TECHNISCHE
UNIVERSITÄT
DARMSTADT


Summer School

Heavy Ion Collisions in the QCD phase diagram

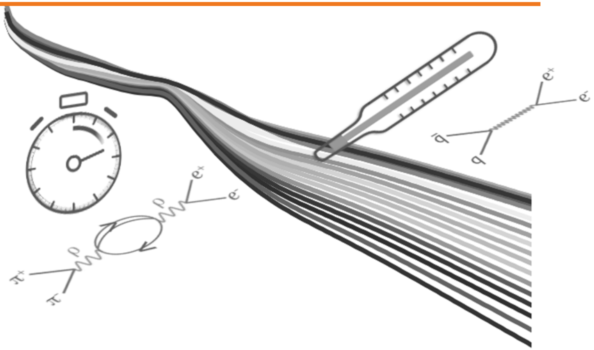
cnrs GDR Groupement de recherche
QCD Chromodynamique quantique

June 27-July 8, 2022 Subatech, Nantes (France)

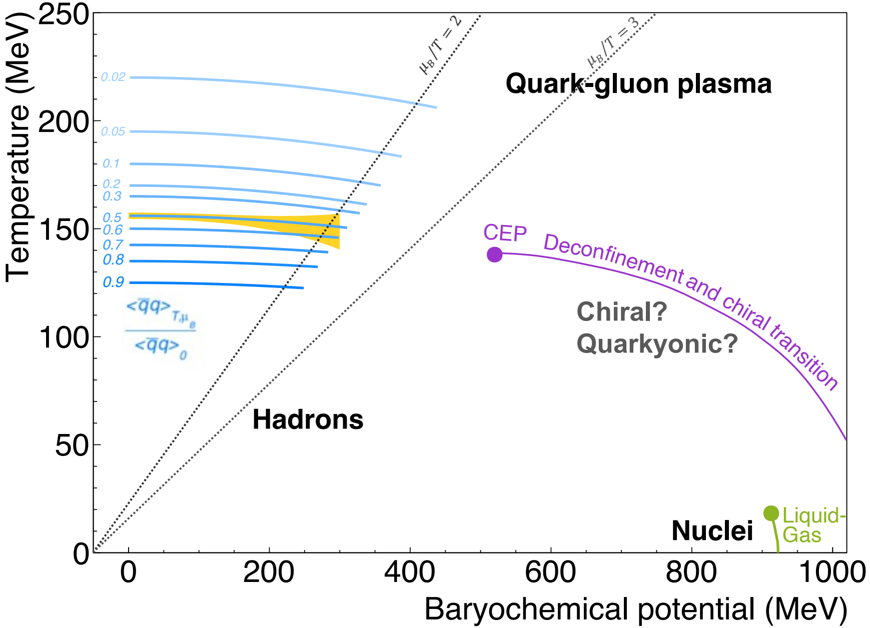
HADRONS IN MEDIUM

Tetyana Galatyuk
Technical University Darmstadt / GSI
04 July, 2022

Lecture 1



Searching for landmarks of the QCD matter phase diagram



Borsanyi *et al*. [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141

- **Vanishing μ_B, high T (lattice QCD):**
  - crossover from hadronic to partonic medium
    - $T_{pc} = 156.5 \pm 1.5$ MeV (physical quark masses, $T_c = 132^{+3}_{-6}$ MeV at chiral limit)
  - no critical point indicated by lattice QCD at $\mu_B^{CEP}/T_c < 3$

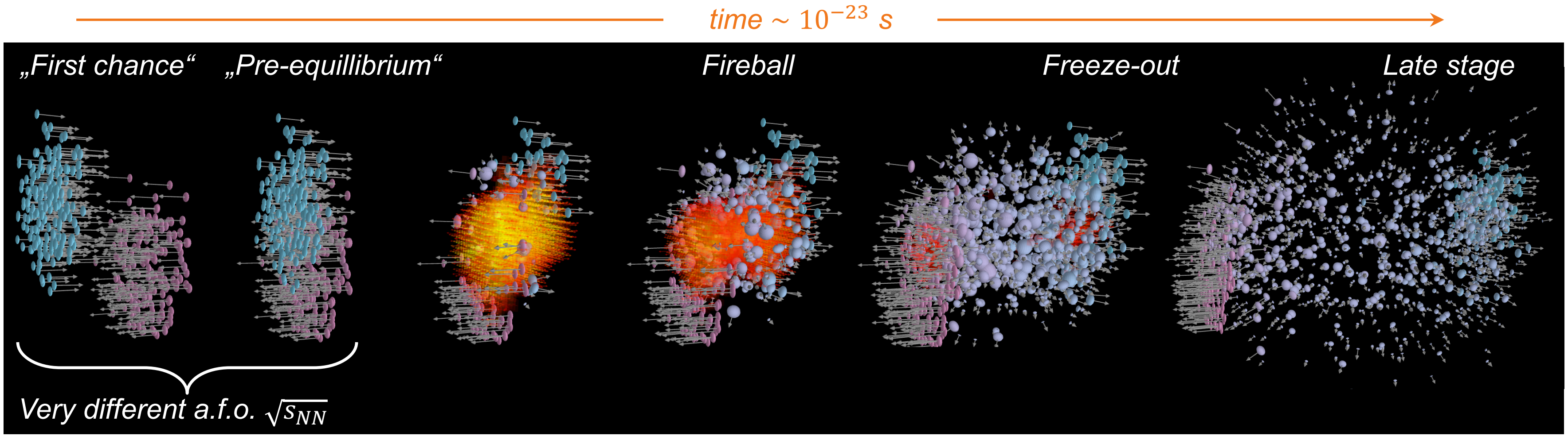
Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Ding *et al.*, [HotQCD], PRL 123 (2019) 6, 062002
Dini *et al.*, Phys.Rev.D 105 (2022) 3, 034510

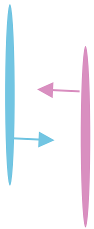
- **Large μ_B, moderate T (lQCD inspired effective theories):**
  - limits of hadronic existence?
  - 1st order transition?
  - QCD critical point?
  - equation-of-state of dense matter?

Worldwide experimental and theory efforts

Relevance for astrophysics

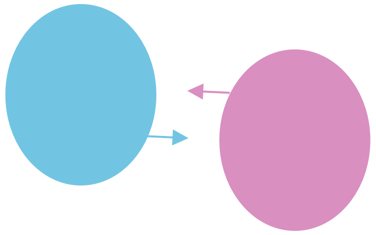
Accessible through heavy-ion collisions at relativistic energies





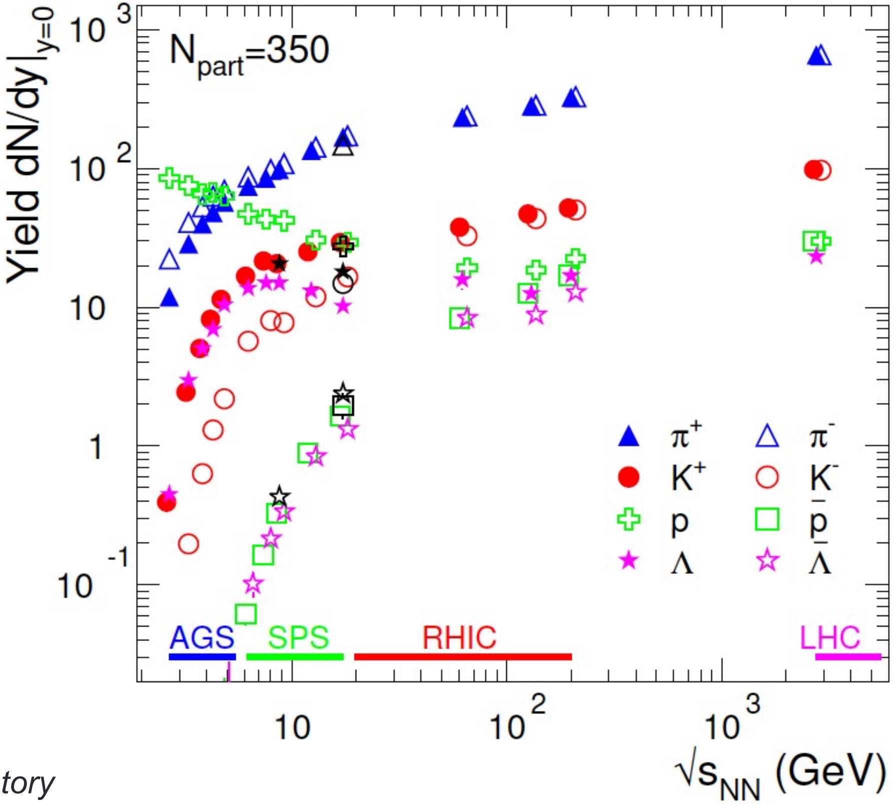
LHC energies $\sqrt{s_{NN}} = 2\,TeV$
parton+parton collisions

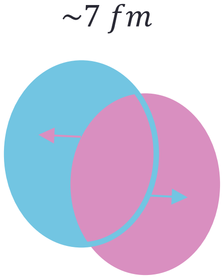
SIS18 energies $\sqrt{s_{NN}} = 2\,GeV$
nuclear stopping



Hadron yields at freeze-out

compilation A. Andronic

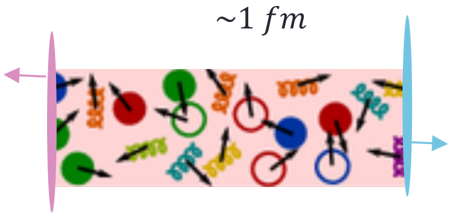




$N_{particles} \gg N_{anti-particles}$

Baryon-dominated matter

NS merger matter in the laboratory



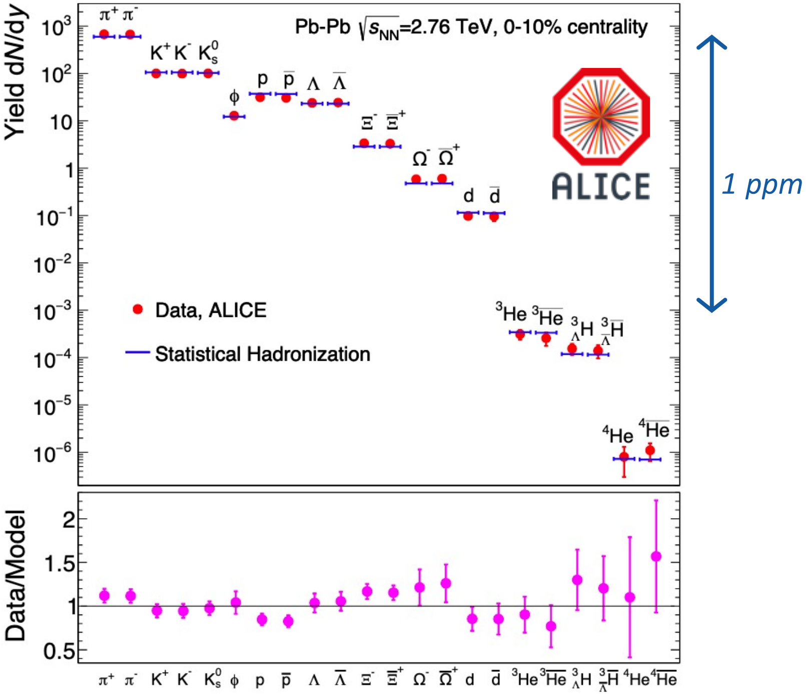
Lots of particles, mostly newly created ($E = mc^2$)

$N_{particles} = N_{anti-particles}$

Early Universe in the laboratory

Are we creating a thermal medium in experiments?

