Correlations in ultra-relativistic nuclear collisions with strings

Martin Rohrmoser
work with Wojciech Broniowski

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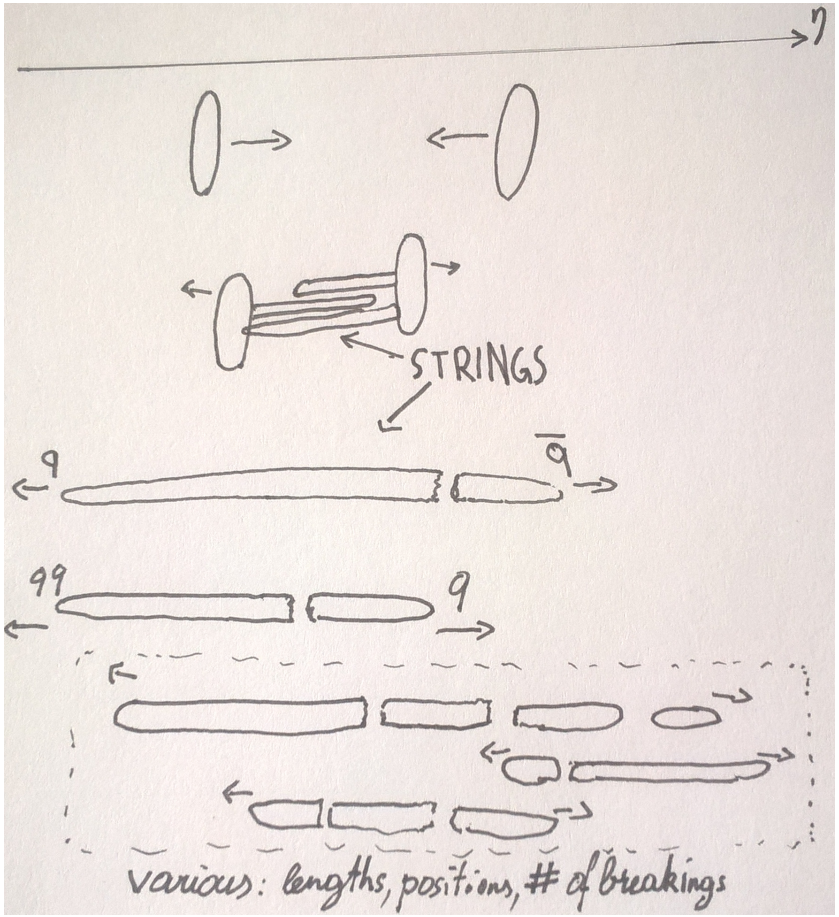
NATIONAL SCIENCE CENTRE POLAND

Uniwersytet Jana Kochanowskiego w Kielcach

Radiation via strings



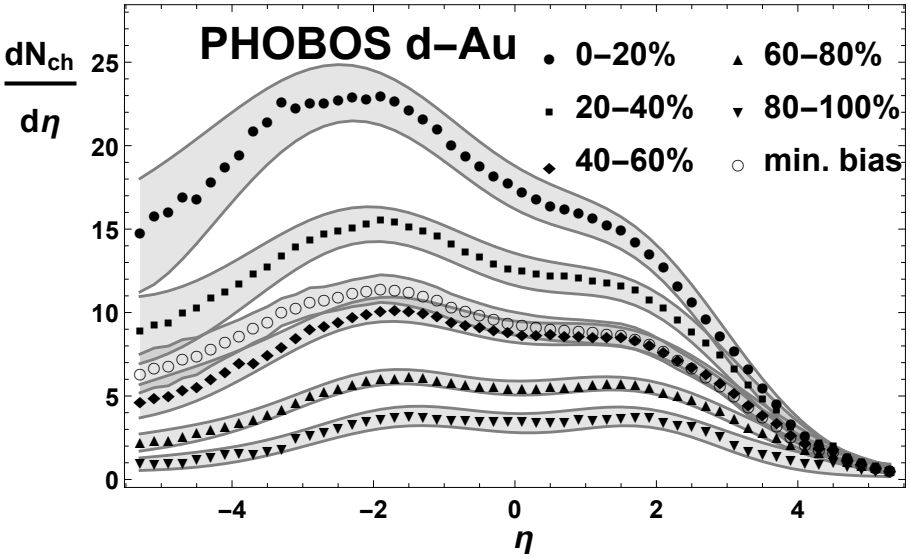
Emission from Strings
$\Rightarrow$ Correlations

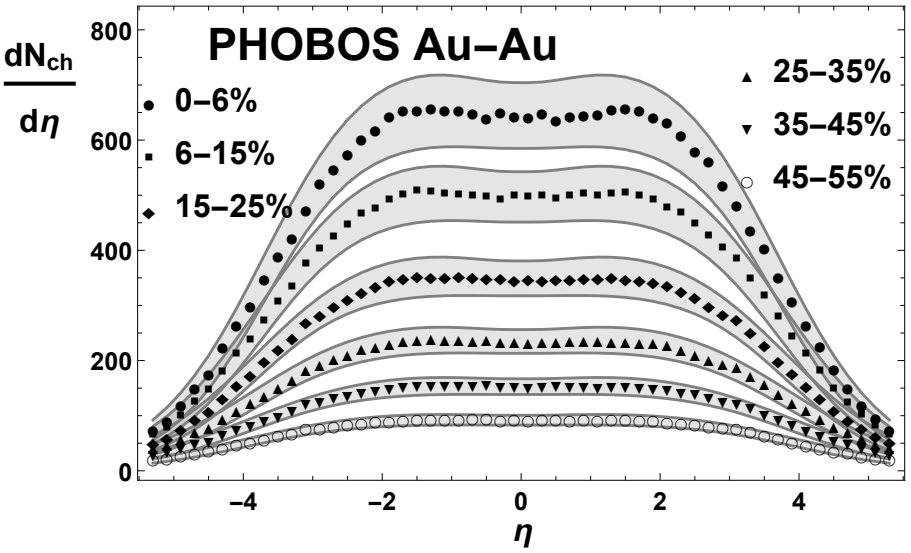
Fluctuations of strings
$\Rightarrow$ Fluctuations in η!

Lund model [Andersson], dual parton model [Capella et al.]
Monte-Carlo codes: HIJING, PYTHIA, AMPT...

Goal: Describe fluctations semianalytically in a generic approach
$\rightarrow$ Constraints for models?

