Properties of Open and Hidden Charm Mesons in Pionic Matter

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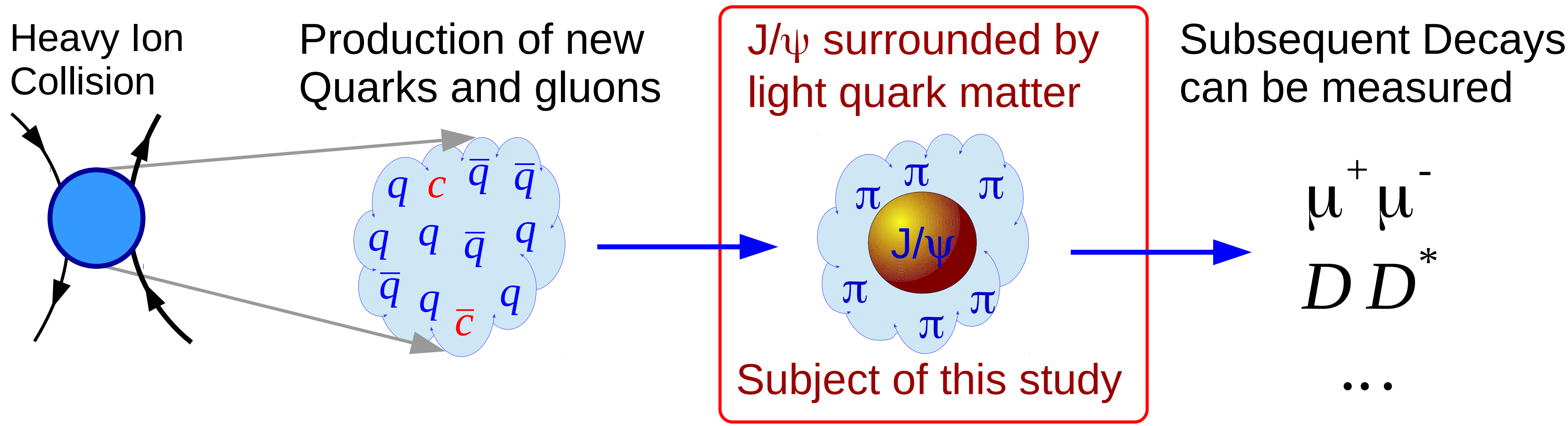
Motivation

