Stable Asymptotically Free Extensions (SAFEs) of the Standard Model

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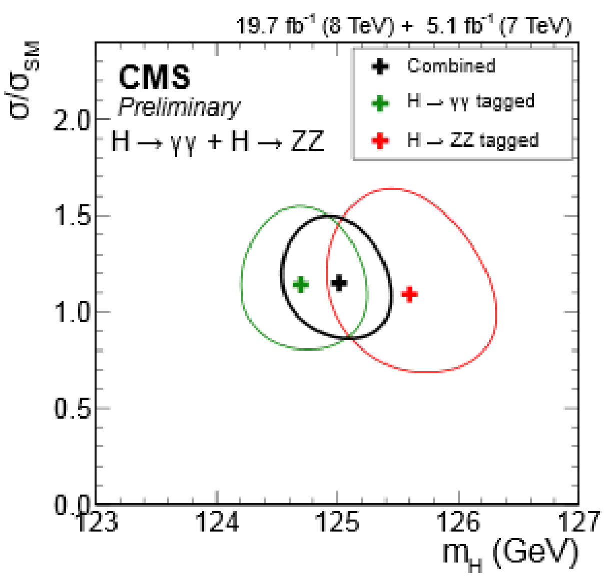
B. Holdom, JR, C. Zhang, JHEP 1503 (2015) 028 [arXiv:1412.5540 [hep-ph]]

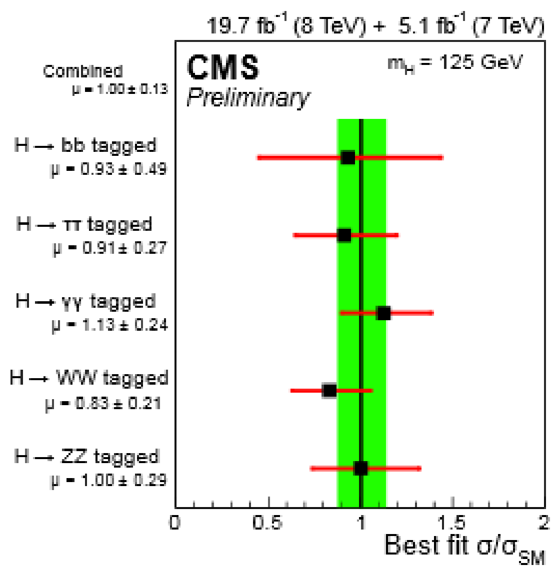
Outline

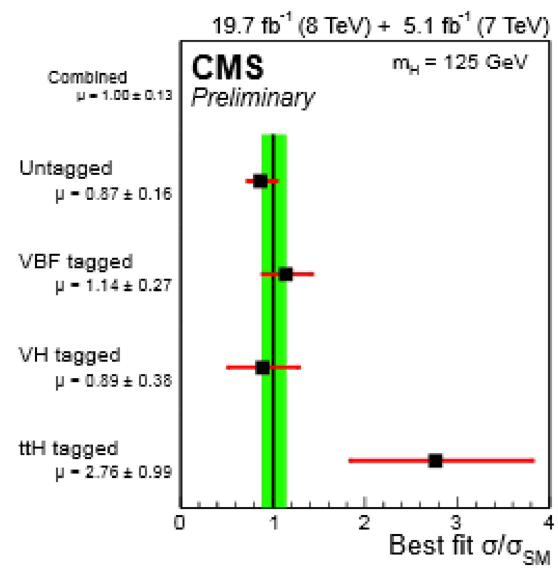
- Motivation
- CAFEs
- SAFEs
- The Simplest Model
- Summary

Higgs Discovery

- The 125GeV Higgs discovered on LHC in 2012
- So far, couplings, spin and parity compatible with SM
- For the first time, we have an Elementary Scalar!







