Flavor and new Physics

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(DESY)

Cargese 2012: Across the TeV frontier with the LHC

Lecture 1

blackboard

Determining the CKM matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Parameterisations

V_{CKM} 3x3 unitary matrix ($V^{+}V=1$) with 1 phase.

PDG parameterisation

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

($c_{12}=\cos\theta_{12}$, $s_{12}=\sin\theta_{12}$,...)

Parameterisations

V_{CKM} 3x3 unitary matrix ($V^{+}V=1$) with 1 phase.

PDG parameterisation

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($c_{12}=\cos\theta_{12}$, $s_{12}=\sin\theta_{12}$,...)

From experiment we find a strong hierarchy:

s_{12} = 0.22 >> **s_{23}** = $O(10^{-2})$ >> **s_{13}** = $O(10^{-3})$

Reveals an almost diagonal (λ = 0.22) structure:

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Wolfenstein Parameterisation

Wolfenstein '83

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$A, \rho, \eta \sim 0.8, 0.2, 0.3$$

η measures CPV

Wolfenstein Parameterisation

Wolfenstein '83

Choose parameters that make hierarchy obvious

$s_{12} \equiv \lambda$ $\quad s_{23} \equiv A\lambda^2$ $\quad s_{13}\, e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$A, \rho, \eta \sim 0.8, 0.2, 0.3$

η measures CPV

Unitarity triangles

CKM Matrix is unitary $\mathbf{V}^\dagger\mathbf{V} = \mathbf{V}\mathbf{V}^\dagger = \mathbf{1}$

$$\underbrace{\mathbf{V}_{i1} (\mathbf{V}_{j1})^*}_{\vec{a}} + \underbrace{\mathbf{V}_{i2} (\mathbf{V}_{j2})^*}_{\vec{b}} + \underbrace{\mathbf{V}_{i3} (\mathbf{V}_{j3})^*}_{\vec{c}} = \mathbf{0} \quad \text{for } \mathbf{i} \neq \mathbf{j}$$

vectors in complex plane: $\vec{a} + \vec{b} + \vec{c} = 0$

Unitarity triangles

CKM Matrix is unitary $\mathbf{V^\dagger V = VV^\dagger = I}$

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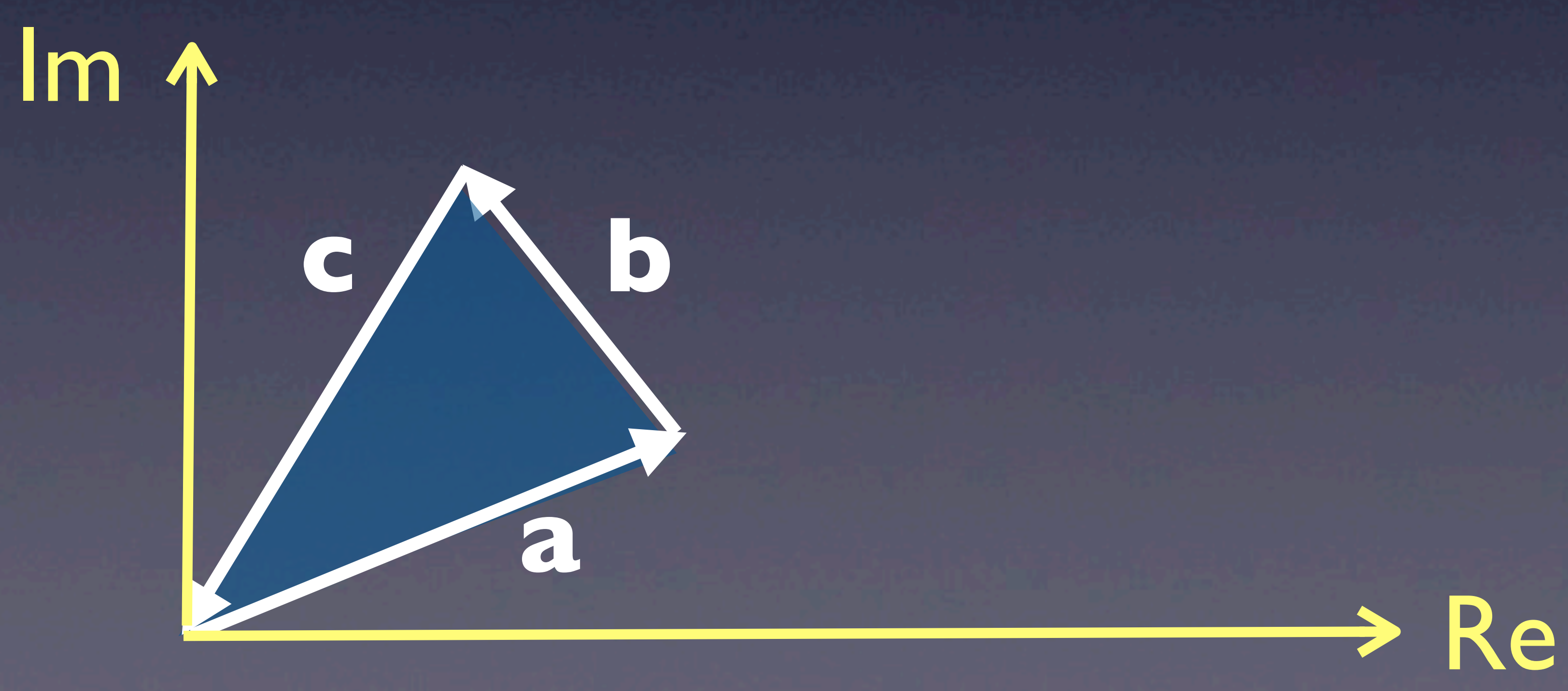
vectors in complex plane: $\vec{a} + \vec{b} + \vec{c} = 0$



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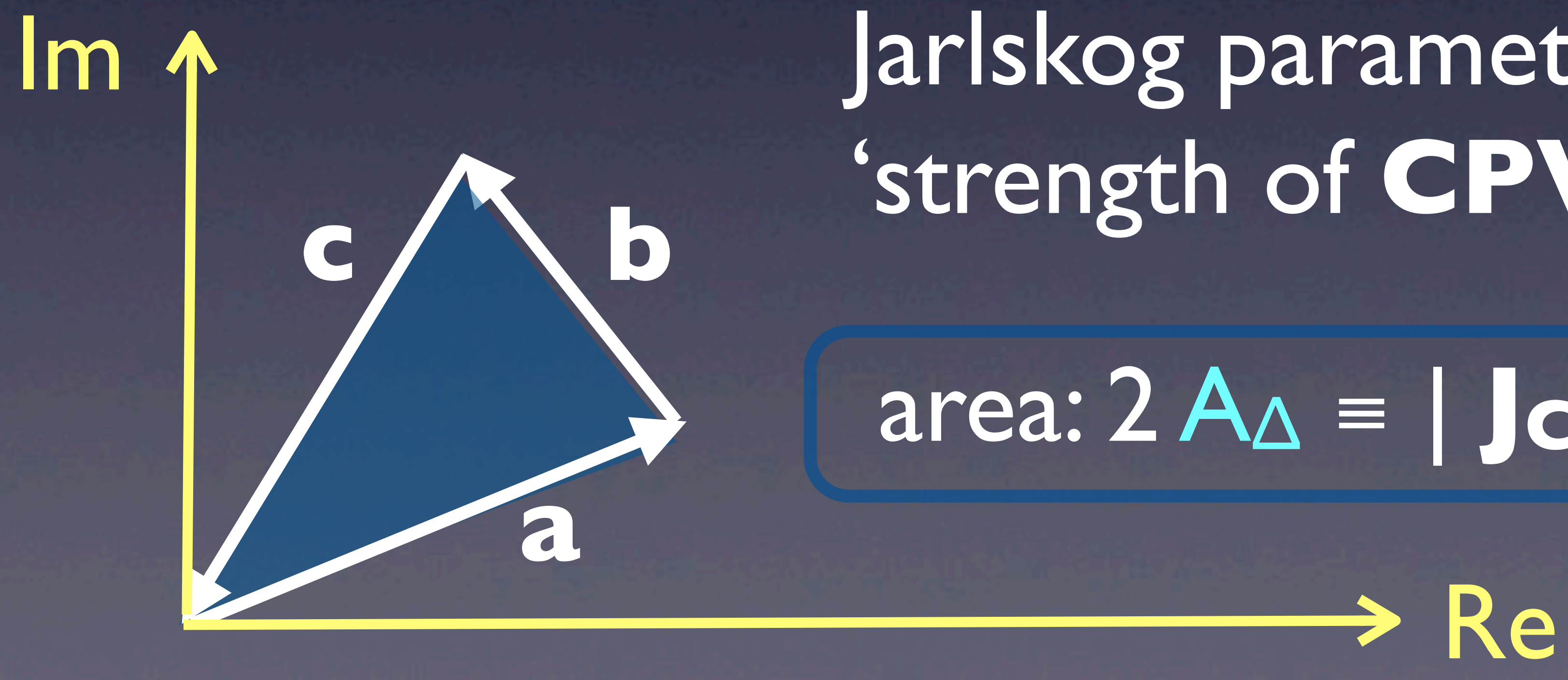


Jarlskog parameter $\mathbf{J_{CP}}$:
'strength of **CPV**'

$$\boxed{\text{area: } 2\,A_\Delta \equiv |\,\mathbf{J_{CP}}\,|}$$

The Unitarity triangle

$$\mathbf{V_{i1} (V_{j1})^* + V_{i2} (V_{j2})^* + V_{i3} (V_{j3})^* = 0} \quad \text{for } \mathbf{i \neq j}$$

of the **3x2 = 6** possible triangles pick one which has sides a,b,c of similar length (try!).

