Signatures Of Composite Quarks And Leptons In Flavour Physics

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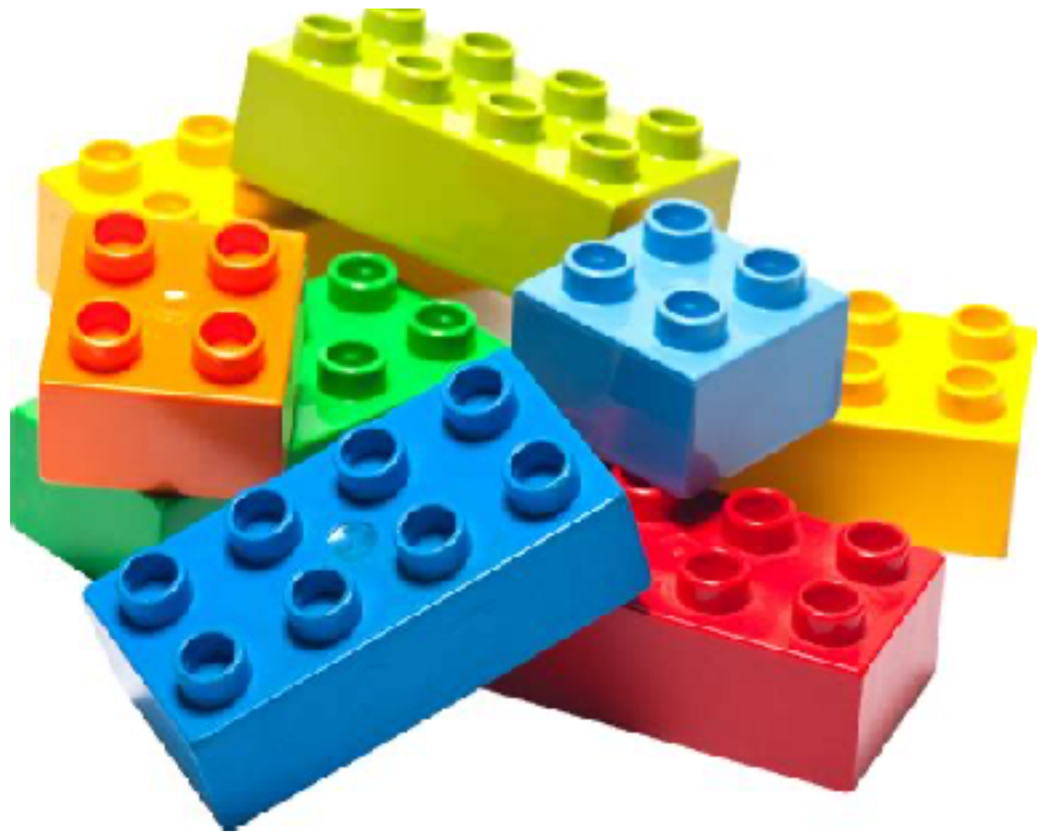
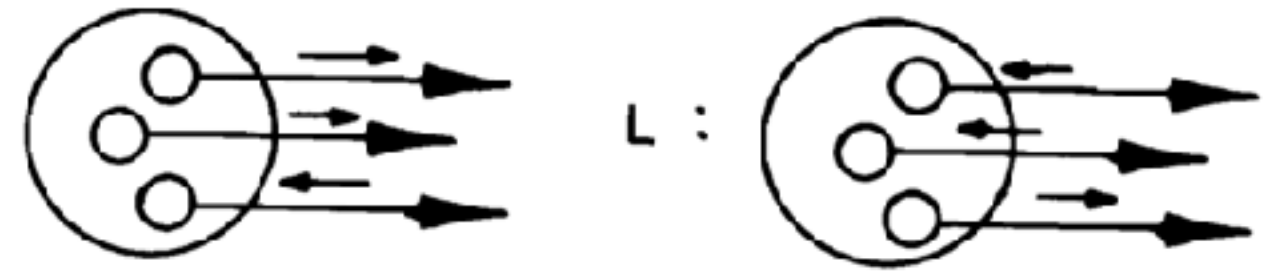
MORIOND ELECTROWEAK | LA THUILE, IT | MARCH 2026

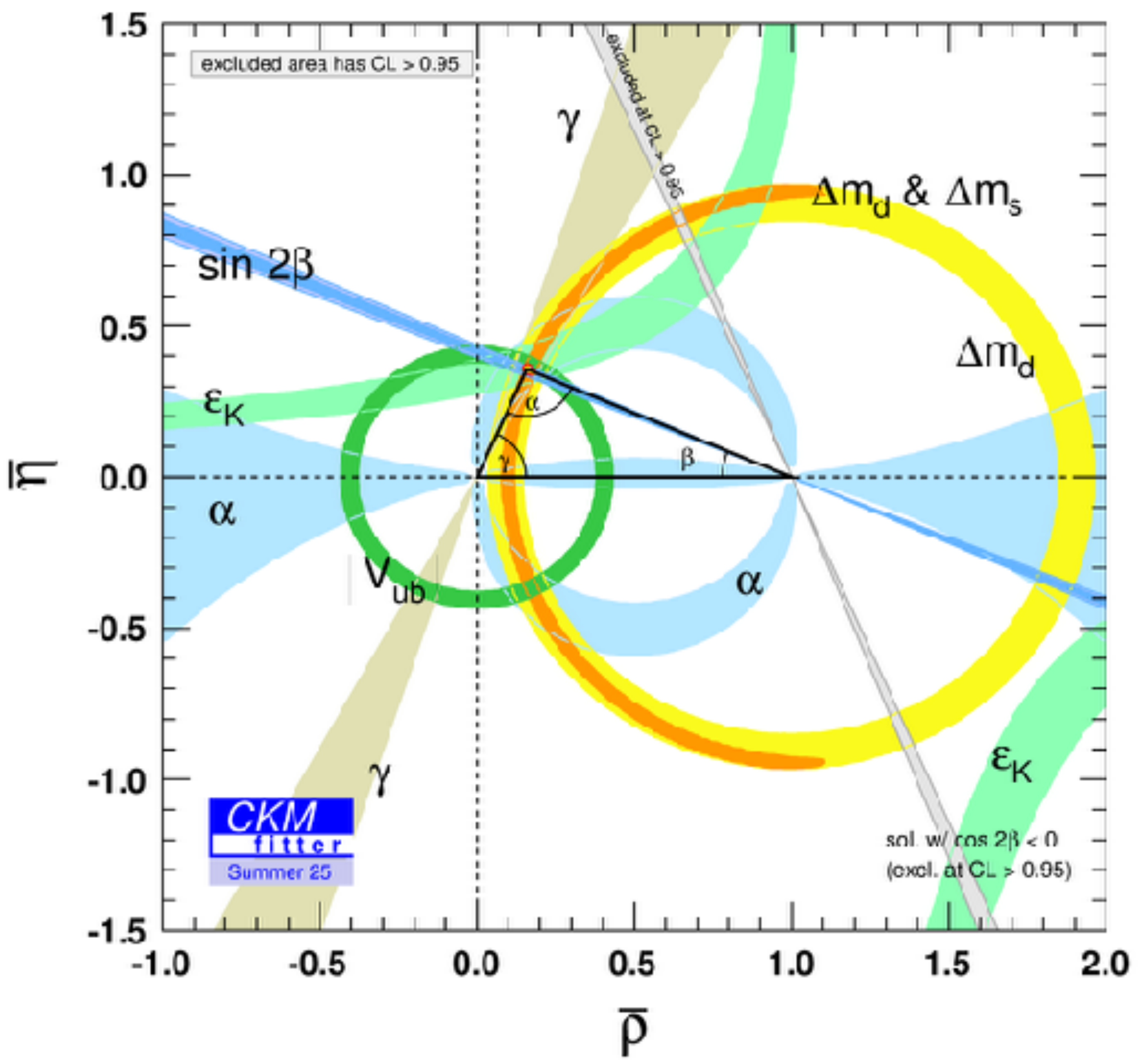
Outline Of Talk

COMPOSITE
QUARKS AND LEPTONS

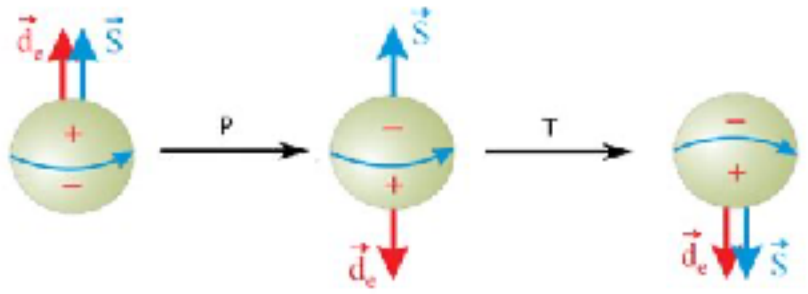


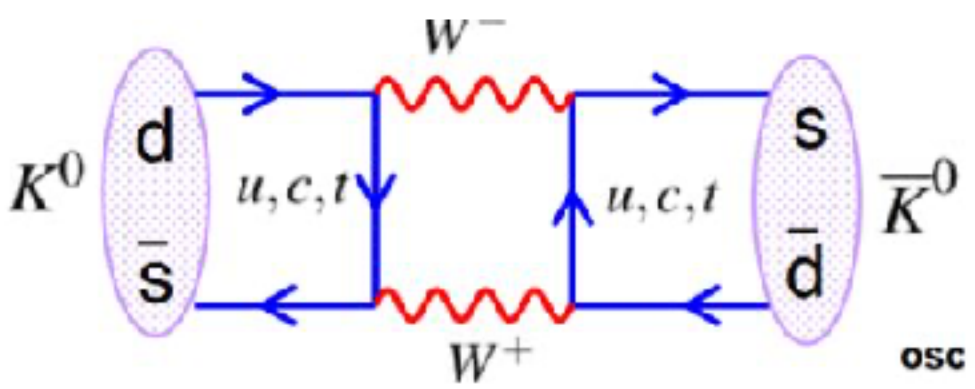


YUKAWAS



FLAVOUR PROBES





Mu2e

Basic Goals

1. Sensible theory of composite quarks/leptons at high scales.
2. Connection between composite dynamics and flavour.
3. Flavour physics is competitive with other probes (e.g. proton decay).

COMPOSITE DYNAMICS

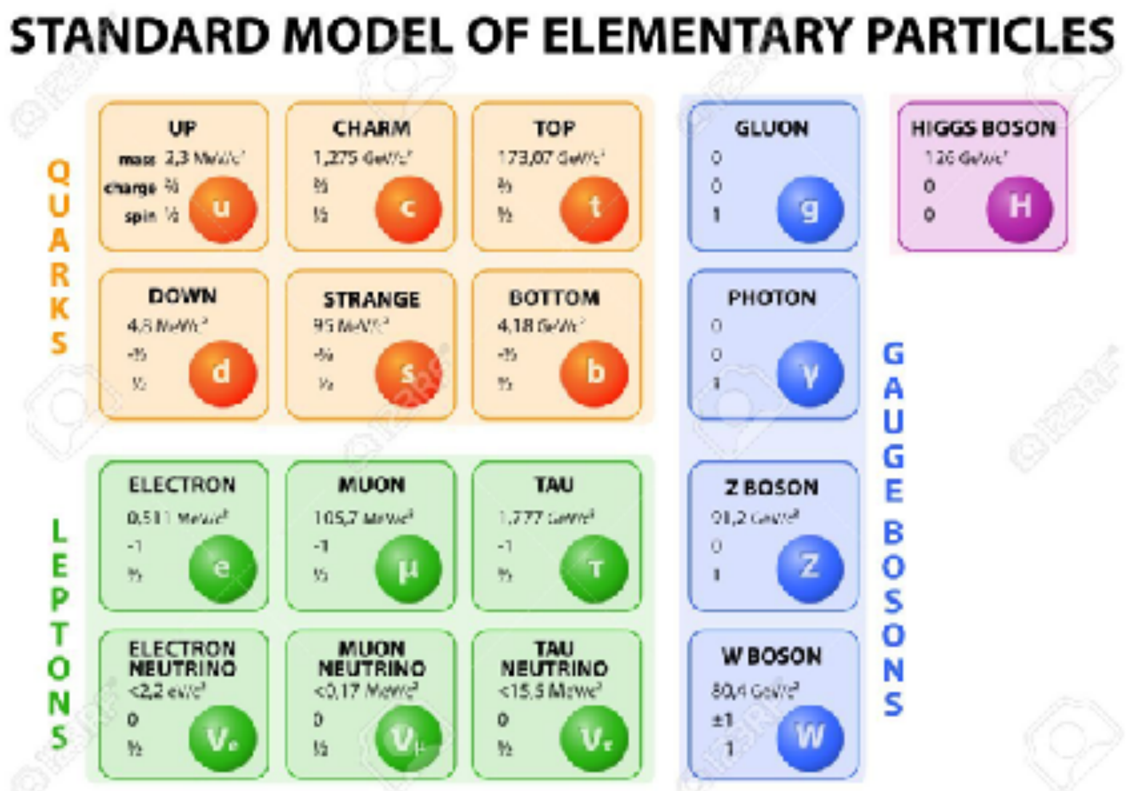
WHATS A PREON?

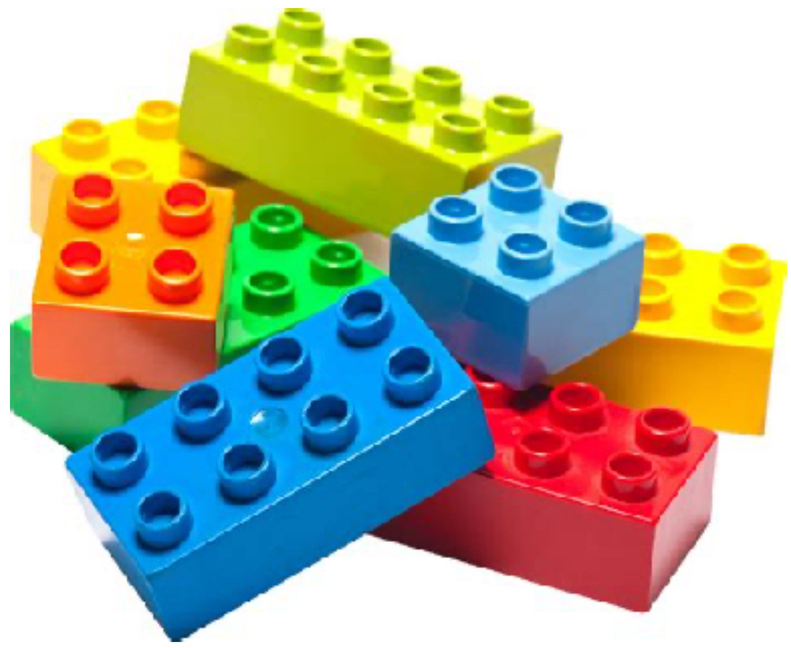
YUKAWA STRUCTURE

FITTING THE DATA

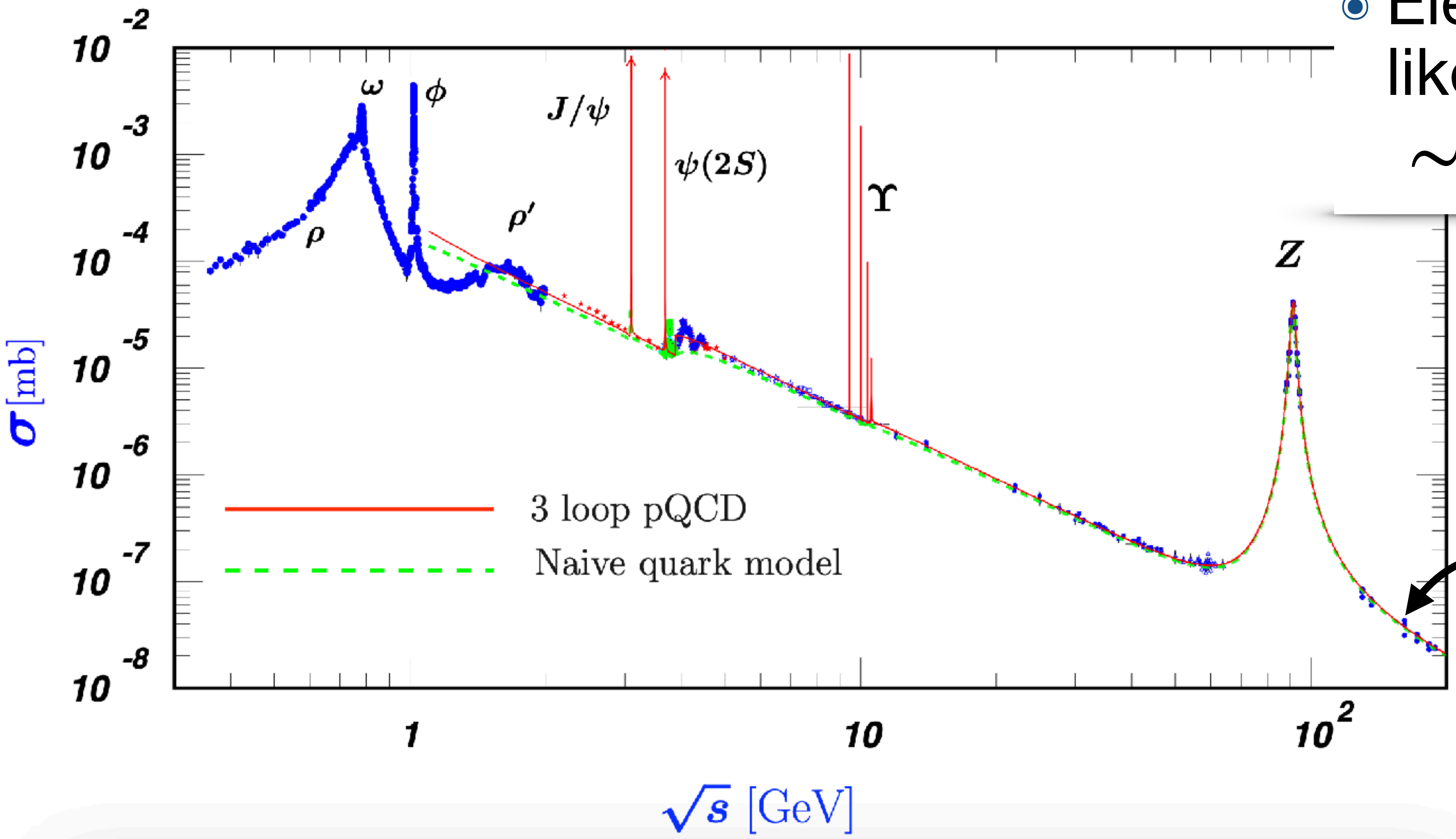
FLAVOUR PHYSICS

PROBING COMPOSITE SCALES





Are Leptons Composite?



