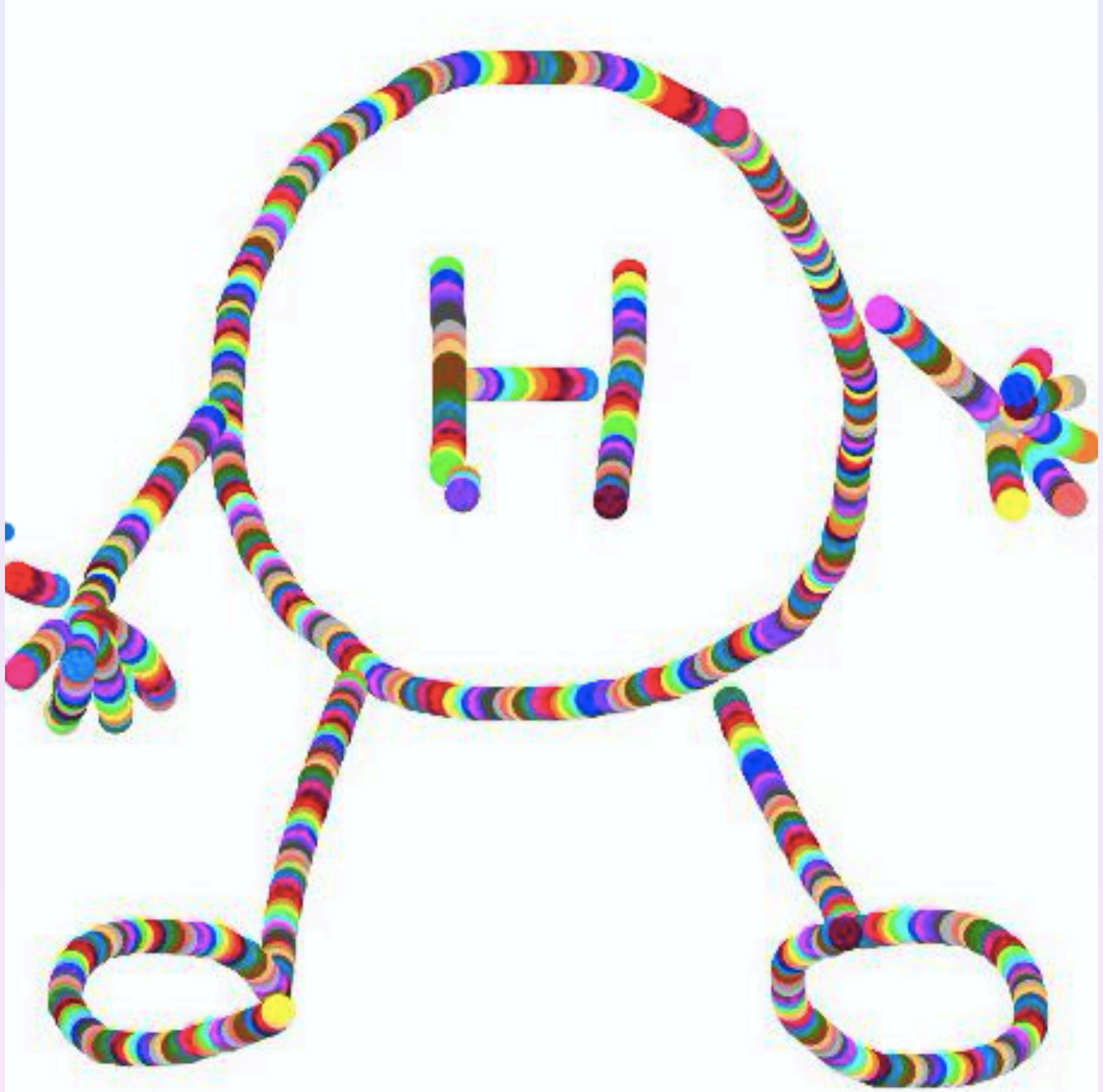
Composite Higgs Models

Ramona Gröber

IPPP,
Durham University



Higgs Couplings

10/11/2017

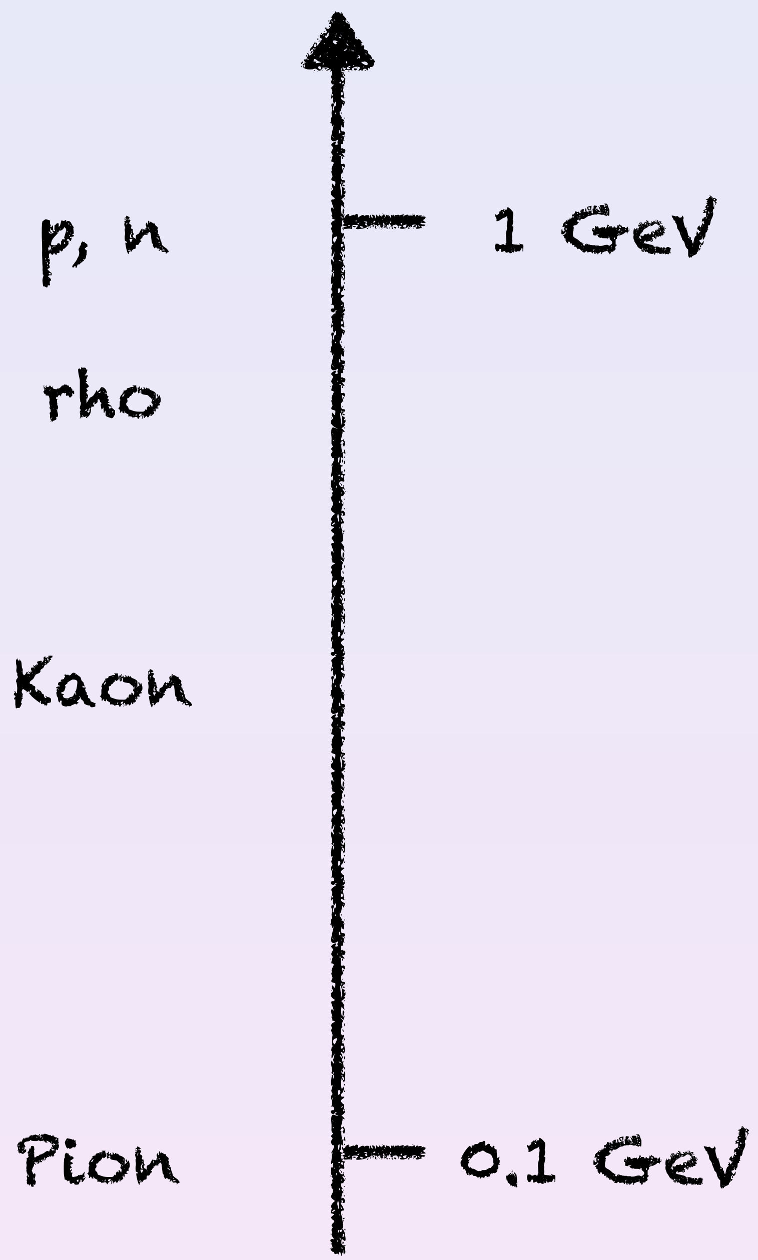
Outline

- Introduction to Composite Higgs Models
  - Composite scalars in QCD
  - Composite Higgs Models
  - Lagrangian
  - Partial compositeness

- How can we test Composite Higgs Models at the LHC?
  - Higgs couplings
  - Resonances
  - Non-linearities

- Non-minimal Composite Higgs Models
  - Dark matter

Composite Scalars in QCD



Spectrum of QCD:
Scalars without hierarchy problem

The QCD scale cuts their quantum corrections naturally off

Pions as pseudo-Nambu Goldstone bosons, naturally much lighter than QCD scale

QCD scale is natural,
can be largely separated from any high scale due to logarithmical running

Composite Higgs Models

[Georgi, Kaplan '84]

light, since pseudo-Goldstone boson

spin 0: H, ...

spin 1/2: T, B, $X^{5/3}$,...

spin 1: ρ, a,...

strongly interacting sector

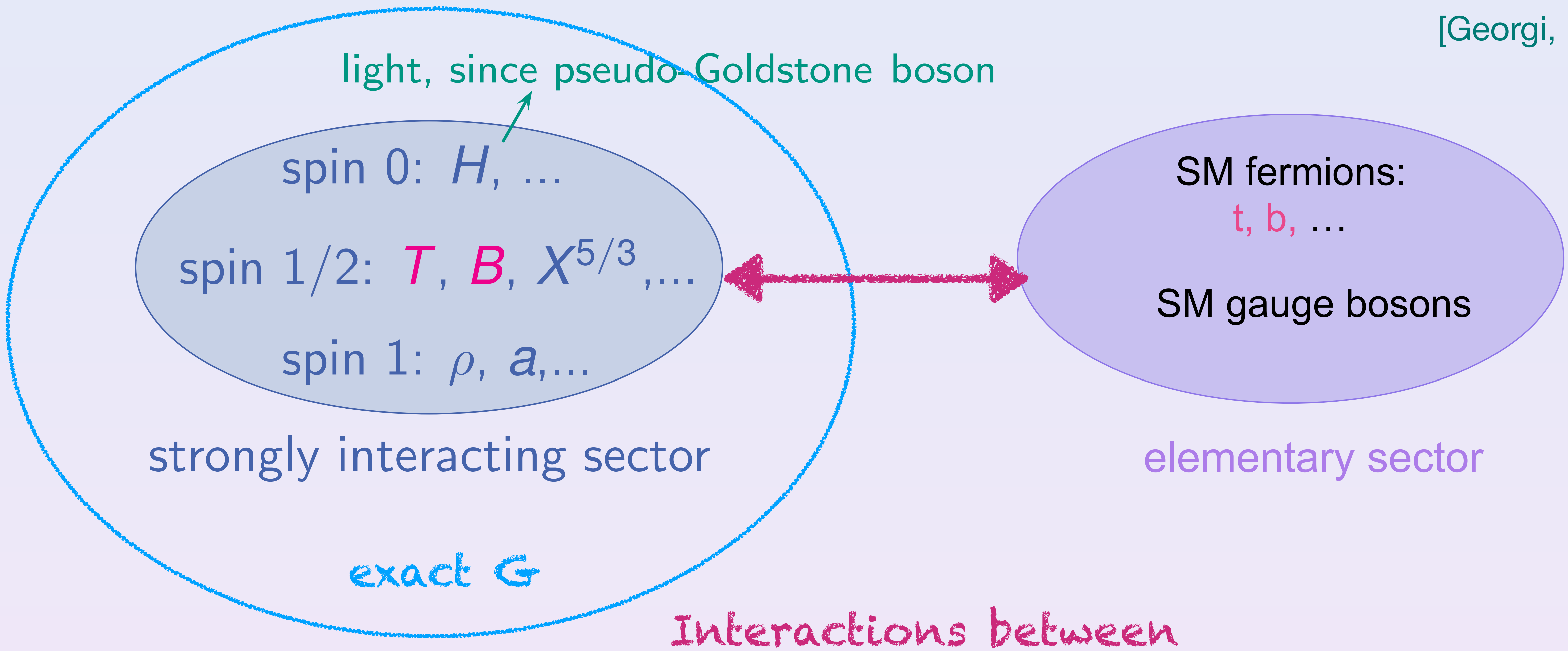
SM fermions:
t, b, ...

SM gauge bosons

elementary sector

Composite Higgs Models

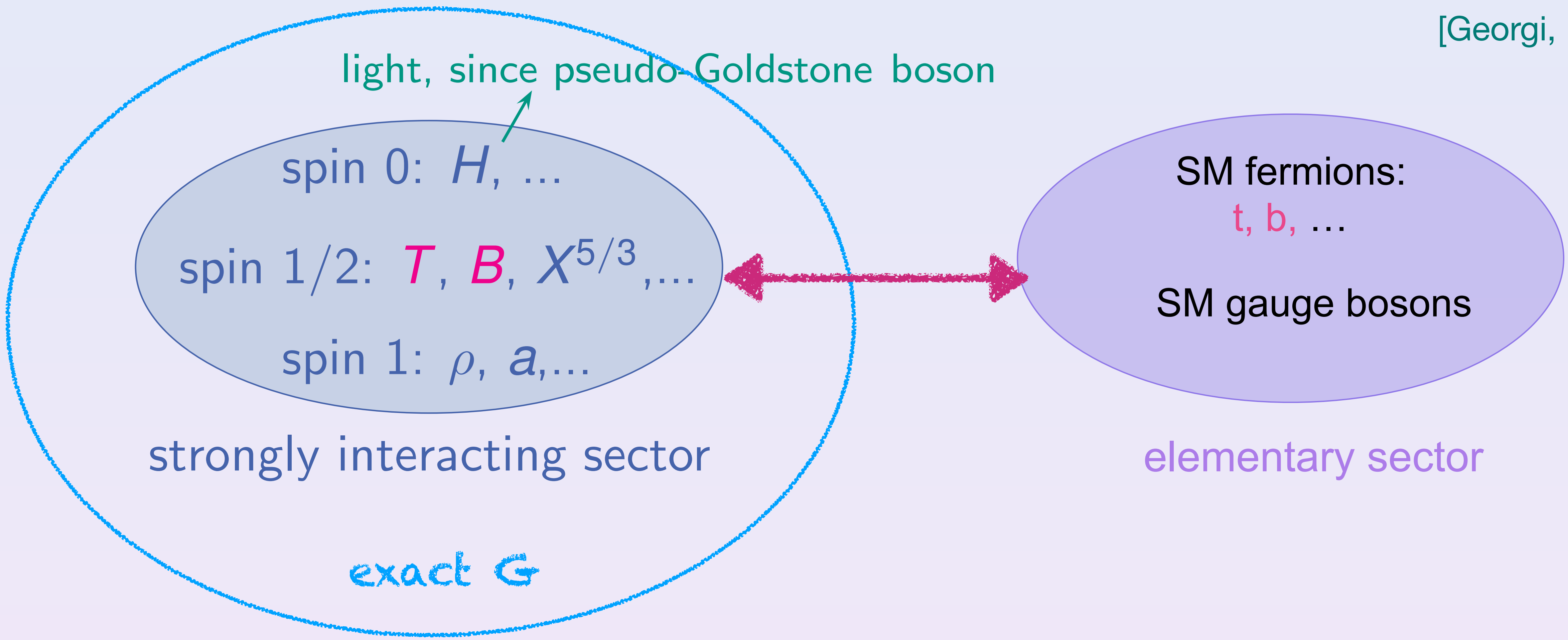
[Georgi, Kaplan '84]



Interactions between elementary and strongly interacting sector break G at scale f; coset G/H should contain the SM gauge group

Composite Higgs Models

[Georgi, Kaplan '84]



Higgs mass generated by quantum corrections

Partial compositeness: top quark mass generated by linear interactions with strongly interacting sector

Lagrangian for a Composite Higgs

Requirements:

- the unbroken group H contains the SM gauge group G

$$G \to H \subset SU(2) \times U(1)$$

- The coset space G/H contains at least 4 Goldstone bosons (corresponding to the Higgs doublet)

- Custodial symmetry: to be conform with EWPTs

$$H \subset SU(2)_R \times SU(2)_L$$

Minimal model: [Agashe, Contino, Pomarol '04]

$$SO(5) \times U(1)/SO(4) \times U(1)$$

contains 4 Goldstone bosons (3 the usual Goldstones + Higgs boson)

Lagrangian for a Composite Higgs

Lagrangian from CCWZ construction: [Callan, Coleman, Wess, Zumino'69]

Goldstone matrix (X denote the broken generators) $U = e^{-i\frac{\sqrt{2}}{f}\pi^{\hat{a}}X^a}$

Defining

$$iU^{-1}\partial_\mu U = d_{\mu,a}X^a + e_{\mu,a}T^a$$

the Lagrangian is

$$\mathcal{L} = \frac{f^2}{4}\mathrm{Tr}(d_\mu d^\mu)$$

Minimal model:

more details in [Panico, Wulzer '15]

We take a $\Sigma_0 = (0,0,0,0,1)^T$ to project on coset space.

Then

$$\mathcal{L} = \frac{f^2}{2}\left(D_\mu \Sigma\right)^\dagger D^\mu \Sigma, \quad \text{with } \Sigma = U\Sigma_0,$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{g^2}{4} f^2 \sin^2\left(\frac{h}{f}\right) W^+_\mu W^{\mu -} + \frac{g^2}{8c_W^2} f^2 \sin^2\left(\frac{h}{f}\right) Z_\mu Z^\mu .$$

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leads to non-linearities

$$\xi = \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

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$$\xi = \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

$$\frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1-\xi}$$

Partial compositeness

[Kaplan '91]

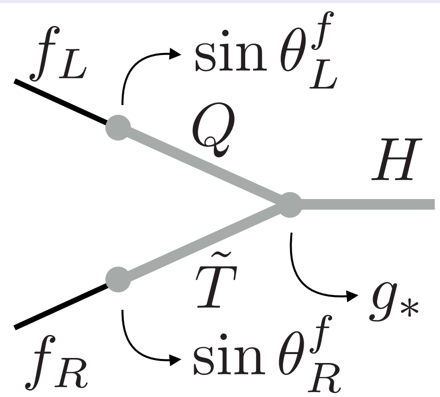
Elementary fermions mix with strong-interacting sector by linear couplings

$$\mathcal{L} = \lambda_L \bar{q}_L \mathcal{O}_R + \lambda_R \bar{t}_R \mathcal{O}_L$$

Mixing with top partners generate the top Yukawas

[Panico, Wulzer '15]

$y_t =$



$= g_* \cdot \sin\theta_L^f \cdot \sin\theta_R^f$

If we are only interested in the non-linearities:

Example : fermions transforming in the fundamental of SO(5)

$$Q_L^{2/3} = \frac{1}{\sqrt{2}}\left(d_L,\, -id_L,\, u_L,\, iu_L,\, 0\right)^T, \quad U_R = \frac{1}{\sqrt{2}}\left(0,\, 0,\, 0,\, 0,\, \sqrt{2}u_R\right)^T$$

$$\mathcal{L}_Y = f\left[-y_u(\overline{U_R}\Sigma)(\Sigma^T Q_L^{2/3}) - y_d(\overline{D_R}\Sigma)(\Sigma^T Q_L^{-1/3})\right] + \text{h.c.}$$

⟶ MCHM5: $\frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{SM}} = \frac{1-2\xi}{\sqrt{1-\xi}}$ MCHM10: $\frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{SM}} = \frac{1-2\xi}{\sqrt{1-\xi}}$ MCHM4: $\frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{SM}} = \sqrt{1-\xi}$

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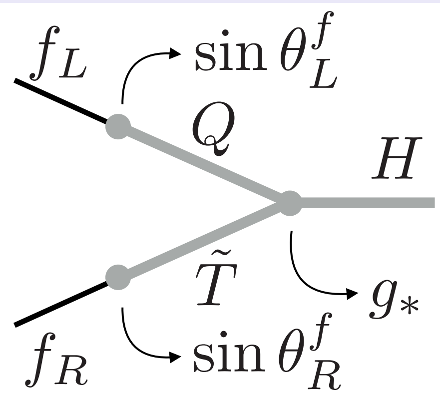

$= g_* \cdot \sin\theta_L^f \cdot \sin\theta_R^f$

The couplings break the global symmetry explicitly

⟶ Connection between top partner masses and Higgs mass

$$\frac{m_h^2}{m_t^2} \simeq \frac{N_c}{\pi^2}\frac{m_\psi^2}{f^2}$$

Low tuning = light top partner masses

[Matsedonskyi, Panico, Wulzer '12, Marzocca, Serone, Shu '12, Pomarol, Riva '12, Panico, Redi, Tesi, Wulzer '12, Pappadopulo, Thamm, Torre '13]

How to test whether the Higgs is Composite?

- Higgs coupling modifications

- more resonances from the strongly-interacting sector

- non-linearities in Higgs interactions

How to test whether the Higgs is Composite?

- Higgs coupling modifications

In SO(5)/SO(4) models: $\frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1-\xi}$

Holds true also in other models, e.g. SO(6)/SO(5) with dark matter candidate

Higgs self-couplings and couplings to fermion depend on fermion embedding

- more resonances from the strongly-interacting sector

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Probe couplings of n Higgs bosons

$$c_{tt} \neq \frac{3}{2}(c_t - 1) \qquad\qquad c_g \neq c_{gg}$$

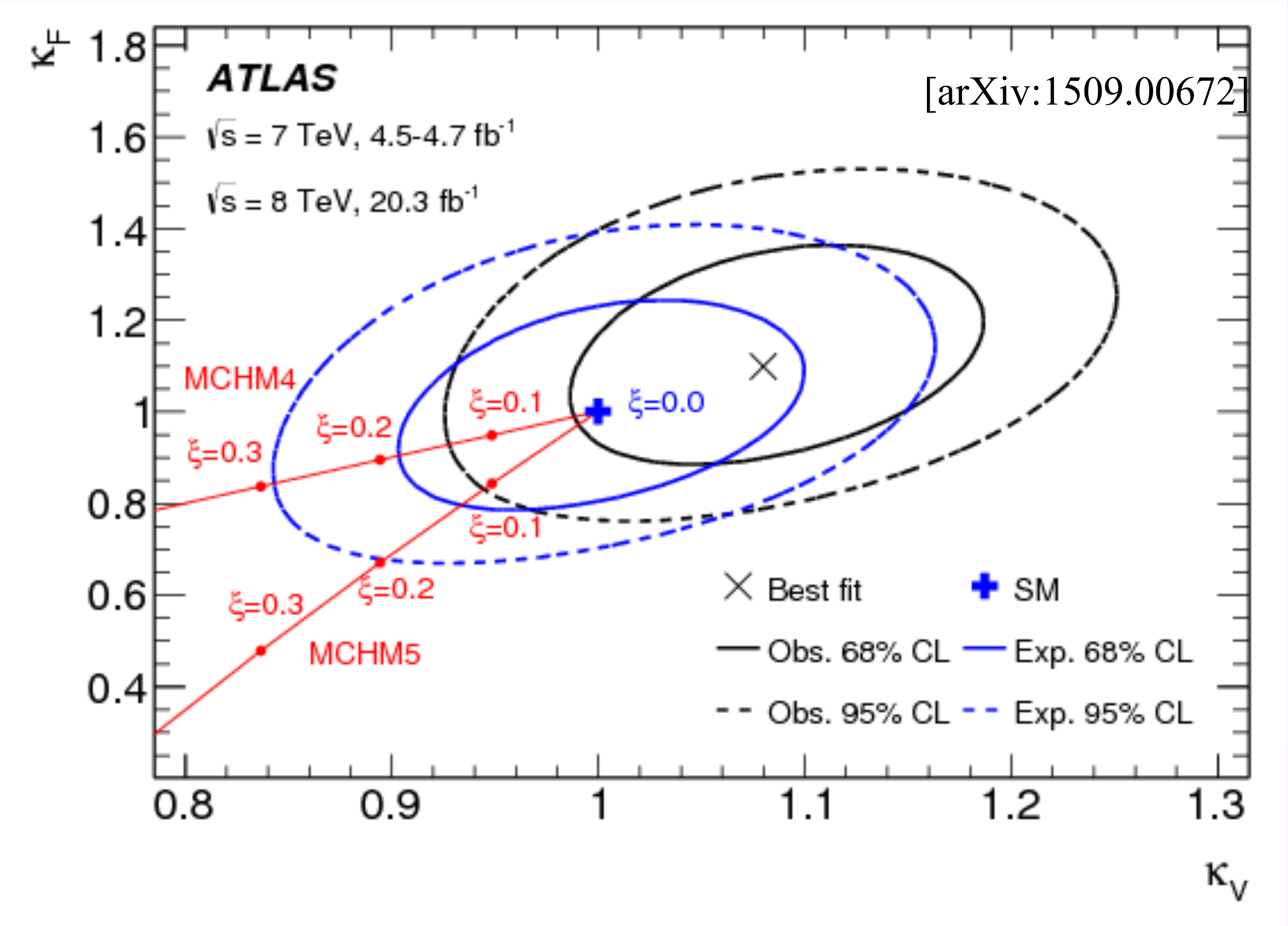
Higgs couplings

MCHM4:

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

MCHM5:

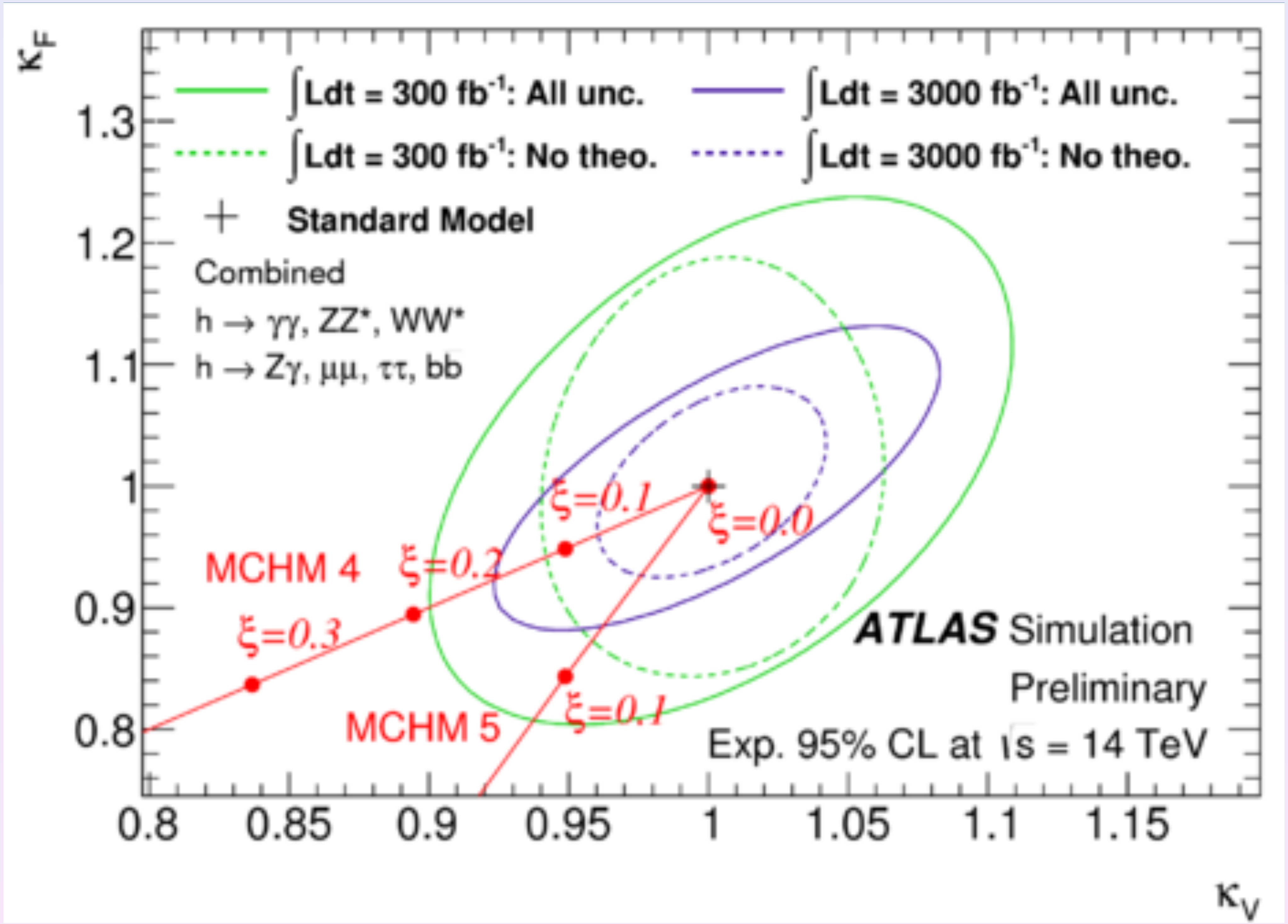
$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$



MCHM4/5: $\kappa_V = \sqrt{1-\xi}$

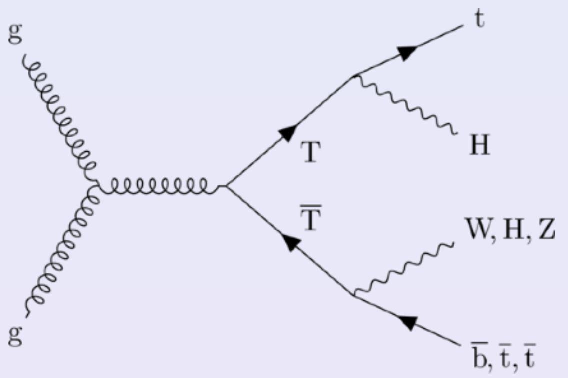
Higgs couplings

talk of M.Testa, HL-LHC workshop

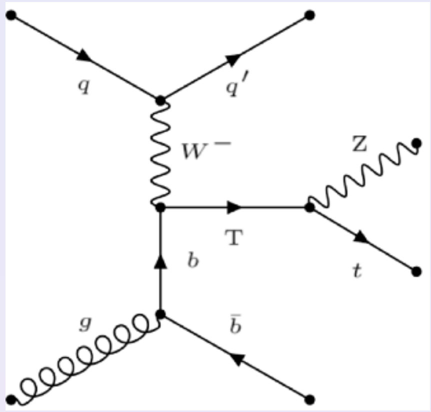


New resonances: Vector-like fermions

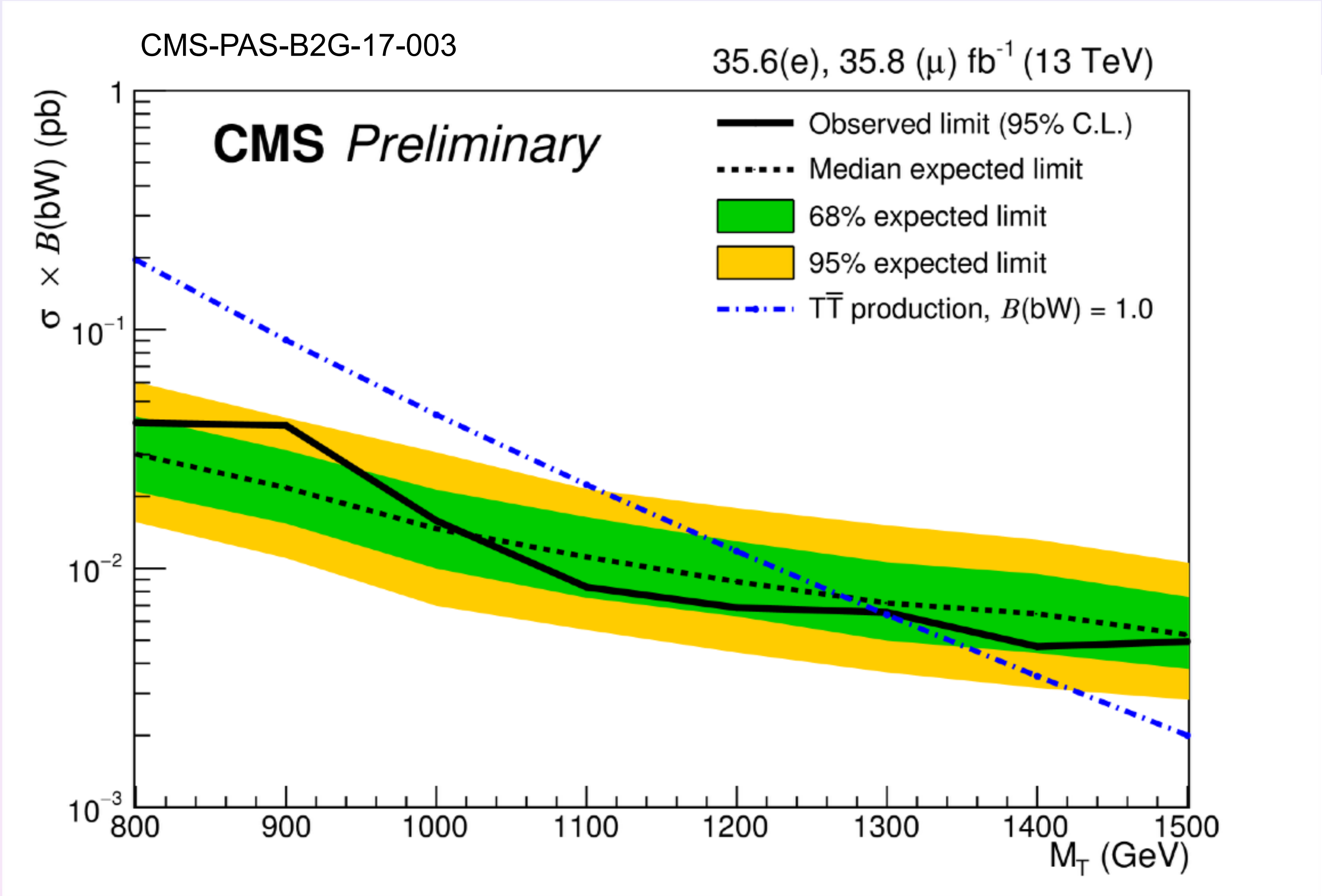
Pair production of VLQs:
pure QCD process, model independent

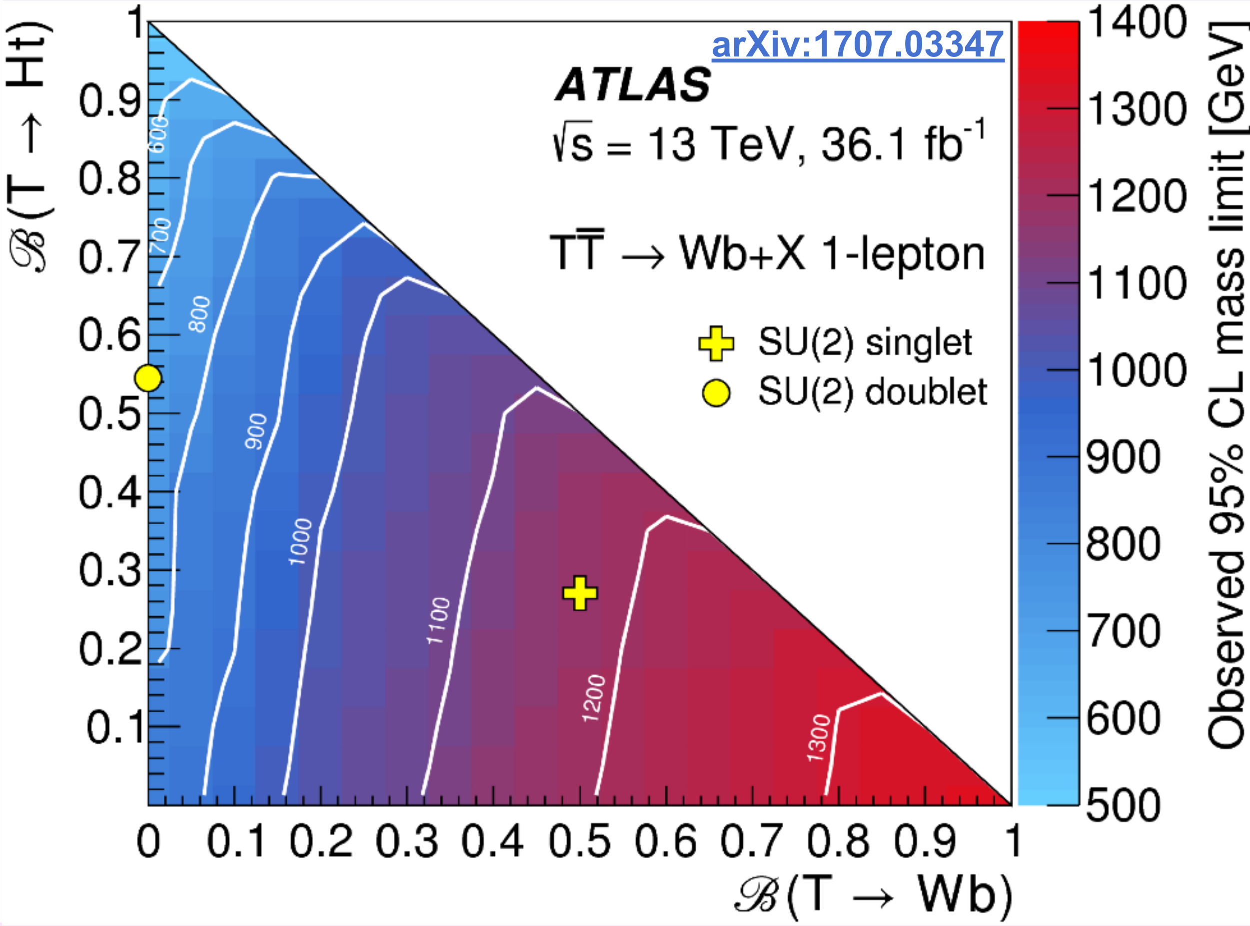


Single production of VLQs:
potentially higher reach, model-dependence



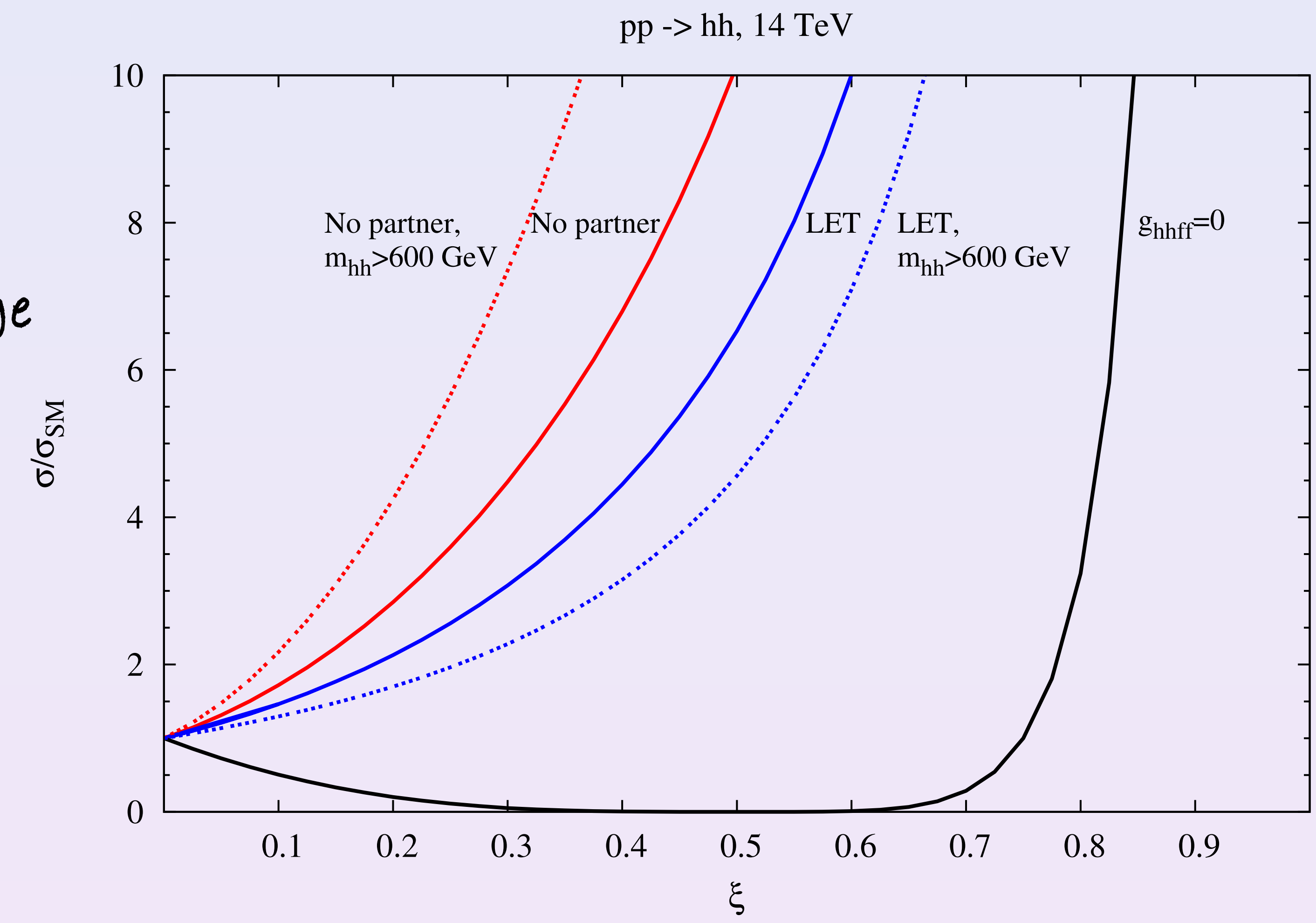
Limits from pair production:





Needs to be probed in multi-Higgs interactions

[Gillioz, RG, Grojean, Mühlleitner, Salvioni '12]



Di-Higgs production via Gluon fusion

New hhff coupling leads to large increase of cross section

[RG, Mühlleitner '10, Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer '12]

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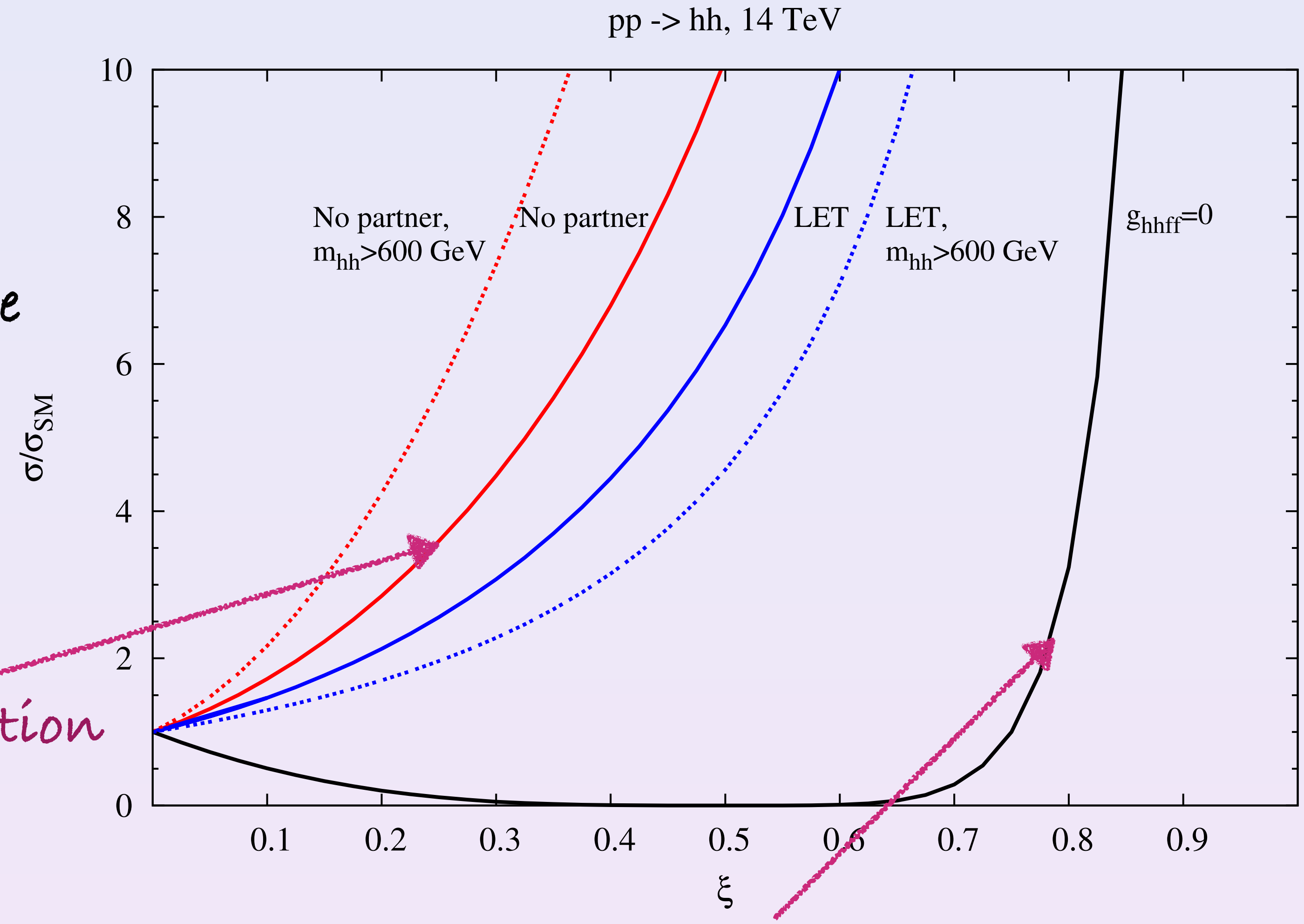

Full LO MCHM5 pp->hh cross section

MCHM5 pp->hh cross section setting hhff coupling to zero

Higgs non-linearities

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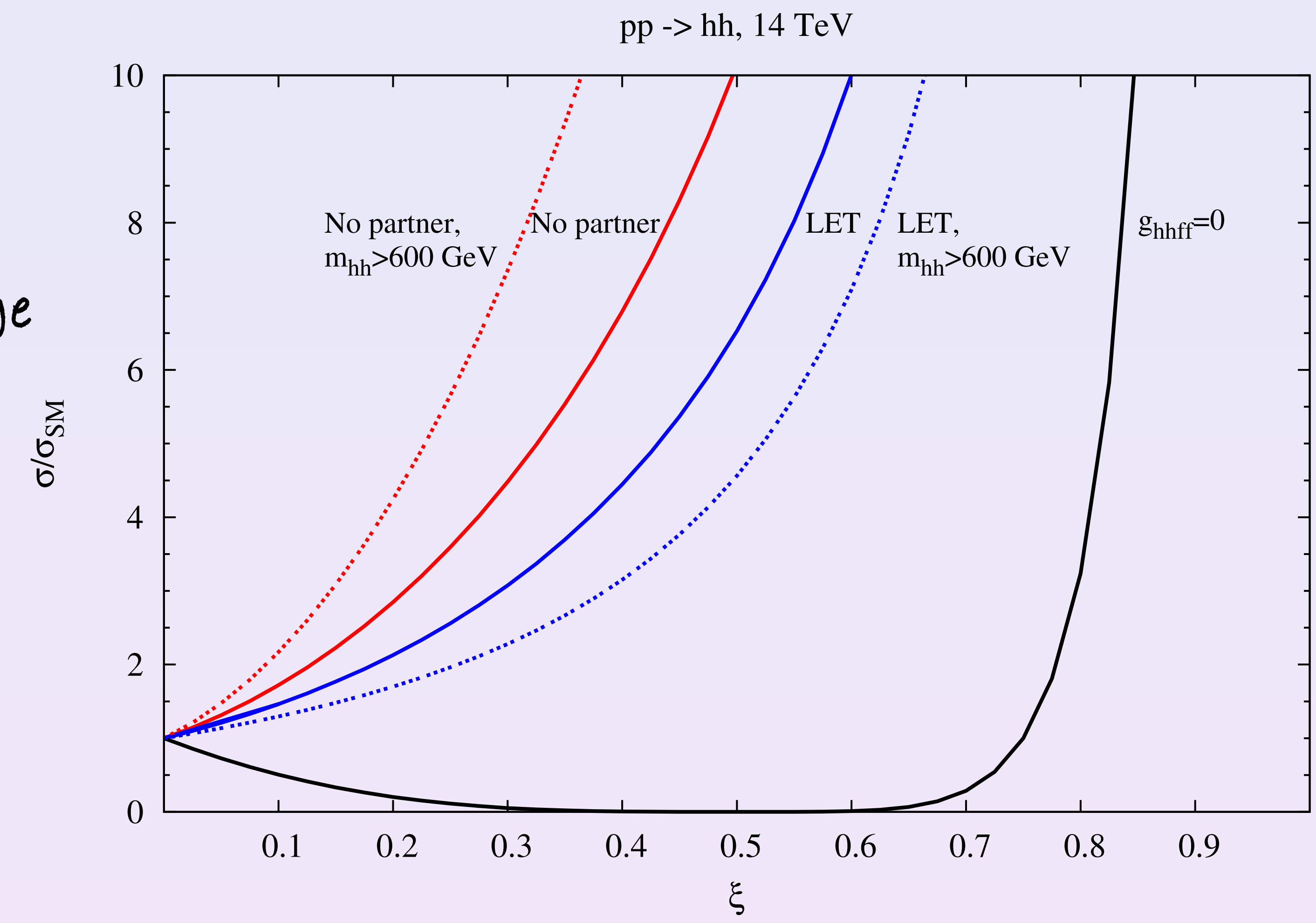

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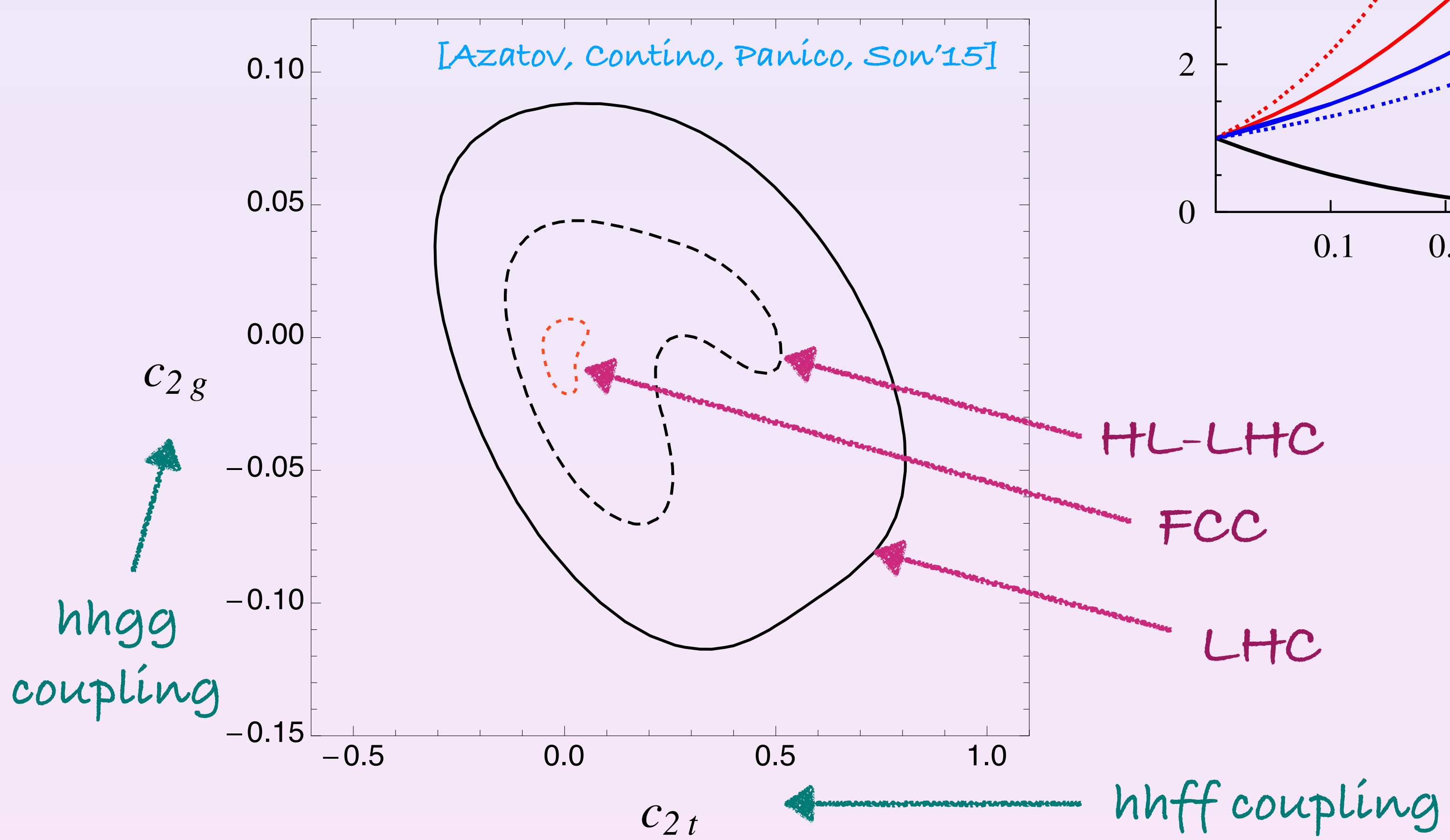
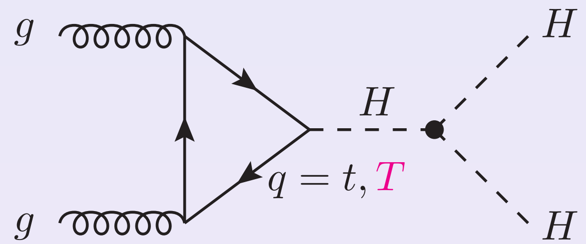


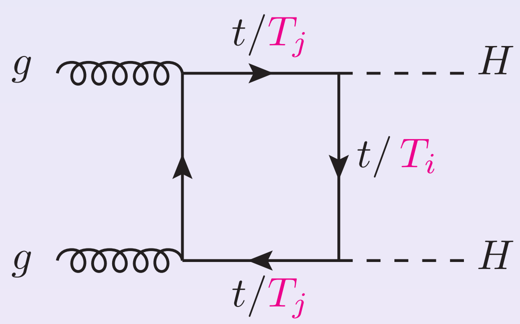
Composite Di-Higgs production

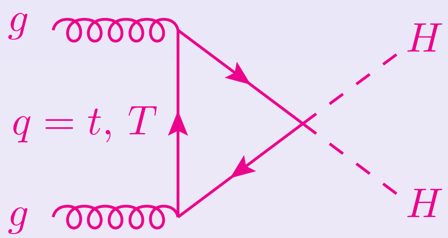
Can the increase in the cross section even be so large that New Physics will be first observed in di-Higgs production?

More freedom necessary than just new parameter ξ

Take a model with top and bottom partners







Composite Di-Higgs production

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Indirect tests:
EWPT, $|V_{tb}| > 0.92$

Higgs couplings:
projected sensitivities

Direct searches:
projected sensitivities
for vector-like quarks

Valid points:
$S_{SM} \pm \beta \sqrt{S_{SM}} \lessgtr S$

$S = \sigma \; BR \; \mathcal{L} \; A$

for $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\bar{\tau}$ final state [Baglio, Djouadi, RG, Mühlleitner, Quevillon, Spira '12]

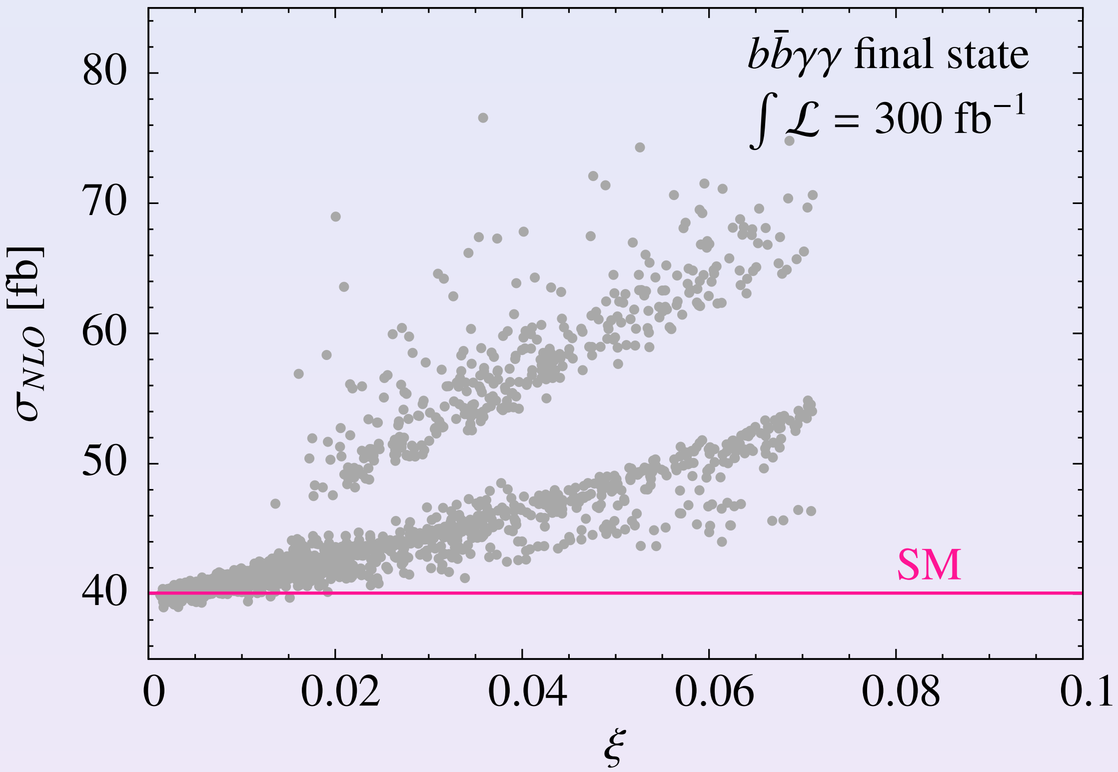
EWPTs from [Gillioz, RG, Kapuvari, Mühlleitner '14]

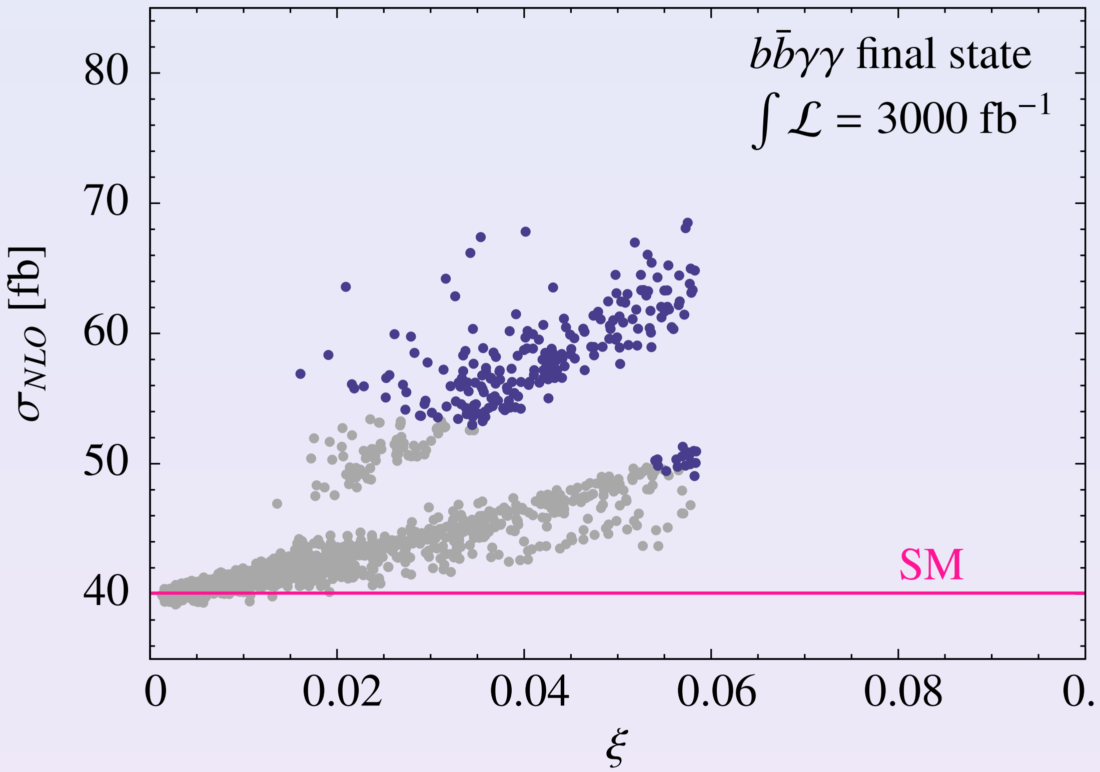
Projected sensitivities for Higgs couplings from [Englert, Freitas, Mühlleitner, Plehn, Rauch, Spira, Walz '14]

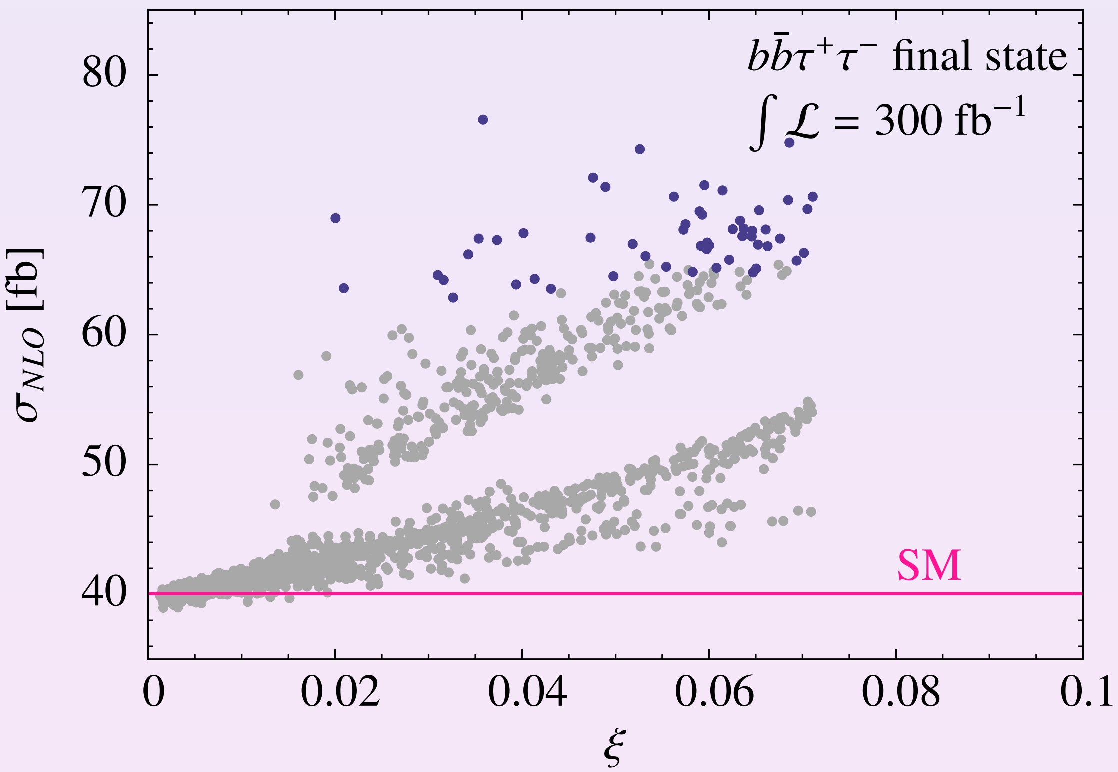
Projected sensitivities for direct searches of VLQs $m \lesssim 1.5$ TeV

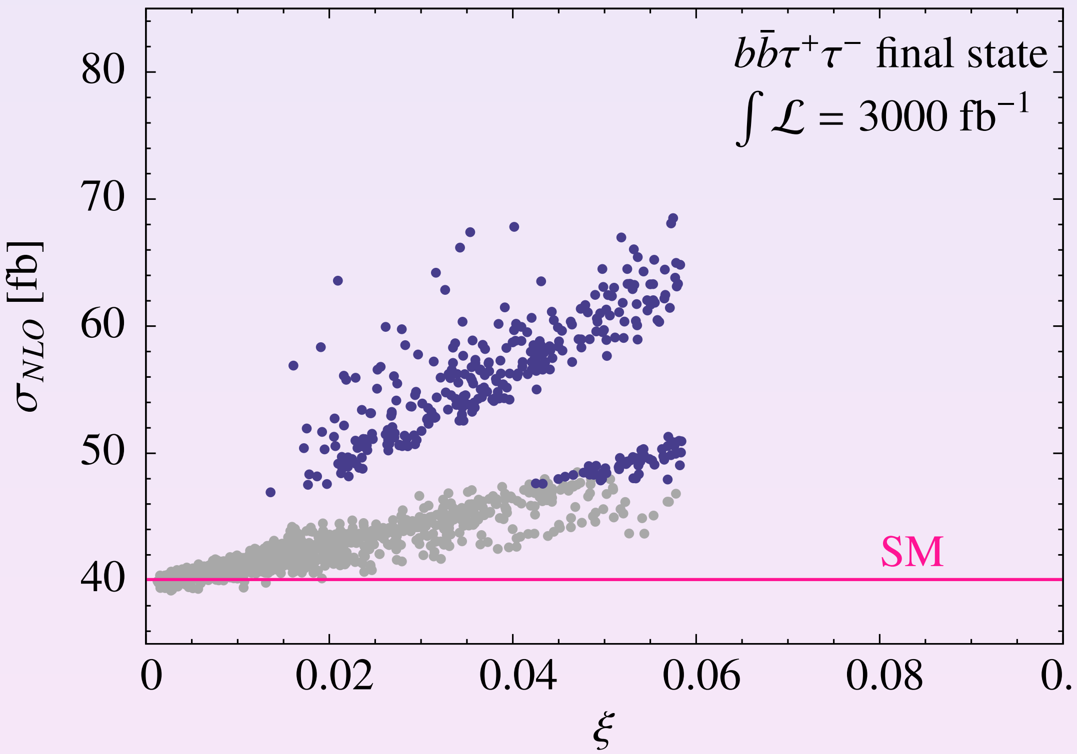
Composite Di-Higgs production

[RG, Mühlleitner, Spira '16]









Non-minimal Composite Higgs Models

[Mrazek et al '11]

G	H	N_G	NGBs rep.$[H]$ = rep.$[SU(2) \times SU(2)]$	
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[Gripaios et al '09; Frigerio et al '12; Marzocca, Urbano '14]
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+2} + \bar{\mathbf{4}}_{-2} = 2 \times (\mathbf{2},\mathbf{2})$	[Mrazek et al '11, De Curtis etal'16]
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[Balkin et al '17]
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	[Chala '12; Ballesteros et al '16]
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	
SO(7)	$[SO(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3 \times (\mathbf{2},\mathbf{2})$	
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2 \times (\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2 \times (\mathbf{2},\mathbf{1})$	
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \times (\mathbf{2},\mathbf{2})$	
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$	

Larger coset space $\longrightarrow$ extended Higgs sector

Non-minimal Composite Higgs Models

If new scalar stable → possible dark matter candidate

i.e. if there is a Z_2 or $U(1)$ symmetry

General parameterisation:

$$L = |D_\mu H|^2 \left[1 - a_1 \frac{S^2}{f^2}\right] + \frac{a_2}{f^2}\partial_\mu |H|^2 (S\partial_\mu S) + \frac{1}{2}(\partial_\mu S)^2 \left[1 - 2a_3 \frac{|H|^2}{f^2}\right]$$
$$- m_\rho^2 f^2 \frac{N_c y_t^2}{(4\pi)^2}\left[-\alpha\frac{|H|^2}{f^2} + \beta\frac{|H|^4}{f^4} + \gamma\frac{S^2}{f^2} + \delta\frac{S^2|H|^2}{f^4}\right] + \left[i\epsilon\frac{y_t}{f^2}S^2\overline{q_L}Ht_R + \text{h.c.}\right] + \cdots$$

Non-minimal Composite Higgs Models

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Annihilation cross section dominated by $H^2 S^2$ interactions

$a = a_1 = a_3 = a_3$

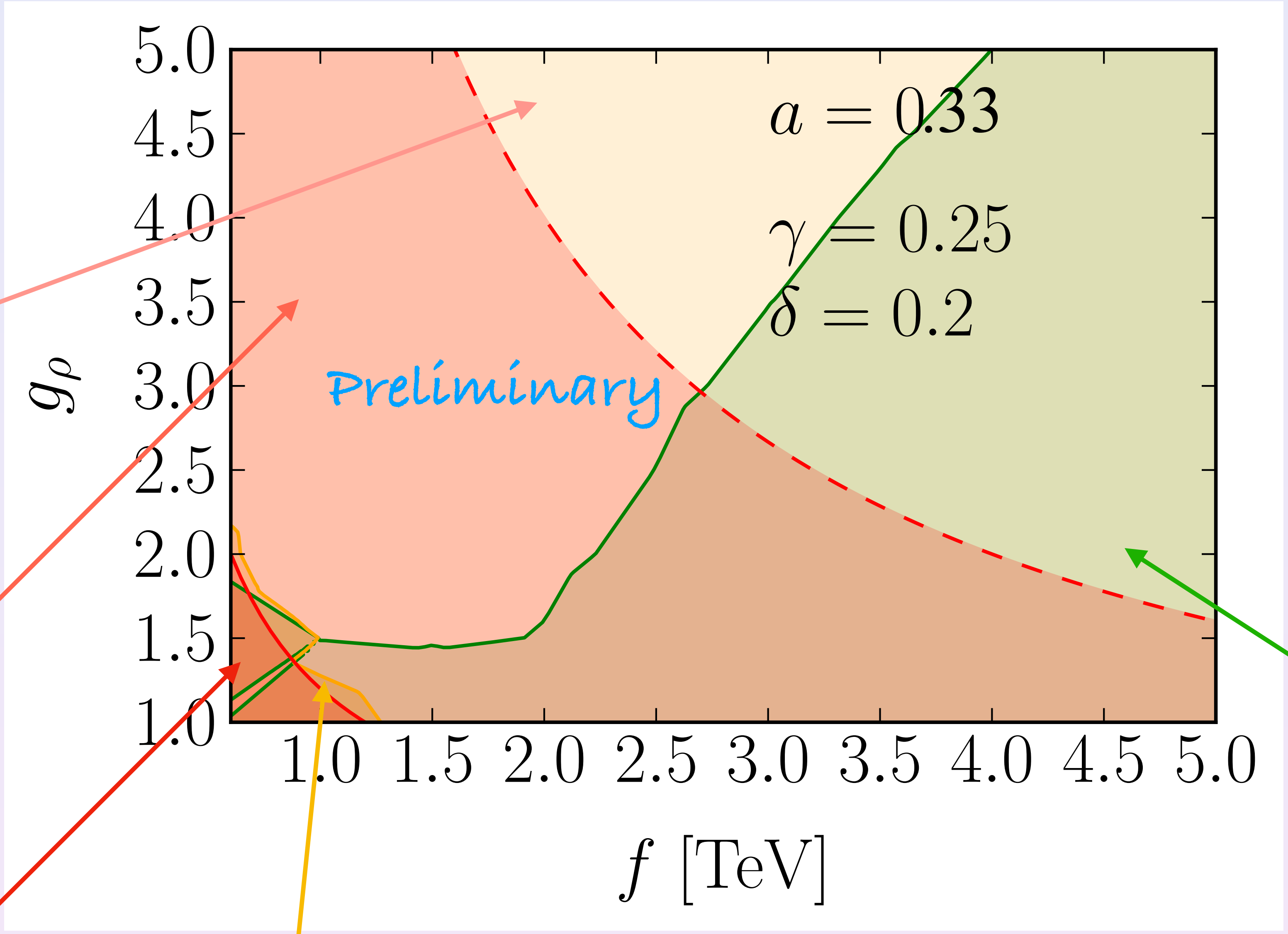
Relic density (if a $\gamma > \delta/10$):

$$\Omega h^2 \propto \frac{f^2}{g_\rho^2} \quad \text{with} \quad m_\rho = g_\rho f$$

Main difference to non-composite case: derivative interactions

SO(6)/SO(5) model

[Chala, RG, Spannowsky preliminary]



future LZ probed

FCC probed

LHC excluded

using VLQlimits [Chala '17]

LUX excluded

Overabundance of dark matter

Conclusion

- Composite Higgs Models viable alternative to Standard Model

- Testable at LHC by
    - Higgs coupling measurements
    - Searches for new resonances
    - Non-linearities

- Composite Dark matter scenarios very predictive
    - Hints to values of f above tuning expectation
    - future colliders and dark matter direct detection experiments will shed light on such scenarios

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Thanks for you attention!