BSM 3/3

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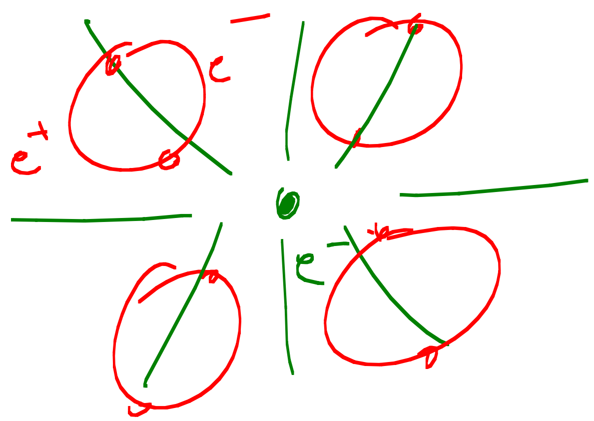

Supersymmetry
(new space-time symmetry)

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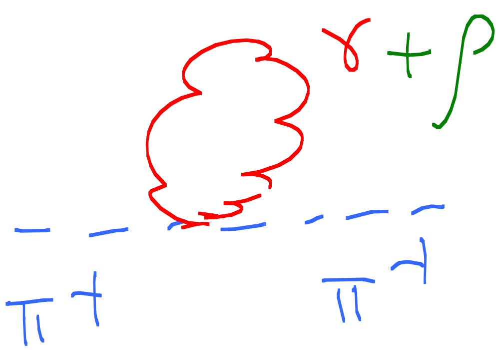
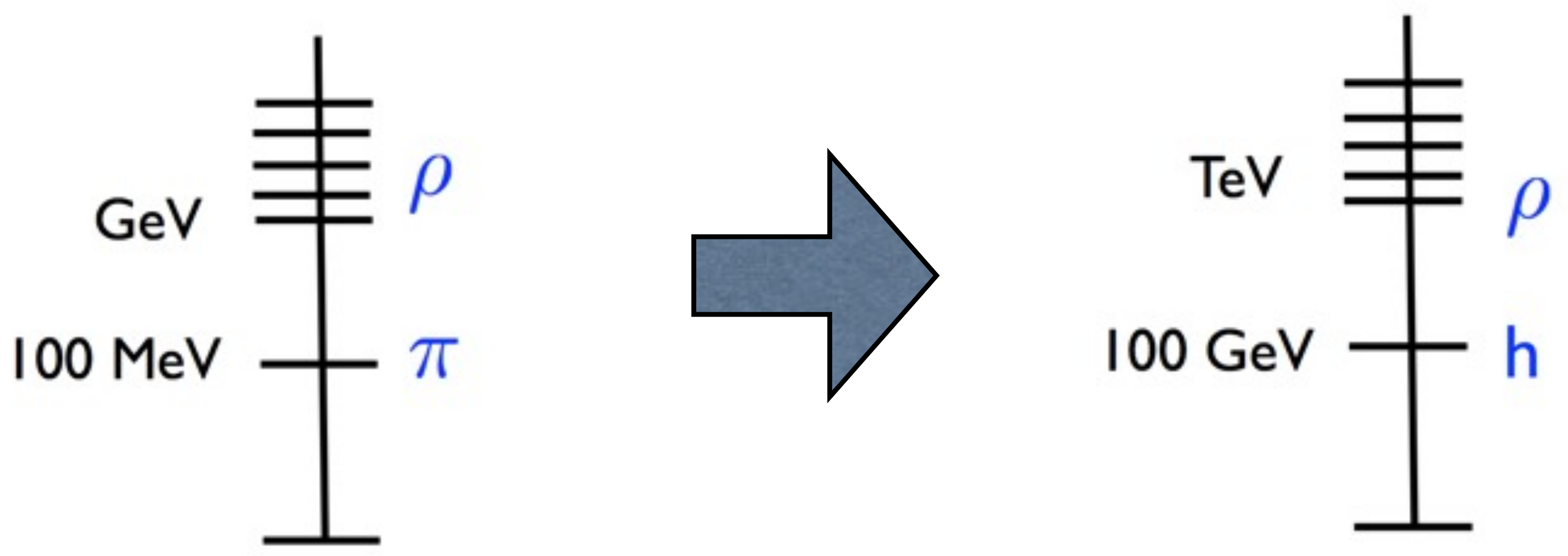


Composite Higgs

Strong EWSB
(Composite Higgs)



QCD　　　　Higgs as a pGB

Why is the Higgs light?

Kaplan; Agashe et. al

Inspired by QCD: (pseudo) scalar pion is the lightest state

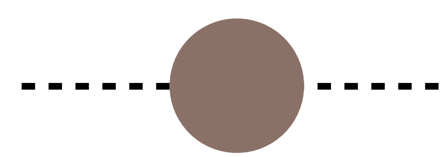
Shift symmetry…

$$\pi \to \pi + c$$

… protects its mass.

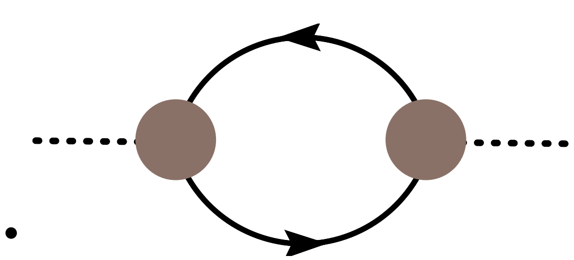
Interactions are perturbative for $E \ll 4\pi f$

No pure composite effects due to Goldstone symmetry



= 0

Shift symmetry broken by elementary-composite couplings:



$$m_h^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

Supersymmetry is a weakly coupled solution to the hierarchy problem. We can extrapolate physics to the Planck scale, complete the MSSM in a GUT.

There is another way and it's already in use. Nature already employs a strongly coupled mechanism to explain why

$$\Lambda_{\rm QCD} \ll M_{\rm Planck}$$

$$\sim 1\,{\rm GeV} \qquad 10^{19}\,{\rm GeV}$$

QCD

David J. Gross

H. David Politzer

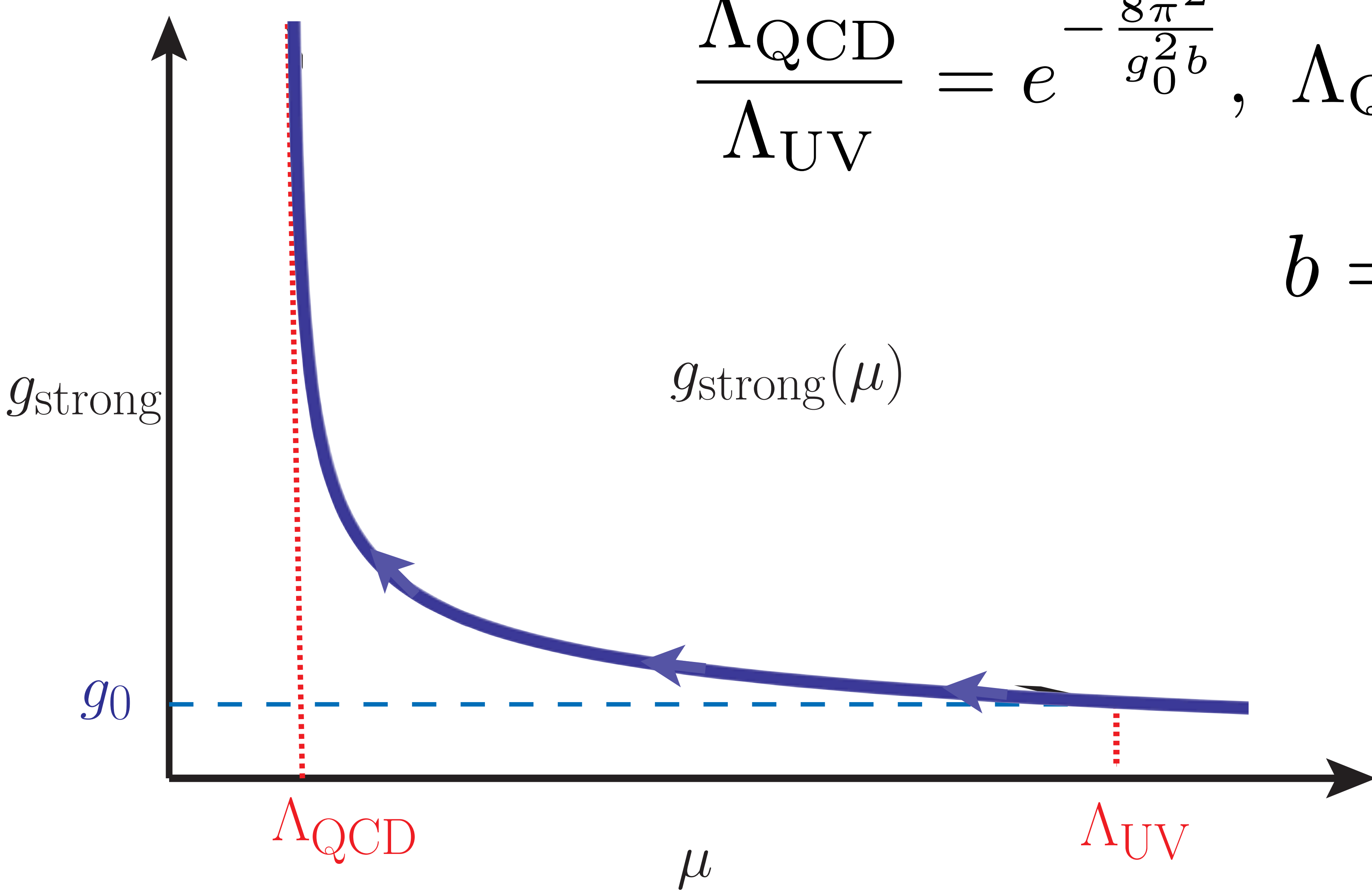
Frank Wilczek

Fix QCD coupling at some high scale

→ exponential hierarchy generated dynamically

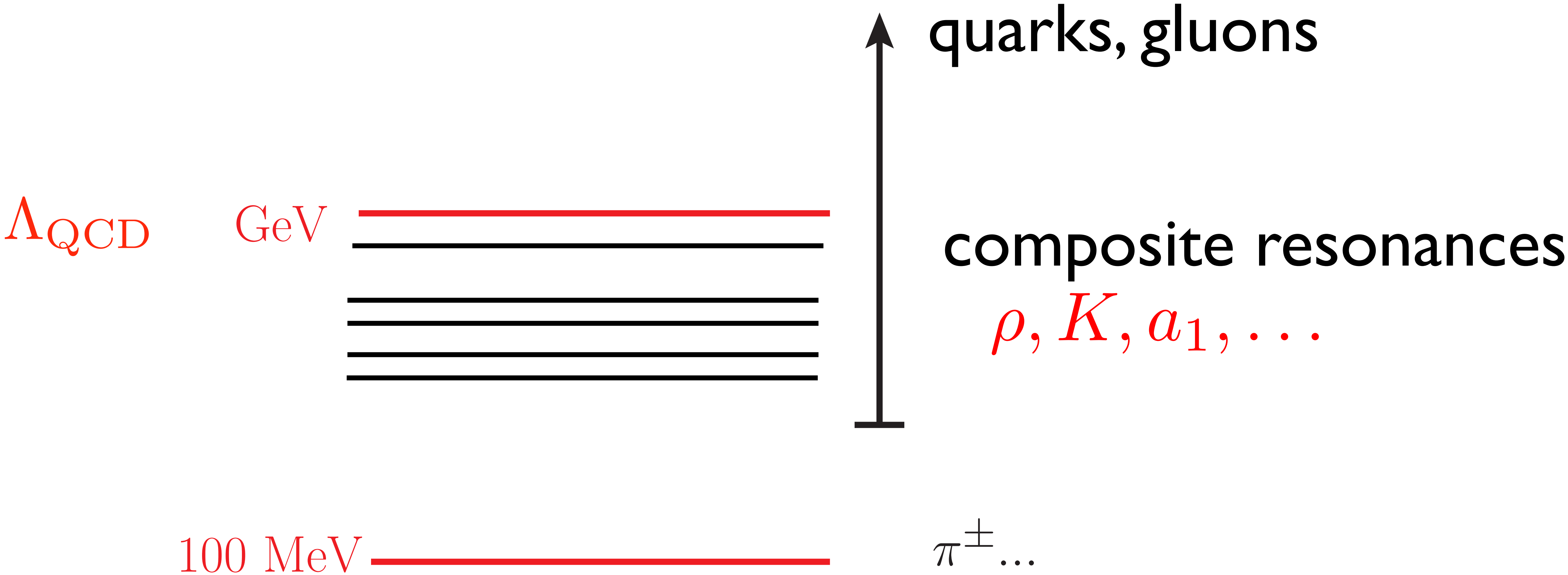
$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \quad \Lambda_{\rm QCD} \leq \ \text{GeV}$$

$$b = 7$$



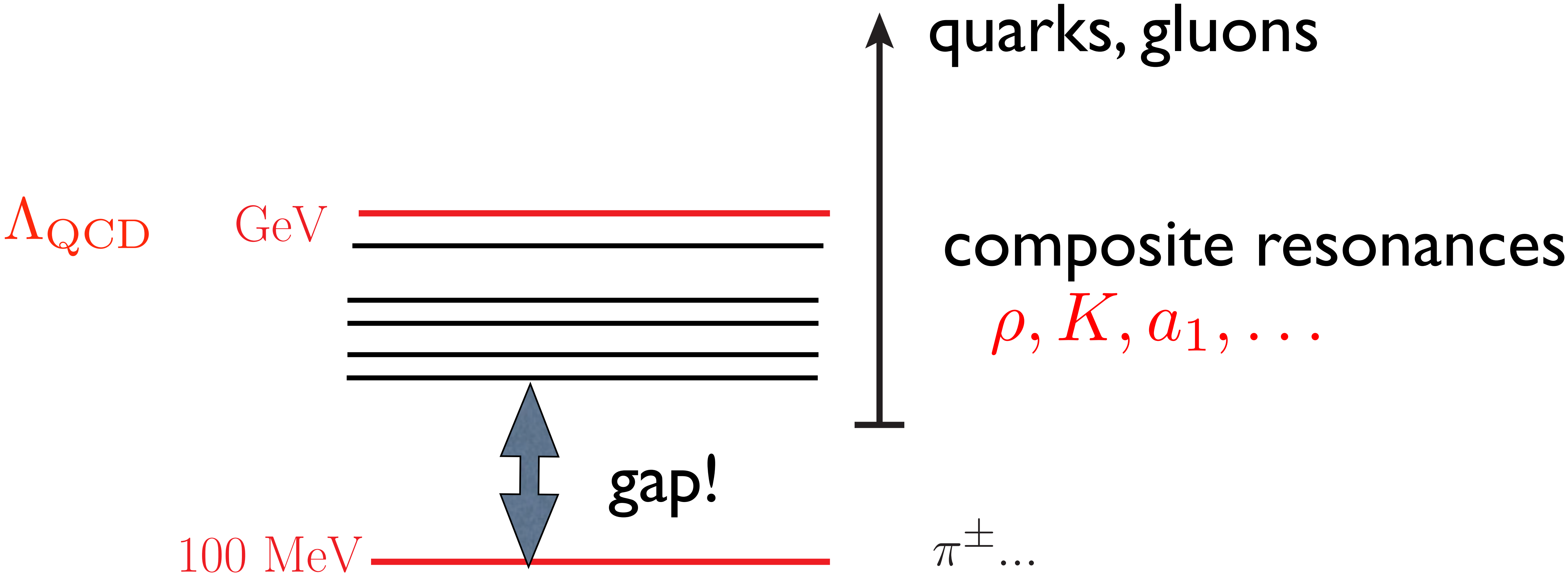
Asymptotic freedom

QCD: composite bound states



At strong coupling, new resonances are generated

QCD: composite bound states



At strong coupling, new resonances are generated

QCD vs. EWSB

QCD dynamically breaks SM gauge symmetry

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

$$\langle \bar{q}_L q_R \rangle \simeq \Lambda_{\rm QCD}^3 \sim \ (\rm GeV)^3$$

QCD vs. EWSB

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$$\langle \bar{q}_L q_R \rangle \simeq \Lambda^3_{\rm QCD} \sim \ (\rm GeV)^3$$

The QCD masses of W/Z are small

$$m_{\rm W,Z} \sim \frac{g}{4\pi}\Lambda_{\rm QCD} \sim 100\ \rm MeV$$

Longitudinal components of W & Z have tiny admixture of pions…

Technicolor

Scaled up version of QCD mechanism

$$\langle \bar{q}'_L q'_R \rangle \sim \Lambda^3_{\rm TC}, \quad \Lambda_{\rm TC} \sim \ {\rm TeV}$$

Technicolor, doesn't have a Higgs …

* the Higgs as the dilaton
as the last bastion …

Composite Higgs

- Want to copy QCD, but extend pion sector (QCD: $\pi^0, \pi^\pm$)
- Higgs as a (pseudo) Goldstone boson

Need to learn about goldstone bosons…

Quantum Protection

Symmetries can soften quantum behaviour

$$\mathcal{L} = |\partial_\mu \phi|^2 + \boxed{\mu^2 |\phi|^2} - \lambda |\phi|^4 + \ldots$$

breaks susy → corrections must be proportional to susy breaking

Shift symmetry

Higgs mass term can be forbidden

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

$$\phi \to e^{i\alpha} \phi$$

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$\phi \to \phi + \alpha$ works!

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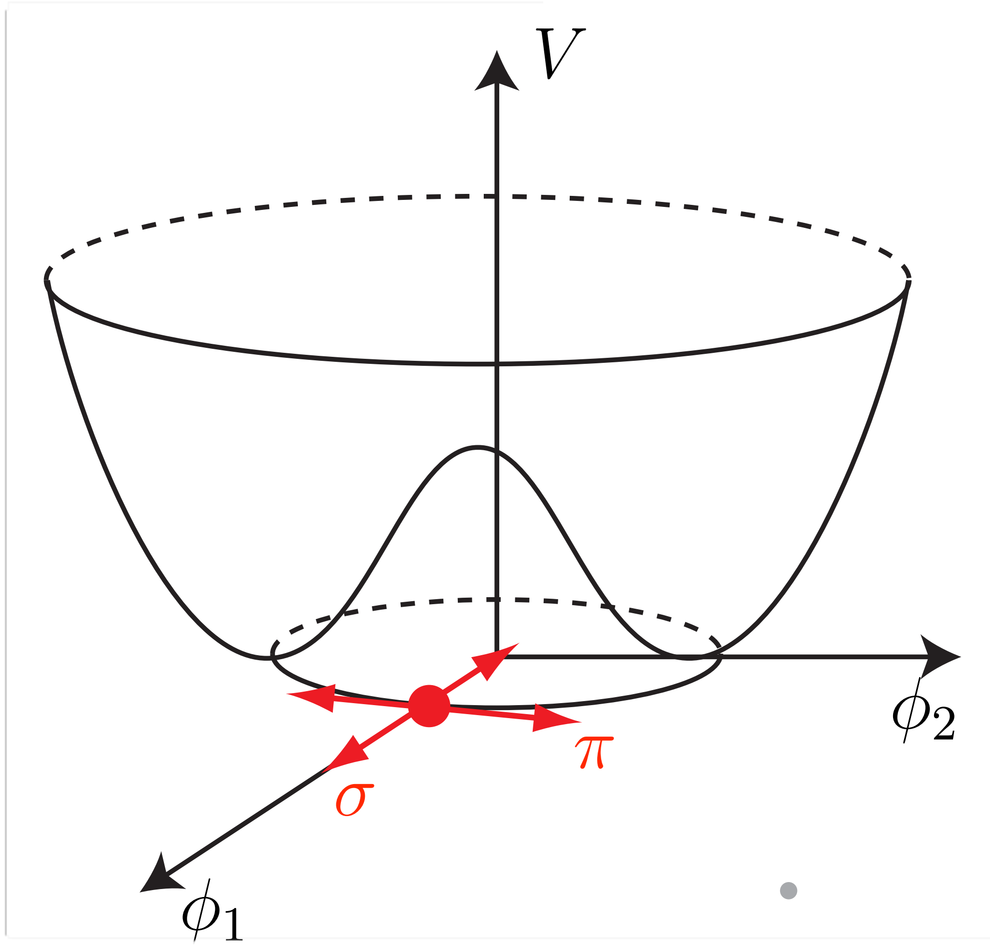
$\phi \to \phi + \alpha$ works!

Can we make the Higgs transform this way?

Spontaneous breaking of U(1)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}}$$



Instead describing this with

$$\phi = \phi_1 + i\phi_2$$

redefine field to

$$\phi(x) = \frac{1}{2} e^{i\pi(x)/f} (f + \sigma(x))$$

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

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$$\partial^\mu \phi^\dagger \partial_\mu \phi = \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma + \frac{1}{2} (1 + \sigma/f)^2 \frac{1}{2} \partial^\mu \pi \partial_\mu \pi$$

$$V(|\phi(x)|^2)$$

$$\mathcal{L} = |\partial_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 + \ldots$$

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no dependence on $\pi(x)$

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no mass term

$$V(|\phi(x)|^2) = V(\sigma(x))$$

no dependence on $\pi(x)$

$$\frac{1}{2}\left(1+\sigma(x)/f\right)^2 \frac{1}{2}\partial^\mu\pi\partial_\mu\pi + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - V(\sigma(x))$$

Using this parameterization there's a new symmetry:

$$\pi(x) \to \pi(x) + \alpha$$

because

$$\partial_\mu(\pi(x) + \alpha) = \partial_\mu\pi(x)$$

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But what happened to the U(1) symmetry ?

Fields are real...

But what happened to the U(1) symmetry ?

$$\phi \to e^{i\alpha}\phi$$

$$e^{i\pi(x)/f}(f+\sigma(x)) \to e^{i\alpha}e^{i\pi(x)/f}(f+\sigma(x))$$

$$\sigma(x) \to \sigma(x)$$
$$\pi(x) \to \pi(x) + \alpha$$

Phase rotation becomes shift symmetry

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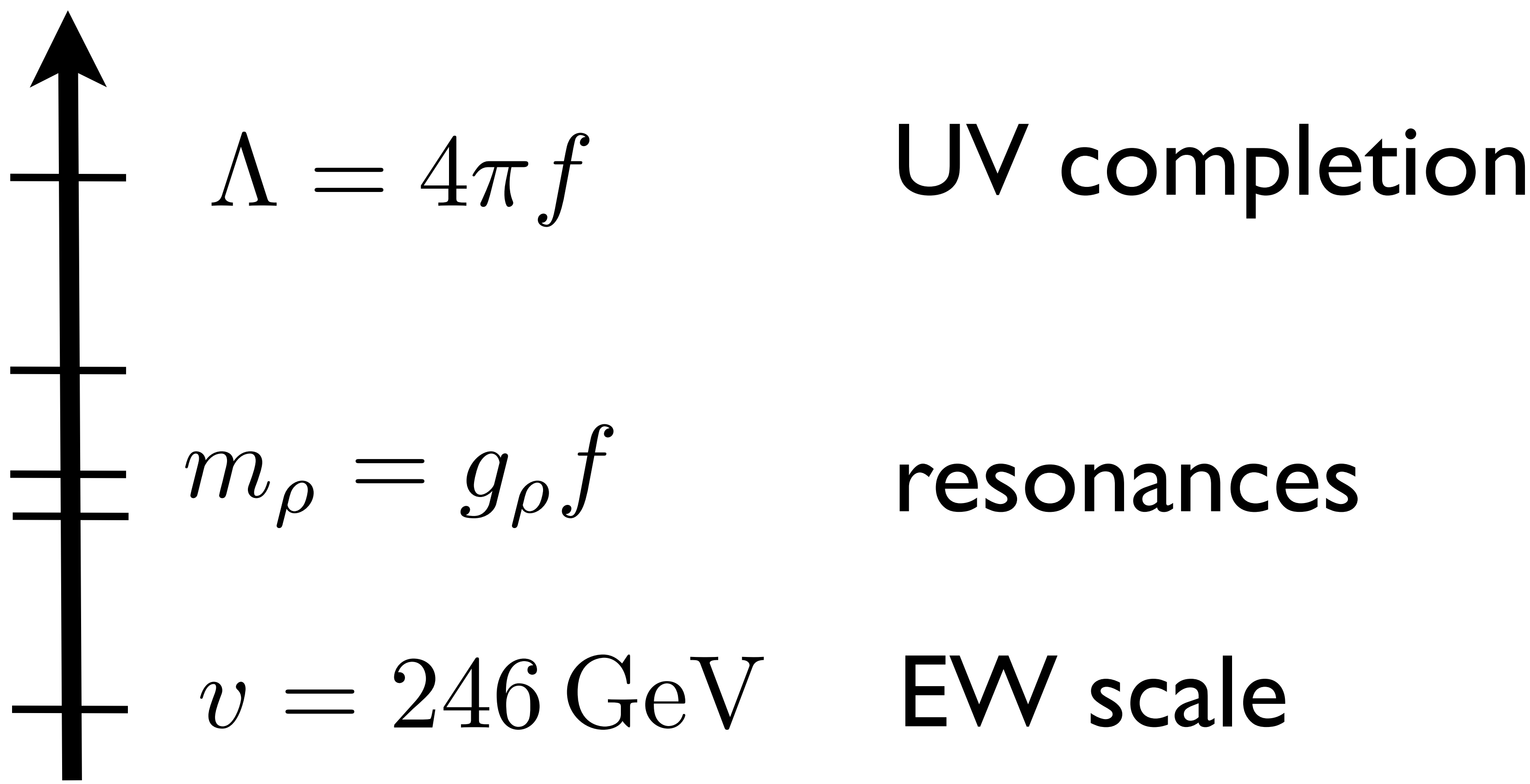
Phase rotation becomes shift symmetry

$\pi(x)$ is massless **but** also no

- gauge couplings
- potential
- yukawas

Semi-realistic model



$\Lambda = 4\pi f$
UV completion
$m_\rho = g_\rho f$
resonances
$v = 246\,\mathrm{GeV}$
EW scale

pGB Higgs

$SU(3) \to SU(2)$

Break symmetry using $\langle \Phi \rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$

Goldstone bosons = # broken generators

$$\Phi = \frac{1}{\sqrt{2}} e^{i\Pi/f} \begin{pmatrix} 0 \\ 0 \\ f + \sigma \end{pmatrix} \qquad \Pi = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta/\sqrt{3} & 0 & H_1 \\ 0 & \eta/\sqrt{3} & H_2 \\ H_1^* & H_2^* & -2\eta/\sqrt{3} \end{pmatrix}$$