Description of rapidity spectra (1/2)





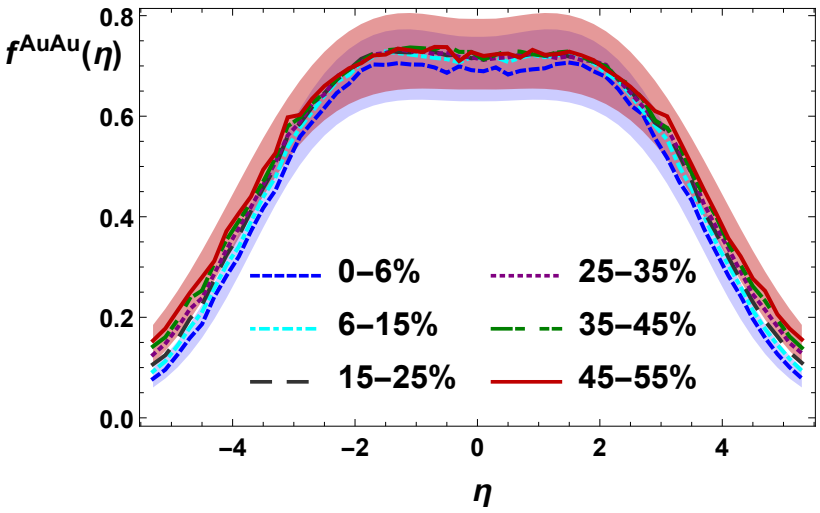
exp. data: [PHOBOS-collaboration].

Wounded Quark Model: $\frac{dN_{\rm ch}}{d\eta} = \langle N_A \rangle f(\eta) + \langle N_B \rangle f(-\eta)$

[Białas, Czyż, Furmański, Fiałkowski, Słomiński, Zieliński].

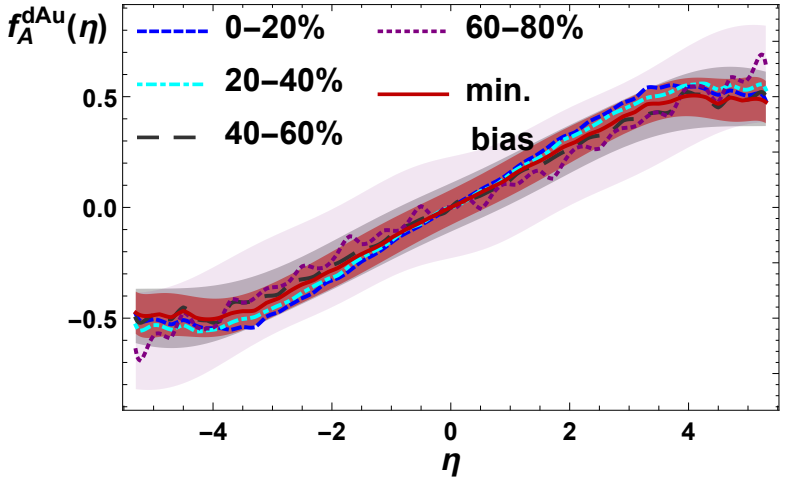
Universality of $f(\eta)$

symmetric part:

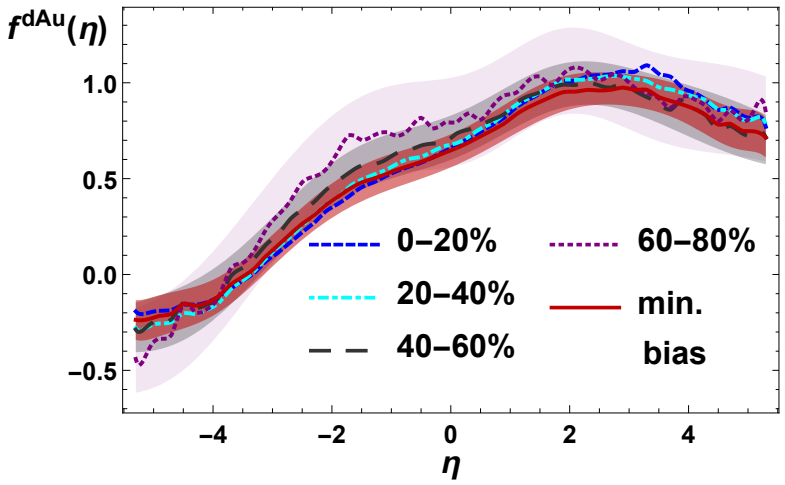


cf. [Barej, Bzdak, Gutowski]

antisymmetric part:



entire profile:



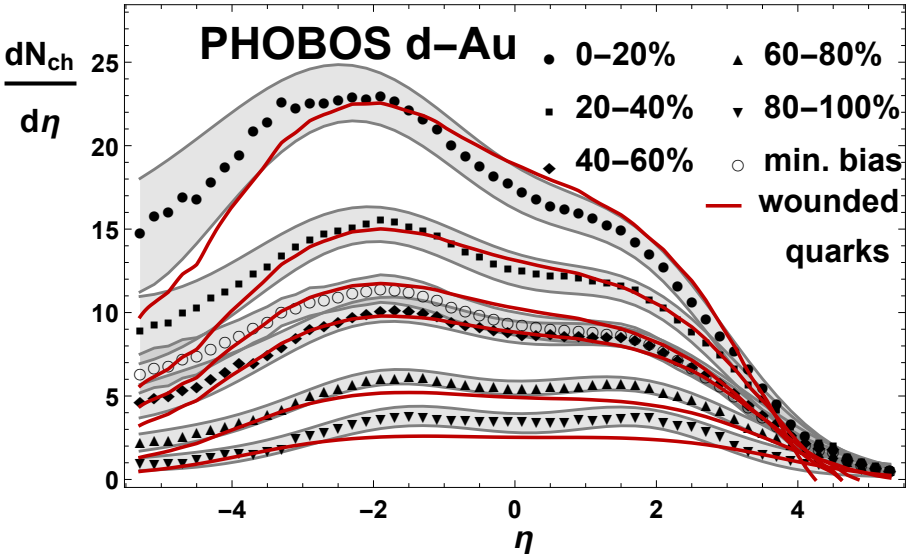
N_A (N_B) radiate independently:

