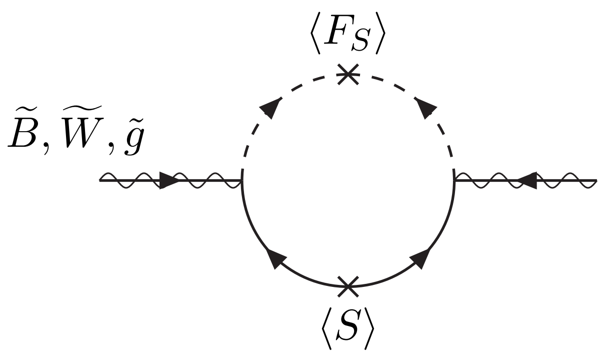
Gauge mediation (loop induced)



$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle}$$

S: messengers which feels SUSY breaking, with SM gauge couplings.

$F_S \approx (\Lambda_S$ = SUSY breaking scale$)^2$ ⇒ SUSY breaking order parameter.

$\langle S \rangle$ mass of the messengers

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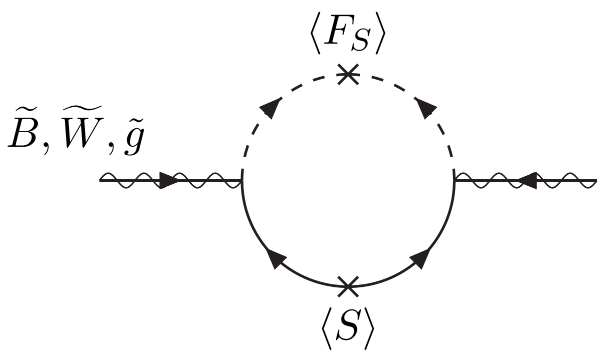

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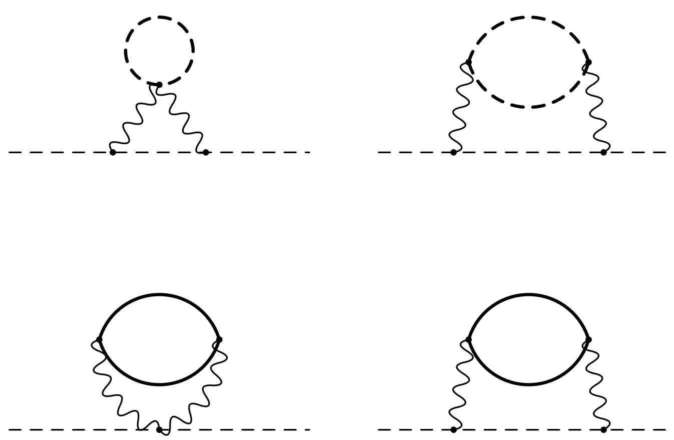

+ ....

$$m^2_{\rm scalar} = \left(\frac{\alpha}{4\pi}\right)^2 M_S^2$$

Gauge mediation

$$M_a = \frac{\alpha_a}{4\pi} M_S, \quad M_S = \frac{\langle F_S \rangle}{\langle S \rangle} \qquad\qquad m^2_{\rm scalar} = \left(\frac{\alpha}{4\pi}\right)^2 M_S^2$$

- $M_a \sim m_{scalar}$
- $M_S \sim$ 10 TeV $\Rightarrow M_a \sim m_{scalar} \sim$ TeV.
- Gravity mediation (also there), but subdominant if $F_S \approx (\Lambda_S)^2 \ll (10^{11}\ \text{GeV})^2$.
- Gauge couplings, just like QED, can be flavor diagonal!!

Gravitino LSP

- Gravitino does not have gauge interactions. Its' mass is still determined by gauge mediation. Gravitino is the LSP.

$$m_{3/2} \sim \frac{F_S}{M_{\rm Pl}} \ll M_{\rm gaugino,\ squark...}$$

- MSSM "LSP", such as a neutralino would be NLSP.

- NLSP decaying into gravitino
  - Could be long lived on collider time scale.

$$\Gamma(\widetilde{N}_1 \to \gamma \widetilde{G}) = 2 \times 10^{-3}\, \kappa_{1\gamma} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}}\right)^5 \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}}\right)^{-4} \text{eV}$$

$$d = 9.9 \times 10^{-3} \frac{1}{\kappa_{1\gamma}} (E^2/m^2_{\widetilde{N}_1} - 1)^{1/2} \left(\frac{m_{\widetilde{N}_1}}{100 \text{ GeV}}\right)^{-5} \left(\frac{\sqrt{\langle F \rangle}}{100 \text{ TeV}}\right)^4 \text{cm}$$

Comments

- Typically assumed bino NLSP, with decay bino⇒photon+gravitino. But, this is not necessary.

  Any superpartner could be NLSP.

  General gauge mediation: Meade, Seiberg, Shih

- No flavor problem!

- Can be low scale, decoupled from unknown high scale physics (string compactification, etc.).

Comments

- Have to assume a more special structure.
  - Messenger sector feels SUSY breaking, also have SM gauge couplings.
  - Gauge coupling unification now needs to be arranged.
- Light Gravitino can not account for dark matter.
  - Other cosmological problems: light moduli...
- μ, B_μ problem.
- Having trouble with giving 125 GeV Higgs mass
  - Need additional structure.

Trying to be smart

- Many mediation mechanisms:
  - Anormaly mediation.
  - Gaugino mediation.
  - Mirage, R-symmetric, μ-driven, U(1)′, ...
- Many challenge: flavor (CP) problem, naturalness, experimental constraints.
- None of them is perfect. Some are getting quite complicated.
- Do we need to be smart? Are we lucky? Experiment will tell.

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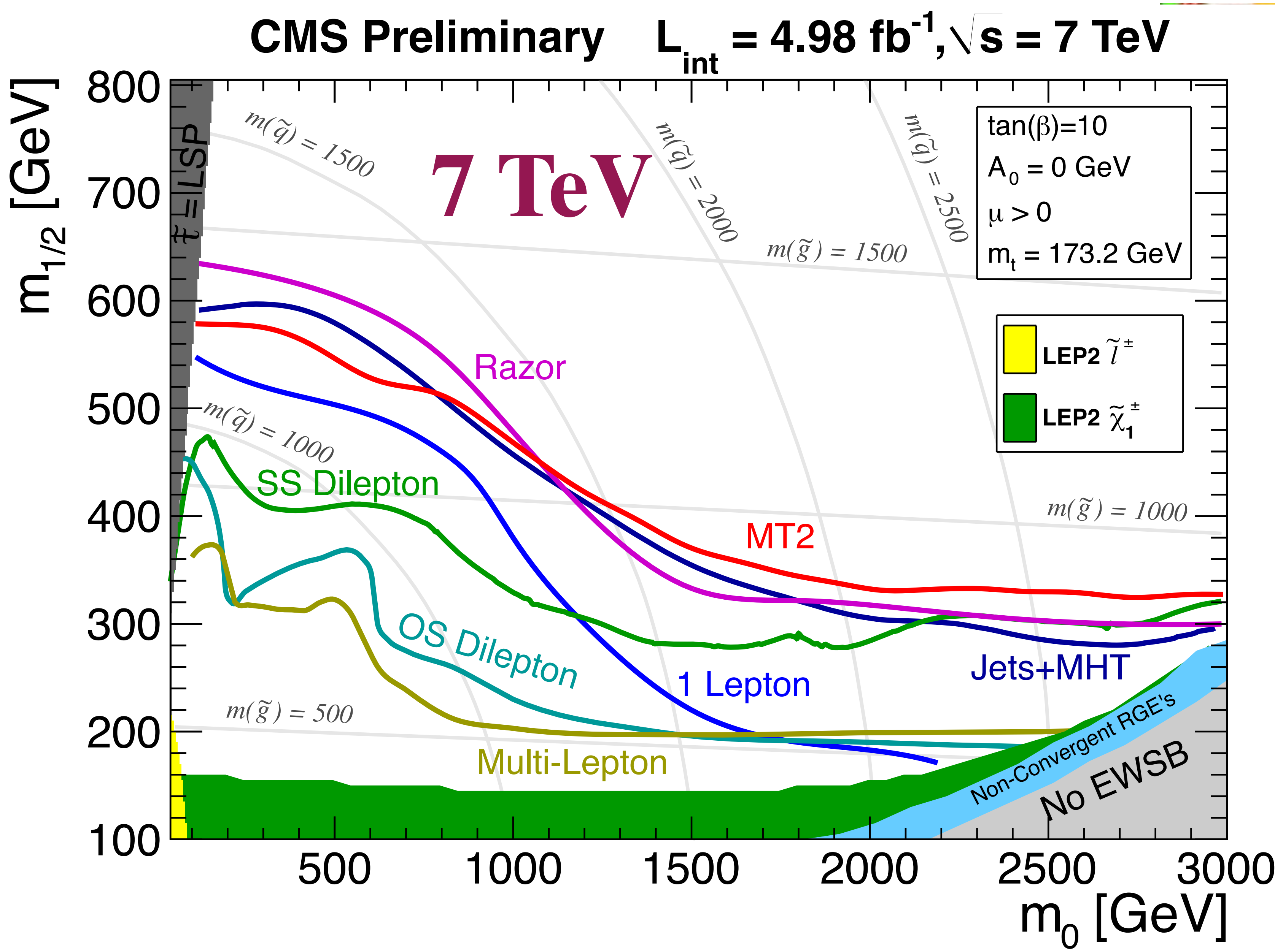
Is Supersymmetry Dead?

