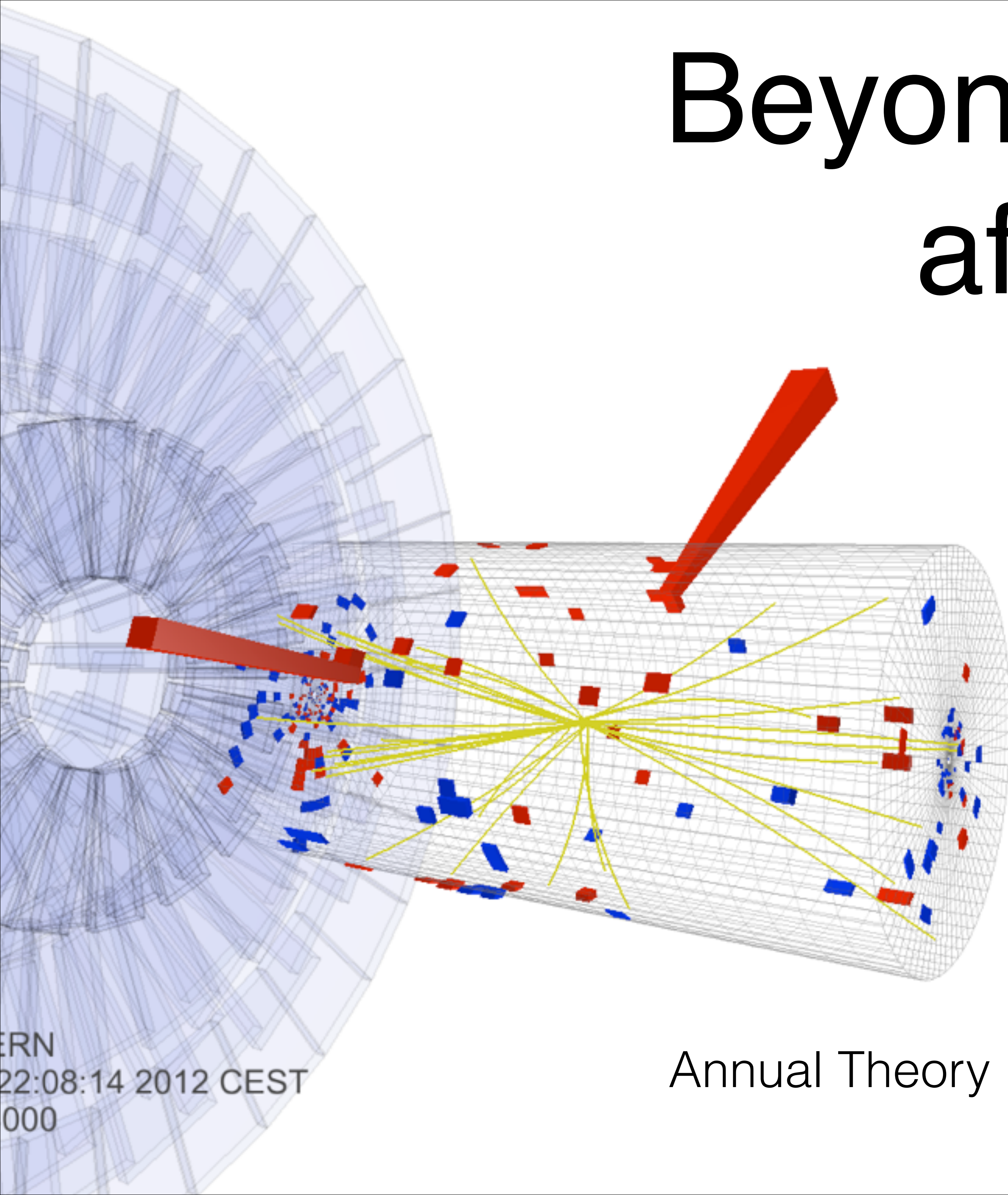
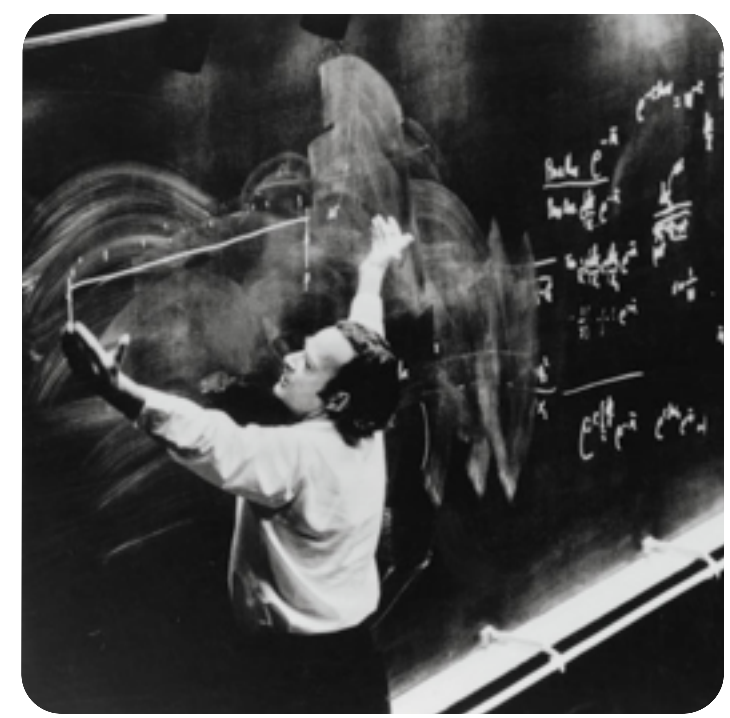
Beyond the SM after LHC8



Andreas Weiler
(DESY&CERN)



Annual Theory Meeting, IPPP Durham
2013/12/16

"I do not mean to say that all these anticipations will withstand the test of experiment on the day such a test would become possible. Since he seeks in all directions one must, on the contrary, expect most of the trails which he pursues to be blind alleys.

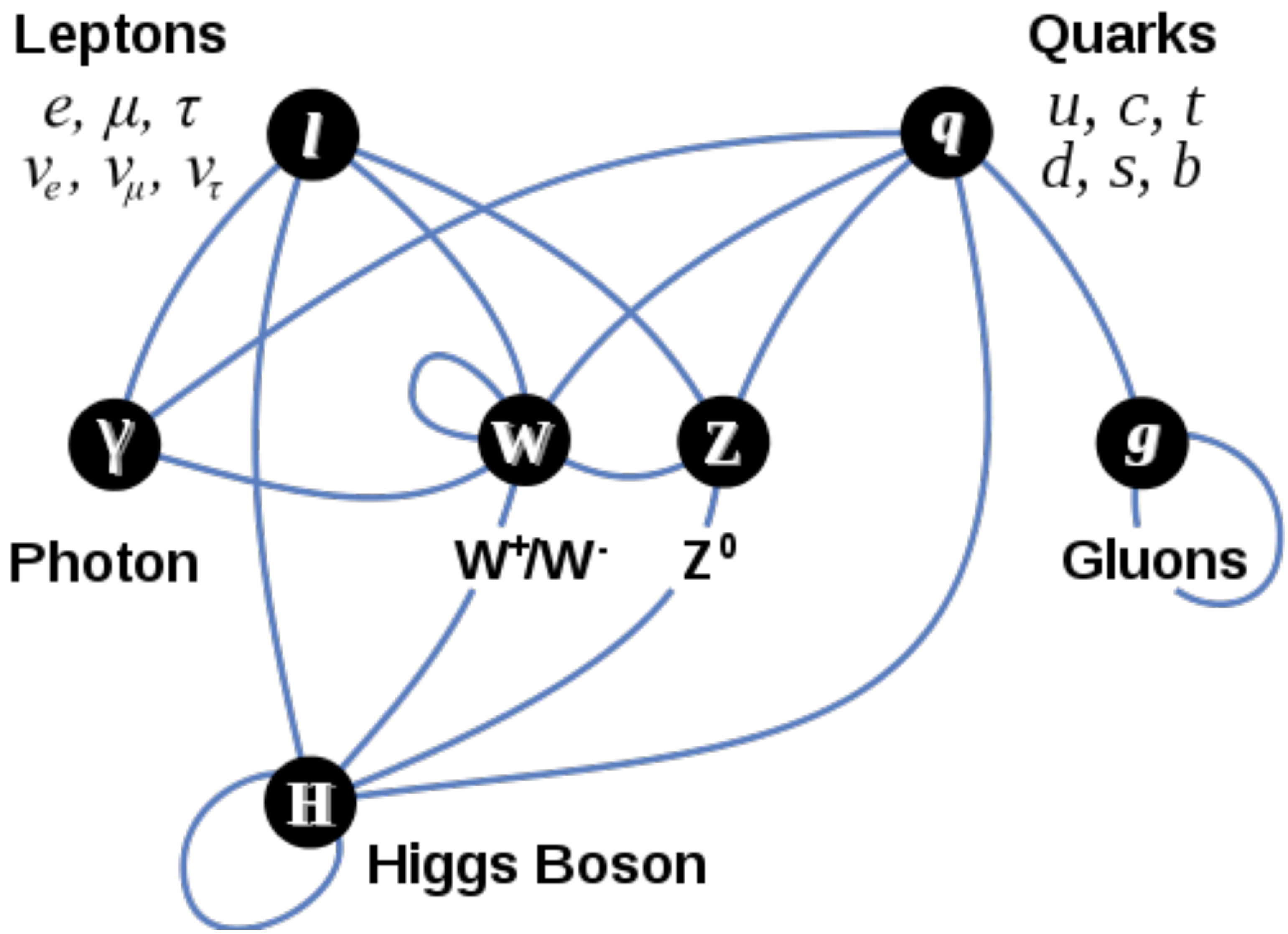
…

–Henri Poincaré's letter of recommendation for A. Einstein, 1911

But one must hope at the same time that one of the directions he has indicated may be the right one, and that is enough. This is indeed how one should proceed. The role of mathematical physics is to ask the right questions, and experiment alone can resolve them. ”

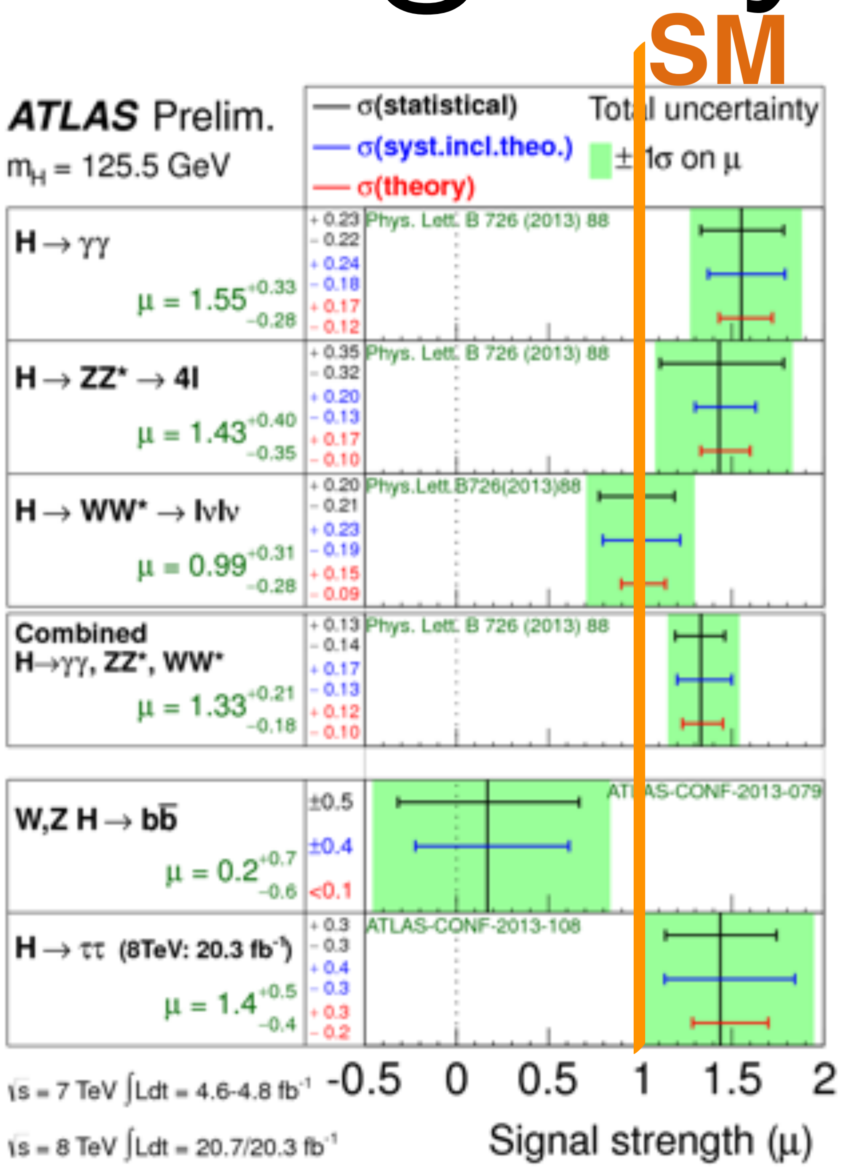
–Henri Poincaré’s letter of recommendation for A. Einstein, 1911

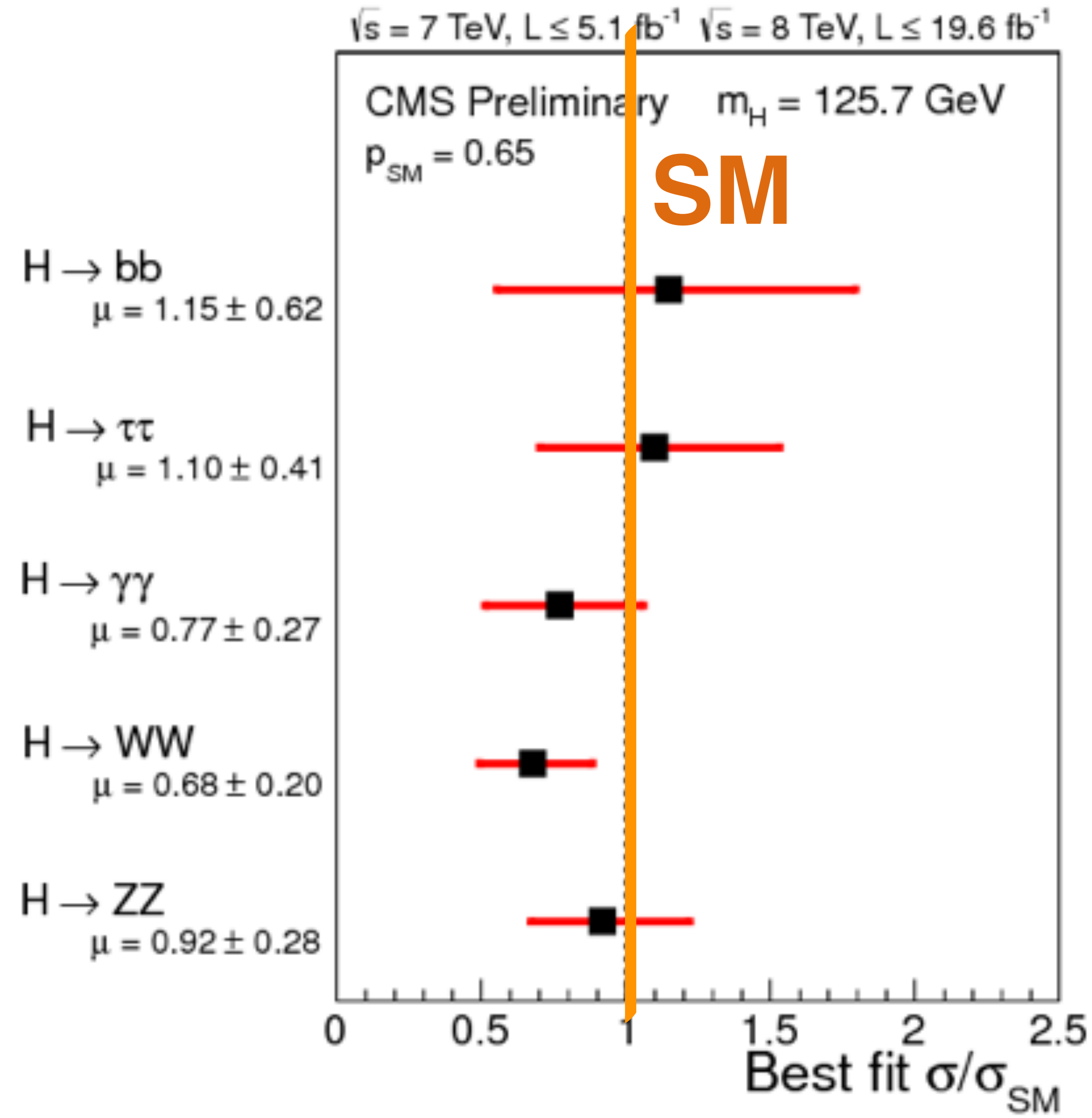
The SM



Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
Quarks
u, c, t
d, s, b
l
q
γ
W
Z
g
Photon
W+/W-
Z0
Gluons
H
Higgs Boson

Legacy of run1 LHC





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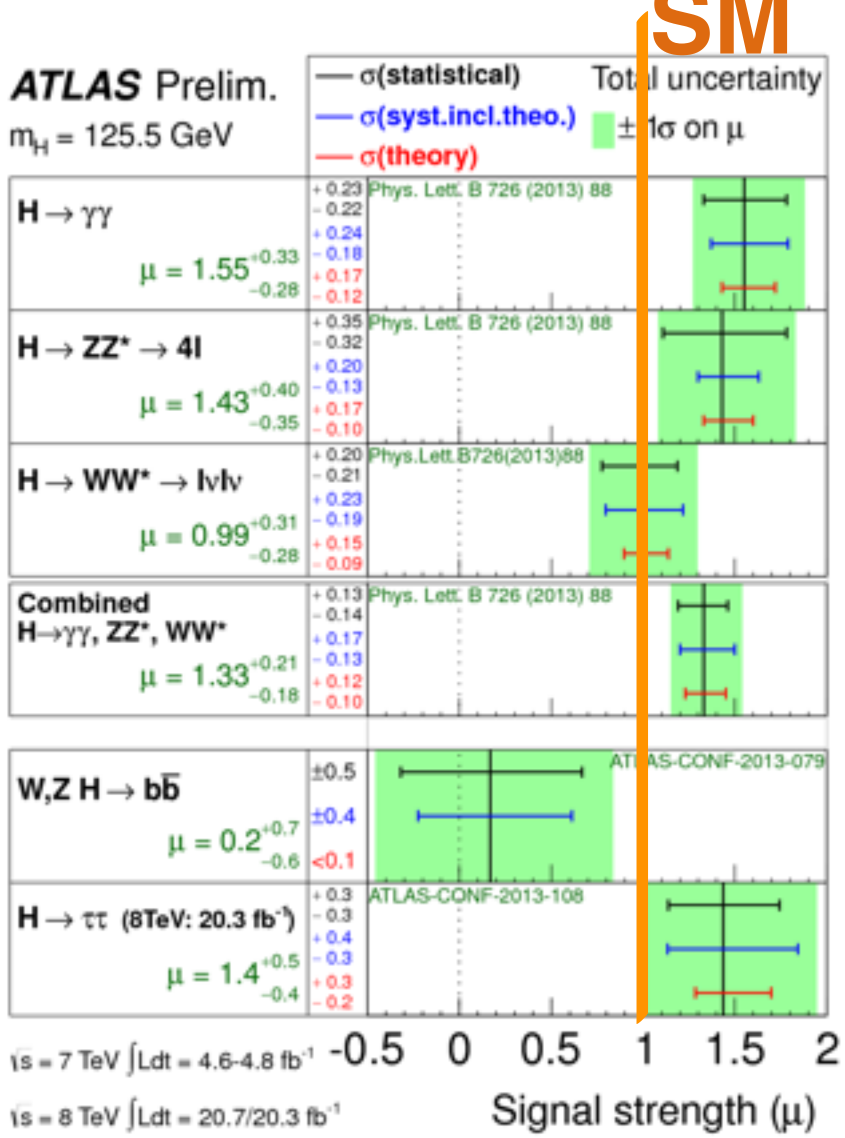
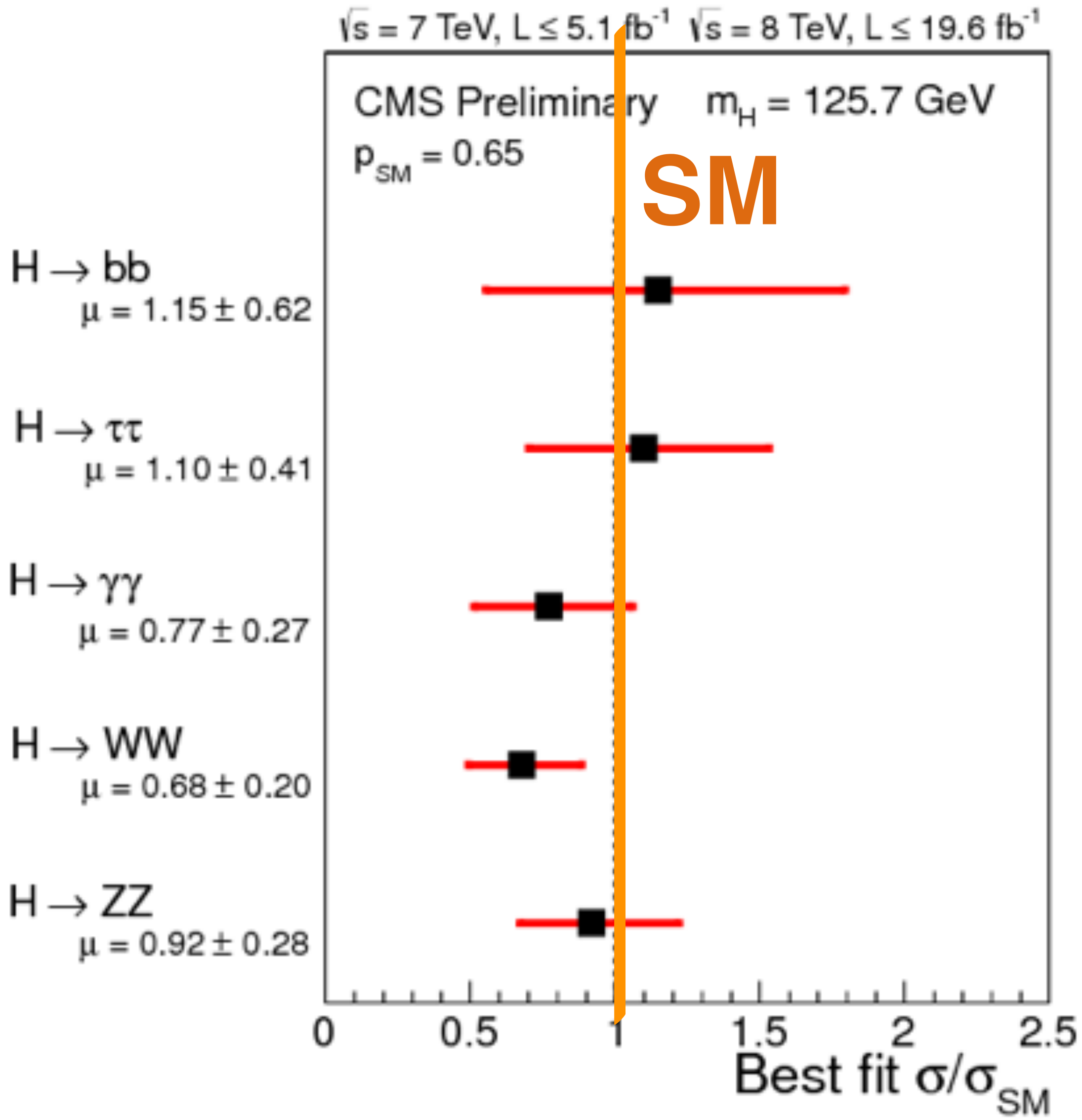
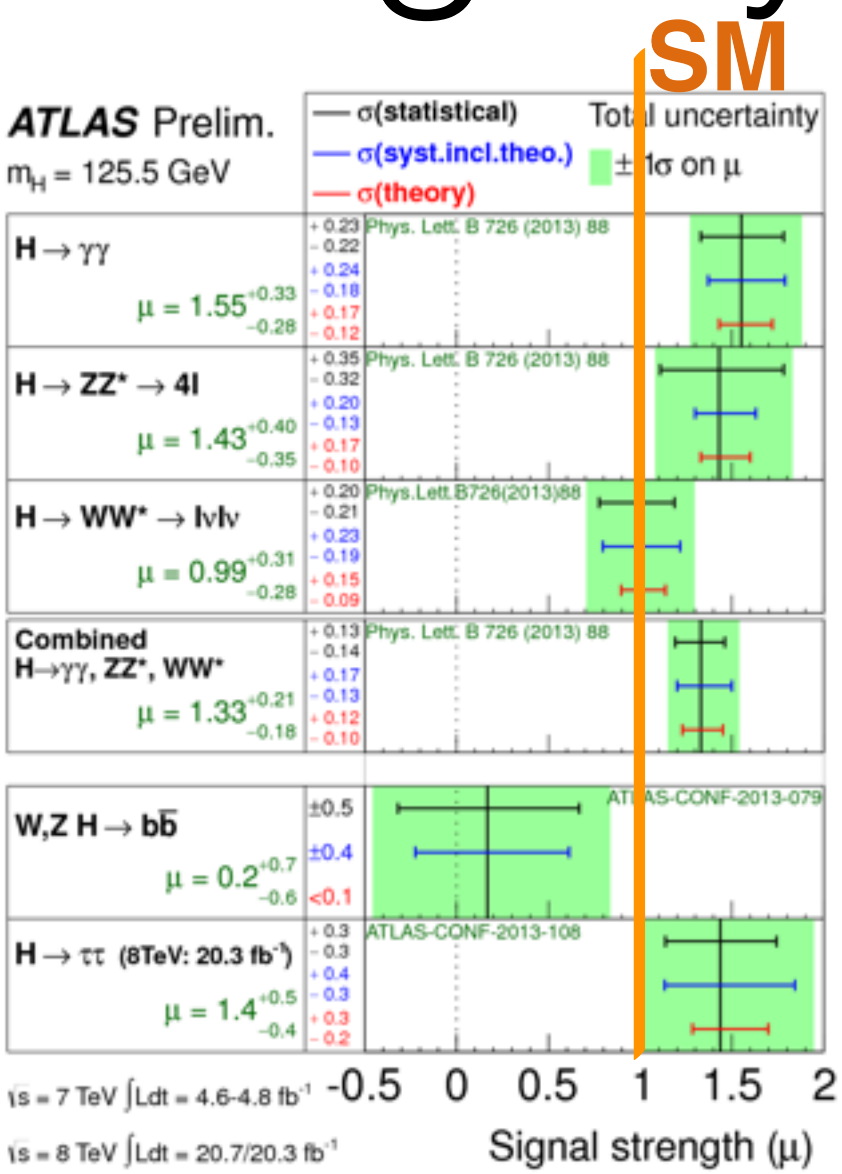
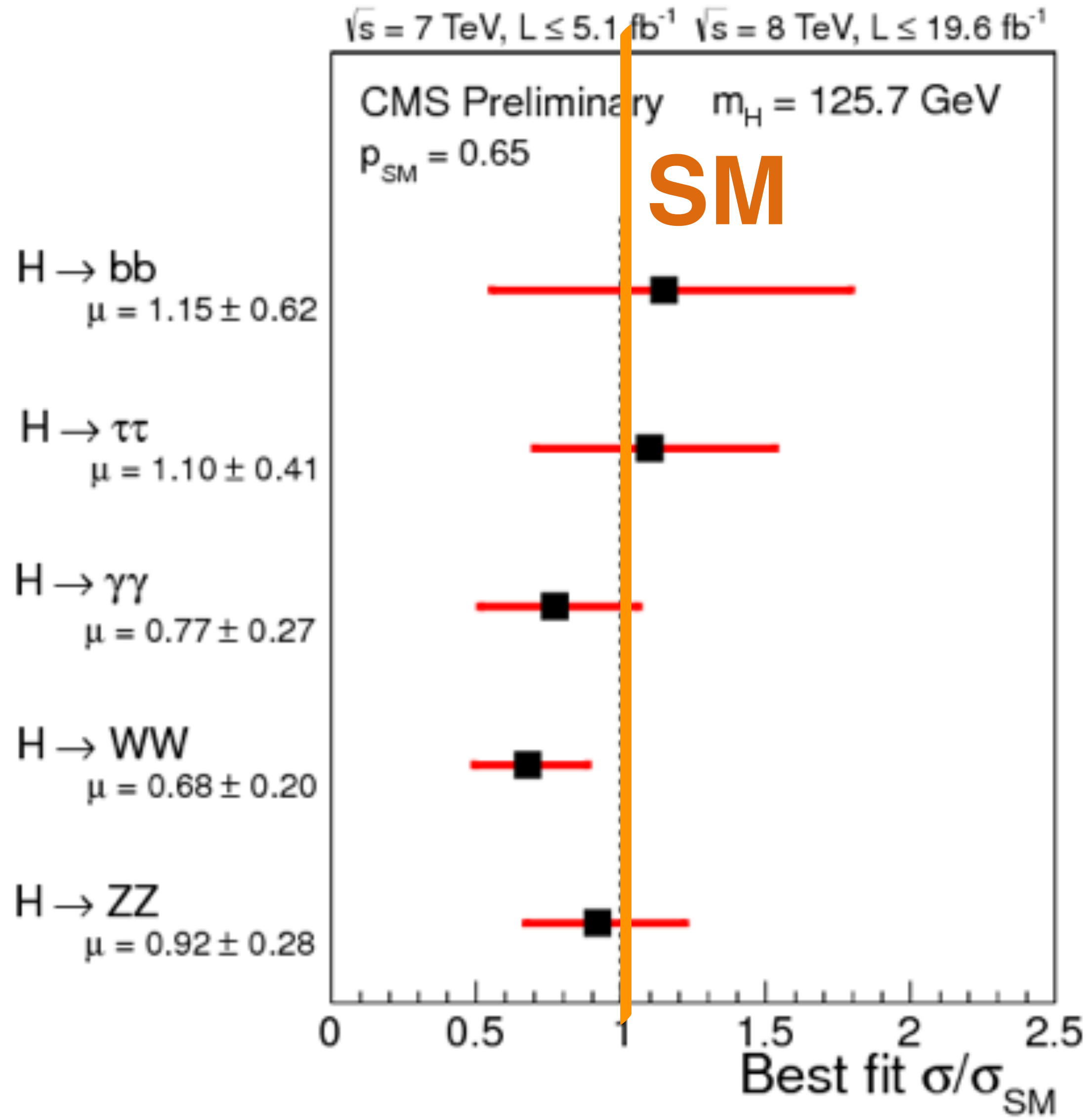




It is the Higgs!

Legacy of run1 LHC

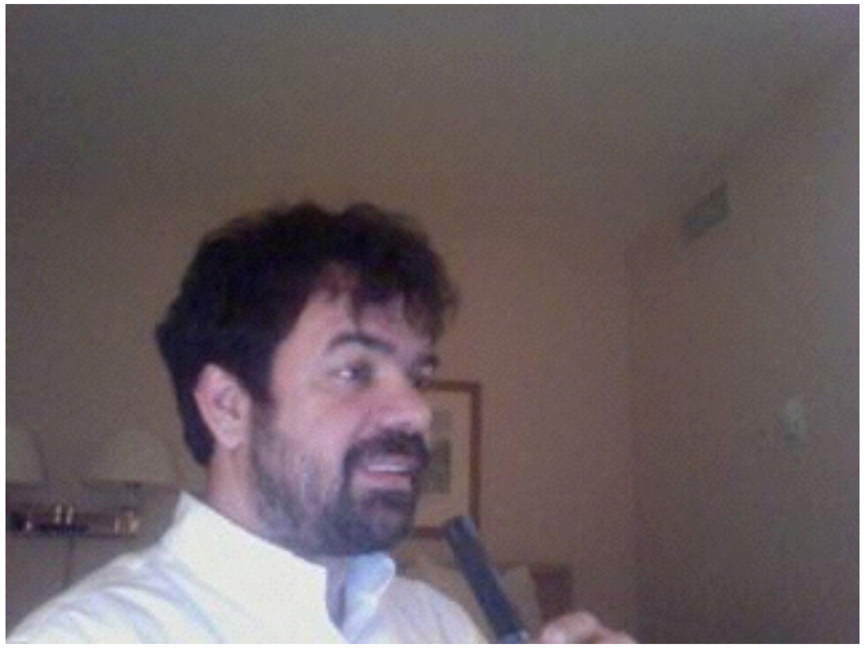




It is the Higgs!

Nobel certified™

Which one is the Brout impostor?



The SM


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

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fermion masses & mixings

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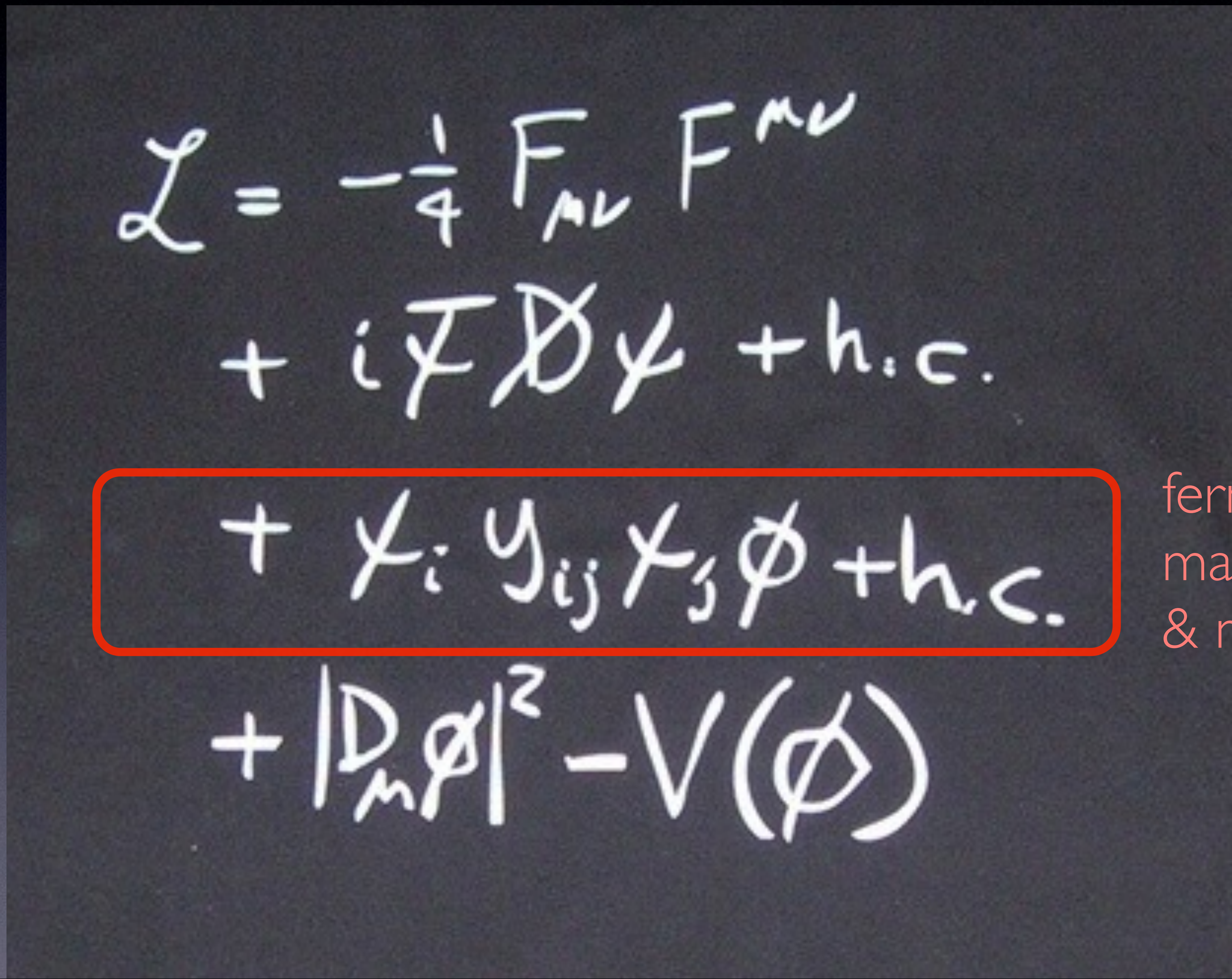
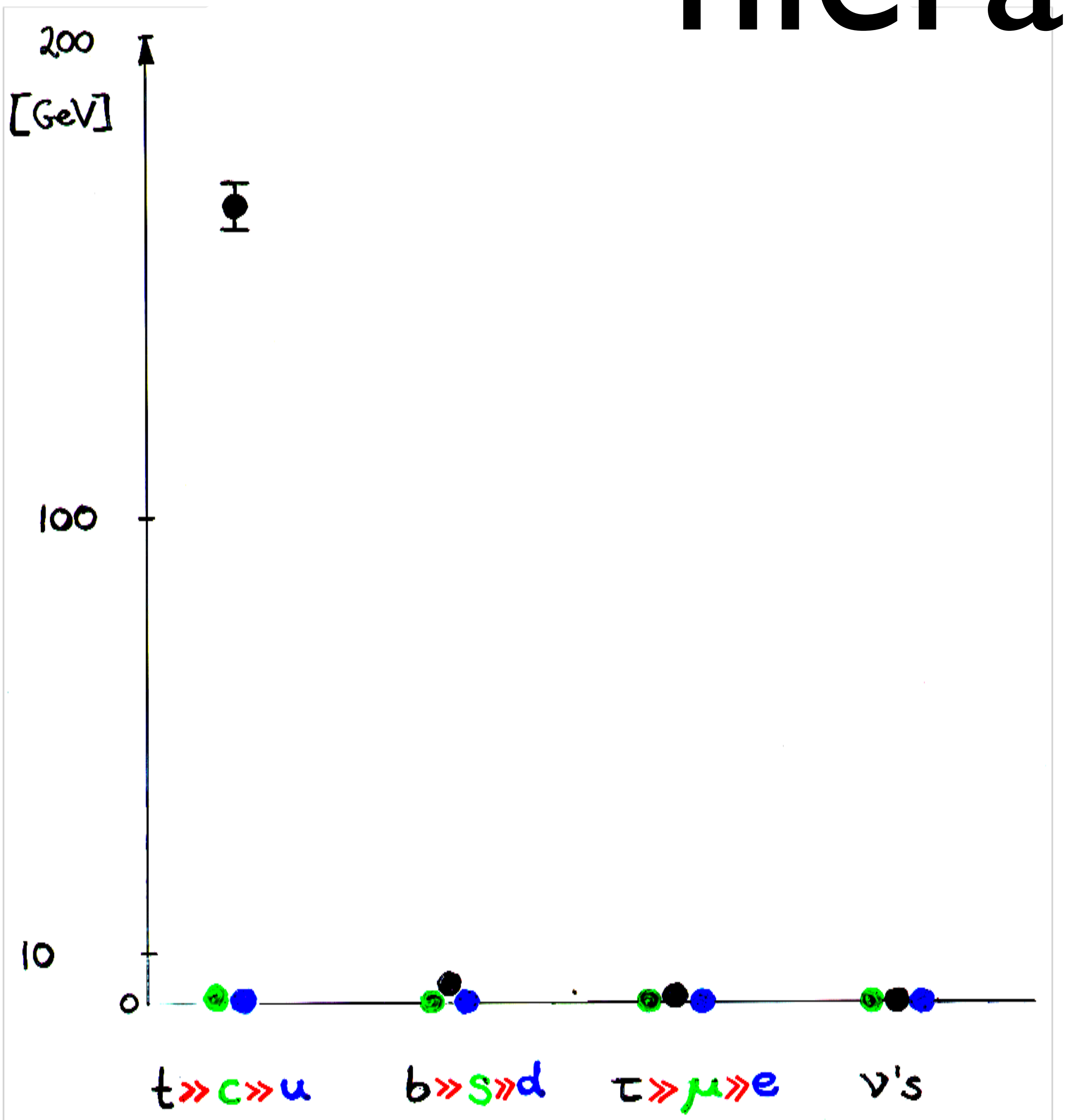
Higgs potential