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Expand

$$\Phi(x) = \begin{pmatrix} H_1(x) \\ H_2(x) \\ -\frac{2}{\sqrt{2}}\eta(x) \end{pmatrix} + \ldots$$

Contains a Higgs: $H = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = SU(2)$ doublet

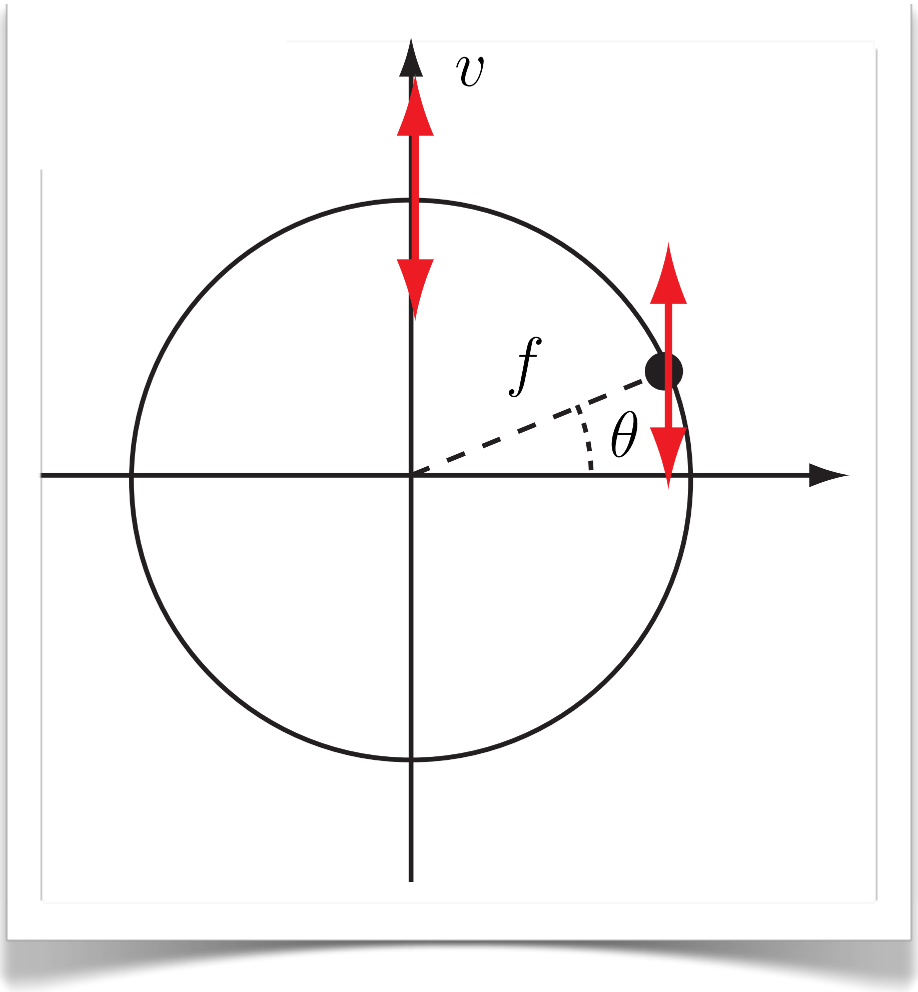
$SU(3) \to SU(2)$

pGB Higgs

Unbroken gauge symmetry in global SU(2), dynamics generates ‘vacuum mis-alignment’

SU(2)$_L$ vs. SU(2)

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin\theta \\ \cos\theta \end{pmatrix}$$ SU(2)$_L$



EW symmetry broken

pGB Higgs

$$\langle \Phi \rangle = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \sin\theta \\ \cos\theta \end{pmatrix}$$

SU(2)$_L$

Electro-weak scale $v = f \sin\theta$

$f \sim$ scale of new physics

$\sin\theta \ll 1 \Leftrightarrow f \gg v$ (SM limit)

$$\Rightarrow \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Collective Breaking

We now want to add a yukawa coupling to give mass to the top quark

$$\lambda_t \bar{Q}_i H_i^c t_R \qquad \text{i: sum over SU(2)}$$

Fundamental field is a triplet

$$\phi = \exp\left\{ i \begin{pmatrix} & & h_1 \\ & & h_2 \\ h_1^* & h_2^* & \end{pmatrix} \right\} \begin{pmatrix} \\ \\ f \end{pmatrix}$$

Top yukawa: 1st try

$$\sum_i^2 \lambda_t \bar{\phi}_i H_i^c t_R$$ works, gives mass to the top

… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:

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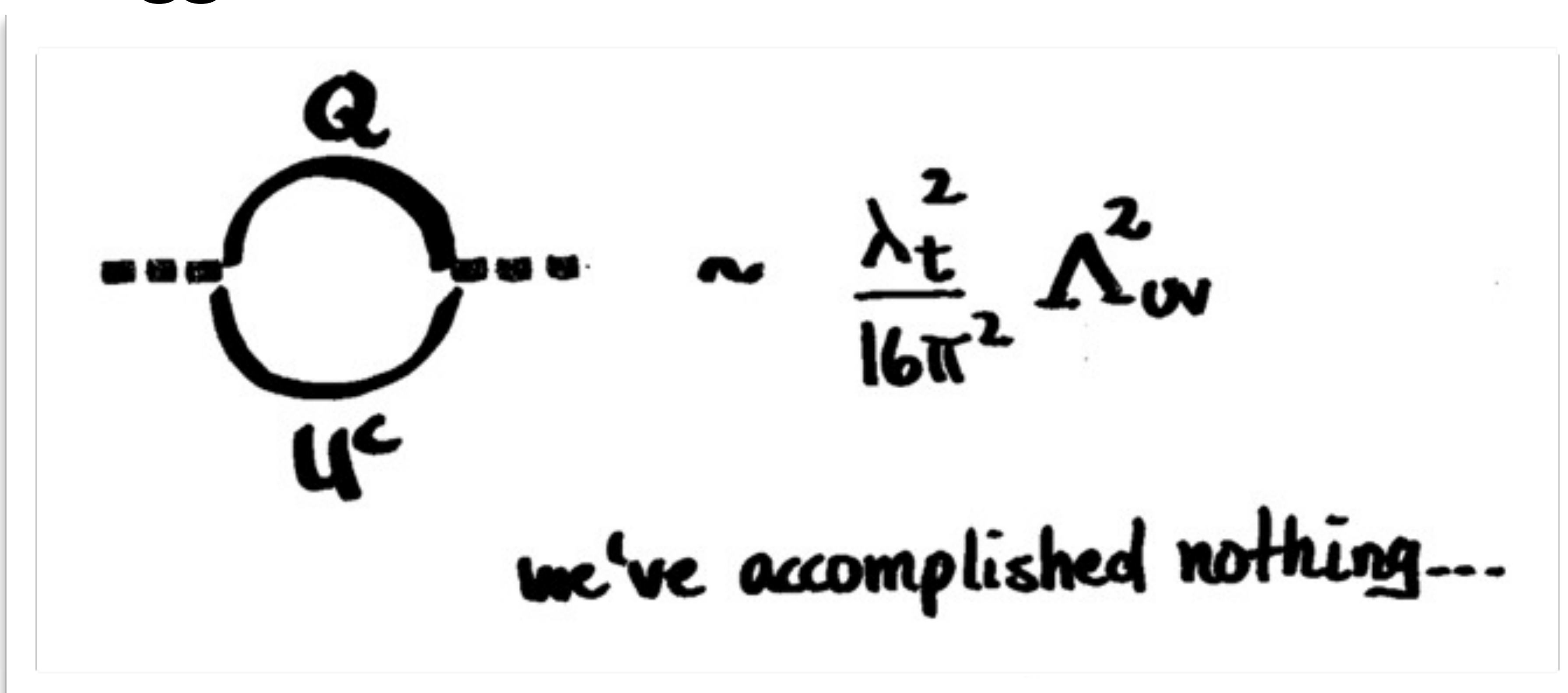
… but breaks SU(3) structure explicitly, does not respect Goldstone symmetry protecting the Higgs mass:



Collective breaking

Example: $SU(3) \rightarrow SU(2)$ (ignore $U(1)_Y$ again)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ {}_2 \end{pmatrix}$$

Gauge full $SU(3)$ ⇒ exact symmetry

$$\Psi_L = \begin{pmatrix} t_L \\ b_L \\ T_L \end{pmatrix} \qquad t_{1R},\, t_{2R},\, b_R$$

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$$\mathcal{L}_{\text{Yukawa}} = y_1 \bar{\Psi}_L \Phi_1 t_{1R} + y_2 \bar{\Psi}_L \Phi_2 t_{2R}$$

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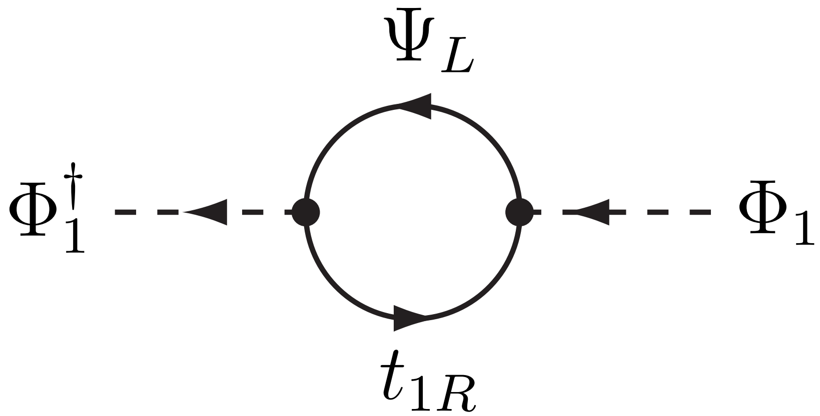
$y_1 \to 0$ ⇒ exact $SU(3)_2 \to SU(2)_2$ and *vice versa*

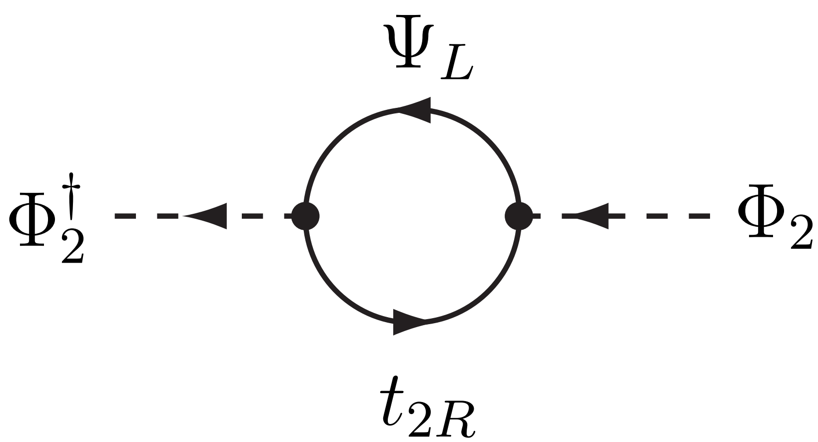
Both $y_1, y_2 \neq 0$ required for non-derivative couplings of PNGB Higgs



$$\sim \underbrace{\frac{y_1^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_2 \to SU(2)_2$

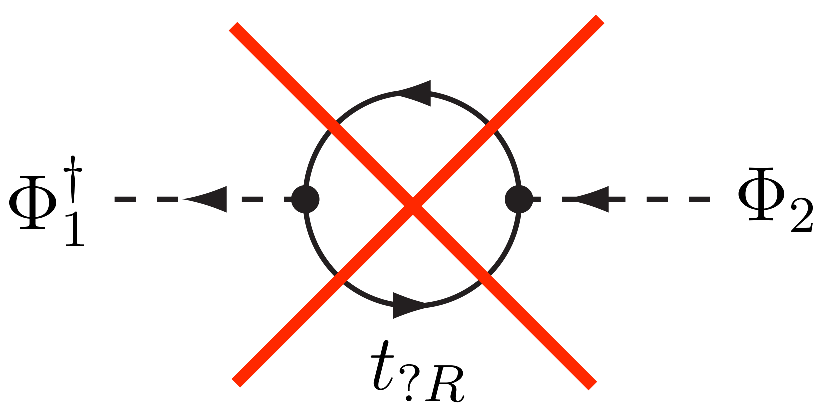
$\Rightarrow$ no PNGB Higgs mass



$$\sim \underbrace{\frac{y_2^2}{16\pi^2}\Lambda^2}$$

preserves $SU(3)_1 \to SU(2)_1$

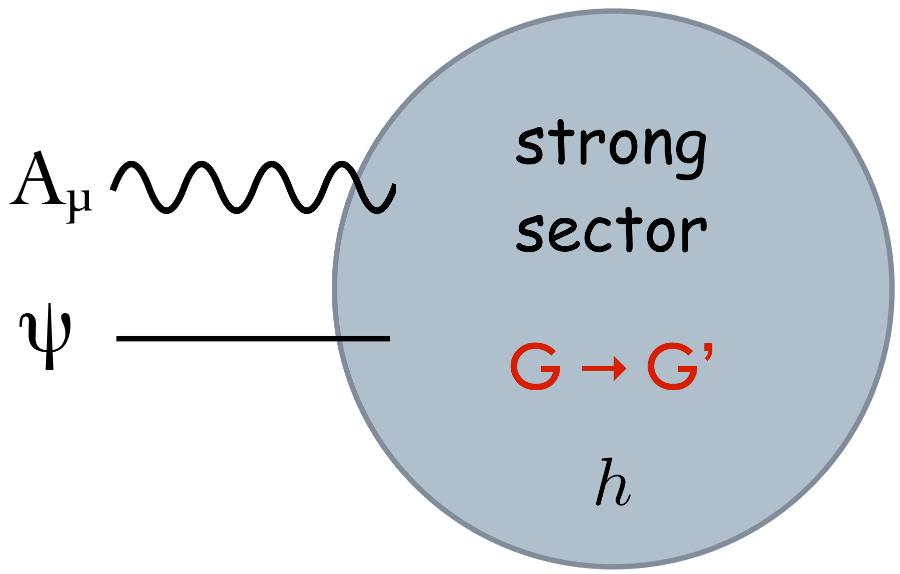
$\Rightarrow$ no PNGB Higgs mass



Not allowed

Minimal composite Higgs

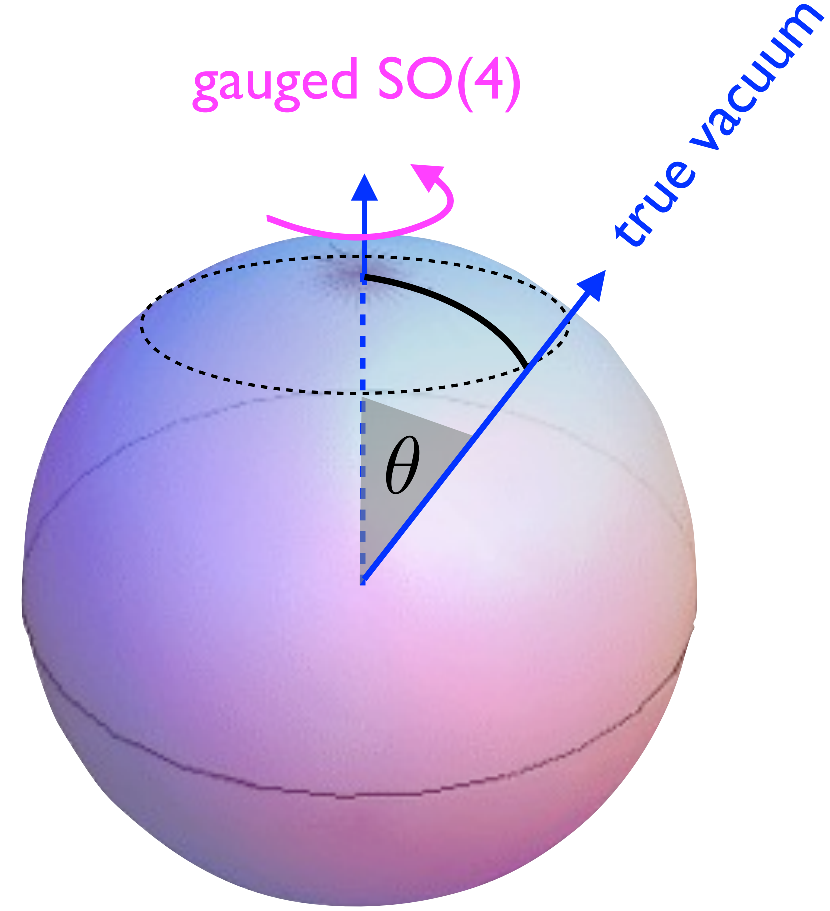
Agashe et. al



Minimal bottom up construction

$$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$$

$SO(5)/SO(4)$



Tree level: gauge SO(4) aligned

Higgs

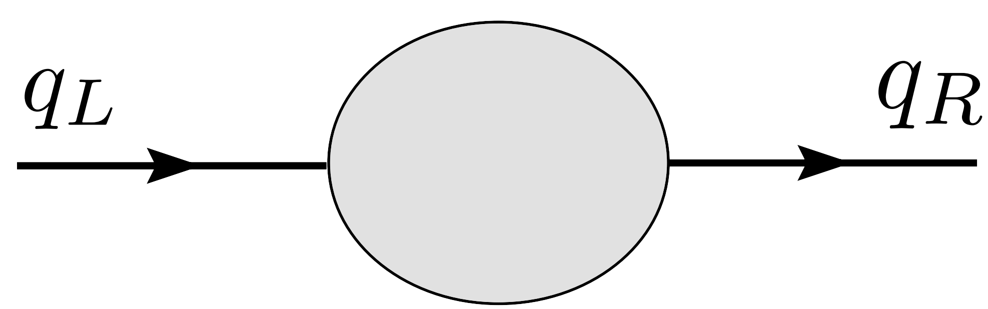
$$\phi = e^{i\pi^{\hat{a}}T^{\hat{a}}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat{\pi}^1\\ \hat{\pi}^2\\ \hat{\pi}^3\\ \hat{\pi}^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta + h(x)/f)\;\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta + h(x)/f)\end{pmatrix}$$

1-loop $\langle\phi(x)\rangle = \theta\cdot f$

eaten by W_L, Z_L

Linear couplings

$$\mathcal{L} = \lambda_L \, \bar{q}_L O_R + \lambda_R \, \bar{u}_R O_L + h.c.$$



$$m_q \sim \frac{\lambda_L(\mu)\lambda_R(\mu)}{g_*} v$$

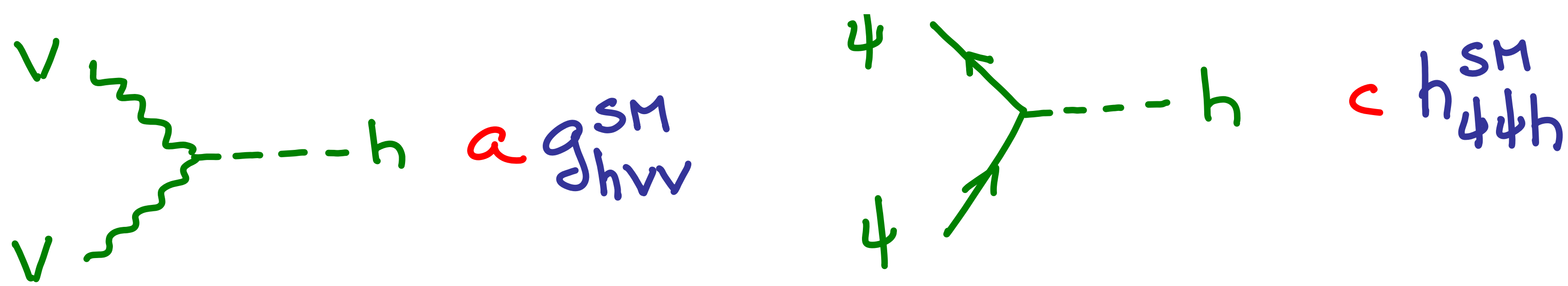
Interesting consequences for flavor...

Deviations from SM Higgs

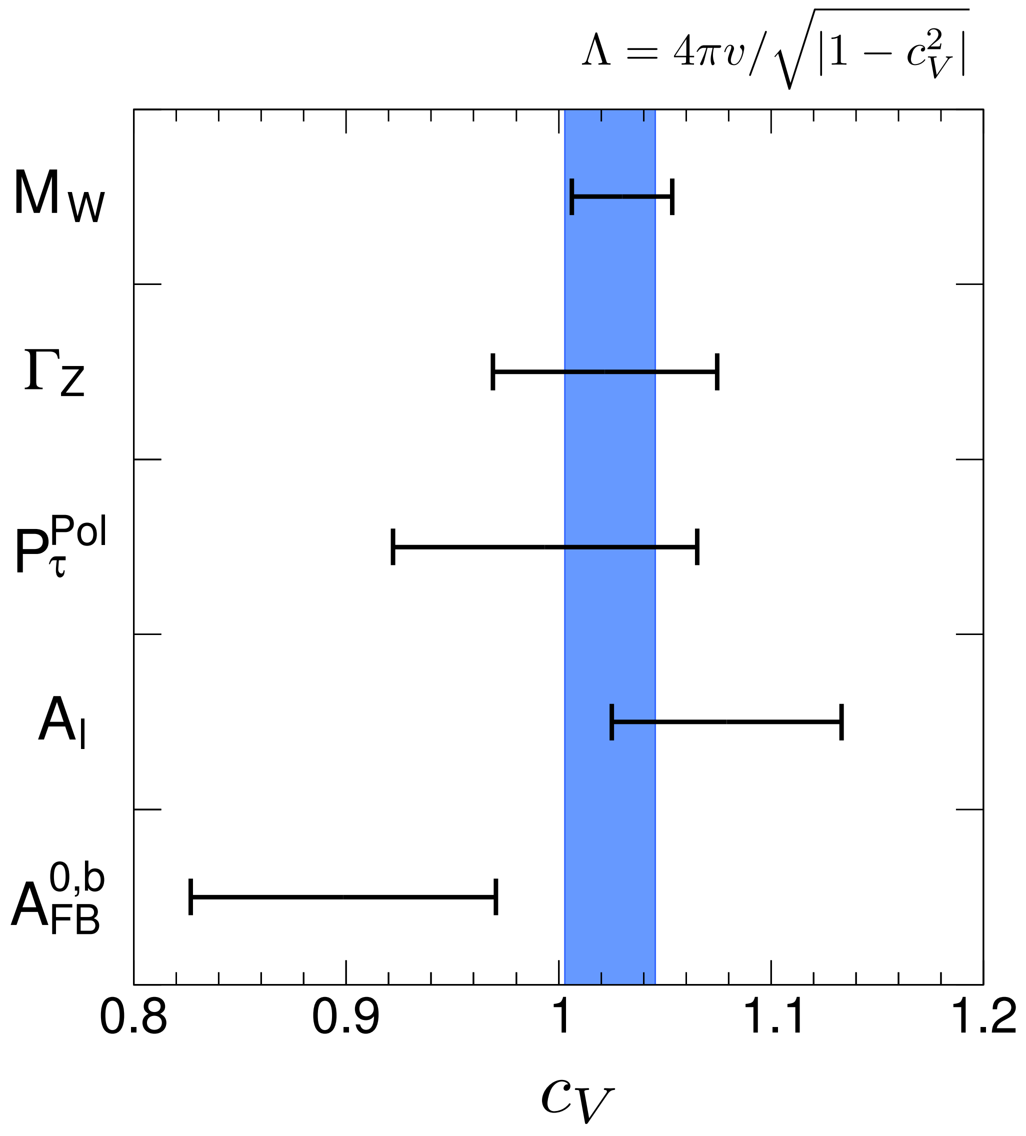
Goldstone boson nature

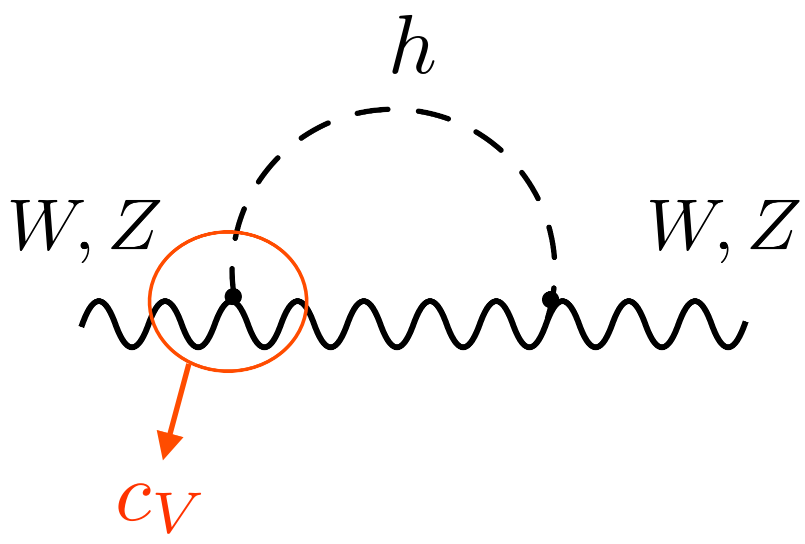
$$f^2\left|\partial_\mu\, e^{i\pi/f}\right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2}\left[\partial_\mu(H^\dagger H)\right]^2 + \frac{c'_H}{2f^4}(H^\dagger H)\left[\partial_\mu(H^\dagger H)\right]^2 + \ldots$$

