Running between colourful and flavourful physics

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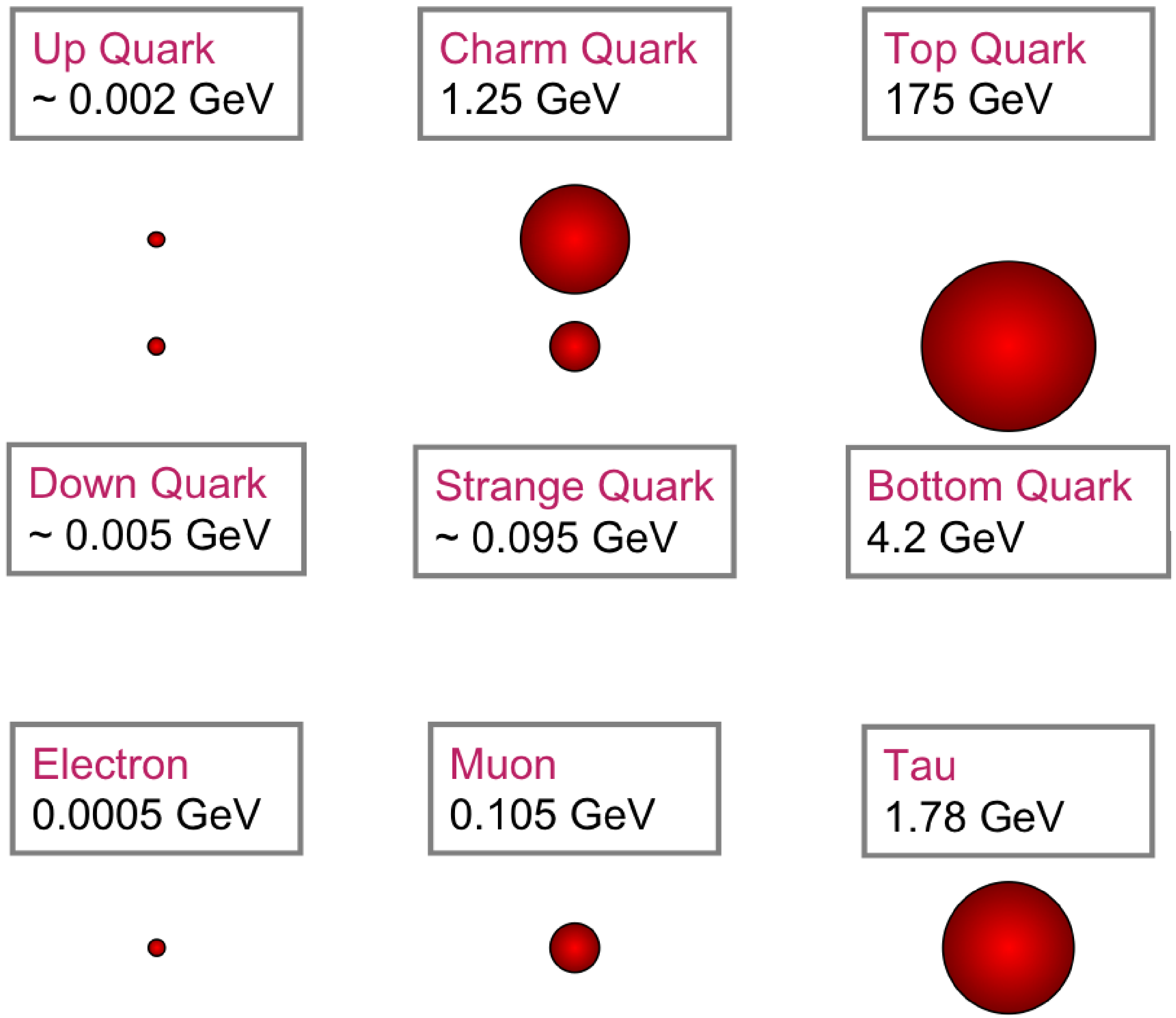
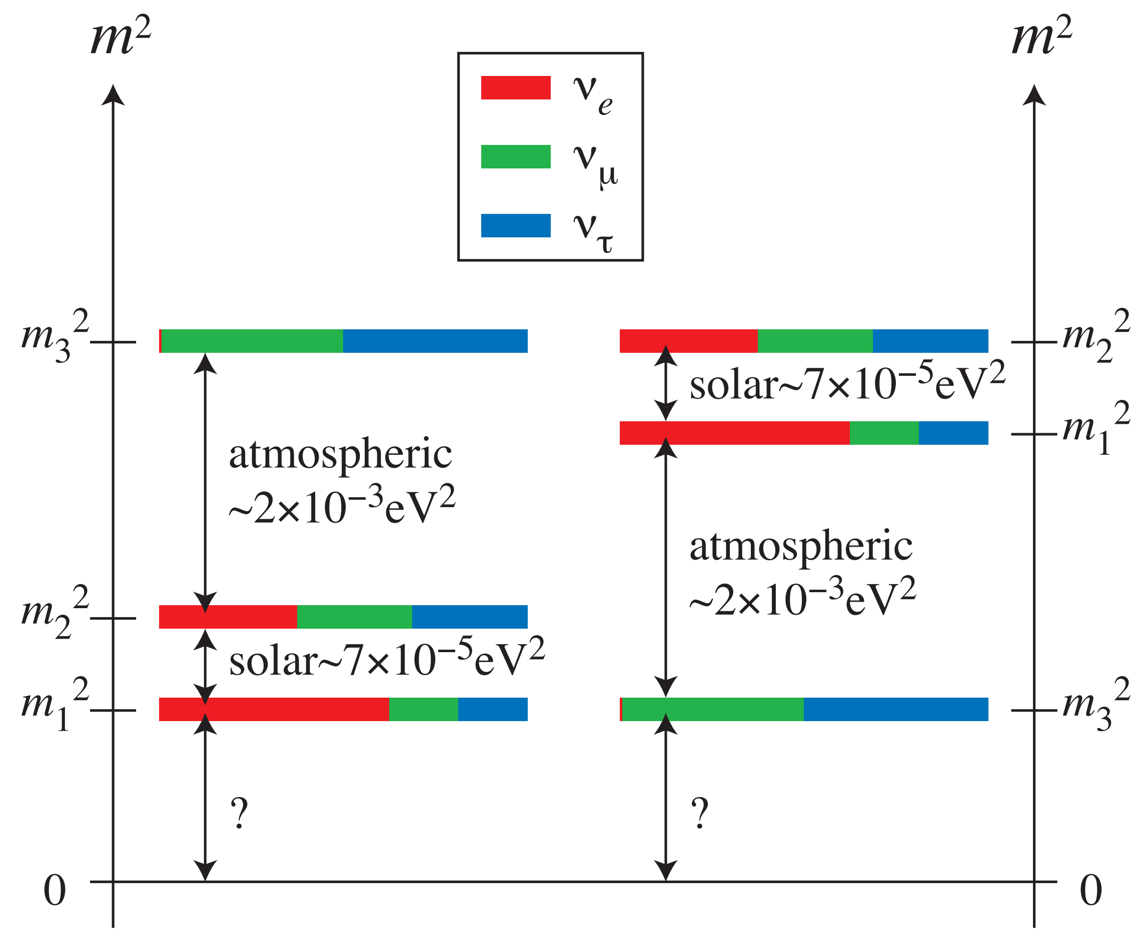
31 October 2016 | | Fellows Day, DESY Hamburg

The Flavour Problem: masses

hep-ph/1301.1340
hep-ph/1405.5495





- Quark masses generically hierarchical
- Charged lepton masses generically hierarchical
- Absolute neutrino mass not yet known, only mass-squared differences up to a sign

The Flavour Problem: mixings

- Mismatch between flavour and mass bases leads to 3 x 3 unitary mixing matrices

Quarks

$$|U_{\rm CKM}| = \begin{pmatrix} \begin{pmatrix} 0.97441 \\ 0.97413 \end{pmatrix} & \begin{pmatrix} 0.22597 \\ 0.22475 \end{pmatrix} & \begin{pmatrix} 0.00370 \\ 0.00340 \end{pmatrix} \\ \begin{pmatrix} 0.22583 \\ 0.22461 \end{pmatrix} & \begin{pmatrix} 0.97358 \\ 0.97328 \end{pmatrix} & \begin{pmatrix} 0.0426 \\ 0.0402 \end{pmatrix} \\ \begin{pmatrix} 0.00919 \\ 0.00854 \end{pmatrix} & \begin{pmatrix} 0.0416 \\ 0.0393 \end{pmatrix} & \begin{pmatrix} 0.99919 \\ 0.99909 \end{pmatrix} \end{pmatrix}$$

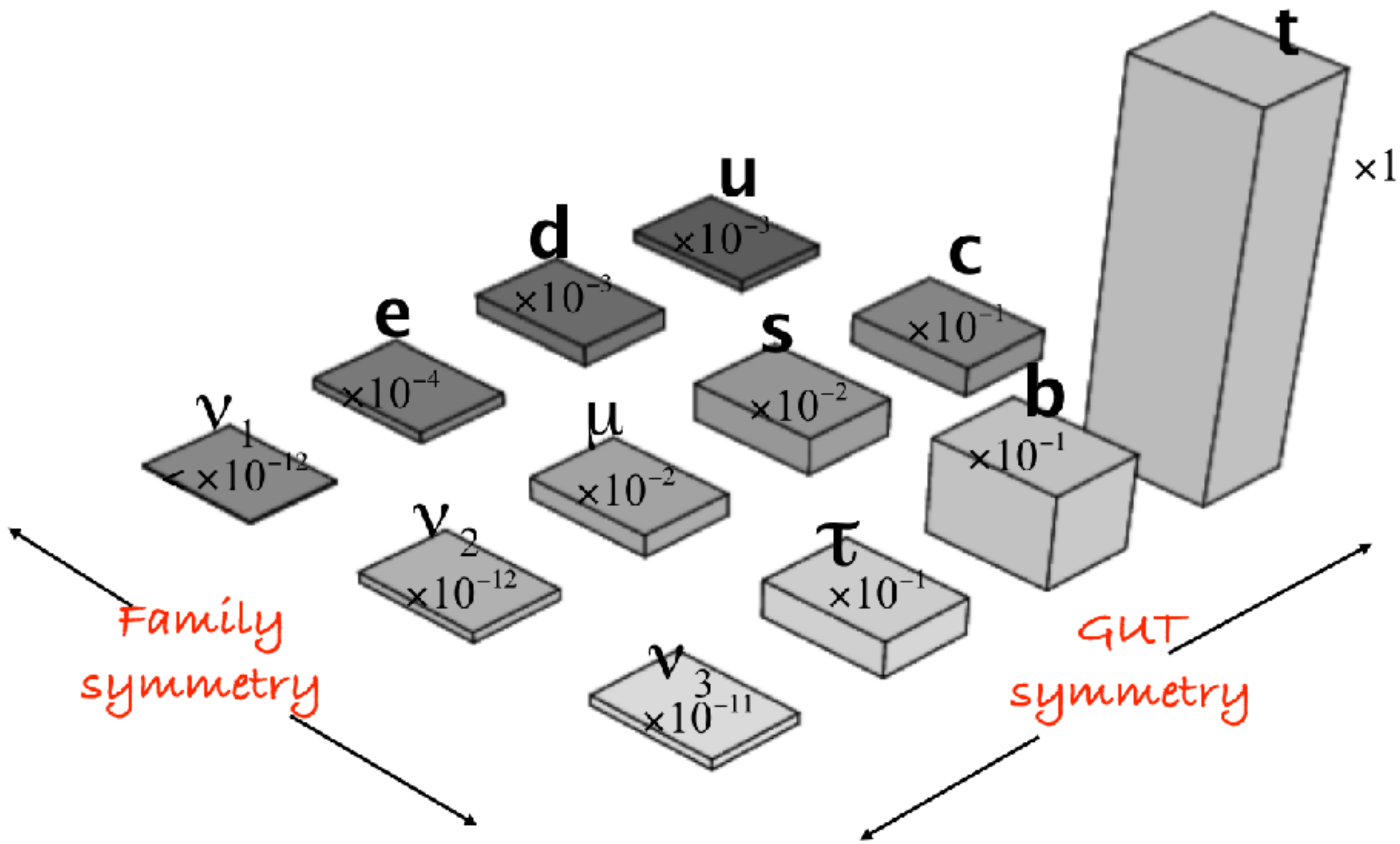
- Hierarchical
- Small exterior off diagonal elements
- Naively approximates an orthogonal SO(3) rotation about "z"

Leptons

- Non-hierarchical, but:
- 'bi-maximal' (?)
- 'tri-maximal' (?)
- Non-zero 13 element

$$|U_{\rm PMNS}| \begin{pmatrix} \begin{pmatrix} 0.845 \\ 0.791 \end{pmatrix} & \begin{pmatrix} 0.592 \\ 0.512 \end{pmatrix} & \begin{pmatrix} 0.172 \\ 0.133 \end{pmatrix} \\ \begin{pmatrix} 0.521 \\ 0.254 \end{pmatrix} & \begin{pmatrix} 0.698 \\ 0.455 \end{pmatrix} & \begin{pmatrix} 0.782 \\ 0.604 \end{pmatrix} \\ \begin{pmatrix} 0.521 \\ 0.254 \end{pmatrix} & \begin{pmatrix} 0.698 \\ 0.455 \end{pmatrix} & \begin{pmatrix} 0.782 \\ 0.604 \end{pmatrix} \end{pmatrix}$$

Symmetries as solutions



hep-ph/1002.0211
hep-ph/1110.6376
hep-ph/1301.1340

Discrete flavour symmetries

- The data (arguably) indicate some ordering to flavoured parameters—new flavour symmetries can provide for such organization.
- Discrete symmetries (imposed via finite groups) have been favored candidates, especially in the leptonic sector.
- Such discrete symmetries can quantize **precise mixing patterns** and provide interesting relations amongst masses.
- Furthermore, breaking discrete symmetries does not necessitate goldstone modes that could spoil phenomenology, and **vacuum alignment** can also be achieved.
- Discrete symmetries can also be embedded into **Grand Unified Theories**, and could have origins in **extra dimensions**, e.g. heterotic orbifold compactifications, thus naturally connecting them to UV complete theories

Model-independent symmetry searches

(i,j) in $\{S_{iU}, S_{jU}\}$	T_{diag}	b or c	GAP-ID	Group Structure	$\parallel U_{i3}^2 \parallel^T$
(1), $(3)^*$	$[\omega^2, 1, \omega]$	$\frac{1}{2}, \frac{1}{2}^{*\dagger}$	[288, 397]	$Z_3 \times \Delta(96)$	$[.333, .0447, .622]^{*\dagger}$
$(12, 13, 23)^\dagger$	$[1, \omega^2, \omega]$	$\frac{1}{2}, \frac{1}{2}^{*\dagger}$	[96, 64]	$\Delta(96)$	$[.333, .0447, .622]^{*\dagger}$
(2)	$[\omega^2, 1, \omega]$	N.A.	[12, 3]	A_4	N.A.
(1)	$[\omega^2, 1, \omega]$	$\frac{1}{4}, \frac{1}{4}^{*\dagger}$	[288, 397]	$Z_3 \times \Delta(96)$	$[.333, .0447, .622]^{*\dagger}$
$(3)^*$, $(3)^\circ$	$[1, \omega^2, \omega]$	$\frac{1}{4}, \frac{1}{4}^{*\dagger}$	[96, 64]	$\Delta(96)$	$[.333, .0447, .622]^{*\dagger}$
$(12, 13, 23)^\dagger$	$[1, \omega^2, \omega]$	$\frac{1}{5}, \frac{3}{10}^\circ, \frac{1}{5}^\dagger$	[600, 179]	$\Delta(600)$	$[.230, .110, .659]^{\circ\dagger}$
	$[1, \omega^2, \omega]$	$\frac{1}{8}, \frac{1}{8}^{*\dagger}$	[384, 568]	$\Delta(384)$	$[.0976, .247, .655]^{*\dagger}$
	$[1, \omega^2, \omega]$	$\frac{3}{8}, \frac{3}{8}^{*\dagger}$	[384, 568]	$\Delta(384)$	$[.569, .0114, .420]^{*\dagger}$
	$[\omega^2, 1, \omega]$	$\frac{1}{9}, \frac{1}{18}^\circ, \frac{1}{9}^\dagger$	[648, 259]	$\Xi(18, 6)$	$[.0780, .276, .647]^{\circ\dagger}$
	$[\omega^2, 1, \omega]$	$\frac{1}{10}, \frac{2}{5}^\circ$	[450, 20]	$Z_3 \times \Delta(150)$	$[.0637, .299, .638]^\circ$
	$[1, \omega^2, \omega]$	$\frac{1}{10}, \frac{2}{5}^\circ$	[150, 5]	$\Delta(150)$	$[.0637, .299, .638]^\circ$
	$[\omega^2, 1, \omega]$	$\frac{1}{14}, \frac{3}{7}^\circ$	[882, 38]	$Z_3 \times \Delta(294)$	$[.0330, .358, .609]^\circ$
	$[1, \omega^2, \omega]$	$\frac{1}{14}, \frac{3}{7}^\circ$	[294, 7]	$\Delta(294)$	$[.0330, .358, .609]^\circ$
	$[1, \omega^2, \omega]$	$\frac{2}{5}, \frac{1}{10}^{\circ\dagger}$	[600, 179]	$\Delta(600)$	$[.0288, .368, .603]^{\circ\dagger}$
	$[\omega^2, 1, \omega]$	$\frac{1}{18}, \frac{1}{9}^\circ$	[162, 14]	$\Xi(9, 3)$	$[.391, .0201, .589]^\circ$
	$[\omega^2, 1, \omega]$	$\frac{3}{10}, \frac{1}{5}^\circ$	[450, 20]	$Z_3 \times \Delta(150)$	$[.436, .00728, .556]^\circ$
	$[1, \omega^2, \omega]$	$\frac{3}{10}, \frac{1}{5}^\circ$	[150, 5]	$\Delta(150)$	$[.436, .00728, .556]^\circ$
	$[\omega^2, 1, \omega]$	$\frac{5}{14}, \frac{1}{7}^\circ$	[882, 38]	$Z_3 \times \Delta(294)$	$[.541, .00372, .455]^\circ$
	$[1, \omega^2, \omega]$	$\frac{5}{14}, \frac{1}{7}^\circ$	[294, 7]	$\Delta(294)$	$[.541, .00372, .455]^\circ$
	$[\omega^2, 1, \omega]$	$\frac{3}{14}, \frac{2}{7}^\circ$	[882, 38]	$Z_3 \times \Delta(294)$	$[.259, .0890, .652]^\circ$
	$[1, \omega^2, \omega]$	$\frac{3}{14}, \frac{2}{7}^\circ$	[294, 7]	$\Delta(294)$	$[.259, .0890, .652]^\circ$
(2)	$[\omega^2, 1, \omega]$	N.A.	[12, 3]	A_4	N.A.
(3)	$[1, \omega^2, \omega]$	$\frac{1}{11}$	[726,5]	$\Delta(726)$	[.0529, .318, .630]
	$[1, \omega^2, \omega]$	$\frac{2}{11}$	[726,5]	$\Delta(726)$	[.195, .665, .140]
	$[1, \omega^2, \omega]$	$\frac{3}{11}$	[726,5]	$\Delta(726)$	[.381, .0239, .595]
	$[1, \omega^2, \omega]$	$\frac{4}{11}$	[726,5]	$\Delta(726)$	[.552, .00602, .442]
	$[1, \omega^2, \omega]$	$\frac{5}{11}$	[726,5]	$\Delta(726)$	[.653, .0921, .255]

hep-ph/1409.7310
hep-ph/1605.03581

Status of discrete flavour symmetries?

- Multiple symmetries predict the same mixing patterns, and the same symmetry can predict multiple patterns
- In the absence of an exact symmetry, sub-leading corrections become important for phenomenology.
- It is not presently clear that any discrete symmetry can, without special modeling, successfully describe all fermionic structure.
- Vacuum alignment mechanisms are often involved, and additional symmetries often needed.
- It is also not yet clear how such models should be completed/realized in the UV.

Input is needed from UV physics. Guideposts could come from:

- Renormalization Group Evolution
- Anomaly cancellation constraints
- Higher dimensional theories

Projects, ideas, and interests

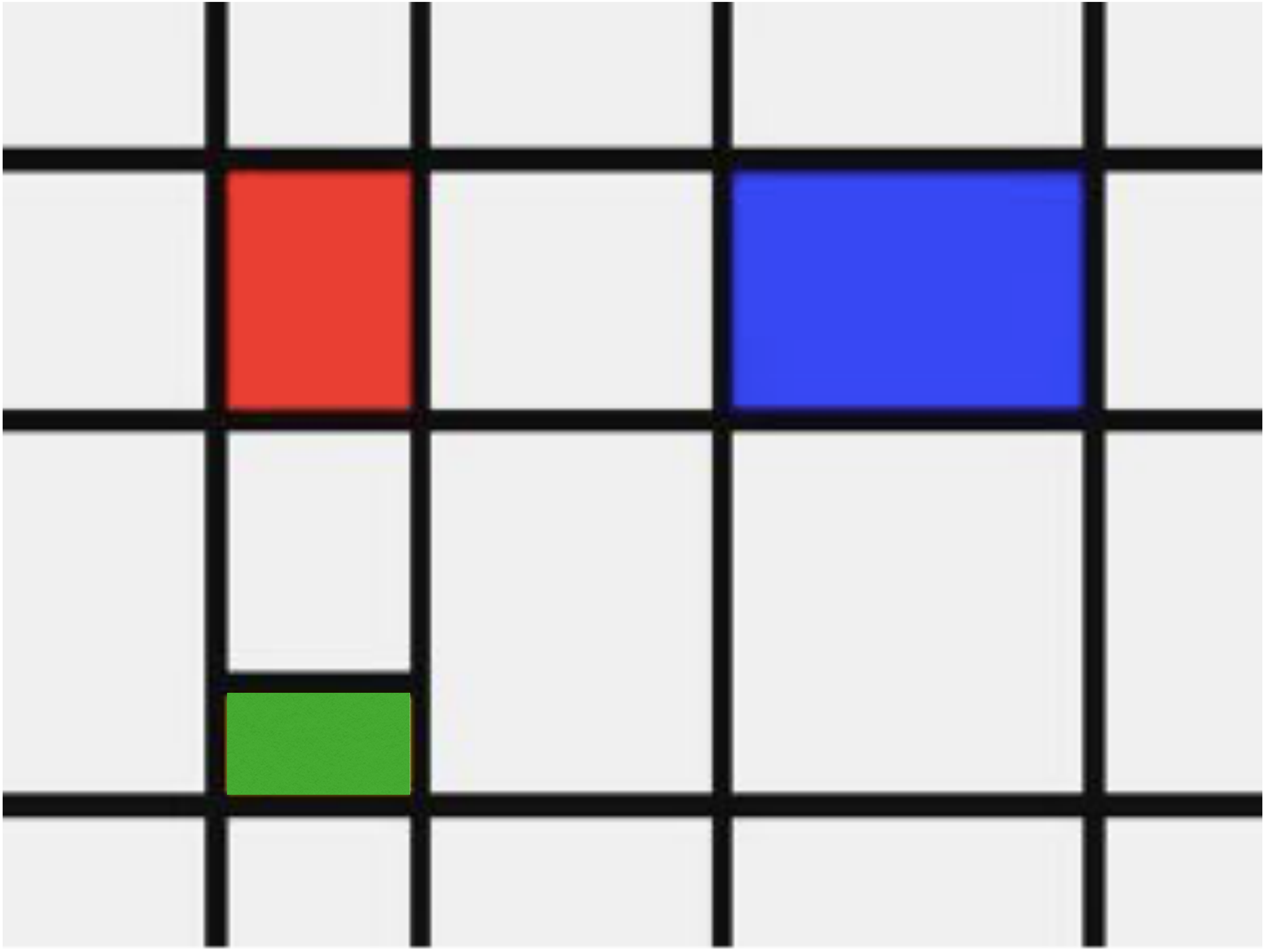
Generalized anomaly constraints -
w/ Sven Krippendorf (Oxford)

Indirect model for quarks and leptons -
w/ GG Ross (Oxford)

Can the RGE for mass and mixing parameters be generalized with an EFT approach?

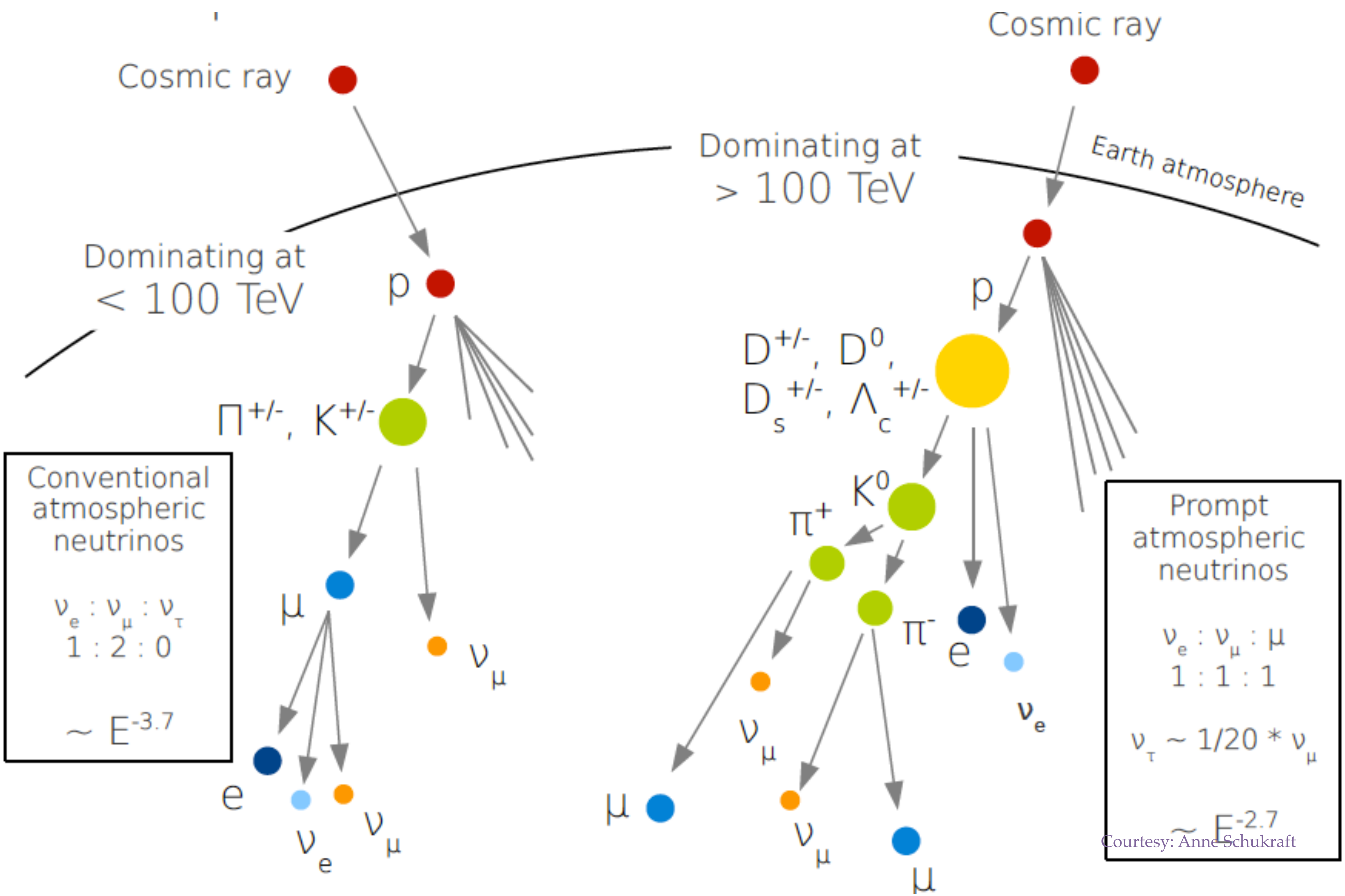
Are there alternative mechanisms/constraints for flavoured vacuum alignment?

What are the connections between flavour and cosmology?



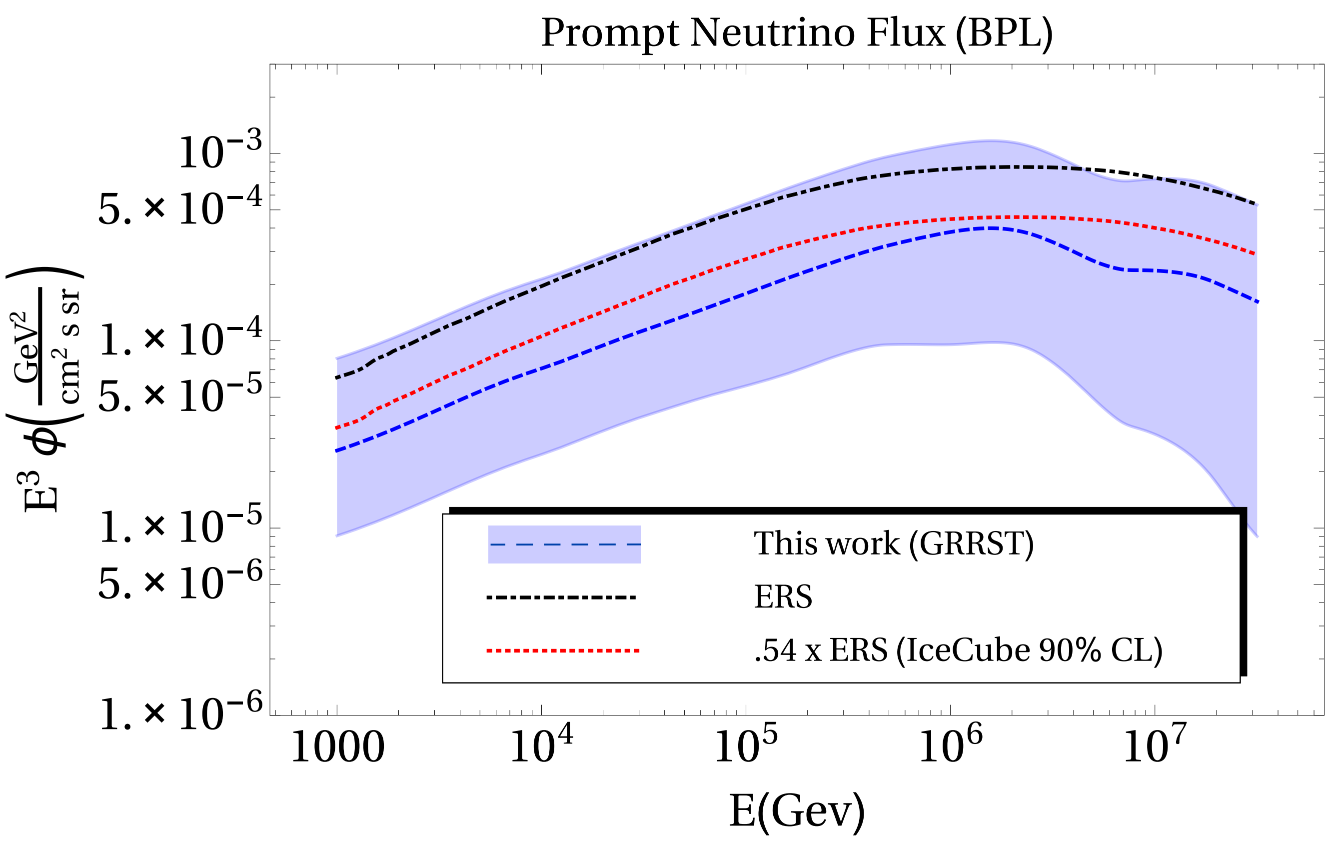
arXiv:1506.08025 + 1511.06346

Atmospheric charm production



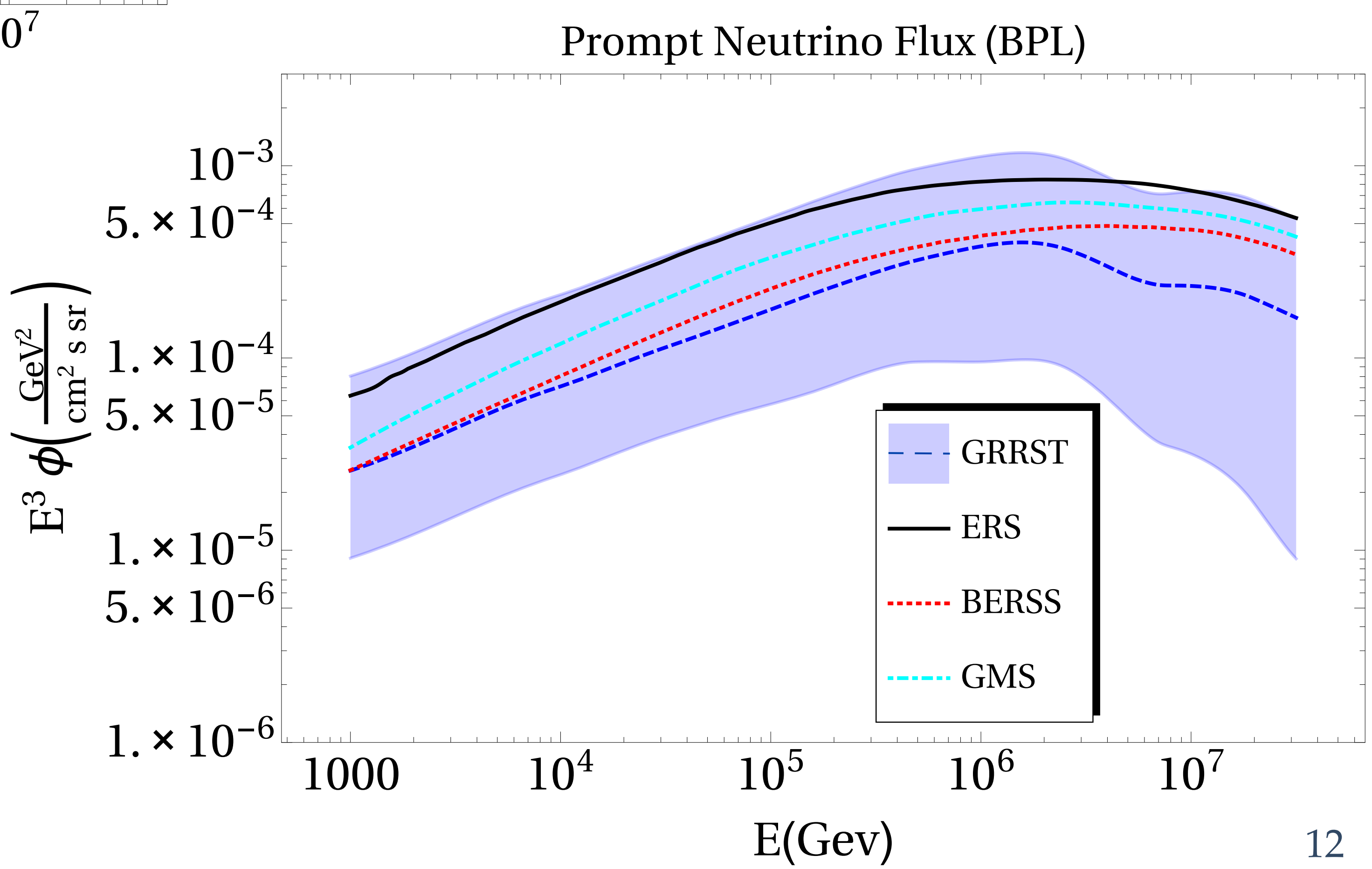
Courtesy: Anne Schukraft

Prompt neutrinos @ terrestrial detectors



- Our central result is just below the most recent IceCube bound, indicating that **a prompt component of the incoming flux should be observed soon**….

