

# Soft hadron(ratio)s at the LHC

May 30, 2007, CERN: LHC predictions workshop

This talk presents some new insights and results but otherwise relies on methods and ideas presented in:

JR and Jean Letessier, *Soft hadron ratios at the LHC*  
arXiv:hep-ph/0506140, Eur.Phys.J.C45:61-72,2006.

Today we also can use some of the results contained in:

Jean Letessier and JR *Strangeness chemical equilibration in QGP at RHIC and LHC.* arXiv:nucl-th/0602047, Phys.Rev.C75:014905,2007.

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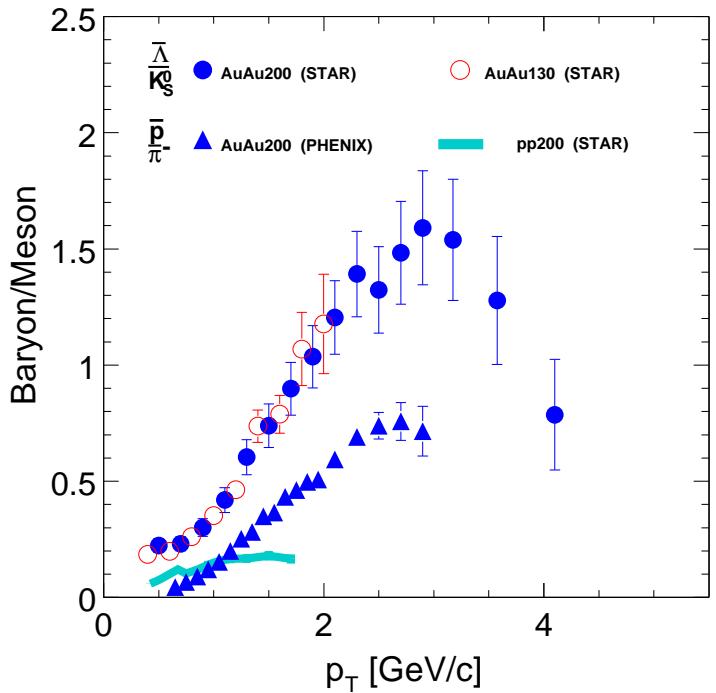
The physics input governing soft hadron production at LHC-Ion relies on (input):

- 1) the entropy content:  $dS/dy \equiv$  multiplicity,  
**not (yet) predictable, straight line extrap.**
- 2) strangeness content  $ds/dy$  and/or  $s/S$   
**strangeness computable within pQCD given entropy**
- 3) nett baryon stopping  $\frac{d(b-\bar{b})}{dy}$ ,  $\frac{b-\bar{b}}{b+\bar{b}} \simeq 0$   
**unknown, very difficult to measure**
- 4) the energy content  $dE/dy$   
baryons stopped more effectively:  $E/(b-\bar{b}) < \sqrt{s_{NN}}/2A$
- 5) (primary) baryon to meson ratio  $(b+\bar{b})/\text{all mesons})$   
**specific to hadronization dynamics, our EPJC pred:**

$$0.07 > \frac{p + \bar{p}}{h^+ + h^-} > 0.04 > \frac{\Lambda + \bar{\Lambda}}{h^+ + h^-} > 0.02,$$

$$0.015 > \frac{\Xi^- + \bar{\Xi}^+}{h^+ + h^-} > 0.004 > \frac{\Omega^- + \bar{\Omega}^+}{h^+ + h^-} > 0.0006.$$

## A non-string mechanism of particle formation clearly visible at RHIC



### Baryon to Meson Ratio

Ratios  $\bar{\Lambda}/K_S$  and  $\bar{p}/\pi$  in Au-Au compared to  $pp$  collisions as a function of  $p_\perp$ . The large ratio at the intermediate  $p_\perp$  region: evidence that particle formation (at RHIC) is distinctly different from fragmentation processes for the elementary  $e^+e^-$  and  $pp$  collisions.