Giudice et al. JHEP 0706 (2007) 045



EW precision tests

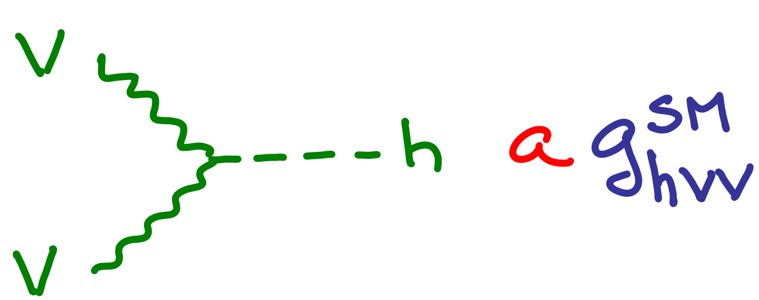


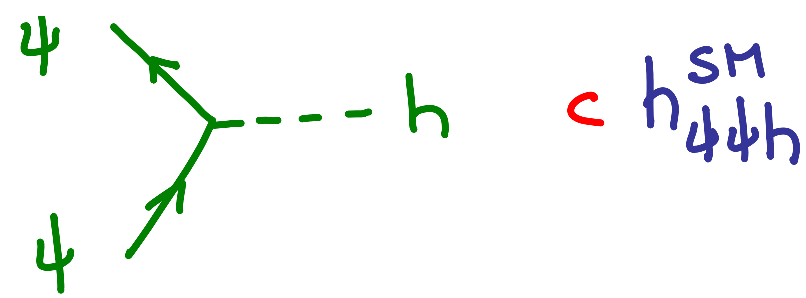


Ciuchini, Franco, Silvestrini, Mishima, arXiv:1306.4644

Higgs couplings

Have been measured to 20-30% precision





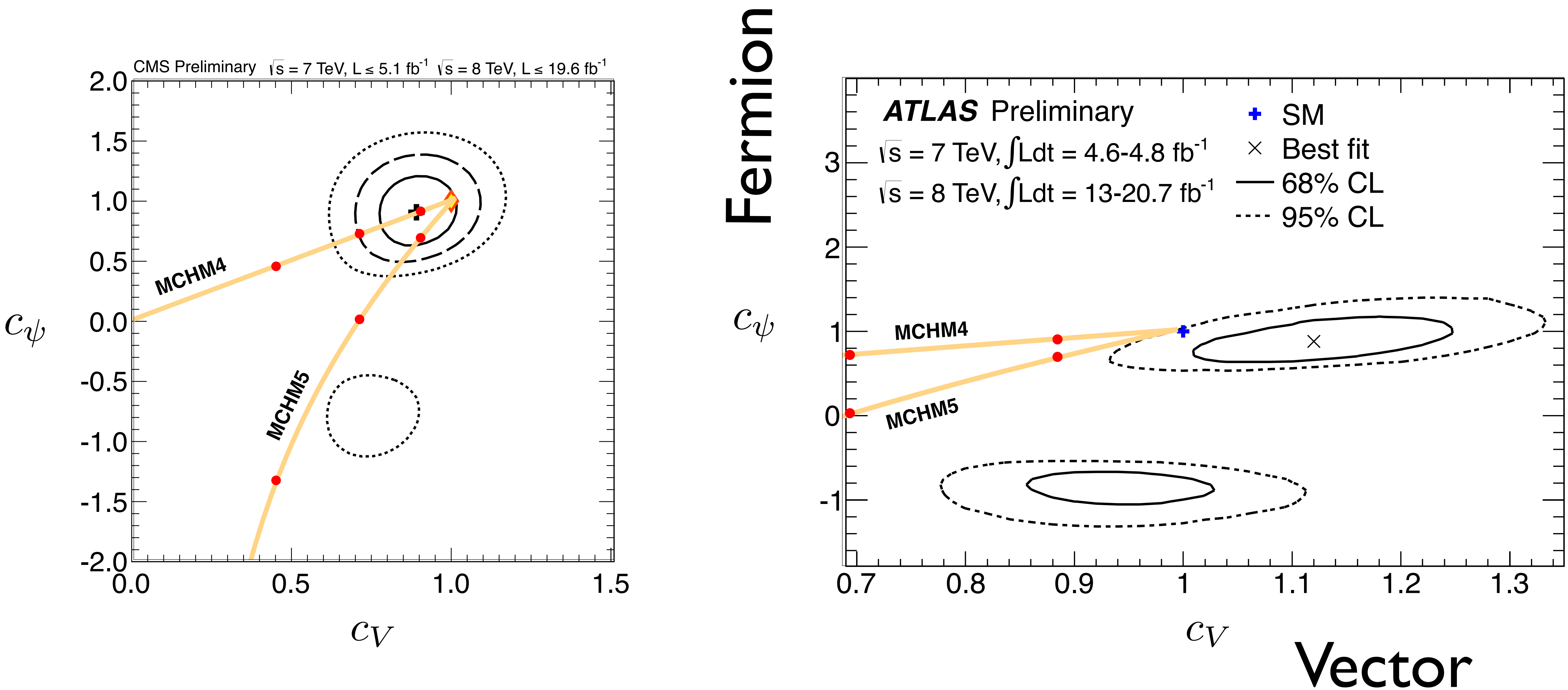
Expect deviations ~ $(v/f)^2$

$$a = \sqrt{1-\xi}$$

$$\xi \equiv \frac{v^2}{f^2}$$

$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

Higgs couplings

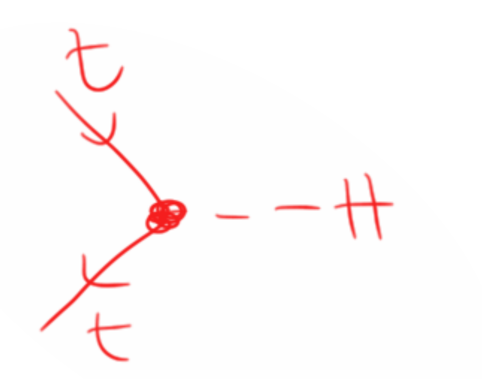


Red points at $\xi \equiv (v/f)^2 = 0.2,\ 0.5,\ 0.8$

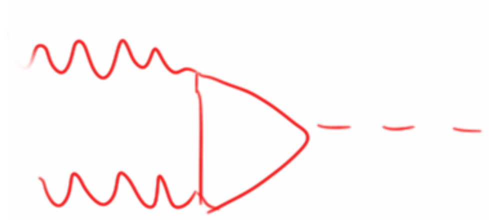
Higgs couplings

SM + $\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$

$$\frac{\sigma(gg \to h)}{\mathrm{SM}} = (1 + (c_g - c_t)v^2)^2$$



Degeneracy 'short-distance' vs 'long-distance'



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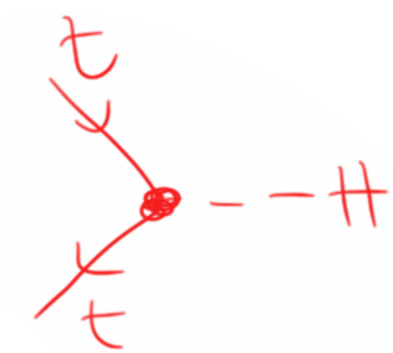

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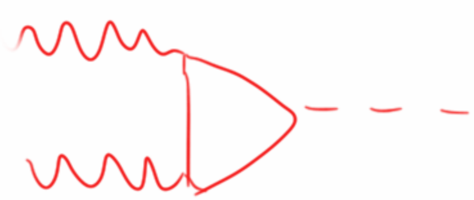
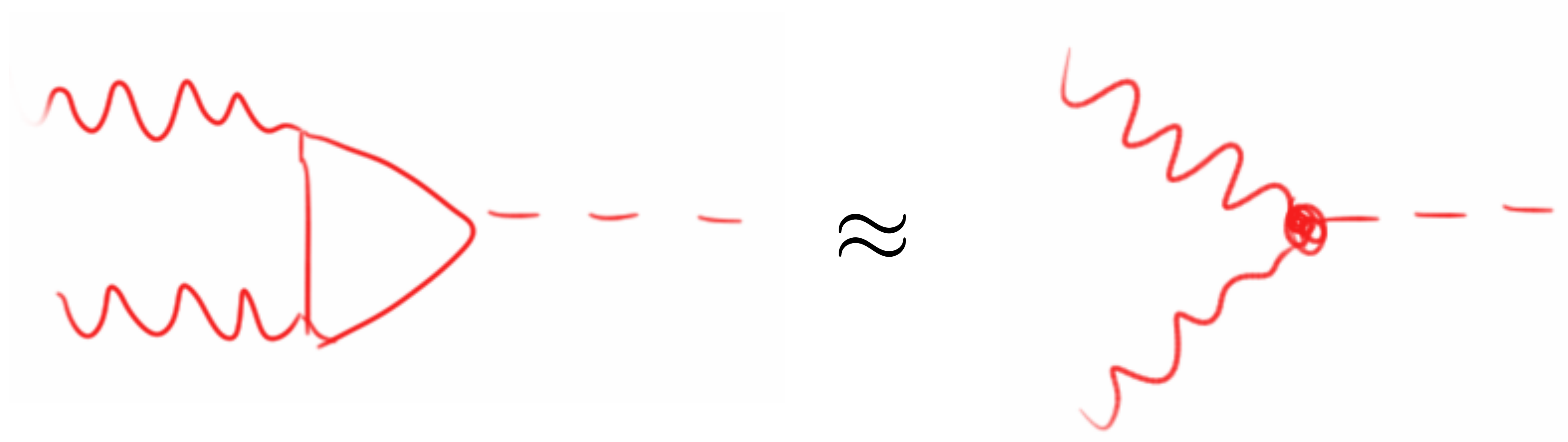


E.g. fermionic top partners MCHM: $\Delta c_t = \Delta c_g$

$$\sigma(pp \to H + X)_{\text{inclusive}}$$

Does not resolve short-distance physics

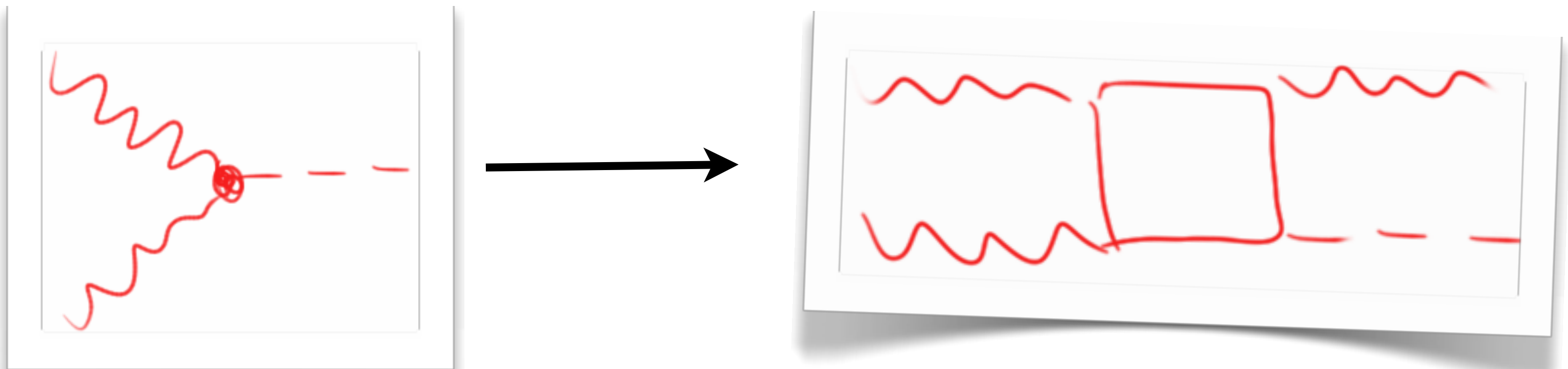


m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. 1306.4581

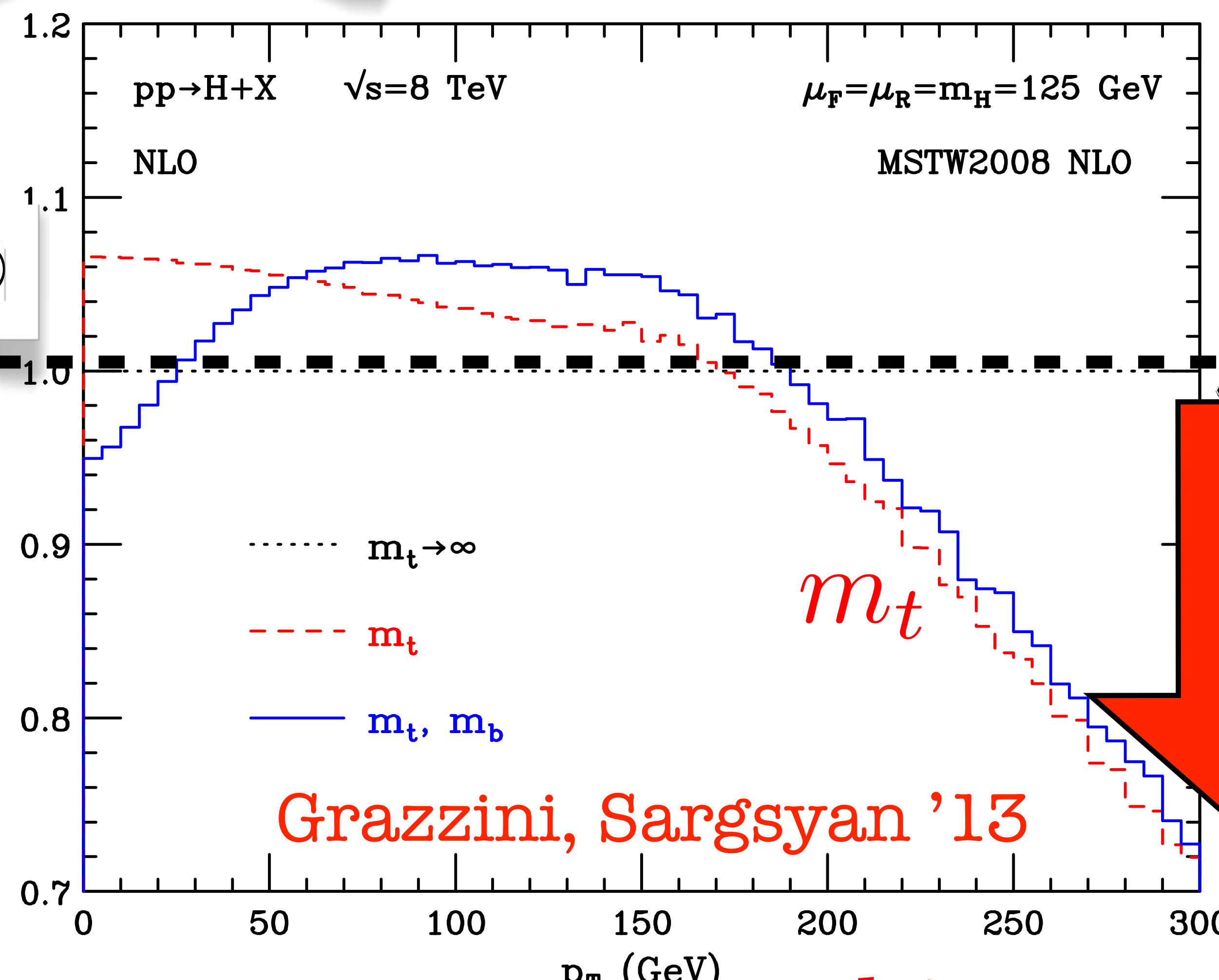
Beyond current observables

Cut the loop open, recoil against hard jet



$p_T \gg m_t$

$m_t \to \infty$



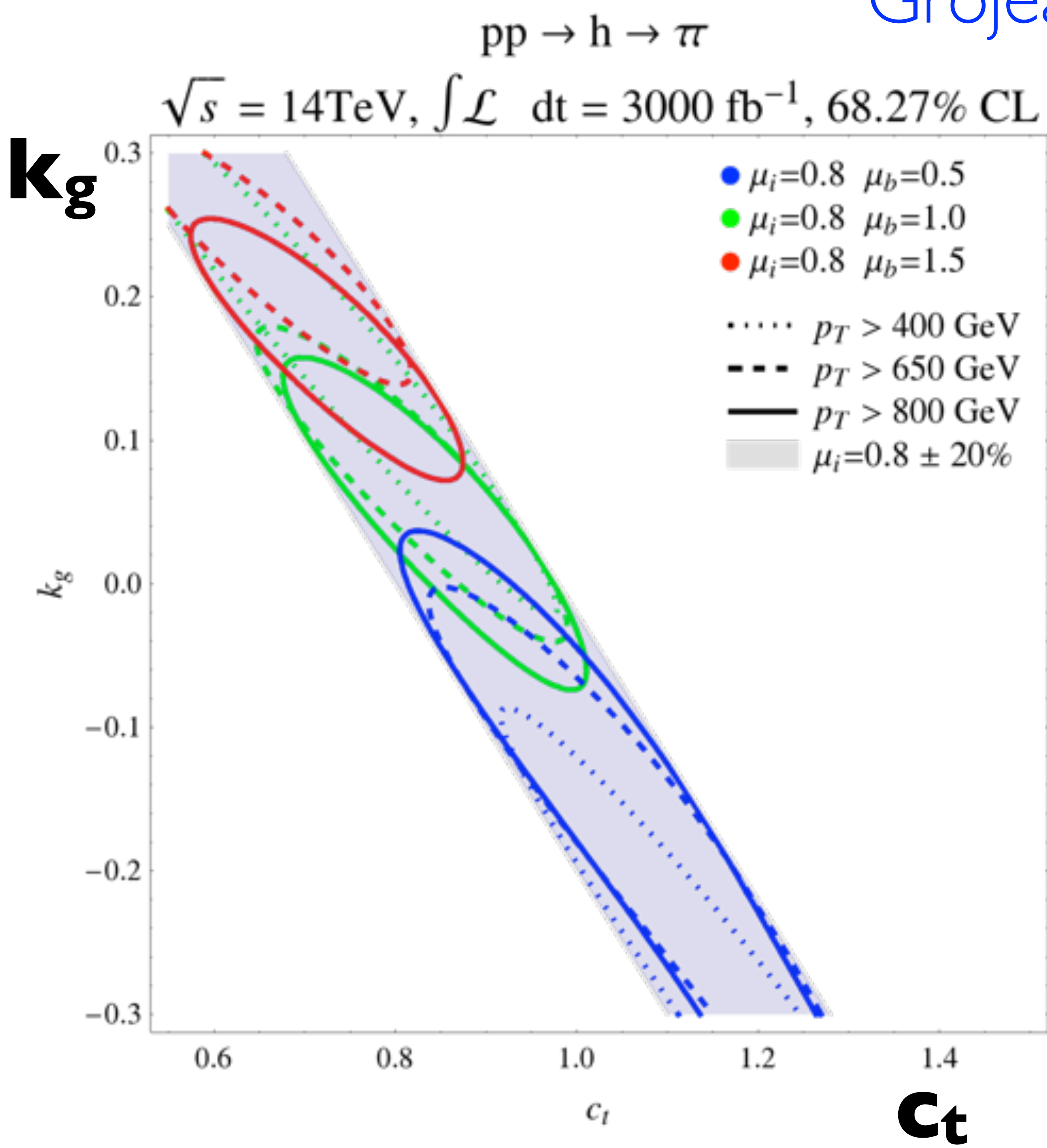
Baur, Glover '90,
Langenegger et. al '06,
1308.4771

high p_T tail resolves loop dynamics

higgs $- p_T$

Complementary to htt

Grojean, Salvioni, Schlaffer, AW, in progress



Competitive/complement to notoriously difficult $h\bar{t}t$ channel

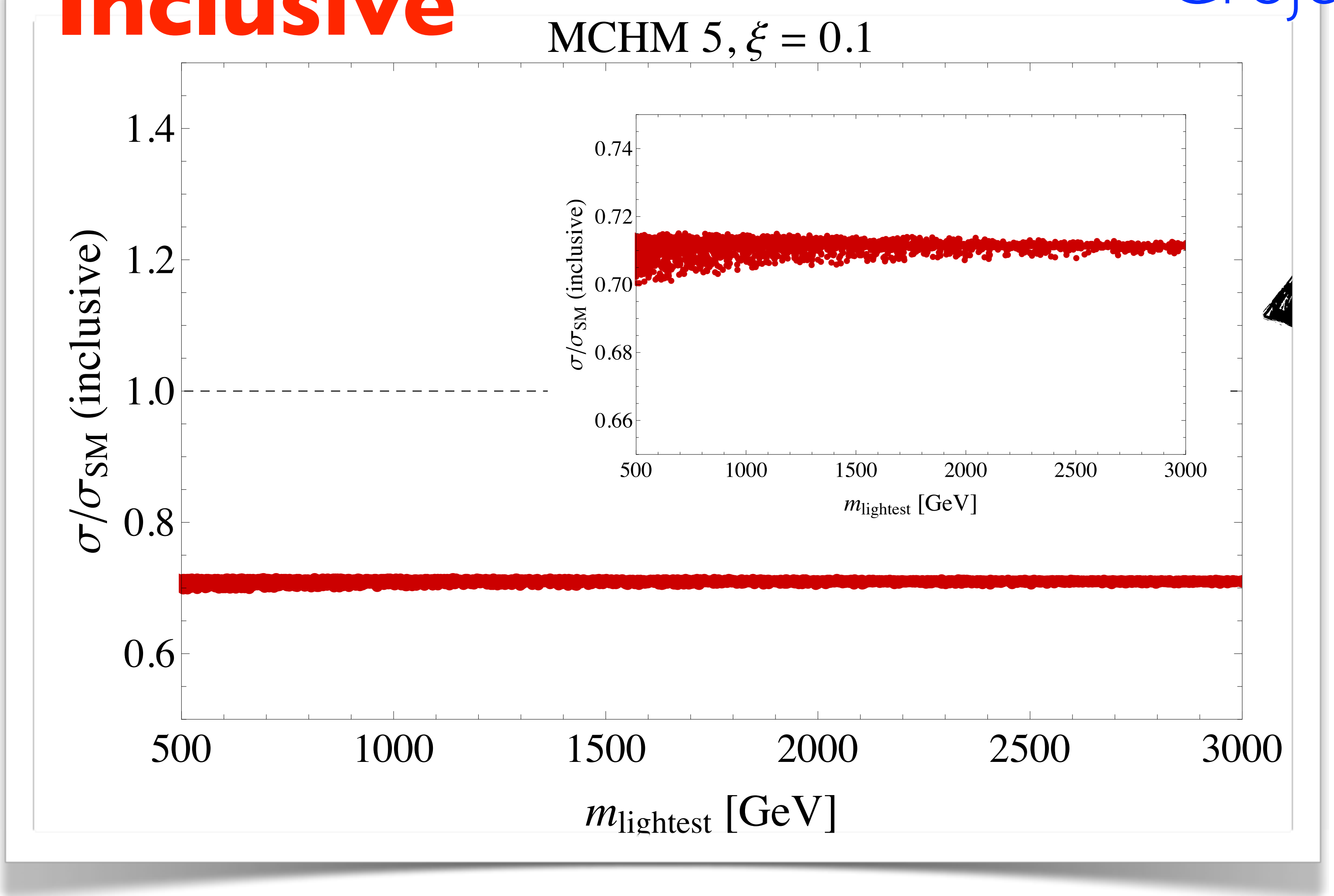
Theory frontier:
NLO_{m_t} not yet calculated,
$1/m_t$ known to $\mathcal{O}(\alpha_S^4)$:
few % up to p_T ~150 GeV

Harlander et al '12

Top partner example

Grojean, Salvioni, Schlaffer, AW

Inclusive



Top partner example

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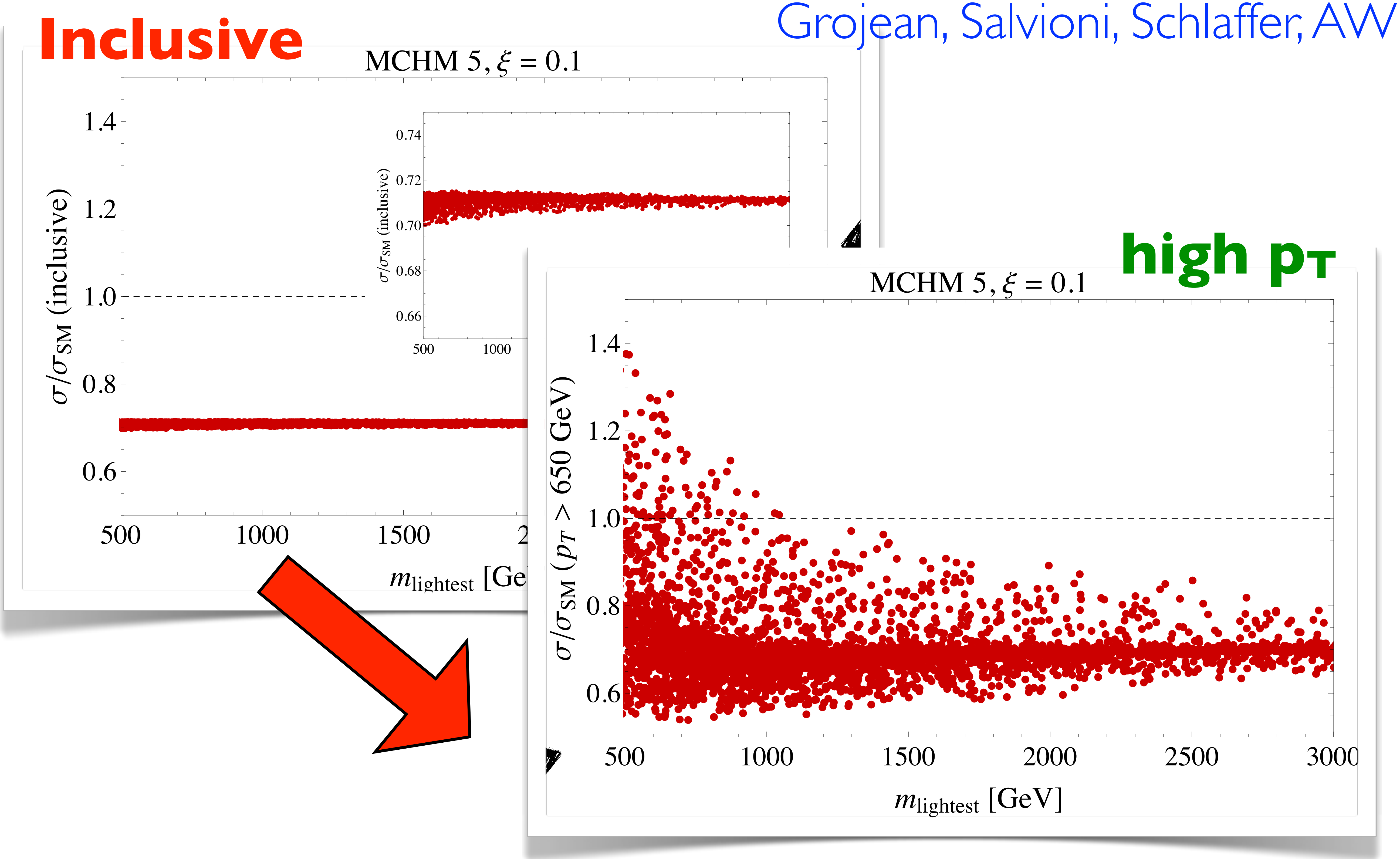


