自然性问题和超对称(SUSY)

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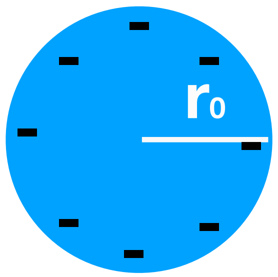
电子质量的自然性问题

Classical description of electron

Borrowed from Hitoshi Murayama, hep-ph/0002232



electron

electrostatic self-energy

Physical mass   Bare mass

$$m_e = m_0 + \delta m, \;\; \delta m = \frac{q^2}{4\pi r_0}$$

No structure of electron: $r_0 < 10^{-19}\mathrm{m}$

$m_p \sim 1 \text{ GeV} \sim 10^{-16}\mathrm{m}$

0.5 = -9999.5 + 10000.   MeV

Large cancellation is needed, unnatural

Solutions

Problem solved by Dirac

Particles get doubled

Quantum Electrodynamics(QED) ⟶ Existence of the positron

The correction:

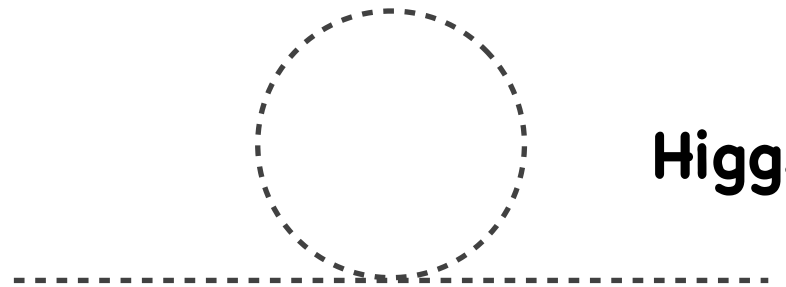
Physical mass   Bare mass   self-energy

$$m_e = m_0 + \delta m, \ \ \delta m = \frac{3q^2}{4\pi} m_0 \log \frac{1}{m_0 r_0}$$

log dependence

Even $r_0 = l_{pl} = 10^{-34} m$, the correction is only few percent

希格斯自然性问题



Higgs

$$m_h^2 = m_0^2 + \delta m^2 \qquad \delta m^2 = \int_0^\Lambda d^4p \frac{1}{p^2} \sim \Lambda^2$$

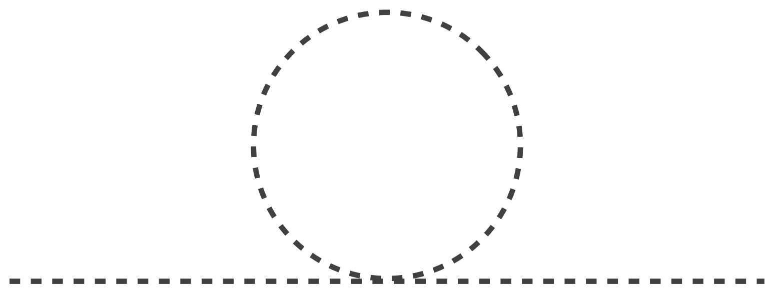
(125 GeV)^2

$$\delta m^2 \sim M_{pl}^2 = (10^{18}\ \mathrm{GeV})^2$$

Much larger cancelation is needed, not natural

希格斯自然性问题

如果用最小减除方案做重整化，发散的依赖项会被抵消项抵消，最后的**Lambda**依赖性消失



$$\mu^{2\epsilon}\int\frac{\mathrm{d}^{\mathrm{d}}k}{(2\pi)^{\mathrm{d}}}\frac{1}{(k^2-m^2)}=-\frac{i\mu^{2\epsilon}}{(4\pi)^{\mathrm{d}/2}}\Gamma(-1+\epsilon)\left(m^2\right)^{1-\epsilon}$$

$$=\frac{i}{16\pi^2}\left[\frac{m^2}{\epsilon}+m^2\log\frac{\bar{\mu}^2}{m^2}+m^2+\mathcal{O}(\epsilon)\right]$$

抵消项消去

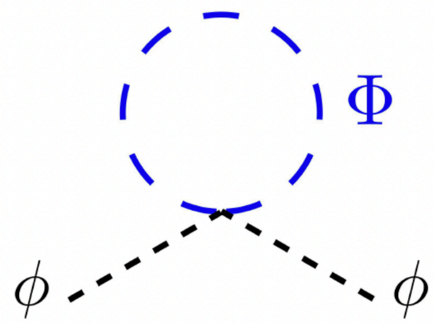
$$\delta m_H^2=-12\lambda m_H^2\left[\log\frac{m_H^2}{\bar{\mu}^2}+1\right]$$

自然性问题到底存不存在?

希格斯自然性问题

假如有两个标量粒子，一个轻一个重

$$\mathcal{L}^{\text{FULL}} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m_{\text{F}}^2 \phi^2 + \frac{1}{2}(\partial_\mu \Phi)(\partial^\mu \Phi) - \frac{1}{2} M^2 \Phi^2 - \frac{1}{4}\kappa \phi^2 \Phi^2 - \frac{1}{4!}\eta \phi^4$$



$$= \frac{i\kappa}{32\pi^2} M^2 \left[\frac{1}{\epsilon} + \log\frac{\tilde{\mu}_M^2}{M^2} + 1 + \mathcal{O}(\epsilon)\right]$$

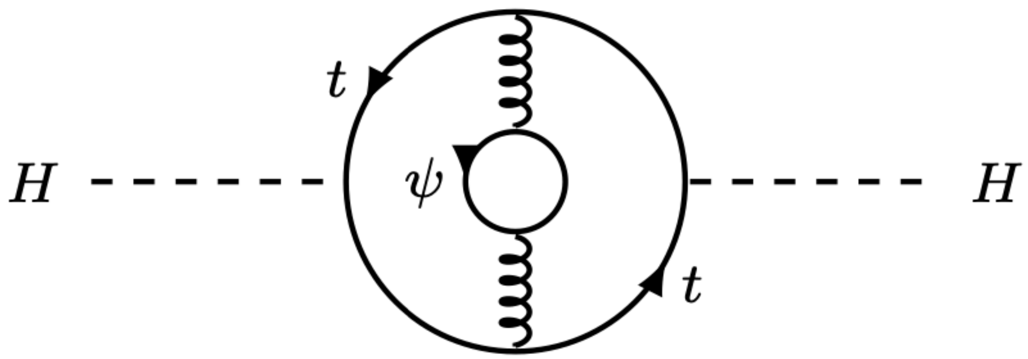
抵消项消去

$$-i\delta m^2 = \frac{i\kappa}{32\pi^2} M^2 \left[\log\frac{\tilde{\mu}_M^2}{M^2} + 1\right]$$

只要希格斯粒子跟其它较重粒子耦合，必然导致较大的质量修正，自然性问题依然存在

希格斯自然性问题

假如不直接跟希格斯耦合，是不是就没问题？比如只加一个新型重夸克？



$$\delta m^2 \sim \left(\frac{1}{16\pi^2}\right)^3 y_t^2 g_s^4 m_\psi^2$$

自然性要求psi质量小于100 TeV

只要有新粒子跟标准模型粒子有耦合，就会贡献希格斯质量！

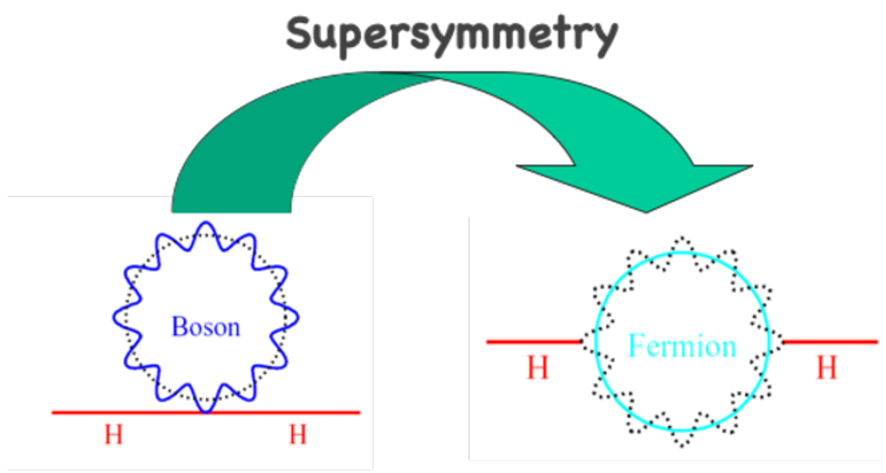
希格斯自然性问题

假如标准模型是终极理论，不再存在任何新的粒子，是不是就没自然性问题了？

- Mpl标度必然存在量子引力理论替代标准模型理论，弦论里预言了非常多的粒子
- 中微子存在质量，为了解释中微子质量必然要加入新的粒子
- 宇宙暴胀要求在高标度存在新的标量粒子
- 是否有大统一(10^16 GeV)？为什么存在三代费米子？不同味夸克的混合起源？
- 暗物质、强CP问题等等

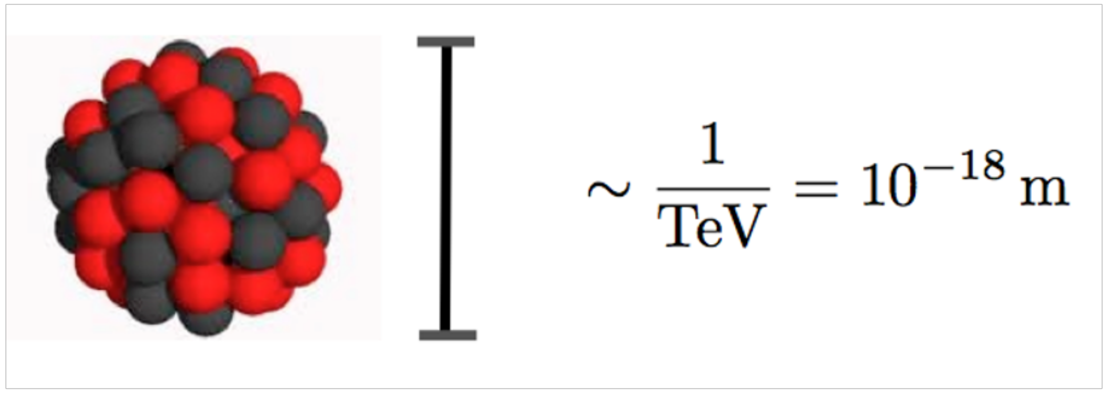
解决方案

超对称：费米子、玻色子贡献抵消

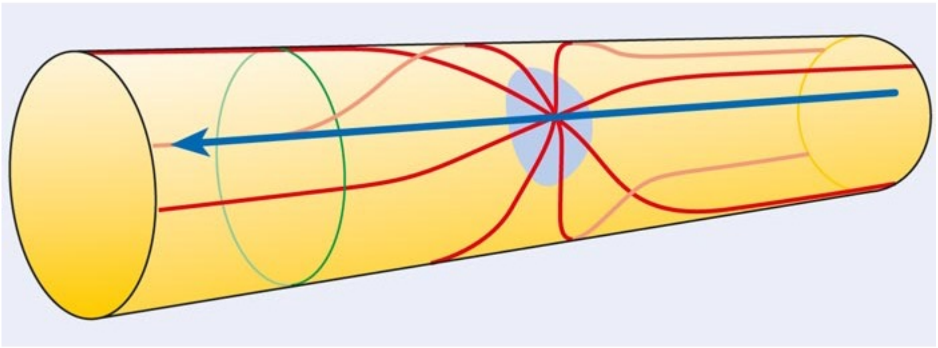


$$\delta m^2 = M_{pl}^2 \to M_{SUSY}^2 \log M_{pl}$$

希格斯粒子不是最基本粒子(复合粒子)



存在额外的维度，引力标度可以更低



What is supersymmetry?