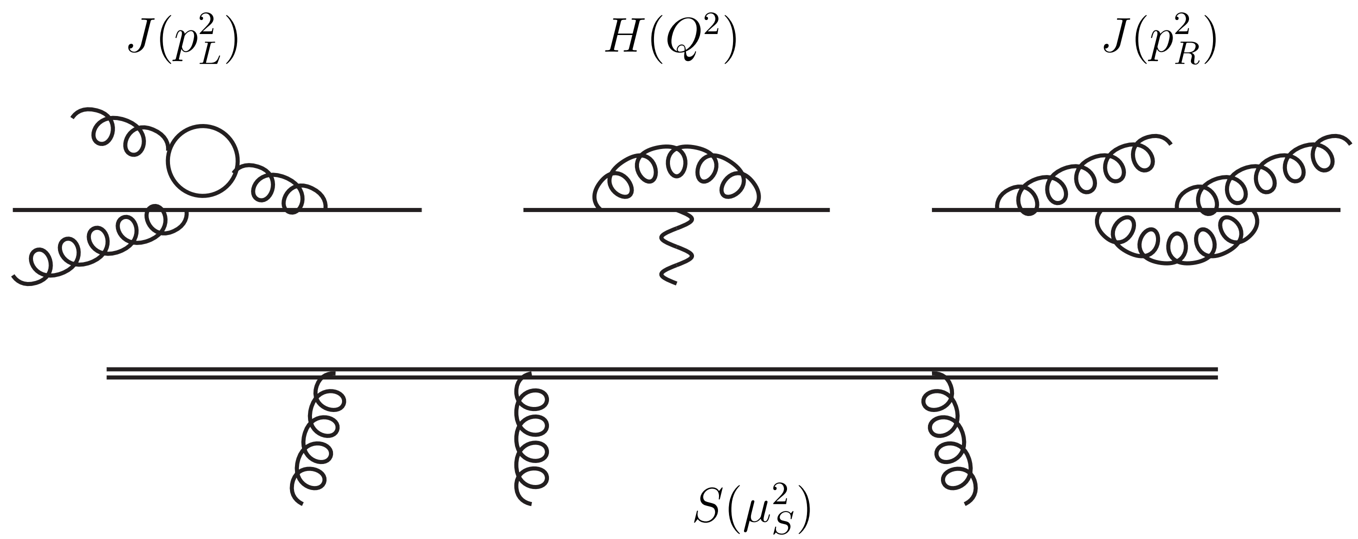
- Our central result is consistent with the recent **BERSS** collaboration, though with **better estimates of the uncertainties**, which also encompass the 2008 **ERS** result and the most recent **GMS** calculation.



SCET, an effective theory of QCD

- SCET permits the derivation of all-order factorization theorems:

$$d\sigma \sim H \cdot \mathcal{J} \otimes \mathcal{J} \otimes \mathcal{S}$$



- Once factorized, we resum logs via RG Equations:

$$\frac{dH(Q^2,\mu)}{d\ln\mu} = \left[2\Gamma_{cusp}\ln\left(\frac{Q^2}{\mu^2}\right) + 4\gamma_H(\alpha_s)\right] H(Q^2,\mu)$$

- To increase the accuracy of the resummations one needs the anomalous dimensions and the matching corrections to higher orders.

Automated calculation of dijet soft functions

Soft function	γ_0^S/C_F	c_1^S/C_F	$\gamma_1^{C_A}$	$\gamma_1^{n_f}$	$c_2^{C_A}$	$c_2^{n_f}$
Thrust [168, 169]	0	$-\pi^2$	15.7945 (15.7945)	3.90981 (3.90981)	−56.4992 (−56.4990)	43.3902 (43.3905)
C-parameter [142]	0	$-\pi^2/3$	15.7947 (15.7945)	3.90980 (3.90981)	−57.9754 (−)	43.8179 (−)
Thresh. Drell-Yan [167]	0	$\pi^2/3$	15.7946 (15.7945)	3.90982 (3.90981)	6.81281 (6.81287)	−10.6857 (−10.6857)
W@large p_T [172]	0	π^2	15.88 (15.7945)	3.905 (3.90981)	−2.65034 (−2.65010)	−25.3073 (−25.3073)

Table 3.3: Anomalous dimensions and finite terms of the renormalized soft function for sample SCET_1 observables. The upper numbers are the numerical results that we obtain with the `SecDec` implementation of our algorithm, and the lower ones correspond to the known analytic expressions.

NNLL resummation of *angularities*

$$\tau_a(X) = \frac{1}{Q}\sum_{i\in X} E_i \left|\sin\theta_i\right|^a \left(1-\left|\cos\theta_i\right|\right)^{1-a}$$

