Aspects of Accidental Symmetries

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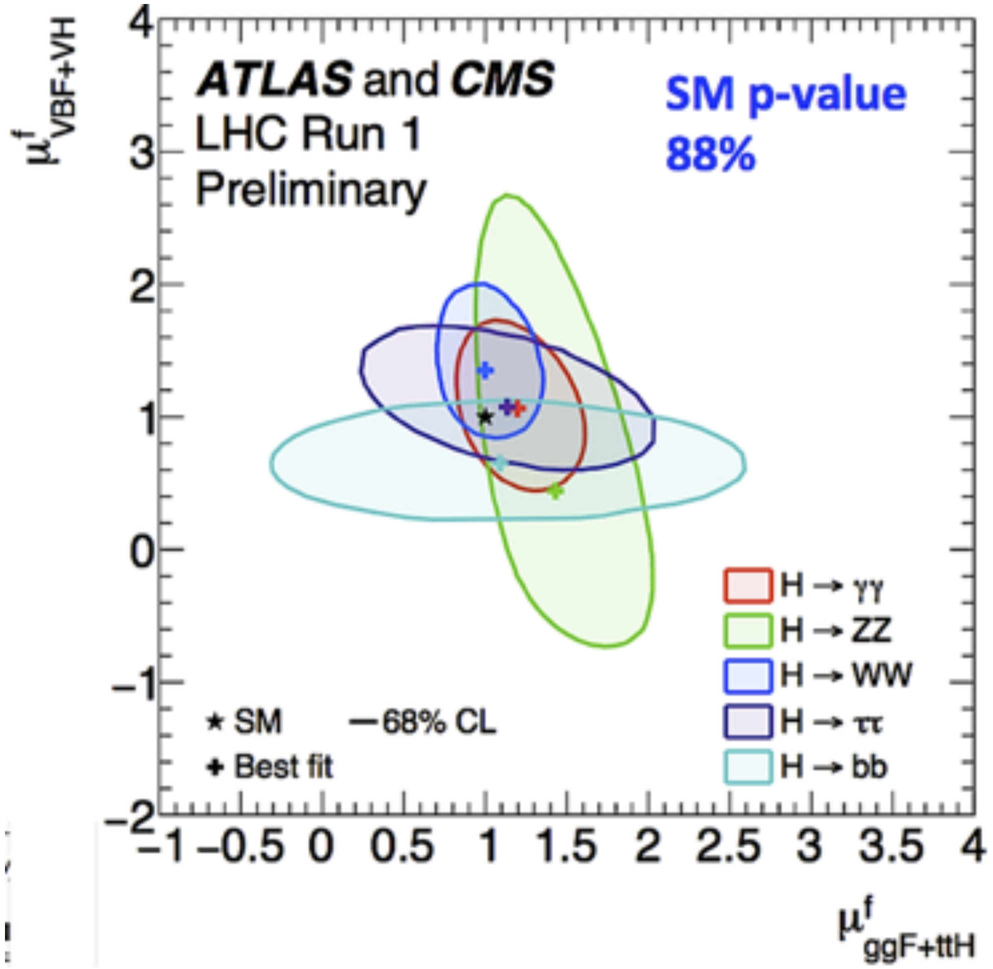
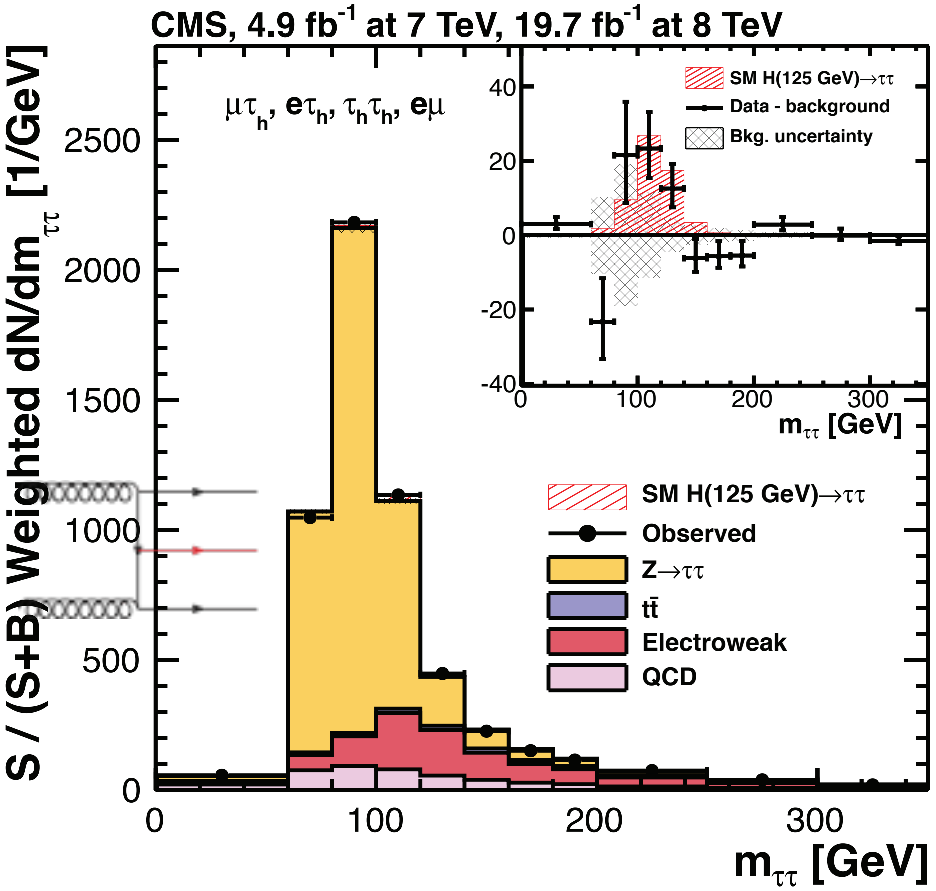
Outline

- Beyond the SM
- Accidental Matter Framework
- Cosmology
- LHC phenomenology
- Conclusions

A brief summary: Higgs Physics

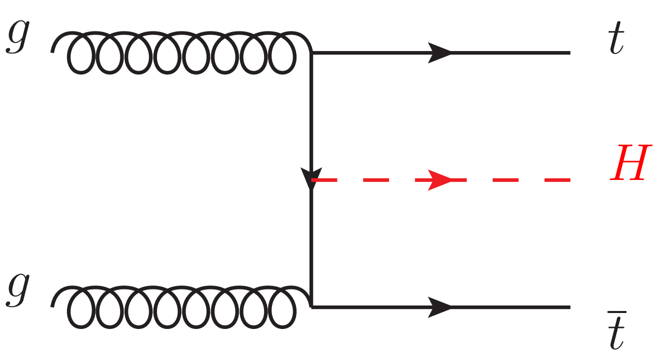
1) Testing the SM Higgs-like scalar*





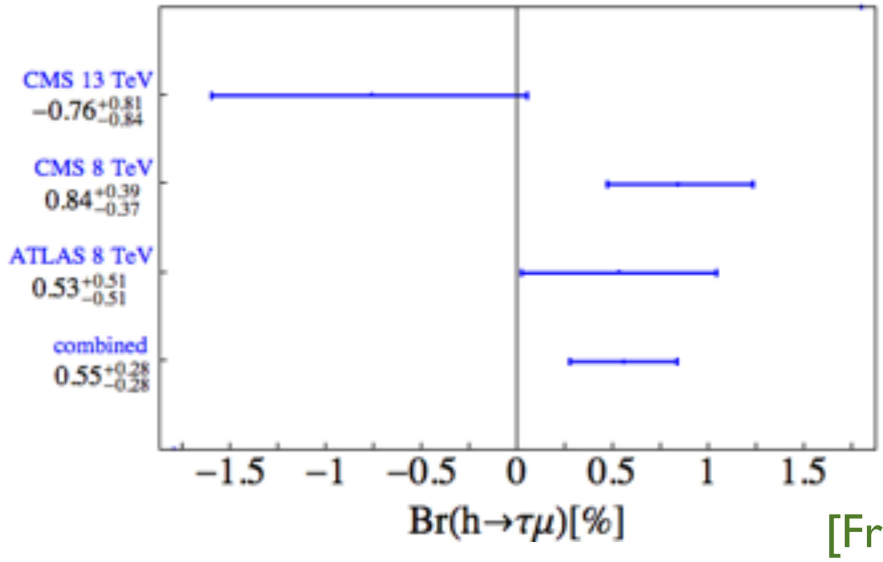
$$h \to \tau^+\tau^-$$

$$\mu = 1.11^{+0.24}_{-0.22}$$



$$\mu_{h\bar{t}t} = 2.0 \pm 0.4$$

[unofficial]



