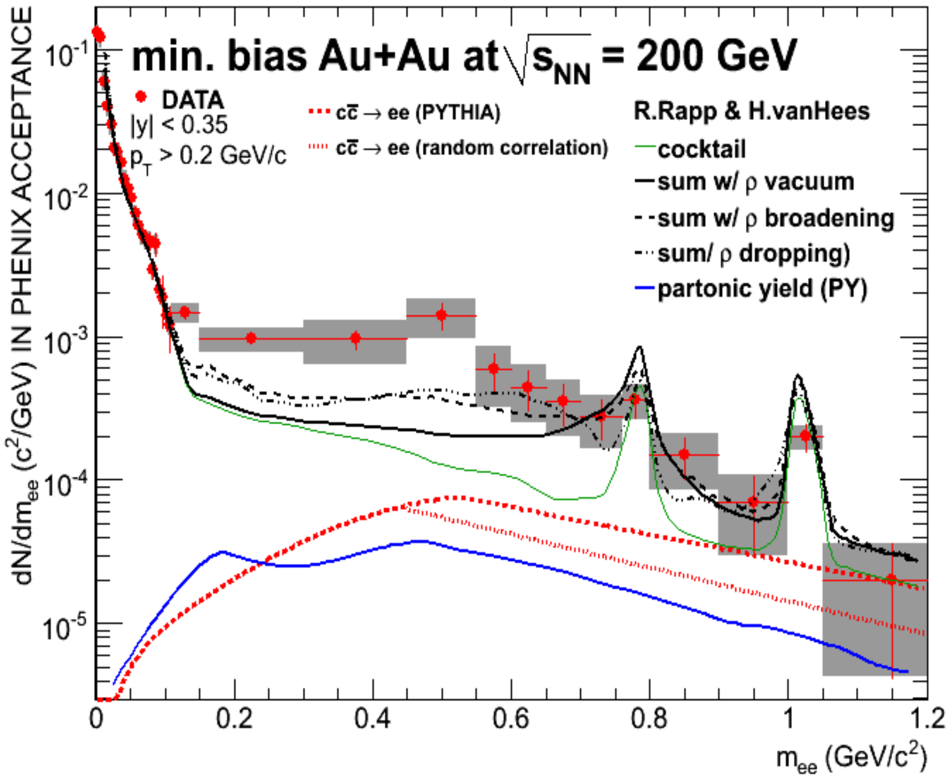


Comparison of thermal emission calculations

Chiral Reduction + Hydro

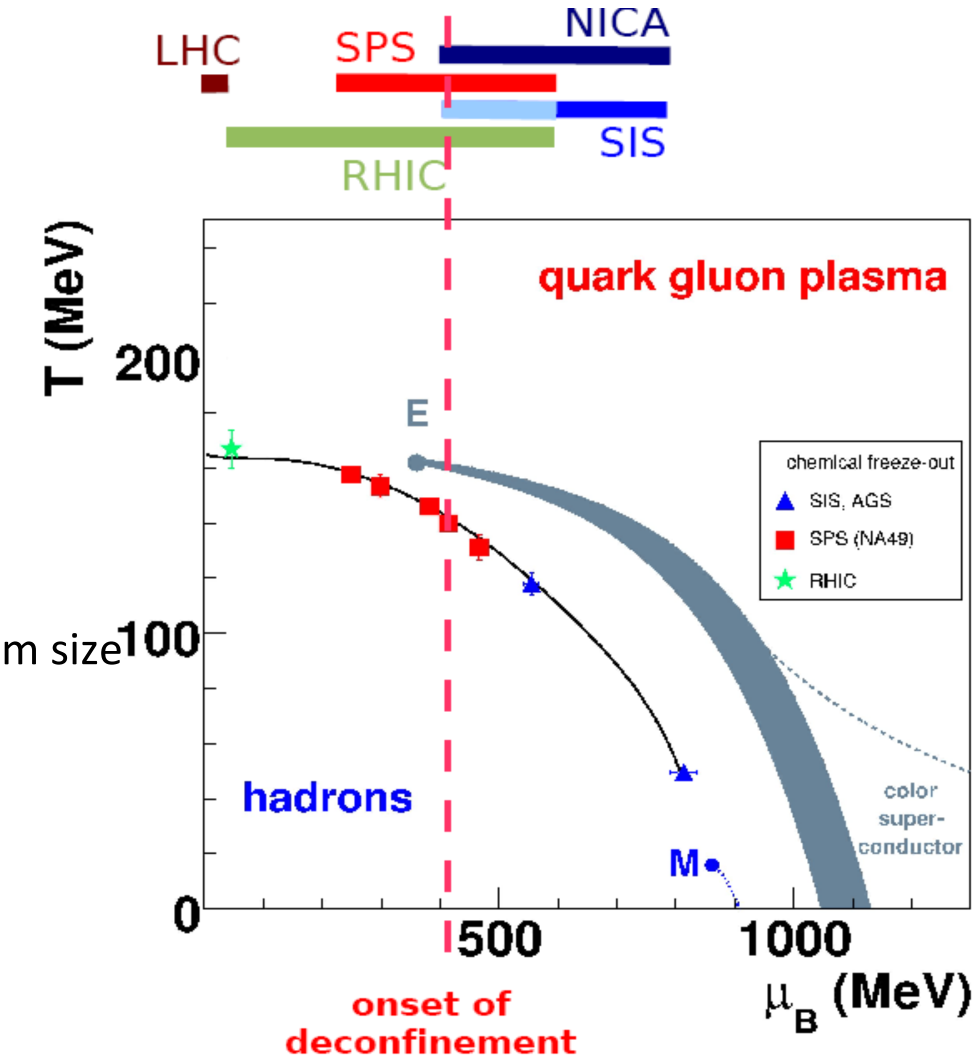


Hadronic Many-Body + Fireball



