Baryonic Spectral Functions above the Deconfinement Phase Transition

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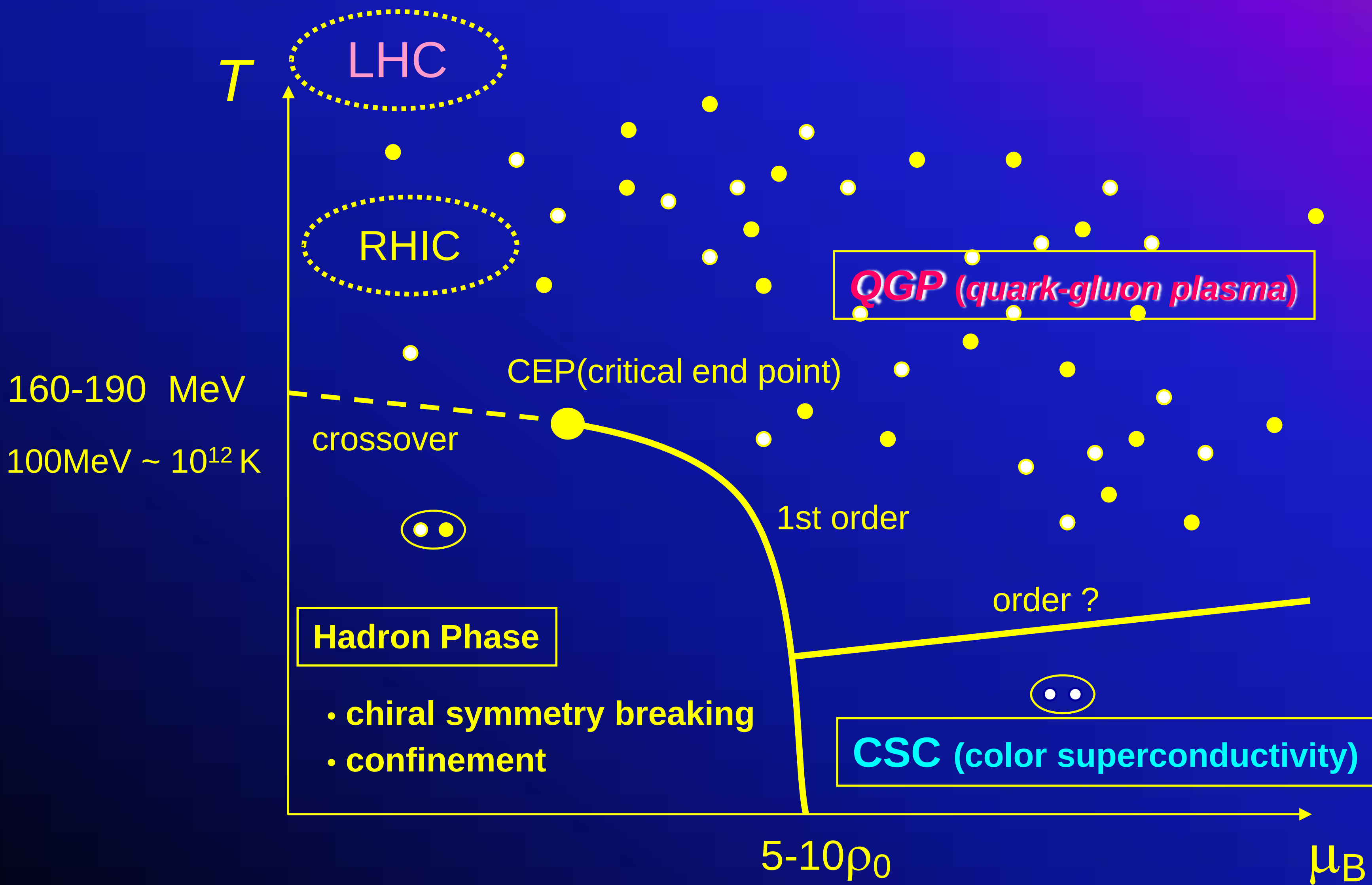
QCD Phase Diagram



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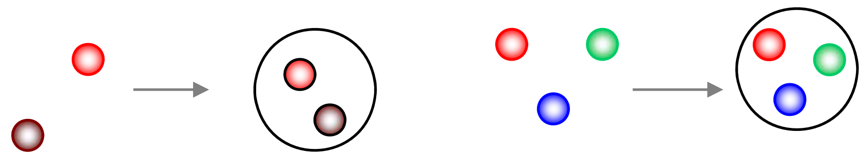
Importance of Understanding Hadrons @Finite T

Success of Recombination @RHIC

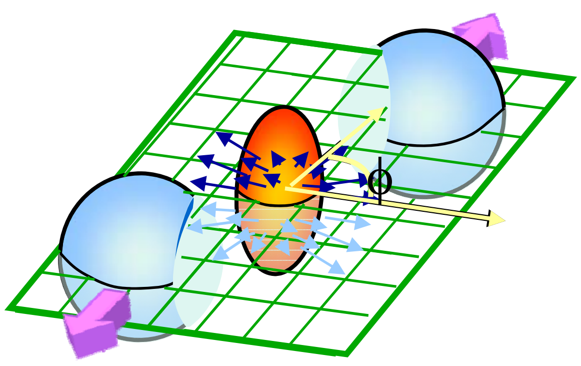


$$v_2^M(p_t) \sim 2 v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) \sim 3 v_2^p\left(\frac{p_t}{3}\right)$$

$$(1+x)^n \sim 1 + nx$$

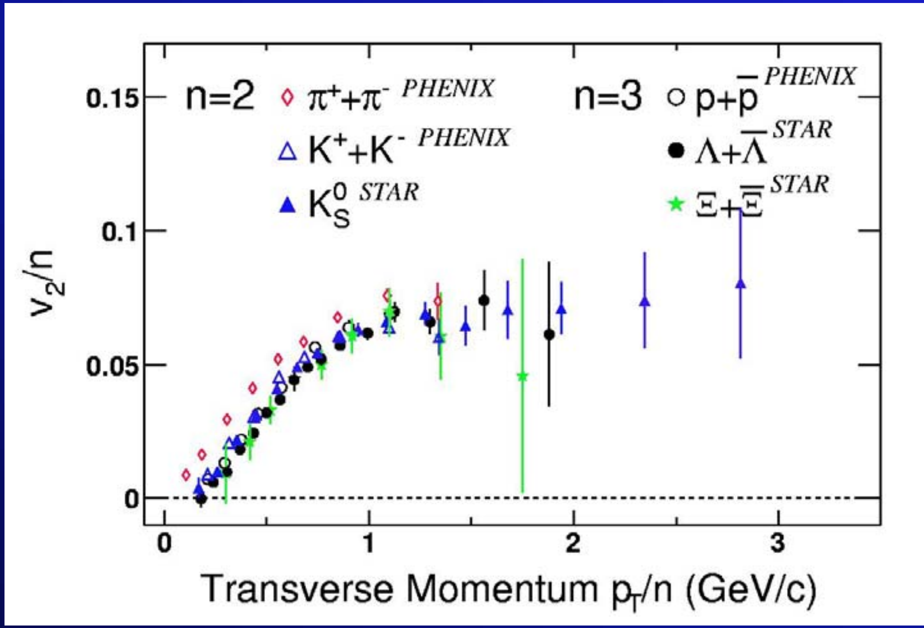
- $v_2^M(p_T^M) : v_2^B(p_T^B) \sim 2 : 3$ for $p_T^M : p_T^B = 2 : 3$

$$\frac{dN_i}{dy d\varphi}\left(\frac{dN_i}{dy d\varphi d^2 p_T}\right) = N_{i0}\left(1 + 2v_1 \cos(\varphi - \varphi_0) + 2v_2 \cos 2(\varphi - \varphi_0) + \cdots\right)$$



Constituent Quark Number Scaling

- $v_2^M(p_T^M) : v_2^B(p_T^B) \sim 2 : 3$ for $p_T^M : p_T^B = 2 : 3$



- Partons are flowing and Partons recombine to make mesons and baryons

Evidence of Deconfinement

Assumption

All hadrons are created at hadronization simultaneously

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Hadrons above T_c?

Hadrons above T_c

- No *a priori* reason that no hadrons exist above T_c
- QGP looks like strongly interacting system (low viscosity...etc.)