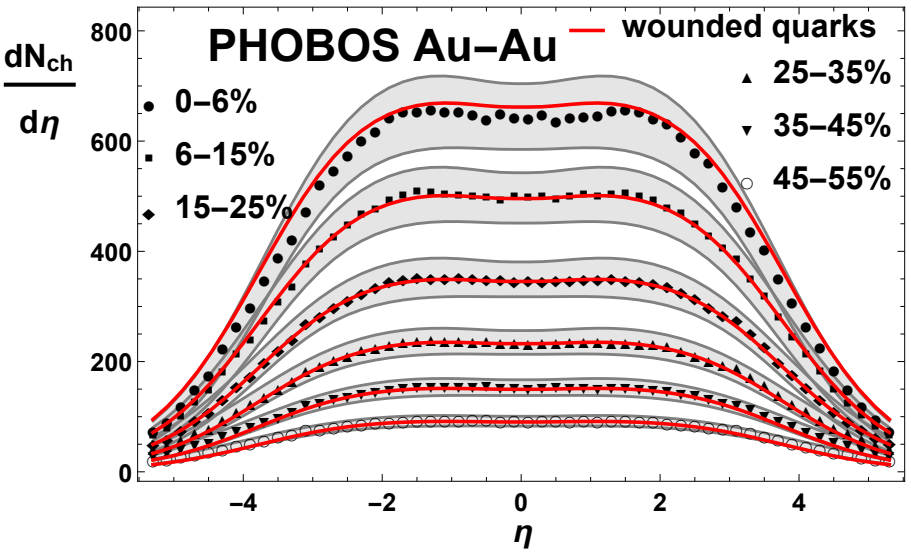
$$\frac{dN_{\mathrm{ch}}}{d\eta} = \langle N_A \rangle f(\eta) + \langle N_B \rangle f(-\eta)$$

$\langle N_A \rangle$, $\langle N_B \rangle$... from Glauber Model Monte-Carlo generator `GLISSANDO`.

[Broniowski, Rybczyński, Bożek, Stefanek].

Description of rapidity spectra (2/2)





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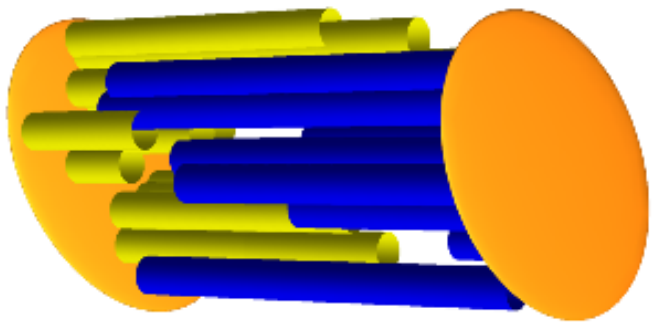
Description of $f(\eta)$ (1/2)

Original Model: 1 end-point fluctuates! [Broniowski, Bożek]

end point 1: rapidity y_1 fluctuates; distribution $g(y_1)$

end point 2: rapidity fixed to beam rapidity y_b



string:

uniform profile of radiation:

$s(\eta, y_1) = \theta(y_1 < \eta < y_b)$

$$f(\eta) = \int_{-y_b}^{y_b} dy_1 g(y_1)\theta(y_1 < \eta < y_b)$$

$$= \int_{-y_b}^{\eta} g(y_1) dy_1$$

$$\Rightarrow f(\eta) = G(\eta) - G(-y_b)$$

with $G(y) = \int^y g(x)dx$.

Description of $f(\eta)$ (2/2)

Alternative model: 2 end-points fluctuate:

For end points y_1 and y_2,
Analogously:

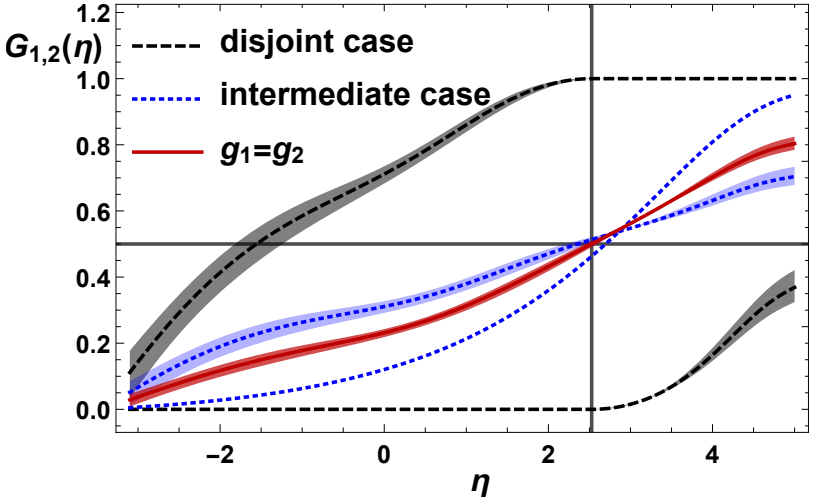
Distributions: $g_1(y_1)$ and $g_2(y_2)$,
CDF's $G_1(y_1)$ and $G_2(y_2)$.

$$\Rightarrow f(\eta) = \omega \left\{ G_1(\eta)[1 - G_2(\eta)] + G_2(\eta)[1 - G_1(\eta)] \right\}$$

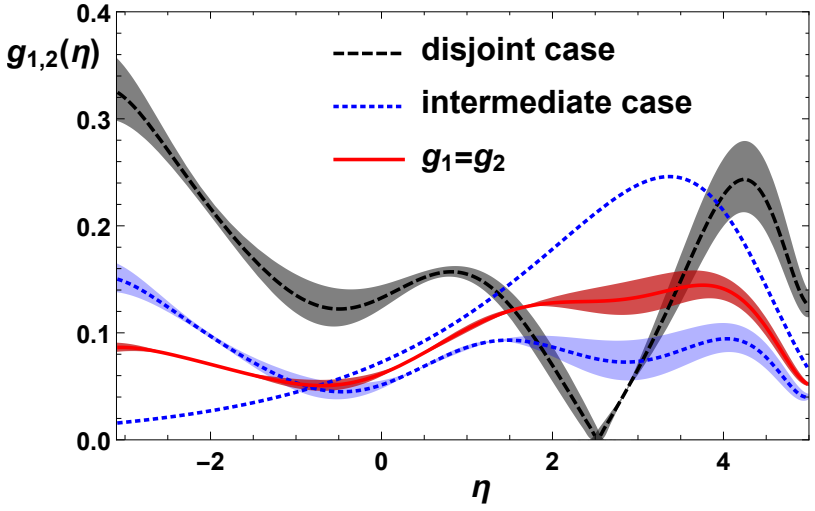
$\Rightarrow$ **Ambiguous solutions G_1 and G_2!**

Ambiguity of string end points

CDF of string-end points:



string-end-point distribution:



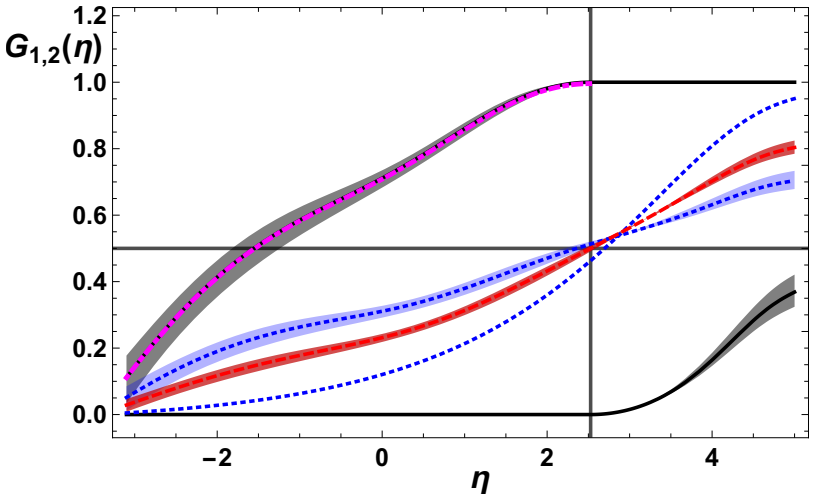
Possible cases:

- $g_1 = g_2$
- intermediate
  here: g_1 from PDF parametrization; g_2 matched to $f(\eta)$!
- disjoint support of g_1 and g_2

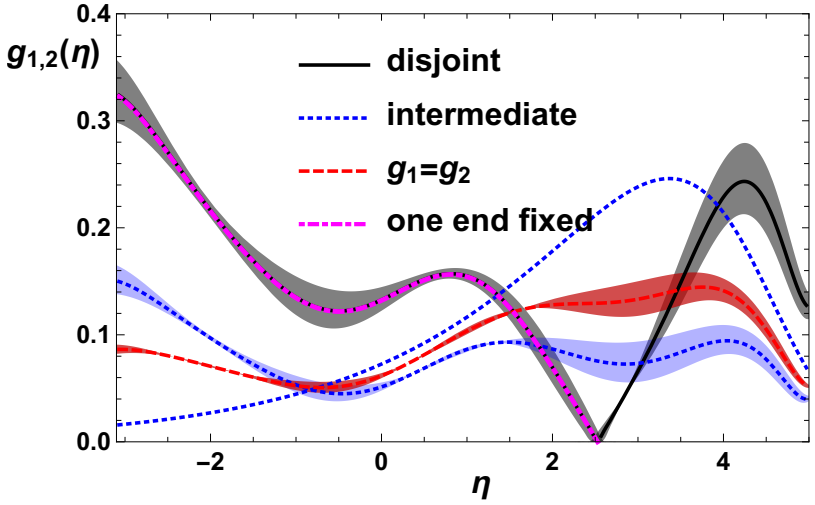
Disjoint case: Limiting case of all possibilities!

Ambiguity of string end points

CDF of string-end points:



string-end-point distribution:



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2-particle-emission

$$f(\eta) = \omega \left\{ G_1(\eta)[1 - G_2(\eta)] + G_2(\eta)[1 - G_1(\eta)] \right\}$$

$$\downarrow$$

generalize

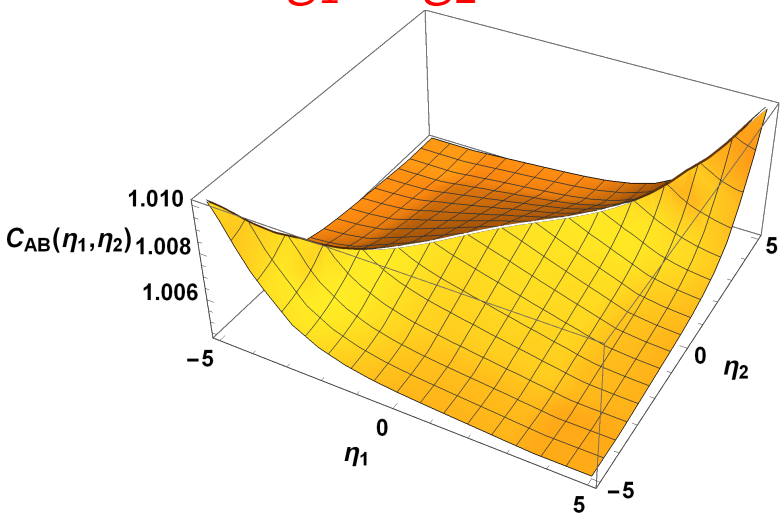
$$\downarrow$$

$$f_2(\eta_1, \eta_2) =$$
$$\omega^2 \{ G_1(\min(\eta_1, \eta_2))[1 - G_2(\max(\eta_1, \eta_2))]$$
$$+ G_2(\min(\eta_1, \eta_2))[1 - G_1(\max(\eta_1, \eta_2))] \}$$

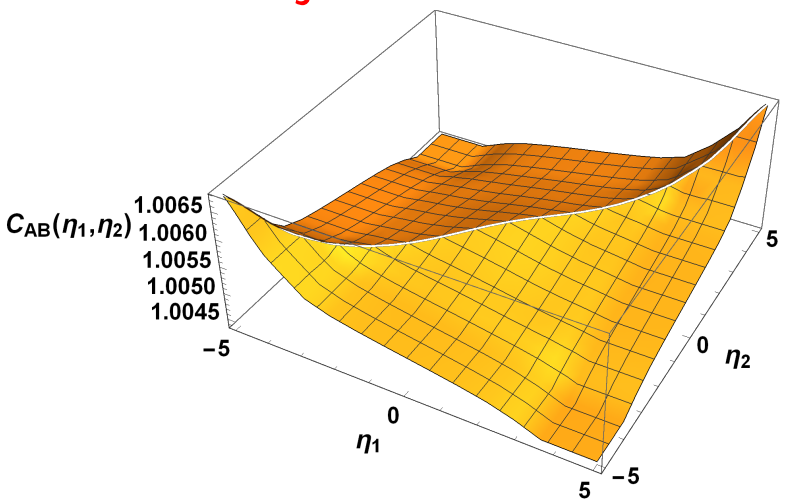
Correlations

$$C_{AB}(\eta_1,\eta_2) = 1 + \frac{\mathrm{cov}_{\mathrm{AB}}(\eta_1,\eta_2)}{f_{AB}(\eta_1)f_{AB}(\eta_2)}$$

$g_1 = g_2$:



disjoint case:



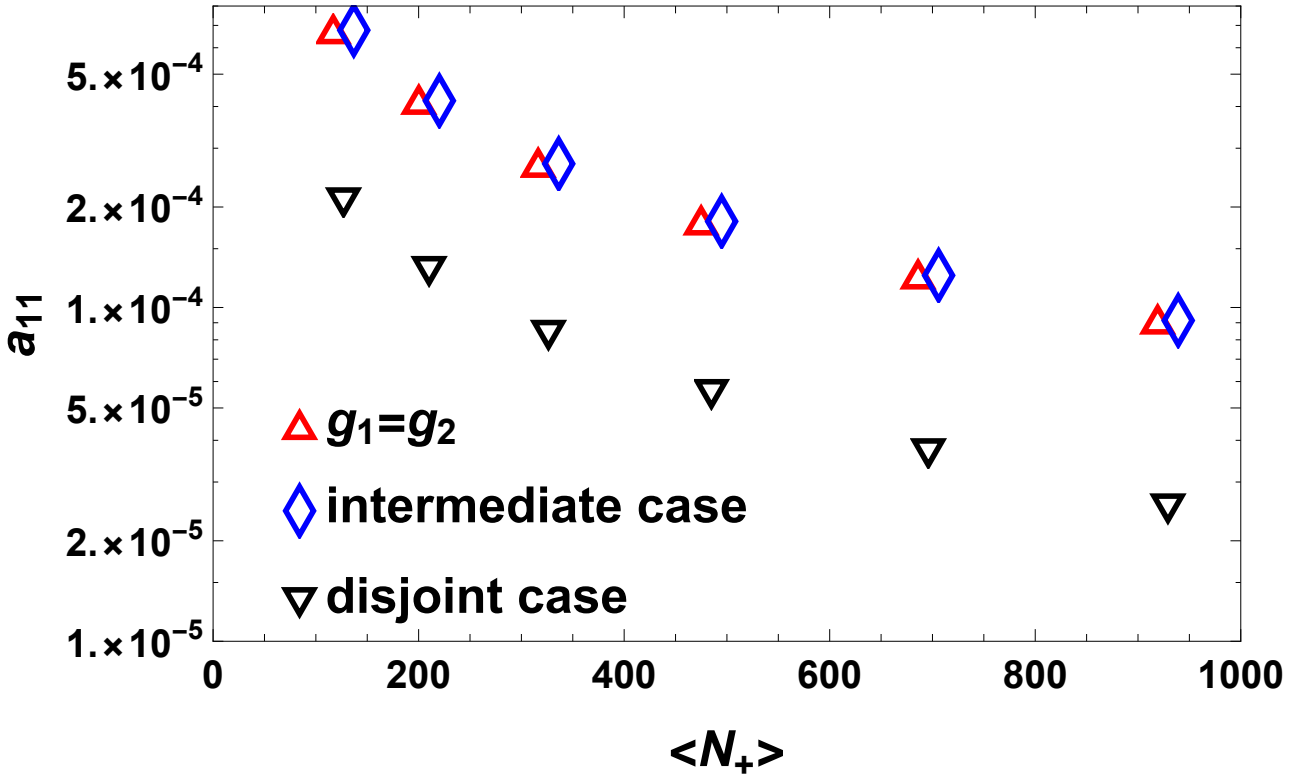
$$\mathrm{cov}_{\mathrm{AB}}(\eta_1,\eta_2) = \overbrace{\langle N_A\rangle \mathrm{cov}(\eta_1,\eta_2) + \langle N_B\rangle \mathrm{cov}(-\eta_1,-\eta_2)}^{\substack{\text{string-end-point fluctuations} \\ =:\ \mathrm{cov}^*_{\mathrm{AB}}(\eta_1,\eta_2)}} + \underbrace{\mathrm{var}(N_A)f(\eta_1)f(\eta_2) + \mathrm{var}(N_B)f(-\eta_1)f(-\eta_2) + \mathrm{cov}(N_A,N_B)\left[f(\eta_1)f(-\eta_2) + f(-\eta_1)f(\eta_2)\right]}_{\text{event by event fluctuations}}$$

$$f_{\mathrm{AB}}(\eta) = \langle N_A\rangle f(\eta) + \langle N_B\rangle f(-\eta)$$

Legendre coefficient a_{11}

[Bzdak, Teany]

$$a_{nm} = \int_{-Y}^{Y} \frac{d\eta_1}{Y} \int_{-Y}^{Y} \frac{d\eta_2}{Y} \frac{1}{\mathcal{N}_C} C(\eta_1, \eta_2) T_n\left(\frac{\eta_1}{Y}\right) T_m\left(\frac{\eta_2}{Y}\right)$$



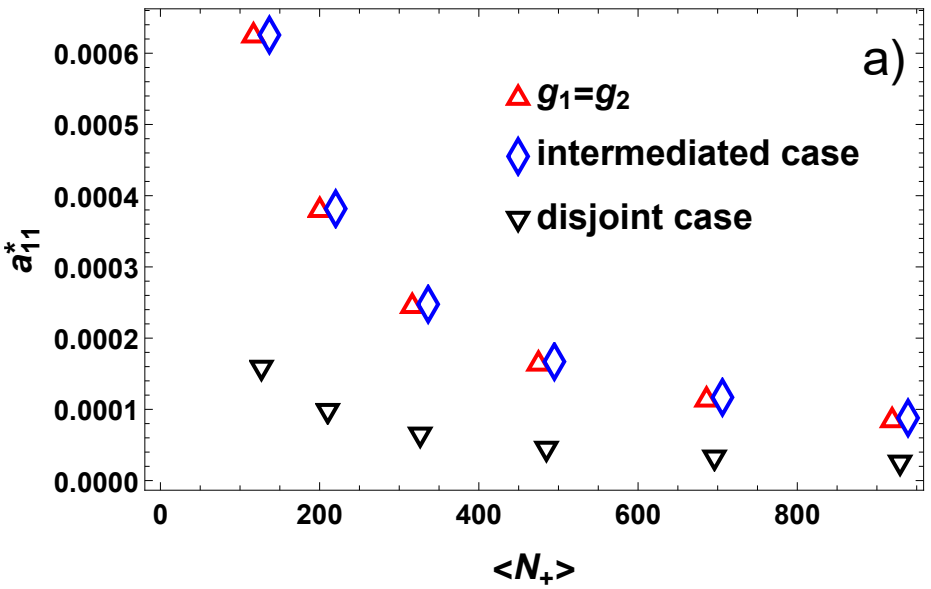
with $Y = 1$ and $\mathcal{N}_C = \int_{-Y}^{Y} \frac{d\eta_1}{Y} \int_{-Y}^{Y} \frac{d\eta_2}{Y} C(\eta_1, \eta_2)$