Future explorations

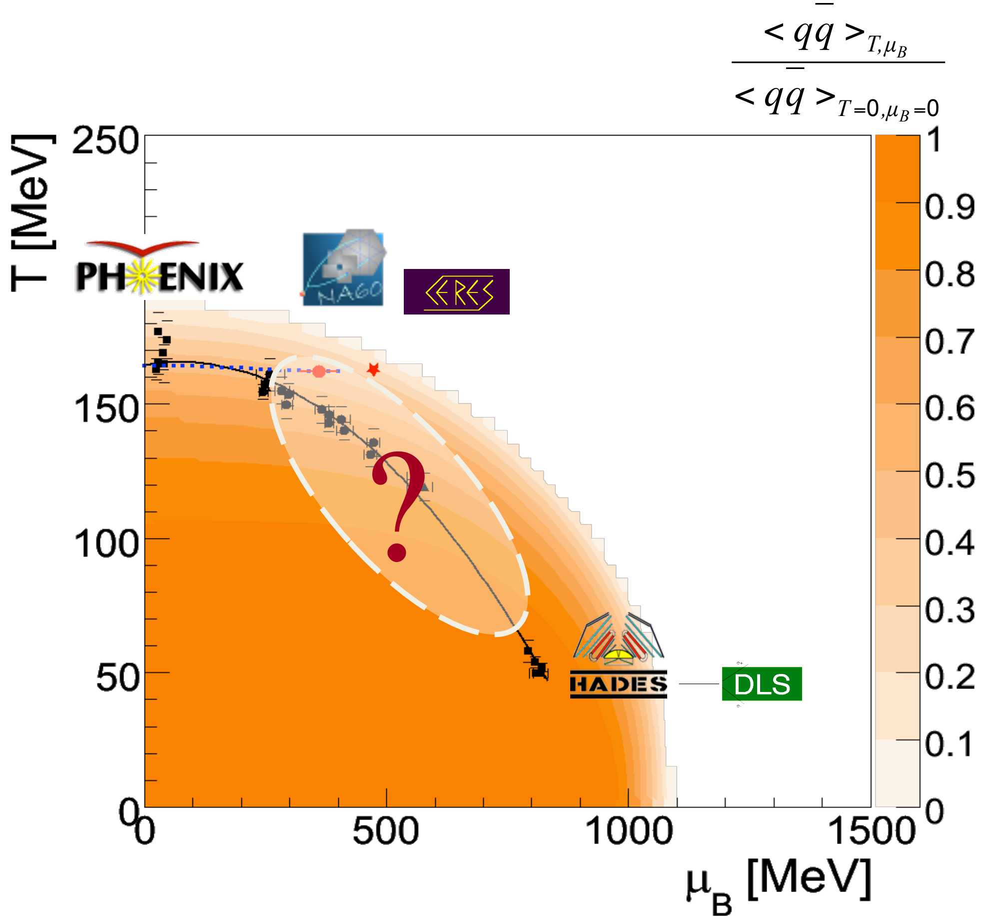
Goal: complete scan of the QCD phase diagram with modern, 2nd generation experiments on the horizon!