New physics & naturalness

Light Higgs

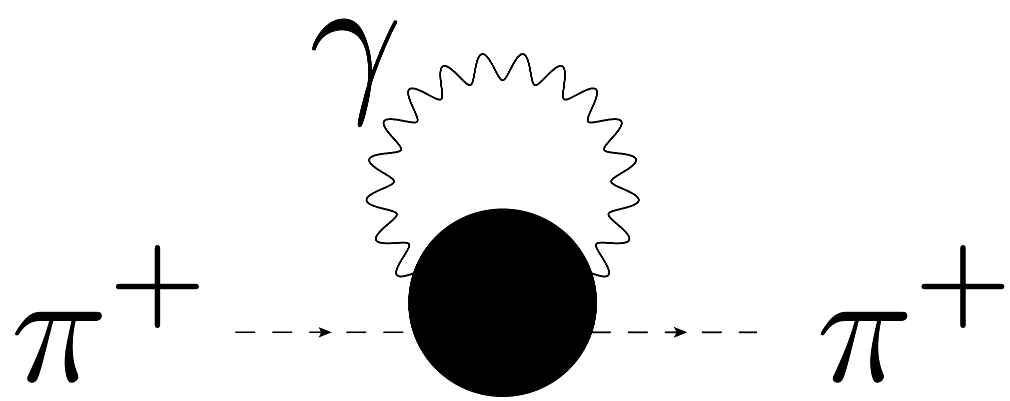
?

light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, …

supersymmetry

light top partners (Q=5/3,2/3,1/3), anything else ?

composite Higgs



Das et al '67

Implications of m$_H$ = 125 GeV

Potential is fully radiatively generated

Agashe et. al

$$V_{gauge}(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\log\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right)$$

$s_h \equiv \sin h/f$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p)\ , \qquad \Pi_1(p) = 2\left[\Pi_{\hat{a}}(p) - \Pi_a(p)\right]$$

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$$\int d^4p\, \Pi_1(p)/\Pi_0(p) \quad < \infty$$

Higgs dependent term
UV finite

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$$\int d^4p\, \Pi_1(p)/\Pi_0(p) \quad < \infty$$

Higgs dependent term
UV finite

→ 'Weinberg sum rules'

$$\lim_{p^2\to\infty} \Pi_1(p) = 0 \ , \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0$$

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)}$$ spin1

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Similarly for SO(5) fermionic contribution

Pomarol et al; Marzocca

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

similar result in deconstruction:
Matsedonskyi et al; Redi et al

5 = 4 + 1 with EM charges 5/3, 2/3, -1/3

Q_4 Q_1

→ solve for m_h = 125 GeV

Light Higgs implies light fermionic top partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

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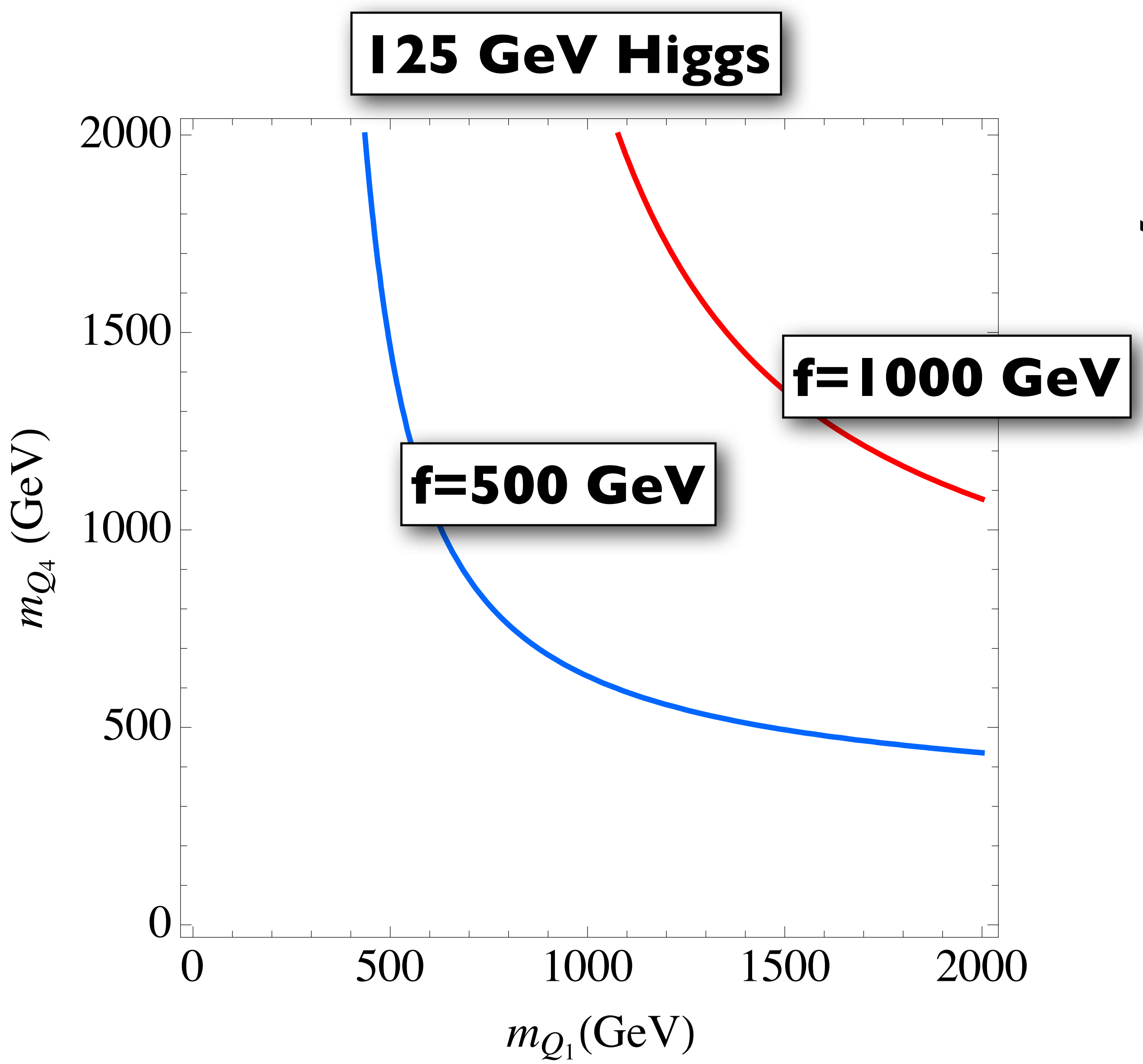
Pomarol et al; Marzocca



5 = 4 + 1

Q_4 Q_1

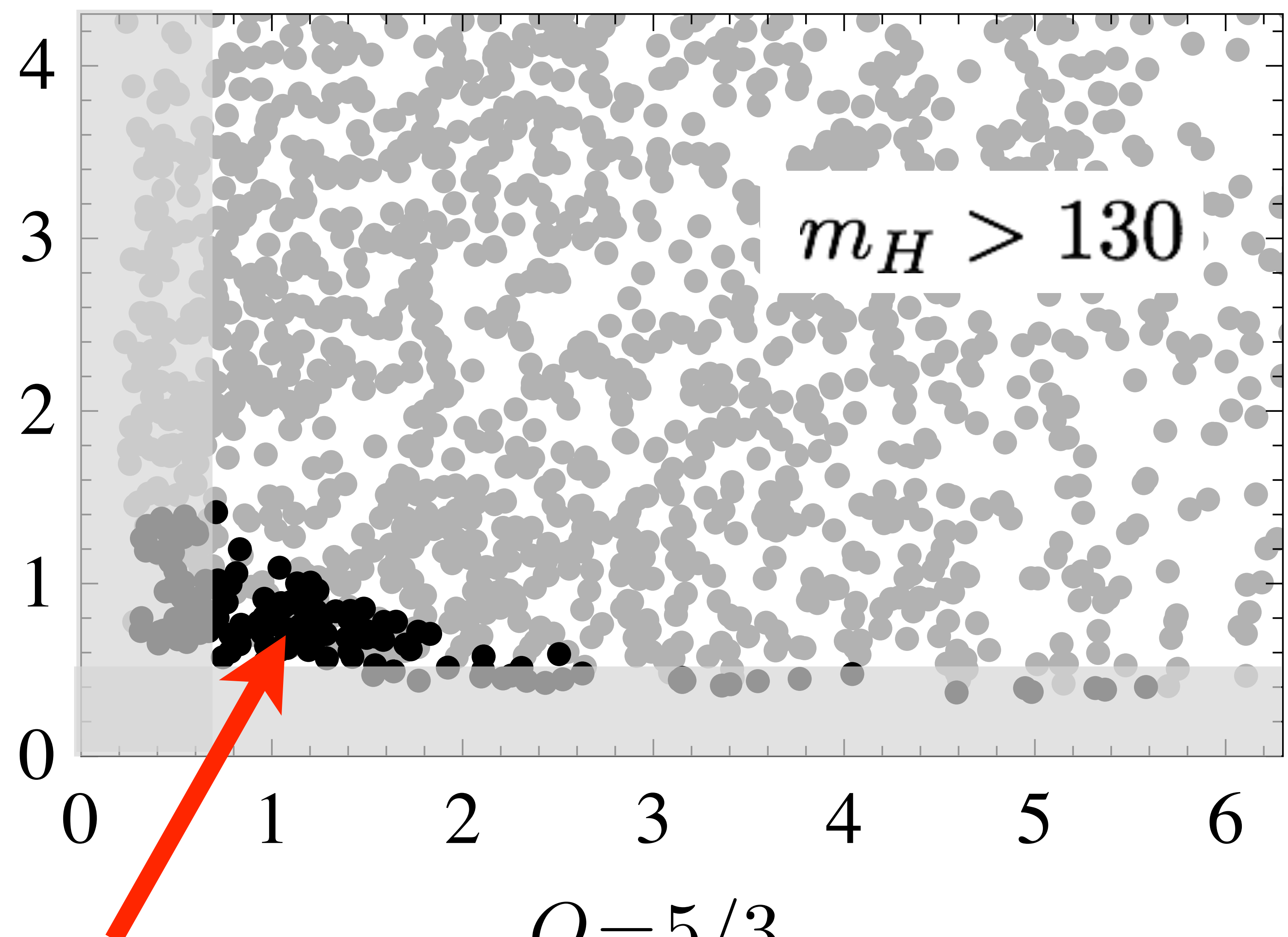
with EM charges 5/3, 2/3,-1/3

Contino et al; Pomarol, Riva; Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu;

Scan over composite Higgs parameter space

$\xi = 0.2$

from 1204.6333



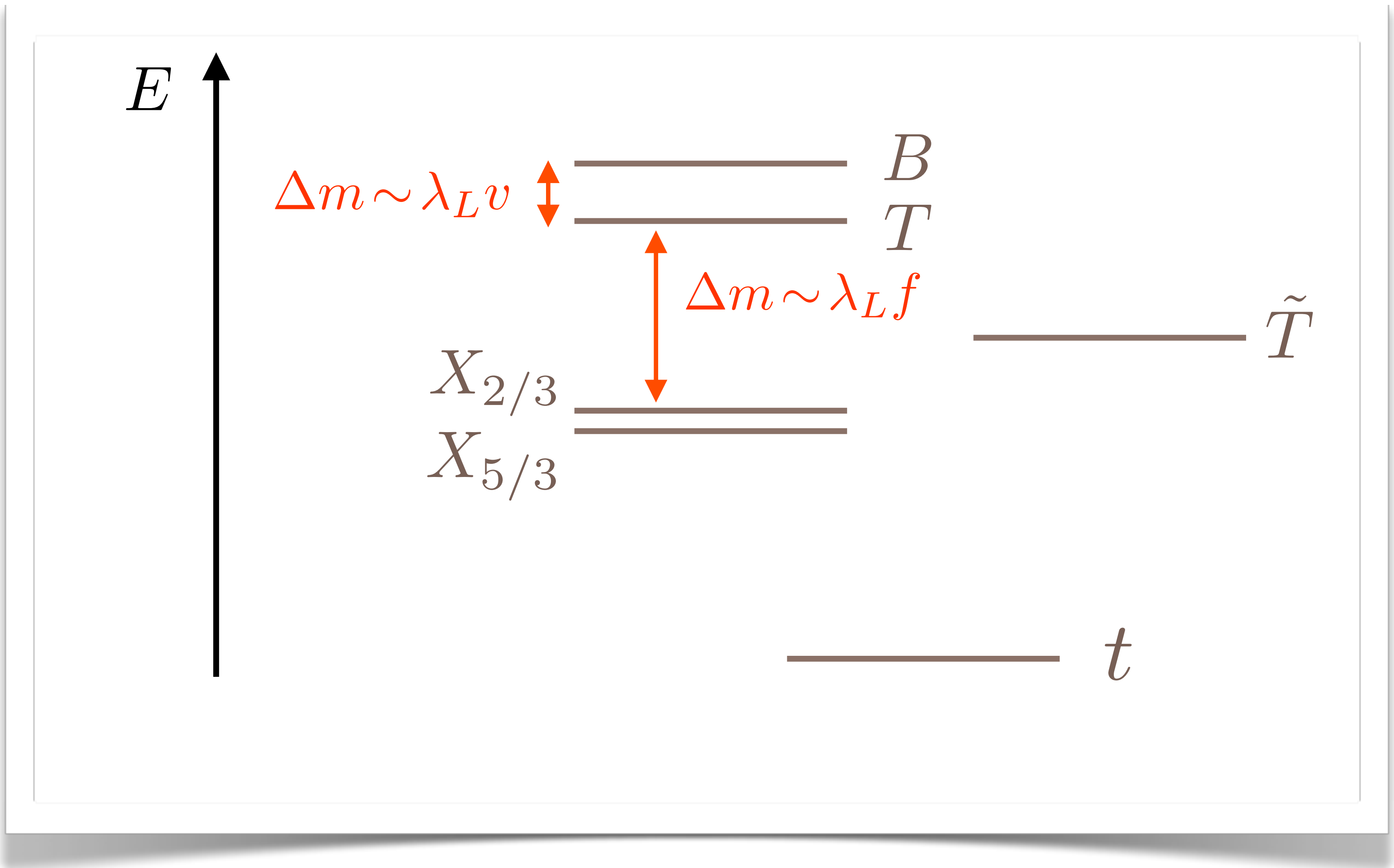
$Q=2/3$

$Q=5/3$

m_H = 115 … 130 GeV

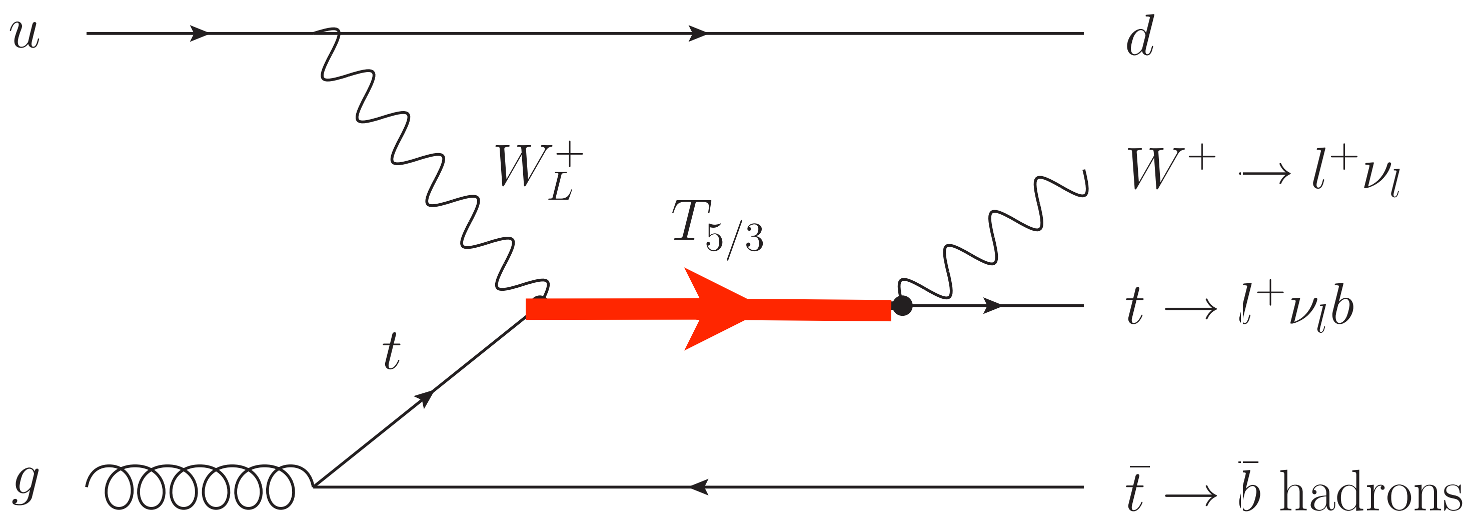
see e.g. ATLAS-CONF-2013-051

Top partners

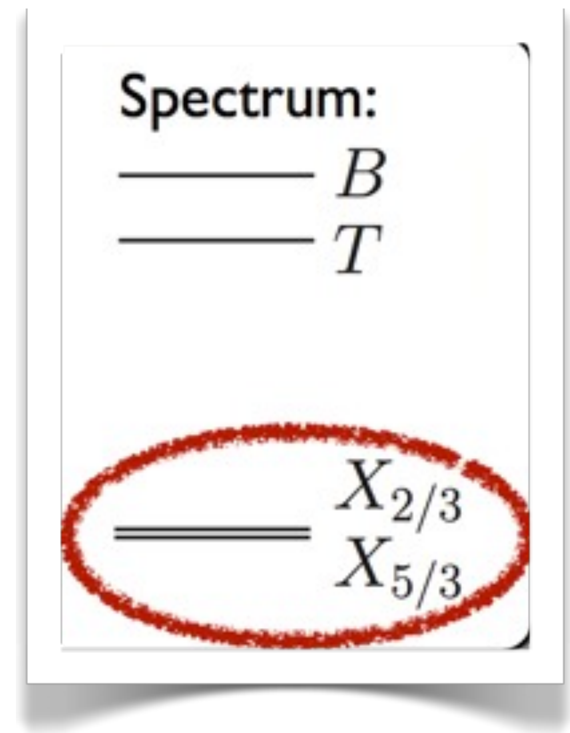


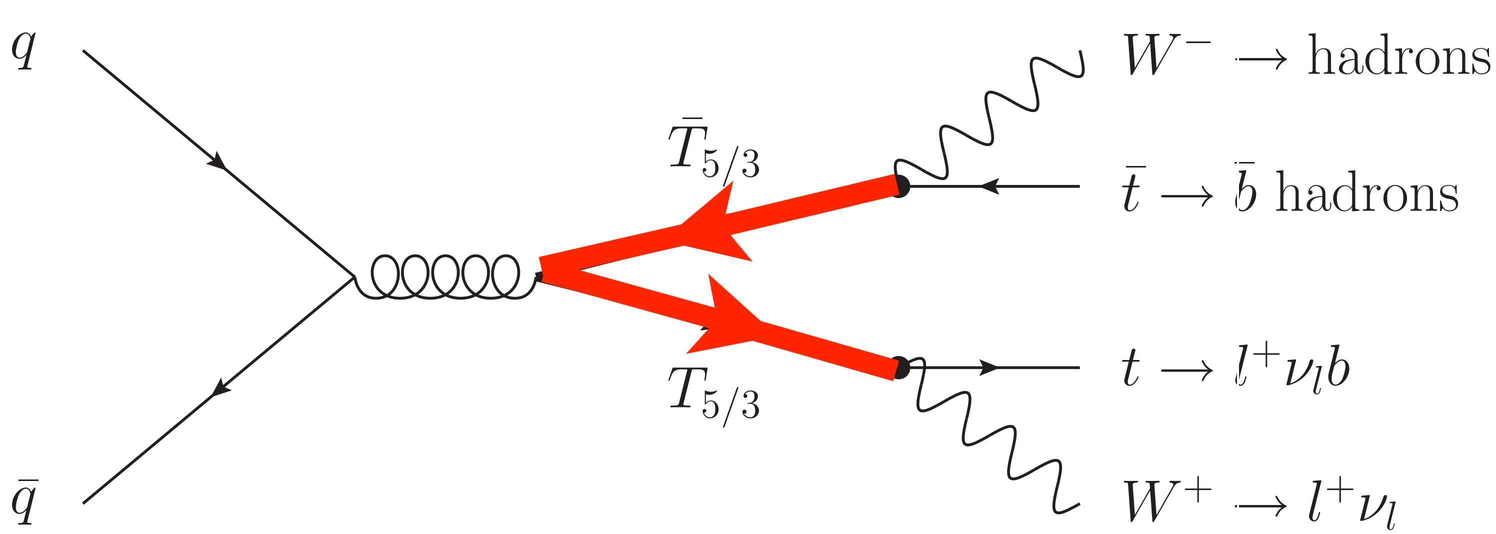
$T_{5/3}$

e.g. Perelstein, Pierce, Peskin
Contino, Servant; Mrazek, Wulzer;
De Simone, Matsedonkyi, Rattazzi, Wulzer