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- Naturalness problem
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  - SM metastability: recover stability by new physics (e.g. more scalars)
  - Higgs quartic couplings Landau poles imply dangerous new mass scales
- Why worry about Landau poles above Planck scale?
  - New physics at Planck scale v.s. Naturalness
    - 2D model of QMG: "gravitational dressing" of QFT [Dubovsky et al., JHEP **1309**, 045 (2013)]
    - Quadratic gravity: asymptotic free + renormalizable [Stelle, Phys. Rev. D **16**, 953 (1977)] [Salvio, Strumia, JHEP **1406**, 080 (2014)]
  - Solve Landau poles in non-gravity QFT

Low Scale Unification

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- Low scale unification: no proton decay by gauge interaction
  - Pati-Salam model [Pati, Salam, Phys. Rev. D **10**, 275 (1974)]

$$SU(4) \times SU(2)_L \times SU(2)_R \to SU(3) \times SU(2)_L \times U(1)_Y$$

    - Unification of lepton and quark: $SU(4) \to SU(3) \times U(1)_{B-L}$
    - SM fermion: $(4,2,1)_L + (4,1,2)_R$ for each family + RH neutrino
  - Trinification [S. L. Glashow, *Fifth Workshop on Grand Unification* (1984)]

$$SU(3) \times SU(3)_L \times SU(3)_R \to SU(3) \times SU(2)_L \times U(1)_Y$$

    - SM fermion: Q_L in $(3,3,1)$, Q_R in $(3,1,3)$, L in $(1,3,3)$
  - Semi-simple non-abelian gauge group

CAFEs

- Completely asymptotic free extension (CAFEs) [Cheng, Eichten, Li, Phys. Rev. D **9**, 2259 (1974)]
  - Non-abelian gauge theories + fermions + scalars: all couplings (gauge, yukawa, quartic) run to zero in the UV
  - Asymptotic free v.s. asymptotic safe: AF is determined by one-loop, while AS relies on higher loop correction [Litim, Sannino, JHEP 1412, 178 (2014)]

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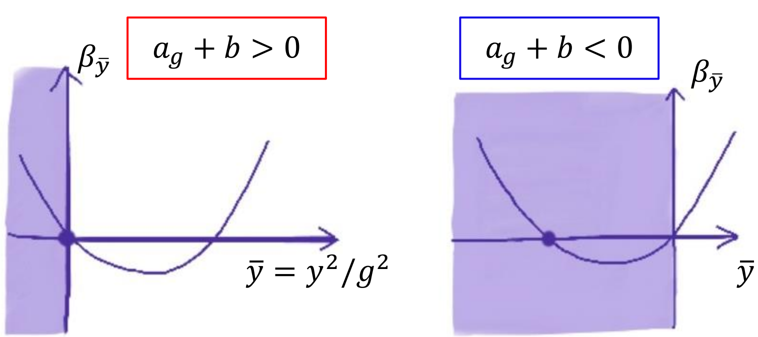
- Simple example: 1 gauge + 1 yukawa + 1 quartic $g^2(t) = -\frac{8\pi^2}{bt}$ $t = \ln(\mu/\Lambda)$ $b < 0$

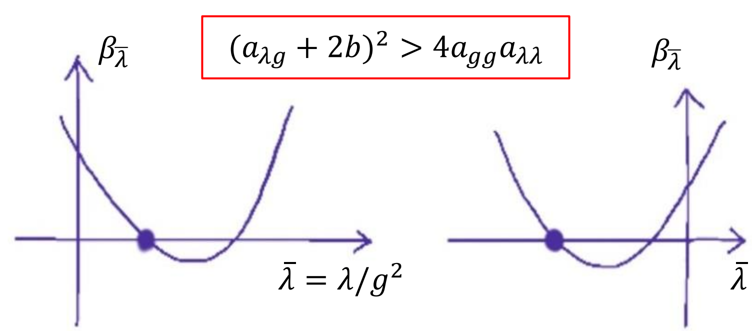
Yukawa coupling

$$(4\pi)^2\beta_y = a_y y^3 - a_g g^2 y \quad (a_y, a_g > 0)$$



Quartic coupling

$$(4\pi)^2\beta_\lambda = a_{\lambda\lambda}\lambda^2 - a_{\lambda g}\lambda g^2 + a_{gg}g^4 \quad (a_{\lambda\lambda}, a_{\lambda g}, a_{gg} > 0)$$

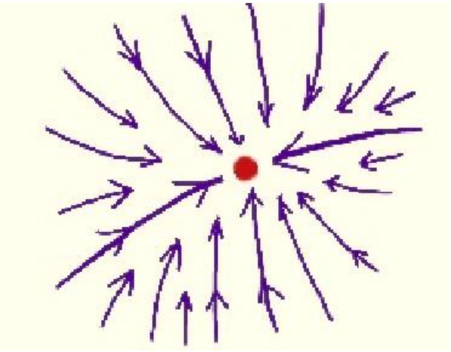


SAFEs

- Stable asymptotic free extension (SAFEs)

