Exotic hadrons from dynamical clustering of quarks in heavy ion collisions

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SQM 2004 — Cape Town — 19. September 2004

Exotic hadrons, the quark model, and heavy ion collisions

The model: quark Molecular Dynamics qMD

Search for exotica with qMD

Focusing on pentaquarks

Conclusion

Exotic hadrons in the quark model of QCD

Common hadrons:

state	quark content
meson	$q\bar{q}$
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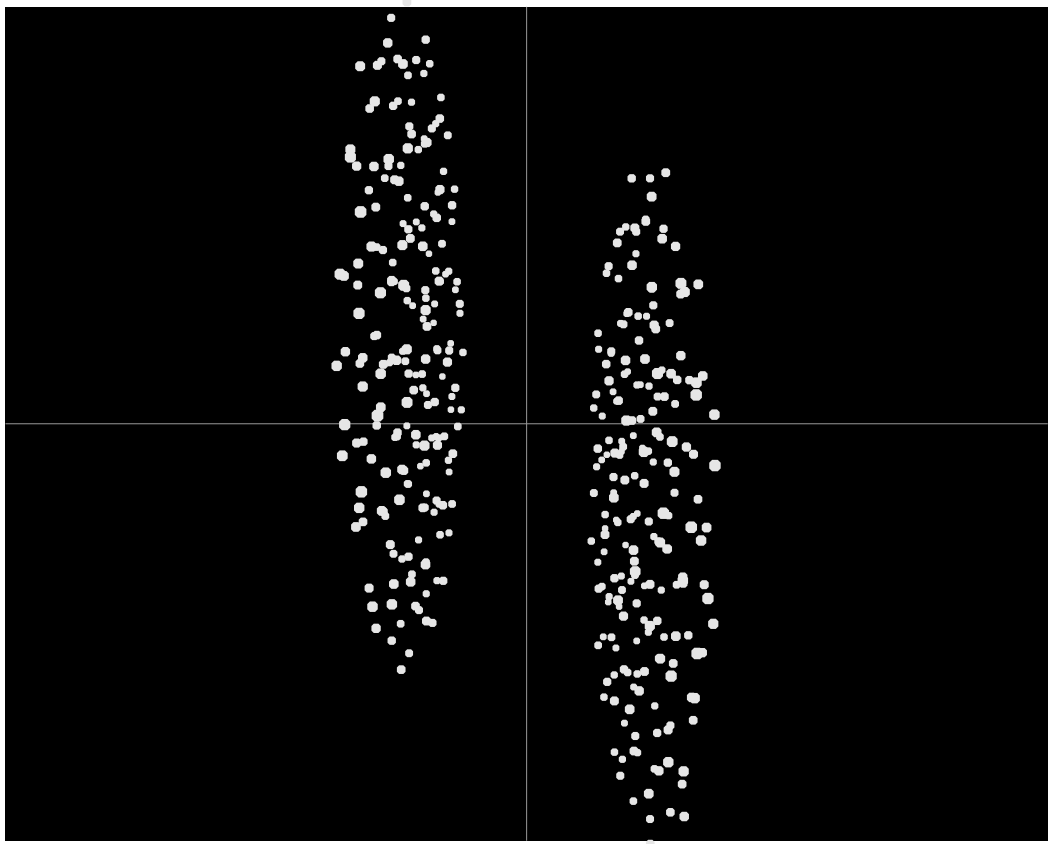
Clustering from heavy ion collisions

UrQMD (zx plane, 20x16 fm): Pb+Pb @ 80 GeV/N, b = 3 fm, t = -1.0 fm/c



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Clustering from heavy ion collisions

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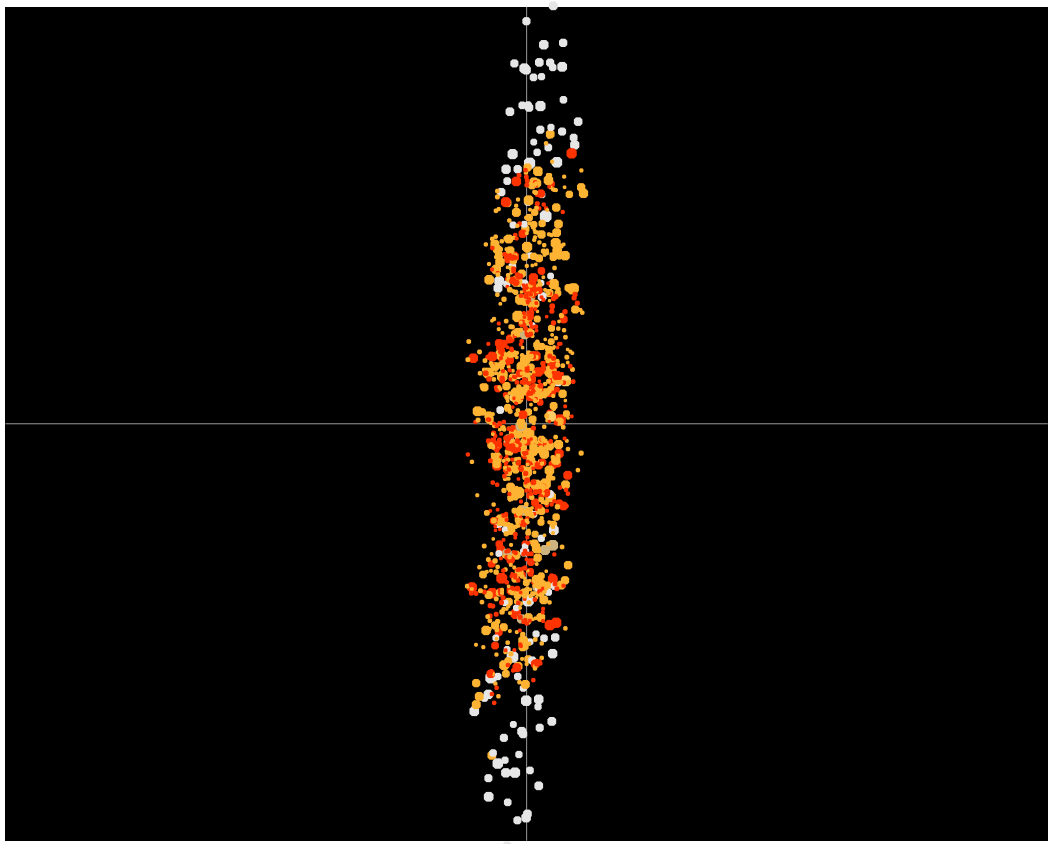

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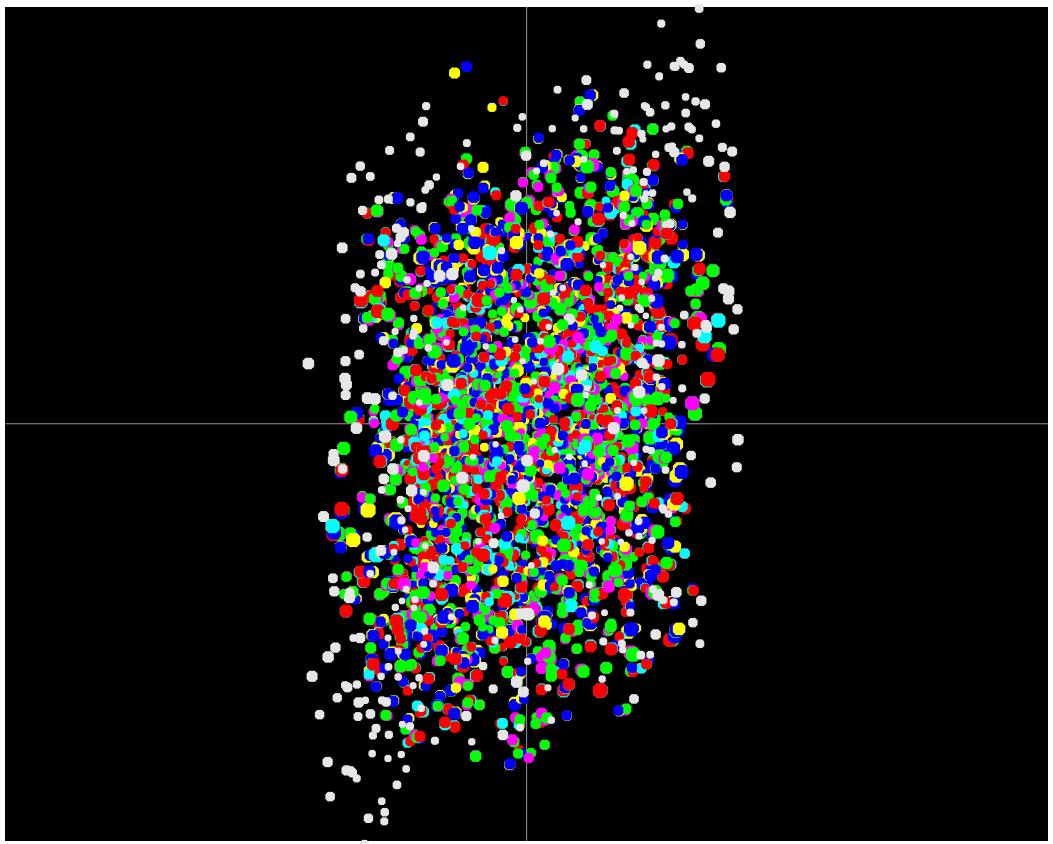
Clustering from heavy ion collisions

qMD (zx plane, 20x16 fm): Pb+Pb @ 80 GeV/N, b = 3 fm, t = 4.0 fm/c



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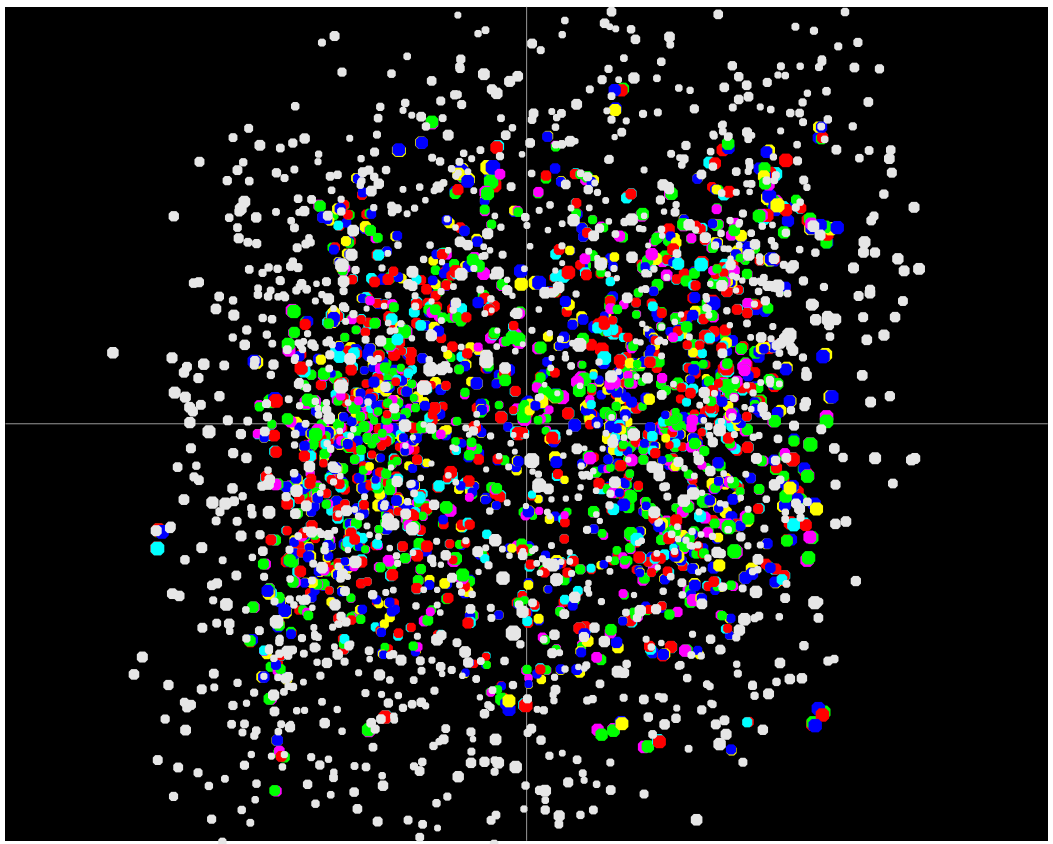
Clustering from heavy ion collisions

qMD (zx plane, 20x16 fm): Pb+Pb @ 80 GeV/N, b = 3 fm, t = 6.5 fm/c



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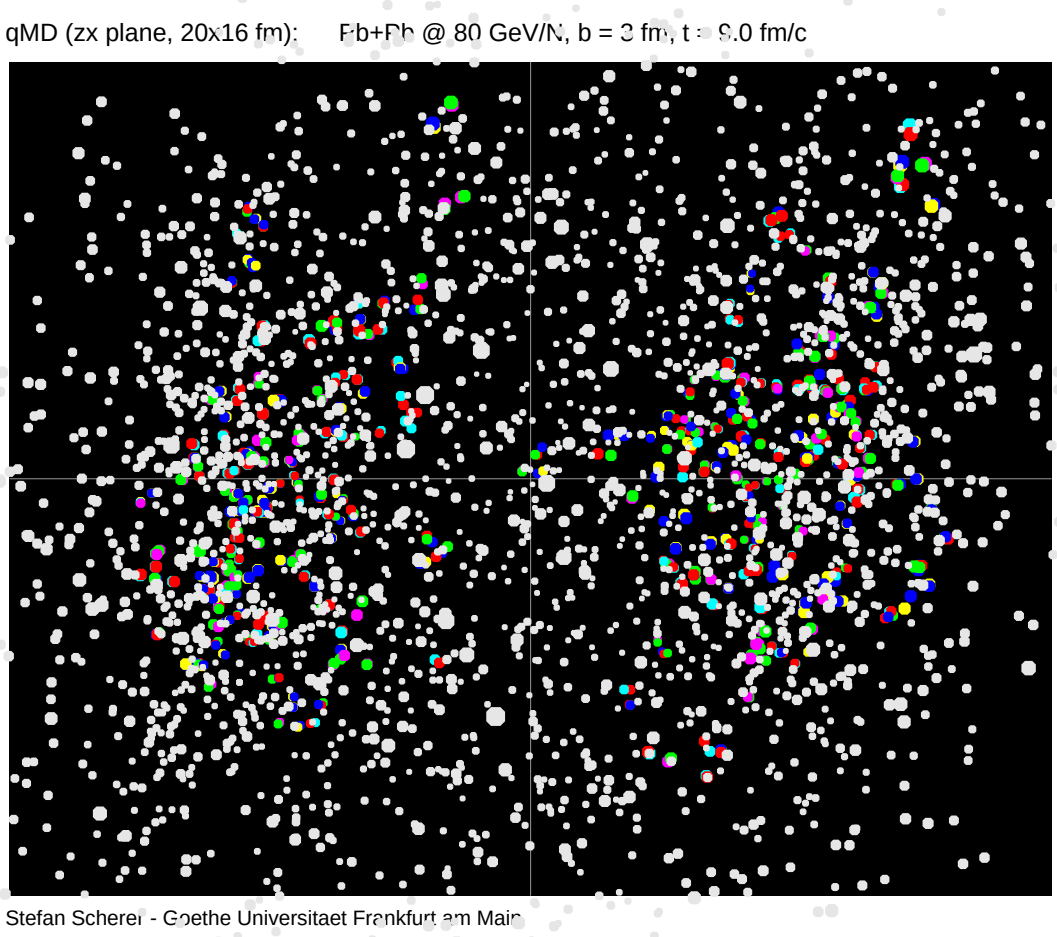

