The chiral anomaly and the eta-prime in vacuum and at low temperatures

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- neglecting quark masses smaller than Λ_{QCD}

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  ⇝ would lead to 9th Goldstone boson
  (flavor singlet with quantum numbers of η, η')

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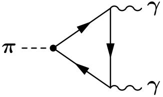
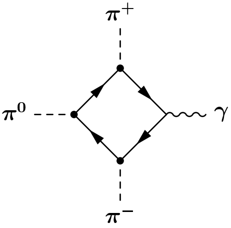
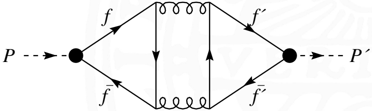
$\hookrightarrow$ experimental fact: nature seems to prefer Lorentz invariance

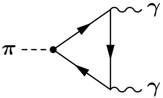
$\hookrightarrow$ consequences ...







Consequences of $U_A(1)$ anomaly in vacuum



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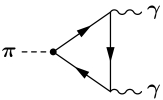

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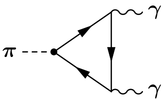

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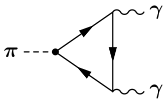

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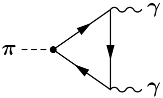

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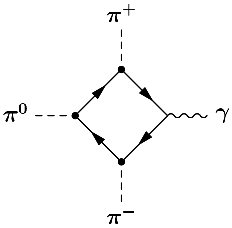
in power counting of chiral perturbation theory:

- anomaly $\sim O(q^4)$
- otherwise $\sim O(q^6)$
  with generic momentum $q \sim m_\pi$

Consequences of $U_A(1)$ anomaly in vacuum II



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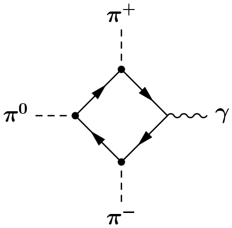

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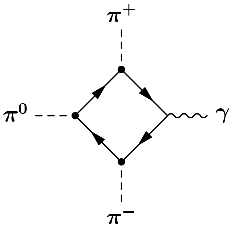

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$\hookrightarrow$ predictive power for reactions $e^+e^- \to 3\pi$ and/or $\gamma + \pi \to 2\pi$ close to threshold? $\rightsquigarrow$ spare slides

Consequences of $U_A(1)$ anomaly in vacuum III

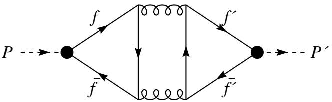

figure from Klabucar/Kekez/Scadron, hep-ph/0012267

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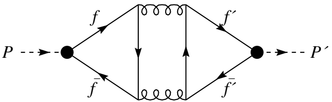

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$$m_{\eta_1}^2 = \frac{2N_f\tau}{f_\pi^2} \sim \frac{1}{N_c}$$

with topological susceptibility $\tau = -i\int d^4x\,\langle 0|\omega(x)\,\omega(0)|0\rangle$
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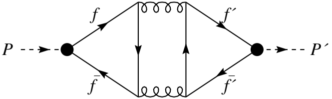

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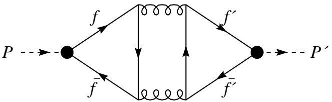

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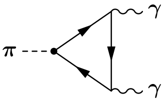
↪ starting point of large-N_c chiral perturbation theory (χPT)
(Kaiser/Leutwyler, EPJ C 17, 623 (2000))

What changes in a medium?

- π-γ-γ coupling in vacuum $\sim 1/f_\pi$



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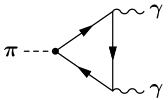

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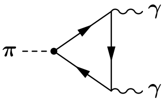

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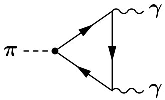

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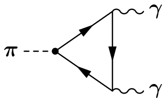
$\hookrightarrow$ but maybe at finite density
(Goda/Jido, PTEP 2014, 3, 033D03 (2014))

$\hookrightarrow$ contradiction? $\rightsquigarrow$ should be resolved



Chiral multiplets

at chiral restoration of SU(3) (no statement about $U_A(1)$ needed!):

- chiral multiplets (L, R) instead of just flavor multiplets

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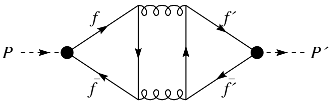
- caveats: only good argument if not strong first-order transition and **if states survive as quasi-particles**



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- outlook: consequences for finite density

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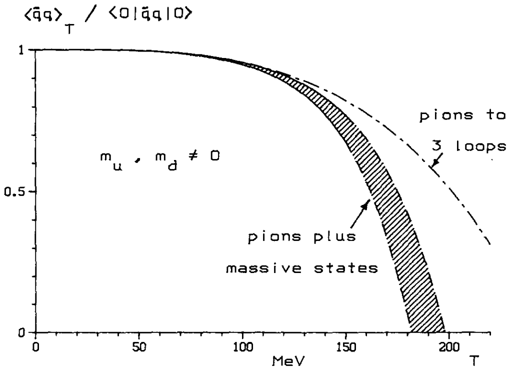
↪ chiral perturbation theory has something to say about not too low temperatures

Drop of quark condensate



- uses interacting pions and resonance gas
- produces realistic transition temperature

Gerber/Leutwyler, Nucl.Phys.B 321, 387 (1989)

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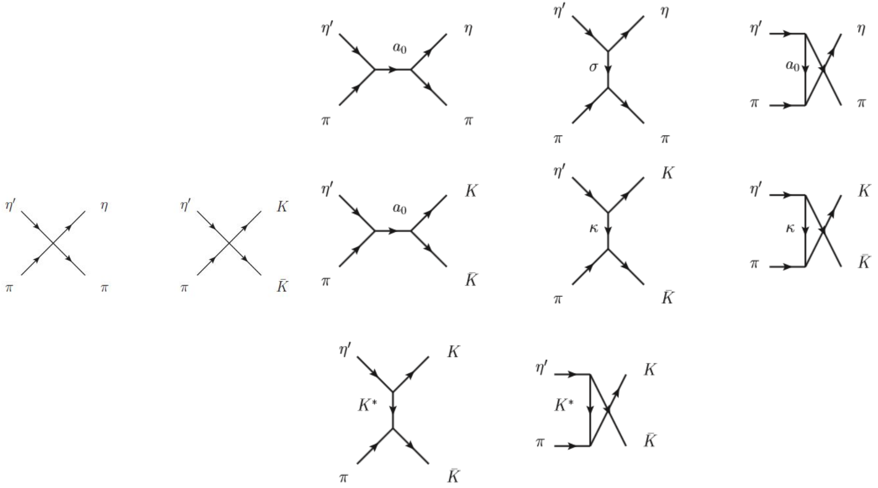
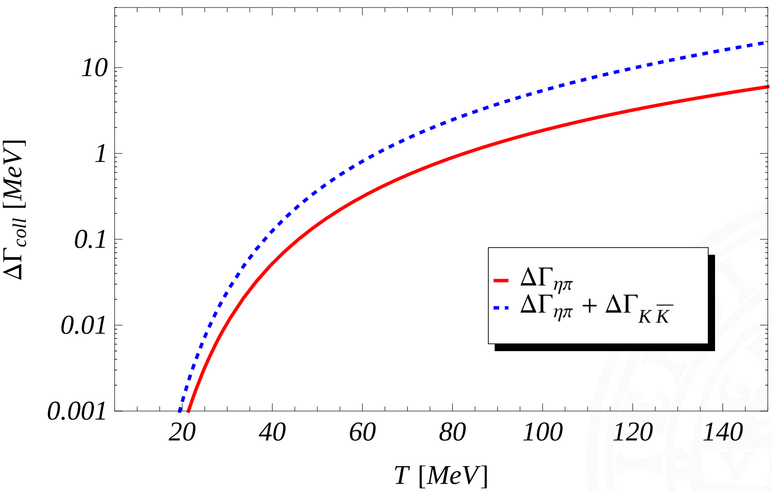
↪ inclusion of resonances as model independent as possible

Processes/diagrams for $\pi\eta'$ scattering



(note: loops are suppressed in the large-N_c limit)

Results: collisional width of η' meson



E. Perotti, C. Niblaeus, SL, Nucl.Phys.A 950 (2016) 29

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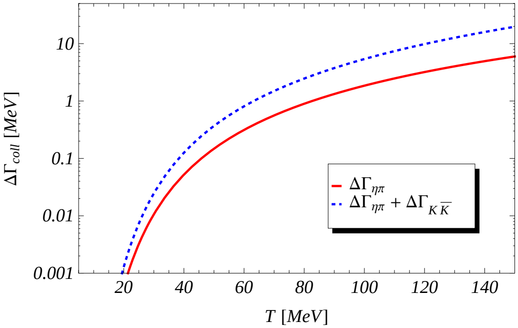

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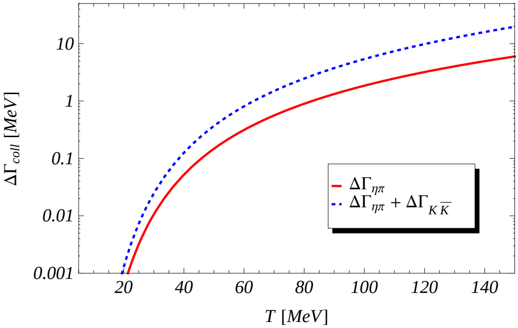

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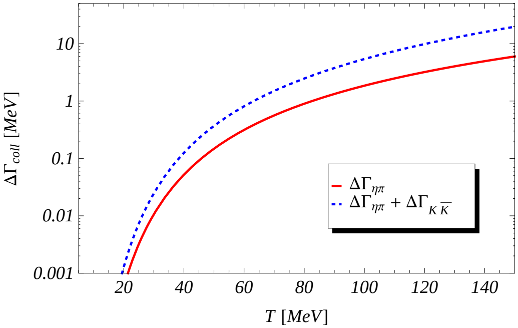

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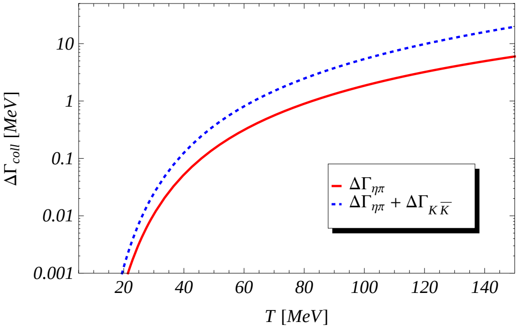

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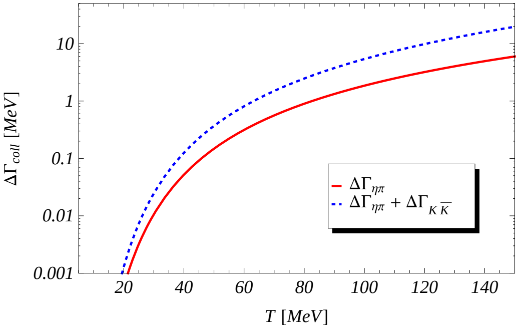

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$\hookrightarrow$ maybe via anomaly driven processes $\eta' \to \gamma\gamma,\ \gamma\pi^+\pi^-$

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$\hookrightarrow$ η' survives as a quasi-particle

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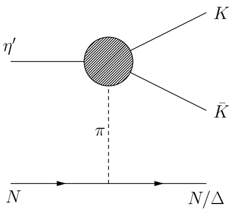
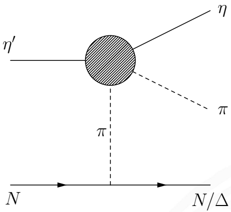
  $\hookrightarrow$ suggests that three-body final states are important! (while most calculations implicitly assume dominance of two-body final states)
- in-medium modifications of $\pi^0 \to \gamma\gamma$, $\eta' \to \gamma\gamma$, $\eta' \to \gamma\pi^+\pi^-$

$\hookrightarrow$ still work left to do for theory

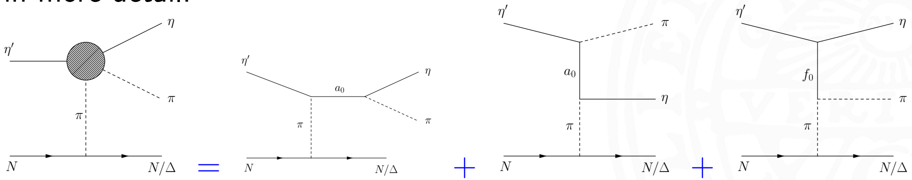
Important processes at finite density

three-body final states!



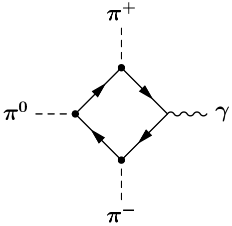


in more detail:



Spare slides

Consequences of $U_A(1)$ anomaly in vacuum II

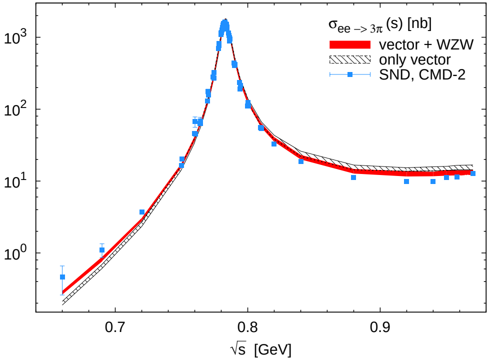


- coupling constant of $\varepsilon^{\mu\nu\alpha\beta}\,\partial_\mu\pi^0\,\partial_\nu\pi^+\,\partial_\alpha\pi^-\,A_\beta \sim O(q^4)$ fixed by anomaly
- corrections (=dominant in absence of anomaly) $\sim O(q^6)$

$\hookrightarrow$ predictive power for reactions $e^+e^- \to 3\pi$ and/or $\gamma + \pi \to 2\pi$ close to threshold?

$\hookrightarrow$ How far is threshold away from idealized case of chiral limit?

$e^+e^- \to 3\pi$



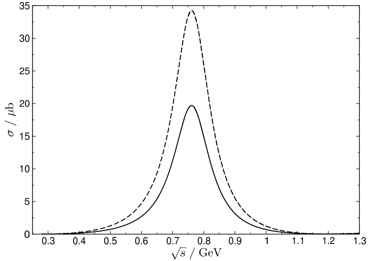
C. Terschlüsen, B. Strandberg, SL, F. Eichstädt, Eur.Phys.J.A 49 (2013) 116

- anomaly caused by Wess-Zumino-Witten (WZW) term
- data dominated by ω vector meson peak

$\hookrightarrow$ anomaly has some effect, but does not dominate a region

$\hookrightarrow$ threshold at $3\,m_\pi$ already quite sizable $\neq$ chiral limit

$\gamma + \pi \to 2\pi$



M. Hoferichter, B. Kubis, D. Sakkas, Phys.Rev.D86, 116009 (2012)

- expect completion of data analysis from COMPASS@CERN
  (pion beam, Primakov effect, cf. J.M. Friedrich, EPJ Web Conf. 199, 01016 (2019))
- calculation includes anomaly and pion-pion rescattering using dispersion theory
- **solid line:** prediction from anomaly
  dashed line: size of anomaly scaled up by about 30%

$\hookrightarrow$ can use whole range to pin down anomaly, not just threshold region

Mass shift?

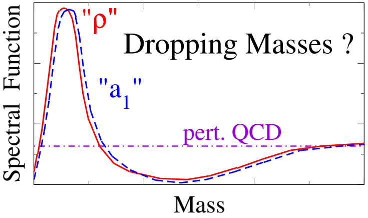
- systematic calculation of thermal modifications of properties of η' using large-N_c chiral perturbation + resonances is interesting

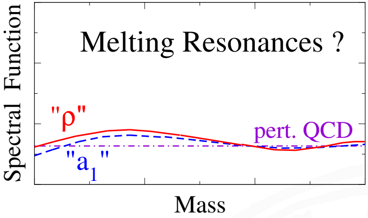
$\hookrightarrow$ mass shift?

$\hookrightarrow$ check first: does η' survive at all in a thermal medium?

- personal history in scepticism against mass shifts ;-)
- hadronic many-body framework often produces broad spectral functions instead of dropping masses
- deconfinement shines out chiral effects

Mass shift vs. broadening

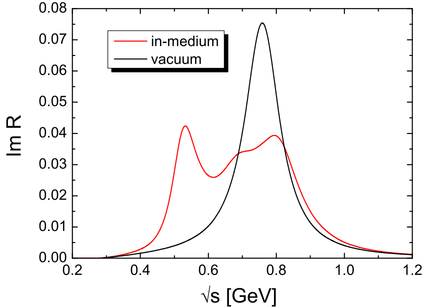




- chiral restoration demands degeneracy of spectra of chiral partners
  (btw: for spin 1: 16-plets, not 18-plets)
- melting of resonances might be hadronic precursor to deconfinement

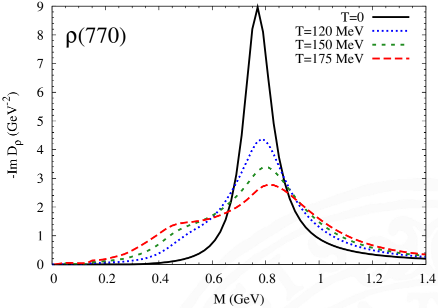
figures from Rapp, Wambach, van Hees, arXiv:0901.3289 [hep-ph]

Much celebrated example: ρ meson



M. Post, SL, U. Mosel,

Nucl.Phys.A 741, 81 (2004)



R. Rapp, J. Wambach, H. van Hees,

arXiv:0901.3289 [hep-ph]

different groups (with different models) obtain
broad ρ meson spectra, essentially no mass shift