Resonance measurements in the QCD crossover regime

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Overview of Topics

- Part1: What is a resonance and how do we measure it
  - A fascinating part of the hadronic world that is difficult to measure

- Part 2: Resonances and chiral symmetry
  - Can mass and width modifications be interpreted ?

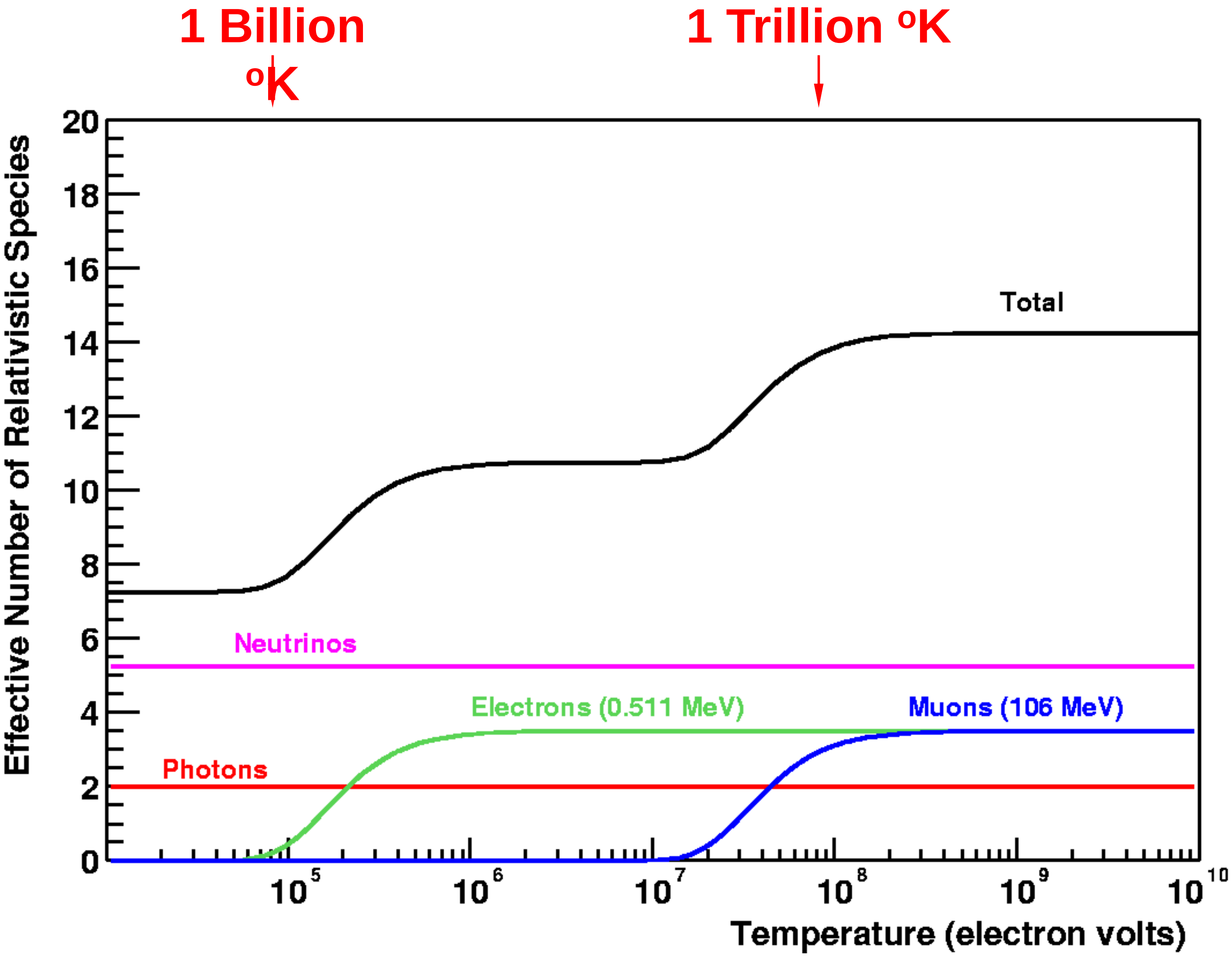
- Part 3: Resonances and the lifetime of the system
  - How does the hadronic system change the yield of resonances ?

- Part 4: Resonances and the Hadron Resonance Gas
  - Interpretation of fluctuation measurements

- Part 5: Looking for exotic states
  - Are there multiquark states in the system ?

Part 1: What is a resonance ?

g_{*S}

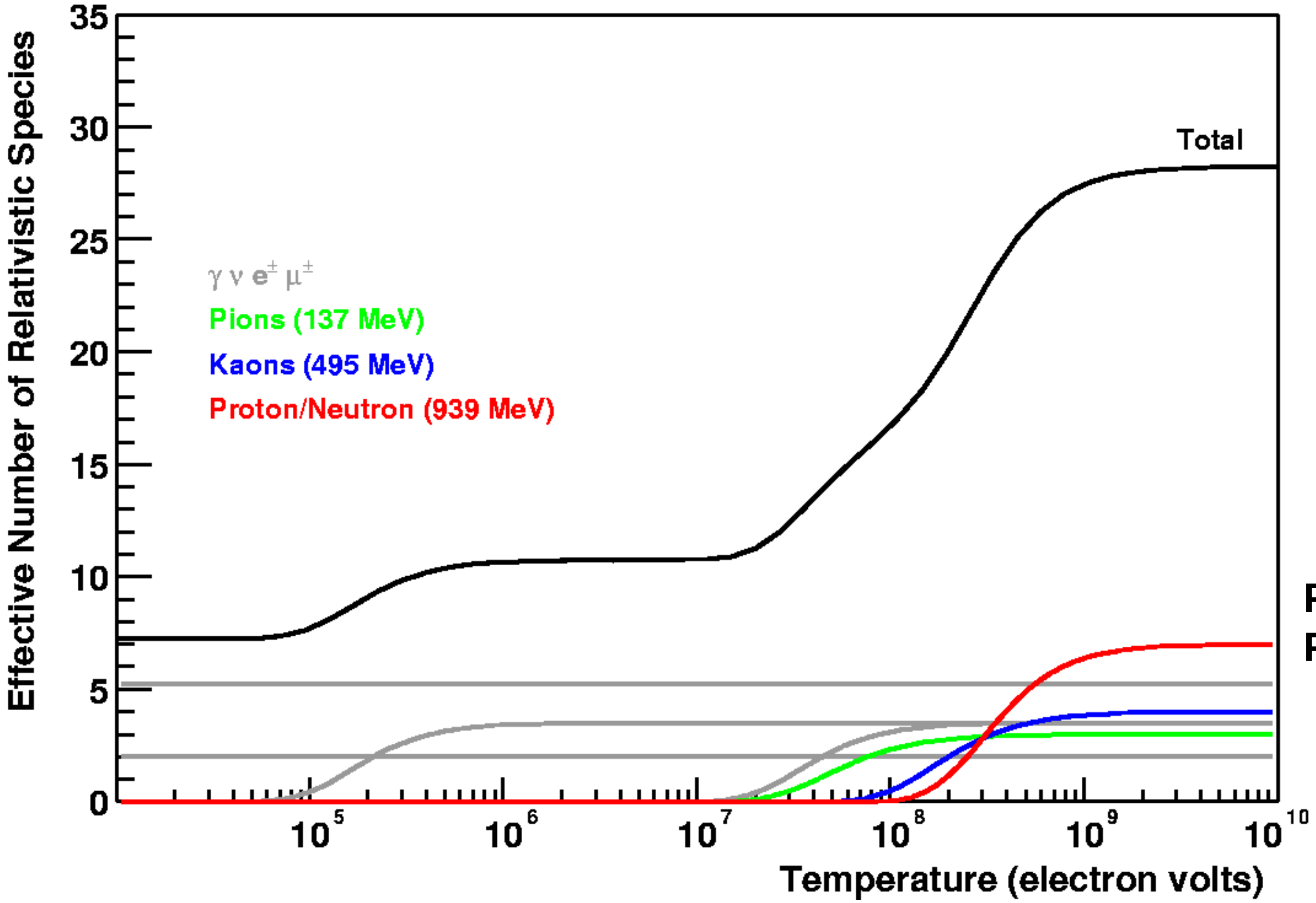


Start with light particles, no strong nuclear force

g_{*S}

1 Billion °K

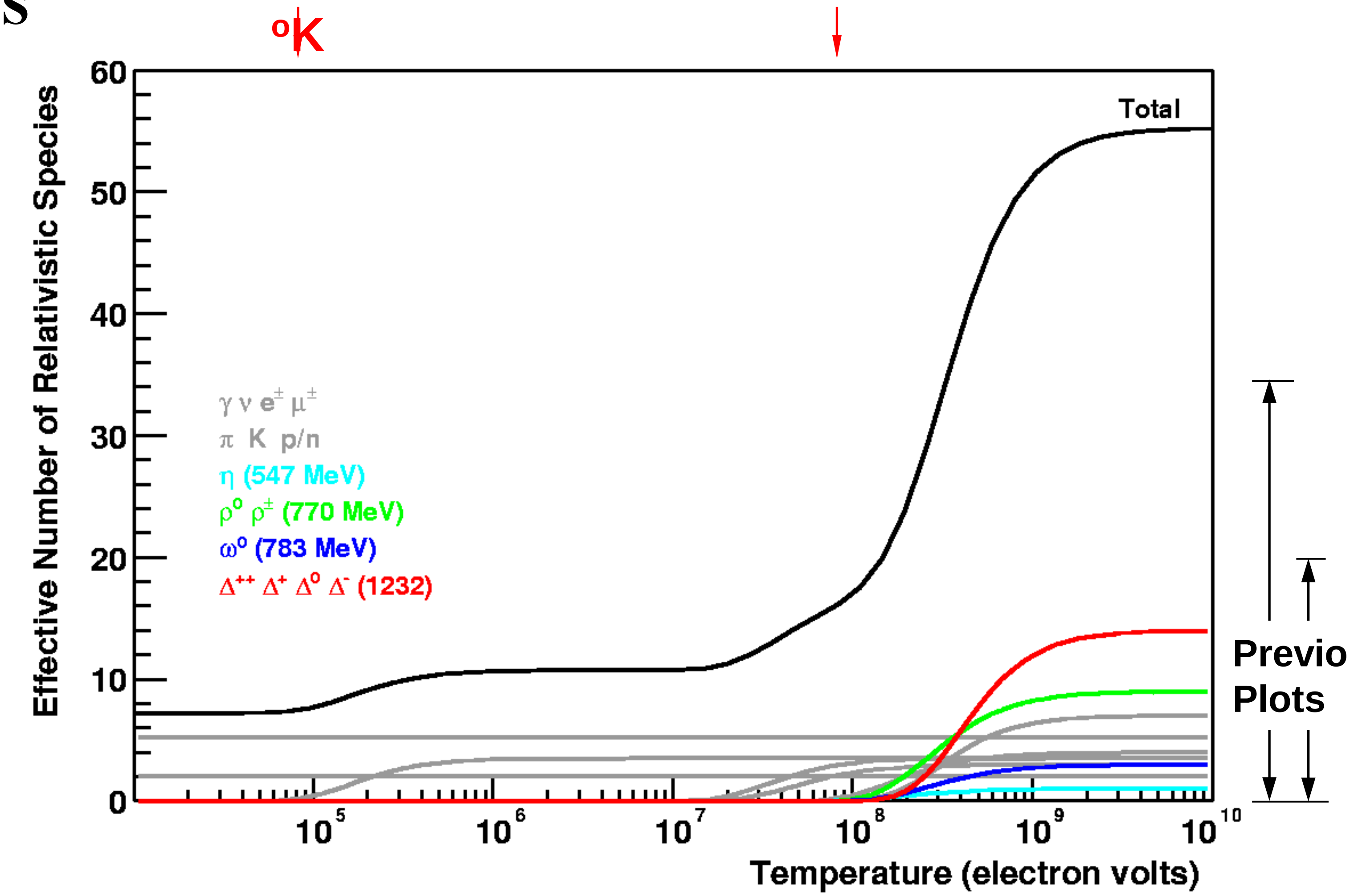
1 Trillion °K



Previous Plot

Now add *hadrons* = feel strong nuclear force

g_{*S}



1 Billion °K

1 Trillion °K

Previous Plots

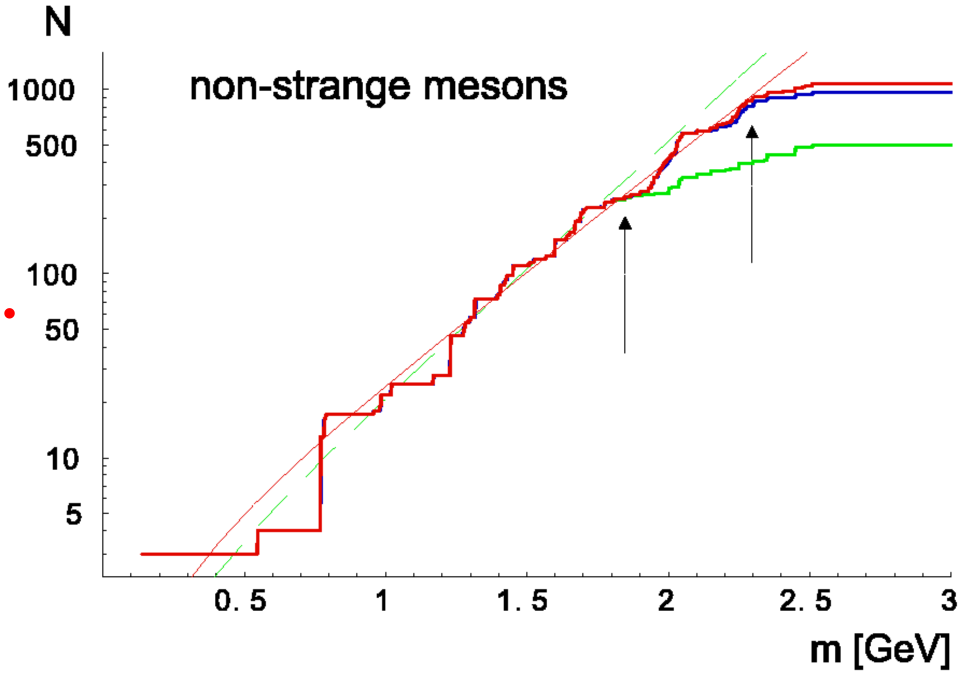
Keep adding more hadrons….

How many hadrons ?

Density of hadron mass states dN/dM increases *exponentially* with mass.

$$\frac{dN}{dM} \sim \exp\left({}^{M}\!/\!_{T_\text{H}} \right)$$

$$T_\text{H} \sim 2\times10^{12}\ {}^{o}\text{K}$$



Broniowski, et.al. 2004

Prior to the 1970's this was explained in several ways theoretically

Statistical Bootstrap **Hadrons made of hadrons made of hadrons…**

Regge Trajectories **Stretchy rotators, first string theory**

QCD to the rescue

Replace Hadrons (messy and numerous)

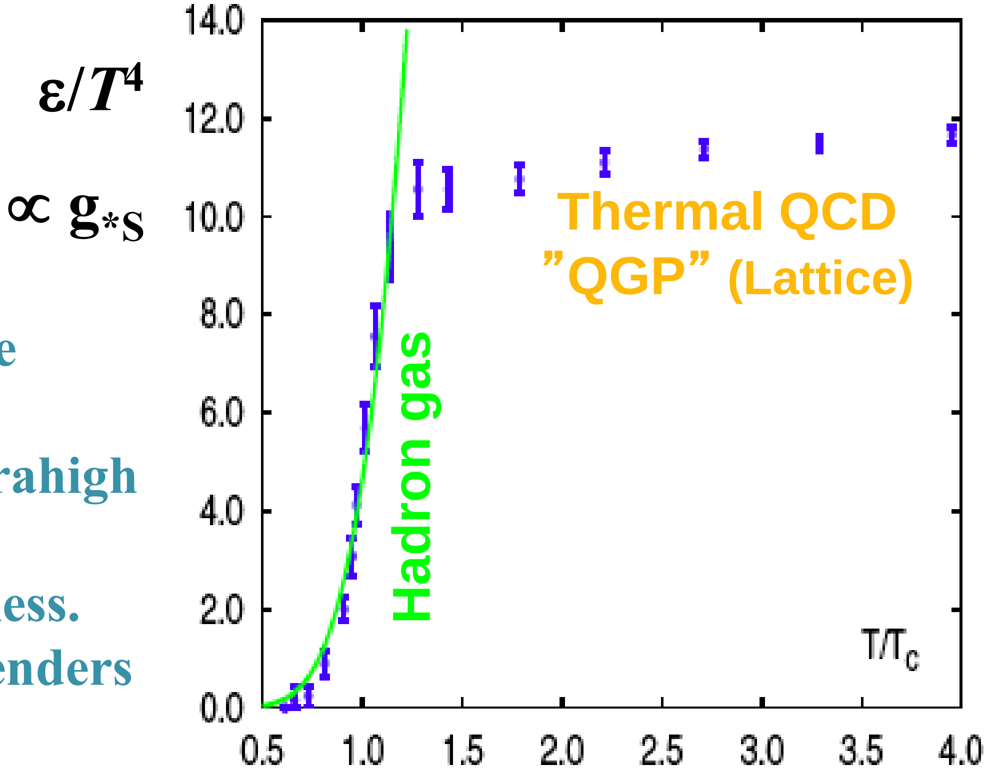
by Quarks and Gluons (simple and few)

"In 1972 the early universe seemed hopelessly opaque…conditions of ultrahigh temperatures…produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly…" Frank Wilczek, Nobel Lecture (RMP 05)

D. Gross
H.D. Politzer
F. Wilczek

American

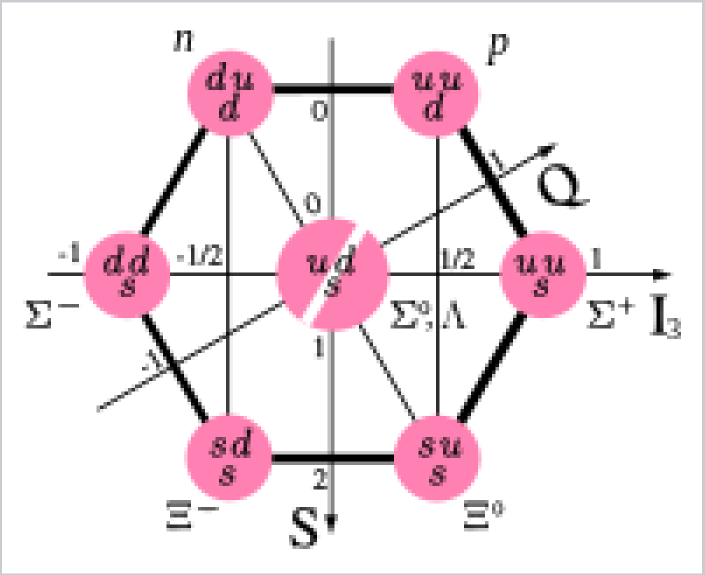
QCD Asymptotic Freedom (1973)



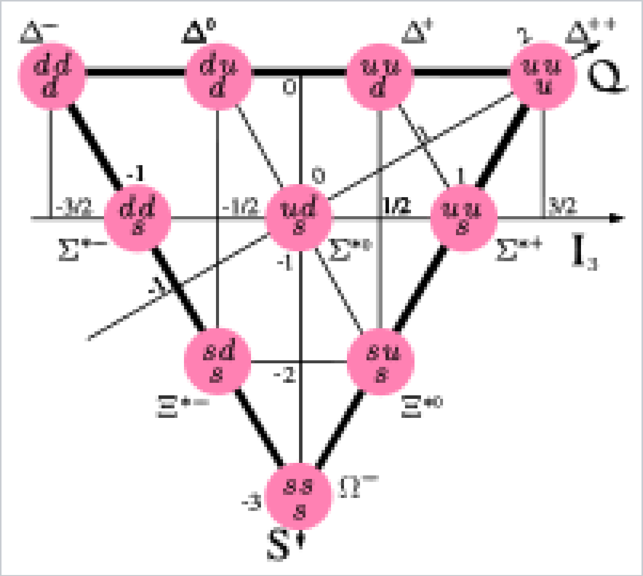
Karsch, Redlich, Tawfik, Eur.Phys.J.C29:549-556,2003

What is a resonance ?

- Hadronic state that decays strongly, i.e. decay is allowed, conserves all quantum numbers, i.e. short lifetime
- Generally an excited state of an existing ground state

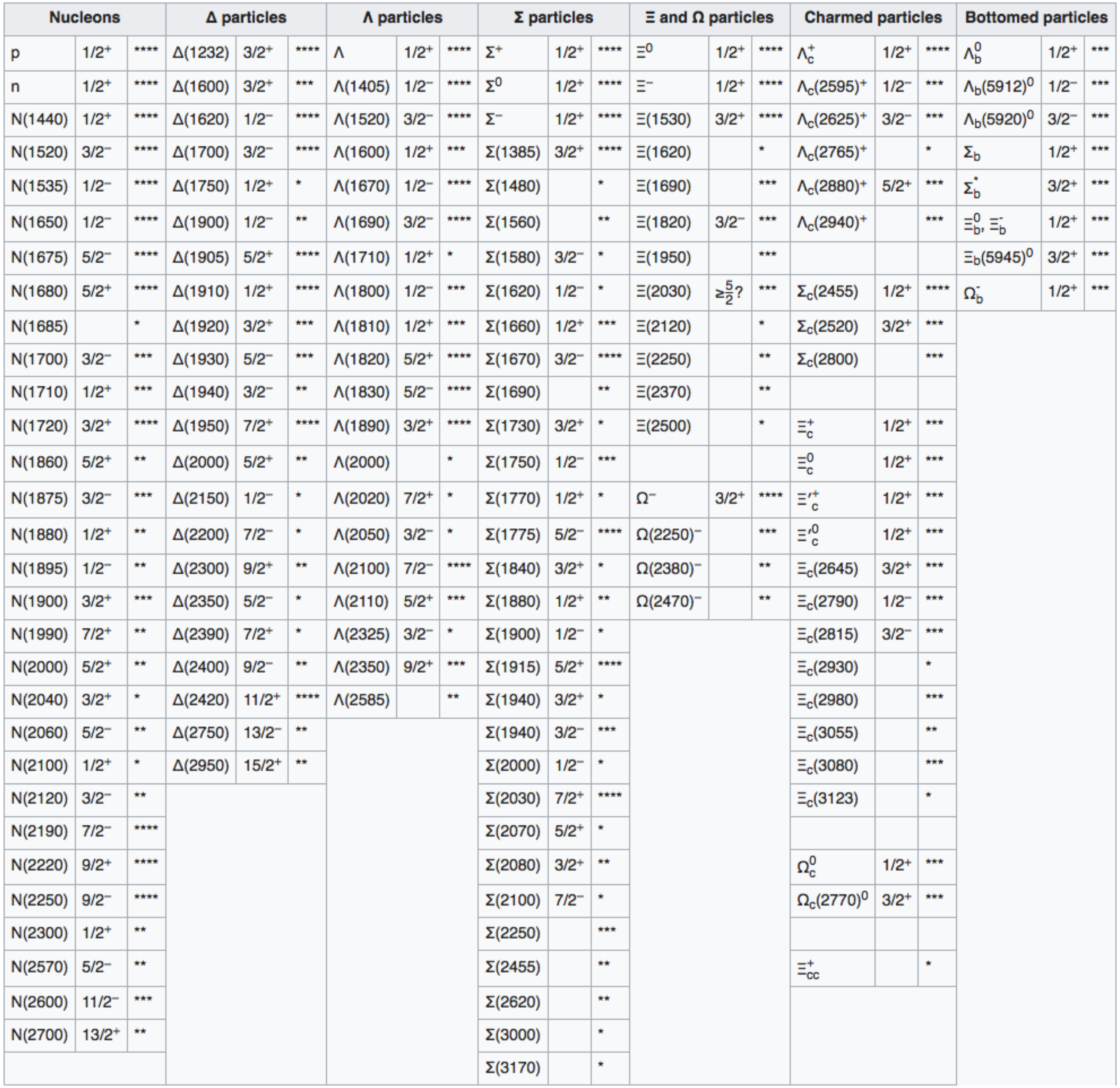


Combinations of three u, d or s-quarks forming baryons with spin-½ form the *baryon octet*



Combinations of three u, d or s-quarks forming baryons with spin-3⁄2 form the *baryon decuplet*.