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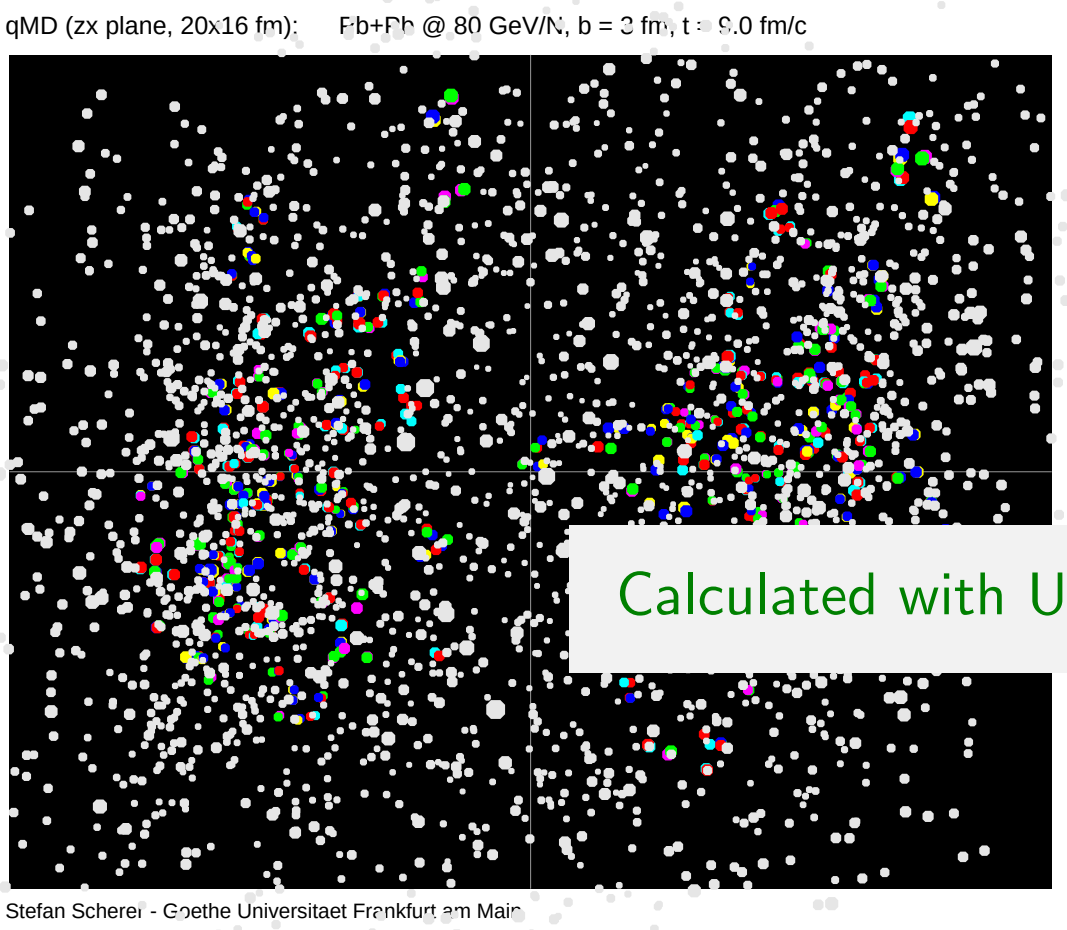
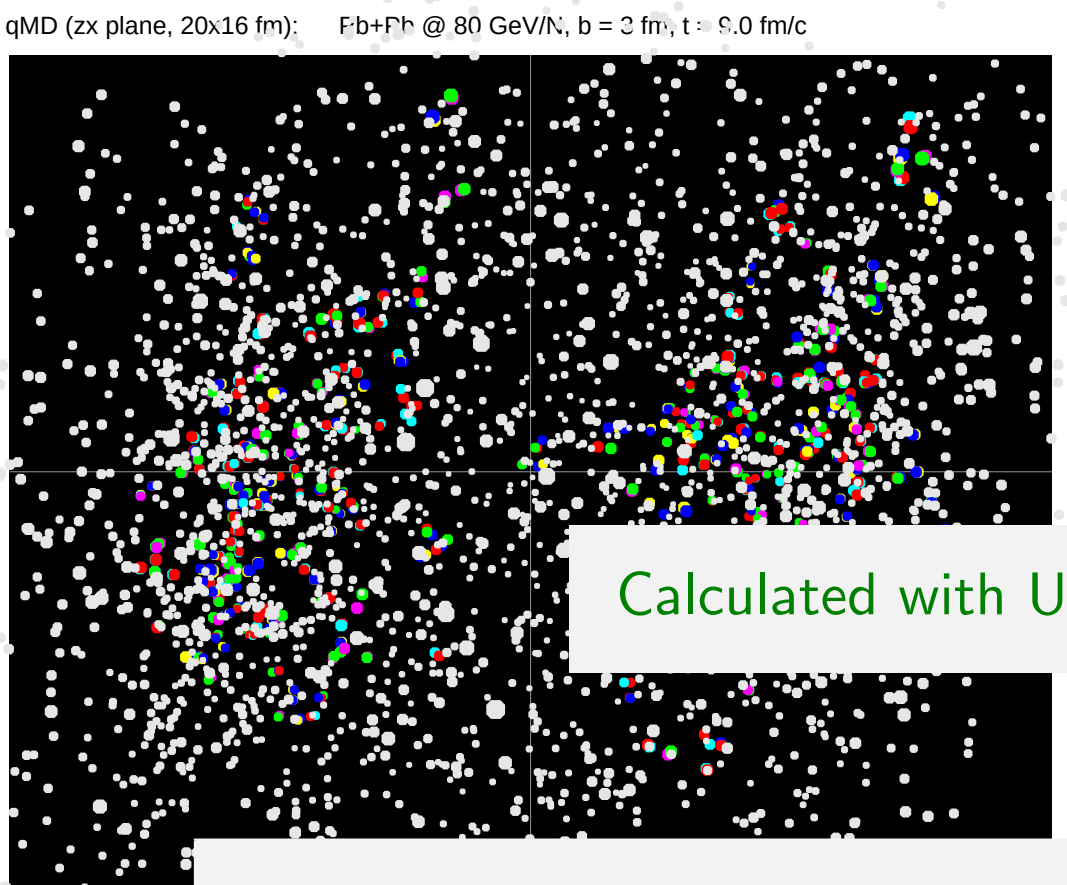


Calculated with UrQMD and qMD

Clustering from heavy ion collisions



Calculated with UrQMD and qMD

$\longrightarrow$ Formation of exotic clusters at hadronization?

qMD: The model Hamiltonian

$$\mathcal{H} = \sum_{i=1}^{N} \sqrt{\vec{\mathbf{p}}_i^2 + m_i^2} + \frac{1}{2} \sum_{i,j} C_{ij} V(|\vec{\mathbf{r}}_i - \vec{\mathbf{r}}_j|)$$

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  - mass m_i ($m_{u,d} = 5$ MeV, $m_s = 150$ MeV, $m_c = 1500$ MeV)
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  - attractive and/or repulsive
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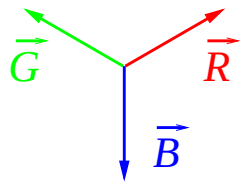

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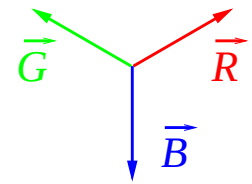

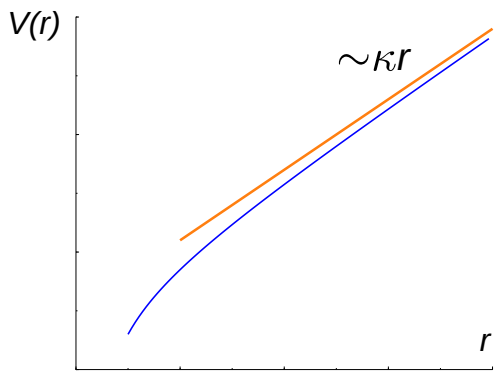

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$$V(r) = -\frac{3}{4}\frac{\alpha_s}{r} + \kappa\, r$$

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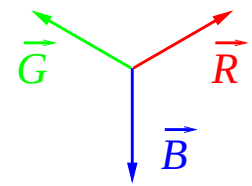

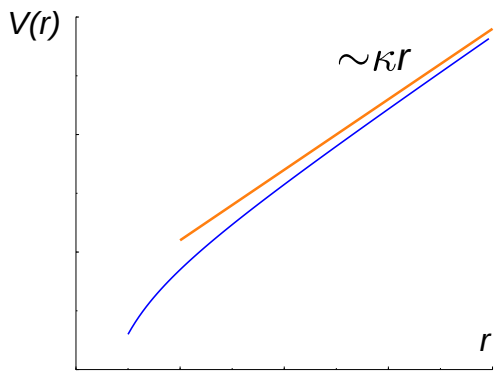

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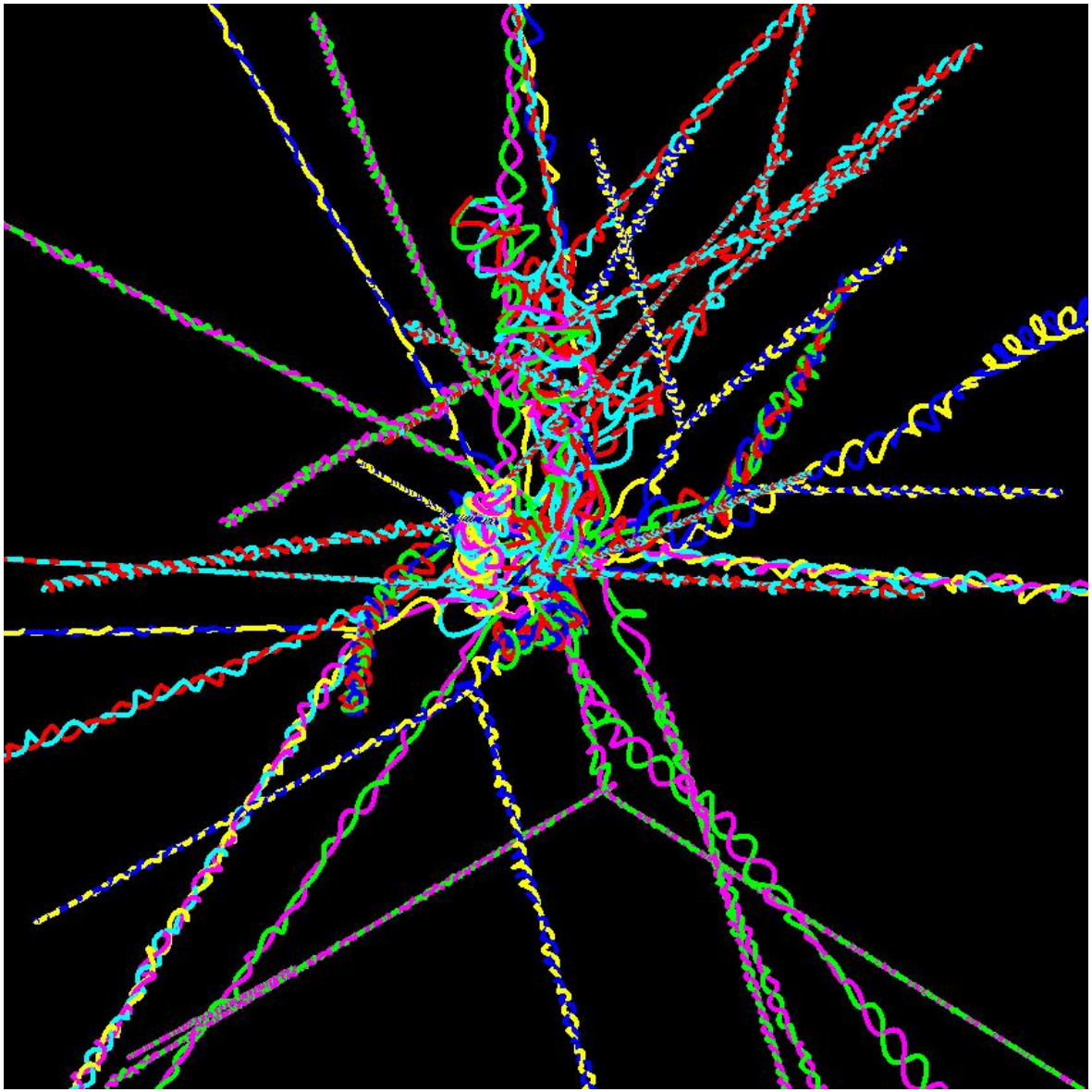

Recipe for hadronization

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– Separation in space
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$$\left|\vec{\mathbf{F}}_{\text{cluster}}\right| = \left|\frac{1}{N_{\text{cluster}}} \sum_{i \in \text{cluster}} \vec{\mathbf{F}}_i\right| < \kappa_{\min} = F_{\text{cut}} \cdot \kappa$$

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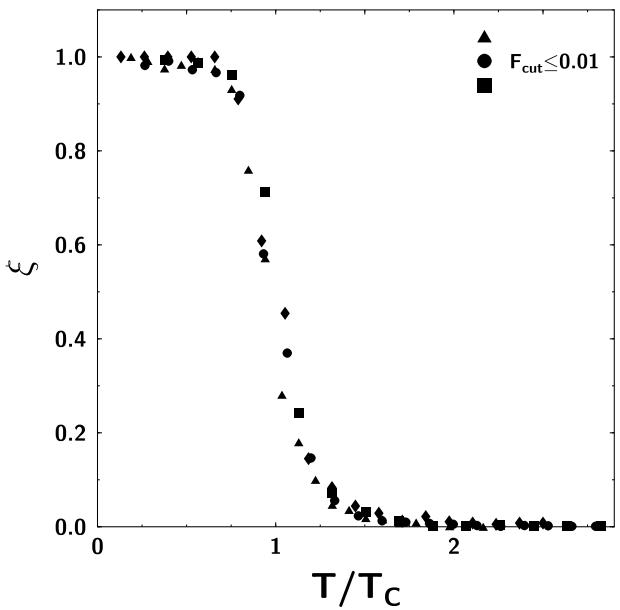
Mapping to hadrons:

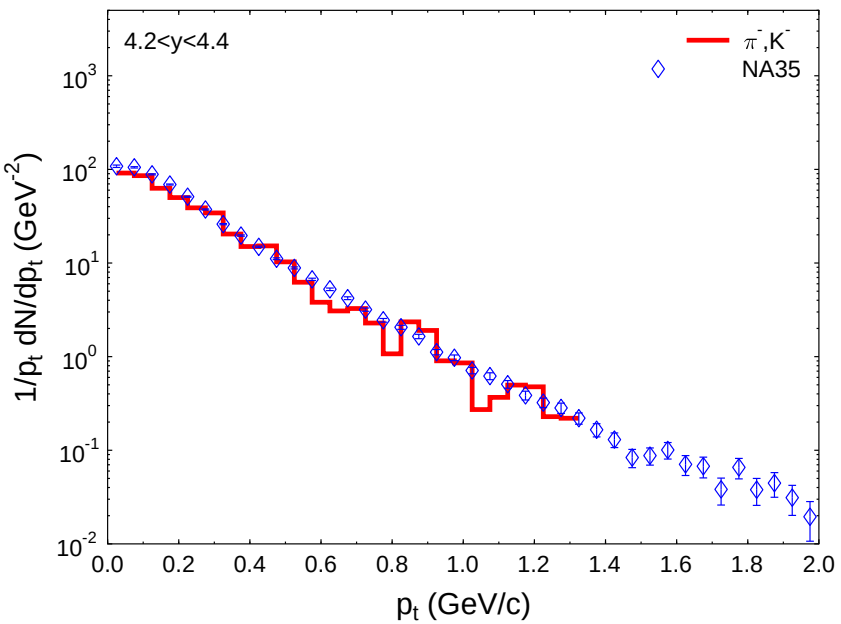
– Quantum numbers
– Momentum conservation
– Energy conservation

$\Big\} \longrightarrow$ Particle of mass $M_H = E_{\text{cluster}}$

References

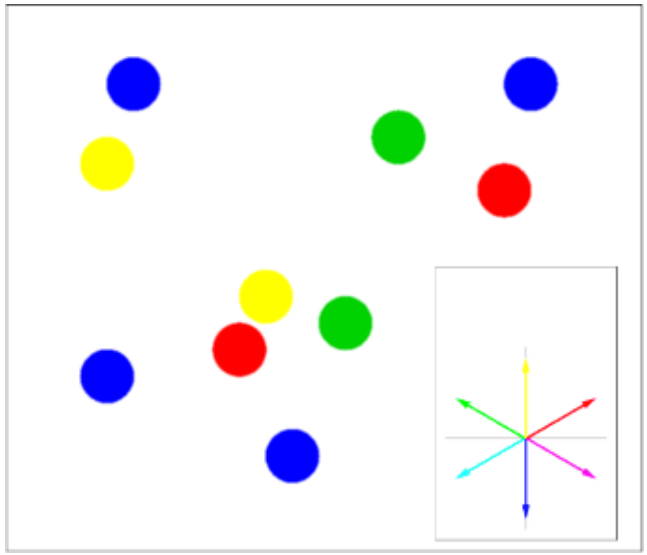
- M. Hofmann et al., Phys. Lett. **B478**, 161 (2000), nucl-th/9908030
- S. Scherer et al., New J. Phys. **3**, 8 (2001), nucl-th/0106036





Search for exotic clusters:

