TESTING TOP-QUARK NEW PHYSICS AT THE LHC WITH ENTAGLEMENT

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a LHC Top Work Group presentation

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together with
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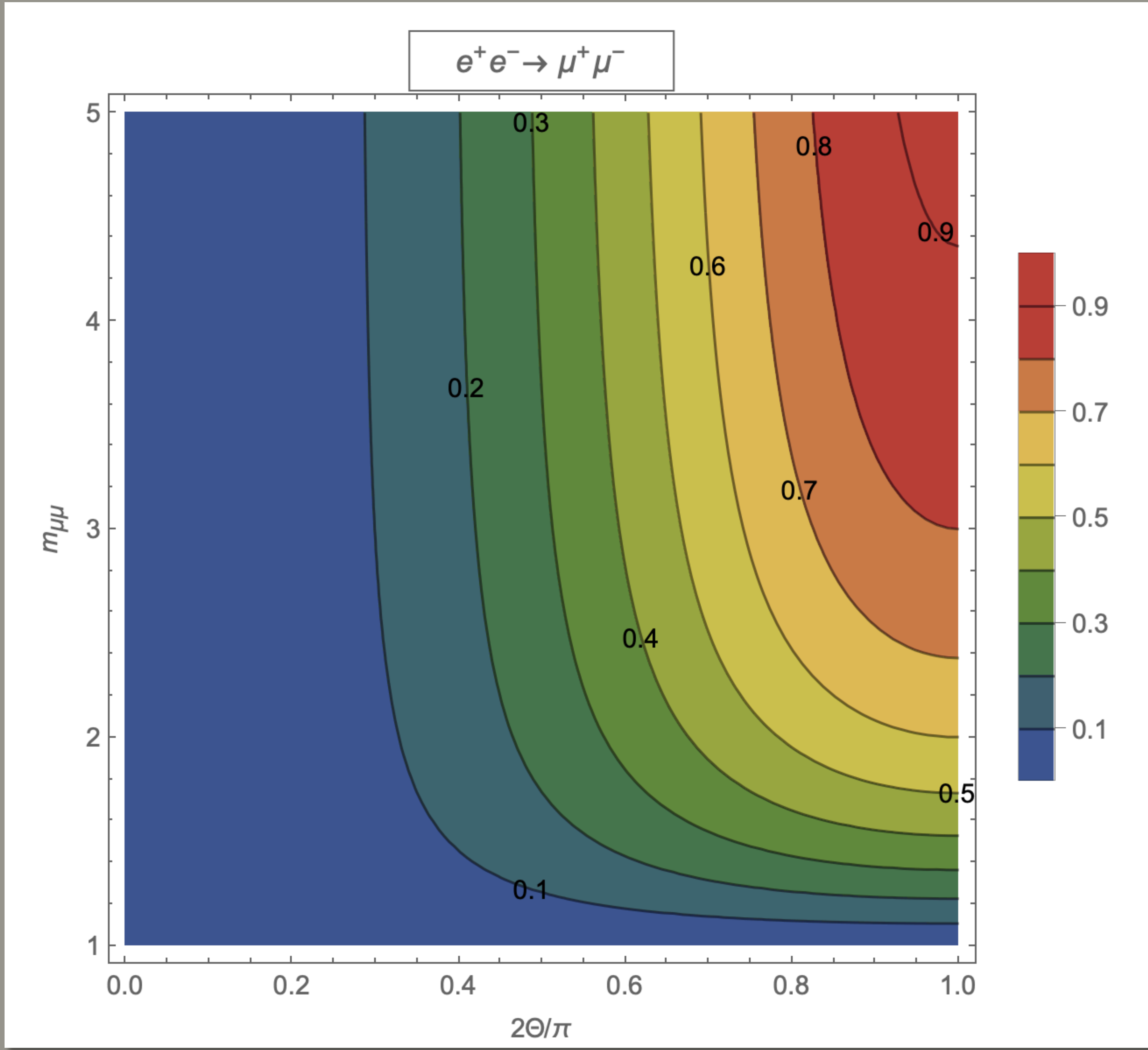
A.Tornqvist,
``Suggestion for Einstein-Podolsky-Rosen Experiments Using Reactions Like $e^+ e^- \to \Lambda \bar{\Lambda} \to \pi^- p \pi^+ \bar{p}$,''
Found. Phys. 11 (**1981**) 171

Y. Afik and J. R. M. de Nova,
``Entanglement and quantum tomography with top quarks at the LHC,''
Eur. Phys. J. Plus 136 (**2021**) 907 [arXiv:2003.02280 [quant-ph]]

key insight: entanglement depends on the kinematical region


$e^+e^- \to \mu^+\mu^-$
5
4
3
2
1
$m_{\mu\mu}$
0.0
0.2
0.4
0.6
0.8
1.0
$2\Theta/\pi$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.9
0.7
0.5
0.3
0.1

observables

$$\rho = \frac{1}{4}\Big[1 \otimes 1 + \sum_i A_i(\sigma_i \otimes 1) + \sum_j B_j(1 \otimes \sigma_j) + \sum_{ij} C_{ij}(\sigma_i \otimes \sigma_j)\Big]$$

- $\rho\,(\sigma_2 \otimes \sigma_2)\,\rho^*\,(\sigma_2 \otimes \sigma_2)$ (concurrence)