The SM

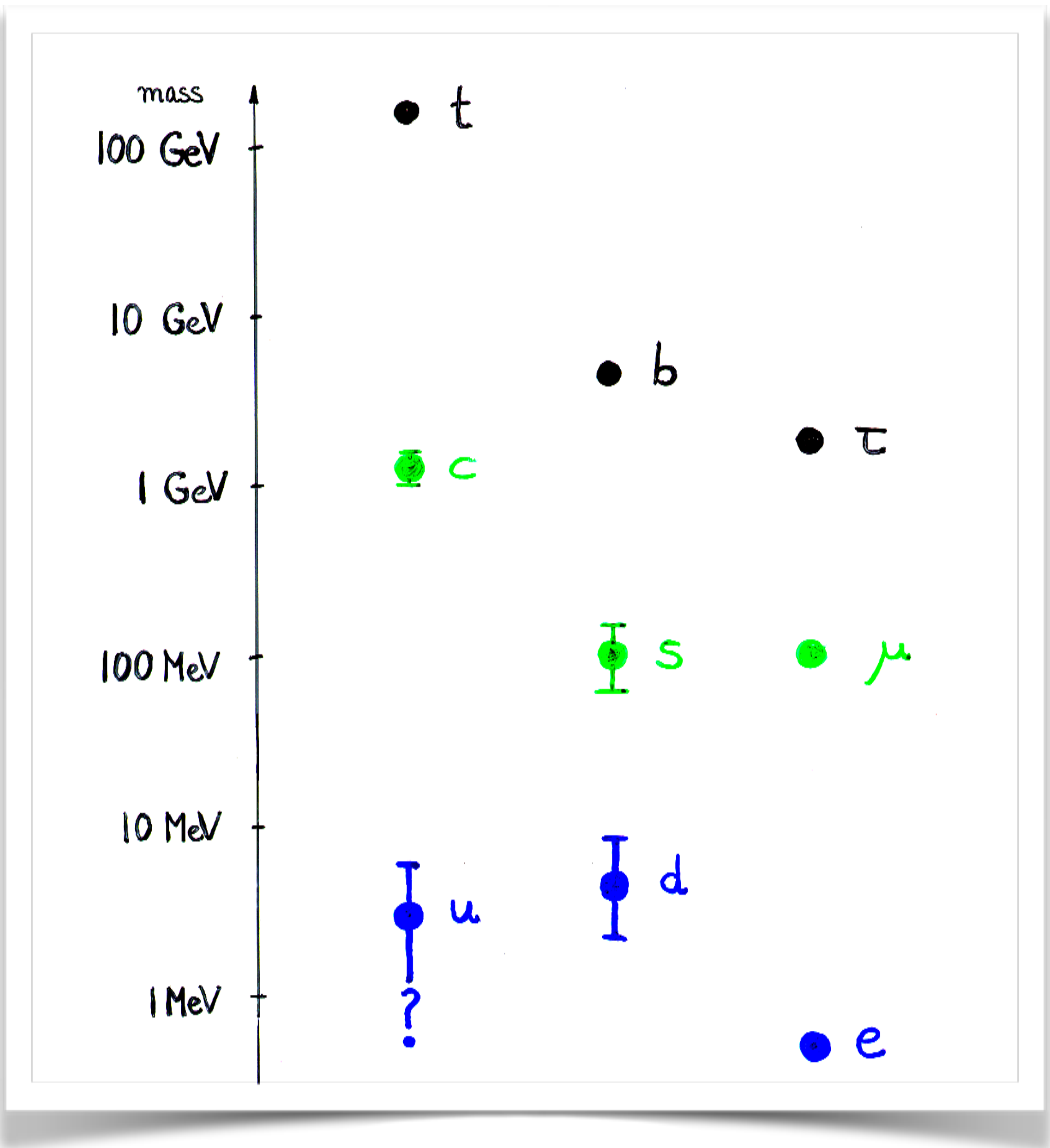


fermion
masses
& mixings

Quark and lepton mass hierarchy



Masses on a log scale



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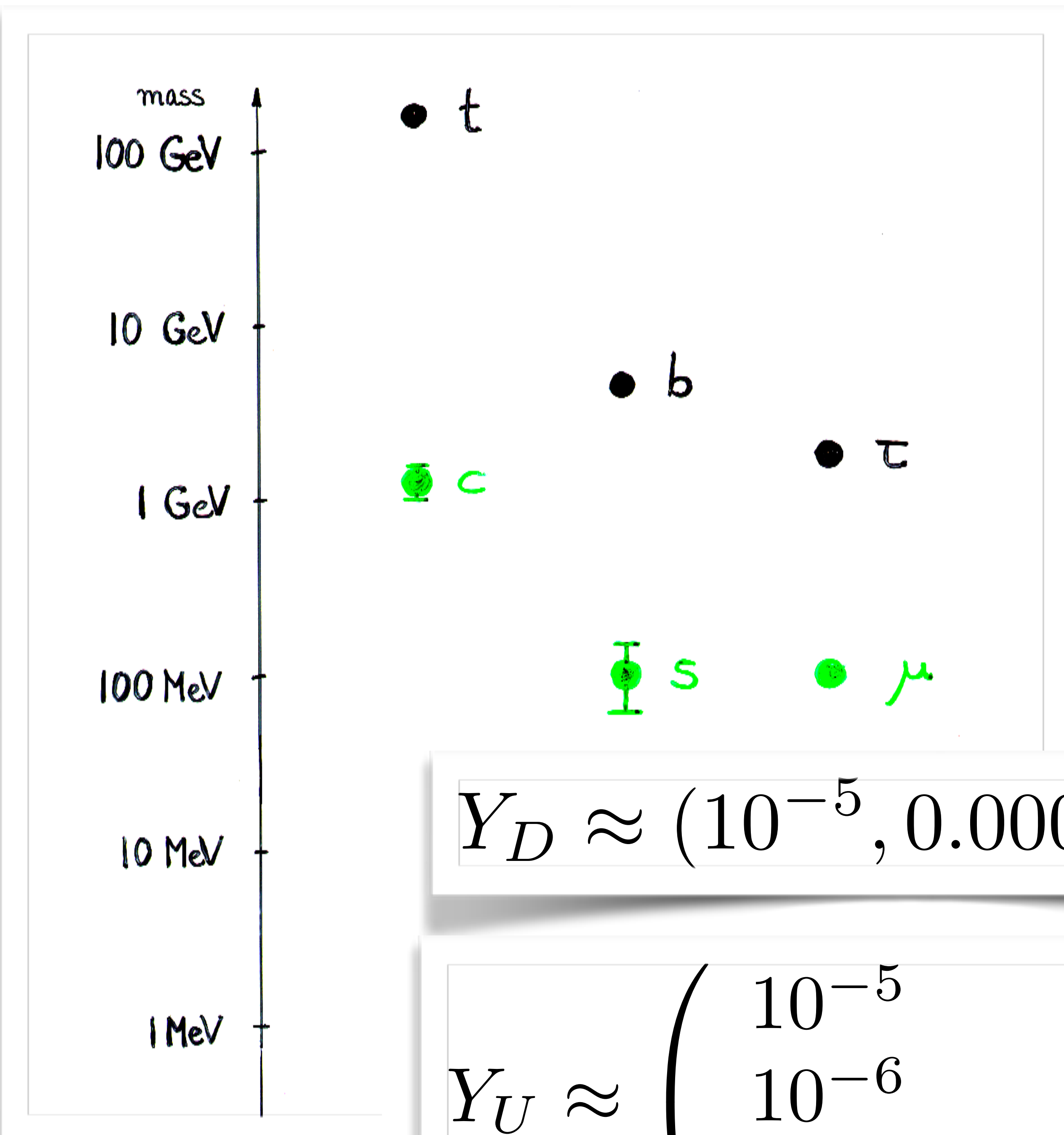

$$\mathcal{L}_{\text{Yuk}} = [Y^U]_{ij}\,\bar{Q}_i H_c u_j + \dots$$

$$Y_D \approx (10^{-5}, 0.0005, 0.026)$$

$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$

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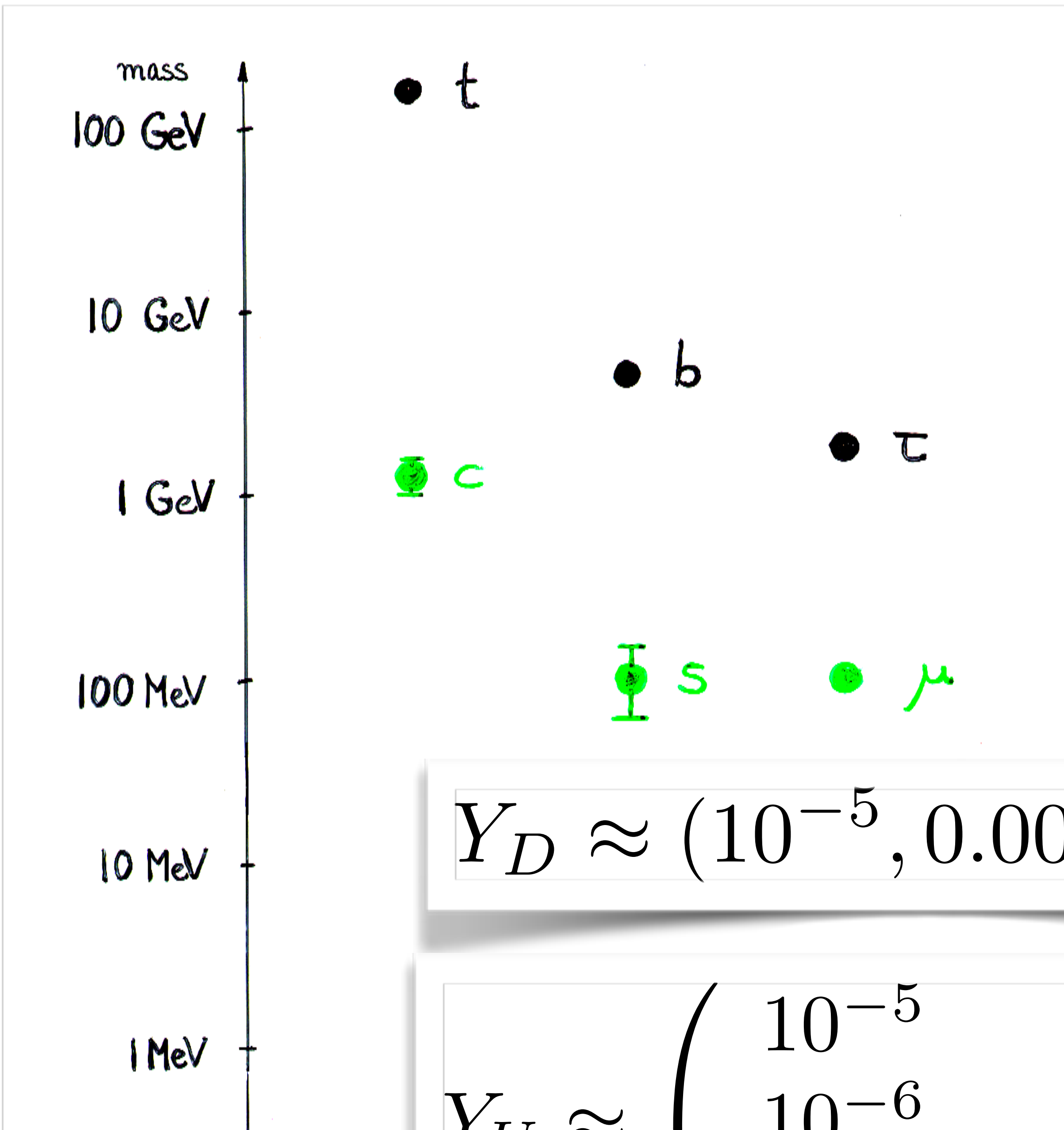

Compare to: $g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{\text{Higgs}} \sim 1/8$

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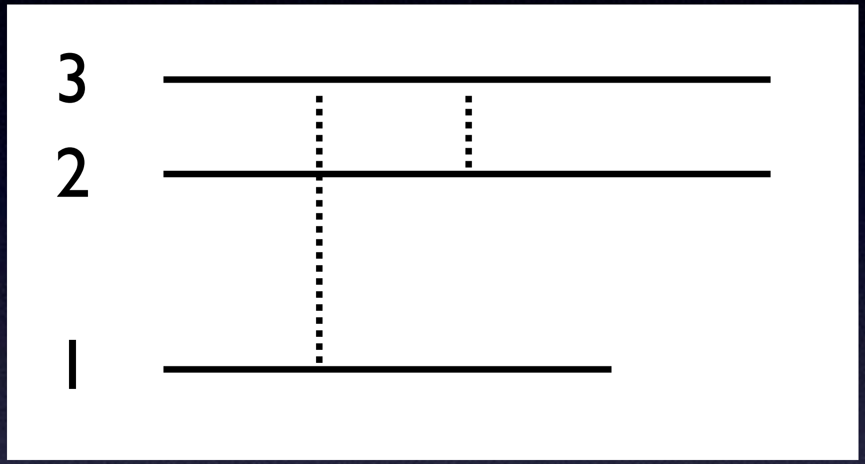
Analog to mysterious spectral lines before QM



$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2}\right) R$$

Explained by Bohr

$$E_n = -\frac{2\pi^2 e^4 m_e}{h^2 n^2}$$

Is there an analogue to the Bohr atom, we might discover at the LHC?

Flavor dynamics @ LHC ?

Exciting possibility

TeV? 10^3 TeV? 10^{16} GeV?

1) Lack of scale

$$\mathcal{L}_{\text{flavor}} = [Y^U]_{ij}\, \bar{Q}_i H_c u_j + \ldots$$

dim 0 + 3/2+1+3/2 = 4

2) Very strong constraints from flavor physics:
Generic flavor dynamics >> 100 TeV

Top as a destabilizing agent

Stability and meta-stability

Cabibbo, Maiani, Parisi, Petronzio, '79; Hung '79; Lindner 86; Sher '89; …

Tree-level

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

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Quantum fluctuations change potential

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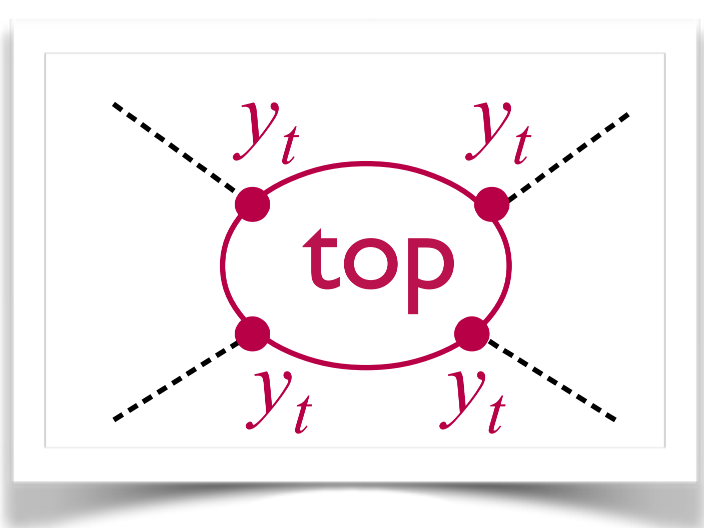
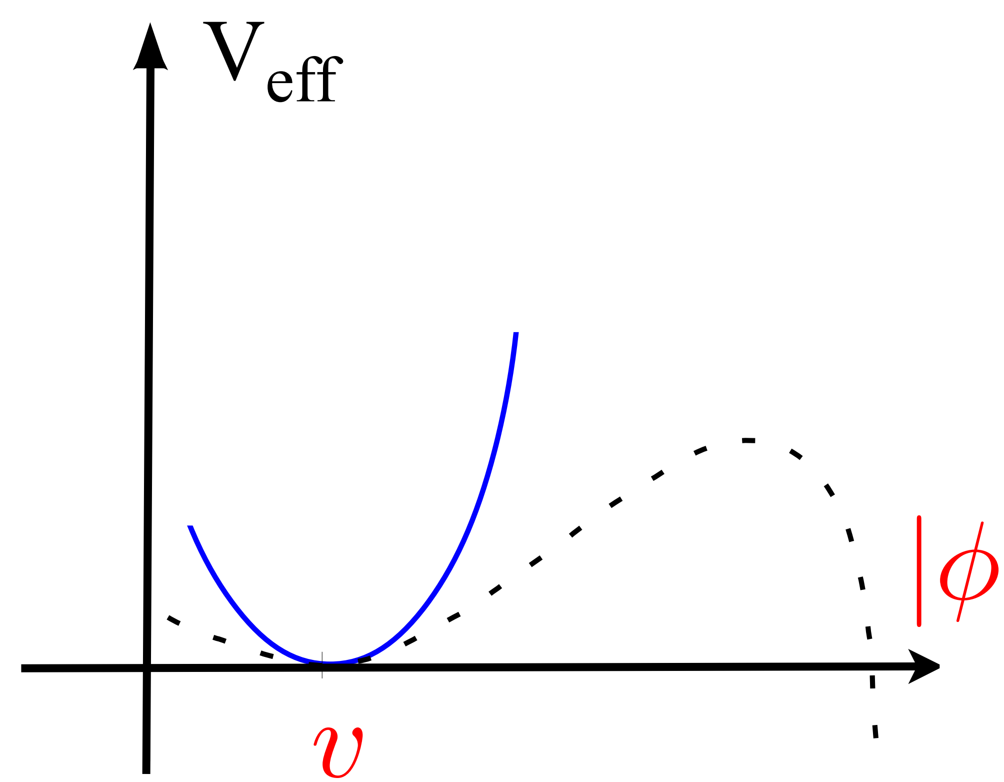


decreasing at large Energies =>



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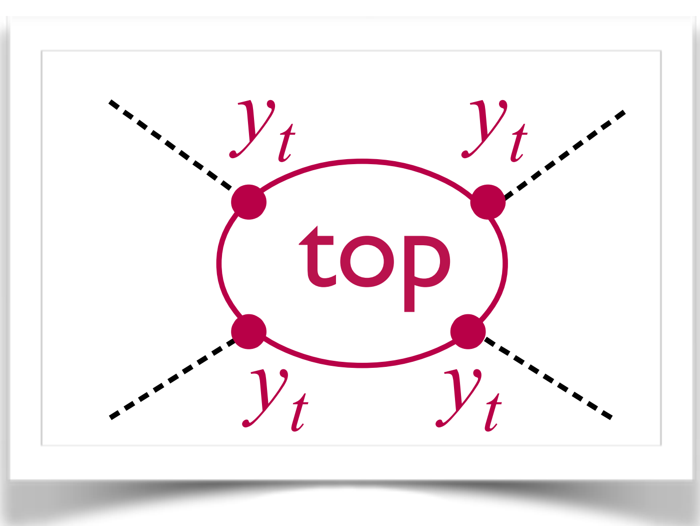

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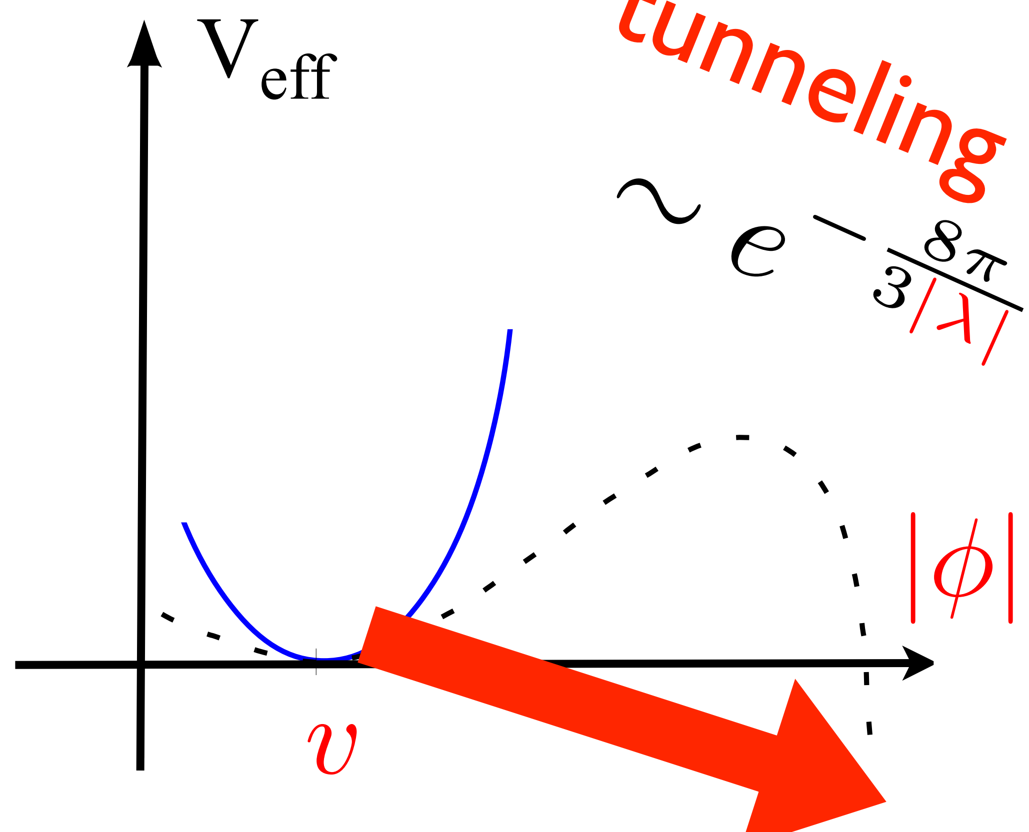
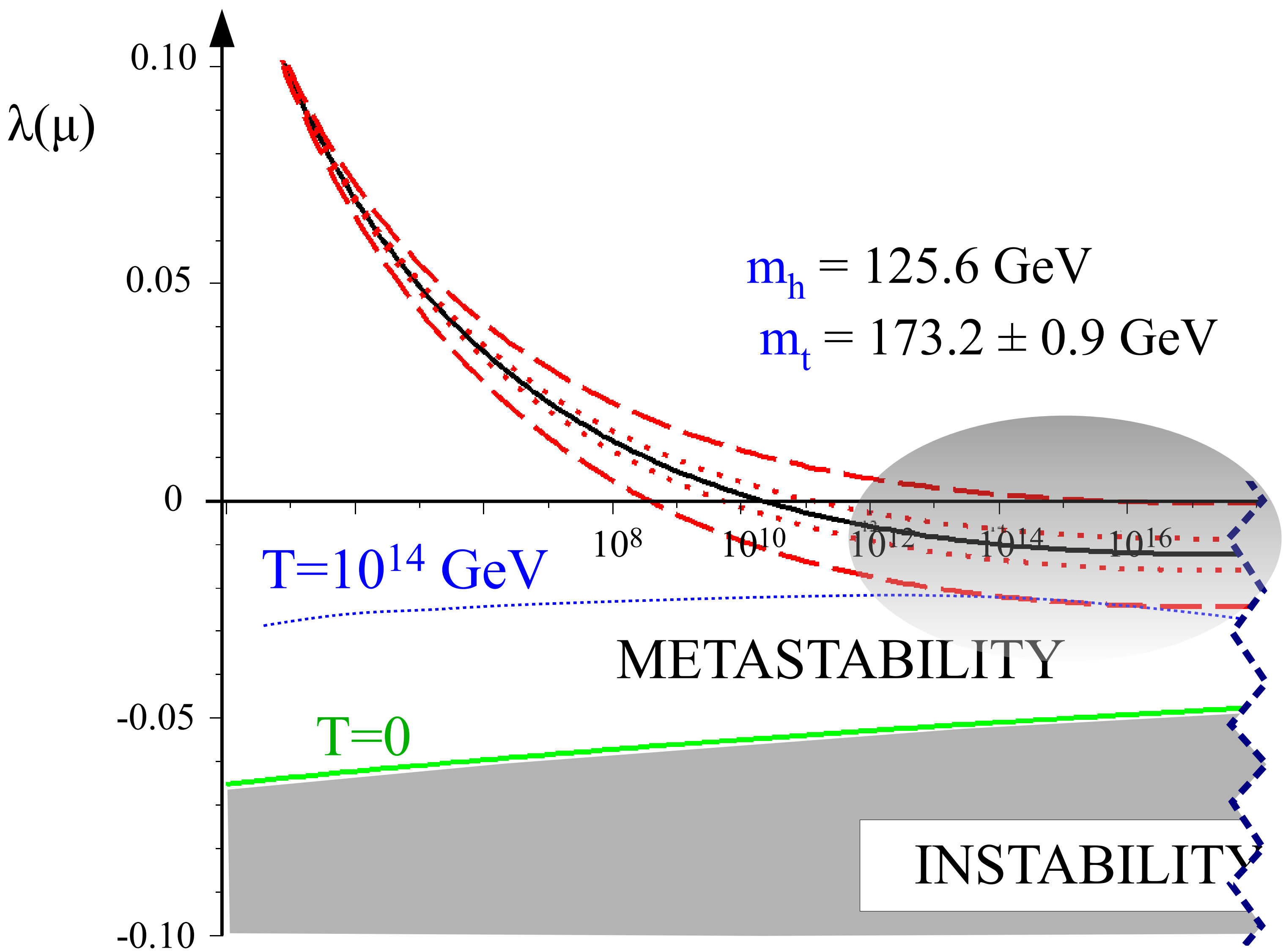


Stability and meta-stability

SM vacuum is unstable but sufficiently long-lived,
(depends on m_{top}, m_{Higgs})

cf Elias-Miro et al. '12
Degrassi et al. '12
Buttazzo et al. '12



Unlikely the full story, assumes nothing but SM up to the Planck scale …

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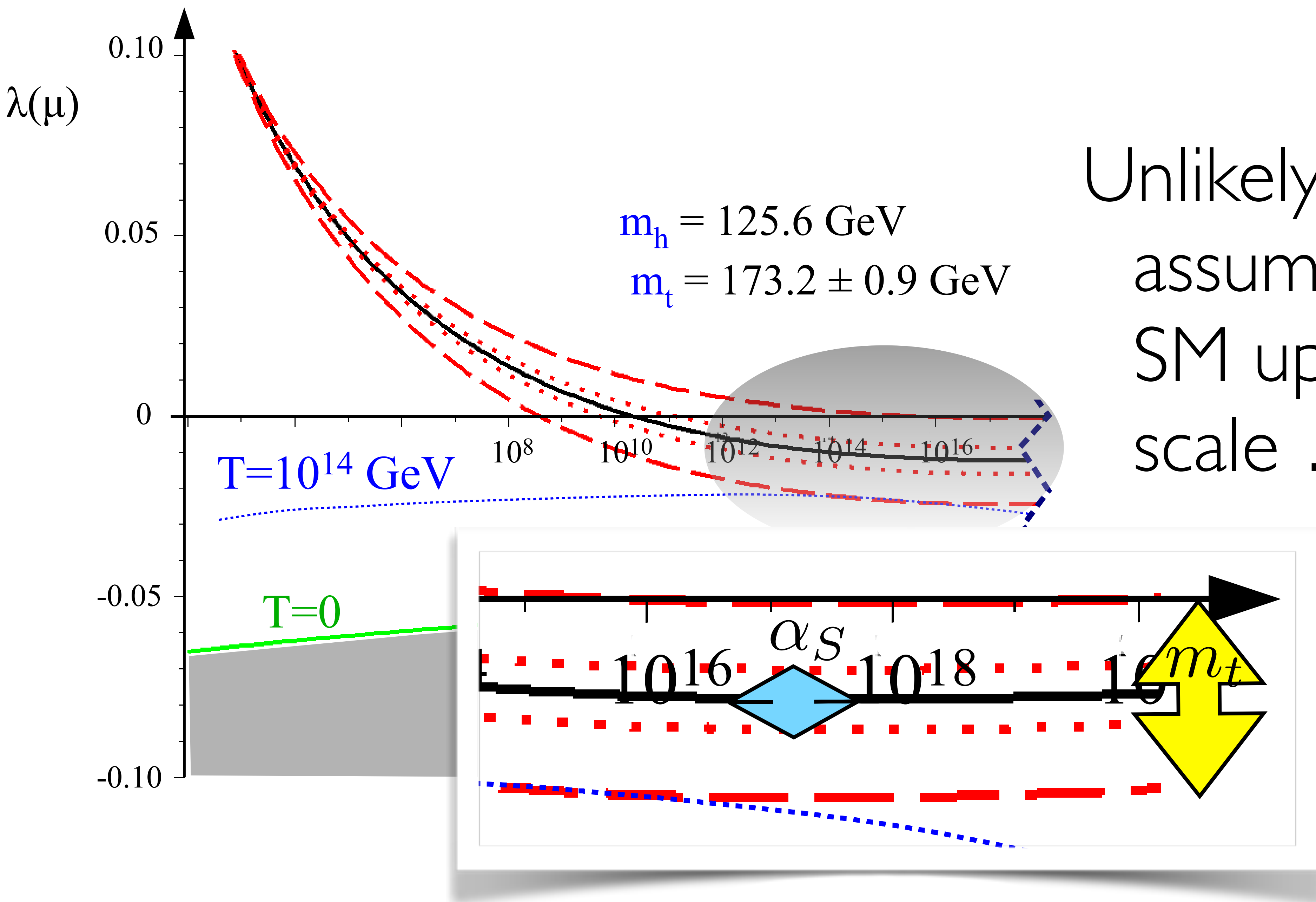


Unlikely the full story, assumes nothing but SM up to the Planck scale …

decisive uncertainty m_{top}

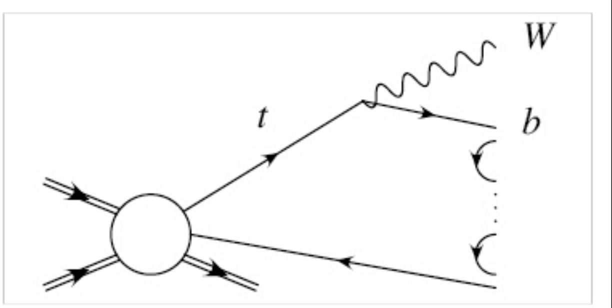
Absolute stability

Degrassi *et al.* '12

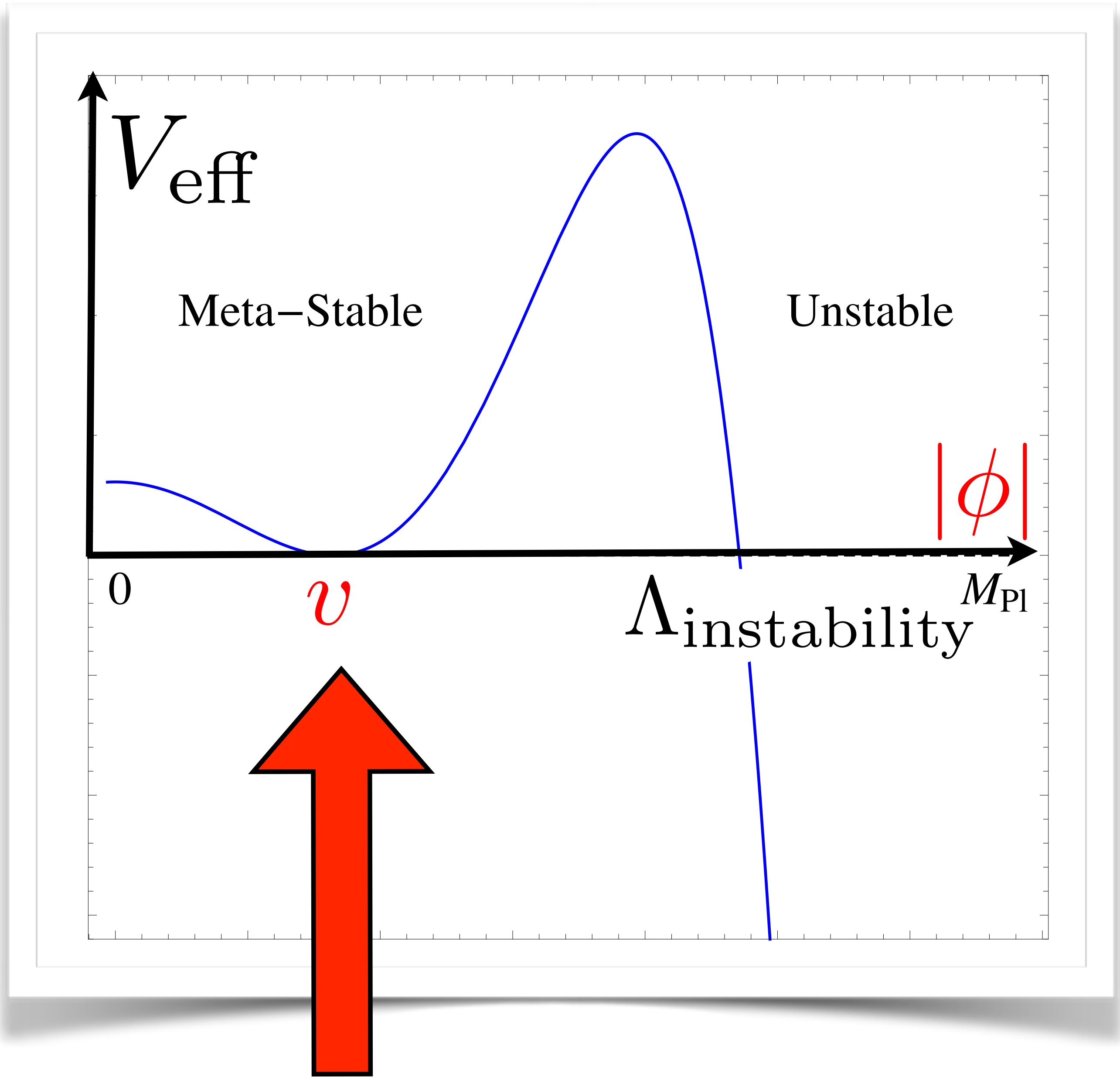
$$M_h\ [\text{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\text{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

- Top mass precision very important, convergence of theory and experiment crucial. Pole mass vs. …

$$m^{\text{exp}} = m_t^{\text{pole}} + \ ?$$

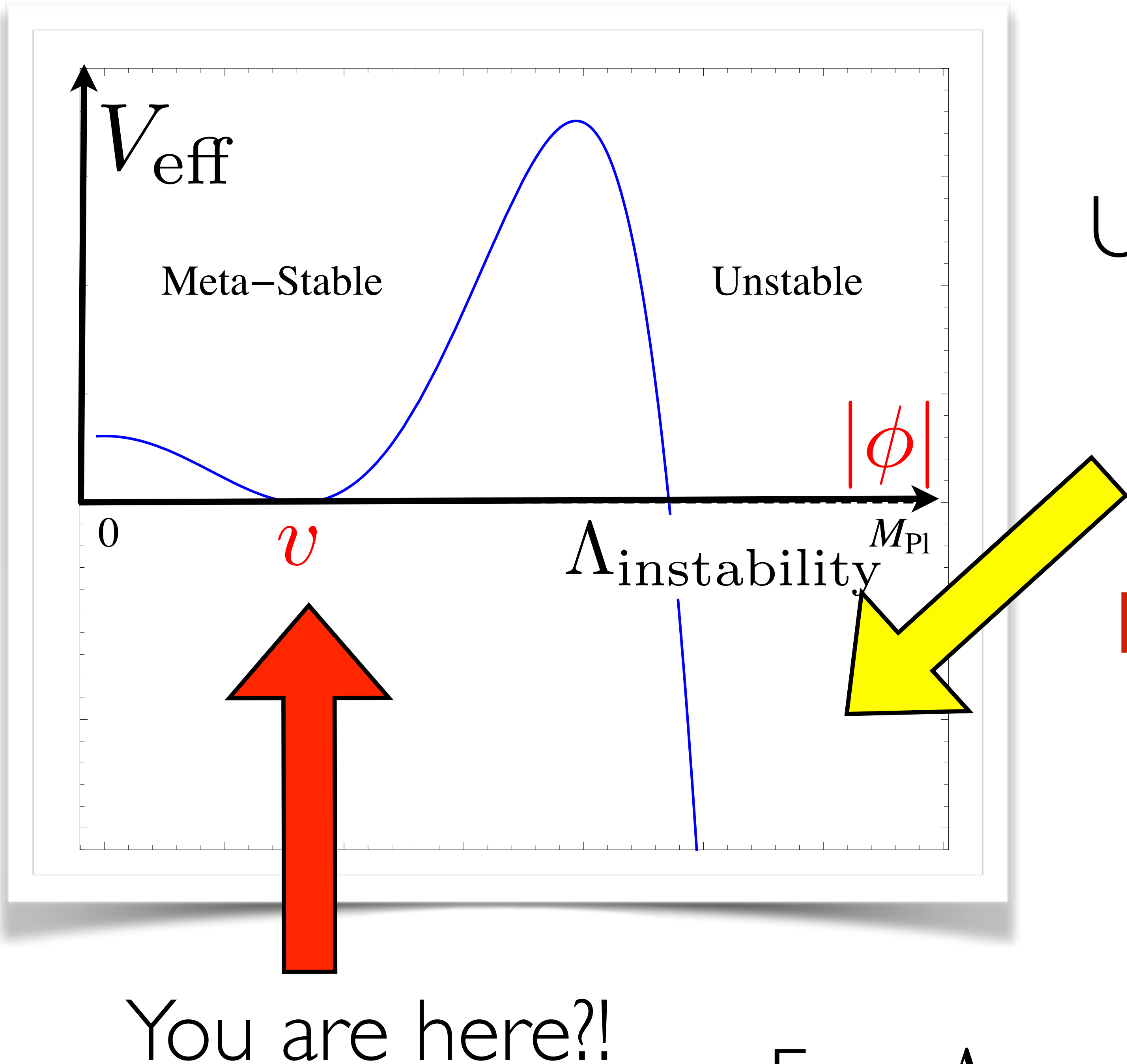


If metastable: How did we end up in the energetically disfavoured vacuum?



You are here?!

If metastable: How did we end up in the energetically disfavoured vacuum?



Universe is overwhelmingly likely to evolve to true ground state

Fine-tuning of initial conditions?

$$\sim \Lambda_{\rm instability}/M_{\rm Planck}$$

For $\Lambda_{\rm instability} \sim 10^{10}\,{\rm GeV} \to 10^{-8}$

Tree-level

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

quantum fluctuations

destabilise Higgs mass^2

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destabilise Higgs mass^2

The hierarchy problem

- The SM is a success also because of its accidental symmetries, all null-tests successful so far

- *B*,*L*, *CP* and flavor are conserved / broken by tiny amounts

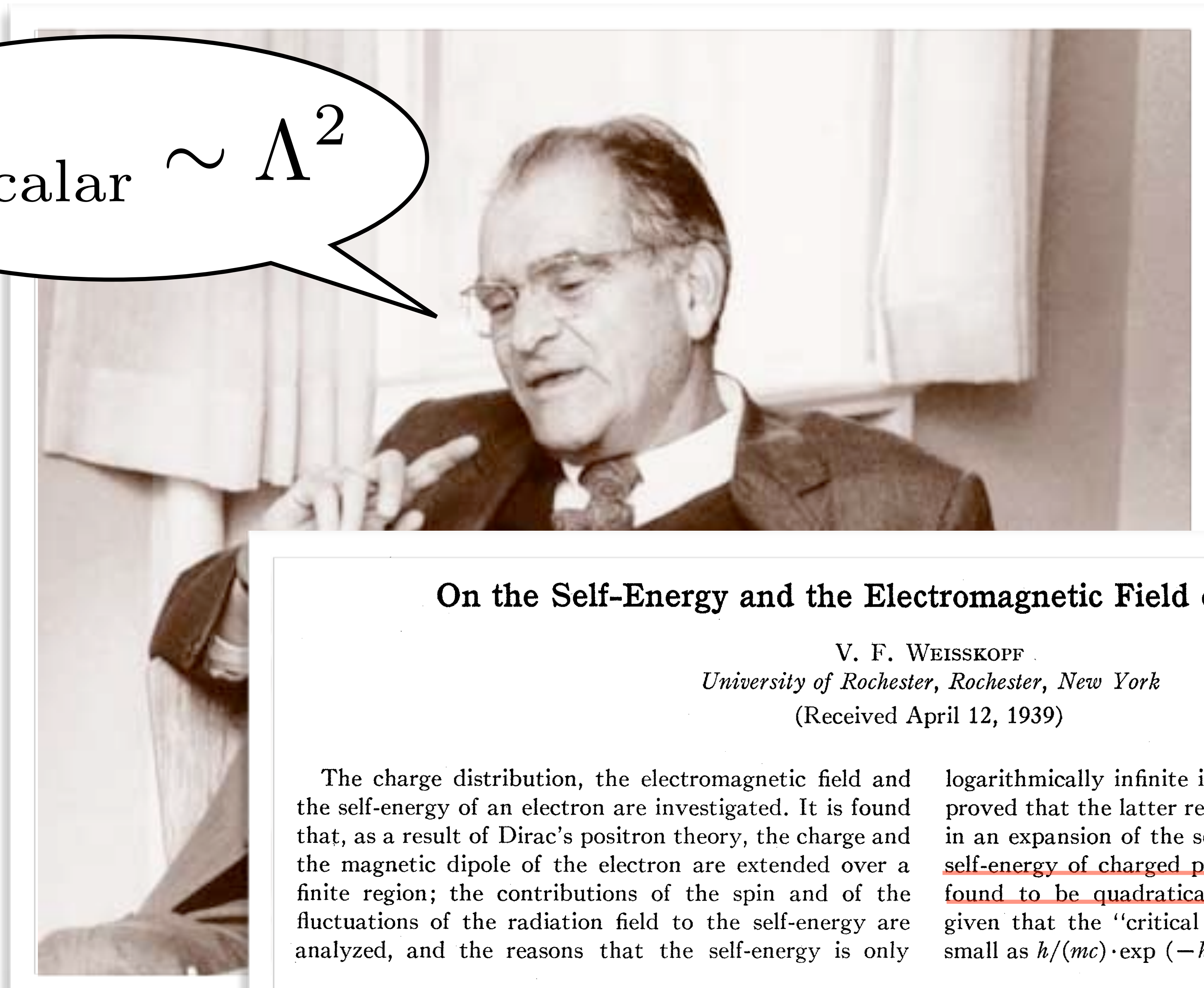
- Broken by irrelevant operators of SM fields, suppressed by a mass scale. Accidental symmetries require a hierarchy of scales!

$$\Lambda_{\rm SM} \ll \Lambda_{\not B}$$

What's the problem?