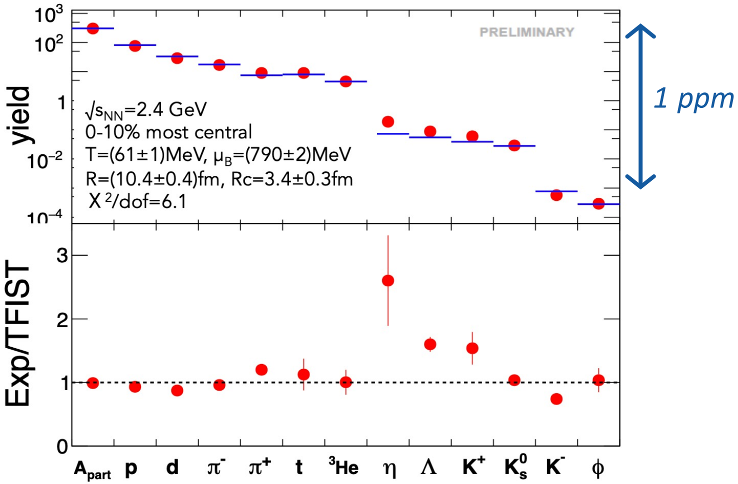
Hadron yields and statistical hadronization model (SHM)



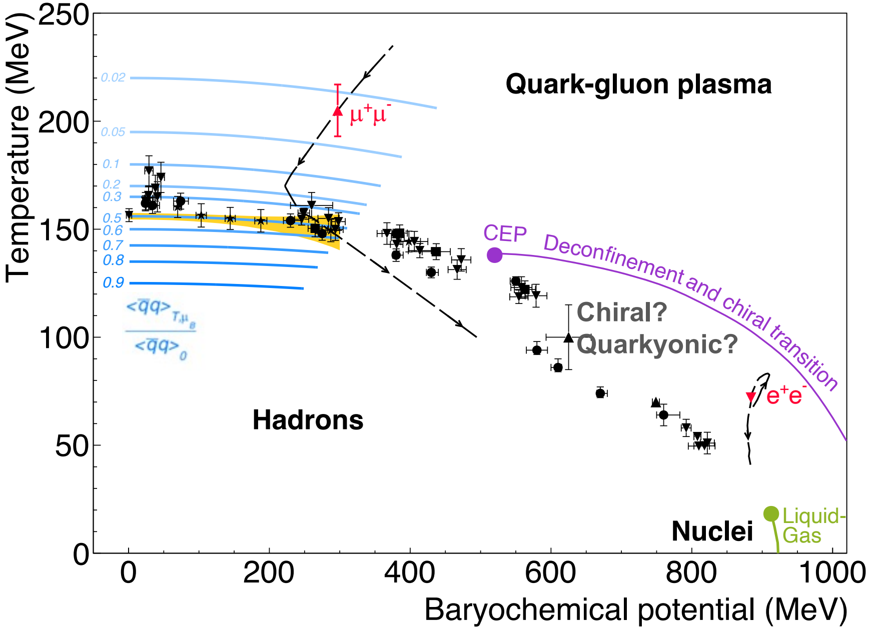
Andronic *et al.*, Nature 561 (2018) no.7723

- Factor 1000 in beam energy / factor ~2 in temperature
- Hadron abundances described in framework of SHM
  - Calculation carried out with vacuum masses!
  - Strangeness canonical treatment at low beam energies
  - Include feed-down from $^4He,\ ^4H,\ ^4Li$

Hahn, Stöcker, NPA 476 (1988) 718-772
Shuryak, Torres-Rincon PRC 101 (2020) 3, 034914



Searching for landmarks of the QCD matter phase diagram



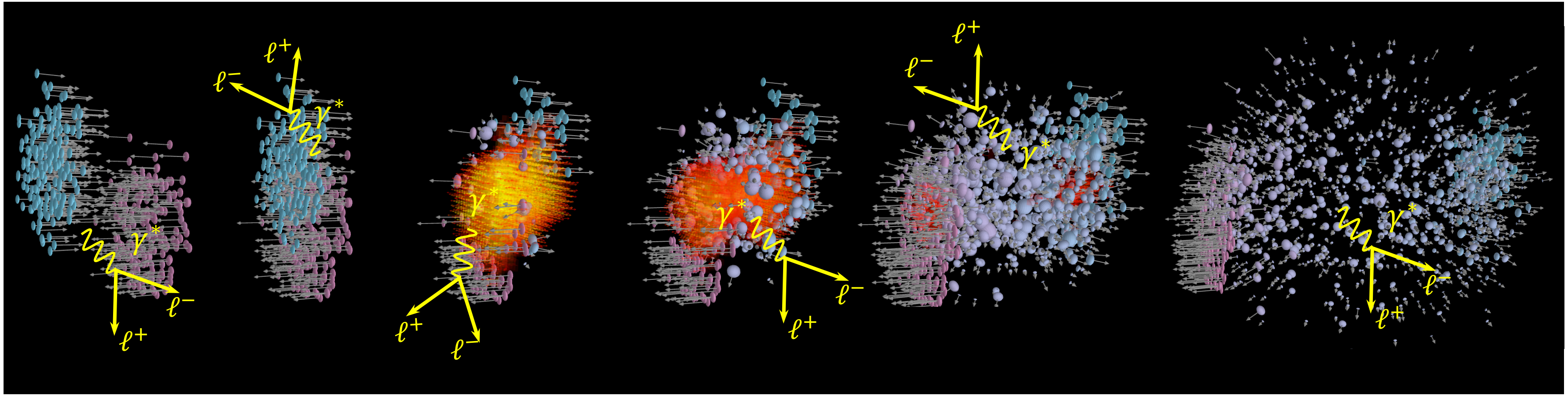
- **Experimental challenge:**
  - locate the onset of new phases of QCD
  - detect the conjectured QCD critical point
  - probe microscopic matter properties

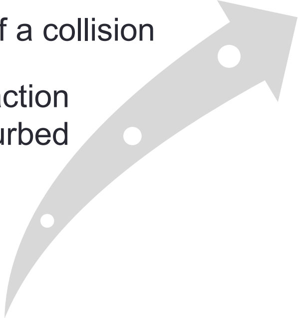
- **Measure with utmost precision:**
  - event-by-event fluctuations (criticality)
  - strangeness (bulk properties)
  - charm (transport properties)
  - dileptons (emissivity)

⇝ Unique role played by electromagnetic radiation

HADES, Nature Phys. 15 (2019) 10, 1040-1045
NA60, Specht *et al.*, AIP Conf.Proc. (2010) 1322
Andronic *et al.*, Nature 561 (2018) no.7723

Electromagnetic radiation (γ, γ^*)





Reflect the whole history of a collision

No strong final state interaction
⇝ leave reaction volume undisturbed

They have a long mean free path
and can carry information from
production site to detectors

Encodes information on matter properties enabling unique measurements

- degrees of freedom of the medium
- restoration of chiral symmetry
- fireball lifetime, temperature, acceleration, polarization
- transport properties

Electromagnetic radiation as multi-messenger of fireball

Spectrometer

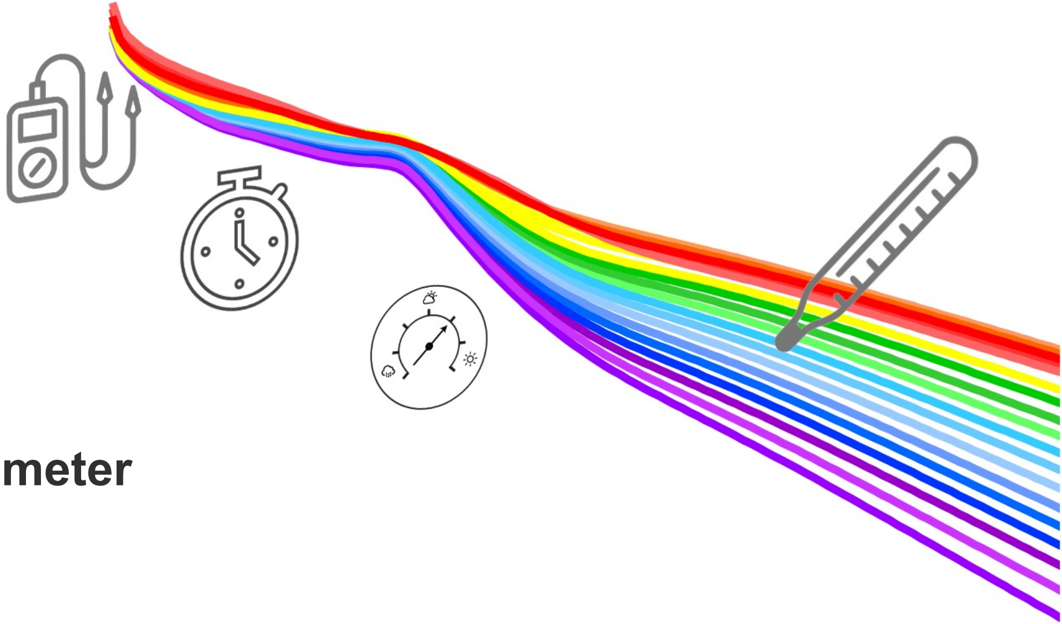
Chronometer

Barometer

Thermometer

Polarimeter

Amperemeter



- Introduction to in-medium properties of hadrons
- Theoretical predictions for in-medium modifications
- Experimental approaches for measuring in medium properties of hadrons

Topics discussed

Electromagnetic production rate

em current-current correlation function

$$\Pi_{em}^{\mu\nu}(q_0, q) = -i\int d^4x\, e^{iq\cdot x}\theta(x^0)\langle[j^\mu(x), j^\nu(0)]\rangle$$

In the quark basis, corresponding to the elementary d.o.f. in the QCD Lagrangian the em current

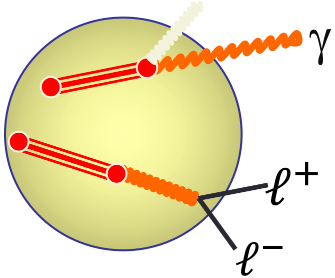
$$j_{em}^\mu = \sum_{i=u,d,s} e_i\bar{q}_i\gamma^\mu q_i = \frac{2}{3}\bar{u}\gamma^\mu u - \frac{1}{3}\bar{d}\gamma^\mu d - \frac{1}{3}\bar{s}\gamma^\mu s$$

Can be rearranged into good isospin states which leads to the hadronic basis according to

$$\begin{aligned} j_{em}^\mu &= \frac{1}{2}\left(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d\right) + \frac{1}{6}\left(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d\right) - \frac{1}{3}\bar{s}\gamma^\mu s \\ &= \frac{1}{\sqrt{2}}j_\rho^\mu + \frac{1}{3\sqrt{2}}j_\omega^\mu - \frac{1}{3}j_\phi^\mu \end{aligned}$$

Electromagnetic spectral function

Determines both photon and dilepton rates



- Photons characterized by “transverse” momentum:

$$q_0 \frac{dN_\gamma}{d^4x d^3q} = -\frac{\alpha_{em}}{\pi^2} f^B(q \cdot u; T)\, Im\Pi_{em}(q_0 = q; \mu_B, T)$$

- Dileptons carry extra information: invariant mass
  → unique direct access to in-medium spectral function

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M^2) f^B(q \cdot u; T)\, Im\Pi_{em}(M, q; \mu_B, T)$$

Lepton phase space factor

Thermal Bose distribution

Spectral function

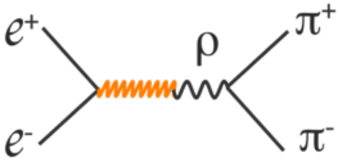
McLerran, Toimela, PRD 31, 545 (1985)
Weldon, PRD42, 2384-2387 (1990)
Gale, Kapusta, PRC 35, 2107 (1987) & NPB 357, 65-89 (1991)

em correlator in the vacuum

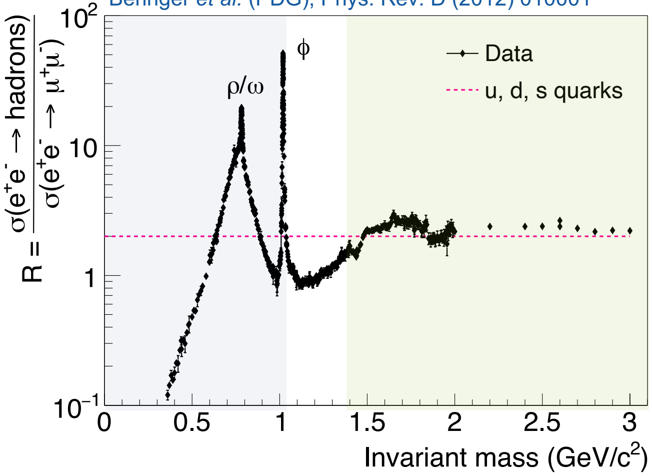
accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