■ Definition of Spectral Function (SPF)

$$\frac{\rho_{\mu\nu}(k_0,\vec{k})}{(2\pi)^3} \equiv \sum_{n,m} \frac{e^{-(E_n-\mu N_n)/T}}{Z} \langle n | J_\mu(0) | m \rangle \langle m | J_\nu(0) | n \rangle (1 \mp e^{-P^0_{mn}/T}) \delta^4(k - P_{mn})$$

$-(+)$: Boson(Fermion)

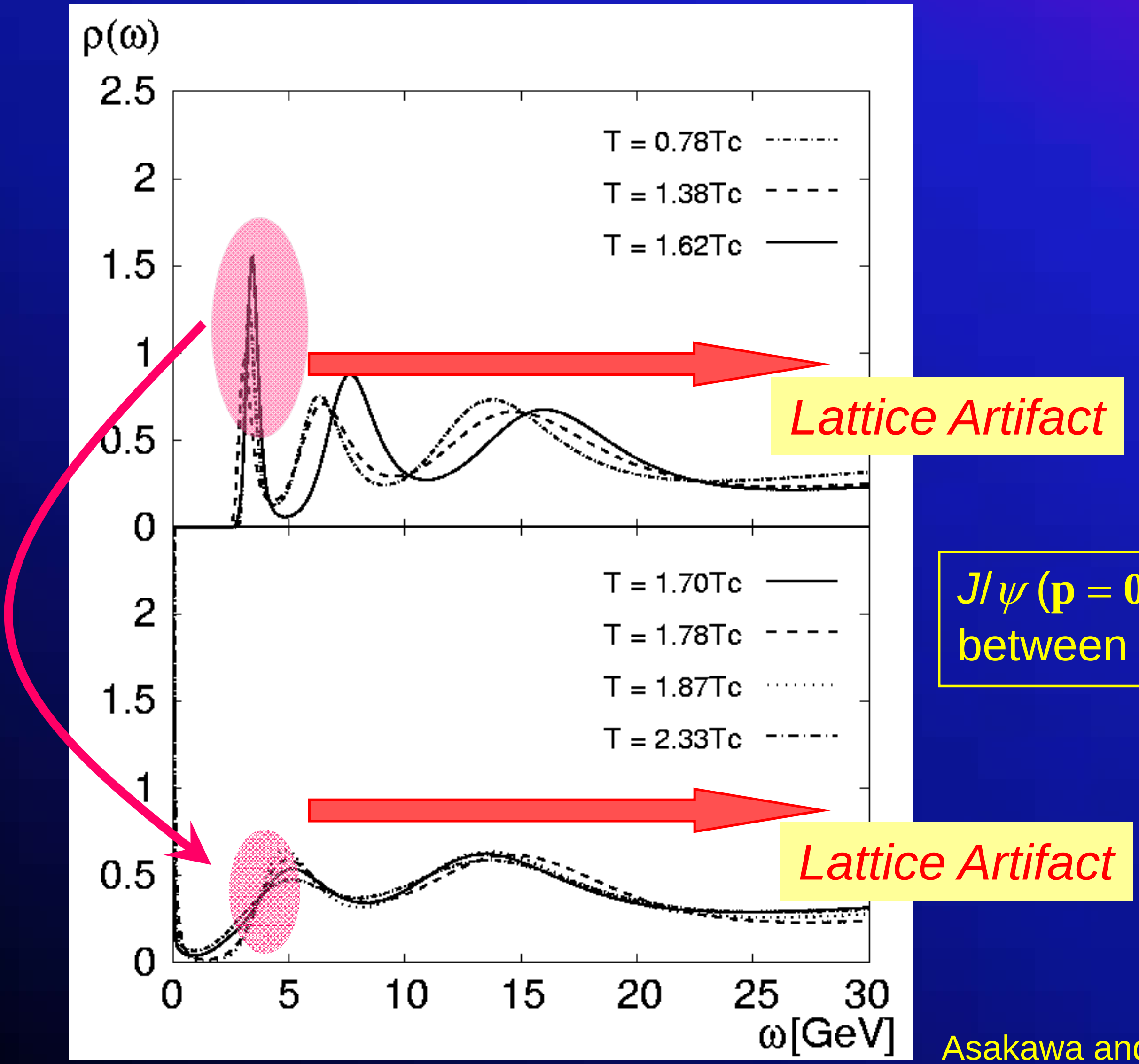
$J_\mu(0)$: A Heisenberg Operator with some quantum #

$|n\rangle$: Eigenstate with 4-momentum P_n^μ

$P_{mn} = P_m - P_n$

- SPF is peaked at particle mass and takes a broad form for a resonance

J/ψ non-dissociation above T_c



J/ψ $(\mathbf{p}=\mathbf{0})$ disappears between $1.62T_c$ and $1.70T_c$

Asakawa and Hatsuda, PRL 2004

Baryon Operators

- Nucleon current

$$J_N(x) = \varepsilon_{abc}\left[s\left(u_a(x)Cd_b(x)\right)\gamma_5 u_c(x) + t\left(u_a(x)C\gamma_5 d_b(x)\right)u_c(x)\right]$$

$s = -t = 1$ Ioffe current

- On the lattice, used $s = 0$, $t = 1$, $u(x) = d(x) = q(x)$, $J_N(x) \to J(x)$

- Euclidean correlation function at zero momentum

$$D(\tau,\vec{0}) = \int d^3x \left\langle J(\tau,\vec{x})\bar{J}(0,\vec{0})\right\rangle$$

$$D(\tau,\vec{0}) = \int_{-\infty}^{\infty} K(\tau,\omega)\rho(\omega)d\omega$$

$$K(\tau,\omega) = \frac{\exp\left(\frac{1}{2}-\tau T\right)\frac{\omega}{T}}{\exp\left(\frac{\omega}{2T}\right)+\exp\left(-\frac{\omega}{2T}\right)}$$

Spectral Functions for Fermionic Operators

$$D(\tau,\vec{0}) = \int d^3x \left\langle J(\tau,\vec{x})\bar{J}(0,\vec{0})\right\rangle$$

$$D(\tau,\vec{0}) = \int_{-\infty}^{\infty} K(\tau,\omega)\rho(\omega)d\omega$$

$$\rho(\omega) = \rho_0(\omega)\gamma^0 + \rho_s(\omega): \qquad \rho_0(\omega),\, \rho_s(\omega)$$ independent

$$= \rho_+(\omega)\Lambda_+\gamma^0 + \rho_-(\omega)\Lambda_-\gamma^0$$

$$\rho_0(\omega) = \rho_0(-\omega), \quad \rho_s(\omega) = -\rho_s(-\omega)$$

$$\rho_+(\omega) = \rho_-(-\omega) = \rho_0(\omega) + \rho_s(\omega) \geq 0$$ semi-positivity

$\rho_+(\omega)\,(\rho_-(\omega))$: neither even nor odd

- For Meson currents, SPF is odd

Thus, need to and can carry out MEM analysis in [-ω_{max}, ω_{max}]

In the following, we analyze $\rho(\omega) \equiv \dfrac{\rho_+(\omega)}{\left|\omega^5\right|}$

Lattice Parameters

1. Lattice Sizes
   $32^3 * 46$ ($T = 1.62T_c$)
   54 ($T = 1.38T_c$)
   72 ($T = 1.04T_c$)
   80 ($T = 0.93T_c$)
   96 ($T = 0.78T_c$)
2. $\beta = 7.0$, $\xi_0 = 3.5$
   $\xi = a_\sigma / a_\tau = 4.0$ (anisotropic)
3. $a_\tau = 9.75 * 10^{-3}$ fm
   $L_\sigma = 1.25$ fm
4. Standard Plaquette Action
5. Wilson Fermion
6. Heatbath : Overrelaxation
   = 1 : 4

   1000 sweeps between measurements
7. Quenched Approximation
8. Gauge Unfixed
9. $\mathbf{p} = \mathbf{0}$ Projection
10. Machine: CP-PACS

Analysis Details

- Default Model

At zero momentum,

$$\rho_+(\omega) = \rho_-(\omega) = \frac{1}{(2\pi)^4} \frac{5}{128} \mathrm{sgn}(\omega)\omega^5$$

Espriu, Pascual, Tarrach, 1983

- Relation between lattice and continuum currents

$$J^{\mathrm{LAT}}(\tau, \vec{x}) = a_\tau^{3/4} a_\sigma^{15/4} \left(\frac{1}{2\sqrt{\kappa_\tau \kappa_\sigma}} \right)^{3/2} \frac{1}{Z_O} J^{\mathrm{CON}}(\tau, \vec{x})$$

• In the following, lattice spectral functions are presented

• $Z_O = 1$ is assumed

- ω_{max} = 45 GeV ~ $3\pi/a_\sigma$ (3 quarks)