- search neighbours around each quark



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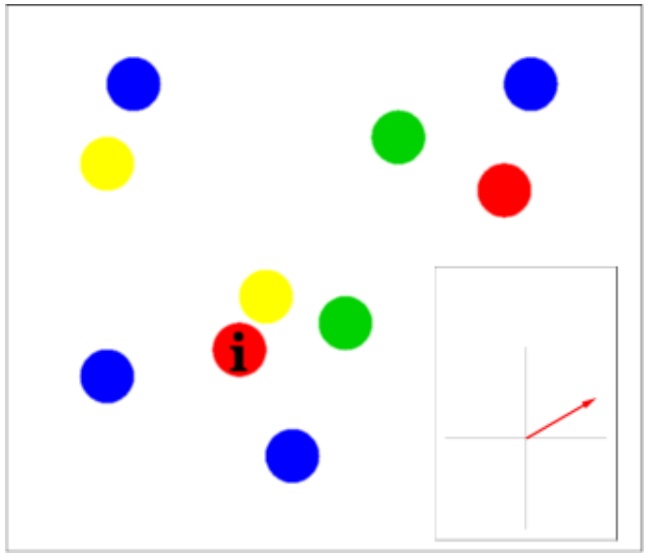

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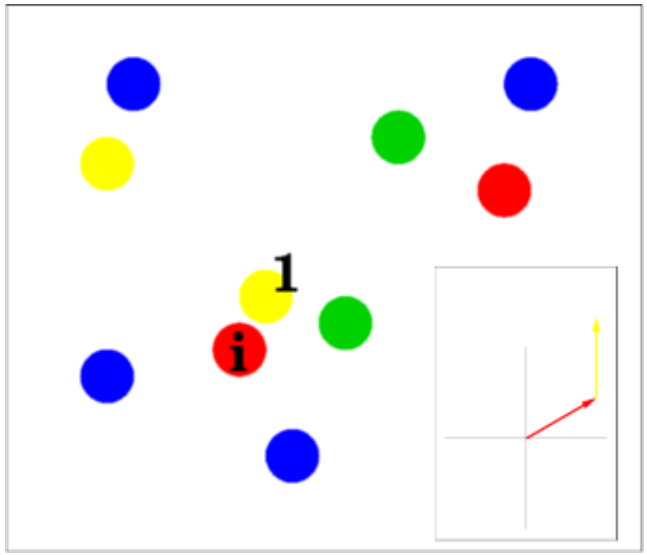

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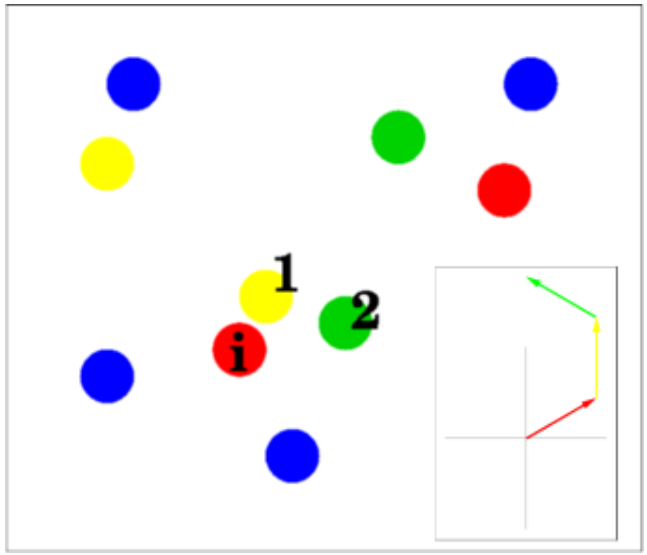

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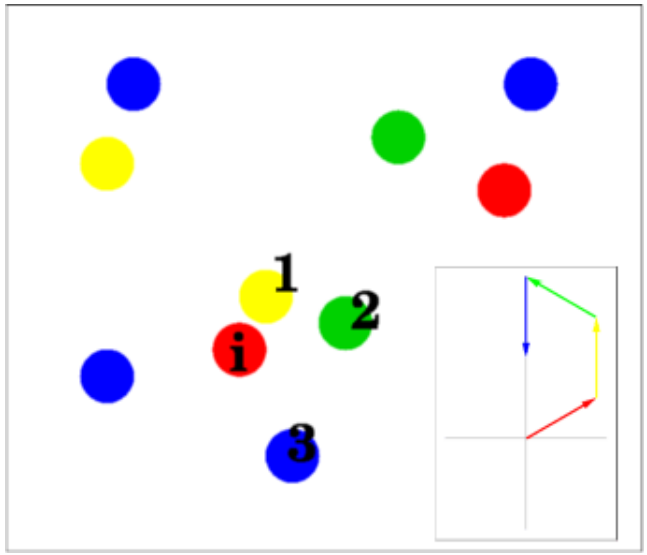

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Search for exotic clusters:

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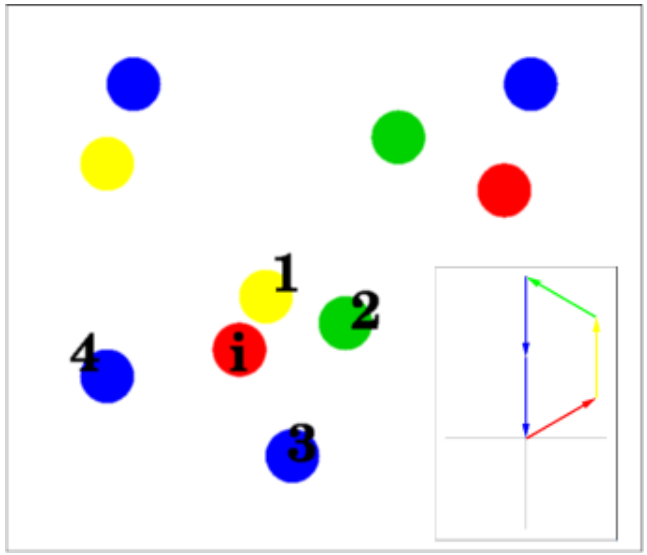
- stop if colour neutral



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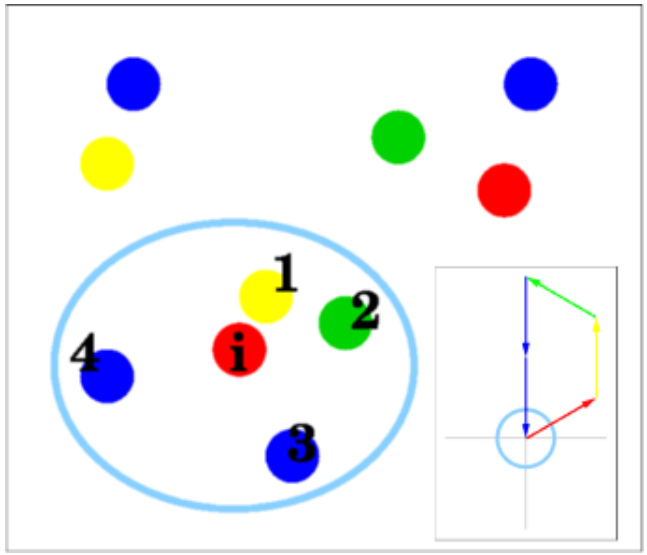
Search for exotic clusters:

- search neighbours around each quark
- stop if colour neutral
- make it a cluster



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Search for exotic clusters:

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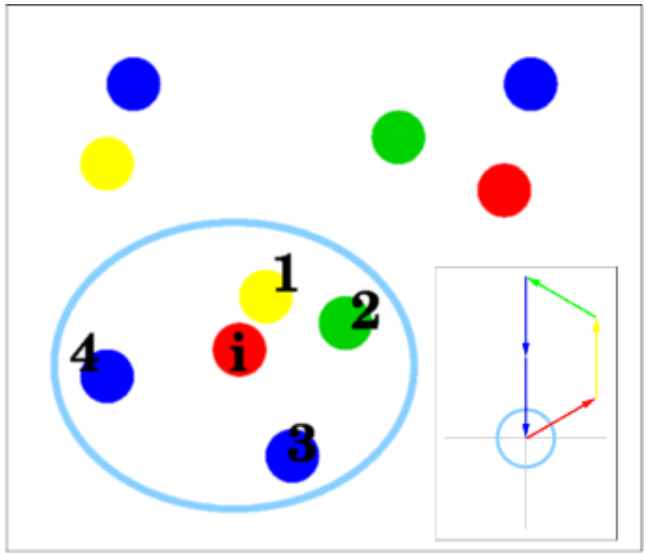
- stop if colour neutral
- make it a cluster
- check at most 5 neighbours



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Initial conditions for qMD:

- CERN-SPS and GSI-SIS/200 energies:
  UrQMD propagation of colliding nuclei
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- CERN-SPS and GSI-SIS/200 energies:
  UrQMD propagation of colliding nuclei
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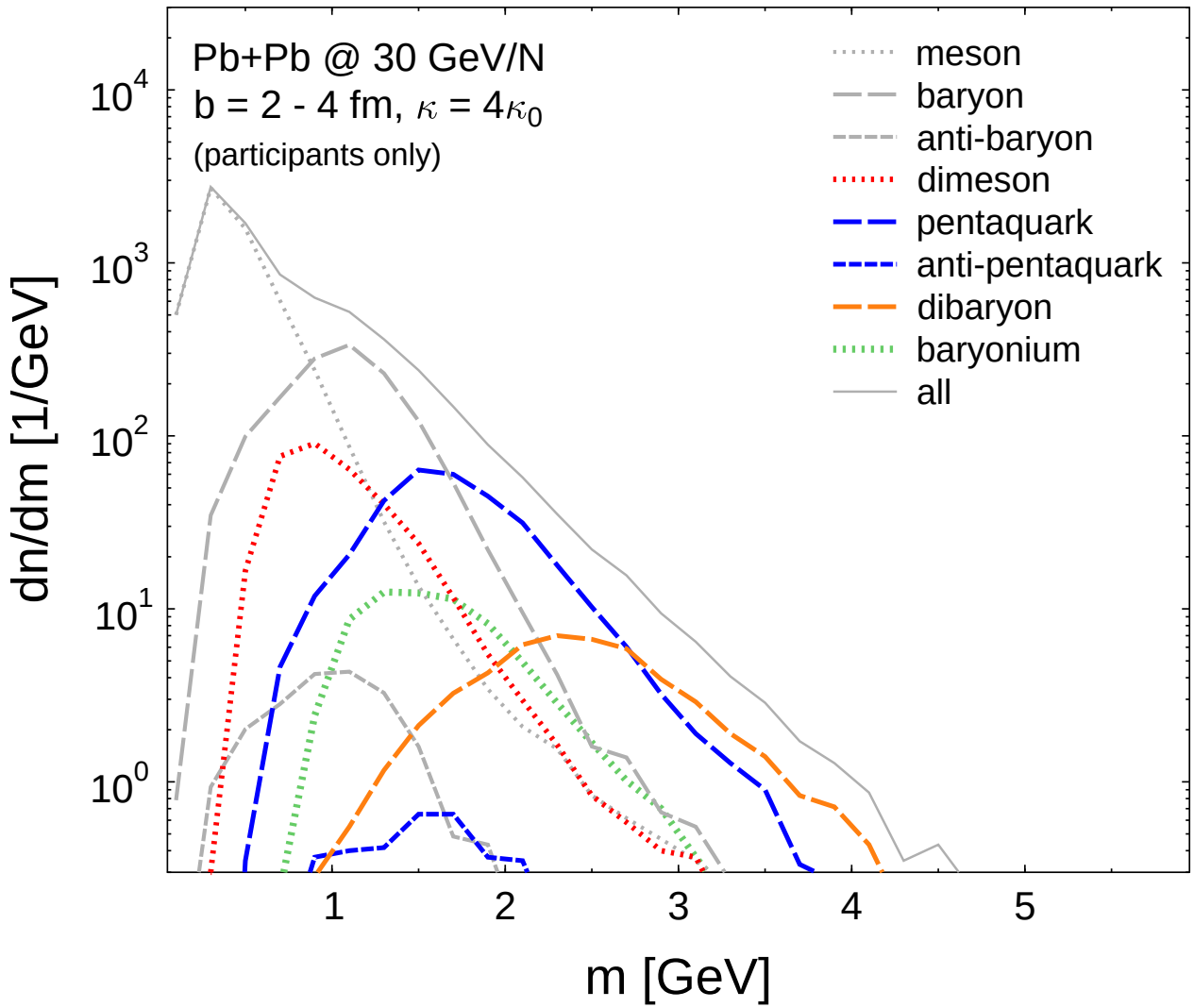
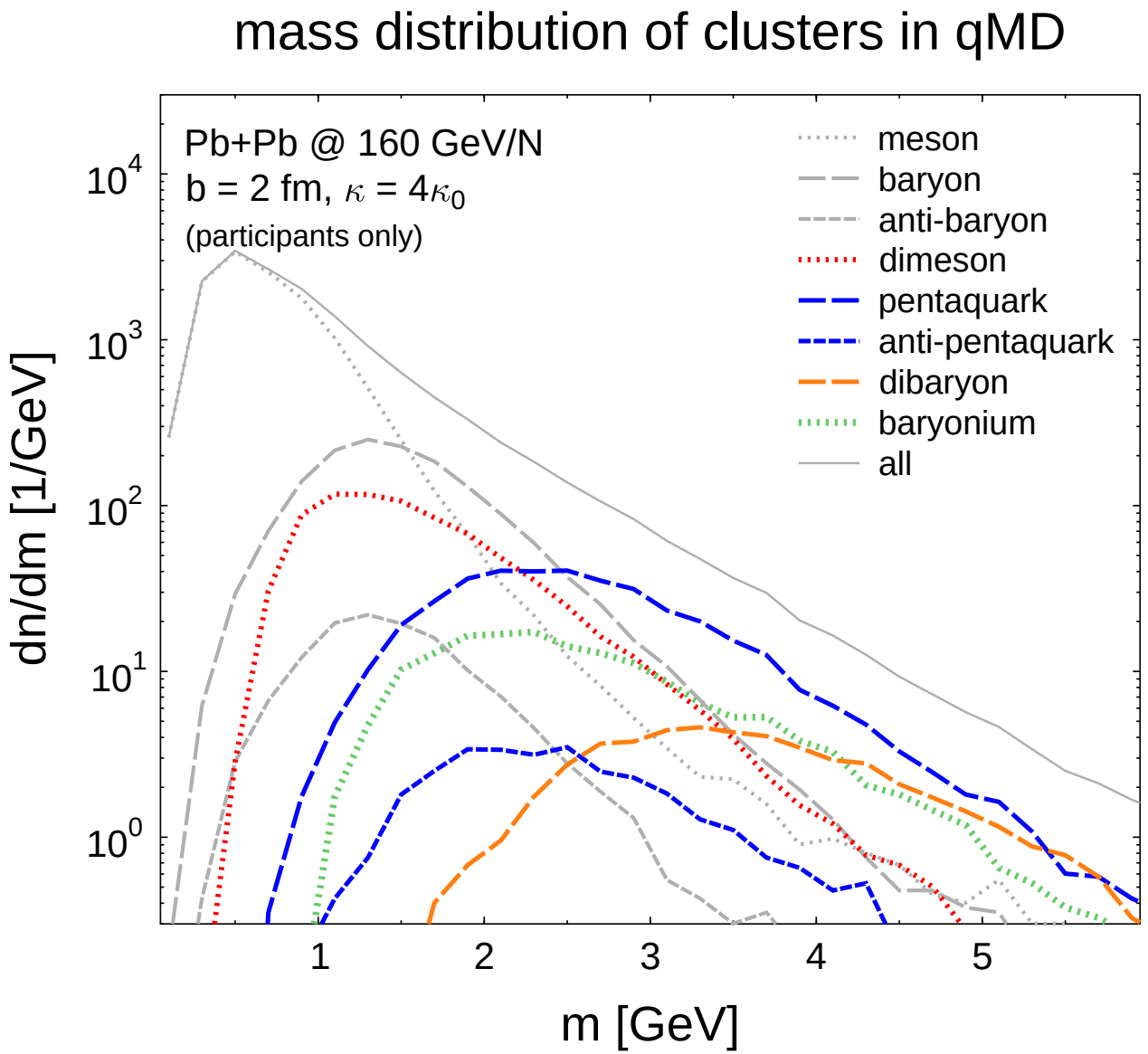
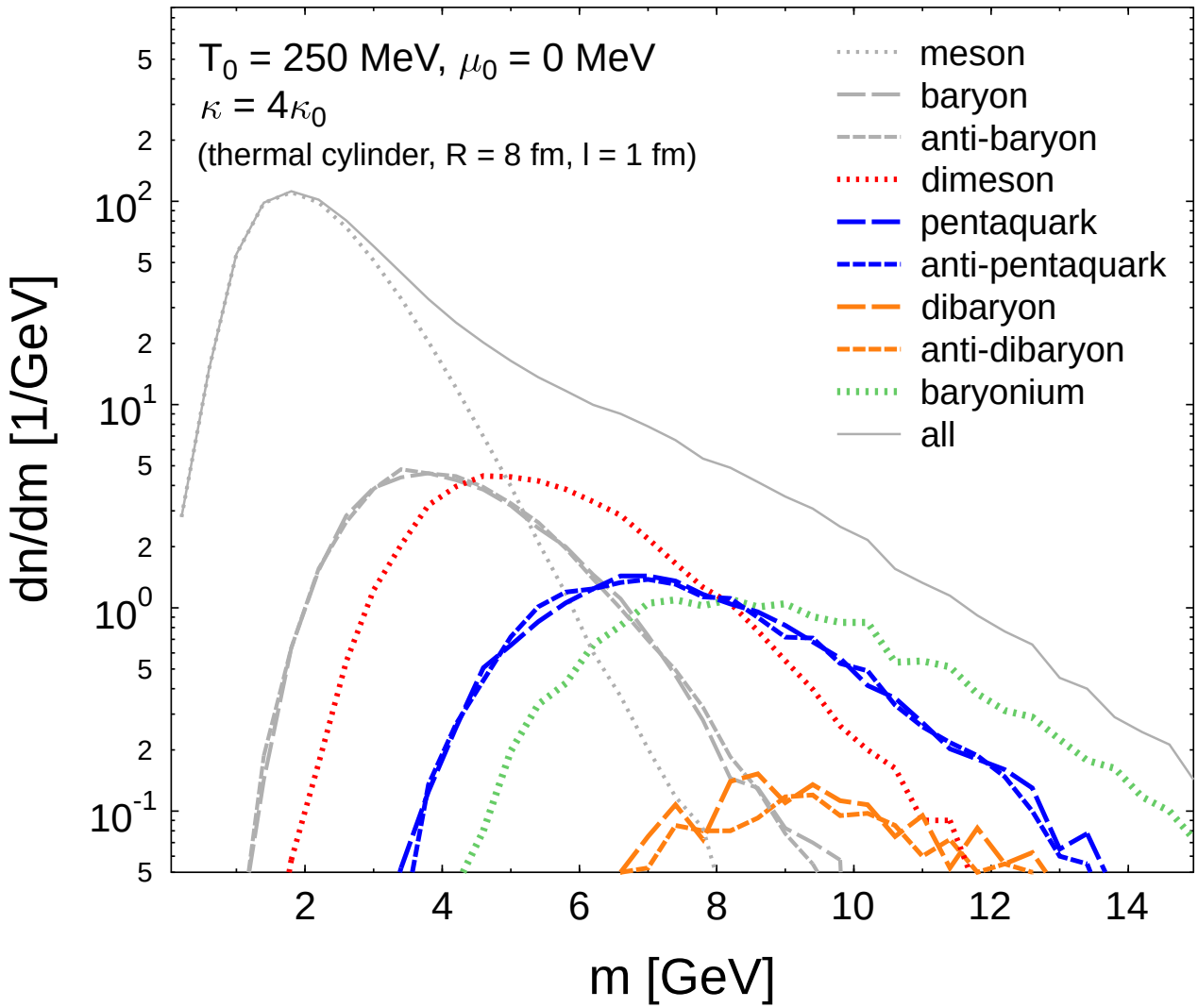
- RHIC energies:
  thermalized quark gas, $T_0 = 250$ MeV
  cylinder with $R = 8$ fm, $l = 1$ fm