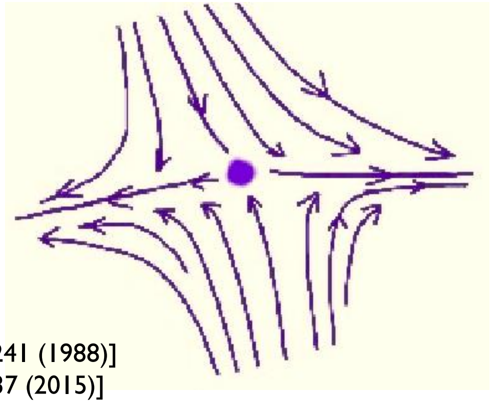
Stable

- Yukawa insignificant
- Quartic push down by gauge



Unstable

- Yukawa help to push down quartic
- UV trajectory constrained



[Callaway, Phys. Rept. **167**, 241 (1988)]
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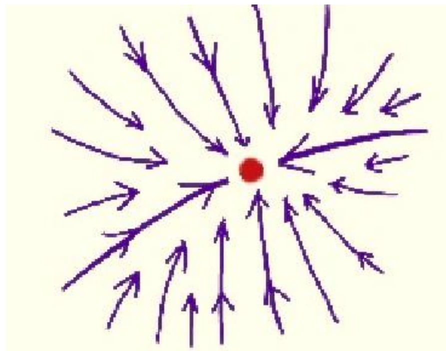

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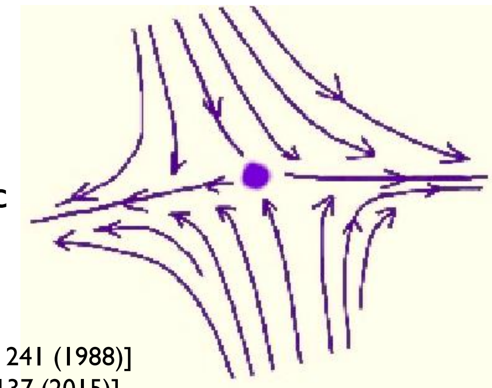

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- SAFEs for semi-simple Lie group
  - Setup: $(1):\ SU(N_A)\times SU(N_B),\quad (2):\ SU(N_A)\times SU(N_B)\times SU(N_C)\quad (N_i \geq 2)$
  - Gauge coupling ratios approach constant: $g_i^2/g_j^2 \to b_j/b_i$