The grand scheme, a stepping stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

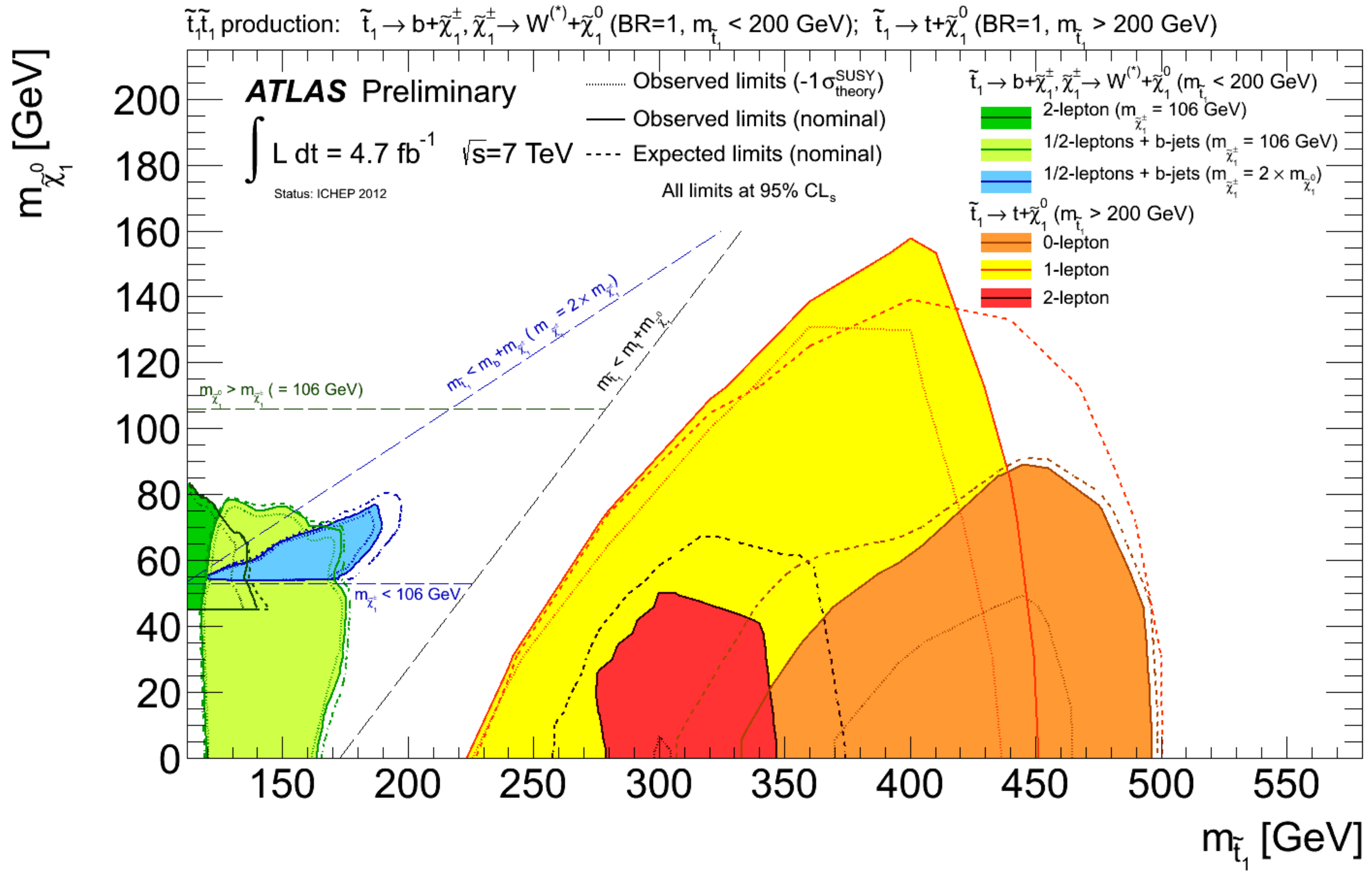
By Davide Castelvecchi | April 25, 2012 | 32

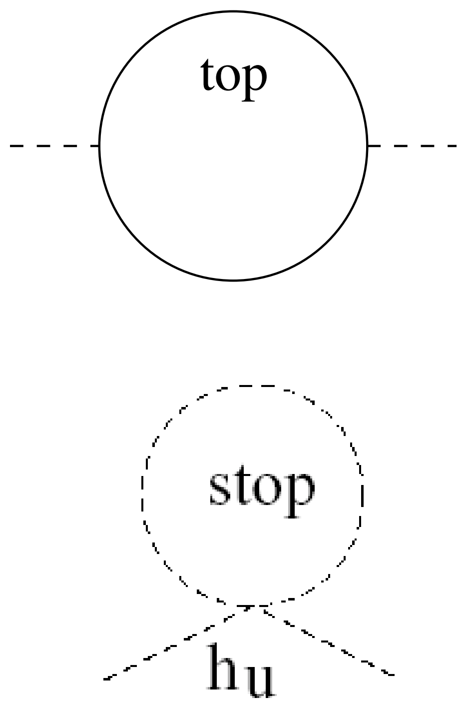
LHC is setting stronger constraints



- Too strong already? No. After all, we can certainly have superpartners at TeV scale, and the theory is reasonably natural.

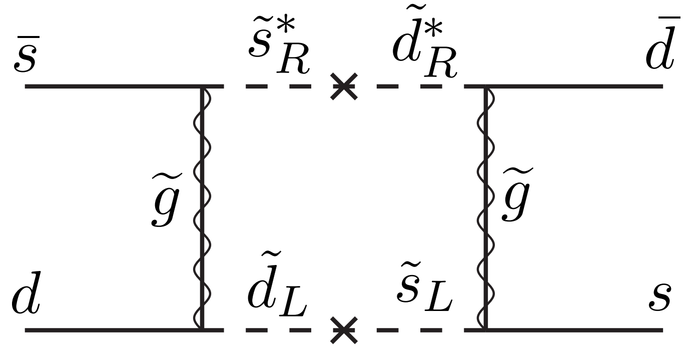
Naturalness in trouble?





- Stop limit is not too strong yet.
  - Needs to be less than TeV for the theory to be natural (or slightly tuned).

What do we expect after all.



Kaon mixing

$$\frac{|\mathrm{Re}[m^2_{\tilde{s}_R^*\tilde{d}_R} m^2_{\tilde{s}_L^*\tilde{d}_L}]|^{1/2}}{m^2_{\tilde{q}}} < \left(\frac{m_{\tilde{q}}}{1000\ \mathrm{GeV}}\right) \times \begin{cases} 0.0016 & \text{for } m_{\tilde{g}} = 0.5 m_{\tilde{q}}, \\ 0.0020 & \text{for } m_{\tilde{g}} = m_{\tilde{q}}, \\ 0.0026 & \text{for } m_{\tilde{g}} = 2 m_{\tilde{q}}. \end{cases}$$

- SUSY flavor problem (last century).
- Scalars probably would be heavy, 10s - 100s TeV.
- Yes, we can be smart. But does nature care?
- Not surprising we have not seen the scalar superpartners.

Heavy scalars

- More fine tuned. Yes. 10^{2-4} more tuned than TeV partners.
  - Still solves most of the naturalness problem (10^{32}).
- On the other hand
  - Simplest solution to the flavor (CP) problems.
  - Higgs mass.