Example: listing of baryonic resonances



Nucleons			Δ particles			Λ particles			Σ particles			Ξ and Ω particles			Charmed particles			Bottomed particles		
p	$1/2^+$	****	Δ(1232)	$3/2^+$	****	Λ	$1/2^+$	****	Σ^+	$1/2^+$	****	Ξ^0	$1/2^+$	****	Λ_c^+	$1/2^+$	****	Λ_b^0	$1/2^+$	***
n	$1/2^+$	****	Δ(1600)	$3/2^+$	***	Λ(1405)	$1/2^-$	****	Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***	$\Lambda_b(5912)^0$	$1/2^-$	***
N(1440)	$1/2^+$	****	Δ(1620)	$1/2^-$	****	Λ(1520)	$3/2^-$	****	Σ^-	$1/2^+$	****	Ξ(1530)	$3/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***	$\Lambda_b(5920)^0$	$3/2^-$	***
N(1520)	$3/2^-$	****	Δ(1700)	$3/2^-$	****	Λ(1600)	$1/2^+$	***	Σ(1385)	$3/2^+$	****	Ξ(1620)		*	$\Lambda_c(2765)^+$		*	Σ_b	$1/2^+$	***
N(1535)	$1/2^-$	****	Δ(1750)	$1/2^+$	*	Λ(1670)	$1/2^-$	****	Σ(1480)		*	Ξ(1690)		***	$\Lambda_c(2880)^+$	$5/2^+$	***	Σ_b^*	$3/2^+$	***
N(1650)	$1/2^-$	****	Δ(1900)	$1/2^-$	**	Λ(1690)	$3/2^-$	****	Σ(1560)		**	Ξ(1820)	$3/2^-$	***	$\Lambda_c(2940)^+$		***	Ξ_b^0, Ξ_b^-	$1/2^+$	***
N(1675)	$5/2^-$	****	Δ(1905)	$5/2^+$	****	Λ(1710)	$1/2^+$	*	Σ(1580)	$3/2^-$	*	Ξ(1950)		***				$\Xi_b(5945)^0$	$3/2^+$	***
N(1680)	$5/2^+$	****	Δ(1910)	$1/2^+$	****	Λ(1800)	$1/2^-$	***	Σ(1620)	$1/2^-$	*	Ξ(2030)	$\geq\frac{5}{2}?$	***	$\Sigma_c(2455)$	$1/2^+$	****	Ω_b^-	$1/2^+$	***
N(1685)		*	Δ(1920)	$3/2^+$	***	Λ(1810)	$1/2^+$	***	Σ(1660)	$1/2^+$	***	Ξ(2120)		*	$\Sigma_c(2520)$	$3/2^+$	***			
N(1700)	$3/2^-$	***	Δ(1930)	$5/2^-$	***	Λ(1820)	$5/2^+$	****	Σ(1670)	$3/2^-$	****	Ξ(2250)		**	$\Sigma_c(2800)$		***			
N(1710)	$1/2^+$	***	Δ(1940)	$3/2^-$	**	Λ(1830)	$5/2^-$	****	Σ(1690)		**	Ξ(2370)		**						
N(1720)	$3/2^+$	****	Δ(1950)	$7/2^+$	****	Λ(1890)	$3/2^+$	****	Σ(1730)	$3/2^+$	*	Ξ(2500)		*	Ξ_c^+	$1/2^+$	***			
N(1860)	$5/2^+$	**	Δ(2000)	$5/2^+$	**	Λ(2000)		*	Σ(1750)	$1/2^-$	***				Ξ_c^0	$1/2^+$	***			
N(1875)	$3/2^-$	***	Δ(2150)	$1/2^-$	*	Λ(2020)	$7/2^+$	*	Σ(1770)	$1/2^+$	*	Ω^-	$3/2^+$	****	$\Xi_c'^+$	$1/2^+$	***			
N(1880)	$1/2^+$	**	Δ(2200)	$7/2^-$	*	Λ(2050)	$3/2^-$	*	Σ(1775)	$5/2^-$	****	$\Omega(2250)^-$		***	$\Xi_c'^0$	$1/2^+$	***			
N(1895)	$1/2^-$	**	Δ(2300)	$9/2^+$	**	Λ(2100)	$7/2^-$	****	Σ(1840)	$3/2^+$	*	$\Omega(2380)^-$		**	$\Xi_c(2645)$	$3/2^+$	***			
N(1900)	$3/2^+$	***	Δ(2350)	$5/2^-$	*	Λ(2110)	$5/2^+$	***	Σ(1880)	$1/2^+$	**	$\Omega(2470)^-$		**	$\Xi_c(2790)$	$1/2^-$	***			
N(1990)	$7/2^+$	**	Δ(2390)	$7/2^+$	*	Λ(2325)	$3/2^-$	*	Σ(1900)	$1/2^-$	*				$\Xi_c(2815)$	$3/2^-$	***			
N(2000)	$5/2^+$	**	Δ(2400)	$9/2^-$	**	Λ(2350)	$9/2^+$	***	Σ(1915)	$5/2^+$	****				$\Xi_c(2930)$		*			
N(2040)	$3/2^+$	*	Δ(2420)	$11/2^+$	****	Λ(2585)		**	Σ(1940)	$3/2^+$	*				$\Xi_c(2980)$		***			
N(2060)	$5/2^-$	**	Δ(2750)	$13/2^-$	**				Σ(1940)	$3/2^-$	***				$\Xi_c(3055)$		**			
N(2100)	$1/2^+$	*	Δ(2950)	$15/2^+$	**				Σ(2000)	$1/2^-$	*				$\Xi_c(3080)$		***			
N(2120)	$3/2^-$	**							Σ(2030)	$7/2^+$	****				$\Xi_c(3123)$		*			
N(2190)	$7/2^-$	****							Σ(2070)	$5/2^+$	*									
N(2220)	$9/2^+$	****							Σ(2080)	$3/2^+$	**				Ω_c^0	$1/2^+$	***			
N(2250)	$9/2^-$	****							Σ(2100)	$7/2^-$	*				$\Omega_c(2770)^0$	$3/2^+$	***			
N(2300)	$1/2^+$	**							Σ(2250)		***									
N(2570)	$5/2^-$	**							Σ(2455)		**				Ξ_{cc}^+		*			
N(2600)	$11/2^-$	***							Σ(2620)		**									
N(2700)	$13/2^+$	**							Σ(3000)		*									
									Σ(3170)		*									

What is a resonance ?

- The width of the resonant state relates to its lifetime
- (Breit-Wigner formalism): $\Gamma = h/\tau$
- Generally an excited state of an existing ground state

- Interesting in RHI physics since the lifetime is often comparable to the lifetime of the generated fireball.
- Lifetimes measured in fm/c ~ 10^{-23} s

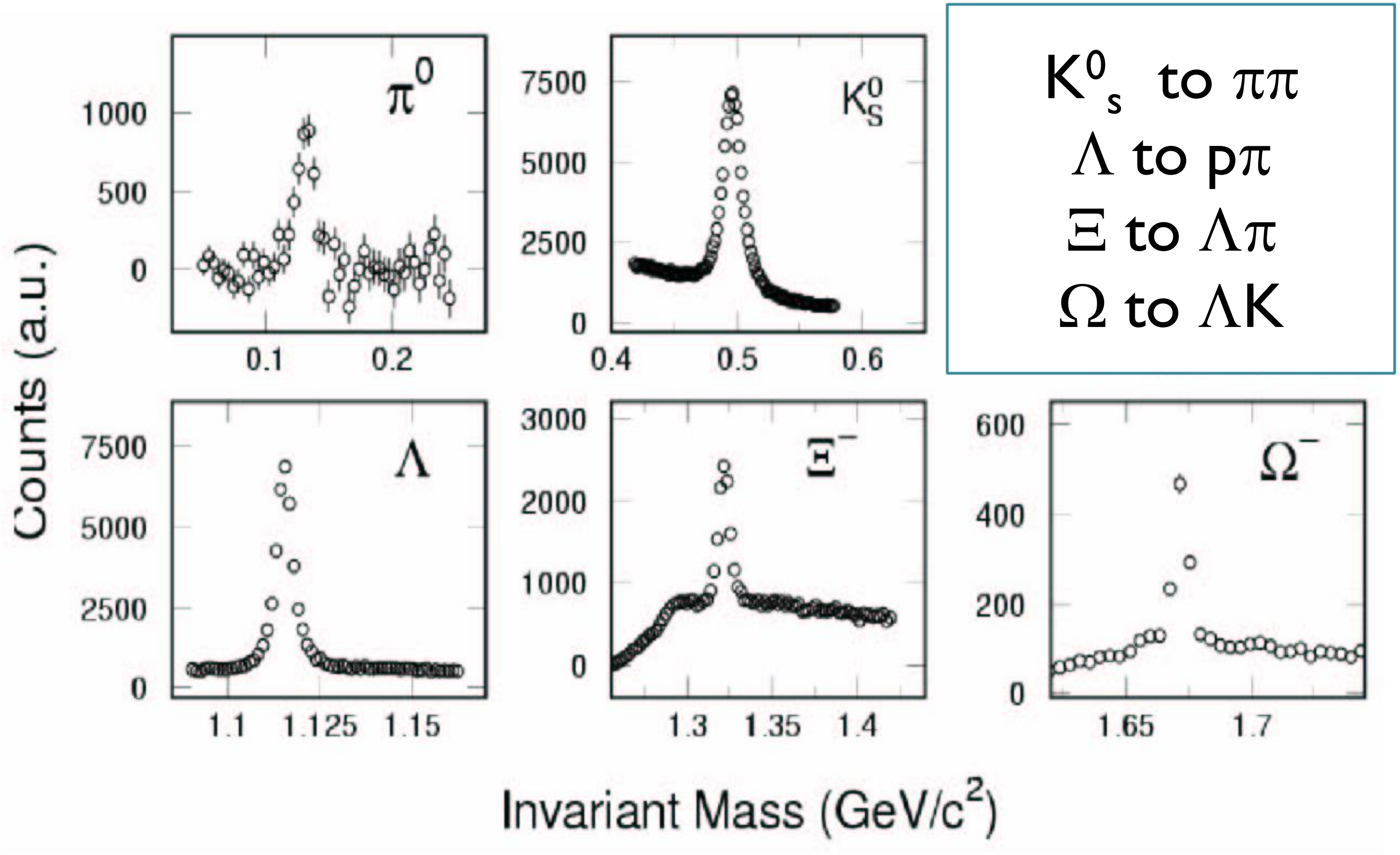
Short resonance life times [fm/c]:

$K^* < \Sigma^* < \Lambda(1520) < \phi$

$4 < 6 < 13 < 40$

- Is the resonance modified through the onset of chiral symmetry restoration ? Can we measure an off-shell resonance through its decay inside the fireball ?

The final product (Example: STAR) for weak decays (ground state baryons and mesons)



K^0_s to ππ

Λ to pπ

Ξ to Λπ

Ω to ΛK

Reconstruct particles in full azimuthal acceptance of STAR!

$$M^2 = (E_1+E_2)^2 - \|\mathbf{p}_1+\mathbf{p}_2\|^2 = m_1^2+m_2^2+2\left(E_1E_2-\mathbf{p}_1\cdot\mathbf{p}_2\right).$$

$$= 2p_{T1}p_{T2}(\cosh(\eta_1-\eta_2)-\cos(\phi_1-\phi_2)).$$

The final product (Example: ALICE) for strong decays (resonant states)

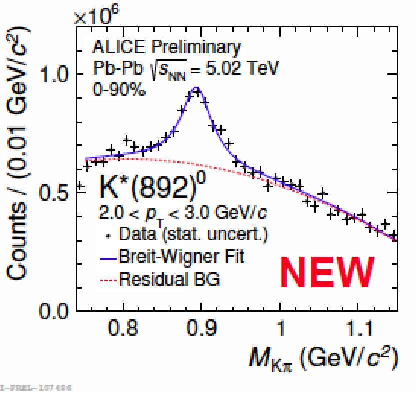
K^{*0}

$d\bar{s}$ → π^-, K^+

B.R. = 66.6%

m = 896 MeV/c^2

Γ = 47.4 MeV/c^2



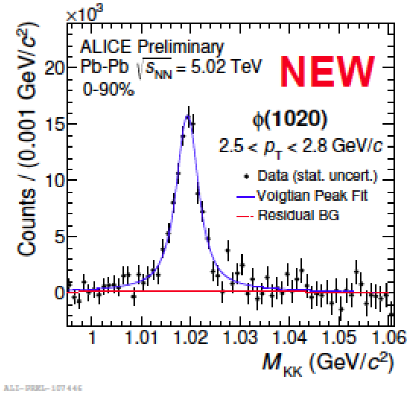
ϕ

$s\bar{s}$ → K^-, K^+

B.R. = 48.9%

m = 1019 MeV/c^2

Γ = 4.266 MeV/c^2



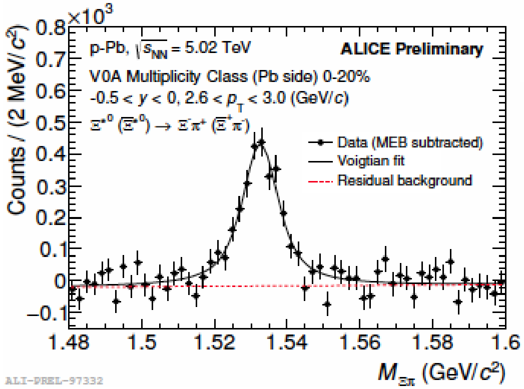
Ξ^{*0}

uss → Ξ^-, π^+

B.R. = 66.7%

m = 1532 MeV/c^2

Γ = 9.1 MeV/c^2



Σ^{*+}

uus → π^-, Λ

B.R. = 87%

m = 1383 MeV/c^2

Γ = 36.0 MeV/c^2

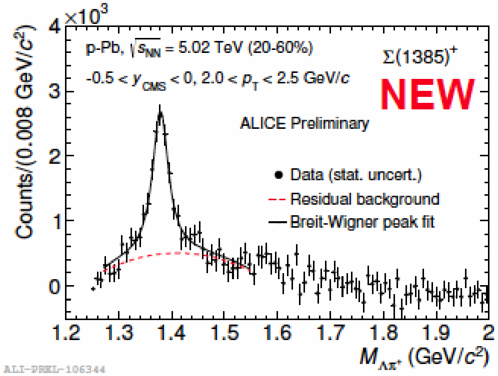
Σ^{*-}

dds → π^+, Λ

B.R. = 87%

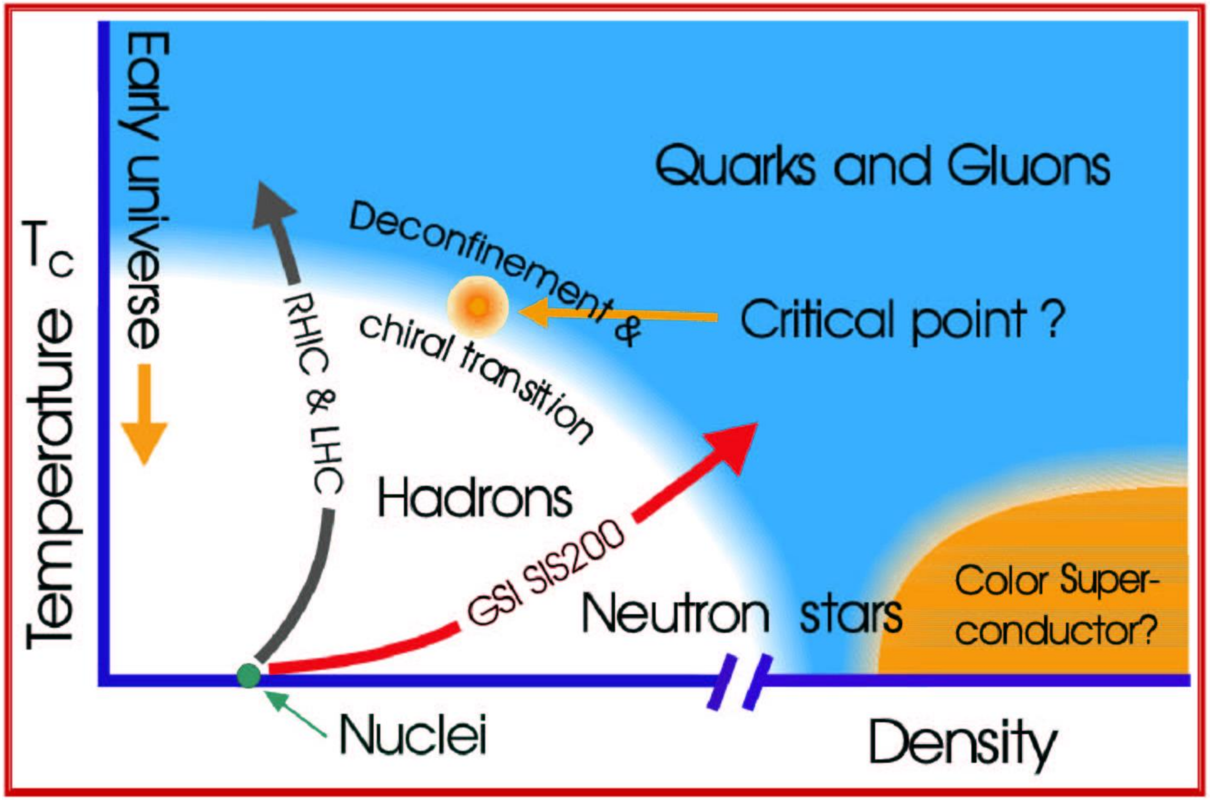
m = 1387 MeV/c^2

Γ = 39.4 MeV/c^2



Topic 2: Resonances and chiral symmetry

What is our mission ?



- Establish the existence of a phase (state) of deconfined and chirally symmetric matter. Determine state variables
- Establish the mechanism of *re*confinement

Lattice QCD: two phase transitions

Chiral symmetry restoration

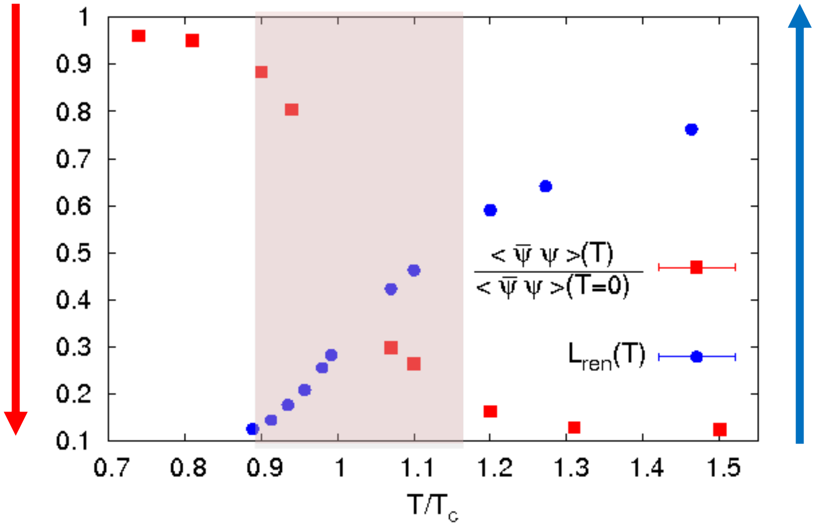
Massive hadrons in the hadron gas are massless partons in the plasma. Mass breaks chiral symmetry, needs to be restored in the plasma

Deconfinement

The quarks and gluons deconfine because energy or parton density gets too high (best visualized in the bag model).

Quark condensate:

Measure of chiral symmetry restoration



Polyakov loop:

Measure of deconfinement

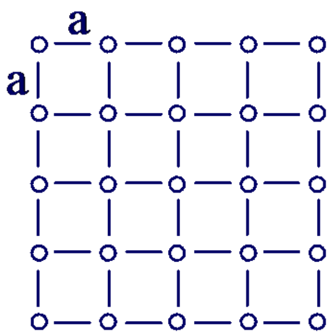
Mechanism of hadronization ? : How do hadrons obtain their mass ?

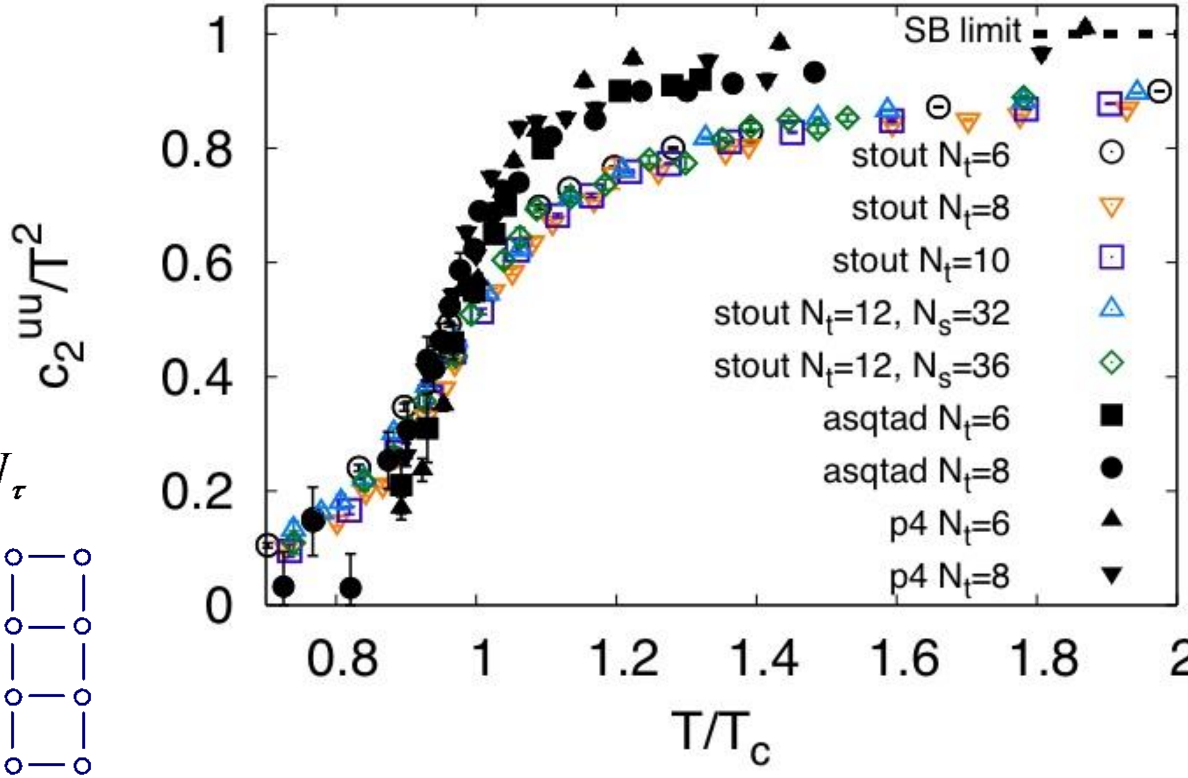
Not a question of Higgs fields, but rather of dynamic masses through gluon fields (quasi-particles, constituent quarks, gluon clusters, color-neutral bound states through recombination ?)

Evolution in lattice QCD = the QCD crossover

the phase transition turns into a crossover due to finer lattice spacing and smaller quark masses = a longer mixed phase ?

$N_s^3 \times N_\tau$





new

old

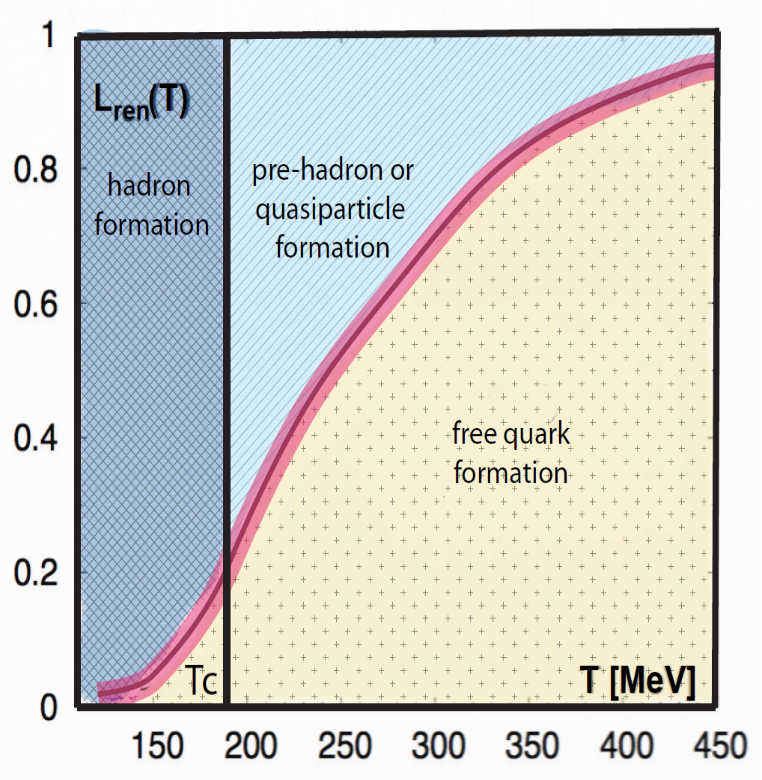
The main transition parameters:

$T_c \sim 154$ MeV $\varepsilon_c \sim 1$ GeV/fm^3

A smooth cross-over

Can we map out (experimentally) and understand (theoretically) *the transition from QCD degrees of freedom to hadronic degrees of freedom through the QCD crossover region*. The emphasis is on *understanding the formation of matter on a microscopic level*. The main tools are flavor specific identified particles and the detectors that enable PID.