- RHIC beam energy scan
  - evolution of medium properties
  - search for CP and PT
- NA61 at SPS (2007 acc. by SPSC)
  - search for CP and PT in energy-system size scan

  Both essentially limited to high yield observables
- FAIR and NICA
  - new accelerator projects
  - FAIR: high intensities! → rare probes!

Searching for the landmarks of the phase diagram of matter



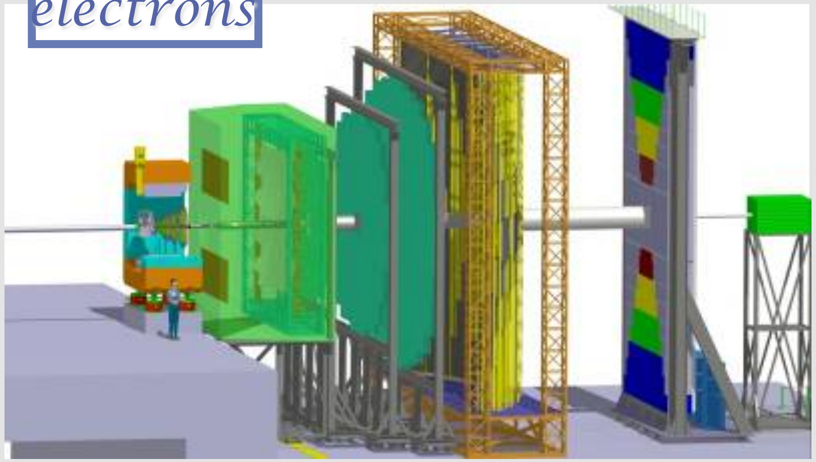
- Highly interesting results from RHIC to SIS → importance of baryons!
- No measurement for beam energies of 2-40 AGeV

- Experimental focus on rare diagnostic probes:
  - Charm:
    - how are the produced charm quarks propagating in the dense phase (J/ψ, ψ‘, D, Λ_c for a complete picture)
  - Low-mass lepton pairs:
    - electromagnetic structure of hadrons,
    - emissivity of dense matter,
    - thermal radiation?

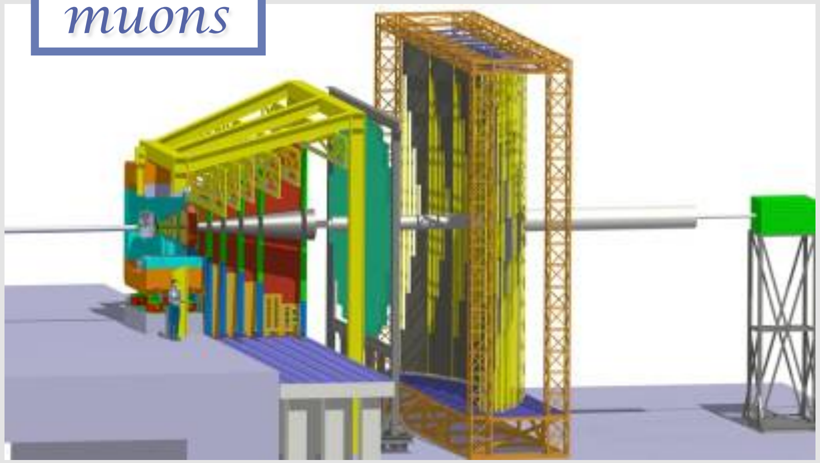
- Fastest HI detector ever: more than one million reactions / second
- Fast high resolution tracking in a compact dipol field directly after the target
- High speed DAQ and trigger
- Excellent particle identification
- Flexible arrangement of PID detectors and calorimeters:

- **Aim:** optimize setup to include both, electron and muon ID

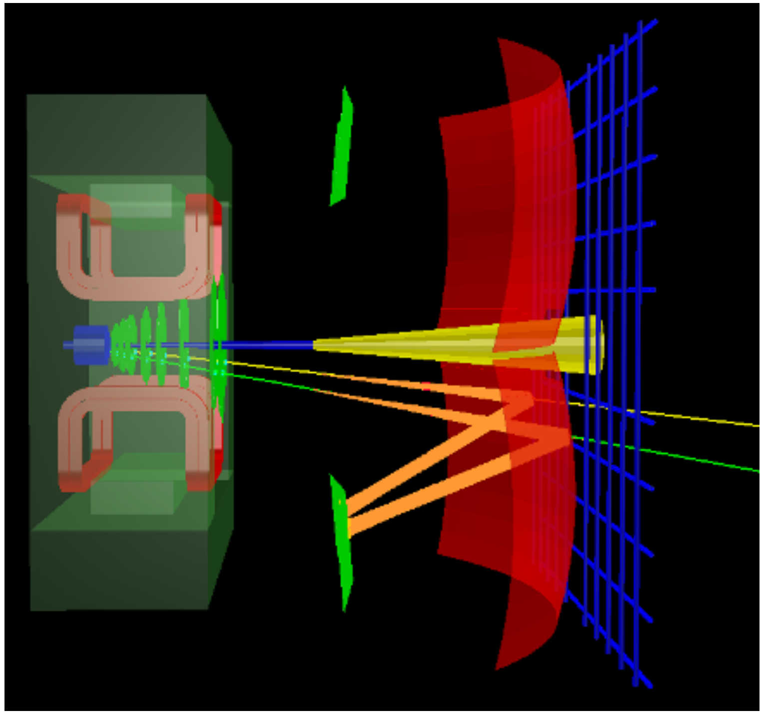
electrons



muons



Dieletron reconstruction in CBM: the challenge



- Without hadron-blind detector before the tracknig
- Background due to material budget of the STS
- Sufficient π discrimination (misidentification $<10^{-4}$)

