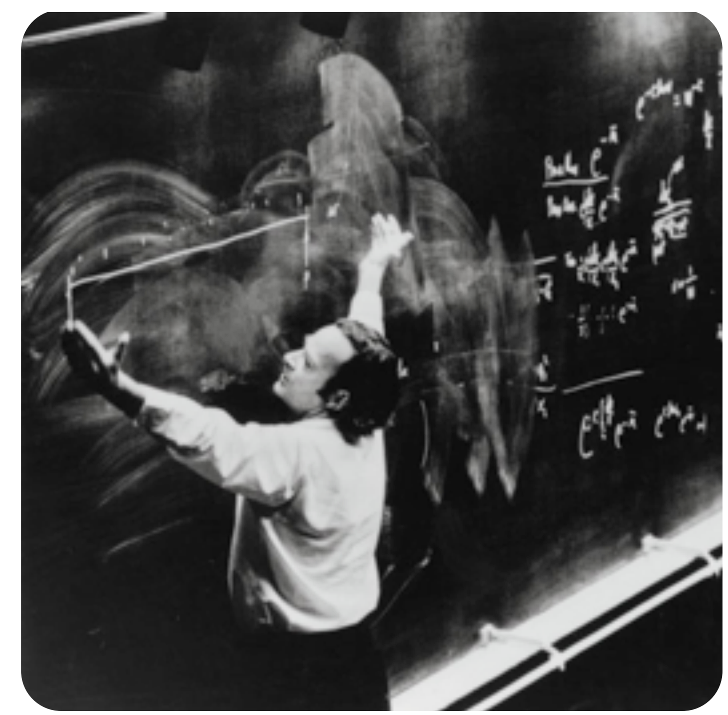
# Flavor at high $p_T$

Andreas Weiler
(DESY)



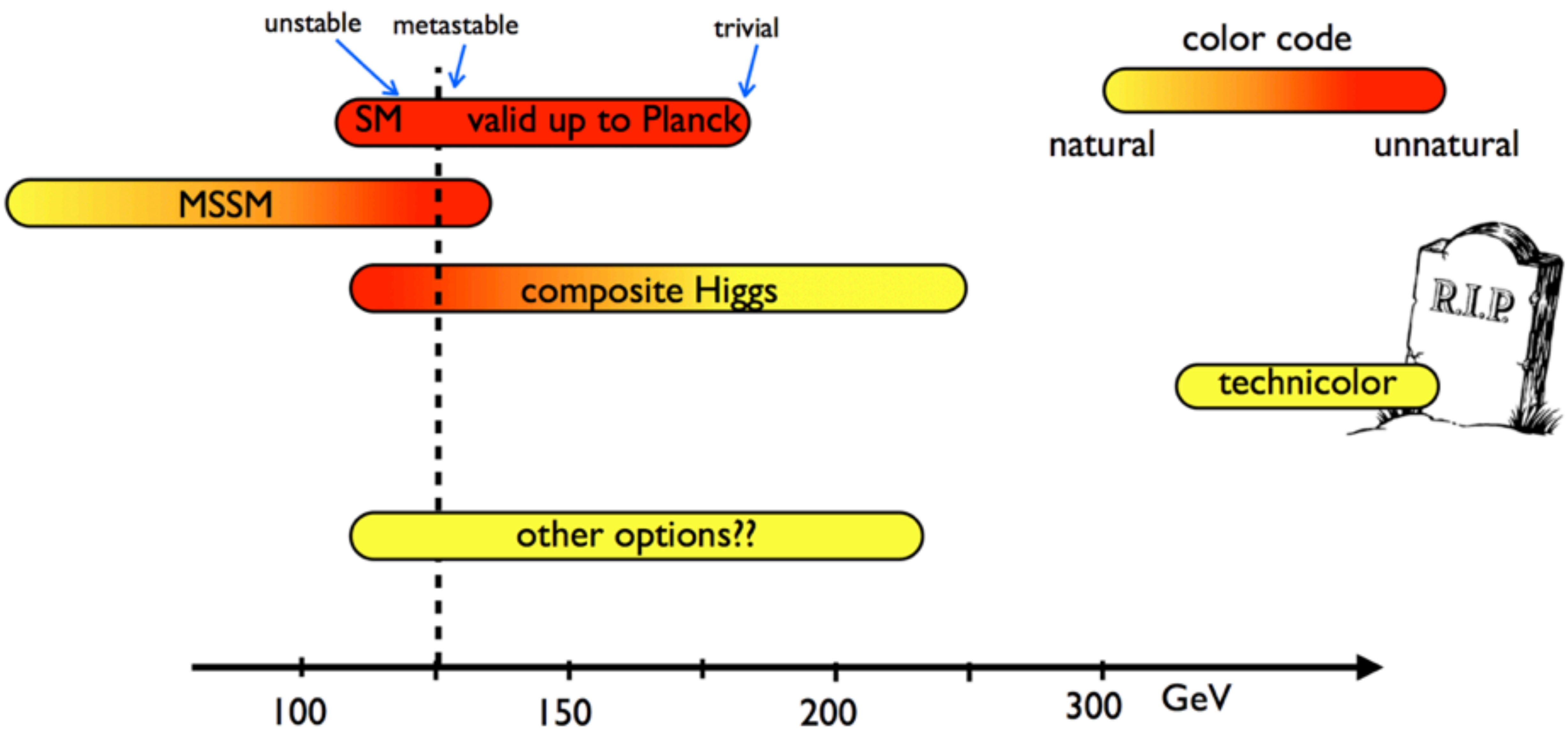
The first three years of the LHC
Schloss Waldthausen, Mainz, March 18–22, 2013

# Importance of flavor at high $p_T$

Flavor can…

- Hide new physics: searches are optimized to the flavor trivial case
- Render new physics more visible, but not in the channels we are studying so far

# WHAT IS THE Higgs MASS TELLING US?




Brando's talk

**Jose Canseco** @JoseCanseco 5h

higgs boson is lighter than i thought. Could it also have no limits in dimension or time.  think about that

Expand

**Jose Canseco** @JoseCanseco 6h

higgs boson is an energy bridge not an enemy

Expand

**Jose Canseco** @JoseCanseco 7h

we are already in the alternative universe I believe or it wont happen for billions of years.  it is okay

Expand

**Jose Canseco** @JoseCanseco 7h

do not fear the higgs bosun

Expand

Jose Canseco

Baseball Player

José Canseco Capas, Jr., is a Cuban-American former Major League Baseball outfielder, and designated hitter who is currently playing for the Rio Grande Valley WhiteWings. Wikipedia

http://www.facebook.com/matt.reece



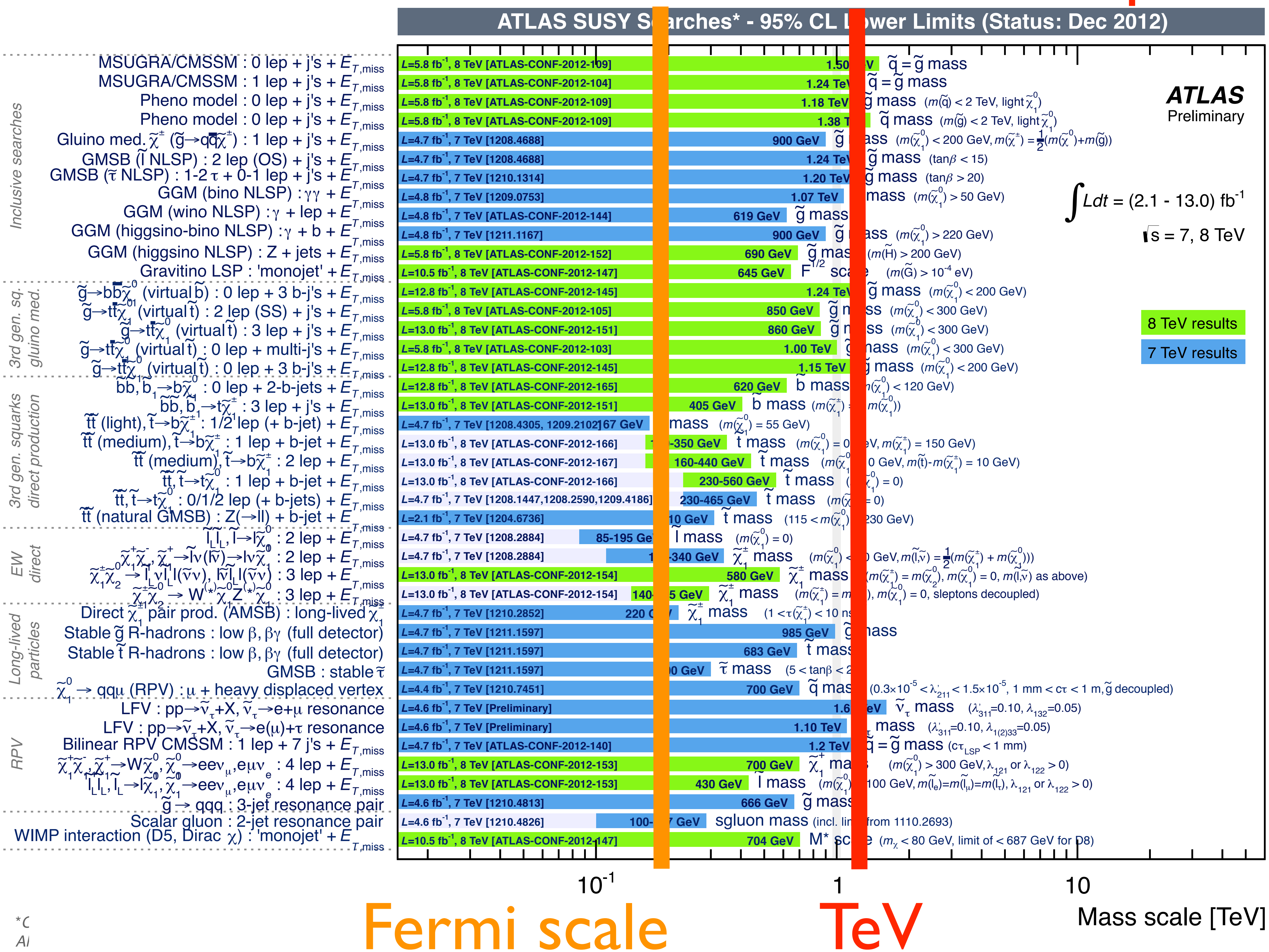
Message to BSM

http://www.facebook.com/matt.reece

# Supersymmetry

# Colored susy > TeV ?

colored sparticles



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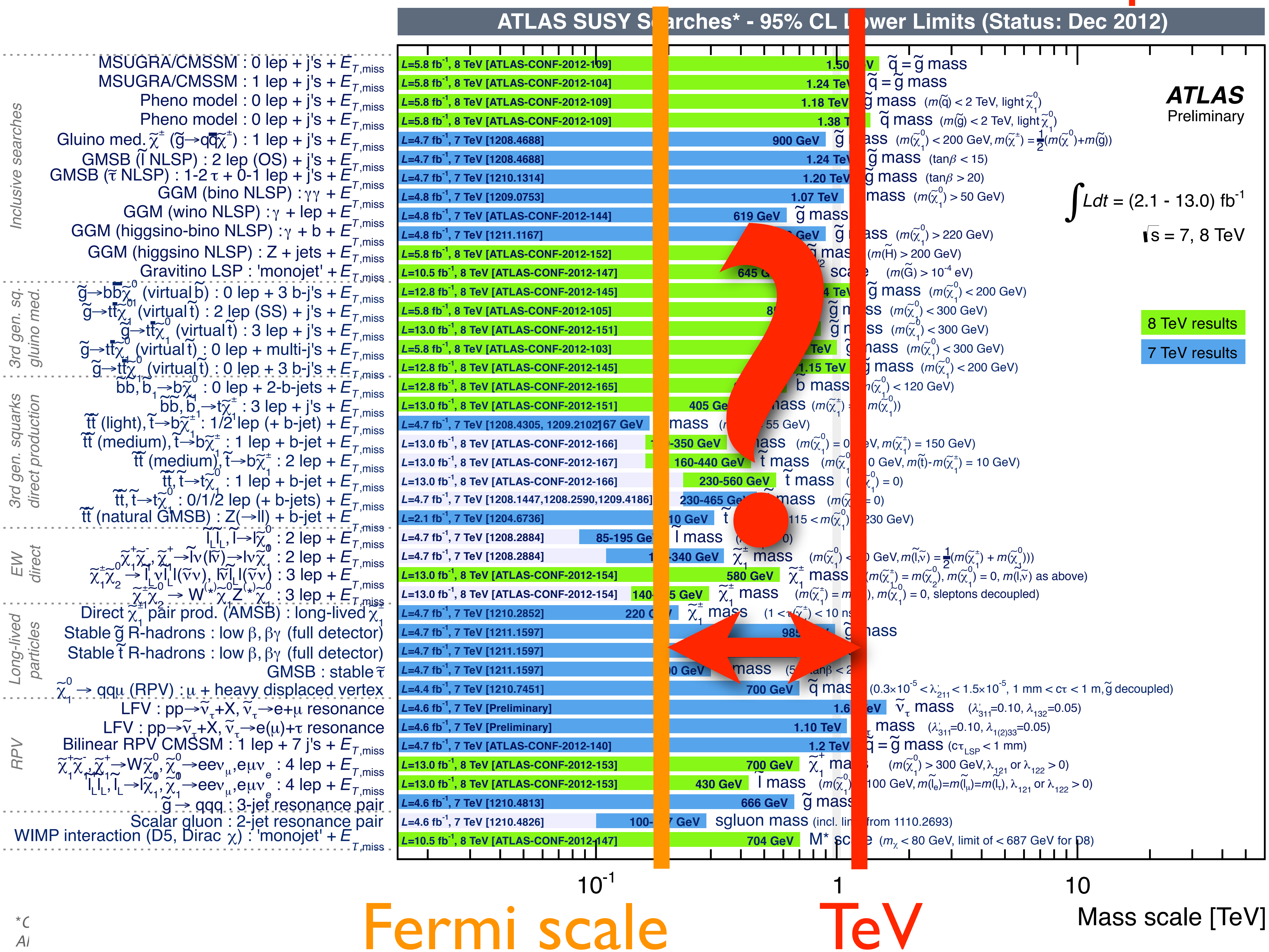


Fermi scale TeV

# ~~Natural~~ Ascetic susy

# Natural EWSB in times of austerity

Barbieri/Guidice

*MSSM,NMSSM, ...*

Fine-tuning of (Higgs mass)$^2$

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m^2_H$$

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Higgsinos

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Higgsinos

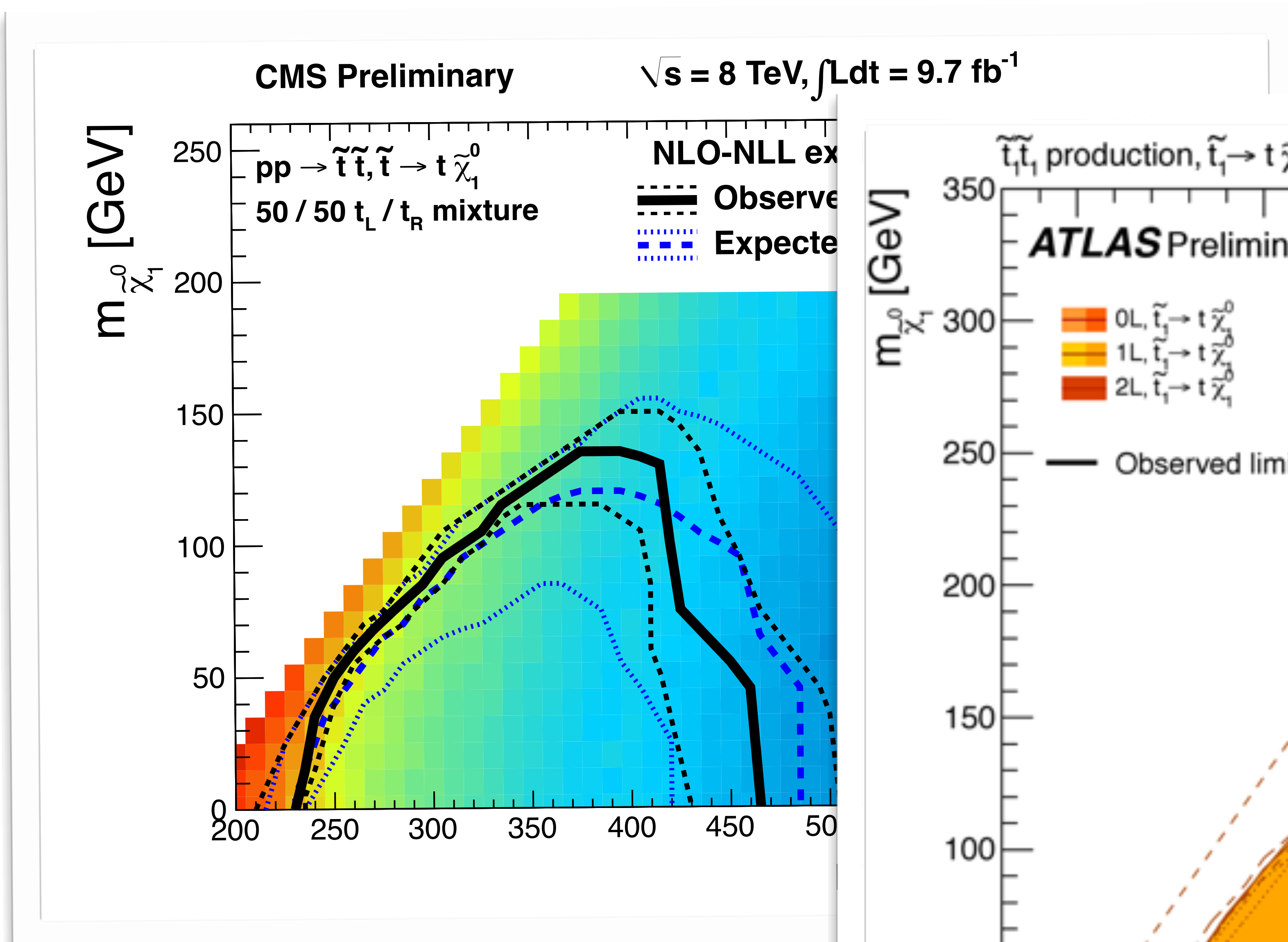
1loop
$$\delta m^2_H|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left( m^2_{U_3} + m^2_{Q_3} + |A_t|^2 \right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

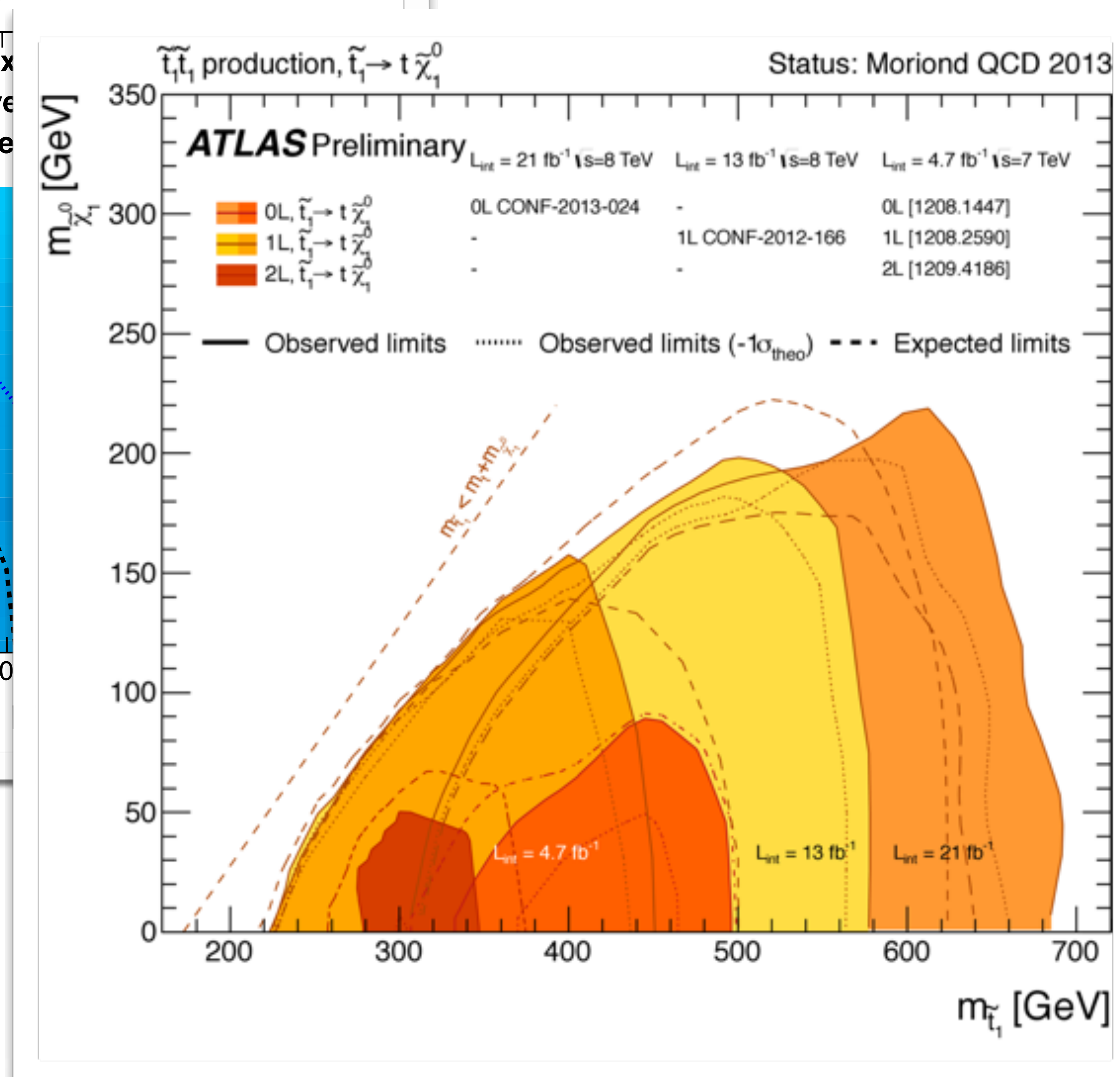
stops, sbottom$_L$

2loop
$$\delta m^2_H|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$$

gluino

# Direct stop searches

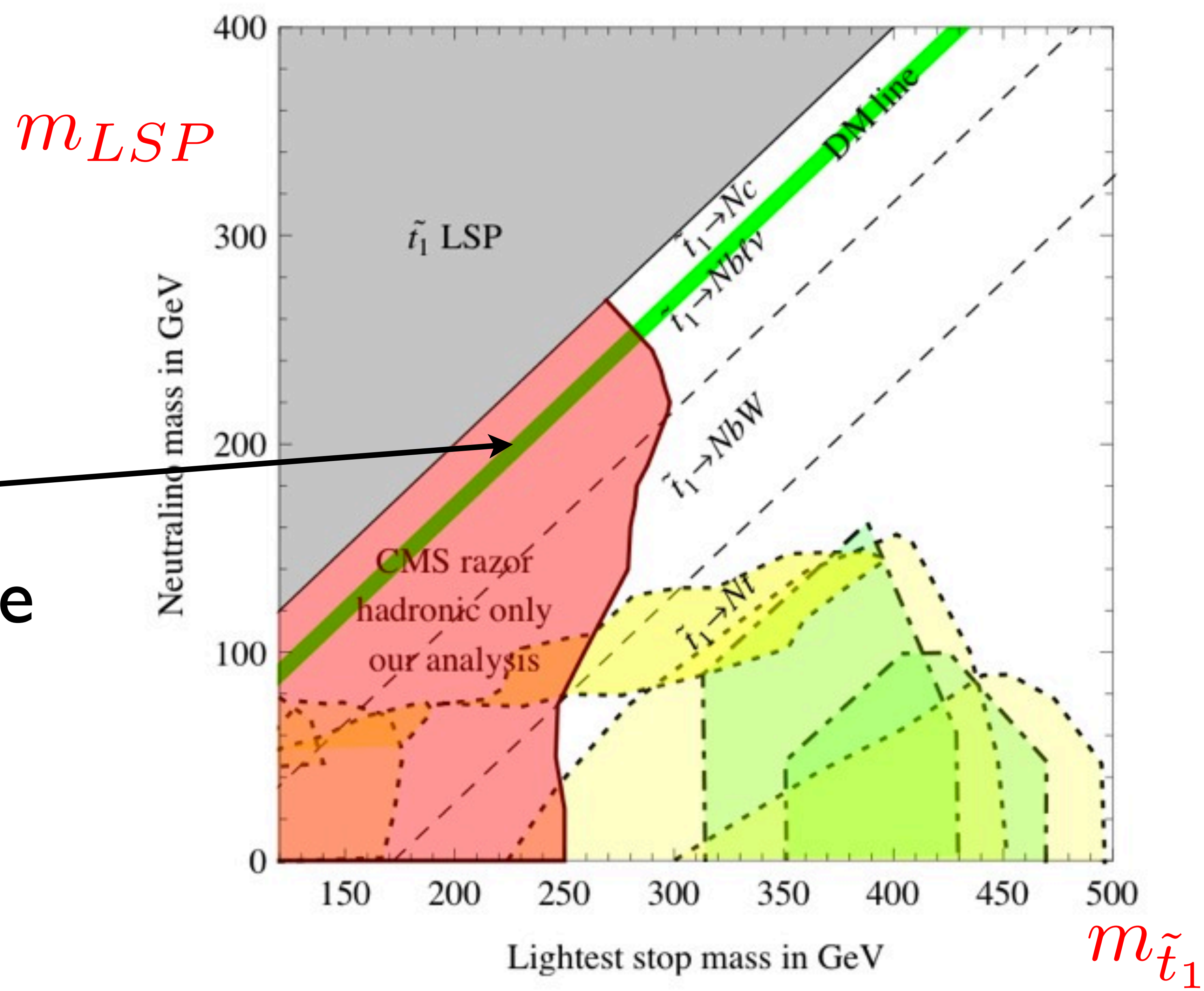


$$(m_{\tilde{t}_1} - m_{LSP}) < 30 - 40\,\mathrm{GeV}$$

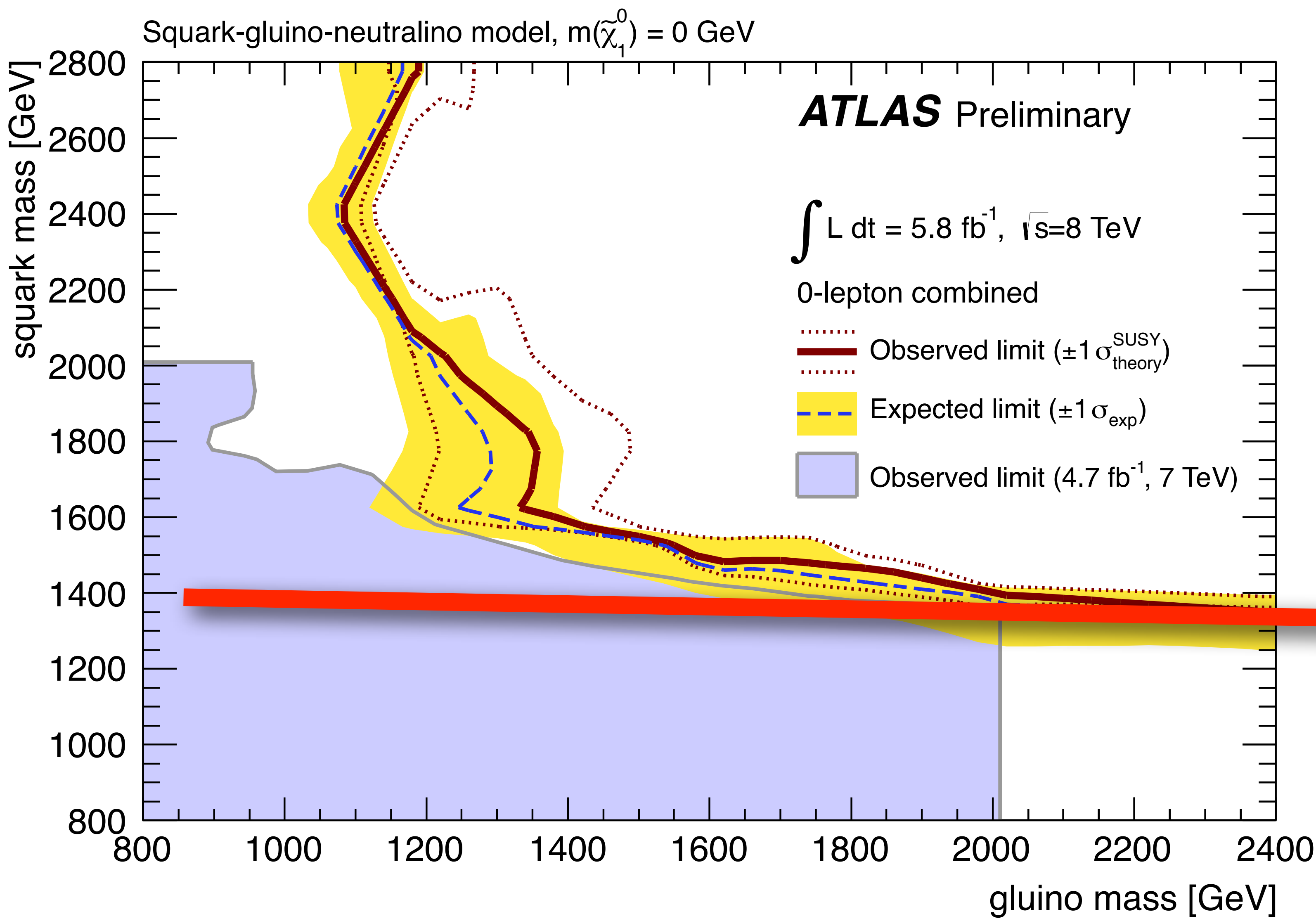
Delgado, Isidori et al.

Leads to the right relic abundance



# Limit on squarks

squarks

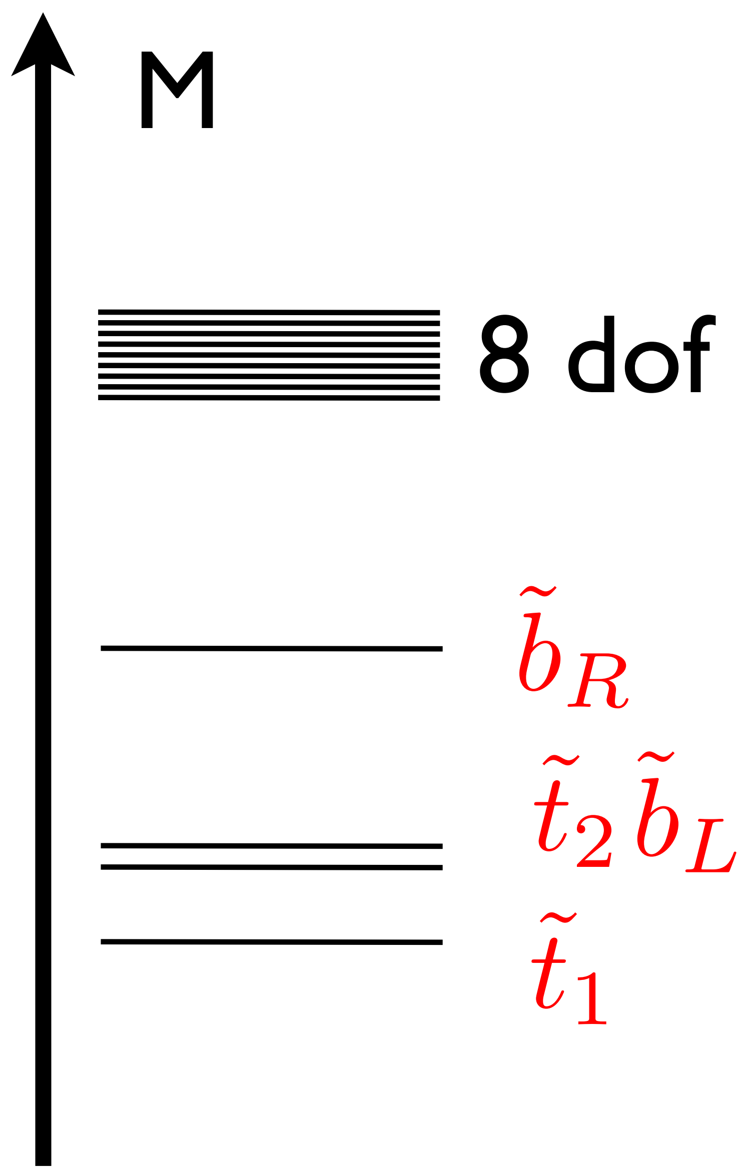



> 1.4 TeV

udcs-squarks

gluino

# Naturalness requires split squarks




$(\tilde{u}, \tilde{d})_L,\ \tilde{u}_R,\ \tilde{d}_R,$

$(\tilde{c}, \tilde{s})_L,\ \tilde{c}_R,\ \tilde{s}_R$

# 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,
tanβ 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!

# SUSY & Flavor

Flavor Bounds (K, D, B, Bs mixing, …) controlled by

$$(\delta^q_{ij})_{MM} = \frac{1}{\tilde{m}_q^2} \sum_\alpha (K^q_M)_{i\alpha} (K^q_M)^*_{j\alpha} \Delta \tilde{m}^2_{q_\alpha}$$

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mixing matrices

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mixing matrices mass splitting

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mixing matrices mass splitting

(m=1TeV)

| $q$ | $ij$ | $(\delta^q_{ij})_{MM}$ | $\langle\delta^q_{ij}\rangle$ |
|---|---|---|---|
| $d$ | 12 | 0.03 | 0.002 |
| $d$ | 13 | 0.2 | 0.07 |
| $d$ | 23 | 0.6 | 0.2 |
| $u$ | 12 | 0.1 | 0.008 |

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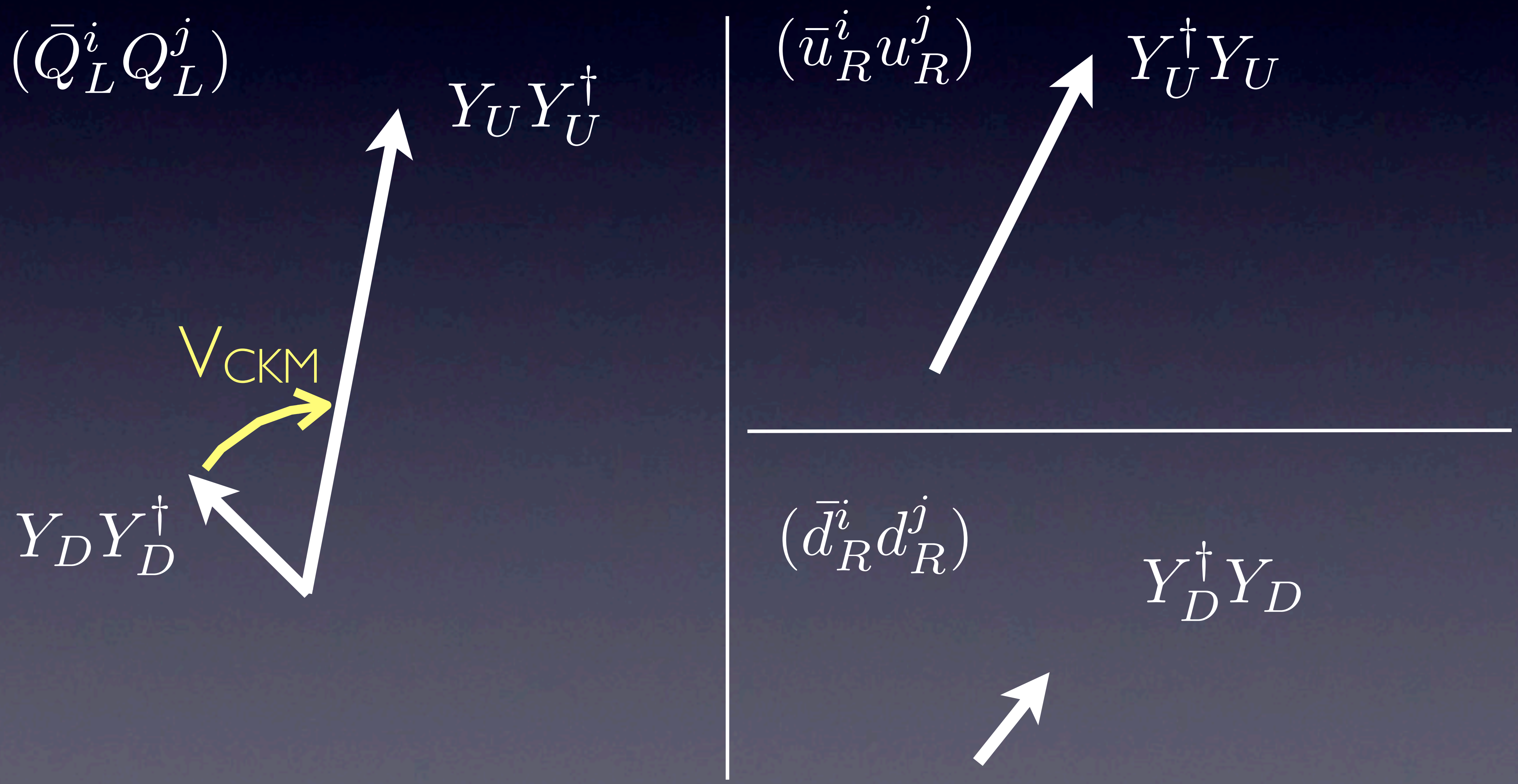
large mixing
means splitting
must be << 1

# Flavor dynamics: alignment

Dynamics (e.g. $U(1)_{horiz.}$) generates hierarchies in masses & mixings. Consequence: partial alignment with SM




+ LR, RL

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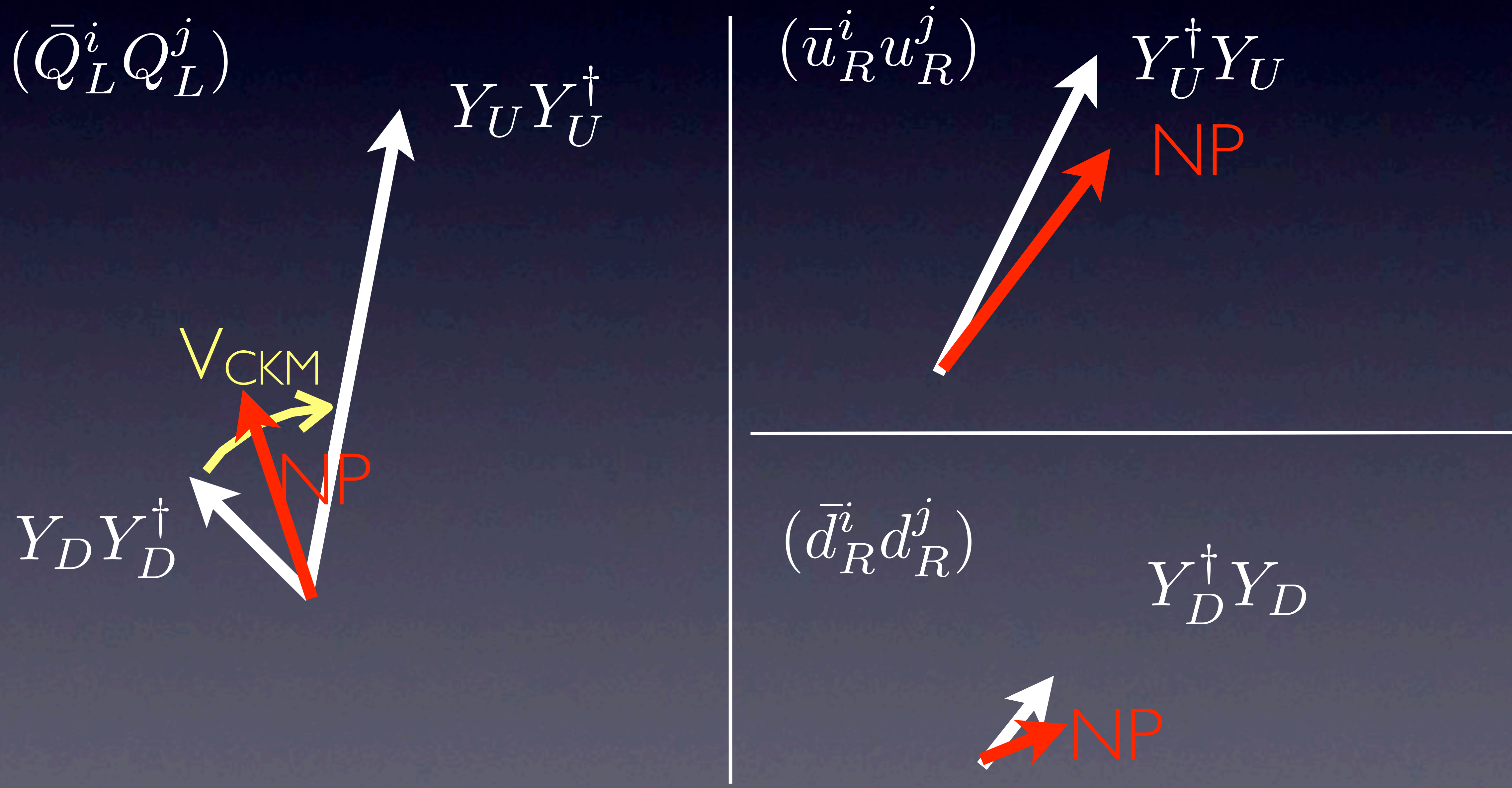
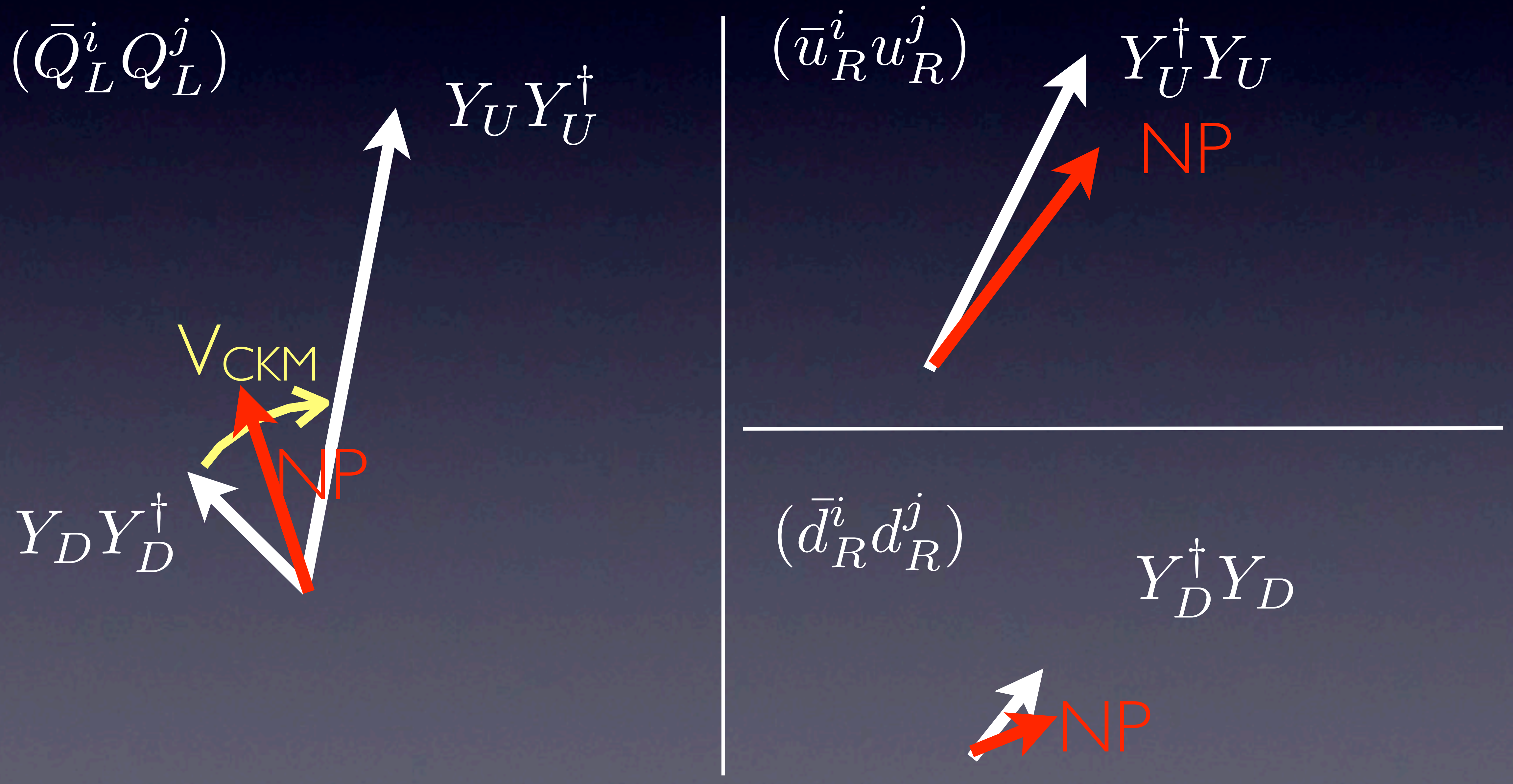



+ LR, RL

Left-handed $(Q_L)$: either aligned with up or downs

Right-handed $(u_R, d_R)$: can be fully aligned



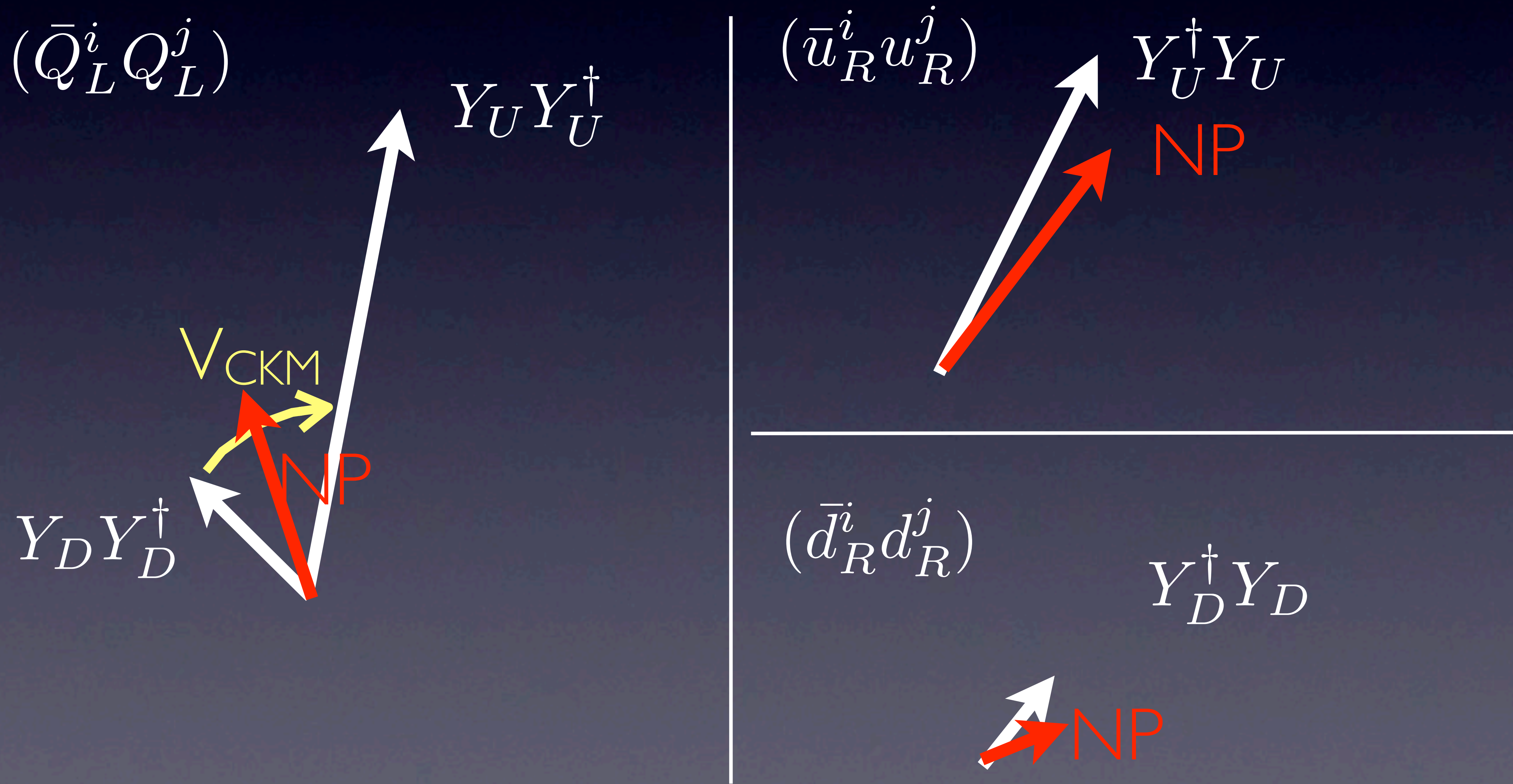

+ LR, RL

Left-handed ($Q_L$): either aligned with up or downs

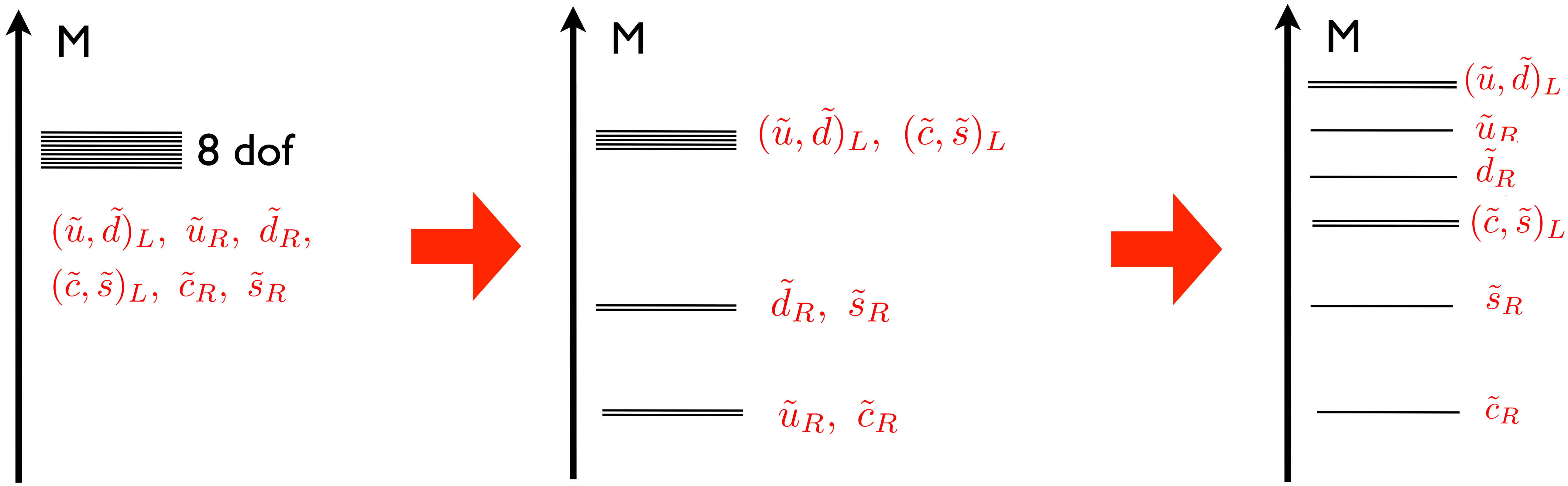
→ **limited splitting**

Right-handed ($u_R$, $d_R$): can be fully aligned

→ **any splitting**




+ LR, RL




Degenerate　　Minimal Flavor　　Anarchy!

mSugra, CMSSM,
pMSSM, ...

# Collider estimate

Cross-sections roughly scale like ~1/m^6.

Example: 8 light squarks → 2 light squarks

Shift limit only by $\sim 4^{1/6} - 1 \approx 25\%$

**→ too naive!**

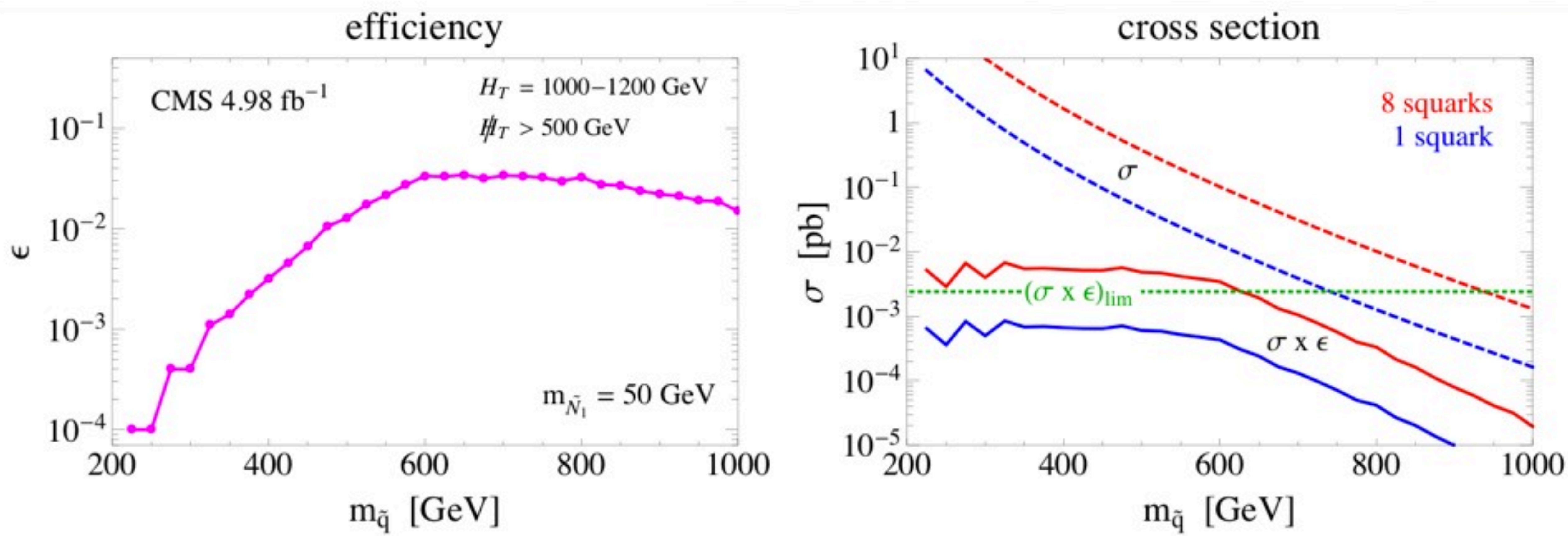
# Dedicated study needed

- Production cross-section can be flavor dependent through p.d.f's (u vs. d, sea vs. valence)
- Experimental efficiencies have thresholds and current limits are on the thresholds

# Light flavor squark searches

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

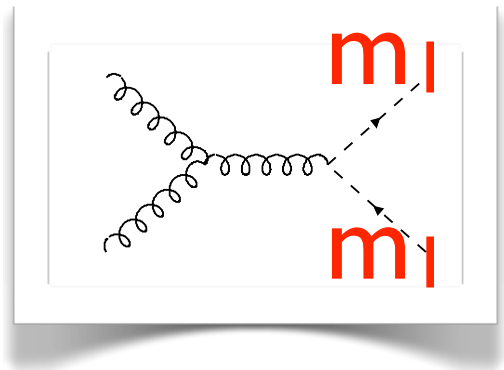
## Effect of the efficiency threshold:



# Pythia/MadEvent

+Prospino/NLLfast
+checks with MLM matched sample

simplified Model
available → CMS



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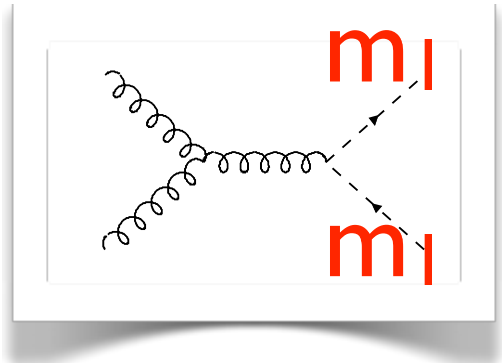


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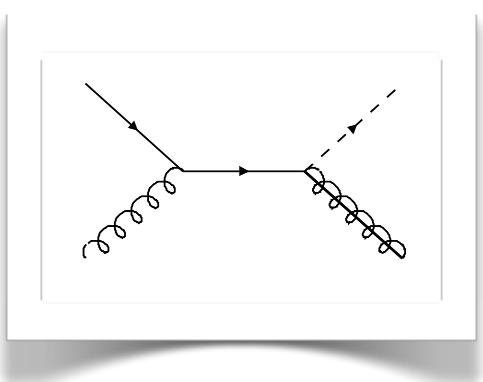
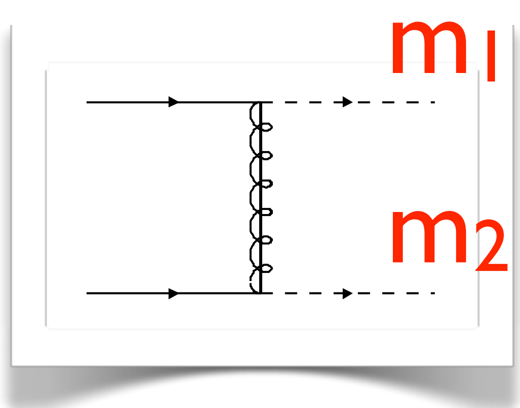
# Atom recast





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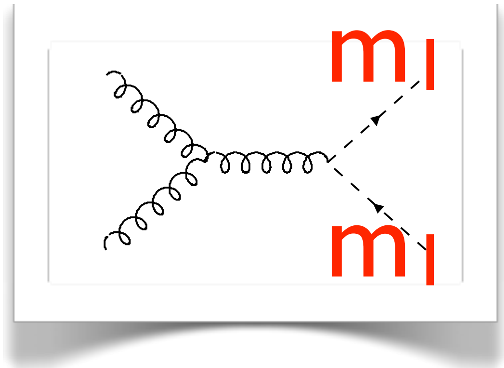
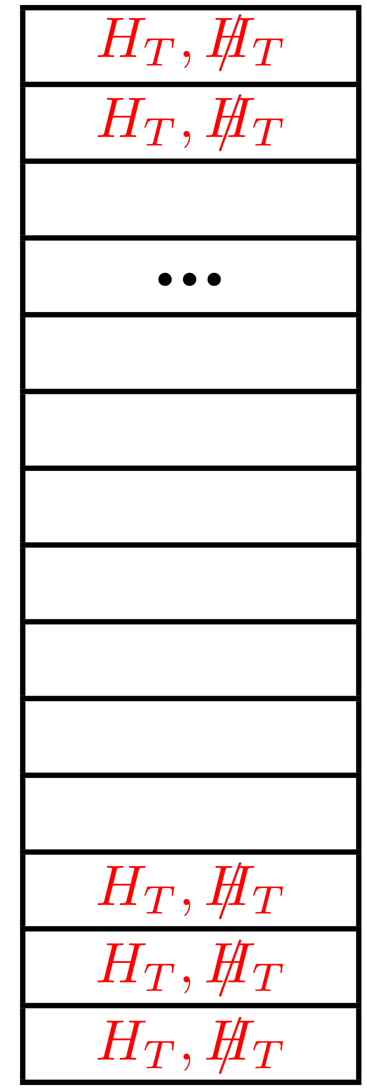



Signal regions

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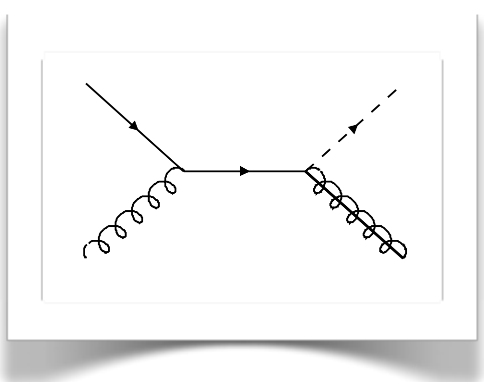
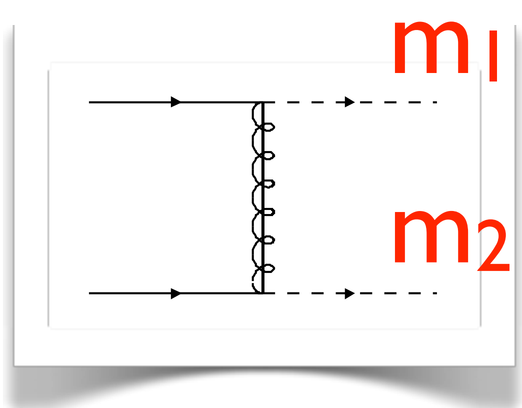
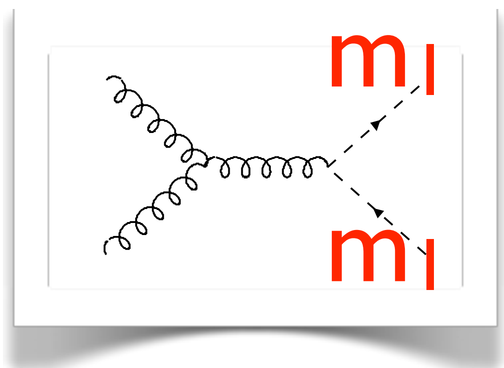




## simplified Model available → CMS




## Signal regions

| |
|---|
| $H_T, \not{H}_T$ |
| $H_T, \not{H}_T$ |
| |
| ... |
| |
| |
| |
| |
| |
| |
| |
| $H_T, \not{H}_T$ |
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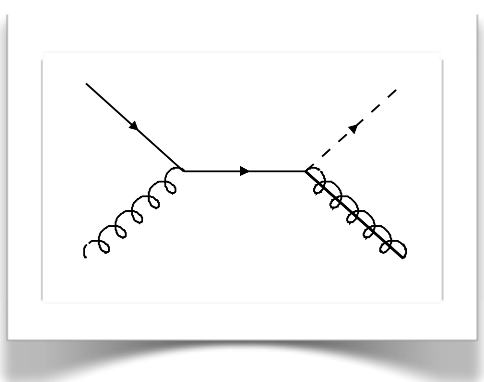
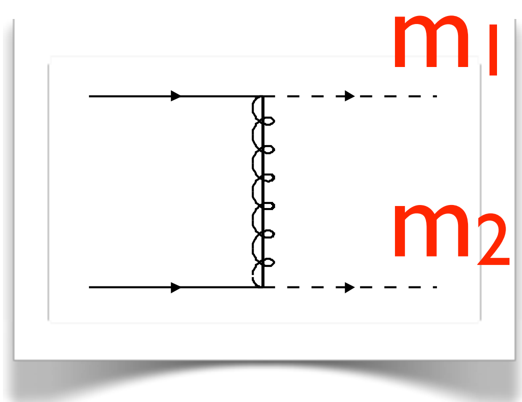
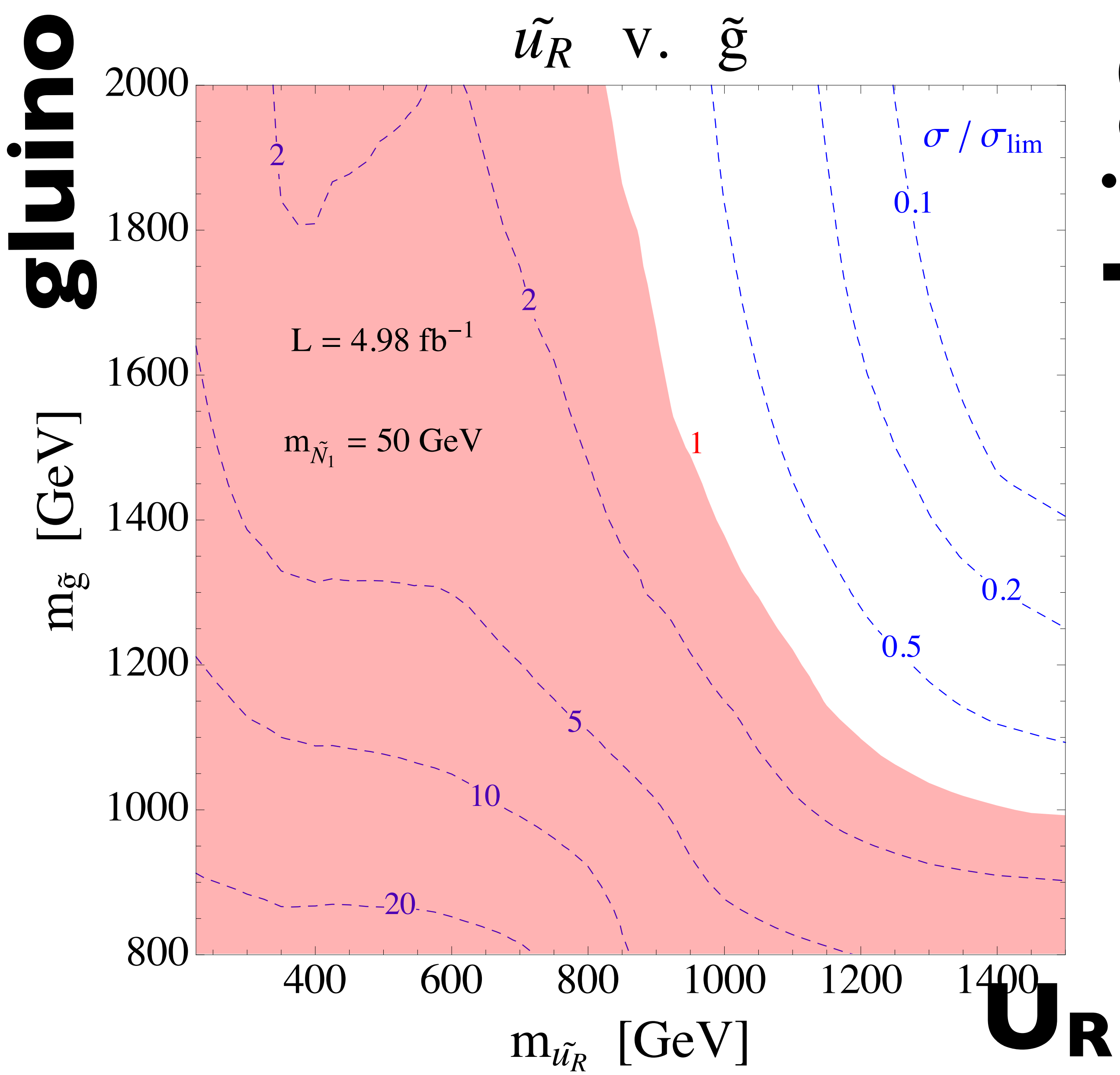
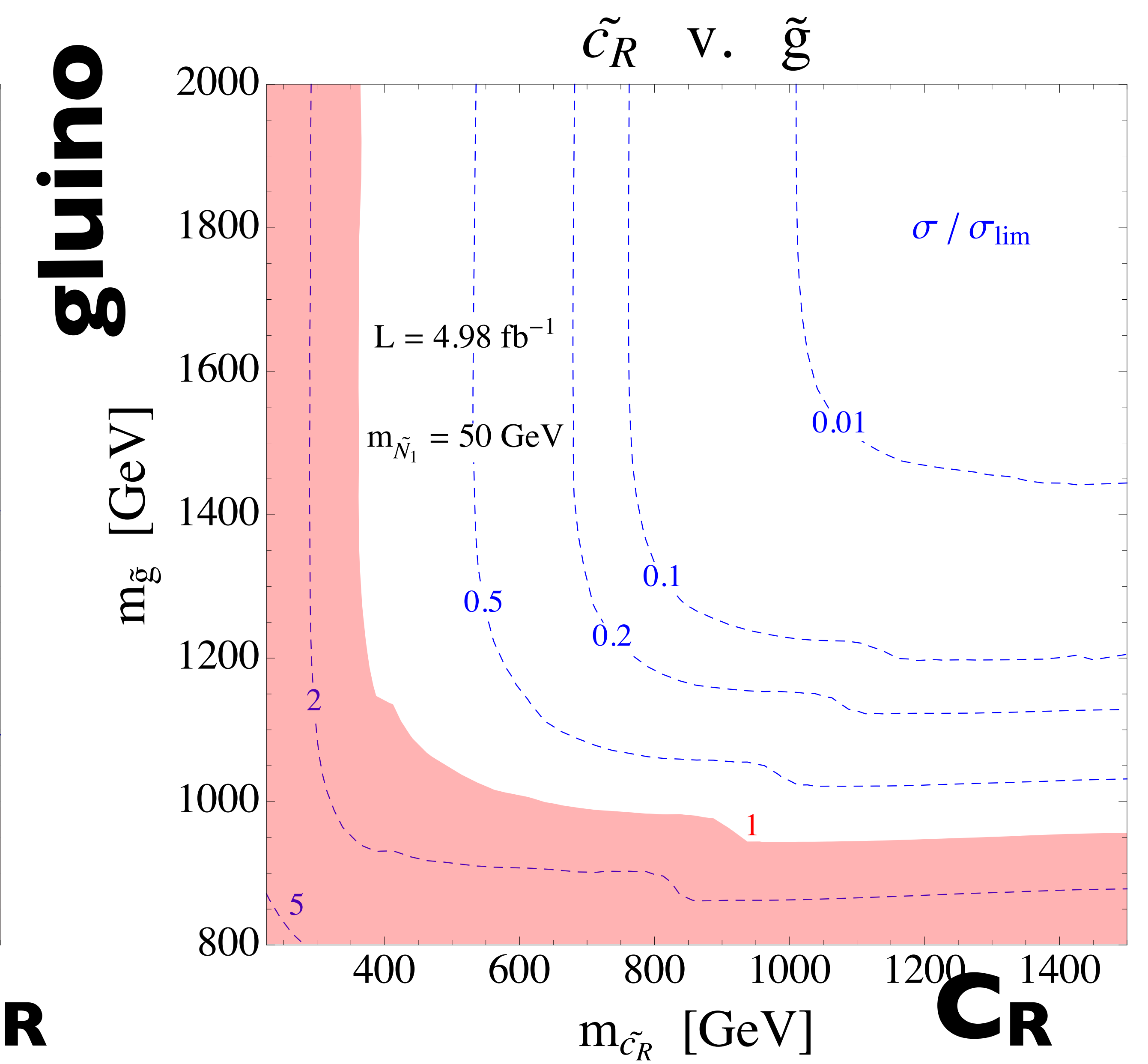





$$\Pi_i \text{poiss}(s_i + b_i \delta b_i)\, \text{gauss}(\delta b_i) \rightarrow CL_s$$




M. Papucci, J. Ruderman
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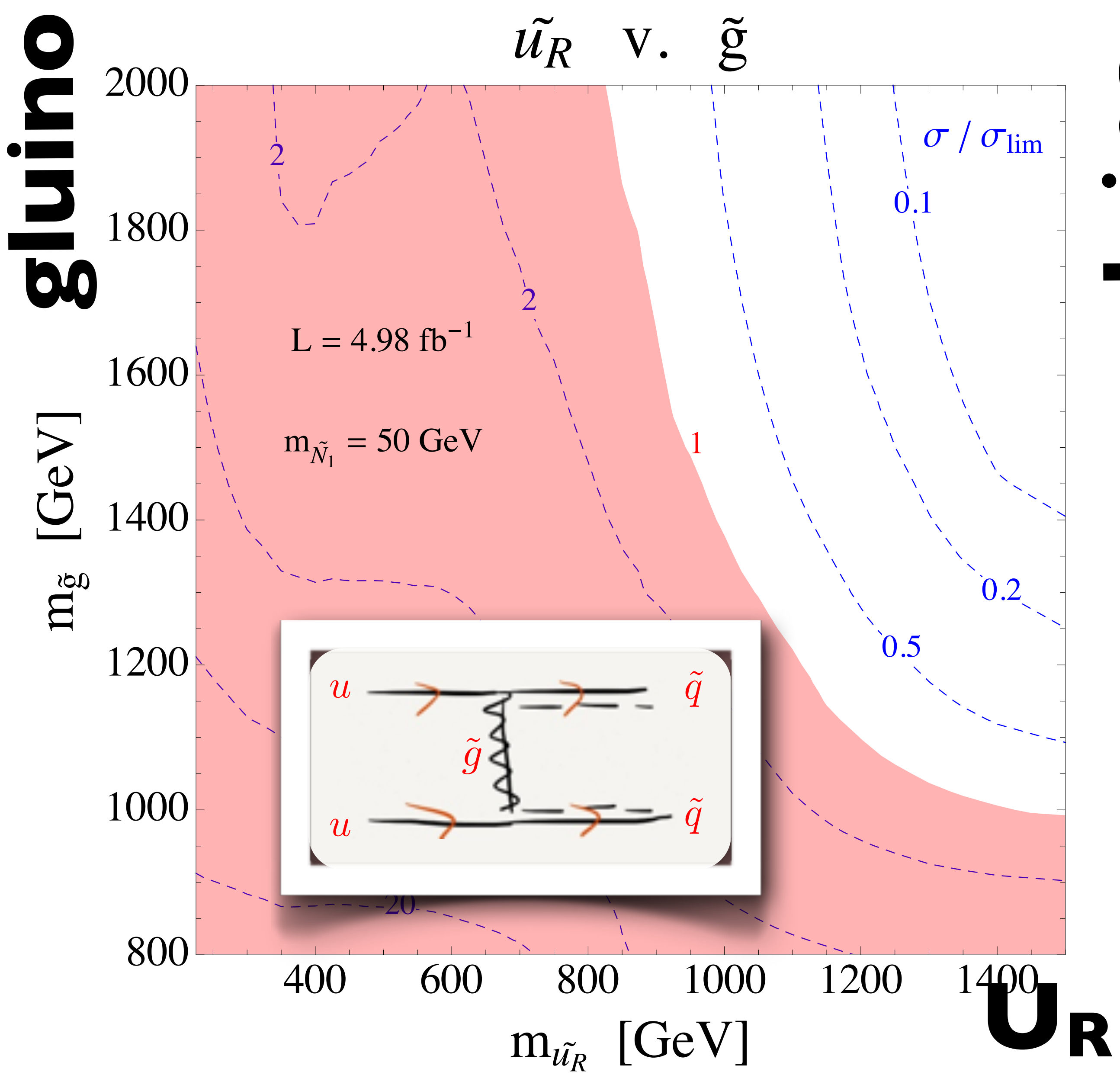
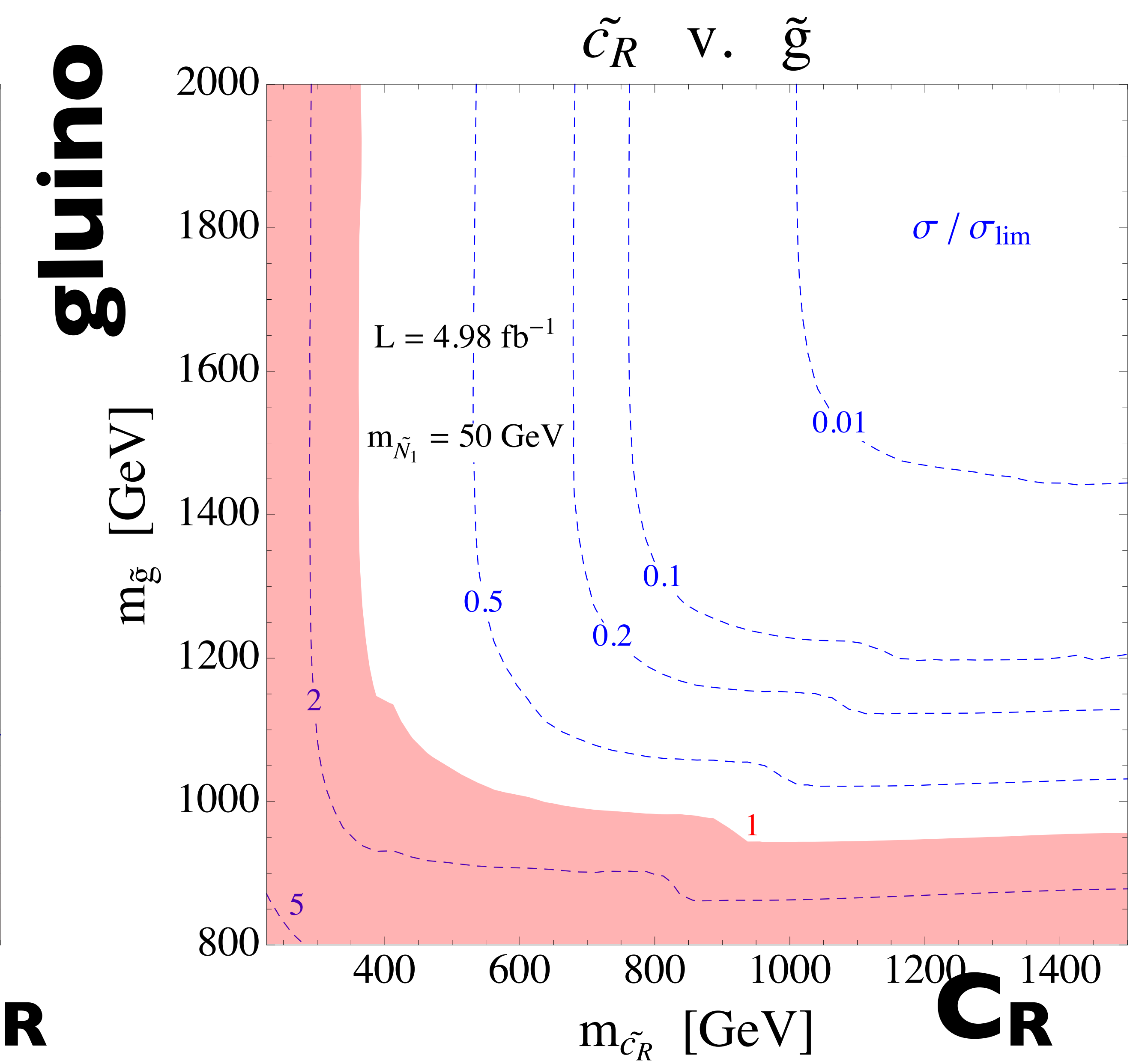


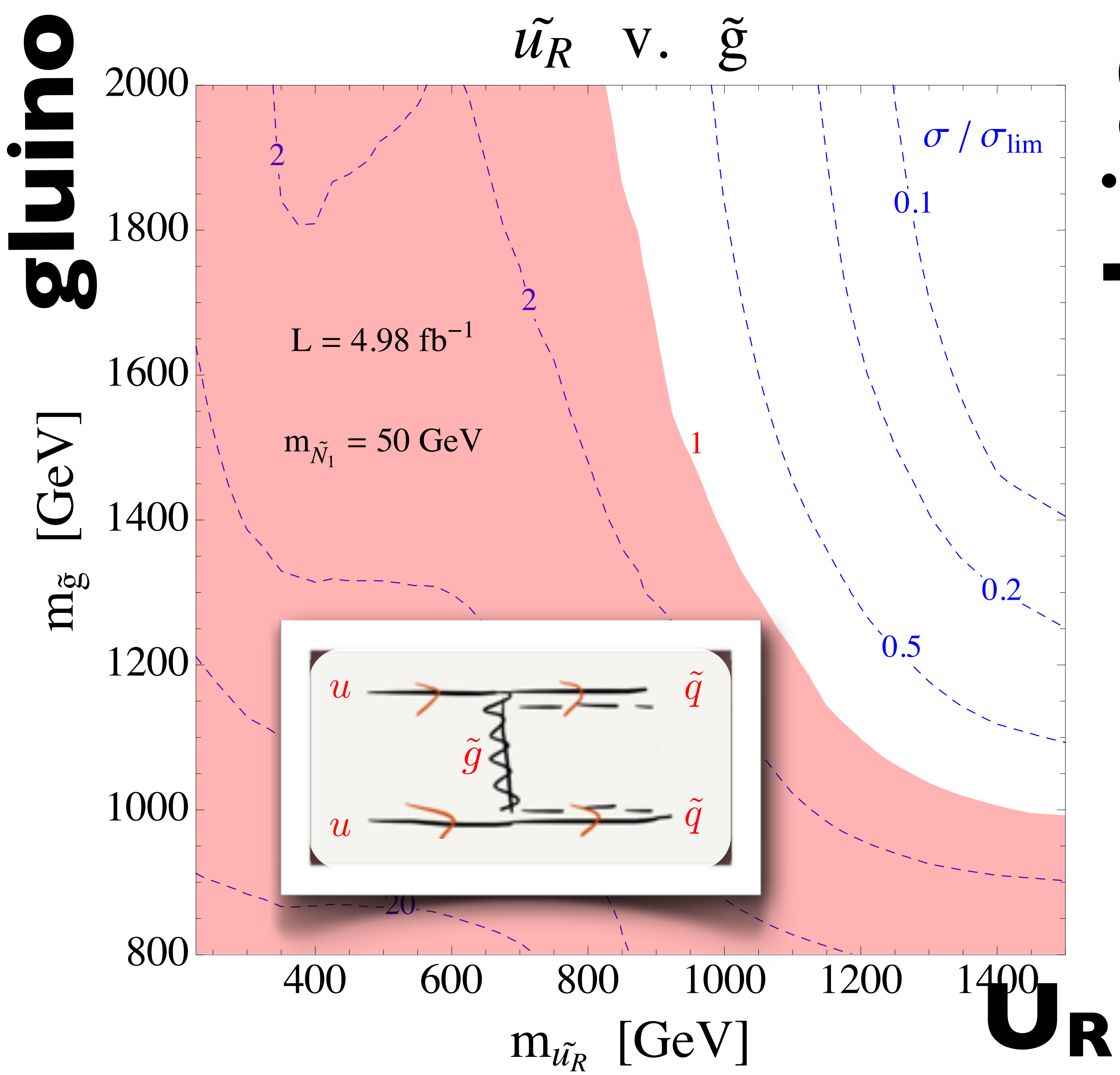



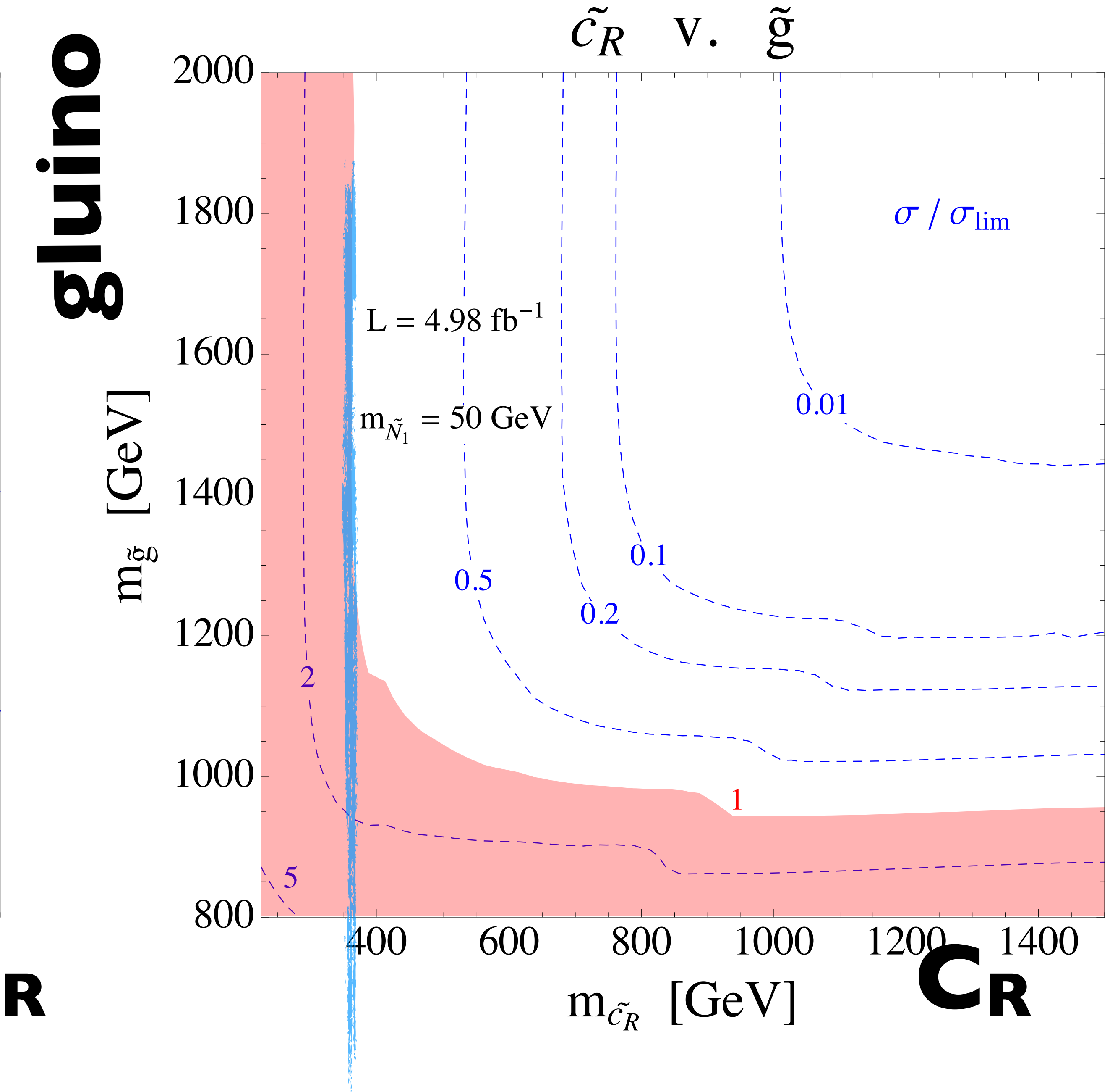

$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\, u_R u_R$$ dim5-operator

$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$

slow decoupling

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




$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5-operator

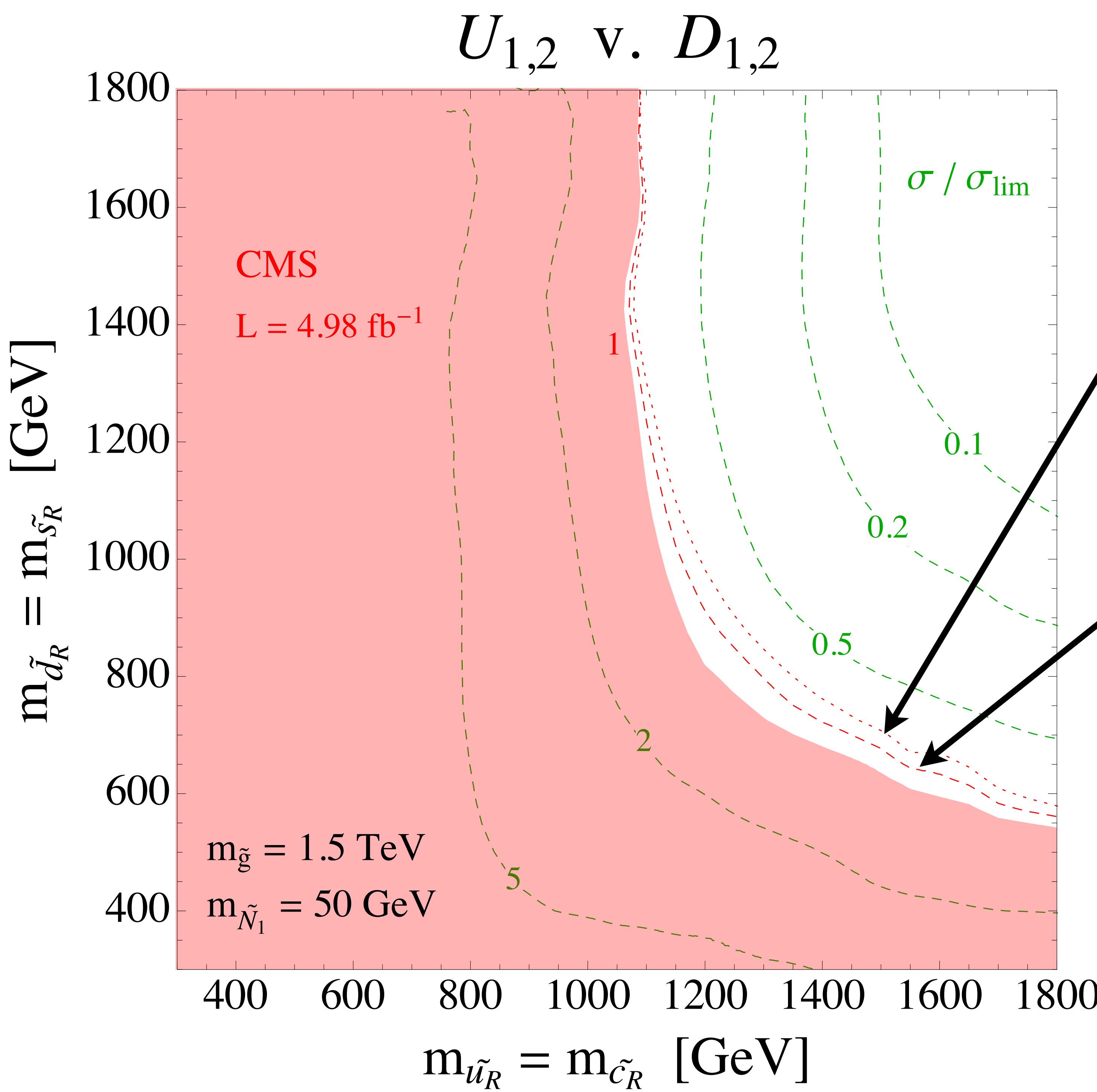
$$\rightarrow \quad \sigma \sim 1/m_{\tilde{g}}^2$$

slow decoupling

**Sea squarks can still be < 350 GeV**

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

# MFV splitting - flavor trivial light squarks

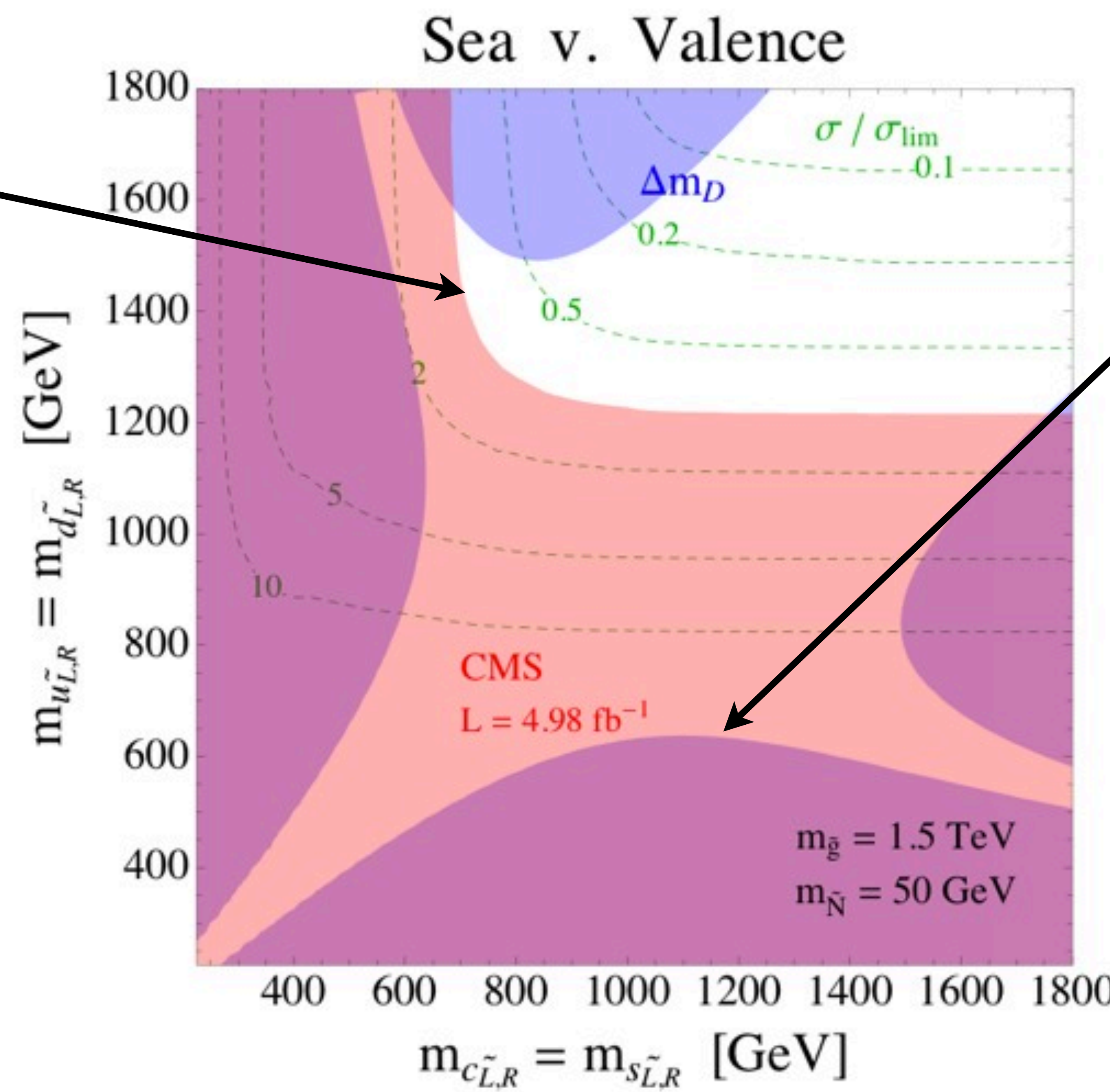



effect of unknown NLO (K=1.5,2)

compared to MadGolem, usually corrections are smaller

# Collider vs. Flavor for sea & valence squarks

Collider constraint (CMS recast)



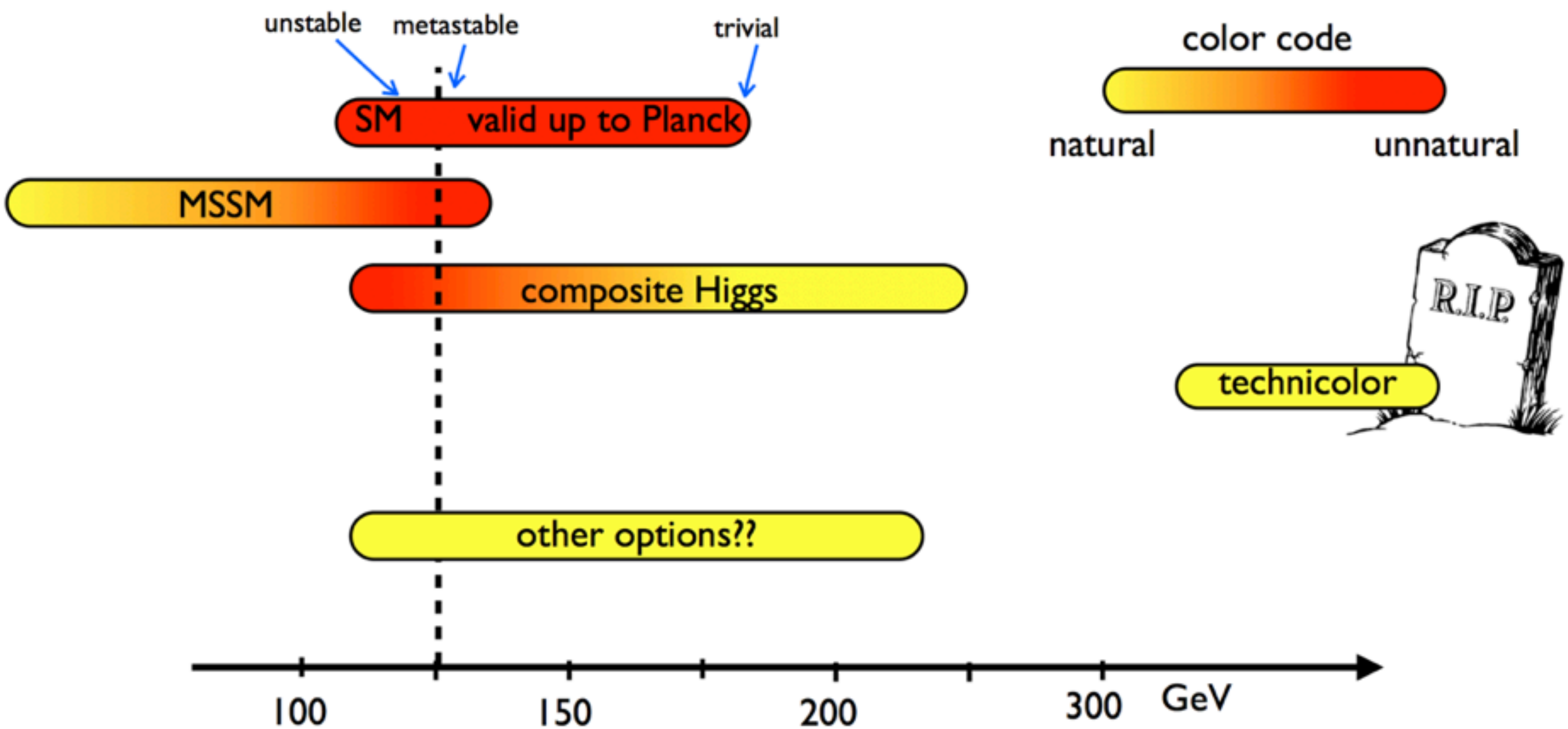

$\Delta M_D$ Flavor limit

$$H_{\rm eff} = C_1\ (\overline{u}^i \gamma_\mu P_L\, c^i)\,(\overline{u}^j \gamma^\mu P_L\, c^j)\ , \qquad x_D \simeq 2.6 \times 10^{10}\ {\rm Re}\ C_1$$

Assuming full down alignment, calculated w/o MIA

# End of Susy

# WHAT IS THE MASS TELLING US?



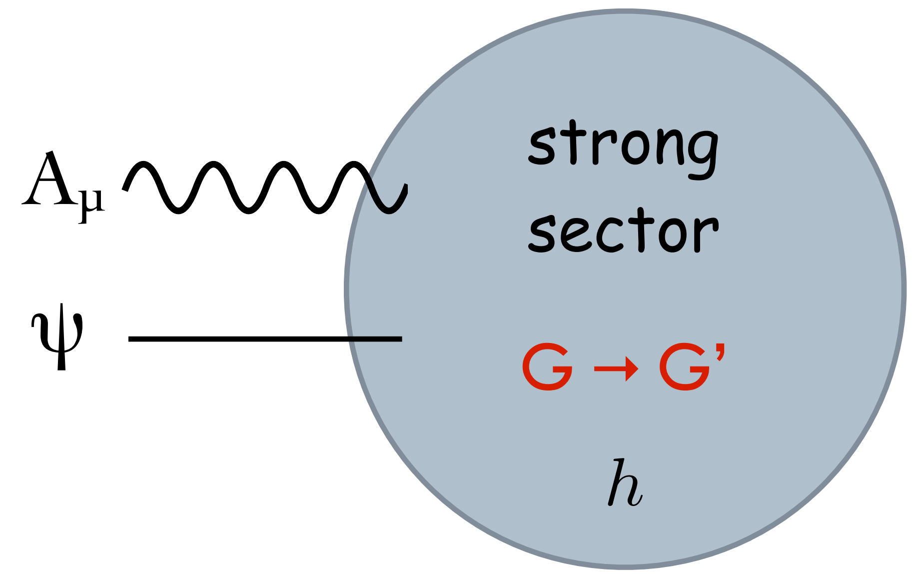

Brando's talk

# Strong EWSB (Composite Higgs)

e.g. SO(5)/SO(4) $\xi = v^2/f^2$

# Why is the Higgs light?

Kaplan; Agashe et. al

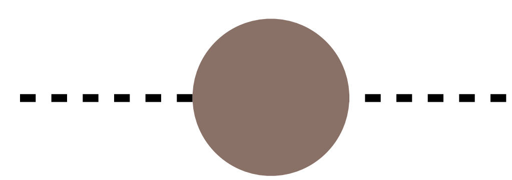



Higgs is a pNGB

Minimal example

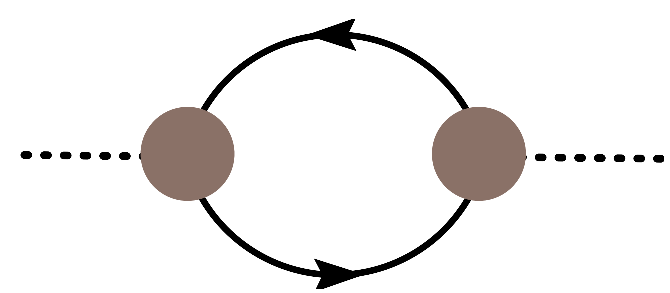
$SO(5) \to SO(4) \sim SU(2)_L \times SU(2)_R$

No pure composite effects, vanish due to NG symmetry



= 0

NG symmetry broken by elementary-composite couplings:

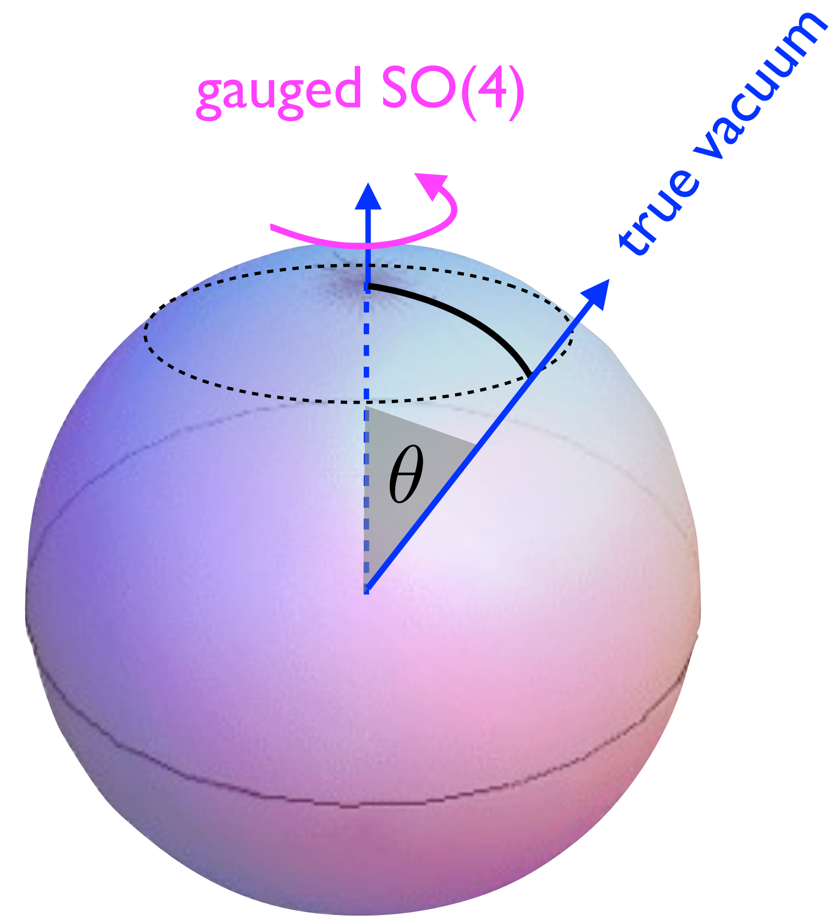


$$m_h^2 \sim \frac{\lambda^2}{16\pi^2} \Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

SILH: Giudice, Grojean, Pomarol, Rattazi

**θ**: misalignment between gauged SO(4) and SO(4)’ preserved in the quantum corrected vacuum



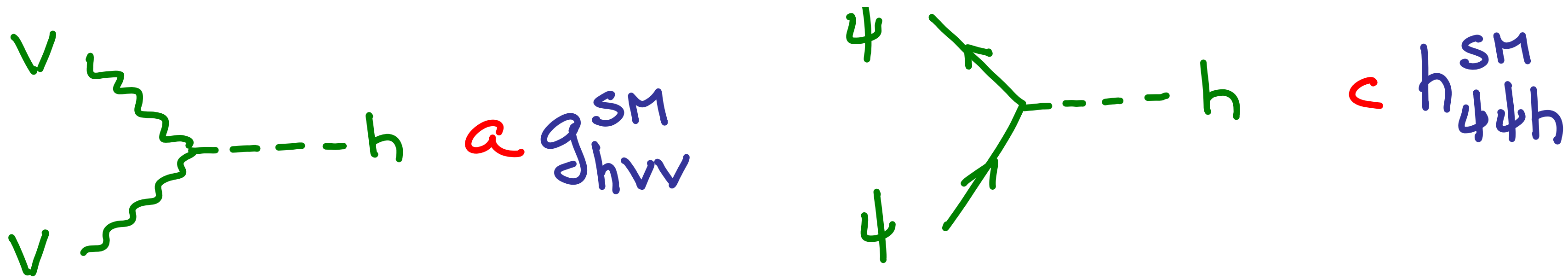

Tree level: gauge SO(4) aligned

Higgs

$$\phi = e^{i\pi^{\hat a}T^{\hat a}/f}\begin{pmatrix}0\\0\\0\\0\\1\end{pmatrix} = \begin{pmatrix}\sin(\pi/f)\times\begin{pmatrix}\hat\pi^1\\\hat\pi^2\\\hat\pi^3\\\hat\pi^4\end{pmatrix}\\ \cos(\pi/f)\end{pmatrix} = \begin{pmatrix}\sin(\theta+h(x)/f)\; e^{i\chi^i(x)A^i/v}\begin{pmatrix}0\\0\\0\\1\end{pmatrix}\\ \cos(\theta+h(x)/f)\end{pmatrix}$$

@ 1-loop <pi> = **θ** * f

eaten by $W_L$, $Z_L$



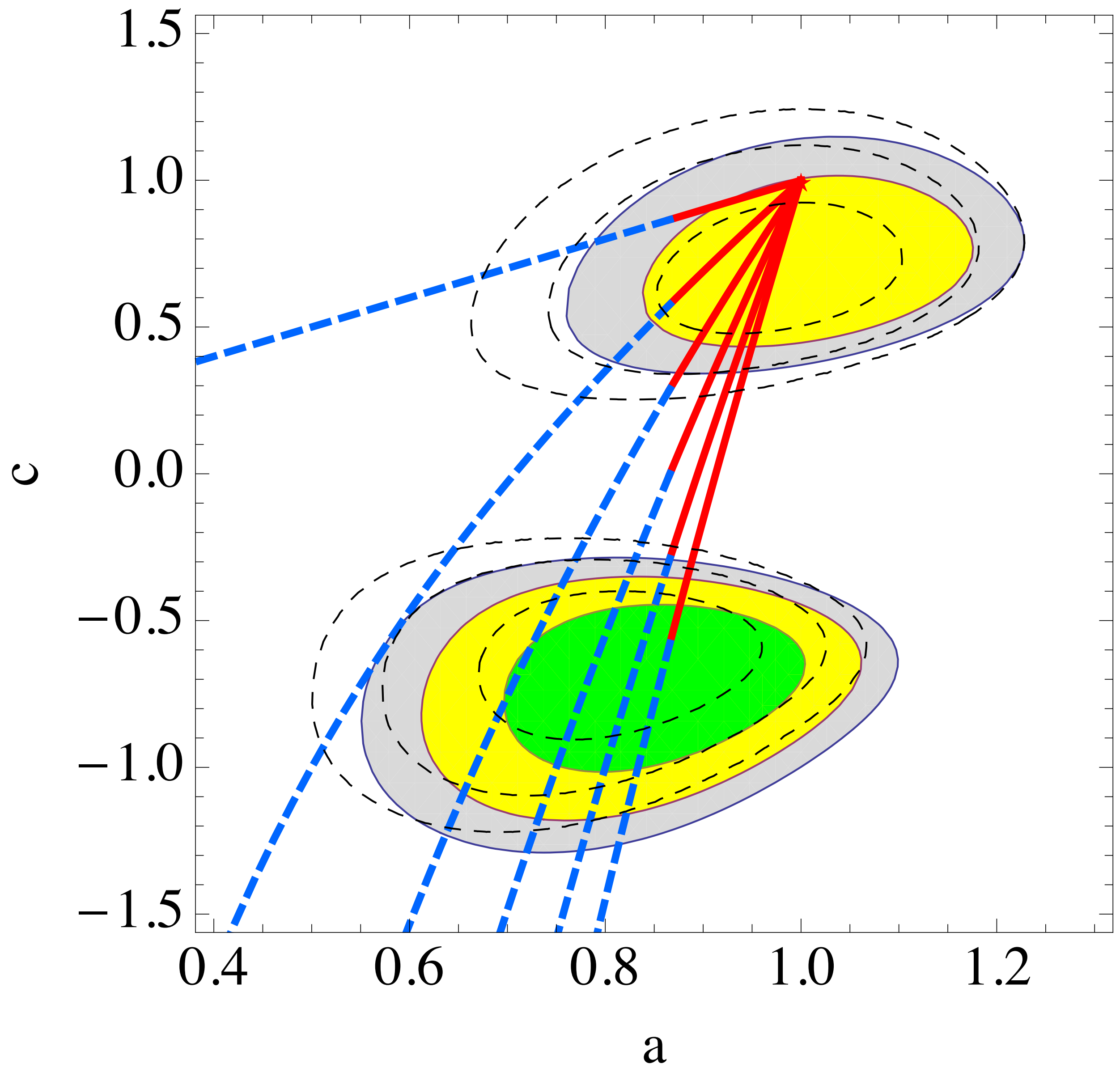

$$a = \sqrt{1-\xi}$$

$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$

$$\xi = \left(\frac{v}{f}\right)^2$$

# Pre-Moriond 2013

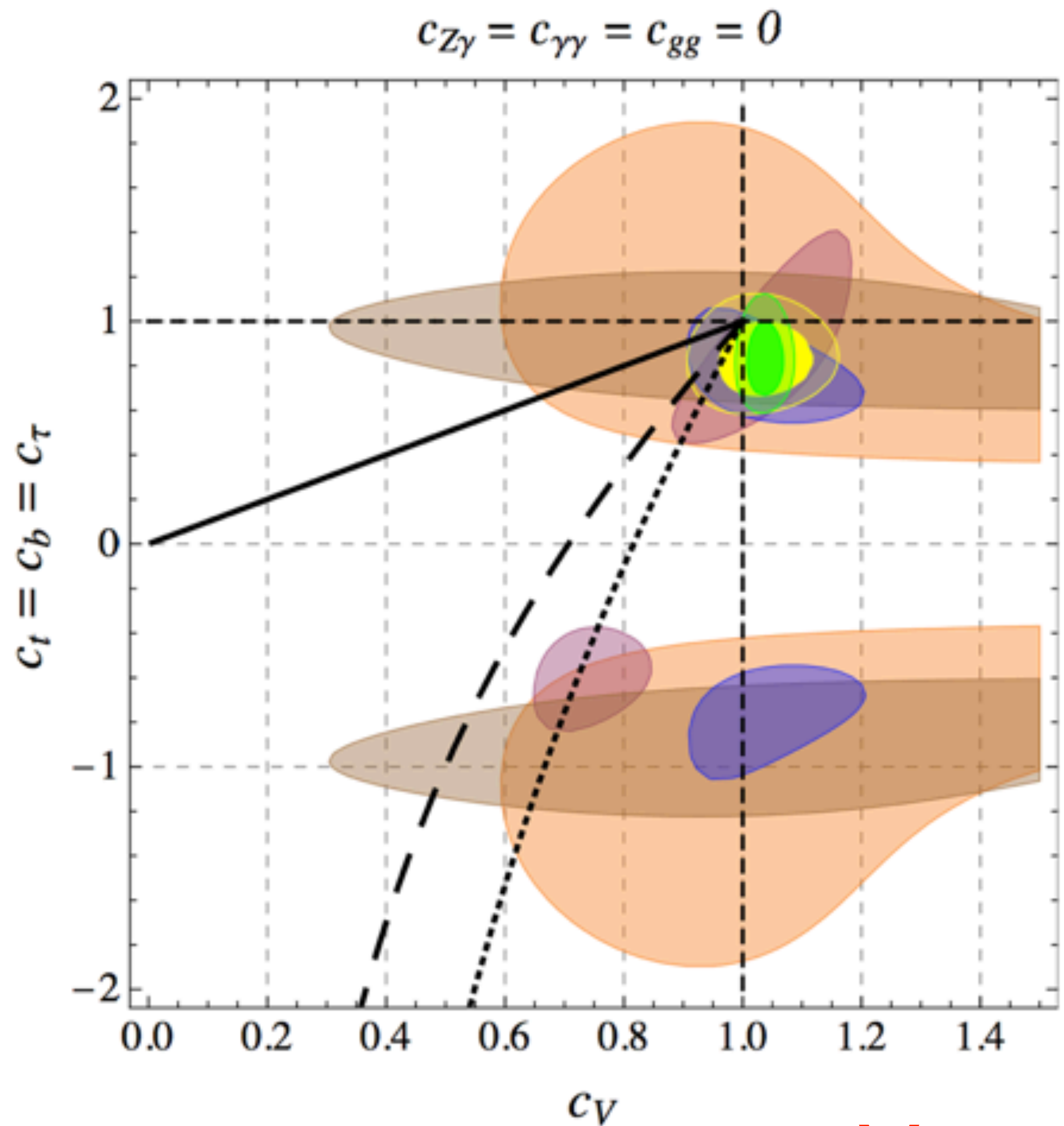
Montull/Riva



# Fit to ATLAS/CMS & Tevatron

post-Moriond fit: see e.g. Giardino et al, Falkowski et al

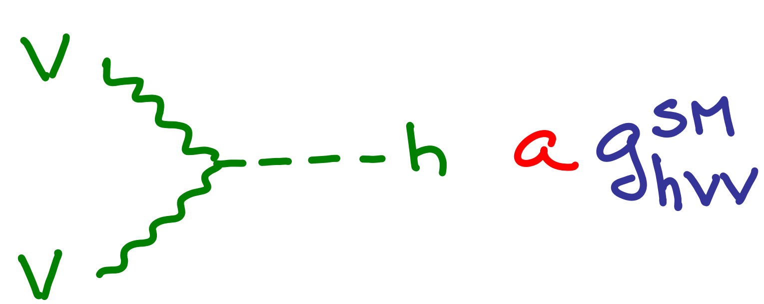
Fermion

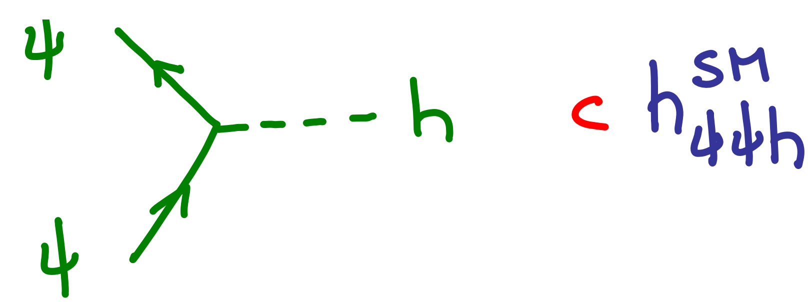



Vector

$$a = \sqrt{1-\xi}$$

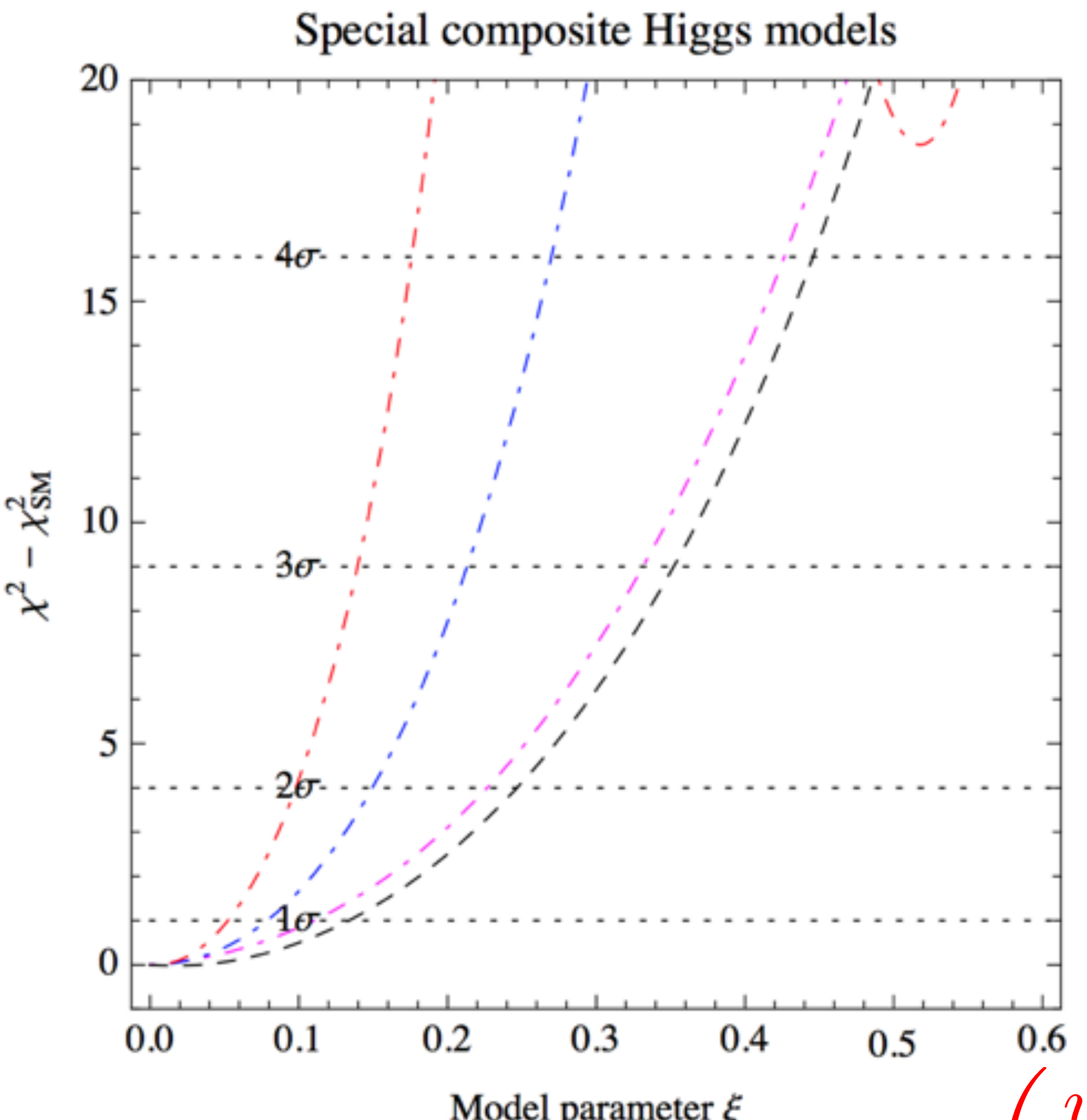
$$c_f = \frac{1-(1+n)\xi}{1-\xi}$$



# Scale of strong SSB

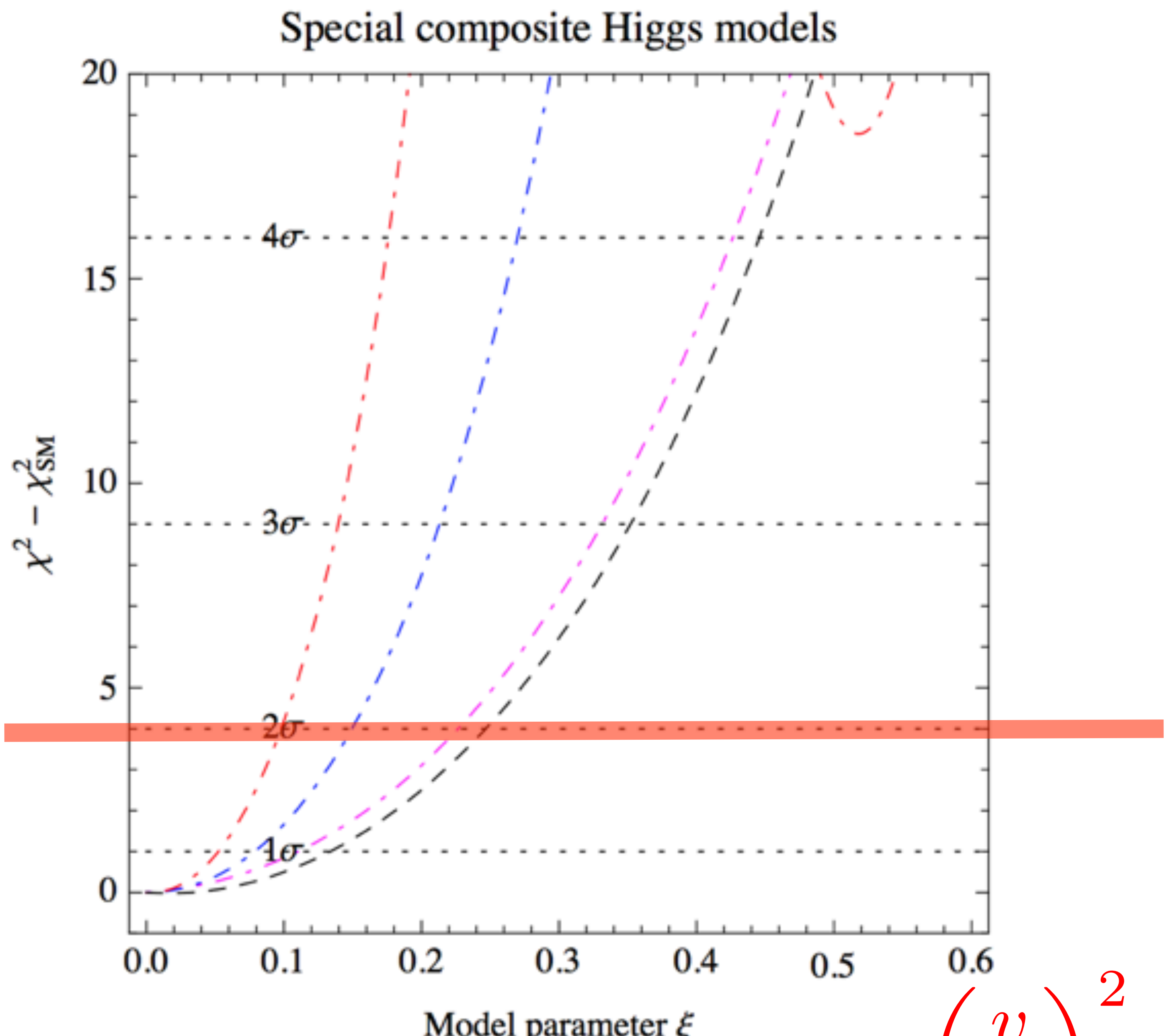
see e.g. Giardino et al




$$\left(\frac{v}{f}\right)^2$$

# Scale of strong SSB

see e.g. Giardino et al

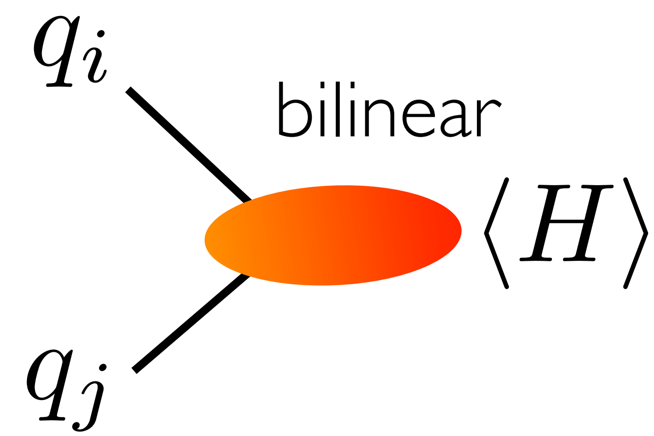



$$\left(\frac{v}{f}\right)^2$$

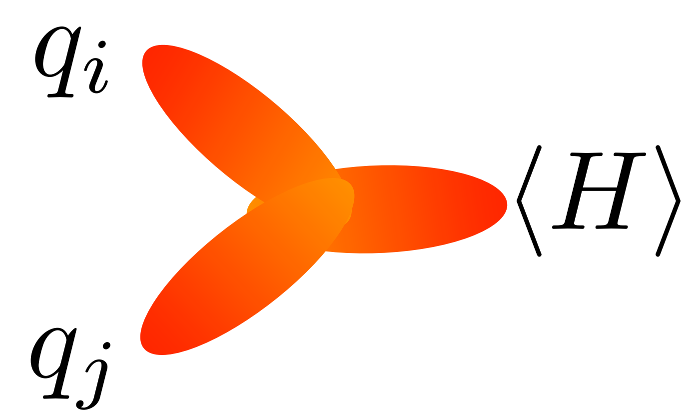
$$f \approx 500 \ldots 800\,\mathrm{GeV}$$

# Addressing flavor...

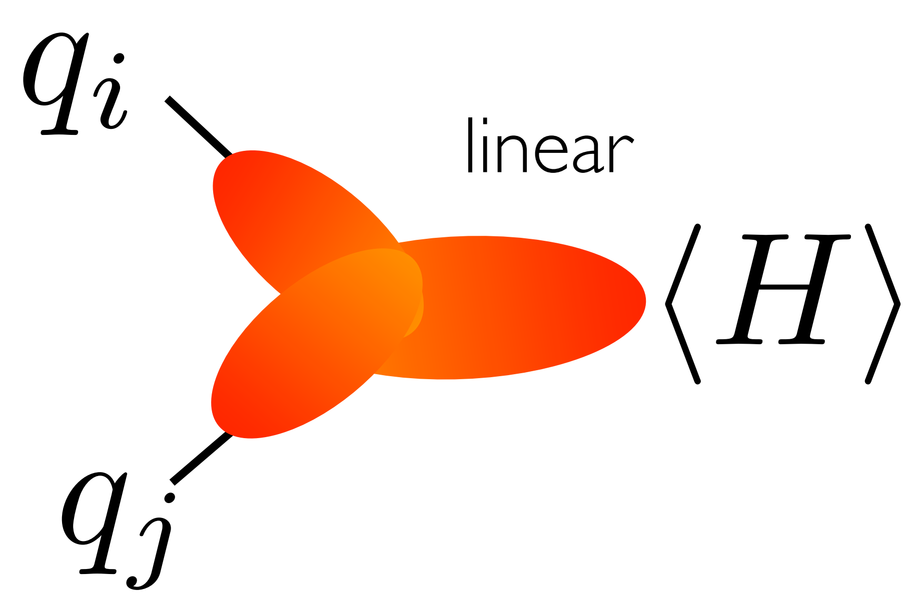
- Classical Techni-color/composite Higgs **failed**, post-modern conformal TC disfavored by CFT theorems




- Full compositeness **excluded** by LEP




- Partial compositeness:



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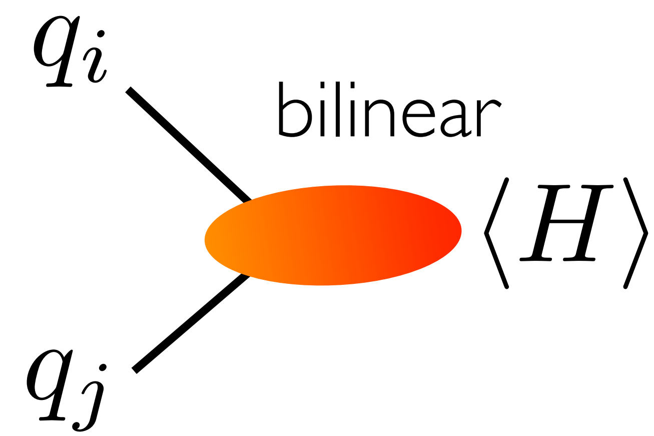


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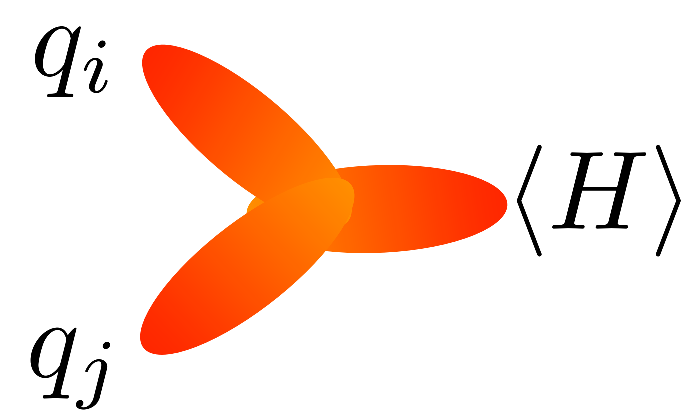


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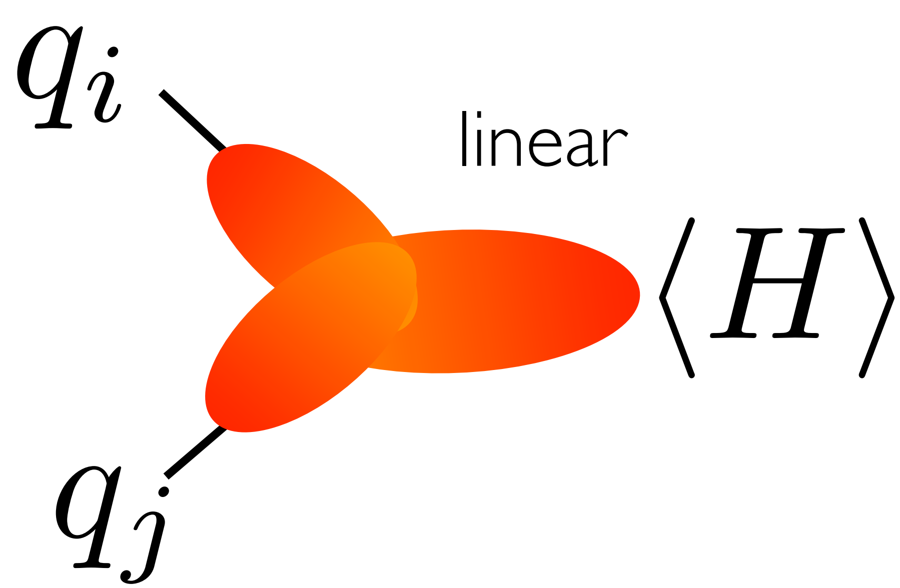


# Partial compositeness

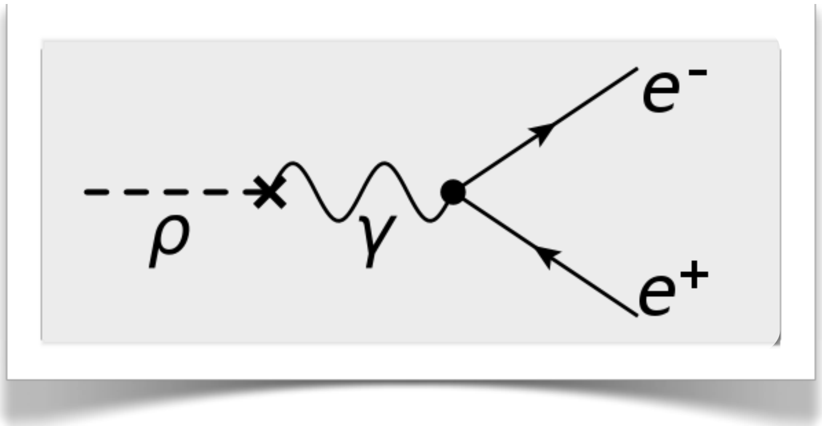
vector-like composite fermion

Fermionic operators can excite composite fermions at low energy:

$$\langle 0|\mathcal{O}|\chi\rangle = \lambda\, f$$

Analogous to photon-rho mixing

$$\mathrm{Br}(\rho \to e^+e^-) \sim 10^{-5}$$




Linear couplings imply mass mixings:

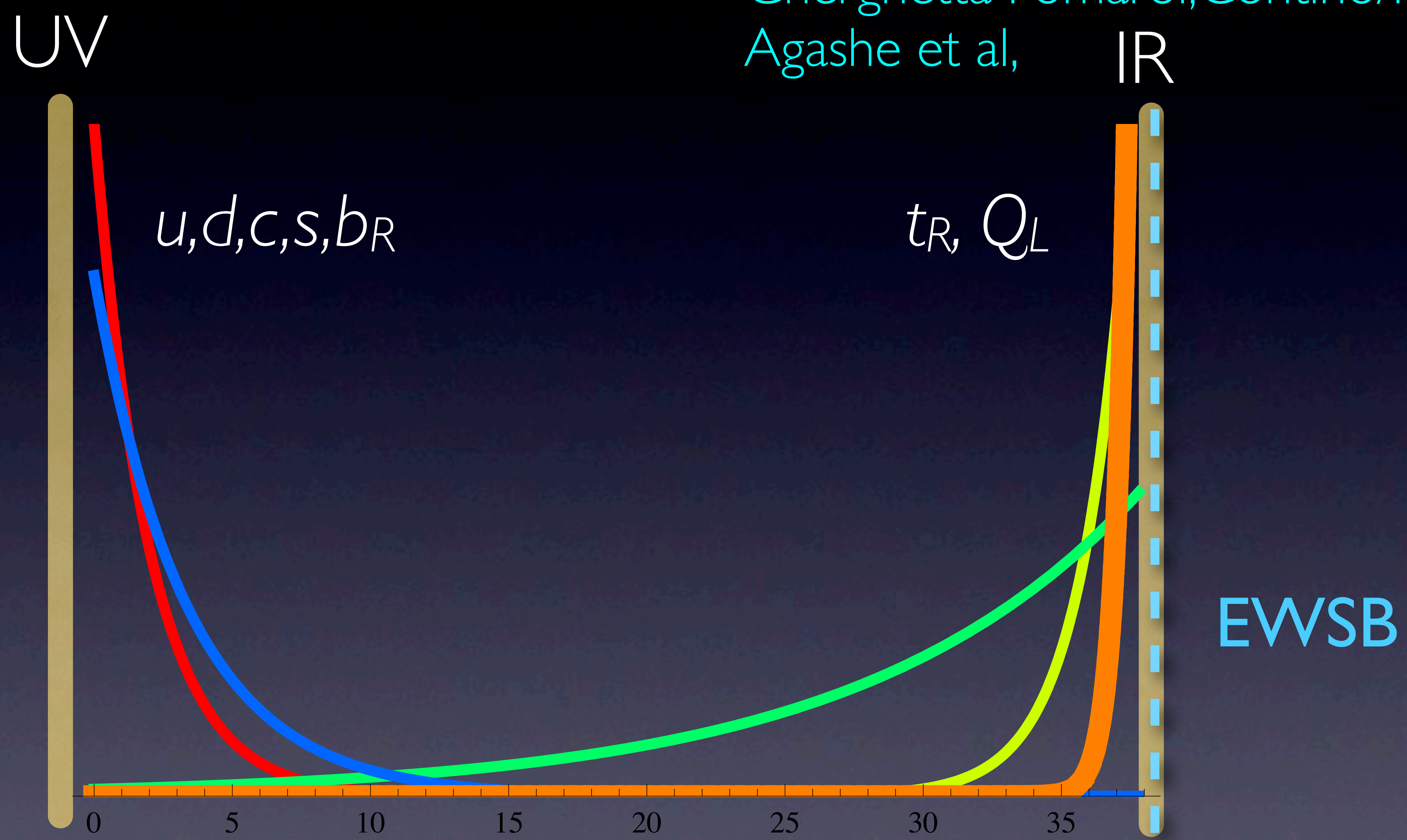
$$\mathcal{L} = \bar{\psi}\, i\partial\!\!\!/\, \psi + \bar{\chi}(\, i\partial\!\!\!/ - m_*)\chi + \lambda f\, \bar{\psi}\chi + h.c.$$

Rotate to mass eigenbasis:

$$\begin{pmatrix}\psi\\ \chi\end{pmatrix} \to \begin{pmatrix}\cos\varphi & \sin\varphi\\ \sin\varphi & \cos\varphi\end{pmatrix}\begin{pmatrix}\psi\\ \chi\end{pmatrix} \qquad \tan\varphi = \frac{\lambda\, f}{m_*}$$

# AdS/CFT inspiration: conformal strong sector induces small mixings

Randall/Sundrum, Grossman/Neubert, Gherghetta Pomarol,Contino/Pomarol Agashe et al,




RGE of $\mathcal{L}_{\rm UV} \supset \lambda \bar{O}_R \psi_L$ UV → IR

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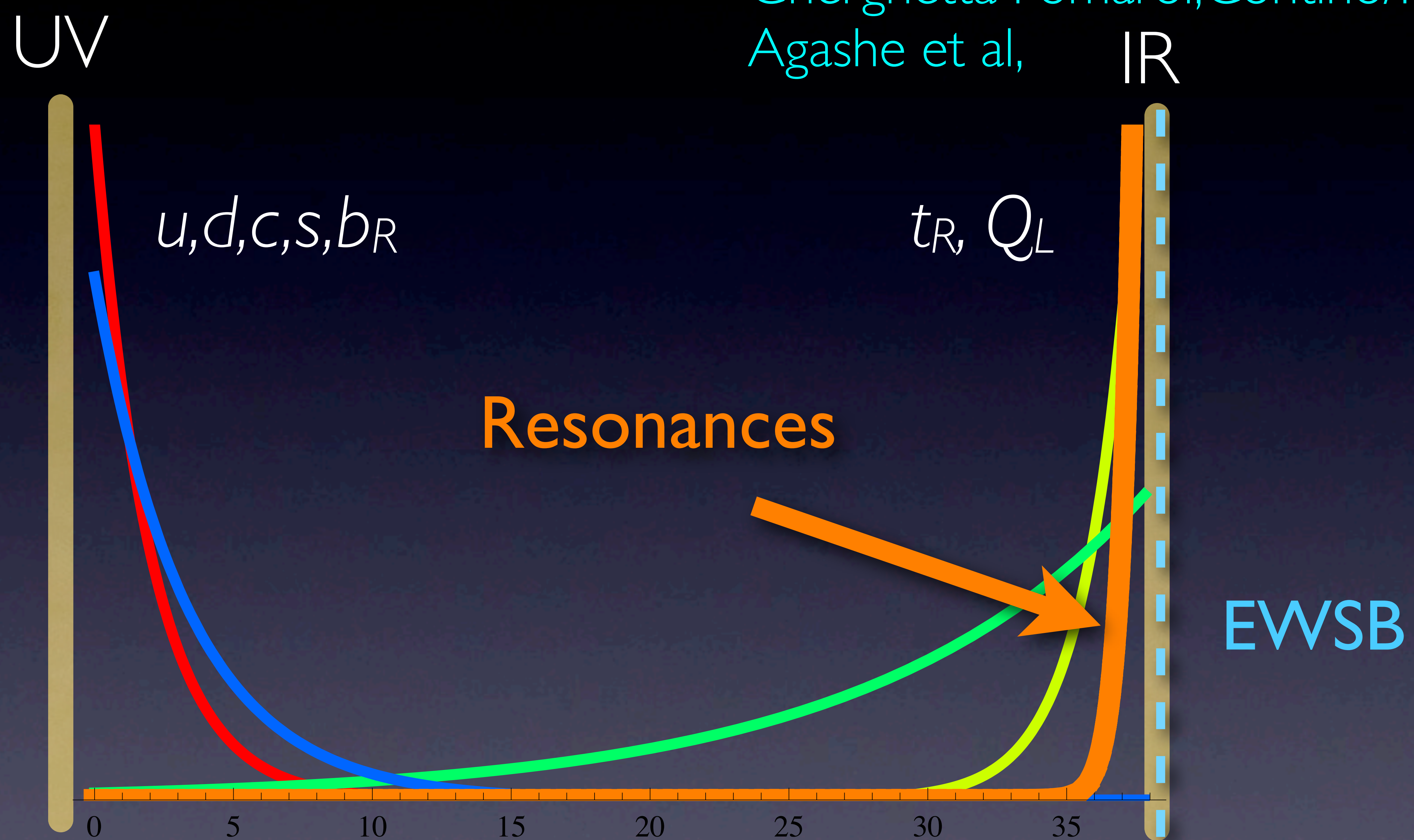


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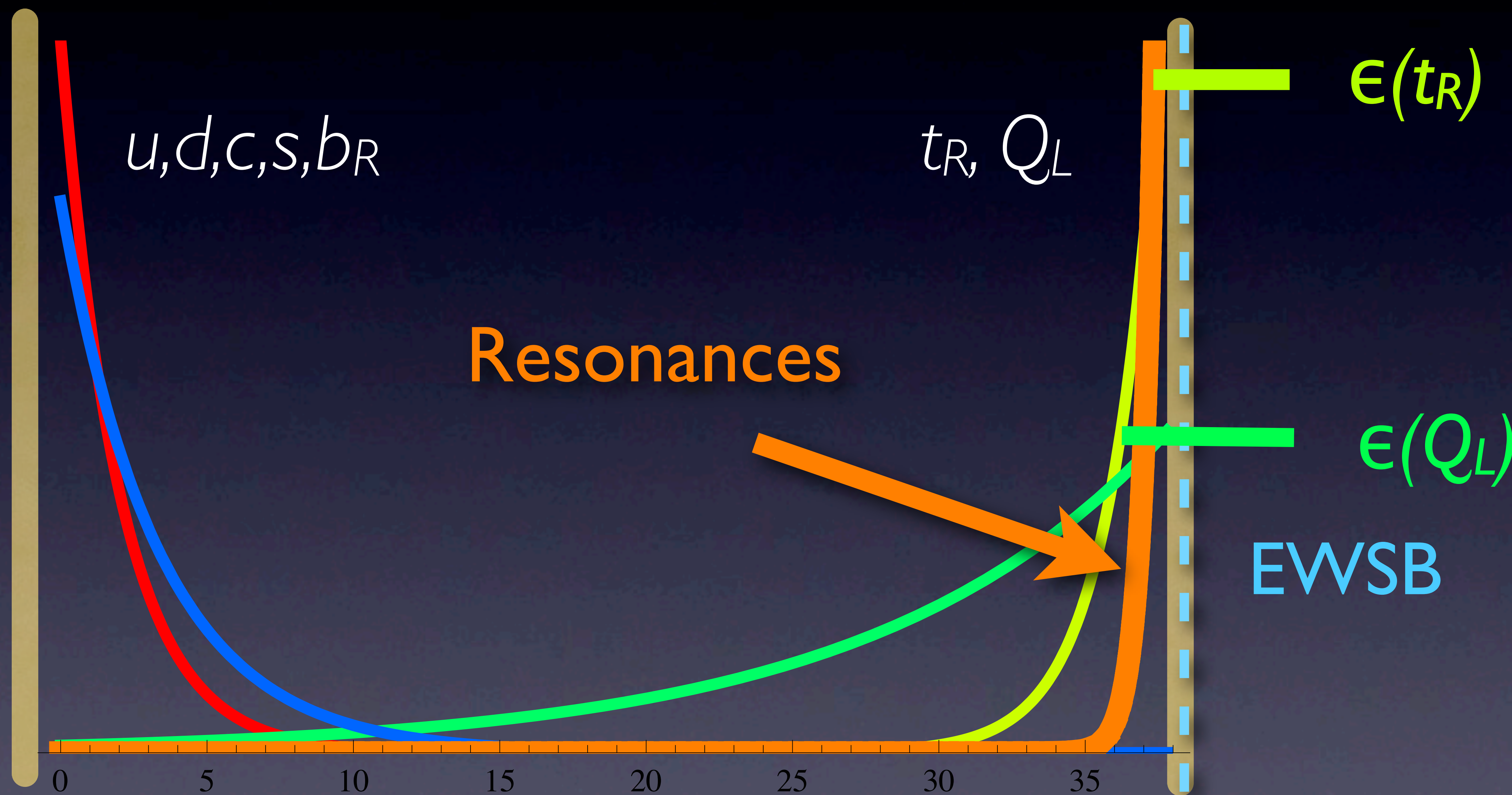
UV IR

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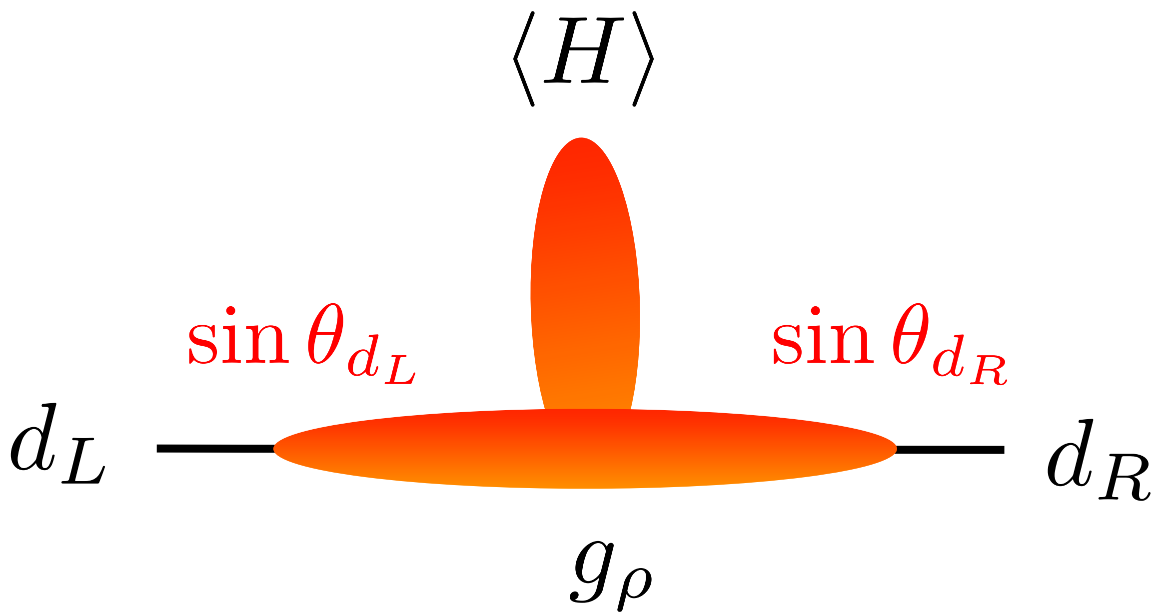
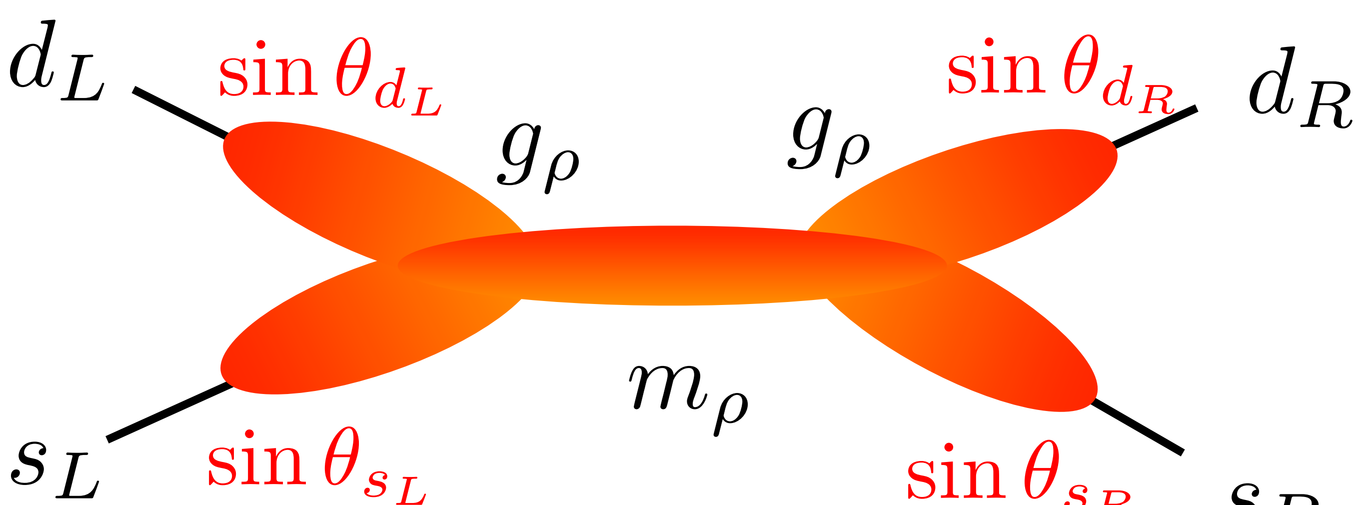
Csaki/Falkowski/AW, Casagrande et al, Agashe et. al, Buras et al. …




## Yukawa

$$g_\rho \sin\theta_{d_L} \langle H \rangle \sin\theta_{d_R} \sim m_d$$



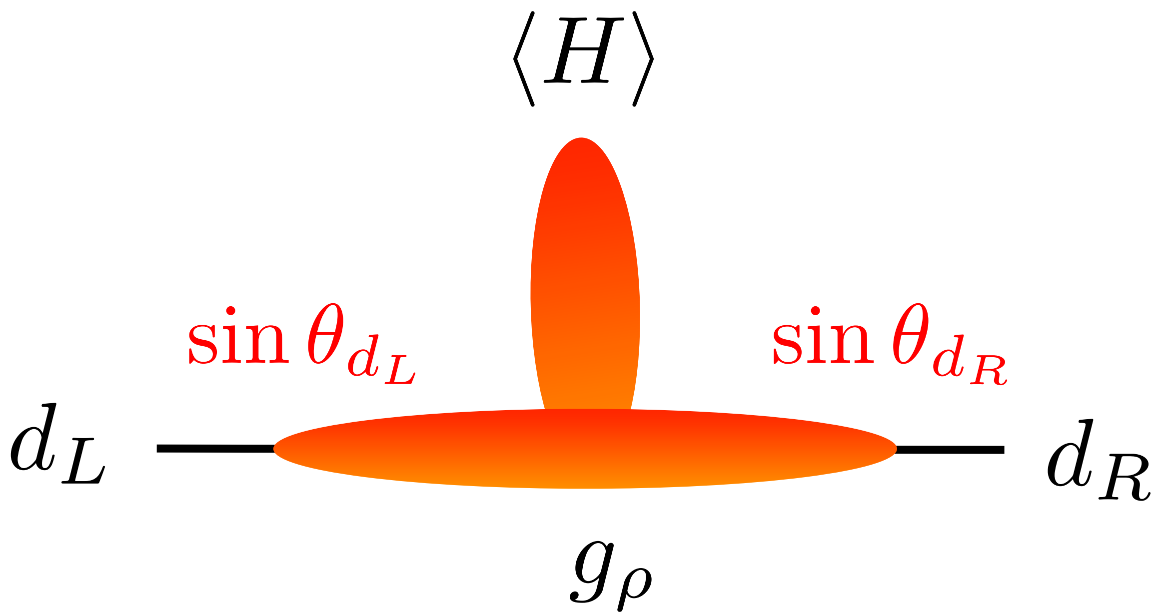

## FCNC

$$\sim s_{d_L} s_{d_L} s_{d_R} s_{s_R} \sim \frac{m_d\, m_s}{v^2}$$

**GIM-like protection**

… almost works $\Lambda_{\epsilon_K} = 10^5\,\text{TeV} \;\rightarrow\; m_\rho \gtrsim 10\,\text{TeV}$

Csaki/Falkowski/AW, Casagrande et al, Agashe et. al, Buras et al. …

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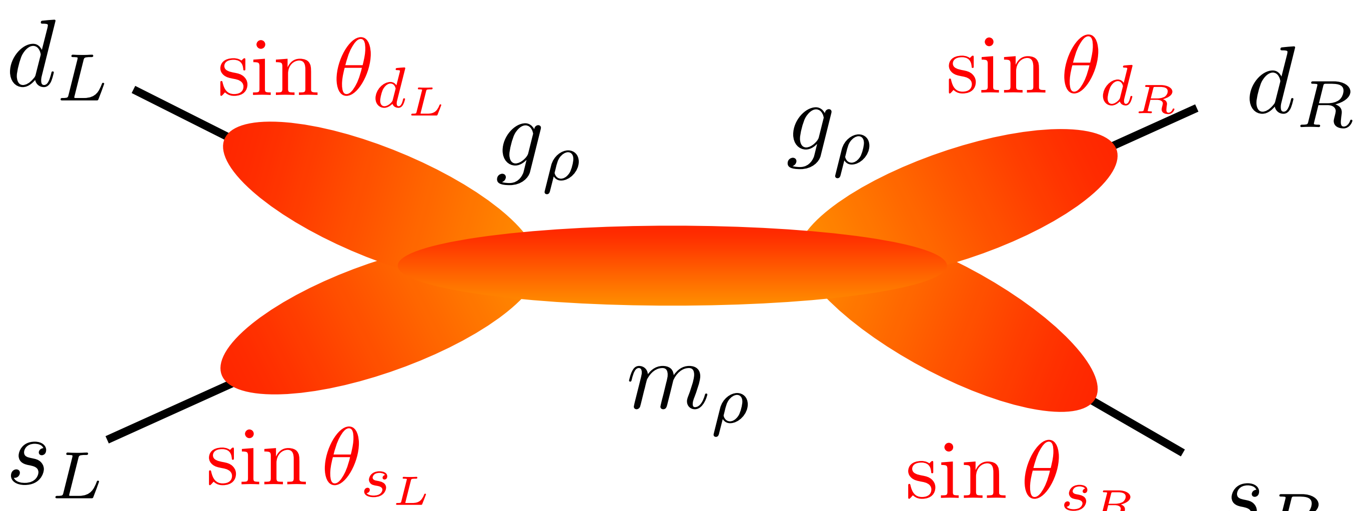


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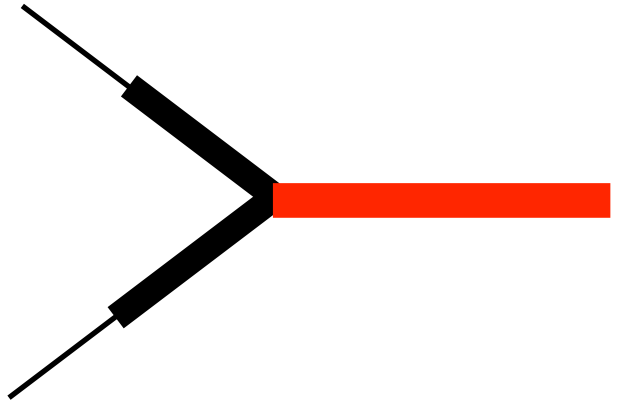


$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \mathcal{O}_q^i + \epsilon_u^i u_L^i \mathcal{O}_u^i + \epsilon_d^i d_L^i \mathcal{O}_d^i$$

Yukawas

$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_\rho$$

$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_\rho$$

ΔF=1

$$\epsilon_q^i \epsilon_u^j g_\rho \times \frac{v}{m_\rho^2} \times \frac{g_\rho^2}{16\pi^2} \quad \bar{q}^i \sigma_{\mu\nu} u^j G_{\mu\nu}$$

ΔF=2

$$\epsilon_q^i \epsilon_d^j \epsilon_q^k \epsilon_d^\ell \times \frac{g_\rho^2}{m_\rho^2} \quad (\bar{q}^i \gamma^\mu d^j)(\bar{q}^l \gamma_\mu d^\ell)$$

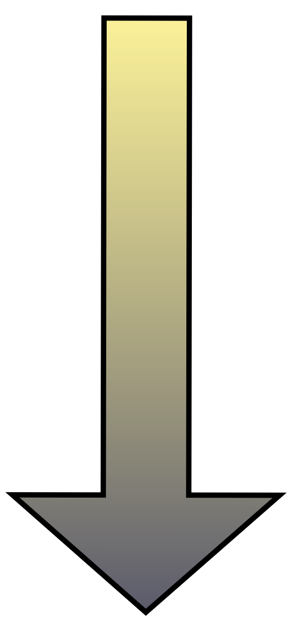
# Flavor Constraints

| | |
|---|---|
| $\epsilon_k$ | $m_\rho \gtrsim 10 \text{ TeV}$ |
| $\epsilon'/\epsilon, \quad b \to s\gamma$ | $m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (10-15) \text{ TeV}$ |
| $d_n$ | $m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (20-40) \text{ TeV}$ |

Agashe et. al; Csaki, Falkowski, AW; Buras et. al.; Neubert et al; Isidori et. al, ...

Partial compositeness not the full story

Strong sector must have some flavor degeneracy:



$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

$$U(2)^3$$

Barbieri et al, Redi,

$$SU(3)$$

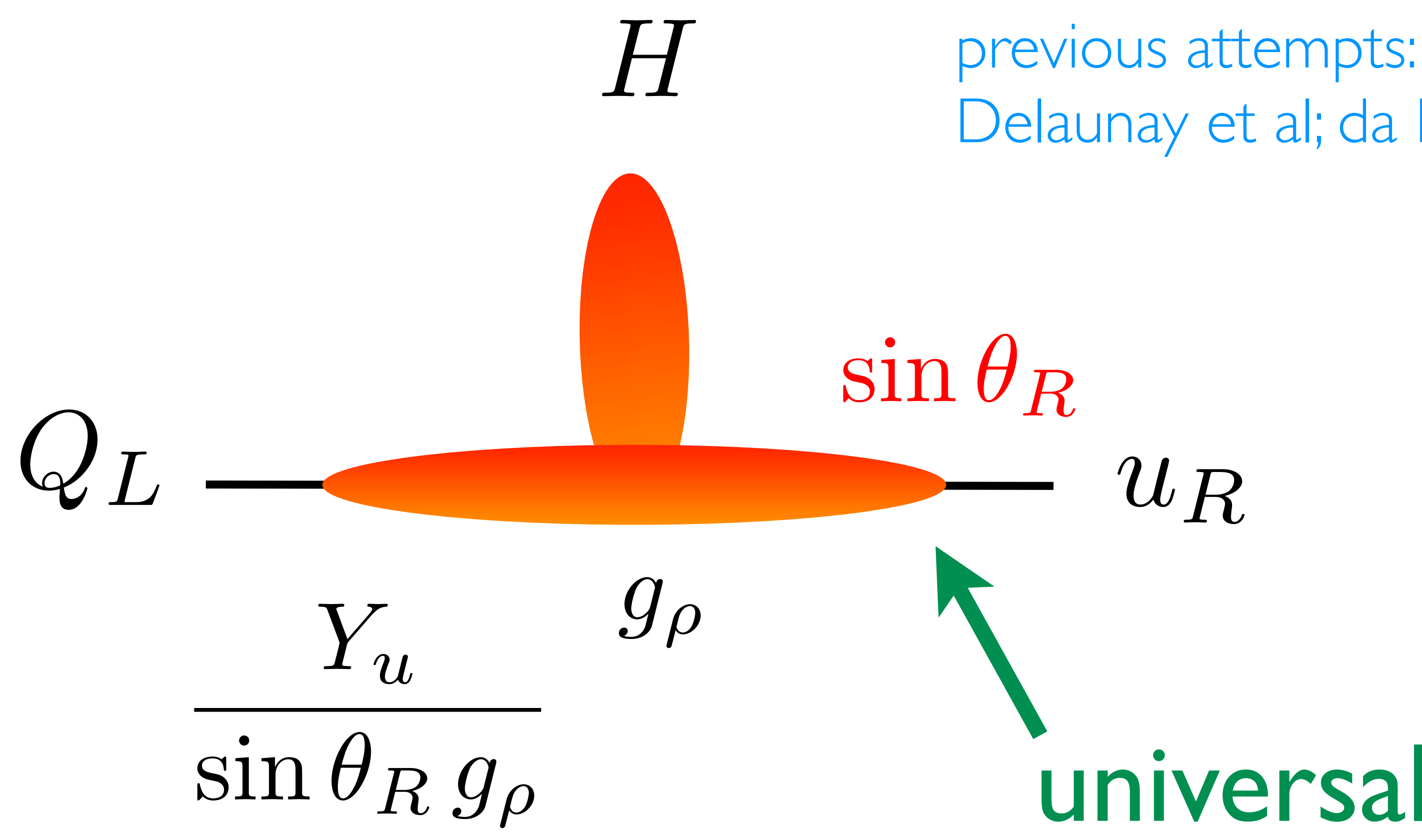
Cacciapaglia, Csaki, Terning, AW; Redi, AW

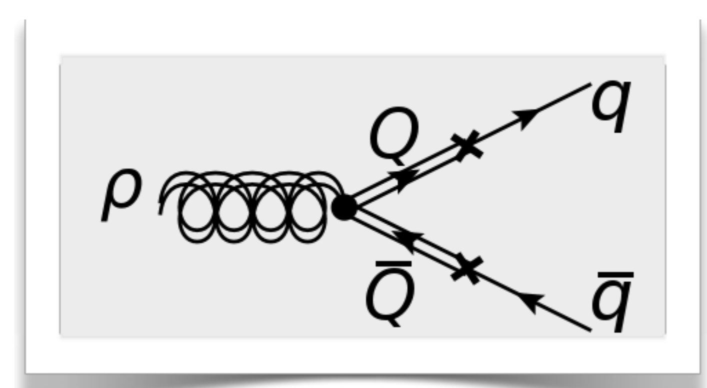
# Tension with FCNCs and CP: MFV

Redi/AW

previous attempts: Csaki,AW et al; Delaunay et al; da Rold; Barbieri et al

Invoke MFV



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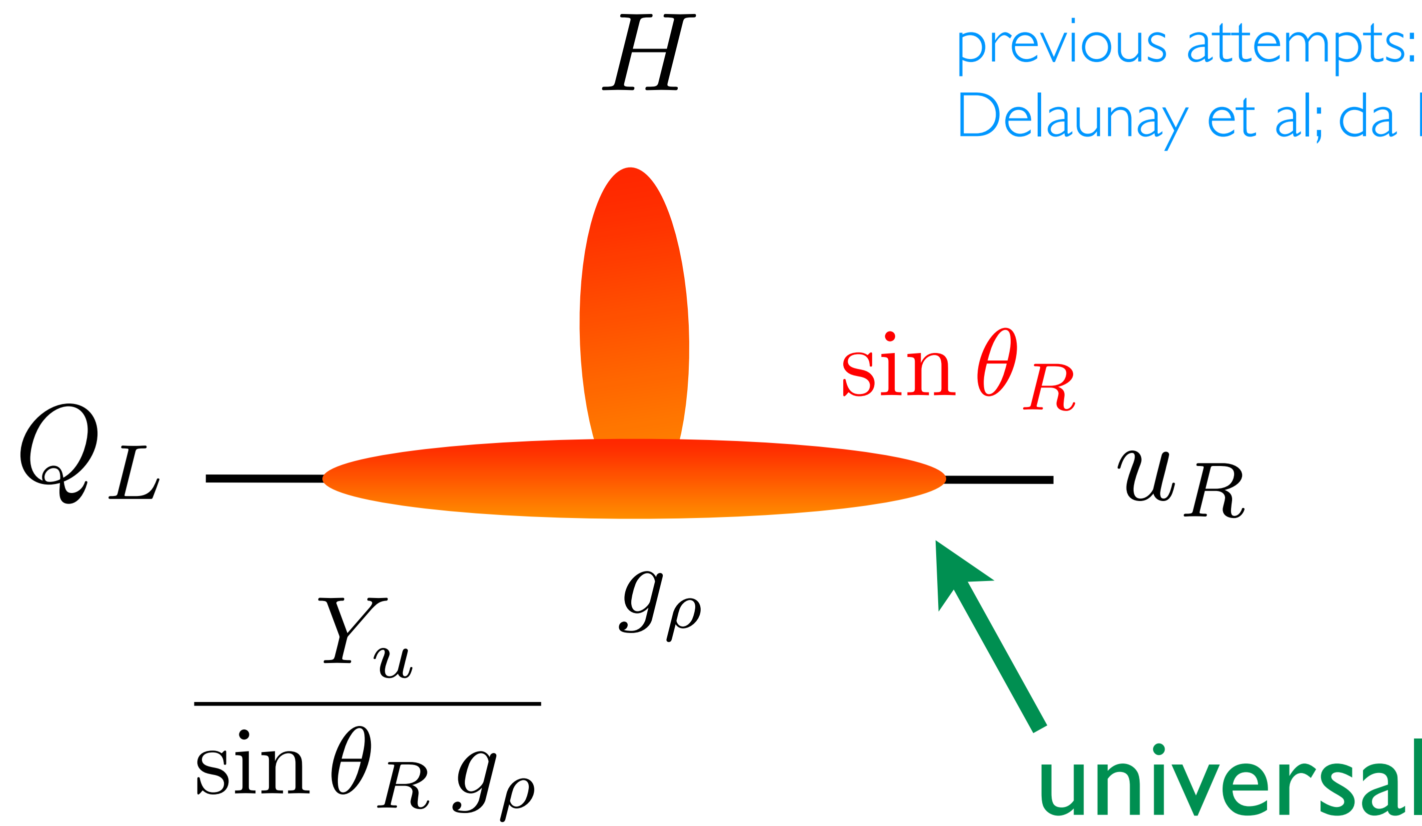
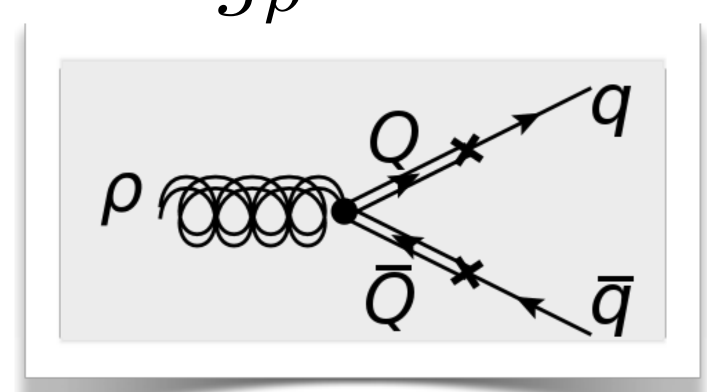



Lower limit on universal compositeness:

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



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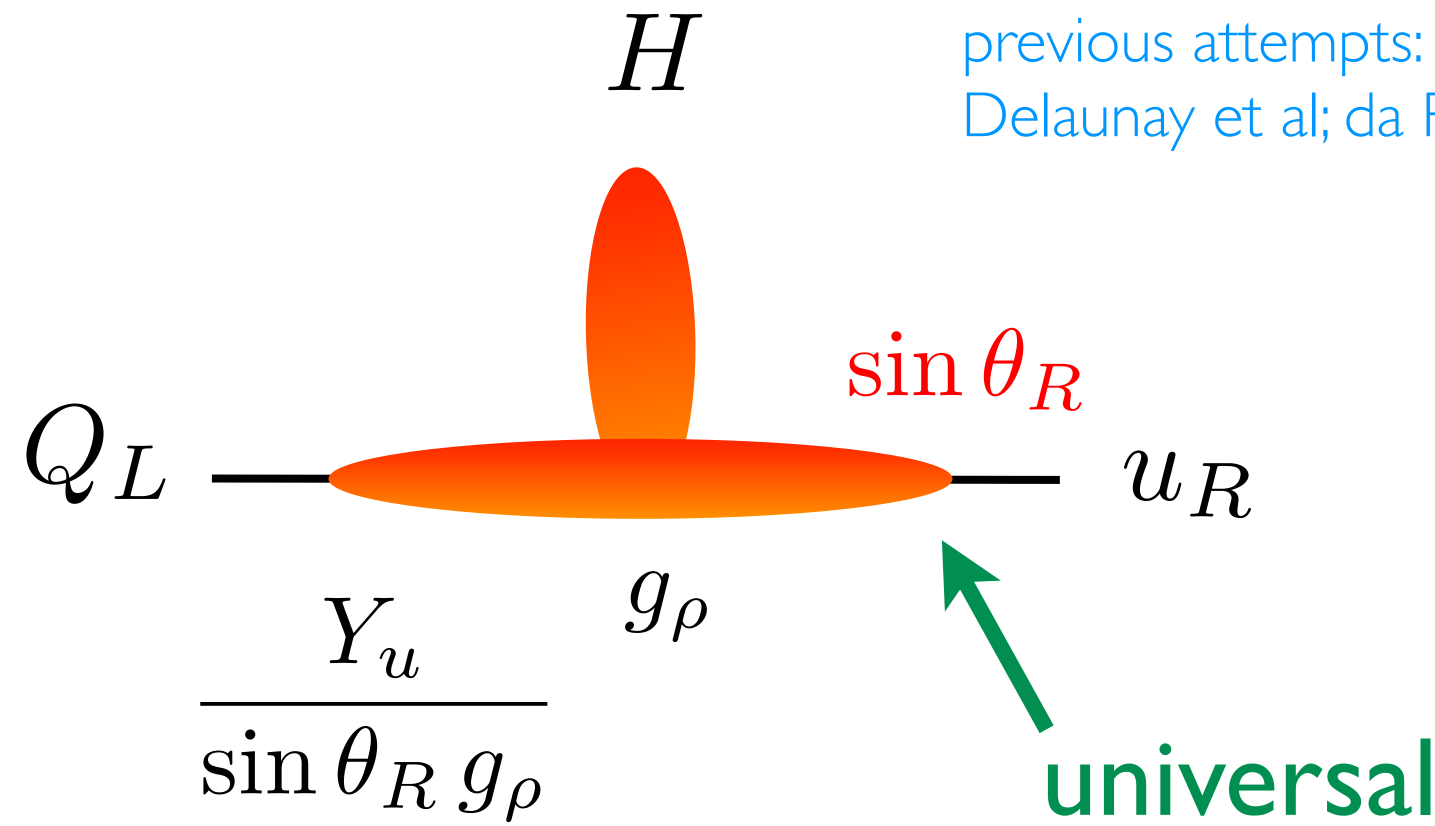


Lower limit on universal compositeness:

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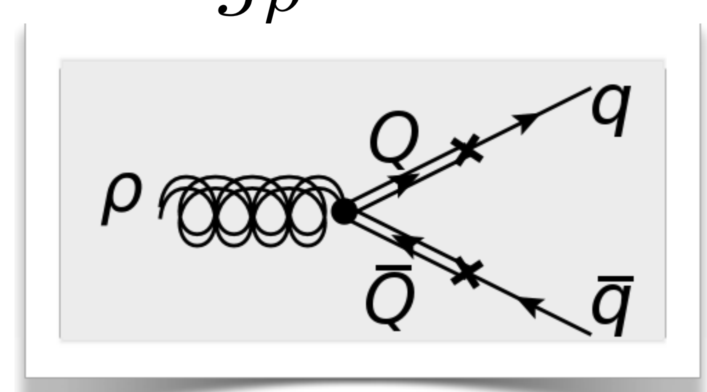
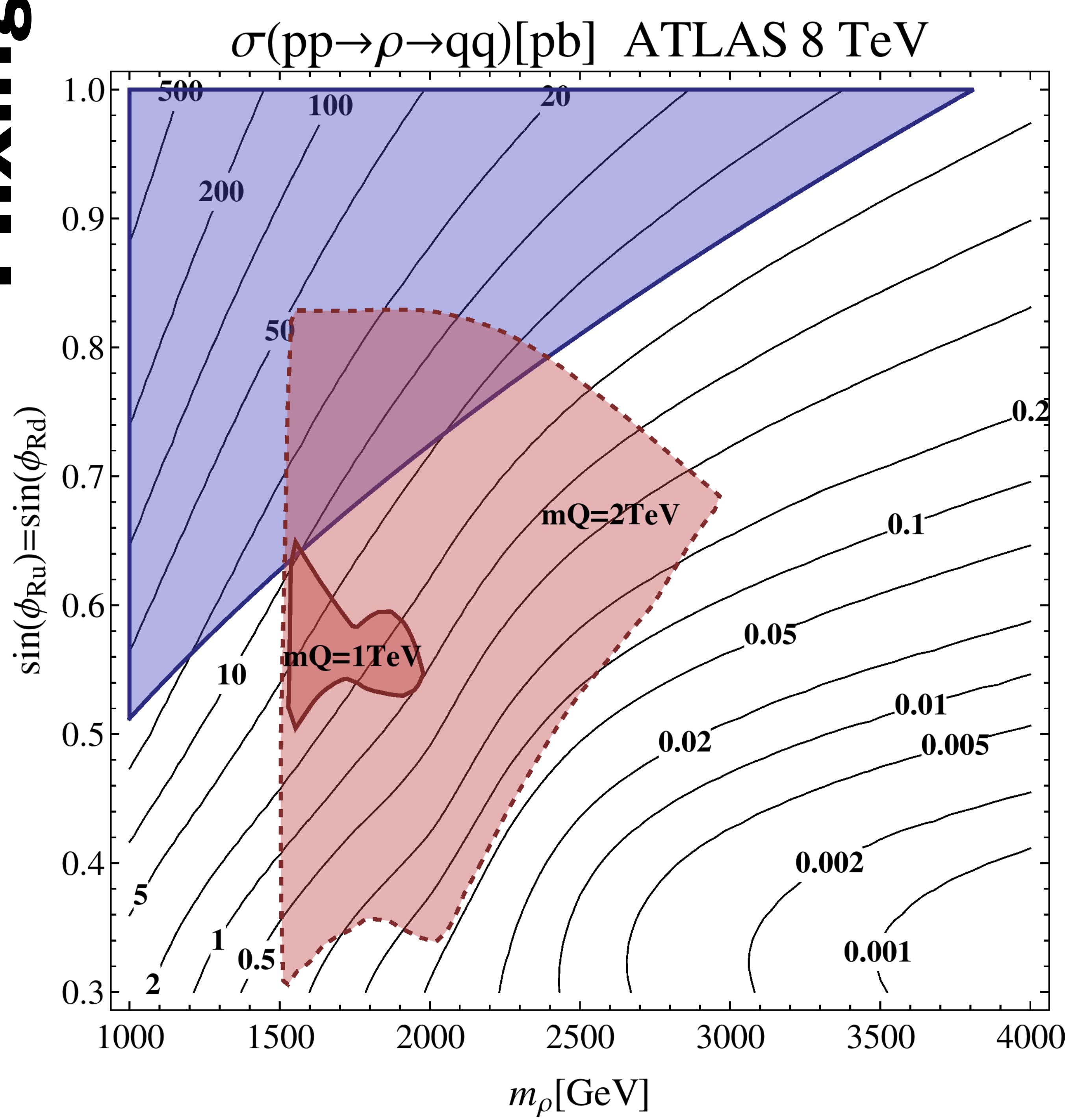
Predict large effects in right-handed quarks (and all possible resonances).



# LHC8 limits

de Vries, Redi, Sanz, AW, in prep.

Mixing




Vector mass

similar plot from CMS

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de Vries, Redi, Sanz, AW, in prep.

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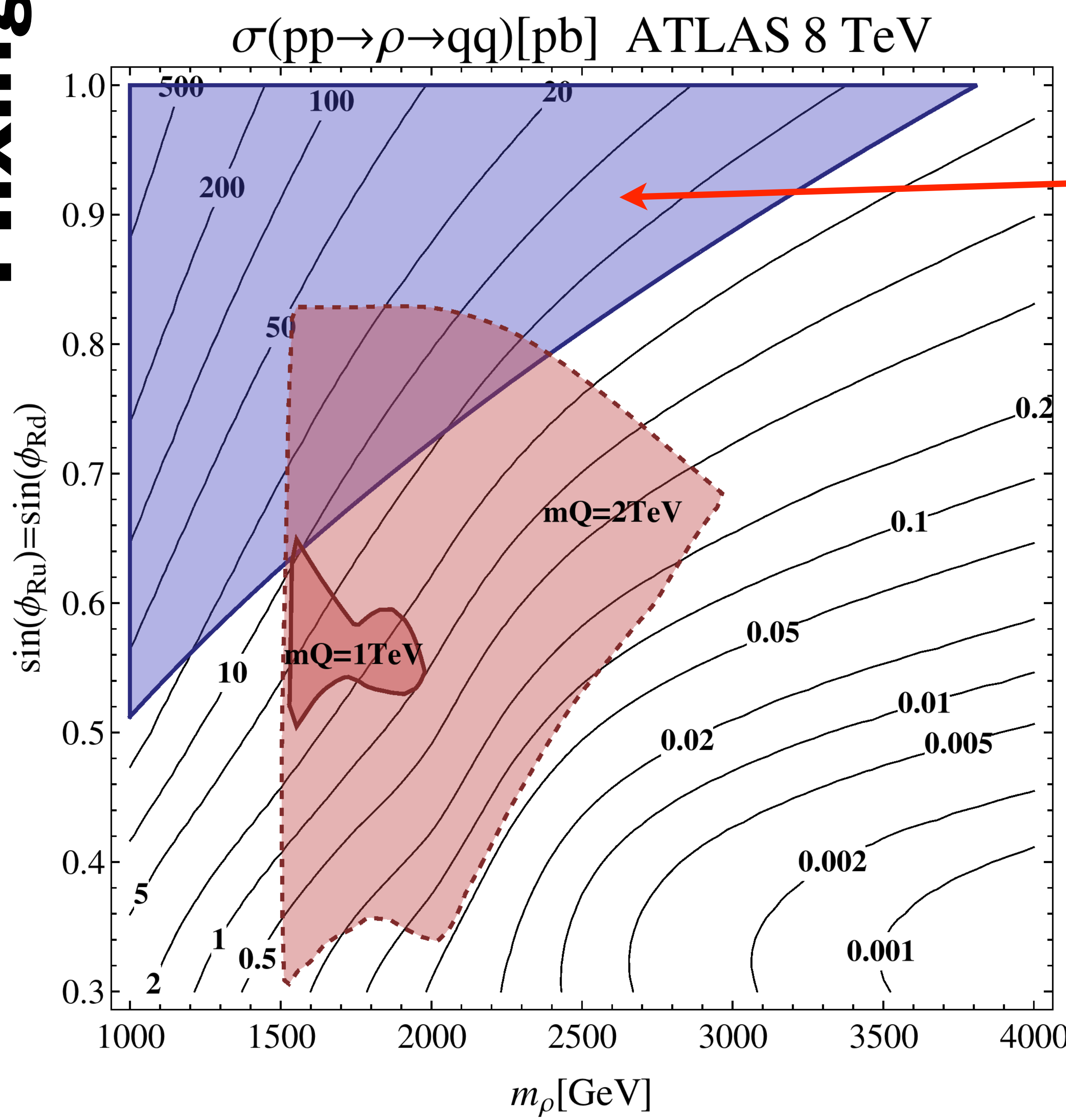
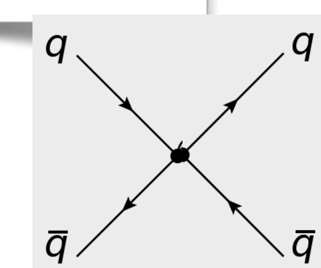



ATLAS dijet angular searches

$$\mathcal{L} \quad \frac{2\pi}{\Lambda^2} \quad q_{L,R}\gamma^\mu q_{L,R} \quad ^2$$

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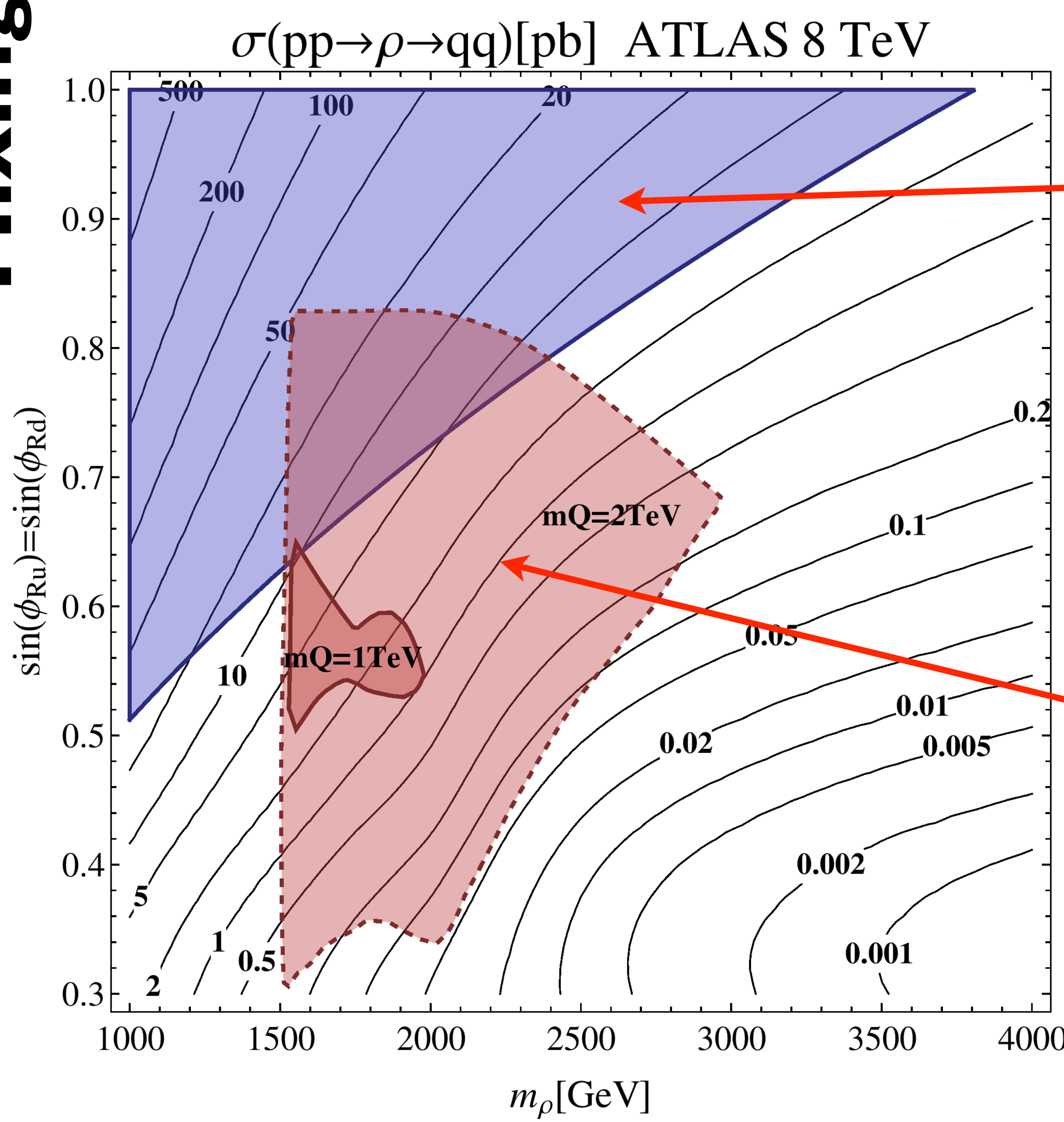


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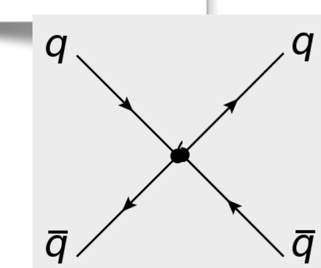
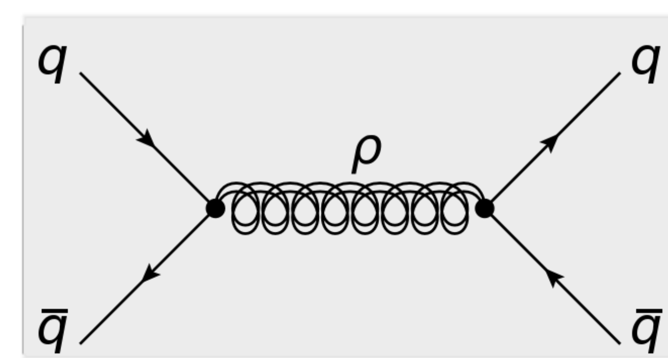
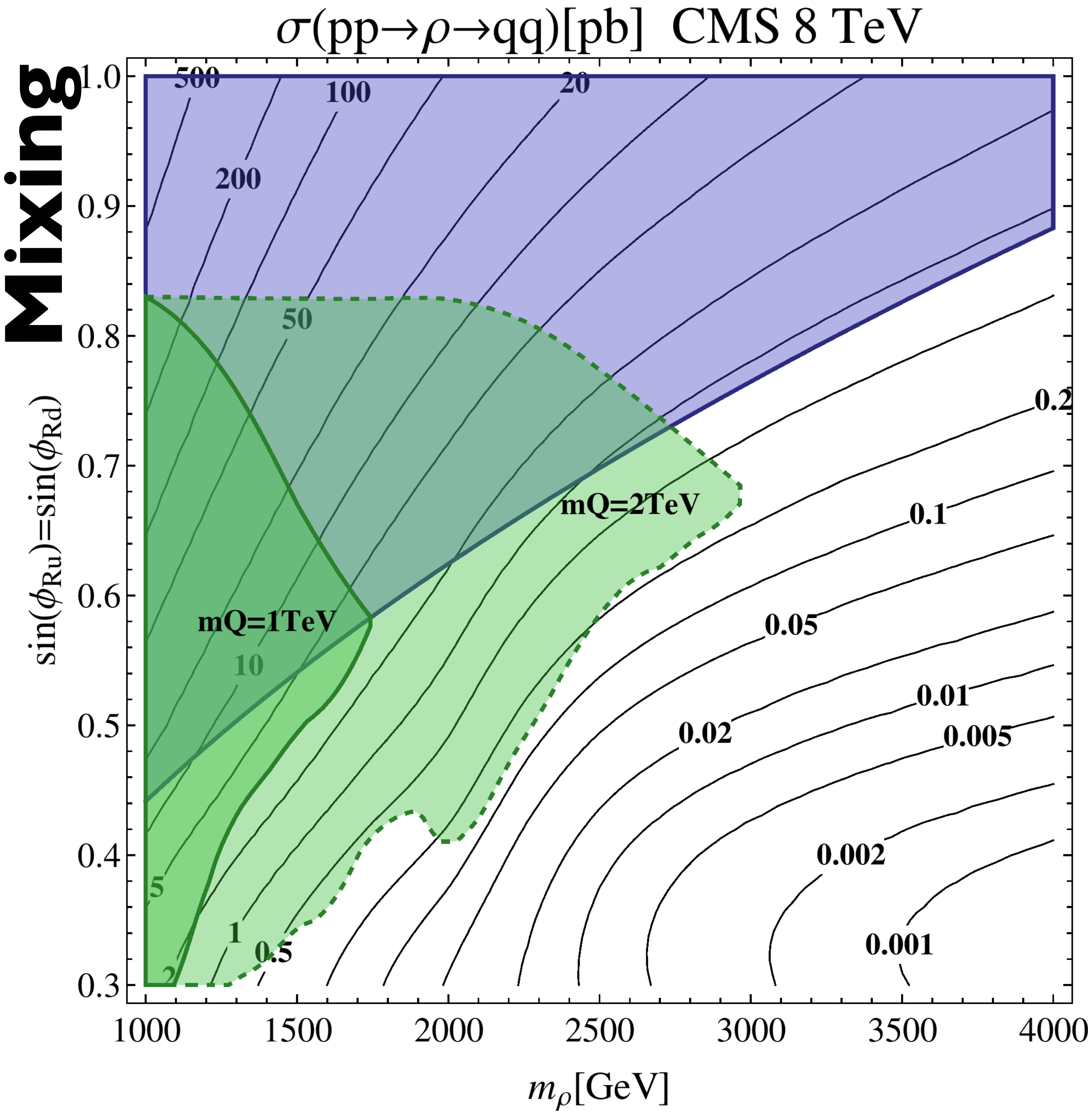



Dijet bump search
ATLAS 8 TeV 13 fb−1 [ATLAS-CONF-2012-148]



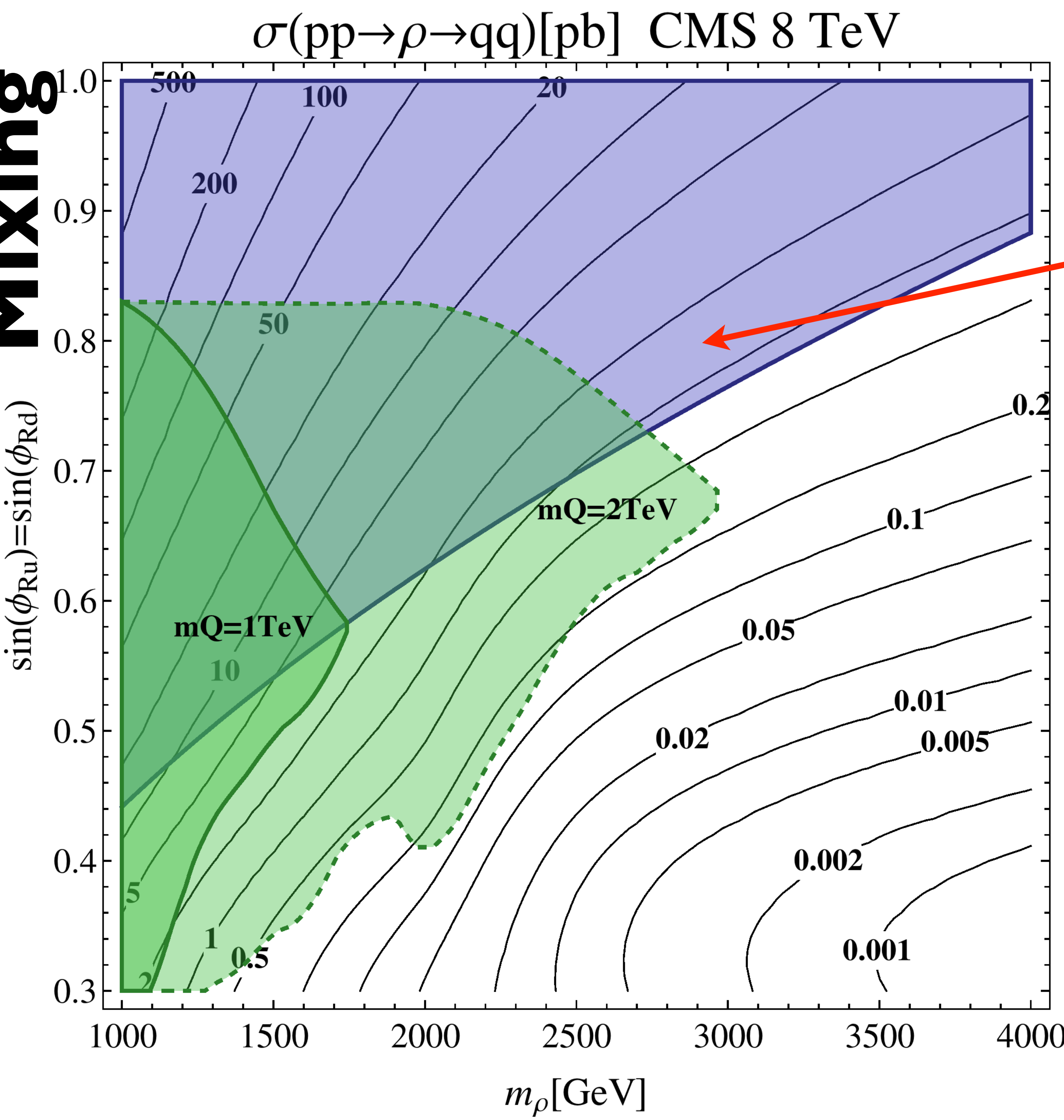

similar plot from CMS




**Mixing**

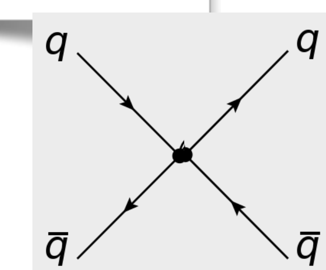
**Vector mass**

Mixing



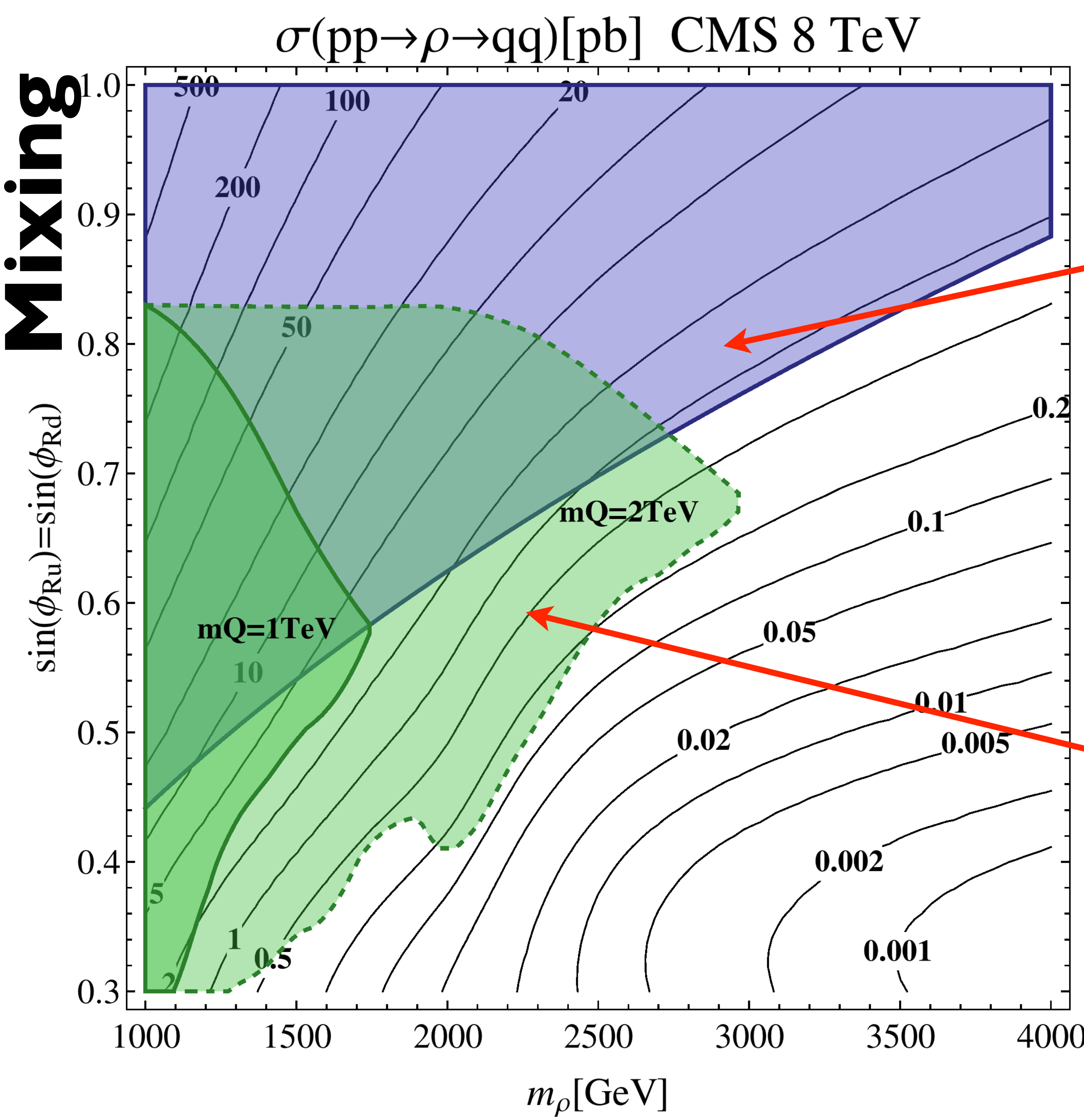

CMS dijet angular searches

$$\mathcal{L} \quad \frac{2\pi}{\Lambda^2} \quad q_{L,R}\gamma^\mu q_{L,R} \quad ^2$$




Vector mass

Mixing




Vector mass

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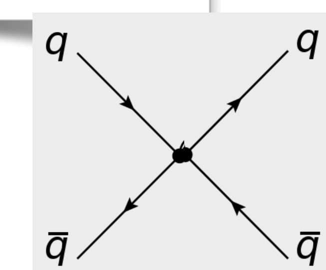
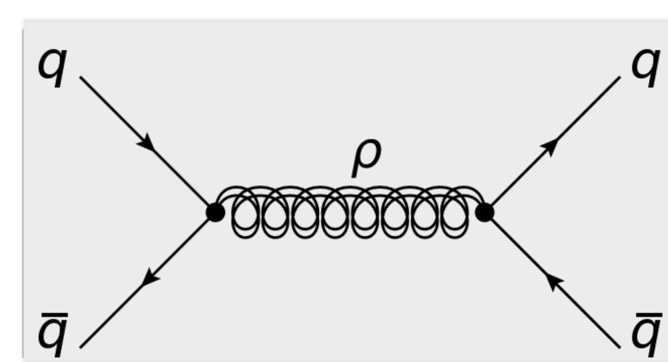
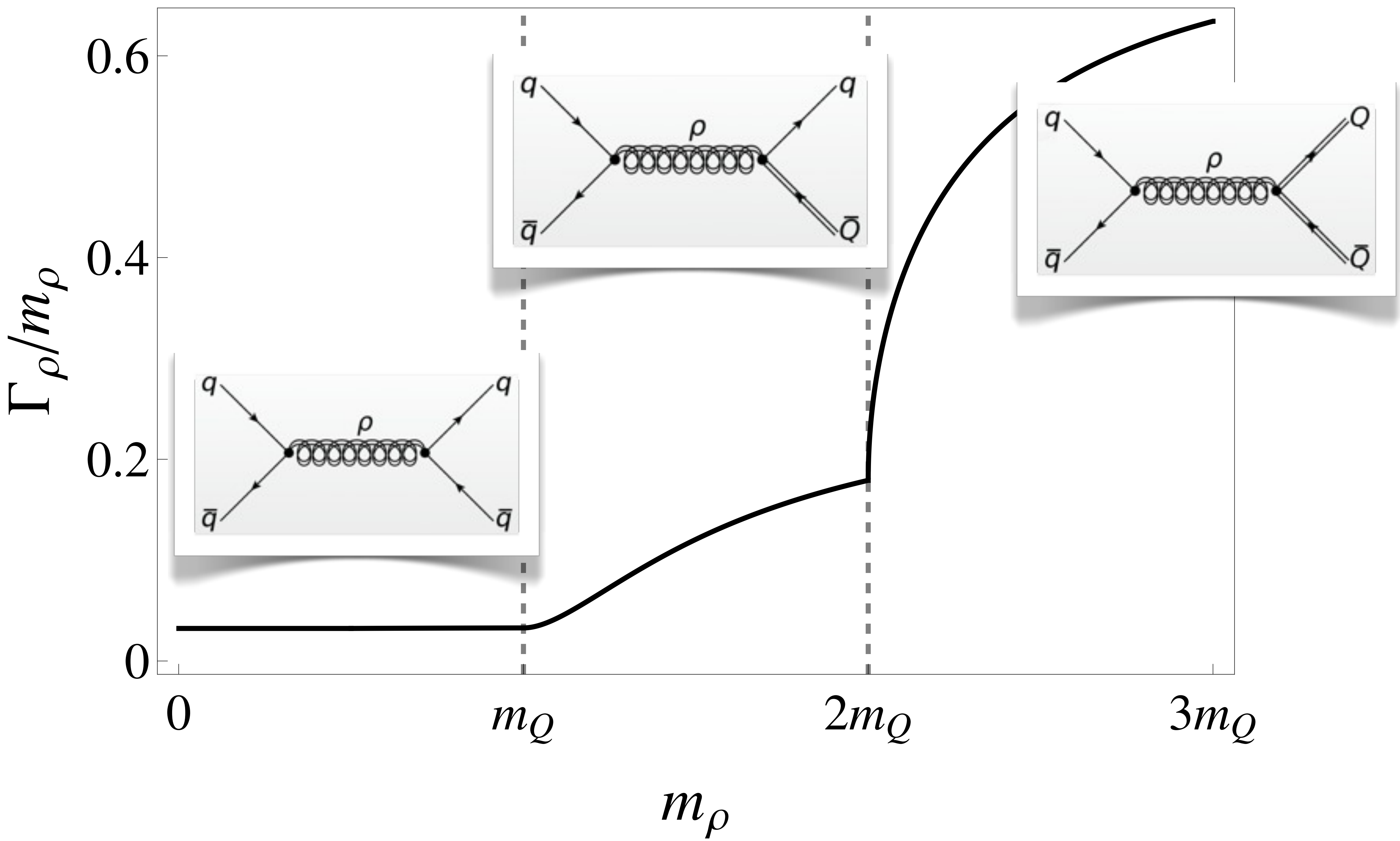


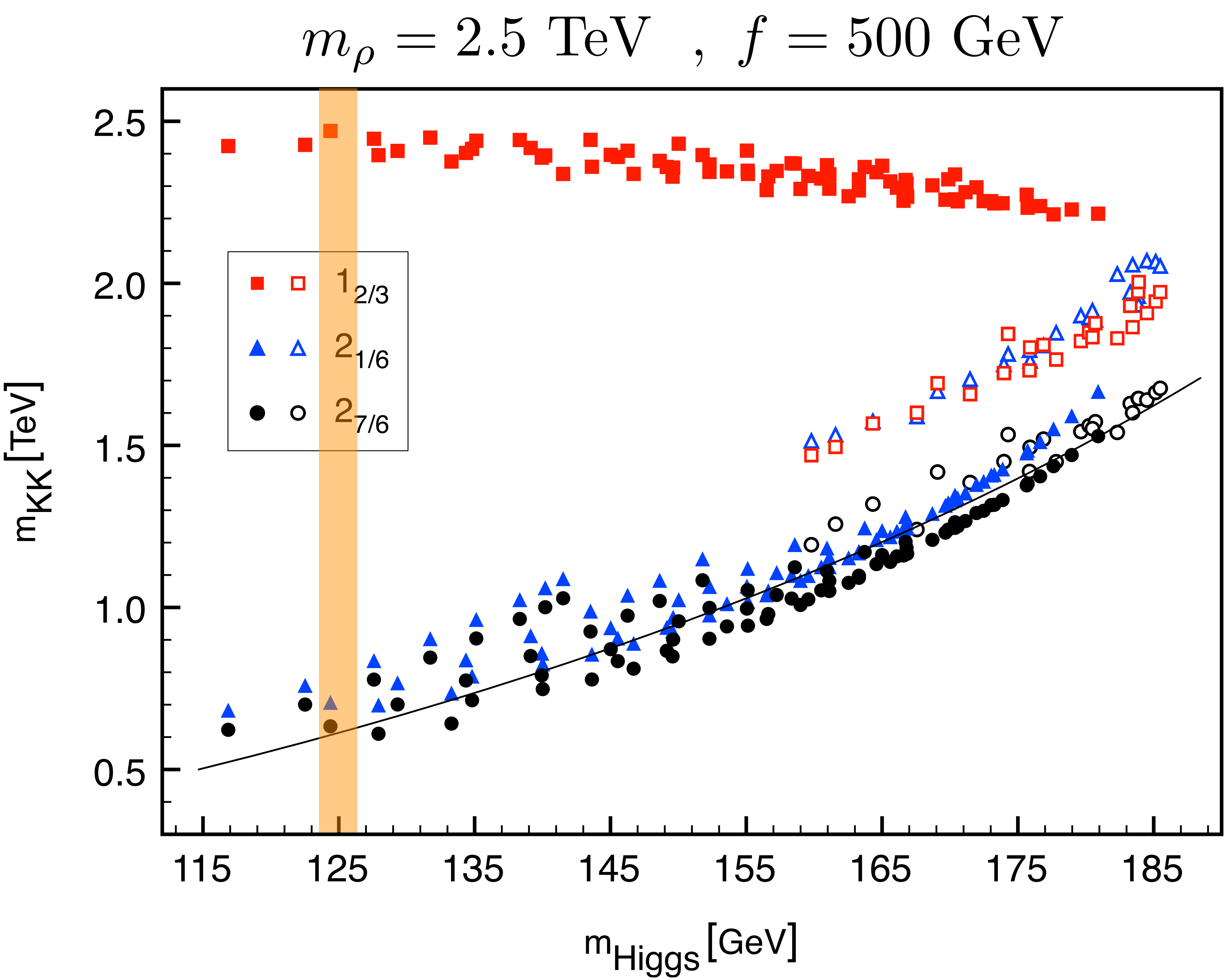

Dijet bump search
CMS



# Octet width vs. fermionic partner mass



# Light Higgs => light fermionic top partners




**Contino** et al 07, Matsedonskyi, et al '12 ; Redi,Tesi 12; Marzocca et al ; Pomarol, Riva 12

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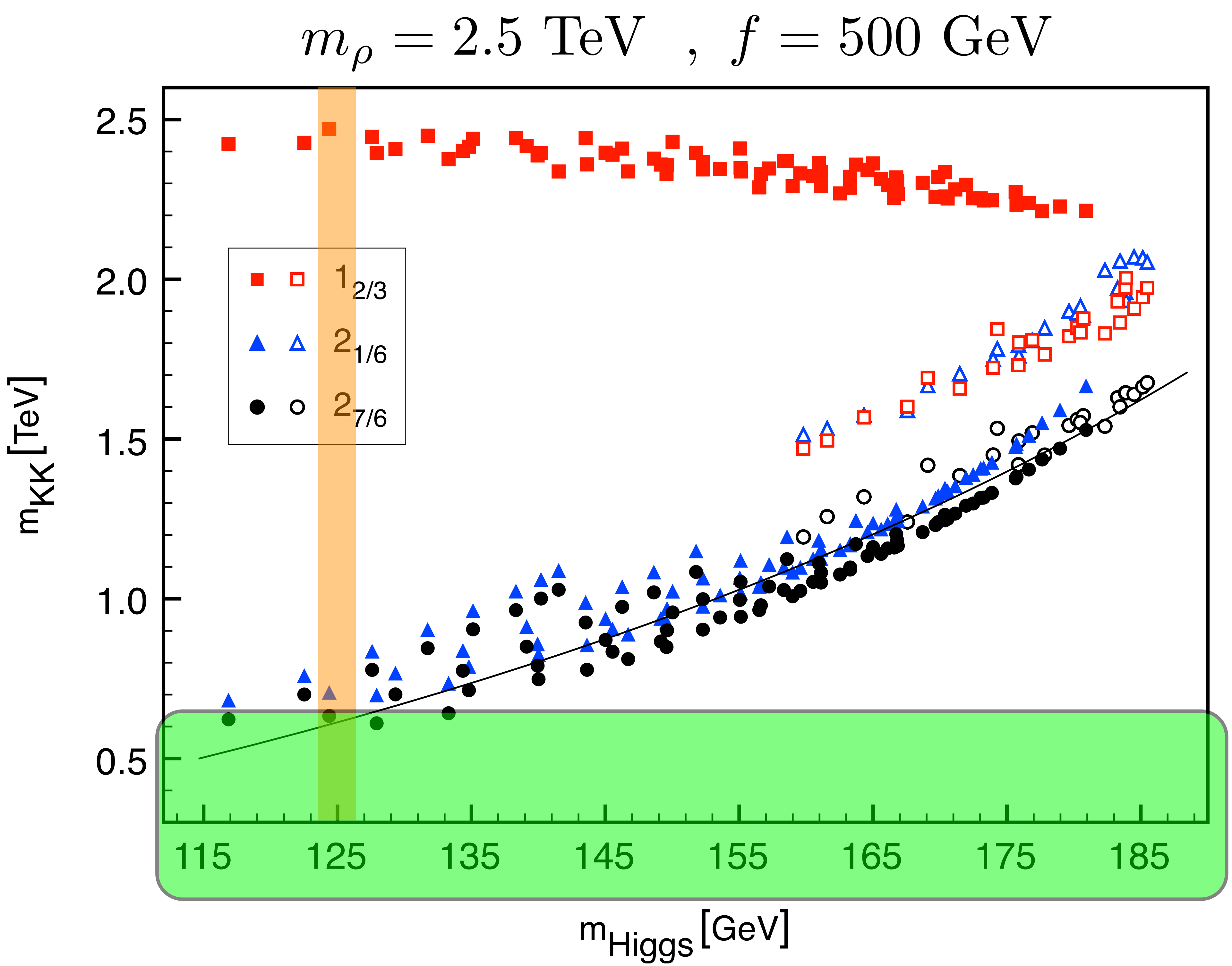


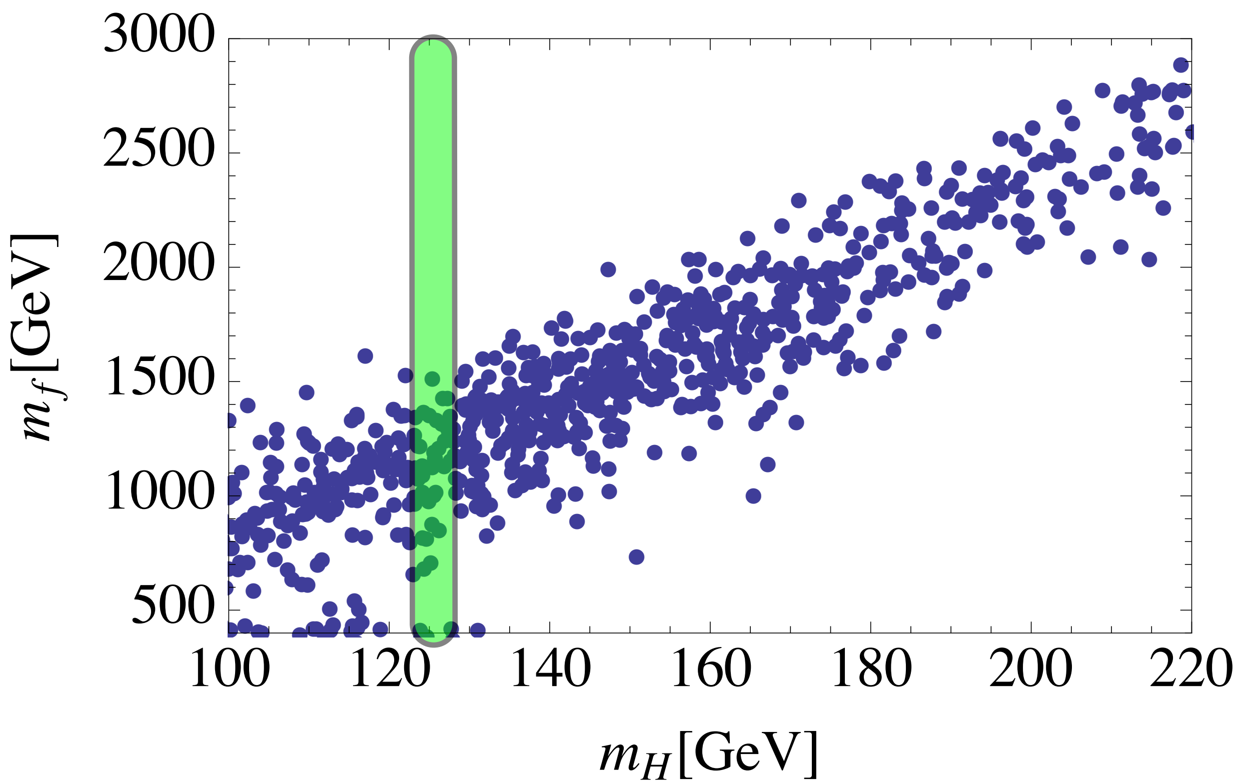

ATLAS: $T_{5/3}$

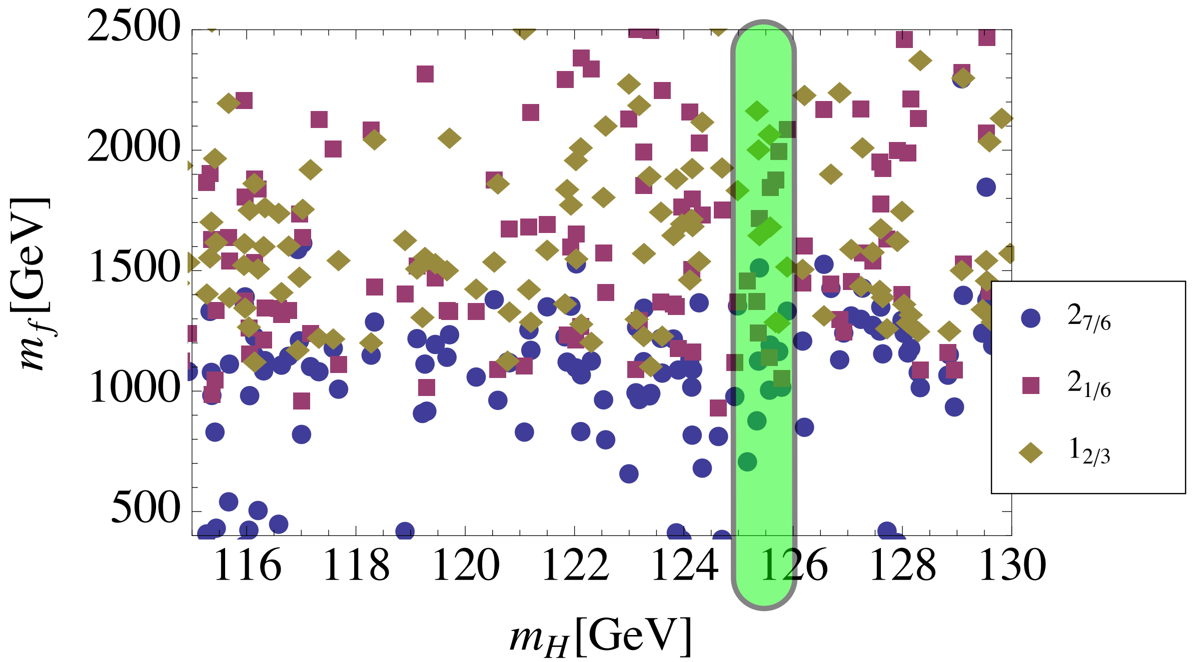
4.7 1/fb, 7 TeV

**Contino** et al 07, Matsedonskyi, et al '12 ; Redi,Tesi 12; Marzocca et al ; Pomarol, Riva 12

# Light Higgs MFV connection

Redi et al



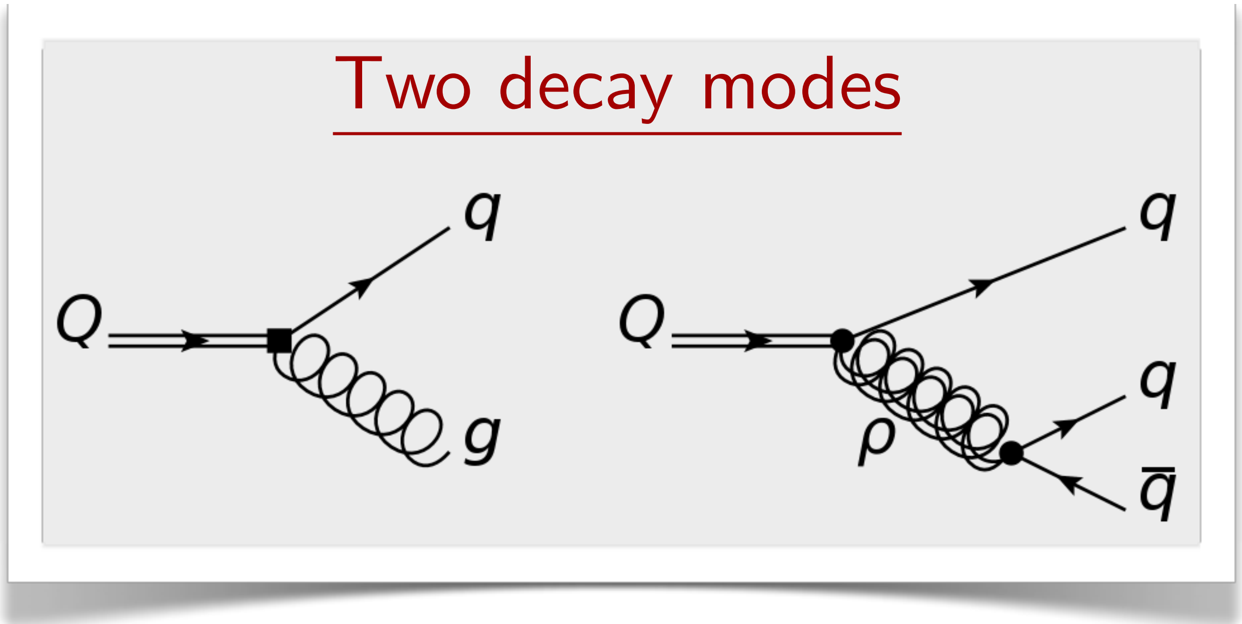




Recalculated Higgs potential for RH - compositeness

**f=800, $g_{rho}$ =3**

# Light Fermionic Partners

deVries, Redi, Sanz, AW, in prep.



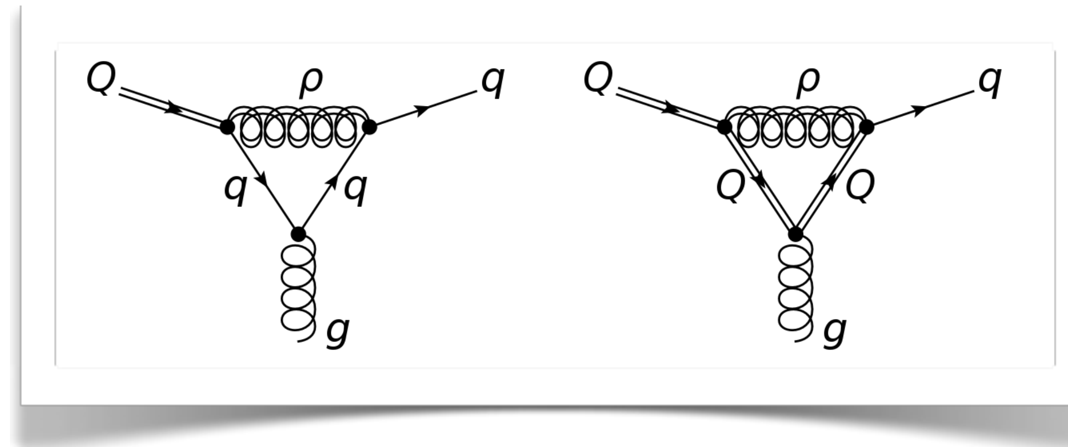

$$\mathcal{L} = \frac{g_s \kappa}{m_Q} \bar{Q} \sigma^{\mu\nu} T^a q G^a_{\mu\nu}$$

chromo-magnetic (loop)

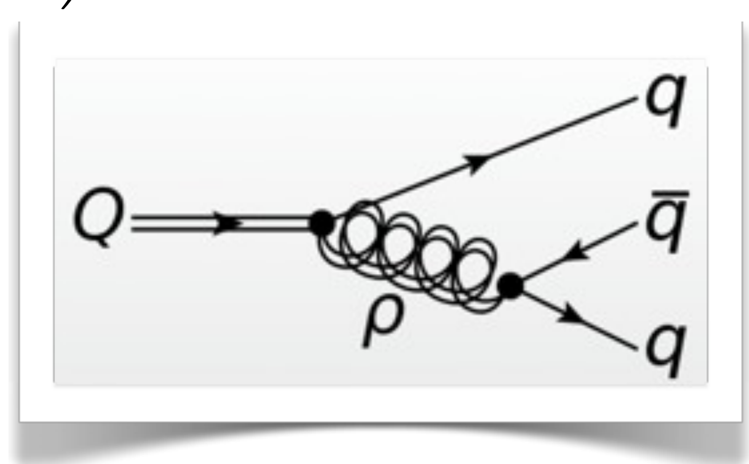
three-body

Both decay modes suppressed
and result in a narrow width

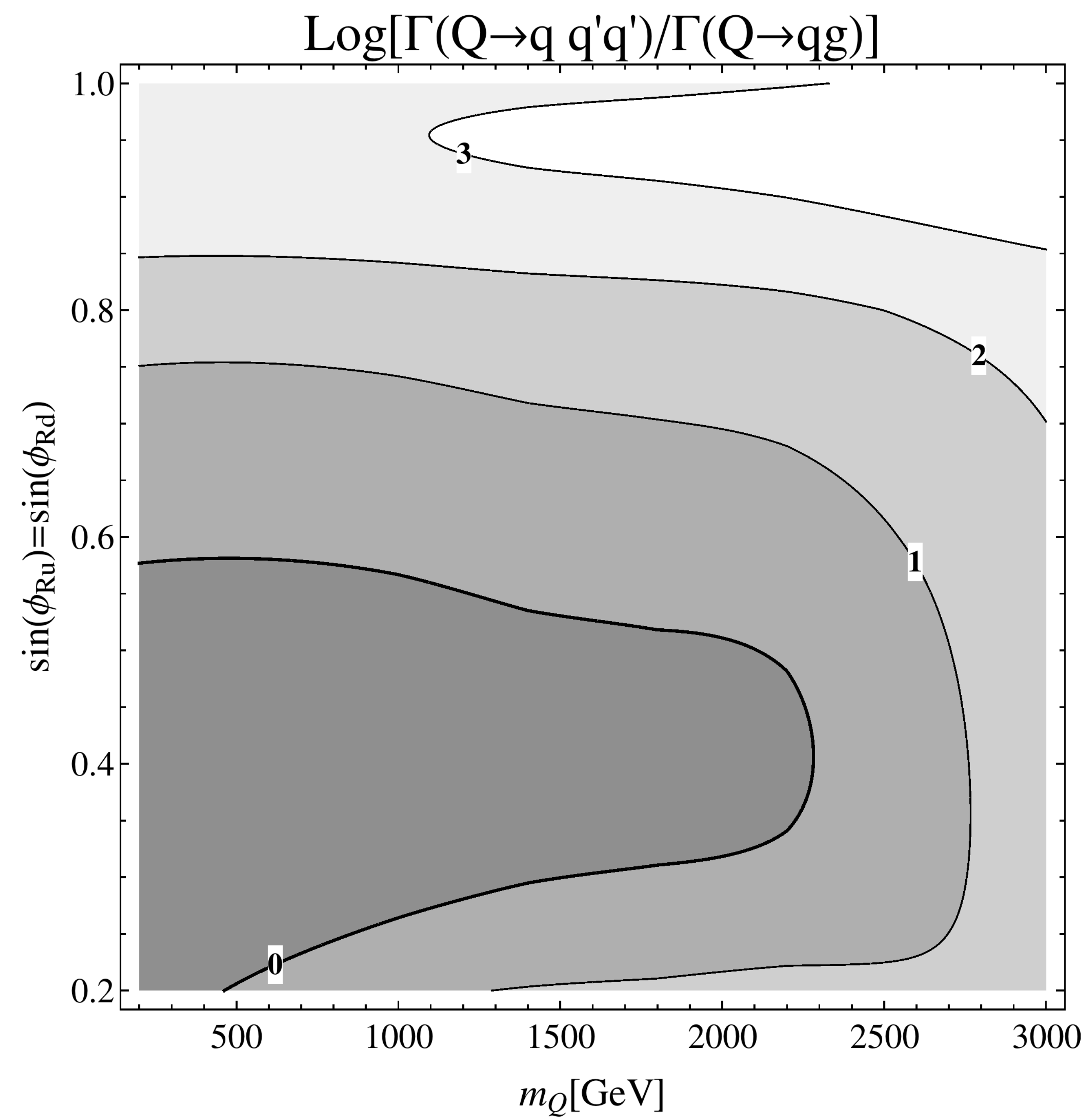
$$\Gamma_{\text{chromo}}(Q \to qg) = \frac{4}{3}\alpha_s \kappa^2 s_{Ru}^2 \frac{1}{m_Q^5} \left| m_Q^2 - m_q^2 \right|^3$$




$$\Gamma^{\rho}_{\text{3-body}}(Q \to q q' \bar{q}') = \begin{cases} \dfrac{\alpha_s^2}{72\,\pi} \left[ |X_L^{qQ}|^2 + |X_R^{qQ}|^2 \right] \displaystyle\sum_{q'} \left[ |X_L^{q'q'}|^2 + |X_R^{q'q'}|^2 \right] & \\ \times \left[ \dfrac{6m_\rho^4 - 3m_Q^2 m_\rho^2 - m_Q^4}{m_Q m_\rho^2} + \dfrac{m_\rho^2 (m_\rho^2 - m_Q^2)}{m_Q^3} \log \dfrac{m_\rho^2 - m_Q^2}{m_\rho^2} \right] & \text{if } m_Q < m_\rho \\ \dfrac{\alpha_s}{6} \left( \dfrac{m_Q^6 - 3m_Q^2 m_\rho^4 + 2m_\rho^6}{m_Q^3 m_\rho^2} \right) \left[ |X_L^{qQ}|^2 + |X_R^{qQ}|^2 \right] & \text{if } m_Q \gg m_\rho \end{cases} \tag{4.2}$$

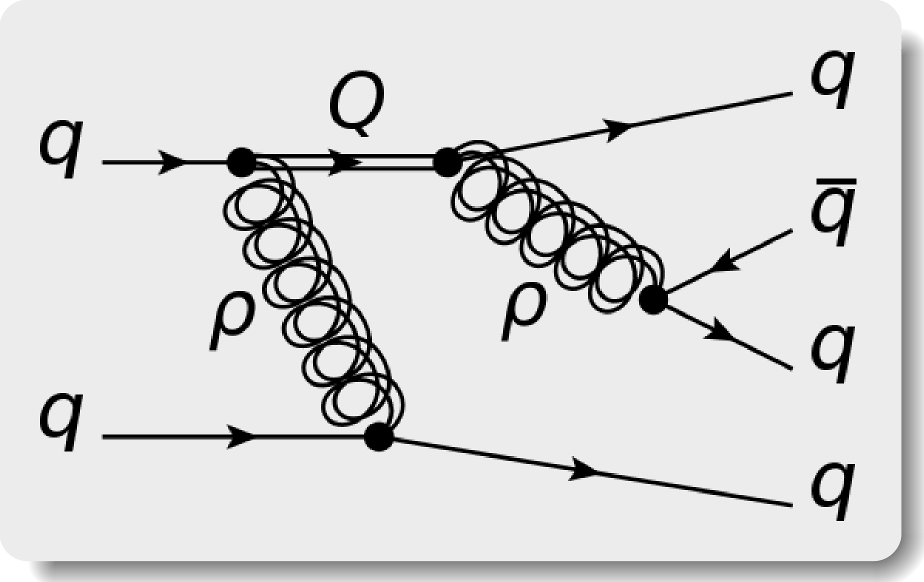


# Two body vs. three body



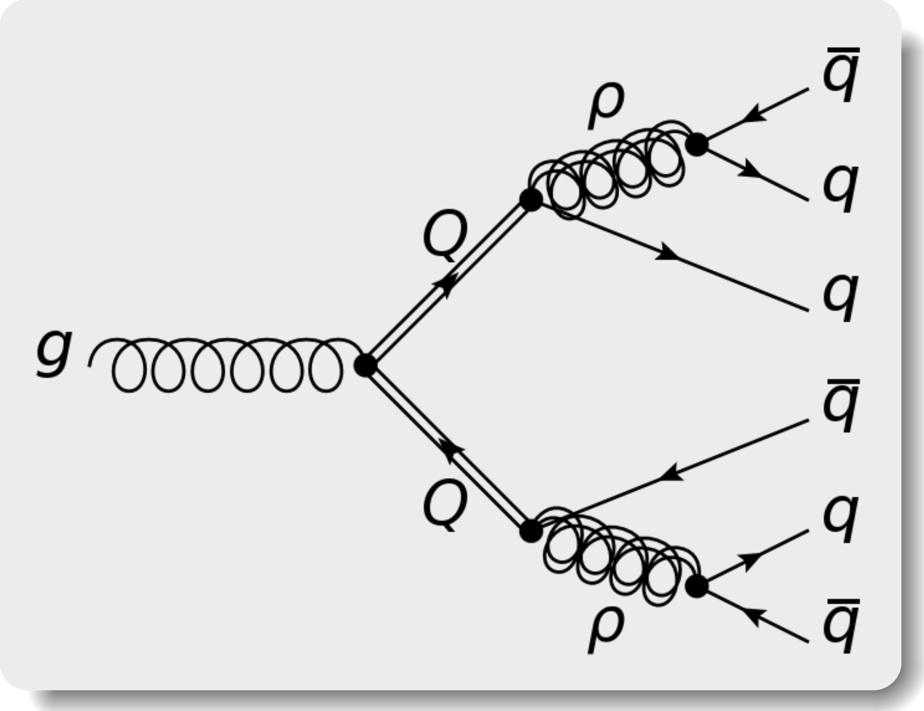
# Search strategies

deVries, Redi, Sanz, AW, in prep.




**Four** jet analysis CMS 7 TeV 2.2 fb−1 [CMS PAS EXO-11-016]

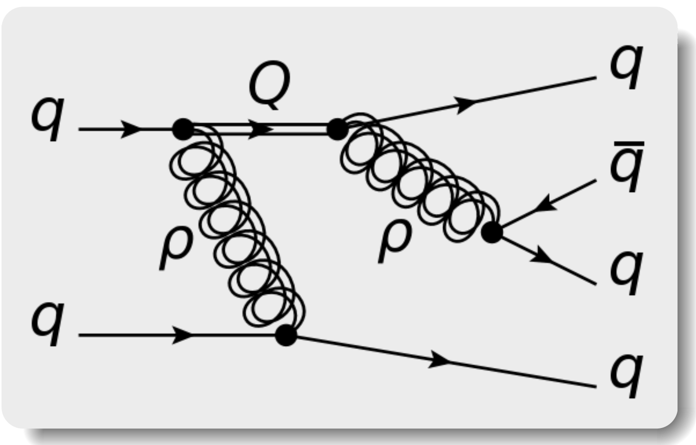
optimized for pair production of two heavy resonances



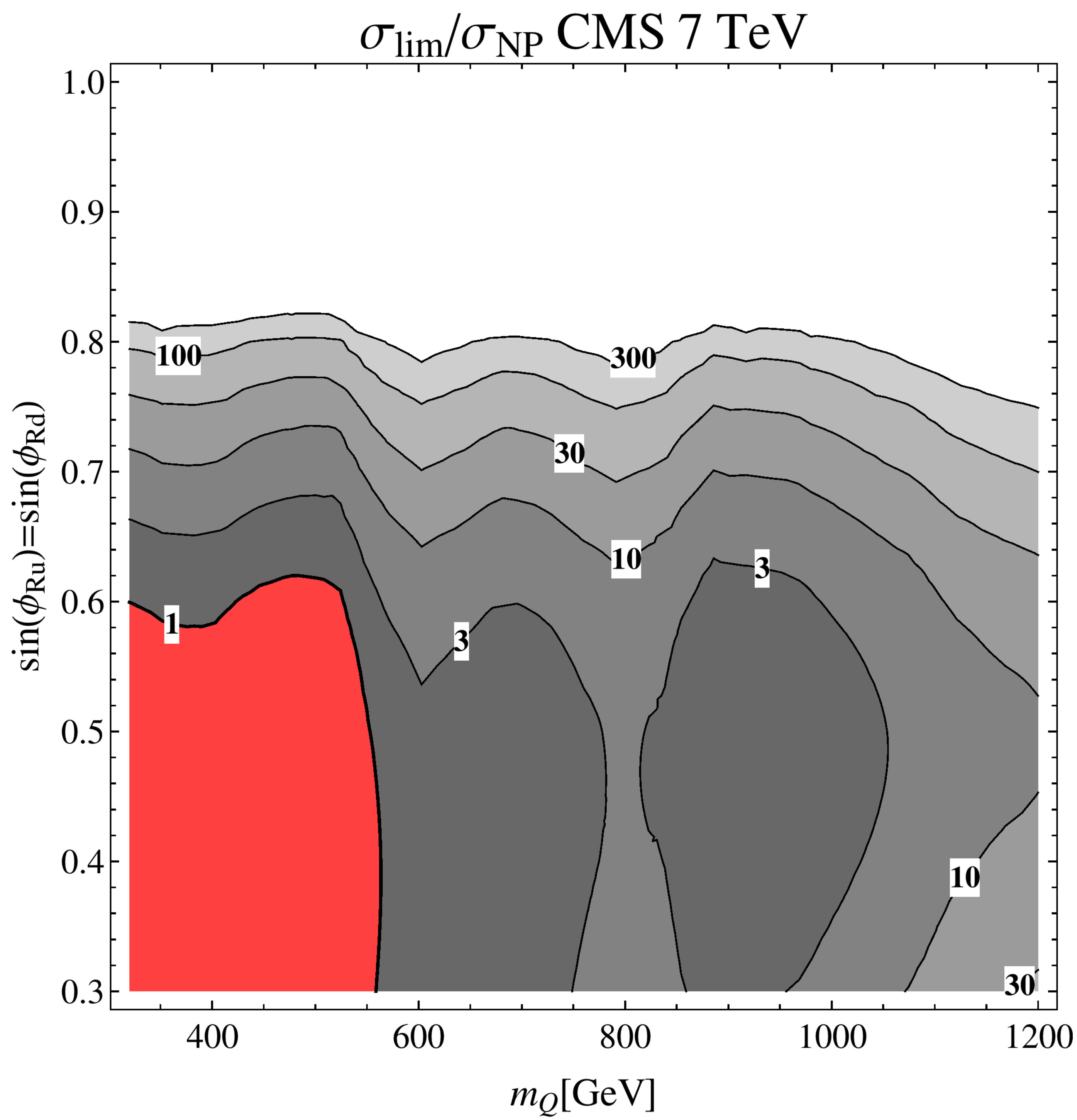

**Six** jet analysis CMS 7 TeV 5.0 fb−1 [CMS-EXO-11-060]

# Recast of RPV 4jet search

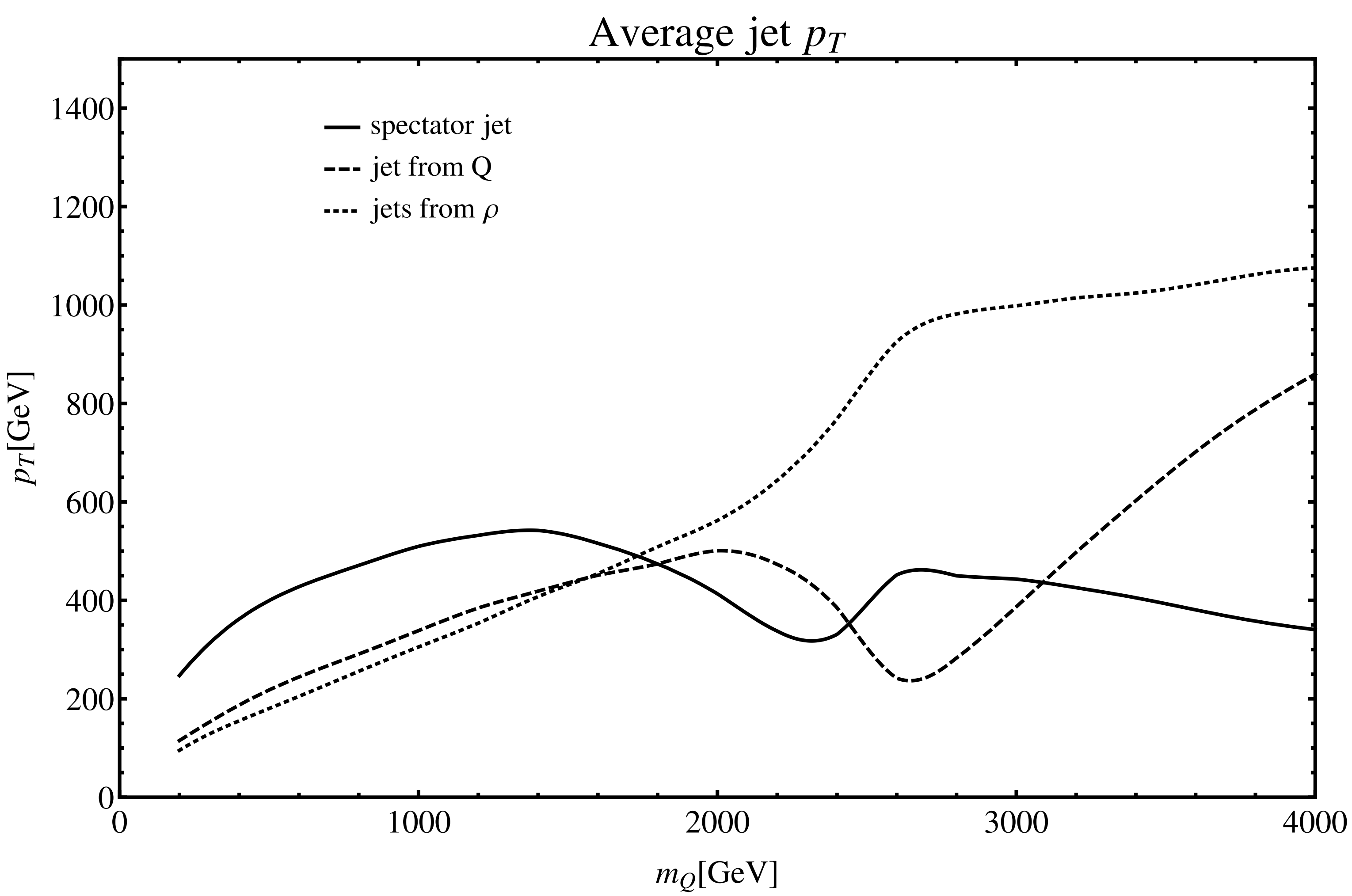
CMS PAS EXO-11-016

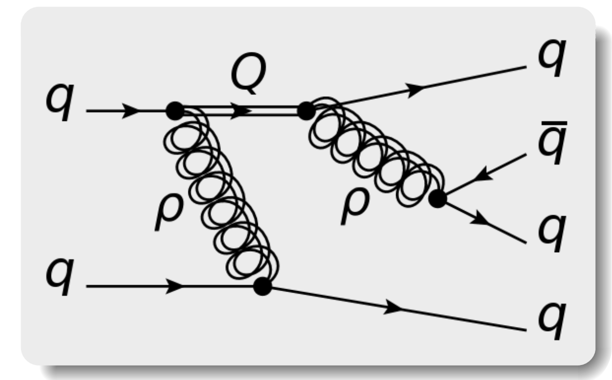



Four jet analysis by CMS 7 TeV 2.2 fb−1
However, optimized for pair production of two heavy resonances



# Dedicated search




mQ = 1 TeV

mrho = 1.5 TeV

- Require four jets with $|\eta| < 2.5$ and $p_T > 150$ GeV.
- The leading jet must have a $p_T$ larger than 500 GeV.
- The other three jets must combine into an invariant mass of more than 1500 GeV.

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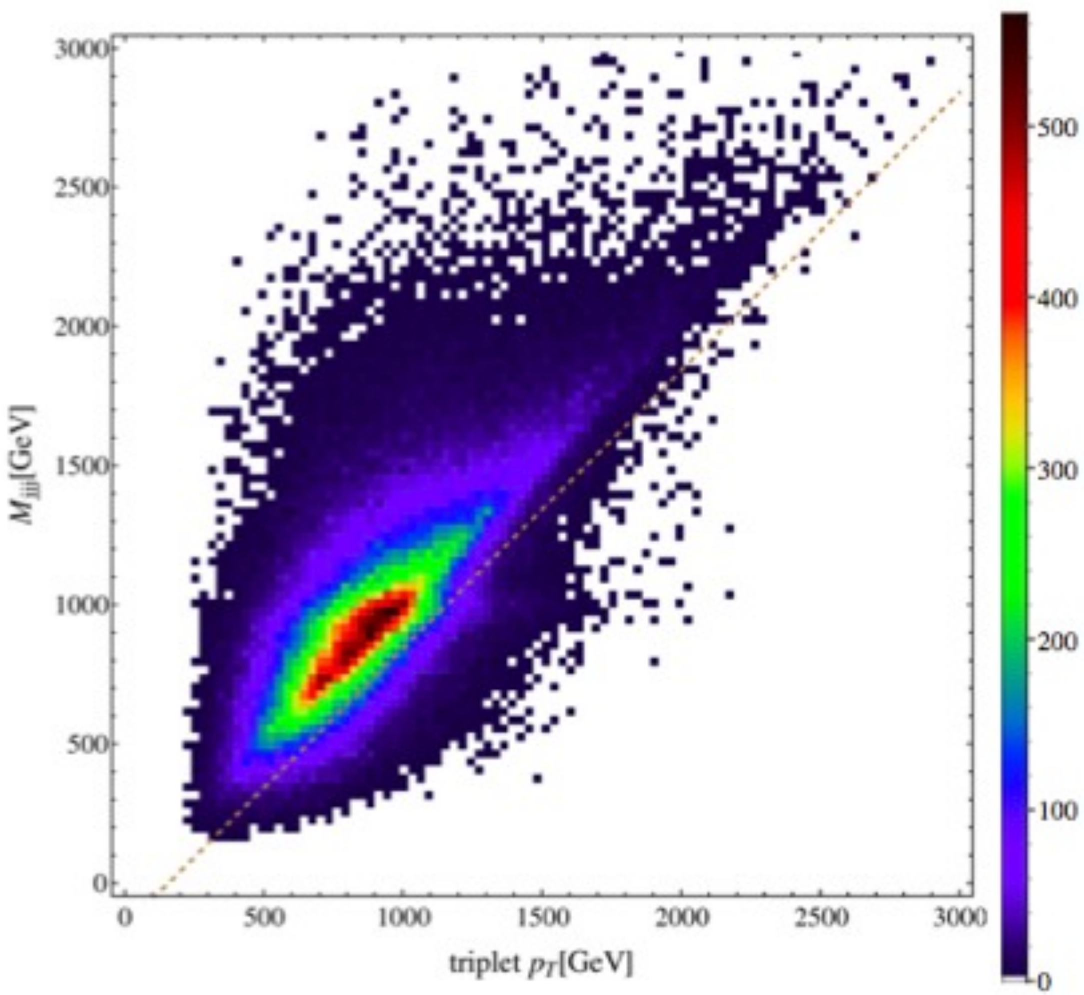


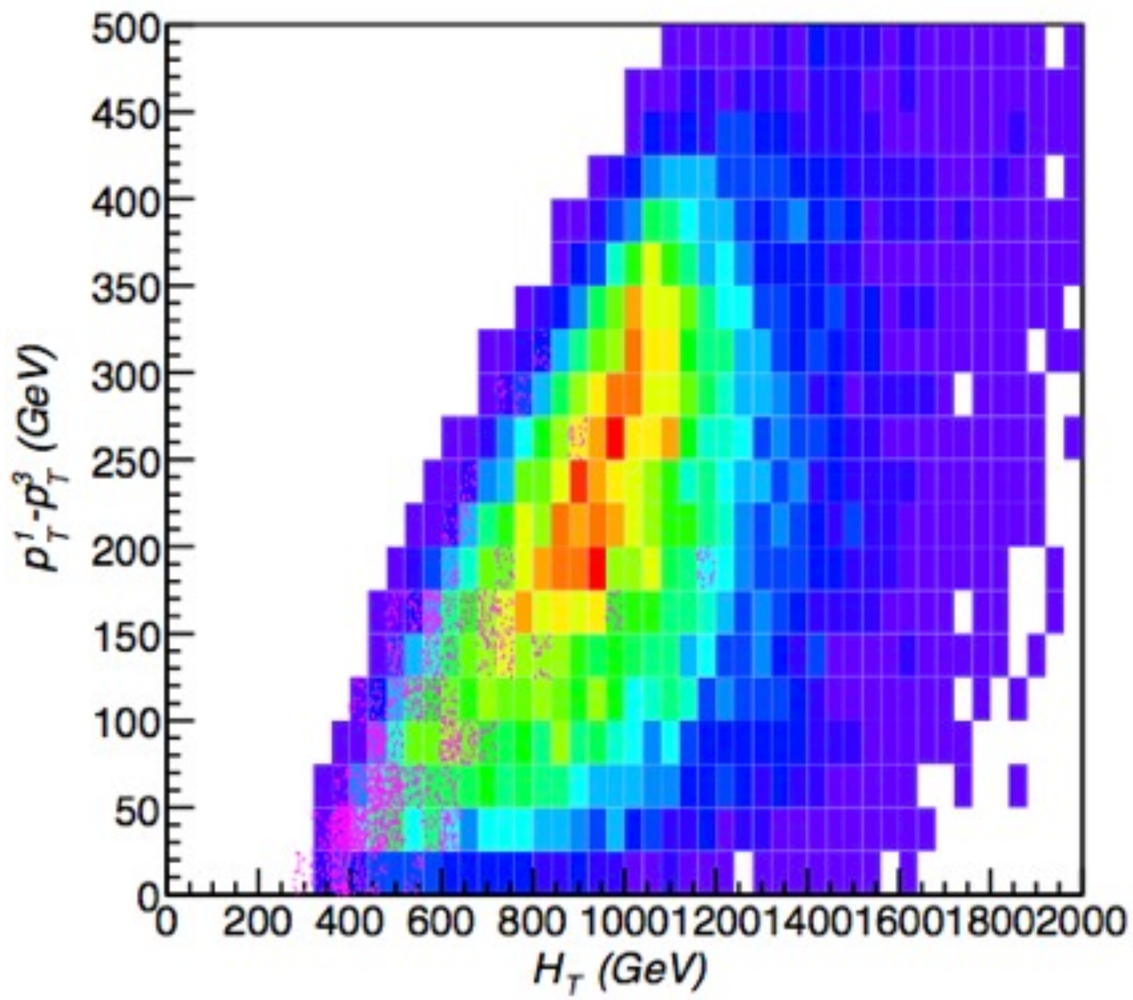


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# Conclusions

- Flavor can hide or enhance visibility at high $p_T$
- In the next years, naturalness on trial: reaching critical sensitivity for scalar/fermion partners
- MFV composite Higgs is very visible, EWPT ok with large compositeness: expect discovery/exclusion with LHC14