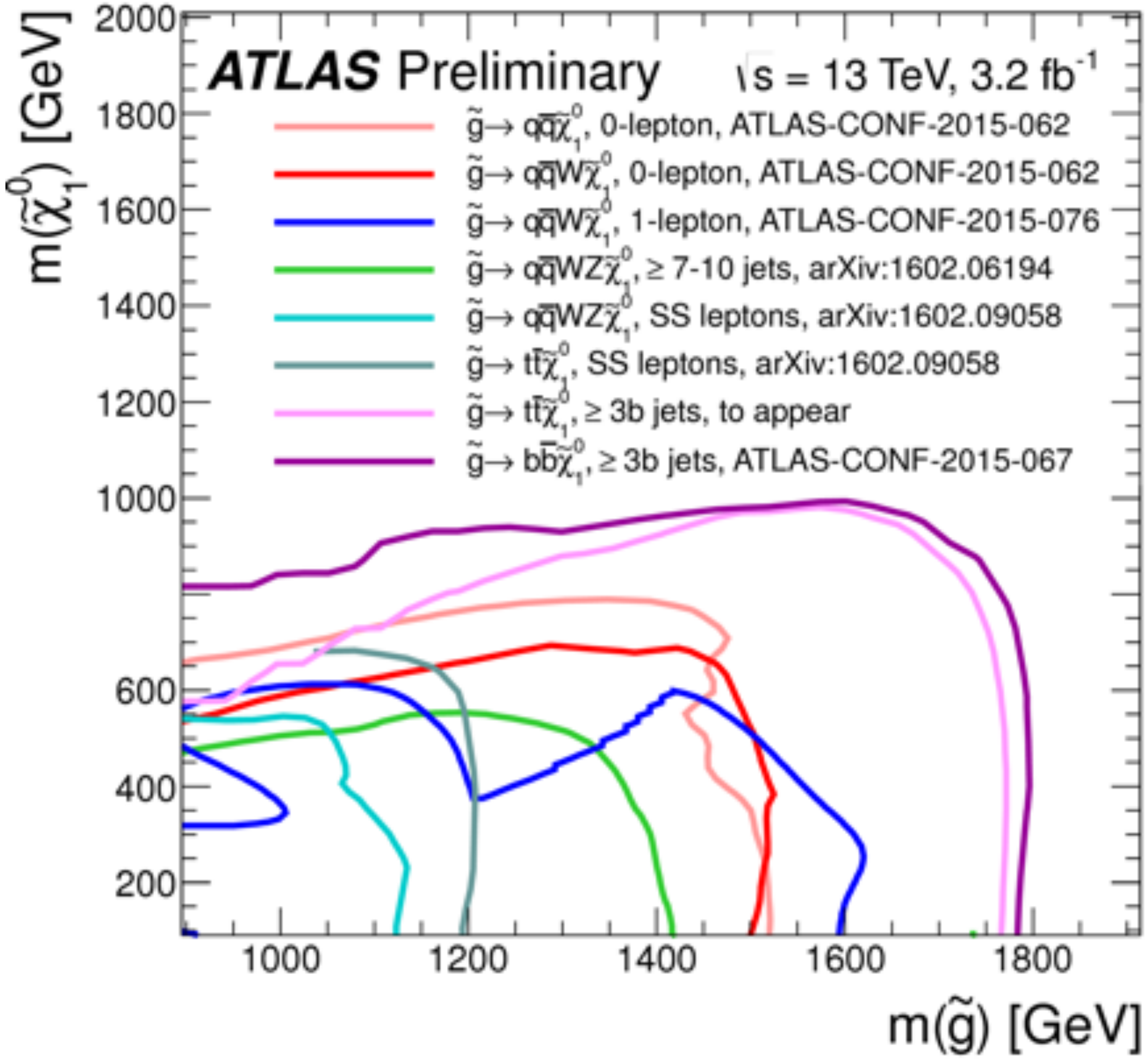
*however

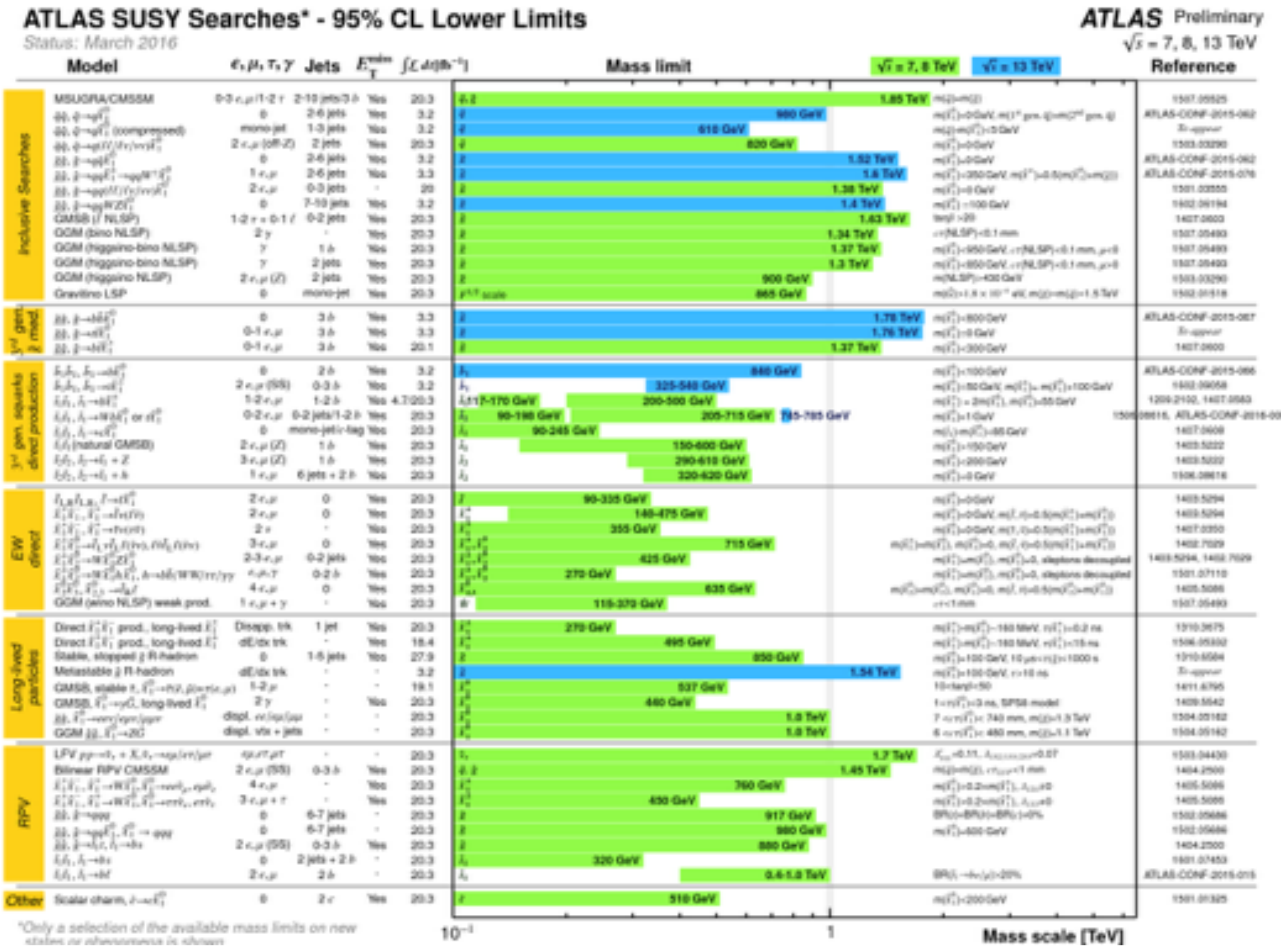
$$h \to \tau\mu$$

[From Adam Falkowski's blog]

A brief summary: Direct Searches

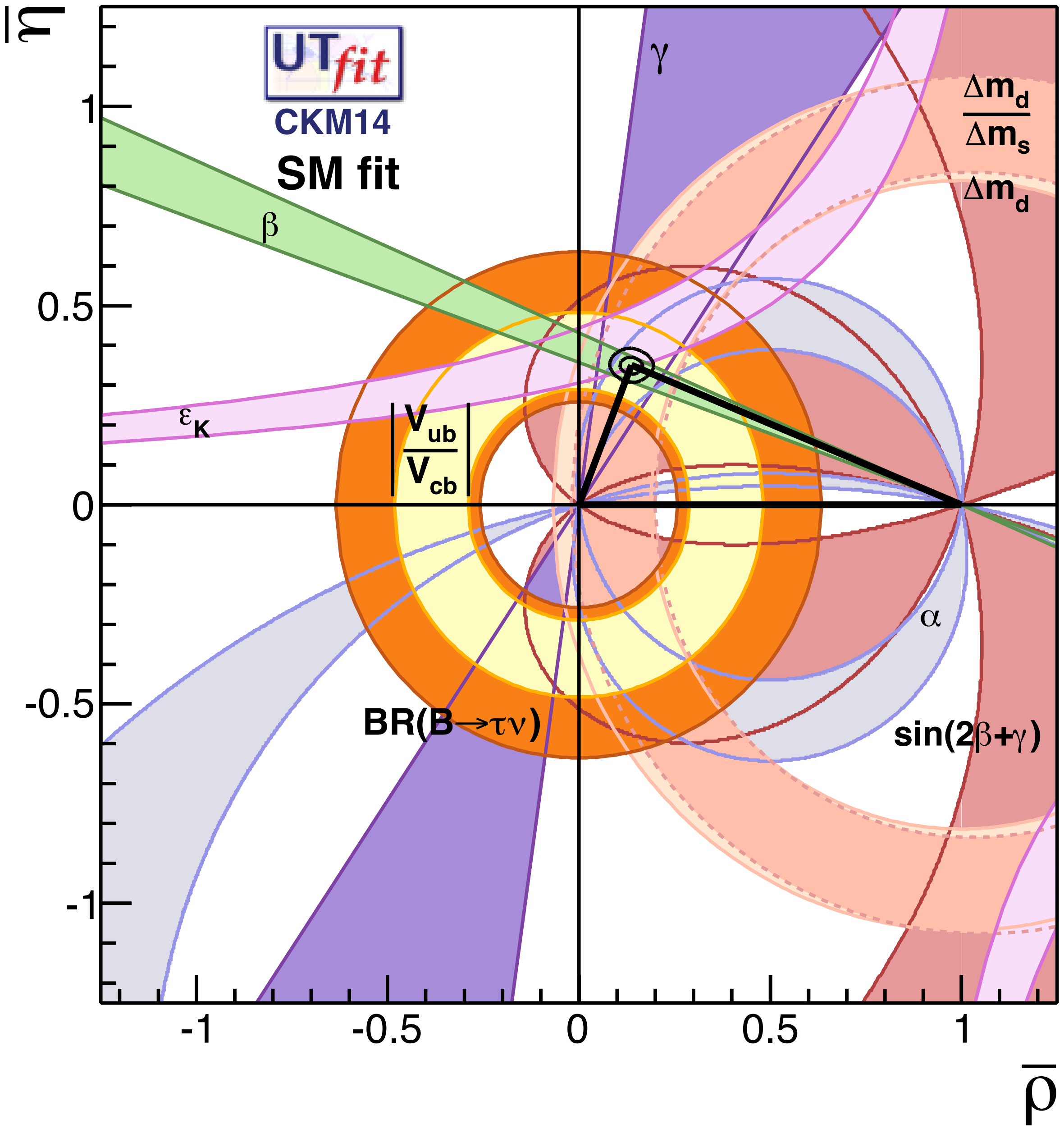
2) No evidence of New Physics from direct searches





A brief summary: Flavour Physics

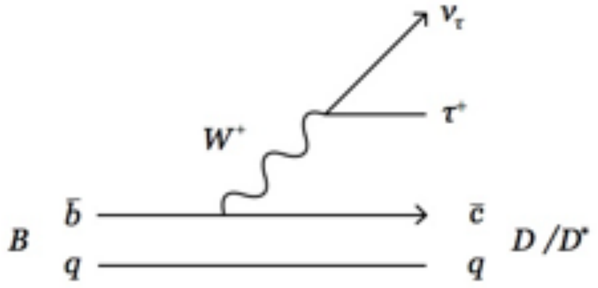
3) No clear* evidence of New Physics from indirect searches



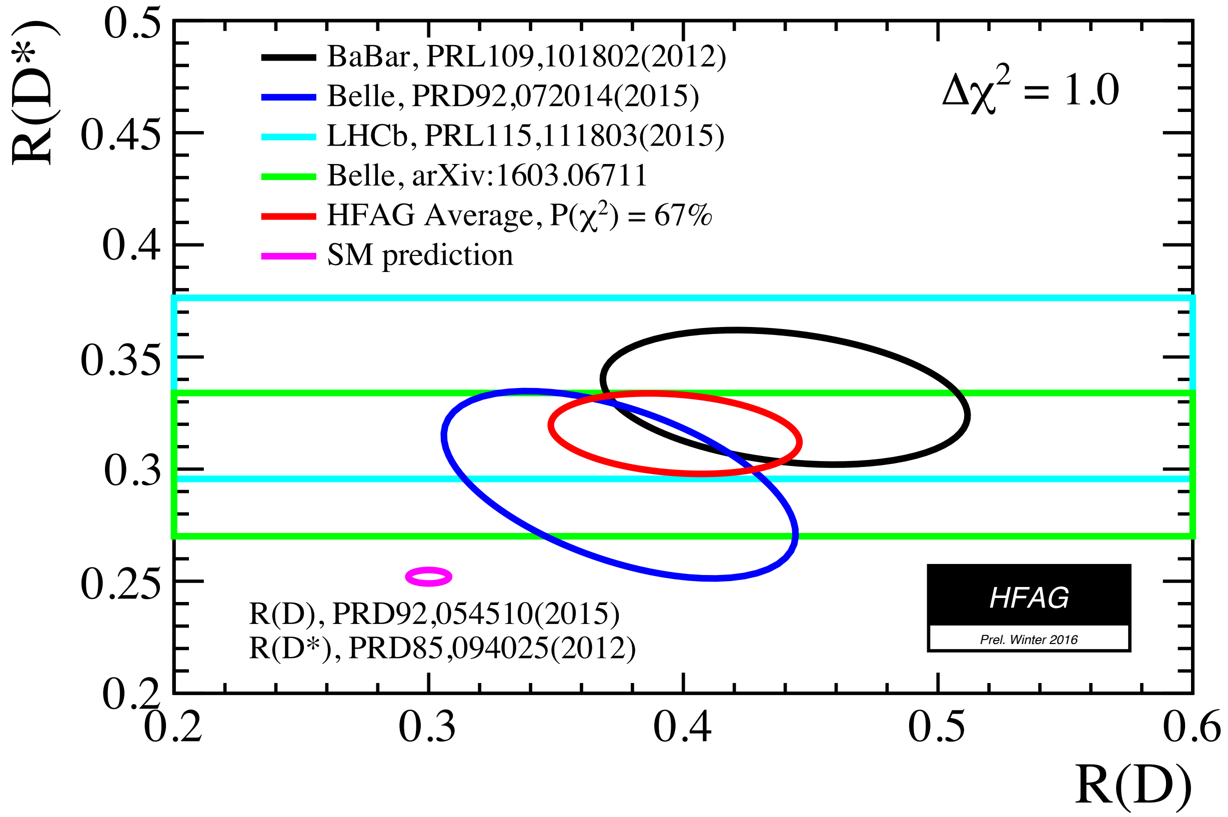
*more details in the next slide

Anomalies in B-meson decays

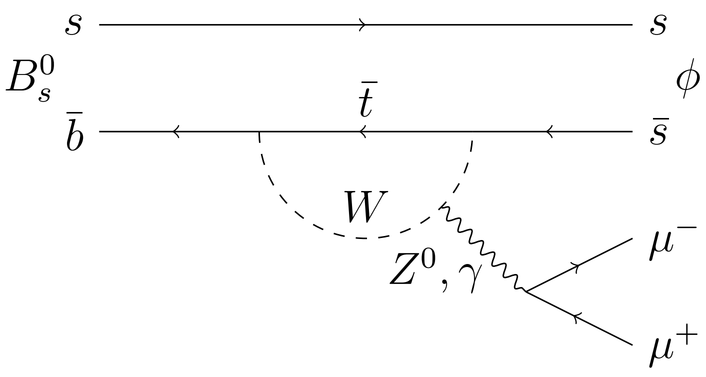
1) Charged Current



$$R(X) = \frac{\mathcal{B}(\bar{B} \to X\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to Xl\bar{\nu})} \qquad X = D, D^* \qquad l = \mu, e$$



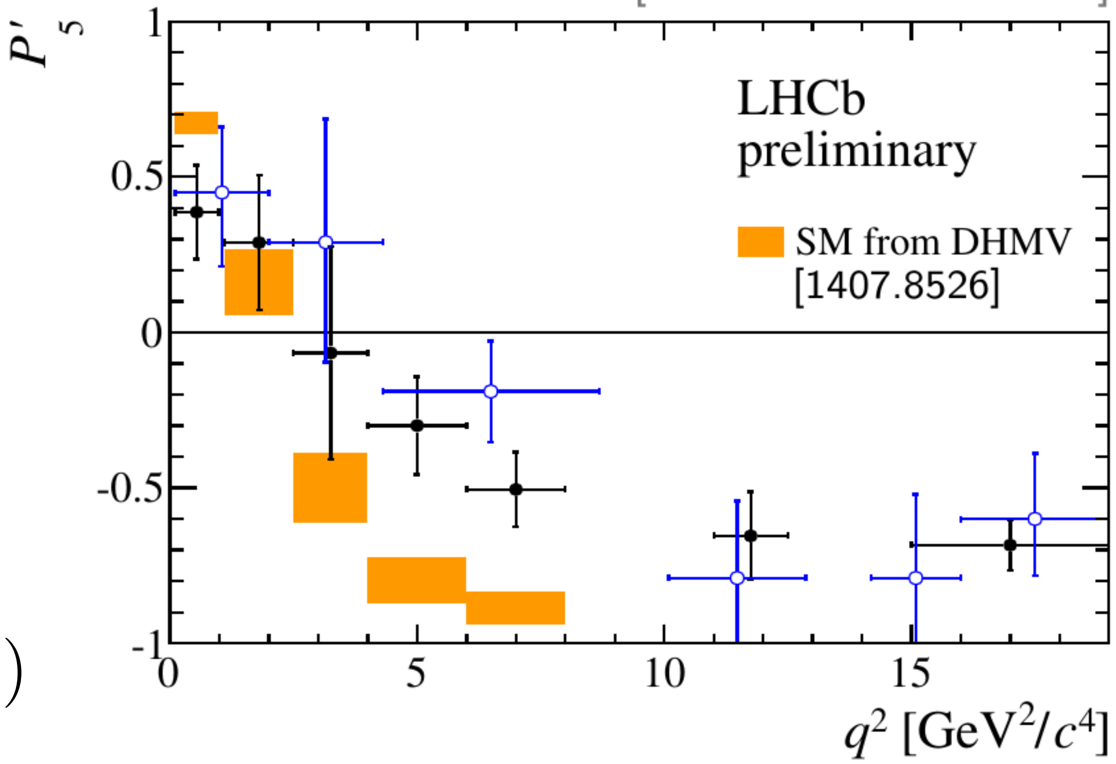
2) Neutral Current



LHCb, 1406.6482, PRL

$$R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

[LHCb-CONF-2015-002]



New Physics

- SM is very successful in describing physics up to the EW scale
- SM is not a complete theory (neutrino masses, dark matter, baryon asymmetry)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

- Big question is $\Lambda?$

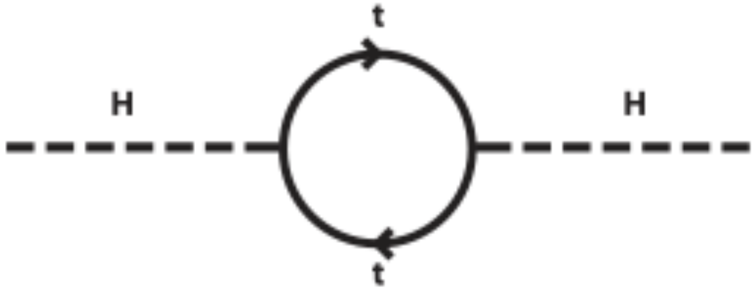
- Unfortunately, no unique indication from observed BSM physics

1. Neutrino masses, from Dirac neutrino to GUT see-saw
2. Dark Matter, from axions to Wimpzillas
3. Baryon asymmetry, from EW baryogenesis to GUT baryogenesis

- However we have some indications….

New Physics from naturalness

- Upper bound from naturalness of the EW scale



$$m_H^2 = m_{\rm tree}^2 + \delta m_H^2$$

$$\delta m_H^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \approx (0.3\,\Lambda)^2$$

$\Lambda \lesssim 100~\mathrm{GeV}$

- Completely natural solution expected at LEP, after LHC $\Lambda \gtrsim 1000~\mathrm{GeV}$

- The Hamletic question: to be or not to be… natural?

1. The orthodox way, "Let us wait a bit more" SUSY, Composite Higgs
2. The insisting way, "Never give up" Relaxion, Twin Higgs
3. The miraculous way, "The top is the top" No, new physics above the top mass
4. The risky way, "Multiverse" Is it possible to get predictions?

- Only "problem" in favour of New Physics at the LHC has an aesthetical/theoretical/ philosophical origin

5. Agnostic way, "Without prejudice" Be open minded, try to find other handles

New Physics from indirect searches

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}}\, O_i^{(d)}(\text{SM fields}).$$

- Lower bounds from experiments $\Lambda \gtrsim \left\{ \begin{array}{lll} c^{1/2} \times 10^{13}\ \text{TeV} & \text{Proton decay} & \text{B, L number} \\ c^{1/2} \times 10^{4}\ \text{TeV} & \text{Flavour Physics} & SU(3)^5 \\ c^{1/2} \times 5\ \text{TeV} & \text{EWPO} & SU(2)_C \\ 1\ \text{TeV} & \text{LHC, direct searches} & \end{array} \right.$

- SM has extra accidental approximates symmetries

- $c \longrightarrow 0$, extra symmetries are required, New Physics can be light

- If New Physics is *generic* then $c = \mathcal{O}(1)$, and $\Lambda \gg v$

- Neutrino Physics fix the scale $\frac{HH\ell\ell}{\Lambda} \rightarrow m_v = \frac{v^2}{\Lambda} = \mathcal{O}(\text{eV}) \rightarrow \Lambda \sim 10^{15}\ \text{GeV}$

Accidental Matter at LHC

[with L. Di Luzio, R. Grober, J.F. Kamenik,
hep-ph/1504.00359,
JHEP 1507 (2015)]

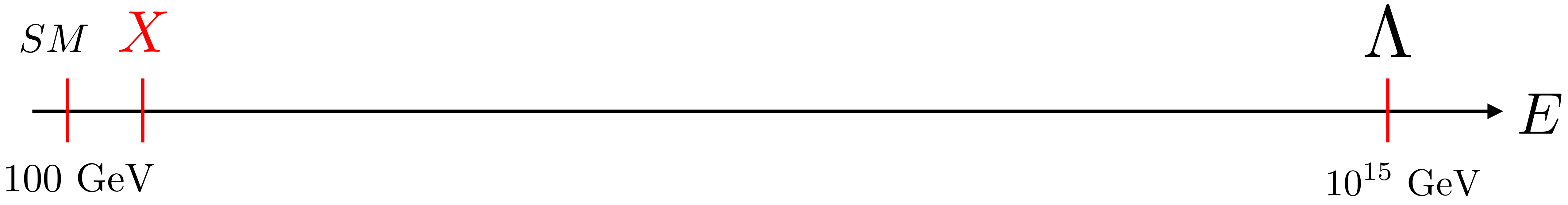
- One may ask the following question:

Which extensions of the SM particle content with masses close to EW scale

1. *form consistent EFTs with a cut-off as high as* $10^{15}\ \mathrm{GeV}$
2. *are cosmologically viable*
3. *automatically preserve the accidental and approximate structure of the SM?*

close to EW scale = LHC target

automatically = without requiring any additional protective mechanism, just gauge symmetry



Accidental Symmetry in the SM

- Fundamental symmetries of SM: Lorentz + gauge symmetry
- Matter content

Spin	SM field	SU(3)	SU(2)	U(1)
0	H	1	2	$+\frac{1}{2}$
1/2	q	3	2	$+\frac{1}{6}$
1/2	u^c	$\overline{3}$	1	$-\frac{2}{3}$
1/2	d^c	$\overline{3}$	1	$+\frac{1}{3}$
1/2	ℓ	1	2	$-\frac{1}{2}$
1/2	e^c	1	1	$+1$

- *Most general* renormalizable Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{kin}} + V(H) + \mathcal{L}_{\text{Yukawa}}$$

- No extra symmetries imposed by hand, however we get various accidental 'gifts'

$\mathcal{L}_{\text{kin}} \supset \sum_f i f^\dagger \sigma^\mu D_\mu f$ invariant under $U(3)^5$

- Yukawa sector breaks this symmetry to

$$U(3)^5 \to U(1)^5 = U(1)_Y \times U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

Accidental Symmetry Beyond the SM

- An example: MSSM

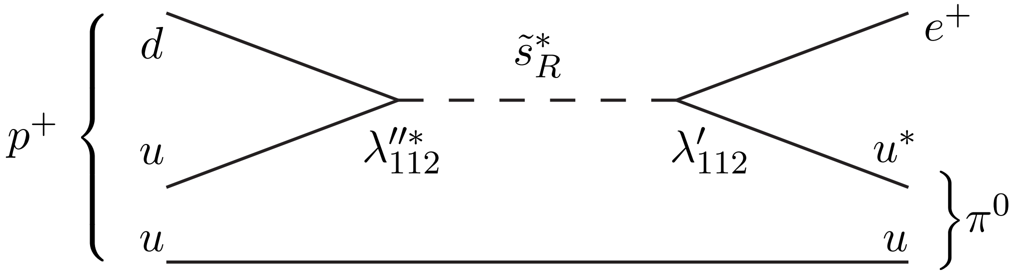
- Most generic renormalizable superpotential wich is SUSY, Lorentz and gauge invariant

$$
\begin{aligned}
W_{RPC} &= y_U^{ij}\hat{q}_i\hat{u}^c_j\hat{h}_u + y_D^{ij}\hat{h}_d\hat{q}_i\hat{d}^c_j + y_E^{ij}\hat{h}_d\hat{\ell}_i\hat{e}^c_j + \mu\,\hat{h}_u\hat{h}_d\,,\\
W_{RPV} &= \mu^i\hat{h}_u\hat{\ell}_i + \tfrac{1}{2}\lambda^{ijk}\hat{\ell}_i\hat{\ell}_j\hat{e}^c_k + (\lambda^{'})^{ijk}\hat{\ell}_i\hat{q}_j\hat{d}^c_k + \tfrac{1}{2}(\lambda^{''})^{ijk}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k
\end{aligned}
$$

- Accidental symmetries of the SM broken
- Dangerous contribution to the proton decay

$$\Gamma_{p\to e^+\pi^0} \sim m^5_{\text{proton}}\sum_{i=2,3}|\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i},$$

$$|\lambda'\lambda''| < 10^{-24}$$



- Possible solution: ad hoc symmetry (ex. R-parity, U(1) Baryon symmetry, ecc.)

- Origin of the problem: gauge quantum numbers of the new states allow couplings with SM fermions at the renormalizable level

Accidentally safe extensions

- We add one single state (a scalar or a fermion) at time that transforms as a irrep. of the SM gauge group

- We have to avoid renormalizable couplings with *SM fermions*

	$\mathcal{O}_{\rm SM}$	SU(3)	SU(2)	U(1)
$\psi_{\rm SM} H (H^\dagger)$	$qH(H^\dagger)$	3	$1 \oplus 3$	$+\frac{2}{3}(-\frac{1}{3})$
	$u^c H(H^\dagger)$	$\overline{3}$	2	$-\frac{1}{6}(-\frac{7}{6})$
	$d^c H(H^\dagger)$	$\overline{3}$	2	$+\frac{5}{6}(-\frac{1}{6})$
	$\ell H(H^\dagger)$	1	$1 \oplus 3$	$0(-1)$
	$e^c H(H^\dagger)$	1	2	$+\frac{3}{2}(+\frac{1}{2})$
$\psi_{\rm SM}\psi_{\rm SM}$	qq	$\overline{3} \oplus 6$	$1 \oplus 3$	$+\frac{1}{3}$
	qu^c	$1 \oplus 8$	2	$-\frac{1}{2}$
	qd^c	$1 \oplus 8$	2	$+\frac{1}{2}$
	$q\ell$	3	$1 \oplus 3$	$-\frac{1}{3}$
	qe^c	3	2	$+\frac{7}{6}$
	$u^c u^c$	$3 \oplus \overline{6}$	1	$-\frac{4}{3}$
	$u^c d^c$	$3 \oplus \overline{6}$	1	$-\frac{1}{3}$
	$u^c \ell$	$\overline{3}$	2	$-\frac{7}{6}$
	$u^c e^c$	$\overline{3}$	1	$+\frac{1}{3}$
	$d^c d^c$	$3 \oplus \overline{6}$	1	$+\frac{2}{3}$
	$d^c \ell$	$\overline{3}$	2	$-\frac{1}{6}$
	$d^c e^c$	$\overline{3}$	1	$+\frac{4}{3}$
	$\ell\ell$	1	$1 \oplus 3$	-1
	ℓe^c	1	2	$+\frac{1}{2}$
	$e^c e^c$	1	1	$+2$

New states and their symmetry

- Adding a new fermion

$$\chi \neq \psi_{\rm SM}, (1,1,0), (1,3,0), (1,3,1), (1,2,\tfrac{3}{2}), (\overline{3},2,\tfrac{5}{6}), (3,2,\tfrac{7}{6}), (\overline{3},3,\tfrac{1}{3}), (3,3,\tfrac{2}{3})$$

- If the irrep of the new state is real, then we have a Majorana field, most general Lagrangian is given by $\mathcal{L} = \mathcal{L}_{\rm SM} + i\chi^\dagger \overline{\sigma}^\mu D_\mu \chi + \dfrac{1}{2} M (\chi^T \epsilon \chi + \text{h.c.})$

- Invariant under $G_\chi = Z_2, \; \chi \to -\chi$

- If Dirac, similarly $\mathcal{L} = \mathcal{L}_{\rm SM} + i\chi^\dagger \overline{\sigma}^\mu D_\mu \chi + i\chi^{c\dagger} \overline{\sigma}^\mu D_\mu \chi^c + M(\chi^T \epsilon \chi^c + \text{h.c.})$

- Invariant under $G_\chi = U(1), \; \chi \to e^{i\theta}\chi$

- Adding a new complex scalar

$$\chi \neq (1,1,1), (1,3,1), (1,1,2), (1,2,\tfrac{1}{2}), (\overline{3},1,\tfrac{1}{3}), (3,1,\tfrac{2}{3}), (\overline{3},1,\tfrac{4}{3}), (3,2,\tfrac{1}{6}), (3,2,\tfrac{7}{6}), (\overline{3},3,\tfrac{1}{3}),$$
$$(6,1,\tfrac{1}{3}), (\overline{6},1,\tfrac{2}{3}), (6,1,\tfrac{4}{3}), (6,3,\tfrac{1}{3}), (8,2,\tfrac{1}{2}) \, .$$

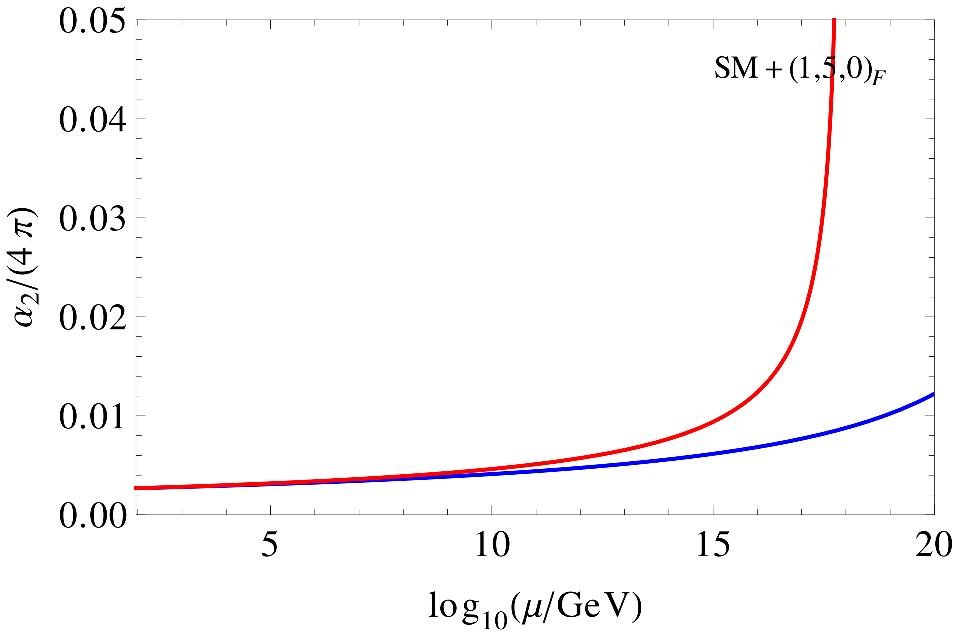
$$\mathcal{L} = \mathcal{L}_{SM} + V(\chi) + \lambda_1 \, \chi^\dagger \chi H^\dagger H + \lambda_2 \, (\chi^\dagger T^a_\chi \chi)(H^\dagger \tau^a H)$$

- Invariant under $G_\chi = U(1), \; \chi \to e^{i\theta}\chi$
- Real scalar $G_\chi = Z_2, \; \chi \to -\chi$

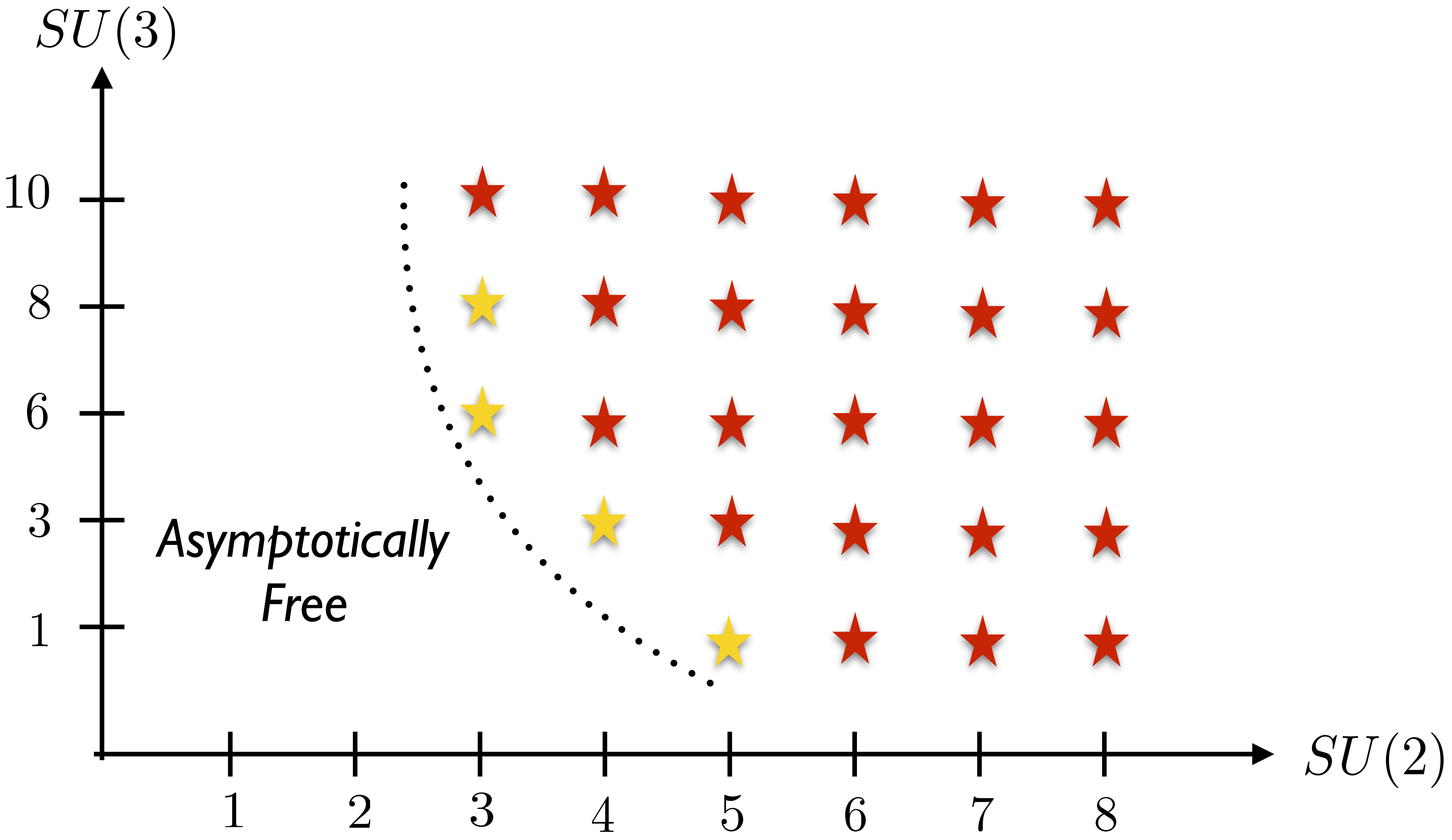
Landau Poles

- Extra matter changes the running of the gauge couplings

$$\mu\frac{d}{d\mu}g_i = -b_i\, g_i^3 \qquad b_i = \text{gauge -matter}$$



- We have to avoid the appearance of Landau poles below the cut-off Λ



- Ex. complex scalars
- (In some cases two loop effects are important)

Cosmology

- At renormalizable level Lightest Particle (LP) is stable

- In this limit, following a standard hot big bang evolution of the universe, we obtain a thermal relic fixed by the annihilation rate $\sigma\left(\chi\chi \to \phi_{SM}\phi_{SM}\right)$

$$\Omega_\chi$$

- Gauge quantum numbers are such that the new state is (part of) the dark matter relic abundance

- Gauge quantum numbers are such that the thermal relic of the new state is not phenomenologically viable

Minimal Dark Matter

Minimal Dark Matter
Cirelli, Fornengo, Strumia,
hep-ph/0512090
NPB (2006)

- A generic irrep under the SM gauge group is (m,n,y)
- DM is colorless m=1
- Direct detection, no coupling with Z-boson, y=0
- No landau poles below GUT, $n \leq 7$
- No dangerous renomalizable couplings, 2 candidates left!

$$(1,7,0)_S \quad m_\chi \approx 25 \text{ TeV} \qquad (1,5,0)_F \quad m_\chi \approx 10 \text{ TeV}$$

- In our analysis, the scalar candidate *not viable*, decays at dimension-5

$$\frac{\chi\chi\chi H^\dagger H}{\Lambda}$$

- In our analysis, value of the mass can be lower than the one required by the relic density

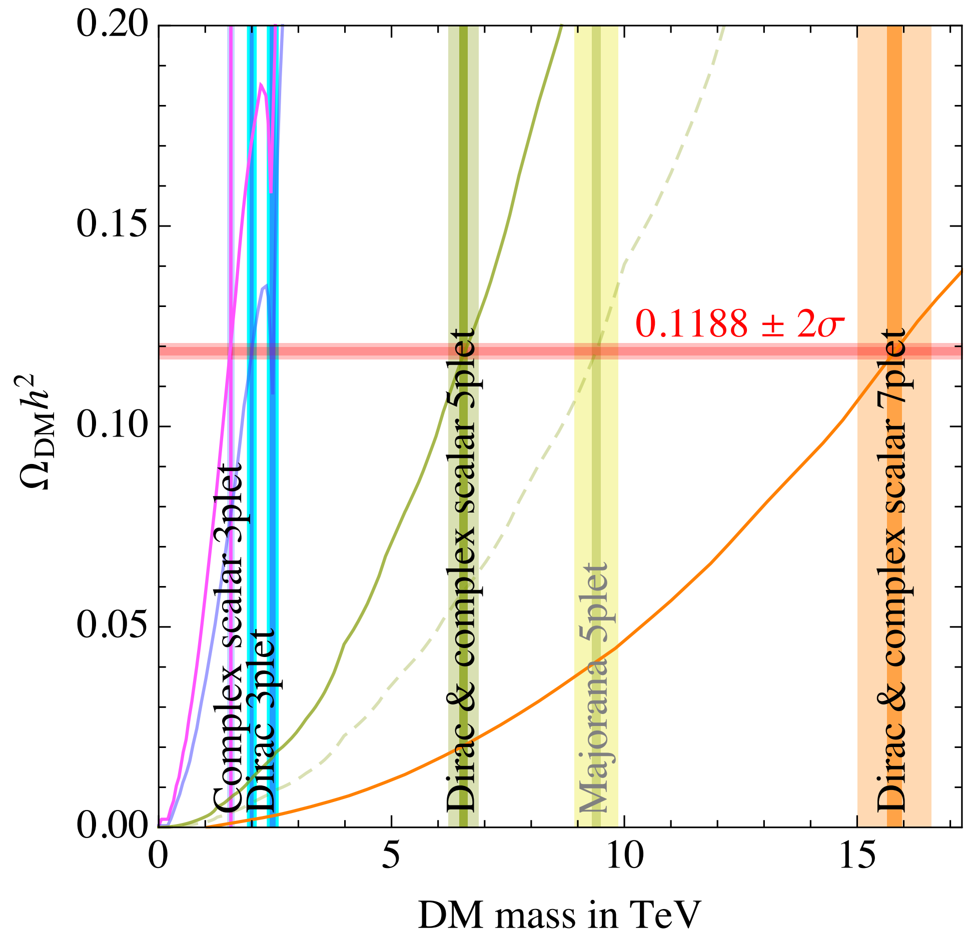
Millicharged Minimal Dark Matter

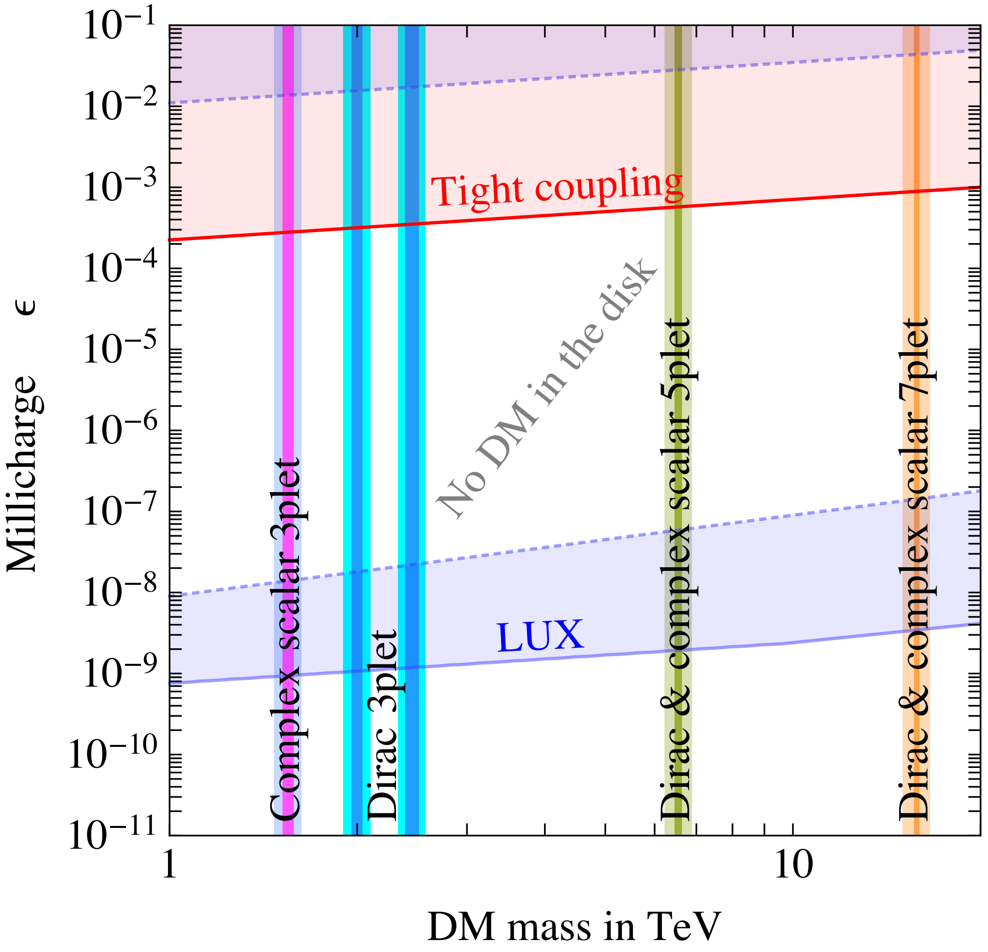
Del Nobile, Nardecchia, Panci,
hep-ph/1512.05353
JCAP (2016)

- In our reasoning, we found another class of candidates

$$(1, n, \epsilon)$$

- Accidental symmetry aries from electromagnetism!
- Accidental symmetry never broken by higher dimensional operators
- Cosmological and direct detection bounds





Dangerous Relics

- Stable charged or coloured relics, are severely bounded.

- At non-renormalizable level accidental symmetries are broken and the LP decays, lifetime depends on dimension of effective operator

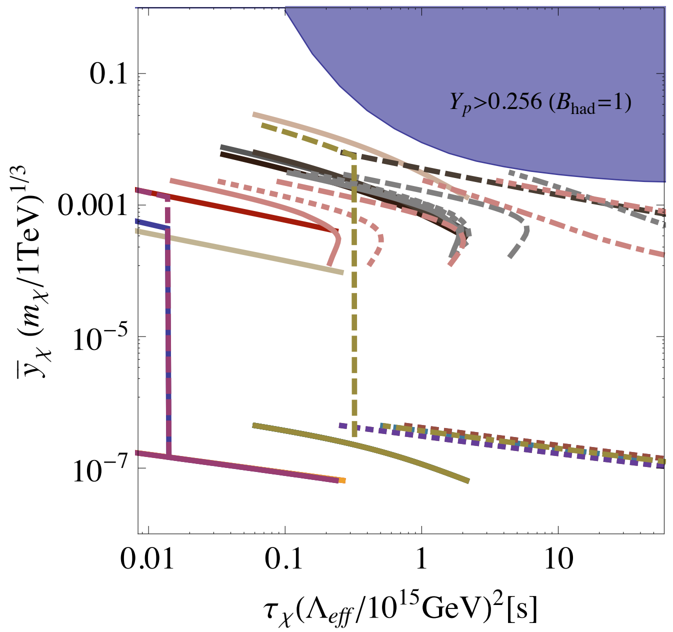
$$\mathcal{L}_{SM} + \mathcal{L}_{\chi} + \sum \frac{1}{\Lambda}\mathcal{O}_5\left(\phi_{SM},\chi\right) + \sum \frac{1}{\Lambda^2}\mathcal{O}_6\left(\phi_{SM},\chi\right) + \ldots$$

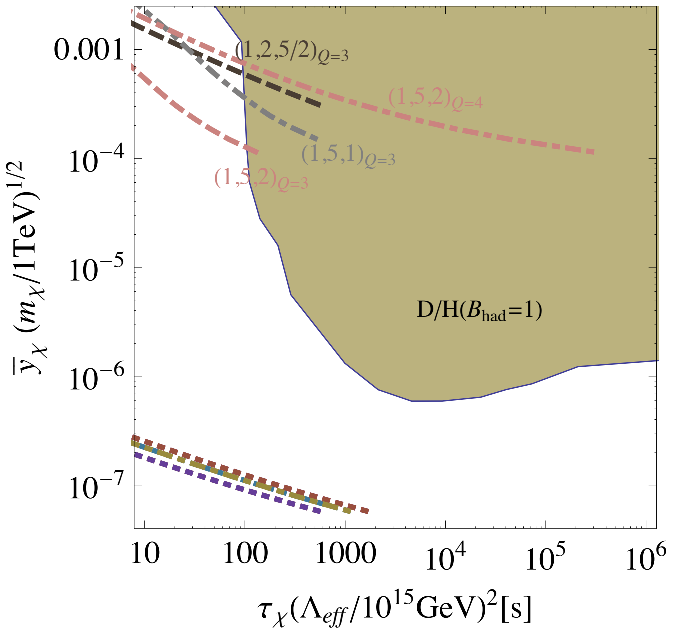
$$\Lambda = 10^{15}\ \text{GeV} \qquad \Gamma_5 \sim \frac{m_\chi^3}{\Lambda^2} \qquad\qquad \Gamma_6 \sim \frac{m_\chi^5}{\Lambda^4}$$

Too slow!

- We have to restrict to irrep such that is possible to have dim-5 operators that generate a sufficiently fast decay.

- Next problem, we have to avoid to spoil the prediction from Big Bang Nucleosynthesis…





Accidental Colourless Matter

Which extensions of the SM particle content with masses close to EW scale

1. *form consistent EFTs with a cut-off as high as* 10^{15} GeV
2. *are cosmologically viable*
3. *automatically preserve the accidental and approximate structure of the SM?*

Spin	χ	Q_{LP}	$\mathcal{O}$	$\dim(\mathcal{O})$	$\Lambda^{2-\text{loop}}_{\text{Landau}}$[GeV]
0	$(1,2,\frac{3}{2})$	1,2	$\chi H^\dagger \ell\ell + \chi^\dagger H^\dagger e^c e^c + D^\mu \chi^\dagger \ell^\dagger \overline{\sigma}_\mu e^c$	5	$\gg M_P\ (g_1)$
0	$(1,2,\frac{5}{2})$	2,3	$\chi^\dagger H e^c e^c$	5	$\gg M_P\ (g_1)$
0	$(1,5,0)$	0,1,2	$\chi HHH^\dagger H^\dagger + \chi W^{\mu\nu} W_{\mu\nu} + \chi\chi\chi H^\dagger H$	5	$\gg M_P\ (g_1)$
0	$(1,5,1)$	-1,0,1,2,3	$\chi^\dagger HHHH^\dagger + \chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$\gg M_P\ (g_1)$
0	$(1,5,2)$	0,1,2,3,4	$\chi^\dagger HHHH$	5	$3.5\times 10^{18}\ (g_1)$
0	$(1,7,0)$	0,1,2,3	$\chi\chi\chi H^\dagger H$	5	$1.4\times 10^{16}\ (g_2)$
1/2	$(1,4,\frac{1}{2})$	-1	$\chi^c \ell HH + \chi\ell H^\dagger H + \chi\sigma^{\mu\nu}\ell W_{\mu\nu}$	5	$8.1\times 10^{18}\ (g_2)$
1/2	$(1,4,\frac{3}{2})$	0	$\chi\ell H^\dagger H^\dagger$	5	$2.7\times 10^{15}\ (g_1)$
1/2	$(1,5,0)$	0	$\chi\ell HHH^\dagger + \chi\sigma^{\mu\nu}\ell H W_{\mu\nu}$	6	$8.3\times 10^{17}\ (g_2)$

(implications of non-renormalizable operators for Minimal Dark Matter work in progress with E. Del Nobile, P. Panci)

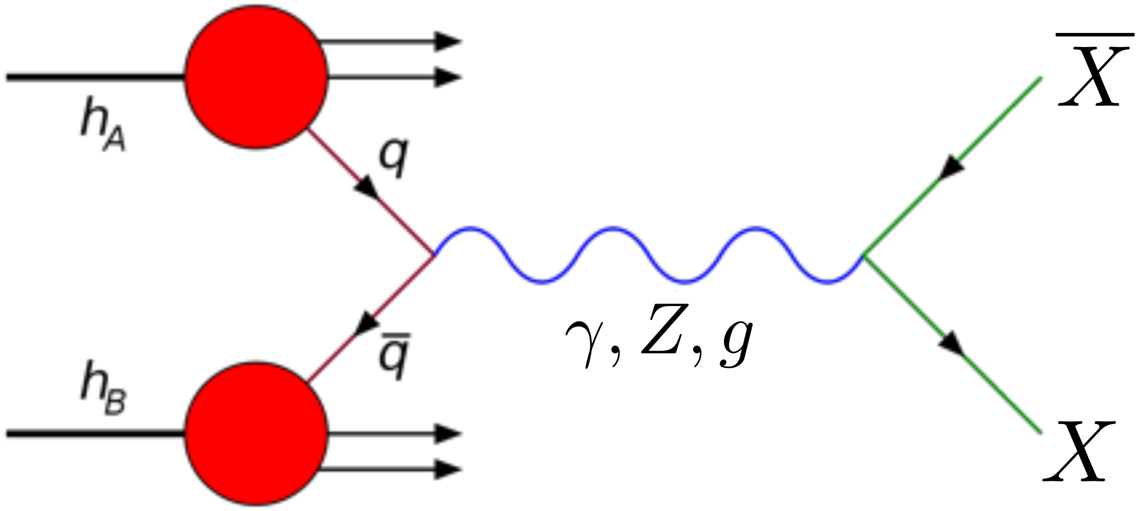
Accidental Coloured Matter

Spin	χ	$Q_{\rm LP}$	$\mathcal{O}$	dim($\mathcal{O}$)	$\Lambda^{2-\rm loop}_{\rm Landau}$[GeV]
0	$(3,1,\frac{5}{3})$	$\frac{5}{3}$	$\chi^\dagger H q e^c + \chi H^\dagger u^c \ell$ $+ D^\mu \chi^\dagger u^{c\dagger} \overline{\sigma}_\mu e^c$	5	$\gg M_P\ (g_1)$
0	$(\overline{3},2,\frac{5}{6})$	$\frac{1}{3}, \frac{4}{3}$	$\chi^\dagger H q q + \chi^\dagger H u^c e^c$ $+\chi H^\dagger q \ell + \chi H^\dagger u^c d^c$ $+\chi H u^c u^c + \chi^\dagger H^\dagger d^c e^c$ $+D^\mu \chi q^\dagger \overline{\sigma}_\mu u^c$ $+D^\mu \chi^\dagger q^\dagger \overline{\sigma}_\mu e^c$ $+D^\mu \chi d^{c\dagger} \overline{\sigma}_\mu \ell$	5	$\gg M_P\ (g_1)$
0	$(\overline{3},2,\frac{11}{6})$	$\frac{4}{3}, \frac{7}{3}$	$\chi H^\dagger u^c u^c + \chi^\dagger H d^c e^c$	5	$5.5 \times 10^{19}\ (g_1)$
0	$(3,3,\frac{2}{3})$	-$\frac{1}{3}, \frac{2}{3}, \frac{5}{3}$	$\chi^\dagger H^\dagger q e^c + \chi H u^c \ell$ $+\chi H^\dagger d^c \ell$ $+D^\mu \chi q^\dagger \overline{\sigma}_\mu \ell$	5	$\gg M_P\ (g_1)$
0	$(3,3,\frac{5}{3})$	$\frac{2}{3}, \frac{5}{3}, \frac{8}{3}$	$\chi^\dagger H q e^c + \chi H^\dagger u^c \ell$	5	$3.2 \times 10^{17}\ (g_1)$
0	$(3,4,\frac{1}{6})$	-$\frac{4}{3}$,-$\frac{1}{3}, \frac{2}{3}, \frac{5}{3}$	$\chi H^\dagger q q + \chi^\dagger H q \ell$	5	$\gg M_P\ (g_2)$
0	$(\overline{3},4,\frac{5}{6})$	-$\frac{2}{3}, \frac{1}{3}, \frac{4}{3}, \frac{7}{3}$	$\chi^\dagger H q q + \chi H^\dagger q \ell$	5	$\gg M_P\ (g_2)$
0	$(\overline{6},2,\frac{1}{6})$	-$\frac{1}{3}, \frac{2}{3}$	$\chi H^\dagger q q + \chi^\dagger H u^c d^c$ $+\chi^\dagger H^\dagger d^c d^c$ $+D^\mu \chi^\dagger q^\dagger \overline{\sigma}_\mu d^c$	5	$\gg M_P\ (g_1)$
0	$(6,2,\frac{5}{6})$	$\frac{1}{3}, \frac{4}{3}$	$\chi^\dagger H q q + \chi H u^c u^c$ $+\chi H^\dagger u^c d^c$ $+D^\mu \chi q^\dagger \overline{\sigma}_\mu u^c$	5	$\gg M_P\ (g_1)$
0	$(\overline{6},2,\frac{7}{6})$	$\frac{2}{3}, \frac{5}{3}$	$\chi^\dagger H d^c d^c$	5	$\gg M_P\ (g_1)$
0	$(8,1,0)$	0	$\chi H q u^c + \chi H^\dagger q d^c$ $+D^\mu \chi D^\nu G_{\mu\nu}$ $+D^\mu \chi q^\dagger \overline{\sigma}_\mu q$ $+D^\mu \chi u^{c\dagger} \overline{\sigma}_\mu u^c$ $+D^\mu \chi d^{c\dagger} \overline{\sigma}_\mu d^c$ $+\chi G^{\mu\nu} G_{\mu\nu} + \chi G^{\mu\nu} B_{\mu\nu}$ $+\chi\chi\chi H^\dagger H$	5	$\gg M_P\ (g_1)$
0	$(8,1,1)$	1	$\chi H^\dagger q u^c + \chi^\dagger H q d^c + D^\mu \chi^\dagger u^{c\dagger} \overline{\sigma}_\mu d^c$ $+\chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$\gg M_P\ (g_1)$
0	$(8,3,0)$	0,1	$\chi H q u^c + \chi H^\dagger q d^c$ $+\chi G^{\mu\nu} W_{\mu\nu}$ $+D^\mu \chi q^\dagger \overline{\sigma}_\mu q$ $+\chi\chi\chi H^\dagger H$	5	$\gg M_P\ (g_1)$
0	$(8,3,1)$	0,1,2	$\chi H^\dagger q u^c + \chi^\dagger H q d^c + \chi\chi\chi^\dagger H^\dagger H^\dagger$	5	$1.0 \times 10^{17}\ (g_1)$
1/2	$(6,1,\frac{1}{3})$	$\frac{1}{3}$	$\chi^c \sigma^{\mu\nu} d^c G_{\mu\nu}$	5	$\gg M_P\ (g_1)$
1/2	$(\overline{6},1,\frac{2}{3})$	$\frac{2}{3}$	$\chi \sigma^{\mu\nu} u^c G_{\mu\nu}$	5	$\gg M_P\ (g_1)$
1/2	$(8,1,1)$	1	$\chi^c \sigma^{\mu\nu} e^c G_{\mu\nu}$	5	$4.0 \times 10^{16}\ (g_1)$

Collider Phenomenology

- Non-renormalizable terms negligible @ collider $\frac{\chi \psi_{SM} H H}{\Lambda}, \frac{\chi \psi_{SM} \psi_{SM} H}{\Lambda}, \ldots$
- G_χ is a good symmetry, important implications:

1. The new exotic fermions and scalars are pair produced



2. Lightest Particle inside the SU(2) multiplet is stable

- We discuss the phenomenology as follows

1. Colourless and charged LP
2. Colourless and neutral LP
3. Coloured multiplets

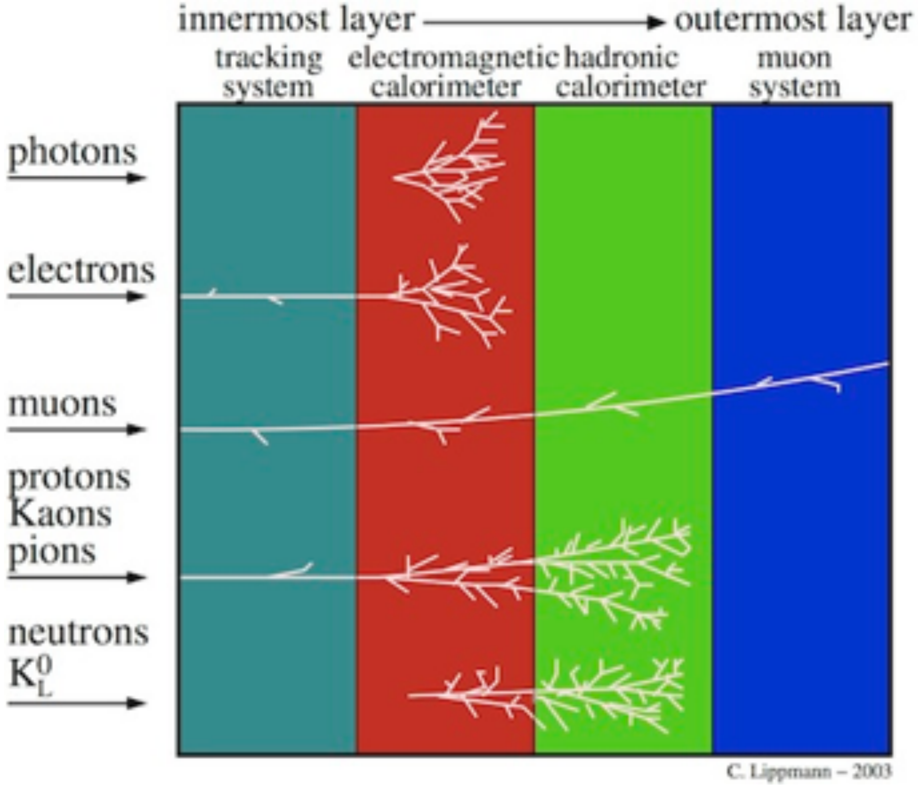
Colourless and Charged LP

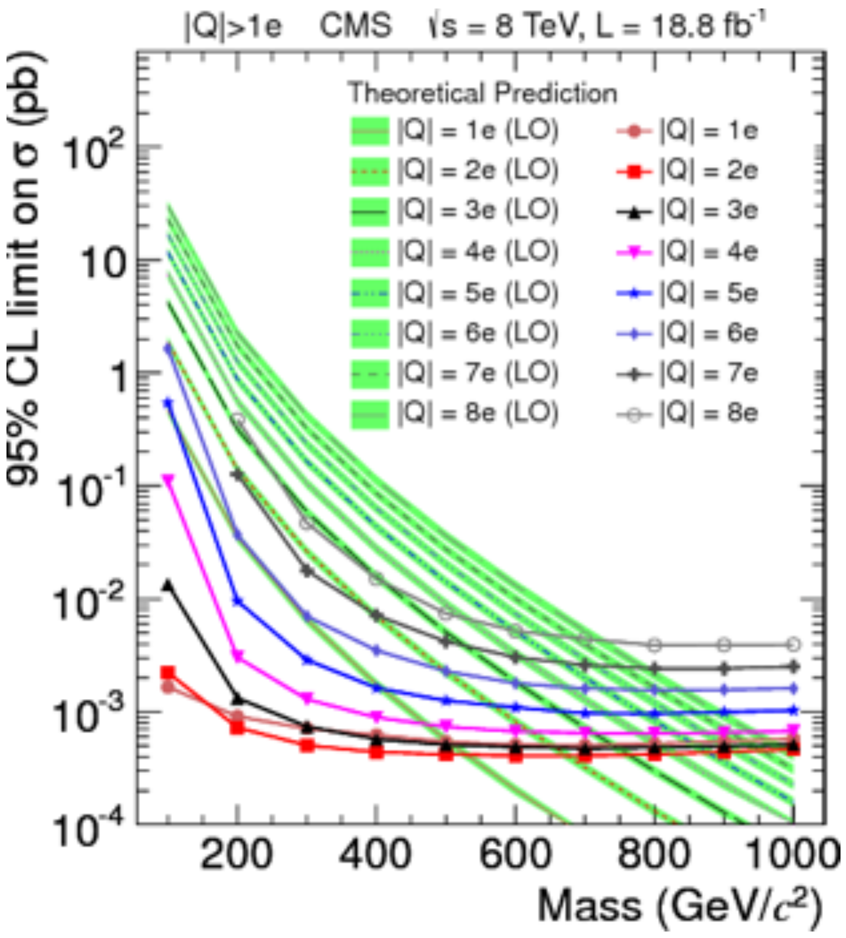
- Charged stable particle will undergo charge exchange with the detector material

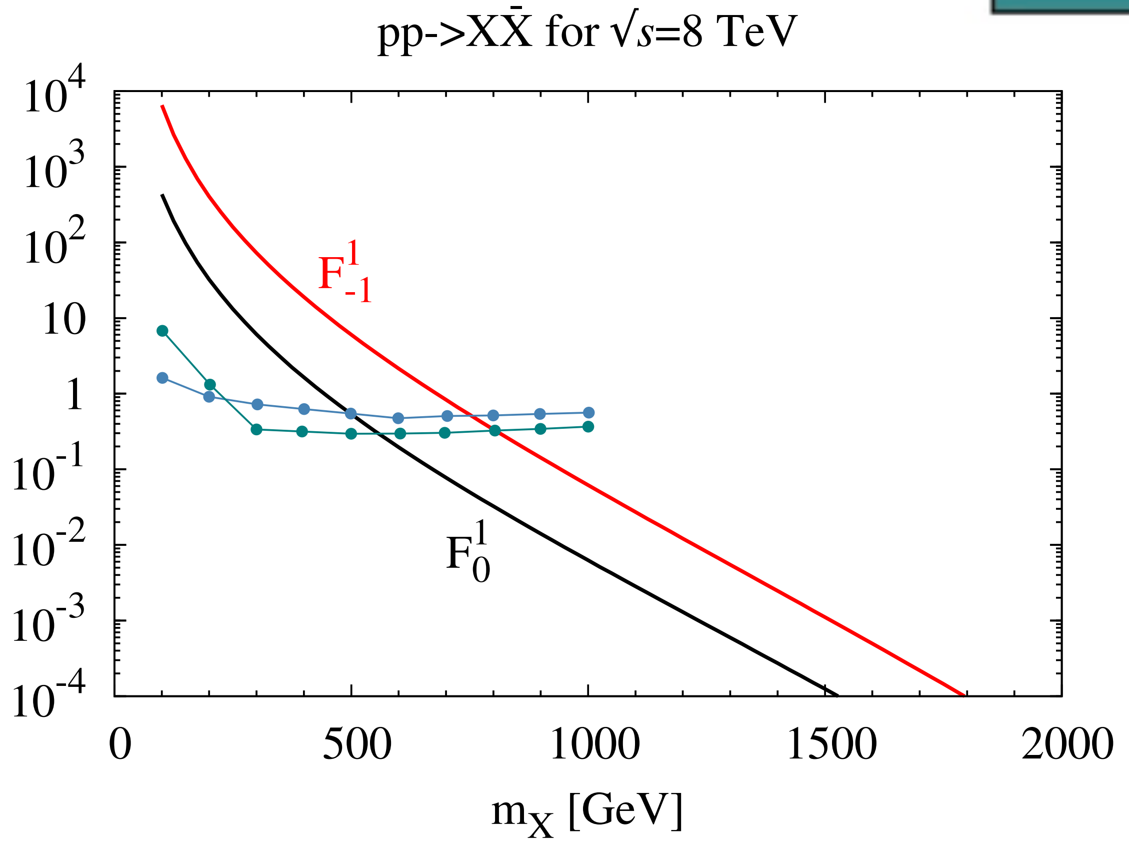
- Energy loss, described by Bethe-Block formula

- LP behaves like a muon, but with different charge and mass

- Various analysis from ATLAS and CMS, we are using CMS [arXiv:1305.0491]



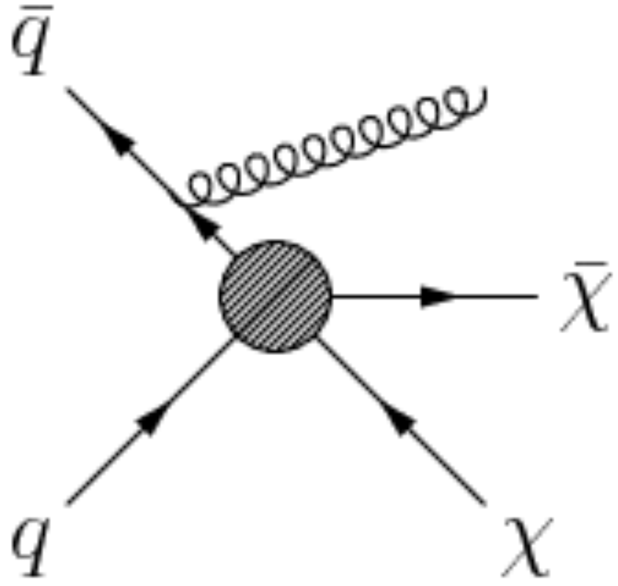




Typical bound

$$m_\chi \gtrsim 500\ \text{GeV}$$

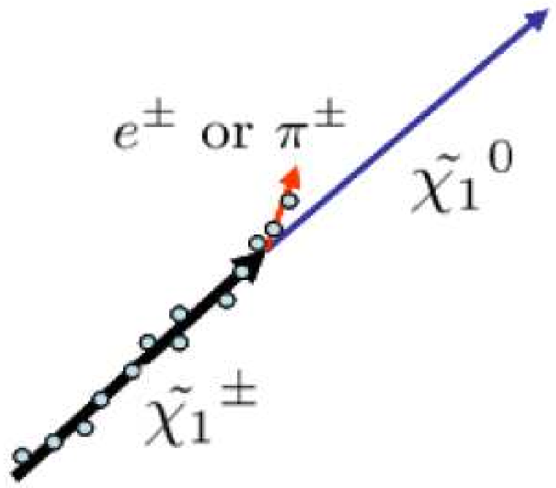
Neutral LP



- Strategy similar to DM models at the LHC

- Mono-x searches, with x=jet,photon, W and Z bosons
- Not very sensitive, strongest constraint is coming from mono-jet searches CMS [arXiv:1408.3583]

- More detailed analysis, Cirelli, Sala, Taoso [arXiv:1407.7058], for the case of a wino-like multiplet (1,3,0)



- Another option: disappearing tracks
- Sensitive if lifetime of the charged state is long enough
- Typically we get shorter lifetime [arXiv:1310.3675]

- Back to LEP: Z width
- Bound $m_\chi > 45\ \mathrm{GeV}$

- Back to LEP: Neutralino searches
- Bound $m_\chi \gtrsim 90\ \mathrm{GeV}$

$$e^+e^- \to \tilde{\chi}_1\tilde{\chi}_1\gamma \to \tilde{\chi}_0\tilde{\chi}_0\gamma + X$$

Coloured Matter

- Coloured, long-lived new particles → Hadronize before decaying
- Large theoretical uncertainties

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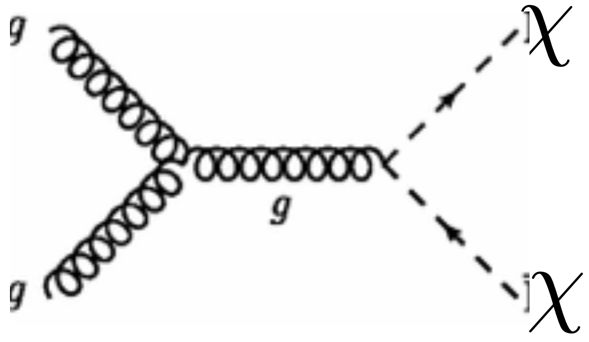
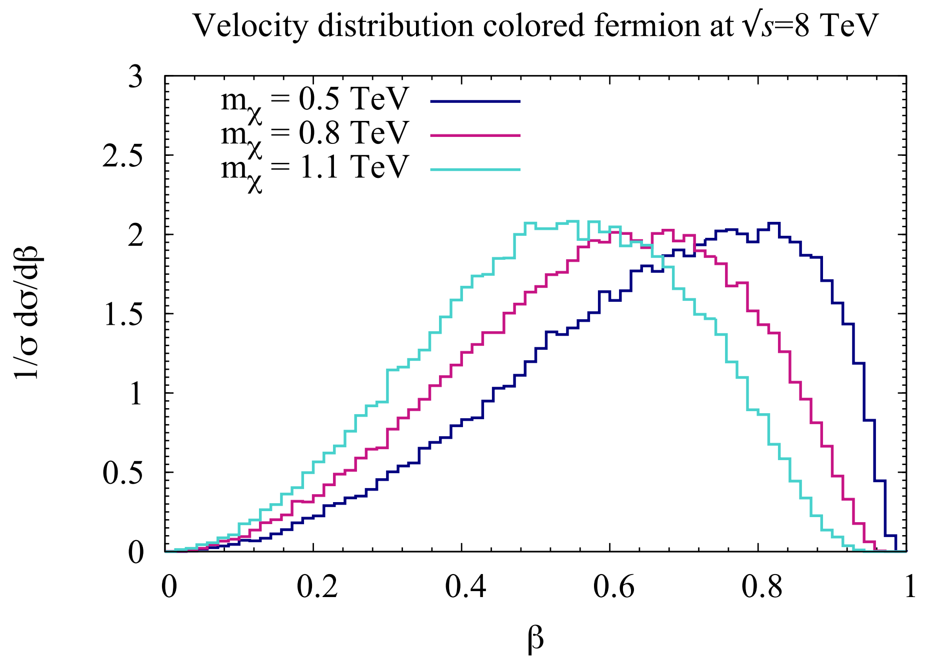
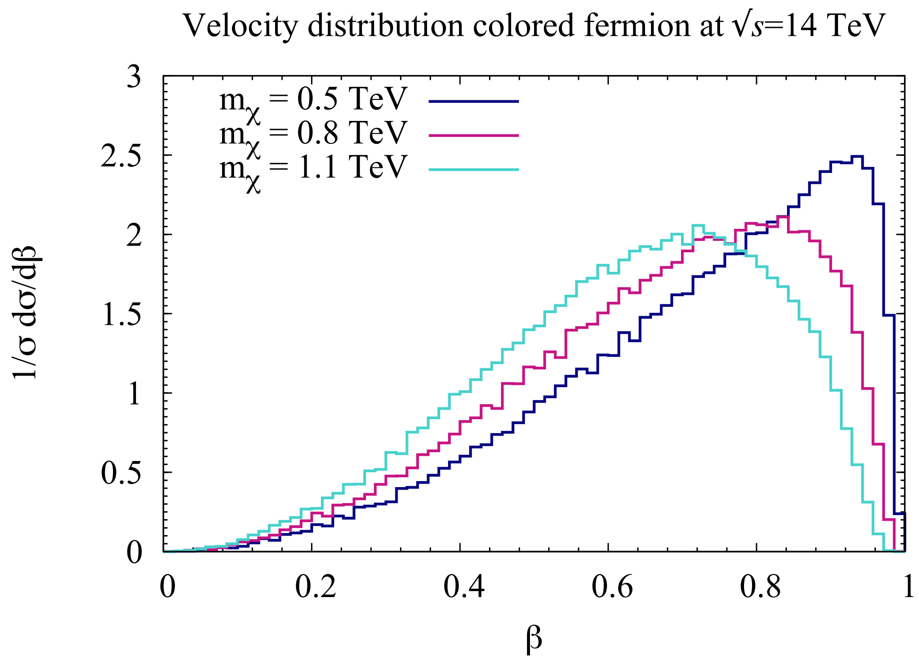
- Physical aspects: 1) Production 2) Hadronization 3) Interactions 4) Stopping & decay
- 1) Production



- Large cross section, due to strong interactions
- Pair production (due to accidental symmetry)
- Fate of the particle depends on velocity at production





Coloured Matter

2. Hadronization

R-hadron	PYTHIA fraction (%)	HERWIG fraction (%)
$R^{+}_{\tilde{g}u\bar{d}}$, $R^{-}_{\tilde{g}d\bar{u}}$	34.2	28.2
$R^{0}_{\tilde{g}u\bar{u}}$, $R^{0}_{\tilde{g}d\bar{d}}$	34.2	28.2
$R^{+}_{\tilde{g}u\bar{s}}$, $R^{-}_{\tilde{g}s\bar{u}}$	9.7	17.5
$R^{0}_{\tilde{g}d\bar{s}}$, $R^{0}_{\tilde{g}s\bar{d}}$, $R^{0}_{\tilde{g}s\bar{s}}$	10.4	26.1
$R^{0}_{\tilde{g}g}$	9.9	—
$R^{++}_{\tilde{g}}$, $R^{-}_{\tilde{g}}$ (anti)baryons	0.1	—
$R^{+}_{\tilde{g}}$, $R^{-}_{\tilde{g}}$(anti)baryons	0.8	—
$R^{0}_{\tilde{g}}$ (anti)baryons	0.7	—

- Interest in triplets,sextet,octets

$$C_3, C_6, C_8$$

- Bound states

$$C_3\bar{q}, C_3 q_1 q_2, \ldots$$
$$C_6 qg, C_6 q\bar{q}q, C_6 \overline{qq}, \ldots$$
$$C_8 \bar{q}q, C_8 q_1 q_2 q_3, C_8 g, \ldots$$

3. Interactions with matter: electromagnetic and strong

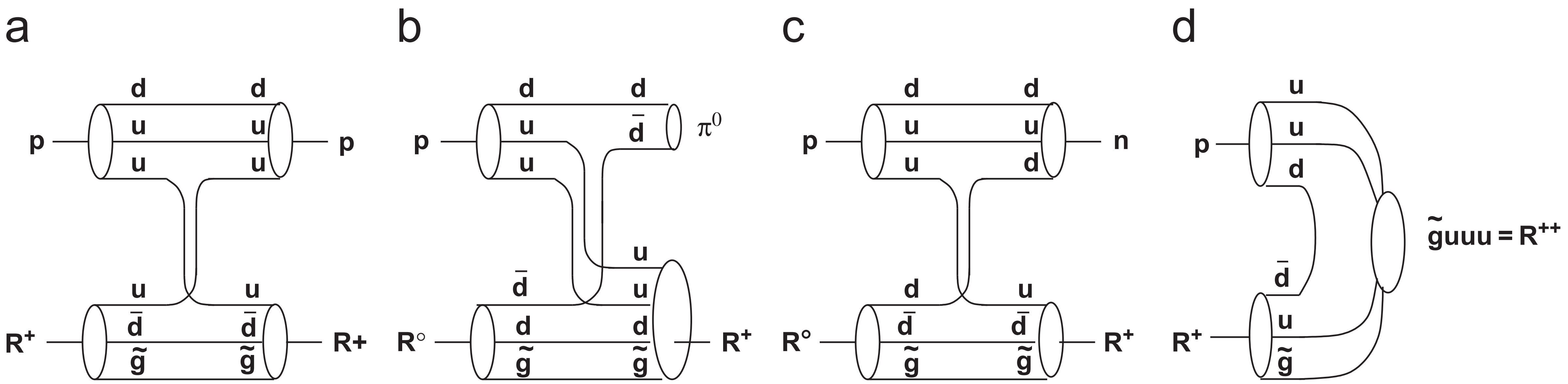


Fig. 13. *R*-hadron–proton scattering processes: (a) elastic scattering; (b) inelastic scattering leading to baryon and charge exchange; (c) inelastic scattering leading to charge exchange; (d) resonance formation.

Coloured Matter & Summary

4. Stopping & decay

- Depending on the mass of the new coloured state, a non-negligible number of particles could stop and decay

@ LHC all searches made in the context of R-hadrons, some results

- Longer time-of-flight + anomalous energy loss (using the the cloud model)

  [CMS arXiv:1305.0491]
  [ATLAS arXiv:1411.6795]

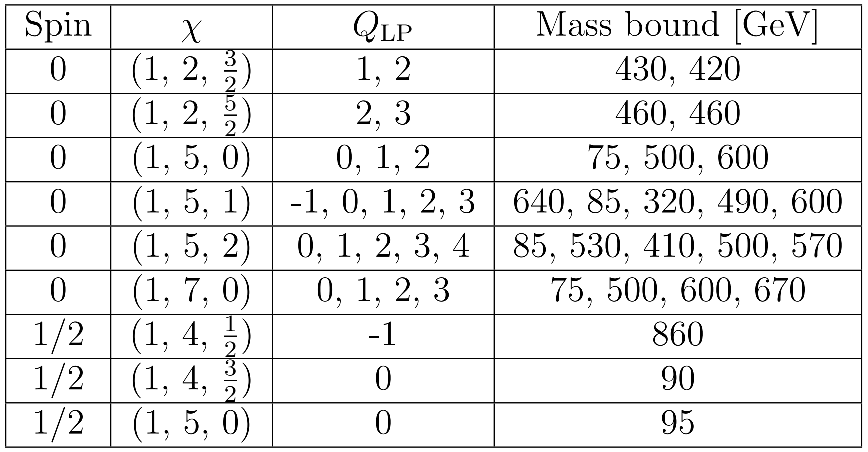
  $m_{\tilde{g}} > 1250\ \mathrm{GeV}$ $m_{\tilde{t}} > 935\ \mathrm{GeV}$

- Out-of-time decay + (extra assumption on the decay, ecc.)

  [ATLAS arXiv:1310.6584] $m_{\tilde{g}} \gtrsim 900\ \mathrm{GeV}$ $m_{\tilde{t}}, m_{\tilde{b}} \gtrsim 350\ \mathrm{GeV}$

- We expect similar bounds in our cases

Summary collider bounds



Spin	χ	Q_{LP}	Mass bound [GeV]
0	$(1, 2, \frac{3}{2})$	1, 2	430, 420
0	$(1, 2, \frac{5}{2})$	2, 3	460, 460
0	(1, 5, 0)	0, 1, 2	75, 500, 600
0	(1, 5, 1)	-1, 0, 1, 2, 3	640, 85, 320, 490, 600
0	(1, 5, 2)	0, 1, 2, 3, 4	85, 530, 410, 500, 570
0	(1, 7, 0)	0, 1, 2, 3	75, 500, 600, 670
1/2	$(1, 4, \frac{1}{2})$	-1	860
1/2	$(1, 4, \frac{3}{2})$	0	90
1/2	(1, 5, 0)	0	95

Conclusions

- LHC so far, Higgs but no answer on the naturalness of the EW scale

- Numerous indirect probes are suggesting that either the NP is highly non generic or the NP is very high

- SM has various accidental and approximate symmetries, we constructed extensions that preserve such a structure

- General prediction: long lived stable particles at the LHC, bounds and phenomenology depends crucially on the nature of the lightest particle