What's the problem?

$$m_{\text{scalar}}^2 \sim \Lambda^2$$



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

The hierarchy problem

$$\beta_{m_h^2} = \frac{dm_h^2}{d\log\bar{\mu}} = \frac{3m_h^2}{8\pi^2}\Big(2\lambda + y_t^2 - \frac{3g^2}{4} - \frac{g'^2}{4}\Big) \qquad \text{(SM)}$$

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SM + heavy Dirac fermion of mass $M >> m_h$ *and yukawa* y

$$\delta m_h^2 = \mathrm{Re}\,\Pi_{hh}|_{p^2=m_h^2} = \frac{y^2}{2(4\pi)^2}\mathrm{Re}\left[\Delta_\epsilon + (m_h^2 - 4M^2)B_0(m_h; M, M) - 2A_0(M)\right]$$

$$= \frac{y^2}{2(4\pi)^2}\left(\Delta_\epsilon + (6M^2 - m_h^2)\log\frac{m_h^2}{\bar{\mu}^2} + f(m_h, M)\right),$$

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$$m_h^2(\Lambda_{\rm SM}) \simeq m_h^2(\Lambda_{\rm NP}) - \mathcal{O}(1)\Lambda_{\rm NP}^2 \log\frac{\Lambda_{\rm NP}}{\Lambda_{\rm SM}}$$

Two contributions in have to balance out with very high accuracy to generate a Higgs boson mass much smaller than $\Lambda_{\rm NP}$

The hierarchy problem

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SM + Dirac fermion of mass *M >> m* —

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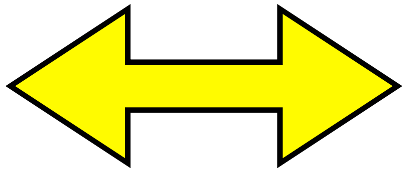
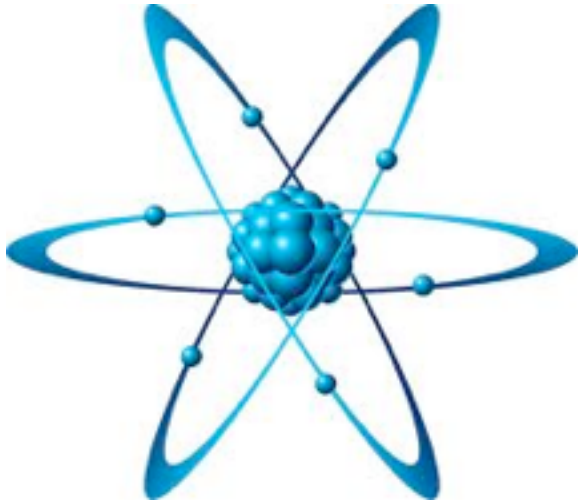
Two contributions in have to balance out with very high accuracy to generate a Higgs boson mass much smaller than $\Lambda_{\rm NP}$

For Λ = M_{Planck}, M_{GUT}, 10 TeV : $\epsilon \sim 10^{-32}, 10^{-28}, 10^{-4}$

Principle: UV insensitivity

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





See e.g. G. Giudice: 1307.7879

Hierarchy problem

- Higgs mass sensitive to thresholds (GUT, gravity)
- Enormous quantum corrections $\mathcal{O}(\mathrm{highest\,scale})$ exceed Higgs mass' physical value: fine-tuned parameters

- - -x- - - - +

bare

See e.g. G. Giudice: 1307.7879

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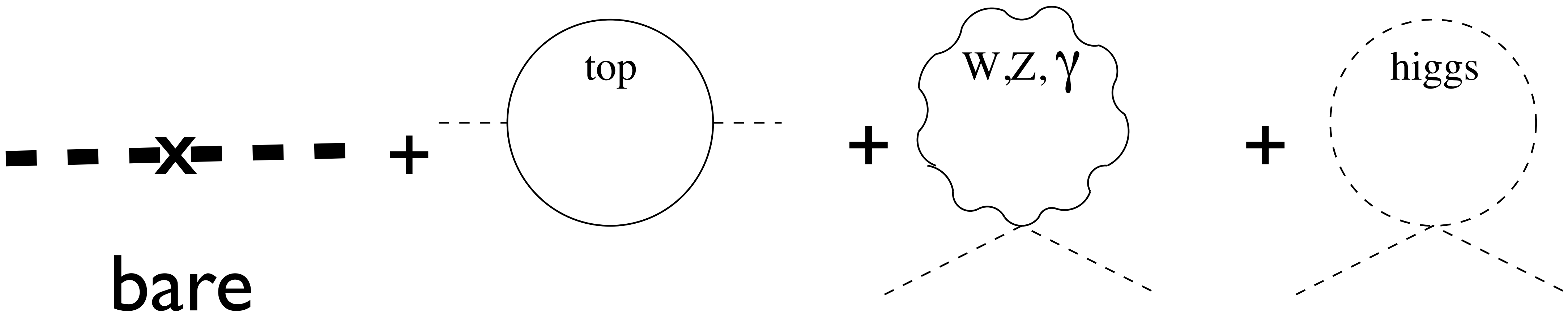
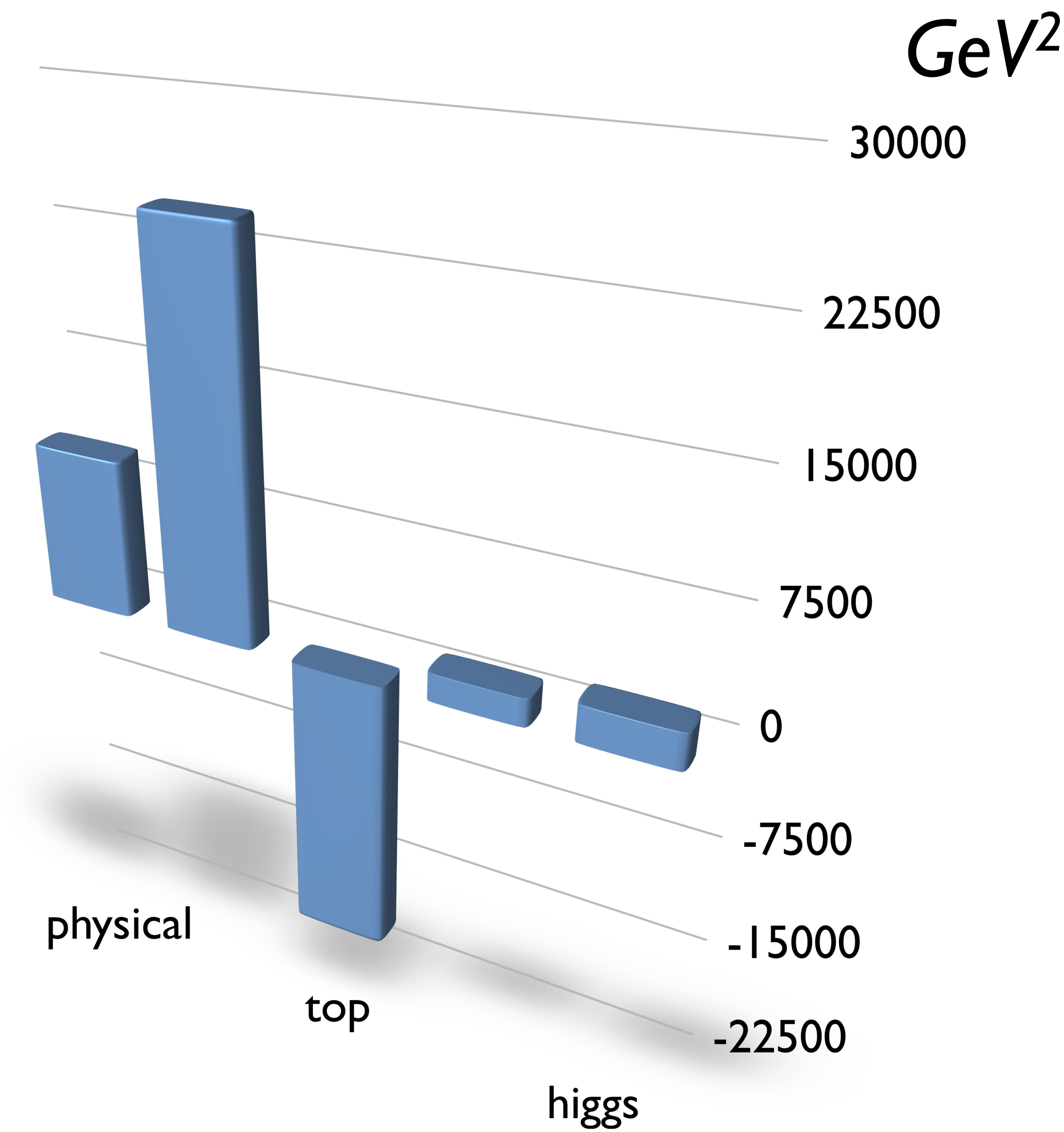


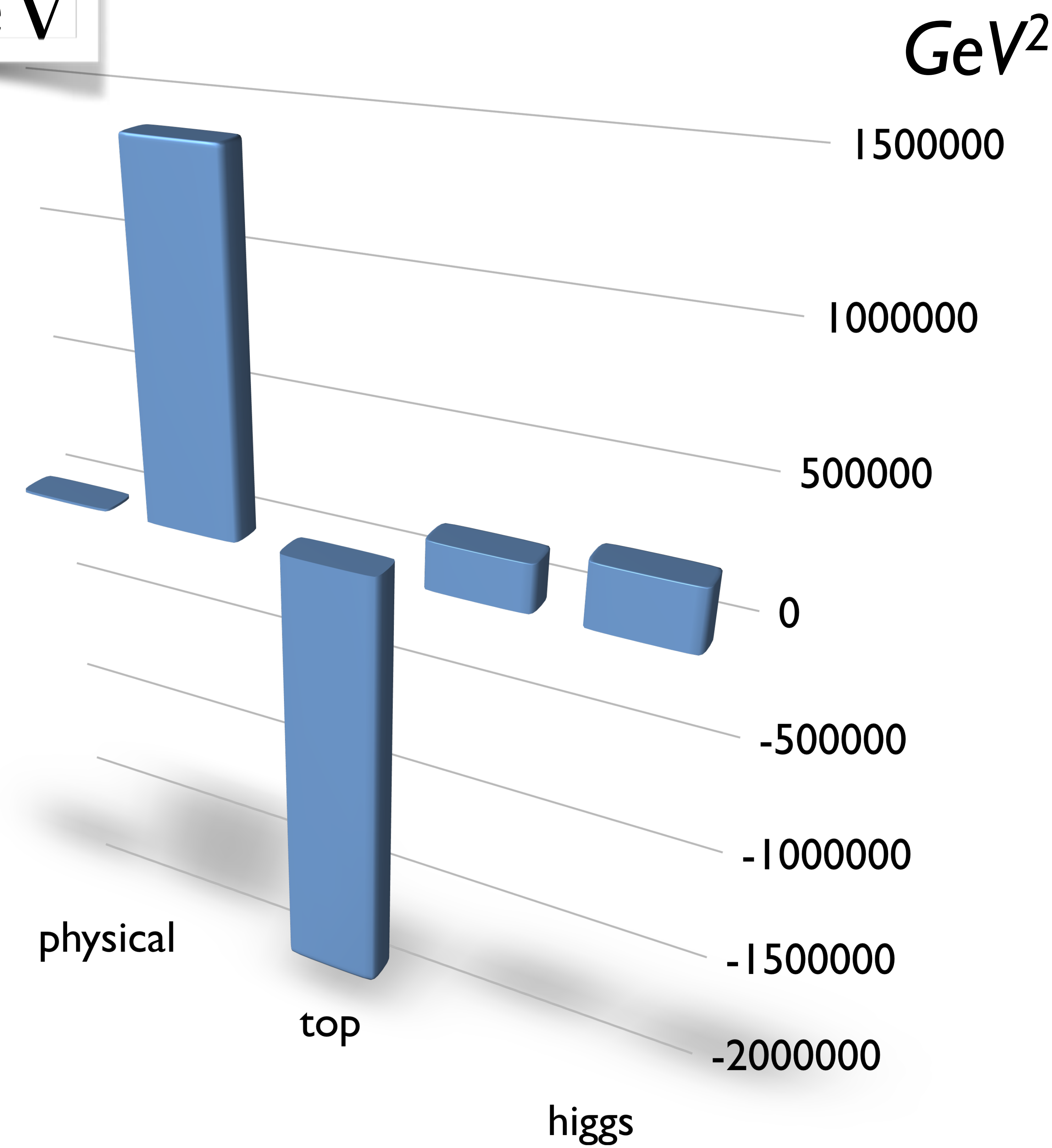
$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$ $\quad \frac{9}{64\pi^2}g^2\Lambda^2$ $\quad \frac{1}{16\pi^2}\lambda^2\Lambda^2$

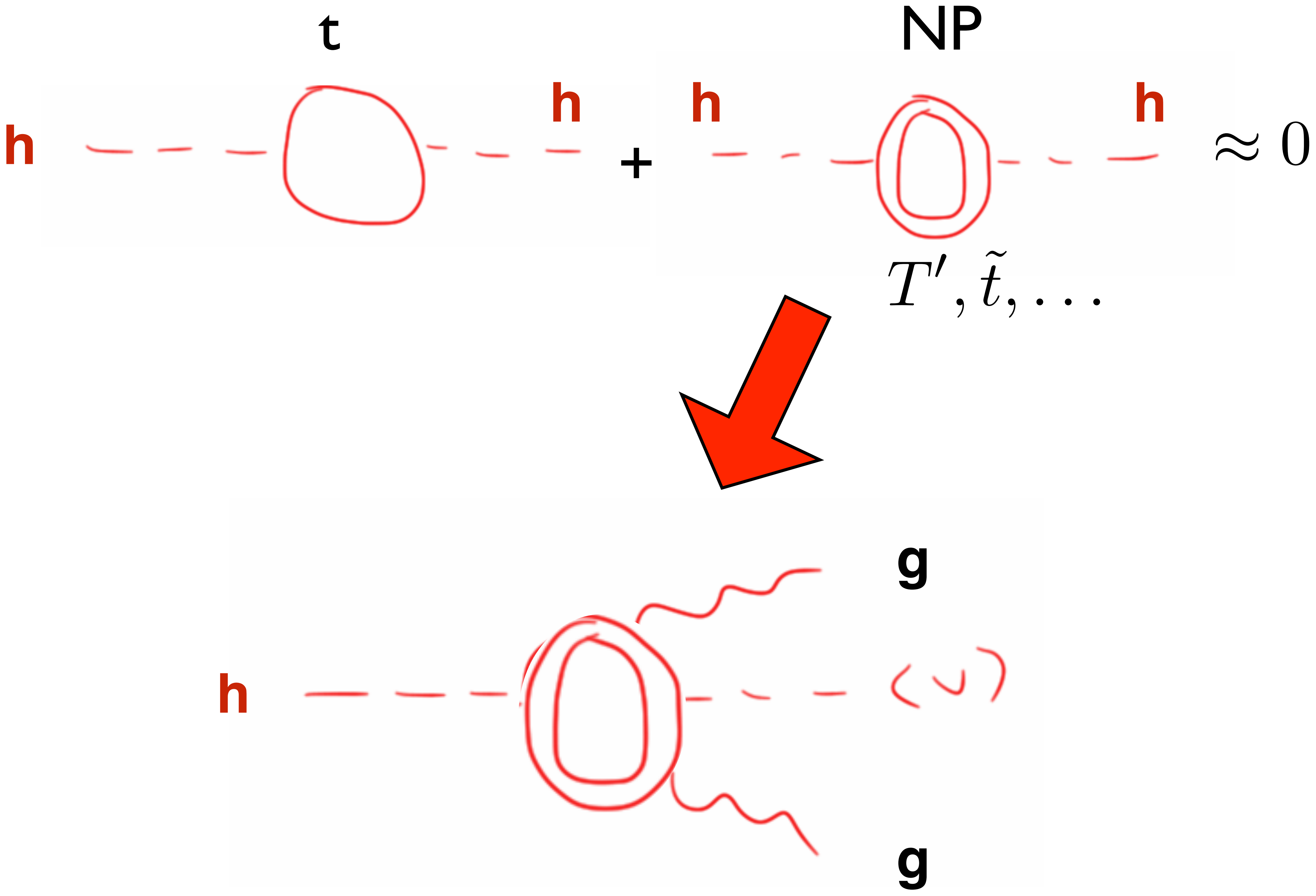
$$m_h^2(\text{physical}) = m_h^2(\text{bare}) + \sum_i a_i \Lambda^2$$

$\Lambda = 1\,\mathrm{TeV}$



$$\Lambda = 10\,\mathrm{TeV}$$





Higgs precision properties expected to change

change Higgs kin. term: VV→h

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

$$\mathcal{O}_6 = \lambda |H|^6$$

LEP1 + MW (per-mille)

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

LEP2: $e^+e^- \to W^+ W^-$ (per-cent)

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

h→γγ

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

GG→h

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$

h→ff

$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

change Higgs kin. term: VV→h

h→γγ

GG→h

h→ff

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$

$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$

$\mathcal{O}_6 = \lambda |H|^6$

$\mathcal{O}$ …

… $B_{\mu\nu}$

… $(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$

… $_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$

$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W_\mu^{a\,\nu} W^b_{\nu\rho} W^{c\,\rho\mu}$

Probed for the first time at LHC!

LEP1 + MW (per-mille)

LEP2:e+e- -> W+ W- (per-cent)

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

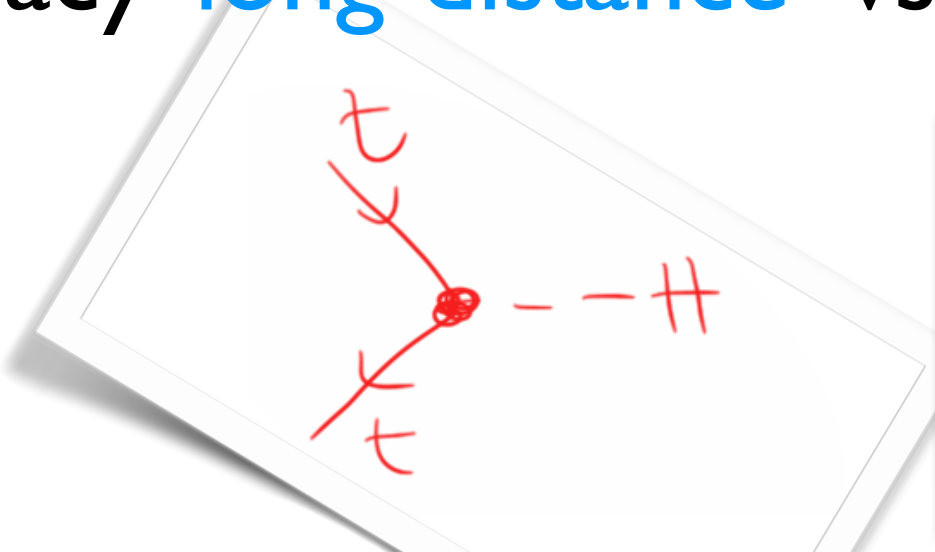
Higgs EFT

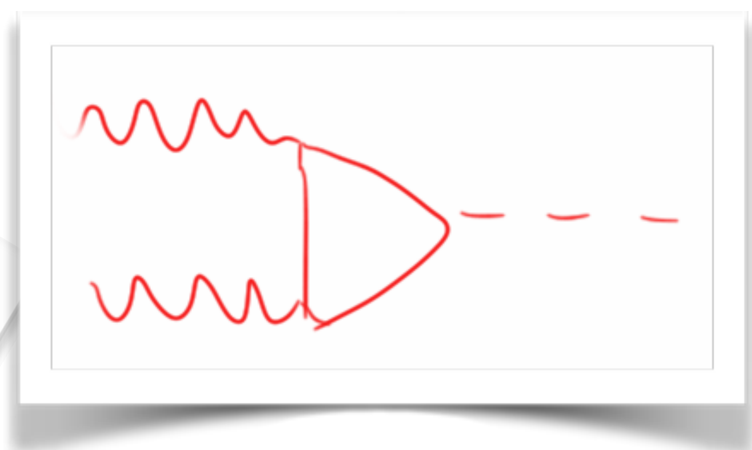
$$\mathcal{O}_t = \frac{y_t}{v^2}|H|^2\bar{Q}_L\tilde{H}t_R\,, \qquad \mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2 G^a_{\mu\nu}G^{a\,\mu\nu}\,,$$

$$\mathcal{L} = \mathcal{L}_{SM} + (1-c_t)\mathcal{O}_t + k_g\mathcal{O}_g\,.$$

$$\mu_{\rm incl}(c_t,k_g) = \frac{\sigma^{\rm BSM}_{\rm incl}(c_t,k_g)}{\sigma^{\rm SM}_{\rm incl}} = (c_t+k_g)^2$$

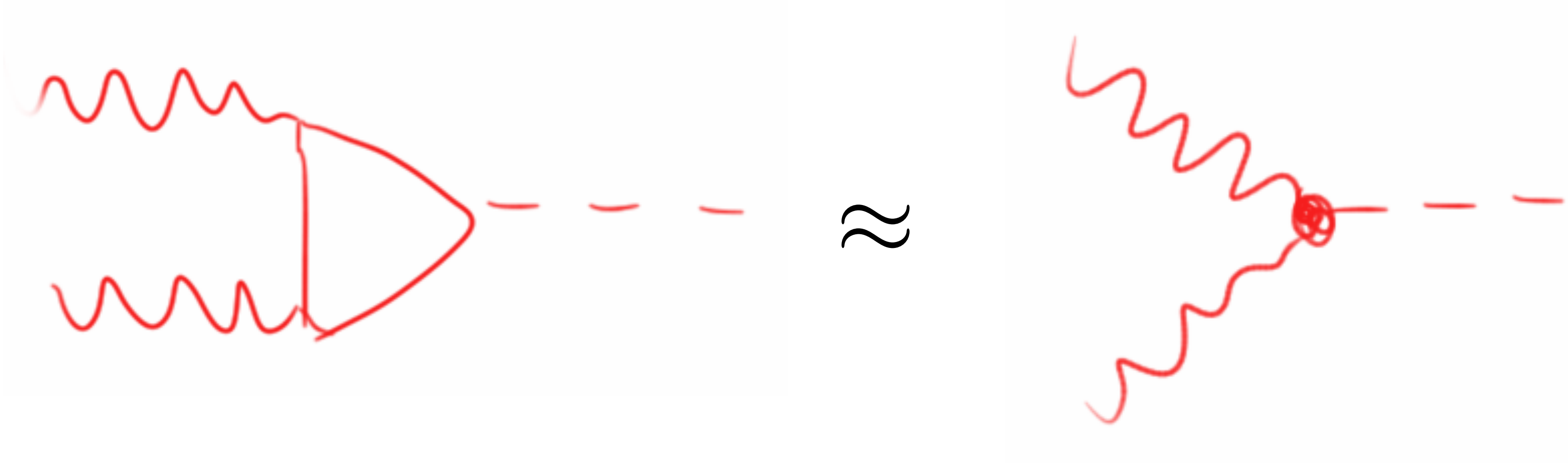
Degeneracy ‘long-distance’ vs ‘short-distance’





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

Does not resolve short-distance physics

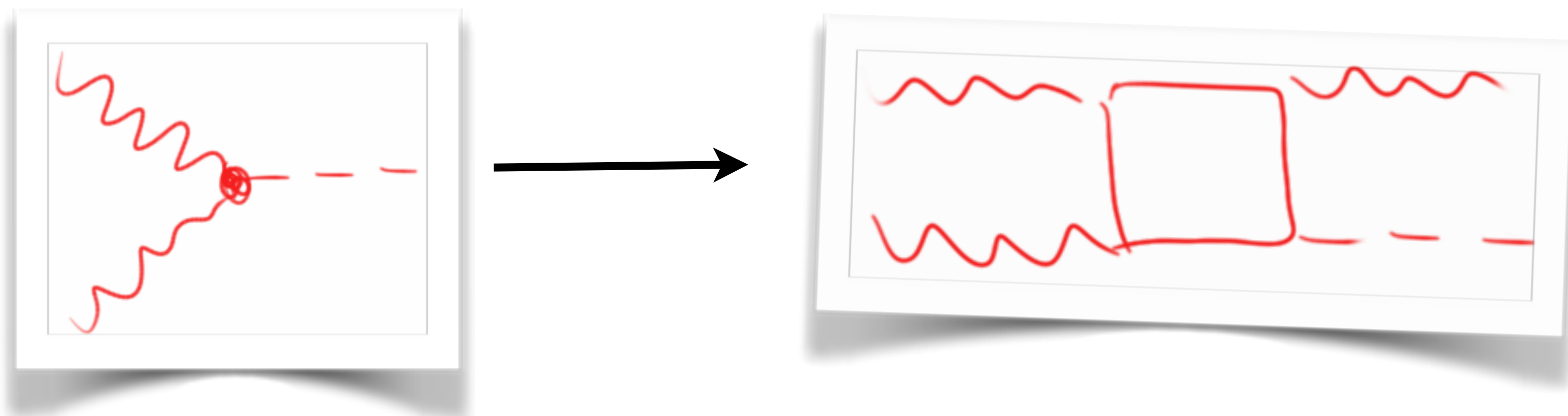


$m_H(\mathrm{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. 1306.4581

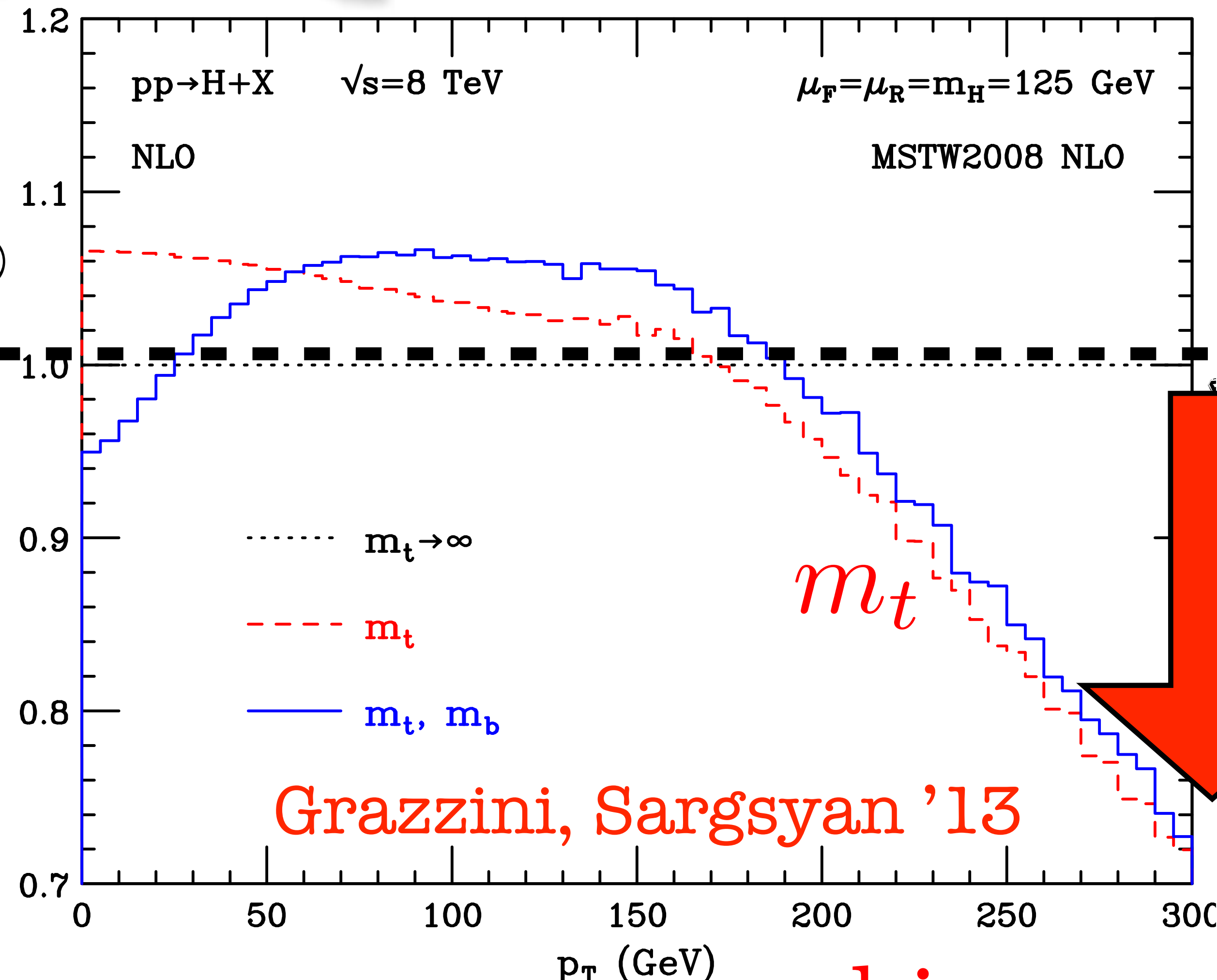
Beyond current observables

Resolve the loop, recoil against hard jet



$p_T \gg m_t$

$m_t \to \infty$



m_t

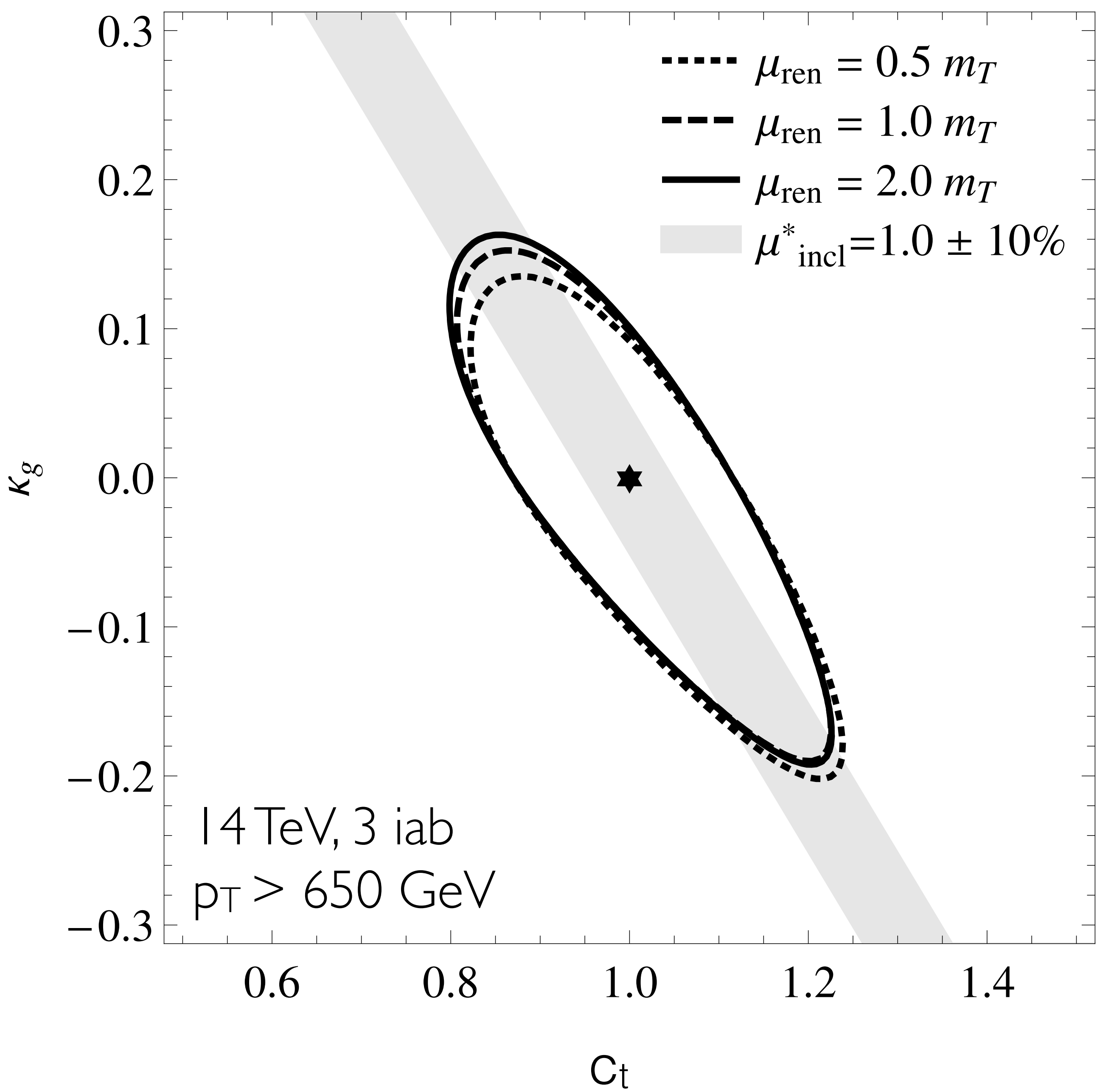
$\text{higgs} - p_T$

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

high p_T tail resolves loop dynamics

see also: 1308.4771, 1308.2225, Azatov, Paul; Englert et al

Boosted Higgs breaks degeneracy

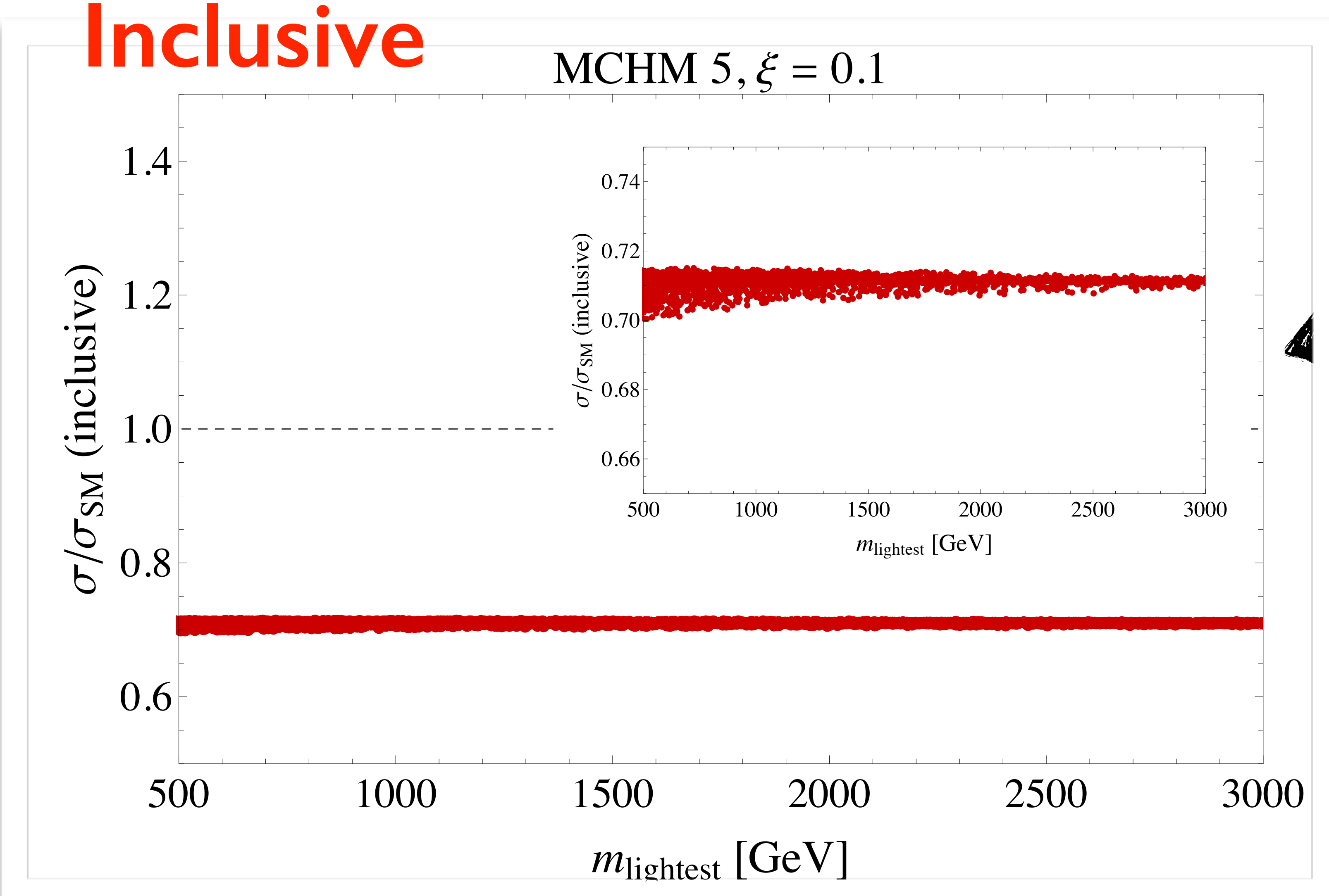


Grojean, Schlaffer, Salvioni, AW

Top partner example

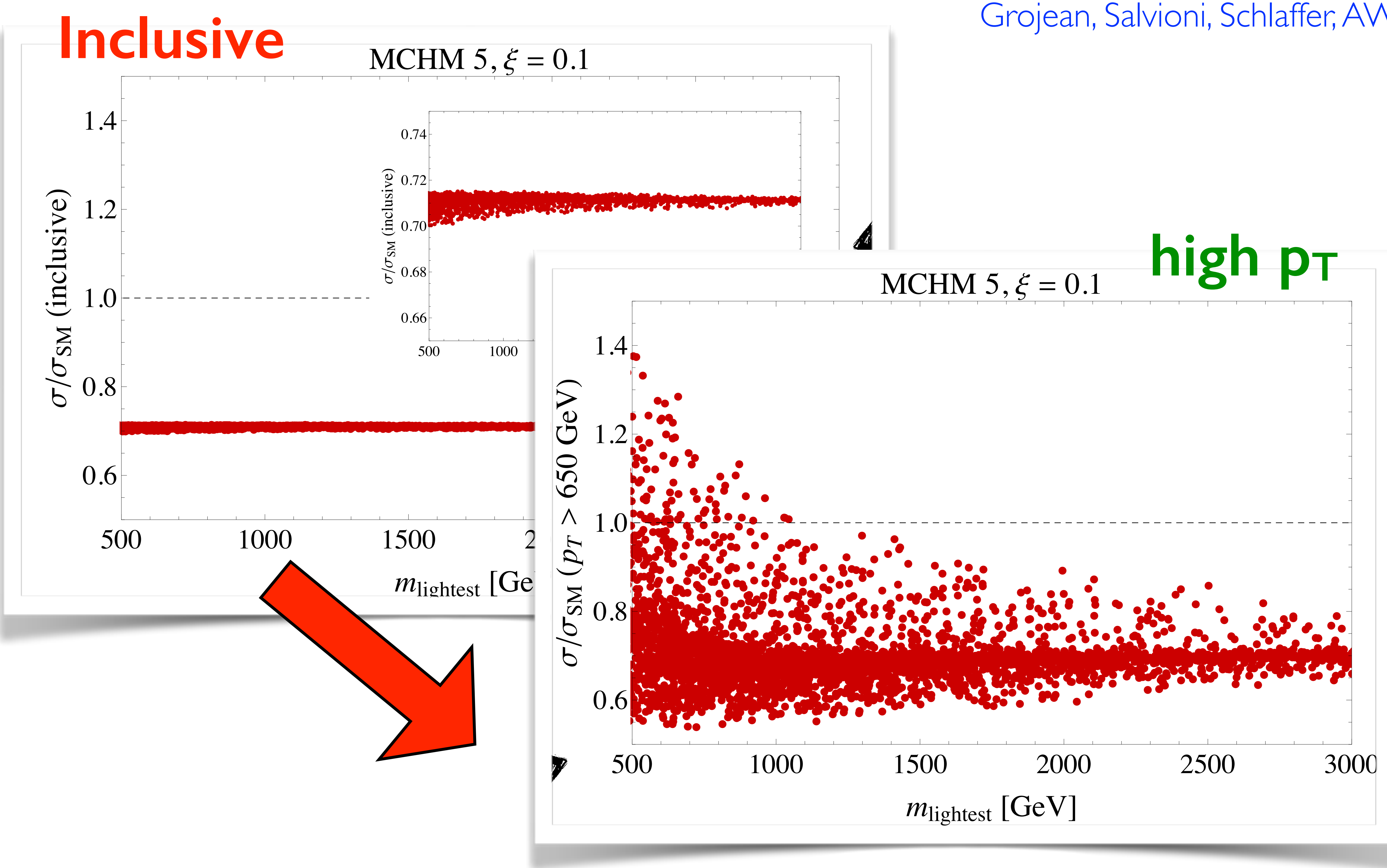
Grojean, Salvioni, Schlaffer, AW

Inclusive



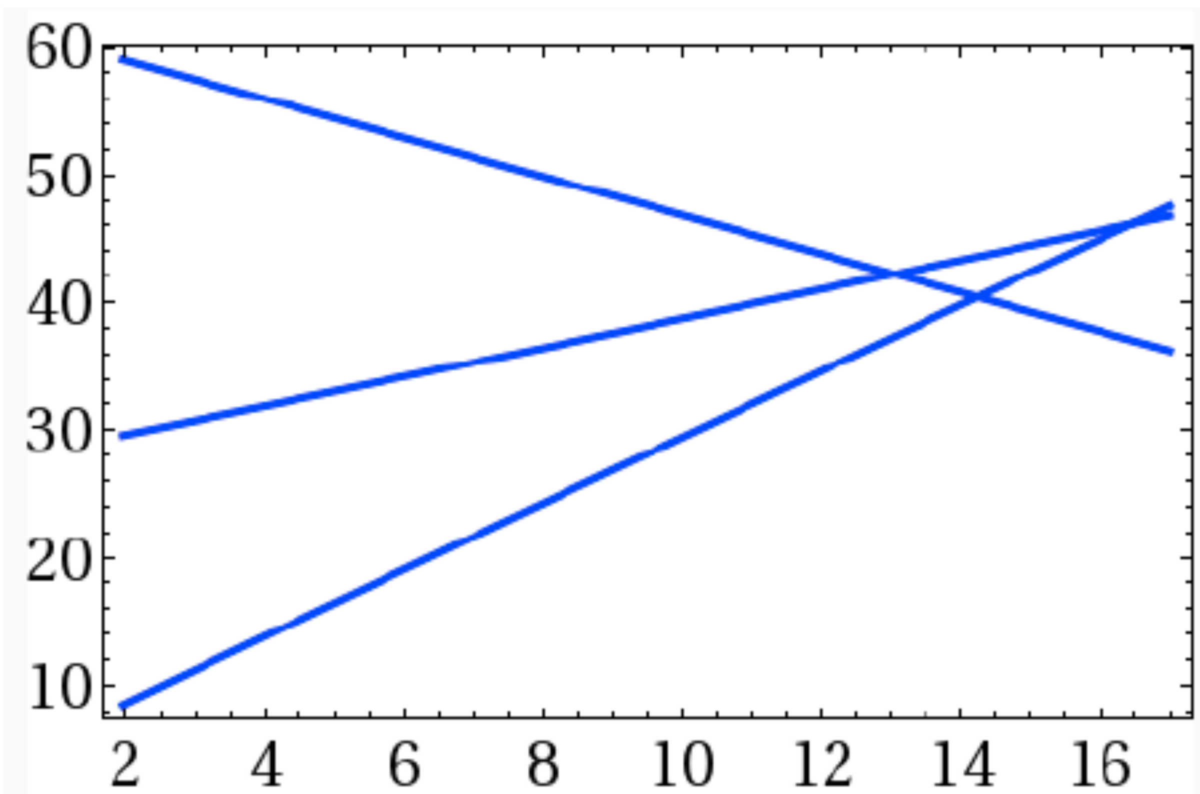
Top partner example

Grojean, Salvioni, Schlaffer, AW

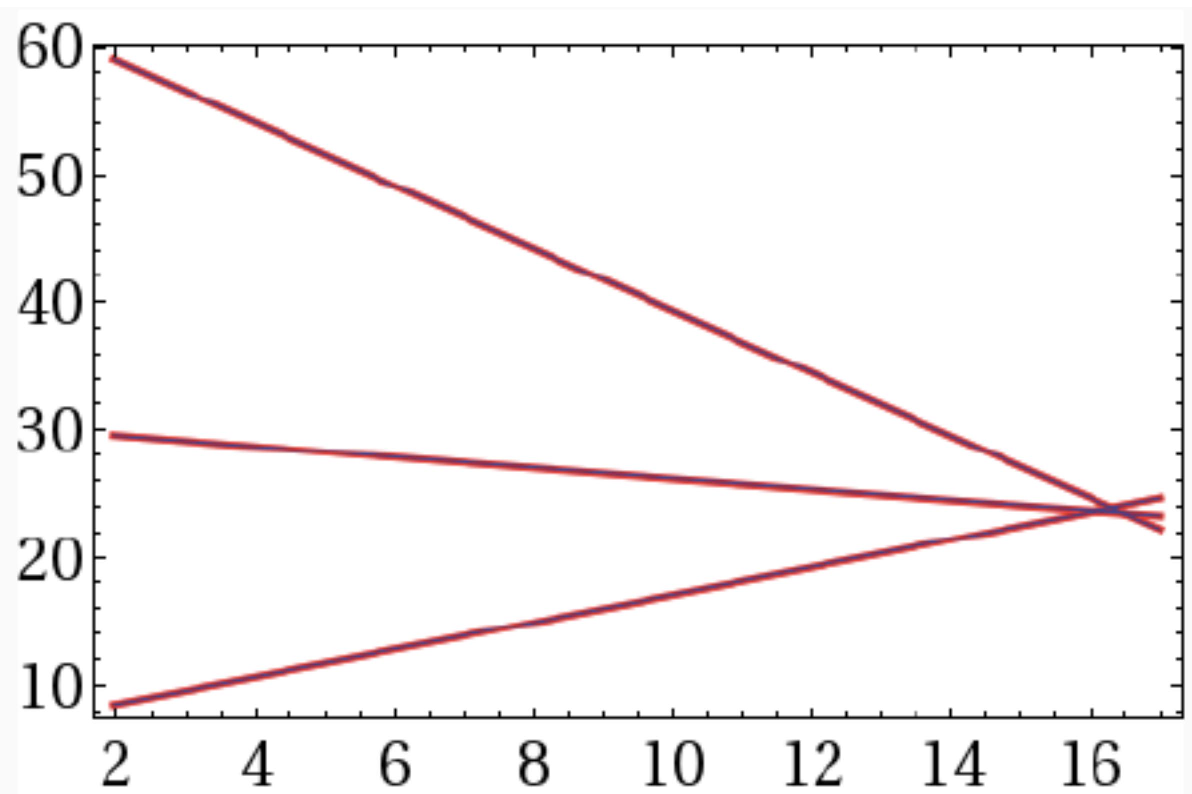


A hint?