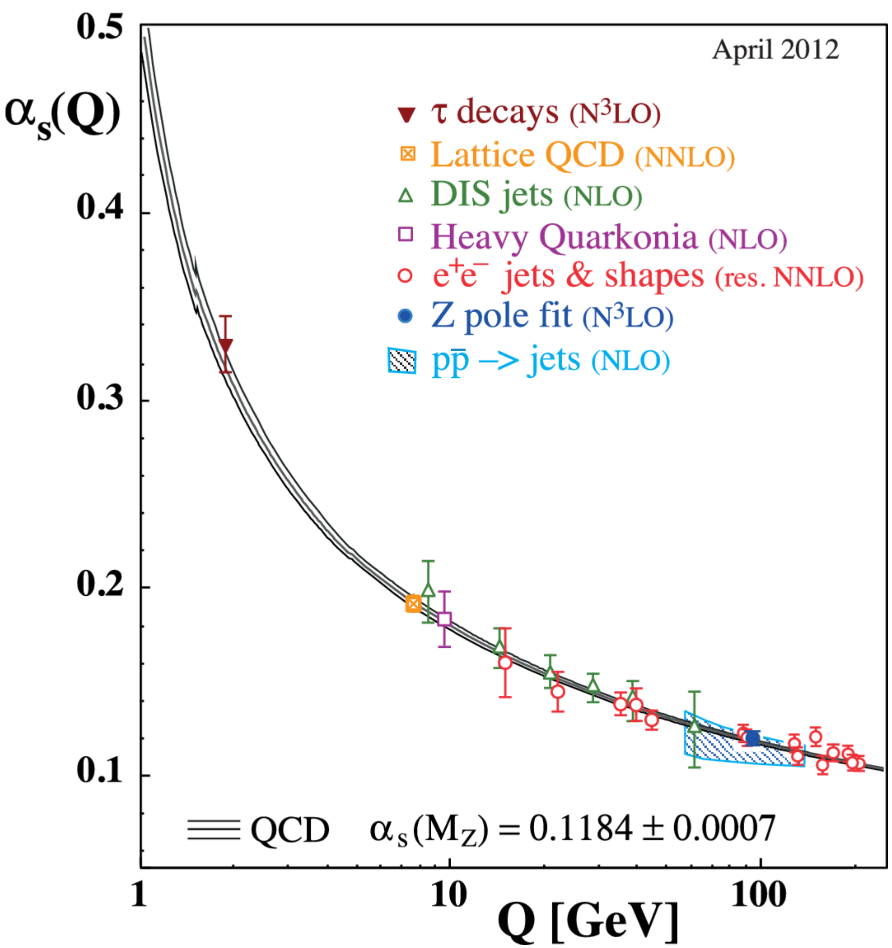


- Previous Studies include
  - Chiral Lagrangians
    Haglin and C. Gale, PRC 63; Blaschke et al., PPNL 9 (2012) 7;...
  - Quark model Calculations
    Zhou and Xu, PRC 85; Maiani et al., NP A 741 (2004) 273,NP A 748 (2005) 209;...
- Here: at the same time
  - Effective Field Theory
  - Unitarized coupled channel approach
  - Many-body techniques
- SU(4) Chiral Lagrangian
  - Effective Lagrangian
  - Unitarized Amplitudes
- Finite Temperatures
  - Imaginary Time Formalism
  - Study spectral function
- Outlook:
  - Other channels, more observables...

Outline

- Motivation
- Framework
  - SU(4) Chiral Lagrangian
  - Lippmann-Schwinger Equation for coupled channels
- In Medium
  - Temperature dependence through Imaginary Time Formalism
  - Self-consistent approach including Pion-Induced Self-Energy
- Results
  - Pion-Induced Width
  - Spectral Functions
- Outlook

Quantum Chromodynamics (QCD)



- High Energies:

  Asymptotic Freedom, perturbation theory
- Low Energies:

  Nonperturbative QCD, Quark Models,

  Lattice, Effective Field Theories

Effective Field Theory (EFT)

- No quarks and gluons
- Mesons as effective d.o.f.:

  $D, J/\psi, \pi, \ldots$

Confinement:

Only color-neutral objects observed

Classic Examples $\longrightarrow$

- Mesons: $q\bar{q}$
- Baryons: qqq

SU(4) Chiral Model

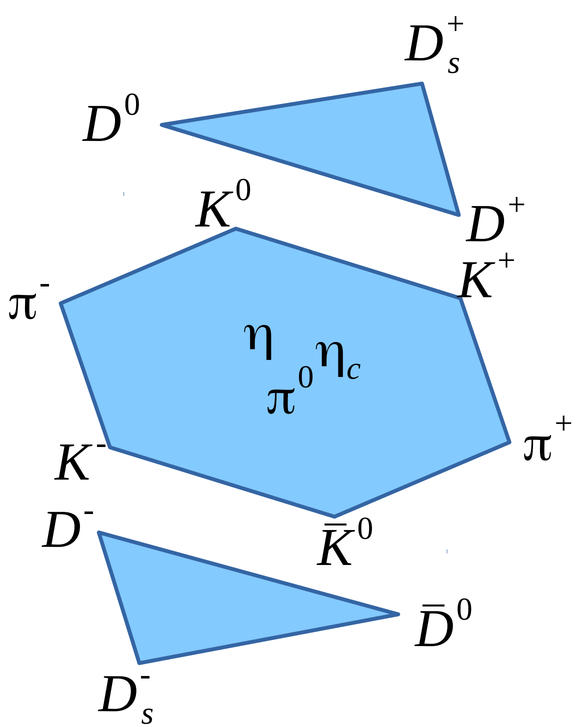
Chiral Perturbation Theory

Weinberg; Gasser & Leutwyler, ...

- Additional $SU(2)_L$ x $SU(2)_R$ symmetry in QCD for massless u/d quarks
- Symmetry spontaneously broken: Pions as Goldstone Bosons

$$L_\pi = \frac{1}{12 F_\pi^2} < [(\partial_\mu \Phi), \Phi][(\partial^\mu \Phi), \Phi] > + \ldots$$

$$\Phi = \begin{pmatrix} \pi^0/\sqrt{2} & \pi^+ \\ \pi^- & -\pi^0/\sqrt{2} \end{pmatrix}$$

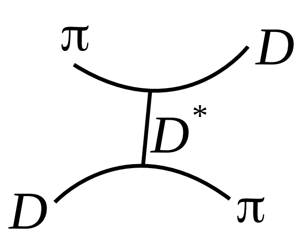


Extension to SU(4)

Gamermann et al., Phys.Rev. D76 (2007) 074016

- Include open/hidden charm and strangeness: K, η, D, η_c
- Suppression Factors:

Leading t-exchange



Suppression Factor for $D\pi \rightarrow D\pi$ is $\gamma = (m_\rho / m_{D^*})^2$

Pseudoscalar-Vector Scattering

Gamermann, Oset, Eur.Phys.J. A33 (2007) 119-131

Extend Framework further to accommodate Vector Mesons:

$$\mathcal{L} = -\frac{1}{4F_\pi^2}\langle J^\mu \mathcal{J}_\mu \rangle \qquad J_\mu = (\partial_\mu \Phi)\Phi - \Phi(\partial_\mu \Phi) \qquad \Phi = \Phi(\pi, \eta, K, D, \eta_c)$$

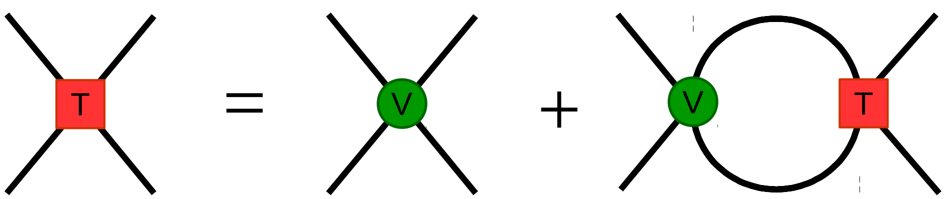
$$\mathcal{J}_\mu = (\partial_\mu \mathcal{V}_\nu)\mathcal{V}^\nu - \mathcal{V}_\nu(\partial_\mu \mathcal{V}^\nu) \qquad \mathcal{V} = \mathcal{V}(\rho, \omega, K^*, D^*, J/\psi)$$

Weinberg-Tomozawa
Type Interactions

$$V \sim \frac{s-u}{4F_\pi^2} \sim p^2$$

Violates Optical Theorem:

$$\mathrm{Im}\, T = |T|^2$$



Solution: Solve
Lippmann Schwinger Equation

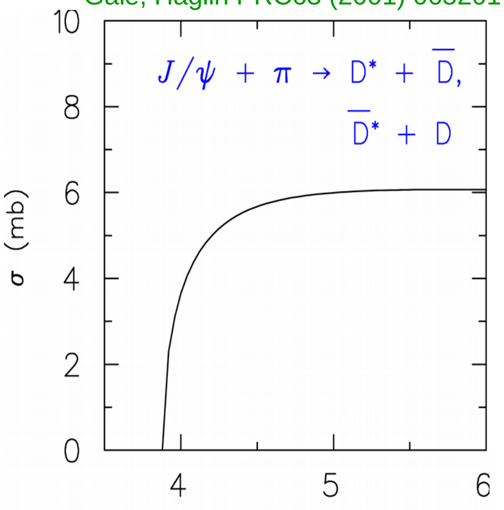
$T = V[1 - GV]^{-1}$ is unitary!

- Loop regularized in dim. regularization
- Allows for dynamical generation of states: X(3872) in DD*, D_{s0}(2317) in DK,…
- Extension of energy range

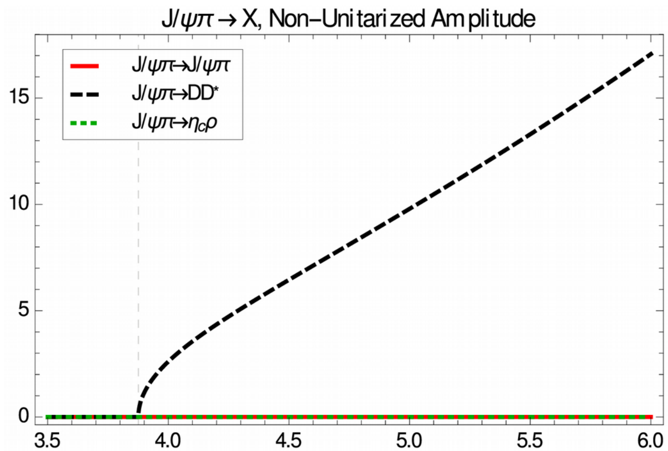
Cross Section J/ψπ → X

Three channels with $I^G(J^{PC}) = 1^+(1^{+-})$: J/ψπ, $\eta_c\rho$ and DD*

Gale, Haglin PRC63 (2001) 065201



Cleven, Magas, Ramos - Preliminary



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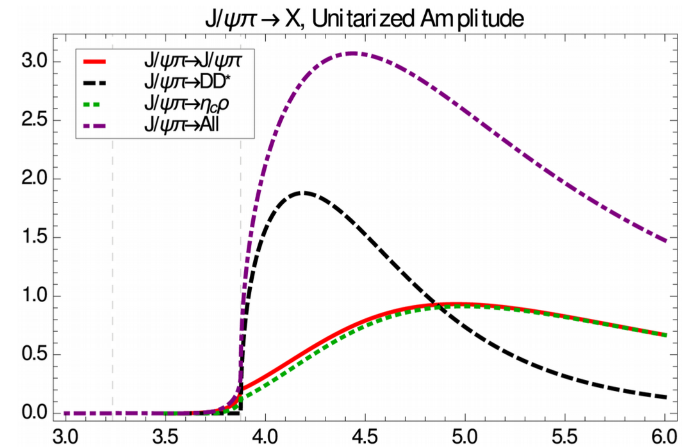
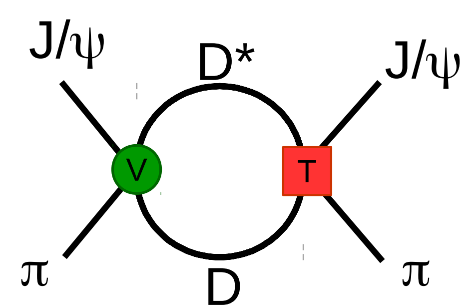


