Search for Physics beyond SM at the Energy Frontier and Precision Frontier

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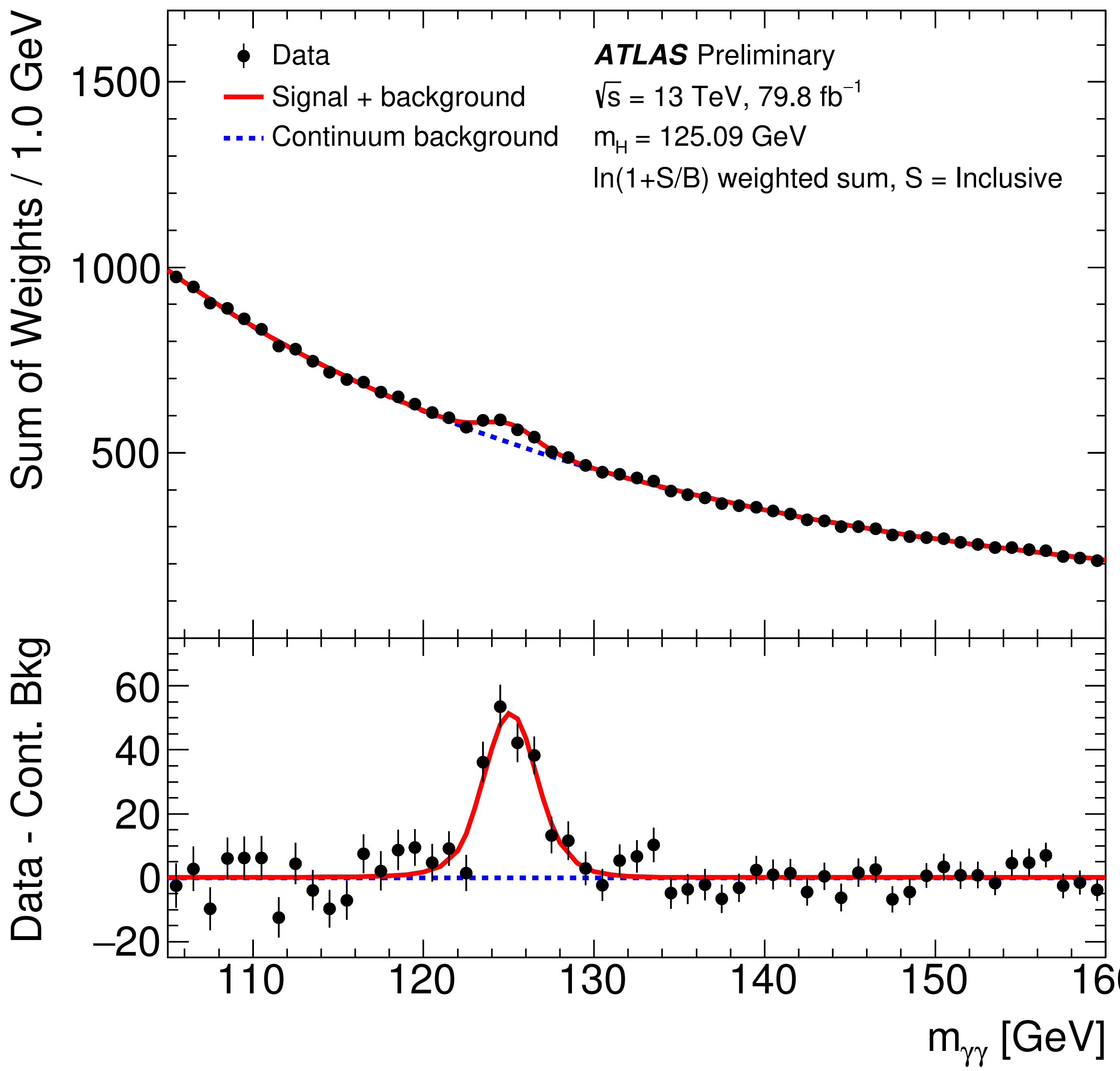
Outline

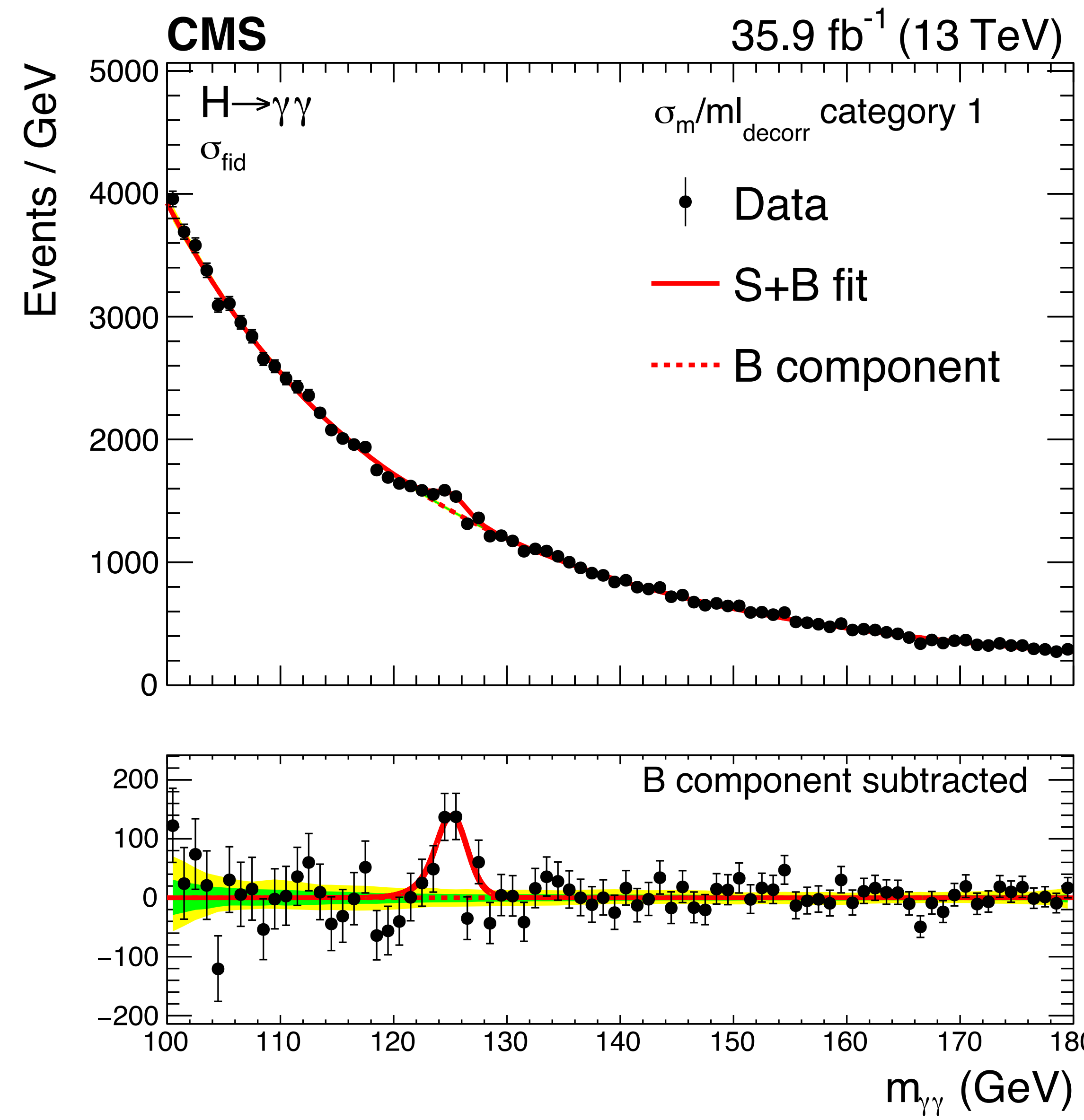
- Physics behind and beyond SM

- Search for BSM at Energy and Precision Frontier

- My Plan at TDLI

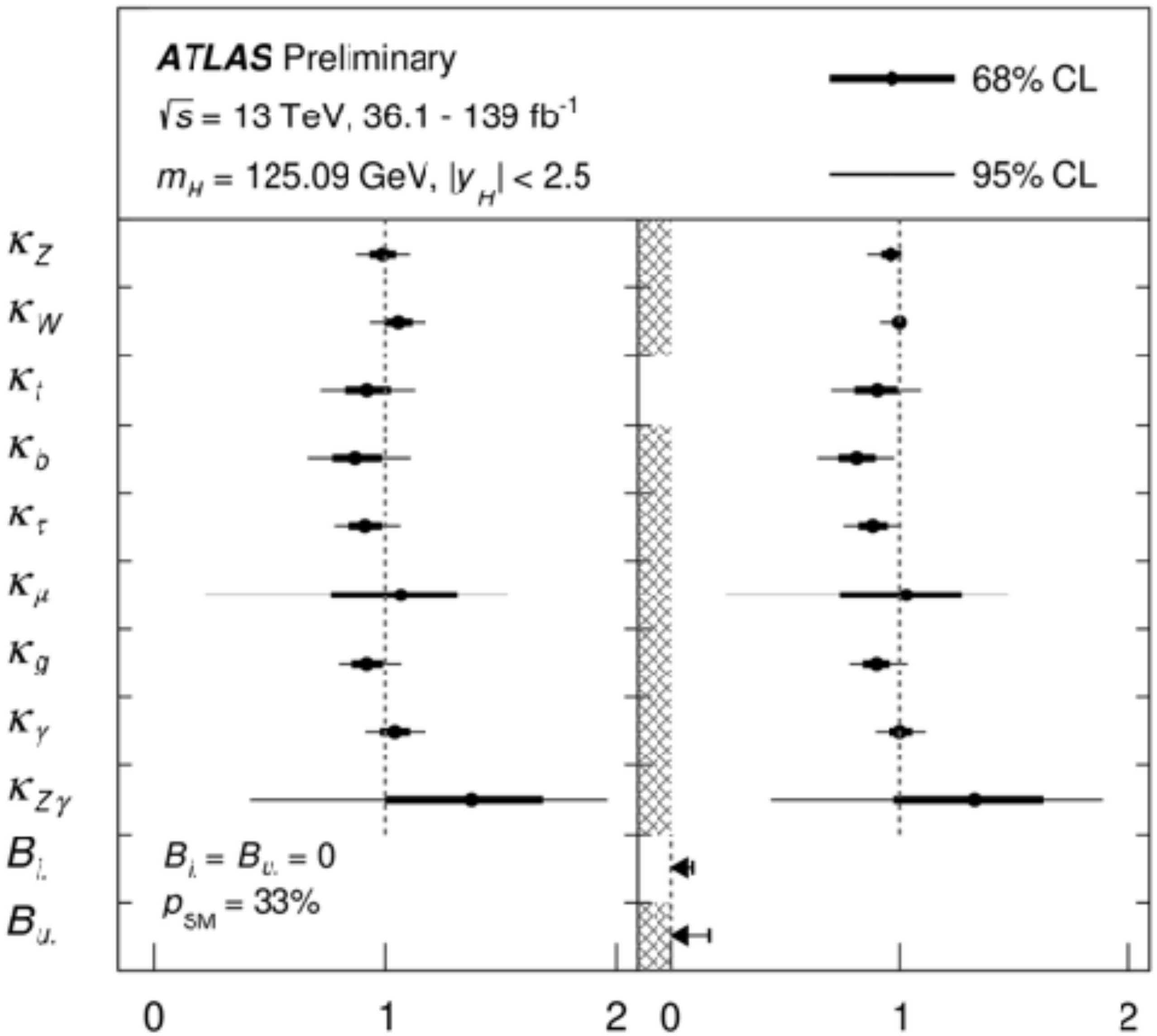
Milestone

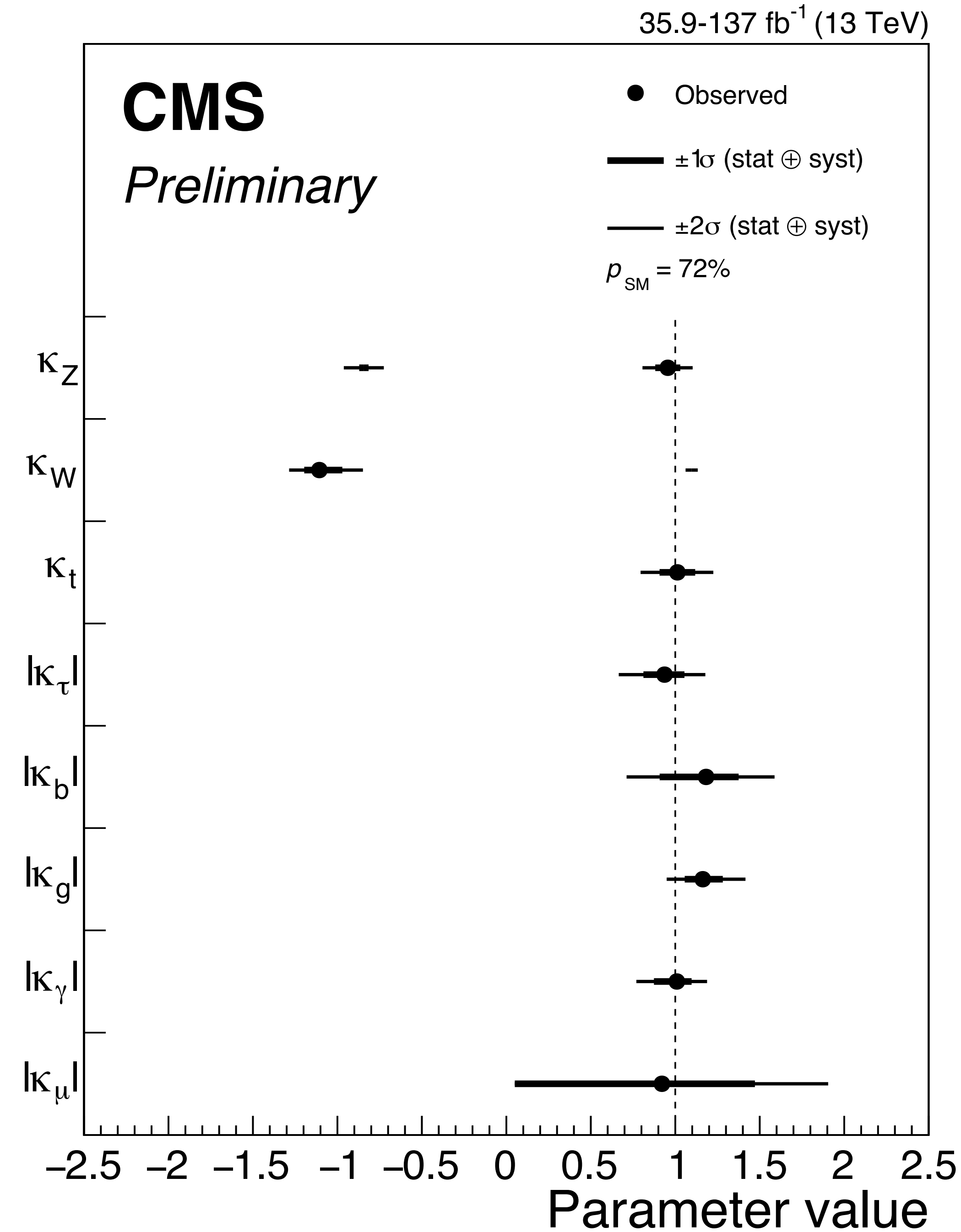




A great leap towards the dynamics of EWSB!

Higgs Coupling Precision





$\mathcal{O}(5\% - 30\%)$ HL-LHC → $\mathcal{O}(2\% - 10\%)$

SM-like!

Behind the SM

- Quantum Mechanics + Lorentz invariance

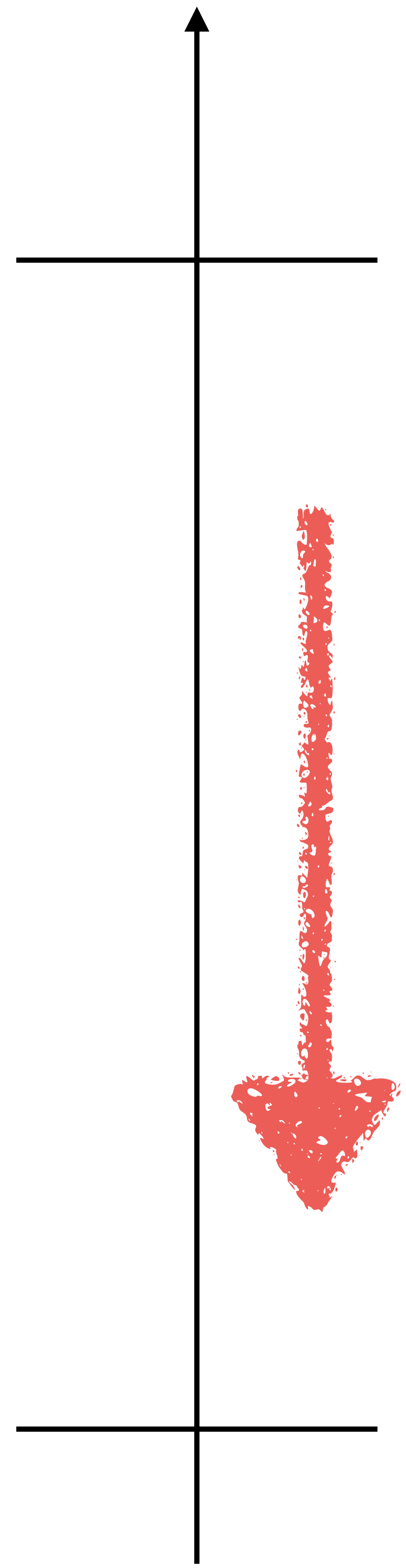
- Gauge invariance

- Renormalizability

Renormalizability as a consequence

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

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



RGE

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

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

Wilson 71'
Wilson and Kogut 74'
Polchinski 83'

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

Physics BSM: Hierarchy problem

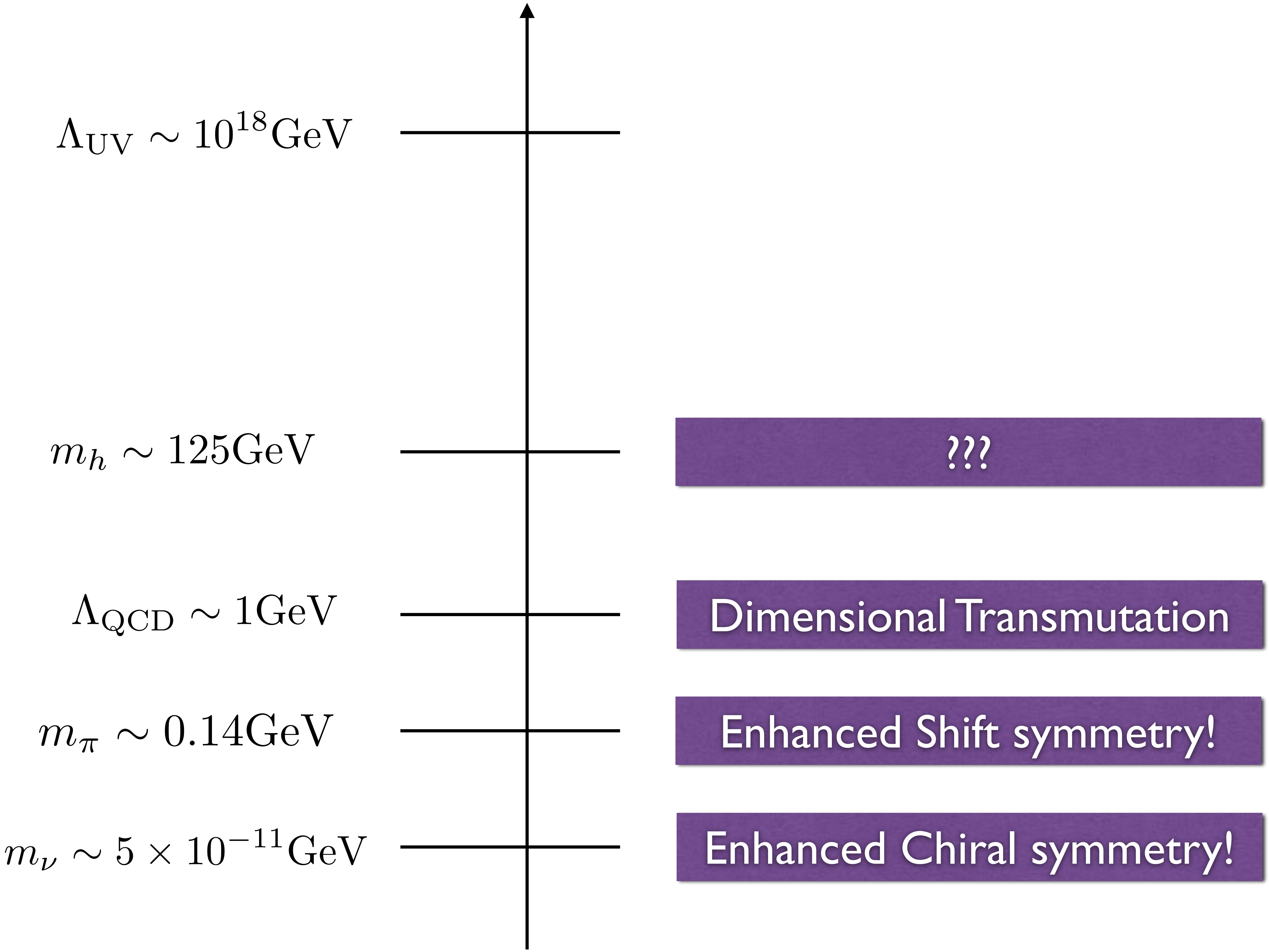
Where is the small electroweak scale coming from?

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

Physics BSM: Empirical Evidence

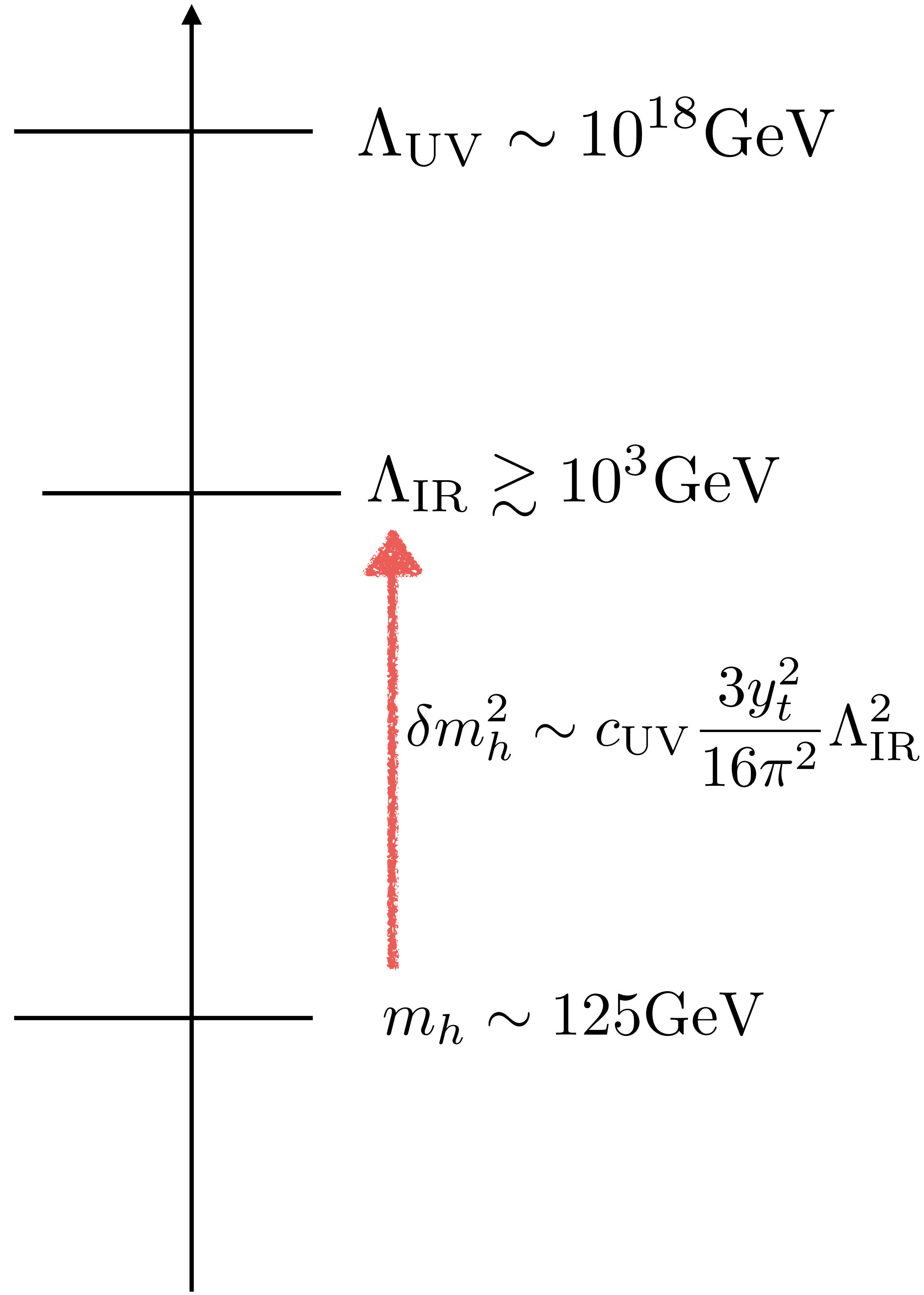
- Baryon Asymmetry
- Dark Matter
- Neutrino Masses
- Flavor Puzzle
- etc.

t' Hooft Naturalness: SM Lesson



Hierarchy problem

Need engineering the UV parameter



Naturalness as Guideline

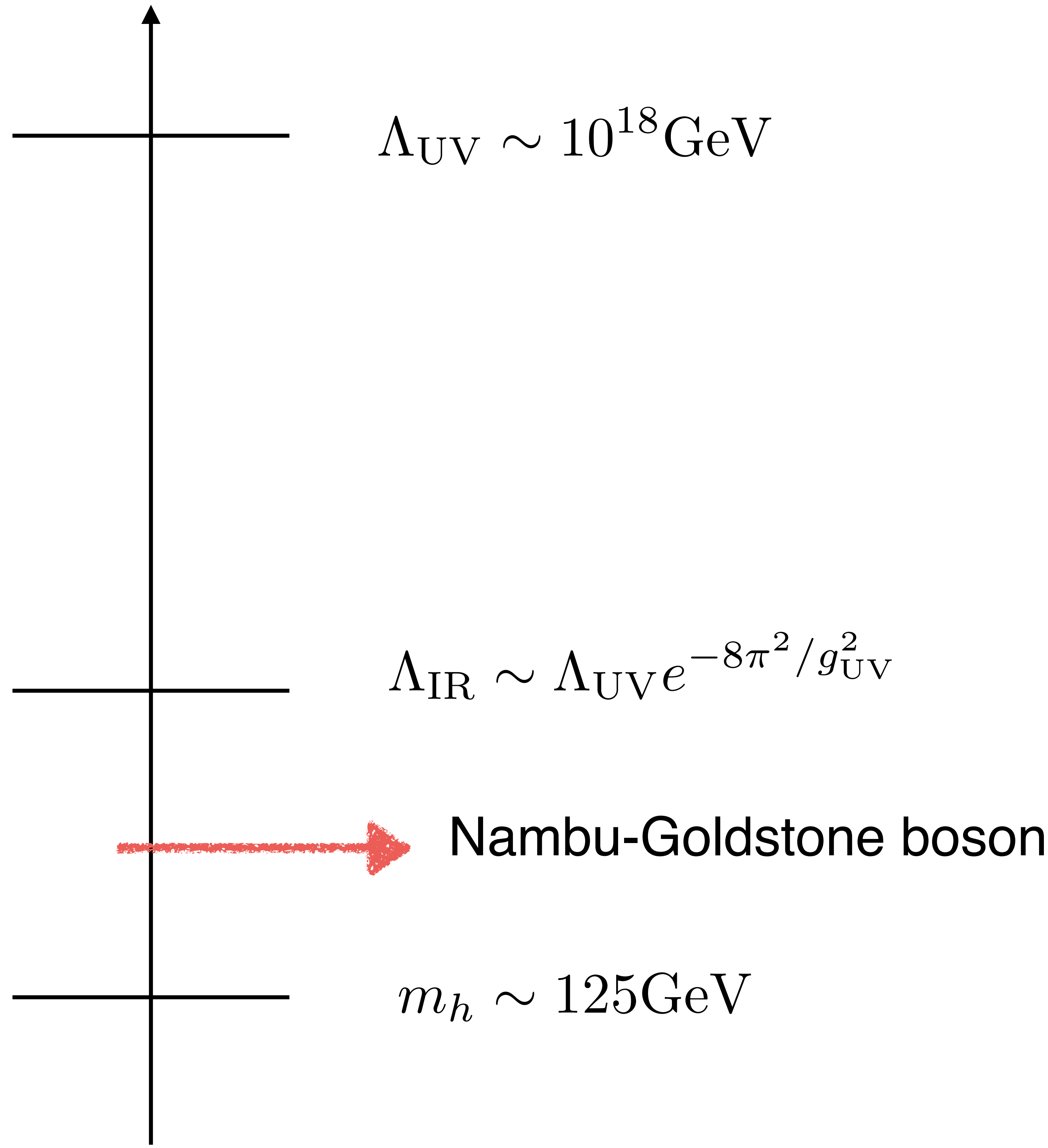
- Compositeness

$$\Lambda_{\mathrm{IR}} \sim \Lambda_{\mathrm{UV}} e^{-8\pi^2/g^2_{\mathrm{UV}}} \Rightarrow \text{Dimensional Transmutation}$$

- Supersymmetry

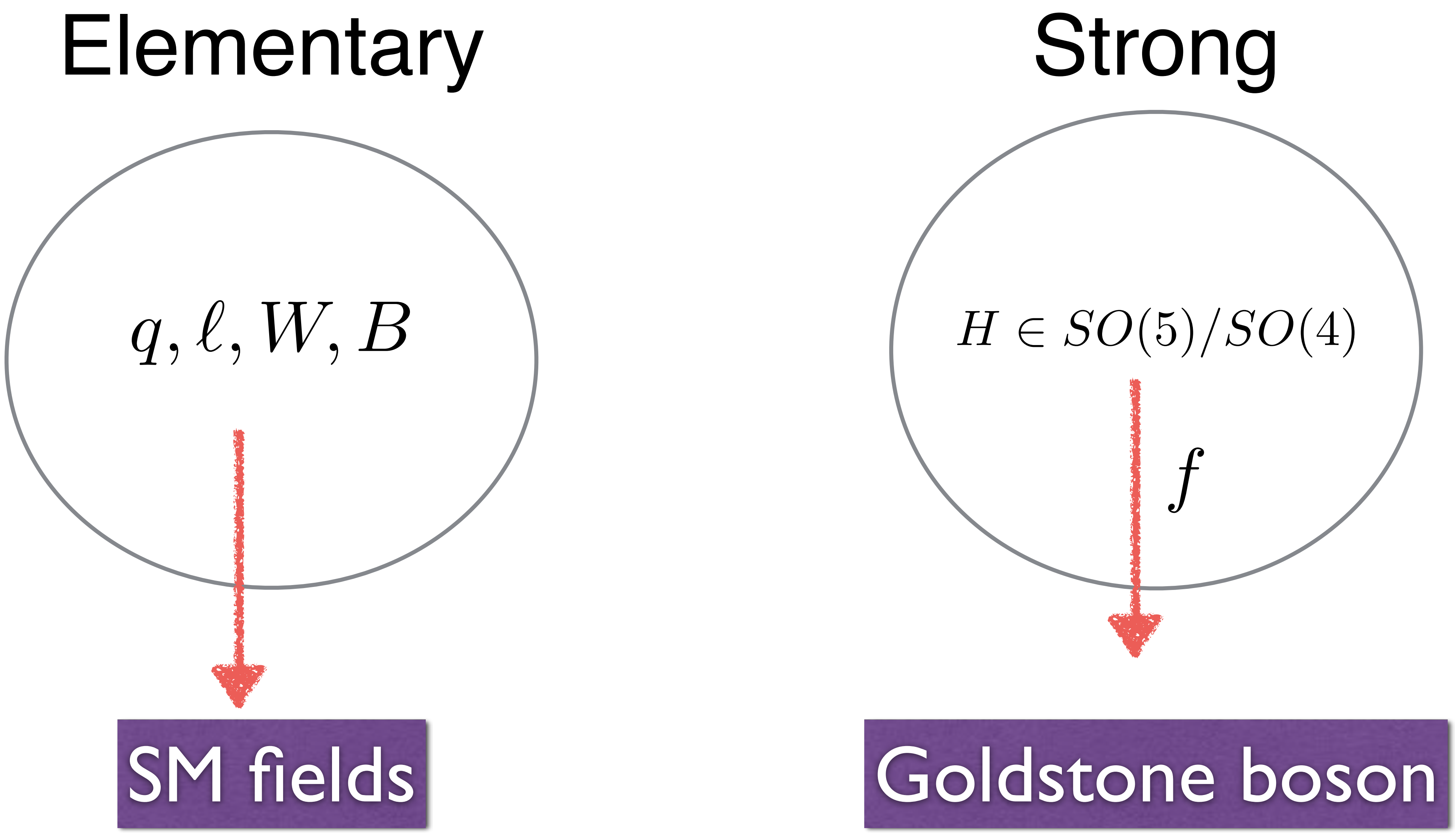
$$Q\,|\phi\rangle = |\psi\rangle \Rightarrow \text{Enhanced chiral symmetry}$$

Compositeness



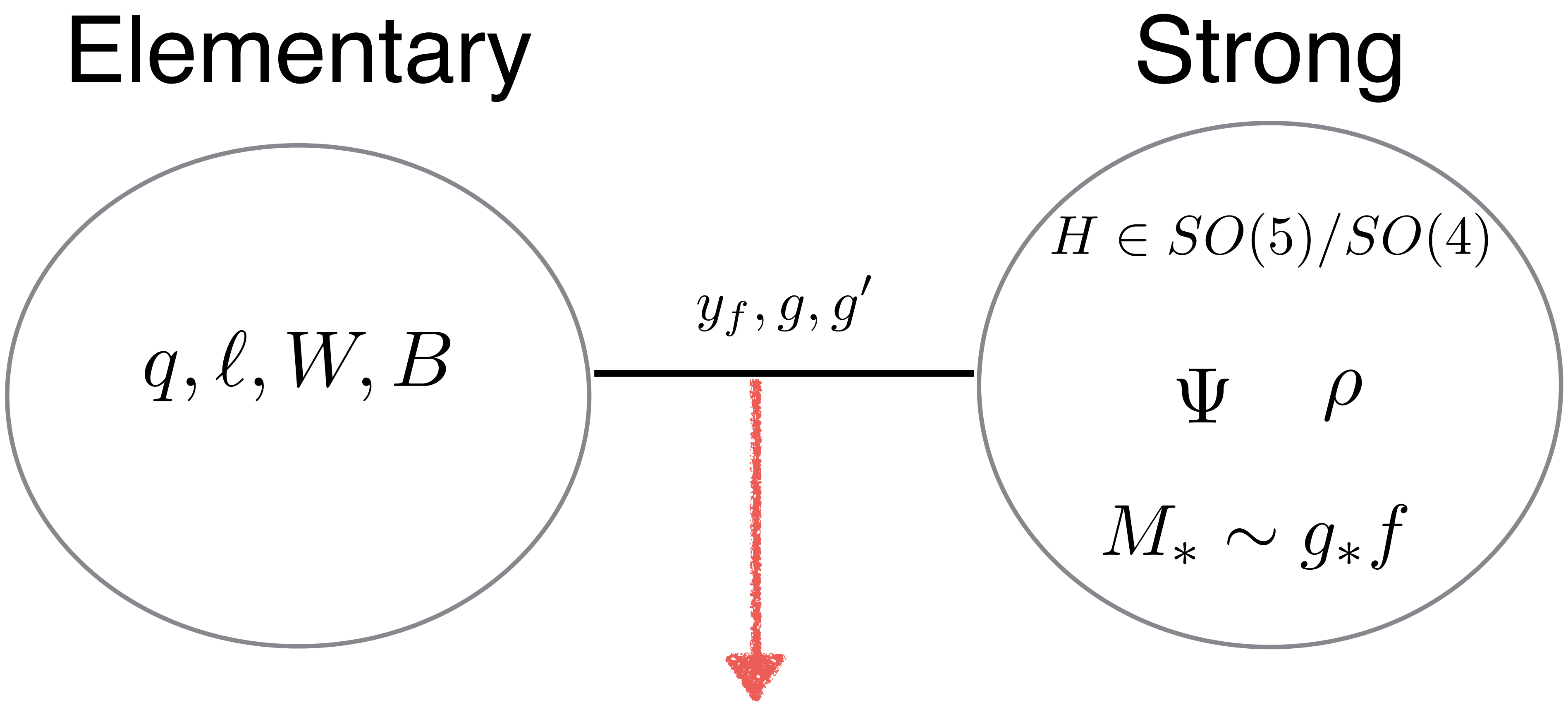
Enhanced shift symmetry!

Composite Higgs models: Assumption I



Kaplan, Georgi & Dimopoulos '83
Contino, Nomura and Pomarol '03
Agashe, Contino and Pomarol '04

Composite Higgs models: Assumption II



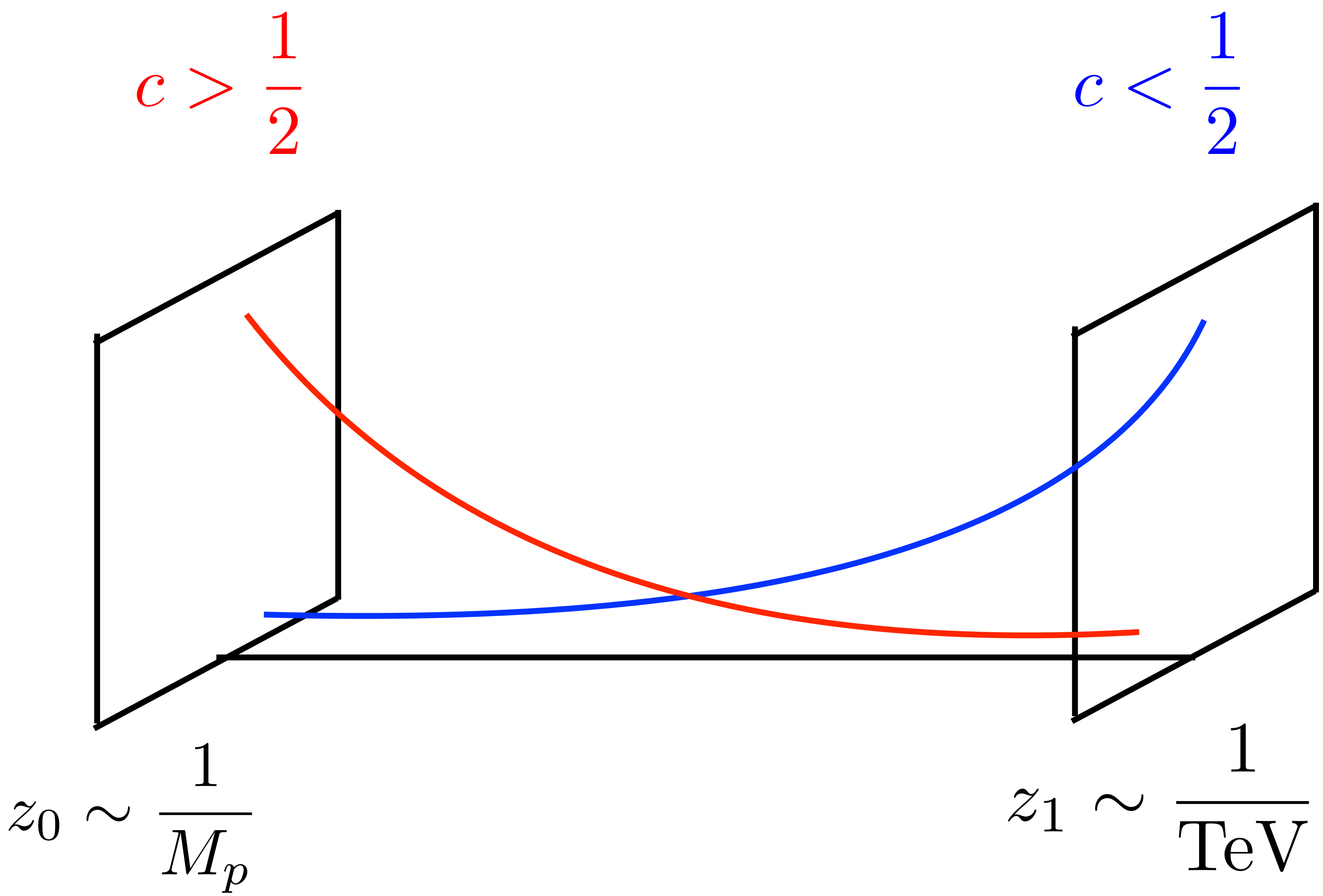
Partial Compositeness

Kaplan, Georgi & Dimopoulos ’83
Contino, Nomura and Pomarol ’03
Agashe, Contino and Pomarol ‘04

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

Measure the fine-tuning

Partial compositeness: AdS



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

Randall and Sundrum 99'
Davoudiasl, Hewett and Rizzo 99'
Pomarol 99'
Grossman and Neubert 99'
Gherghetta and Pomarol 00'

Partial compositeness: CFT

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

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

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

Scale Hierarchy turn to coupling hierarch

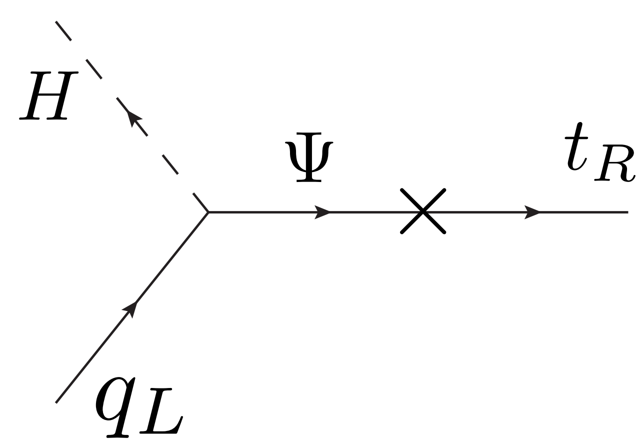
Partial compositeness: top quark mass

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

$$H \in SO(5)/SO(4)$$

$$SU(2)_L \times U(1)_Y \in SO(4)$$

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

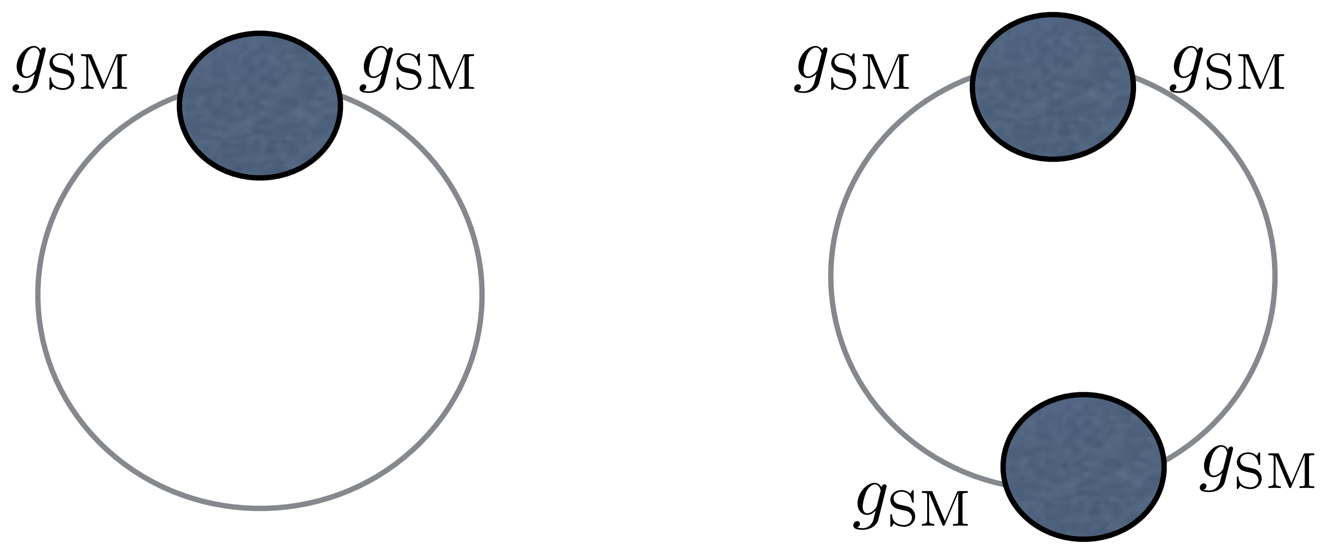


$$\frac{y_L y_R f}{M_\Psi} \bar{q}_L \tilde{H} t_R$$

$$\boxed{y_t \sim \frac{y_L y_R}{g_*}}$$

Light Higgs wants Light top partners

$$V(h) = \frac{N_c m_*^4 y_t^2}{16\pi^2 g_*^2}\left(-a\frac{h^2}{f^2} + \frac{b}{2}\frac{h^4}{f^4} + \frac{c}{3!}\frac{h^6}{f^6}\right)$$



$$v \sim f\sqrt{\frac{a}{b}} \qquad\qquad m_* \sim \frac{450\mathrm{GeV}}{\sqrt{a}}$$

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

Measure the fine-tuning

O. Matsedonskyi, G. Panico & A. Wulzer '12
D. Marzocca, M. Serone & J. Shu '12; A. Pomarol & F. Riva '12

Any questions?

Various Colliders

P5

Energy		Luminosity
	SppC/FCC-hh	20 - 30 ab^{-1}
pCM 10 TeV		
	Muon Collider	$10\,\mathrm{ab}^{-1}$
14 TeV	HL - LHC	3 ab^{-1}
3 TeV	CLIC	5 ab^{-1}
1.96 TeV	Tevatron	10 fb^{-1}
240, 250 GeV	CEPC/FCC-ee/ILC	20/5/2 ab^{-1}
130 - 209 GeV	LEP II	0.75 fb^{-1}
$m_Z \sim$ 91 GeV	LEP I/SLC	0.2 fb^{-1}
⋮	⋮	

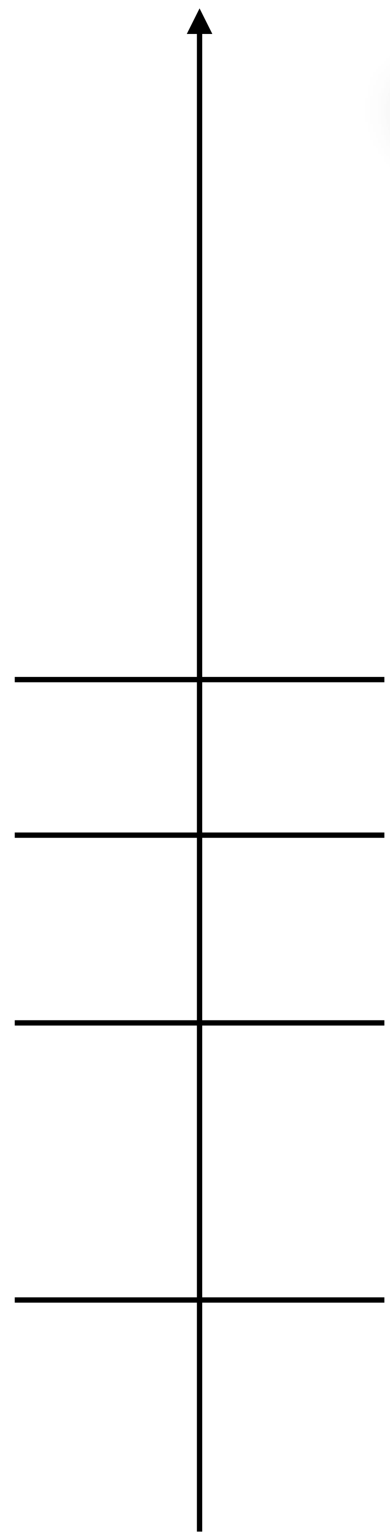
$$\frac{\alpha^2}{\mathrm{TeV}^2} \sim \mathcal{O}(10)\mathrm{fb}$$

Direct Resonance Searches at the LHC

Direct Resonance searches

$$\rho_L = (3,1)$$

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



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

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

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

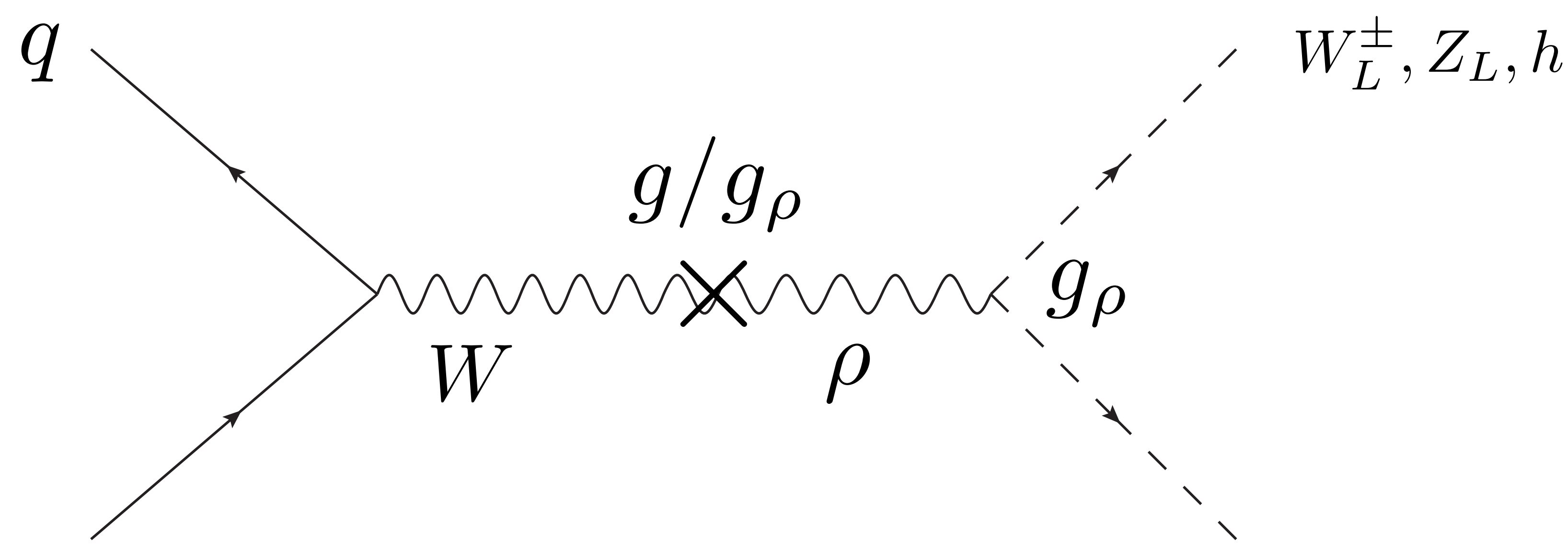
$$H \in SO(5)/SO(4)$$

R. Contino, D. Marzocca, D. Pappadopulo & R. Rattazzi '11

D. Pappadopulo, A. Thamm, R. Torre & A. Wulzer '14

A.D. Simone, O. Matsedonskyi, R.Rattazzi & A.Wulzer'12

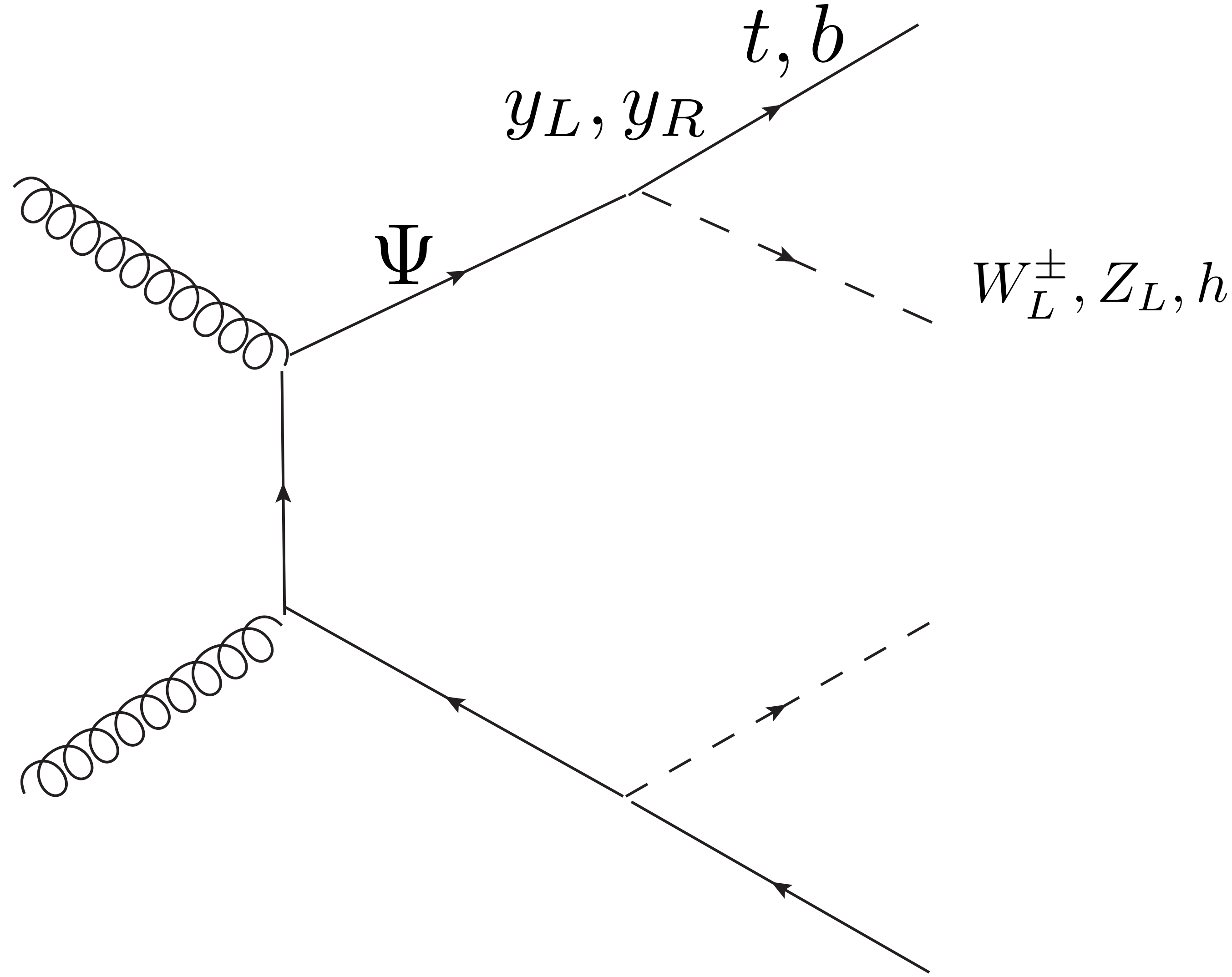
Direct searches: Spin-1



Dibosons provide the smoking gun!

D. Pappadopulo, A. Thamm, R. Torre and A. Wulzer 14’

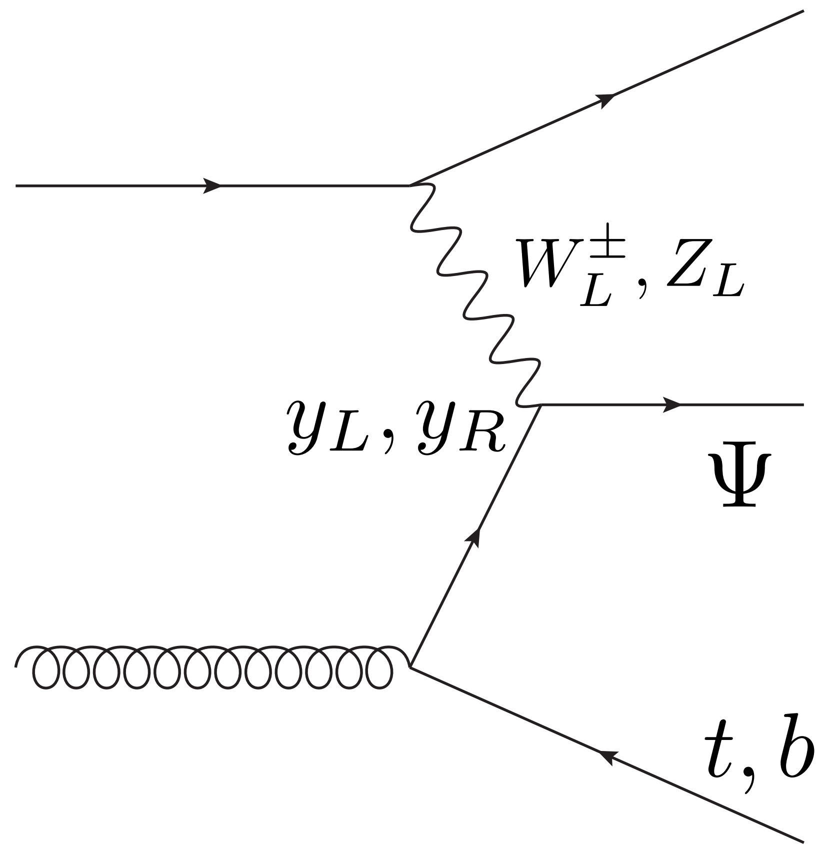
Direct searches: spin-1/2



Top partners

$\Psi \equiv X_{5/3}, T, B$

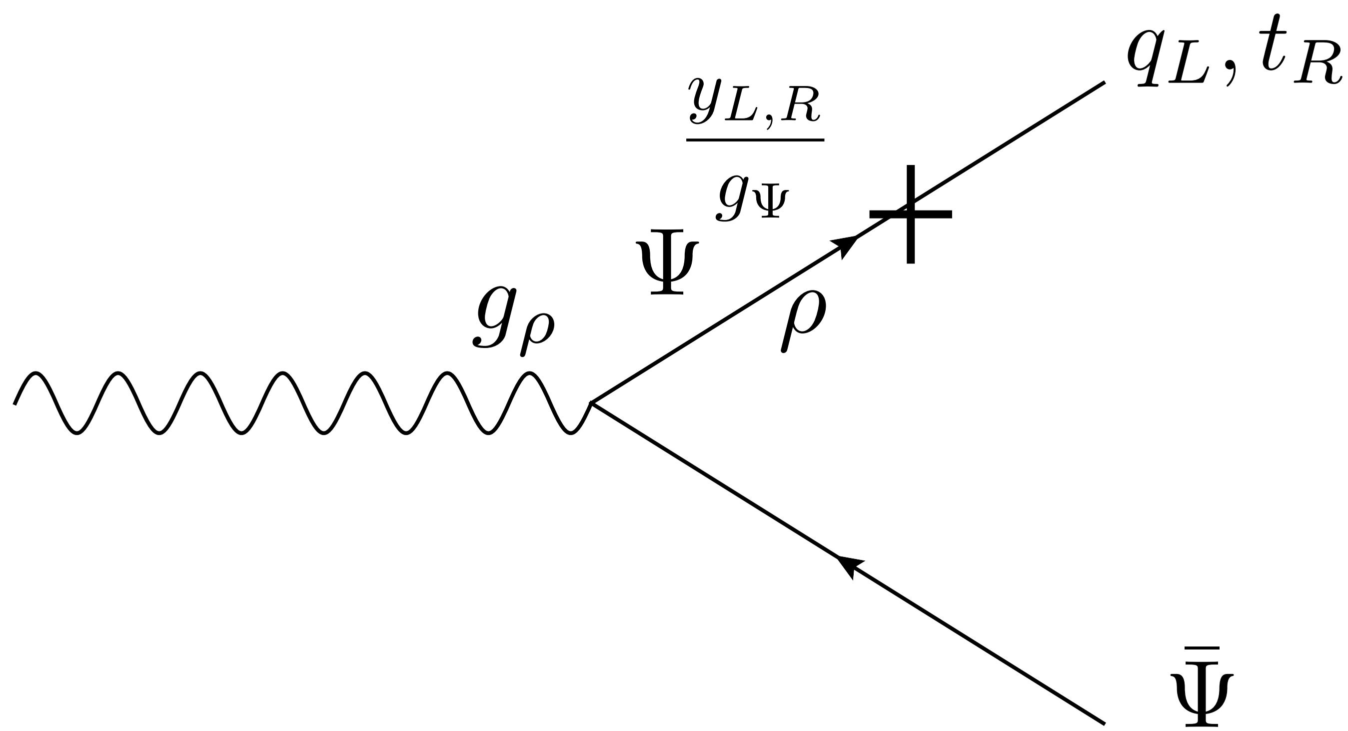
Direct searches: Single production



Lower mass threshold!

A.D. Simone, O. Matsedonskyi, R.Rattazzi & A.Wulzer'12

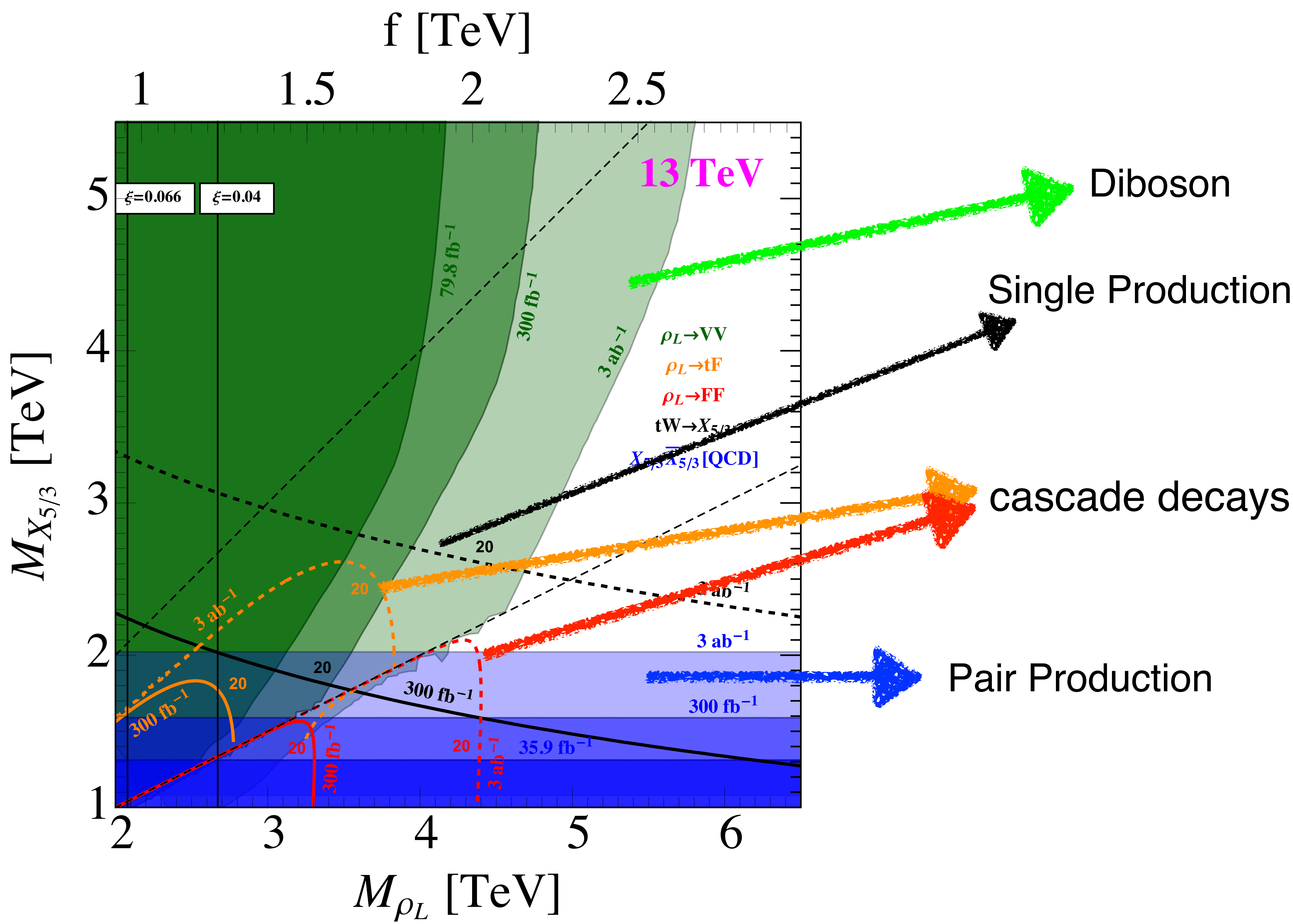
Cascade decays



Have kinematical advantage!

D. Greco and D. L.'14

Bounds and Projections



D. L., L.T. Wang and K. P. Xie '18

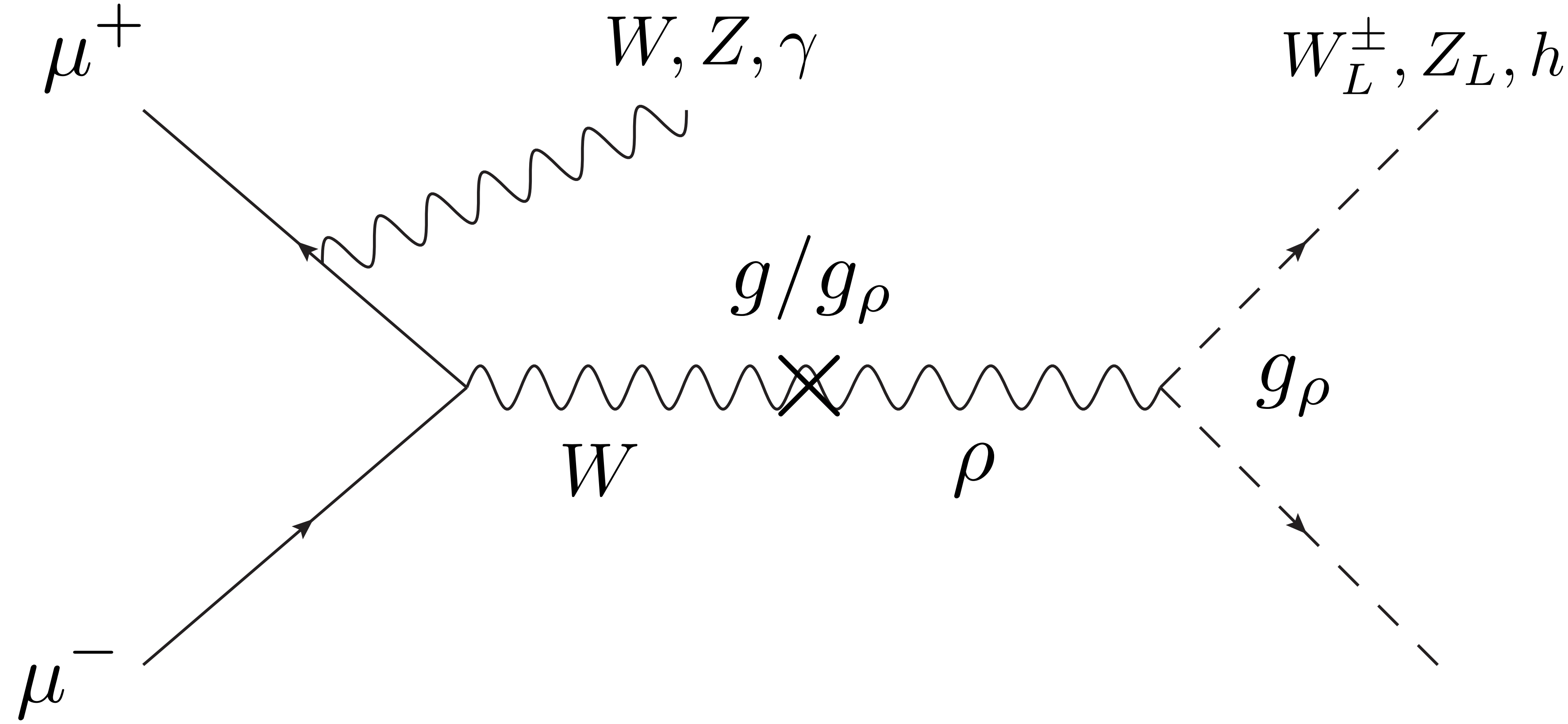
Direct Resonance Searches at Muon Collider

Targets at the Muon Collider

- Probe the on-shell resonances up to kinematical limits

- Measure the couplings as precise as possible

Spin-1 resonances: radiative return

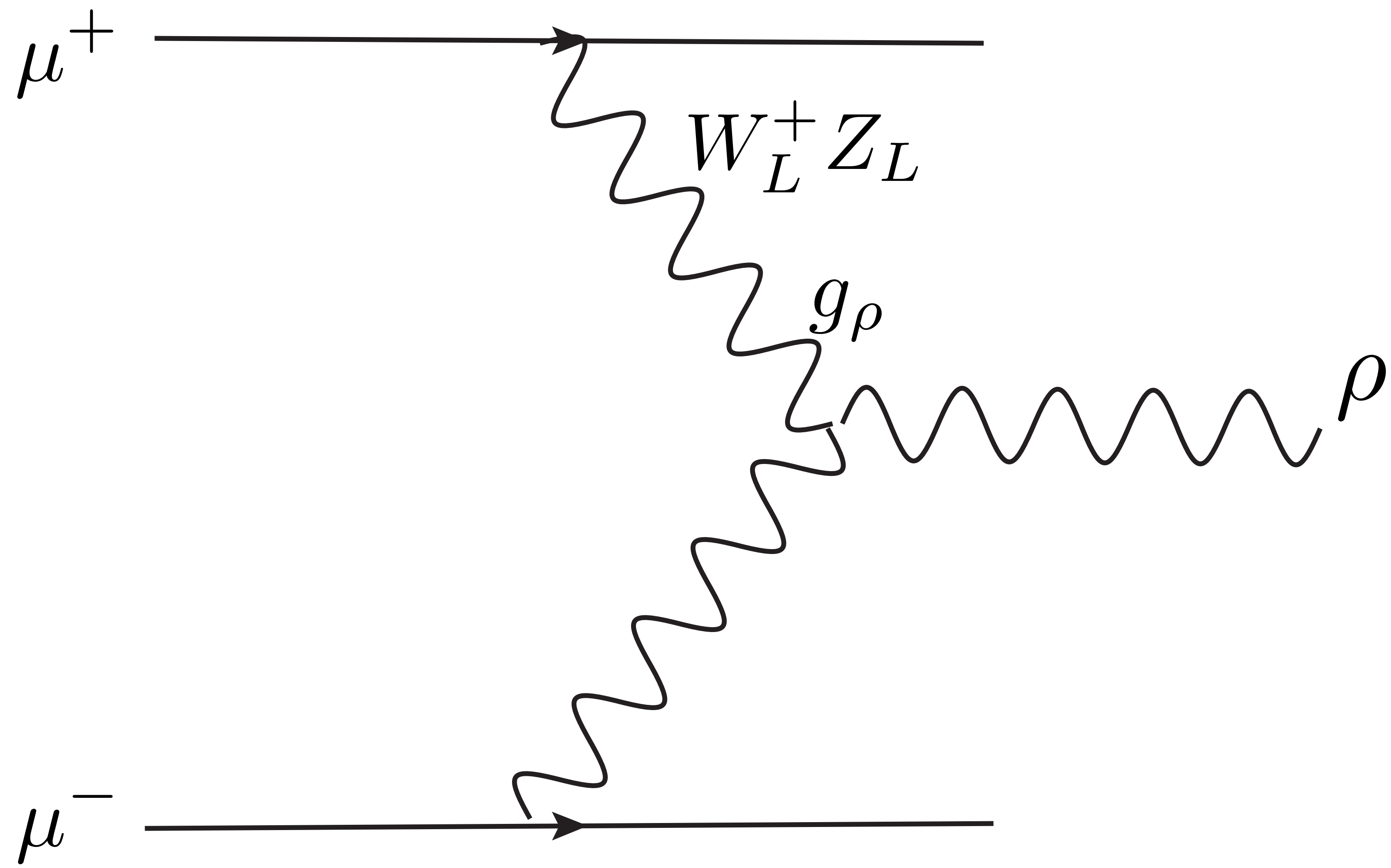


$$\sigma \sim \frac{1}{E_\gamma} \sim \frac{1}{s - M_\rho^2}$$

$$\mathrm{BR}_{VV+Vh} \gtrsim 80\%, \quad \text{for} \quad g_\rho > 3$$

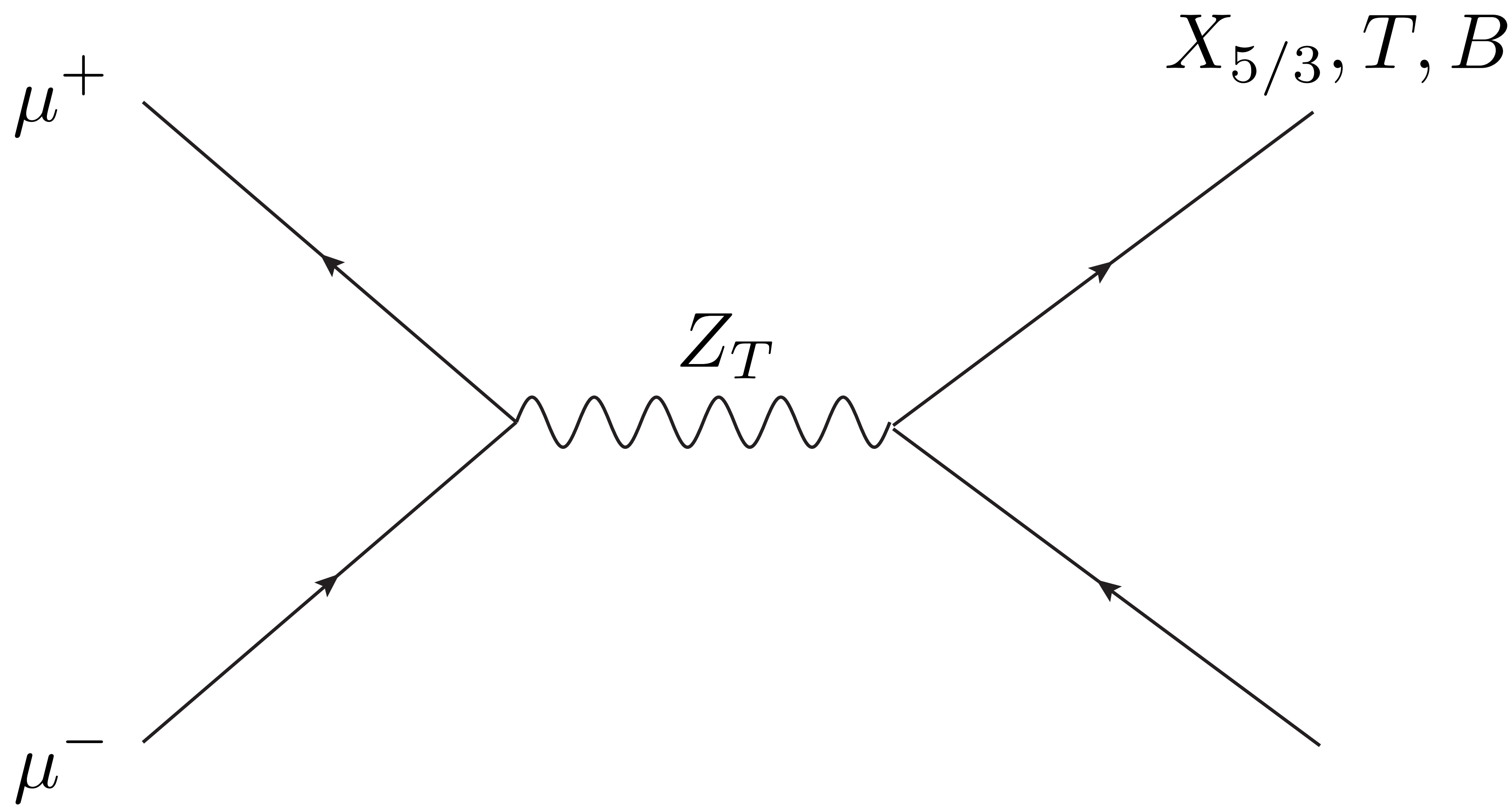
D. L., L.T. Wang and K. P. Xie, '23

Spin-1 resonances: VBF



D. L., L.T. Wang and K. P. Xie, '23

Top partners: DY-like pair



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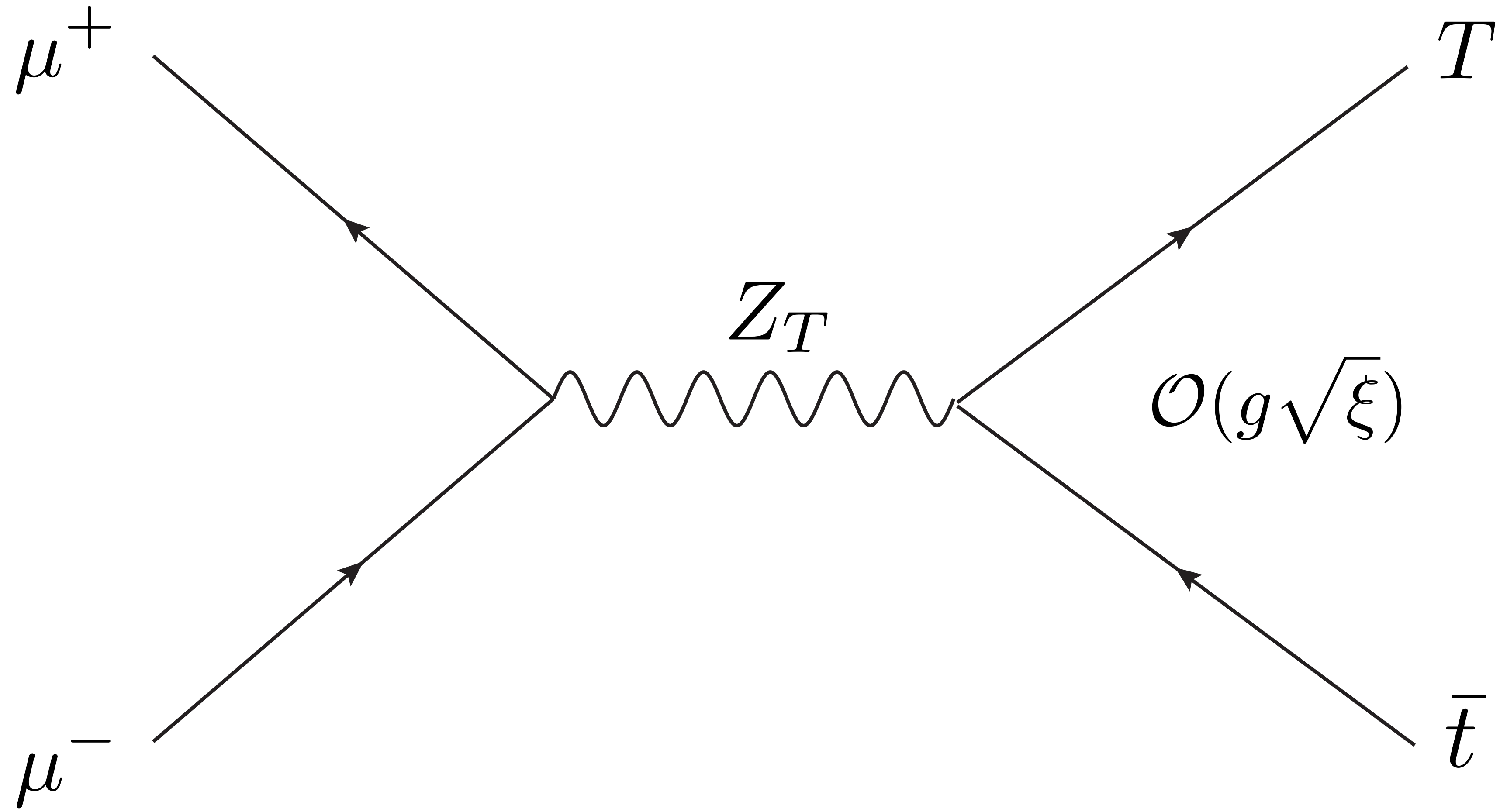
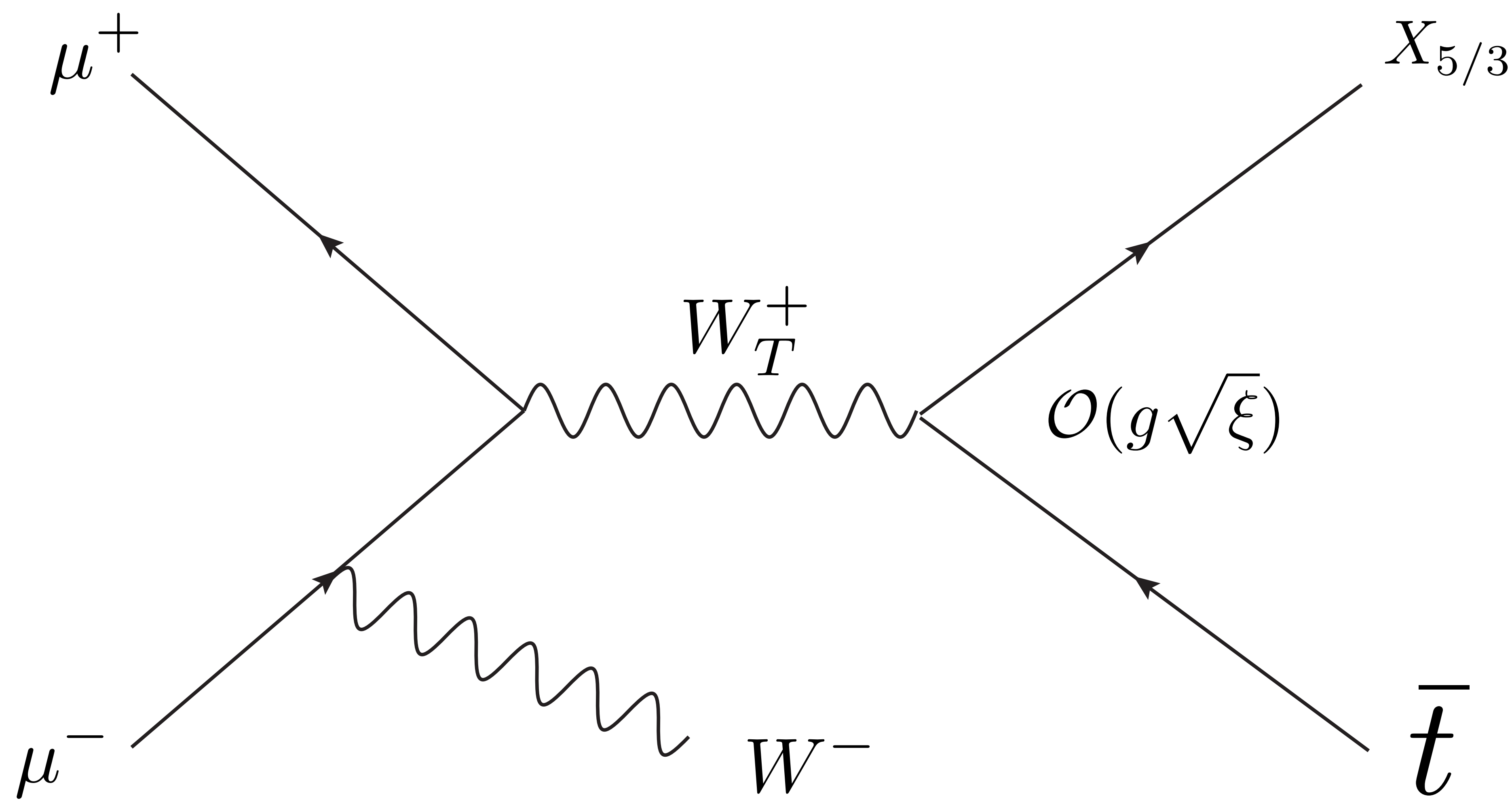
Top partners: DY Single



Top partners: DY-like Single



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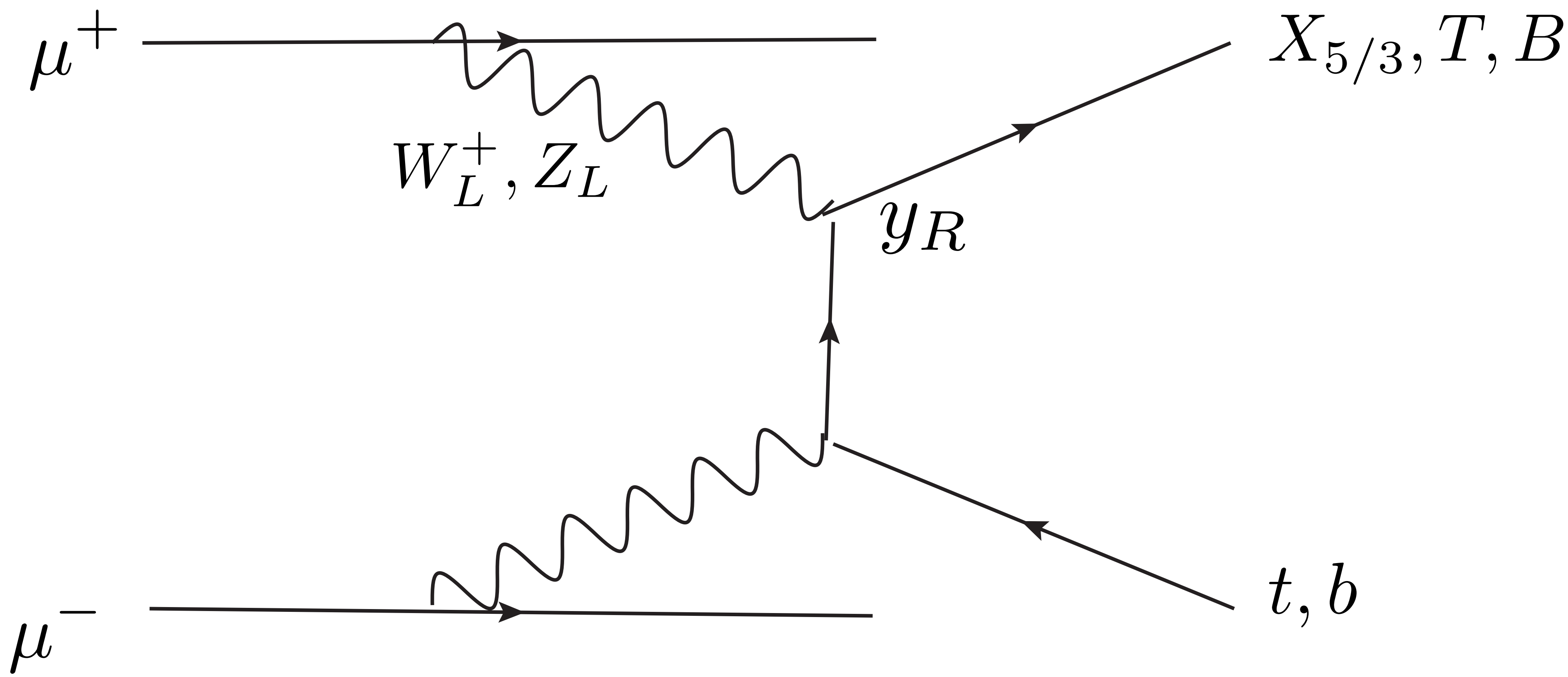
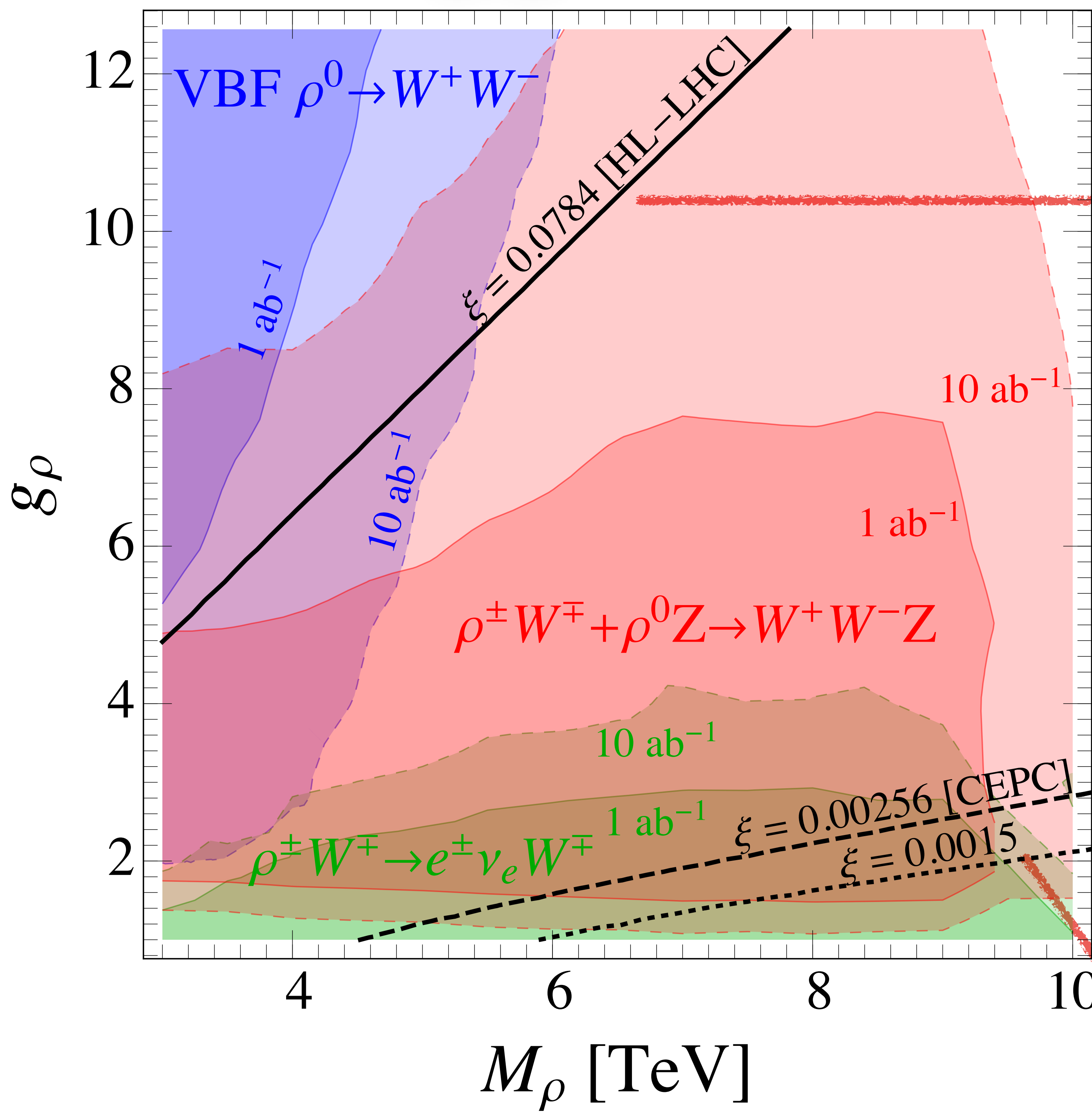
Top partners: VBF



Relevant for large yR

Projection: Spin-1

$$\sqrt{s}_{\mu^+\mu^-} = 10\text{TeV}$$



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

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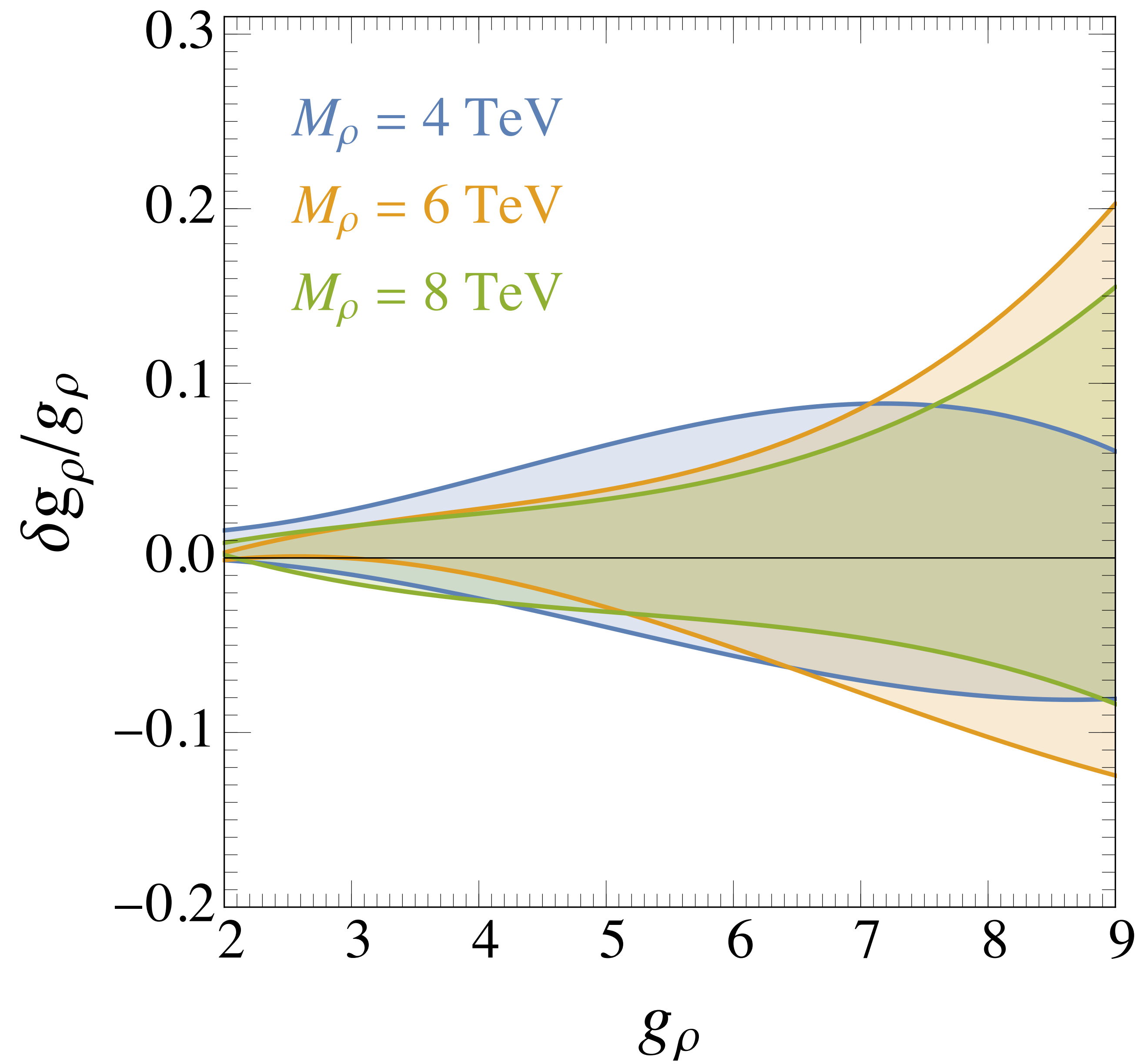
10 TeV Muon Collider

T. Han, D. L., I. Low and X. Wang '20

Coupling Measurement

$$\sqrt{s}_{\mu^+\mu^-} = 10\text{TeV}$$



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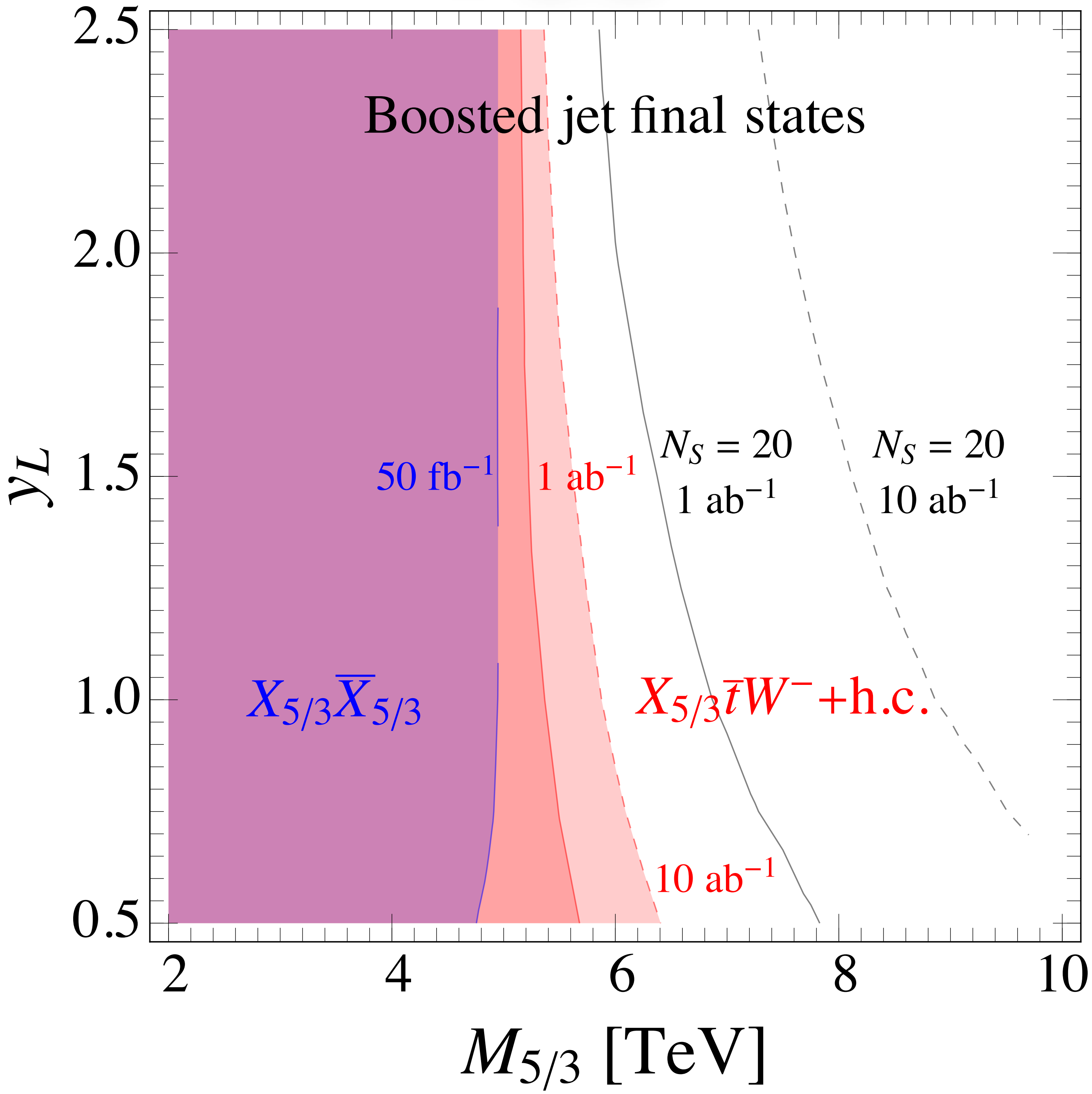
Projection: top partner

$$\sqrt{s}_{\mu^+\mu^-} = 10\text{TeV}$$



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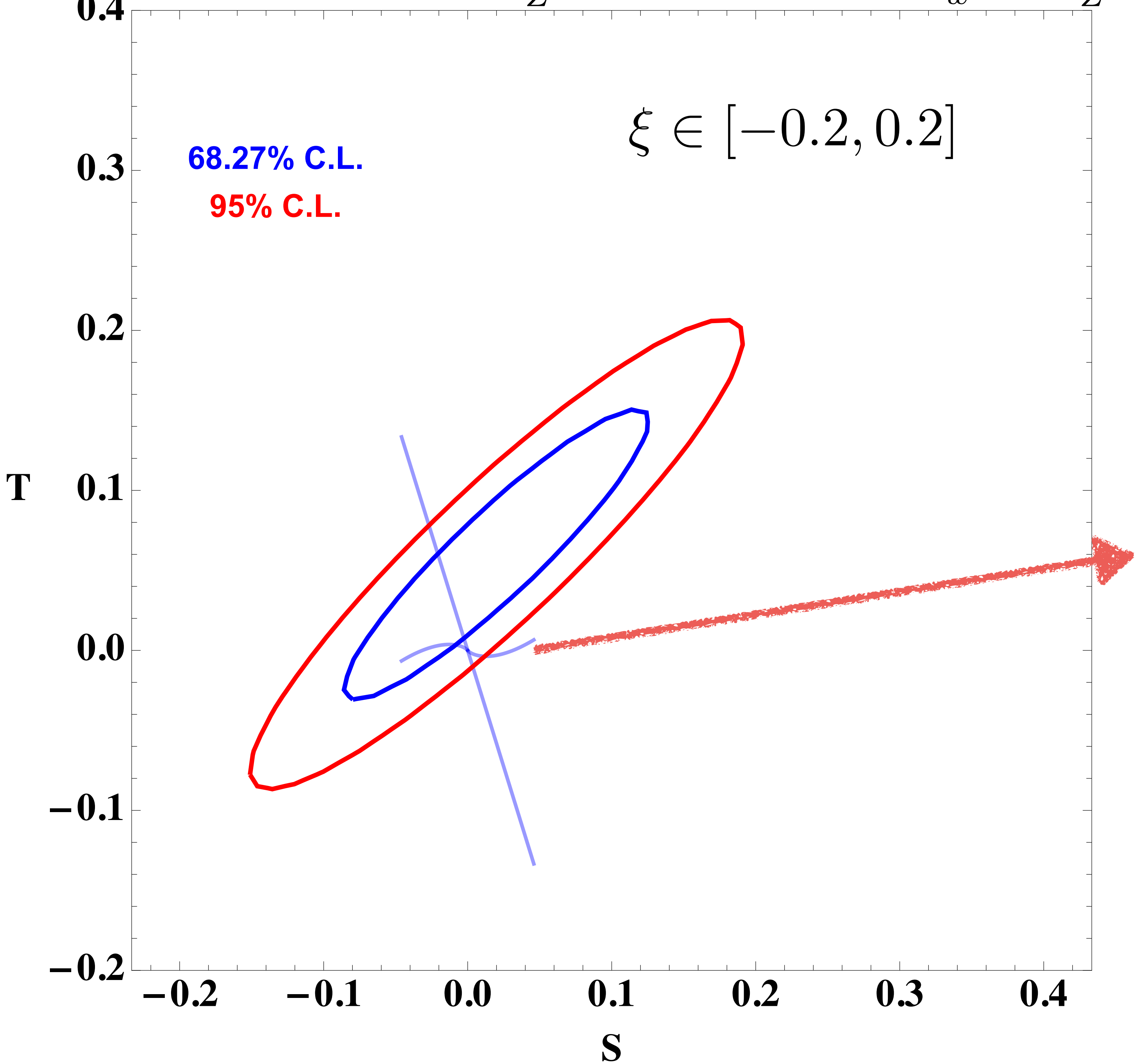
$$\xi = 0.015, f = 2\ \text{TeV}$$

Indirect Signatures

Lesson from Electroweak Precision Test

$$S_H = \frac{\xi}{12\pi} \ln \frac{\Lambda^2}{m_Z^2}, \qquad T_H = -\frac{3}{16\pi} \frac{\xi}{c_w^2} \ln \frac{\Lambda^2}{m_Z^2}$$

$\xi < 5\%$



$$\Delta T_f \sim \frac{3y_L^4}{64\pi^2 g_\Psi^2 \alpha_e}\xi$$

Indirect Signature

- One coupling - one scale

$$m_* \sim g_* f$$

- A set of selection rules

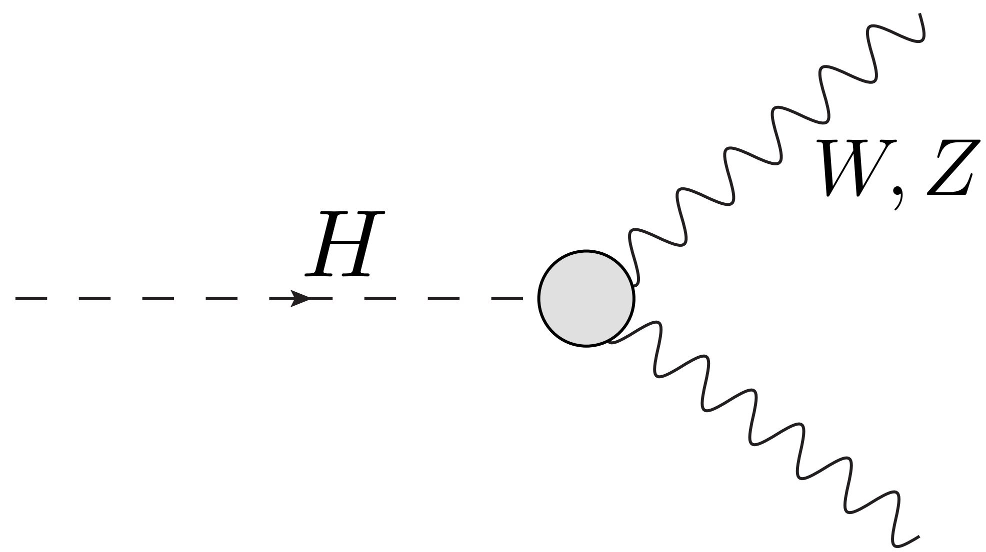
  - Preserve the non-linearity: g_*

  - Explicit breaking

$$y_f, g, g'$$

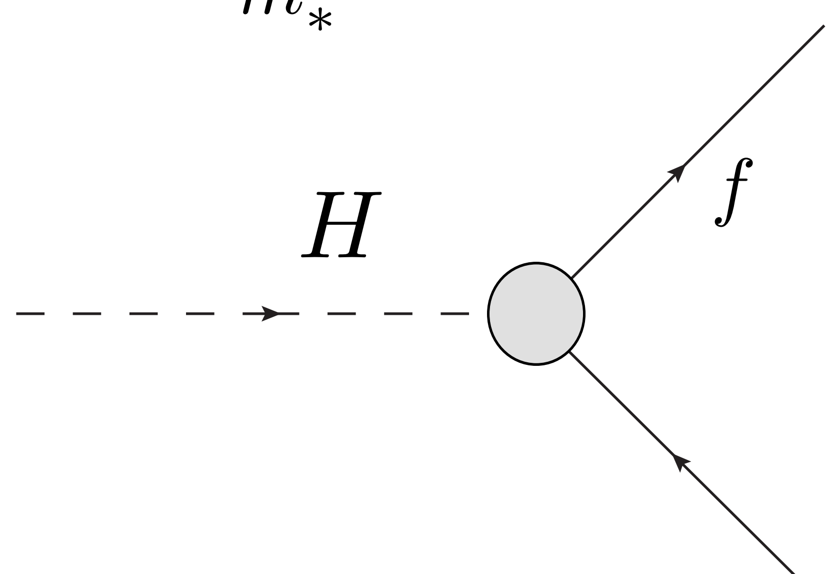
Indirect Signature

$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2m_*^2} \Rightarrow c_H \sim g_*^2$$



$$\sim -g_*^2 \, \frac{v^2}{2m_*^2}$$

$$\mathcal{O}_y = y_f \frac{H^\dagger H}{m_*^2} \bar{f}_L H f_R \Rightarrow c_y \sim g_*^2$$

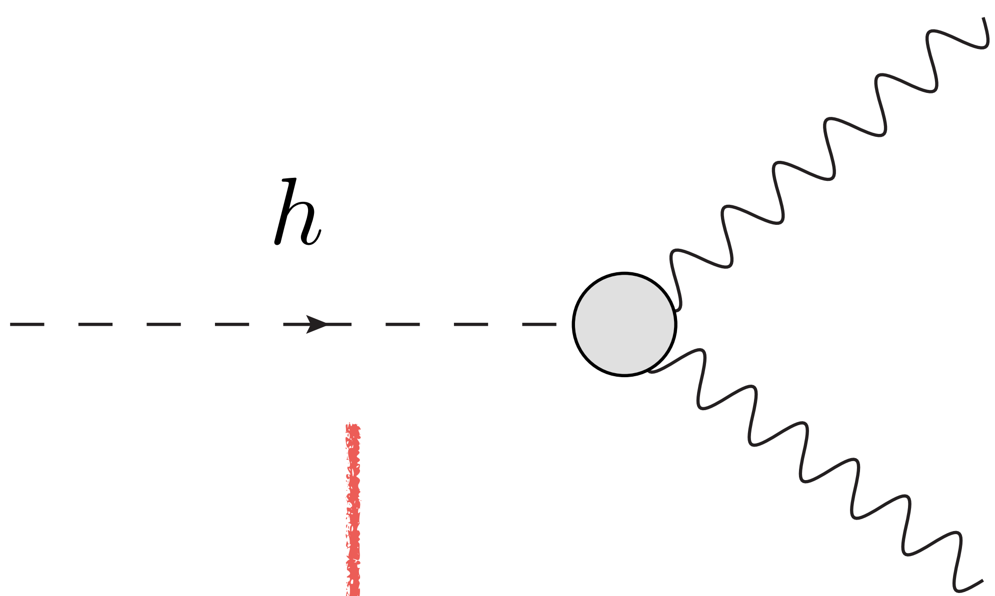


$$\sim -g_*^2 \, \frac{v^2}{2m_*^2}$$

SILH: G.F. Giudice, C. Grojean, A.Pomarol & R.Rattazzi ‘07

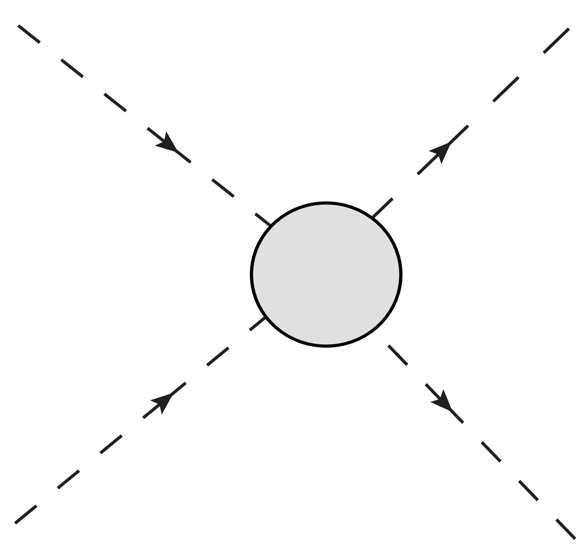
Higgs-Gauge Boson couplings

$$V = W^{\pm}, Z$$



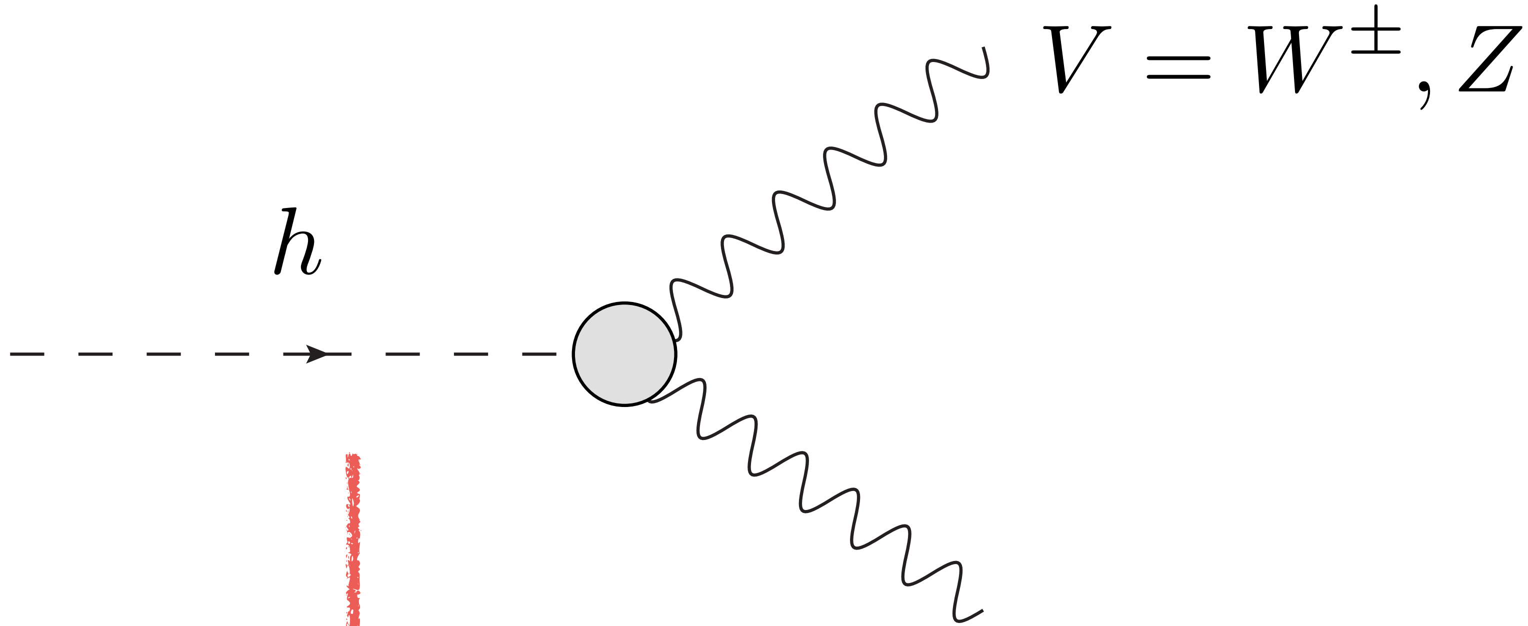
$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2\Lambda^2}$$

V_L, h

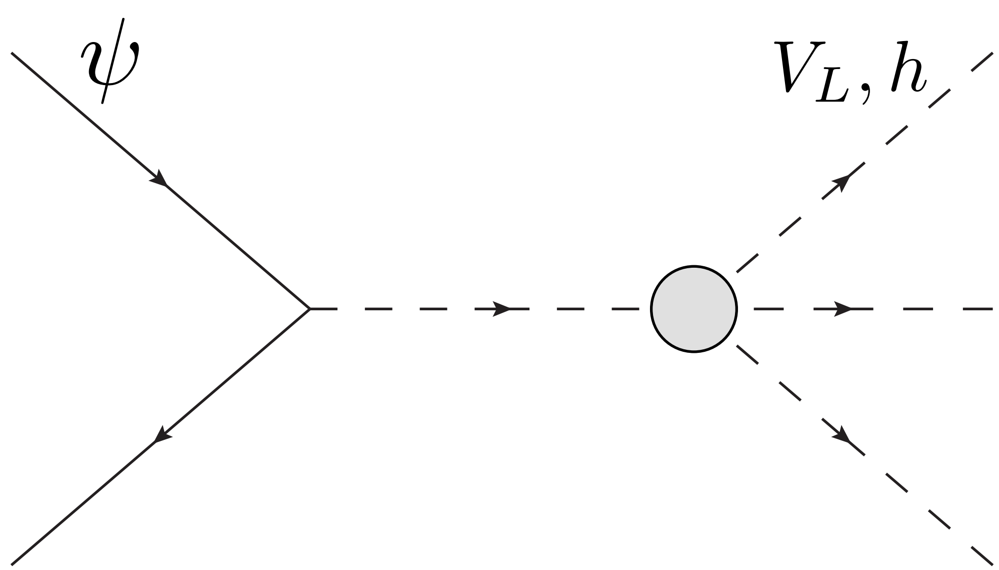


$$\sim c_H \frac{E^2}{\Lambda^2}$$

Higgs-Gauge Boson couplings

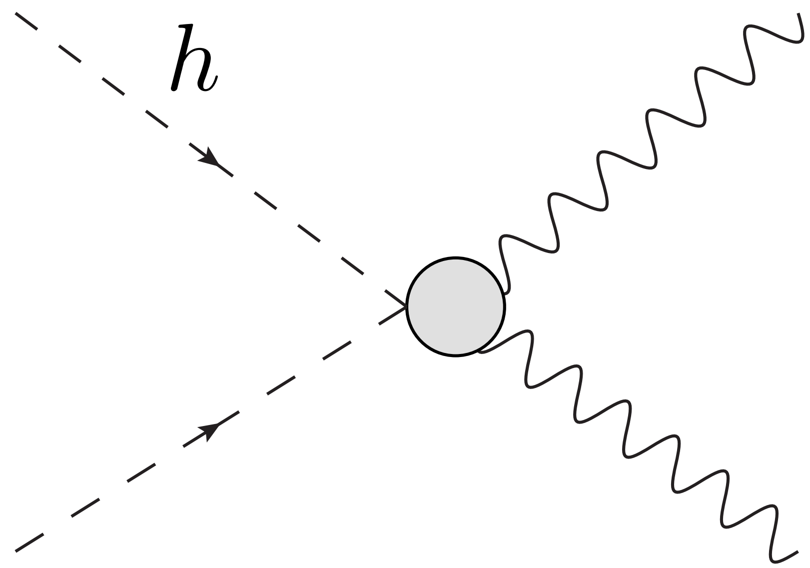


$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2\Lambda^2}$$



$$\sim c_H \frac{E^2}{\Lambda^2}$$

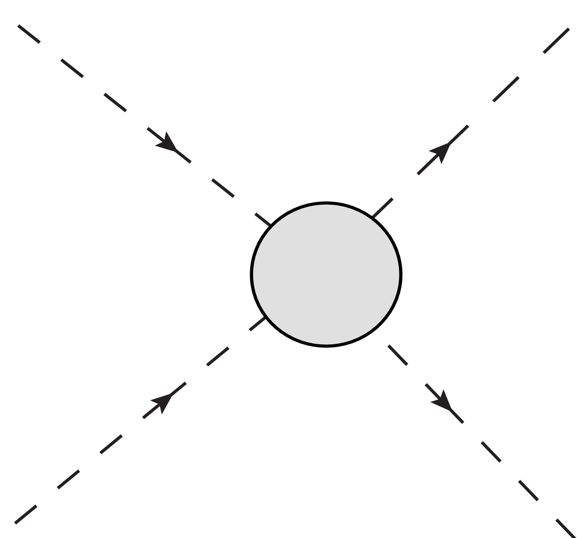
Higgs-Higgs-Gauge Boson couplings



$V = W^{\pm}, Z$

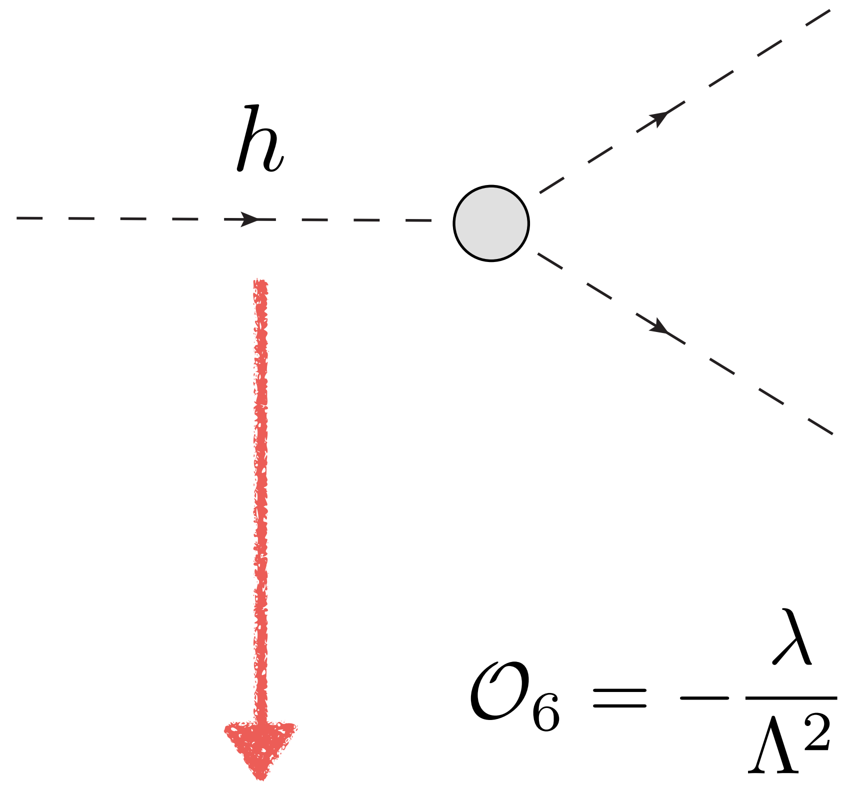
$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2\Lambda^2}$$

V_L, h

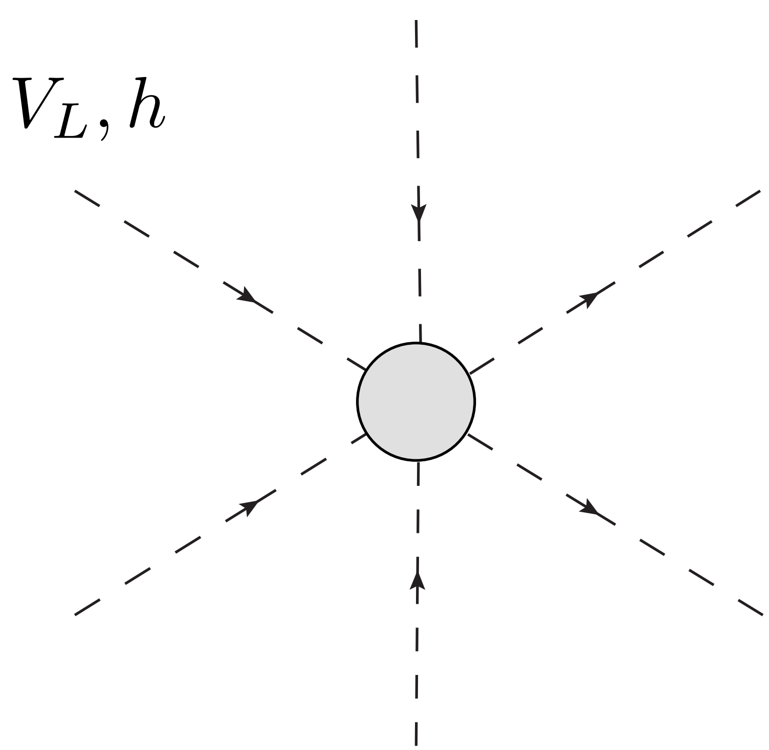


$$\sim c_H \frac{E^2}{\Lambda^2}$$

Higgs self couplings



$$\mathcal{O}_6 = -\frac{\lambda}{\Lambda^2}(H^\dagger H)^3$$

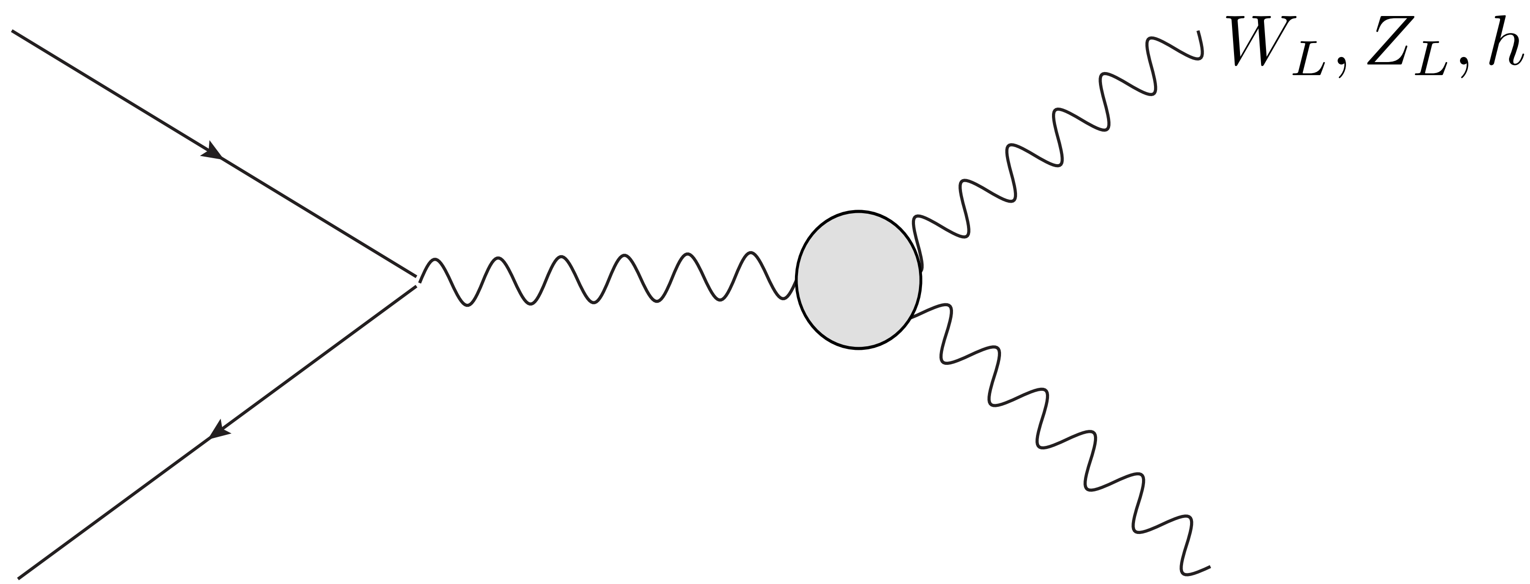


$$\sim c_6 \frac{E^2}{\Lambda^2}$$

S. Chang, M. Luty 19'
A. Falkowski, R. Rattazzi 19'

Indirect Signature

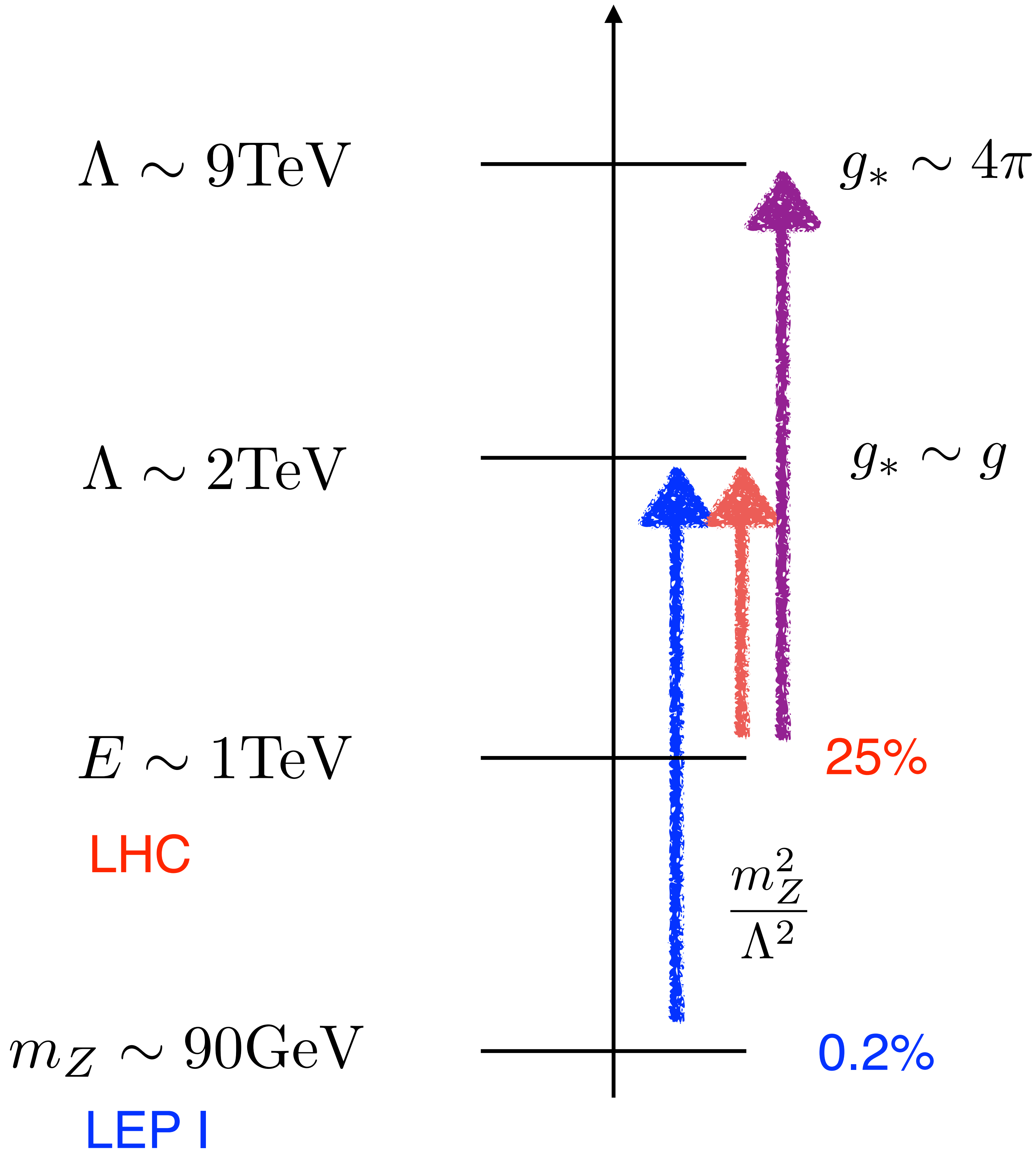
$$\mathcal{O}_W = \frac{ig}{2m_*^2}(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H) D^\nu W^a_{\mu\nu} \Rightarrow c_W \sim 1$$



$$\sim \frac{E^2}{m_*^2}$$

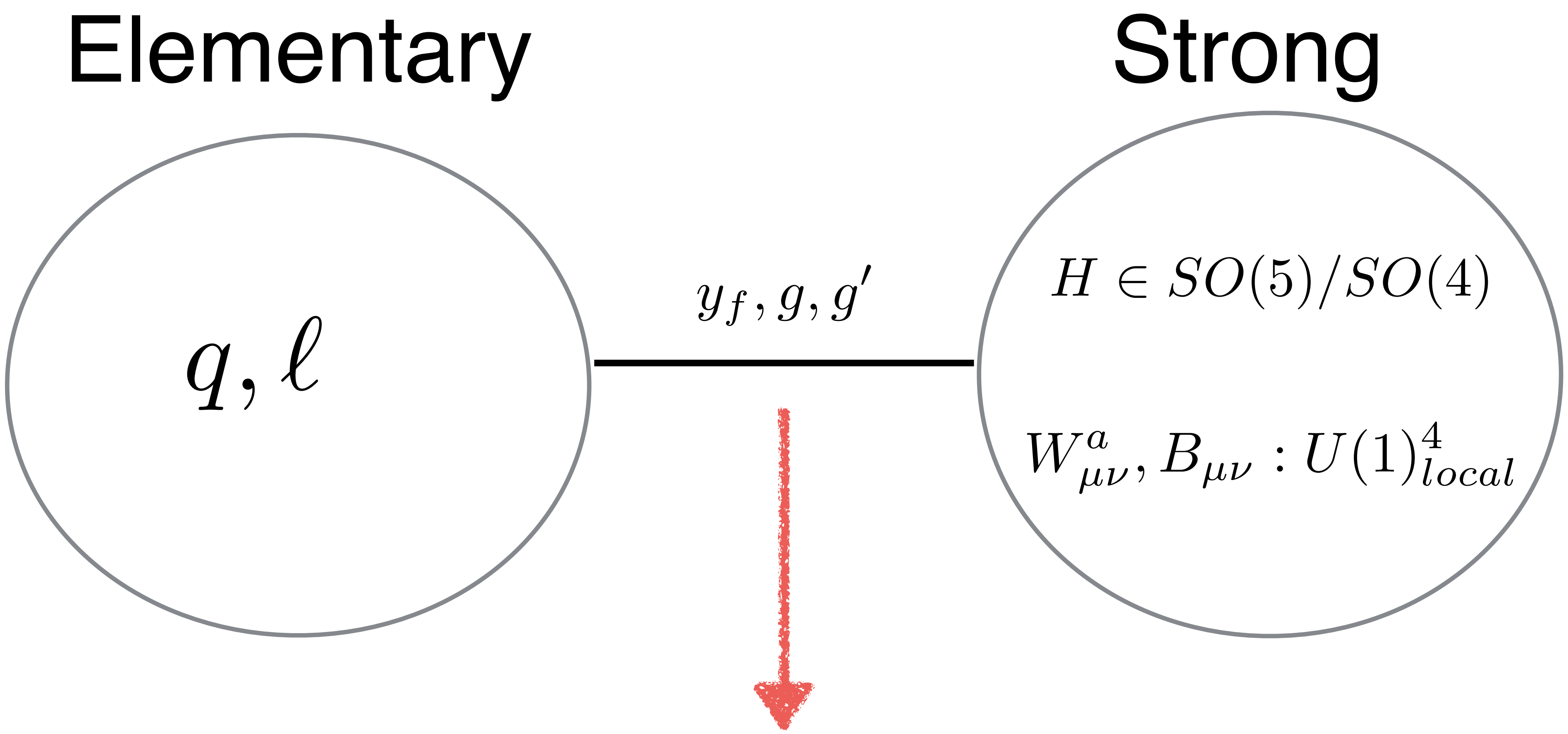
HL-LHC can play a role!

Precision to scale



$$\boxed{\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{g_*}{g}\frac{E^2}{\Lambda^2}}$$

Strong multipole interactions (SMI)



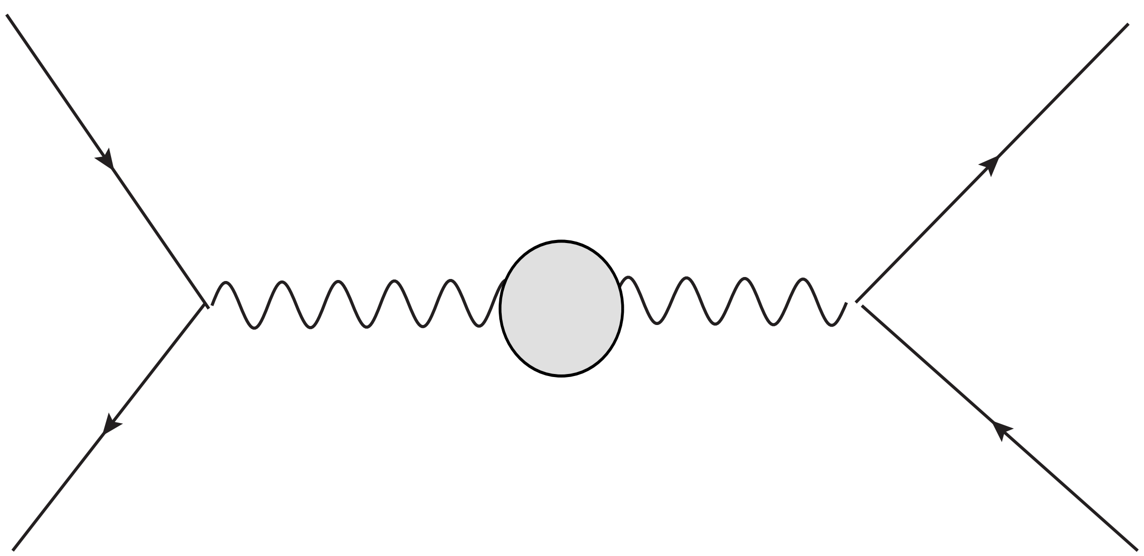
– New power-counting rules

$$W^a_{\mu\nu}, B_{\mu\nu} : g_*$$

D. L., A. Pomarol, R. Rattazzi & F. Riva 16

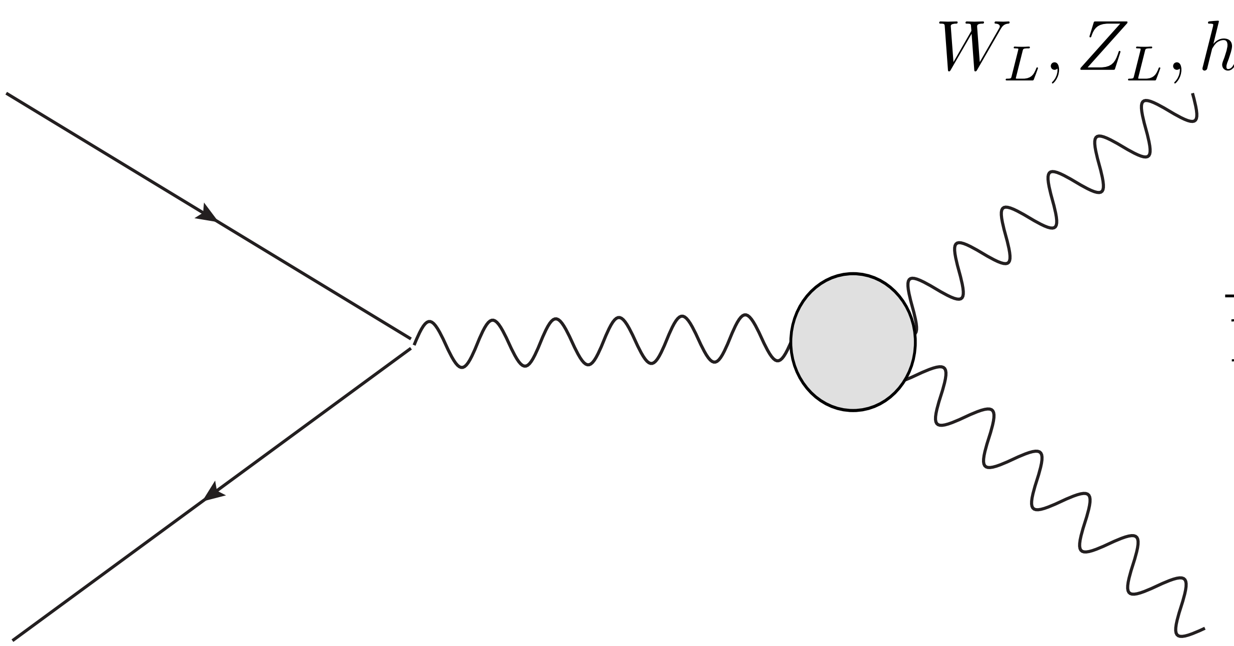
Strong multipole interactions

$$\mathcal{O}_{2W} = -\frac{1}{2m_*^2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu} \Rightarrow c_{2W} \sim \frac{g^2}{g_*^2} \qquad c_{2W} \sim 1$$

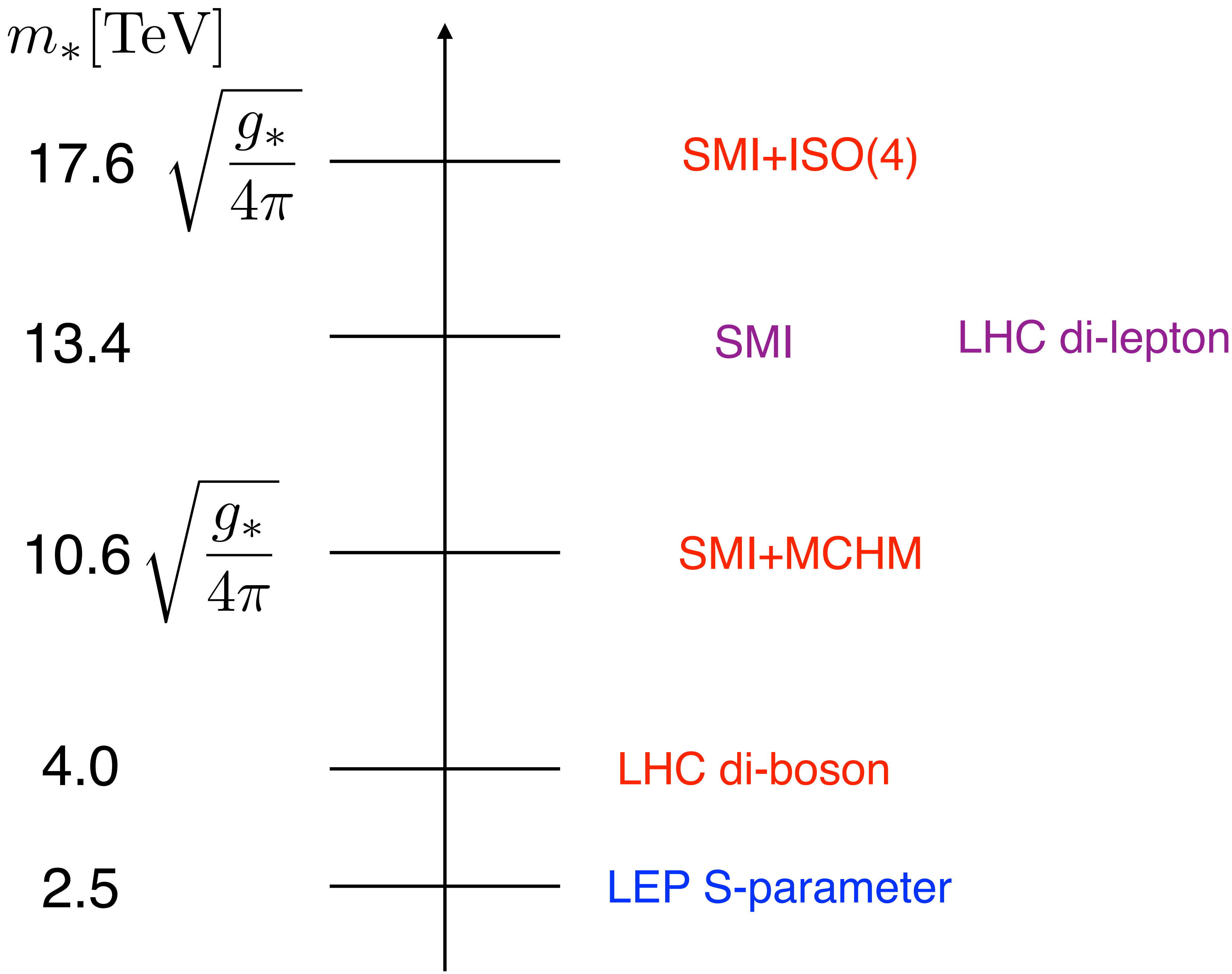


$$\sim \frac{g^2}{g_*^2}\frac{E^2}{m_*^2} \qquad \frac{E^2}{m_*^2}$$

Strong multipole interactions

	SILH	SMI Senario I	Senario 2
$\mathcal{O}_{HW} = \frac{ig}{m_*^2}(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \Rightarrow c_{HW} \sim$	$\frac{g_*^2}{16\pi^2},$	1	$\frac{g_*}{g}$
	$\frac{g_*^2}{16\pi^2}\frac{E^2}{m_*^2}$	$\frac{E^2}{m_*^2}$	$\frac{g_*}{g}\frac{E^2}{m_*^2}$

HL-LHC Reach



D. L. and L.T. Wang '18 see also R. Franceschini et al 17' dilepton: M. Farina et al 16'

Muon g-2

$$\mathcal{O}_{\mu B} = \frac{g' y_\mu}{\Lambda^2} \bar{L}_L \sigma^{\mu\nu} \mu_R H B_{\mu\nu}$$

$$\Delta a_\mu = \frac{4m_\mu^2}{\Lambda^2 \cos\theta_w} c_{\mu B}$$

$\Lambda\,[\mathrm{TeV}]$

$\Delta a_\mu \sim 10^{-9}$

$42\sqrt{\frac{g_*}{4\pi}}$ — Remedios+MCHM $\quad c_{\mu B} \sim \frac{g_*}{g'}$

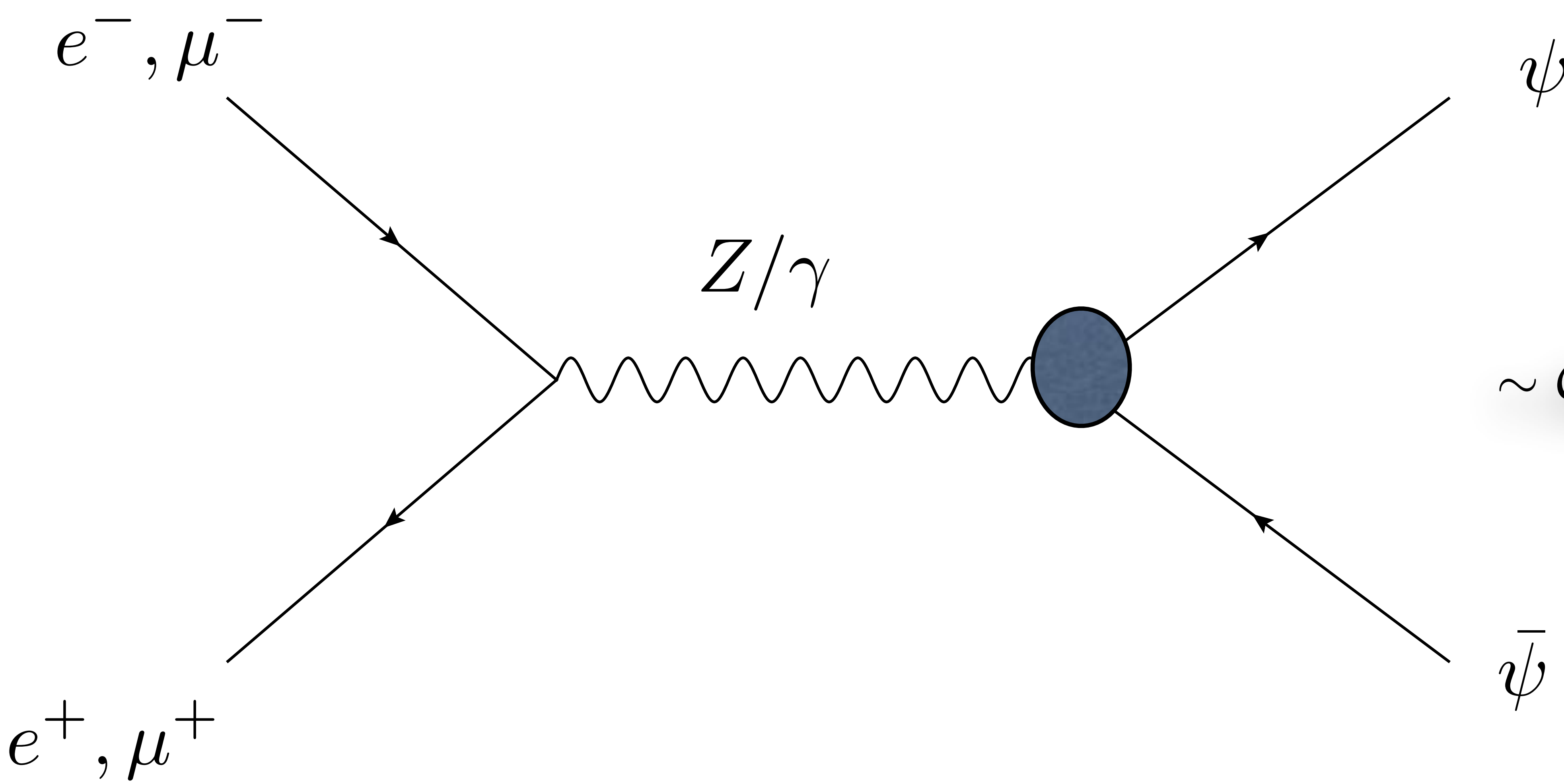
$7\,\frac{g_*}{4\pi}$ — SILH $\quad c_{\mu B} \sim \frac{g_*^2}{(4\pi)^2}$

$\sigma(a_\mu) = 22 \times 10^{-11}$

Fermilab/BNL, '23

Dipole Observables at Colliders

$$\mathcal{O}_{\mu B} = \frac{g' y_\psi}{\Lambda^2} \psi_L^{(\mathbf{2})} \sigma^{\mu\nu} \psi_R H B_{\mu\nu} \qquad \psi = t, b, c, \tau$$



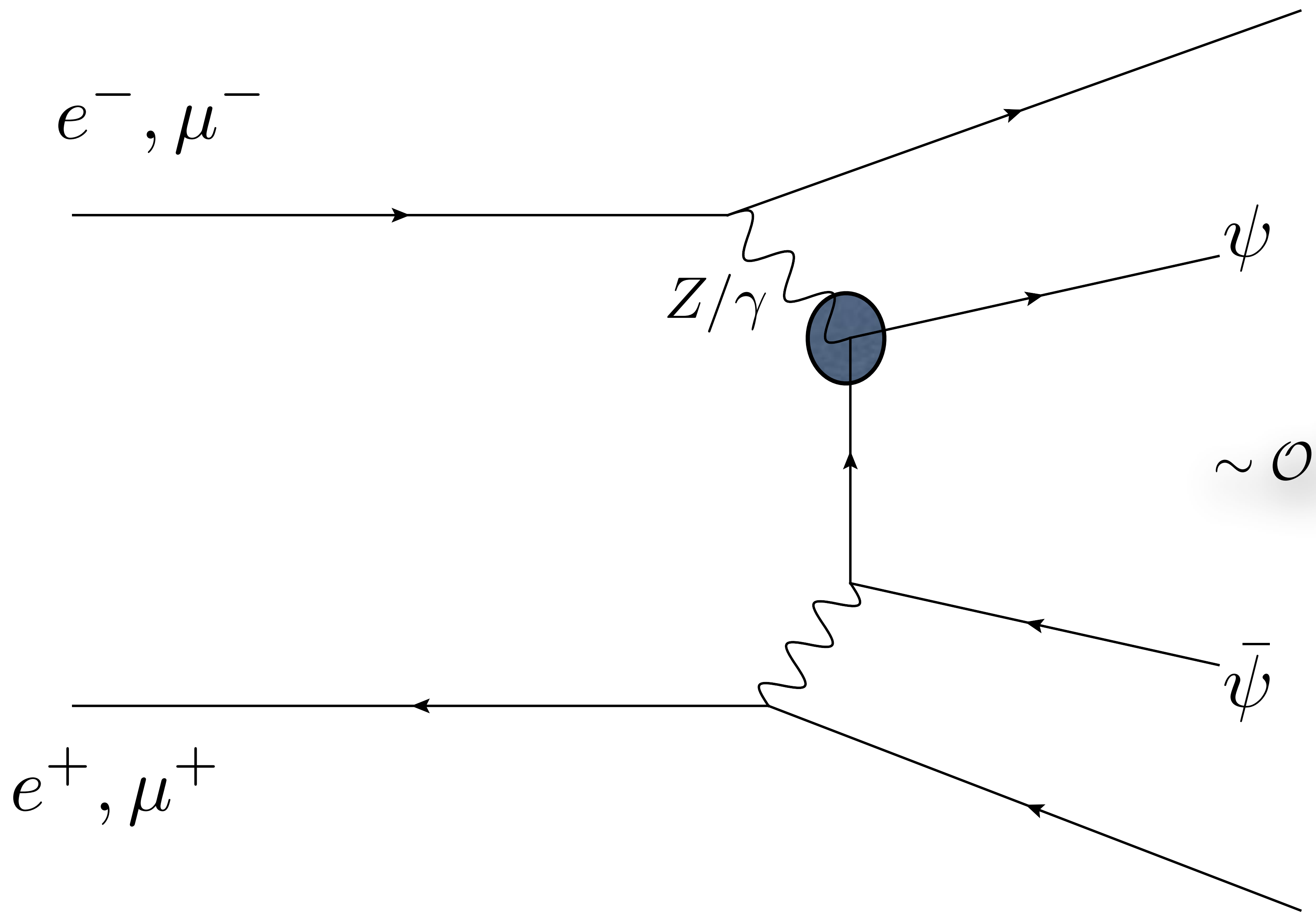
$\sim \mathcal{O}(\frac{E m_\psi}{\Lambda^2})$

T. Han, D. L. and S. Wang, work in progress

Dipole Observables at Colliders

$$\mathcal{O}_{\mu B} = \frac{g' y_\psi}{\Lambda^2} \psi_L^{(\mathbf{2})} \sigma^{\mu\nu} \psi_R H B_{\mu\nu}$$

$$\psi = t, b, c, \tau$$



$$\sim \mathcal{O}(\frac{E m_\psi}{\Lambda^2})$$

T. Han, D. L. and S. Wang, work in progress

Conclusion

- Direct resonance searches and precision measurement are both important

- In addition to resonance searches, HL-LHC is also important for precision measurement

- Muon Collider can do both great!

My Plan at TDLI

TDLI's Vision

桃李荫翳

家安其所

TDLI: A great place for particle physics

- Many great physicists

- Excellent young researchers

- Diverse physics program in both theory and experiments

PandaX, JUNO, IceCube, TRIDENT
LHC/ATLAS, BEPC/BES, CEPC
Muon g-2, DarkSHINE etc.

My Plan at TDLI

- Conduct pioneering research
- Mentoring excellent Ph.D. students
- Help to organize seminars and workshops

My Strength: International Collaborators

- Roberto Contino (Sapienza, Rome), Alex Pomarol (UAB, Barcelona), Riccardo Rattazzi (EPFL), Francesco Riva (UNIGE, Geneva) etc.

- Brian Batell (PITT PACC), Marcela Carena (Fermilab/UChicago), Tao Han (PITT PACC), Ian Low (Northwestern/Argonne), Markus Luty (UC Davis), Carlos Wagner (UChicago/Argonne), Lian-Tao Wang (UChicago), John Terning (UC Davis) etc.

My Strength: Broad Research Topics

- Strong Electroweak Dynamics at Future Colliders

- Light Dark Matter Detection

- On-shell Massive Amplitude

- Etc.

My Strength: Phenomenology of CHMs at Colliders

- Dipole observables at LHC and future colliders

- Composite resonance searches at muon collider

- Higgs coupling measurement at muon colliders

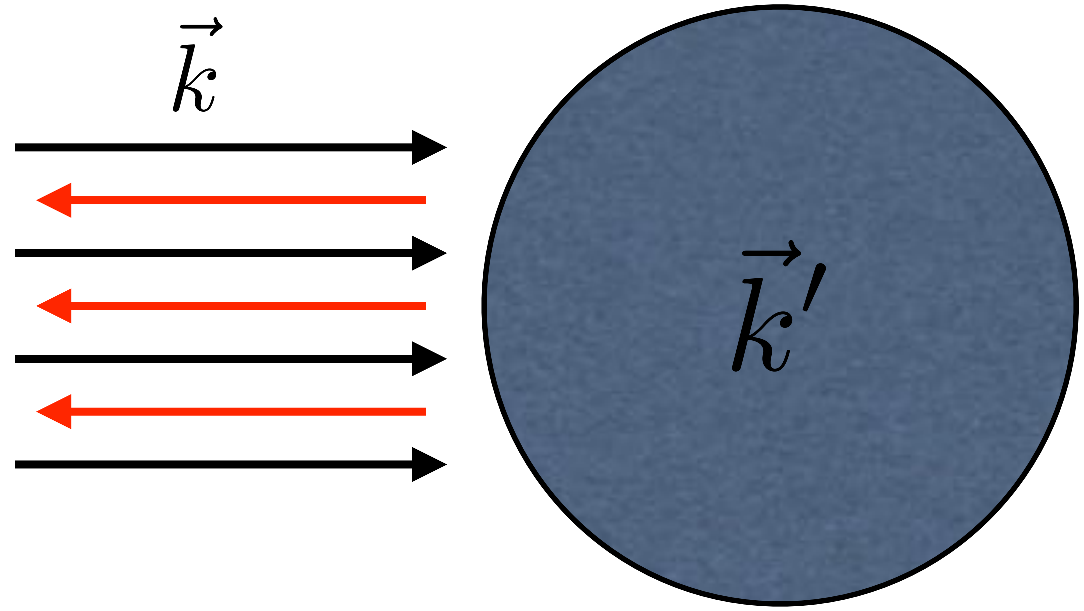
Look forward to collaborations with
excellent theory and experimental colleagues at TDLI!

My Strength: Professional Knowledge of Programming

- FeynRules, FeynCalc
- MadGraph5, Pythia, Delphes
- C++, Python, Mathematica

My Strength: Broad Topics

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f_N}\bar{N}N - \frac{\phi^2}{2f_e}\bar{e}e$$



$$\langle \bar{N}N \rangle = n_N$$

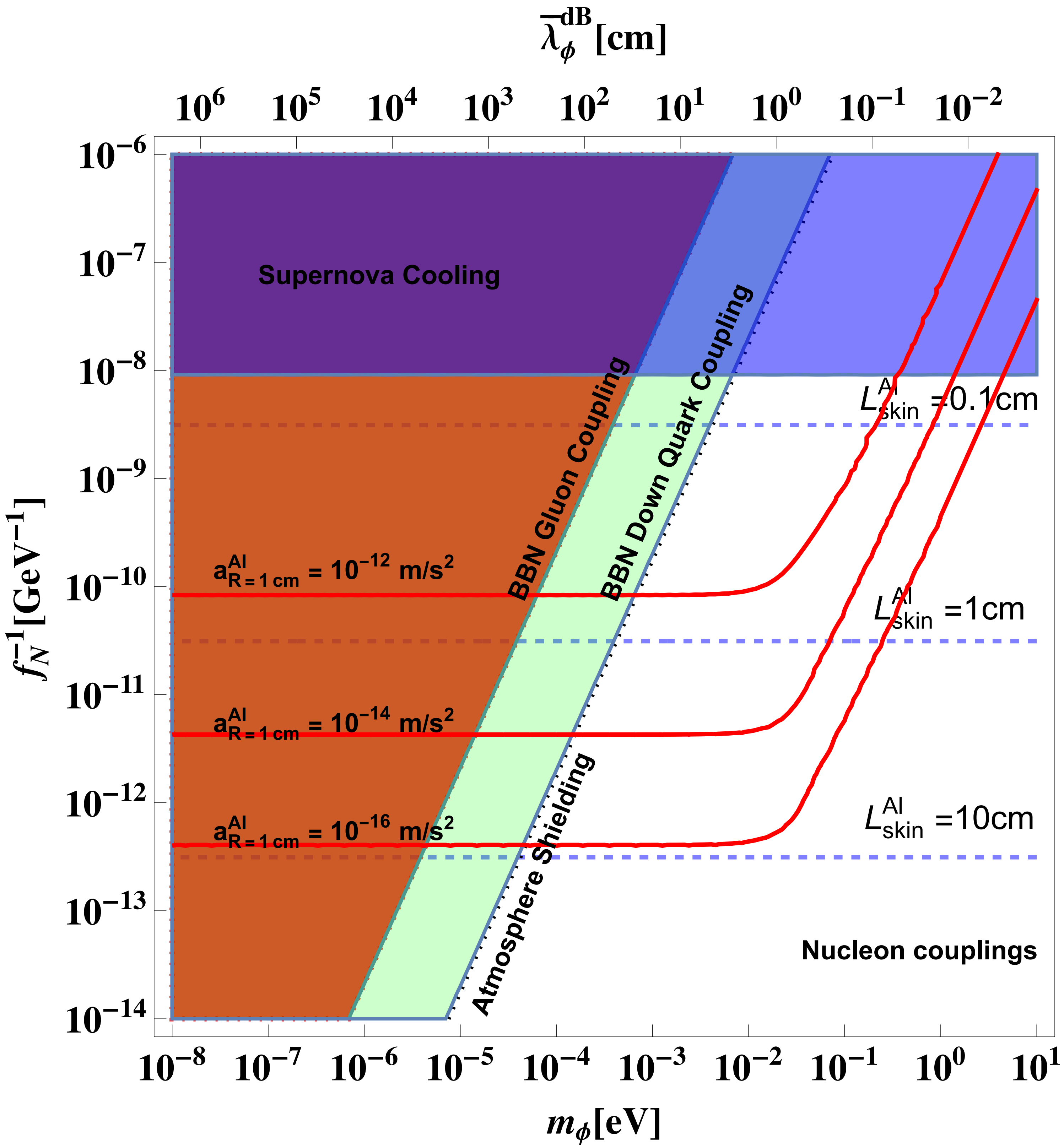
$$\langle \bar{e}e \rangle = n_e$$

$$\vec{k}'^2 = \vec{k}^2 - \frac{n_N}{f}$$

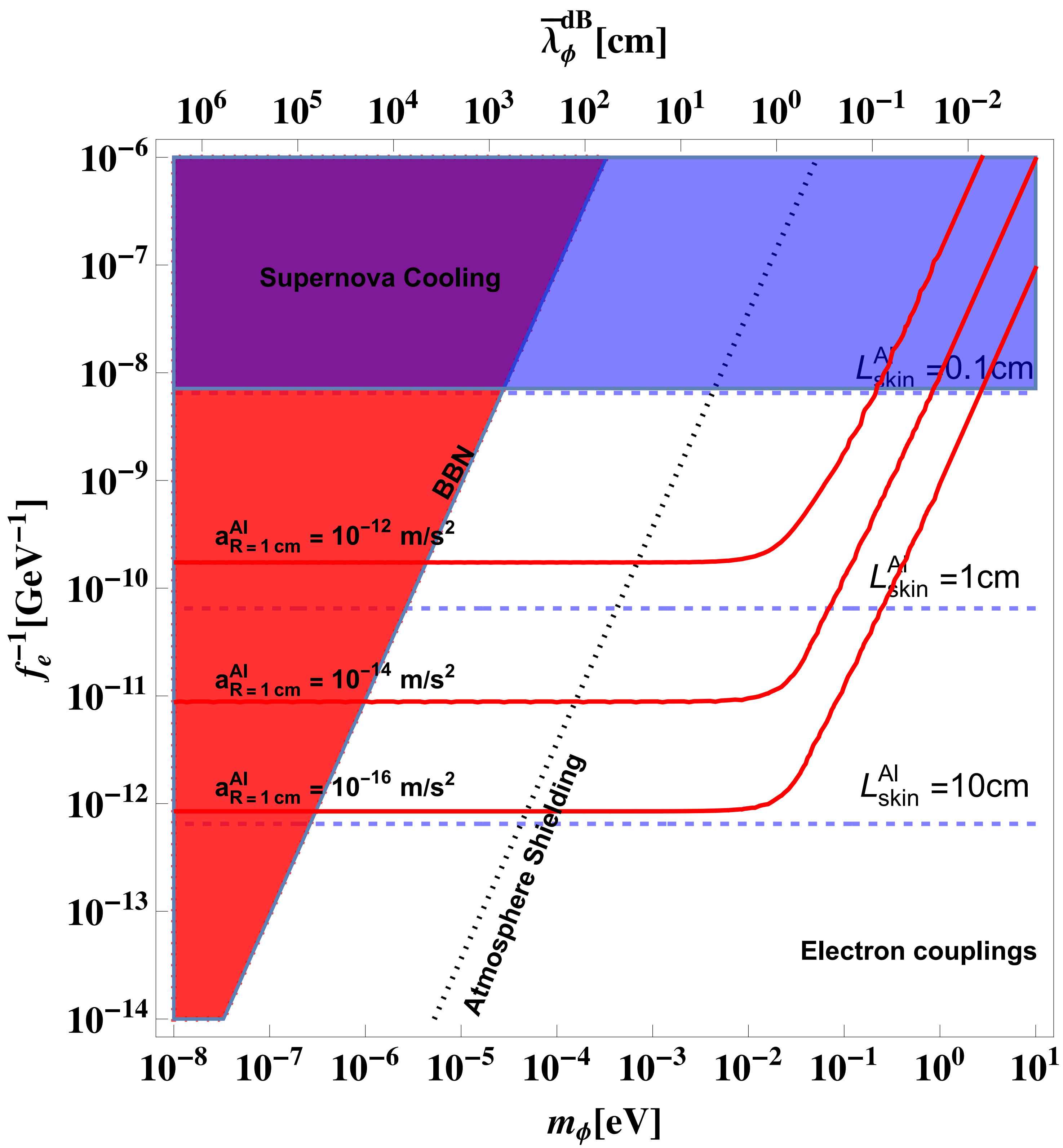
$$a = \frac{F}{M} = \frac{3}{4}\frac{\rho_{\rm DM} v_D^2}{\rho_m R} \sim 1.3 \times 10^{-12} m/s^2 \frac{2.7{\rm g/cm^3}}{\rho_m}\frac{\rm cm}{R}$$

H. Day, D. L., M. Luty and Z. Yue ‘23

My Strength: Broad Topics



My Strength: Broad Topics



My Strength: Strong Background in QFT

- On-shell Massive Amplitudes

  D. Liu and Z. Yin, "Gauge invariance from on-shell massive amplitudes and tree-level unitarity," 2022.
  H.Y. Lai, D. Liu and J. Terning, "The constructive methods for massive particles in QED," 2023.

- Soft Theorem for the Goldstino

  D. Liu and Z. Yin, work in progress

My Strength: Organizing Seminar and Conference

- Seminar organizer at Argonne, UC Davis, PITT PACC

- Conference organizer
  Local organizer, BOOST 23, LBNL
  Organizer, Muon Collider Physics Benchmark Workshop, PITT PACC

TDLI's Vision

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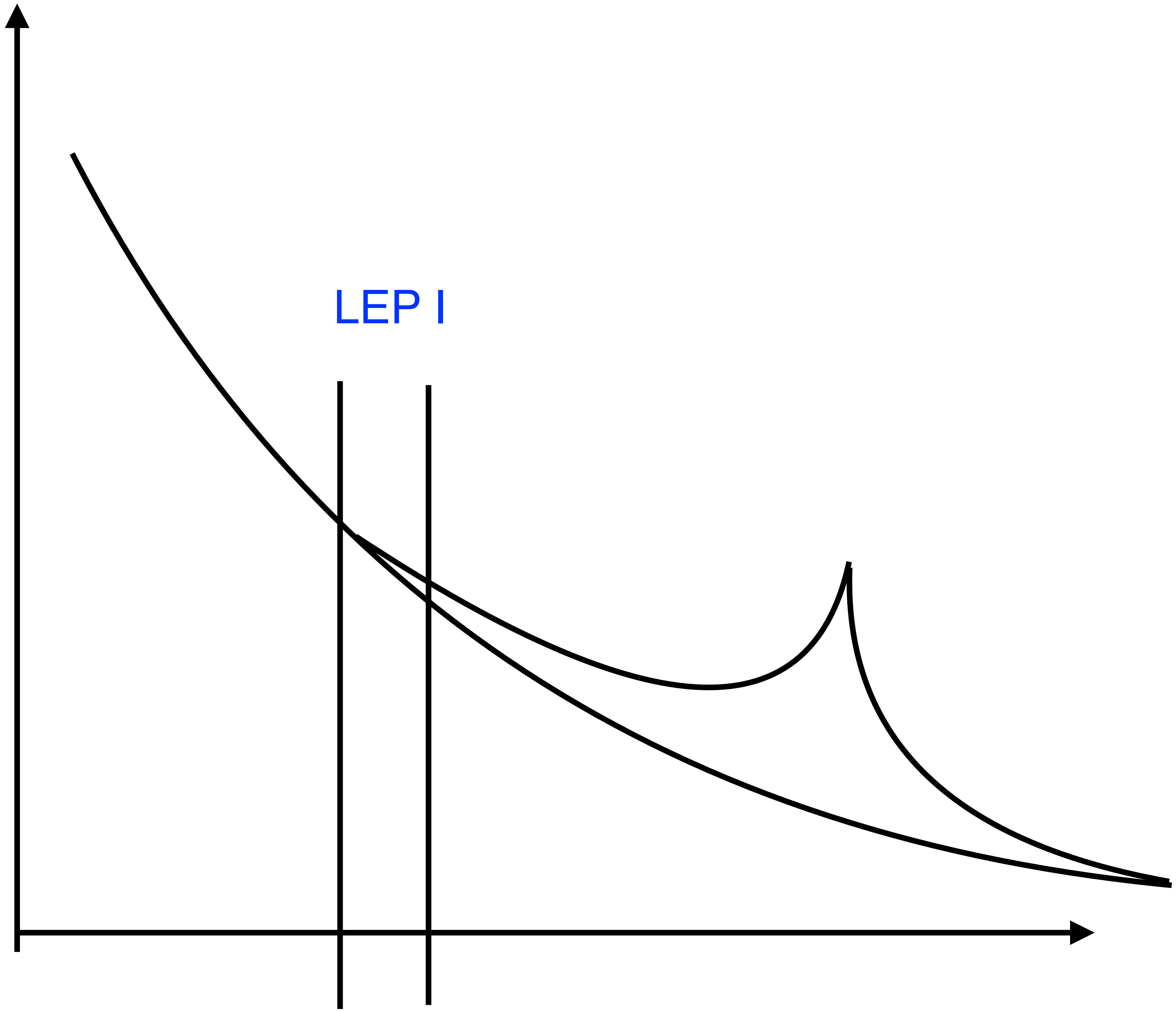
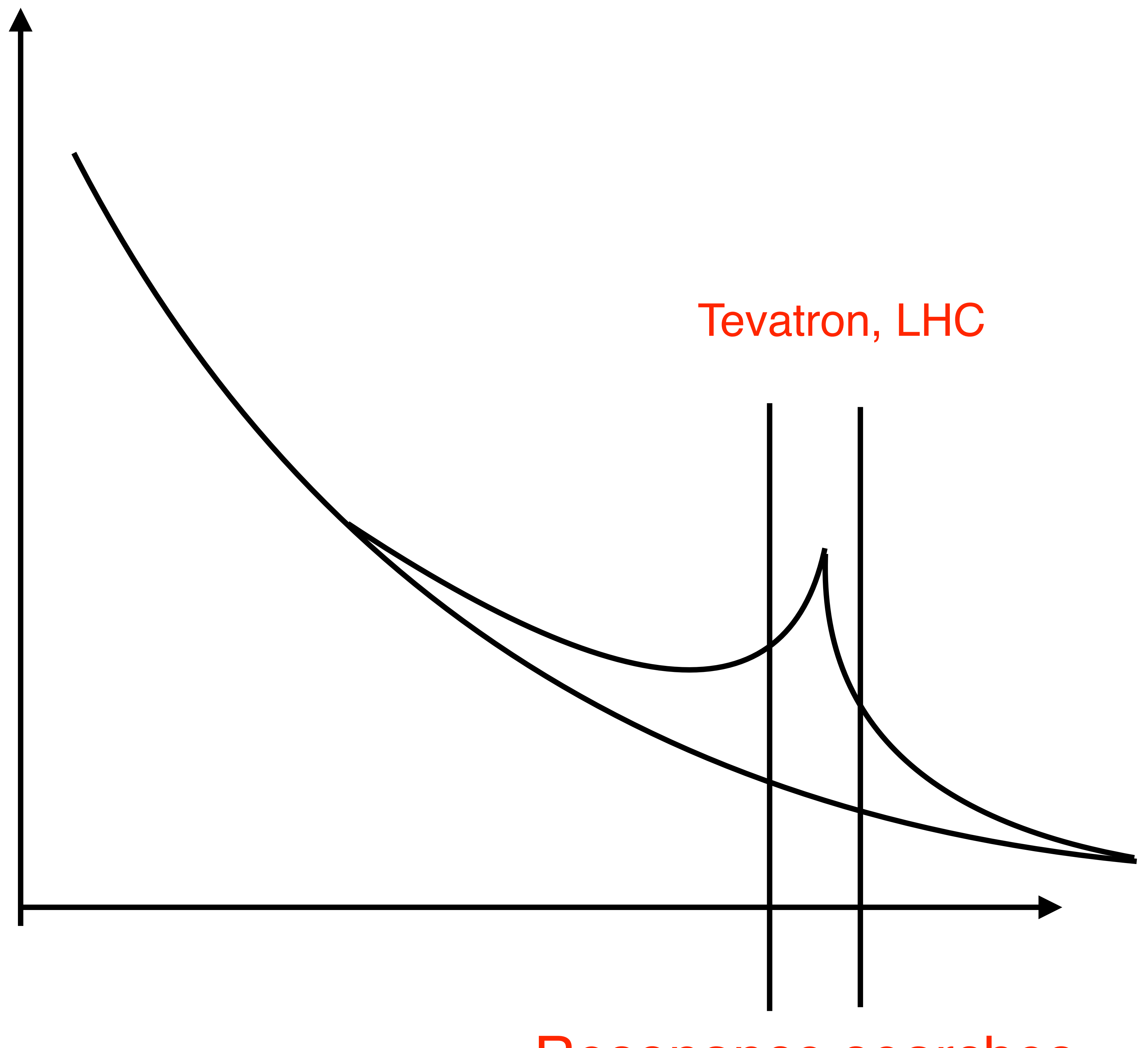
Back-up Slides

Two approaches for new physics

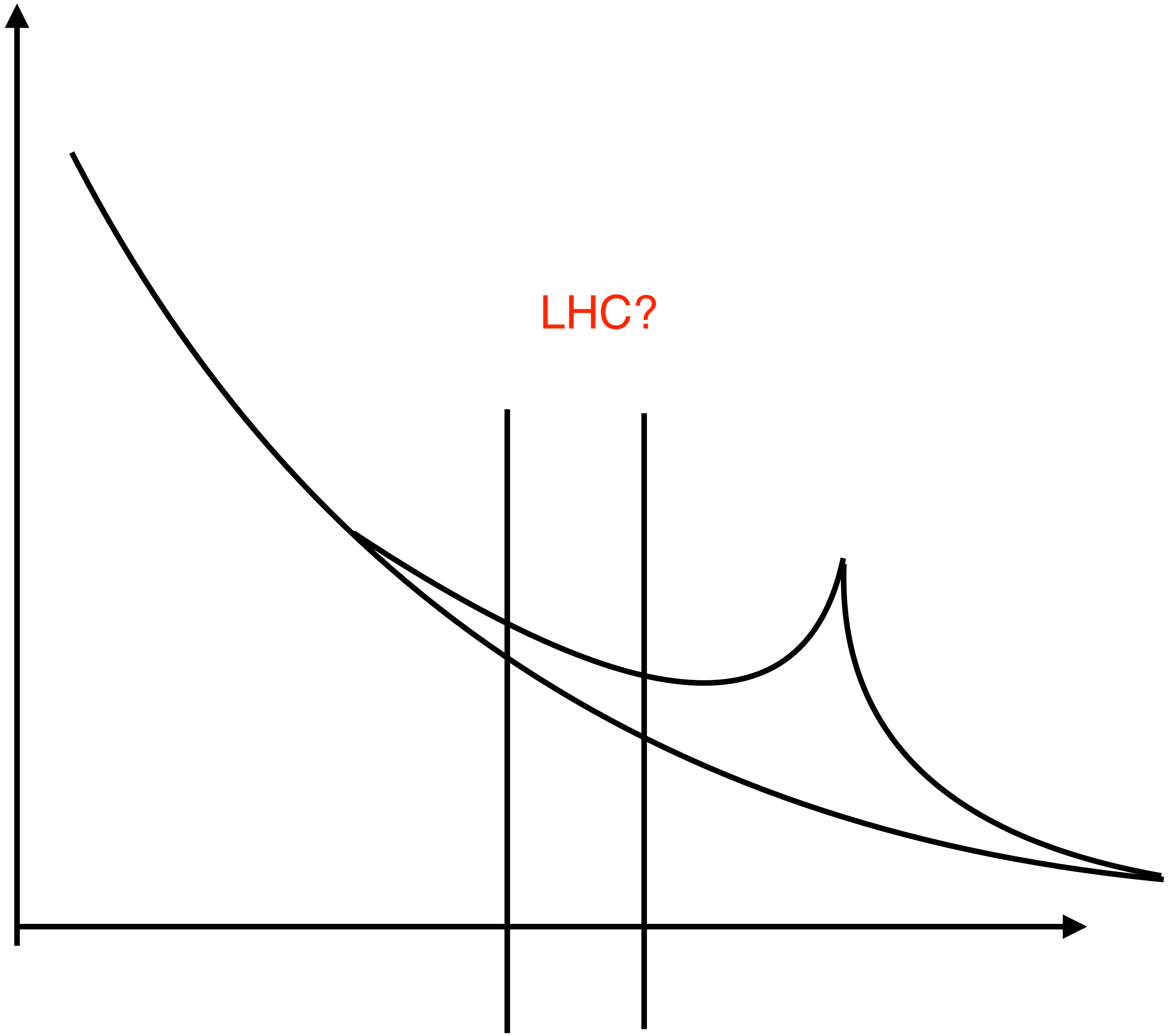


Precision measurement

Two approaches for new physics



Can HL-LHC do precision measurement?



Uncertainty

- Lepton colliders: ~ 0.1%

- Hadron Colliders: 3% - 20%

Higgs mass stability - Option I

Remedios + MCHM

$$SO(5)\times \widetilde{SU}(2)/SO(4)\times \widetilde{SU}(2)$$

H $\qquad$ $W^a_{\mu\nu}$

D. L., A. Pomarol, R. Rattazzi & F. Riva 16

Higgs mass stability - Option II

$$\boxed{\text{Remedios} + ISO(4)}$$

$$SO(5)$$

$$[T^{\hat{a}}, T^{\hat{b}}] = 0 \qquad \Big\downarrow \quad \text{Inonu-Wigner Contraction}$$

$$ISO(4) \simeq T^4 \ltimes SO(4)$$

$$\Big\downarrow$$

$$W^a_{\mu\nu} : (3,1)$$

D. L., A. Pomarol, R. Rattazzi & F. Riva 16

Effective Operators

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu}, \qquad \mathcal{O}_{2B} = -\frac{1}{2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}, \qquad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_{\mu} W^b_{\nu\rho} W^{c\rho\mu}, \qquad \mathcal{O}_T = \frac{g^2}{2}(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu) H$$

$$\mathcal{O}^u_R = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R, \qquad \mathcal{O}^d_R = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}^q_L = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L, \qquad \mathcal{O}^{(3)q}_L = ig^2 \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \cdots$$

Helicity structure for WW

$$q_L \bar{q}_R \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_B$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
$(\pm, \mp)$	1	0	0	0	0	0
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	$\frac{E^2}{\Lambda^2}$

$$q_R \bar{q}_L \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_B$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
$(\pm, \mp)$	0	0	0	0	0	0
$(0, 0)$	1	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{E m_W}{\Lambda^2}$	$\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	$\frac{m_W^2}{\Lambda^2}$

Light Scalar Dark Matter Model

$$\Delta\mathcal{L} = -\frac{\phi^2}{2f_N}\bar{N}N - \frac{\phi^2}{2f_e}\bar{e}e$$

Number density

$$\langle \bar{N}N \rangle = n_N$$

$$\langle \bar{e}e \rangle = n_e$$

Damping can occur when

$$\vec{k}^2 < \frac{n_N}{f}$$

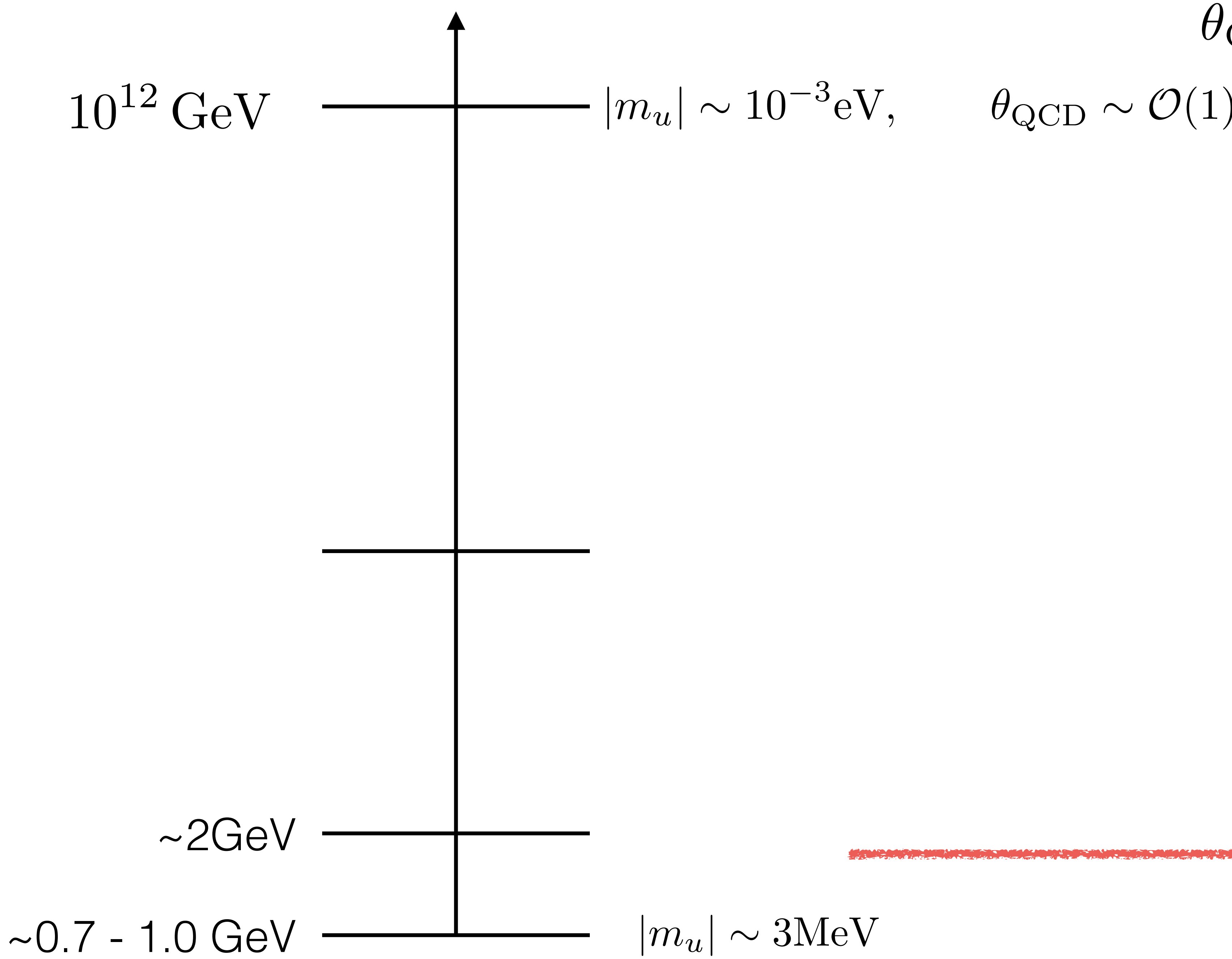
$$\bar{\lambda}_{dB} = \frac{1}{m_\phi v} \sim 2.0 \times 10^{-2}\mathrm{cm}\frac{\mathrm{eV}}{m_\phi}$$

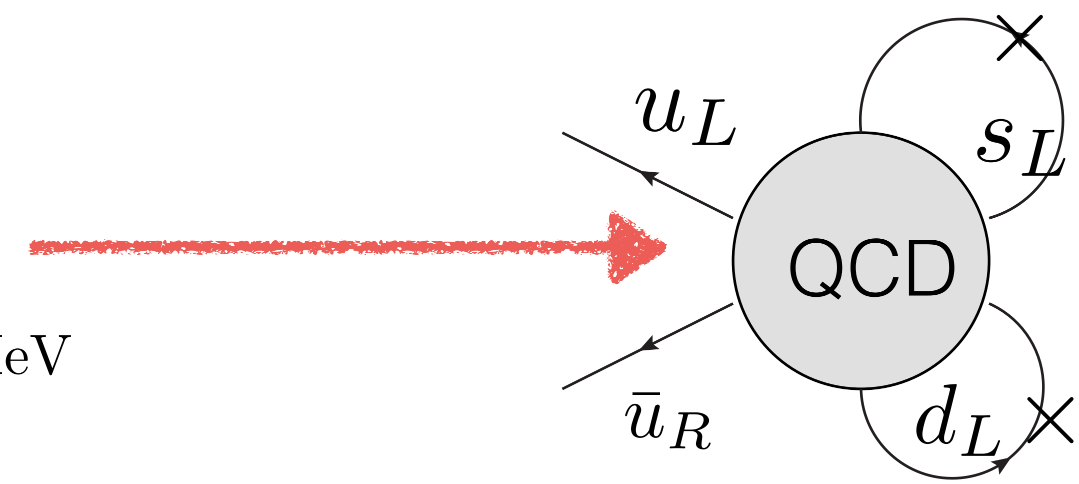
$$\lambda_{sd} = 1/\sqrt{\frac{n}{f}} \sim 5.6 \times 10^{-2}\mathrm{cm} \times \sqrt{\frac{\frac{f}{10^8\,\mathrm{GeV}}}{\frac{\rho_{\mathrm{matt}}}{2.7\ \mathrm{g/cm^3}}}}$$

$$d_{\mathrm{Atom,Atom}} \sim \quad \mathring{\mathrm{A}} = 10^{-8}\mathrm{cm}$$

Neutrino and Strong CP

$$\theta_{\rm QCD} = \arg[m_u]$$



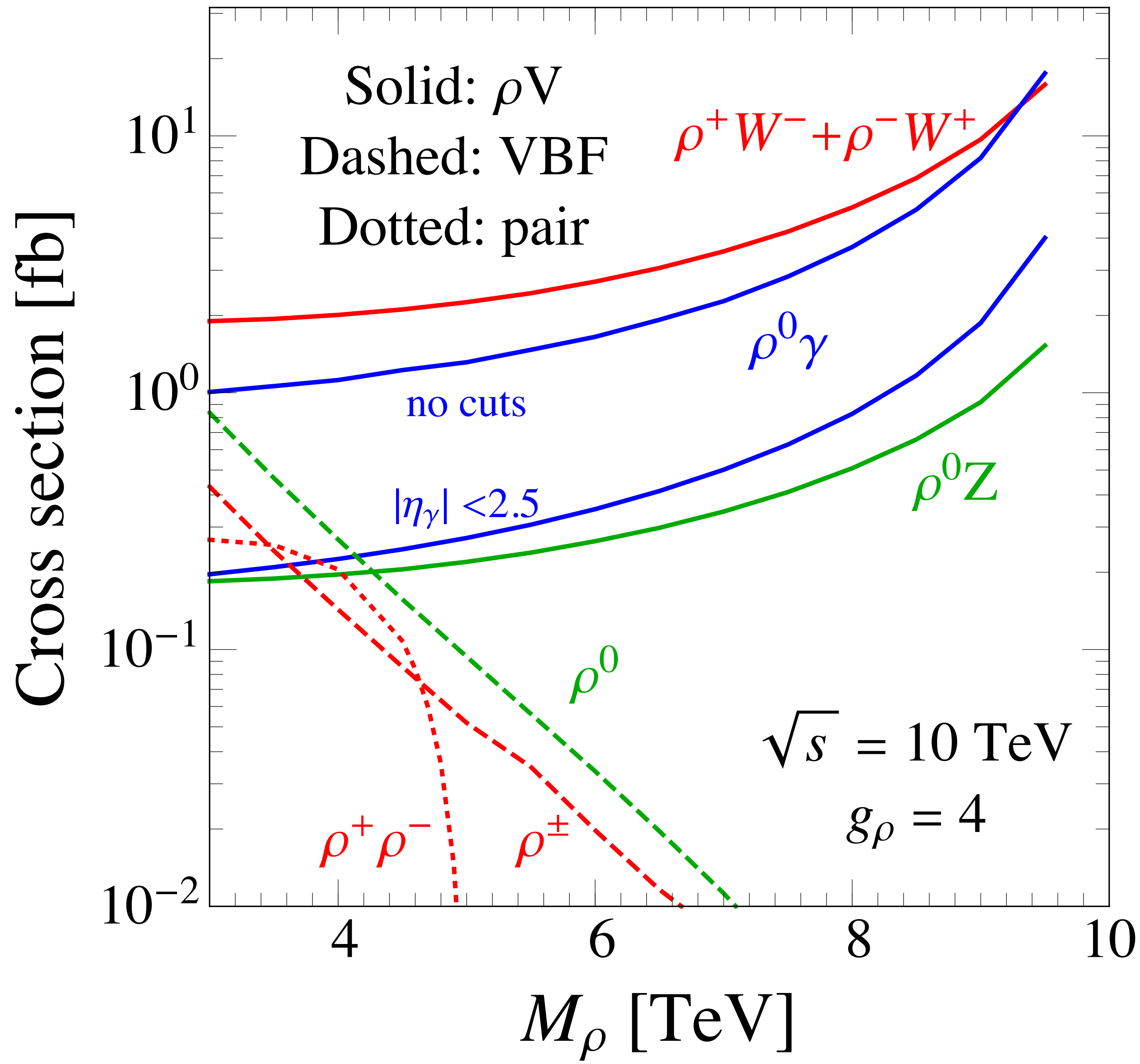


$$m_u^{inst} \sim \frac{m_d^H m_s^H}{\Lambda}$$

M. Carena, D. L., J. Liu, N. Shah, C.W.Wagner and X.P. Wang '19

Spin-1 resonances: XS

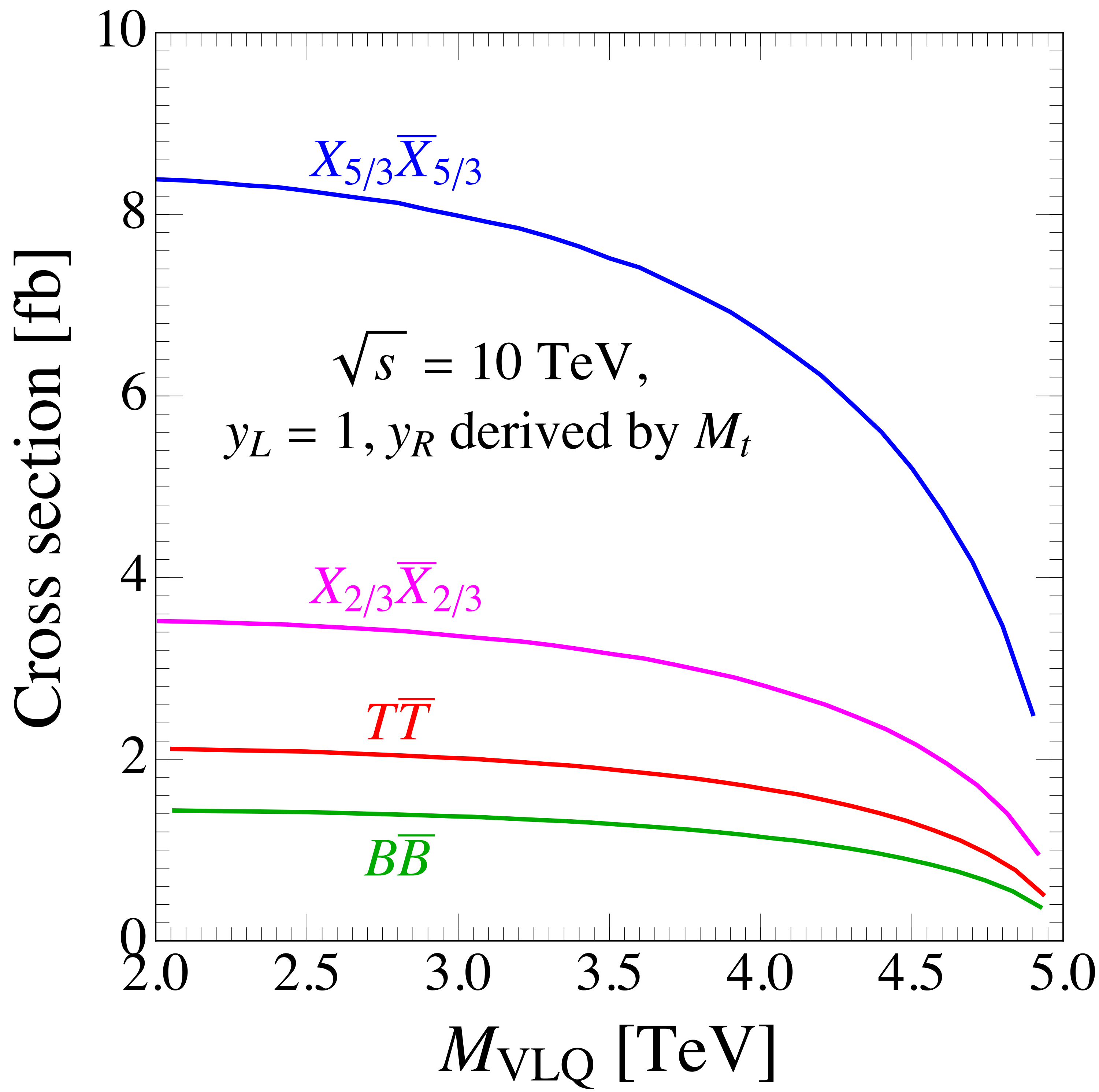
$\sqrt{s}_{\mu^+\mu^-} = 10\text{TeV}$ $\qquad L = 10\,\text{ab}^{-1}$



$N \sim \mathcal{O}(100)$

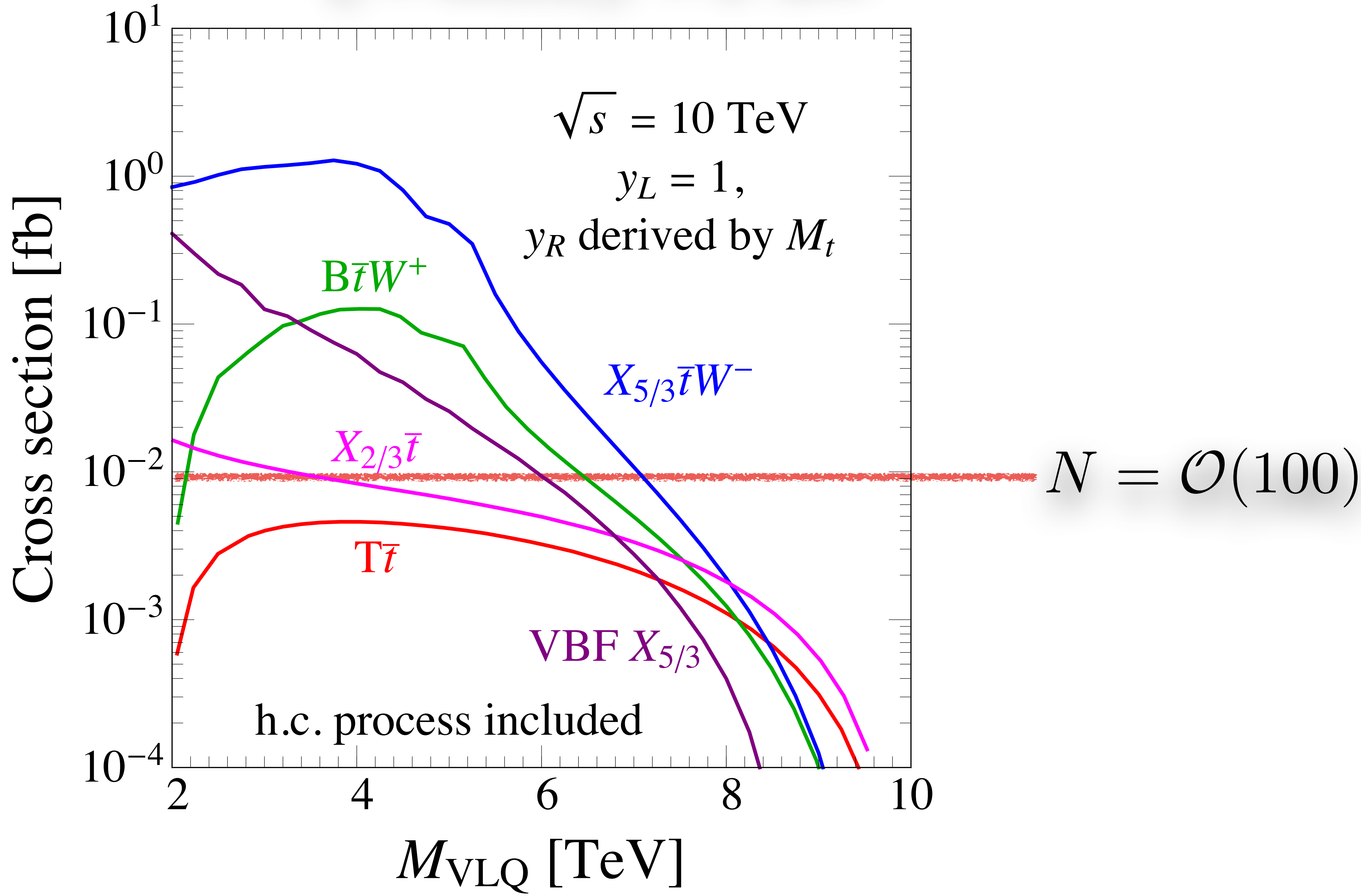
D. L., L.T. Wang and K. P. Xie, '23

Top partners: Pair production XS

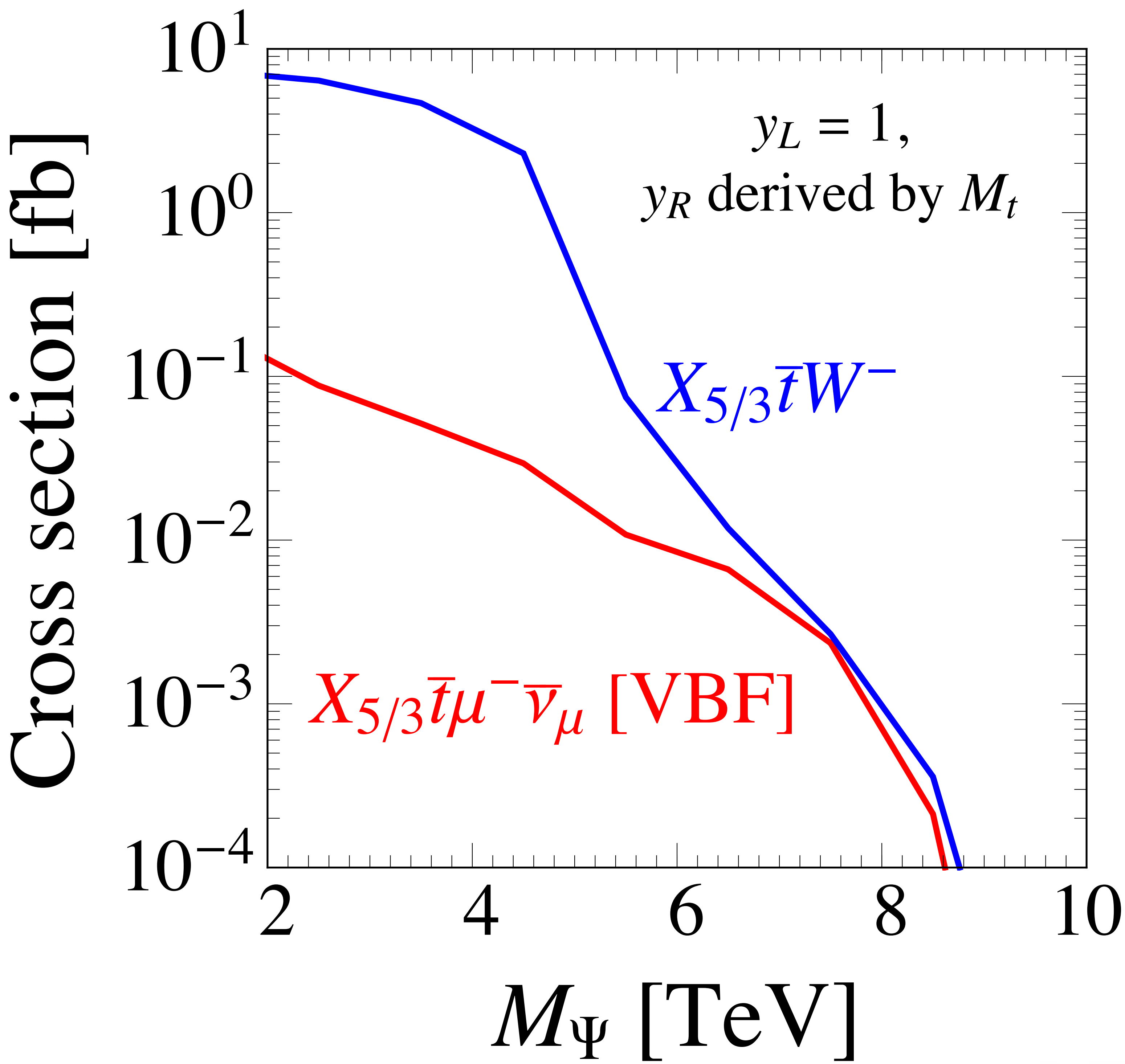


Top partners: Single production

$\xi = 0.015, f = 2$ TeV

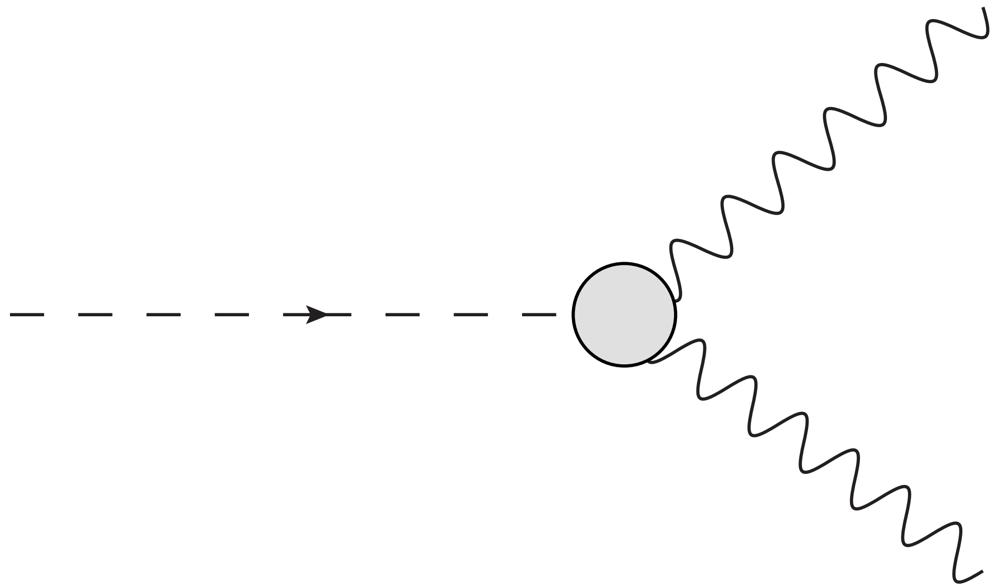


Top partners: VBF Production XS

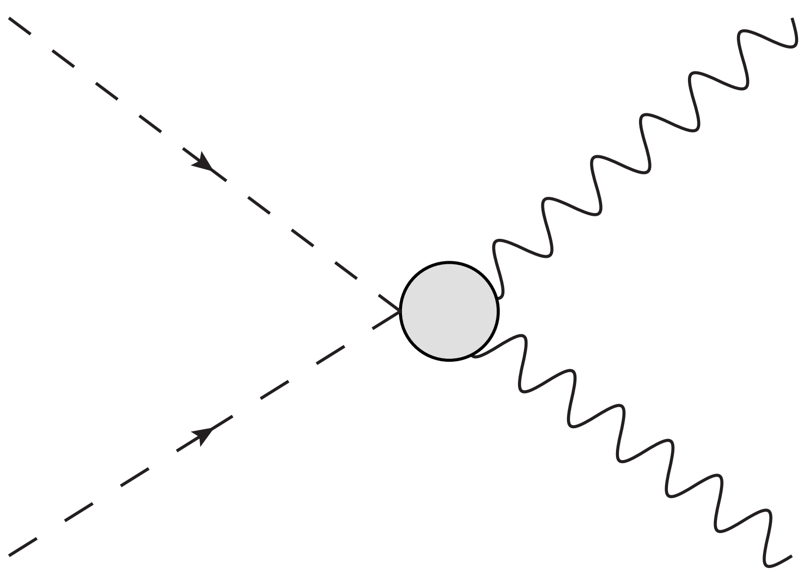


$\xi = 0.015, f = 2$ TeV

Prediction from Higgs non-linearity



$$2a\frac{h}{v}\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)$$



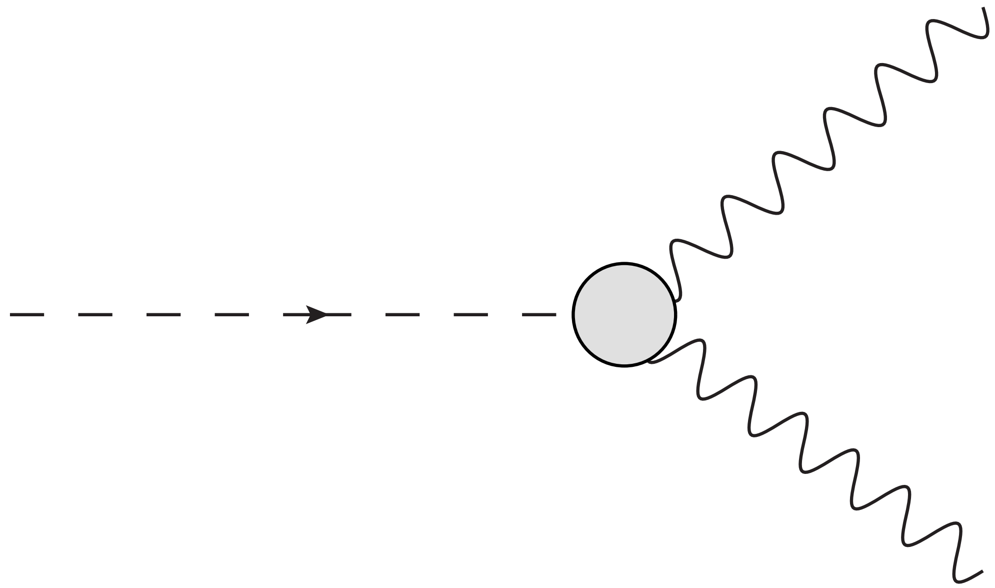
$$b\frac{h^2}{v^2}\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)$$

	SMEFT	Non-linearity
$\frac{1-b}{4(1-a)}$	1	$\frac{\xi}{2(1-\sqrt{1-\xi})} \sim 1 - \frac{1}{4}\xi$

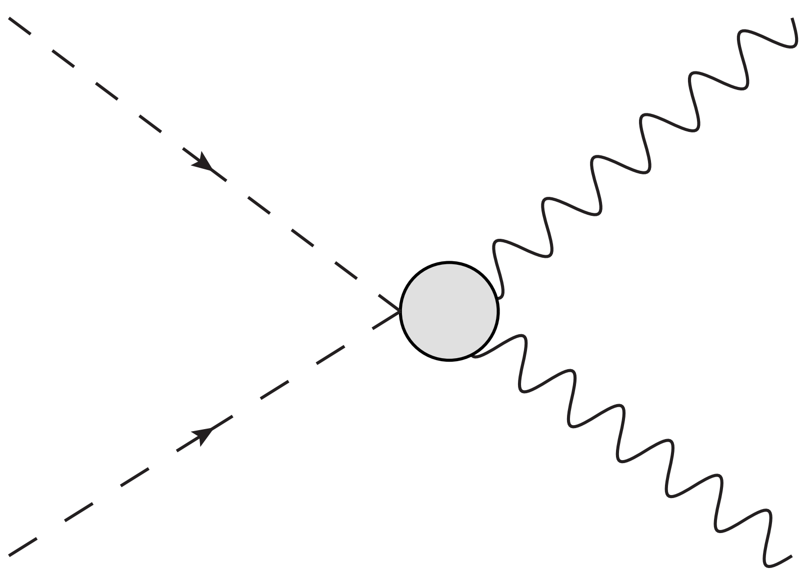
R. Contino et al ‘13

D. L., I. Low and Z. Yin ‘18

Prediction from Higgs non-linearity



$$C_3^h \frac{h}{v} Z_\mu \mathcal{D}^{\mu\nu} A_\nu \qquad C_4^h \frac{h}{v} Z_{\mu\nu} A^{\mu\nu}$$

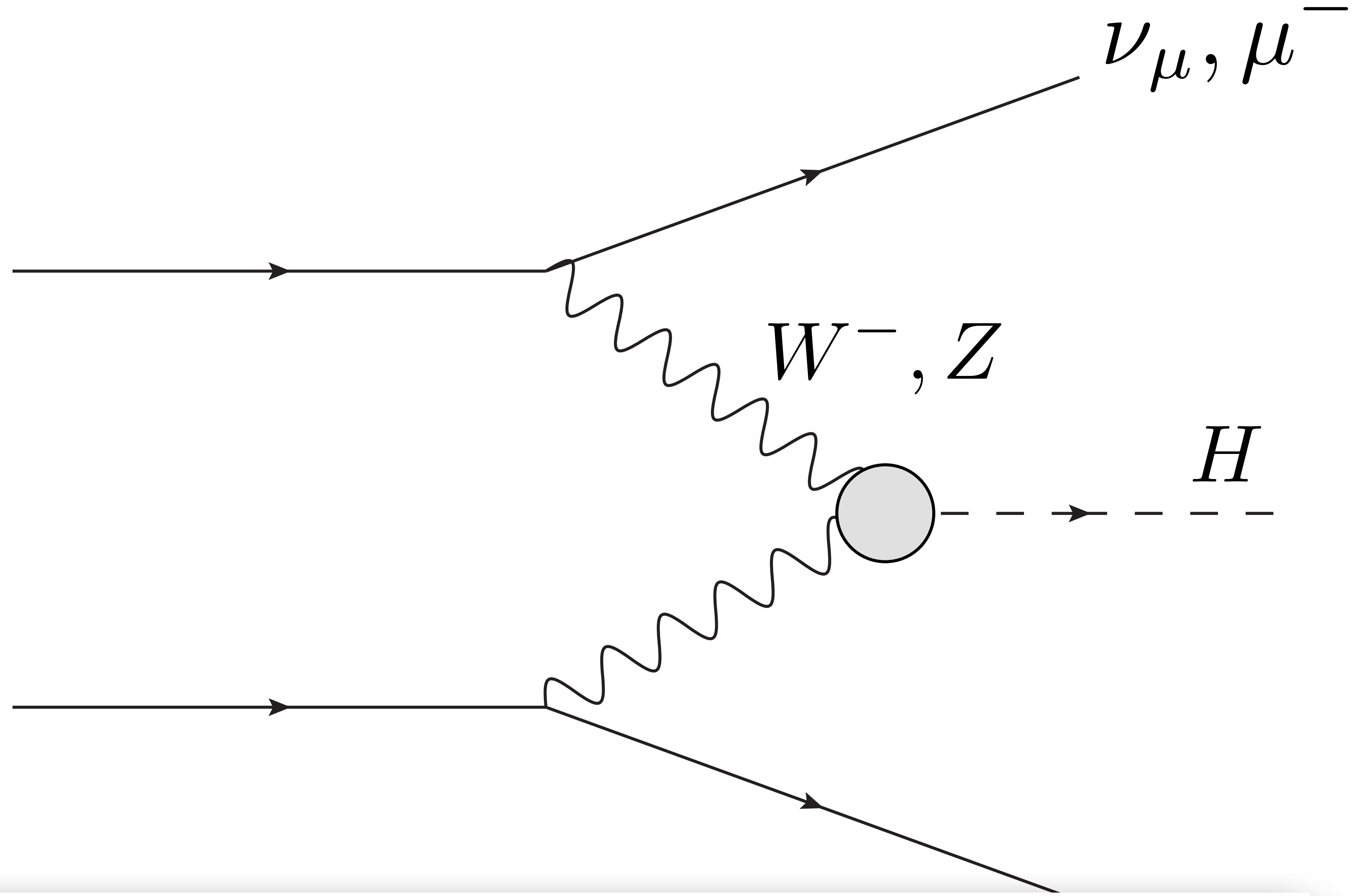


$$C_3^{2h} \frac{h^2}{v^2} Z_\mu \mathcal{D}^{\mu\nu} A_\nu \qquad C_4^{2h} \frac{h^2}{v^2} Z_{\mu\nu} A^{\mu\nu}$$

		SMEFT	Non-linearity
$\frac{2C_3^{2h}}{C_3^h}$	$\frac{2C_4^{2h}}{C_4^h}$	1	$\cos\theta = \sqrt{1-\xi}$

D. L., I. Low and Z. Yin, PRL '18

VBF Single Higgs

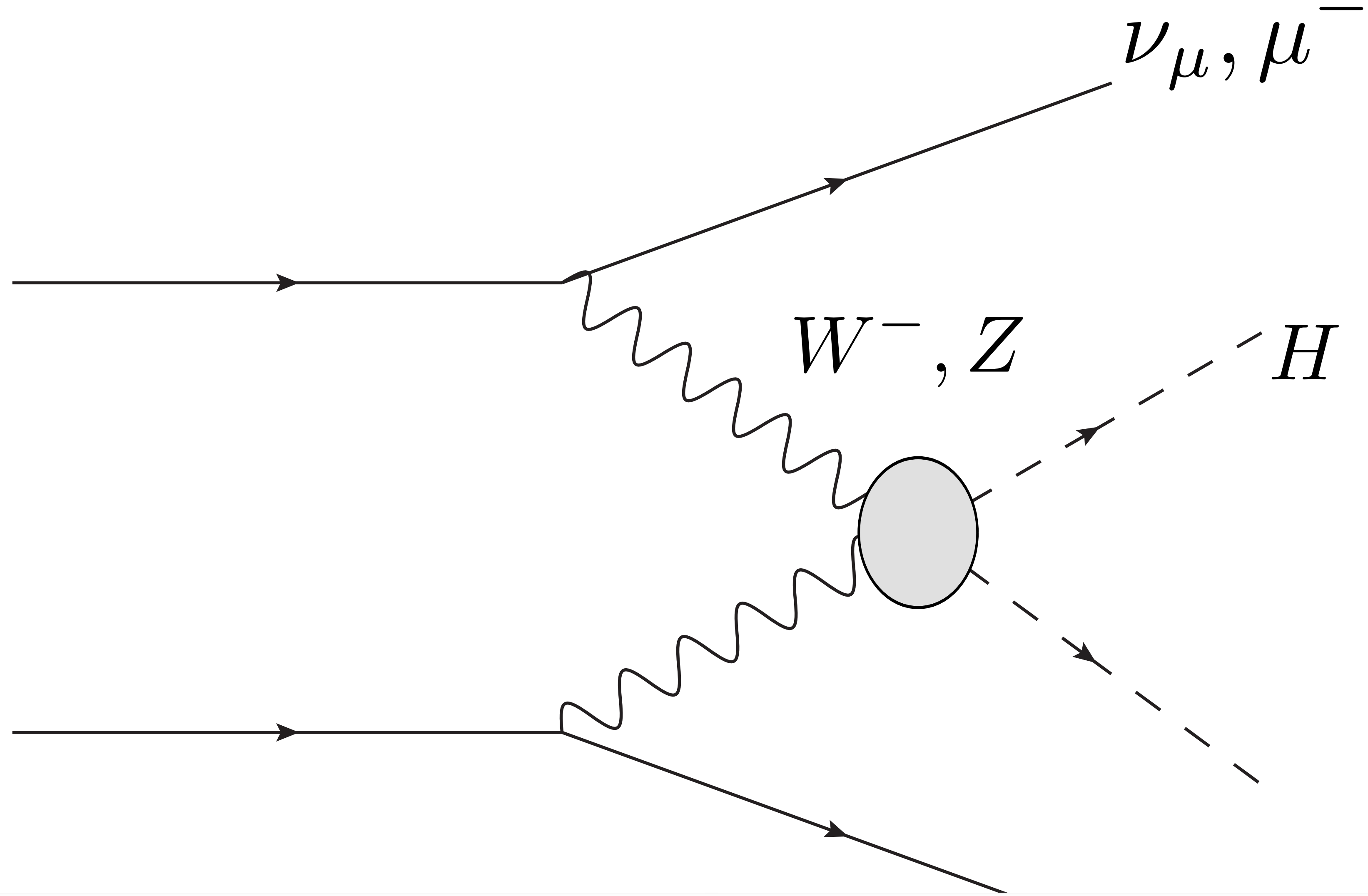


$\sqrt{s}$ (TeV) / benchmark lumi (ab^{-1})	3 / 1	6 / 4	10 / 10	14 / 20	30 / 90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

$\mathcal{O}(10^7)\, H$

$\frac{S}{B} \sim \frac{1}{4}$

VBF Double Higgs



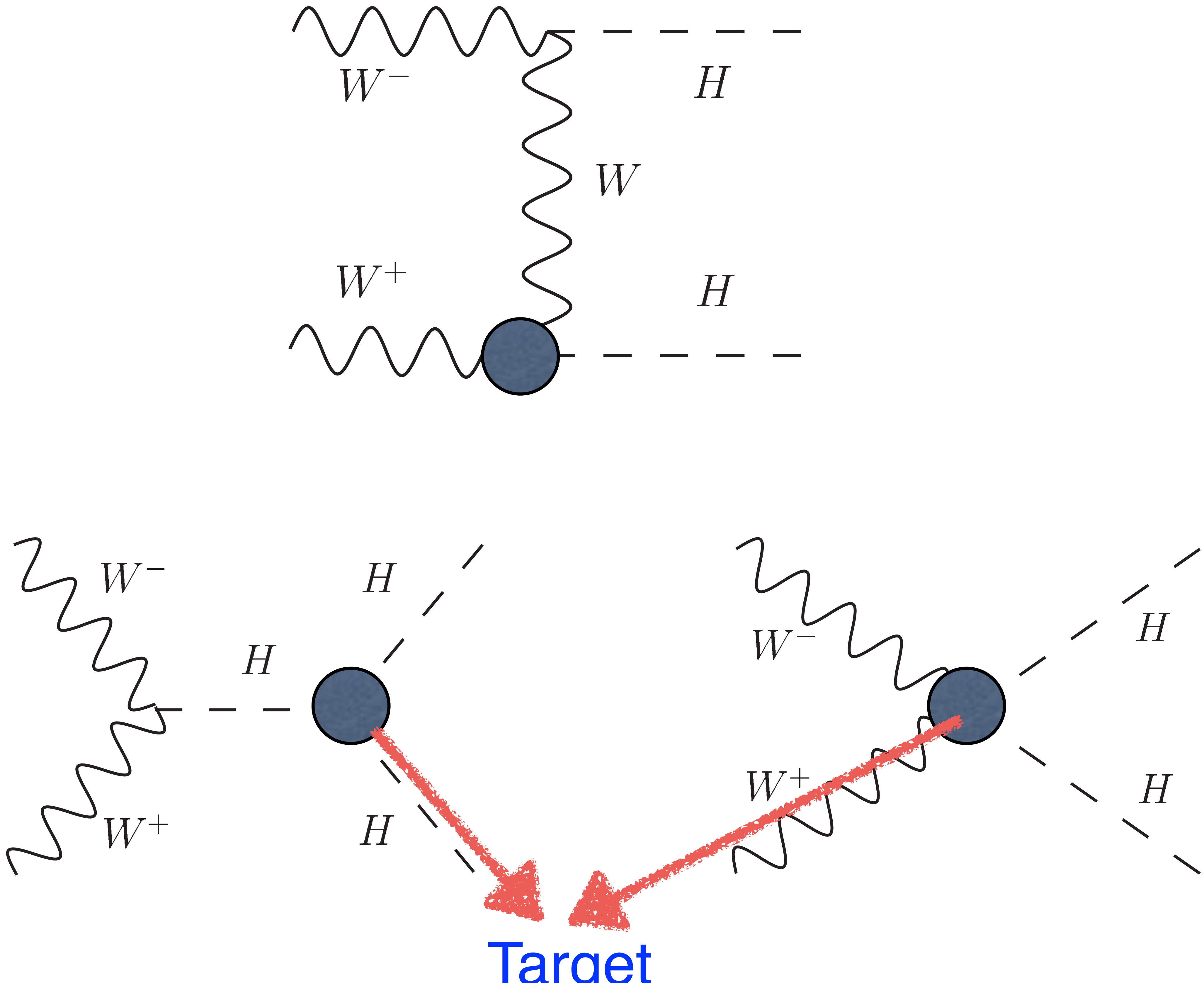
$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZZ$	57	130	200	260	420

fb

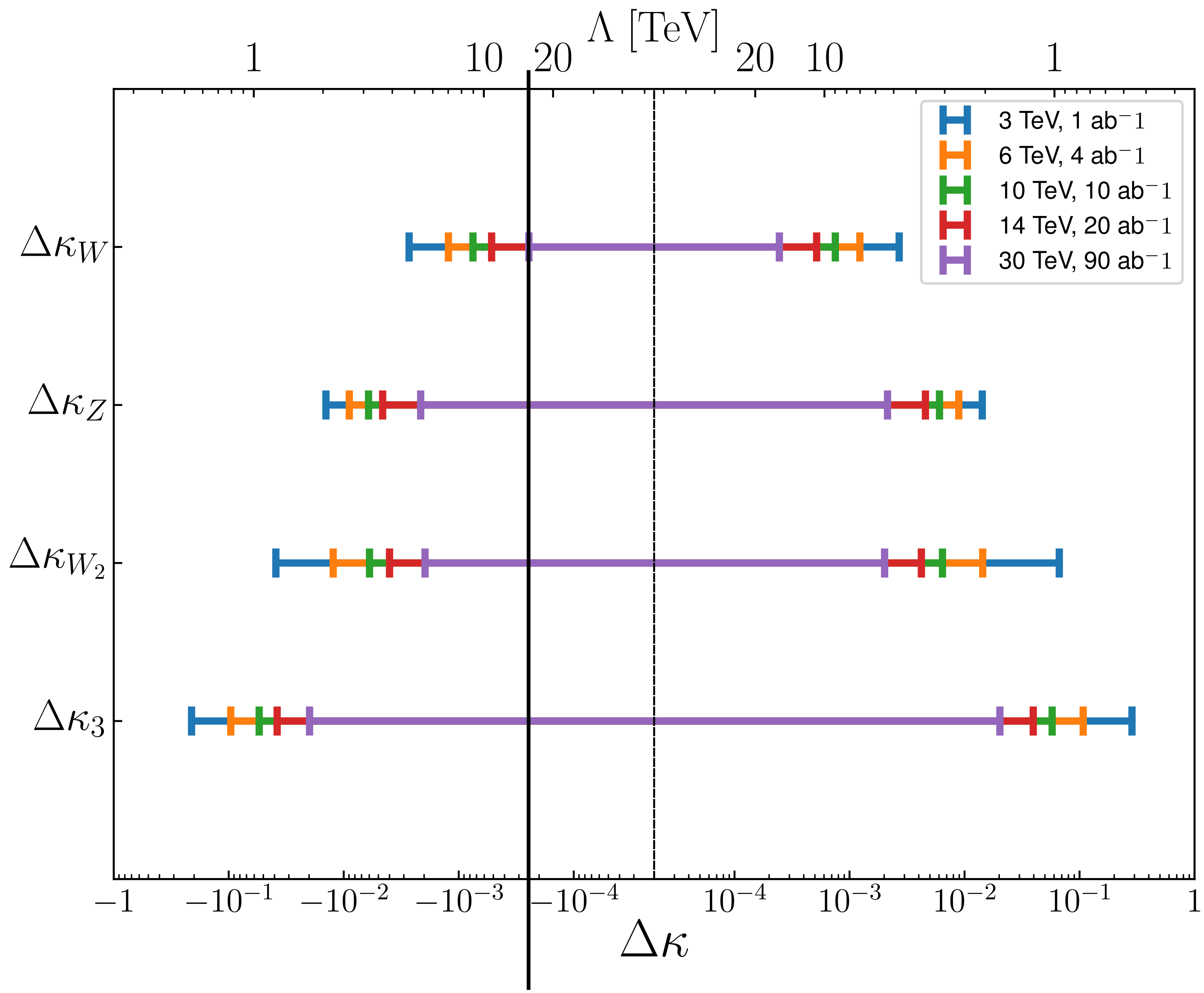
$\mathcal{O}(10^4)\, HH$

$\frac{S}{B} \sim 0.02$

VBF Double Higgs



Result Summary



10 - 20 TeV

Implication: Composite Higgs Models

$$\Delta\kappa_W = -\frac{1}{2}\xi$$

$$\xi < 0.15\%$$

$$f > 6.4\mathrm{TeV}$$

$$\Delta\kappa_{W_2} = -2\xi$$

$$\xi < 0.31\%$$

$$f > 4.4\mathrm{TeV}$$

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

$10\ \mathrm{TeV}\ @\ 10\ \mathrm{ab}^{-1}$

$95\ \%\mathrm{CL}$

Implication: Nonlinearity Test

$$\mathcal{O}_H = \frac{c_H}{2f^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \qquad \mathcal{O}'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu |H|^2 \partial^\mu |H|^2$$

$$\Delta\kappa_W = -\frac{1}{2}\xi + \left(\frac{3}{8}c_H^2 - \frac{c'_H}{4}\right)\xi^2$$

$$\Delta\kappa_{W_2} = -2\xi + \left(3c_H^2 - \frac{3c'_H}{2}\right)\xi^2$$

PNGB

$$c'_H = 2c_H^2$$

Promising for $\xi \gtrsim 0.1$

R.C., C. G., D. P. , R. R., A. T. 13'
DL, I. Low, Z. Yin, PRL 18'