### description in SHM: nonequilibrium parameters needed

- $\gamma_q$  ( $\gamma_s, \gamma_c, \dots$ ):  $u, d$  ( $s, c, \dots$ ) quark phase space yield, absolute chemical equilibrium:  $\gamma_i \rightarrow 1$

$$\frac{\text{baryons}}{\text{mesons}} \propto \frac{\gamma_q^3}{\gamma_q^2} \cdot \left( \frac{\gamma_s}{\gamma_q} \right)^n$$

- $\gamma_s/\gamma_q$  shifts the yield of strange vs non-strange hadrons:

$$\frac{\bar{\Lambda}(\bar{u}\bar{d}\bar{s})}{\bar{p}(\bar{u}\bar{u}\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \quad \frac{K^+(u\bar{s})}{\pi^+(u\bar{d})} \propto \frac{\gamma_s}{\gamma_q}, \quad \frac{\phi}{h} \propto \frac{\gamma_s^2}{\gamma_q^2}, \quad \frac{\Omega(sss)}{\Lambda(sud)} \propto \frac{\gamma_s^2}{\gamma_q^2},$$

Hadron production in a given window of rapidity is constrained by:

- 6) Strangeness balance  $\langle s \rangle = \langle \bar{s} \rangle$
- 7) Net charge per net baryon ratio  $Q/b = 0.4$
- 8) Chemical equilibrium (if assumed)

Conflicts with dynamics

- 9) Matter flow dynamics:

explosive break up:  $\frac{E}{TS} > 1$ ; mixed phase  $\frac{E}{TS} < 1$

The rate of momentum flow vector  $\vec{\mathcal{P}}$  at the surface of the fireball is obtained from the energy-stress tensor  $(T_{kl}) \equiv \mathcal{T}$

$$\vec{\mathcal{P}} \equiv \hat{\mathcal{T}} \cdot \vec{n} = P\vec{n} + (P + \varepsilon) \frac{\vec{v} \cdot \vec{n}}{1 - \vec{v}^2}.$$

$P$  and  $\varepsilon$ : local in QGP pressure, energy density,  $\vec{v}$  local flow velocity,  $\vec{n}$  surface normal. Use Gibbs-Duham relation  $P + \varepsilon = T\sigma + \sum \mu_i \nu_i$  to arrive at:

$$\frac{E}{TS} = (1 + \delta) \left( 1 + \frac{(\vec{v} \cdot \vec{n})^2}{1 - v^2} \right) - \frac{\mathcal{P} \cdot \vec{n}}{T\sigma}, \quad \delta_B \equiv \frac{\mu_b}{T} \frac{1}{S/B} \ll 1$$

$\mathcal{P} \cdot \vec{n} = 0$  in explosive break up, for mixed phase/chem. equilibrium  $\frac{\mathcal{P} \cdot \vec{n}}{T\sigma} \simeq 1/6$

## BULK YIELD OBSERVABLE: Strangeness / Entropy in QGP

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$s/S$ : ratio of the number of active degrees of freedom,

For chemical equilibrium:

$$\frac{s}{S} \simeq = \frac{1}{4} \frac{n_s}{n_s + n_{\bar{s}} + n_q + n_{\bar{q}} + n_G} = \frac{\frac{g_s}{2\pi^2} T^3 (m_s/T)^2 K_2(m_s/T)}{(g 2\pi^2/45) T^3 + (g_s n_f/6) \mu_q^2 T} \simeq \frac{1}{35} = 0.0286$$

