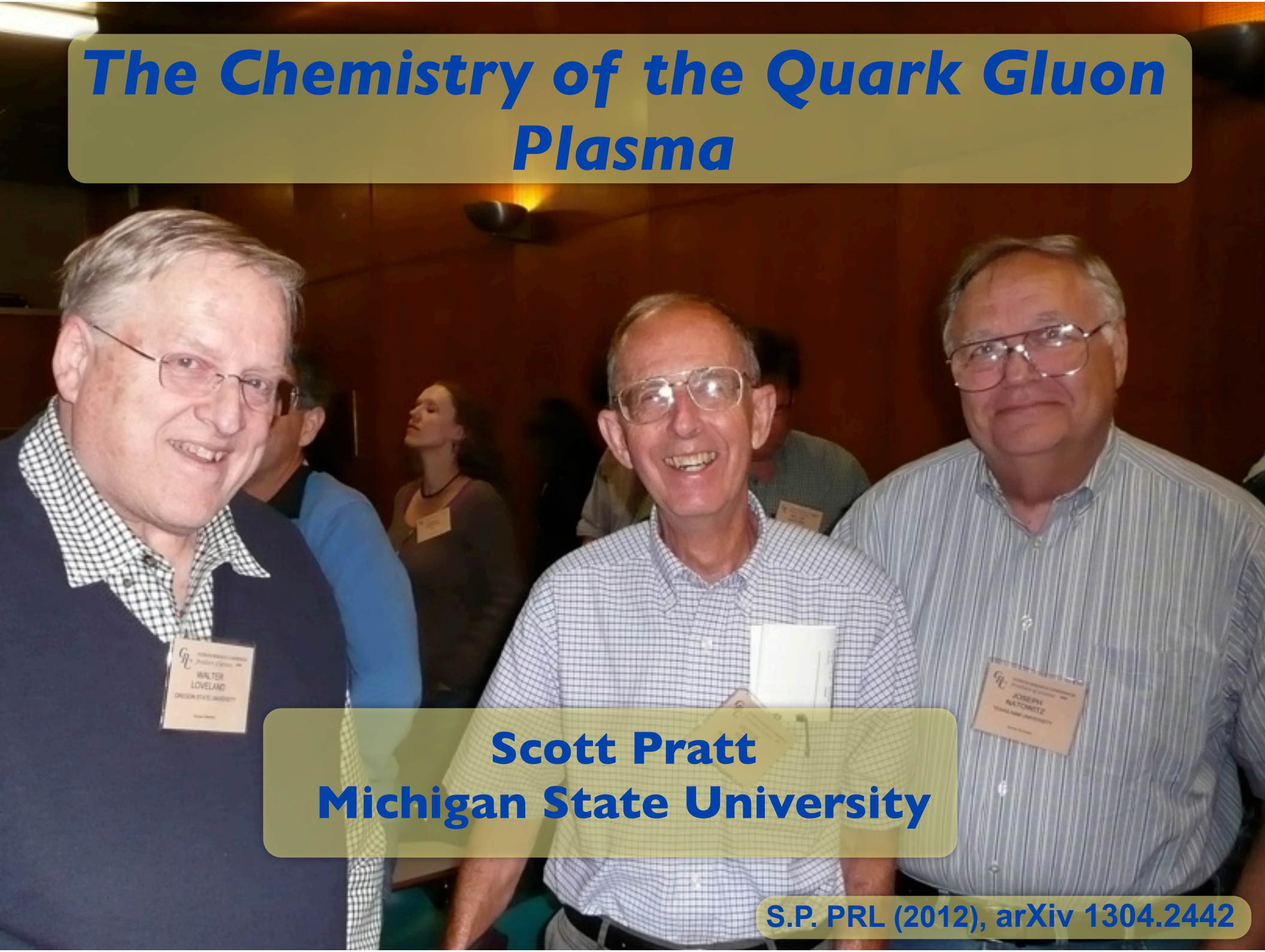
The Chemistry of the Quark Gluon Plasma



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S.P. PRL (2012), arXiv 1304.2442

QGP Chemistry Basics

- 52 ~massless degrees of freedom
- Strongly interacting
- Conserved: up-ness, down-ness, strangeness, color
  Not conserved: quark number
- Lattice measures charge fluctuations:

$$\chi_{ab} \equiv \langle Q_a Q_b \rangle / V$$

Parton gas:

$$\chi_{ab}^{\mathrm{QGP}} = (n_a + n_{\bar{a}})\delta_{ab}$$

a,b = uds

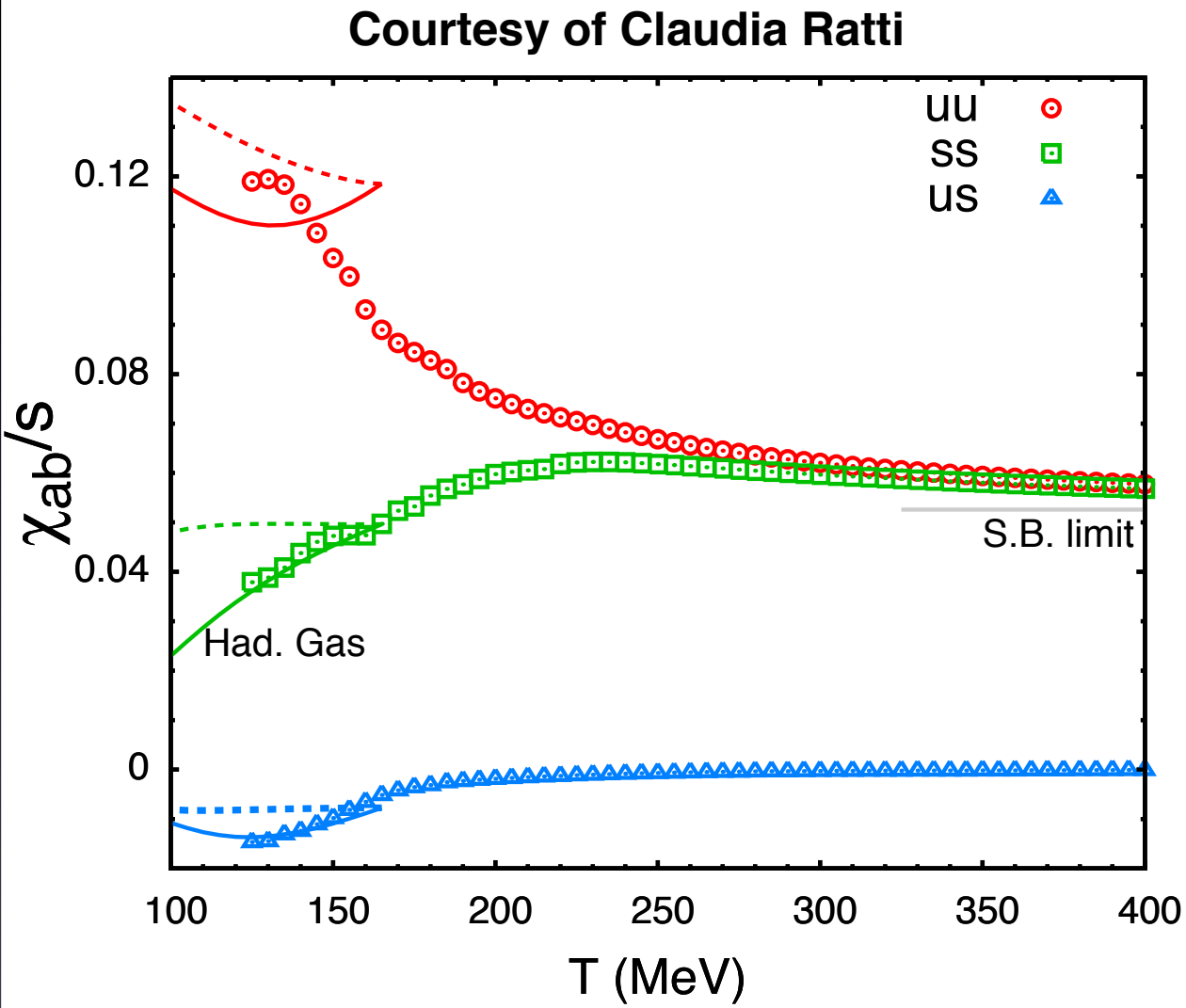
Hadron gas:

$$\chi_{ab}^{HAD} = \sum_{\alpha} n_\alpha q_{\alpha,a} q_{\alpha,b}$$

$\alpha = \pi^+, \pi^-, \pi^0, K^+ \ldots$

Lattice Charge Fluctuations

scaled by entropy



Parton gas:

