The Other Fermion-Compositeness

Brando Bellazzini

IPhT - CEA/Saclay

based on 1705.xxxx
with F. Riva, J.Serra and F. Sgarlata

Planck 2017, Warsaw May 22nd

or…

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Quarks and Leptons as Composite Pseudo-Goldstini

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Did Thompson discover SUSY in 1897 ??

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- possibly motivated
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no small couplings w/o reasons

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L~3000/fb in 2035 at LHC while E=13-14 TeV;
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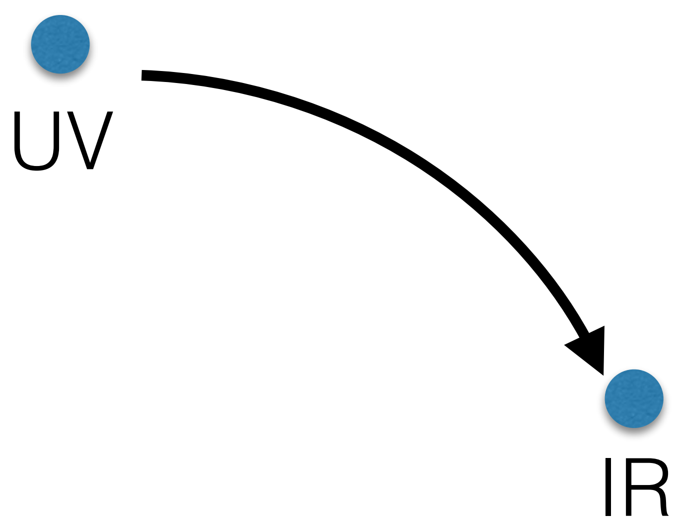
The EFT paradigm



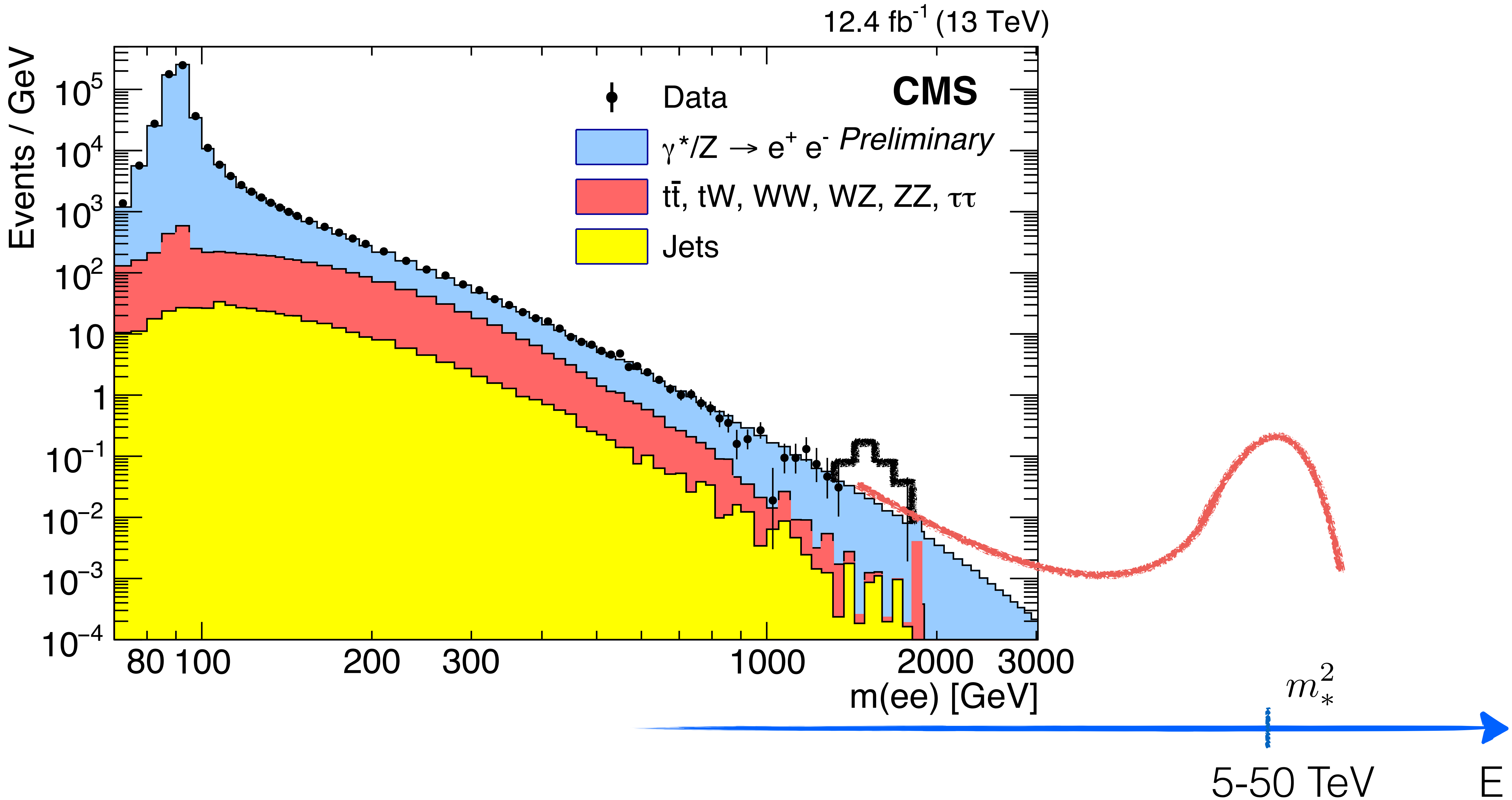
$$\mathcal{L}_{\mathcal{IR}} = \mathcal{L}^{SM}_{\Delta\leq 4} + \sum_i c_i \frac{\mathcal{O}_i(x)}{\Lambda_{UV}^{\Delta-4}}$$

EFT encodes UV-info via c_i

small parameter E/Λ_{UV}

Power counting = understanding = symmetries

Heavy strongly coupled Physics



large couplings from a strong sector help

e.g. in CHM: $\mathcal{L} = \frac{g_*^2}{m_*^2}(\partial H^2)^2$ $\quad [\mathcal{M}(2 \to 2)] = [g_*^2]$

SYMMETRY <—> DIMENSIONS

Higher dim-operators may dominate the amplitude within EFT

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Amplitude runs fast within the validity of EFT

How fast?

what the landscape of consistent EFTs?

The more irrelevant, the more SM-like at low-energy

$$\left.\begin{array}{ll} \text{CH, Goldstones} & (\partial\pi)^2\pi^2 \\ \text{4-Fermions} & (\bar\psi\gamma^\mu\psi)^2 \\ & \dots \end{array}\right\} \sim E^2$$

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can amplitudes be softer than E^4? **No!**

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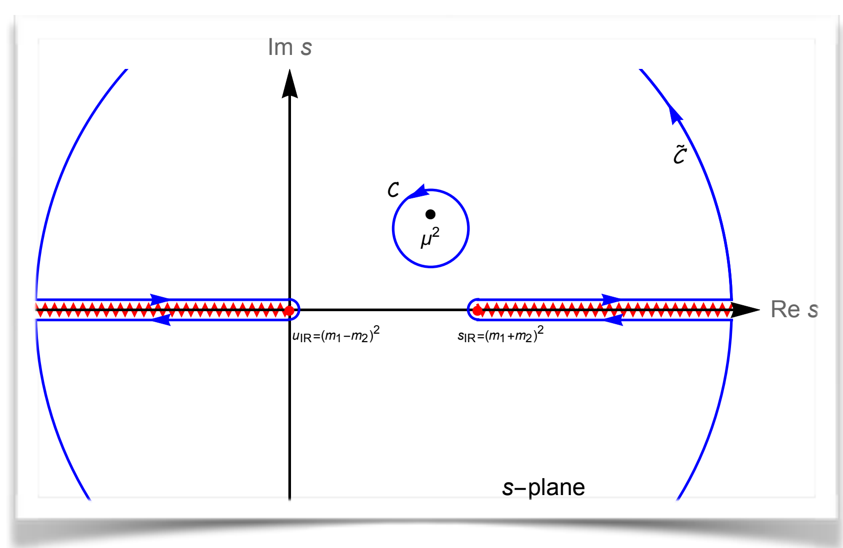
B.B. 1605.06111

Universal statement irrespectively spins



unitarity+crossing+analyticity of UV theory

Example

Higher-Derivatives partial compositeness

$$\psi \to \psi + \xi \qquad \mathcal{L}_{mix} = \lambda\, \partial_\mu \psi \mathcal{O}^\mu$$

$$\mathcal{L}_{eff} = \frac{g_*^2}{m_*^6} (\partial_\nu \psi^\dagger)^2 (\partial_\mu \psi)^2 + \ldots \longrightarrow \qquad \mathcal{M}(2 \to 2) = g_*^2 (E/m_*)^6$$

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doesn't admit a local unitary UV completion

The Only two fermion-compositeness

$$\mathcal{M}(\psi\psi \to \psi\psi)$$

$E^2 \quad (\bar\psi\gamma^\mu\psi)^2$

$E^4 \quad \bar\psi^2\partial^2\psi^2$

"Chiral-compositeness"
only one tested so far at LHC

vs

"Goldstino-Compositeness"
the one presented below

non-linear SUSY
$$\begin{cases} \psi(x) \longrightarrow \psi(x(x')) + \xi \\ x \longrightarrow x^\mu + i\xi\sigma^\mu\psi^\dagger(x) - i\psi(x)\sigma^\mu\xi^\dagger \end{cases}$$

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Manifesto:
quarks and/or leptons as composite pseudo-Goldstini
what are the experimental bounds? Generic Predictions?