with  $\mathcal{O}(\alpha_s)$  interaction  $s/S \rightarrow 1/31 = 0.0323$

CENTRALITY  $A$ , and ENERGY DEPENDENCE:  $\gamma_s^Q$

Chemical non-equilibrium occupancy of strangeness  $\gamma_s^Q$

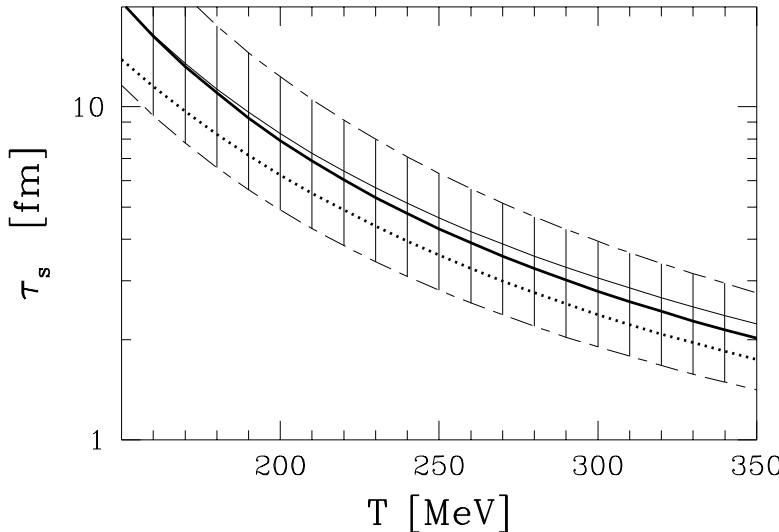
$$\frac{s}{S} = \frac{0.03 \gamma_s^Q}{0.4 \gamma_G + 0.1 \gamma_s^Q + 0.5 \gamma_q^Q + 0.05 \gamma_q^Q (\ln \lambda_q)^2} \rightarrow 0.03 \gamma_s^Q.$$

## Time evolution of $s^Q/S^Q$ , $\gamma_s^Q$ drop superscript $Q$

strangeness production dominated by **thermal gluon fusion**  $GG \rightarrow s\bar{s}$   
 at 10% level also: quark-antiquark fusion, primary parton/string  
 dynamics; **outcome depends on entropy content, not on mix of pa-**  
**rameters.**

$$\frac{d}{d\tau} \frac{s}{S} = \frac{g_s}{g} z^2 K_2(z) \left[ \frac{d\gamma_s}{d\tau} + \gamma_s \frac{d \ln[g_s z^2 K_2(z)/g]}{d\tau} \right] \quad z = \frac{m_s}{T}$$

$$\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d \ln[g_s z^2 K_2(z)/g]}{d\tau} = \frac{A_G}{2n_s^\infty} [\gamma_G^2 - \gamma_s^2] + \frac{A_q}{2n_s^\infty} [\gamma_q^2 - \gamma_s^2]$$



pQCD invariant production rate  $A$ :

