Exotic Strange States
and their relevance to understanding hadronization

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and Exotica Production at the LHC
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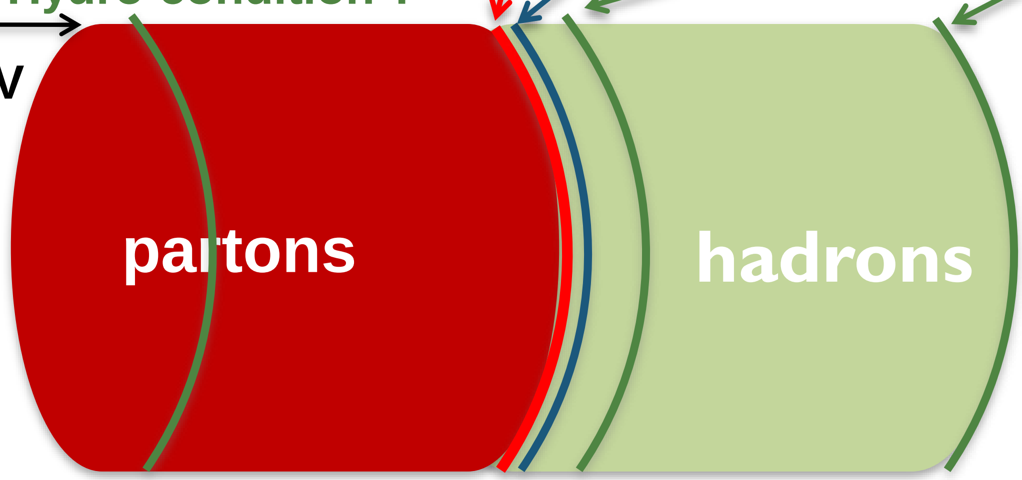
Evolution of a RHIC heavy ion collision
(as a function of temperature and time)

Model:	lQCD	SHM	Blastwave	
Effect:	hadronization	chemical f.o.	kinetic f.o.	
Freeze-out surface:	T_{crit}	T_{ch}	$T_{kin}(\Xi,\Omega)$	$T_{kin}(\pi,k,p,\Lambda)$
Temperature (MeV):	151	148	148	80
Expansion velocity (c):			β=0.45	β=0.6

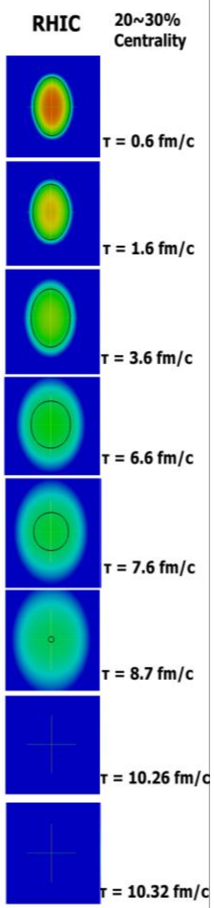
Hydro condition ?

T_{init}
370 MeV



τ_0 τ_{QGP}

Experiment: time: ~5 fm/c ~4 fm/c
(STAR, PRL 97:132301,(2006))



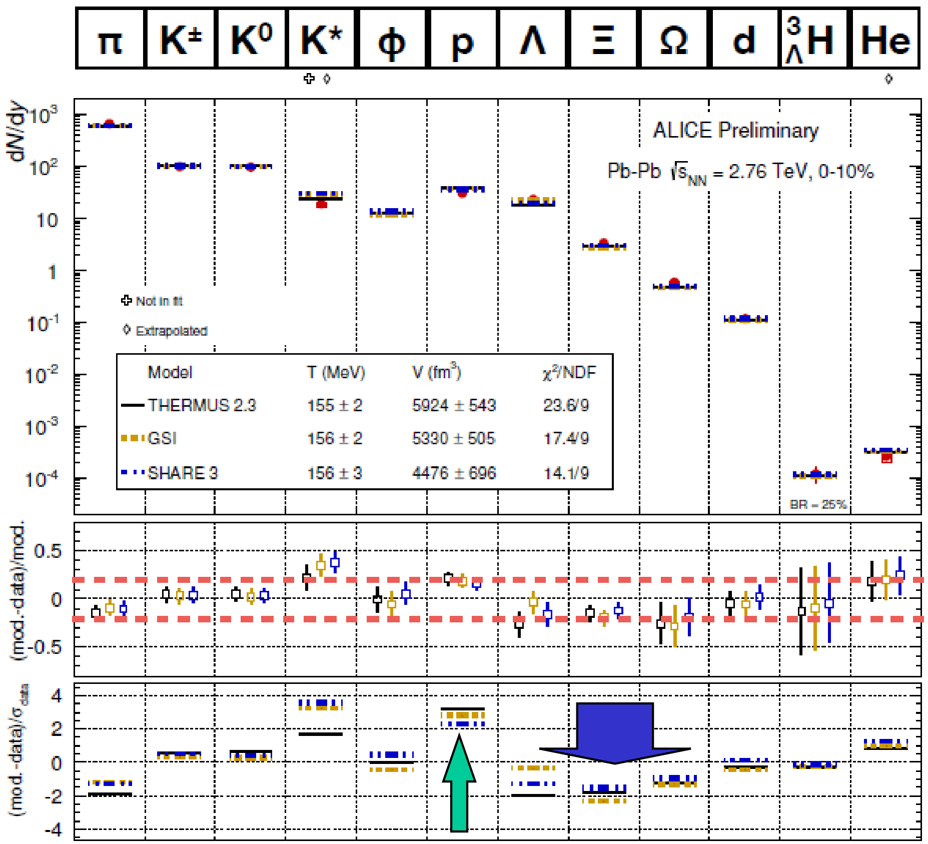
References:

Lattice QCD:
arXiv:1005.3508
arXiv:1107.5027

Statistical Hadronization:
hep-ph/0511094
nucl-th/0511071

Blastwave:
nucl-ex/0307024
arXiv:0808.2041

Chemical freeze-out parameters at RHIC & LHC: The ‘proton or strange quark anomaly ?’



M. Floris (ALICE), Quark Matter 2014 Proceedings

This looks like a good fit, but it is not

χ^2/NDF improves from 2 to 1 when pions and protons are excluded.

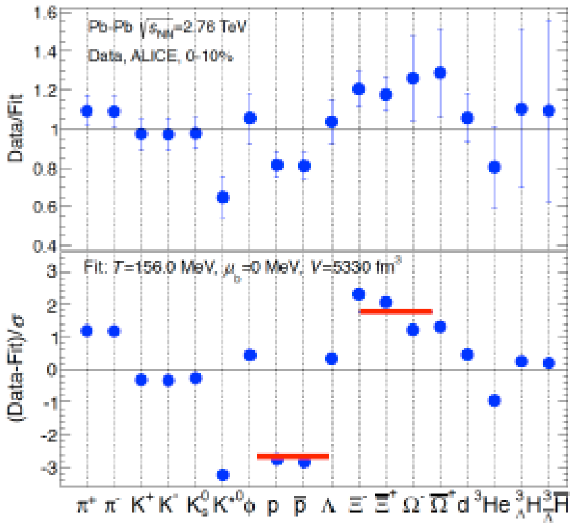
Fit to pions and protons alone yield a temperature of 148 MeV.

<u>Several alternate explanations:</u>

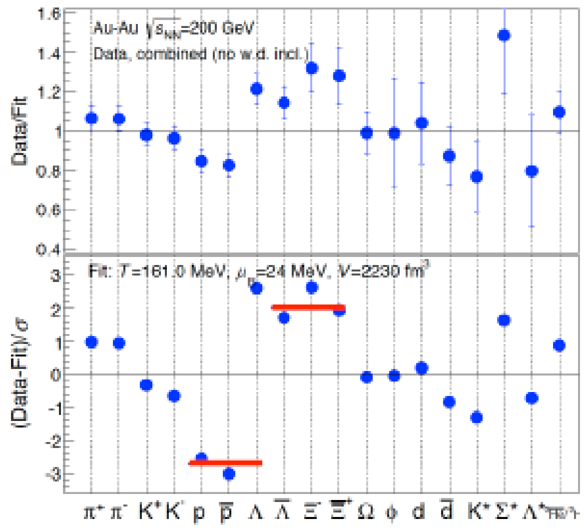
- ***<u>Different T_{ch} for light and strange</u>***
- Inclusion of Hagedorn states
- Non-equilibrium fits
- Baryon annihilation

Surprisingly consistent trends in SHM fits at higher collision energies

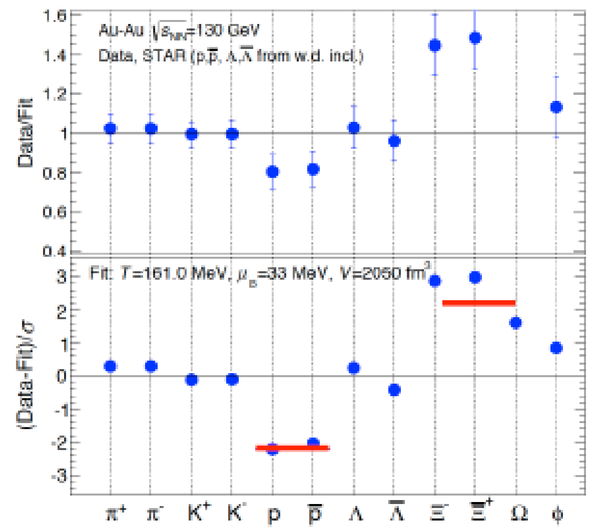
LHC 2.76 TeV



RHIC 200 GeV



RHIC 130 GeV



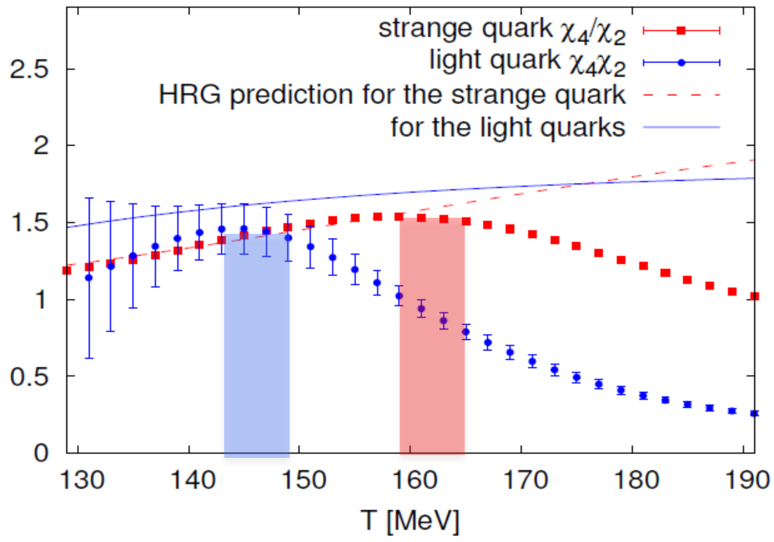
Fits from A. Andronic et al., Hadronization Workshop, Trento, Oct. 2014

<u>Our interpretation:</u> light quark baryons are low, strange quark baryons are high

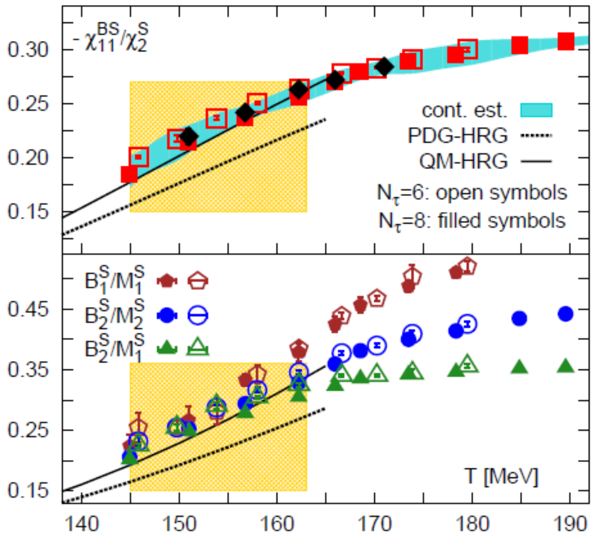
High precision lattice QCD indicates tension between light and strange quark freeze-out

Two groups (WB Coll. & Hot QCD), different approaches, but similar results based on susceptibilities of conserved charges near QCD crossover

WB result (PRL 111, 202302 (2013)):
χ_4/χ_2 indicates flavor dependence of chemical freeze-out

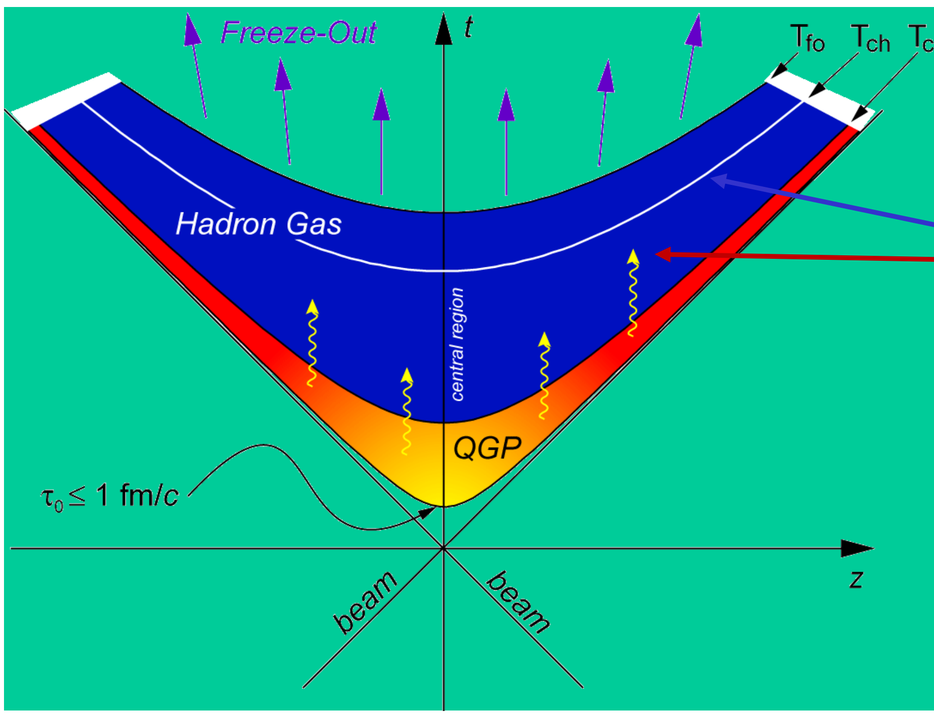


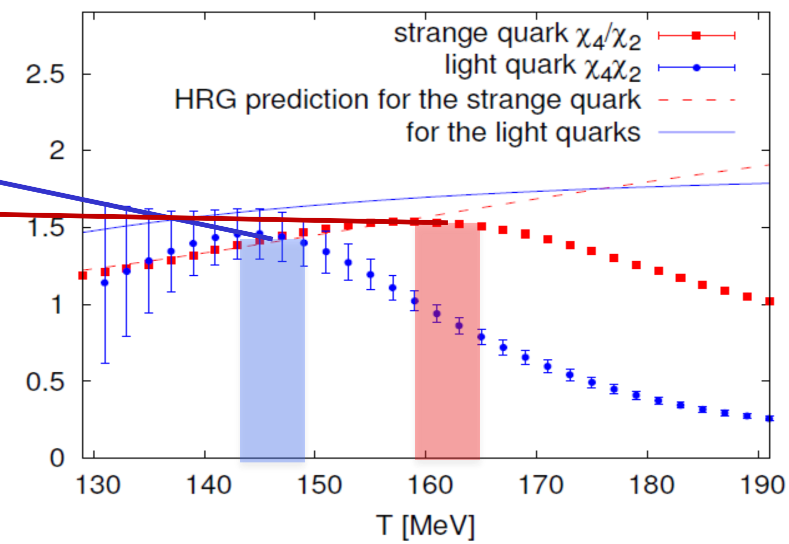
HotQCD result (PRL 113, 072001 (2014)):
χ_{BS}/χ_s indicates necessity of yet undetected strange states to conserve common freeze-out



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

Enhances probability for Omega's and strangelets, strange clusters

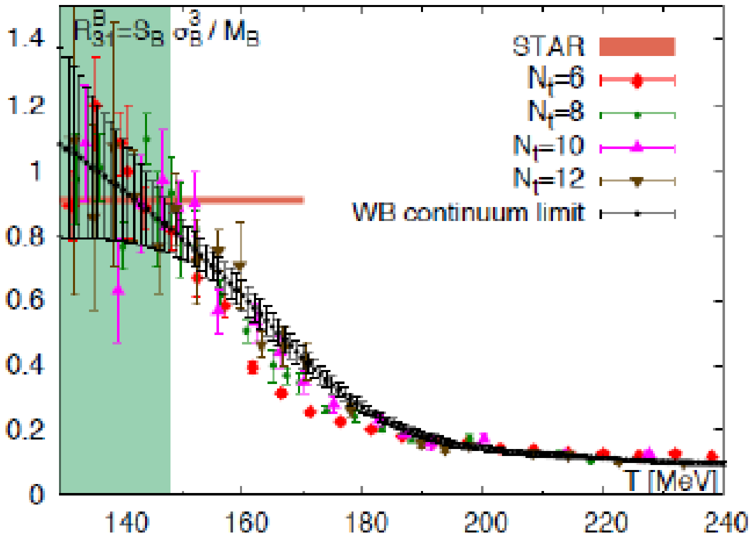




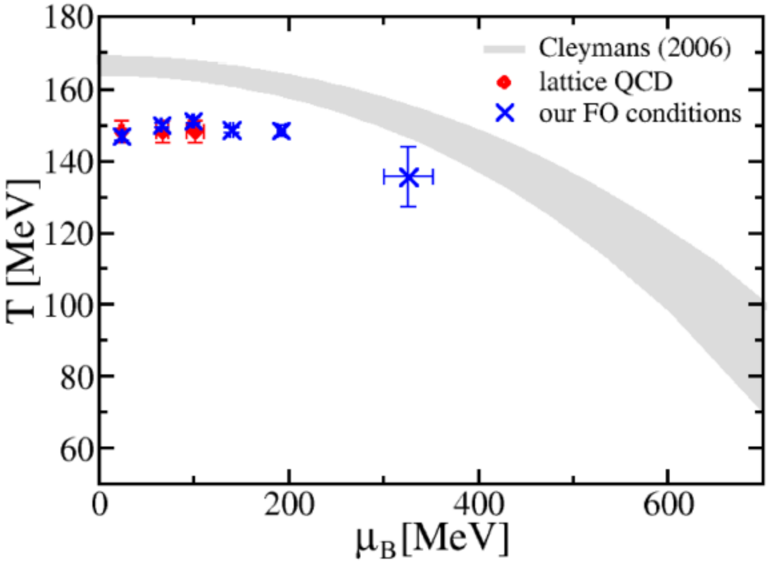
R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

What can happen in ΔT = 20 MeV ?

A lattice QCD analysis of RHIC fluctuation data of light quark dominated quantum numbers (net-electric charge and net-protons) finds a T_{ch} drop of about 20 MeV relative to SHM fits including strangeness



lattice QCD : S. Borsanyi et al., arXiv:1403.4576



HRG: P. Alba et al., PLB 738 (2014) 305

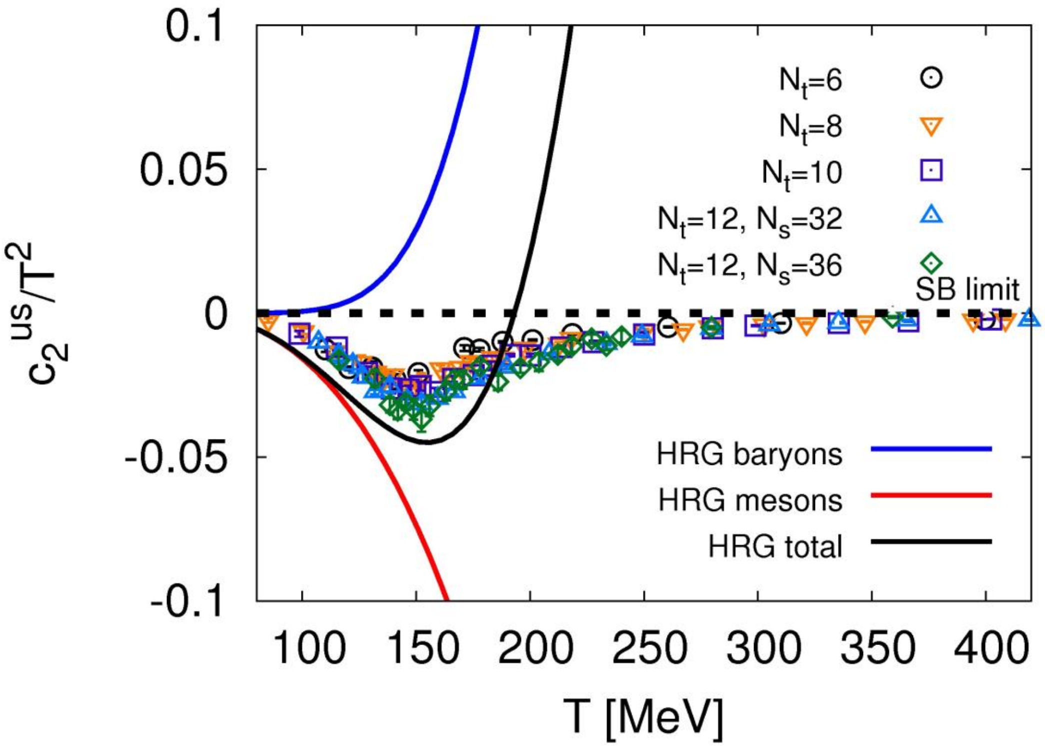
A 20 MeV drop can be translated into a 2 fm/c time window.

Strangeness wants to freeze-out, light quarks do not.

Can there be measurable effects ?

Can there be a mixed phase of degrees of freedom ?

Any more clues from lattice and HRG models ?: Baryon-meson dependence in light-strange correlator



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

lQCD:
S. Borsanyi et al.,
JHEP 1201 (2012) 138
arXiv:1112.4416

- Baryonic bound states more likely the higher the temperature.
- Upswing in lattice correlator shows that baryon contribution rises with T, but the correlator never turns positive -> the contribution of bound states above T_c must be predominantly of mesonic nature until final deconfinement

In both cases (flavor hierarchy or resonance production): Enhancement of strange states near the chemical freeze-out

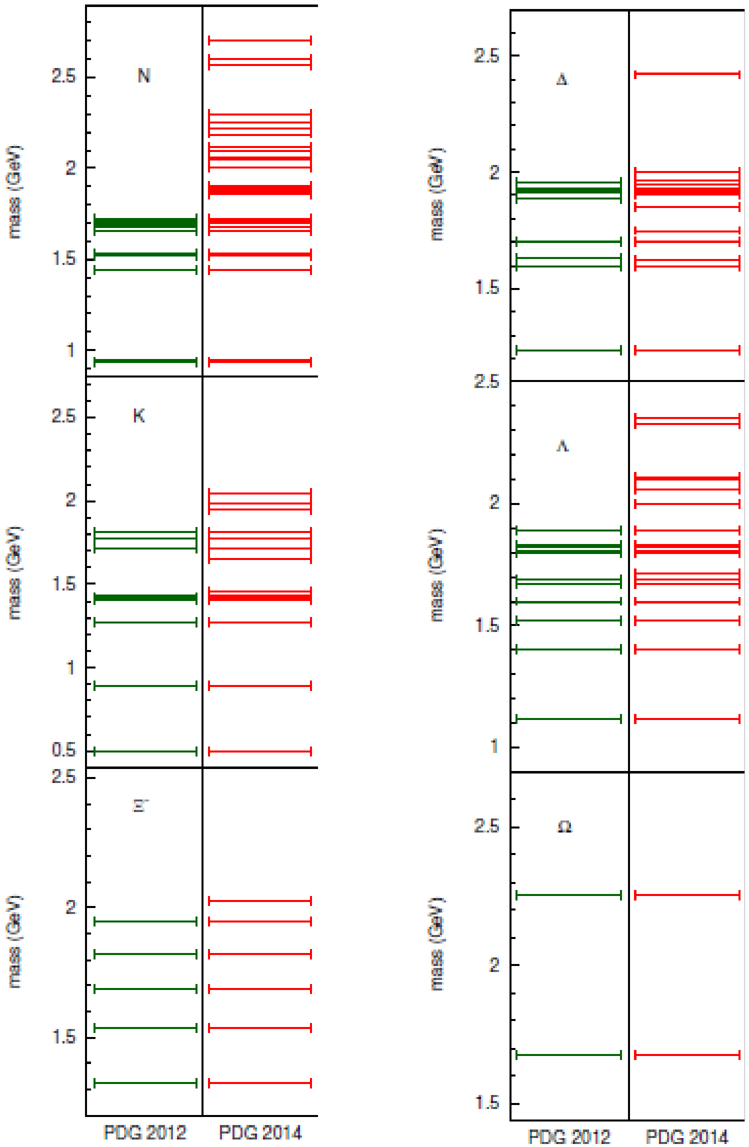
Three options *from the mundane to the exotic:*

1.) a new strangeness enhancement

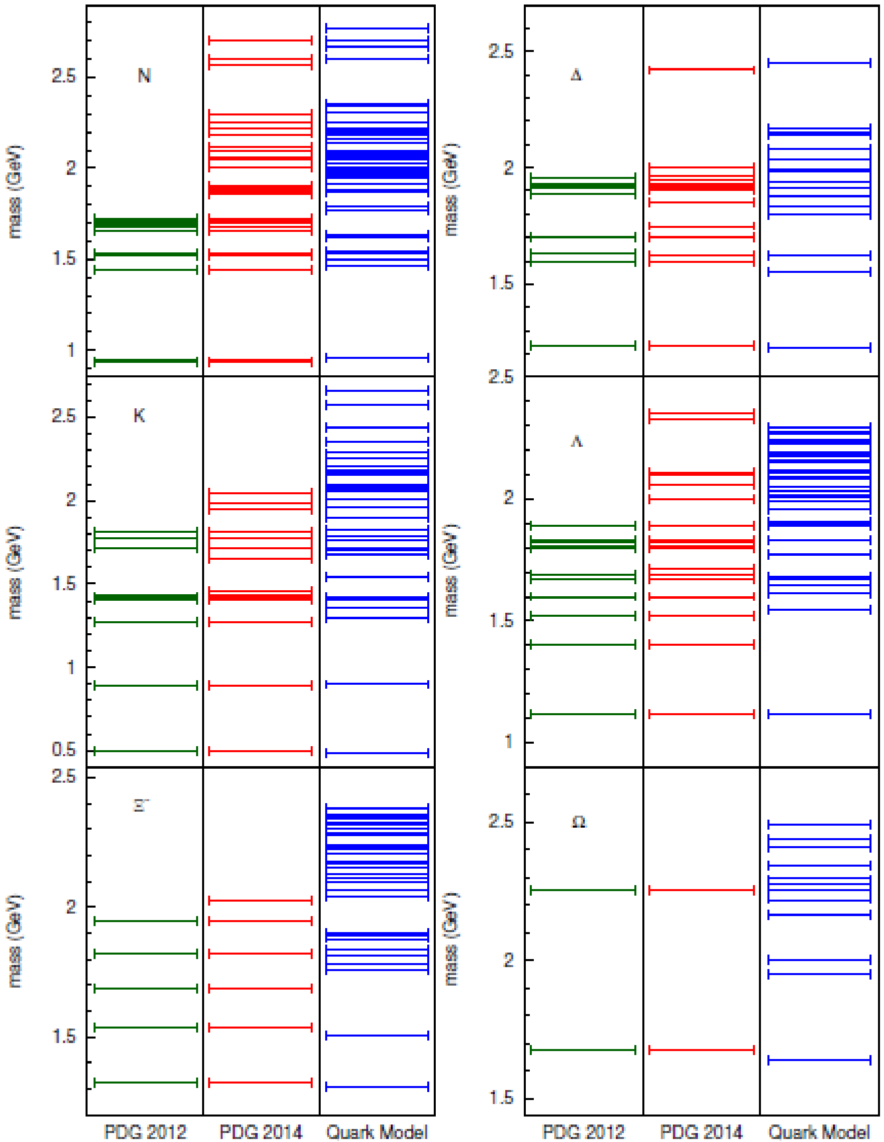
Enhancement factors from 146 to 166 MeV:
(assuming V= 5570 fm^3 and V= 1760 fm^3, respectively)
Λ yield increases by 20%, Ξ yield increases by 30%, Ω yield increases by 44%

2.) higher strange states based on excited states in Quark Model

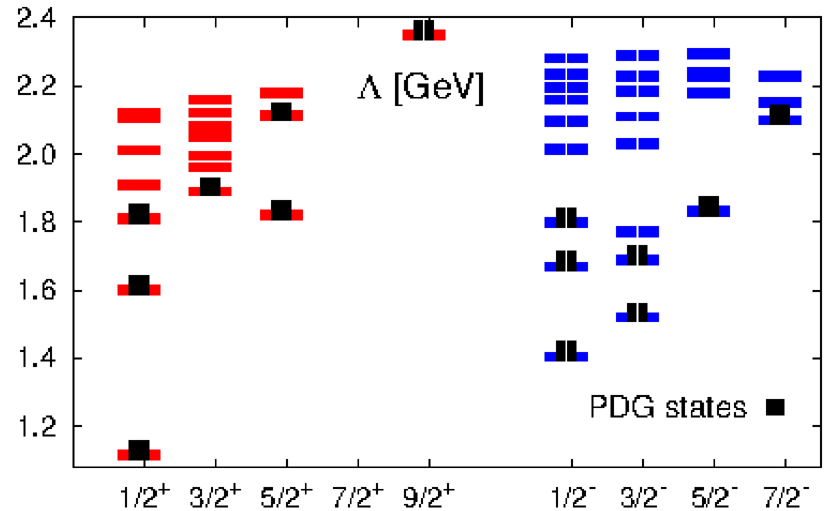
3.) exotic quark configurations



Higher Strange States based on new measurements (e.g. PDG-2012 to PDG-2014)



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

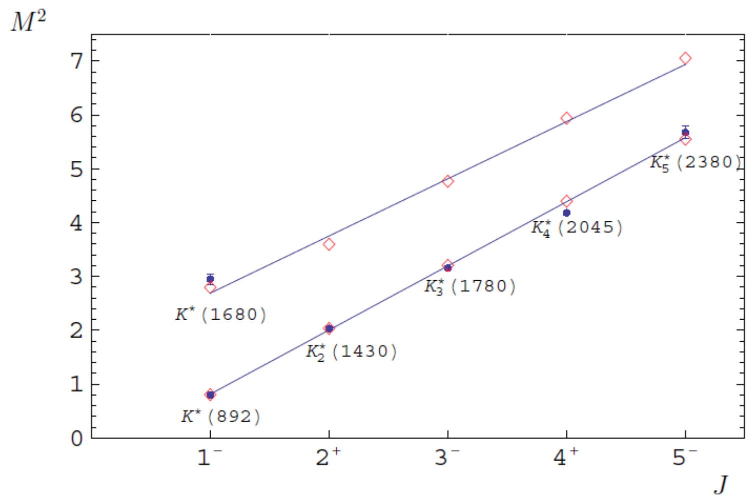


Details from Quark Model calculations

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

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

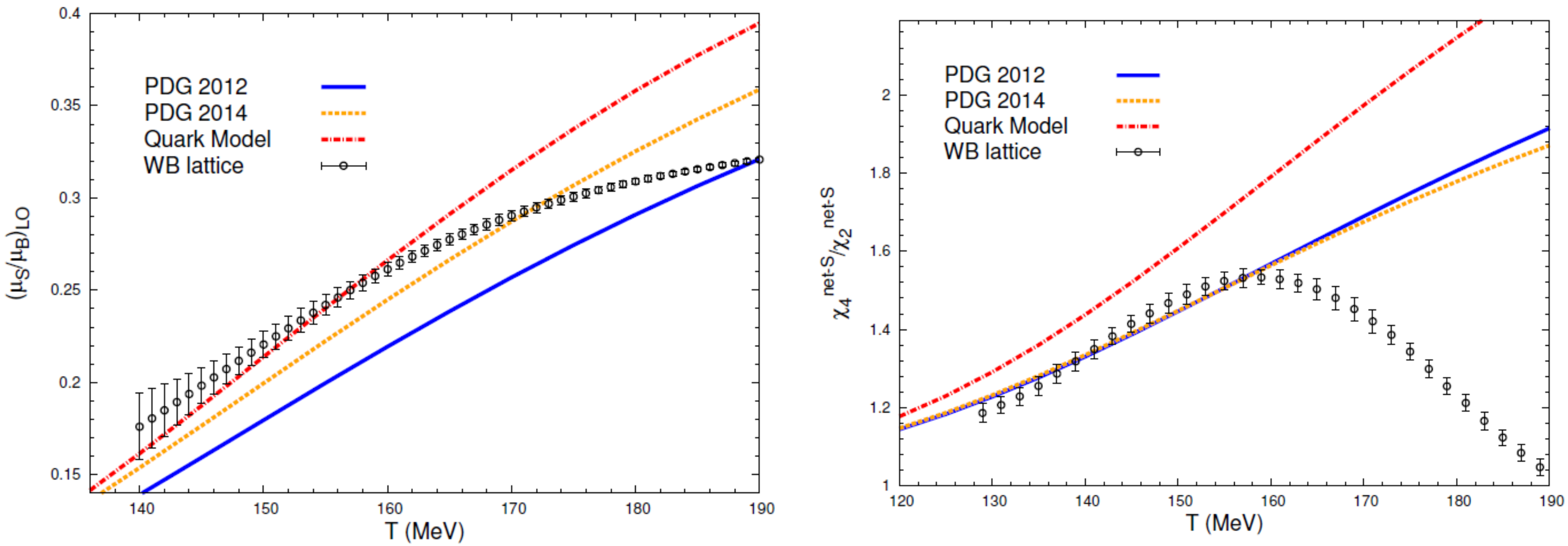
$n^{2S+1}L_J$	J^P	Theory $q\bar{s}$	Experiment $I=1/2$	Experiment mass	$n^{2S+1}L_j$	J^P	Theory $q\bar{s}$	Experiment $I=1/2$	Experiment mass
1^1S_0	0^-	482	K	493.677(16)	3^1S_0	0^-	2065		
1^3S_1	1^-	897	K^*	891.66(26)	3^3S_1	1^-	2156		
1^3P_0	0^+	1362	K_0	1425(50)	2^3D_1	1^-	2063		
1^3P_2	2^+	1424	K_2^*	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 favourable

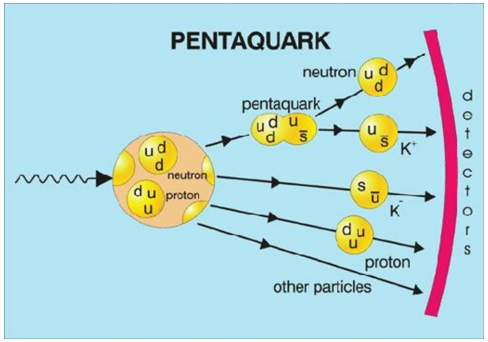
Comparison of lattice QCD susceptibilities to HRG model calculations based on different hadron spectra input (Alba, Bellwied, Mantovani, Ratti, to be published)

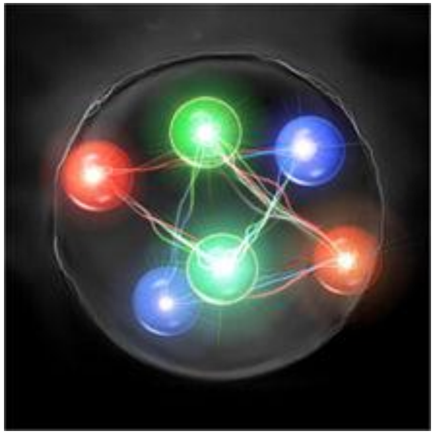


Just adding unverified states might help for certain susceptibilities but worsen agreement with others. <u>We need to experimentally verify possible higher states.</u>

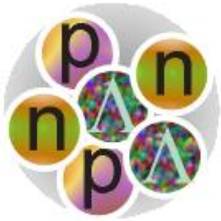
Multi-quark states

Endless possibilities of increasing complexity (all allowed theoretically)

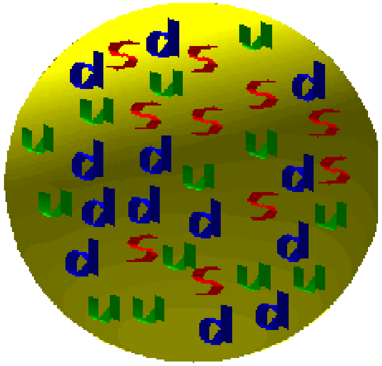




single Λ hypernucleus



double Λ hypernucleus

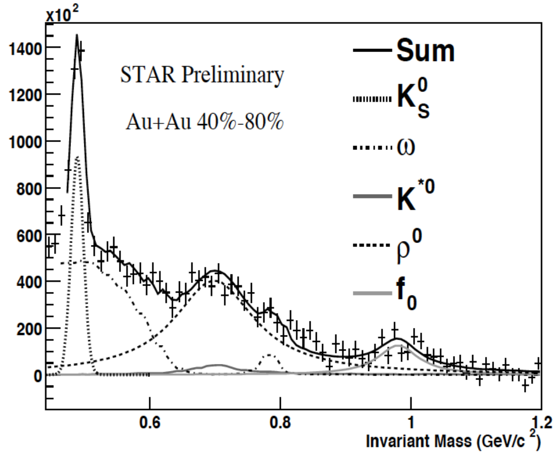


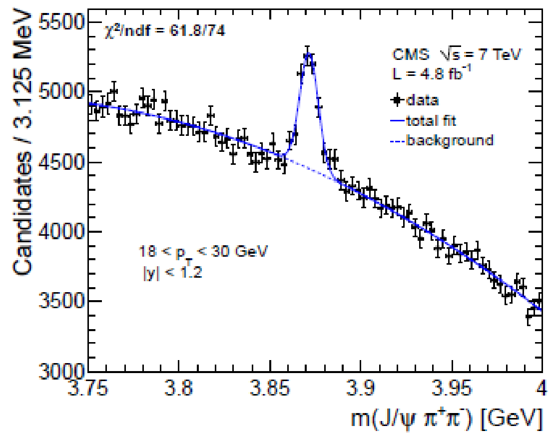
- all involve strangeness

-but not many dominated by strangeness

Exotic states within the Standard Model

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



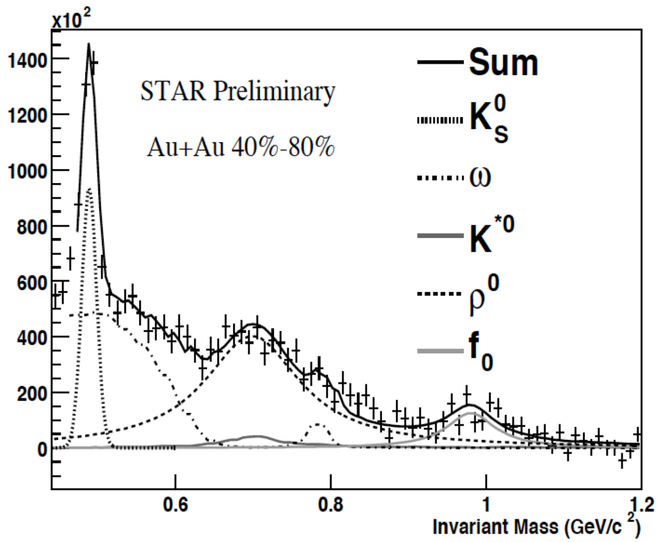


ExHIC Collaboration (2011):

Particle	m (MeV)	g	I	J^P	$2q/3q/6q$	$4q/5q/8q$	Mol.	RHIC $2q/3q/6q$	RHIC $4q/5q/8q$	RHIC Mol.	RHIC Stat.	LHC $2q/3q/6q$	LHC $4q/5q/8q$	LHC Mol.	LHC 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

Last week's LHCb penta-quark announcement
(arXiv:1507.03414)

In the charm sector: J/ψ p

More relevant for this talk: the strange sector: $\Xi\pi$ (NA49, PRL 92 (2004) 042003 (unverified)

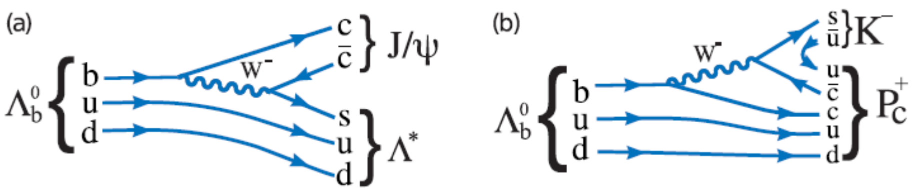


Figure 1: Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

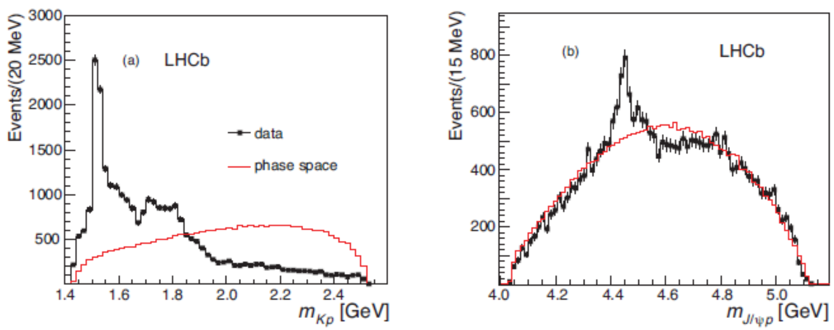
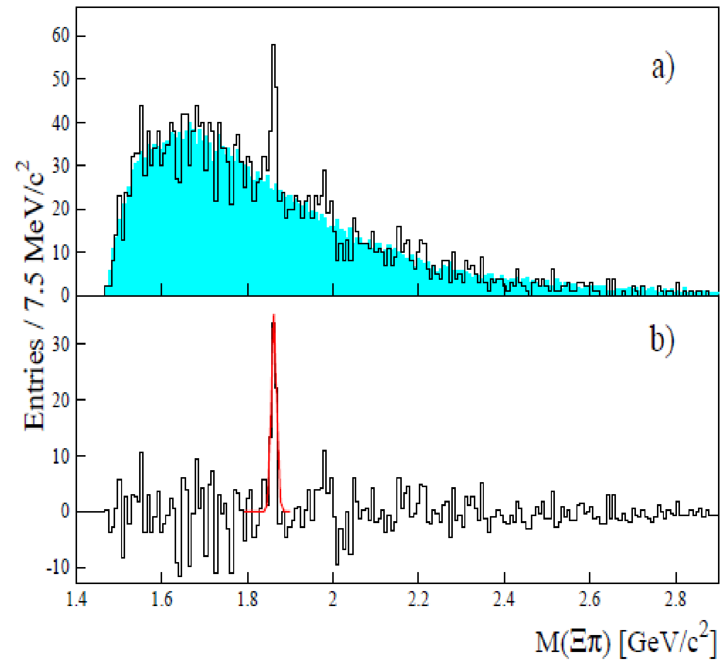
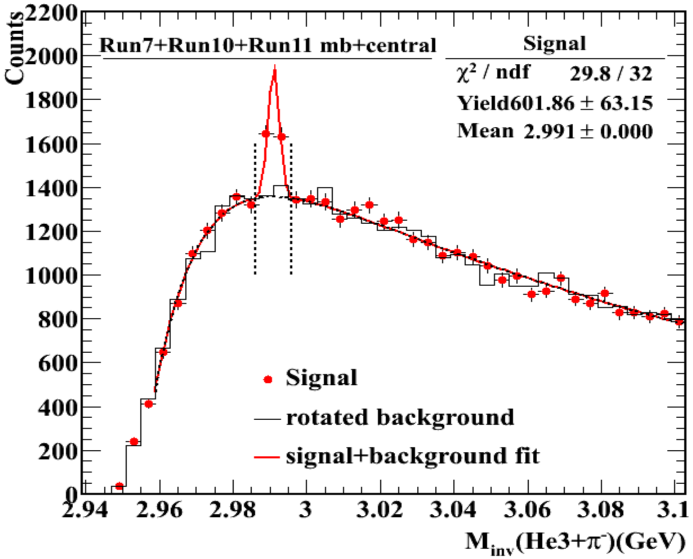


Figure 2: Invariant mass of (a) $K^- p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays.



- But is the formation of these states dominated by the heavier quarks ?

Hyper-Matter at RHIC (STAR, Science 328, 58 (2010))



	7.7GeV	11.5GeV	19.6GeV
Events	~4M	~11M	~31M
^{3}He(anti)	8587(0)	7161(0)	6321(0)
Hypertriton	46±17	41±17	42±14

	27GeV	39GeV	200GeV
Events	~49M	~118M	~223M
^{3}He(anti)	5312(19)	6456(133)	5822(2213)
Hypertriton	46±16	88±21	83±20

	Hypertriton yield per event	Net proton density ($dN_{\Delta p}/dy$)	Baryo chemical potential
7.7 GeV	1.15×10^{-5}	60	450 MeV
11.5 GeV	3.7×10^{-6}		375 MeV
19.6 GeV	1.35×10^{-6}	26	300 MeV
27 GeV	1.77×10^{-6}		270 MeV
39 GeV	7.46×10^{-7}		200 MeV
200 GeV	3.77×10^{-7}	8	20 MeV

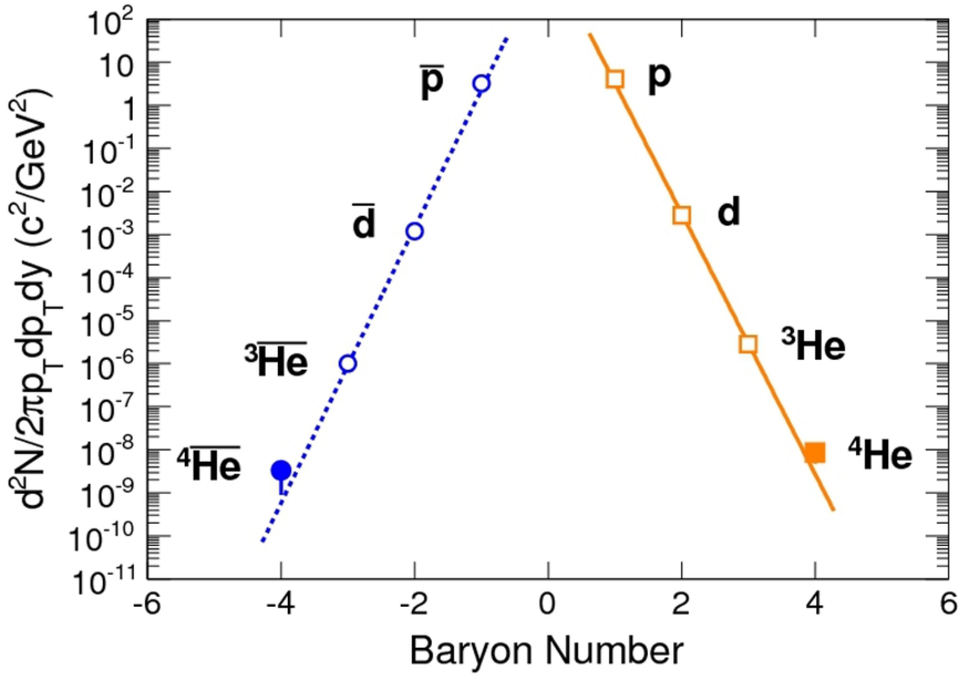
- Hyper-Matter clearly dominated by light quarks (baryon-chemical potential)

-Maybe even formed after hadronization through coalescence

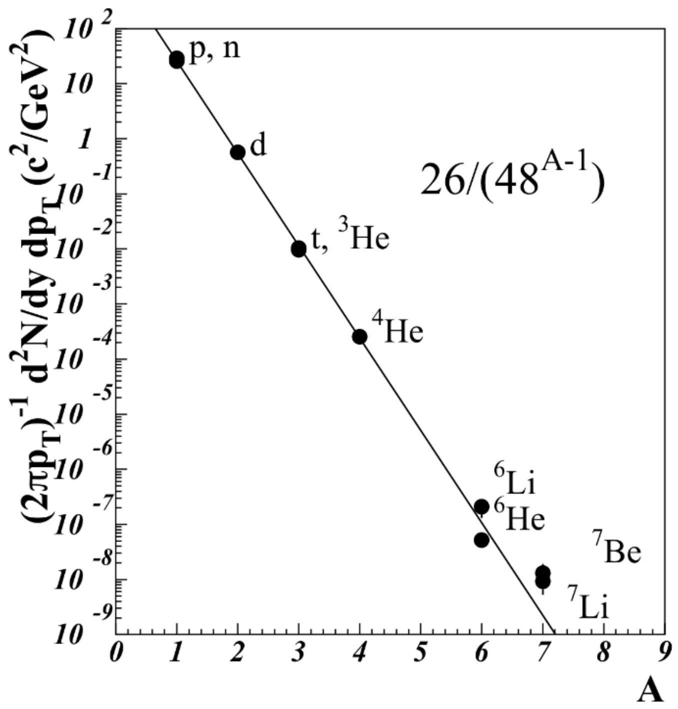
-Likely not a good indicator of flavor hierarchy

When is Hyper-Matter formed ?

STAR measurement.



E864 measurement.

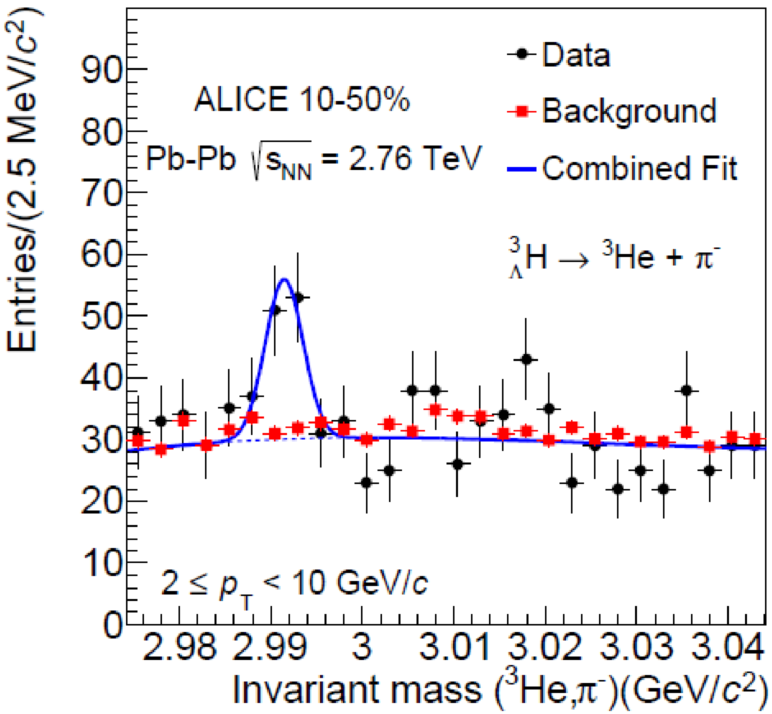


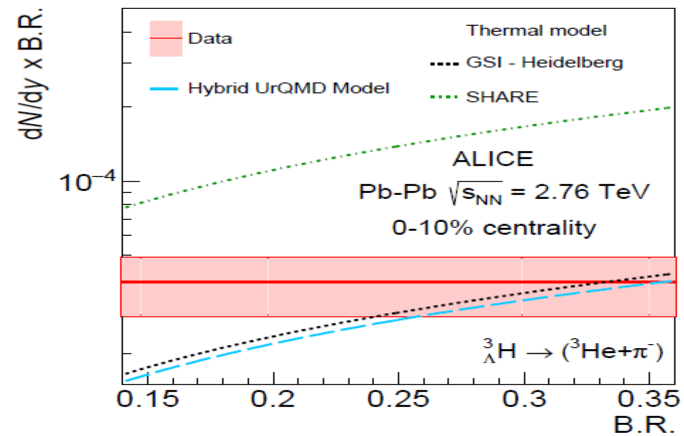
- yields follow hadronic coalescence theory (Sato et al., PLB 98, 153 (1981)

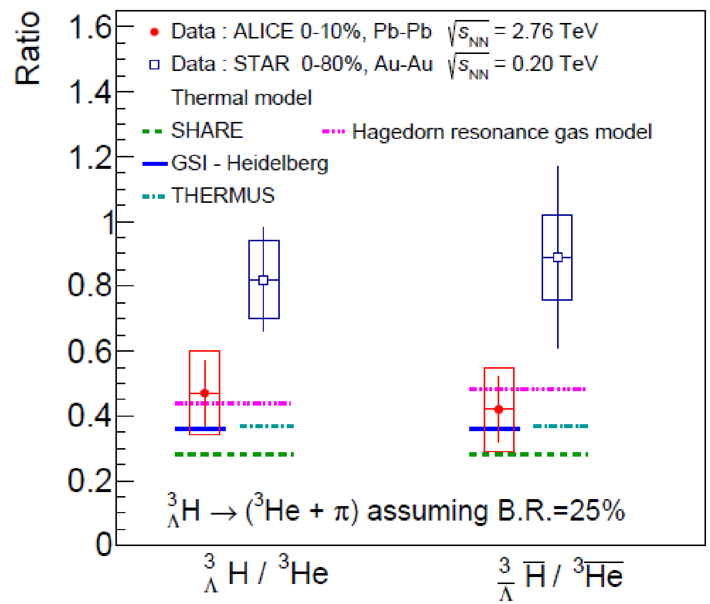
- but yields are also well described by SHM (see PBM talk) (at low T_{ch})

-true for matter and Hyper-matter

Hyper-Matter in ALICE (arXiv:1506.08453)







- Additional evidence for Hyper-Matter production dominated by light quarks (baryo-chemical potential)

-Likely not a good indicator of flavor hierarchy

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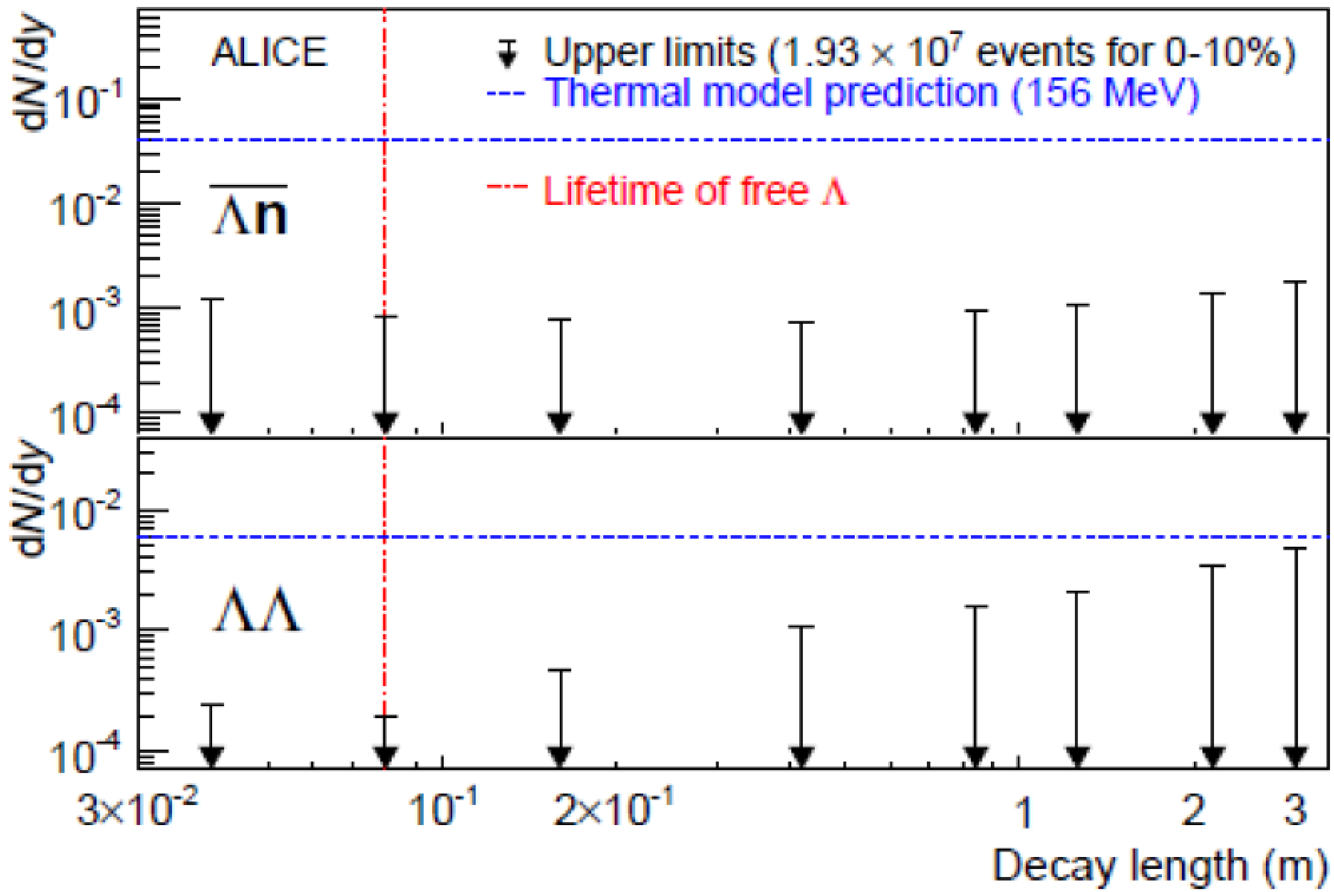
H-Dibaryons in ALICE (arXiv.1506.07499)



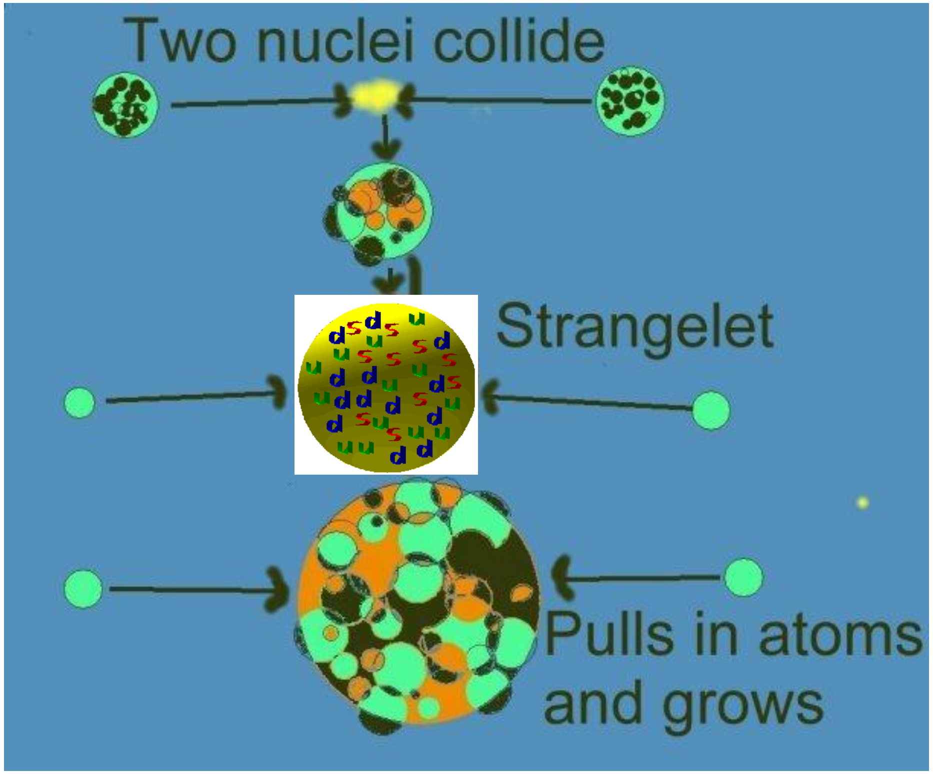
- negative result

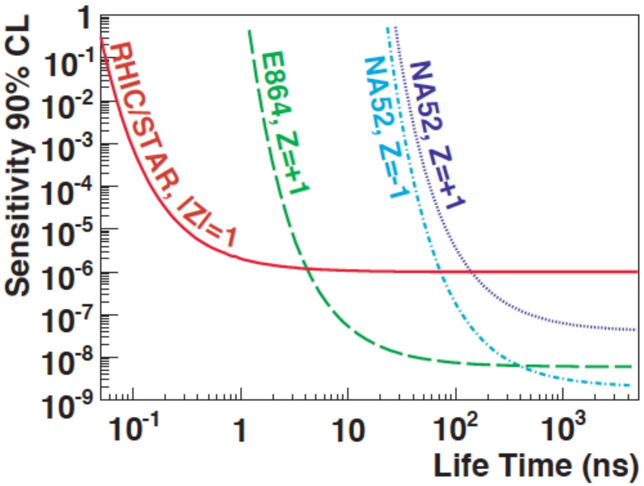
-but again: likely light quark dominated

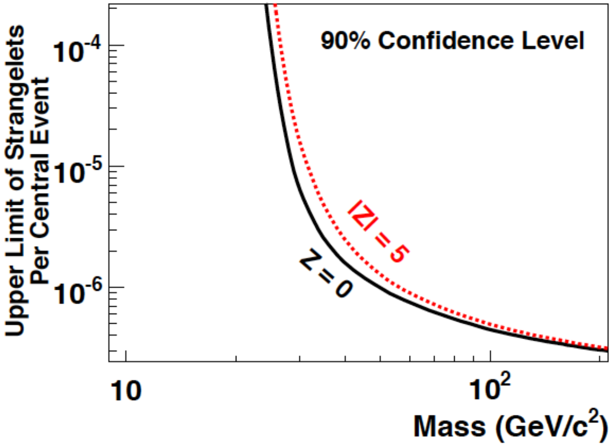
- formed after hadronization through $\Lambda\Lambda$ coalescence ?

Strangelets should be strangeness dominated

Direct formation from plasma, definitely not formed hadronically







- still *negative results from RHIC (see Aihong's talk)*

Conclusions – Discussion points

- conserved quantum number fluctuation measurements also allow us to determine freeze-out surfaces from first principle (lattice QCD) and might hint at an *intriguing flavor hierarchy during the QCD transition*.

- any flavor dependencies in the chemical freeze-out have to be determined by the flavor composition of the final hadron

- *we have evidence for strangeness enhancement*, but the more light quarks are part of the final hadron composition, the smaller the enhancement effect.

- *singly strange hyper-matter seems to be well described by SHMs, which assume a common freeze-out near the light quark freeze-out.*

- *if enhanced strangeness exists in the crossover region it should populate either high lying multi-strange resonances, multi-quark states (tetra- or penta-quark strange states) or multi-strange clusters (strangelets).*

-there is lot of excitement in the exotica sector and the LHC can contribute significantly in the strange and charm sector.

- *details of the hadronization and freeze-out processes are intrinsically locked into the formation of exotic states and need to be unlocked for a basic understanding of matter formation.*