SM

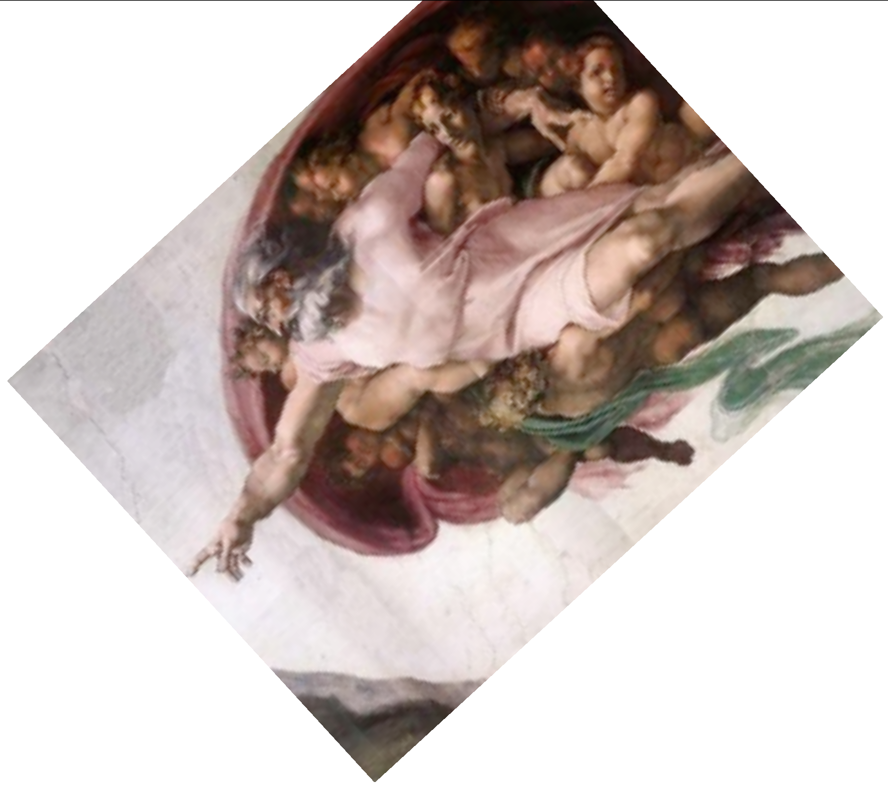


MSSM

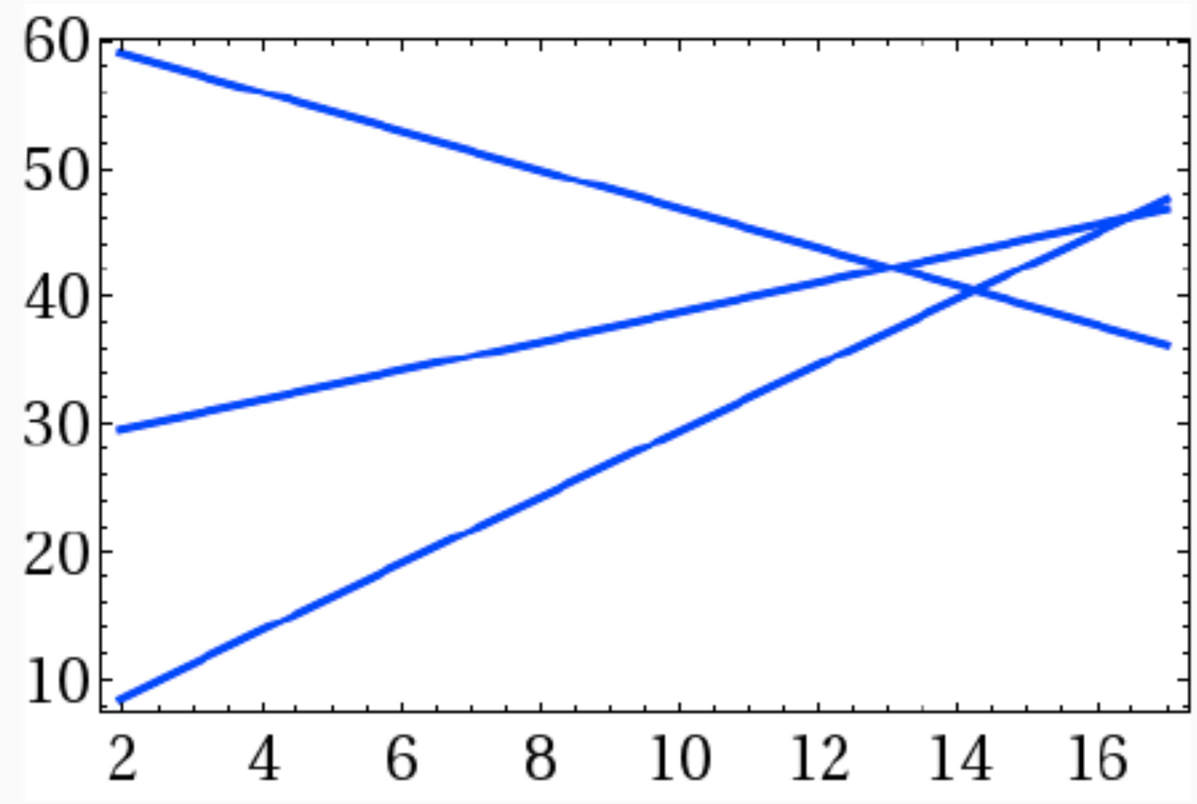


Gauge Coupling running at two loops

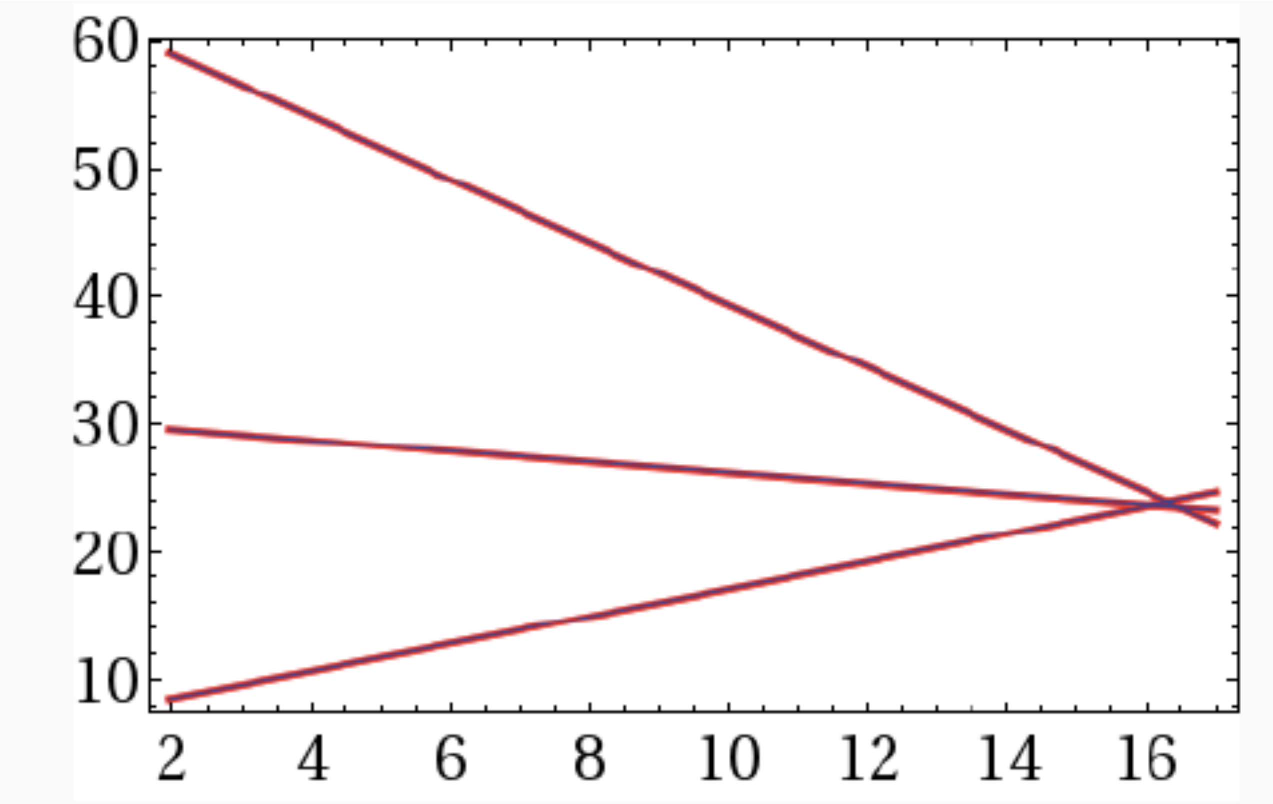
A hint?



SM



MSSM



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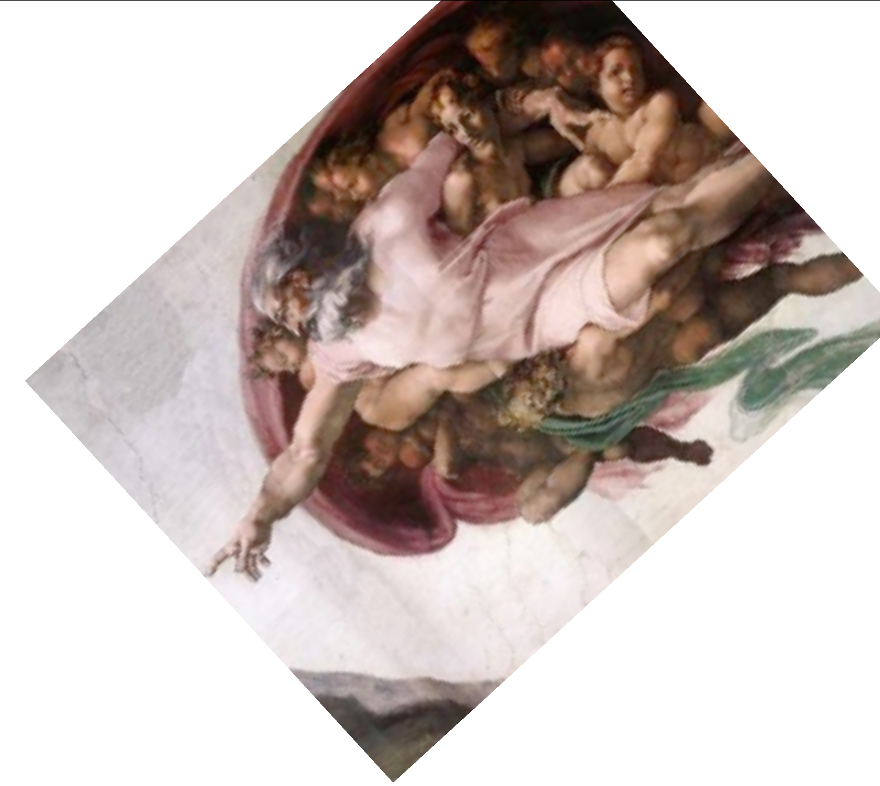
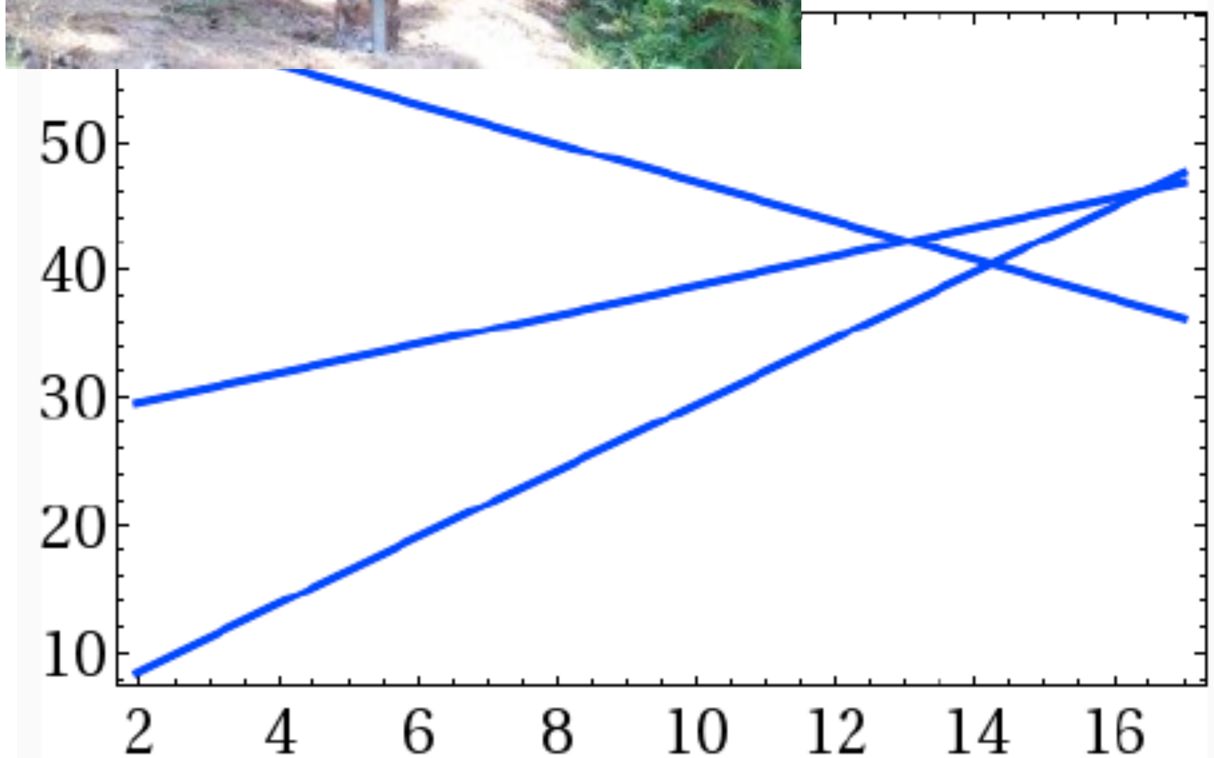
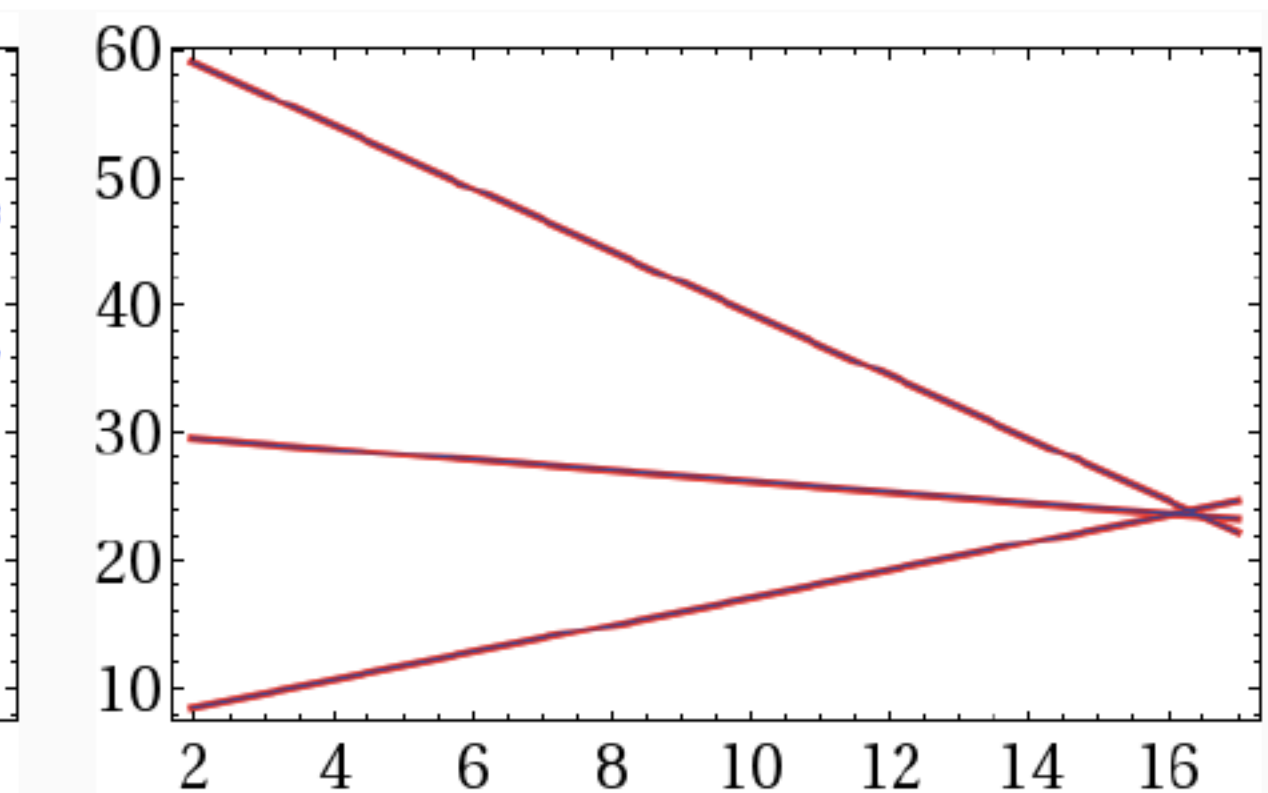


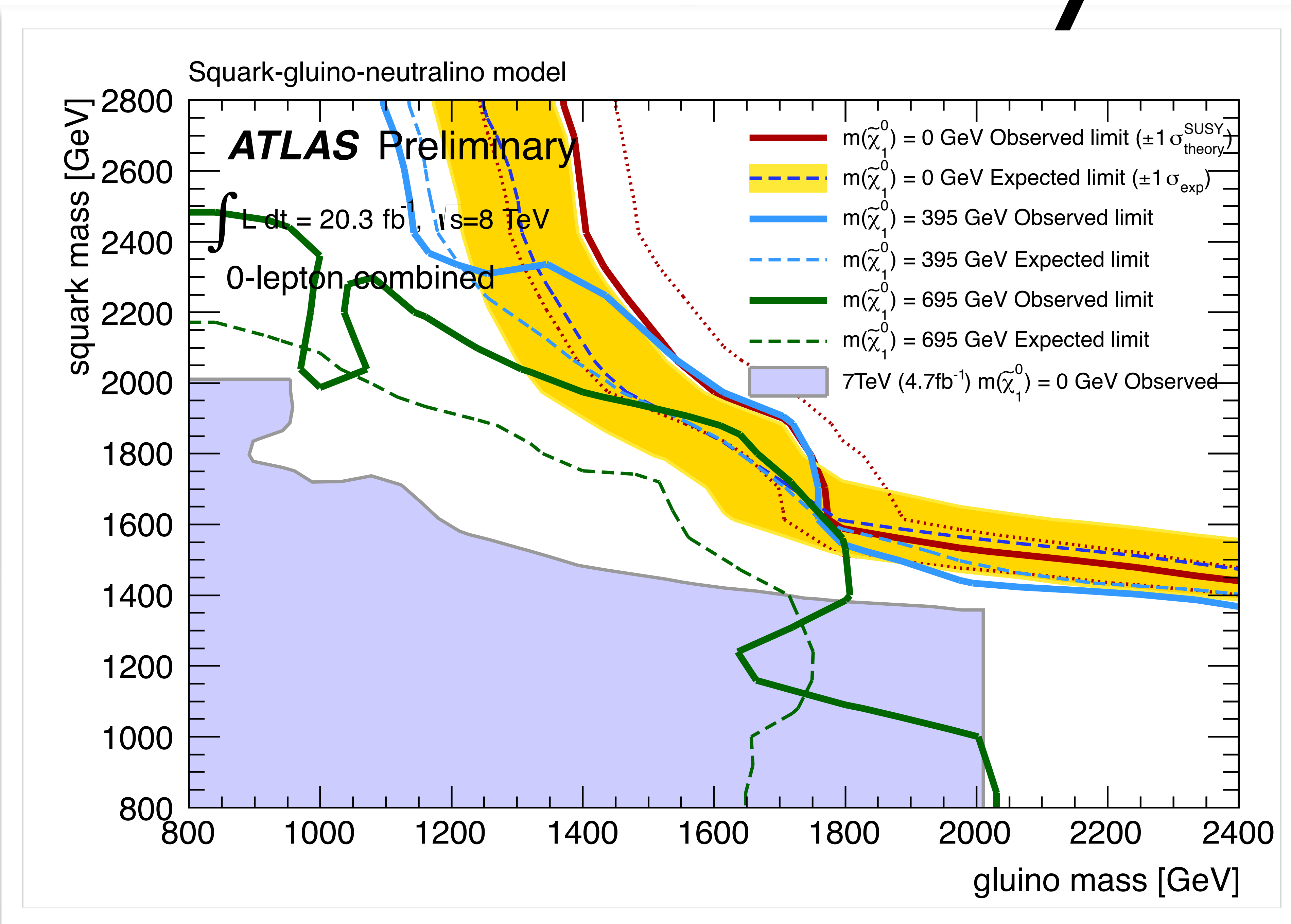


MSSM



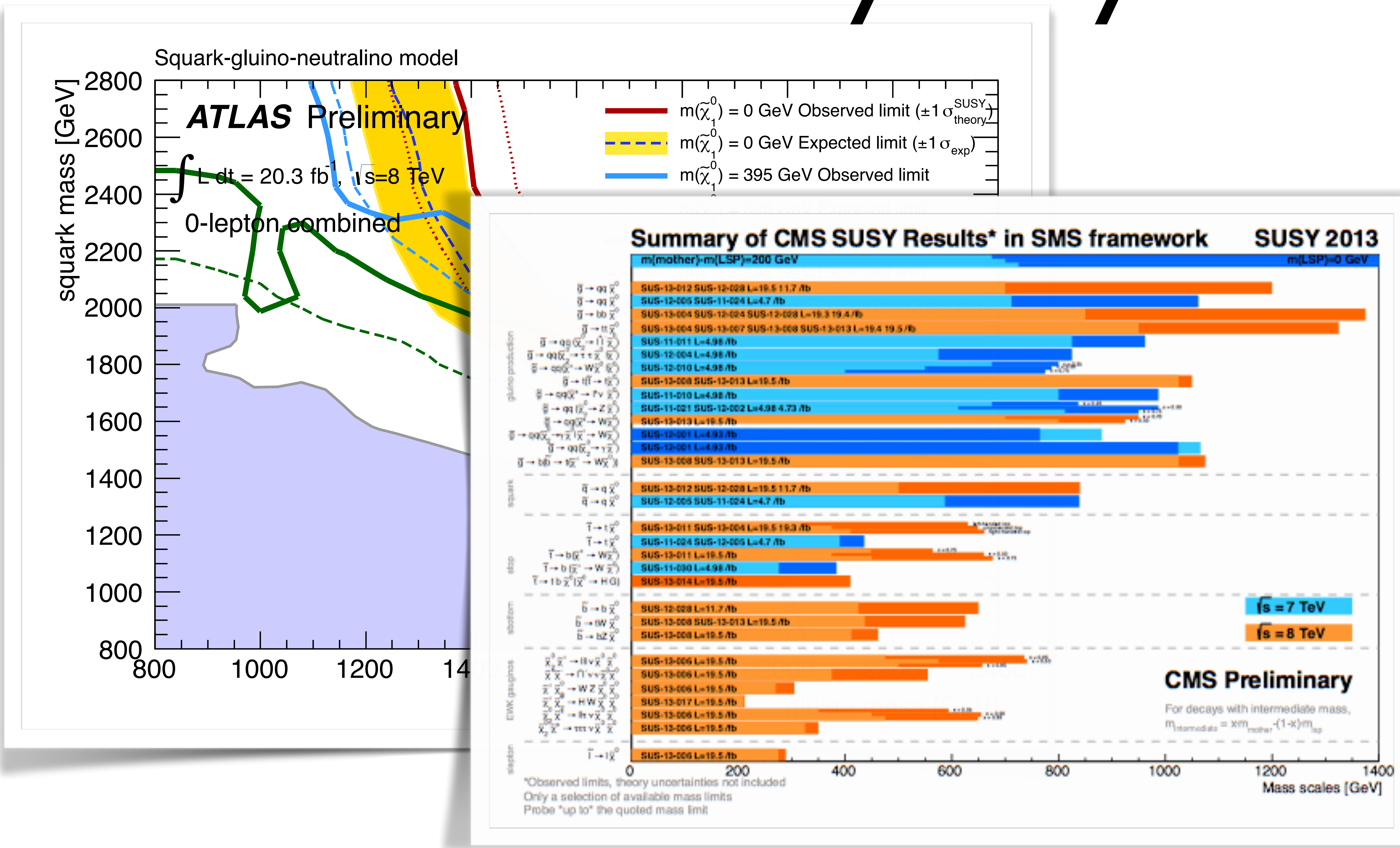
Gauge Coupling running at two loops

Where is everybody?



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

Where is everybody?

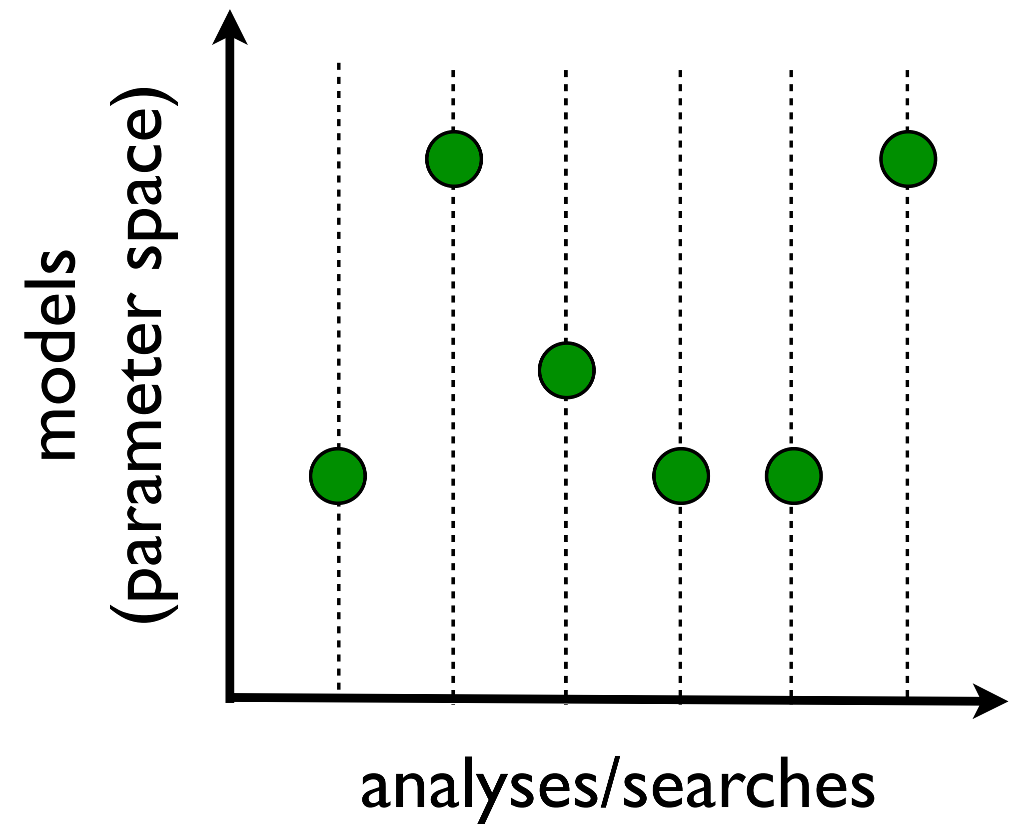


Blind spots? Squeezed Spectra? R-parity Violation? Third-Generation? EW-inos?

{

What do we actually know?

ATLAS and CMS present their results only in particular slices of the parameter space of a few models.



Theorists want to constrain as many models (large parameter space) as possible using as many analyses as possible. Are we missing interesting models? Parameter points of low sensitivity?

To address this issue we have developed

Fastlim **Atom**

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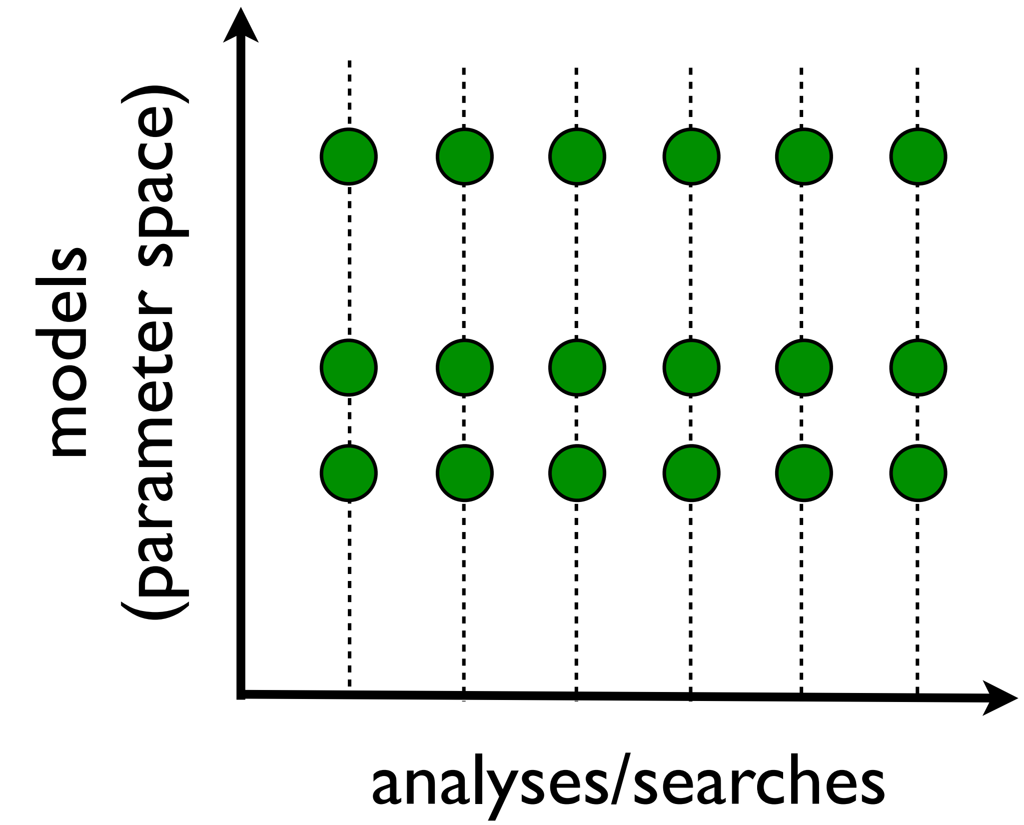

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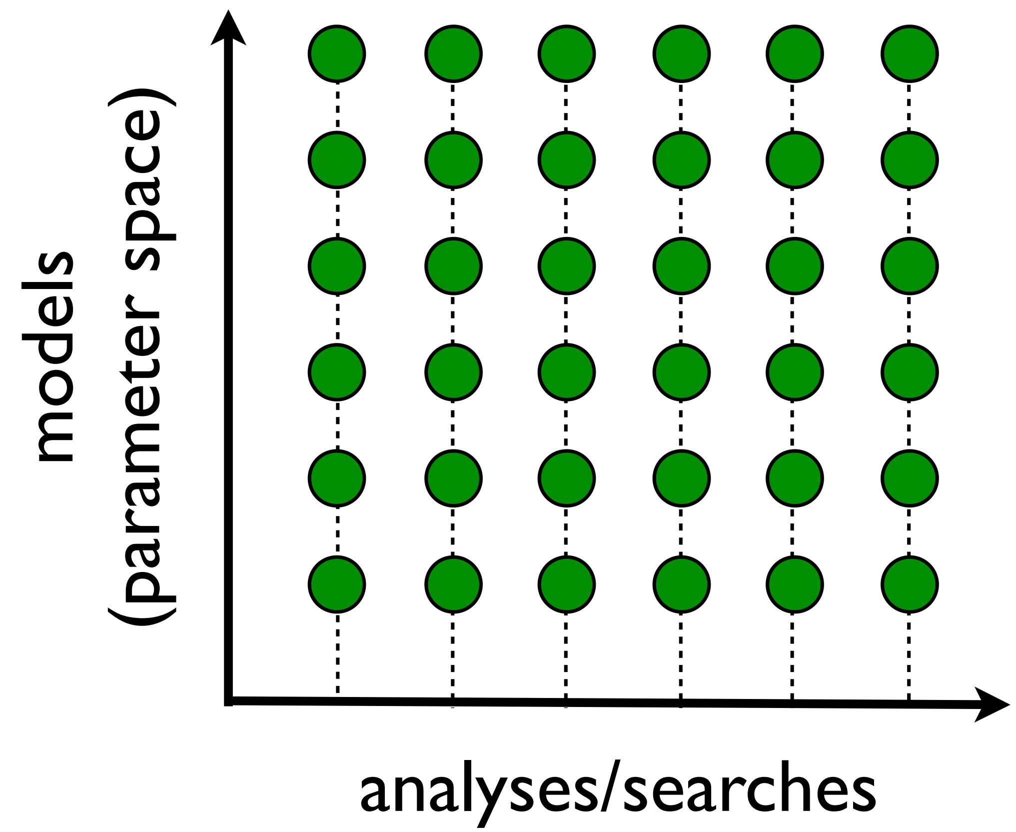


Theorists want to constrain as many models (large parameter space) as possible using as many analyses as possible. Are we missing interesting models? Parameter points of low sensitivity?

To address this issue we have developed

Fastlim **Atom**

How to find the limit on your model?

Signal Regions

ATLAS-CONF-2011-086

Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets
E_T^{miss} [GeV]	> 130	> 130	> 130
Leading jet p_T [GeV]	> 130	> 130	> 130
Second jet p_T [GeV]	> 40	> 40	> 40
Third jet p_T [GeV]	–	> 40	> 40
Fourth jet p_T [GeV]	–	–	> 40
$\Delta\phi(\text{jet}_i, E_T^{miss})_{min}$ $(i = 1, 2, 3)$	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25
m_{eff} [GeV]	> 1000	> 1000	> 1000

Process	Signal Region		
	≥ 2 jets	≥ 3 jets	≥ 4 jets
Prediction	12.1 ± 2.8	10.1 ± 2.3	7.3 ± 1.7
Observed	10	8	7

statistically consistent

How to evaluate $N_{\rm SUSY}$?

by Feynman diagram calc.