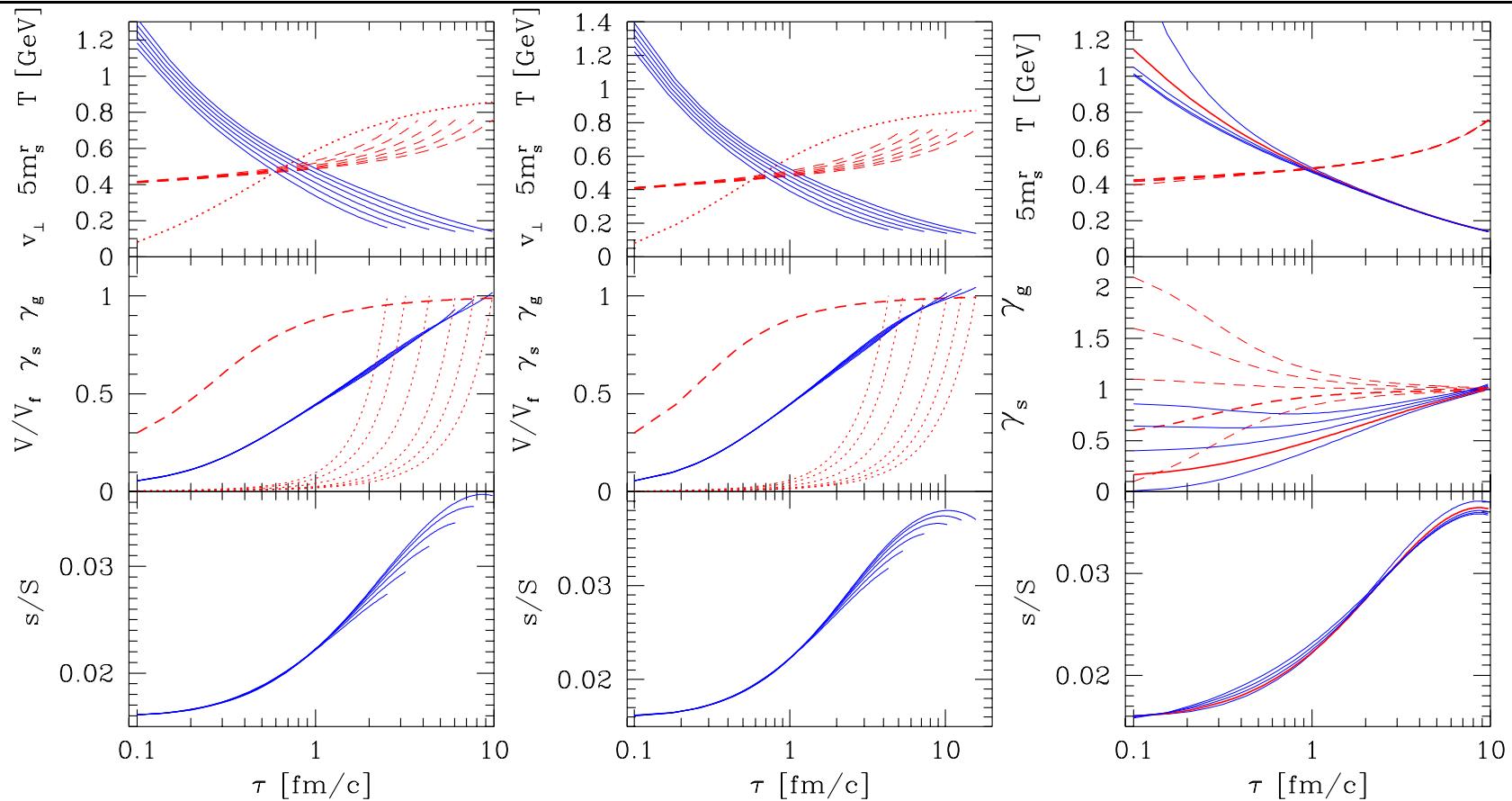
$$A^{12 \rightarrow 34} \equiv \frac{1}{1 + \delta_{1,2}} \rho_1^\infty \rho_2^\infty \langle \sigma_s v_{12} \rangle_T^{12 \rightarrow 34}.$$

and the related characteristic time constant  
 $\tau_s$ :

$$2\tau_s \equiv \frac{\rho_s(\infty)}{A^{gg \rightarrow s\bar{s}} + A^{q\bar{q} \rightarrow s\bar{s}} + \dots}$$

To integrate the equation for  $s/S$  we need to understand  $T(\tau)$ . Hydrodynamic expansion with Bjørken scaling motivates simple model assumptions.