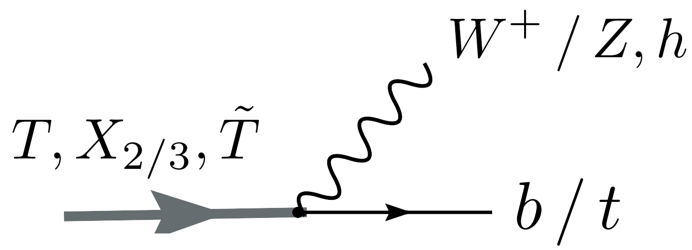
Single

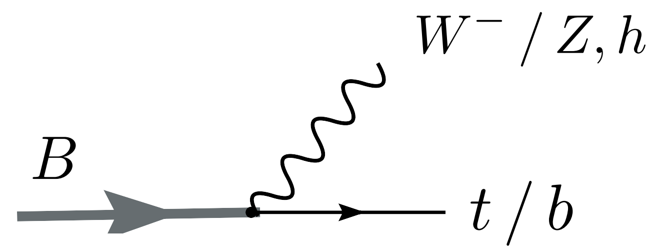


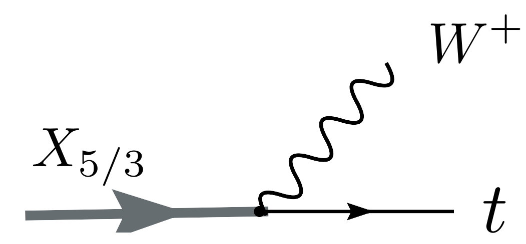


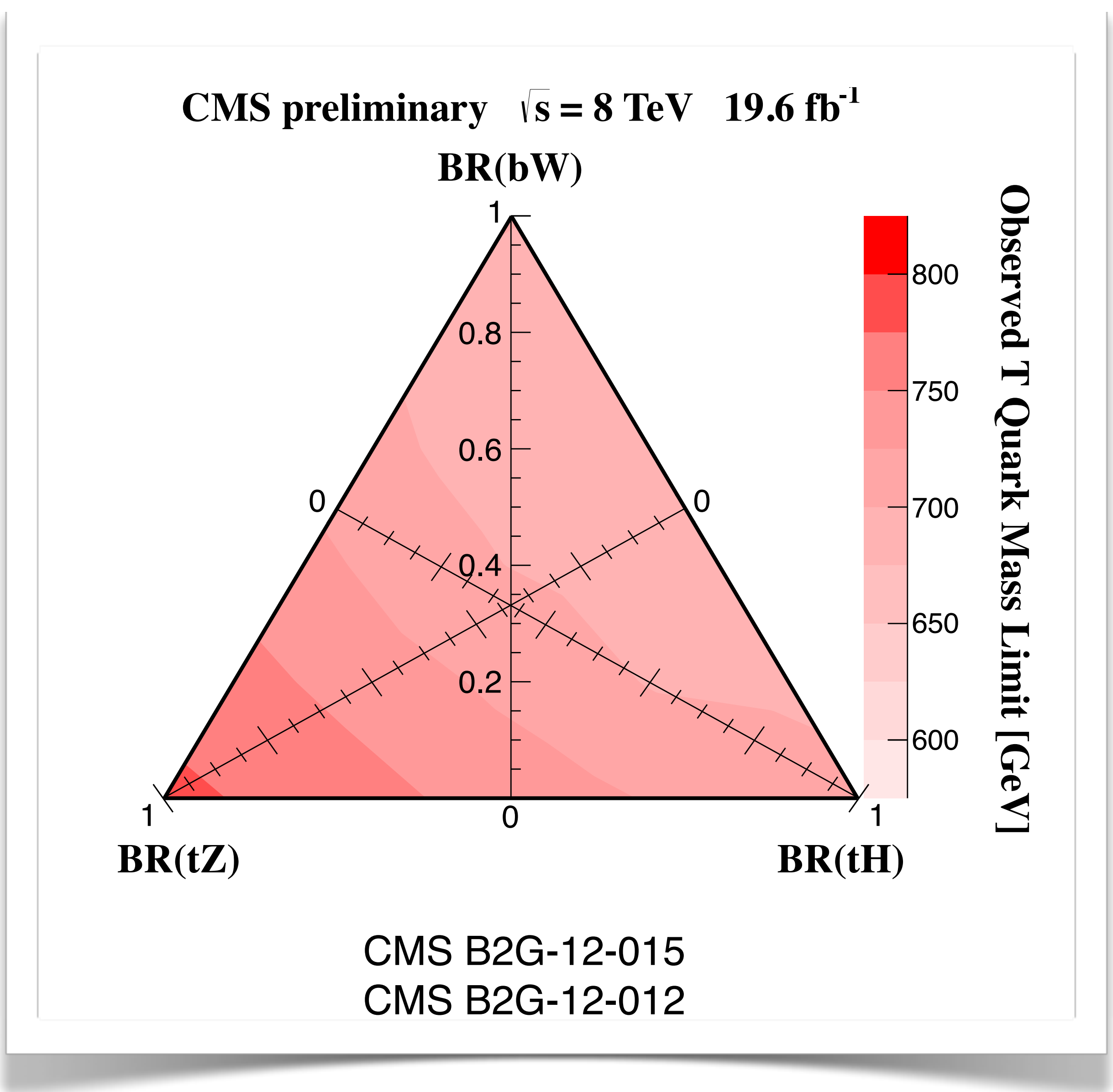
Double

Decay modes



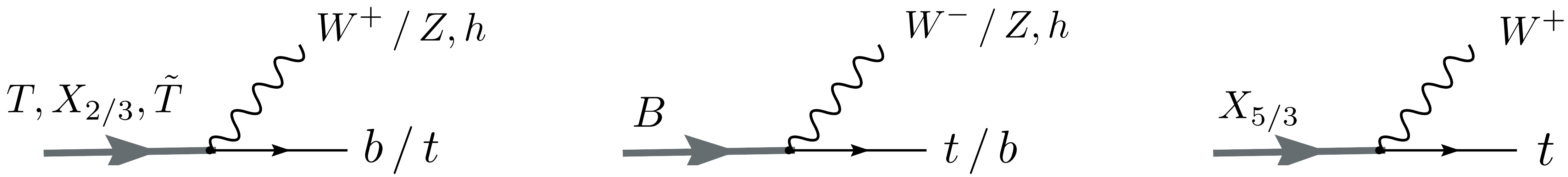






Current limits
> 700 - 800 GeV

Decay modes



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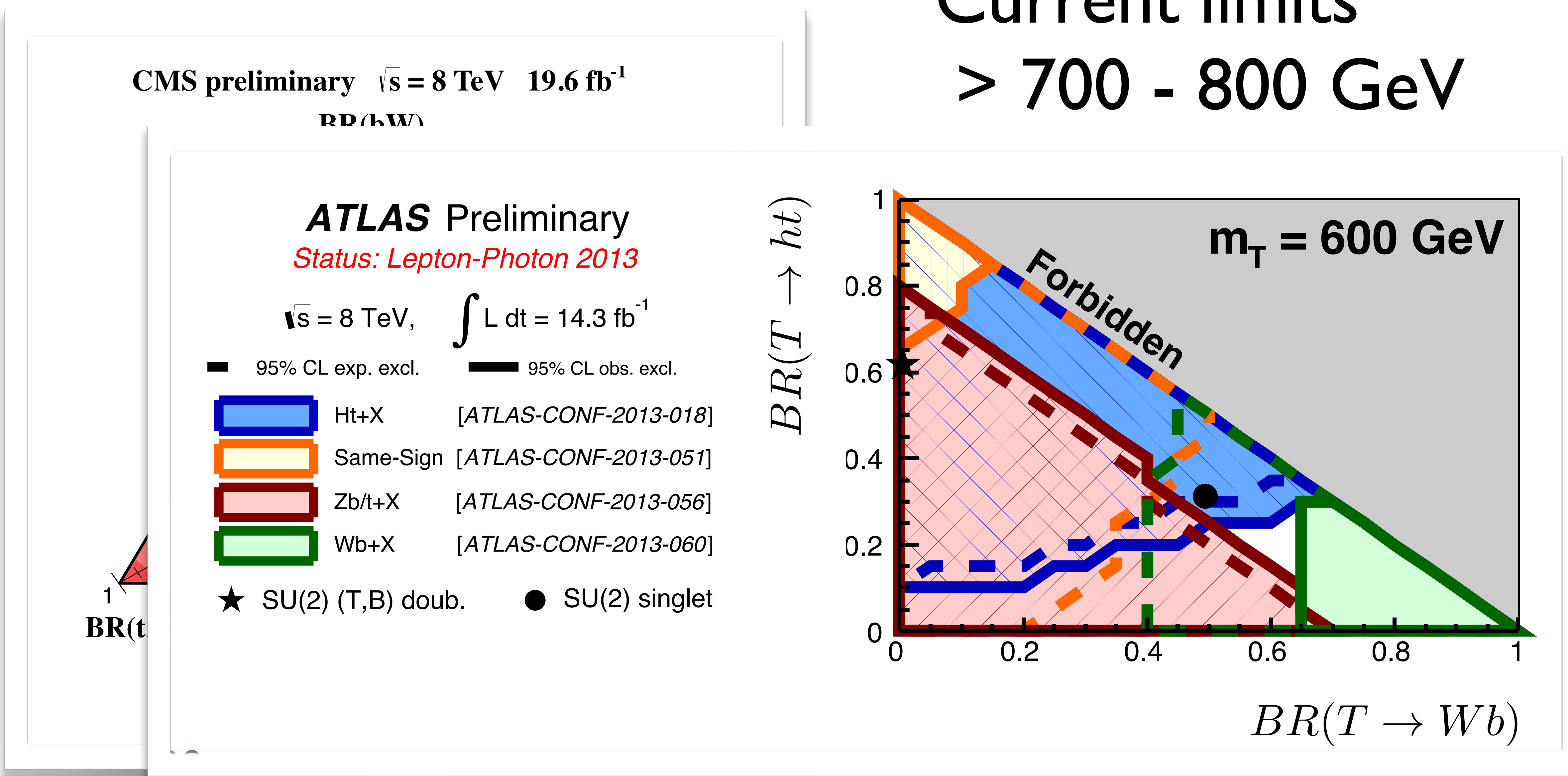


Flavor used to be a show-stopper

CPV in Kaon mixing

$$|\epsilon| = 2.3 \times 10^{-3} \implies \frac{M_{ETC}}{g_{ETC}\sqrt{\mathrm{Im}(V_{sd}^2)}} \gtrsim 16,000\,\mathrm{TeV}$$

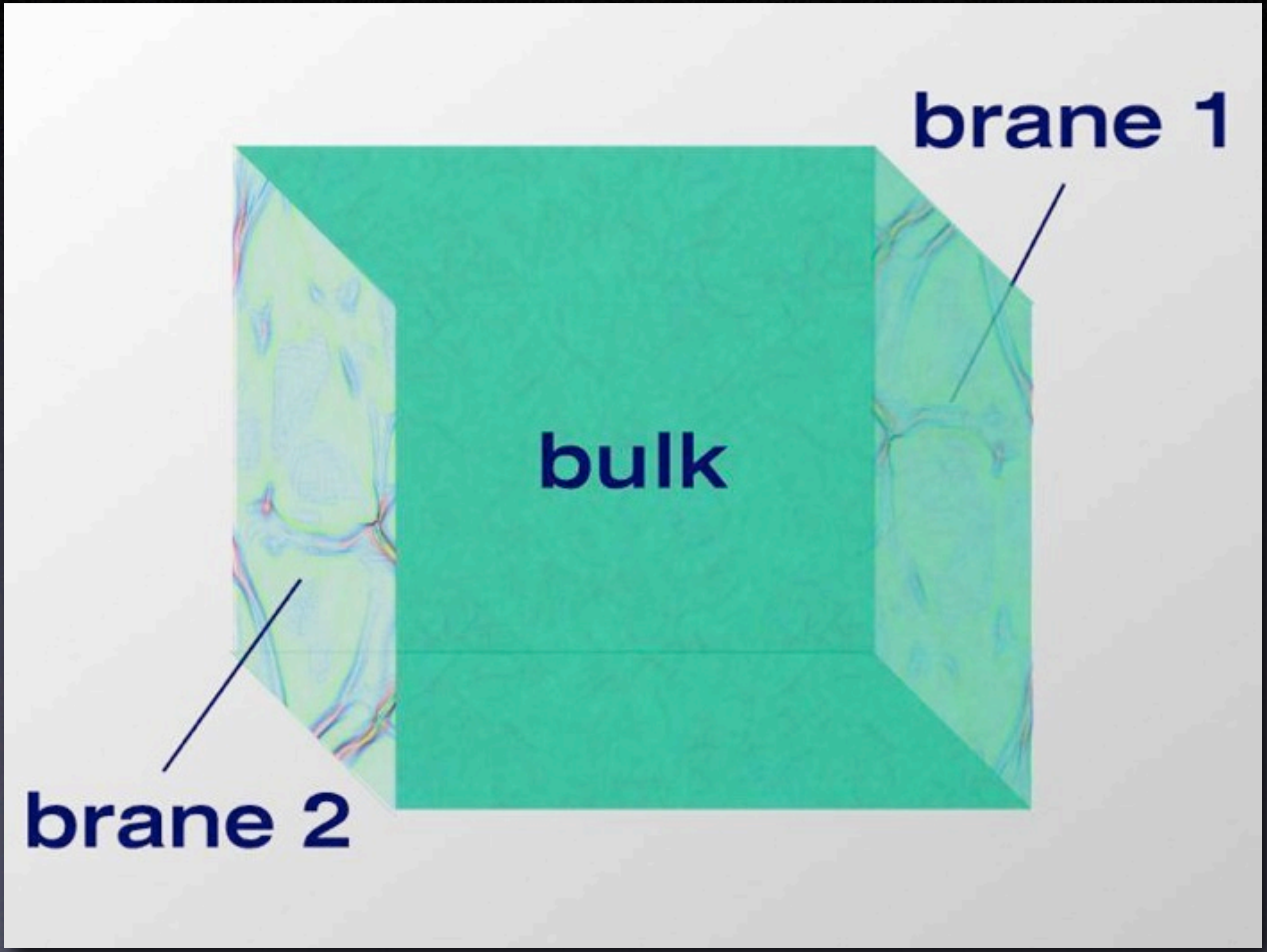
$$m_{q,\ell,T}(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2}\langle \bar{T}T\rangle_{ETC} \lesssim \frac{0.1\,\mathrm{MeV}}{|V_{sd}|^2 N^{3/2}}$$ **vs. m_{top}**

“Into the Extra-dimension and back”

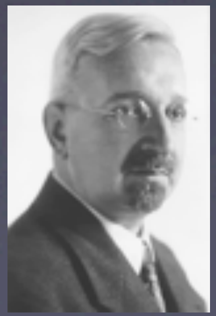
Exciting journey…

Depends on the perspective…

Extra-dimensions

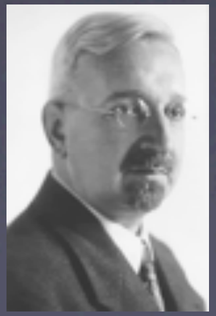


General Properties of ED theories



General Properties of ED theories

Compact Extra-dimension => momentum in ED direction is quantized: p_{ED} = n/(size of ED)



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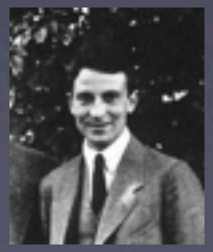
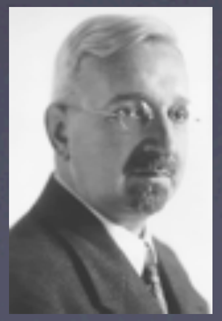
$$p^2 = m^2 \quad \Rightarrow \quad p_{5D}^2 = p^2 - (n/R)^2 = m^2$$

4D   5D





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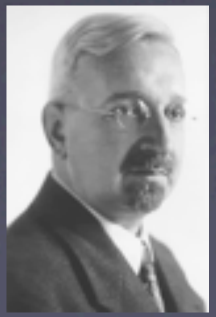
4D   5D

Two pictures (n/R on LHS or RHS):

1) 5D field with quantized momentum and mass m^2



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4D   5D

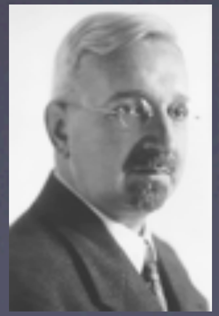
Two pictures (n/R on LHS or RHS):

1) 5D field with quantized momentum and mass m^2

2) infinite tower of 4D fields labeled by 5 momentum n/R with masses

$$M_n^2 = m^2 + (n/R)^2$$

new particles: Kaluza Klein (KK) modes



The SM flavor puzzle

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

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

Why this structure?

Other dimensionless parameters of the SM:

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

Log(SM flavor puzzle)

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

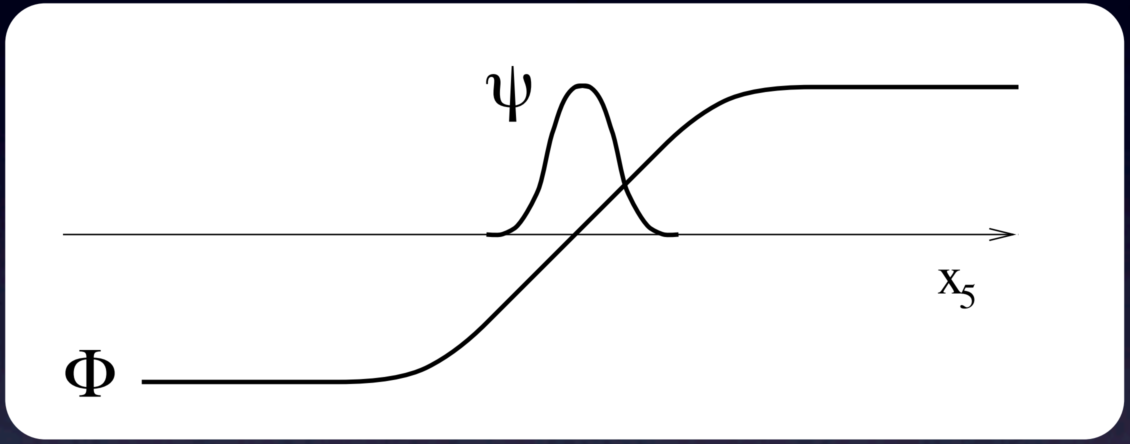
$$-\log|Y_U| \approx \begin{pmatrix} 12 & 7 & 5 \\ 14 & 6 & 3 \\ 18 & 9 & 0 \end{pmatrix}$$

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

Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization



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

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

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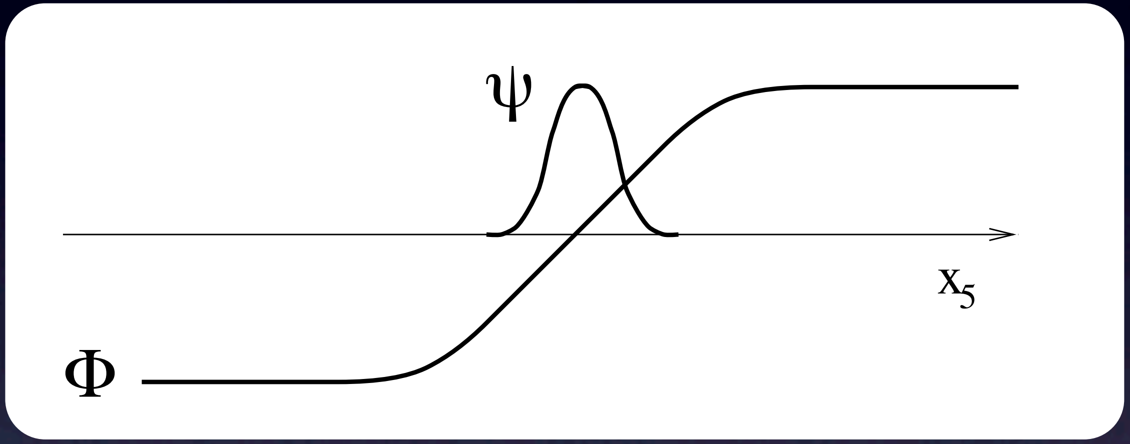

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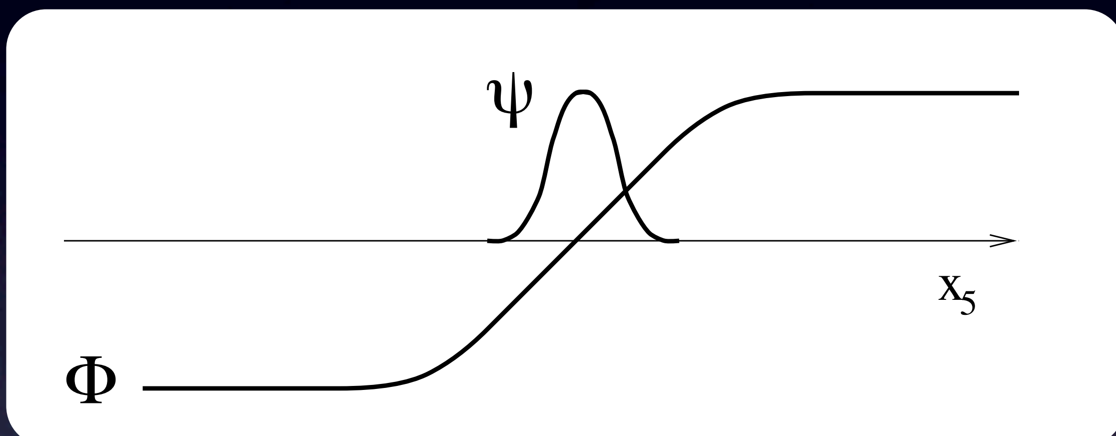

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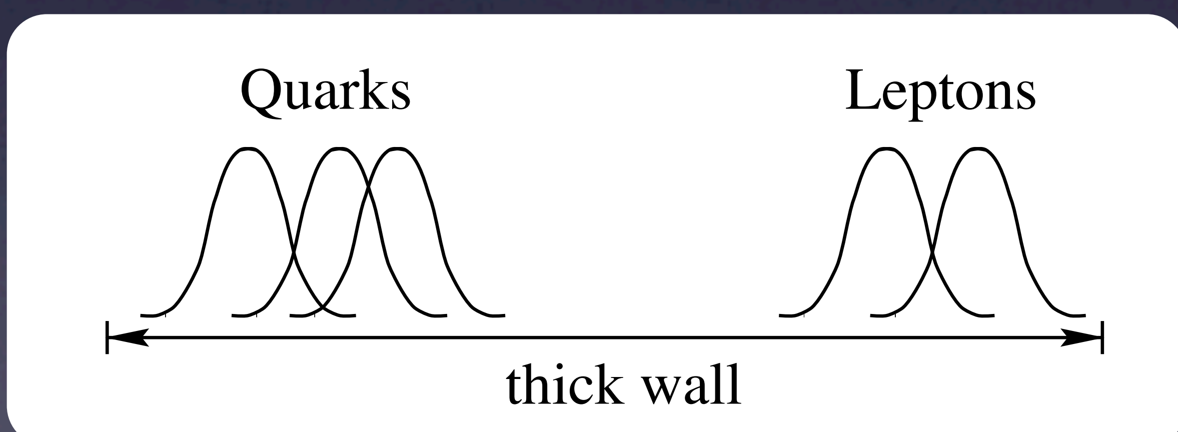

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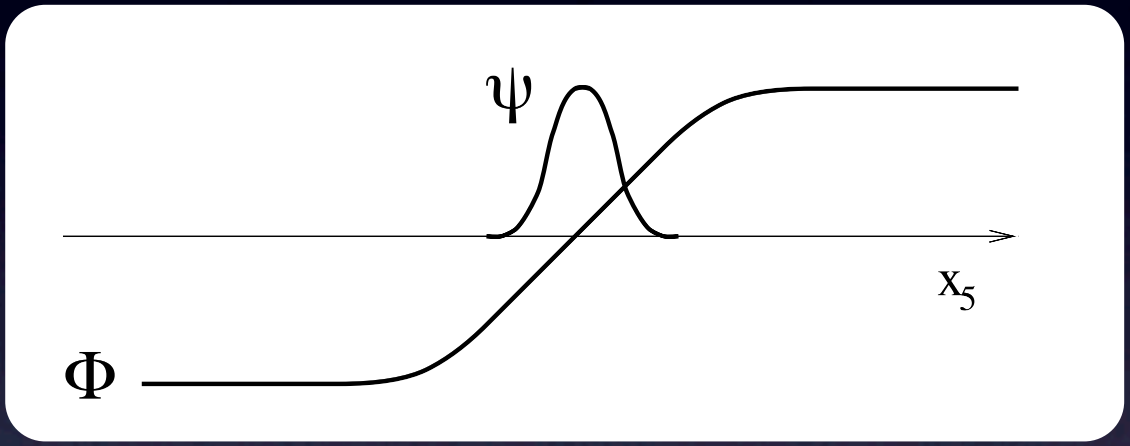

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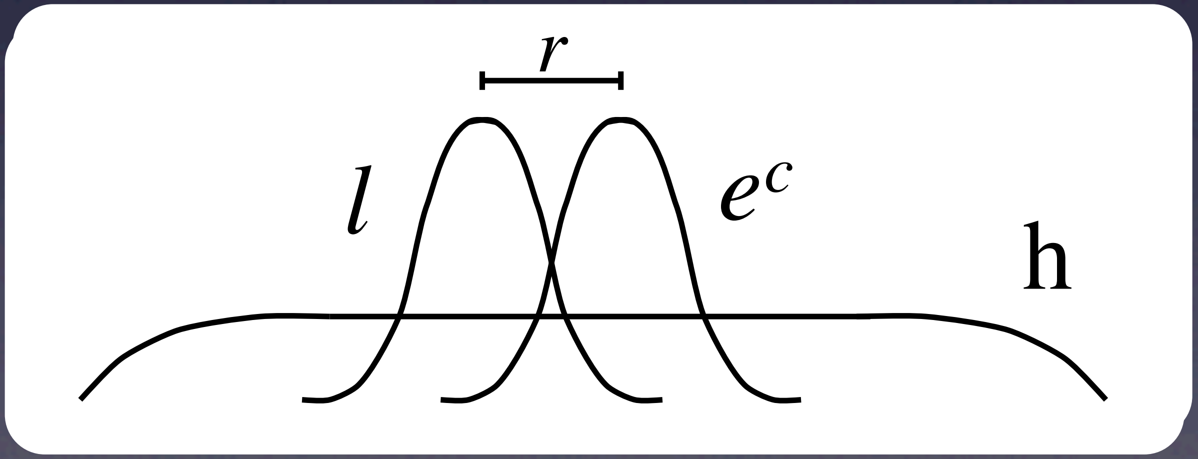
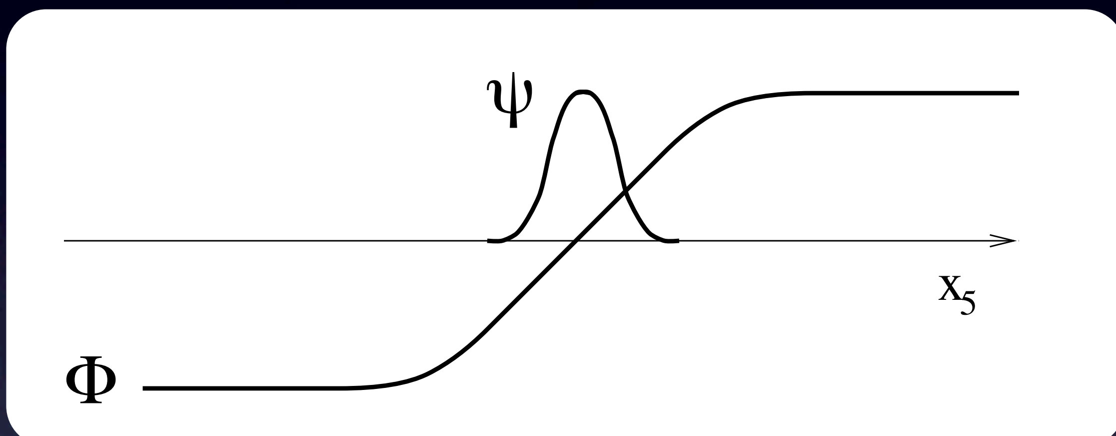


Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization



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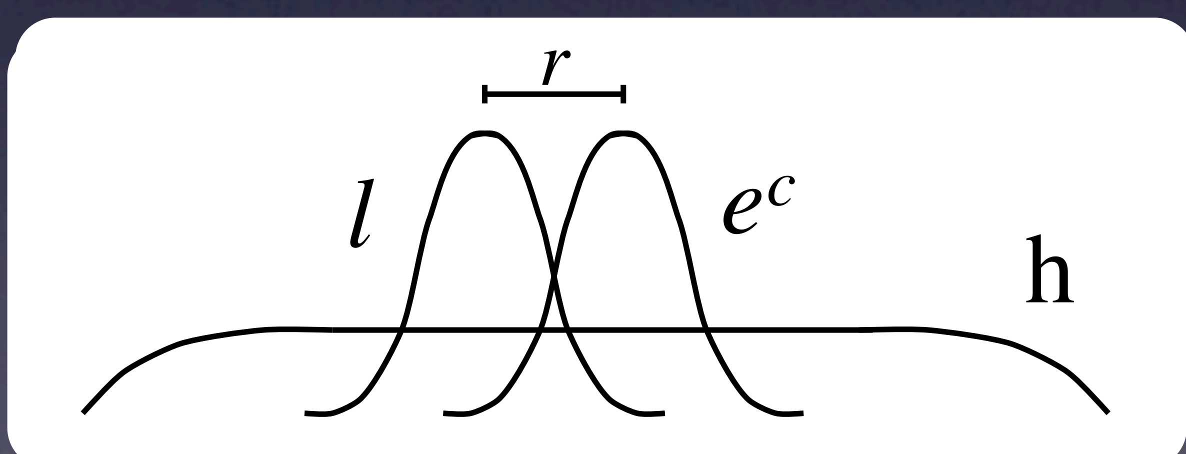

$$\int dx_5 \; \phi_l(x_5) \; \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int dx_5 \; e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5 - r)^2} = e^{-\mu^2 r^2/2}$$

Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

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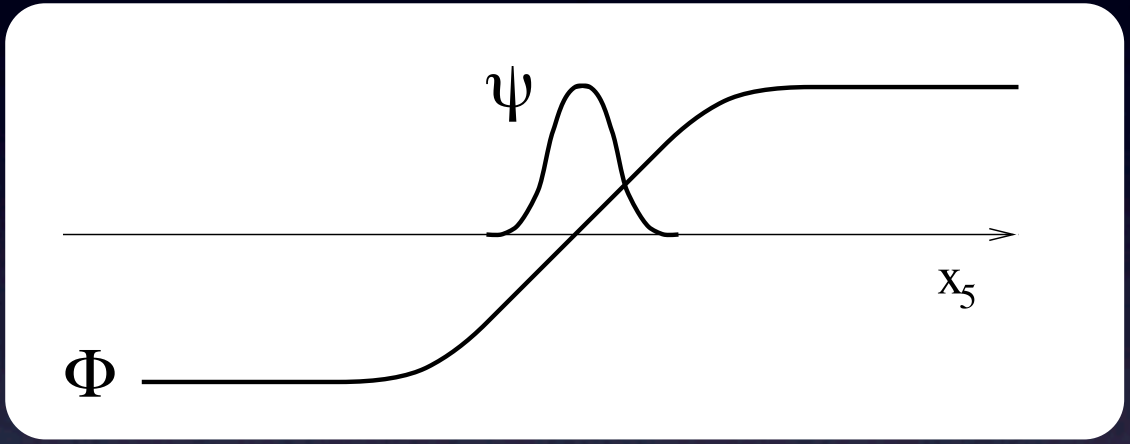

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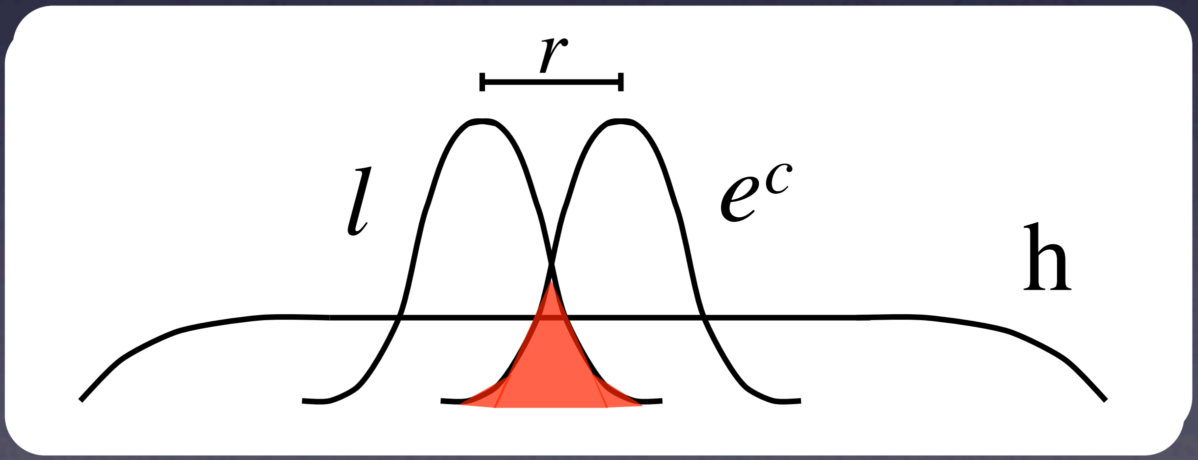

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Arkani-Hamed, Schmaltz

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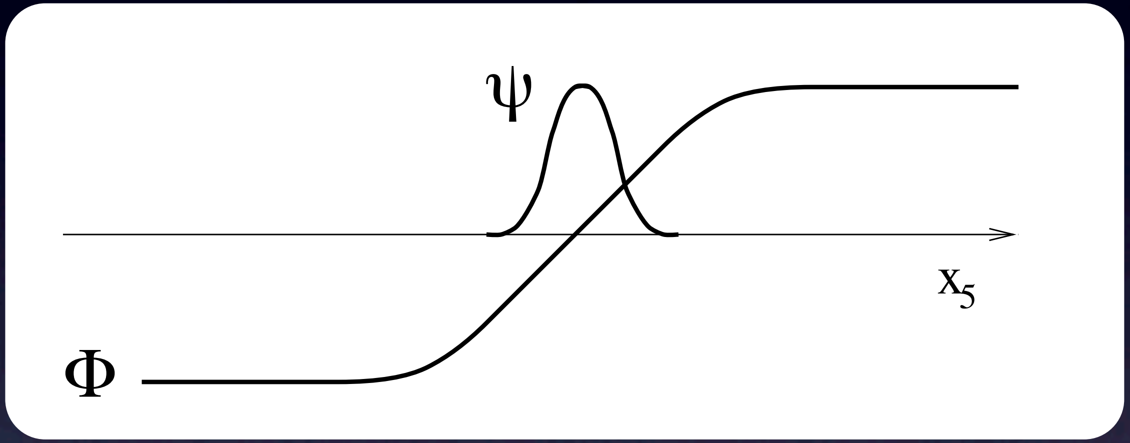

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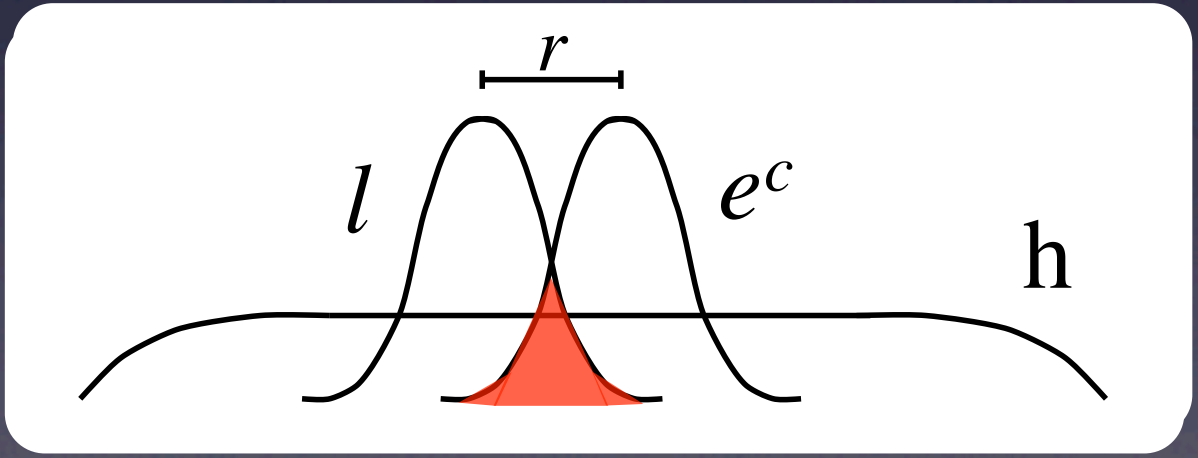

Log(flavor hierarchy)!

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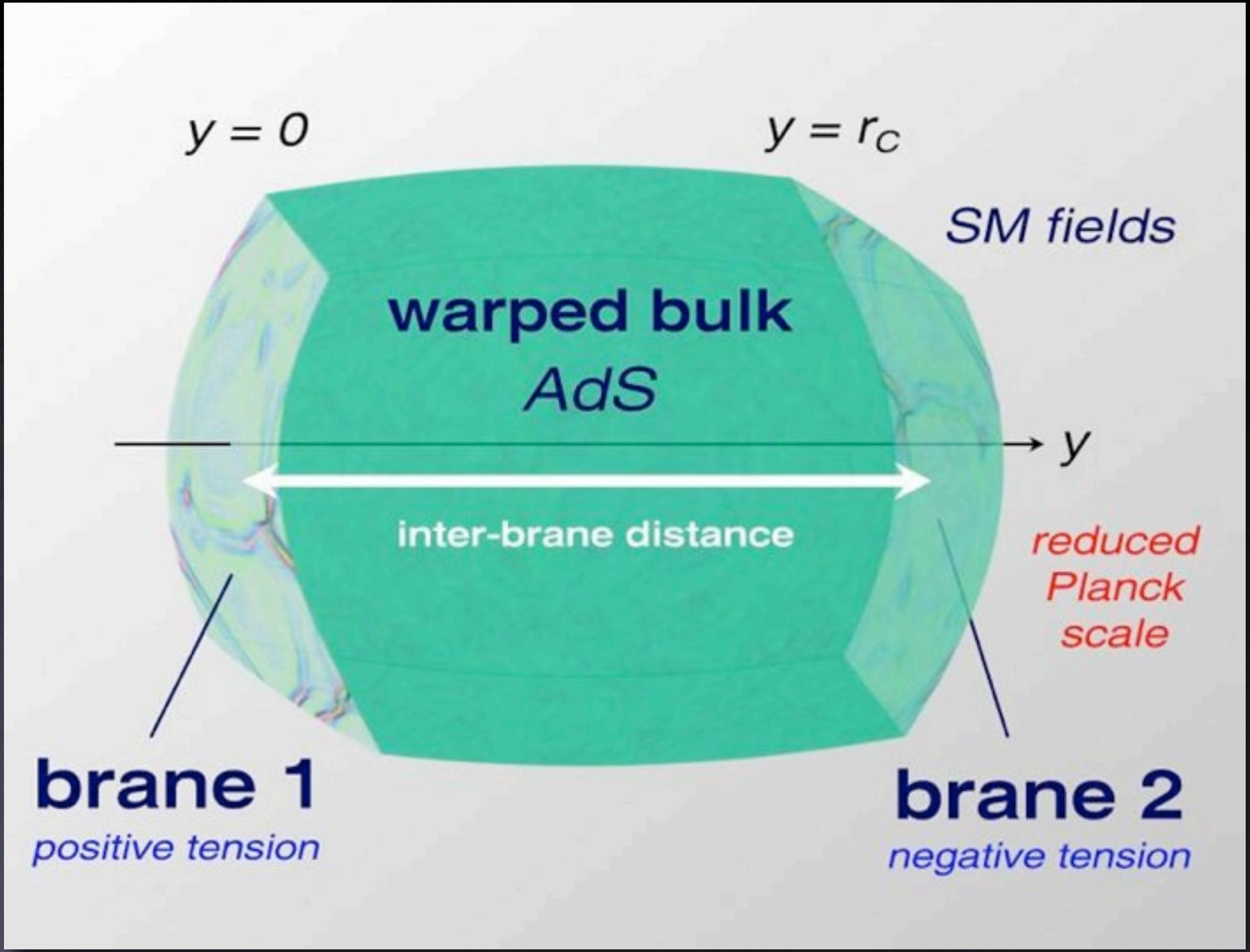
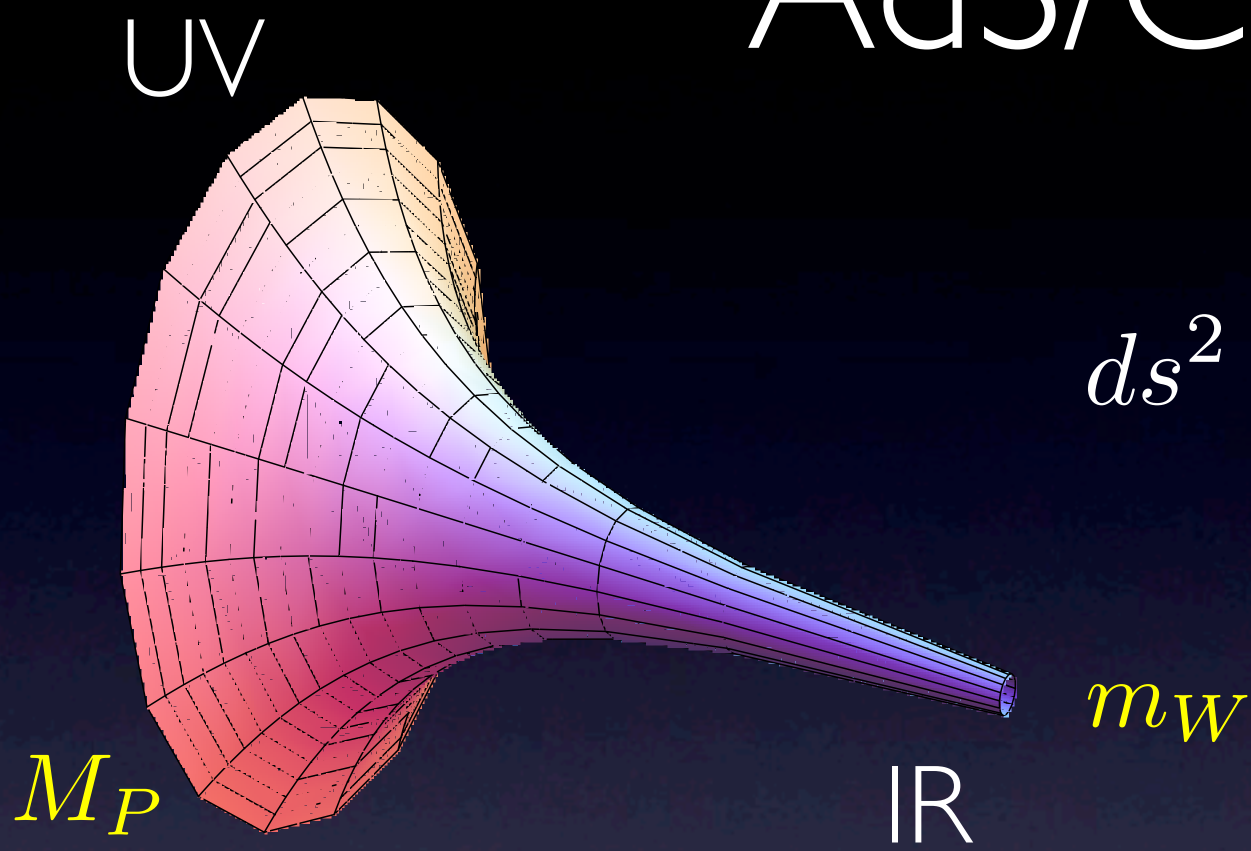
Warped Extra Dimensions



AdS/CFT dictionary



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

Randall, Sundrum

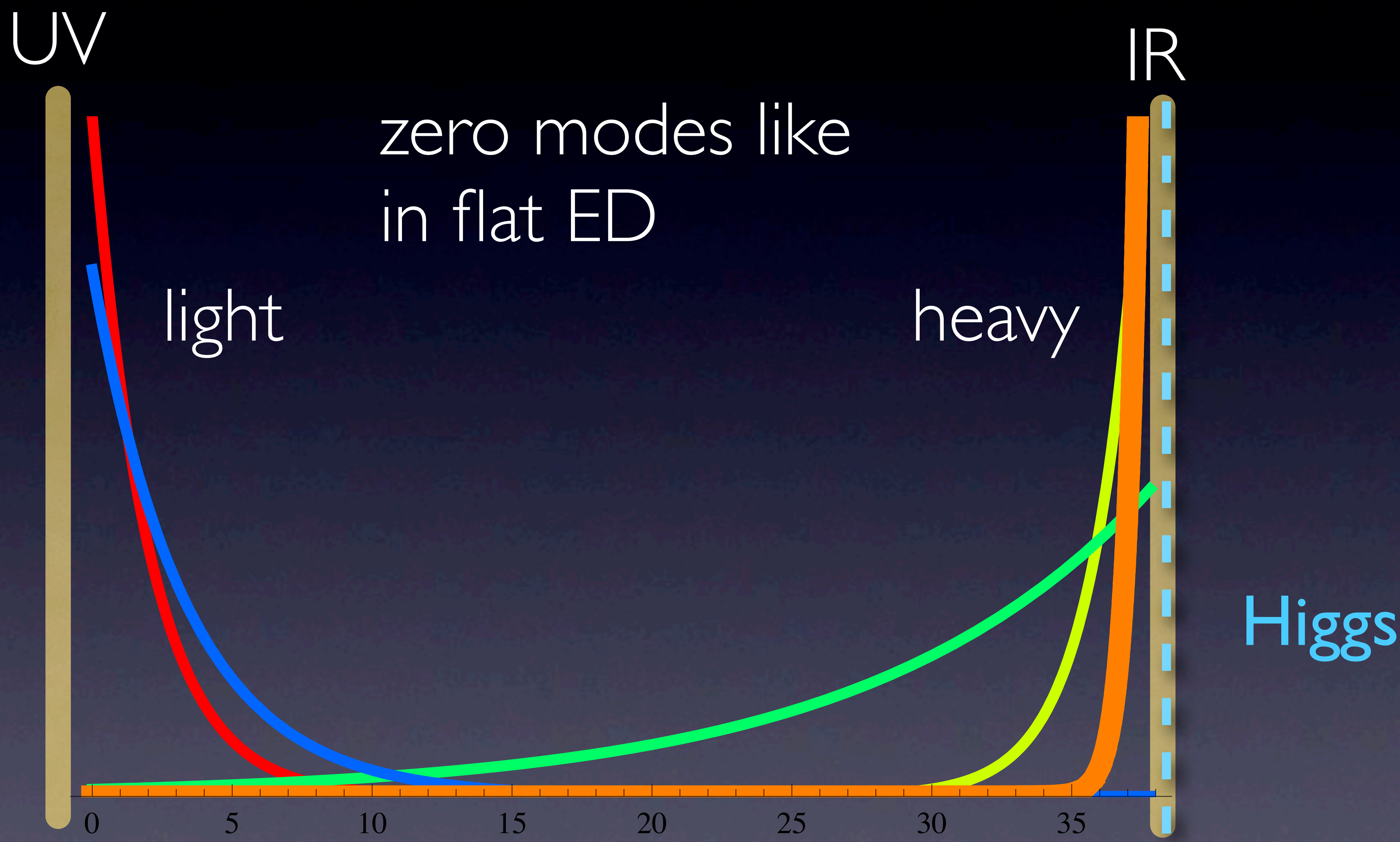
Anti-de-Sitter (AdS)	⟷	Conformal (CFT)
Compactification	⟷	Mass gap
Red-shifting of scales	⟷	Dimensional trans-mutation

$$m_W = \sqrt{\frac{g(IR)}{g(UV)}}\, M_P \ll M_P$$

$$m_W \sim e^{-4\pi/\alpha} M_P$$

Flavor in RS

Grossman, Neubert; Gherghetta, Pomarol; Huber;



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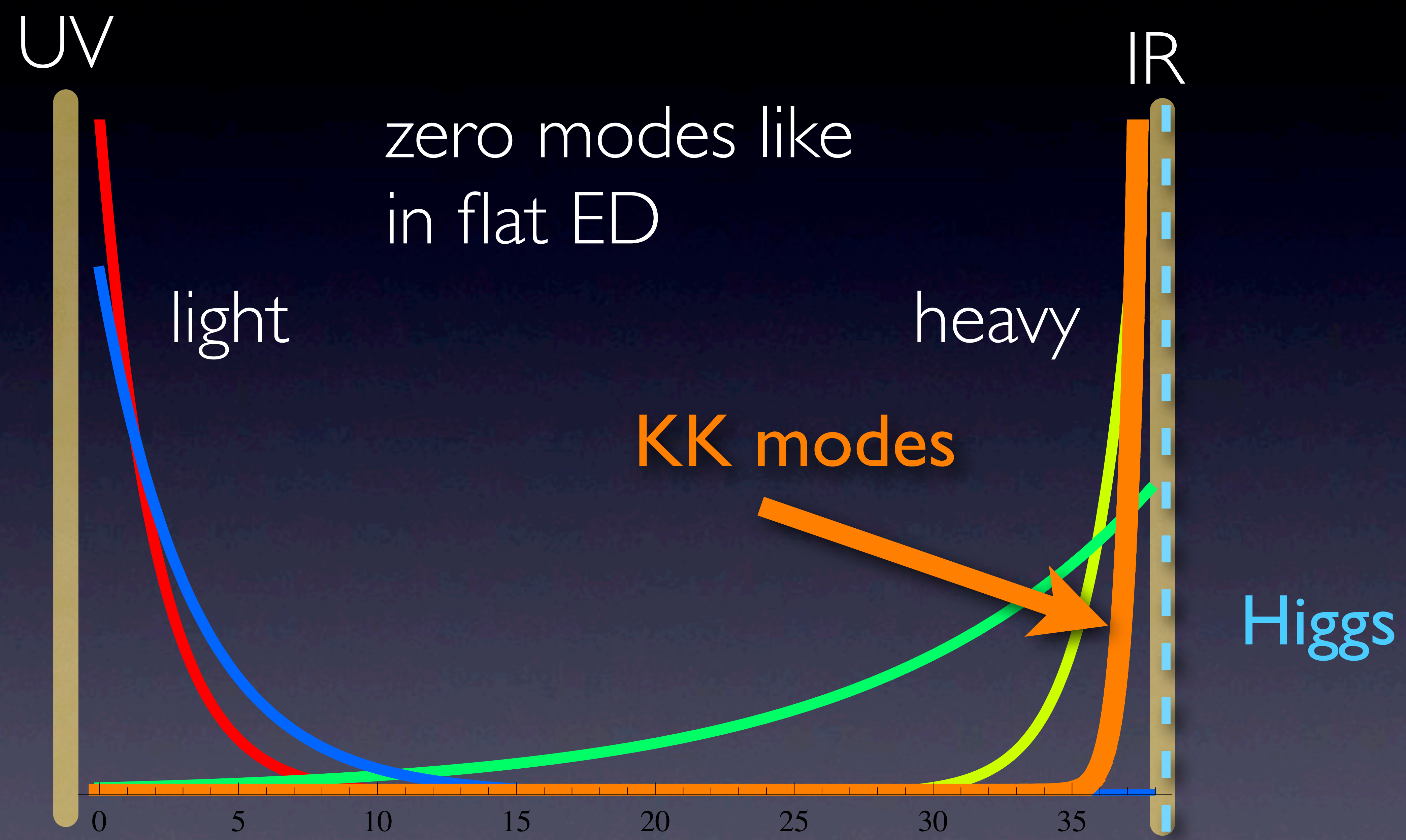

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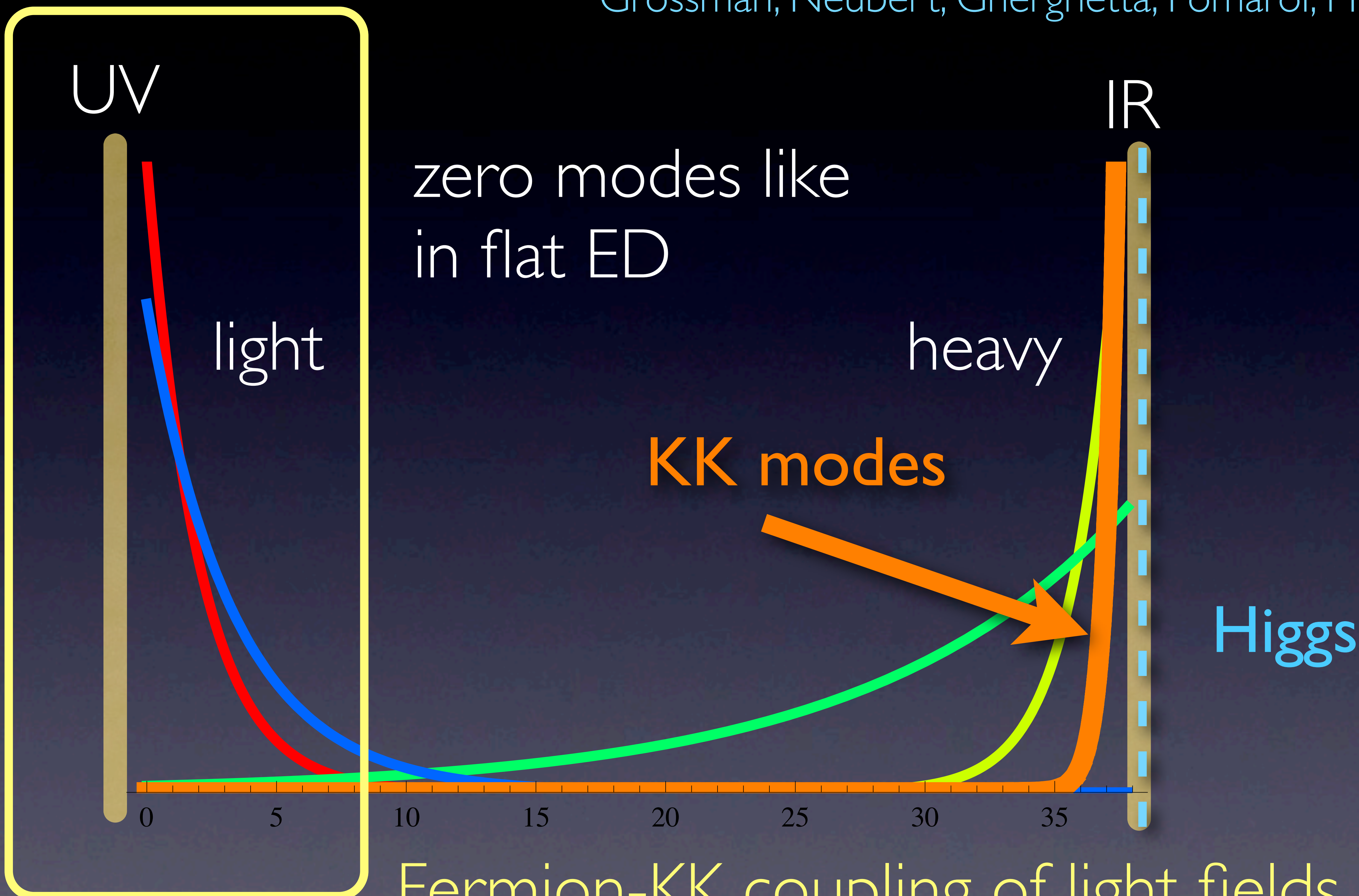

Fermion-KK coupling of light fields almost universal!