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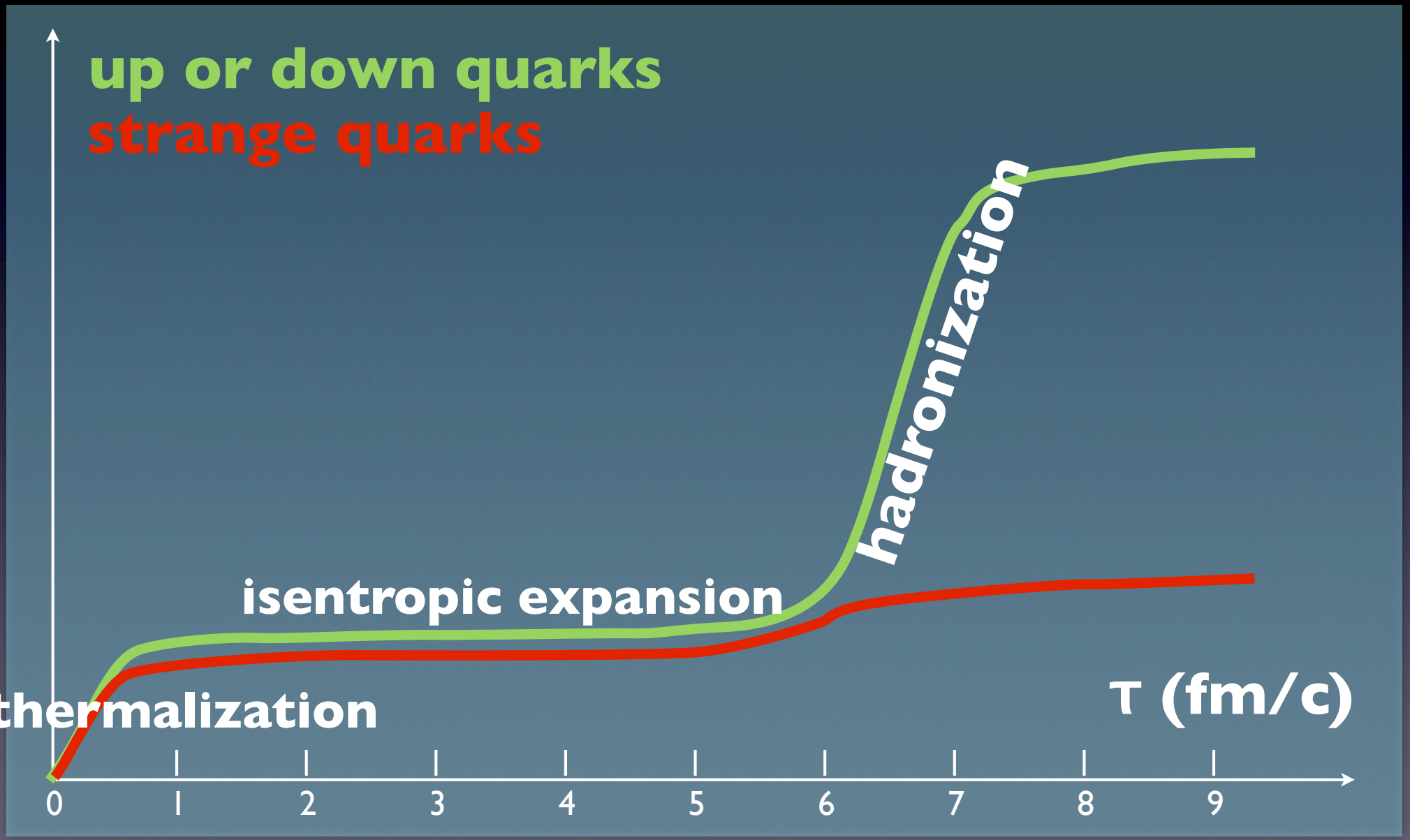
off-diagonal elements (V.Koch, PRL 2005)