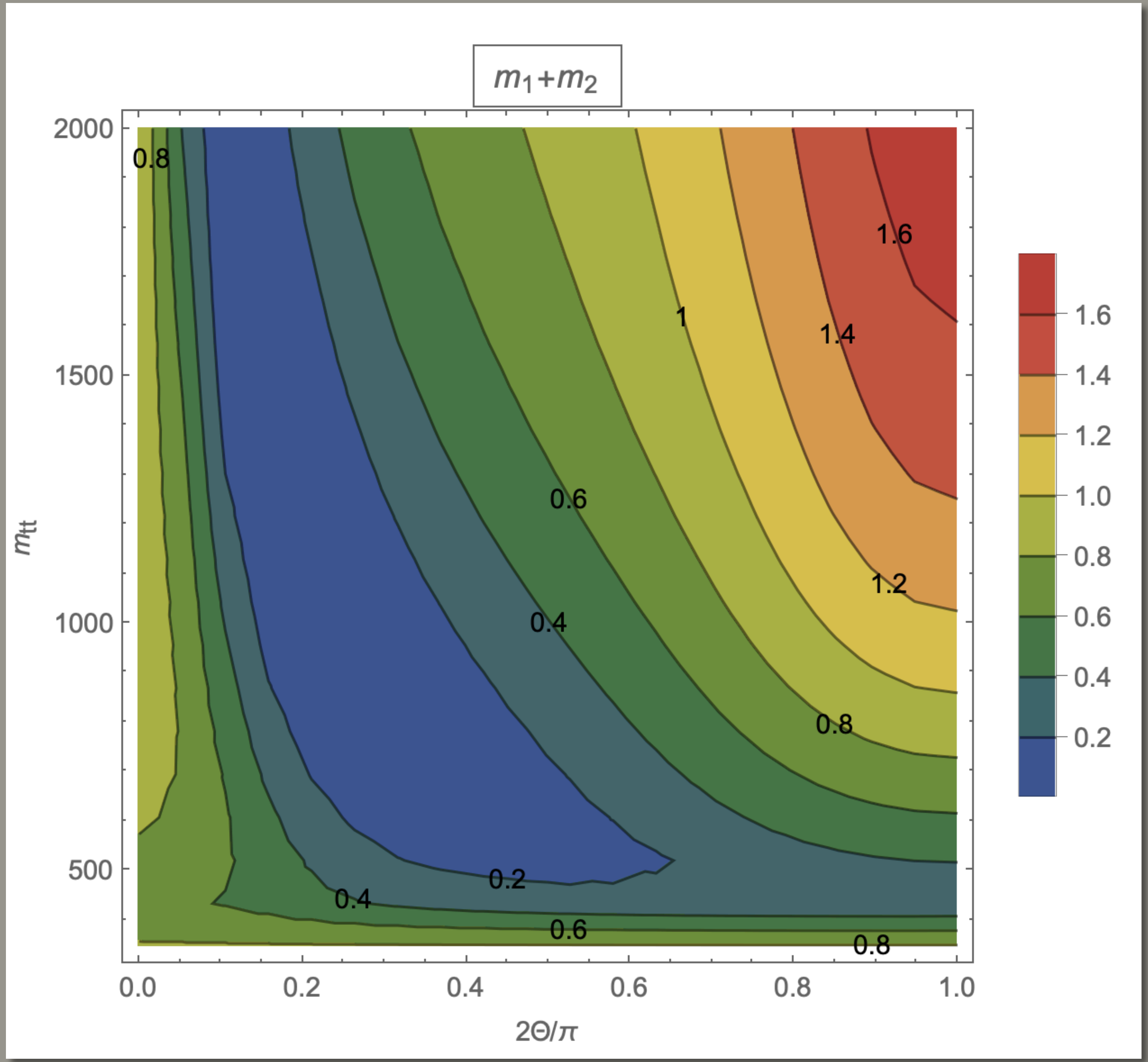
  $C[\rho] = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$

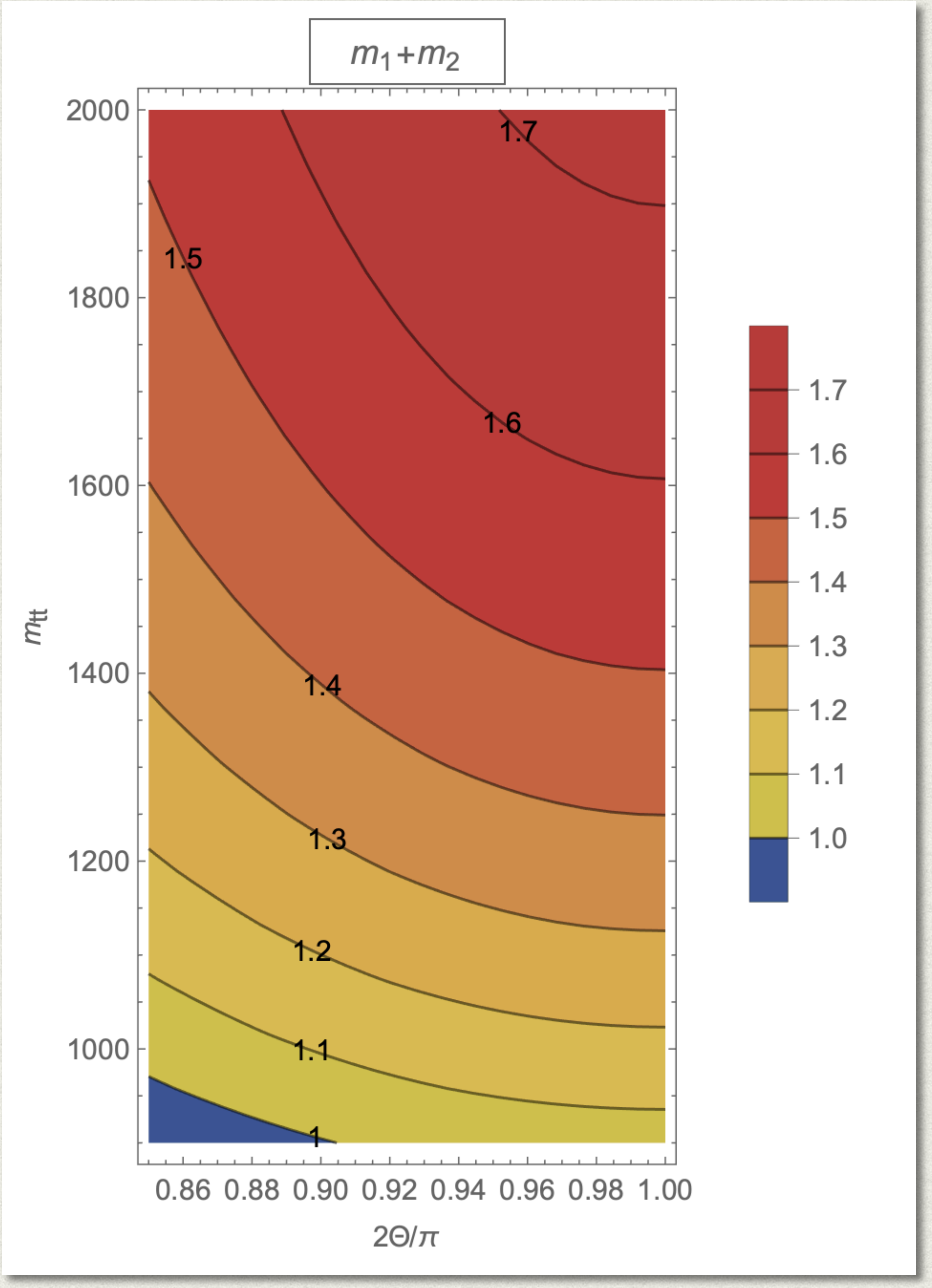
- $M = C^T C \quad m_1 + m_2$ (best for Bell inequalities)

F. Clauser, M.A. Horne, A. Shimony and R.A. Holt, Phys. Rev. Lett. 23 (1969) 880

R. Horodecki et al., Phys. Lett. A200 (1995) 34

the study of entanglement leads to that of Bell inequalities violation





what is the uncertainty?