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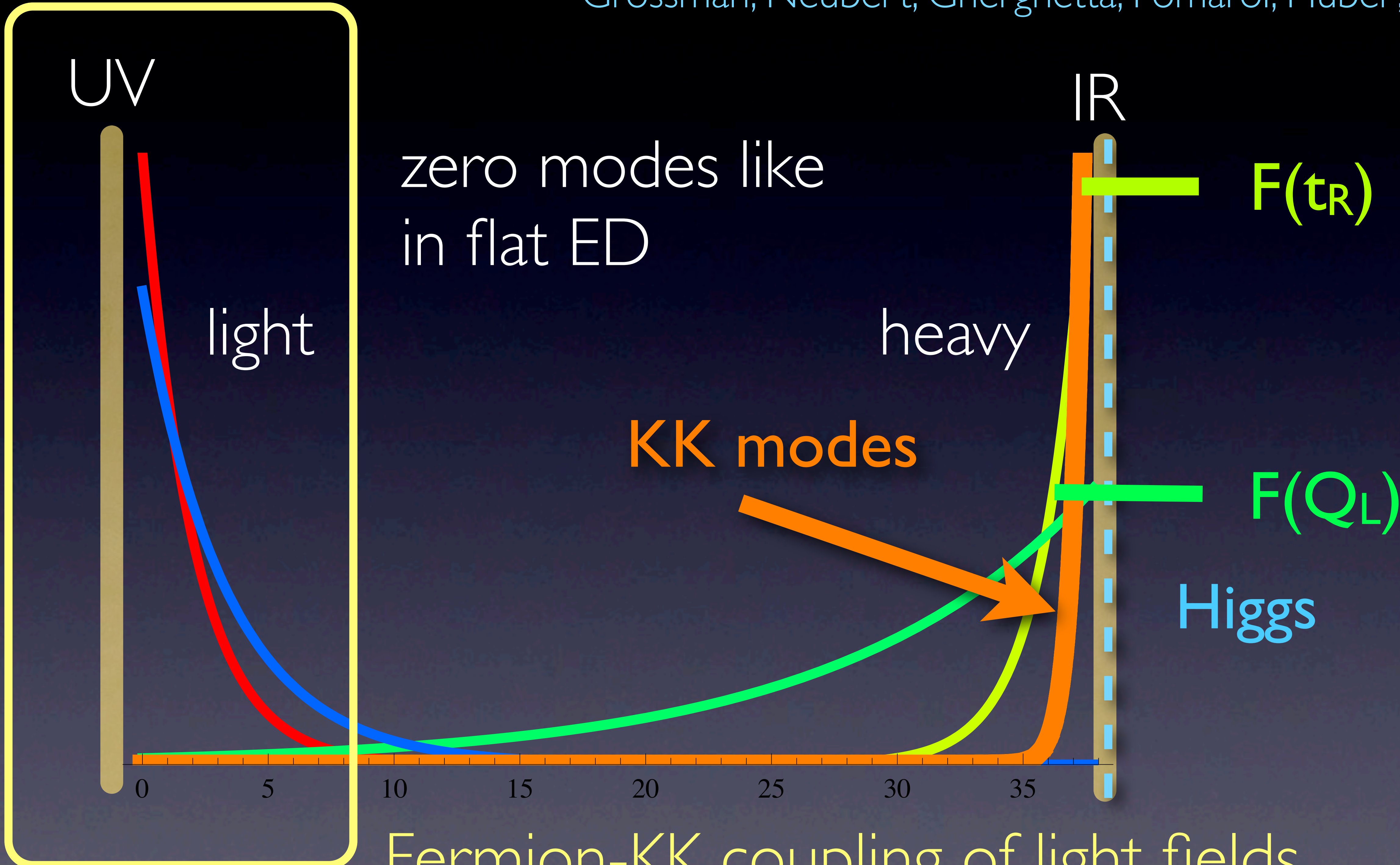

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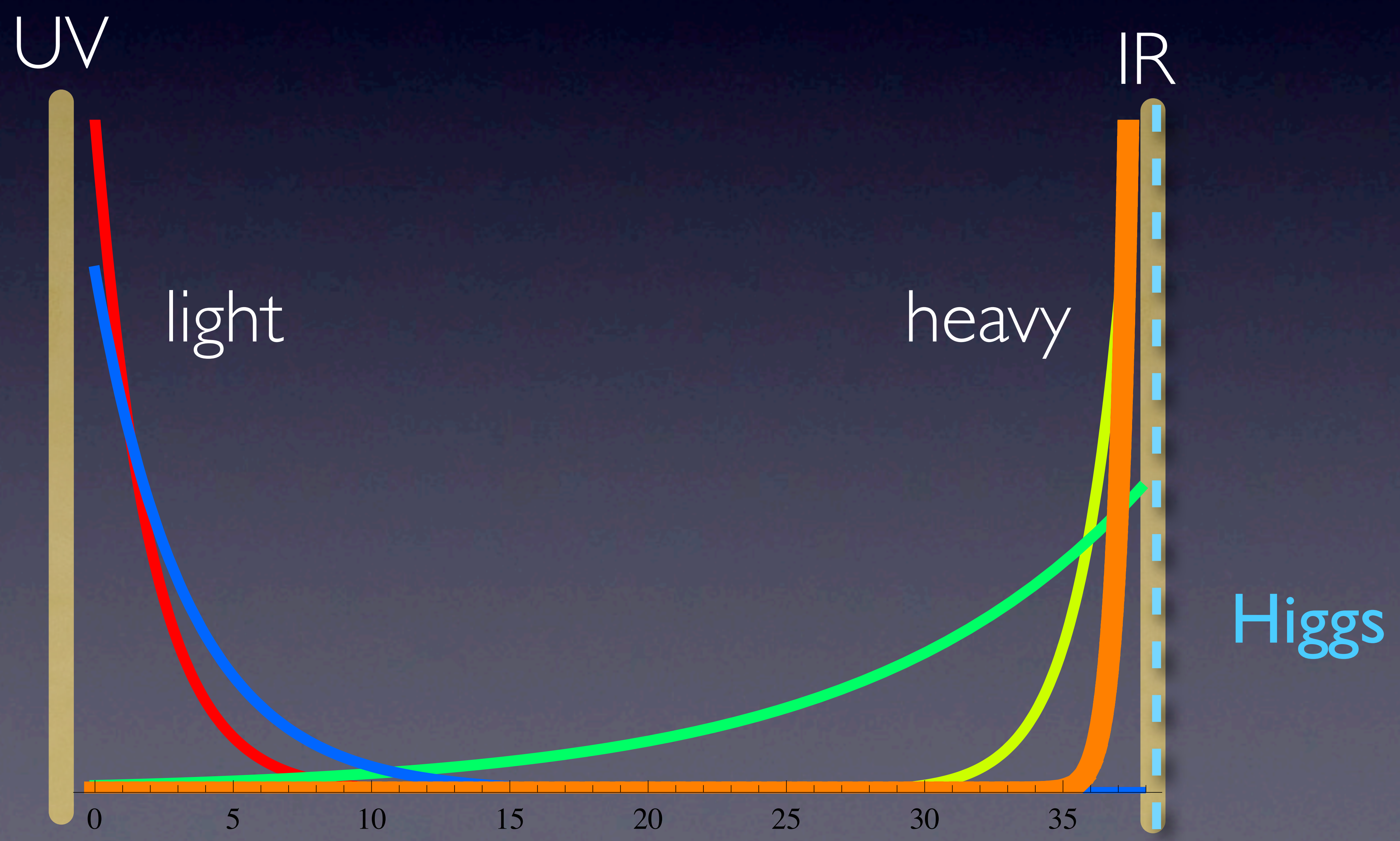
Fermion zero mode on the IR brane

$$F(c) \sim \begin{cases} (\mathrm{TeV}/\mathrm{Planck})^{c-\frac{1}{2}} & c > 1/2 \\ \sqrt{1-2c} & c < 1/2 \end{cases}$$



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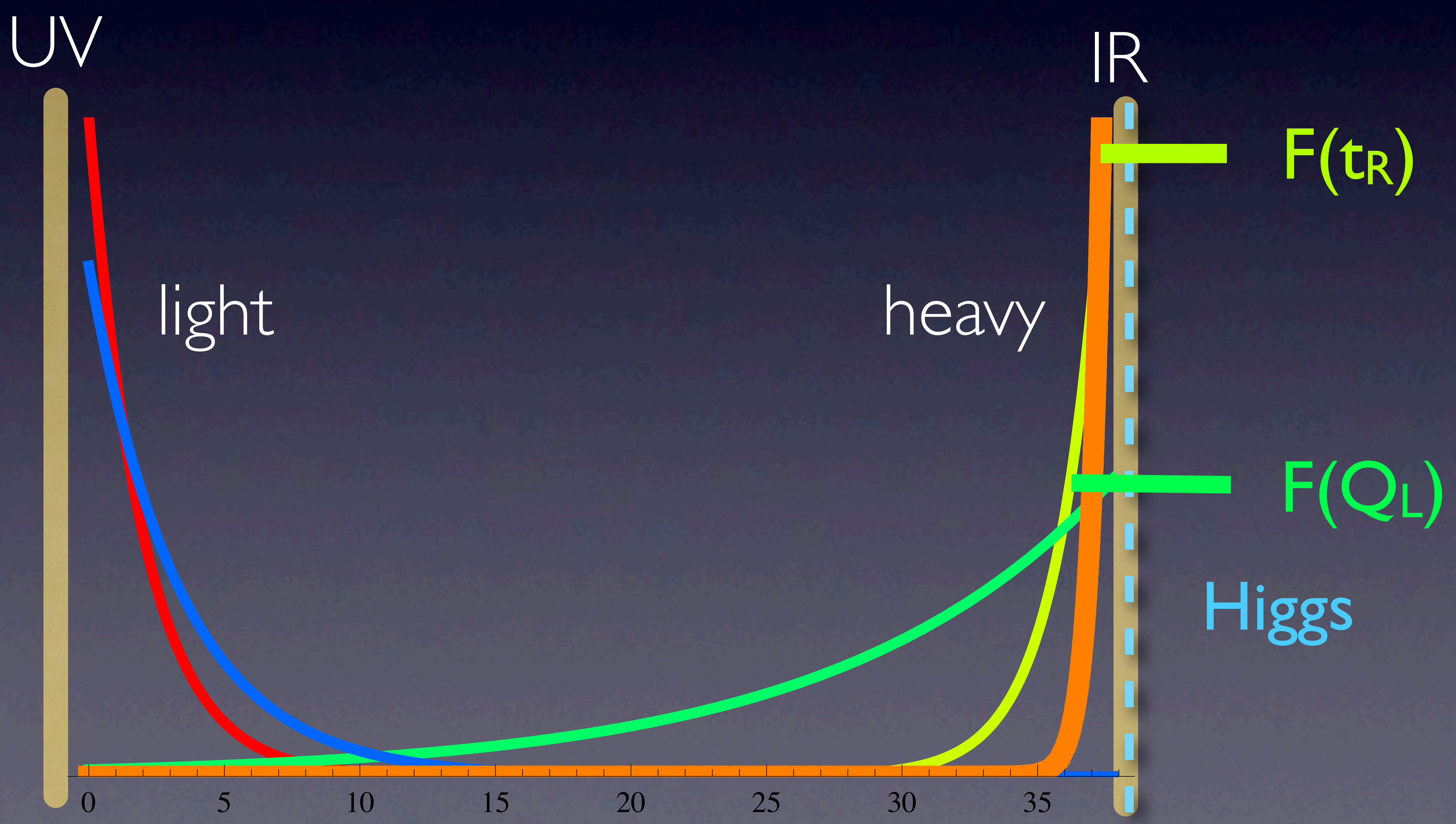
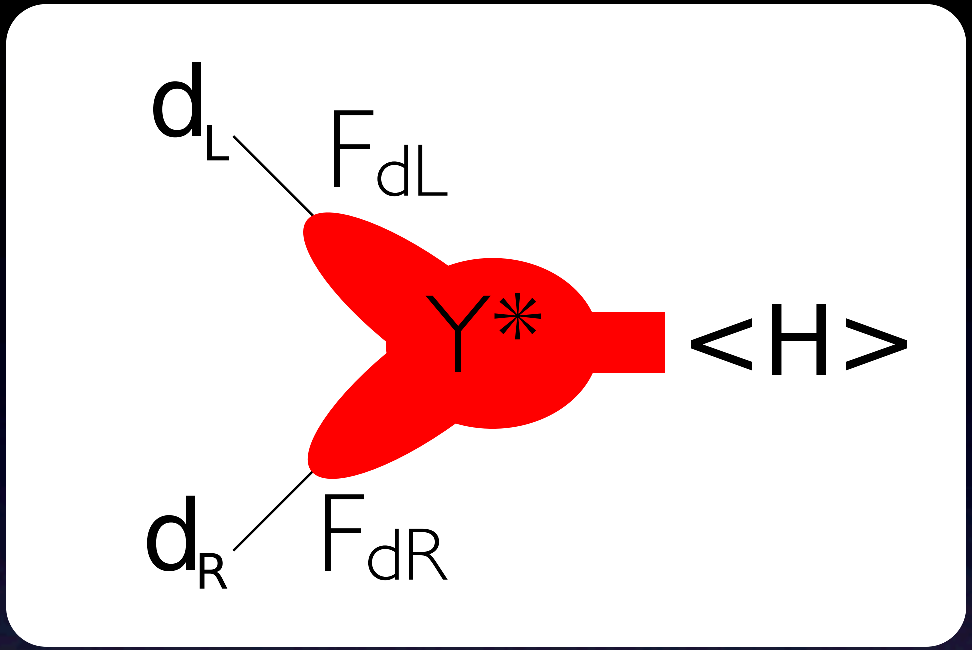


RS GIM - partial compositeness

Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



Flavor hierarchy from hierarchy in F_i

$$m_d \sim v\, F_{d_L} Y^* F_{d_R}$$

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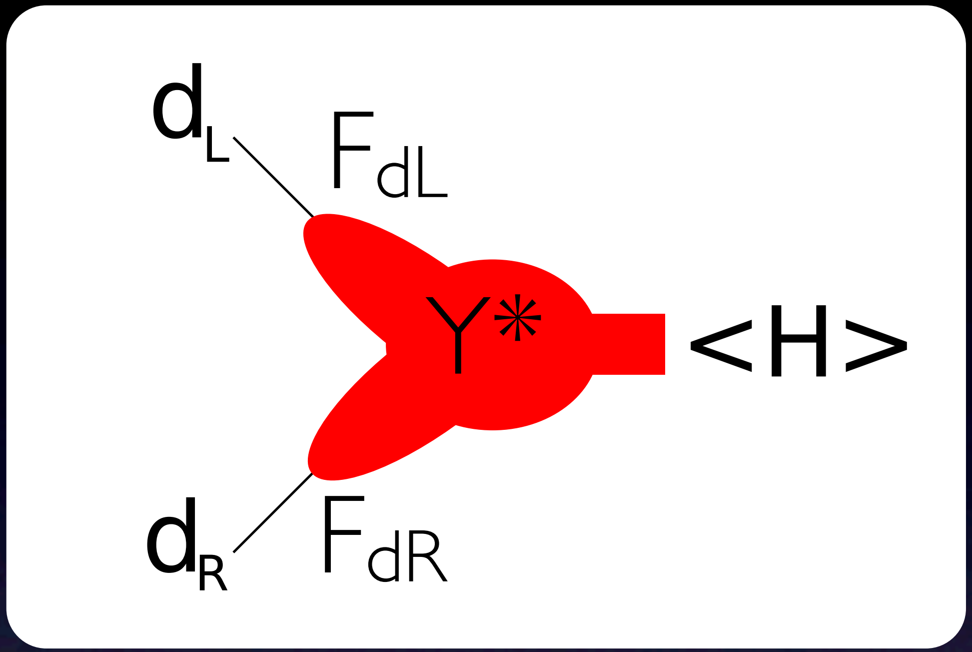

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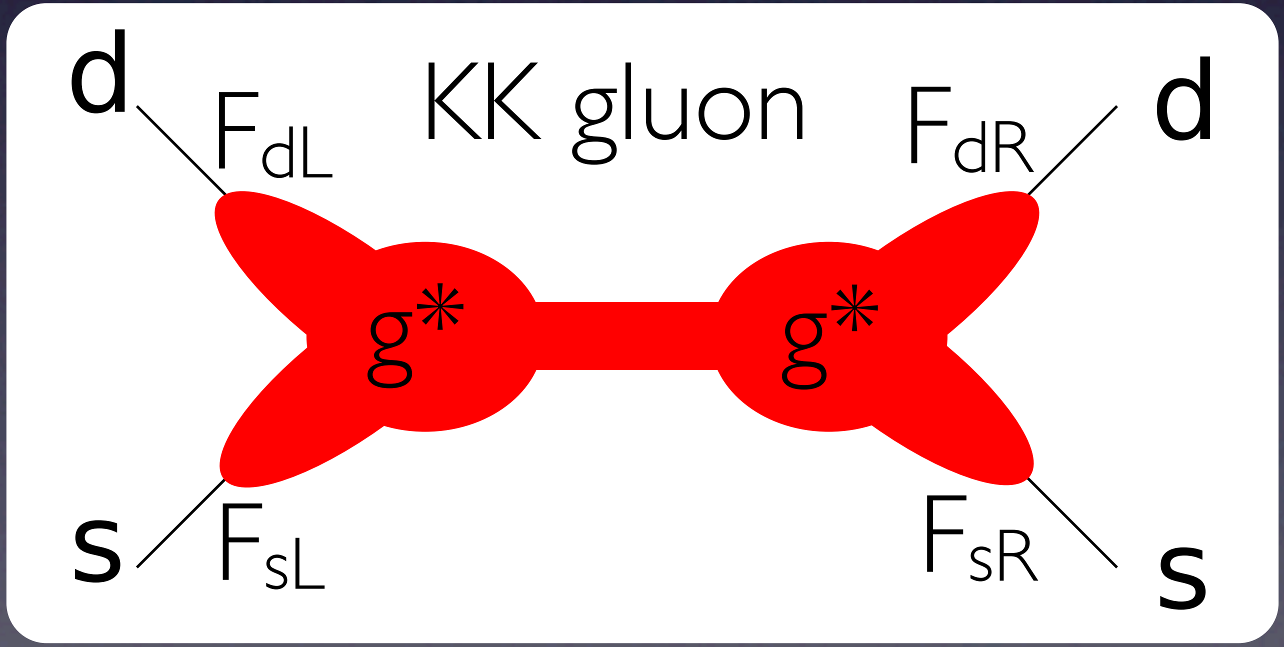


KK gluon FCNCs proportional to the same small F_i :

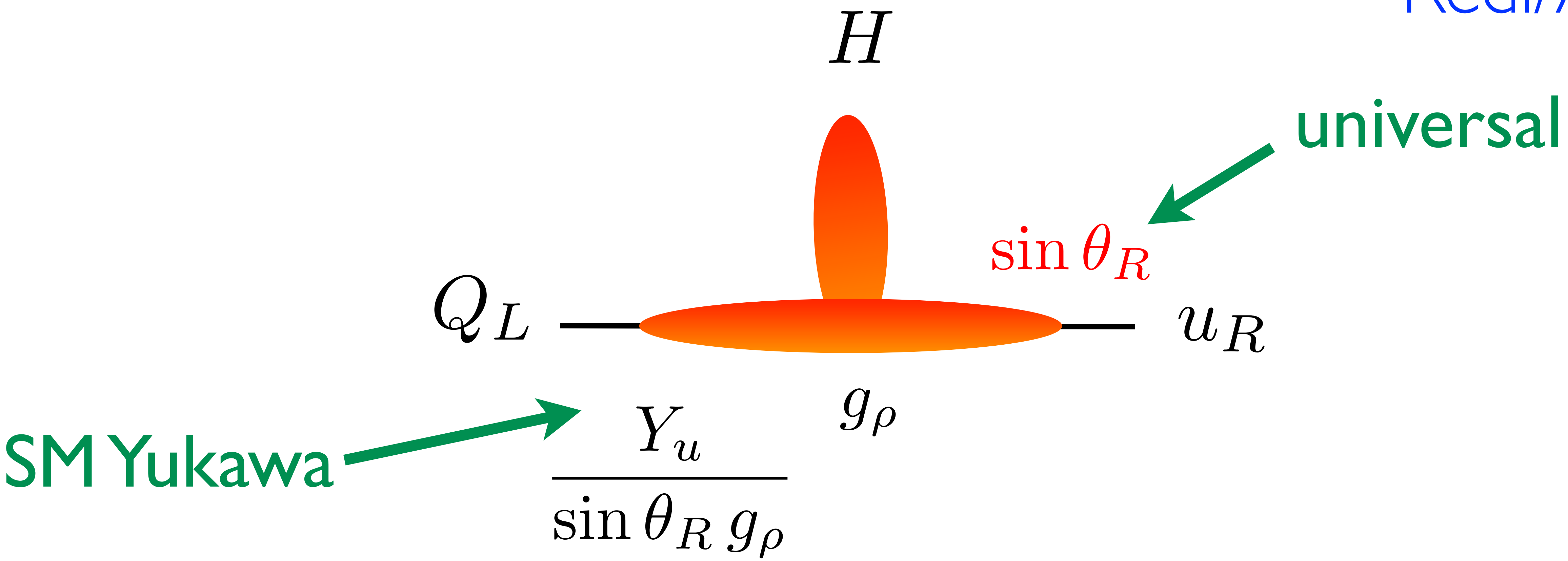
$$\sim \frac{(g^*)^2}{M_{KK}^2} F_{d_L} F_{d_R} F_{s_L} F_{s_R}$$

$$\sim \frac{(g^*)^2}{M_{KK}^2} \frac{m_d\, m_s}{(vY^*)^2}$$

Back to 4D …

A Minimal Flavor Violating Composite Higgs

Redi/AW*



*for RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al

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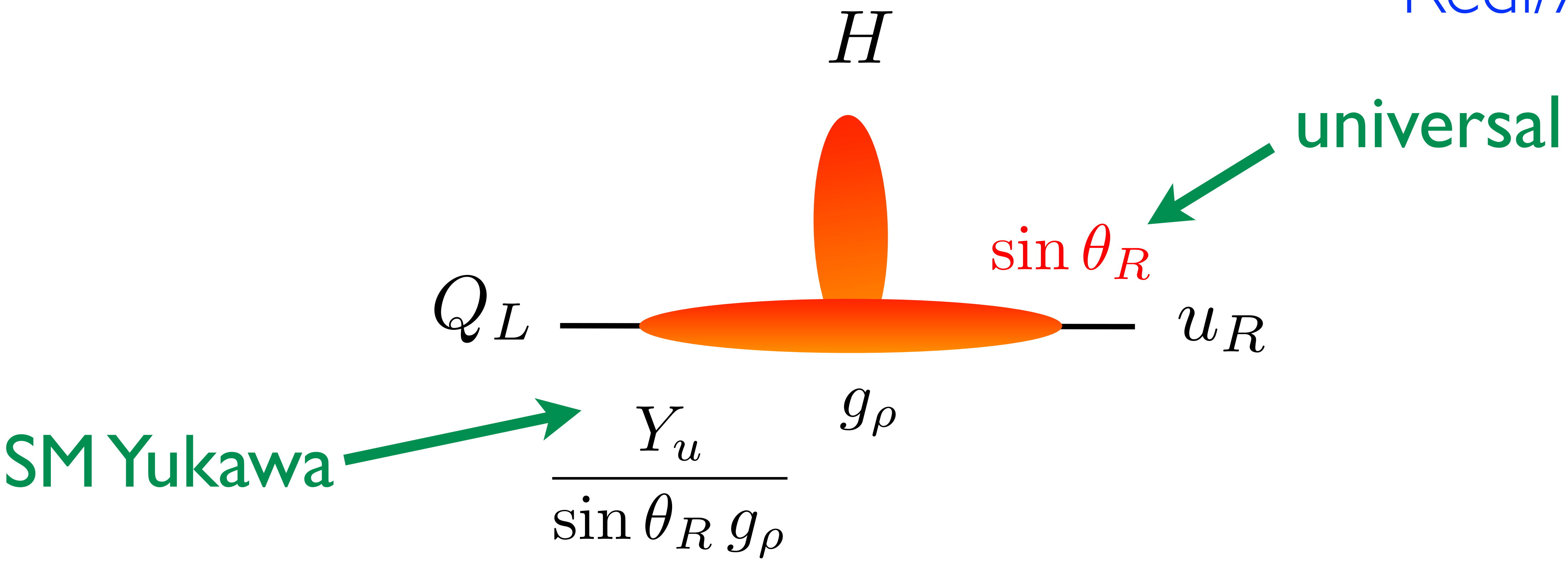

Composite *u,d* quarks, very large cross-sections

m_{top} : $$\sin\theta_R \gtrsim \frac{1}{g_\rho} \sim \frac{1}{8}$$

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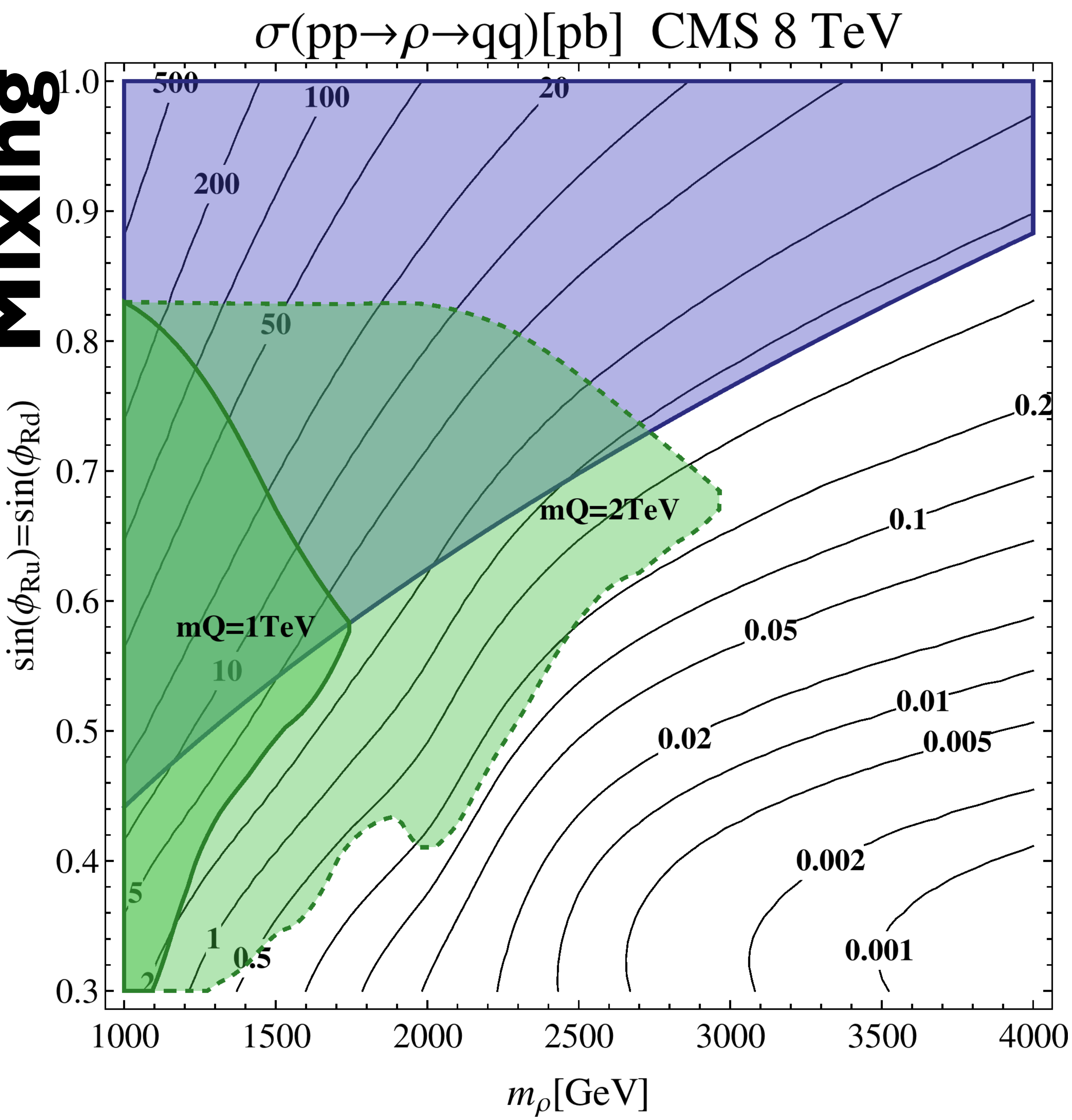
LHC8 limits