Stat. and Syst. Error Analyses in MEM

Generally,

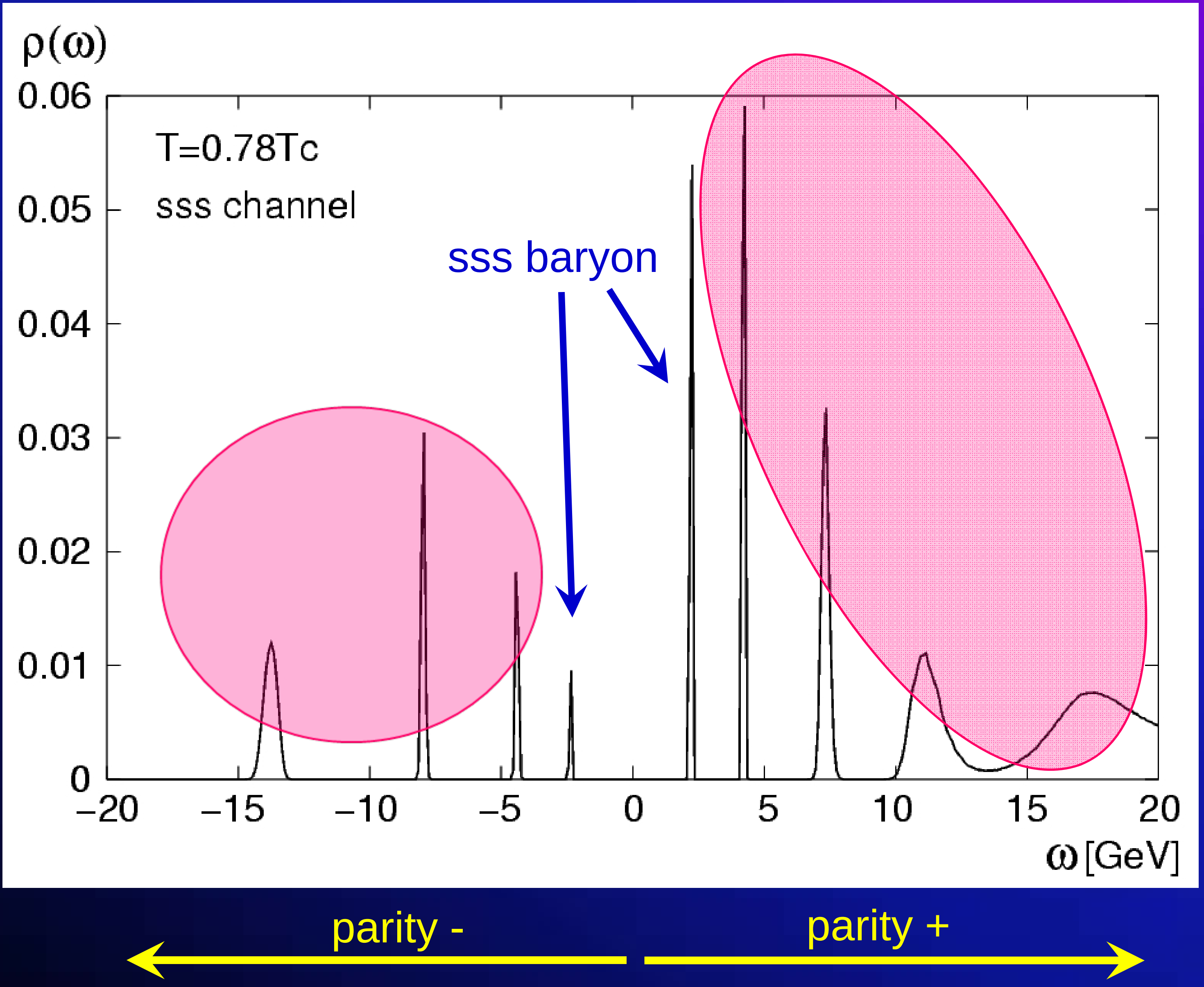
The *Larger the Number of Data Points* and the *Lower the Noise Level* → *The closer the result is to the original image*

Need to do the following:

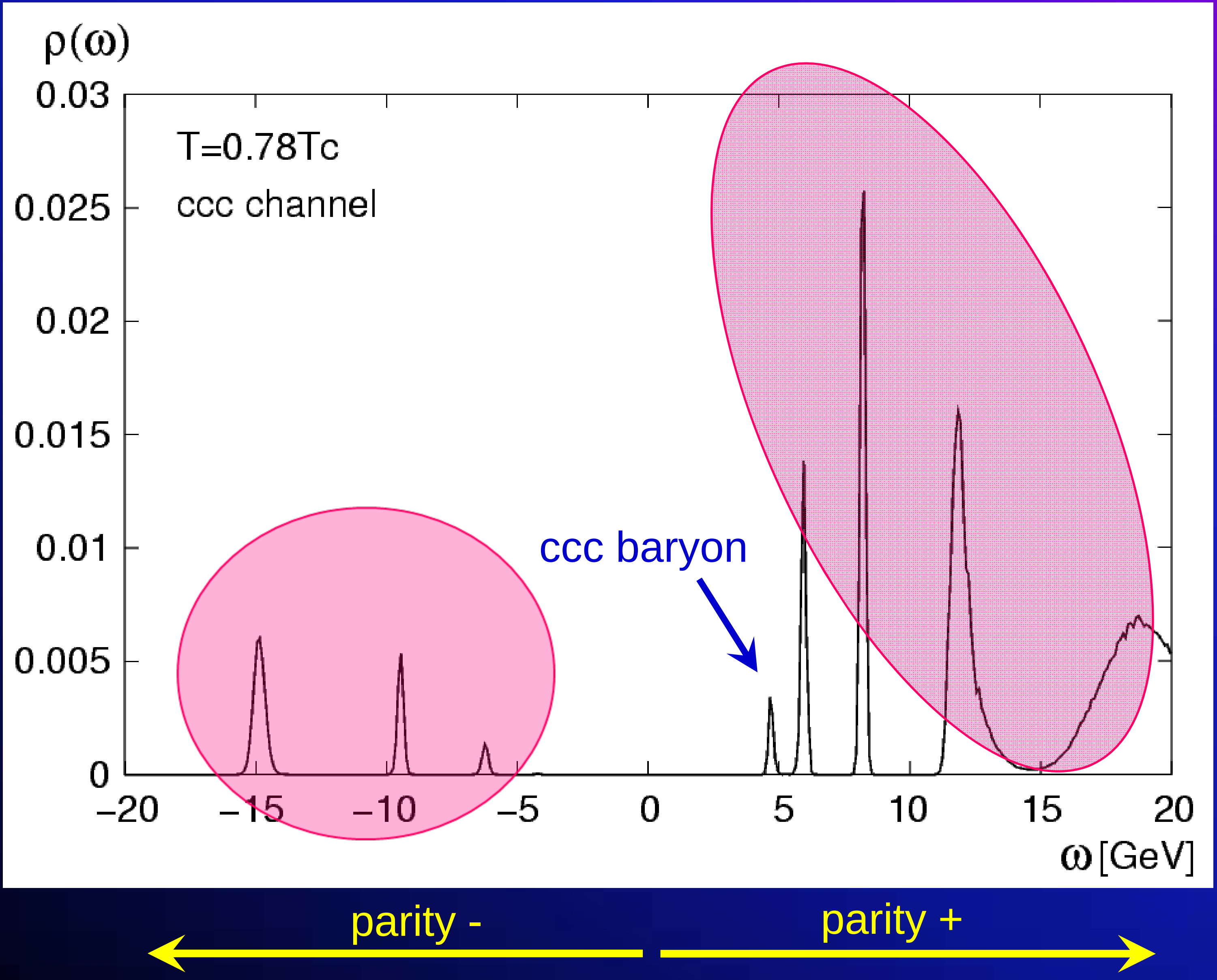
- Put Error Bars and Make Sure Observed Structures are Statistically Significant → Statistical
- Change the Number of Data Points and Make Sure the Result does not Change → Systematic