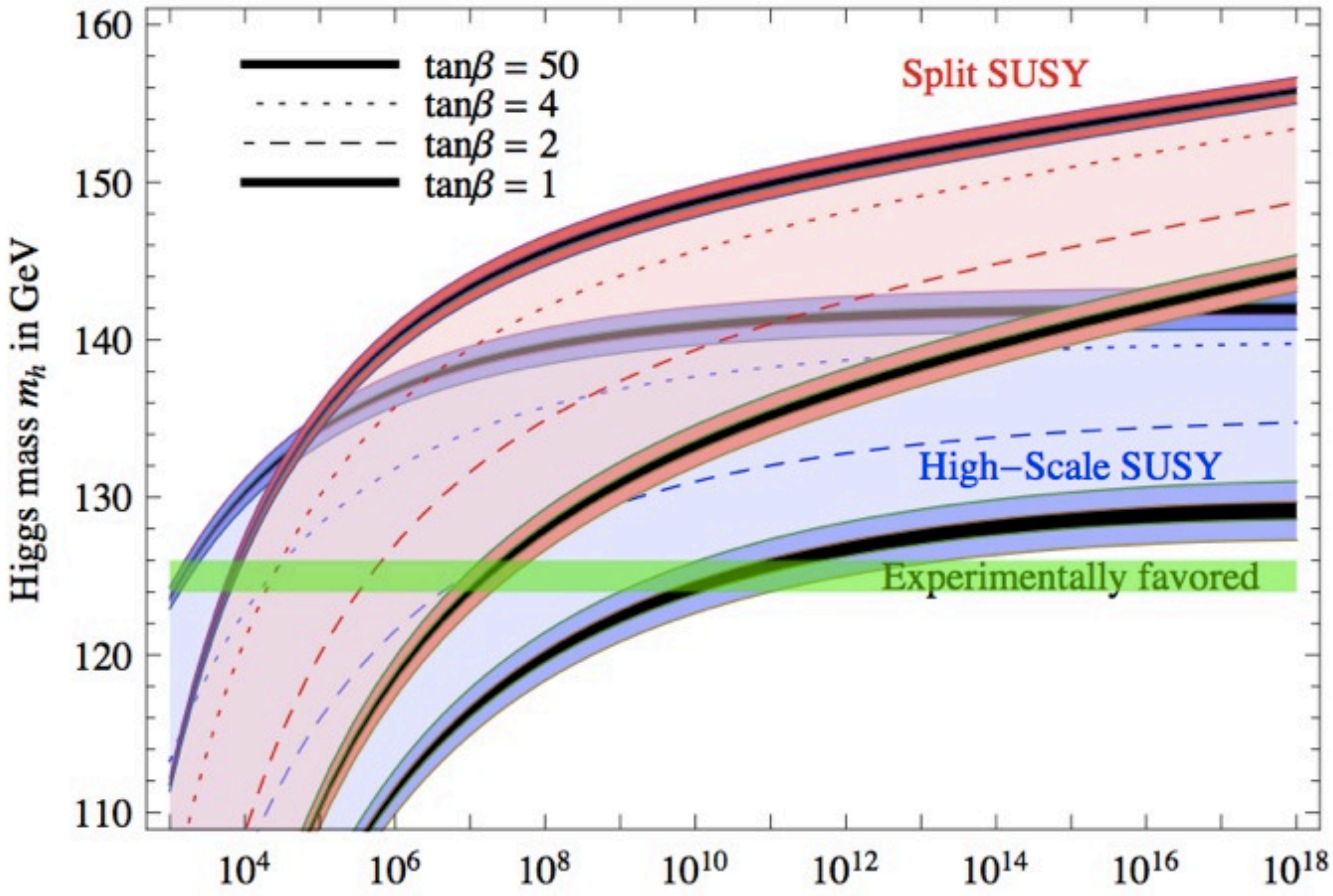
SUSY.

- Minimal Supersymmetric Standard Model (MSSM)
  - $$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$
    $$\phi \to \frac{1}{\sqrt{2}}(v + h(x)) \quad m_h = \sqrt{2\lambda}v = \sqrt{\lambda}\left(2\sqrt{2}\frac{m_W}{g_W}\right)$$
  - In MSSM, at leading order λ is fixed by SM electroweak gauge couplings

$$m_h^2 = m_Z^2 \cos^2 2\beta + \text{loop} \qquad \text{loop} \propto \log\left(\frac{M_{\text{SUSY}}}{M_{\text{top}}}\right)$$

☐ Need $M_{SUSY} \gg M_{top}$ since m_h(125 GeV) > m_Z(90 GeV)

M_h=125 GeV in MSSM



M_{SUSY} (GeV)

Giudice, Strumia, 2011

- Is heavy scalar reasonable? Maybe.

Many recent models: Acharya, et al. 07; Everett, et. al. 08;
Langacker et. al. 07; Heckman et al. 08; Sundrum 09; Barbieri et. al., 10.....

So, what's left for the LHC?

- Perhaps the gauginos are light.
  - It is quite generic to expect fermions are lighter than the scalars. There is additional protection for the fermion masses (that's why it is natural).
  - Many recent models:
  - Langacker, Paz, LTW, Yavin, 0710.1632
  - Verlinde, LTW, Wijnholt, Yavin, 0711.3214
  - Acharya, Bobkov, Kane, Kumar, 0801.0478
  - Nakamura, Okumura, Yamaguchi, 0803.3725
  - Everett, Kim, Ouyang, Zurek, 0806.2330
  - Hackman, Vafa, 0809.3452
  - Sundrum, 0909.5430
  - Barbieri, Bertuzzo, Farina, Lodone, Rappadopulo, 1004.2256 ....

A promising scenario.

Heavy squarks

$m_{\tilde{t},\tilde{b}} < m_{\tilde{u},\tilde{d}}$

$\tilde{u}, \ \tilde{d}, \ \ldots$

$\tilde{t}, \ \tilde{b}$

10s - 100s TeV

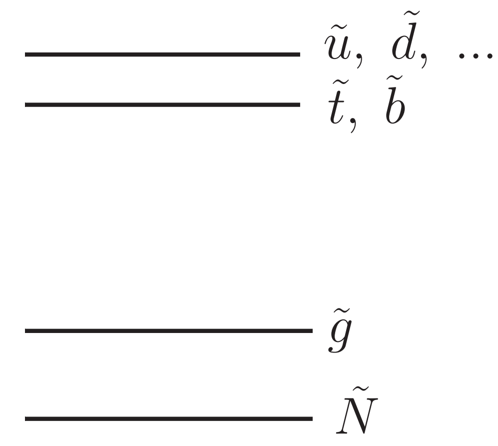
Light gaugino

$\tilde{g}$

$\tilde{N} \quad \tilde{C}^{\pm}$

100s GeV - TeV

3rd vs first two generations

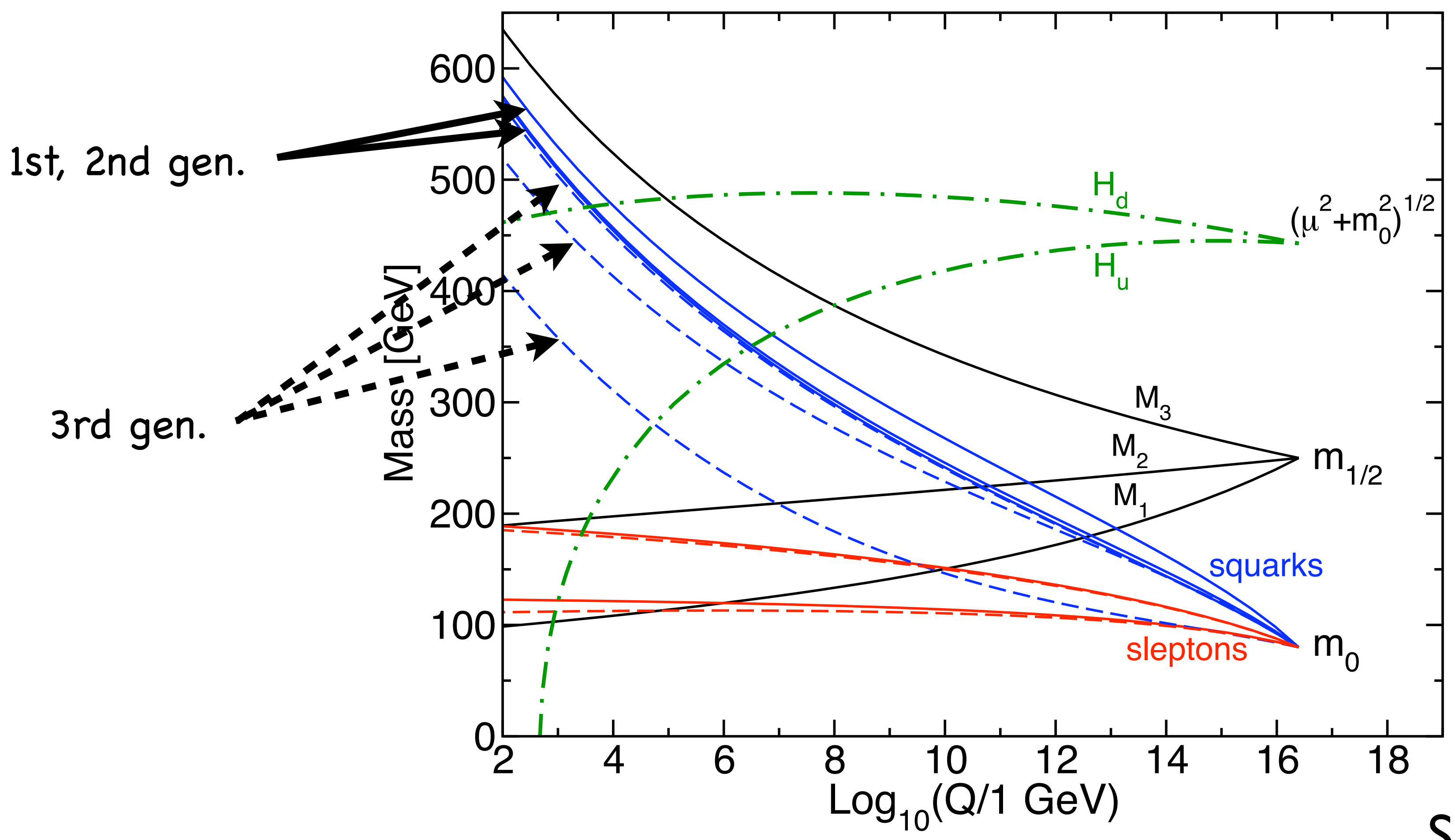


- RGE.

$$\frac{dm^2_{\tilde{t},\tilde{b}}}{dt} = \frac{1}{16\pi^2}|y_{t,b}|^2(m^2_{H_{u,d}} + m^2_{Q_3} + m^2_{\tilde{t}_R,\tilde{b}_R}) + ...$$

$t = \log(Q)$

same as 1, 2 gen.