spin correlations of top quarks

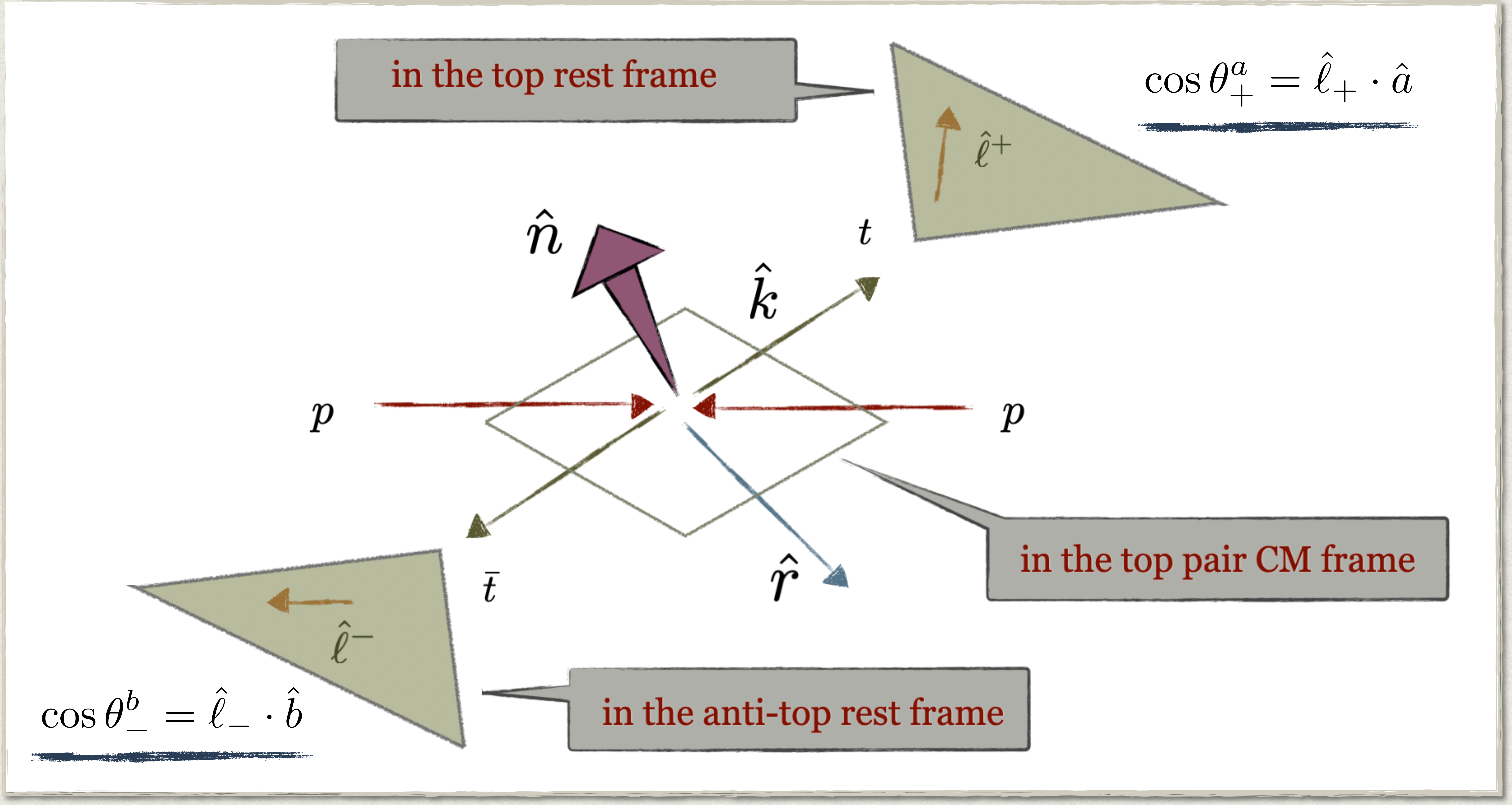
at the level of pseudo-observables: significance of 20!

at the level of observables: significance of 2 (?)

spin correlations of final leptons in the detector

Down the rabbit hole

$$pp \to t + \bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + E_T^{\text{miss}}$$



$$\hat{r} = \frac{1}{r}(\hat{p} - y\hat{k})$$

$$y = \hat{p} \cdot \hat{k}$$

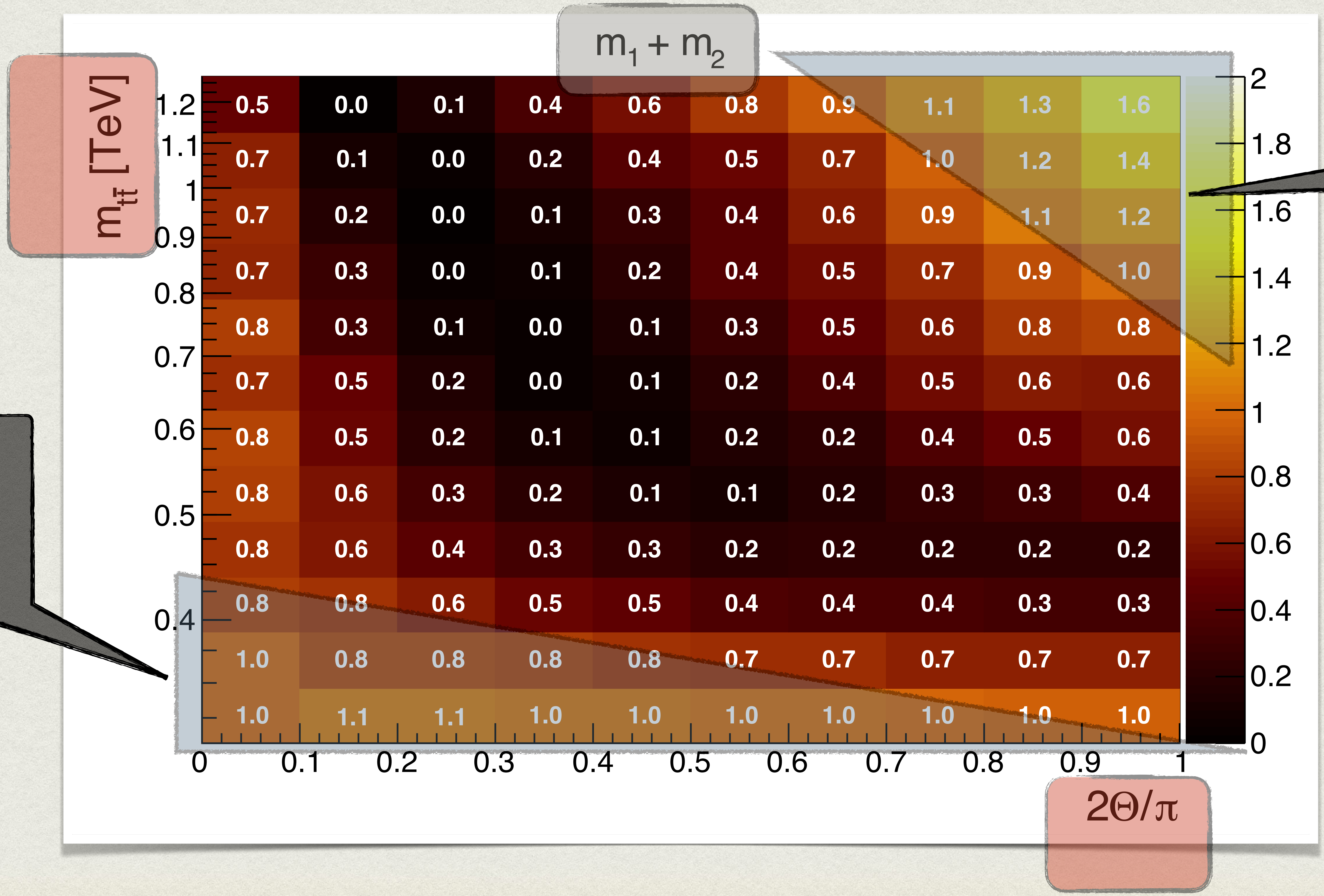
$$r = \sqrt{1 - y^2}$$

$$\hat{n} = \frac{1}{r}(\hat{p} \times \hat{k})$$

W. Bernreuther, D. Heisler and Z. G. Si, JHEP 12, 026 (2015)

analysis

MF, R. Floreanini, G. Panizzo, PRL 127 (2021) 16



both qq and gg give top pair max. entangled

only gg gives top pair max. entangled

An intrinsically *differential* observable

· **increasing** the **cell size** decreases the *expected* value of $m_1 + m_2$ (expected feature considering its meaning)