mass distribution of clusters in qMD

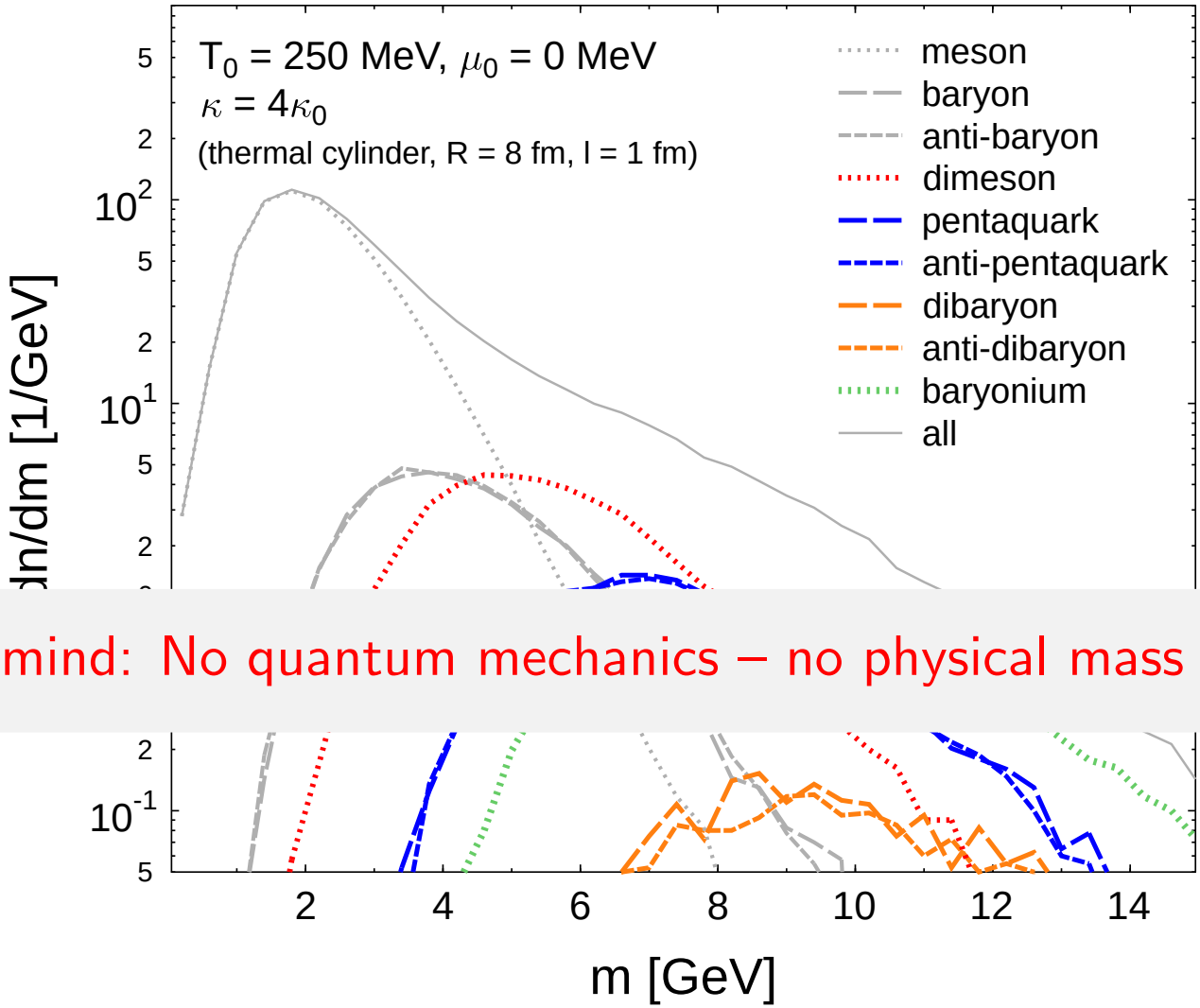



mass distribution of clusters in qMD
Pb+Pb @ 160 GeV/N
b = 2 fm, $\kappa = 4\kappa_0$
(participants only)
meson
baryon
anti-baryon
dimeson
pentaquark
anti-pentaquark
dibaryon
baryonium
all
dn/dm [1/GeV]
10^4
10^3
10^2
10^1
10^0
1
2
3
4
5
m [GeV]