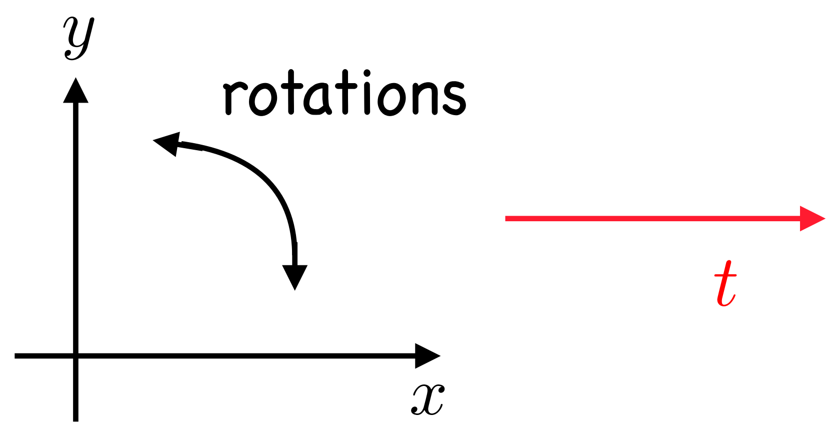
Supersymmetry is a space-time symmetry

Symmetry: physics laws do not change with transformations

Galilean Space-Time Model

$(x, y, z; t)$

$\mathbf{F} = m\mathbf{a}$



Superspace **"Super-rotations"**

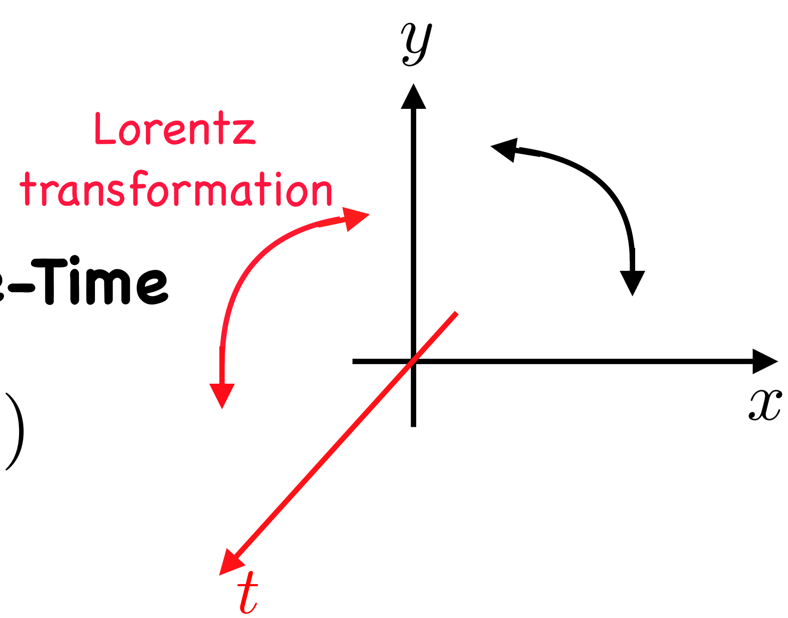
超空间

$(x, y, z, t, \theta, \bar{\theta})$

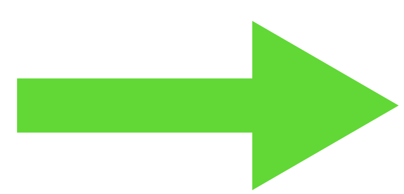
Einstein Space-Time

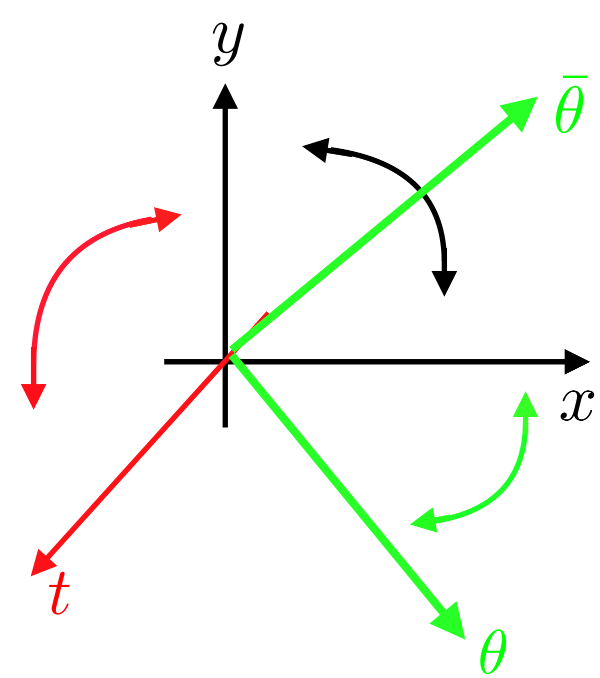
(x, y, z, t)

$E = mc^2$



Supersymmetry

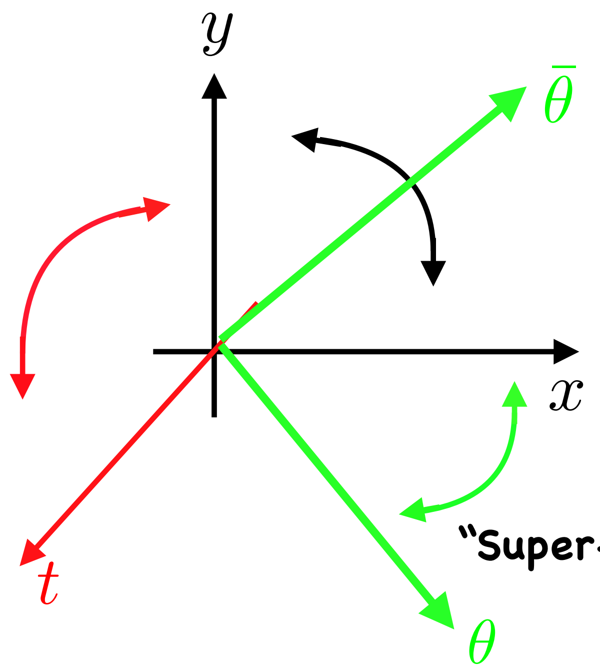




What is supersymmetry?

Superspace

$(x, y, z, t, \theta, \bar{\theta})$



Any fields can be written as

$$\Phi(x, y, z, t, \theta, \bar{\theta}) = \phi(x, y, z, t) + \psi(x, y, z, t)\theta + \ldots$$

boson **fermion**

"Super-rotations" can change bosons and fermions into each other

Supersymmetry is also a symmetry between fermions and bosons

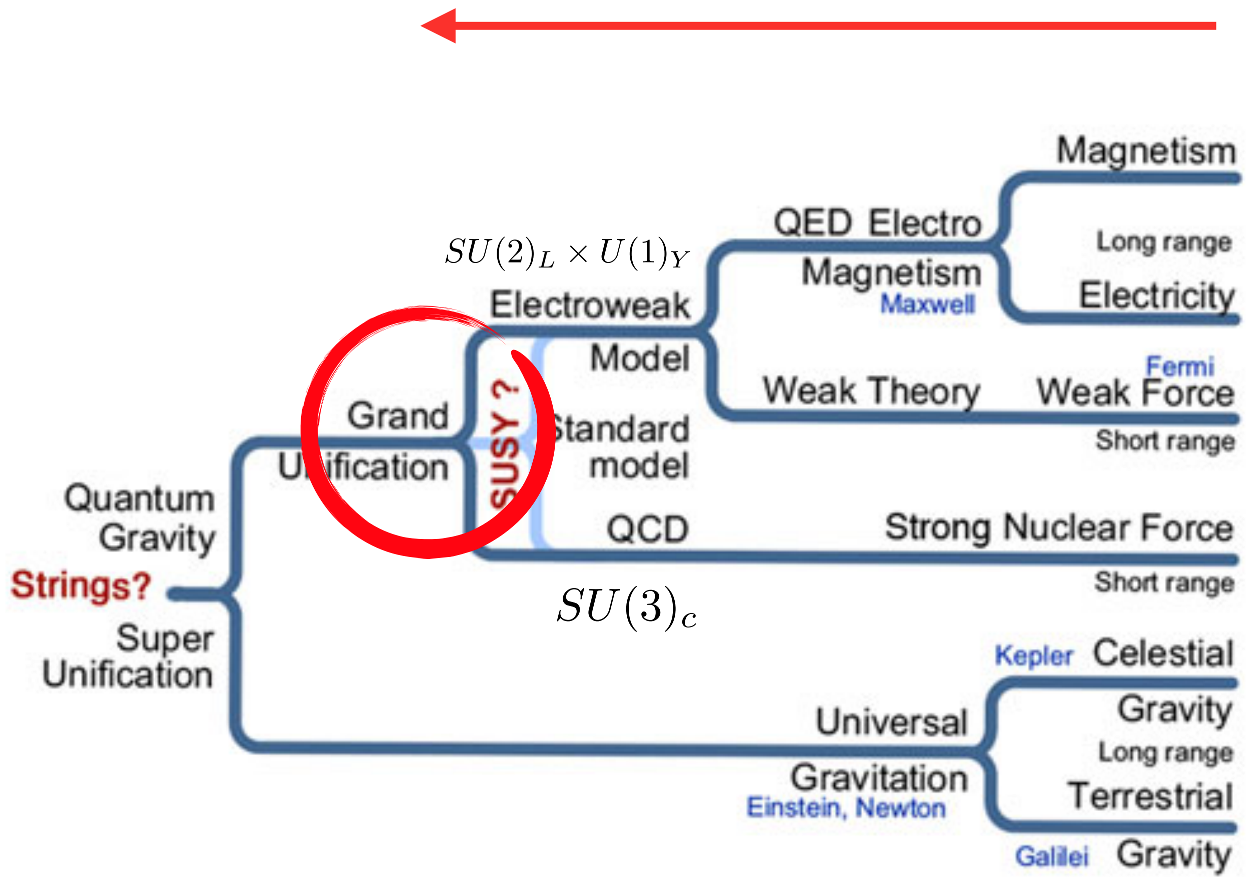
$$|\mathbf{F}\rangle \longleftrightarrow |\mathbf{B}\rangle$$

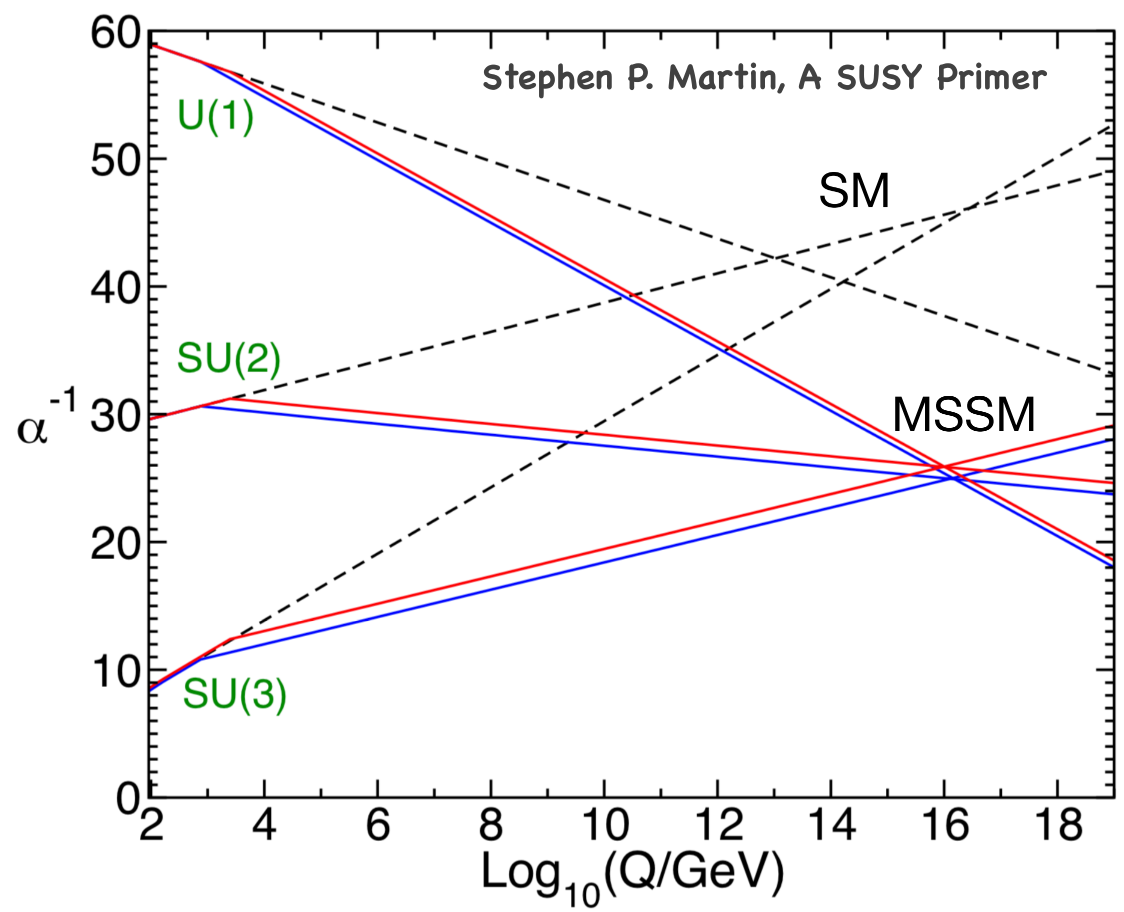
If we have supersymmetry, we should have both bosons and fermions!

Why supersymmetry?

- 自然性问题
- 大统一
- 暗物质

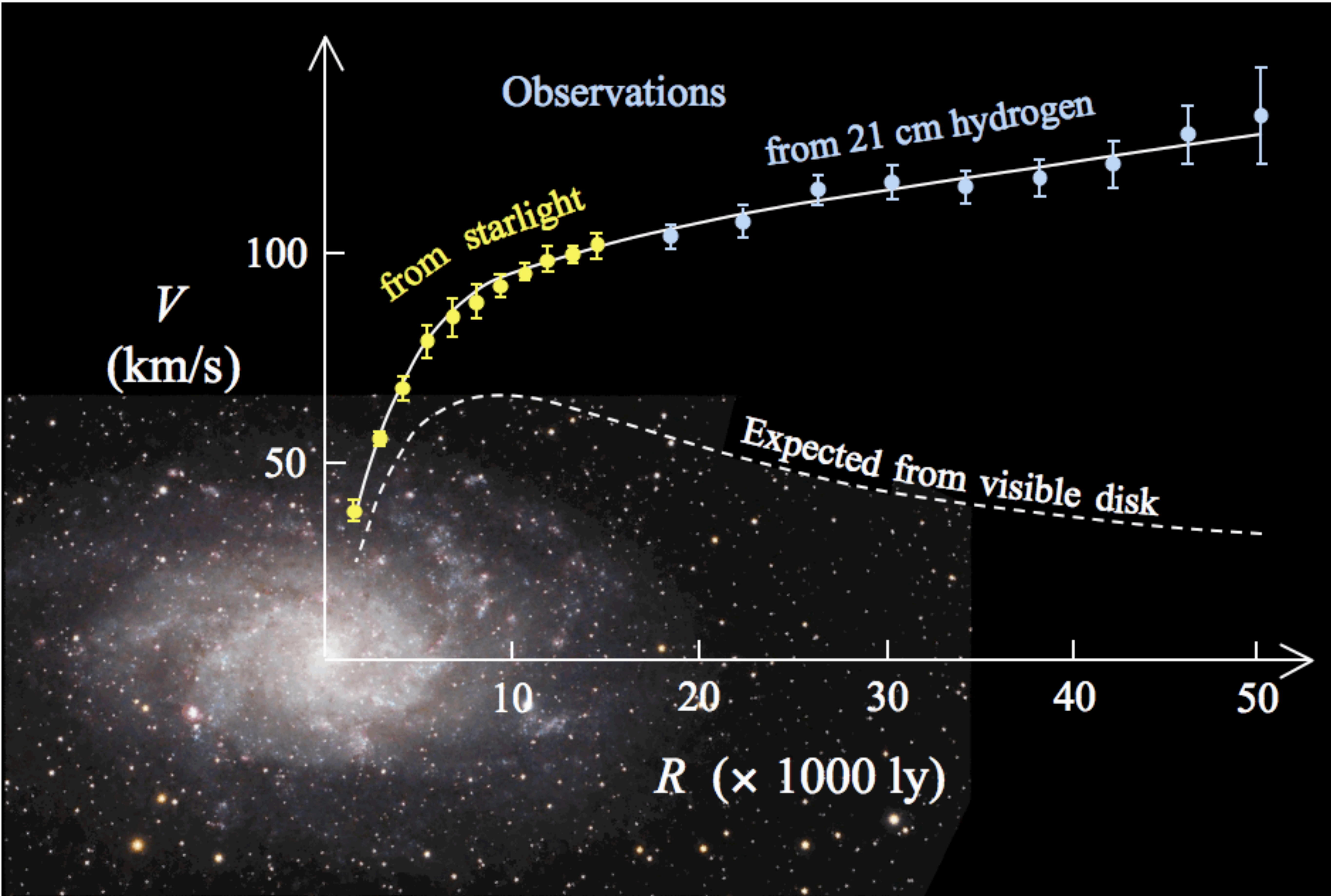
Why supersymmetry: unification of forces





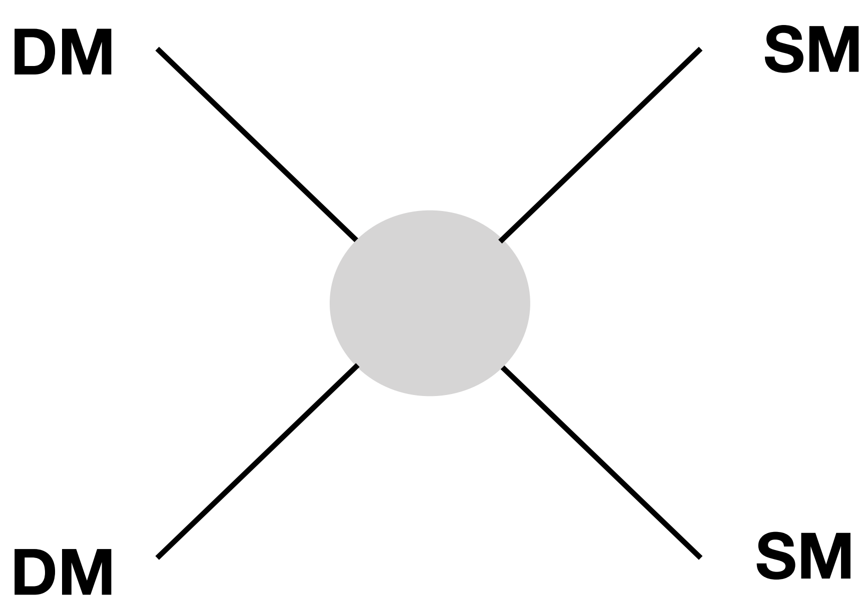
Unification at 1% level at GUT for SUSY partner mass around TeV

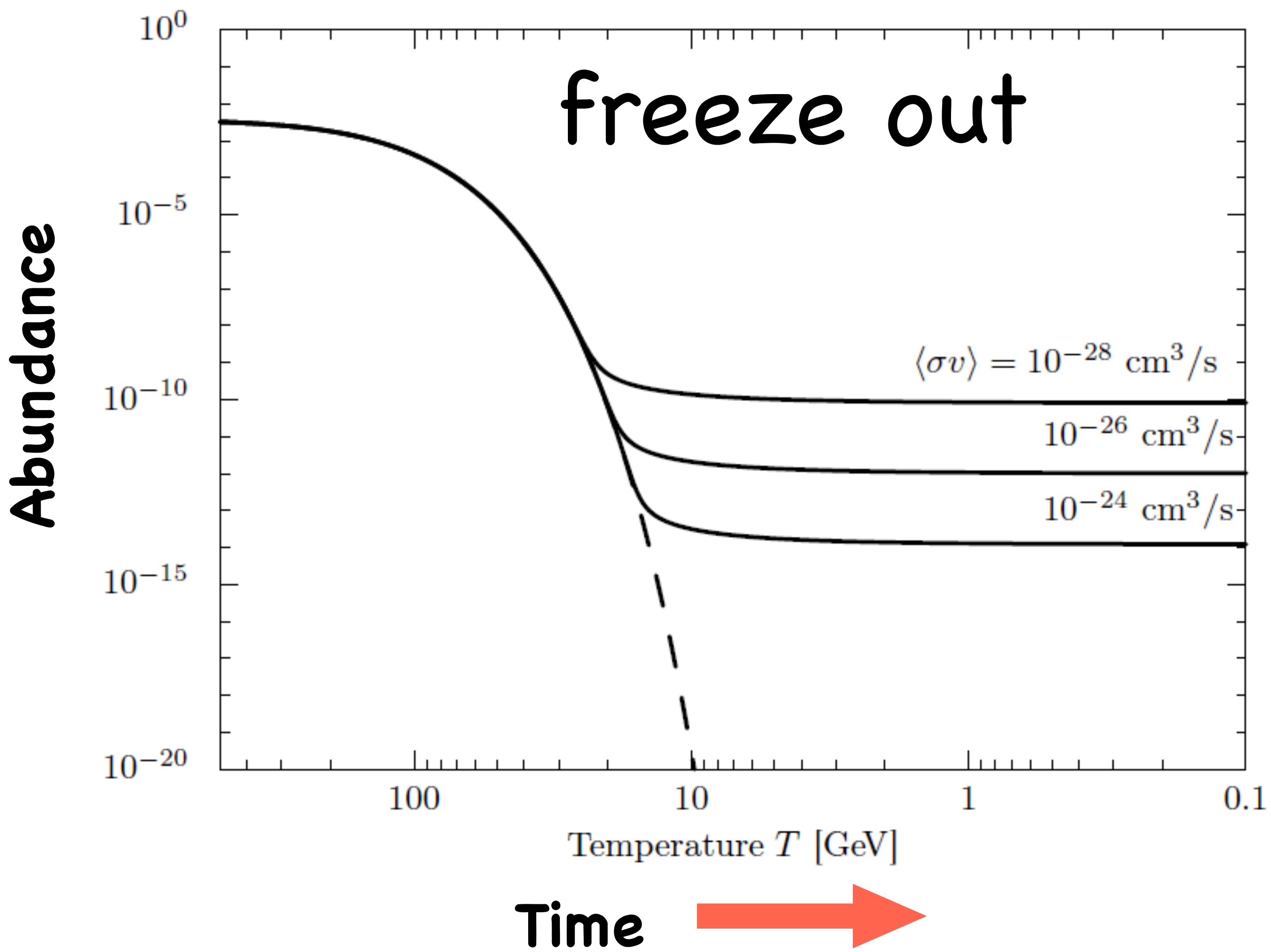
Why supersymmetry: dark matter



Weakly interacting massive particles (WIMP)

DM annihilation in early universe → Abundance





WIMP "miracle"

$$\Omega h^2 \simeq 0.1(\frac{<\sigma v>}{10^{-26}\mathrm{cm}^3/\mathrm{s}})^{-1}$$

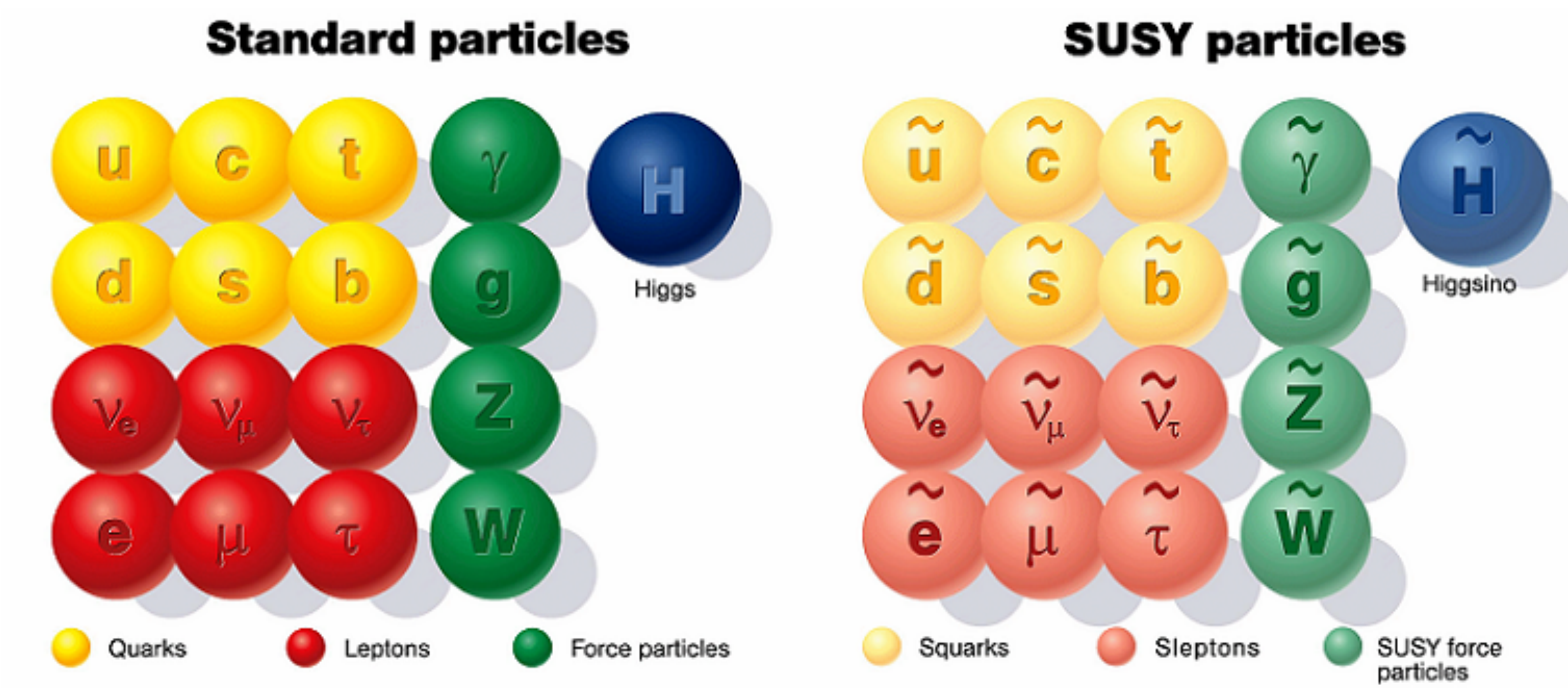
$$10^{-26}\mathrm{cm}^3/\mathrm{s} \simeq 10^{-9}\mathrm{GeV}^{-2} \sim \frac{\mathrm{g}_2^2}{4\pi}\frac{1}{\mathrm{m}_{\mathrm{DM}}^2}$$

$$m_{DM} = O(1)\mathrm{TeV}$$

A scale very close to electroweak scale!
Or SUSY scale

Minimal supersymmetric standard model (MSSM)

SM → MSSM

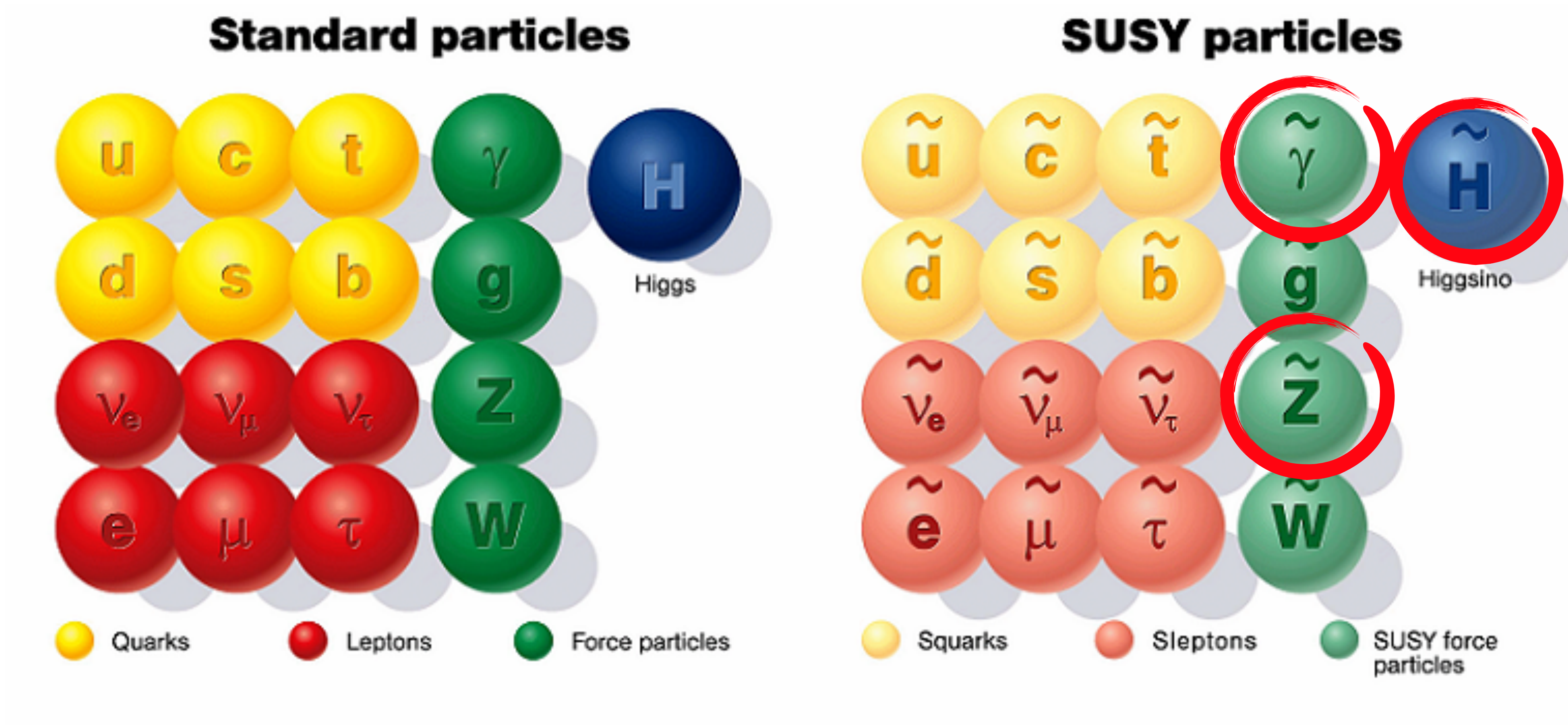


SM: fermion ⟶ sfermion

SM: scalar or gauge field ⟶ -ino

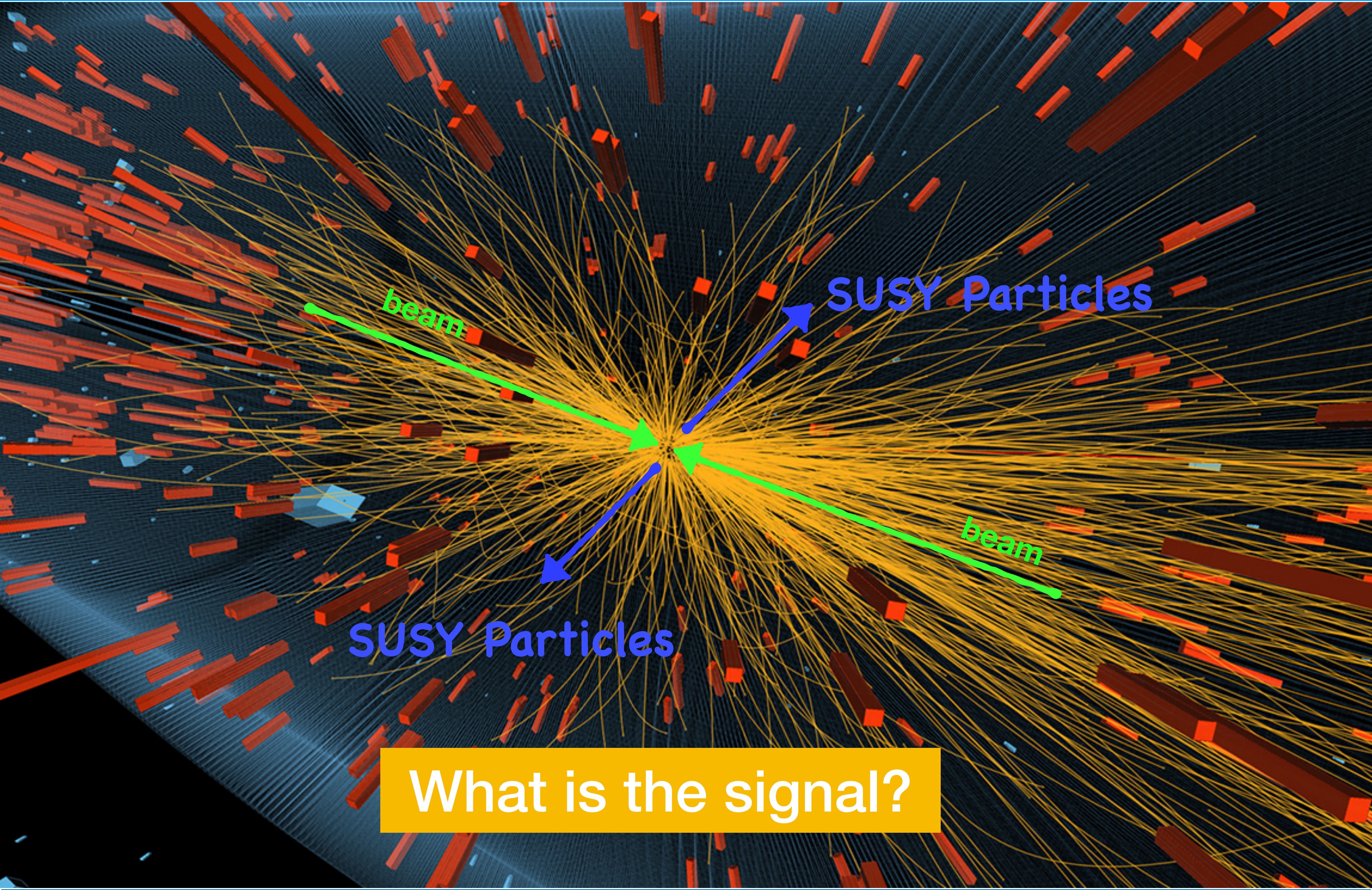
Dark Matter in MSSM

R parity +1 -1



Lightest is stable, neutral: dark matter candidate!

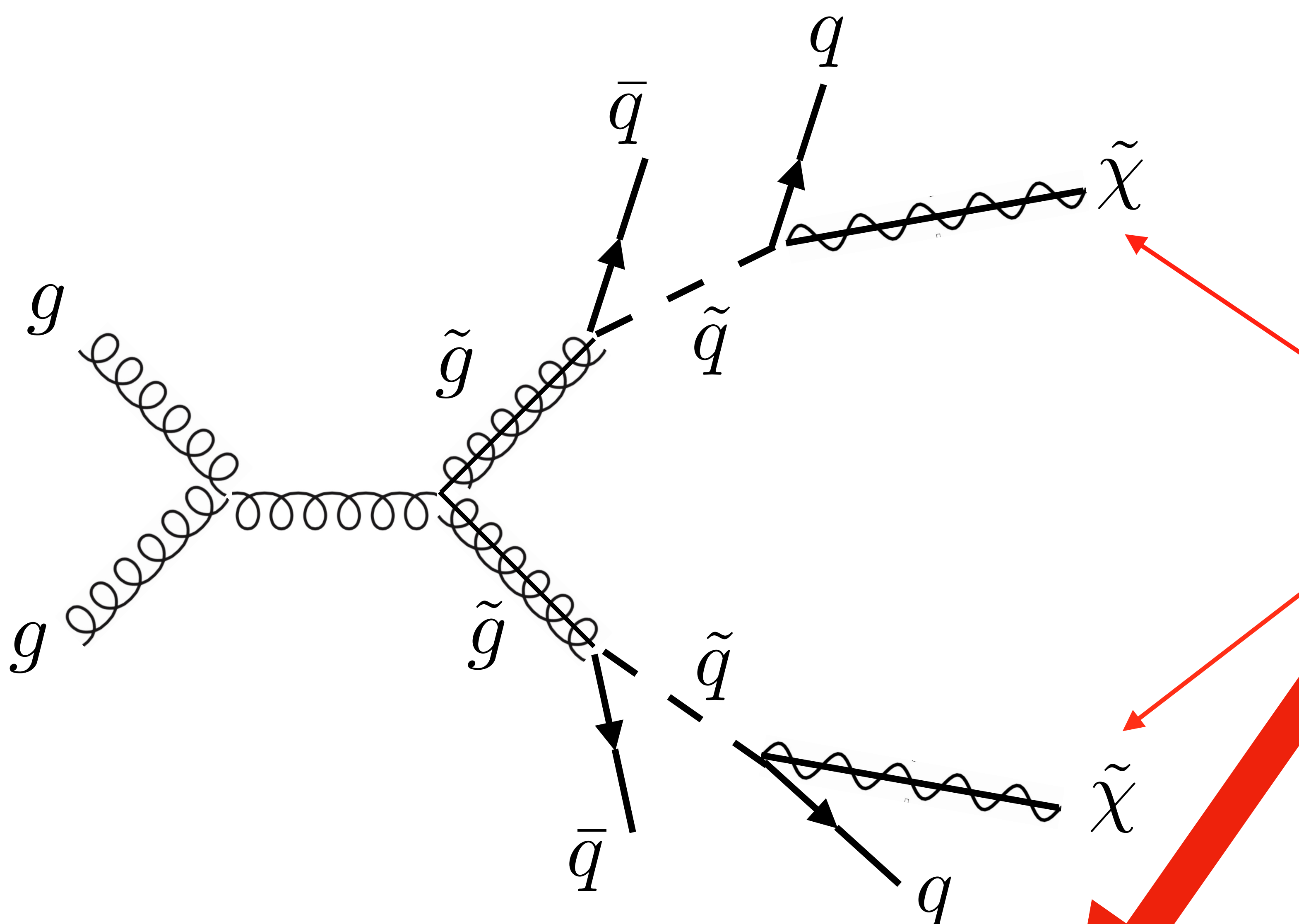
How to probe SUSY particles: Large Hadron collider(LHC)



What is the signal?

Typical SUSY signal(model dependent)

Gluino production → **Cascade decay**

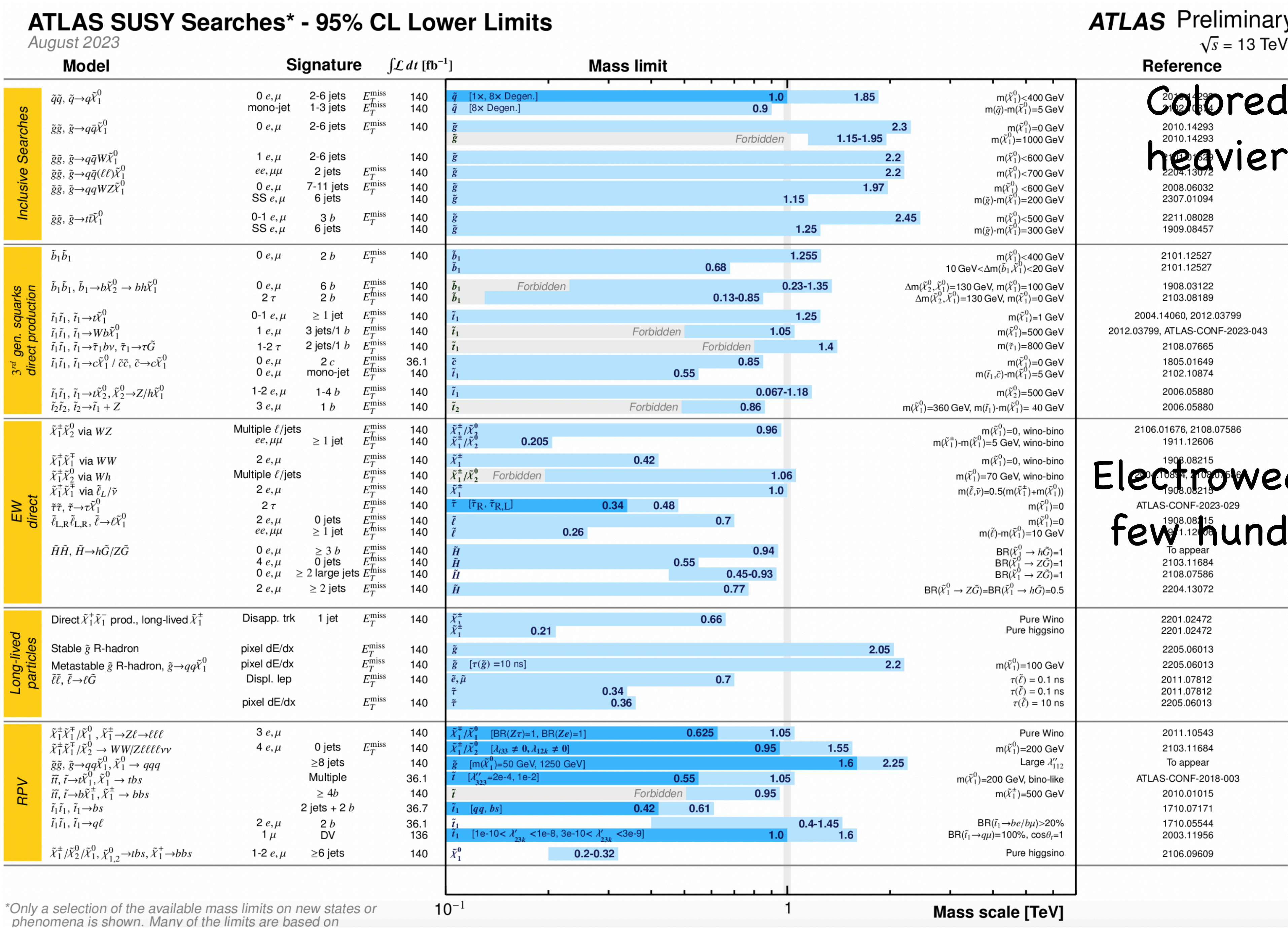


Lightest SUSY particle(dark matter)

Contribute to: $pp \to \bar{q}q\bar{q}q + E_T^{miss} + X$

SM: $Z \to \nu\nu / W \to l\nu$

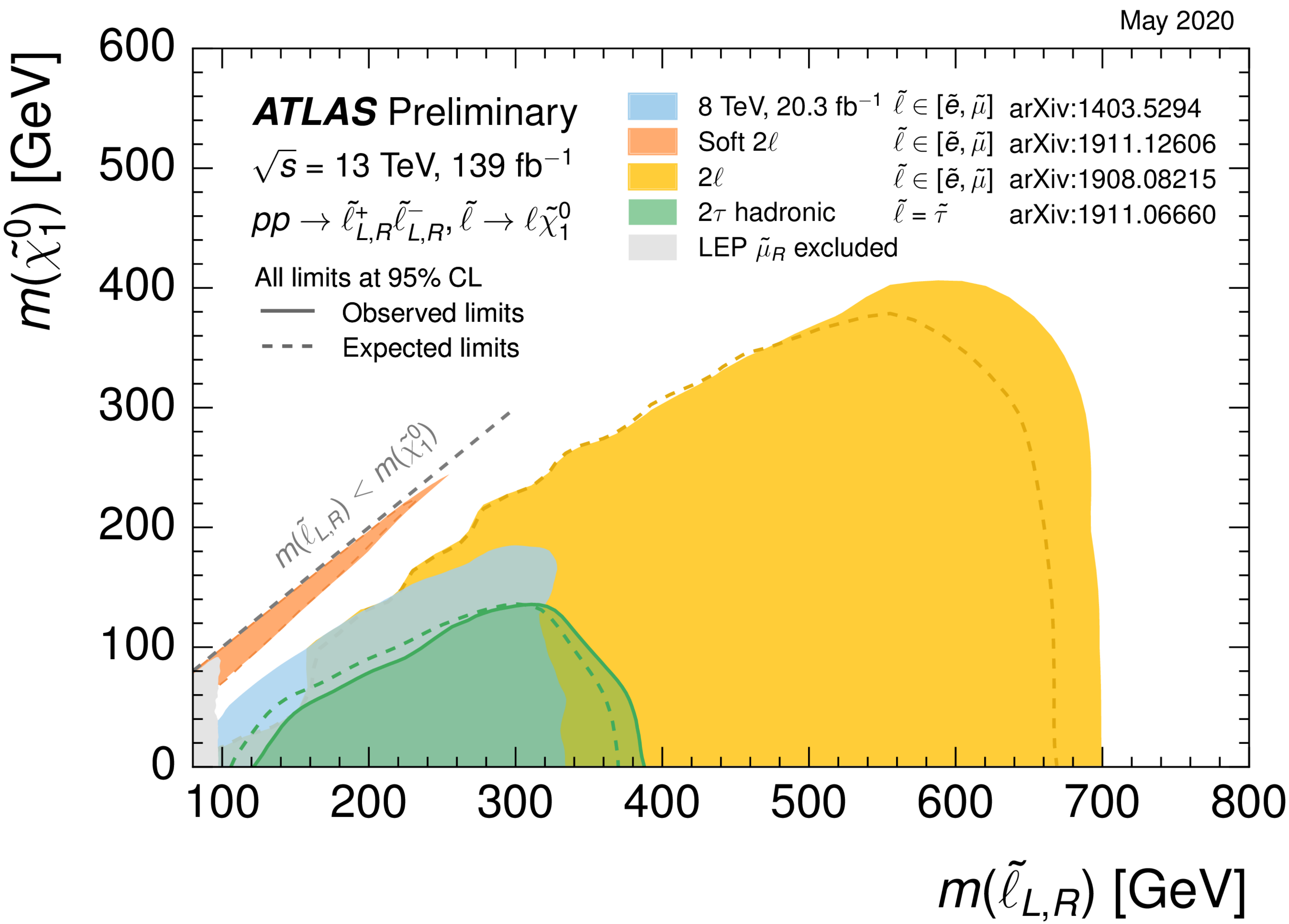
SUSY searches



Colored sparticles should heavier than 1-2 TeV

Electroweak particles could be few hundred GeV

Slepton searches



Can be as light as hundred GeV

Natural SUSY

Naturalness guideline

Higgsino mass

$$(|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2)$$

$$m_h^2 = m_0^2 + \delta m^2$$

Log dependence

$$\delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

stop contribution

All of the same order, no fine-tuning, totally natural

Higgs partner

$\tilde{H}$ **~ 100-200 GeV**

Top quark partner

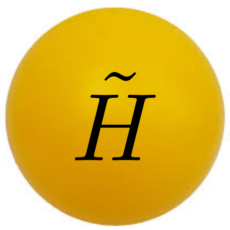
$\tilde{t}$ **~ TeV**

Also dark matter candidate

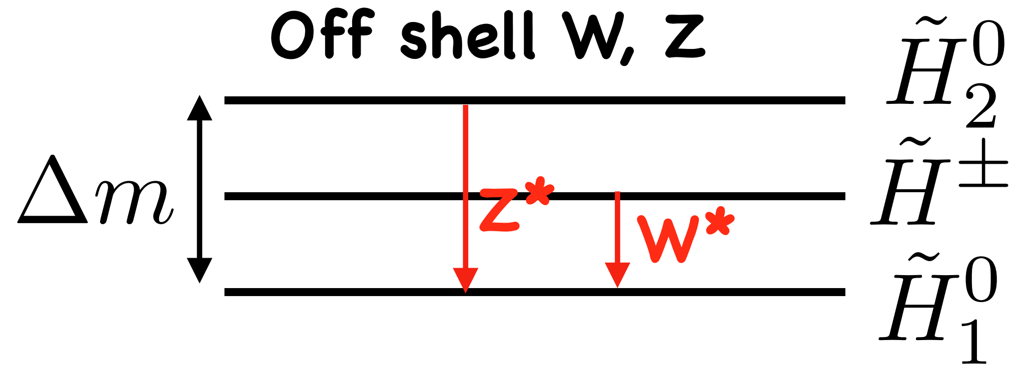
Can we directly look for Higgs partner?

Its mass close to Higgs mass(125 GeV)

Higgs partner



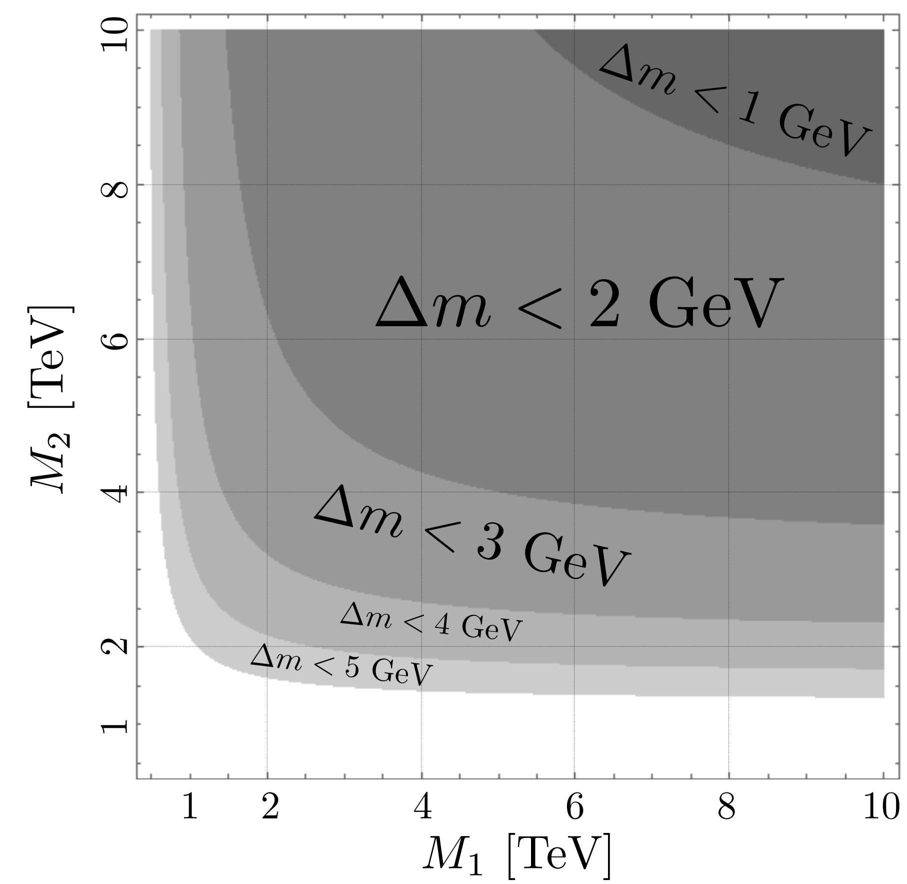
~ 100-200 GeV



The decay products are not easy to be identified by detector, all behave as missing energy.

$$p_T \lesssim \Delta m$$

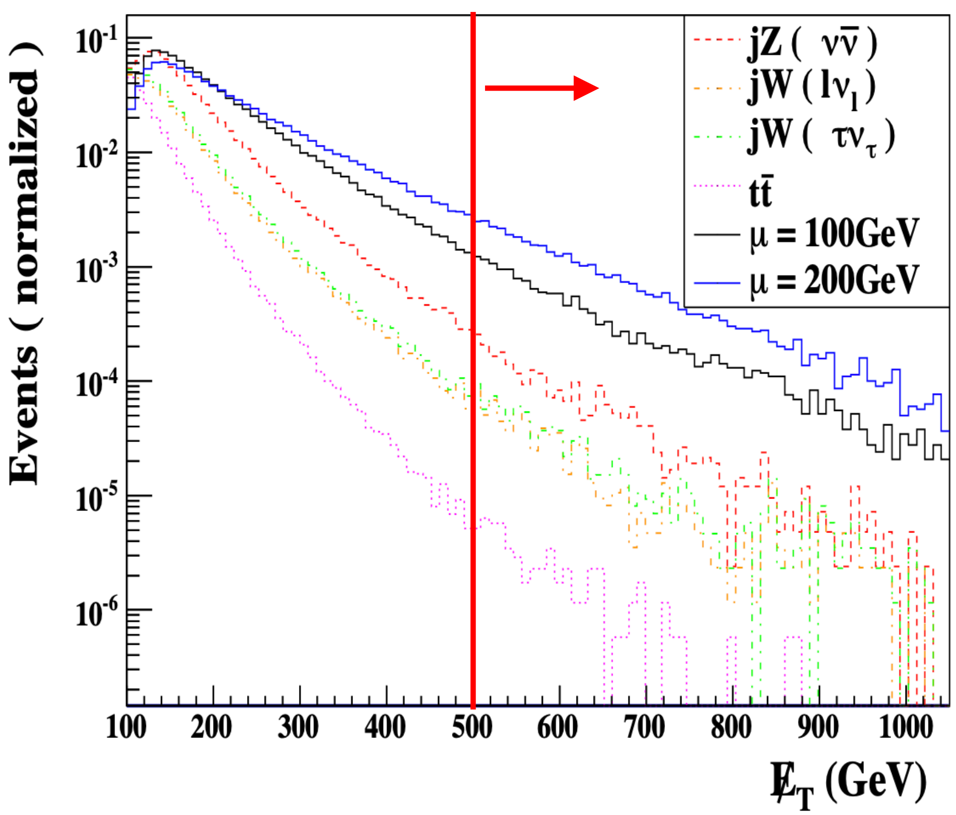
83] and to have $|\eta| < 2.5$. All electron and muon candidates must have $p_T > 20$ GeV and survive the overlap removal procedure. Signal leptons are chosen from the candidates with the following isolation

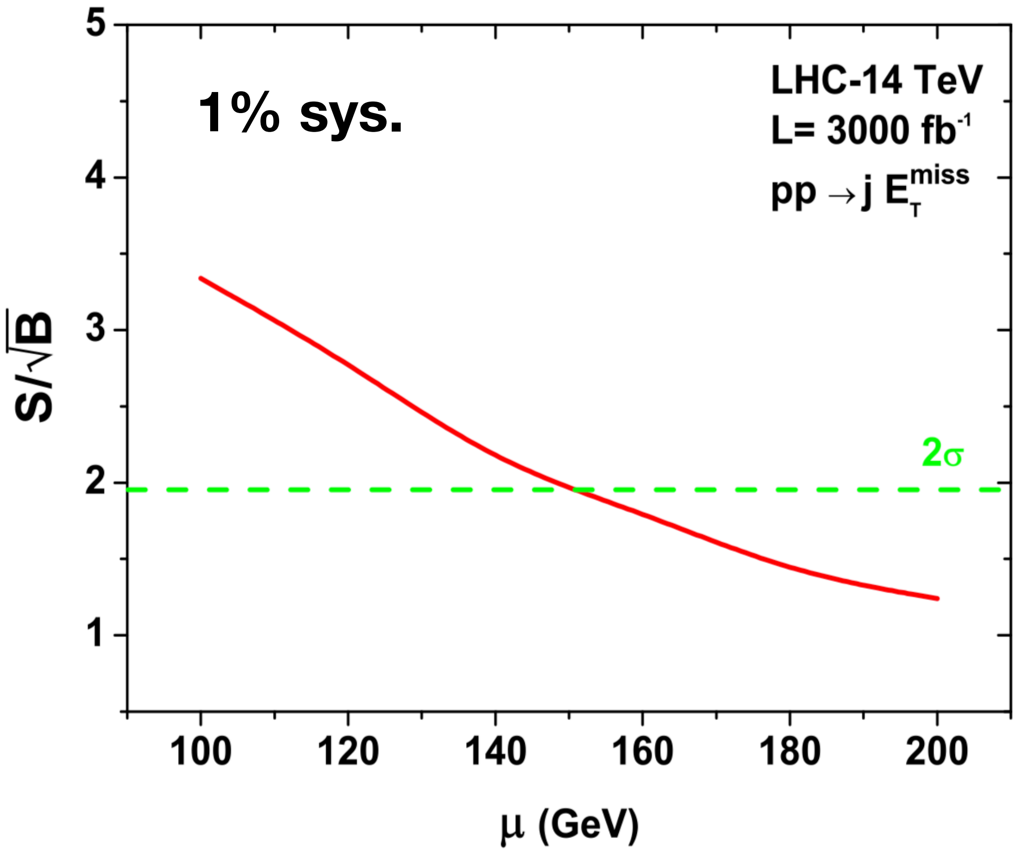


寻找希格斯伴子

"Probing Light Higgsinos in Natural SUSY from Monojet Signals at the LHC"

CH, A. Kobakhidze, N. Liu, A. Saavedra, L. Wu and J. M. Yang, JHEP 1402, 049 (2014)

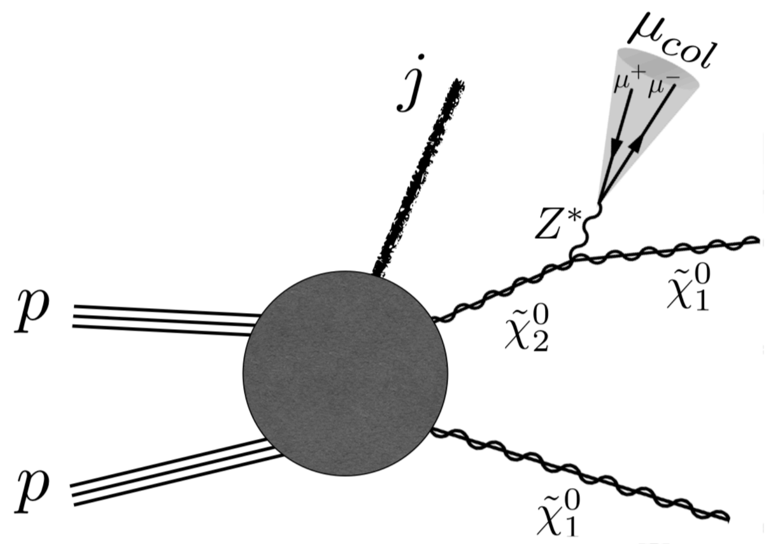




如果希格斯伴子在希格斯质量附近(125 GeV), 将来的LHC能够探测到

"Accessing the core of naturalness, nearly degenerate higgsinos, at the LHC"

CH, D. Kim, S. Munir and M. Park, JHEP 1504, 132 (2015)



Jet + Missing energy+ 2 soft leptons

Search for new physics in events with two soft oppositely charged leptons and missing transverse momentu

CMS Collaboration (Albert M Sirunyan (Yerevan Phys. Inst.) *et al.*). Jan 5, 2018. 28 pp.

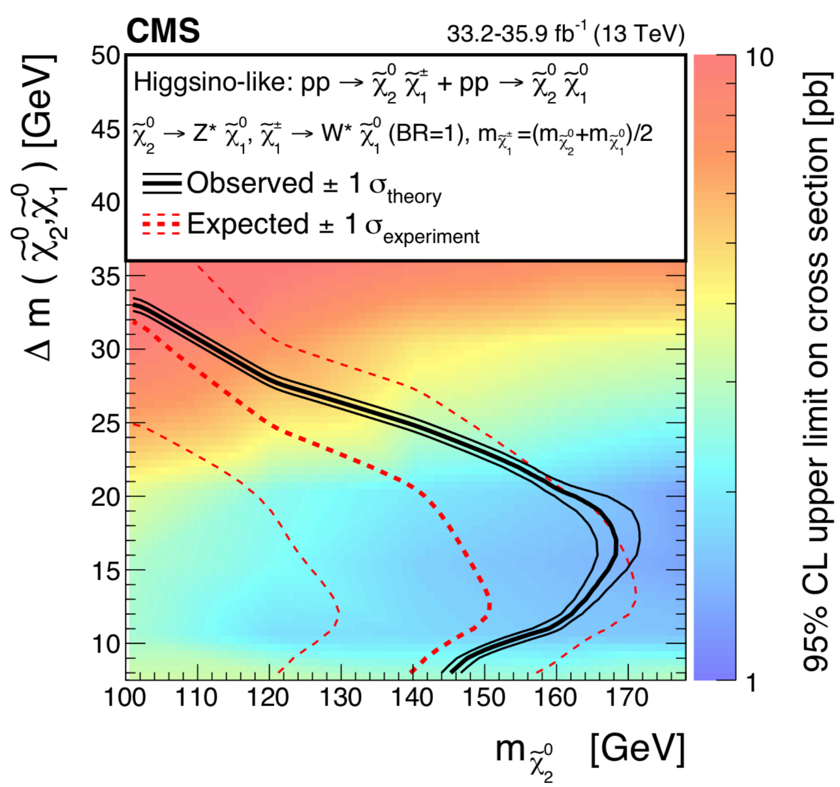
Published in **Phys.Lett. B782 (2018) 440-467**

CERN-EP-2017-336, CMS-SUS-16-048

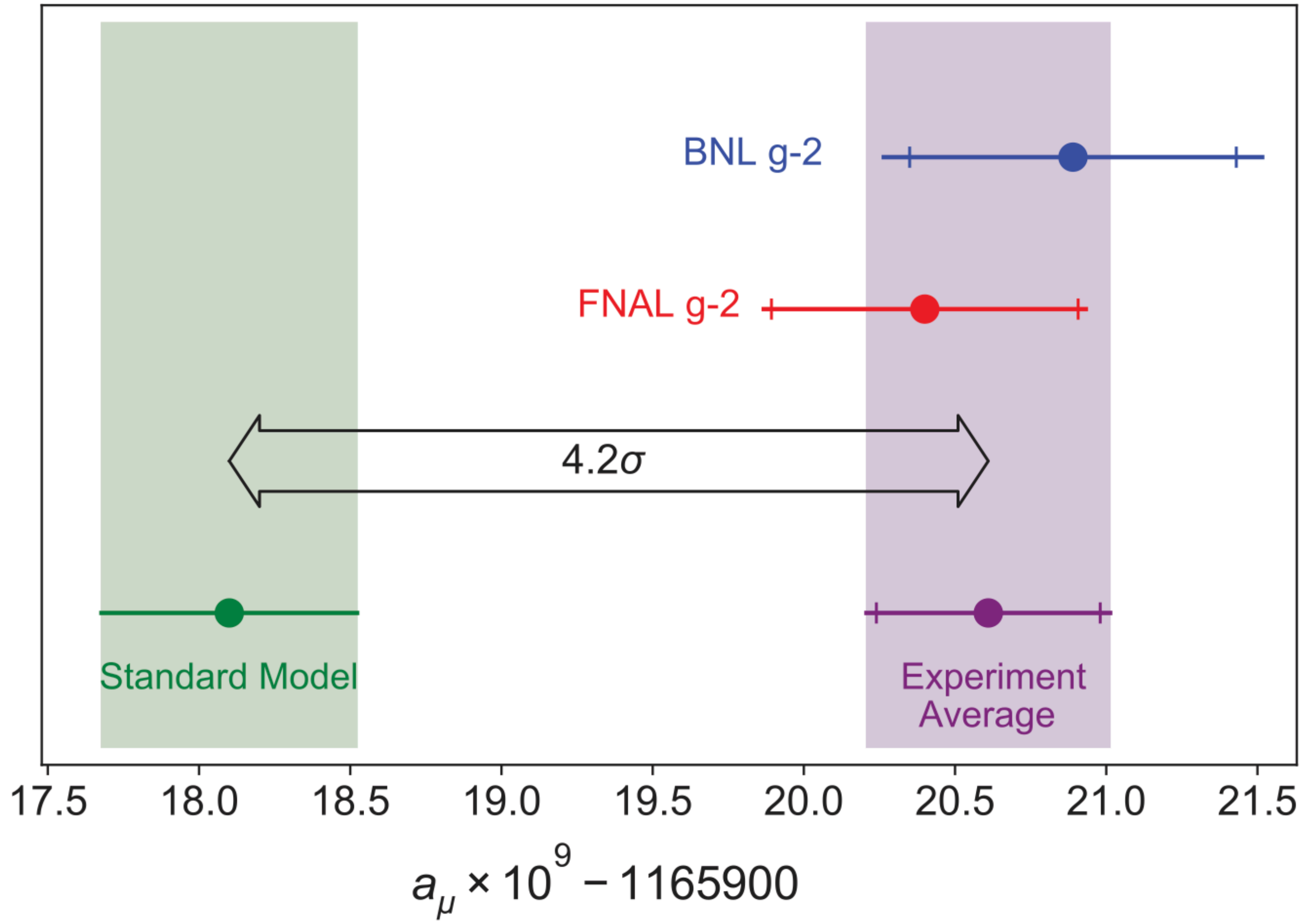
DOI: 10.1016/j.physletb.2018.05.062

e-Print: **arXiv:1801.01846 [hep-ex]** | **PDF**

The leading and subleading muon (electron) are required to satisfy $p_T > 5\,\text{GeV}$, $|\eta| < 2.4$ (2.5). A requirement of $p_T < 30\,\text{GeV}$ on the leptons is also applied; this threshold is identified

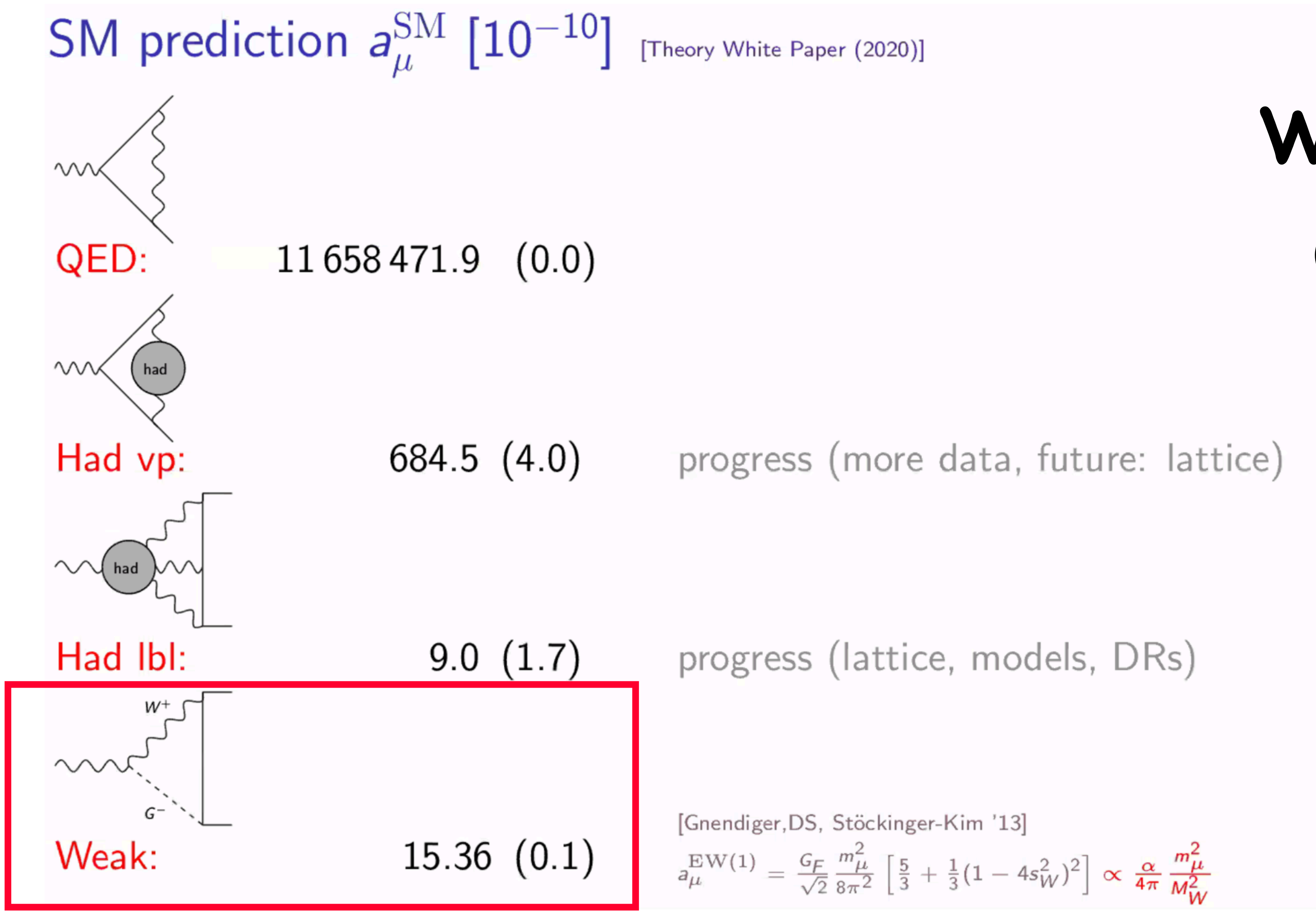


Muon g-2: observation and theory prediction



$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$$

New physics at electroweak scale



Why new particle mass @electroweak scale?

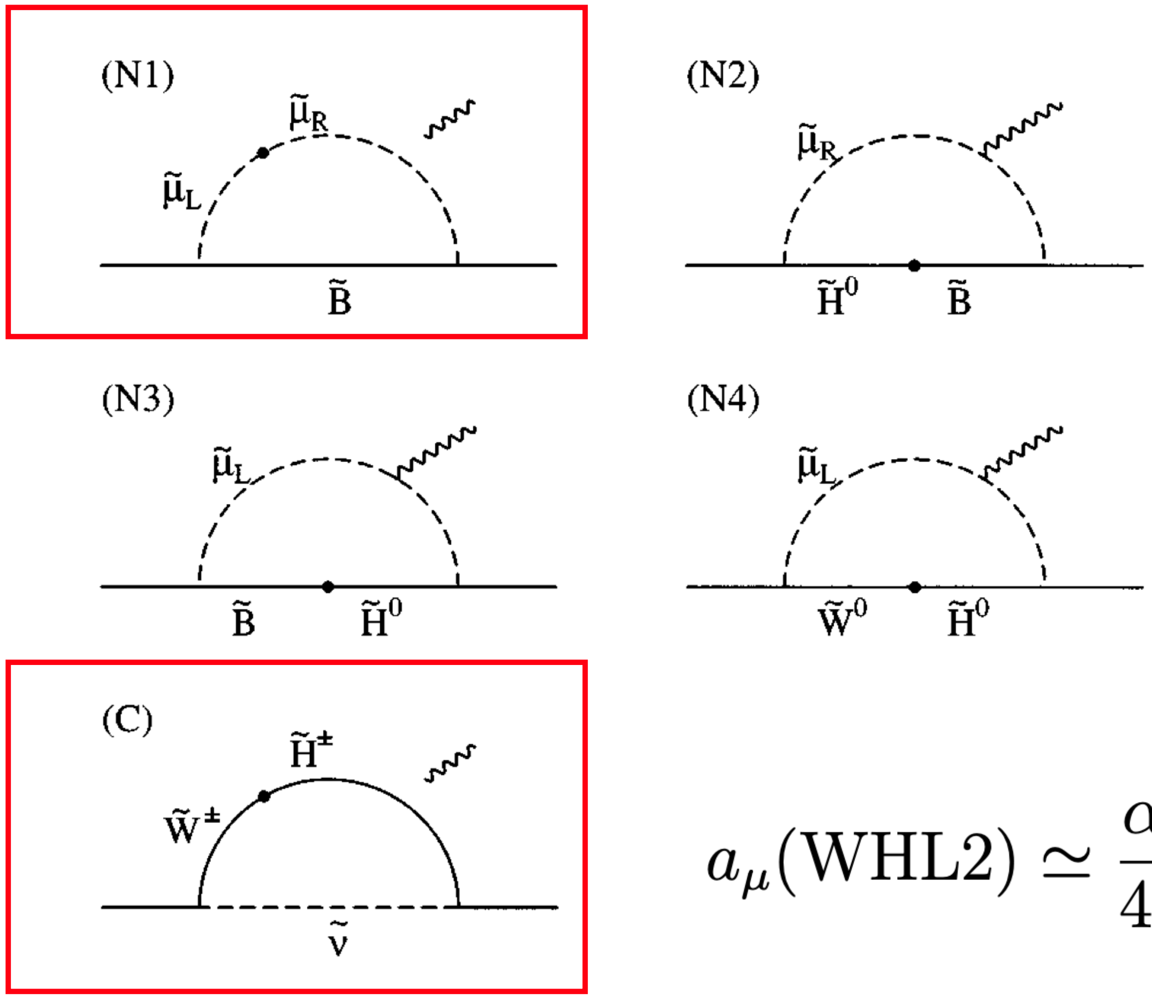
At hand

- **Naturalness problem**
- **WIMP dark matter**

SUSY incorporates two, providing an attractive solution

SUSY contribution to g-2

$$a_\mu(\mathrm{BLR}) \simeq \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1 \mu}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2}\tan\beta\cdot f_N\left(\frac{m_{\tilde{\mu}_R}^2}{M_1^2},\frac{m_{\tilde{\mu}_R}^2}{M_1^2}\right)$$

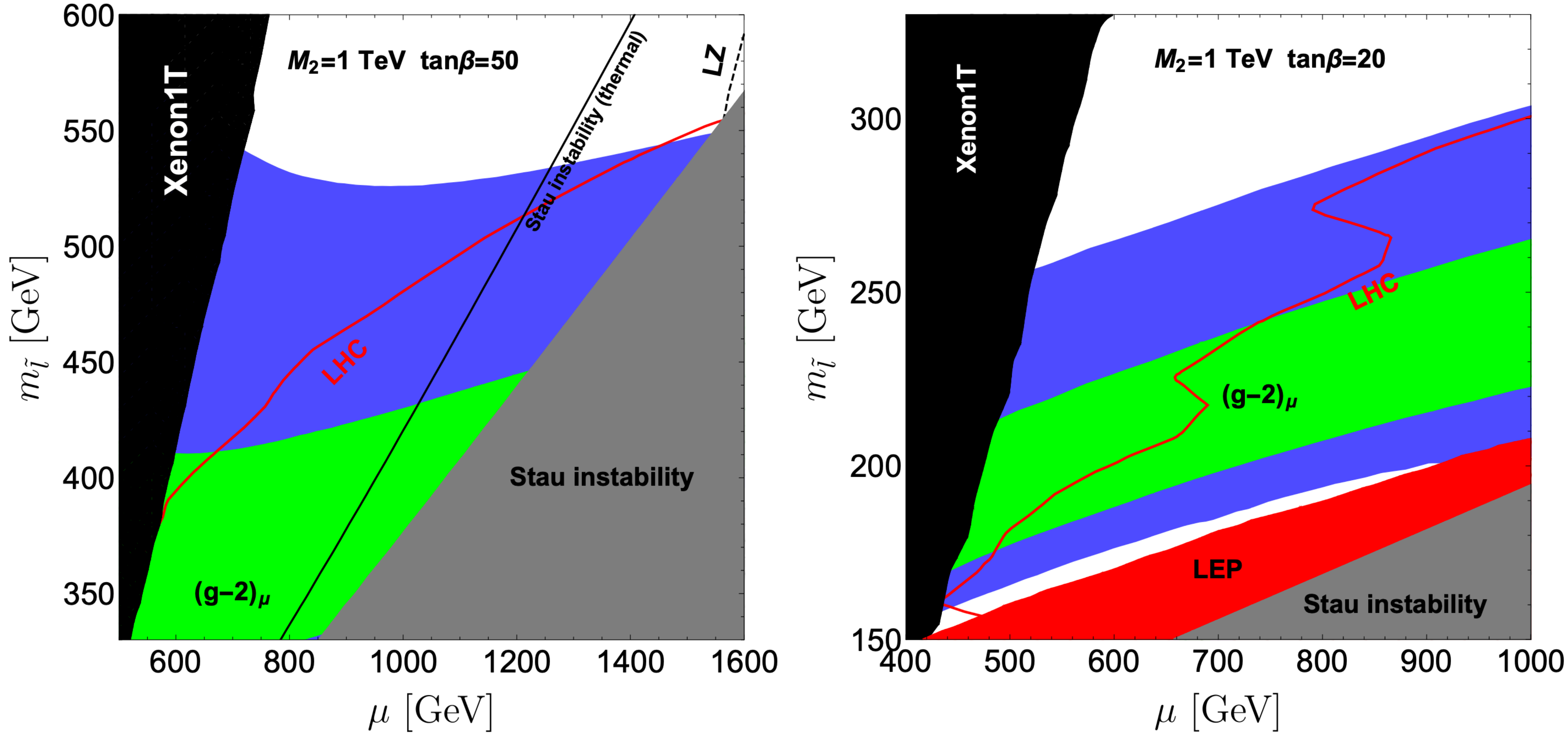


$$a_\mu(\mathrm{WHL2}) \simeq \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_C\left(\frac{M_2^2}{m_{\tilde{\nu}_\mu}^2},\frac{\mu^2}{m_{\tilde{\nu}_\mu}^2}\right)$$

Related parameters: wino mass, bino mass, higgsino mass, slepton masses

SUSY to explain muon g-2 anomaly

P. Cox, CH, T.T. Yanagida, arXiv: 2104.03290



Strong limit from LHC and stau instability!

结论

- 超对称仍然是非常有吸引力的超出标准模型候选者之一
- 近些年LHC的结果没有找到新的粒子让大家有所失望
- 如果超对称在更高的标度，我们需要更强大的对撞机