Two waves of quark production



Problems with Comparing Experiment to Lattice

1. Lattice = Grand Canonical (Particle Bath)
   Experiment = Canonical (net charge = 0)

2. Charge created at hadronization

3. One measures hadrons -- not uds

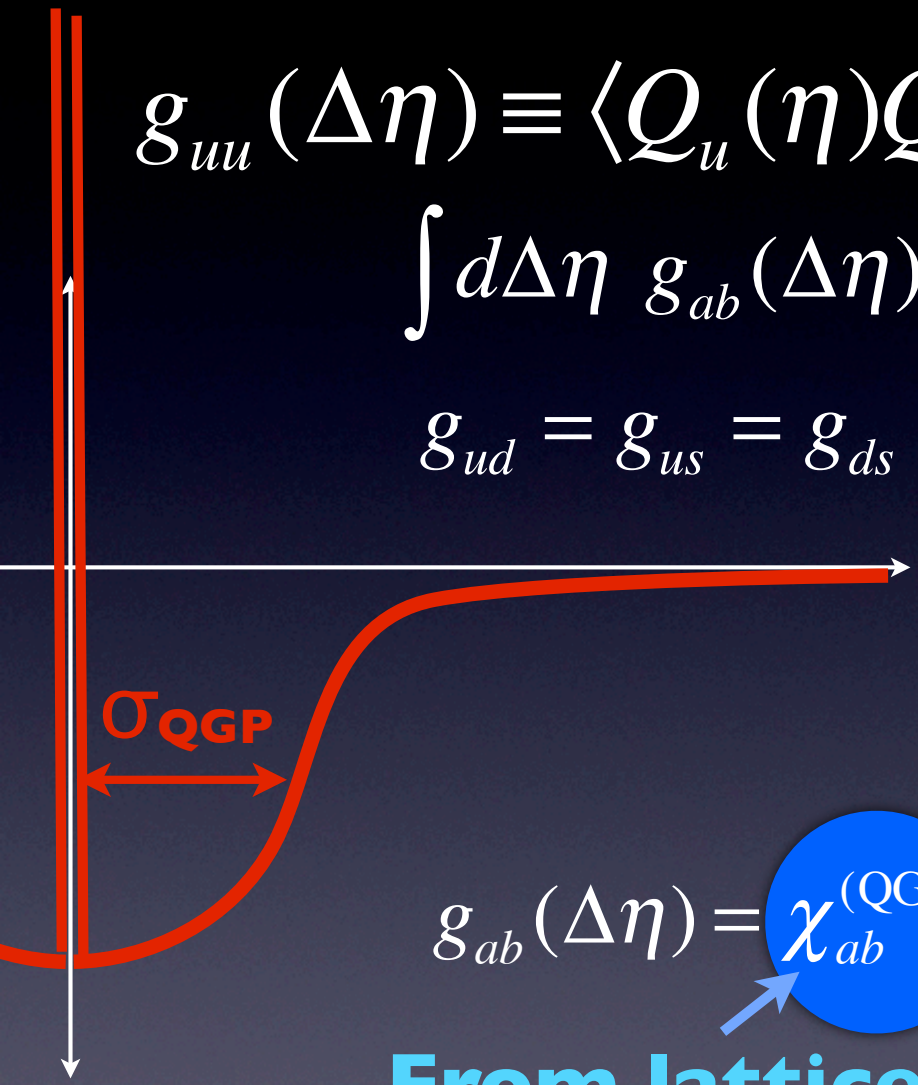
4. One measures momenta, not positions

I. Before hadronization

$$g_{uu}(\Delta\eta) \equiv \langle Q_u(\eta) Q_u(\eta+\Delta\eta)\rangle$$

$$\int d\Delta\eta \; g_{ab}(\Delta\eta) = 0$$

$$g_{ud} = g_{us} = g_{ds} = 0$$



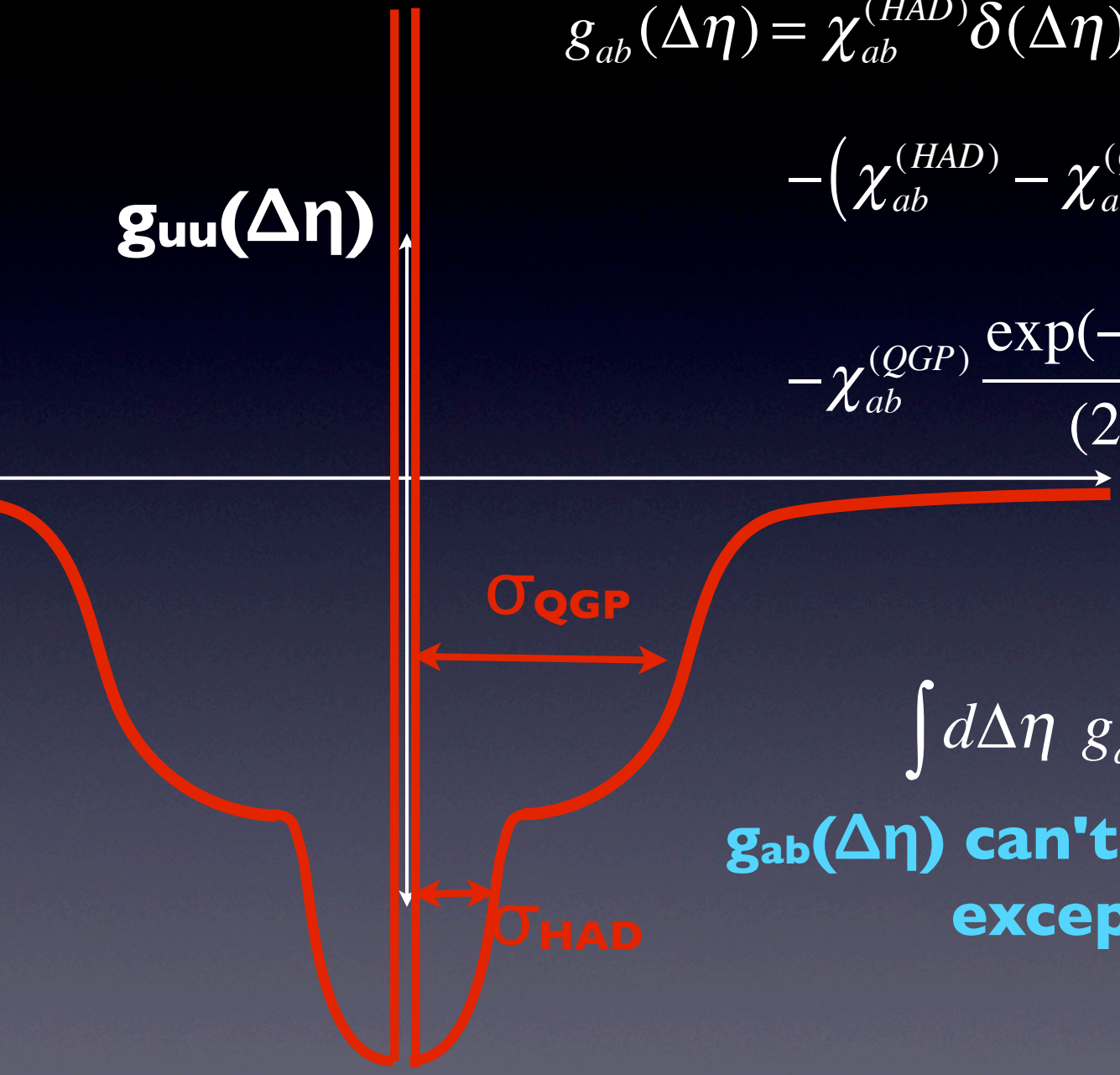
only extra parameter

$$g_{ab}(\Delta\eta) = \chi_{ab}^{(\mathrm{QGP})} \left\{ \delta(\Delta\eta) - \frac{\exp(-\Delta\eta^2 / 2\sigma^2_{(\mathrm{QGP})})}{(2\pi\sigma^2_{(\mathrm{QGP})})^{1/2}} \right\}$$

From lattice!

2. Just after hadronization

$$g_{ab}(\Delta\eta) = \chi_{ab}^{(HAD)}\delta(\Delta\eta) - \left(\chi_{ab}^{(HAD)} - \chi_{ab}^{(QGP)}\right)\frac{\exp(-\Delta\eta^2 / 2\sigma_{(HAD)}^2)}{(2\pi\sigma_{(HAD)}^2)^{1/2}} - \chi_{ab}^{(QGP)}\frac{\exp(-\Delta\eta^2 / 2\sigma_{(QGP)}^2)}{(2\pi\sigma_{(QGP)}^2)^{1/2}}$$



$$\int d\Delta\eta \; g_{ab}(\Delta\eta) = 0$$

$g_{ab}(\Delta\eta)$ can't change suddenly except at $\Delta\eta=0$

2. Just after hadronization
Summarizing...

$$-g'_{ab}(\Delta\eta) = \chi_{ab}^{(QGP)} \frac{e^{-\Delta\eta^2/2\sigma^2_{(QGP)}}}{\sqrt{2\pi\sigma^2_{(QGP)}}} + (\chi_{ab}^{(HAD)} - \chi_{ab}^{(QGP)}) \frac{e^{-\Delta\eta^2/2\sigma^2_{(HAD)}}}{\sqrt{2\pi\sigma^2_{(HAD)}}}$$

$$\chi_{ab}^{(HAD)} \equiv \sum_{\alpha \in \text{hadrons}} n_\alpha q_{\alpha,a} q_{\alpha,b}$$

$$\chi_{ab}^{(QGP)} \equiv 2 n_a \delta_{ab}$$

3. But, we measure $G_{\alpha\beta}$ not g_{ab}!!!

$\alpha,\beta=\pi,p,K...$ $a,b=u,d,s$

$$G_{\alpha\beta}(\Delta\eta) \equiv \langle [n_\alpha - n_{\bar{\alpha}}][n_\beta - n_{\bar{\beta}}] \rangle$$

$$e.g., \quad G_{pK^-} = \langle [n_p - n_{\bar{p}}][n_{K^-} - n_{K^+}] \rangle$$

Generalized Balance Function (aside from factor of $\langle n_\beta \rangle$)

Analogous problem...

Given $\delta\rho_a$ and n_α, find δn_α

Solution: assign chemical potential

$$\delta n_\alpha = \langle n_\alpha \rangle \left(e^{\mu_a q_{\alpha,a}/T} - 1 \right)$$

$$\delta\rho_a = \sum_\alpha \delta n_\alpha q_{\alpha,a} \approx \sum_{\alpha b} \langle n_\alpha \rangle q_{\alpha a} q_{\alpha b} \frac{\mu_b}{T} = \sum_b \chi_{ab}^{(\mathrm{had})} \frac{\mu_b}{T}$$

$$\frac{\mu_a}{T} = \sum_b (\chi^{-1})_{ab} \delta\rho_b$$

$$\delta n_\alpha = \langle n_\alpha \rangle \sum_b q_{\alpha a} (\chi^{-1})_{ab} \delta\rho_b$$

3. Back to our problem...

Given: $$g'_{ab}(\Delta\eta) = \left\langle \delta\rho_a(0)\delta\rho_b(\Delta\eta)\right\rangle = \sum_{\alpha\beta}\left\langle n_\alpha(0) q_{\alpha,a} n_\beta(\Delta\eta) q_{\beta,b}\right\rangle$$

Assume: $$\left\langle n_\alpha(0) n_\beta(\Delta\eta)\right\rangle = \left\langle n_\alpha\right\rangle\left\langle n_\beta\right\rangle \exp\left\{\sum_{ab}\mu_{ab}(\Delta\eta) q_{\alpha,a} q_{\beta,b}\right\}$$

Solution:

$$\left\langle \delta n_\alpha(0)\delta n_\beta(\Delta\eta)\right\rangle = \left\langle n_\alpha\right\rangle\left\langle n_\beta\right\rangle \sum_{abcd} q_{\alpha a}\, \chi^{(HAD)-1}_{ac}\, g'_{cd}(\Delta\eta)\, \chi^{(HAD)-1}_{db}\, q_{\beta b}$$

3. Putting this together

$$-G'_{\alpha\beta}(\Delta\eta) = w_{\alpha\beta}^{(\mathrm{QGP})} \frac{e^{-\Delta\eta^2/2\sigma^2_{(QGP)}}}{\sqrt{2\pi\sigma^2_{(QGP)}}} + w_{\alpha\beta}^{(\mathrm{HAD})} \frac{e^{-\Delta\eta^2/2\sigma^2_{(HAD)}}}{\sqrt{2\pi\sigma^2_{(HAD)}}}$$

$$w_{\alpha\beta}^{(\mathrm{QGP})} = -2\sum_{abcd} \langle n_\alpha \rangle q_{\alpha,a} \chi^{-1(HAD)}_{ab} \chi^{(QGP)}_{bc} \chi^{-1(HAD)}_{cd} \langle n_\beta \rangle q_{\beta,d}$$

$$w_{\alpha\beta}^{(HAD)} = -2\sum_{ab} \langle n_\alpha \rangle q_{\alpha,a} \chi^{-1(HAD)}_{ab} \langle n_\beta \rangle q_{\beta,b} - w_{\alpha\beta}^{(QGP)}$$