- Electrons point-like up to at least ~ 100 GeV.

LEP-data

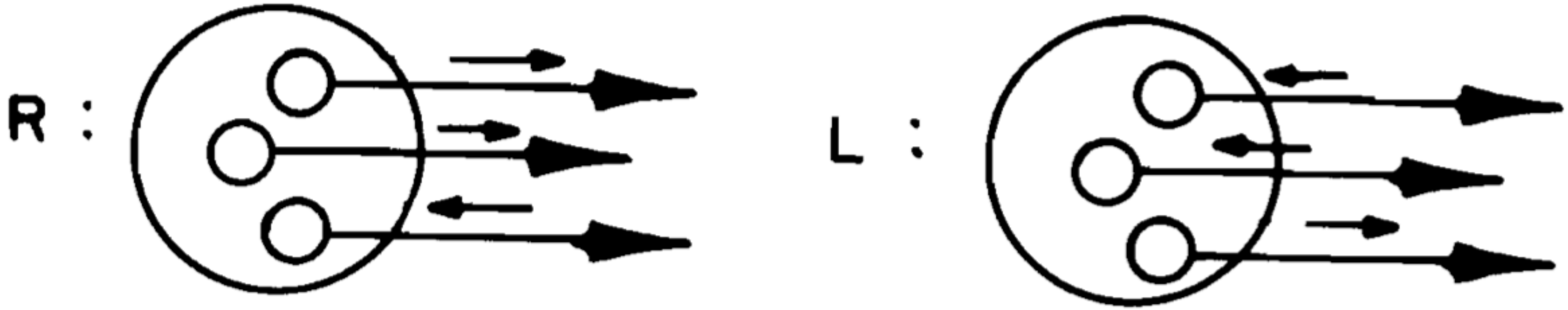
Are Leptons Composite?

Particle	Mass	Inverse Radius
Atom	~10 GeV	~keV
Nucleus	~10 GeV	~100 MeV
Nucleons	~ 1 GeV	~ 1 GeV
Pions	~ 100 MeV	~300 MeV
Electron ?	~ 1 MeV	***> 1 TeV***

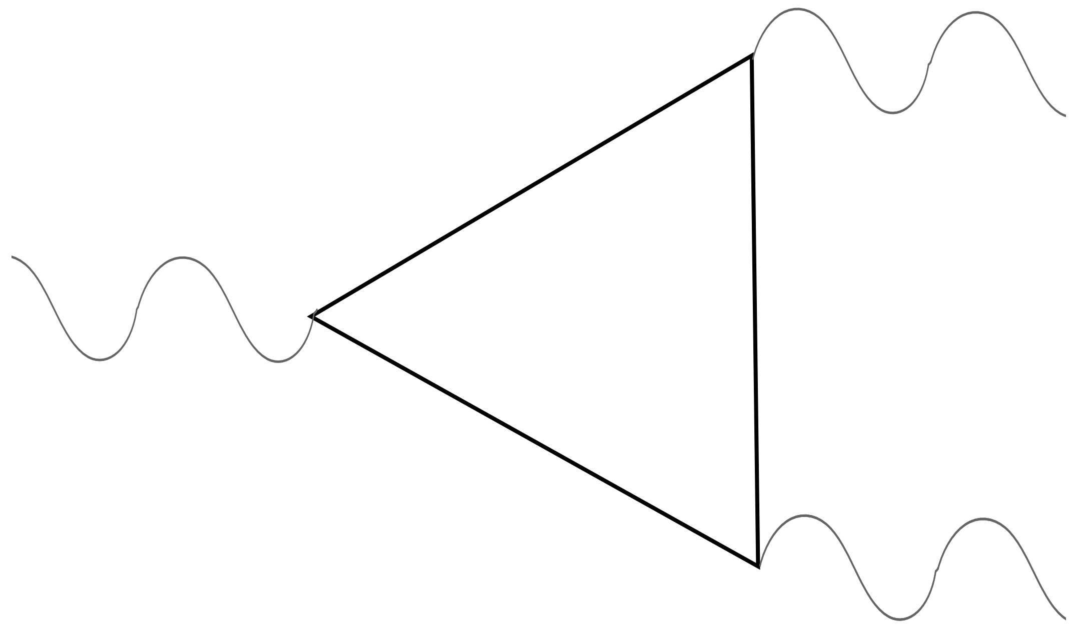
- Challenge.
- Find models with $R^{-1} \gg m$.

Massless Composite Fermions

- Solution was found in 1980 (Dimopolous, Susskind, Raby).
- Relies on confining ***chiral gauge theories***.
- Main tools: large-N & 't Hooft anomaly matching.



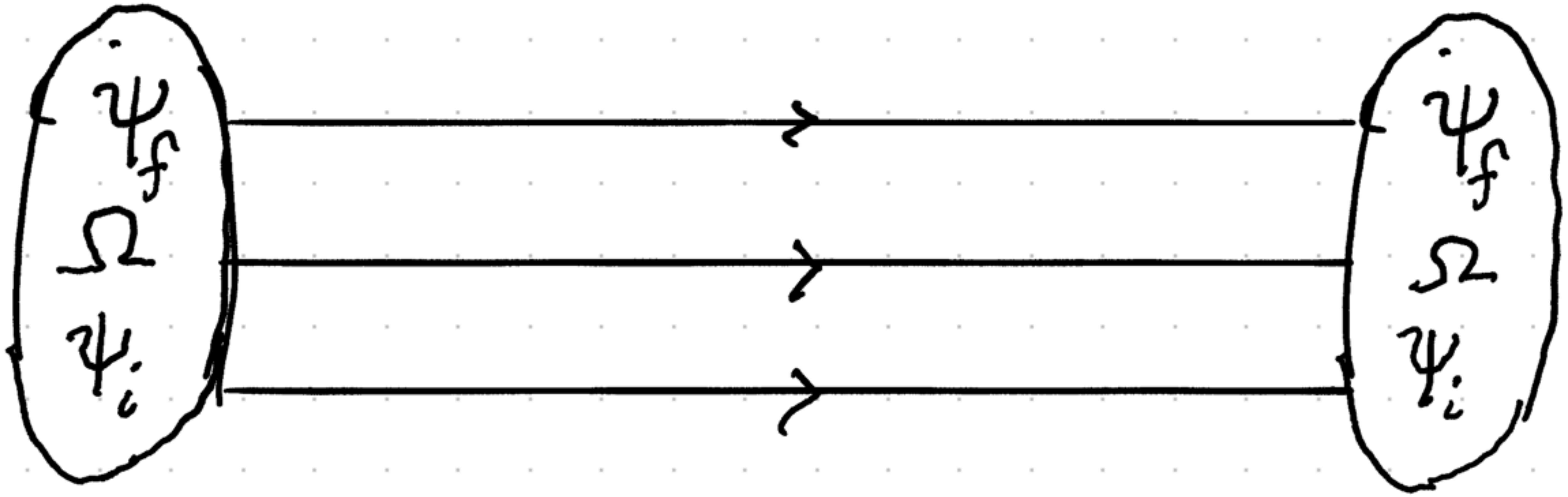
A Specific Class Of $SU(N)$



$N + 4$ fundamentals

1 conjugate symmetric

HEALTHY THEORY



- Anomaly free. ✓
- 't Hooft matching?
- Large-N ✓

SU(15) Proposal

PHYSICAL REVIEW LETTERS **128**, 241804 (2022)

Quark and Lepton Compositeness: A Renormalizable Model

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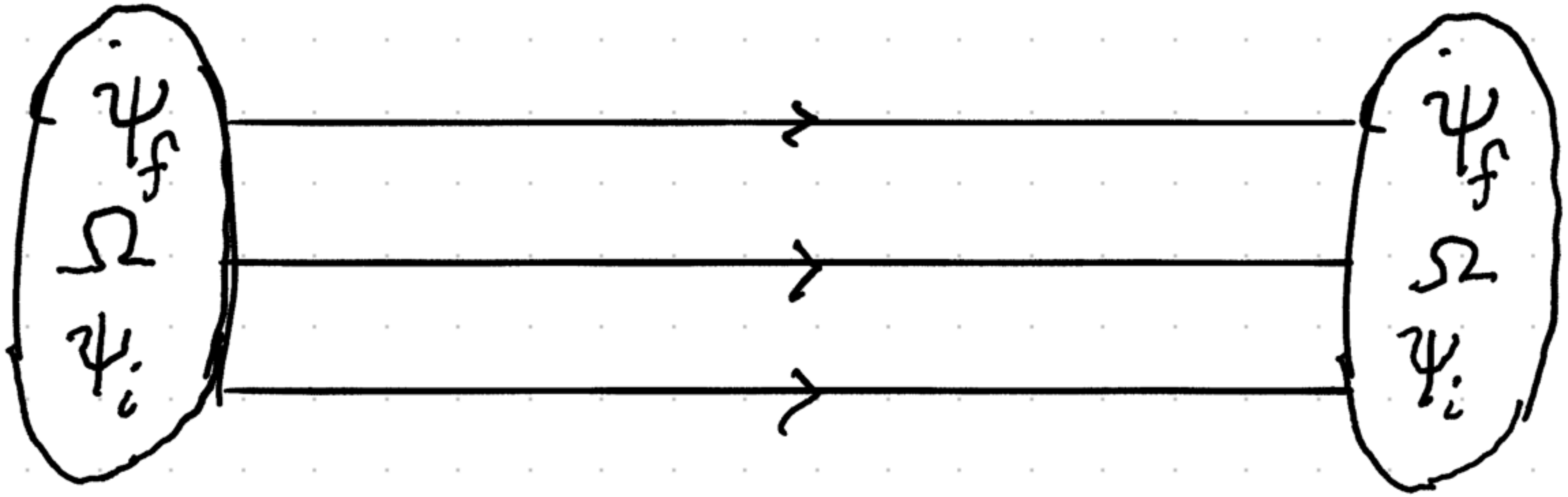
(Received 30 December 2021; accepted 13 May 2022; published 15 June 2022)

HEALTHY

PLAUSIBLE PATH TO SM



- Anomaly free. ✓
- 't Hooft matching? ✓
- Large-N ✓

Fermions As Pre-Baryons

$$Q_i \sim (\psi_Q \Omega \psi_i)$$

GAUGE COUPLINGS

FLAVOUR

$$e_i^c \sim (\psi_E \Omega \psi_i)$$

STANDARD MODEL FERMIONS ARE "PRE-BARYON" BOUND STATES

SM-CHARGES

Field	Spin	$SU(15)_p$	$SU(3)_c \times SU(2)_W \times U(1)_Y$
ψ_Q	$1/2$	$\square$	$(3, 2, +1/6)$
ψ_U	$1/2$	$\square$	$(\bar{3}, 1, -2/3)$
ψ_D	$1/2$	$\square$	$(\bar{3}, 1, +1/3)$
ψ_L	$1/2$	$\square$	$(1, 2, -1/2)$
ψ_E	$1/2$	$\square$	$(1, 1, +1)$
$\psi_1, \psi_2, \psi_3, \psi_4$	$1/2$	$\square$	$(1, 1, 0)$
Ω	$1/2$	$\overline{\square\square}$	$(1, 1, 0)$

SM-SINGLETS

Connection To Flavour

Field	Spin	$SU(15)_{\rm p}$	$SU(3)_c \times SU(2)_W \times$
ψ_Q	$1/2$	$\Box$	$(3, 2, +1/6)$
ψ_U	$1/2$	$\Box$	$(\bar{3}, 1, -2/3)$
ψ_D	$1/2$	$\Box$	$(\bar{3}, 1, +1/3)$
ψ_L	$1/2$	$\Box$	$(1, 2, -1/2)$
ψ_E	$1/2$	$\Box$	$(1, 1, +1)$
$\psi_1, \psi_2, \psi_3, \psi_4$	$1/2$	$\Box$	$(1, 1, 0)$
Ω	$1/2$	$\overline{\Box\Box}$	$(1, 1, 0)$

$SU(4)_F$

REQUIRED BY ANOMALY CANCELLATION

- Spontaneous breaking.

$$SU(4)_F \to SU(3)_F$$

The Fourth Generation

- Vevs will break $SU(4)_F \to SU(3)$.
- There is ***only one*** $SU(3)$ (as opposed to the SM's 5).

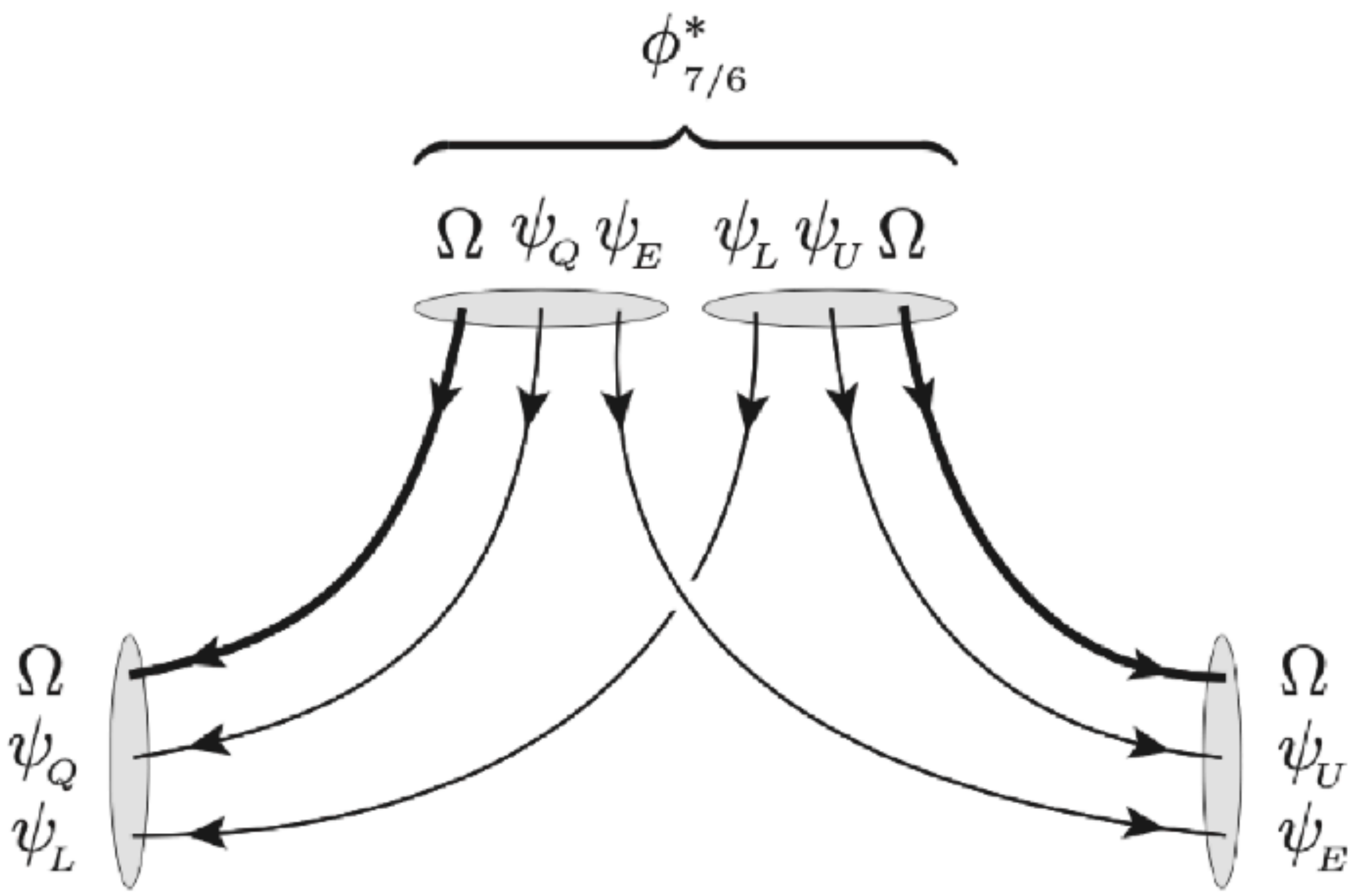
$$\phi_{1/6}^{(i)} \sim ([Q\Omega\psi_i]\ [\psi_D\Omega\psi_L])$$

$$\langle\phi_{1/6}^{(i)}\rangle \equiv \varphi_{1/6}\delta^{i4}$$

THIS ***DEFINES*** THE 3-GENERATIONS OF THE SM

Flavour Breaking VeVs

- Model has ***too many*** light fermions.
- Need SSB to generate Dirac mass terms.
- Very heavy (above the TeV scale).



- Creates heavy vector-likes.
- Potential collider signatures.
- Leaves ***just*** the 3-SM generations as light.