· In order to **increase statistical significance, statistically combine measurements** on different cells

Results

bins

$$\frac{2\,\Theta}{\pi} \gtrsim 0.7 \qquad m_{t\bar{t}} \gtrsim 0.9 \text{ TeV}$$

1.1	1.3	1.6
1.0	1.2	1.4
0.9	1.1	1.2

null hypothesis: $m_1 + m_2 \leq 1$

Hypothesis test

$$\chi^2 = \sum_i \frac{(1 - m_1^i - m_2^i)^2}{s_i^2}$$

violation: 98% CL w/ Run II data (139 fb-1)
99.99% CL with Run III

systematic uncertainties (e.g. from unfolding) not included

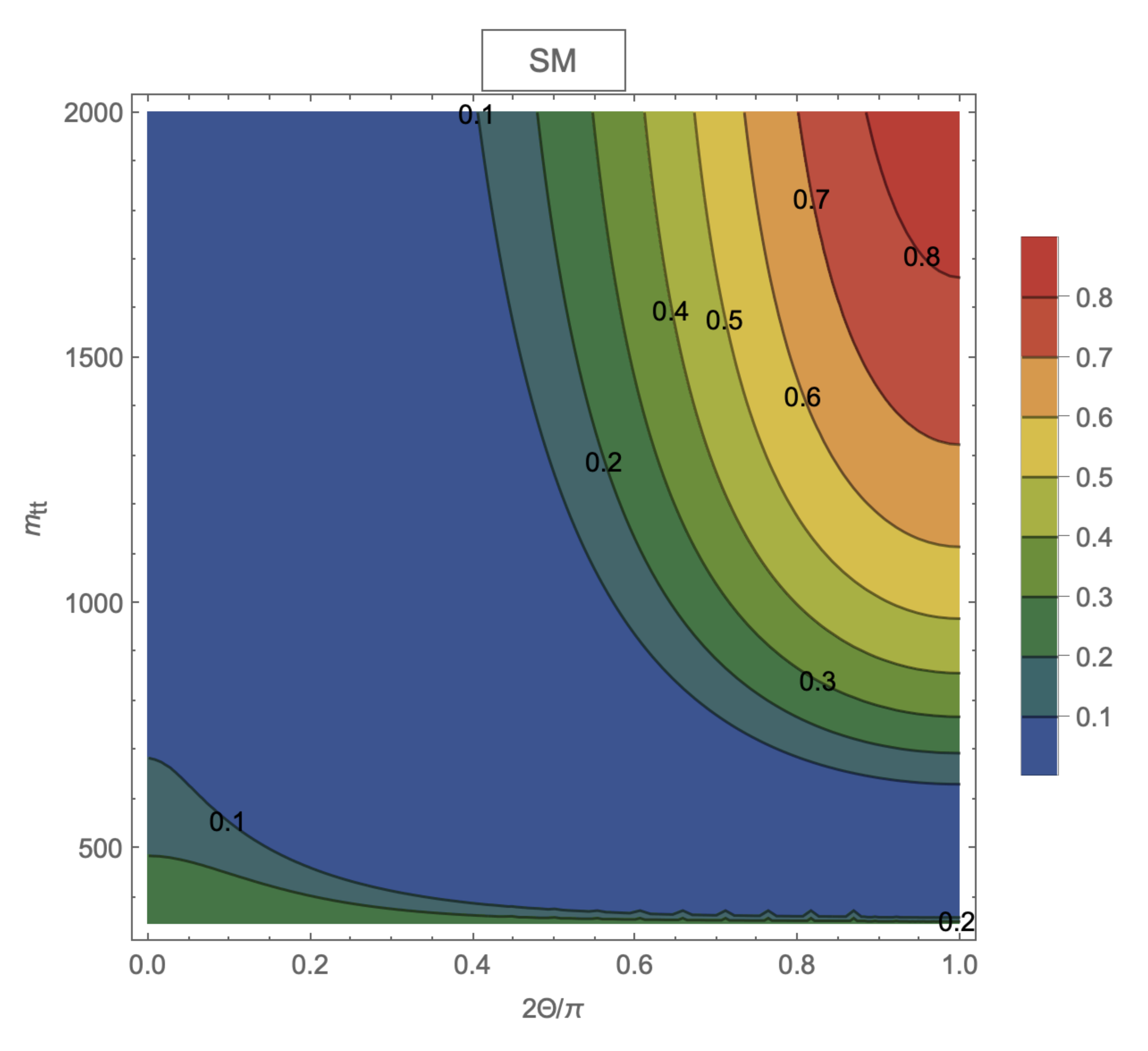
can we use entanglement to study new physics?
it would be a new and powerful tool

