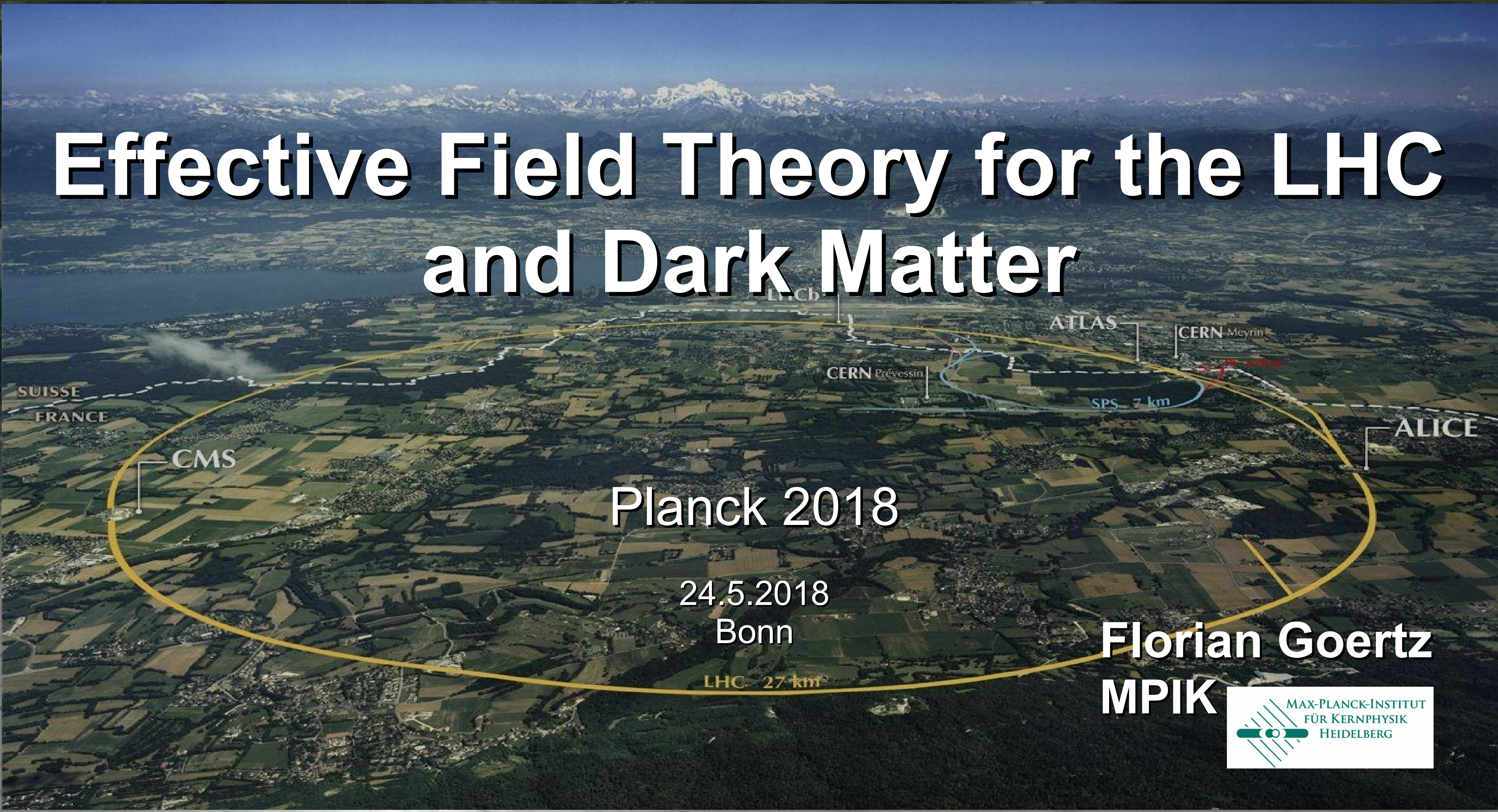
Effective Field Theory for the LHC and Dark Matter



Planck 2018

24.5.2018
Bonn

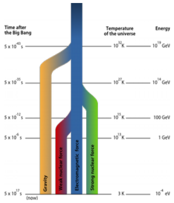
Florian Goertz
MPIK
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Contino, Falkowski, FG, Grojean, Riva, JHEP07(2016)144

FG, 1711.03162 Alanne, FG, 1712.07626

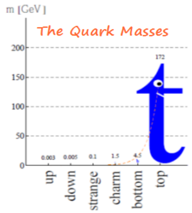
Physics Beyond the SM

The SM does not explain everything!

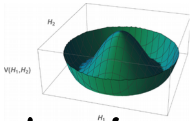


- Gravity $\not\subset$ SM
- Hierarchy Problem: $m_h << M_{PL}$

- Tiny Neutrino Masses
- Grand Unification of Forces?

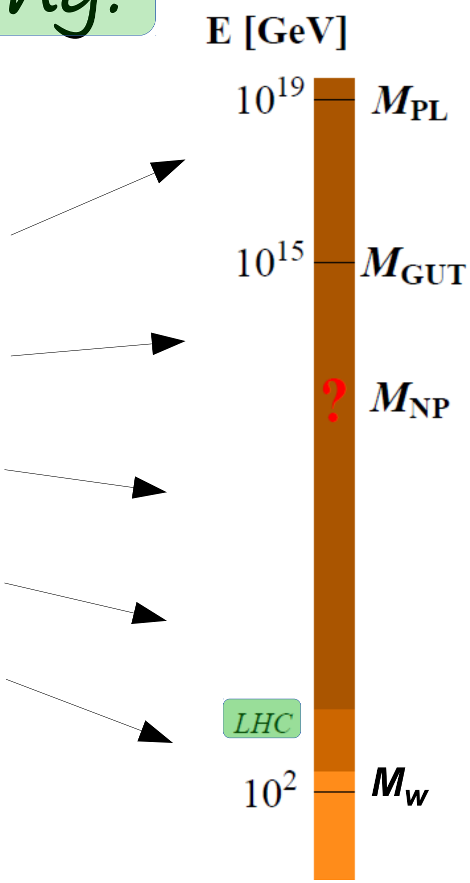


- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\not\in$ SM
- Trigger for Symmetry-Breaking Potential?



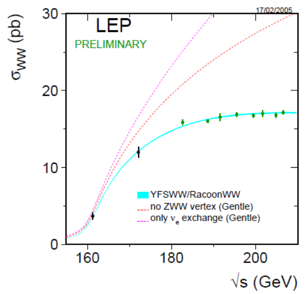
- Strong CP Problem
- Some Hints in Flavor/Precision Physics

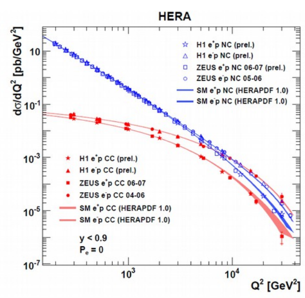
.....

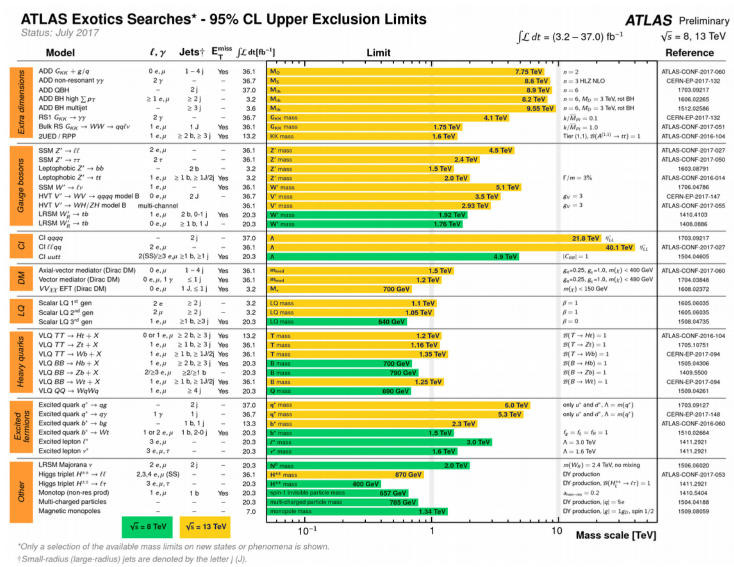


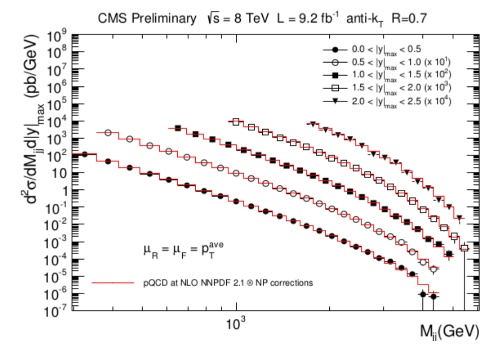
Physics Beyond the SM

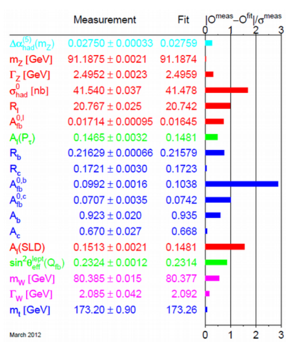
vs. **The SM is a Success Story**

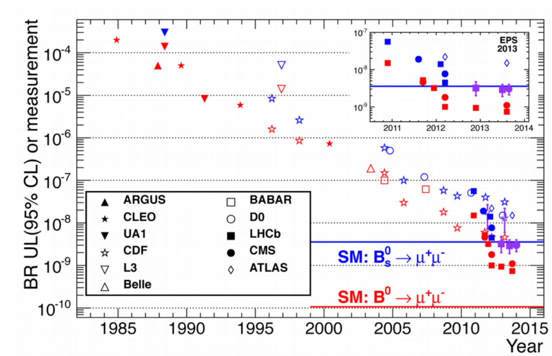












New Physics should be rather heavy

(or very weakly coupled to the SM)

Effective Field Theory (EFT) Approach to NP

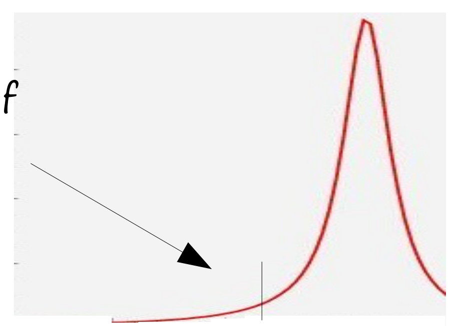
- NP at $\Lambda \gg M_{EW}$, not directly accessible → well described by operators with $d[\mathcal{O}] > 4$

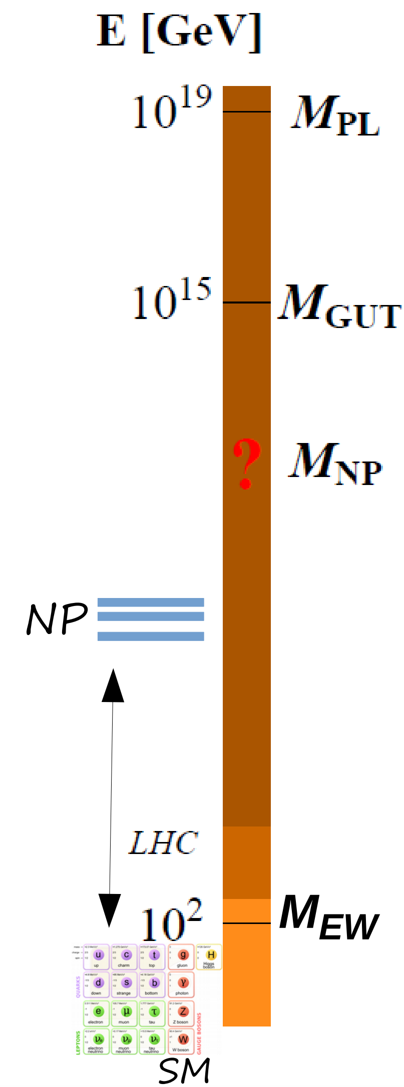
$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{D=6} + \mathcal{O}(E^4/\Lambda^4)$$

local operators = New Physics
SM field content + gauge symmetries

Effects scale like E^2/Λ^2
→ suppressed by mass scale of heavy new physics

Probe effects of NP in the tail





Weinberg, Wilson, Callen, Coleman, Wess, Zumino, …

Effective Field Theory (EFT) Approach to NP

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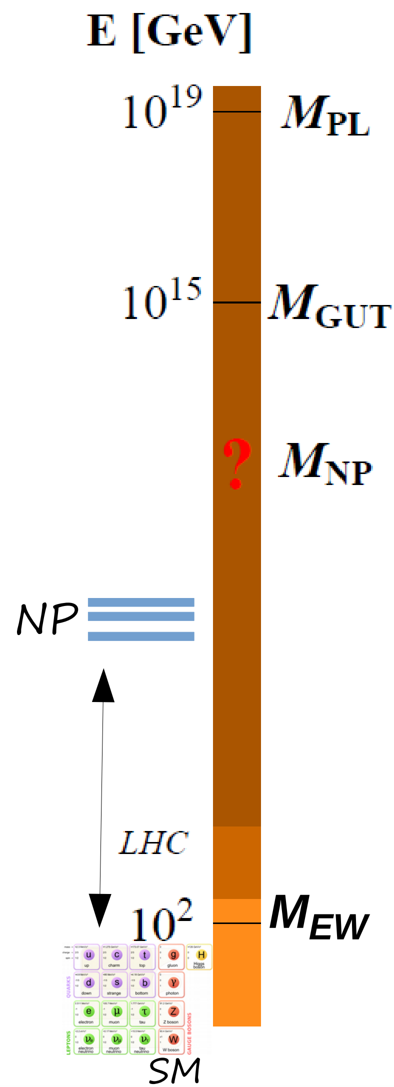
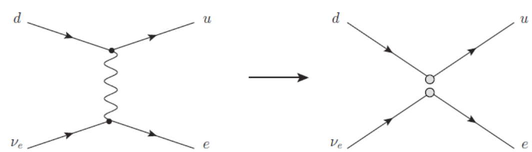
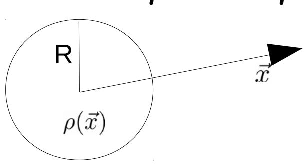


c.f. Fermi Theory



$$\mathcal{L}_{eff} = -\frac{g^2}{8m_W^2}C_1(\mu)(\bar{e}\,\nu_e)_{V-A}(\bar{u}\,d)_{V-A}$$

c.f. multipole expansion



$|\vec{x}| \gg R$:

$$\phi(\vec{x}) = \frac{1}{4\pi}\left(\frac{q}{|\vec{x}|} + \vec{p}\cdot\frac{\vec{x}}{|\vec{x}|^3} + \frac{1}{2}\sum_{i,j} Q_{ij}\frac{x_i x_j}{|\vec{x}|^5} + \cdots\right) \quad \left[\begin{array}{l} q = \int \rho(\vec{x})d^3x\,,\ \vec{p} = \int \vec{x}\rho(\vec{x})d^3x\,, \\ Q_{ij} = \int (3x_ix_j - |\vec{x}|^2\delta_{ij})\rho(\vec{x})d^3x \end{array}\right]$$

allows for gradual progress: Fermi Theory → SM → 'New SM'

EFT Approach to New Physics

- Full set of non-redundant operators (i.e., basis):

  59 D=6 operators (2499 including full flavor structure)

  [assuming B&L conservation]

Buchmuller, Wyler, NPB 268(1986)621-653

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

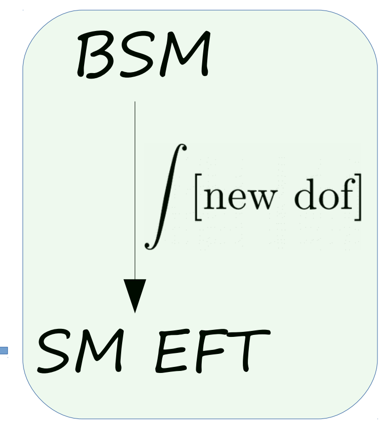
Alonso, Jenkins, Manohar, Trott, 1312.2014

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

Table 3: Four-fermion operators.



Constrain C_i

[One way to go, given the lack of evidence in favor of concrete models]

For non-linear realization, see Grinstein, Trott 0704.1505

Contino, Grojean, Moretti, Piccinini, Rattazzi 1002.1011

1) Validity of EFT Description?

→ EFT approach to NP: parametrize BSM physics via coefficients of D>4 operators and constrain them from experimental data

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8} + \ldots$$

→ provide guidance for constructing UV completion

→ EFT Limits can be translated to various models

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constraints on $C_i^{(D)}$ can be set 'without further assumptions':

When is bound meaningful/when is it appropriate to truncate at D=6?

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➡ Interpretation requires assumptions ...

Validity of EFT Description?

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \mathcal{O}(E^4/\Lambda^4)$$

➡ <u>*Interpretation requires assumptions*</u>

$$C^{(D)} \equiv C_i^{(D)}(M_k, g_k)$$

NP masses (integrated out) → M_k

couplings → g_k

Validity of EFT Description?

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \mathcal{O}(E^4/\Lambda^4)$$

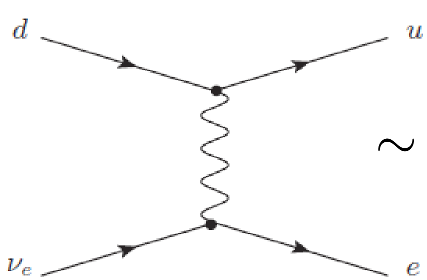
➡ <u>*Interpretation requires assumptions*</u>

expansion only valid if $M_k \gg M_{\mathrm{cut}}$ ⬌ Measurements constrain $C_i^{(6)}(M_k, g_k)$

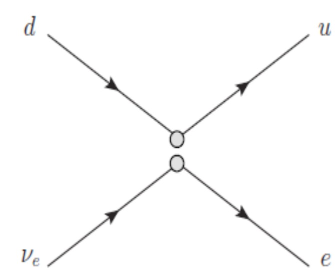
$M_k \sim \Lambda$

$\neq \Lambda^{-2}$

maximal scale E of process (momentum transfer)



$$\sim \frac{g^2}{p^2 - m_W^2} = -\frac{g^2}{m_W^2} + \mathcal{O}(p^2/m_W^4) \longrightarrow$$



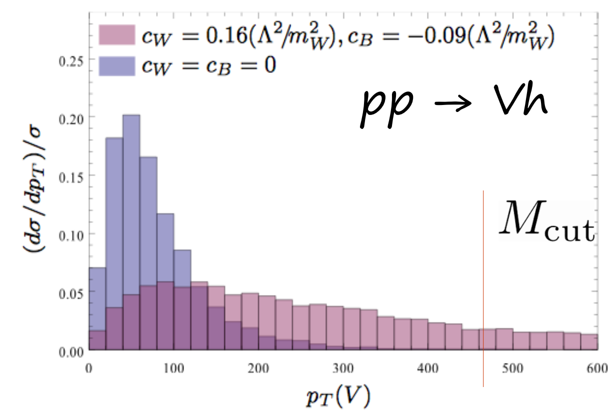
Validity of EFT Description?

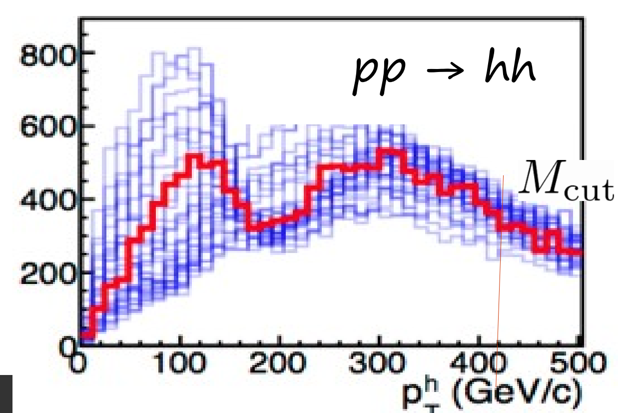
In fact: Experimental constraints: $C_i < \delta_i^{\rm exp}(M_{\rm cut})$

- Depend on upper value allowed for *kinematic variables* that set scale of process = $M_{\rm cut}$
- In some cases fixed by kinematics: on-shell Higgs decays, e+e- collisions

2→2 at LHC (WW, hV, hj, hh, ...): $M_{\rm cut}$ in general not fixed!

- Large E is just interesting range where pronounced sensitivity to NP is expected





Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320, ...

Kinematic distributions

Carvalho, Dall''Osso, Dorigo, FG, Gottardo, Tosi, 1507.02245
Azatov, Contino, Panico, Son, 1502.00539

Necessity of Power Counting

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \mathcal{O}(E^4/\Lambda^4)$$

→ Interpretation requires assumptions

expansion only valid if $M_k \gg M_{\rm cut}$ ⟺ Measurements constrain $C_i^{(6)}(M_k, g_k)$

$M_k \sim \Lambda$, $\quad C_i^{(6)}(M_k, g_k) \neq \Lambda^{-2}$

→ Accessing validity requires (broad) assumptions about underlying UV theory → some degree of model dependence

↓

Power Counting

↓

Quantify EFT uncertainty: missing terms of $O(E^4/\Lambda^4)$

[here and in following truncate at D=6]

Necessity of Power Counting

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8} + \dots$$

* Note that $\mathrm{C}_i^{(D)} \sim \frac{(\text{coupling})^{n_i-2}}{(\text{high mass scale})^{D-4}}$, n_i = #fields

$\mathcal{O}_1 = \bar{e}_L \gamma_\rho \nu_L^e \; \bar{\nu}_L^\mu \gamma_\rho \mu_L$

↓ n=4

Luty, ph/9706235

Cohen, Kaplan, Nelson, ph/9706275

Giudice, Grojean, Pomarol, Rattazzi, ph/0703164

Necessity of Power Counting

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8} + \ldots$$

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$\mathcal{O}_1 = \bar{e}_L \gamma_\rho \nu_L^e \; \bar{\nu}_L^\mu \gamma_\rho \mu_L$ → n=4

* Commonly assumed power counting: one scale Λ + one coupling g_*

→ $C_i^{(6)} \sim g_*^{n_i-2}/\Lambda^2$

Bounds $\frac{g_*^{n_i-2}}{\Lambda^2} < \delta_i^{\rm exp}(M_{\rm cut})$ → bound $\Lambda(g_*)$, depending on coupling strength

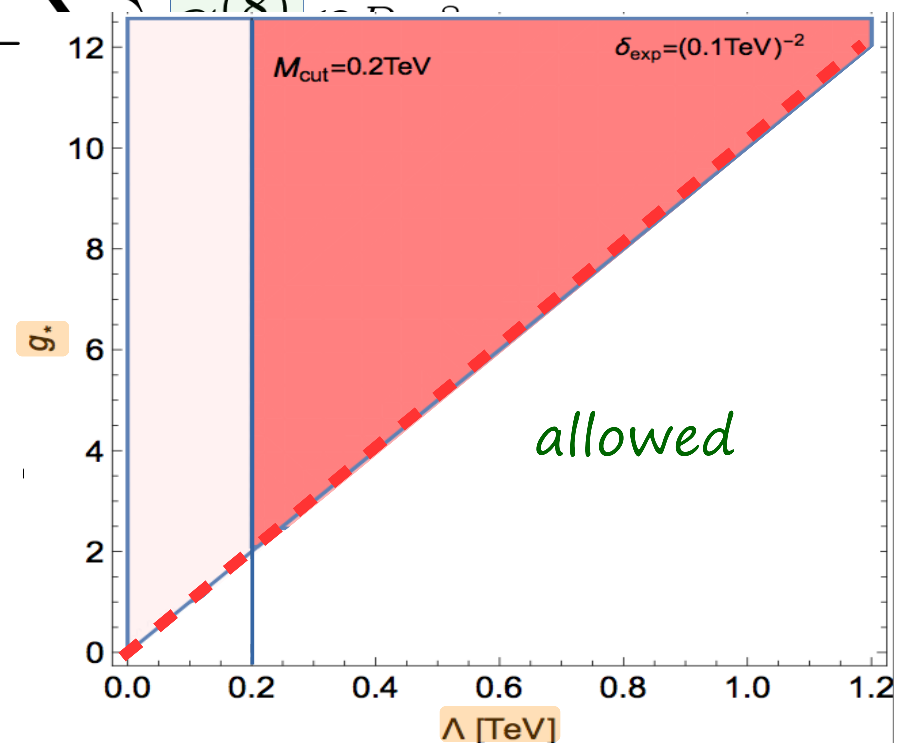
→ can assess their validity

Necessity of Power Counting

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}^{D \leq 4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8}$$

* Note that $\mathrm{C}_i^{(D)} \sim \frac{(\text{coupling})^{n_i - 2}}{(\text{high mass scale})^{D-4}}$,

* Commonly assumed power counting:



Bounds $\frac{g_*^{n_i - 2}}{\Lambda^2} < \delta_i^{\mathrm{exp}}(M_{\mathrm{cut}})$ → bound $\Lambda\,(g_*)$, depending on coupling strength

→ can assess their validity

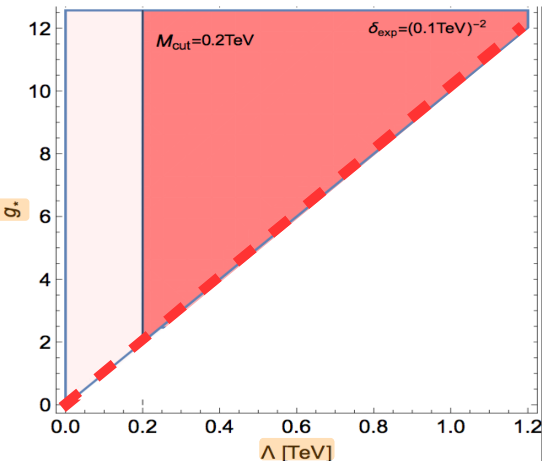
Power Counting → Validity of Bounds

Chosing $M_{\text{cut}} = \kappa\Lambda;\ \kappa \in [0,1]$ allows to set bounds in (g_*, Λ) plane, automatically consistent with the EFT:

$$\frac{c_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\text{exp}}(\kappa\Lambda)$$

For each Λ derive bound on $c_i^{(6)}(g_*)$, employing only data below $M_{\text{cut}} = \kappa\Lambda;\ \kappa \in [0,1]$

$$\kappa^2 = \frac{M_{\text{cut}}^2}{\Lambda^2}:$$ tolerated (naive) error due to neglecting higher-derivative (D=8) operators



See also Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320; Greljo, Isidori, Lindert, Marzocca, 1512.06135; Azatov, Contino, Panico, Son, 1502.00539; Berthier,Trott, 1502.02570, 1508.05060; Aguilar-Saavedra, Perez-Victoria, 1103.2765; Englert, Spannowsky, 1408.5147 Abdallah et al., 1409.2893; Racco, Wulzer, Zwirner, 1502.04701

Power Counting → EFT Error

Chosing $M_{\rm cut} = \kappa\Lambda;\ \kappa \in [0,1]$ allows to set bounds in (g_*, Λ) plane, automatically consistent with the EFT:

$$\frac{c_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(\kappa\Lambda)$$

For each Λ derive bound on $c_i^{(6)}(g_*)$, employing only data below $M_{\rm cut} = \kappa\Lambda;\ \kappa \in [0,1]$

Error:

$$\kappa_E^2 = \frac{M_{\rm cut}^2}{\Lambda^2}$$ (higher-derivative operators)

$$\kappa_v^2 = \frac{g_*^2 v^2}{\Lambda^2}$$ (addtl. Higgs fields → vev)

D=8 operators contributing to same vertex

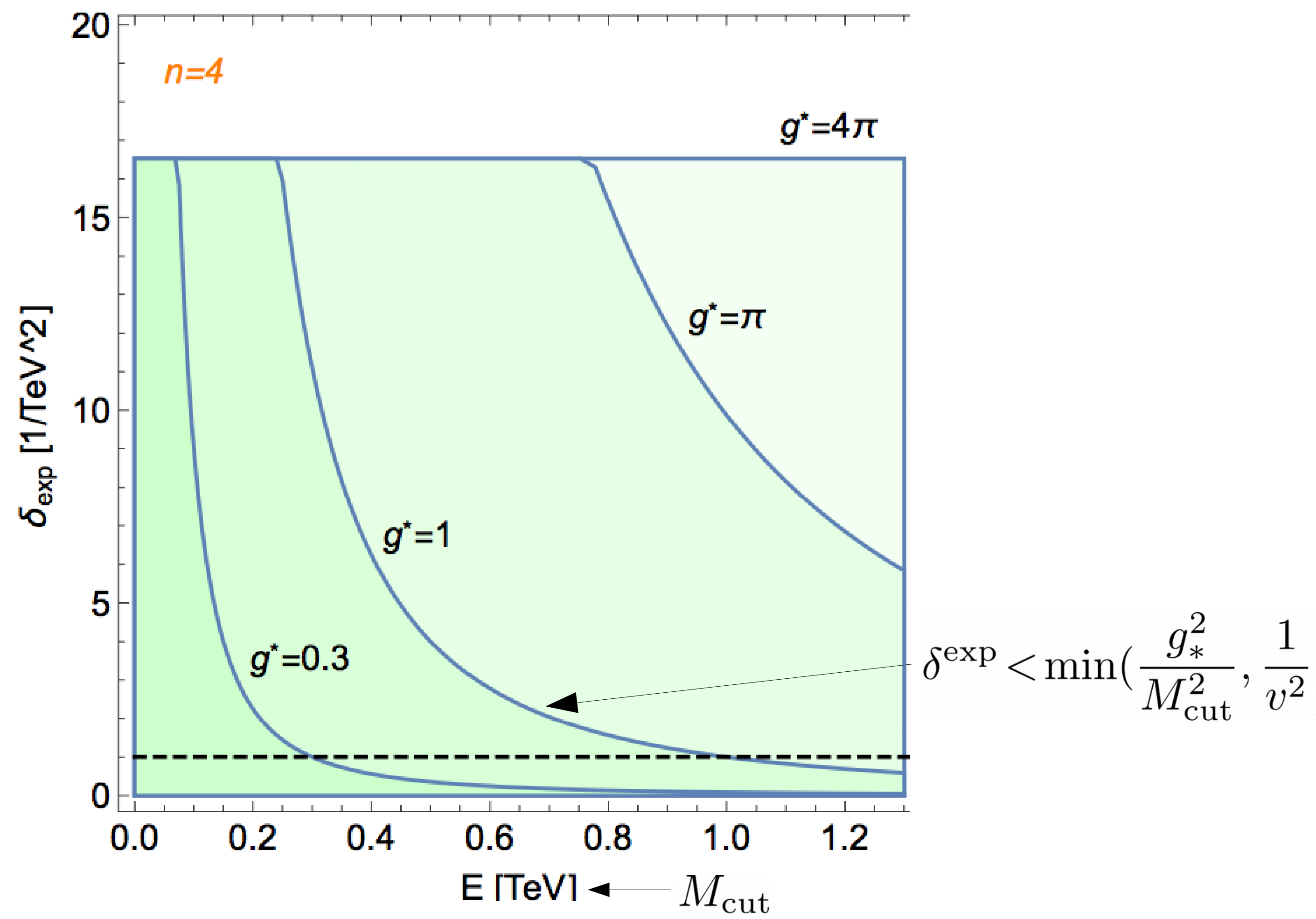
e.g. : $|H|^2 \bar{Q}_L H d_R$

Accuracy Required for Consistent Bound

$$\frac{g_*^2}{\Lambda^2} < \delta_i^{\text{exp}}(M_{\text{cut}})$$

$$\kappa^2 = \frac{\max(M_{\text{cut}}^2, g_*^2 v^2)}{\Lambda^2} \overset{!}{<} 1$$

$$\delta^{\text{exp}} < \min(\frac{g_*^2}{M_{\text{cut}}^2}, \frac{1}{v^2})$$



Stronger constraints at fixed M_{cut} → validity range extended to smaller g*

Assume n_i=4

'Illustrative' plot: for large $M_{\text{cut}}, \delta^{\text{exp}}$ (neglected) quadratic D=6 terms become relevant

Example: Hypothetical Measurement of $\sigma(pp \to W^+ h)$

$$\frac{\sigma}{\sigma_{SM}} \approx \left(1 + 160\,\delta g_L^{Wq} \frac{M_{Wh}^2}{\text{TeV}^2}\right)^2$$

combination of EFT coefficients

- Consider vector-triplet model

$$\delta g_L^{Wq} = v^2 \frac{g_*^2}{M_V^2} \qquad (g_H = -g_q \equiv g_*)$$

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
$\sigma/\sigma_{\rm SM}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

95% CL bounds

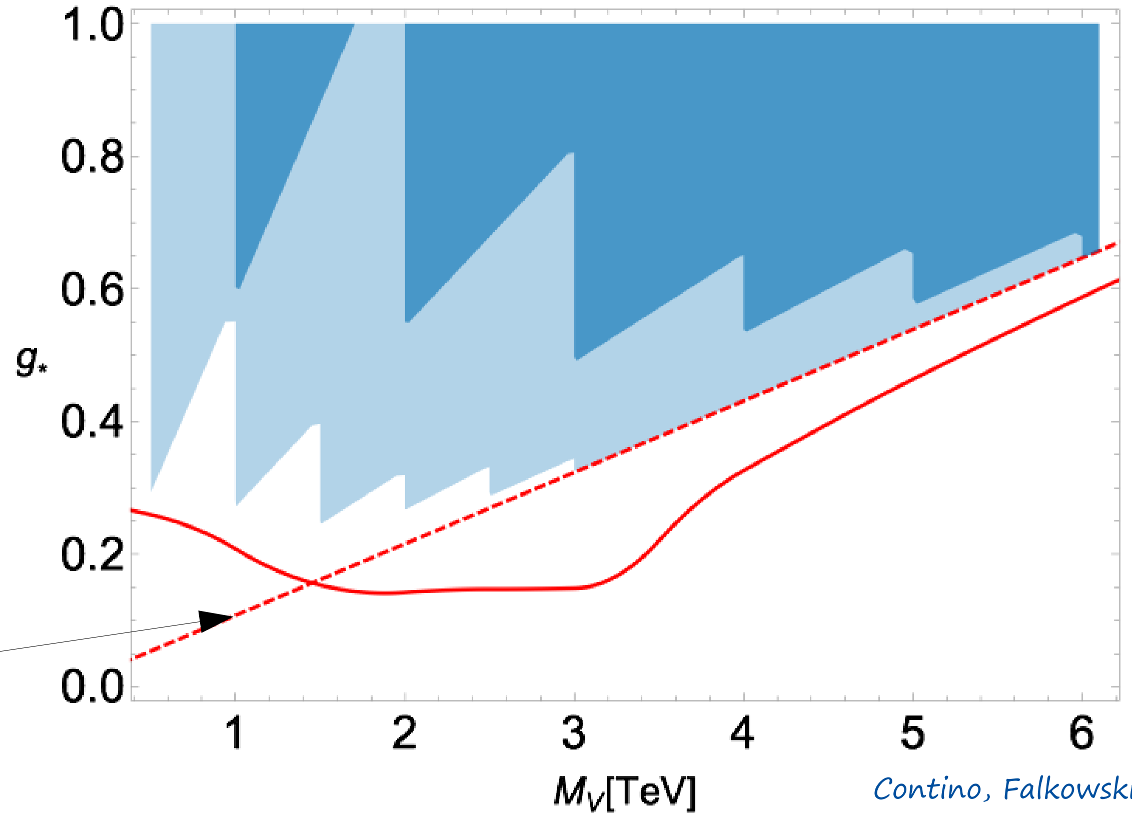
$M_{\rm cut}$[TeV]	0.5	1	1.5	2	2.5	3
$\delta g_L^{Wq} \times 10^3$	[-70, 20]	[-16,4]	[-7,1.6]	[-4.1,1.1]	[-2.7,0.8]	[-2.2,0.7]

combine bins up to M_{cut}

Contino, Falkowski, FG, Grojean, Riva, 1604.06444

See also Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320

Consistent Procedure of Setting Limits



Inconsistent to use full dataset for low M_V

Contino, Falkowski, FG, Grojean, Riva, 1604.06444

- red: Limits from full resonance model
- red, dashed: Limits from EFT using full dataset
- dark (light) blue: consistent EFT analysis using only data with $\mathrm{M}_{Wh} < M_{\mathrm{cut}} = \kappa M_V$, κ=0.5 (1)

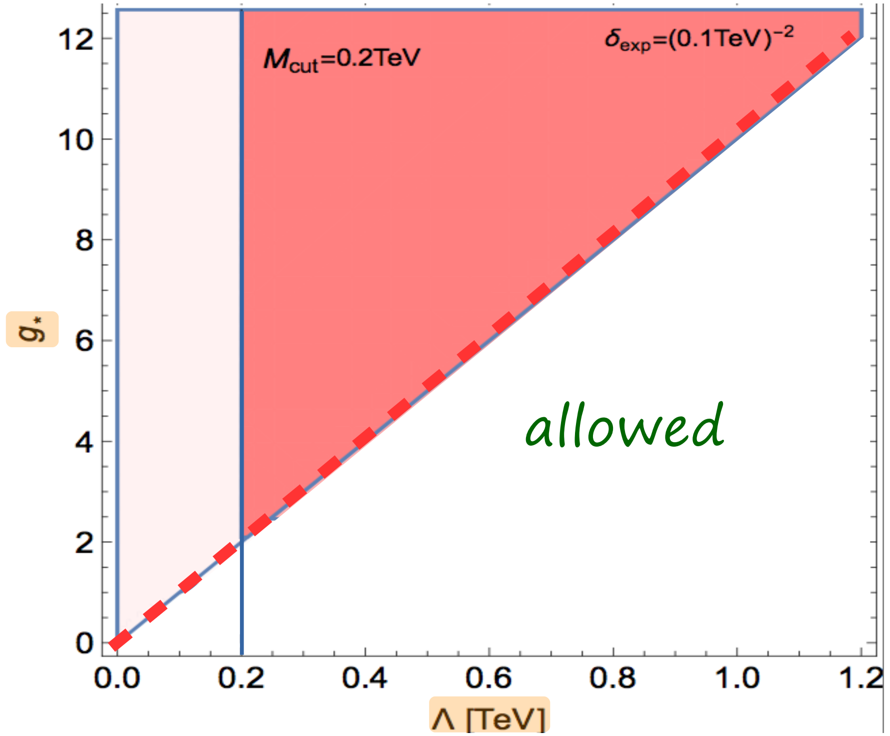
→ Experimental results should be reported as function of M_{cut}

Accessing Masses Directly in EFT?

Intrinsic limitation of EFT approach: only access ratio g_*/Λ (flat direction)

⬇

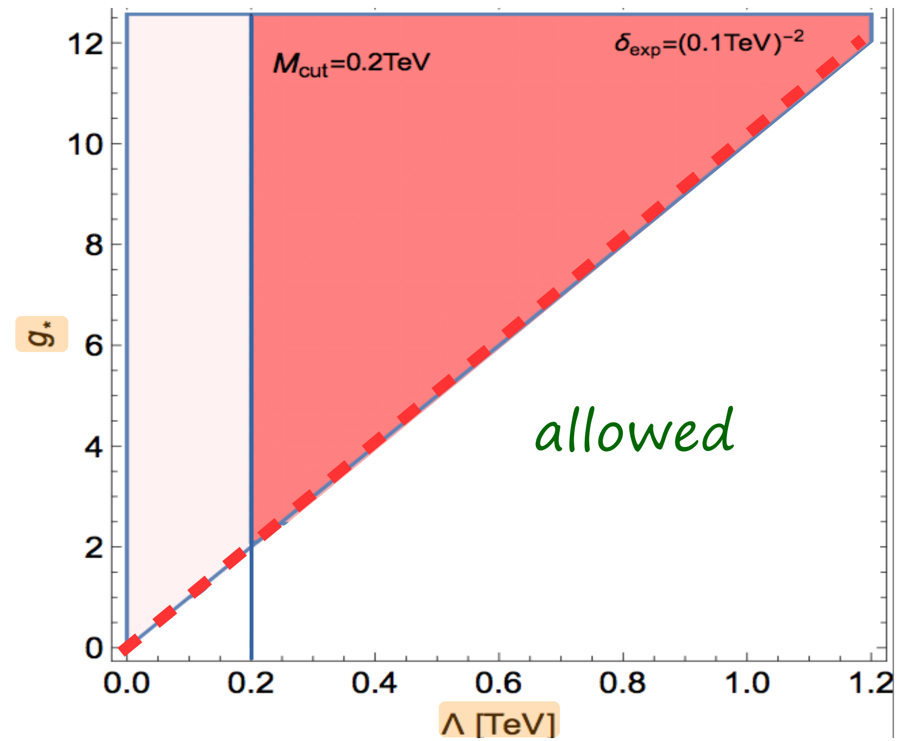
Possible to lift this degeneracy, employing same power counting as before?



Accessing Masses Directly in EFT?

Intrinsic limitation of EFT approach: only access ratio g_*/Λ (flat direction)

Possible to lift this degeneracy, employing same power counting as before?



- Yes: study correlations between observables with 'different g_* dependence'

FG, 1711.03162

Scaling of Operators

$\mathcal{O}_{y_f} = \lvert H\rvert^2 \bar{f}_L H f_R$
$\mathcal{O}_{4f} = \bar{f}\gamma^\mu f\, \bar{f}\gamma_\mu f$
$\mathcal{O}_6 = \lvert H\rvert^6$
$\mathcal{O}_{3V} = \frac{1}{3!}F_{abc}V_\mu^{a\nu}V_{\nu\rho}^b V^{c\rho\mu}$

$\mathcal{O}_{VV} = \lvert H\rvert^2 V_{\mu\nu}^a V^{a\mu\nu}$
$\mathcal{O}_V = \frac{i}{2}(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H)D^\nu W_{\mu\nu}^a$
$\mathcal{O}_{2V} = -\frac{1}{2}(D_\rho V_{\mu\nu}^a)^2$
$\mathcal{O}_{HV} = i(D^\mu H)^\dagger\sigma^a(D^\nu H)V_{\mu\nu}^a$
$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$

	$\mathcal{O}_{y_f}$	$\mathcal{O}_{4f}$	$\mathcal{O}_6$	$\mathcal{O}_{3W,3G}$
A	$y_f g_*^2$	$\lambda^{4f} g_*^2$	g_*^4	g_*
B	$y_f g_*^2$	$\lambda^{4f} g_*^2$	$\frac{y_t^2}{16\pi^2} g_*^4$	$\frac{g_*^2}{16\pi^2} g_*$

ALH-like, integrating out narrow (scalar) resonance

Liu, Pomarol, Rattazzi, Riva, 1603.03064

SILH-like (→ loop suppressions)

Giudice, Grojean, Pomarol, Rattazzi, hep-ph/0703164

↓ induce

1) a relative shift in yukawa couplings δy_f $\qquad \delta y_f = v^3/(\sqrt{2}m_f)\; c_{y_f}$

2) the coefficient C_9 of the four-fermion operator $\mathcal{O}_9 \equiv \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$ $\qquad C_9 = \frac{\sqrt{2}\pi}{\alpha\, G_F V_{tb}V_{ts}^*}\; c_{s_L b_L \ell\ell}$

3) a relative deviation in the Higgs self coupling $\delta\lambda$ $\qquad \delta\lambda = 2v^4/m_h^2\; c_6$

4) the triple-gauge coupling (TGC) λ_Z $\qquad \lambda_Z = -6g^2\; c_{3W}$

FG, 1711.03162

Combined Constraints

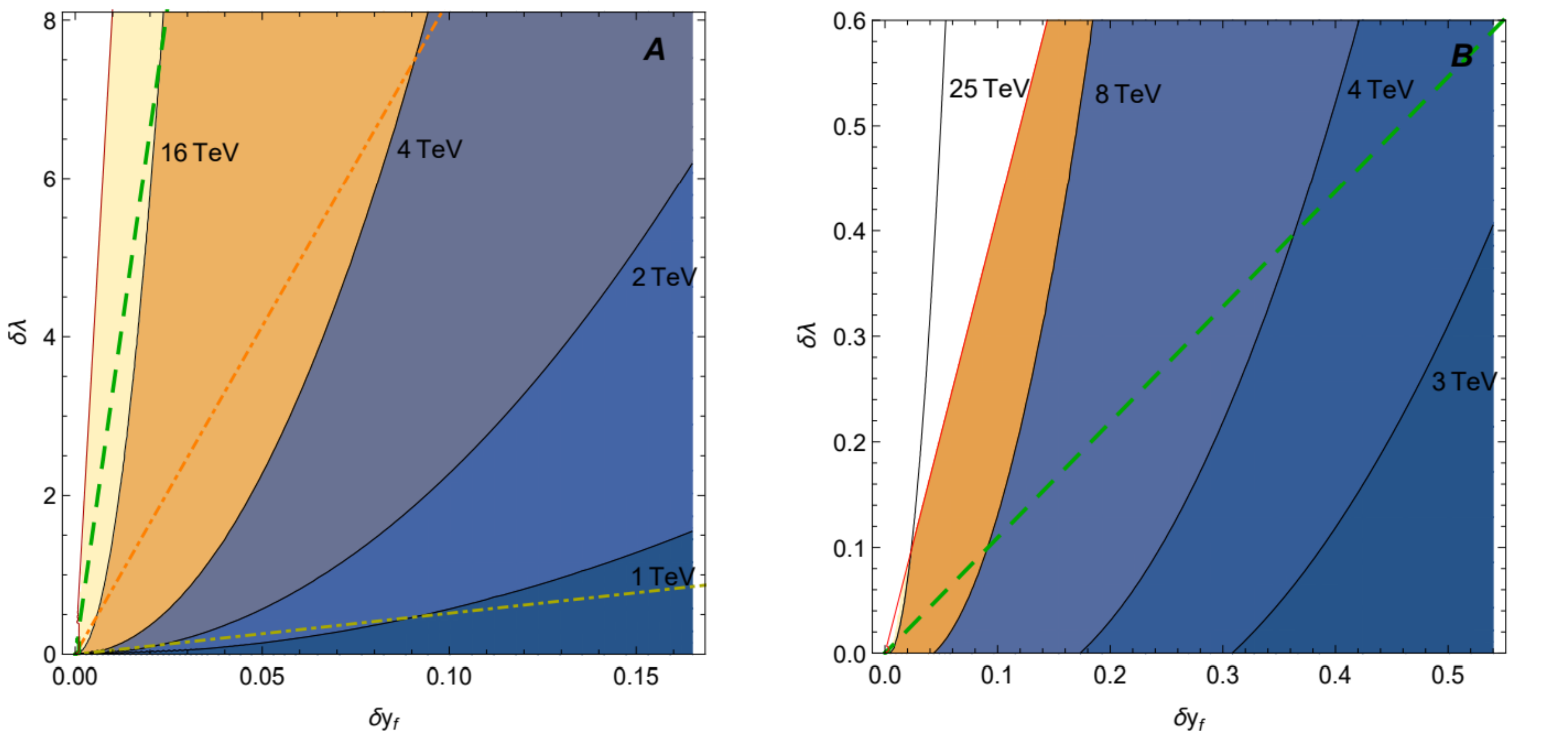
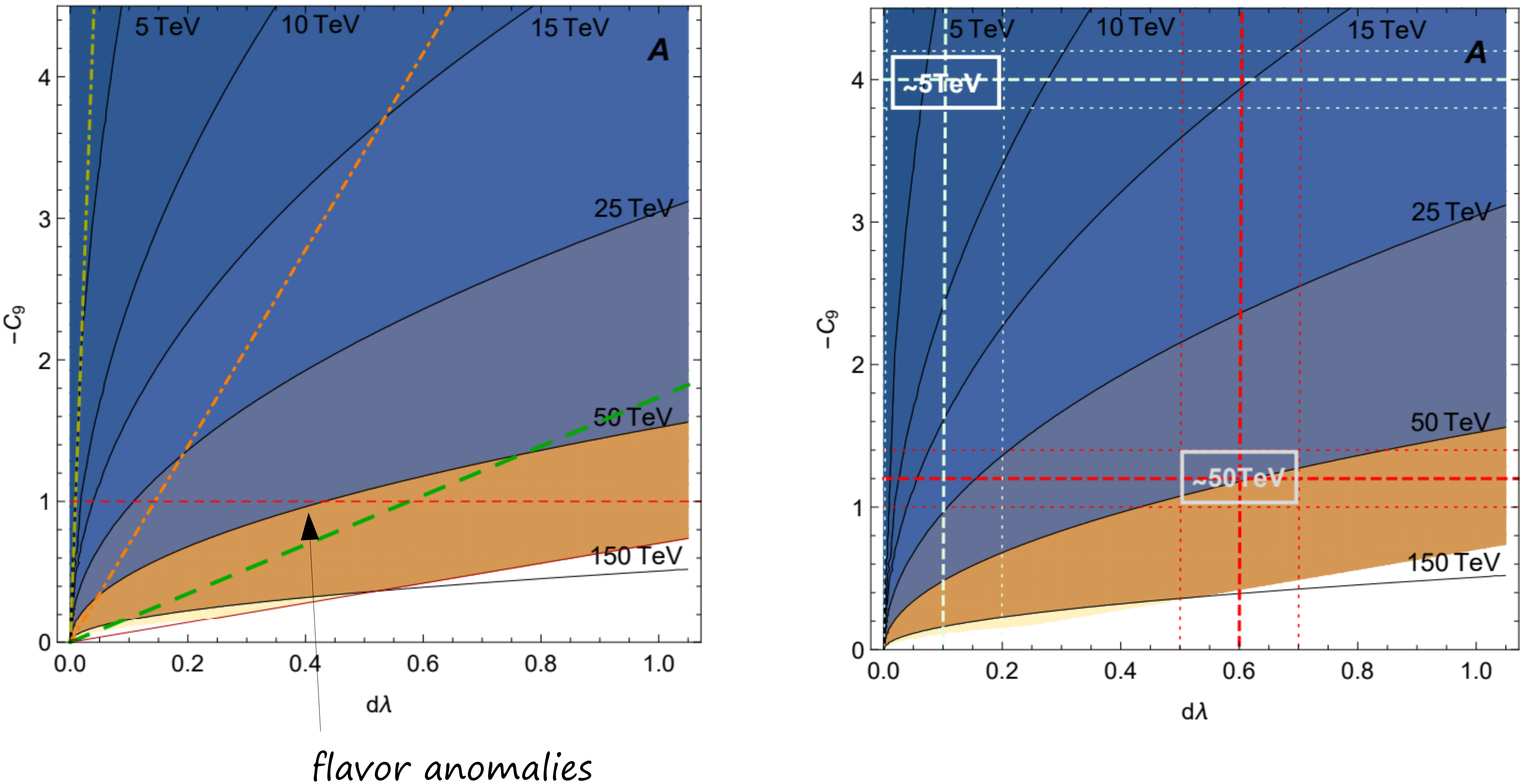


Figure 1. NP mass M in dependence on the variation in the Yukawa couplings (δy_f) and in the triple-Higgs self coupling ($\delta\lambda$) in Scenario **A** (left) and **B** (right). The colored lines denote NP couplings of $g_* = 1, 4, 8, 4\pi$, respectively (from yellow to red).

FG, 1711.03162

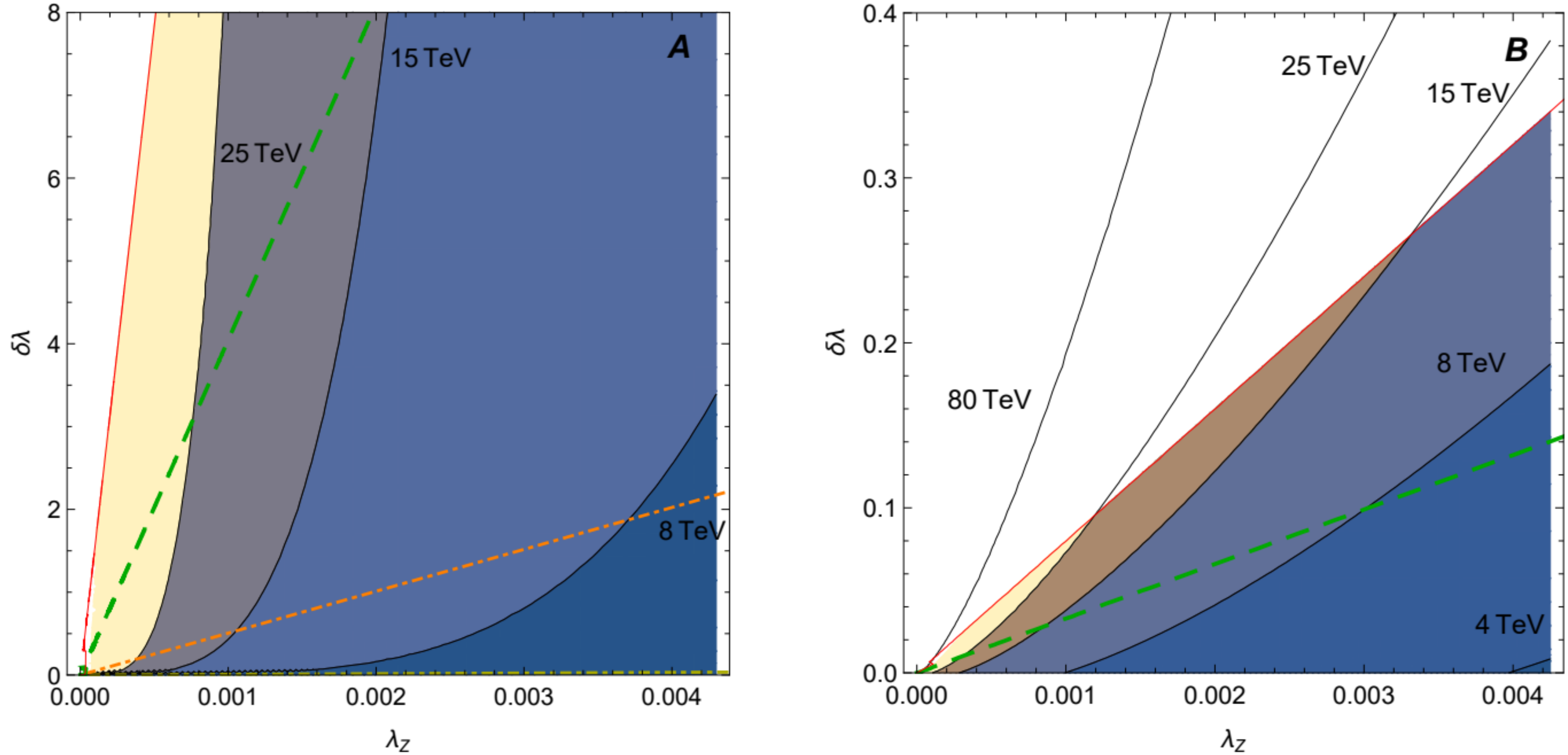
Combined Constraints



FG, 1711.03162

Planck 2018

Combined Constraints



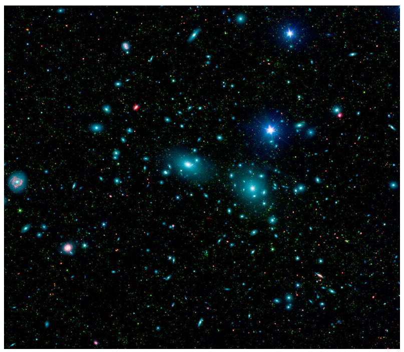
→ Access Masses / Rule out UV Paradigms

FG, 1711.03162

3) EFT for Dark Matter

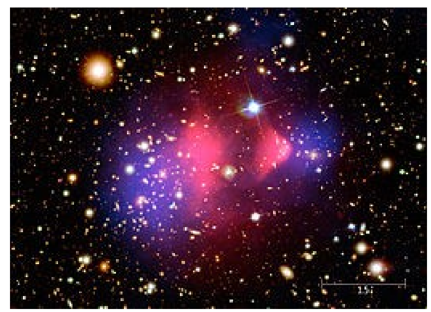
Luminous matter cannot explain many observations

- luminous matter not sufficient to keep clusters bound



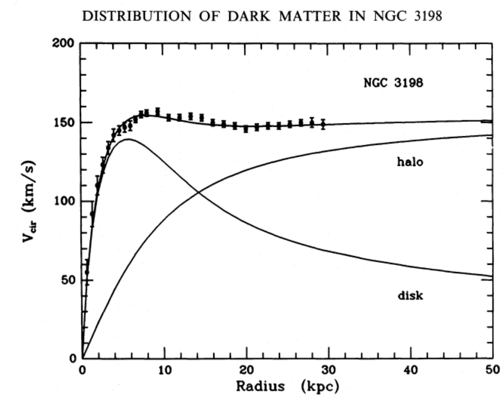
Coma Cluster, NASA, Zwicky

- Bullet Cluster:
  Optical observation (x-ray) vs. grav. lensing



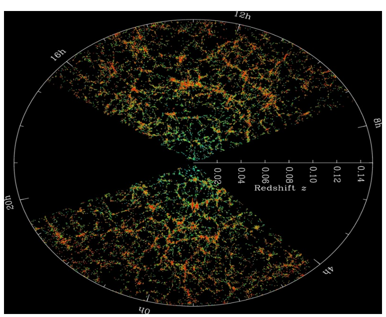
NASA, ...

- rotation curves of galaxies



Albada, Bahcall, Begeman, Sanscisi, APJ, 295, 305-313 (1985)

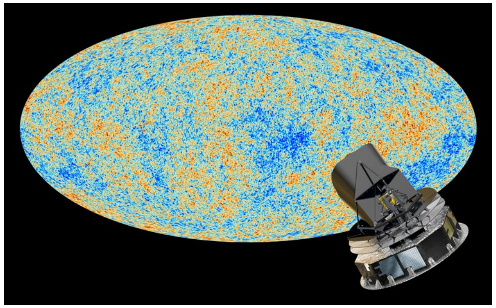
- large-scale structure formation



Sloan Digital Sky Survey

+ BBN, Lyman-α forest, ...

- CMB



ESA

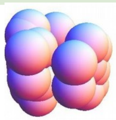
- All these observations can be explained by the presence of **Dark Matter**... What is its origin?

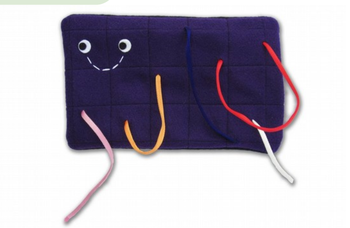
Dark Matter

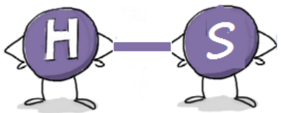
DM Candidates in ‘UV complete’ models

- Lightest SUSY partner (Neutralino ...)
- Lightest Kaluza-Klein excitation (KK parity)

- Composite scalar
- Sterile neutrino
- Higgs-Portal DM
- Extended Higgs sectors
- Axions, ALPs
- ...



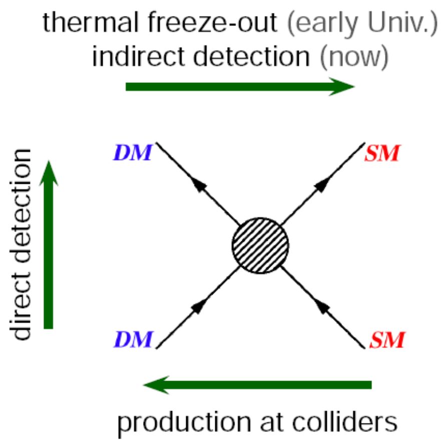




Dark Matter

→ DM searches:

- indirect detection
- direct detection
- collider

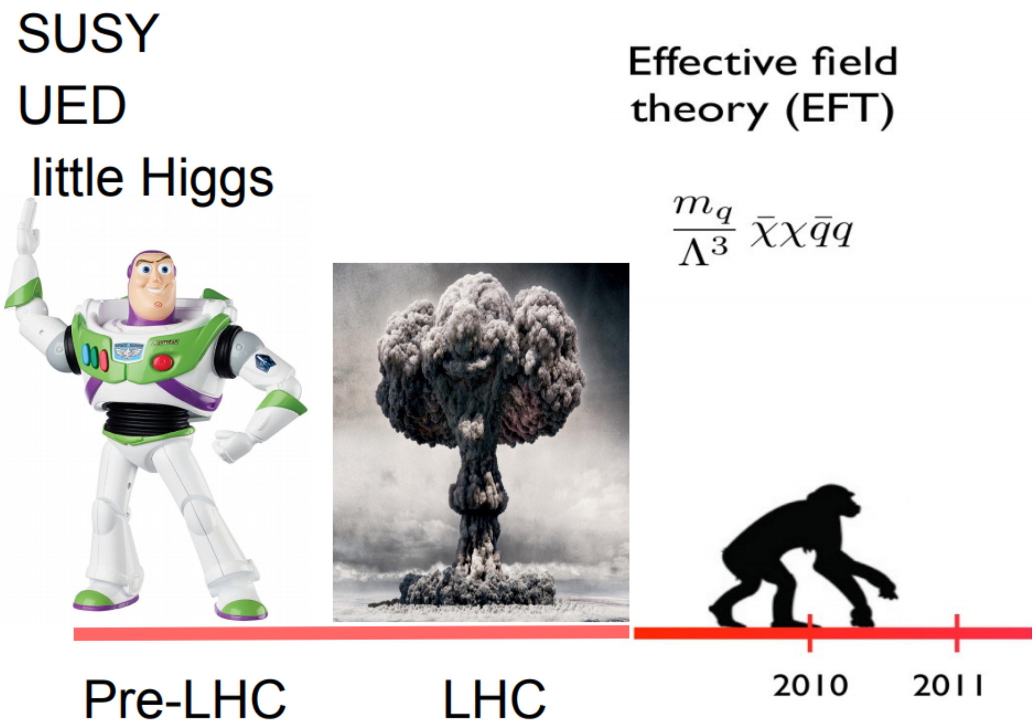


→ Combined effort to understand the nature of DM!

Generic ('Model-independent') framework?

Theoretical Description

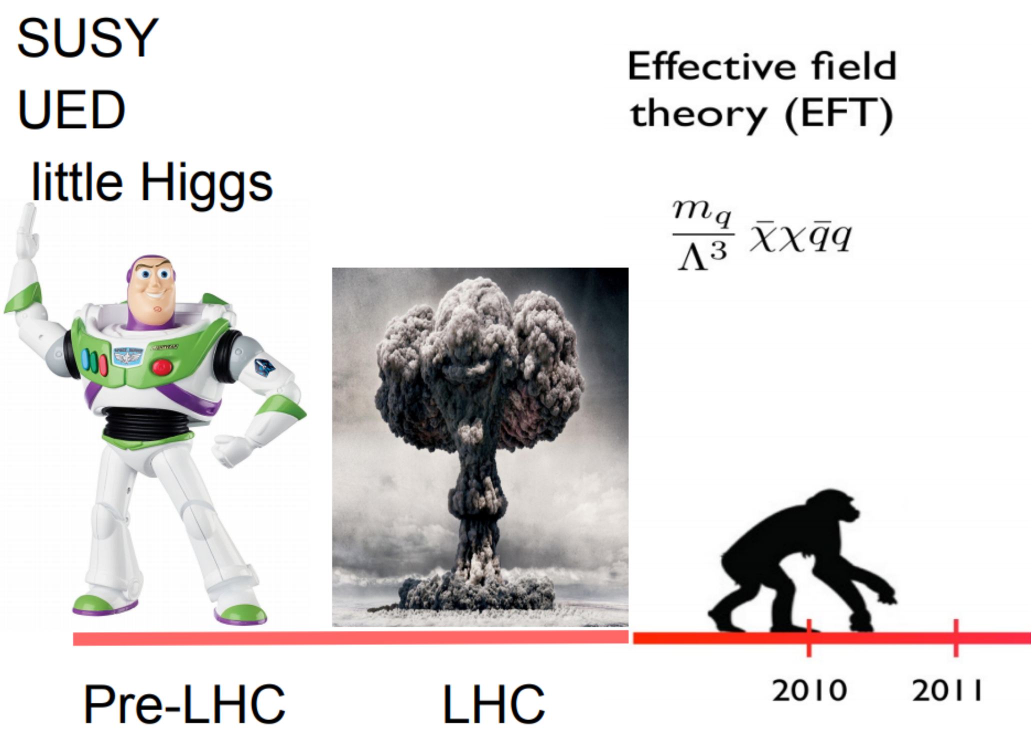
From full theories to EFT



G. Polesello, U. Haisch

Theoretical Description

From full theories to EFT



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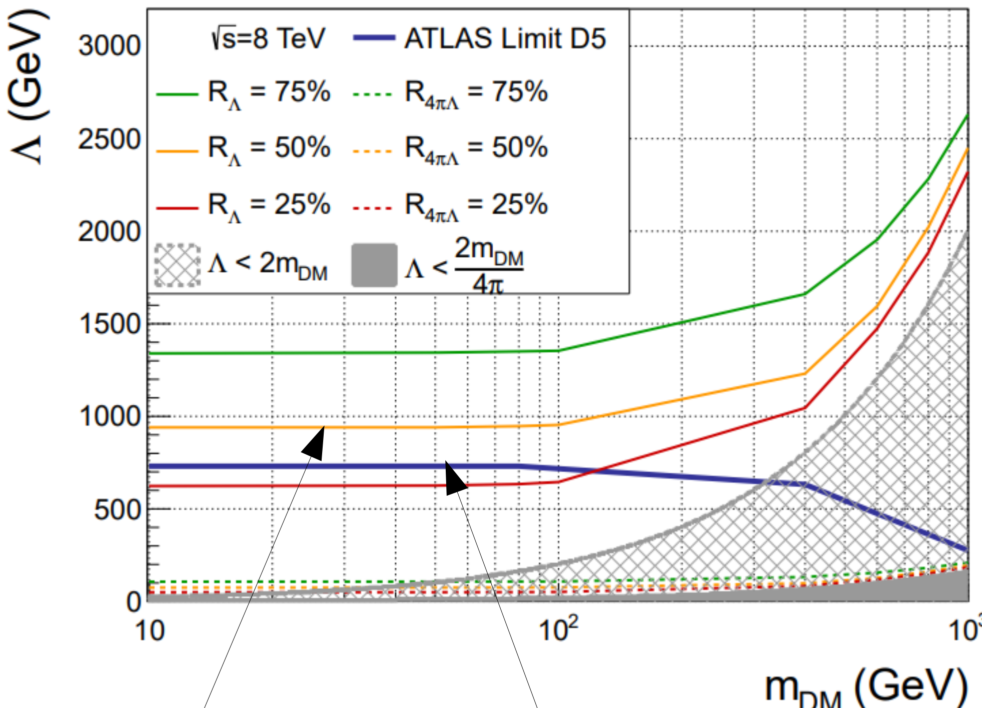
EFT vs. LHC



50% of all events lie above Λ ⟷ LHC limit

very questionable...

Morgante, 1409.6668
Busoni, De Simone, Morgante, Riotto, 1307.2253

Theoretical Description

From full theories to EFT and back

SUSY
UED
little Higgs

Effective field theory (EFT)

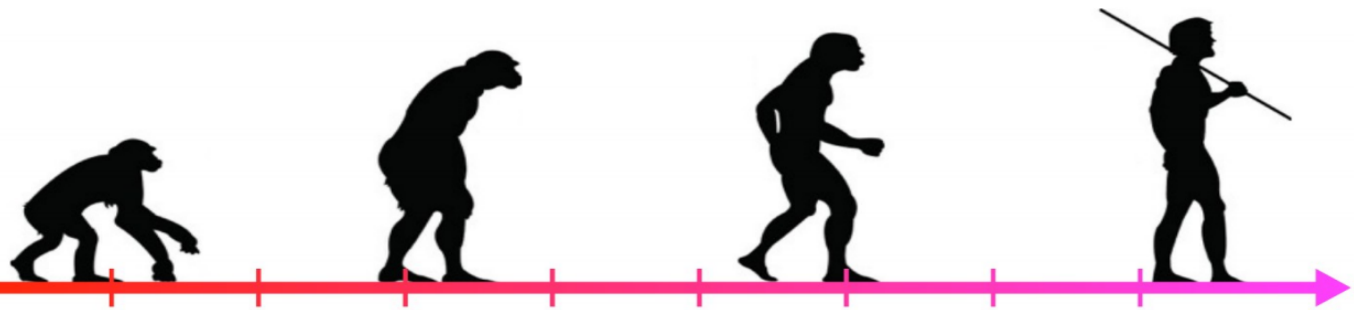
$$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$$

Simplified models

$$g_\chi\bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

‚Consistent' simplified models / ‚UV complete' models

$$g_\chi\bar{\chi}\chi s + Y_q\bar{q}Hq + \mu s|H|^2$$



Pre-LHC LHC 2010 2011 2012 2013 2014 2015 2016 2017

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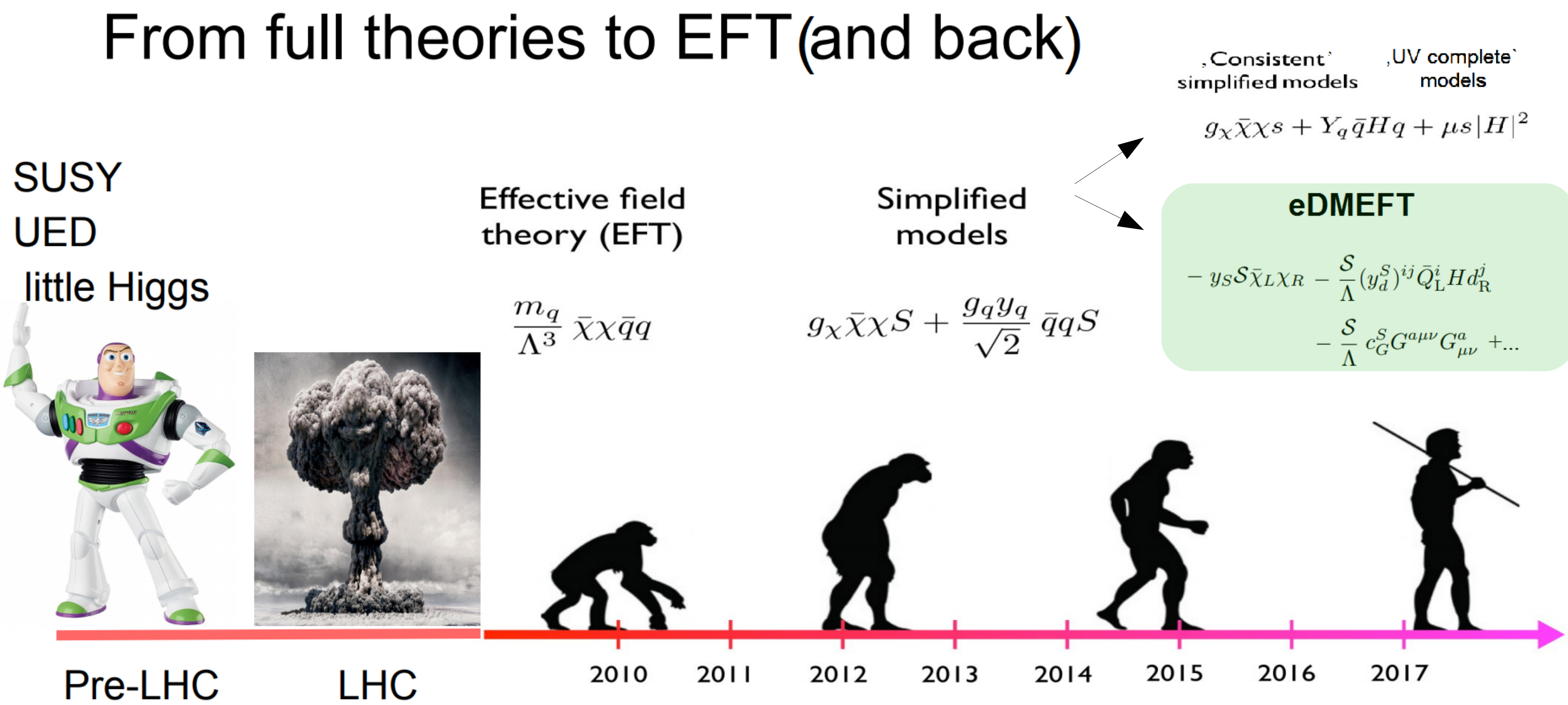
Alternative (keep 'model independence'): Extended DM EFT



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DM EFT vs Simplified Models

DM EFT	Simpl. Models
'model independent'	rather specific
'proper' QFT	gauge inv./unitarity?
LHC validity questionable	valid for LHC searches

$$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$$

DM

$$g_\chi\bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

DM mediator

Shepherd, Tait, Zaharijas, 0901.2125
Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, 1005.1286, 1008.1783
Bai, Fox, Harnik, 1005.3797
Busoni, De Simone, (Gramling), Morgante, Riotto, 1307.2253, 1402.1275
Bruggisser, Riva, Urbano, 1607.02475

Alwall, Schuster, Toro, 0810.3921
De Simone, Giudice, Strumia, 1402.6287
Abdallah et al, 1506.03116
Kahlhoefer, Hoberg, Schwetz, Vogl, 1510.02110
Boveia et al, 1603.04156
De Simone, Jacques, 1603.08002
Englert, McCullough, Spannowsky, 1604.07975

Extended Dark Matter EFT

eDMEFT
'minimal' assumptions
'proper' QFT
valid for LHC searches

Alanne, FG, 1712.07626

$$- y_S \mathcal{S} \bar{\chi}_L \chi_R - \frac{\mathcal{S}}{\Lambda} (y_d^S)^{ij} \bar{Q}_\mathrm{L}^i H d_\mathrm{R}^j$$

$$- \frac{\mathcal{S}}{\Lambda} c_G^S G^{a\mu\nu} G_{\mu\nu}^a + \dots$$

Extended Dark Matter EFT

- Keep mediator:

  LHC Applicability $\rightarrow$ Exploit synergies in combining DD + ID + LHC

- Construct all *gauge invariant* ops of SM + DM + med.:

  Correlations induced by gauge symmetry

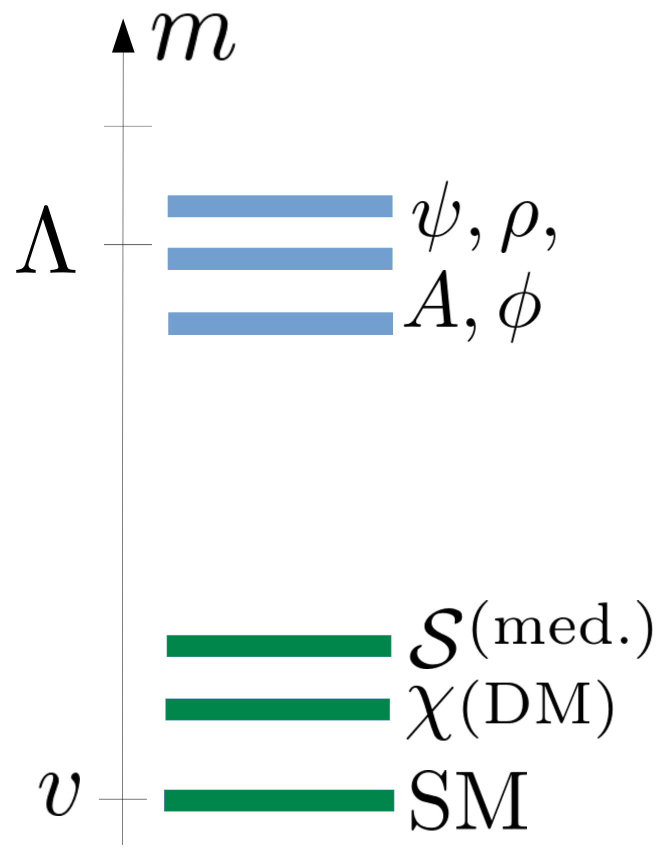
- Allow for $D > 4$ operators:

  New sector likely richer than just DM + mediator

Extended Dark Matter EFT

eDMEFT
'minimal' assumptions
'proper' QFT
valid for LHC searches

$$- y_S \mathcal{S} \bar{\chi}_L \chi_R - \frac{\mathcal{S}}{\Lambda} (y_d^S)^{ij} \bar{Q}_L^i H d_R^j$$
$$- \frac{\mathcal{S}}{\Lambda} c_G^S G^{a\mu\nu} G^a_{\mu\nu} + \ldots$$



Extended Dark Matter EFT

- Fermionic or scalar DM with (pseudo-)scalar mediator:

Leading effects at D=5

→ *limited number of free couplings*

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\mathcal{S}\chi} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin+mass} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\rm L}^i H f_{\rm R}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\mathcal{S}\chi} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin+mass} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
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\end{aligned}
$$

Higgs-mediator portal

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

mediator-DM int.

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\mathcal{S}\chi} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin+mass} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
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Extended Dark Matter EFT

Fermionic DM with scalar mediator:

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\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} \quad = \quad & \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
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\end{aligned}
$$

portal-like D=5 terms

Extended Dark Matter EFT

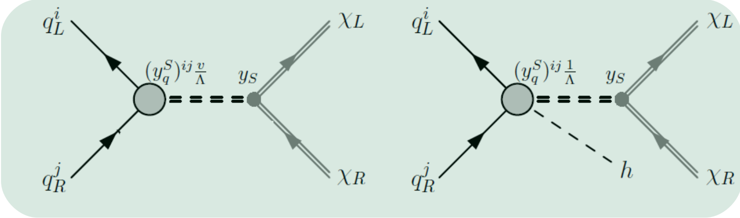
Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS}|H|^2\mathcal{S}^2 - y_S \mathcal{S}\bar{\chi}_L\chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda}\left[c_{\lambda S}\mathcal{S}^4 + c_{HS}|H|^2\mathcal{S}^2 + c_{\lambda H}|H|^4\right] \\
&- \frac{\mathcal{S}}{\Lambda}(y_f^S)^{ij}\bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)}\mathcal{S}^2 + y_H^{(2)}|H|^2}{\Lambda}\bar{\chi}_L\chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda}\frac{1}{16\pi^2}\sum_{V=G,B,W} C_V^S V_{\mu\nu}V^{\mu\nu}
\end{aligned}
$$

Gauge inv. couplings to SM!

Inevitably links DM to DM+H production!

Correlates different LHC observables → test nature of dark sector!



Extended Dark Matter EFT

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&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Higgs-DM portal and (med.)^2-DM^2 → assoc. prod.?

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\mathcal{S}\chi} \quad = \quad & \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin+mass}} - V(\mathcal{S}) \\
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- \quad & \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
- \quad & \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\text{L}}^i H f_{\text{R}}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
- \quad & \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

← gluon-fusion, VBF prod., ...

Extended Dark Matter EFT

Fermionic DM with scalar mediator:

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{\mathcal{S}\chi} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin+mass} - V(\mathcal{S}) \\
&- \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2 - y_S \mathcal{S} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 \right] \\
&- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\rm L}^i H f_{\rm R}^j - \frac{y_S^{(2)} \mathcal{S}^2 + y_H^{(2)} |H|^2}{\Lambda} \bar{\chi}_L \chi_R + \text{h.c.} \\
&- \frac{\mathcal{S}}{\Lambda} \frac{1}{16\pi^2} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}
\end{aligned}
$$

Scaling: $c_{\lambda S} \sim c_{HS} \sim c_{\lambda H} \sim g_*^3 \,,\; y_f^S \sim y_f g_* \,,\; y_{S,H}^{(2)} \sim g_*^2 \,, c_V^S \sim g_*$

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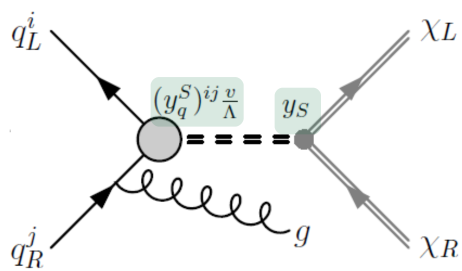
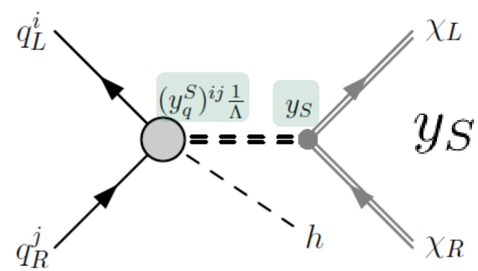
Phenomenology

Capture all kinds of production/scattering mechanisms of DM

- LHC Observables: mono-jet, mono-Higgs, ...

$$\frac{\mathcal{S}}{\Lambda}(y_f^S)^{ij}\,\bar{F}_{\rm L}^i H f_{\rm R}^j$$





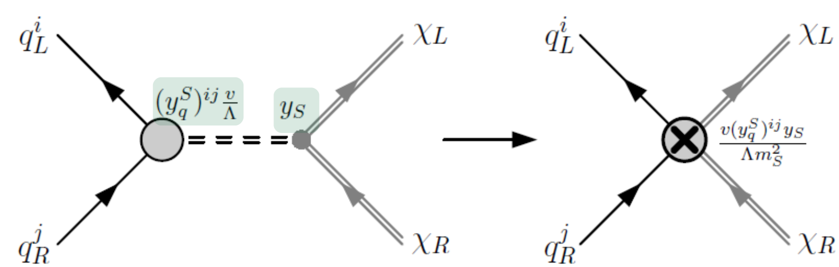
$y_S \mathcal{S} \bar{\chi}_L \chi_R$

$E \sim m_S$ (?!)

[always turn on 2 couplings ...]

Explore correlations in proper EFT

- Direct Detection: DM-nucleon interaction

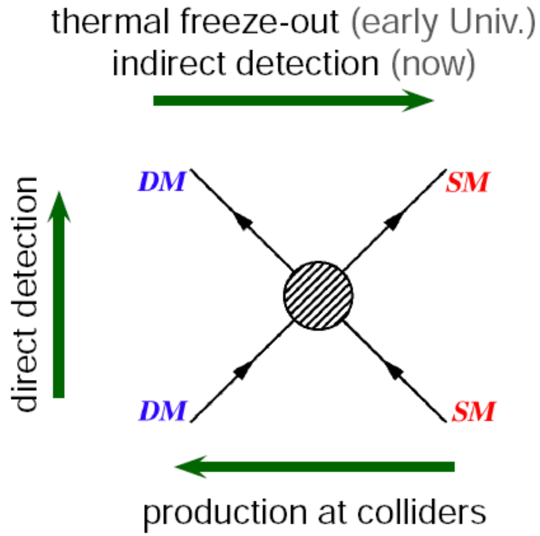


$E \ll m_S$

Phenomenology

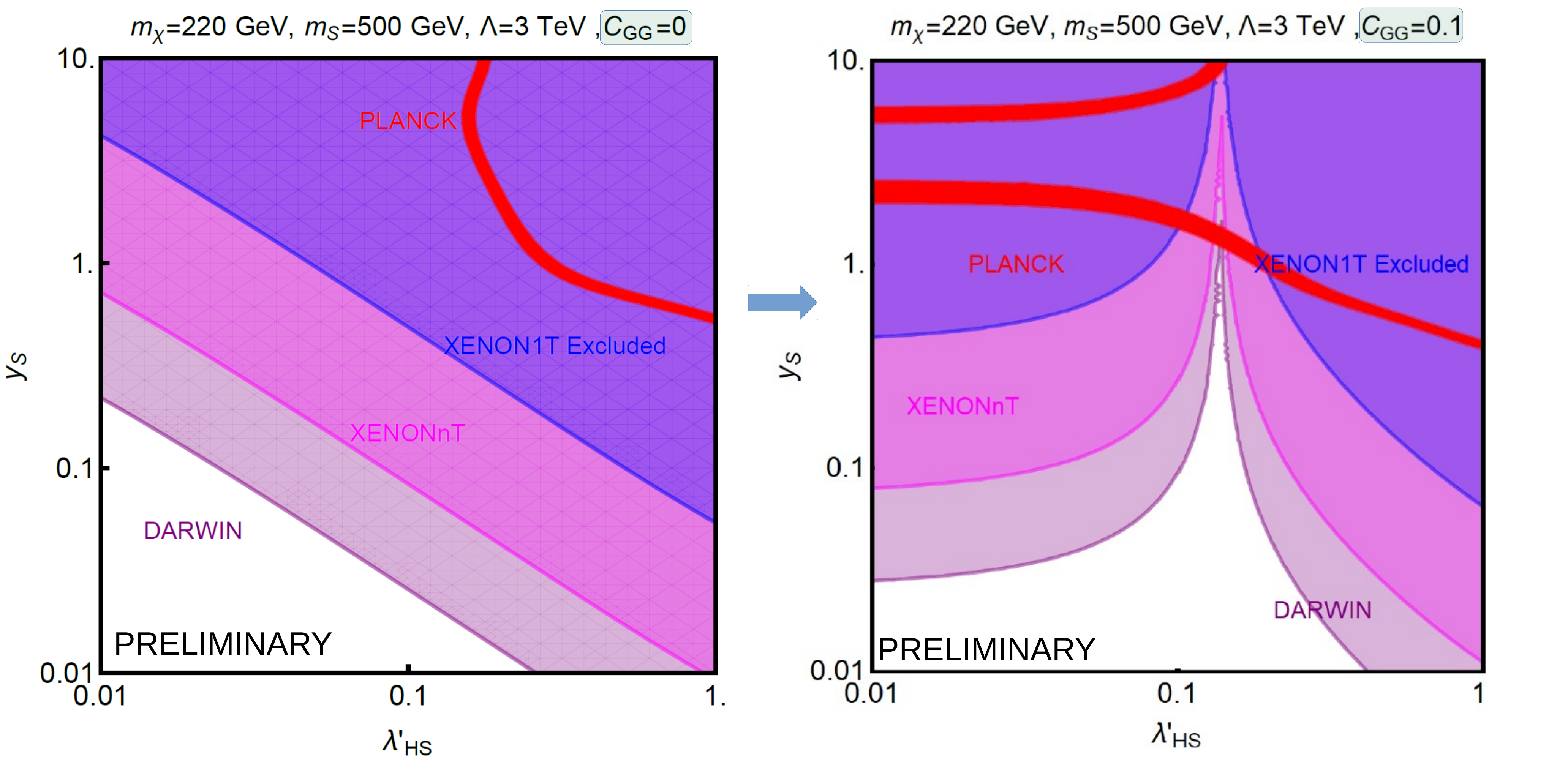
- Confront LHC with direct detection and relic abundance
- Can address the question:

Given constraints from relic density and direct detection, which mono-X cross sections can be expected at the LHC?



Global Picture of Constraints

- Most interesting case: more than 2 couplings present



➡ open parameter space of Portal DM, ...

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Matching to UV Theories

- 2HDM + scalar + DM

integrate out H_2:
$$c_{HS} = -2\lambda_{12}^{S}\lambda_{12}^{2S} v/M_{H_2}$$
$$c_{\lambda H} = 2Z_6\lambda_{12}^{S} v/M_{H_2}$$
$$y_q^S = \lambda_{12}^{S}\eta_q/(\tan_\beta M_{H_2})$$

- Composite mediators $y_q^{\tilde{S}} = y_q \Lambda/f$

$$y_{\tilde{S}} = y_\chi$$

→ Interpret exclusion in terms of models, Scrutinize validity of EFT

- NMSSM (singlino DM), VL fermions, ...

Conclusions

EFTs are a valuable tool to explore UV completion of the SM

- C_i can be extracted in agnostic way, interpretation requires assumptions
- Power counting scheme allows to asses error in determination of D=6 coefficients and, eventually, to access Λ

Conclusions

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- C_i can be extracted in agnostic way, interpretation requires assumptions
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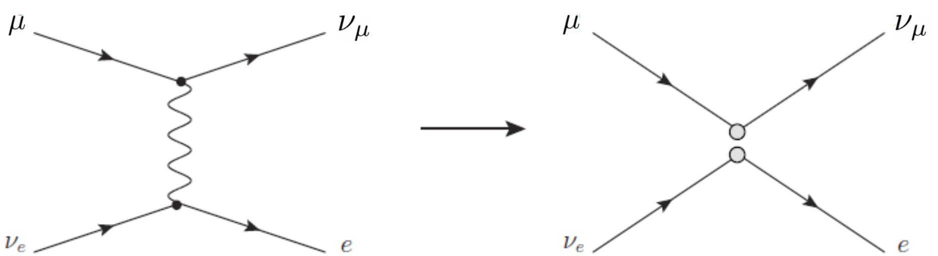
eDMEFT:

- Framework to study correlations between different DM observables (incl. LHC), maintaining gauge invariance and allowing for richer NP sector
- Potentially opening 'new' viable parameter regions for DM

Backup

Well-Known Example: Fermi Theory of Weak Interactions



$$\mathcal{L}_{\rm eff} \supset \frac{c_1}{\Lambda^2} \underbrace{(\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu)}_{\mathcal{O}_1} + \text{h.c.}\,, \qquad \frac{c_1}{\Lambda^2} = -\frac{g^2/2}{m_W^2} = -\frac{2}{v^2}$$

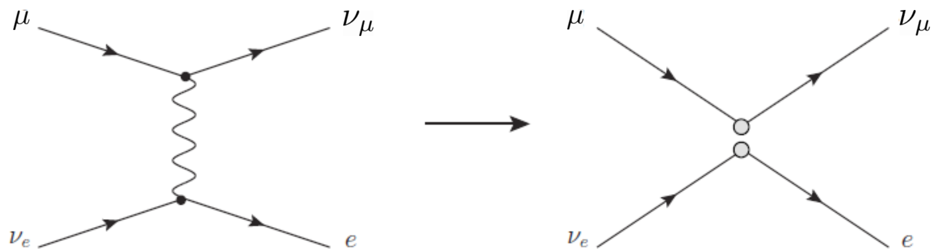
Describes muon decay $\mu \to e\nu\nu$, inelastic scattering $\nu e \to \nu\mu$, ...

- From low energy measurement (muon decay) no identification

  $c_1 = -g^2/2 \sim -0.2; \quad \Lambda = m_W \sim 80\,\text{GeV}$ possible, only constrain ratio

$$c_1/\Lambda^2 = -2\sqrt{2}G_F \sim -3.3\times 10^{-5}\,\text{GeV}^{-2}$$

Well-Known Example: Fermi Theory of Weak Interactions



$$\mathcal{L}_{\text{eff}} \supset \frac{c_1}{\Lambda^2} \underbrace{(\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu)}_{\mathcal{O}_1} + \text{h.c.}\,, \qquad \frac{c_1}{\Lambda^2} = -\frac{g^2/2}{m_W^2} = -\frac{2}{v^2}$$

$$c_1/\Lambda^2 = -g^2/2m_W^2 \sim -3.3 \times 10^{-5}\,\text{GeV}^{-2}$$

Assumption for g	$\Lambda = m_W$
4π	1.5 TeV
1	123 GeV
10^{-4}	12 MeV

$< m_\mu \rightarrow$ no consistent extraction

Explicit Example of Limit-Setting Procedure

- Consider $q\bar{q} \to Vh$ in Vector-Triplet Model

$$\mathcal{L} \supset i g_H \tilde{V}^i_\mu H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q \tilde{V}^i_\mu \bar{q}_L \gamma_\mu \sigma^i q_L$$

Integrate out $\tilde{V}$

$$\mathcal{L} \supset \frac{h}{v}\left(\delta c_z m_Z^2 Z_\mu Z_\mu + 2\sqrt{g_L^2 + g_Y^2} Z_\mu \sum_{f=u,d,e,\nu} \delta g_L^{Zf} \bar{f} \bar{\sigma}_\mu f \right)$$

$$\delta c_z = -\frac{3v^2}{2M_V^2} g_H^2, \qquad [\delta g_L^{Zu}]_{11} = -[\delta g_L^{Zd}]_{11} = -\frac{v^2}{2M_V^2} g_H g_q \,.$$

- Corrects $q\bar{q} \to Zh$ (as well as $q\bar{q} \to Wh$)
- Amplitude for longitudinal V grows as square of partonic COM energy

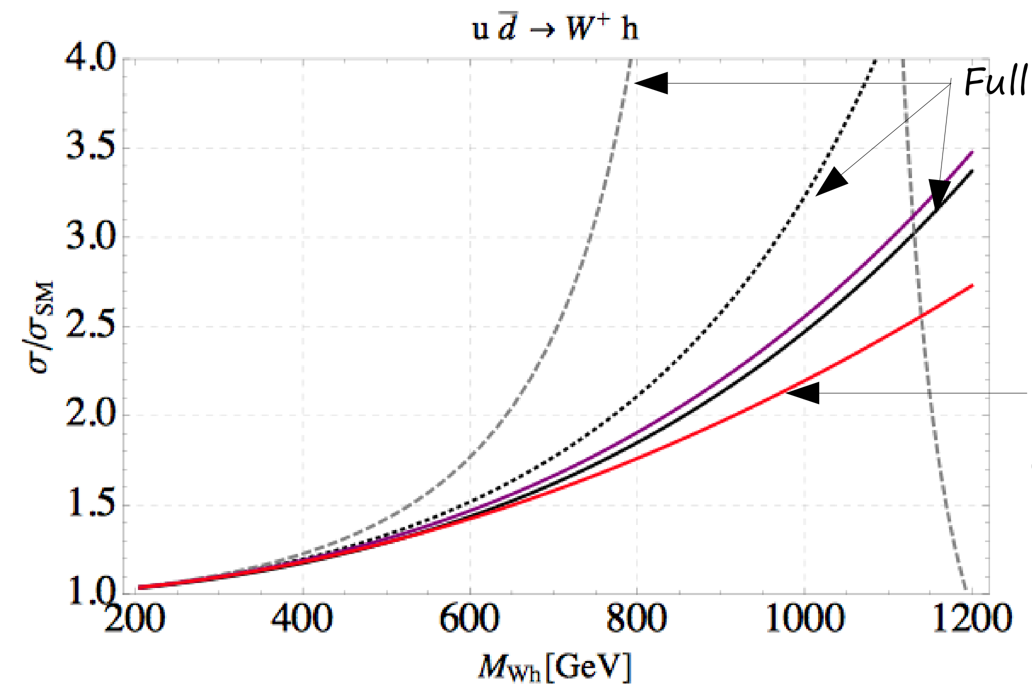
→ important effects at large $s = M_{Wh}^2$ ⟹ EFT validity?

See also Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320

Consider 3 Scenarios

- **Strongly coupled:** $M_V = 7\ \text{TeV},\ g_H = -g_q = 1.75$
- **Moderately coupled:** $M_V = 2\ \text{TeV},\ g_H = -g_q = 0.5$
- **Weakly coupled:** $M_V = 1\ \text{TeV},\ g_H = -g_q = 0.25$

- Lead to same effective coefficients, however vastly different range of EFT validity



Full model (weakly → strongly)

Starts to deviate later!

Linear EFT

(+quadratic terms: purple)

Hypothetical Measurement of $\sigma(pp \to W^+ h)$

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
$\sigma/\sigma_{\rm SM}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

95% CL bounds

$M_{\rm cut}$[TeV]	0.5	1	1.5	2	2.5	3
$\delta g_L^{Wq} \times 10^3$	[-70, 20]	[-16,4]	[-7,1.6]	[-4.1,1.1]	[-2.7,0.8]	[-2.2,0.7]

Combine bins up to M_{cut}

$$\frac{\sigma}{\sigma_{SM}} \approx \left(1 + 160\, \delta g_L^{Wq} \frac{M_{Wh}^2}{\rm TeV^2}\right)^2$$

consider only $\delta g_L^{Wq} \equiv [\delta g_L^{Zu}]_{11} - [\delta g_L^{Zd}]_{11}$

Remark on Importance of D=8 Operators

- In general D=8 contributions suppressed, as discussed before, however can become important (while still EFT converges) in case

  1) Symmetry suppressing D=6 operator but not D=8 contribution
  (e.g. shift symmetry suppressing $|H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$)

  2) Zero at leading order:
  Corrections appearing first at D=8 level without symmetry reason
  (e.g. s-channel production of neutral gauge-boson pairs)

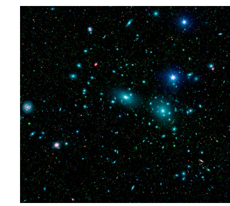
  3) Selection Rules inherited from UV dynamics
  (e.g. light Dilaton coupling to D=4 stress-energy tensor)

  4) Fine Tuning

* Loop/NLO corrections including D=6 operators? Important in case weakly constrained coefficient enters beyond LO in well-measured quantity (while tree-level correction small), or where large SM k-factors!

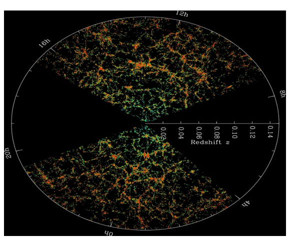
See also: Giudice, Grojean, Pomarol, Rattazzi, ph/0703164; Liu, Pomarol, Rattazzi, Riva, 1603.03064;
Azatov, Contino, Panico, Son, 1502.00539; Degrande, 1308.6323; Azatov, Contino, Machado, Riva, 1607.05236

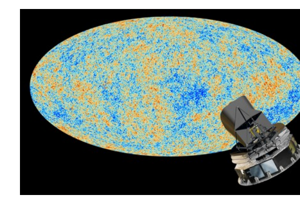
Dark Matter



- *Viable candidate for DM:*

electrically neutral,
cosmologically stable,
colorless particle,
with abundance in agreement with Ω_{DM}



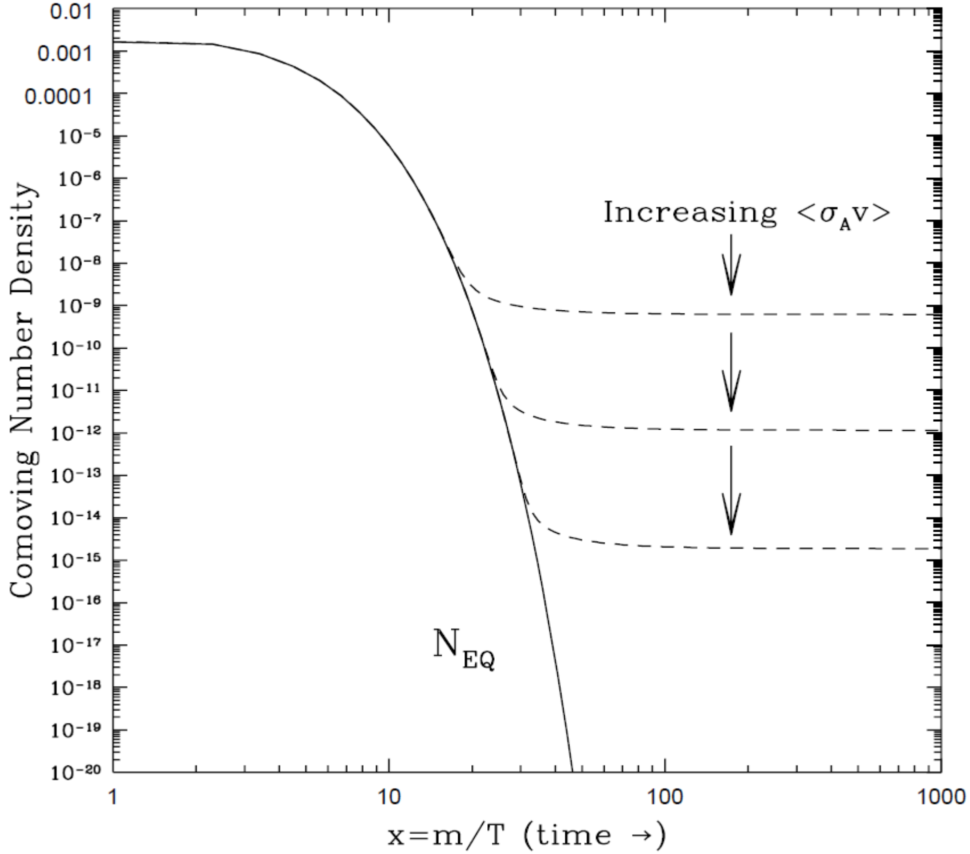


structure formation → cold (non-relativistic) dark matter preferred

↓

weakly interacting massive particle (WIMP)

WIMP Miracle



$$< \sigma_{X\bar{X}}|v| >= a + b < v^2 > + \mathcal{O}(v^4)$$

$$x \equiv m_X/T$$

WIMP

$m_X \sim \text{GeV} - \text{TeV}$, weak scale $< \sigma_{X\bar{X}}|v| >$

↓

$x_{FO} \sim 20 - 30$ (freeze-out temperature)

$$\sim 1$$

→ Correct Relic Abundance $\Omega_X h^2 \approx 0.1 \left(\frac{x_{\rm FO}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}\left(\frac{a + 3b/x_{\rm FO}}{3\times 10^{-26}\text{cm}^3/\text{s}}\right)^{-1}$

Hooper, 0901.4090

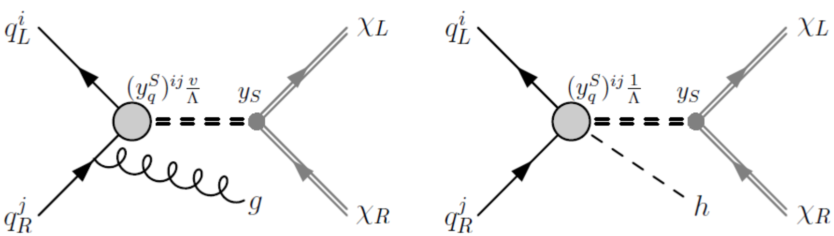
external dof ~80

$$\langle\sigma v\rangle_0 = 3 \cdot 10^{-26}\ \text{cm}^3\text{s}^{-1} \qquad \Omega h^2 \propto \langle\sigma v\rangle^{-1}$$

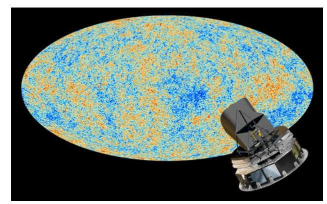
Phenomenology

'toy (simplistic) example':
always turn on 2 couplings only

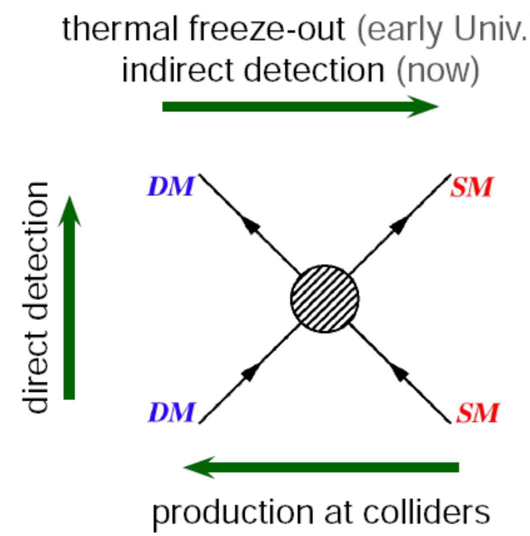
$q\bar{q}$ induced



Relic abundance $(m_\chi > m_S)$



$$\langle \sigma v \rangle (\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$



DD: scattering off nuclei

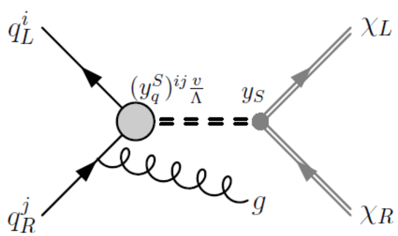
$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi \Lambda^2 m_S^4 m_u^2}$$

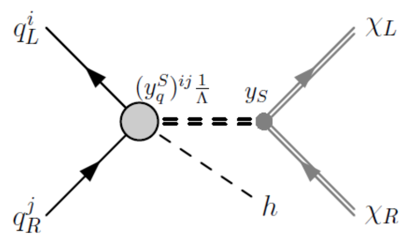
$$\langle N | m_q \bar{q} q | N \rangle \equiv m_N f_N^q$$

$$\mu_N \equiv \frac{m_\chi m_N}{m_\chi + m_N} \qquad m_N = (m_p + m_n)/2$$

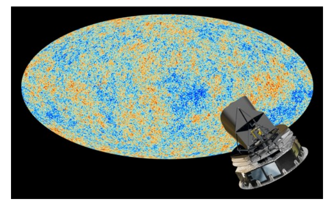
Phenomenology

$q\bar{q}$ induced



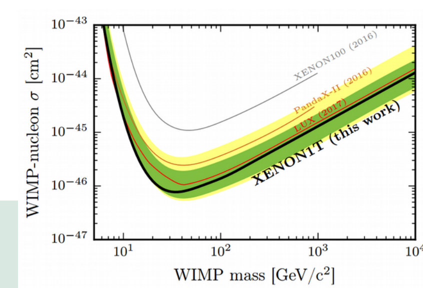


Relic abundance $(m_\chi > m_S)$



$$\langle\sigma v\rangle(\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

fix y_S



DD: scattering off nuclei

$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$

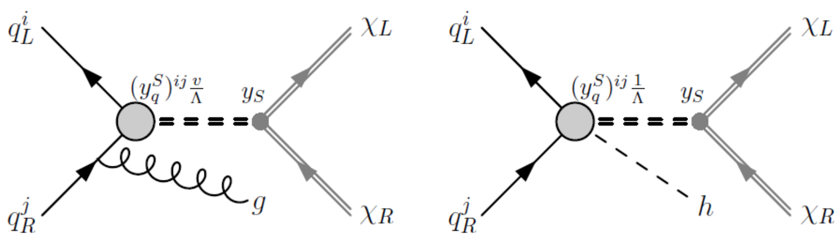
$$\frac{|(y_u^S)^{11}|}{\Lambda} \lesssim 2.9 \times 10^{-3} f_{\rm rel}^{-1/4} \left(\frac{m_S}{1\,\mathrm{TeV}}\right)^2 \mathrm{TeV}^{-1}$$

$$\langle N|m_q\bar{q}q|N\rangle \equiv m_N f_N^q$$

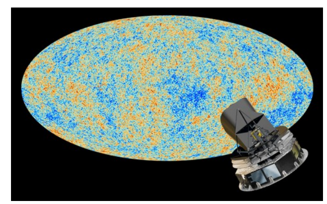
$$\mu_N \equiv \frac{m_\chi m_N}{m_\chi + m_N} \qquad m_N = (m_p + m_n)/2$$

Phenomenology

$q\bar{q}$ induced



Relic abundance $(m_\chi > m_S)$

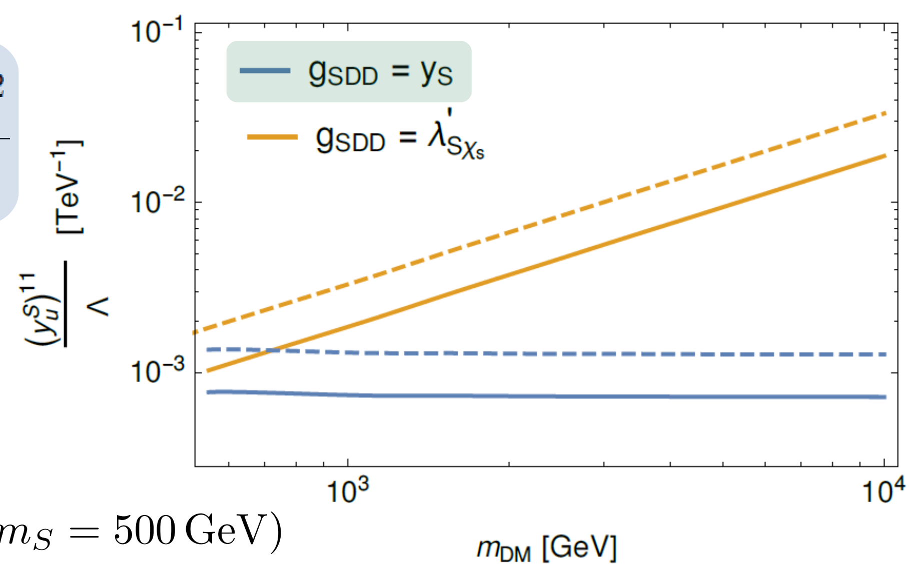


$$\langle\sigma \mathrm{v}\rangle(\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

fix y_S

DD: scattering off nuclei

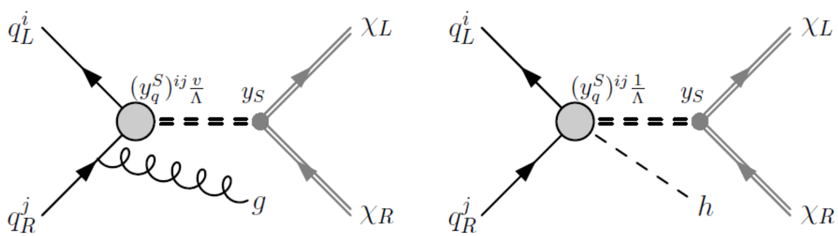
$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$



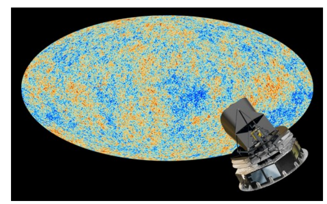
$(m_S = 500\,\mathrm{GeV})$

Phenomenology

$q\bar{q}$ induced



Relic abundance $(m_\chi > m_S)$



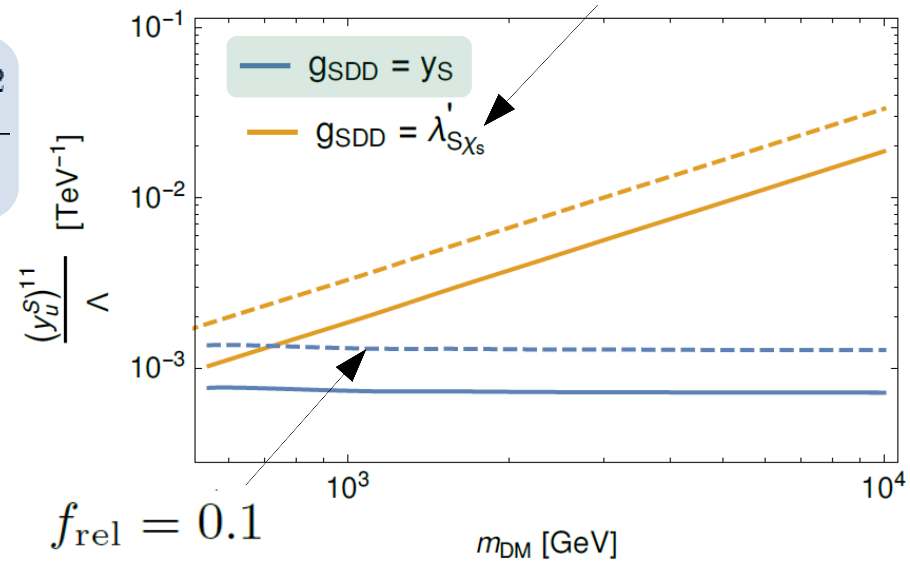
$$\langle \sigma \mathrm{v} \rangle (\chi\chi \to SS) \approx 2.0 \times 10^{-26}\,\mathrm{cm^3 s^{-1}}\, y_S^4 \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2$$

→ fix y_S

DD: scattering off nuclei

$$\sigma_N = \frac{y_S^2[(y_u^S)^{11})]^2 (f_N^u)^2 m_N^2 \mu_N^2 v^2}{2\pi\Lambda^2 m_S^4 m_u^2}$$

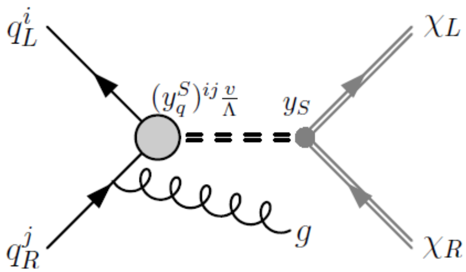
Scalar DM → later

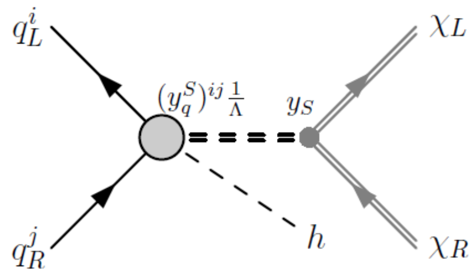


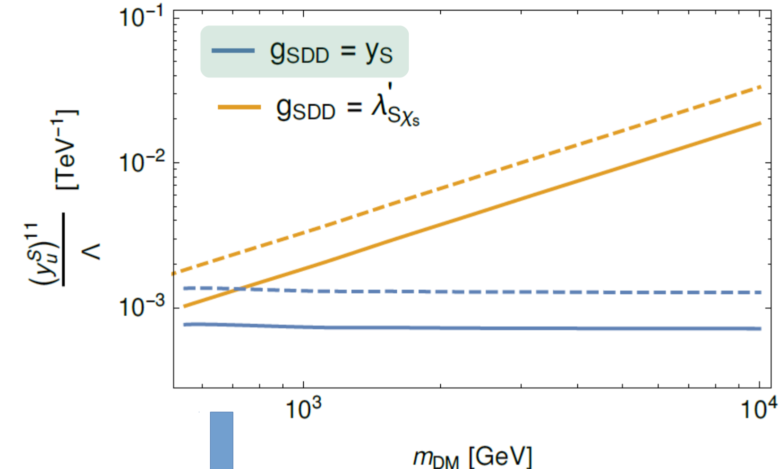
$f_{\rm rel} = 0.1$

LHC cross sections

$u\bar{u}$ induced







$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 3.0\cdot 10^{-7}\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.5\cdot 10^{-8}\,\mathrm{fb},$$

$$\sigma_{h+\not{E}_T}|_{m_\chi=500\,\mathrm{GeV}} \lesssim 2.0\cdot 10^{-8}\,\mathrm{fb},$$
$$\sigma_{h+\not{E}_T}|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.4\cdot 10^{-8}\,\mathrm{fb}$$

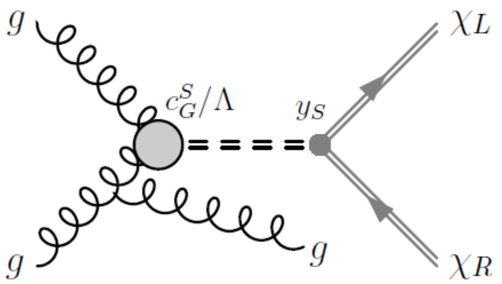
- Consider

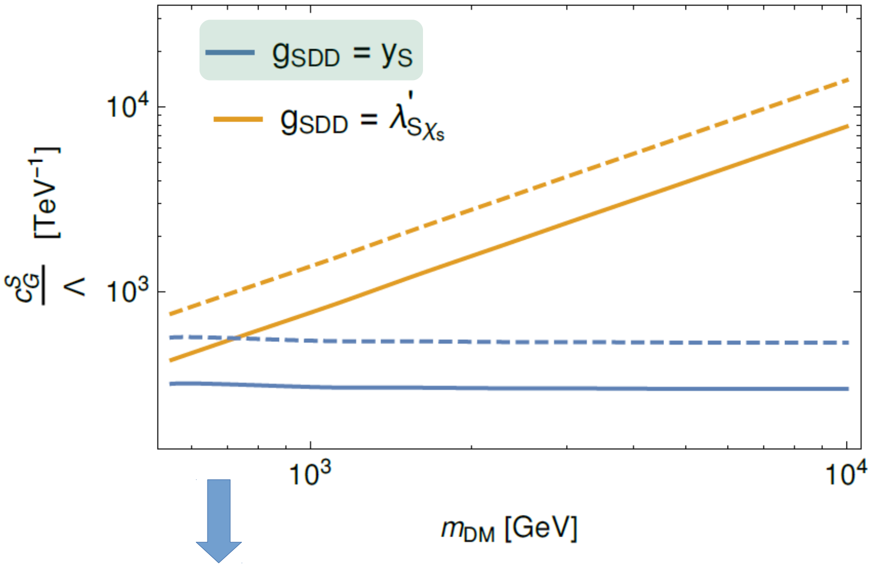
$$(m_S = 400\,\mathrm{GeV}, m_{\chi_s} = 500\,\mathrm{GeV}),$$
$$(m_S = 500\,\mathrm{GeV}, m_{\chi_s} = 1\,\mathrm{TeV})$$

not visible (just for illustration)
→ more interesting (e.g.): $b\bar{b}$ induced

LHC cross sections

gg induced





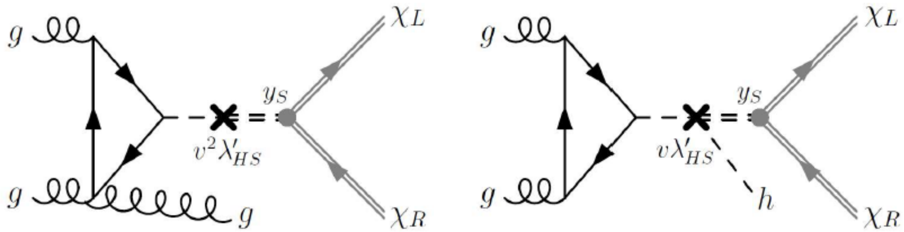
$$\sigma_j|_{m_\chi = 500\,\text{GeV}} \lesssim 1.9 \cdot 10^3\ \text{fb},$$
$$\sigma_j|_{m_\chi = 1\,\text{TeV}} \lesssim 250\ \text{fb}$$

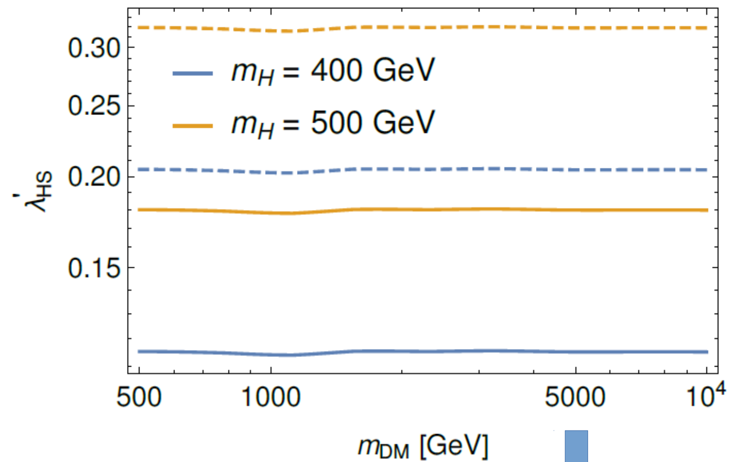
- Consider

$$(m_S = 400\,\text{GeV}, m_{\chi_s} = 500\,\text{GeV}),$$
$$(m_S = 500\,\text{GeV}, m_{\chi_s} = 1\,\text{TeV})$$

LHC cross sections

Higgs - mediator portal

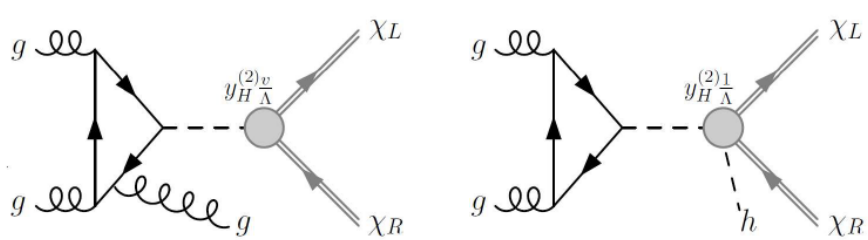


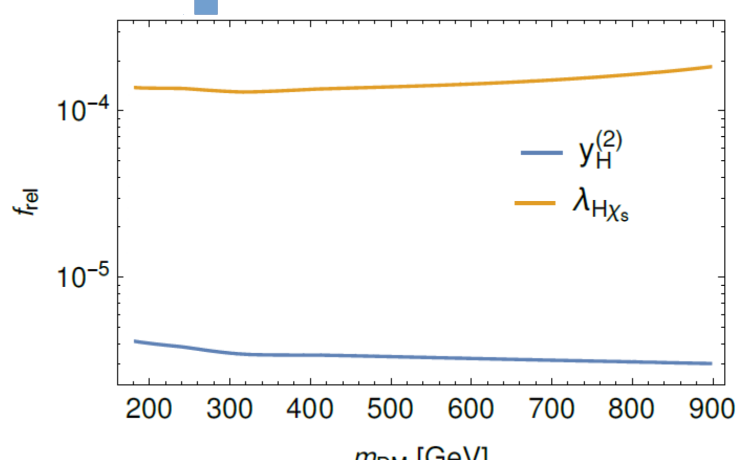


$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 1.1\cdot 10^{-3}\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.3\cdot 10^{-4}\,\mathrm{fb}$$

$$\sigma_j|_{m_\chi=500\,\mathrm{GeV}} \lesssim 49\,\mathrm{fb},$$
$$\sigma_j|_{m_\chi=1\,\mathrm{TeV}} \lesssim 3.3\,\mathrm{fb}$$

Higgs - DM portal





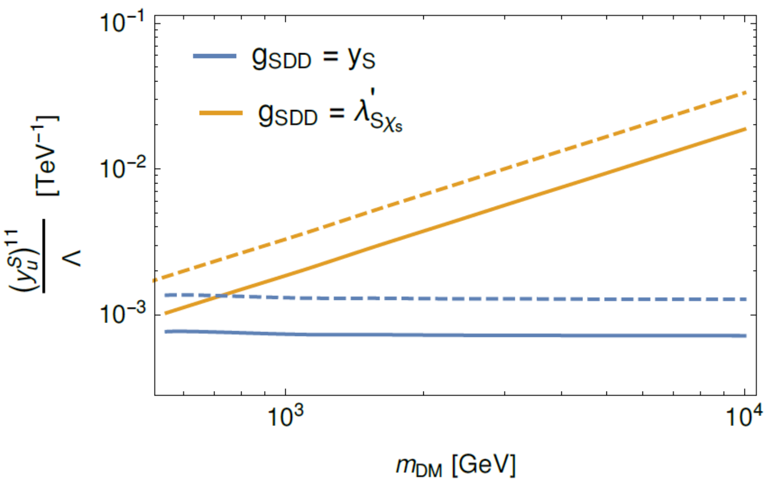
Scalar Dark Matter

$$\mathcal{L}_{\rm eff}^{\mathcal{S}\chi_s} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} - V(\mathcal{S}) - V(\chi_s) - \lambda'_{HS} v |H|^2 \mathcal{S} - \lambda_{HS} |H|^2 \mathcal{S}^2$$

$$- \frac{\lambda'_{S\chi_s}}{2\sqrt{2}} v\, \mathcal{S}\chi_s^2 - \lambda_{S\chi_s} \mathcal{S}^2 \chi_s^2 - \lambda_{H\chi_s} |H|^2 \chi_s^2$$

$$- \frac{\mathcal{S}}{\Lambda} \left[c_{\lambda S} \mathcal{S}^4 + c_{HS} |H|^2 \mathcal{S}^2 + c_{\lambda H} |H|^4 + c_{S\chi_s} \mathcal{S}^2 \chi_s^2 + c_{\lambda\chi_s} \chi_s^4 + c_{H\chi_s} |H|^2 \chi_s^2 \right]$$

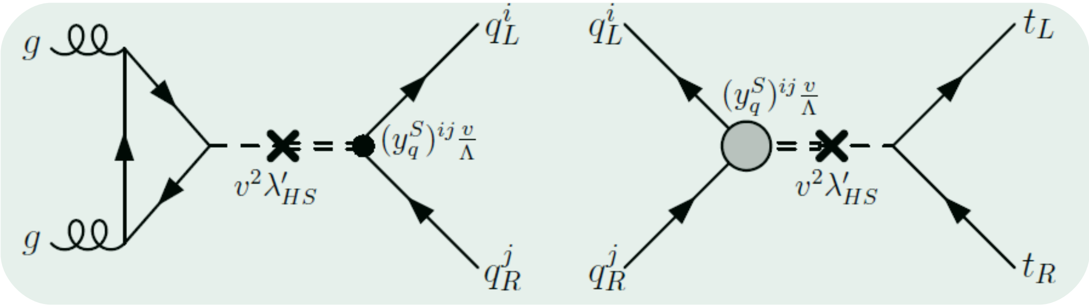
$$- \frac{\mathcal{S}}{\Lambda} (y_f^S)^{ij} \bar{F}_{\rm L}^i H f_{\rm R}^j - \frac{\mathcal{S}}{16\pi^2 \Lambda} \sum_{V=G,B,W} C_V^S V_{\mu\nu} V^{\mu\nu}$$



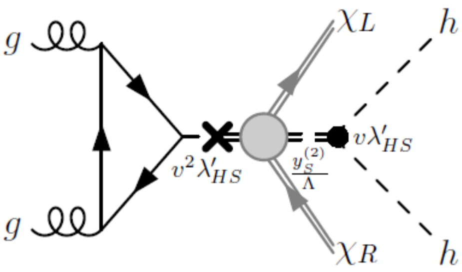
similar story...

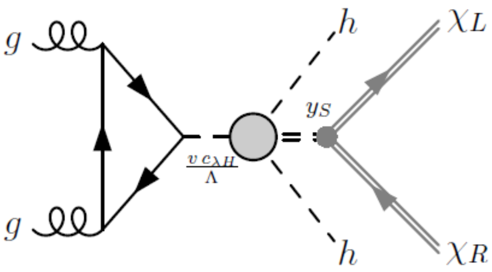
Further Processes

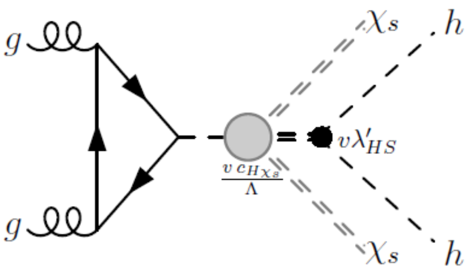
- Resonance Search for Mediator

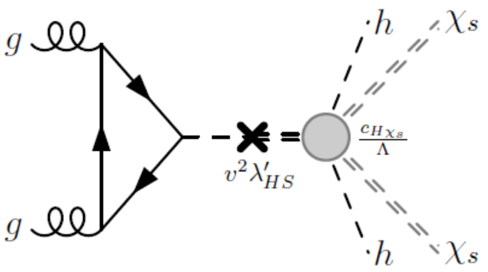


- Higgs Pair + MET ?









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