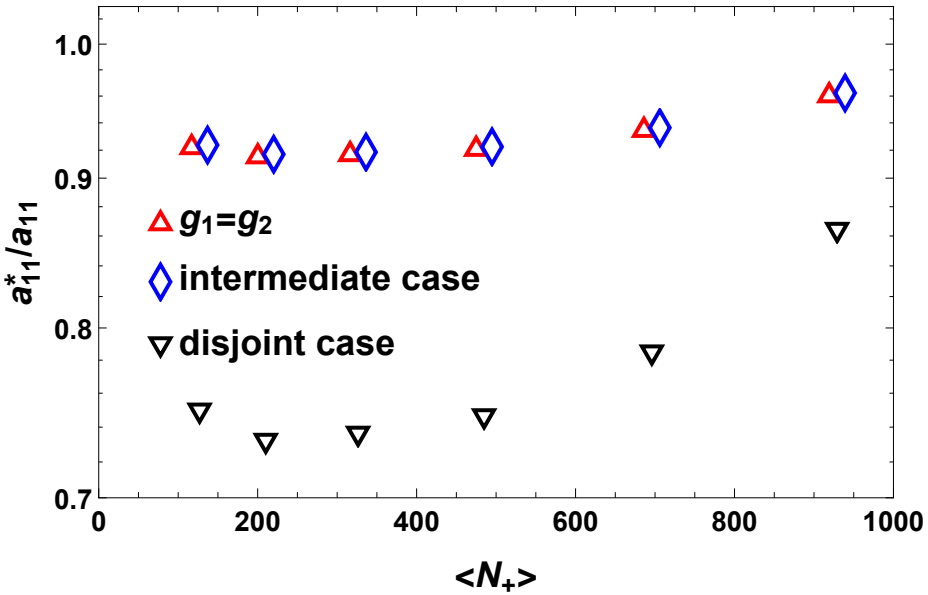
$$N_+ = N_A + N_B$$

Contributions from string fluctuations

$$a^*_{nm} = \int_{-Y}^{Y} \frac{d\eta_1}{Y} \int_{-Y}^{Y} \frac{d\eta_2}{Y} \frac{1}{\mathcal{N}_C} C^*(\eta_1, \eta_2)\, T_n\left(\frac{\eta_1}{Y}\right)\, T_m\left(\frac{\eta_2}{Y}\right)$$

$$C^*_{AB}(\eta_1, \eta_2) = 1 + \frac{\mathrm{cov}^*_{\mathrm{AB}}(\eta_1,\eta_2)}{f_{AB}(\eta_1) f_{AB}(\eta_2)}$$

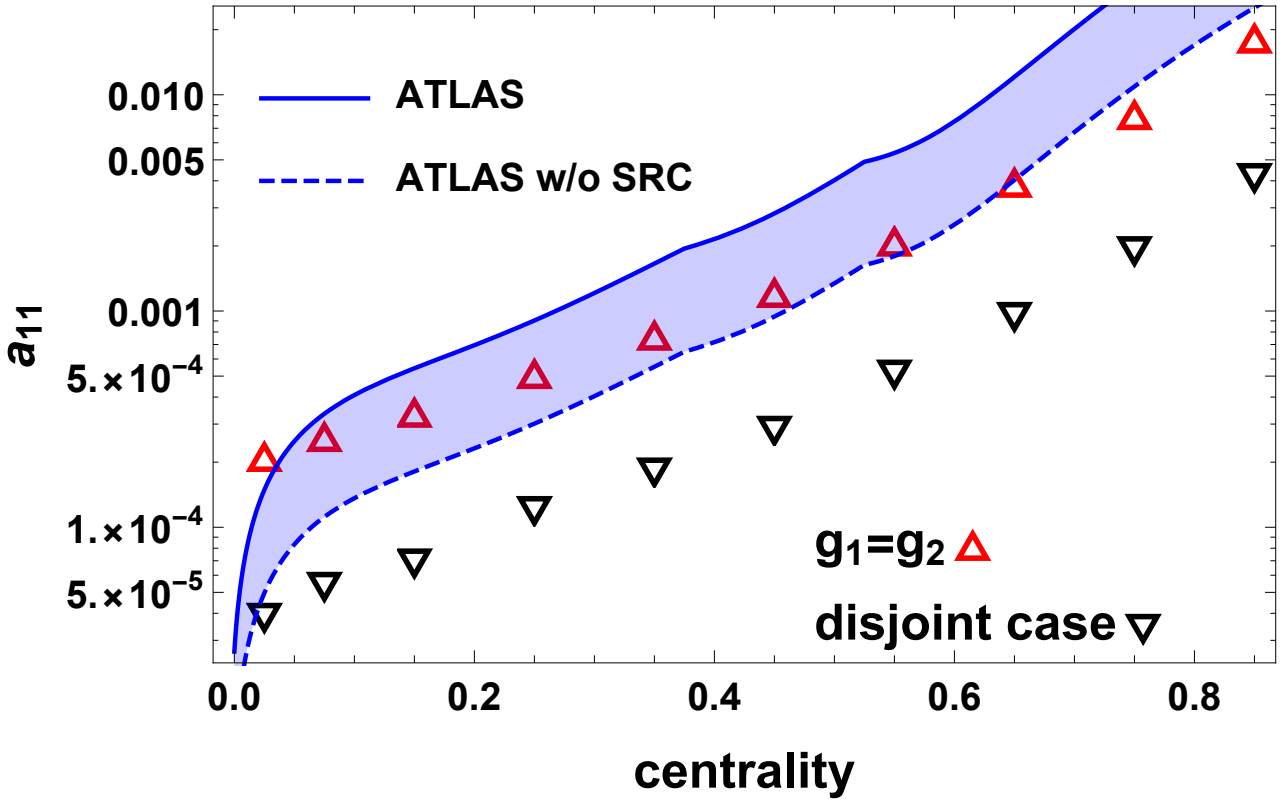




$$\mathrm{cov}_{\mathrm{AB}}(\eta_1, \eta_2) = \mathrm{cov}^*_{\mathrm{AB}}(\eta_1, \eta_2) + \underbrace{\mathrm{var}(N_A) f(\eta_1) f(\eta_2) + \mathrm{var}(N_B) f(-\eta_1) f(-\eta_2) + \mathrm{cov}(N_A, N_B)\left[f(\eta_1) f(-\eta_2) + f(-\eta_1) f(\eta_2)\right]}_{\text{event by event fluctuations}}$$

Results for LHC-energies:

Data from [ATLAS-CONF-2015-020, ATLAS-CONF-2015-020]



2-end fluctuations necessary!