prefactors depend only only on yields and χ_{ab} from lattice

3. Prefactors...

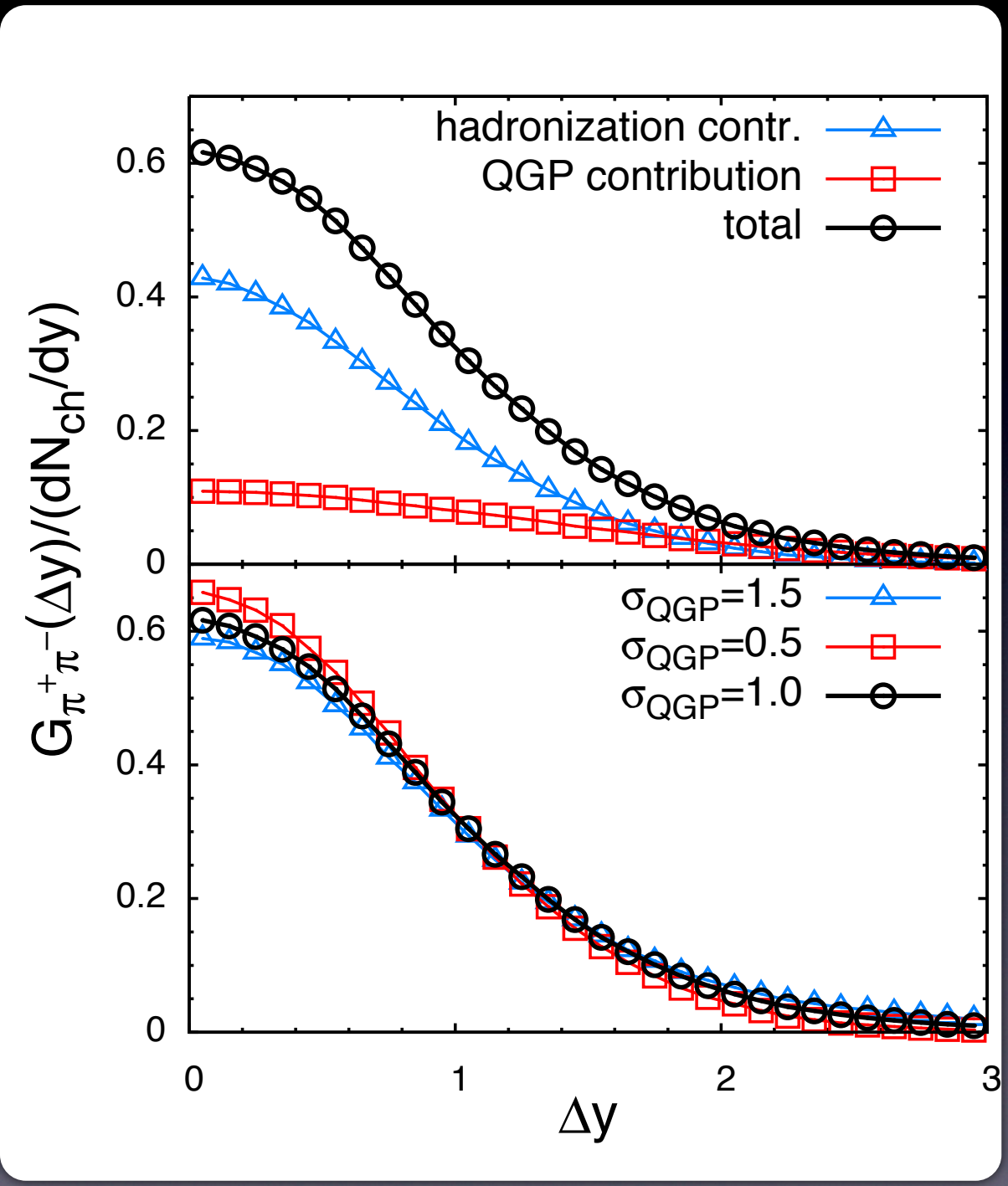
(QGP,HAD)

	p	Λ	Σ^+	Σ^-	Ξ^0	Ξ^-	Ω^-	π^+	K^+
$\bar{p}$	0.441,-0.066	0.485,-0.162	0.491,-0.146	0.479,-0.178	0.535,-0.242	0.529,-0.258	0.578,-0.338	0.006, 0.016	-0.044, 0.096
$\bar{\Lambda}$	0.183,-0.061	0.242,-0.094	0.242,-0.094	0.242,-0.094	0.302,-0.128	0.302,-0.128	0.361,-0.161	0.000,-0.000	-0.059, 0.033
$\bar{\Sigma}^-$	0.074,-0.022	0.097,-0.038	0.099,-0.033	0.095,-0.043	0.122,-0.049	0.120,-0.054	0.144,-0.064	0.002, 0.005	-0.023, 0.016
$\bar{\Sigma}^+$	0.072,-0.027	0.097,-0.038	0.095,-0.043	0.099,-0.033	0.120,-0.054	0.122,-0.049	0.144,-0.064	-0.002,-0.005	-0.025, 0.011
$\bar{\Xi}^0$	0.046,-0.021	0.069,-0.029	0.070,-0.028	0.069,-0.031	0.093,-0.036	0.092,-0.038	0.115,-0.045	0.001, 0.001	-0.023, 0.008
$\bar{\Xi}^+$	0.046,-0.022	0.069,-0.029	0.069,-0.031	0.070,-0.028	0.092,-0.038	0.093,-0.036	0.115,-0.045	-0.001,-0.001	-0.023, 0.007
$\bar{\Omega}^+$	0.009,-0.005	0.015,-0.007	0.015,-0.007	0.015,-0.007	0.021,-0.008	0.021,-0.008	0.027,-0.009	-0.000,-0.000	-0.006, 0.001
π^-	0.119, 0.318	0.000,-0.000	0.239, 0.636	-0.239,-0.636	0.119, 0.318	-0.119,-0.318	-0.000,-0.000	0.239, 0.636	0.119, 0.318
K^-	-0.175, 0.384	-0.627, 0.352	-0.603, 0.417	-0.651, 0.288	-1.055, 0.385	-1.079, 0.321	-1.507, 0.354	0.024, 0.064	0.452, 0.031

prefactors completely determined by χ_{QGP} and final-state hadronic yields

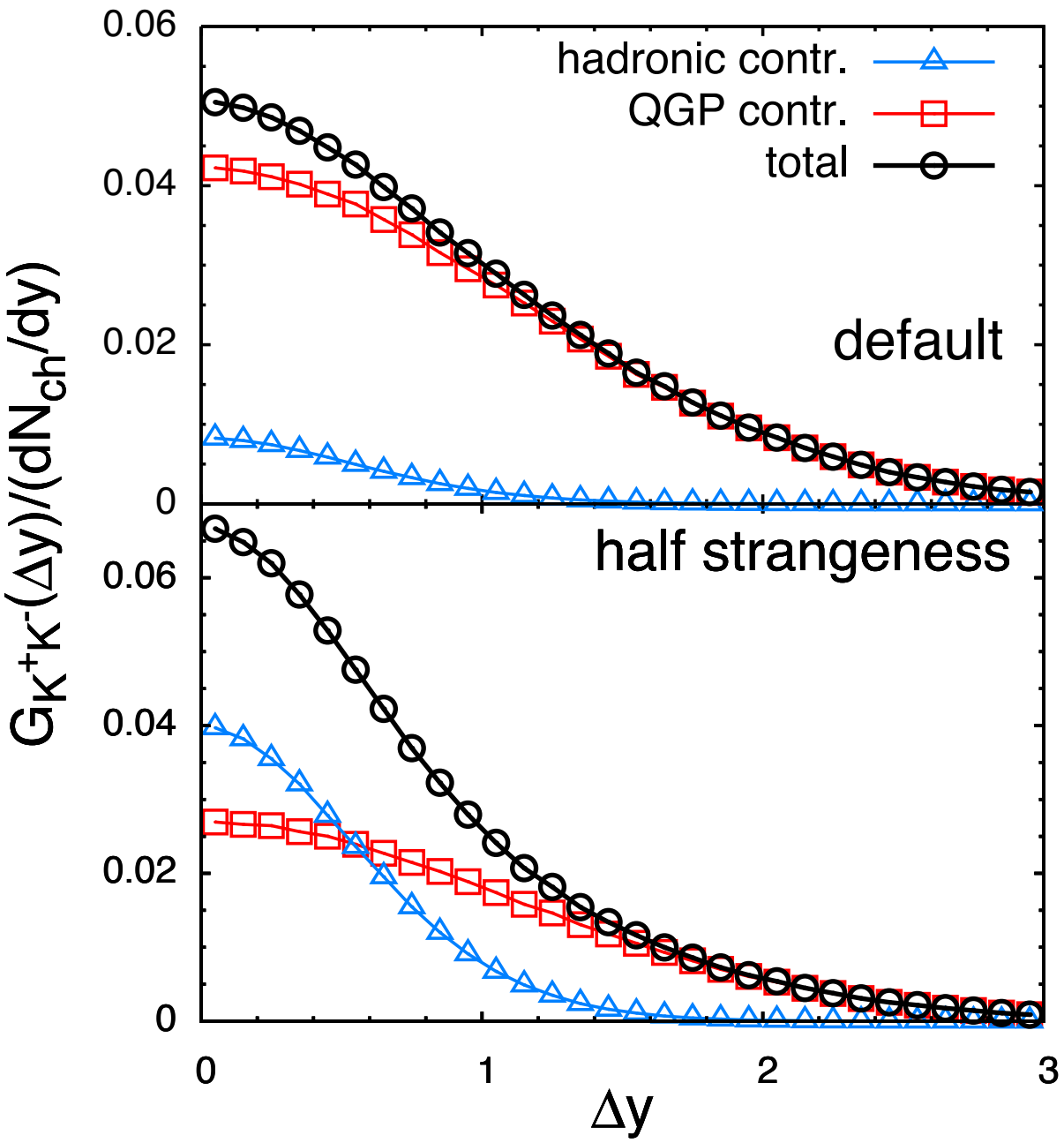
4. Use blast-wave to go from coordinate space η to momentum-space rapidity (Monte Carlo + decays) Use STAR parameters fit to spectra (T and $u_{\perp}$)