modern incarnation of
Akulov-Volkov 1972
Bardeen-Visnjic (1982)

revived in Liu-Pomarol-Rattazzi-Riva
1603.03064

"Goldstino-Compositeness"

strong-sector

$\mathcal{N} - SUSY / Poincare$

χ_i

$\mathcal{N} - \text{Goldstini}$

$m_* \quad g_* \quad \epsilon_{\cancel{\text{susy}}}$

$F \sim m_*^2 / g_*$

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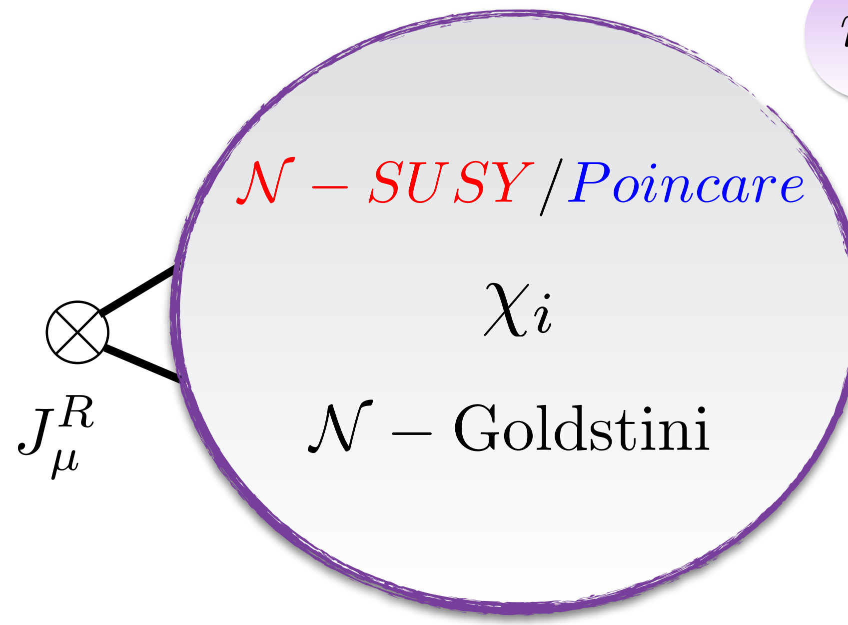

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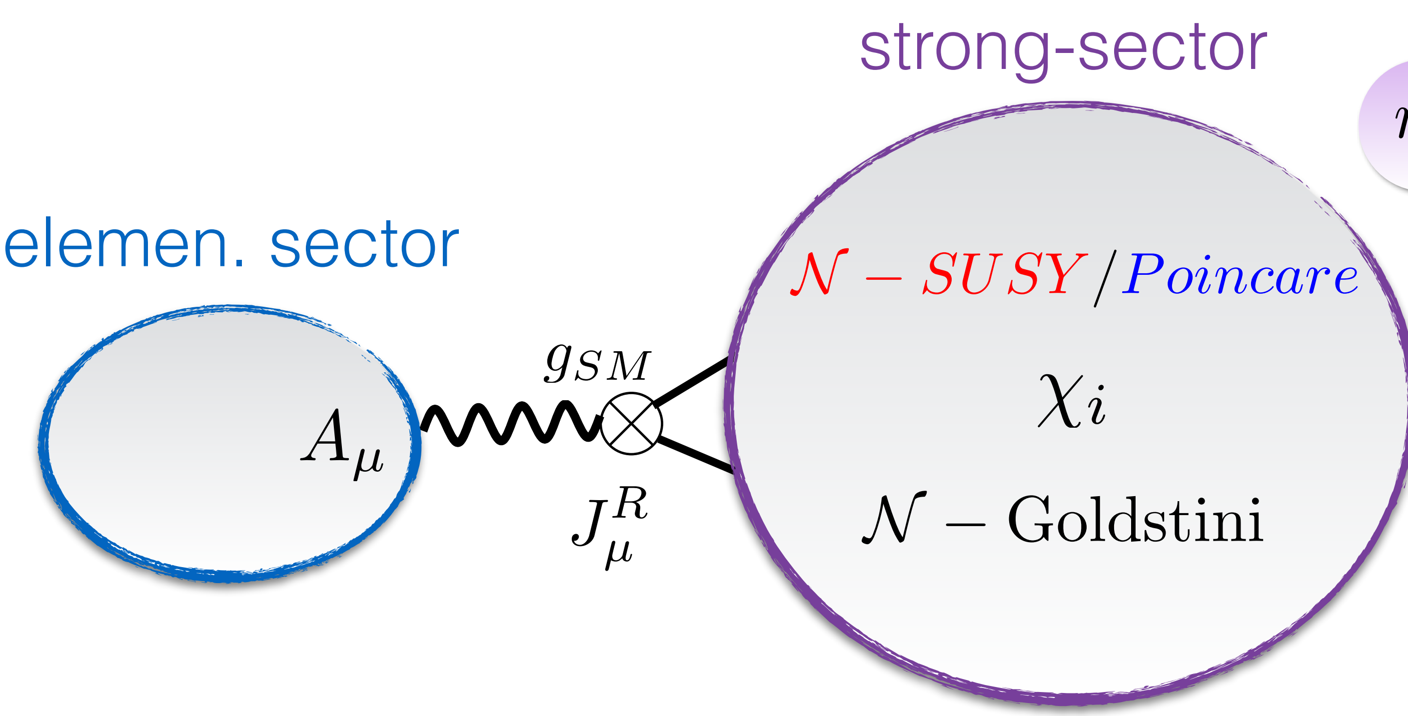

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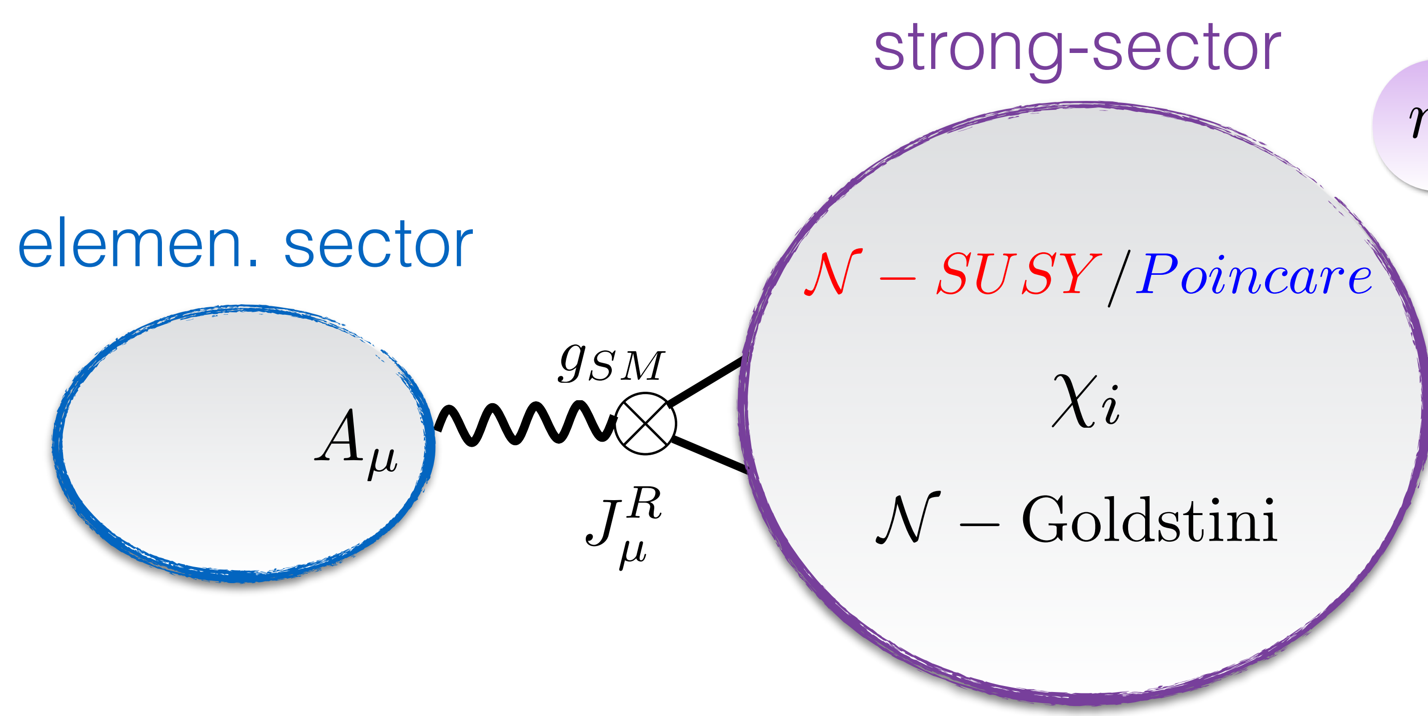

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(caveats…)
no goldstino mass yet

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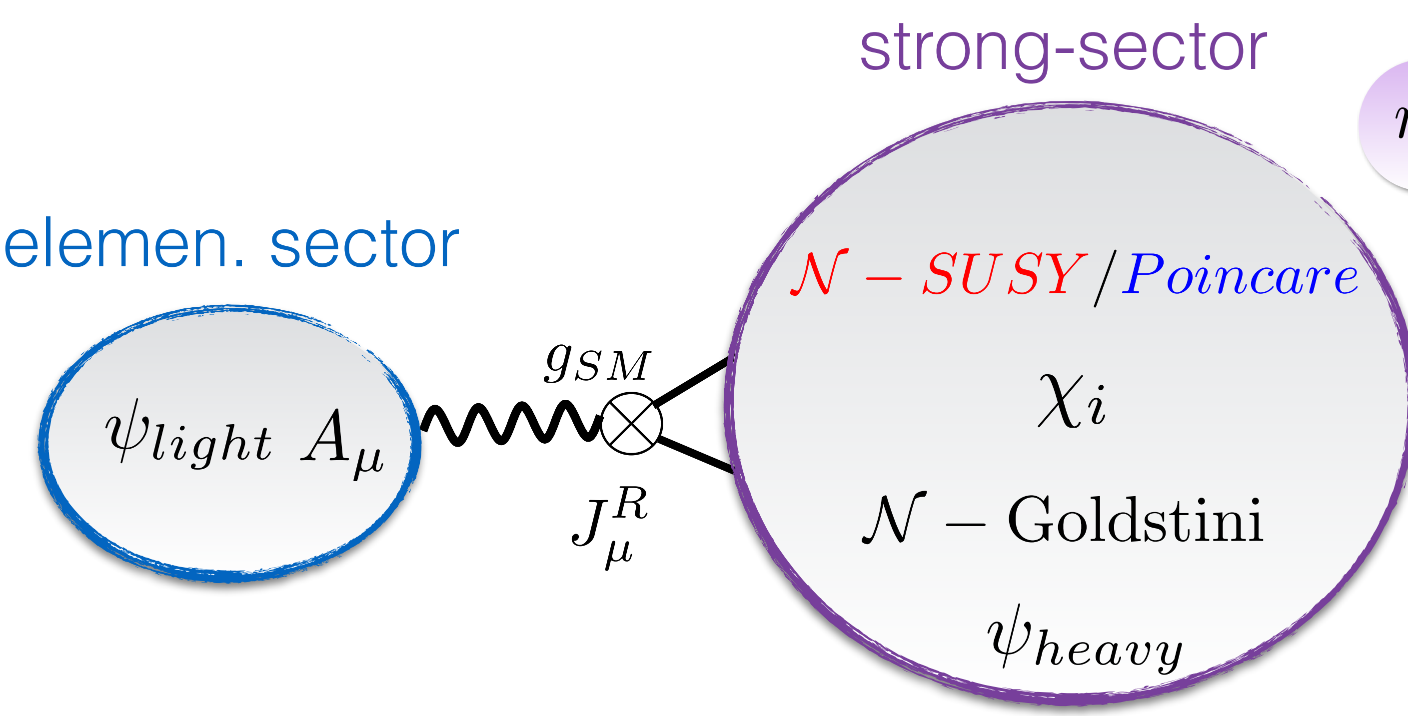

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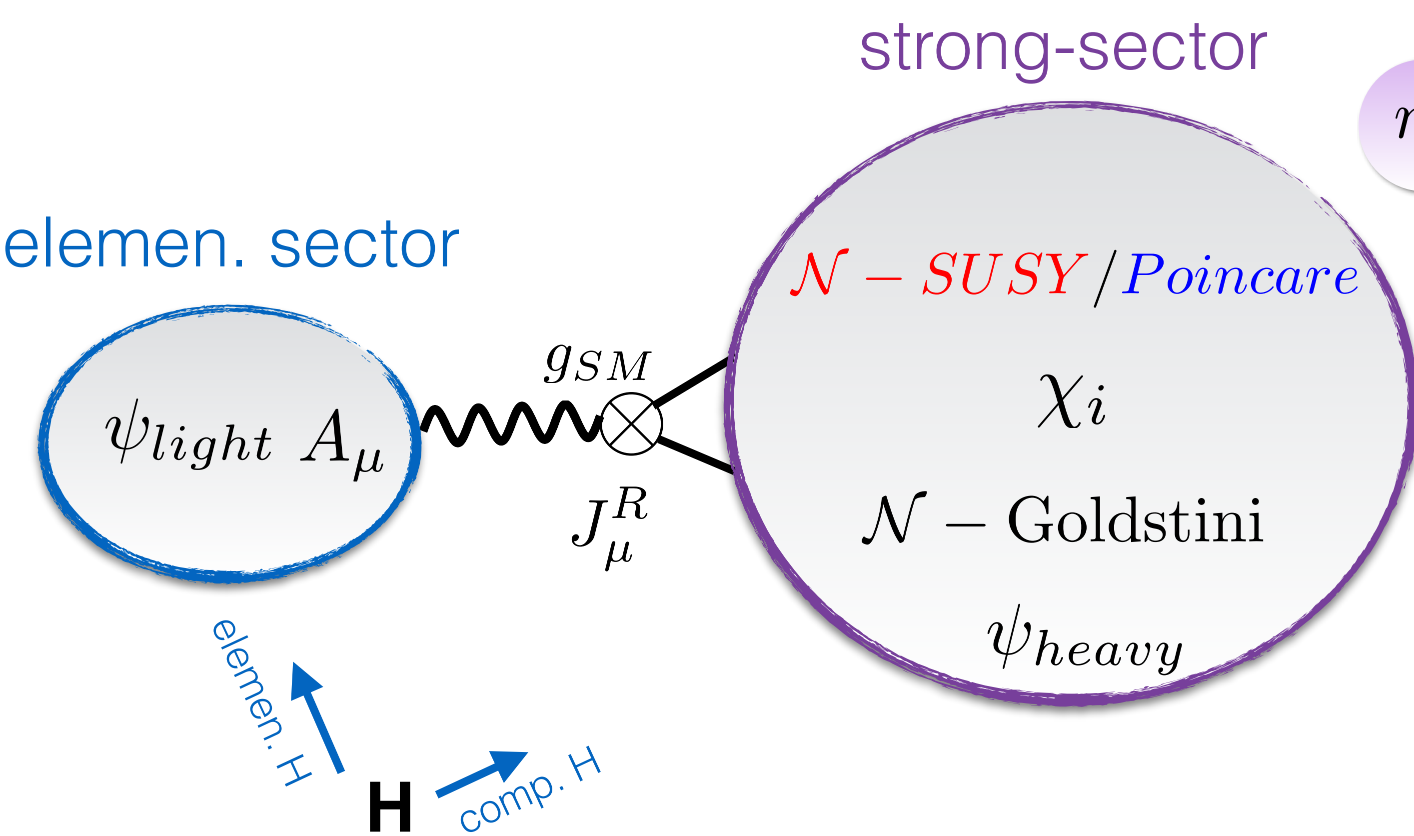

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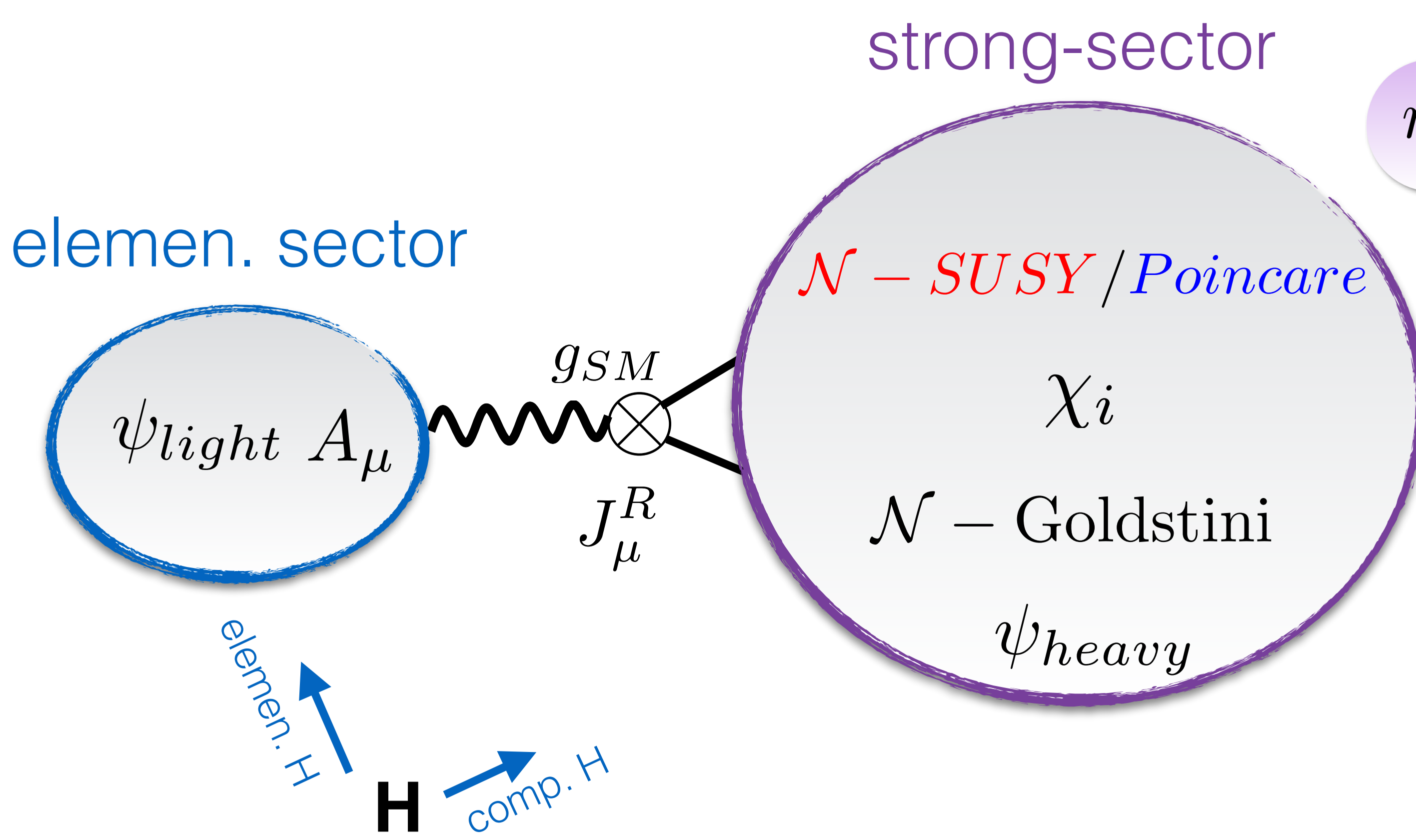

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dynamical assumption:
broken by Yukawa’s only i.e. Minimal Flavor Violation
$\chi_i y^{ij} \chi_j H$ breaks SUSY too

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Goldstini EFT

Coset space $\mathcal{N}-SUSY/Lorentz$ $x \to g(x) \sim g(x)h(x)$

local Lorentz

"gravity theory"

composite metric
composite veilbein

$g_{\mu\nu}(\chi,\chi^\dagger)$ $E_\mu{}^a(\chi,\chi^\dagger)$

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fermionic & spacetime shift

invariant action $$S_{\rm SUSY}[\chi, \Phi] = \int d^4x \det E\ \mathcal{L}(\nabla_a\chi(x), \Phi(x), \nabla_a\Phi(x), F_{bc}{}^a(x), \ldots) = \int d^4x \sqrt{-\det g}\ \mathcal{L}$$

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composite veilbein $E_\mu{}^a(\chi, \chi^\dagger)$

invariant action $S_{\rm SUSY}[\chi, \Phi] = \int d^4x \,\det E\, \mathcal{L}(\nabla_a \chi(x), \Phi(x), \nabla_a \Phi(x), F_{bc}{}^a(x), \ldots) = \int d^4x \sqrt{-\det g}\, \mathcal{L}$

$$\det\left[\delta_\mu^a - i\chi^{j\dagger}\bar{\sigma}^a \partial_\mu \chi_j + i\partial_\mu \chi^{j\dagger}\bar{\sigma}^a \chi_j\right]\{-F^2 + \ldots\}$$

most relevant term:

CC contribution from SUSY-breaking

Goldstini EFT

Coset space $\mathcal{N}-SUSY/Lorentz$ $\quad x \to g(x) \sim g(x)h(x)$

local Lorentz

composite metric
composite veilbein

"gravity theory"

$g_{\mu\nu}(\chi, \chi^\dagger) \quad E_\mu{}^a(\chi, \chi^\dagger)$

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$$\det\left[\delta^a_\mu - i\chi^{j\dagger}\bar\sigma^a\partial_\mu\chi_j + i\partial_\mu\chi^{j\dagger}\bar\sigma^a\chi_j\right]\{-F^2 + \ldots\}$$

most relevant term:
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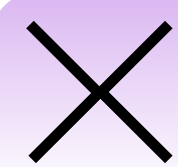
canonical K.T.+ $\int d^4x \frac{1}{F^2}(\chi_i^\dagger\partial_\mu\chi_j^\dagger)(\partial^\mu\chi^i\chi^j) + \ldots$

Goldstino 4-fermion interactions


$= \frac{E^4}{F^2}$

accidentally maximally R-symmetric

$F^2 \sim m_*^4/g_*^2$

More Couplings

model indep. coupling (well, not quite)

accidentally Maximal R-sym

naked terms	SUSY dressing	leading 4-body interactions
$-F^2$	$-F^2\sqrt{-\det g}$	$\frac{1}{F^2}(\chi_i^\dagger \partial_\mu \chi_j^\dagger)(\partial^\mu \chi^i \chi^j)$
$(\frac{i}{2}\psi_i^\dagger \bar{\sigma}^\mu \partial_\mu \psi^i(x) + h.c)$	$\det E(\frac{i}{2}\psi_i^\dagger \bar{\sigma}^a \nabla_a \psi^i(x) + h.c)$	$-\frac{1}{F^2}(\psi_i^\dagger \bar{\sigma}^a \partial_\mu \psi^i)(\chi_j^\dagger \bar{\sigma}^\mu \partial_a \chi^j)$
$-\frac{1}{4}F^A_{\mu\nu}F^{A\,\mu\nu}$	$-\sqrt{-\det g}\,\frac{1}{4}F^A_{\mu\nu}F^A_{\rho\sigma}g^{\mu\rho}g^{\nu\sigma}$	$-\frac{1}{4F^2}F^A_{\mu\nu}F^{A\,\mu}_{\ \ \rho}\left(i\chi_i^\dagger \bar{\sigma}^{\{\rho}\partial^{\nu\}}\chi^i + \text{h.c.}\right)$
$\partial_\mu \phi^{i\dagger}\partial_\mu \phi_i$	$\sqrt{-\det g}\,g^{\mu\nu}\partial_\mu \phi^{i\dagger}\partial_\nu \phi_i$	$\frac{1}{2F^2}\left(i\chi_j^\dagger \bar{\sigma}^{\{\mu}\partial^{\nu\}}\chi^j + \text{h.c.}\right)\partial_\mu \phi^{i\dagger}\partial_\nu \phi_i$

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$-\frac{1}{4}F^A_{\mu\nu}F^{A\,\mu\nu}$	$-\sqrt{-\det g}\,\frac{1}{4}F^A_{\mu\nu}F^A_{\rho\sigma}g^{\mu\rho}g^{\nu\sigma}$	$-\frac{1}{4F^2}F^A_{\mu\nu}F^{A\,\mu}_{\ \ \rho}\left(i\chi_i^\dagger\bar\sigma^{\{\rho}\partial^{\nu\}}\chi^i+\text{h.c.}\right)$
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some
model dep.
coupling

$R-symmetry$	SUSY Lgrangian	Leading interactions
ψ =singlet	$c_i^j\det E\,(\nabla_a\chi^{i\dagger}\bar\sigma^b\nabla^a\chi_j)(\psi^\dagger\bar\sigma_b\psi)$	$c_i^j\frac{1}{F^2}(\partial_\nu\chi^{i\dagger}\bar\sigma^\mu\partial^\nu\chi_j)(\psi^\dagger\bar\sigma_\mu\psi)$
π =singlet, GB	$d_i^j\det E\,\left(\nabla_a\chi^{i\dagger}\bar\sigma^b\nabla^a\chi_j\right)\nabla_b\pi$	5-body or $\propto$ masses
π =fund., GB	$c\det E\,\left(\nabla_a\chi^\dagger\bar\sigma^bT^A\nabla^a\chi\right)\left(i\pi^\dagger T^A\overleftrightarrow{\nabla}_b\pi\right)$	$\frac{c}{F^2}\,\left(\partial_\mu\chi^\dagger\bar\sigma^\nu T^A\partial^\mu\chi\right)\left(i\pi^\dagger T^A\overleftrightarrow{\partial}_\nu\pi\right)$

More Couplings

model indep. coupling
(well, not quite)

accidentally Maximal R-sym

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$(\frac{i}{2}\psi_i^\dagger\bar{\sigma}^\mu\partial_\mu\psi^i(x)+h.c)$	$\det E(\frac{i}{2}\psi_i^\dagger\bar{\sigma}^a\nabla_a\psi^i(x)+h.c)$	$-\frac{1}{F^2}(\psi_i^\dagger\bar{\sigma}^a\partial_\mu\psi^i)(\chi_j^\dagger\bar{\sigma}^\mu\partial_a\chi^j)$
$-\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu}$	$-\sqrt{-\det g}\,\frac{1}{4}F^A_{\mu\nu}F^A_{\rho\sigma}g^{\mu\rho}g^{\nu\sigma}$	$-\frac{1}{4F^2}F^A_{\mu\nu}F^{A\mu}{}_{\rho}\left(i\chi_i^\dagger\bar{\sigma}^{\{\rho}\partial^{\nu\}}\chi^i+\text{h.c.}\right)$
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all dim-8

More Couplings

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$-\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu}$	$-\sqrt{-\det g}\,\frac{1}{4}F^A_{\mu\nu}F^A_{\rho\sigma}g^{\mu\rho}g^{\nu\sigma}$	$-\frac{1}{4F^2}F^A_{\mu\nu}F^{A\mu}_{\ \ \rho}\left(i\chi_i^\dagger\bar\sigma^{\{\rho}\partial^{\nu\}}\chi^i+\text{h.c.}\right)$
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all dim-8

Explicit breaking

	elementary	composite (remedios)
gauge	$\mathcal{L}_{\text{gauge}}=-\frac{1}{4g^2}F^{A\,2}_{\mu\nu}+V^A_\mu R^{A\,\mu}$	$\mathcal{L}_{gauge}=\frac{1}{4g_*^2}F^A_{\mu\nu}F^A_{\rho\sigma}g^{\mu\rho}g^{\nu\sigma}+qV^A_\mu R^{A\,\mu}+\ldots$ $q \ll 1$
Yukawa	$\mathcal{L}_Y=\chi_i y^{ij}\chi_j H+\text{h.c.}$	
other	$(\det E)\,\chi_i\sigma^{ab}\chi_j\mathbb{F}_{ab}=\chi_i\sigma^{\mu\nu}\chi_jF_{\mu\nu}+\ldots$ ←	suppressed by MFV

Embeddings Quarks and Leptons

PG	$G_{Gauge} \times G_{Flav}$	$\mathcal{N}_{min}$
e^c	$U(1)_Y$	$\mathcal{N}=1$
L_e	$U(1)_Y \times SU(2)_L$	$\mathcal{N}=2$
$L_e,\, e^c$	$U(1)_Y \times SU(2)_L \times U(1)_{L_e}$	$\mathcal{N}=3^*$
$L_e,\, e^c,\, \nu_e^c$	$U(1)_Y \times SU(2)_L \times U(1)_{L_e} \times U(1)_A$	$\mathcal{N}=4^*$
d^c or u^c	$U(1)_Y \times SU(3)_C$	$\mathcal{N}=3$
$\boldsymbol{e^c}$	$U(1)_Y \times SU(3)_{l_R}^{Flav}$	$\mathcal{N}=3$
$\boldsymbol{L}$	$U(1)_Y \times SU(2)_L \times SU(3)_L^{Flav}$	$\mathcal{N}=6$
$\boldsymbol{L},\, \boldsymbol{e^c}$	$U(1)_Y \times SU(2)_L \times U(1)_L \times SU(3)_L^{Flav}$	$\mathcal{N}=9$
$\boldsymbol{L}, \boldsymbol{e^c}, \boldsymbol{\nu^c}$	$U(1)_Y \times SU(2)_L \times U(1)_L \times [SU(3)^{Flav}]^3$	$\mathcal{N}=12^*$
$\boldsymbol{d^c}$ or $\boldsymbol{u^c}$	$U(1)_Y \times SU(3)_C \times SU(3)_{d(u)}^{Flav}$	$\mathcal{N}=9$
$\boldsymbol{Q}$	$U(1)_R \times SU(2)_L \times SU(3)_C \times SU(3)_Q^{Flav}$	$\mathcal{N}=18$
$\boldsymbol{d^c},\, \boldsymbol{u^c}$	$[U(1)_Y]^2 \times SU(2)_L \times [SU(3)_C]^2 \times [SU(3)^{Flav}]^2$	$\mathcal{N}=18$
$\boldsymbol{Q}, \boldsymbol{d^c}, \boldsymbol{u^c}, \boldsymbol{X}_{-2/3,1/3}$	$[U(1)_Y]^2 \times SU(2)_L \times [SU(3)_C]^3 \times U(1)_B \times [SU(3)^{Flav}]^3$	$\mathcal{N}=72\,(36)$
$\boldsymbol{L}, \boldsymbol{e^c}, \boldsymbol{\nu^c}, \boldsymbol{Q}, \boldsymbol{d^c}, \boldsymbol{u^c}, \boldsymbol{X}_{-2/3,1/3}$	$[U(1)_Y]^4 \times [SU(2)_L]^2 \times [SU(3)_C]^3 \times U(1)_B \times U(1)_L \times [SU(3)^{Flav}]^6$	$\mathcal{N}=84\,(48)$

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all quarks $\quad \mathcal{N}=36 \quad \mathbf{36} = \mathbf{18}_q \oplus \mathbf{9}_d \oplus \mathbf{9}_u$ doesn't work! need to get antifundamental $\quad \mathbf{3}\otimes\mathbf{3} = \mathbf{3}^* \oplus \mathbf{6}$

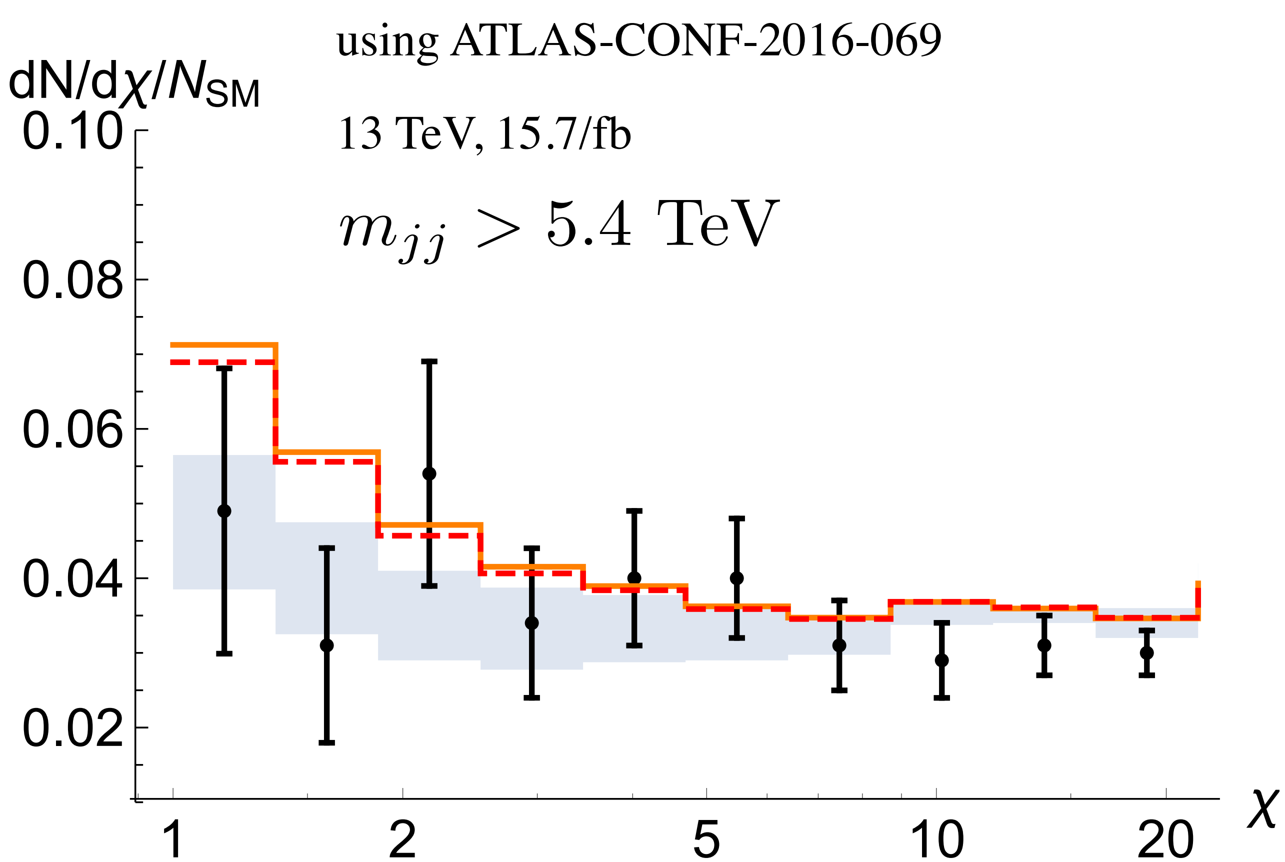
$$\mathcal{N}=72 \qquad \mathbf{72}_r = \begin{pmatrix} \boldsymbol{q} \\ \boldsymbol{u}^c \\ \boldsymbol{X}_{-2/3} \\ \boldsymbol{d}^c \\ \boldsymbol{X}_{1/3} \end{pmatrix}$$

generic prediction of maximal R-symmetry

exotic color 6-plets **X**, they are flavour triplets too

Bounds from Dijets

test dR compositeness



$$\chi \equiv e^{|y_{j_1} - y_{j_2}|} = \frac{1+\cos\theta}{1-\cos\theta}$$

$p_T(j_1) > 450$ GeV

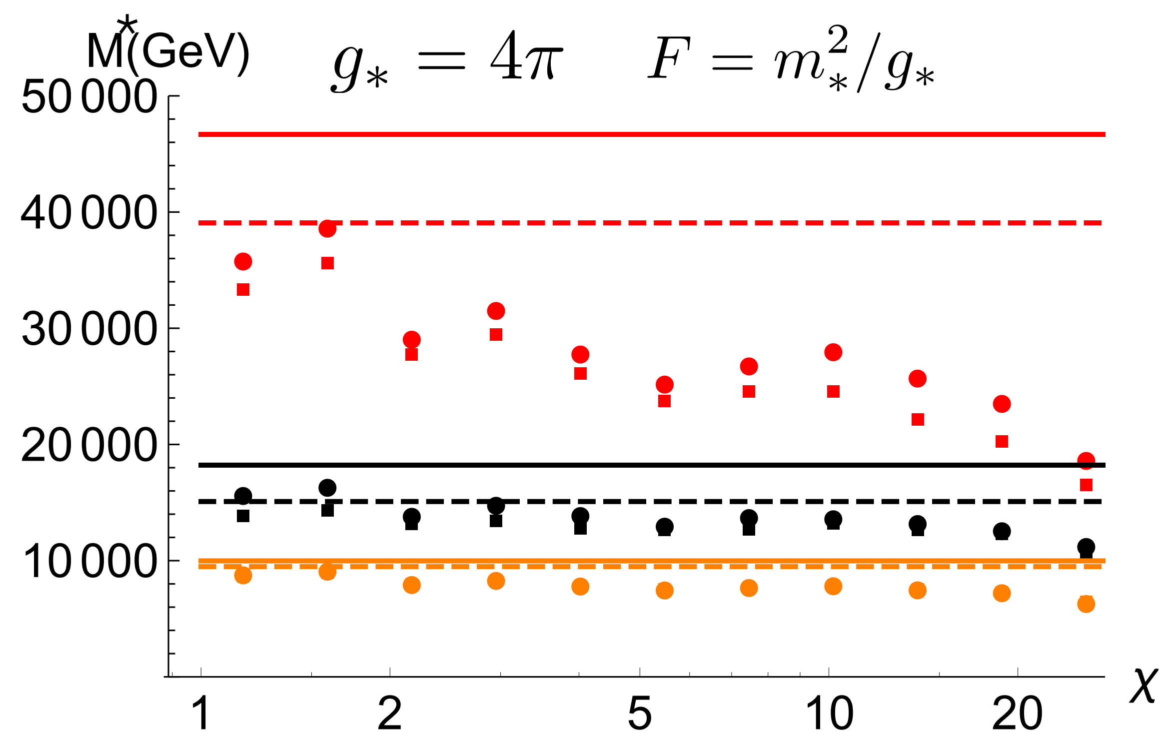
$(y_{j_1} + y_{j_2})/2 < 1.1$

$|y_{j_1} - y_{j_2}|/2 < 1.7$

$\sigma_{SM}^{cuts} = 50.8 \pm 9.1$ fb

dim-8 Goldstino-Compositeness

dim-6 chiral-compositeness



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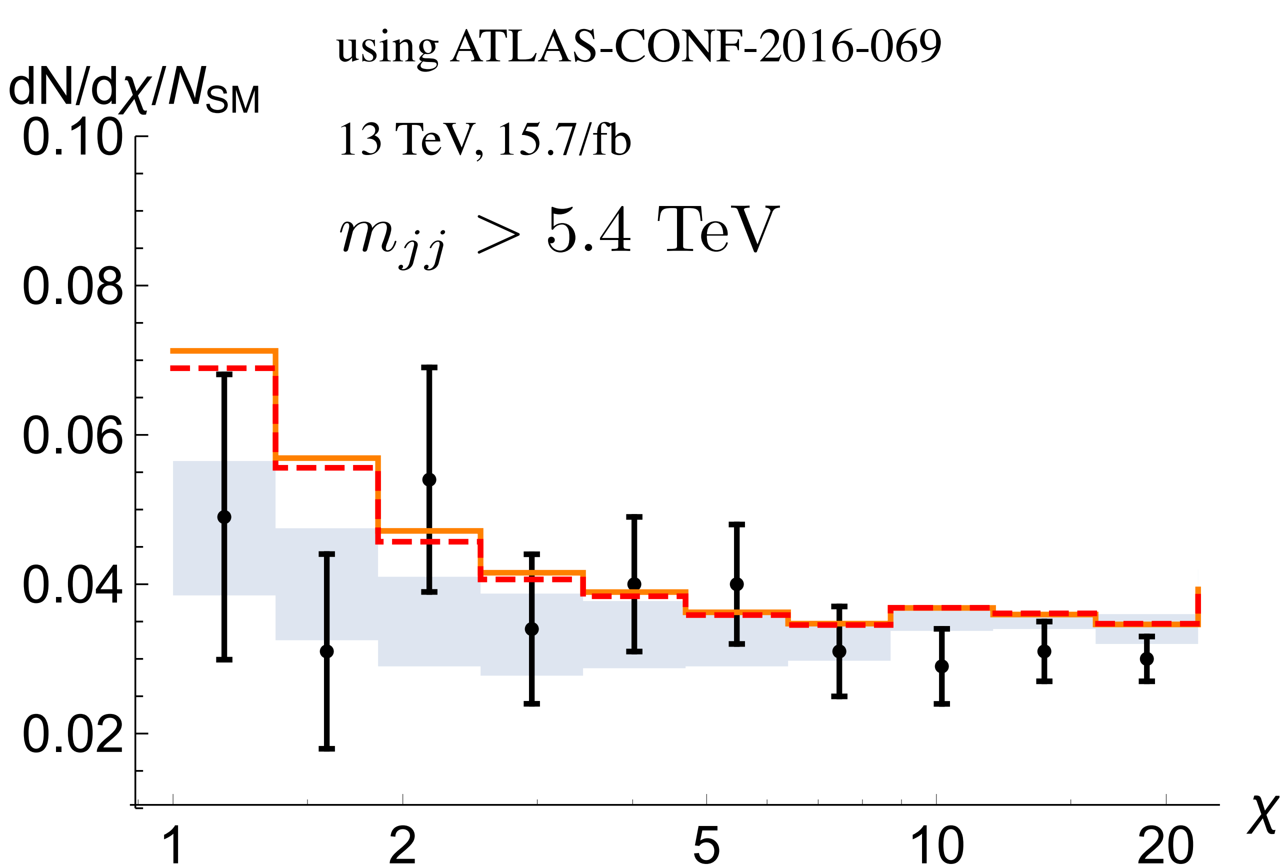

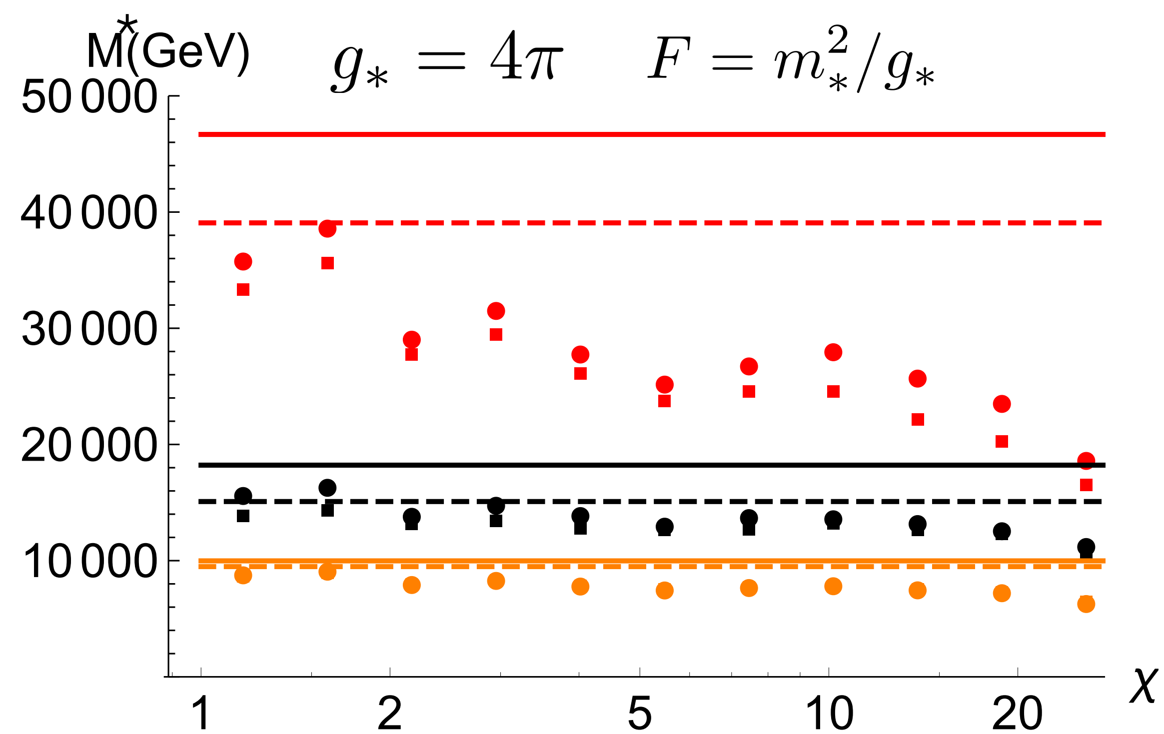

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from 50 TeV to 10 TeV!

Chiral- vs Goldstino-compositeness

dim-6 Chiral-Compositeness

dR

$$m_* \gtrsim \begin{cases} (g_*/4\pi)\ 47\ \text{TeV}\ (\text{positive}) \\ (g_*/4\pi)\ 39\ \text{TeV}\ (\text{negative}) \end{cases}$$

dim-8 Goldstino-compositeness

$$m_* \gtrsim \begin{cases} \sqrt{g_*/4\pi}\ 10\ \text{TeV}\ (\text{positive}) \\ \sqrt{g_*/4\pi}\ 9.5\ \text{TeV}\ (\text{negative}) \end{cases}$$

Goldstini	$\sqrt{F}$ (TeV)
d_R	2.2
u_R	3.3
u_R, d_R	3.5
q_L	3.5
q_L, d_R	3.6
q_L, u_R	4.0
q_L, u_R, d_R	4.1

EFT consistency: $m_* > m_{jj}$ $\quad g_* \gtrsim 2$ or $g_* \gtrsim 4$ strongly-coupled th.

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bounds rescaling

dim-8 $\sim$ dim-6 $\times (E/m_*)^2$

$$m_*^{(8)} \sim m_*^{(6)} \cdot \underbrace{\left(\frac{m_{jj}^{cut}}{m_*^{(6)}}\right)}_{0.1}{}^{1/2} \left(\frac{g_*^{(8)}}{g_*^{(6)}}\right)^{1/2}$$

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fixed coupling

$$m_*^{(8)} \sim 0.3 m_*^{(6)}$$

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fixed mass

$$g_*^{(8)} \sim 10\, g_*^{(6)}$$

fixed coupling

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bounds rescaling

dim-8 $\sim$ dim-6 $\times (E/m_*)^2$

$$m_*^{(8)} \sim m_*^{(6)} \cdot \underbrace{\left(\frac{m_{jj}^{cut}}{m_*^{(6)}}\right)^{1/2}}_{0.1} \left(\frac{g_*^{(8)}}{g_*^{(6)}}\right)^{1/2}$$

fixed mass

$$g_*^{(8)} \sim 10\, g_*^{(6)}$$

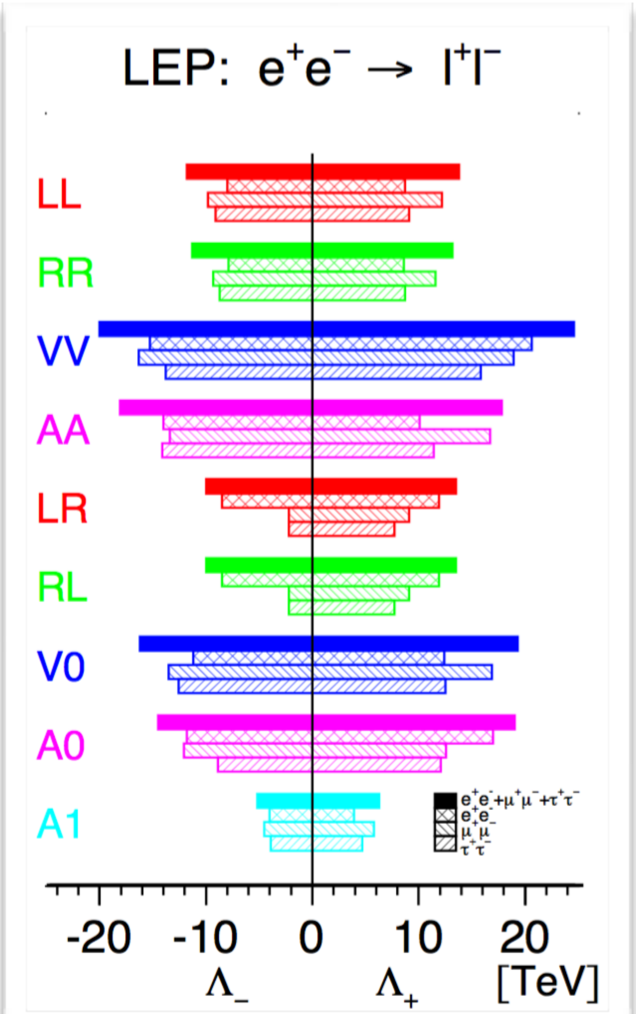
fixed coupling

$$m_*^{(8)} \sim 0.3 m_*^{(6)}$$

weaker bound on Goldstino-Compositeness: <u>huge impact for FCC-hh @ 100 TeV</u>

Bounds from Dileptons

LEP combination 1302.3415



$$\left(\frac{2\pi}{\Lambda_\pm^2}\right)\bar{e}_R\gamma^\mu e_R\bar{e}_R\gamma_\mu e_R$$

chiral-compositeness (RR)

$$\Lambda_\pm \gtrsim 9 \text{ TeV} \Rightarrow \boxed{m_*^{(6)} > (g_*^{(6)}/4\pi)\, 45 \text{ TeV}}$$

Goldstino-Compositeness of eR?

rough estimate from rescaling dim-6

$$m_*^{(8)} \sim m_*^{(6)} \cdot \underbrace{\left(\frac{m_{ee}^{cut}}{m_*^{(6)}}\right)^{1/2}}_{0.005} \left(\frac{g_*^{(8)}}{g_*^{(6)}}\right)^{1/2}$$

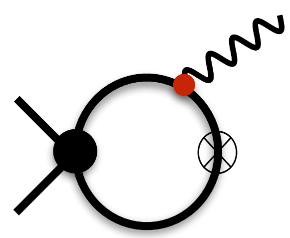
$$\boxed{m_*^{(8)} \gtrsim \left(g_*^{(8)}/4\pi\right)^{1/2} 3 \text{ TeV}}$$

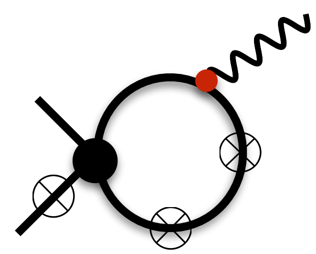
our analysis: ~2 TeV

PRECISION MEASUREMENTS?

Fermion-Gauge	**Fermion-Higgs**
$\mathcal{O}_B^\psi = D^\nu B_{\mu\nu}(\bar\psi_{L,R}\gamma^\mu\psi_{L,R})$	$\mathcal{O}_{L,R}^\psi = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar\psi_{L,R}\gamma^\mu\psi_{L,R})$
$\mathcal{O}_W^\psi = D^\nu W^a_{\mu\nu}(\bar\psi_L\sigma^a\gamma^\mu\psi_L)$	$\mathcal{O}_L^{(3)\,\psi} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar\psi_L\sigma^a\gamma^\mu\psi_L)$
	$\mathcal{O}_{y_\psi} = \lvert H\rvert^2\bar\psi_L H\psi_R$
Dipoles	**Four-Fermions**
$\mathcal{O}_{DB} = \bar\psi_L\sigma^{\mu\nu}H\psi_R B_{\mu\nu}$	$\mathcal{O}_{4\psi} = \bar\psi\gamma_\mu\psi\bar\psi\gamma^\mu\psi$
$\mathcal{O}_{DW} = \bar\psi_L\sigma^{\mu\nu}\sigma^a H\psi_R W^a_{\mu\nu}$	
$\mathcal{O}_{DG} = \bar\psi_L\sigma^{\mu\nu}HT^A\psi_R G^A_{\mu\nu}$	

muon g-2 $\sim \left(\frac{m_\mu}{m_*}\right)^2 \times \left(\frac{y_\mu^2}{16\pi^2}\right)^{0,1}$

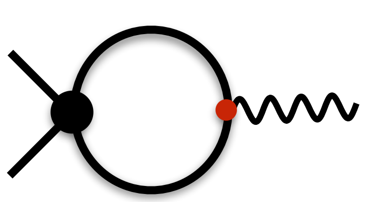




μ_R **and** L_μ **PGoldstini**

$m_* > 3.1$ TeV

Z-couplings (LEP-1)



$c^\psi_{W,B} \sim \frac{g}{m_*^2}$

$c^\psi_{L,R} \sim c_L^{(3)\,\psi} \sim c_{4\psi} \sim \frac{g^2}{m_*^2}$

$m_* \gtrsim 2.5$ TeV

Conclusions

- *The future of the LHC are tests for deviations from the SM*
  - *important to have a complete picture of how the SM can emerge from completely different dynamics, in particular strongly coupled which have the strongest effects*

- *There exist only two fermion-compositeness: Chiral- and Goldstino-compositeness*

  - Goldstino-Compositeness is controlled by SUSY-breaking power counting
  - SUSY put to good use, although very unusually and with different scope

- *We tested Goldstino-Compositeness for the first time*

  - Fully composite light-quarks as pseudo-Goldstini in the 10 TeV range (as opposed to ~50 TeV)
  - Fully composite electron as pseudo-Goldstino in the few TeV range (as opposed to ~45 TeV)
  - Did Thompson discover SUSY in 1897? We addressed this question looking at data

- *Maximal R-symmetry and Goldstino-compositeness of all quarks predict light coloured exotics 6-plets (look for it!)*

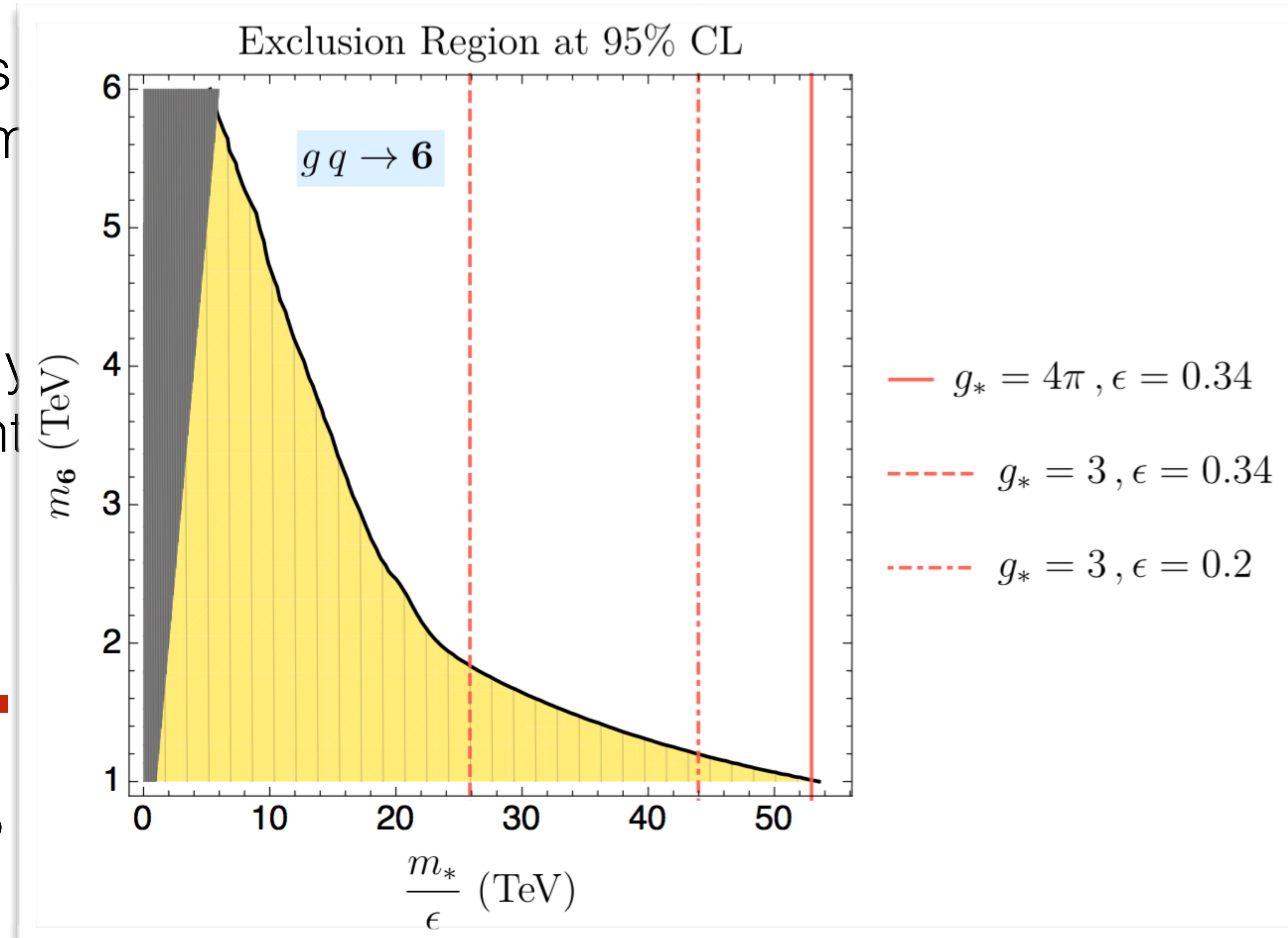
thank you!

backup slides

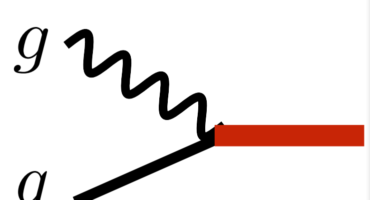
WHAT ABOUT THE EXOTIC 6-PLETS?

if left- and right-handed quarks
(and maximal R-sym

no majorana mass and anomaly
need to marry them with right



singly produced



$$\mathbf{8} \otimes \mathbf{3}^* = \mathbf{6}$$

leading op.'s ~ $\left(\frac{g_s}{2m_*}\epsilon\right) \cdot Y_{2/3}\sigma^{\{\mu\nu\}}u^c_{-2/3}G_{\mu\nu}$

narrow $\Gamma(Y \to qg) \sim \alpha_s \epsilon^2 \frac{m_X^3}{4m_*^2}$

Quarks as Pseudo-Goldstini

RH-down	$\mathcal{N}=3$	$U(1)_R \times SU(3)_R = U(1)_Y \times SU(3)_{Color}$	$\mathbf{3}^* = \chi_i = d_i^c$
	$\mathcal{N}=9$	$U(1)_R \times SU(9)_R \supset U(1)_Y \times SU(3)_{Color} \times SU(3)_{d^c}$	$\mathbf{9}^*_{1/3} = (\mathbf{3}^*, \mathbf{3}^*)_{1/3} = \boldsymbol{d}_j^c$

Quarks as Pseudo-Goldstini

RH-down $\mathcal{N}=3$ $U(1)_R \times SU(3)_R = U(1)_Y \times SU(3)_{Color}$ $\mathbf{3}^* = \chi_i = d_i^c$

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all RH-down+up $\mathcal{N}=18$ $U(1)_R \times SU(18)_R \supset U(1)_R \times U(1)_S \times SU(9) \times SU(9) \supset [U(1)]^2 \times [SU(3)]^4$

$$\mathbf{18}^*_{-1/6} = (\mathbf{9}^*, \mathbf{1})_{-1/6,-1/2} \oplus (\mathbf{1}, \mathbf{9}^*)_{1/6,1/2} = (\mathbf{3}^*, \mathbf{3}^*, \mathbf{1}, \mathbf{1})_{-1/6,-1/2} \oplus (\mathbf{1}, \mathbf{1}, \mathbf{3}^*, \mathbf{3}^*)_{-1/6,1/2} = \begin{pmatrix} \boldsymbol{u}_j^c \\ \boldsymbol{d}_j^c \end{pmatrix}$$

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LH-quarks $\mathcal{N}=18$ $U(1)_R \times SU(18)_R \supset U(1)_R \times SU(2) \times SU(9) \supset U(1)_R \times SU(2)_W \times SU(3)_C \times SU(3)_{q_L}$

$$\chi_i = \mathbf{18}_{1/6} = (\mathbf{2}, \mathbf{9})_{1/6} = (\mathbf{2}, \mathbf{3}, \mathbf{3})_{1/6} = \boldsymbol{q}_{ij}$$

Quarks as Pseudo-Goldstini

RH-down $\mathcal{N}=3$ $U(1)_R \times SU(3)_R = U(1)_Y \times SU(3)_{Color}$ $\mathbf{3}^* = \chi_i = d_i^c$

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$$\chi_i = \mathbf{18}_{1/6} = (\mathbf{2}, \mathbf{9})_{1/6} = (\mathbf{2}, \mathbf{3}, \mathbf{3})_{1/6} = \boldsymbol{q}_{ij}$$

all quarks $\mathcal{N}=36$ $\mathbf{36} = \mathbf{18}_q \oplus \mathbf{9}_d \oplus \mathbf{9}_u$ doesn't work! need to get antifundamental $\mathbf{3} \otimes \mathbf{3} = \mathbf{3}^* \oplus \mathbf{6}$

$\mathcal{N}=72$ $$\mathbf{72}_r = \begin{pmatrix} \boldsymbol{q} \\ \boldsymbol{u}^c \\ \boldsymbol{X}_{-2/3} \\ \boldsymbol{d}^c \\ \boldsymbol{X}_{1/3} \end{pmatrix}$$

generic prediction of maximal R-symmetry

exotic color 6-plets **X**, they are flavour triplets too

Goldstino-Compositeness of Leptons

right-handed $\mathcal{N}=1$ $U(1)_R = U(1)_Y$ $e^c = (\mathbf{1},\mathbf{1})_1$

$\mathcal{N}=3$ $U(1)_R \times SU(3)_R = U(1)_Y \times SU(3)_{flavor}$ $\boldsymbol{e}^c = \mathbf{3}_1 = (e^c, \mu^c, \tau^c)_1$

flavor

left-handed $\mathcal{N}=2$ $U(1)_R \times SU(2)_R = U(1)_Y \times SU(2)_W$ $L = (\mathbf{1},\mathbf{2})_{-1/2}$

$\mathcal{N}=6$ $U(1)_R \times SU(6)_R \supset U(1)_Y \times SU(2)_W \times SU(3)_{flavour}$ $\chi_{i=(j,k)} = \boldsymbol{L}_j = (L_j^e, L_j^\mu, L_j^\tau)$

all leptons $\mathcal{N}=12$

$$\mathbf{12} = (\mathbf{6},\mathbf{1})_{-1/2} \oplus (\mathbf{1},\mathbf{6})_{1/2} = (\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{1})_{-1/2,0} \oplus (\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1})_{1/2,1/2} \oplus (\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{3})_{1/2,-1/2} = \begin{pmatrix} \boldsymbol{L} \\ \boldsymbol{e}^c \\ \boldsymbol{\nu}^c \end{pmatrix}$$

$$SU(12) \supset SU(6) \times SU(6) \times U(1)_A \supset SU(2)_W \times \underbrace{SU(3) \times SU(3) \times SU(3)}_{\text{flavor}} \times \underbrace{U(1)_A \times U(1)_B}_{U_{Y=A+B}}$$

Goldstino-Compositeness of Leptons

right-handed $\mathcal{N}=1$ $U(1)_R = U(1)_Y$ $e^c = (\mathbf{1},\mathbf{1})_1$

$\mathcal{N}=3$ $U(1)_R \times SU(3)_R = U(1)_Y \times SU(3)_{flavor}$ $\boldsymbol{e}^c = \mathbf{3}_1 = (e^c,\mu^c,\tau^c)_1$

flavor

left-handed $\mathcal{N}=2$ $U(1)_R \times SU(2)_R = U(1)_Y \times SU(2)_W$ $L = (\mathbf{1},\mathbf{2})_{-1/2}$

$\mathcal{N}=6$ $U(1)_R \times SU(6)_R \supset U(1)_Y \times SU(2)_W \times SU(3)_{flavour}$ $\chi_{i=(j,k)} = \boldsymbol{L}_j = (L^e_j, L^\mu_j, L^\tau_j)$

all leptons $\mathcal{N}=12$

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Goldstino-Compositeness of Leptons

right-handed

$\mathcal{N}=1 \qquad U(1)_R = U(1)_Y \qquad e^c = (\mathbf{1},\mathbf{1})_1$

$\mathcal{N}=3 \qquad U(1)_R \times SU(3)_R = U(1)_Y \times SU(3)_{flavor} \qquad \boldsymbol{e}^c = \mathbf{3}_1 = (e^c, \mu^c, \tau^c)_1$

flavor

left-handed

$\mathcal{N}=2 \qquad U(1)_R \times SU(2)_R = U(1)_Y \times SU(2)_W \qquad L = (\mathbf{1},\mathbf{2})_{-1/2}$

$\mathcal{N}=6 \qquad U(1)_R \times SU(6)_R \supset U(1)_Y \times SU(2)_W \times SU(3)_{flavour} \qquad \chi_{i=(j,k)} = \boldsymbol{L}_j = (L^e_j, L^\mu_j, L^\tau_j)$

all leptons $\qquad \mathcal{N}=12$

$$\mathbf{12} = (\mathbf{6},\mathbf{1})_{-1/2} \oplus (\mathbf{1},\mathbf{6})_{1/2} = (\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{1})_{-1/2,0} \oplus (\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1})_{1/2,1/2} \oplus (\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{3})_{1/2,-1/2} = \begin{pmatrix} \boldsymbol{L} \\ \boldsymbol{e}^c \\ \boldsymbol{\nu}^c \end{pmatrix}$$

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Gauging R-symmetry

without SUGRA explicit breaking

$$[R^a_{SU(\mathcal{N})_R}, Q^i] = (T^a)^i{}_j\, Q^j\,, \qquad [R_{U(1)_R}, Q^i] = Q^i$$
$$[R^a_{SU(\mathcal{N})_R}, Q^\dagger_i] = -\left(\overline{T}^a\right)^i{}_j\, Q^\dagger_j\,, \qquad [R_{U(1)_R}, Q^\dagger_i] = -Q^\dagger_i$$

R is not an invariant sub-algebra

more prosaically, the R-current doesn't respect the shift symmetry

$$R^{A\,\mu} = \frac{1}{F^2} T_a{}^{\mu} \chi^\dagger \bar{\sigma}^a T^A \chi = (\chi^\dagger \bar{\sigma}^a T^A \chi) \left(\delta^\mu_a + \frac{i}{2F^2} \chi^{j\dagger} \bar{\sigma}^\mu \overleftrightarrow{\partial}_a \chi_j + \dots \right)$$

with SUGRA: gauging R is OK in principle

(see e.g. Drainer '95)

superpotential is charged

BUT

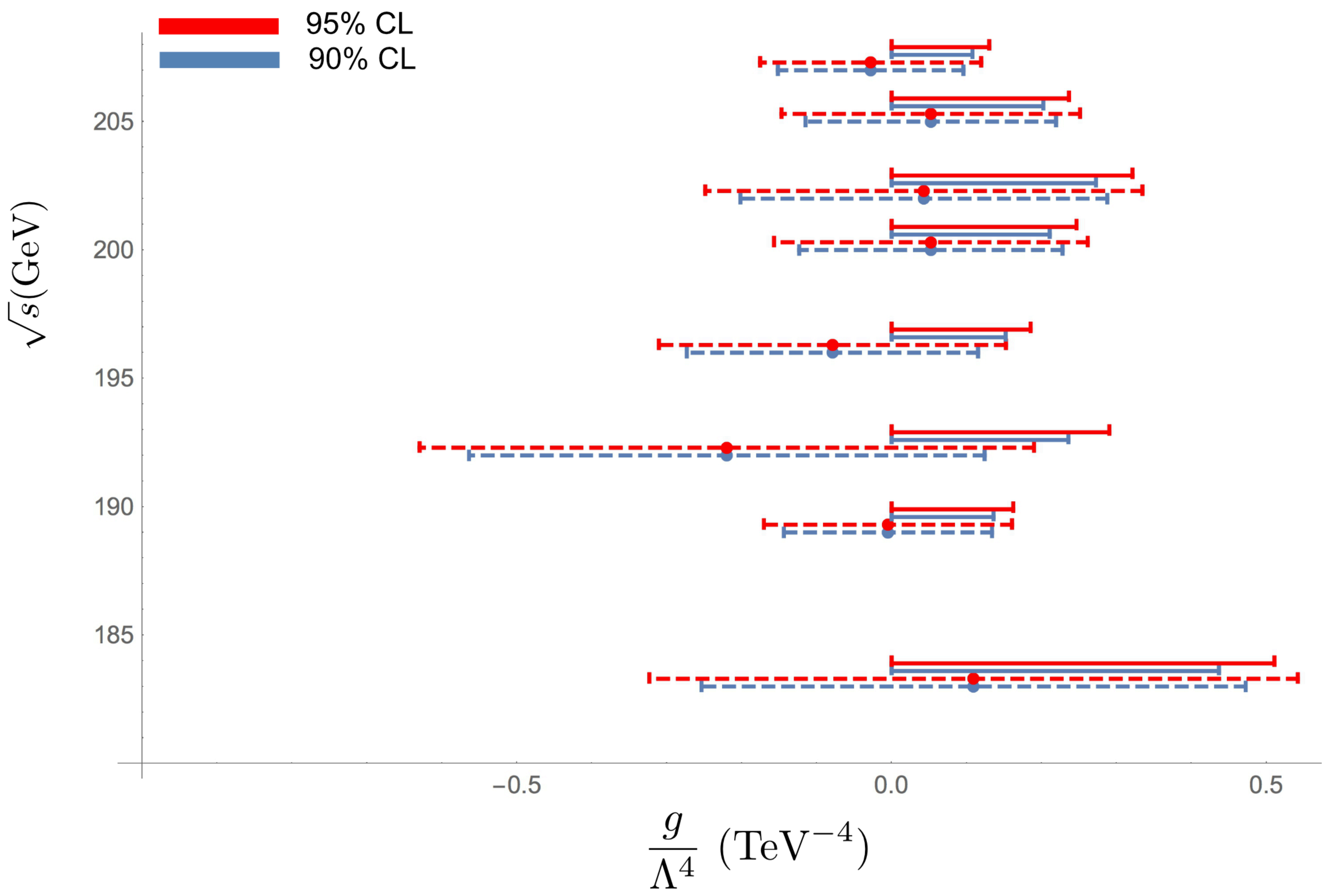
1) vanishing CC requires R broken near Planck $\quad CC \sim F^2 - |W|^2/m^2_{Pl}$

2) SUGRA adds N-gravitini that eat the Goldstini

gravity is breaking SUSY explicitly in our setup:

no-SUGRA!

POSITIVITY



95% CL
90% CL
205
200
195
190
185
$\sqrt{s}(\mathrm{GeV})$
−0.5
0.0
0.5
$\frac{g}{\Lambda^4}$ (TeV^{-4})

4-fermion with two derivatives

R-currents

$U(1)$	$U(1)\times SU(N)$	$U(1)\times SU(N_C)\times SU(N_F)$
$(\partial\chi^\dagger)\chi^\dagger(\partial\chi)\chi$	$\partial_\mu\bar{\chi}_a\bar{\chi}_b\partial^\mu\chi^a\chi^b$	$\partial{\chi^\dagger}^{\alpha}_{a}{\chi^\dagger}^{\beta}_{b}\partial\chi^a_\alpha\chi^b_\beta$
	$\partial_\mu\bar{\chi}_a\bar{\chi}_b\partial^\mu\chi^b\chi^a$	$\partial{\chi^\dagger}^{\alpha}_{a}{\chi^\dagger}^{\beta}_{b}\partial\chi^a_\beta\chi^b_\alpha$
		$\partial{\chi^\dagger}^{\alpha}_{a}{\chi^\dagger}^{\beta}_{b}\partial\chi^b_\alpha\chi^a_\beta$
		$\partial{\chi^\dagger}^{\alpha}_{a}{\chi^\dagger}^{\beta}_{b}\partial\chi^b_\beta\chi^a_\alpha$

$$R^{A\,\mu}=\frac{1}{F^2}T_a{}^{\mu}\chi^\dagger\bar{\sigma}^aT^A\chi=\left(\chi^\dagger\bar{\sigma}^aT^A\chi\right)\left(\delta^\mu_a+\frac{i}{2F^2}\chi^{j\dagger}\bar{\sigma}^\mu\overleftrightarrow{\partial}_a\chi_j+\dots\right)$$