Flavour Breaking Spurions

- Model must contain explicit $SU(4)_F$ breaking.
- Vev is naturally correlated with direction of explicit breaking.

$$\mathscr{L} \sim \lambda^{ij} A \psi_i \psi_j + \tilde{\lambda}^{ij} \tilde{A} \psi_i \psi_j$$

- ***Minimum of two*** independent spurions for ***misaligned*** CKM.

The Higgs Sector

- Light Higgs will require ***fine-tuning*** (we will live with it).
- Attractive binding can produce vevs.
- Constituents with QCD + large Yukawa couplings.

$$H_{u,d}^{(34)} \sim \left([Q\Omega\psi_3]\ [\psi_{U,D}\Omega\psi_4] \right)$$

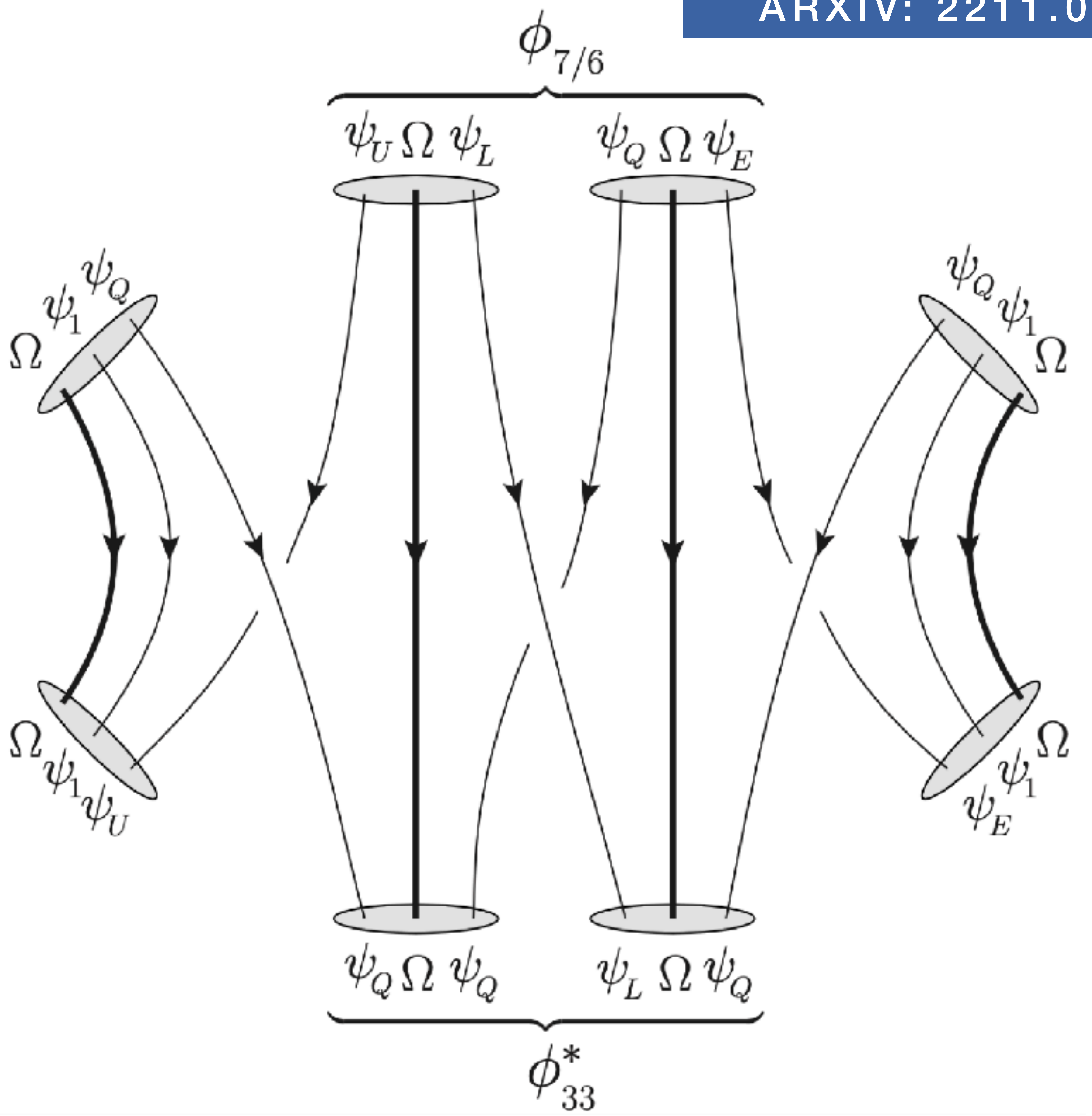
- We follow the original paper and assume a 3-4 (top+vector-like) composite Higgs sector (type-II 2HDM).

Proton Decay

ASSI, DOBRESCU (2022)
ARXIV: 2211.02211

$$\frac{\Lambda_{\text{pre}}}{|C_8|^{1/4}} > 1.0 \times 10^4 \text{ TeV} \left(\frac{m_{7/6} m_{33}}{1 \text{ TeV}^2}\right)$$

- Baryon violation first appears at dimension-8.
- Controlled by vevs in the theory.
- 10^4 TeV $\rightarrow$ Flavour!



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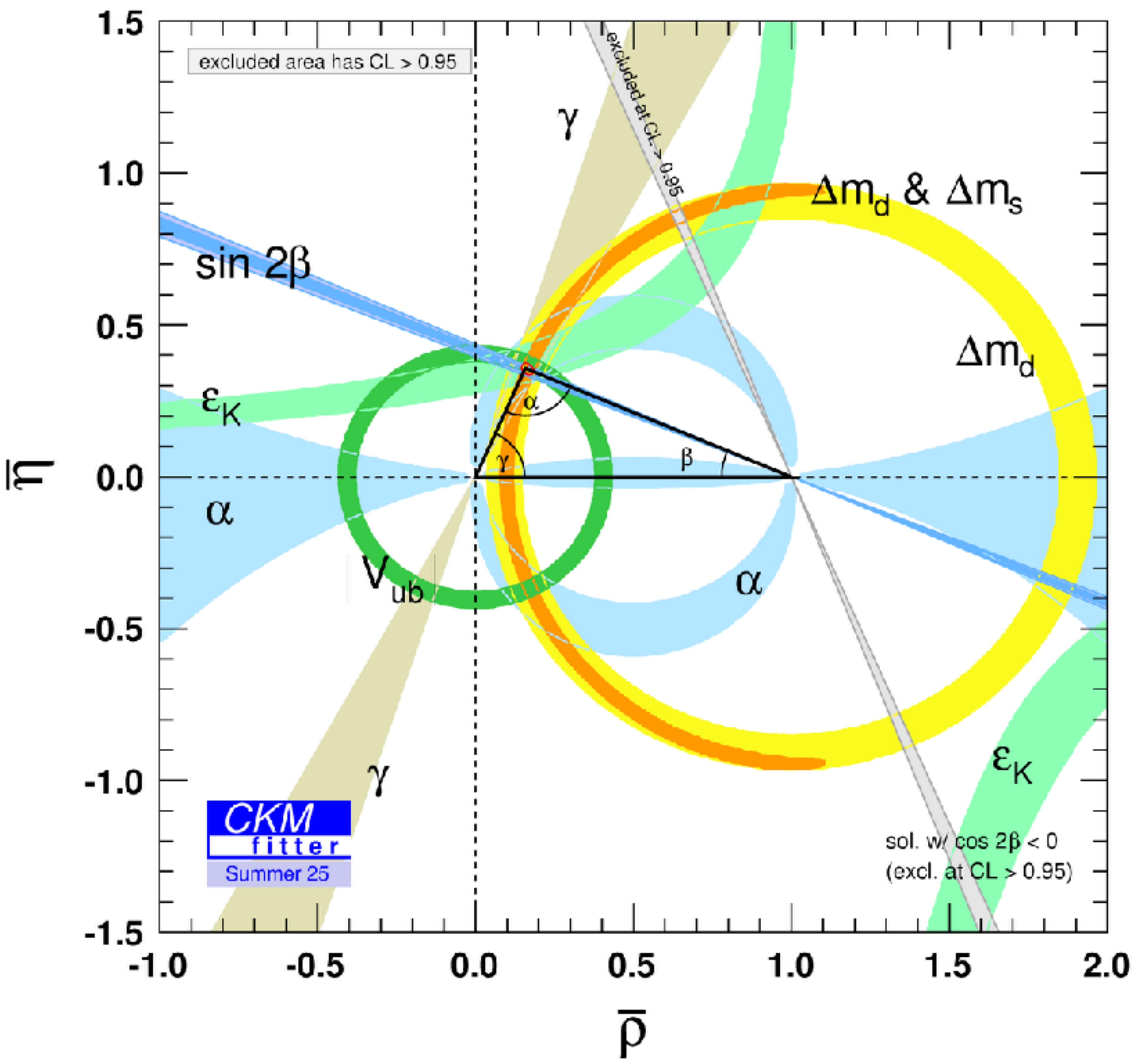


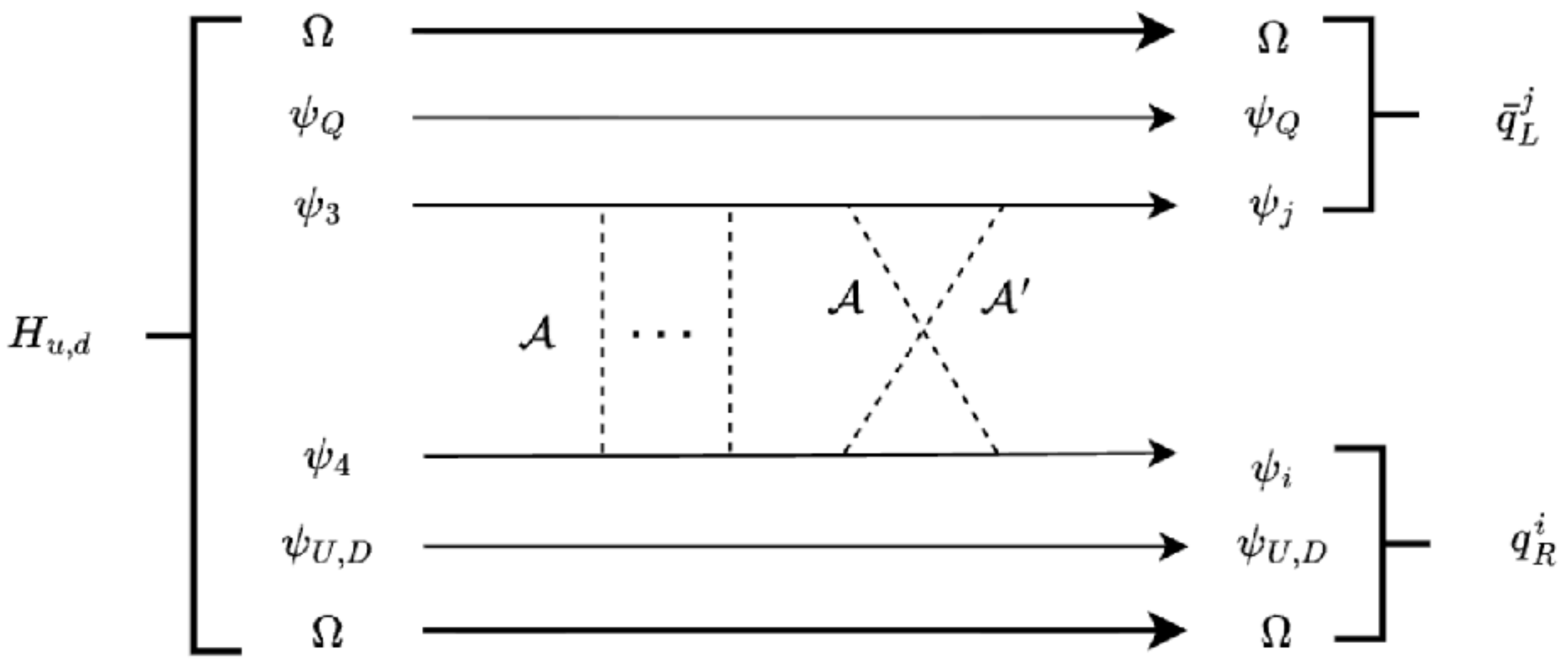
Radiative Misalignment

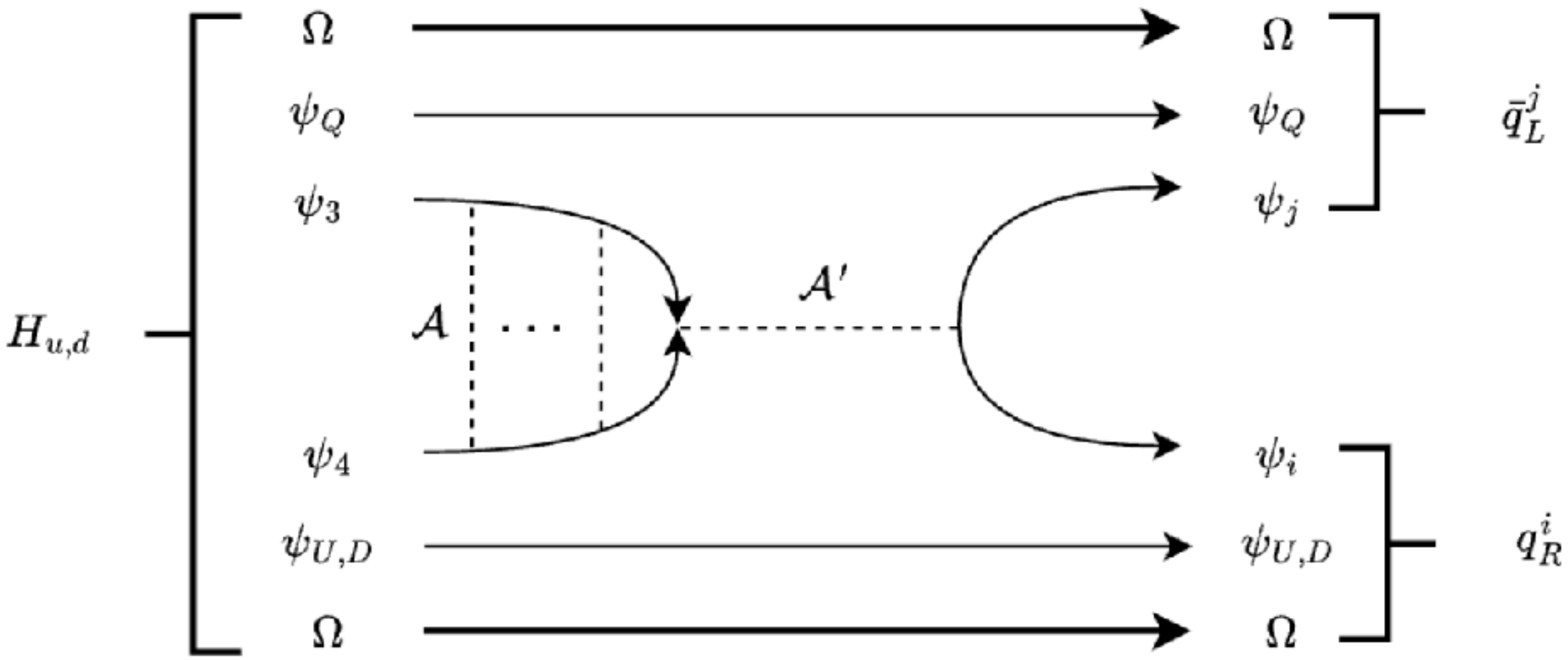
- Isospin-like symmetry under $\psi_U \leftrightarrow \psi_D$ for $\alpha_Y \to 0$.
- CKM-mixing angles generated at $O(\alpha_Y)$.

$$H_u \leftrightarrow H_d$$

- Requires λ_{44} to be very large (multiple spurions).
- We assume $\lambda_{44} \gtrsim \lambda_{33} \gg 1$.