Low-mass regime LMR

em spectral function is saturated by light vector mesons (VMD $J^P = 1^-$ for both γ^* and VM, **ρ playing a dominant role**)

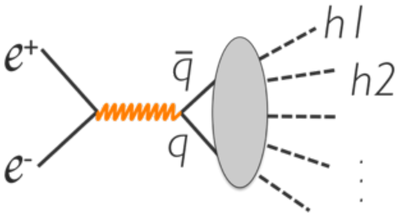


Beringer *et al.* (PDG), Phys. Rev. D (2012) 010001



Intermediate-mass regime IMR

perturbative QCD continuum (quark degrees of freedom)



$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

$$Im\Pi_{em}^{vac} = -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\cdots\right)N_c \sum_{q=u,d,s}(e_q)^2$$

Sakurai, Ann.Phys. 11 (1960)

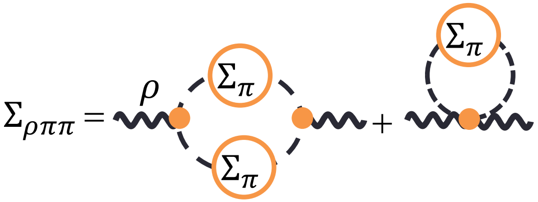
In-medium spectral functions from hadronic many body theory

ρ meson in medium interacts with hadrons from heat bath

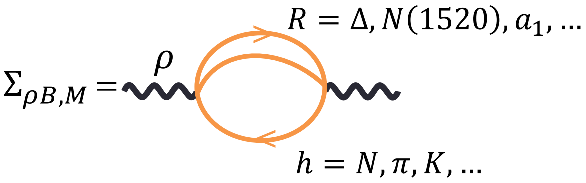
additional contributions to the ρ-meson self-energy

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

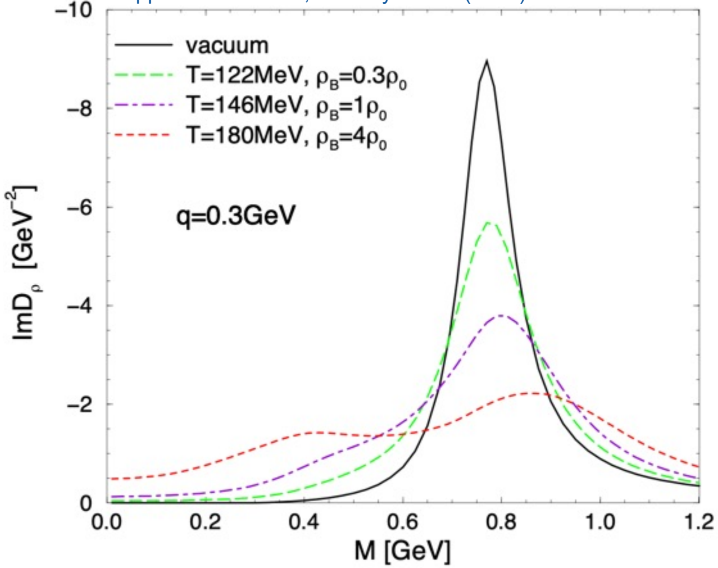
in-medium pion cloud



direct ρ-hadron scattering



Rapp and Wambach, Eur.Phys.J. A6 (1999)



↝ **ρ-peak undergoes a strong broadening**
↝ **baryonic effects are crucial**

Alam *et al.*, Annals Phys.286 (2001) 159 (2001)
Leupold, Metag, Mosel, Int.J.Mod.Phys. E19 (2010) 147
Rapp, Acta Phys.Polon. B42 (2011) 2823-2852

em spectral functions – connection to chiral symmetry χ_c

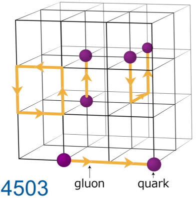
- Chiral symmetry = fundamental symmetry of QCD for massless quarks ($m = 0$)

$$\mathcal{L}_{QCD} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a,\mu\nu} + \bar{\psi}(i\gamma_{\mu}D^{\mu} - m)\psi$$

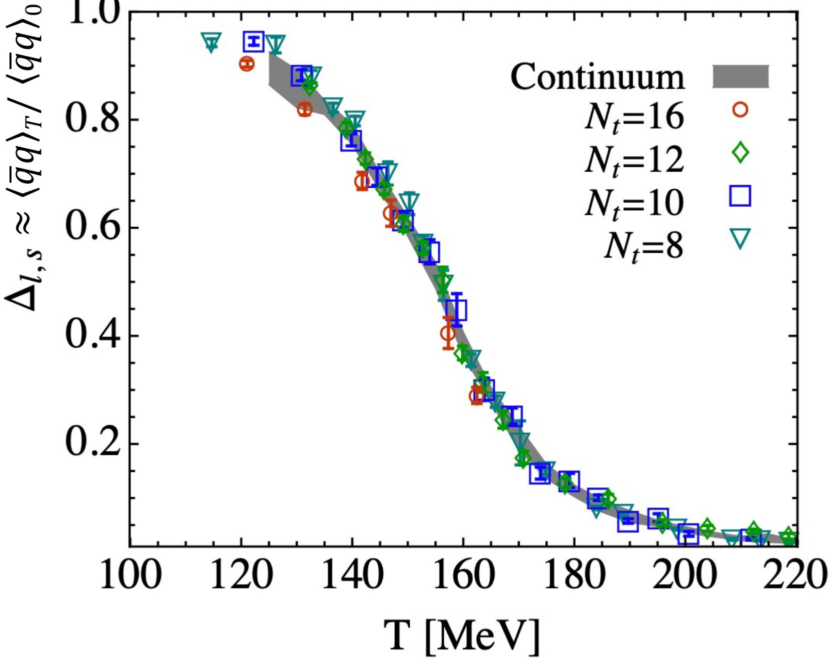
- Chiral symmetry is **explicitly broken** by the finite masses of the current (u, d, s) quarks

- Chiral symmetry is **spontaneously broken**, and much more strongly so, because of the existence of a non-vanishing vacuum expectation value of the scalar quark condensate – an order parameter for chiral phase transition

$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \cong (-250\ MeV)^3$$



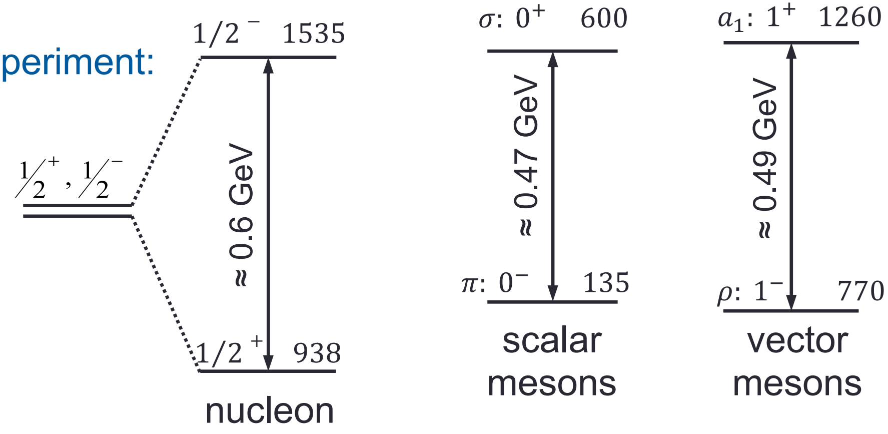
Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503



Consequences

- 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: $J^P = 1/2^+$; chiral partner $N^*(1535)$: $J^P = 1/2^-$ mass degenerate??

Experiment:



Chiral symmetry is broken in hadronic sector

“Chiral partners” split: $\Delta M \cong 0.5$ GeV

Entire spectral shape matters

em spectral functions – connection to chiral symmetry χ_c

Weinberg, Phys. Rev. Lett. 18 (1967) 507

- **QCD and chiral sum rules** relate moments of the isovector-vector and -axialvector spectral functions to order parameters of spontaneously broken χ_c

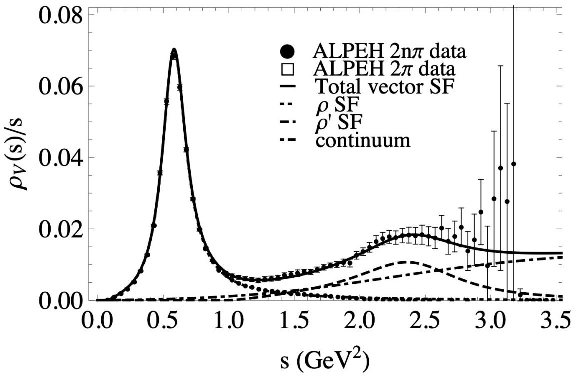
$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

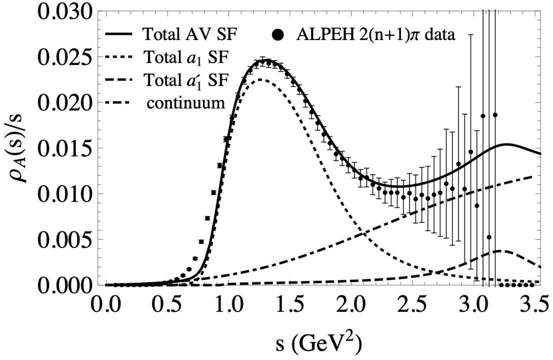
- … accurately satisfied in vacuum

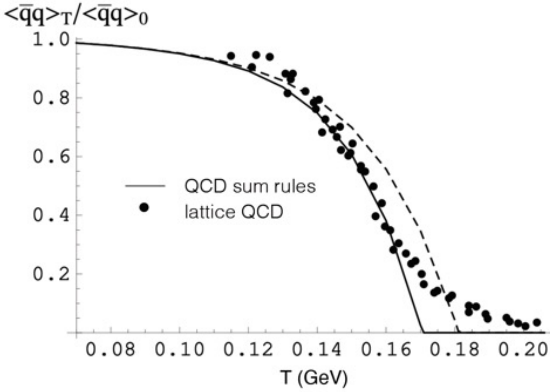
Hohler and Rapp, Annals Phys. 368 (2016) 70-109
Holt, Hohler, Rapp, Phys.Rev. D87 (2013) 076010

- … remain valid in medium

Kapusta and Shuryak, Phys.Rev. D49 (1994) 4694

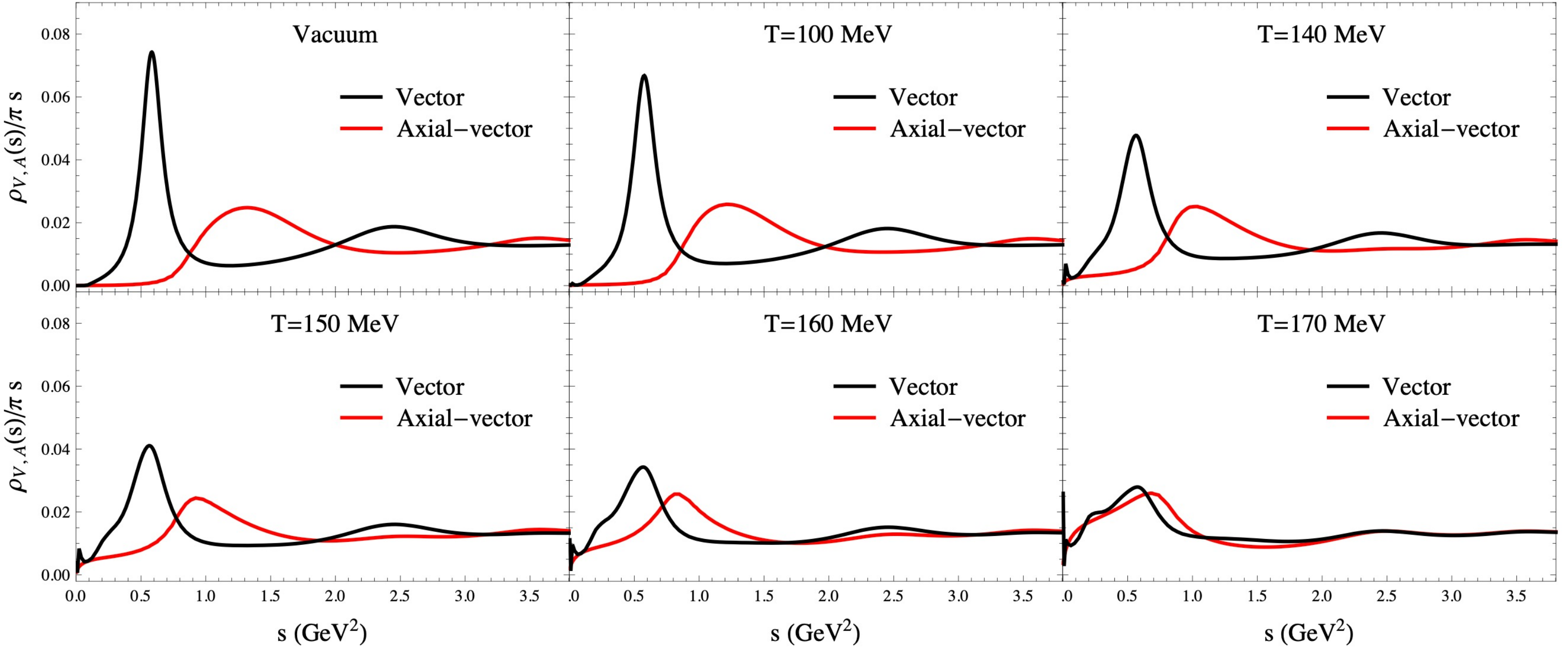






How does chiral symmetry restoration affect hadrons / quarks?