- No LO contact interaction J/ψπ → J/ψπ
- Unitarized amplitude has contributions through coupled channels



Clearly, a new analysis using these techniques is called for

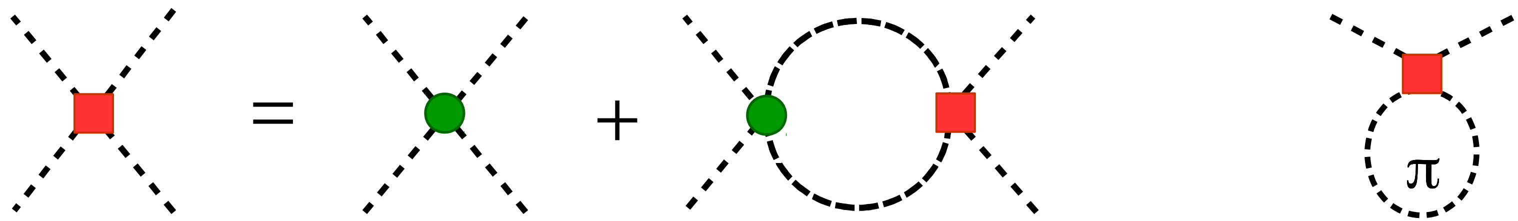
Modifications from Temperature and Medium

- Imaginary Time Formalism: $q^0 \rightarrow i\omega_n = i2\pi nT$, $\quad \int \frac{d^4q}{(2\pi)^4} \rightarrow iT\sum_i \int \frac{d^3q}{(2\pi)^3}$

  T>0 MeV breaks Lorentz Symmetry → treat p^0 and $\vec{p}$ separately

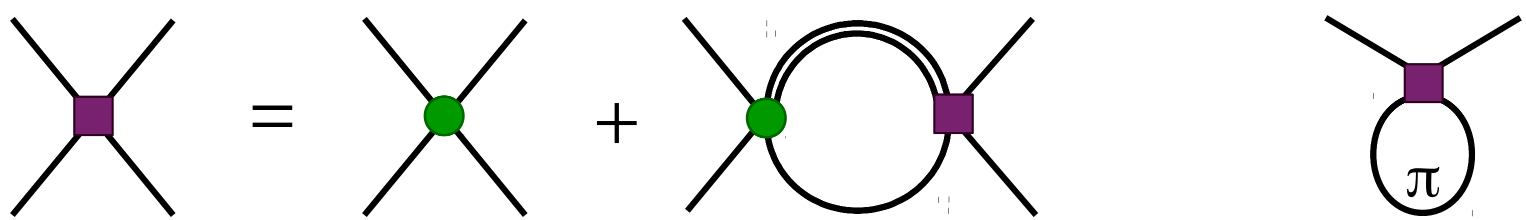
- Self Consistent Incorporation of Self Energy

Free Space



T = V + V G T $\qquad \Sigma(q^0, \vec{q})$

Medium



T(T) = V + V G(T) T(T) $\qquad \Sigma(\omega_n, \vec{q}, T)$

$= [q^2 - m^2]^{-1}$ $\qquad = [(i\omega_n) - \vec{q}^2 - m^2]^{-1}$ $\qquad = [(i\omega_n) - \vec{q}^2 - m^2 + \Sigma(\omega_n, \vec{q}, T)]^{-1}$

Loops as a Function of Temperature

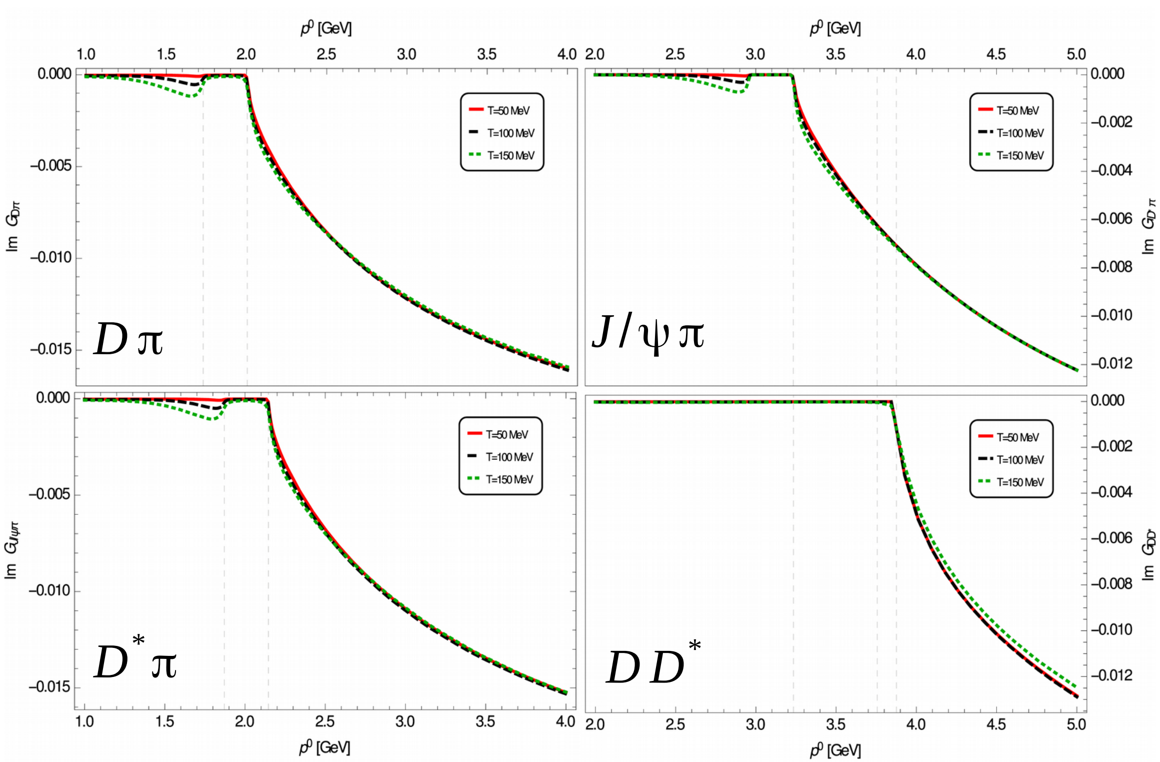
Temperature-dependence enters through loops (Here: Vacuum Case)

$$\int \frac{d^3 q}{(2\pi)^3}\left[\frac{-\omega_1-\omega_2}{2\omega_1\omega_2}\frac{1+f(\omega_1,T)+f(\omega_2,T)}{E^2-(\omega_1+\omega_2)^2+i\epsilon}+\frac{\omega_1-\omega_2}{2\omega_1\omega_2}\frac{f(\omega_1,T)-f(\omega_2,T)}{E^2-(\omega_1-\omega_2)^2+i\epsilon}\right]$$

$$f(\omega,T)=\frac{1}{1-\exp(\omega/T)}$$

$$w_1=\sqrt{m_1^2+q^2},\quad w_2=\sqrt{m_2^2+(\vec{q}+\vec{p})^2}$$

Imaginary Part of the Two-Body Loop (at rest)



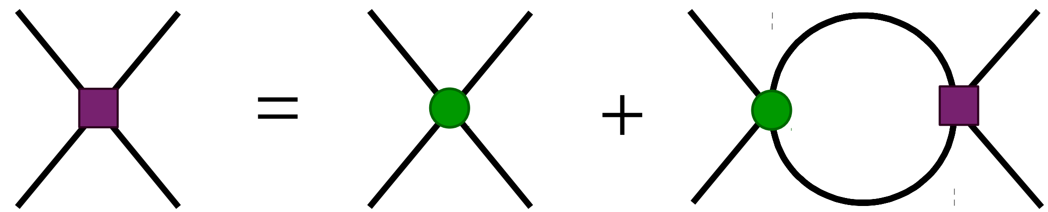
Cleven, Magas, Ramos - Preliminary

- First Term:
  - Right-Hand Cut from m_1+m_2
  - Dominated by Vacuum Contr.
- Second Term:
  - Left-Hand Cut from $|m_1-m_2|$
  - Vanishes for $T\rightarrow 0$ or $m_1 = m_2$
- Largest effect for channels w/ π

T-Matrix as a Function of Temperature

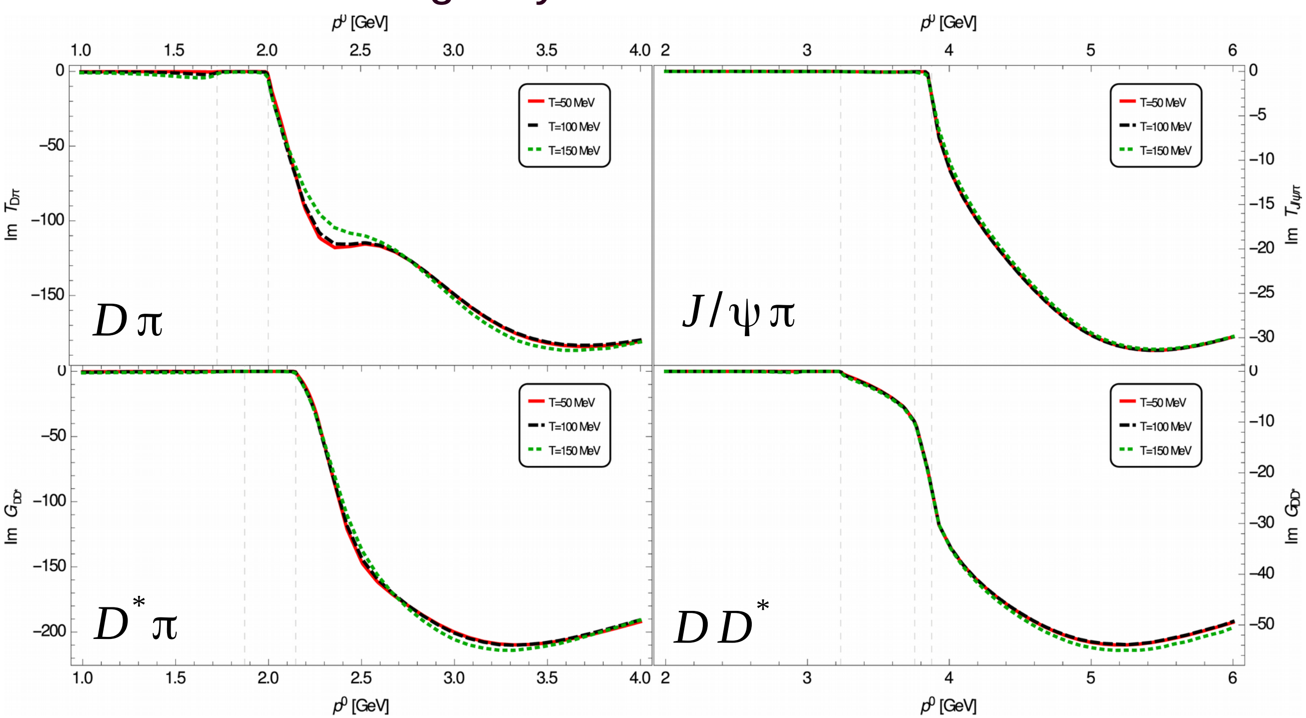
- Use On-Shell Formalism:

  $T = V(1-GV)^{-1}$
- Coupled Channel Calculation
- Temperature enters through loops



$T(T) \;=\; V \;+\; V\; G(T)\; T(T)$

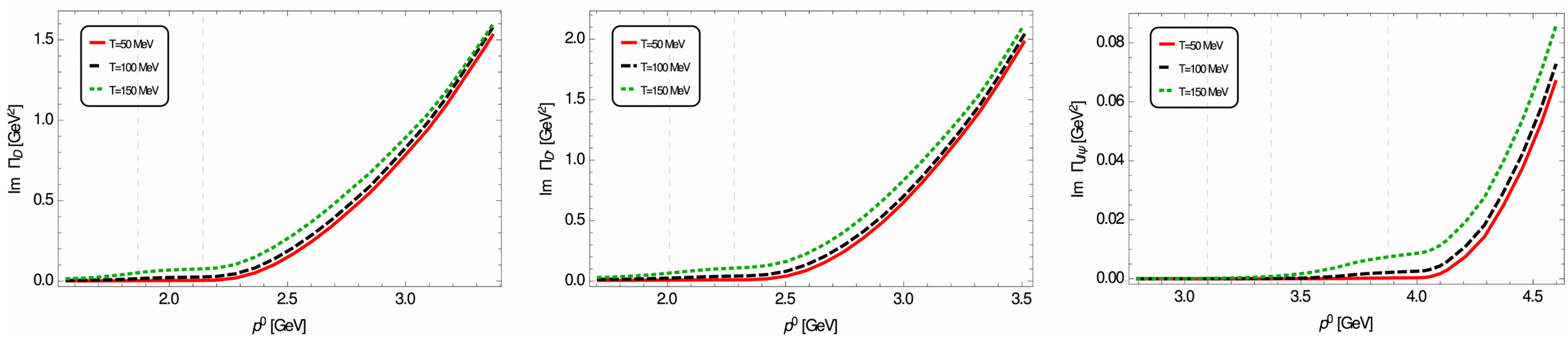
Imaginary Part of the T-Matrix

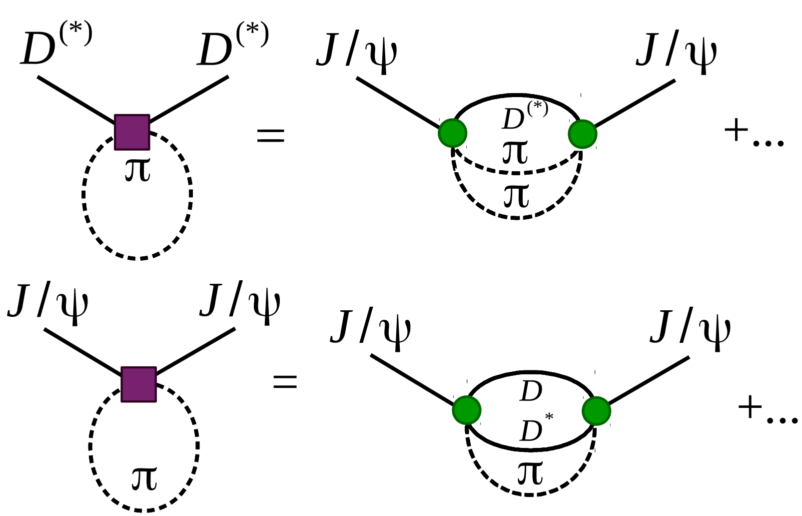


- Open Charm:
  - I=1/2: $D^{(*)}\pi$, $D^{(*)}\eta$ I=3/2: $D^{(*)}\pi$
  - $T = T_{1/2} + 2T_{3/2}$
  - $D^{(*)}\eta$ negligible
- Hidden Charm (I=1, $J^{PC}=1^{+-}$):
  - $J/\psi\pi$, $D^*\bar{D}$+c.c, $\eta_c\rho$
  - $\eta_c\rho$ has little to no effect
  - $V(J/\psi\pi \rightarrow J/\psi\pi)$ vanishes

Pion induced self-energy

$$\Pi(p^0,\vec{p};T)=\int\frac{d^3q}{(2\pi)^3}\int d\omega\left[\frac{f(\Omega,T)-f(\omega_q)}{p^0+\omega_q-\Omega+iE}+\frac{1+f(\Omega,T)+f(\omega_q)}{p^0-\omega_q-\Omega+iE}\right](-1/\pi)\frac{\mathrm{Im}\,T(\Omega,\vec{p}+\vec{q};T)}{2\omega_q}$$





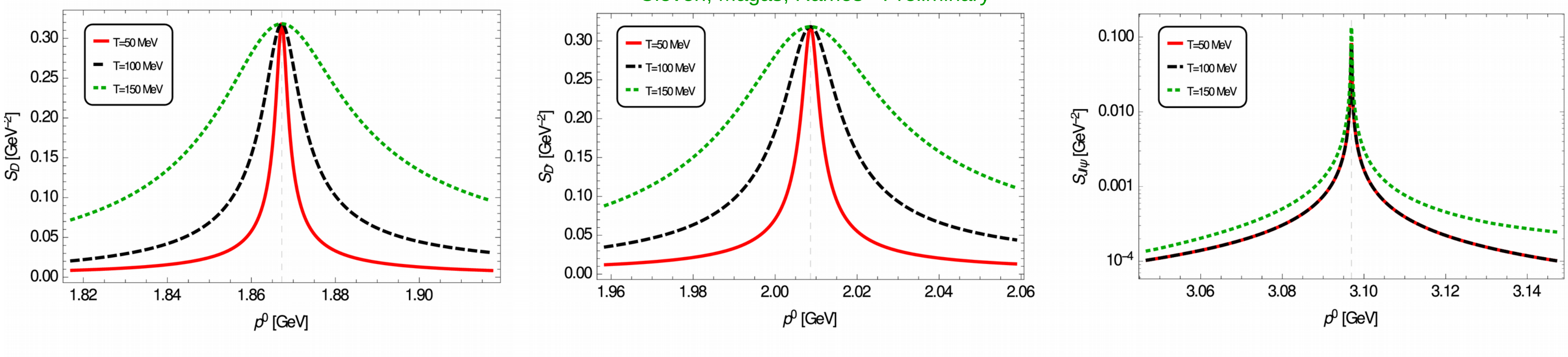
- Integral for the imaginary part is finite!
- One order of magnitude between the open and hidden charm mesons for high energies
- Larger impact between $[M-m_\pi, M+2m_\pi]$ for $D^{(*)}$ ($J/\psi\pi$ dominated by DD^* loop)

Spectral Function

$$S = -\frac{1}{\pi} \operatorname{Im} \frac{1}{(p^0)^2 - \vec{p}^2 - m^2 - \Pi - i m \Gamma_0}$$

- Γ_0 – Vacuum Width
- Π(p,T) – Self-Energy from Pion Bath

Cleven, Magas, Ramos - Preliminary

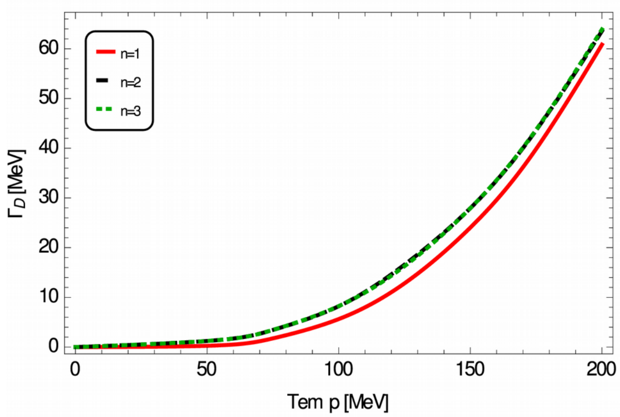


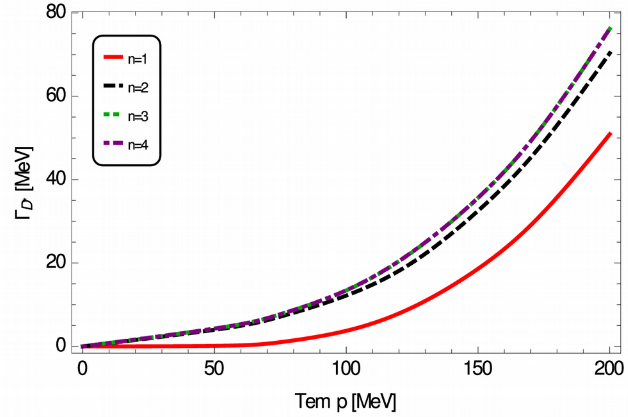
- Charmed Mesons
  - Sizable Effect (Linear Plot)
  - Width from pionic bath exceeds vacuum width Γ_{D^*}=83 keV
- J/ψ
  - Log. Plot
  - For T = 50 Mev and 100 MeV Γ=93 keV dominates

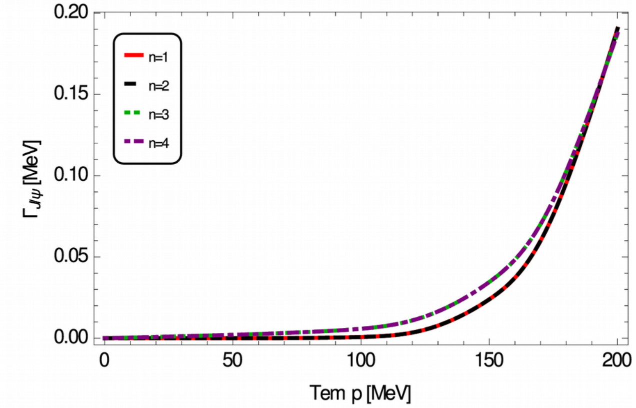
Spectal Functions can be used for Simulations!

Pion induced Width

Width from Pion-Induced Self-Energy $\Gamma_\pi(T) = \mathrm{Im}\,\Pi(M, \vec{p}=0; T)$







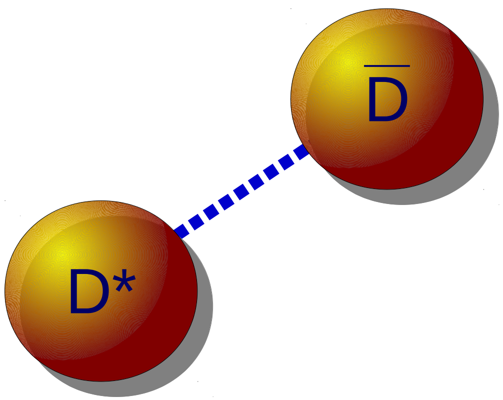
Charmed Mesons:

- Self-Consistency after 3-4 Iterations
- Slightly broader D* spectral function affects Width
- Width in the single MeV regime up to T=100 MeV, rises up to 80 MeV for T=200 MeV

J/ψ:

- Iterations 1-2: Dressed J/ψ
  Iterations 3-4: Dressed $D^{(*)}$
- Dressing the charmed mesons has large effect
- Width 1-2 Order of Magnitude smaller than for Charmed Mesons

Outlook: Exotica/Hadronic Molecules



- In $I^G(J^{PC}) = 1^+(1^{+-})$: $Z_c(3900)$
  - Seen in $Y(4260) \to Z_c(3900)\pi \to J/\psi\,\pi\pi,\ h_c\pi\pi$
  - Charmonium Exotic, couples strongly to DD*
  - Not incorporated in current Framework

- Other Exotica: X(3872) in DD*, $D_{s0}(2317)$ in DK, $D_{s1}(2460)$ in D*K
- As Hadronic Molecules dynamically generated in interactions of their constituents
- How do these behave in a hot pion bath?
- Can this behaviour help us to understand their nature?

Summary

- Unitarized SU(4) Meson-Meson Scattering
- In Medium
  - Temperature dependence through imaginary time formalism
  - Self-consistent approach including Pion-Induced Self-Energy
- Observables Pion-Induced Width, Spectral Function
- Outlook
  - Framework applicable to Open/Hidden Charm Exotica
    in molecular interpretation

Thank you!