in any MEM analysis

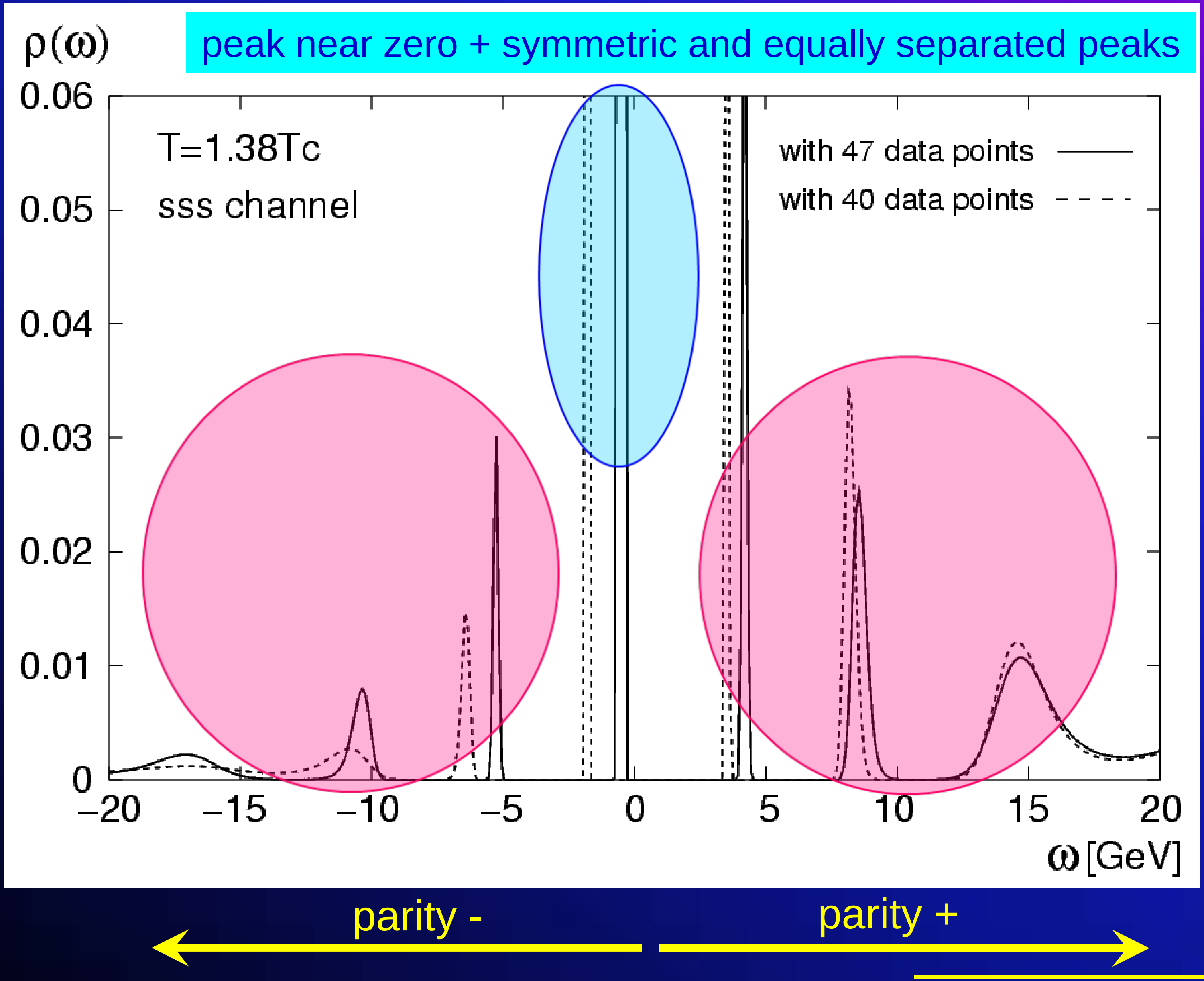
Below T_c: Light Baryon



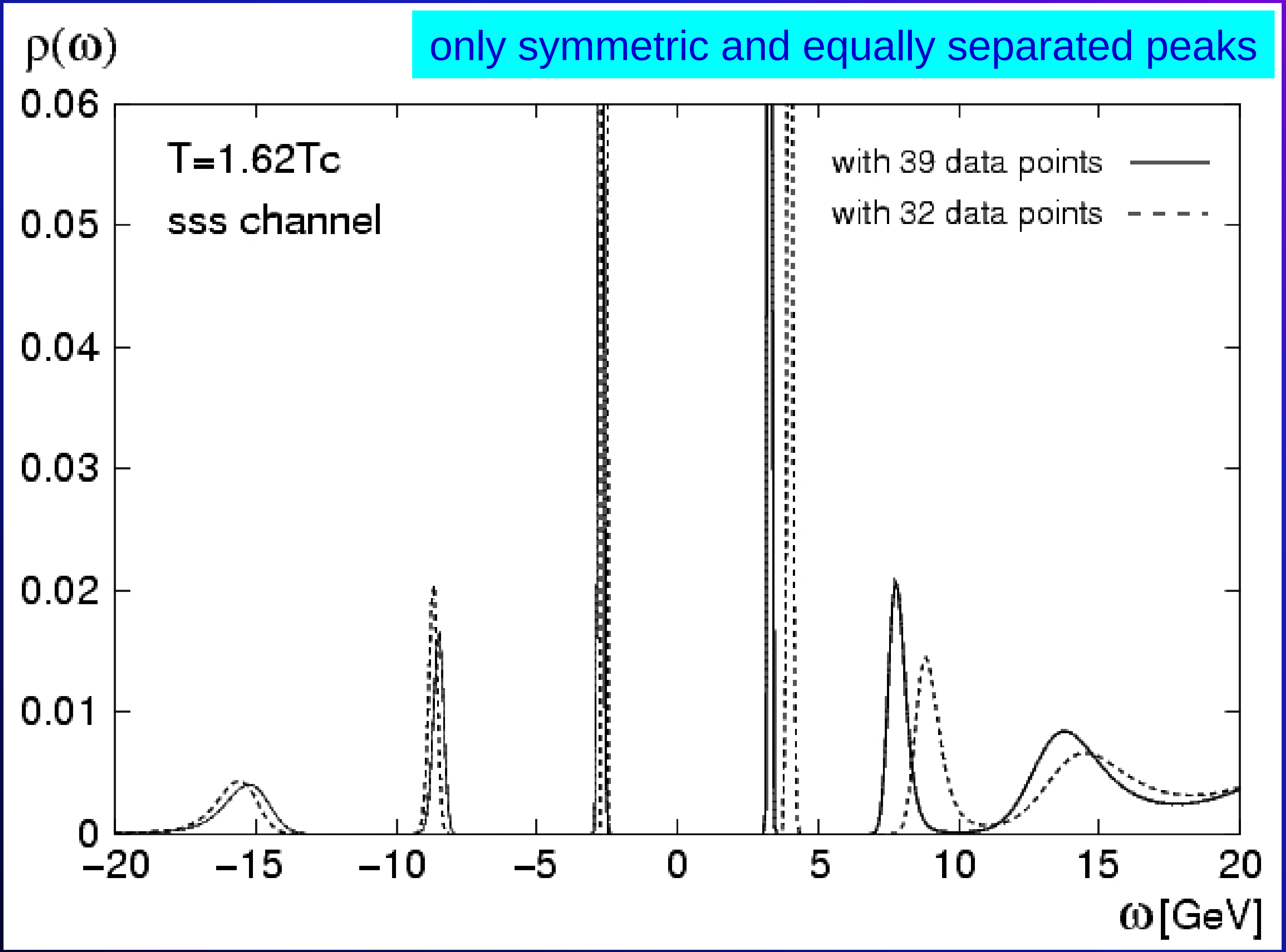
Below T_c: Charm Baryon



Above T_c: Light Baryon



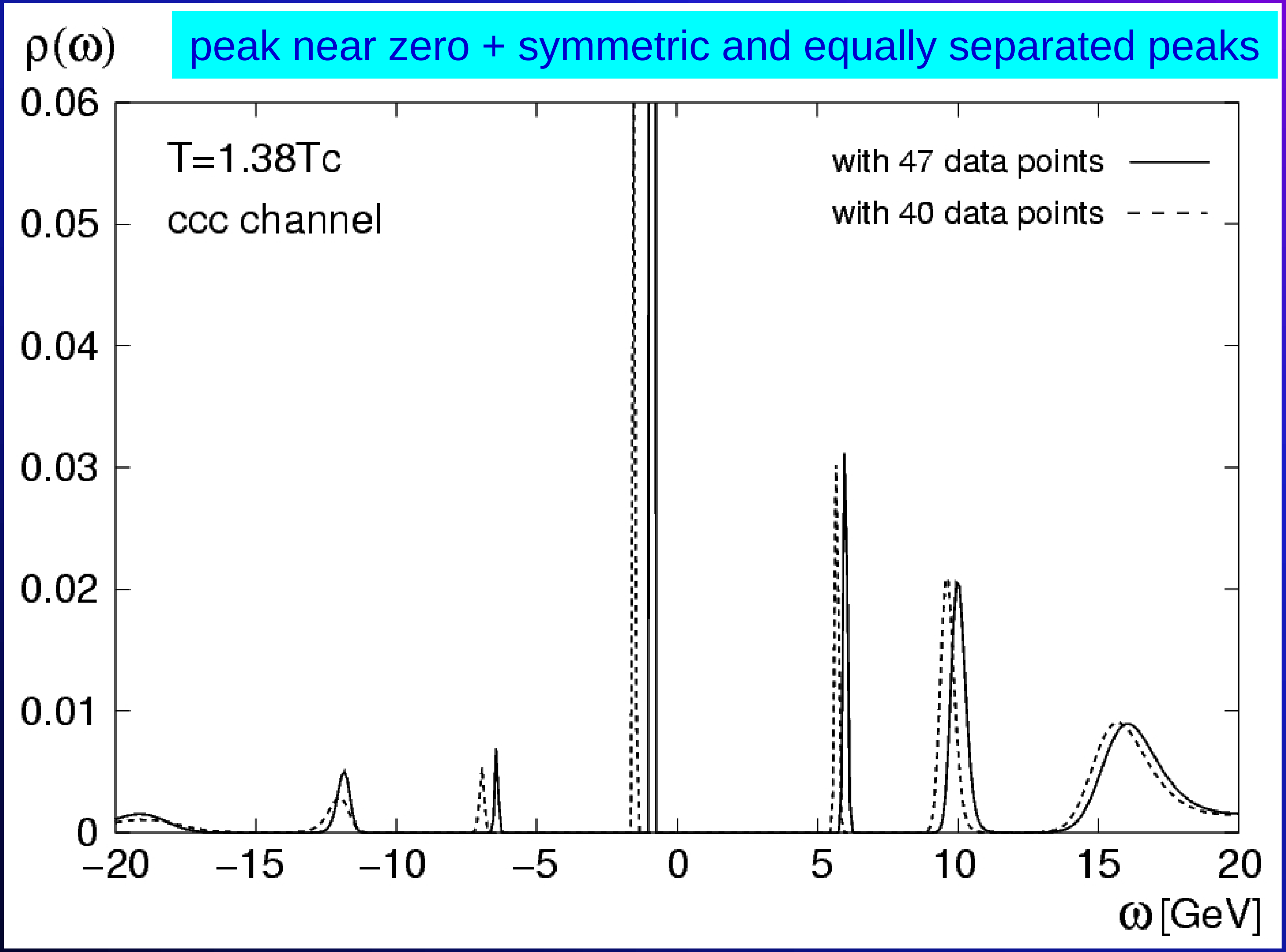