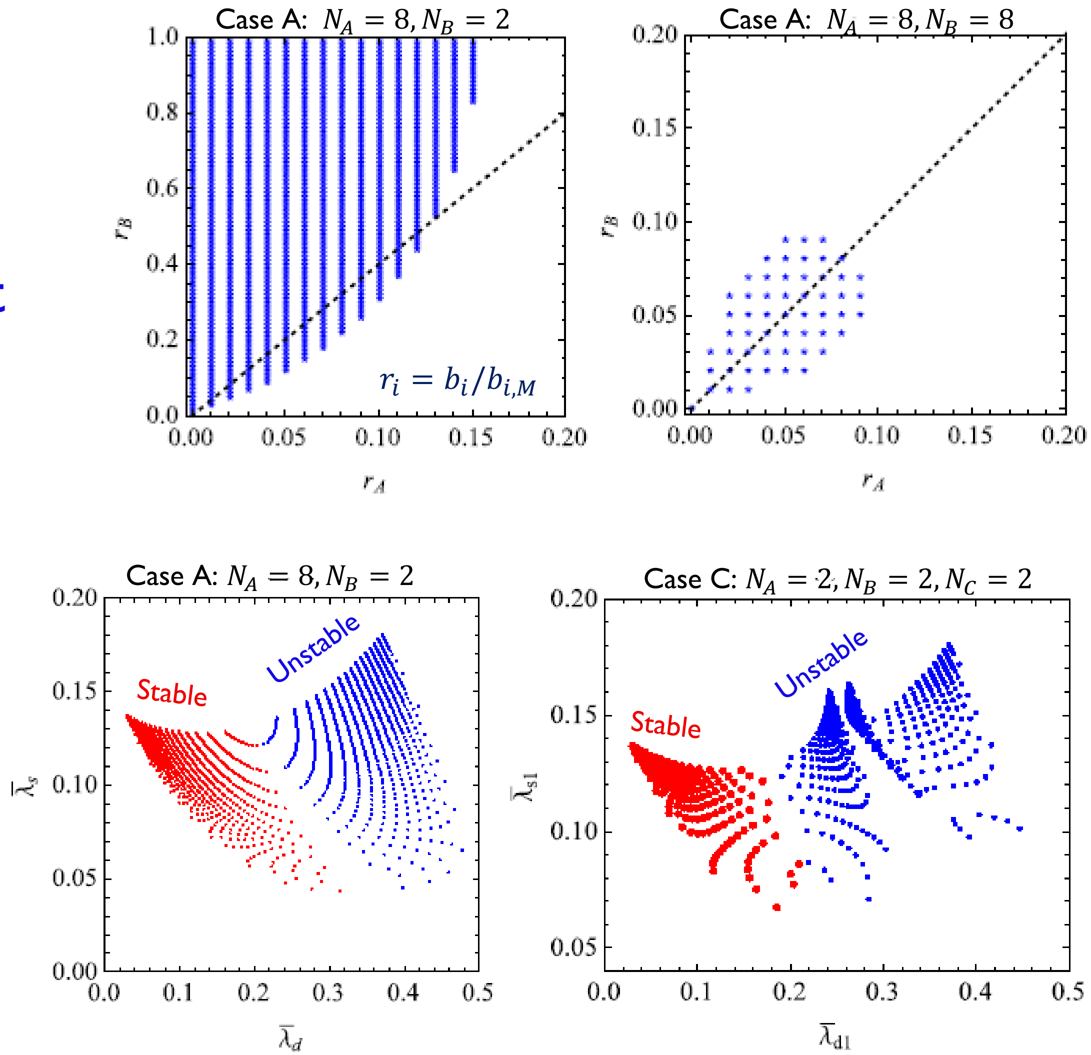
- Scalar sector: fundamental representation

(1) { Case A: (N_A, N_B); Case B: (N_A, N_B) and $(N_A, 1)$ }

(2) { Case C: $(N_A, N_B, 1)$ and $(N_A, 1, N_C)$; Case D: (N_A, N_B, N_C) }

General Features of SAFEs

- A large gauge group and big hierarchy in the sizes of the different gauge groups help
- Gauge coupling of the largest group is constrained to run the slowest, i.e. vector-like fermions only charged under the largest gauge group needed.
- Among all UVFPs there is always one that is UV stable.
- Rare to see negative quartic couplings.



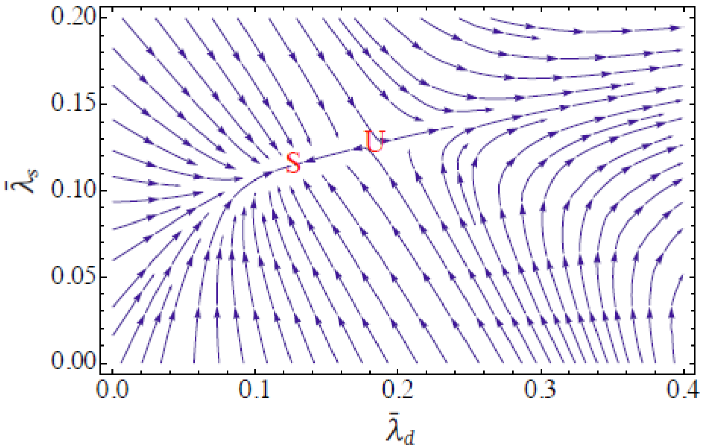
The Simplest Model (Pati-Salam)

- Model setup: only one (4, 2, 1) for the Higgs doublet

$$V_4 = \lambda_d \Phi^*_{ik}\Phi_{ik}\Phi^*_{jl}\Phi_{jl} + \lambda_s \Phi^*_{ik}\Phi_{il}\Phi^*_{jl}\Phi_{jk}$$