## Strangeness production at LHC after tuning RHIC, with $dS/dy|_{\text{LHC}} = 4dS/dy|_{\text{RHIC}}$



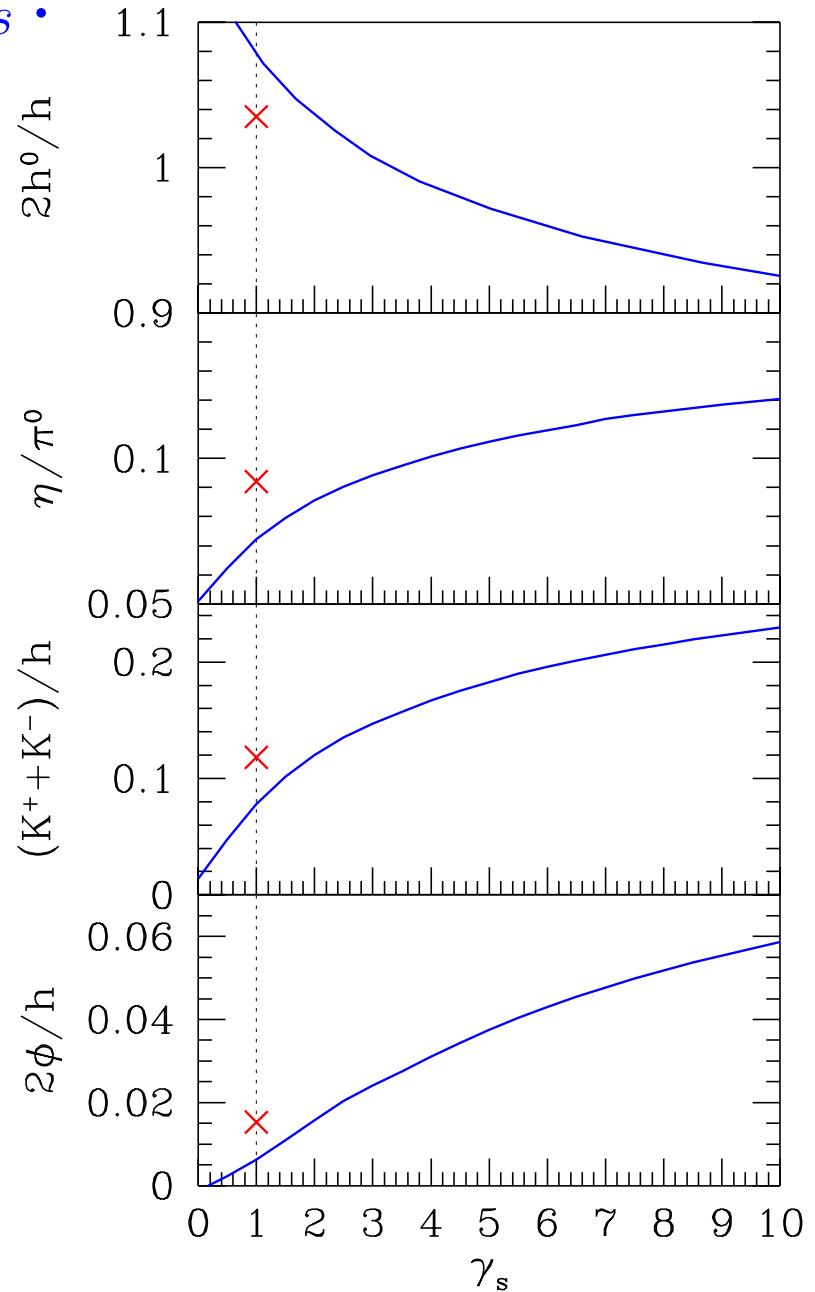
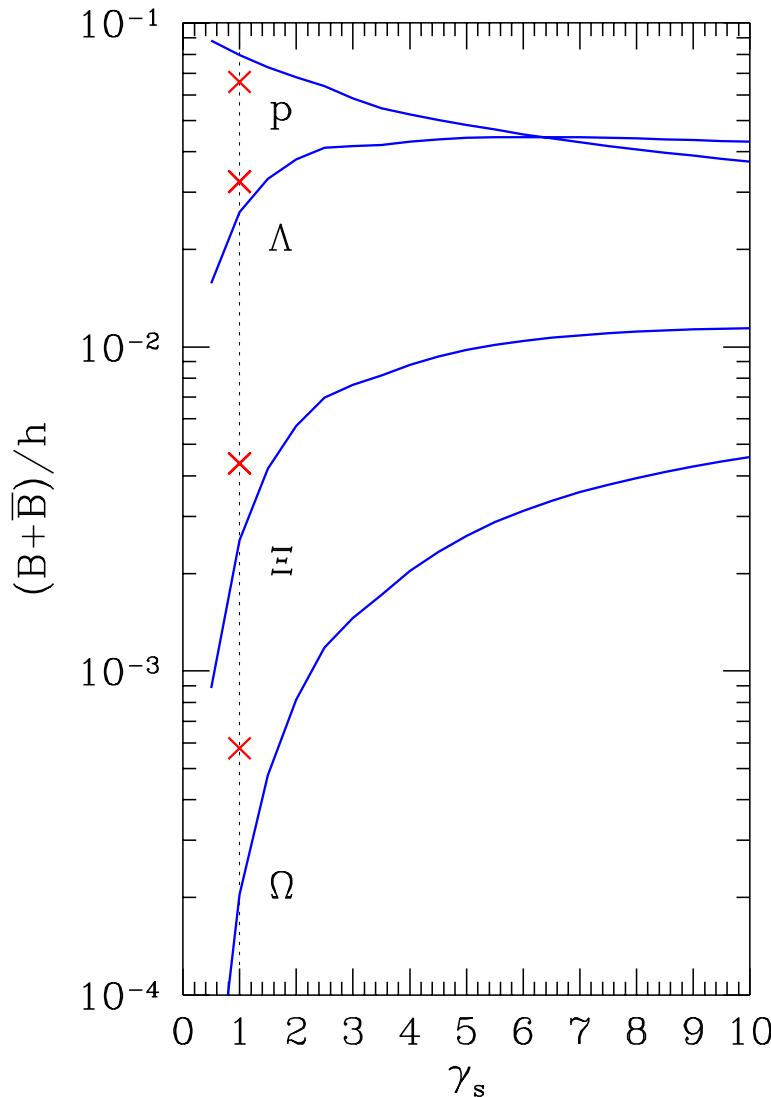
### LHC differences to RHIC

- There is a significant increase in initial temperature and gluon occupancy  $\gamma_g$  to accommodate increased initial pre-thermal evolution entropy.
- There is about twice longer expansion time to the freeze-out condition, since there is 4 times entropy content at similar hadronization  $T_h$ .
- There is over saturation of  $s/S, \gamma_s$  in QGP, and thus a much greater oversaturation in hadron phase space (for  $T_h < 240$  MeV)

**NOTE:**  $s/S$  measures chemical equilibration in QGP and number of strange to all degrees of freedom. Study as function of centrality to see saturation.

# EPJ-C ratios as function of $\gamma_s^H$ :

**Fixed:**  $\gamma_q$  at max,  
 $E/b = 412 \pm 20$  GeV,



$dp/dy$	25/63.6	50/102	98/189	130/198
$dh_{\text{ch}}^{\text{vis}}/dy$	2950	3000	3120	3400
$s/S$	<b>0.041</b>	<b>0.038</b>	<b>0.039</b>	<b>0.027</b>
$E/b$	<b>500</b>	<b>500</b>	<b>500</b>	<b>500</b>
$E/TS$	<b>0.92</b>	<b>0.99</b>	<b>1.01</b>	<b>0.98</b>
$P/E$	<b>0.17</b>	<b>0.16</b>	<b>0.15</b>	<b>0.15</b>
$dV/dy$	<b>14541</b>	<b>5481</b>	<b>1507</b>	<b>1610</b>
$T$	<b>134.0</b>	<b>143.6</b>	<b>170.4</b>	<b>175.7</b>
$\mu_{\text{B,S}}$	3.0, 0.4	2.1, 0.4	1.8, 0.6	1.7, 0.6
$\gamma_q$	<b>0.98</b>	<b>1.35</b>	<b>1.49</b>	<b>1.47</b>
$\gamma_s$	<b>2.36</b>	<b>2.34</b>	<b>2.14</b>	<b>1.31</b>
$dN/dy$				
$0.1 \cdot \pi^\pm, \pi^0$	<b>98,116</b>	<b>102, 116</b>	<b>100,111</b>	<b>122,135</b>
$0.1 \cdot \pi^\pm, \pi^0$	<b>122,148</b>	<b>125, 145</b>	<b>126,144</b>	<b>141,159</b>
$K^\pm$	<b>299</b>	<b>246</b>	<b>220</b>	<b>71</b>
$\phi$	<b>64</b>	<b>44</b>	<b>43</b>	<b>21</b>
$\Lambda$	<b>30/53</b>	<b>46/71</b>	<b>81.5/124</b>	<b>68.5/90</b>
$\Xi$	<b>10</b>	<b>11.4</b>	<b>18.5</b>	<b>9.7</b>
$\Omega$	<b>2.95</b>	<b>2.8</b>	<b>4.9</b>	<b>1.7</b>
$K^0(892)$	<b>64</b>	<b>60</b>	<b>67</b>	<b>55.1</b>
$\Delta^0 = \Delta^{++}$	<b>4.6</b>	<b>9.7</b>	<b>20</b>	<b>27.8</b>
$\Lambda(1520)$	<b>1.8</b>	<b>3.0</b>	<b>7.0</b>	<b>6.2</b>
$\Sigma(1385)$	<b>3.5</b>	<b>5.6</b>	<b>10.5</b>	<b>9.1</b>
$\Xi(1530)$	<b>3.2</b>	<b>3.9</b>	<b>6.9</b>	<b>3.8</b>
$\rho^0$	<b>70</b>	<b>84</b>	<b>106</b>	<b>134</b>
$f_0(980)$	<b>5.0</b>	<b>6.5</b>	<b>8.6</b>	<b>11.2</b>

