Towards an (un)Natural Weak Scale

Josh Ruderman
UC Berkeley
@IPMU, 12/3

Michal Czakon, Alexander Mitov, Michele Papucci, JTR, Andreas Weiler, *to appear.*

Lawrence Hall, David Pinner, JTR, *to appear.*

$$m_h \approx 125 \text{ GeV}$$

natural

$\tilde{m} \approx m_h$

fine-tuned

$\tilde{m} \gg m_h$

where are the stops?

multiverse?

this talk:

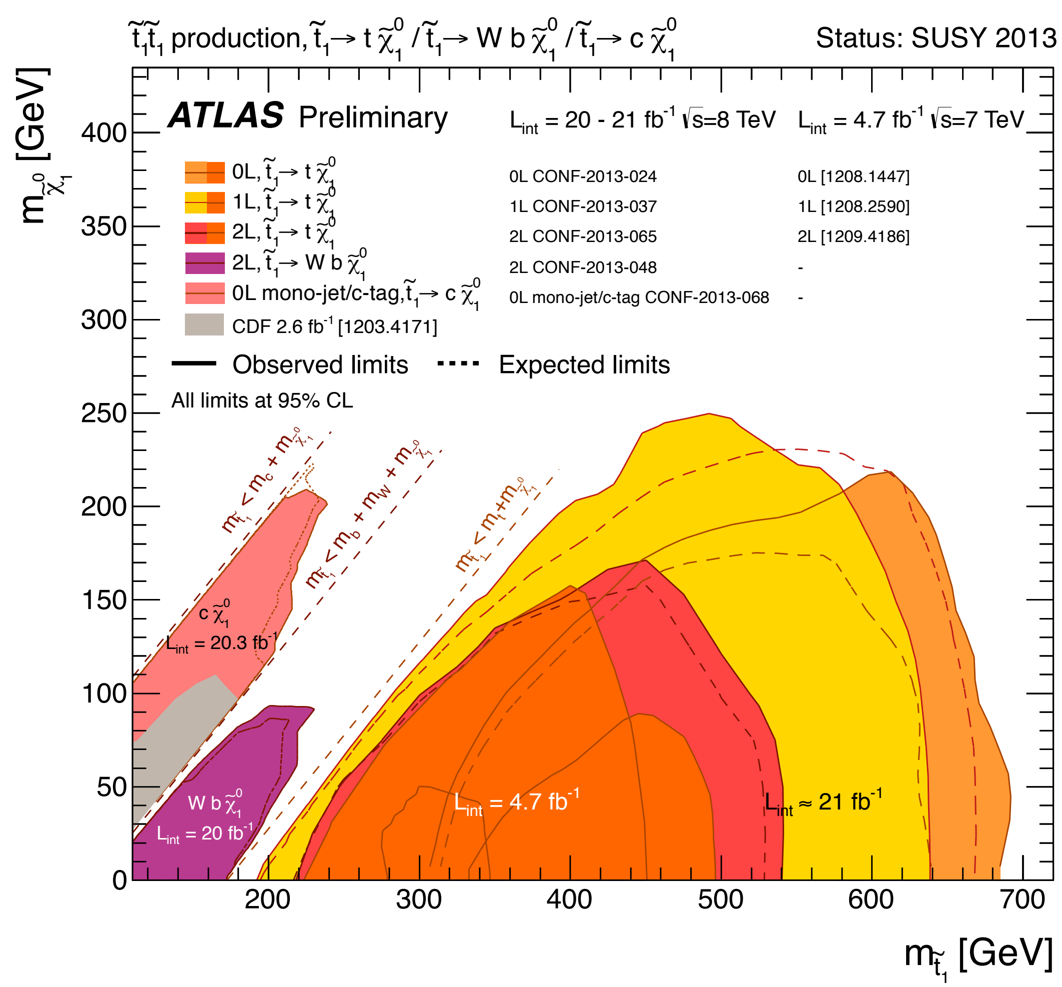
part I: closing the light stop window (stealth stop)