@Higher T



parity -

parity +

Above T_c: Charm Baryon



parity -

parity +

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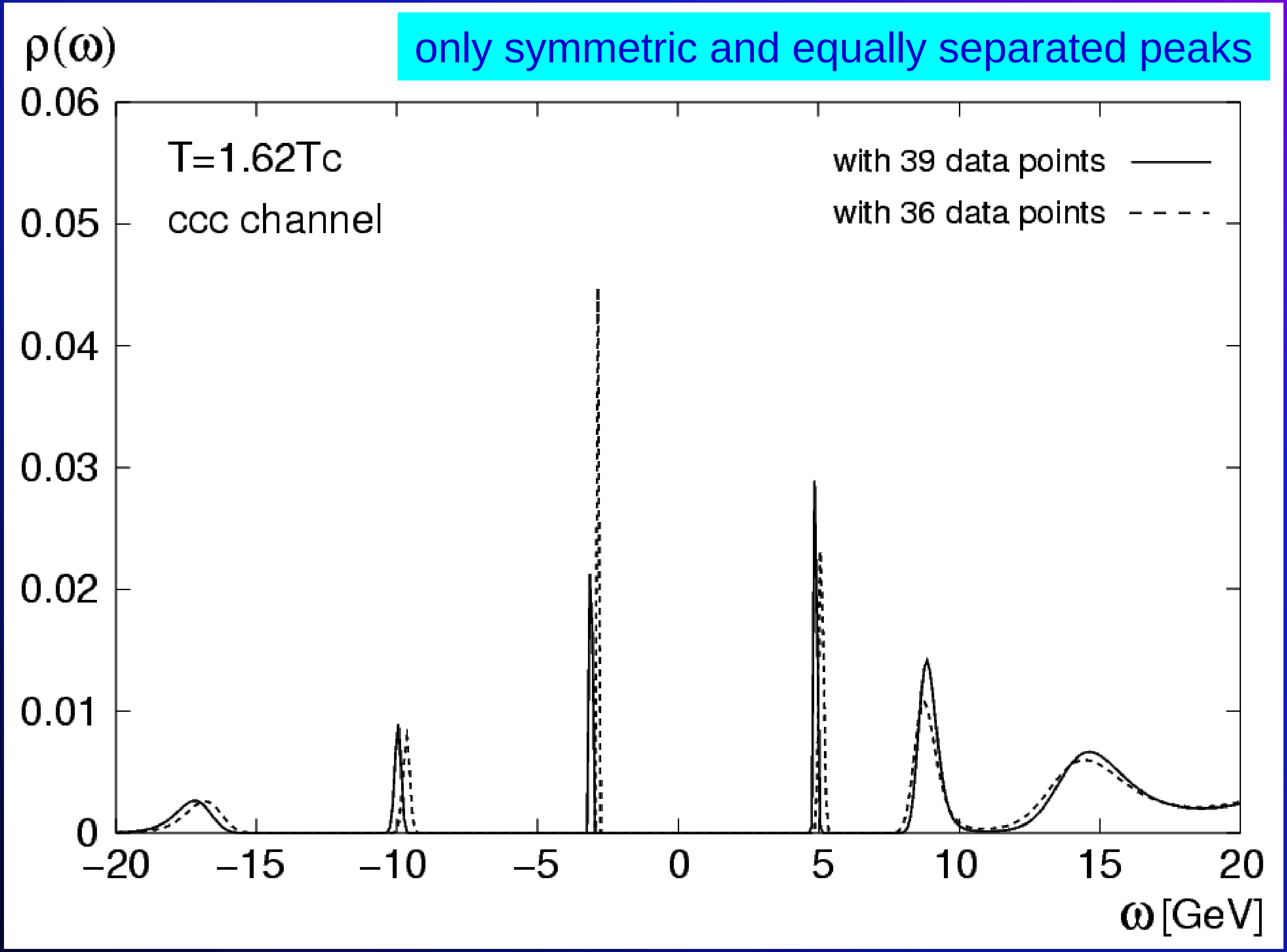
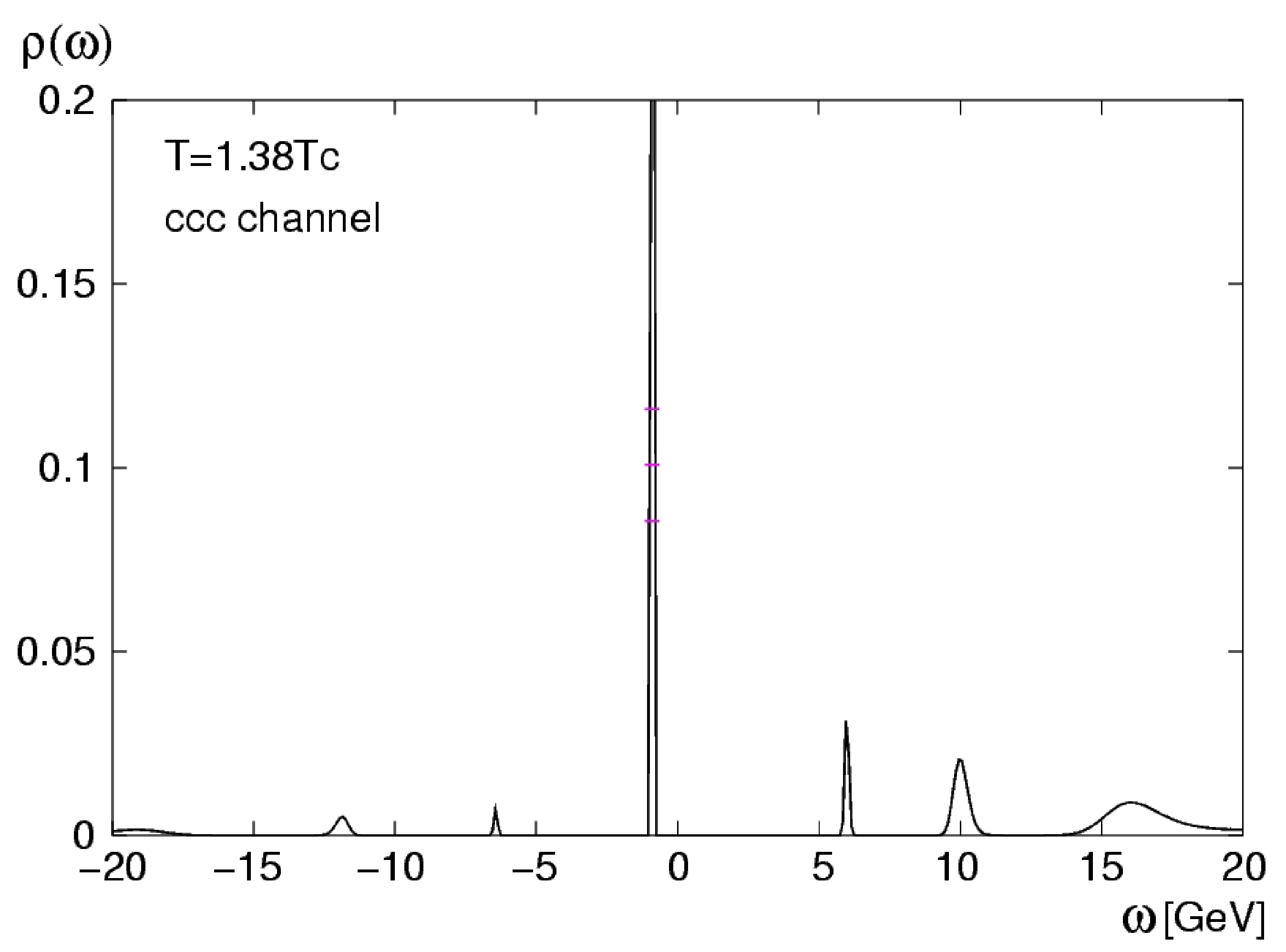
@Higher T



parity -

parity +

Statistical Analysis: Charm Baryon

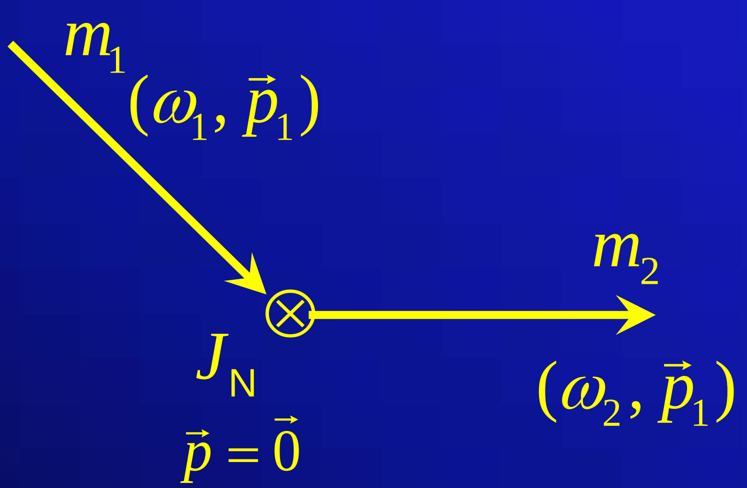


Peak near zero is statistically significant

Origin of Near Zero Structure

Scattering Term

- Scattering term at $\vec{p} = \vec{0}$ a.k.a. Landau damping



- This term is non-vanishing only for

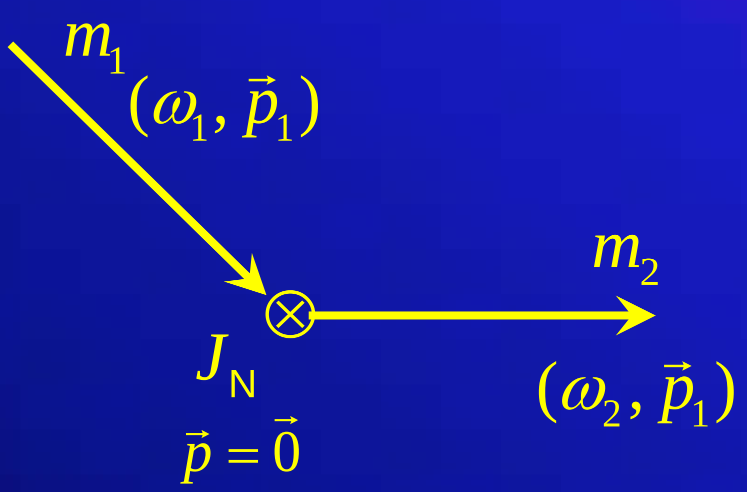
$$0 < |\omega_2 - \omega_1| \leq |m_2 - m_1|$$

- For J/ψ (m_1=m_2), this condition becomes

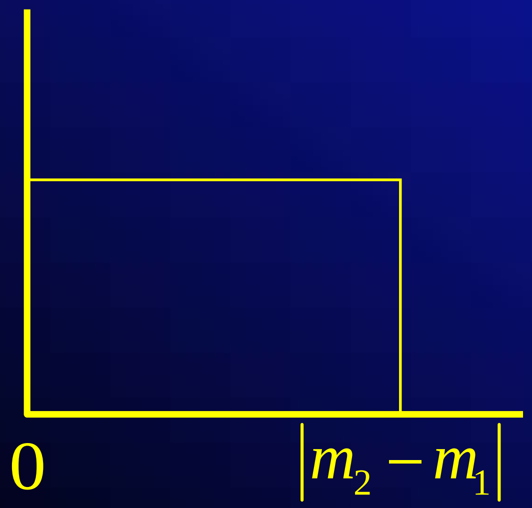
$$0 < |\omega_2 - \omega_1| \leq \varepsilon$$ ⇐ zero mode

cf. QCD SR (Hatsuda and Lee, 1992)

Scattering Term (two body case)

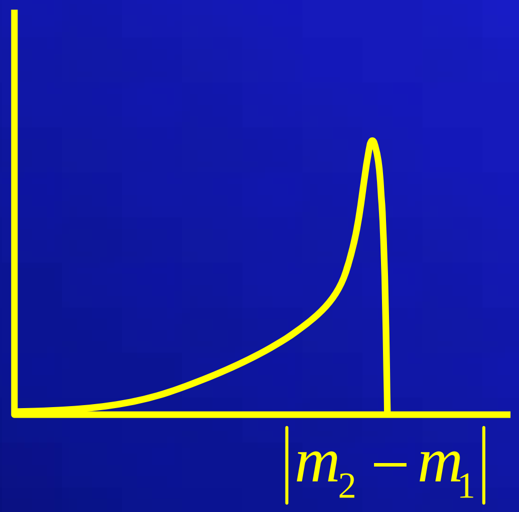


- This term is non-vanishing only for $0 < |\omega_2 - \omega_1| \le |m_2 - m_1|$



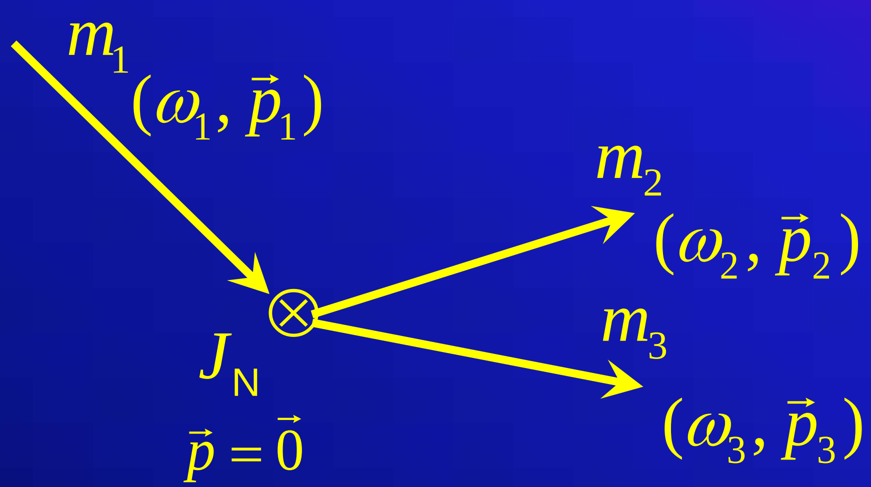
$T \ll m_1, m_2$

$|\vec{p}_1| \sim 0$



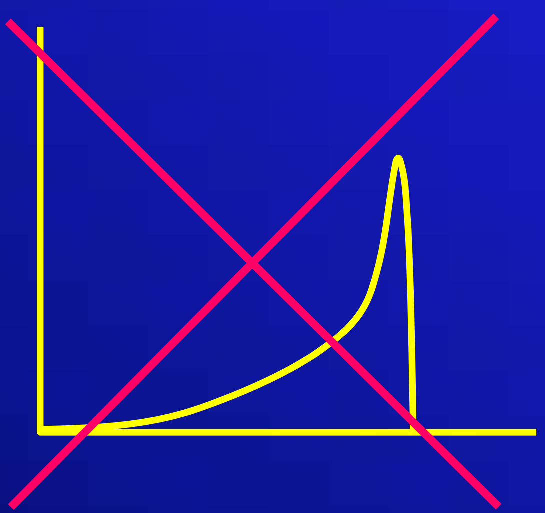
(Boson-Fermion case, e.g. Kitazawa et al., 2008)

Scattering Term (three body case)



$T \ll m_1, m_2, m_3$

$|\vec{p}_1| \sim 0$



Origin of Symmetric Structure

- Wilson Doublers

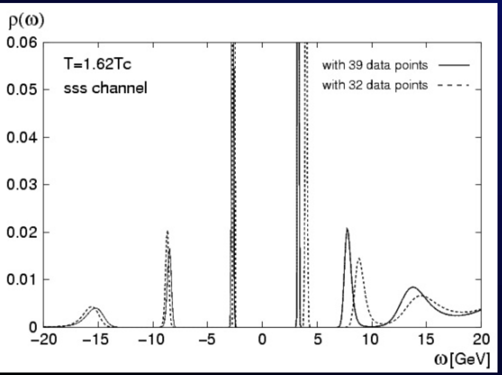
Mass of Wilson Doublers with r = 1 in the continuum limit

$$m + \frac{2n_\pi}{a}$$

n_π: numer of momentum components equal to π (1,2,3)

- If quark mass can be neglected:
  - Masses of Baryons with Doublers
  - Scattering term peaks with quark-doubler, doubler-doubler pairs

