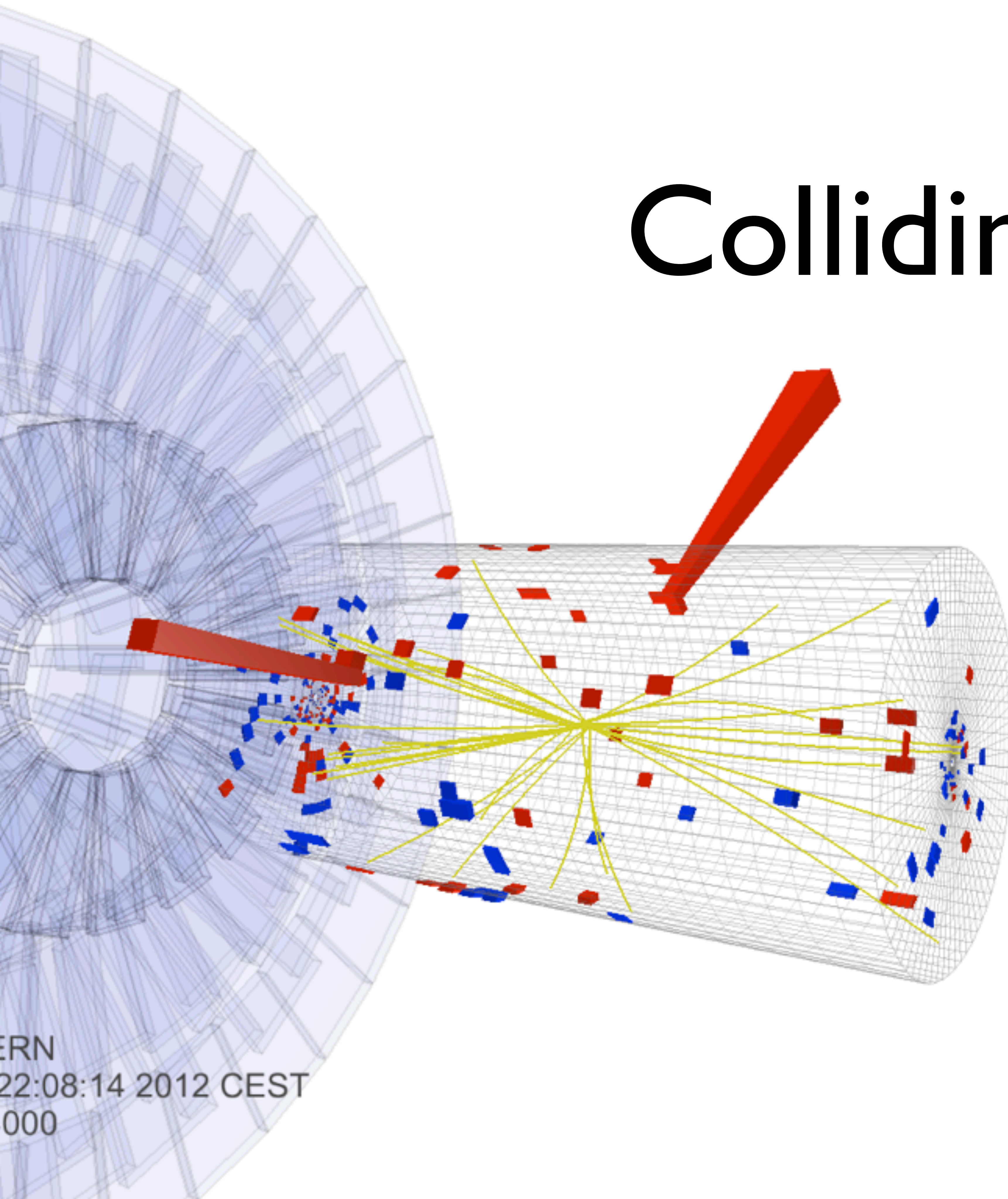
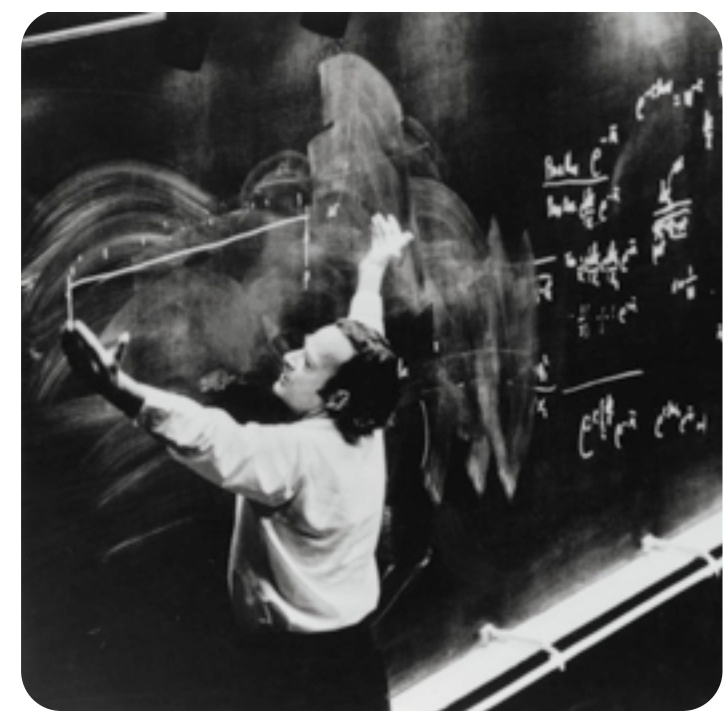
Colliding Sflavors



Andreas Weiler
(DESY)



SUSY 2013
ICTP Trieste

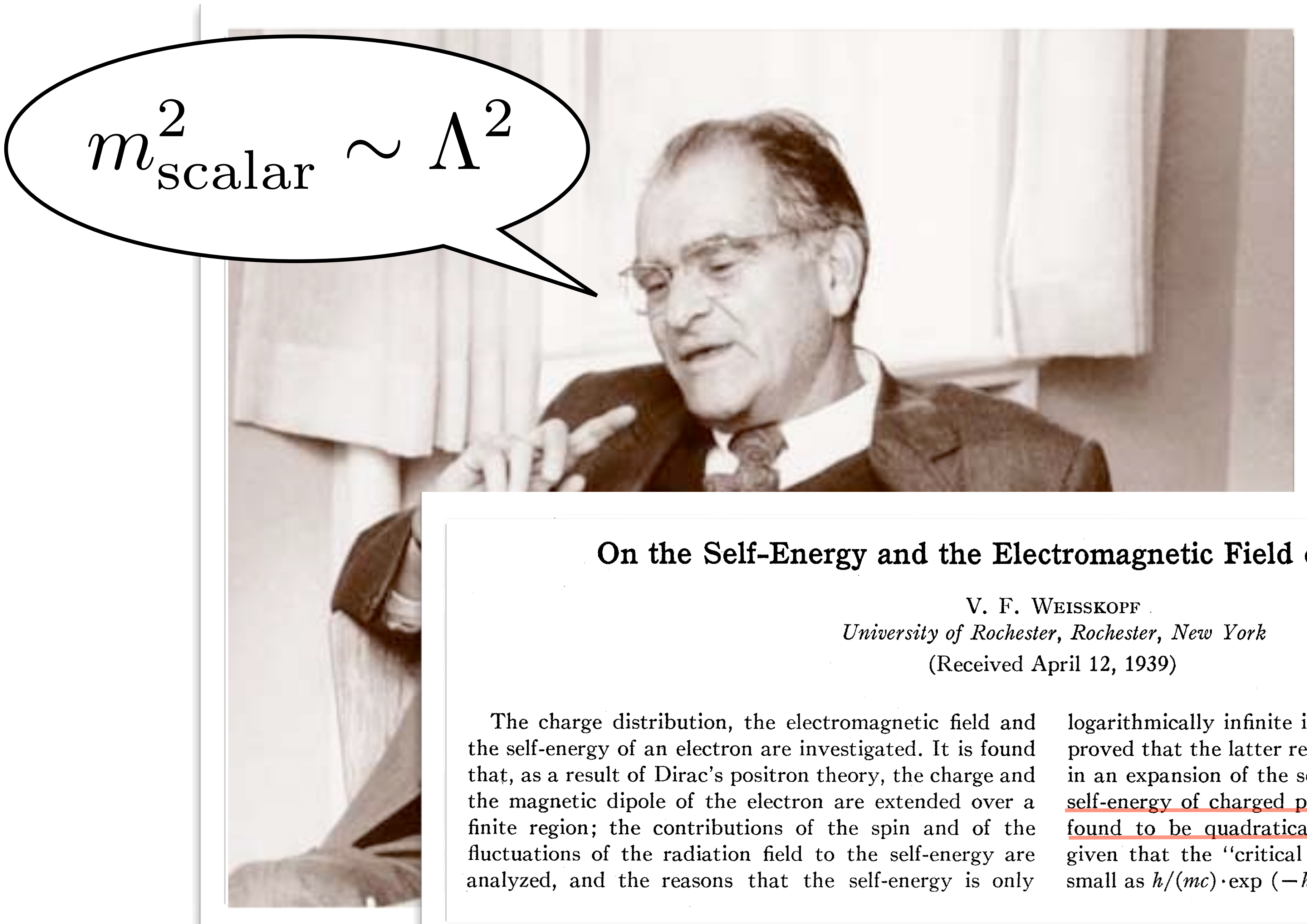
The best of times…

- LHC is performing beyond expectations
- ATLAS & CMS have discovered a new particle, the SM Higgs ?
- New physics searches start to corner most motivated models: entering critical territory

*terms and conditions apply

Why BSM at the LHC?

Why BSM at the LHC?



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

Naturalness is the worst motivation
to expect new physics at the LHC, except
for all the others.

New physics & naturalness in times of austerity

Light Higgs

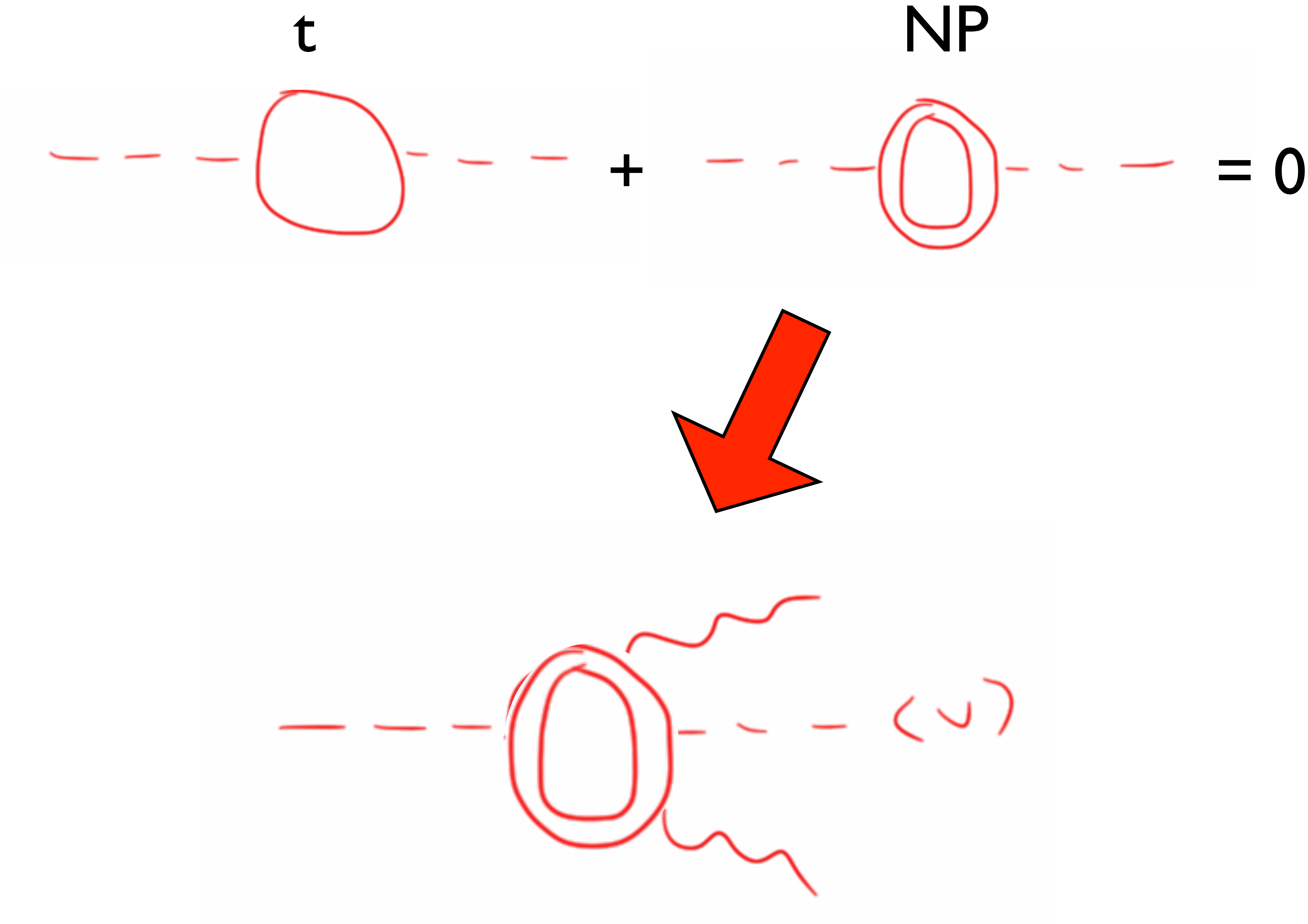
light stops$_{1,2}$, sbottom$_L$, higgsinos, gluinos, …

supersymmetry

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

composite Higgs

?

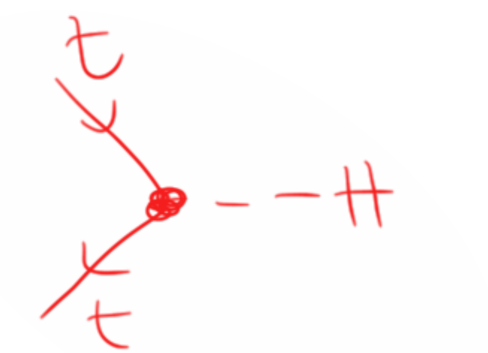

t
NP
+
= 0

Higgs properties

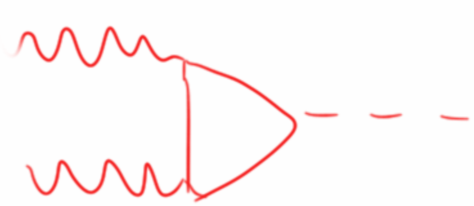
see talks by Contino, Dasu, Vossebeld

SM + $\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F^2_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$

$$\frac{\sigma(gg \to h)}{\mathrm{SM}} = (1 + (c_g - c_t)v^2)^2$$



Degeneracy 'short-distance' vs 'long-distance'



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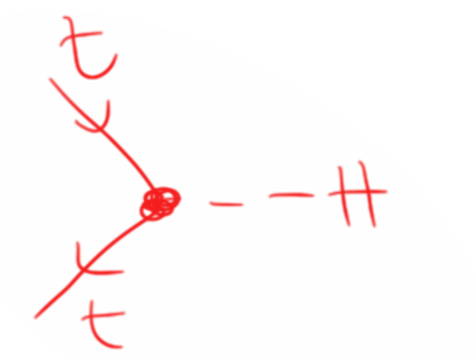

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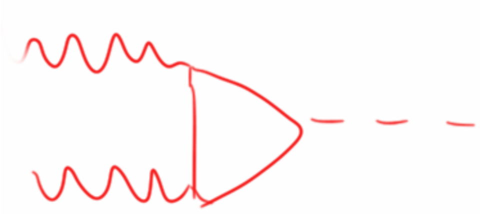
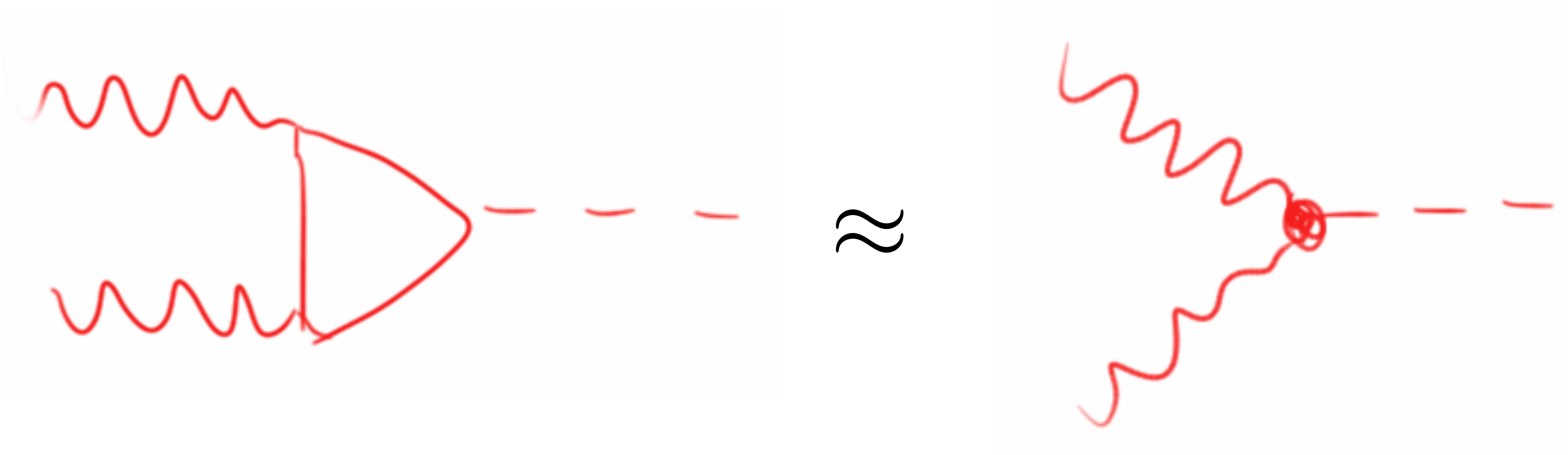


E.g. fermionic top partners MCHM: $\Delta c_t = \Delta c_g$

$$\sigma(pp \to H + X)_{\text{inclusive}}$$

Does not resolve short-distance physics

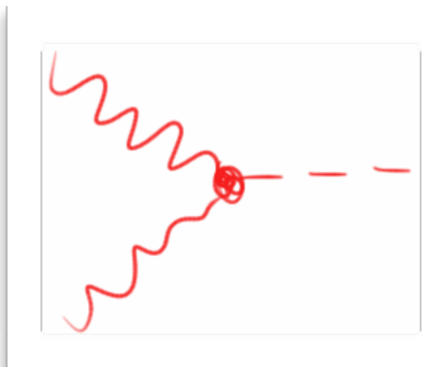


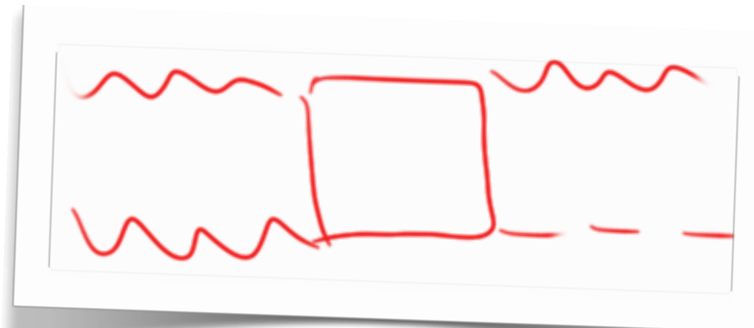
$m_H(\text{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t \to \infty)}$	$\frac{\sigma_{NLO}(m_t, m_b)}{\sigma_{NLO}(m_t \to \infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. 1306.4581

Beyond current observables

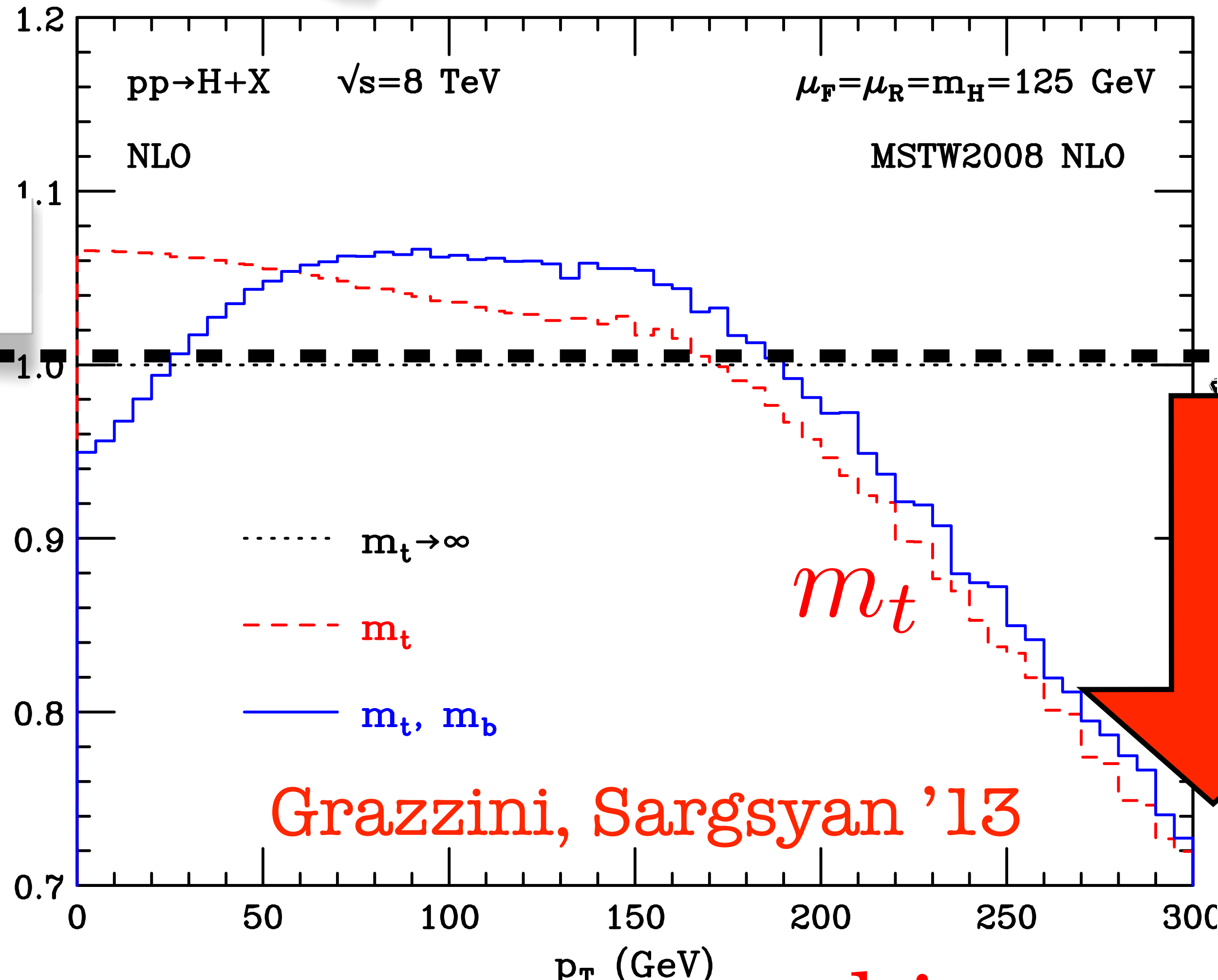
Cut the loop open, recoil against hard jet





$p_T \gg m_t$

$m_t \to \infty$



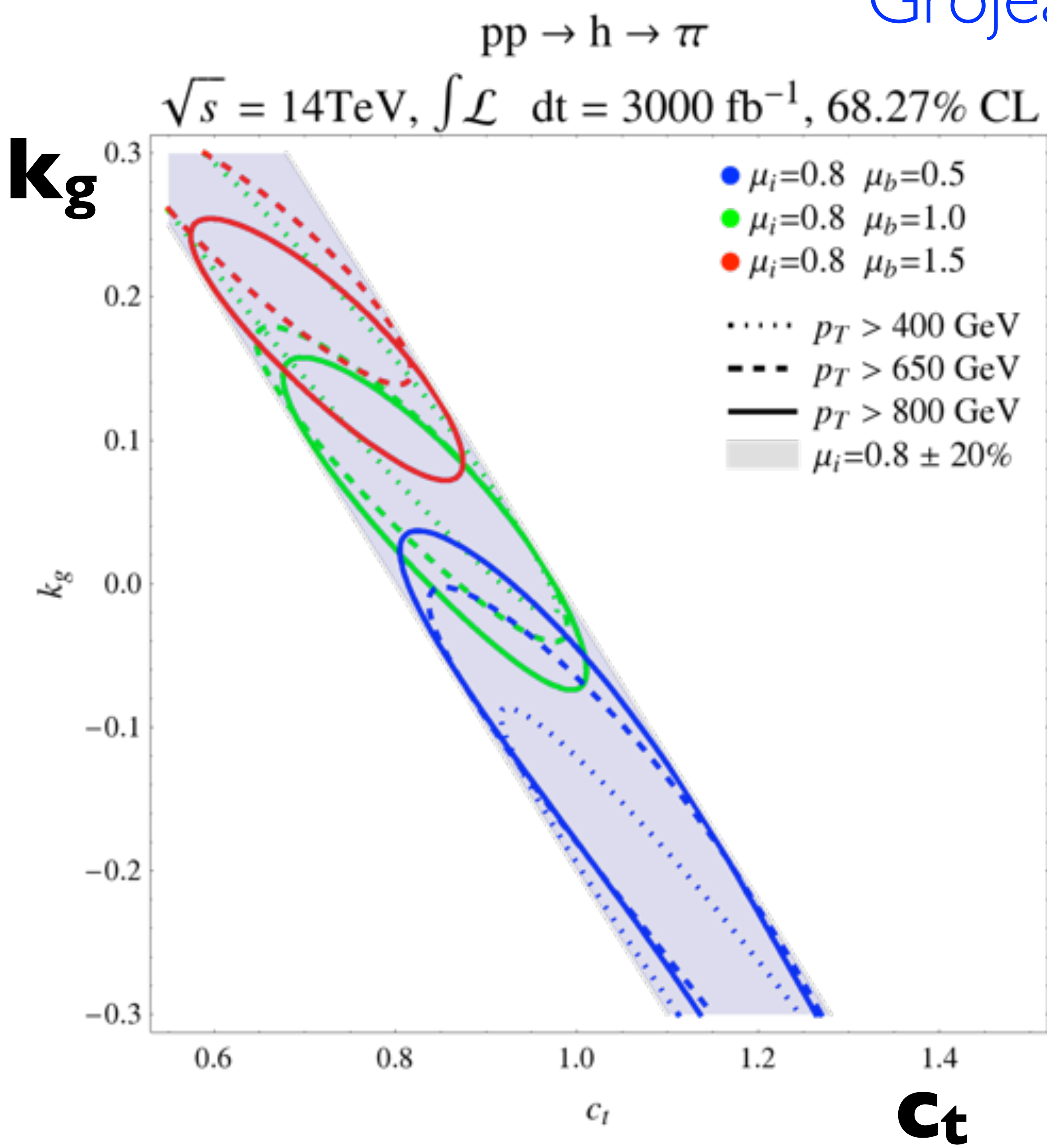
Baur, Glover '90,
Langenegger et. al '06,
1308.4771

high p_T tail resolves loop dynamics

$\text{higgs} - p_T$

Complementary to htt

Grojean, Salvioni, Schlaffer, AW, in progress



Competitive/complement to notoriously difficult $h\bar{t}t$ channel

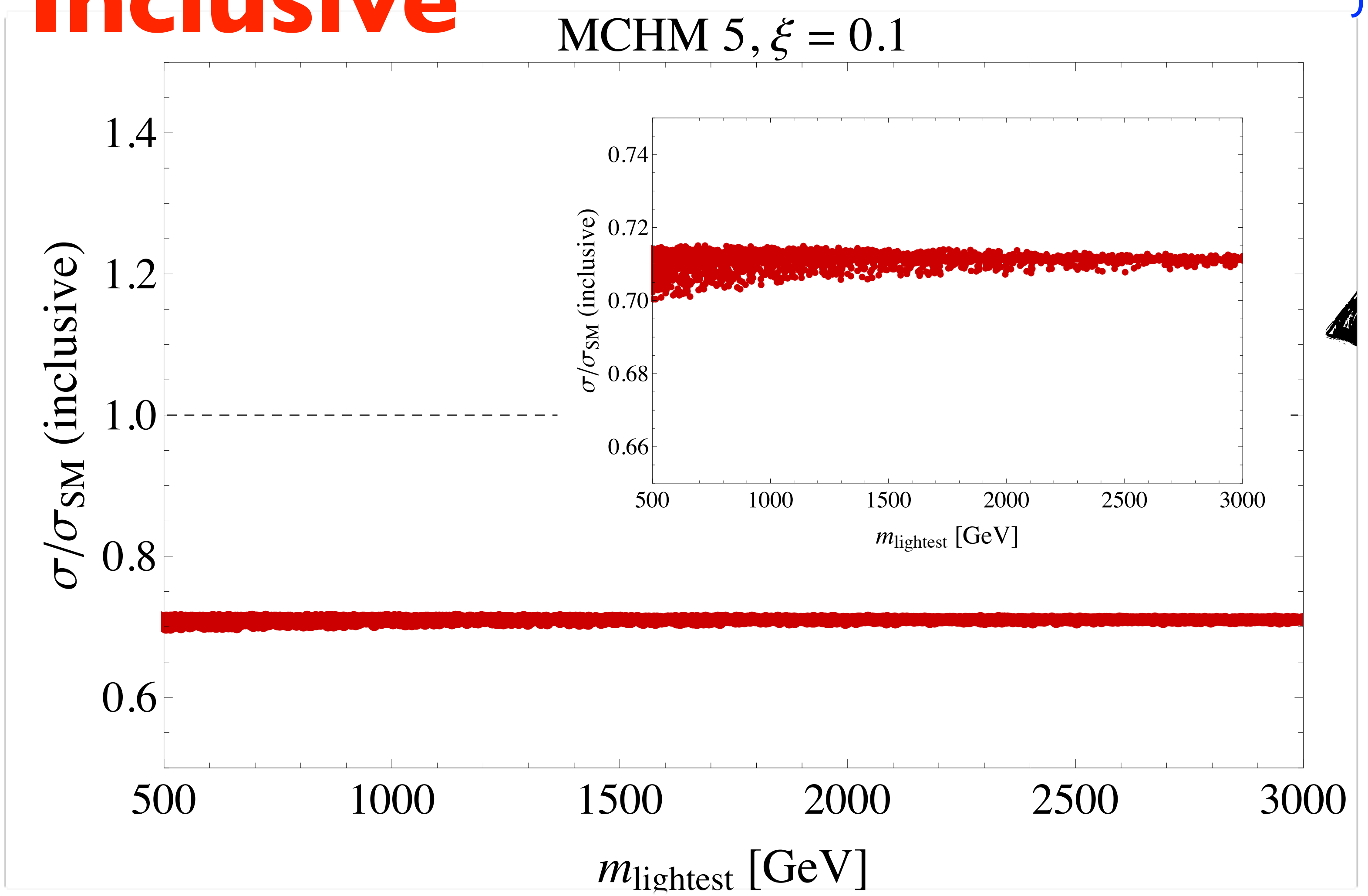
Theory frontier:
NLO_{m_t} not yet calculated,
$1/m_t$ known to $\mathcal{O}(\alpha_S^4)$:
few % up to p_T ~150 GeV

Harlander et al '12

Top partner example

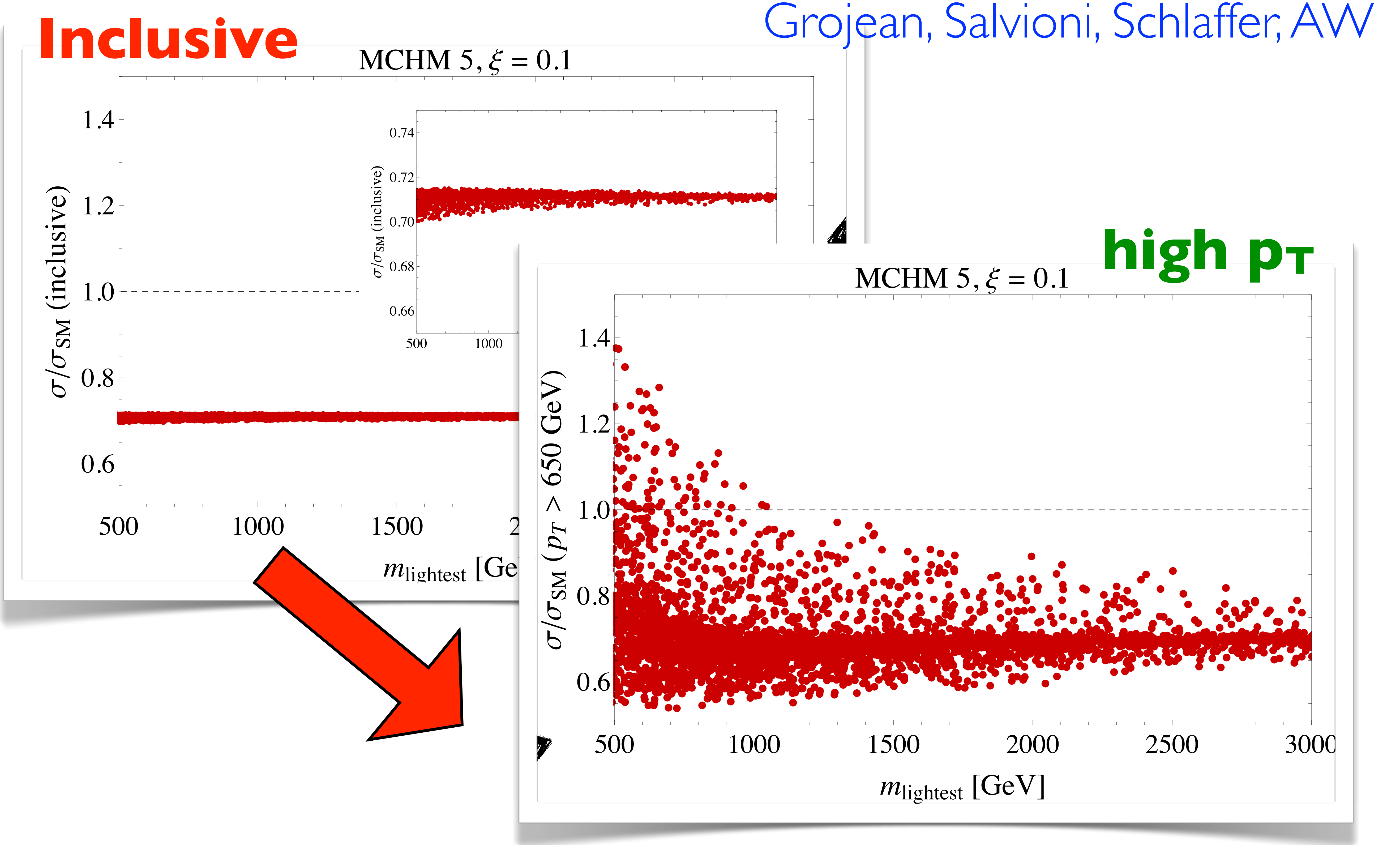
Grojean, Salvioni, Schlaffer, AW

Inclusive

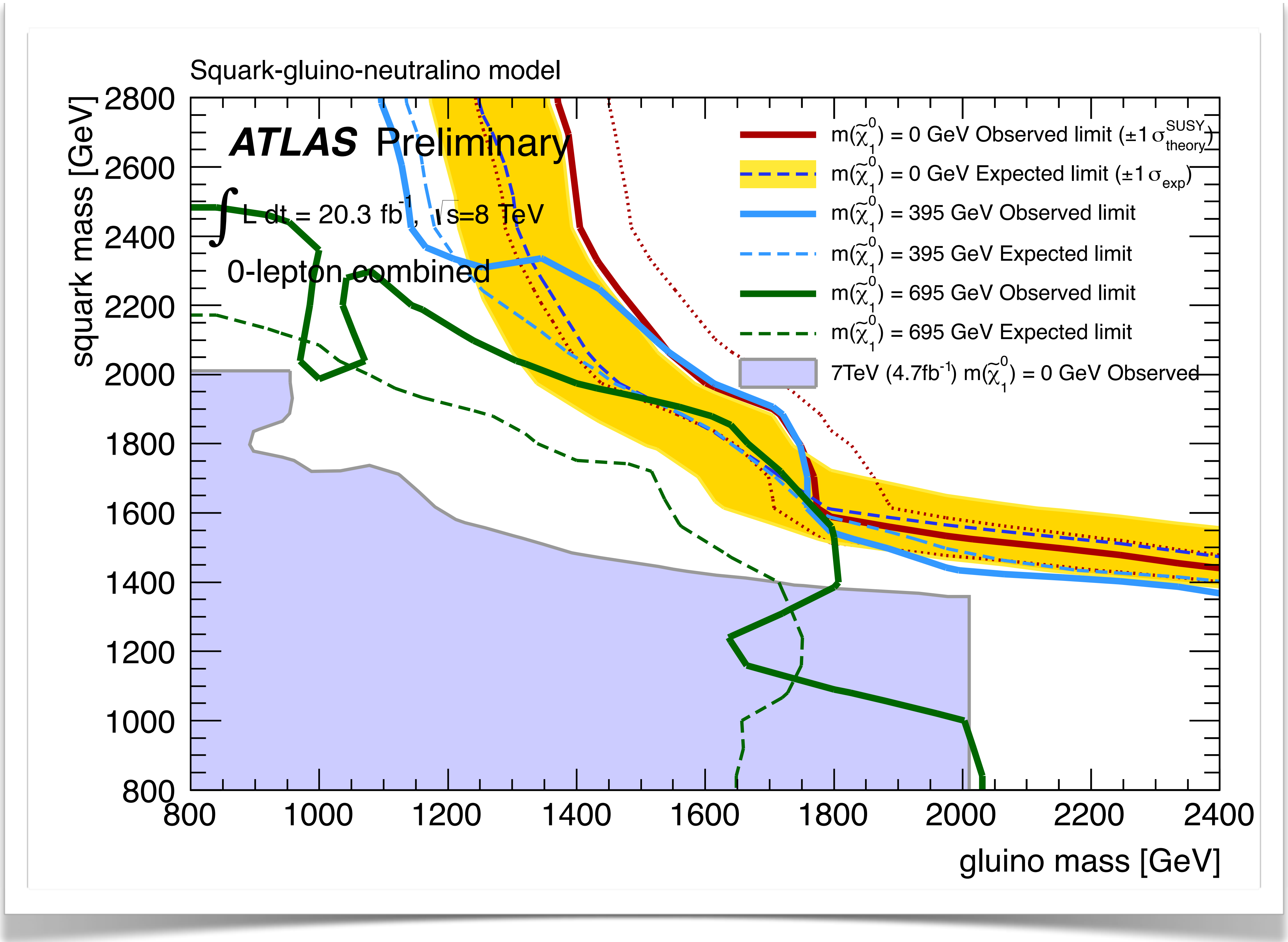


Top partner example

Grojean, Salvioni, Schlaffer, AW

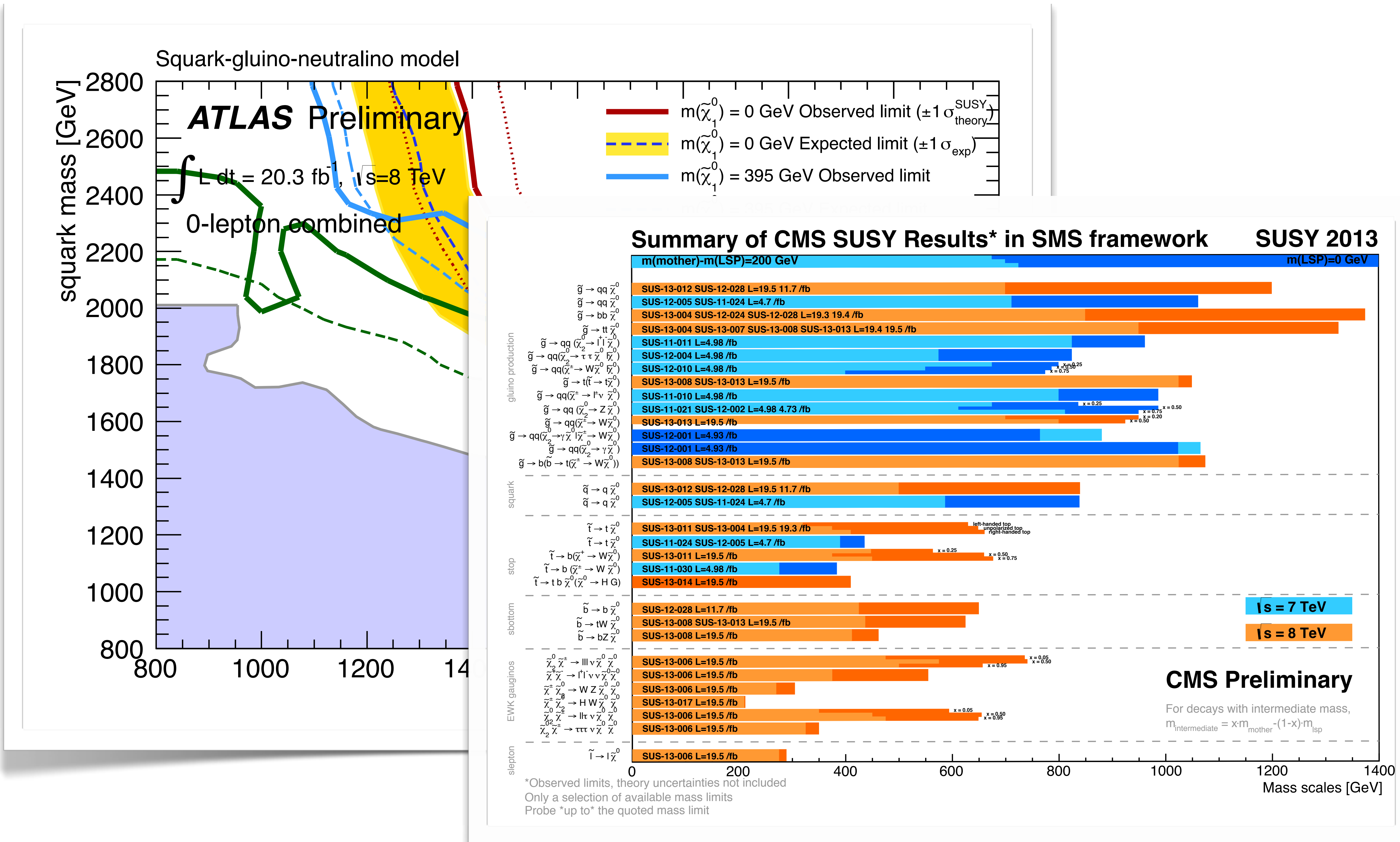


No superpartners under the lamp-post



Blind spots? Squeezed Spectra? R-parity Violation? Third-Generation? EW-inos?

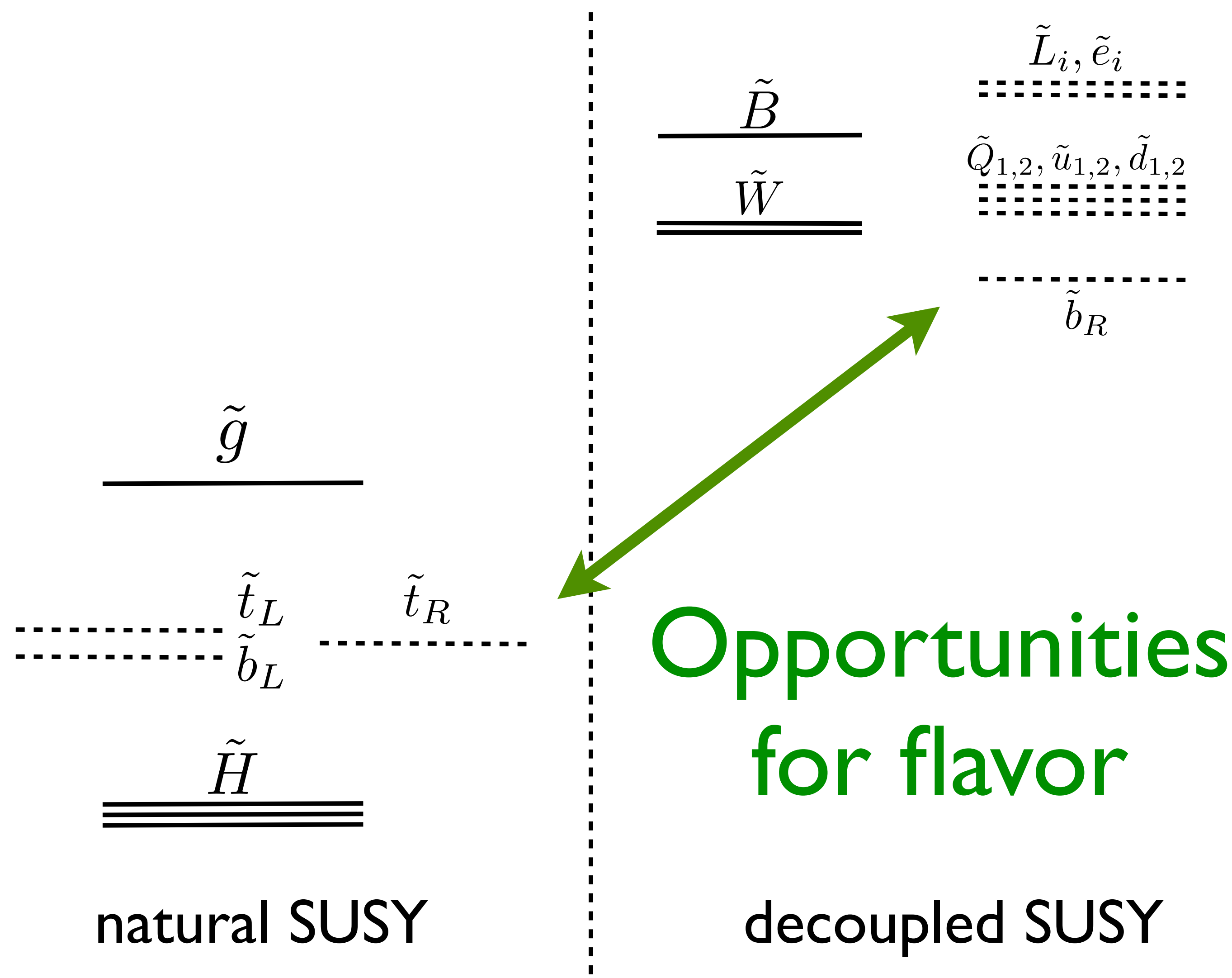
No superpartners under the lamp-post



Blind spots? Squeezed Spectra? R-parity Violation? Third-Generation? EW-inos?

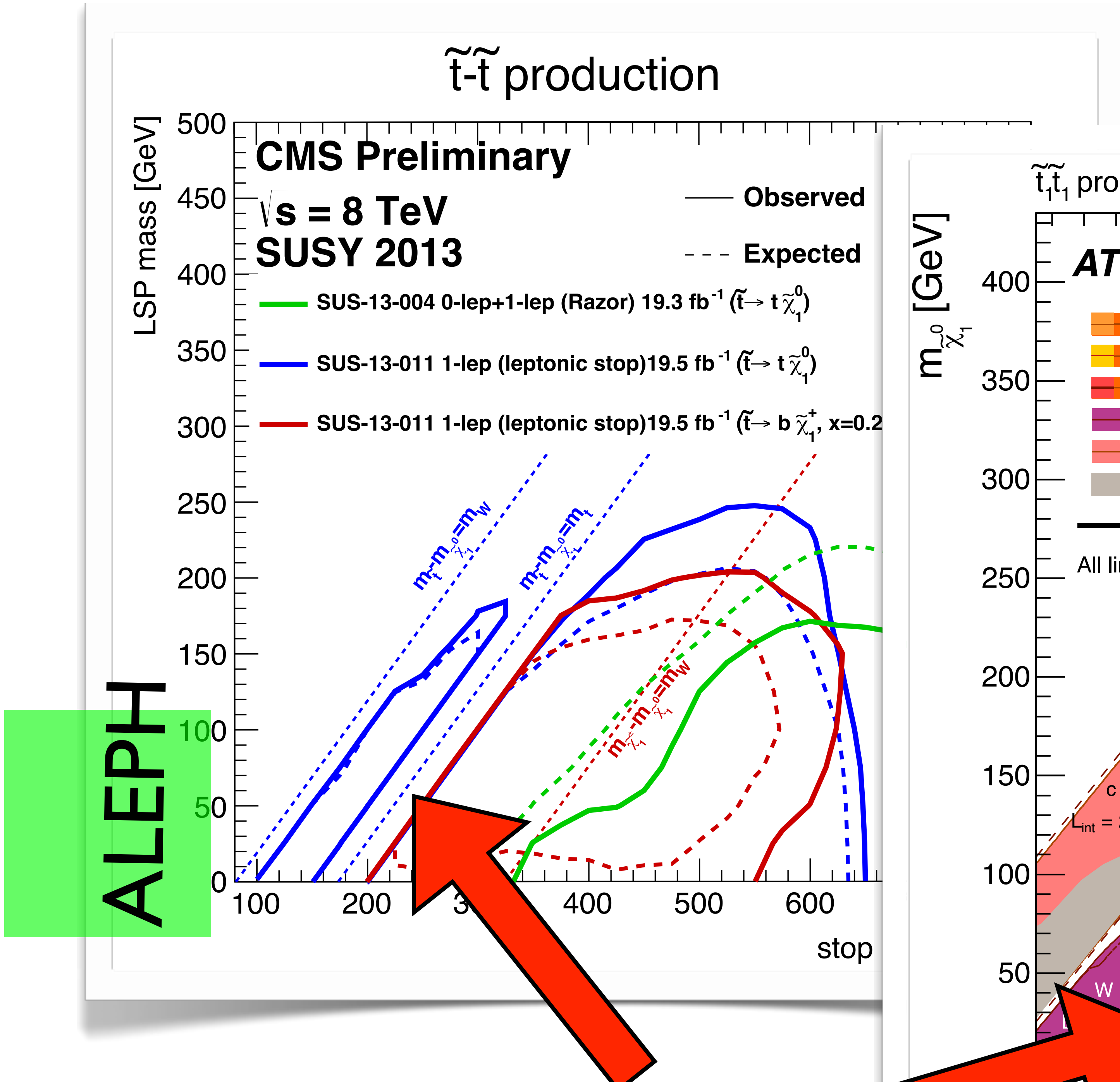
Reason for optimism: natural susy

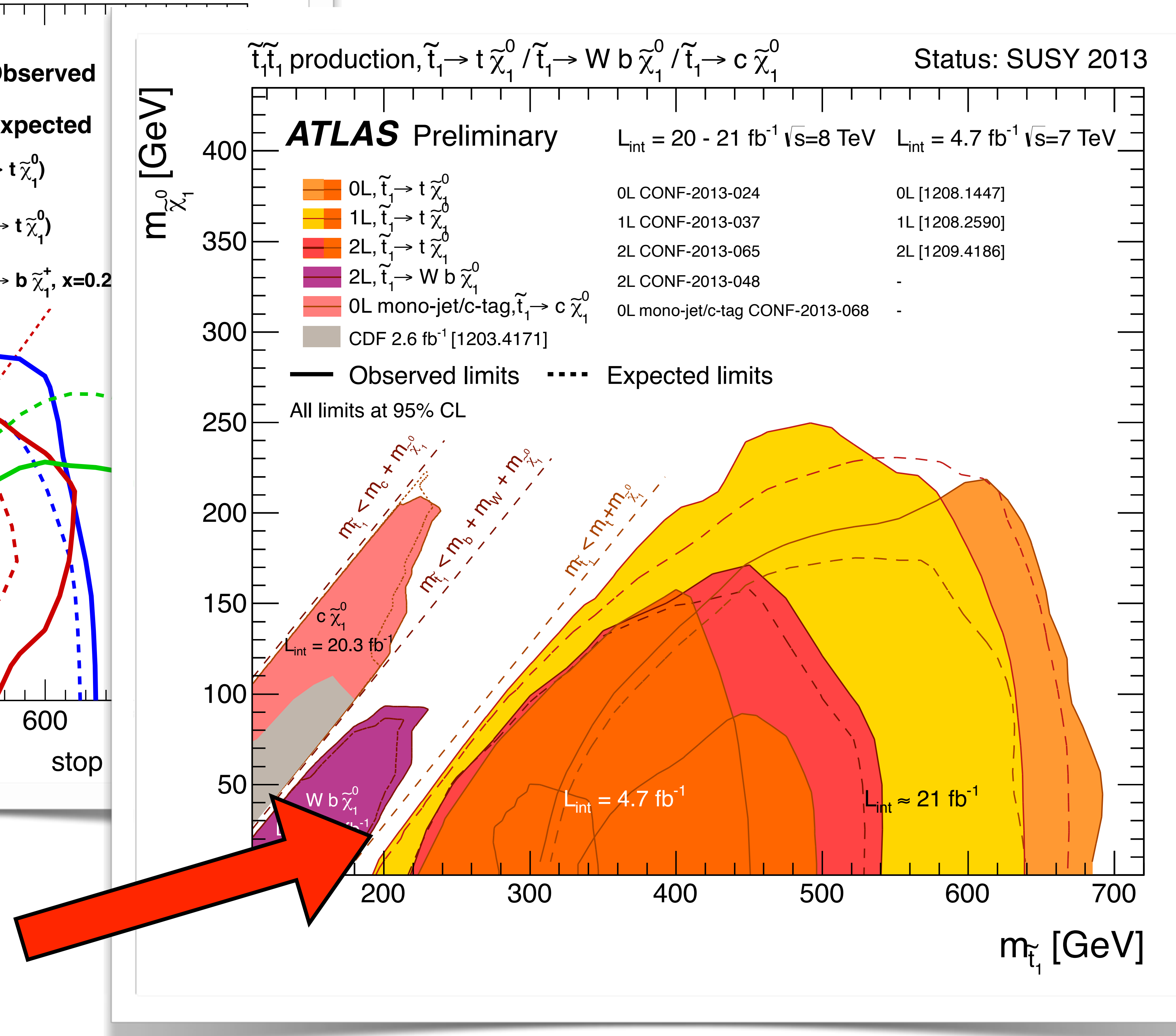
Scale	δm_H^2
multi TeV	<<
$\approx 1000\,\mathrm{GeV}$	2loop
$\approx 500\,\mathrm{GeV}$	1loop
$\approx 250\,\mathrm{GeV}$	tree



quantitative discussion on tuning
→ talk by Baryakhtar

Direct stop searches





Something hiding here?

Relax & Wait?

vs.

Relax & Wait?

vs.

Let's check!

Hiding in top cross-section measurement?

NNLO calculation of top cross-section

Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)

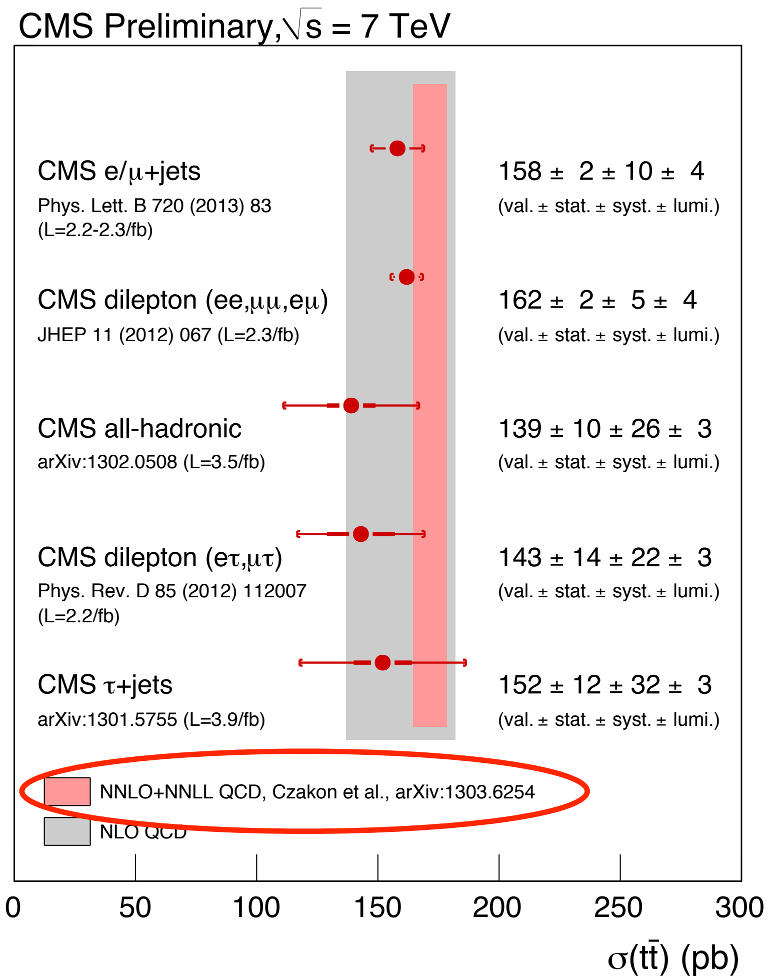
Czakon/Mitov '13

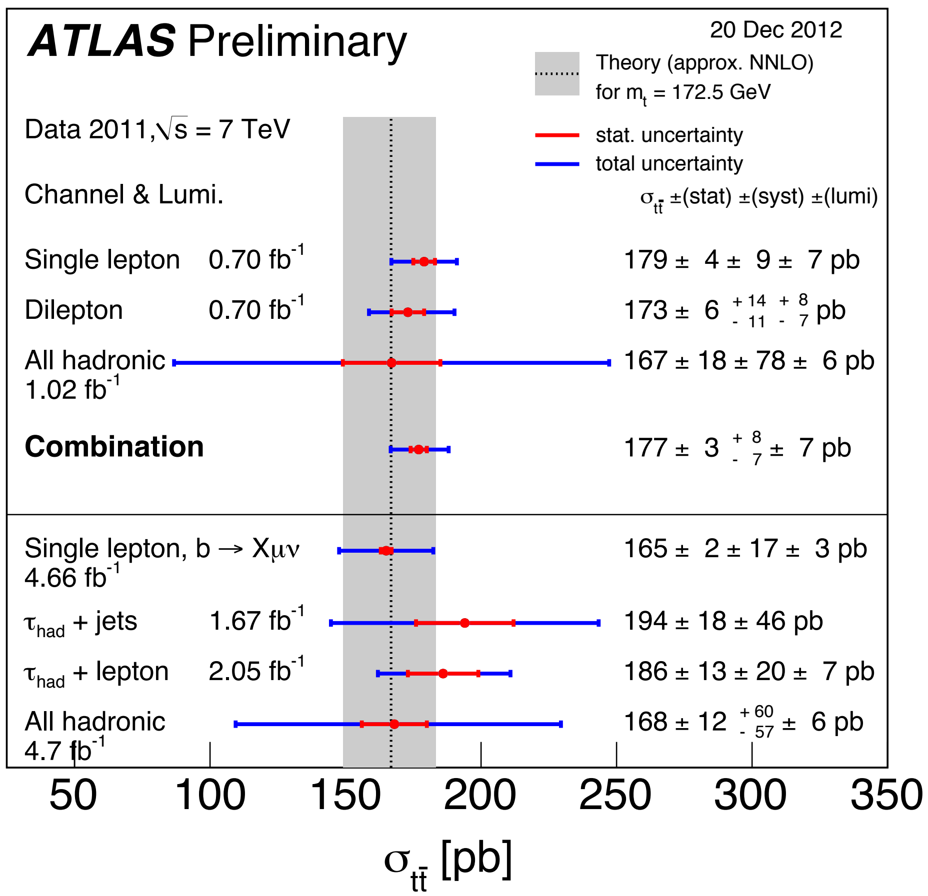
Stop contribution at $m_{stop} = m_{top}$

$\sigma_{stop}/\sigma_{top}$ ~ 17% @ 7 TeV

top cross section

experiment:





theory:

The total top quark pair production cross-section at hadron colliders through $\mathcal{O}(\alpha_S^4)$

Michał Czakon and Paul Fiedler
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany

Alexander Mitov
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
(Dated: March 26, 2013)

NNLO+NNLL

$$\sigma_{t\bar{t}} = 172^{+4.4}_{-5.8}(\text{scale})^{+4.7}_{-4.8}(\text{pdf})\ \text{pb}$$

MC mockup

$$\frac{\sigma_{\rm exp}^{\rm top}}{\rm SM} = 1 + \frac{\epsilon_{\tilde{t}}}{\epsilon_t}\frac{\sigma^{\rm stop}}{\sigma_{\rm SM}^{\rm top}}$$

measurement

Theory NNLO+NNLL

by Feynman diagram calc. (Prospino, NLLfast, ...)

$$N^{(i)}_{\mathrm{SUSY}} = \boxed{\epsilon^{(i)}_{\mathrm{SUSY}}} \cdot \sigma_{\mathrm{SUSY}} \cdot \mathcal{L}_{\mathrm{int}}$$

fixed

requires a chain of MC simulations

$$\epsilon^{(i)}_{\mathrm{SUSY}} = \lim_{N^{\mathrm{gen.}}_{\mathrm{MC}} \to \infty} \frac{N^{(i)}_{SR}\left(\begin{array}{c}\text{Events fall into} \\ \text{Signal Region } (i)\end{array}\right)}{N^{\mathrm{gen.}}_{MC}}$$

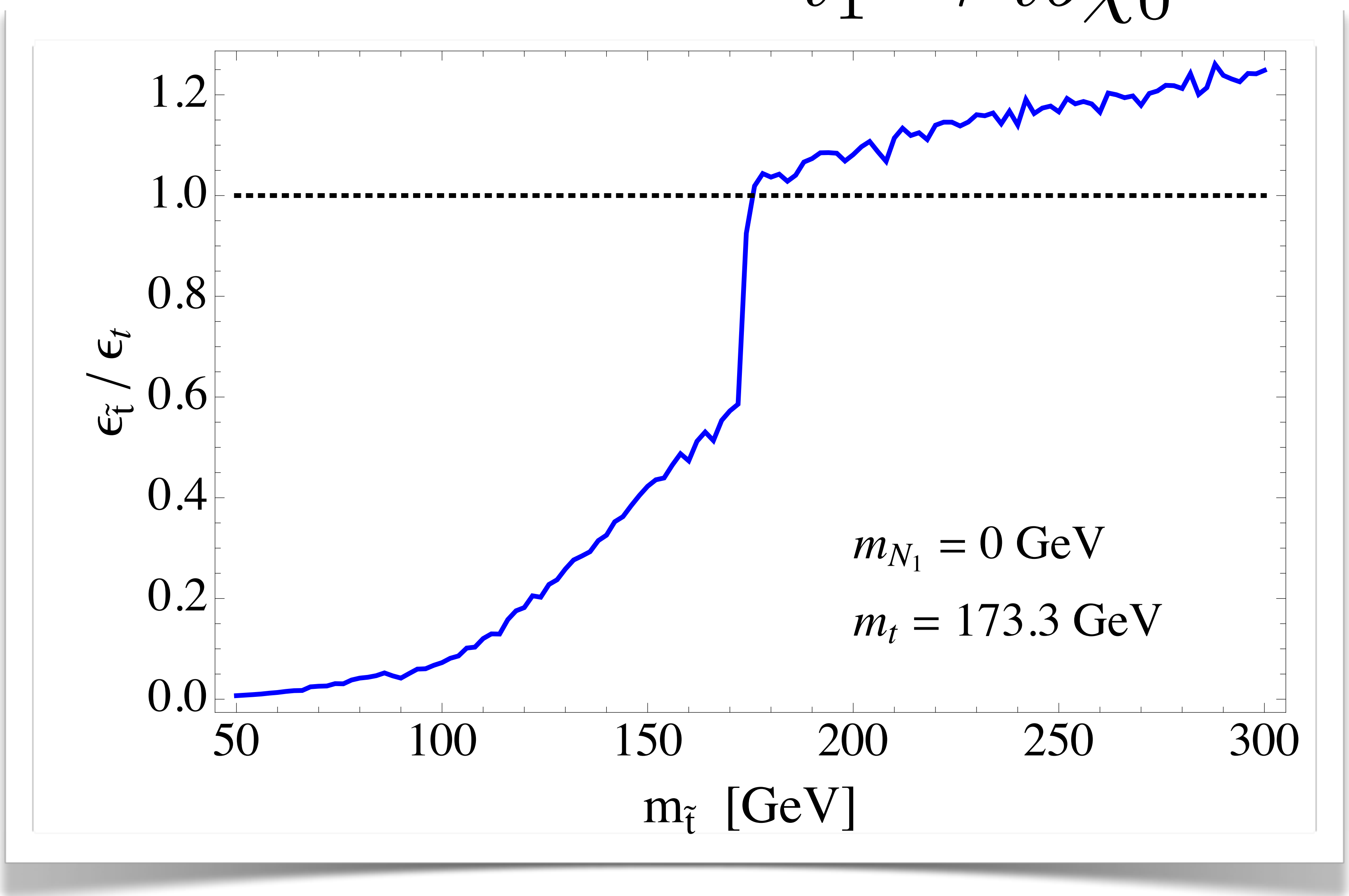
Re-cast top x-sec measurement

Czakon, Mitov, Papucci, Ruderman, AW to appear

Di-leptonic tops (CMS-TOP-11-005)

Recast cuts: relative stop/top efficiency

$$\tilde{t}_1 \to tb\chi_0$$



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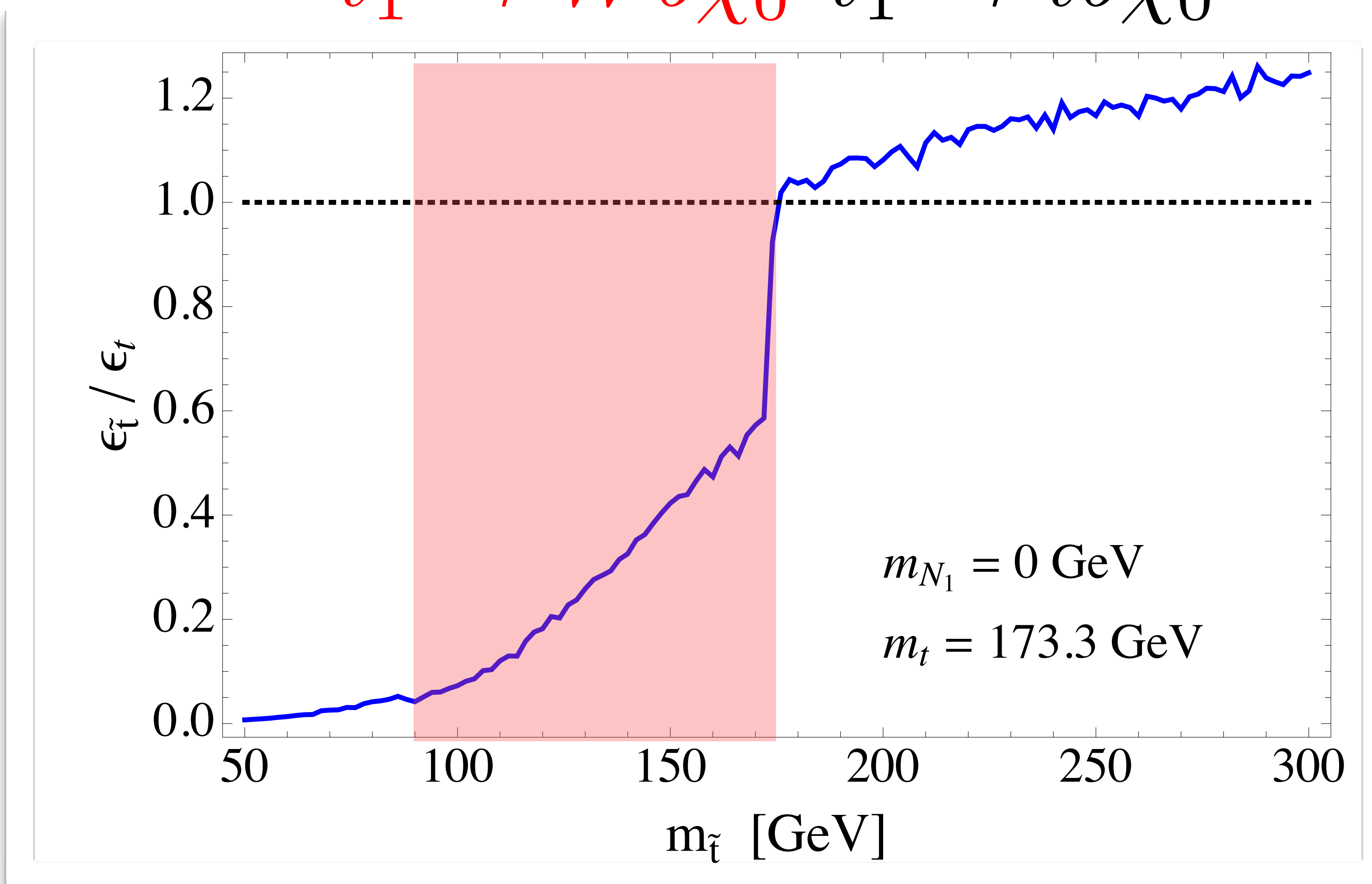
$\tilde{t}_1 \to W b \chi_0$ $\tilde{t}_1 \to t b \chi_0$



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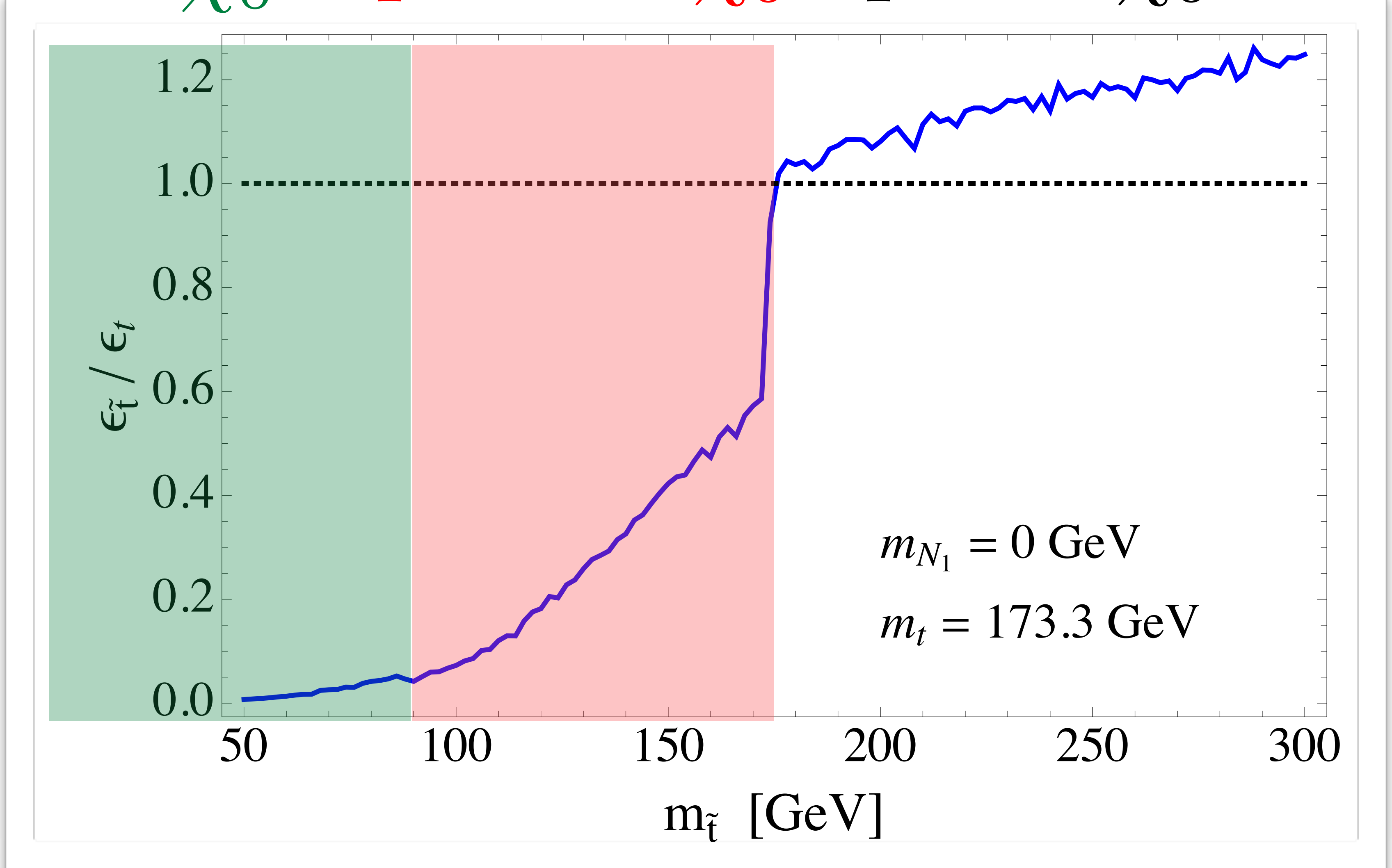
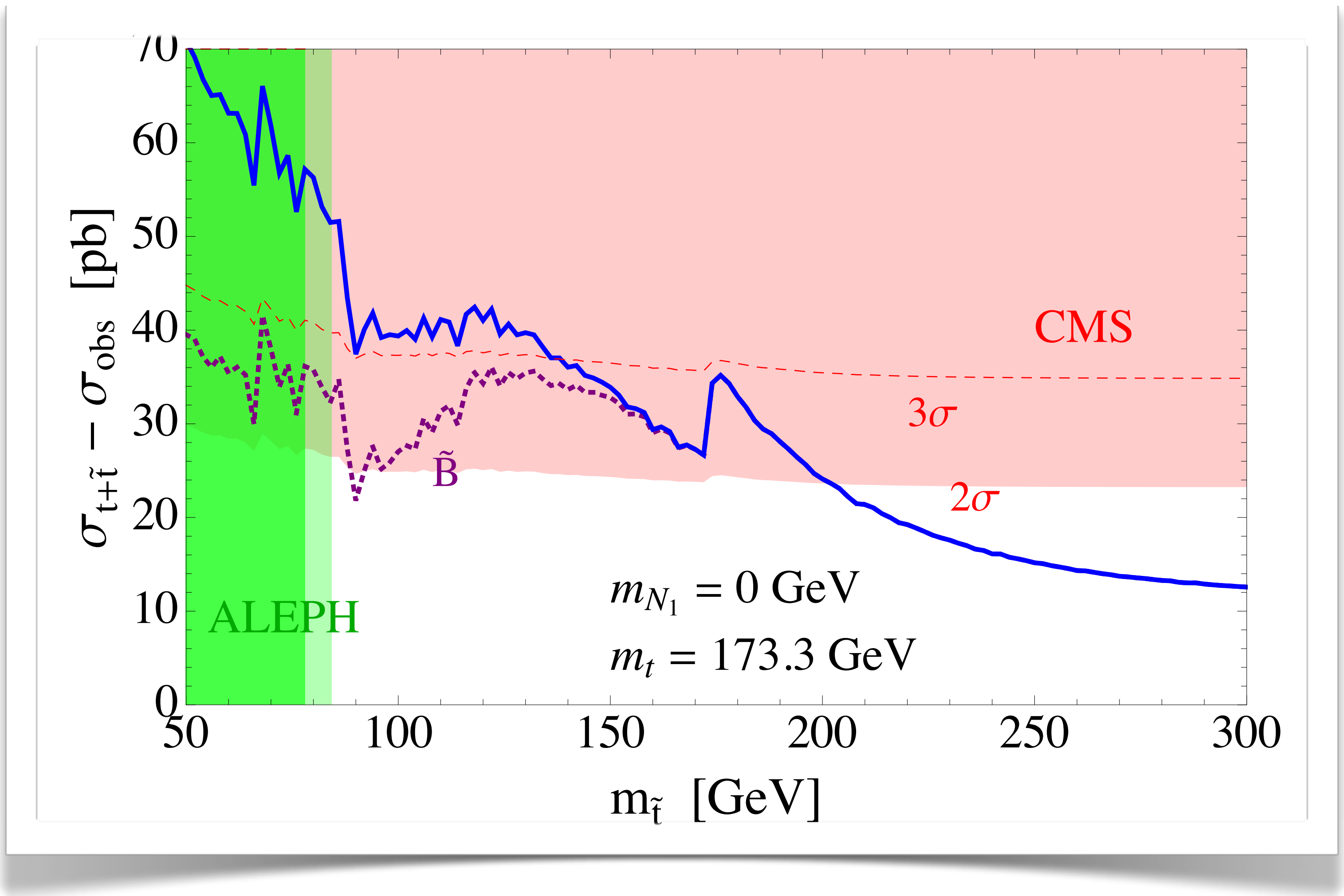
$\tilde{t}_1 \to l\nu b\chi_0$ $\tilde{t}_1 \to Wb\chi_0$ $\tilde{t}_1 \to tb\chi_0$



Stealth stop limit

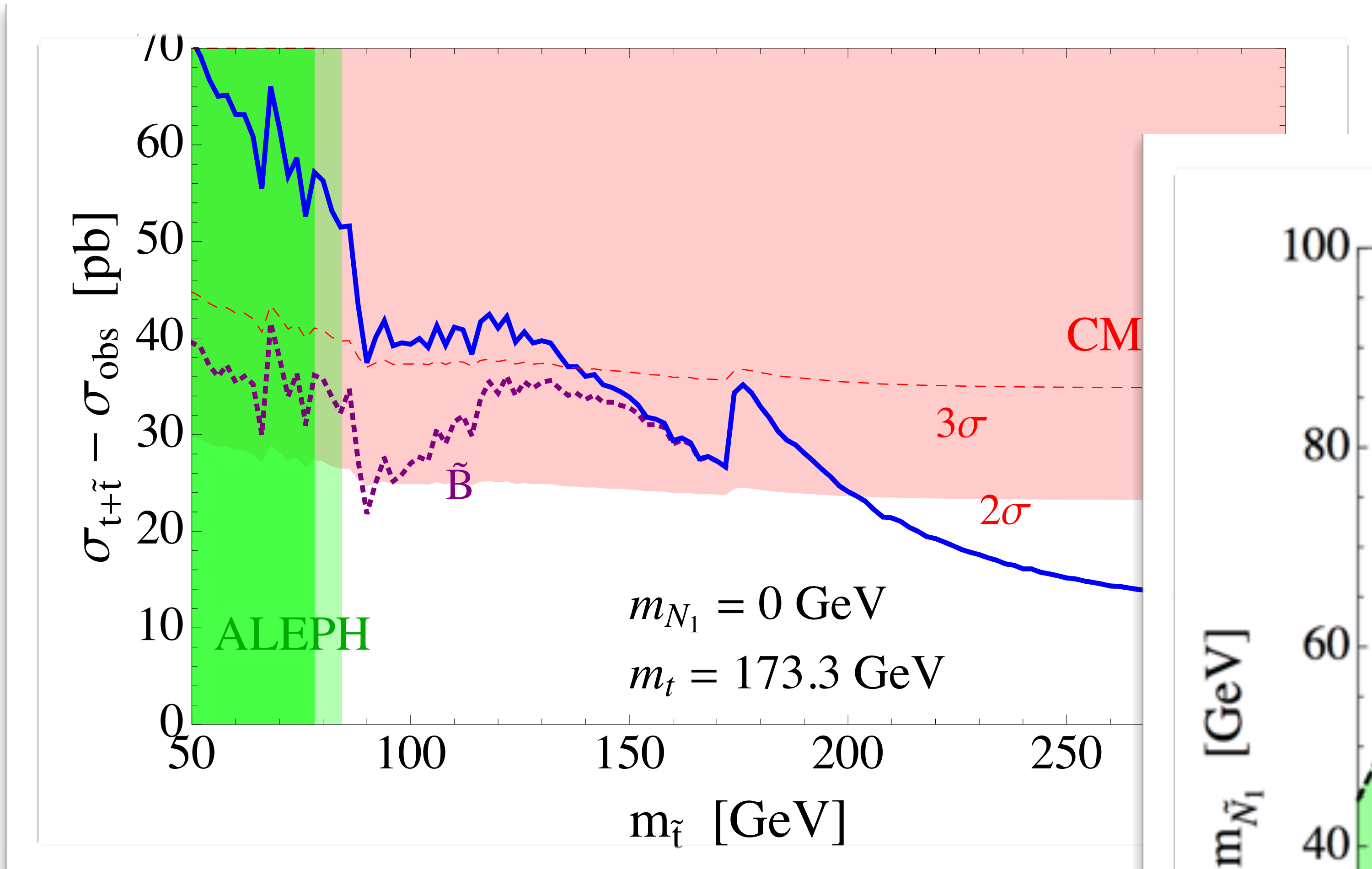
Czakon, Mitov, Papucci, Ruderman, AW to appear

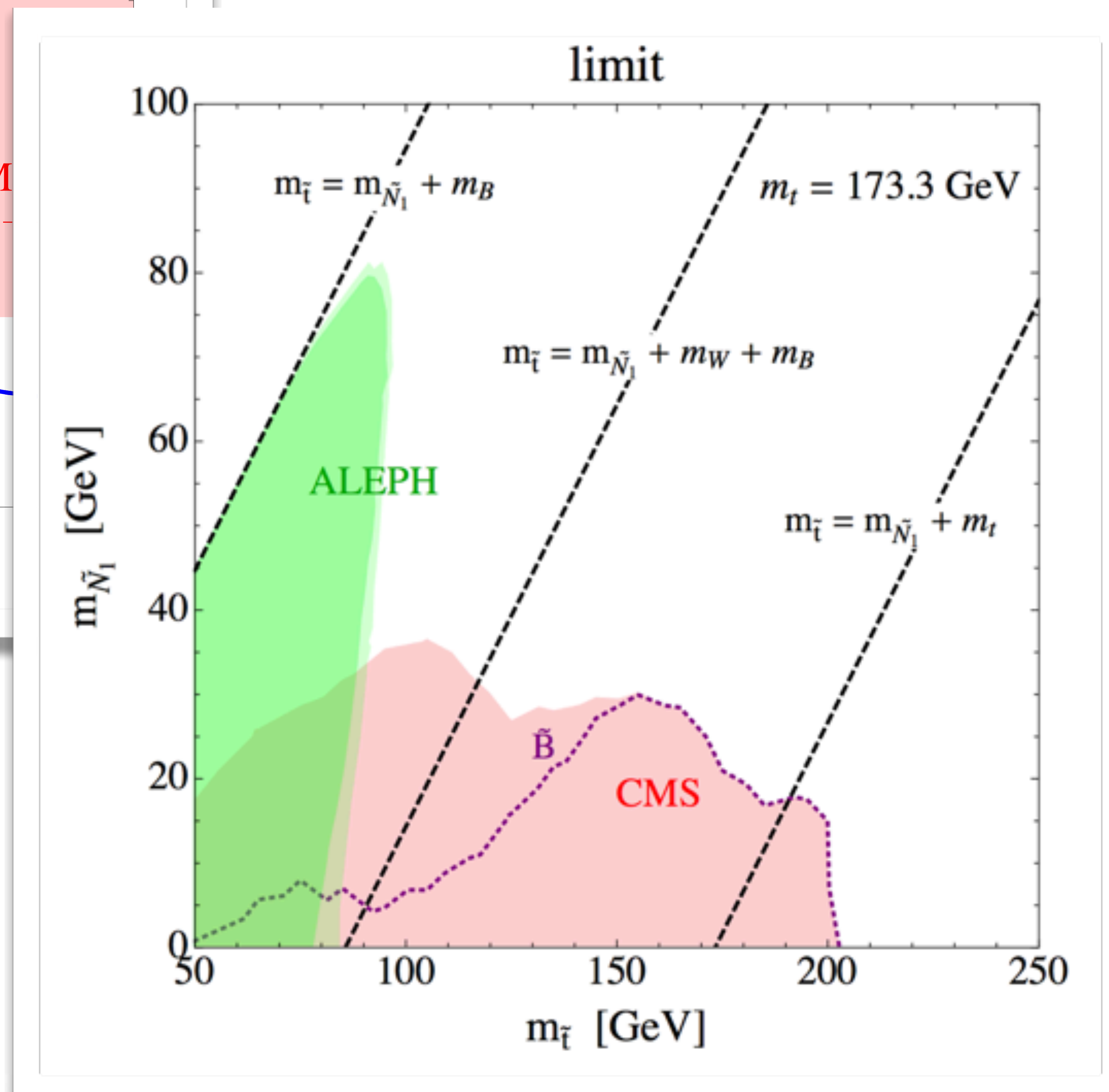


 → $Br(t \to \tilde{t}_1 \chi_0) = 0.1$

Stealth stop limit

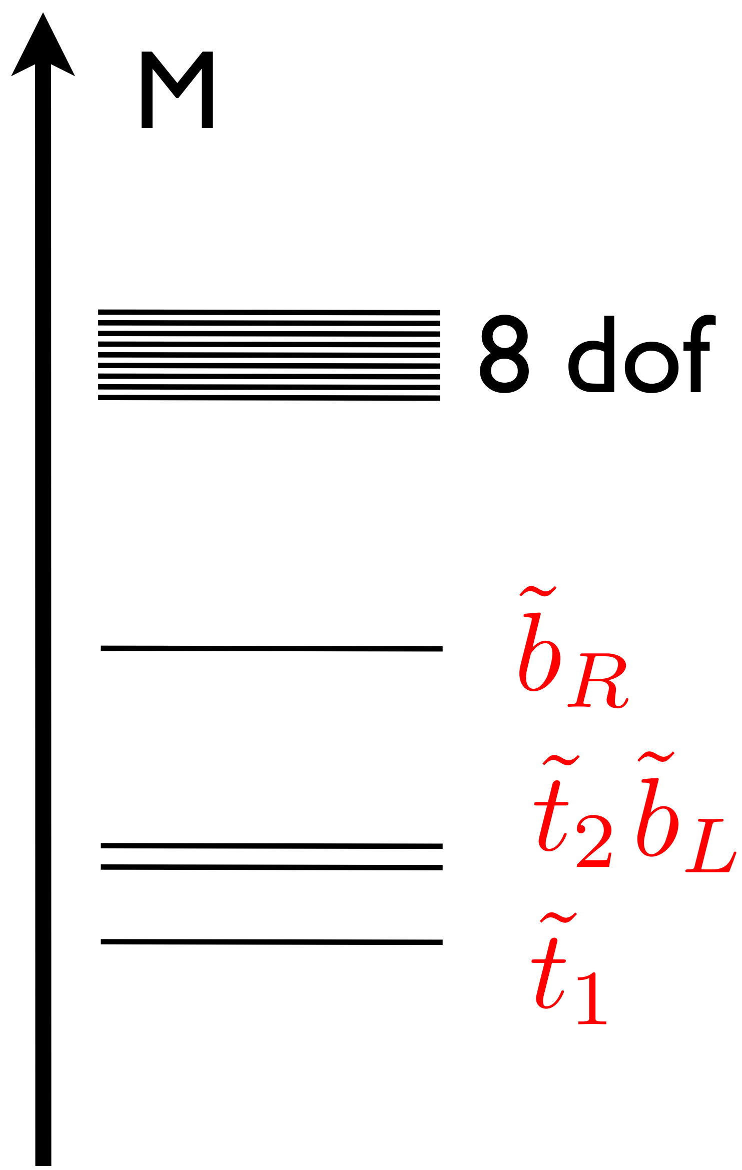
Czakon, Mitov, Papucci, Ruderman, AW to appear





$\rightarrow \quad Br(t \rightarrow \tilde{t}_1 \chi_0) = 0.1$

Naturalness prefers 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,
tanß moderate

Higgs fine-tuning = RGE mass splitting

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1-loop, LLog, tanß moderate

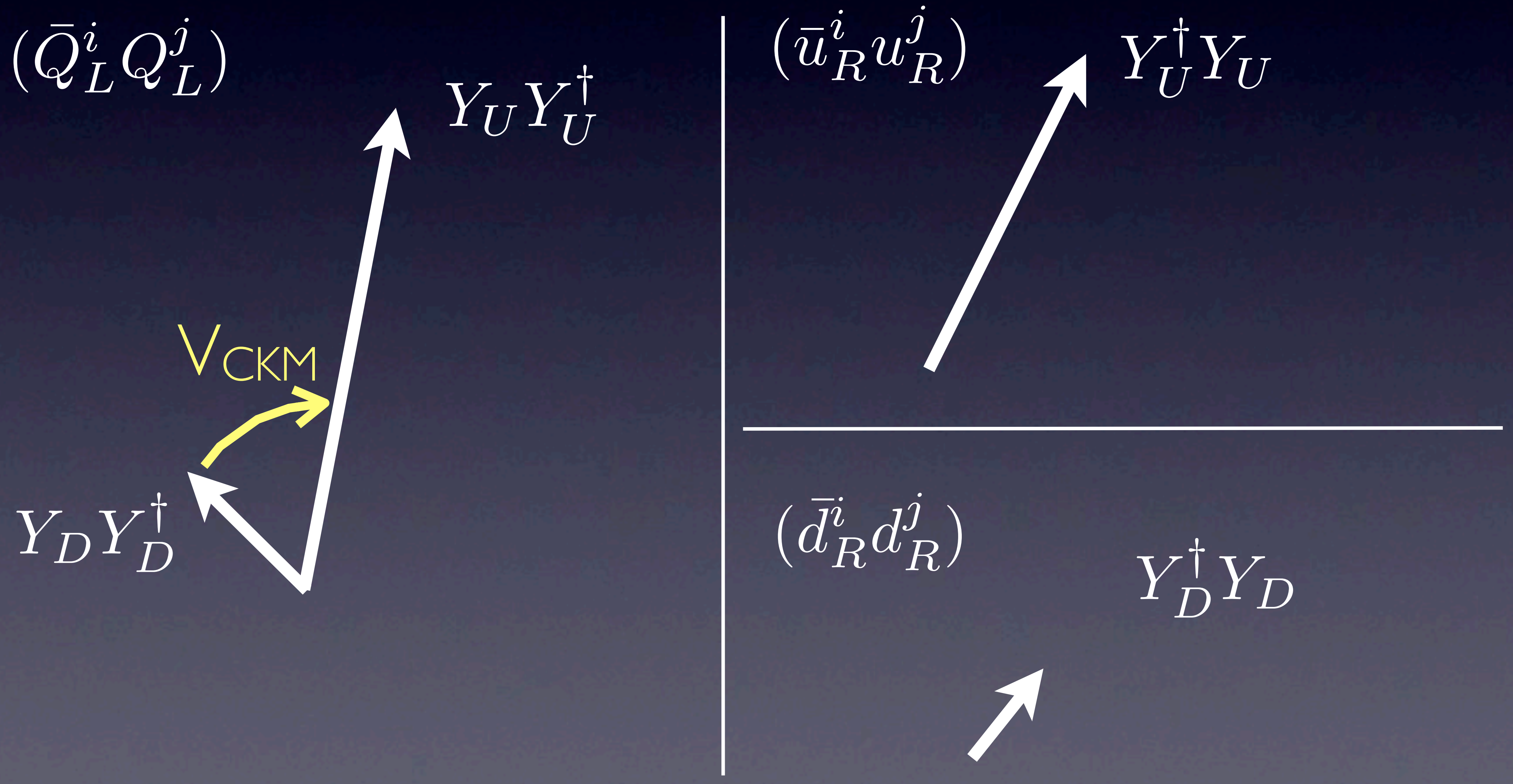
Higgs fine-tuning = RGE mass splitting

→ Flavor non-trivial susy breaking!

talks by → Brümmer, Galon, Ziegler

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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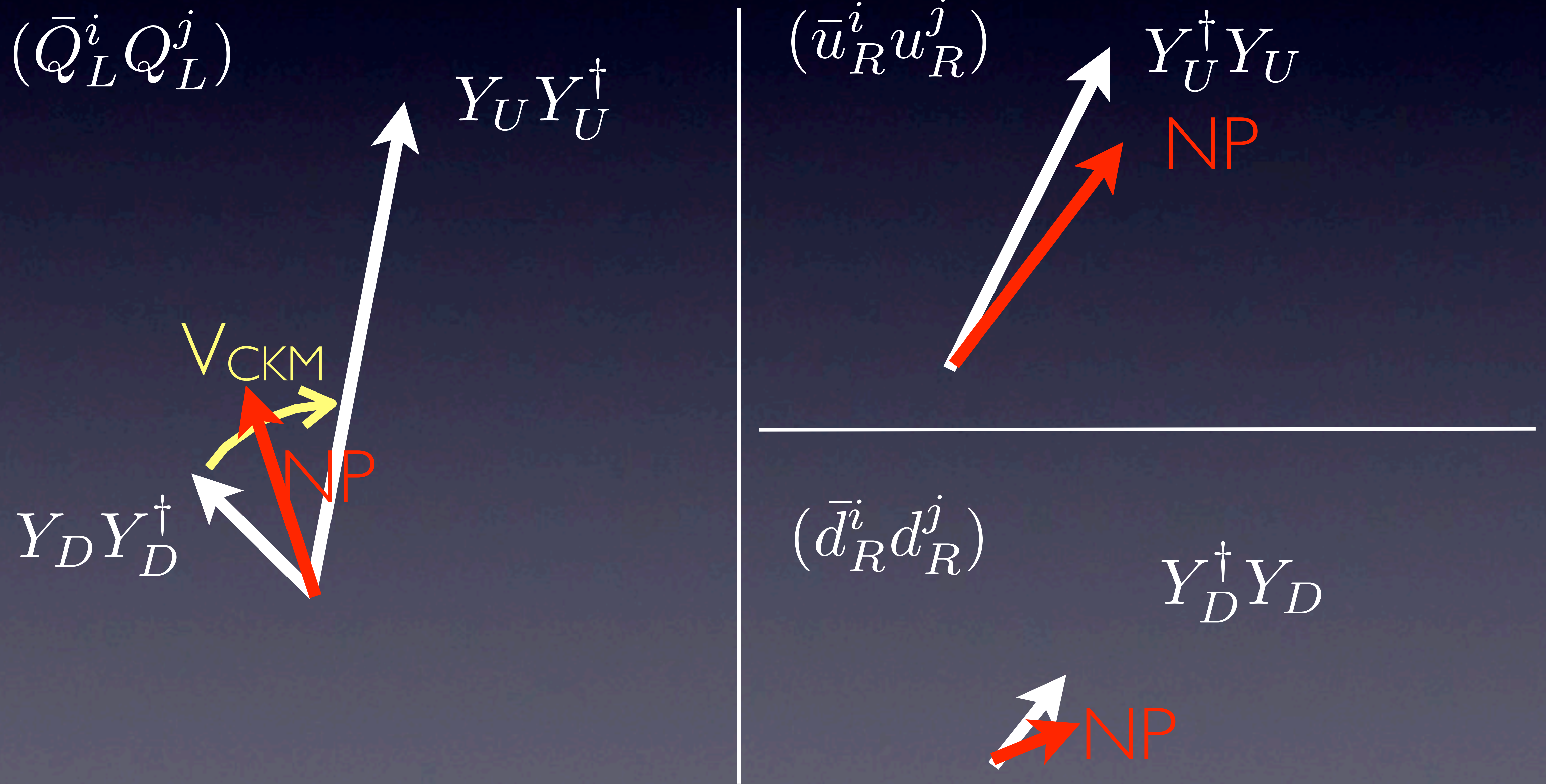
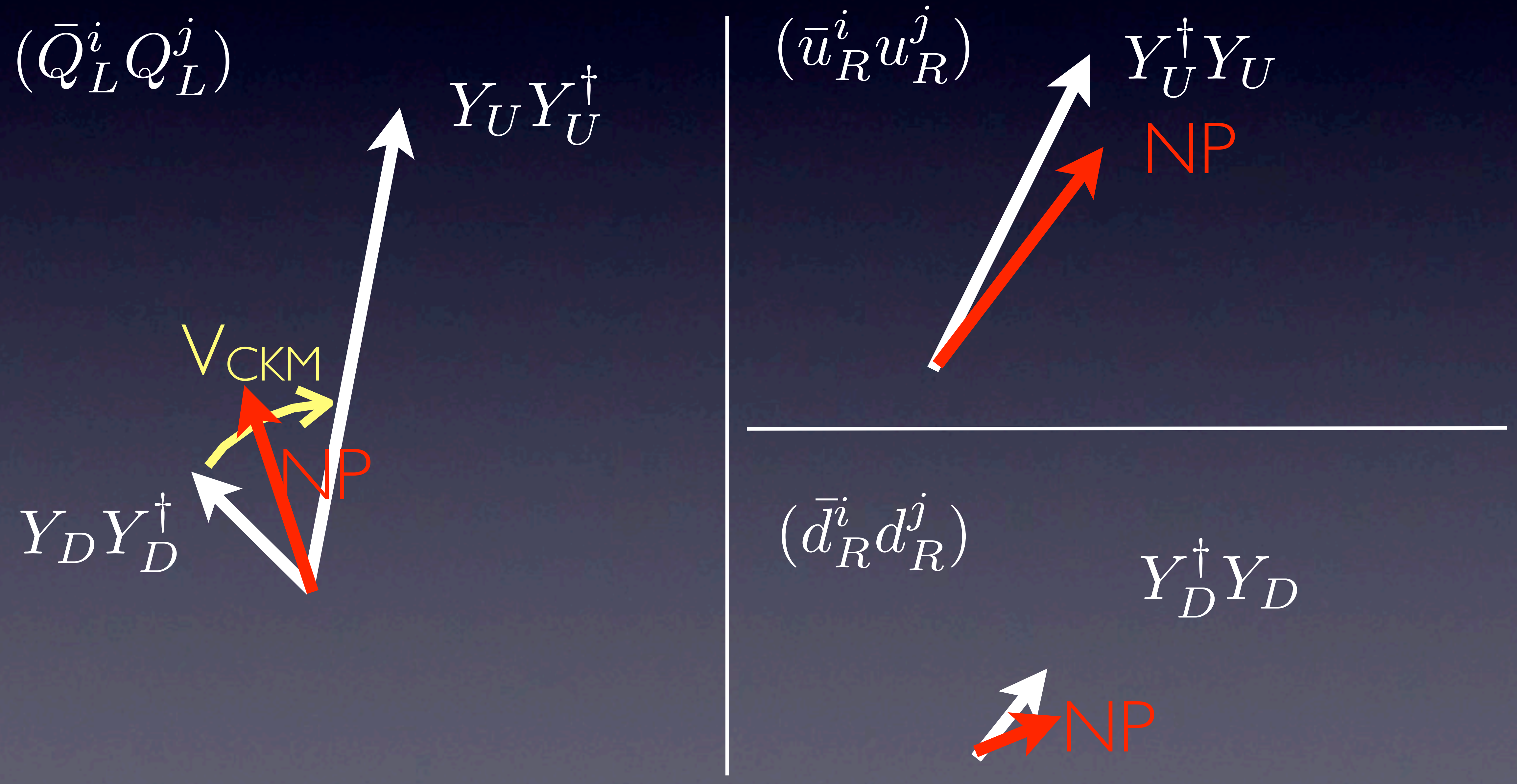


+ LR, RL

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

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



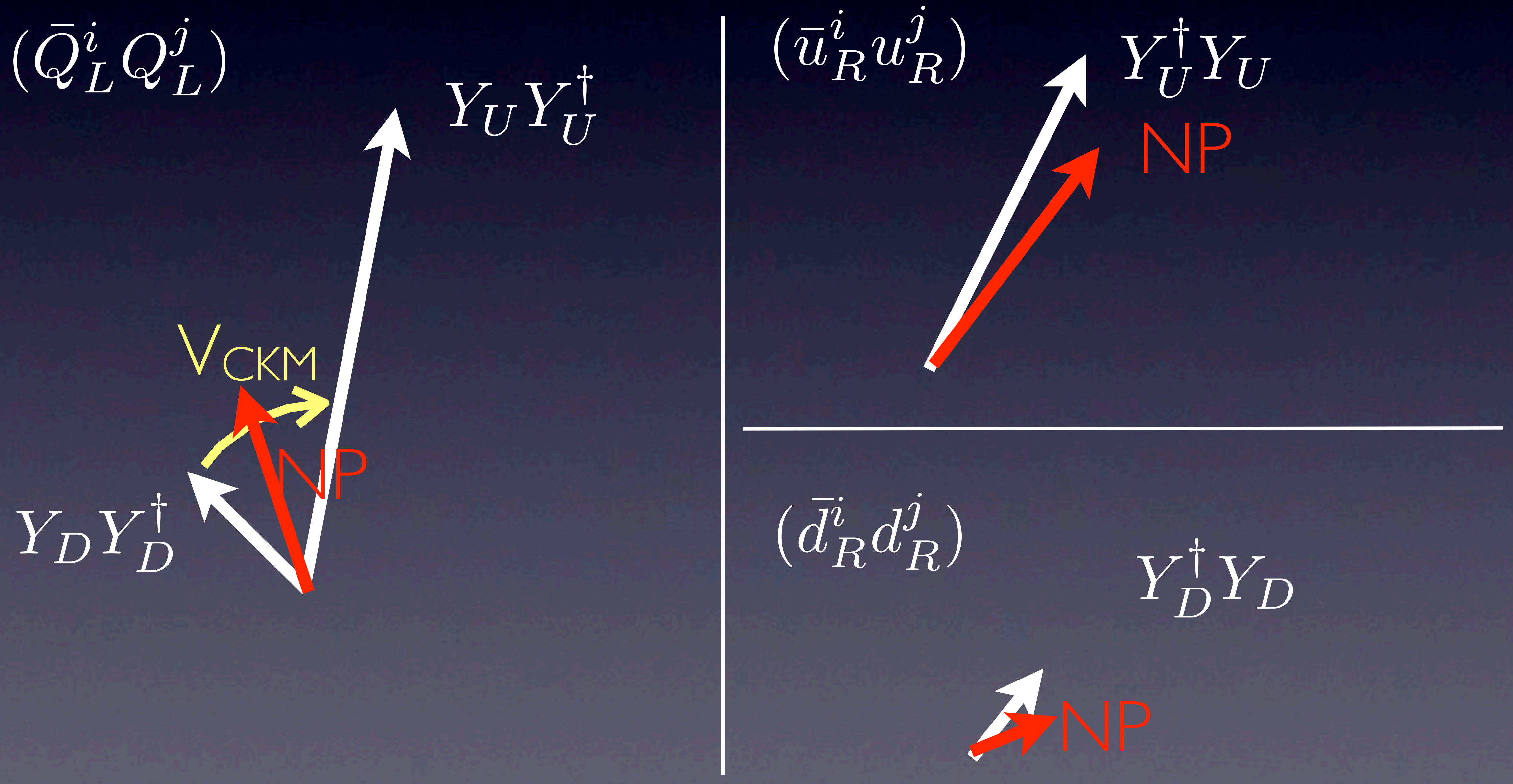
+ LR, RL

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

Alignment

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

Alignment

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

mixing / misalignment between
SM Yukawas and squark mass matrices

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Seiberg & Nir

mixing / misalignment between
SM Yukawas and squark mass matrices

If by symmetry: K_{ij} ~ diagonal, O(1) mass splittings ok.

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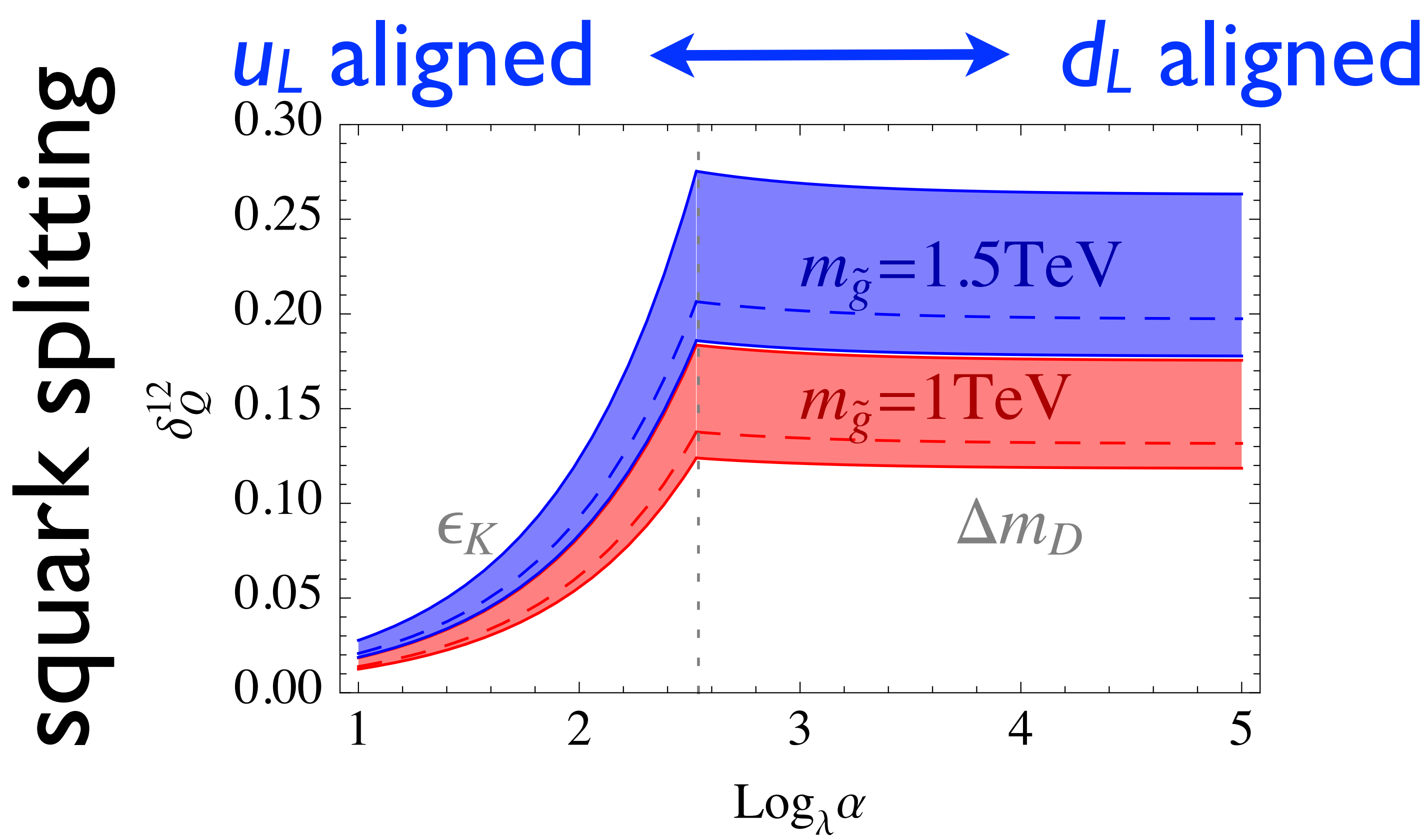
Gedalia et. al



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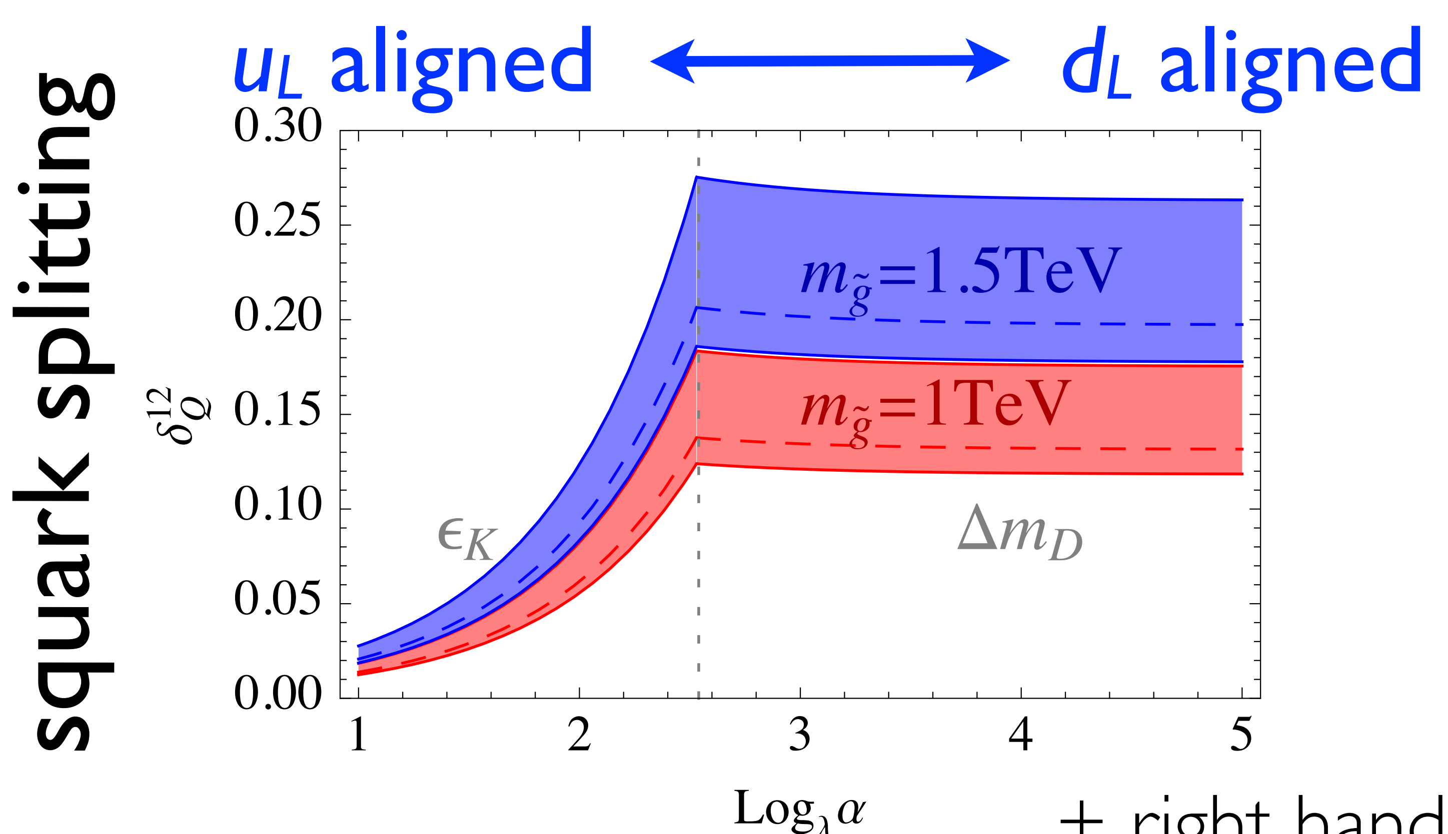


Example:

m_{gluino} = 1.3 TeV

m_{Q1} = 550 GeV

m_{Q2} = 950 GeV

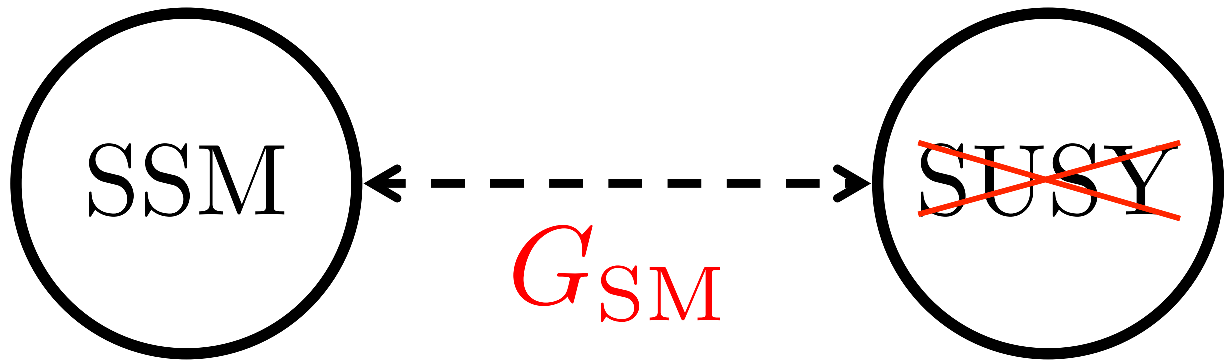
+ right handed squarks split by arbitrary amount

Flavor vs. squark masses: summary

- Generic 1-2 splitting has to be small, **but**:
- Can split vertically: split Q_L^i vs u_R^i vs d_L^i
- Can split horizontally, if squark mixing aligned (as consequence of flavor model)

Gauge Mediation

see e.g. Giudice/Rattazzi review

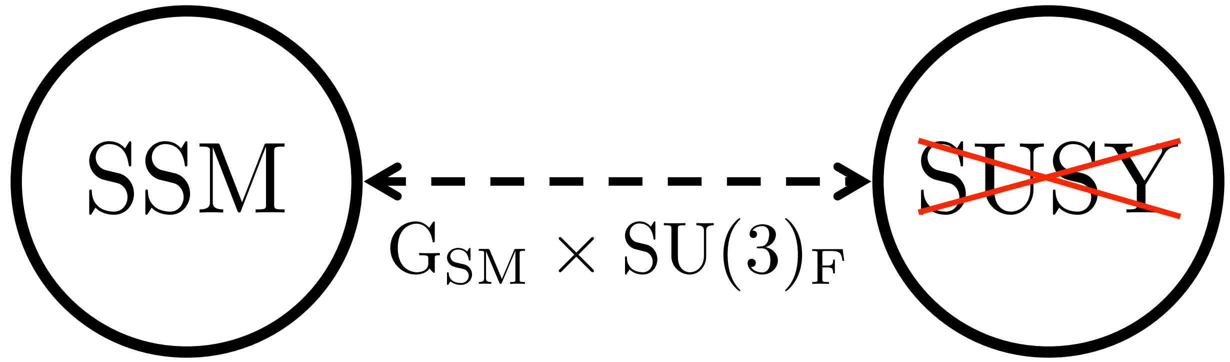


$$G_{\rm SM} = SU(3) \times SU(2) \times U(1)$$

Degenerate quarks!

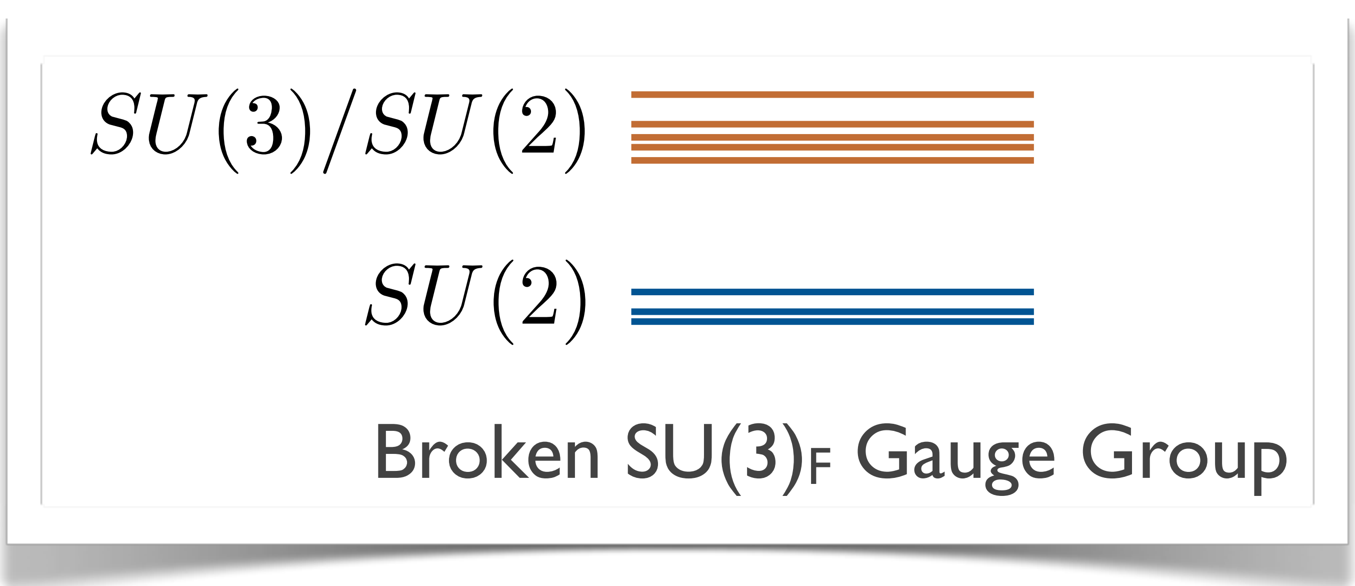
Flavor Gauge Mediation

U(1): Kaplan, Kribs '99; Craig, McCullough, Thaler '12



* Anomaly-free diagonal subgroup of SM flavour symm'

$$Y_U \approx \mathrm{diag}\,(0, 0, 1)$$



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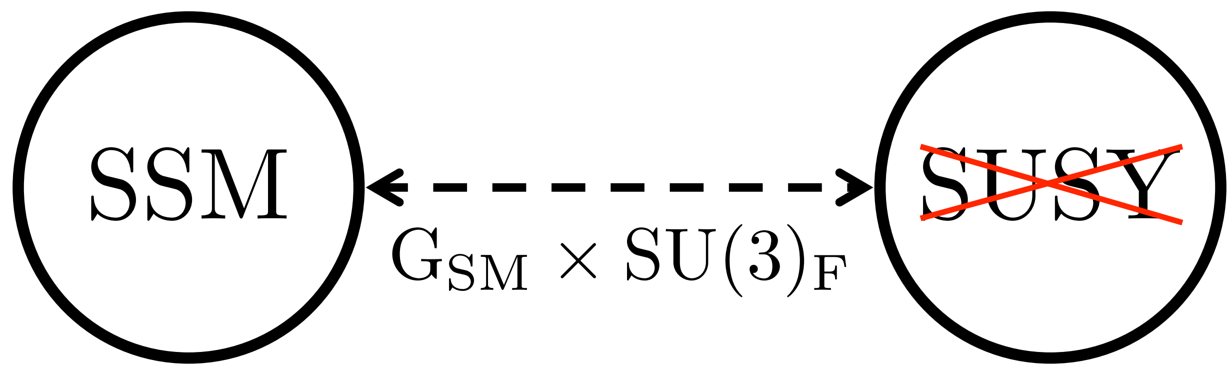

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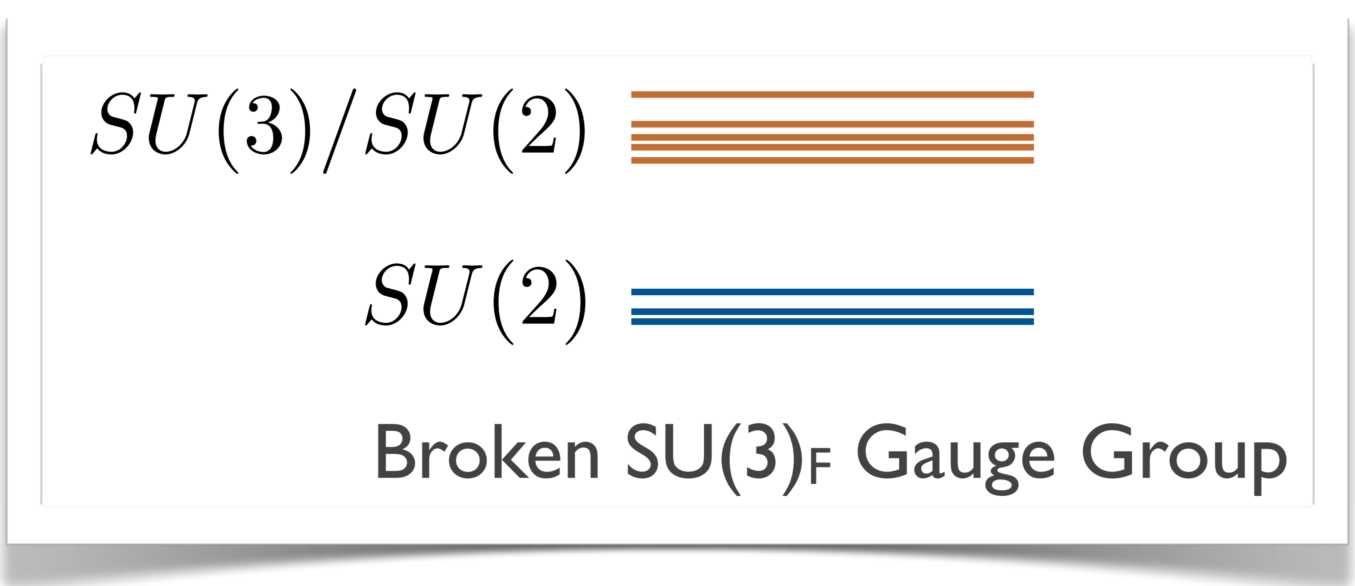
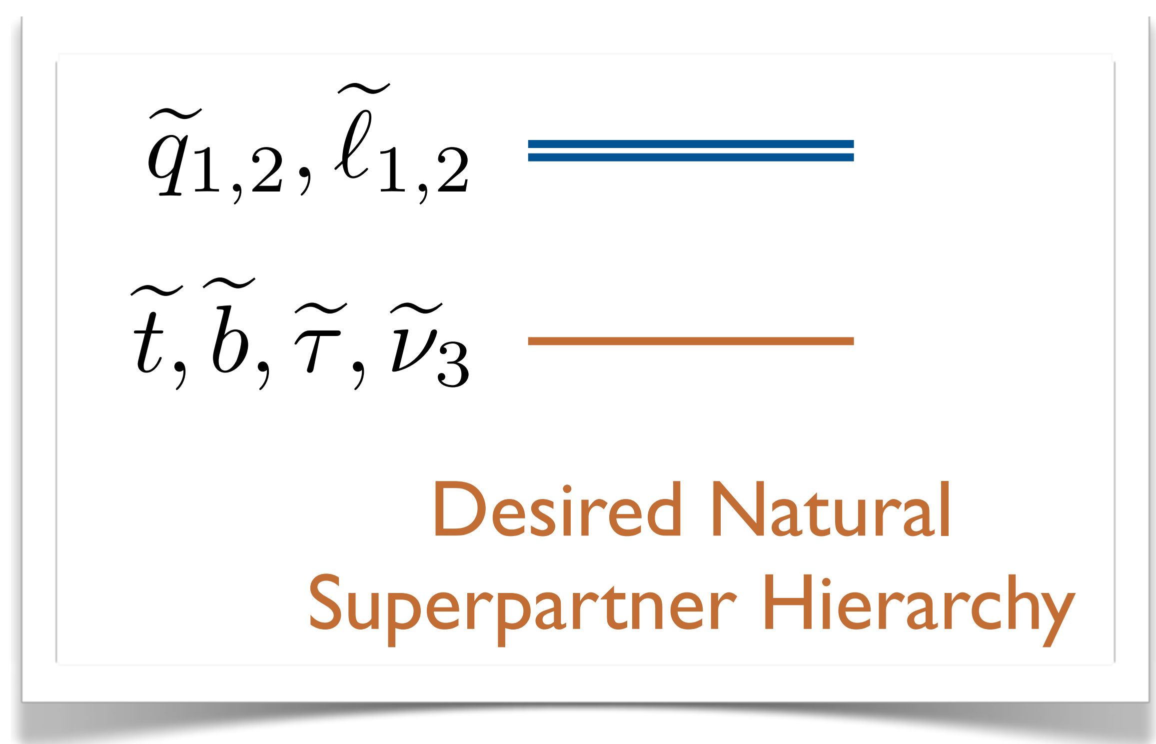
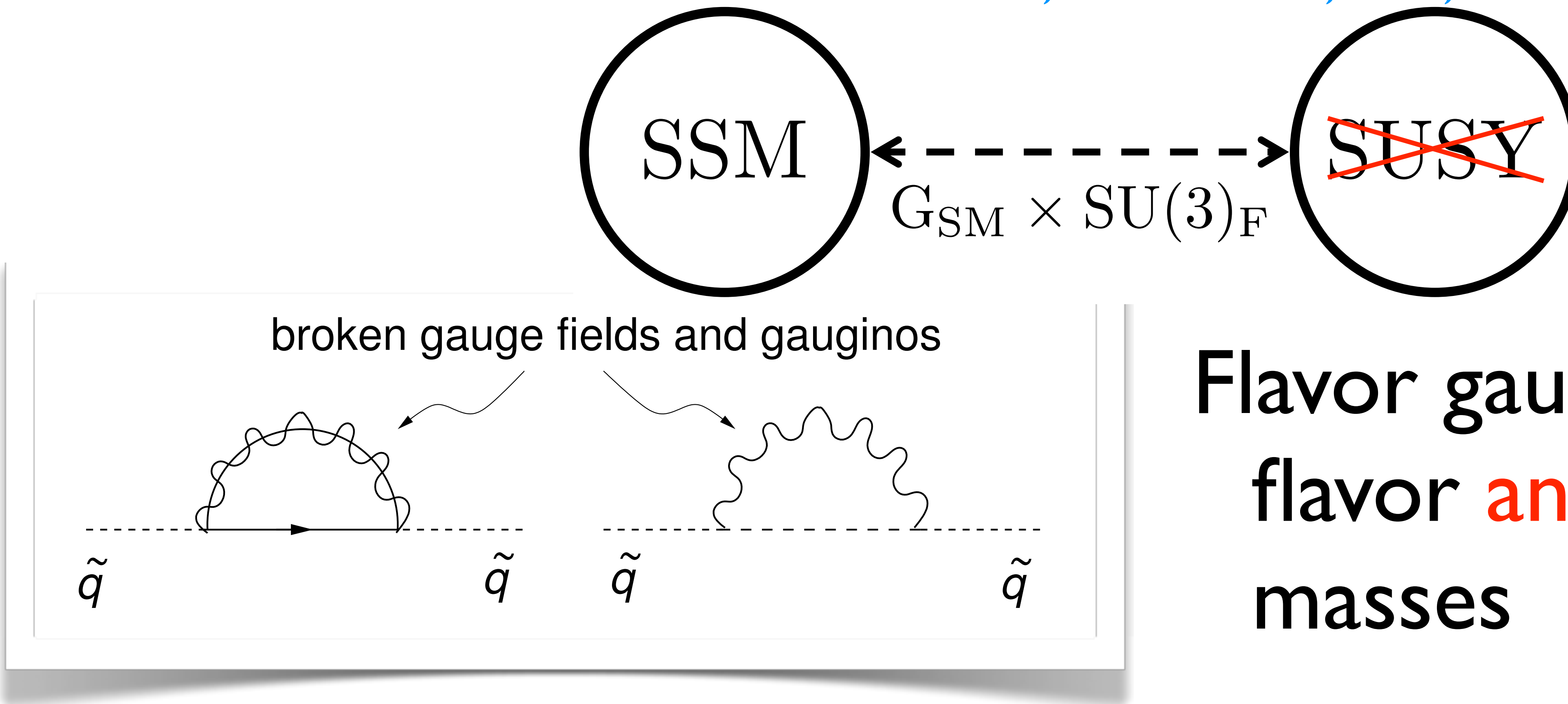




Flavor Gauge Messengers

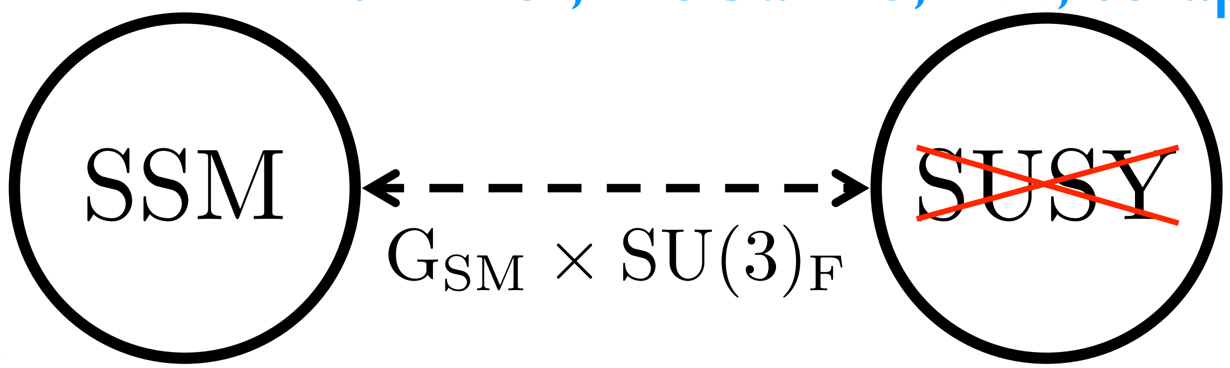
Brümmer, McGarrie, AW, to appear → Brümmer talk

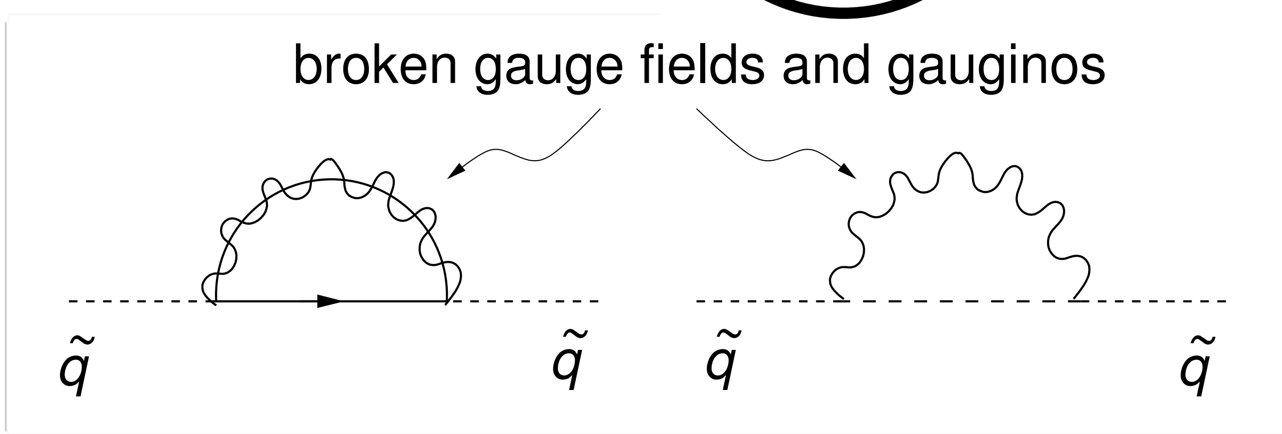


Flavor gauge bosons with flavor and susy breaking masses

Flavor Gauge Messengers

Brümmer, McGarrie, AW, to appear → Brümmer talk





Flavor gauge bosons with flavor and susy breaking masses

$SU(3)_F \to SU(2)_F$

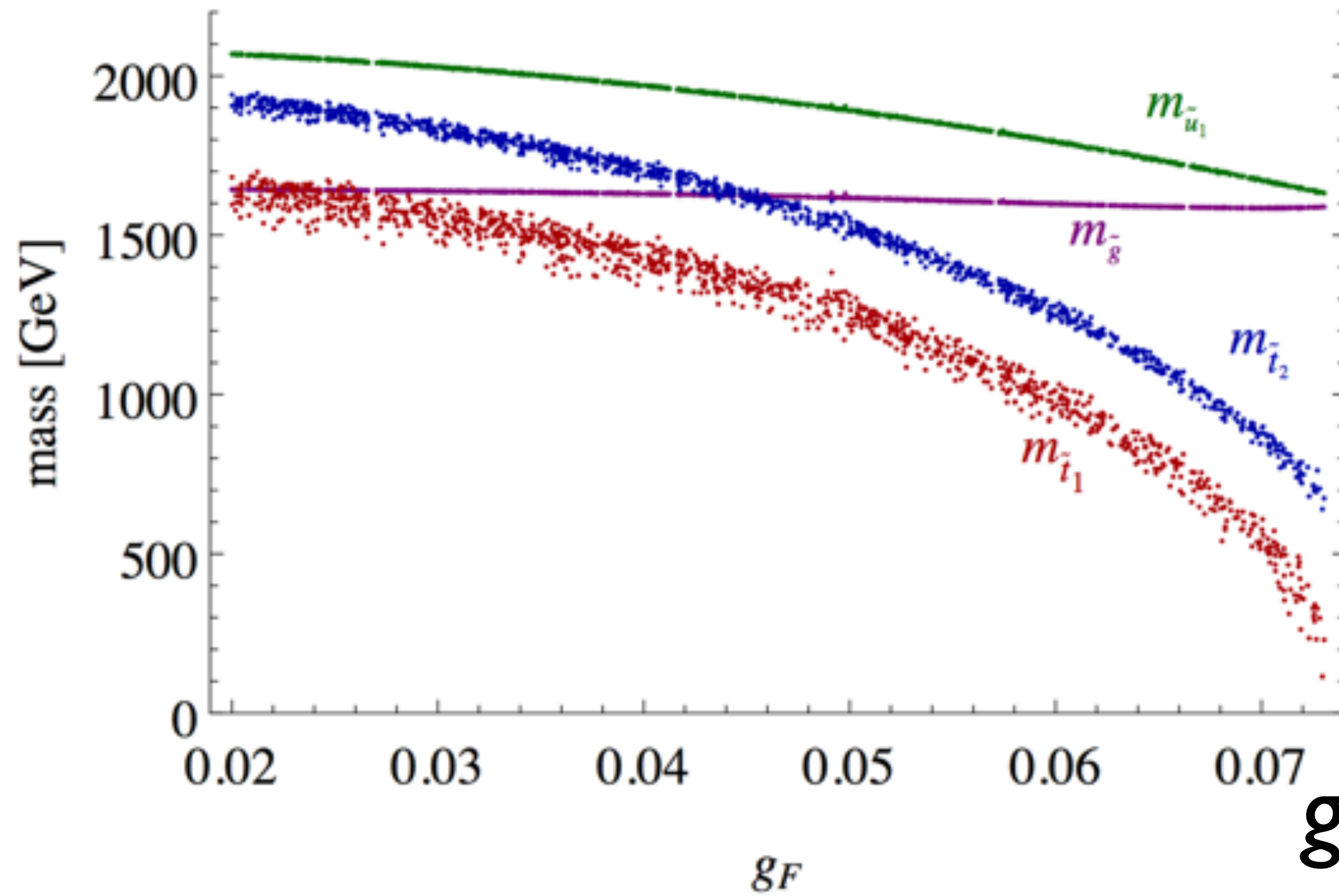
$$\delta m^2_{Q,U,D} = -\frac{g_F^2}{16\pi^2}\frac{F^2}{M^2}\left[\begin{pmatrix} \frac{7}{6} & 0 & 0 \\ 0 & \frac{7}{6} & 0 \\ 0 & 0 & \frac{8}{3} \end{pmatrix} + \mathcal{O}(\epsilon^2)\right]$$

tachyonic contribution

e.g. Intrilligator et al

Split spectrum

Brümmer, McGarrie, AW



$m_{squark\,12}$

m_{stop}

g_{Flavor}

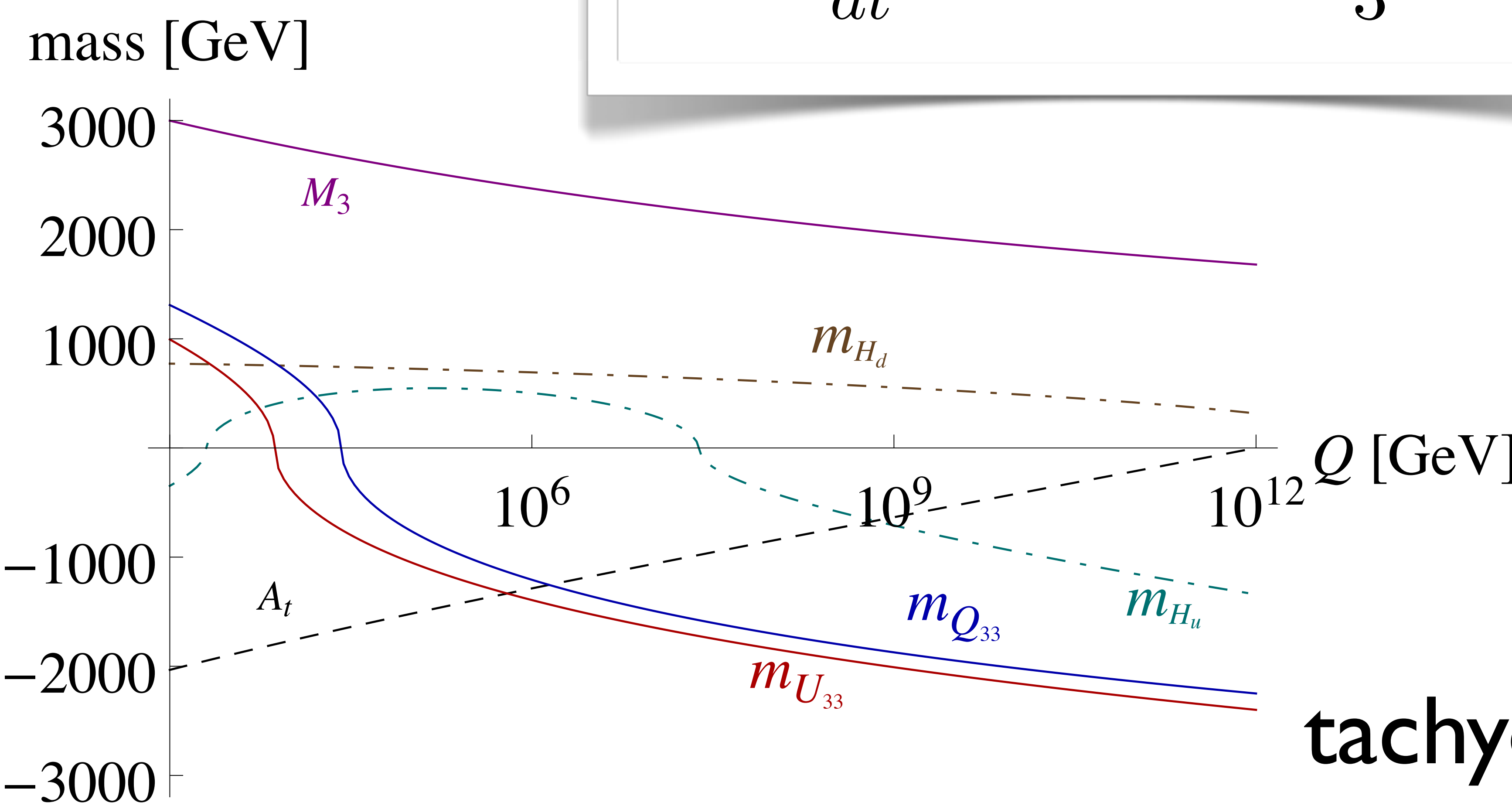
Requiring $m_H = 125$, keeping standard gauge mediation parameters fixed, NMSSM example

w/ Spheno, Porod '03, → talks by Mühlleitner, Badziak,

A-terms through RGE

→ D. Shih's talk, Draper et al.

$$16\pi^2 \frac{dA_t}{dt} \approx 12 y_t^2 A_t + \frac{32}{3} g_3^2 M_3$$



tachyonic stops
at messenger scale

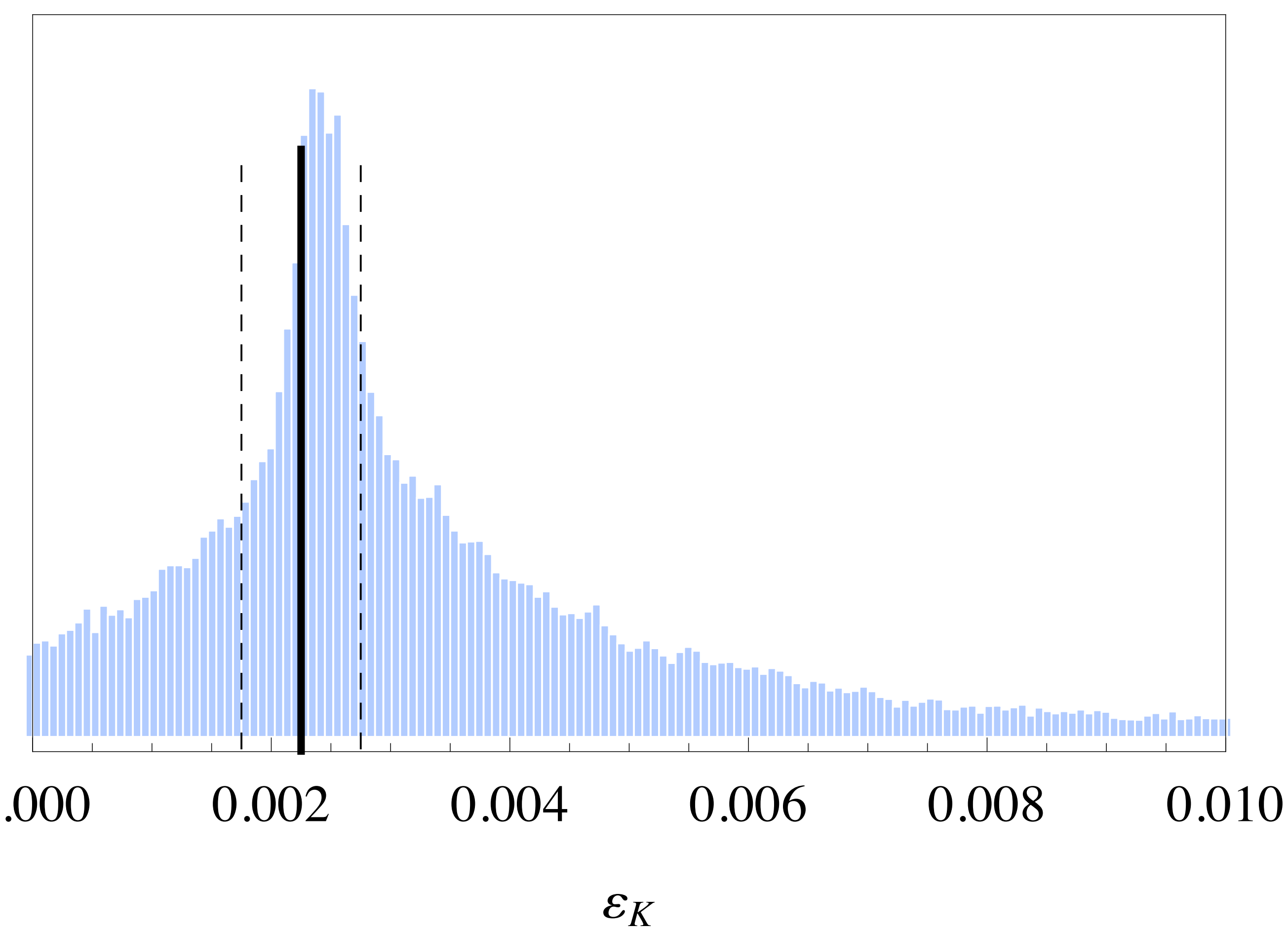
FCNC's under control

F. Brümmer, M. McGarrie, AW

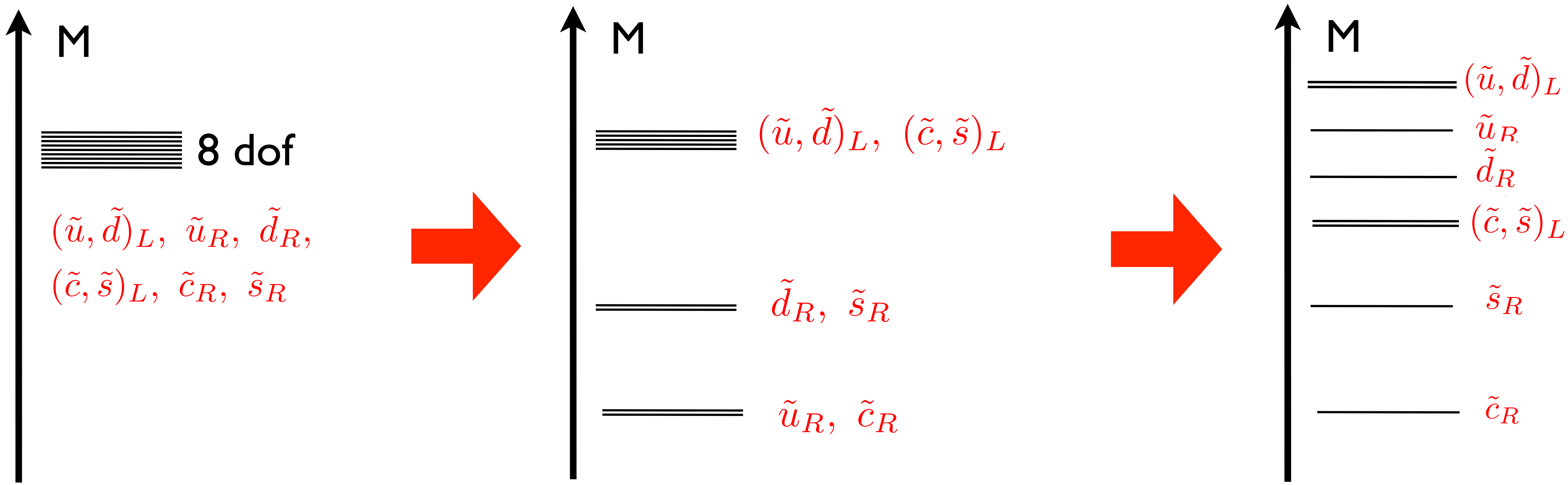
- Embed in explicit flavor-(toy)-model
- Hierarchical masses and mixing → squark - quark alignment

Strongest constraint

ϵ_K

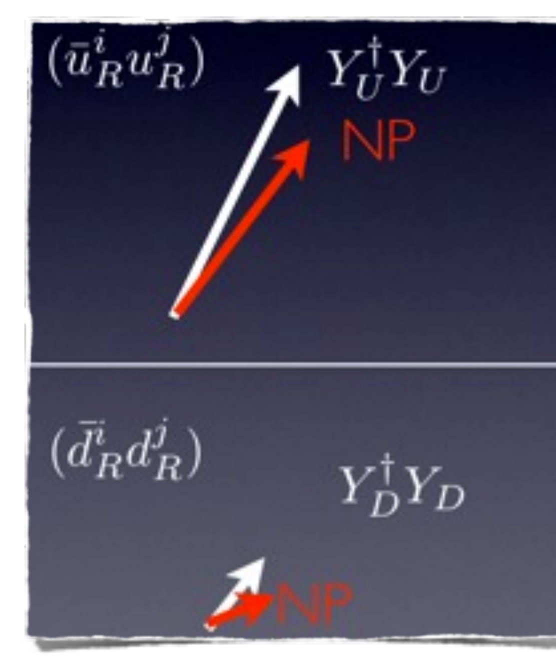


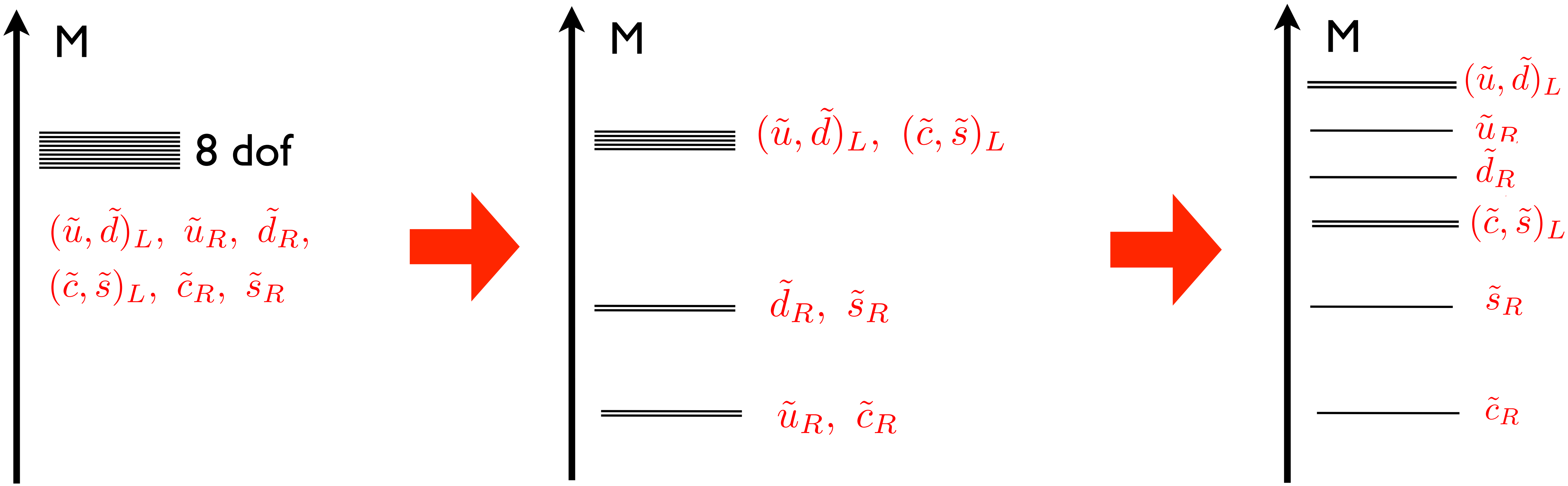
→ talk by Galon



Degenerate | **Minimal Flavor** | **Anarchy!**

mSugra, CMSSM, pMSSM, …





Degenerate | Minimal Flavor | Anarchy!

mSugra, CMSSM,
pMSSM, . . .

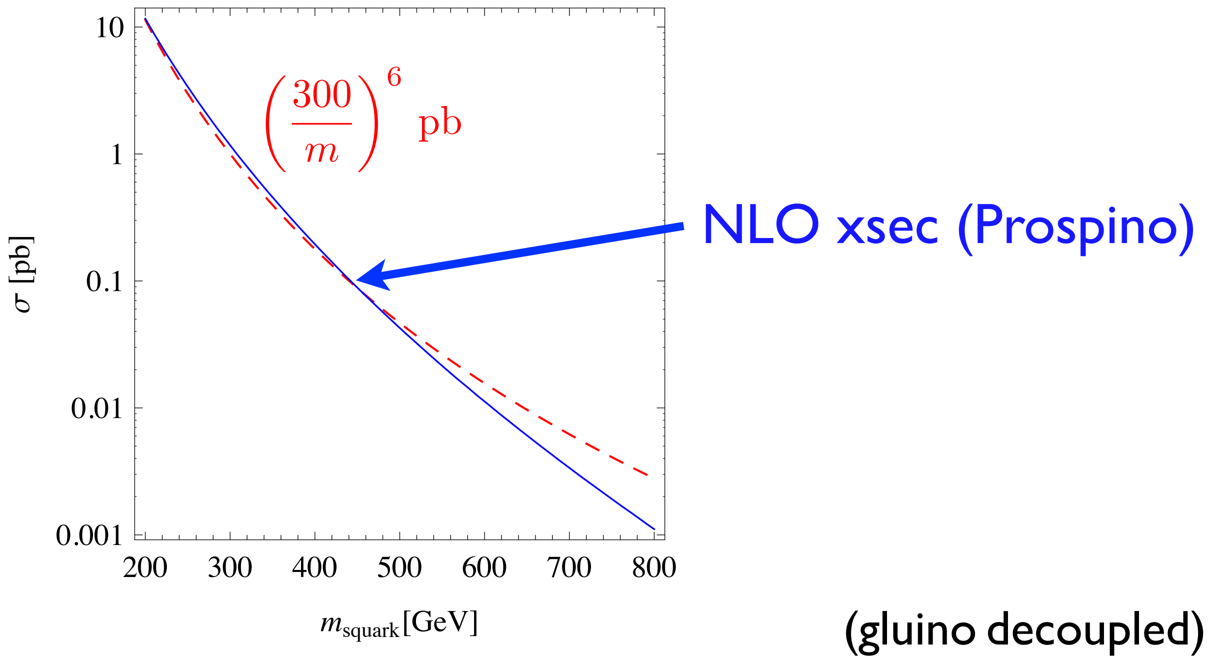
Consider beyond-MFV susy spectra.
Sensitivity can change dramatically...

?

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

8 degenerate squarks
→ e.g. 2 light sflavors

$$\sigma(pp \to \tilde{u}_R \tilde{u}_R^*) \propto \frac{1}{m^6}$$ (roughly)



(gluino decoupled)

$$8/m^6 = 6/m_H^6 + 2/m_L^6$$

$$(m_L/m_H) = (1/4)^{1/6} \sim 0.8$$

too naive !

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

8 degenerate squarks
→ e.g. 2 light sflavors

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

↗

8 degenerate squarks
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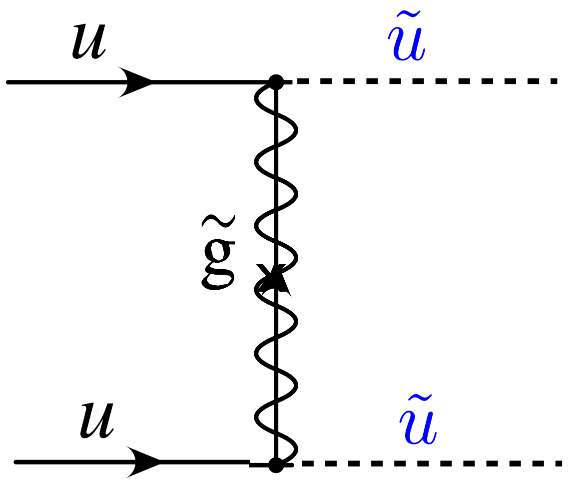

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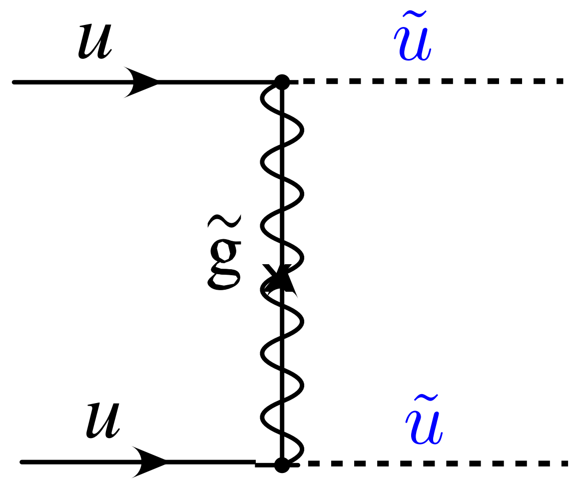

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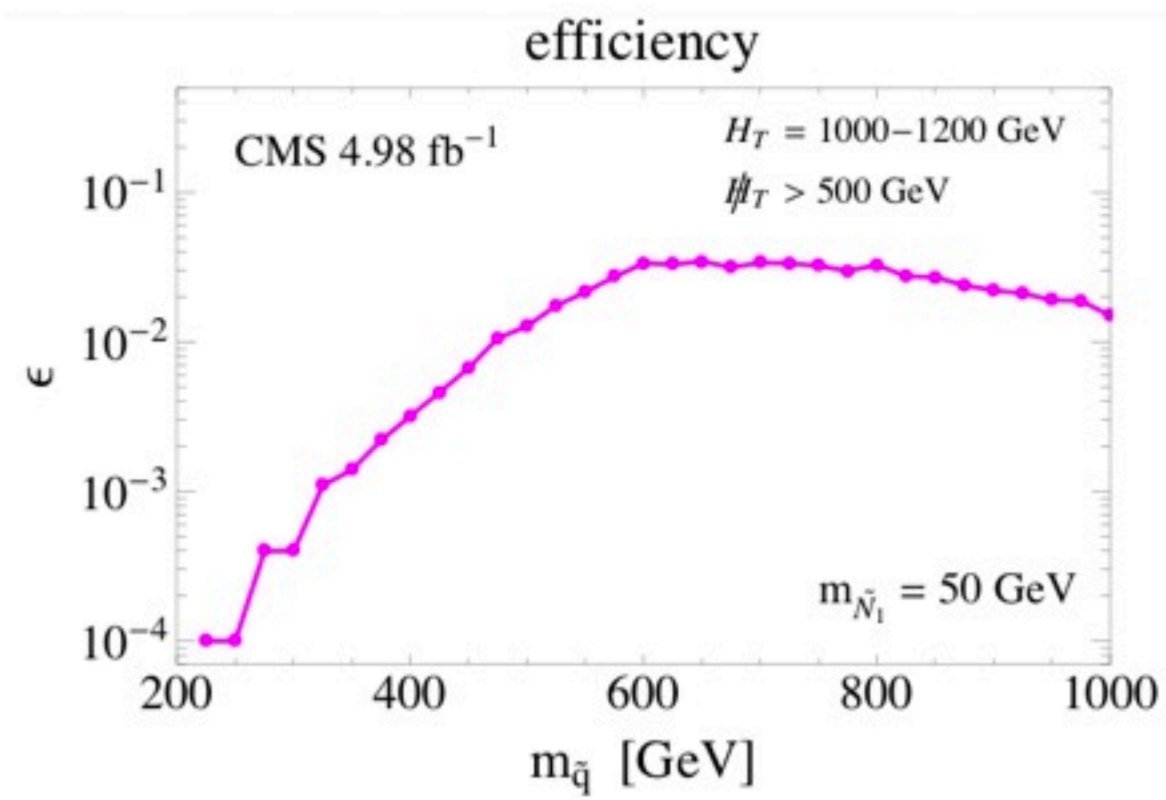

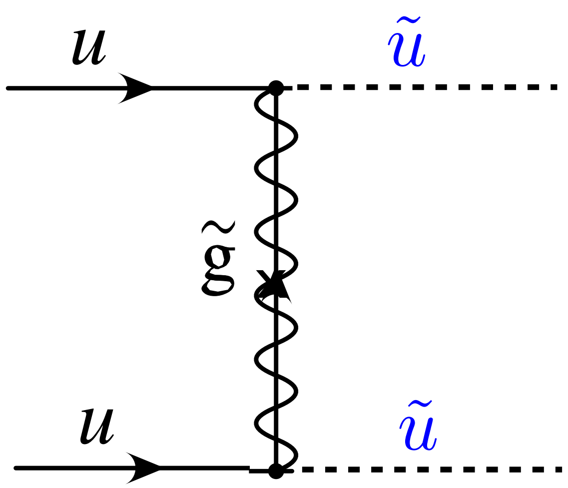

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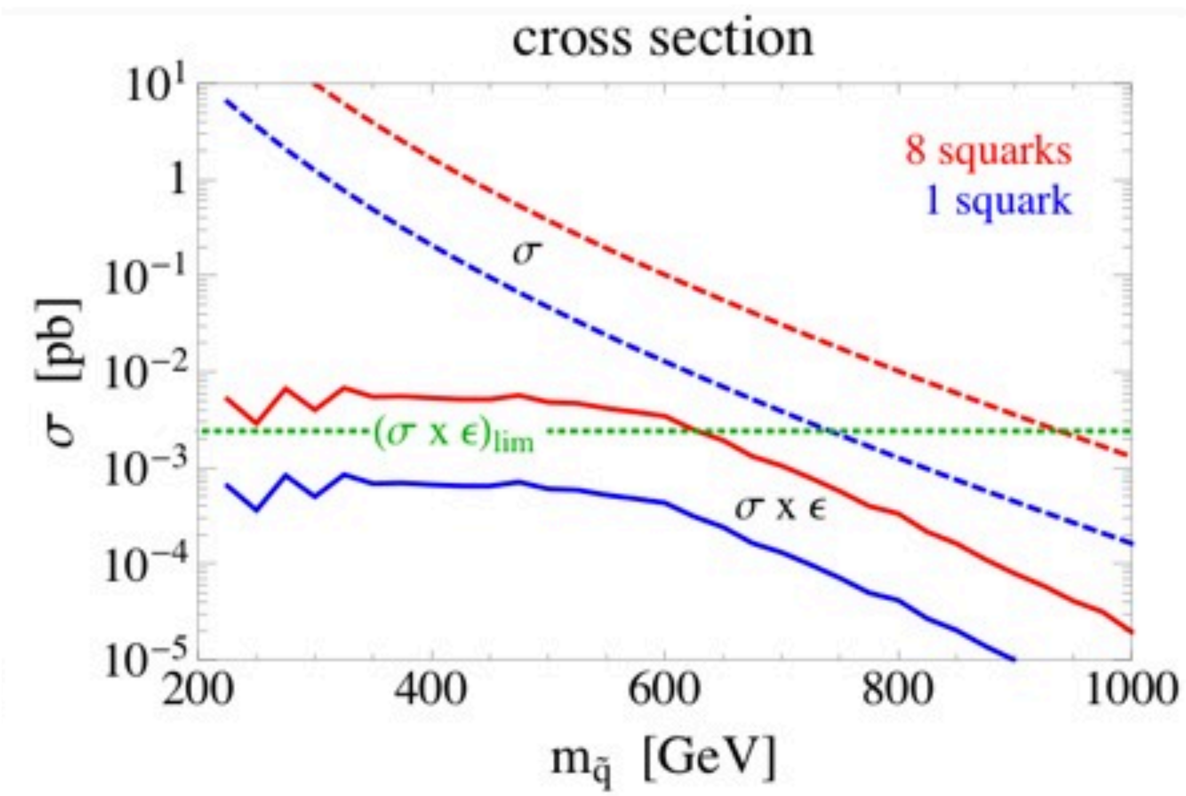
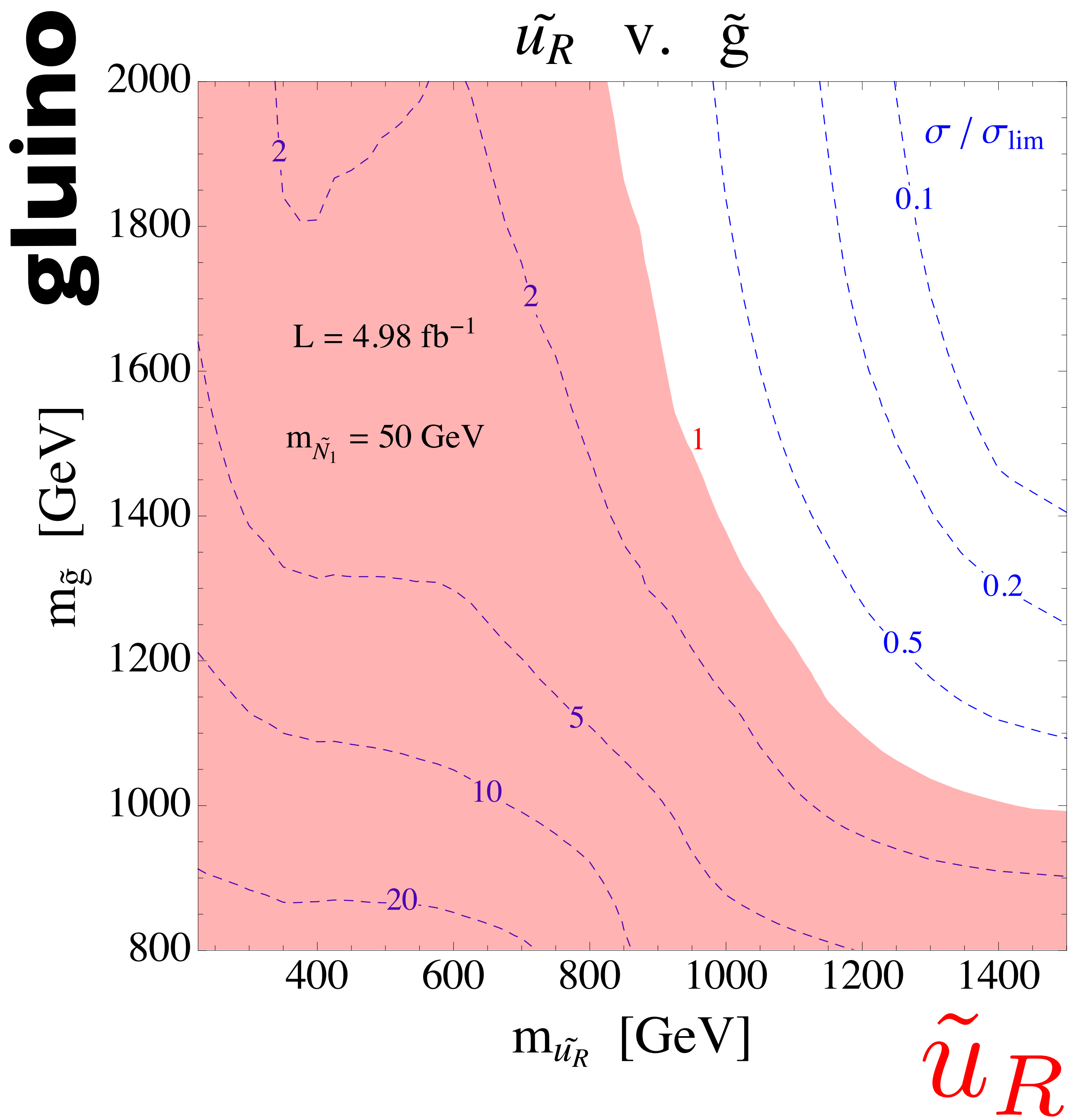
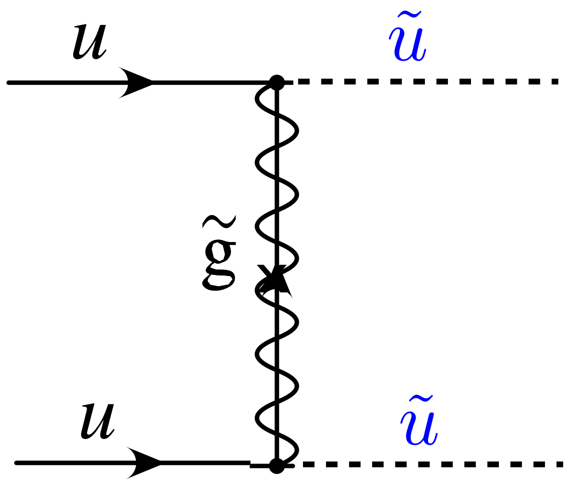


Single Sflavor vs. Gluino

Papucci, Ruderman, Perez, Mahbubani, AW



Driven by



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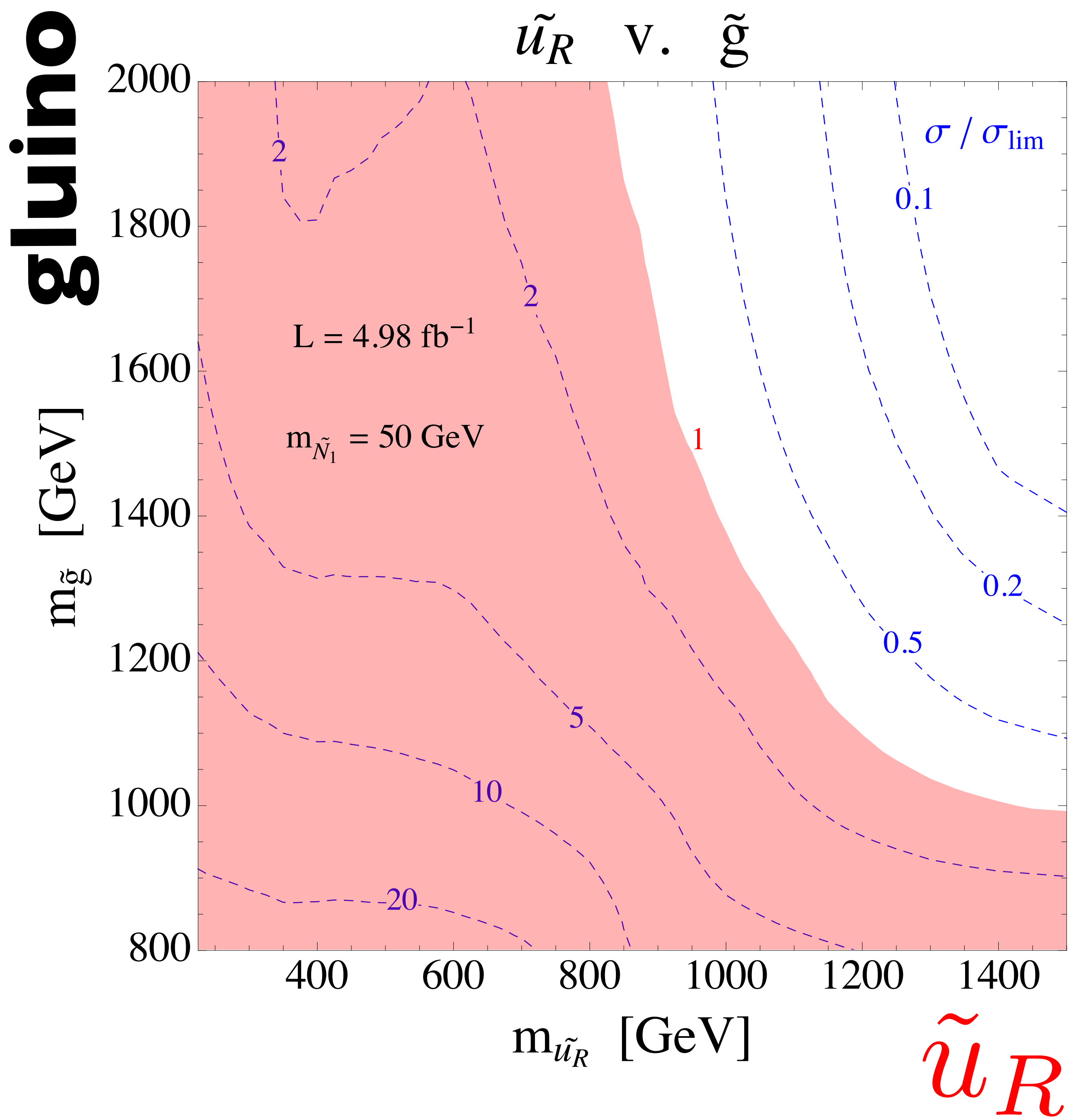
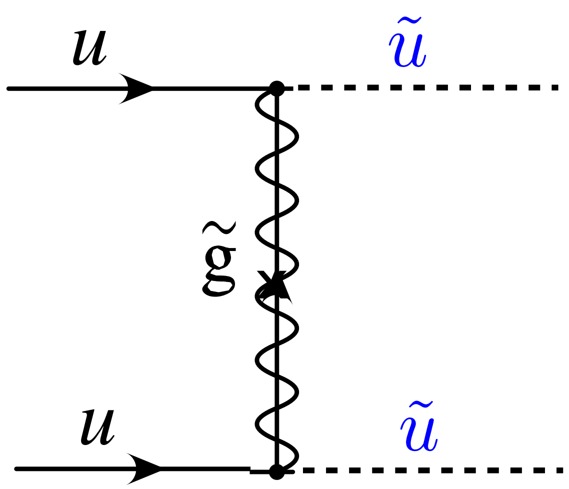


Driven by



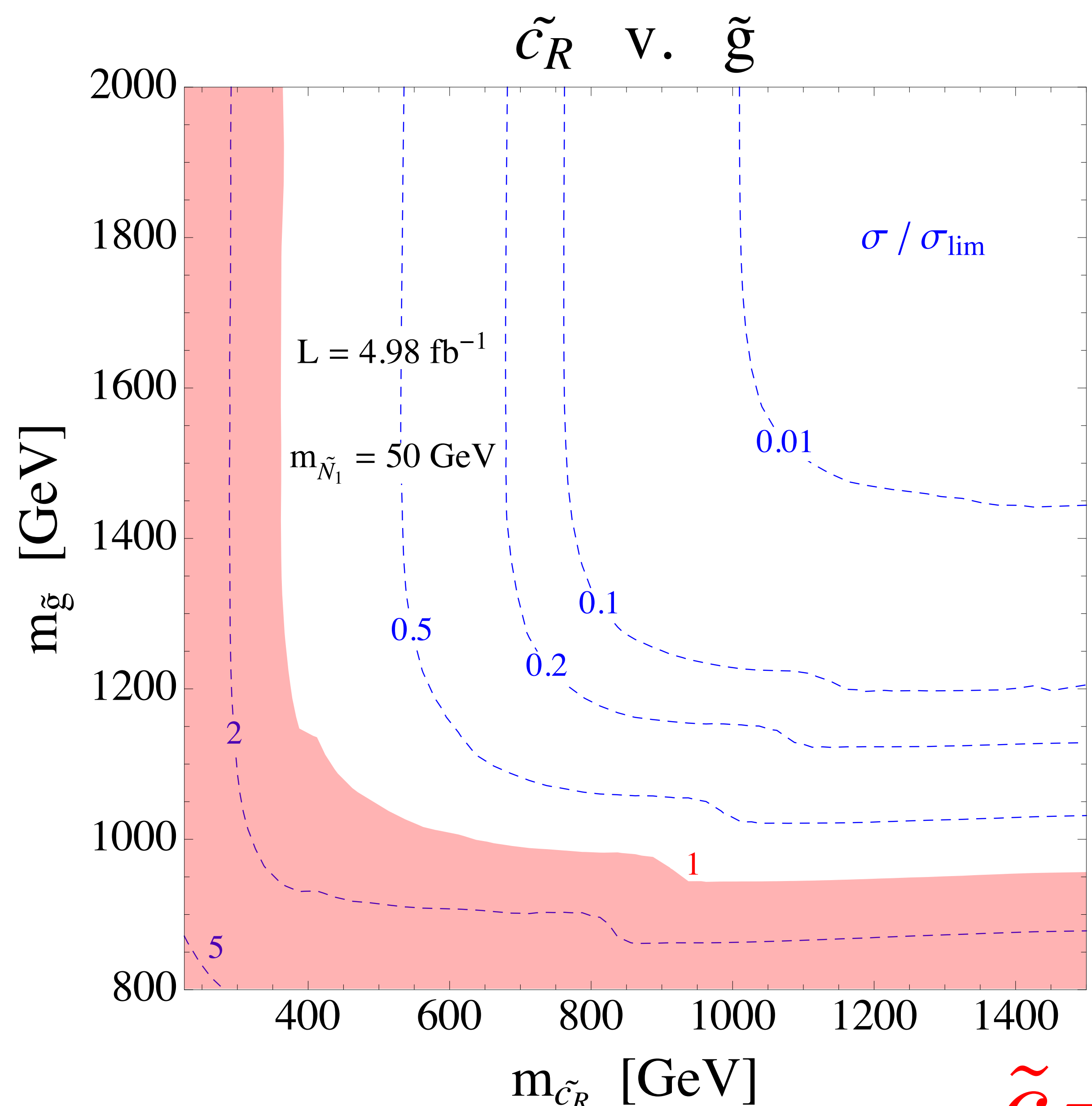
$$\frac{1}{m_{\tilde{g}}}\tilde{q}\tilde{q}\,u_R u_R$$ dim5-op.

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

slow decoupling

Single Sflavor vs. Gluino

Papucci, Ruderman, Perez, Mahbubani, AW, PRL



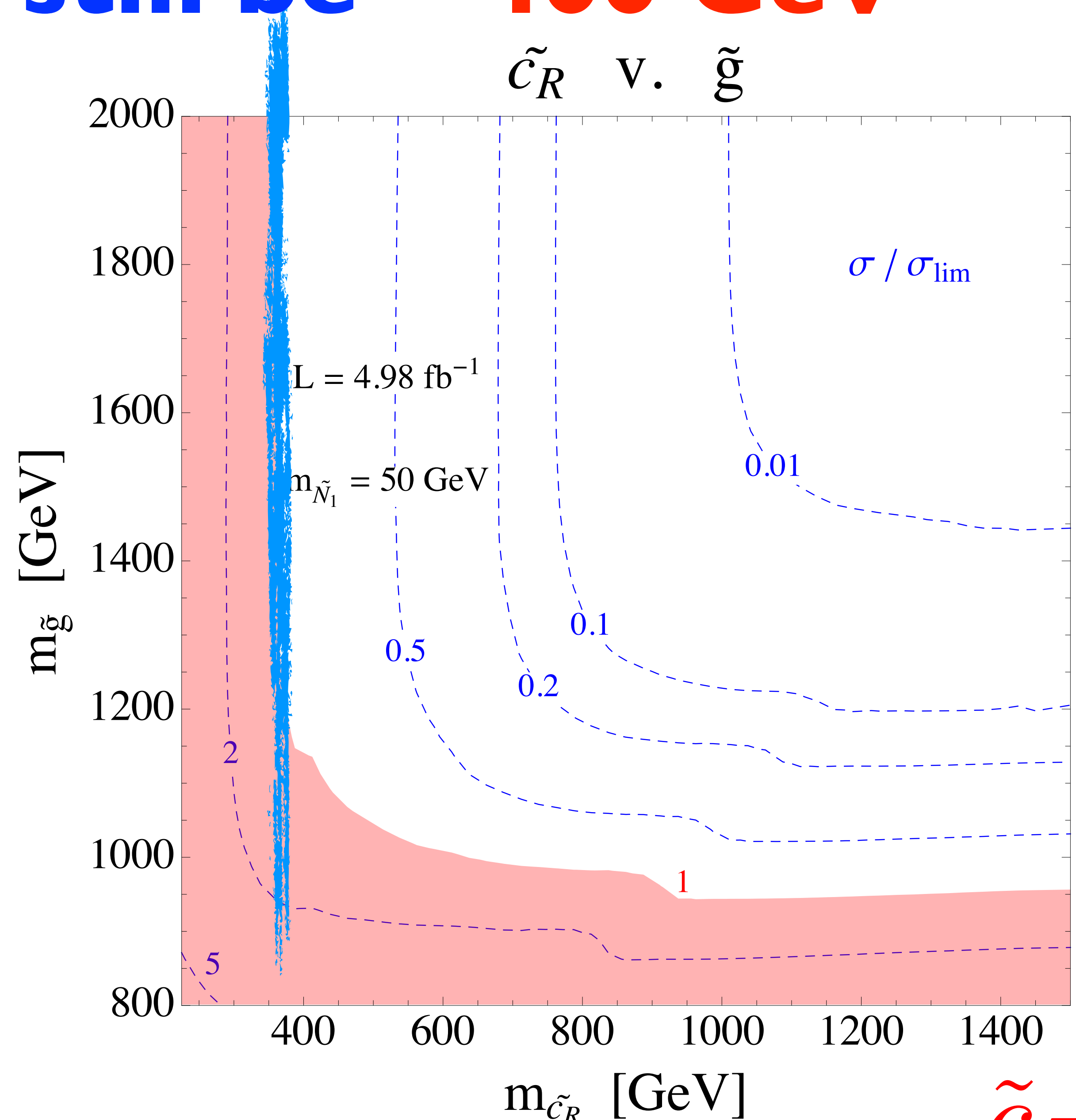
$\tilde{c}_R$

$m_{\rm LSP} = 50\,{\rm GeV}$

Single Sflavor vs. Gluino

Papucci, Ruderman, Perez, Mahbubani, AW, PRL

Sea squarks can still be ~ 400 GeV

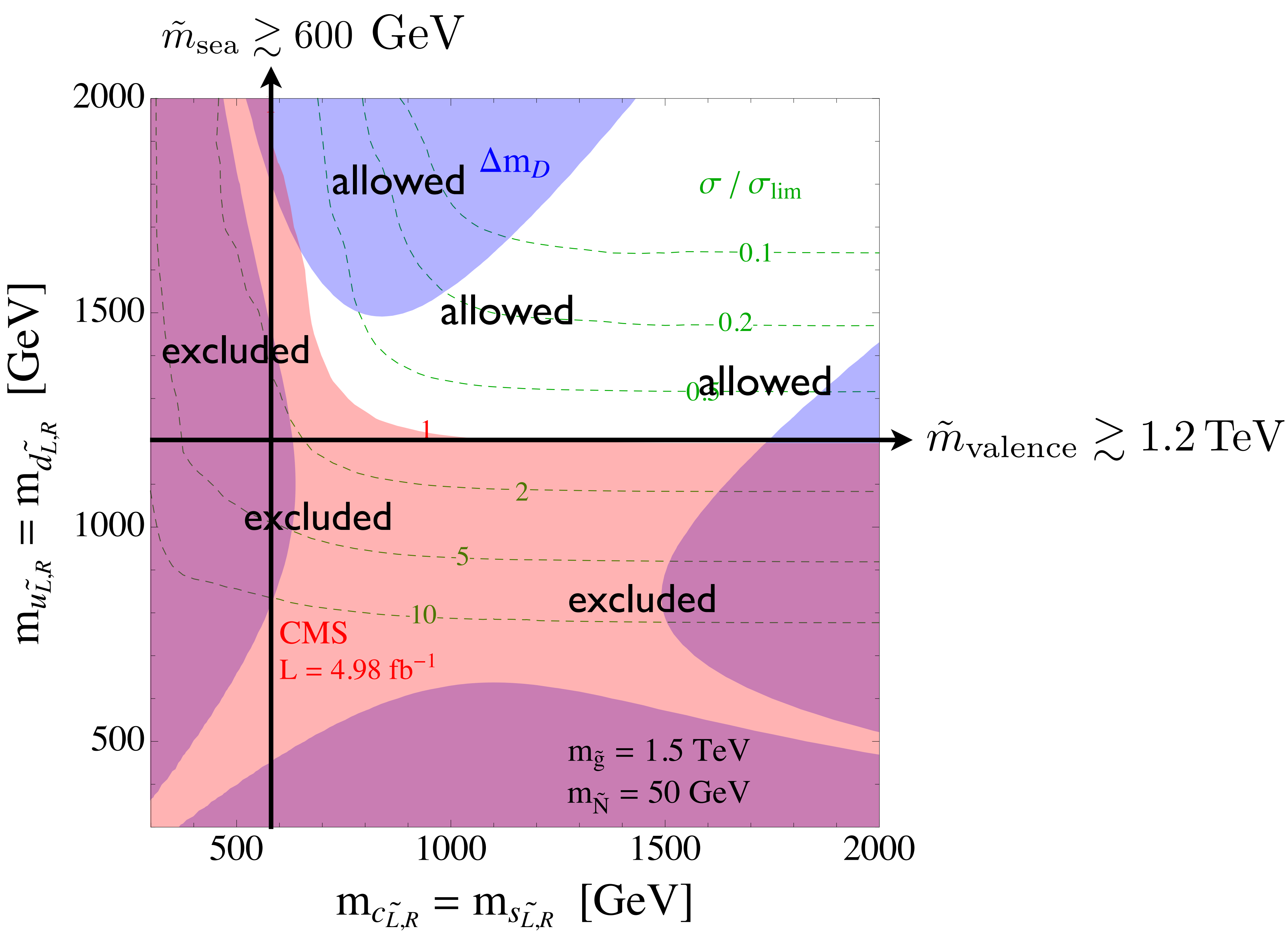


$\tilde{c}_R$

$m_{\rm LSP} = 50\,{\rm GeV}$

All 4 ‘sea’-squarks can be light

sea vs. valence



Mahbubani, Papucci, GP, Ruderman & Weiler (12).

In absence of discoveries,
need to make full use of LHC measurements,
need to ensure we have as large coverage as possible

FastLim

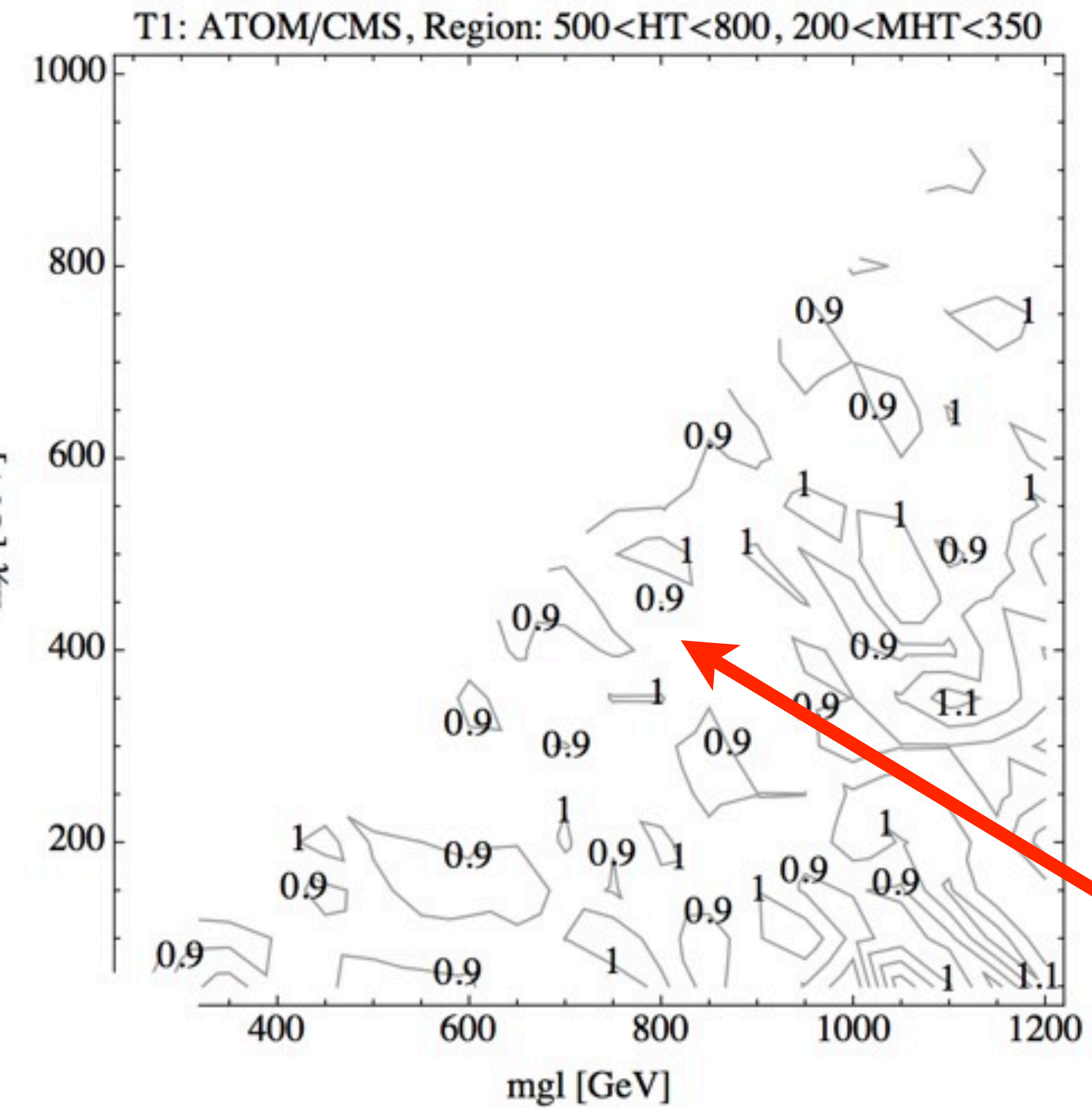
Sakurai, Papucci (LBNL), AW, Zeune

- Typically takes 2-3h to evaluate one parameter point to check if excluded
- Map to extended simplified model basis, pre-evaluate efficiencies, NLO cross-sections
- Factorize CPU costly evaluation: likelihoods within seconds
- Check coverage of full models

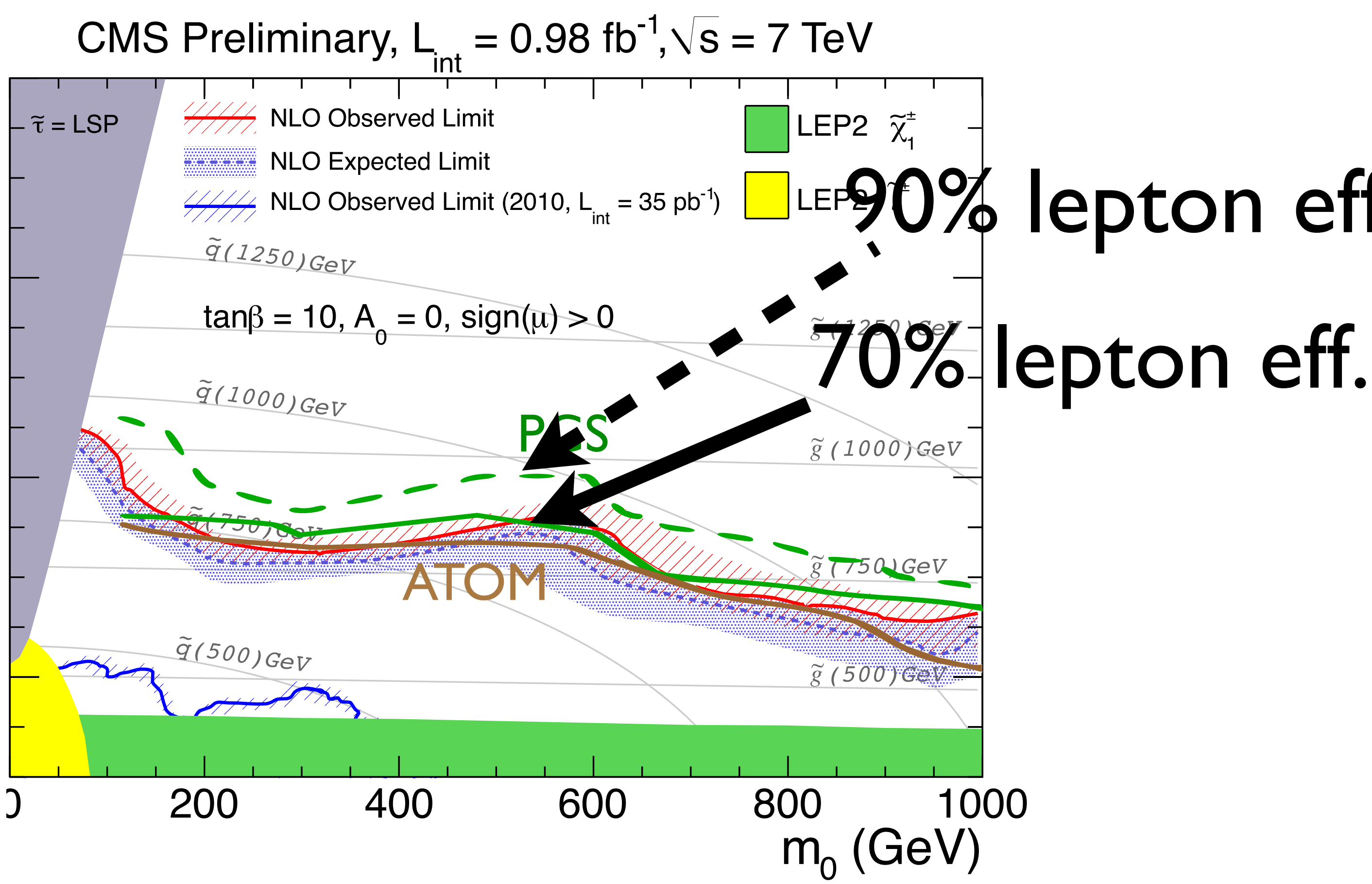
→ see also talk by Lessa/ Waltenberger

Thorough Validation

Gluino simplified model



Same-Sign dilepton CMS

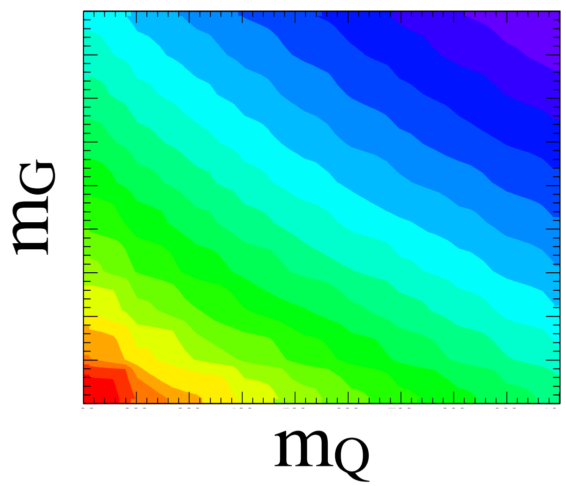


ratio of ATOM/CMS efficiencies

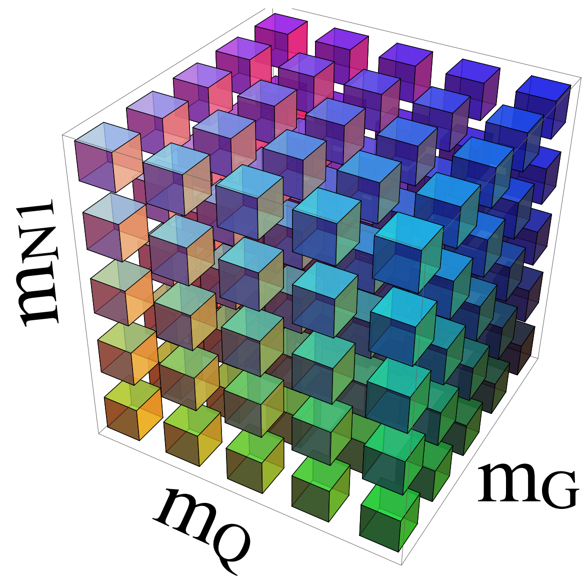
FastLim

Xsec

$\sigma_{QQ}, \sigma_{GG}, \sigma_{QG}$



$\epsilon^{(i)}_{\mathrm{proc}(a)}$



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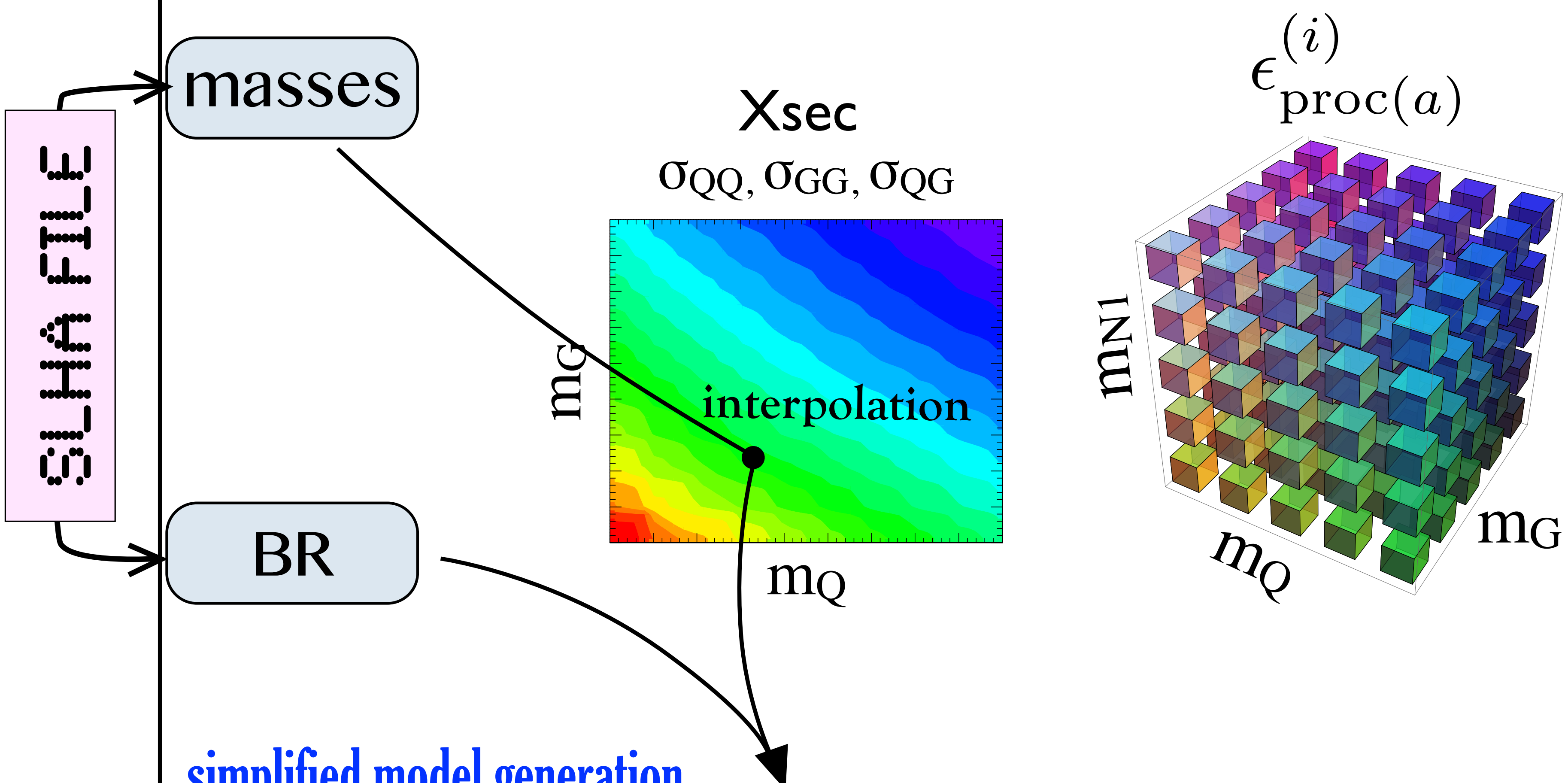
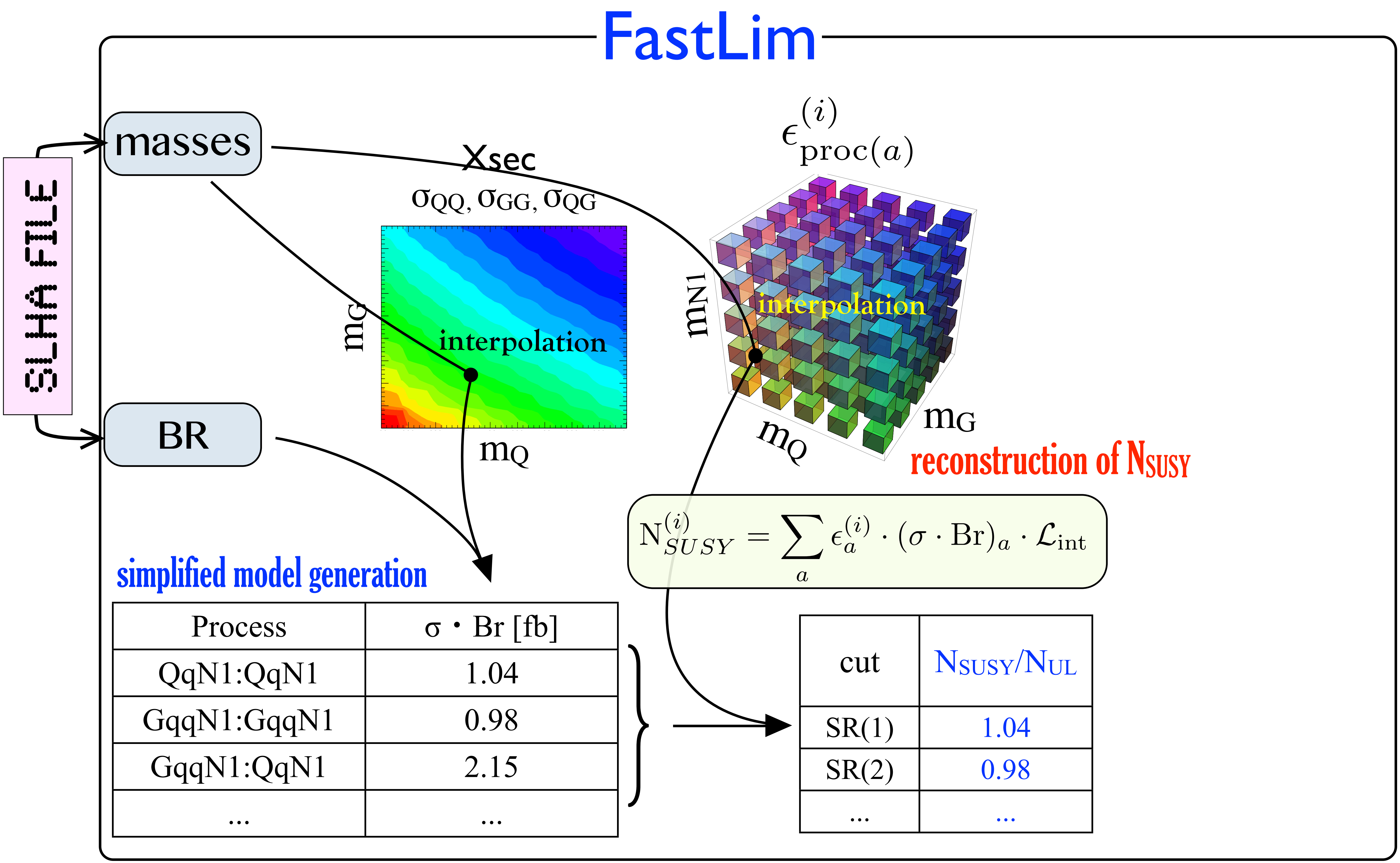
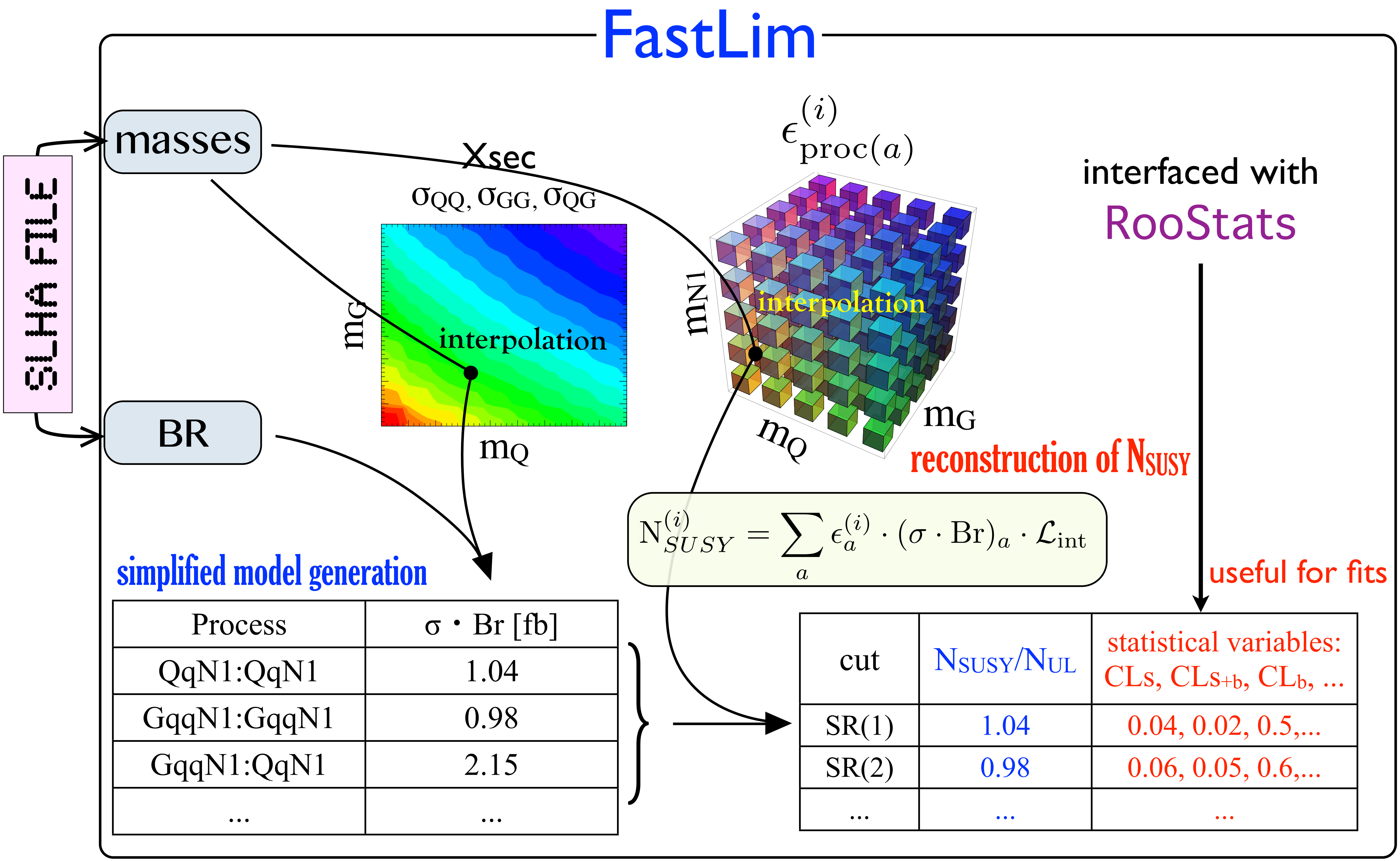


simplified model generation

Process	σ • Br [fb]
QqN1:QqN1	1.04
GqqN1:GqqN1	0.98
GqqN1:QqN1	2.15
...	...


FastLim
SLHA FILE
masses
BR
Xsec
σQQ, σGG, σQG
mG
mQ
interpolation
$\epsilon^{(i)}_{\mathrm{proc}(a)}$
mN1
interpolation
mG
mQ
reconstruction of NSUSY
$\mathrm{N}^{(i)}_{SUSY} = \sum_a \epsilon^{(i)}_a \cdot (\sigma \cdot \mathrm{Br})_a \cdot \mathcal{L}_{\mathrm{int}}$
simplified model generation
Process | σ · Br [fb]
QqN1:QqN1 | 1.04
GqqN1:GqqN1 | 0.98
GqqN1:QqN1 | 2.15
... | ...
cut | NSUSY/NUL
SR(1) | 1.04
SR(2) | 0.98
... | ...


FastLim
SLHA FILE
masses
BR
Xsec
$\sigma_{QQ}, \sigma_{GG}, \sigma_{QG}$
m_G
m_Q
interpolation
$\epsilon^{(i)}_{\mathrm{proc}(a)}$
m_{N1}
interpolation
m_G
m_Q
reconstruction of N_{SUSY}
interfaced with
RooStats
$N^{(i)}_{SUSY} = \sum_a \epsilon^{(i)}_a \cdot (\sigma \cdot \mathrm{Br})_a \cdot \mathcal{L}_{\mathrm{int}}$
useful for fits
simplified model generation
Process | σ · Br [fb]
QqN1:QqN1 | 1.04
GqqN1:GqqN1 | 0.98
GqqN1:QqN1 | 2.15
... | ...
cut | N_{SUSY}/N_{UL} | statistical variables: CLs, CLs+b, CLb, ...
SR(1) | 1.04 | 0.04, 0.02, 0.5,...
SR(2) | 0.98 | 0.06, 0.05, 0.6,...
... | ... | ...

simplified processes

your favourite models

Kazuki's joke

Conclusions

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

LHC_{14} will be decisive:
2 x energy, sensitive to 4 x tuning

Many non-lamppost signatures still to be explored

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

LPCC

LHC Physics Centre at CERN

LPCC simplified models coordination workshop

Oct 29th / 30th 2013 @ CERN

There are at least 4 – 5 pheno groups working with simplified models results. In this LPCC workshop we want to start to loosely coordinate the effort between the different pheno groups. One common vision is to provide interoperability between SMS interpretation building blocks.