In-medium em spectral functions – connection to chiral symmetry χ_c

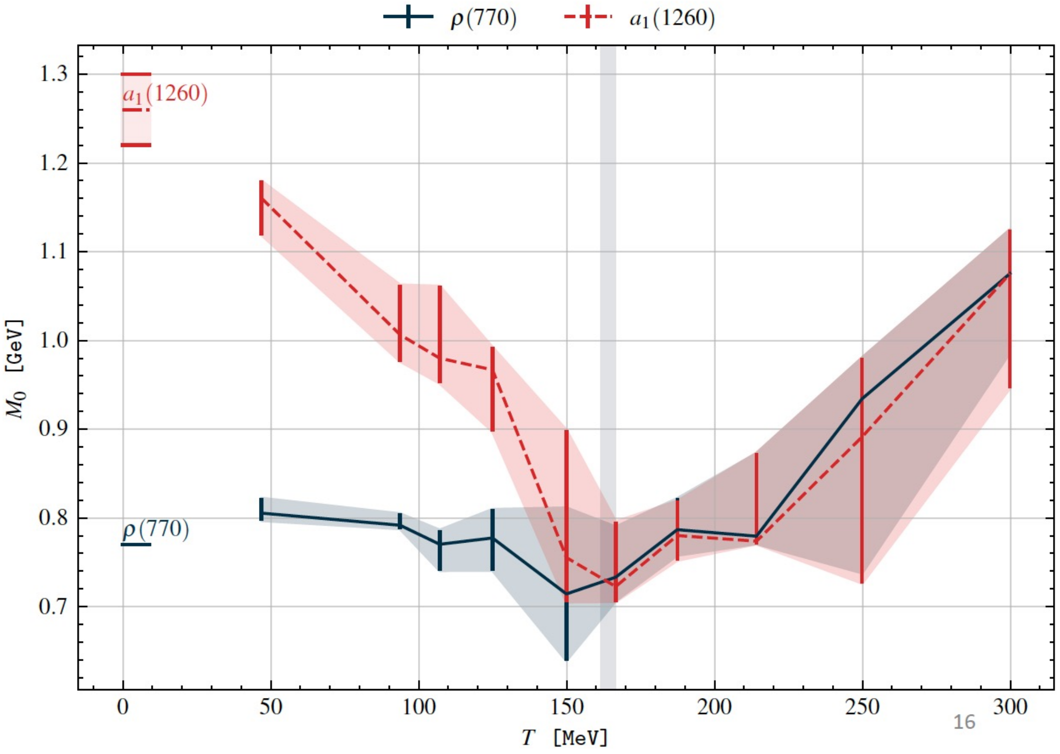


ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

Hohler and Rapp, PLB 731 (2014) 103

Light mesons: lattice-QCD results

- **Restoration** of chiral symmetry at finite T and μ_B manifestsitself through mixing of vector and axial-vector correlators
- ρ/a_1 degeneracy emerges at thermal transition

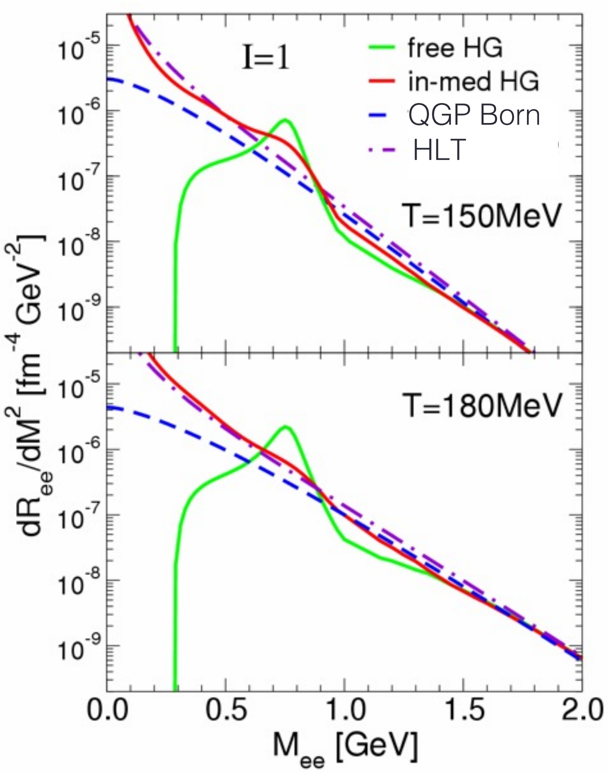


Aartz, QM2022, April 2022

See also:
Aarts *et al.*, Phys. Rev. D 92 (2015) no.1, 014503
Allton *et al.*, PoS LATTICE2015 (2016) 183
Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
Tripolt, Jung, Tanji, v. Smekal, Wambach, NPA982 (2019) 775
Fu, Pawlowski and Rennecke, Phys. Rev. D101 (2020) no.5, 054032

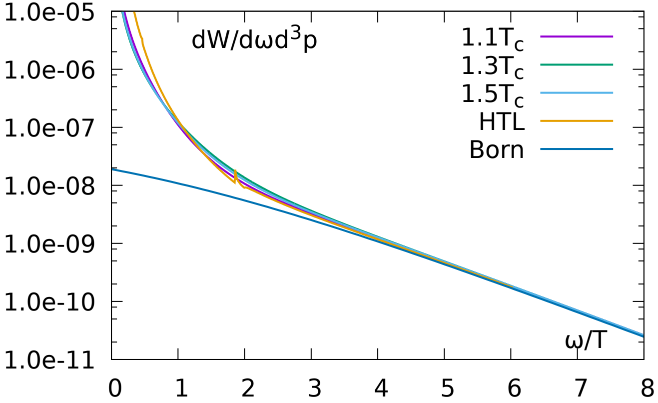
Degrees of freedom of the medium

Quark-to-hadron transition



Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

Thermal dilepton rate in 2-flavor QCD (quenched lattice QCD)



Ding *et al.*, Phys.Rev.D 83 (2011) 034504
Ding *et al.*, Phys.Rev.D 94 (2016) 3, 034504

⇝ ρ-meson melts

⇝ spectral function merges into QGP description

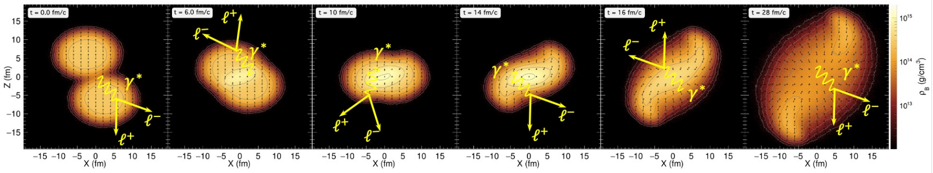
Direct evidence for transition hadrons to quarks and gluons?

„If you want to detect something new, build a dilepton spectrometer“

S. Ting

Dilepton invariant mass spectra

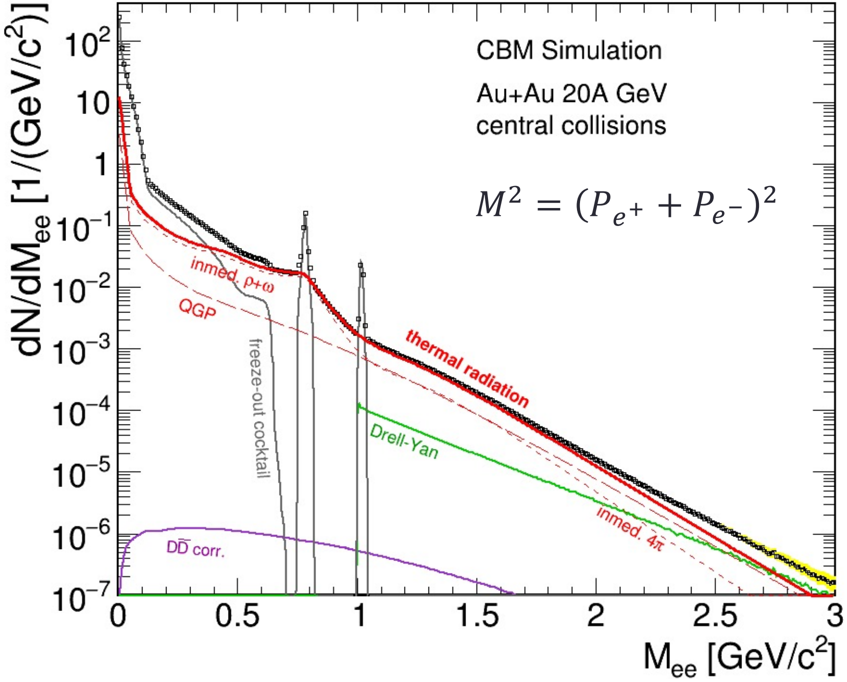
Characteristic features



first chance collisions

thermal radiation

freeze-out



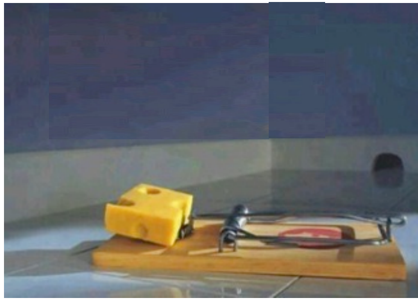
i. First chance collisions, pre-equillibrium:
  - ☐ $q(N)\bar{q}(N) \longrightarrow e^+e^-X$
  - ☐ $NN \rightarrow RN \longrightarrow e^+e^-NN$
  - ☐ *(charm*

ii. Thermal radiation from QGP and hadronic matter:
  - ☐ $q\bar{q} \rightarrow e^+e^-$, $\pi^+\pi^- \rightarrow e^+e^-$
  - ☐ short-lived states Δ, N^*, …
  - ☐ multi-meson reactions (‘4π’): $\pi\rho, \pi\omega, \pi a_1$,

iii. Decays of long-lived mesons:
  - ☐ $\pi^0, \eta, \omega, \varphi$, correlated $D\bar{D}$ pairs, …