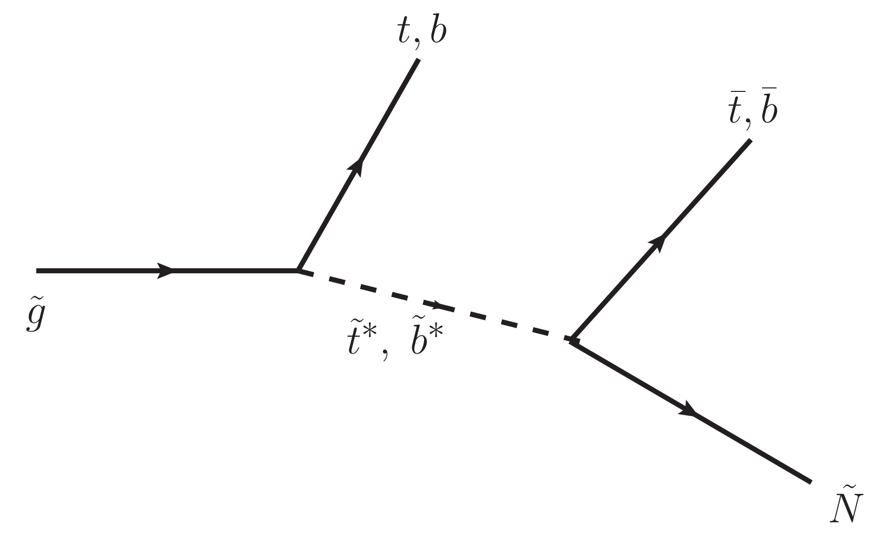
S. Martin

A promising, and complicated, scenario.

Kane, Kuflik, Lu and LTW, 1101.1963

$> \text{TeV}$ — $\tilde{u},\ \tilde{d},\ \ldots$; $\tilde{t},\ \tilde{b}$

$\sim 100\text{s GeV}$ — $\tilde{g}$; $\tilde{N}\quad \tilde{C}^{\pm}$



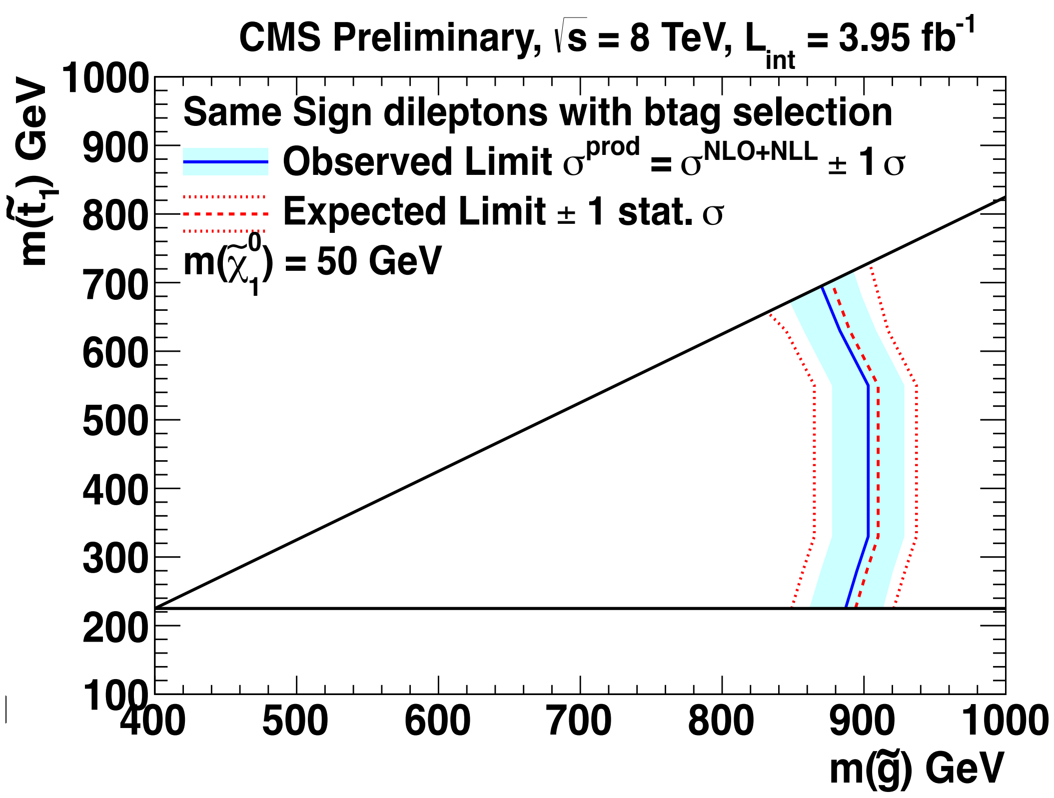
The Dominant channel

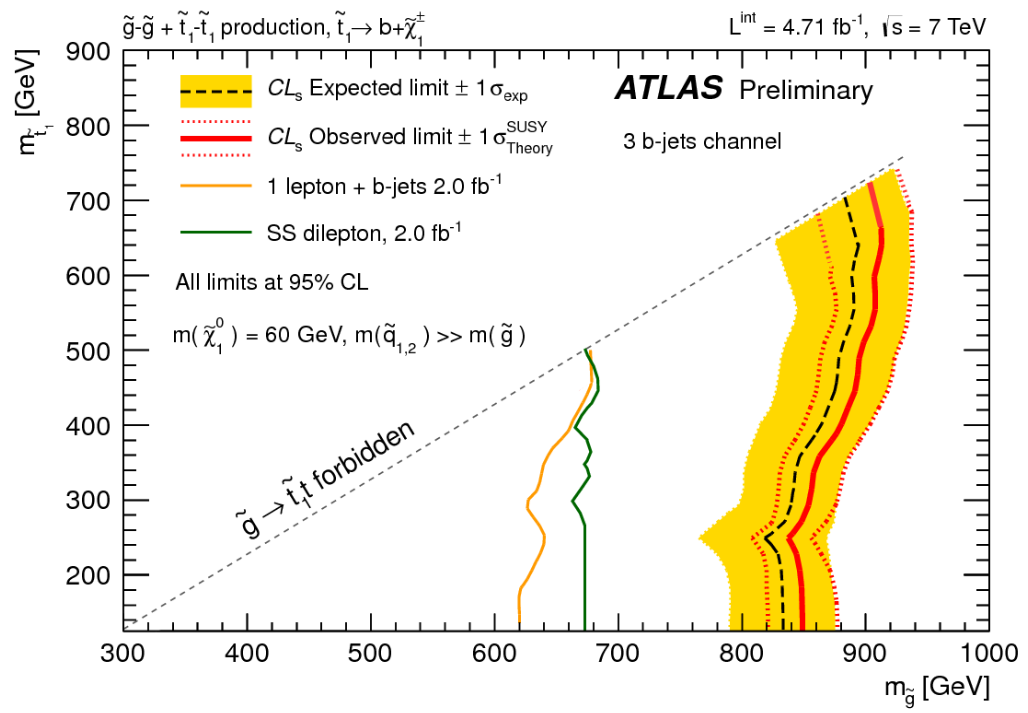
$$p\,p \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}(\text{or } t\bar{t}b\bar{b},\ t\bar{t}t\bar{b}\ \ldots)$$

$$\tilde{g} \to t\bar{t}(b\bar{b}) + \tilde{N},\ \text{or}\ \ t\bar{b} + \tilde{C}^- \quad t \to b\ell^+\nu$$

- Multiple b, multiple lepton final state.
  - Good early discovery potential.
  - Challenging to interpret: top reconstruction difficult.

Search is on:


CMS Preliminary, √s = 8 TeV, L_int = 3.95 fb^-1
Same Sign dileptons with btag selection
Observed Limit σ^prod = σ^NLO+NLL ± 1 σ
Expected Limit ± 1 stat. σ
m(χ̃_1^0) = 50 GeV
m(t̃_1) GeV
m(g̃) GeV


g̃-g̃ + t̃_1-t̃_1 production, t̃_1→ b+χ̃_1^±
L^int = 4.71 fb^-1, √s = 7 TeV
ATLAS Preliminary
3 b-jets channel
CL_s Expected limit ± 1 σ_exp
CL_s Observed limit ± 1 σ^SUSY_Theory
1 lepton + b-jets 2.0 fb^-1
SS dilepton, 2.0 fb^-1
All limits at 95% CL
m(χ̃_1^0) = 60 GeV, m(q̃_1,2) >> m(g̃)
g̃ → t̃_1t forbidden
m_t̃1 [GeV]
m_g̃ [GeV]

Alternative SUSY

- Kill the missing energy
  - Controlled R-parity violation.
  - Stealth SUSY. (squeezing the spectrum).

J. Fan, M. Reece, J. Ruderman

- Alter some standard SUSY channels
  - R-symmetric ⇒ no same sign dilepton, different jet + MET

Kribs, Martin, ...

Large extra-dimension

Arkani-Hamed, Dimopoulos, Dvali.

See a good recent review in TASI lecture by Hsin-Chia Cheng

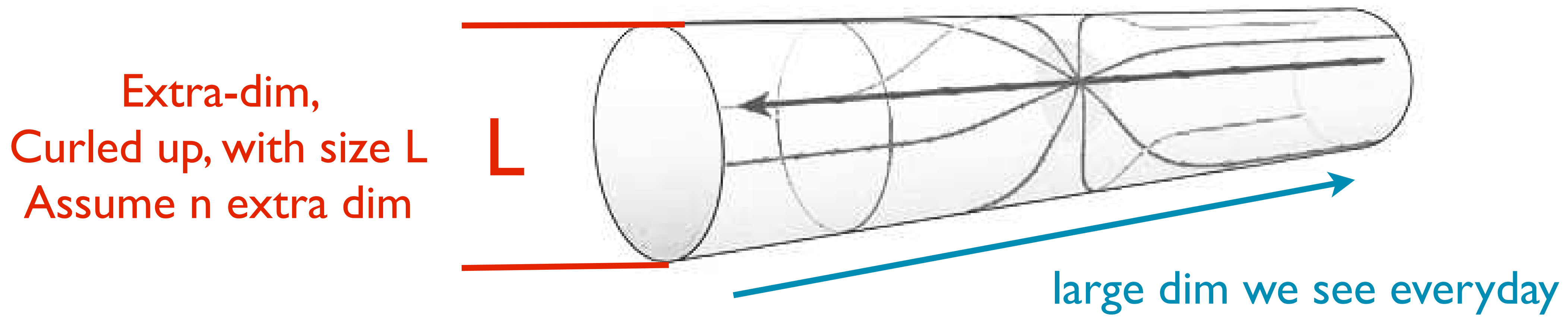
Another approach to naturalness

- Remember that the problem is the disparity between the fundamental scale, M_{Pl} (quantum gravity), and the scale of weak interaction, m_W.

- What if there is no difference big between the quantum gravity scale and the weak scale to begin with?
  - large M_{Pl}, or gravity being very weak, needs to be an illusion.

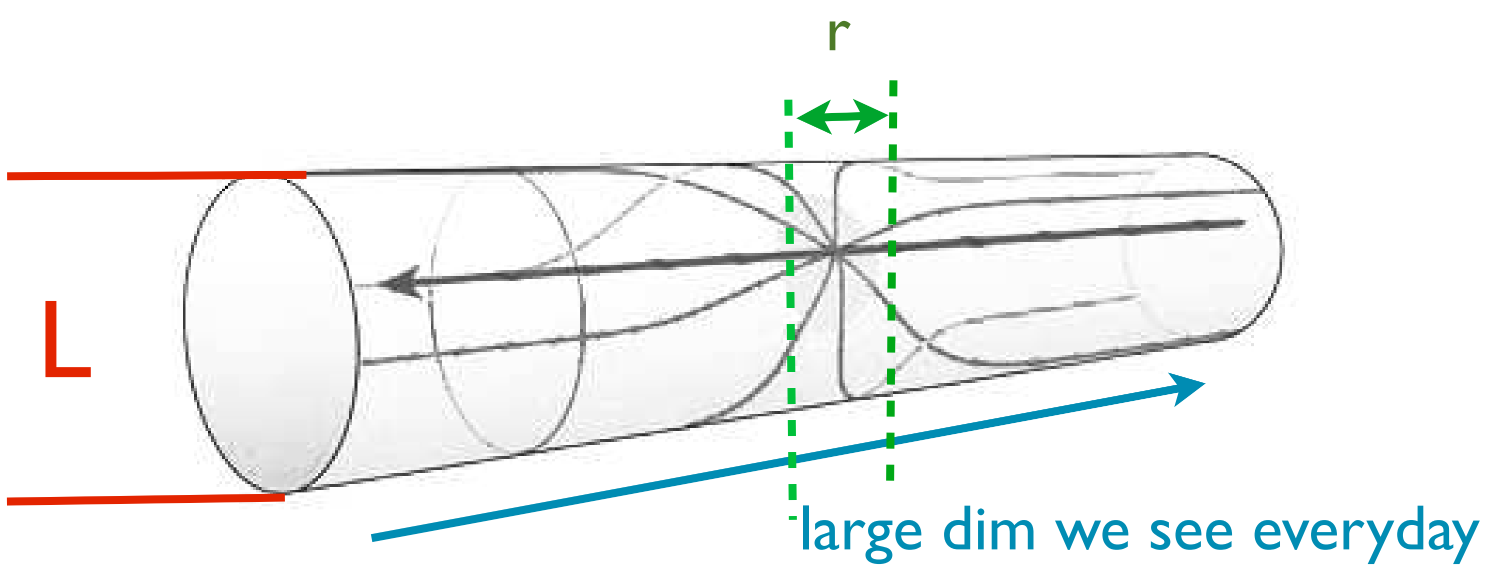
- How is the possible?

Gravity with extra-dimension



Gravity with extra-dimension

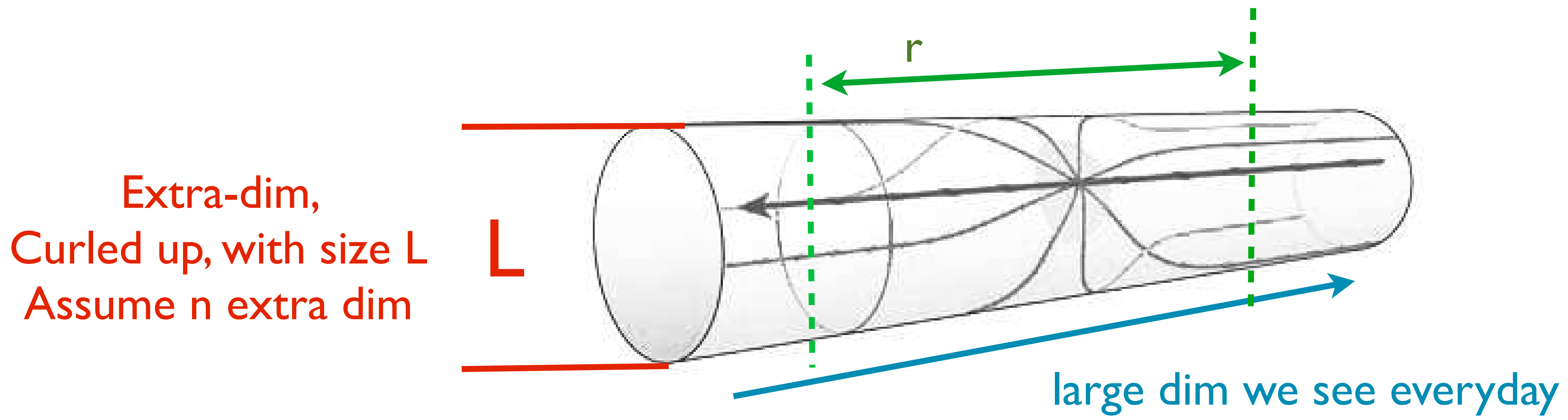
Extra-dim,
Curled up, with size L
Assume n extra dim



$$F(r) \sim \frac{1}{M_{pl(4+n)}^{n+2}} \frac{m_1 m_2}{r^{n+2}}, \quad \text{for } r \ll L$$

See full n+4 dimsions
n+4 dim Gauss' law

Gravity with extra-dimension



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Force line cannot spread in extra dim
normal 4-dim Gauss' law

