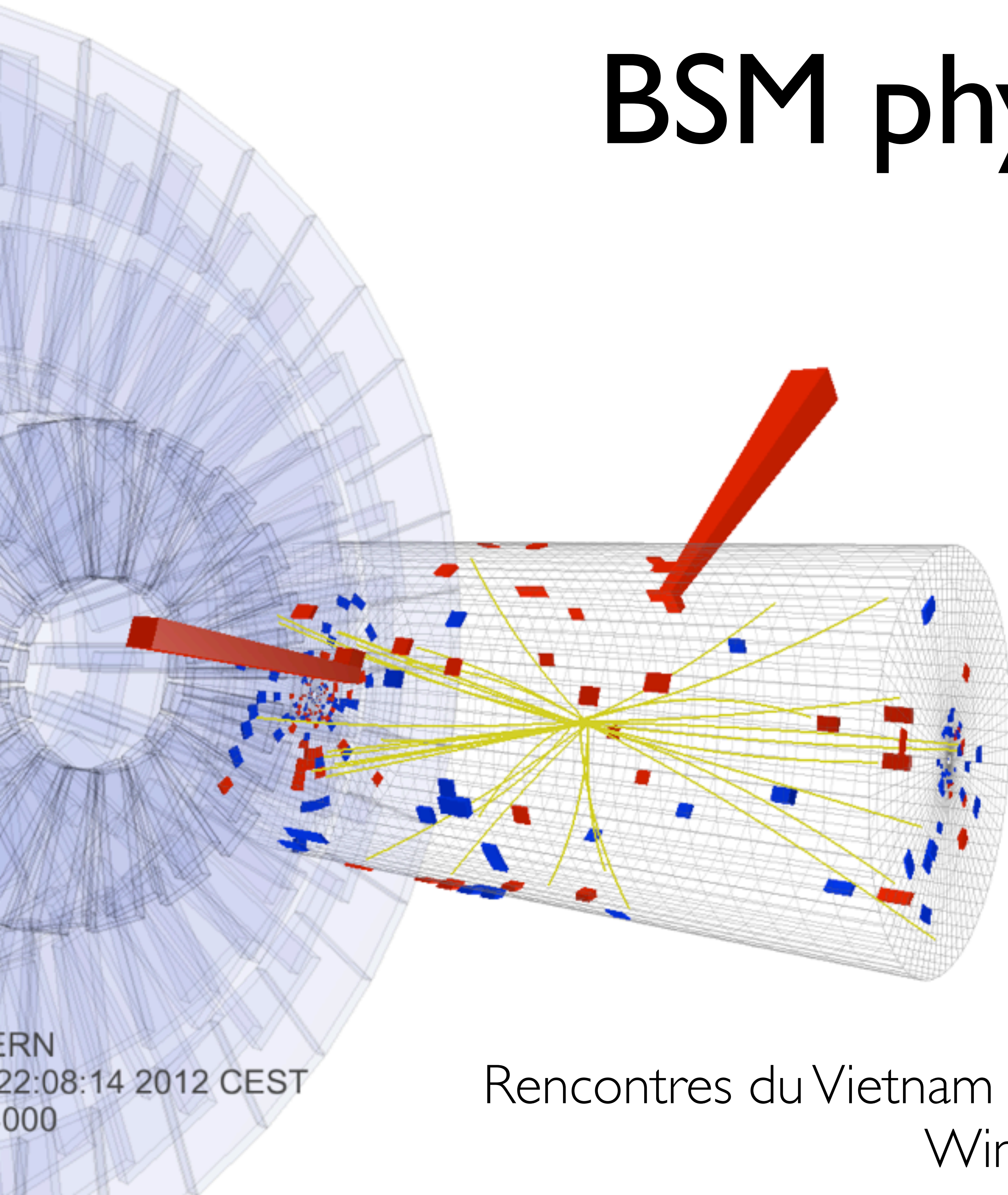
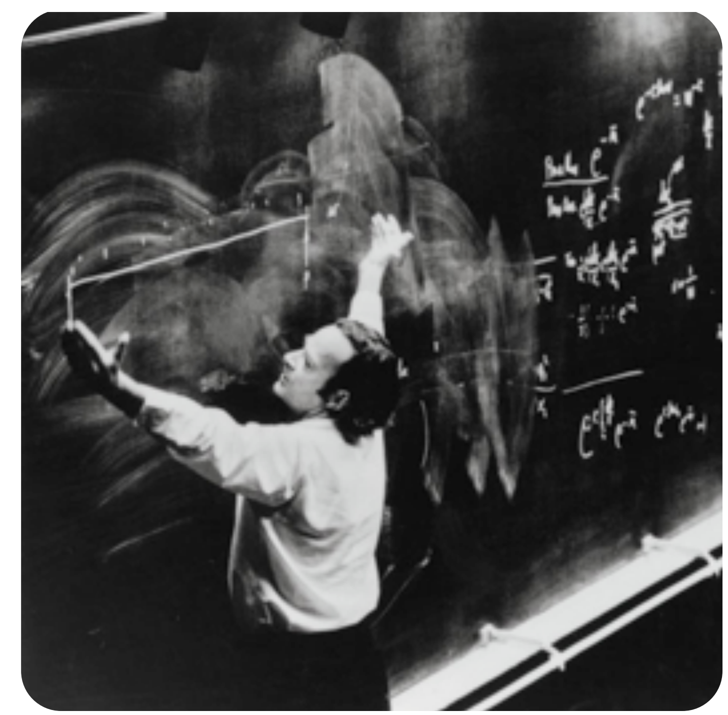
# BSM physics after LHC8

Andreas Weiler
(DESY)



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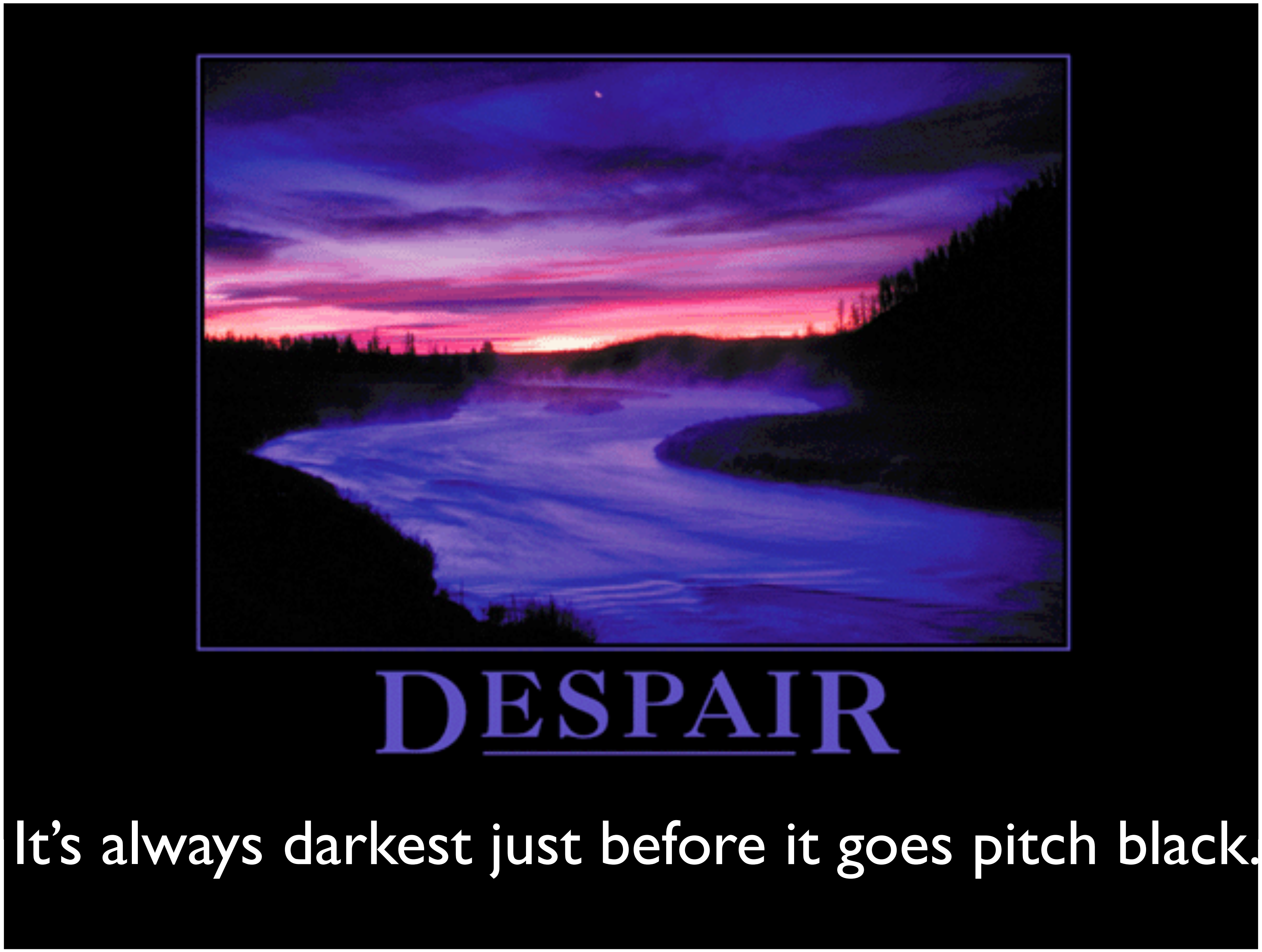
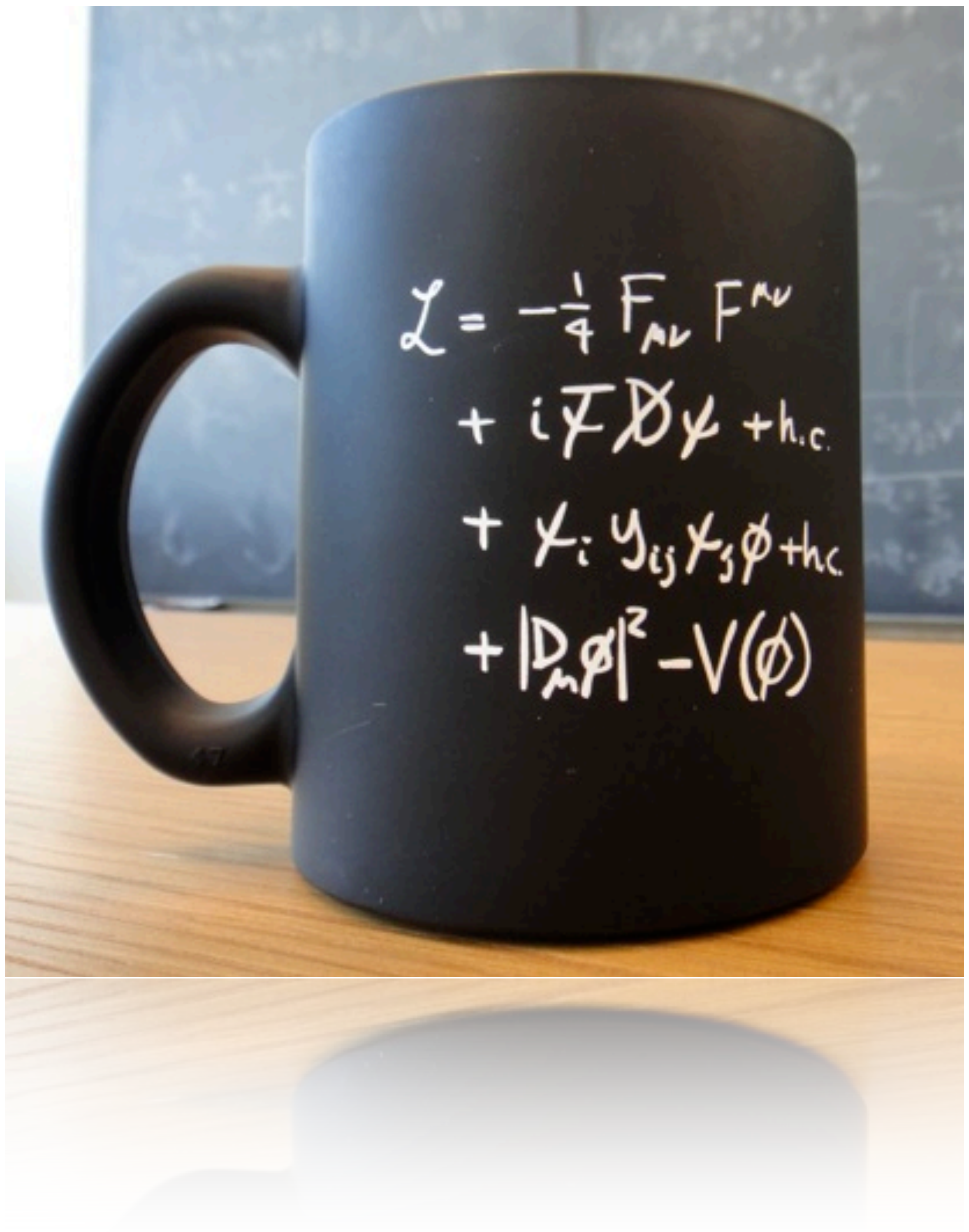
# De-motivation



# The SM rules




Agrees with all collider-based tests

Accidental symmetries of SM are fully observed (B,L)

Small breaking of global symmetries (flavor, $SU(2)_V$) measured as predicted

| broken symmetry | operators | scale$\Lambda$ |
|---|---|---|
| $B, L$ | $(QQQL)/\Lambda^2$ | $10^{13}$ TeV |
| flavor (1,2$^{\text{nd}}$ family), CP | $(\bar{d}s\bar{d}s)/\Lambda^2$ | 1000 TeV → $10^5$ TeV |
| flavor (2,3$^{\text{rd}}$ family) | $m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$ | 50 TeV |

Generic new physics must be at $\Lambda \gg \text{TeV}$

Flavor must be aligned with the SM,
or SM-like

# LHC BSM summary:

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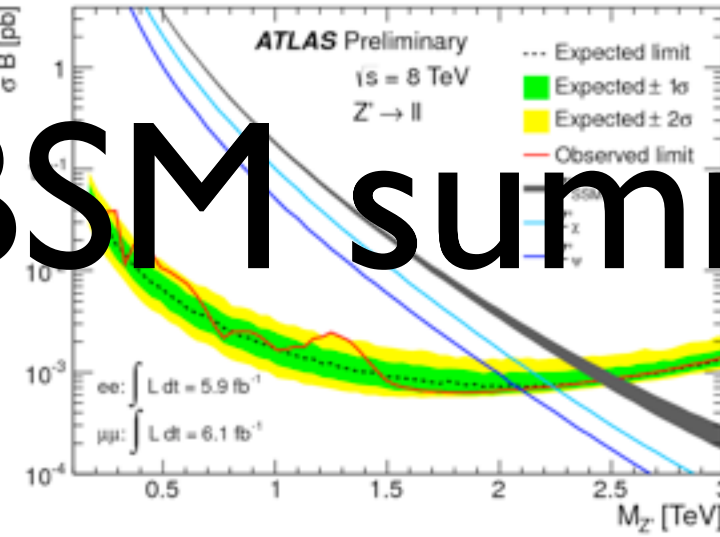

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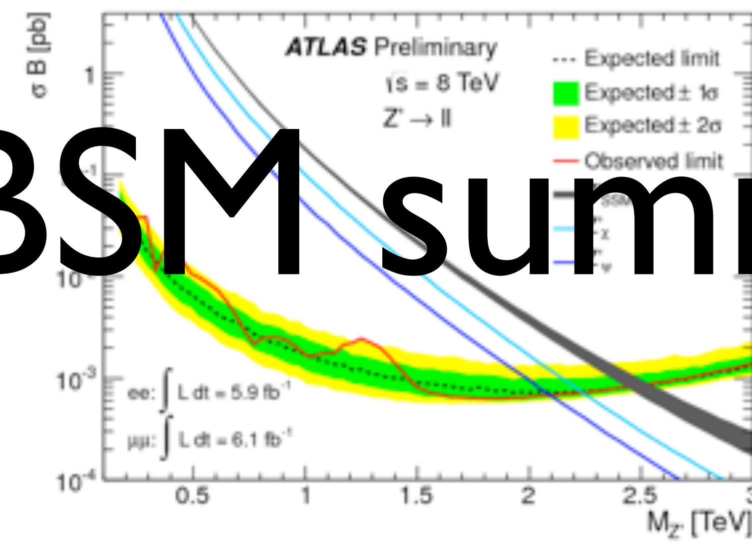


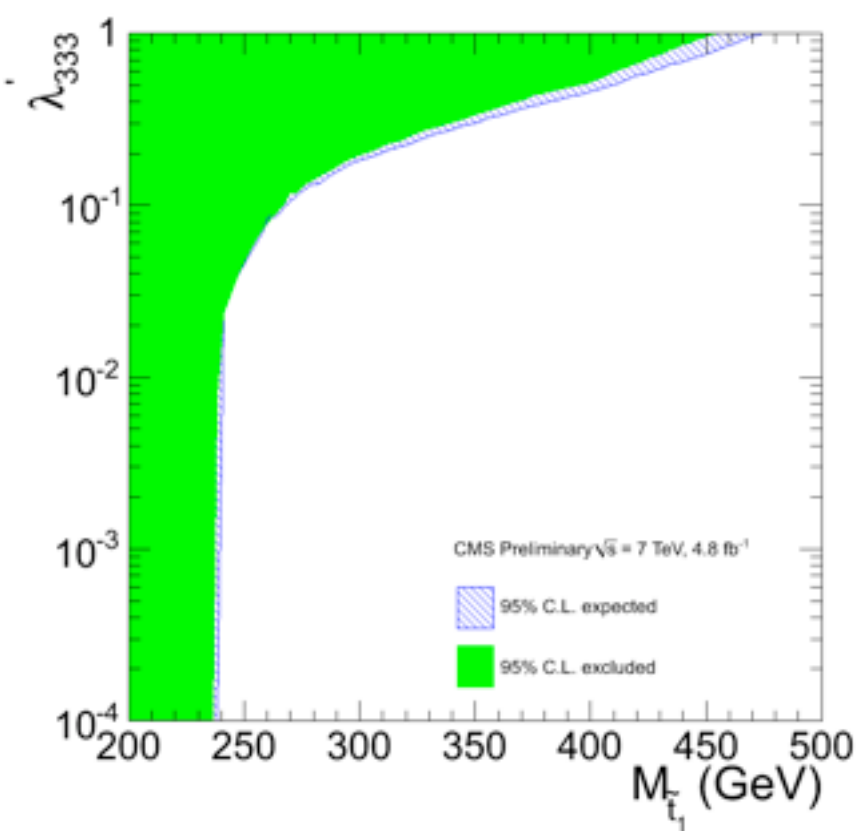

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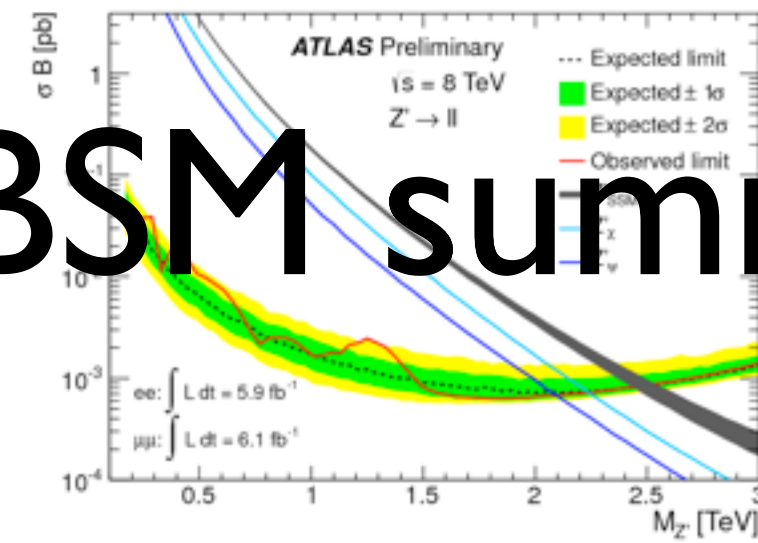


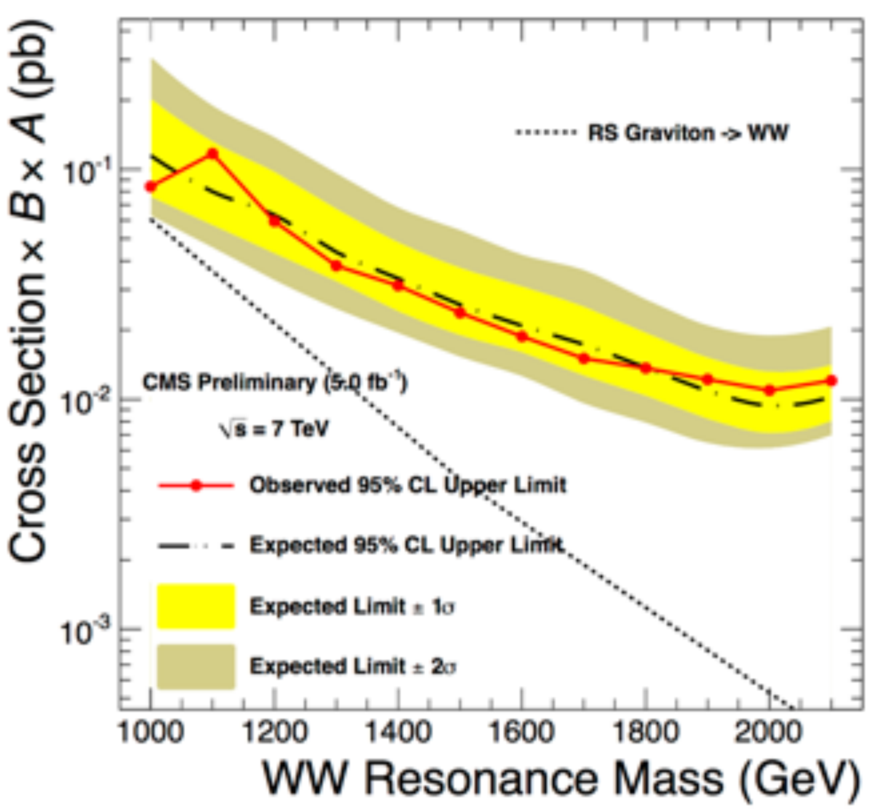


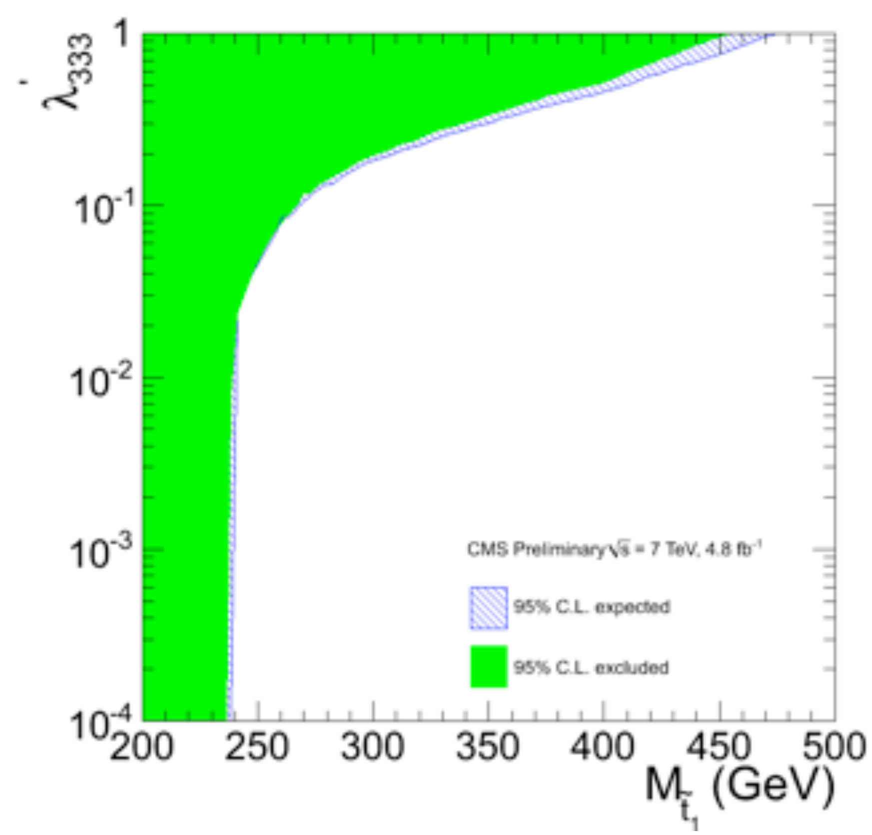

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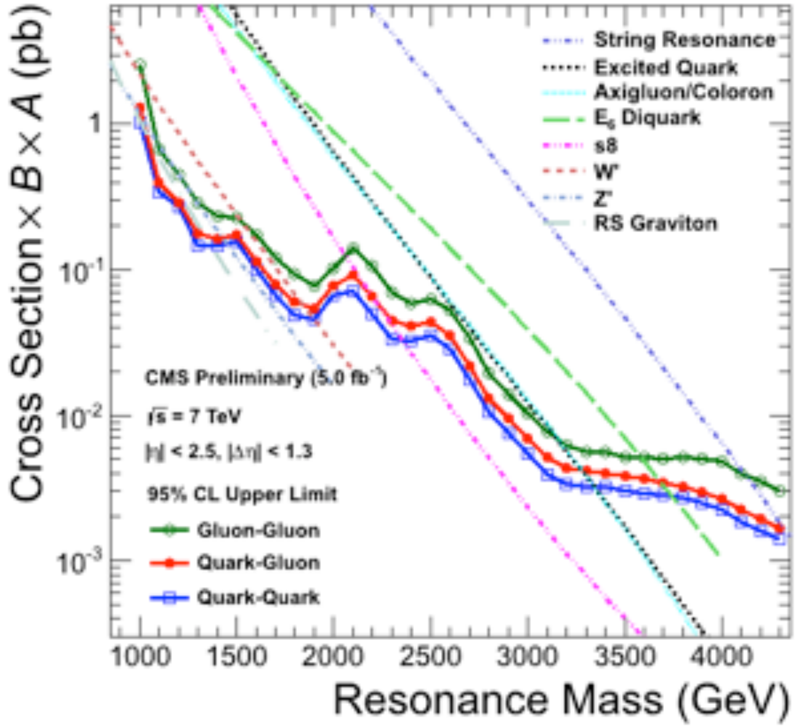


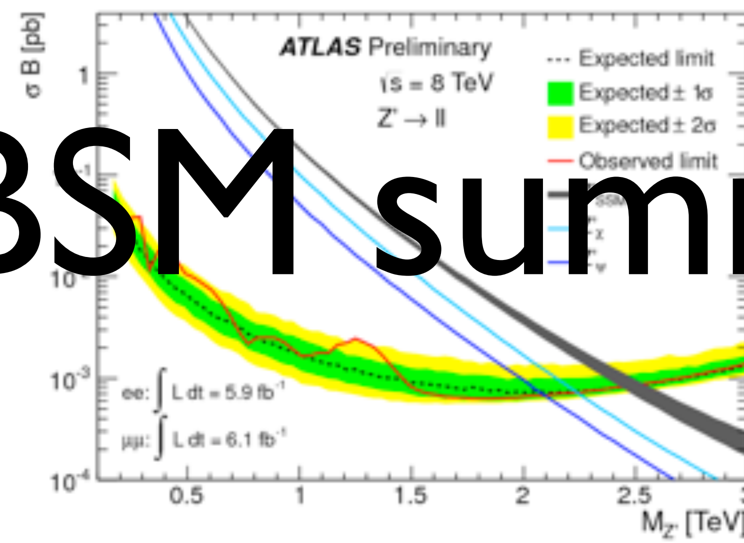


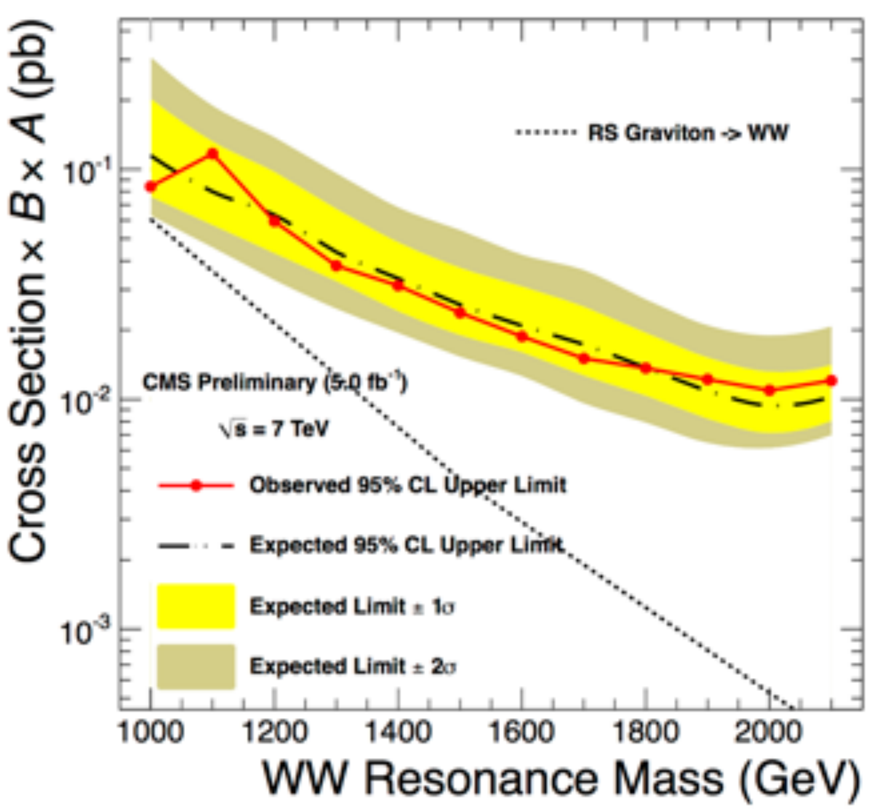


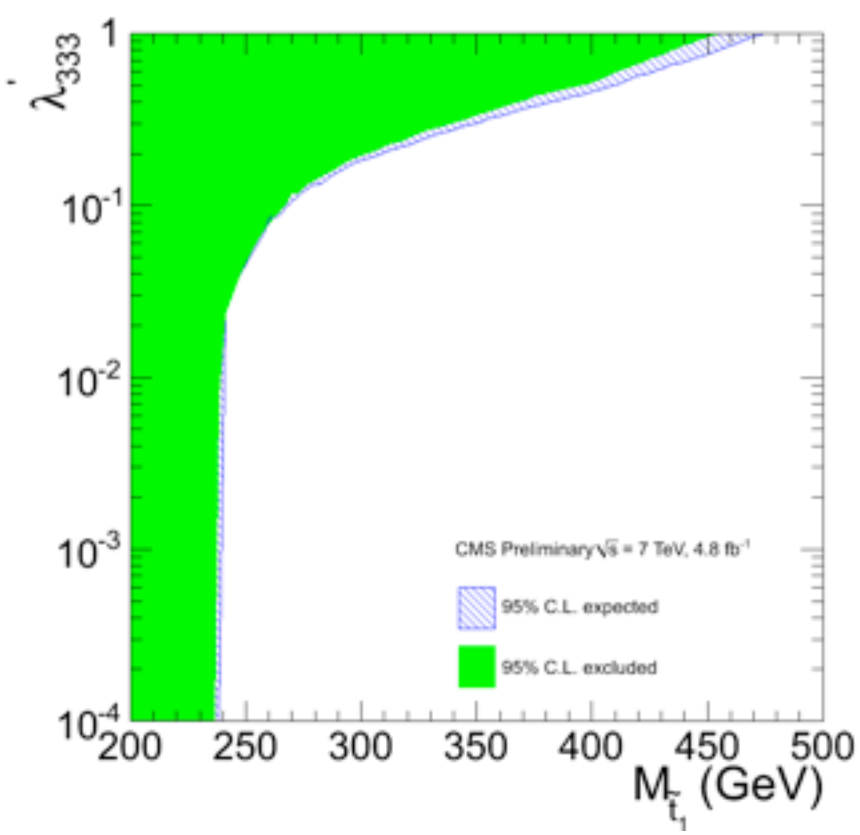

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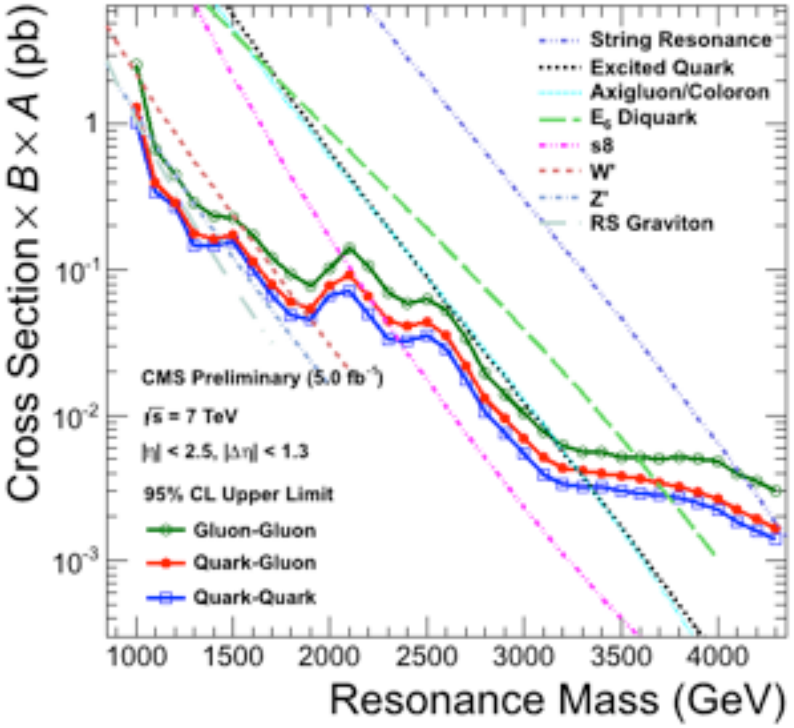


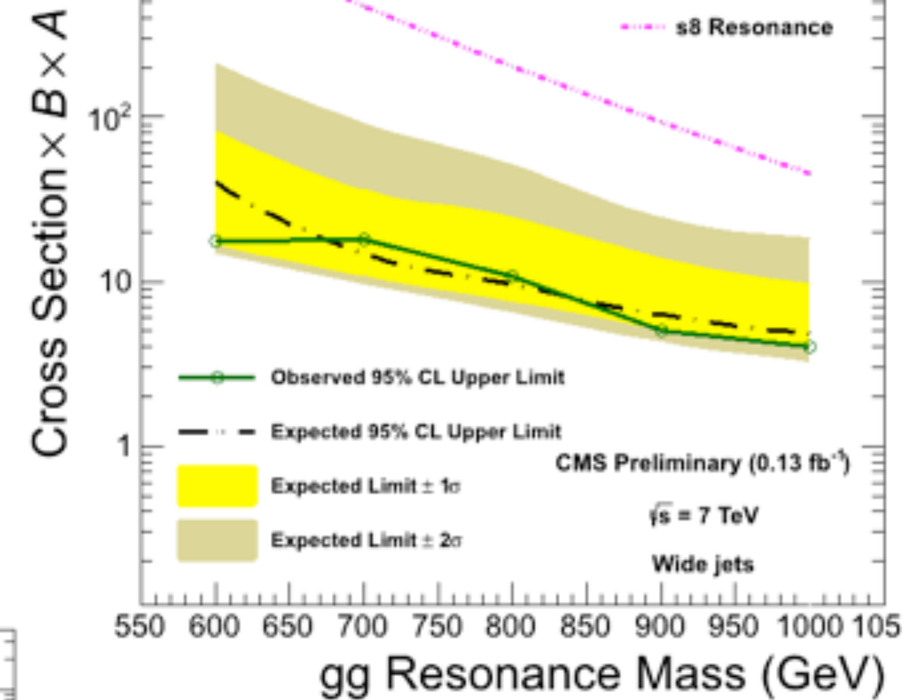


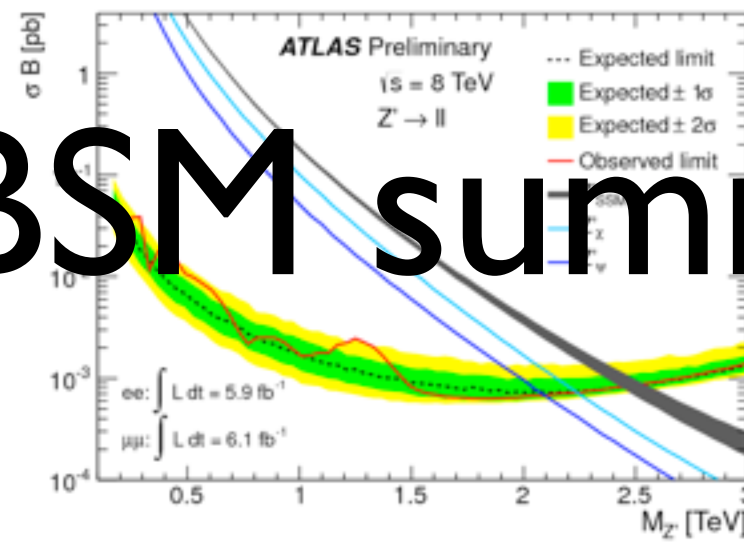


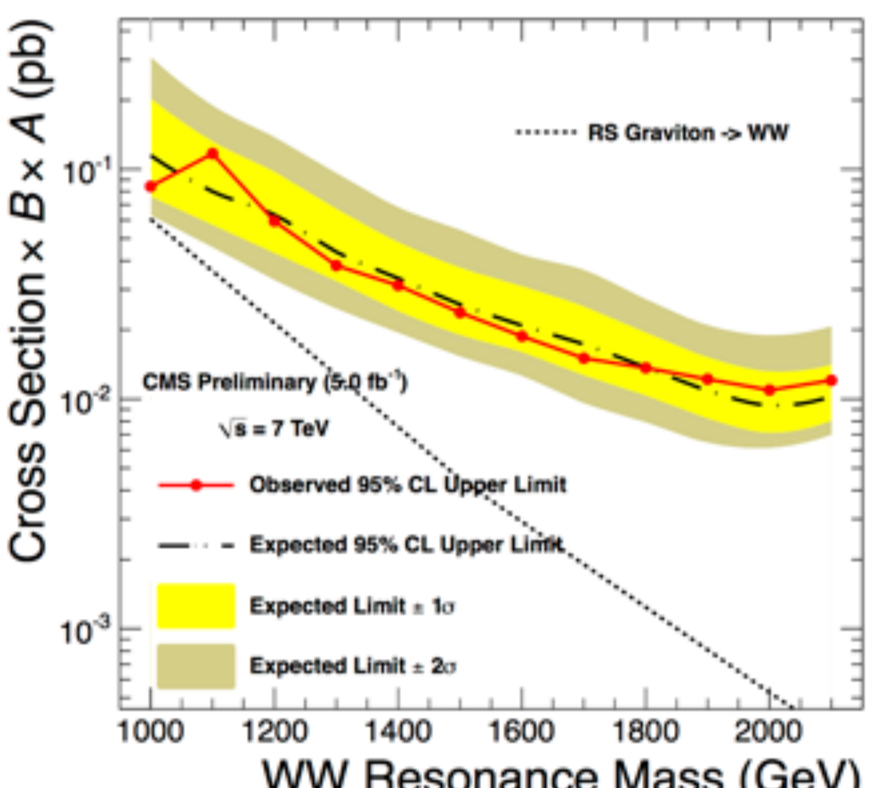


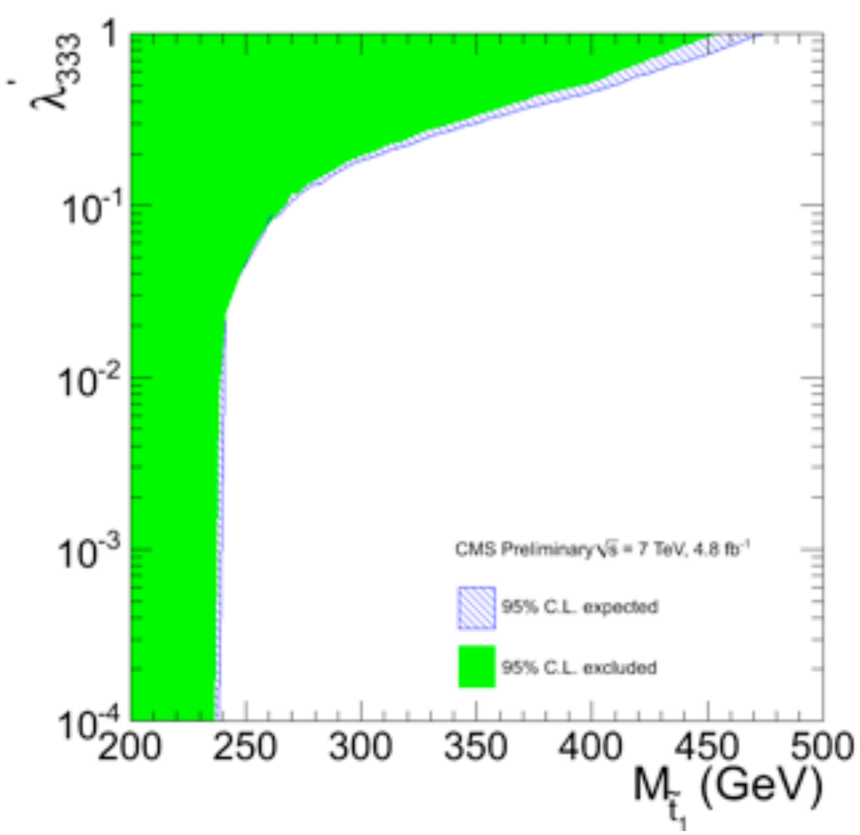

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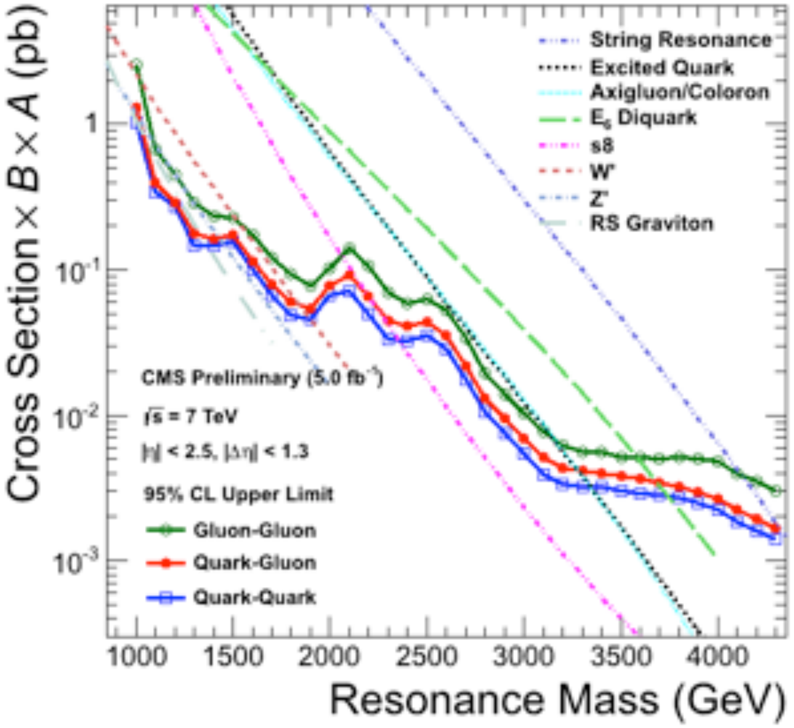


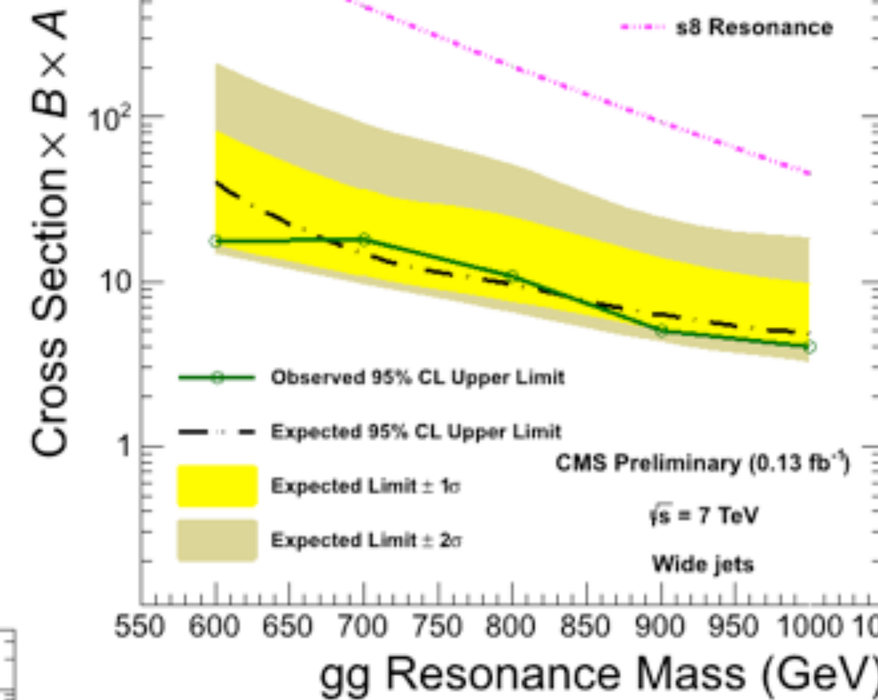


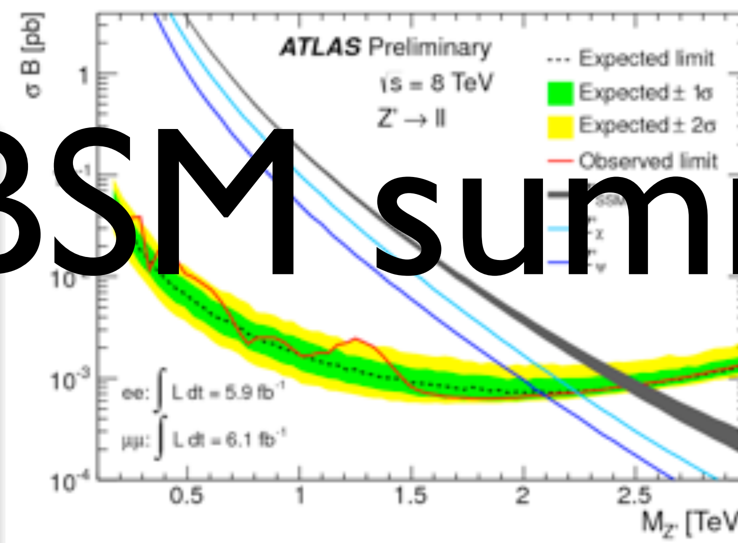


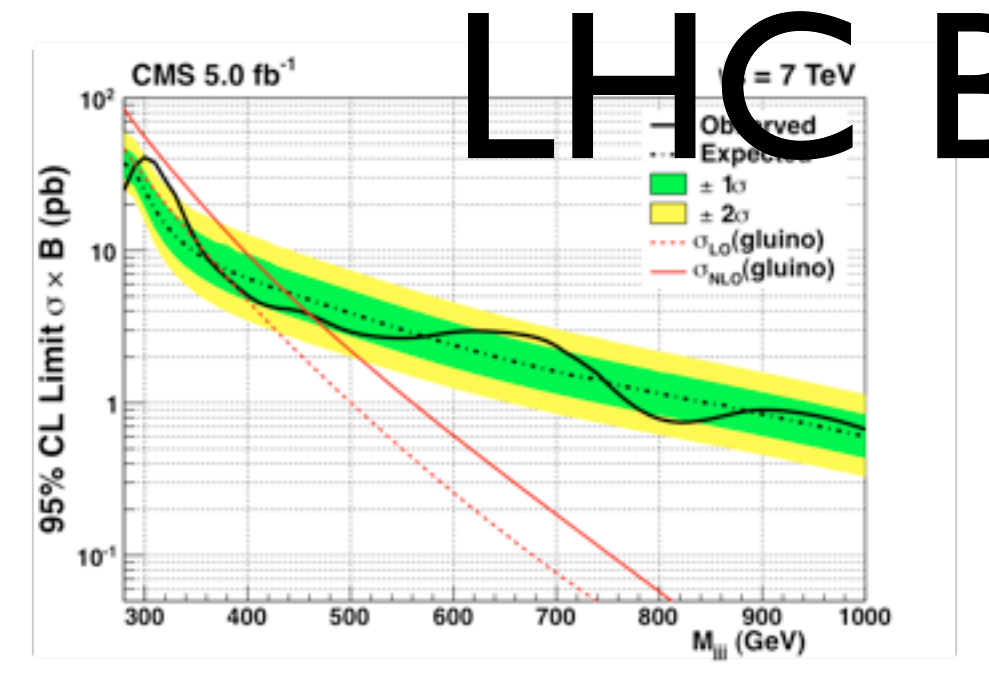


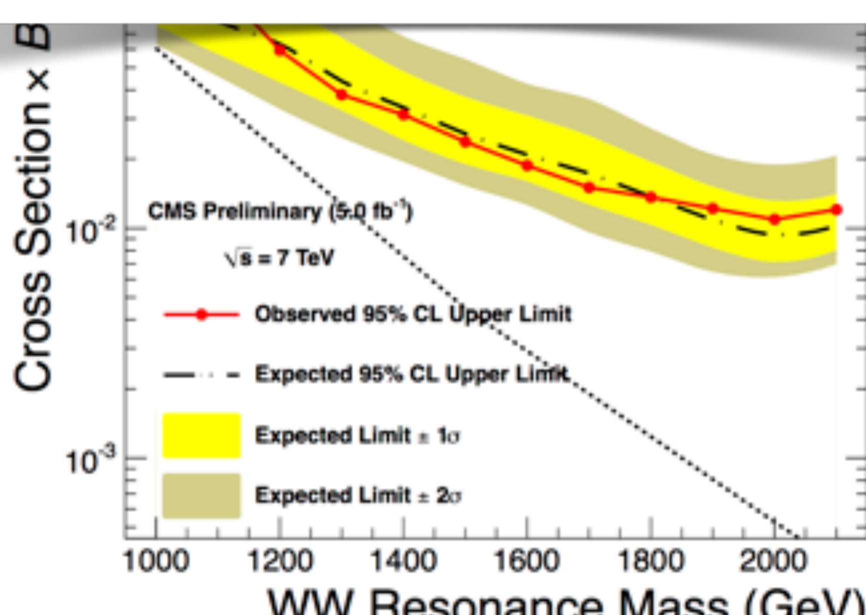


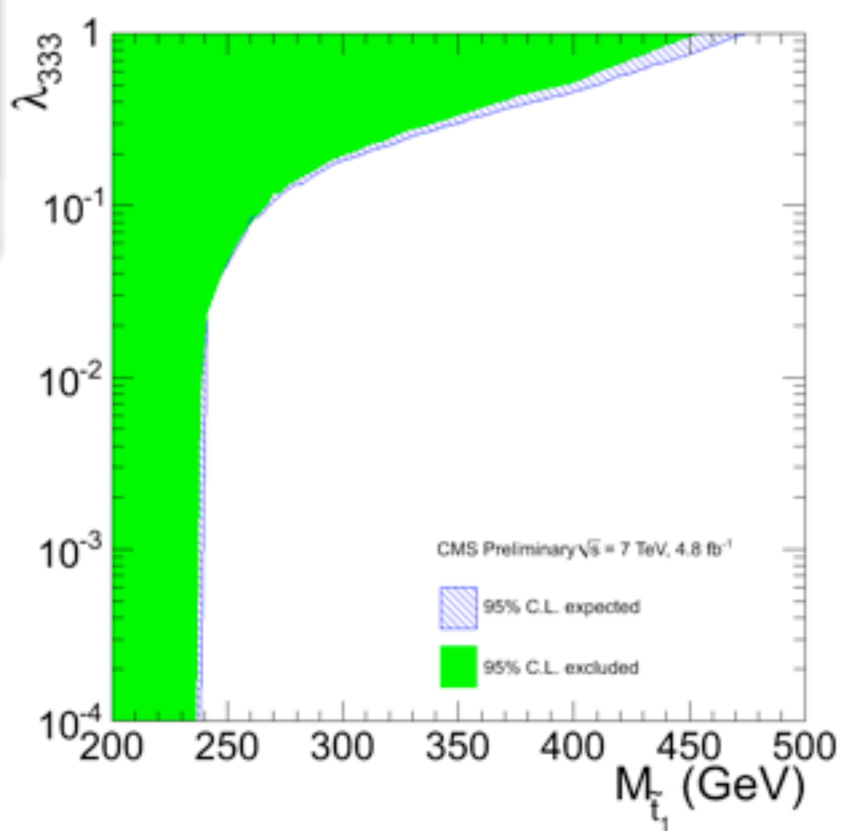

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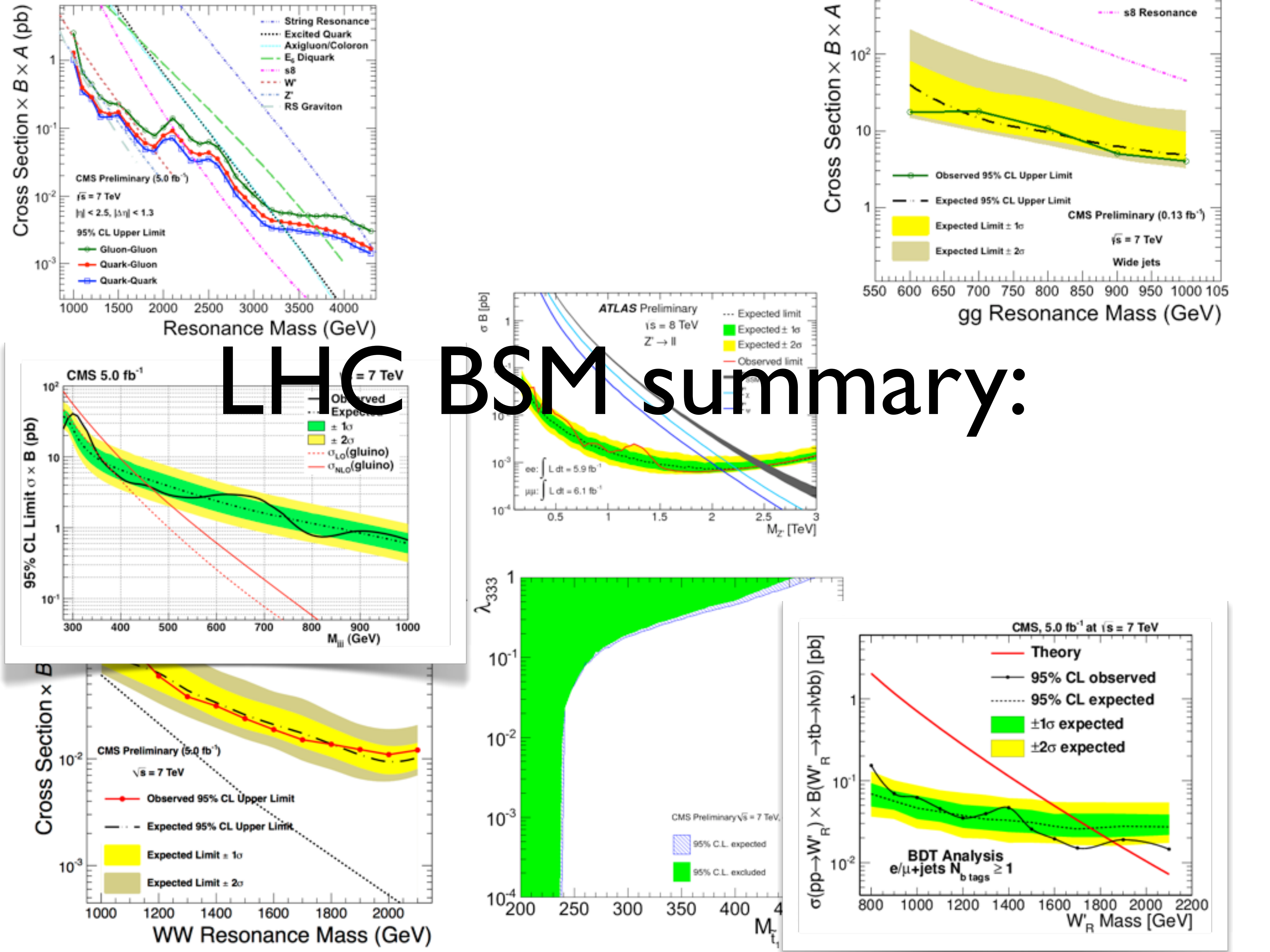

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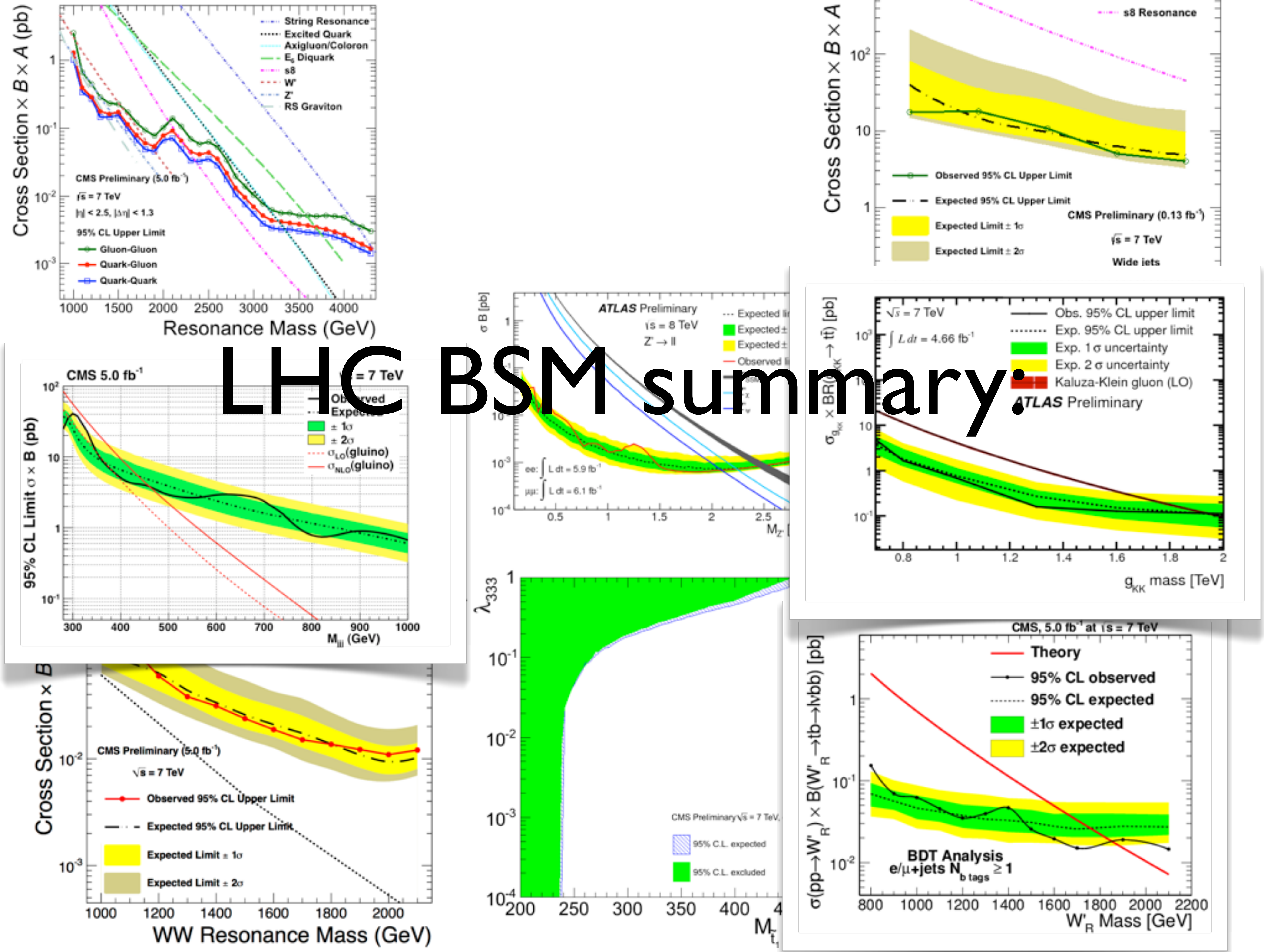

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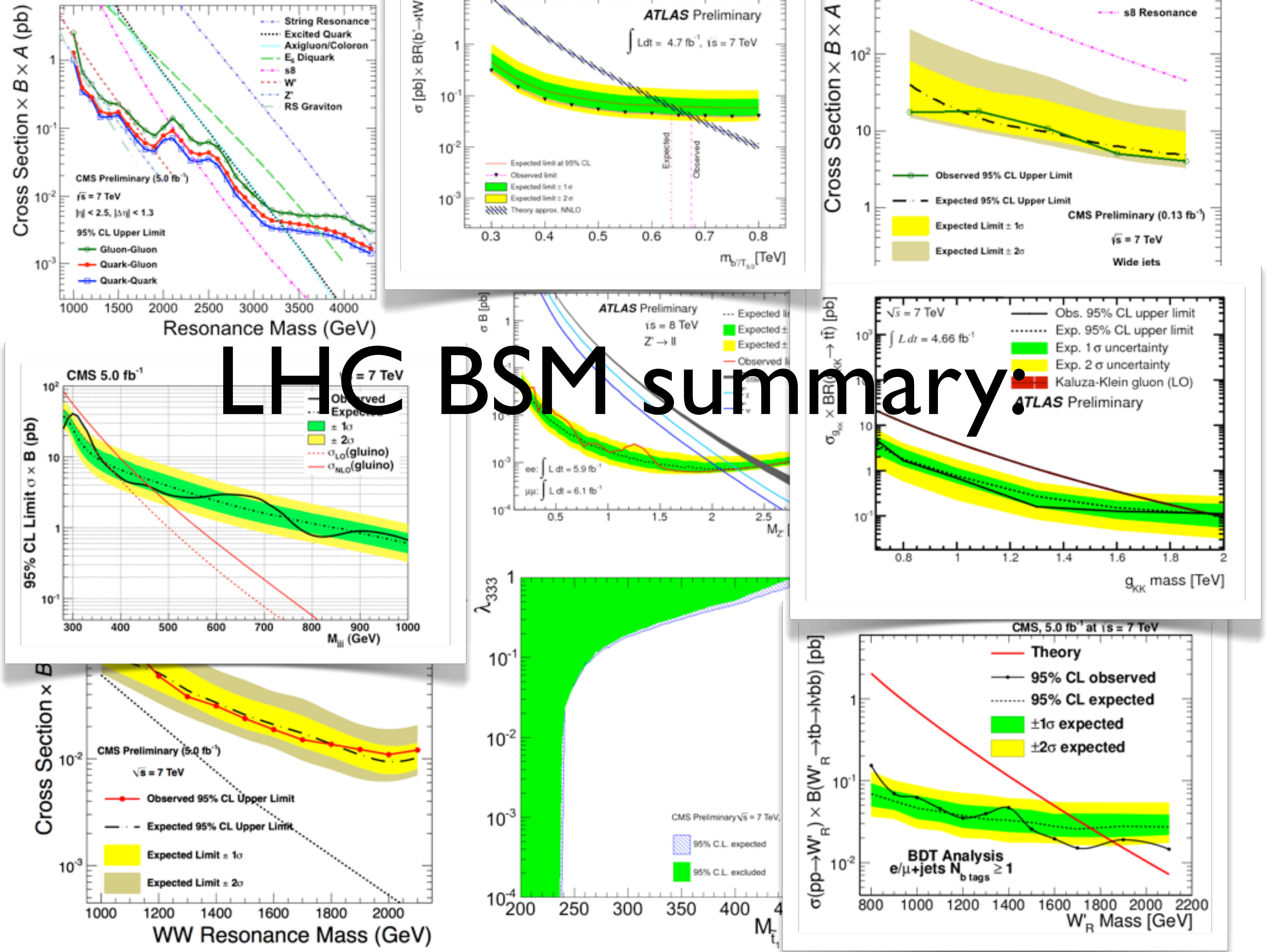
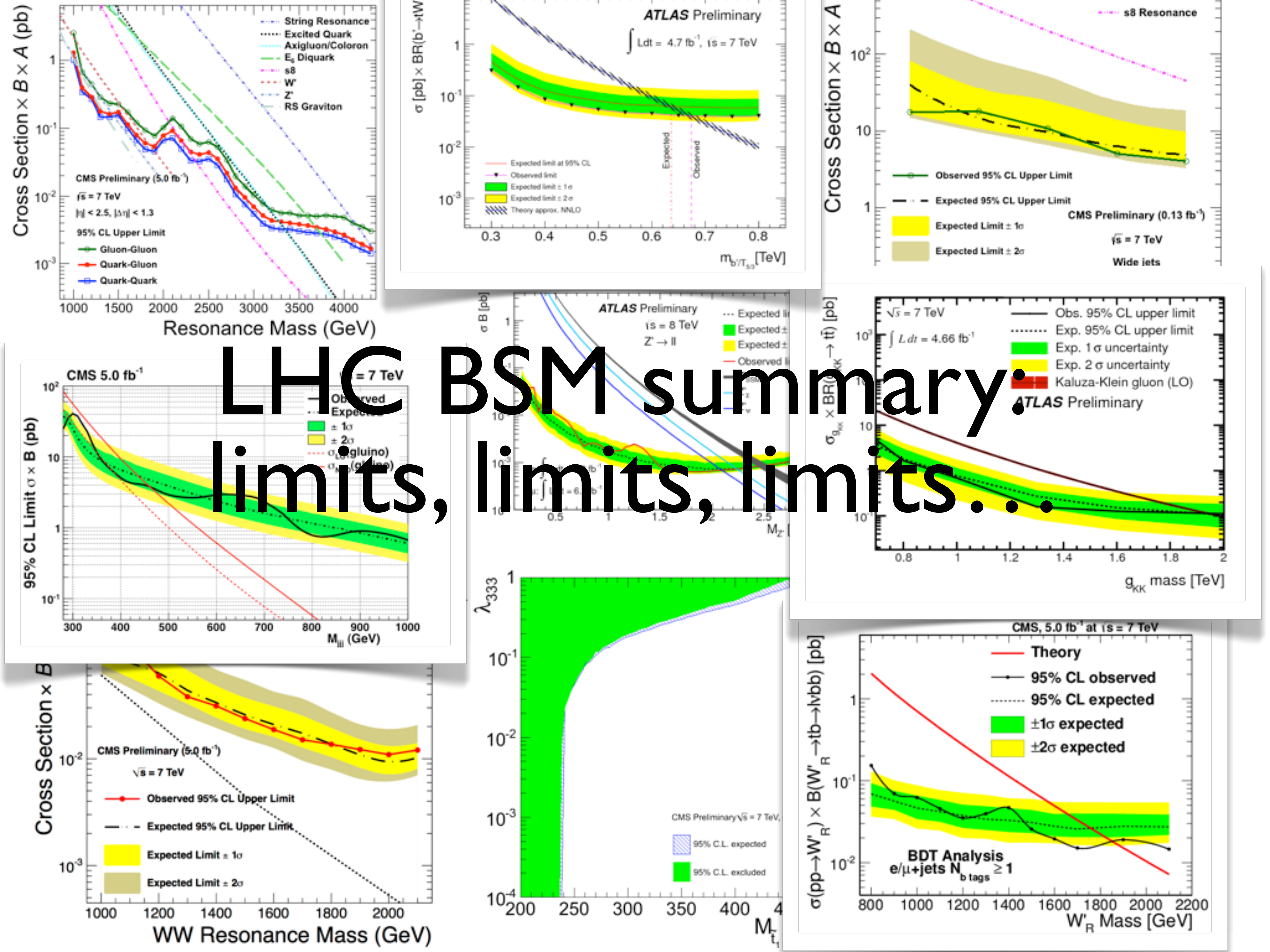


# LHC BSM summary: limits, limits, limits . . .



# Why go beyond the SM?

Dark matter?
Dark Energy?
Origin of quark mass and mixing hierarchies?
Strong CP?
EW strong coupling/unitarity problem?
Matter-Antimatter asymmetry?
Neutrino masses?
Inflation?
Quantum instability of Higgs mass?
Charge quantization (GUT?)?
Quantum Gravity?
. . .
✓

# Why expect new physics at the LHC?

Dark matter? $10^{-15}$ GeV ? $10^{12}$ GeV ?

~~Dark Energy?~~

Origin of quark mass and mixing hierarchies?

~~Strong CP?~~

**EW strong coupling/unitarity problem**

Matter-Antimatter asymmetry? 100 GeV? $10^{13}$ GeV ?

Neutrino masses? $10^{13}$ GeV ? 100 GeV?

~~Inflation?~~

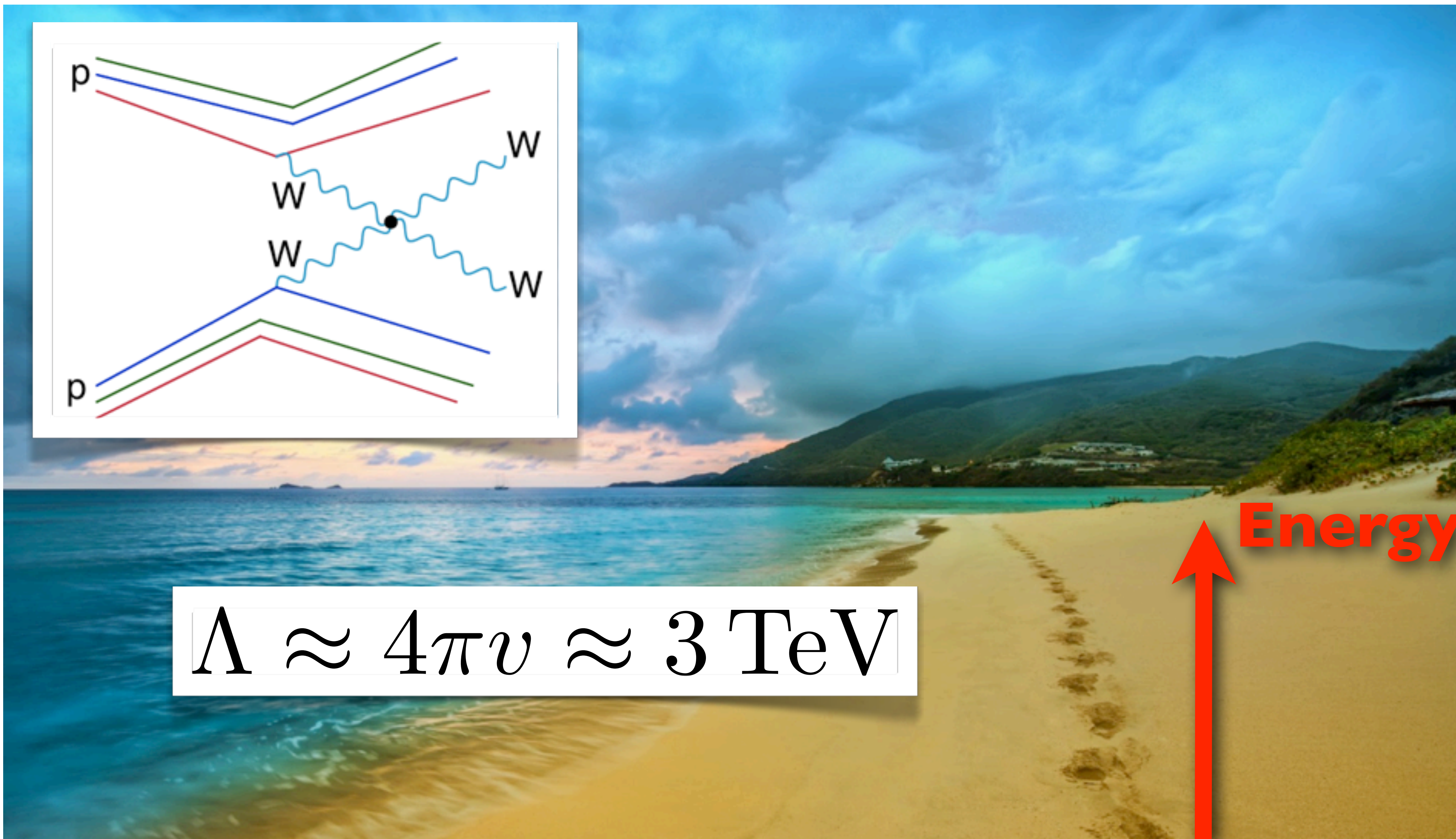
**Quantum instability of the Higgs mass**

~~Charge quantization (GUT?)?~~

Quantum Gravity? TeV or $M_{Planck}$ . . .

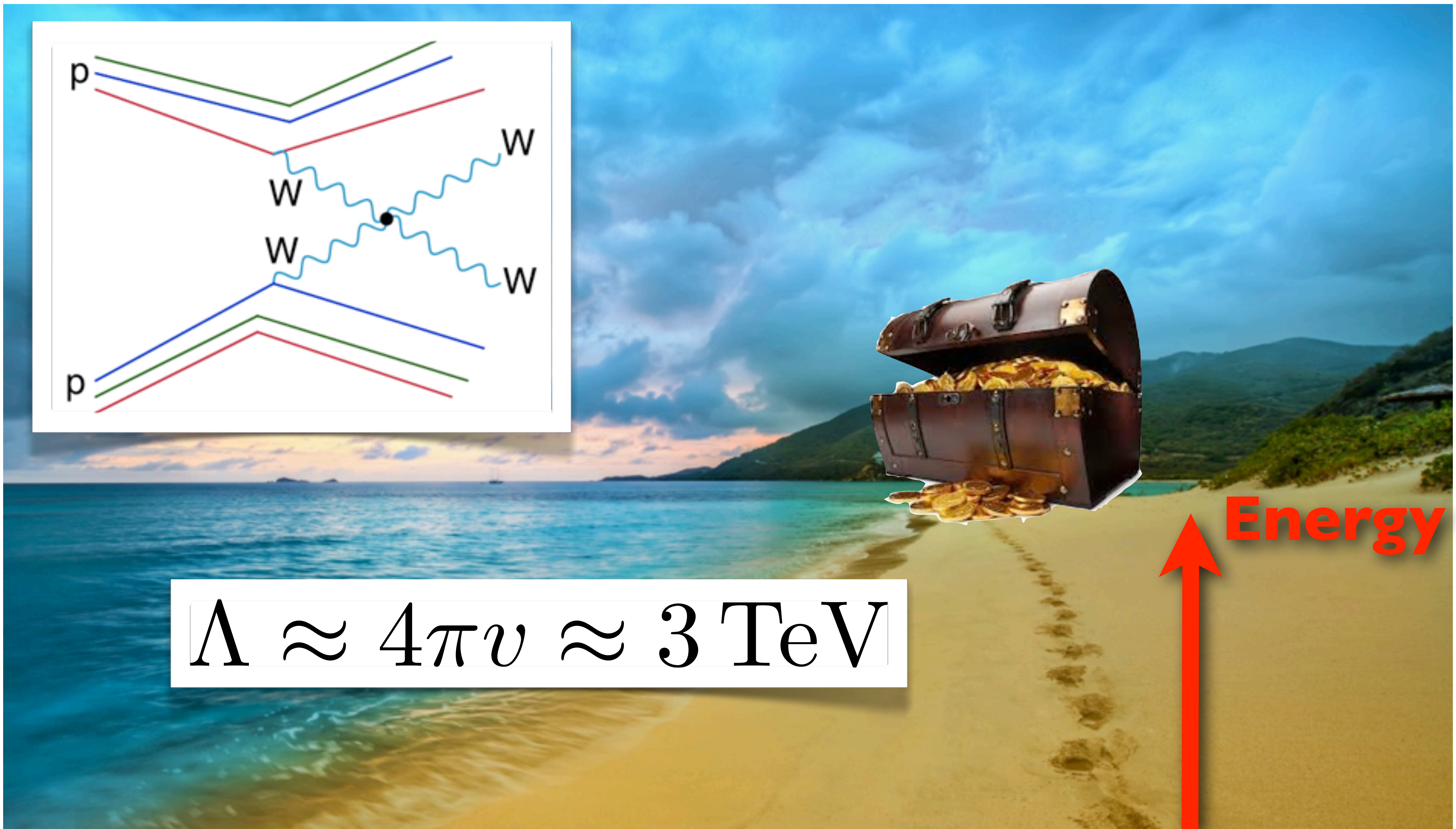
. . .

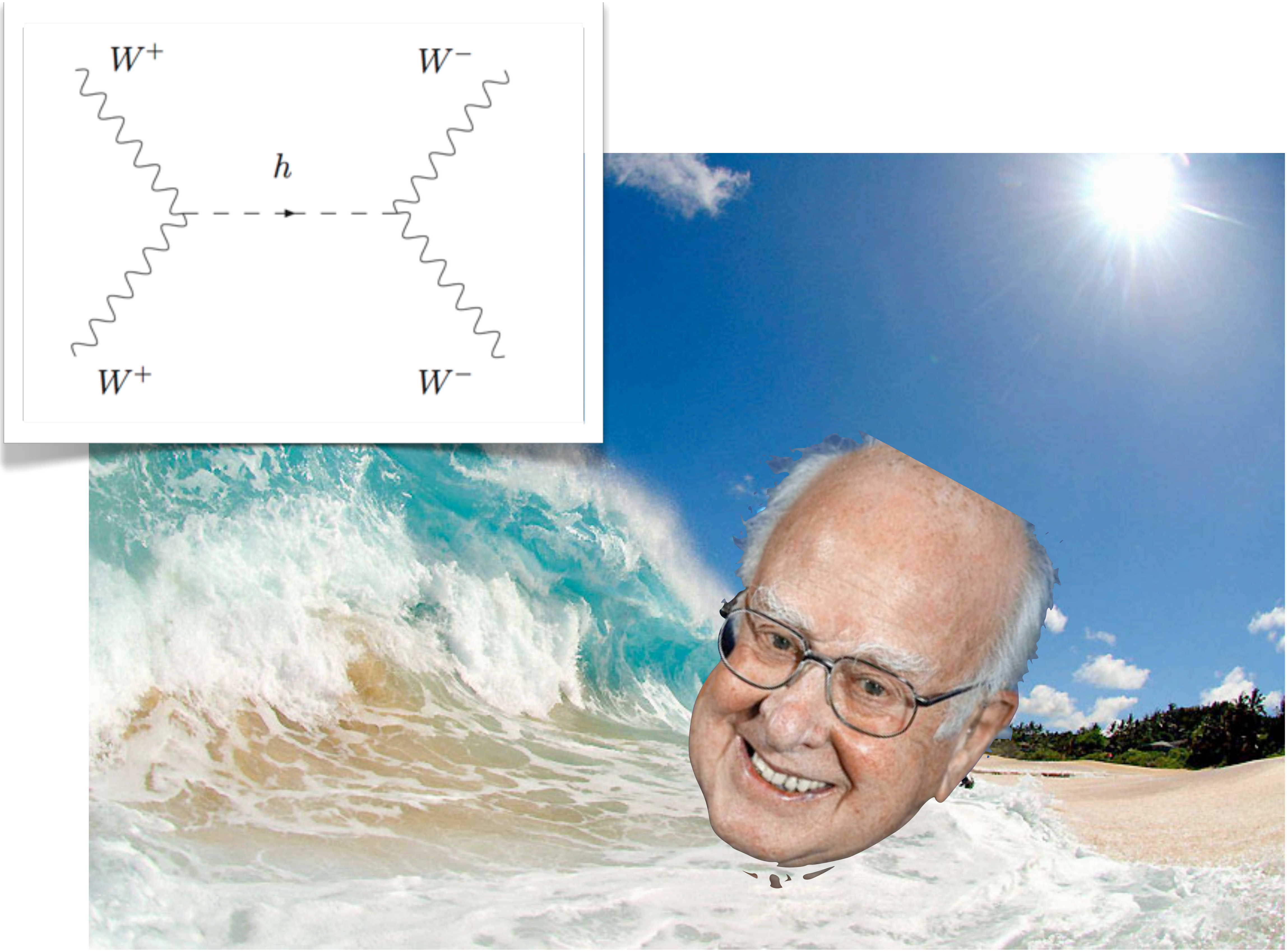
# Before the Higgs discovery




$$\Lambda \approx 4\pi v \approx 3\,\mathrm{TeV}$$

# Before the Higgs discovery

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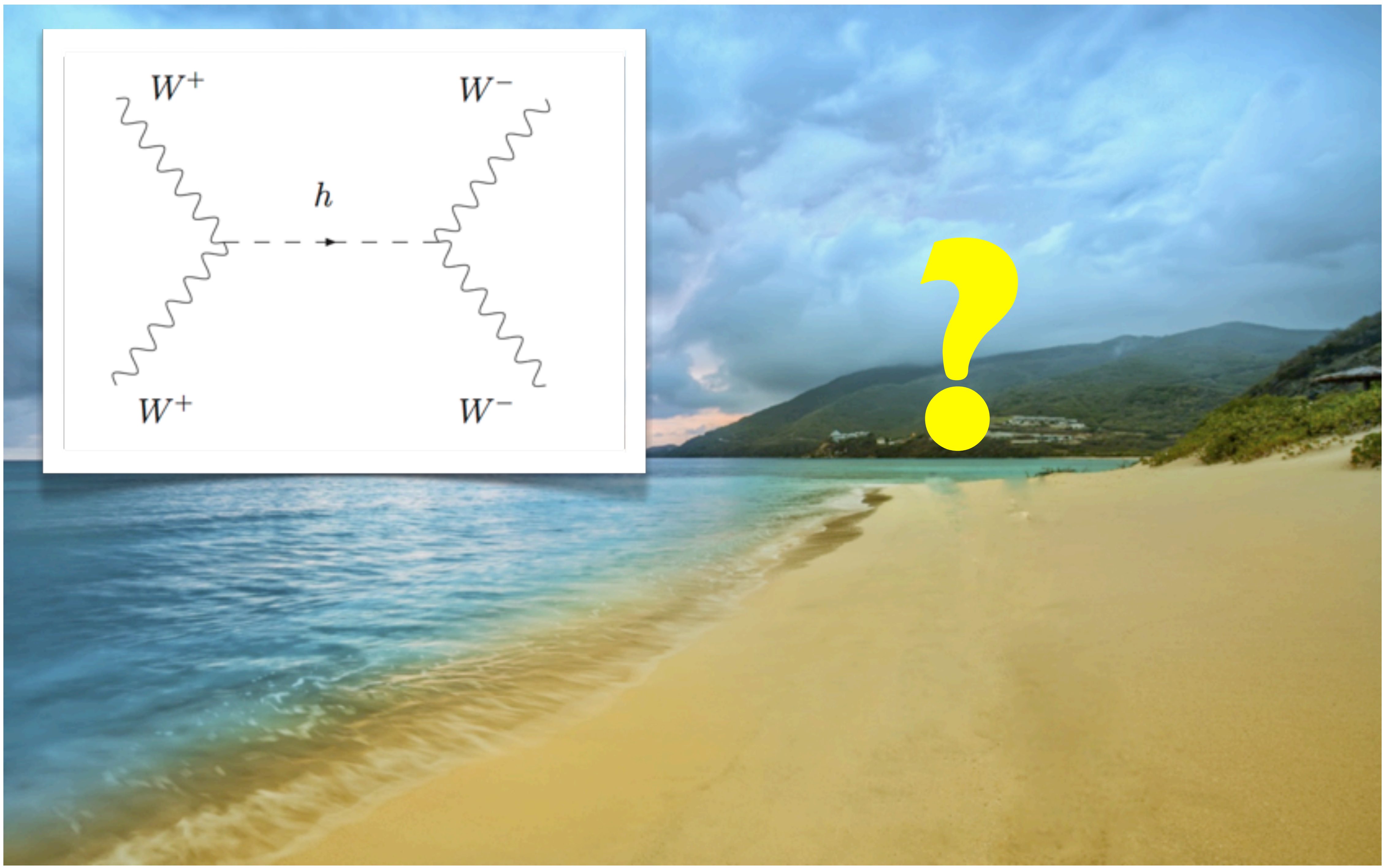
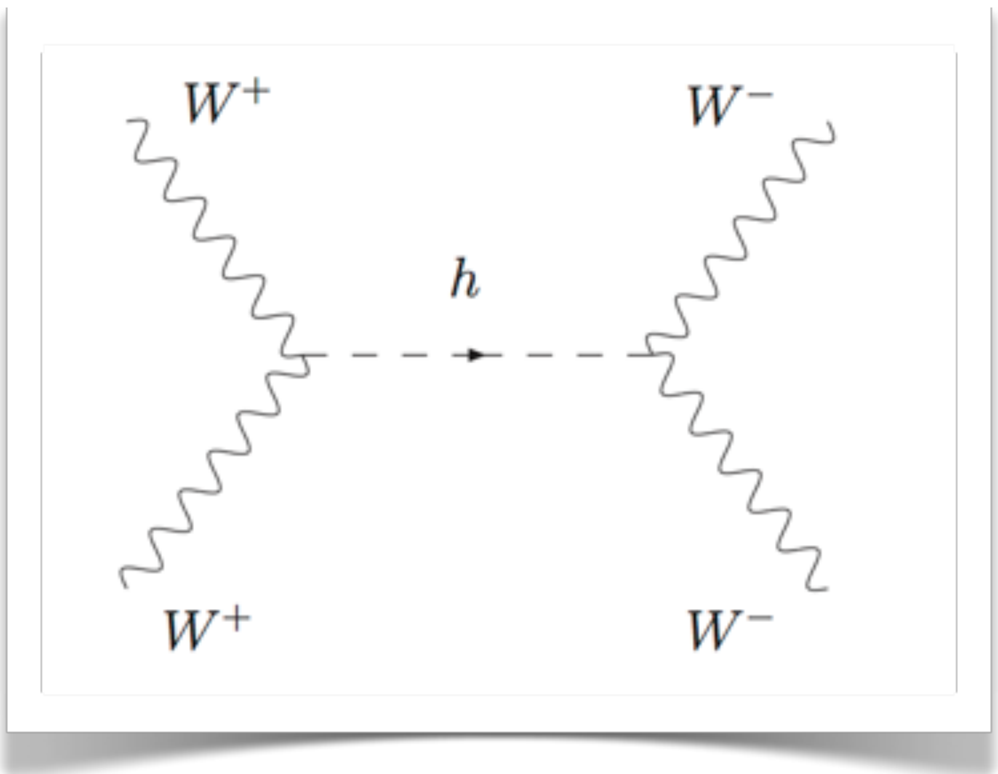
# Adding SM-like Higgs

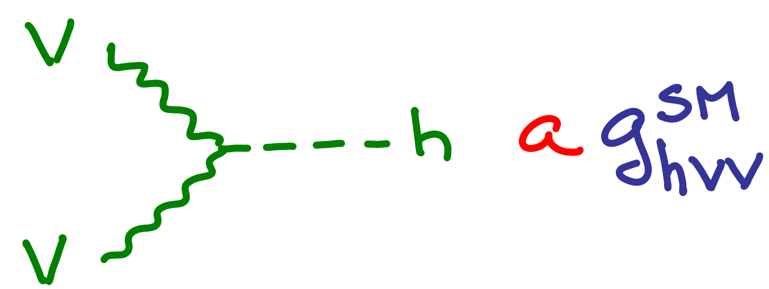
SM works up to $\Lambda \gg \mathrm{LHC}$



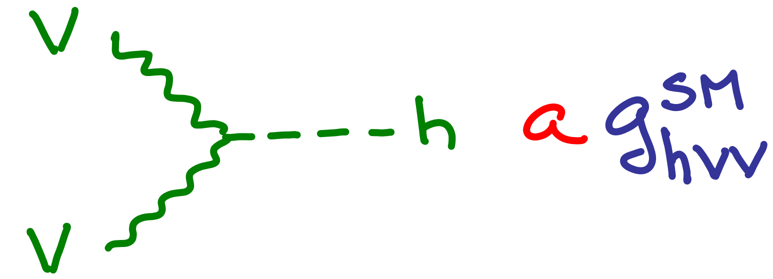
# Adding SM-like Higgs

What if the coupling is not exactly like in the SM?




$$\Lambda \approx 4\pi v \longrightarrow \frac{4\pi v}{\sqrt{1-a^2}}$$




$$\Lambda \approx 4\pi v \longrightarrow \frac{4\pi v}{\sqrt{1-a^2}}$$

Even if we measure $a < 1$, no guarantee for new physics in reach of LHC.

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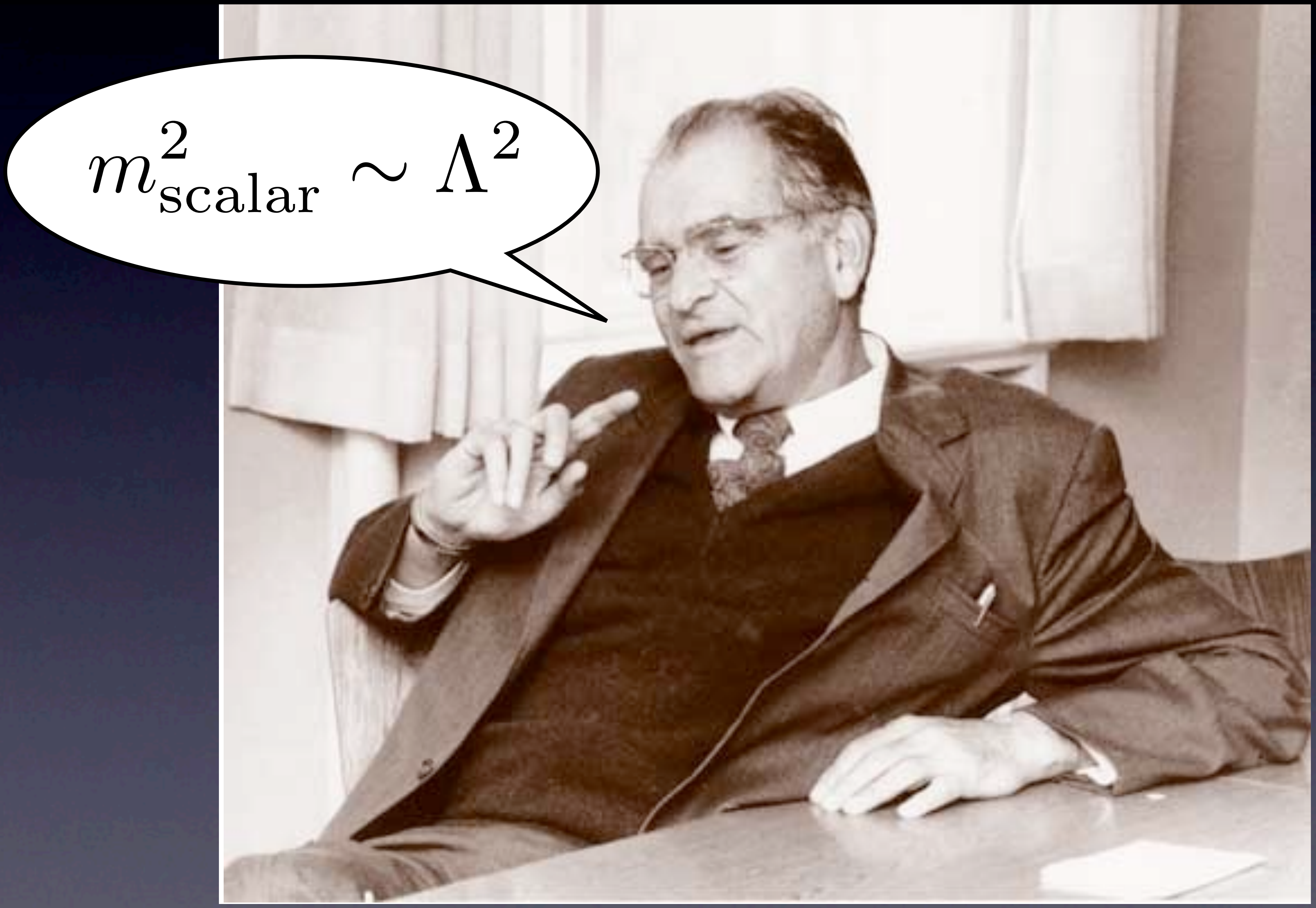
**Example:** composite pseudo-Goldstone Higgs:

$$a = \sqrt{1-(v/f)^2} \approx 0.8\ldots 0.9$$

$$\Lambda > 6\ldots 8\,\mathrm{TeV}$$

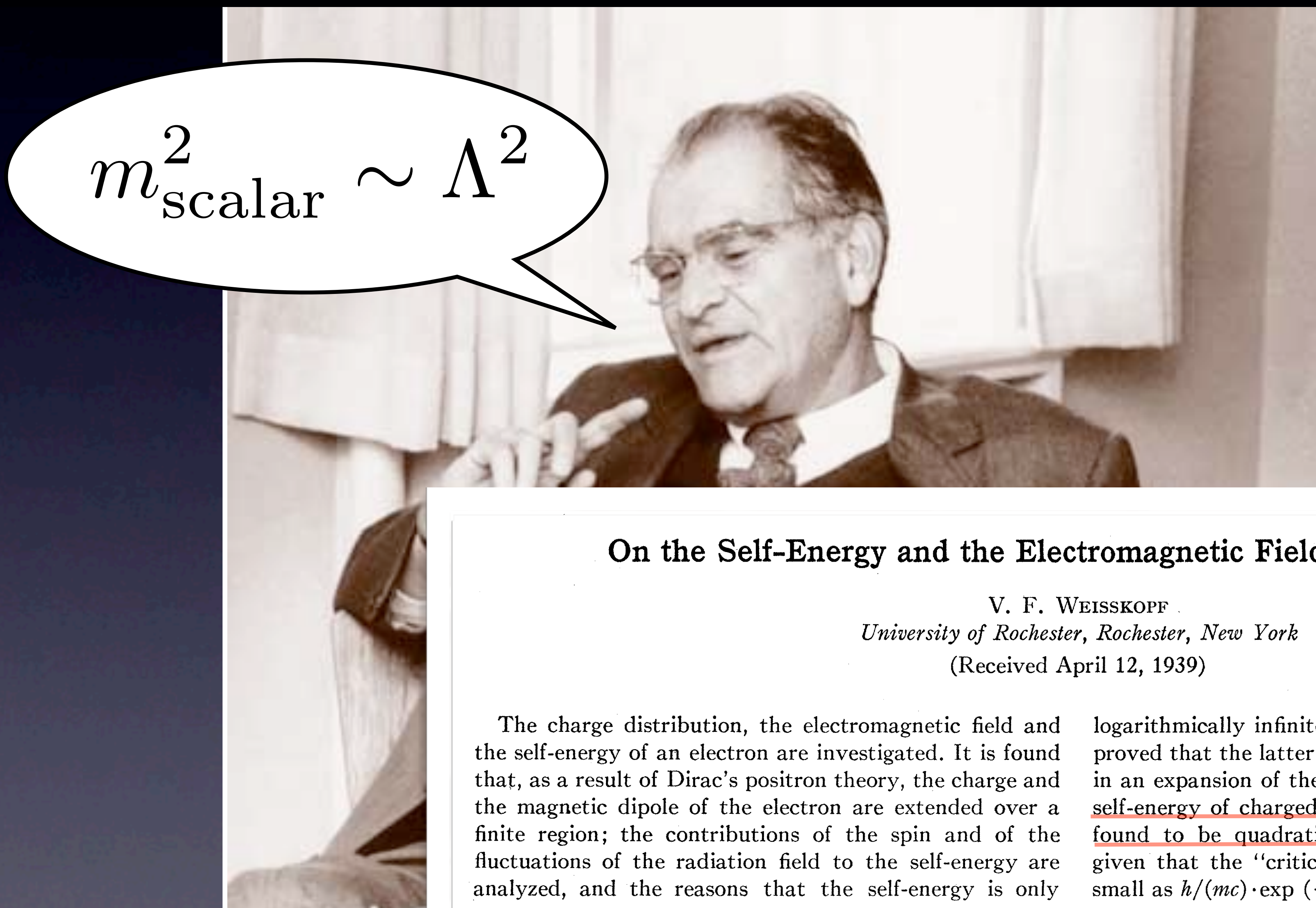
# So what should be our guiding principle?

# “What’s the problem?”




Weisskopf, Phys. Rev.56 (**1939**) 72

# "What's the problem?"




**On the Self-Energy and the Electromagnetic Field of the Electron**

V. F. Weisskopf
*University of Rochester, Rochester, New York*
(Received April 12, 1939)

The charge distribution, the electromagnetic field and the self-energy of an electron are investigated. It is found that, as a result of Dirac's positron theory, the charge and the magnetic dipole of the electron are extended over a finite region; the contributions of the spin and of the fluctuations of the radiation field to the self-energy are analyzed, and the reasons that the self-energy is only logarithmically infinite in positron theory are given. It is proved that the latter result holds to every approximation in an expansion of the self-energy in powers of $e^2/hc$. The self-energy of charged particles obeying Bose statistics is found to be quadratically divergent. Some evidence is given that the "critical length" of positron theory is as small as $h/(mc) \cdot \exp(-hc/e^2)$.

Weisskopf, Phys. Rev.56 (**1939**) 72

# A light Higgs is unnatural

$$V(h) = \epsilon \Lambda^2 h^2 + \lambda h^4$$

For $\epsilon = \pm\, \mathcal{O}(1)$

$$\langle h \rangle = 0$$

$$\langle h \rangle = \Lambda$$

Need: $\sqrt{\epsilon} \sim m_W / \Lambda$

See e.g. G. Giudice: 1307.7879

# Naturalness*

- Higgs mass is sensitive to high scale threshold (GUT, gravity,...)
- Enormous quantum corrections $\mathcal{O}(\text{highest scale})$ exceed Higgs mass physical value, need to fine-tune parameters

Naturalness : absence of special conspiracies between phenomena occurring at very different length scales

* Caveat emptor: What about the other naturalness disaster (CC)?
Physics at $M_{Planck}$ might be very different. Multiverse alternative?

**Example:** add a very heavy scalar to the SM

$M_\Phi \gg m_H$ with $\lambda_\Phi |H|^2 |\Phi|^2$

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- Quadratic corrections: $\delta m_H^2 \approx \frac{\lambda_\Phi}{16\pi^2} M^2 \ln \frac{M^2}{\Lambda^2} + \ldots$

- Need new physics to soften UV dependence, e.g. supersymmetry

**Example:** add a very heavy scalar to the SM

$M_\Phi \gg m_H$ with $\lambda_\Phi |H|^2 |\Phi|^2$

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- Need new physics to soften UV dependence, e.g. supersymmetry

$$\delta m_H^2 = \frac{3y_t^2}{8\pi^2} \tilde{m}_t^2 \ln \frac{\tilde{m}_t^2}{\Lambda^2} + \ldots$$

… but new degrees better not be too far above $m_H$

# Electro-weak symmetry breaking & new physics in times of austerity

**Light Higgs**

- light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, . . .

  supersymmetry

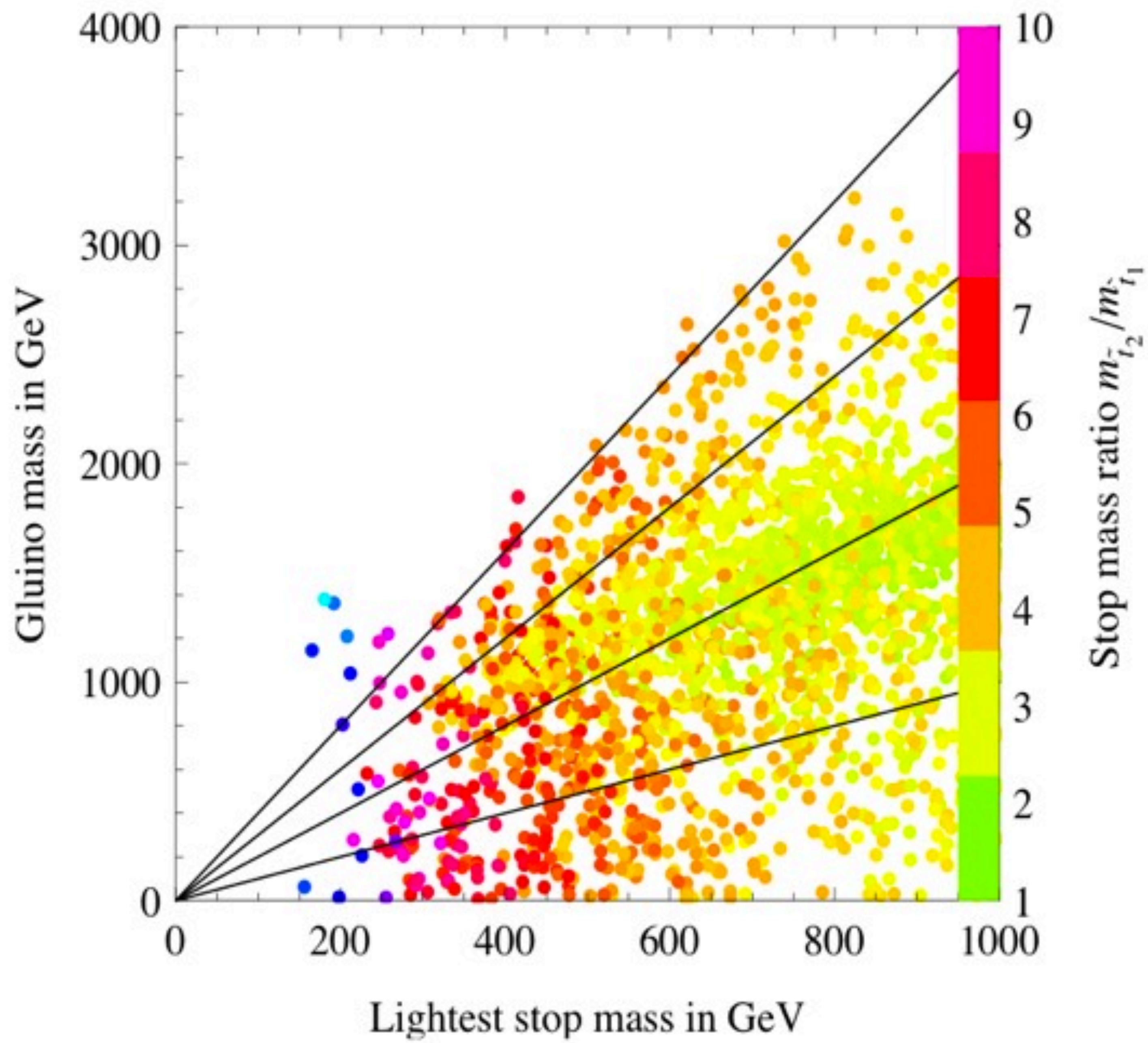
- light top partners (Q=5/3,2/3,1/3), anything else ?

  composite Higgs

- ?

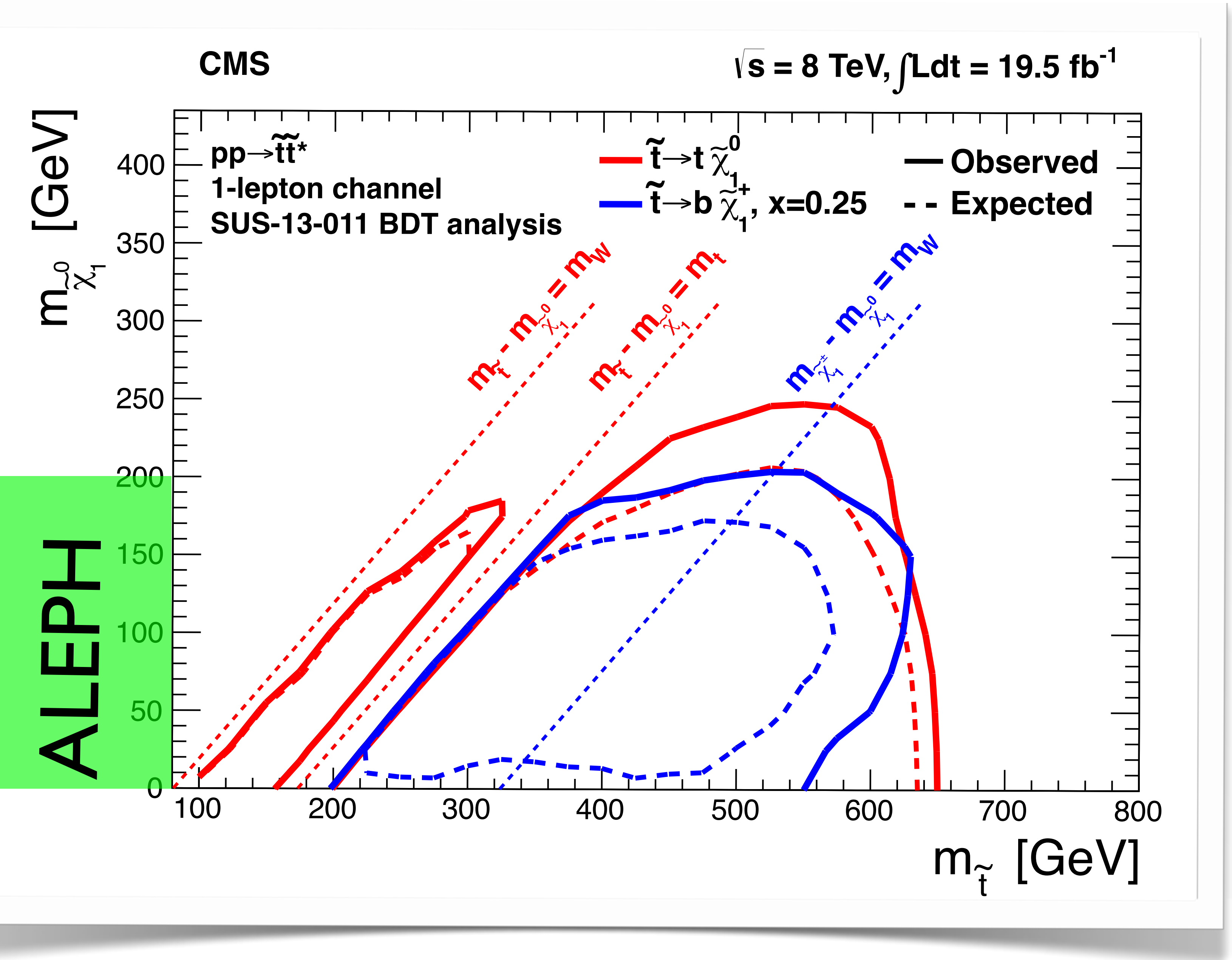
# MSSM stops vs. mH

Delgado et al.




Even easier in NMSSM, …

# Direct stop searches



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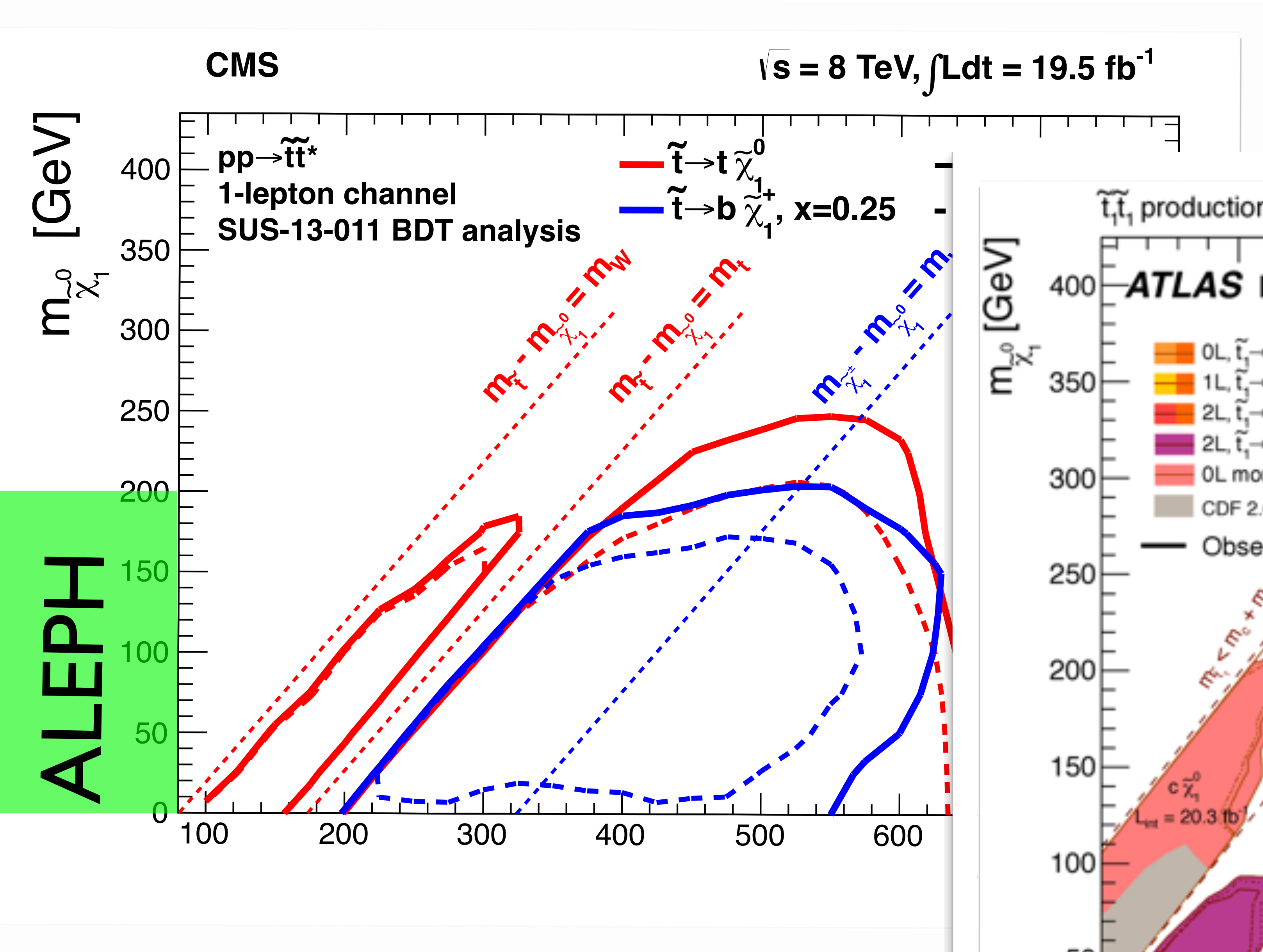
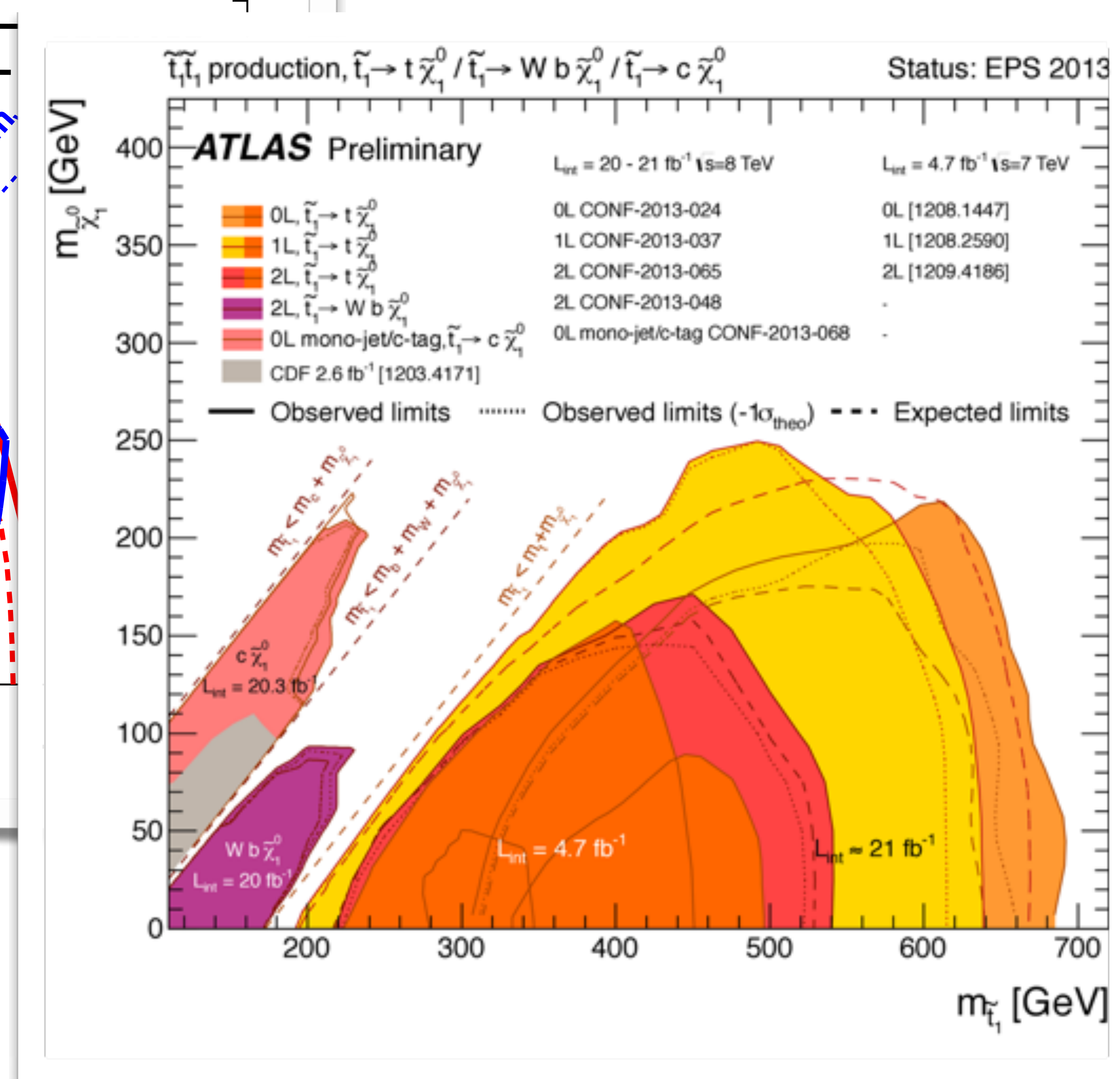
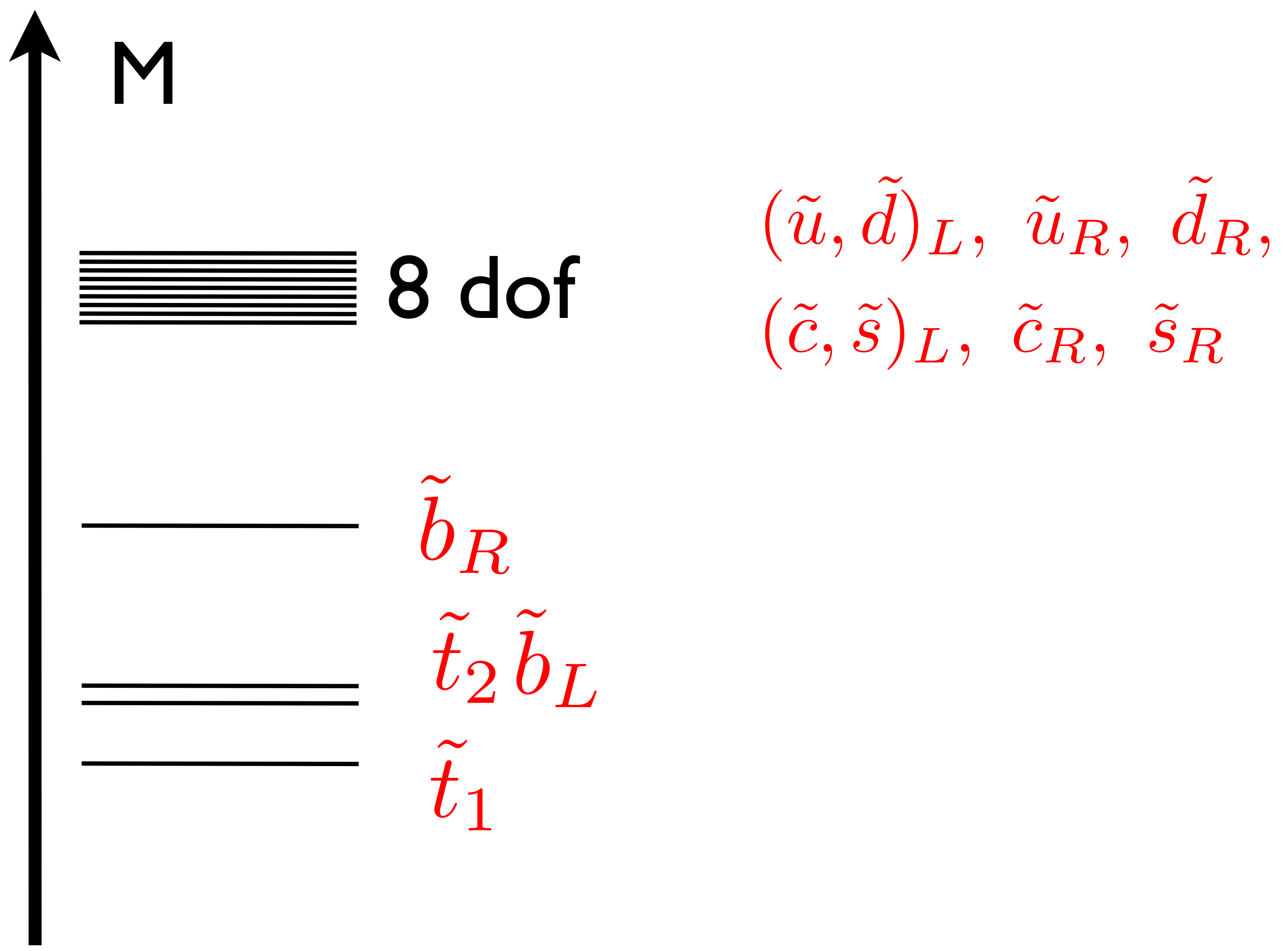


# Naturalness prefers split squarks



# Splitting via RGE?

Papucci, Ruderman, AW '11

Splitting via renormalization group does not help

$$\delta m_H^2 \simeq 3\left(m_{Q_3}^2 - m_{Q_{1,2}}^2\right) \simeq \frac{3}{2}\left(m_{U_3}^2 - m_{U_{1,2}}^2\right)$$

1-loop, LLog, tanß moderate

Higgs fine-tuning = RGE mass splitting

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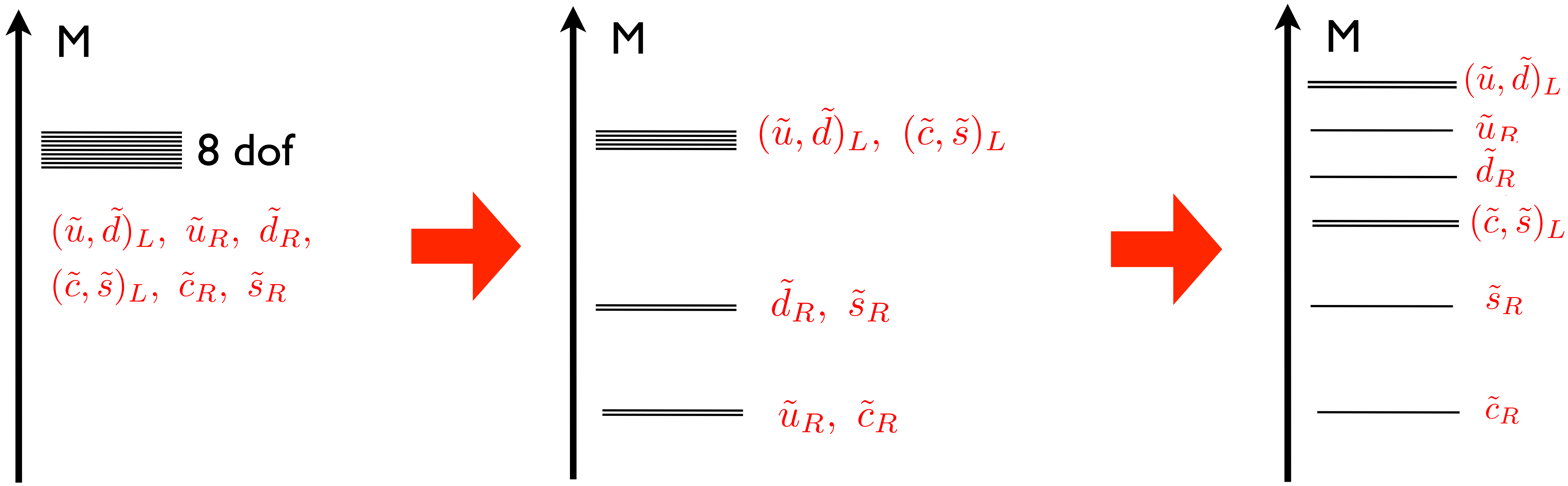
1-loop, LLog, tanß moderate

Higgs fine-tuning = RGE mass splitting

→ Flavor non-trivial susy breaking!

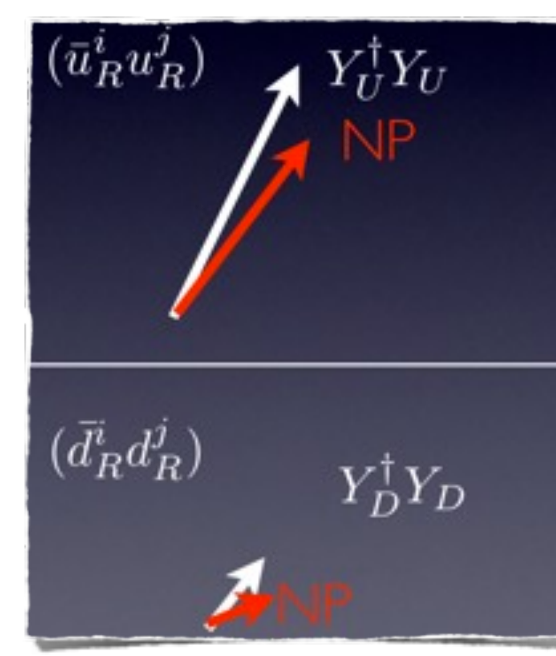



Degenerate

Minimal Flavor

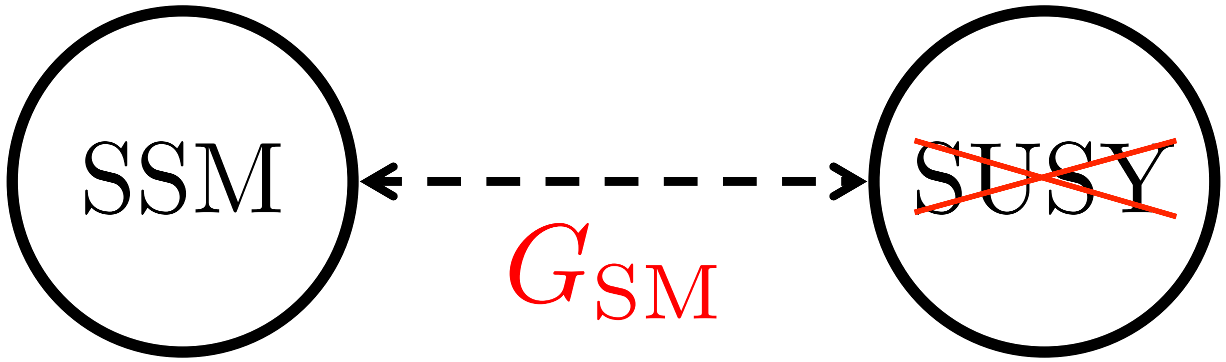
Anarchy!

mSugra, CMSSM,
pMSSM, ...



# Gauge Mediation

see e.g. Giudice/Rattazzi review

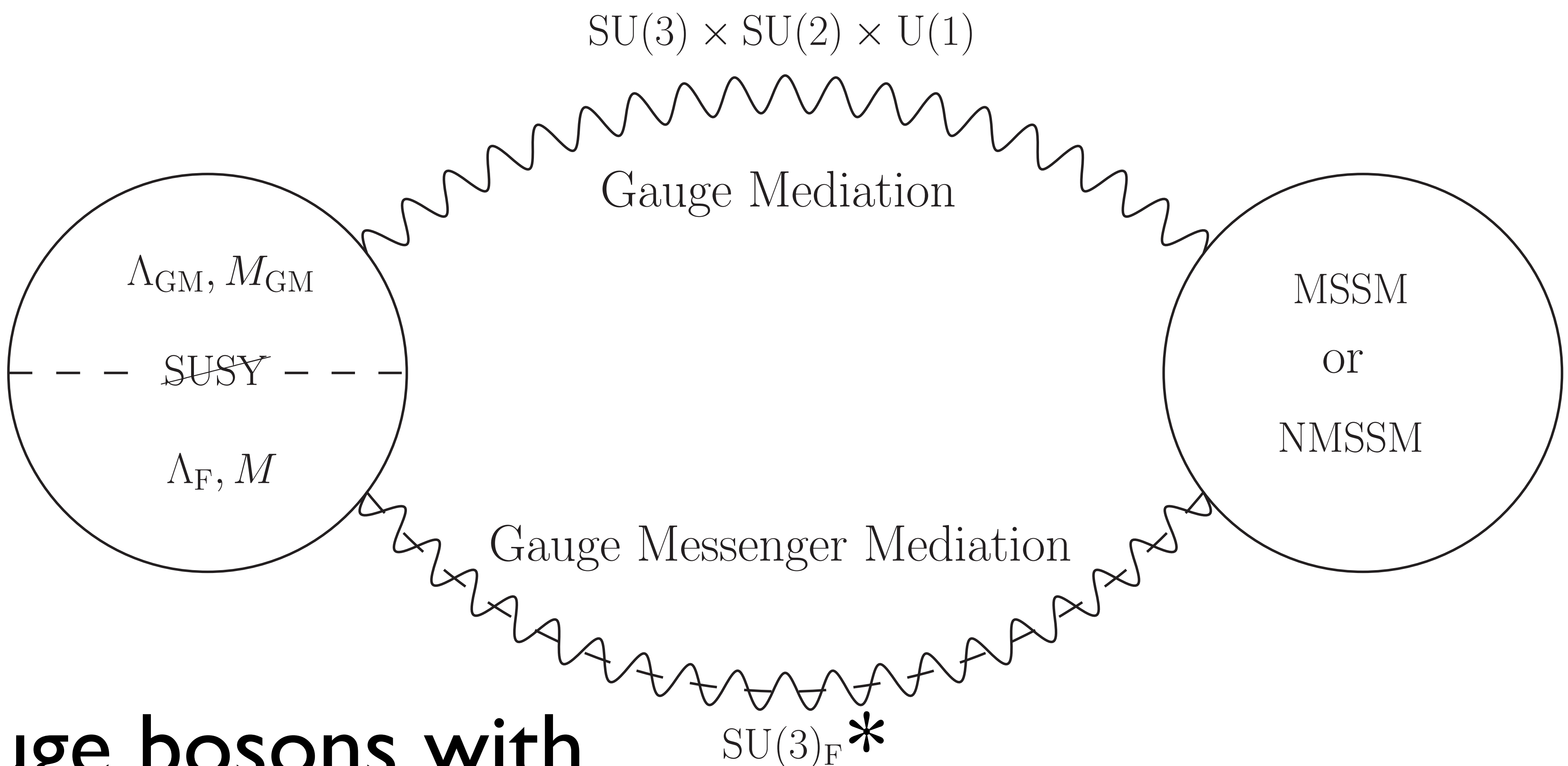



$$G_{\mathrm{SM}} = SU(3) \times SU(2) \times U(1)$$

Degenerate quarks!

# Split spectrum from flavor gauge mediation

U(1): Kaplan, Kribs '99; Craig, McCullough, Thaler '12
Brümmer, McGarrie, AW (to appear)



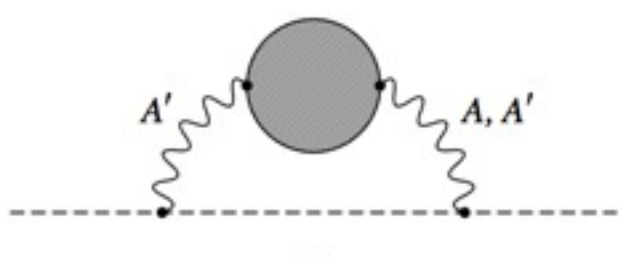

Flavor gauge bosons with flavor and susy breaking masses

* Diagonal, anomaly-free subgroup of SM w/o Yukawas
$SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$

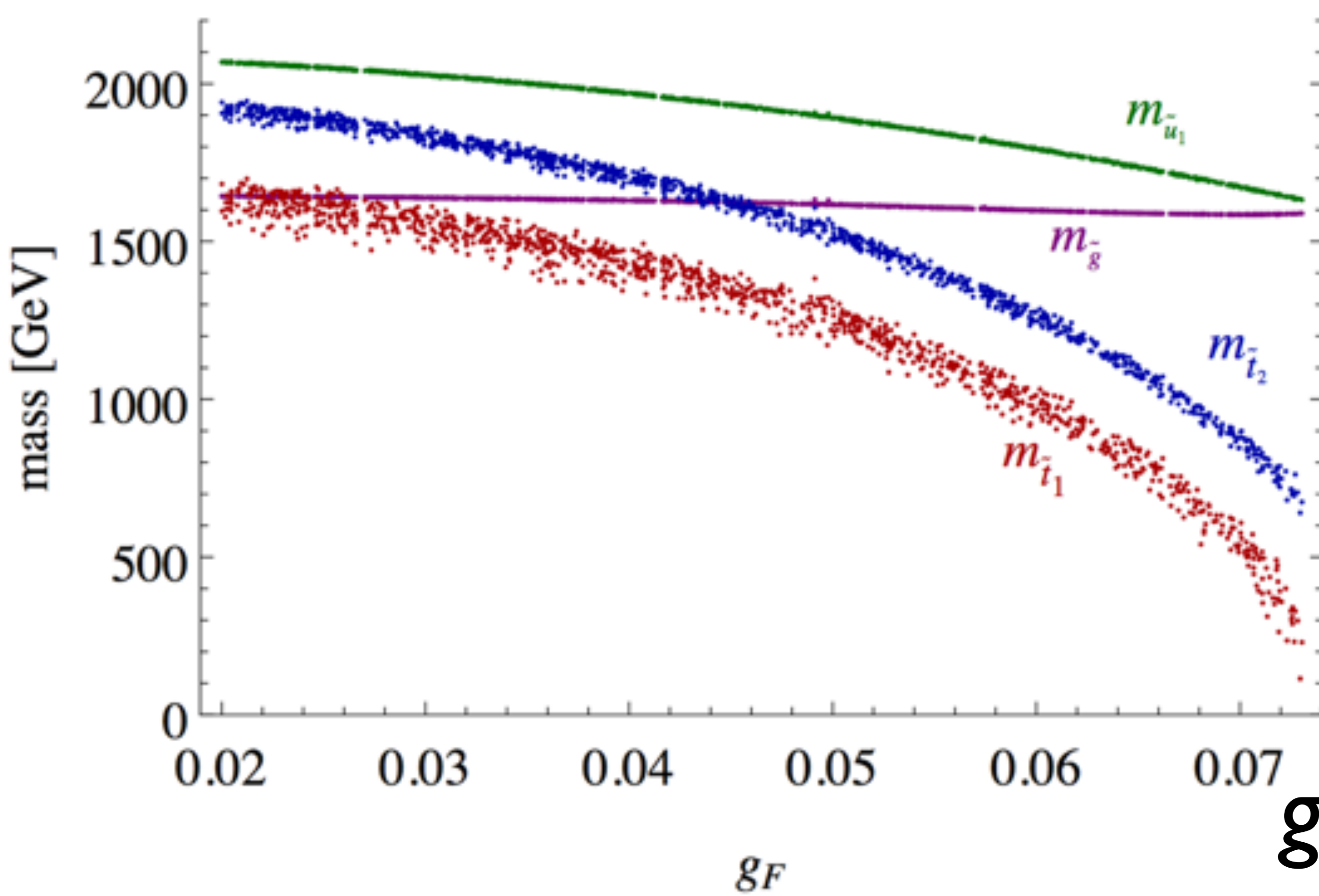
# Natural Split spectrum

Brümmer, McGarrie, Weiler (to appear)

## Negative contribution from gauge messengers



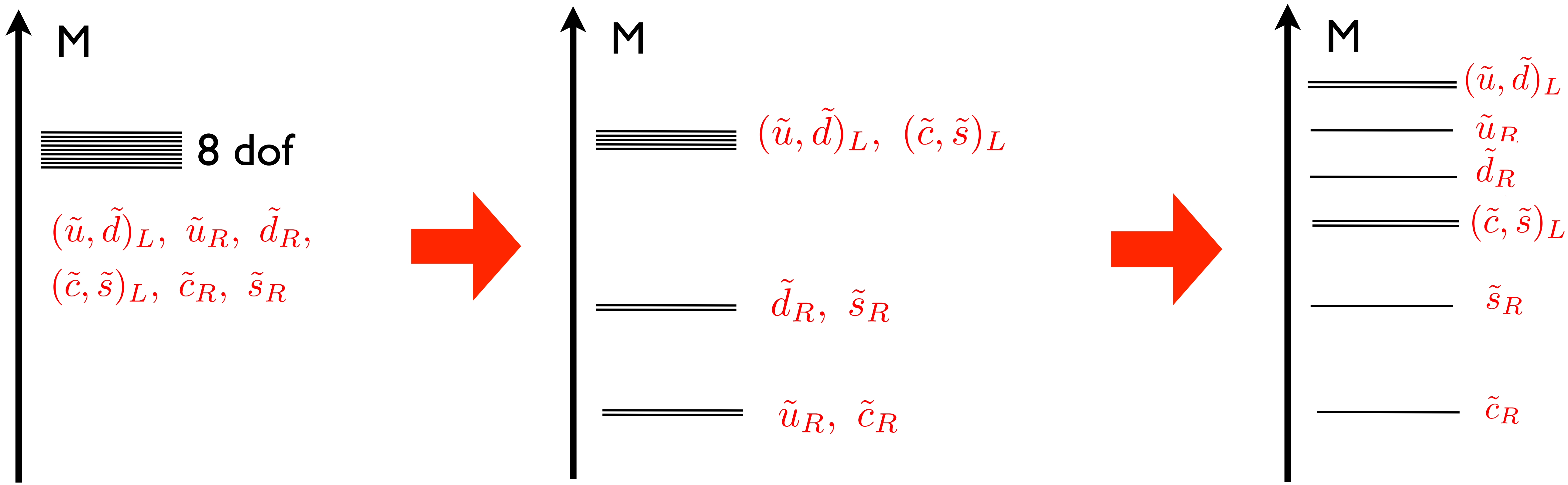

$$\delta m^2_{Q,U,D} = -\frac{g_F^2}{16\pi^2}\frac{F^2}{M^2}\left[\begin{pmatrix} \frac{7}{6} & 0 & 0 \\ 0 & \frac{7}{6} & 0 \\ 0 & 0 & \frac{8}{3} \end{pmatrix} + \mathcal{O}(\epsilon^2)\right]$$




$m_{squark12}$

$m_{stop}$

$g_{Flavor}$




Degenerate | Minimal Flavor | Anarchy!

mSugra, CMSSM,
pMSSM, . . .

Consider beyond MFV susy searches.
Sensitivity can change dramatically...

$$N_{\text{signal}} = [\text{multiplicity}] \times [\text{pdfs}] \times [\text{signal efficiency}]$$

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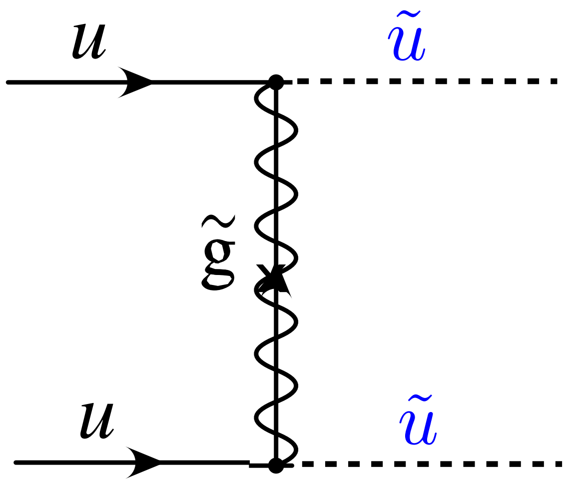
↗

8 degenerate squarks
→ 1 light squark flavor

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8 degenerate squarks

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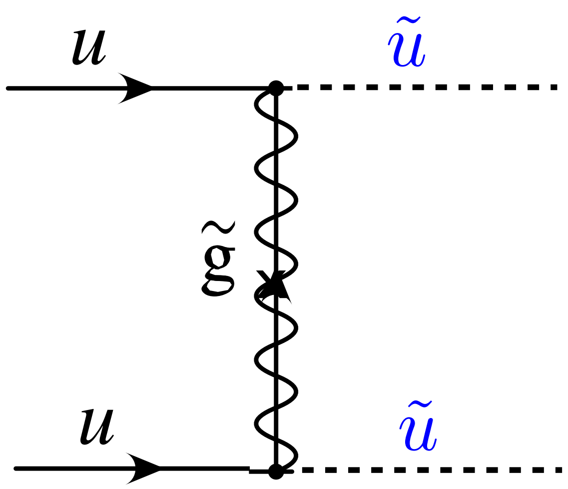


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8 degenerate squarks
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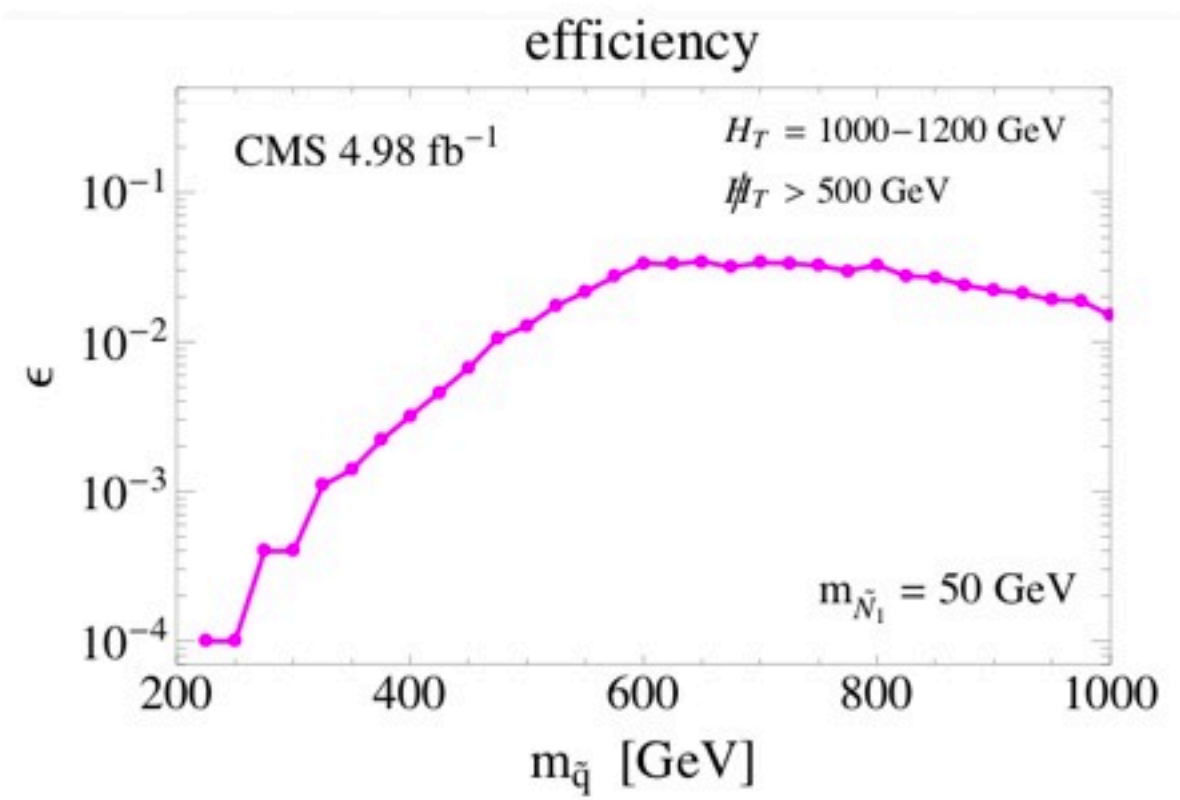
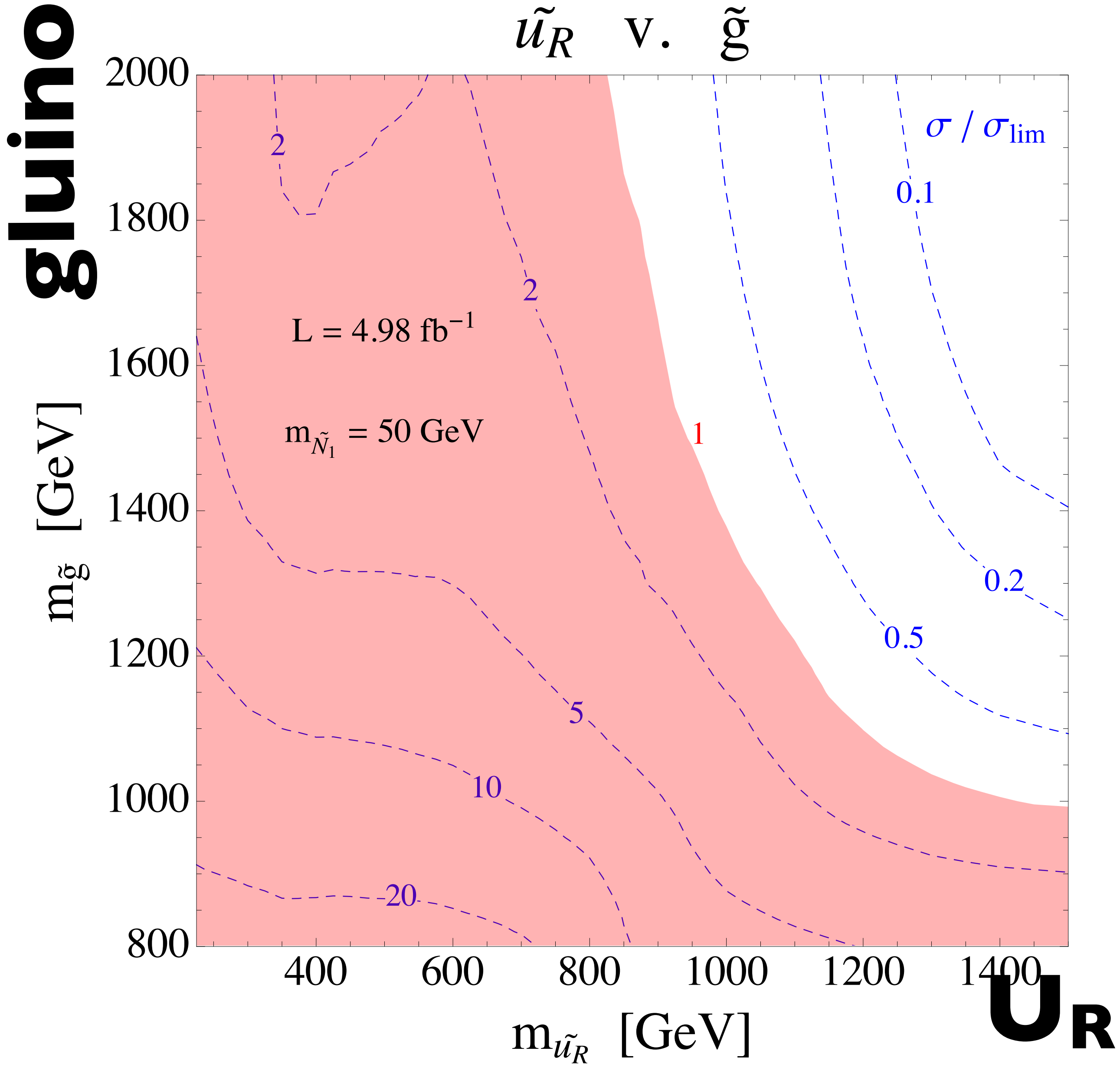
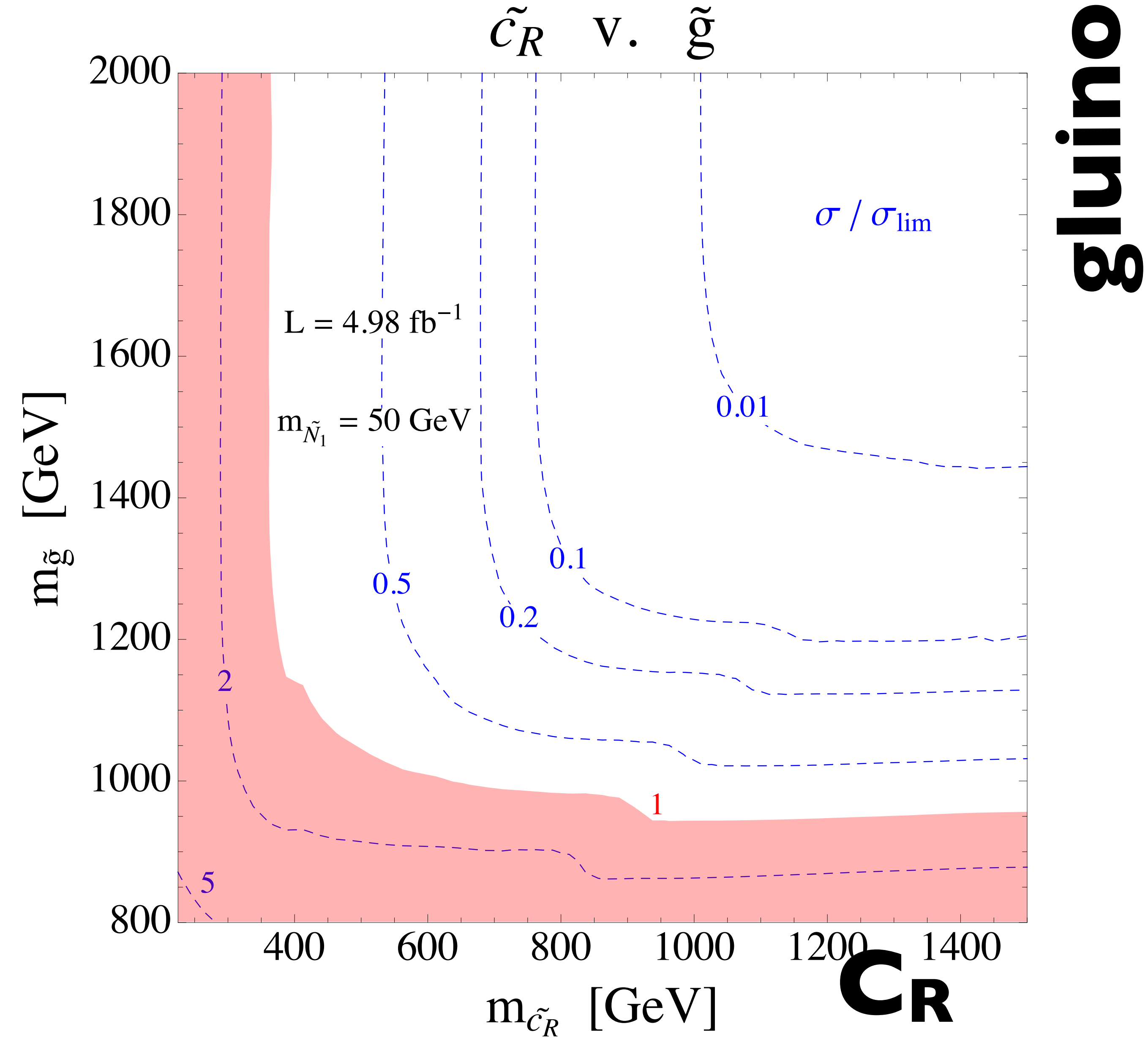
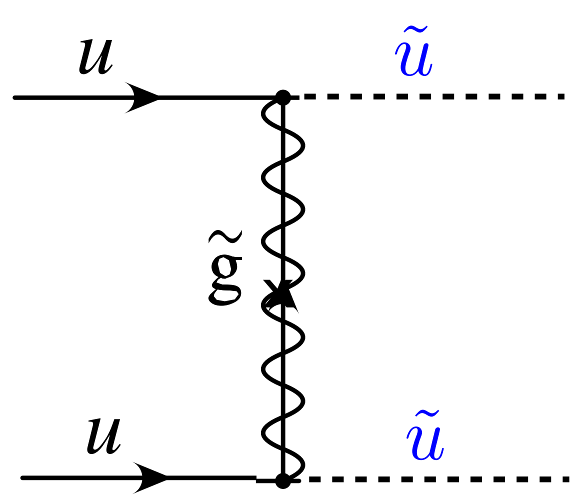


M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW

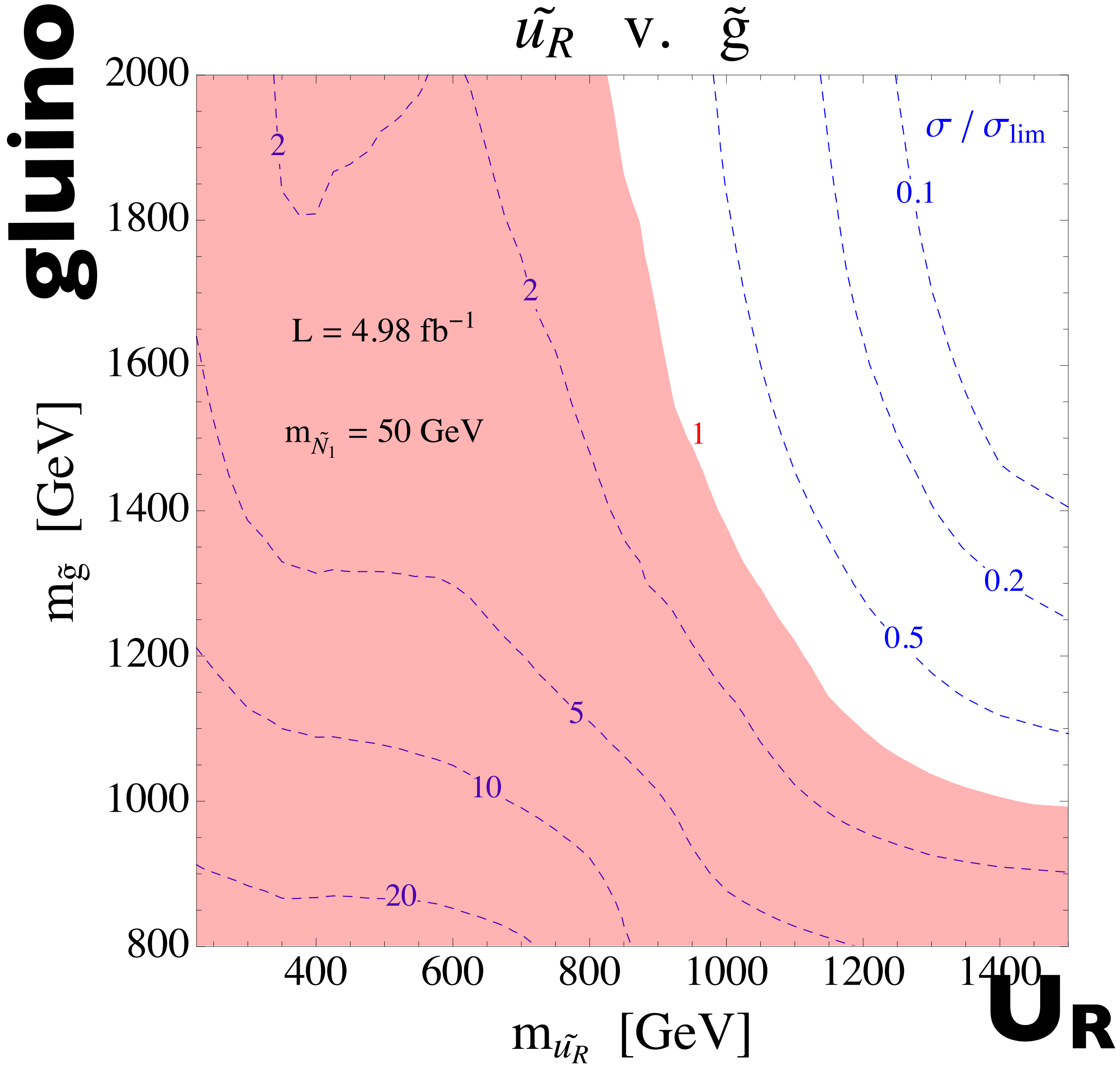


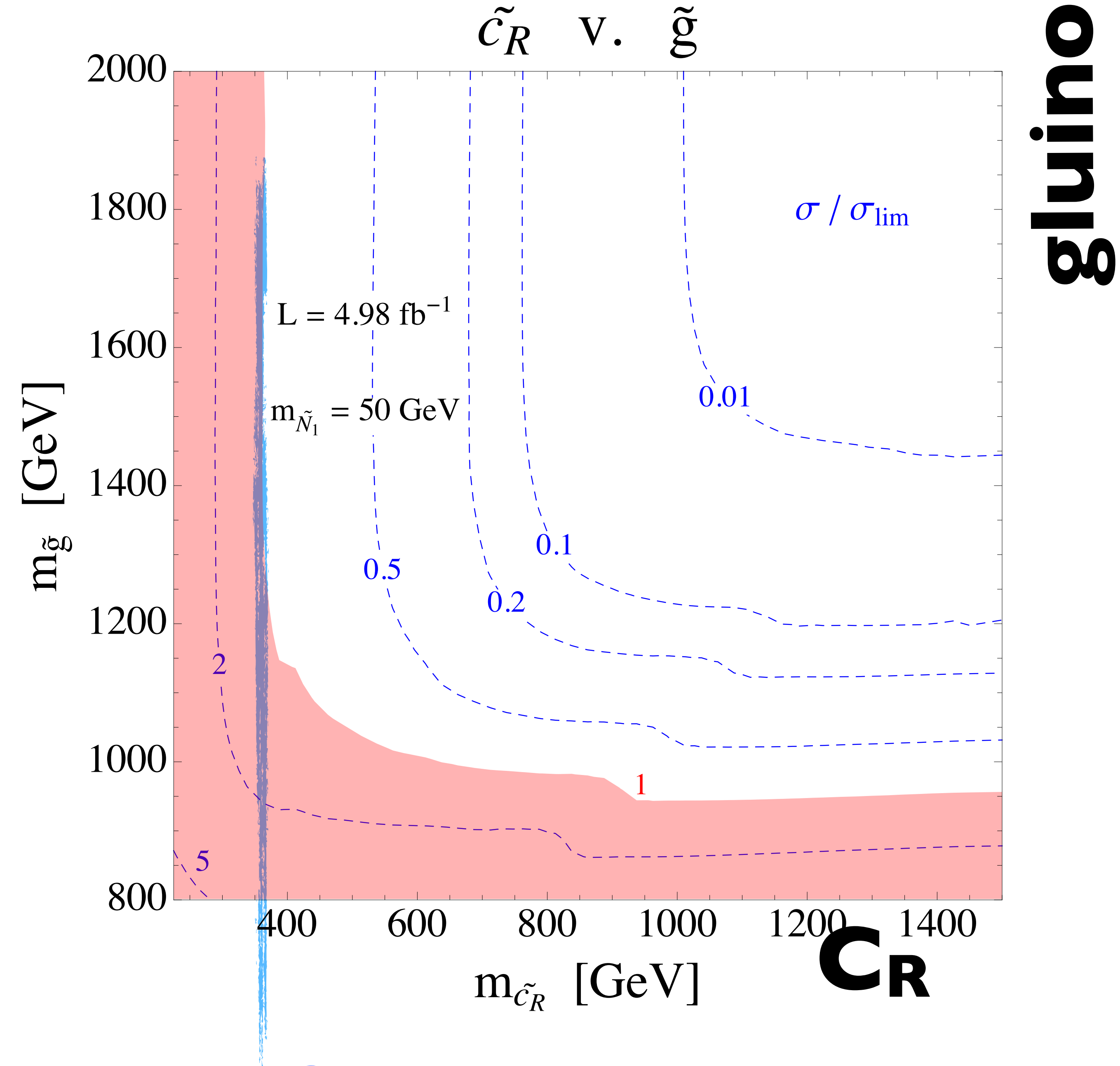



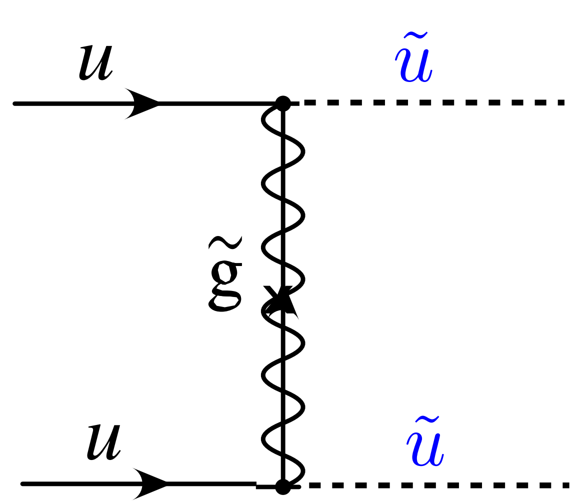




Recent update
(e.g. CMS PAS SUS-13-012)

M. Papucci, J. Ruderman
G. Perez, R. Mahbubani, AW



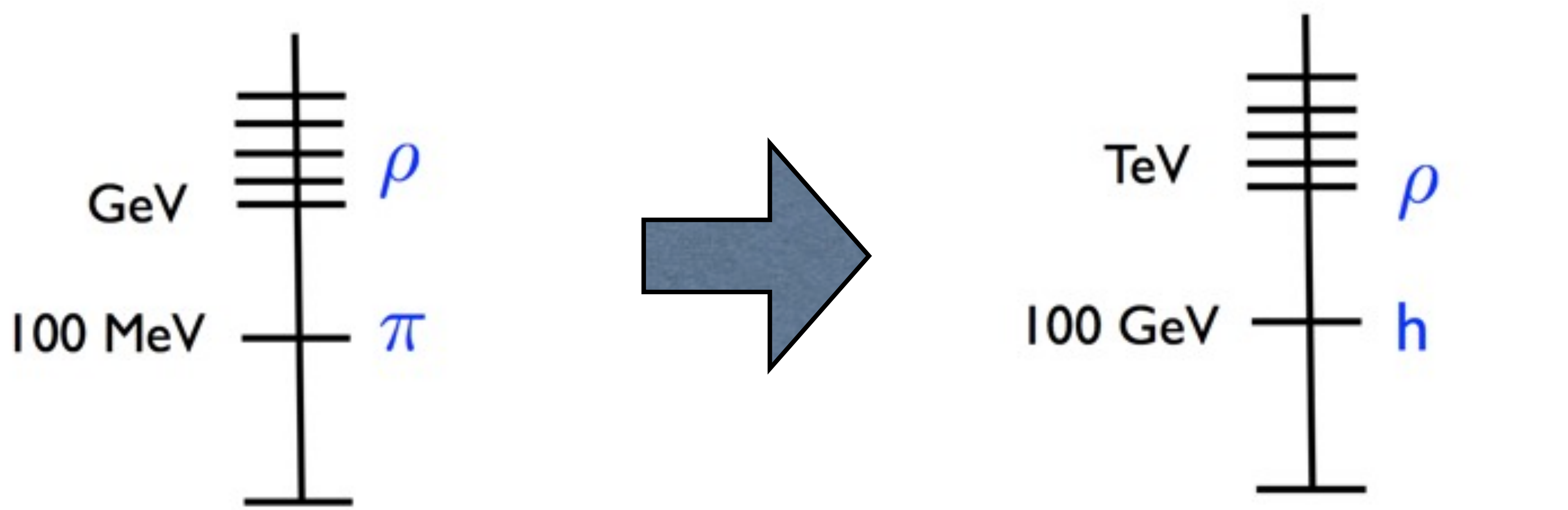




**Sea squarks can still be < 400 GeV**

Recent update
(e.g. CMS PAS SUS-13-012)

# Strong EWSB
# (Composite Higgs)




QCD

Higgs as a pGB

# Why is the Higgs light?

Kaplan; Agashe et. al

Inspired by QCD: (pseudo) scalar pion is the lightest state

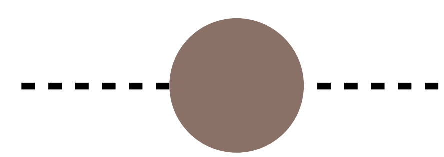
Shift symmetry…

$$\pi \to \pi + c$$

… protects its mass.

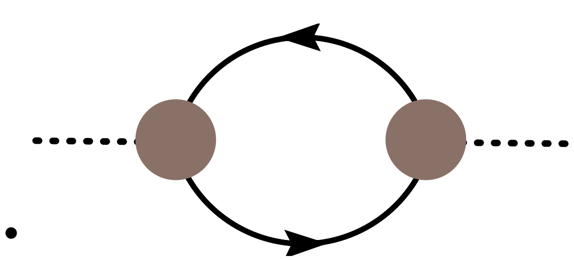
Interactions are perturbative for $E \ll 4\pi f$

No pure composite effects due to Goldstone symmetry



= 0

Shift symmetry broken by elementary-composite couplings:



$$m_h^2 \sim \frac{\lambda^2}{16\pi^2} \Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

# Light Higgs implies light fermionic top partners

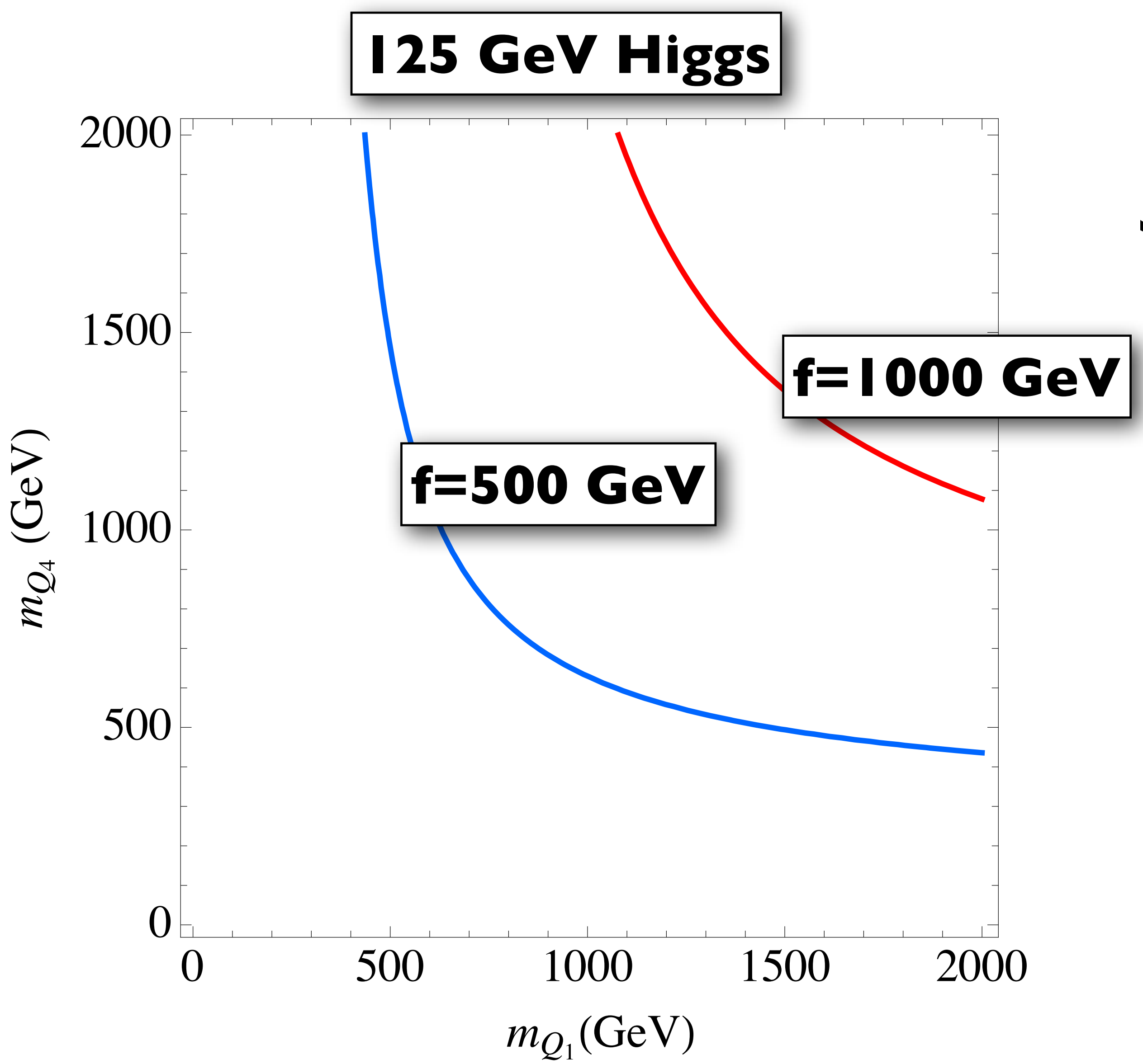
$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

Pomarol, Riva 12

# Light Higgs implies light fermionic top partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

Pomarol, Riva 12




5 = 4 + 1

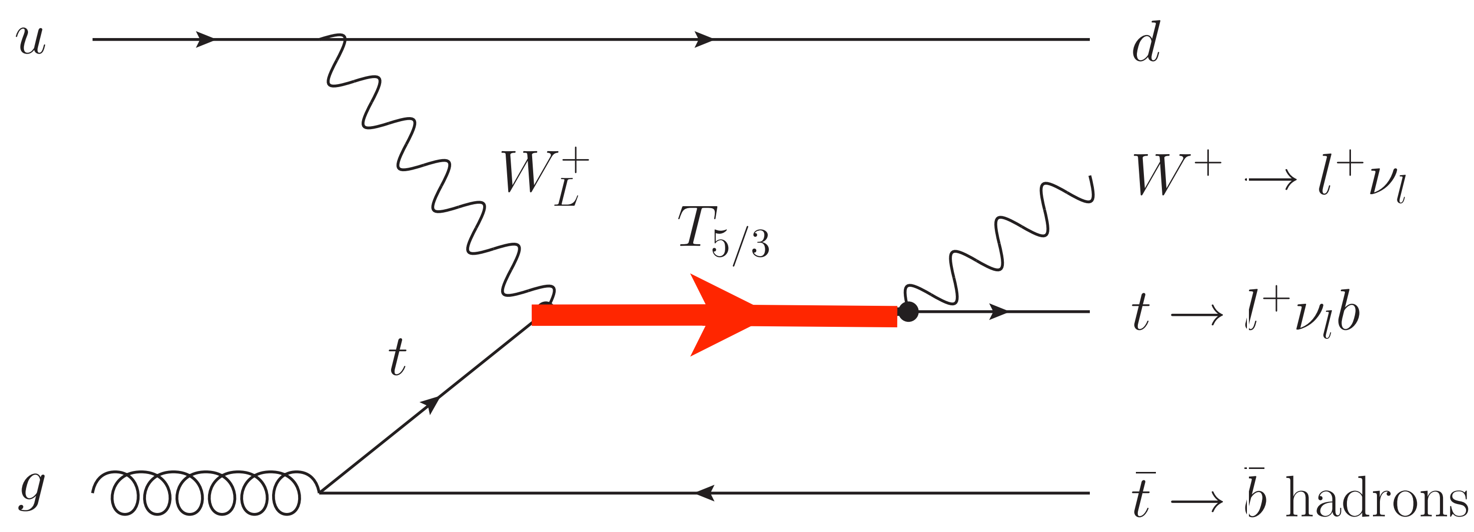
$Q_4$ $Q_1$

with EM charges 5/3, 2/3,-1/3

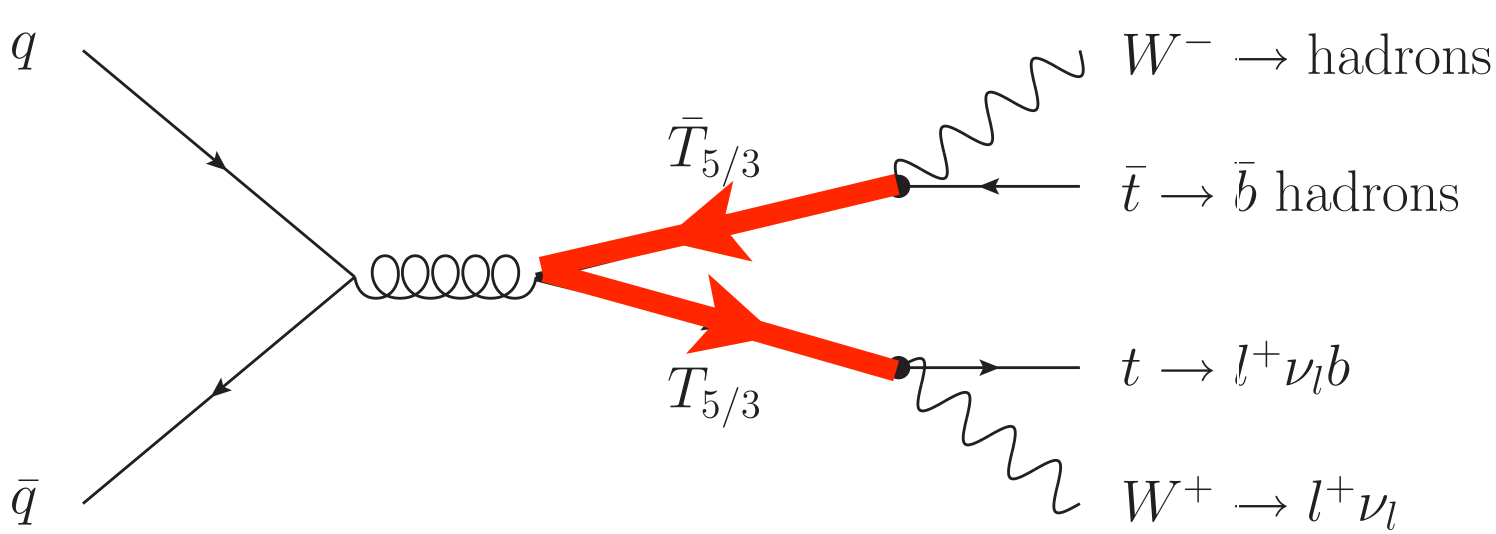
Contino et al; Pomarol, Riva; Matsedonskyi,Panico,Wulzer; Redi,Tesi; Marzocca,Serone,Shu;

e.g. Perelstein, Pierce, Peskin
Contino, Servant; Mrazek, Wulzer;
De Simone, Matsedonkyi, Rattazzi, Wulzer

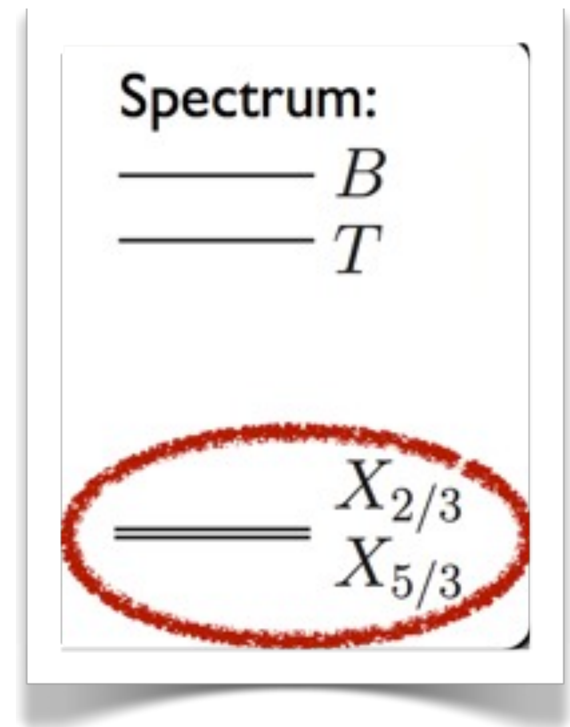
$T_{5/3}$



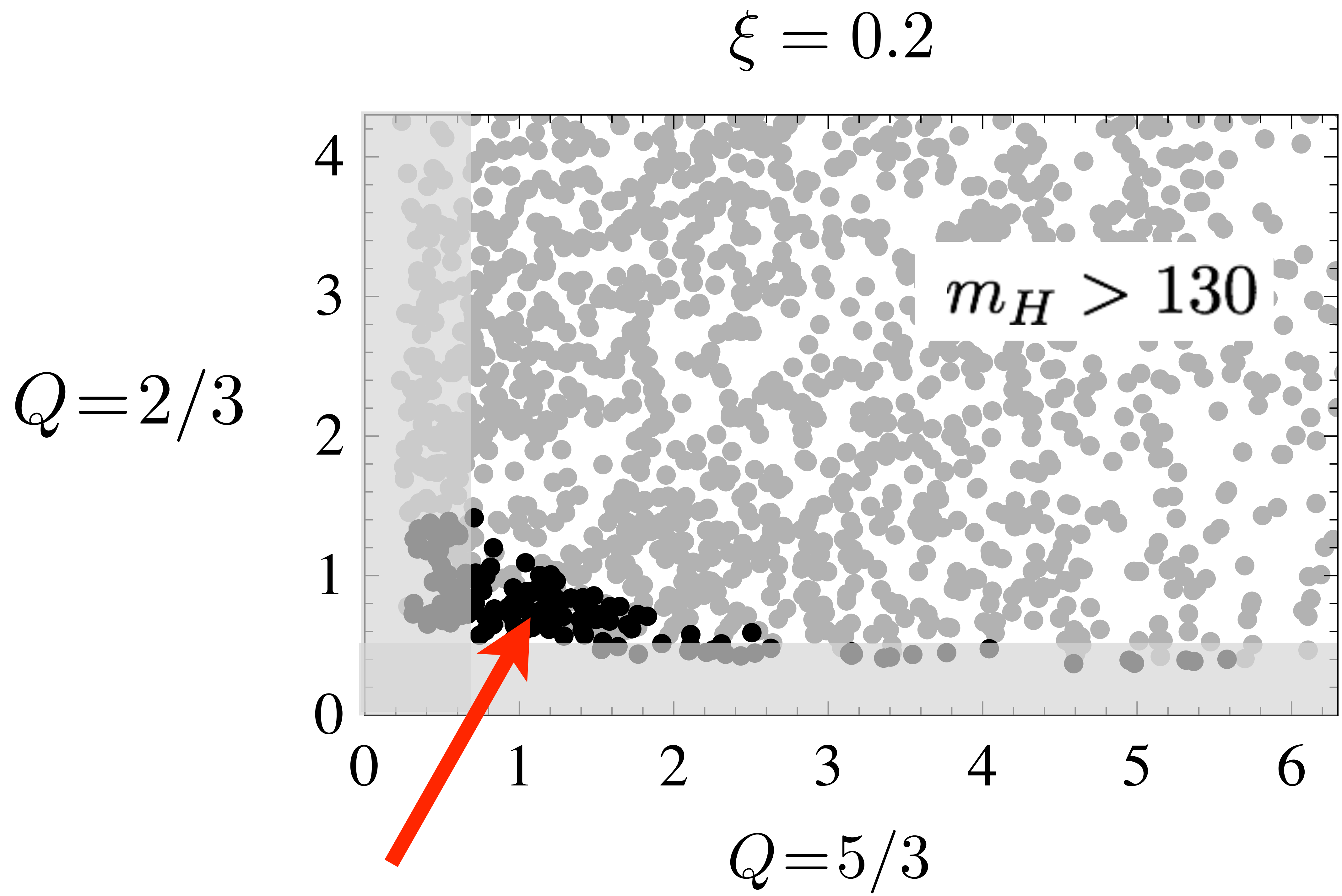

Single




Double



from 1204.6333




$m_H$ = 115 … 130 GeV

see e.g. ATLAS-CONF-2013-051

# Flavor used to be a show-stopper

CPV in Kaon mixing

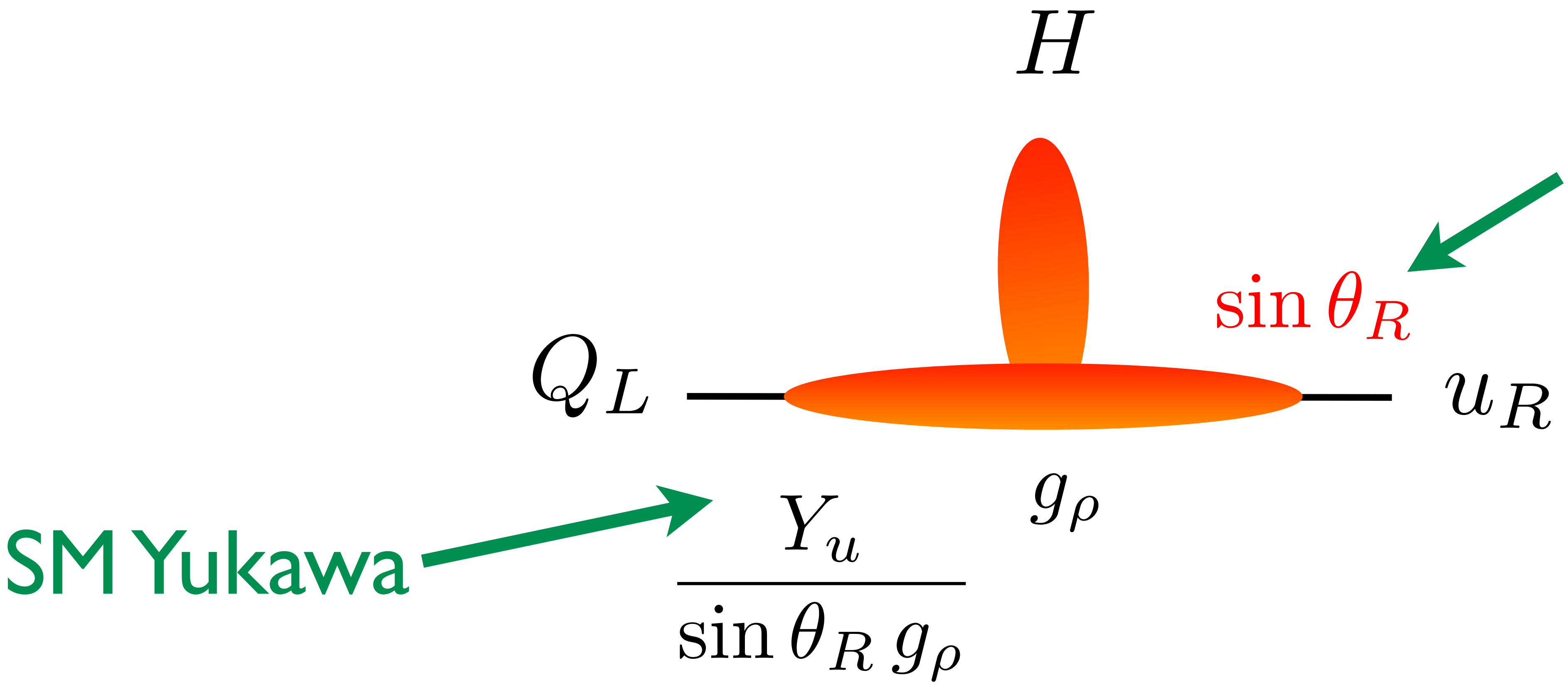
$$|\epsilon| = 2.3 \times 10^{-3} \implies \frac{M_{ETC}}{g_{ETC}\sqrt{\mathrm{Im}(V_{sd}^2)}} \gtrsim 16,000\,\mathrm{TeV}$$

$$m_{q,\ell,T}(M_{ETC}) \simeq \frac{g_{ETC}^2}{2M_{ETC}^2}\langle\bar{T}T\rangle_{ETC} \lesssim \frac{0.1\,\mathrm{MeV}}{|V_{sd}|^2 N^{3/2}}$$

**vs. $m_{top}$**

# A Minimal Flavor Violating Composite Higgs

Redi/AW*




*for RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al

# A Minimal Flavor Violating Composite Higgs

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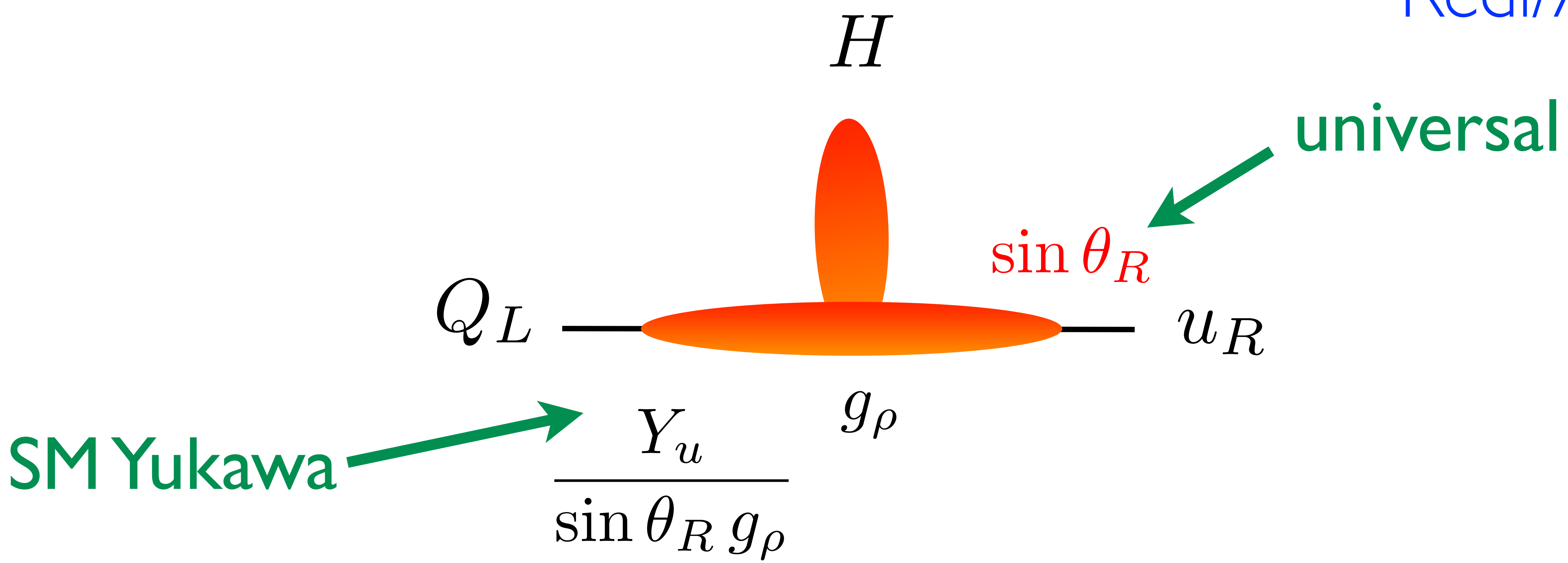
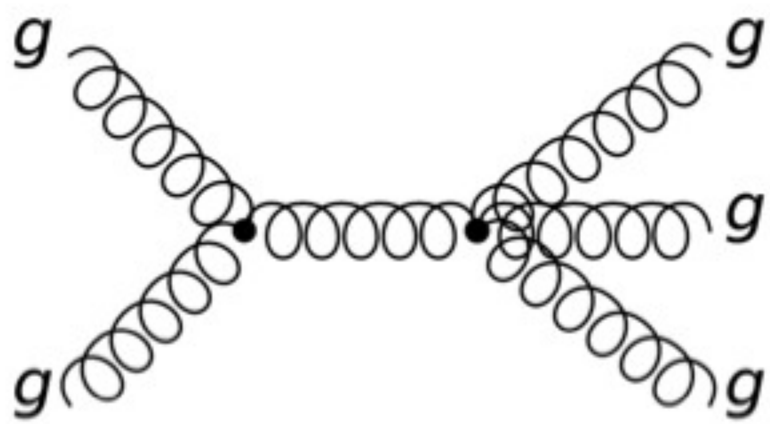
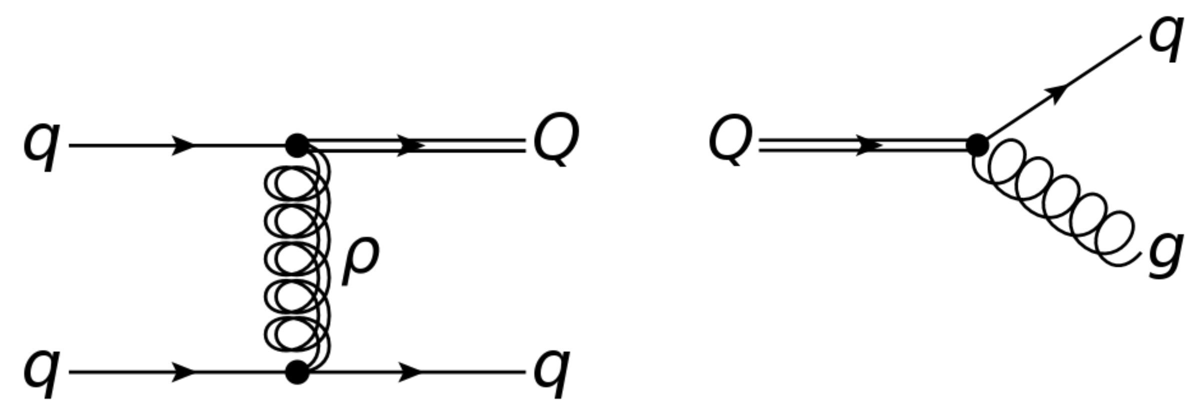



Composite *u,d* quarks, spectacular signals!

$m_{top}$ :  $$\sin\theta_R \gtrsim \frac{1}{g_\rho} \sim \frac{1}{8}$$

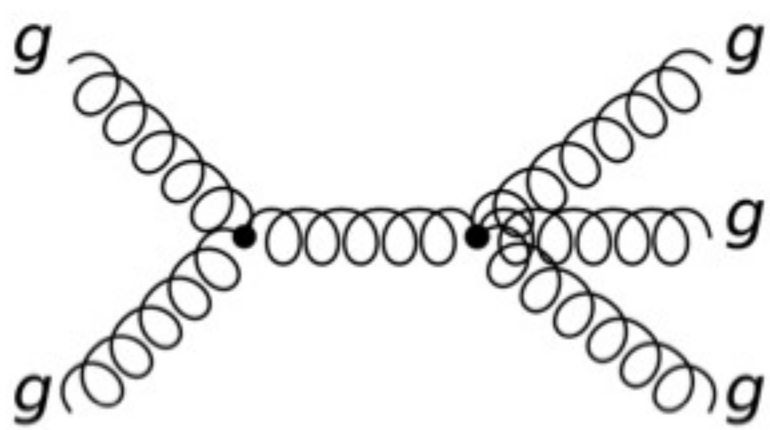
*for RS realization: Csaki,AW et al; Delaunay et al; da Rold; see also Barbieri et al



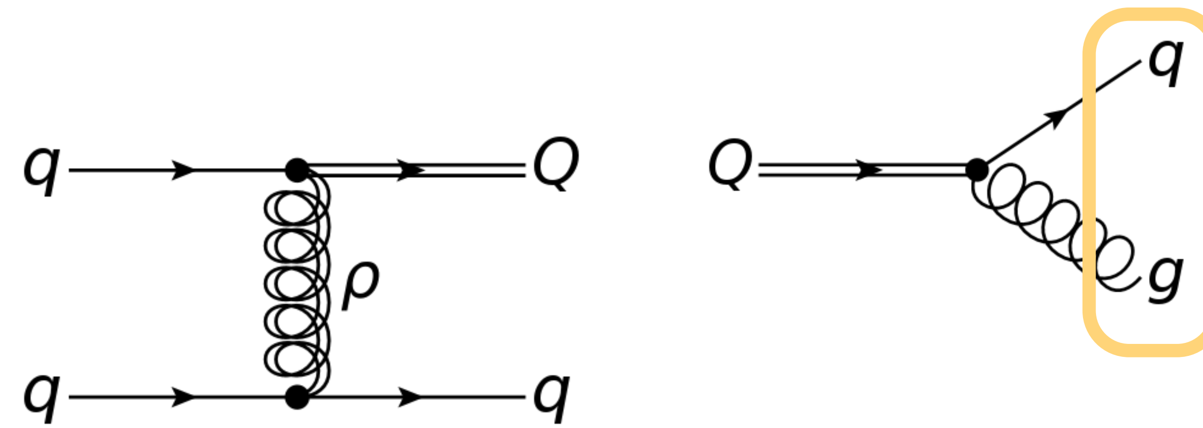

QCD vs. Composite Partners

bump in sub-leading jets




QCD

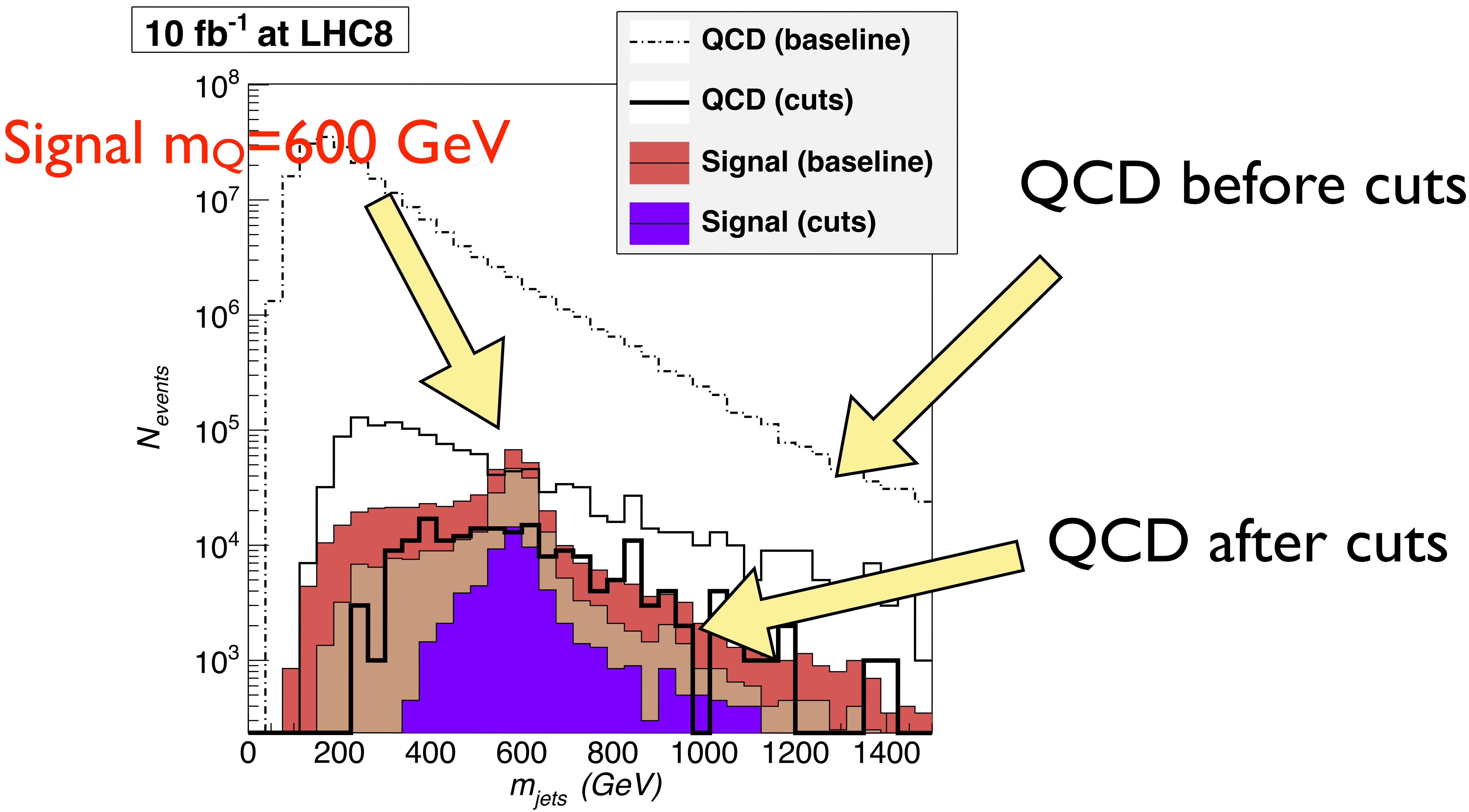
vs.




Composite Partners

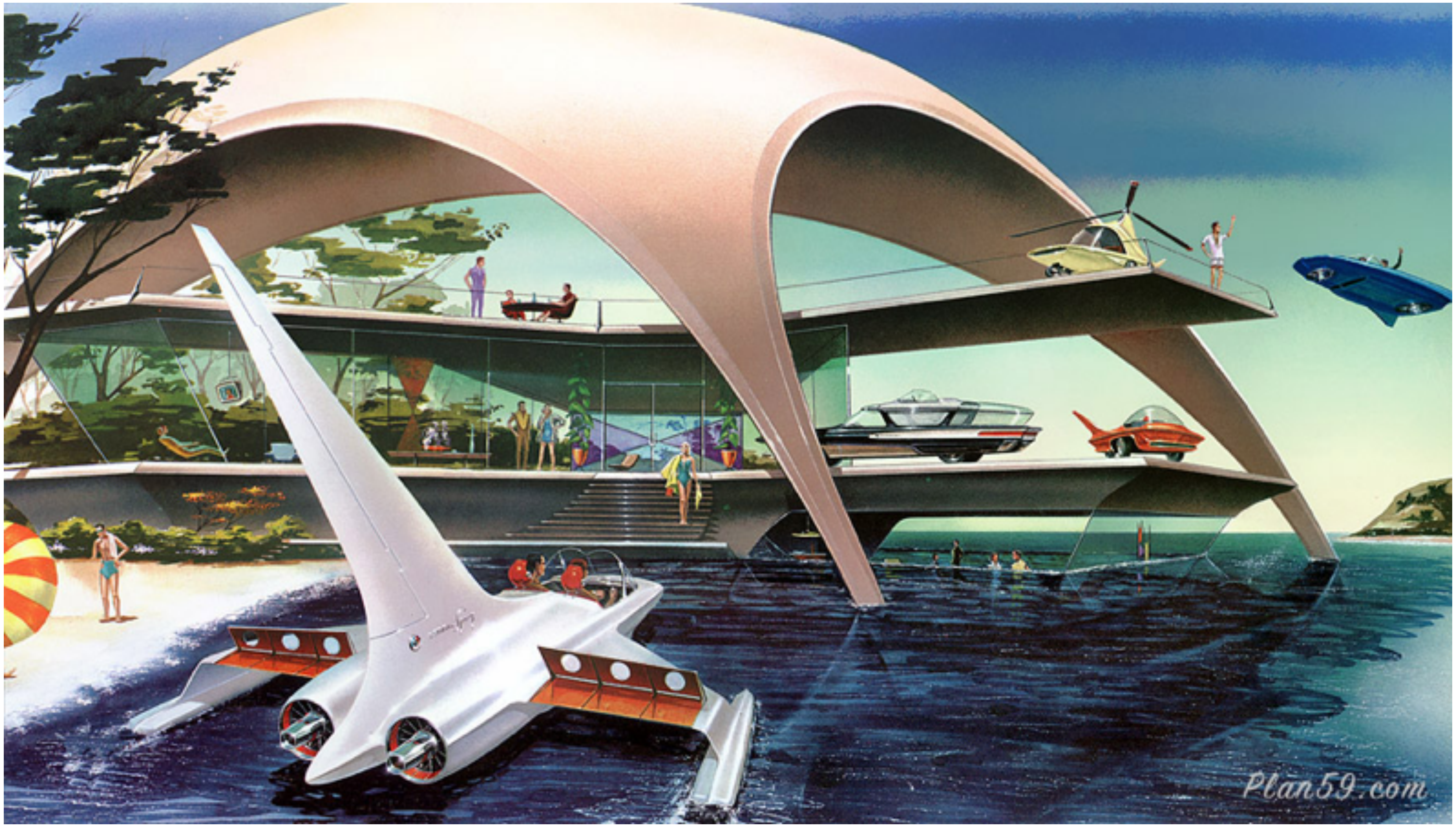
# Discovery potential of a dedicated search

deVries, Redi, Sanz, AW, '13

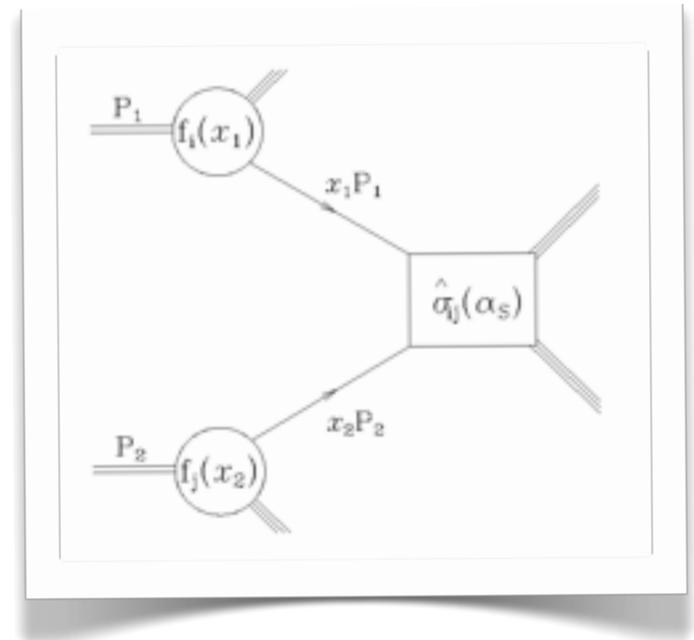



heavier signal easier, 3jet final state easier, no optimization

# The Future



# What will we be sensitive to?




Simple exercise, parton luminosities:

$$\sigma(M^2) = \sum_{i,j} \int_{M^2/s}^{1} d\tau \, \mathcal{L}_{ij}(\tau) \, \hat{\sigma}(s\tau)$$

Partonic cross-section scales as $\hat{\sigma} \propto \frac{1}{M^2}$

with $M = \sqrt{\hat{s}}, \; M_{Z'}, \; 2\, m_{\text{squark}}, \ldots$

# Mass reach?

$$\frac{N_{\text{events}}(M^2_{\text{high}}, s_{\text{high}}, L_{\text{high}}[\text{fb}^{-1}])}{N_{\text{events}}(M^2_{\text{low}}, s_{\text{low}}, L_{\text{low}}[\text{fb}^{-1}])} = 1$$

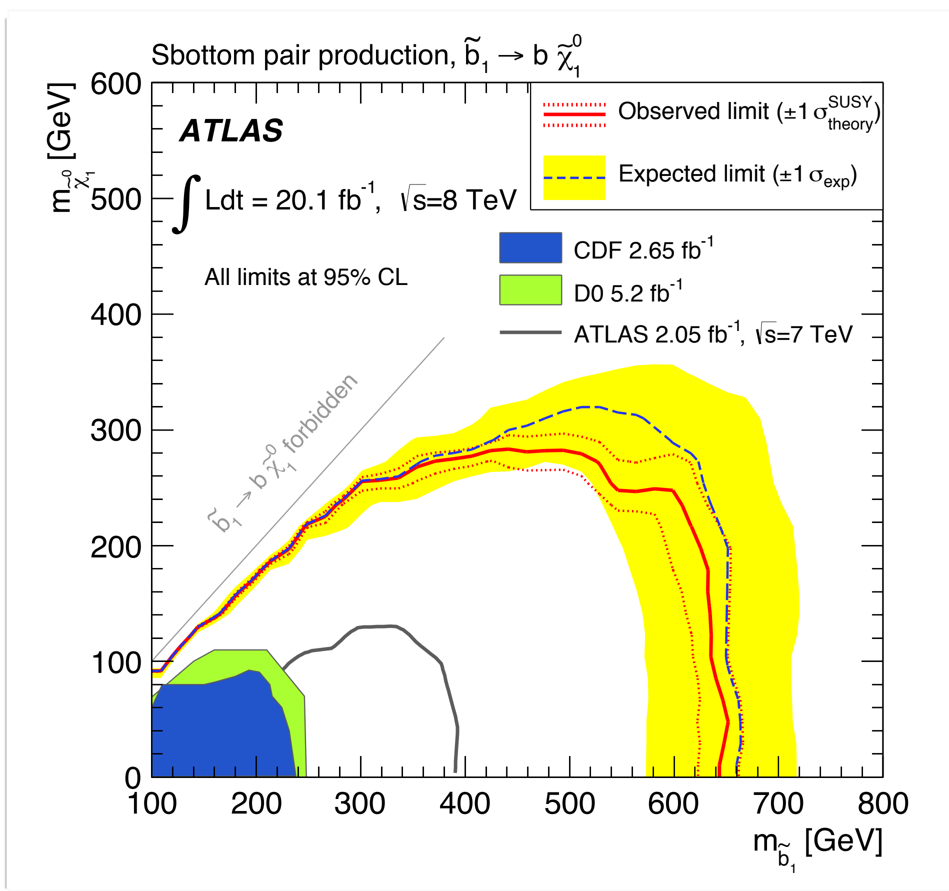
Solve for $M^2_{\text{high}}$ .

# Check: ATLAS direct sbottom

$[95\% CL, m_{LSP} = 0\,\mathrm{GeV}]$

$7\,\mathrm{TeV},\ 2.05\,\mathrm{fb}^{-1}$ **>400 GeV**

ATLAS



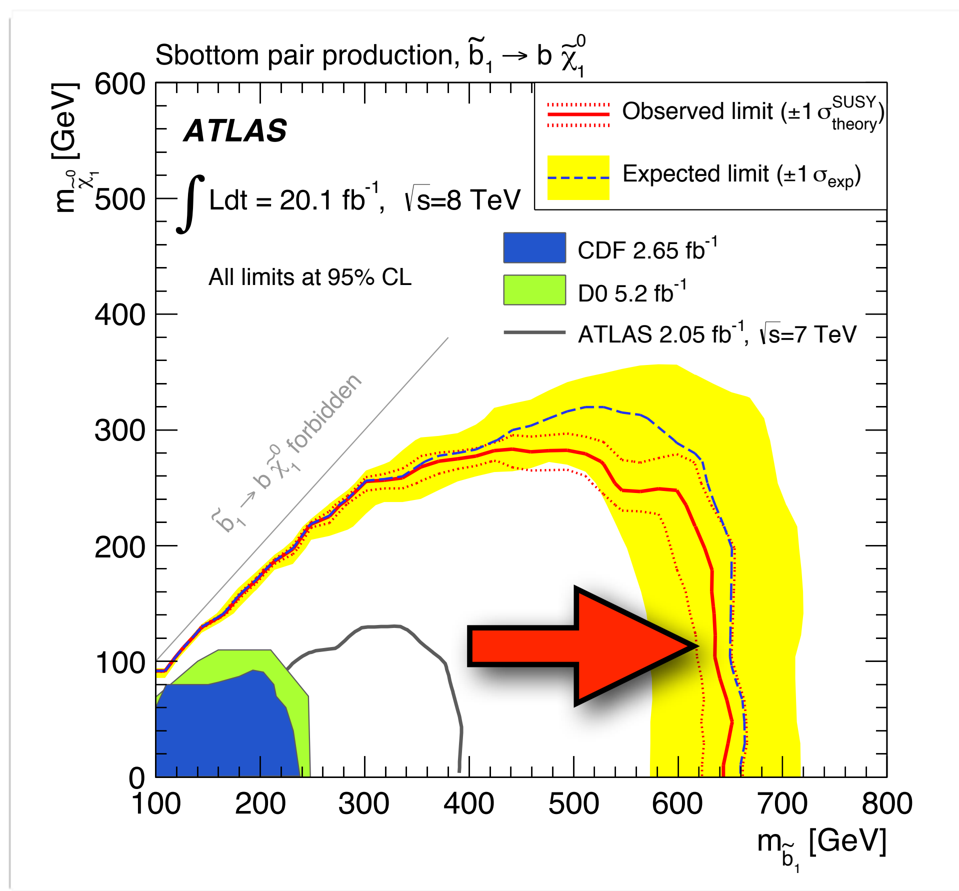

1308.2631

# Check: ATLAS direct sbottom

$[95\% CL, m_{LSP} = 0\,\mathrm{GeV}]$

$7\,\mathrm{TeV},\ 2.05\,\mathrm{fb}^{-1}$ >400 GeV
ATLAS

$8\,\mathrm{TeV},\ 20.1\,\mathrm{fb}^{-1}$ >640 GeV
ATLAS




1308.2631

# Check: ATLAS direct sbottom

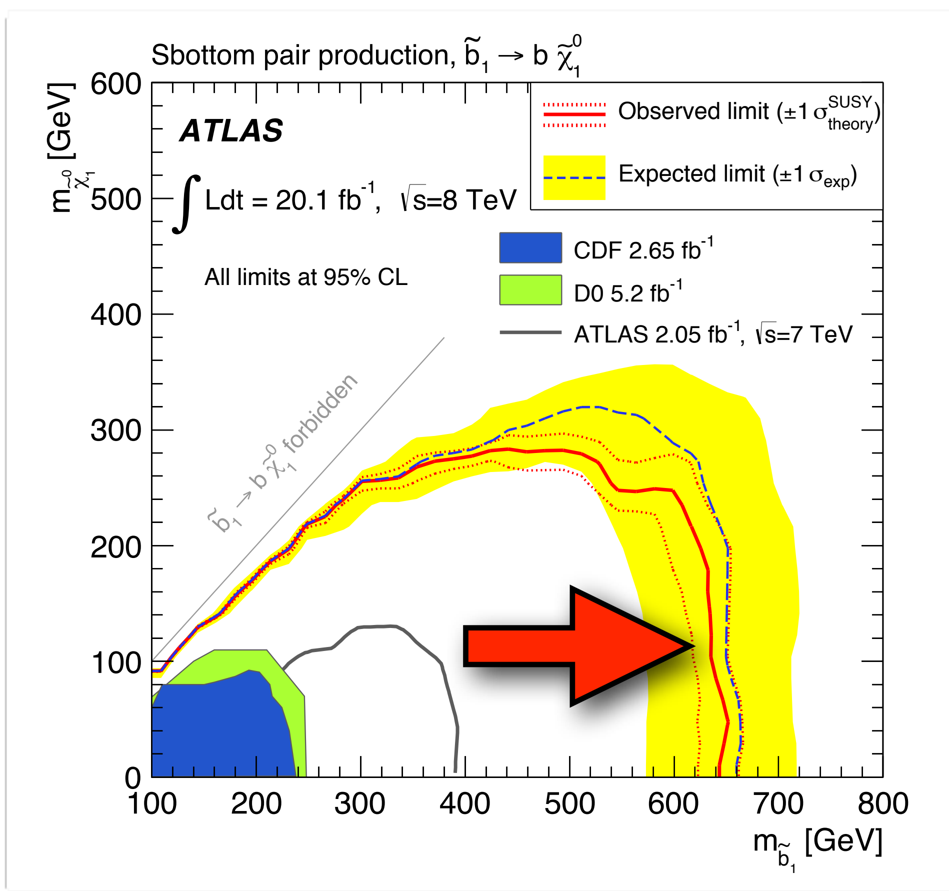
$[95\% CL, m_{LSP} = 0\,\mathrm{GeV}]$

$7\,\mathrm{TeV},\ 2.05\,\mathrm{fb}^{-1}$ >400 GeV
ATLAS

$8\,\mathrm{TeV},\ 20.1\,\mathrm{fb}^{-1}$ >640 GeV
ATLAS

>620 GeV ✓
parton lumi

Parton luminosity estimate using gg-pdf's




1308.2631

# 8 TeV, 20 $fb^{-1}$ → 14 TeV, 300 $fb^{-1}$

G. Salam, AW

**Gluon** initiated processes (e.g. direct stop/sbottom)

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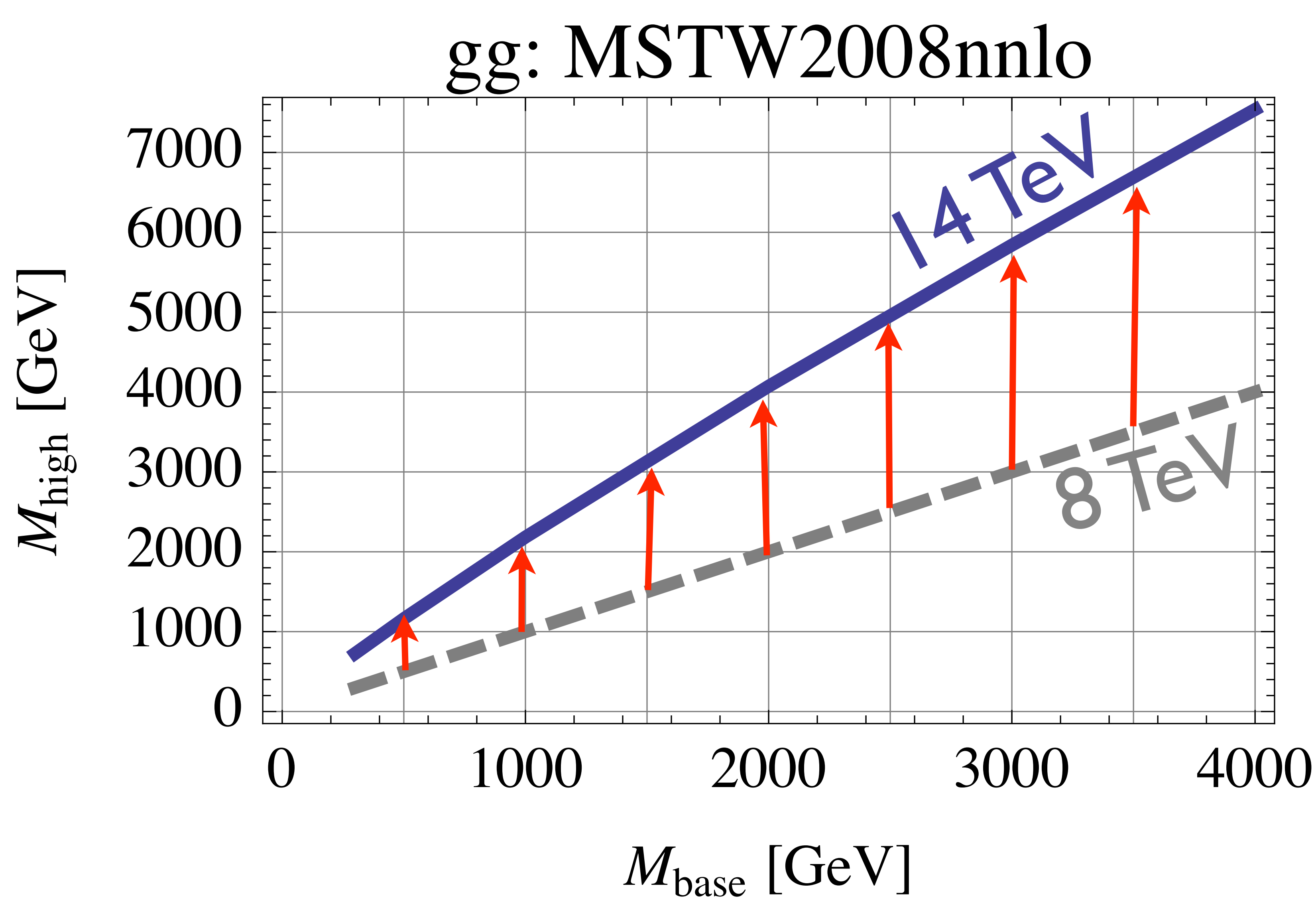

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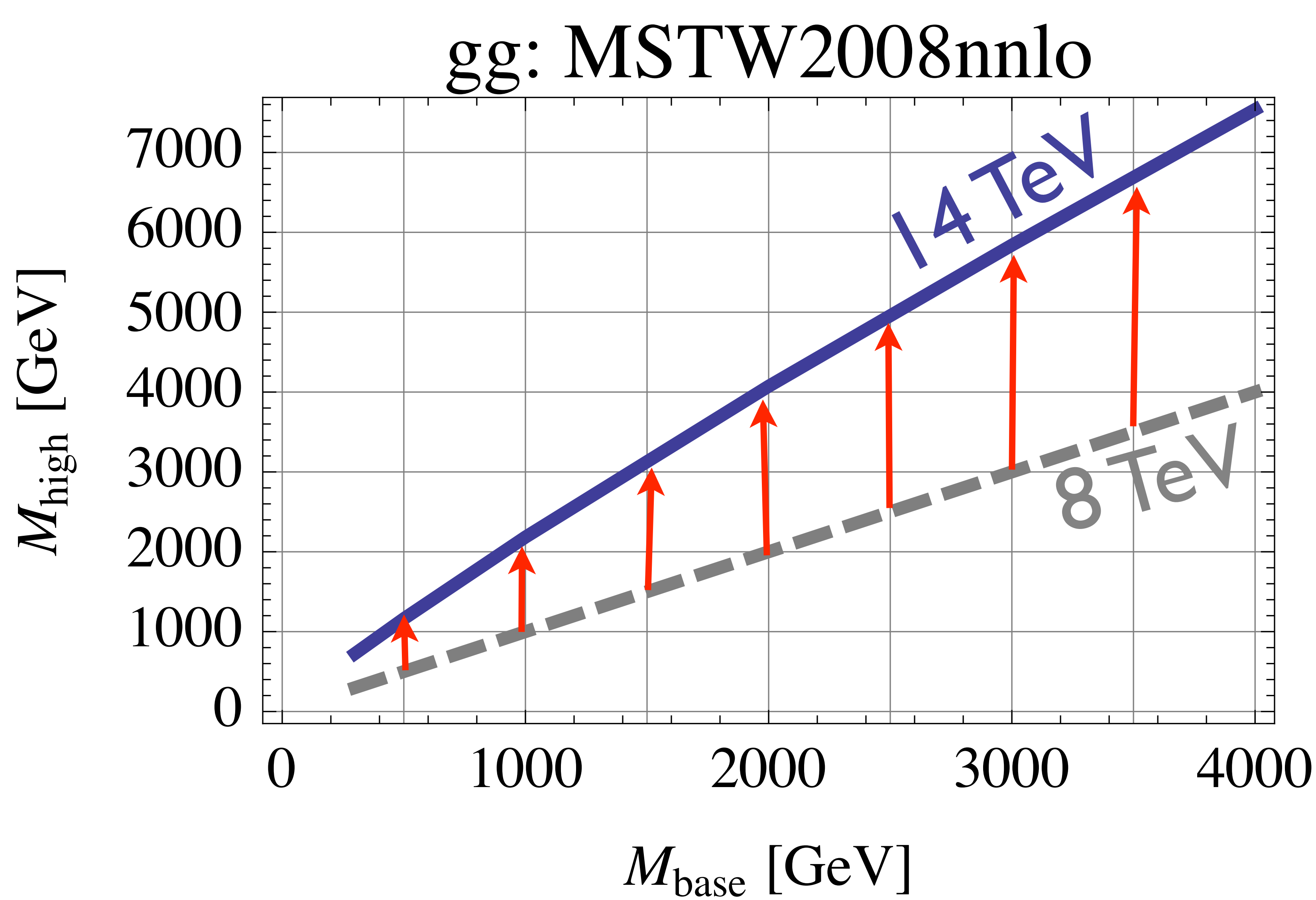
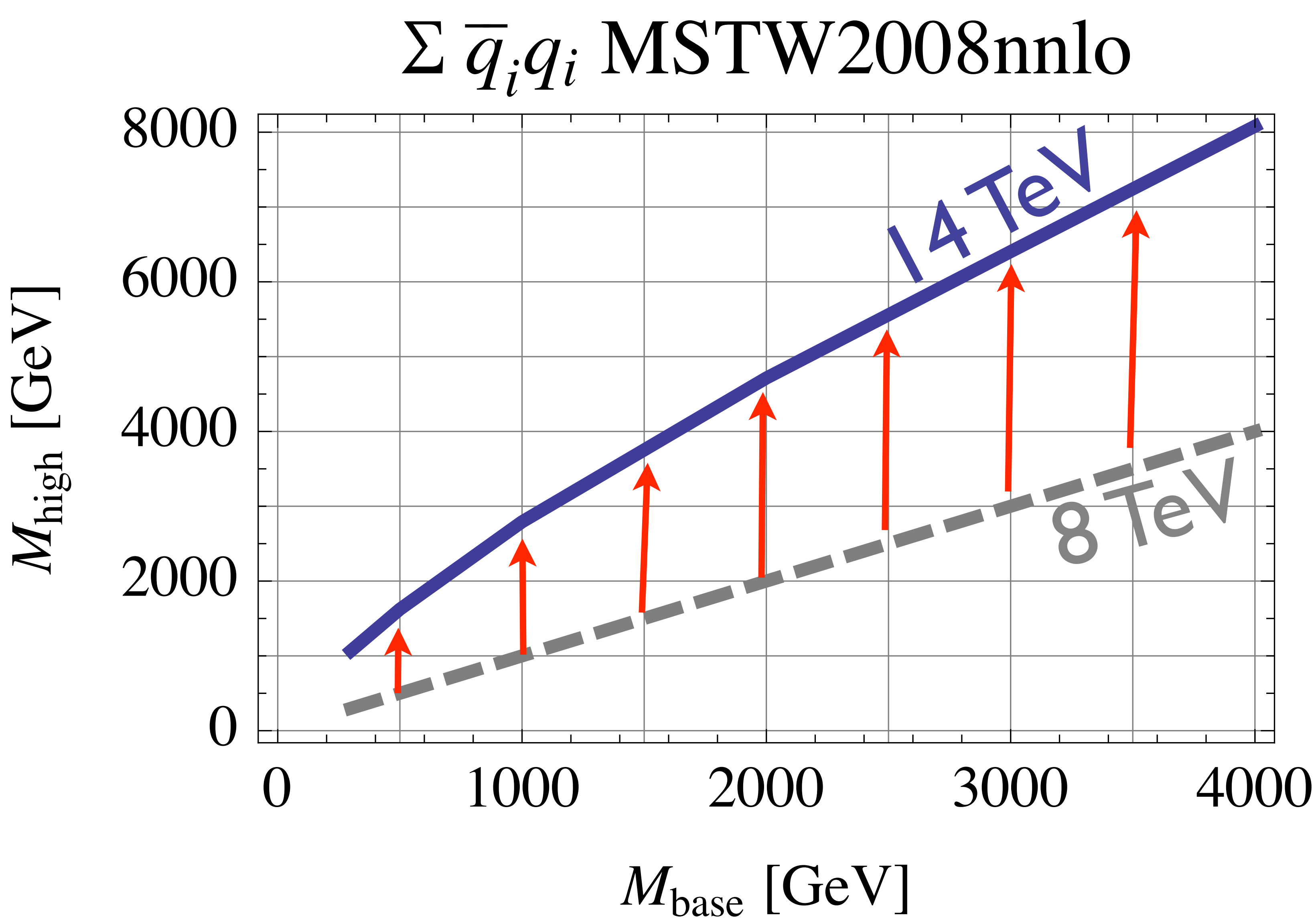



| 20 fb$^{-1}$ $M_{7TeV}$ | 300 fb$^{-1}$ $M_{14TeV}$ |
|---|---|
| 500 | 1150 |
| 1000 | 2200 |
| 2000 | 4100 |

# 8 TeV, 20 fb$^{-1}$ → 14 TeV, 300 fb$^{-1}$

G. Salam, AW

$\sum_i \bar{q}_i q_i$ initiated processes (e.g. Z', … )




| 20 fb$^{-1}$ | 300 fb$^{-1}$ |
|---|---|
| $M_{7TeV}$ | $M_{14TeV}$ |
| 500 | 1600 |
| 1000 | 2800 |
| 2000 | 4750 |

# High luminosity LHC

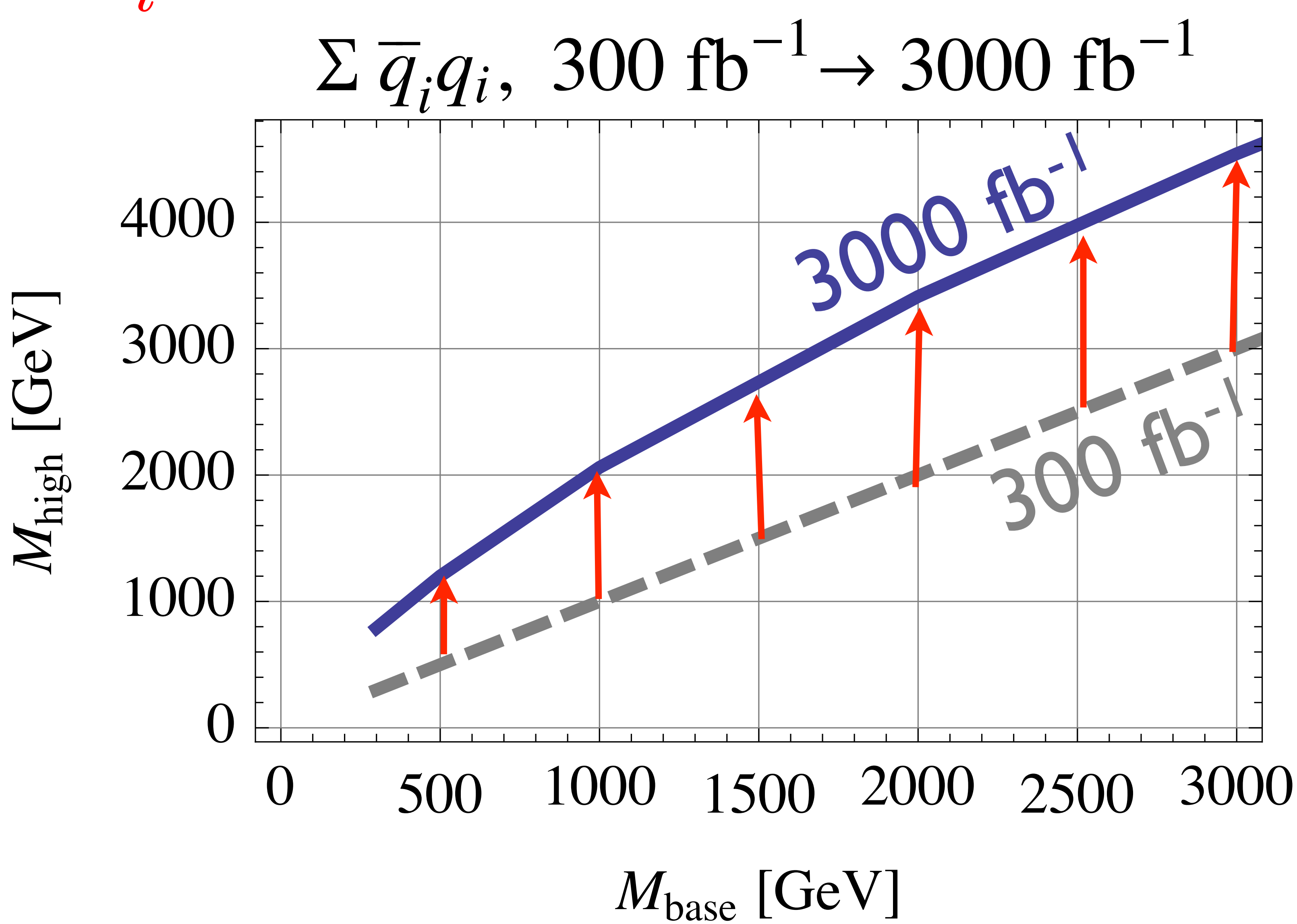
300 $fb^{-1}$ → 3000 $fb^{-1}$ @ 14 TeV

# HL-LHC

# 300 $fb^{-1}$ → 3000 $fb^{-1}$ @ 14 TeV

G. Salam, AW

$\sum_i \bar{q}_i q_i$ initiated processes (e.g. Z', … )




| 14 TeV $M_{300\ ifb}$ | 14 TeV $M_{3000\ ifb}$ |
|---|---|
| 300 | 800 |
| 500 | 1200 |
| 1000 | 2050 |
| 2000 | 3400 |

# HL-LHC

# 300 fb$^{-1}$ → 3000 fb$^{-1}$ @ 14 TeV

G. Salam, AW

$\sum_i \bar{q}_i q_i$ initiated processes (e.g. Z', … )

Impressive relative improvement for lower x-sec processes (e.g. EW production, rare decays, difficult spectra, … )

| 14 TeV | 14 TeV |
|---|---|
| $M_{300\ ifb}$ | $M_{3000\ ifb}$ |
| 300 | 800 |
| 500 | 1200 |
| 1000 | 2050 |
| 2000 | 3400 |

0 500 1000 1500 2000 2500 3000

$M_{\text{base}}$ [GeV]

# Outlook

The battle for a natural resolution of the hierarchy problem goes on

LHC14 will be decisive: 2xEnergy → 4xTuning

Flavor non-trivial signals to be explored,
charm tagging, bumps in sub-leading jets

‘Absence of evidence is not evidence of absence’,
still: some experimental guidance would be nice.