Quark Yukawas





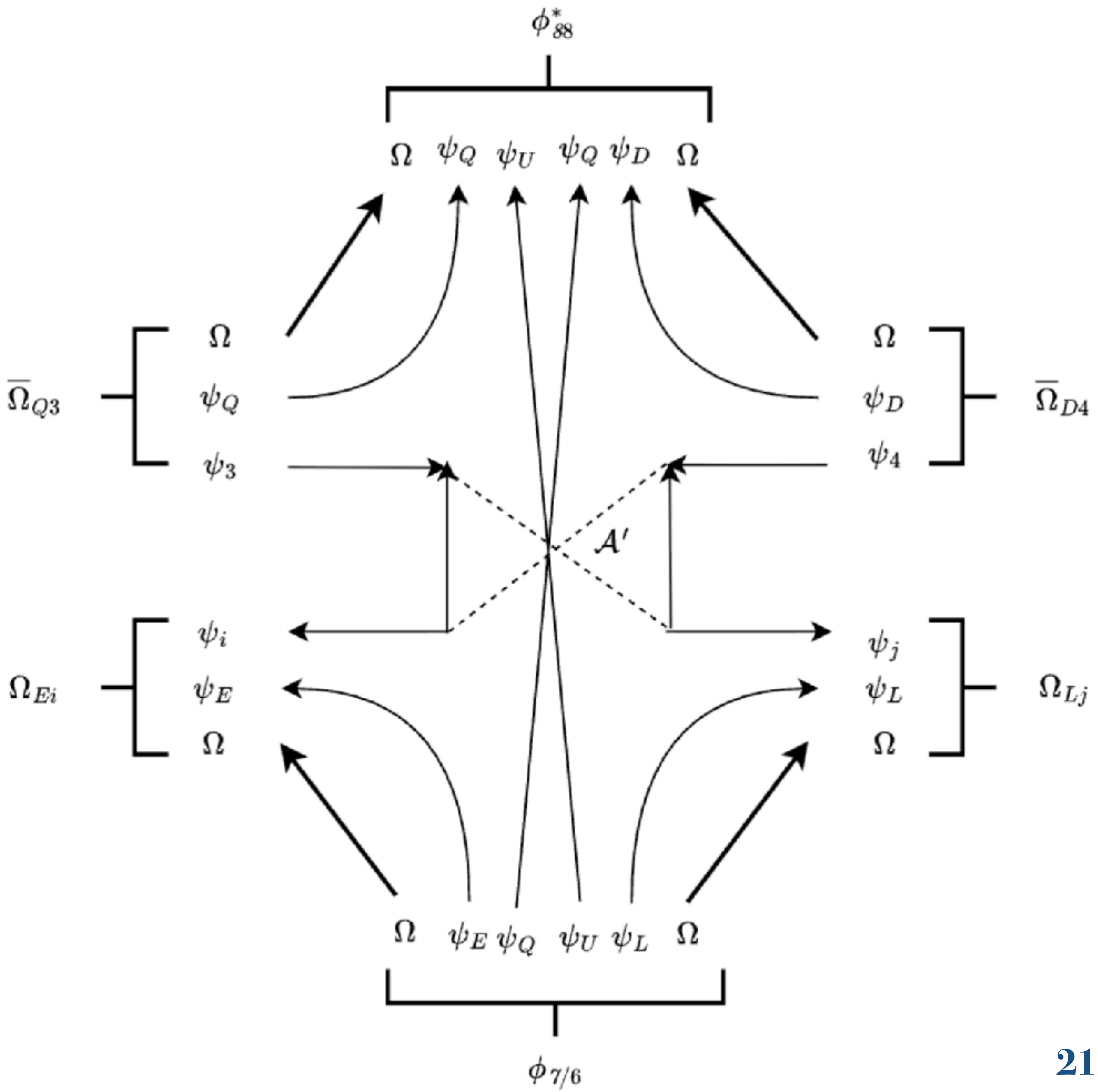
Quark Yukawas

$$Y_{ij}^{(u,d)} = J^{u,d}\begin{pmatrix} \tilde\lambda_{43}\tilde\lambda_{11}^* & \tilde\lambda_{43}\tilde\lambda_{12}^* & \tilde\lambda_{43}\tilde\lambda_{13}^* \\ \tilde\lambda_{43}\tilde\lambda_{21}^* & \tilde\lambda_{43}\tilde\lambda_{22}^* & \tilde\lambda_{43}\tilde\lambda_{23}^* \\ \tilde\lambda_{43}\tilde\lambda_{31}^* & \tilde\lambda_{43}\tilde\lambda_{32}^* & \tilde\lambda_{43}\tilde\lambda_{33}^* \end{pmatrix} + \begin{pmatrix} 0 & 0 & G^{u,d}\tilde\lambda_{31}^*\tilde\lambda_{43} \\ 0 & 0 & G^{u,d}\tilde\lambda_{32}^*\tilde\lambda_{43} \\ I^{u,d}\tilde\lambda_{33}\tilde\lambda_{41}^* & I^{u,d}\tilde\lambda_{33}\tilde\lambda_{42}^* & F_1^{u,d}\tilde\lambda_{33}\tilde\lambda_{43}^* + F_2^{u,d}\tilde\lambda_{33}^*\tilde\lambda_{43} \end{pmatrix},$$

- Differences between up/down $\sim O(\alpha_Y/\pi)$.
- Sufficient to generate necessary CKM misalignment.

Lepton Yukawas

- Harder to couple leptons to (composite) Higgs.
- Need vevs to "eat" preons.
- Suppressed by $1/N$.



Lepton Yukawas

- Same structure as quarks.
- Different "pre-hadronic" matrix elements.

$$(Y_\ell)_{ij} = \frac{1}{N} J^\ell \tilde{\lambda}_{43} \tilde{\lambda}^*_{ij} + \frac{1}{N} \begin{pmatrix} 0 & 0 & G^\ell \tilde{\lambda}^*_{31} \tilde{\lambda}_{43} \\ 0 & 0 & G^\ell \tilde{\lambda}^*_{32} \tilde{\lambda}_{43} \\ I^\ell \tilde{\lambda}_{33} \tilde{\lambda}^*_{41} & I^\ell \tilde{\lambda}_{33} \tilde{\lambda}^*_{42} & F^\ell_1 \tilde{\lambda}_{33} \tilde{\lambda}^*_{43} + F^\ell_2 \tilde{\lambda}^*_{33} \tilde{\lambda}_{43} \end{pmatrix}$$

Finding Benchmarks

- Demand $X^{u,d} \sim X(1 + Q_{u,d}\delta_X)$.
- Float non-perturbative matrix elements $|X| \sim (0.3,3)$.
- Radiative misalignment by NDA $|\delta_X| \sim \alpha_Y/\pi \sim 0.006$.
- Numerical search minimizing loss function.

$$\text{Yukawas} \;\rightarrow\; \lambda_{ij}\,,\,\tilde{\lambda}_{ij} \;\rightarrow\; \text{Flavour Pheno}$$

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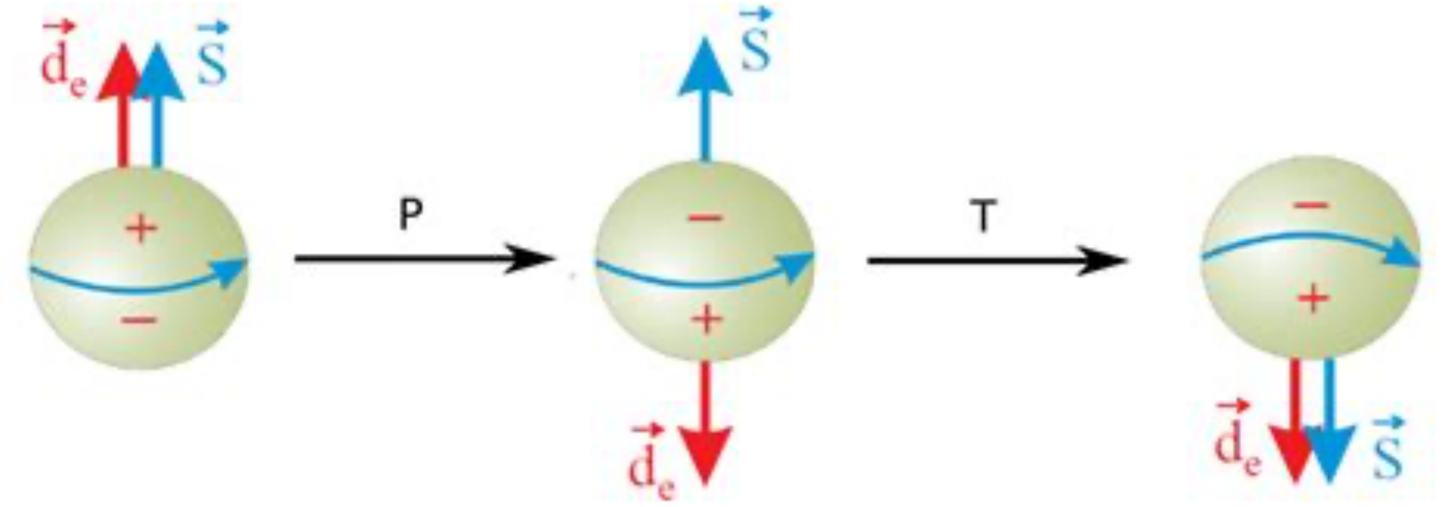
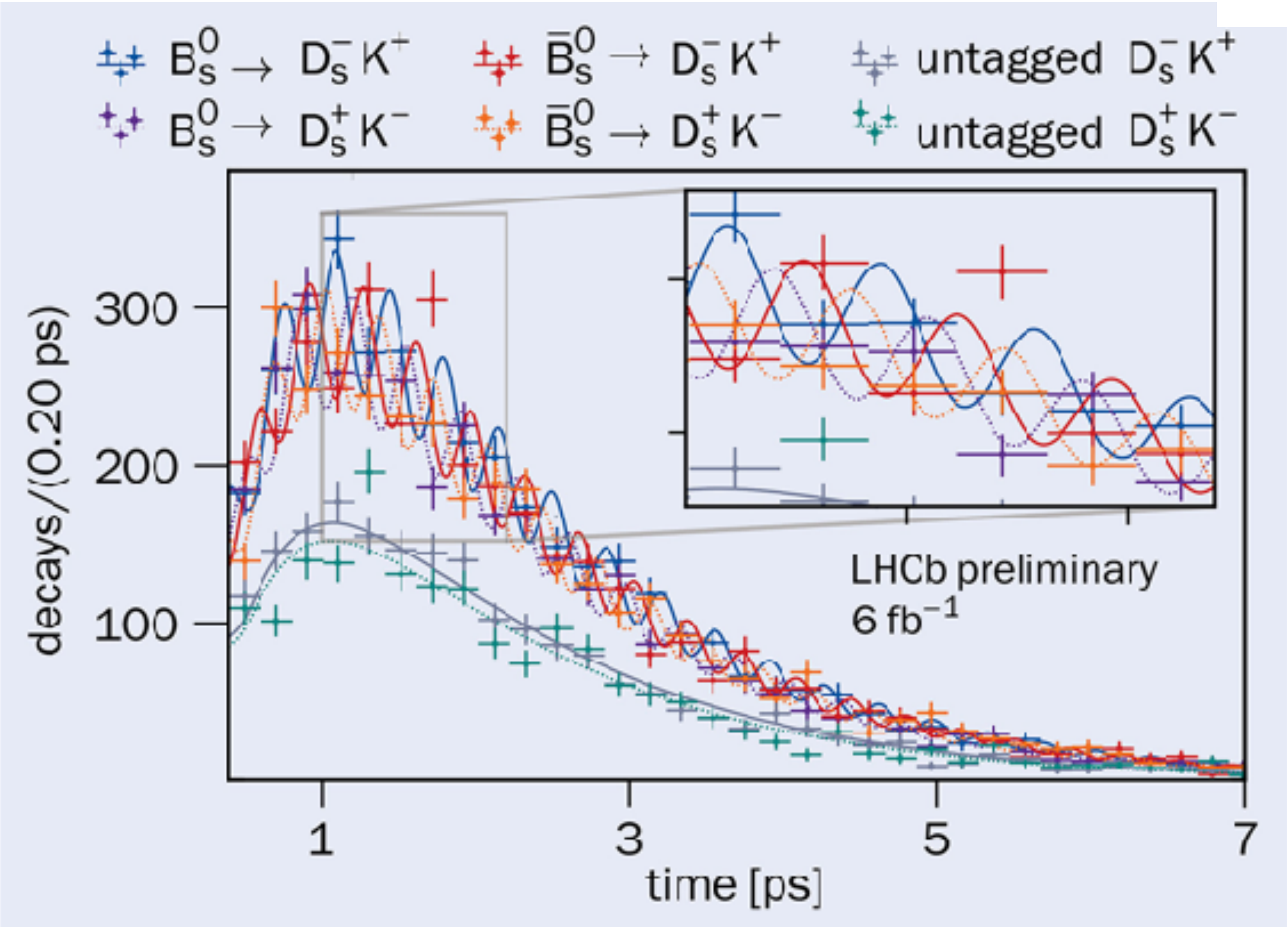
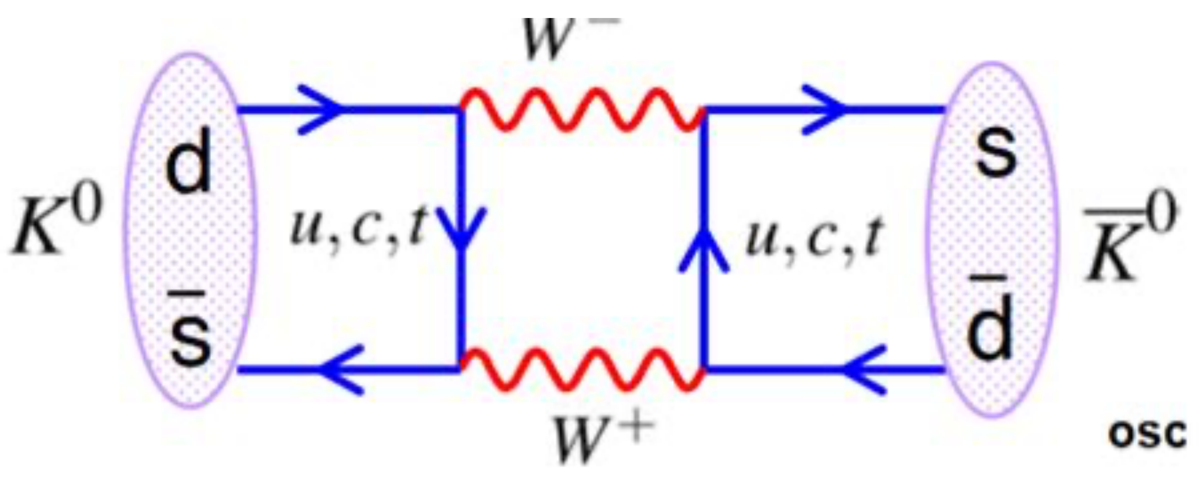
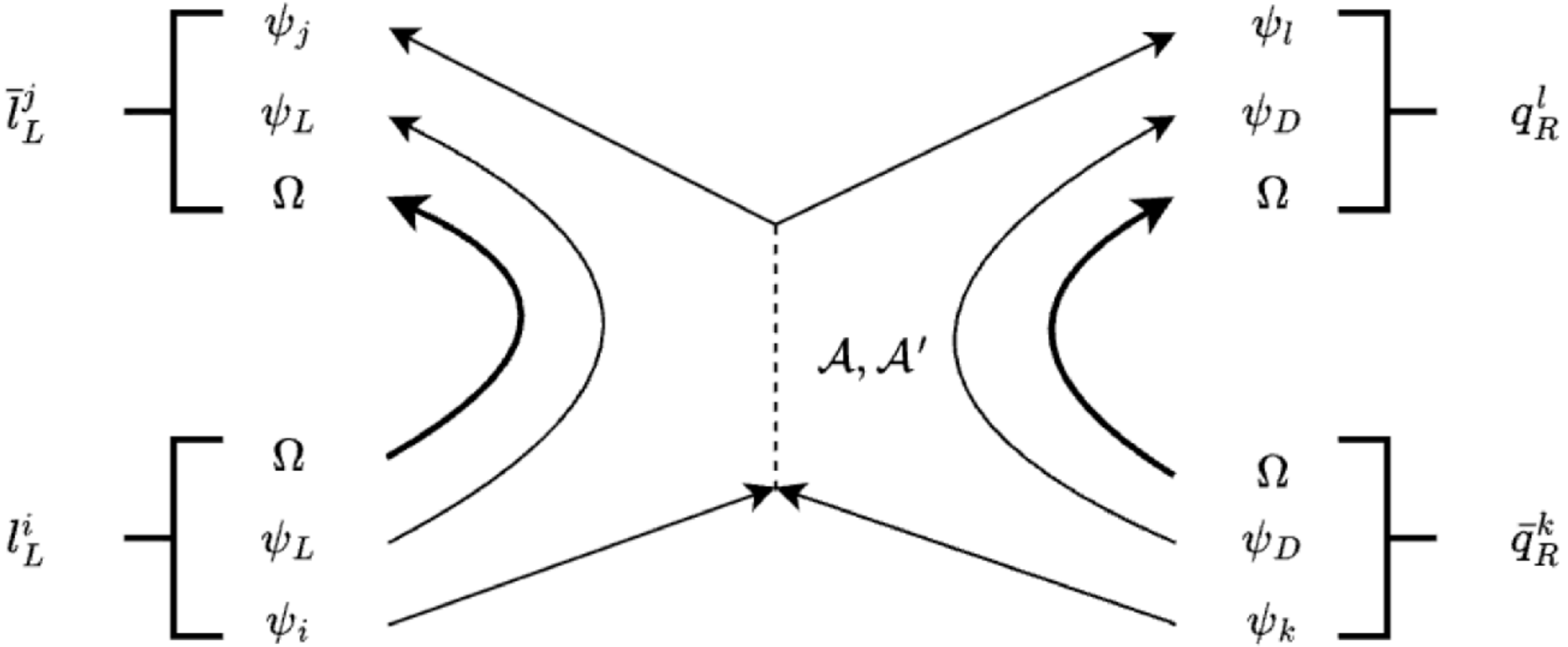