$e^+ e^- \gamma$

1.2%

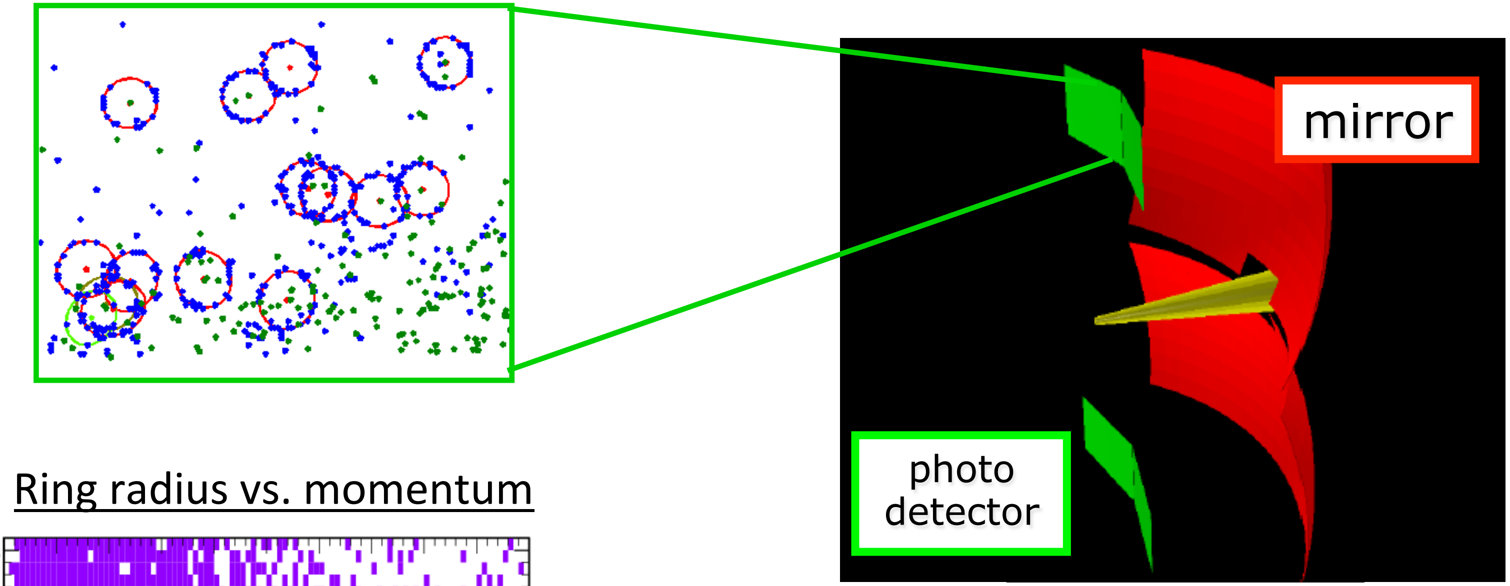
↑

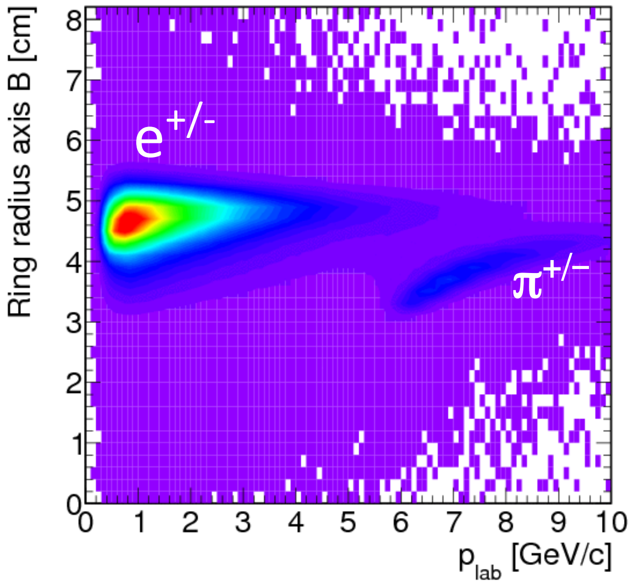
~350 $\pi^0 \rightarrow$ 98.8% $\gamma\gamma$

~3 $\gamma_{target} \rightarrow e^+e^-$

~700 $\pi^{+/-}$ could be identified as an electron

Electron identification in RICH

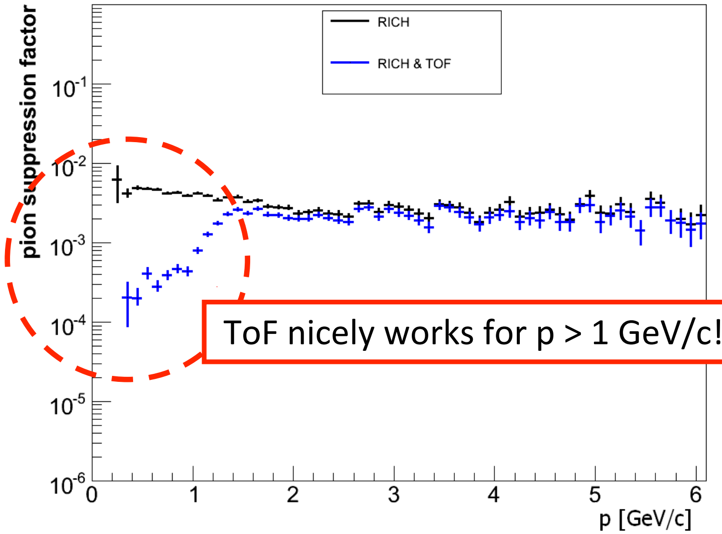



Ring radius vs. momentum

- RICH: strategy and R&D
  - Conventional design based on commercial products
  - Float glass mirror (carbon as backup)
  - Multi-anode PMT photodetector

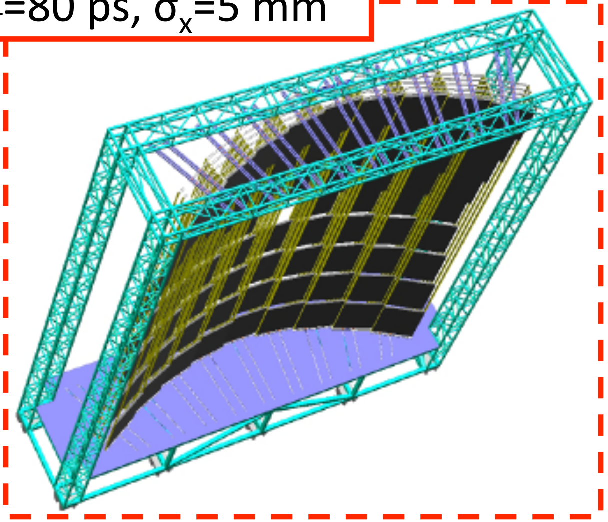
Electron identification using Time-Of-Flight information

π supression factor

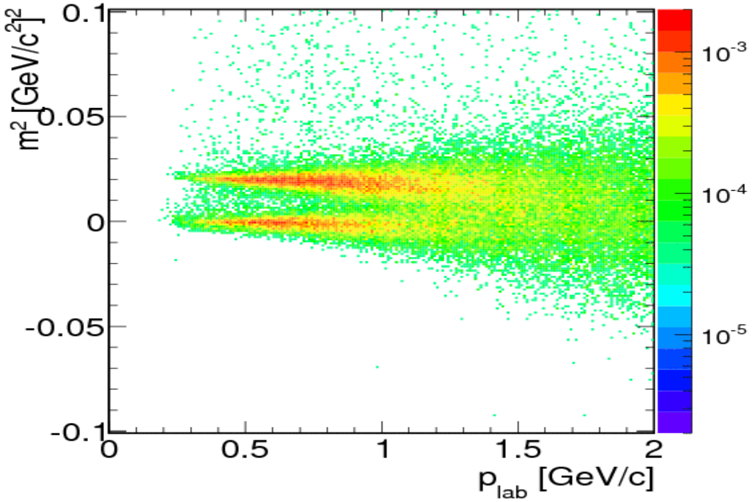


ToF nicely works for p > 1 GeV/c!

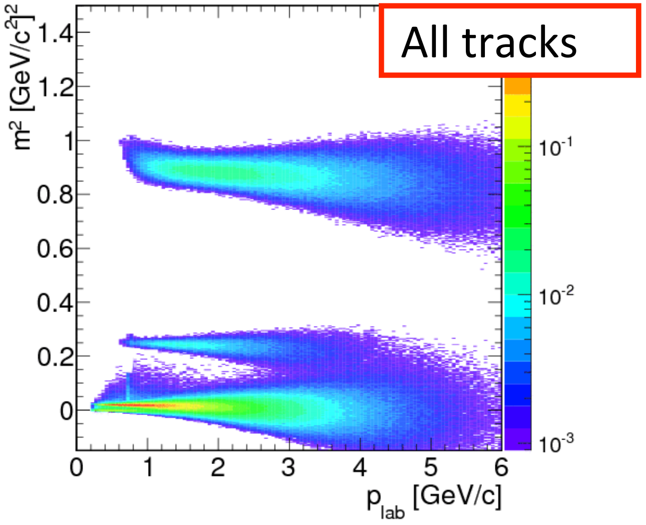
σ_T=80 ps, σ_x=5 mm



RICH identified electrons in TOF



m^2 vs momentum distribution



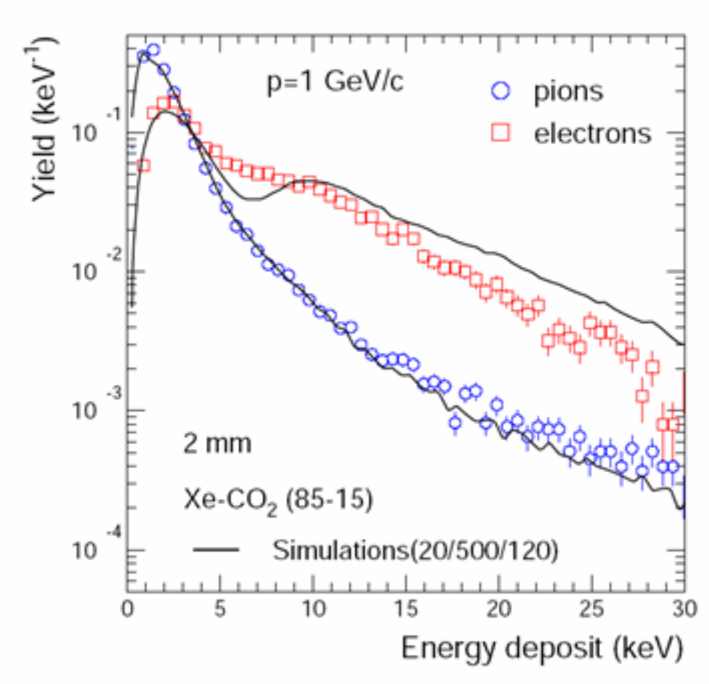
All tracks

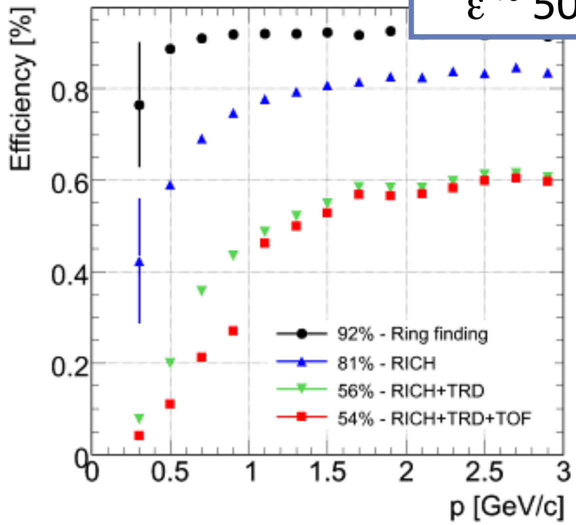
Electron identification using TRD

- TRD: strategy and R&D
  - Thin gap design based on ALICE TRD

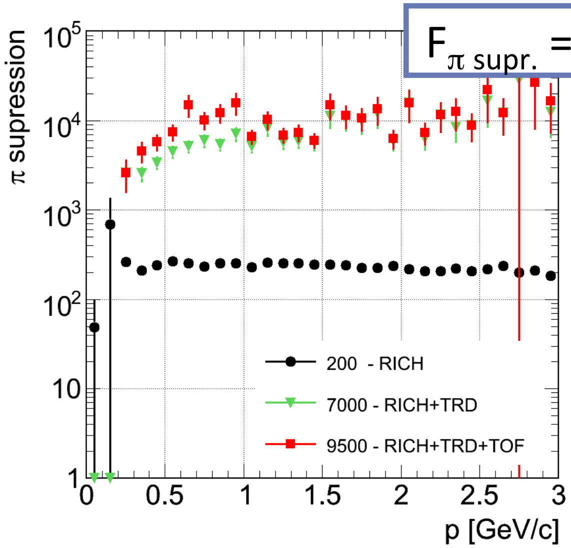
- 3 TRD detectors, each consist of 4 layers

Use statistical analysis of the energy loss spectra to further discriminate π



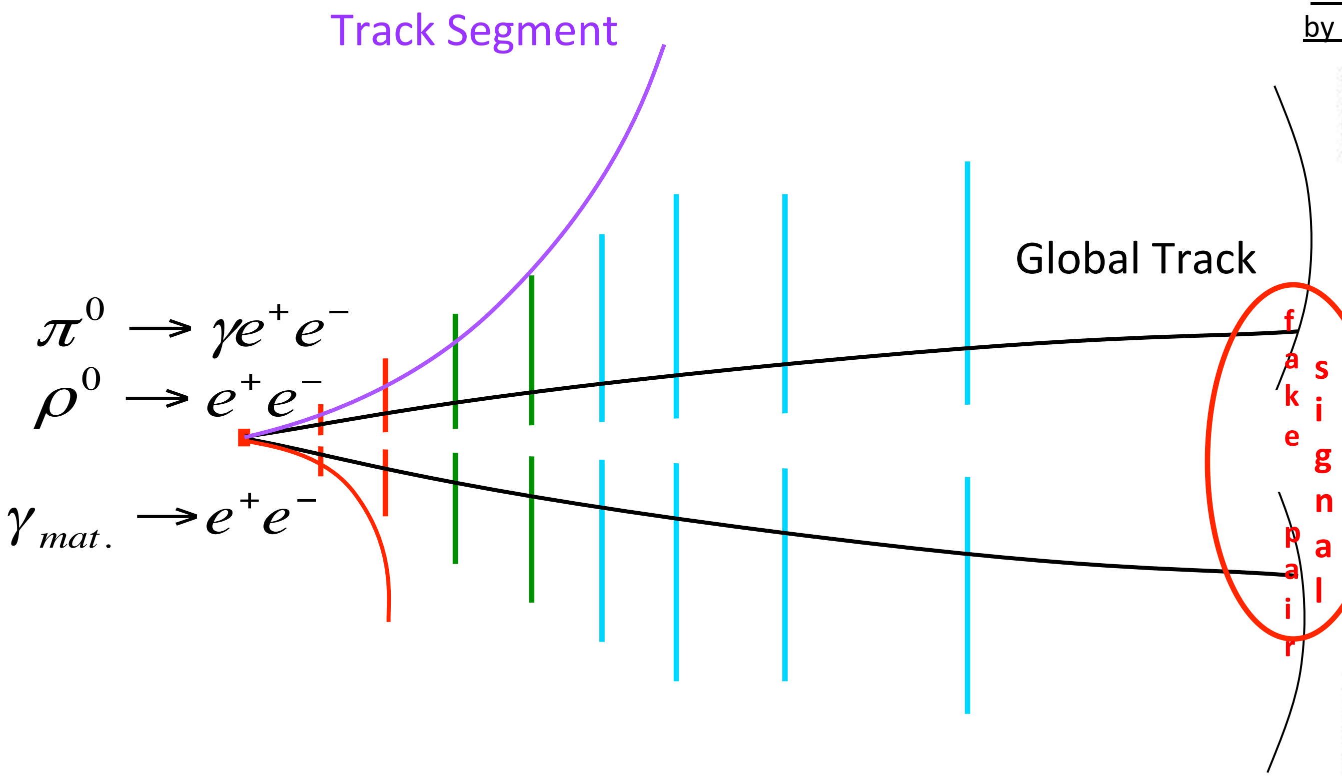


ε ~ 50%



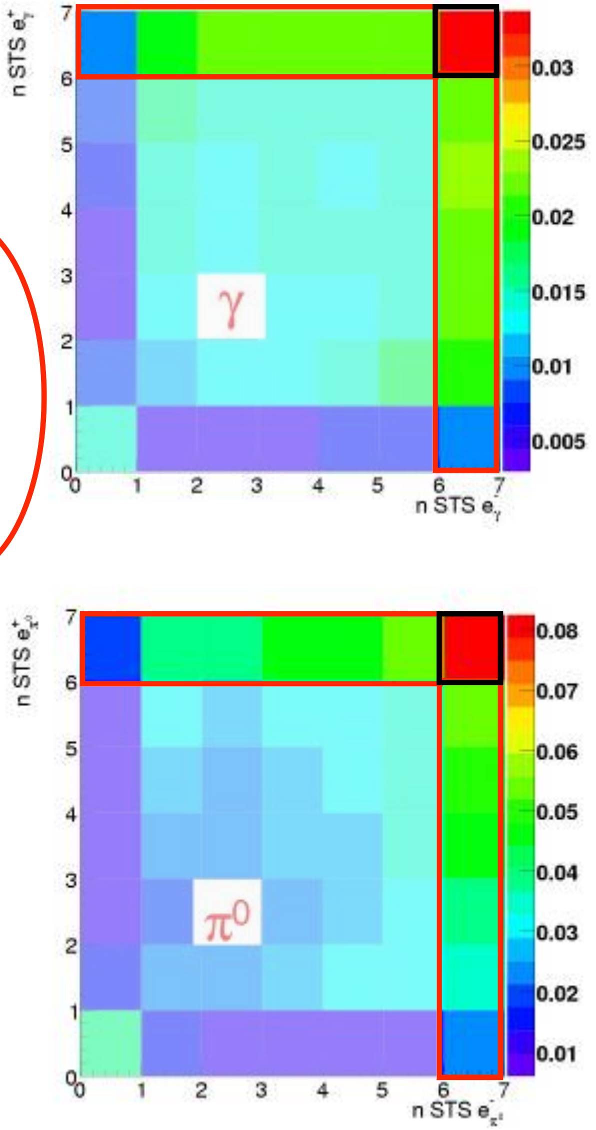
$F_{\pi\ \mathrm{supr.}} = 9500$

Combinatorial background topology



$$\pi^0 \rightarrow \gamma e^+ e^-$$
$$\rho^0 \rightarrow e^+ e^-$$
$$\gamma_{mat.} \rightarrow e^+ e^-$$

Correlation of the number of STS traversed by e^+e^- pairs from γ conversion and π^0-Dalitz



Small (moderate) opening angle and/or asymmetric laboratory momenta.

Track Fragment - x, y position; no charge information

Track Segment - reconstructed track

Global Track - identified in RICH

The muon option

- Goal:
  - Clean dilepton signal for charm measurement and low-mass pairs
- Challenge:
  - μ at low energies!
    - Large energy loss and substantial multiple scattering of muons in the absorber
  - High areal particle rates in first detector.
    - smallest pad 2.8 × 2.8 mm^2
    - 0.7 hit/cm^2 ≅ 0.4 μA/cm^2 (full intensity)
- Strategy:
  - Identification after hadron absorber with intermediate tracking layers
  - Detector technology still under discussion, probably combination of several depending on rates
  - Triple GEM detectors with pad read-out