Pb-Pb collisions:

- ATLAS data at $\sqrt{s_{NN}} = 2.76\,TeV$
- model predictions for $\sqrt{s_{NN}} = 5.02\,TeV$

SRC...short range correlations

Summary

- Semianalytic description of radiation in heavy-ion collisions.
- String fluctuations are dominant contribution to correlations.
- 2-end point fluctuations contribute to correlations $\rightarrow$ necessary for description of Pb-Pb data from the LHC!

Some details: [arXiv:1809.08666 [nucl-th]]

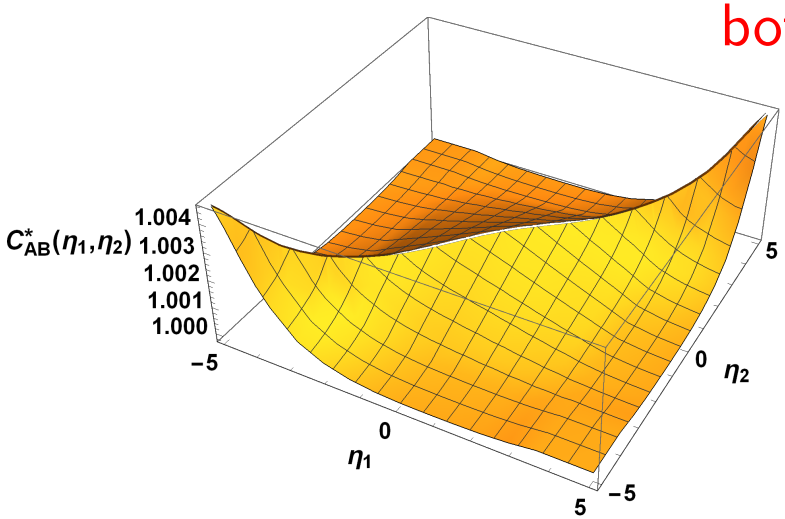
Thank you for your attention!

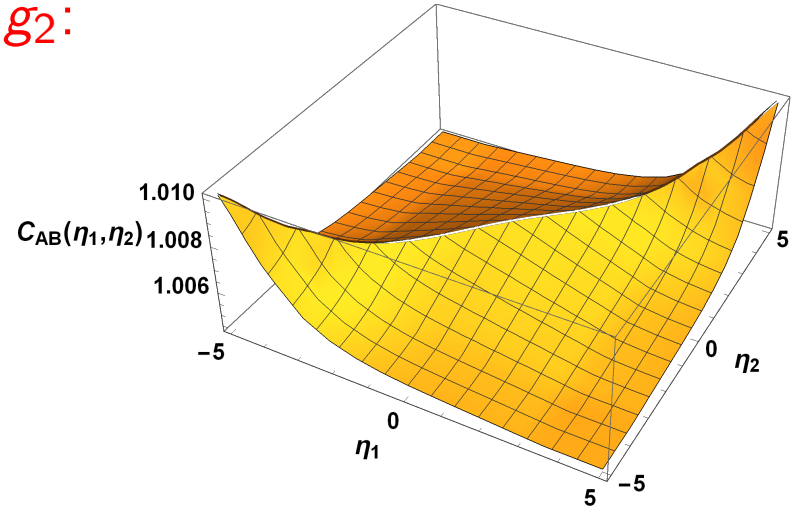
BACK-UP SLIDES

Correlations from string fluctuations

$$C^*_{AB}(\eta_1,\eta_2) = \frac{\langle N_A\rangle \mathrm{cov}(\eta_1,\eta_2) + \langle N_B\rangle \mathrm{cov}(-\eta_1,-\eta_2)}{f_{AB}(\eta_1) f_{AB}(\eta_2)}$$

both $g_1 = g_2$:





with $f_{\mathrm{AB}}(\eta) = \langle N_A\rangle f(\eta) + \langle N_B\rangle f(-\eta)$

Constraints G_1 & $G_2(1/3)$

$$f(\eta) = \omega \left\{ G_1(\eta)[1 - G_2(\eta)] + G_2(\eta)[1 - G_1(\eta)] \right\}$$

$$G_{1,2}(\eta) \in [0,1] \text{ and continuous}$$
$$\Rightarrow \exists \eta_1^{(0)}, \eta_2^{(0)} :$$

$$\begin{aligned} \eta_1^{(0)} &: \; G_1(\eta_1^{(0)}) = \tfrac{1}{2}, \\ \eta_2^{(0)} &: \; G_2(\eta_2^{(0)}) = \tfrac{1}{2}. \end{aligned}$$

$$\Rightarrow$$

$$\omega = 2f(\eta_1^{(0)}) = 2f(\eta_2^{(0)}).$$

Constraints G_1 & G_2(2/3)

$$\text{With } H_i(\eta) = G_i(\eta) - \tfrac{1}{2}:$$
$$f(\eta) = \omega\left\{G_1(\eta)[1 - G_2(\eta)] + G_2(\eta)[1 - G_1(\eta)]\right\}$$

$$\Leftrightarrow$$
$$H_1(\eta)H_2(\eta) = \tfrac{1}{4} - \tfrac{1}{2\omega}f(\eta)$$

$$\Rightarrow$$
$$G_{1,2}(\eta) \in [0,1]$$
$$\Leftrightarrow H_{1,2}(\eta) \in [-1/2, 1/2]$$
$$\Rightarrow$$
$$f(\eta) \in [0,\omega]$$
$$f(\eta_{\max}) \in [\omega/2, \omega]$$

Constraints G_1 & G_2(3/3)

$f(\eta_{\max}) = \omega/2$:

$$H_1(\eta) = \sqrt{\frac{1}{4} - \frac{1}{2\omega} f(\eta)}\,\mathrm{sgn}(\eta - \eta_0) s(\eta)$$
$$H_2(\eta) = \sqrt{\frac{1}{4} - \frac{1}{2\omega} f(\eta)}\,\mathrm{sgn}(\eta - \eta_0)/s(\eta)$$

We used $s(\eta) = 1$.