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

fixed

requires a chain of MC simulations

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

`HepMC file`

↓

AToM

(Automated Testing of Models)

- "Detector simulation": reconstruct jets, b-jet, iso-leptons, ...
- Event analyses: ATLAS and CMS searches are implemented

↓

efficiencies of all the signal/ control regions implemented together with their uncertainties

Plots

momenta of reco-objects

with Michele Papucci (Berkely/U. Michigan), Kazuki Sakurai (King's College)

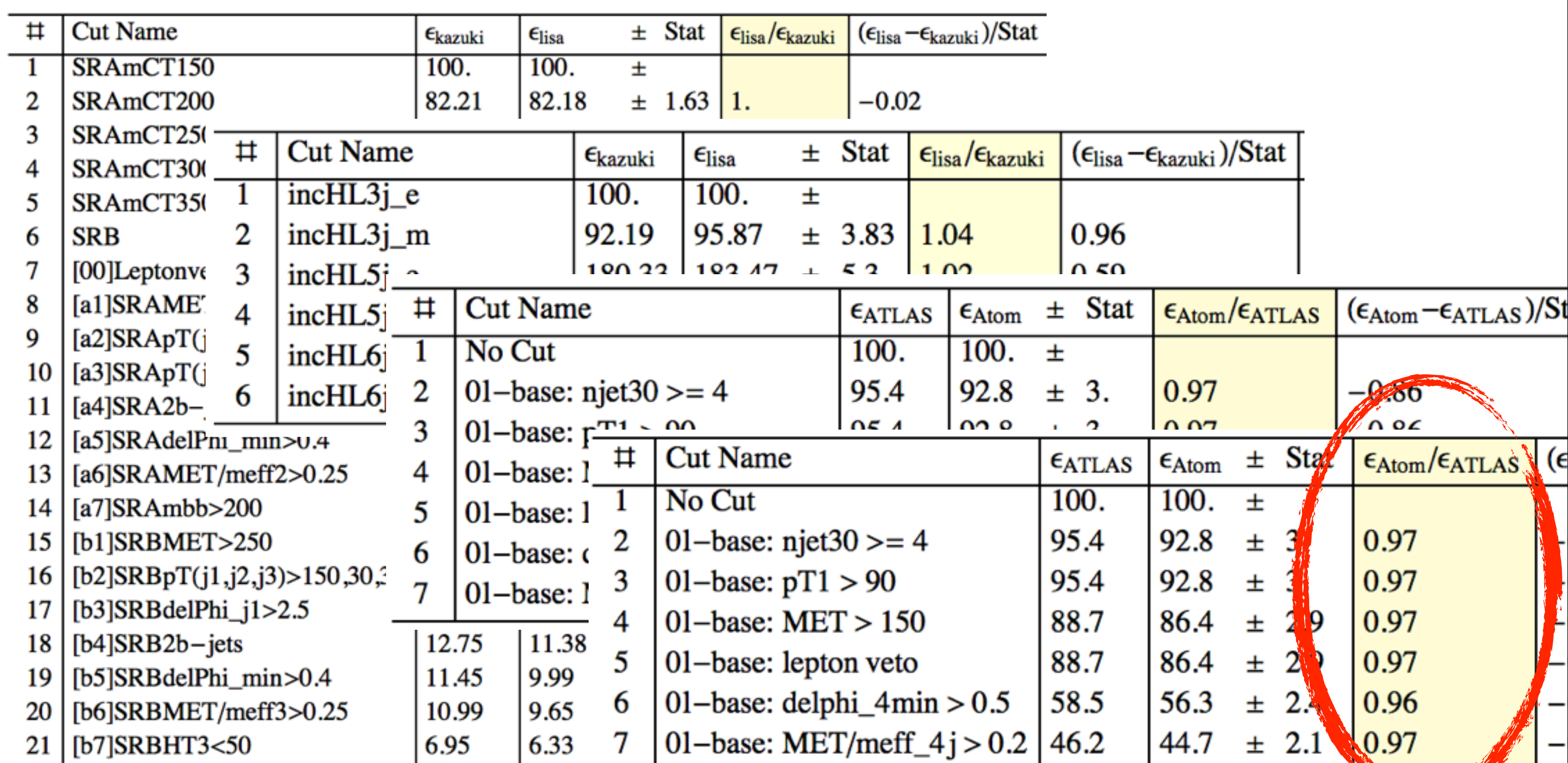
Analyses

- >200 analyses have been implemented and available

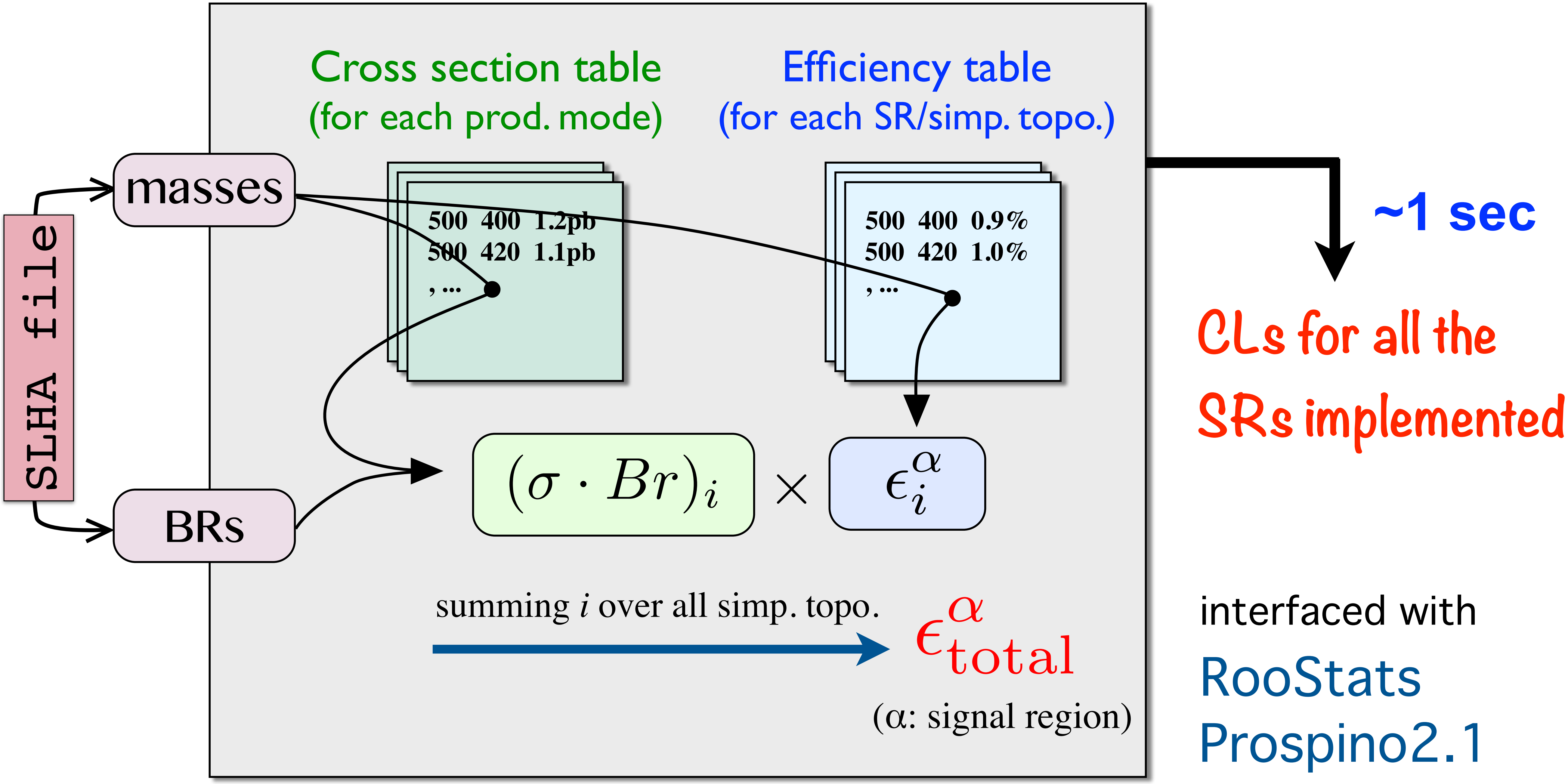
  Update: all 2013 ATLAS SUSY MET analyses have been implemented

- Analyses have been validated (thanks to ATLAS's cut-flow tables)

agreements are (most of the times) as good as 90%



What does Fastlim do?



interfaced with
RooStats
Prospino2.1

with Michele Papucci (Berkely/U. Michigan),
Kazuki Sakurai (King's College), Lisa Zeune (DESY)

A fast evaluation of N_{SUSY}

$\mathrm{Q} = \tilde{q}$

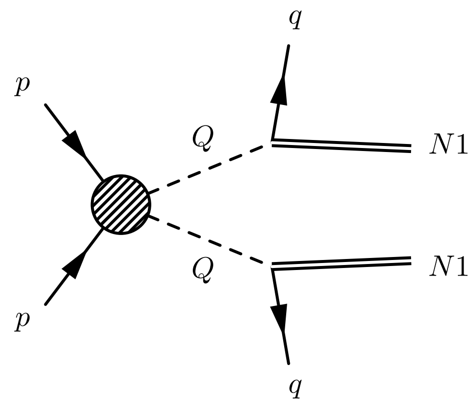
$\mathrm{G} = \tilde{g}$

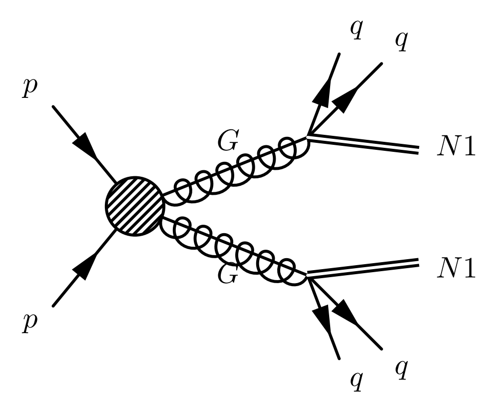
$\mathrm{N1} = \tilde{\chi}_1^0$

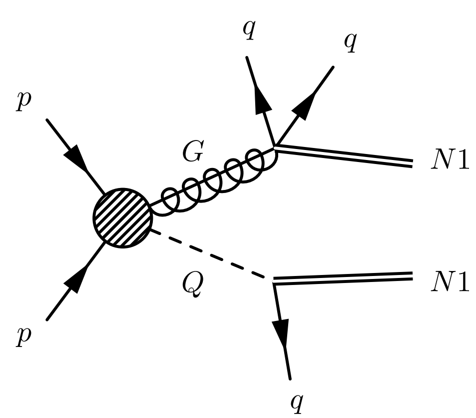
- We propose a new approach to estimate N_{SUSY}

Key Idea: to reconstruct N_{SUSY} using simplified model processes

$$\mathrm{N}^{(i)}_{SUSY} = \left\{ \begin{array}{c} \mathrm{N}_{\mathrm{QqN1:QqN1}} \\ + \\ \mathrm{N}_{\mathrm{GqqN1:GqqN1}} \\ + \\ \mathrm{N}_{\mathrm{GqqN1:QqN1}} \\ + \\ \vdots \end{array} \right.$$







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$$N_{SUSY}^{(i)} = \left\{ \begin{array}{l} N_{QqN1:QqN1} = \varepsilon_{QqN1:QqN1}(mQ, mN1) \cdot \sigma_{QQ} \cdot BR_{QqN1:QqN1} \cdot L_{int} \\ \quad + \\ N_{GqqN1:GqqN1} = \varepsilon_{GqqN1:GqqN1}(mG, mN1) \cdot \sigma_{GG} \cdot BR_{GqqN1:GqqN1} \cdot L_{int} \\ \quad + \\ N_{GqqN1:QqN1} = \varepsilon_{GqqN1:QqN1}(mQ, mG, mN1) \cdot \sigma_{GQ} \cdot BR_{GqqN1:QqN1} \cdot L_{int} \\ \quad + \\ \quad \vdots \end{array} \right.$$

A fast evaluation of N_{SUSY}

$Q = \tilde{q}$

$G = \tilde{g}$

$N1 = \tilde{\chi}_1^0$

Efficiencies for simplified processes depend only on a few mass parameters

$$N_{SUSY}^{(i)} = \begin{cases} N_{QqN1:QqN1} = \varepsilon_{QqN1:QqN1}(mQ, mN1) \cdot \sigma_{QQ} \cdot BR_{QqN1:QqN1} \cdot L_{int} \\ + \\ N_{GqqN1:GqqN1} = \varepsilon_{GqqN1:GqqN1}(mG, mN1) \cdot \sigma_{GG} \cdot BR_{GqqN1:GqqN1} \cdot L_{int} \\ + \\ N_{GqqN1:QqN1} = \varepsilon_{GqqN1:QqN1}(mQ, mG, mN1) \cdot \sigma_{GQ} \cdot BR_{GqqN1:QqN1} \cdot L_{int} \\ + \\ \vdots \end{cases}$$

A fast evaluation of N_{SUSY}

$Q = \tilde{q}$

$G = \tilde{g}$

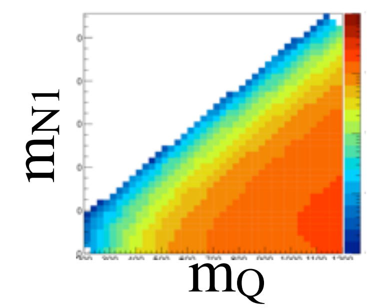
$N1 = \tilde{\chi}^0_1$

- Once one has the efficiency tables for the simplified model processes, one can read off the efficiencies and re-assemble N_{SUSY} of your model.

no MC simulation is required !

$N^{(i)}_{SUSY} =$

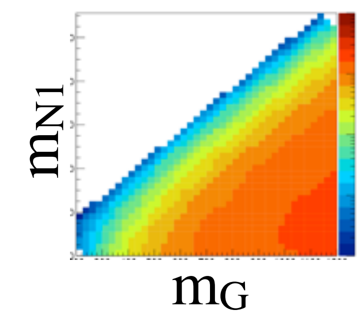
$N_{QqN1:QqN1} =$



$\cdot\ \sigma_{QQ} \cdot BR_{QqN1:QqN1} \cdot L_{int}$

$+$

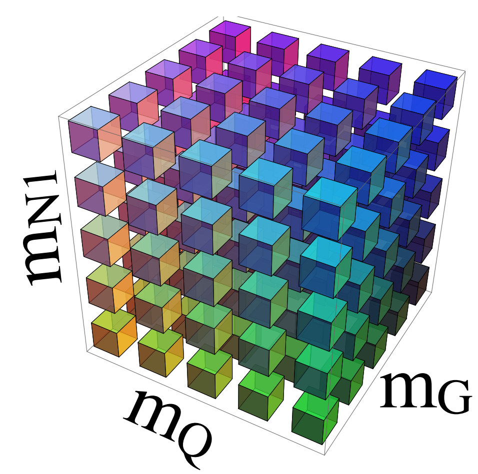
$N_{GqqN1:GqqN1} =$



$\cdot\ \sigma_{GG} \cdot BR_{GqqN1:GqqN1} \cdot L_{int}$

$+$

$N_{GqqN1:QqN1} =$



$\cdot\ \sigma_{GQ} \cdot BR_{GqqN1:QqN1} \cdot L_{int}$

$+$

$\vdots$

- If you are interested in testing it, contact Kazuki Sakurai or me

}

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

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

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

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

Higgsinos

Natural EWSB & SUSY

Fine-tuning of (Higgs mass)^2

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

Higgsinos

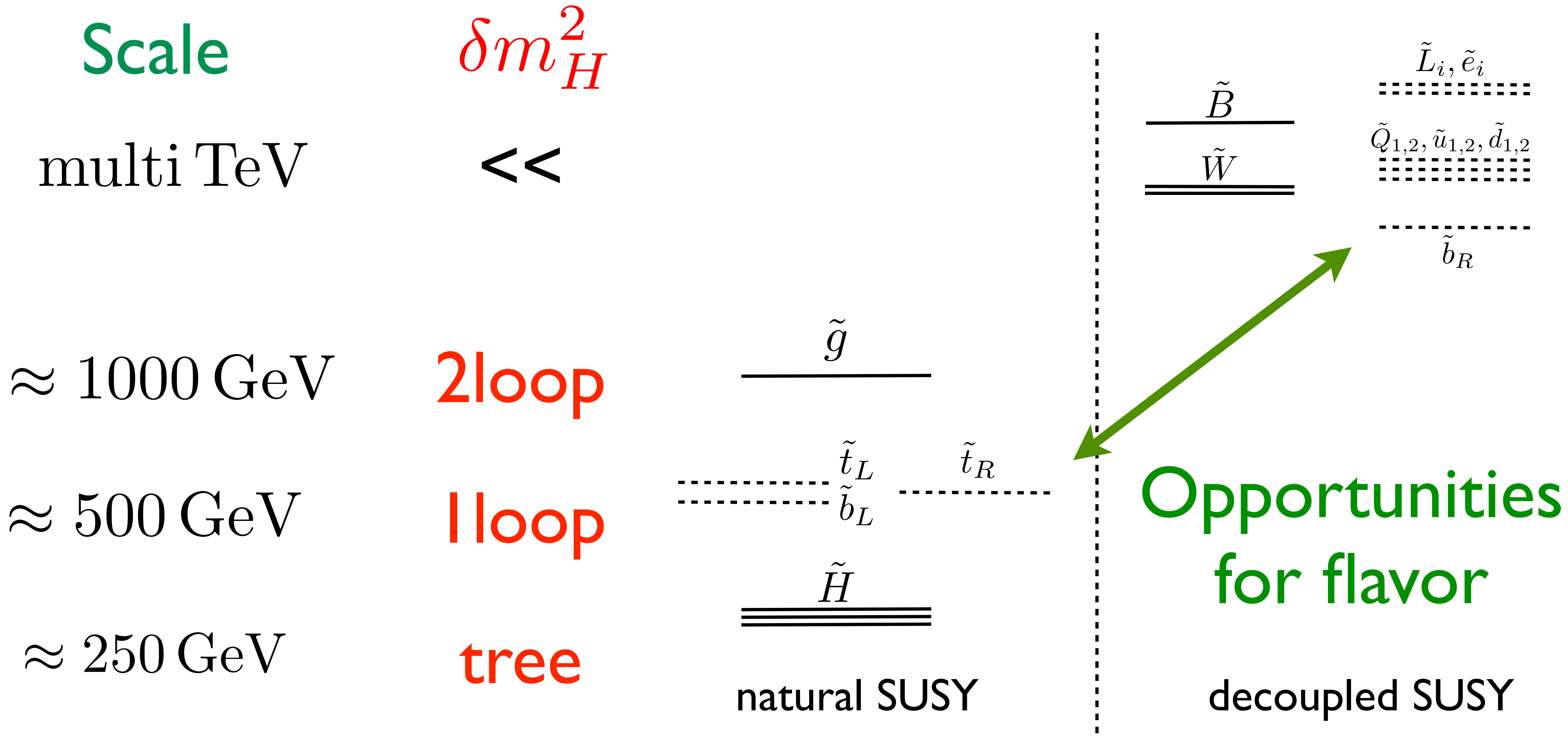
1loop $$\delta m^2_H|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{U_3} + m^2_{Q_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

stops, sbottom$_L$

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

gluino

Reason for optimism: natural susy



Splitting via RGE?

Papucci, Ruderman, AW

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

Splitting via RGE?

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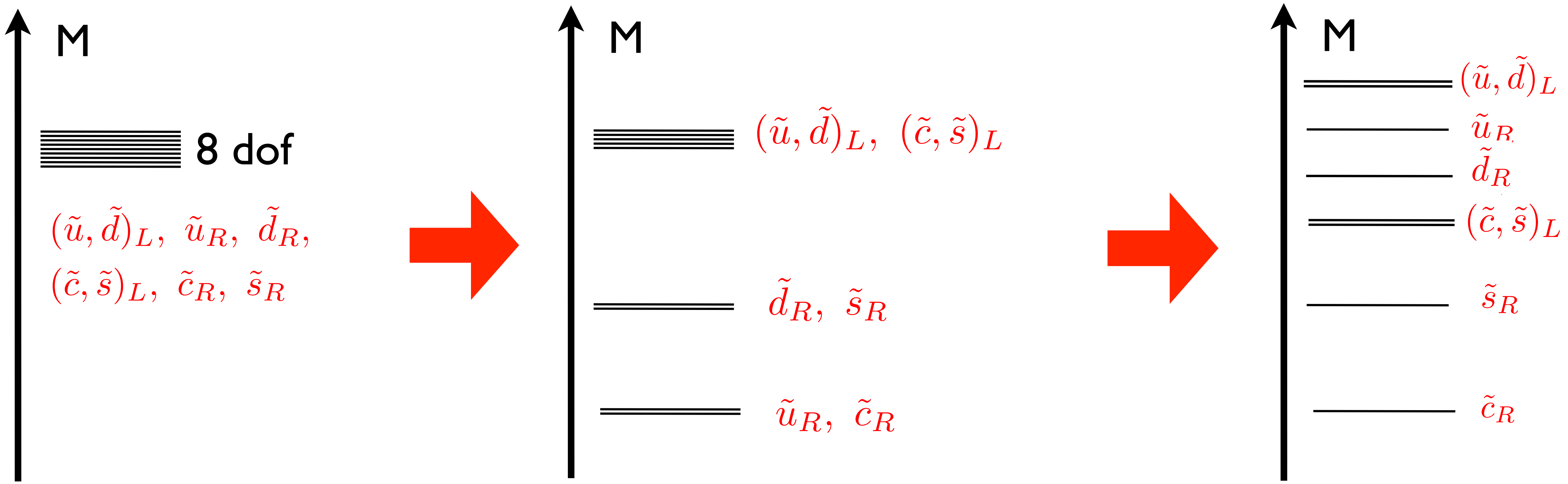
1-loop, LLog, tanß moderate

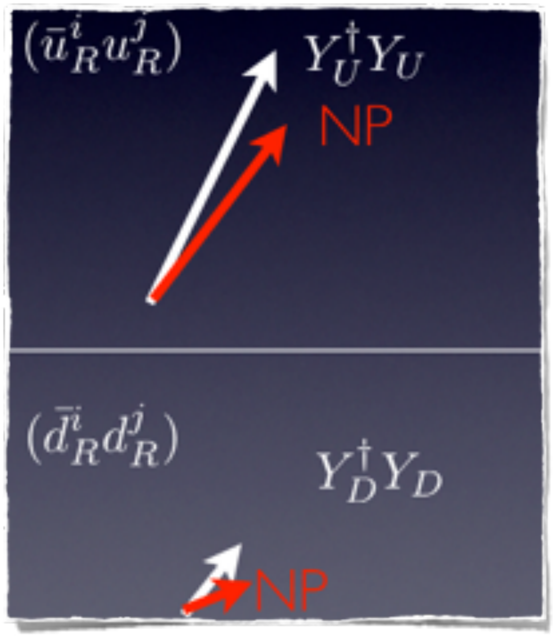
Higgs fine-tuning = RGE mass splitting

→ Flavor non-trivial susy breaking!



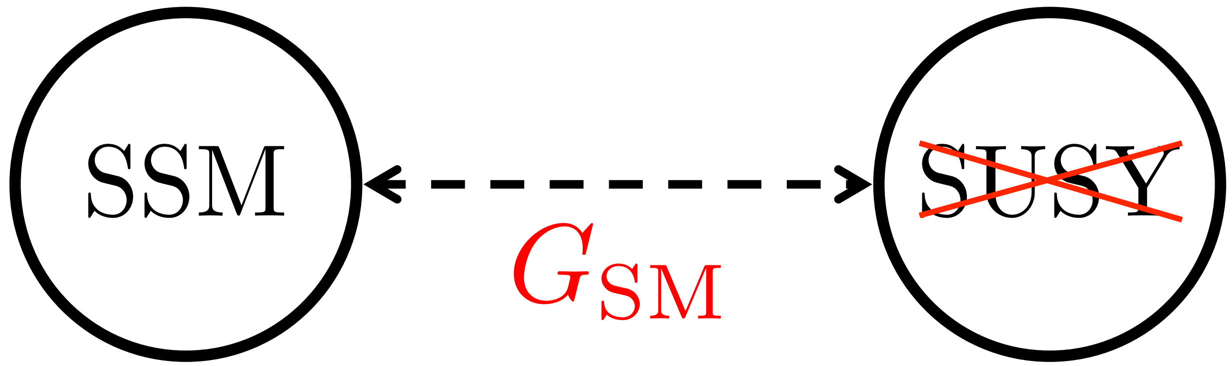
Degenerate | Minimal Flavor | Anarchy!

mSugra, CMSSM,
pMSSM, . . .



Gauge Mediation

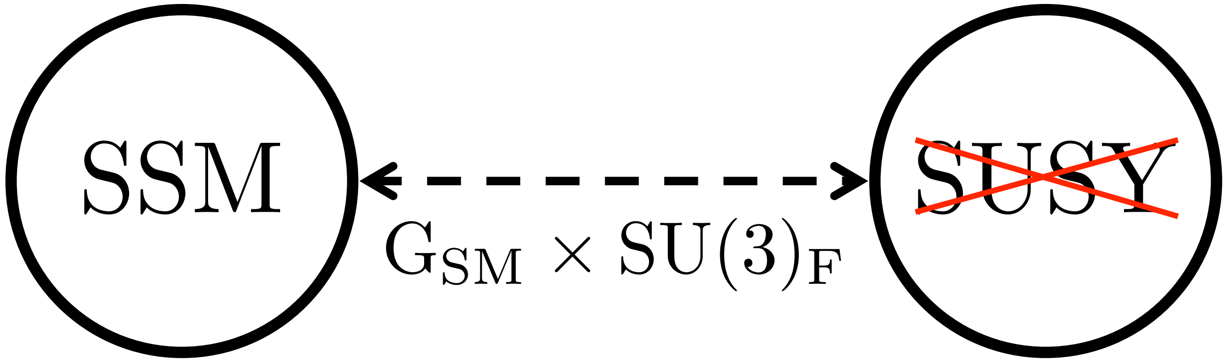
see e.g. Giudice/Rattazzi



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

Flavor Gauge Mediation

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



- Gauge flavor group $SU(3)_F$ *
- Break flavor and susy simultaneously, e.g.

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

$\Sigma,\ \Sigma'$ in $\bar{\mathbf{6}}$ of $\mathrm{SU}(3)_\mathrm{F}$

$$W = \frac{\Sigma}{\Lambda} H_u Q U + \frac{\Sigma'}{\Lambda} H_d Q D$$

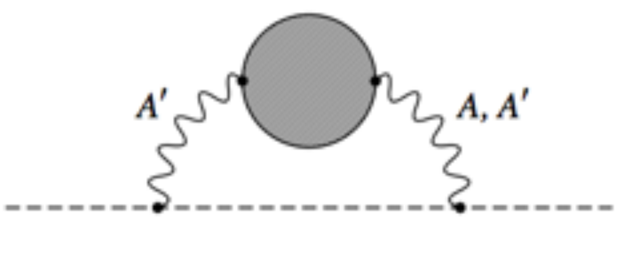
$$\langle \Sigma \rangle / \Lambda = Y_u \qquad \langle X \rangle = (0,\ 0,\ F_X \theta^2)^T$$

=> $$\delta m^2_{Q_I} = -\frac{g_\mathrm{F}^2}{16\pi^2} \frac{|F_X|^2}{|\Sigma_{33}|^2} \begin{pmatrix} \frac{13}{24} & 0 & 0 \\ 0 & \frac{13}{24} & 0 \\ 0 & 0 & \frac{7}{6} \end{pmatrix}$$

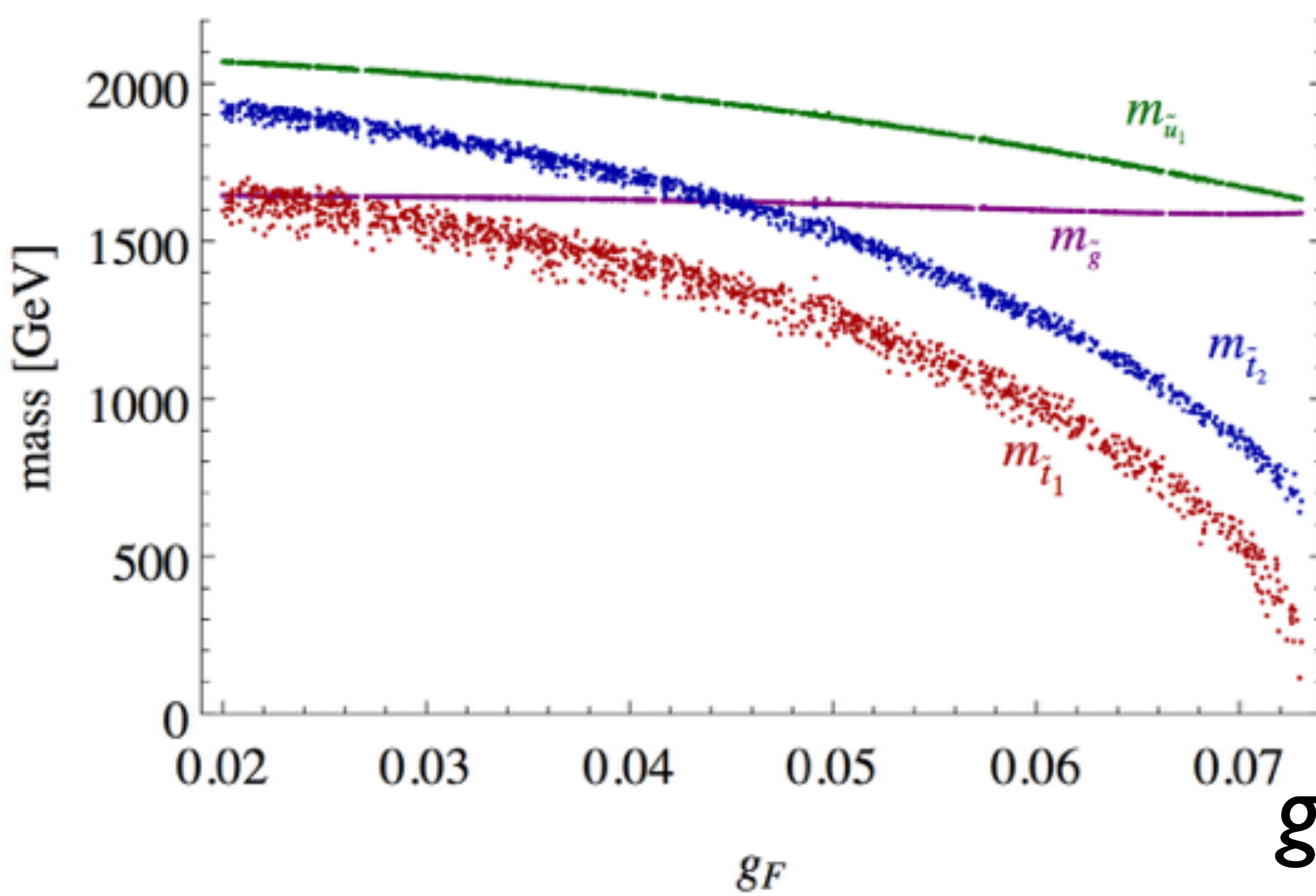
Natural Split spectrum

Brümmer, McGarrie, Weiler

Tachyonic 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}

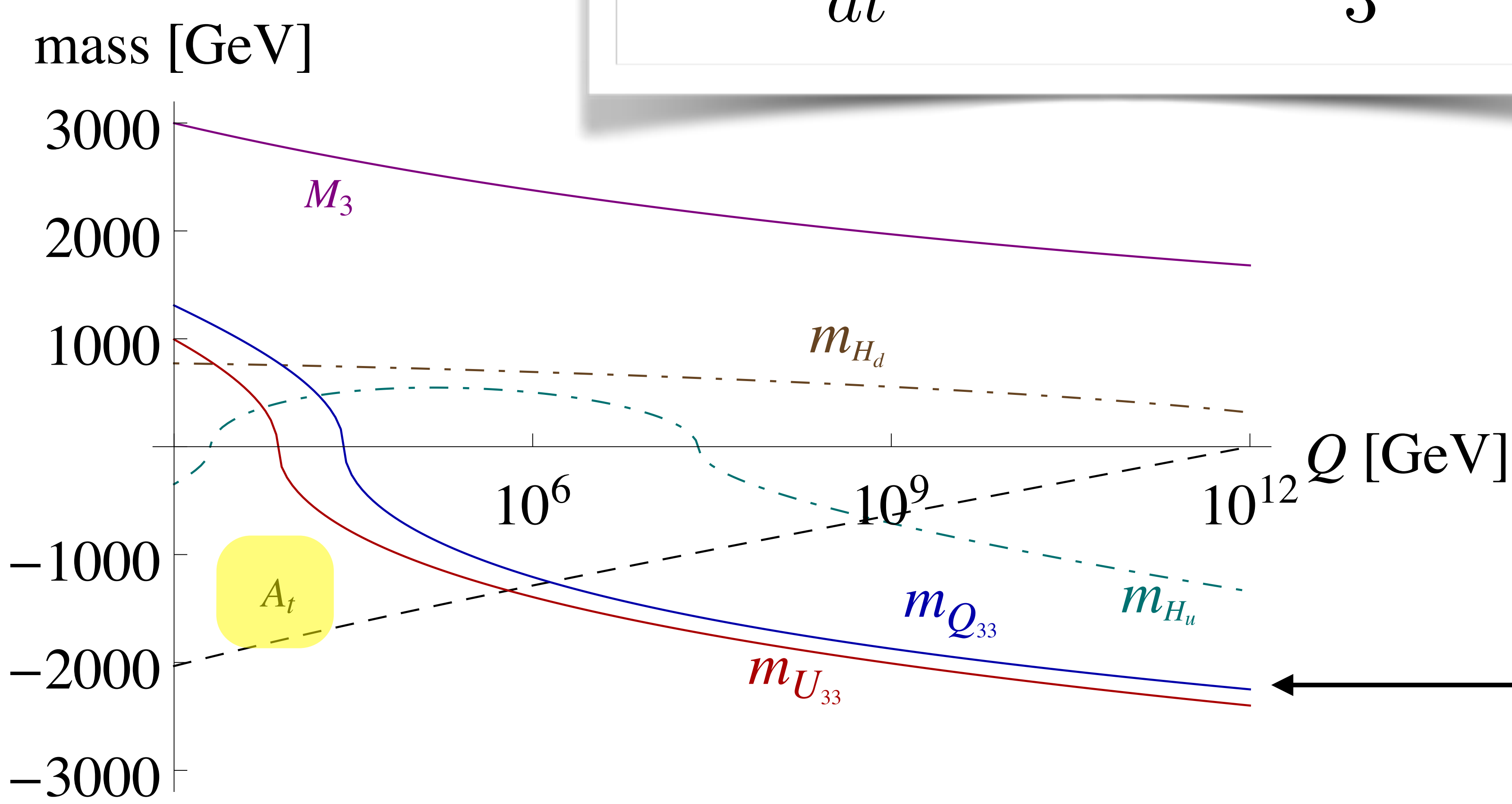
g_{Flavor}

A-terms through RGE

see e.g. Shih et al

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

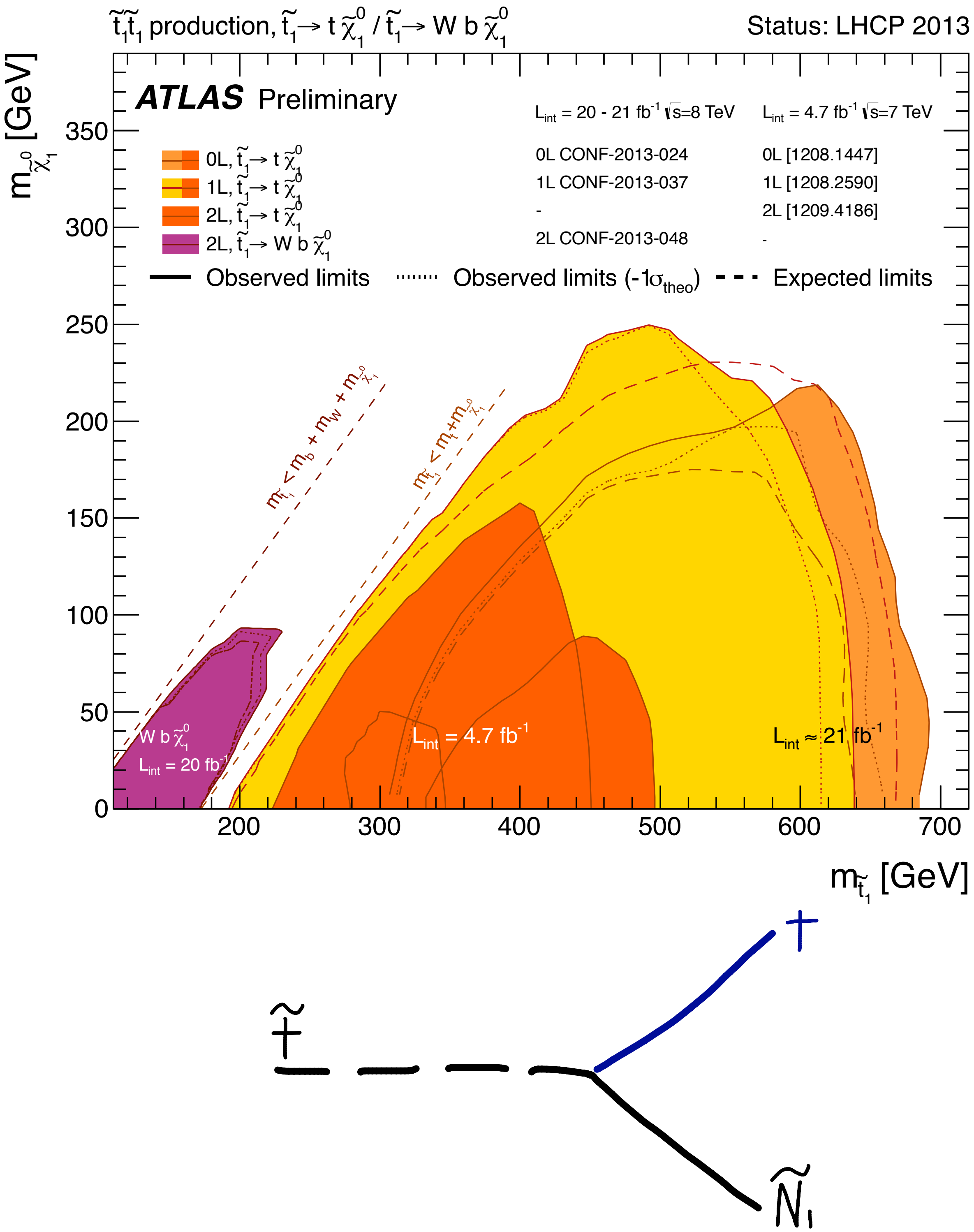
$$16\pi^2 \frac{dA_t}{dt} \approx 12 y_t^2 A_t + \frac{32}{3} g_3^2 M_3$$



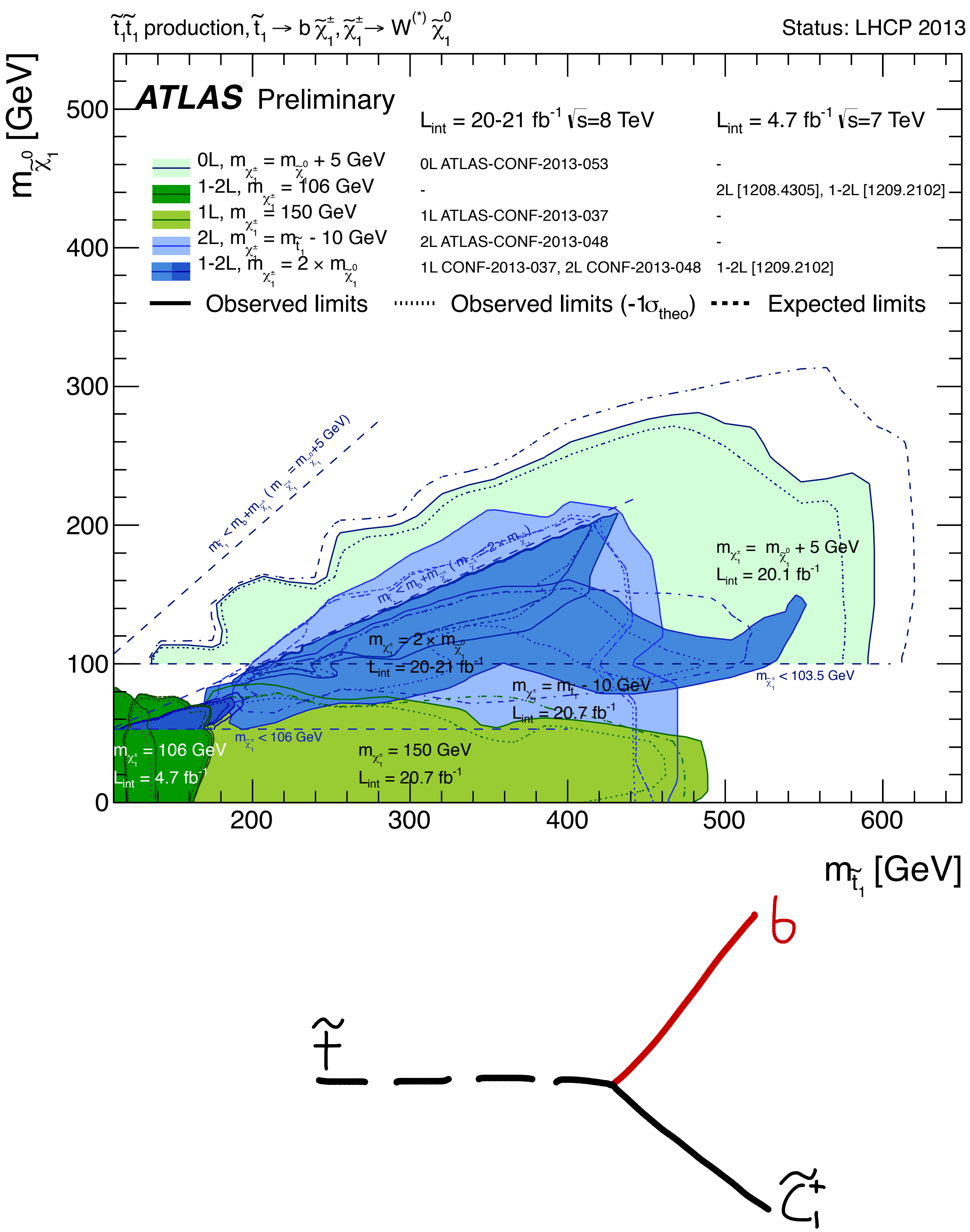
tachyonic stops at messenger scale

F. Brümmer, M. McGarrie, AW

stop limits



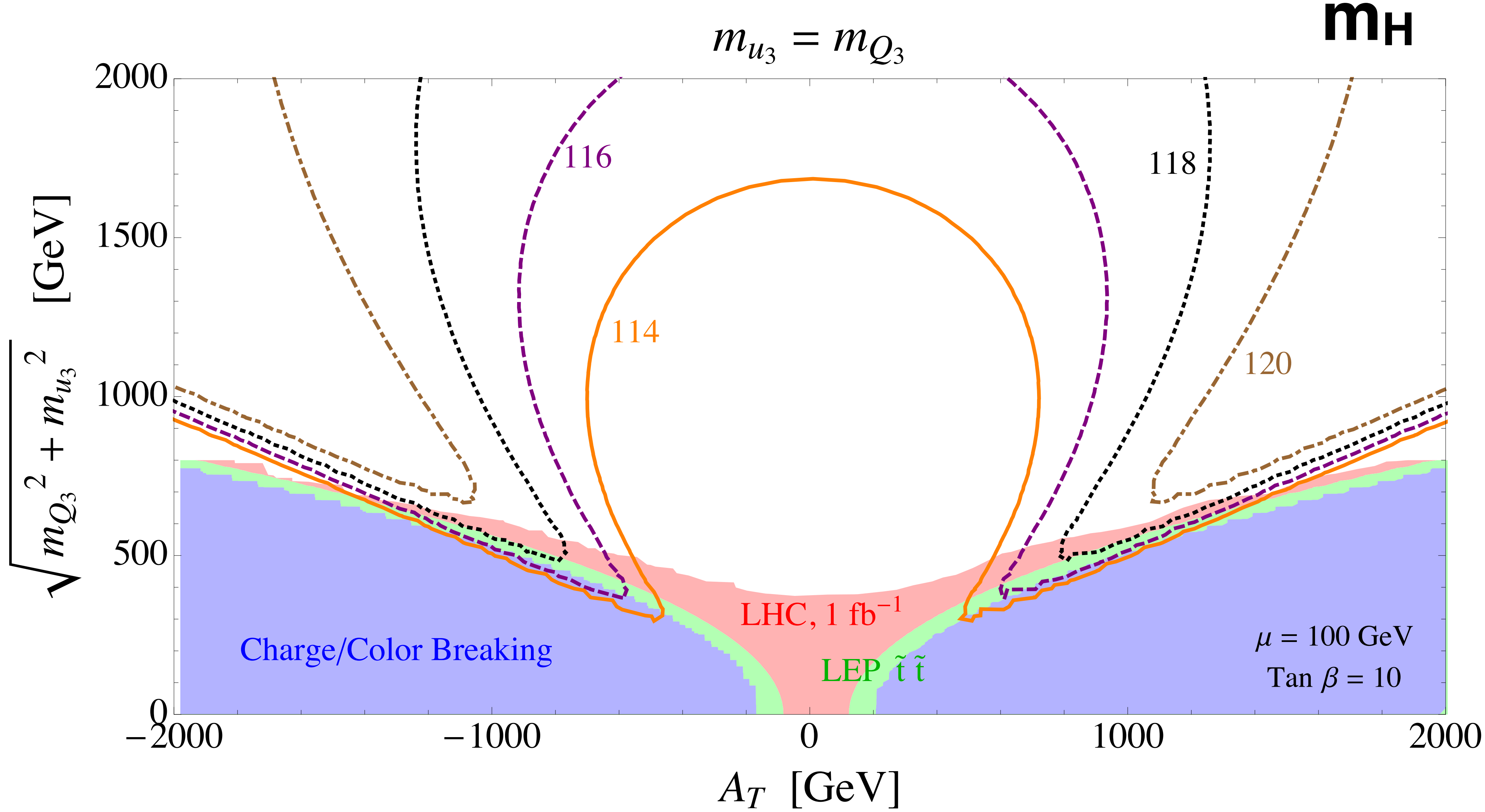
$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$
Status: LHCP 2013
ATLAS Preliminary
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$ 0L CONF-2013-024 0L [1208.1447]
1L, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$ 1L CONF-2013-037 1L [1208.2590]
2L, $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$ - 2L [1209.4186]
2L, $\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$ 2L CONF-2013-048 -
Observed limits
Observed limits (-1σ_{theo})
Expected limits
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
W b $\tilde{\chi}_1^0$
L_{int} = 20 fb^{-1}
L_{int} = 4.7 fb^{-1}
$L_{int} \approx$ 21 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
t
$\tilde{t}$
$\tilde{N}_1$



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to W^{(*)}\,\tilde{\chi}_1^0$
Status: LHCP 2013
ATLAS Preliminary
L_{int} = 20-21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$ + 5 GeV 0L ATLAS-CONF-2013-053 -
1-2L, $m_{\tilde{\chi}_1^\pm}$ = 106 GeV - 2L [1208.4305], 1-2L [1209.2102]
1L, $m_{\tilde{\chi}_1^\pm}$ = 150 GeV 1L ATLAS-CONF-2013-037 -
2L, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1}$ - 10 GeV 2L ATLAS-CONF-2013-048 -
1-2L, $m_{\tilde{\chi}_1^\pm}$ = 2 × $m_{\tilde{\chi}_1^0}$ 1L CONF-2013-037, 2L CONF-2013-048 1-2L [1209.2102]
Observed limits
Observed limits (-1σ_{theo})
Expected limits
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$ + 5 GeV
L_{int} = 20.1 fb^{-1}
$m_{\tilde{\chi}_1^\pm}$ = 2 × $m_{\tilde{\chi}_1^0}$
L_{int} = 20-21 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1}$ - 10 GeV
L_{int} = 20.7 fb^{-1}
$m_{\tilde{\chi}_1^\pm}$ = 106 GeV
L_{int} = 4.7 fb^{-1}
$m_{\tilde{\chi}_1^\pm}$ = 150 GeV
L_{int} = 20.7 fb^{-1}
$m_{\tilde{\chi}_1^\pm}$ < 103.5 GeV
$m_{\tilde{\chi}_1^\pm}$ < 106 GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
b
$\tilde{t}$
$\tilde{C}_1^+$

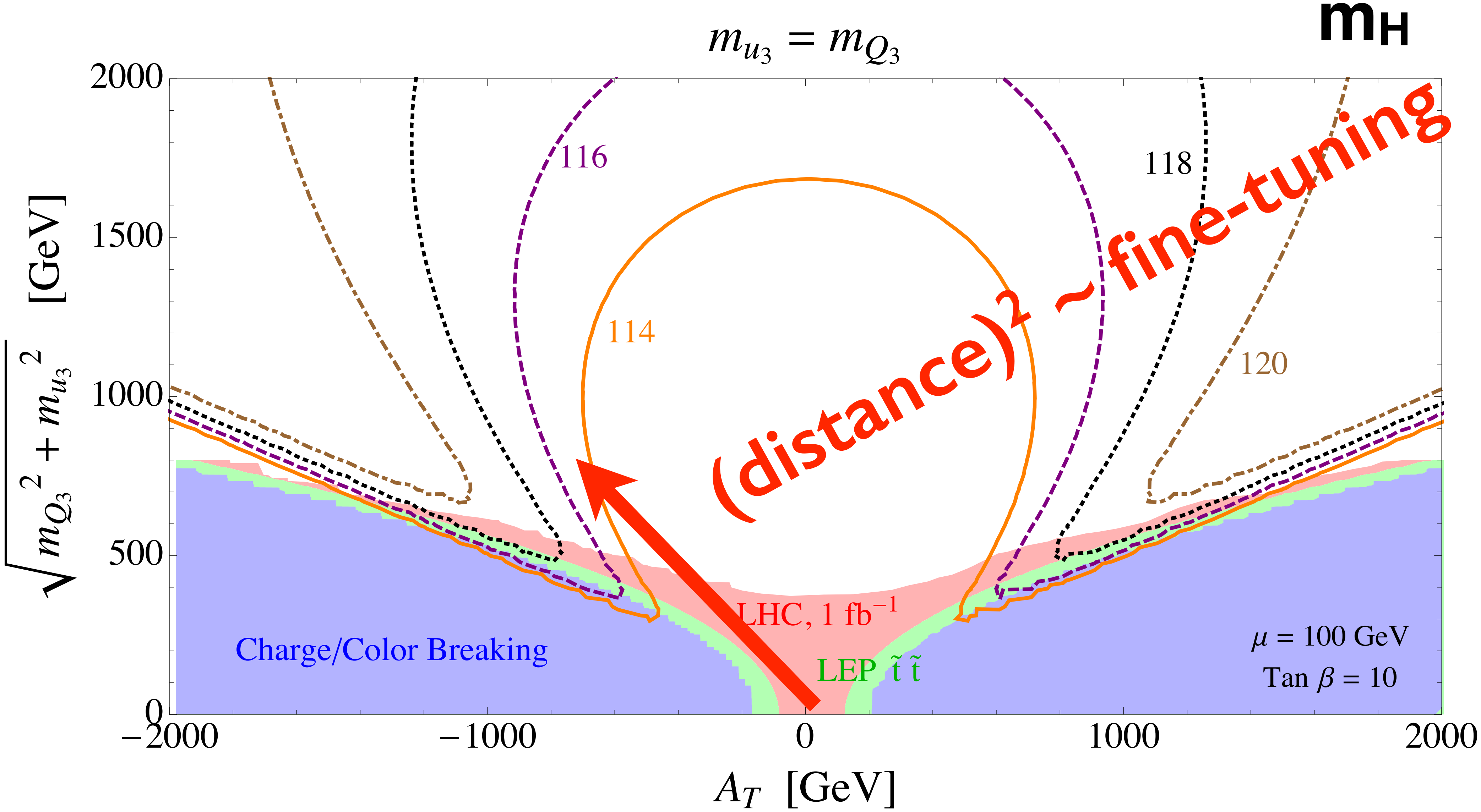
Papucci, Rudermann, AW

m_H



Papucci, Rudermann, AW

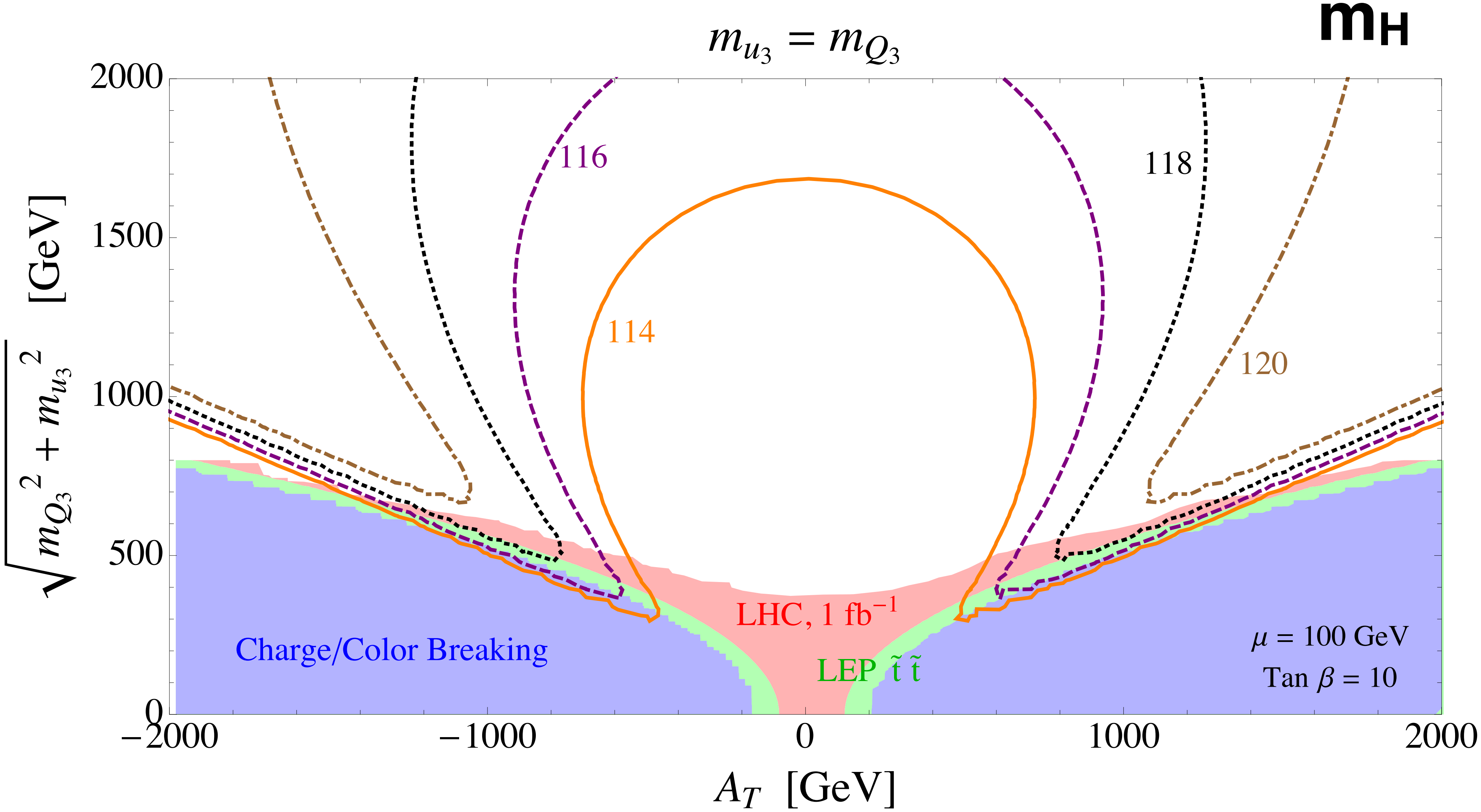
m_H



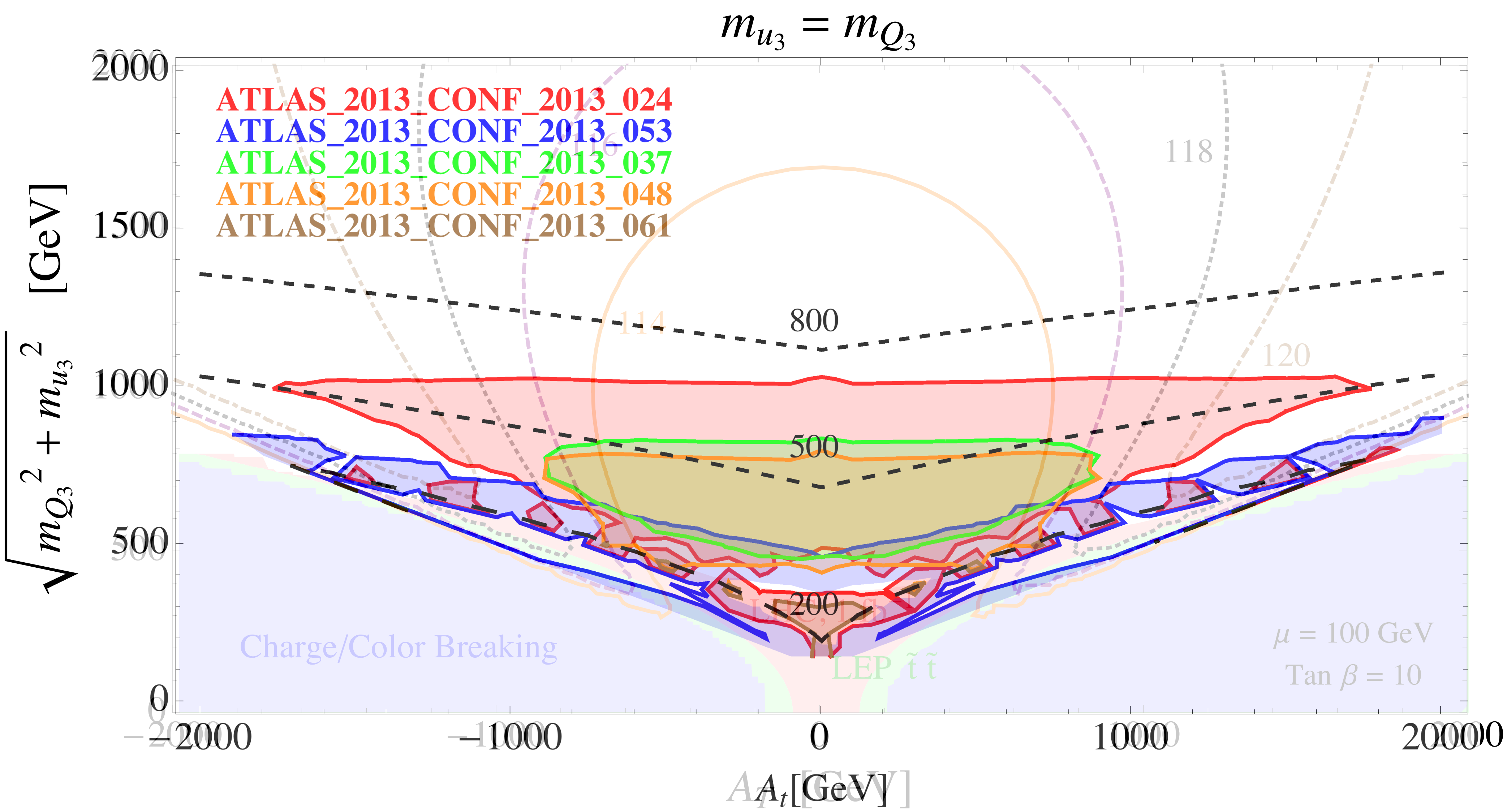
$$\delta m_H^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\text{TeV}} \right)$$

1 fb^{-1} 7 TeV Limits

Papucci, Rudermann, AW

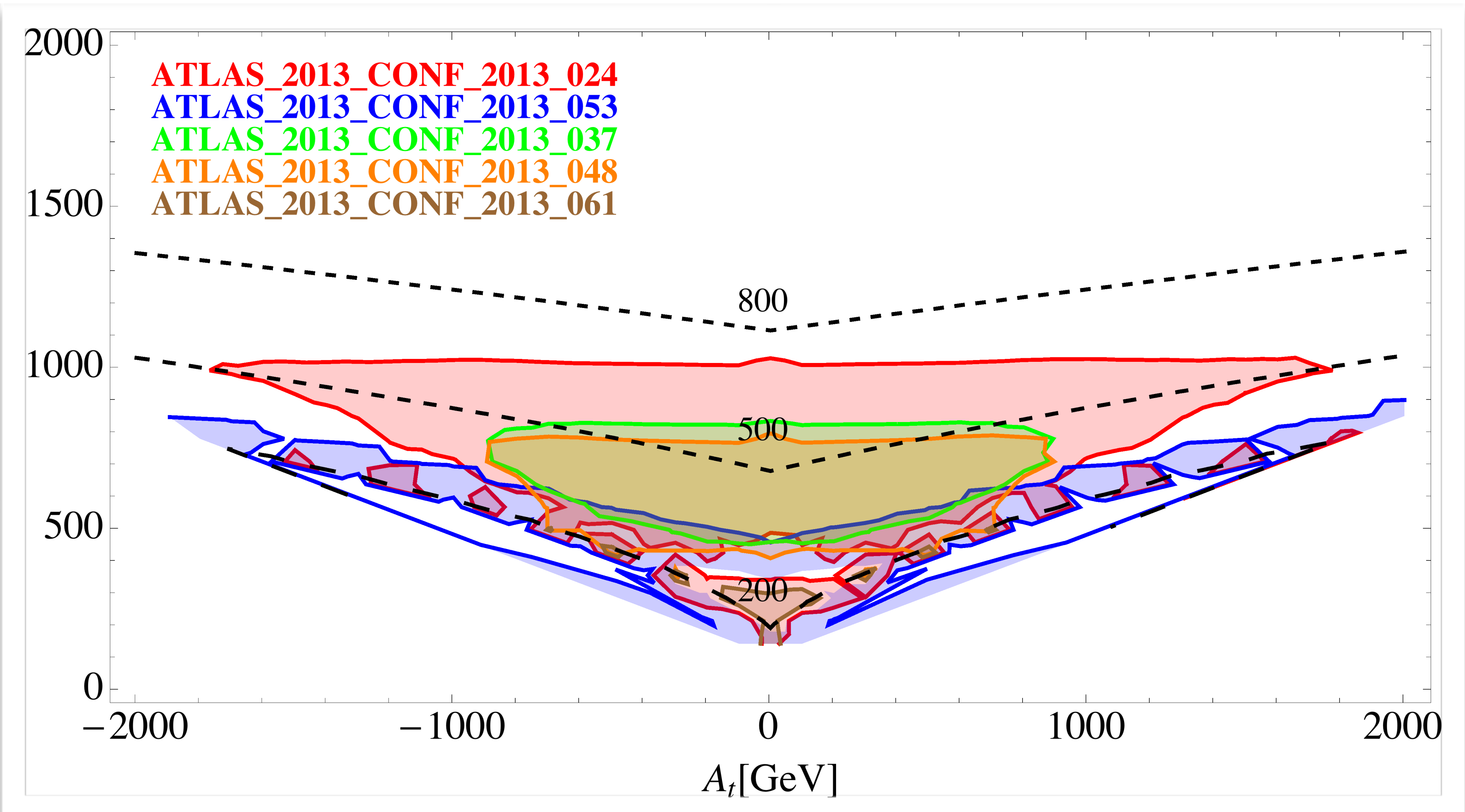


20 fb^{-1} 8 TeV Limits (fastlim)



Papucci,Sakurai, AW, Zeune

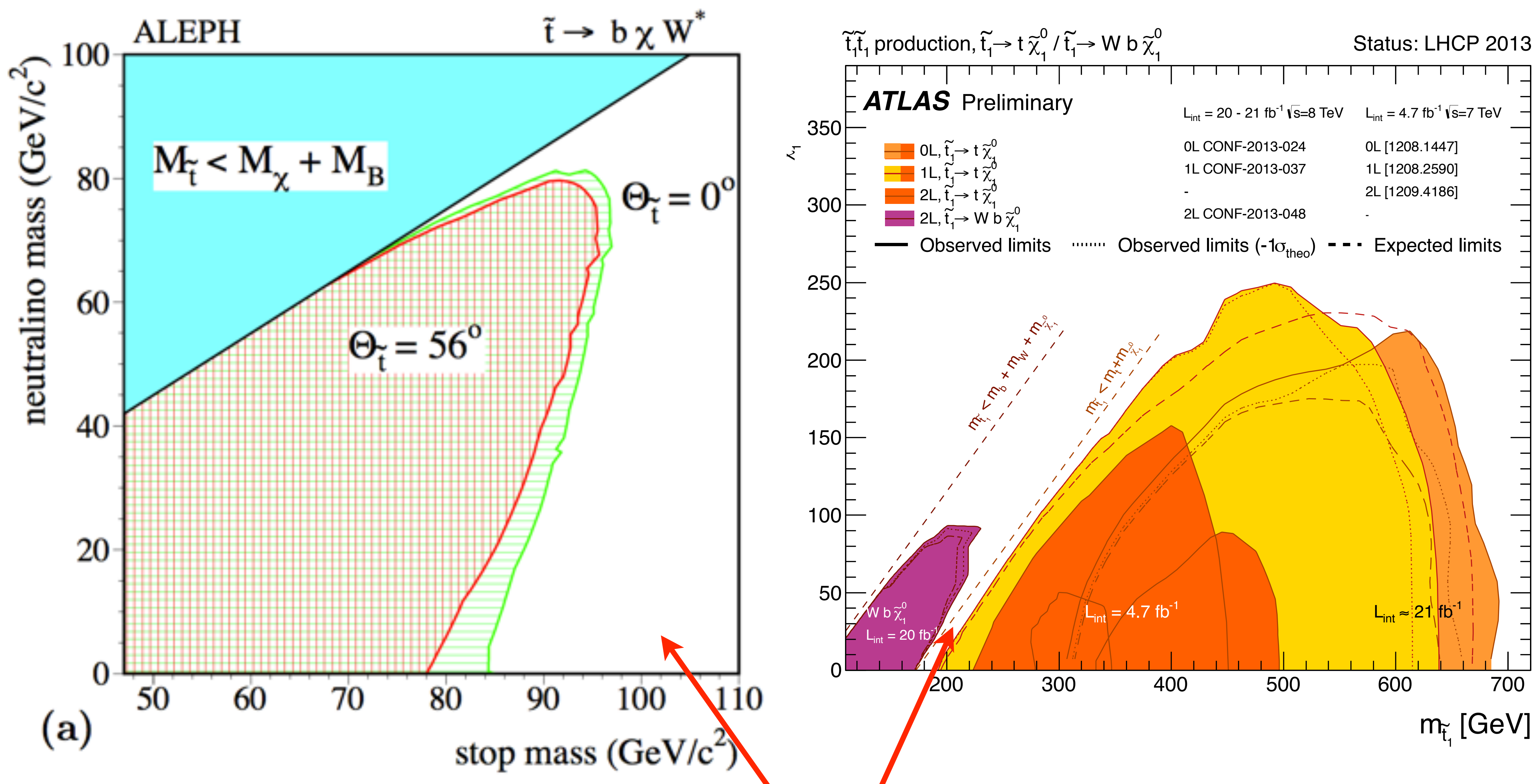
20 fb^{-1} 8 TeV Limits (fastlim)



Papucci,Sakurai, AW, Zeune

killing the stealth stop

stop gaps



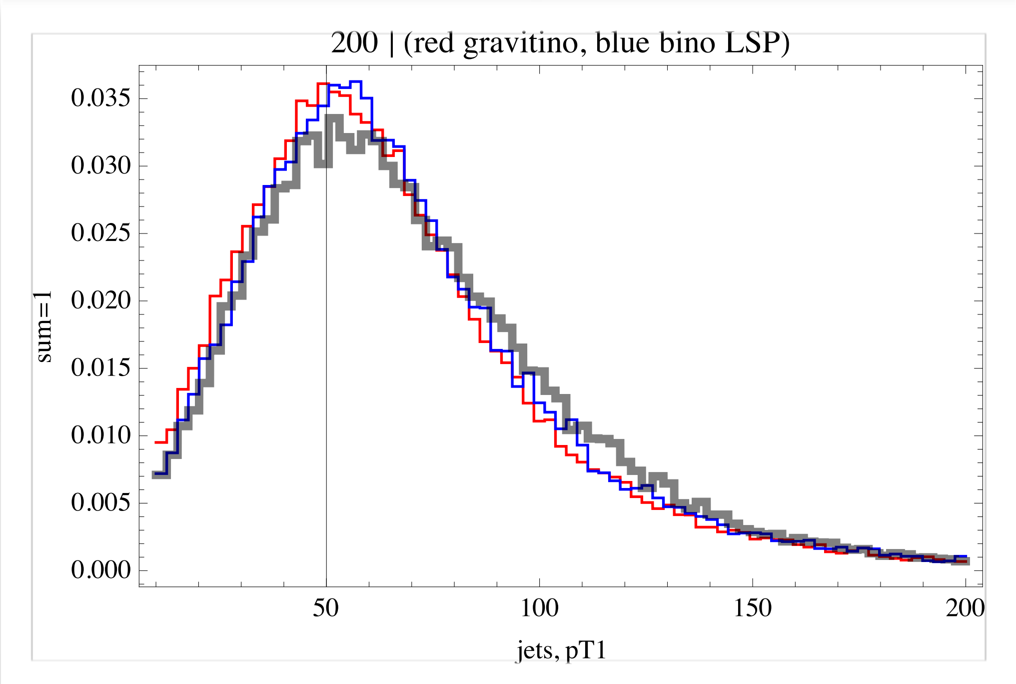
gaps

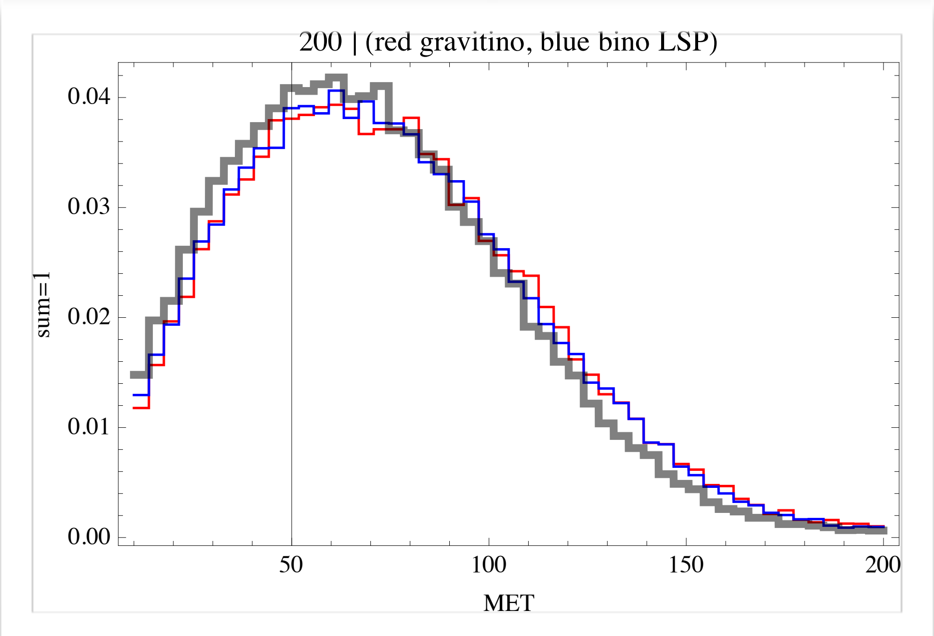
$$m_{\tilde{t}} \approx 80 - 110,\ 170 - 190 \text{ GeV}$$

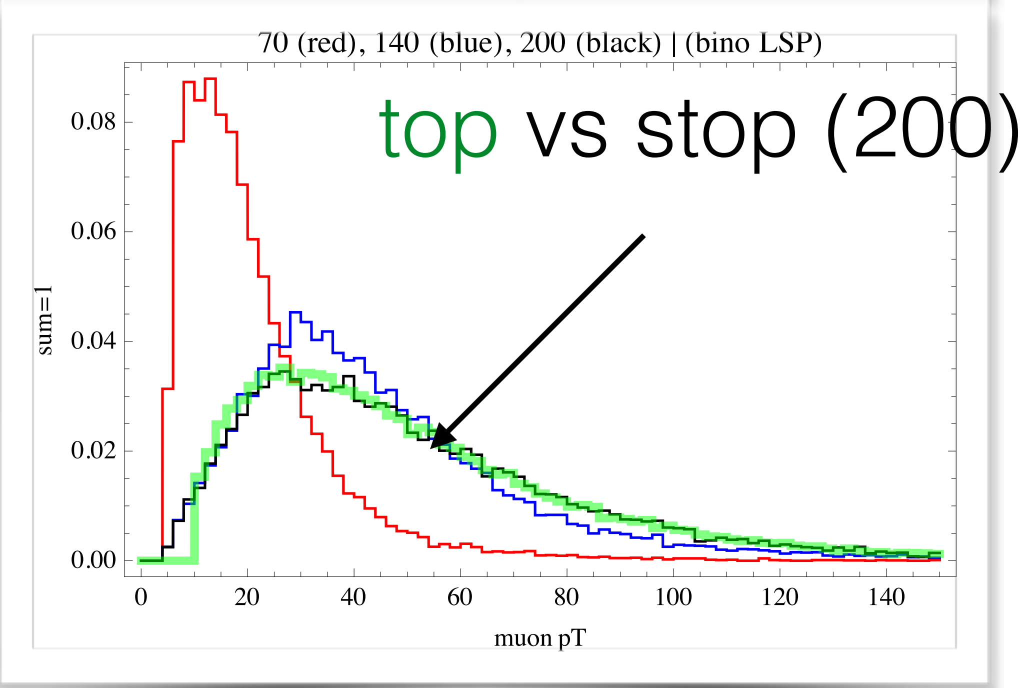
Stealthy stop

If $m_{\tilde{t}_1} \approx m_t$,decay $\tilde{t}_1 \to t\chi_0$

is 'one-body'







Relax & Wait?

vs.

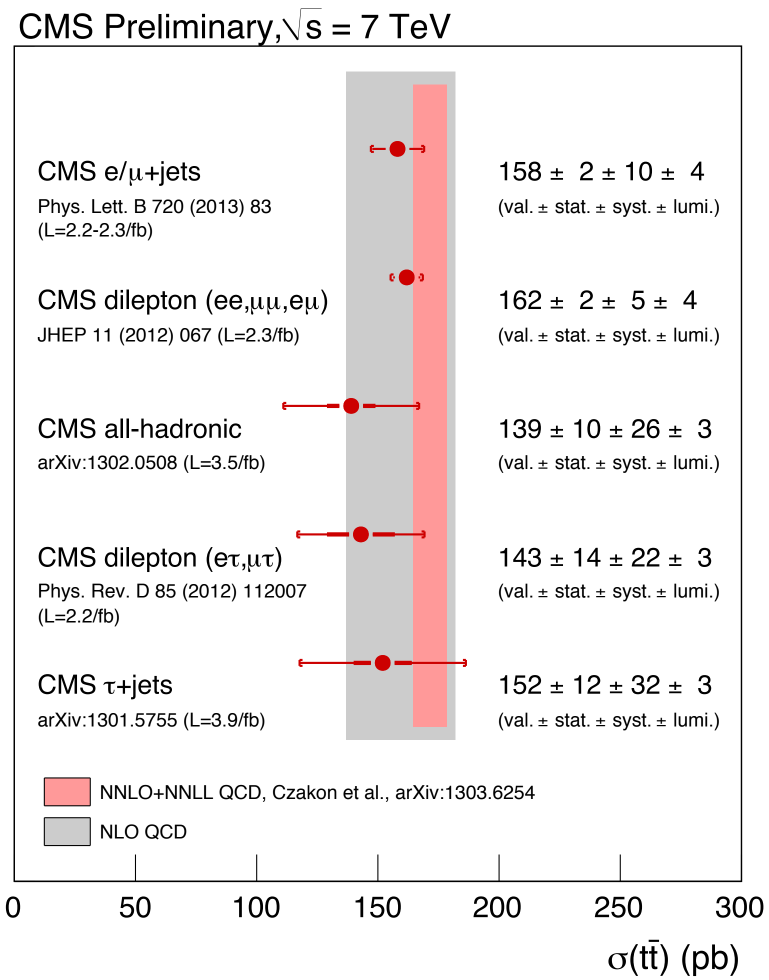
Relax & Wait?

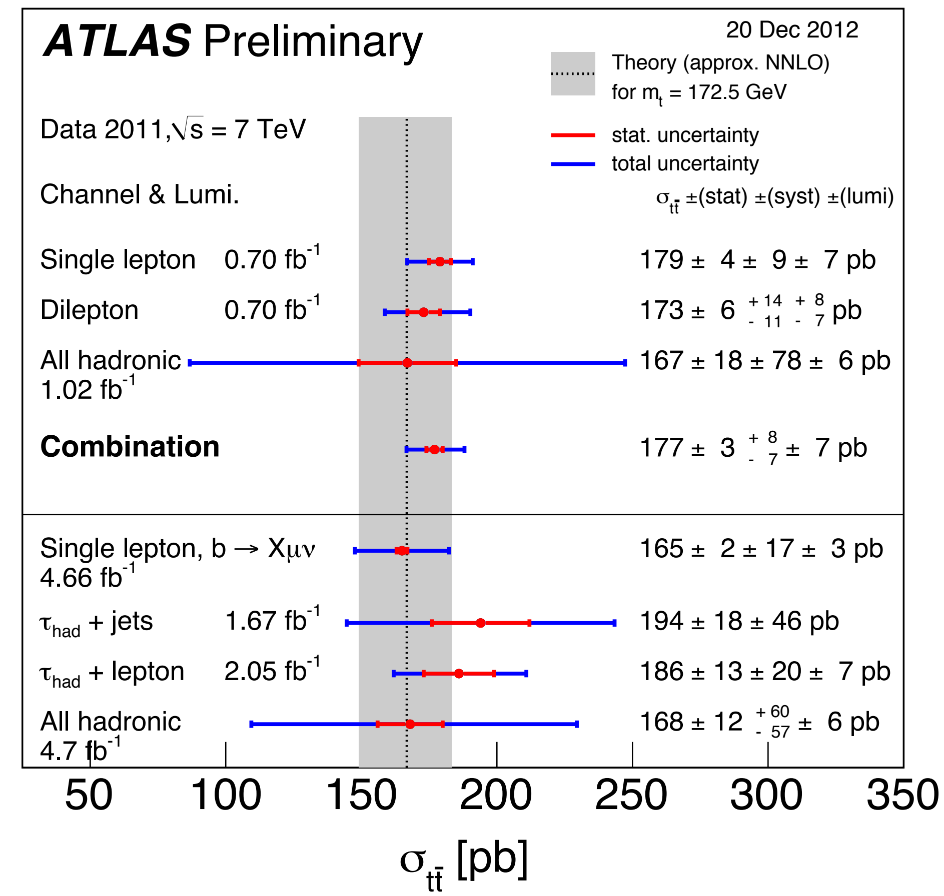
vs.

Let's check!

top cross section

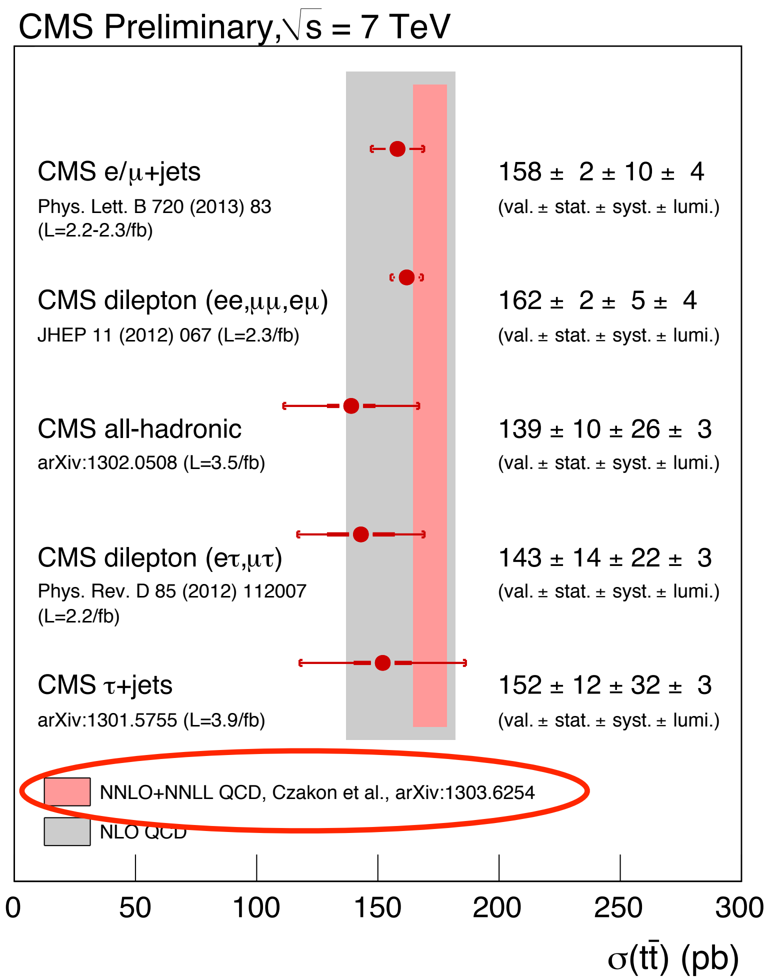
experiment:

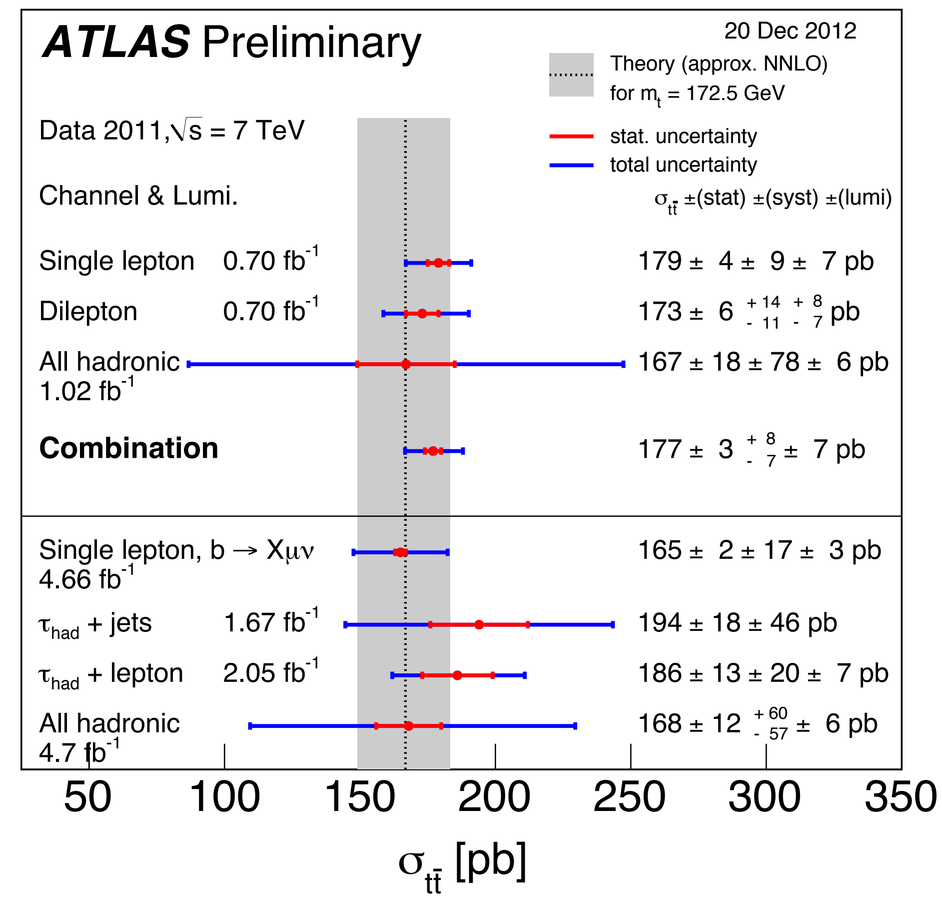




top cross section

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

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

top cross section

the numbers (7 TeV)

$$\sigma_{t\bar{t}} = 172 \text{ pb}$$

NNLO:

$$\delta\sigma_{\text{th}} = 10 \text{ pb} \quad (5.7\%)$$

NLO:

$$\delta\sigma_{\text{th}} = 20 \text{ pb} \quad (12\%)$$

$$\delta\sigma_{\text{exp}} = 7 \text{ pb} \quad (4.2\%)$$

$$\sigma_{\tilde{t}\tilde{t}^*}(m_{\tilde{t}} = m_t) = 26 \text{ pb} \quad (15\%)$$

MC mockup

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

measurement

Theory NNLO+NNLL

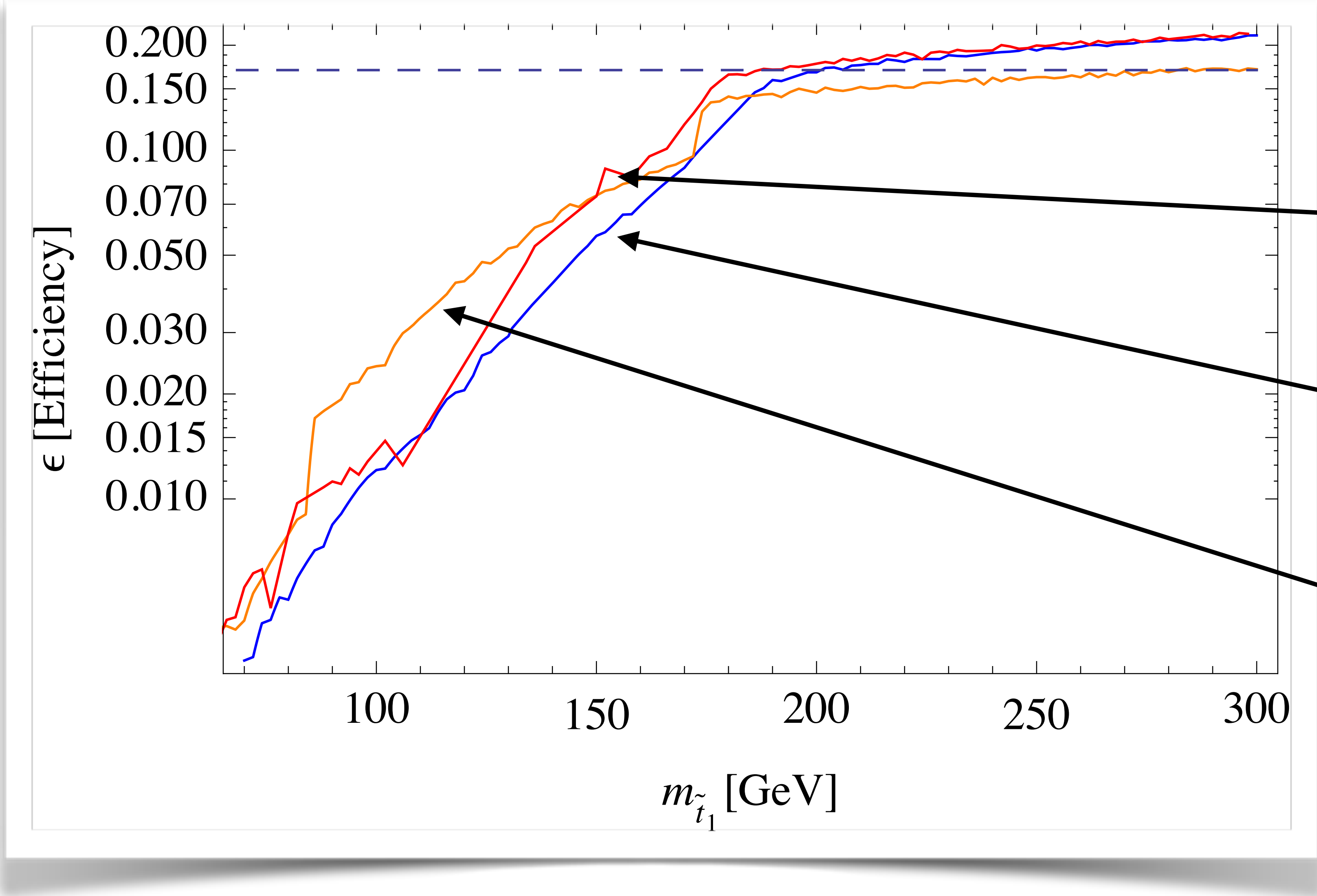
Re-cast top x-sec measurement

Czakon/Mitov/Papucci/Ruderman/AW '13

Di-leptonic top (CMS-TOP-11-005), cut & count

Efficiency:

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



top

Full Matrix-element Bino-LSP

Full Matrix-element Gravitino-LSP

Small Width Approx. Bino-LSP

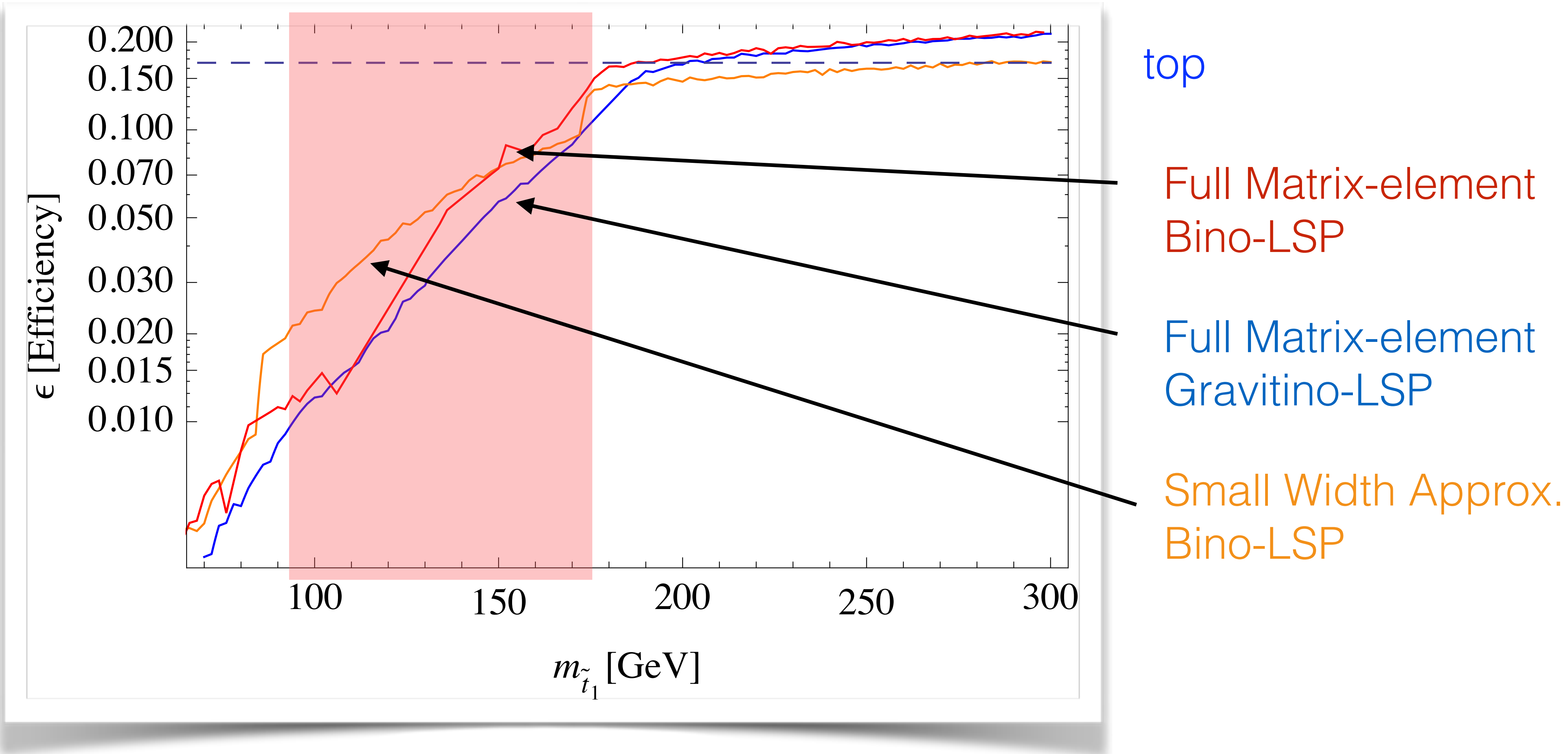
Re-cast top x-sec measurement

Czakon/Mitov/Papucci/Ruderman/AW '13

Di-leptonic top (CMS-TOP-11-005), cut & count

Efficiency:

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



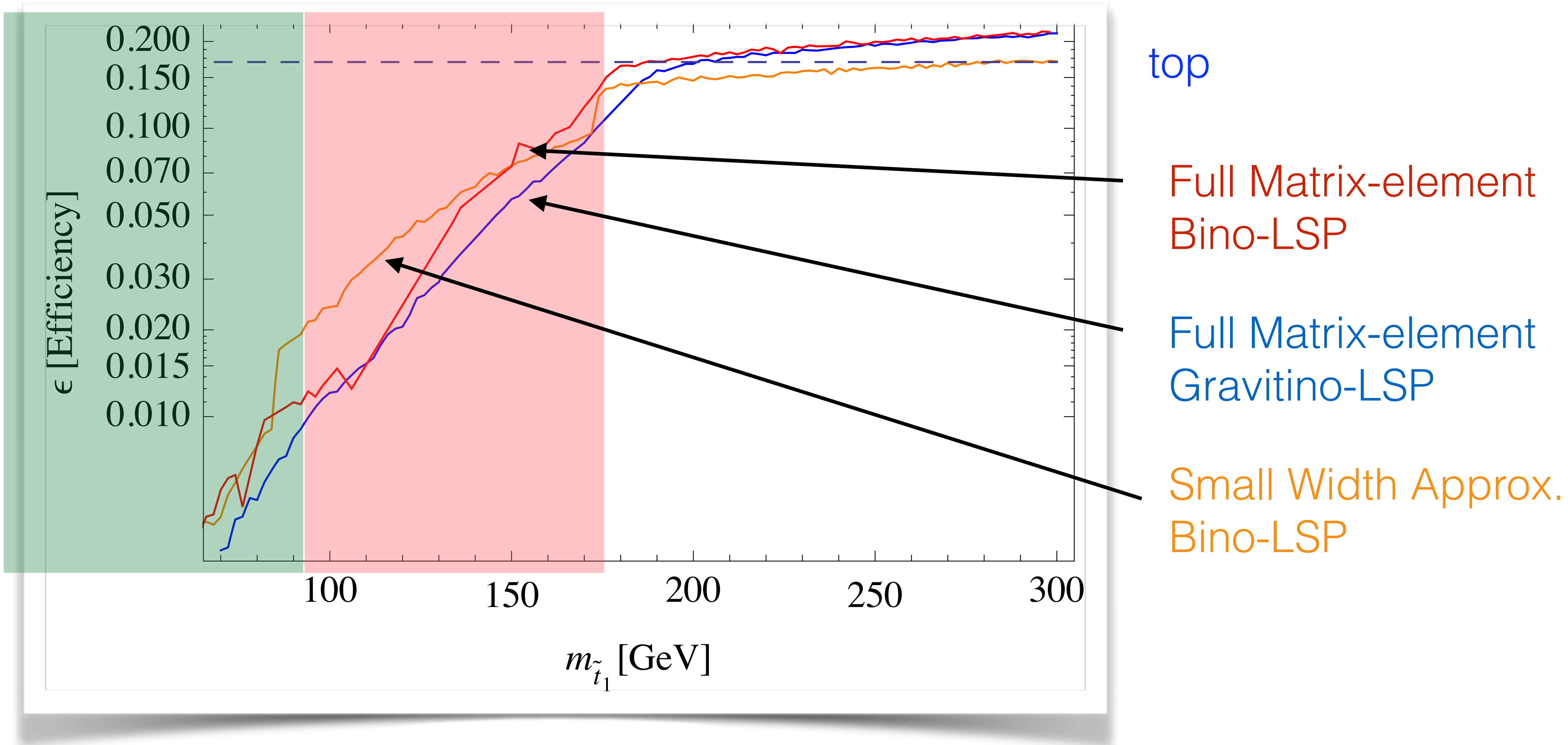
Re-cast top x-sec measurement

Czakon/Mitov/Papucci/Ruderman/AW '13

Di-leptonic top (CMS-TOP-11-005), cut & count

Efficiency:

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



stop -> gravitino + X

$$\psi_\mu \to -\sqrt{\frac{2}{3}}\,\frac{\partial_\mu \psi}{m_{\tilde{G}}}$$

Goldstino limit ($E >> m_{3/2}$)

$$\mathcal{L}_{\tilde{t}t\tilde{G}} = \frac{i}{F}\,\partial_\nu \tilde{t}^*\,\partial_\mu \overline{\psi}\gamma^\nu\gamma^\mu\,(c_{\tilde{t}}P_L + s_{\tilde{t}}P_R)\,t + \mathrm{h.c.}$$

$$\mathcal{L}_{\tilde{t}Wb\tilde{G}} = \frac{\sqrt{2}}{F}\,g\,c_{\tilde{t}}\,\left(W_\mu^+\,\tilde{t}^*\,\partial^\mu\overline{\psi}P_L b + W_\mu^-\,\tilde{t}\,\overline{b}P_R\,\partial^\mu\psi\right)$$

Couples to ~~susy~~, additional $(m_{\tilde{t}_1} - m_t)^2$ **suppression**

stop -> gravitino + X

$$\psi_\mu \to -\sqrt{\frac{2}{3}}\,\frac{\partial_\mu \psi}{m_{\tilde{G}}}$$

Goldstino limit ($E >> m_{3/2}$)

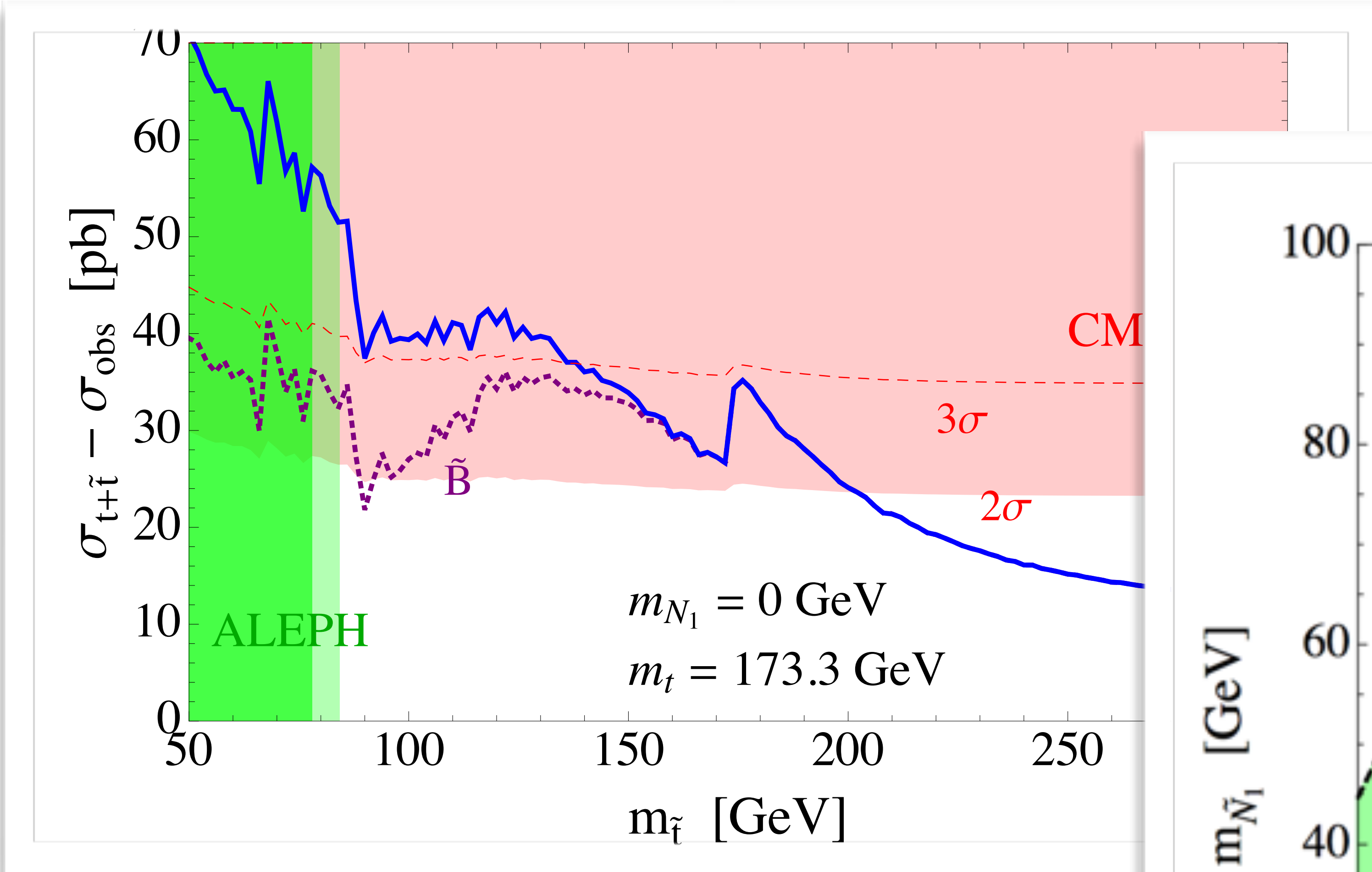
$$\mathcal{L}_{\tilde{t}t\tilde{G}} = \frac{i}{F}\,\partial_\nu \tilde{t}^*\,\partial_\mu \overline{\psi}\gamma^\nu\gamma^\mu\,(c_{\tilde{t}}P_L + s_{\tilde{t}}P_R)\,t + \mathrm{h.c.}$$

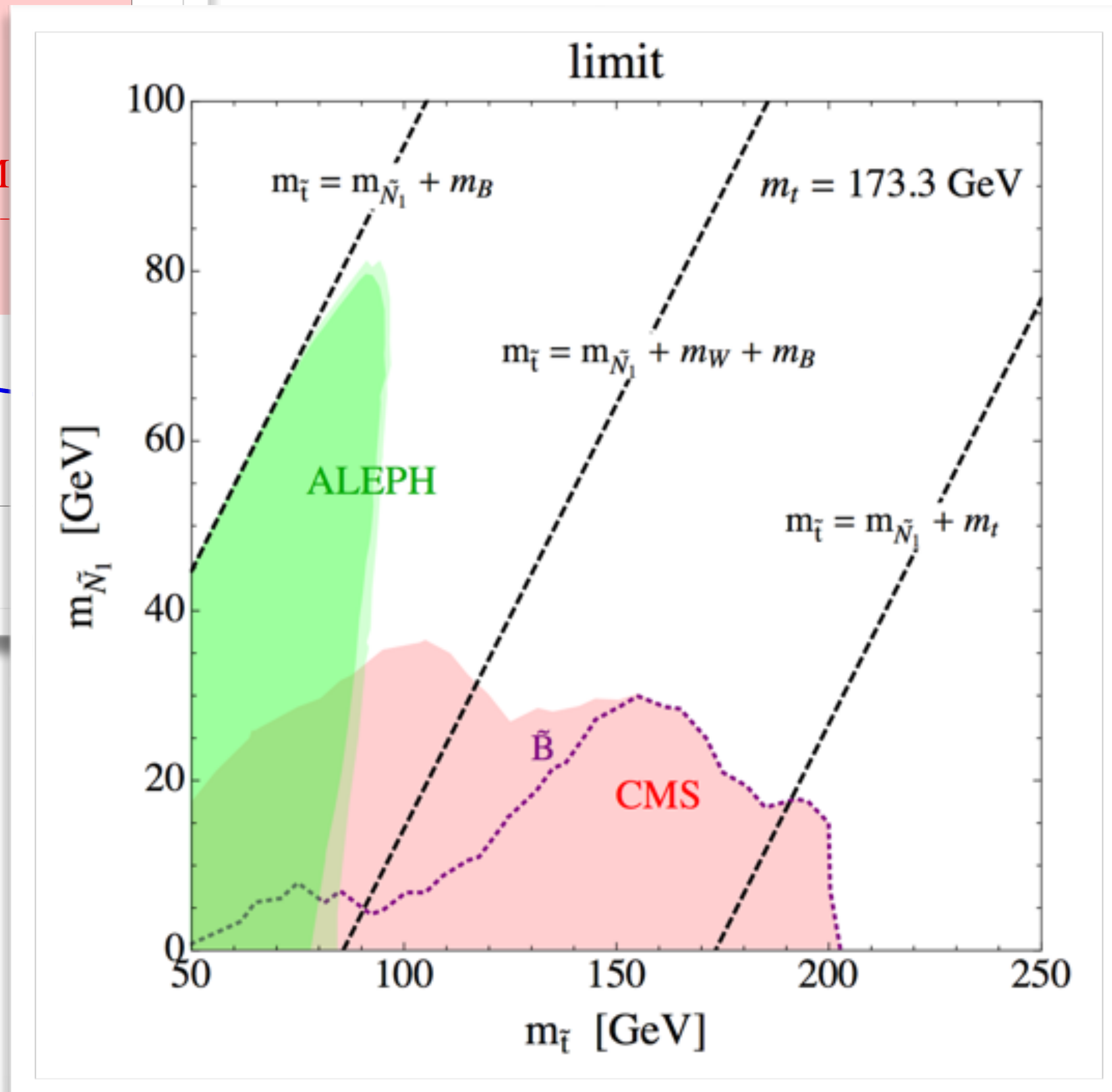
$$\mathcal{L}_{\tilde{t}Wb\tilde{G}} = \frac{\sqrt{2}}{F}\,g\,c_{\tilde{t}}\left(W^+_\mu\,\tilde{t}^*\,\partial^\mu\overline{\psi}P_L b + W^-_\mu\,\tilde{t}\,\overline{b}P_R\,\partial^\mu\psi\right)$$

Couples to ~~susy~~, additional $(m_{\tilde{t}_1} - m_t)^2$ suppression

Stealth stop exclusion

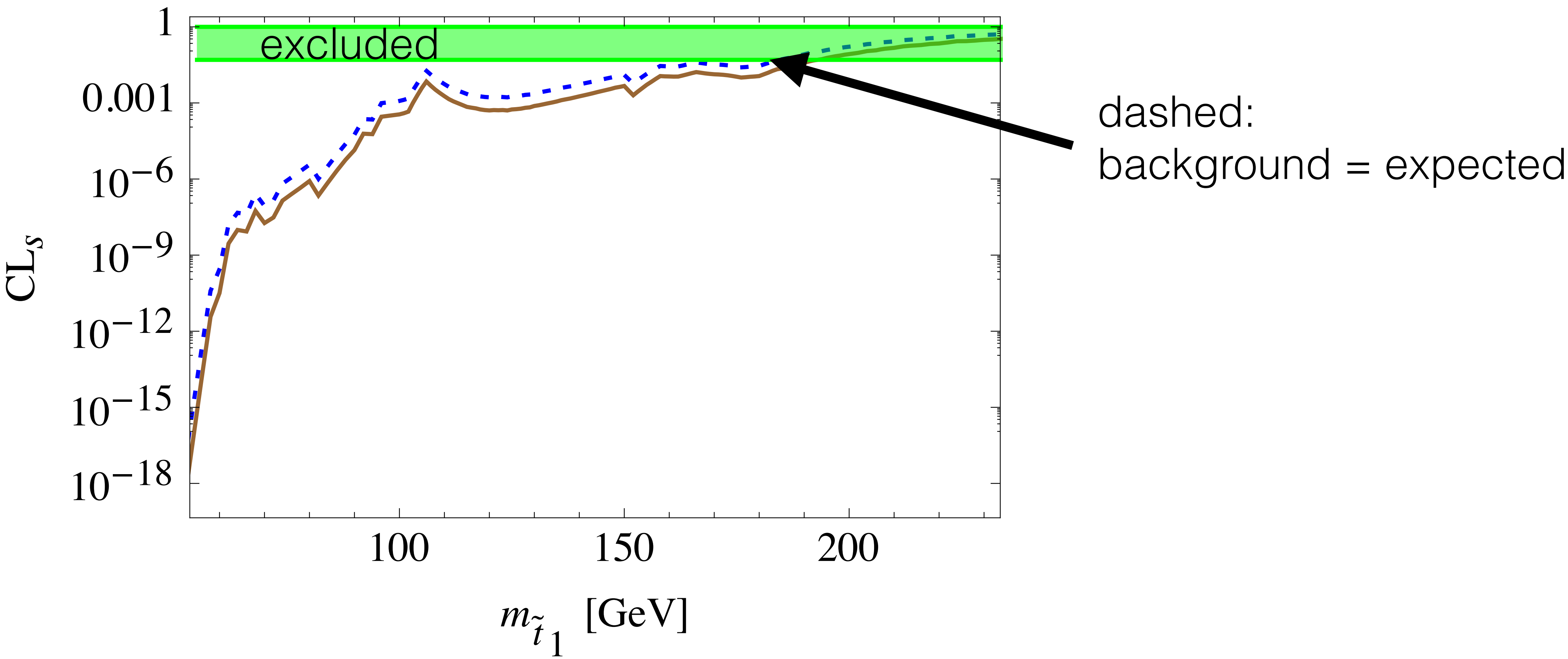
Czakon/Mitov/Papucci/Ruderman/AW '13





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

Exclusion vs. fluctuations



$CL_s = CL_{s+b}/CL_s$ reduces impact of under-fluctuation of background. Even if we set background to expectation, exclusion persists.

Natural

I
Supersymmetry

II
Strong EWSB dynamics
(composite Higgs)

III
Large Extra Dimensions

Un-natural

IV
Multiverse (anthropic principle)

$10^{1000\ldots}$ vacua
of which many have a hierarchy

Expect: just SM + Higgs
+ (possibly weak scale DM)

Natural

I
Supersymmetry

II
Strong EWSB dynamics
(composite Higgs)

III
Large Extra Dimensions

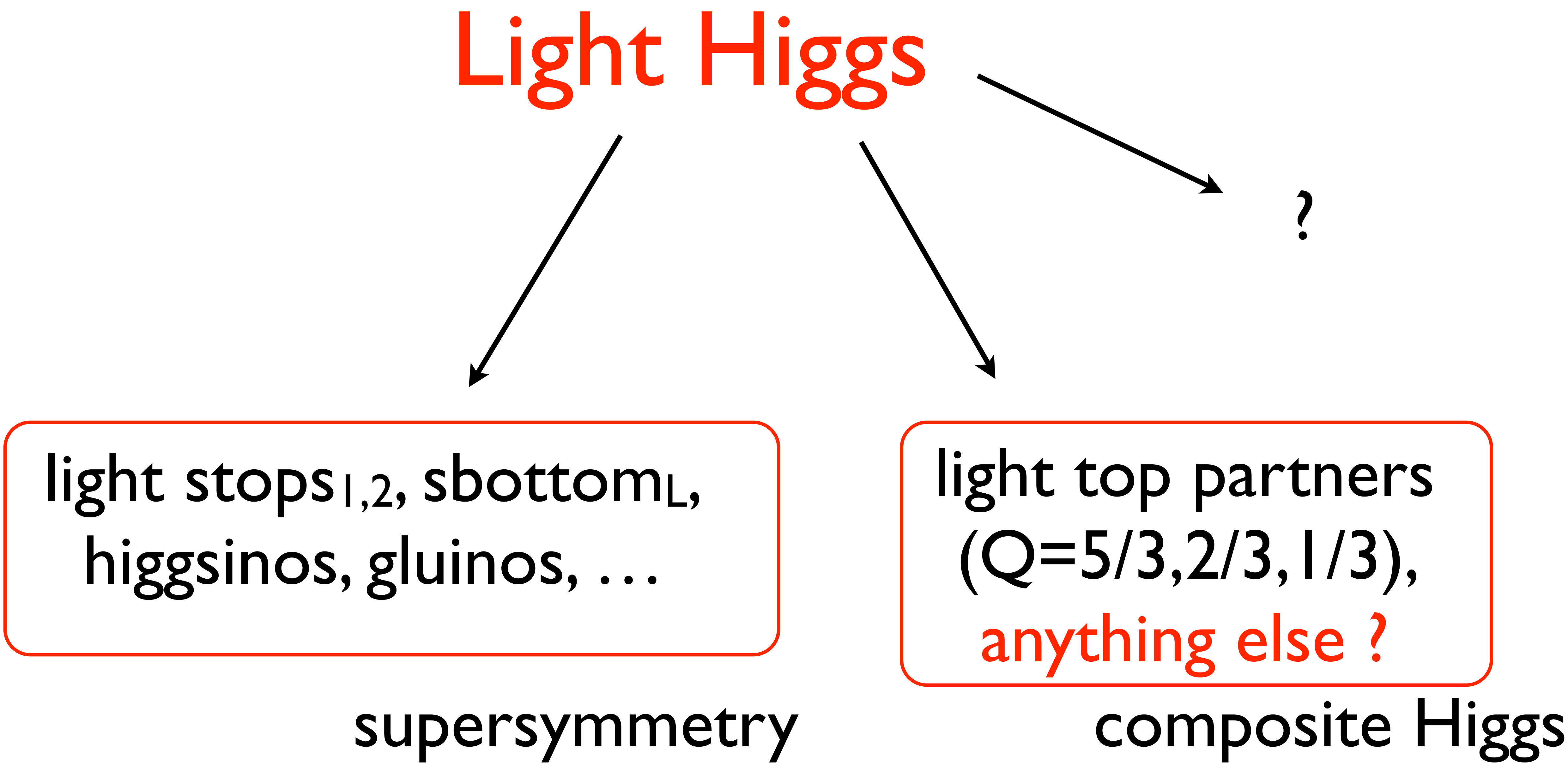
Natural

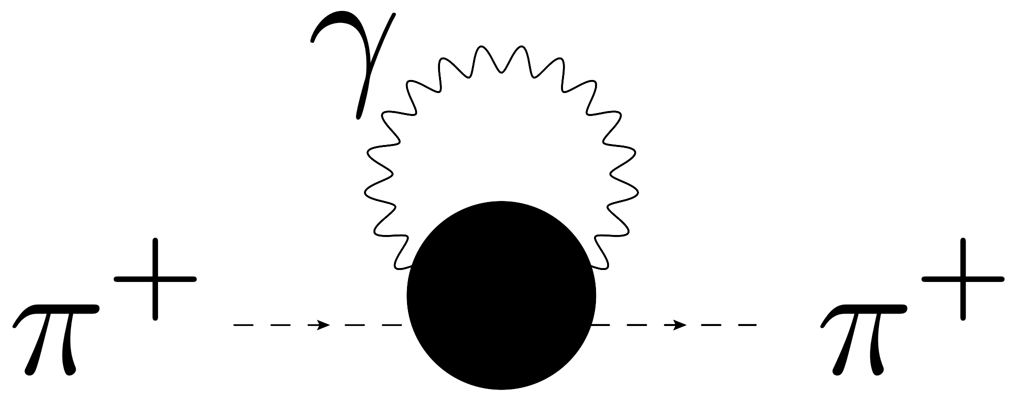
I
Supersymmetry

II
Strong EWSB dynamics
(composite Higgs)

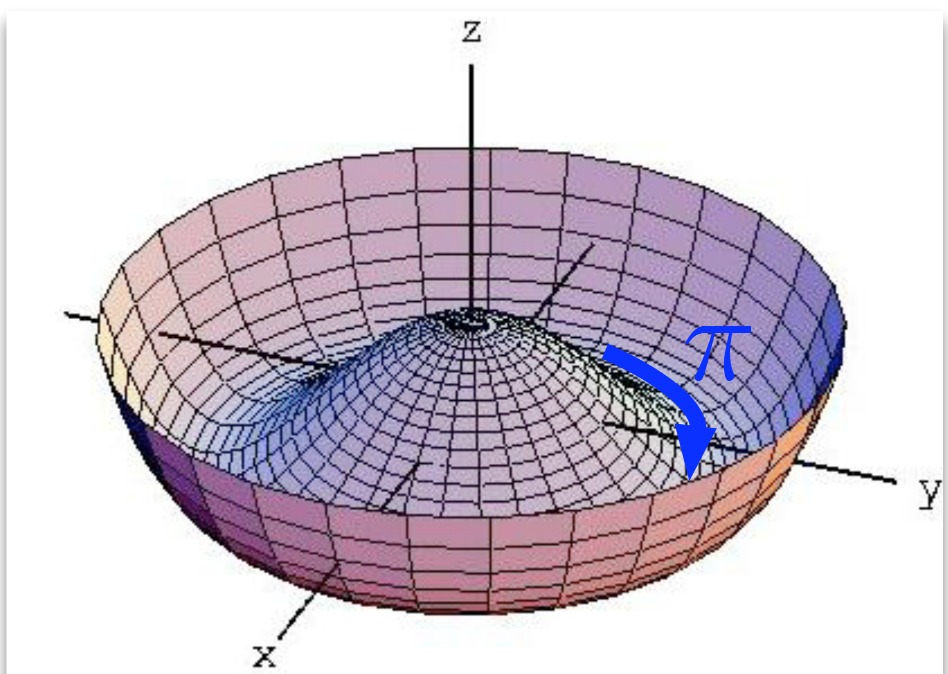
III
Large Extra Dimensions

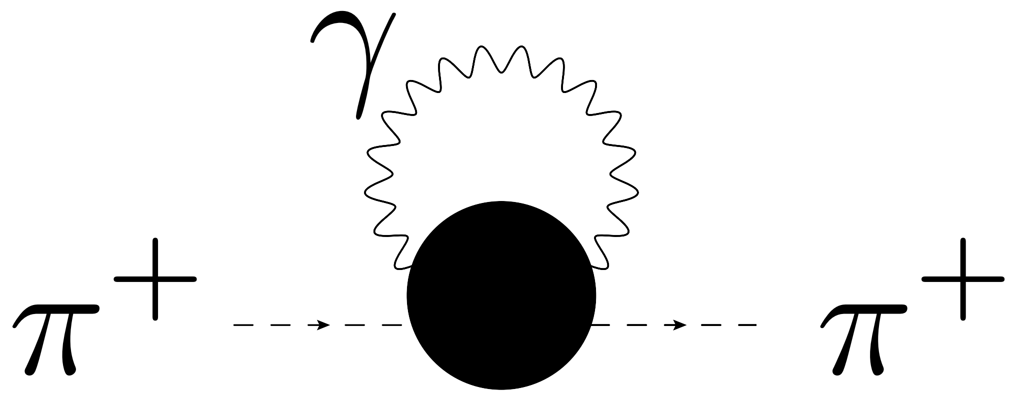
New physics & naturalness



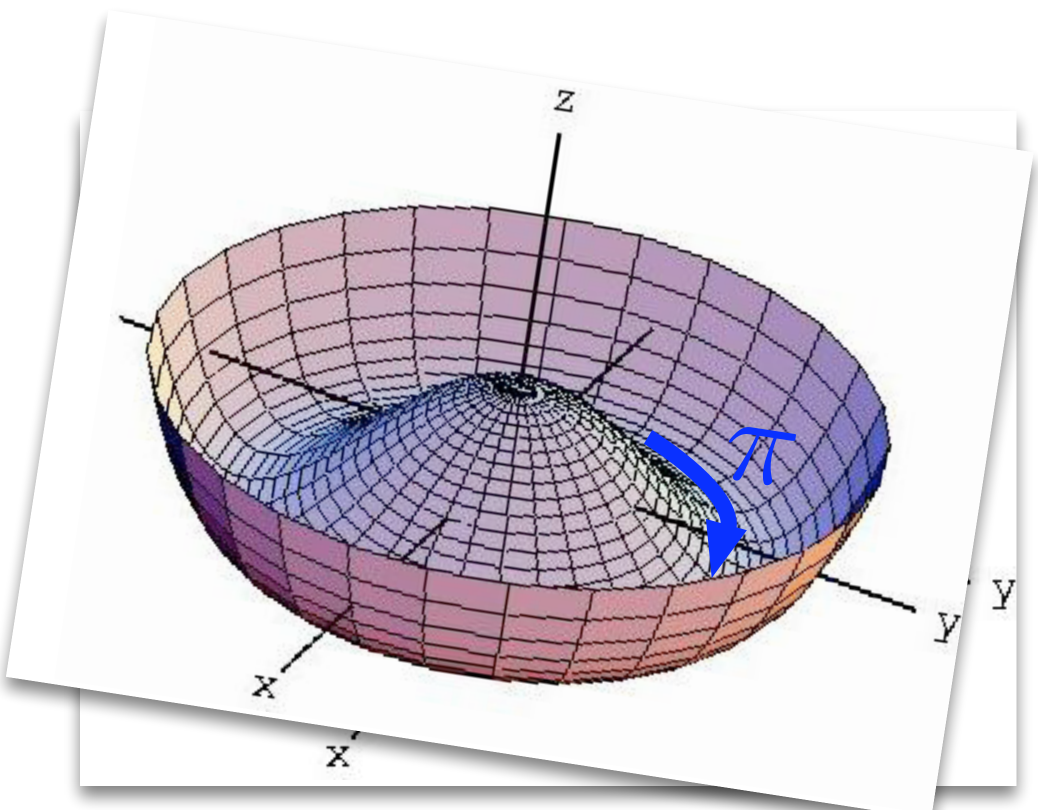


Das et al '67





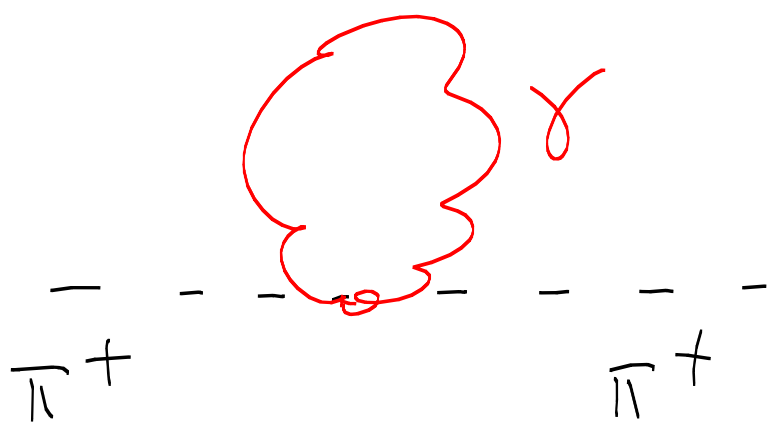
Das et al '67



Potential tilted:
due to quark masses
and gauging of EM

GB → *pGB*

Neutral-charged pion mass difference: natural resolution

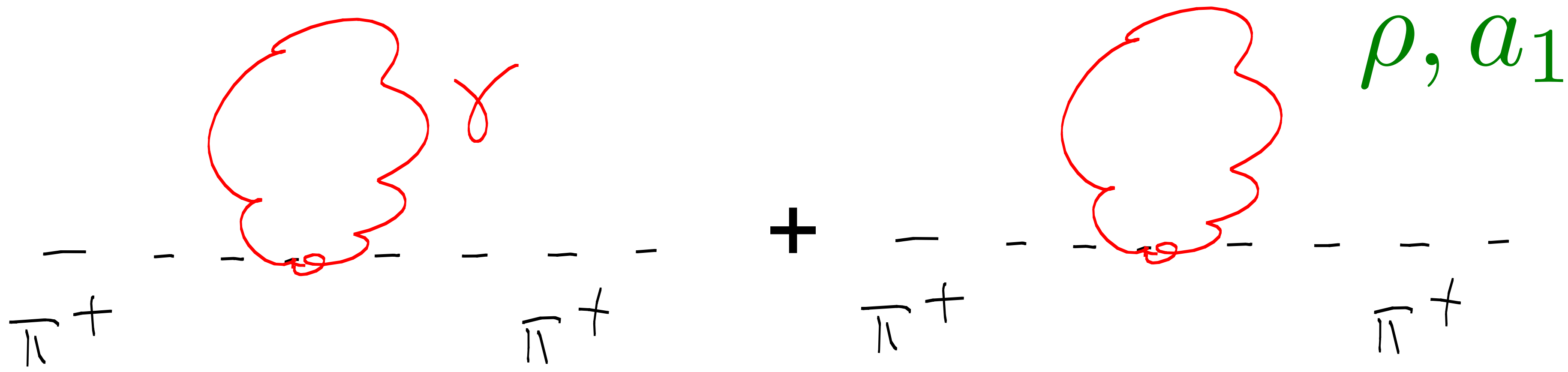


$$\delta m^2_{\pi^+} \sim \frac{3\alpha}{4\pi}\Lambda^2 < (m^2_{\pi^+} - m^2_{\pi^0})_{\rm exp} \approx (4\,{\rm MeV})^2$$

Expect $\to \Lambda < 850\,{\rm MeV}$

Das et al '67

Neutral-charged pion mass difference: natural resolution



$$\delta m^2_{\pi^+} \sim \frac{3\alpha}{4\pi}\Lambda^2 < (m^2_{\pi^+} - m^2_{\pi^0})_{\rm exp} \approx (4\,{\rm MeV})^2$$

Expect $\rightarrow \Lambda < 850\,{\rm MeV}$

'New physics': comes in at $m_\rho = 770\,{\rm MeV}$

Das et al '67

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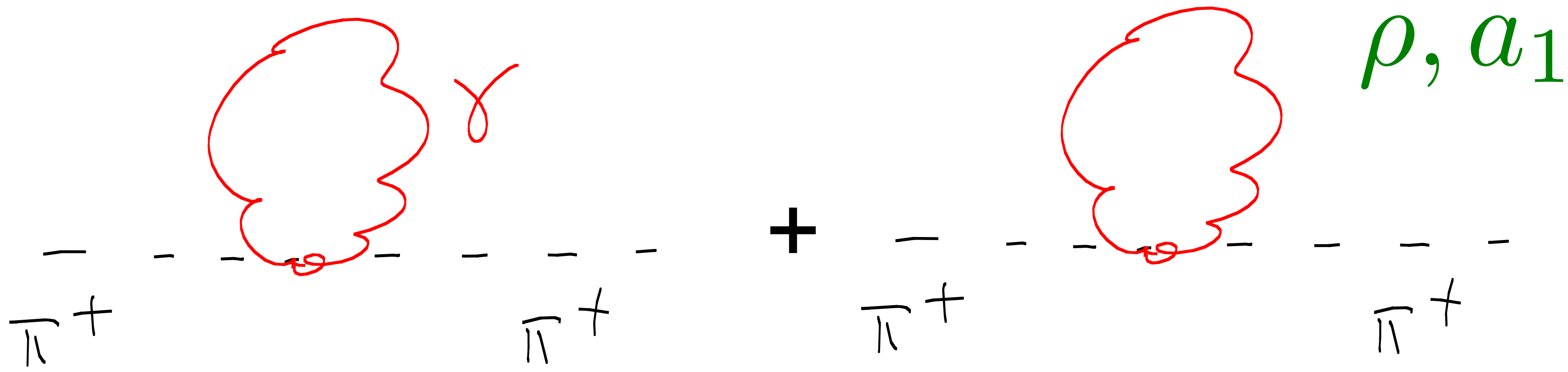

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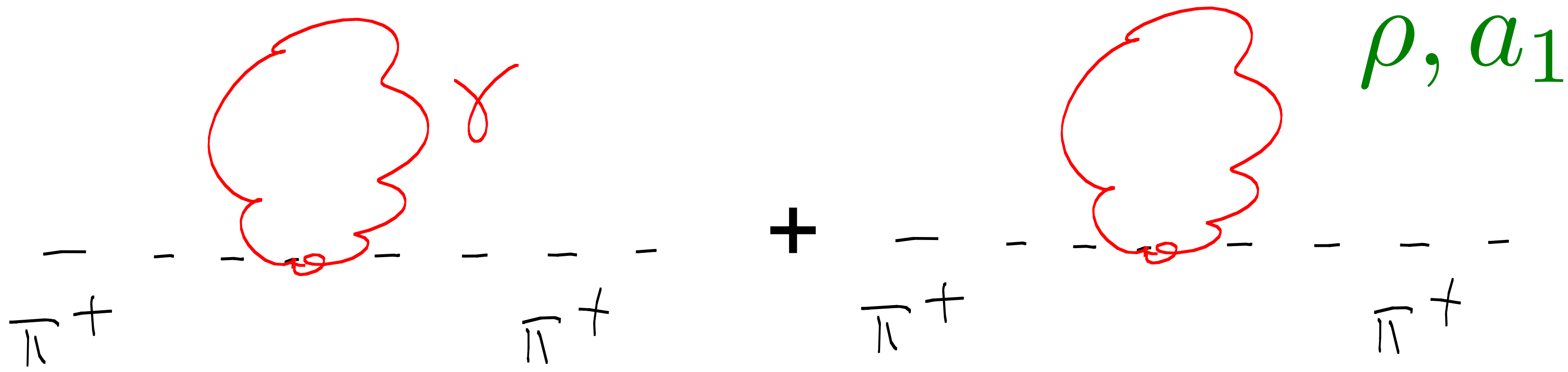

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Expect $\rightarrow \Lambda < 850\,\mathrm{MeV}$

'New physics': comes in at $m_\rho = 770\,\mathrm{MeV}$

Das et al '67

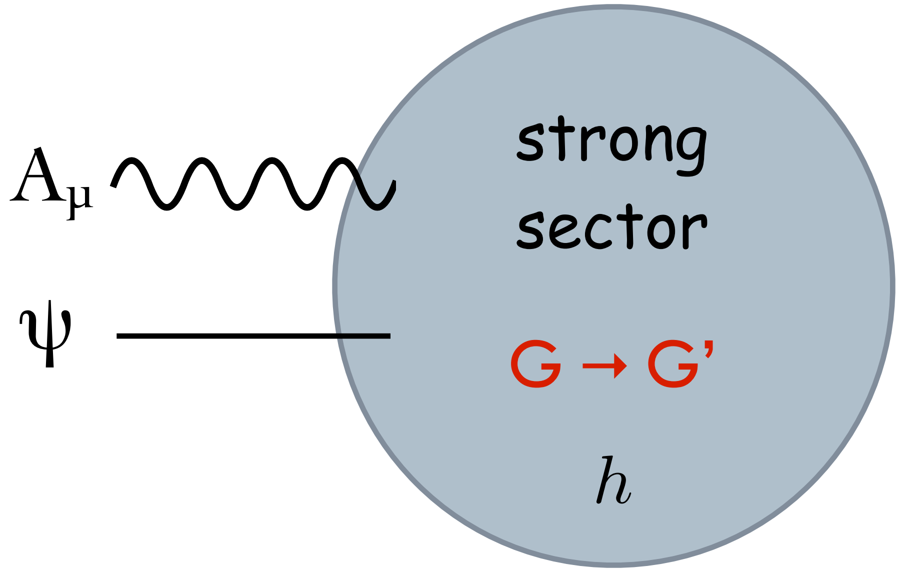
$$m^2_{\pi^\pm} - m^2_{\pi_0} \simeq \frac{3\,\alpha_{em}}{4\pi}\,\frac{m^2_\rho m^2_{a_1}}{m^2_{a_1} - m^2_\rho}\,\log\left(\frac{m^2_{a_1}}{m^2_\rho}\right)$$

$$(m_{\pi^\pm} - m_{\pi_0})|_{\rm TH} \simeq 5.8\,\mathrm{MeV} \; !$$

Why is the Higgs light?

Kaplan; Agashe et. al

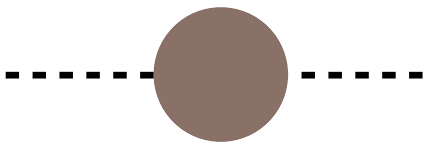
Higgs is a pNGB



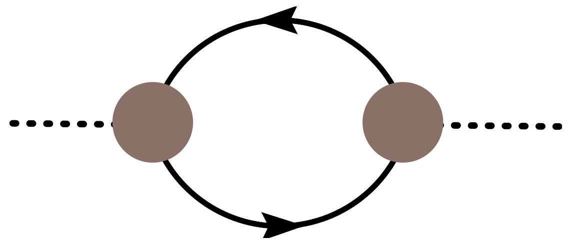
Minimal example

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

No pure composite effects,
vanish due to NG symmetry



NG symmetry broken by
elementary-composite couplings:

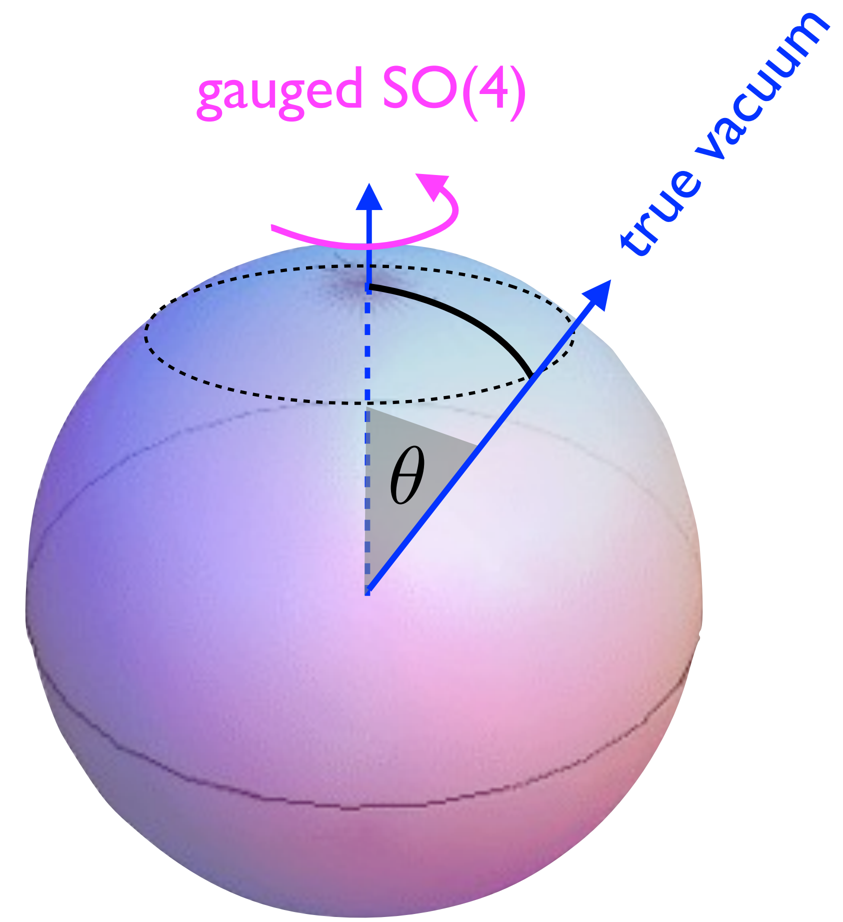


$$m_h^2 \sim \frac{\lambda^2}{16\pi^2}\,\Lambda_{comp}^2$$

$$\lambda \ll 4\pi$$

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

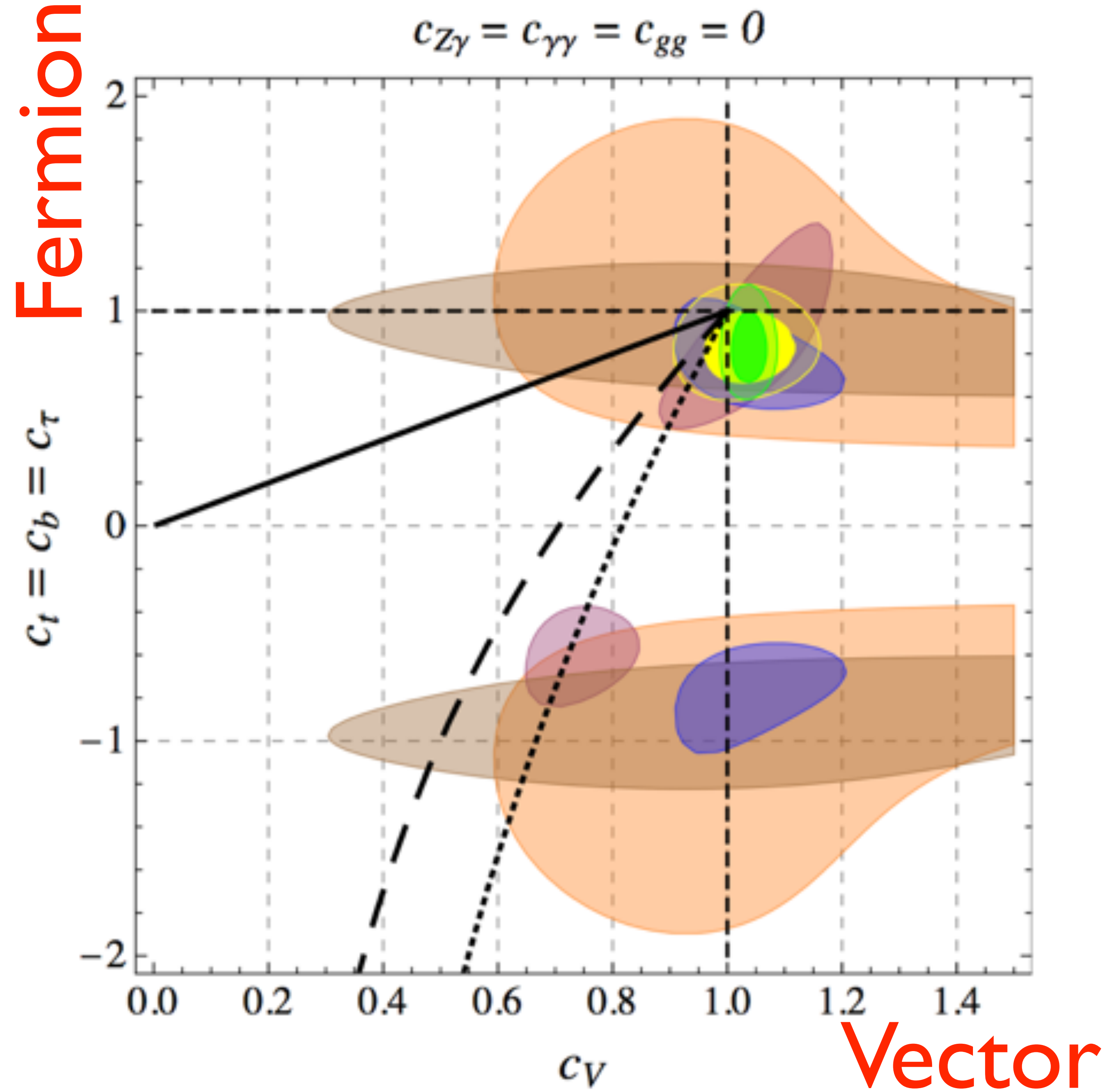
Higgs

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

@ 1-loop: < $\hat{\pi}^4$ > = θ * f

eaten by W_L, Z_L

Composite Higgs vs. LHC data

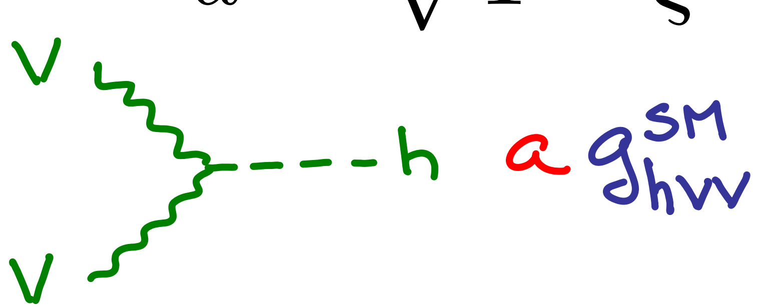


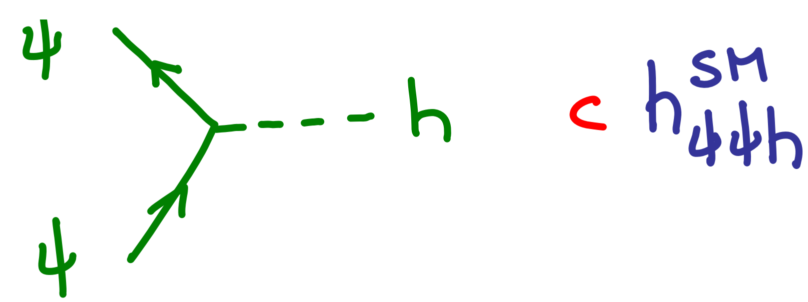
post-Moriond fit: see e.g. Giardino et al, Falkowski et al

Limit

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

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





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

Implications of m_H = 125 GeV

Potential is fully radiatively generated

Agashe et. al

$$V_{gauge}(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\log\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right) \qquad s_h \equiv \sin h/f$$

$$\Pi_0(p) = \frac{p^2}{g^2} + \Pi_a(p)\ , \qquad \Pi_1(p) = 2\left[\Pi_{\hat{a}}(p) - \Pi_a(p)\right]$$

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Higgs dependent term
UV finite

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Higgs dependent term
UV finite

→ 'Weinberg sum rules'

$$\lim_{p^2\to\infty} \Pi_1(p) = 0\ , \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0$$

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)}$$

spin1

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spin 1

Similarly for SO(5) fermionic contribution

Pomarol et al; Marzocca

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

similar result in deconstruction:
Matsedonskyi et al; Redi et al

5 = 4 + 1 with EM charges 5/3, 2/3,-1/3

Q_4 Q_1

→ solve for m_h = 125 GeV

Light Higgs implies light fermionic top partners

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

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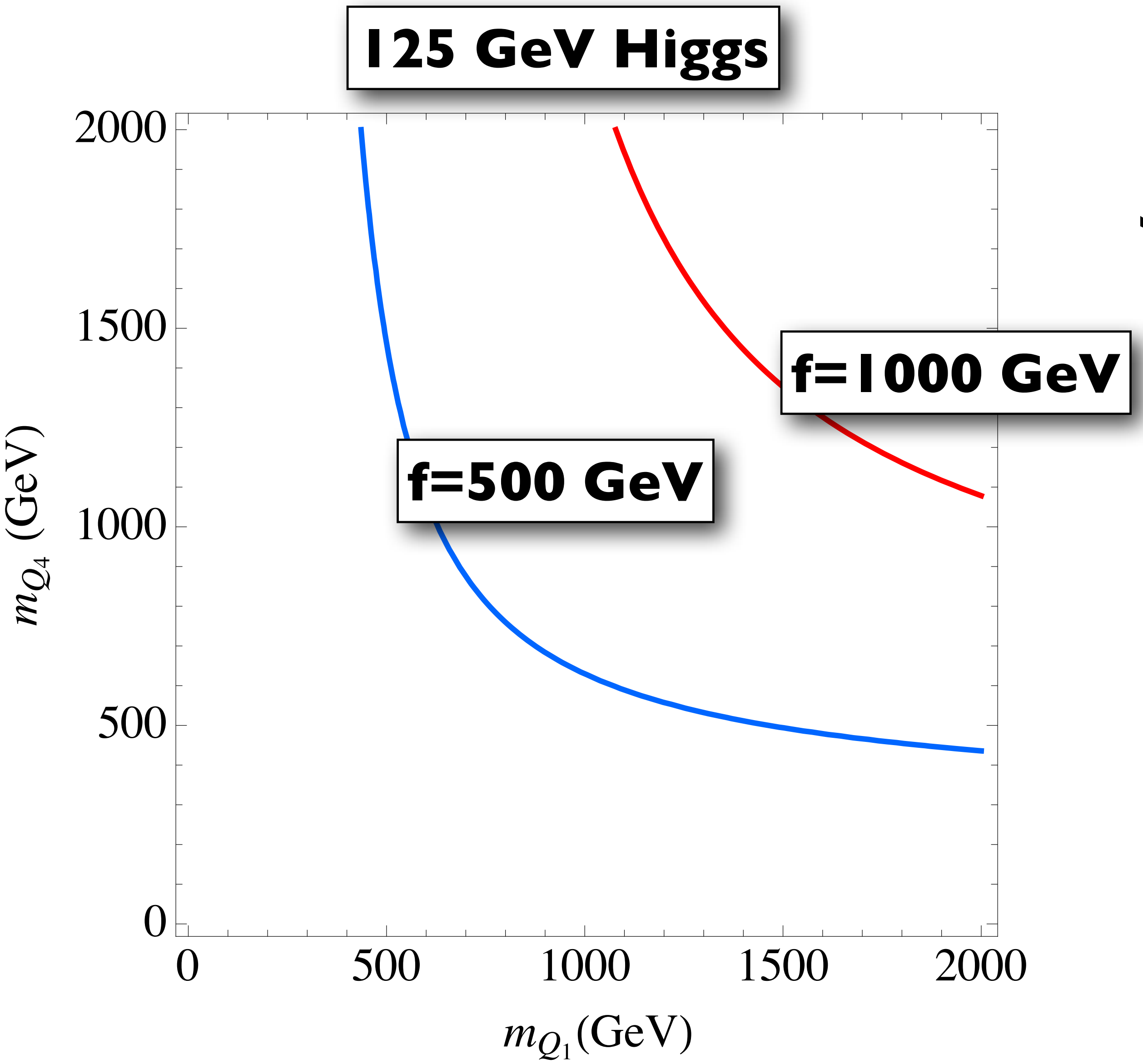


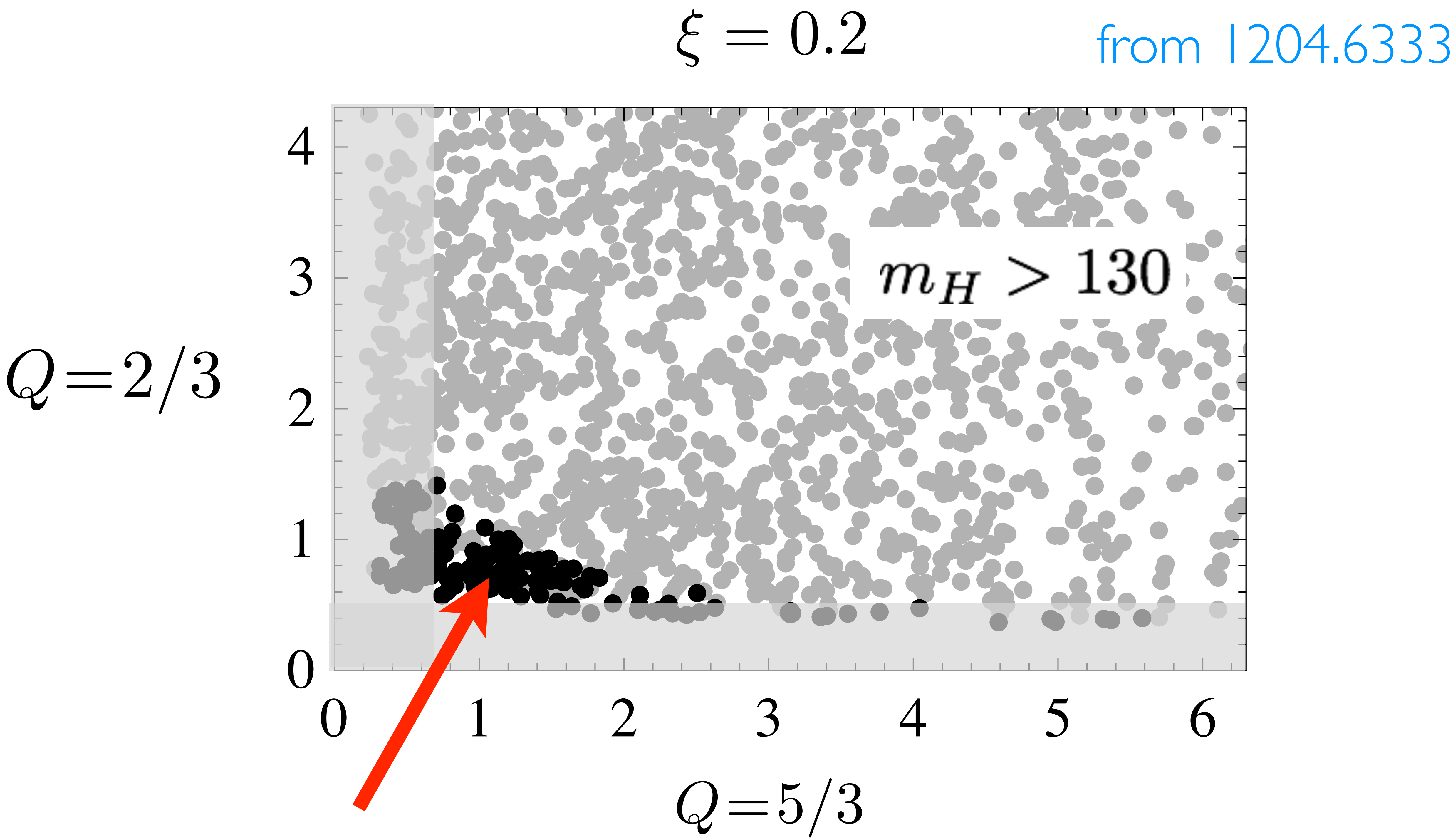
5 = 4 + 1

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;

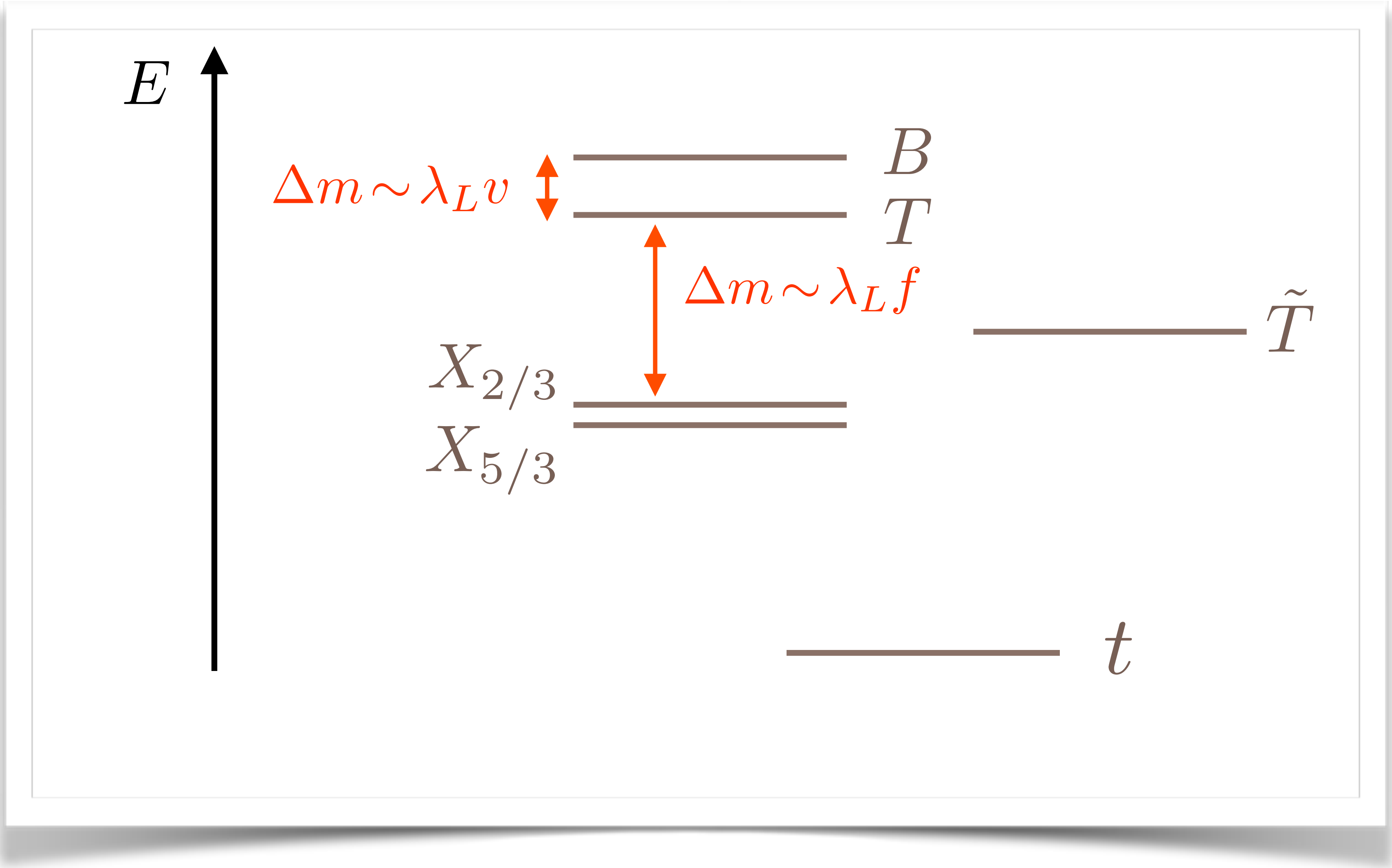
Scan over composite Higgs parameter space



m_H = 115 … 130 GeV

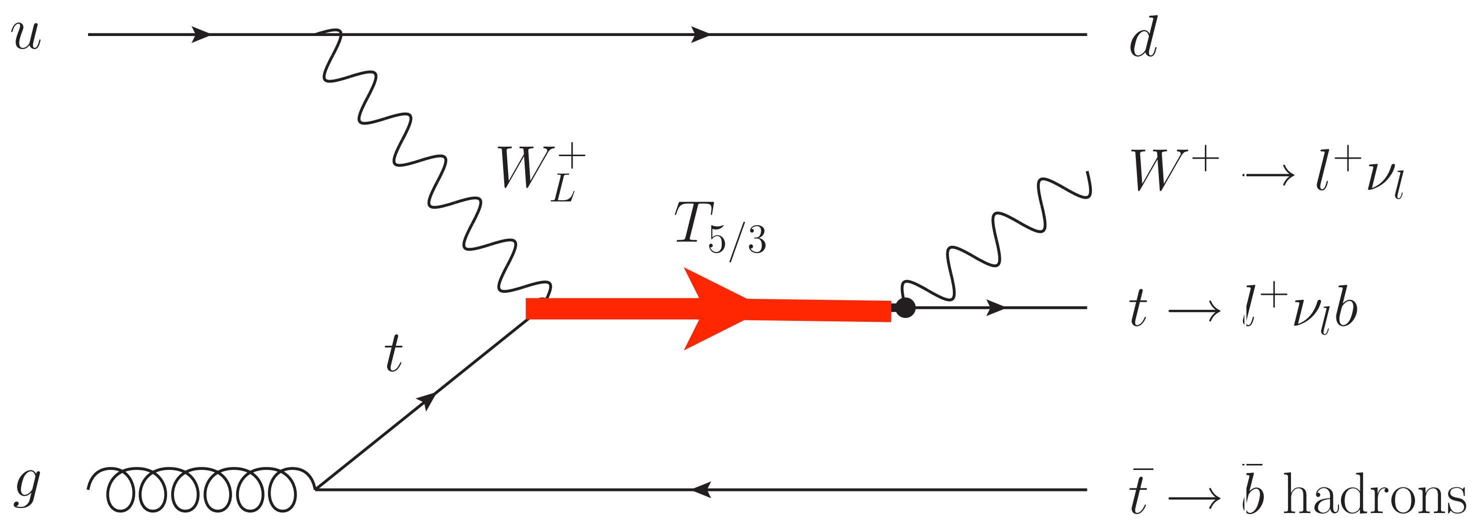
see e.g. ATLAS-CONF-2013-051

Top partners

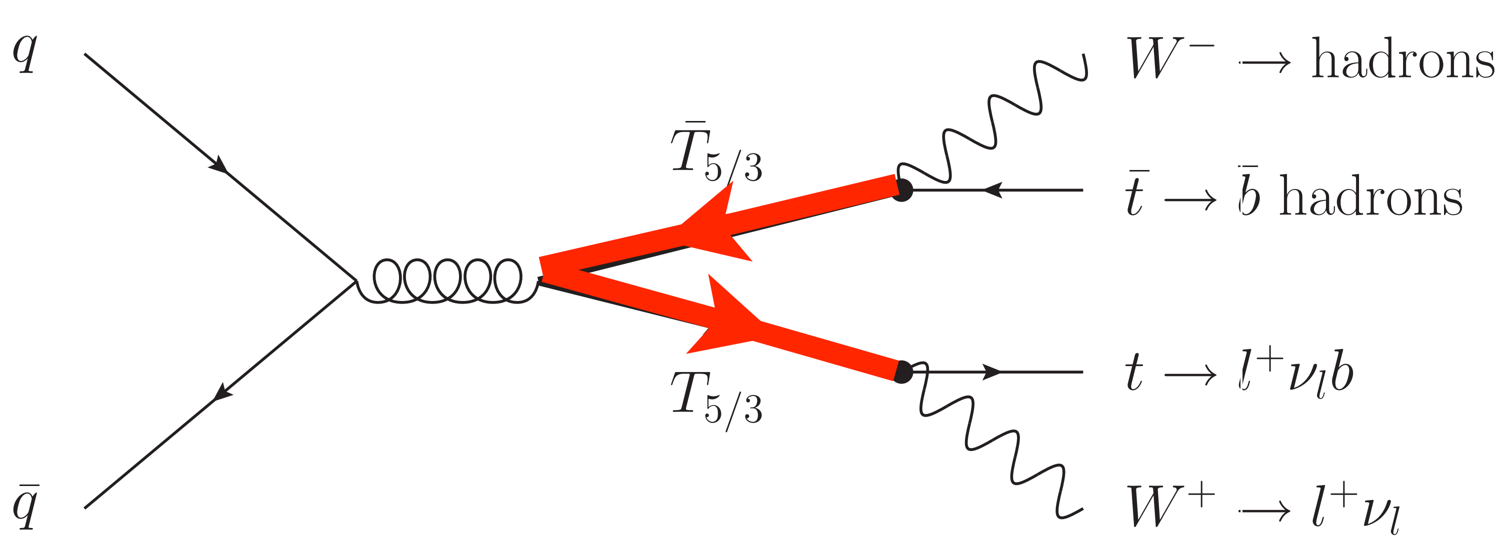


e.g. Perelstein, Pierce, Peskin
Contino, Servant; Mrazek, Wulzer;
De Simone, Matsedonkyi, Rattazzi, Wulzer;
Spannowsky et al

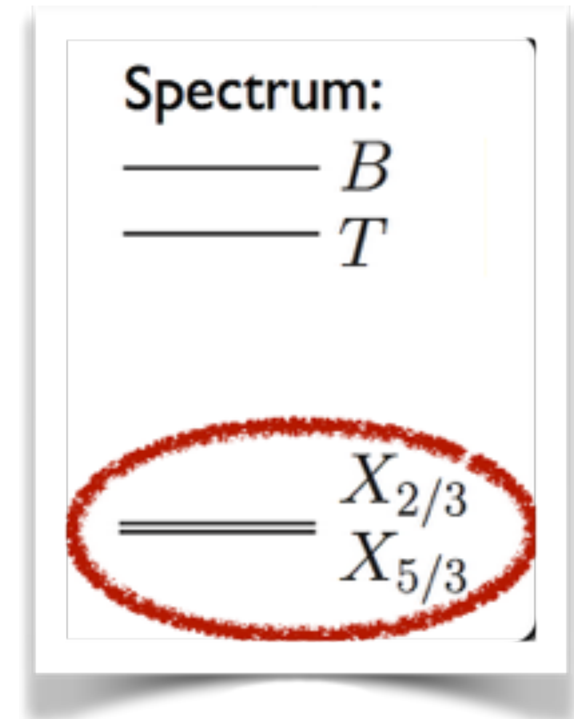
$T_{5/3}$



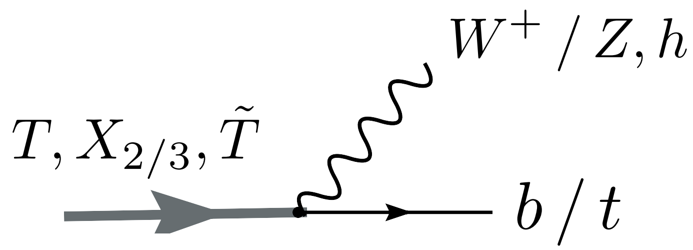
Single

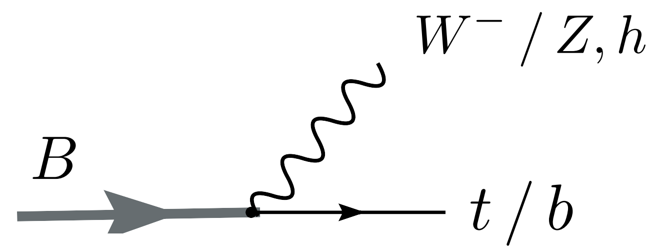


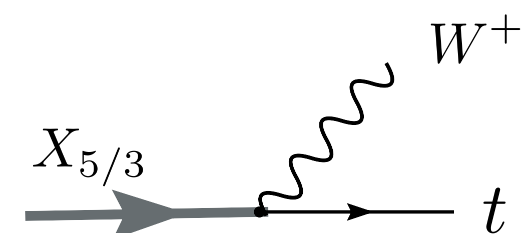
Double

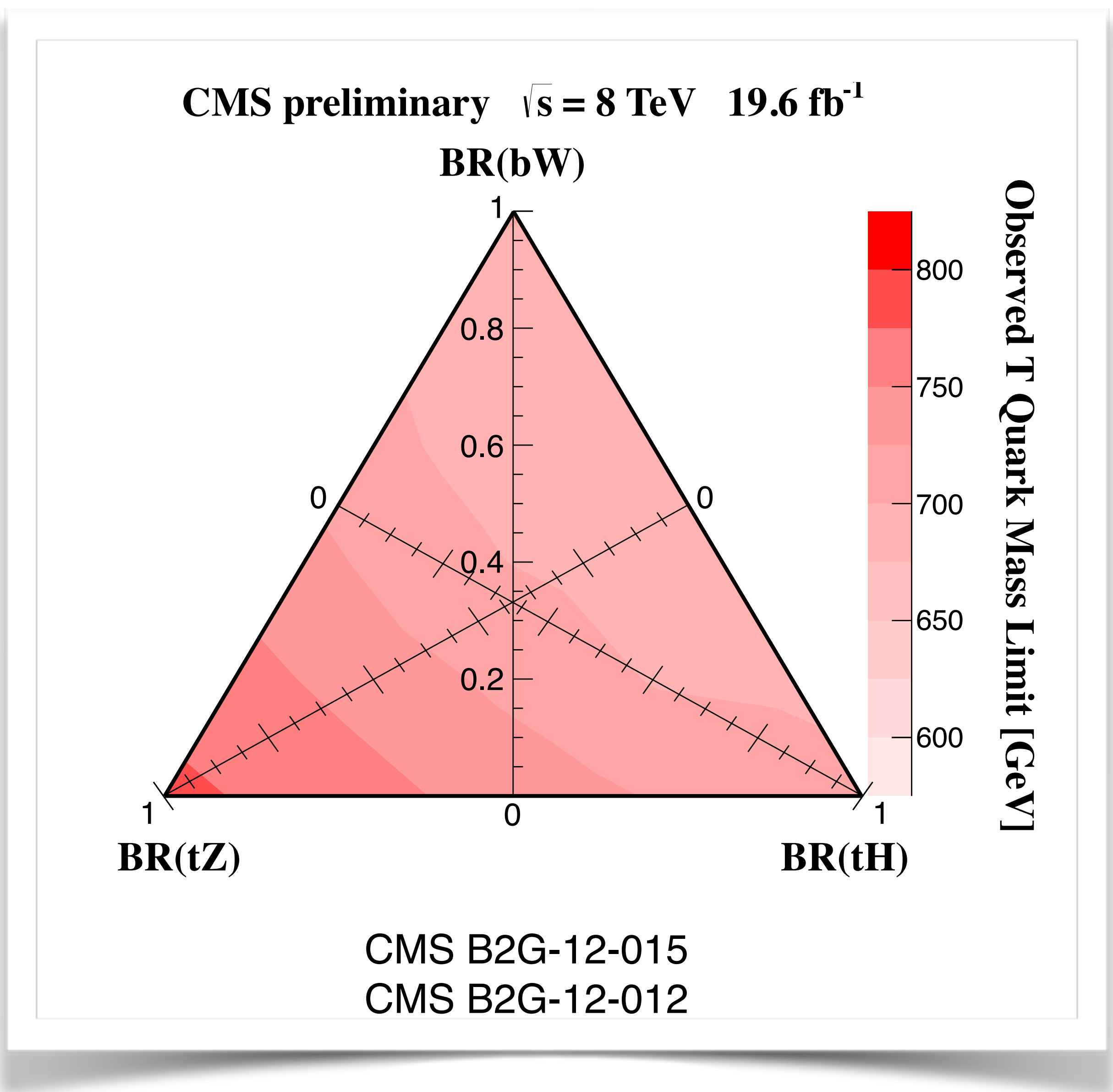


Decay modes





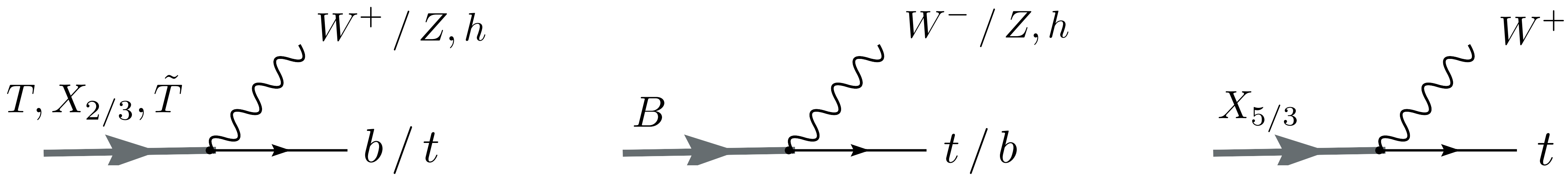




Current limits

> 700 - 800 GeV

Decay modes



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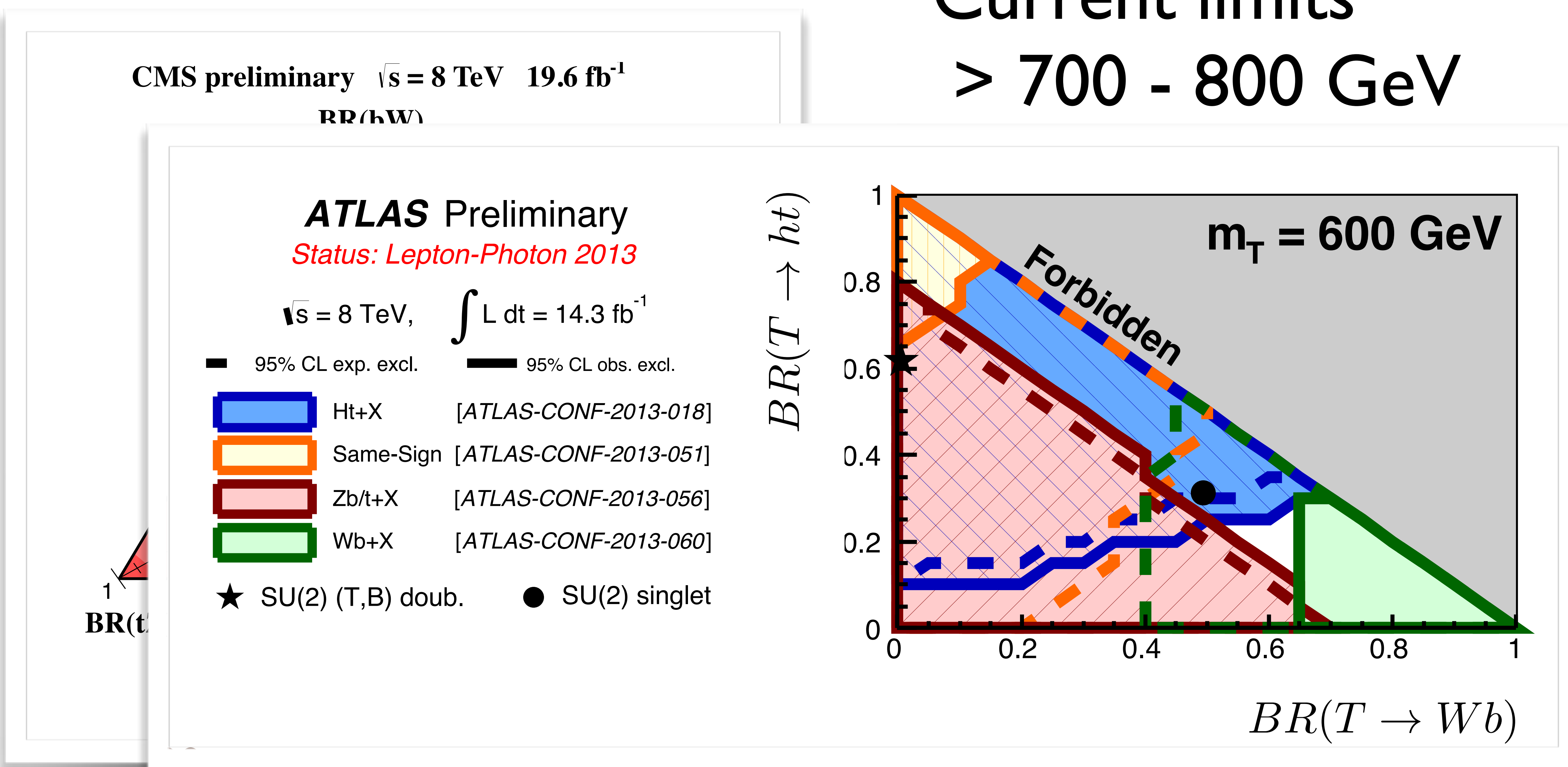
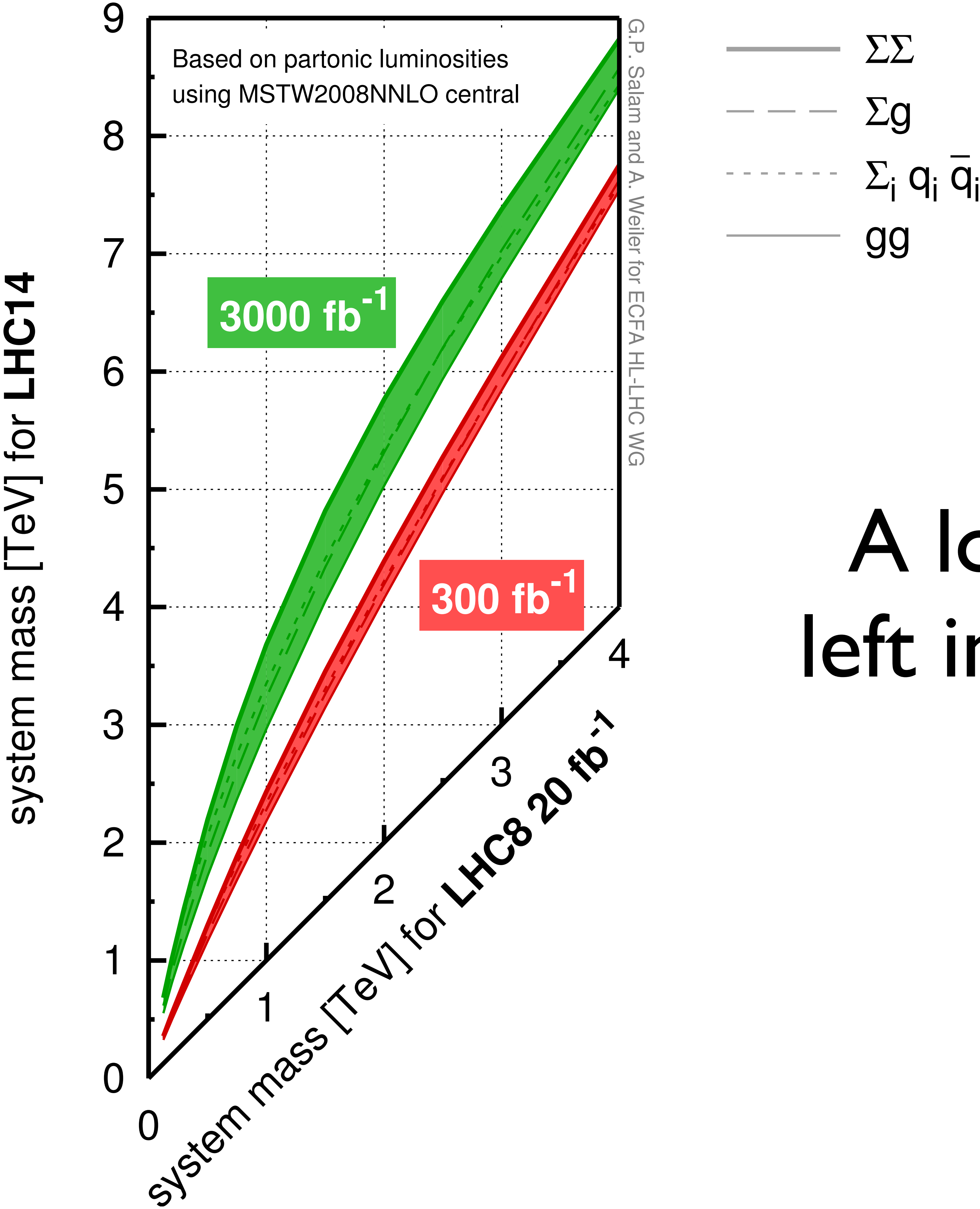


Outlook



A lot of juice left in the LHC!

Conclusions

The battle for a natural resolution of the hierarchy problem goes on, top partner searches are at the frontier

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

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