mass distribution of clusters in qMD

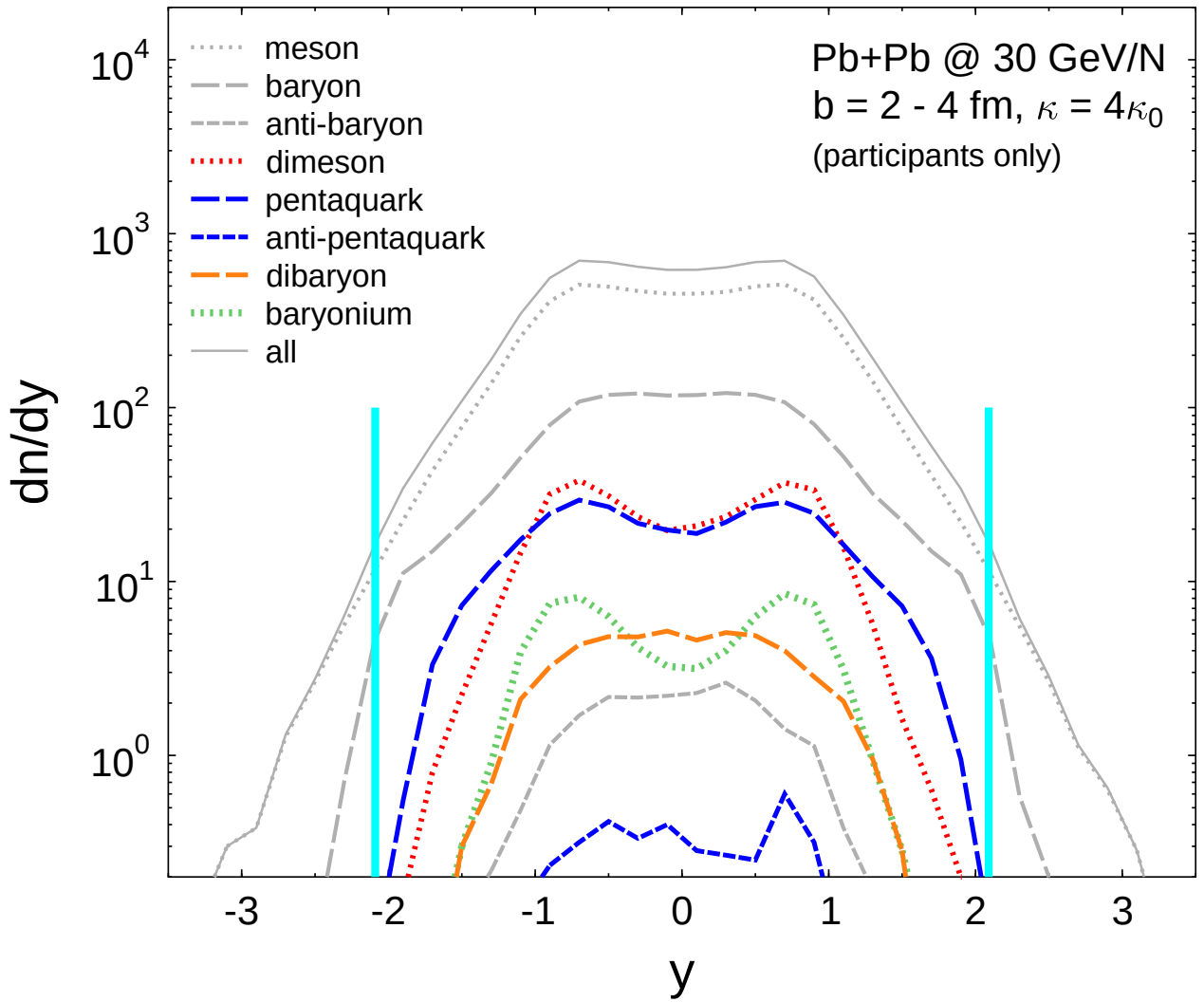


mass distribution of clusters in qMD

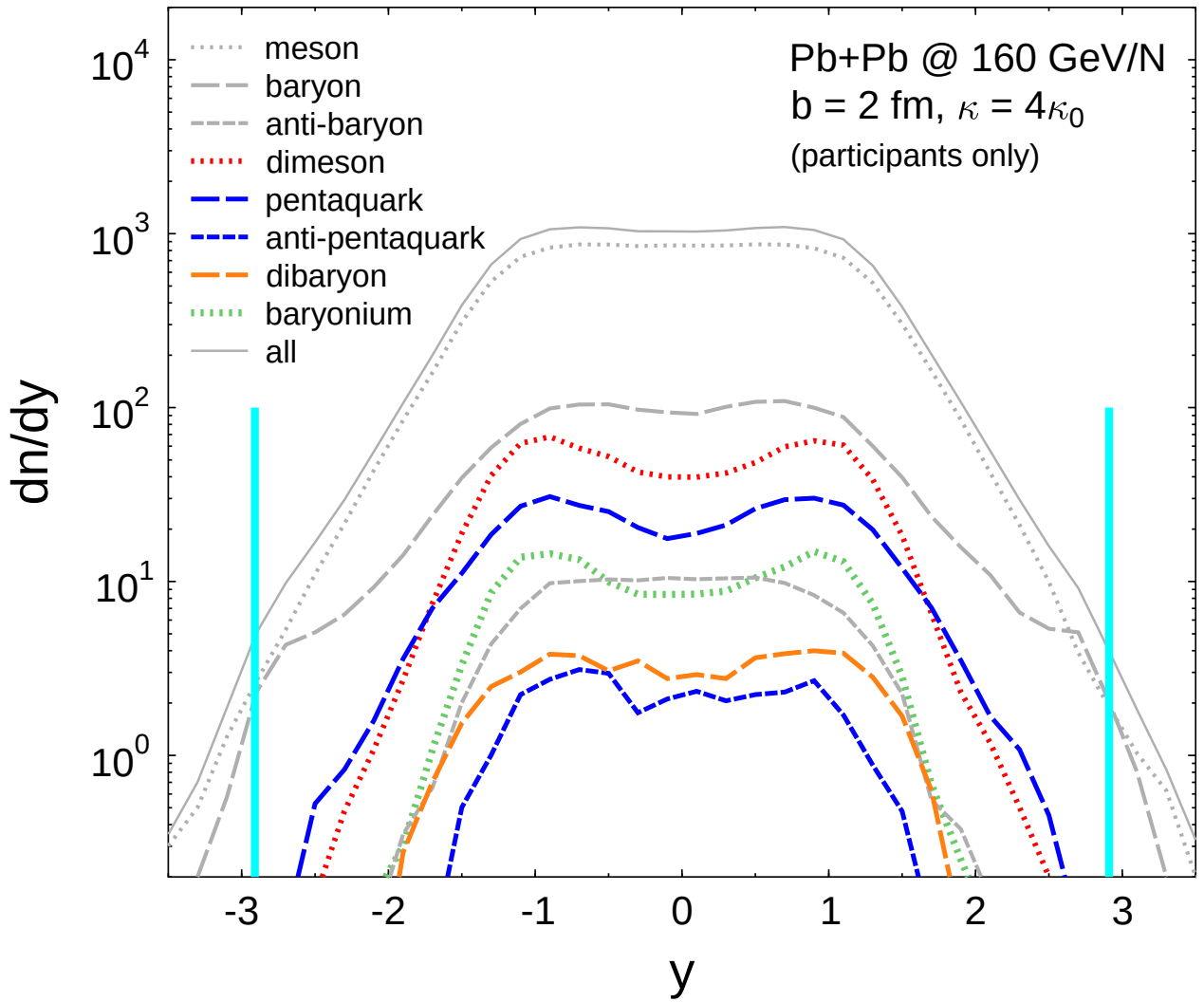


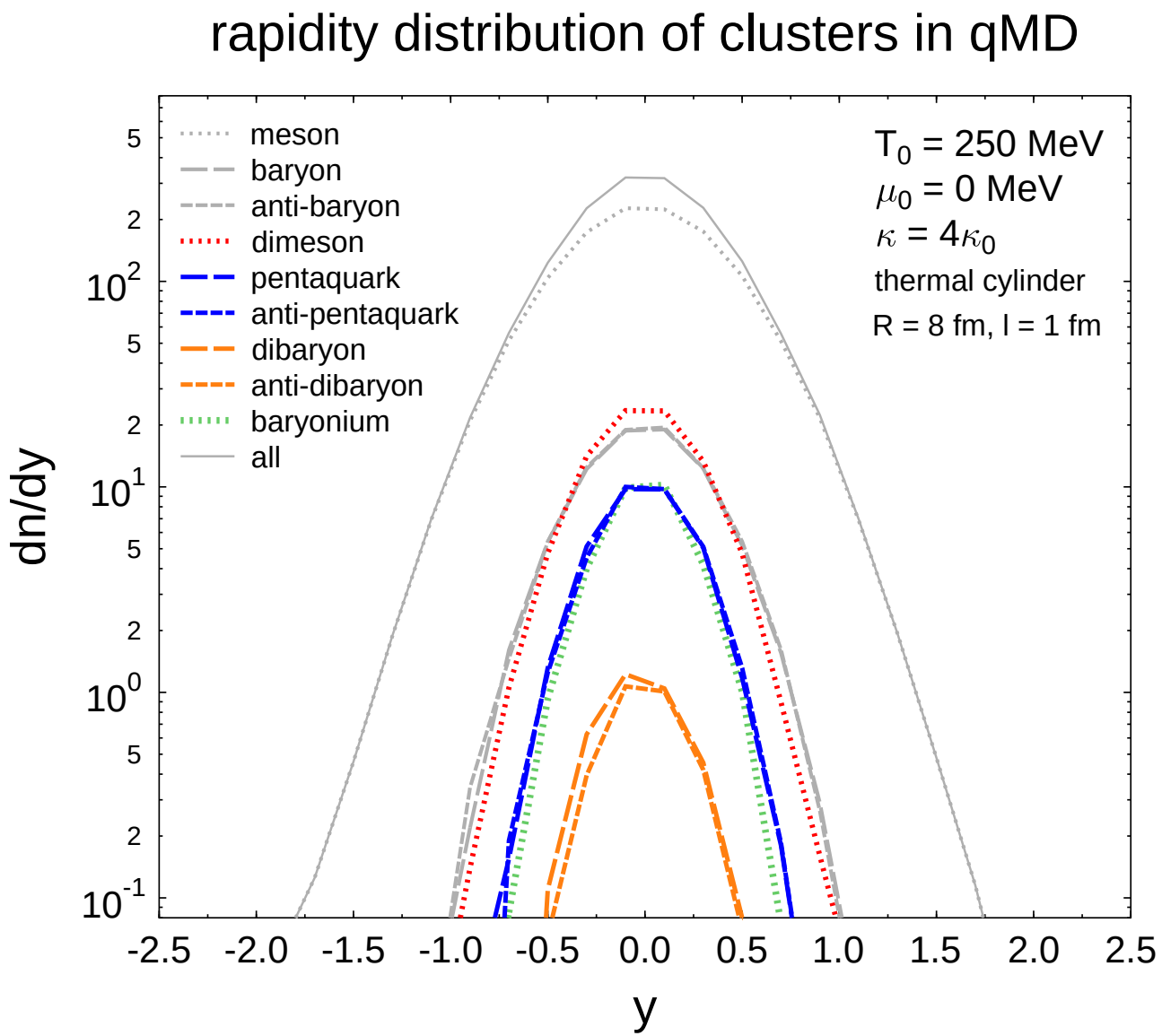
Keep in mind: No quantum mechanics – no physical mass spectrum!

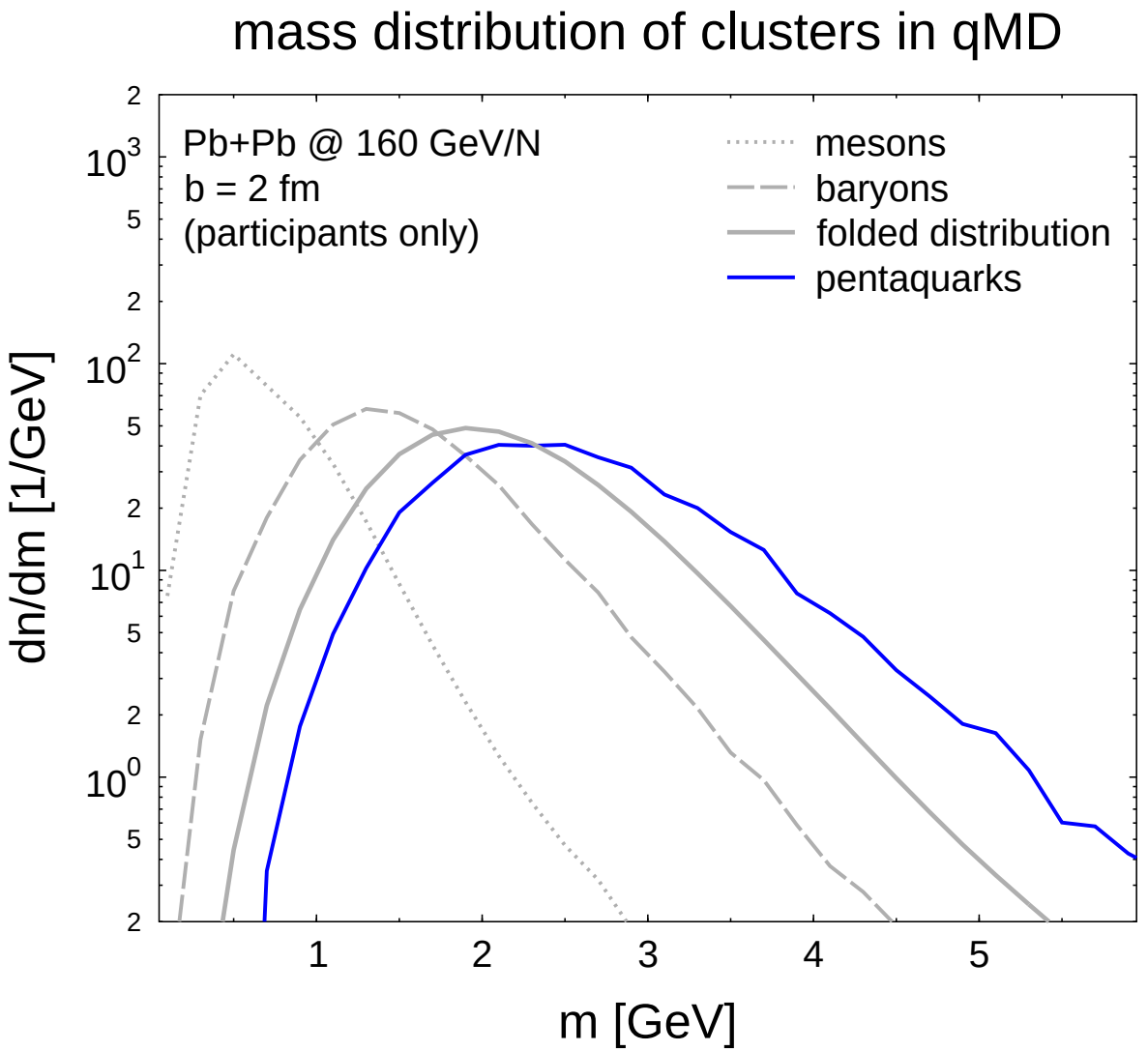
rapidity distribution of clusters in qMD



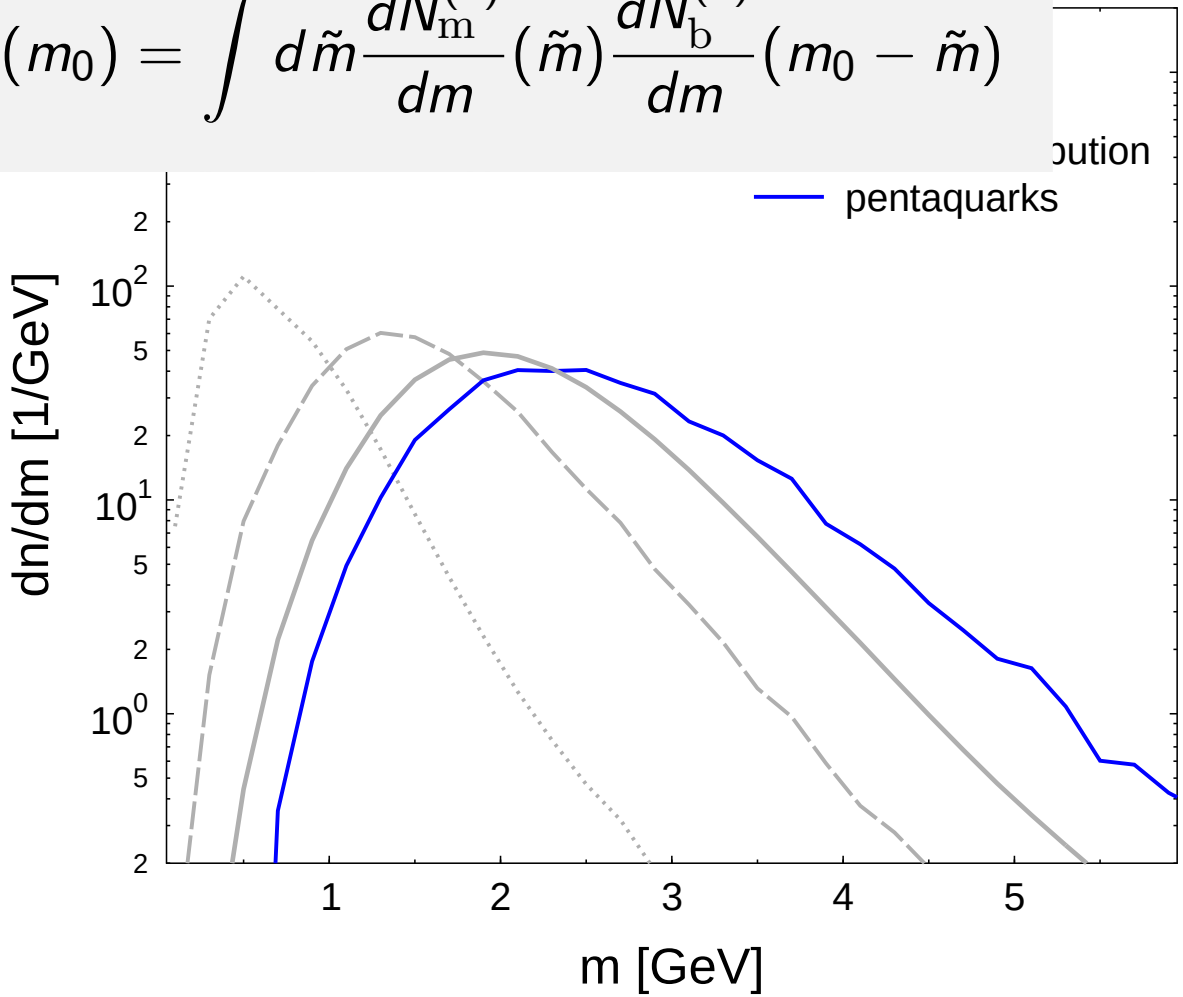
rapidity distribution of clusters in qMD




rapidity distribution of clusters in qMD
meson
baryon
anti-baryon
dimeson
pentaquark
anti-pentaquark
dibaryon
anti-dibaryon
baryonium
all
T0 = 250 MeV
μ0 = 0 MeV
κ = 4κ0
thermal cylinder
R = 8 fm, l = 1 fm
dn/dy
y
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5


mass distribution of clusters in qMD
Pb+Pb @ 160 GeV/N
b = 2 fm
(participants only)
mesons
baryons
folded distribution
pentaquarks
dn/dm [1/GeV]
m [GeV]

$$\frac{dN_{\mathrm{p}}^{(\mathrm{naive})}}{dm}(m_0) = \int d\tilde{m} \frac{dN_{\mathrm{m}}^{(3)}}{dm}(\tilde{m}) \frac{dN_{\mathrm{b}}^{(3)}}{dm}(m_0 - \tilde{m})$$