The Unitarity triangle

$$V_{i1}(V_{j1})^* + V_{i2}(V_{j2})^* + V_{i3}(V_{j3})^* = 0 \quad \text{for } i \neq j$$

of the **3x2 = 6** possible triangles pick one which has sides a,b,c of similar length (try!).

$$\begin{array}{ccccccc} V_{ud}(V_{ub})^* & + & V_{cd}(V_{cb})^* & + & V_{td}(V_{tb})^* & = & 0 \\ \lambda^3 A(\rho+i\eta) & - & \lambda^3 A & + & \lambda^3 A(1-\rho-i\eta) & = & 0 \end{array}$$

The Unitarity triangle

$$V_{i1}\,(V_{j1})^* + V_{i2}\,(V_{j2})^* + V_{i3}\,(V_{j3})^* = 0 \quad \text{for } i \neq j$$

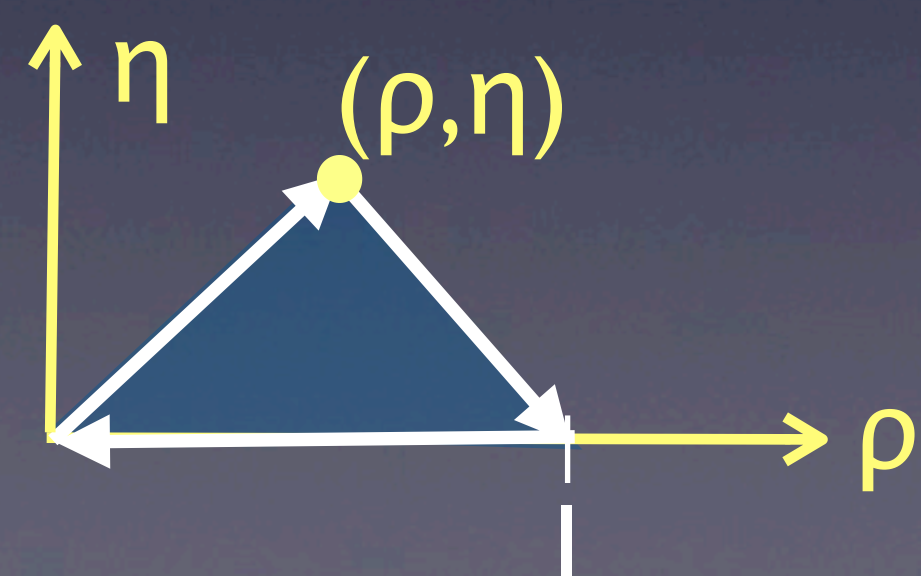
of the **3x2 = 6** possible triangles pick one which has sides a,b,c of similar length (try!).

$$V_{ud}\,(V_{ub})^* + V_{cd}\,(V_{cb})^* + V_{td}\,(V_{tb})^* = 0$$

$$\lambda^3 A(\rho + i\eta) - \lambda^3 A + \lambda^3 A(1 - \rho - i\eta) = 0$$

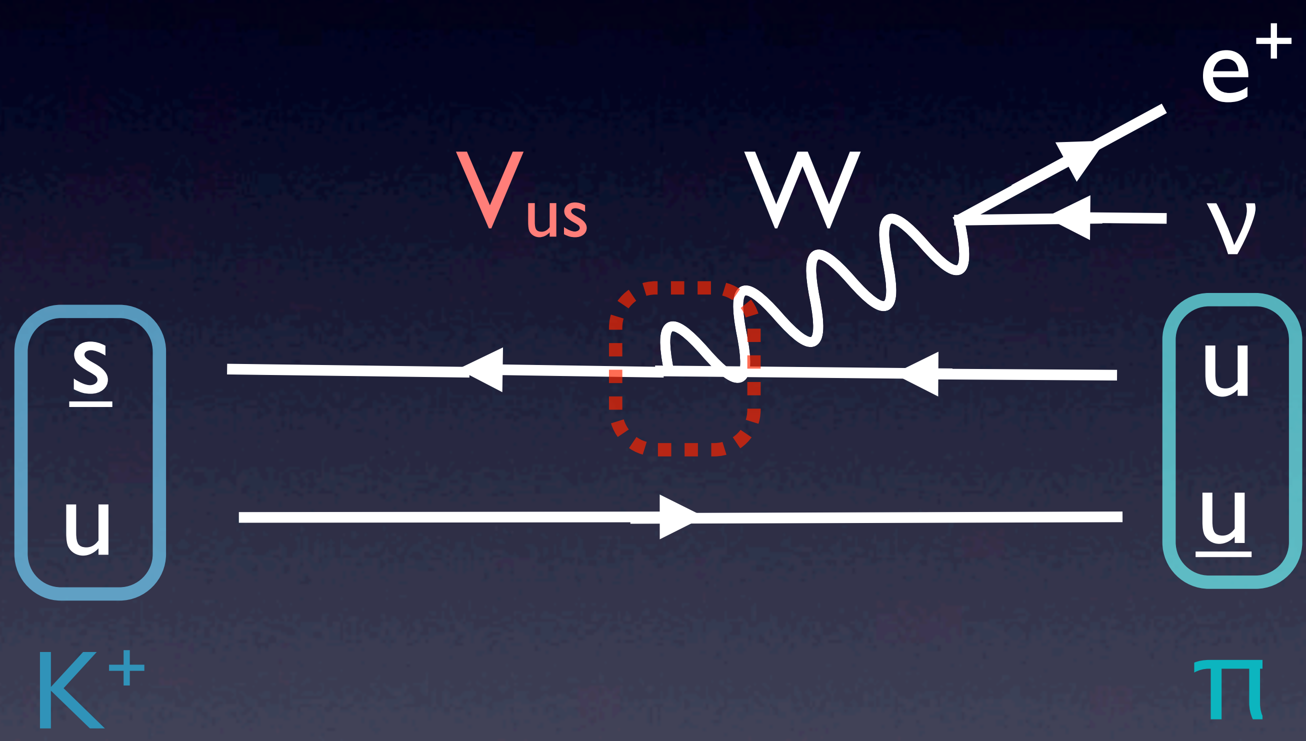
Divide by $\lambda^3 A = |V_{cd}\,(V_{cb})^*|$:

$$\rho + i\eta + (1 - \rho - i\eta) - 1 = 0$$



Direct Determination of the CKM matrix

1) $|V_{us}| = \lambda$ from $K^+ \to \pi^0 e^+ \nu_e$

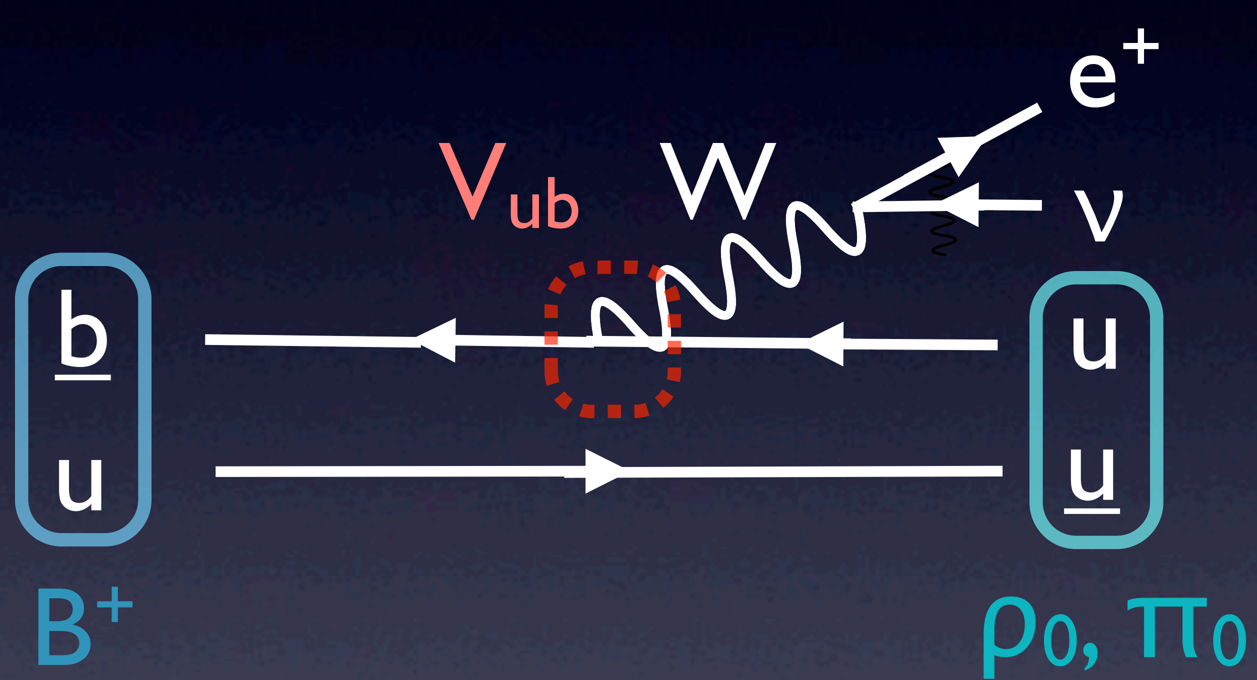


Result: $|V_{us}| = 0.2245 \pm 0.0016$

from: Moulson '07, KLOE, ISTRA+, NA48, KTEV

Side remark: Partonic vs Hadronic

Free quarks are easy...



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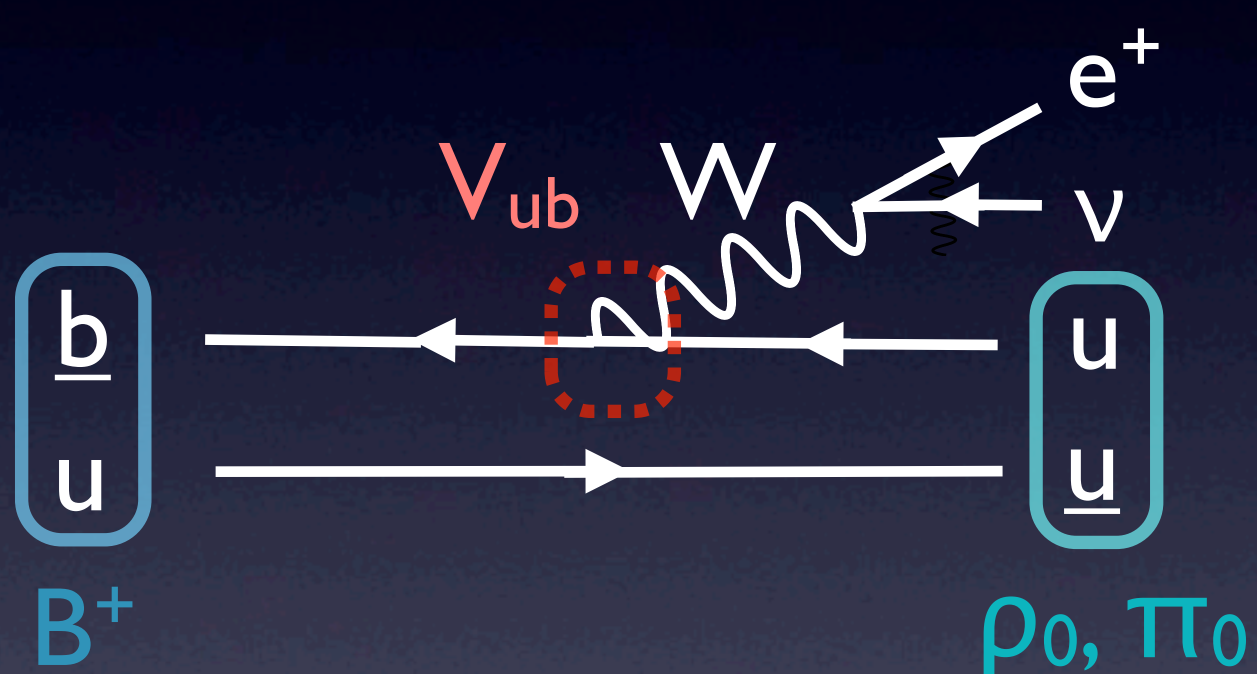

$$\Gamma(b \to u l \bar{\nu}) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5$$

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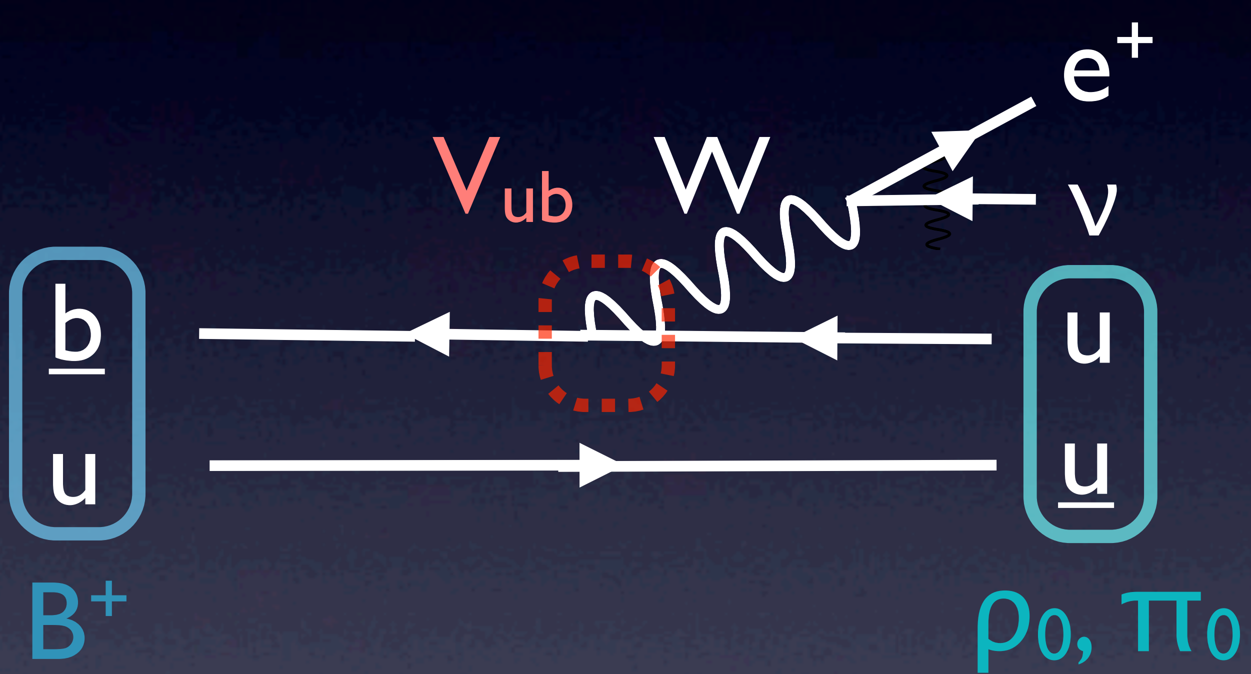
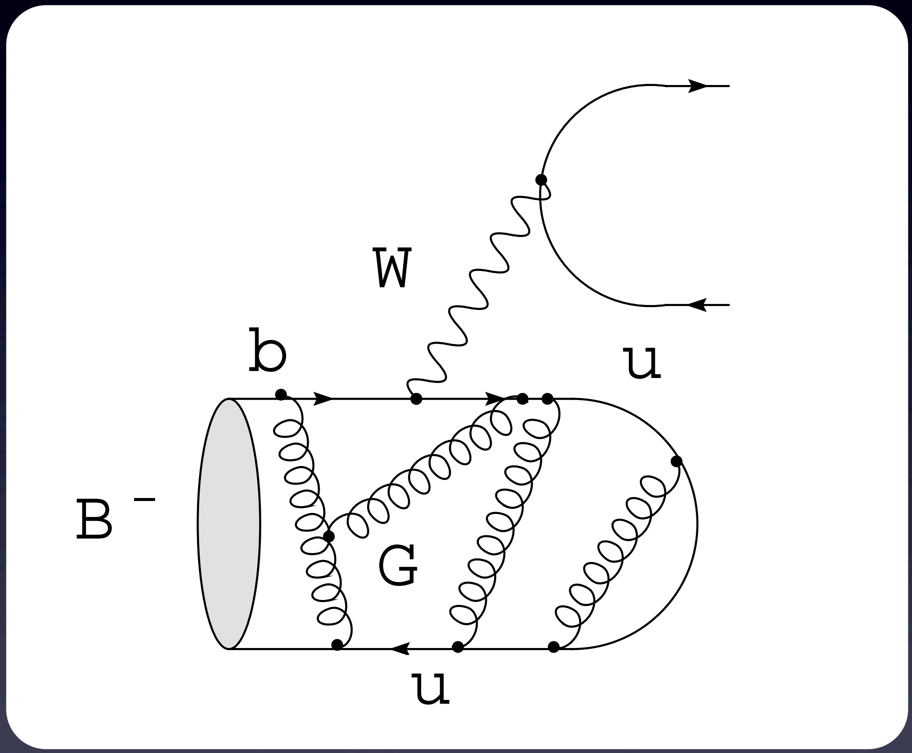
Hadrons not so much





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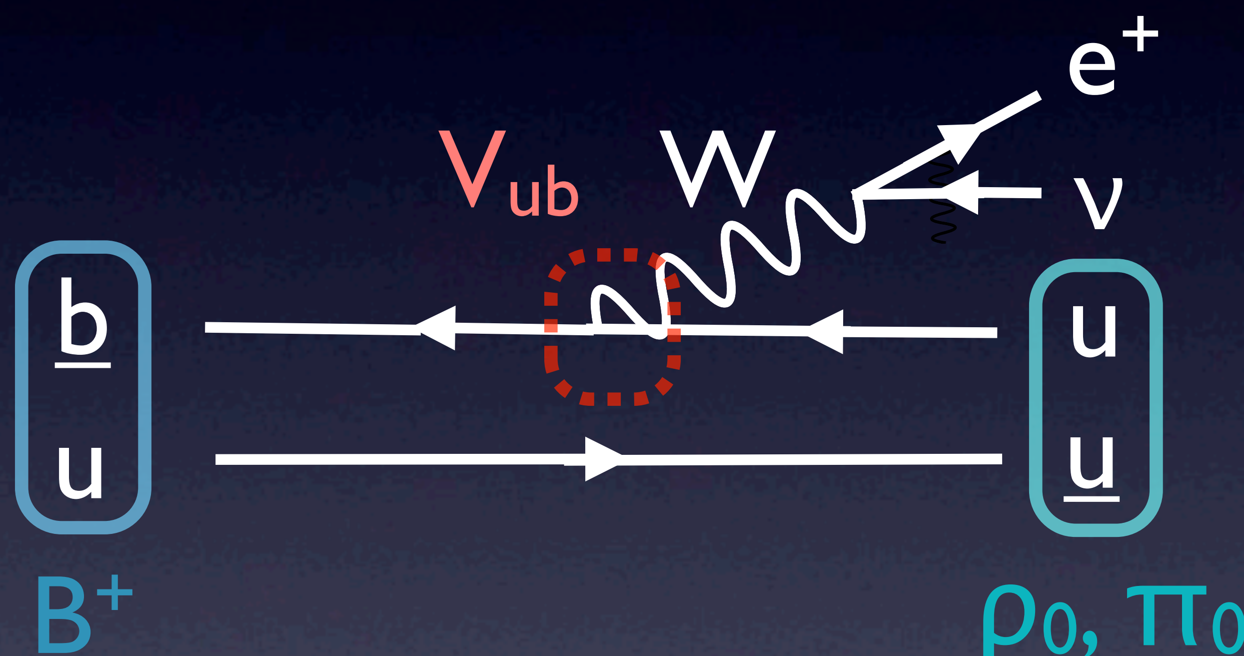
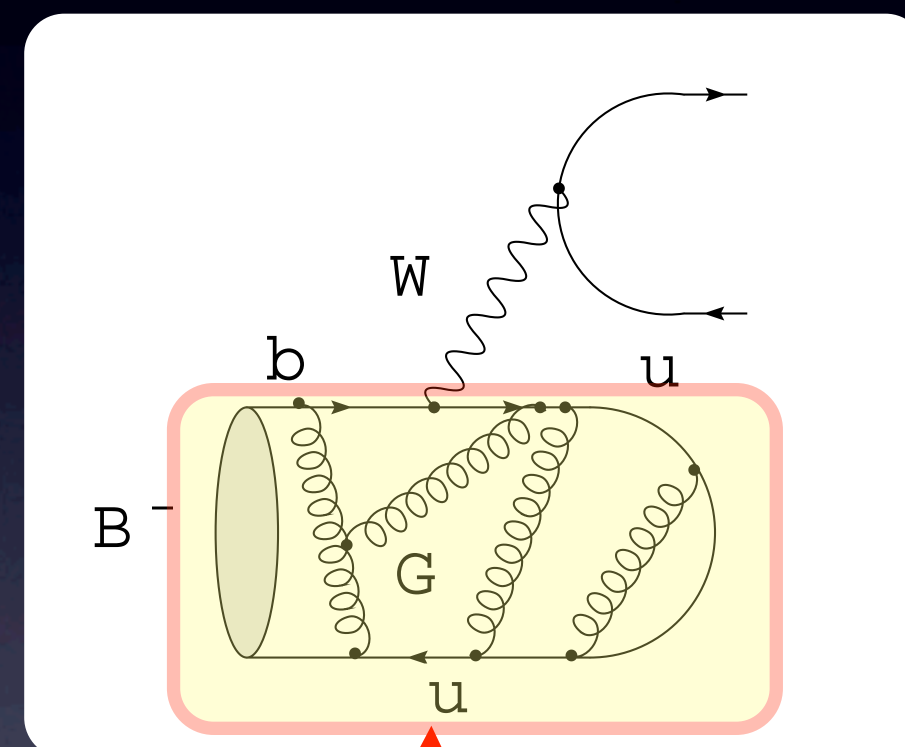


$$\Gamma(b \to ul\bar{\nu}) = \frac{G_F^2}{192\pi^2}|V_{ub}|^2 m_b^5$$

Hadrons not so much

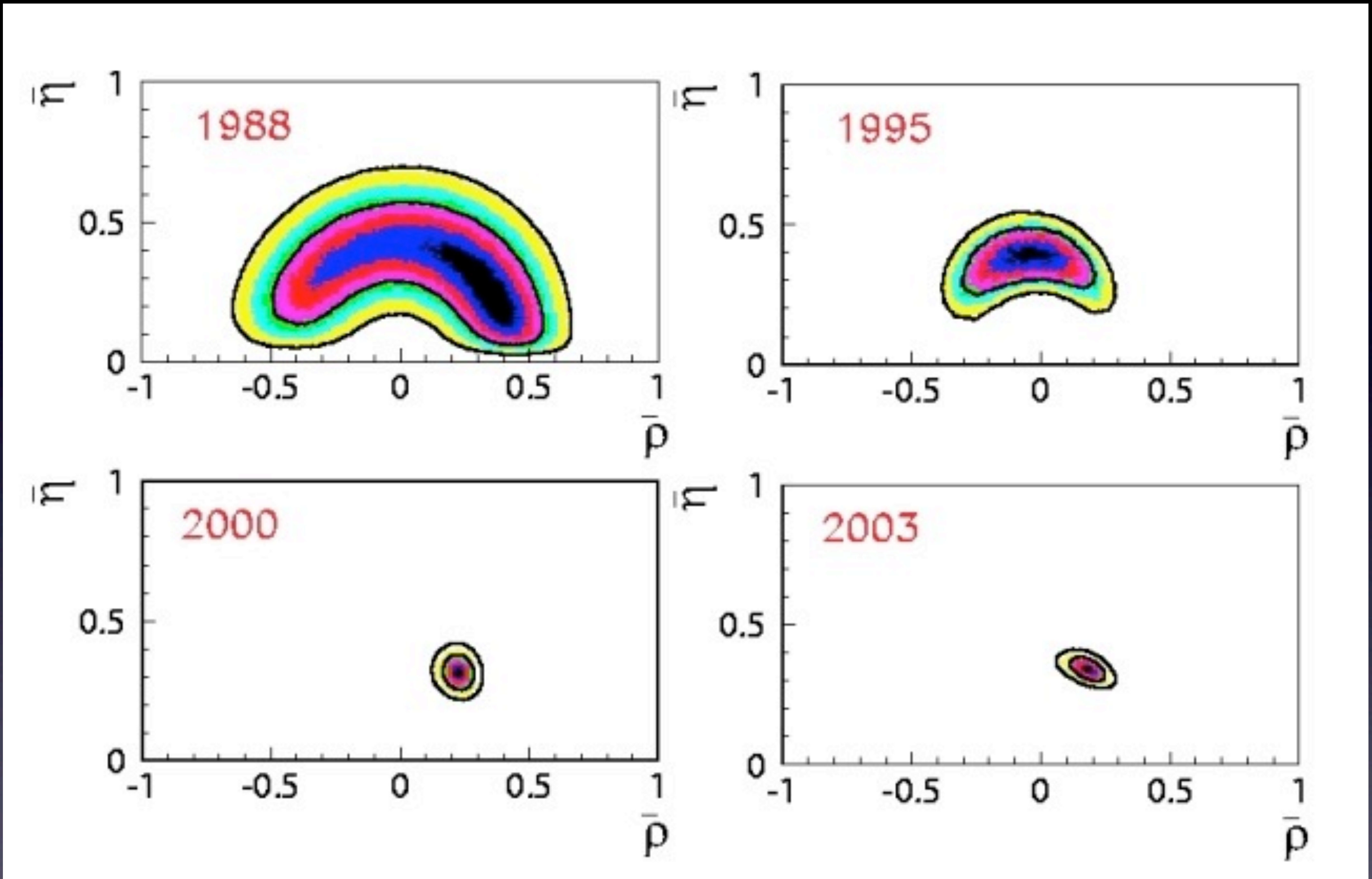


hadronic matrix element

$$\boxed{\langle 0|\bar{u}\gamma^\mu(1-\gamma_5)b|B^-\rangle}$$

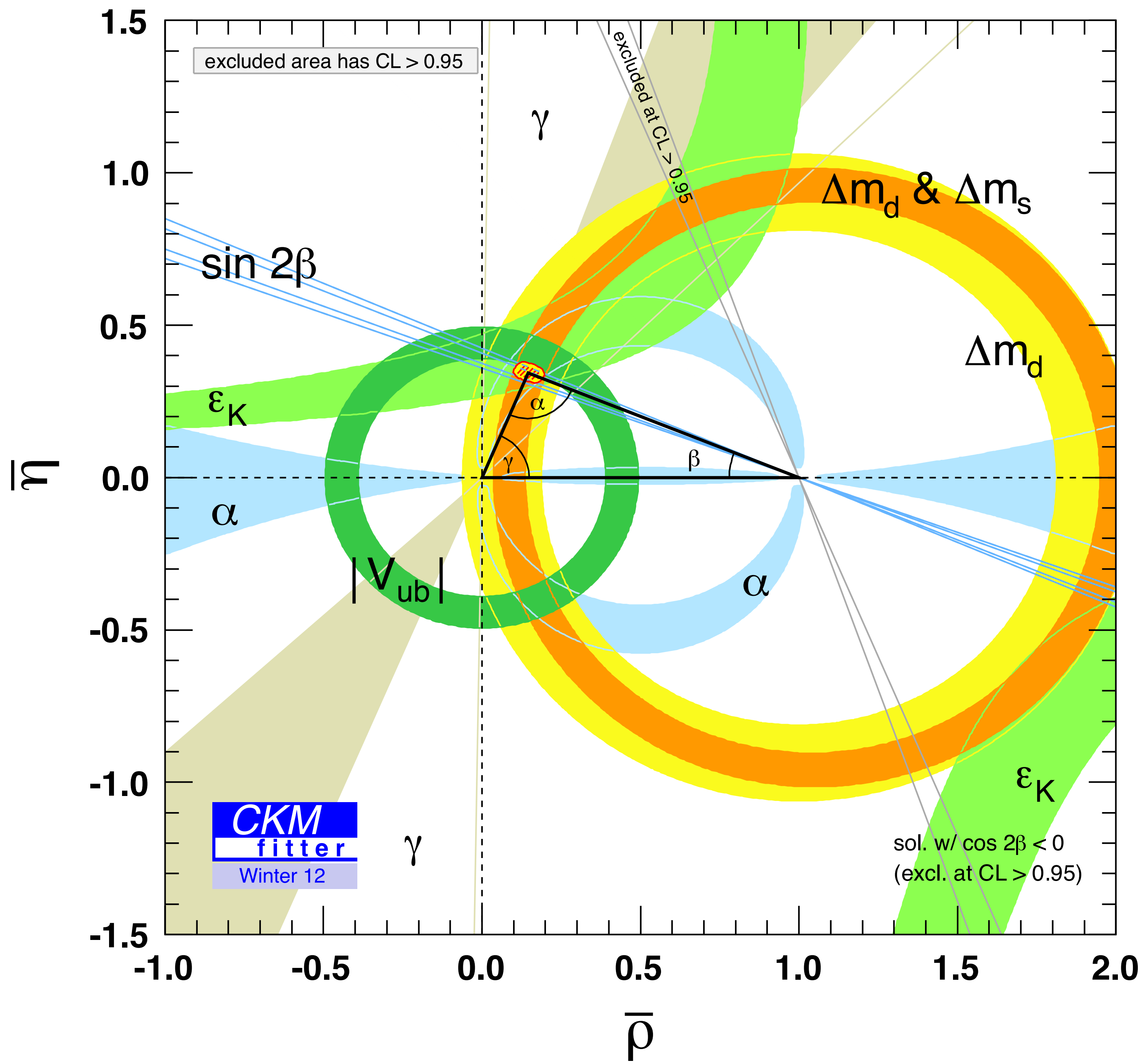
lattice QCD or inclusive decays

• • •

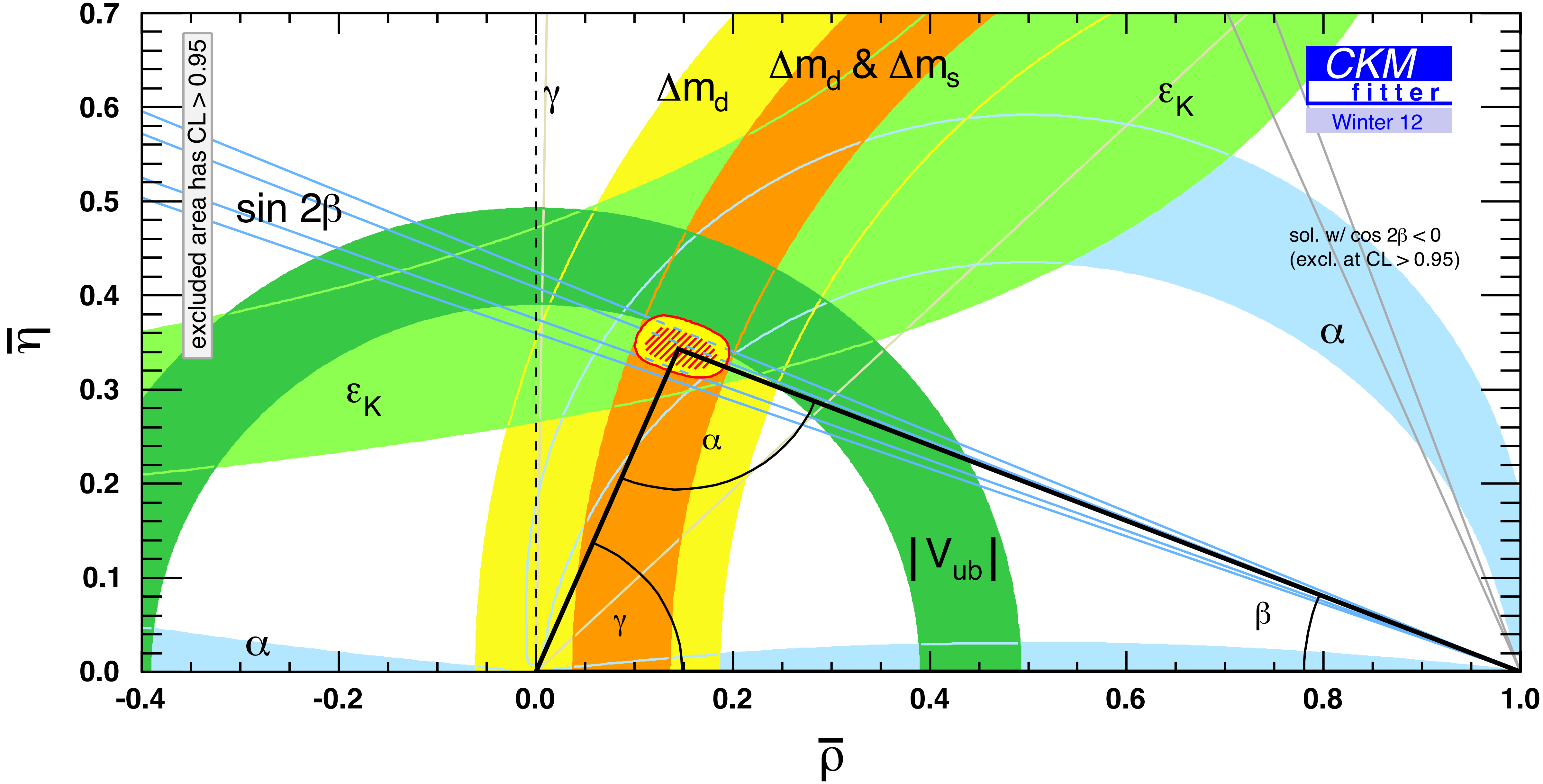


source: utfit.org

unitarity triangle ’12



Zoom



CKM fitter
Winter 12
excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_d & Δm_s
ε_K
ε_K
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
α
α
γ
β
|V_ub|
η̄
ρ̄
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0

- The SM is the dominant source for the observed flavor and CP violation.

Flavor changing neutral currents

blackboard

FCNC limits

UTfit 08, Isidori, Perez, Nir '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		Δm_{B_s}
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	3.7×10^2		Δm_{B_s}

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$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
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$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
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UTfit 08, Isidori, Perez, Nir '10

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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM structure…

UTfit 08, Isidori, Perez, Nir '10

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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM structure…

… or exist only at very high scales (10^2 - 10^5 TeV)

Lecture 2

The flavor puzzle

FCNC limits

UTfit 08, Isidori, Perez, Nir '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Observables
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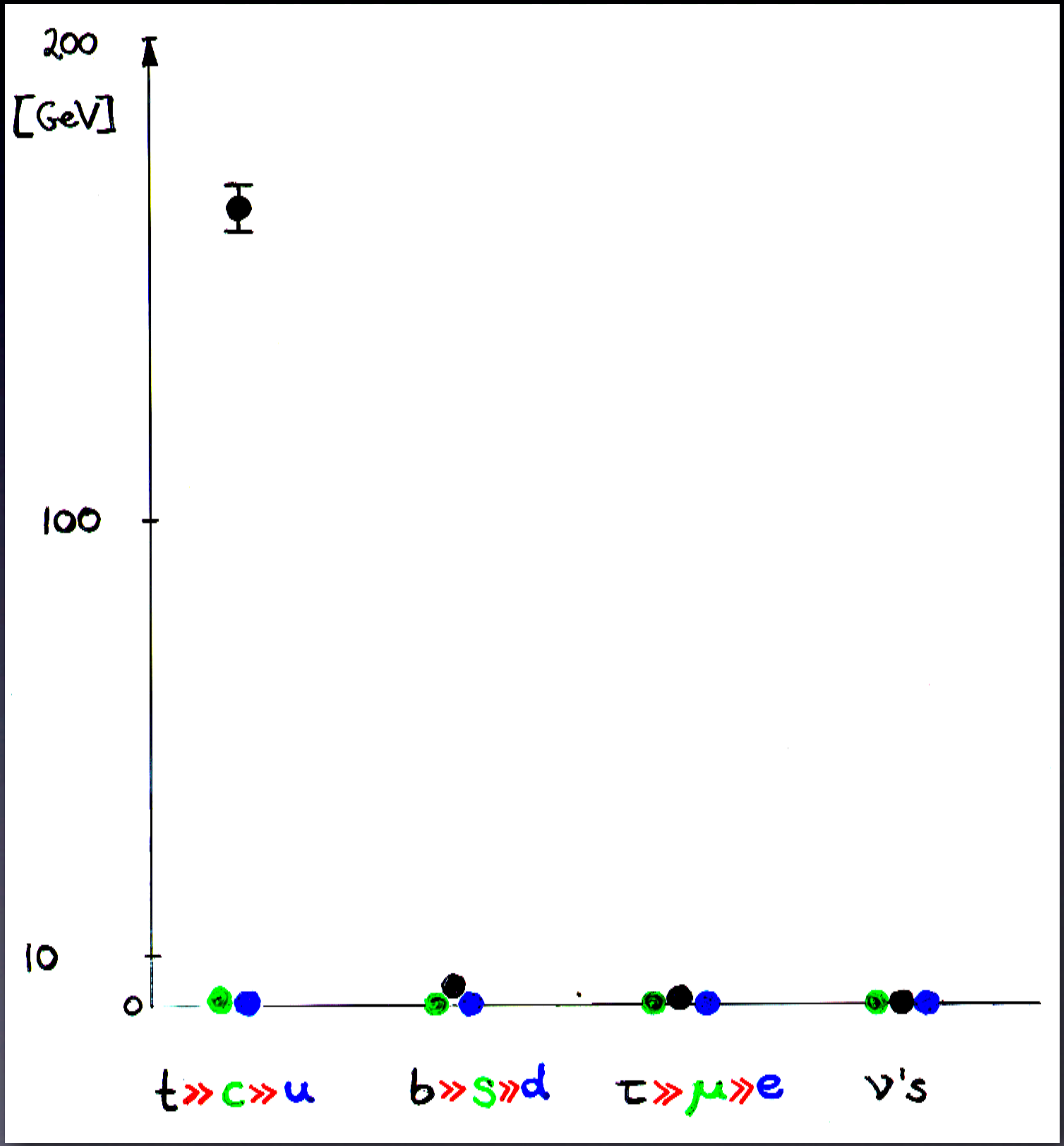
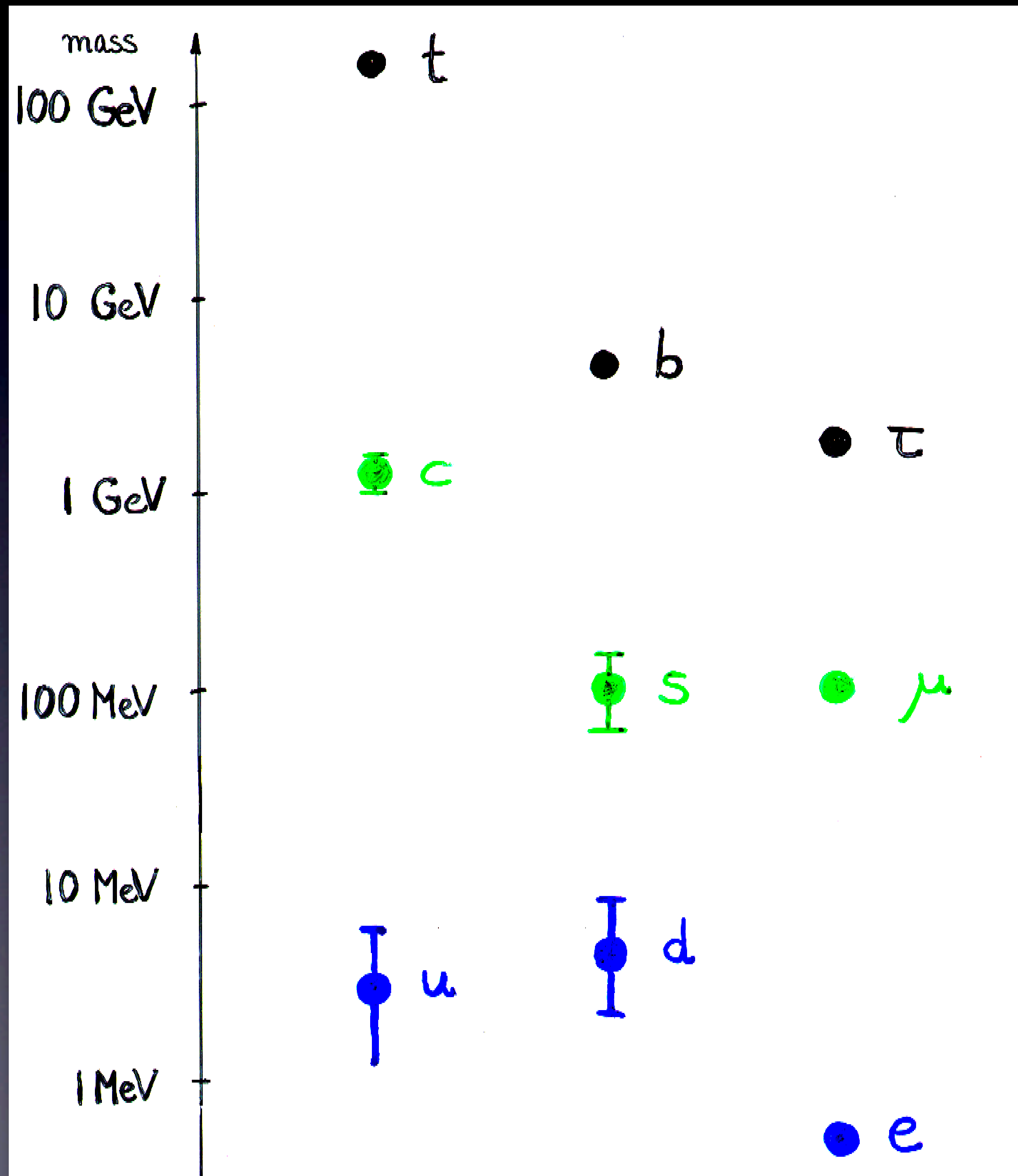
Quark and Lepton mass hierarchy



LHC view

Masses on a Log-scale



The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\left(2\cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

$$Y_U \approx \begin{pmatrix} 6\cdot 10^{-6} & -0.001 & 0.008+0.004i \\ 1\cdot 10^{-6} & 0.004 & -0.04+0.001 \\ 8\cdot 10^{-9}+2\cdot 10^{-8}i & 0.0002 & 0.98 \end{pmatrix}$$

Why this structure?

Other dimensionless parameters of the SM:

$g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{Higgs} \sim 1$,

The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\left(2\cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

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Why this structure?

Other dimensionless parameters of the SM:

g_s ~1, g ~ 0.6, g' ~ 0.3, λ_{Higgs} ~ 1, $|\theta| < 10^{-9}$

Log(SM flavor puzzle)

$$-\log|Y_D| \approx \mathrm{diag}\begin{pmatrix}11 & 8 & 4\end{pmatrix}$$

$$-\log|Y_U| \approx \begin{pmatrix} 12 & 7 & 5 \\ 14 & 6 & 3 \\ 18 & 9 & 0 \end{pmatrix}$$

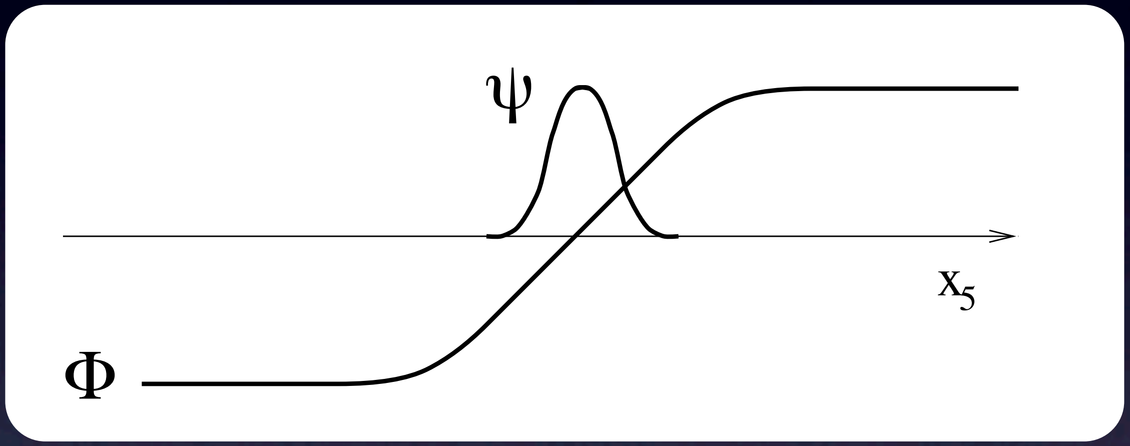
If $Y = e^{-\Delta}$, then the Δ don't look crazy.

Flavor from Geometry

Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization



$$\mathcal{S} = \int \mathrm{d}^5x \sum_{i,j} \bar{\Psi}_i [i\,\partial\!\!\!/_5 + \lambda\Phi(x_5) - m]_{ij}\Psi_j$$

$$\Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} = \begin{pmatrix} \psi_L^0 \\ 0 \end{pmatrix} + \mathrm{KK\,modes}$$

Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

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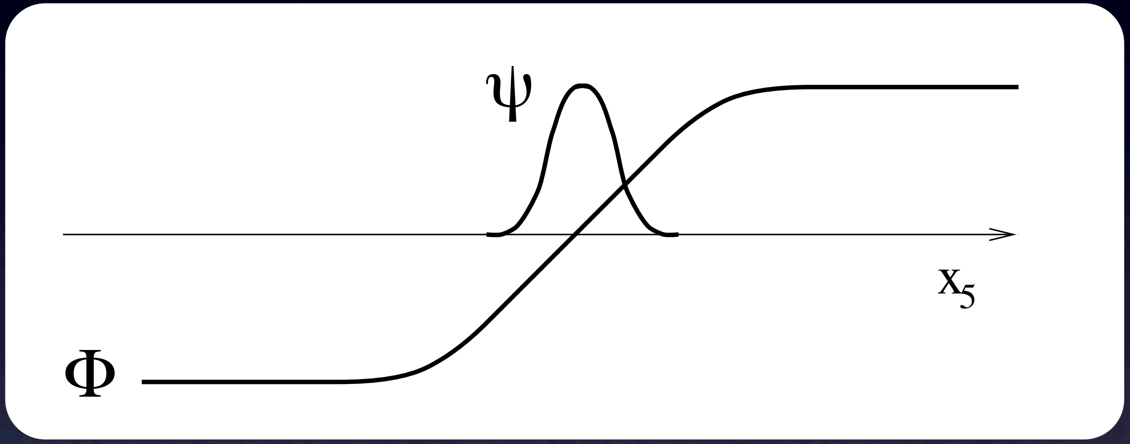

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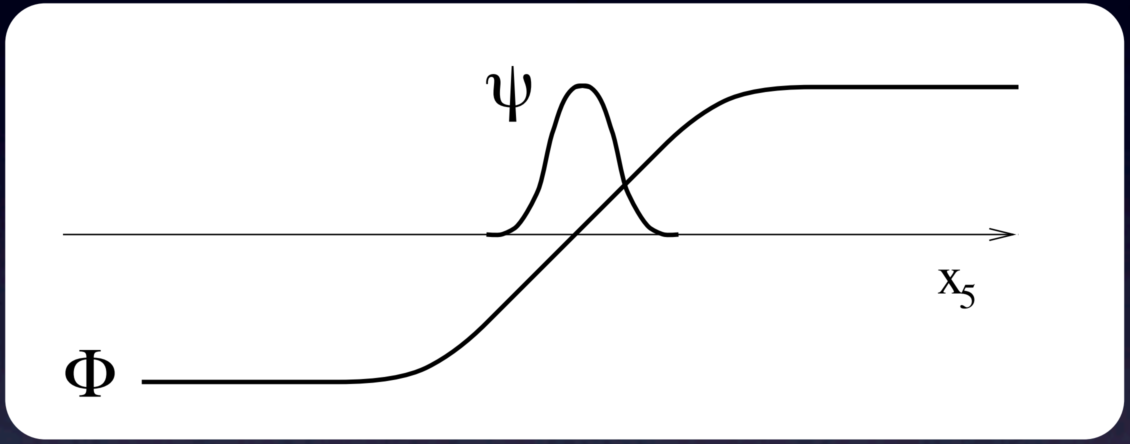

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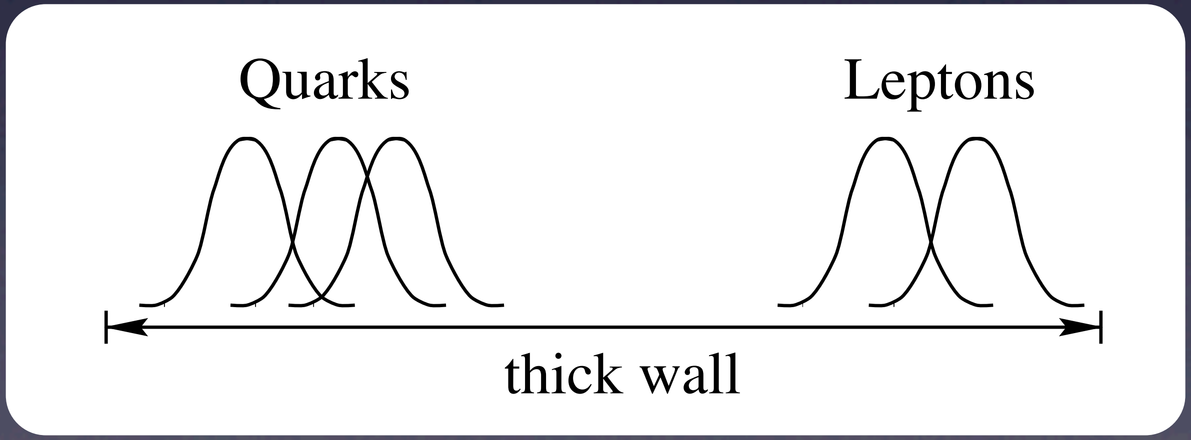
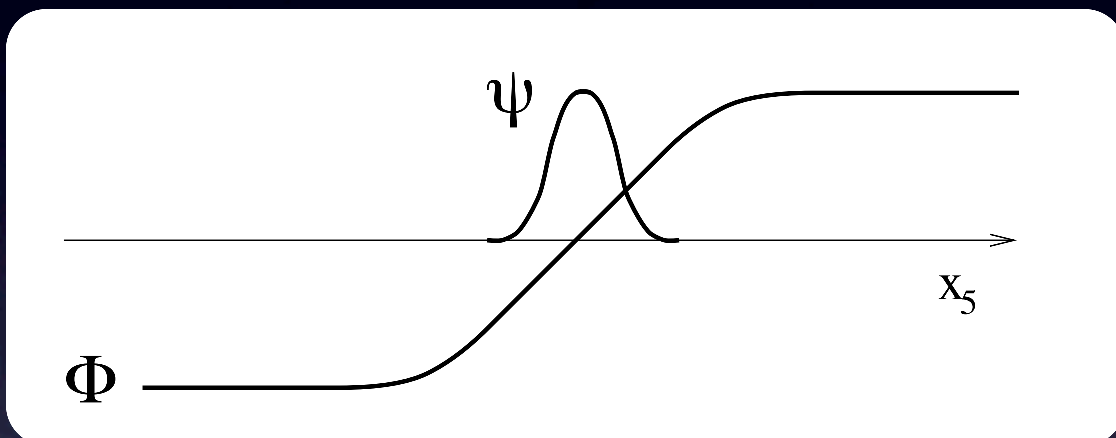


Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization



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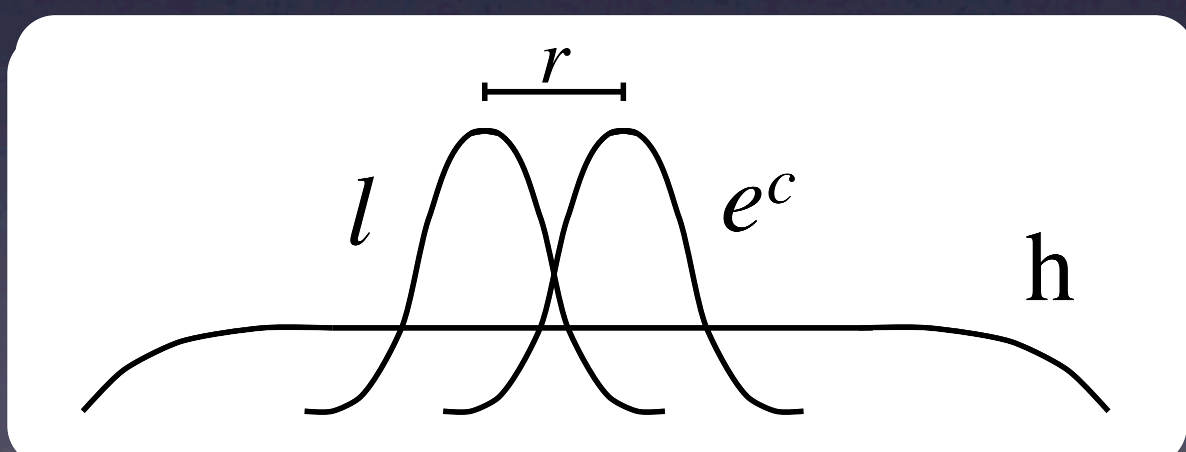

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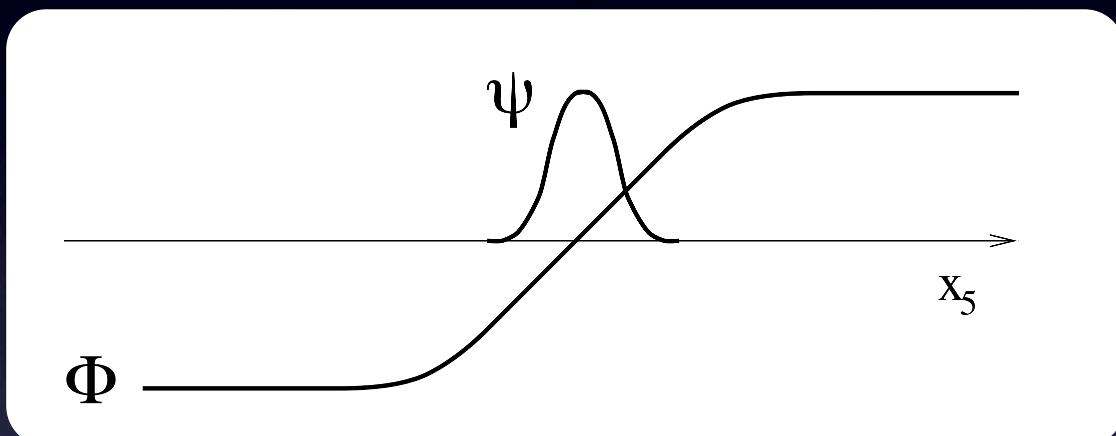

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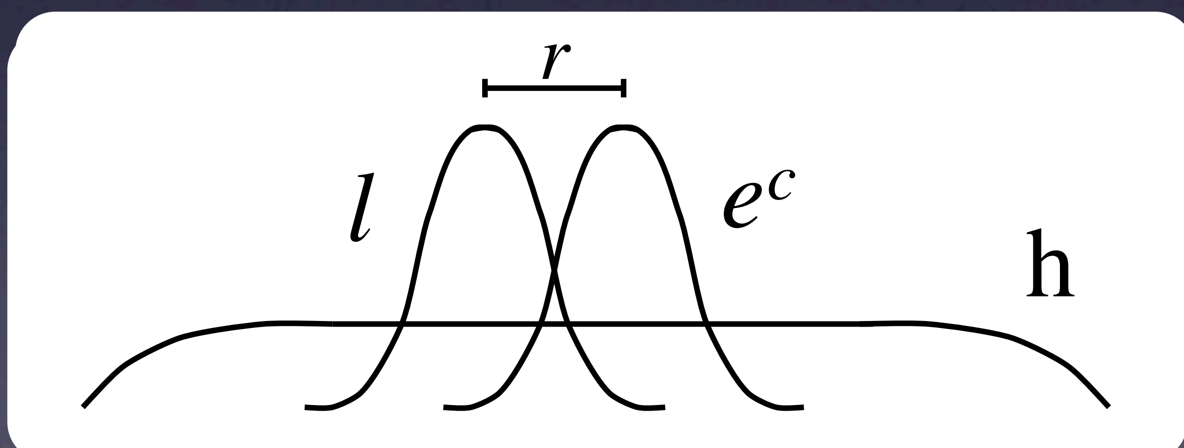

$$\int \mathrm{d}x_5\ \phi_l(x_5)\ \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int \mathrm{d}x_5\ e^{-\mu^2 x_5^2} e^{-\mu^2(x_5-r)^2} = e^{-\mu^2 r^2/2}$$

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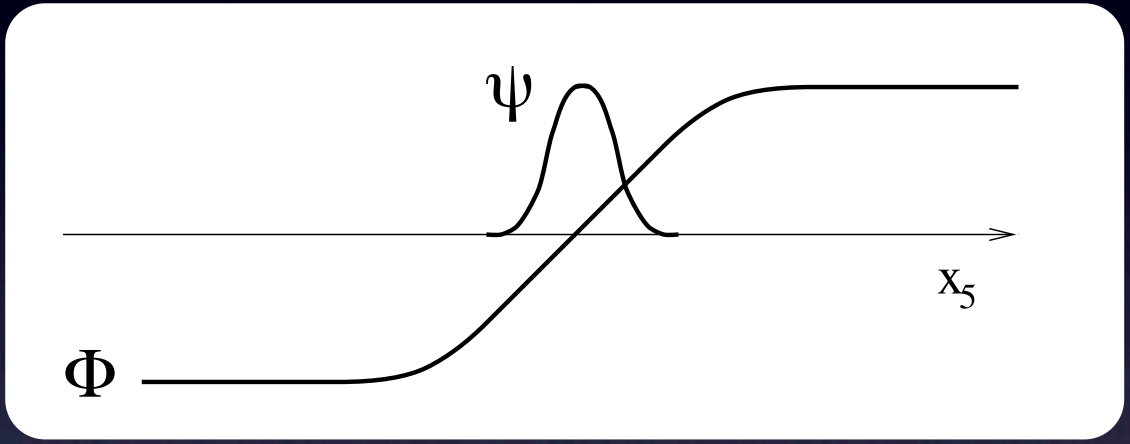

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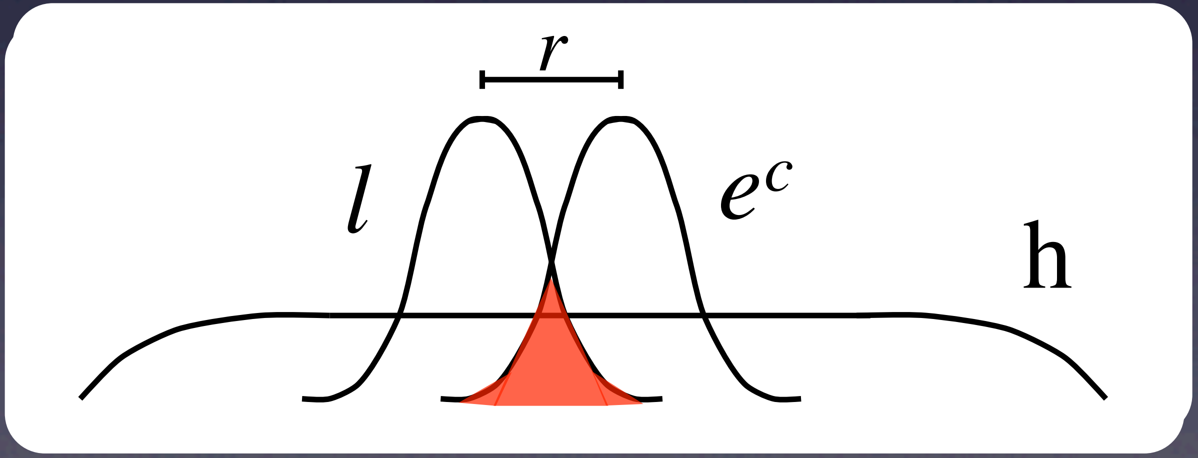

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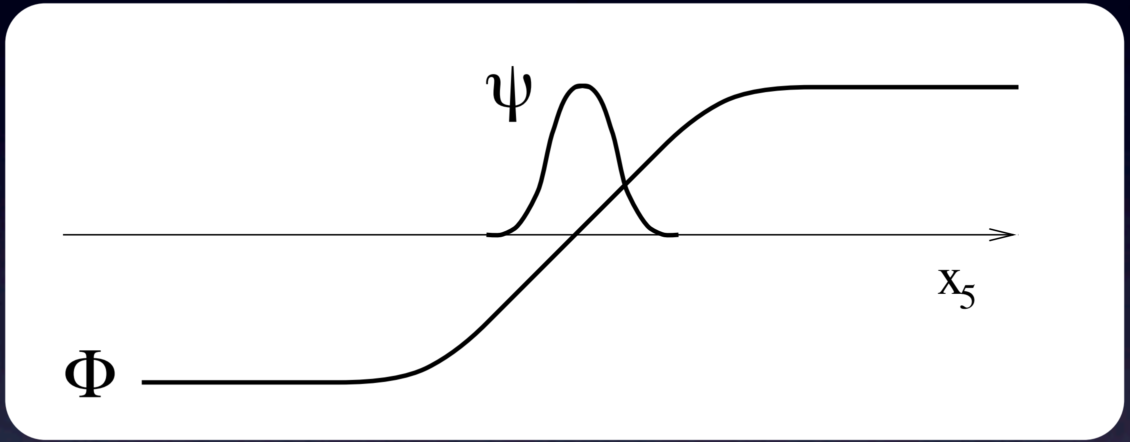

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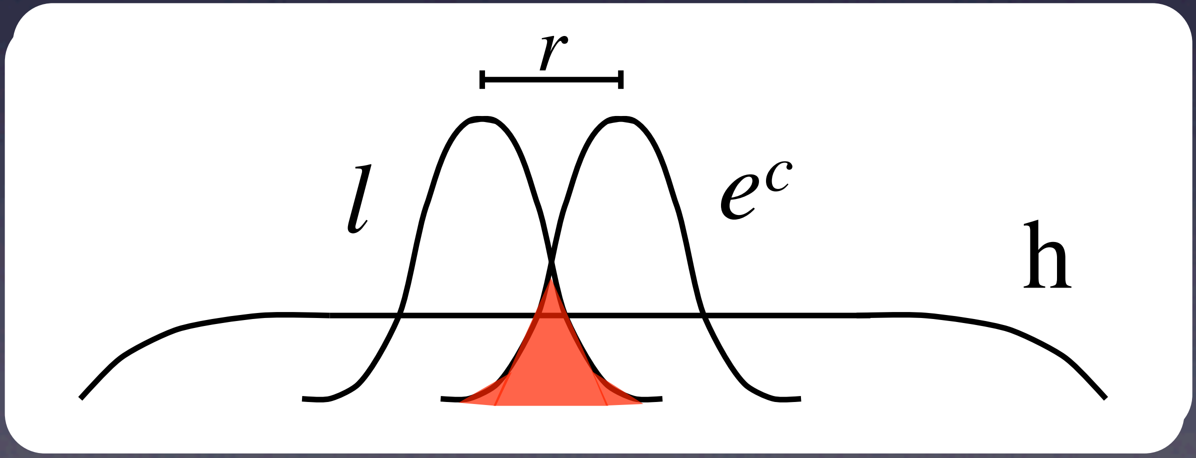


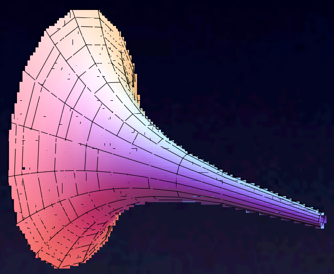
Log(flavor hierarchy)!

$$\int dx_5\ \phi_l(x_5)\ \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int dx_5\ e^{-\mu^2 x_5^2} e^{-\mu^2(x_5-r)^2} = e^{-\mu^2 r^2/2}$$

$$ds^2 = dx_\mu dx_\nu - dy^2$$

$$\downarrow$$

Randall, Sundrum



$$ds^2 = \left(\frac{R}{z}\right)^2 (dx_\mu dx_\nu - dz^2) \ .$$

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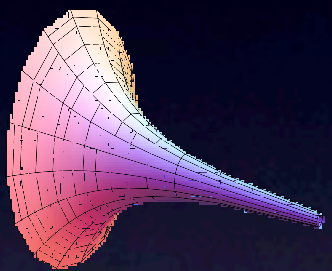
Randall, Sundrum



$$ds^2 = \left(\frac{R}{z}\right)^2 (dx_\mu dx_\nu - dz^2) .$$

✓ AdS/CFT intuition: reappraisal of strong EW symmetry breaking (composite Higgs, technicolor,…)

Flavor in RS

Grossman, Neubert; Gherghetta, Pomarol; Huber;

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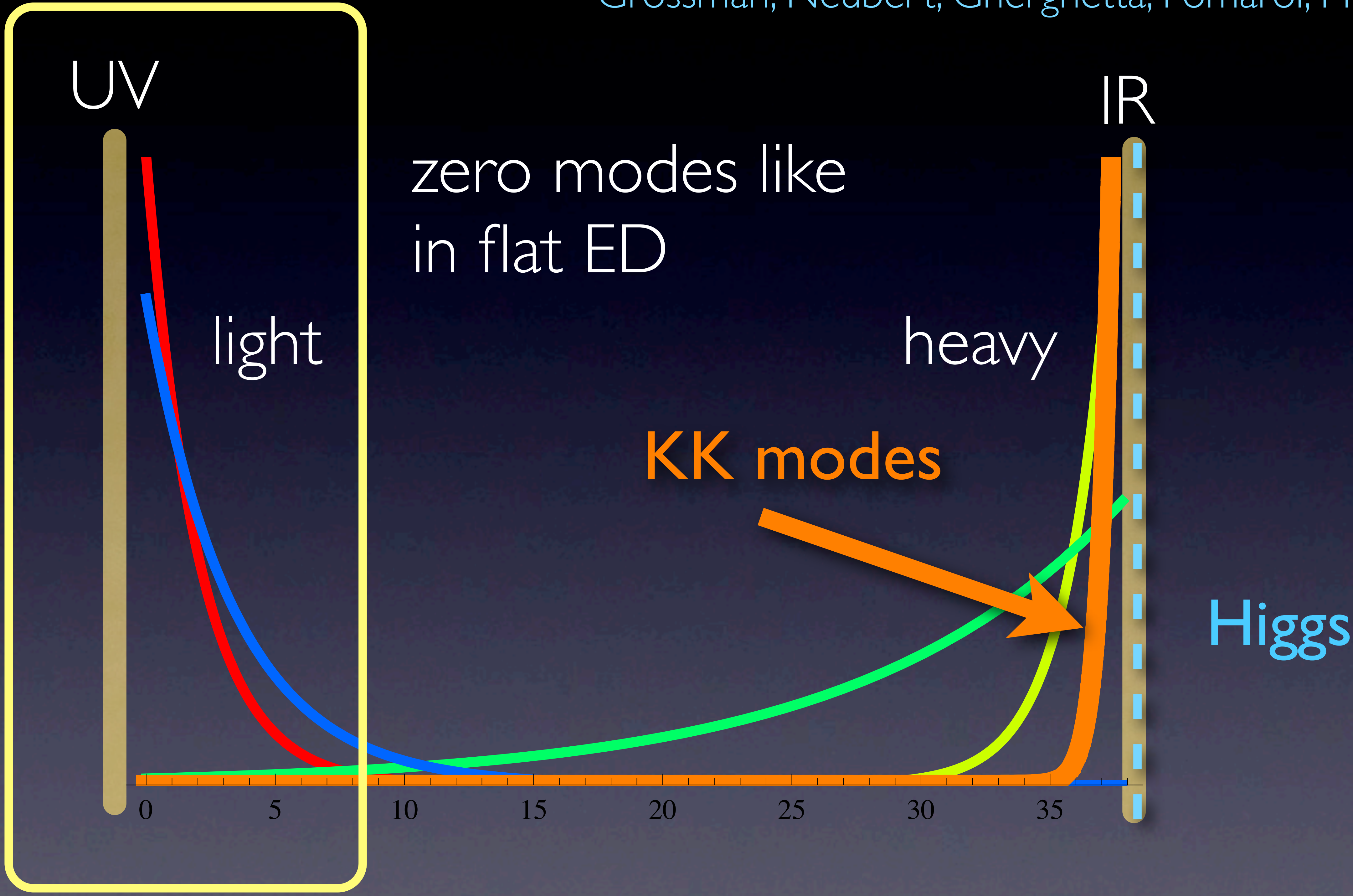

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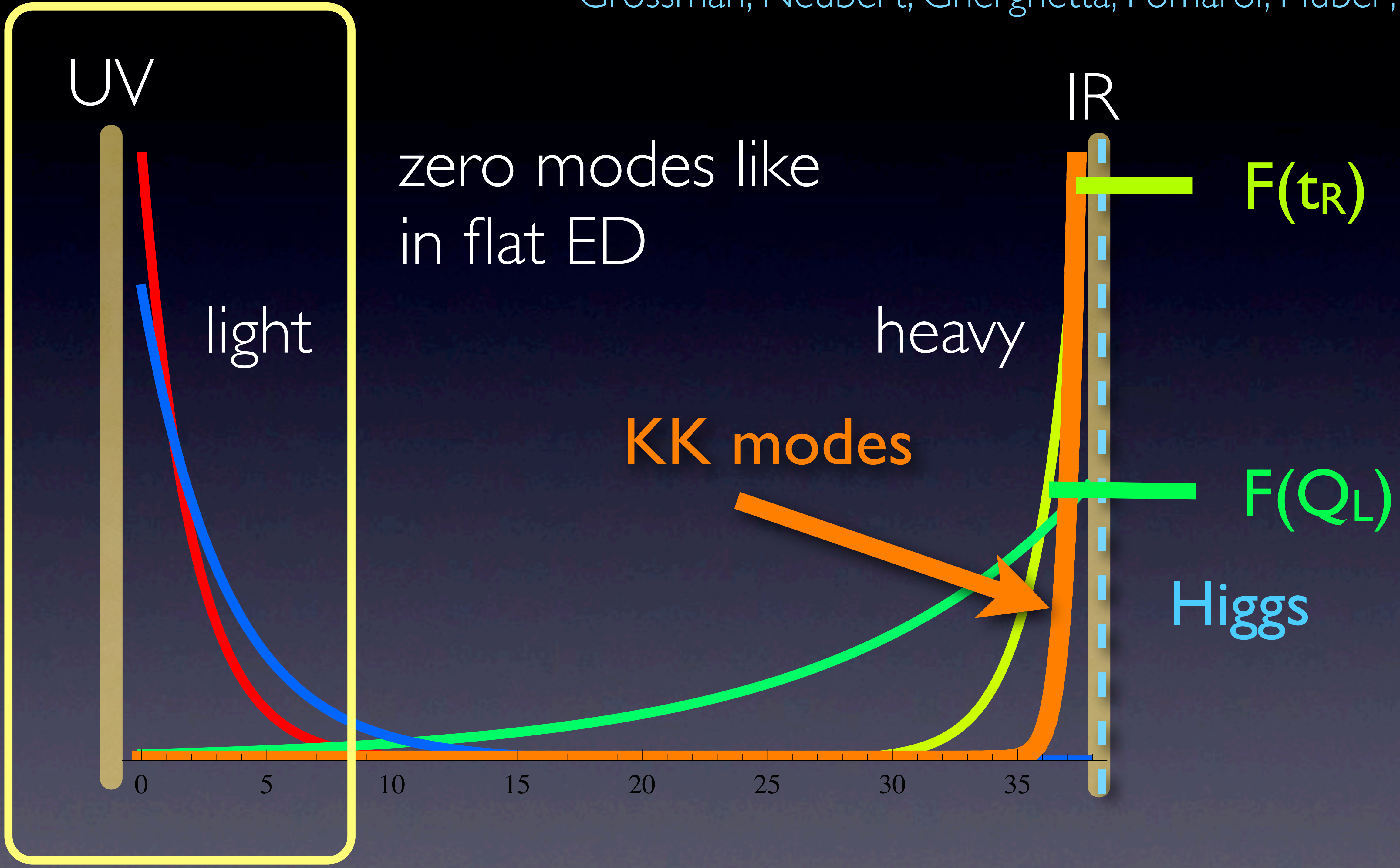


Two ways of giving mass to fermions…

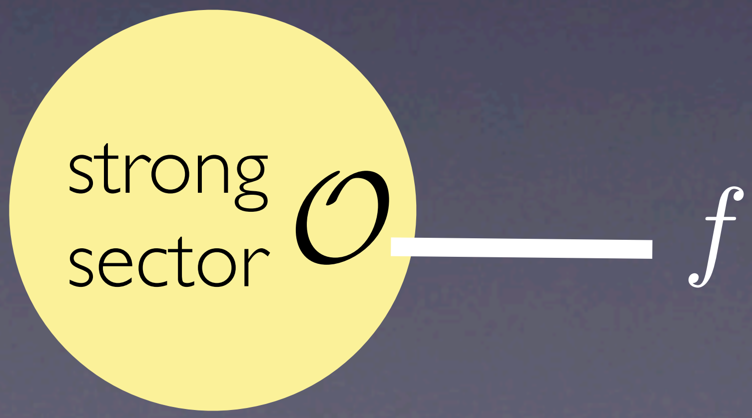
Bi-linear:

$$\mathcal{L} = y f_L \mathcal{O}_H f_R, \quad \mathcal{O}_H \sim (1,2)_{\frac{1}{2}}$$

Linear:

D.B. Kaplan '91

$$\mathcal{L} = y f_L \mathcal{O}_R + y_R f_R \mathcal{O}_L + m \mathcal{O}_L \mathcal{O}_R, \quad \mathcal{O}_R \sim (3,2)_{\frac{1}{6}}$$



Partial compositeness

$$\mathcal{L} = \mathcal{L}_{elem}(g_{elem}) + \mathcal{L}_{comp}(g_*) + \mathcal{L}_{mix}$$

$$1 \lesssim g_* \lesssim 4\pi$$

$$|SM\rangle = \cos\phi|elem.\rangle + \sin\phi|comp.\rangle$$

$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

Contino,Kramer, Son, Sundrum

1) Linear coupling of SM fields to composites

$$\mathcal{L}_{\rm UV} \supset \lambda \bar{\mathcal{O}}_R \psi_L$$

Contino, Pomarol

2) Strong sector conformal over some energy range

$$\mu \frac{d\lambda}{d\mu} = \gamma\lambda \qquad \gamma = \dim[\mathcal{O}_\mathcal{R}] + 3/2 - 4$$

$$\lambda \sim \left(\frac{\rm TeV}{M_{Pl}}\right)^\gamma$$

AdS/CFT translation:

$$\gamma = c - \frac{1}{2}$$

Partial compositeness

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$$|SM\rangle = \cos\phi|elem.\rangle + \boxed{\sin\phi}|comp.\rangle$$

$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

Degree of compositeness: $\boxed{\sin\phi = F(c) \sim \left(\frac{\mathrm{TeV}}{\mathrm{M_{pl}}}\right)^{c-\frac{1}{2}}}$

Flavor from symmetries

Hierarchies from symmetries

Froggatt, Nielsen '79

Add horizontal U(1)$_F$, flavon Φ_F ($m_\Phi \sim \Lambda$, q_F = -1)

$$Y_d^{ij} \left(\frac{\Phi_F}{\Lambda}\right)^{-q_i+h+d_j} \bar{Q}_L^i H D_R^j$$

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$$\Big\downarrow$$

$U(1)_F$ broken by $F = \langle\mathbf{\Phi}_F\rangle$, $\quad F < \Lambda$

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$U(1)_F$ broken by $F = \langle\Phi_F\rangle$, $\quad F < \Lambda$

$$Y_{eff,d}^{ij} = Y_d^{ij} \left(\frac{F}{\Lambda}\right)^{-q_i+h+d_j}$$

=> hierarchies

Similar results…

hierarchical Yukawa

anarchic ("structure-less")

$$\mathrm{Mass}_{ij} \propto Y_{ij} e^{-MR(c_i+c_j)}$$ split fermions/RS

$$\propto Y_{ij} \left(\frac{\mu_{\mathrm{low}}}{\mu_{\mathrm{high}}}\right)^{\gamma^i+\gamma^j}$$ strong dynamics

$$\propto Y_{ij} \left(\frac{\langle\Phi\rangle}{M_{\mathrm{mess}}}\right)^{Q^i-Q^j}$$ Froggatt-Nielsen

'Tutte le strade portano a Roma'