⇒ Approximately equally separated and symmetric in ω



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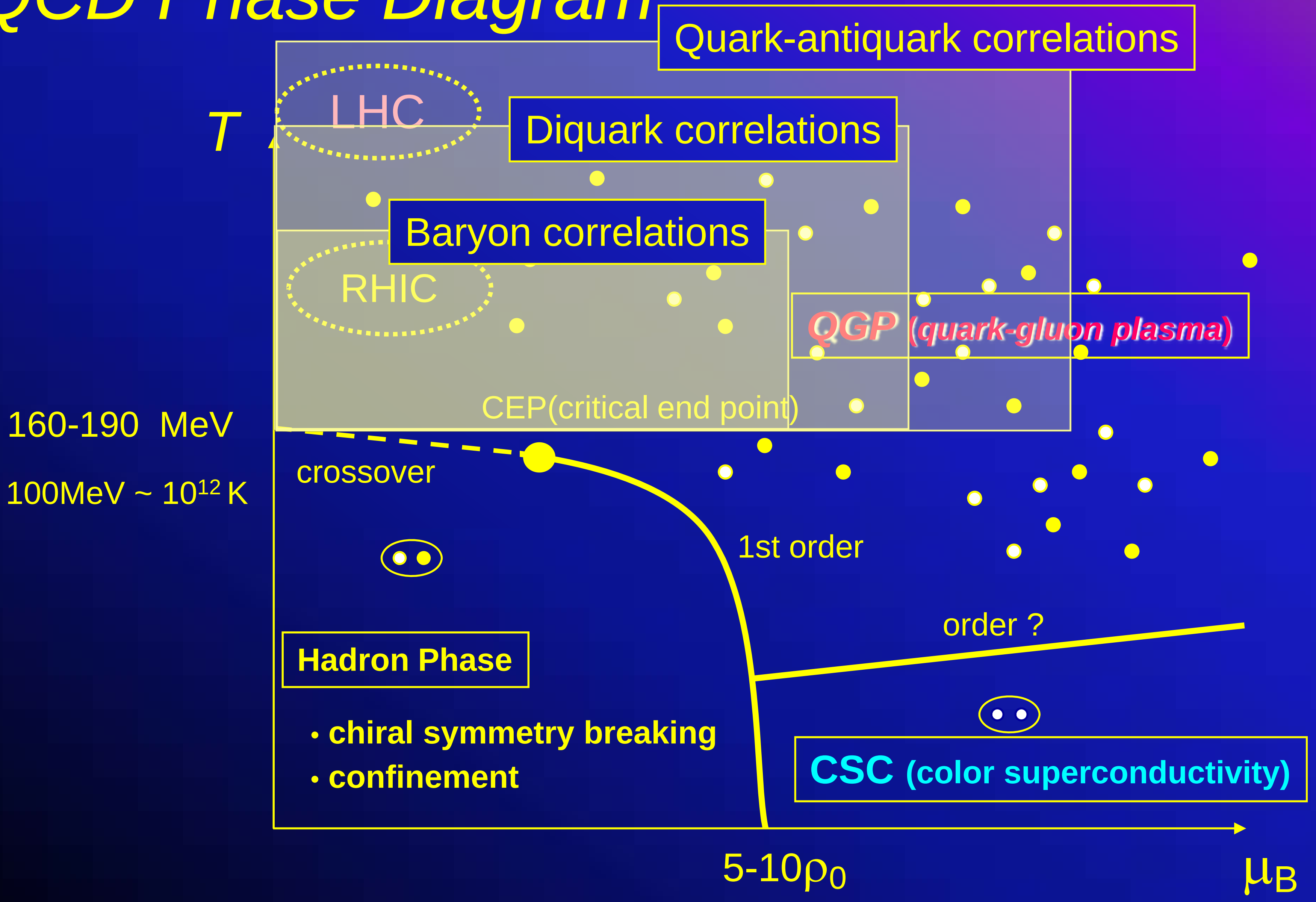
QCD Phase Diagram



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Summary

- Baryons disappear just above T_c

- A sharp peak with negative parity near ω=0 is observed in baryonic SPF above T_c

  This can be due to diquark-quark scattering term and imply the existence of diquark correlation above T_c

- Diquarks disappear below meson disapperance temperature

- Direct measurement of SPF diquark operators with MEM is desired

- To understand doubler contribution, calculation with finer lattice is desired

Microscopic Understanding of QGP

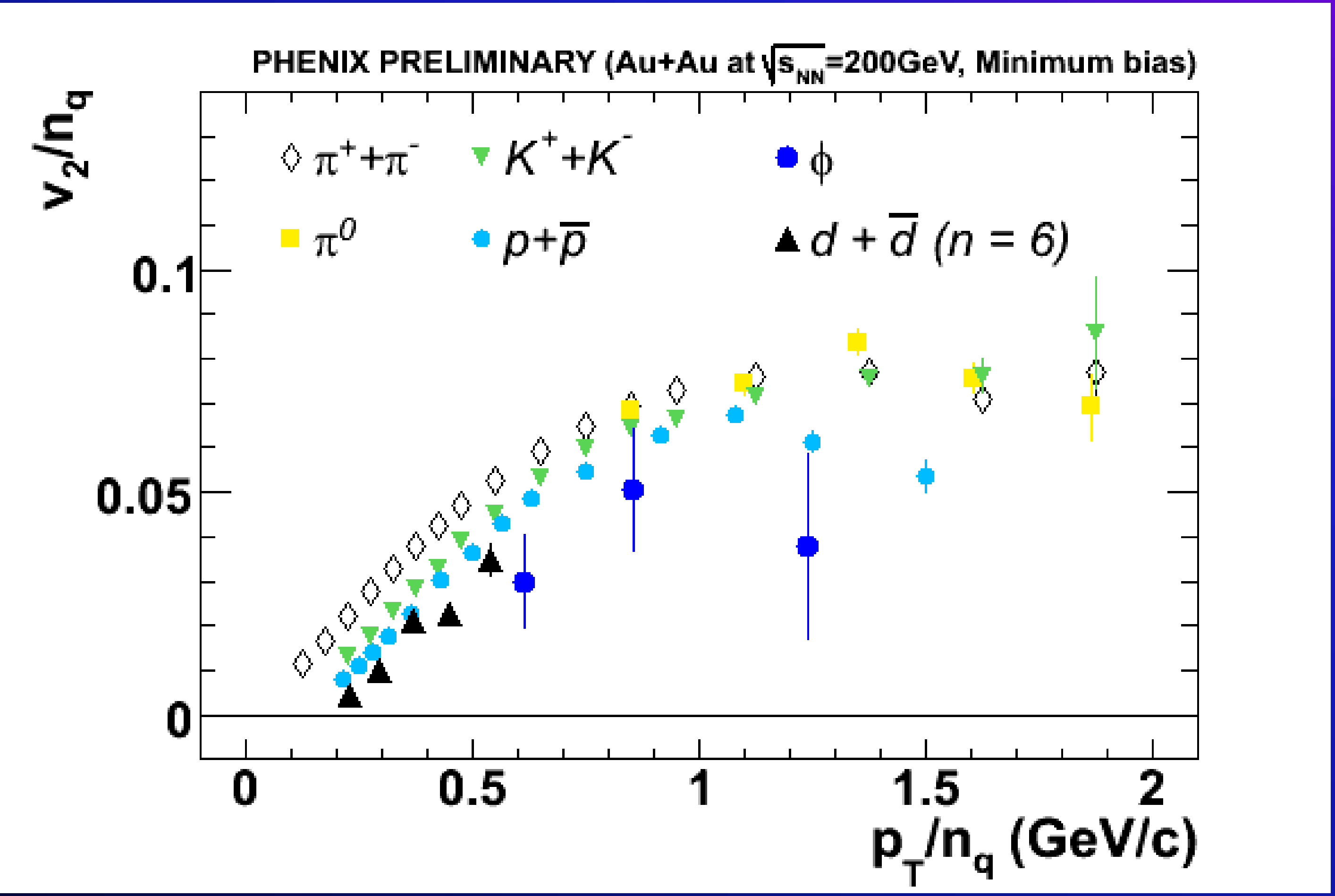
Importance of Microscopic Properties of matter,
in addition to Bulk Properties

- In condensed matter physics, common to start from one particle states, then proceed to two, three, ... particle states (correlations)

Spectral Functions:

- One Quark —— need to fix gauge
- Two Quarks
  - ✓ mesons
    - ✓ color singlet
    - • octet —— need to fix gauge
  - ➢ diquarks —— need to fix gauge
- Three Quarks
  - ✓ baryons
- ......