Fields	Number	$SU(4)$	$SU(2)_L$	$SU(2)_R$
F_L	n_F	4	2	1
F_R	n_F	4	1	2
$f_{L,R}$	n_f	4	1	1
Φ	1	4	2	1

SAFEs: $|b_4| < 0.44, 2n_F + n_f = 21$



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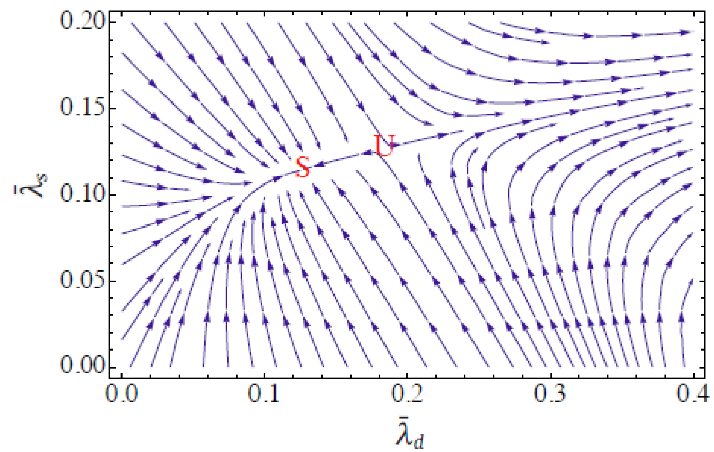
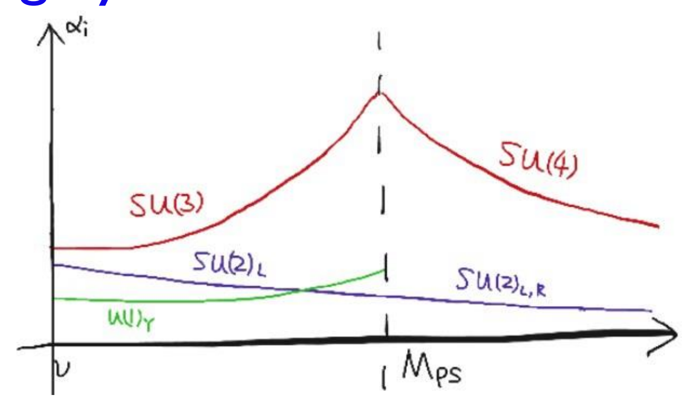


- Pati-Salam symmetry broken by strong dynamics
  - $2n_F + n'_f = 15$: large $SU(3)$ $\beta_c > 0$ and large IRFP of $SU(4)$
  - Dynamically generated yukawa



Summary

- UV complete non-abelian gauge theory containing truly elementary scalar fields without UV Landau poles.
- Search for SAFEs for semi-simple gauge group, as motivated by low scale unification model.
- SAFEs for model building: gauge group with sizes in large hierarchy; fewer scalars; more fermions only charged under the largest gauge group.
- The simplest model is Pati-Salam with only one scalar to for the SM Higgs doublet. Need strong dynamics to break down Pati-Salam symmetry and generate SM yukawa couplings.

Thank You!

Four Benchmarks

- **Case A:** $SU(N_A) \times SU(N_B)$ **with** (N_A, N_B)

$$V_4 = \lambda_d \Phi^*_{ik} \Phi_{ik} \Phi^*_{jl} \Phi_{jl} + \lambda_s \Phi^*_{ik} \Phi_{il} \Phi^*_{jl} \Phi_{jk}$$

- **Case B:** $SU(N_A) \times SU(N_B)$ **with** (N_A, N_B) **and** $(N_A, 1)$

$$V_4 = \lambda_{d1} \Phi^{(1)*}_{ik} \Phi^{(1)}_{ik} \Phi^{(1)*}_{jl} \Phi^{(1)}_{jl} + \lambda_{s1} \Phi^{(1)*}_{ik} \Phi^{(1)}_{il} \Phi^{(1)*}_{jl} \Phi^{(1)}_{jk} + \lambda_2 \Phi^{(2)*}_{i} \Phi^{(2)}_{i} \Phi^{(2)*}_{j} \Phi^{(2)}_{j}$$
$$+ 2\lambda_{d12} \Phi^{(1)*}_{ik} \Phi^{(1)}_{ik} \Phi^{(2)*}_{j} \Phi^{(2)}_{j} + 2\lambda_{s12} \Phi^{(1)*}_{ik} \Phi^{(1)}_{jk} \Phi^{(2)*}_{j} \Phi^{(2)}_{i}.$$