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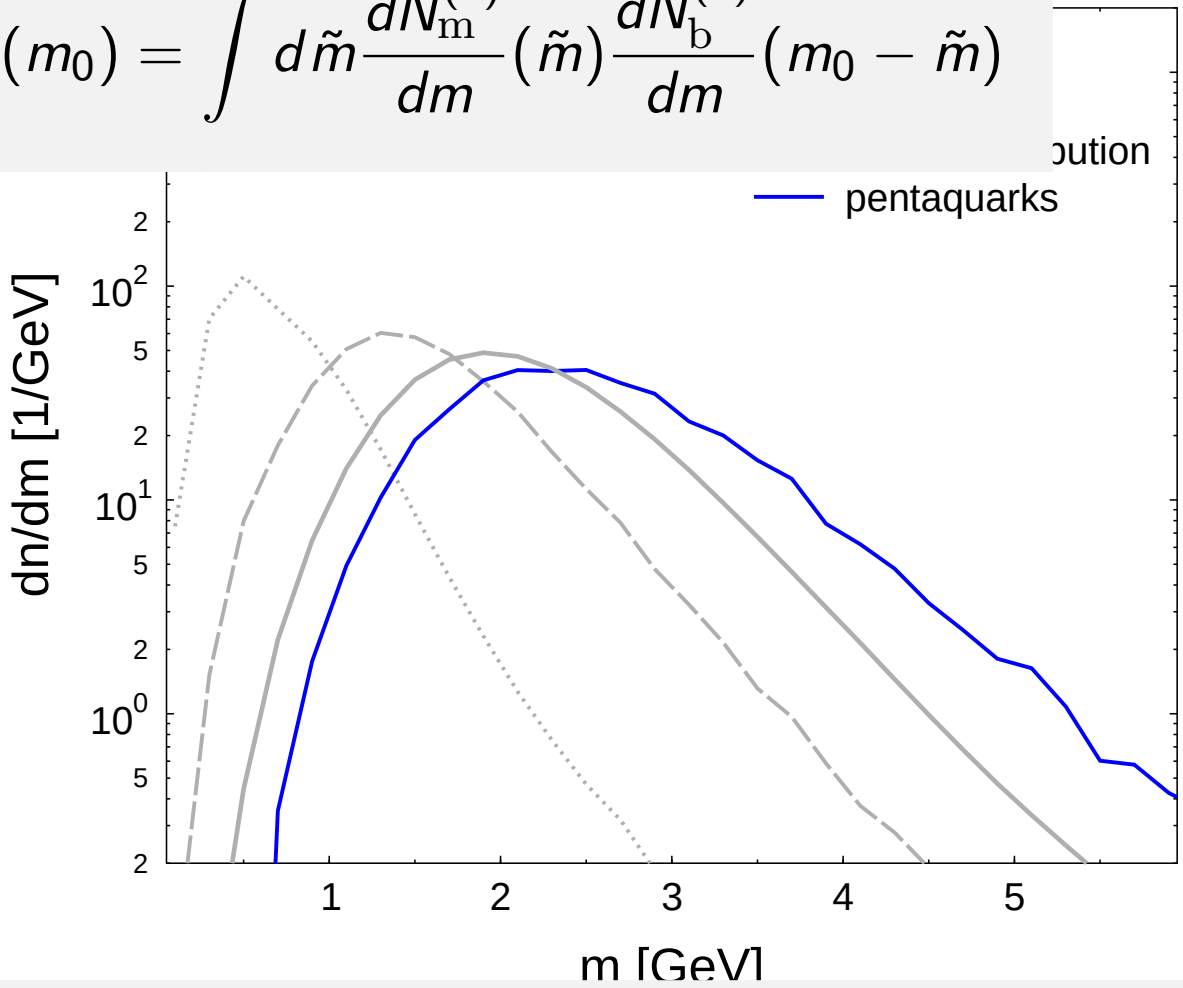
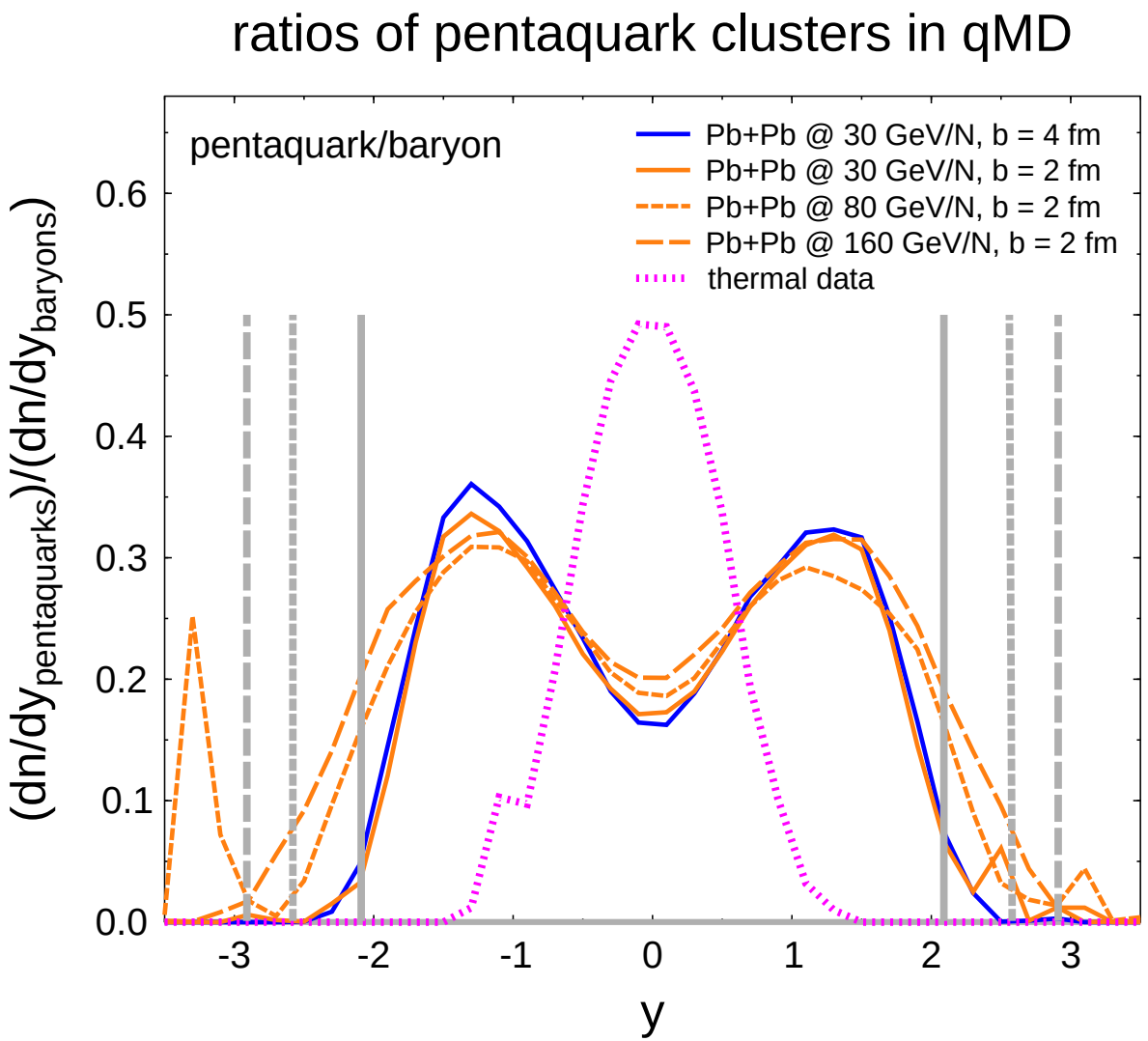
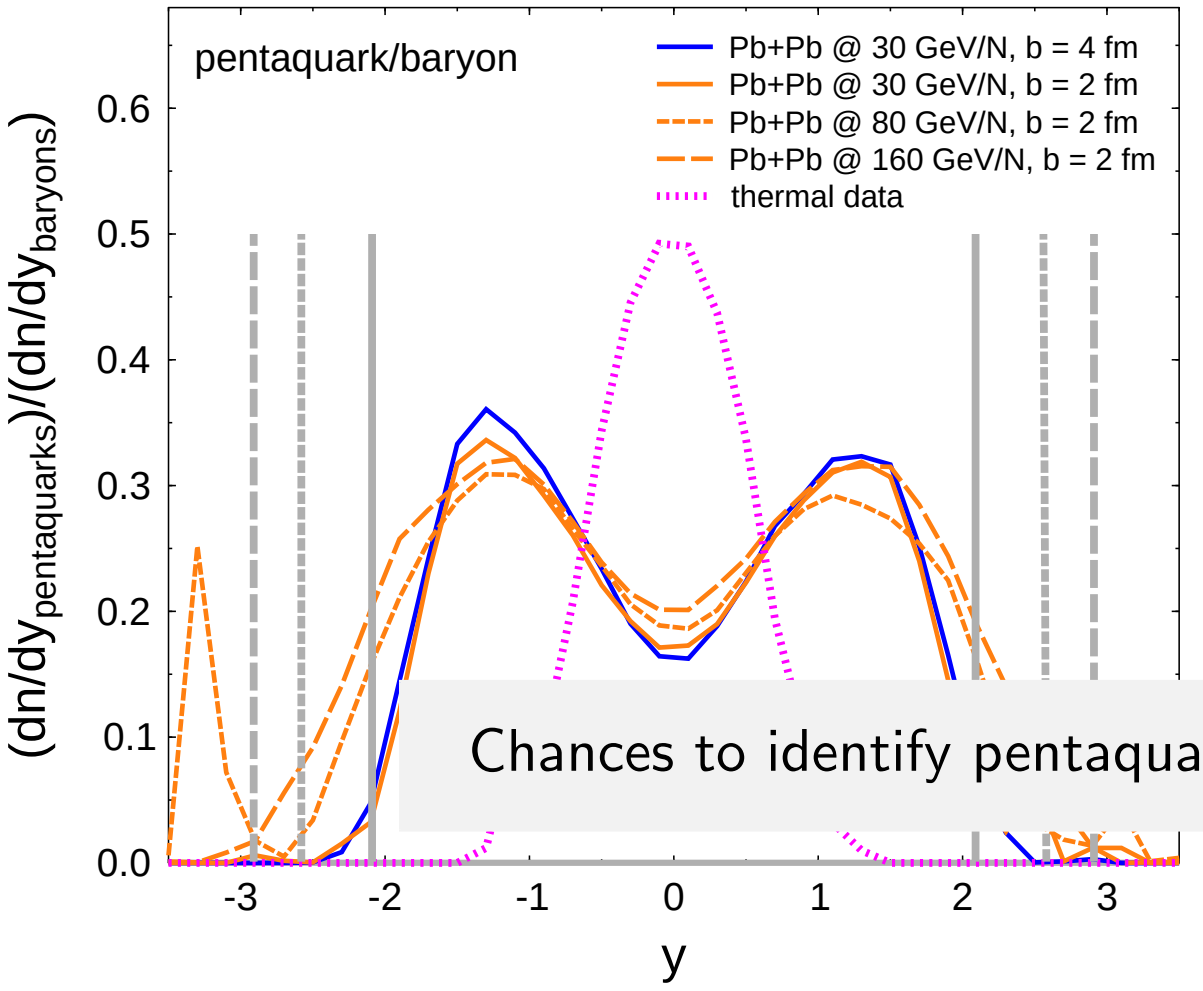


Mass of pentaquark clusters $\sim$ 200 MeV higher than molecule mass!


ratios of pentaquark clusters in qMD
pentaquark/baryon
Pb+Pb @ 30 GeV/N, b = 4 fm
Pb+Pb @ 30 GeV/N, b = 2 fm
Pb+Pb @ 80 GeV/N, b = 2 fm
Pb+Pb @ 160 GeV/N, b = 2 fm
thermal data
(dn/dy_pentaquarks)/(dn/dy_baryons)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-3
-2
-1
0
1
2
3
y

ratios of pentaquark clusters in qMD



Chances to identify pentaquark clusters!

SU(3) multiplet structure of pentaquark states

$$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} \otimes \overline{\mathbf{3}} = 3 \cdot \mathbf{1} \oplus 8 \cdot \mathbf{8} \oplus 4 \cdot \mathbf{10} \oplus 2 \cdot \overline{\mathbf{10}} \oplus 3 \cdot \mathbf{27} \oplus \mathbf{35}$$

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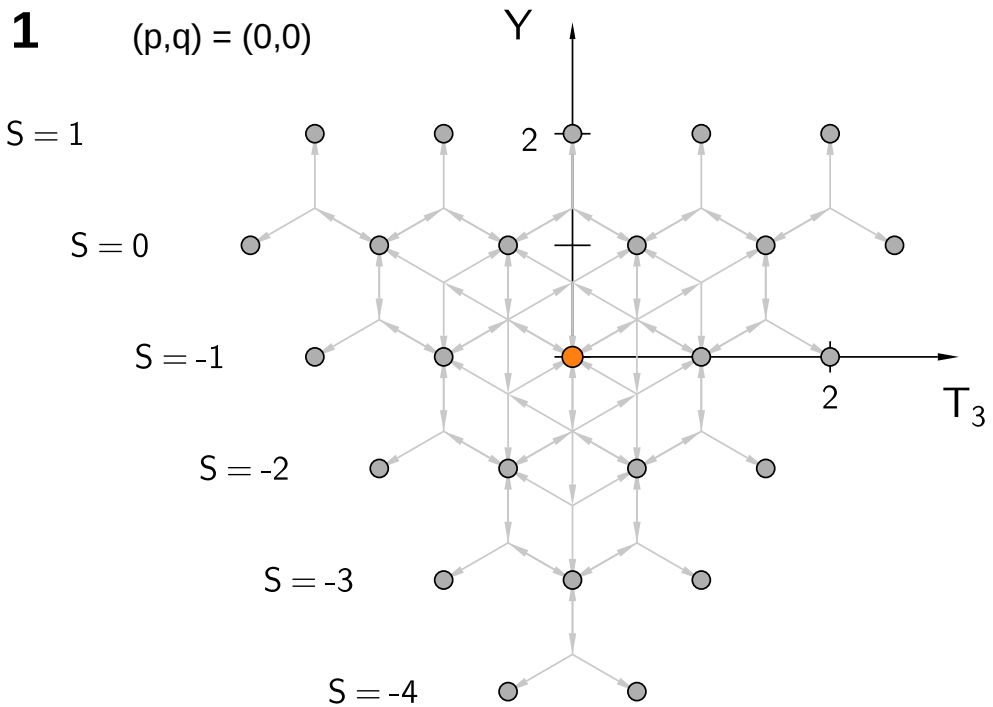

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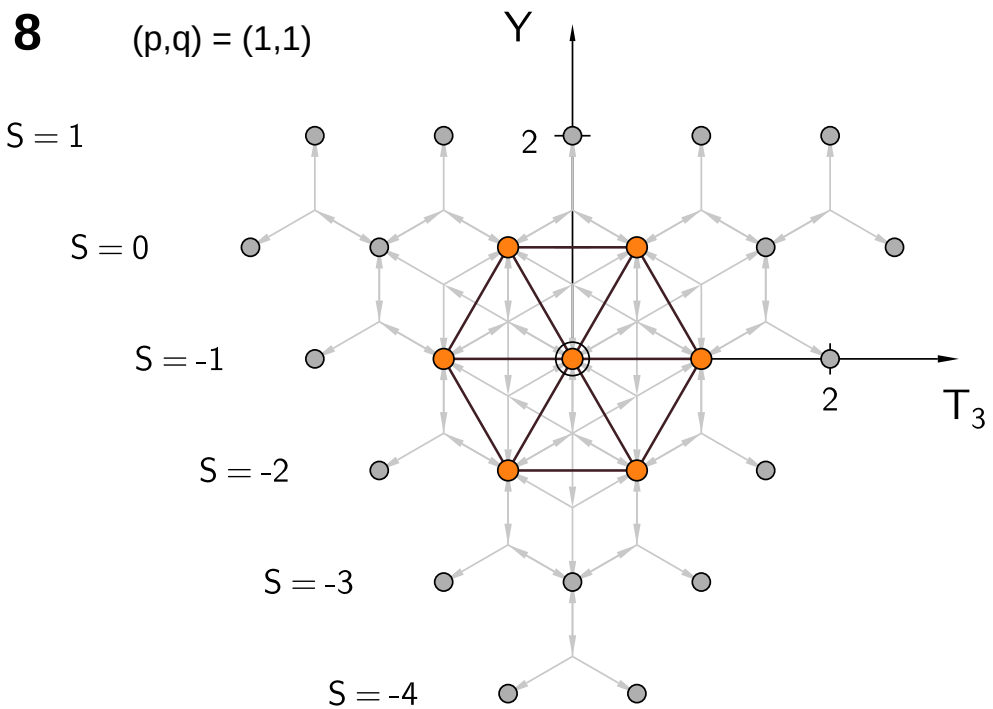

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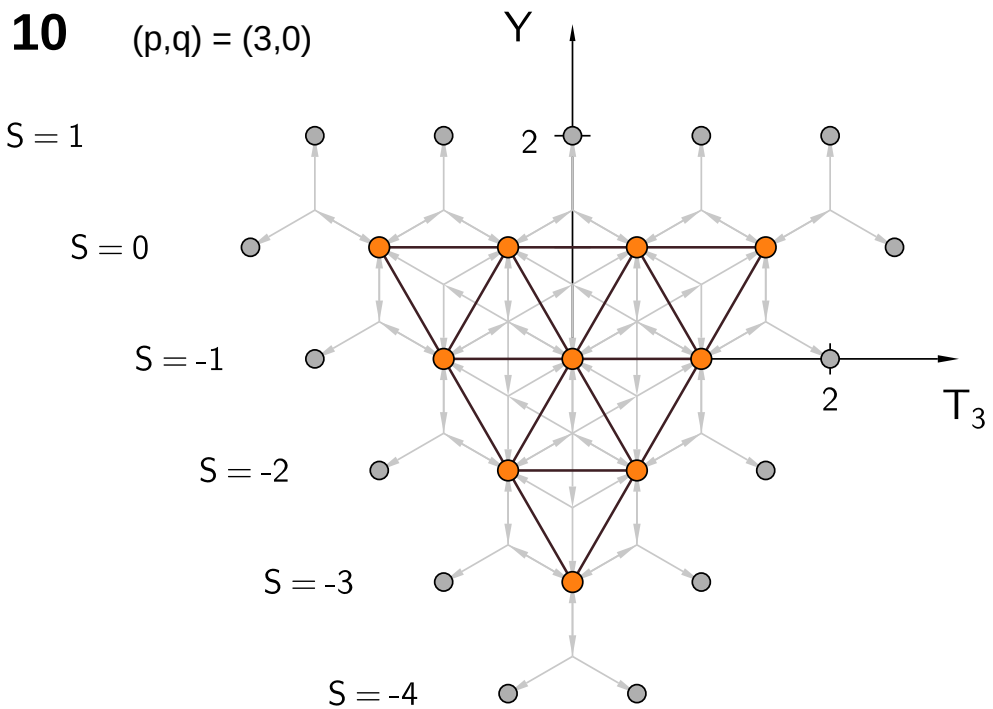

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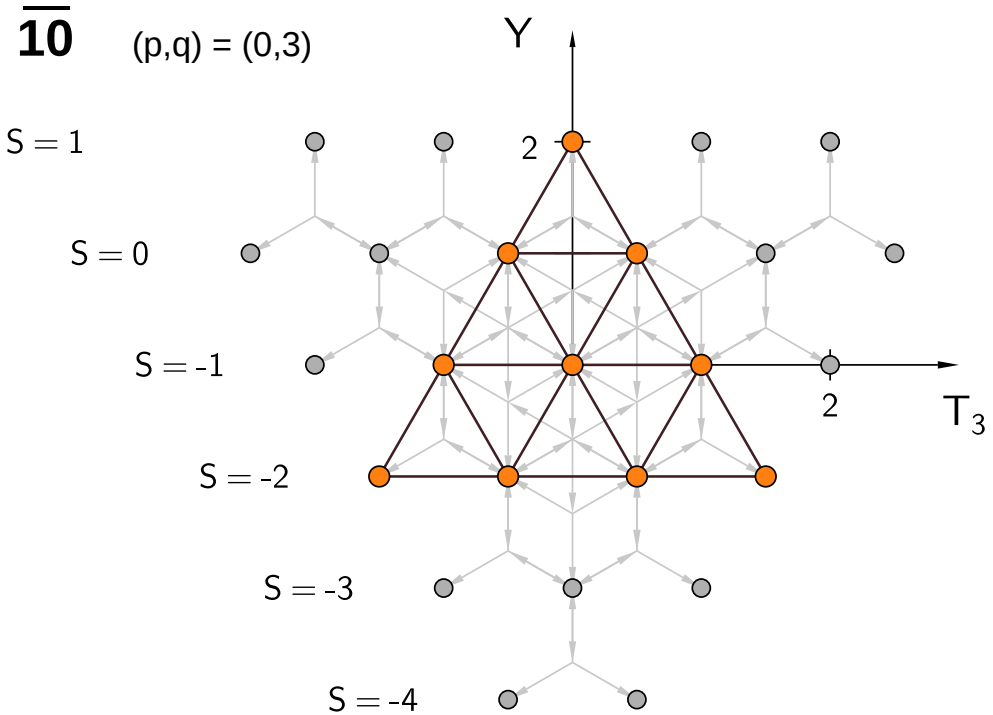