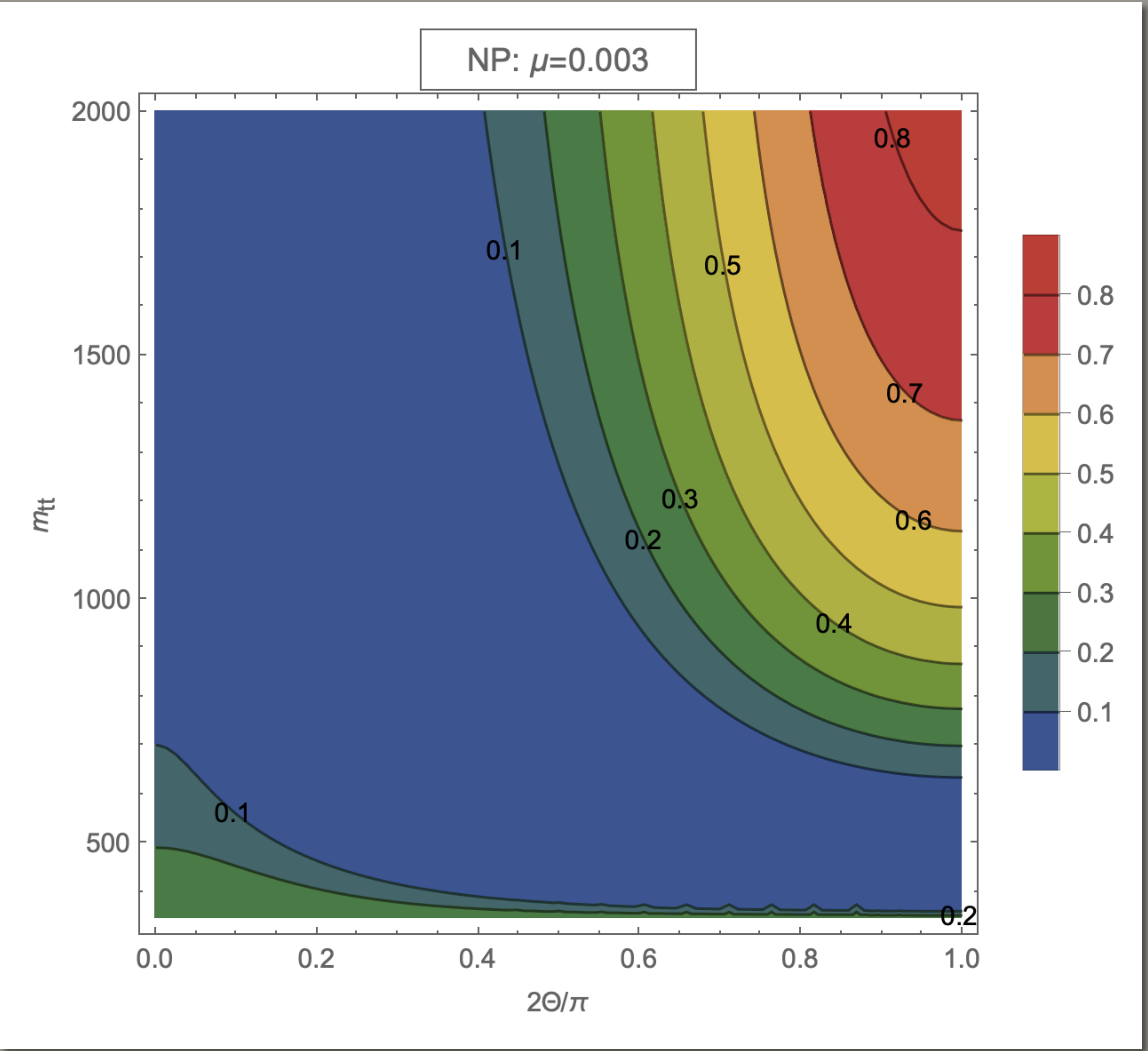
example: magnetic dipole moment in top-gluon interaction

$$\mathcal{L}_{\rm dipole} = -\mu\, \frac{g_s}{2m_t}\, \bar{t}\, \sigma^{\mu\nu}\, T^a\, t\, G^a_{\mu\nu}$$

$$-g_s \bar{q} \gamma^\mu T^a t G^a_\mu$$

sign


SM
2000
1500
1000
500
m_{tt}
0.0
0.2
0.4
0.6
0.8
1.0
2Θ/π
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

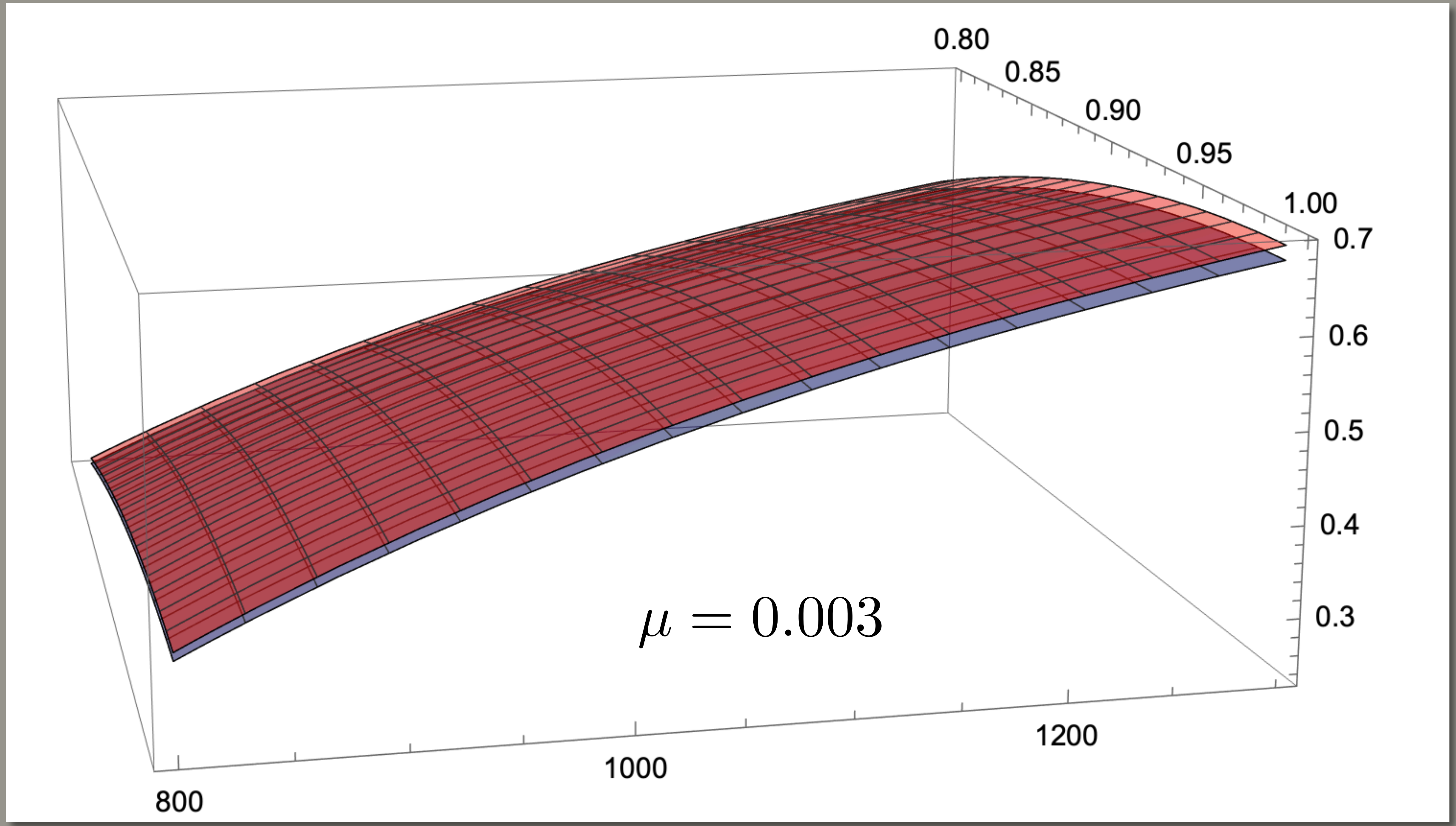

NP: μ=0.003
2000
1500
1000
500
m_{tt}
0.0
0.2
0.4
0.6
0.8
1.0
2Θ/π
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

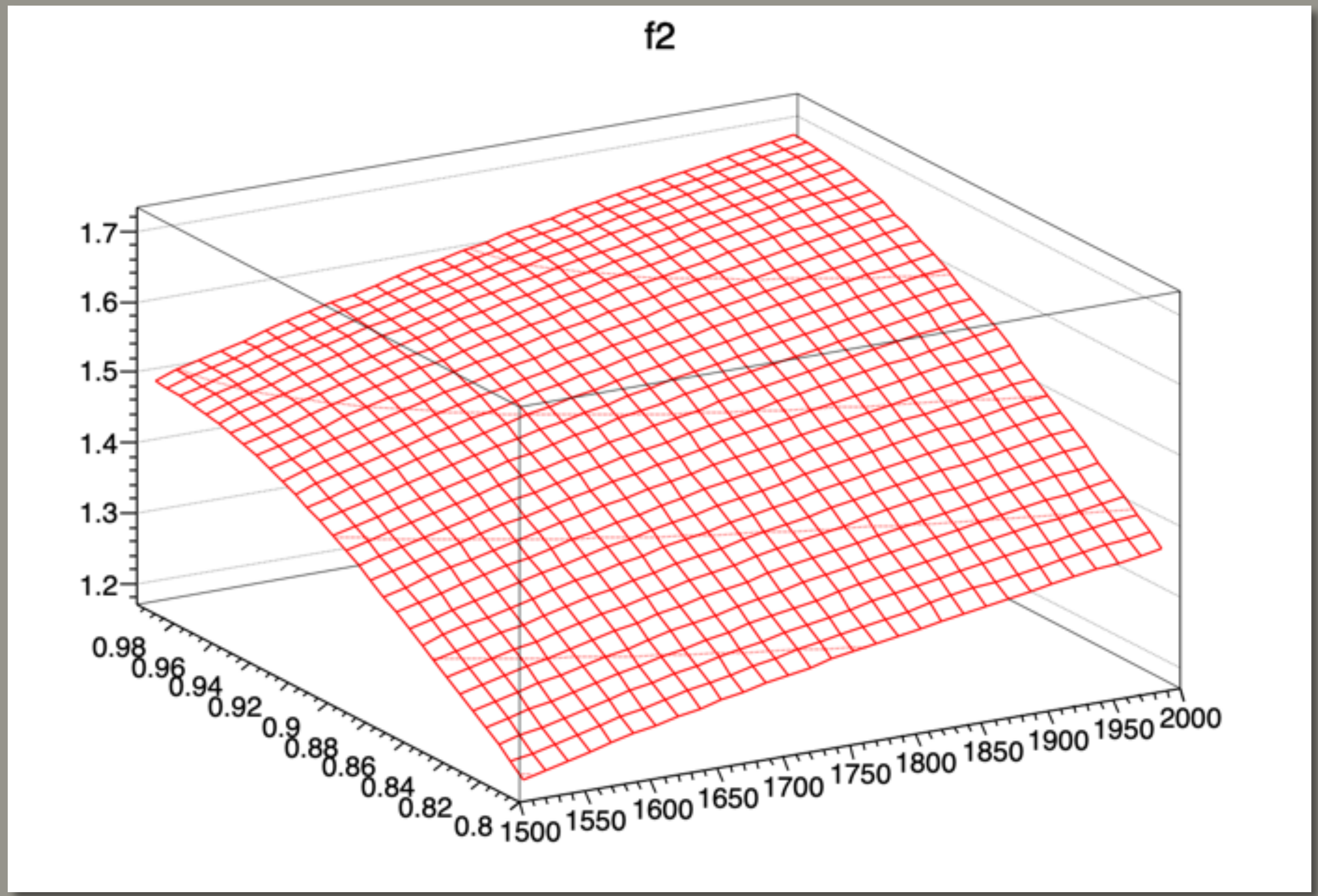
$$\rho = \frac{1}{4}\Big[1 \otimes 1 + \sum_i A_i(\sigma_i \otimes 1) + \sum_j B_j(1 \otimes \sigma_j) + \sum_{ij} C_{ij}(\sigma_i \otimes \sigma_j)\Big]$$

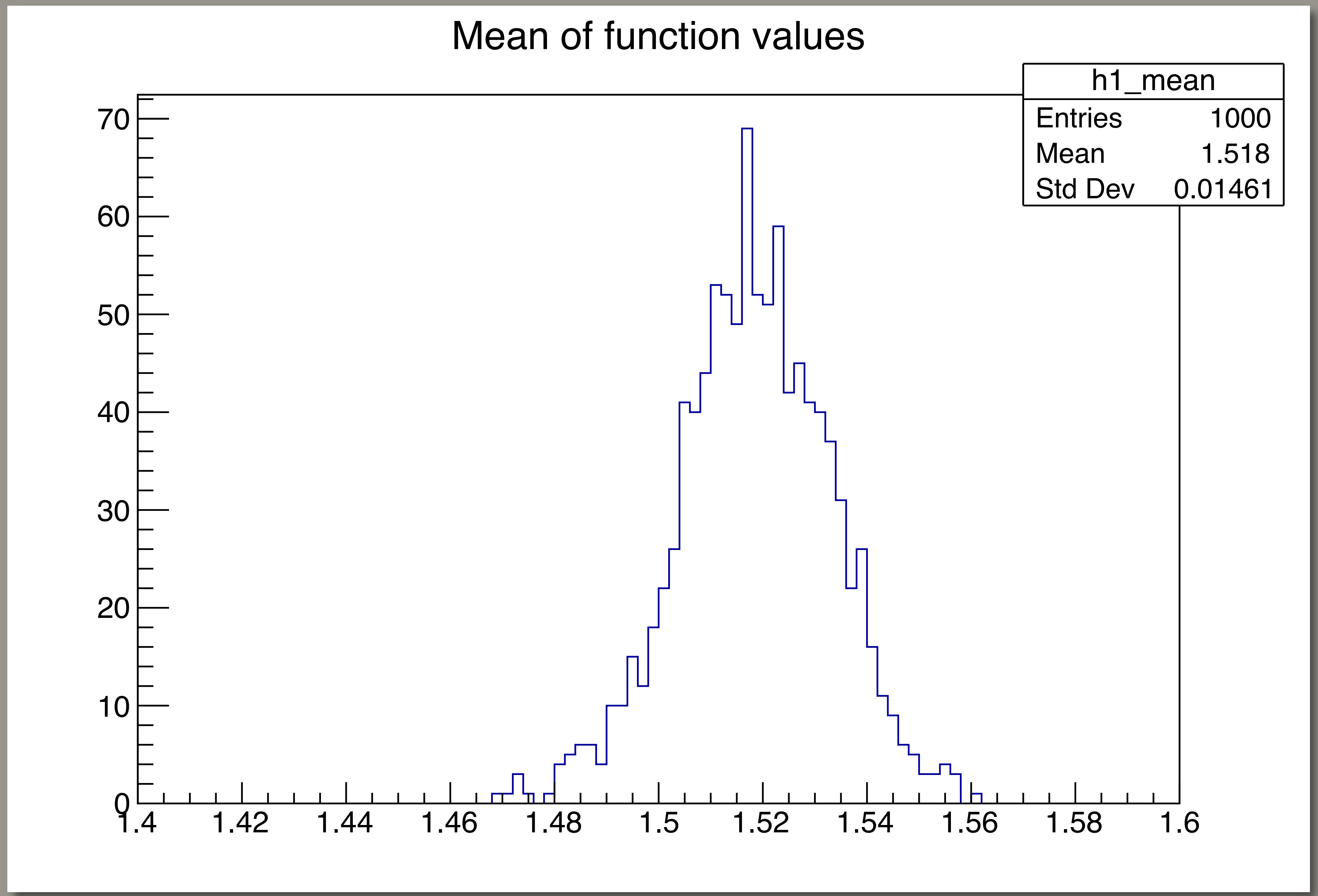
consistency conditions on density matrix

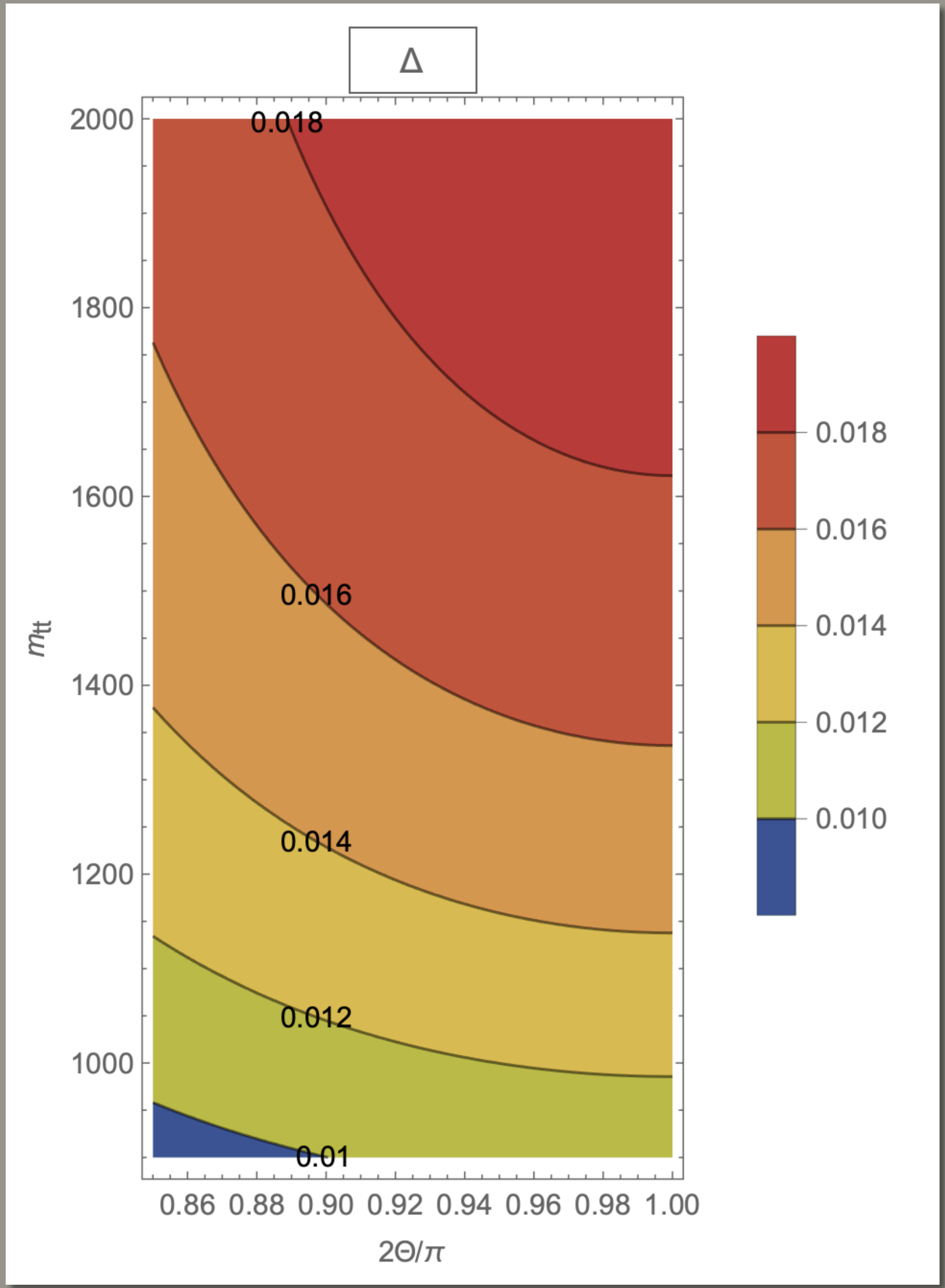
Hermitian, Tr =1, definite positive

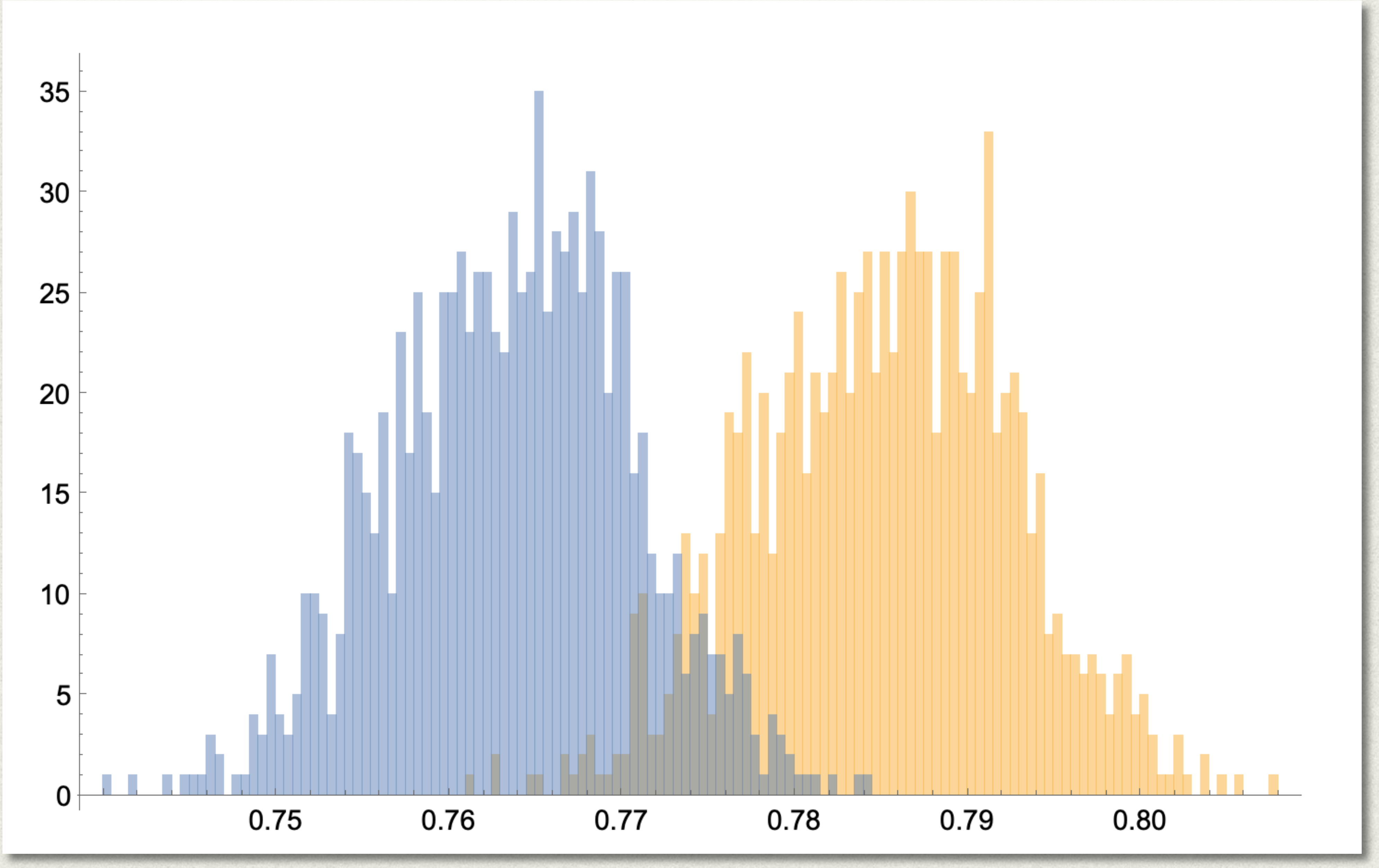
again, what is the uncertainty?




f2
1.7
1.6
1.5
1.4
1.3
1.2
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000


Mean of function values
h1_mean
Entries 1000
Mean 1.518
Std Dev 0.01461
70
60
50
40
30
20
10
0
1.4
1.42
1.44
1.46
1.48
1.5
1.52
1.54
1.56
1.58
1.6





$$\mu = 0.003$$

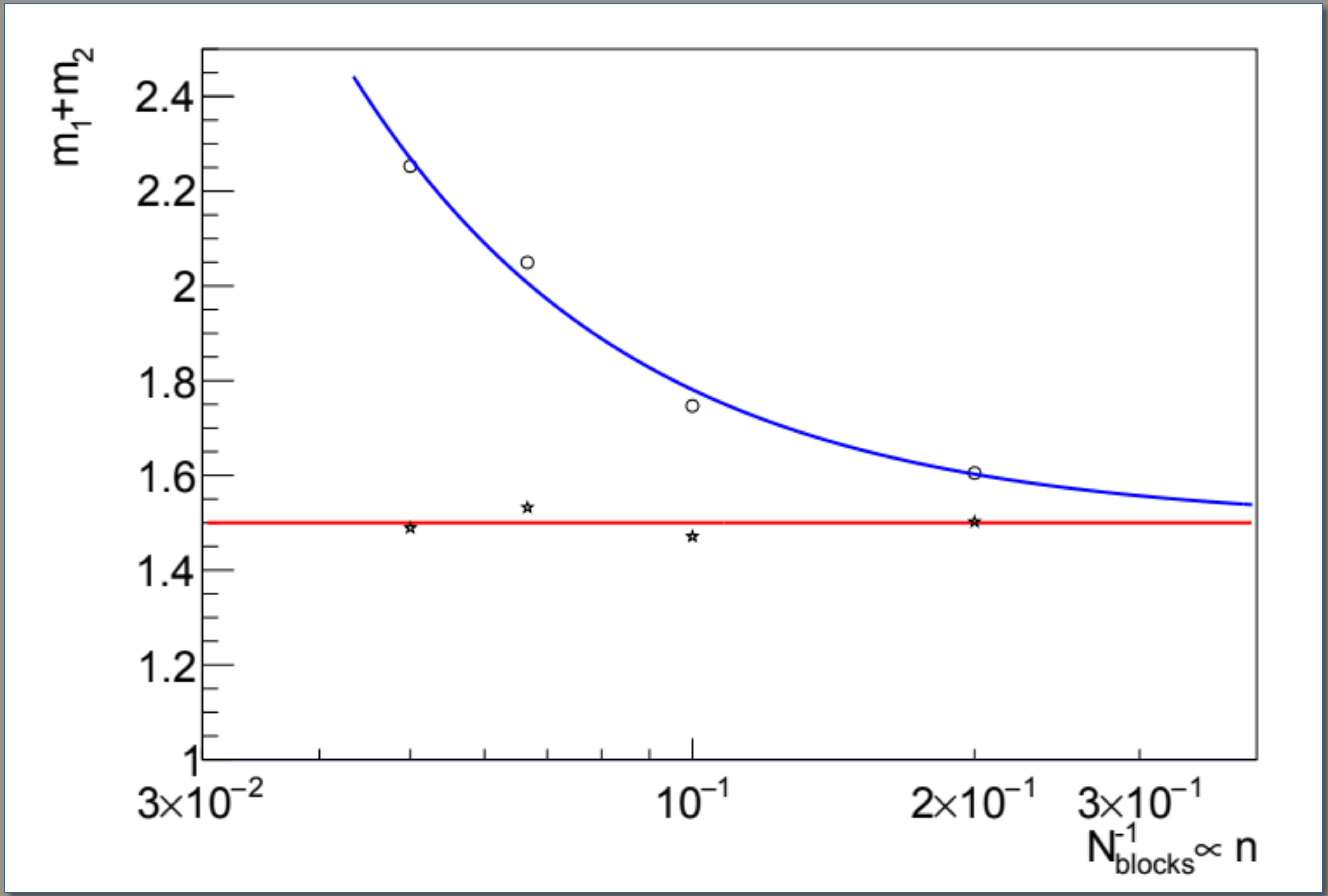
significance: 3

	(run 2) $\mathcal{L} = 140\ \text{fb}^{-1}$	(Hi-Lumi) $\mathcal{L} = 3\ \text{ab}^{-1}$
events	387	8294

TABLE I. Number of expected events in the kinematical region $m_{tt} > 900$ GeV and $0.85 < x < 1$.

in case someone asks

consistent estimator



$m_{t\bar{t}} \simeq 1.1\text{TeV}\ 2\Theta/\pi \simeq 0.95$

MadGraph5 (NNPDF23)
DELPHES (fast simulation ATLAS detector)

Event generation

exactly two opposite sign leptons (e,mu) of different flavor

- at least 2 anti-k_t jets with R=0.4
- at least 1 b-tagged jet
- $p_T > 25$ GeV $|\eta| < 2.5$ jets
- $p_T > 20$ GeV $|\eta| < 2.47$ leptons
- neutrino weighting technique (top quark momenta)

W. Bernreuther, D. Heisler and Z. G. Si, JHEP 12, 026 (2015)
Y. Afik and J. R. M. de Nova, Eur.Phys.J.Plus 136 (2021) 9, 907

Implementing at the LHC

$$pp \to t + \bar{t} \to \ell^{\pm}\ell^{\mp} + \text{jets} + E_T^{\text{miss}}$$

$$\xi_{ab} = \cos\theta_+^a \cos\theta_-^b$$

3 x 3 matrix

	label	$\hat{\mathbf{a}}$	$\hat{\mathbf{b}}$
transverse	n	$\text{sign}(y_p)\ \hat{\mathbf{n}}_p$	$-\text{sign}(y_p)\ \hat{\mathbf{n}}_p$
r axis	r	$\text{sign}(y_p)\ \hat{\mathbf{r}}_p$	$-\text{sign}(y_p)\ \hat{\mathbf{r}}_p$
helicity	k	$\hat{\mathbf{k}}$	$-\hat{\mathbf{k}}$

$$C_{ab}\left[\sigma(m_{t\bar{t}}, \cos\Theta)\right] = -9\ \frac{1}{\sigma}\int d\xi_{ab}\frac{d\sigma}{d\xi_{ab}}\xi_{ab}$$

diagonalization for each value
of invariant mass and scattering angle

$$m_1 + m_2 > 1$$