The experimental challenge …

There is no such thing as a free lunch

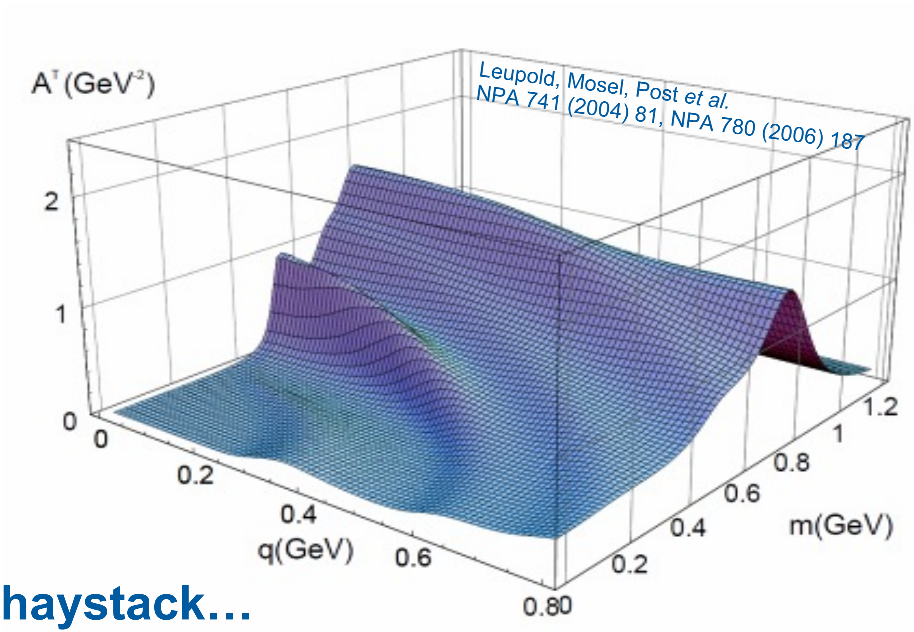


- Lepton pairs are rare probes (α^2)
- At few GeV energy regime $Yield_\omega \times \Gamma_{ee}/\Gamma_{tot}$
  ~10 decay per 1.000.000 events

- Large combinatorial background
  - in e^+e^- from Dalitz decays ($\pi^0 \rightarrow e^+e^-\gamma$) and conversion pairs
  - in $\mu^+\mu^-$: weak π, K decays

- Isolate the contribution to the spectrum from the hot/dense stage

- Strong momentum dependence of in-medium SF
- Modifications most pronounced at small momenta
- Mid-rapidity, low-$M_{\ell\ell}$, low-p_T coverage (acceptance correction)



Leupold, Mosel, Post *et al.* NPA 741 (2004) 81, NPA 780 (2006) 187

Looking for a needle in haystack…

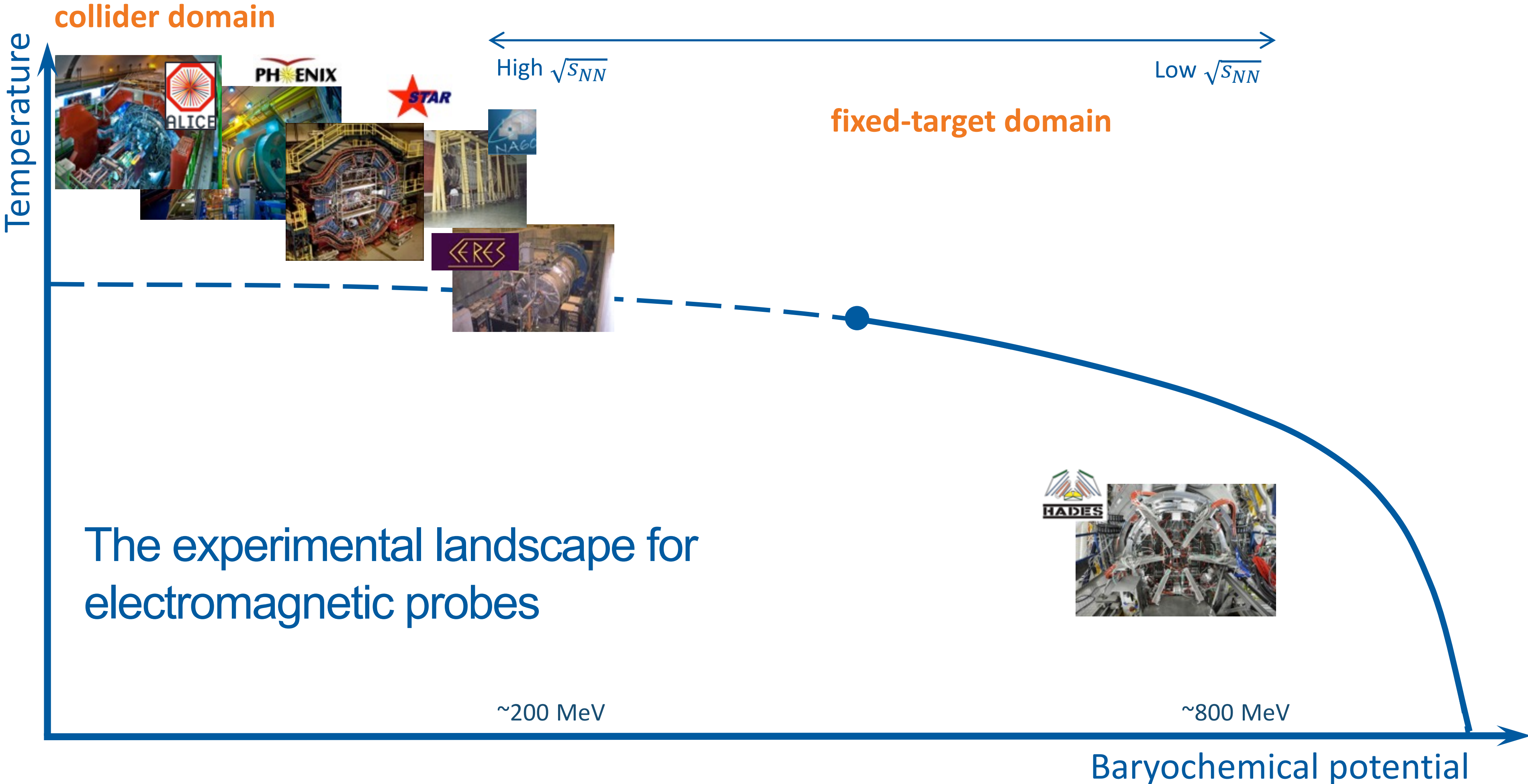
Italian Artist Sven Sachsalber looked for a needle in haystack

(November 2014)

… he has gone through periods of doubt
and serious discouragement

… but after 2 days, he found it !

The experimental landscape for electromagnetic probes



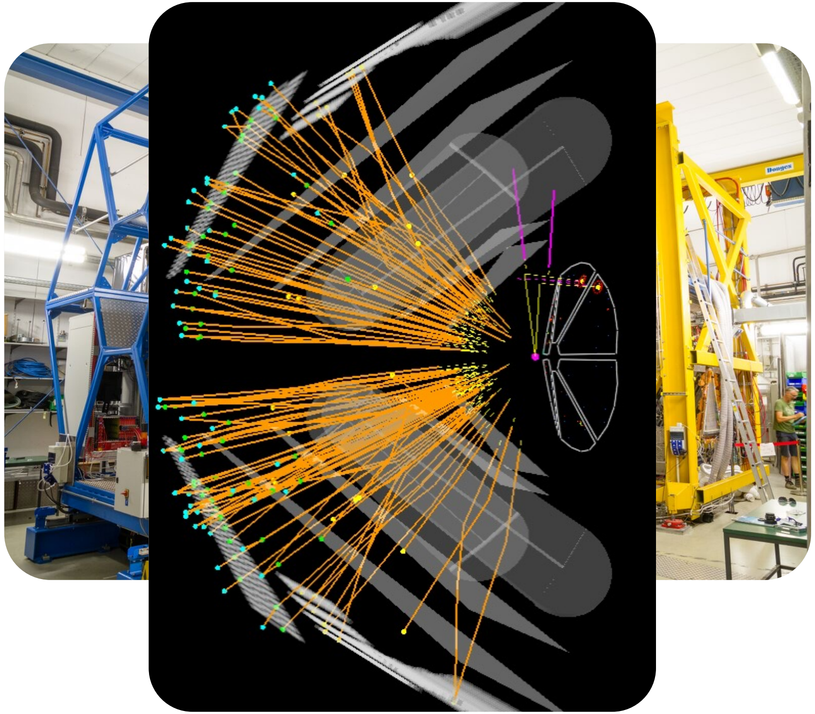
collider domain

High $\sqrt{s_{NN}}$

Low $\sqrt{s_{NN}}$

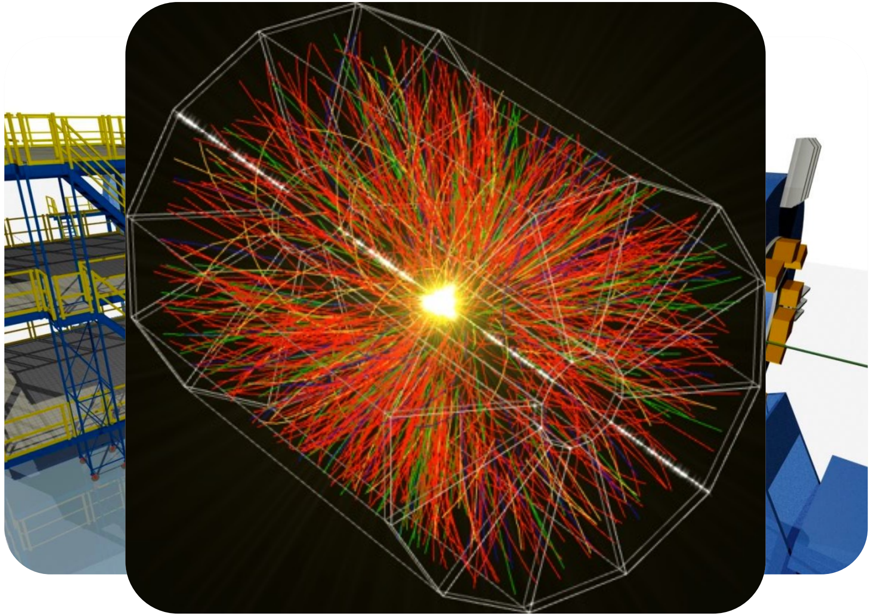
fixed-target domain

High Acceptance DiElectron Spectrometer
HADES at SIS18, GSI



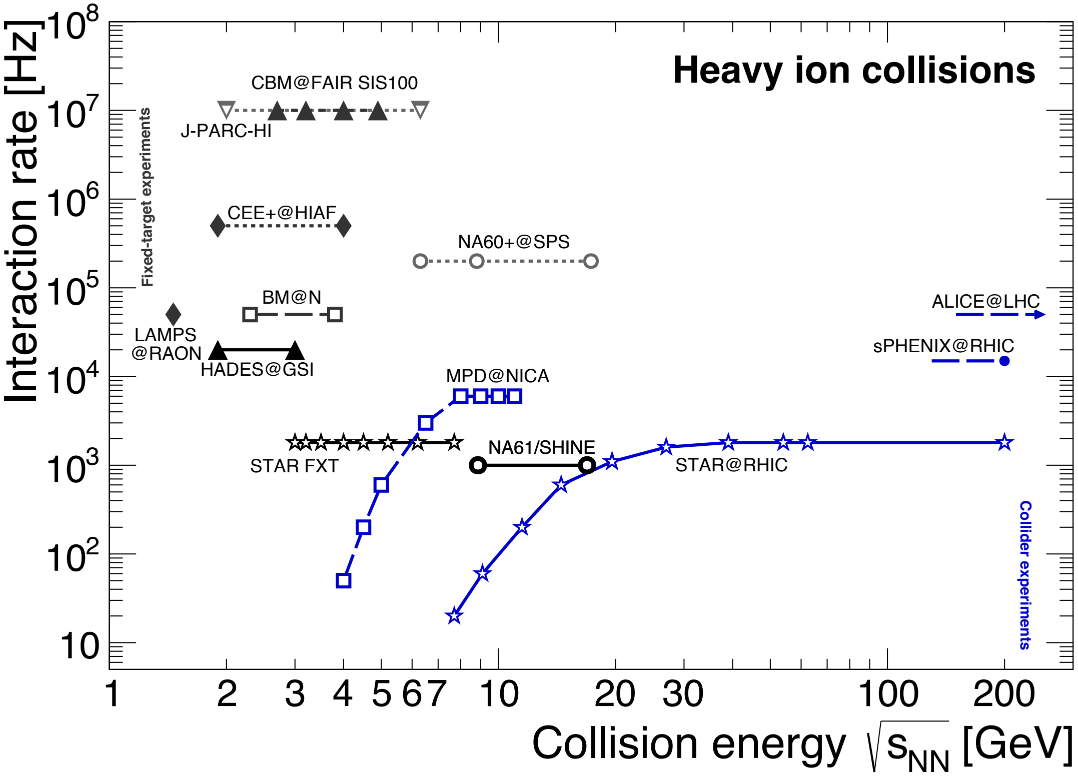
fixed-target experiment

Solenoidal Tracker At RHIC
STAR at RHIC, BNL



collider experiment

Quest for utmost precision and sensitivity for rare signals



- Decisive parameters for data quality:
  - interaction rates (*IR*)
  - signal-to-combinatorial background ratio (S/CB): effective signal size: $S_{\mathrm{eff}} \sim IR \times S/CB$