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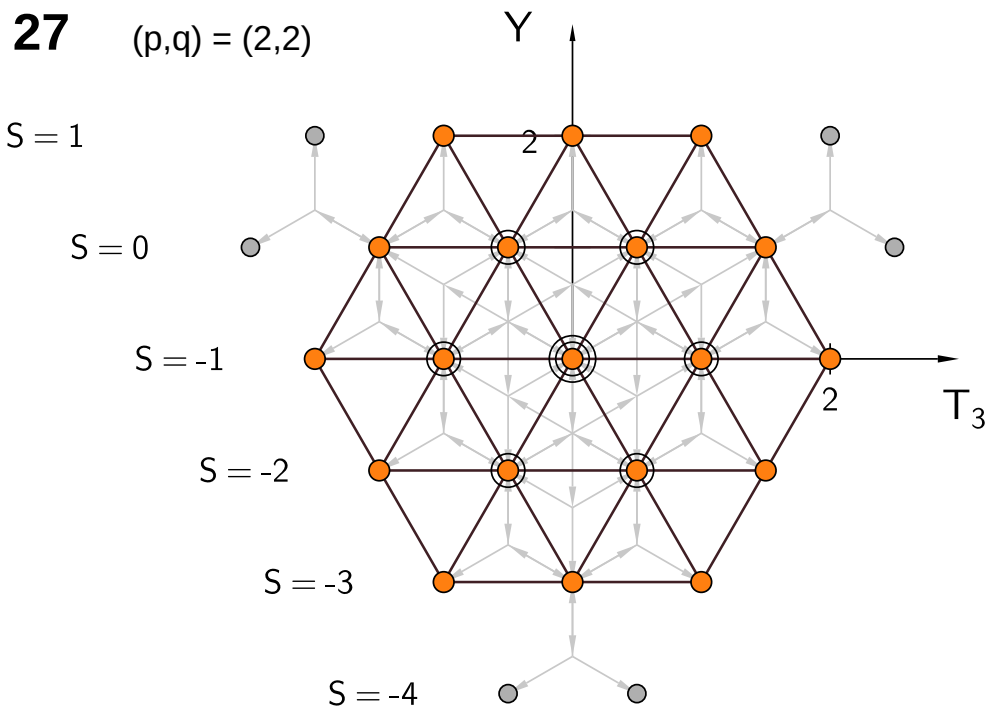

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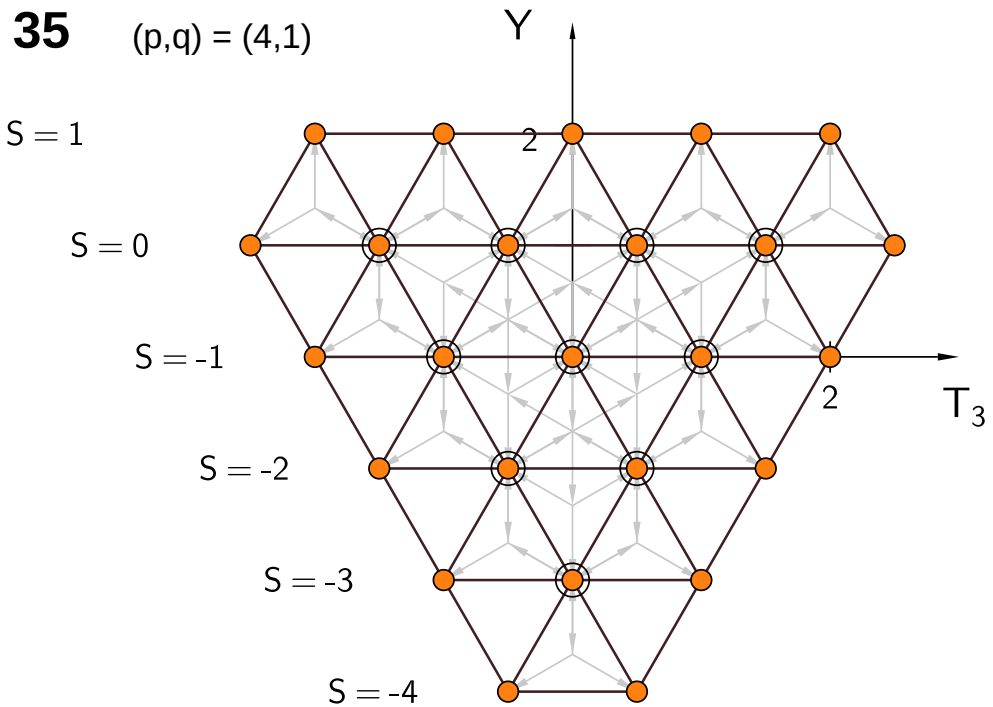

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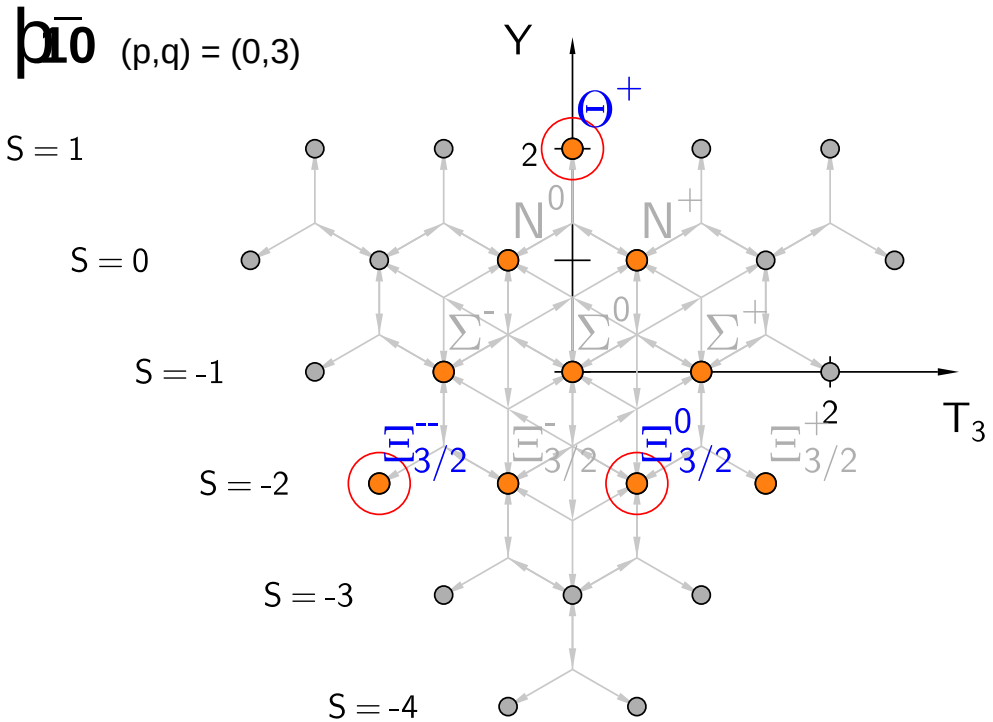

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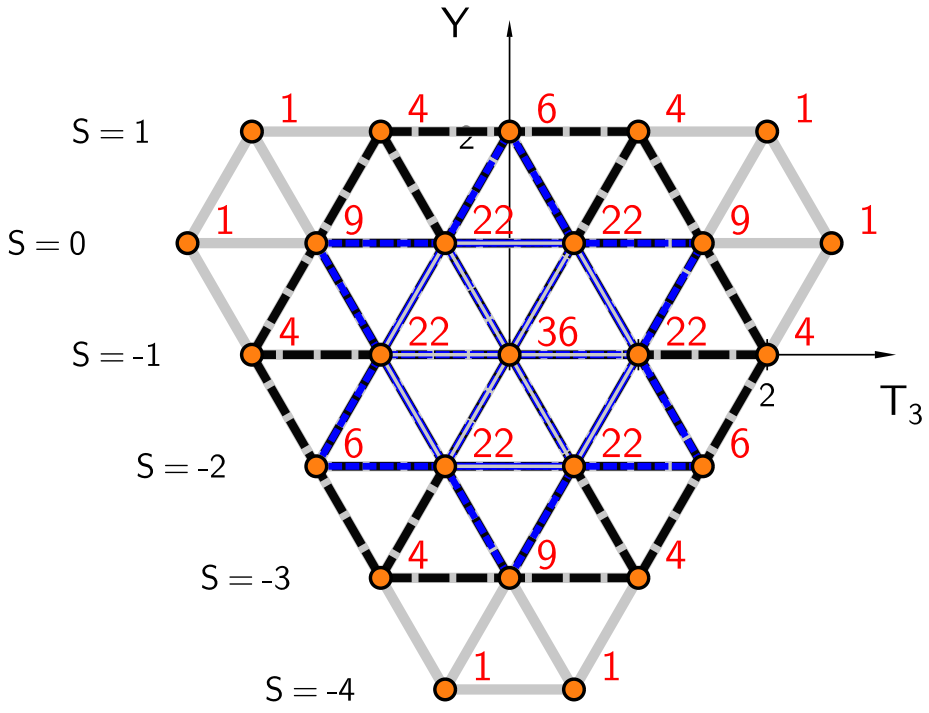


16: $\overline{\mathbf{10}}$, **27**, **35**

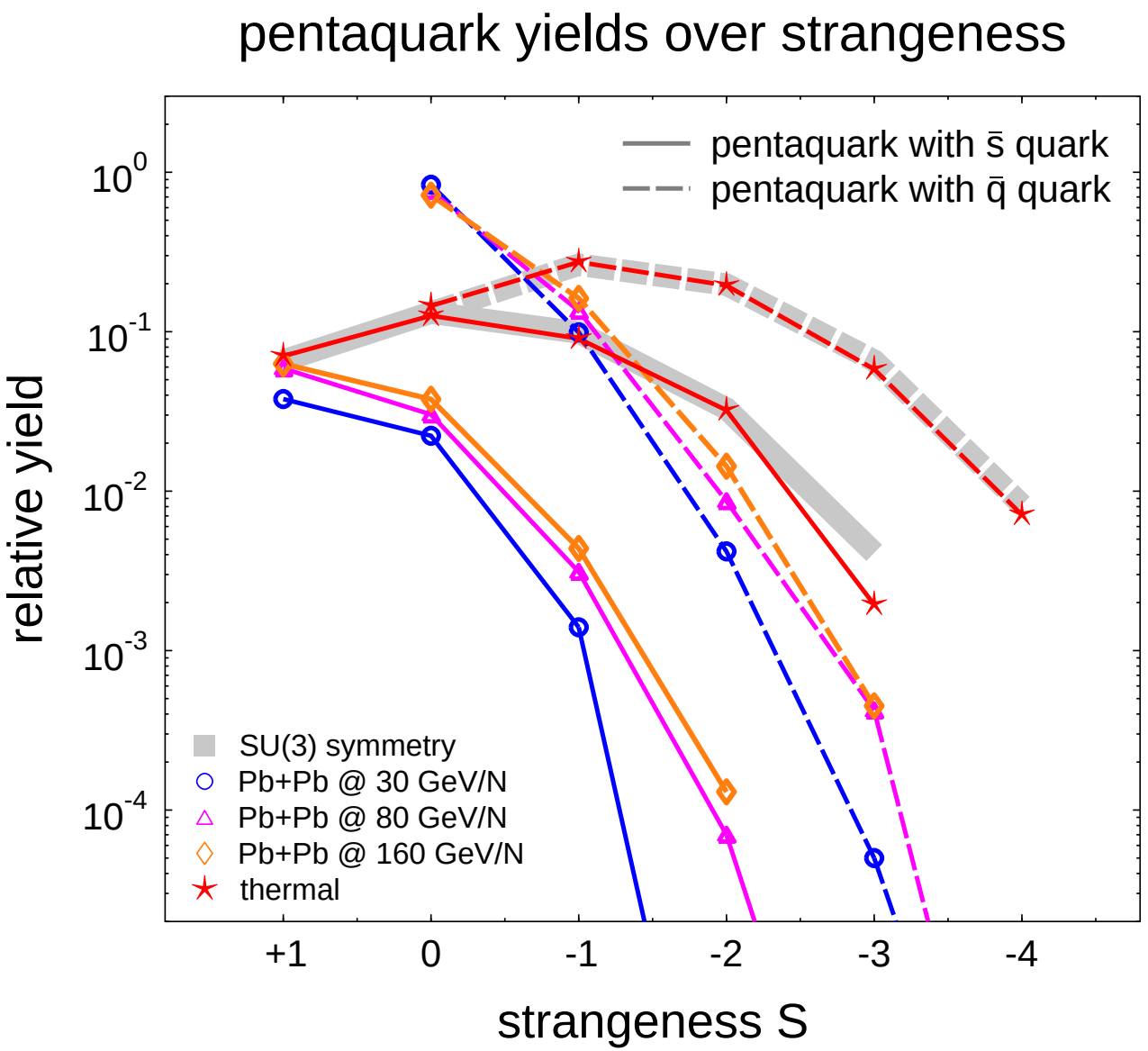
64: **8**, **10**, $\overline{\mathbf{10}}$, **27**, **35**

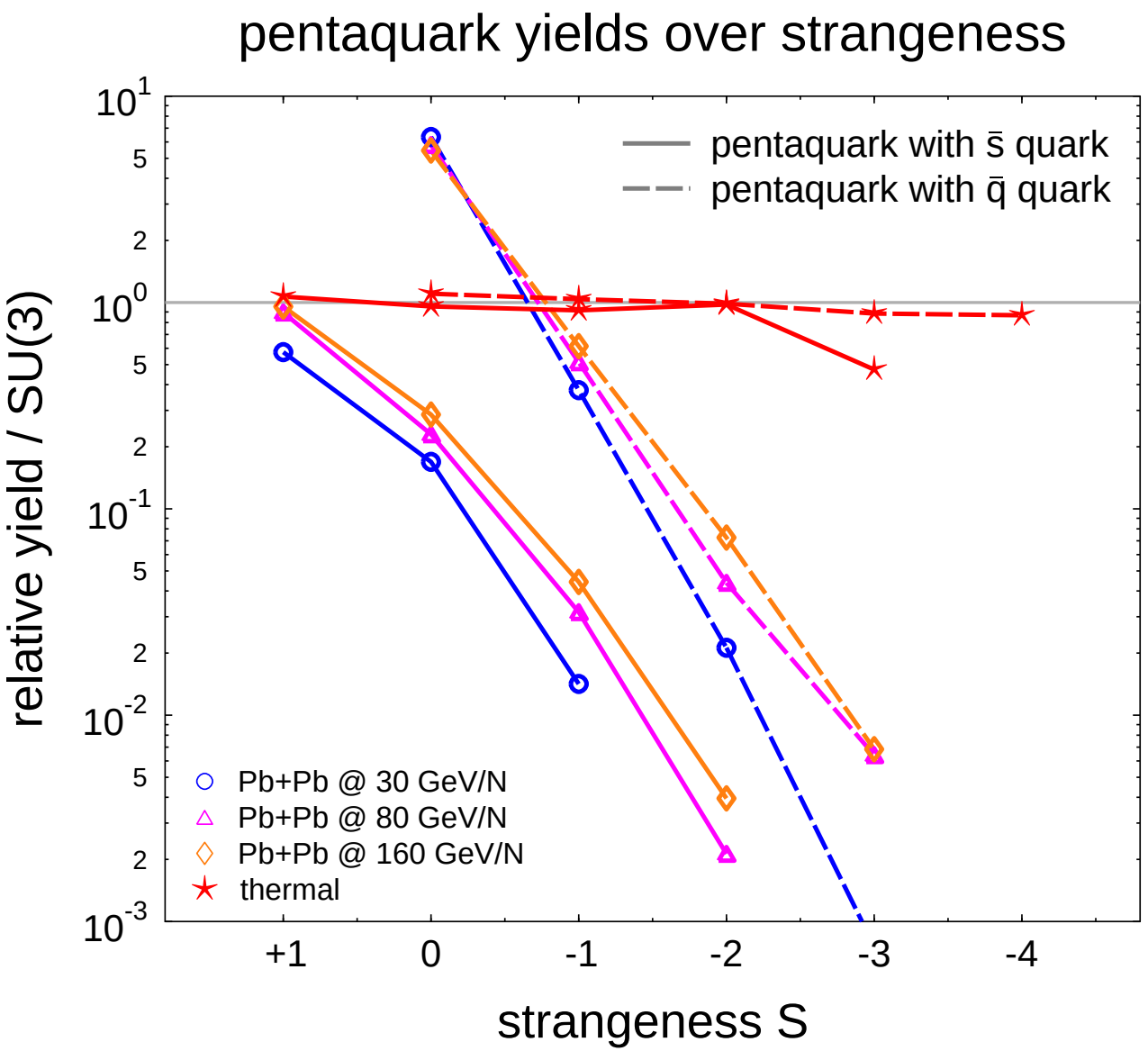
88: **1**, **8**, **10**, $\overline{\mathbf{10}}$, **27**, **35**

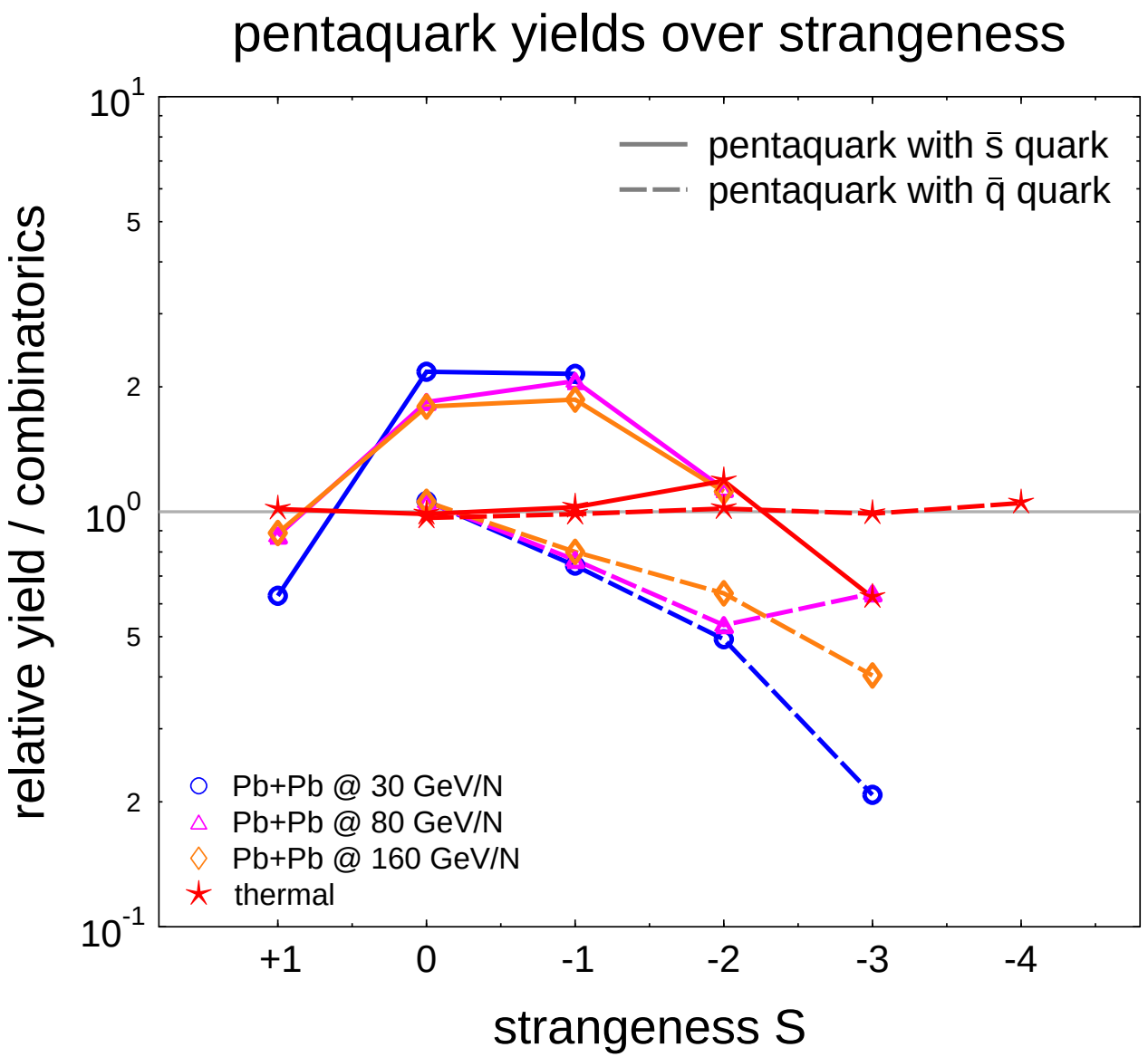
56: **8**, **10**, $\overline{\mathbf{10}}$, **27**, **35**

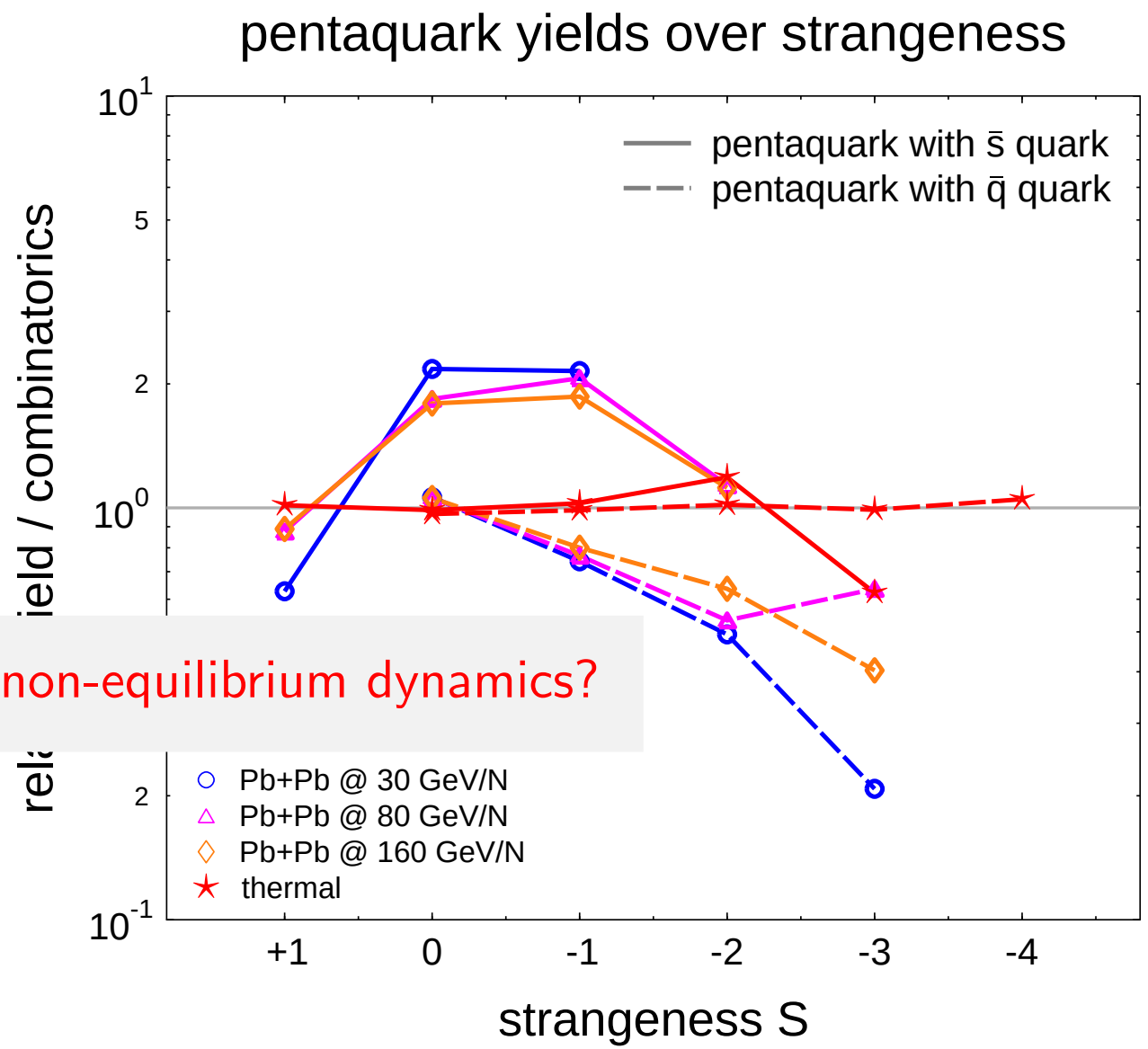
17: **10**, **27**, **35**

2: **35**

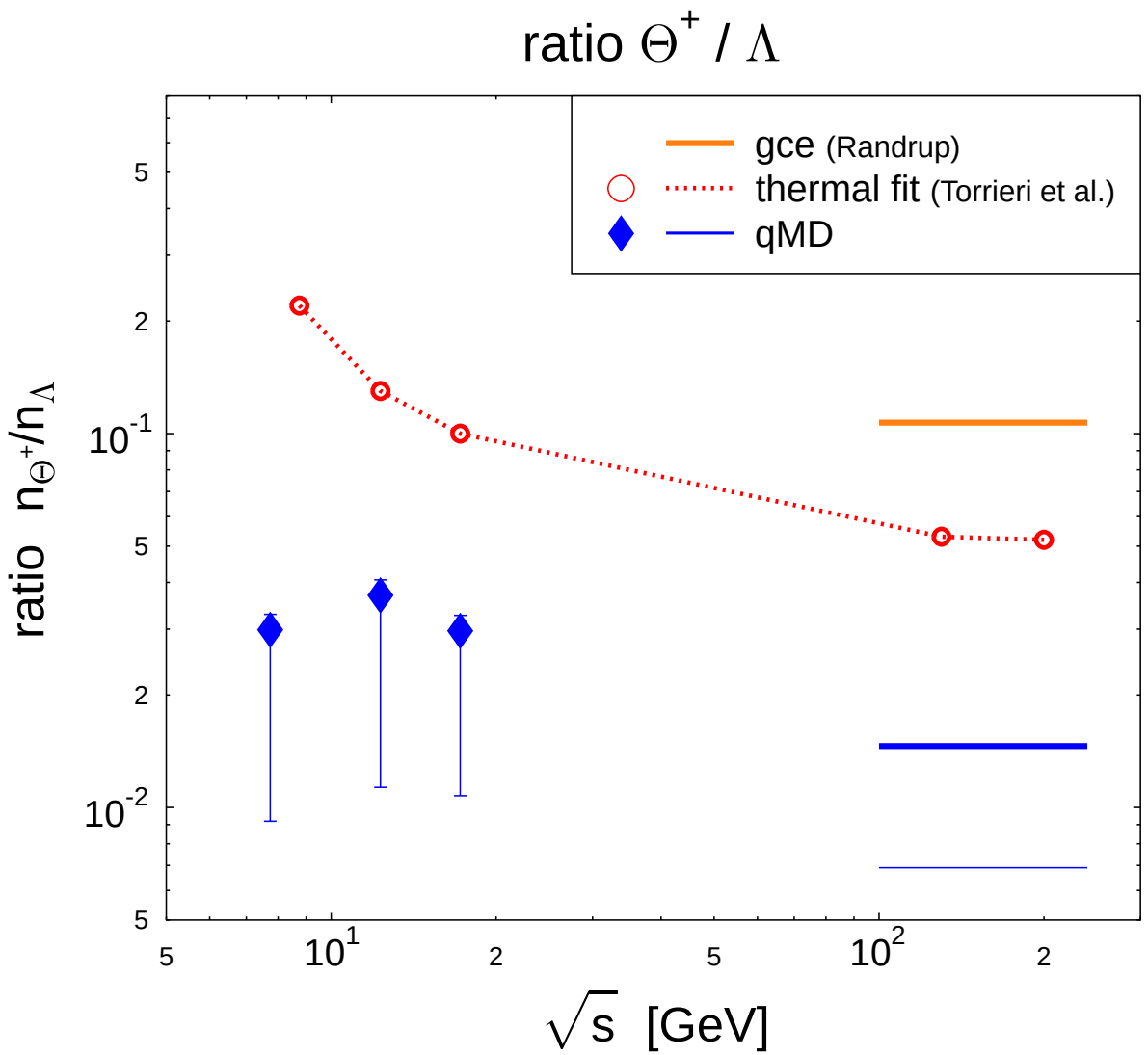

pentaquark yields over strangeness
pentaquark with s̄ quark
pentaquark with q̄ quark
relative yield
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
SU(3) symmetry
Pb+Pb @ 30 GeV/N
Pb+Pb @ 80 GeV/N
Pb+Pb @ 160 GeV/N
thermal
+1
0
-1
-2
-3
-4
strangeness S

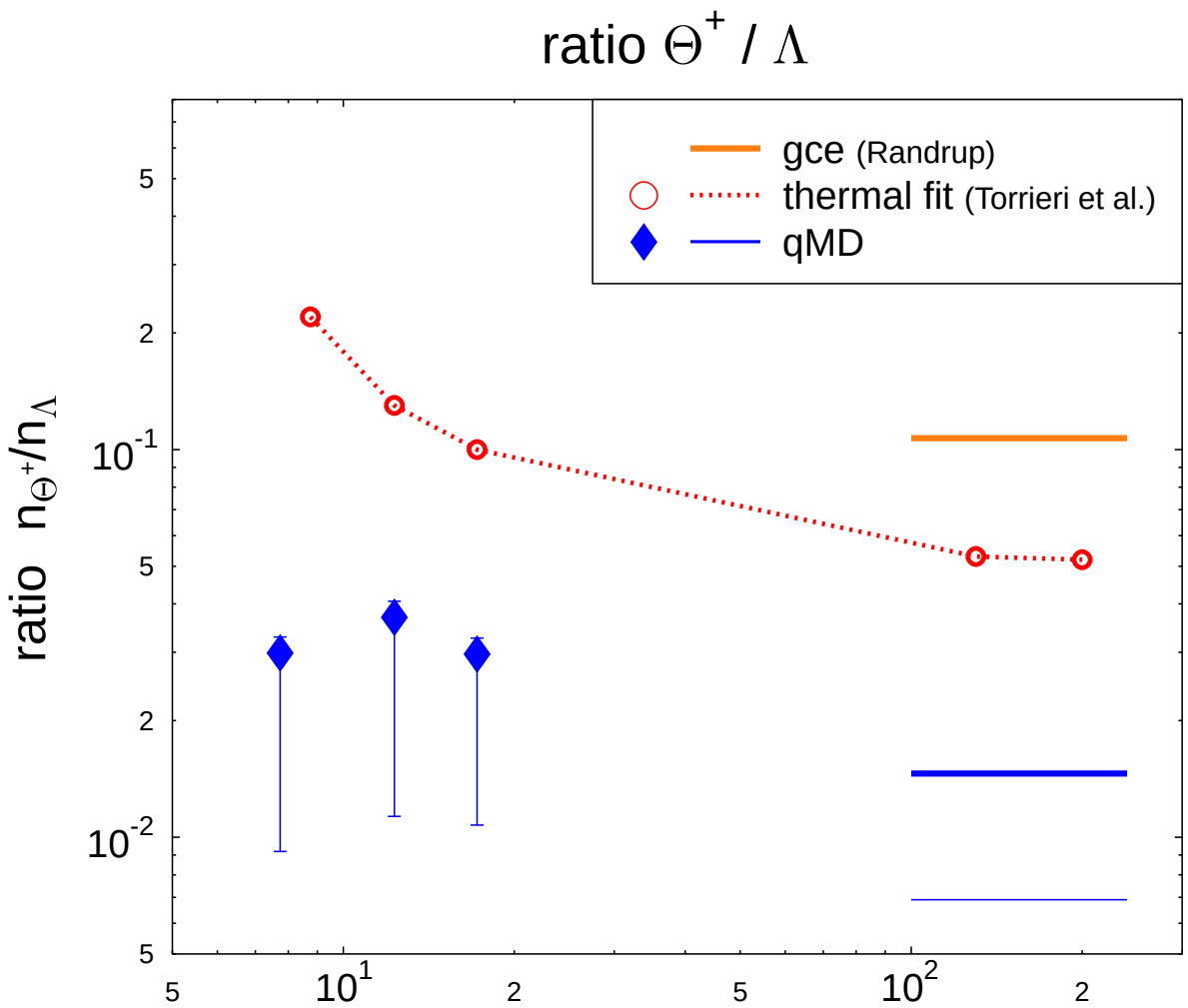

pentaquark yields over strangeness
relative yield / SU(3)
strangeness S
pentaquark with s̄ quark
pentaquark with q̄ quark
Pb+Pb @ 30 GeV/N
Pb+Pb @ 80 GeV/N
Pb+Pb @ 160 GeV/N
thermal
+1
0
-1
-2
-3
-4


pentaquark yields over strangeness
relative yield / combinatorics
strangeness S
pentaquark with s̄ quark
pentaquark with q̄ quark
Pb+Pb @ 30 GeV/N
Pb+Pb @ 80 GeV/N
Pb+Pb @ 160 GeV/N
thermal
10^1
5
2
10^0
5
2
10^-1
+1
0
-1
-2
-3
-4



Hint at non-equilibrium dynamics?


ratio Θ^+ / Λ
gce (Randrup)
thermal fit (Torrieri et al.)
qMD
ratio n_{Θ^+}/n_Λ
$\sqrt{s}$ [GeV]



"Primordial" pentaquarks – no rescattering!

Conclusion

- qMD model used to search for exotic quark clusters

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Conclusion

- qMD model used to search for exotic quark clusters
- Chances to identify pentaquark states?
- Strangeness distribution a probe of thermalization and homogenization?
- High exotica yields are strongly reduced by size of multiplets involved!
- Θ^+ yield less than in GCE and thermal models