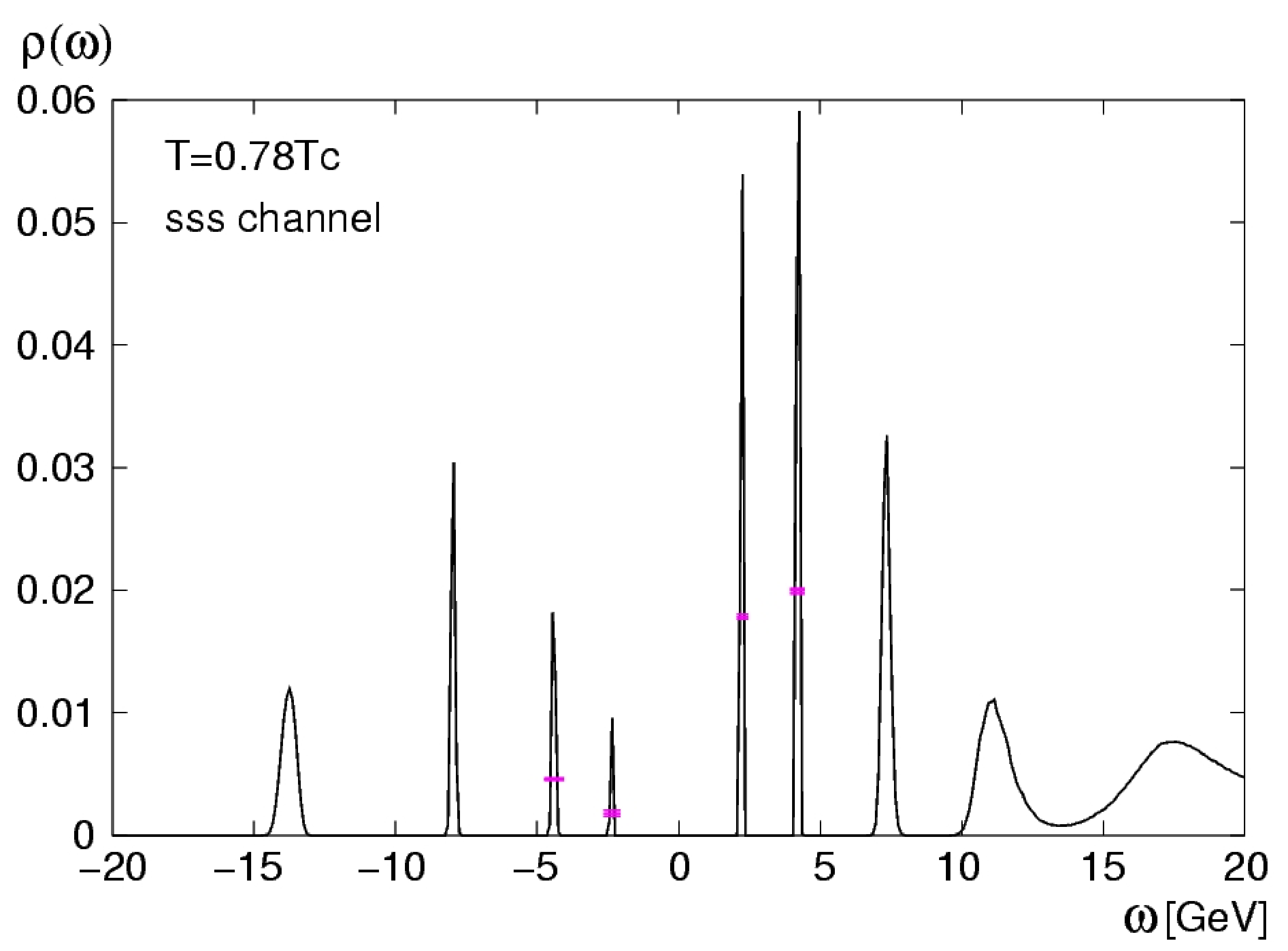
Meson-Baryon Universality



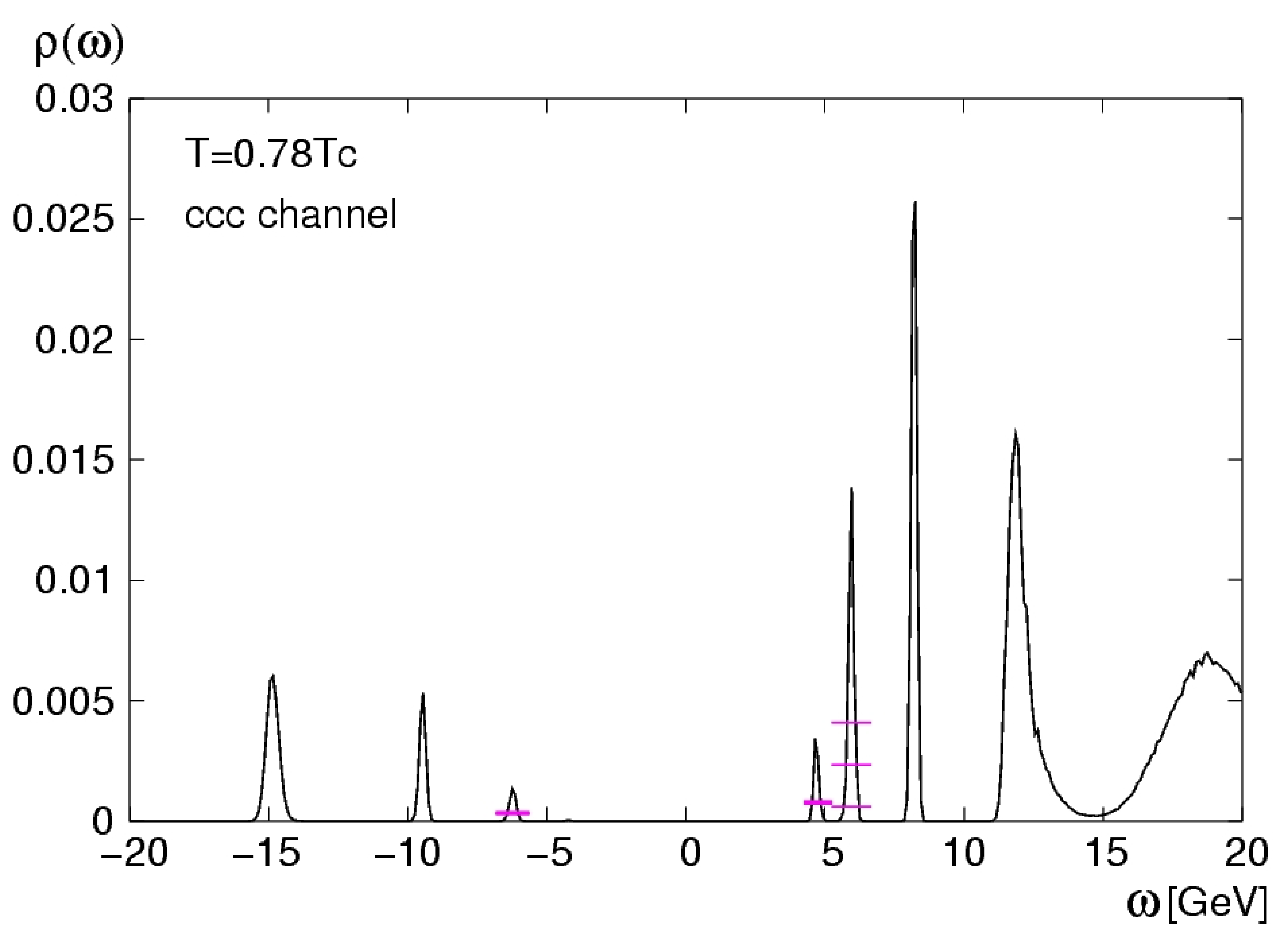
Partons are flowing and Partons recombine to make mesons and baryons

Evidence of Deconfinement !

Statistical Analysis below T_c

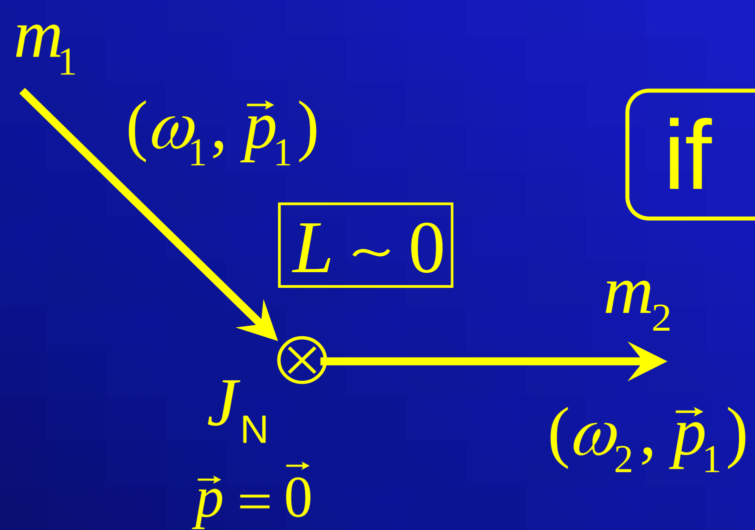


Statistical Analysis below T_c



Negative parity: a possible interpretation

anti-quark: parity -



if 0^+

then: parity $-$

$T \ll m_1, m_2$
$|\vec{p}_1| \sim 0$