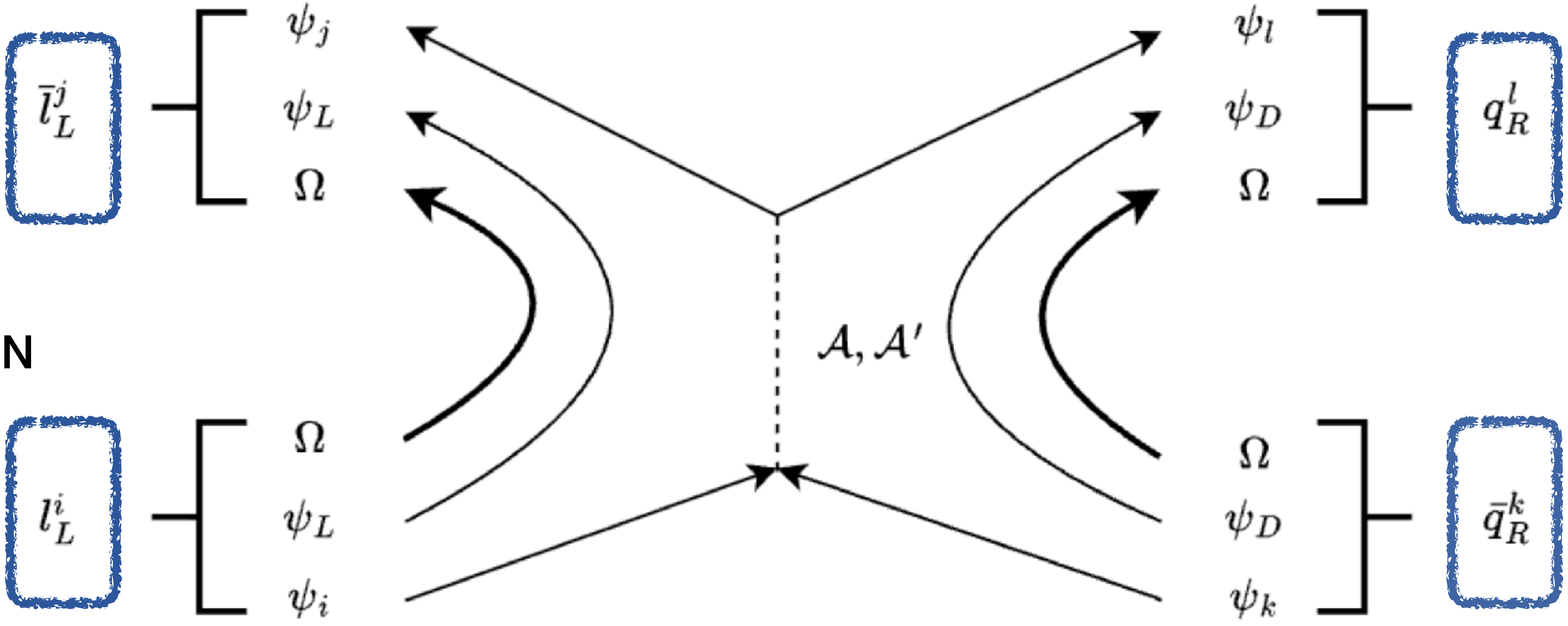


Correlated Flavour Pheno



$$-\left(\lambda_{jk}\lambda^*_{il} + \tilde{\lambda}_{jk}\tilde{\lambda}^*_{il}\right)(\bar{\ell}_i\gamma^\mu P_L \ell_j)(\bar{q}_k\gamma_\mu P_R q_l)$$

Correlated Flavour Pheno

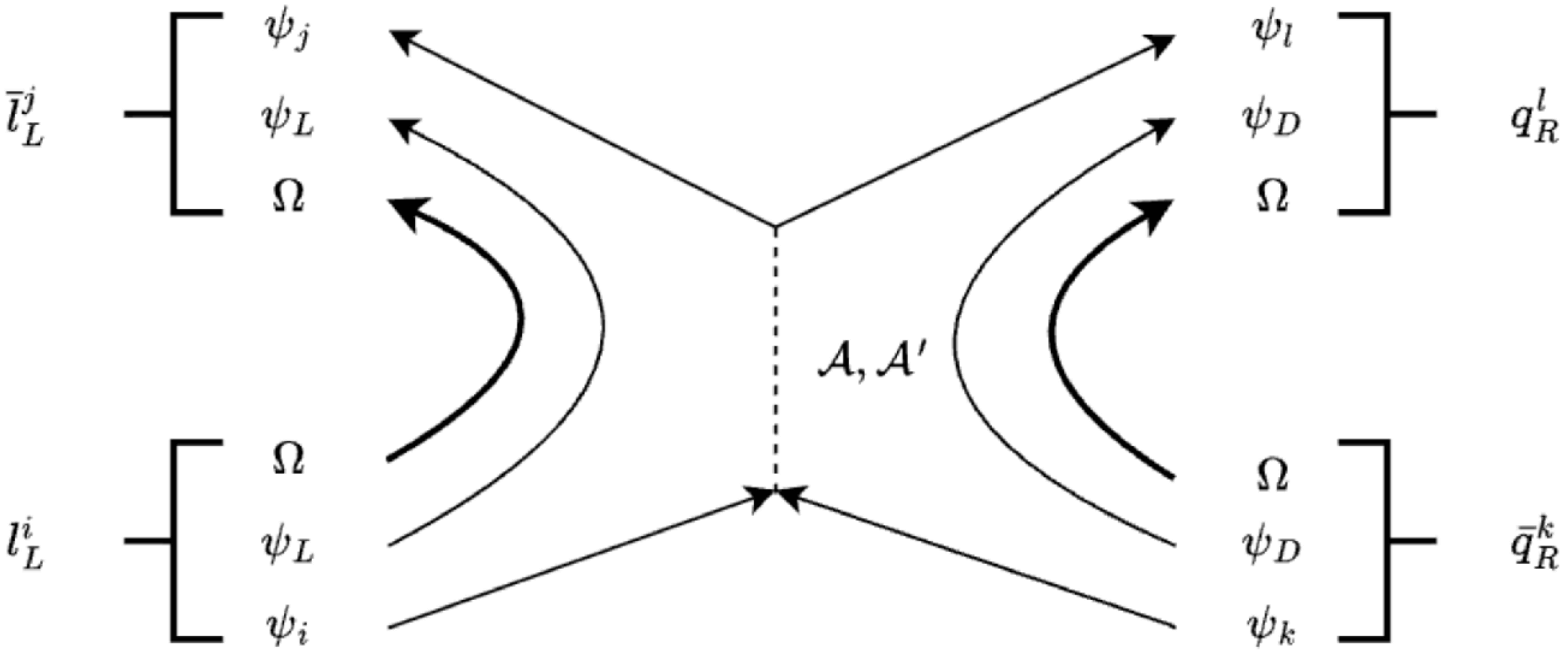


$$-\left(\lambda_{jk}\lambda_{il}^{*}+\tilde{\lambda}_{jk}\tilde{\lambda}_{il}^{*}\right)(\bar{\ell}_i\gamma^\mu P_L\ell_j)(\bar{q}_k\gamma_\mu P_R q_l)$$

Correlated Flavour Pheno

LH ROTATION

$(U_\ell)_{ej}$



RH ROTATION

$(V_q^\dagger)_{ku}$

$$-\left(\lambda_{jk}\lambda_{il}^{*} + \tilde{\lambda}_{jk}\tilde{\lambda}_{il}^{*}\right)(\bar{\ell}_i\gamma^\mu P_L \ell_j)(\bar{q}_k\gamma_\mu P_R q_l)$$

CONSTRAINED BY YUKAWAS

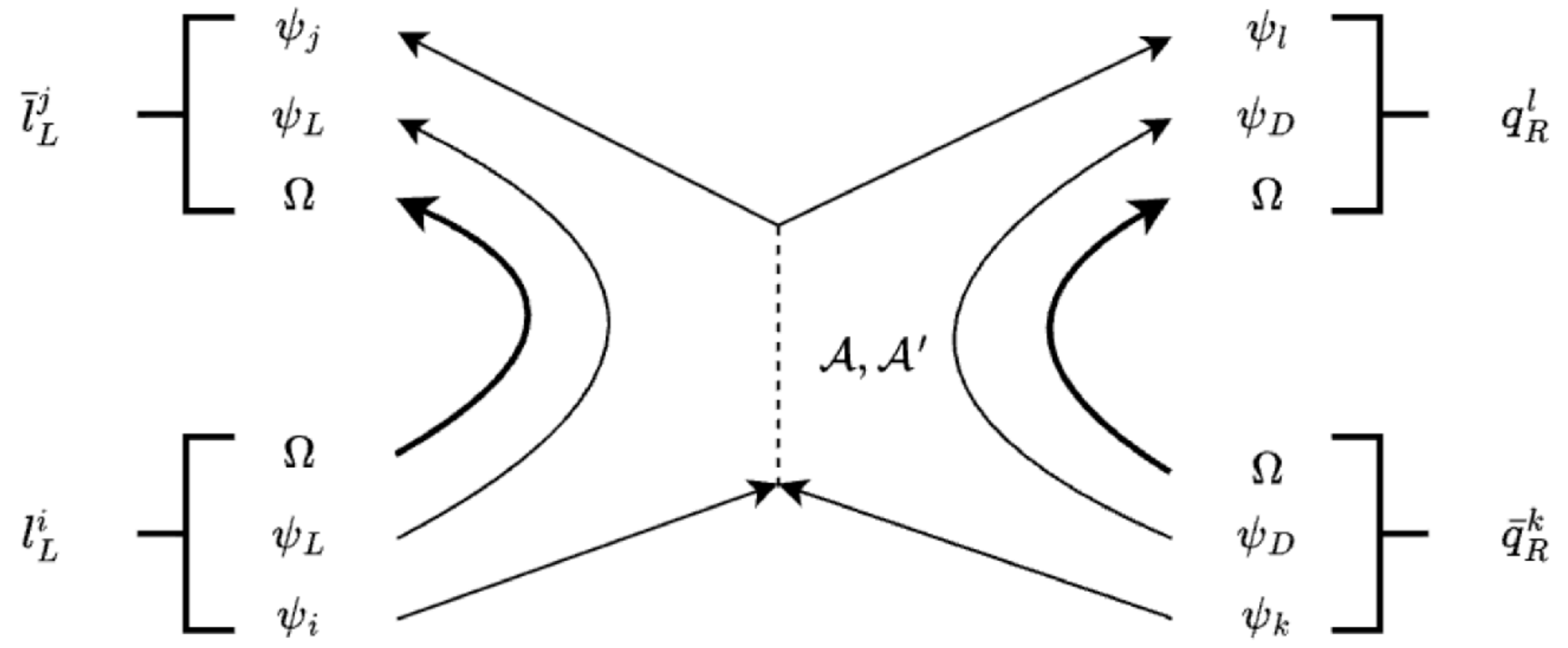
Example: $K \to \pi\nu\nu$

$$\mathcal{C}_{ii} = \Big[(U_d)_{2k}(\lambda^*_{ki}\lambda_{il} + \tilde{\lambda}^*_{ki}\tilde{\lambda}_{il})(U_d^\dagger)_{l1} - (V_d)_{2k}(\lambda_{ki}\lambda^*_{il} + \tilde{\lambda}_{ki}\tilde{\lambda}^*_{il})(V_d^\dagger)_{l1}\Big]$$

$$\mathcal{L}^{\Delta S=1}_{\rm eff} \sim \frac{1}{\Lambda^2_{\rm pre}}(\bar{s}\,\gamma^\mu d)\sum_i(\bar{\nu}_i\,\gamma_\mu P_L \nu_i)\mathcal{C}_{ii} \;+\; \text{h.c.}\,,$$

$$\Lambda_{\rm pre} \gtrsim 10^2\ \text{TeV} \times \sqrt{\ldots}$$

FLAVOUR STRUCTURES



Related: $\mu \to e$ Conversion

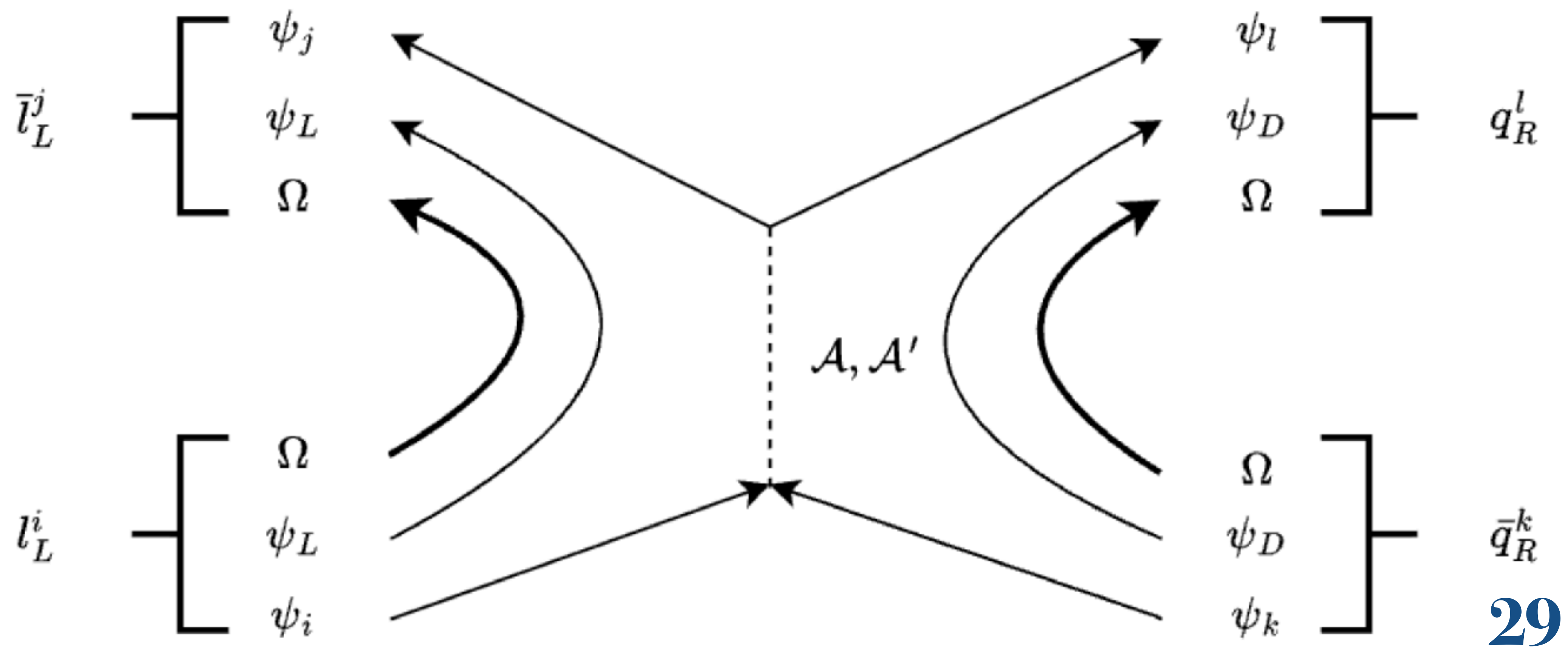
$$\mathcal{L} \sim \frac{1}{\Lambda_{\text{pre}}^2} (\bar{e}\gamma^\beta [C_L P_L + C_R P_R] \mu)(\bar{q}\gamma_\beta q)$$

$$C_L = (U_\ell^\dagger)_{j2}(U_\ell)_{1i}\left[\left(\lambda_{jl}\lambda_{ik}^* + \tilde{\lambda}_{jl}\tilde{\lambda}_{ik}^*\right)(U_q^\dagger)_{l1}(U_q)_{1k} - \left(\lambda_{jk}\lambda_{il}^* + \tilde{\lambda}_{jk}\tilde{\lambda}_{il}^*\right)(V_q^\dagger)_{l1}(V_q)_{1k}\right]$$

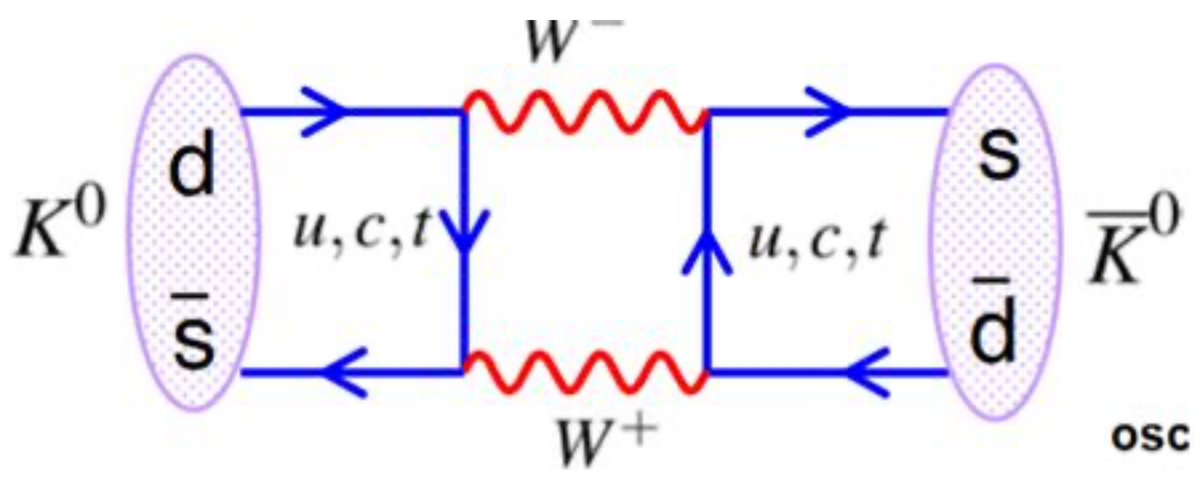
$$C_R = (V_\ell^\dagger)_{j2}(V_\ell)_{1i}\left[\left(\lambda_{ik}\lambda_{jl}^* + \tilde{\lambda}_{ik}\tilde{\lambda}_{jl}^*\right)(V_q^\dagger)_{l1}(V_q)_{1k} - \left(\lambda_{il}\lambda_{jk}^* + \tilde{\lambda}_{il}\tilde{\lambda}_{jk}^*\right)(U_q^\dagger)_{l1}(U_q)_{1k}\right]$$

