4th Lepton Family in Technicolor

Francesco Sannino

CP3 - Origins

Particle Physics & Origin of Mass

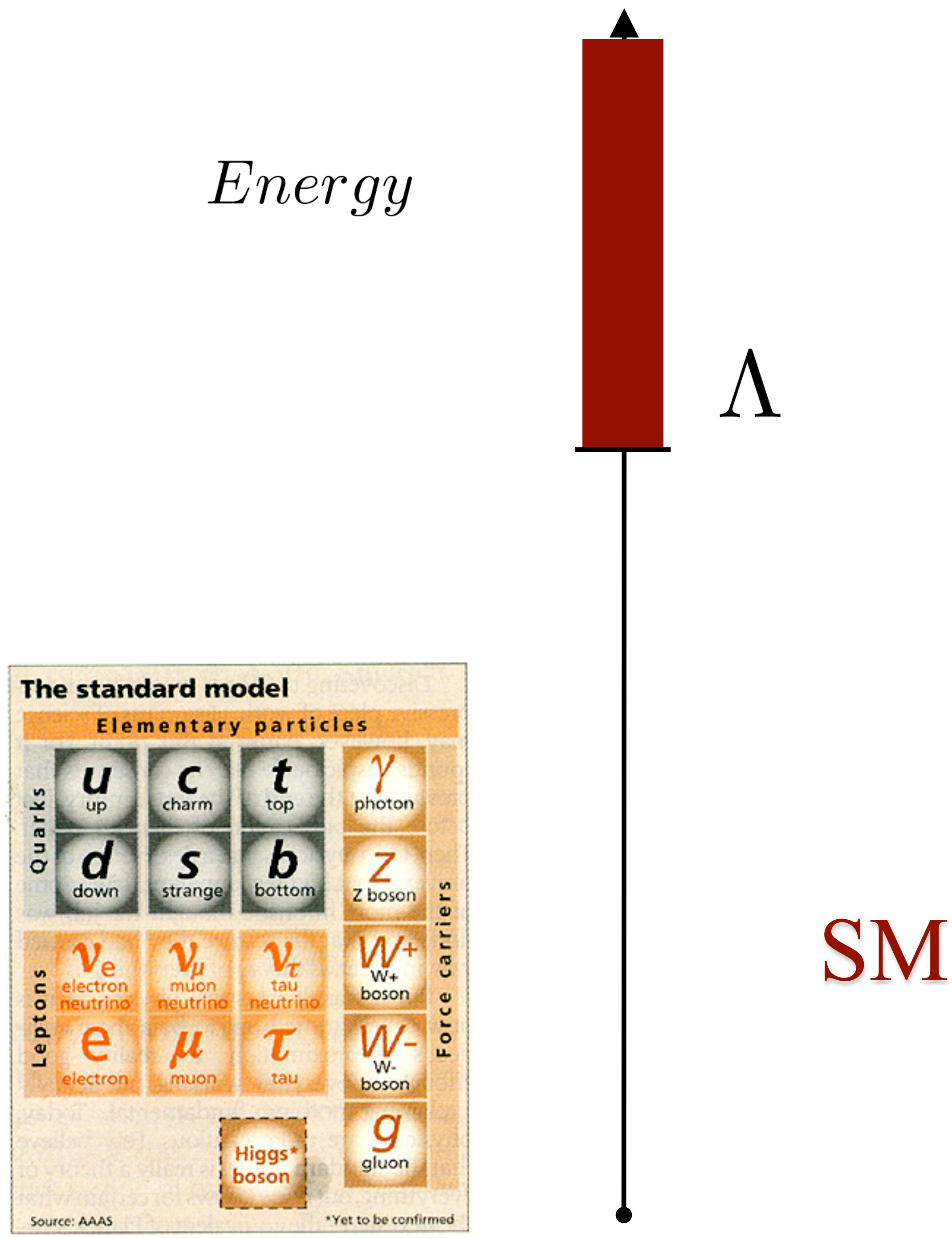
13 April 2011 @ Portoroz - Slovenia

FS: 0911.0931

Riddles


Atoms
4%
Electro
Magnetic
Strong
Weak
Gravity
Dark Energy
74%
Dark Matter
22%
?
?

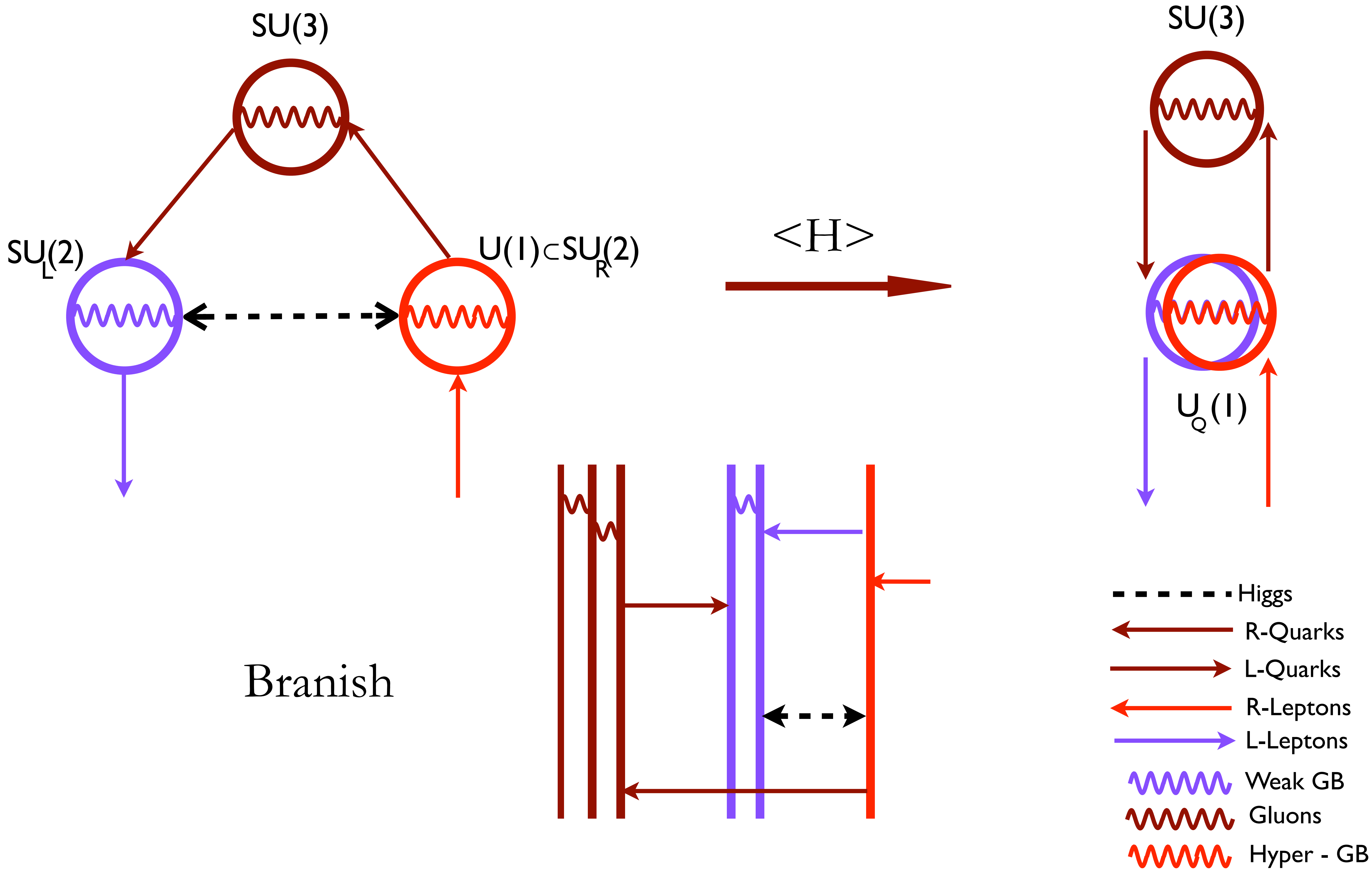
Low Energy Theory



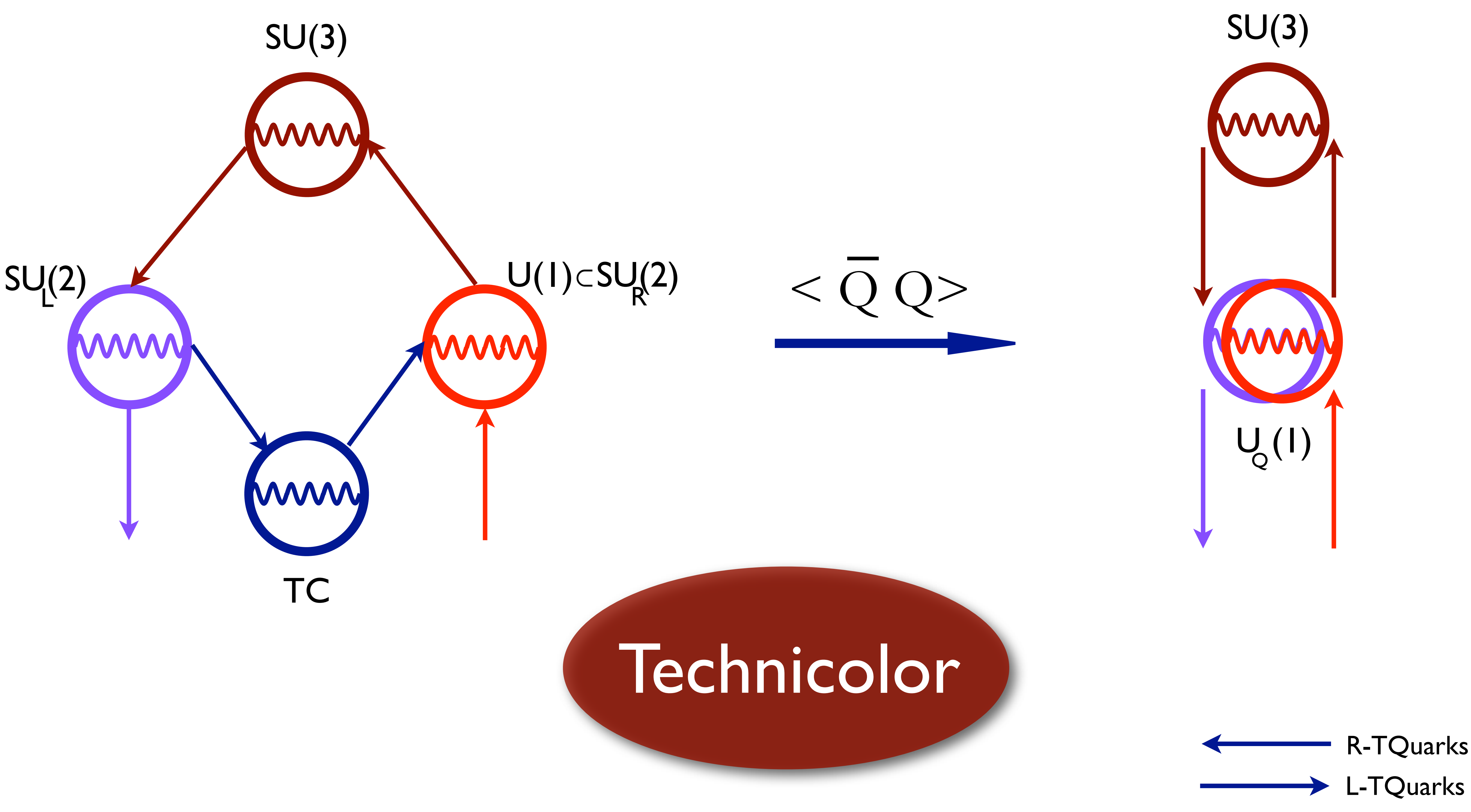
CP^3 - Origins

Particle Physics & Origin of Mass

SM - cartoon



Technicolor - Geometry



Dynamical EW Breaking

$$L(H) \to -\frac{1}{4} F^{a\mu\nu} F^{a}_{\mu\nu} + i\,\bar{Q}\gamma^{\mu} D_{\mu} Q + \cdots$$

Dots are partially fixed by Anomalies as well as other principles

$$\cdots \qquad \to \qquad L(\text{New SM Fermions})$$

QCD-like TC

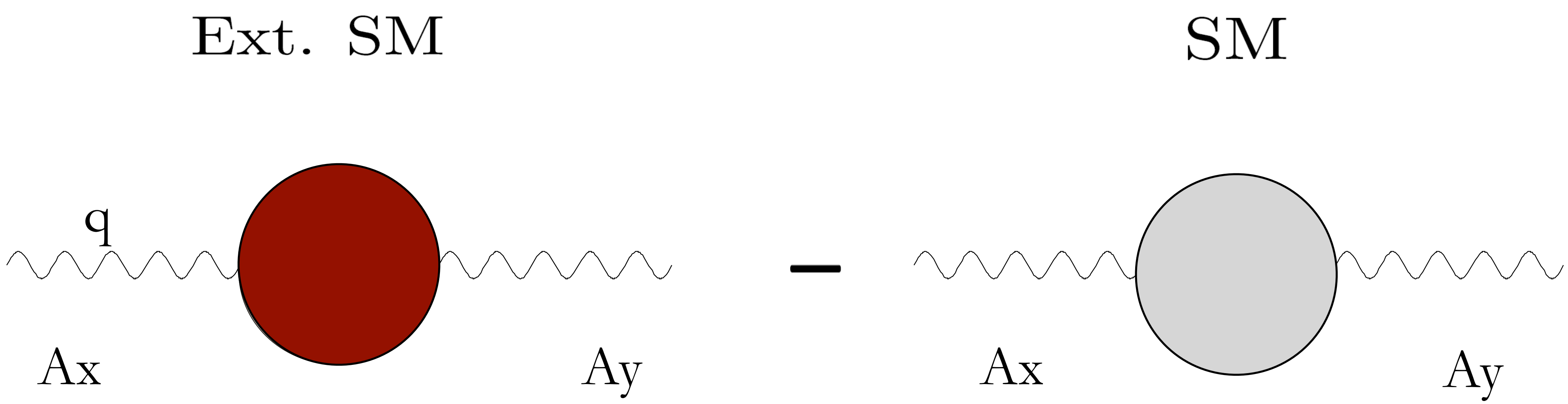
New Strong Interactions at ~ 250 GeV
[Weinberg, Susskind]

Natural to use QCD-like dynamics.

$$SU(N)_{TC} \times SU(3)_C \times SU_L(2) \times U_Y(1)$$

$$\langle Q^f \widetilde{Q}_{f'} \rangle = \Lambda_{TC}^3 \qquad \Lambda_{TC} \simeq 1 \text{ TeV}$$

S & T



$$\Pi^{\mu\nu}_{XY}(q^2) = \Pi_{XY}(q^2) g^{\mu\nu} + \cdots$$

Kennedy-Lynn, Peskin-Takeuchi, Altarelli-Barbieri, Bertolini- Sirlin, Marciano-Rosner

S & T

S-measures the left - right type current correlator

$$S = -16\pi \frac{\Pi_{3Y}(m_Z^2) - \Pi_{3Y}(0)}{m_Z^2}$$

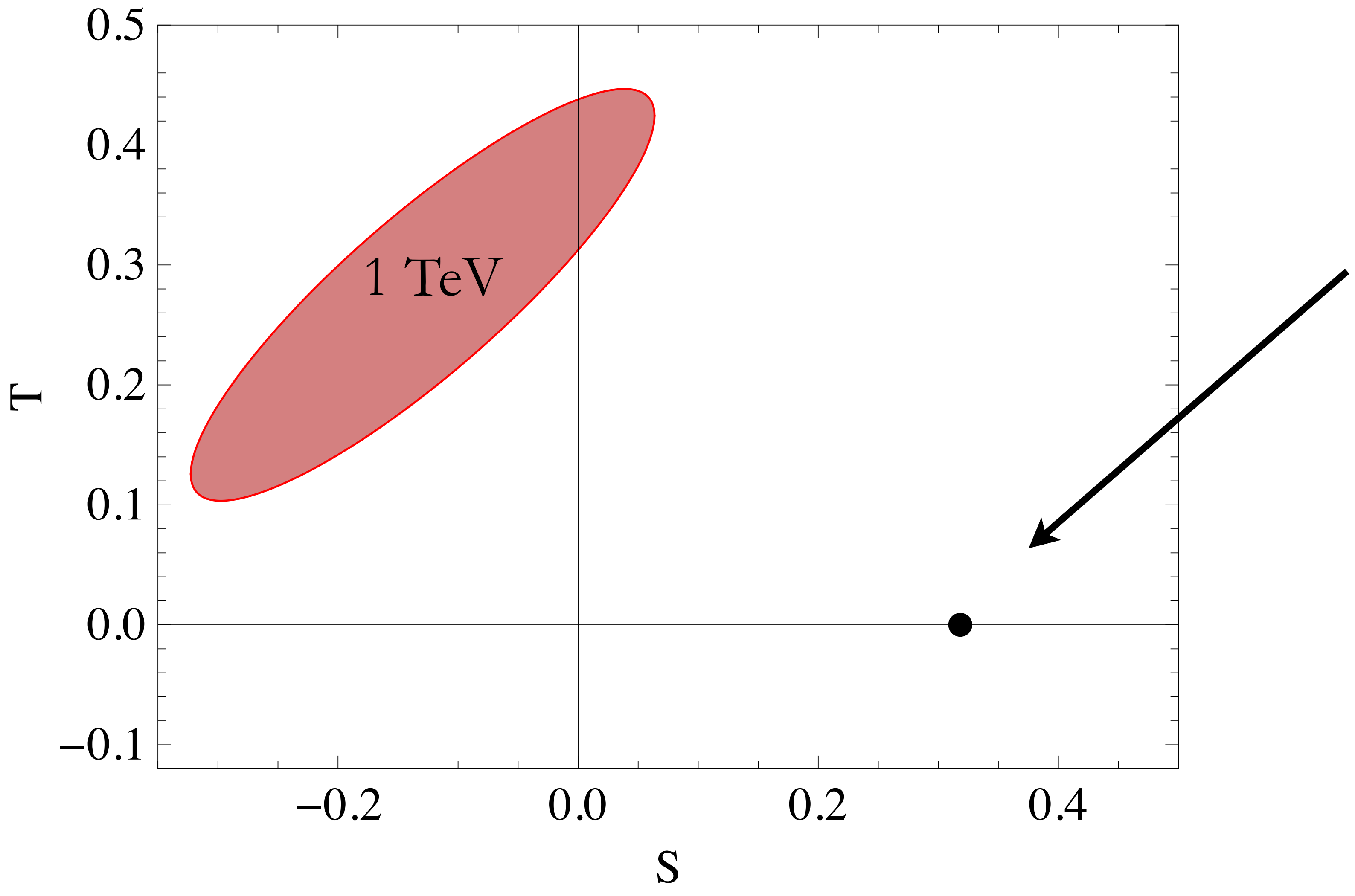
T-measures deviations from

$$m_{\mathrm{W}}^2 = \cos^2\theta_{\mathrm{W}}\, m_{\mathrm{Z}}^2$$

$$T = 4\pi \frac{\Pi_{11}(0) - \Pi_{33}(0)}{s_W^2 c_W^2 m_Z^2}$$

Need novel dynamics

Large & Positive S from QCD-like Technicolor

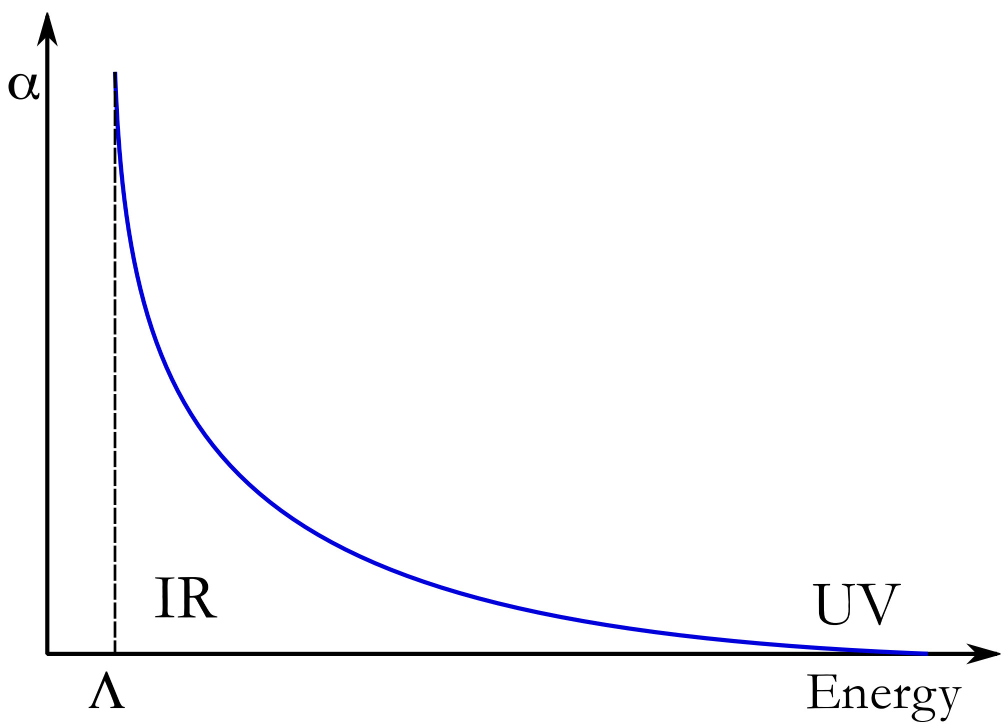


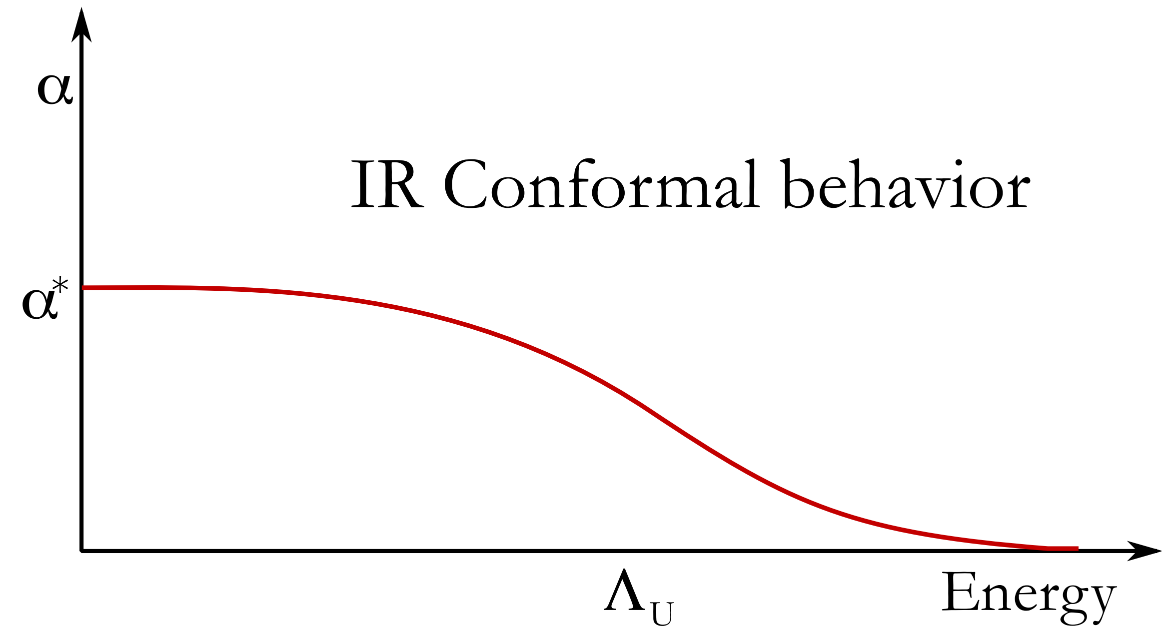
SU(3) + 1 Fund. Doublet

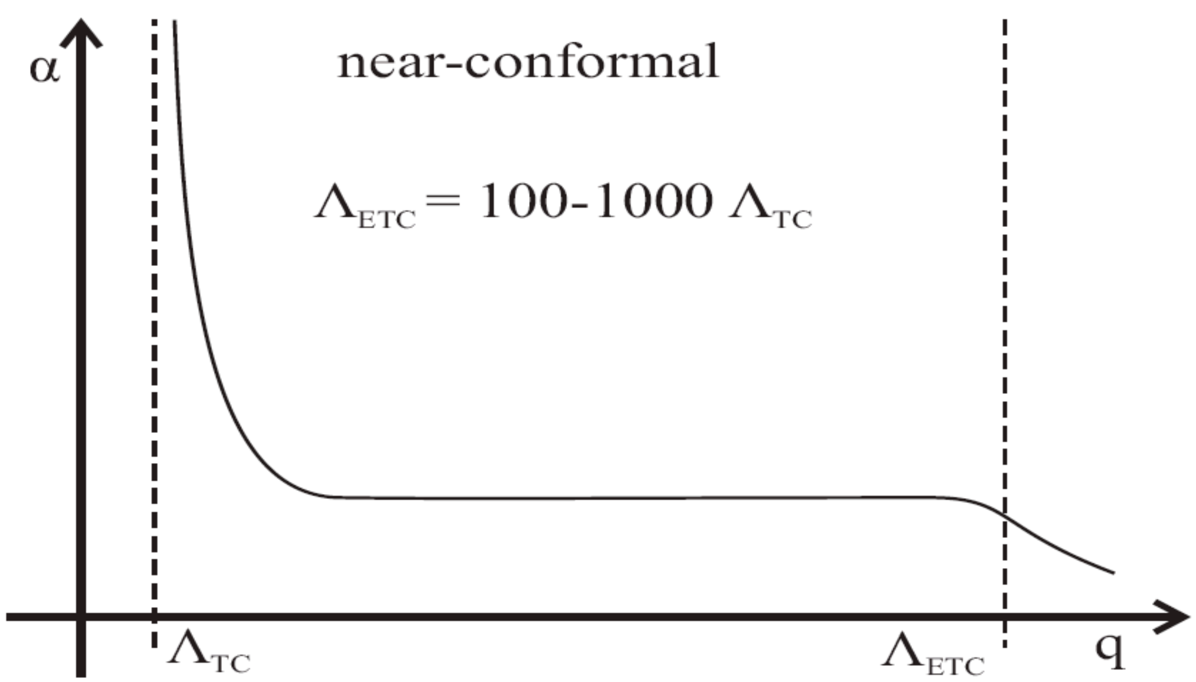
Weinberg, Susskind

Novel type of dynamics

Near Conformal







S-parameter

$$S_{WTC} < S_{TC}$$

Appelquist, F.S. 98

Da Silva, Duan, F.S. 99

How low can S be ?

F.S. 2010

$$S \geq \frac{1}{6\pi}\frac{N_f}{2}d(R)$$

Strong constraint

Conjecture obtained comparing exact results with QCD

In fact ...

$$S = S_{(W)TC} + S_{NS}$$

Offset the first term

Rule:

Find WT minimizing the lower bound for S

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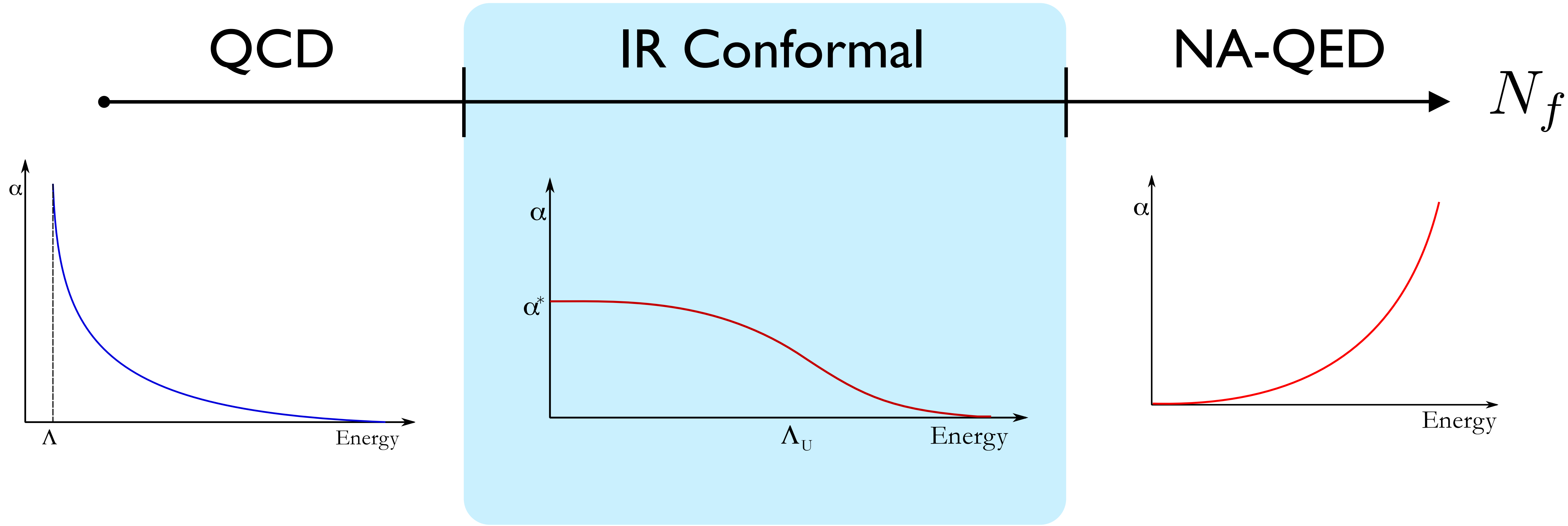
Gauge Theory Knobs

Gauge Group, i.e. SU, SO, SP

Matter Representation

# of Flavors per Representation

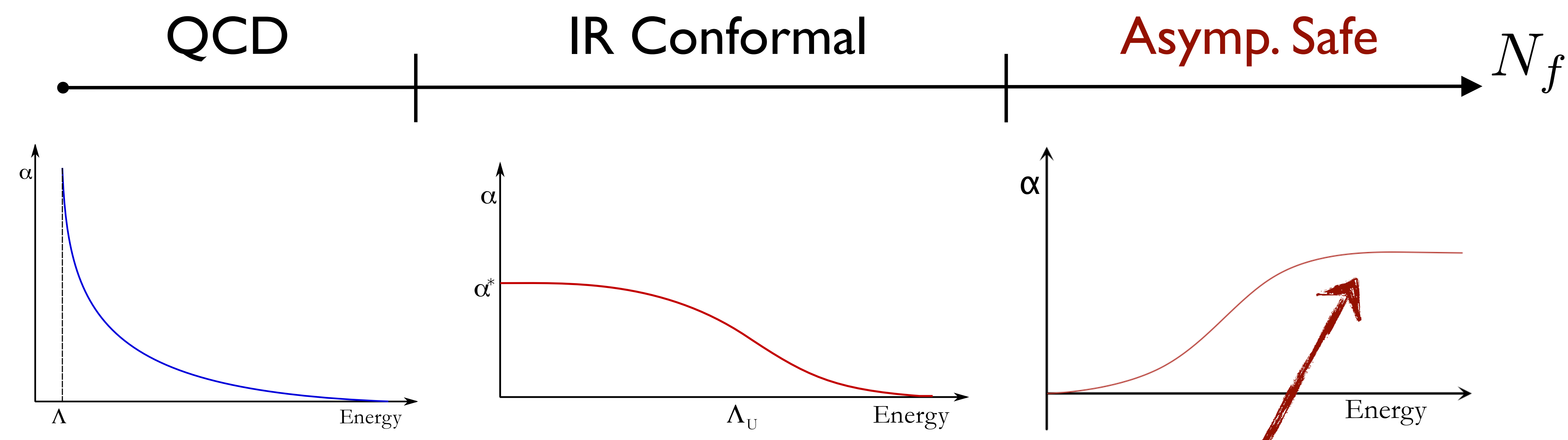


A novel phase @ large Nf

Interesting structure at large Nf

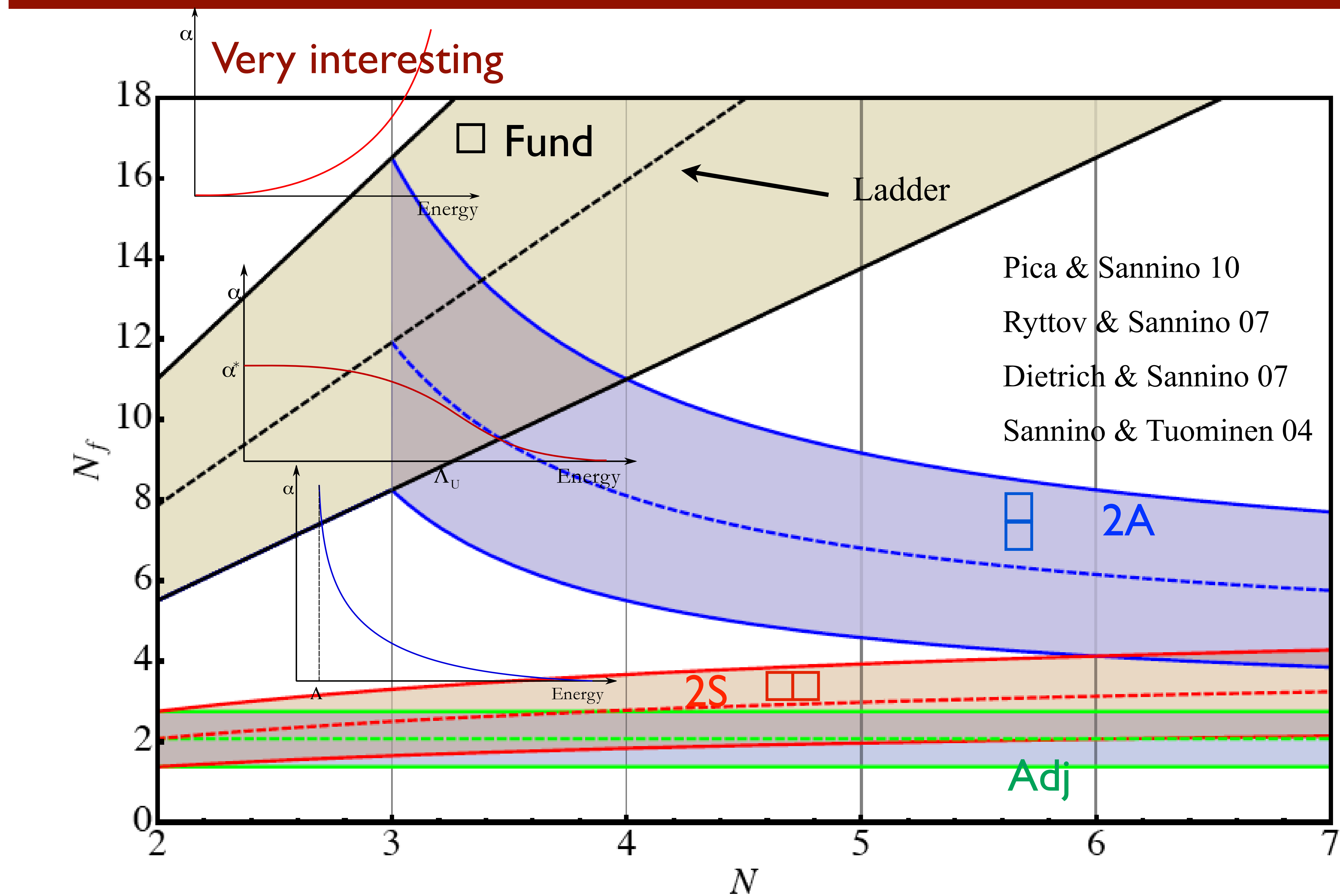
Pica & Sannino 10

Entire series at large Nf is known



$$\alpha_{UV} = \frac{3\pi}{T_F N_f}$$

SU(N) Phase Diagram



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Minimal models of Technicolor

- Minimal WT

$SU(2)_{TC}$ $\square\!\square$

U **N**

D **E**

FS, Tuominen 04
Dietrich, FS, Tuominen 05

- Next to MWT

$SU(3)_{TC}$ $\square\!\square$

FS, Tuominen 04
Dietrich, FS, Tuominen 05

- Orthogonal

$SO(4)_{TC}$ $\square$ Frandsen, FS 09

- Ultra MT

$SU(2)_{TC}$ $\square$ Ryttov, FS 08

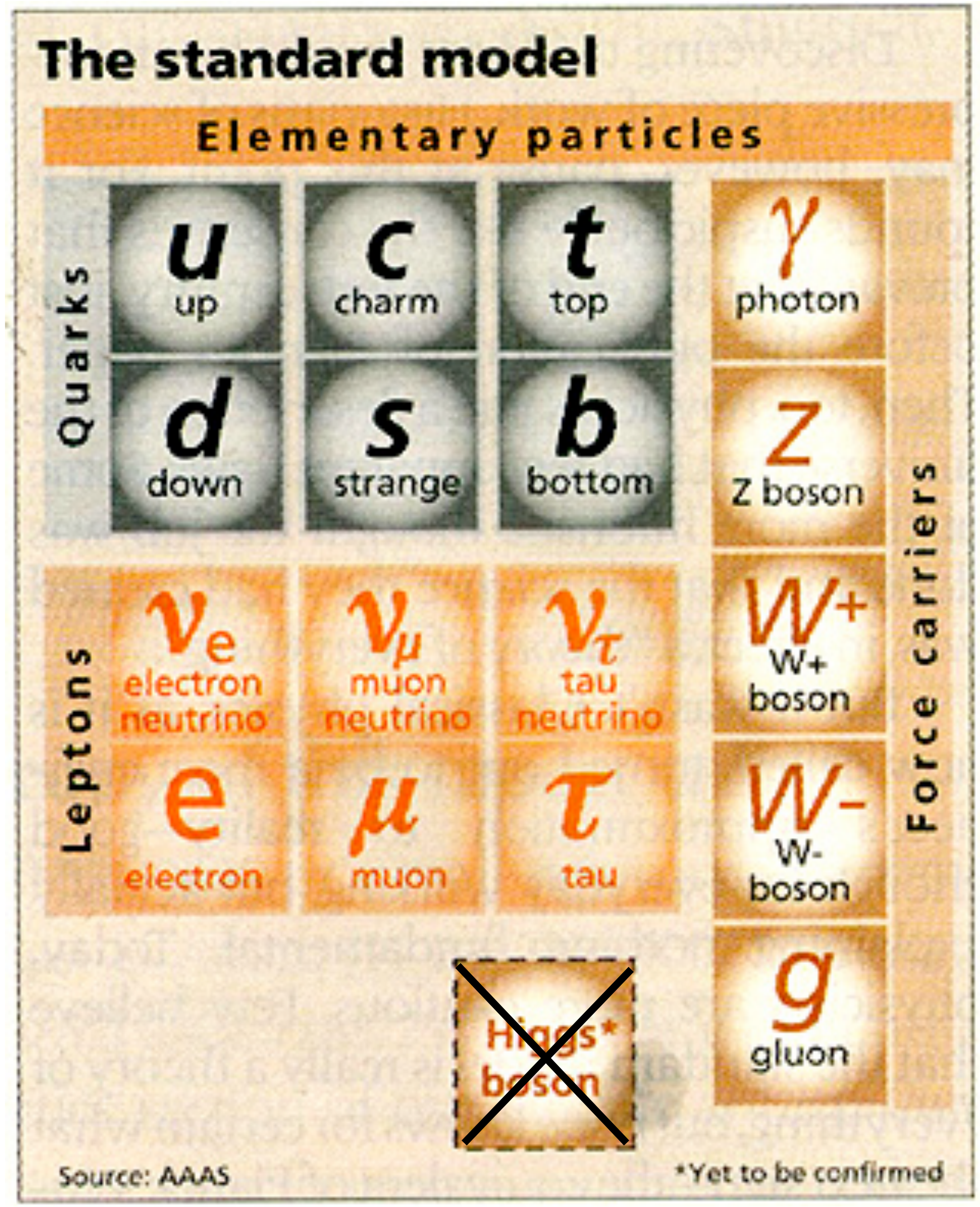
- Less minimal models + ETC

Farhi and Susskind 79;
Eichten and Lane 89;
Appelquist and Terning 94;
Appelquist, Christensen, Pia and Shrock 04
Evans and FS 08
Ryttov and Shrock 09,10

- Effective Theories

Appelquist, Da Silva, FS 99;
Da Silva, Duan, F.S. 99
Foadi, Frandsen, Ryttov, F.S. 07
Lane and Martin 09

Minimal Walking Technicolor



U(1)

SU(2)

SU(3)

N
Extra Neutrino

ζ
Extra Electron

U
t-up

G
t-glue

D
t-down

SU(2)

F.S. + Tuominen 04

Dietrich, F.S., Tuominen 05

U and D: Adj of SU(2)

S beyond TC...

$$S = S_{(W)TC} + S_{NS}$$

Offset the first term

New Leptons

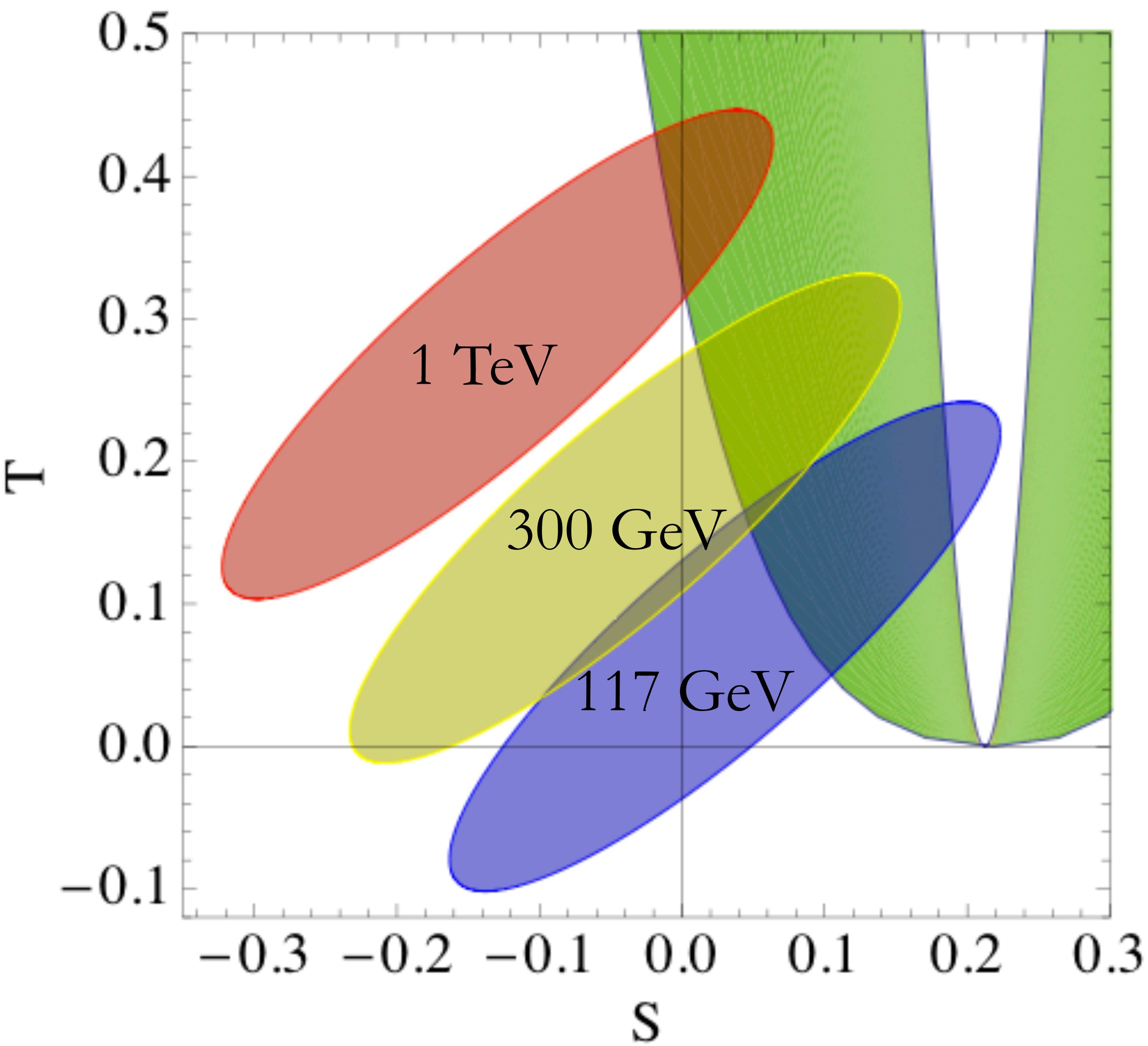
$$\text{Fermions :} \qquad \psi_L = \begin{pmatrix} \psi_{1L} \\ \psi_{2L} \end{pmatrix}, \qquad \psi_{1R}\,, \qquad \psi_{2R}$$

$$\text{Hypercharge :} \qquad Y\,, \qquad Y + \frac{1}{2}, \qquad Y - \frac{1}{2}$$

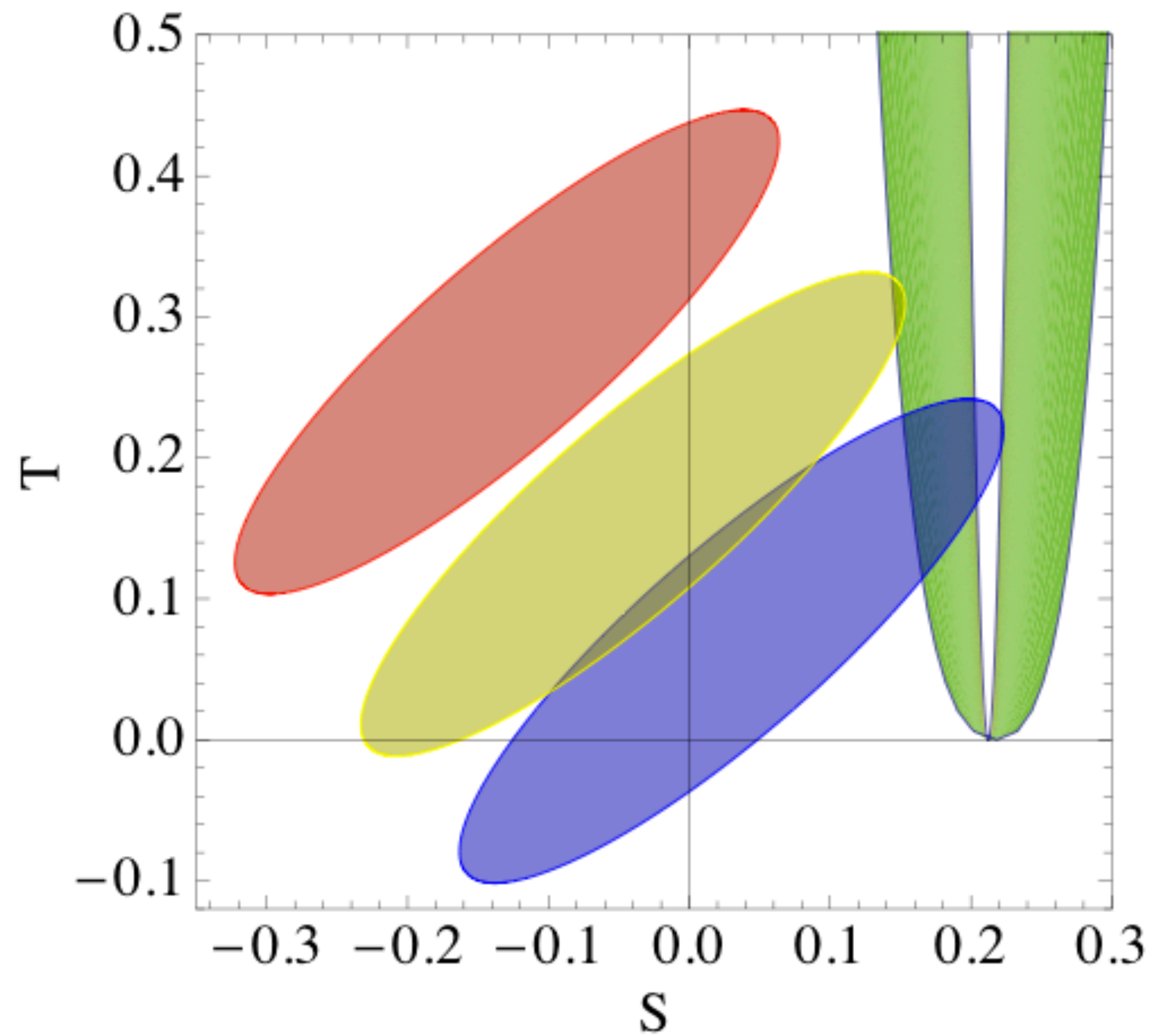
$$S_{\text{Leptons}} = \frac{1}{6\pi}\left[1 - 2Y \ln\left(\frac{M_1}{M_2}\right)^2 + \frac{1+8Y}{20}\left(\frac{m_Z}{M_1}\right)^2 + \frac{1-8Y}{20}\left(\frac{m_Z}{M_2}\right)^2 + O\left(\frac{m_Z^4}{M_i^4}\right)\right]$$

$$M_{1,2}^2 \gg m_Z^2$$

New Leptons & Precision Data



Exotic Leptonic hypercharge Y=-3/2



Standard Model Leptonic hypercharge

MWT Features

- The most economical WT theory
- Compatible with precision measurements
- Possible DM candidates and Unification
- Can support 1st order Electroweak Phase Transition
- Features a light composite Higgs
  Dietrich, F.S., Tuominen 05.
  Da Silva, Doff, Natale 08, 09.
- Lattice studies have begun

MWT Effective Lagrangian

$$\mathcal{L}(\text{Composites}) + \mathcal{L}(\text{Mixing with SM}) + \mathcal{L}(\text{New Leptons}) + \mathcal{L}(\text{SM} - \text{Higgs})$$

Composite Higgs — H

Composite Axial - Vector States — $R_{1,2}$

Heavy Electron — ζ

2 Heavy Majoranas — N_1 N_2

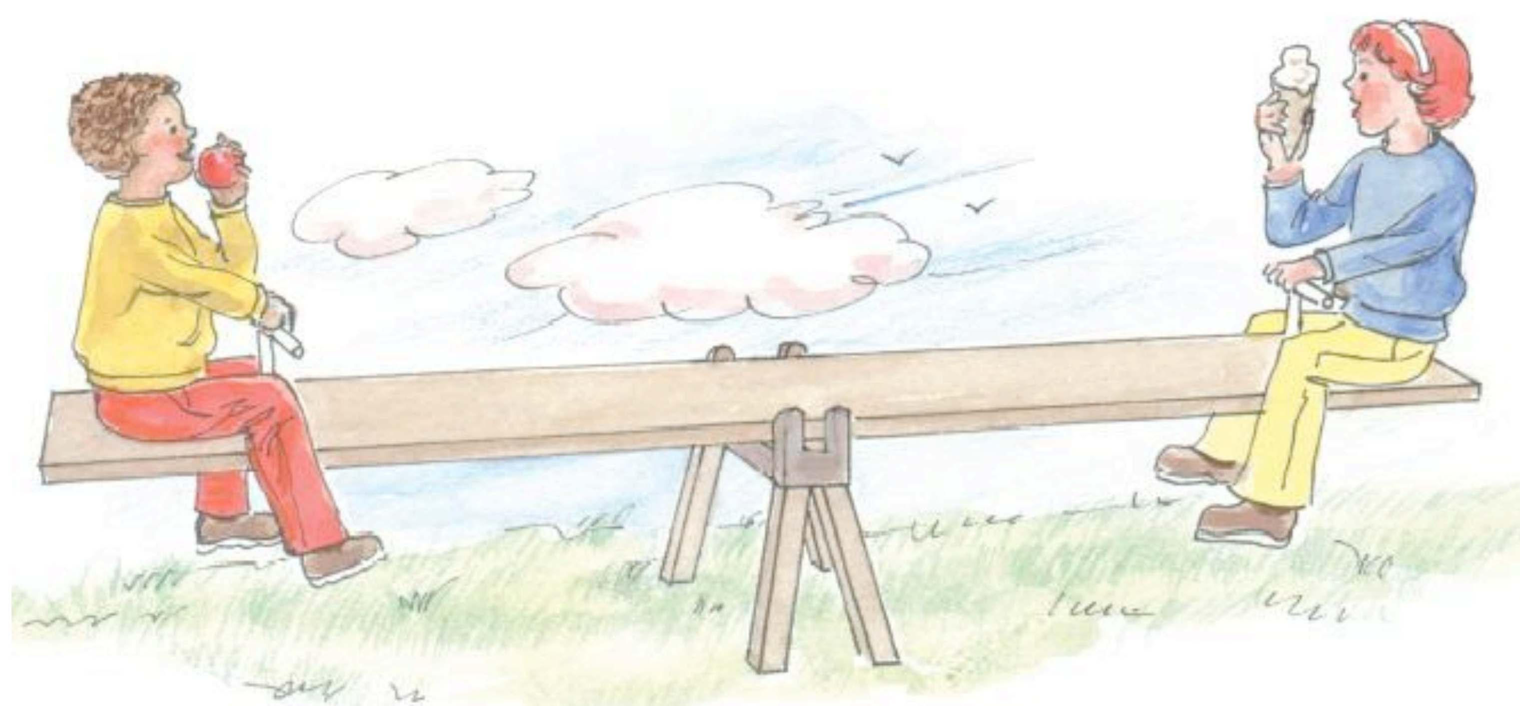
Frandsen, Masina, Sannino 09

Hapola, Masina, Sannino 11

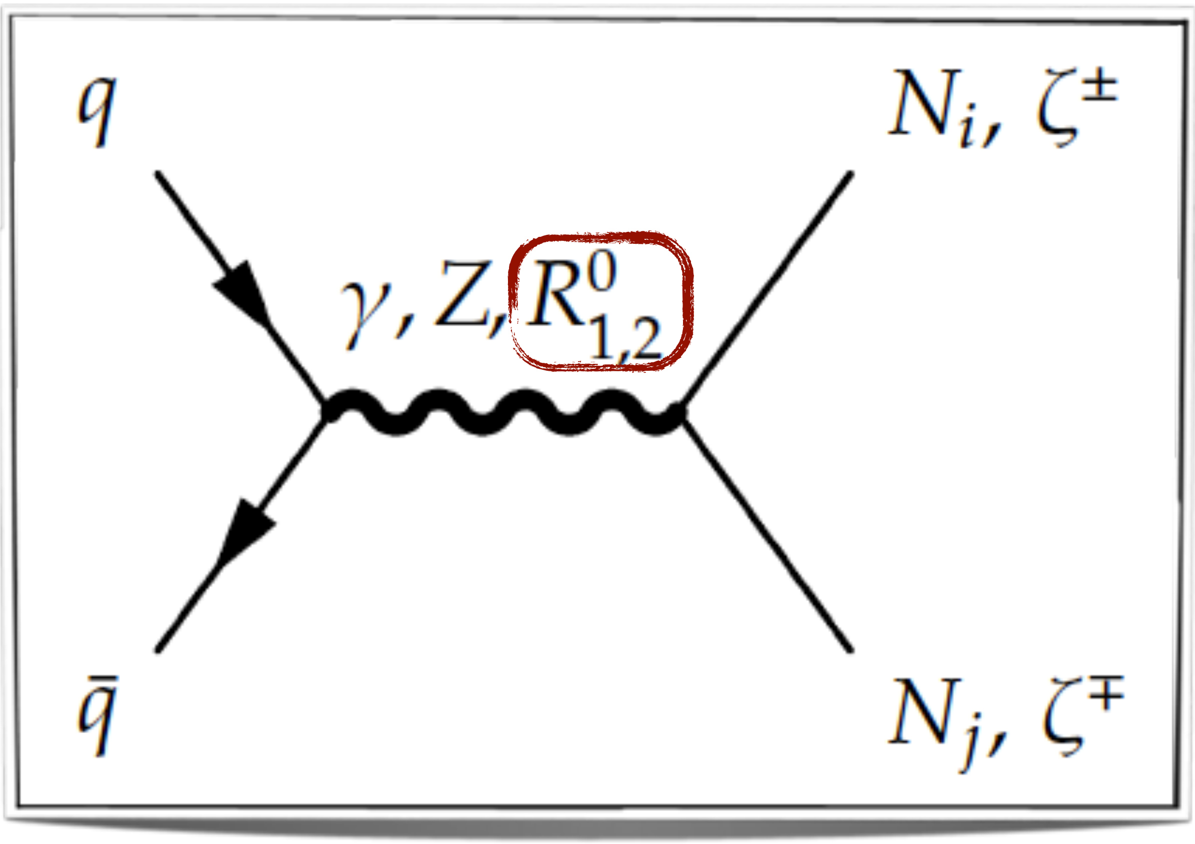
Electroweak vs Light See-saw

Light generations standard see-saw

EW see-saw

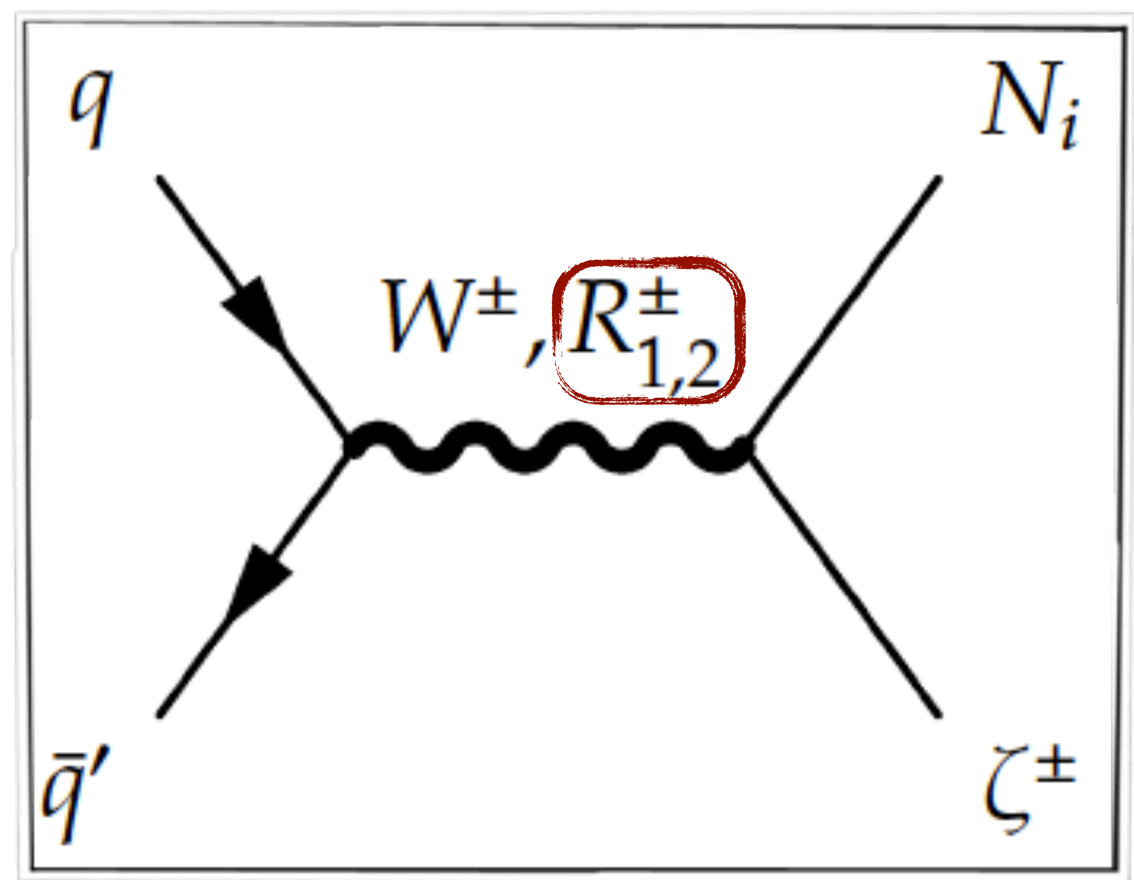


$pp \to \zeta^+\zeta^-, \quad N_iN_j, \quad \zeta N_j$



$$pp \to Z/\gamma/R^0_{1,2} \to \zeta^+\zeta^-$$

$$pp \to Z/R^0_{1,2} \to N_iN_j$$

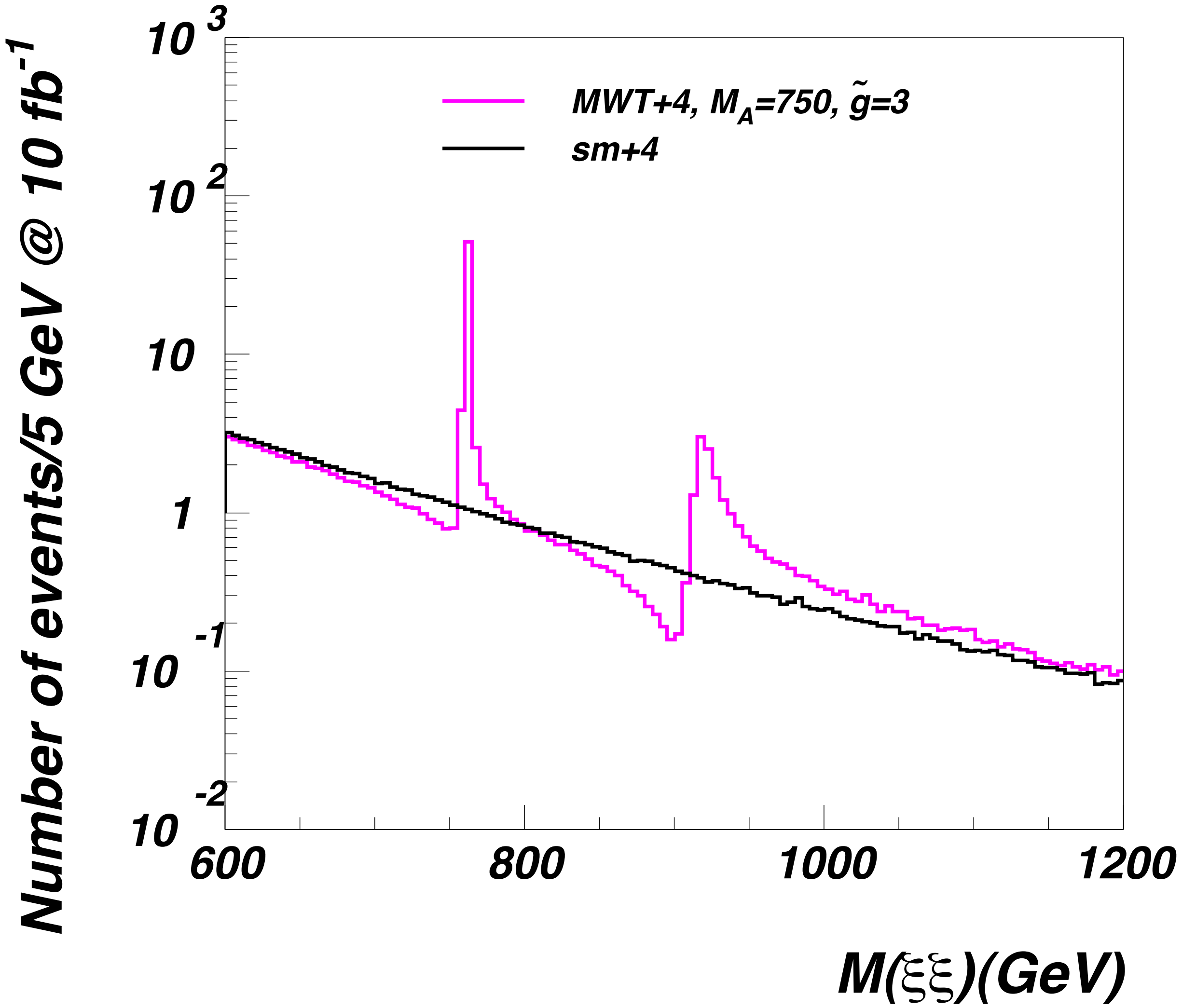


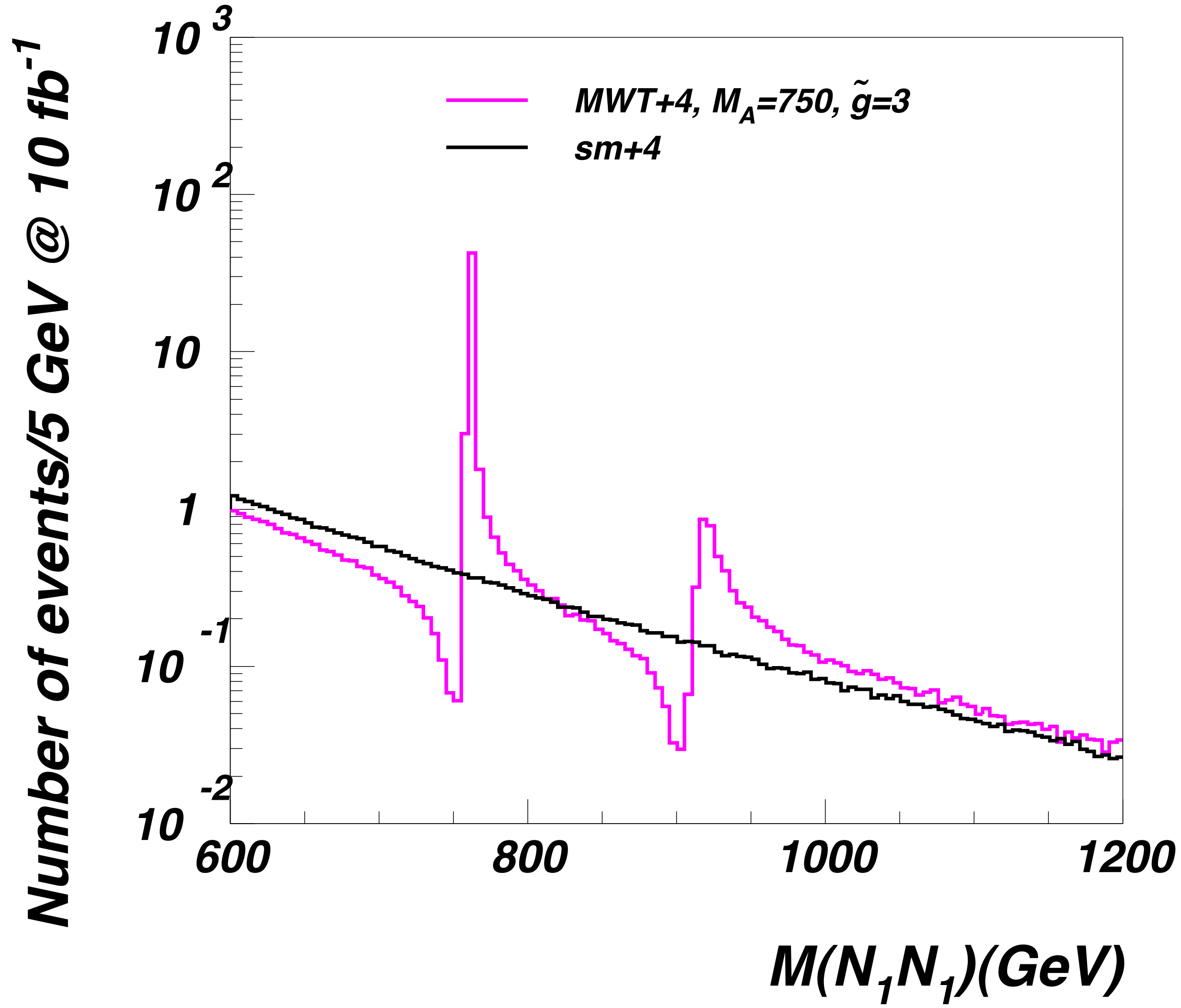
$$pp \to W^\pm/R^\pm_{1,2} \to \zeta^\pm N_i$$

Frandsen, Masina, Sannino 09

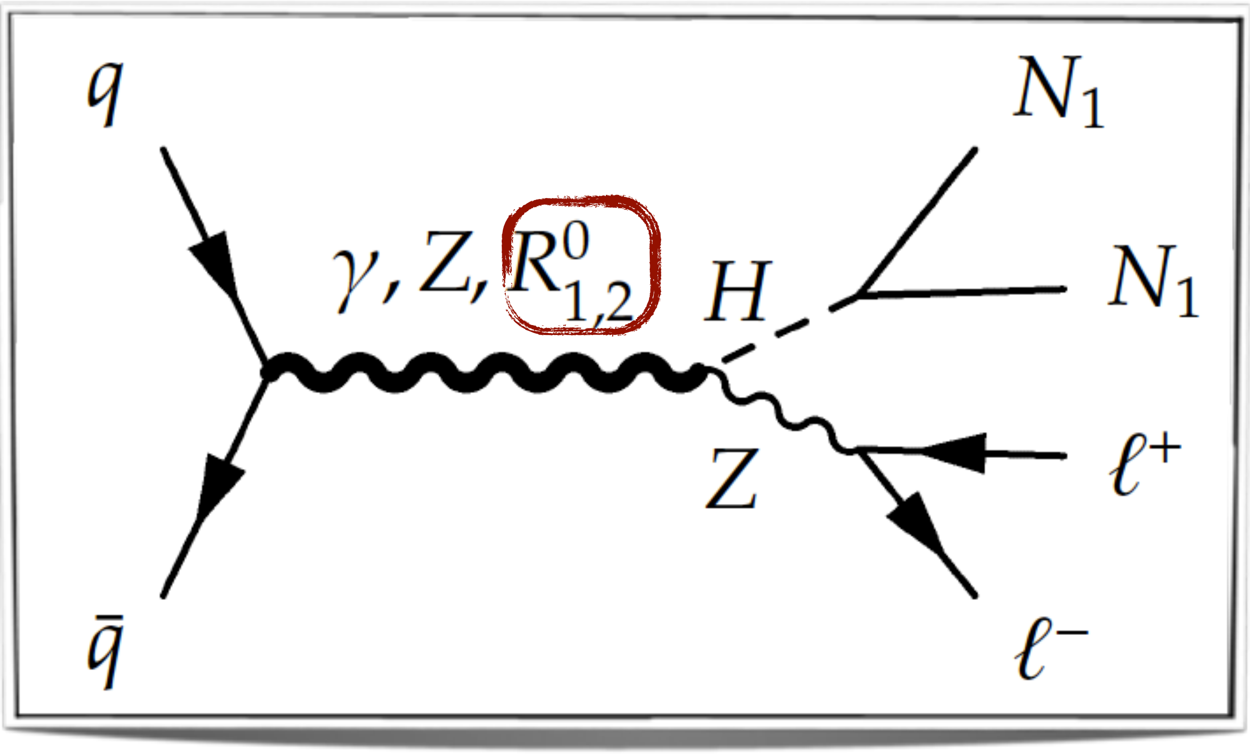
Hapola, Masina, Sannino 11

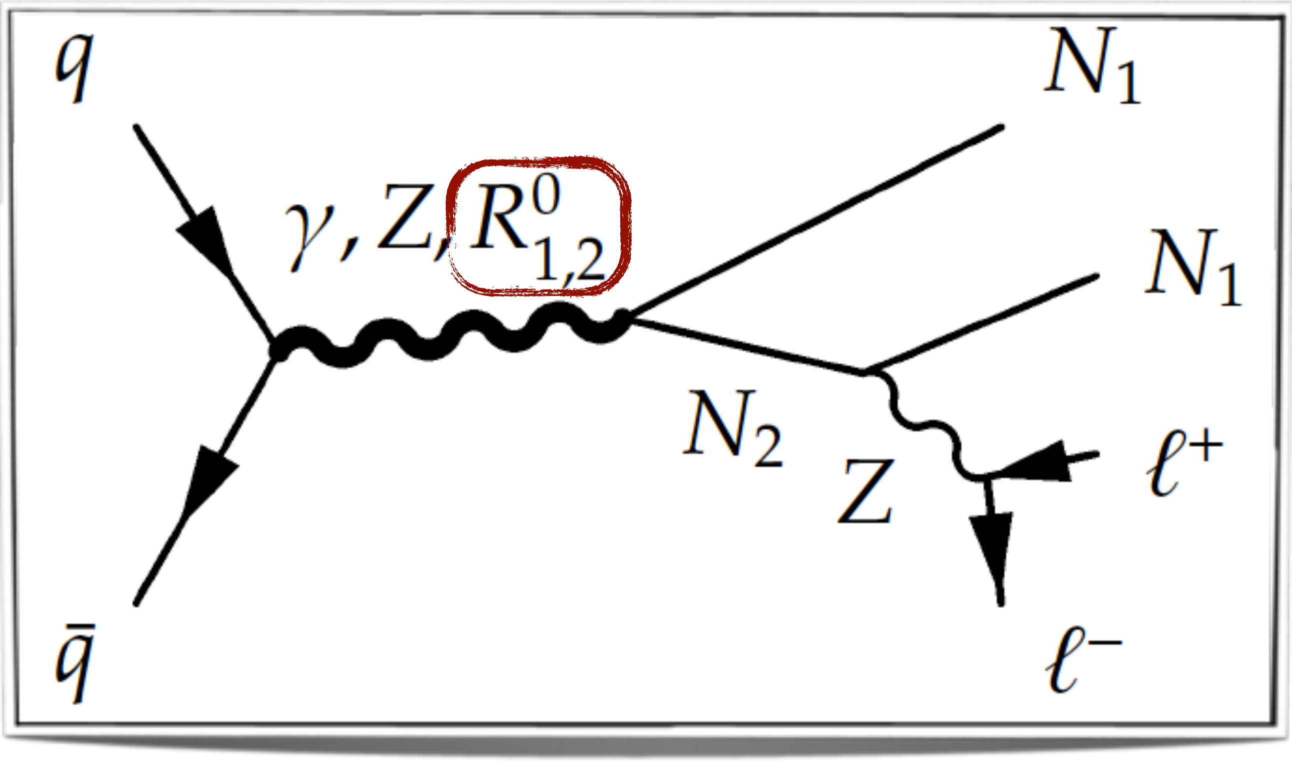
$pp \rightarrow \zeta^+\zeta^-, \quad N_i N_j$



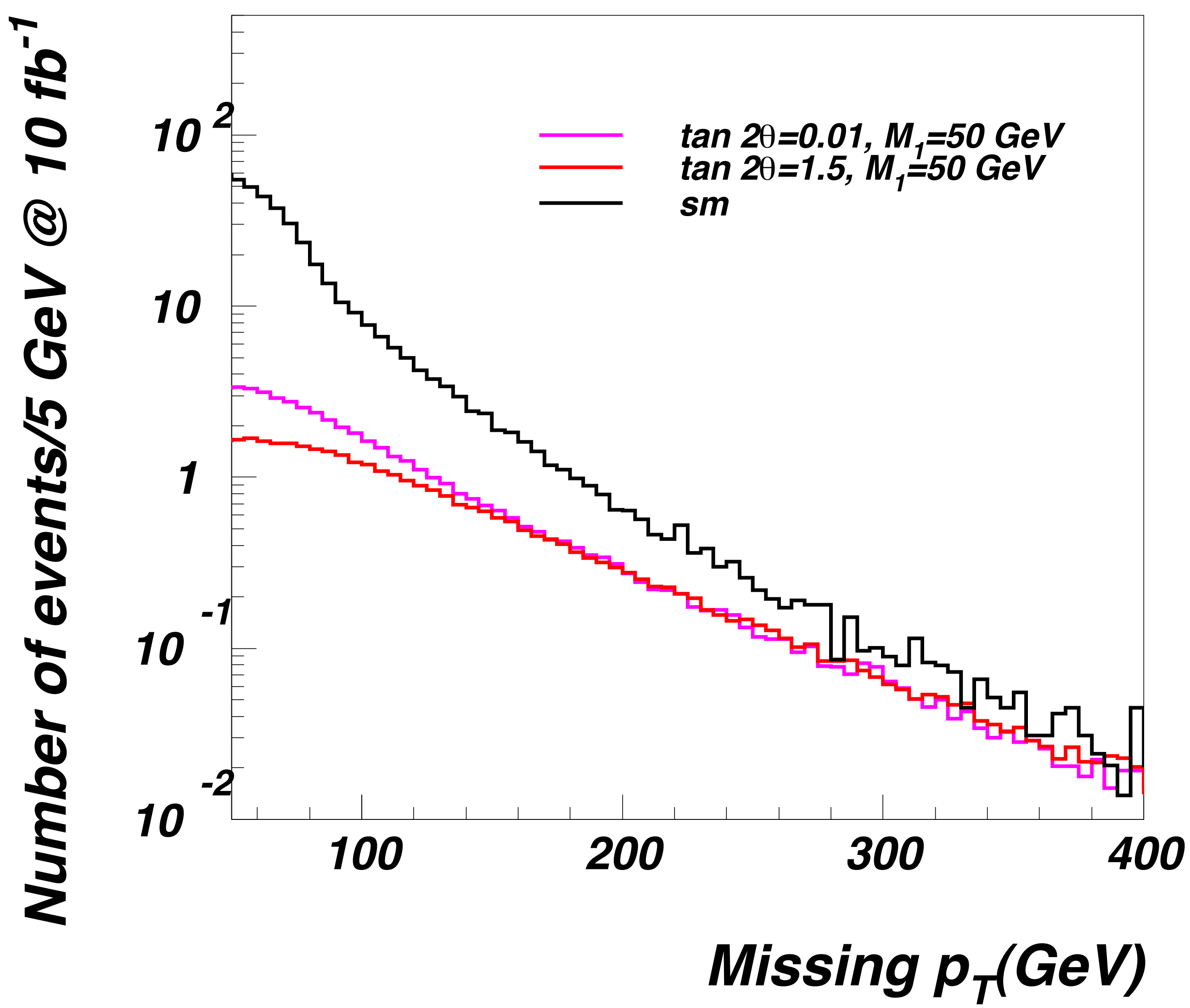


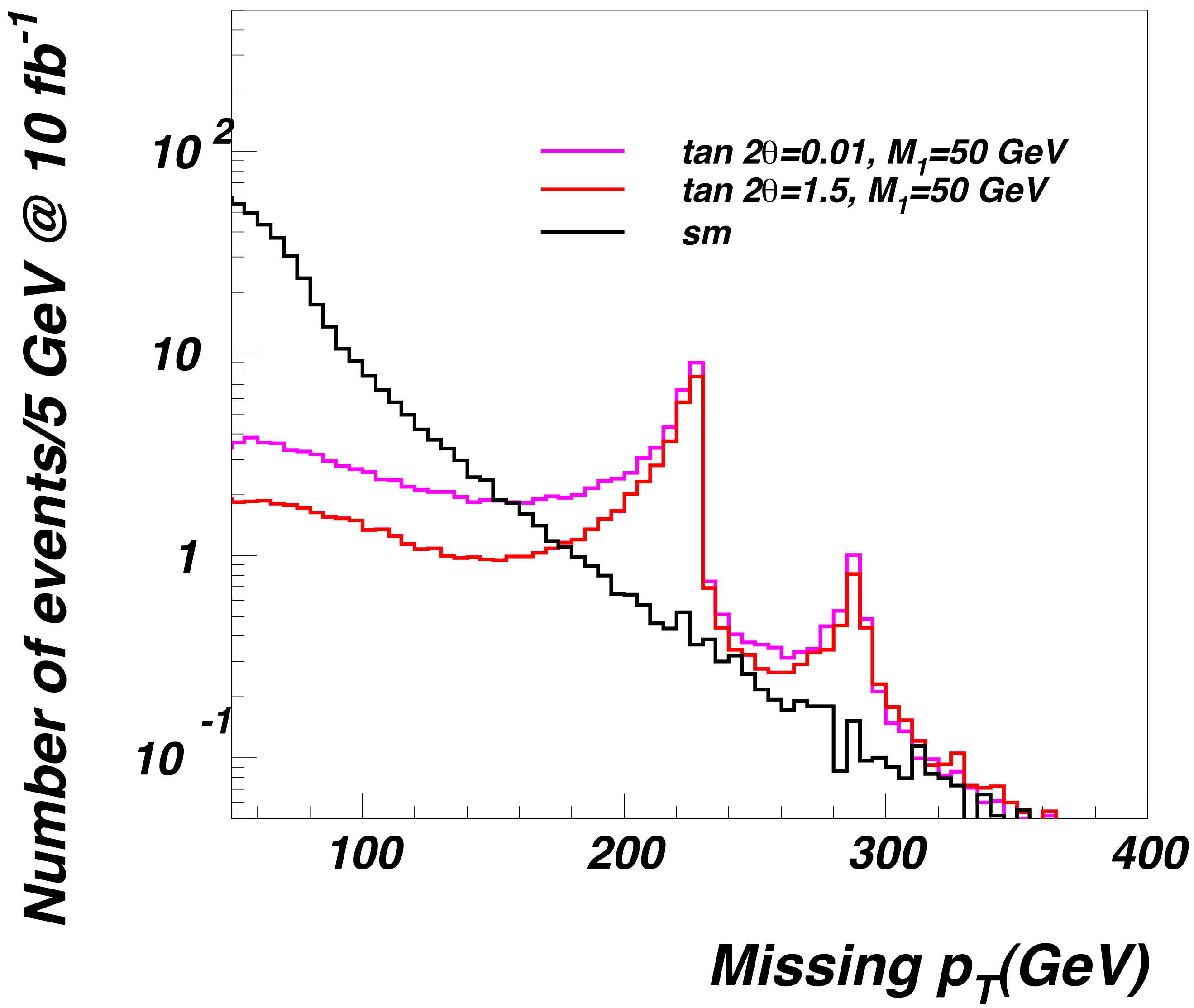
$pp \to HV$





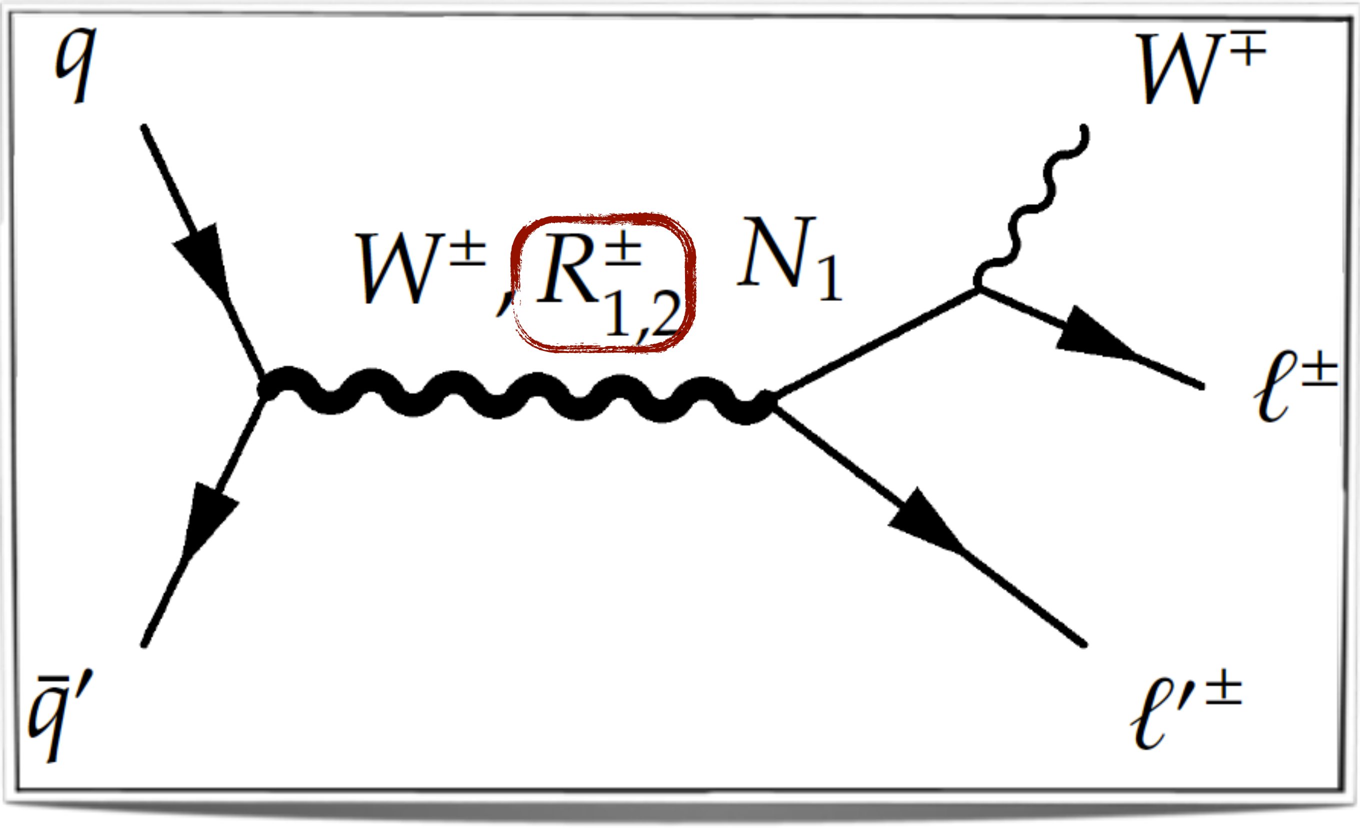
$pp \to Z N_1 N_1 \to \ell^+ \ell^- N_1 N_1$

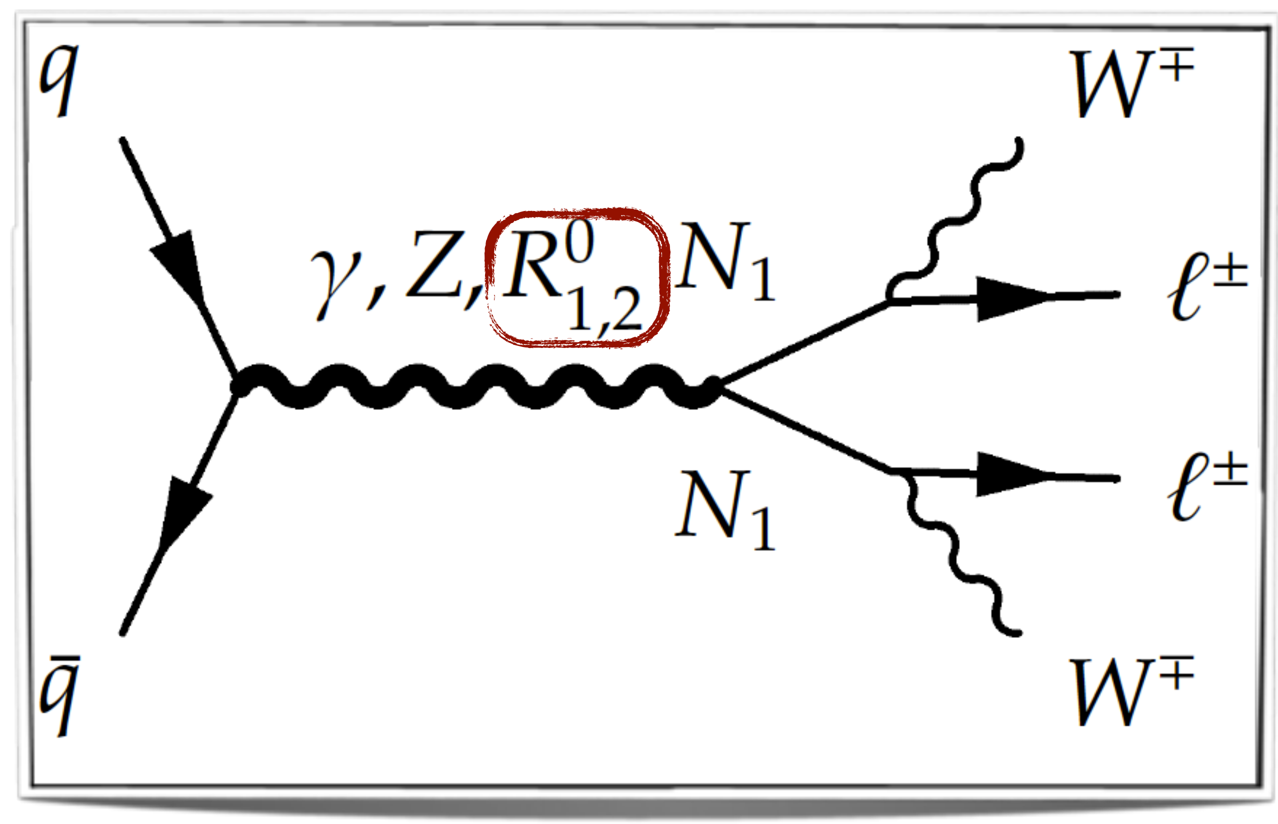




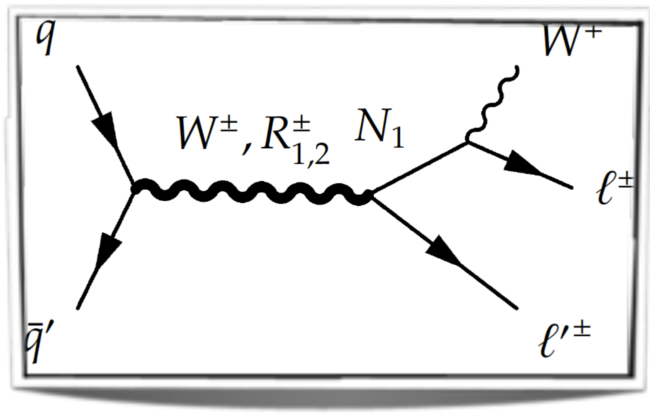
$$|\eta^\ell| < 2.5\,, \quad p_T^\ell > 10\ \mathrm{GeV}\,, \quad \Delta R(\ell\ell) > 0.4$$

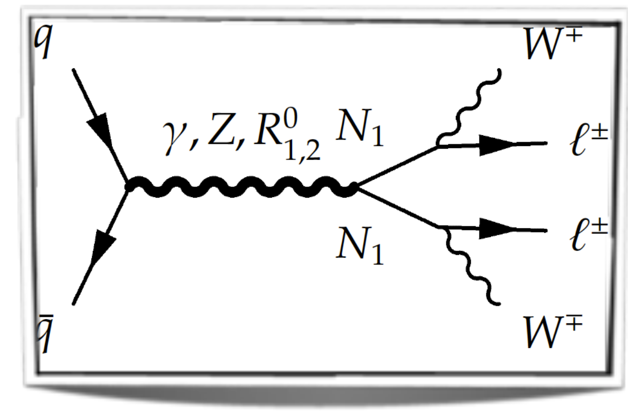
Promiscuous heavy leptons

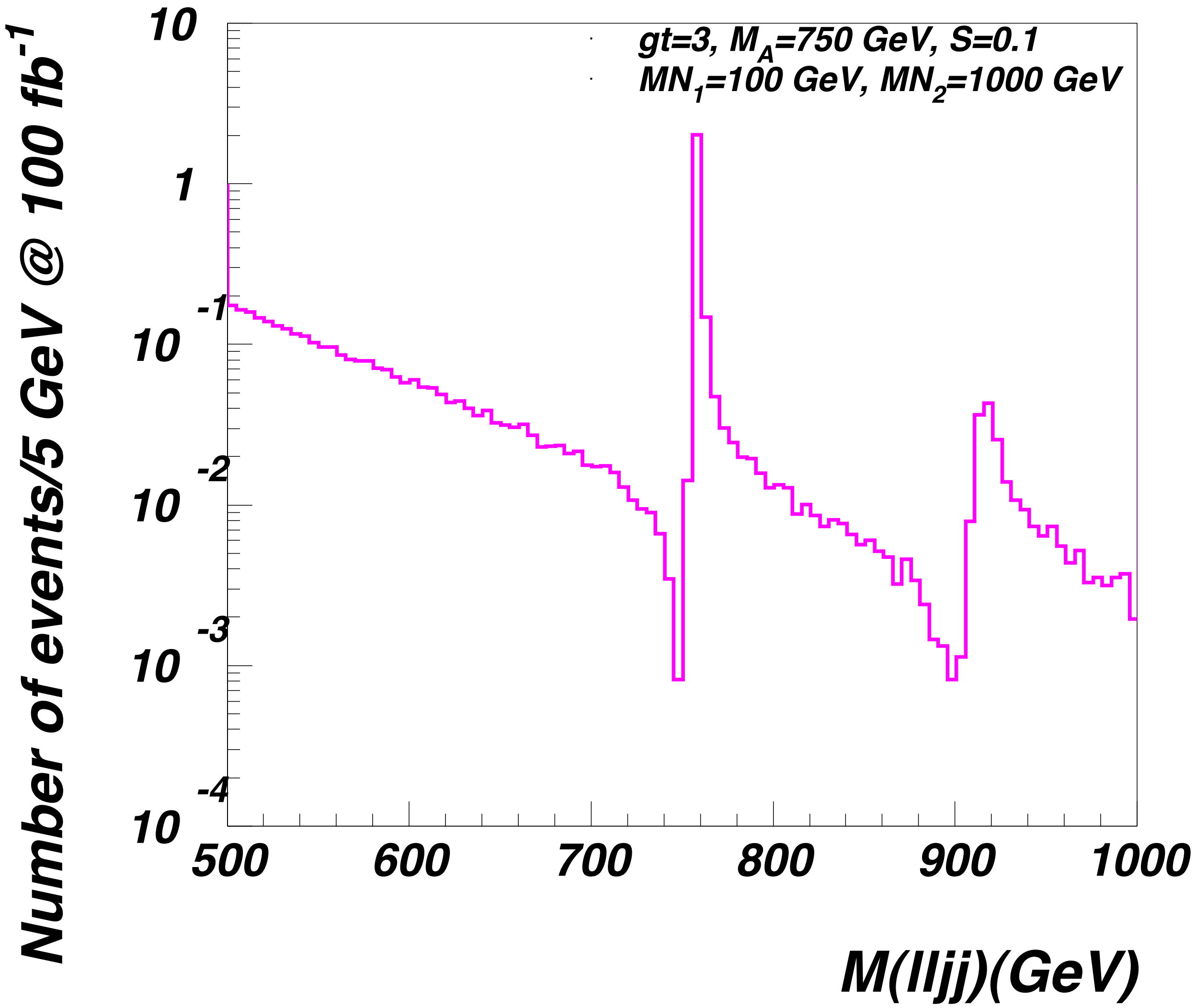


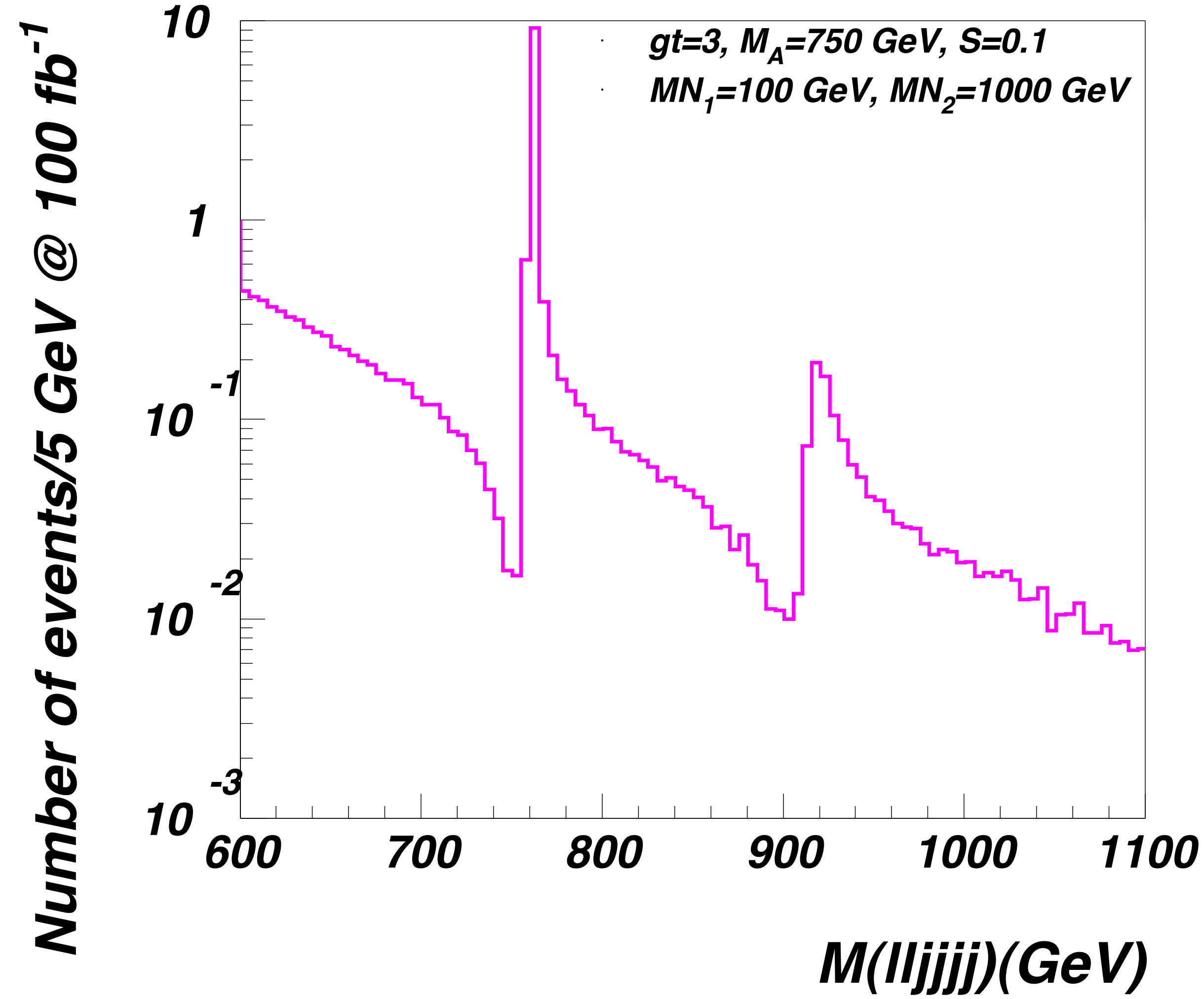


$$pp \to N_1 \mu^- \to \mu^- \mu^- jj \qquad pp \to N_1 N_1 \to \mu^- \mu^- jjjj$$









$$|\eta^j| < 3 \,, \quad p_T^j > 20 \text{ GeV} \,, \quad \Delta R(\ell j) > 0.5$$

Conclusions

- Minimal Models of Technicolor
- 4th Lepton Family is natural in Technicolor
- Striking signatures
- Cosmology/dark matter... in progress.

Natural 4th Lepton Family in TC

$$SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times U(1)_Y$$

$$L_\zeta = (\nu_{\zeta\,L} \ \ \zeta_L)^T \sim (1, 2, -1/2)$$

$$\zeta_R \sim (1, 1, -1), \quad \nu_{\zeta\,R} \sim (1, 1, 0)$$

See-saw

$$\mathcal{L}_{\zeta}^{\rm mass} = -m_\zeta \, \overline{\zeta} \, \zeta - \frac{1}{2} \left[\left(\begin{array}{cc} \overline{\nu_{\zeta L}} & \overline{(\nu_{\zeta R})^c} \end{array} \right) \left(\begin{array}{cc} 0 & m_D \\ m_D & m_R \end{array} \right) \left(\begin{array}{c} (\nu_{\zeta L})^c \\ \nu_{\zeta R} \end{array} \right) + h.c. \right] \, ,$$

N_1 N_2

$$M_1 = \frac{m_R}{2} \left(\sqrt{1 + 4 \frac{m_D^2}{m_R^2}} - 1 \right)$$

$$M_2 = \frac{m_R}{2} \left(\sqrt{1 + 4 \frac{m_D^2}{m_R^2}} + 1 \right)$$

$$\tan 2\theta = \frac{2 m_D}{m_R}$$

SM Fermion Masses

Extending Technicolor

$$\bar{L} \cdot H e_R \qquad \longrightarrow \qquad \bar{L} \frac{\bar{Q}Q}{\Lambda^2_{ETC}} e_R$$

Different Approaches

Scalar-less New Gauge Interactions (Extended TC)

Marry SUSY and Technicolor

Add New Scalars in the Flavor Sector

.....

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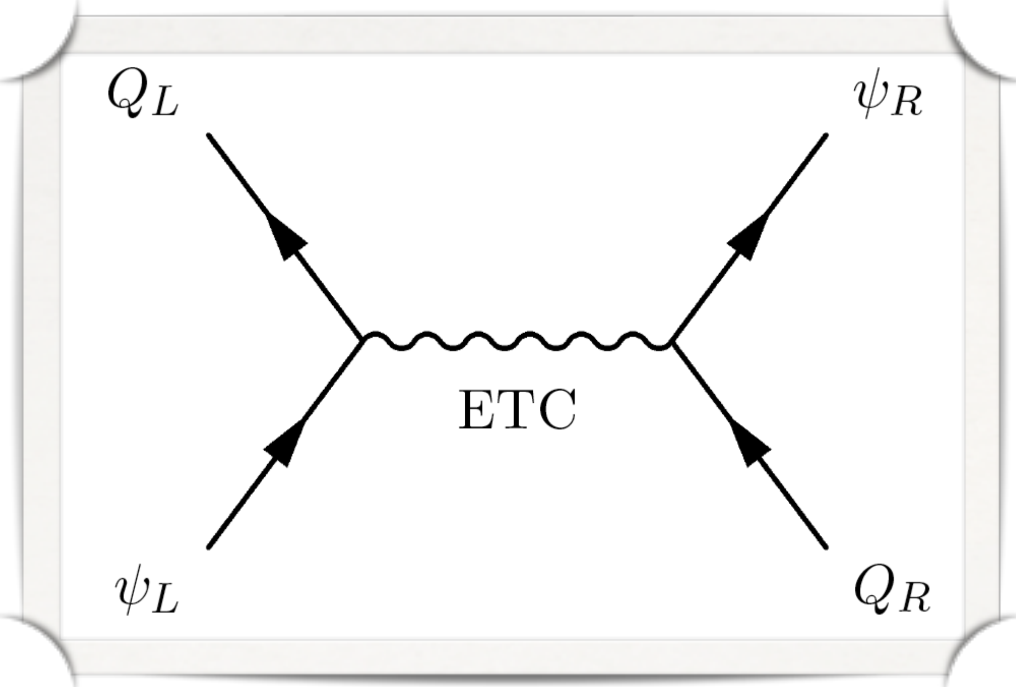
Extended Technicolor



Eichten & Lane 80

Recent investigations
Ryttov & Shrock 10

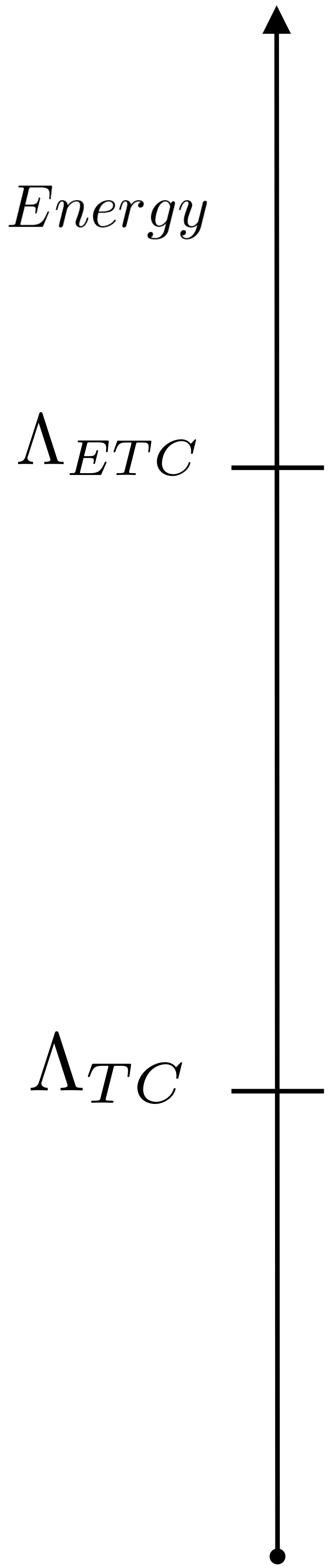
Modifies TC dynamics

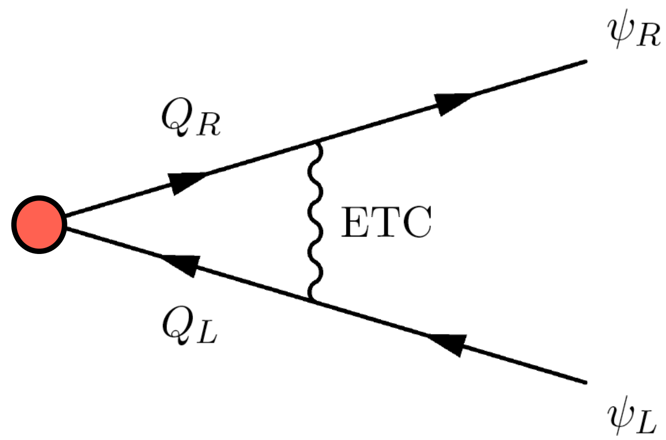
$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}_LT^aQ_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_LT^a\psi_R\bar{\psi}_RT^b\psi_L}{\Lambda^2_{ETC}} + \dots$$

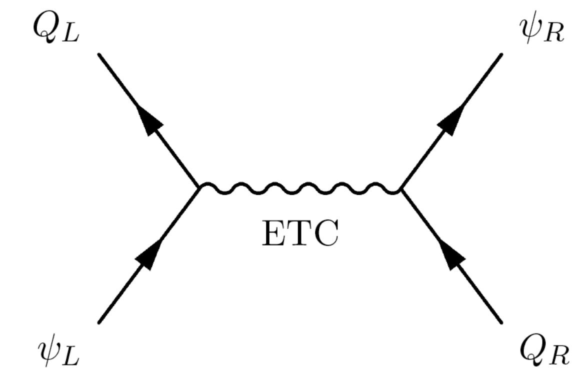
PNG Masses

SM-Fermion Masses

FCNC Operators







$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC}$$

Electroweak breaks

$$< \bar{Q}Q >_{ETC} \approx < \bar{Q}Q >_{TC} \sim \Lambda^3_{TC}$$

$$m_{\rm f} \approx \frac{g^2_{ETC}}{\Lambda^2_{ETC}} < \bar{Q}Q >_{ETC} \quad \ll \quad m_{\rm Top}$$

Mass enhancement

$$\langle \bar{Q}Q_{ETC} \rangle = \exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu))\right) \langle \bar{Q}Q_{TC} \rangle$$

QCD-Like

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu))\right) \quad \sim \quad (\ln(\Lambda_{ETC}/\Lambda_{TC}))^{\gamma_m}$$

Near the conformal window

$$\exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} d\ln(\mu)\ \gamma_m(\alpha(\mu))\right) \quad \sim \quad (\Lambda_{ETC}/\Lambda_{TC})^{\gamma_m(\alpha^\star)}$$

Fermion Mass Enhancement

$$m_{\mathrm{f}} \approx \frac{g_{ETC}^2}{\Lambda_{ETC}^2} < \bar{Q}Q >_{ETC} = \frac{g_{ETC}^2}{\Lambda_{ETC}^2} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma_m(\alpha^*)} < \bar{Q}Q >_{TC}$$

Need large anomalous dimension, around $\gamma_m(\alpha^*) \sim 1.7$