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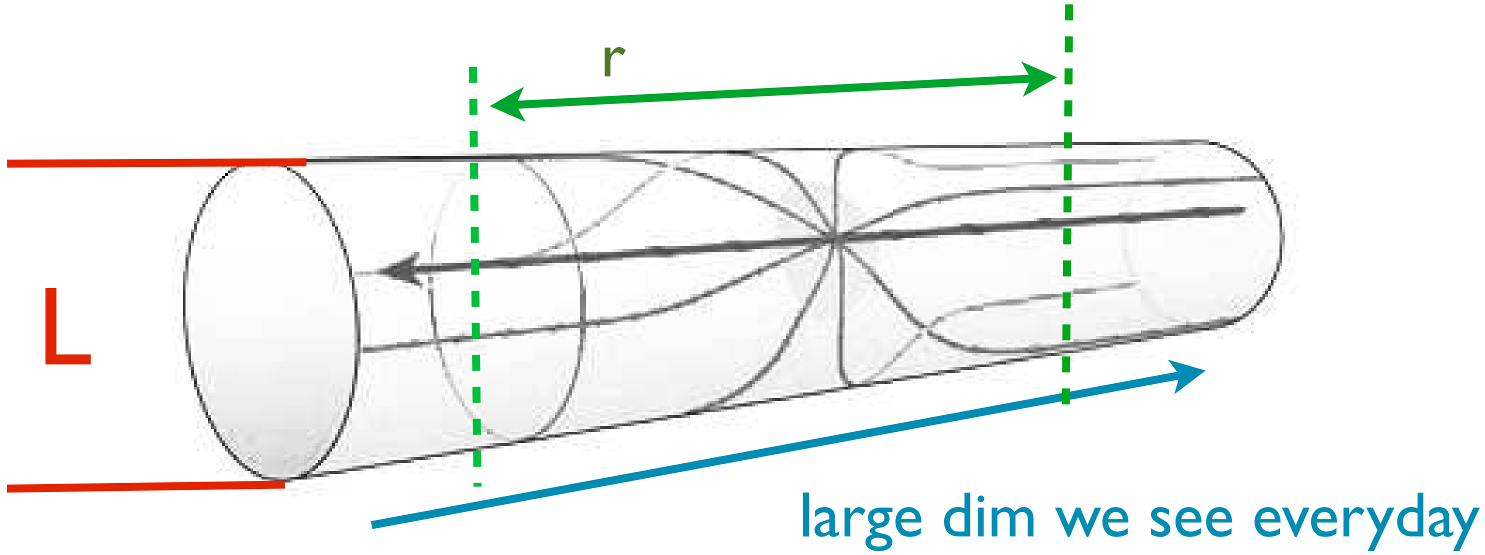

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At long distances, one can reproduce 4-D gravity if we idenify

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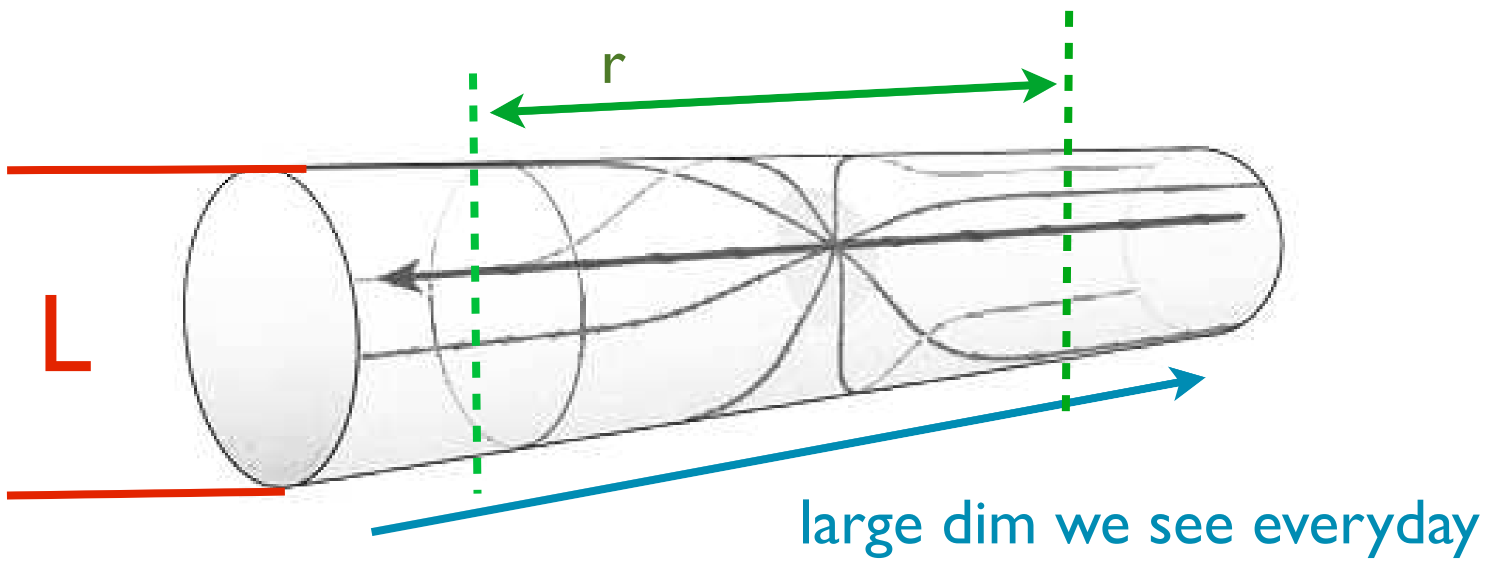

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large 4D Planck scale
weak gravity

Gravity with extra-dimension

Extra-dim,
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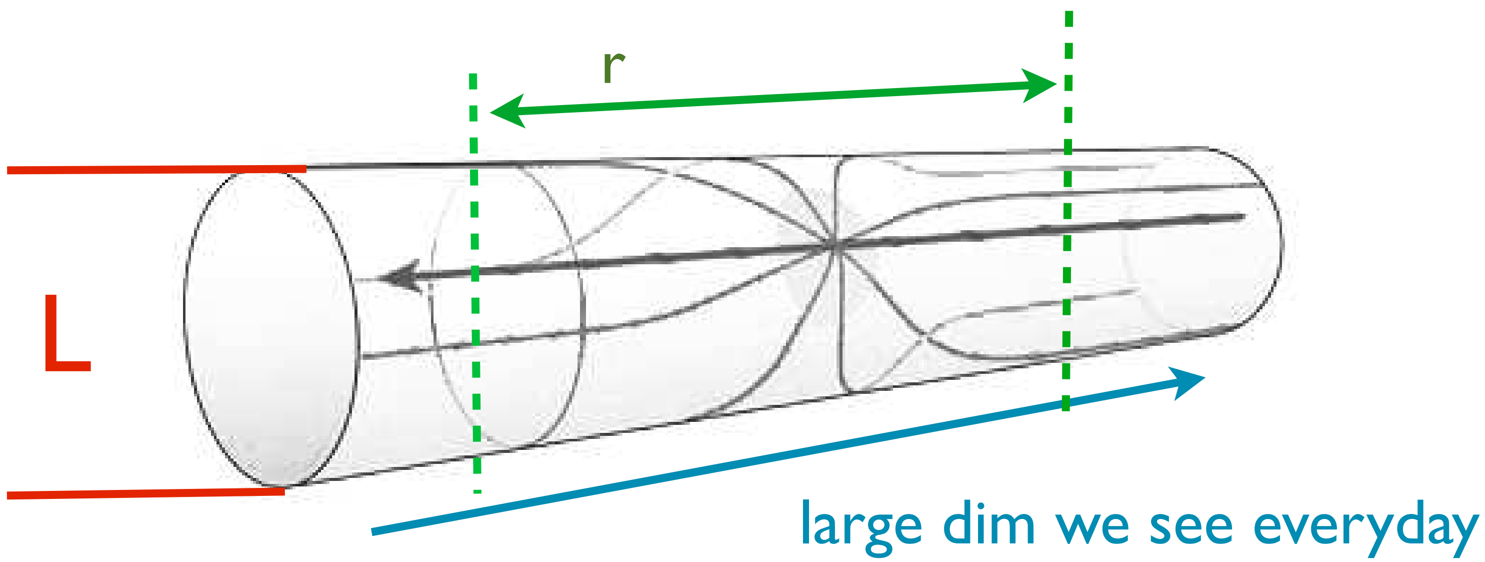

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large 4D Planck scale
weak gravity

4+n Planck scale
fundamental quantum gravity scale

Large extra dimension

No large separation with weak scale, want to choose

$$M_{pl(4+n)} \sim \text{ TeV}$$

$$\begin{aligned} n &= 1 \Rightarrow L \sim 10^{15} \text{ cm } (> 1 \text{ AU}), \text{ obviously ruled out,} \\ n &= 2 \Rightarrow L \sim 1 \text{ mm }, \text{ allowed in 1998, but current bound } L < 200\,\mu\text{m} \\ n &= 3 \Rightarrow L \sim 10^{-6} \text{ cm }. \end{aligned}$$

Large extra dimension

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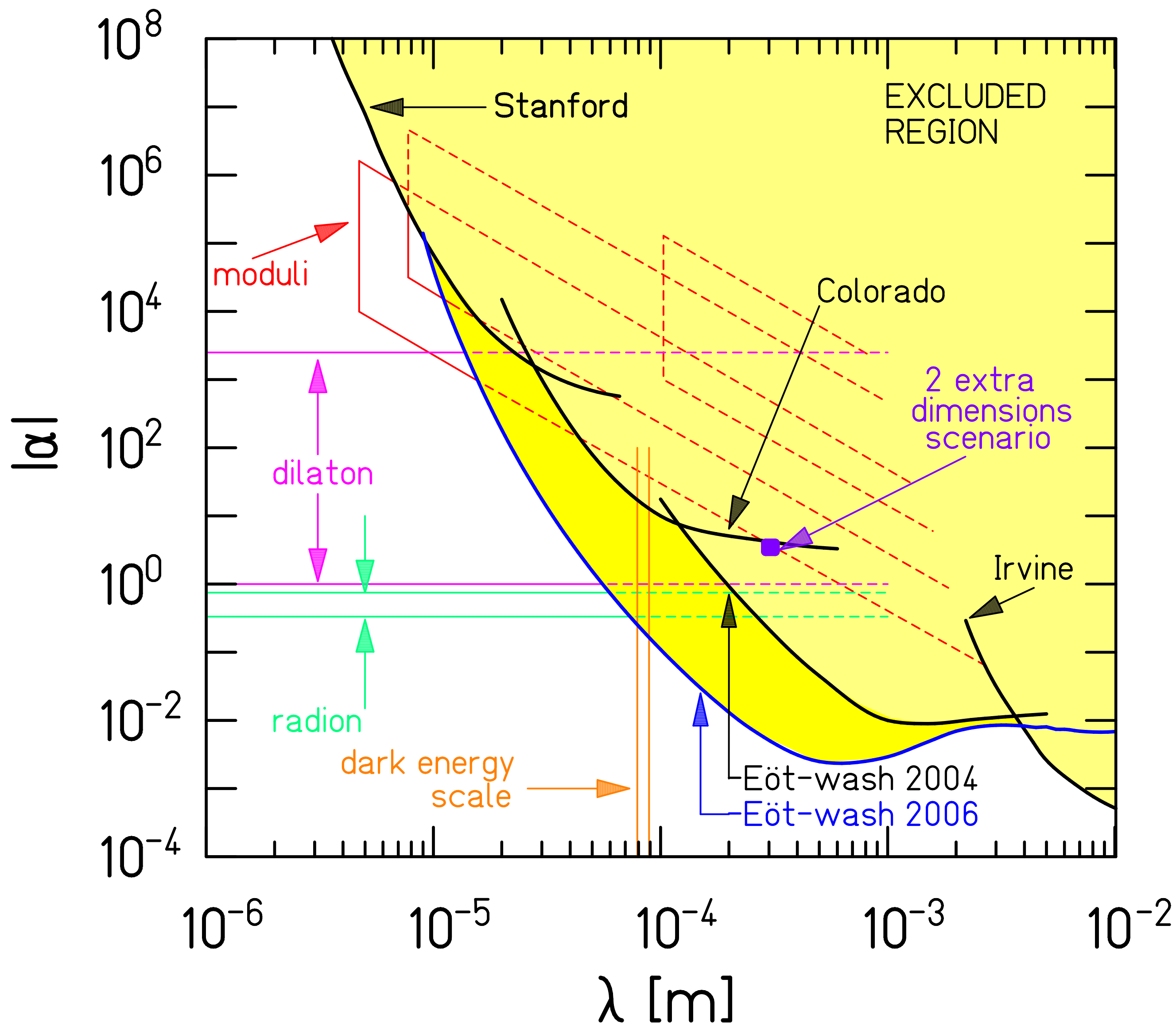
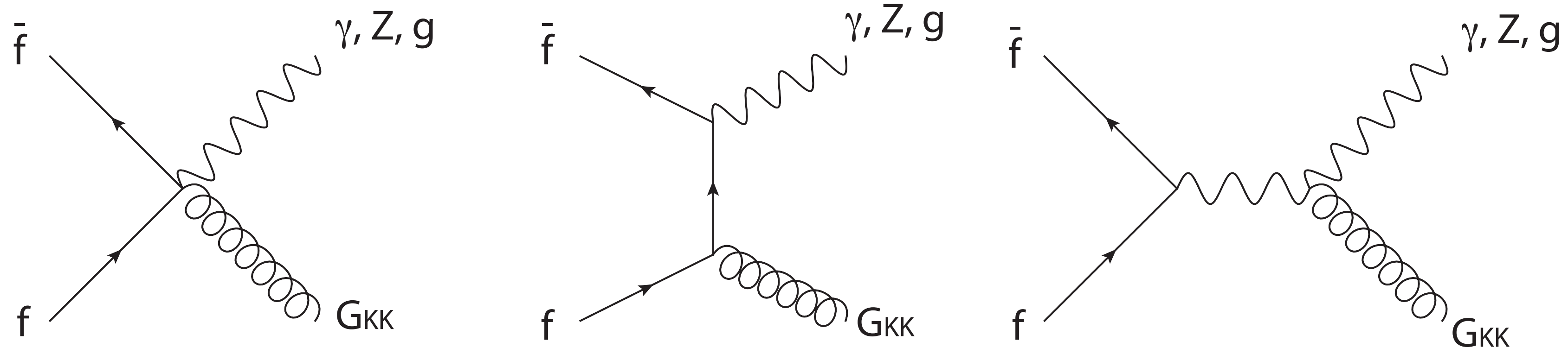
Precision test of gravity



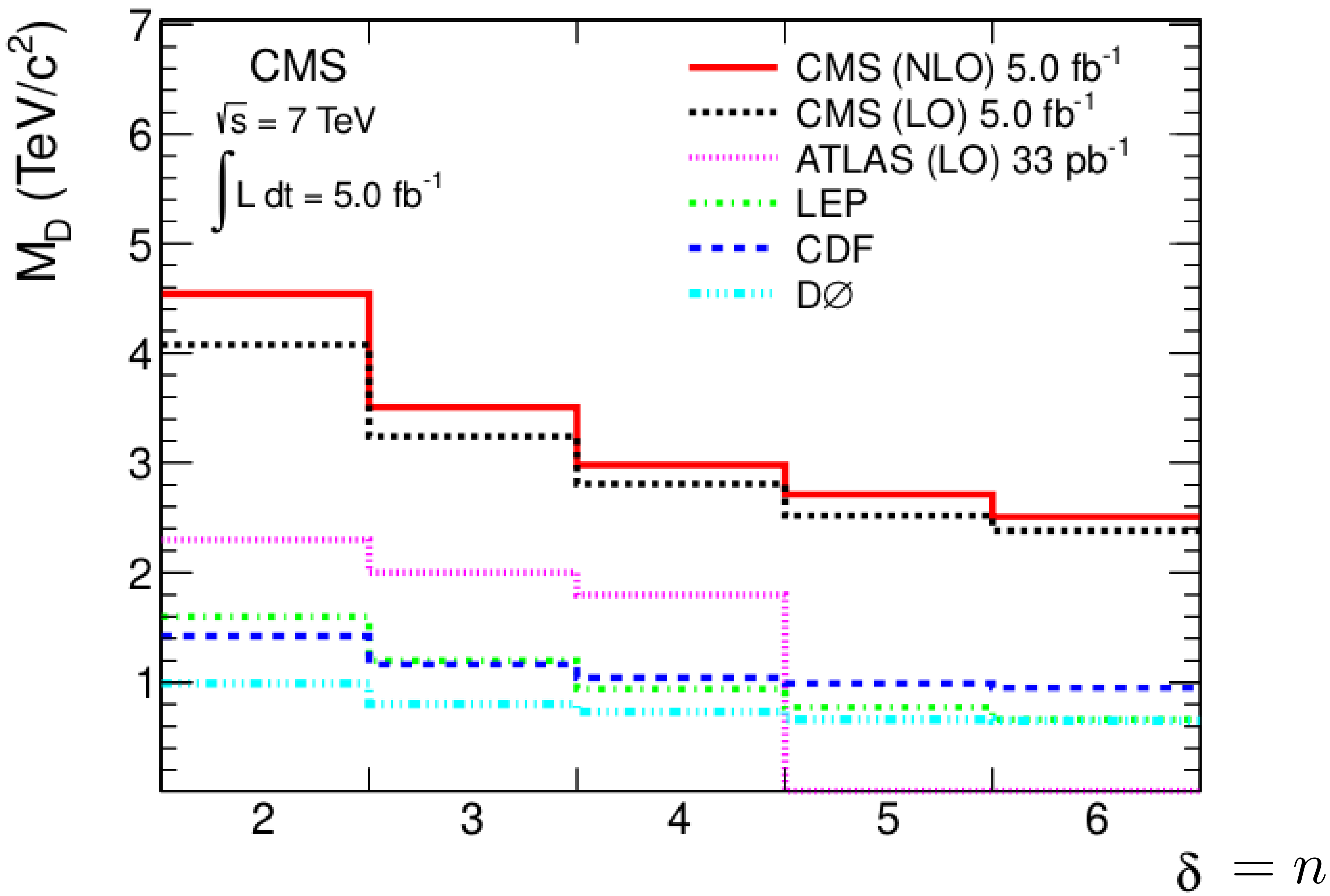
$$V(r) = -G_N \frac{m_1 m_2}{r} \left(1 + \alpha e^{-r/\lambda}\right)$$

Collider signals.



- Production of excitation of the graviton in the extra-dimension, KK-modes ⇒ missing energy
  - $m_{KK\text{-}graviton} \approx L^{-1}$ (like freq of vibration modes in a box of size L).
  - KK-graviton coupling $M_{pl(4+n)}^{-1} \approx TeV^{-1}$
  - Monojet, monophoton, Z, plus missing energy

Collider limits



More ambitious

- What can we expect if reach quantum gravity scale?
  - Make microscopic blackholes!
  - Microscopic blackholes will immediately evaporate (Hawking radiation).
  - "lighting up the LHC like a Christmas tree" (not yet).

Blackhole production

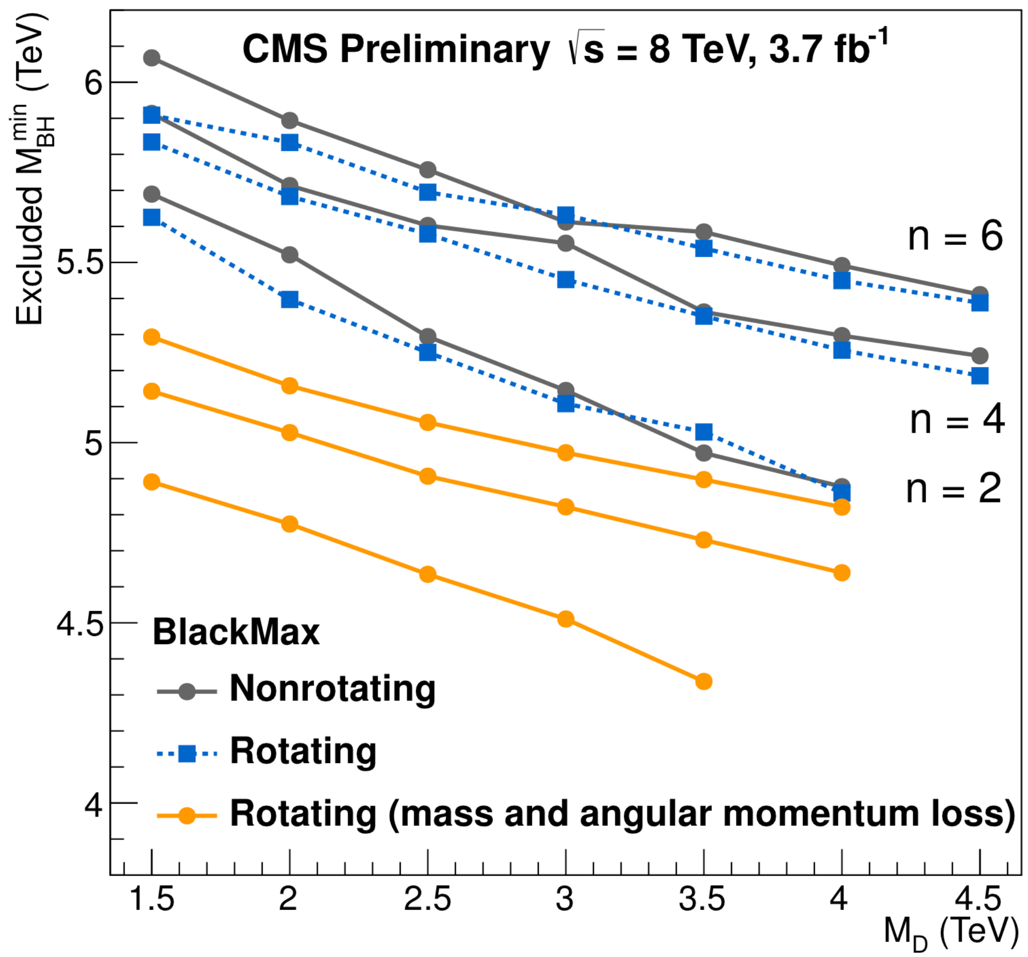
- Size of 4+n dimensional blackhole

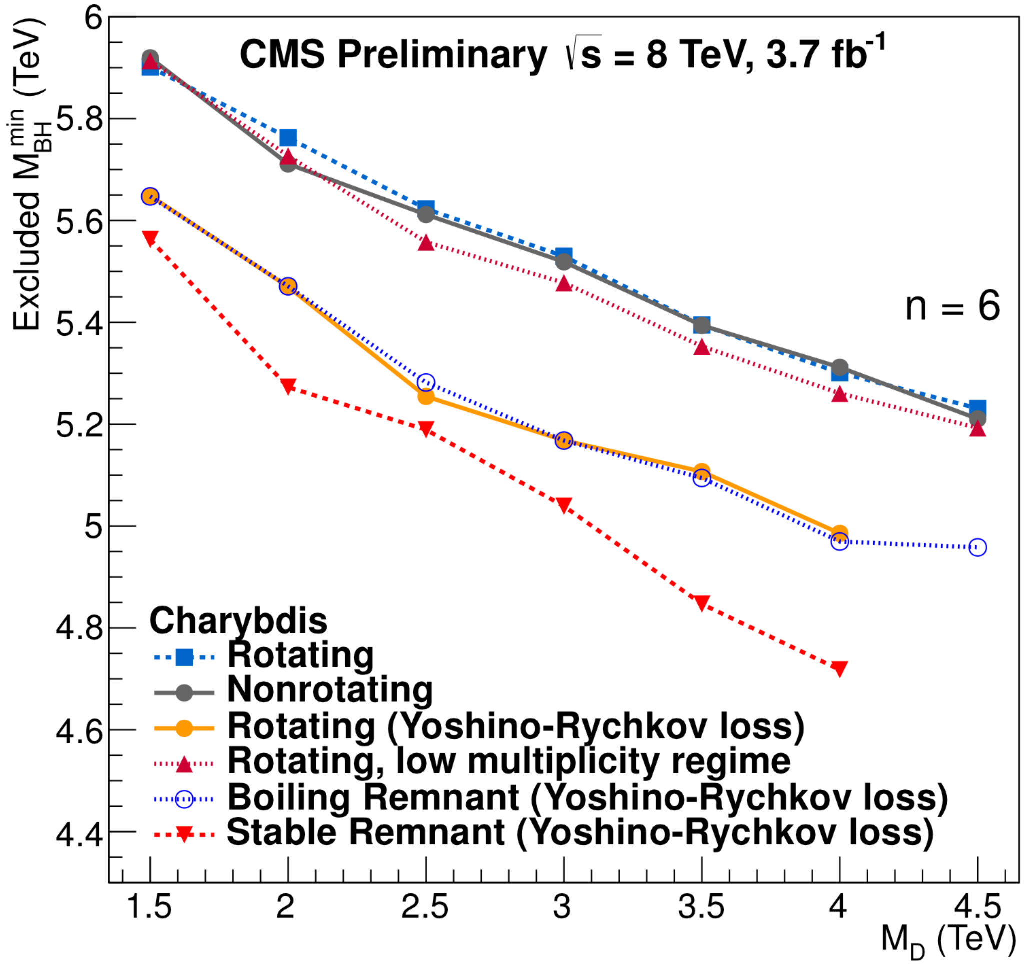
$$R_s \sim \frac{1}{M_{pl,4+n}} \left(\frac{M_{BH}}{M_{pl,4+n}} \right)^{\frac{1}{n+1}}$$

- Strongly coupled, geometrical cross section, sizable.

$$\sigma(M_{BH}) \approx \pi R_s^2 \sim \frac{1}{M_{pl,4+n}^2} \left(\frac{M_{BH}}{M_{pl,4+n}} \right)^{\frac{2}{n+2}} \qquad M_{BH} \sim \sqrt{\hat{s}}$$

Blackhole limits





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- All true. However,
  - This is new scenario in which the the naturalness problem could be solved.
  - Nothing cancels the divergences. Quantum gravity takes care of everything.
- Unlikely? Yes. But very exciting if it is true.
  - Like winning lottery.