Can we determine *the state variables of a deconfined, yet collective, state that existed only microseconds after the Big Bang* and forms the basis of matter formation in the universe. The emphasis is *on establishing its magnitude of collectivity and its unique properties as a state between the hadron gas phase and the weak coupling limit of asymptotic freedom.*



Bellwied et al., PLB 691 (2010) 208

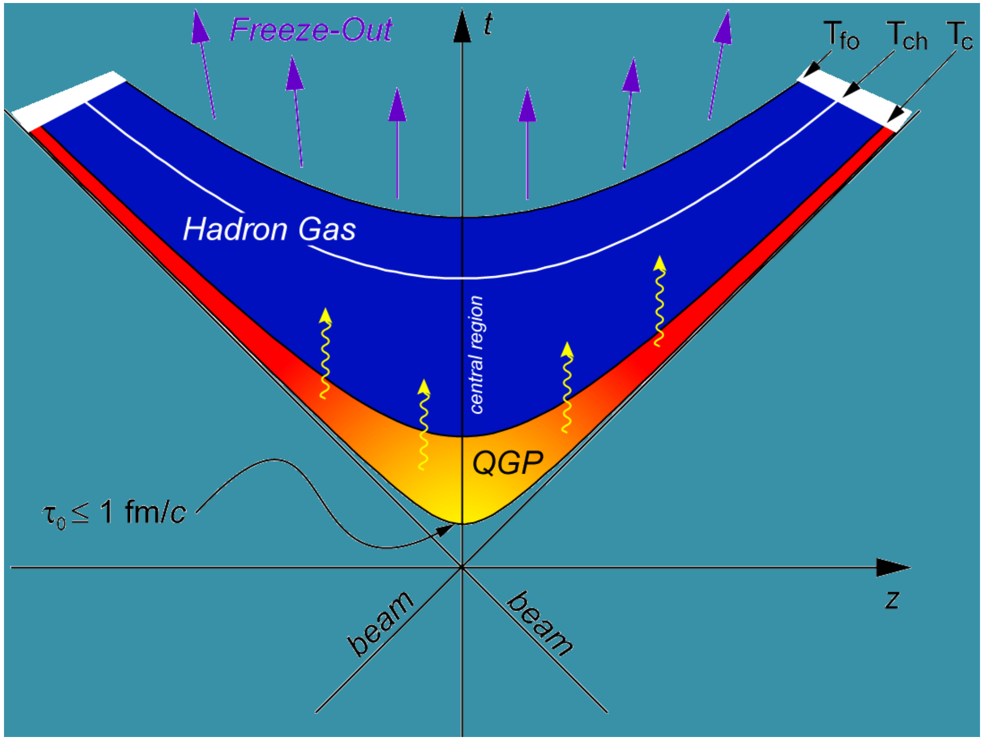
Evolution in Space-time

Requirements for deconfined matter formation (based on lattice QCD calculations) are met at RHIC and LHC:

Initial energy density:
$\varepsilon \geq 10$ GeV/fm^3
(model dependent)

Initial Temperature:
$T_{RHIC} \sim 350$ MeV
$T_{LHC} > 500$ MeV

Gluon density @ RHIC:
dN/dy ~ 800-1200

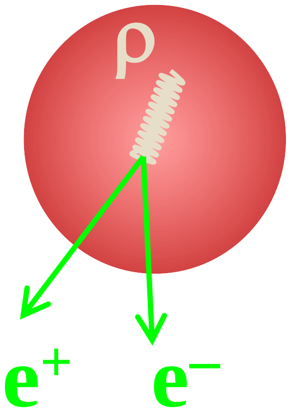


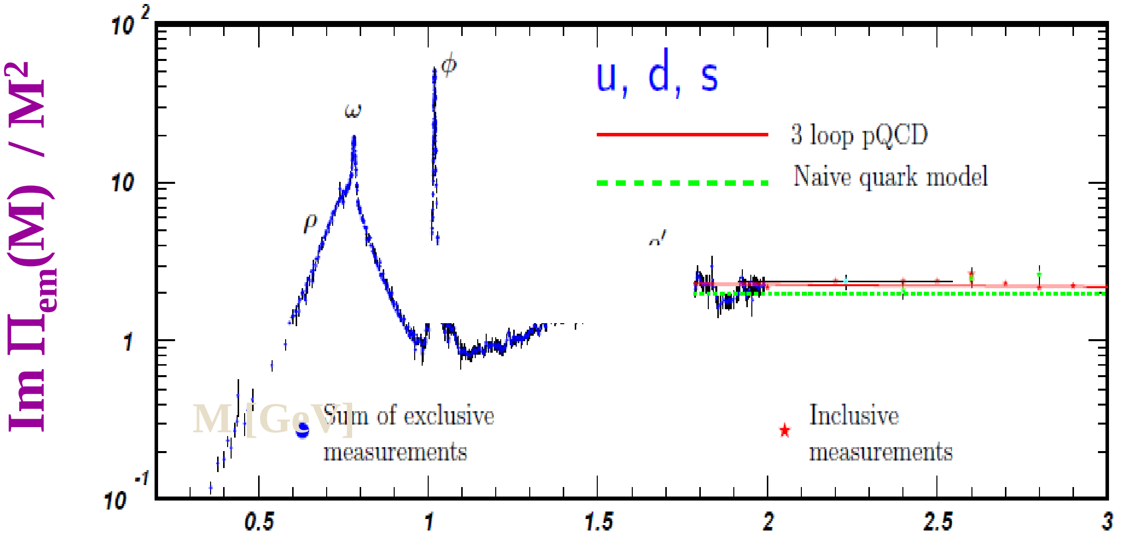
Experimental tools are in place
to study the new phase and *re*confinement

Resonance medium modification: EM spectral functions

Thermal Dilepton Rate

$$\frac{dR}{d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(q_0,T) \; \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$

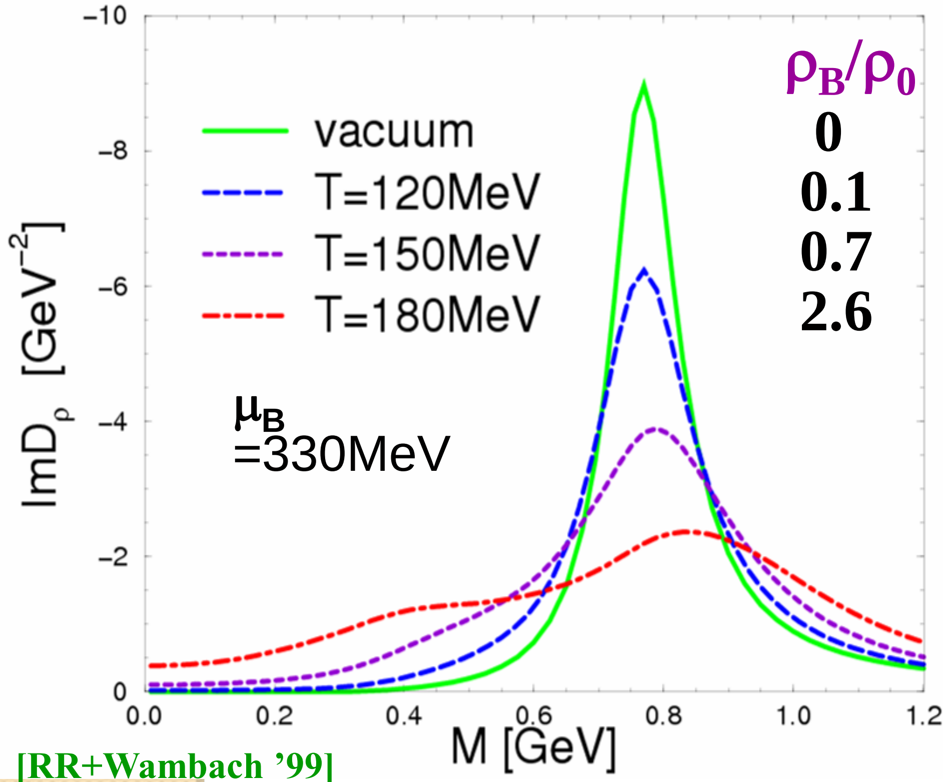




- **Hadronic Resonances**
  - **change in degrees of freedom**
  - **restoration of chiral symmetry**

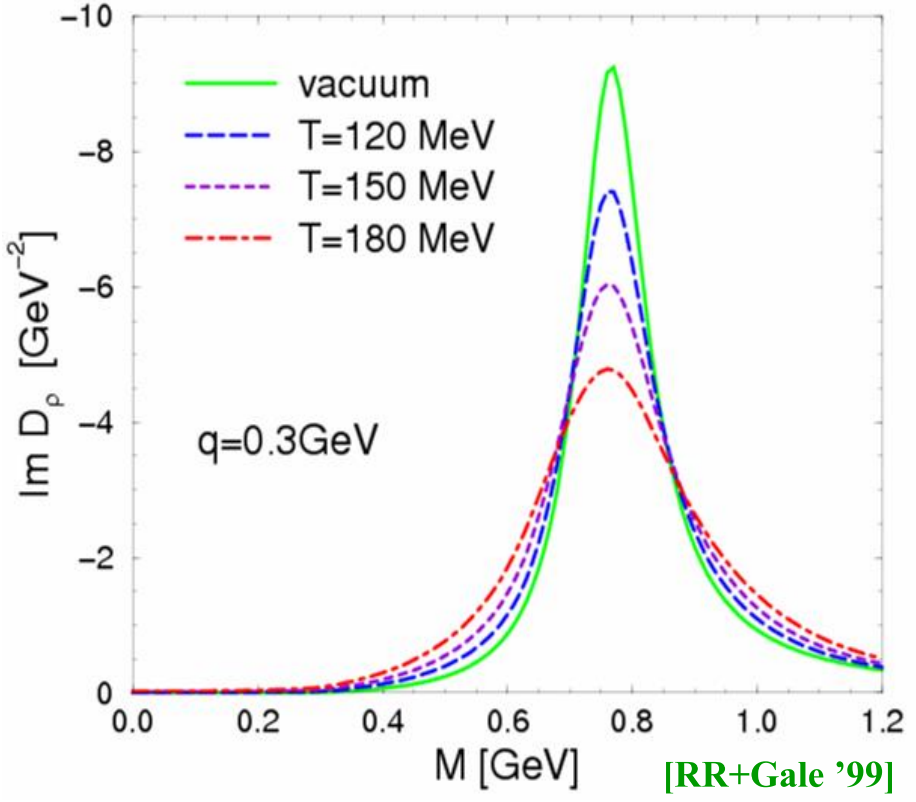
In-medium ρ-meson spectral functions

Hot + Dense Matter



[RR+Wambach '99]

Hot Meson Gas



[RR+Gale '99]

- **ρ-meson "melts" in hot/dense matter**
- **baryon density ρ_B more important than temperature**

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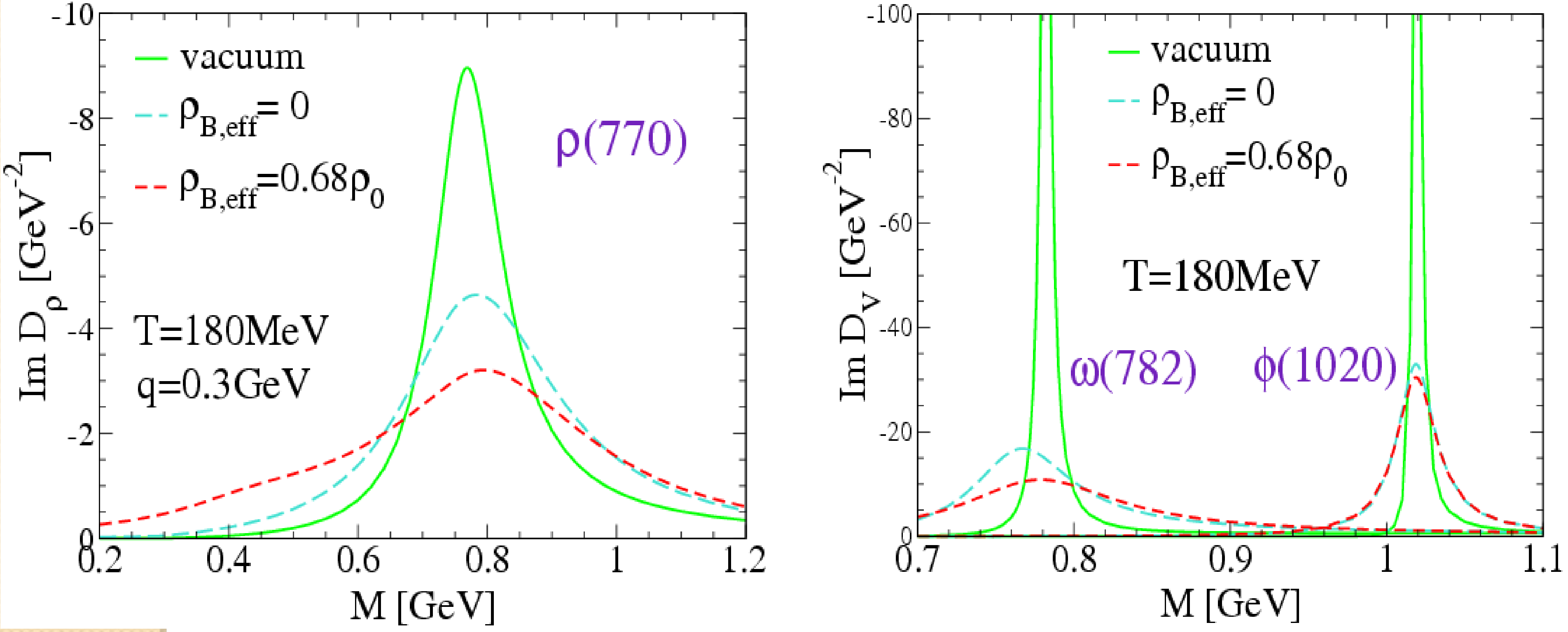
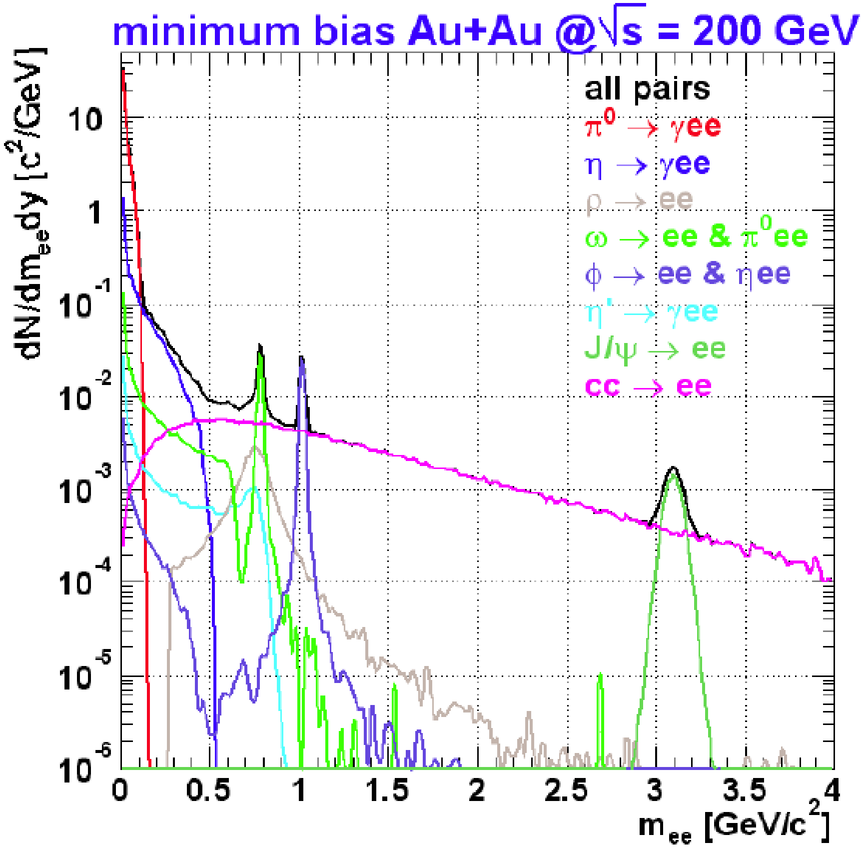
In-medium vector mesons at RHIC/LHC



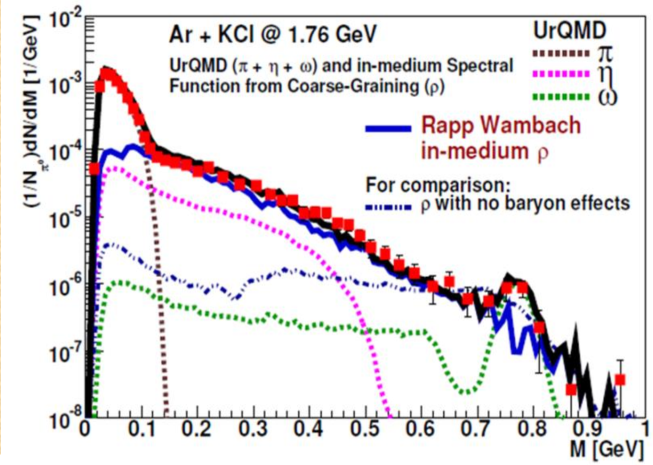
ω also melts, φ more robust ↔ OZI

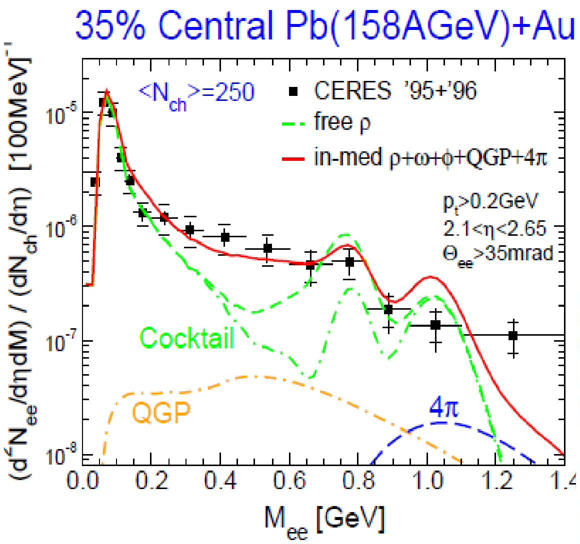
Properties of the QGP

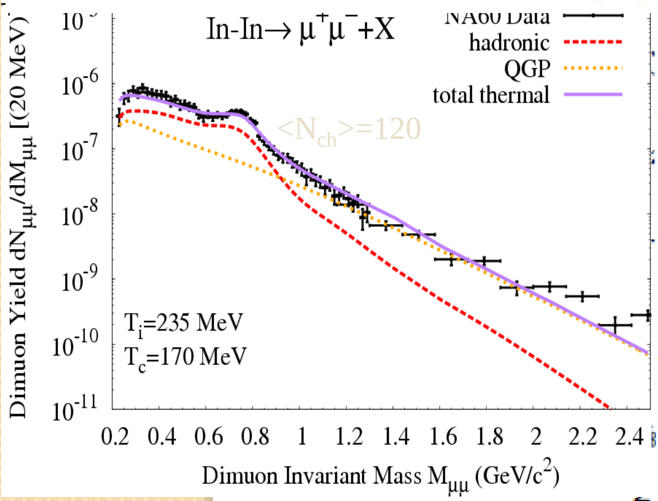
- What is its temperature?
  - measure thermal photons
- Does it restore chiral symmetry?
  - modification of the vector mesons
- How does it affect heavy quarks?
  - modification of the intermediate mass region
- All these questions can be answered by measuring dileptons (e^+e^- or $\mu^+\mu^-$)
  - no strong final state interactions:
    - leave collision system unperturbed
    - emitted at all stages: need to disentangle contributions

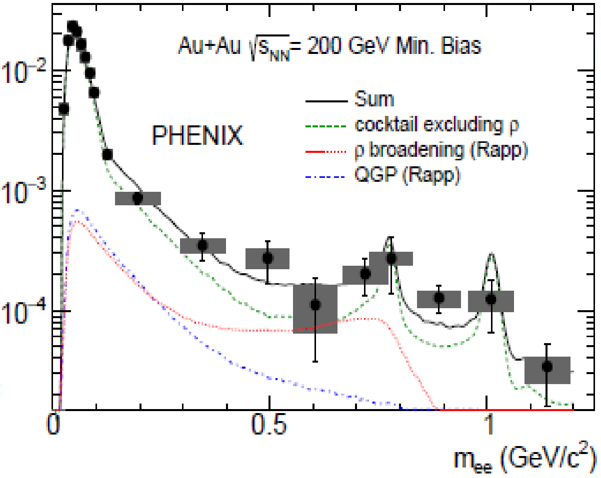


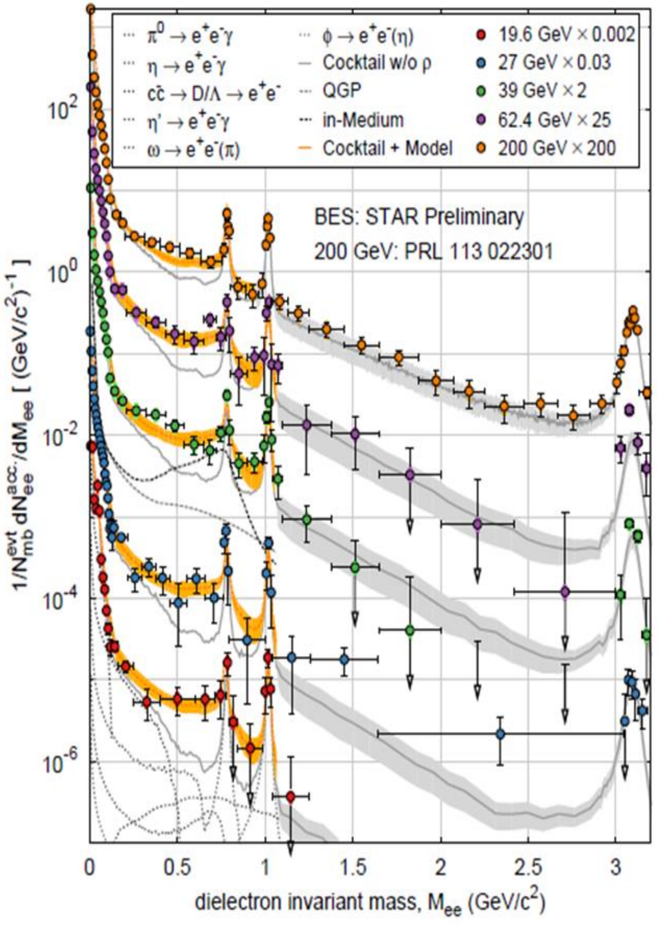
30 years: di-leptons in heavy ion collisions











- **Robust understanding across QCD phase diagram: QGP + hadronic radiation with melting ρ resonance**

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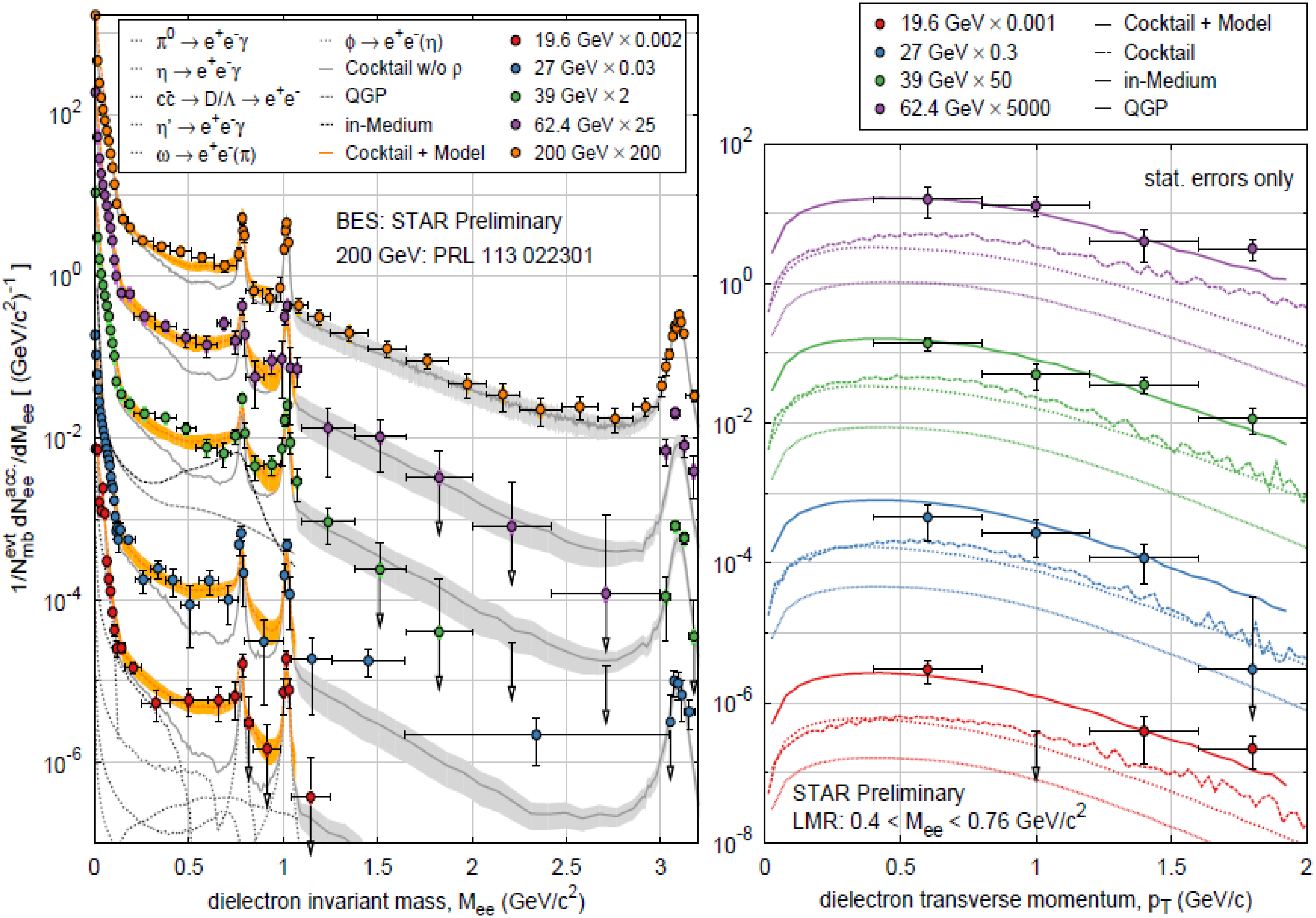
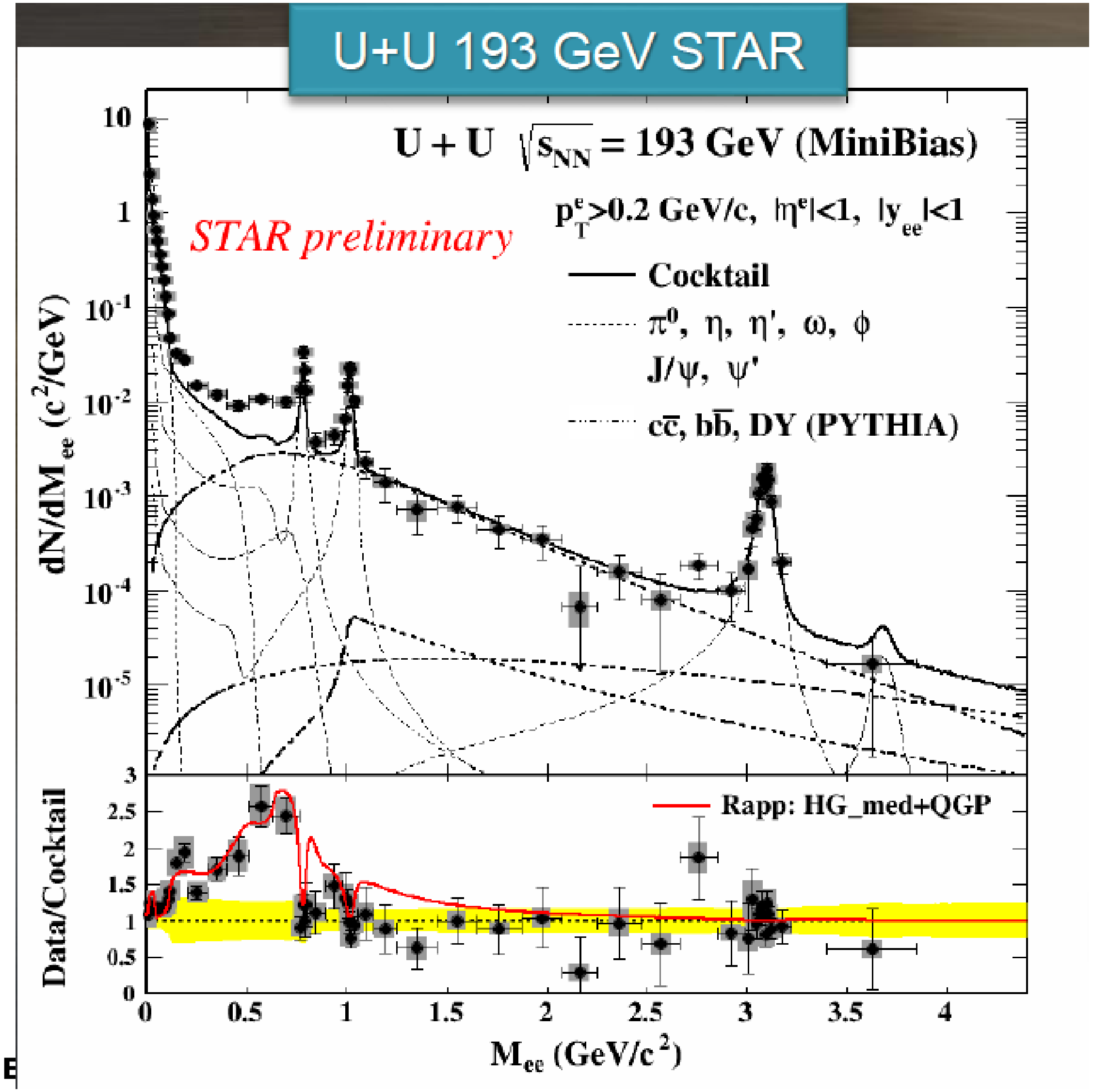
Excitation function from 20-200 GeV



- compatible with predictions from melting ρ meson

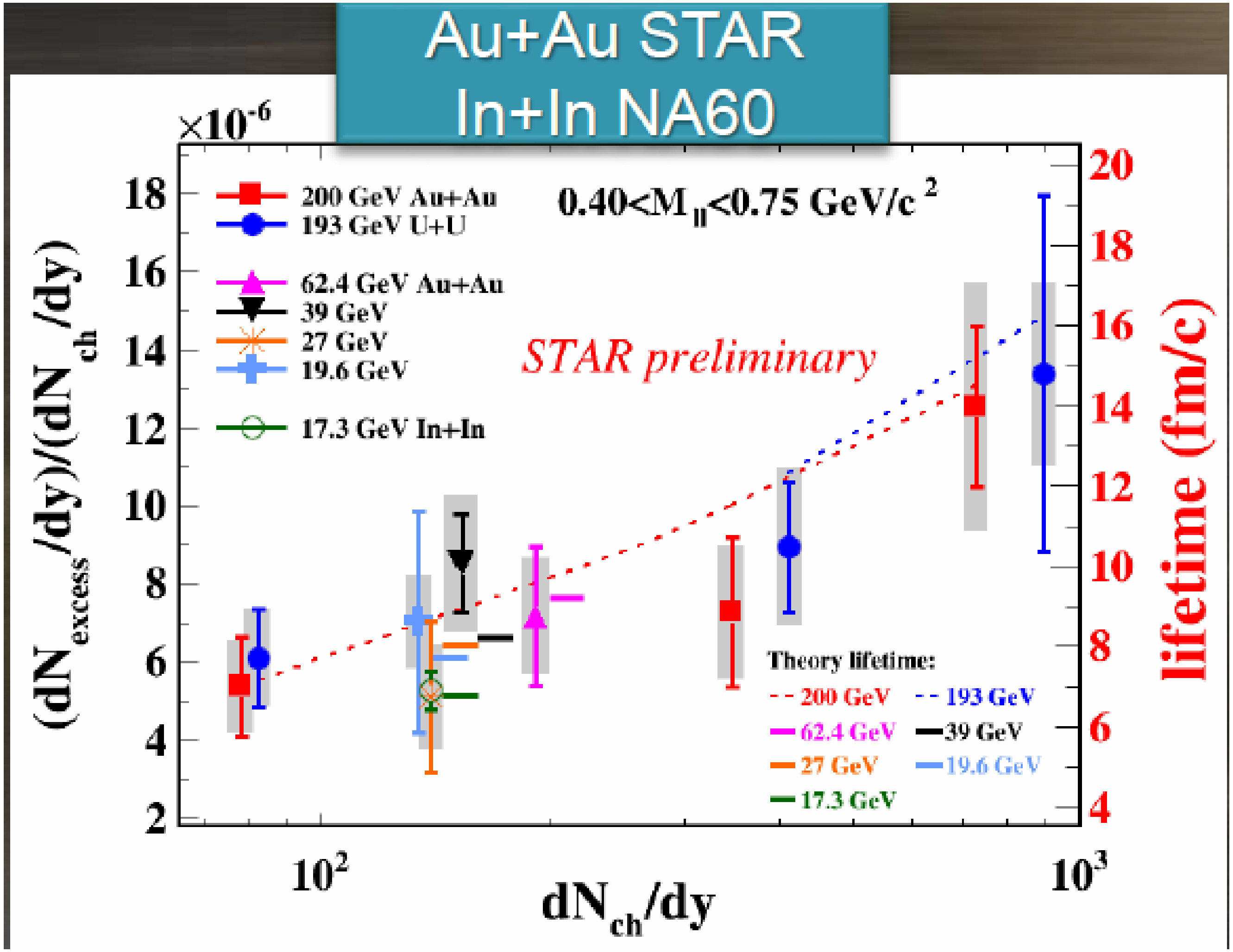
It works even for the heaviest system



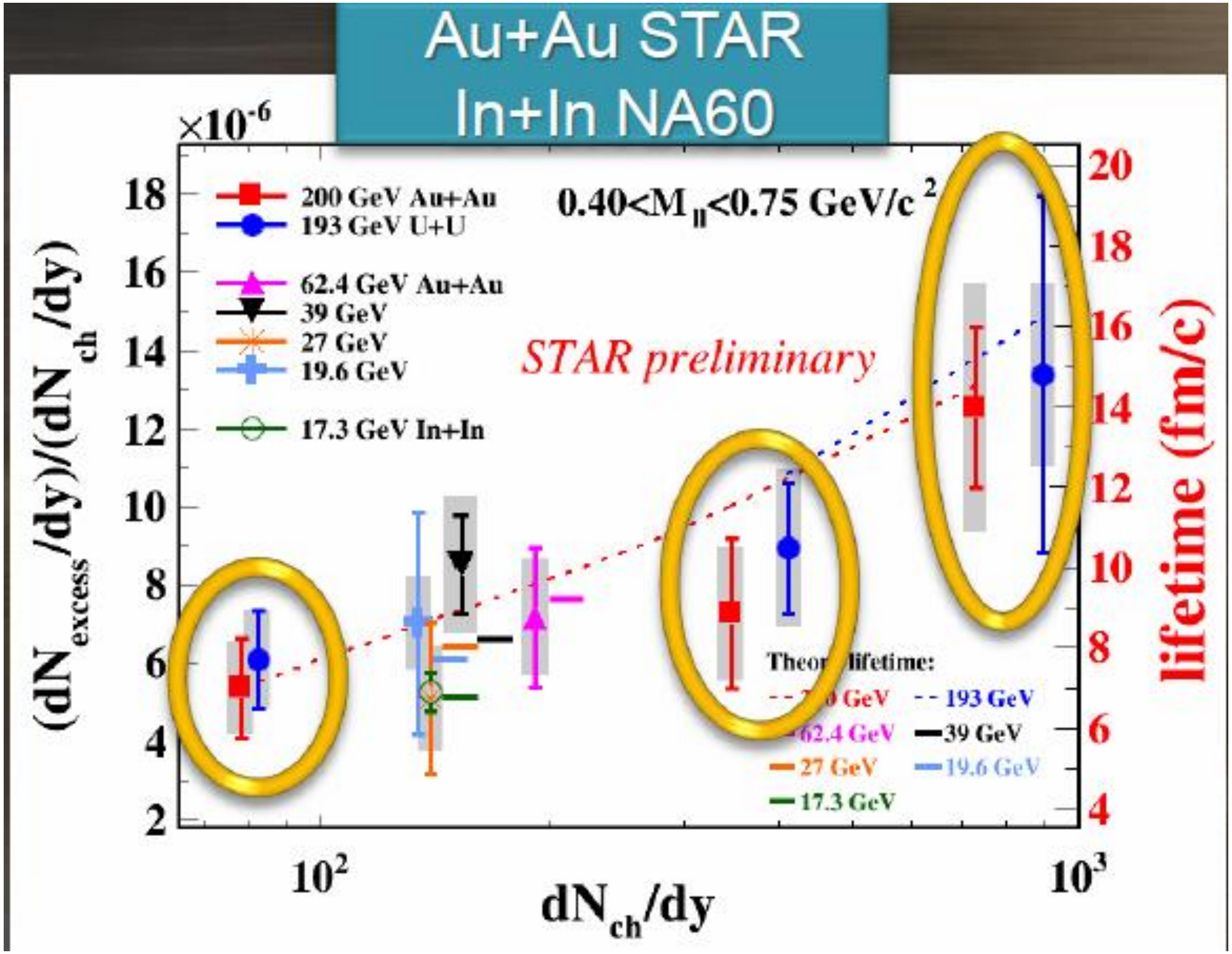
U+U 193 GeV STAR

Topic 3: Resonances and the lifetime of the system

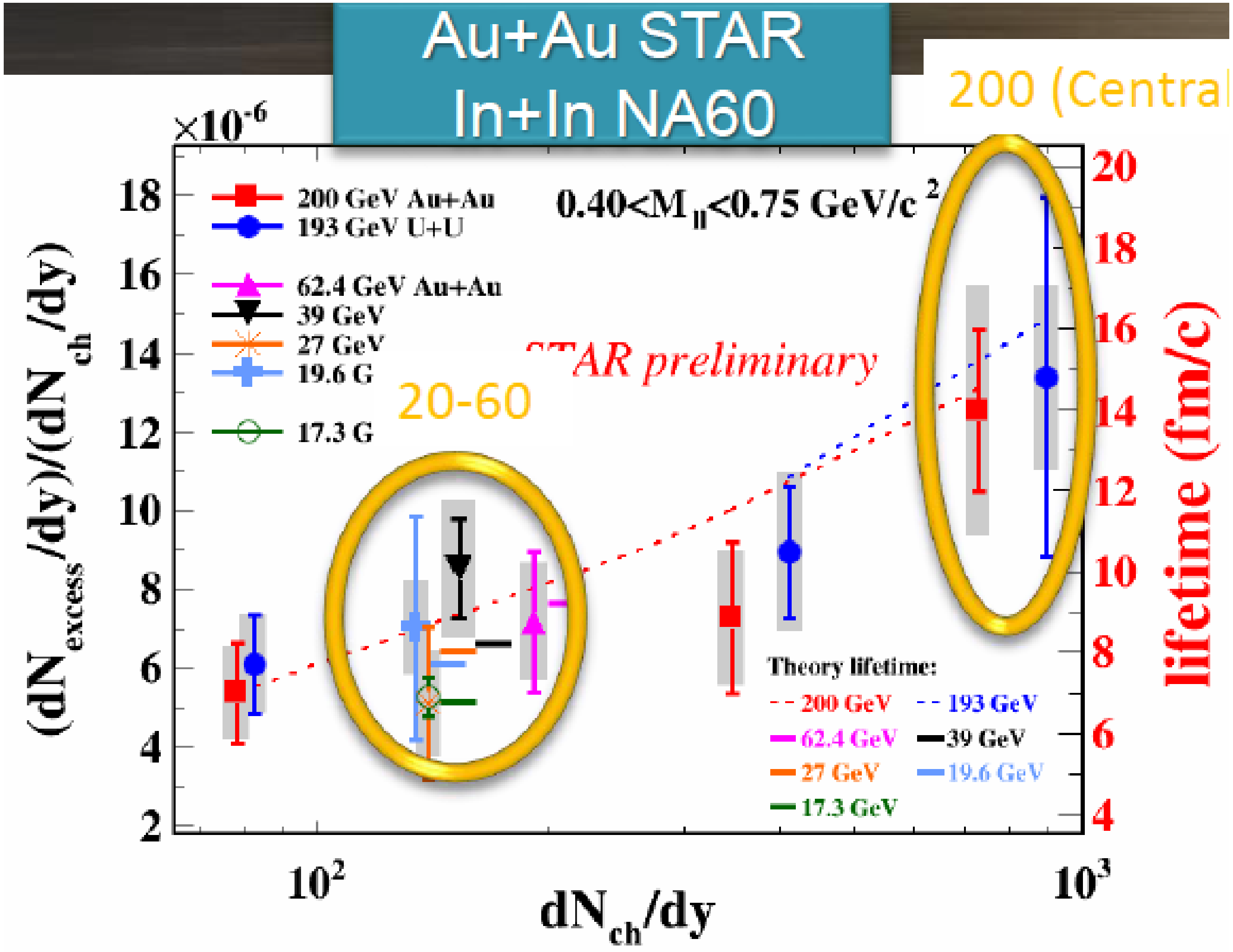
Relationship between excess and lifetime of the source



Increase as a function of centrality



Increase as a function of energy

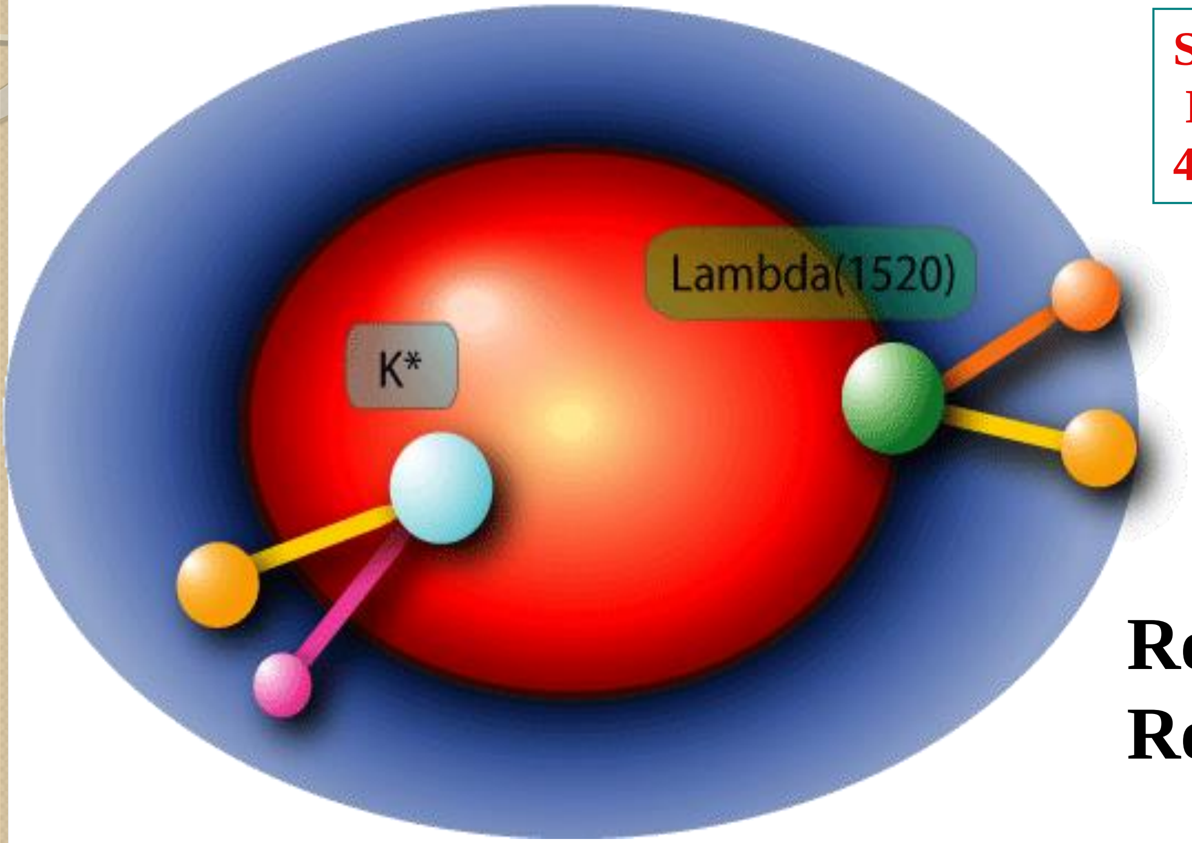


Au+Au STAR
In+In NA60

200 (Central

20-60

Strange resonances in medium



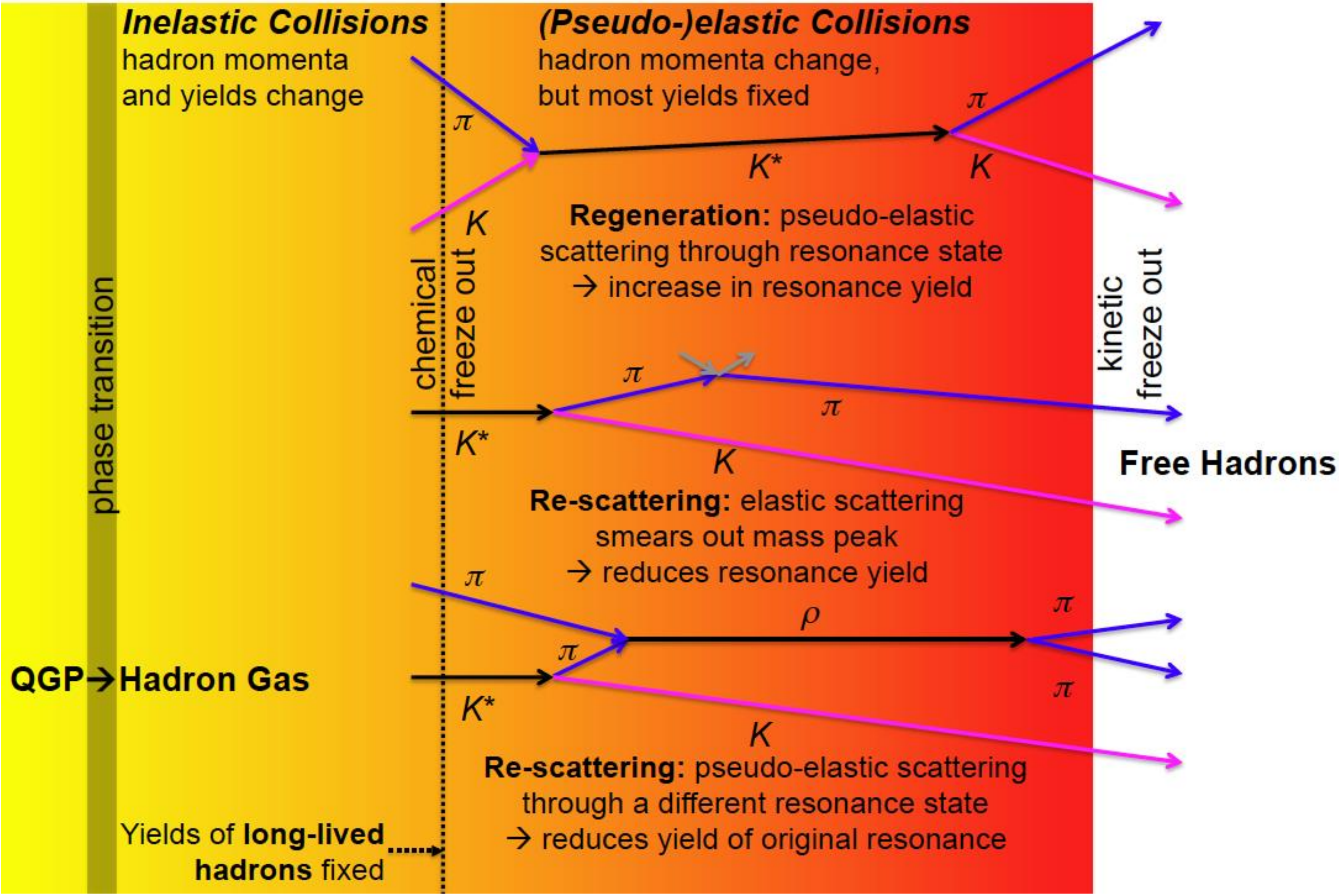
Short life times [fm/c]:
K* < Σ*< Λ(1520) < ϕ
4 < 6 < 13 < 40

Rescattering vs. Regeneration ?

Red: before chemical freeze out
Blue: after chemical freeze out

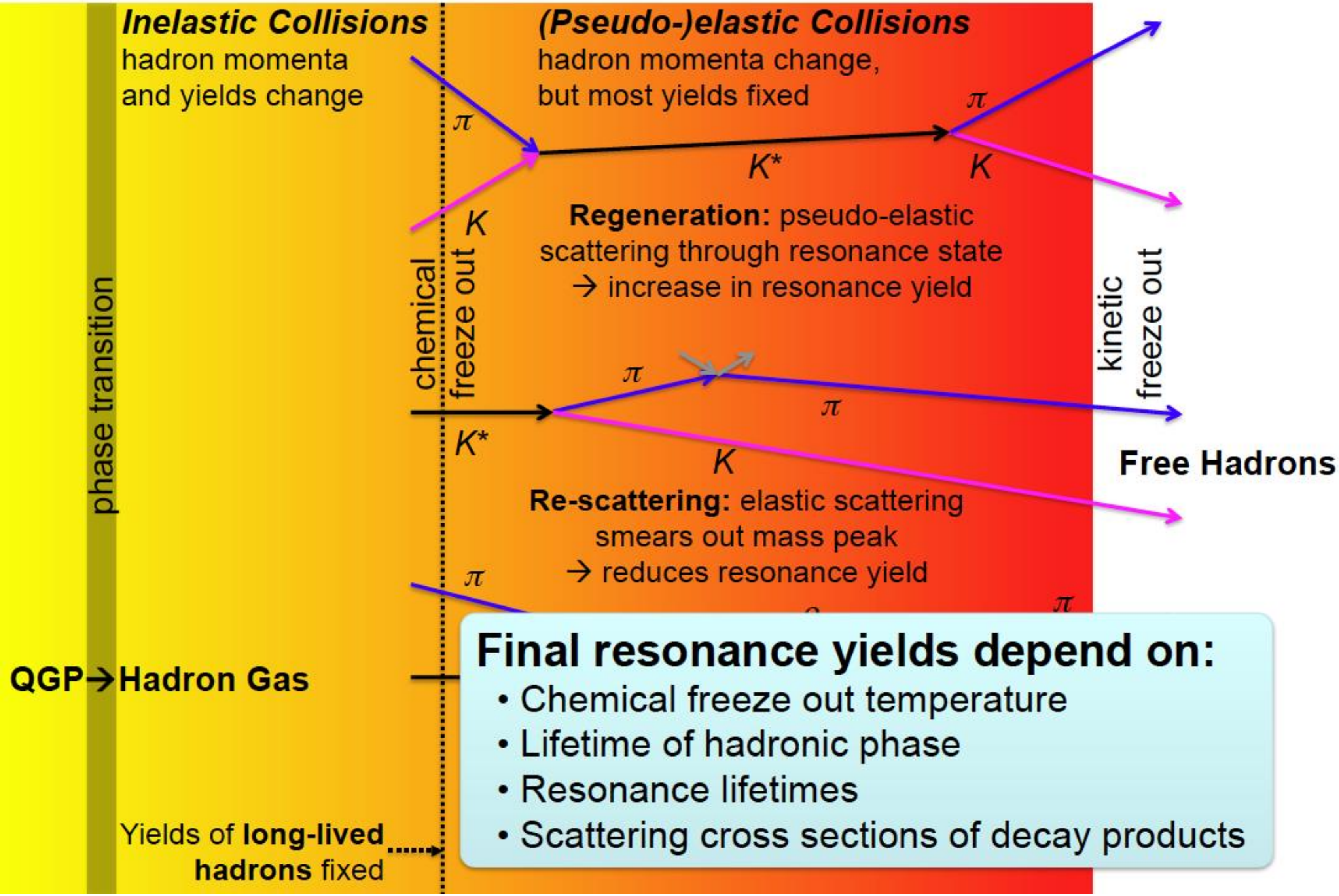
Medium effects on resonance and their decay products before (inelastic) and after chemical freeze out (elastic).

What happens in the experiment ?



R. BELLWIED

Sensitive to many different observables



Inelastic Collisions
hadron momenta
and yields change

phase transition

chemical freeze out

(Pseudo-)elastic Collisions
hadron momenta change,
but most yields fixed

Regeneration: pseudo-elastic scattering through resonance state
→ increase in resonance yield

Re-scattering: elastic scattering smears out mass peak
→ reduces resonance yield

kinetic freeze out

Free Hadrons

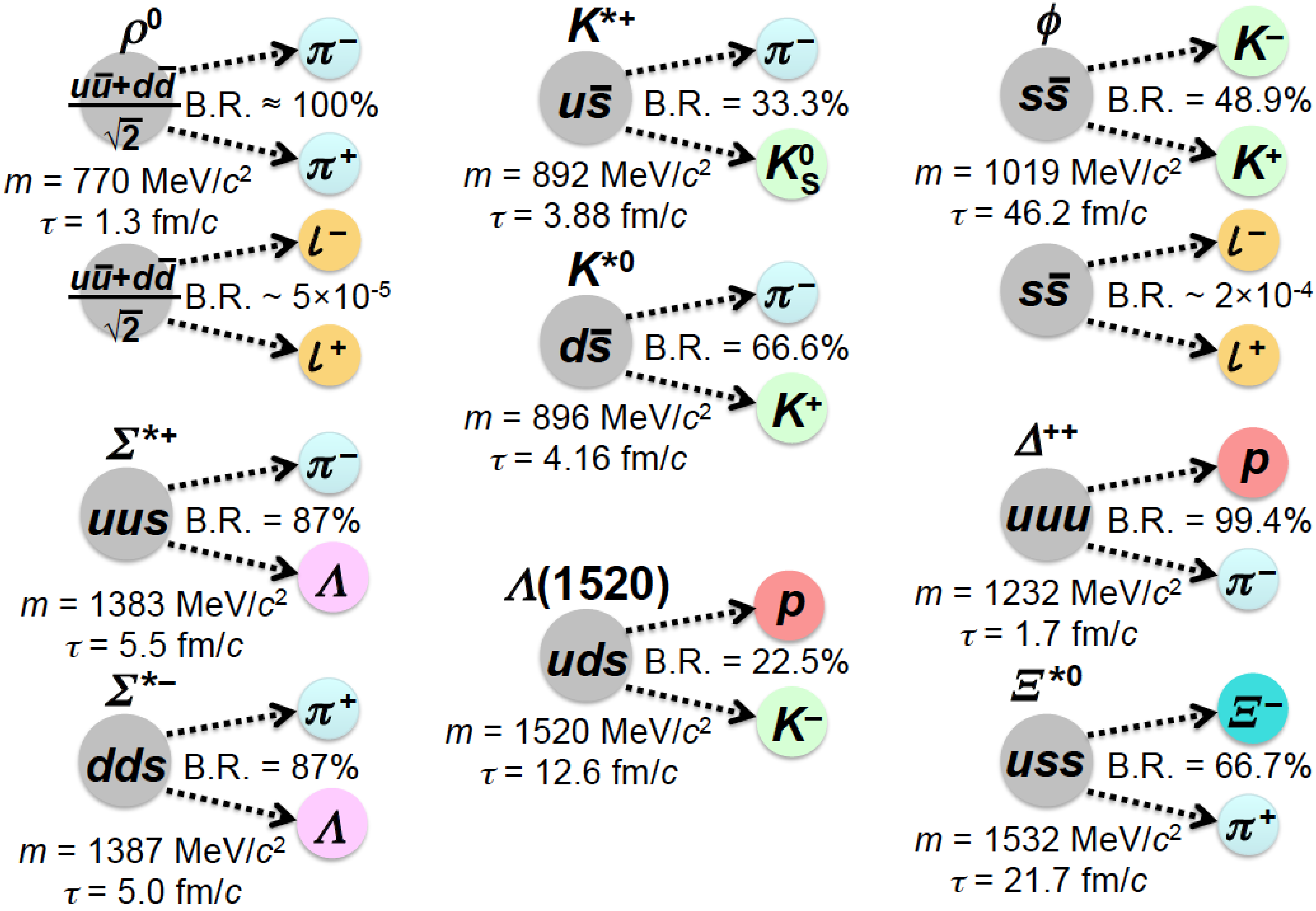
QGP→Hadron Gas

Yields of **long-lived hadrons** fixed

Final resonance yields depend on:

- Chemical freeze out temperature
- Lifetime of hadronic phase
- Resonance lifetimes
- Scattering cross sections of decay products

with many different measurements



ρ^0

$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$ B.R. ≈ 100%

π^-

π^+

m = 770 MeV/c^2

τ = 1.3 fm/c

$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$ B.R. ~ 5×10^{-5}

l^-

l^+

Σ^{*+}

uus B.R. = 87%

π^-

Λ

m = 1383 MeV/c^2

τ = 5.5 fm/c

Σ^{*-}

dds B.R. = 87%

π^+

Λ

m = 1387 MeV/c^2

τ = 5.0 fm/c

K^{*+}

$u\bar{s}$ B.R. = 33.3%

π^-

K^0_S

m = 892 MeV/c^2

τ = 3.88 fm/c

K^{*0}

$d\bar{s}$ B.R. = 66.6%

π^-

K^+

m = 896 MeV/c^2

τ = 4.16 fm/c

$\Lambda(1520)$

uds B.R. = 22.5%

p

K^-

m = 1520 MeV/c^2

τ = 12.6 fm/c

ϕ

$s\bar{s}$ B.R. = 48.9%

K^-

K^+

m = 1019 MeV/c^2

τ = 46.2 fm/c

$s\bar{s}$ B.R. ~ 2×10^{-4}

l^-

l^+

Δ^{++}

uuu B.R. = 99.4%

p

π^-

m = 1232 MeV/c^2

τ = 1.7 fm/c

Ξ^{*0}

uss B.R. = 66.7%

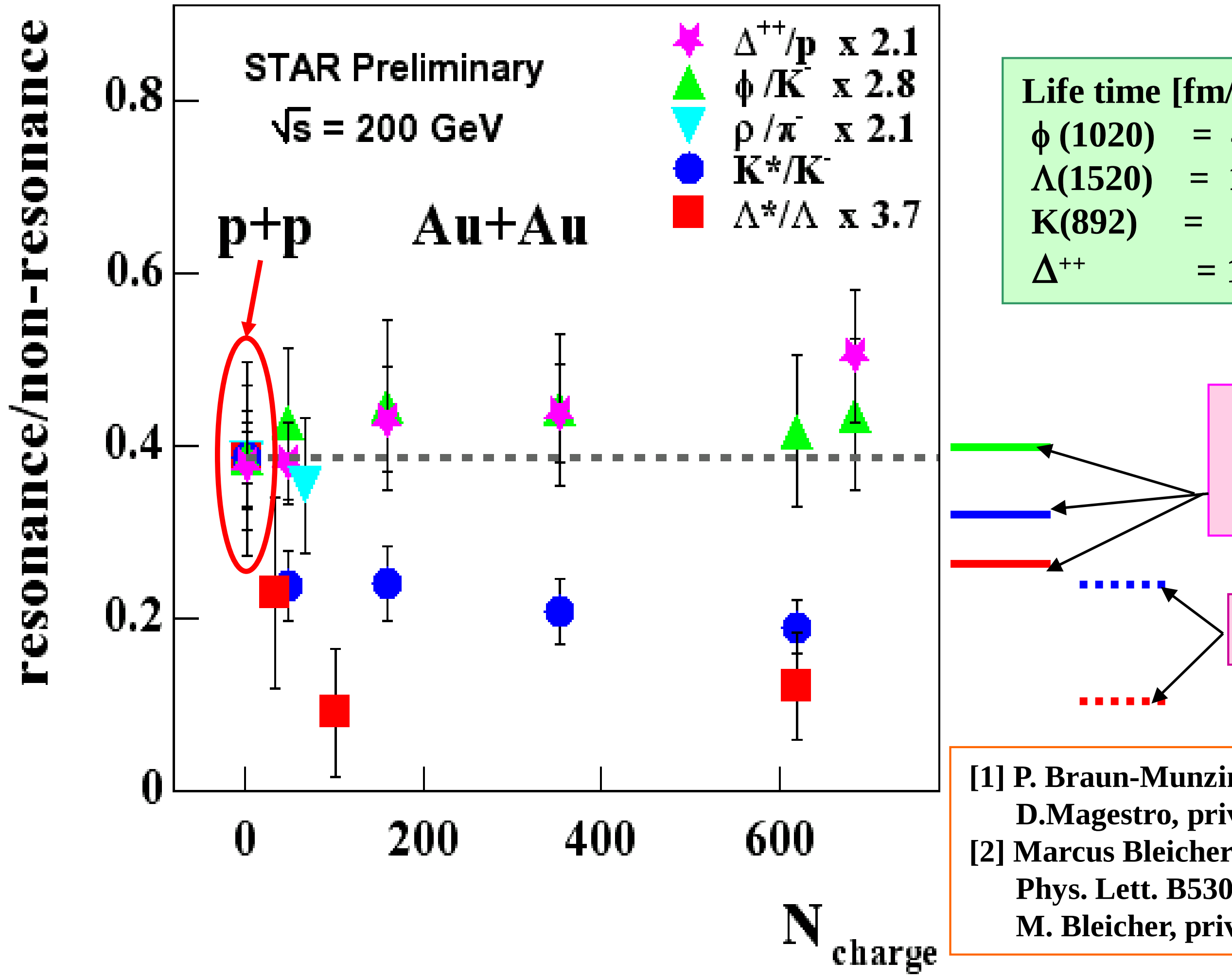
Ξ^-

π^+

m = 1532 MeV/c^2

τ = 21.7 fm/c

Particle Yield Ratios in STAR



Life time [fm/c] :

ϕ (1020) = 40

Λ(1520) = 13

K(892) = 4

Δ^{++} = 1.7

Thermal model [1]:

T = 177 MeV

μ_B = 29 MeV

UrQMD [2]

[1] P. Braun-Munzinger et.al., PLB 518(2001) 41
D.Magestro, private communication

[2] Marcus Bleicher and Jörg Aichelin
Phys. Lett. B530 (2002) 81-87.
M. Bleicher, private communication

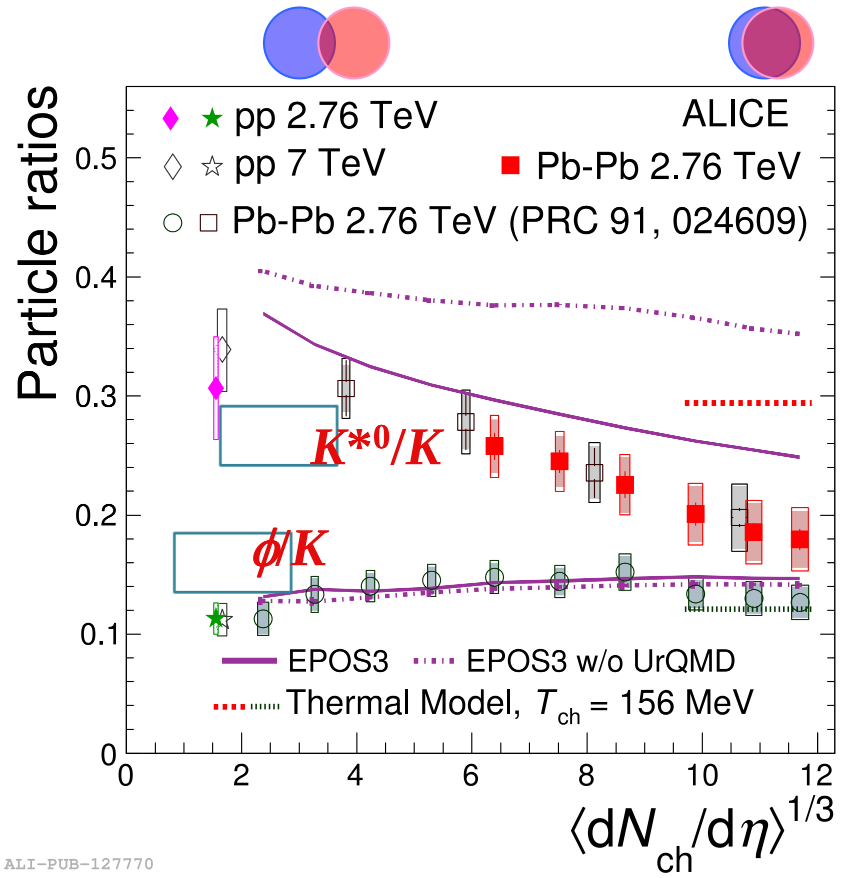
Rescattering and regeneration is needed !

Strength can determine hadronic/partonic lifetime

R. BELLWIED

Particle Yield Ratios in ALICE

- Suppression of K^{*0}/K in central Pb+Pb w.r.t. peripheral Pb+Pb, $p+p$ and thermal model
  - Qualitatively described by EPOS with UrQMD
- No suppression of ϕ/K
  - Central Pb+Pb consistent with thermal model
- Suggests that K^{*0} re-scattering is dominant over regeneration
  - Lifetime of K^{*0} = 4.16 fm/c
  - Lifetime of ϕ = 46.2 fm/c
  - Re-scattering not significant for ϕ
- Estimate hadronic phase lifetime (model-dependent): $\Delta t \geq 2.4$ fm/c



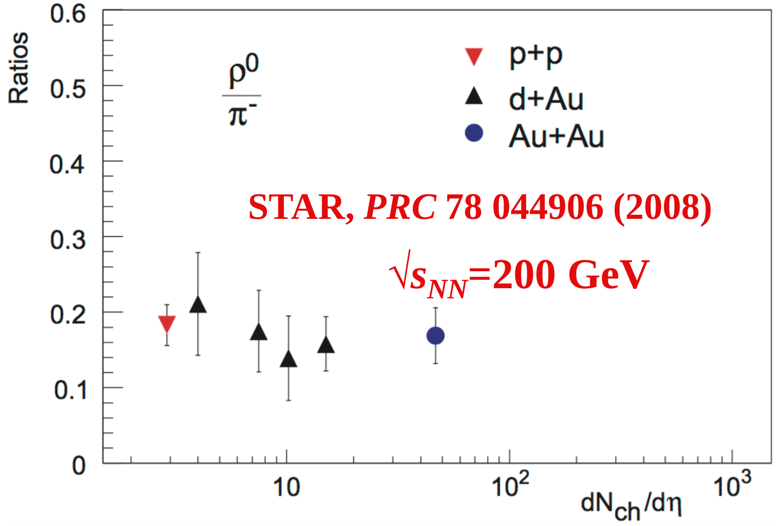
Plotted as function of $\langle dN_{ch}/d\eta \rangle^{1/3}$: proxy for system radius (*cf.* femtoscopy studies)

PRC 91 024609 (2015)
PRC 95 064606 (2017)
EPOS: *PRC* 93 014911 (2016)

$\tau(\rho^0)$ = 1.3 fm/c

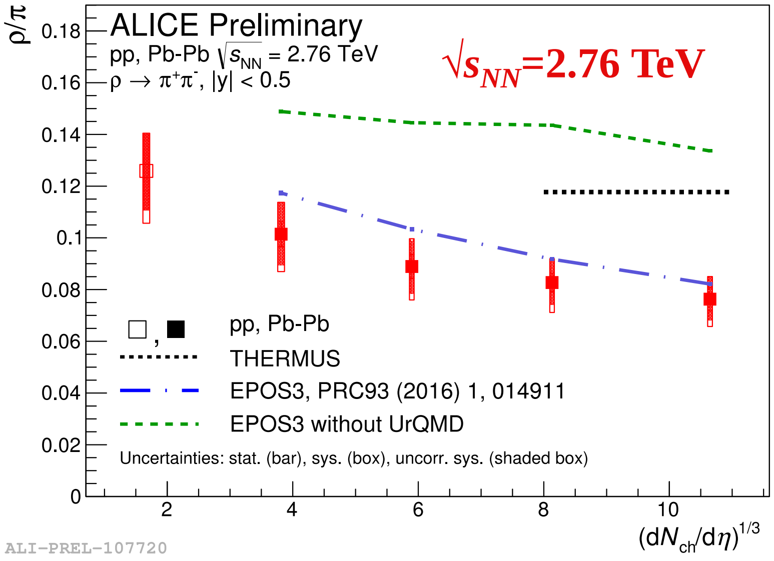
$\rho^0 + \Delta^{++}$

$\tau(\Delta^{++})$ = 1.7 fm/c

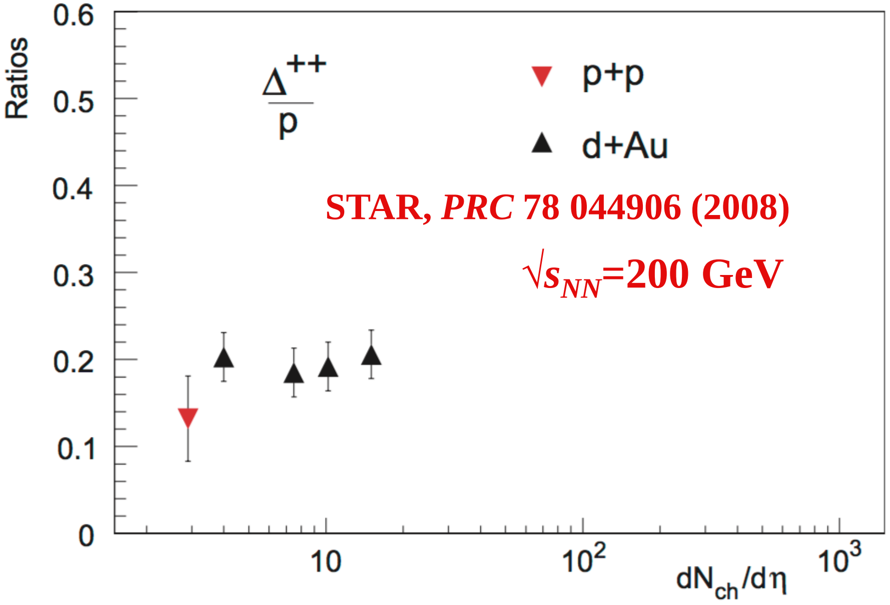


STAR, *PRC* 78 044906 (2008)

$\sqrt{s_{NN}}$=200 GeV



$\sqrt{s_{NN}}$=2.76 TeV

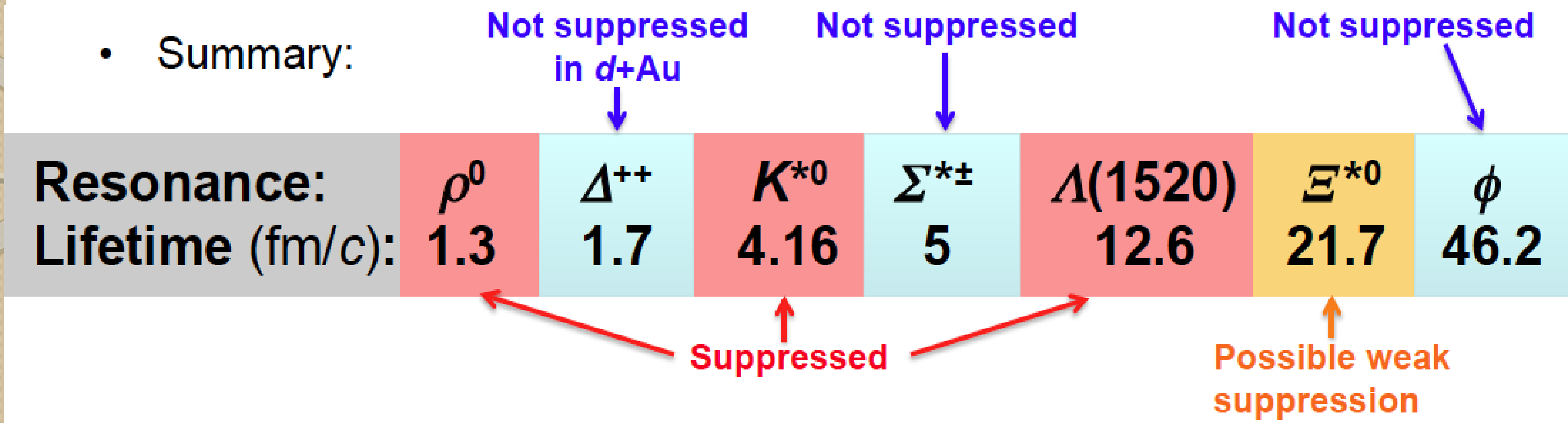


STAR, *PRC* 78 044906 (2008)

$\sqrt{s_{NN}}$=200 GeV

Summary: resonance yield measurements

- Summary:



Resonance:	ρ^0	Δ^{++}	K^{*0}	$\Sigma^{*\pm}$	$\Lambda(1520)$	Ξ^{*0}	ϕ
Lifetime (fm/*c*):	**1.3**	**1.7**	**4.16**	**5**	**12.6**	**21.7**	**46.2**

Not suppressed in *d*+Au

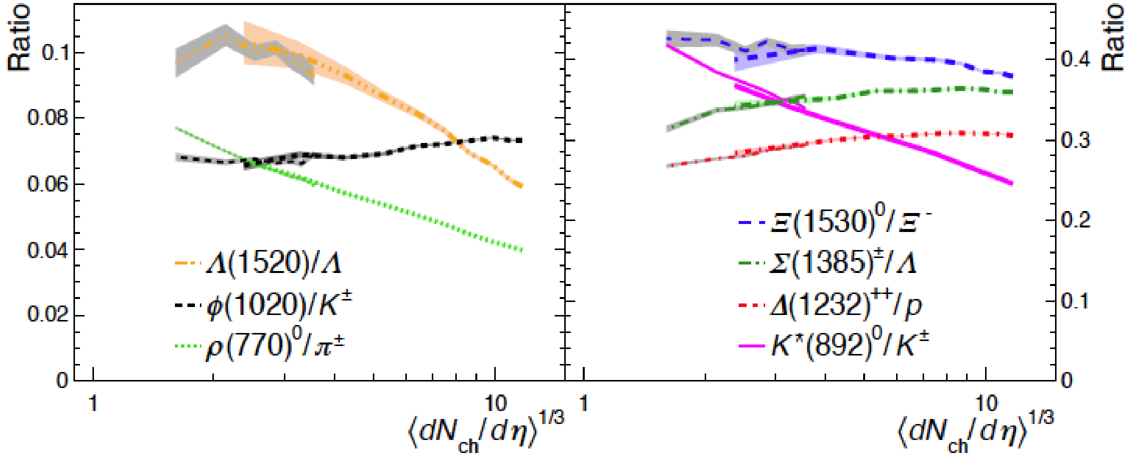
Not suppressed

Not suppressed

Suppressed

Possible weak suppression

- Shorter-lived resonances suppressed, but lifetime not only factor
  - Scattering cross sections
  - Competition between regeneration and re-scattering
- EPOS w/ UrQMD qualitatively describes (non-)suppression patterns



Topic 4: Resonances and the HRG

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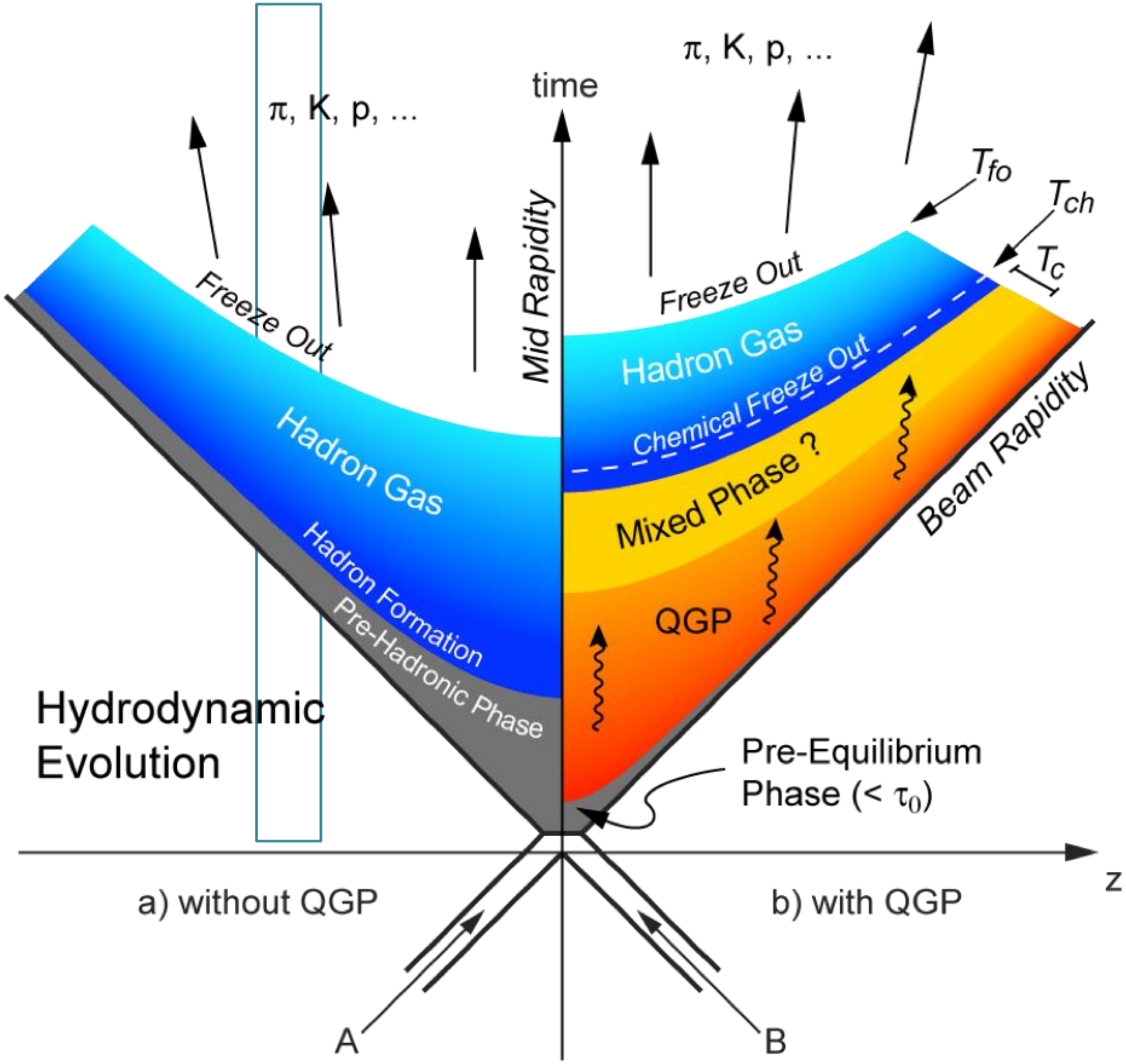
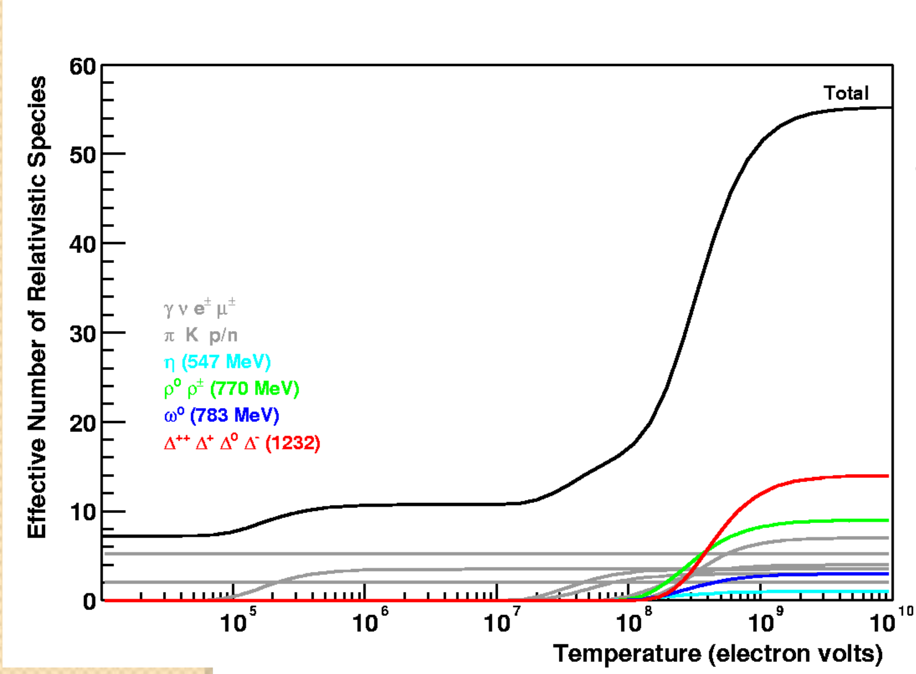
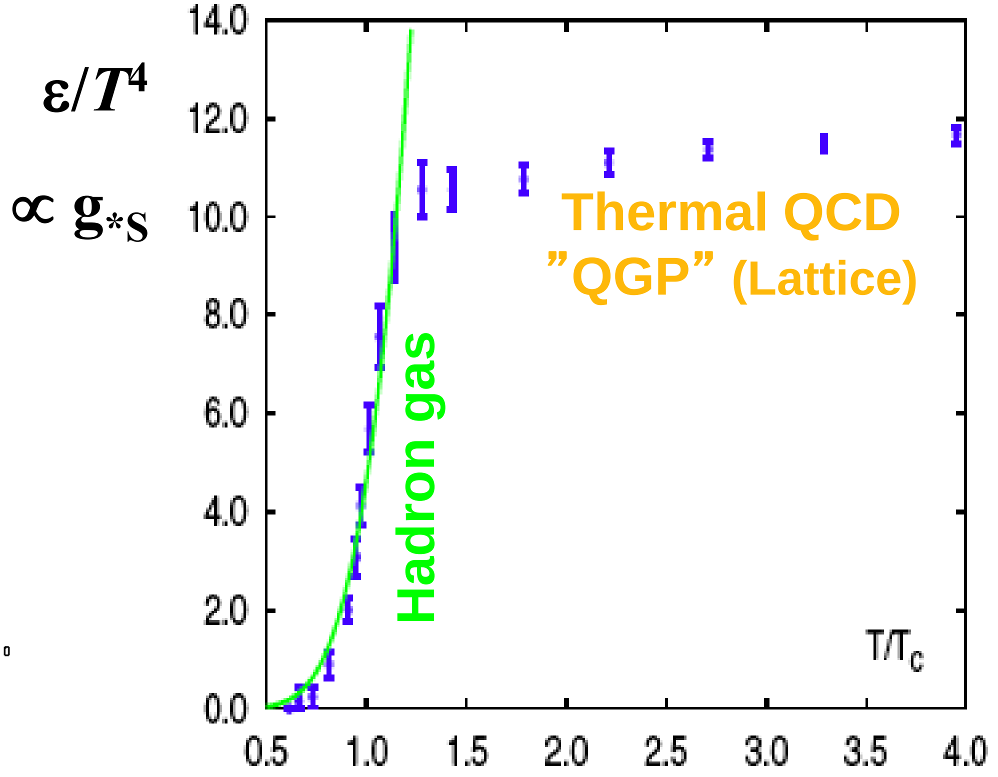
Describing the transition hadronically



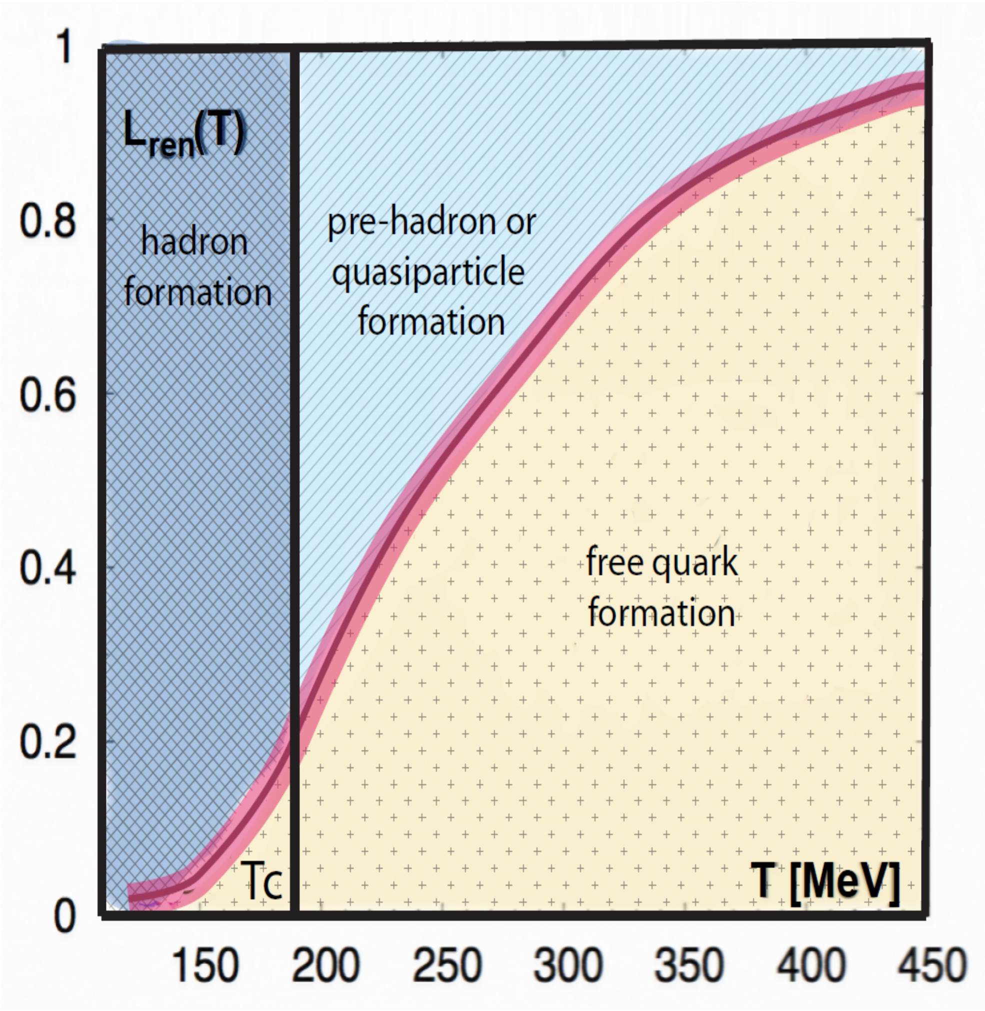
The more resonances I add the better the agreement with lattice QCD at high T ? Transition/ Chemical Freeze-out T get pushed out to higher temperature ?





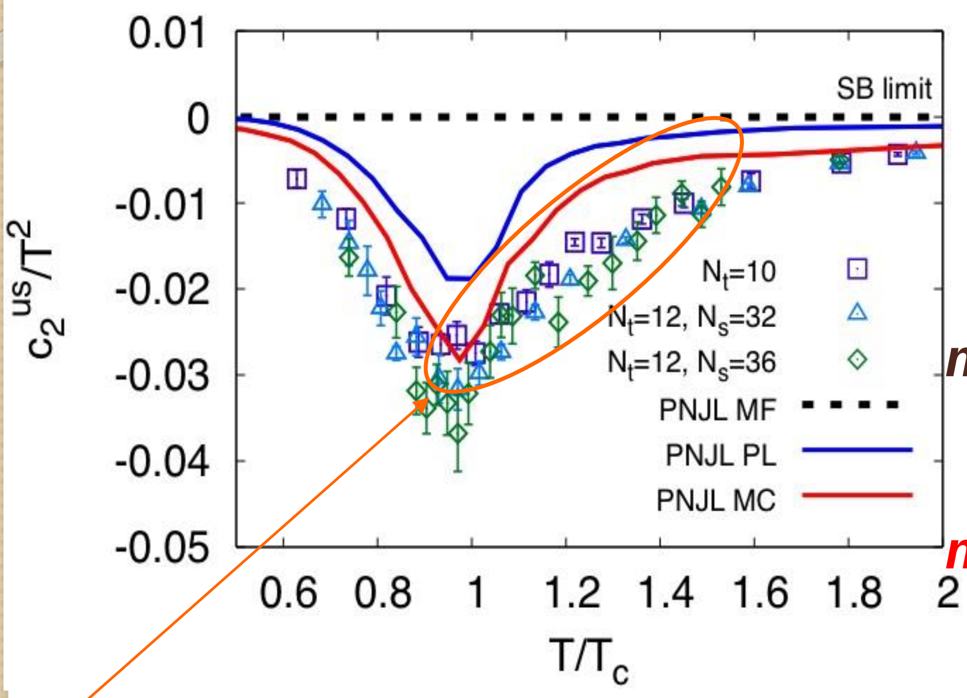
A smooth cross-over

The smoother the crossover the more contributions from hadronic degrees of freedom ?



Indication of bound states in non-diagonal susceptibility correlators

(C. Ratti et al., PRD 85, 014004 (2012))

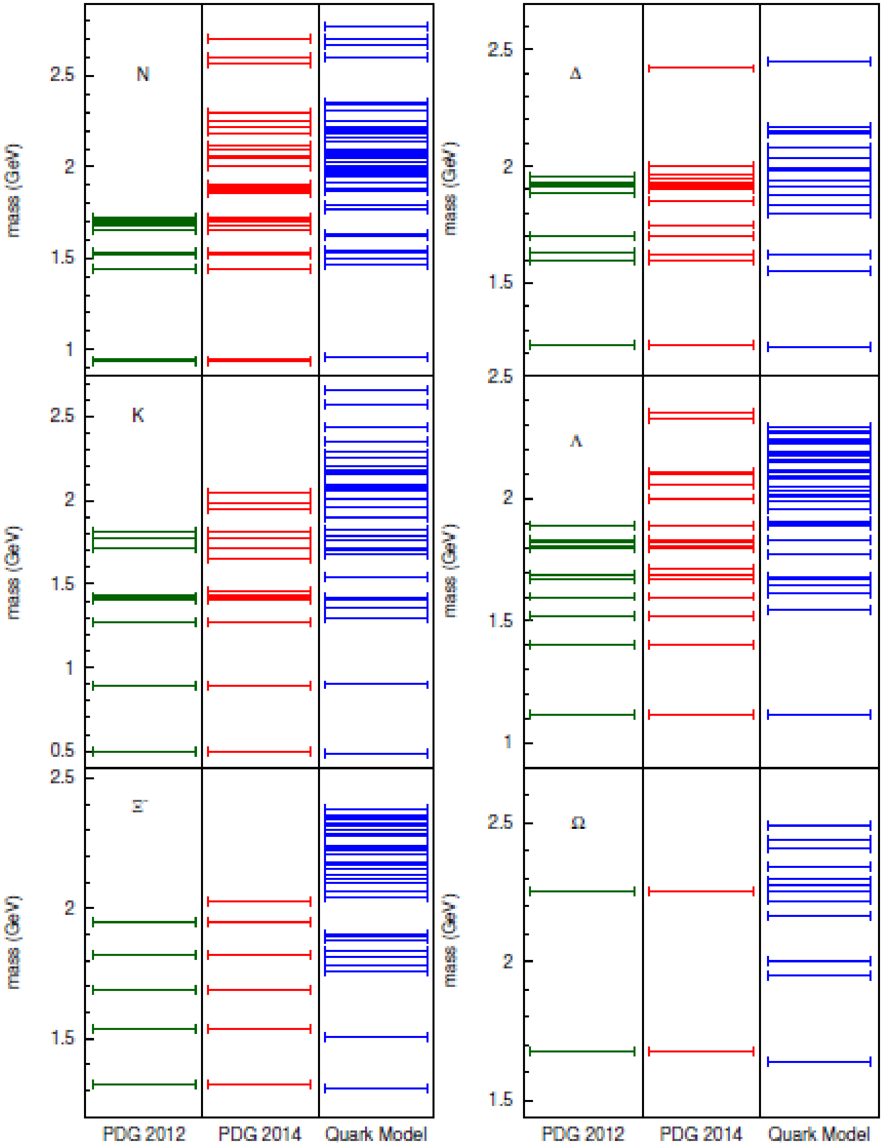


<u>PNJL variations</u>

PNJL-MF:
pure mean field calculation
PNJL-PL:
mean field plus Polyakov loop fluctuations
PNJL-MC:
mean field plus all fluctuations (incl. chiral and Kaon condensate fluctuations)

Conclusion: even the inclusion of *all possible flucutations* is *not sufficient* to describe lattice data above Tc.
<u>There has to be a contribution from bound states</u>

The incomplete HRG input spectrum



First suggested as a possible ‘solution’ to the different flavor surfaces by Bazavov et al. (PRL (2014), arXiv:1404.6511)

Higher Strange States based on Quark Model Calculations (e.g. PRD79, 114029 (2009))

A more detailed study by P.Alba et al., (arXiv:1702.01113)

Details from Quark Model calculations

(e.g. Ebert et al., PRD79 (2009) 114029)

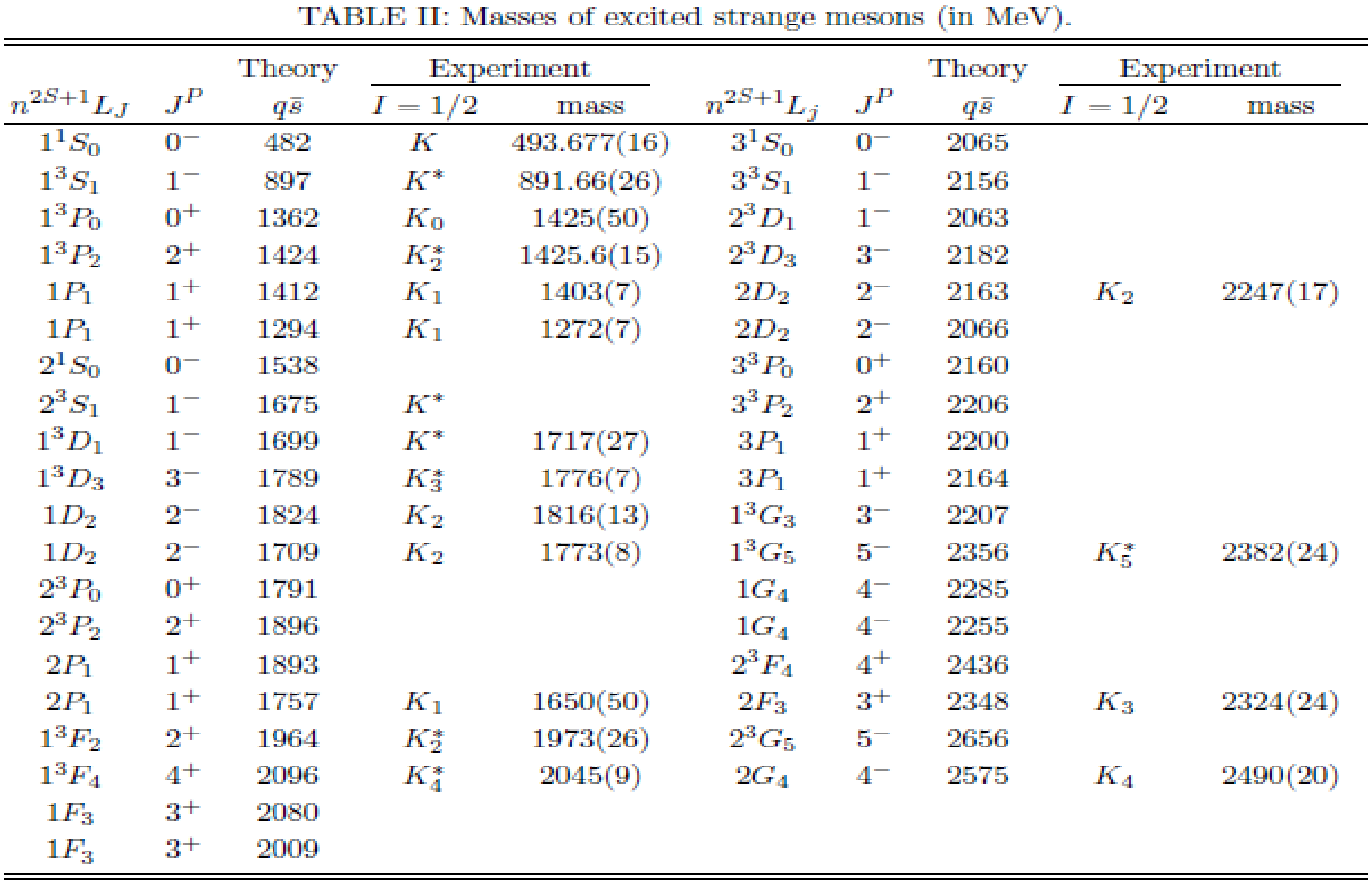
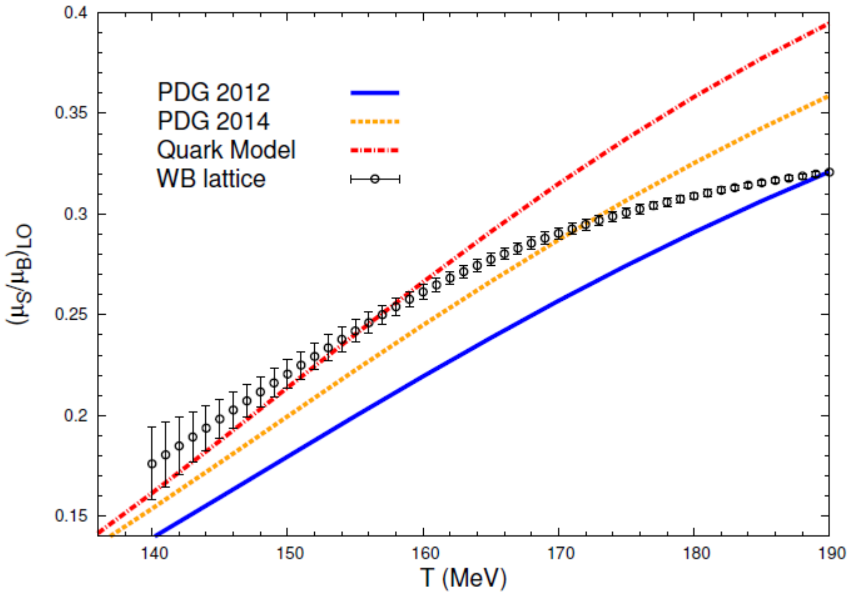


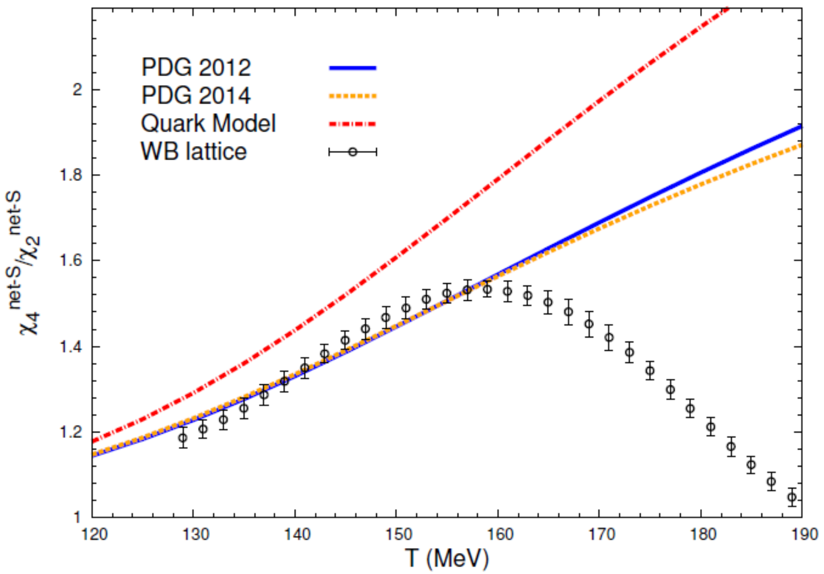
TABLE II: Masses of excited strange mesons (in MeV).

		Theory	Experiment				Theory	Experiment	
$n^{2S+1}L_J$	J^P	$q\bar{s}$	$I=1/2$	mass	$n^{2S+1}L_j$	J^P	$q\bar{s}$	$I=1/2$	mass
1^1S_0	0^-	482	K	493.677(16)	3^1S_0	0^-	2065		
1^3S_1	1^-	897	K^*	891.66(26)	3^3S_1	1^-	2156		
1^3P_0	0^+	1362	K_0	1425(50)	2^3D_1	1^-	2063		
1^3P_2	2^+	1424	K_2^*	1425.6(15)	2^3D_3	3^-	2182		
$1P_1$	1^+	1412	K_1	1403(7)	$2D_2$	2^-	2163	K_2	2247(17)
$1P_1$	1^+	1294	K_1	1272(7)	$2D_2$	2^-	2066		
2^1S_0	0^-	1538			3^3P_0	0^+	2160		
2^3S_1	1^-	1675	K^*		3^3P_2	2^+	2206		
1^3D_1	1^-	1699	K^*	1717(27)	$3P_1$	1^+	2200		
1^3D_3	3^-	1789	K_3^*	1776(7)	$3P_1$	1^+	2164		
$1D_2$	2^-	1824	K_2	1816(13)	1^3G_3	3^-	2207		
$1D_2$	2^-	1709	K_2	1773(8)	1^3G_5	5^-	2356	K_5^*	2382(24)
2^3P_0	0^+	1791			$1G_4$	4^-	2285		
2^3P_2	2^+	1896			$1G_4$	4^-	2255		
$2P_1$	1^+	1893			2^3F_4	4^+	2436		
$2P_1$	1^+	1757	K_1	1650(50)	$2F_3$	3^+	2348	K_3	2324(24)
1^3F_2	2^+	1964	K_2^*	1973(26)	2^3G_5	5^-	2656		
1^3F_4	4^+	2096	K_4^*	2045(9)	$2G_4$	4^-	2575	K_4	2490(20)
$1F_3$	3^+	2080							
$1F_3$	3^+	2009							

Simple expansion of higher spin parity states, but not all states might be energetically favorable

Comparison of lattice QCD susceptibilities to HRG model calculations with different hadron spectra input





Adding unverified states might help for certain susceptibilities but worsens agreement with others. There are many Quark Models with different numbers of ‘extra states’ depending on the quark interaction.

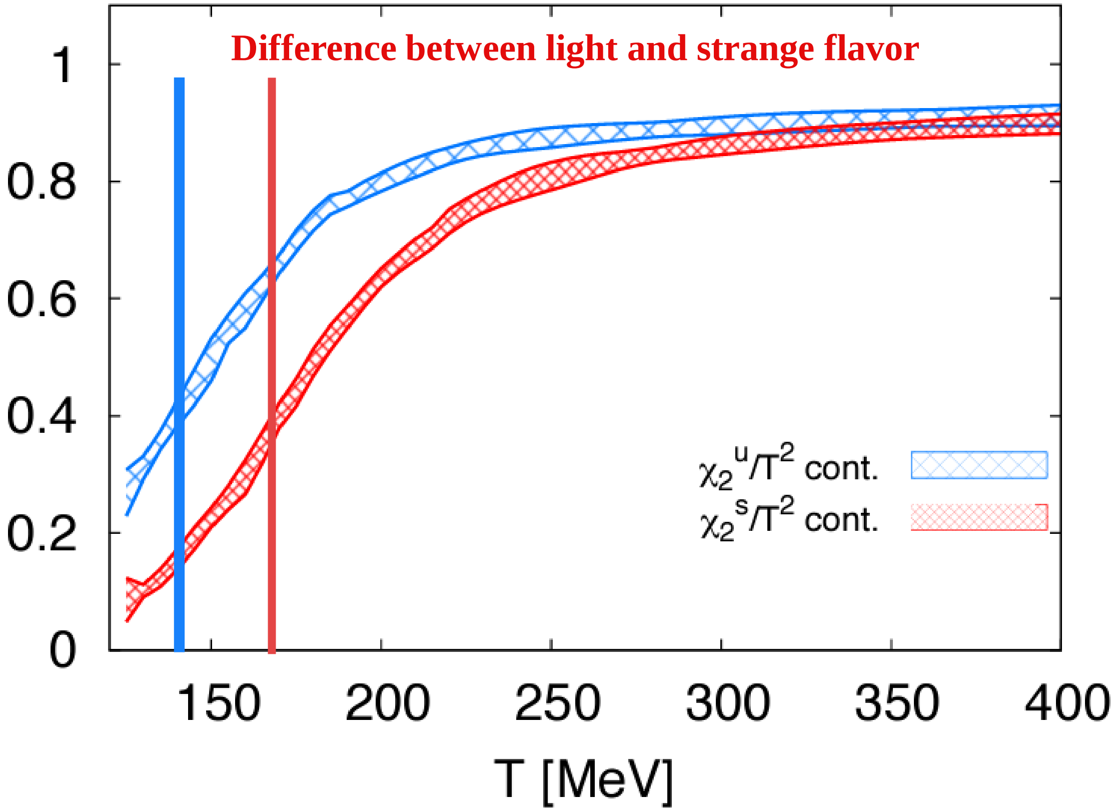
We need to experimentally verify possible higher states.

Best compromise seems to be PDG2016+ (incl. all 1-star resonances), see P.Alba et al., arXiv:1702.01113

The comparison to lattice QCD has predictive power !

Topic 5: Multi-quark states

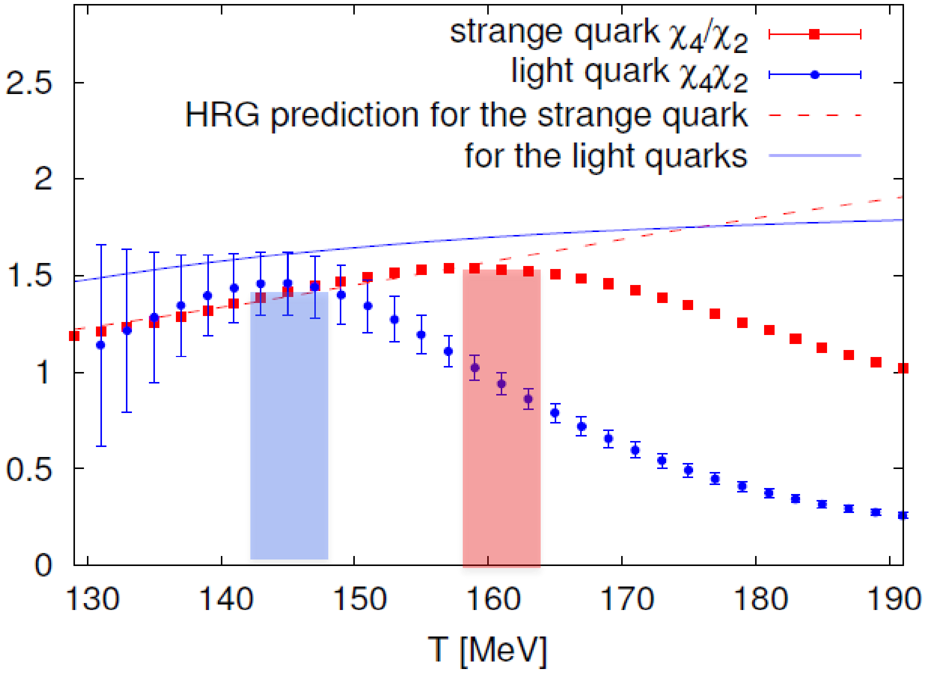
Indication of flavor dependence in diagonal susceptibility correlators



C. Ratti et al., PRD 85, 014004 (2012)
R. Bellwied, arXiv:1205.3625

Direct determination of freeze-out parameters from first principles (lattice QCD)

$$\kappa_B\sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)}\left[\frac{1+\frac{1}{2}\frac{\chi^B_6(T)}{\chi^B_4(T)}(\mu_B/T)^2+\ldots}{1+\frac{1}{2}\frac{\chi^B_4(T)}{\chi^B_2(T)}(\mu_B/T)^2+\ldots}\right]$$



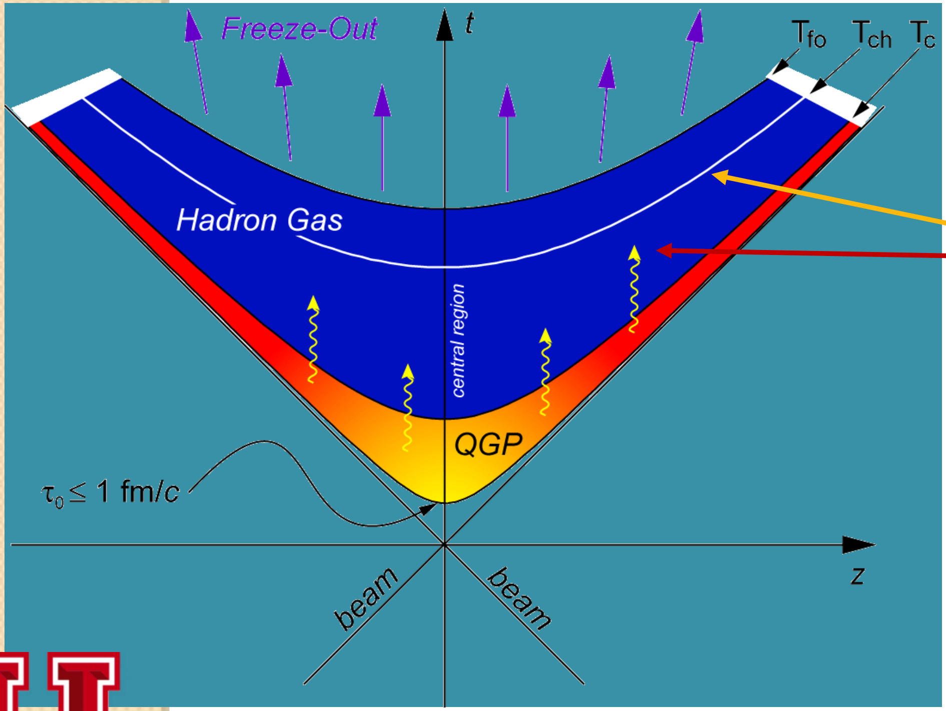
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

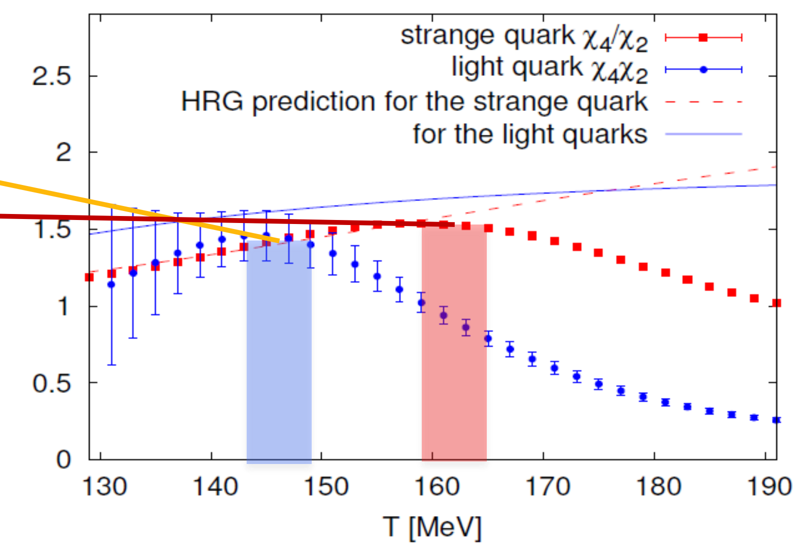
Susceptibility ratios are a model
Independent measure of the chemical freeze-out temperature
near μ=0.
(Karsch, arXiv:1202.4173)

In a regime where we have flavor (quark mass) dependent susceptibility ratios there might be no single freeze-out surface

But: a separate freeze-out surface for strange and light particles should lead to a preference of strange states and ultimately pure strange states

Enhances probability for Omega's and strangelets, strange clusters

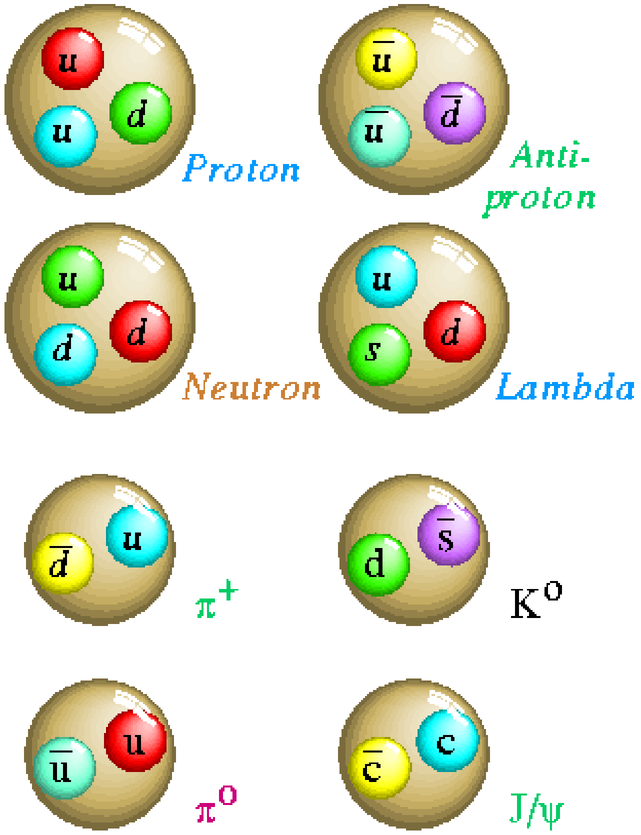




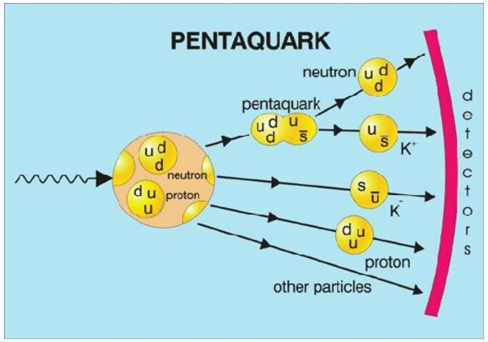
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

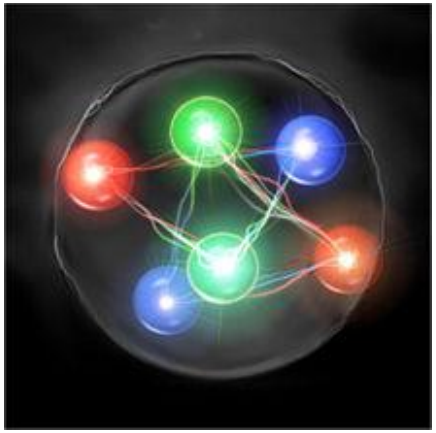
Why only three quark states ?

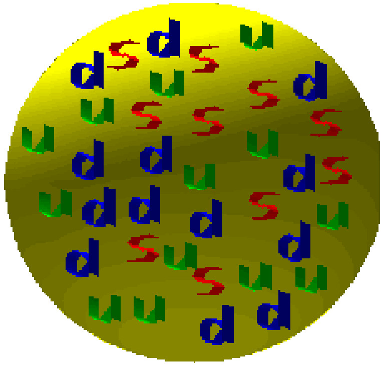
The standard two and three quark states as we know them



Endless possibilities of increasing complexity (all allowed theoretically)

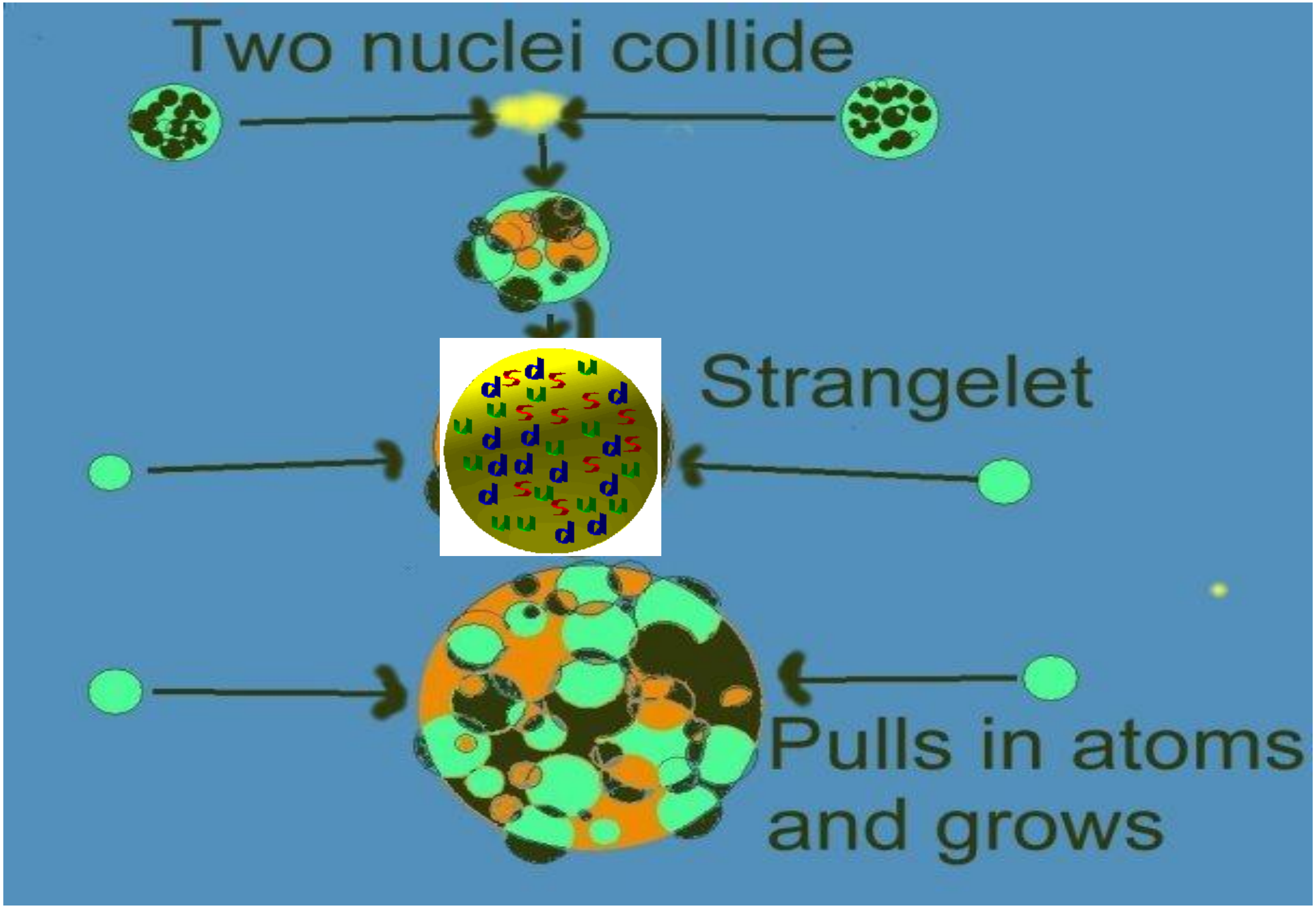






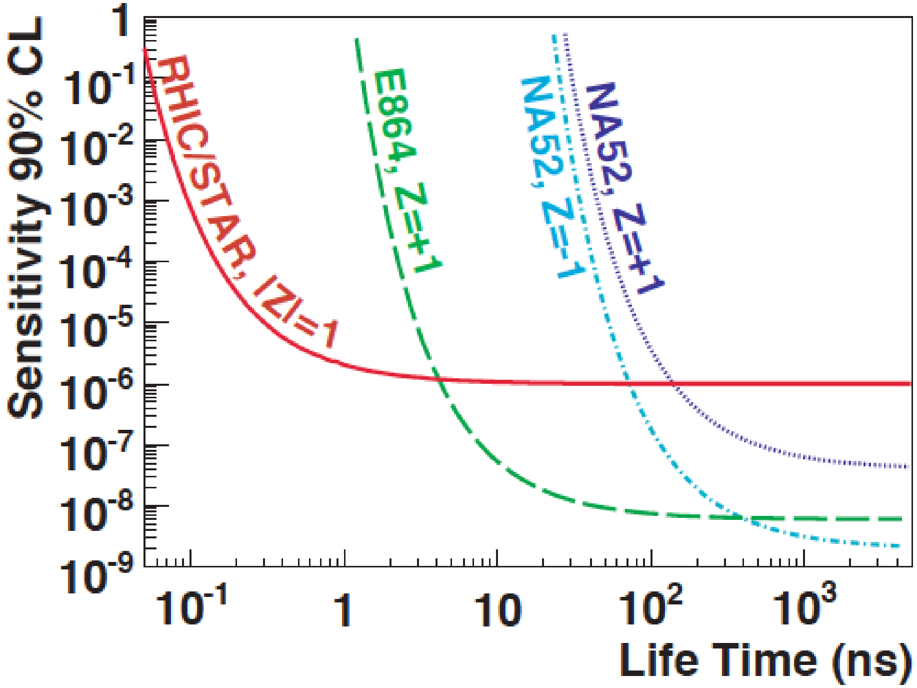
all involve strangeness

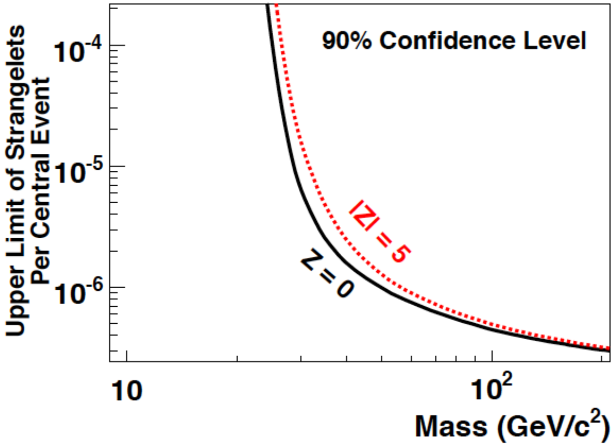
Could there be stable strange matter ?



Strangelets should be strangeness dominated

Direct formation from plasma, definitely not formed hadronically

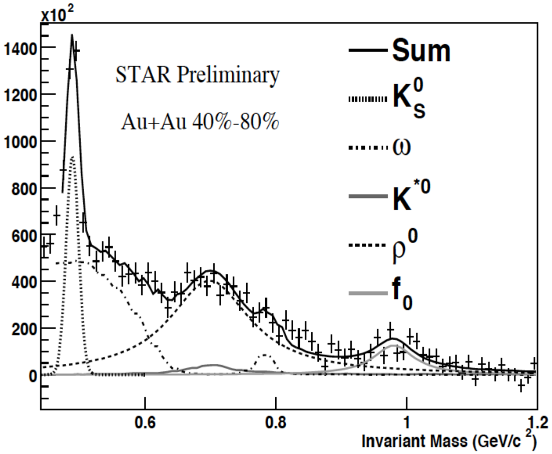


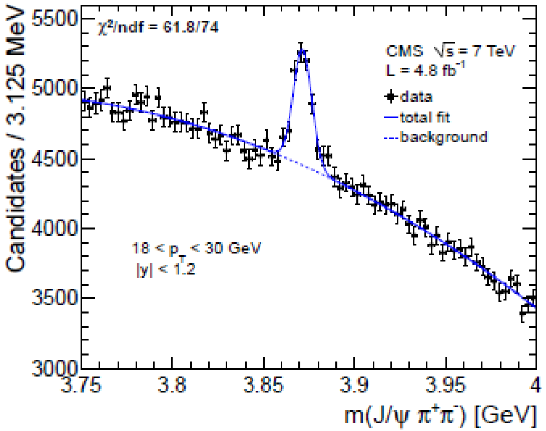


Only *negative results from RHI collisions*

Exotic states within the Standard Model

Exotic states measured at RHIC and the LHC (strange and charm sector)



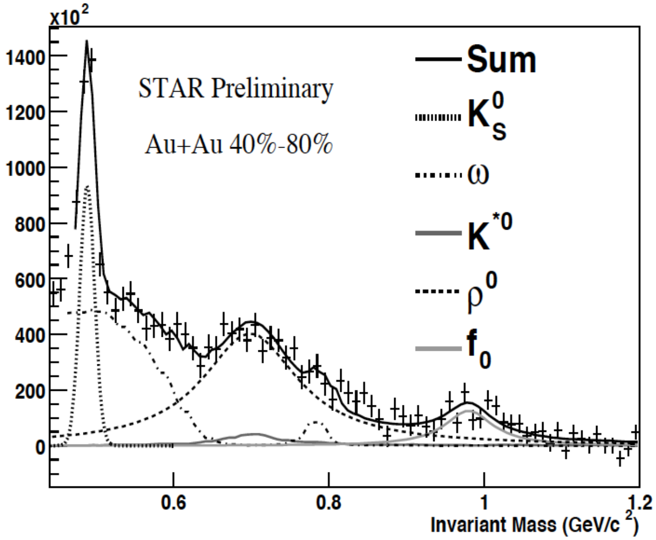


ExHIC Collaboration (2011):

								RHIC				LHC			
Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.	$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
Mesons															
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	$3.8, 0.73(s\bar{s})$	0.10	13	5.6	$10, 2.0\ (s\bar{s})$	0.28	36	15
$a_0(980)$	980	3	1	0^+	$q\bar{q}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$	11	0.31	40	17	31	0.83	1.1×10^2	46
$K(1460)$	1460	2	1/2	0^-	$q\bar{s}$	$q\bar{q}q\bar{s}$	$\bar{K}KK$	—	0.59	3.6	1.3	—	1.6	9.3	3.2
$D_s(2317)$	2317	1	0	0^+	$c\bar{s}(L=1)$	$q\bar{q}c\bar{s}$	DK	1.3×10^{-2}	2.1×10^{-3}	1.6×10^{-2}	5.6×10^{-2}	8.7×10^{-2}	1.4×10^{-2}	0.10	0.35
T_{cc}^{1}[a]	3797	3	0	1^+	—	$qq\bar{c}\bar{c}$	$\bar{D}\bar{D}^*$	—	4.0×10^{-5}	2.4×10^{-5}	4.3×10^{-4}	—	6.6×10^{-4}	4.1×10^{-4}	7.1×10^{-3}
$X(3872)$	3872	3	0	$1^+, 2^{-}$[c]	$c\bar{c}(L=2)$	$q\bar{q}c\bar{c}$	$\bar{D}D^*$	1.0×10^{-4}	4.0×10^{-5}	7.8×10^{-4}	2.9×10^{-4}	1.7×10^{-3}	6.6×10^{-4}	1.3×10^{-2}	4.7×10^{-3}
$Z^+(4430)$[b]	4430	3	1	0^-[c]	—	$q\bar{q}c\bar{c}(L=1)$	$D_1\bar{D}^*$	—	1.3×10^{-5}	2.0×10^{-5}	1.4×10^{-5}	—	2.1×10^{-4}	3.4×10^{-4}	2.4×10^{-4}
T_{cb}^{0}[a]	7123	1	0	0^+	—	$qq\bar{c}\bar{b}$	$\bar{D}B$	—	6.1×10^{-8}	1.8×10^{-7}	6.9×10^{-7}	—	6.1×10^{-6}	1.9×10^{-5}	6.8×10^{-5}
Baryons															
$\Lambda(1405)$	1405	2	0	$1/2^-$	$qqs(L=1)$	$qqqs\bar{q}$	$\bar{K}N$	0.81	0.11	1.8–8.3	1.7	2.2	0.29	4.7–21	4.2
$\Theta^+(1530)$[b]	1530	2	0	$1/2^+$[c]	—	$qqqq\bar{s}(L=1)$	—	—	2.9×10^{-2}	—	1.0	—	7.8×10^{-2}	—	2.3
$\bar{K}KN$[a]	1920	4	1/2	$1/2^+$	—	$qqqs\bar{s}(L=1)$	$\bar{K}KN$	—	1.9×10^{-2}	1.7	0.28	—	5.2×10^{-2}	4.2	0.67
$\bar{D}N$[a]	2790	2	0	$1/2^-$	—	$qqqq\bar{c}$	$\bar{D}N$	—	2.9×10^{-3}	4.6×10^{-2}	1.0×10^{-2}	—	2.0×10^{-2}	0.28	6.1×10^{-2}
$\bar{D}^*N$[a]	2919	4	0	$3/2^-$	—	$qqqq\bar{c}(L=2)$	$\bar{D}^*N$	—	7.1×10^{-4}	4.5×10^{-2}	1.0×10^{-2}	—	4.7×10^{-3}	0.27	6.2×10^{-2}
Θ_{cs}[a]	2980	4	1/2	$1/2^+$	—	$qqqs\bar{c}(L=1)$	—	—	5.9×10^{-4}	—	7.2×10^{-3}	—	3.9×10^{-3}	—	4.5×10^{-2}
BN[a]	6200	2	0	$1/2^-$	—	$qqqq\bar{b}$	BN	—	1.9×10^{-5}	8.0×10^{-5}	3.9×10^{-5}	—	7.7×10^{-4}	2.8×10^{-3}	1.4×10^{-3}
B^*N[a]	6226	4	0	$3/2^-$	—	$qqqq\bar{b}(L=2)$	B^*N	—	5.3×10^{-6}	1.2×10^{-4}	6.6×10^{-5}	—	2.1×10^{-4}	4.4×10^{-3}	2.4×10^{-3}
Dibaryons															
H[a]	2245	1	0	0^+	$qqqqss$	—	ΞN	3.0×10^{-3}	—	1.6×10^{-2}	1.3×10^{-2}	8.2×10^{-3}	—	3.8×10^{-2}	3.2×10^{-2}
$\bar{K}NN$[b]	2352	2	1/2	0^-[c]	$qqqqqs(L=1)$	$qqqqqq\,s\bar{q}$	$\bar{K}NN$	5.0×10^{-3}	5.1×10^{-4}	0.011–0.24	1.6×10^{-2}	1.3×10^{-2}	1.4×10^{-3}	0.026 – 0.54	3.7×10^{-2}
$\Omega\Omega$[a]	3228	1	0	0^+	$ssssss$	—	$\Omega\Omega$	3.2×10^{-5}	—	1.5×10^{-5}	6.4×10^{-5}	8.6×10^{-5}	—	4.4×10^{-5}	1.9×10^{-4}
H_c^{++}[a]	3377	3	1	0^+	$qqqqsc$	—	$\Xi_c N$	3.0×10^{-4}	—	3.3×10^{-4}	7.5×10^{-4}	2.0×10^{-3}	—	1.9×10^{-3}	4.2×10^{-3}
$\bar{D}NN$[a]	3734	2	1/2	0^-	—	$qqqqqq\,q\bar{c}$	$\bar{D}NN$	—	2.9×10^{-5}	1.8×10^{-3}	7.9×10^{-5}	—	2.0×10^{-4}	9.8×10^{-3}	4.2×10^{-4}
BNN[a]	7147	2	1/2	0^-	—	$qqqqqq\,q\bar{b}$	BNN	—	2.3×10^{-7}	1.2×10^{-6}	2.4×10^{-7}	—	9.2×10^{-6}	3.7×10^{-5}	7.6×10^{-6}

An Example: the f0

					Coalescence: *meson*	*tetra-quark*	*molecule*
Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.
Mesons							
$f_0(980)$	980	1	0	0^+	$q\bar{q}, s\bar{s}(L=1)$	$q\bar{q}s\bar{s}$	$\bar{K}K$



LHC			
$2q/3q/6q$	$4q/5q/8q$	Mol.	Stat.
10, 2.0 ($s\bar{s}$)	0.28	36	15

- yield tells us something about the quark configuration

-Strangeness enhancement could affect yield as well

-But the purer the s-state the more likely the enhancement effect

LHCb penta-quark announcement

(arXiv:1507.03414)

In the charm sector: $J/\psi\, p$

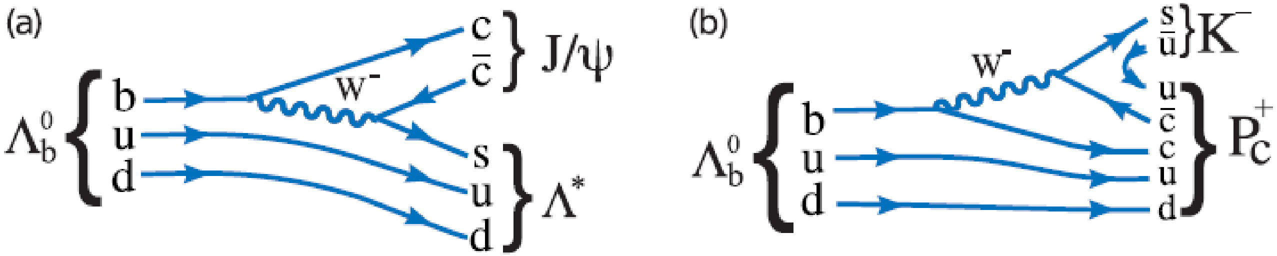


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

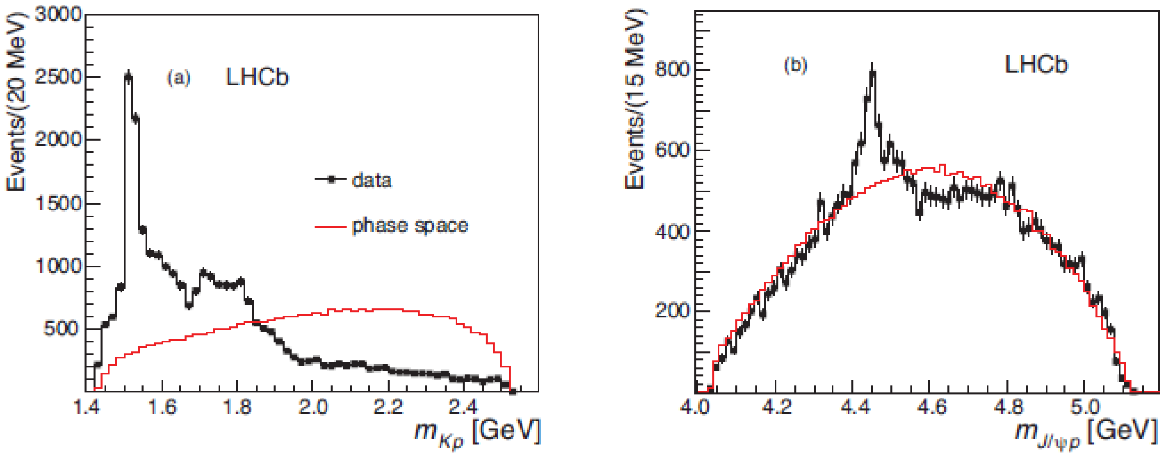


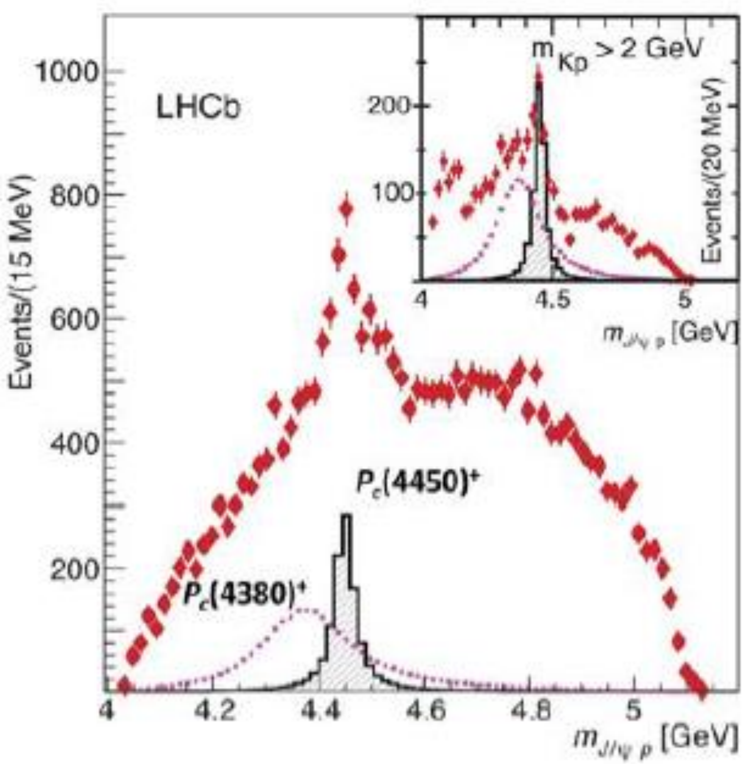
Figure 2: Invariant mass of (a) K^-p and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays.

Exotica:

Penta- and Tetra-quarks from LHCb

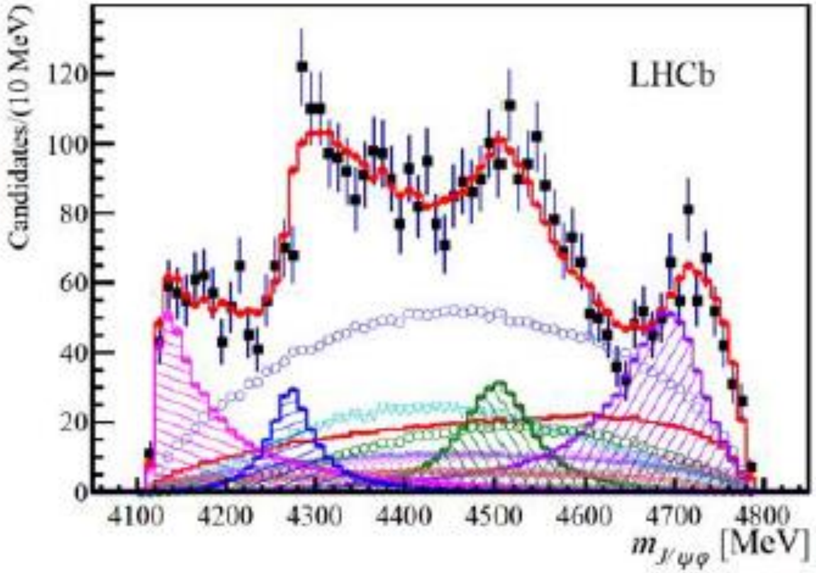
Penta-quark in 2015, 9σ evidence by 2016

In the charm sector: J/ψ p resonance
In Λ_b decays to J/ψ p K^-



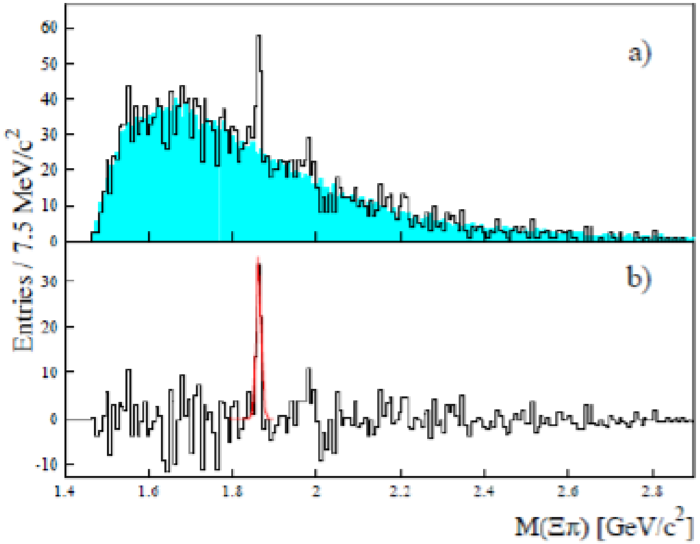
Tetra-quarks in 2016

In the charm sector: J/ψ ϕ resonance
In B^+ decays to J/ψ ϕ K^+

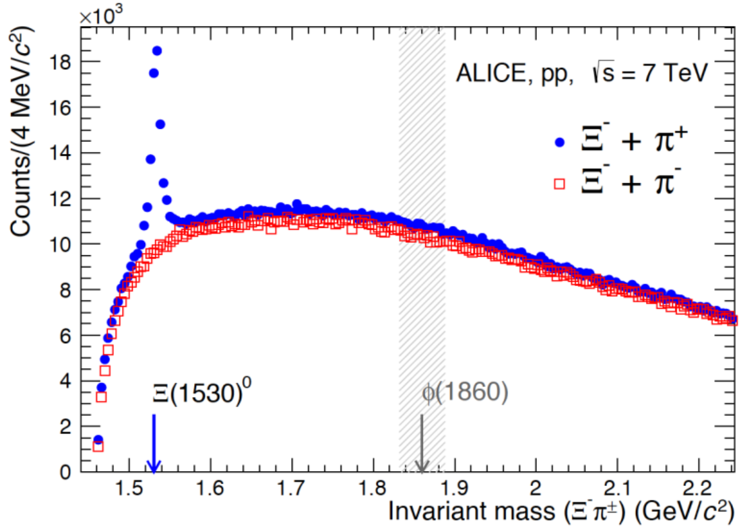


Why nothing in the strange sector ?

Exotica in strange sector ?



- Famous pentaquark candidate from NA49
- (2008) in $\Xi\pi$ channels (ϕ(1860)) (dsdsubar)
- Never retracted, never confirmed

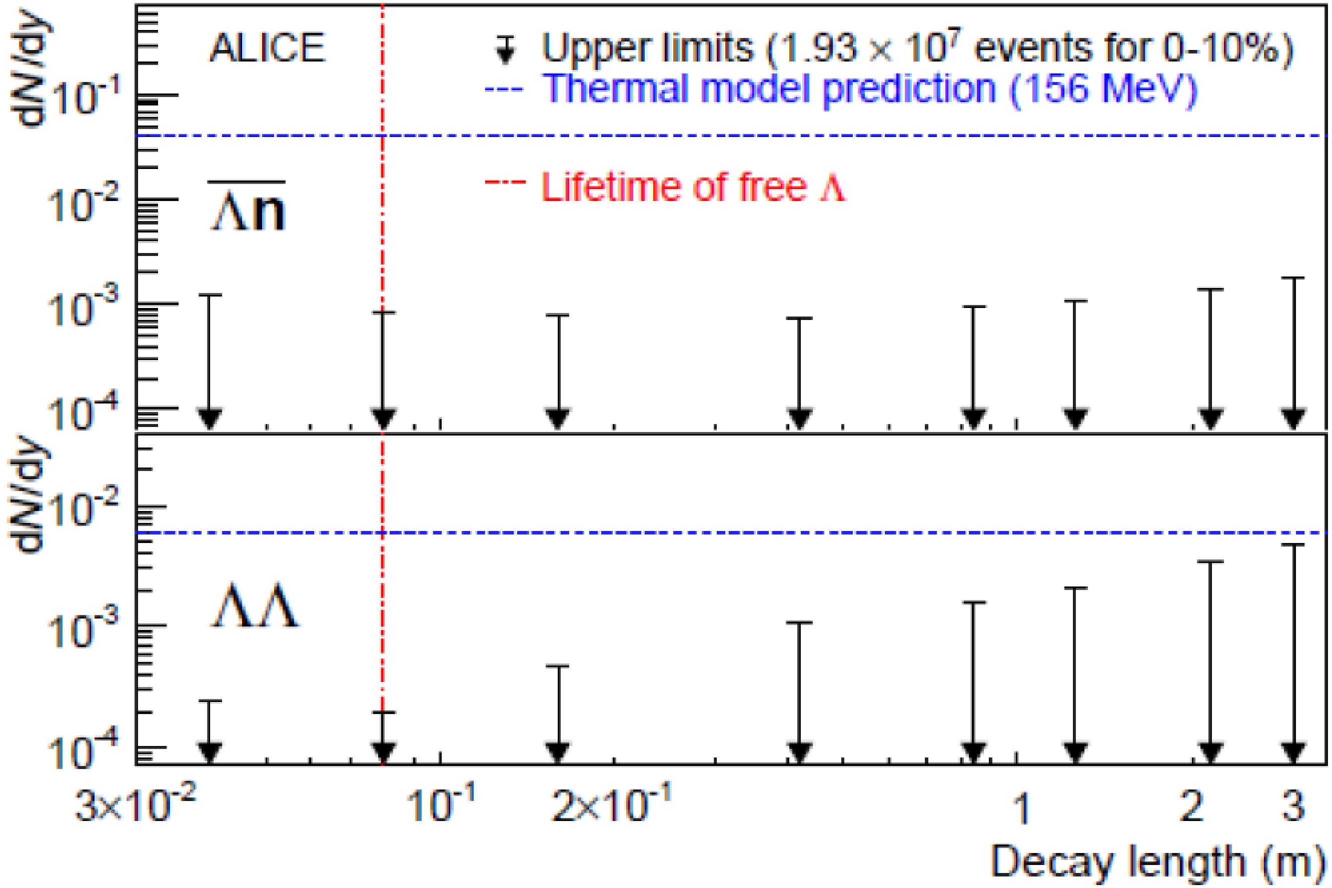


No evidence for H-dibaryon or ϕ(1860) in ALICE data.

Maybe we are looking in the wrong channels. In the charm sector all tetra and penta-quarks seem to require closed charm components.

Keep looking !!

H-Dibaryons in ALICE (arXiv.1506.07499)



- negative result

-but again: likely light quark dominated

- formed after hadronization through $\Lambda\Lambda$ *coalescence ?*

Summary – Discussion points

- Short lived hadronic resonances are difficult to measure but they carry a large amount of information

- The significant broadening of the low mass vector mesons signals chiral symmetry restoration. The merging of chiral partners would be the ultimate proof.

- The lifetime of the partonic and the interacting hadronic phase of the fireball evolution is well constrained through yield variations of short lived resonances.

- The inclusion of not yet measured hadronic resonances in order to describe the hadronic phase improves the agreement with lattice QCD in the low temperature regime. The comparisons have predictive power regarding the probability of finding new resonances.

-A possible flavor hierarchy in the QCD crossover should lead to more strange baryonic and mesonic resonances as well as multi-quark states.

- *Resonances are a rich and very exciting field – experimentally and theoreticallly*