$$\Lambda_{\text{pre}} \gtrsim 10^4 \text{ TeV} \times \sqrt{\ldots}$$

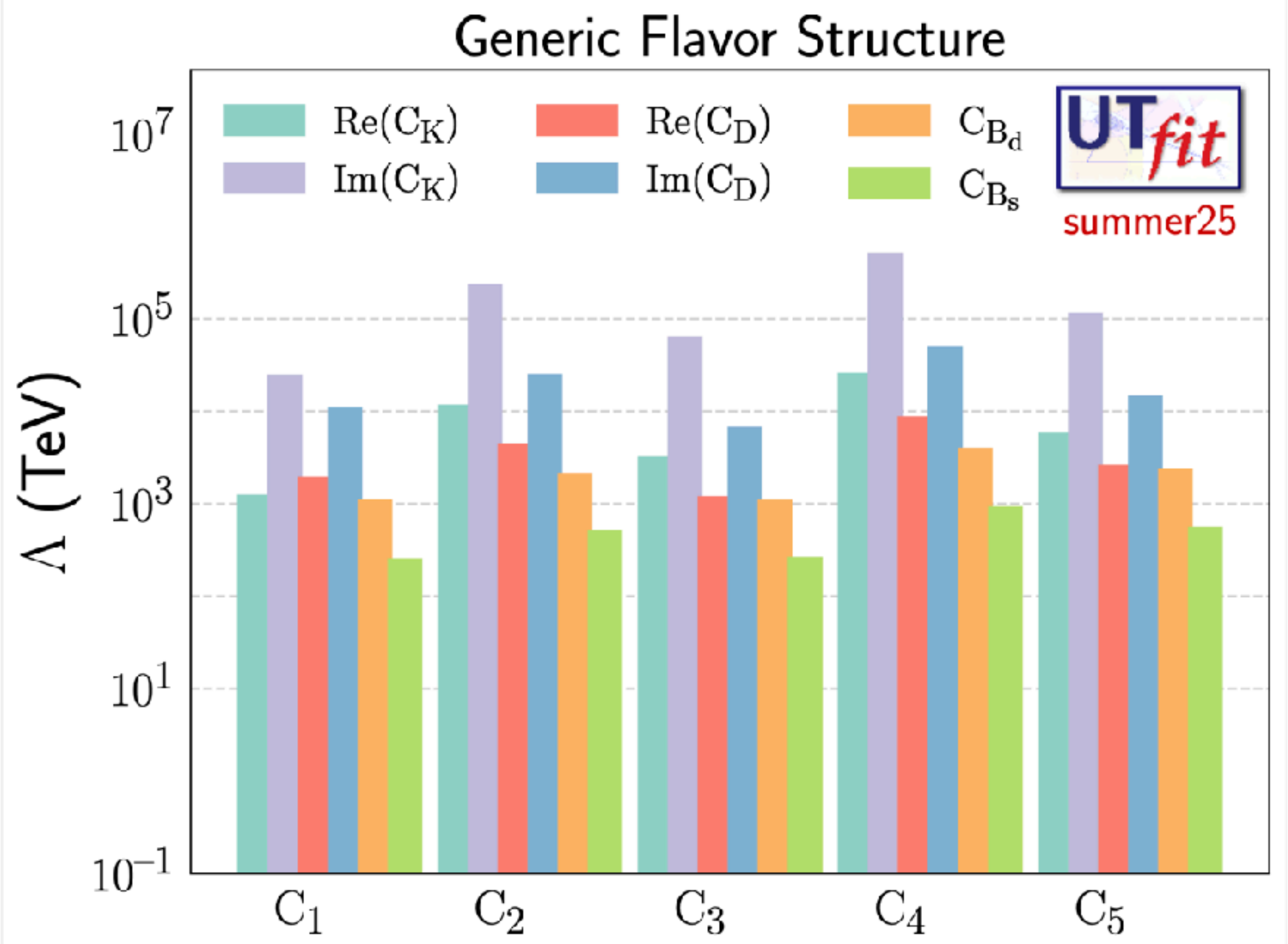
FLAVOUR STRUCTURES

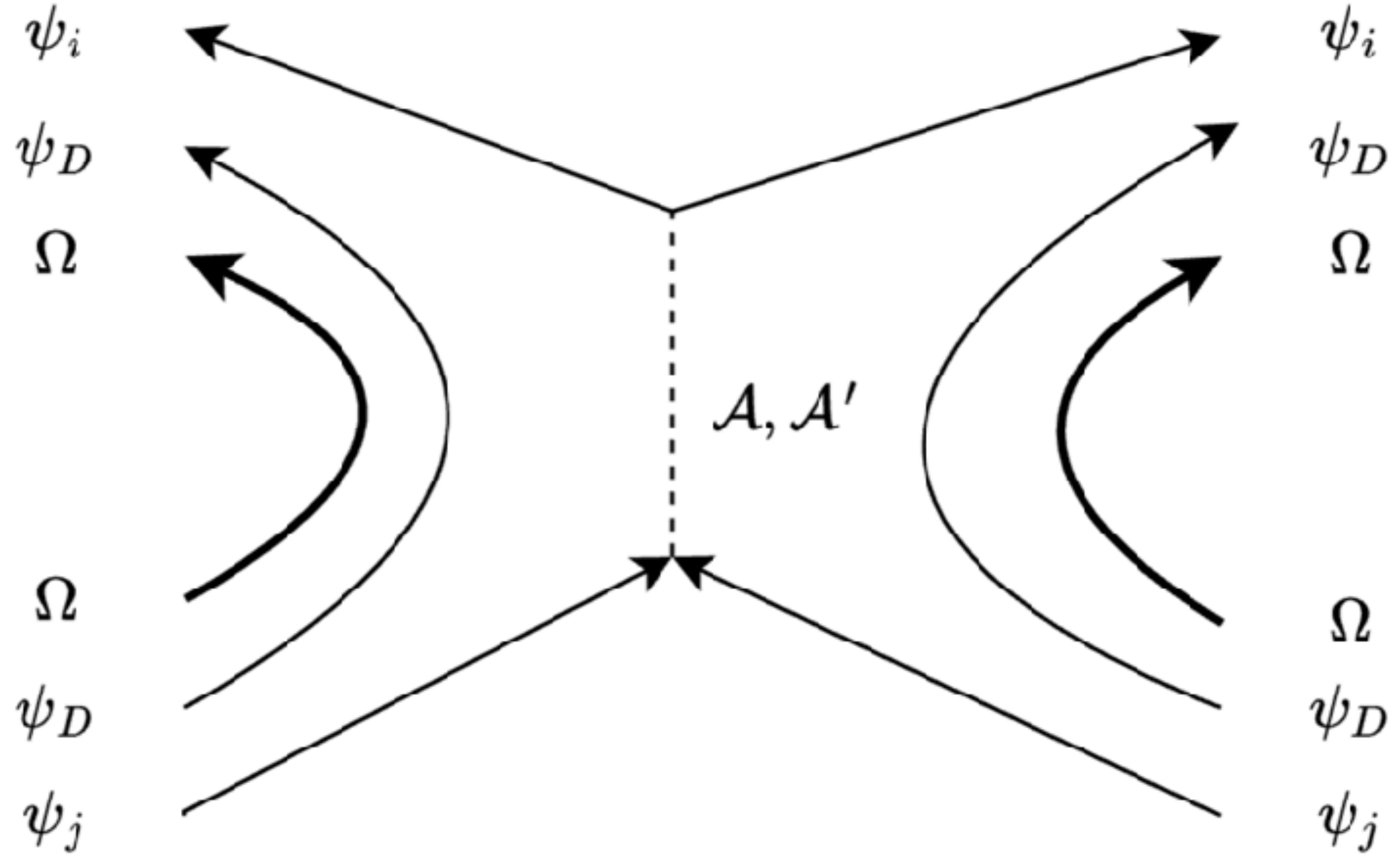


Example: Kaon Mixing



$$(\bar{s}^a_L \gamma^\mu d_{La})(\bar{s}^b_R \gamma_\mu d_{Rb})$$





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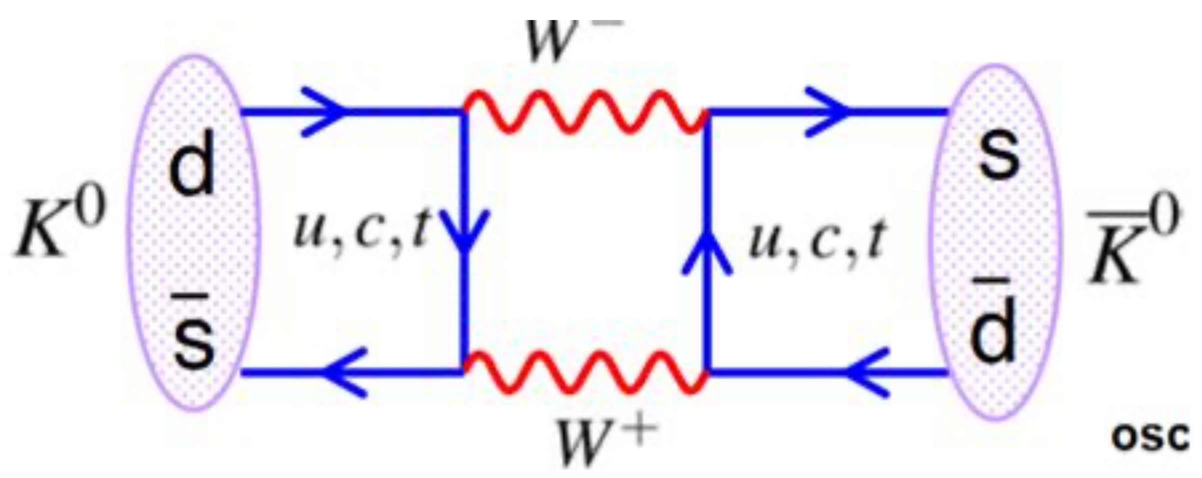
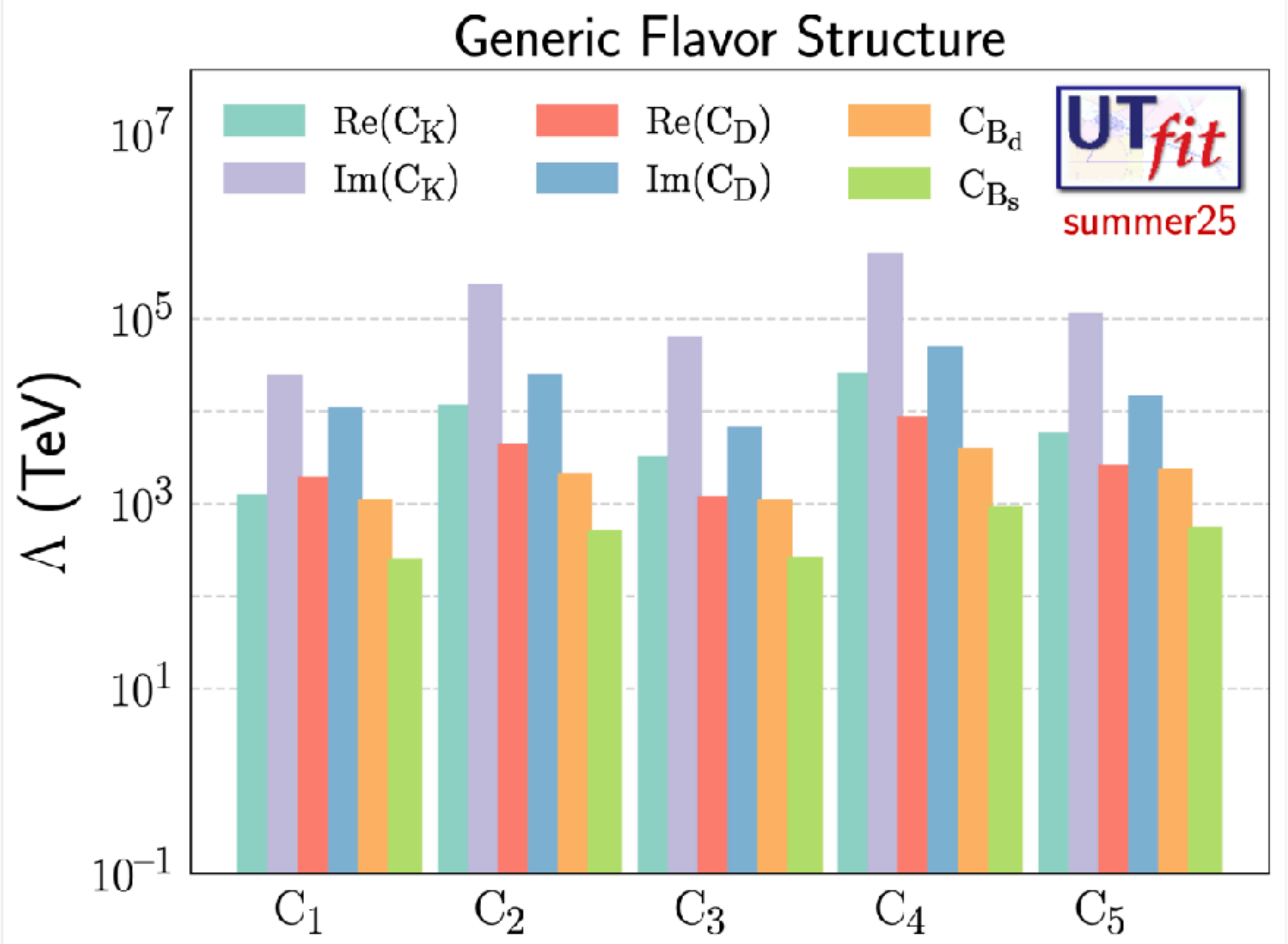
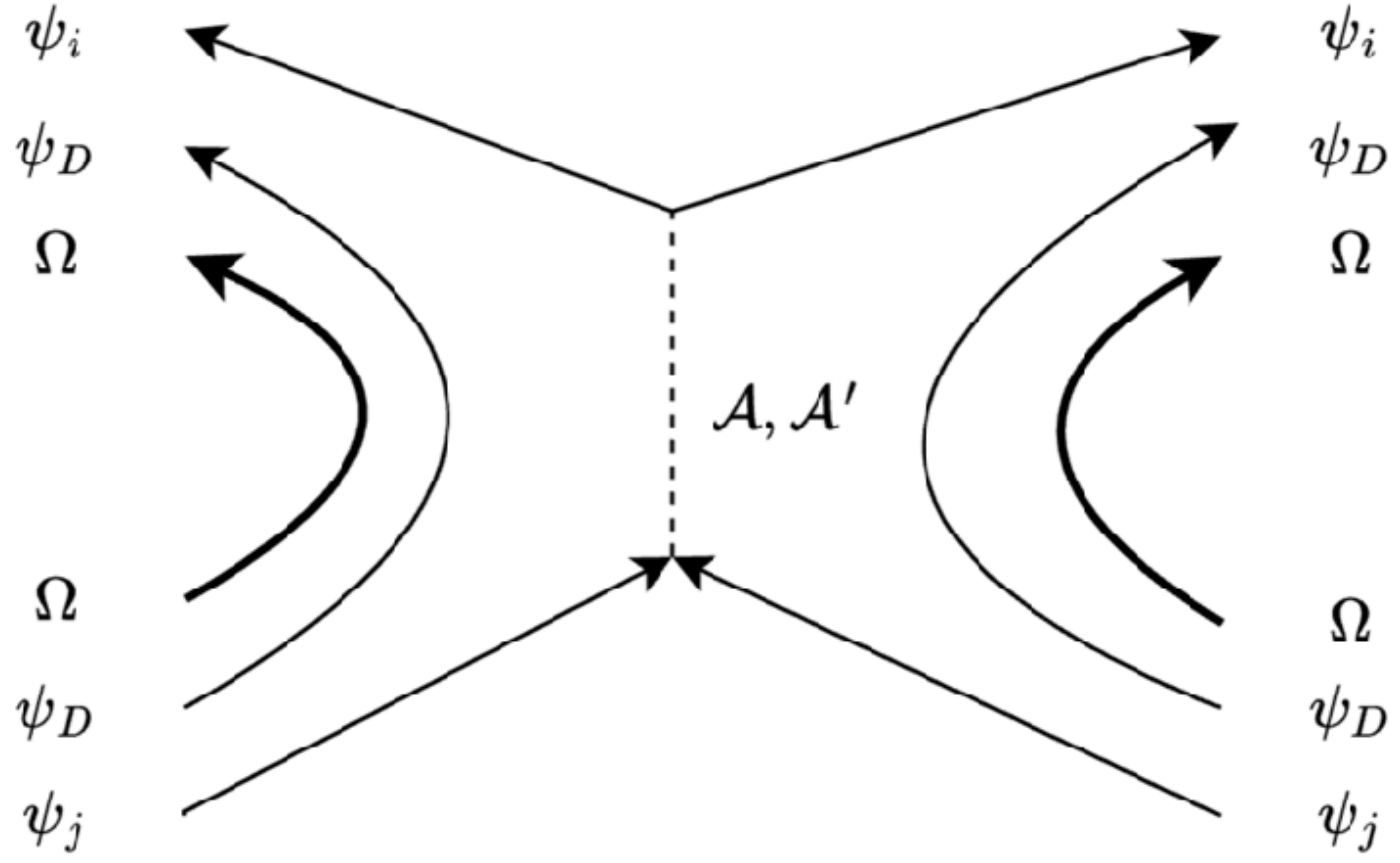


$$(\bar{s}^a_L \gamma^\mu d_{La})(\bar{s}^b_R \gamma_\mu d_{Rb}) \to \underbrace{(\bar{s}^b_L d_{La})(\bar{s}^a_R d_{Rb})}_{O_5}$$

Fierz





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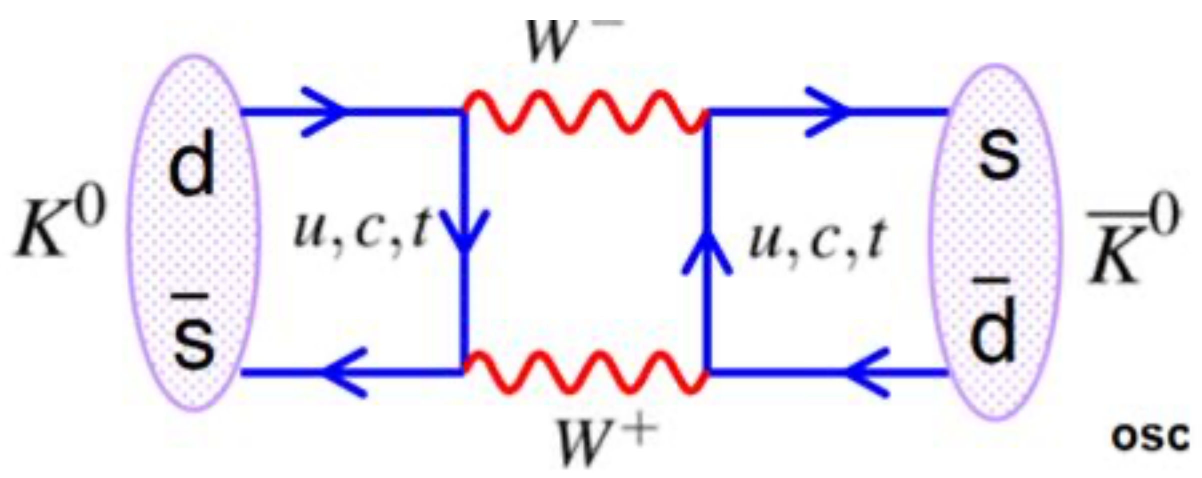
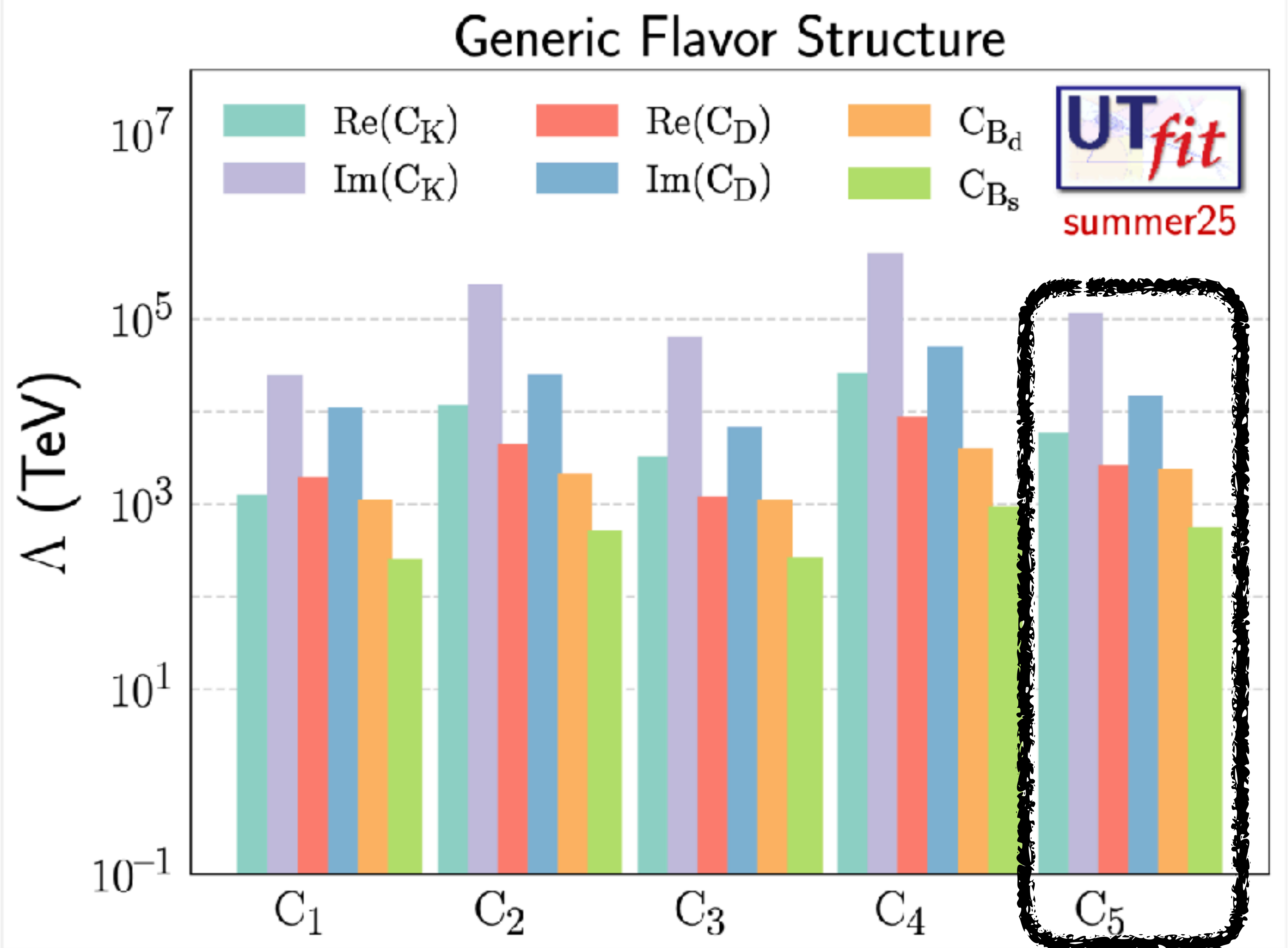


$$(\bar{s}^a_L \gamma^\mu d_{La})(\bar{s}^b_R \gamma_\mu d_{Rb}) \to \underbrace{(\bar{s}^b_L d_{La})(\bar{s}^a_R d_{Rb})}_{O_5}$$

Fierz

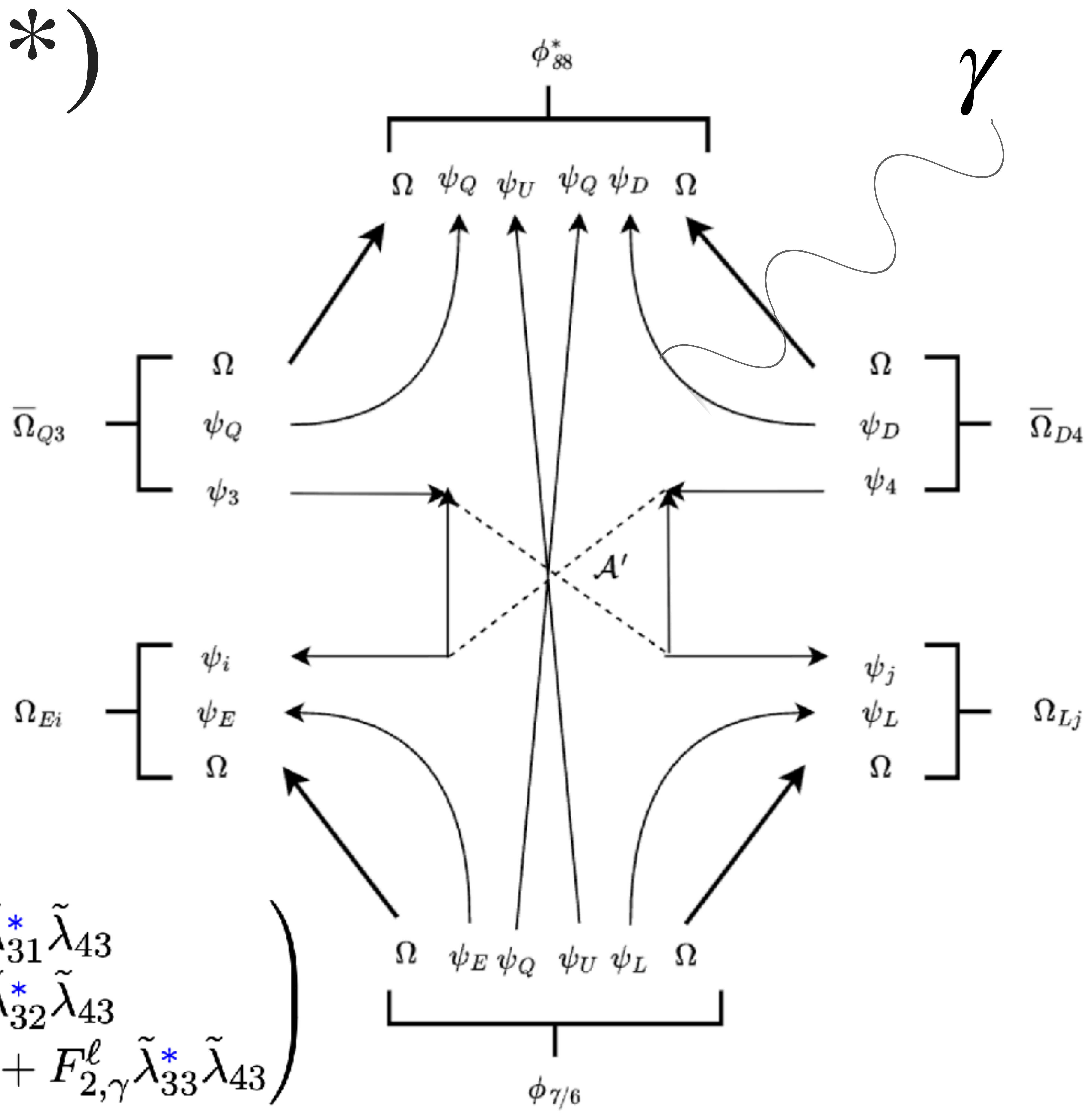


$$\Lambda_{\text{pre}} \gtrsim 10^5 \text{ TeV} \times \sqrt{\ldots}$$

FLAVOUR STRUCTURES

Example: $\mu \to e\gamma^{(*)}$

- Same structure as Yukawas.
- Different matrix elements.
- Misalignment allows transitions.



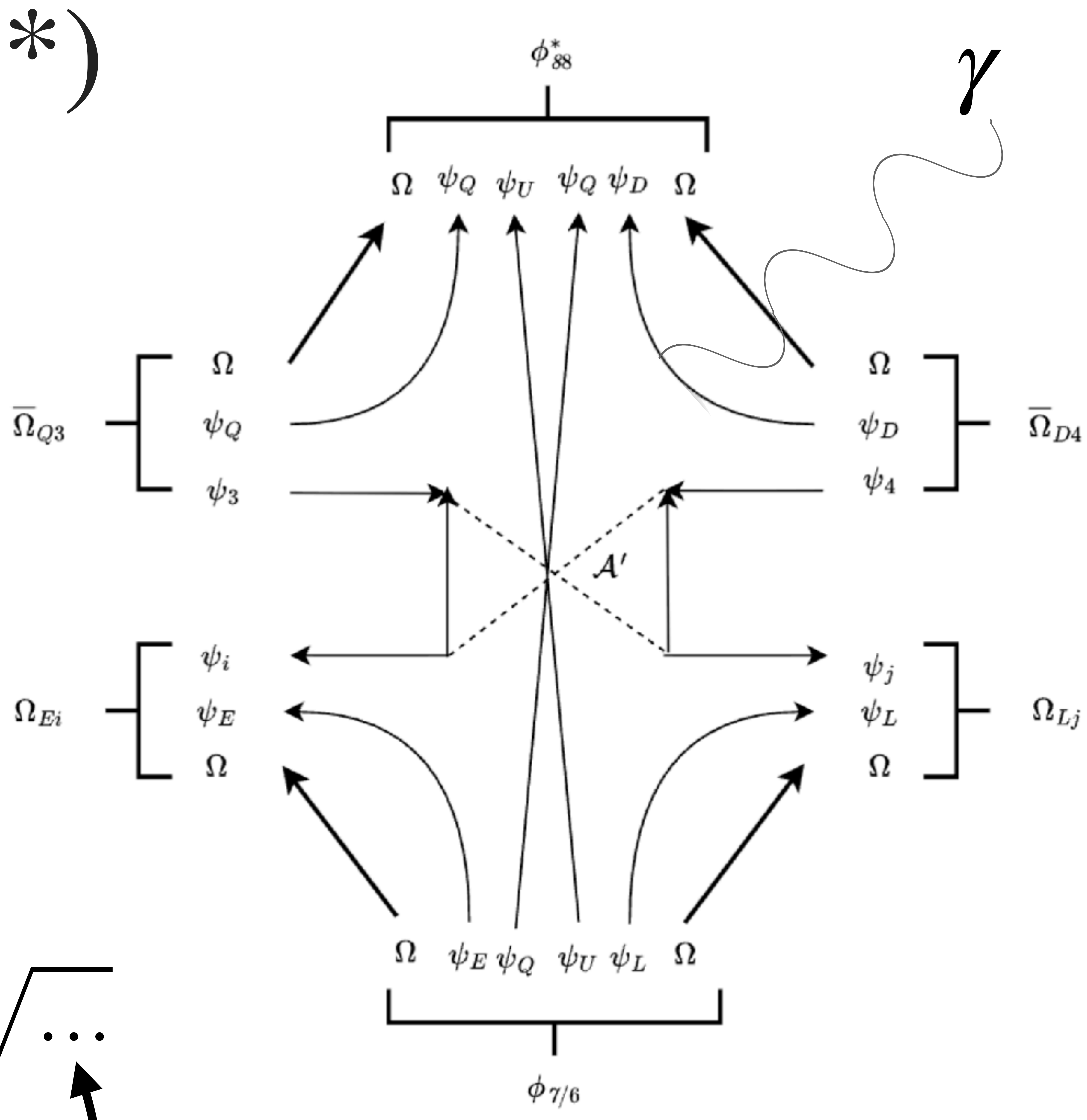
$$(Y_\gamma)_{ij} = \frac{1}{N} J^\ell_\gamma \tilde{\lambda}_{43} \tilde{\lambda}^*_{ij} + \frac{1}{N} \begin{pmatrix} 0 & 0 & G^\ell \tilde{\lambda}^*_{31} \tilde{\lambda}_{43} \\ 0 & 0 & G^\ell_\gamma \tilde{\lambda}^*_{32} \tilde{\lambda}_{43} \\ I^\ell_\gamma \tilde{\lambda}_{33} \tilde{\lambda}^*_{41} & I^\ell \tilde{\lambda}_{33} \tilde{\lambda}^*_{42} & F^\ell_{1,\gamma} \tilde{\lambda}_{33} \tilde{\lambda}^*_{43} + F^\ell_{2,\gamma} \tilde{\lambda}^*_{33} \tilde{\lambda}_{43} \end{pmatrix}$$

Example: $\mu \to e\gamma^{(*)}$

- Same structure as Yukawas.
- Different matrix elements.
- Misalignment allows transitions.

$$\Lambda_{\text{pre}} \gtrsim 10^4 \text{ TeV} \times \sqrt{\ldots}$$

FLAVOUR STRUCTURES



Example: Electron EDM

$$\mathscr{L} \sim \left[c\ \bar{e}_L \sigma_{\mu\nu} e_R + c^*\ \bar{e}_R \sigma_{\mu\nu} e_L \right] F^{\mu\nu}$$

$$\tilde{d}_e \sim \frac{1}{N} \frac{e \langle H_d \rangle}{\Lambda^2_{\rm pre}} \, \mathrm{Im} \left[(V_\ell)_{1i} (Y_\gamma)_{ij} (U_\ell^\dagger)_{j1} \right]$$

EDM ARRISES AT TREE-LEVEL

Example: Electron EDM

JILA HgF^+ 2212.11841

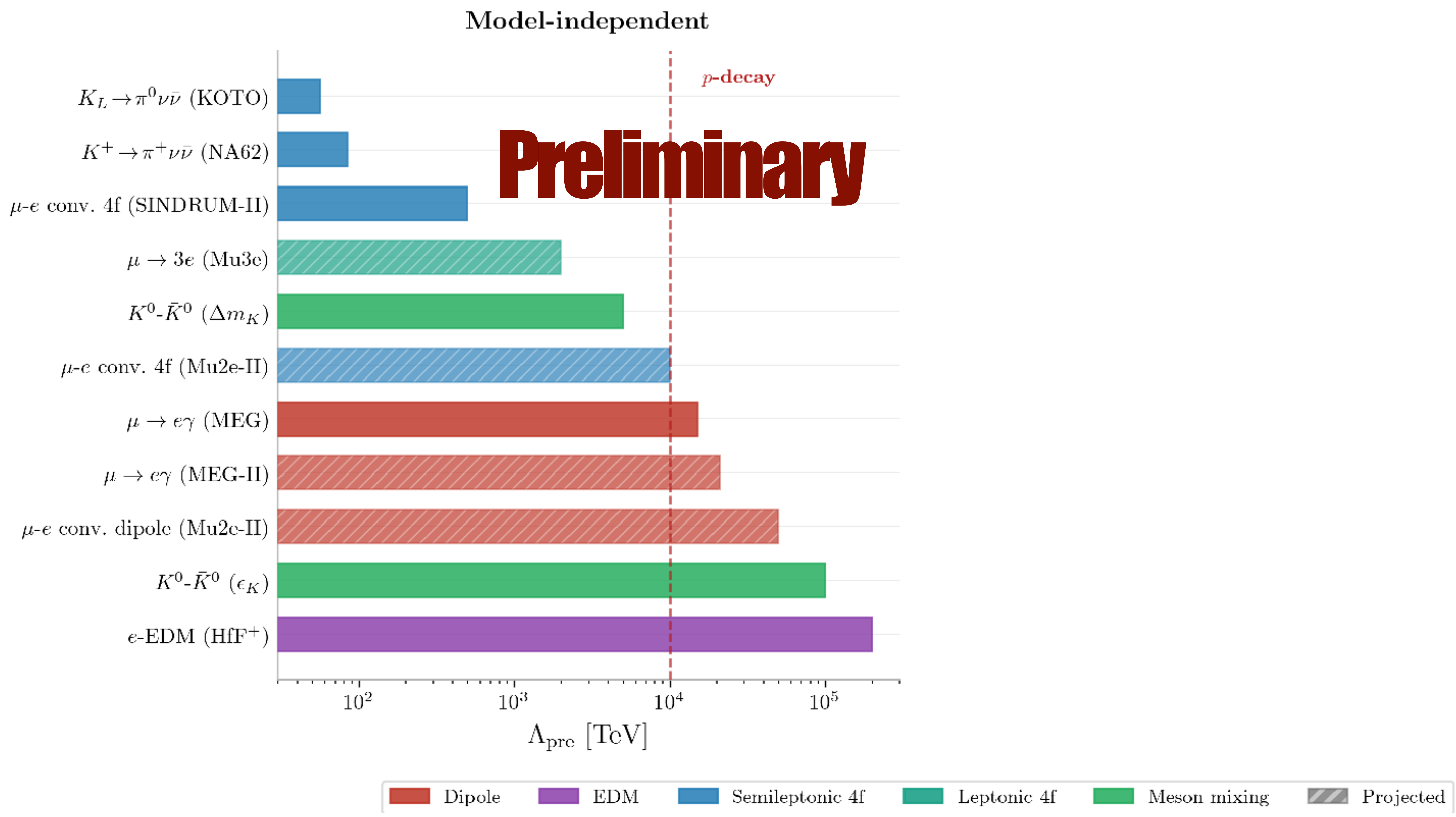
$$\tilde{d}_e \leq 4.1 \times 10^{30}\ e\ \mathrm{cm} \quad \Longrightarrow \quad \Lambda_{\mathrm{pre}} \gtrsim 5 \times 10^5\ \mathrm{TeV}\sqrt{\mathrm{Im}[\ldots]}$$