...similar plot using ATLAS results

de Vries, Redi, Sanz, AW, 13

Mixing



Vector mass

LHC8 limits

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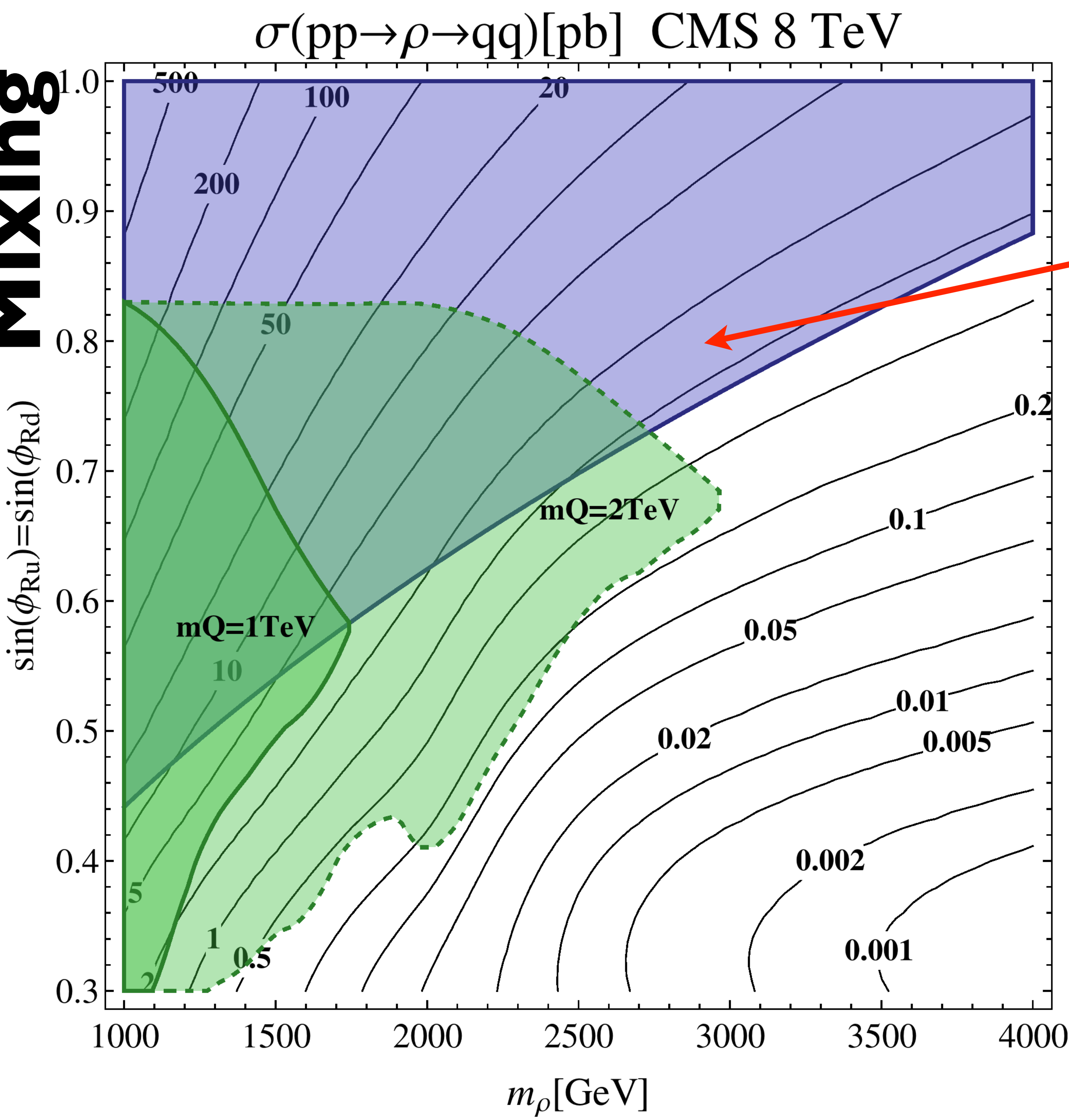
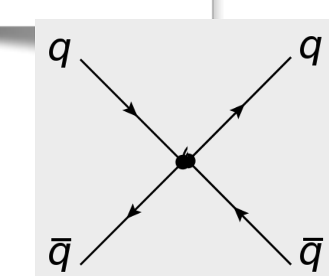


CMS dijet angular searches

$$\mathcal{L} = \frac{2\pi}{\Lambda^2}\left(\bar{q}_{L,R}\gamma^{\mu} q_{L,R}\right)^2$$



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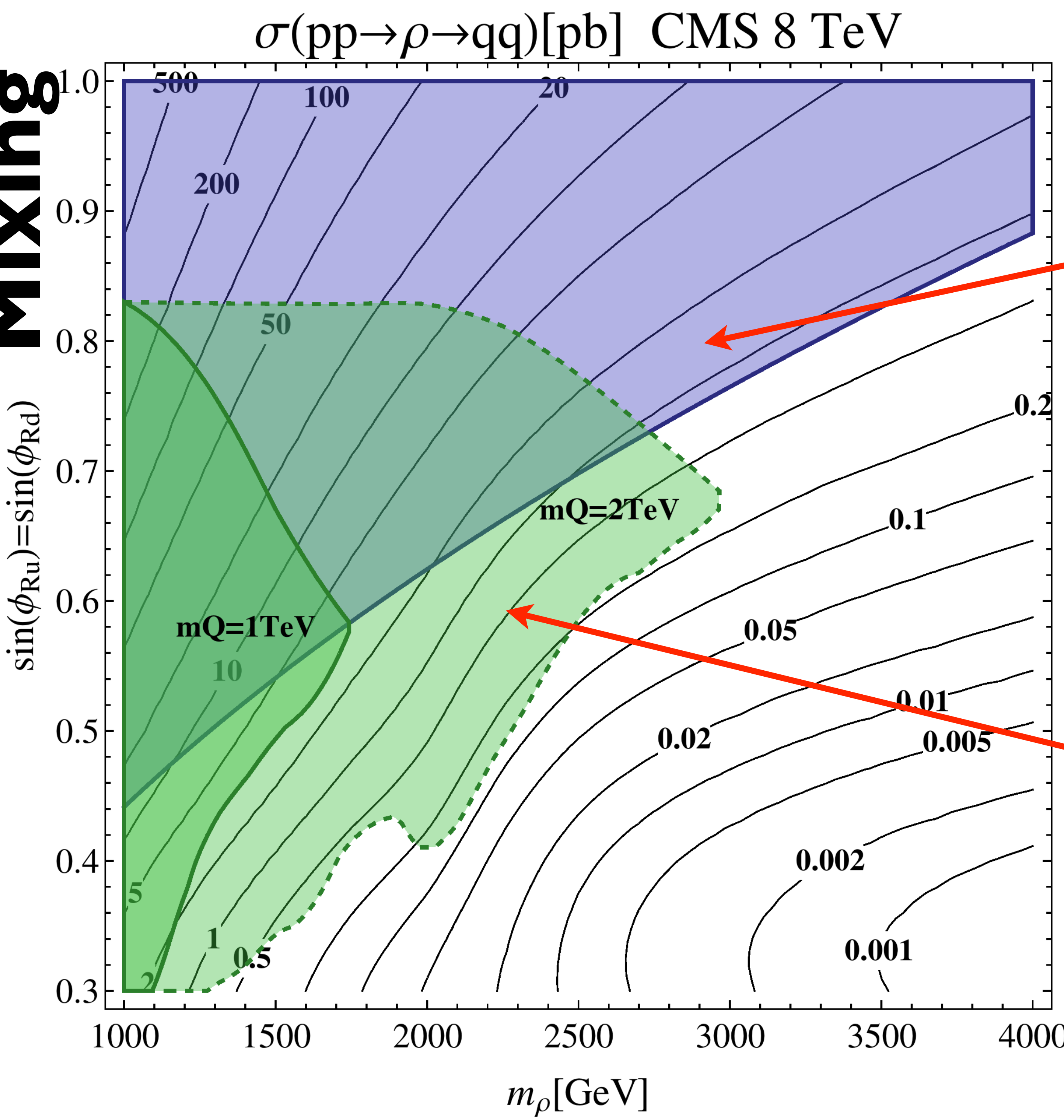

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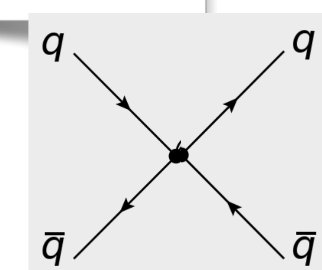
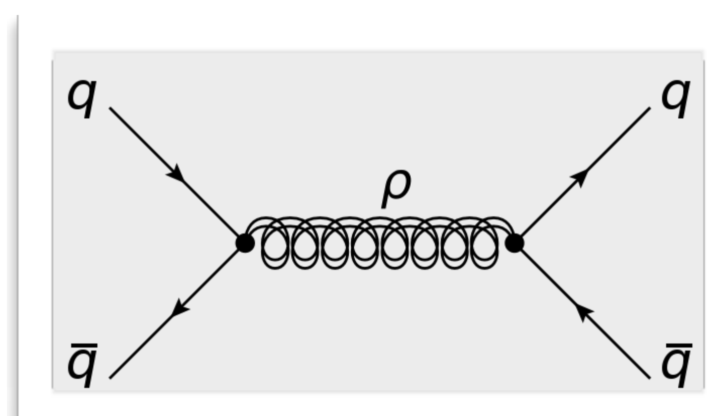
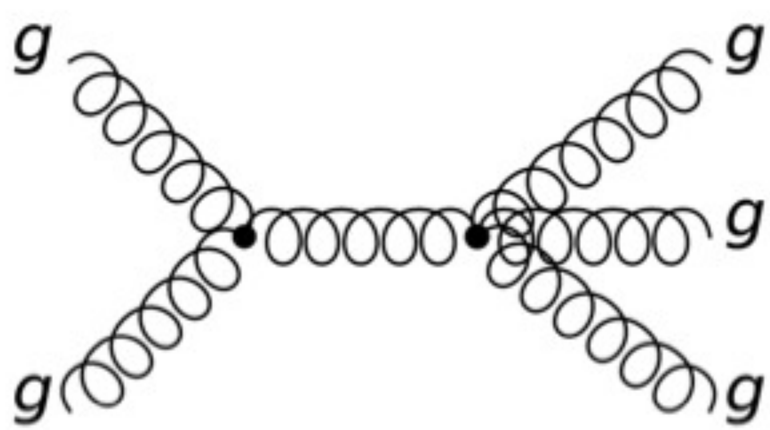
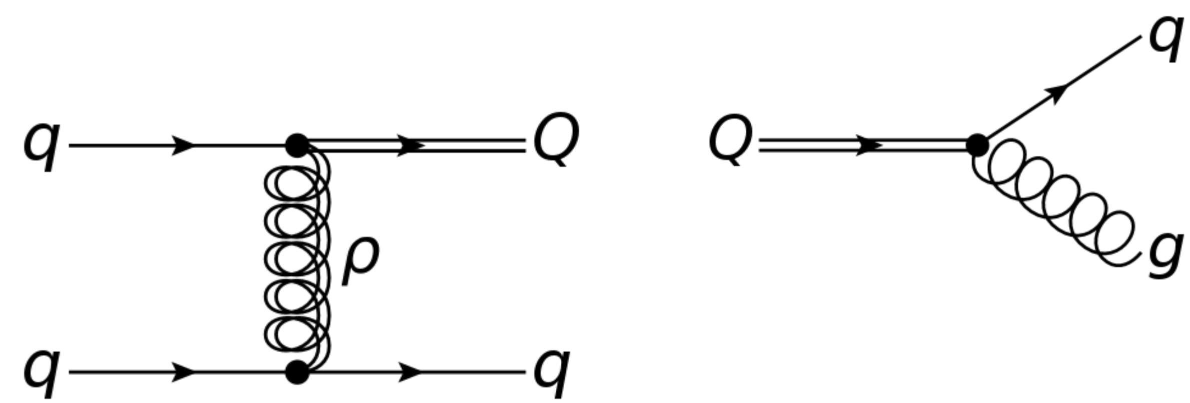


Dijet bump search
CMS

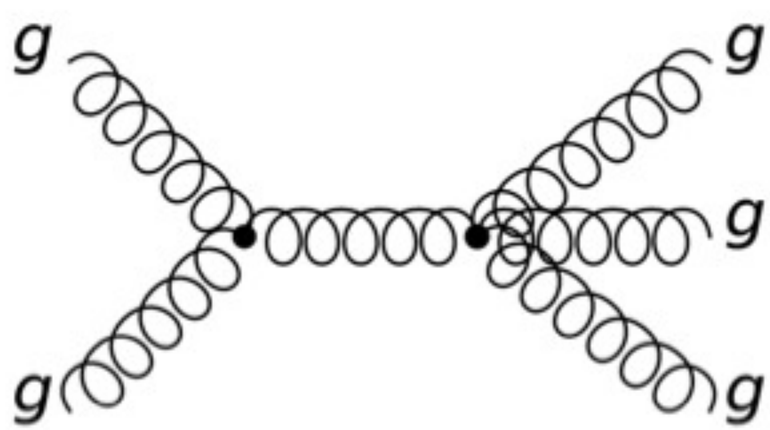


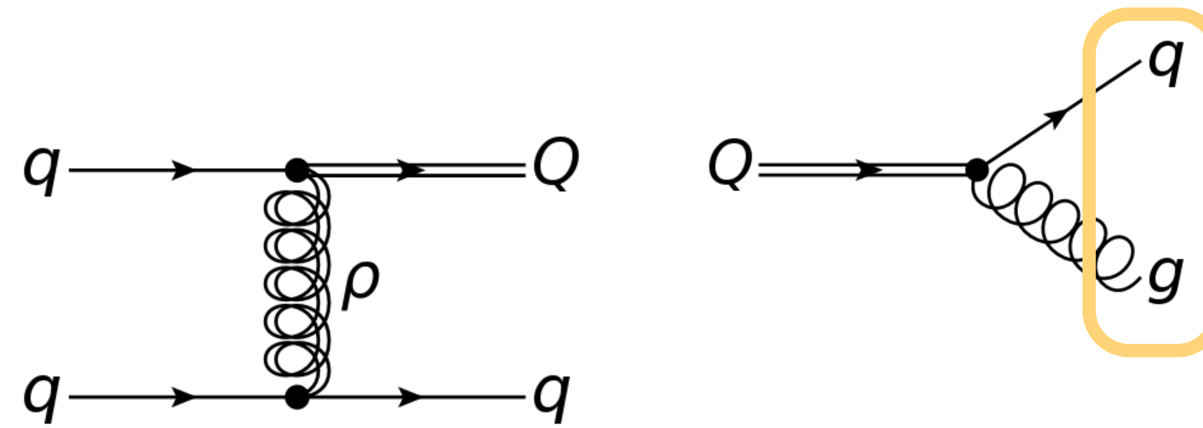




QCD vs. Composite Partners

bump in sub-leading jets





QCD vs. Composite Partners

Dedicated search

deVries, Redi, Sanz, AW, '13

Cut-flow	$m_Q = 600$ GeV		$m_Q = 1200$ GeV	
	signal	QCD	signal	QCD
p_T leading jet > 450 GeV	0.51	0.0067	0.90	0.0067
$H_T > m_Q$	0.51	0.0067	0.80	0.0015
$\|m_{jj} - m_Q\| < (30, 50)$ GeV	0.15	0.00037	0.11	2.5×10^{-5}
$\Delta\phi_{jj} > 1.5$	0.045	9.9×10^{-5}	0.060	2.1×10^{-7}

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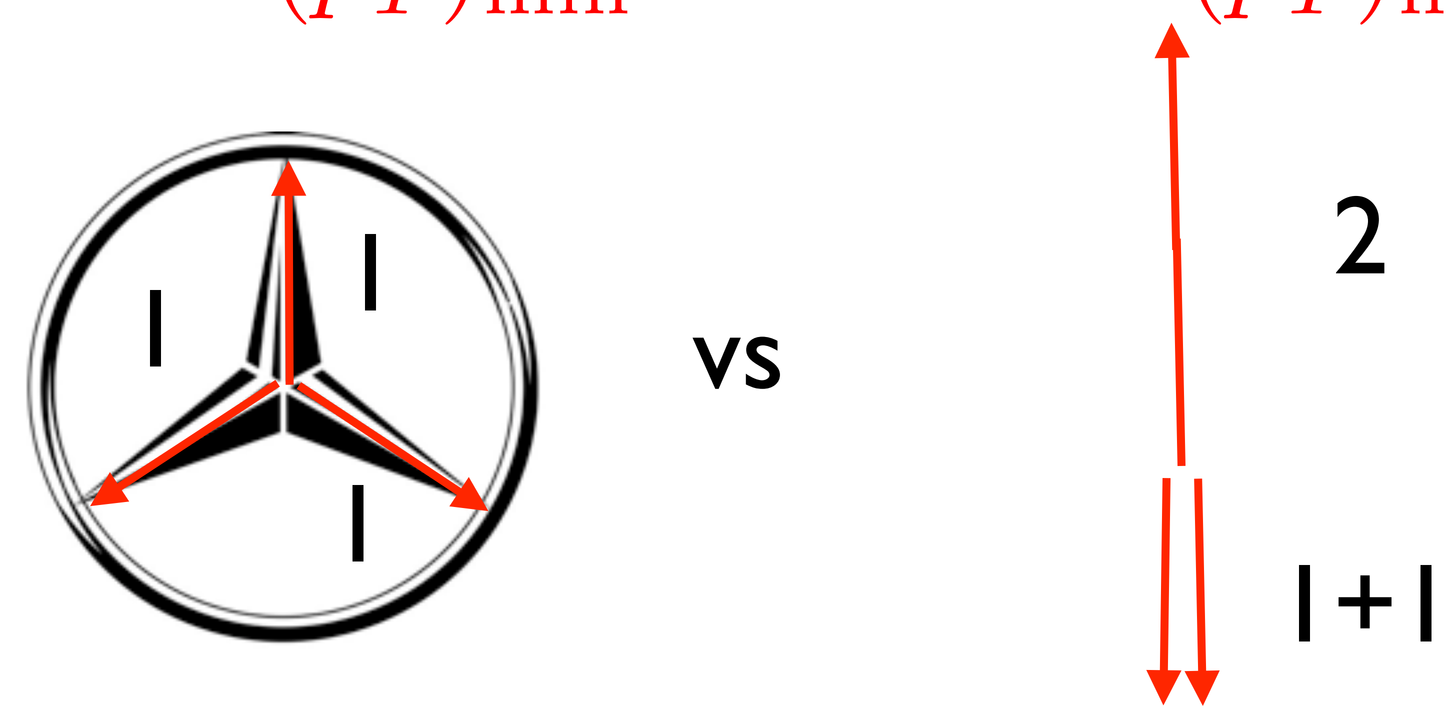
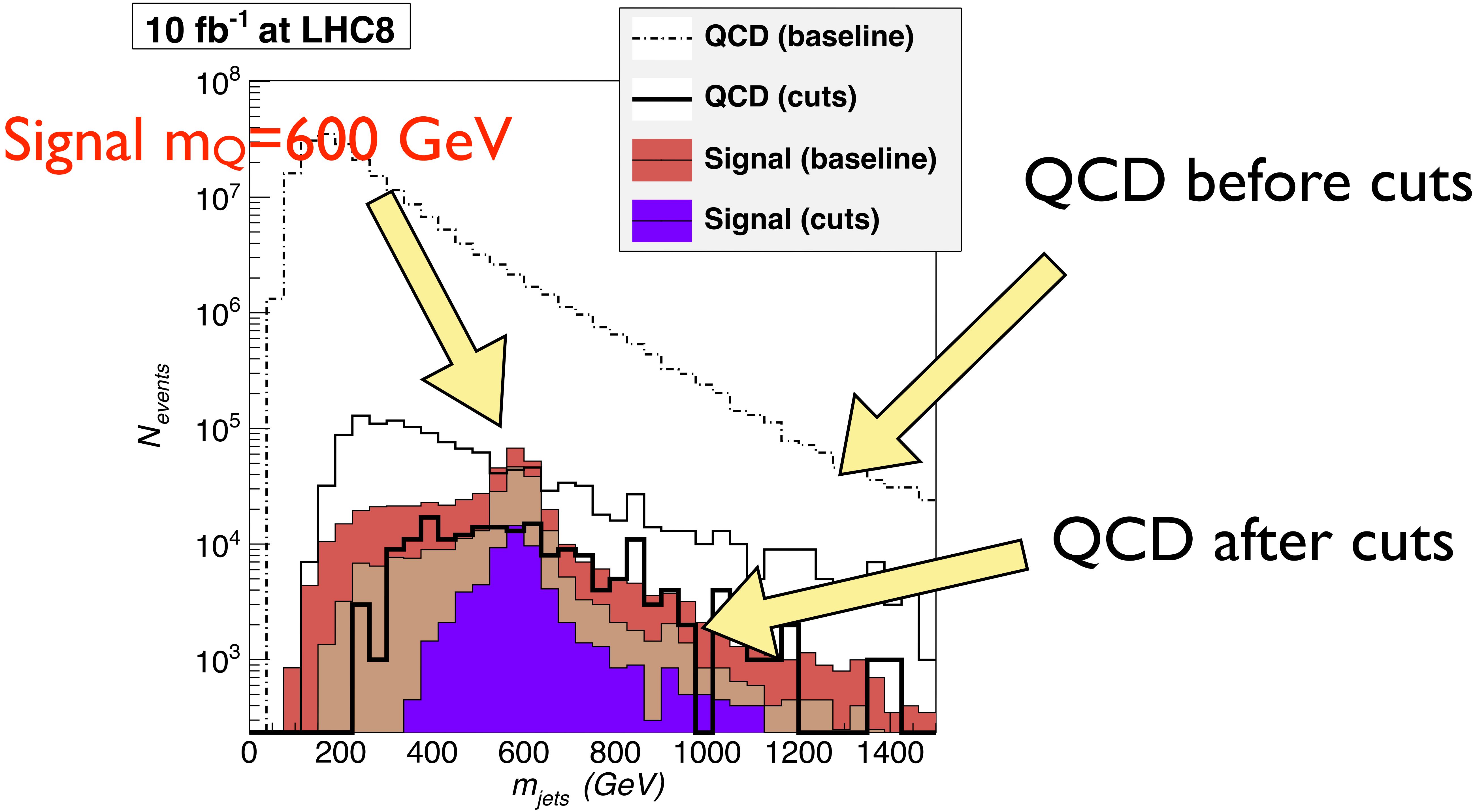
QCD prefers mercedes

$M \sim 3(p_T)_{\rm min}$ $\qquad$ $M \sim 4(p_T)_{\rm min}$



Discovery potential of a dedicated search

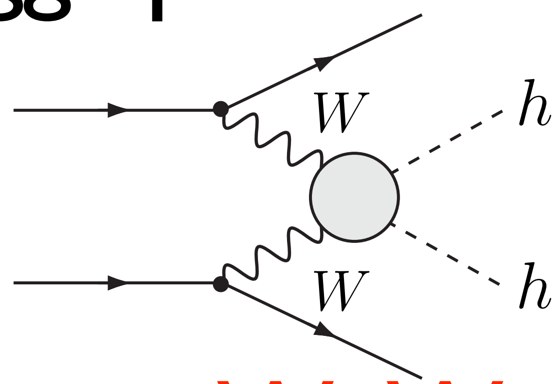
deVries, Redi, Sanz, AW, '13



heavier signal easier, 3jet final state easier, no optimization

Composite Higgs

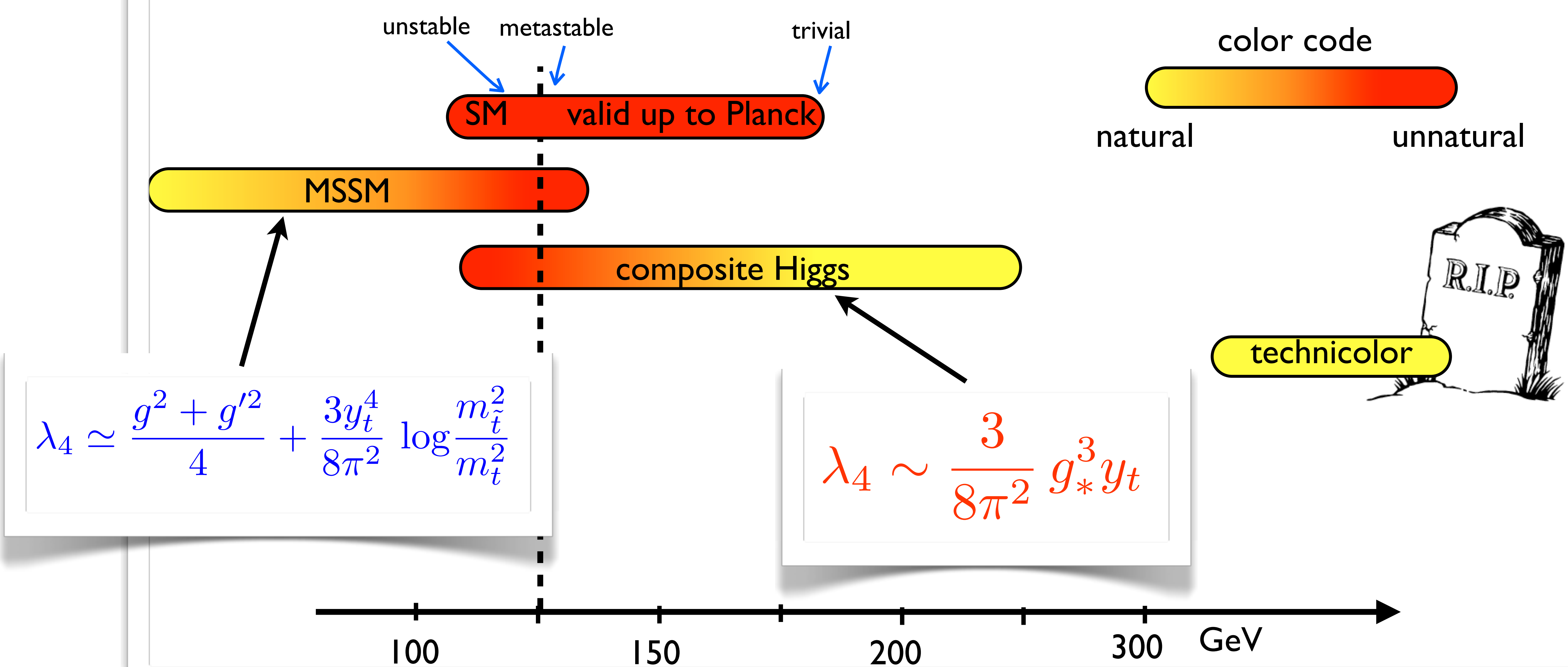
- 'SM-like' light Higgs
- Correlated deviations in Higgs couplings, e.g. $g_{hVV} = g_{hVV}^{(\mathrm{SM})} \cos\theta \quad (V = W,\ Z)$
- Double Higgs production smoking gun



- Keep an eye on $W_L W_L \rightarrow W_L W_L$
- Top partners (Q = 5/3, 2/3, -1/3)

Conclusion

WHAT IS THE MASS TELLING US?



Bellazzini

Conclusions

The battle for a natural resolution of the hierarchy problem goes on

Where is everybody?

LHC_{14} will be decisive