- **Case C:** $SU(N_A) \times SU(N_B) \times SU(N_C)$ **with** $(N_A, N_B, 1)$ **and** $(N_A, 1, N_C)$

$$V_4 = \lambda_{d1} \Phi^{(1)*}_{ik} \Phi^{(1)}_{ik} \Phi^{(1)*}_{jl} \Phi^{(1)}_{jl} + \lambda_{s1} \Phi^{(1)*}_{ik} \Phi^{(1)}_{il} \Phi^{(1)*}_{jl} \Phi^{(1)}_{jk} + \lambda_{d2} \Phi^{(2)*}_{ia} \Phi^{(2)}_{ia} \Phi^{(2)*}_{jb} \Phi^{(2)}_{jb} + \lambda_{s2} \Phi^{(2)*}_{ia} \Phi^{(2)}_{ib} \Phi^{(2)*}_{jb} \Phi^{(2)}_{ja}$$
$$+ 2\lambda_{d12} \Phi^{(1)*}_{ik} \Phi^{(1)}_{ik} \Phi^{(2)*}_{ja} \Phi^{(2)}_{ja} + 2\lambda_{s12} \Phi^{(1)*}_{ik} \Phi^{(1)}_{jk} \Phi^{(2)*}_{ja} \Phi^{(2)}_{ia},$$

- **Case D:** $SU(N_A) \times SU(N_B) \times SU(N_C)$ **with** (N_A, N_B, N_C)

$$V_4 = \lambda_d \Phi^*_{ika} \Phi_{ika} \Phi^*_{jlb} \Phi_{jlb} + \lambda_{s1} \Phi^*_{ika} \Phi_{jka} \Phi^*_{jlb} \Phi_{ilb}$$
$$+ \lambda_{s2} \Phi^*_{ika} \Phi_{ila} \Phi^*_{jlb} \Phi_{jkb} + \lambda_{s3} \Phi^*_{ika} \Phi_{ikb} \Phi^*_{jlb} \Phi_{jla}.$$

SAFEs Candidates (upper bound on $r_i = b_i / b_{i,M}$)

(a) Case A

N	2	3	4	5	6	7	8
2	0	0	0.03	0.08	0.11	0.14	0.15
3	0	0	0	0.04	0.08	0.10	0.13
4	0.03	0	0	0.02 0.06	0.05	0.08	0.10
5	0.08	0.04	0.06 0.02	0.03 0.03	0.04 0.09	0.06	0.08
6	0.11	0.08	0.05	0.09 0.04	0.06 0.06	0.06 0.12	0.07
7	0.14	0.10	0.08	0.06	0.12 0.06	0.08 0.08	0.07 0.13
8	0.15	0.13	0.10	0.08	0.07	0.13 0.07	0.09 0.09

Pati-Salam with (4,2,1)

(b) Case B

N	2	3	4	5	6	7	8
2	0	0	0	0	0	0	0
3	0	0	0	0	0*	0*	0*
4	0	0	0	0	0.01 0.08	0.01 0.08	0.01 0.08
5	0.02	0	0	0	0.01 0.06	0.02 0.13	0.02 0.13
6	0.07	0.03	0.03 0.01	0.01 0.01	0.02 0.03	0.03 0.09	0.03 0.16
7	0.10	0.06	0.04	0.07 0.03	0.04 0.03	0.03 0.05	0.04 0.10
8	0.12	0.09	0.06	0.05	0.08 0.04	0.05 0.04	0.05 0.07

(c) Case C1

N	2	3	4	5	6	7	8
2	0	0	0.03	0.08	0.11	0.13	0.14
3	0	0	0	0.04	0.07	0.10	0.12
4	0	0	0	0	0.04	0.07	0.09
5	0	0	0	0	0	0.04	0.06
6	0.03	0	0	0	0	0	0.04
7	0.06	0	0	0	0	0	0
8	0.09	0.03	0	0	0	0	0

(d) Case D

N	(2,2)	(3,2)	(i,j)
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0.03	0	0
7	0.06	0	0
8	0.08	0.02	0