FLAVOUR STRUCTURES

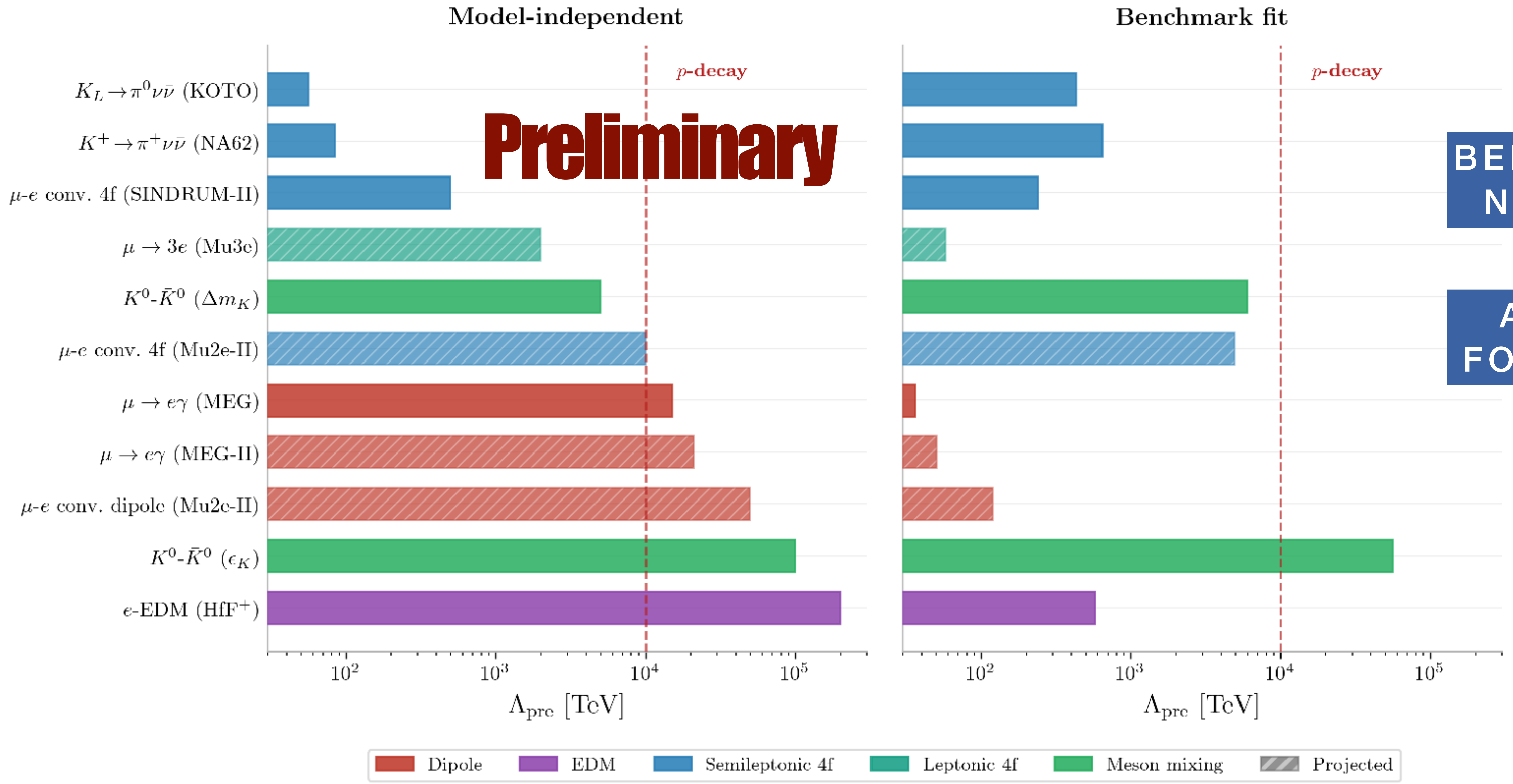
$$\tilde{d}_e \sim \frac{1}{N}\frac{e\langle H_d\rangle}{\Lambda_{\mathrm{pre}}^2}\,\mathrm{Im}\left[(V_\ell)_{1i}(Y_\gamma)_{ij}(U_\ell^\dagger)_{j1}\right]$$

EDM HAS NO LOOP SUPPRESSION

Bigger Picture



Bigger Picture



BENCHMARK IS NOT UNIQUE

ACCOUNTS FOR YUKAWAS

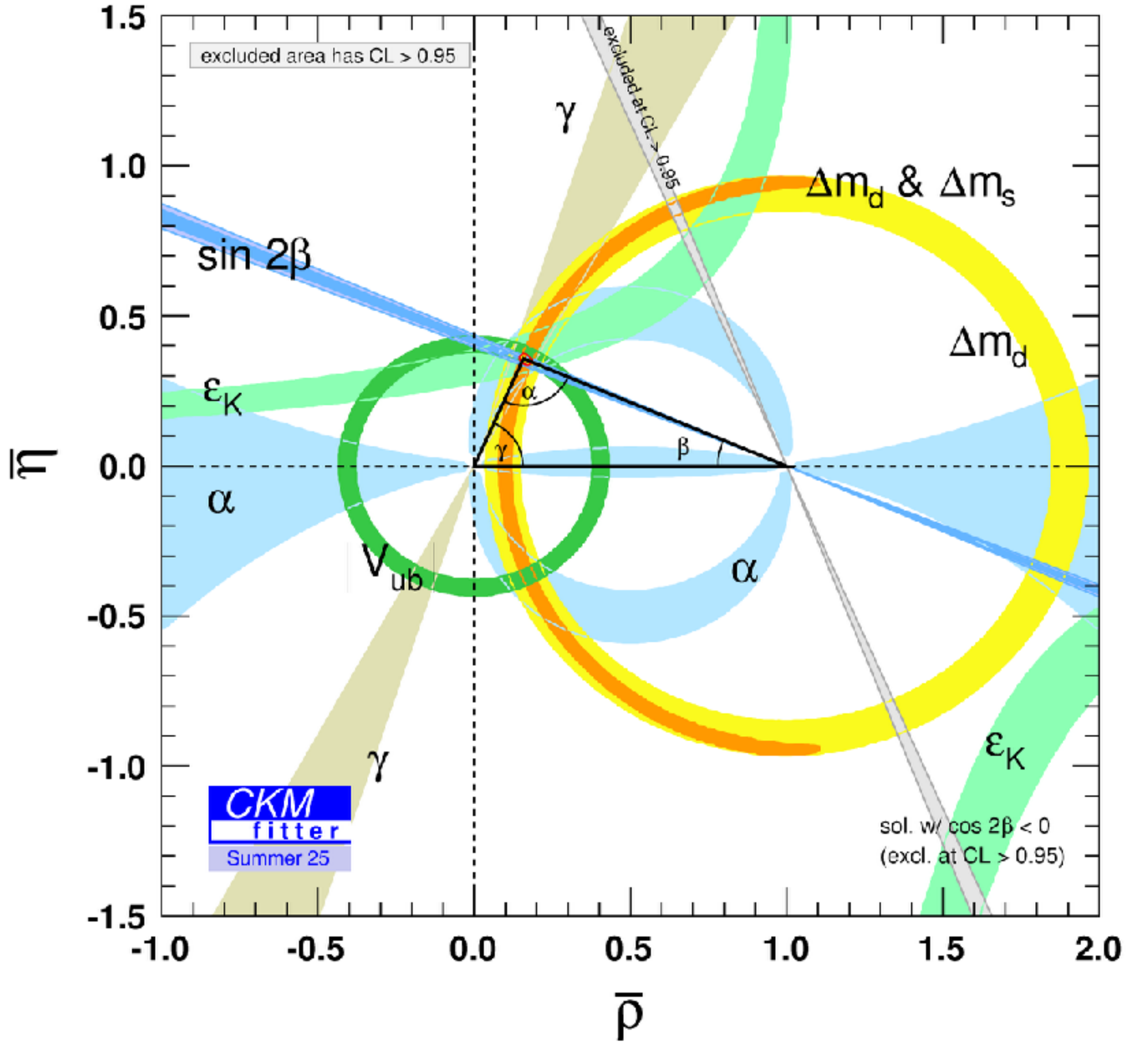
Conclusions & Outlook

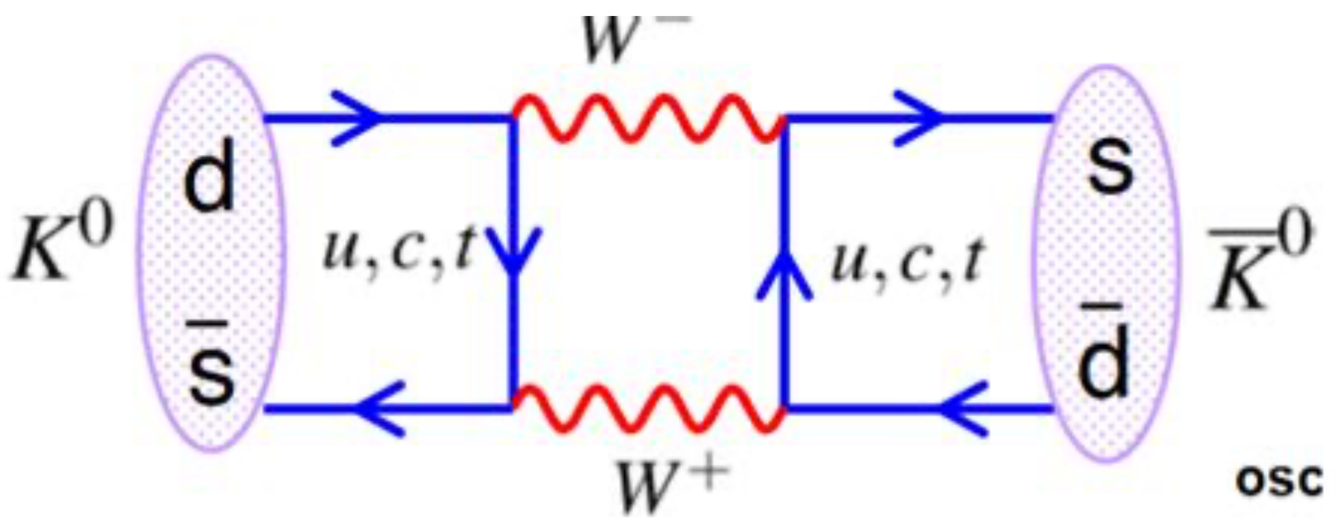
FLAVOUR SIGNATURES OF QUARK AND LEPTON COMPOSITENESS

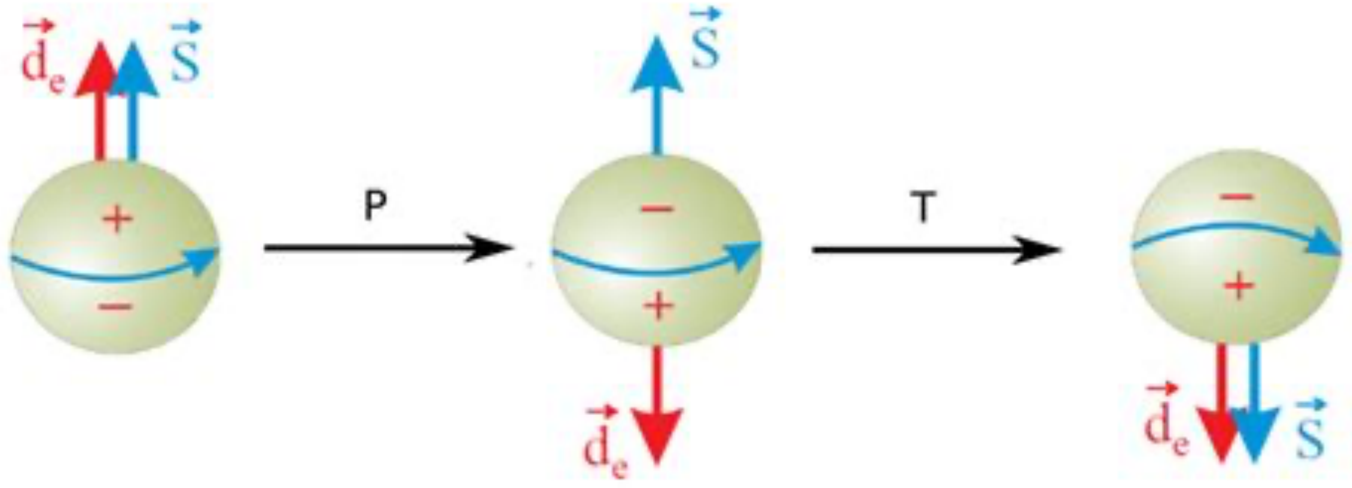
1. Sensible theory of composite quarks/leptons at high scales.

2. Connection between composite dynamics and flavour.

3. Flavour physics is competitive with other probes (e.g. proton decay).







Backups

A Specific Class Of CGTs

$SU(15)$

Fields

$$\psi_a = \square$$

$$\Omega^{ab} = \overline{\square\square}$$

Anomaly Coefficients

$$A(\psi_a) = 1$$

$$A(\Omega^{ab}) = -(N+4)$$

A Healthy Anomaly Free Theory

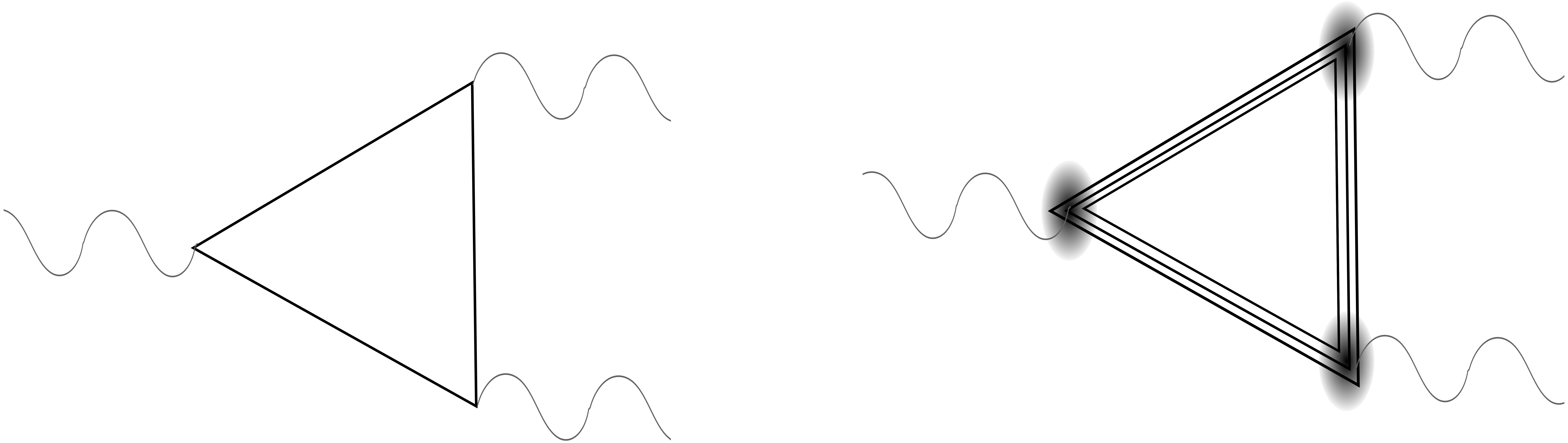
$$\Omega^{ab} + \ \psi_a^{(i)} \ i \in \{1, \ldots, N+4\}$$

Composite Fermions

$$f^{(ij)} \sim (\psi_a^{(i)} \Omega^{ab} \psi_b^{(j)})$$

Anomaly Matching Works!

$z_\Omega = -19/17 z_\psi$
$SU(15)^2 \otimes U(1)$



$$285 z_\psi^3 + 120 z_\Omega^3 \quad \leftarrow U(1)^3 \rightarrow \quad 171(2z_\psi + z_\Omega)^3$$

$$285 z_\psi + 120 z_\Omega \leftarrow \text{gravity}^2 \otimes U(1) \rightarrow 171(2z_\psi + z_\Omega)$$