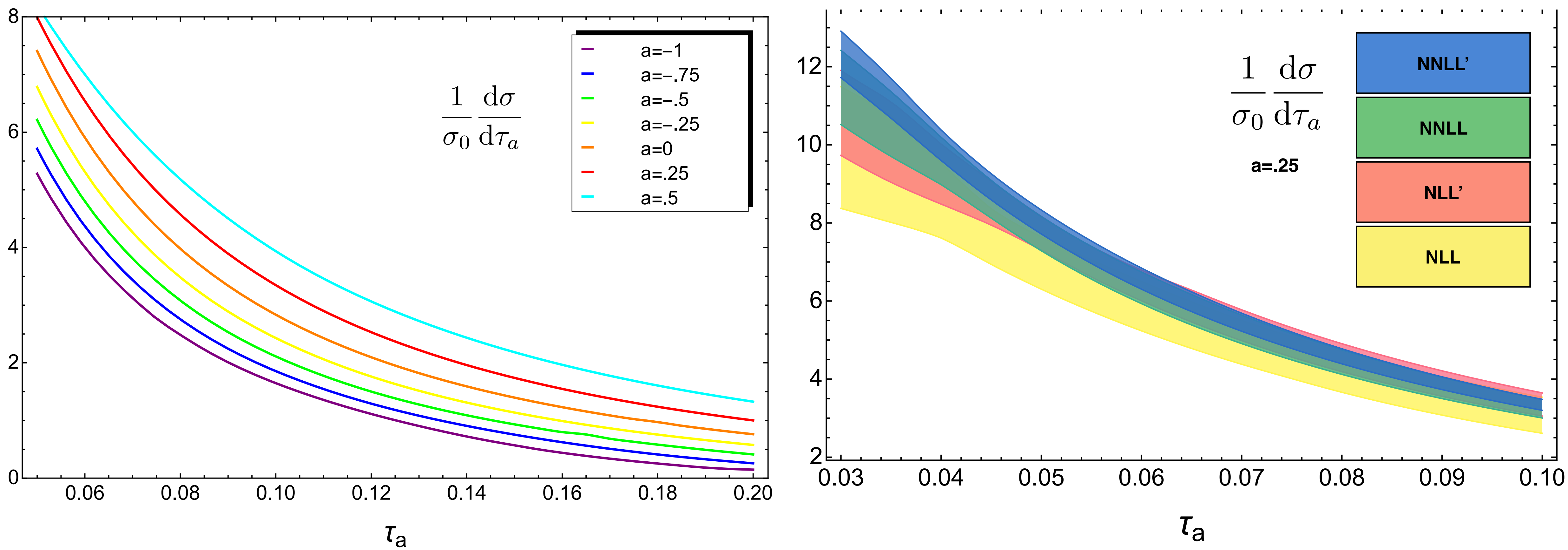


Figure 3.6: *LEFT*: The central values of the NNLL′ resummed and $\mathcal{O}(\alpha_s^2)$ matched angularity distributions at all 7 values of the parameter a. *RIGHT*: Theory bands demonstrating the convergence between NLL → NNLL′ resummations. The plot is for $a = .25$. $Q = 91.2$ GeV in both plots.

NNLL resummation of *angularities*

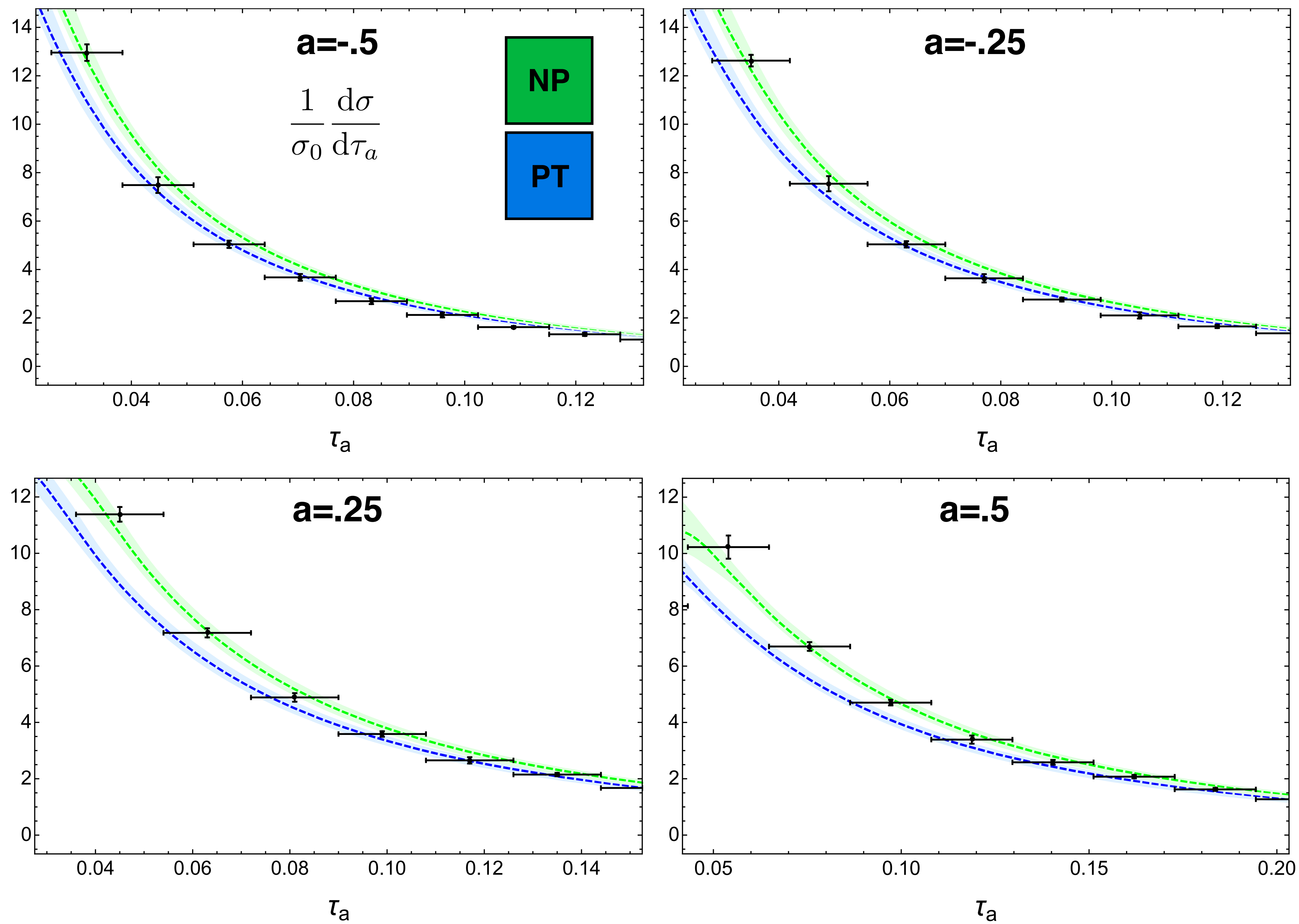


Figure 3.7: NNLL$'$ resummed and $\mathcal{O}(\alpha_s^2)$ matched angularity distributions at four values of the parameter a, $a \in \{-.5, -.25, .25, .5\}$. The blue (PT) curves represent the purely perturbative cross-section, whereas the green (NP) curves are shifted according to (3.126). $Q = 91.2$ GeV in all four plots.

Projects, ideas, and interests

Finalizing automated calculation of NNLO soft functions
w/ Guido Bell (Siegen) and Rudi Rahn (Bern)

NNLL resummation of angularities
w/ Chris Lee (LANL), Andrew Hornig, and Guido Bell

What's the value of the strong coupling constant at M_{Z}?

Are there any other systematic uncertainties in the prompt atmospheric neutrino flux?

What can SCET say about the (forward) production of heavy mesons?