$\pi^+\pi^-$

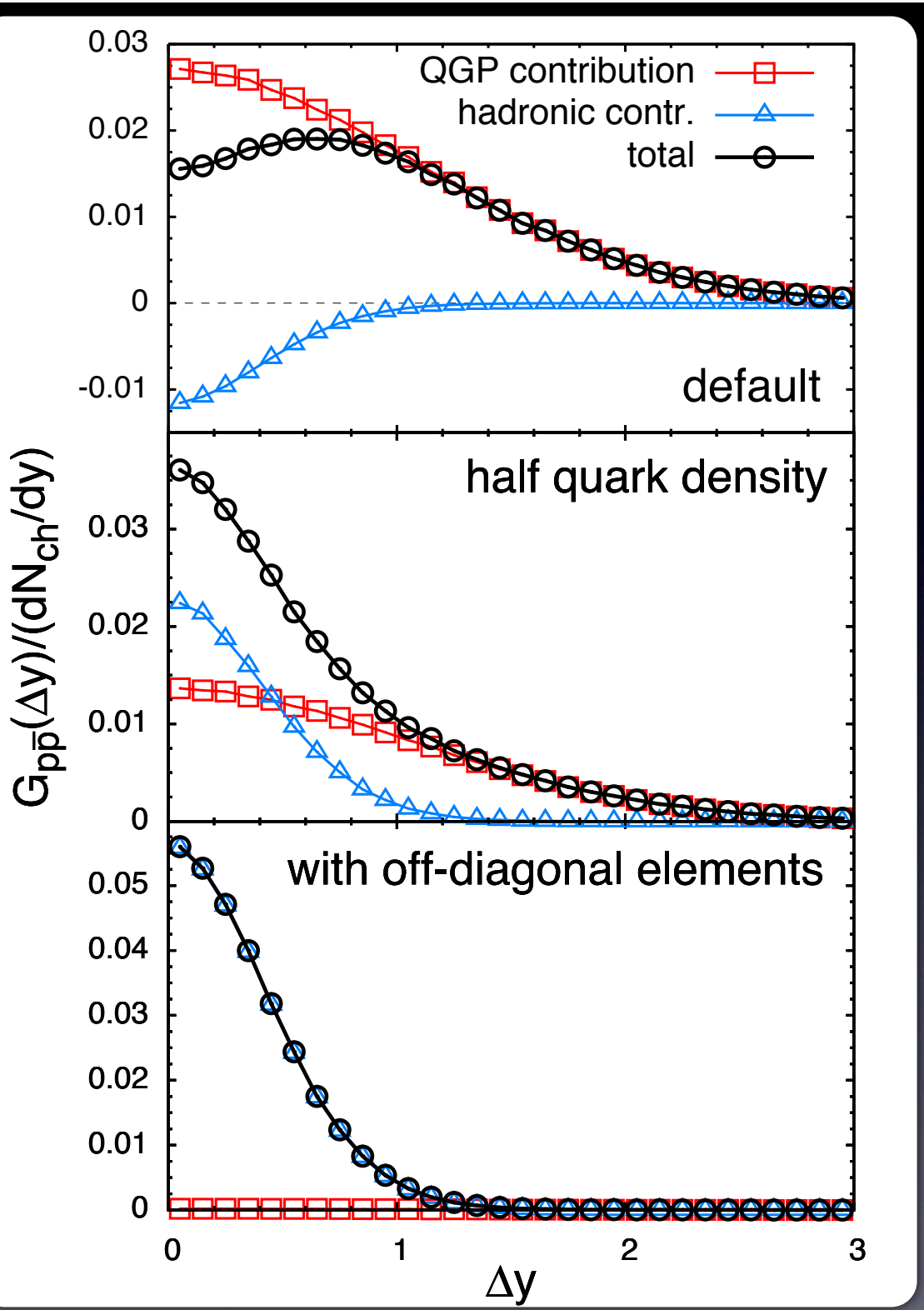


- **Hadronization part narrower**
- **Can't well separate components due to thermal smearing acceptance**
- **narrows with centrality**

K^+K^-

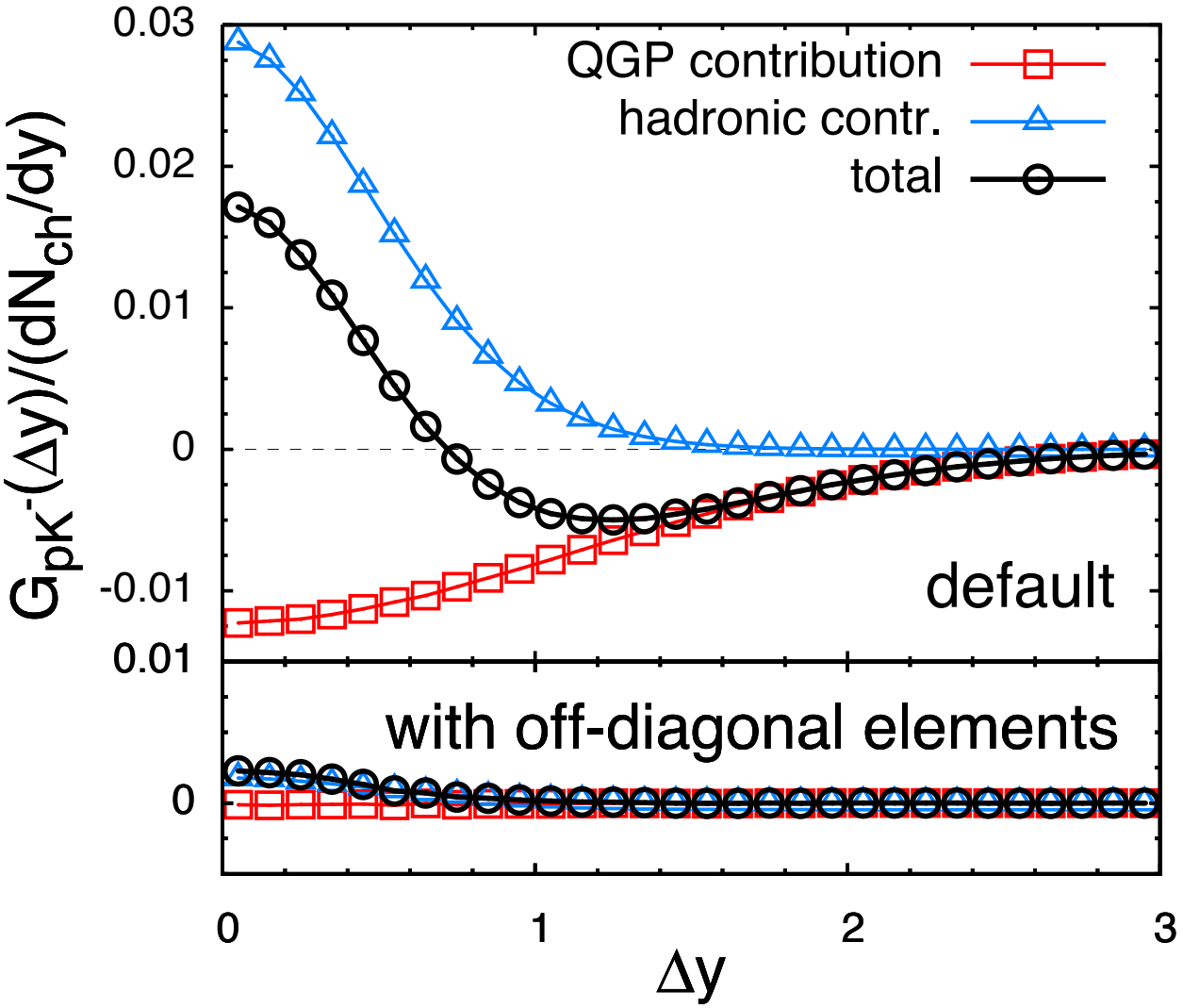


- **Little hadronic contribution**
- **Can test whether QGP is rich in strangeness**



p-pbar

- hadron contribution negative
- tests two-wave nature
- no narrowing with centrality
- sensitive to quark density of QGP

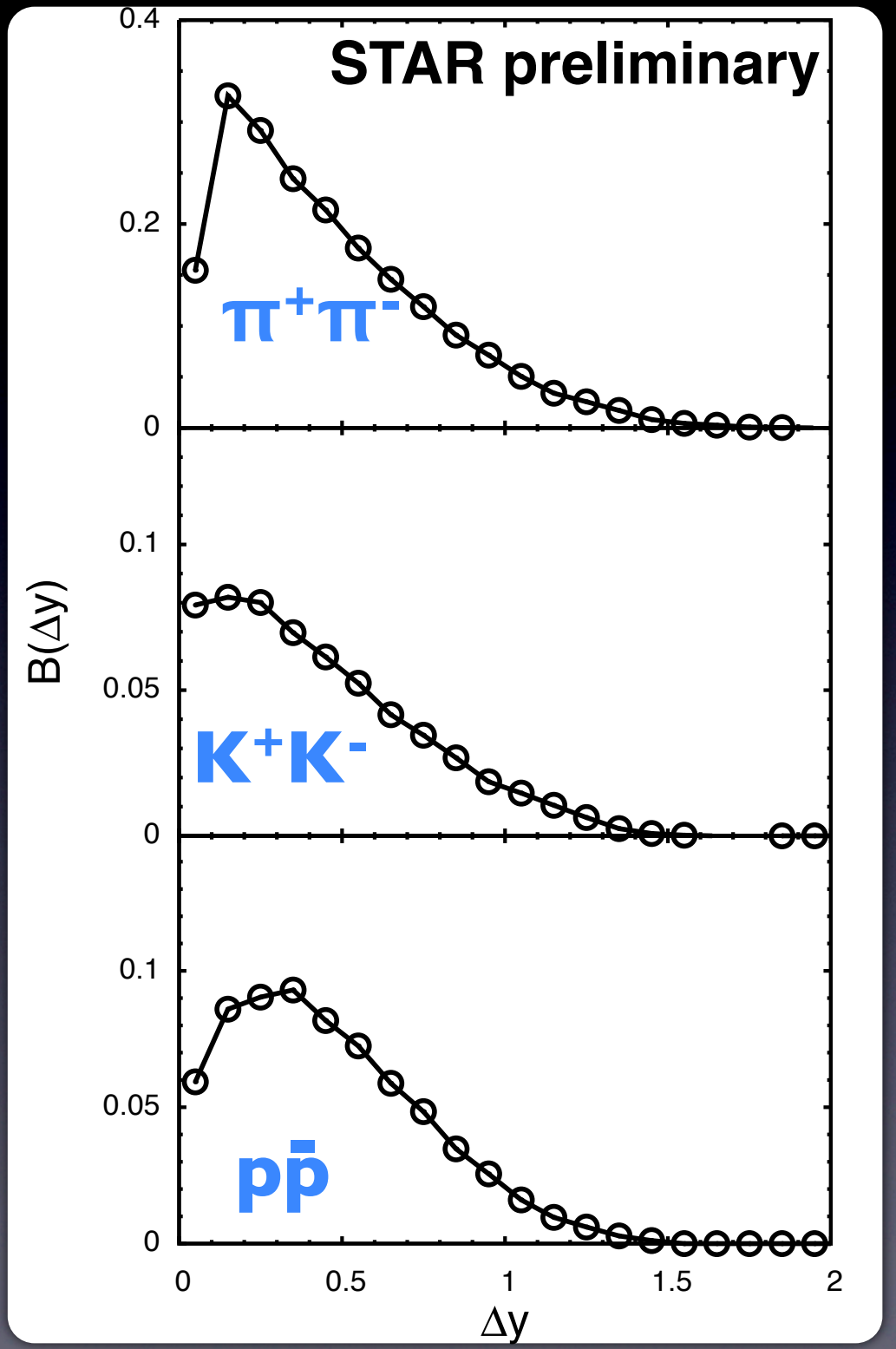


pK-

- QGP contribution negative
- dips negative
- too narrow for one source

from STAR (balance functions)

thesis of Hui Wang (2012)



Single source won't work
KK broader than ππ!
pp̄ broader than both
-- and has dip !!

Compare to Blast Wave

7 parameters:

T_{blast}=102 MeV

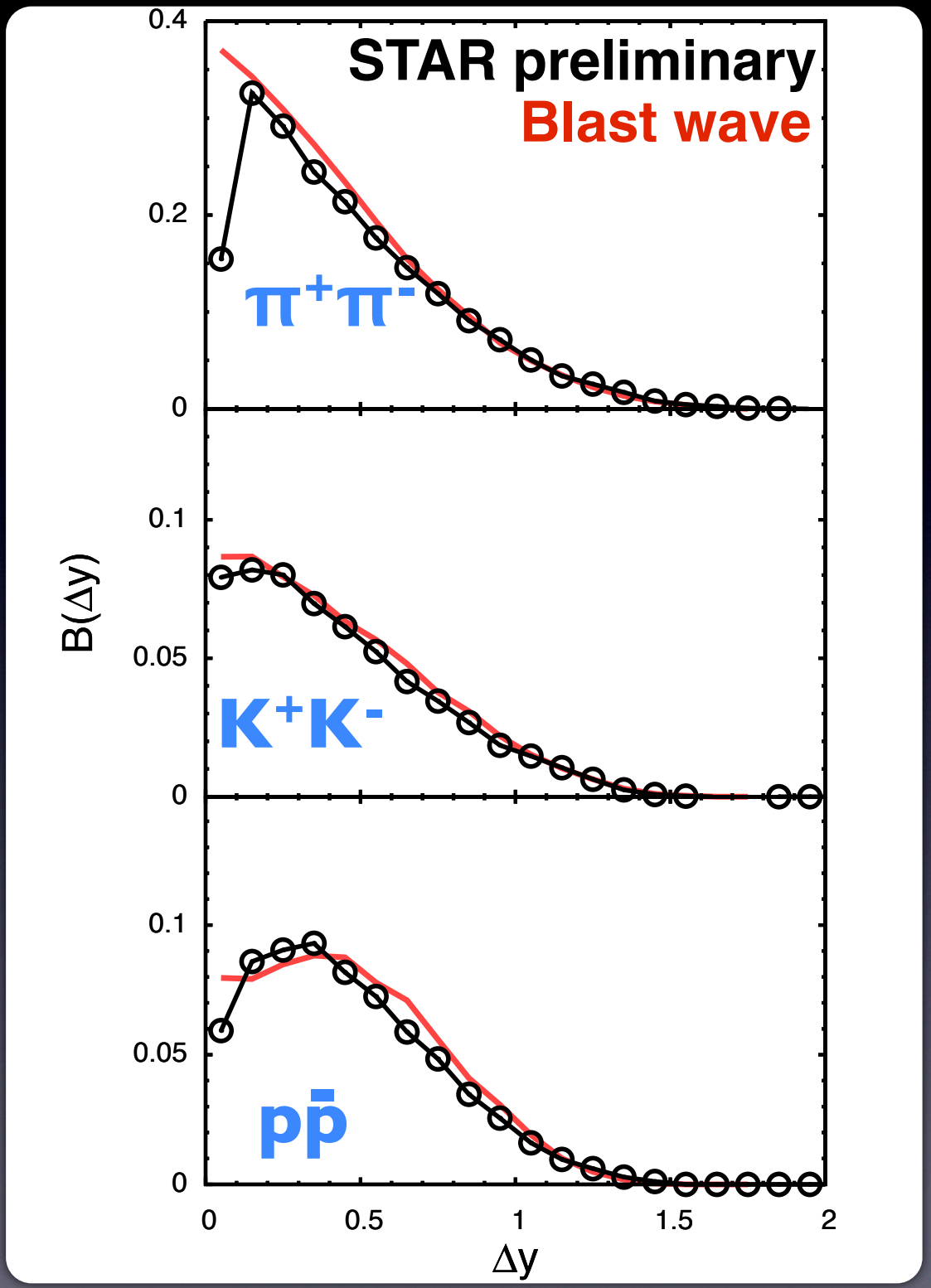
$u_{\perp}$=0.732

σ_{qgp}=1.0, σ_{had}=0,

quark/hadron=1,

s/(ud)=0.95

B suppression=0.72



5 Parameter MCMC

$0.3 < \sigma_{qgp} < 1.5$

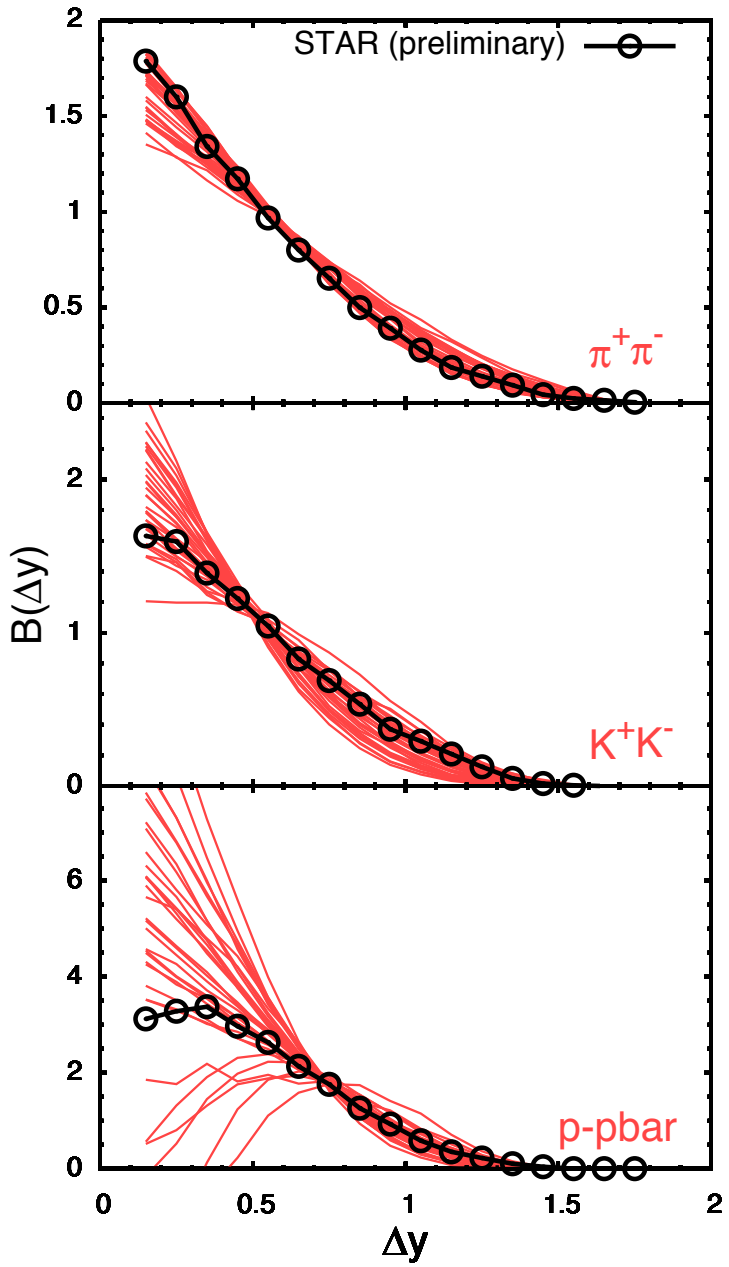
$0 < \sigma_{had}/\sigma_{qgp} < 1$

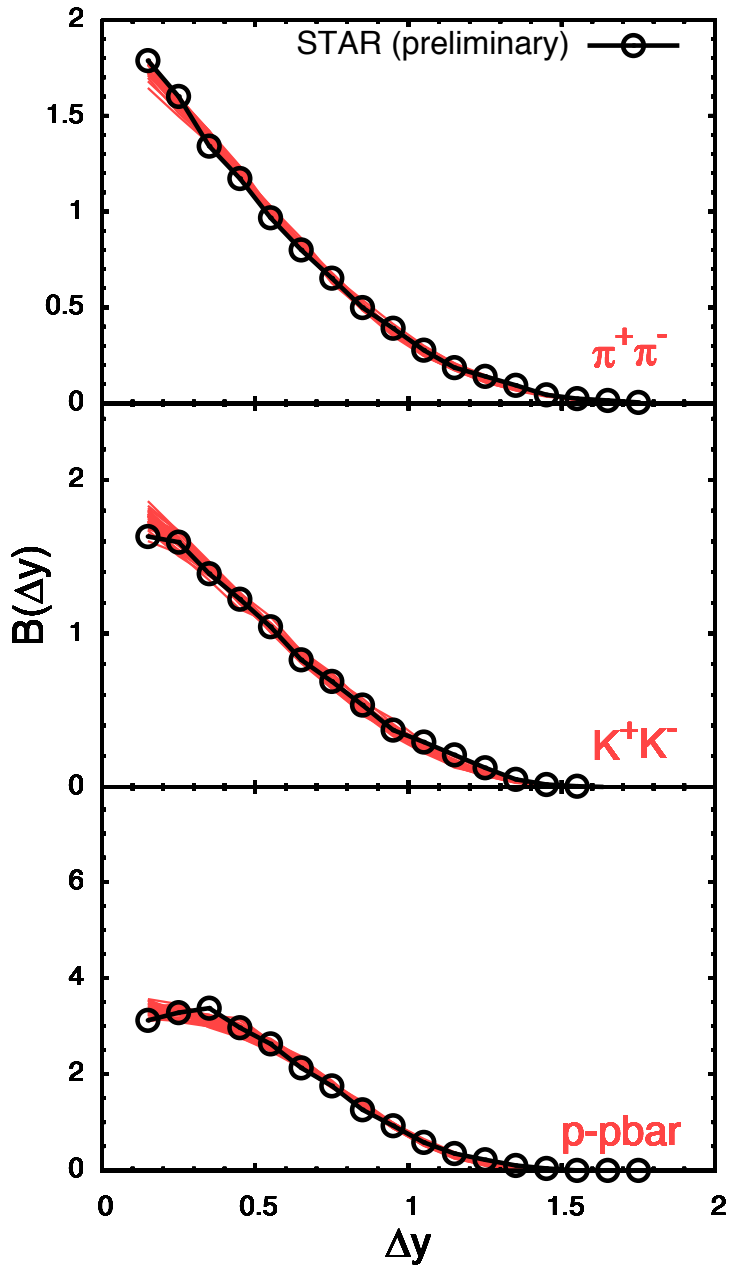
0.5<quark/hadron<1.5 0<

s/(ud) <1

0.5 < B suppression < 1

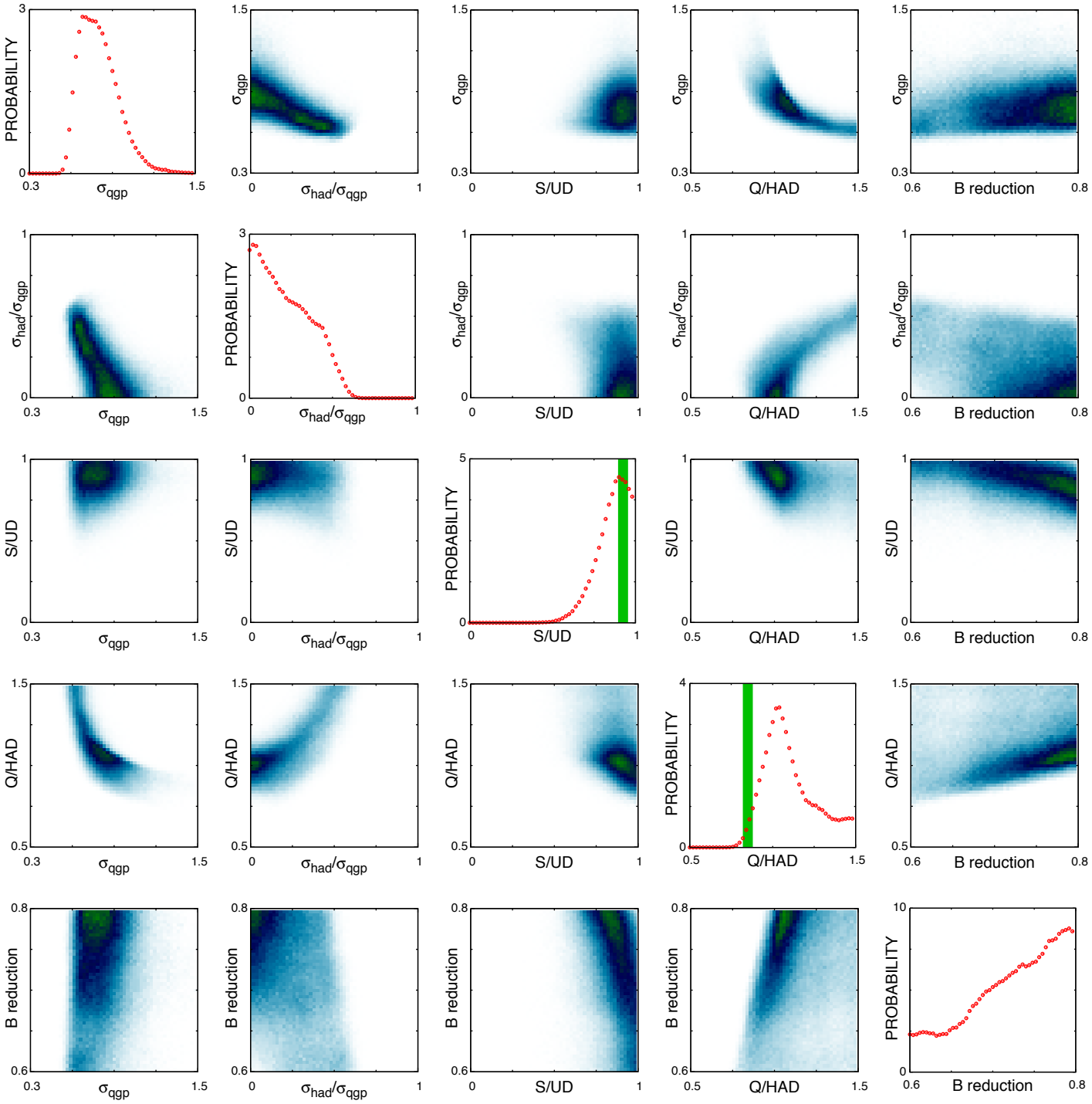
Charge Balance Functions (STAR)
Prior vs. Posterior

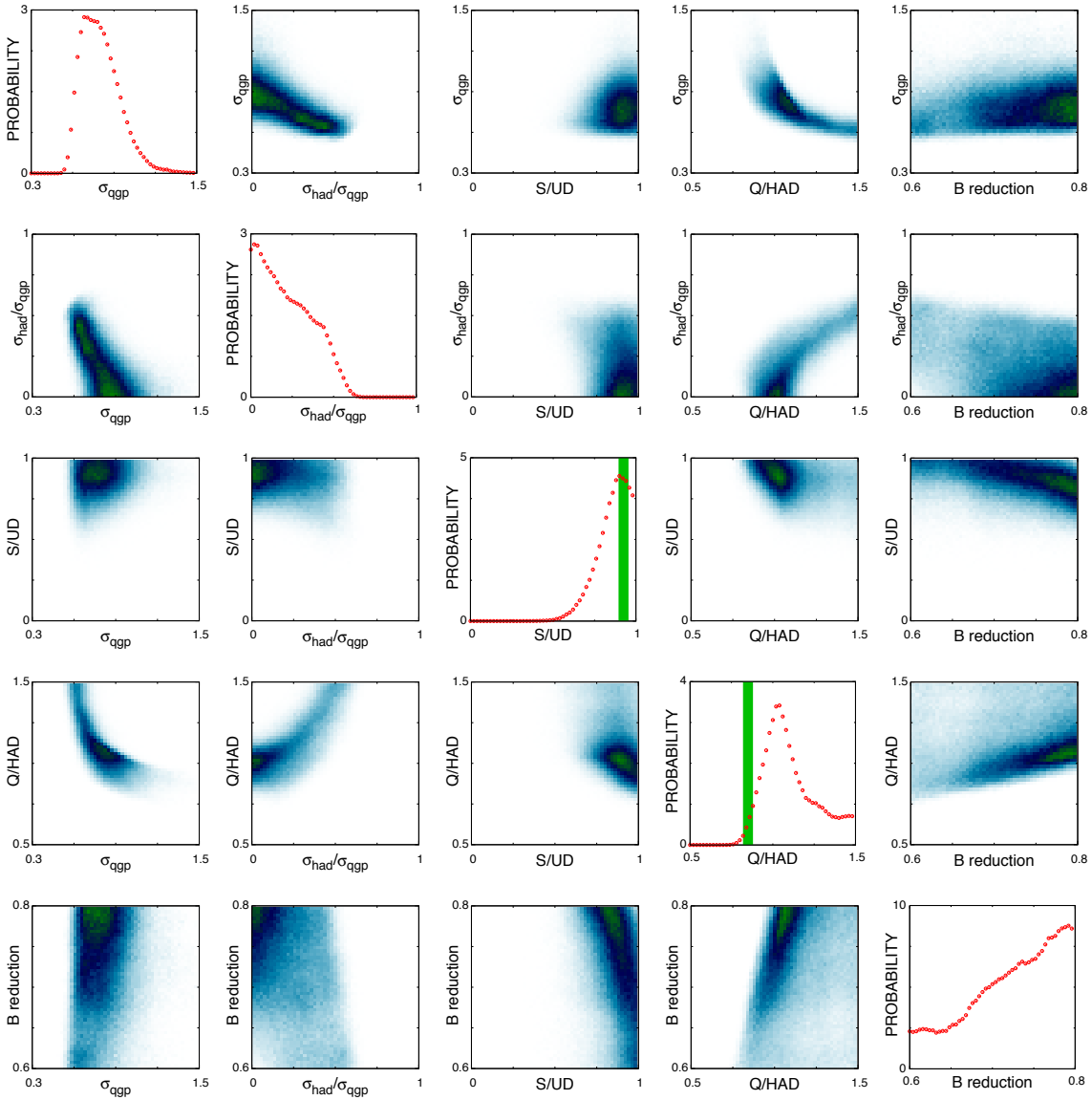




arXiv:1304.2442

MCMC Results





MCMC Results

- $\sigma_{qgp} \approx 0.85$
- $\sigma_{had} \approx 0.25$
- ud/hadron should have been 25% lower
- s/hadron as expected
- Two waves validated

To-Do List: (Experiment)

- Understand normalization mismatch of 20%
  - Experimental efficiency?
  - Long-range correlations? (ATLAS/CMS)
- Other charge combinations, e.g. pK
- σ_ϕ vs σ_η
- B(Q_{out},Q_{side},Q_{long})
- pp collisions

To-Do List: (Theory)

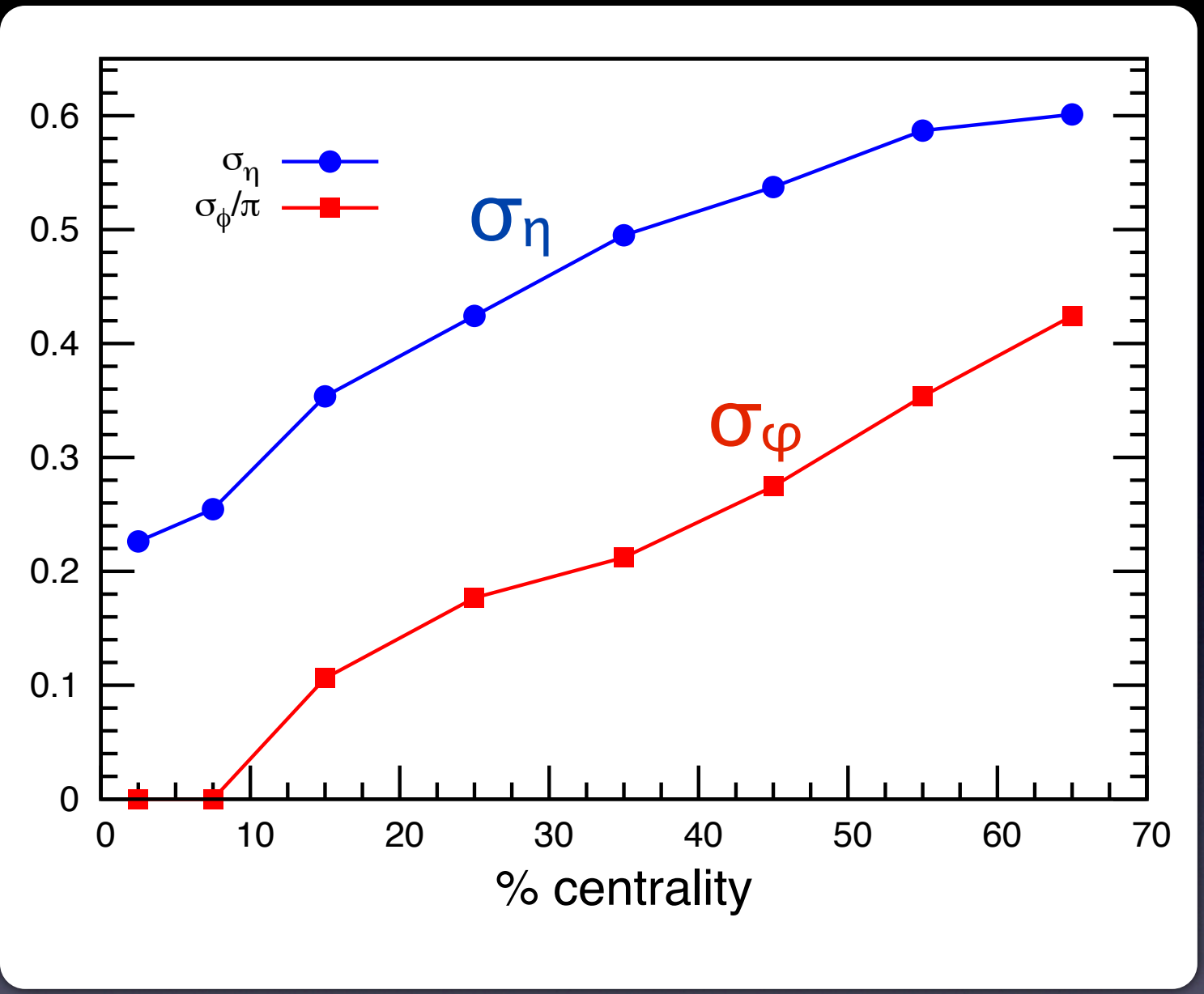
- **Continuous creation/annihilation**

$$g'_{ab}(\Delta\eta,\tau) = \int_0^\tau d\tau' \frac{d\chi_{ab}}{d\tau'} \frac{e^{-\Delta\eta^2/2\sigma^2(\tau,\tau')}}{\sqrt{2\pi\sigma^2(\tau,\tau')}}$$

- **Realistic models**

$$g'_{ab}(x_1,x_2) = \int_0^\tau d^4x' D_a(x',x_1) D_b(x',x_2) \frac{d\chi_{ab}}{d\tau'}(x')$$

- **non-zero baryon density**
- **pp/e^+e^- collisions need theory**
- **How do quarks arise from gluons/string/fluxtubes?**



bonus slide
BF Widths

Narrowing B(Δη) *suggests* delayed hadronization
(Bass, Danielewicz and SP, PRL 2001)
Narrowing B(Δφ) signals radial flow
(Bozek, PLB 2005)