$f(\eta_{\max}) = \omega$:

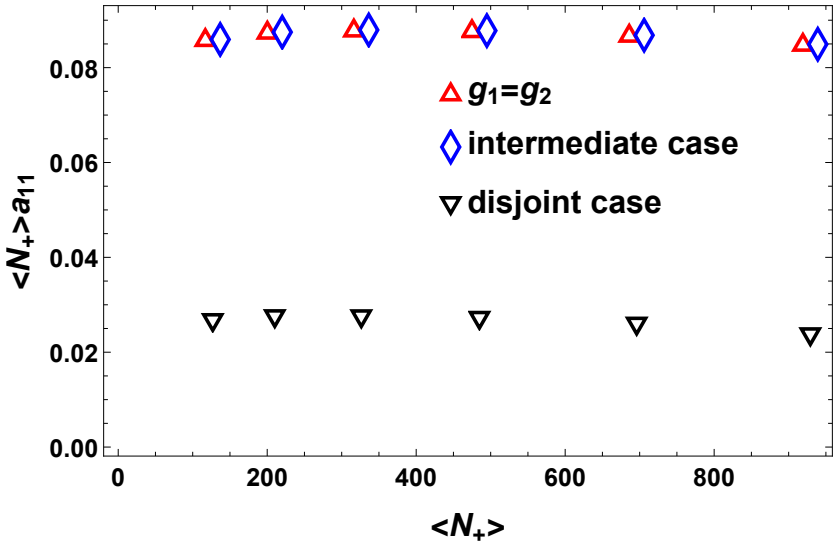
$$H_1(\eta) = -\frac{1}{2}\theta(\eta_0 - \eta) + \left[\frac{1}{2} - \frac{1}{\omega} f(\eta)\right]\theta(\eta - \eta_0)$$
$$H_2(\eta) = -\left[\frac{1}{2} - \frac{1}{\omega} f(\eta)\right]\theta(\eta_0 - \eta) + \frac{1}{2}\theta(\eta - \eta_0)$$

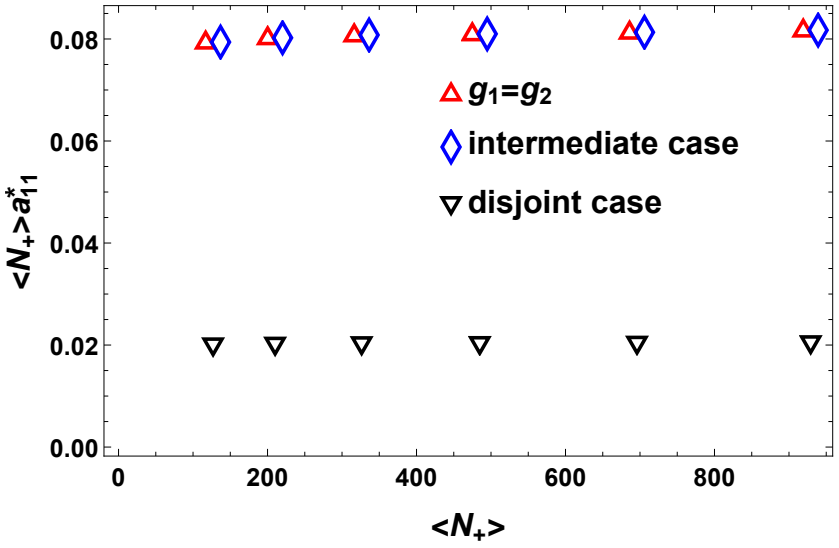
intermediate case ($\omega/2 < f(\eta_{\max}) < \omega$):

$$H_2(\eta) = \frac{\frac{1}{4} - \frac{1}{2\omega} f(\eta)}{H_1(\eta)}$$

for a given $H_1(\eta)$.

Scaling with $\langle N_+ \rangle$

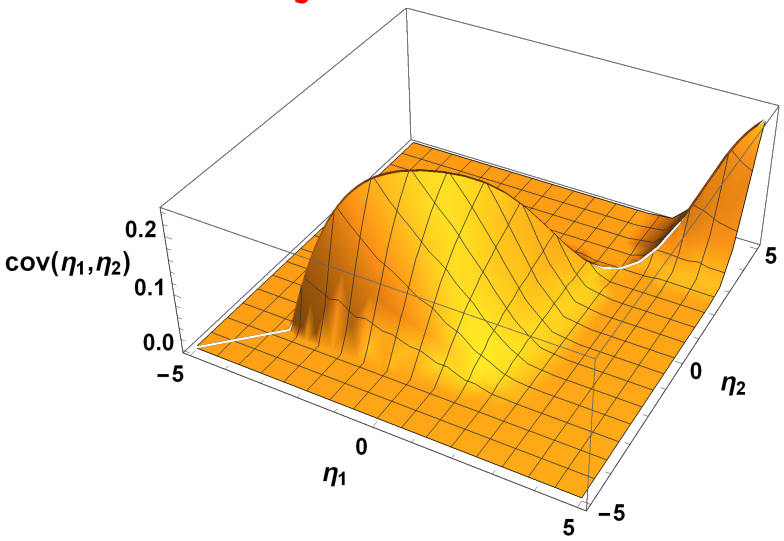




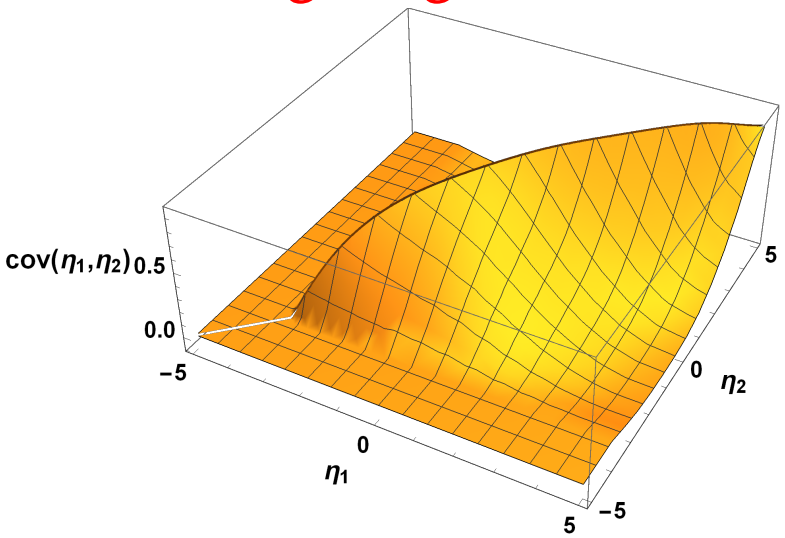
Covariances

$$\mathrm{cov}(\eta_1, \eta_2) = f_2(\eta_1, \eta_2) - f(\eta_1) f(\eta_2)$$

disjoint case:



$g_1 = g_2$:



intermediate: