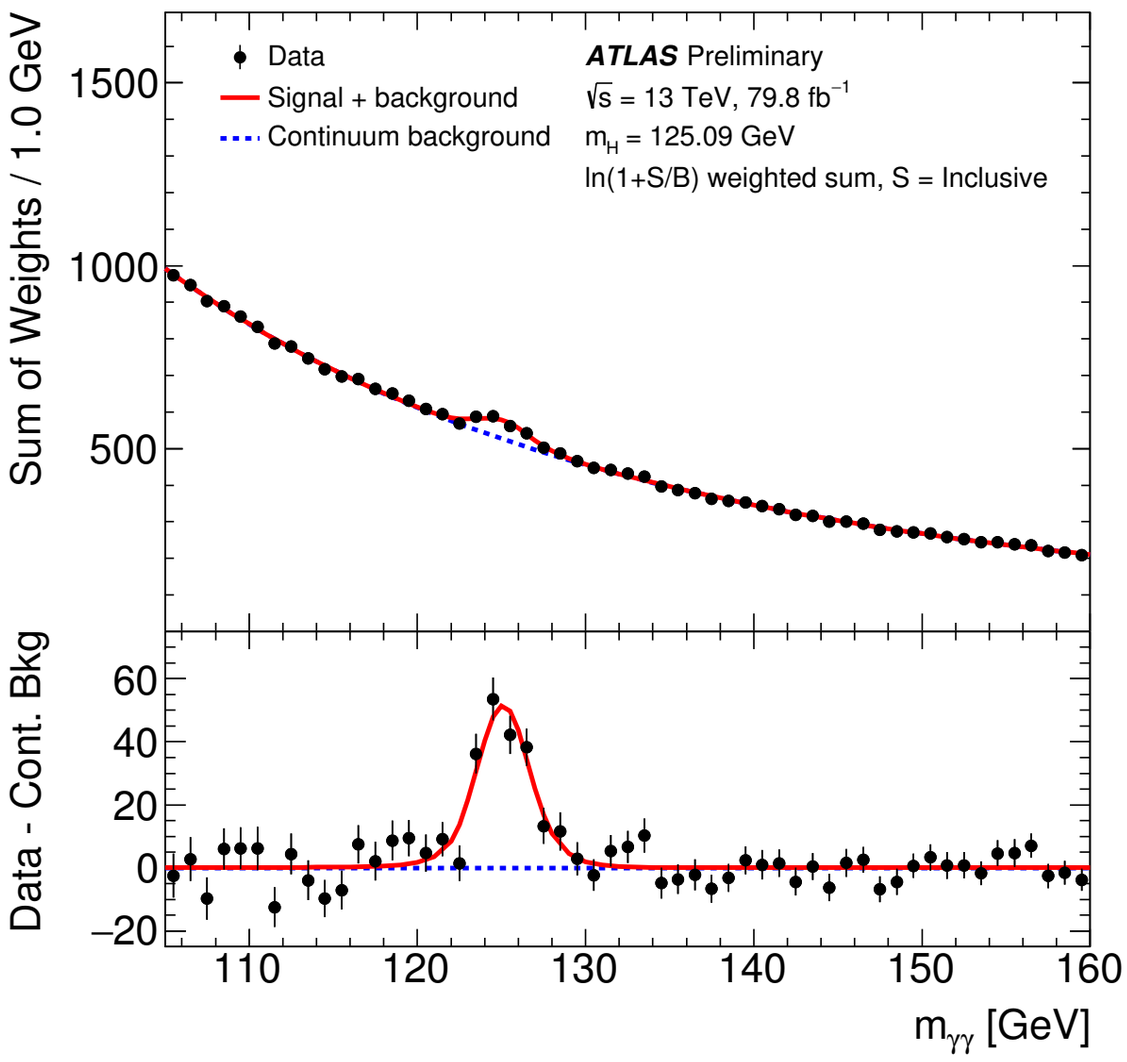
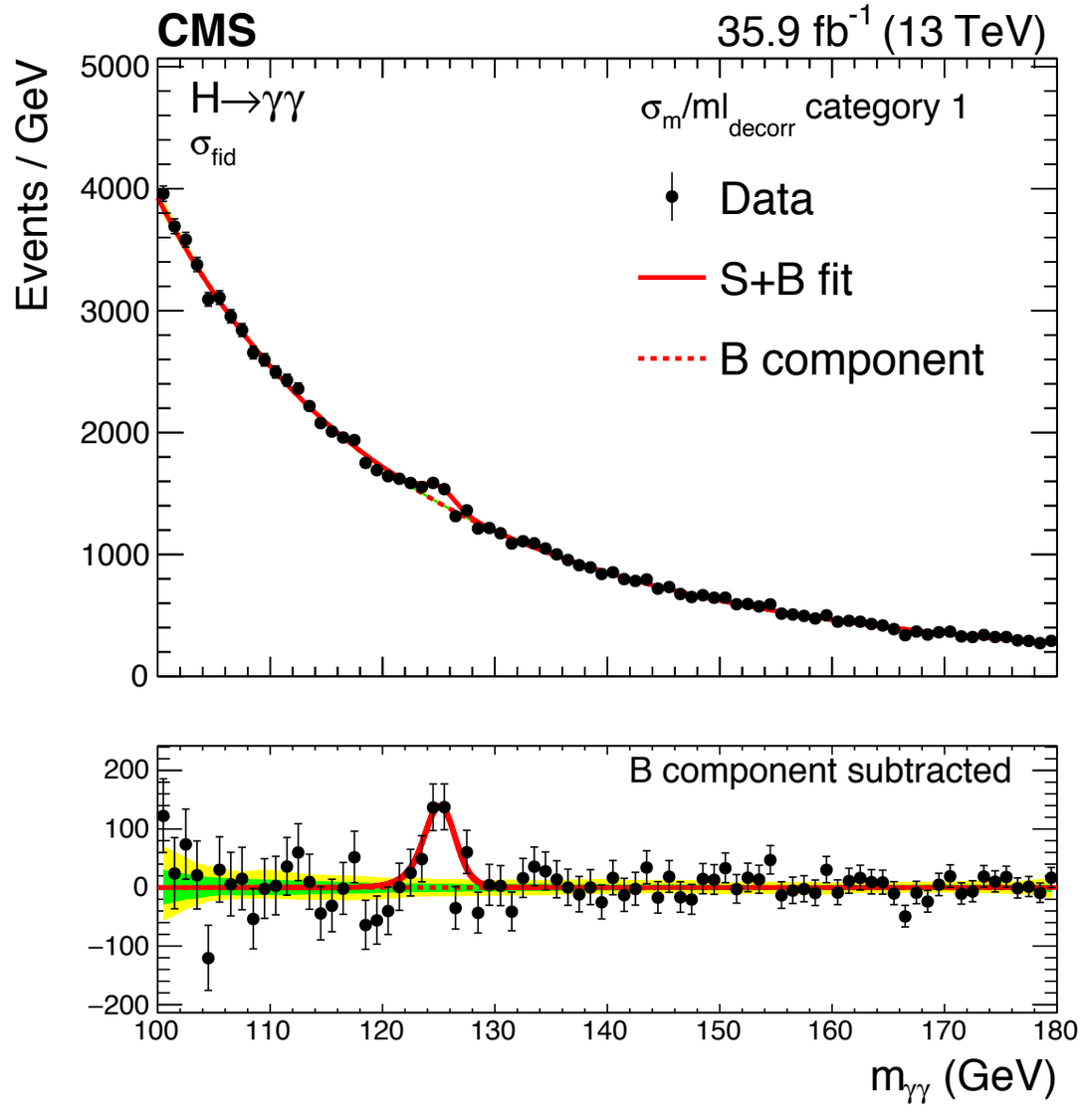
Composite Higgs models at the High Energy Muon Collider

Da Liu

UC, Davis

Milestone





A great leap towards the dynamics of EWSB!

Behind the SM

- Quantum Mechanics + Lorentz invariance

- Gauge invariance

- Renormalizability

Renormalizability as a consequence

$$\Lambda_{\rm UV} \lesssim 10^{18}{\rm GeV}$$

$$\mathcal{L} \sim (\partial\phi)^2 + m^2\phi^2 + \lambda_4\phi^4 + \lambda_6\phi^6 + \lambda_8\phi^8 + \cdots$$

RGE

$$m_t, m_{W,Z} \sim \mathcal{O}(100{\rm GeV})$$

Wilson 71'
Wilson and Kogut 74'
Polchinski 83'

$$\mathcal{L} \sim (\partial\phi)^2 + m^2\phi^2 + \lambda_4\phi^4 + \mathcal{O}\left(\frac{E^2}{\Lambda_{\rm UV}^2}\right)$$

Behind the SM

- SM as an effective field theory

- C, CP, U(3)^5 are all accidental symmetries

- All the terms consistent with symmetries will be generated from RGE

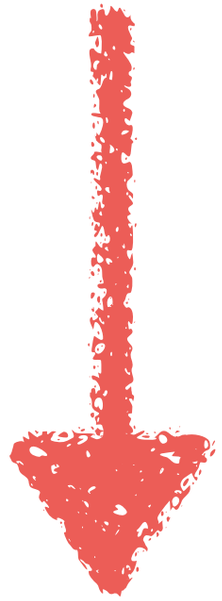
Hierarchy problem/guideline/paradox

Where is the electroweak scale coming from?

$$\frac{m_h^2}{M_P^2} \sim 10^{-34}$$

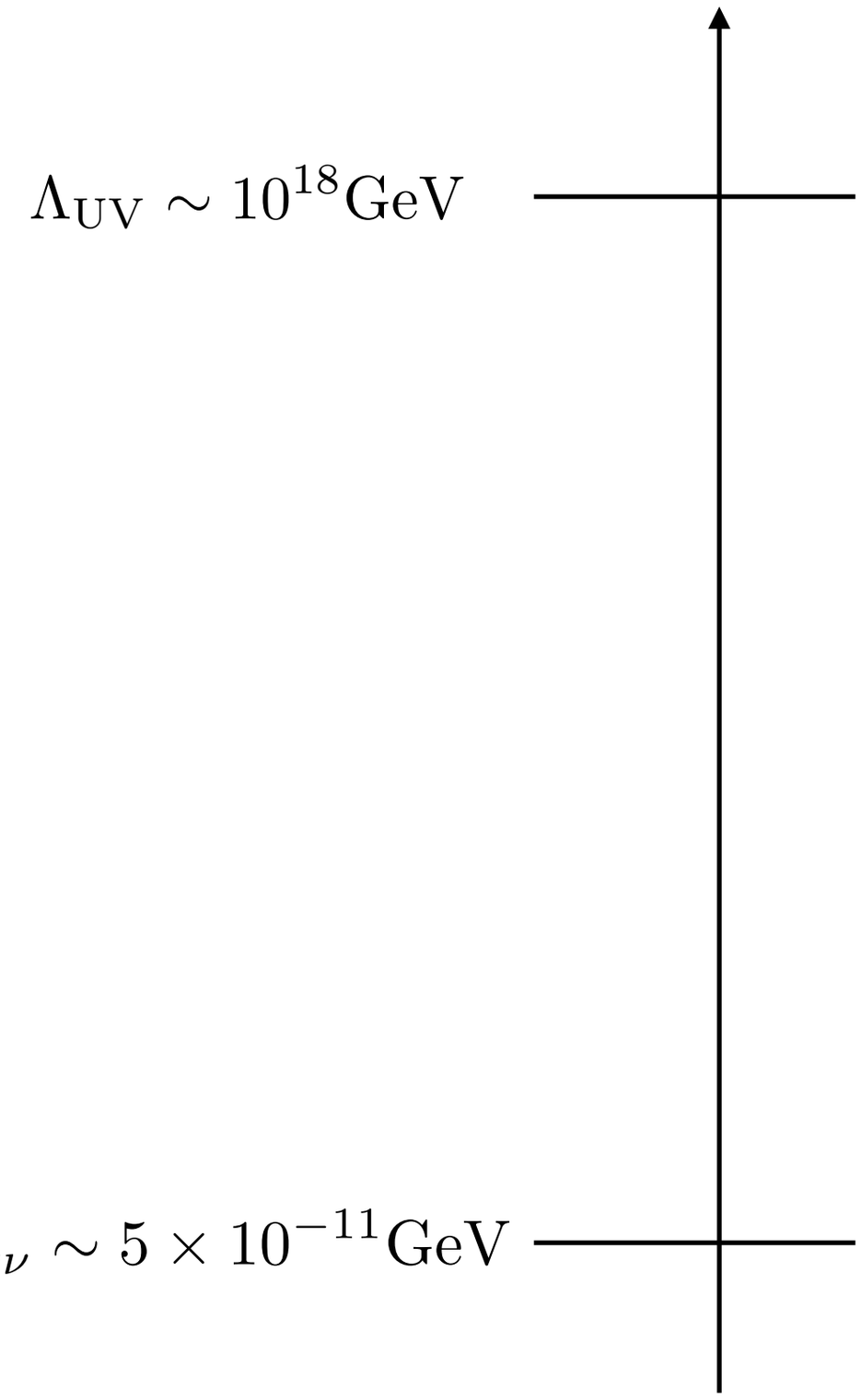
t' Hooft Naturalness

A small parameter is natural
if setting it to zero leads to an enhanced symmetry



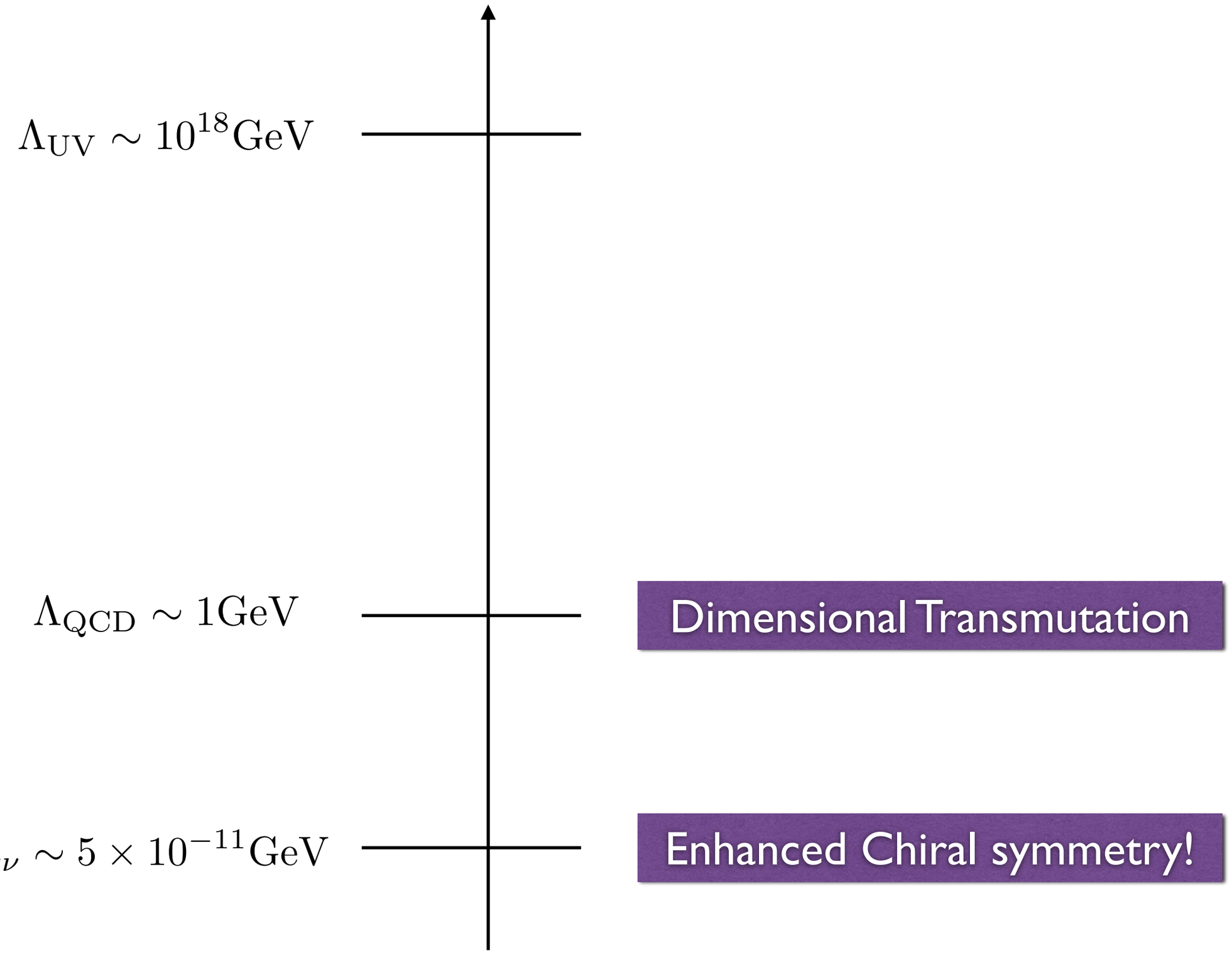
Guideline for model building

t' Hooft Naturalness: SM Lesson

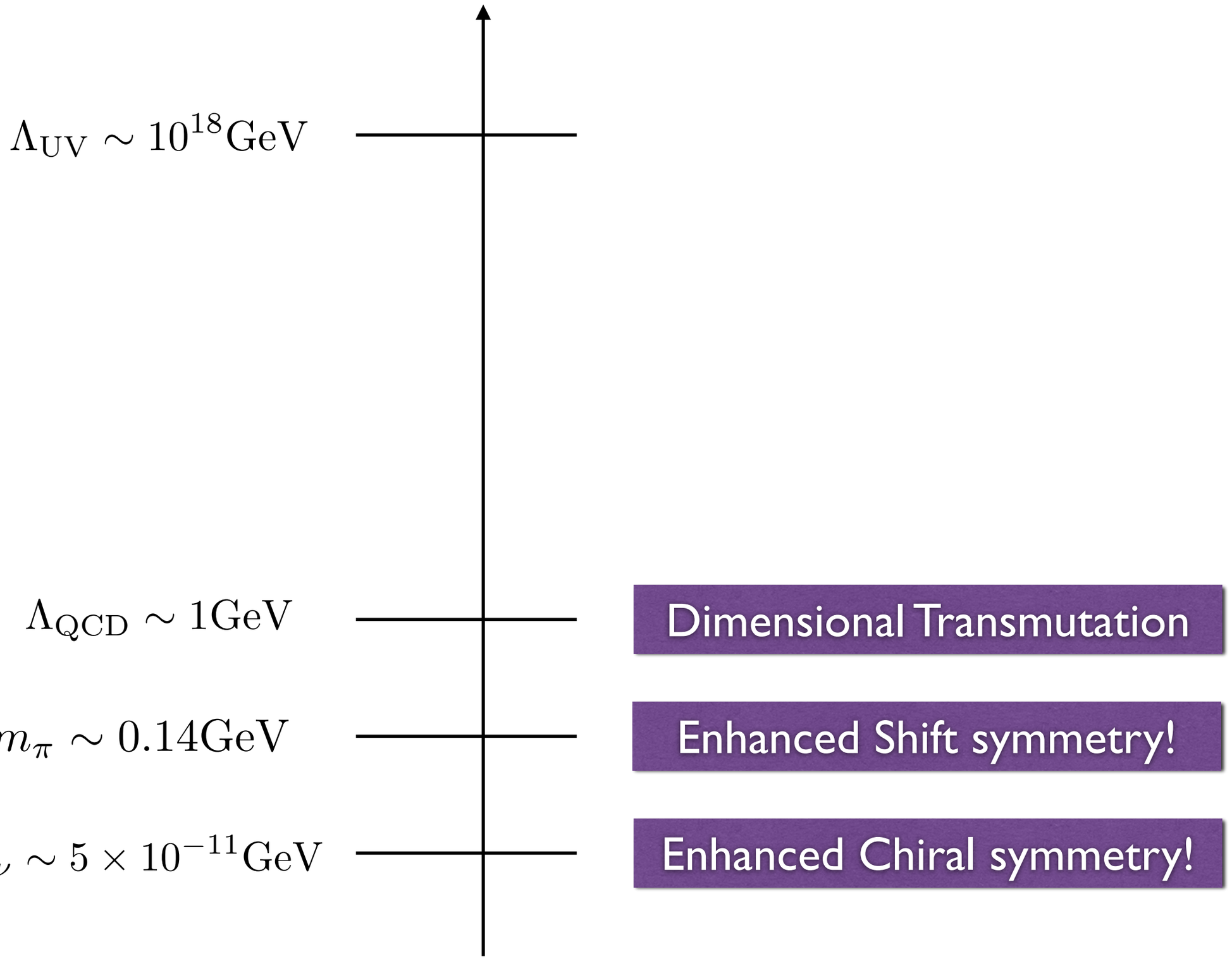


Enhanced Chiral symmetry!

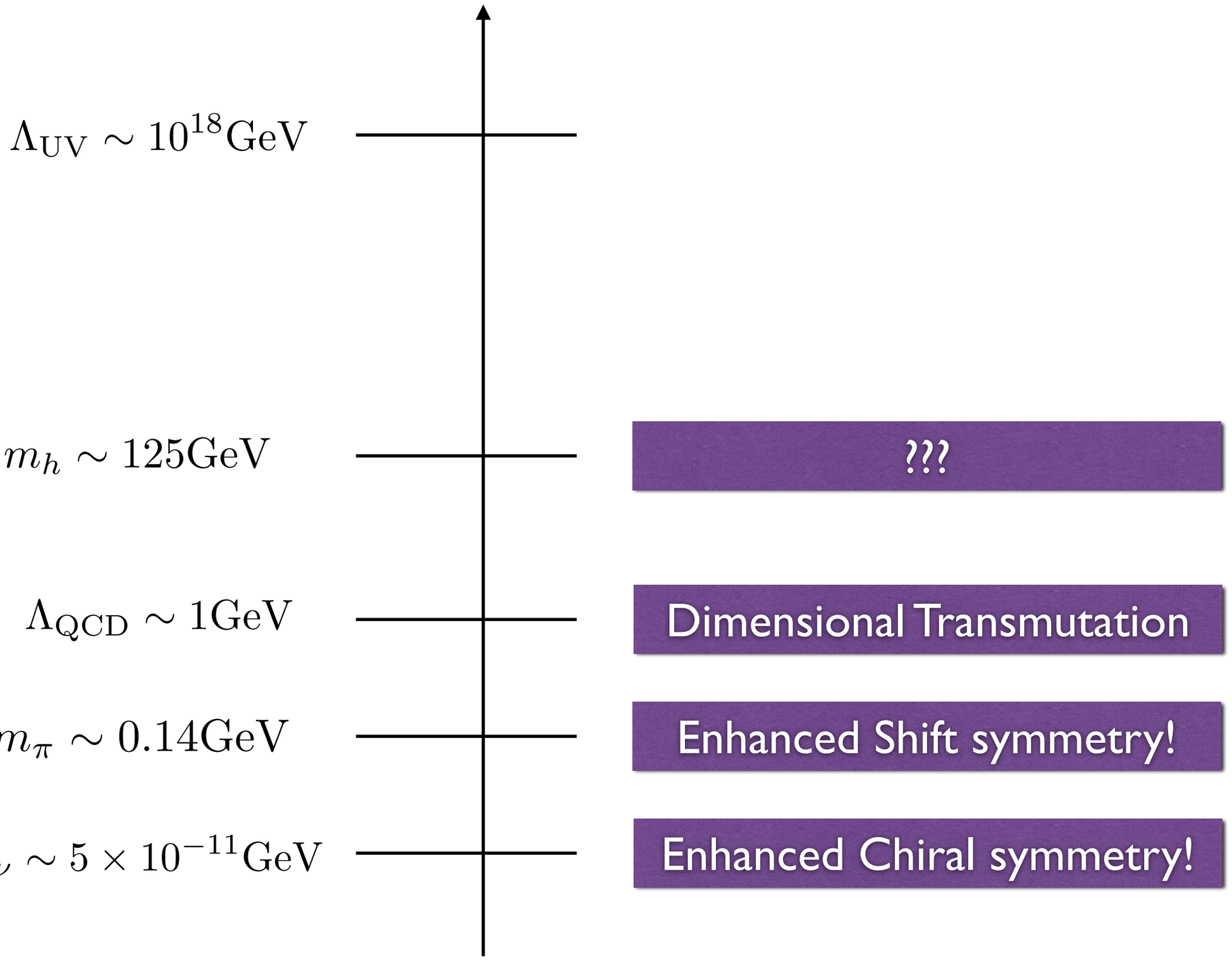
t' Hooft Naturalness: SM Lesson



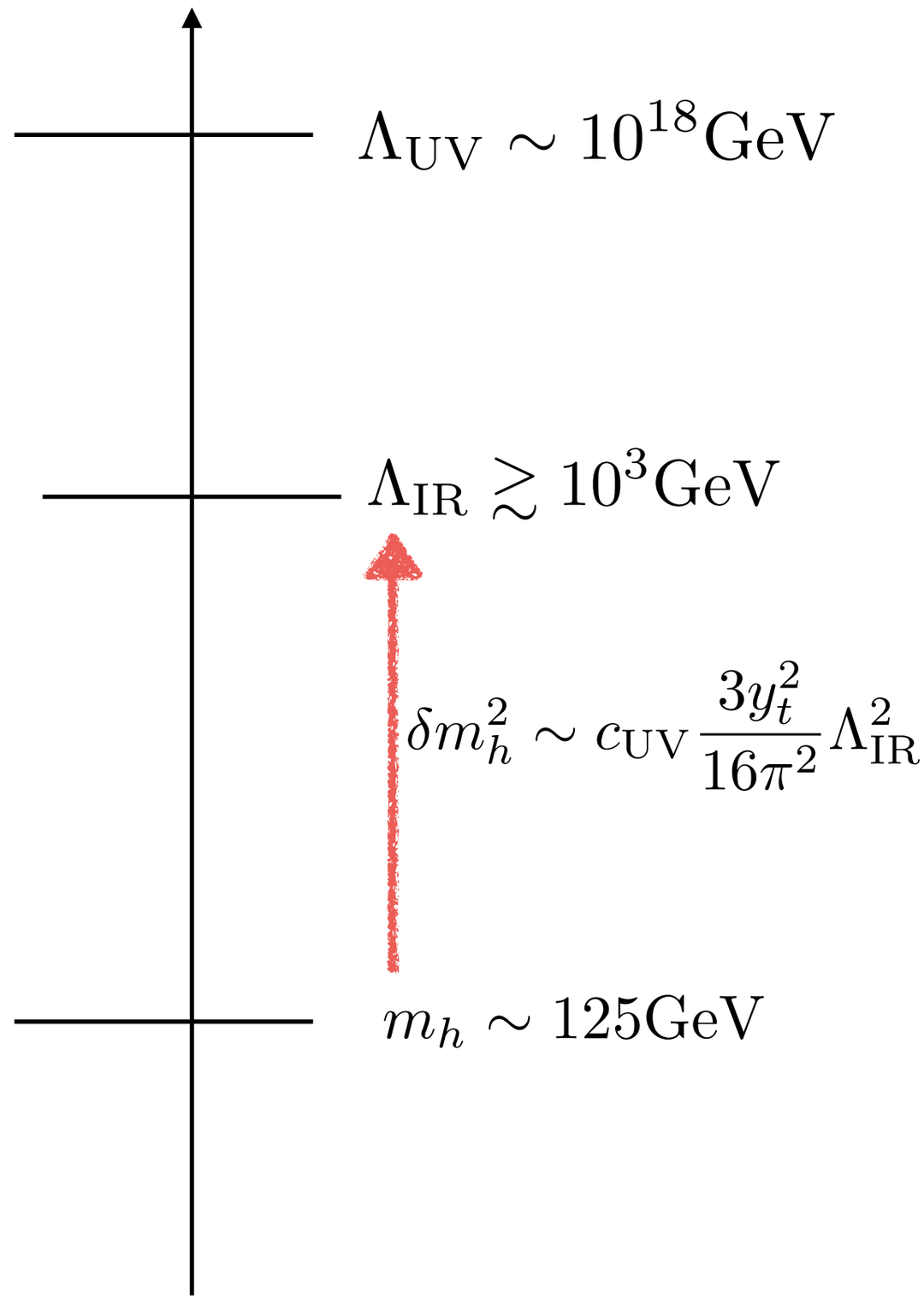
t' Hooft Naturalness: SM Lesson



t' Hooft Naturalness: SM Lesson



Hierarchy problem



Need engineering the UV parameter

Naturalness as Guideline

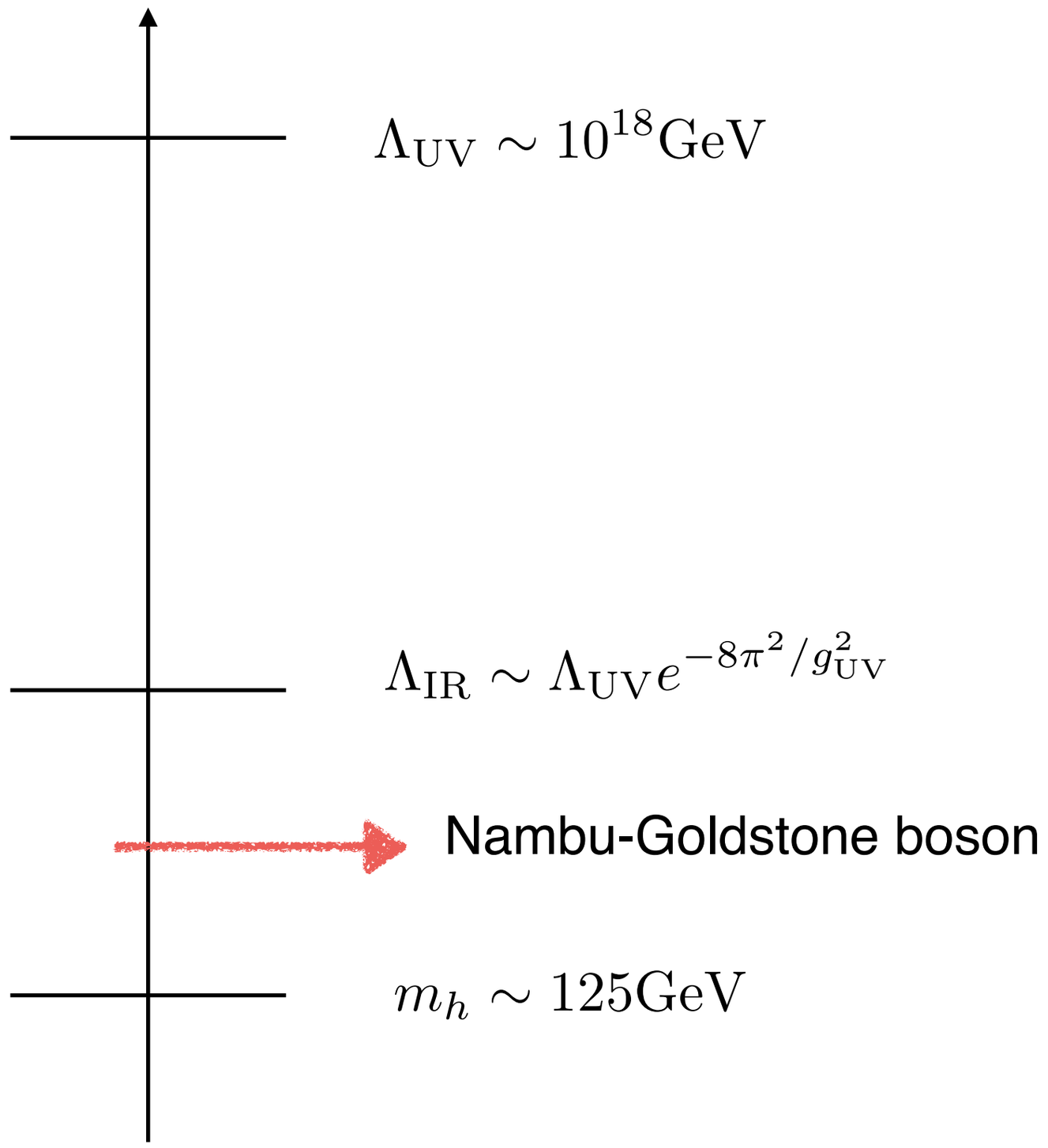
- Compositeness

$$\Lambda_{\rm IR} \sim \Lambda_{\rm UV} e^{-8\pi^2/g^2_{\rm UV}}$$ ⇒ Dimensional Transmutation

- Supersymmetry

$$Q\,|\phi\rangle = |\psi\rangle$$ ⇒ Enhanced chiral symmetry

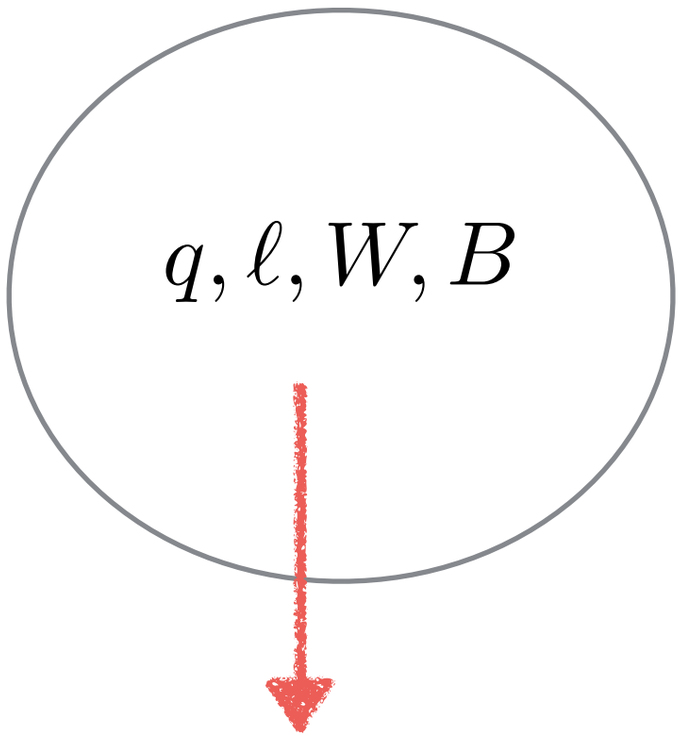
Compositeness



Enhanced shift symmetry!

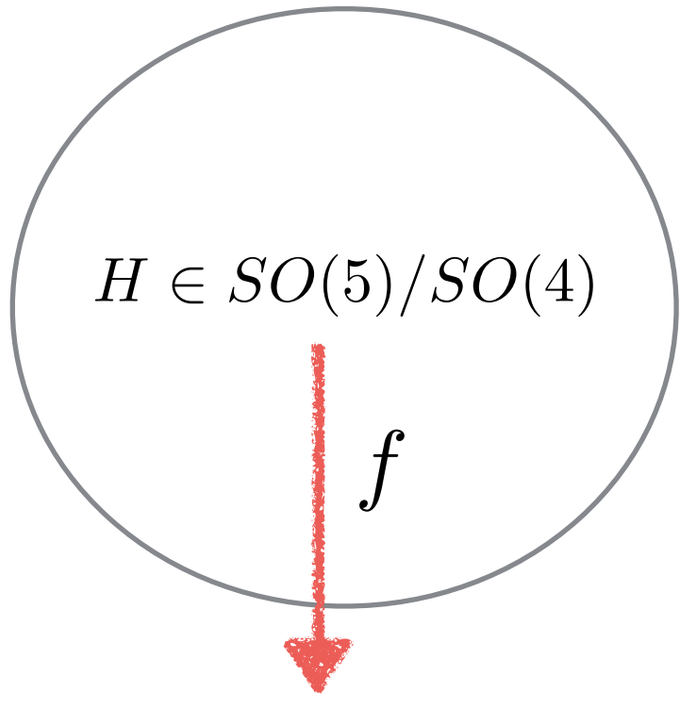
Composite Higgs models: Assumption I

Elementary



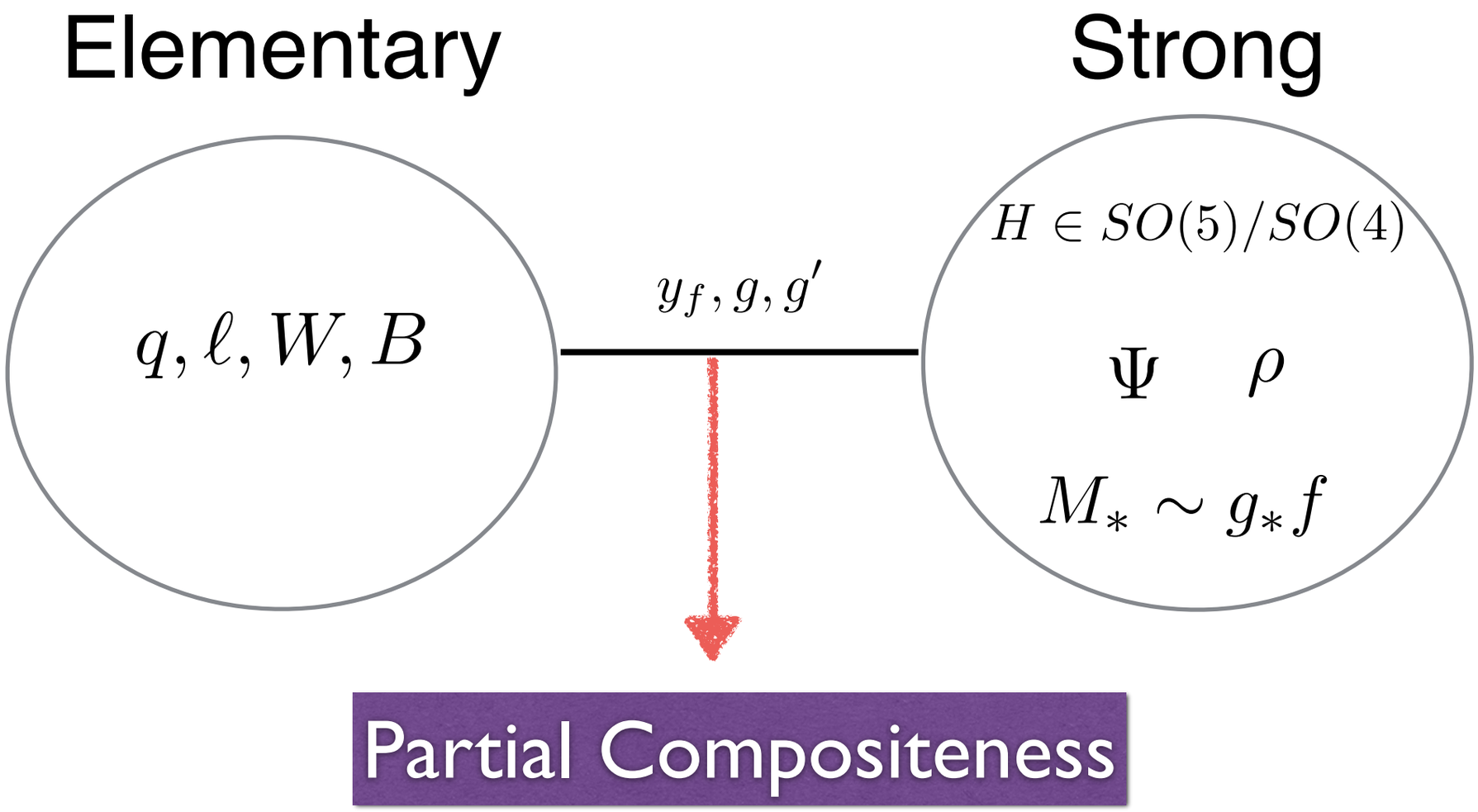
Kaplan, Georgi & Dimopoulos ’84

Strong



Contino, Nomura and Pomarol ‘03
Agashe, Contino and Pomarol ‘04

Composite Higgs models: Assumption II



Kaplan, Georgi & Dimopoulos ’84

Contino, Nomura and Pomarol ‘03
Agashe, Contino and Pomarol ‘04

Partial compositeness: CFT

$$y_L \bar{q}_L^{I_L} \mathcal{O}_{I_L} + y_R \bar{q}_R^{I_R} \mathcal{O}_{I_R}$$

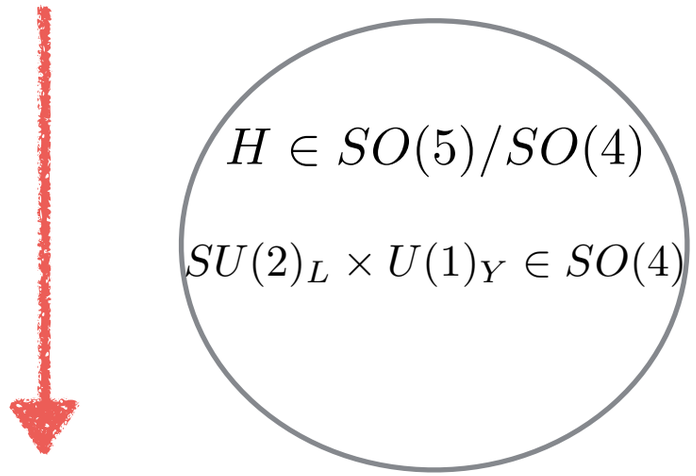
$$d_{\mathcal{O}} = \frac{3}{2} + |c + \frac{1}{2}|$$

$$y_{L,R}^{\mathrm{IR}} \sim y_{L,R}^{\mathrm{UV}} \left(\frac{\Lambda_{\mathrm{IR}}}{\Lambda_{\mathrm{UV}}} \right)^{d_{\mathcal{O}_{L,R}} - \frac{5}{2}}$$

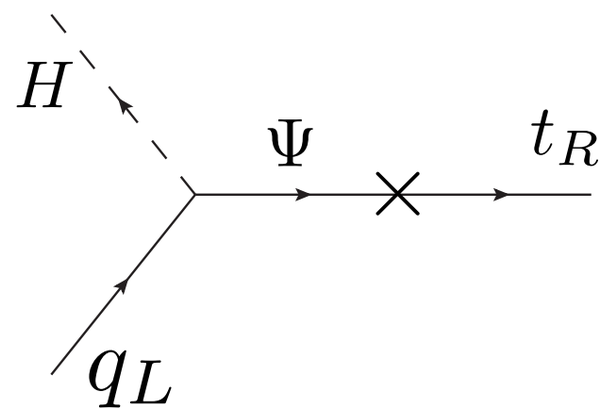
Scale Hierarchy turn to coupling hierarch

Partial compositeness: top quark mass

$$y_L \bar{q}_L^{I_L} \mathcal{O}_{I_L} + y_R \bar{t}_R^{I_R} \mathcal{O}_{I_R}$$

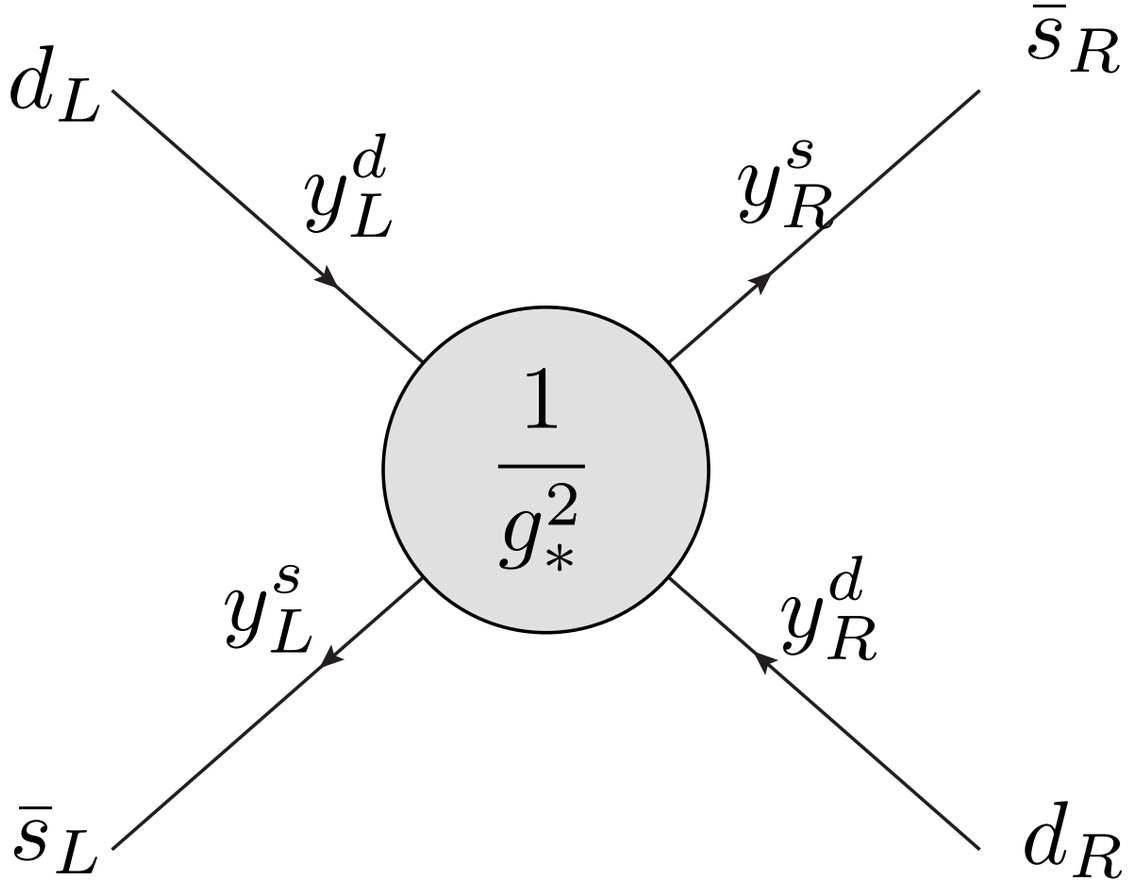


$$y_L \bar{q}_L H \Psi_R + y_R f \bar{t}_R \Psi_L$$



$$\frac{y_L y_R f}{M_\Psi} \bar{q}_L \tilde{H} t_R \qquad y_t \sim \frac{y_L y_R}{g_*}$$

Partial compositeness: Flavor



$$\sim \frac{y_d y_s}{m_*^2} \longrightarrow m_* > 12 \text{ TeV}$$

B. Keren-Zur et al, 1205.5803

Targets at the Muon Collider

- Probe the on-shell resonances up to kinematical limits

- Measure the couplings as precise as possible

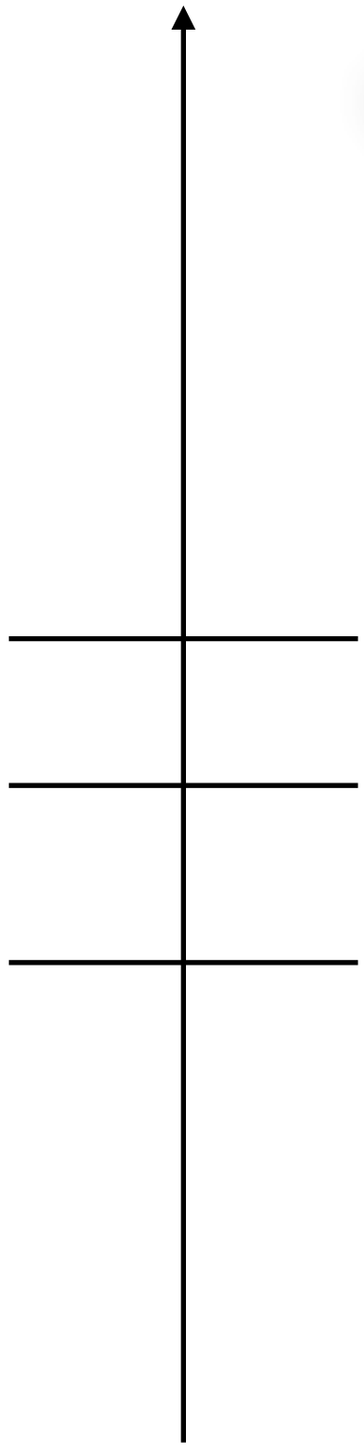
See also the talk by R. Franceschini

Direct Resonance searches

$\rho_L = (3,1)$

$$Q_X = \begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}_{\frac{7}{6}} \qquad Q = \begin{pmatrix} T \\ B \end{pmatrix}_{\frac{1}{6}}$$

$m_\rho = a_\rho g_\rho f$



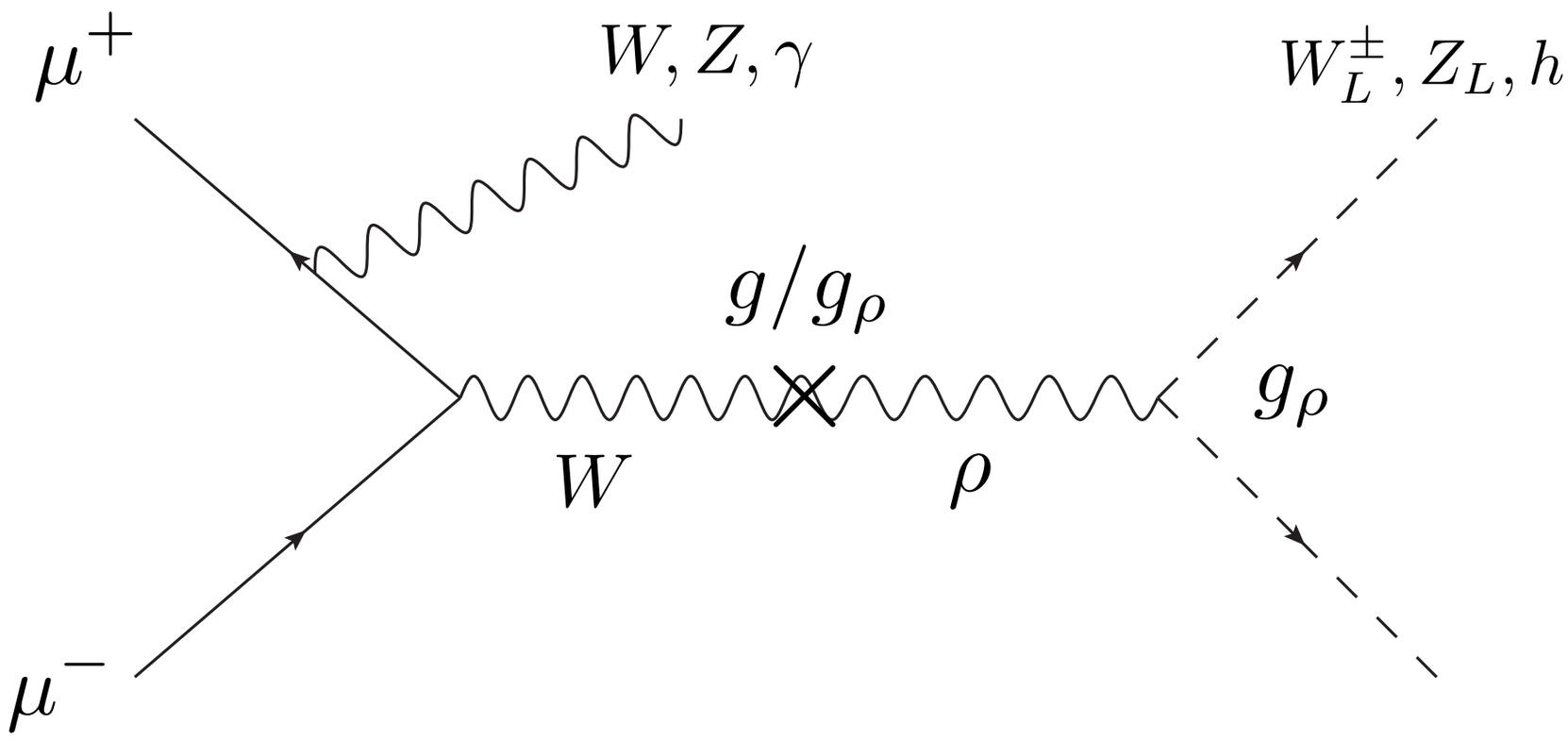
$$M_T = \sqrt{M_\Psi^2 + y_L^2 f^2}$$

$$M_{X_{5/3}} = M_\Psi$$

R.C., D.M., D.P. & R.R. ‘11

A.D.S., O.M., R.R. & A.W.‘12

Spin-1 resonances: DY-like



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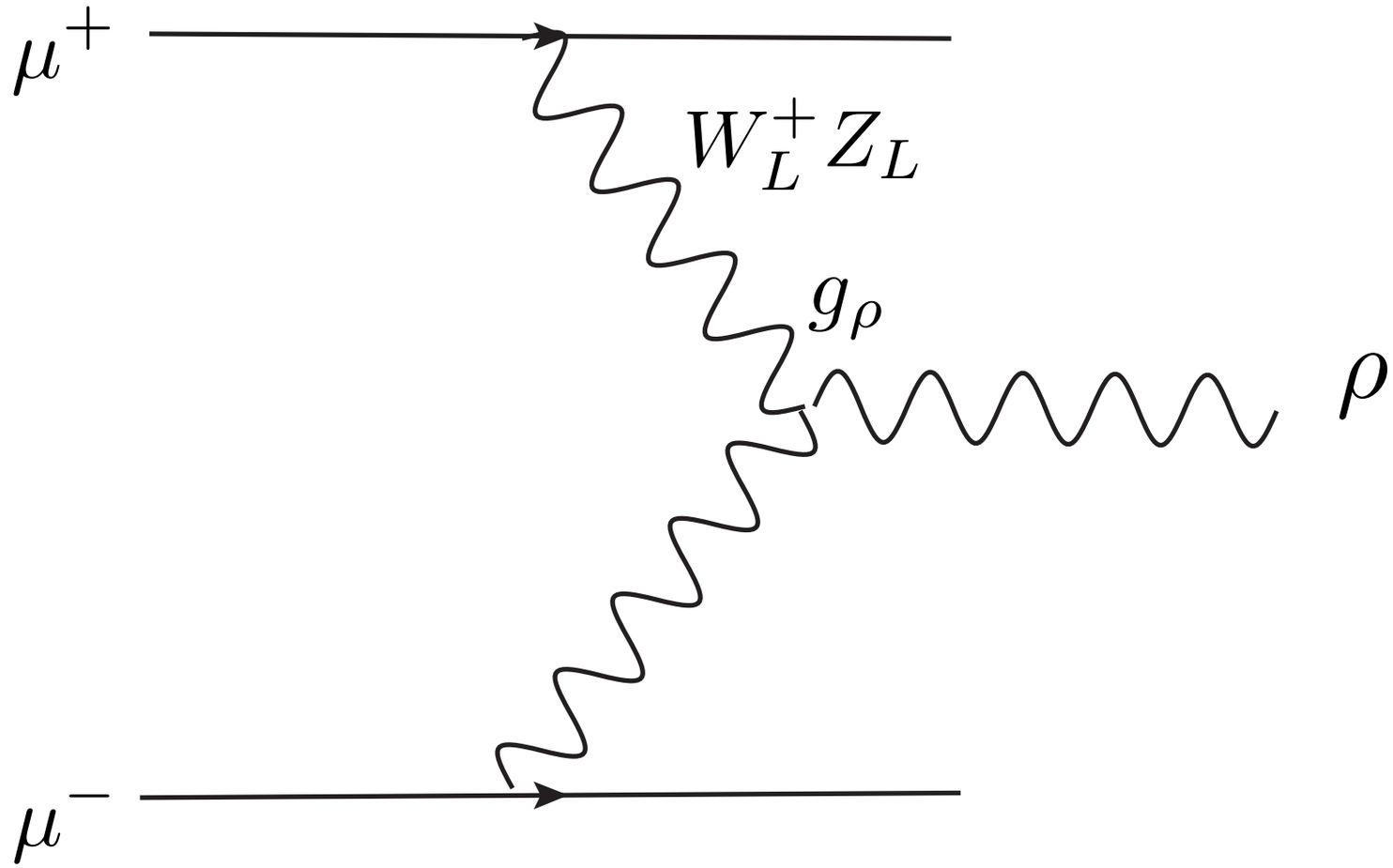
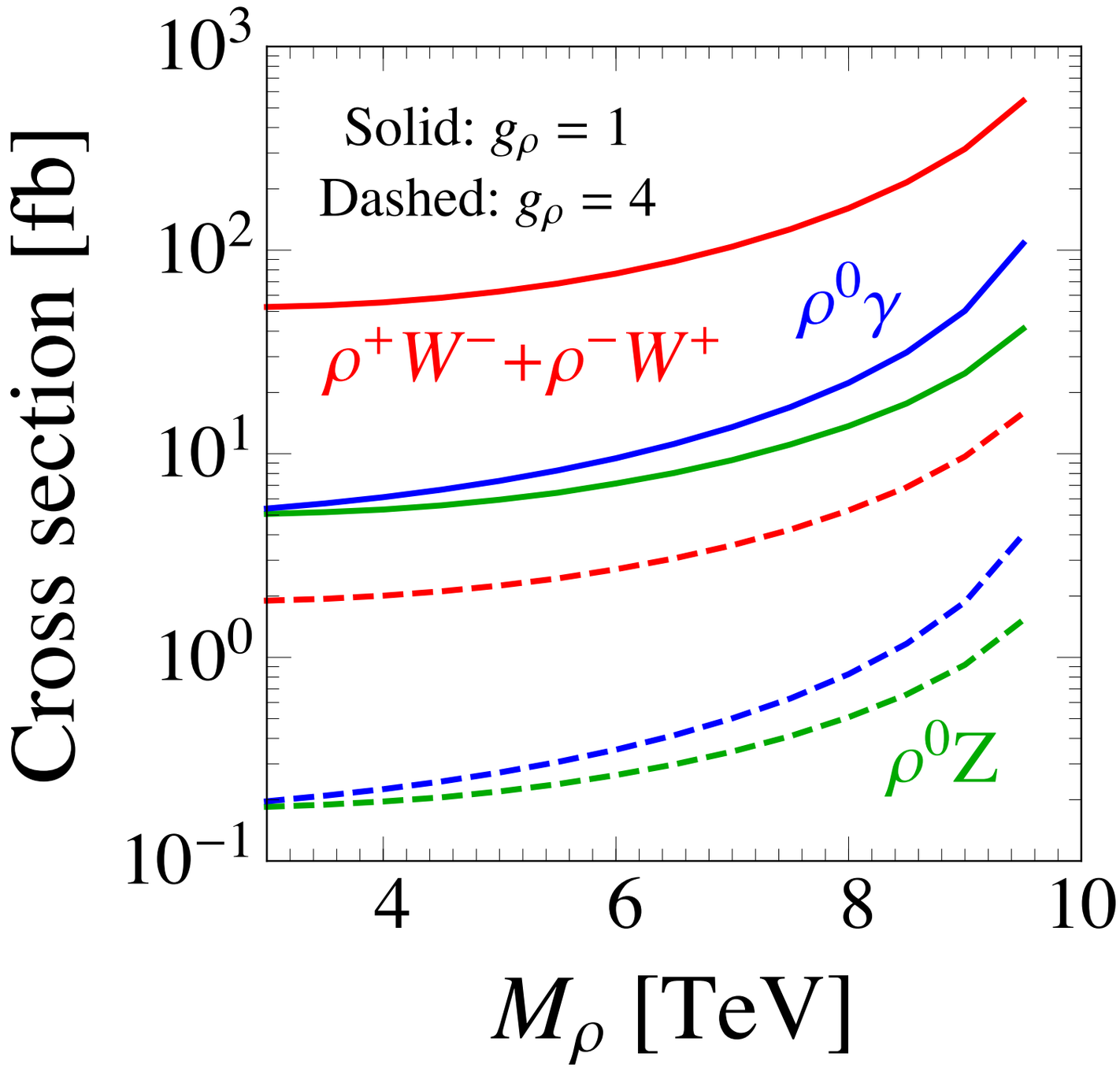
Working in progress

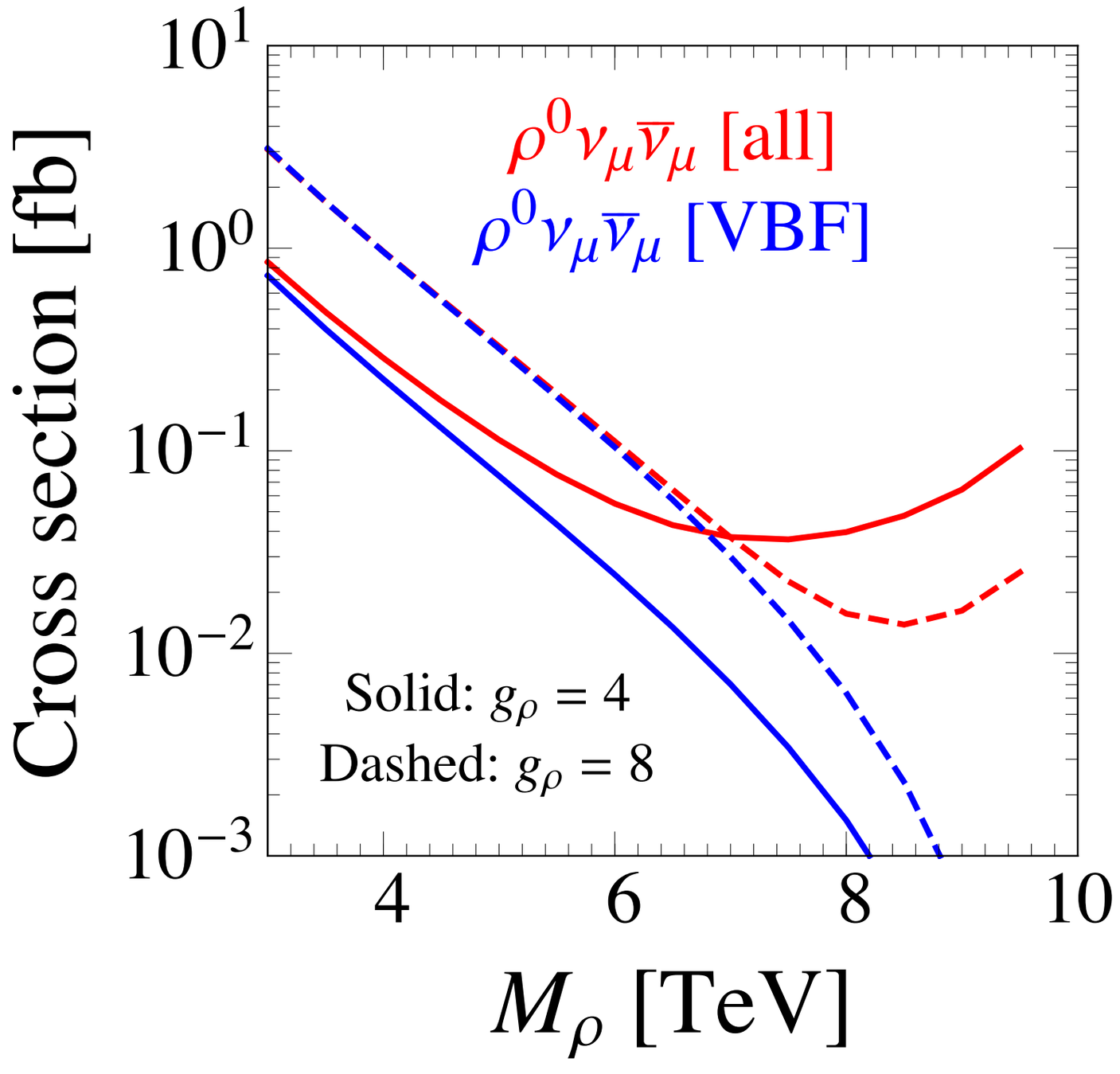
Spin-1 resonances: VBF



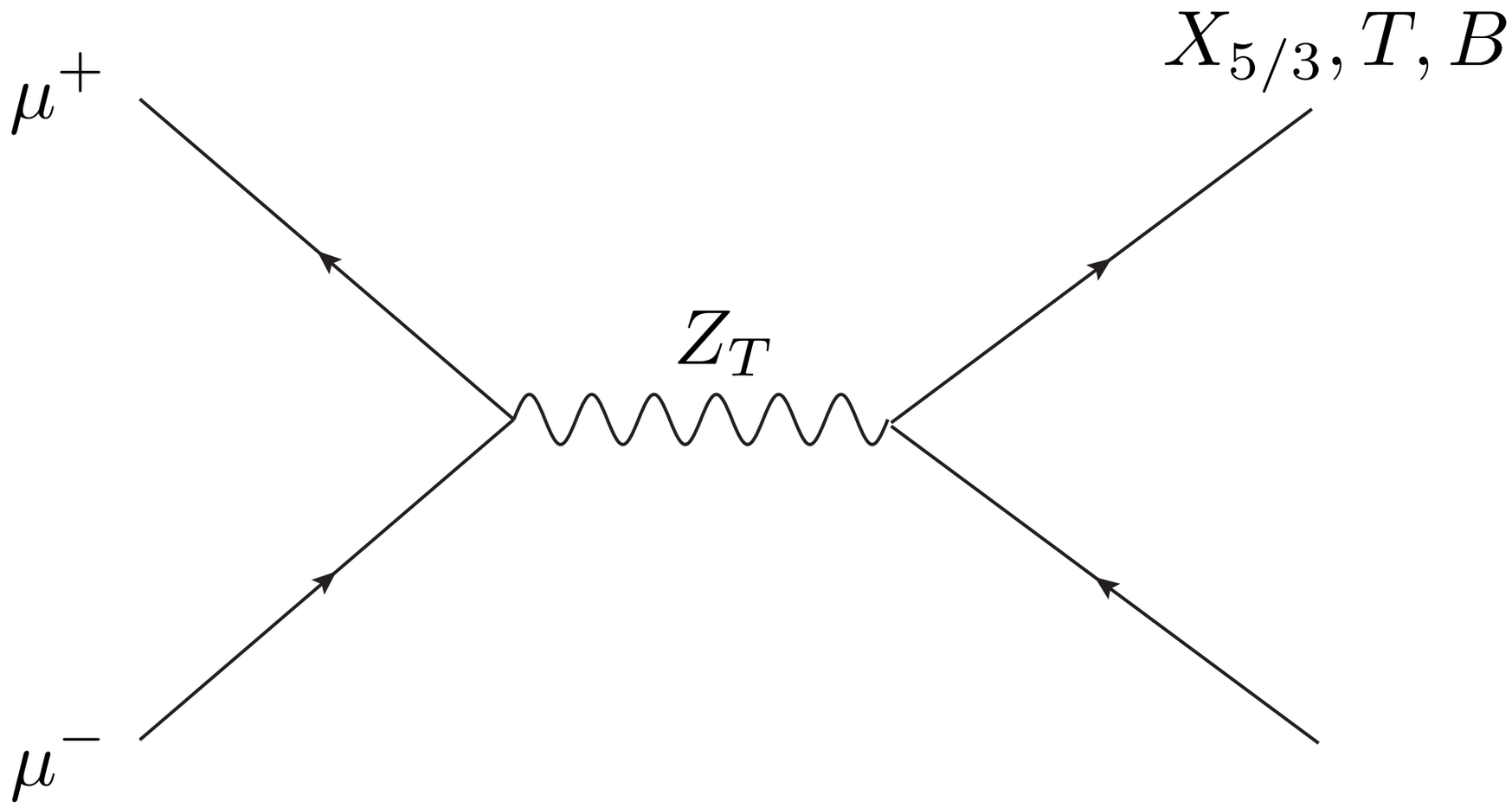
Spin-1 resonances: XS



Spin-1 resonances: VBF



Top partners: DY Pair



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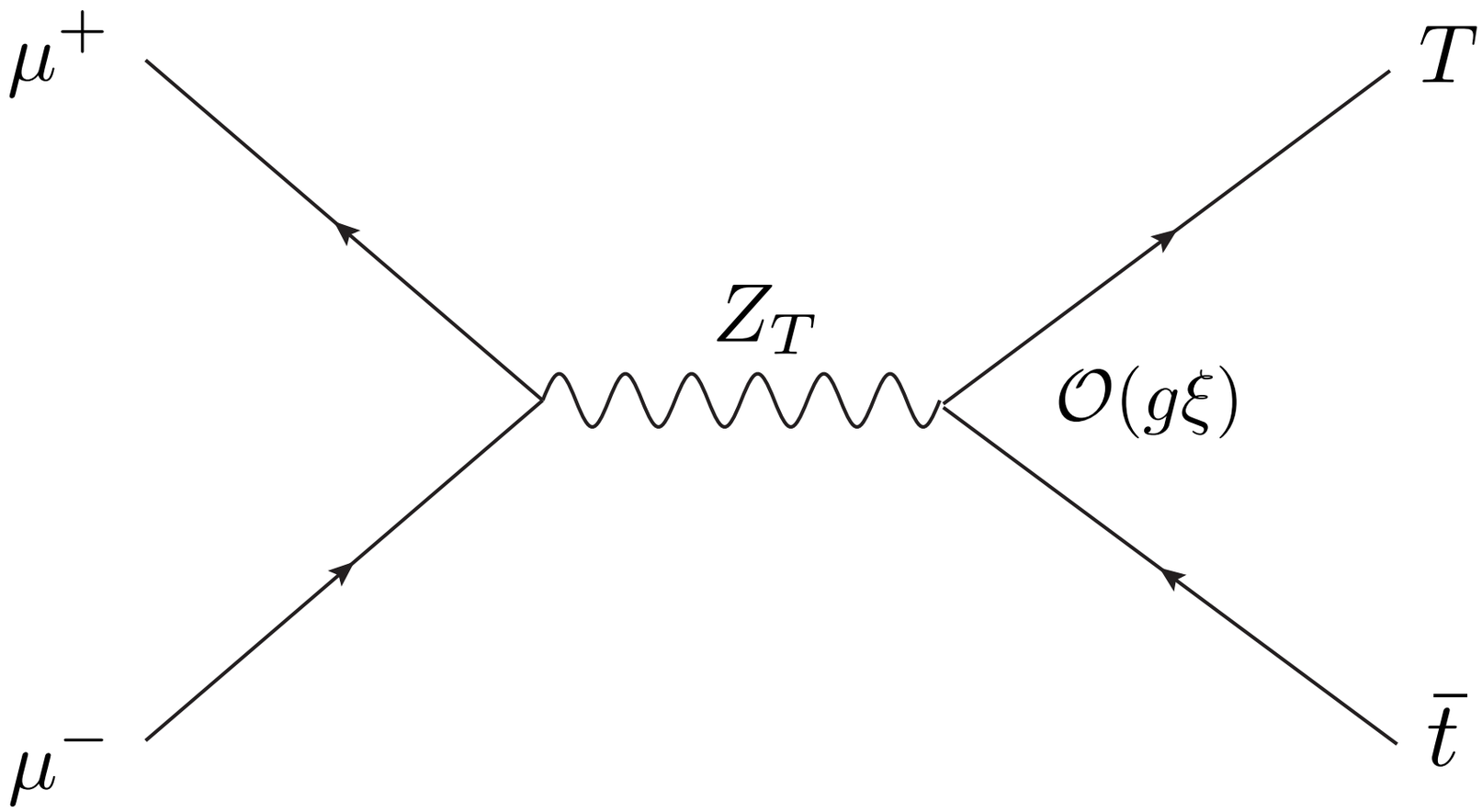
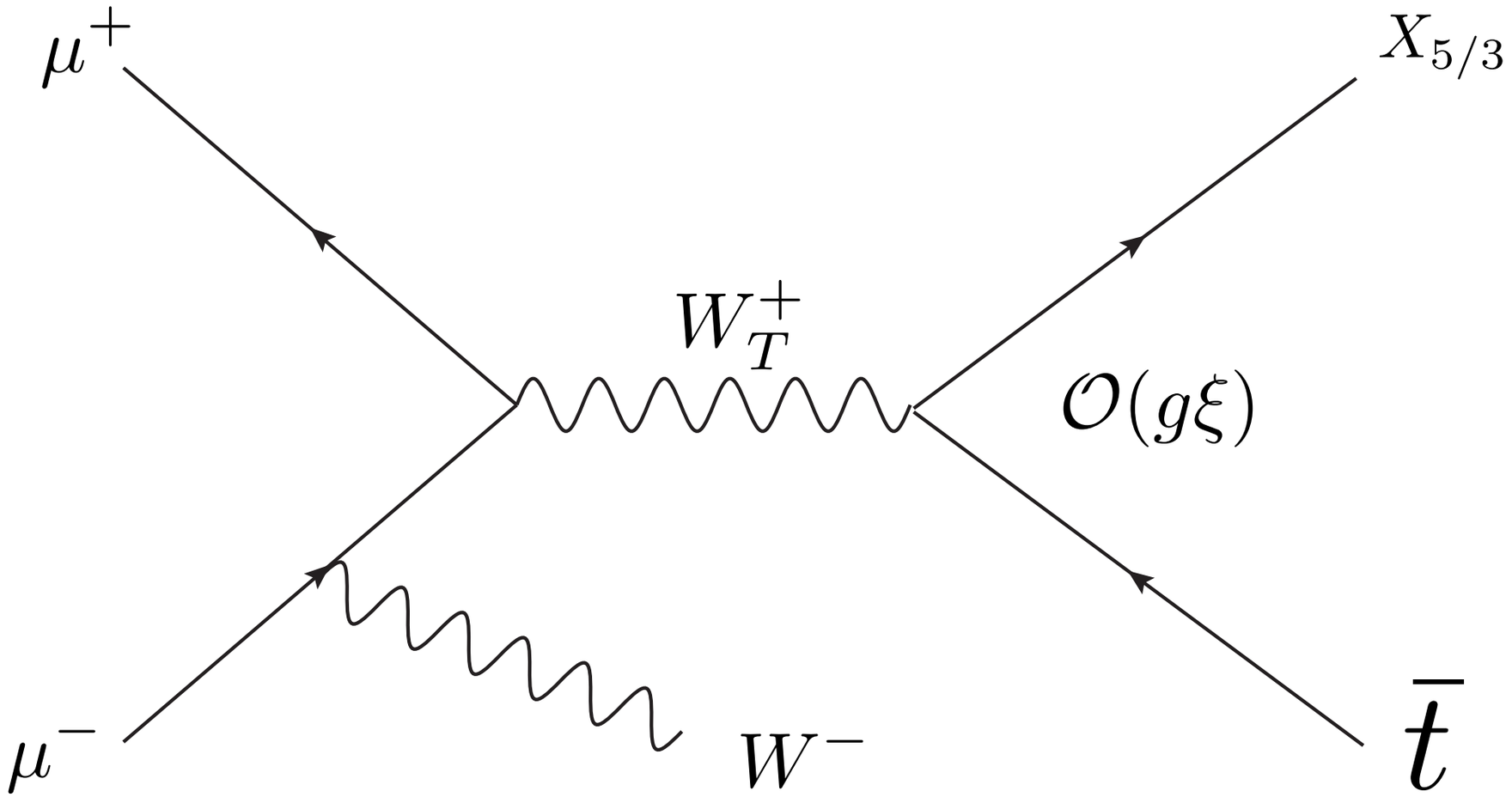
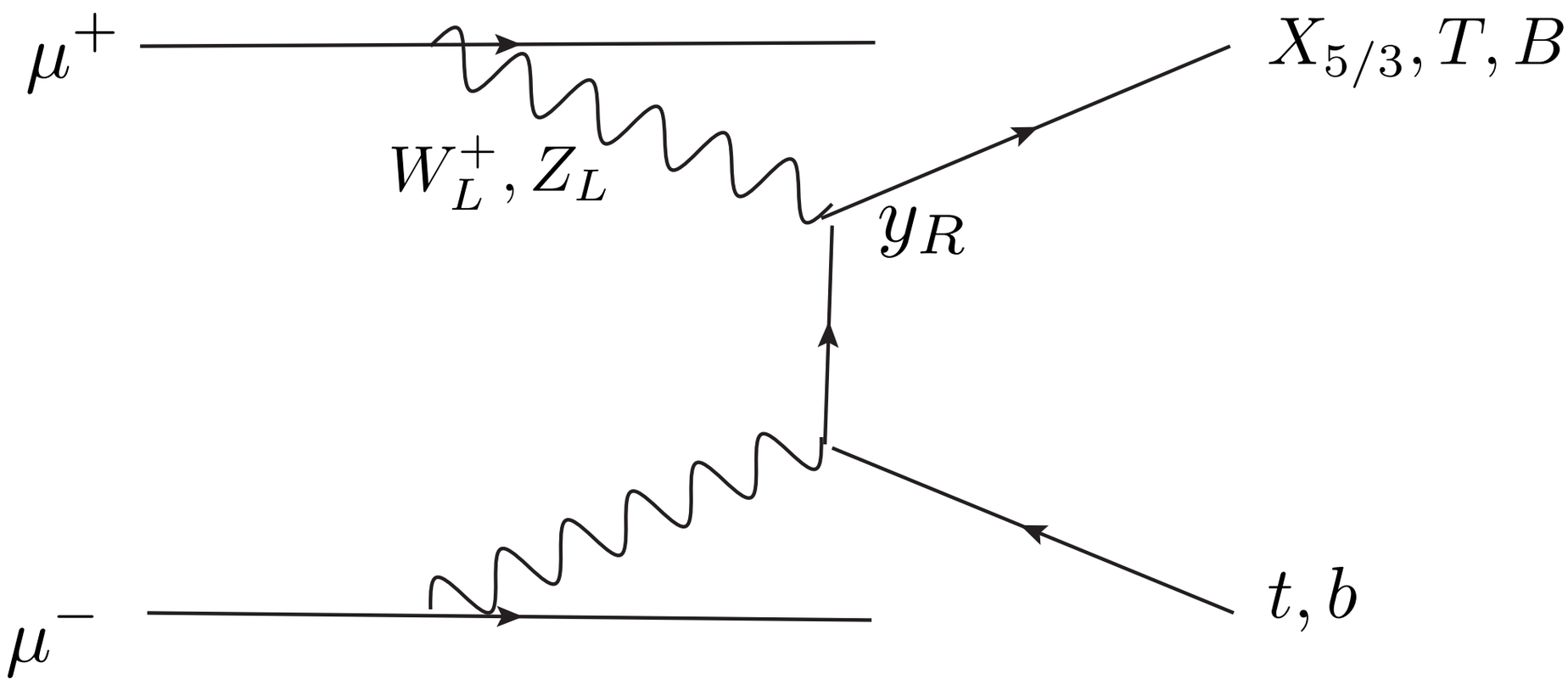
Top partners: DY Single



Top partners: DY-like Single

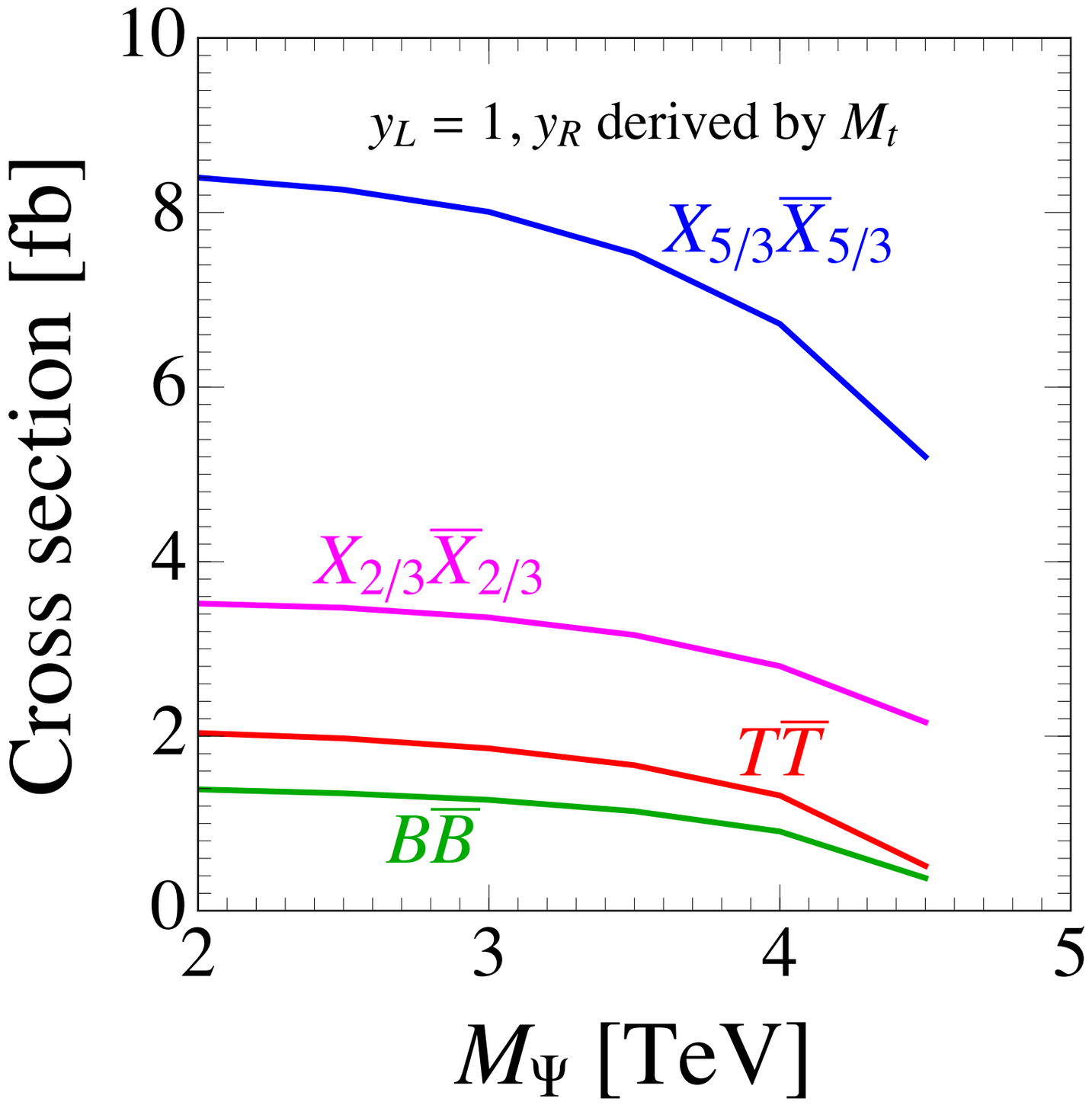


Top partners: VBF



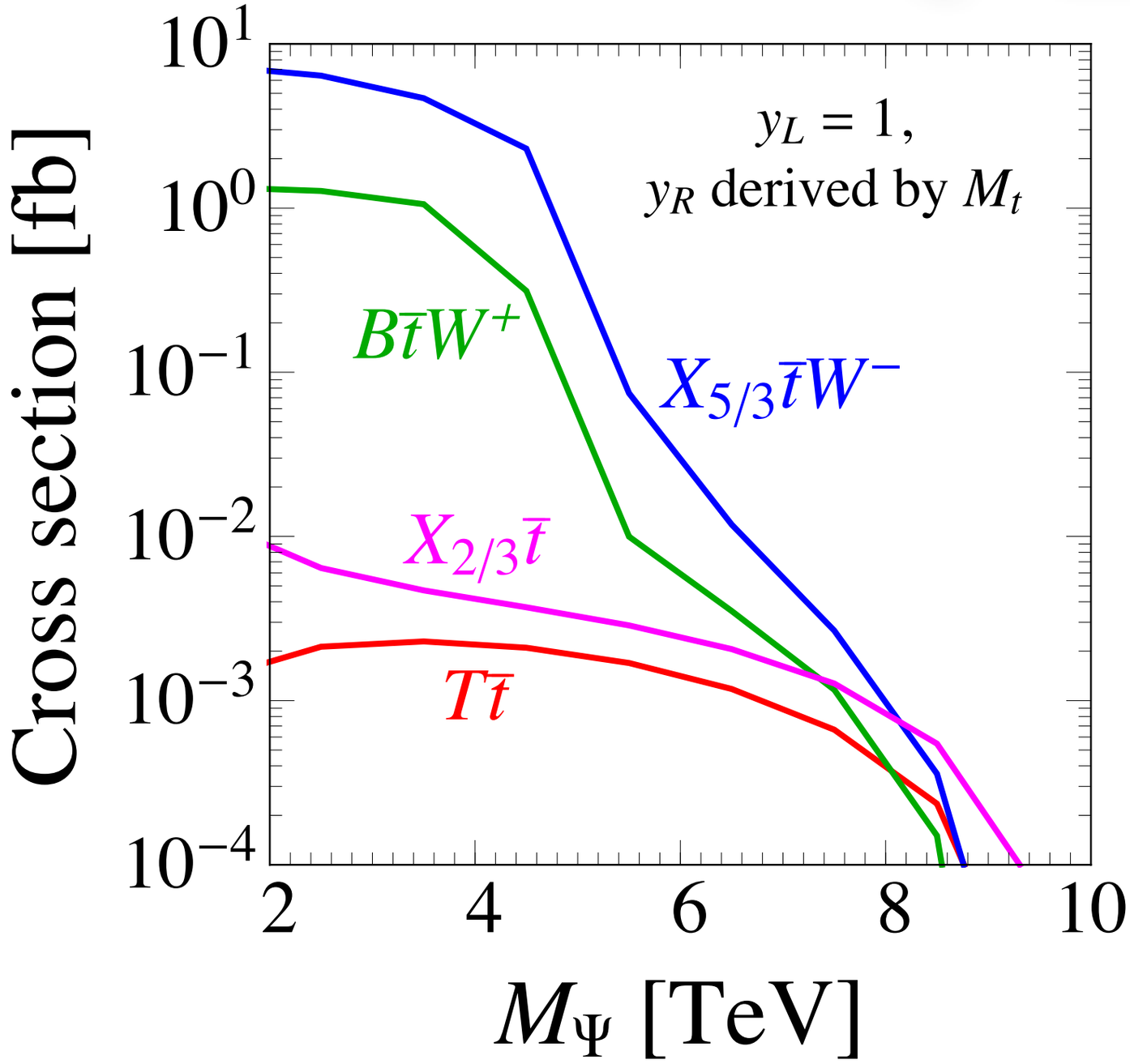
Relevant for large yR

Top partners: Pair production XS



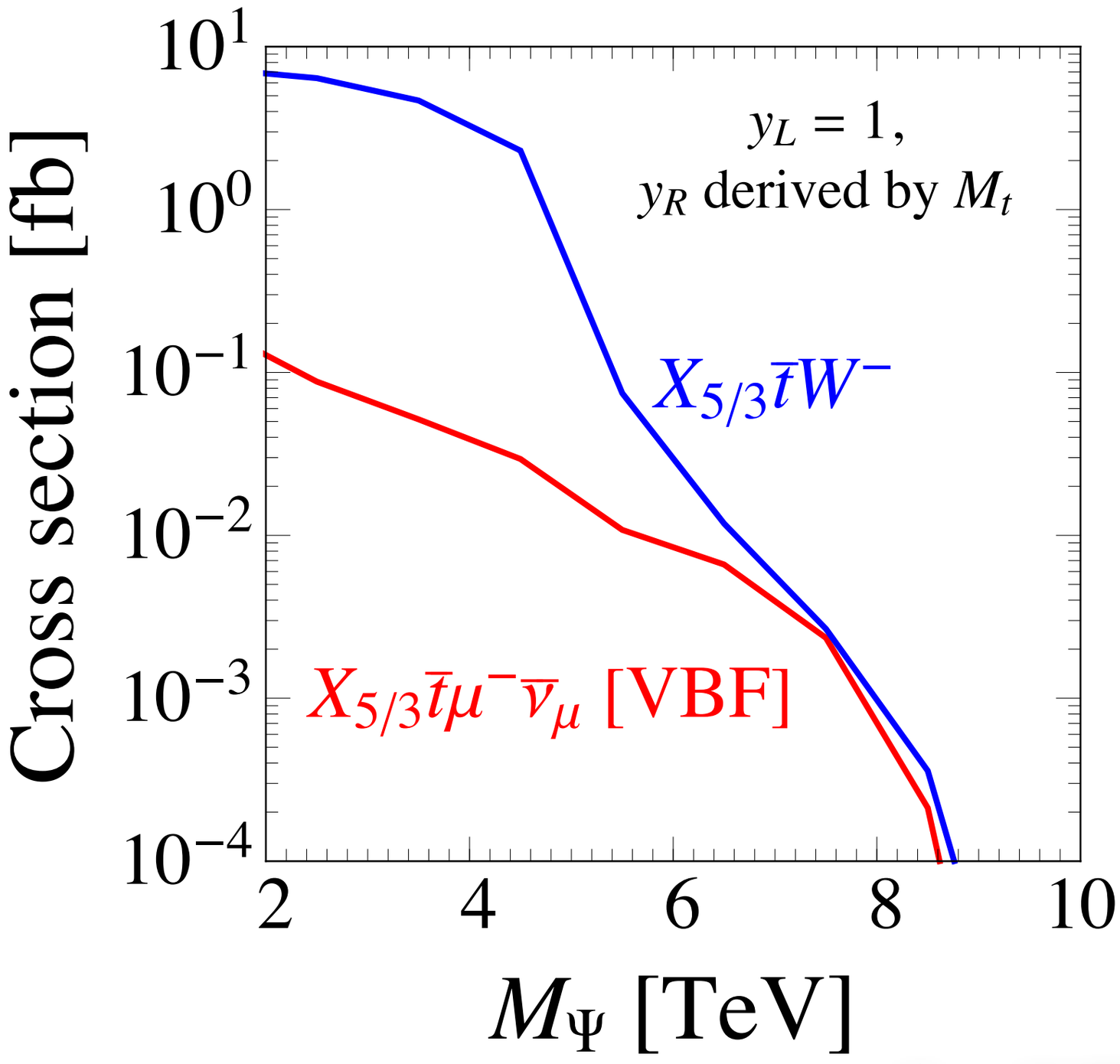
Top partners: XS

$\xi = 0.015, f = 2$ TeV



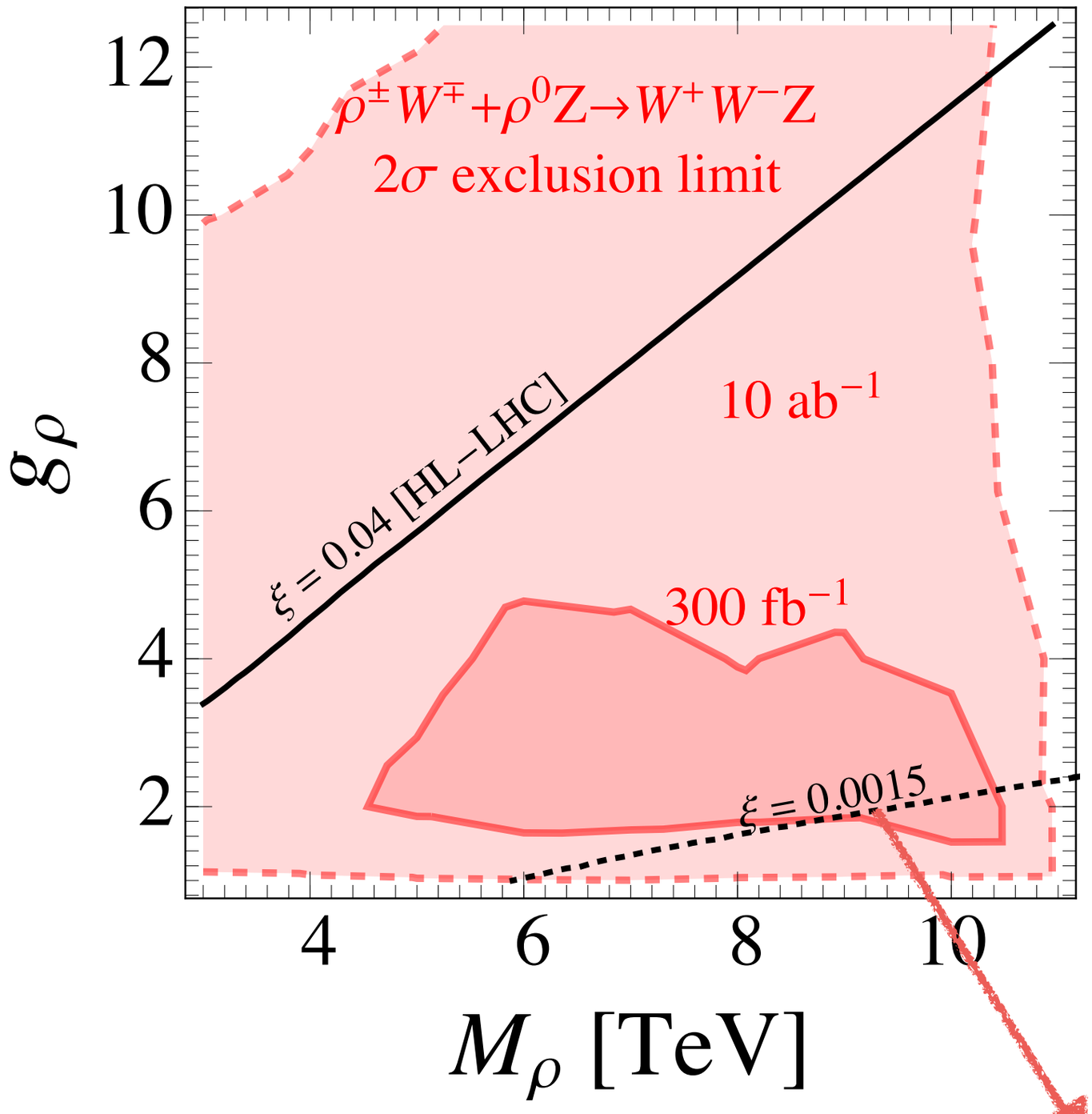
Pair production is included when possible

Top partners: VBF Production XS



$\xi = 0.015, f = 2$ TeV

Projection: Spin-1



$$M_\rho = \frac{1}{\sqrt{2}} g_\rho f$$

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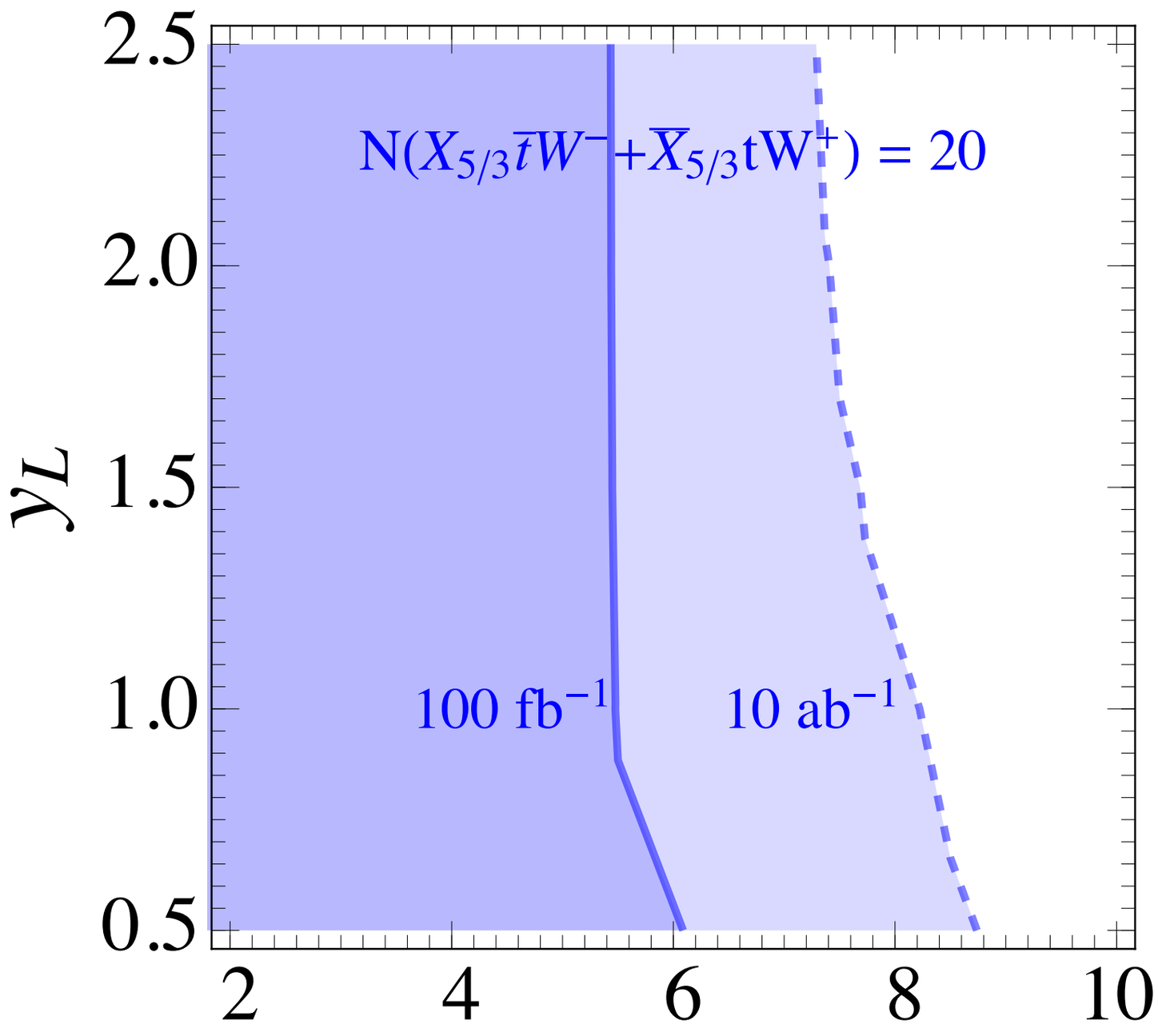
10 TeV Muon Collider
see T. Han, DL, I. Low and X. Wang

Projection: top partner



$\xi = 0.015, f = 2\ \mathrm{TeV}$

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Conclusion

- Compositeness is an elegant way to address the hierarchy problem.

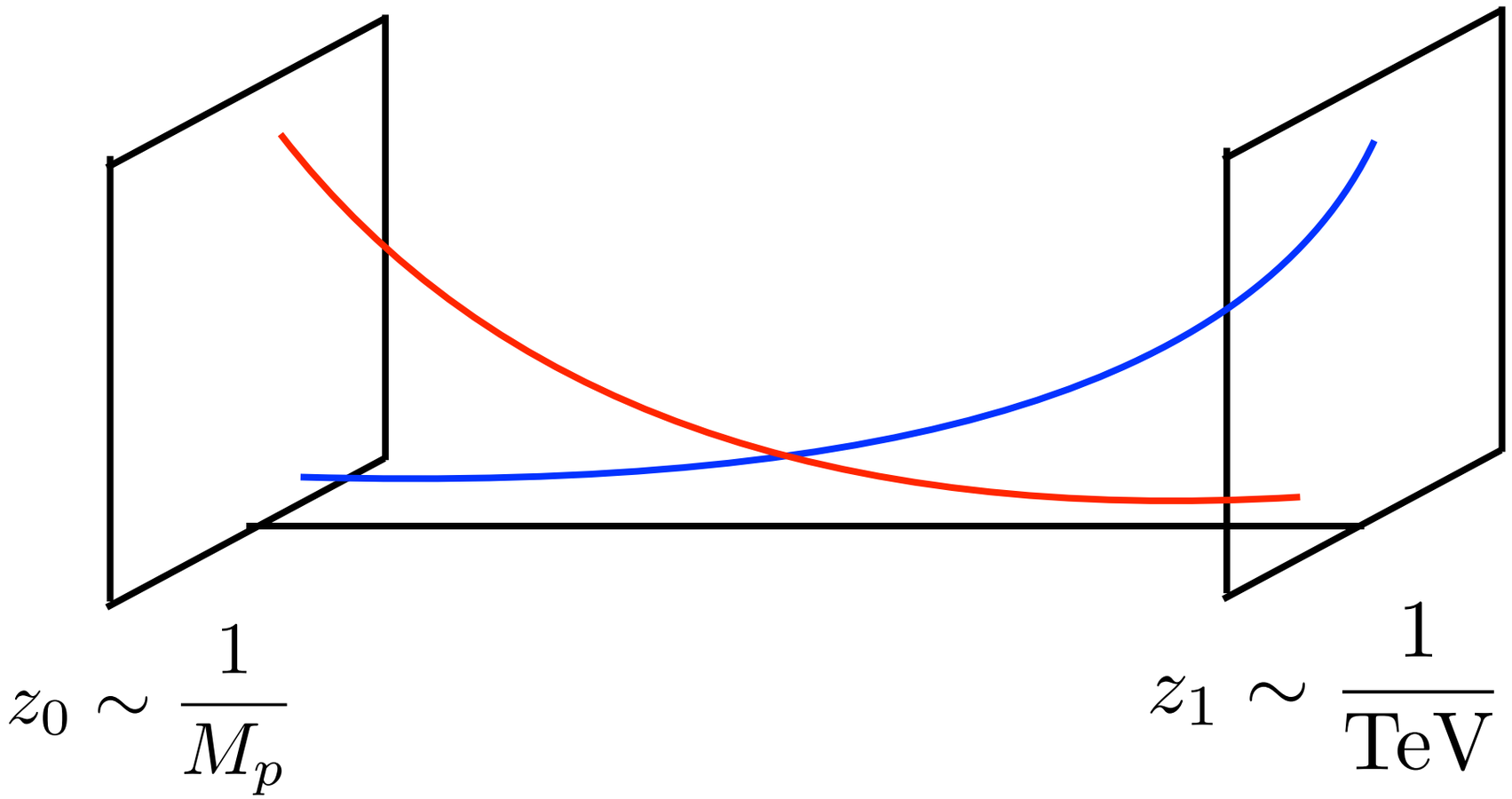
- Prospects at high energy muon collider are under careful scrutiny

Back-up Slides

Partial compositeness: AdS

$c > \frac{1}{2}$

$c < \frac{1}{2}$



$z_0 \sim \frac{1}{M_p}$

$z_1 \sim \frac{1}{\mathrm{TeV}}$

$$\boxed{c = \frac{M_\Psi}{k}}$$

Randall and Sundrum 99'
Davoudiasl, Hewett and Rizzo 99'
Pomarol 99'

Pomarol 99'
Grossman and Neubert 99'
Gherghetta and Pomarol 00'