TG, NPA 982 (2019), update 2021 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Dilepton analysis strategy

Tracking

Lepton identification

π^0 and γ conversion rejection

Pairing

Subtraction of background
(like-sign or event mixing)

Efficiency correction

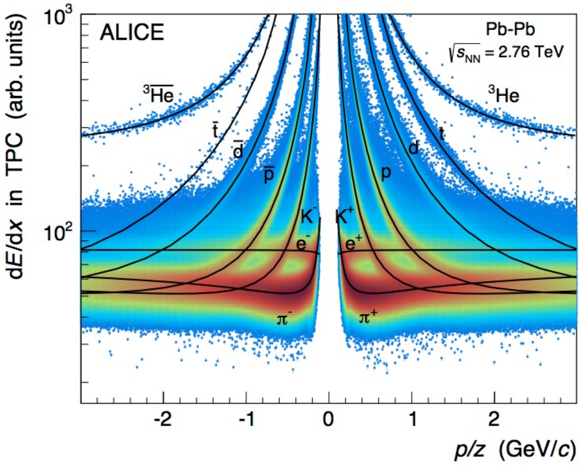
Isolation of excess radiation

Acceptance correction

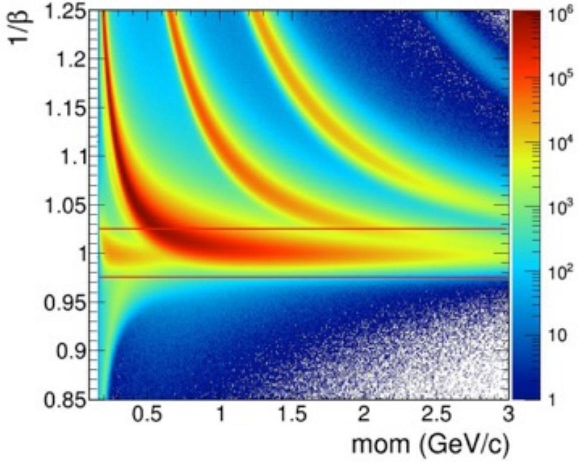
Electron identification by means of

momentum, specific energy loss, velocity, RICH information

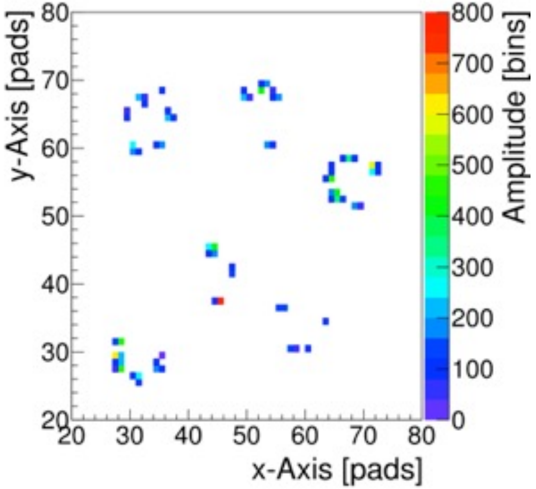
dE/dx in Time Projection Chamber



Velocity in Time-of-Flight



Rings in RICH



All combined in a multivariate analysis (neural network)
⇝ best purity and efficiency

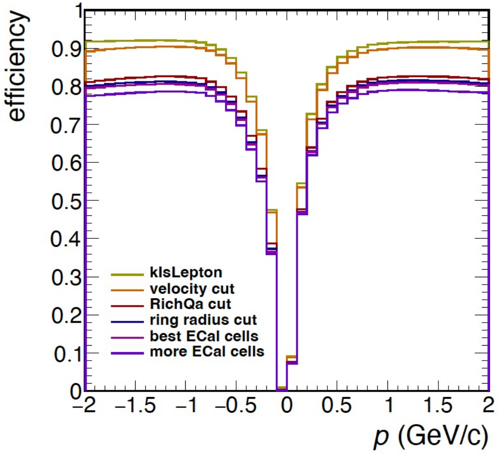
π suppression factor vs electron efficiency

why so important?

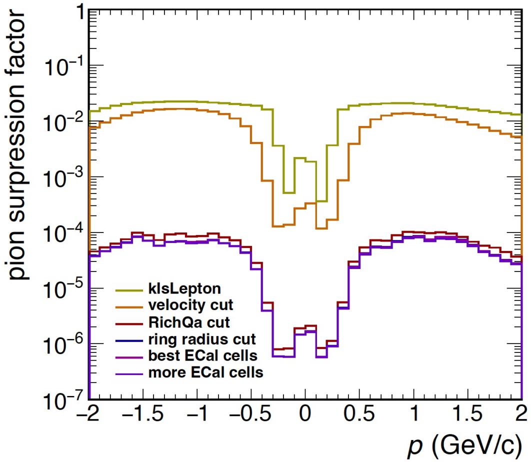
$\rho \longrightarrow \pi^+\pi^-$ BR $\sim 100\%$

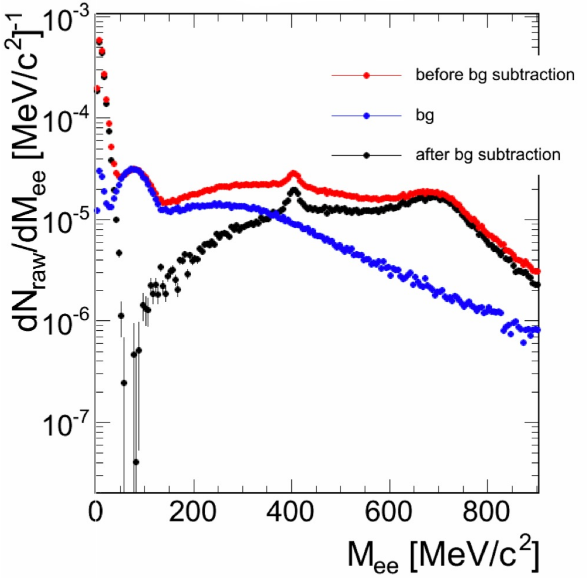
$\rho \longrightarrow e^+e^-$ BR $= 4.72\times10^{-5}$

Efficiency: ratio of reconstructed leptons to the accepted



π suppression factor: ratio of pions identified as electrons to pions in RICH acceptance

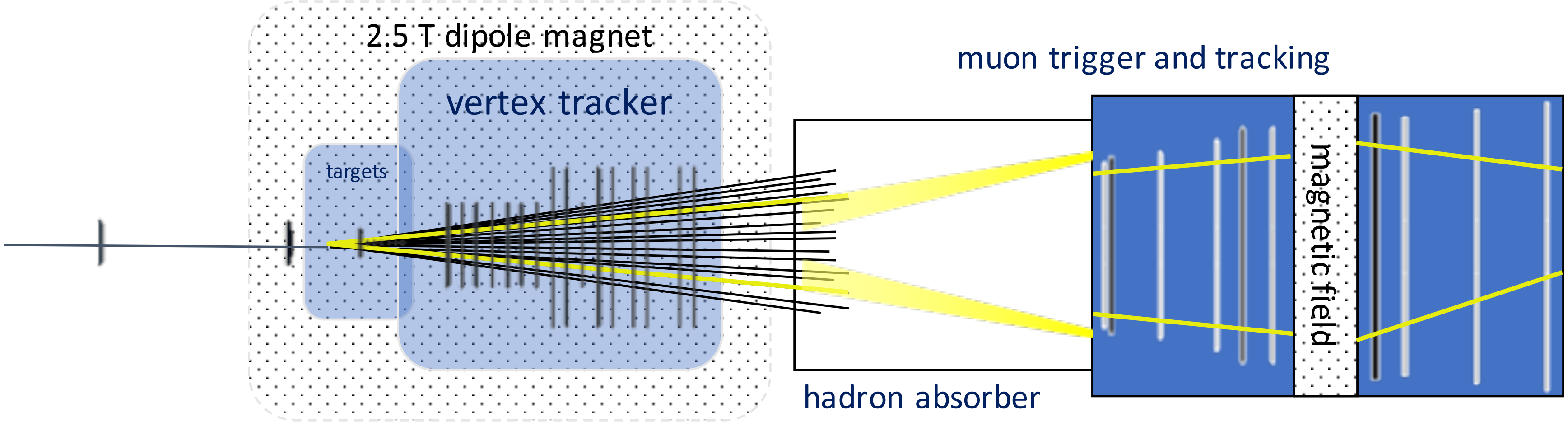




e^+e^- spectrum in case RICH is excluded from electron ID

Muon identification

Using hadron absorber technique



- 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)

Characteristics of the background

small (moderate) opening angle and/or asymmetric laboratory momenta

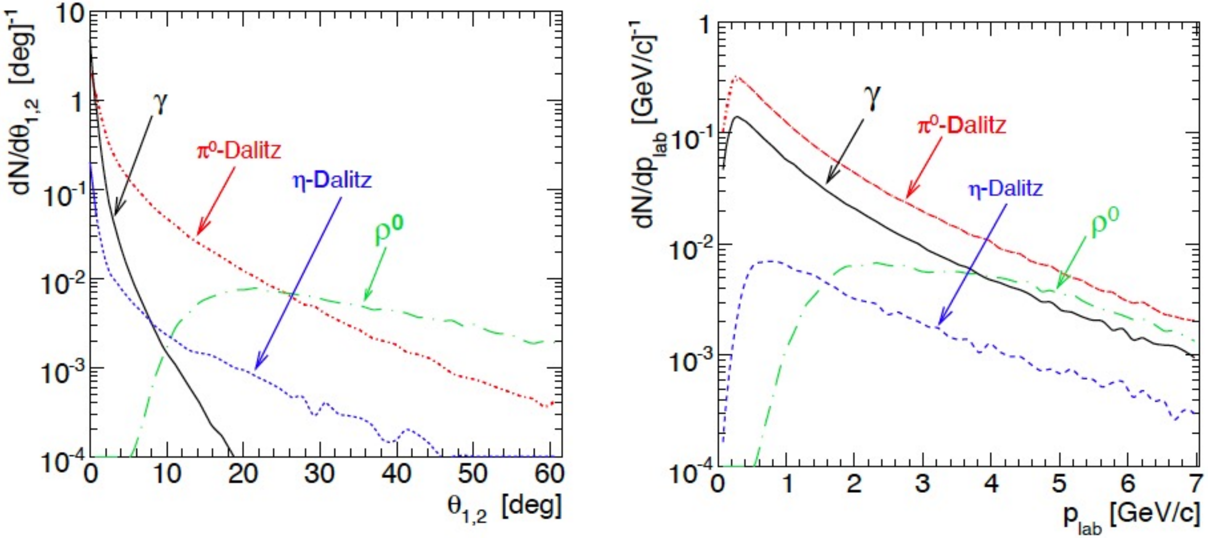
$e^+e^-\gamma$

1.2%

↑

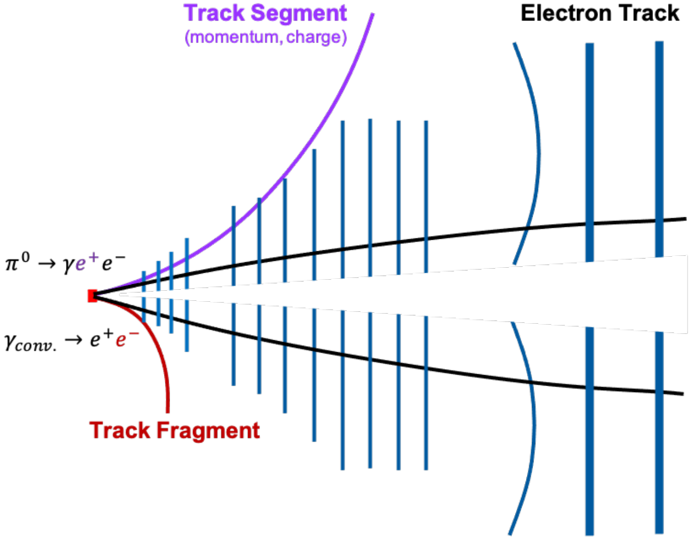
~350 $\pi^0 \rightarrow 98.8\%\ \gamma\gamma$

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

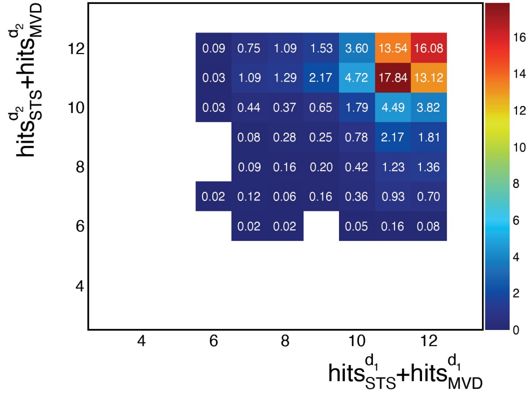


700 $\pi^{\pm}$ could be identified as an electron

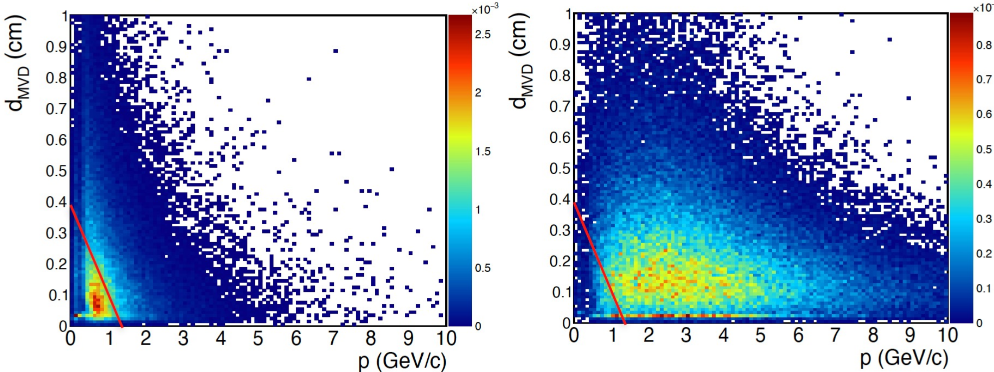
Combinatorial background topology



correlation of the number of MVD+STS traversed by e^+e^- pairs from γ



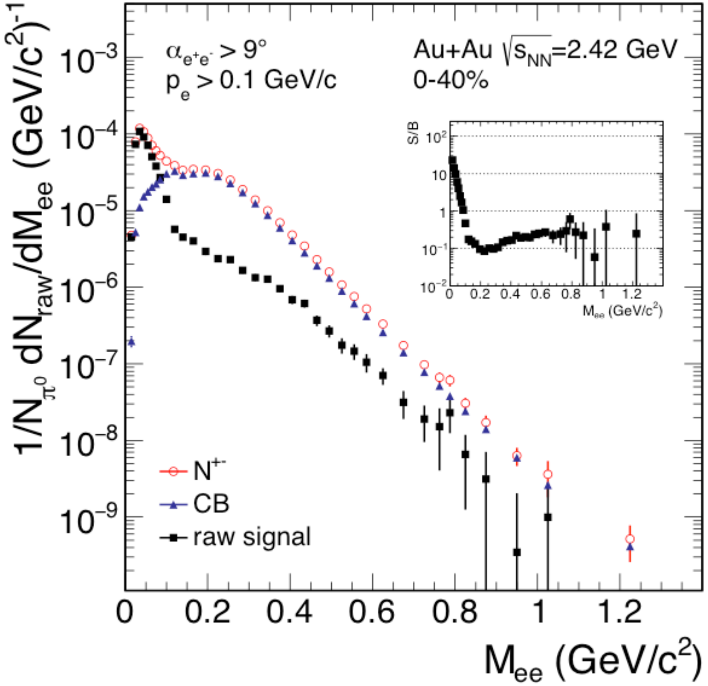
- ○ excellent double-hit resolution ($< 100\mu m$) provides substantial close pair rejection capability
- ○ distance between identified track from γ (left) and ρ (right) to its closest neighbout in the MVD



Track Fragment - x, y position; no charge information
Track Segment - reconstructed track (momentum, charge)
Global Track - identified in RICH, TRD, TOF

Raw signal extraction

- $M_{ll} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$



$$\left\langle N_{+-}^{Signal}\right\rangle = \langle N_{+-}\rangle - \left\langle N_{+-}^{CB}\right\rangle$$

Estimation of combinatorial background

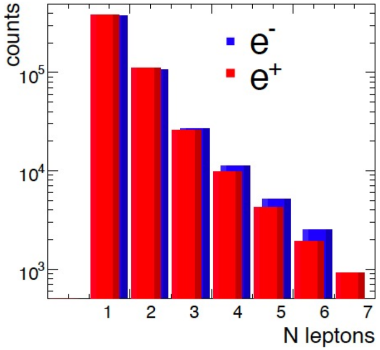
same-event like-sign method (M<0.3 GeV)

$$\left\langle N_{+-}^{CB}\right\rangle = 2\sqrt{\langle N_{++}\rangle\langle N_{--}\rangle}$$

$$\left\langle N_{+-}^{CB}\right\rangle = \langle N_{++}\rangle + \langle N_{--}\rangle$$

- ⤳ preserves all possible correlations
- ⤳ provide proper normalization
- ⤳ BUT limited statistics

Follow Poisson distribution

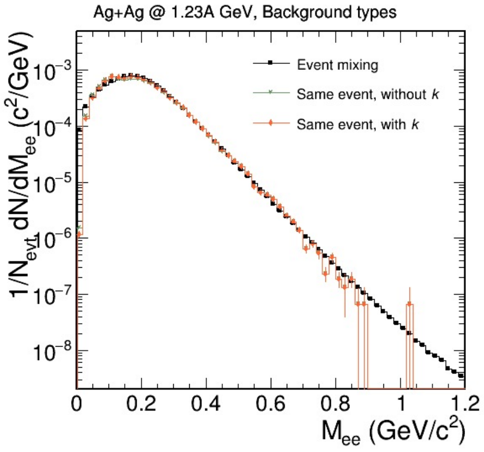


event mixing (M>0.3 GeV)

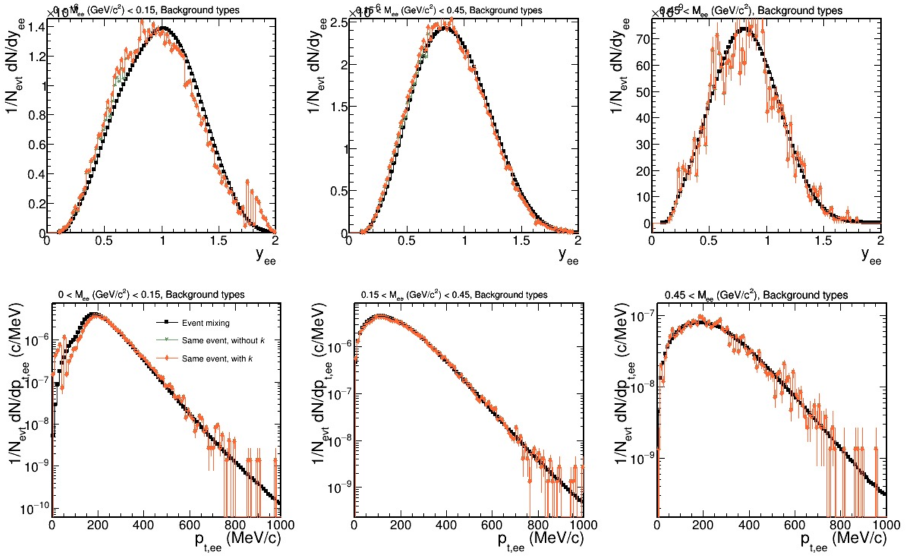
- ⤳ all correlations are destroyed
- ⤳ BUT almost unlimited statistics
- ⤳ normalization to same-event CB

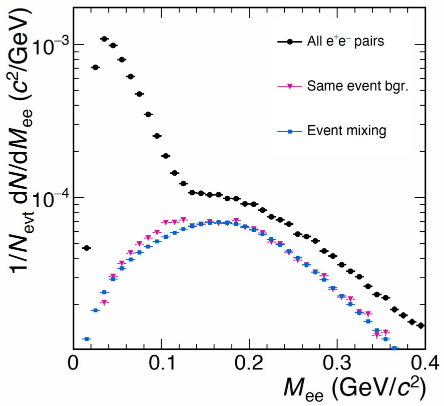
Same-event vs event mixing

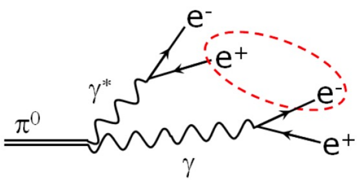
normalization in $0.3 < \frac{M_{ee}}{GeV} < 0.5$



Check agreement in y_{ee} and $p_{t,ee}$

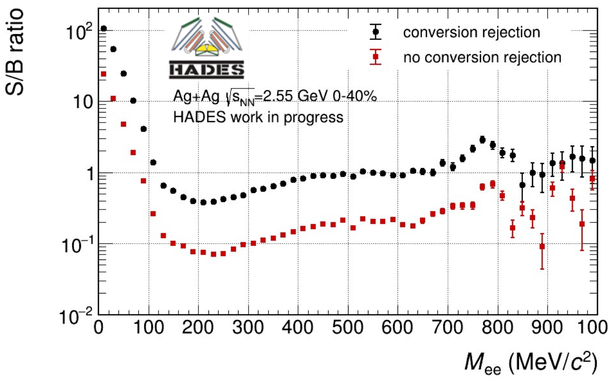


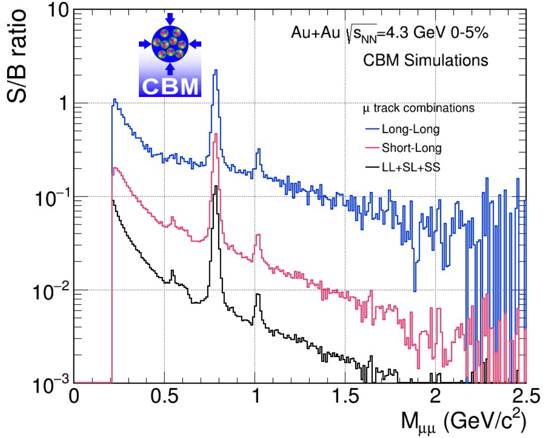




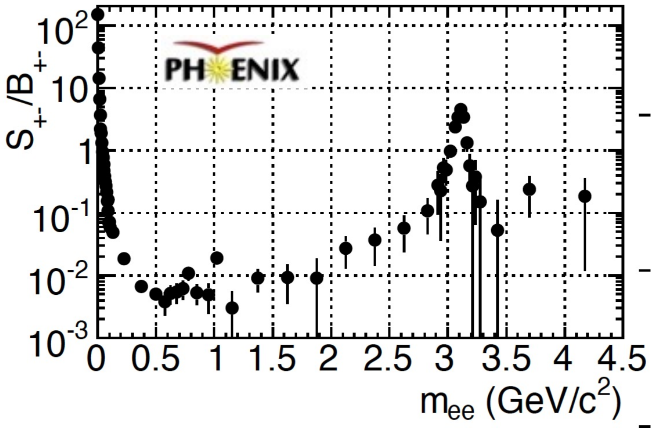
correlated CB

Consequences of poor signal-to-CB





S/B ~ 1/500 (!) for minimum bias events

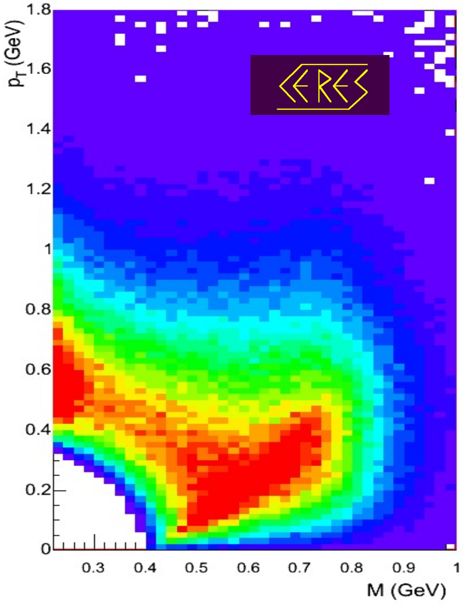


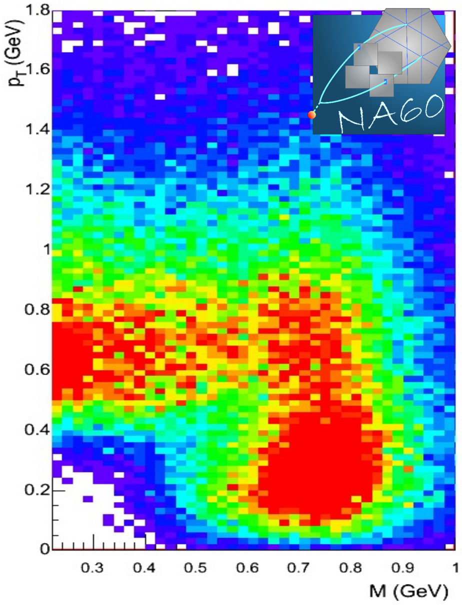
- Statistical error of signal depends on magnitude of CB, not S! $\Delta S = \sqrt{2 \cdot CB}$ (for $S \ll CB$)
- "Background free equivalent" signal S_{eq}
  - signal with same relative error in a situation with zero background $S_{eq} = S \times S / 2 \cdot CB$
  - example: signal $S = 10^4$ pairs measured with a $\frac{S}{CB} = \frac{1}{250}$ has the same relative statistical error as $S_{eq} = 20$ pairs measured in free CB conditions
- Systematic uncertainty in S
  - dominated by systematic uncertainty in CB
  - example: even if the event mixing technique is mastered to a fantastic precision of $\pm 0.25\%$, the resulting systematic uncertainty in S is $> 50\%$ (assuming $S/CB = 1/250$). Even in an infinite statistics measurement the systematic uncertainty will be huge.

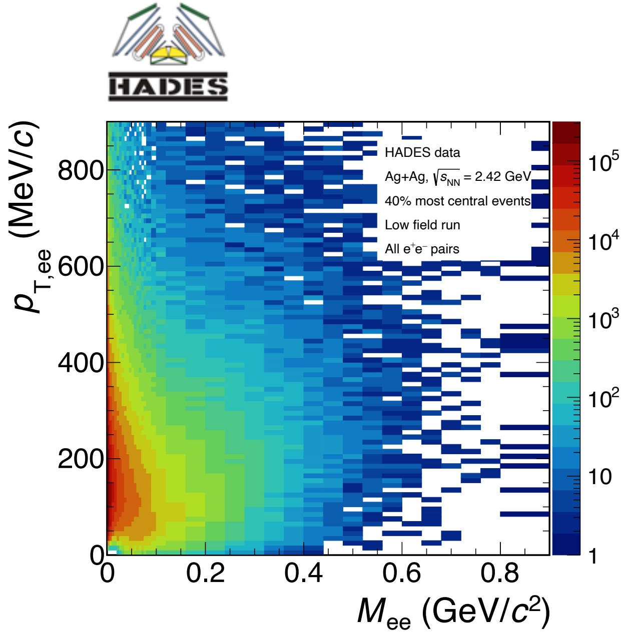
Efficiency (and acceptance*) corrections

* acceptance corrections are applied to the excess radiation only

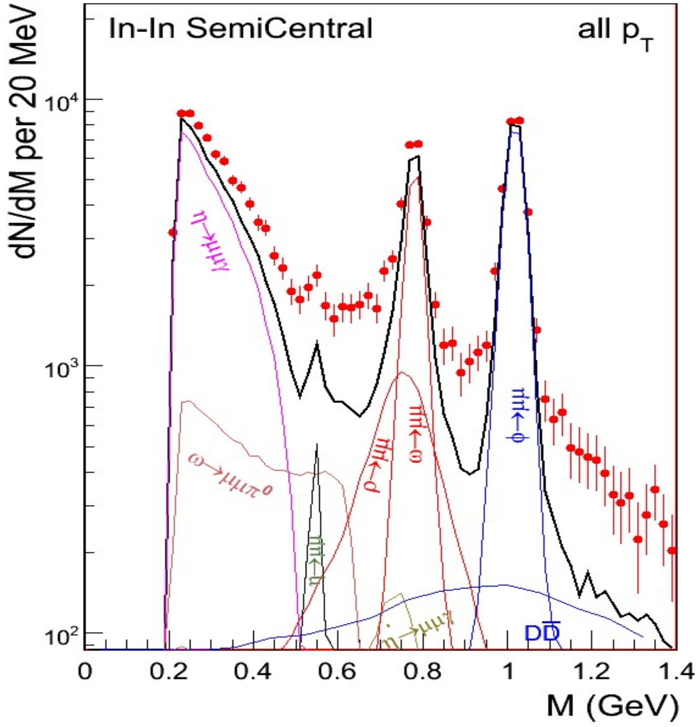
- Single leg eff./acc. matrix (p, θ, φ) from track embedding to real/sim data
- Done on pair level after CB subtraction (1-D)
- Necessary prerequisite - detailed understanding of detector sim







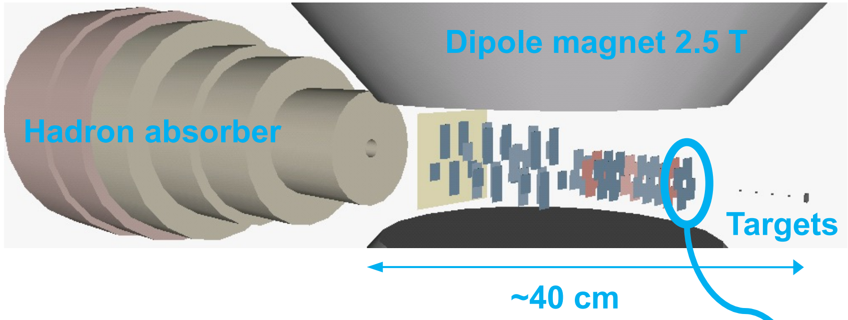
Isolation of excess dimuons at SPS

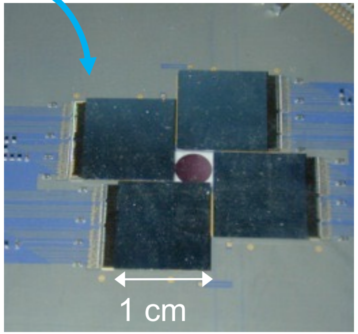


- Isolation of excess by subtraction of **measured** decay cocktail (without ρ), based solely on local criteria for the major sources η, ω and ϕ
  - ω and ϕ: fix yields such as to get, after subtraction, a **smooth** underlying continuum
  - η: fix yield at p_T >1 GeV profiting from the very high sensitivity of the spectral shape of the Dalitz decay to any underlying admixture from other sources; lower limit from peripheral data

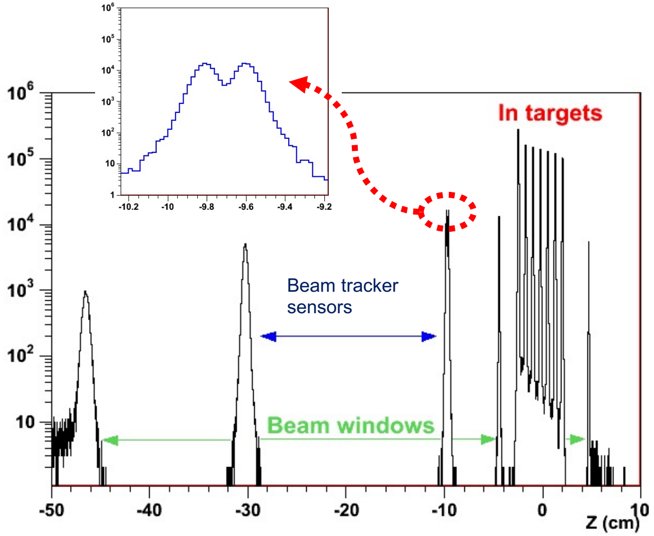
Clear excess of data above decay ‘cocktail’.
But, what is the spectral shape of the excess?

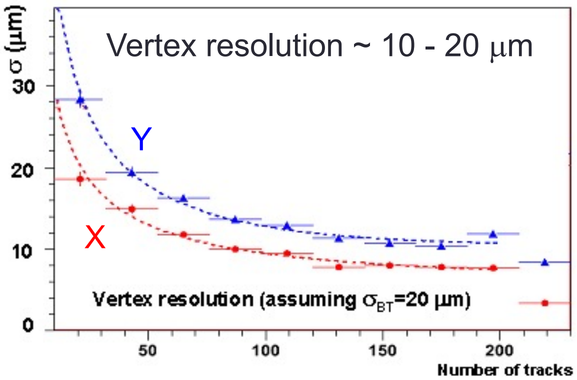
NA60 pixel vertex spectrometer





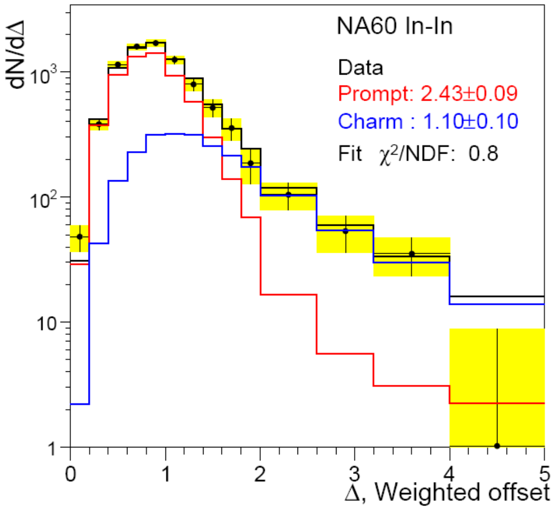
- 12 tracking points with good acceptance
  - 8 small 4-chip planes
  - 8 large 8-chip planes in 4 tracking stations
- ~3% X_0 per plane
  - 750 μm Si readout chip
  - 300 μm Si sensor
- 800000 readout channels in 96 pixel assemblies





Disentangling the sources in the IMR

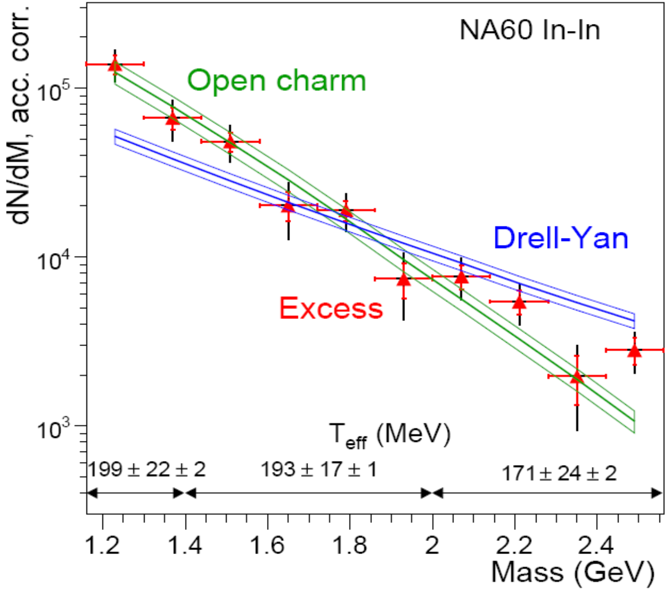
Separation of prompt muon production from semi-leptonic open charm decays



Fit of weighted offset distribution with charm decay and prompt contributions

⇒ **excess due to prompt muons**

Decomposition of total di-muon yield into Drell-Yan, open charm and prompt excess



Excess and open charm have similar slopes; excess = thermal radiation

Thank you for your attention!