$dp/dy$	25.5/63.1	51/119	93/182	143/235
$dh_{\text{ch}}^{\text{vis}}/dy$	2908	3262	3262	3174
$s/S$	<b>0.040</b>	<b>0.041</b>	<b>0.037</b>	<b>0.033</b>
$E/b$	<b>500</b>	<b>500</b>	<b>500</b>	<b>534</b>
$E/TS$	<b>0.92</b>	<b>0.92</b>	<b>0.89</b>	<b>0.98</b>
$P/E$	<b>0.17</b>	<b>0.15</b>	<b>0.15</b>	<b>0.15</b>
$dV/dy$	<b>14033</b>	<b>3838</b>	<b>1538</b>	<b>225</b>
$T$	<b>134.0</b>	<b>163.3</b>	<b>192.3</b>	<b>254.6</b>
$\mu_{\text{B,S}}$	3.0, 0.4	2.4, 0.6	2.3, 0.1	3.5, 1.7
$\gamma_q$	<b>1</b>	<b>1</b>	<b>1</b>	<b>1</b>
$\gamma_s$	<b>2.36</b>	<b>1.90</b>	<b>1.42</b>	<b>1.05</b>
$dN/dy$				
$0.1 \cdot \pi^\pm, \pi^0$	<b>97,115</b>	<b>92,105</b>	<b>106,118</b>	<b>104,113</b>
$0.1 \cdot \pi^\pm, \pi^0$	<b>120,146</b>	<b>117, 138</b>	<b>133,152</b>	<b>127,142</b>
$K$	<b>294</b>	<b>254</b>	<b>231</b>	<b>171</b>
$\phi$	<b>61</b>	<b>60</b>	<b>48</b>	<b>30</b>
$\Lambda$	<b>30/52</b>	<b>56/93</b>	<b>80/121</b>	<b>91/125</b>
$\Xi$	<b>9.65</b>	<b>16.1</b>	<b>18.0</b>	<b>14.8</b>
$\Omega$	<b>2.8</b>	<b>5.24</b>	<b>5.4</b>	<b>4.4</b>
$K^0(892)$	<b>62</b>	<b>72</b>	<b>76</b>	<b>59</b>
$\Delta^0 = \Delta^{++}$	<b>4.7</b>	<b>10.4</b>	<b>19.3</b>	<b>28</b>
$\Lambda(1520)$	<b>1.7</b>	<b>4.4</b>	<b>7.7</b>	<b>11</b>
$\Sigma(1385)$	<b>3.5</b>	<b>7.0</b>	<b>10.2</b>	<b>11</b>
$\Xi(1530)$	<b>3.1</b>	<b>5.9</b>	<b>7.1</b>	<b>6.5</b>
$\rho^0$	<b>70</b>	<b>90</b>	<b>119</b>	<b>124</b>
$f_0(980)$	<b>4.9</b>	<b>7.3</b>	<b>9.8</b>	<b>8.8</b>

## LESSONS

The measurement of  $p, \Lambda, \pi$  suffers from significant weak decay (50% level) contribution and cannot be used to identify hadronization mechanisms of hadronization.

Strangeness/entropy enhancement easily observed, WD contamination not an issue.

Statistical hadronization cannot reach high baryon to meson yields predicted by Topor-Pop and collaborators.

Resonances very clearly provide the sole path to the understanding of the hadronization of the bulk.

## QUESTION: