The experimental quest for in-medium effects
Episode I

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The standard model and QCD

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

- Strong interaction:
  - binds quarks into hadrons
  - binds nucleons into nuclei
- Described by QCD:
  - interaction between particles carrying color charge (quarks, gluons)
- Mediated by strong force carriers (gluons)
- Very successful theory
  - jet production
  - particle production at high p_T
  - heavy flavor production
  - ...
- ***… but with outstanding puzzles***

Two puzzles in QCD: confinement

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- Nobody ever succeeded in detecting an isolated quark
- Quarks seem to be permanently confined within protons, neutrons, pions and other hadrons
- It looks like one half of the fundamental fermions are not directly observable...

… how does this come about?

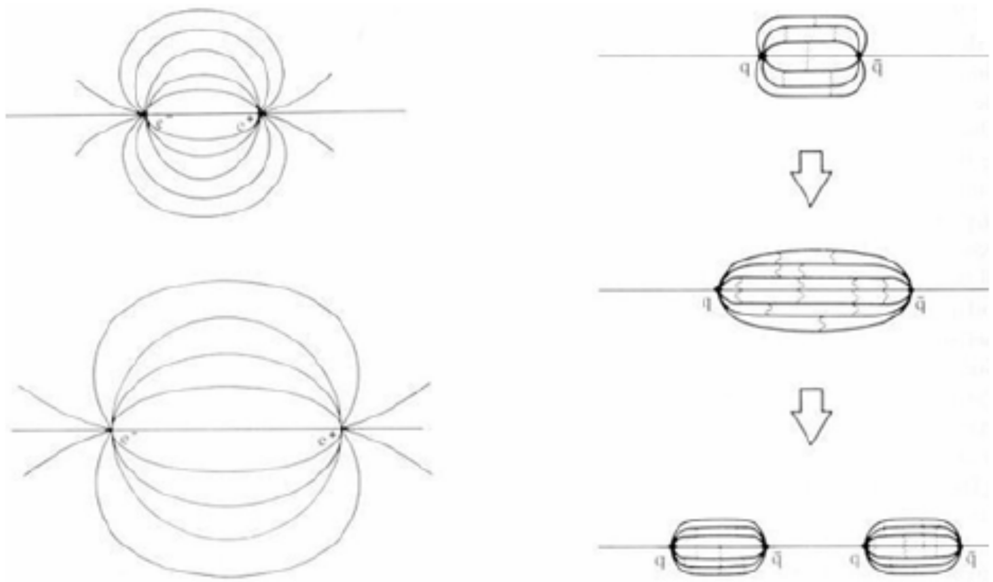
QCD confinement

- If the distance between two quarks gets larger, more and more
- gluons contribute to the interaction between the quarks.

- Hence the potential energy grows with increasing distance.

- At some point, enough energy is stored in the field to produce
- a pair of quarks out of the vacuum (observed as jet).

$$V(r) \propto -\frac{\alpha_s(r)}{r} + \kappa r$$



Two puzzles in QCD: hadron masses

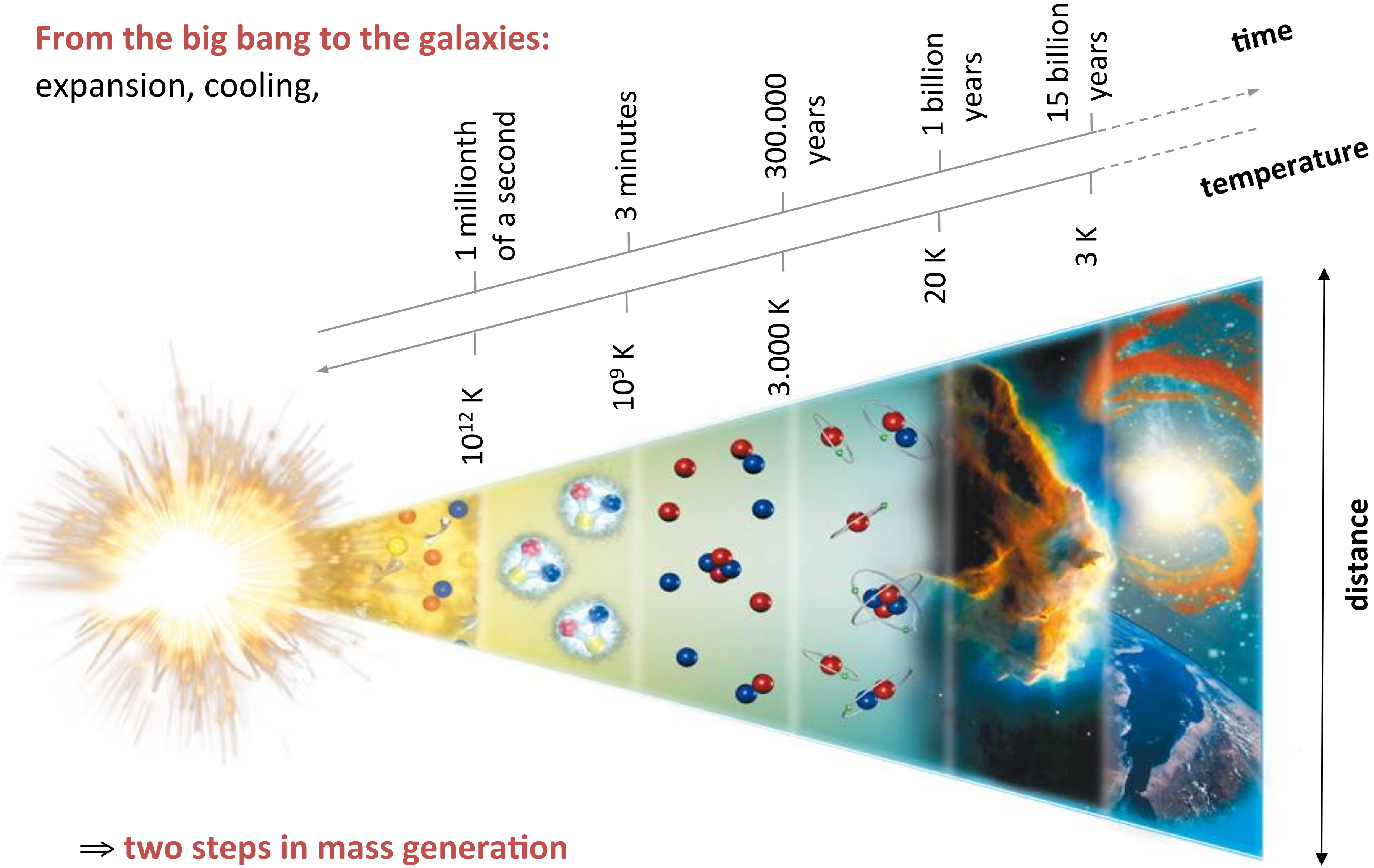
- A proton is thought to be made of two u and one d quarks
- The sum of their masses is around 12 MeV
- ***... but the proton mass is 938 MeV!***

How does nature generate massive hadrons from nearly mass-less quarks?

Evolution of the Universe

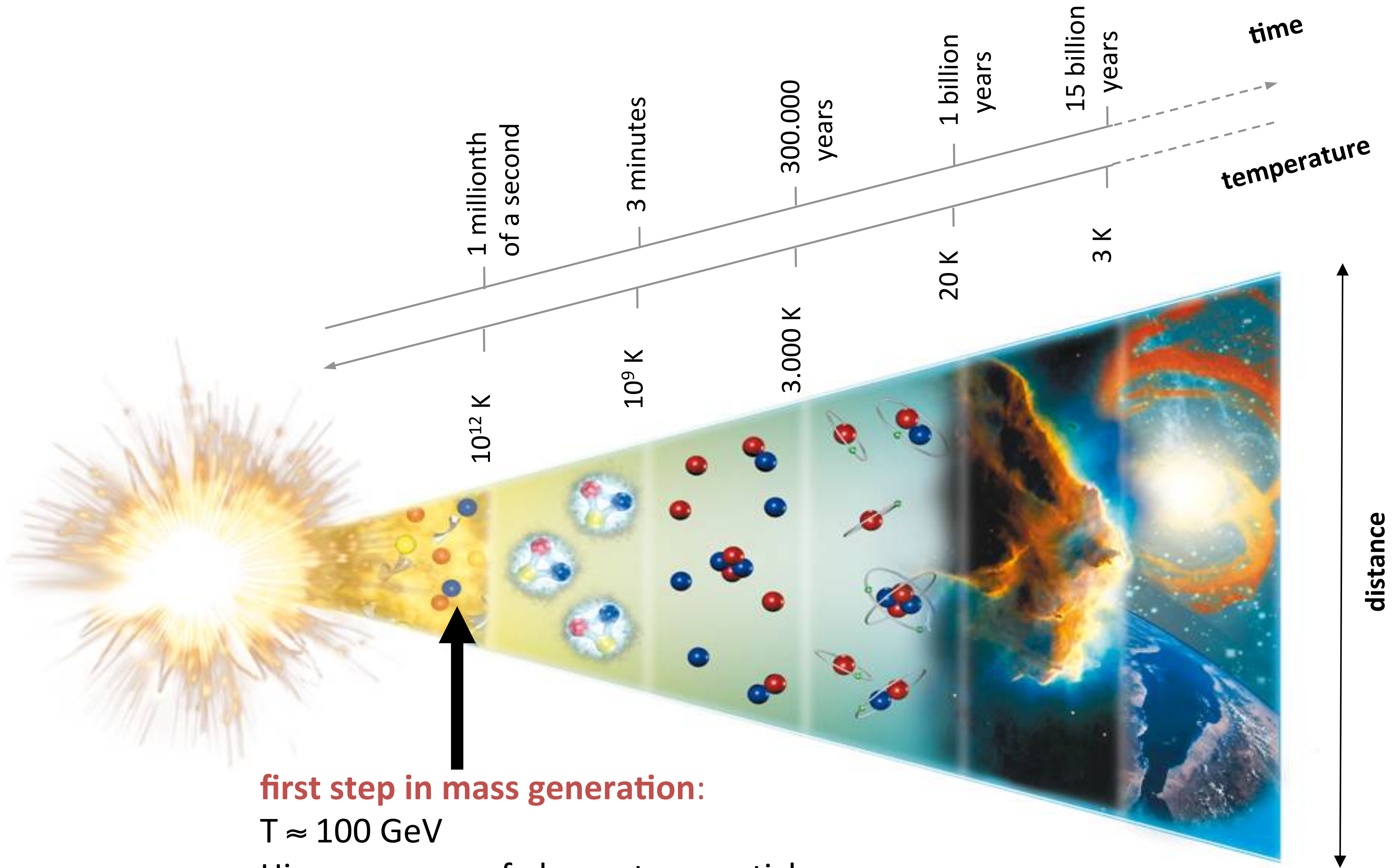
From the big bang to the galaxies:

expansion, cooling,



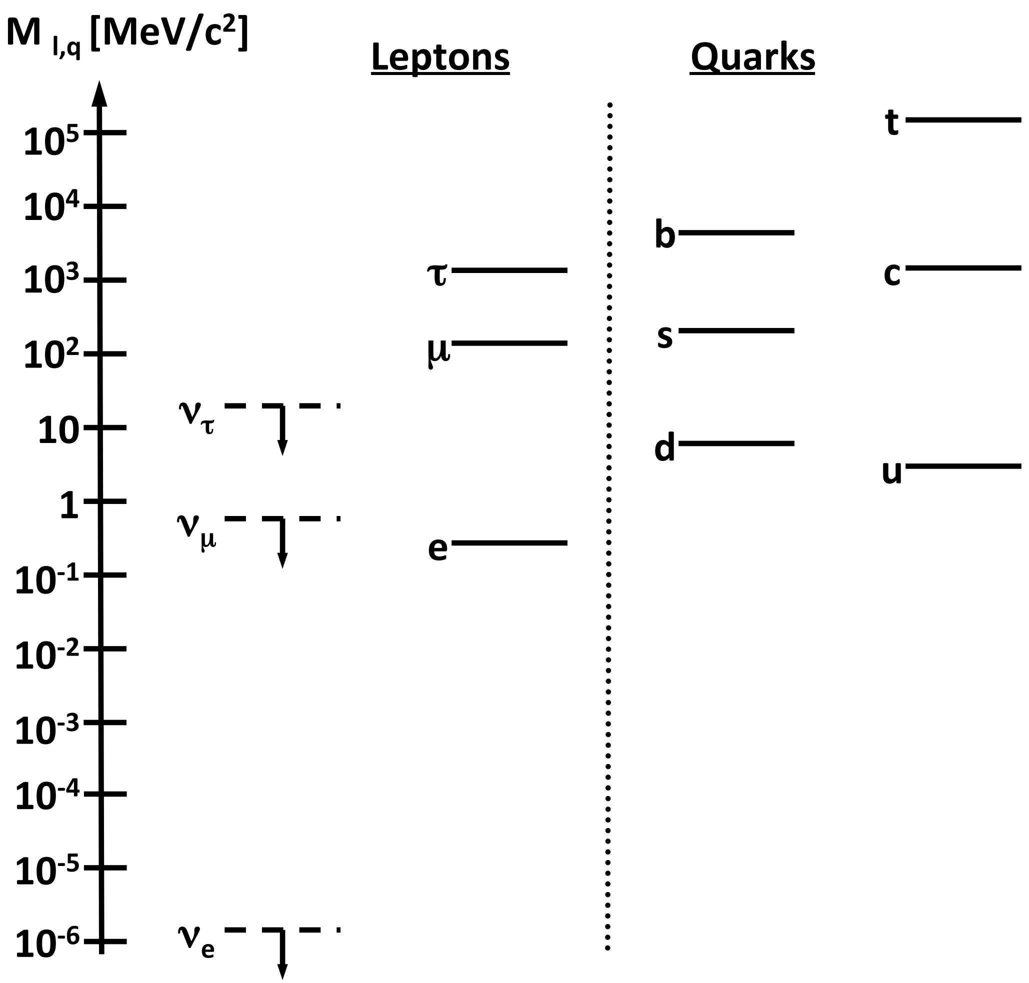
⇒ **two steps in mass generation**

Evolution of the Universe



first step in mass generation:
T ≈ 100 GeV
Higgs ⇔ mass of elementary particles

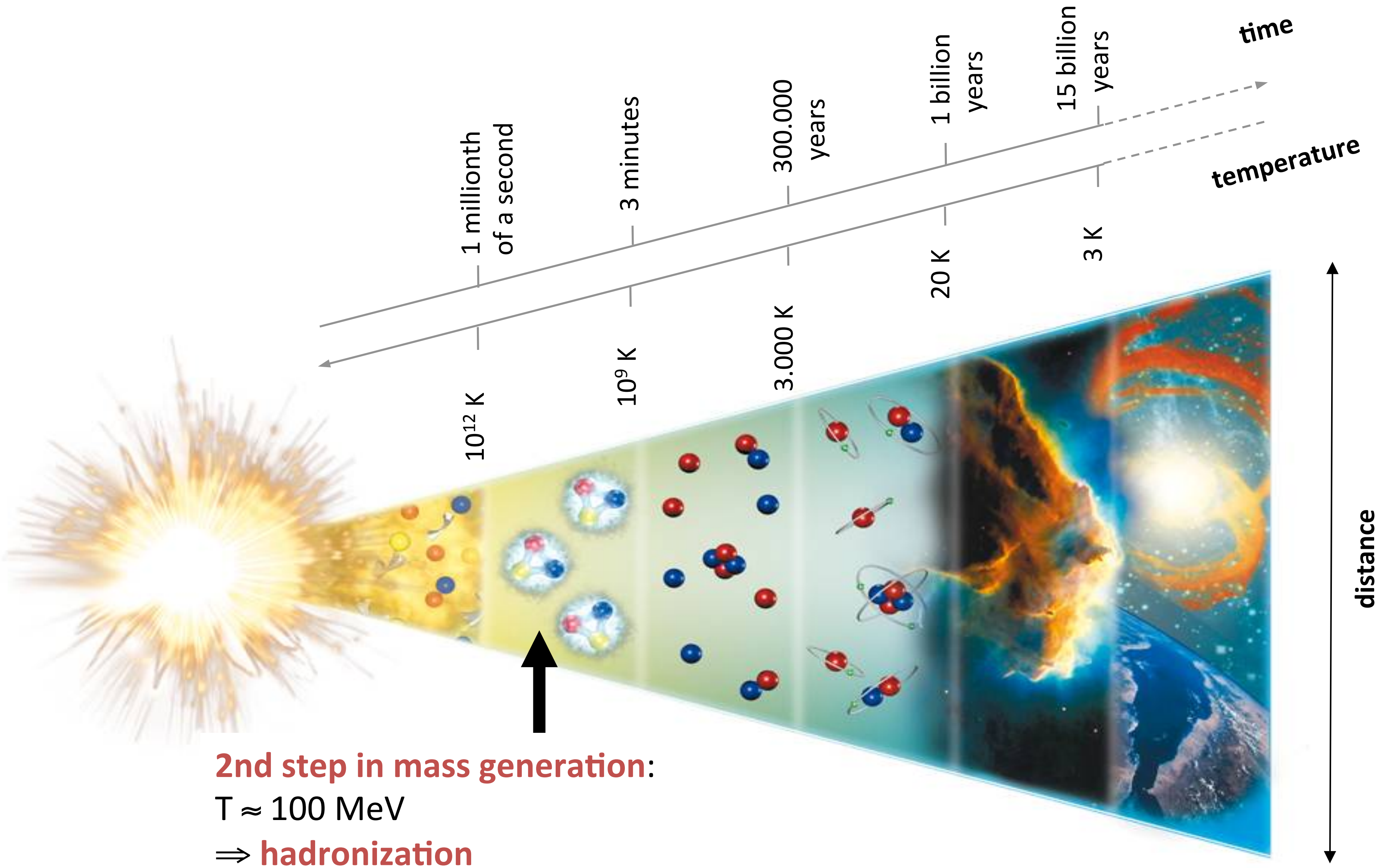
Masses of quarks and leptons



masses of elementary particles
(quarks, leptons) generated
by interaction with Higgs-field

⇒ search for **Higgs-particle** (LHC)

Evolution of the Universe



2nd step in mass generation:
T ≈ 100 MeV
⇒ **hadronization**

Condensation in vacuum

- **Higgs generates ~2% and**

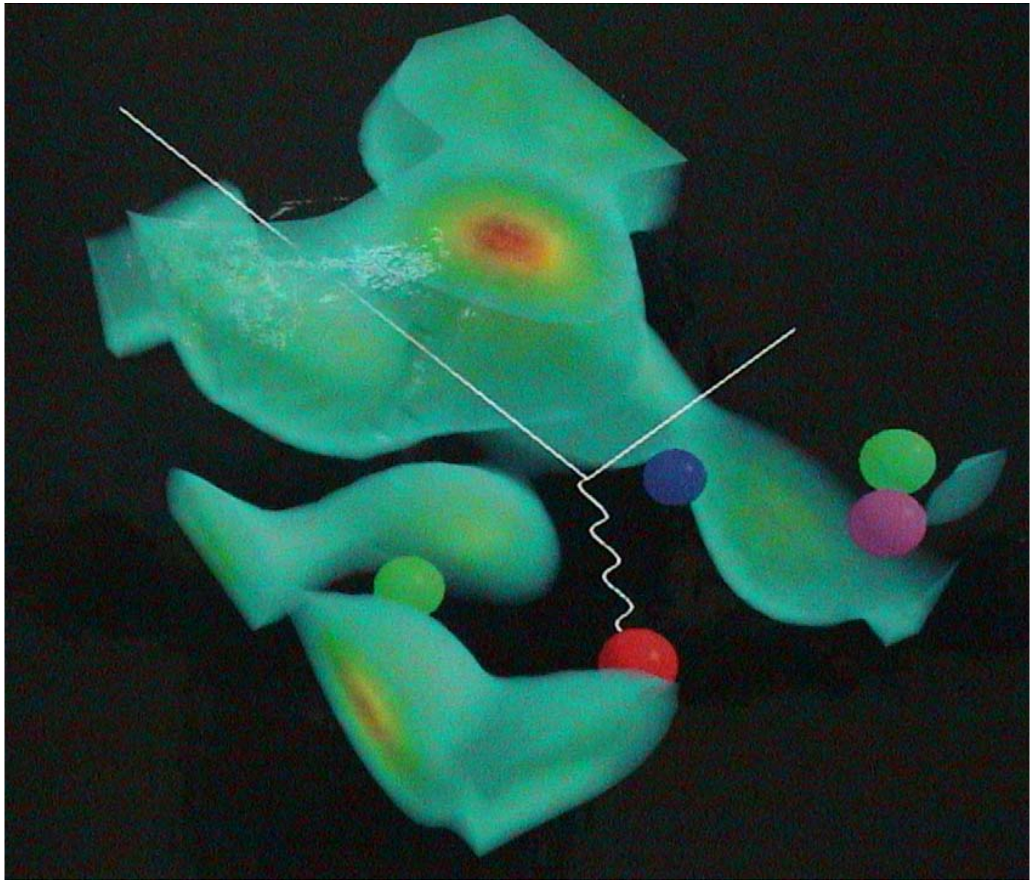
  QCD generates 98% of the mass of ordinary matter !!!

- **How can we experimentally prove this scenario?**

- Experiments at the large hadron collider (LHC) at CERN will search the Higgs particle, the missing piece in the Standard Model.

- However, the chiral condensate cannot be studied this way, it is not an observable. Theoretical models are used to link observables to the quark-condensate.

The nucleon is a complex object



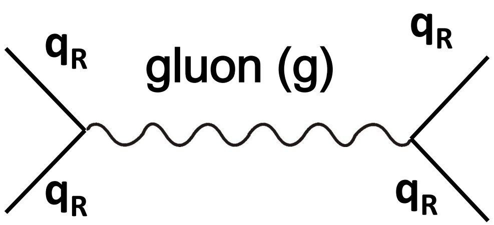
Hadrons are very complex excitations of valence quarks in the present of quark and gluon condensates.

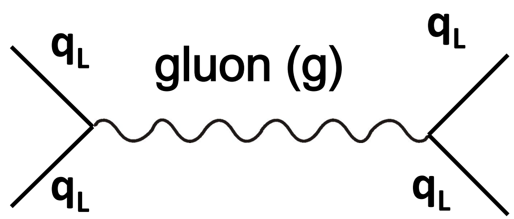
nucleon: mass not determined by sum of constituent masses $m = E/c^2$; „mass without mass“ (Wilczek) mass given by energy stored in motion of quarks and by energy in color gluon fields

Role of chiral symmetry

Chiral symmetry = fundamental symmetry of QCD for massless quarks (m_q=0)

In the interaction among quarks by gluon exchange right-handed quarks q_R (spin and momentum parallel) stay right-handed and left-handed quarks q_L stay left-handed → chirality is conserved

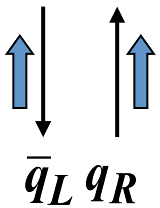




For m_q= 0 the QCD Lagrangian is invariant under the $SU(3)_R \otimes SU(3)_L$ transformations

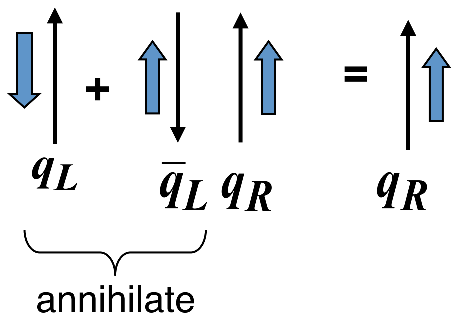
Chiral symmetry breaking

The ground state of QCD (vacuum) is populated by quark – anti-quark pairs (*<qqbar>* condensate) and does not share the symmetry of the Lagrangian



chiral condensate

A left-handed quark q_L can be converted into a right-handed quark q_R *(*spin and momentum parallel*)* by interaction with a scalar *q – anti-q* pair



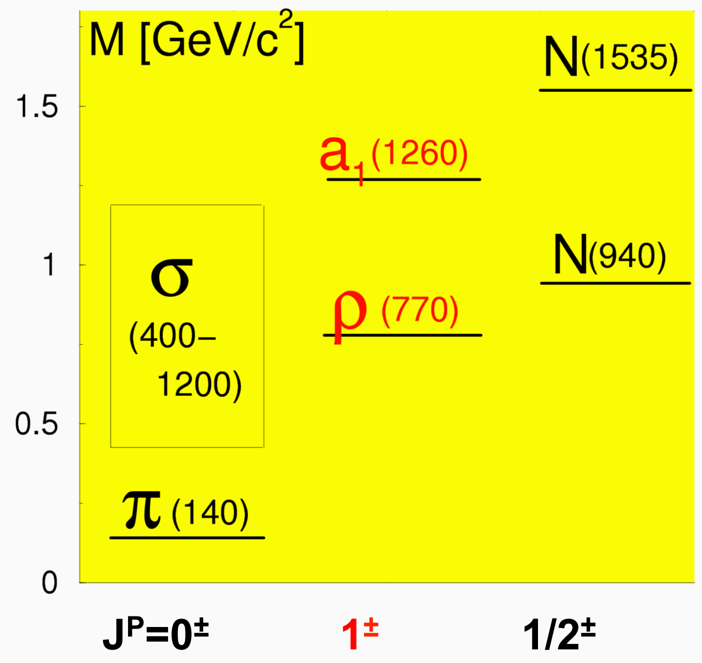
Due to the condensate

chiral symmetry is broken!

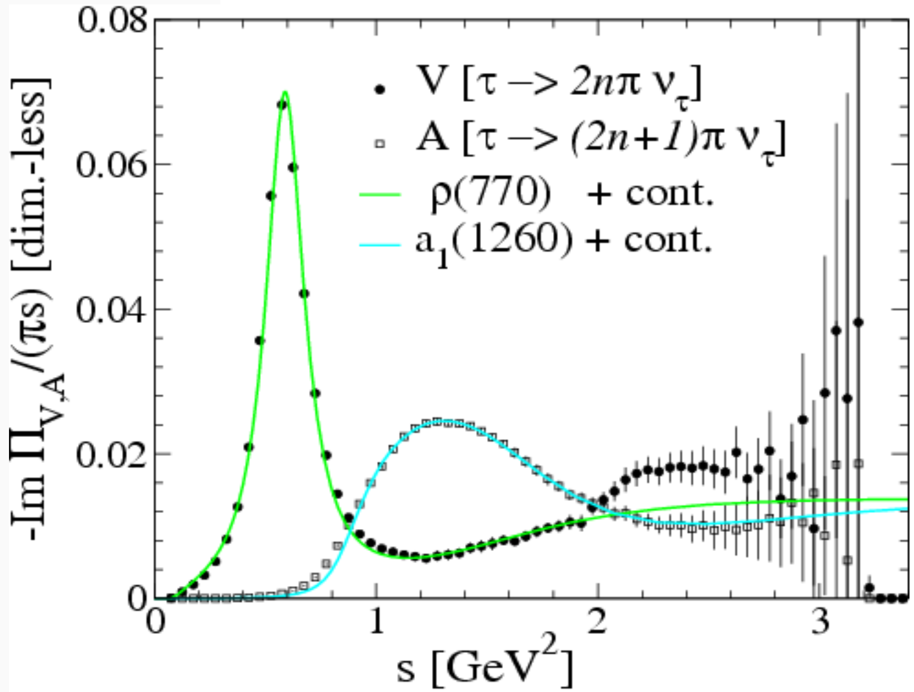
- **If chiral symmetry** were to hold also in the **hadronic sector** we would expect chiral partners with same spin but opposite parity to be **degenerate in mass:**
  - e.g., nucleon N: $J^\pi = 1/2^+$; chiral partner: $J^\pi = 1/2^-$ mass degenerate??

"chiral partners" split: ***ΔM ≈ 0.5GeV***

mass split comparable to hadron masses



Axial-/Vector Correlators



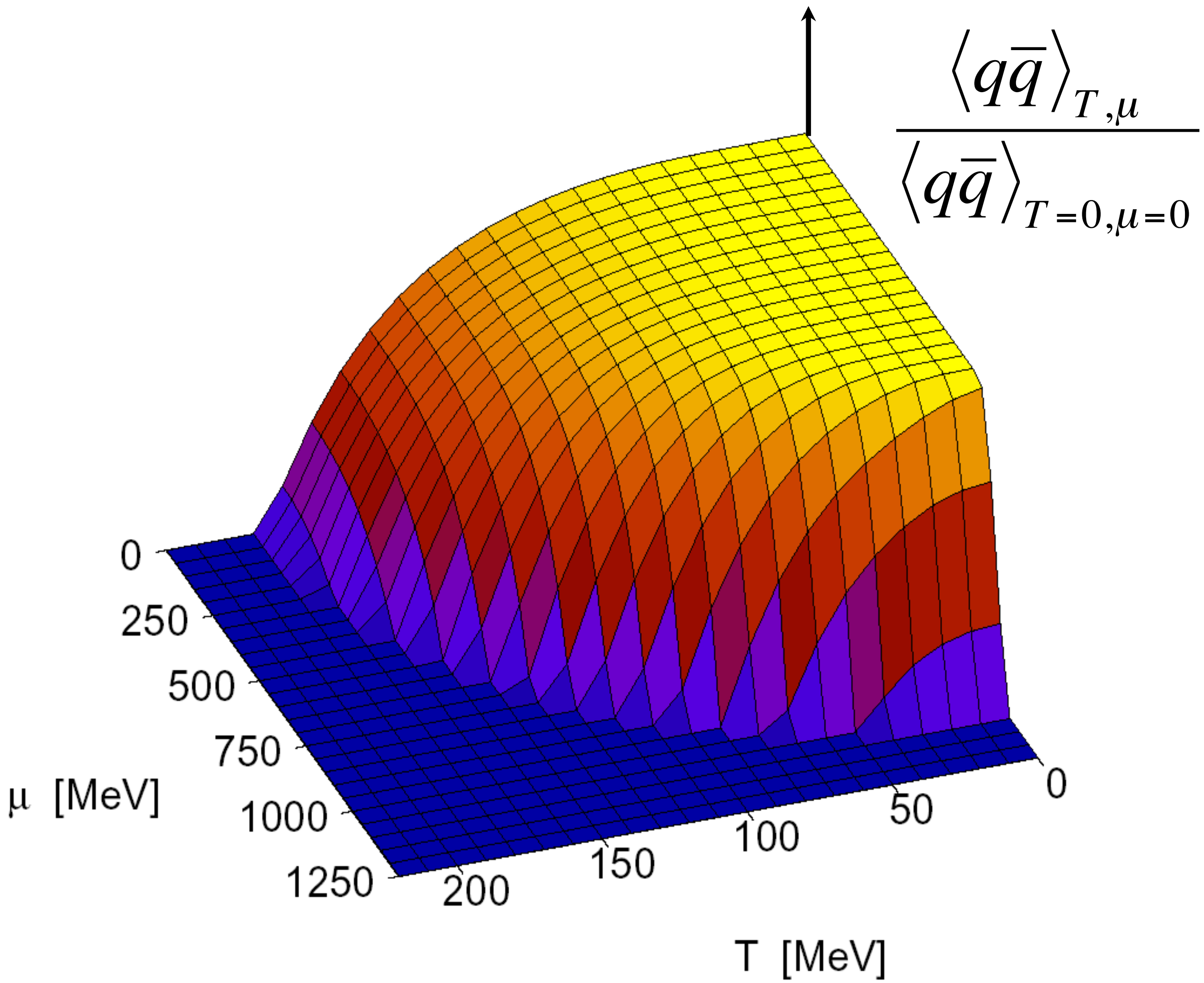
The quest

What happens if nuclear matter is compressed or heated?

- Compressed (μ_B):
  - ➠ Less volume for a given number of baryons
  - ✦ Less condensate

- Heated (T):
  - ➠ Additional pions
  - ✦ Less condensate

Properties of condensate in-medium



B.J. Schäfer and J.Wambach

However

$\langle \boldsymbol{q\bar{q}} \rangle$

is not an observable!!

QCD sum rules

- However, $\langle q\bar{q} \rangle$ **is not an observable!!**

- **QCD sum rules** provide a link between hadronic observables and condensates:
  (*T. Hadsuda and S. Lee, PRC 46 (1992) R34;   S. Leupold and U. Mosel, PRC58 (1998) 2939*)

$$\frac{Q^2}{24\pi^2}\int ds \frac{R(s)}{\left(s+Q^2\right)^2} = \frac{1}{16\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)+\frac{1}{Q^4}\left[m_q\langle \bar{q}q\rangle + \frac{1}{24}\left\langle \frac{\alpha_s}{\pi}G^2\right\rangle\right] + \text{higher order terms}$$

hadronic spectral function:
$$R(s) \sim F^2 \frac{1}{\pi}\frac{\sqrt{s}\,\Gamma(s)}{\left(s-M_\rho^{\,2}\right)^2 + s\left(\Gamma(s)\right)^2}$$

- Chiral condensate related only to integral over hadronic spectral functions;
  → spectral function are constrained, but not determined

⇒ **Hadronic models are still needed for specific predictions of hadron properties !!**

Medium modifications of hadrons

- Many models:
  - hadron mass and quark condensate are linked →
  - expect modification of hadron spectral properties (mass m, width Γ)

  - How is this realized?
    - ➢ Do the masses drop to zero (or simply change)?
    - ➢ Do the widths' increase (melting resonances)?

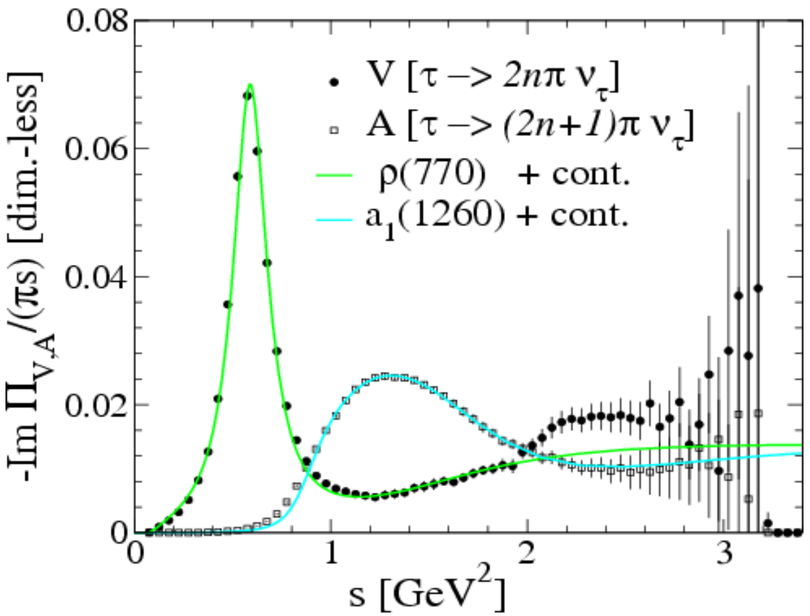
  - Good questions, without (obvious) good answers

  - … at least chiral partners should become degenerate.

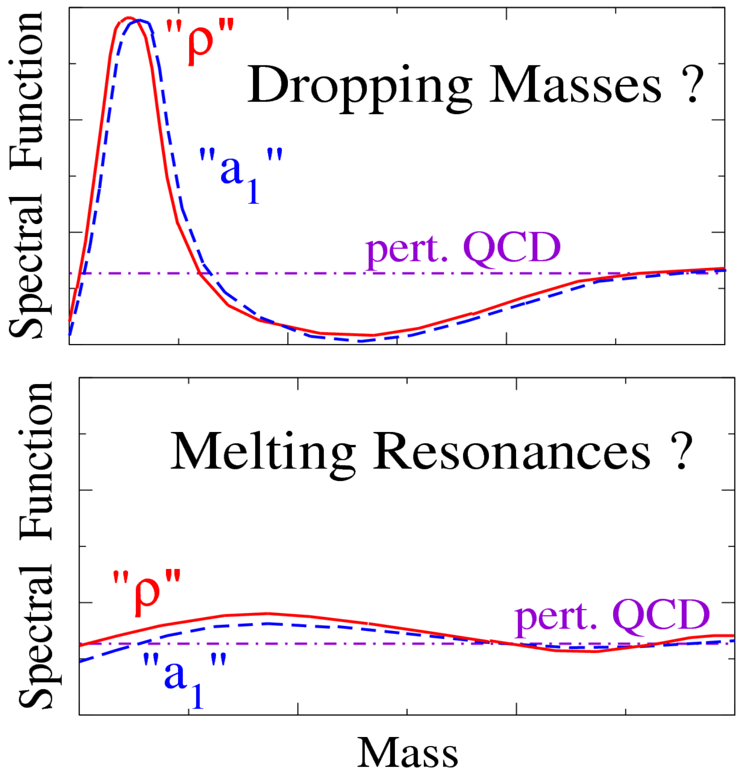
Chiral symmetry restoration

- Light-quark sector of QCD: chiral symmetry
  - Spontaneously broken in vacuum
  - High temperature/density: restoration of chiral symmetry

Vacuum Vector and Axial vector spectral functions, hadronic τ decays

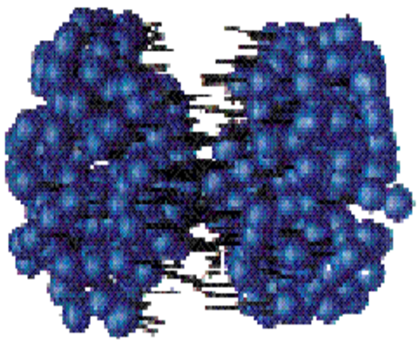


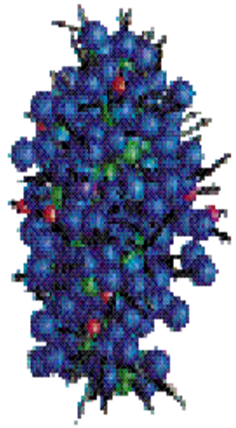
Medium Schematic scenarios for chiral symmetry restoration

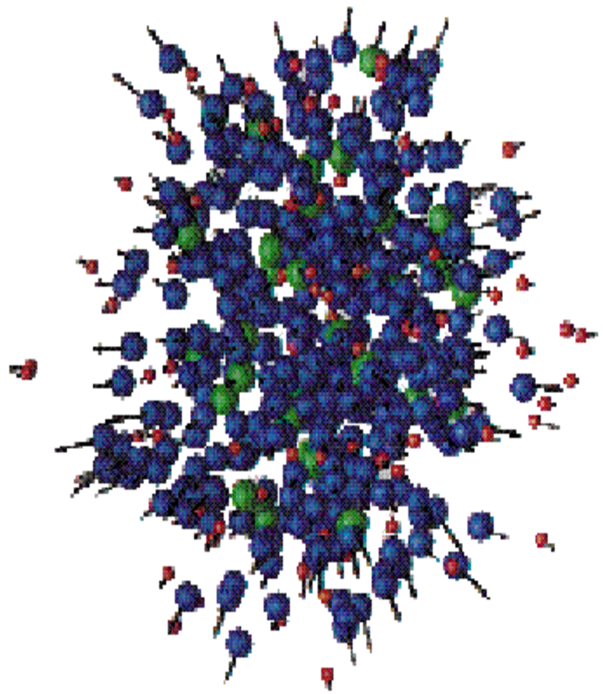


Dileptons as probes in heavy-ion collisions

A+A at E_{kin} = 2 GeV/u







two colliding nuclei

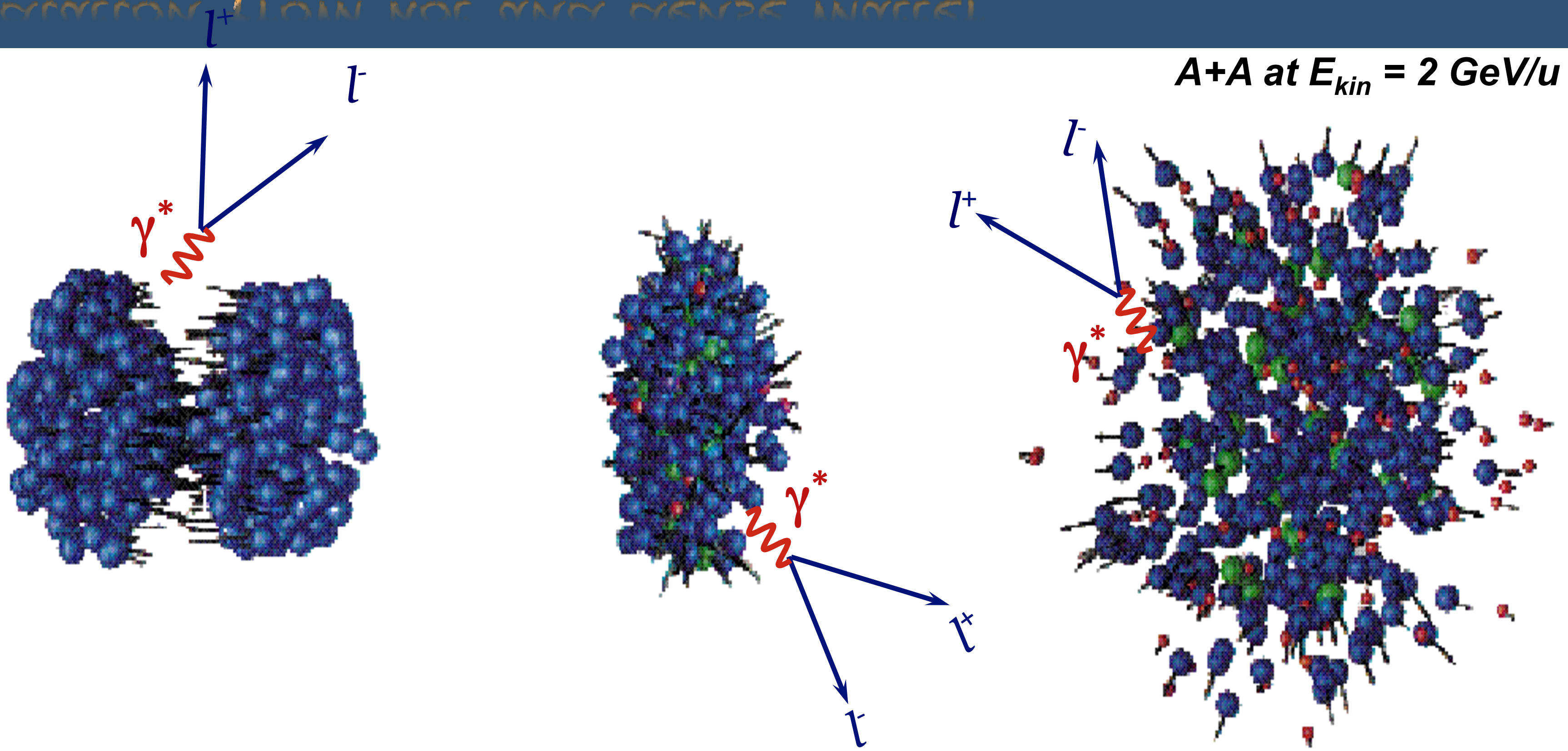
formation of highly compressed and heated collision zone
$\tau \cong 10^{-23}$ s

explosion of collision zone

Challenge:

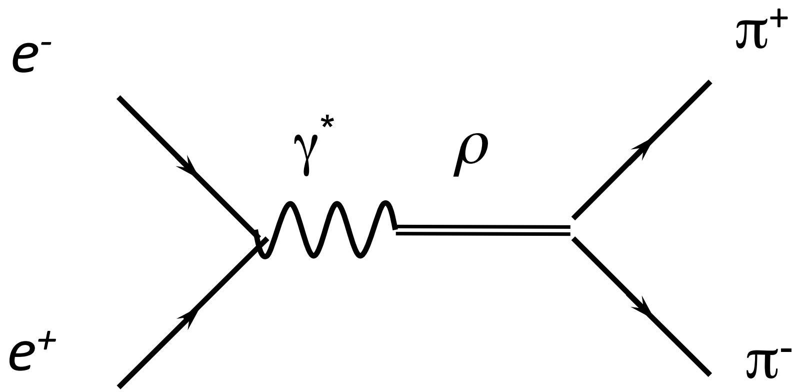
Extract information on the high density phase

Radiation from hot and dense matter



- The dilepton signal contains **contributions from throughout the collision**
- No strong final state interactions
  → **leave reaction volume undisturbed**
- Probes the **electromagnetic structure of dense/hot hadronic matter**

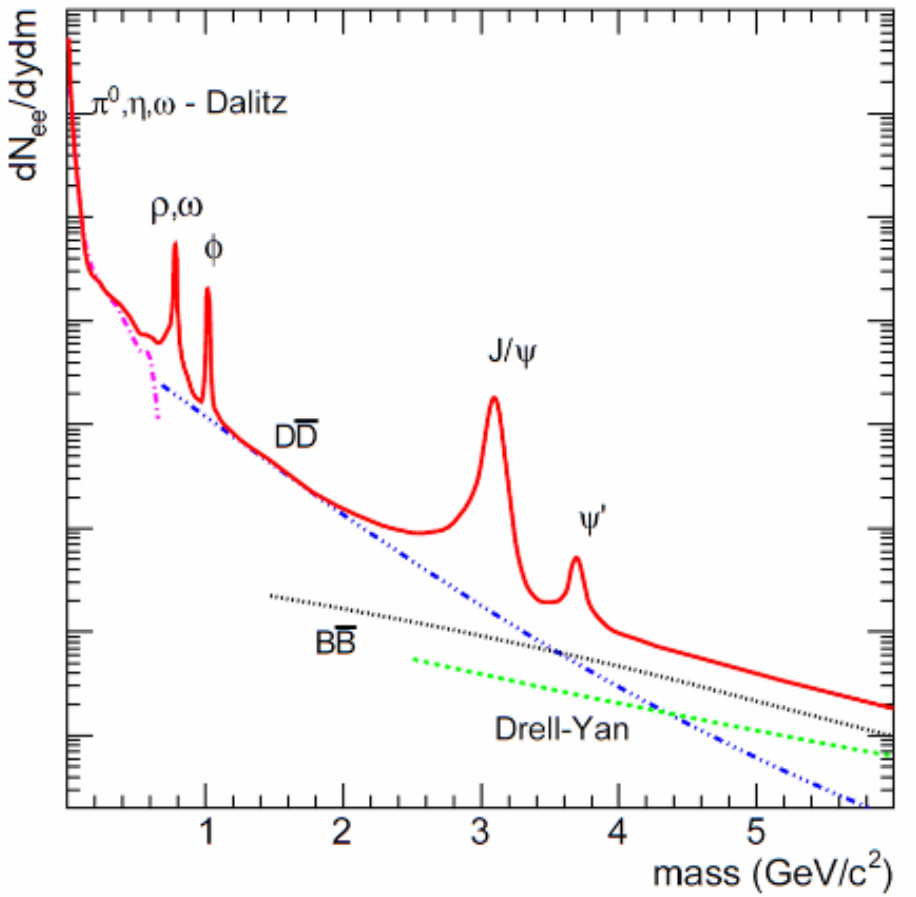
Vector mesons Dominance Model



- *$J^P = 1^-$* for both γ^* and Vector Meson
- Strong coupling of γ^* to Vector Meson
  → Vector Meson Dominance model
- *Observable:* vector mesons (ρ, ω, ϕ).

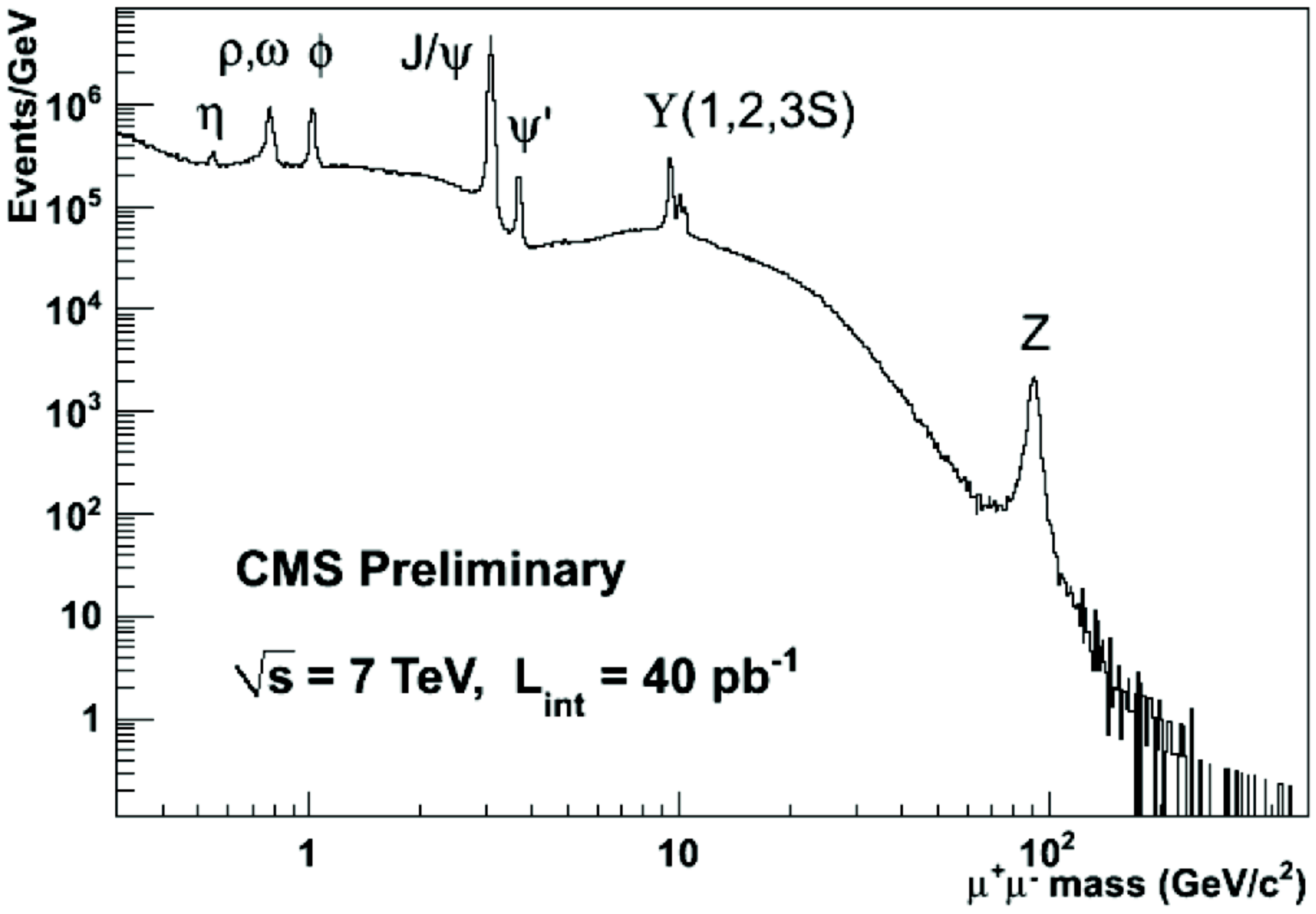
Observable: vector mesons

Schematical spectral distribution of lepton pairs emitted in ultra-relativistic heavy ion collisions

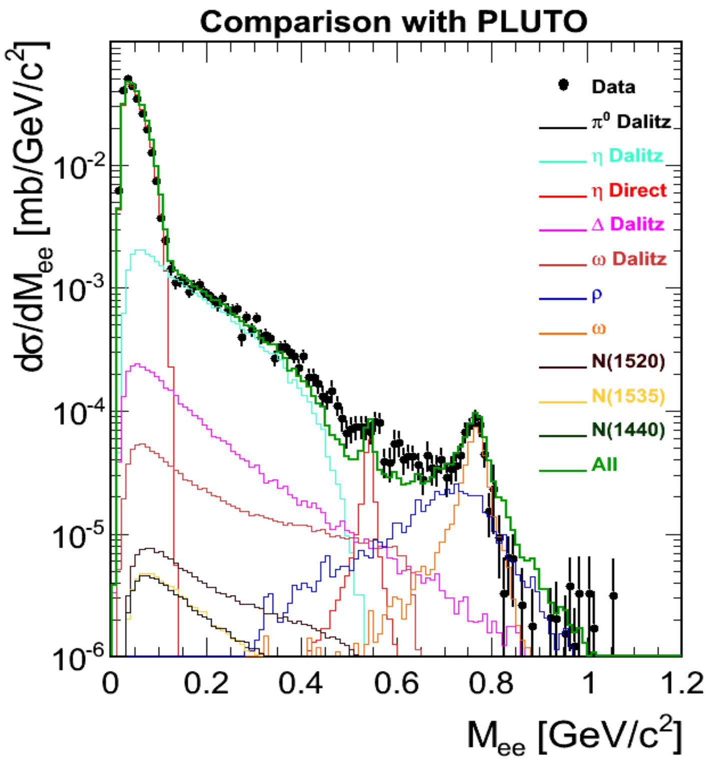


$$M_{l^+l^-} = 2 \cdot sin\frac{\theta_{l^+l^-}}{2} \cdot \sqrt{p_{l^+} \cdot p_{l^-}}$$

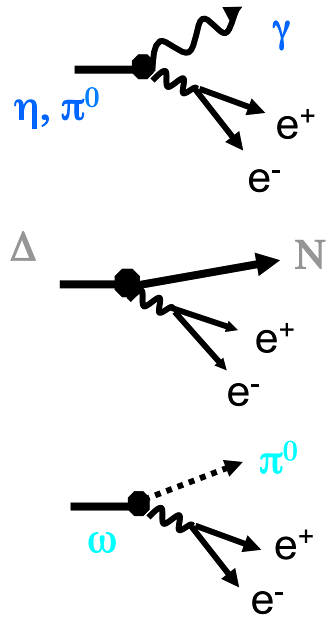
Dimuon spectrum from pp at LHC



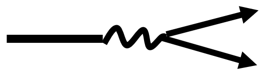
The electron pair cocktail at low beam energies



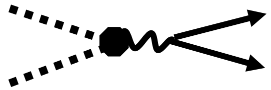
Dalitz-decays (continuum)



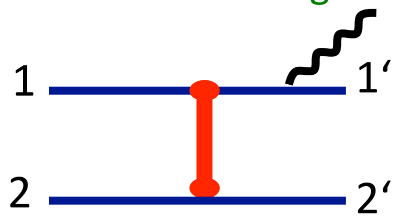
Two body meson decays (peaks):



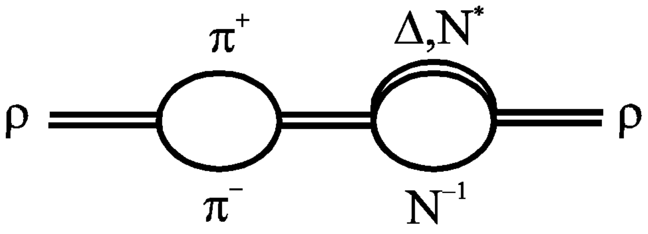
Annihilation



NN Bremsstrahlung

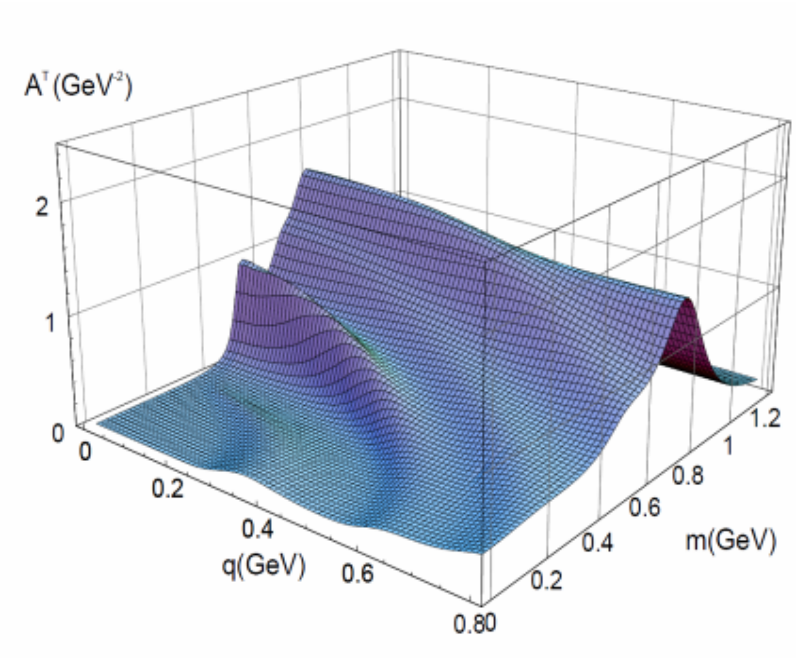


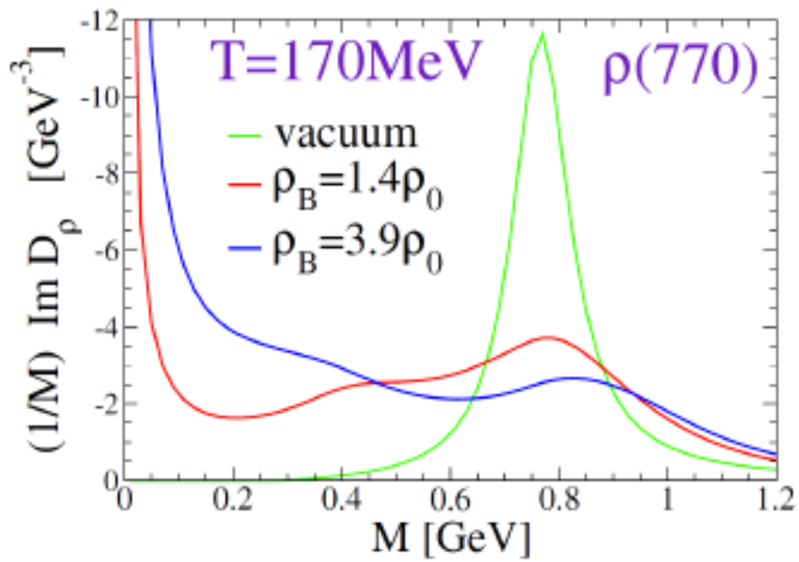
Spectral function of the ρ-meson in-medium



$$D_\rho(M,q;\mu_B,T) = \frac{1}{\left[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}\right]}$$

Additional contributions to the ρ-meson self-energy in the medium





M. Post et al., nucl-th/0309085

Theoretical guidance

More predictions for in-medium properties of the ρ meson:

	mass of ρ	width of ρ
Pisarski 1982	↘	↗
Leutwyler et al 1990 (π,N)	→	↗
Brown/Rho 1991	↘	→
Hatsuda/Lee 1992	↘	→
Dominguez et. al1993	→	↗
Pisarski 1995	↗	↗
Rapp 1996	→	↗

One example where experiments have the potential to guide the theory

Experimental approach

Hadron decay in the medium: $H \rightarrow X_1 + X_2$

- reconstruction of invariant mass from 4-momenta of decay products:

$$m_H(\rho, T, \vec{p}) = \sqrt{(p_1 + p_2)^2}$$

- compare $m_H(\rho, T, \vec{p} \rightarrow 0)$ with m_H listed in PDG

- ensure that decays occur in the medium:

$\rightarrow$ select shortlived mesons ($c\tau = \frac{\hbar c}{\Gamma}$; ρ: 1.3 fm; ω: 23 fm; ϕ: 46 fm)

$\rightarrow$ cut on low meson momenta

- avoid distortion of 4-momenum vectors by final state interaction

⇒ dilepton spectroscopy: $\rho, \omega, \phi \rightarrow e^+e^-$

Low-mass dileptons: what is been measured?

...a needle in a haystack

- Lepton pairs are rare probes (branching ratio < 10^{-4})
- at SIS energies sub-threshold vector meson production

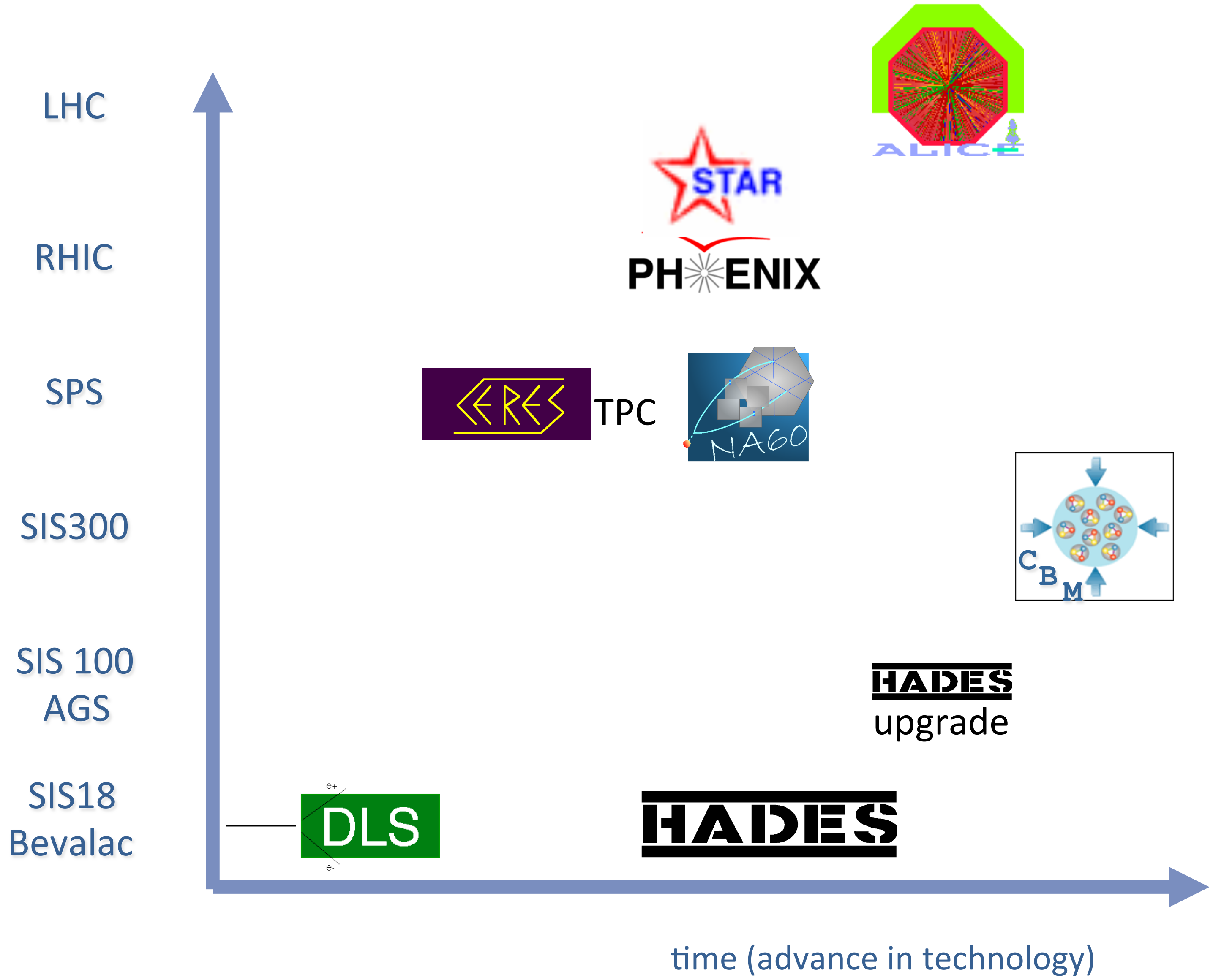
- Large combinatorial background in e^+e^- from:
  - Dalitz decays (π^0)
  - Conversion pairs

- Isolate the contribution to the spectrum from the dense stage

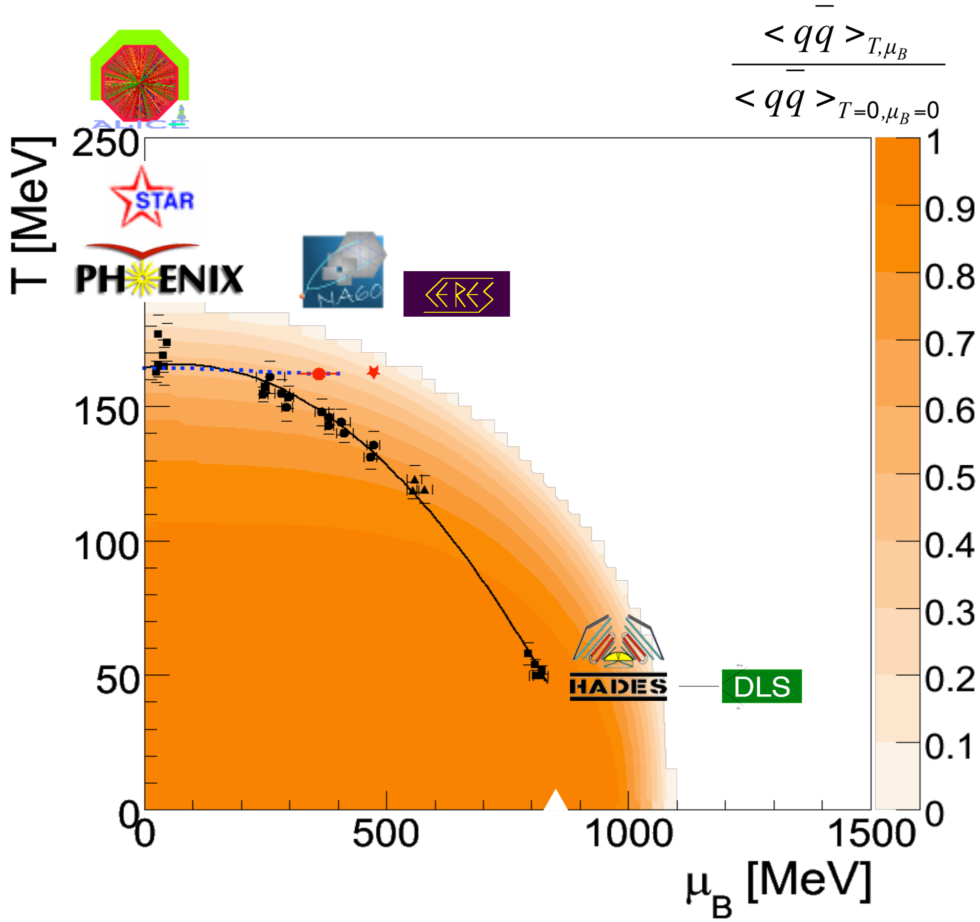
Why not $\rho \rightarrow \pi^{+}\pi^{-}$?

The branching ratios for hadronic decays of vector mesons are typically 4 orders of magnitude larger that for dilepton decays

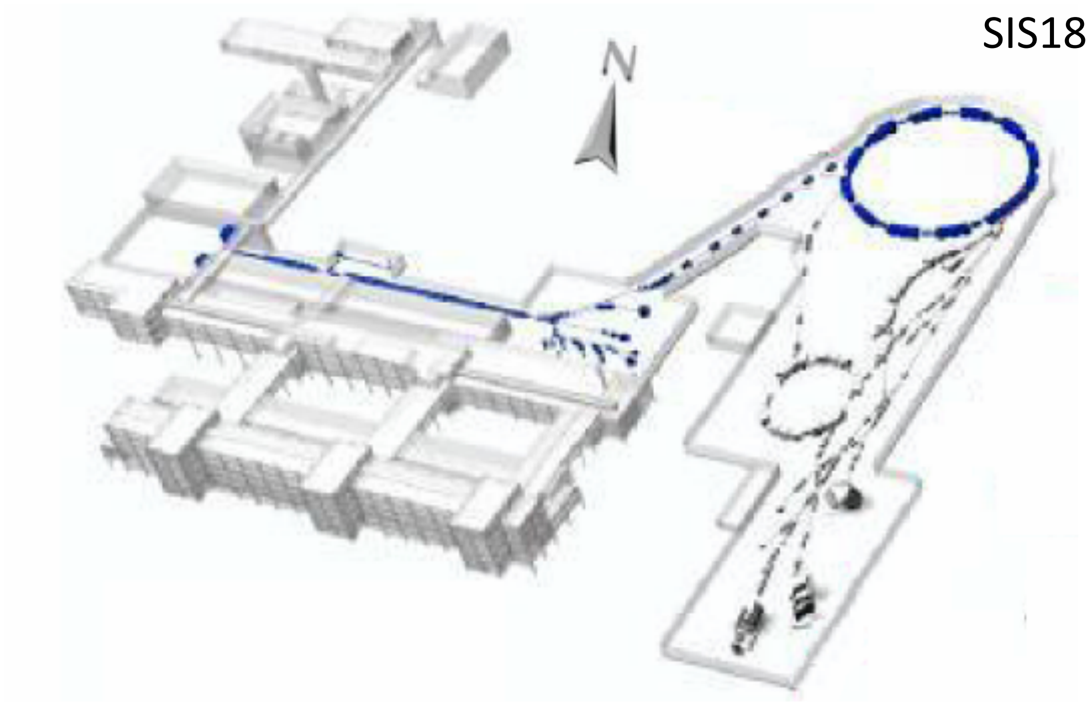
Experiments addressing lepton pairs in HIC



Searching for the landmarks of the phase diagram of matter



The HADES at GSI



SIS18

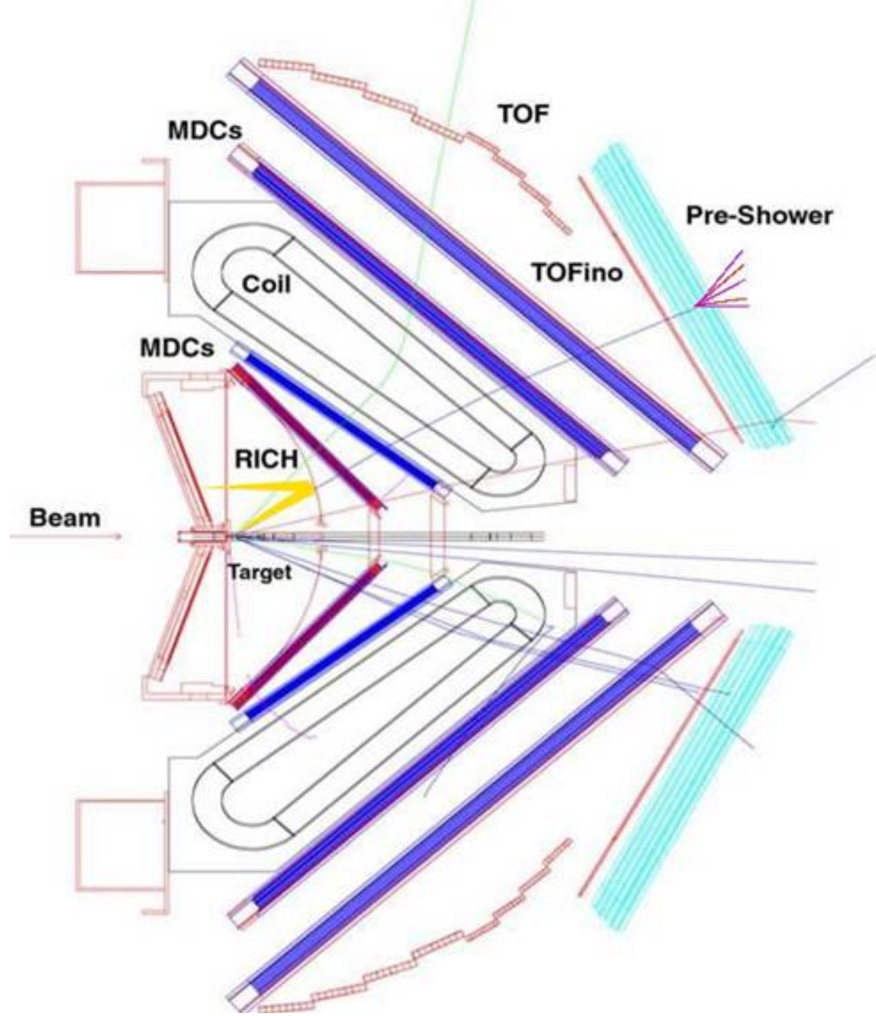
High Acceptance DiElectron spetrometer

HADES experiment

Spectrometer with a...

- High geometrical acceptance
  - Full azimuth, polar angles 18° - 85°
  - Pair acceptance ≈ 0.35
- High invariant mass resolution (3% at ρ/ω pole mass)
  - Low-mass tracking (superconducting toroidial magnet & multi-wire drift chamber (MDC), single cell resolution ≈100 μm)
- Powerful PID capabilities: d/π/K/p/e
  - RICH, TOF/TOFino, Pre-Shower, FW hodoscope: added 2007
- High background rejection & rate capability, dedicated LVL2 trigger:
  - LVL1: charge particle multiplicity
  - LVL2: single electron trigger

Cut View



Just few steps ;)

tracking

↓

electron identification

↓

π^0-Dalitz and γ-conversion rejection

↓

pairing

↓

subtraction of background
(like-sign or mixed events)

↓

efficiency correction

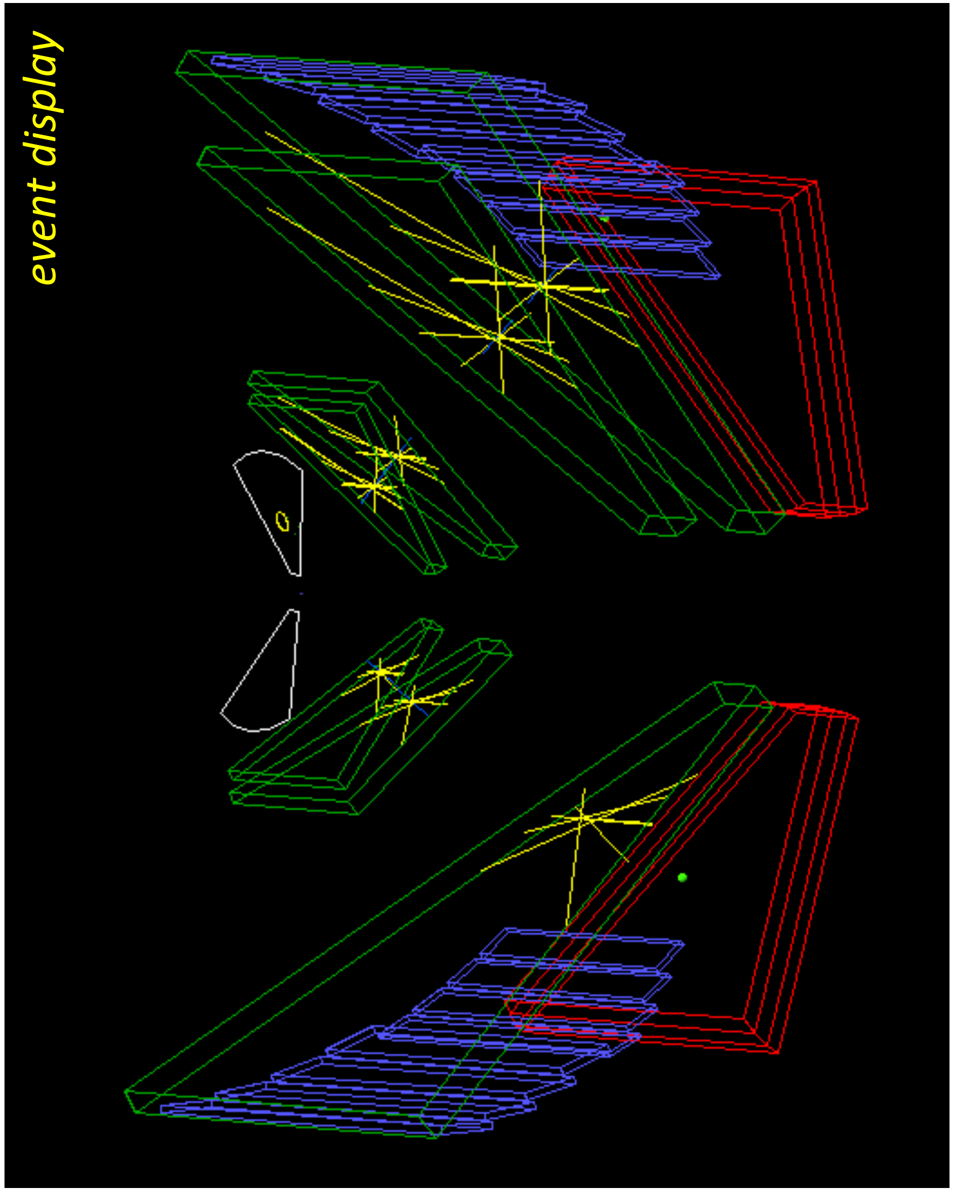
↓

mass spectrum

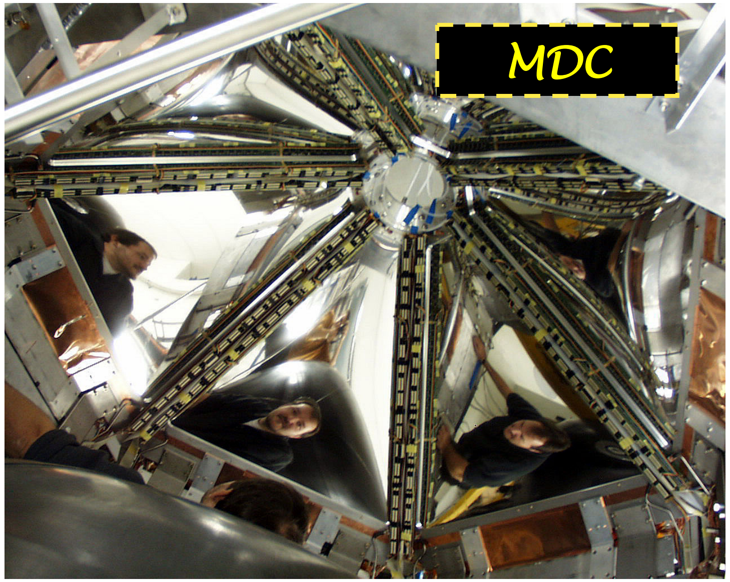
How to reconstruct γ*

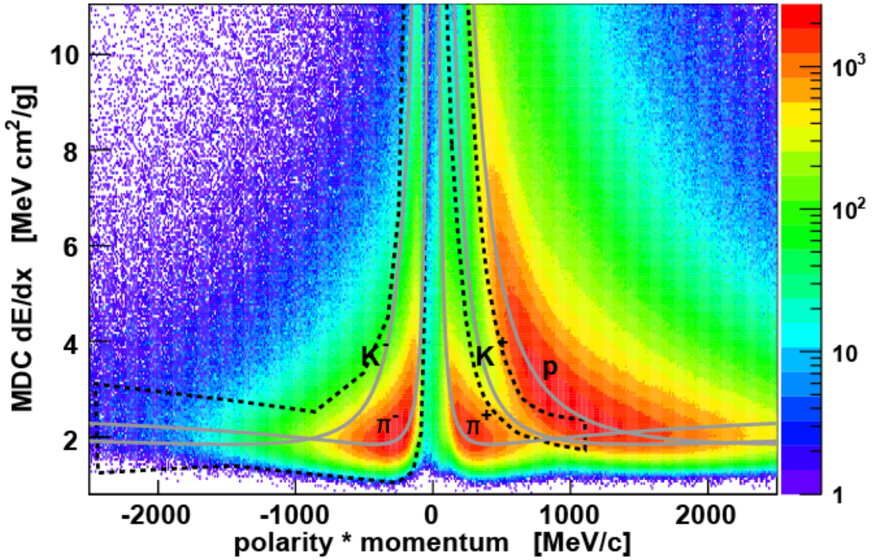
$$M_{l+l-} = 2 \cdot sin\frac{\theta_{l+l-}}{2} \cdot \sqrt{p_{l+} \cdot p_{l-}}$$

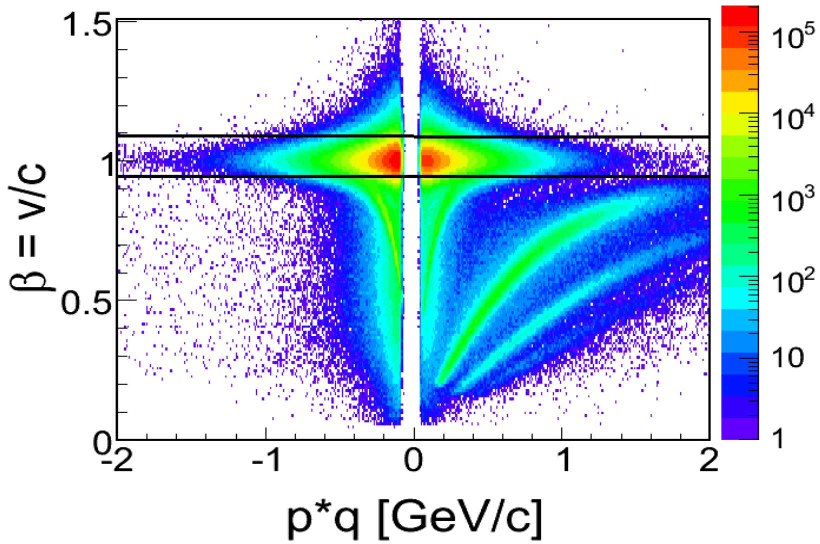
- Efficient track reconstruction
- Precise momentum determination
- Excellent electron/hadron identification



Particle identification

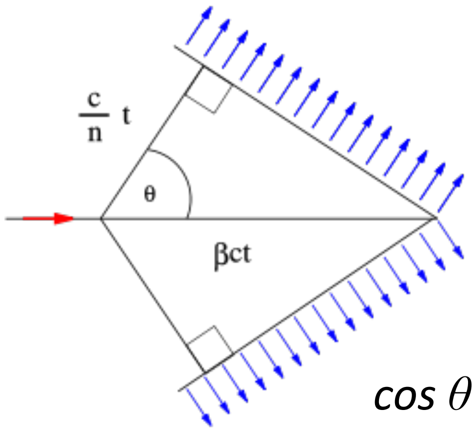






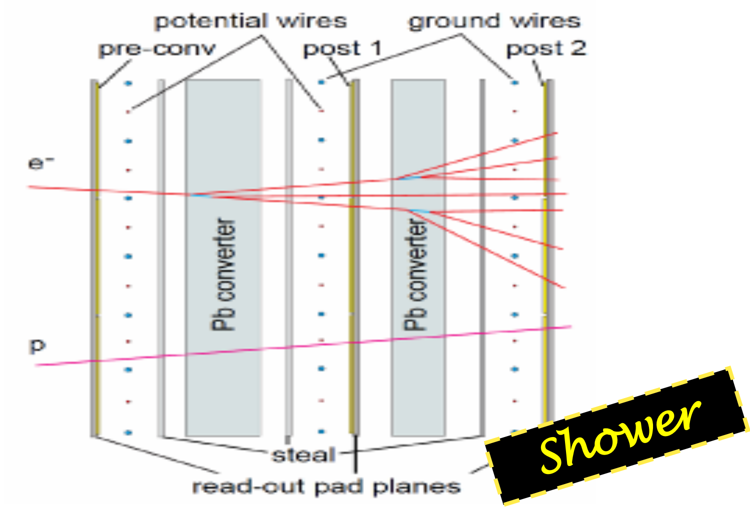
Electron identification

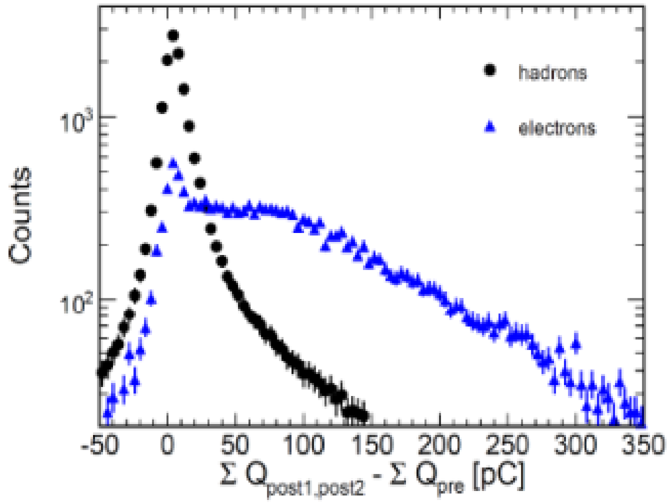
Using Cherenkov effect



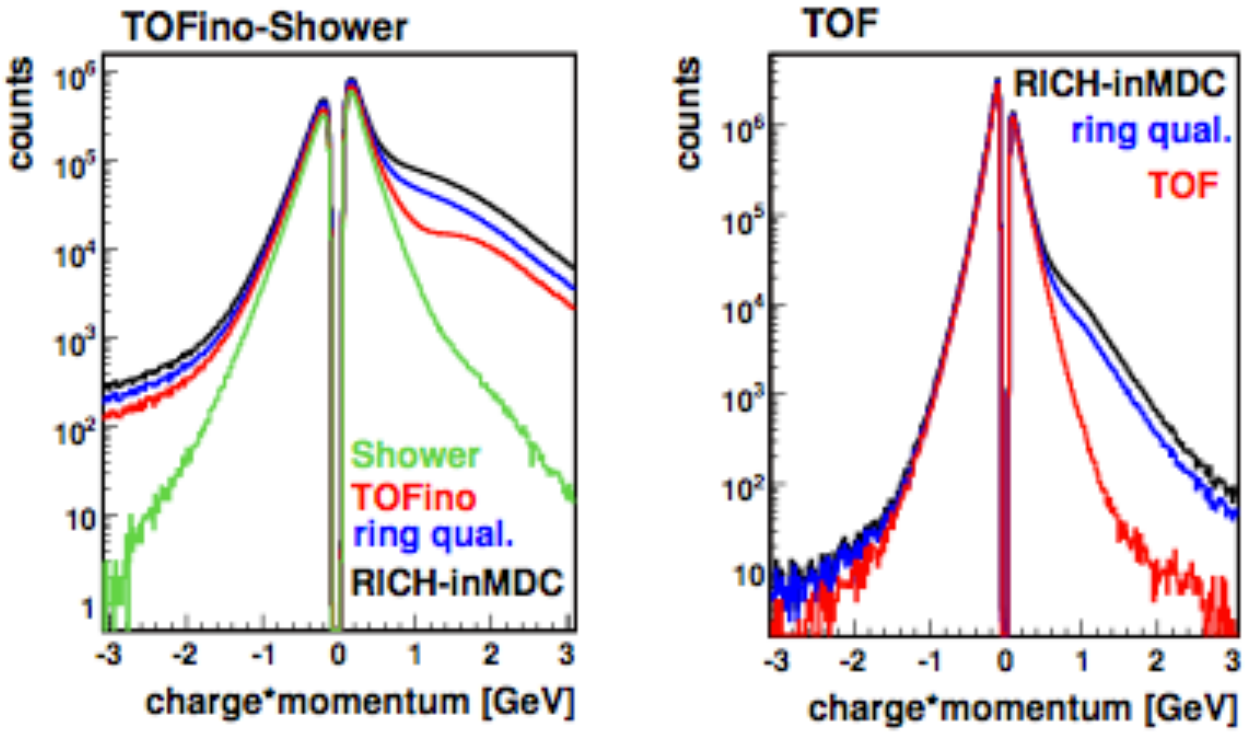
$\cos\theta = 1 / (n \cdot \beta)$

Using Information on EM shower





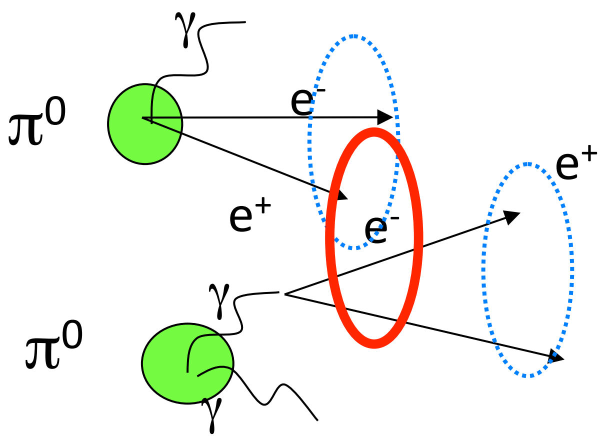
Single electron spectra

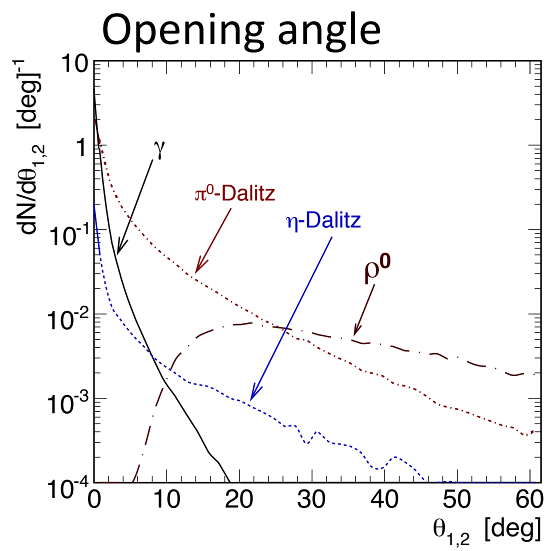


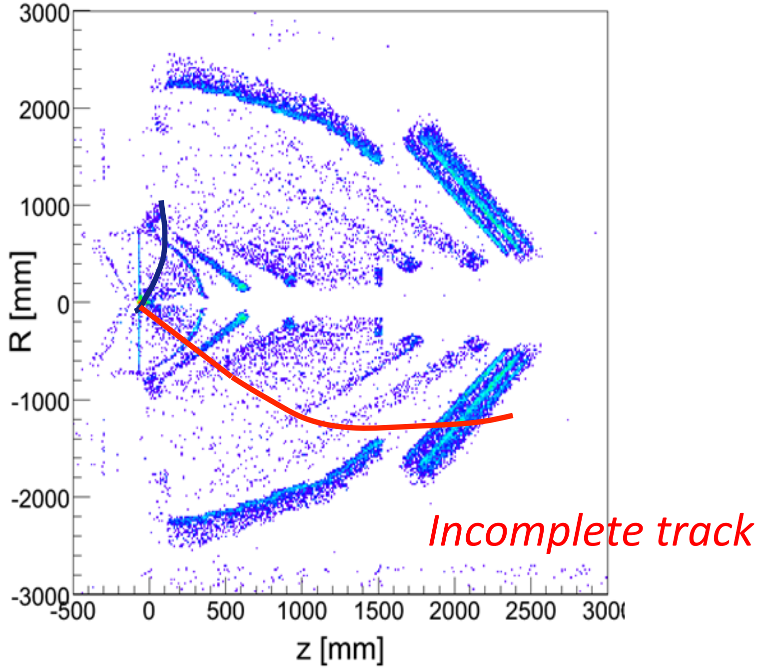
Clean electrons...

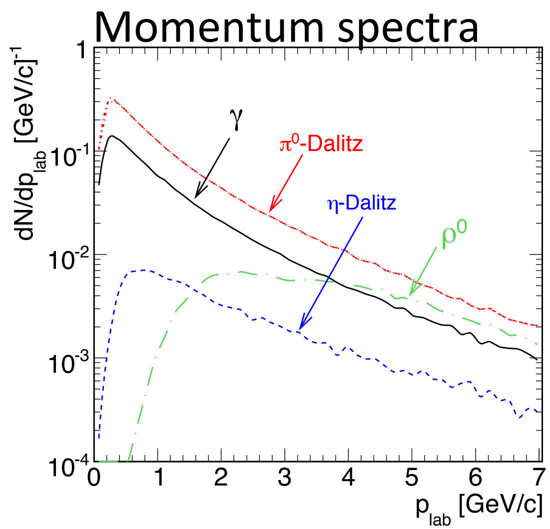
... but mainly from π^0 Dalitz decays or from γ conversion

Combinatorial background

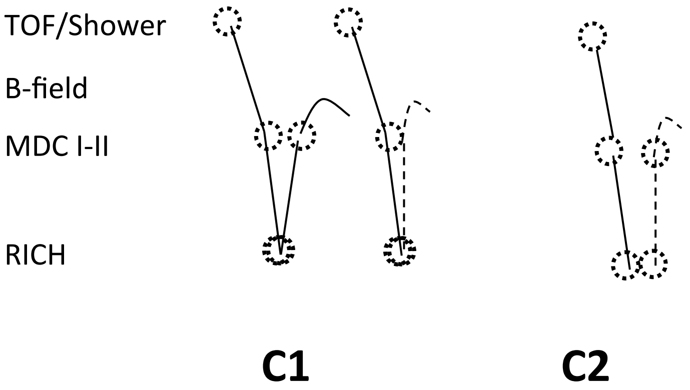








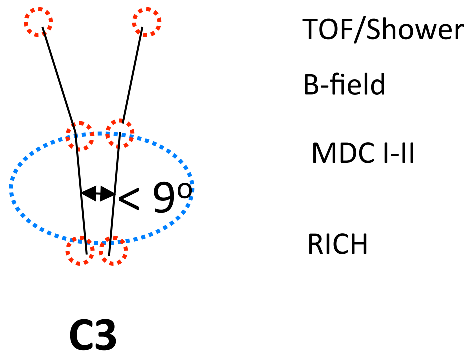
Background rejection



"Conversion rejection":

- C1, C2 = "close pair candidates" !

→ Remove the track if a non-fitted track candidate is within 10°



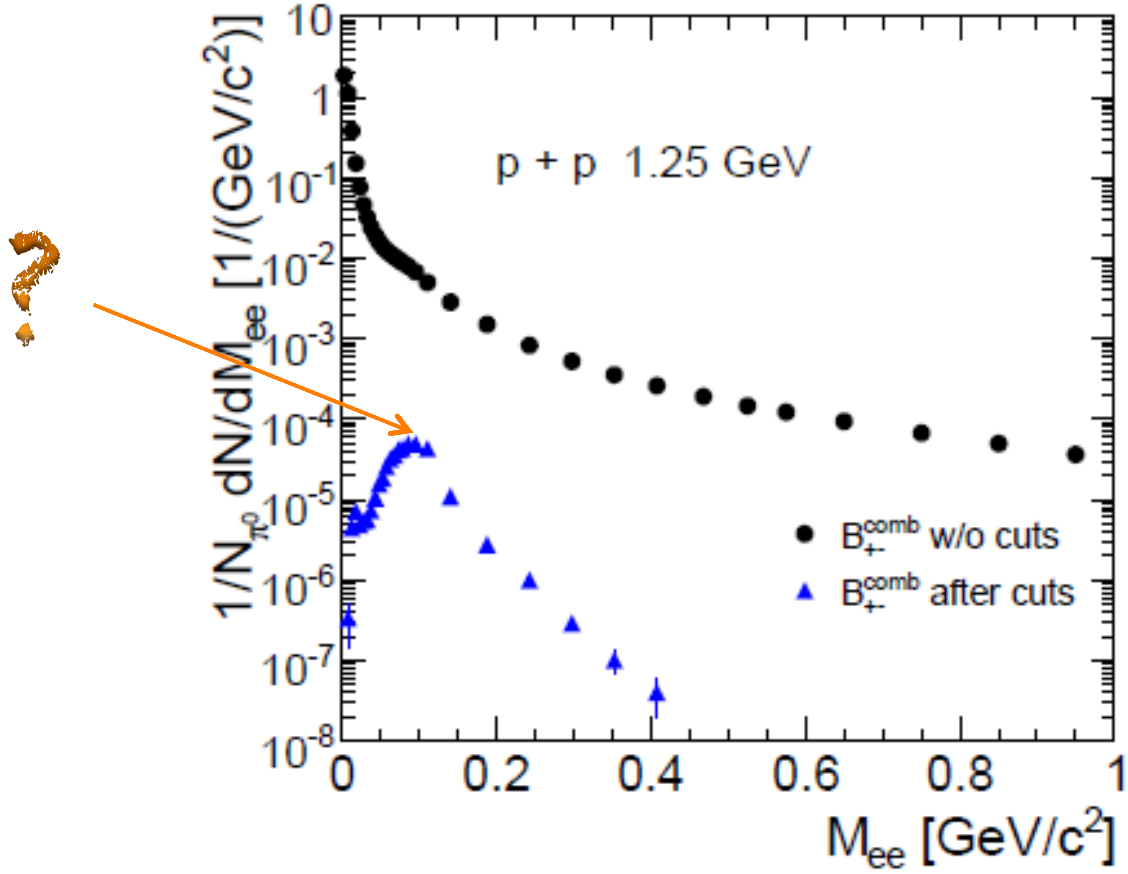
"π^0-Dalitz rejection":

- C3: opening angle < 9°

→ Remove both tracks from the sample

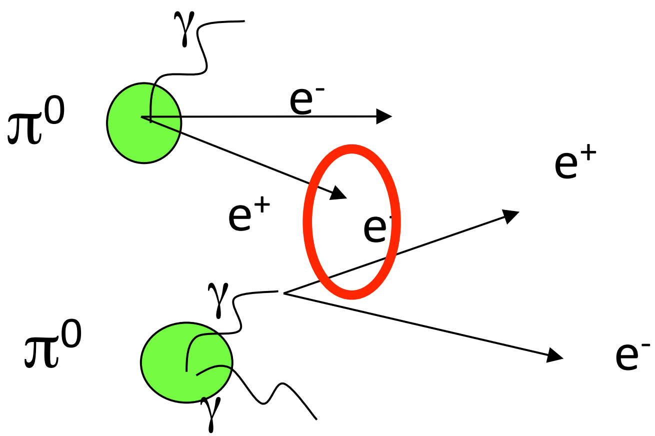
Result

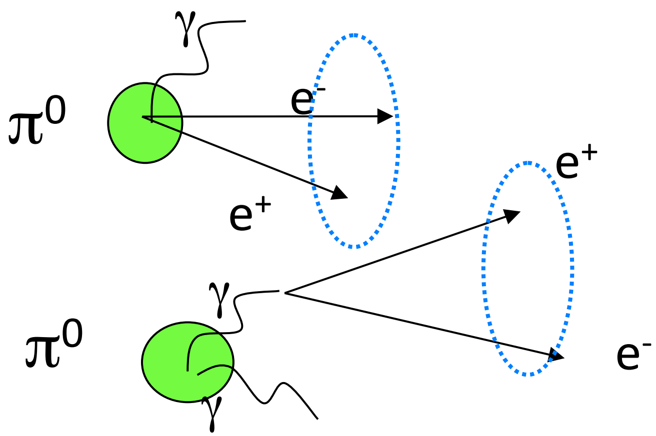
Invariant mass spectra of the CB



Reconstruction of the combinatorial background

- N_{e+e-} - all unlike-sign pairs
- CB – combinatorial background
- $S_{e+e-} = N_{e+e-}$ - CB

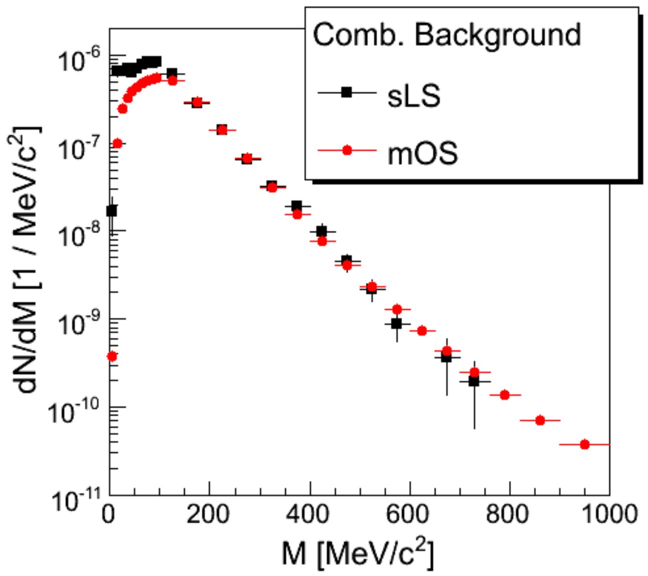


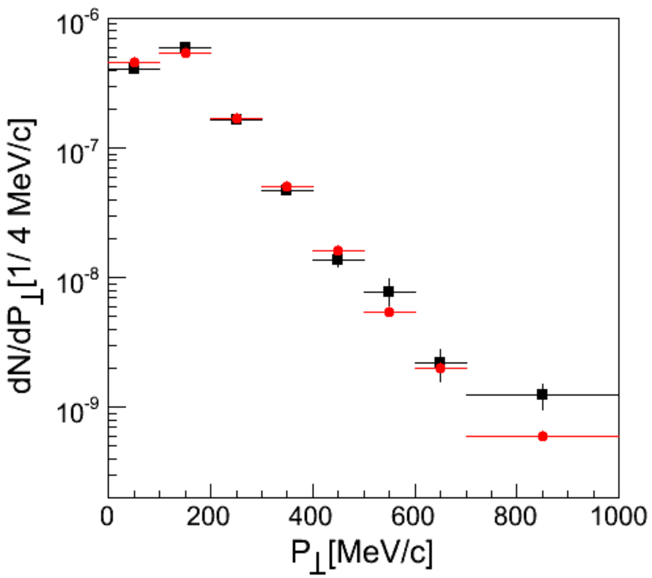


Uncorrelated background → Event mixing

Correlated background → Like sign method

Reconstruction of the combinatorial background





- Same event like-sign:

$$CB_{geom.} = 2 \cdot \sqrt{N_{e^+e^+} \cdot N_{e^-e^-}}$$
$$CB_{arith.} = N_{e^+e^+} + N_{e^-e^-}$$

- Event mixing:
  - inherently independent

➢ Normalization done between 150-550 MeV/c^2 M_{ee}

➢ sLS and mOS CB show same behavior for M_{ee}>150 MeV/c^2

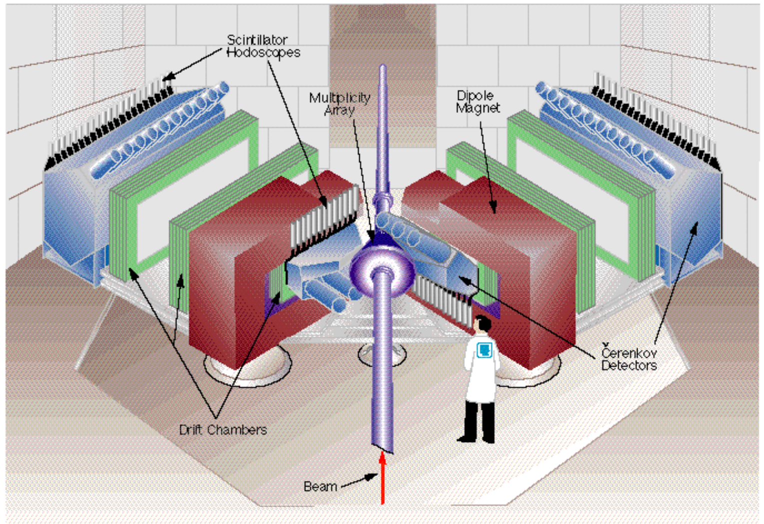
➢ For M_{ee}<150 MeV/c^2 deviations due to correlated background $\pi \to \gamma\gamma \to eeX$

What is known at few GeV regime?

DiLepton Spectrometer

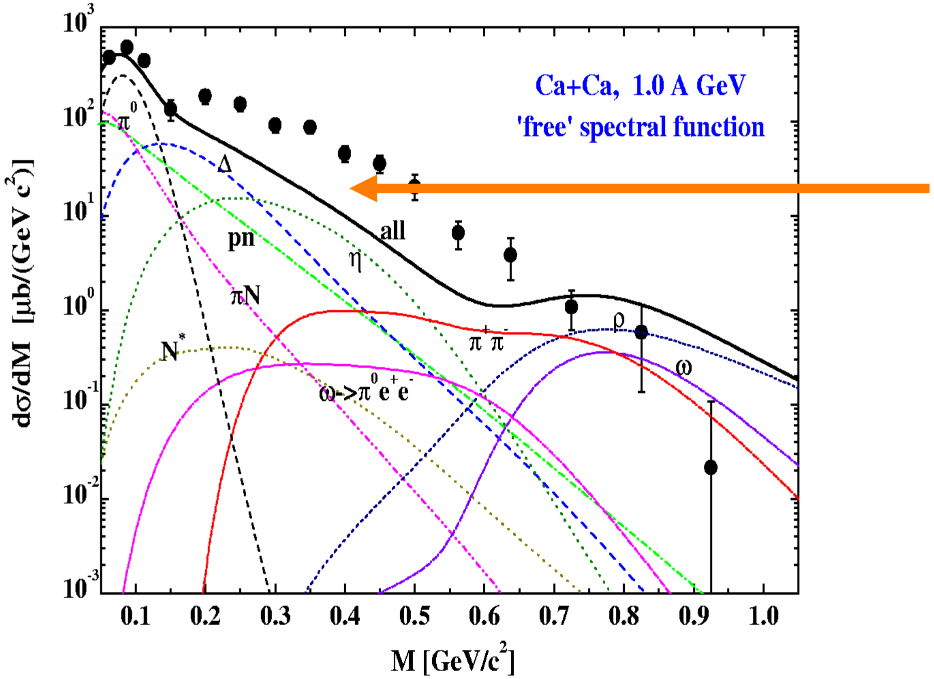
- 1988 – 1993 at Bevalac
- 2 Arm-Spectrometer
  - Minimum opening angle: 40°
  - Each arm: 40° in Φ, ±7.5° in Θ
  - Trigger on electron-pairs
  - Opening angle 40°
  - Quasi-tracking: p > 0.05 GeV/c
  - Mass resolution: 15% at ω pole mass
  - 30-40% systematical error
- pp/pd, Ca+Ca, C+C

DiLepton Spectrometer



DLS: enhanced dilepton yields in A+A

Ca+Ca at E_{kin}=2 GeV/u

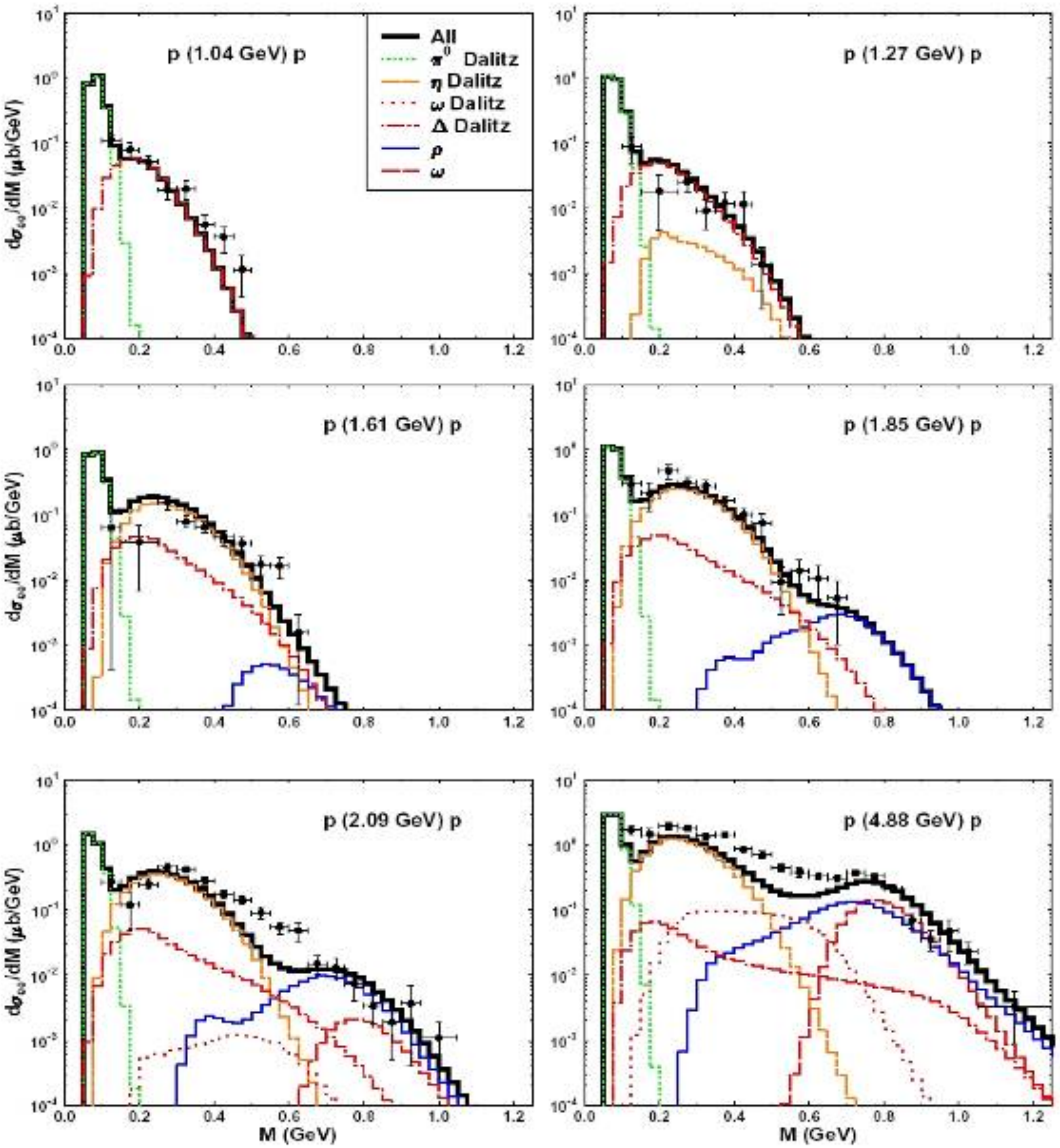


Strong dilepton enhancement over hadronic cocktails

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

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

DLS p+p data vs. model

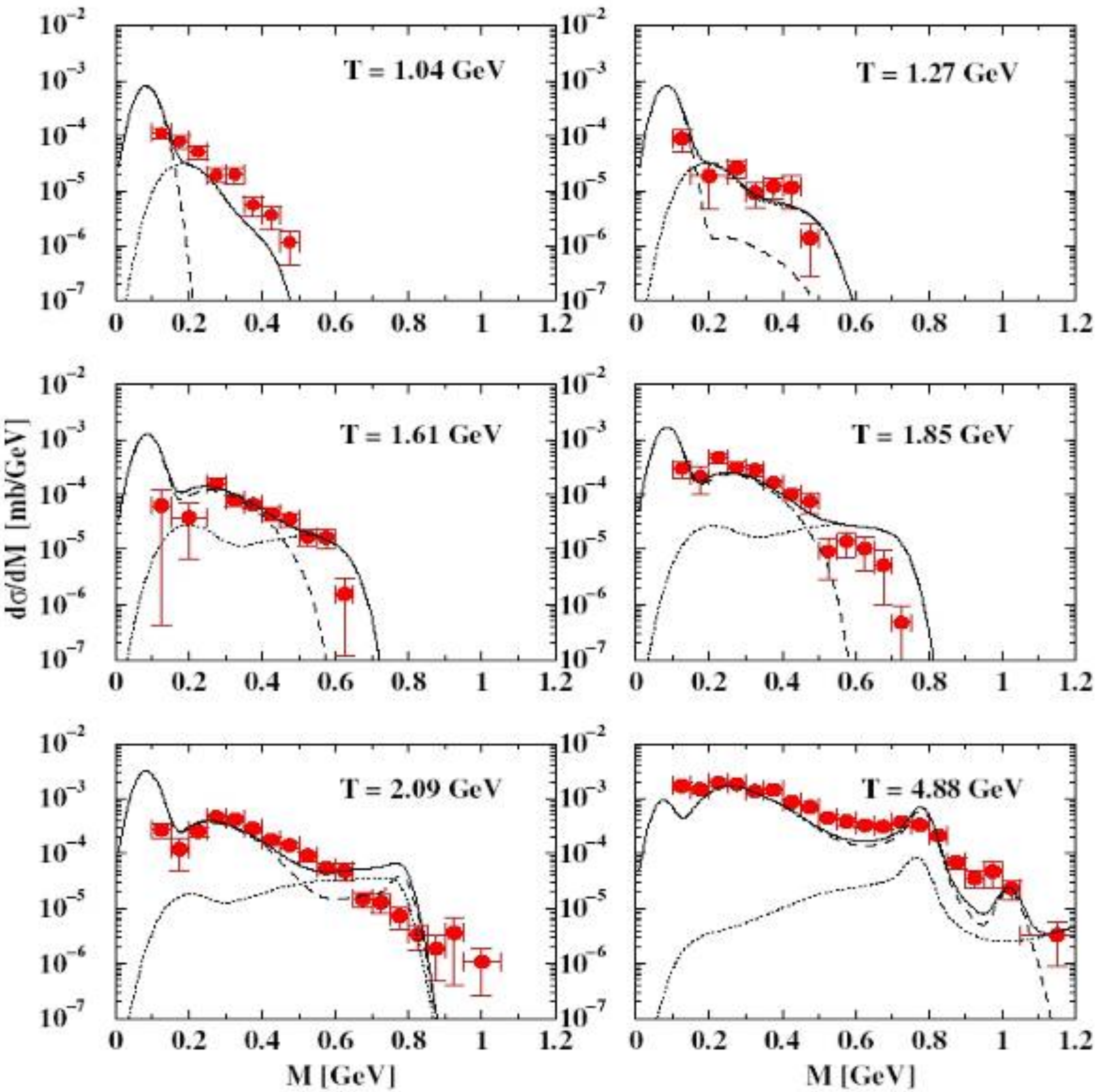


Data:
Wilson et al. PRC 57 (1997) 1865

Theory (folded with the DLS response):
C. Ernst et al.
PRC 58 (1998) 447

UrQMD 1.3

DLS p+p data: more and different models …

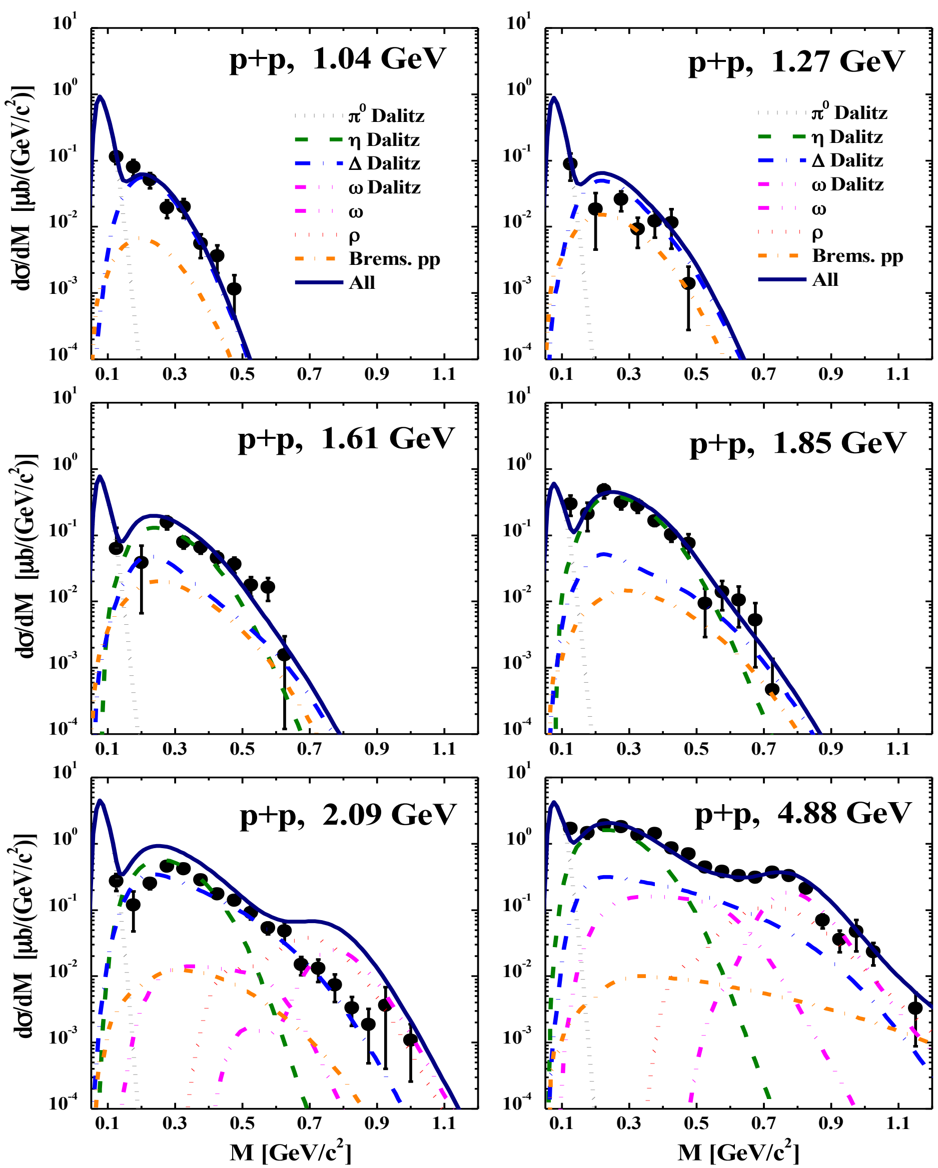


Data:
Wilson et al. PRC 57 (1997) 1865

Theory (folded with the DLS response):
Faessler, Fuchs et al.
J. Phys. G29 (2003) 603
(Resonances + decays)

RQMD

DLS p+p data: ... and more models



Data:
Wilson et al. PRC 57 (1997) 1865

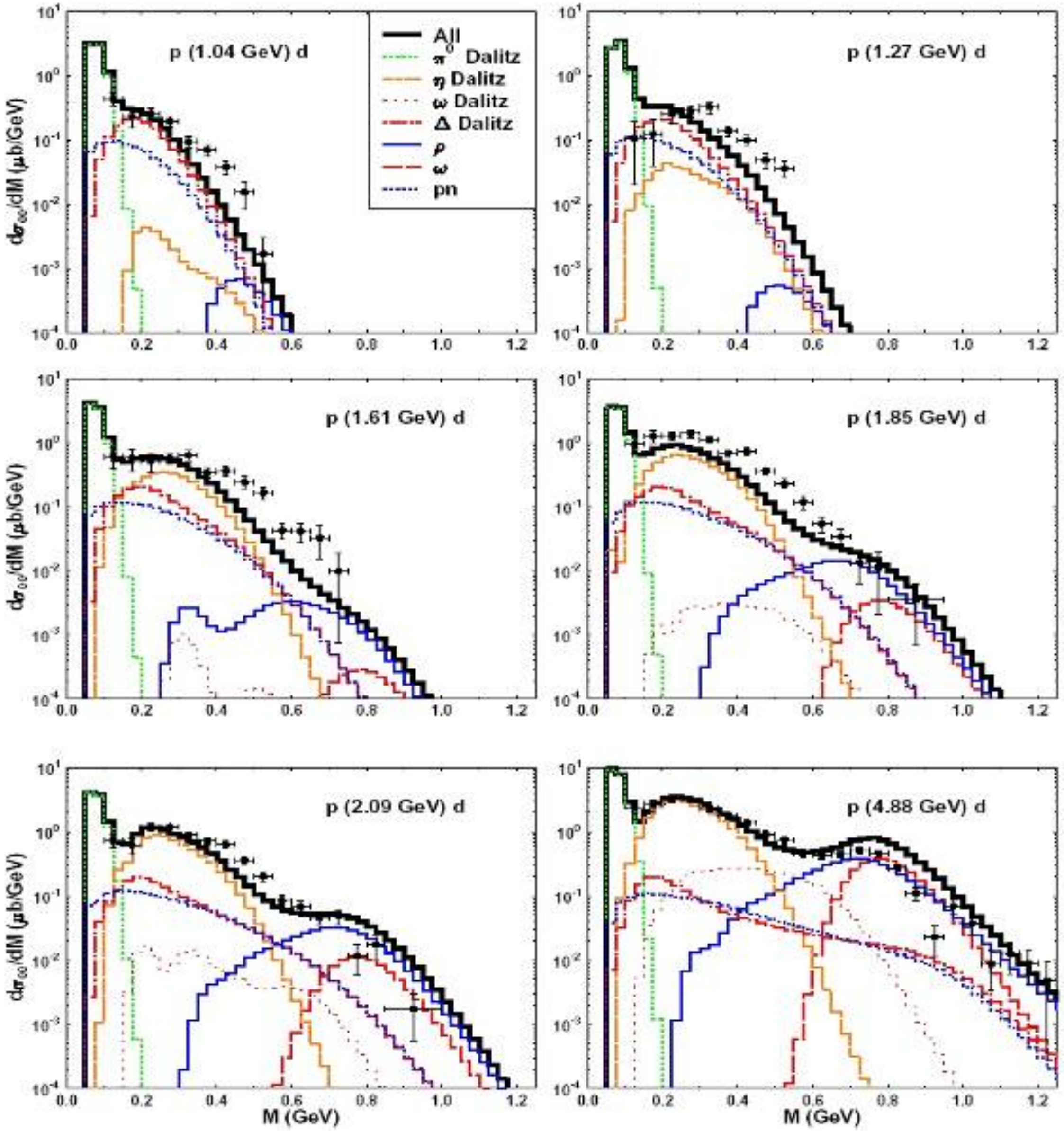
Theory (folded with the DLS response):
Bratkovskaya et al., HSD model
(NN Bremstrahlung a-la Kaptari *et al.*, 2006)

HSD

DLS p+p data: fair agreement with theory

The real trouble starts with p+d data!

DLS p+d data vs. model

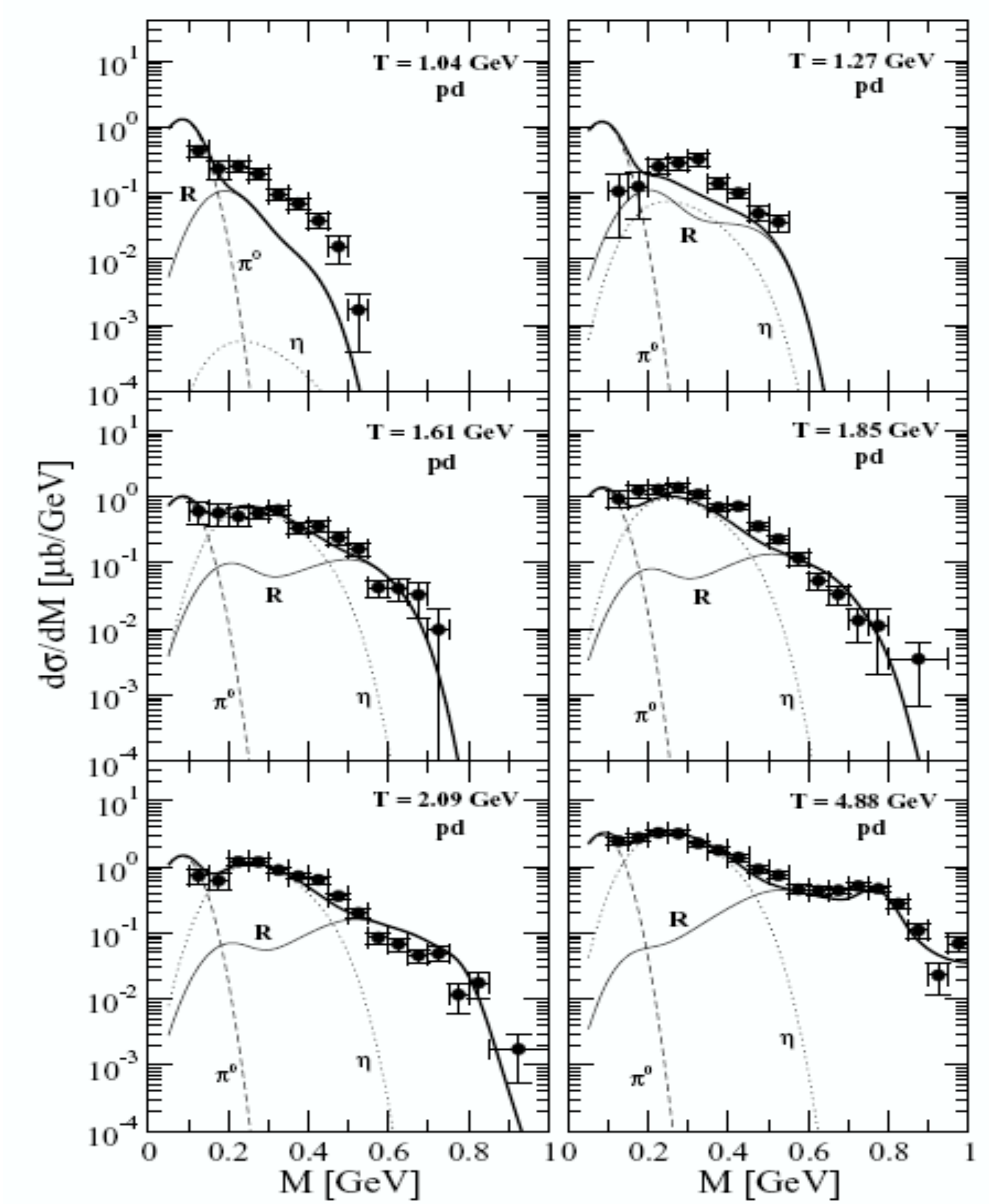


Data:
Wilson et al. PRC 57 (1997) 1865

Theory (folded with the DLS response):
C. Ernst et al.
PRC 58 (1998) 447

UrQMD 1.3

DLS p+d data: more and different models …

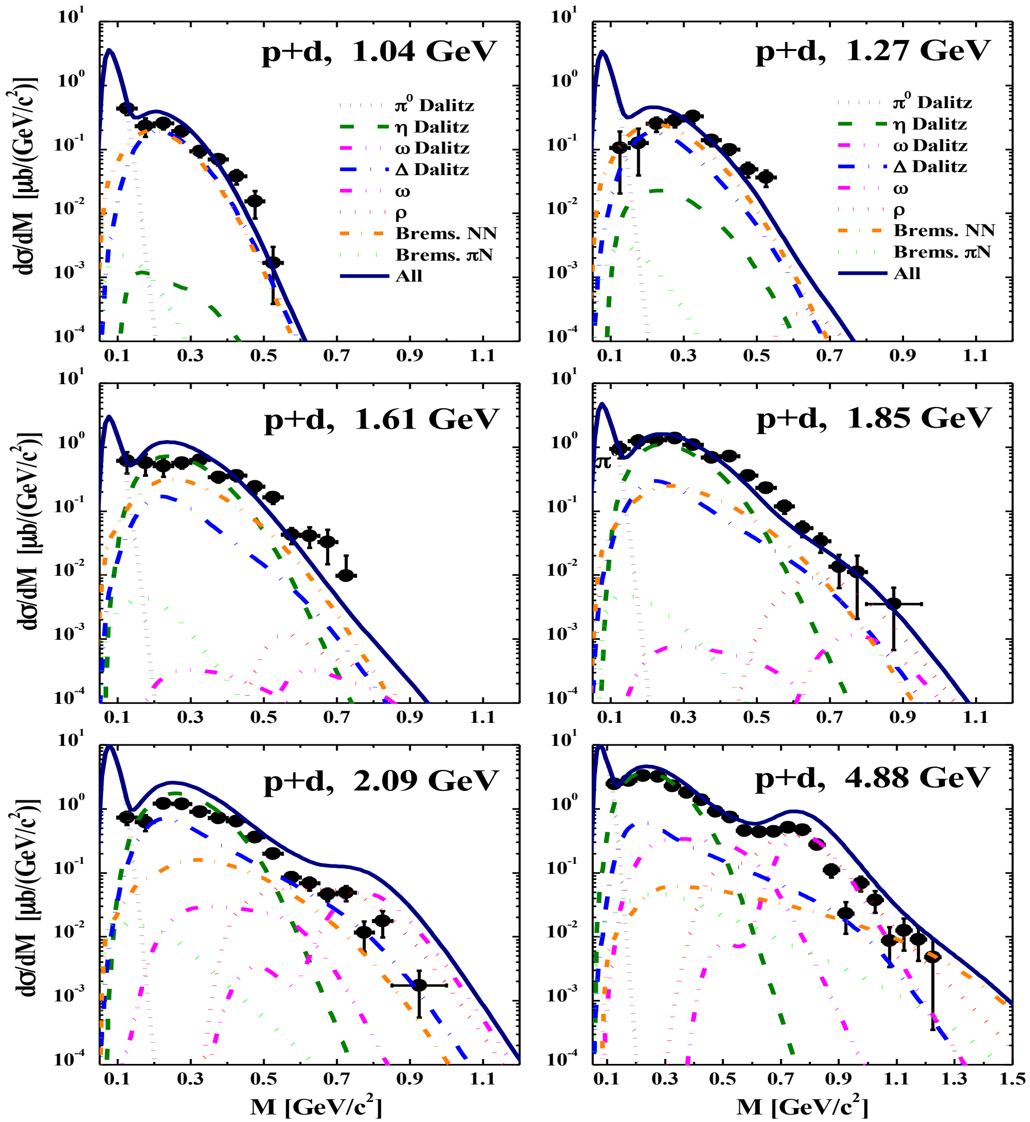


Data:
Wilson et al. PRC 57 (1997) 1865

Theory (folded with the DLS response):
Faessler, Fuchs et al.
J. Phys. G29 (2003) 603
(Resonances + decays)

RQMD

DLS p+d data: ... and more models



Data:
Wilson et al. PRC 57 (1997) 1865

Theory (folded with the DLS response):
Bratkovskaya et al., HSD model
(NN Bremstrahlung a-la Kaptari *et al.*, 2006)

HSD

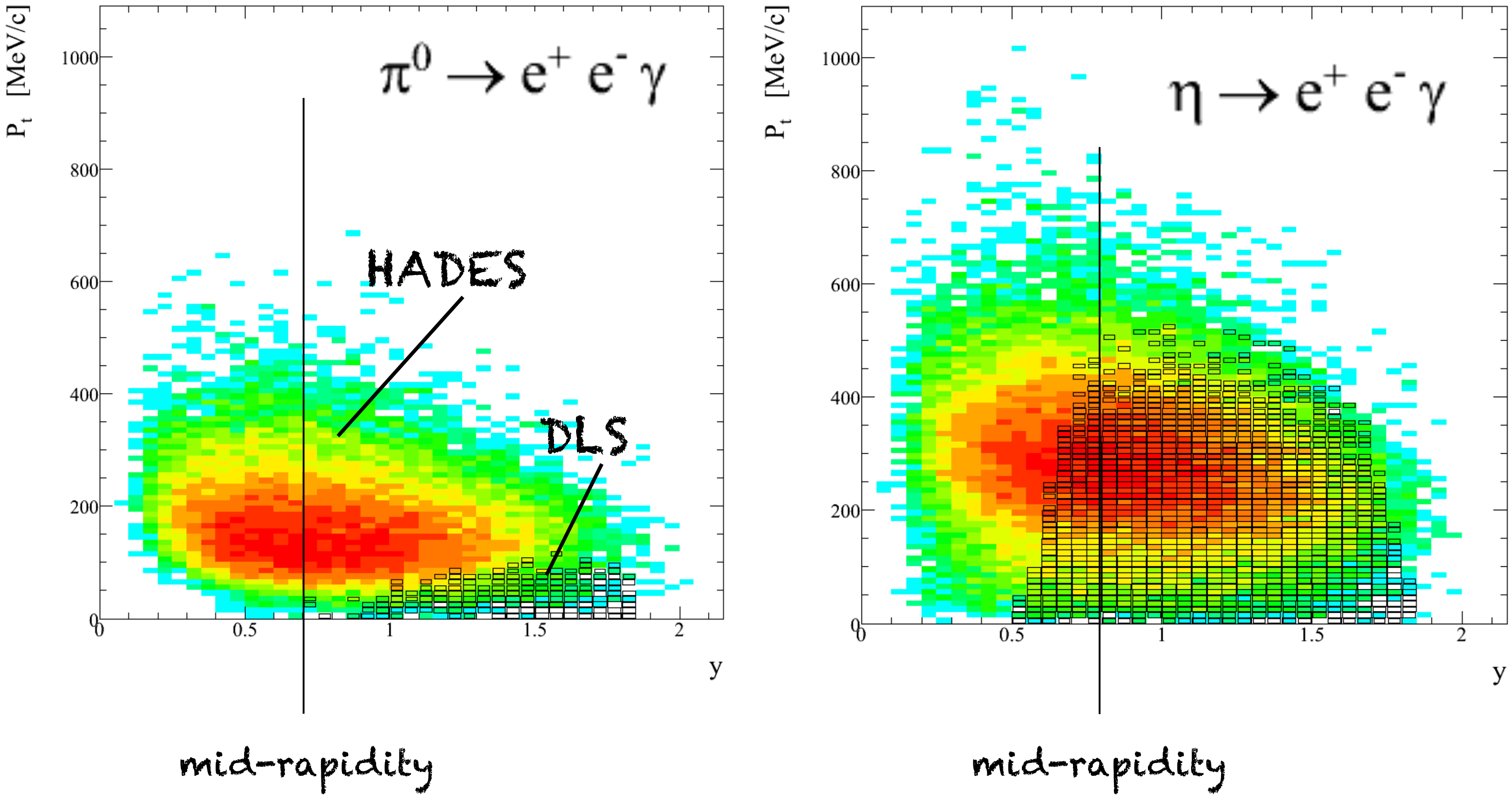
DLS p+d data: not described by theory!

pp vs. pd : What's different?

DLS "pd Puzzle"?

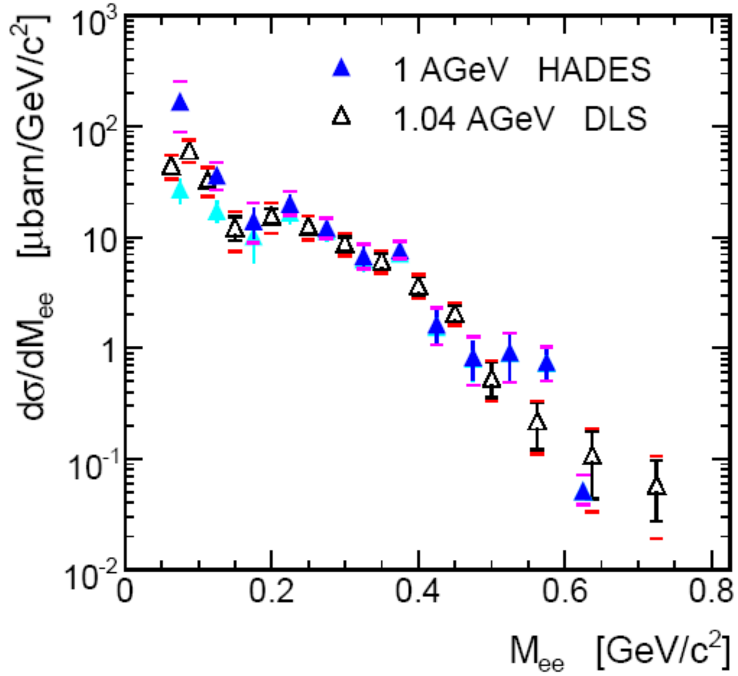
Validate on DLS: is data correct?

Phase space coverage: HADES vs. DLS

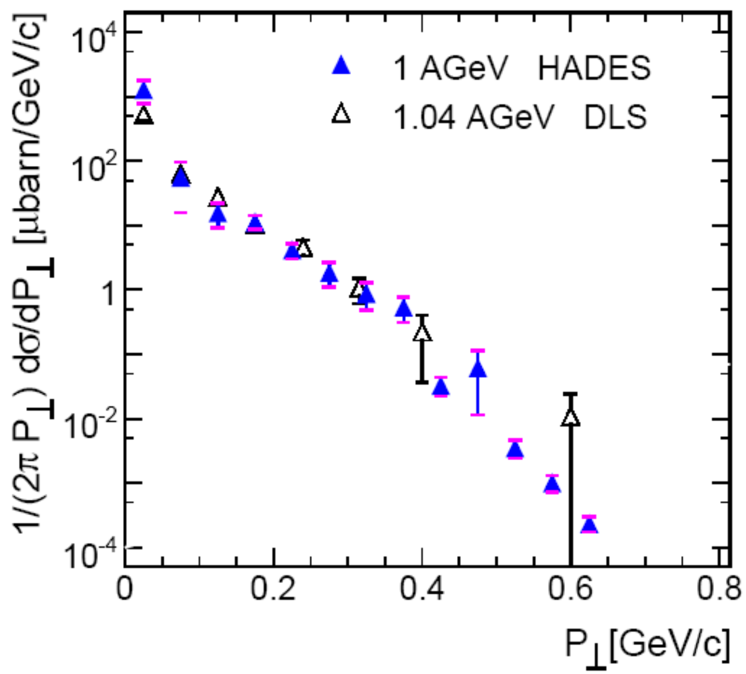


For a comparison of HADES and DLS results the HADES yield has to be extrapolated to full phase space

Direct comparison



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



J. Carroll – presentation

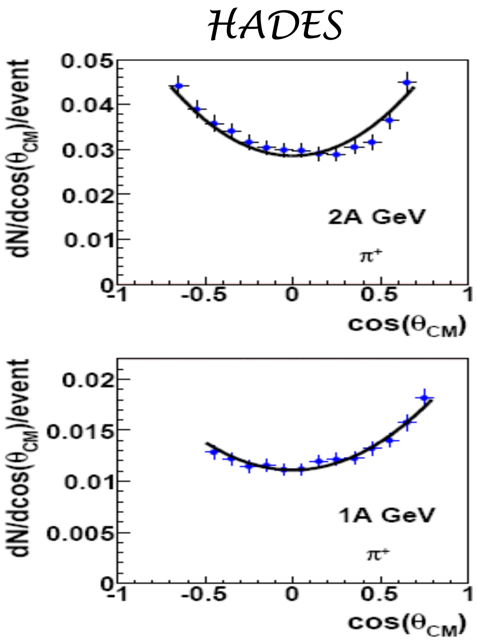
International Workshop on Soft Dilepton Production
August 20-22,1997, LBNL

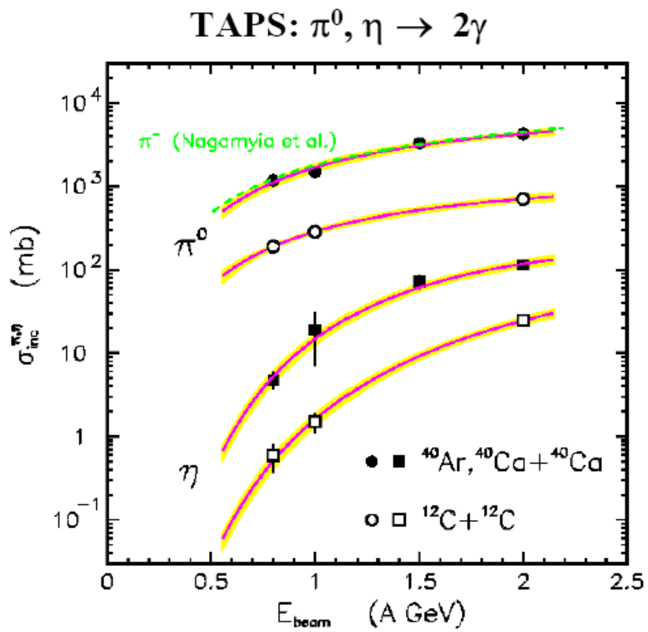
→ HADES and DLS data agree

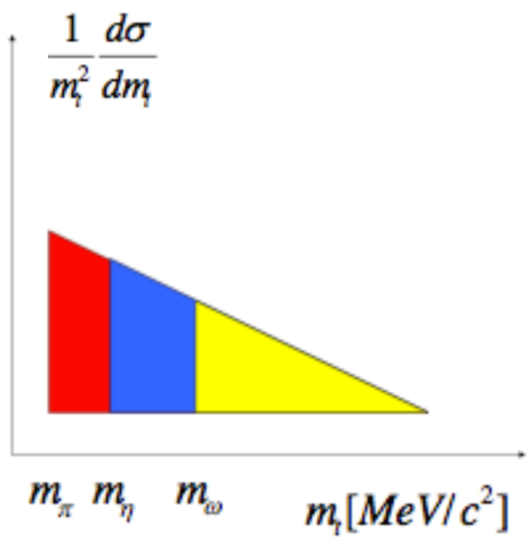
Hadronic cocktail

HADES Cocktail = long lived mesonic components

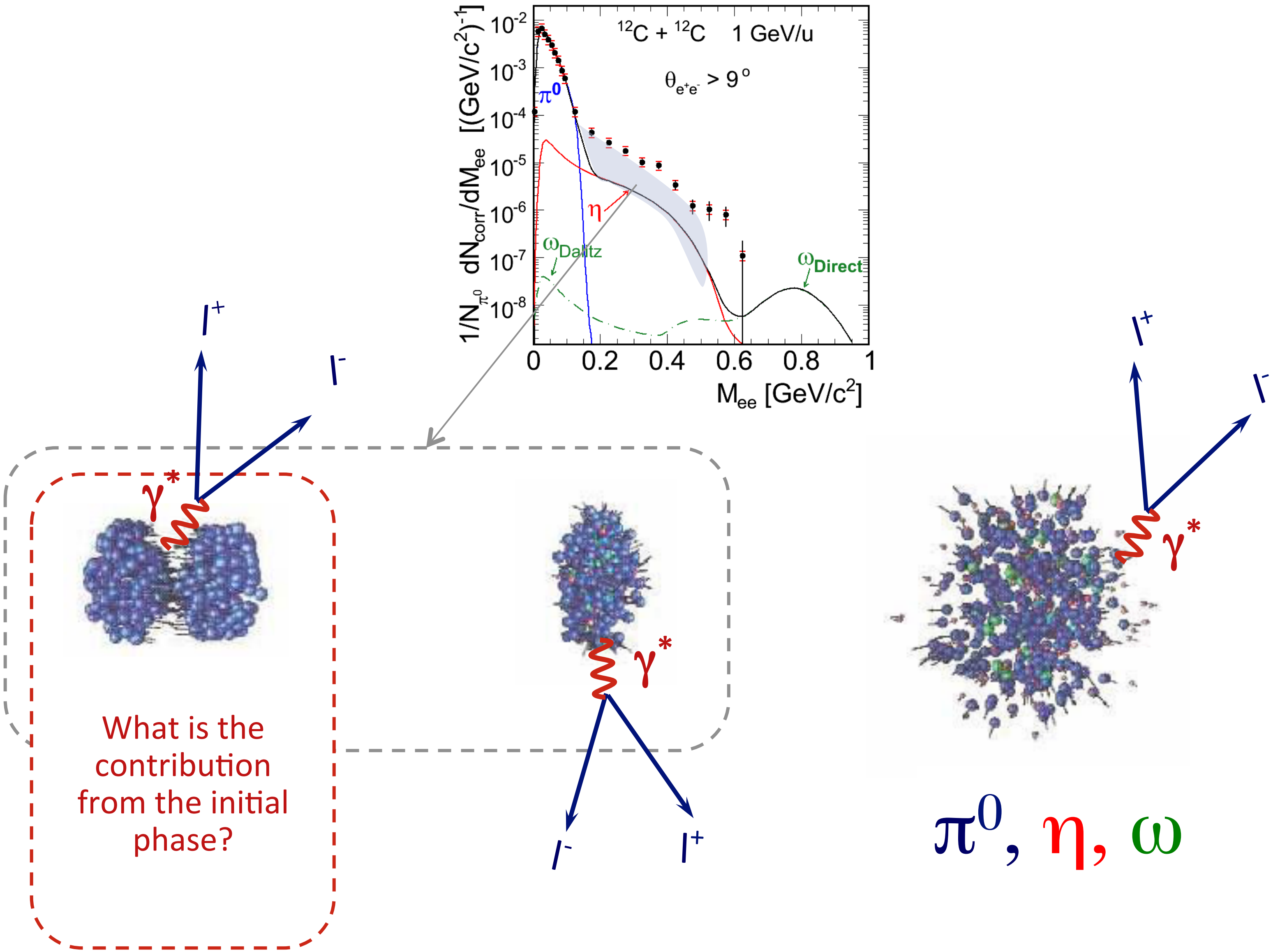
- π^0 thermal source, anisotropic angular distribution according to measured $\pi^{+/-}$
- η isotropic
- ω m_T scaling isotropic decay pattern







What is missing?



Elementary reactions

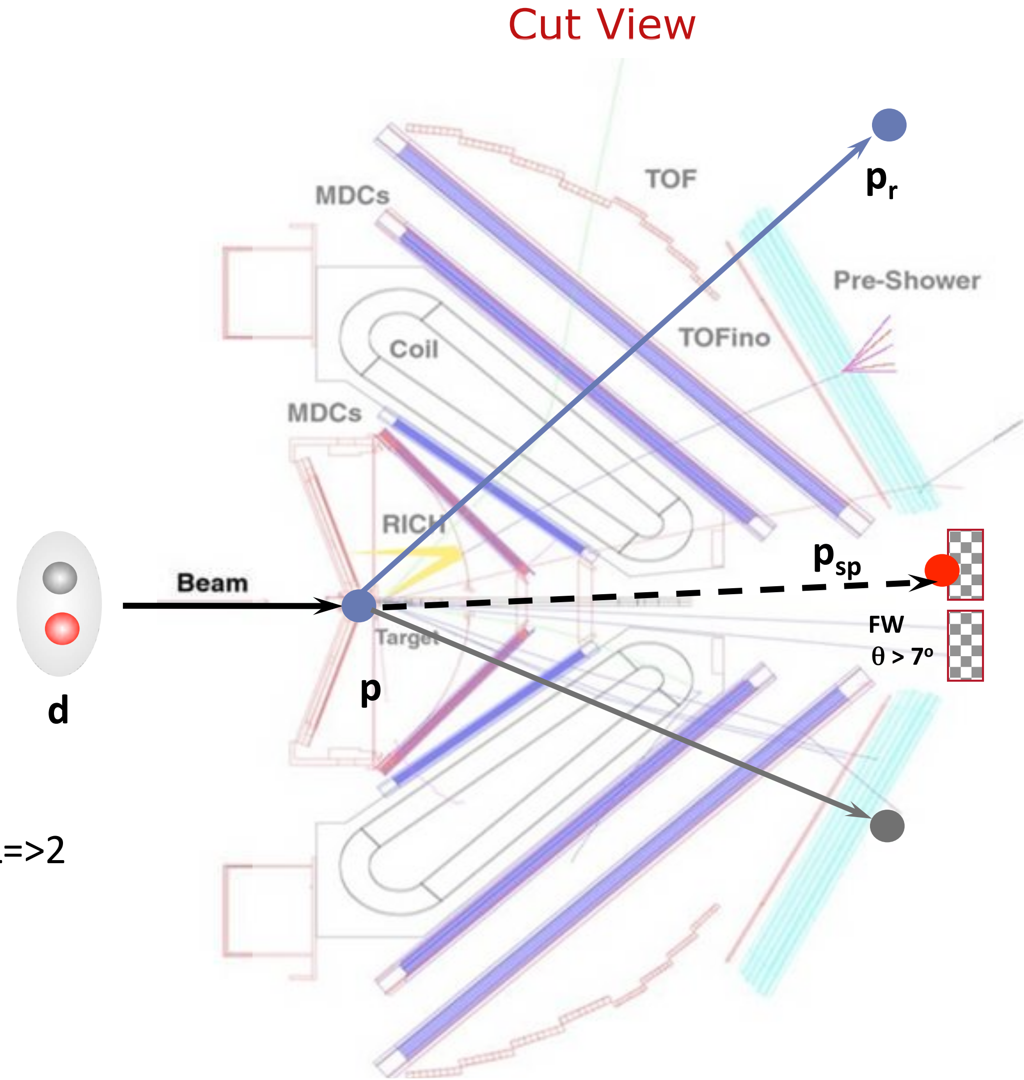
- Beam energy E_{beam} = 1.25 GeV ($s<s_{thres}$ for η production)
- LH2 target

p+p:

- one week of running in April 2006
- ~$2.6*10^9$ LVL1 events collected (MUL=>3 trigger)

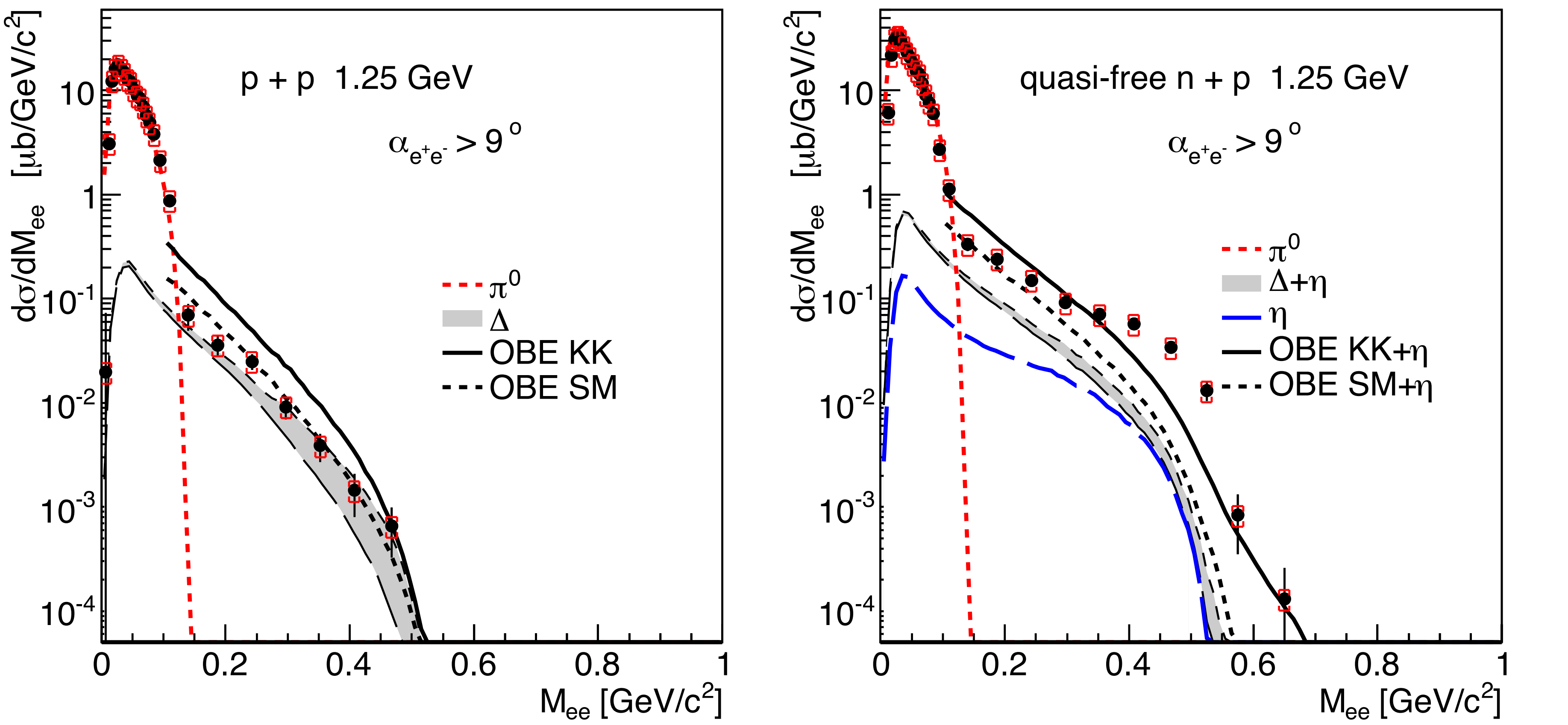
d+p:

- two weeks of running in April 2007
- ~$4.8{\cdot}10^9$ LVL1 events collected (MUL=>2 && FW "p spectator") tag on np → e^+e^- X reactions



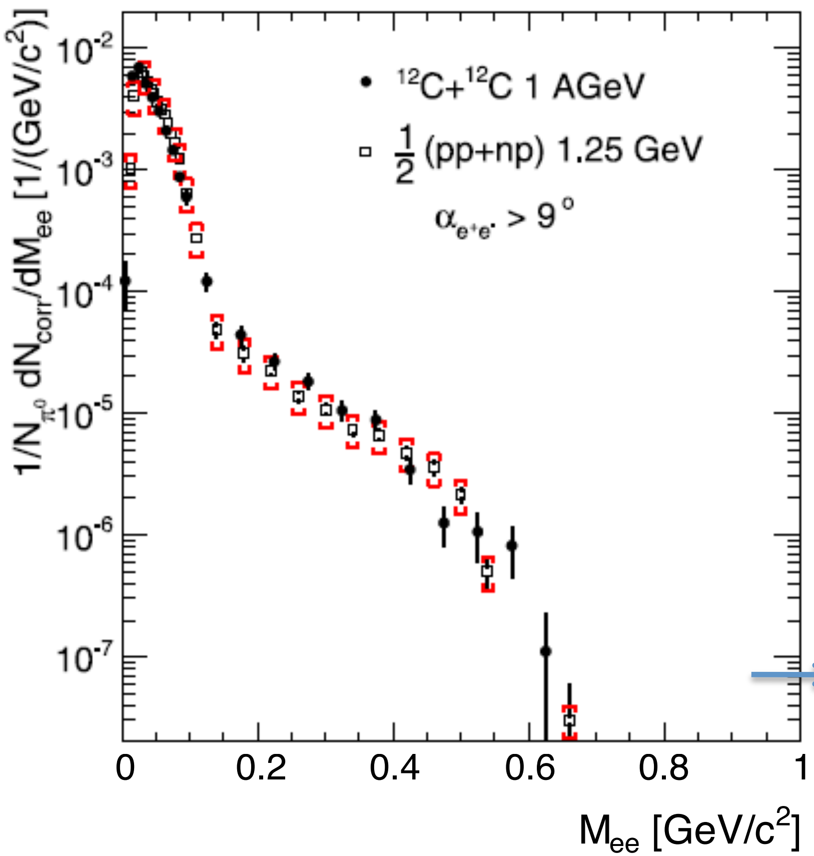
HADES pp and dp (tagged n) data vs. models

"If you are out to describe the truth, leave elegance to the tailor"+ + A. Einstein



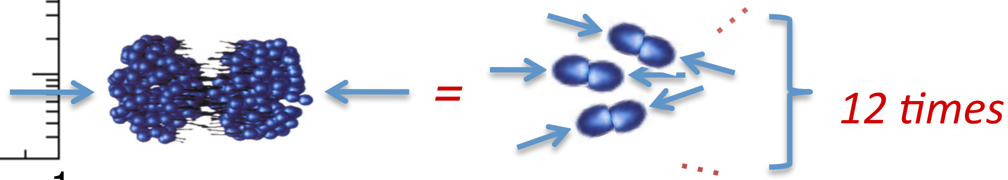
Origin of the low-mass pair excess in C+C collisions

Comparison of C+C to N+N collisions



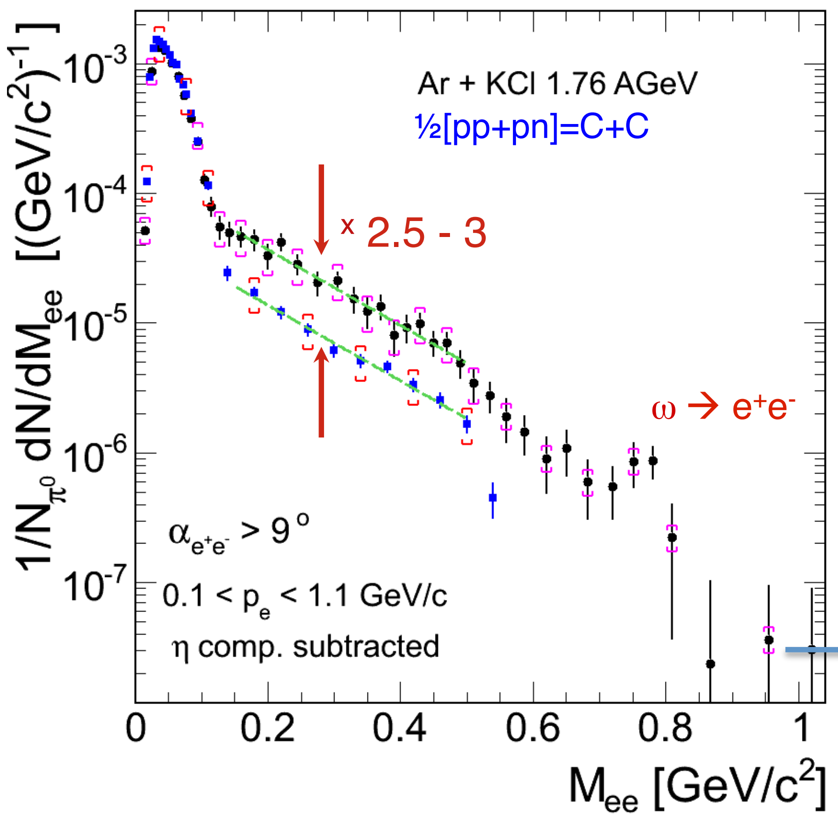
- C+C data reproduced (within 20%) by superposition of N+N interactions
- Pair excess observed in C+C data has been traced back to anomalous pair production in n+p collisions

*C+C = 12 * (Nukelon+Nukleon)?*



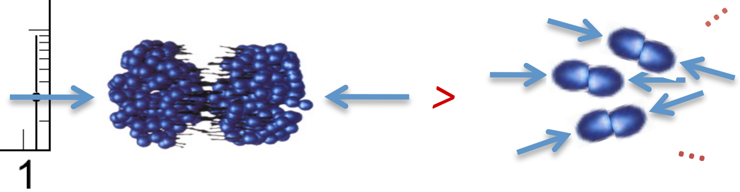
Is there physics beyond free NN?

<u>Efficiency corrected dielectron spectra</u>
<u>from Ar+KCl at E_{kin} = 1.76 GeV/u</u>



- First observation of w→e^+e^- peak in heavy-ion collisions at SIS energies
- First evidence for „true“ excess (strong excess above the “reference cocktail”)

*Is Ar+KCl = 40 * (Nukelon+Nukleon)?*



40 times

Summary: HADES and DLS

- Origin of the low-mass dielectron pair excess in nucleus-nucleus collisions at 1-2 GeV/*u* established

- *p+p* and *n+p* data are critical test for theoretical input
- light systems (i.e *C+C*) can be described by superposition of *NN* interactions

- "DLS puzzle"?
    - experimentally – solved
    - theoretically – only after *n+p* data is consistently explained

LESON: know your reference!