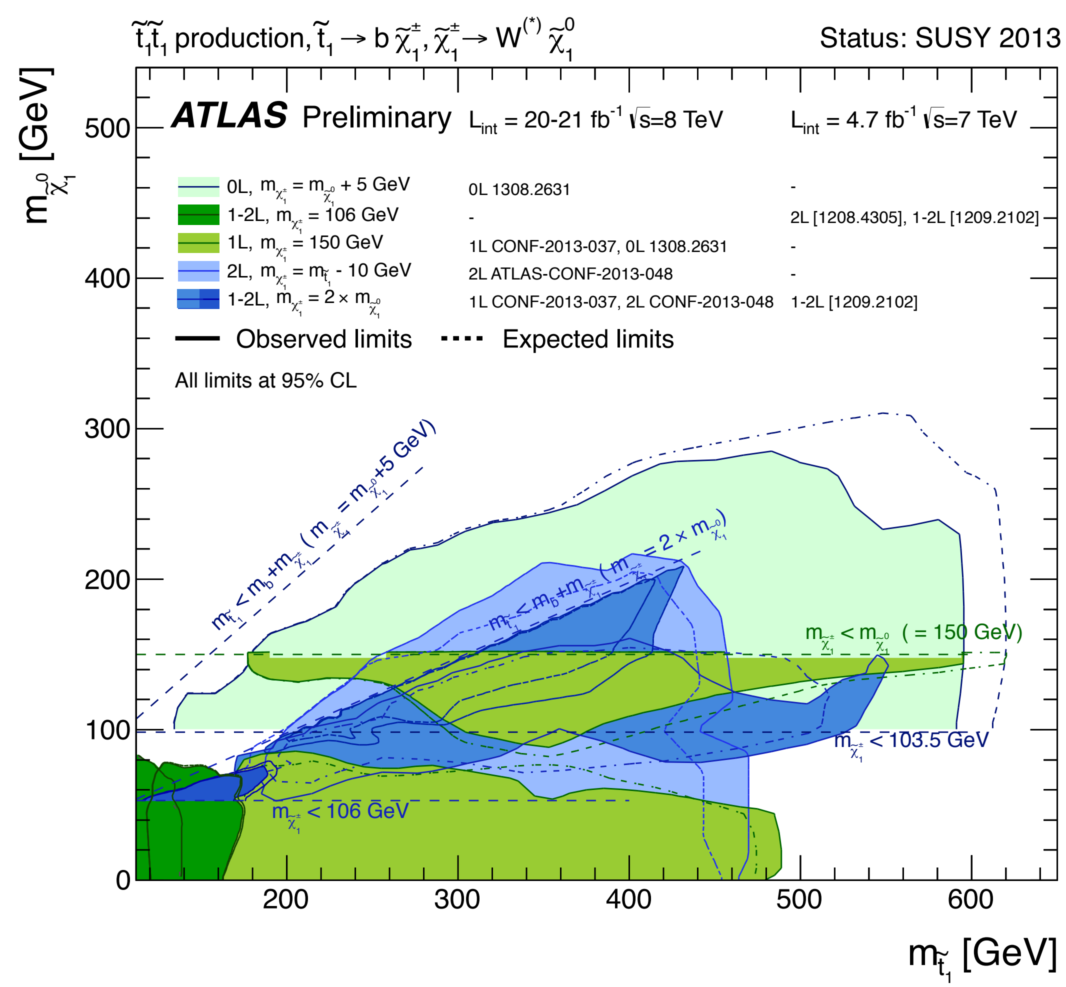
part II: the weak scale from BBN

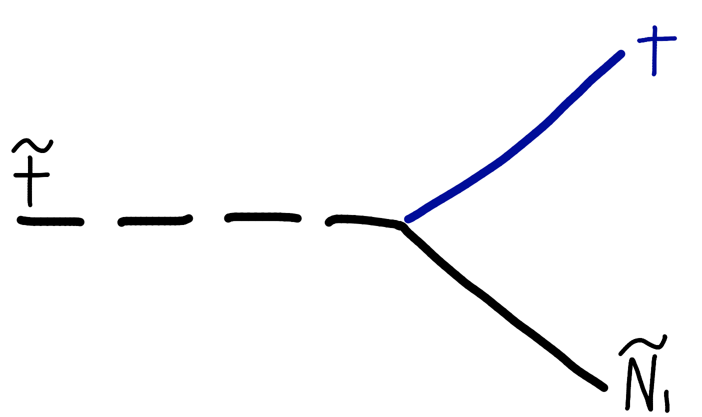
1. killing the stealth stop

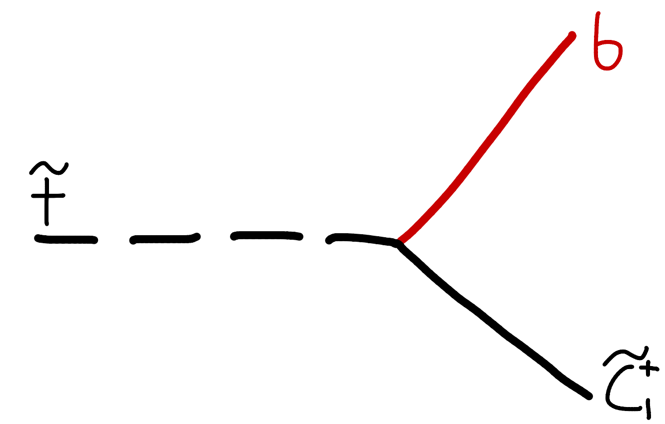
Michal Czakon, Alexander Mitov, Michele Papucci, JTR,
Andreas Weiler, *to appear.*

state of stops

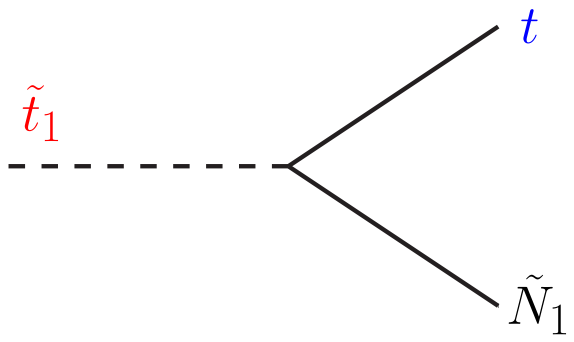


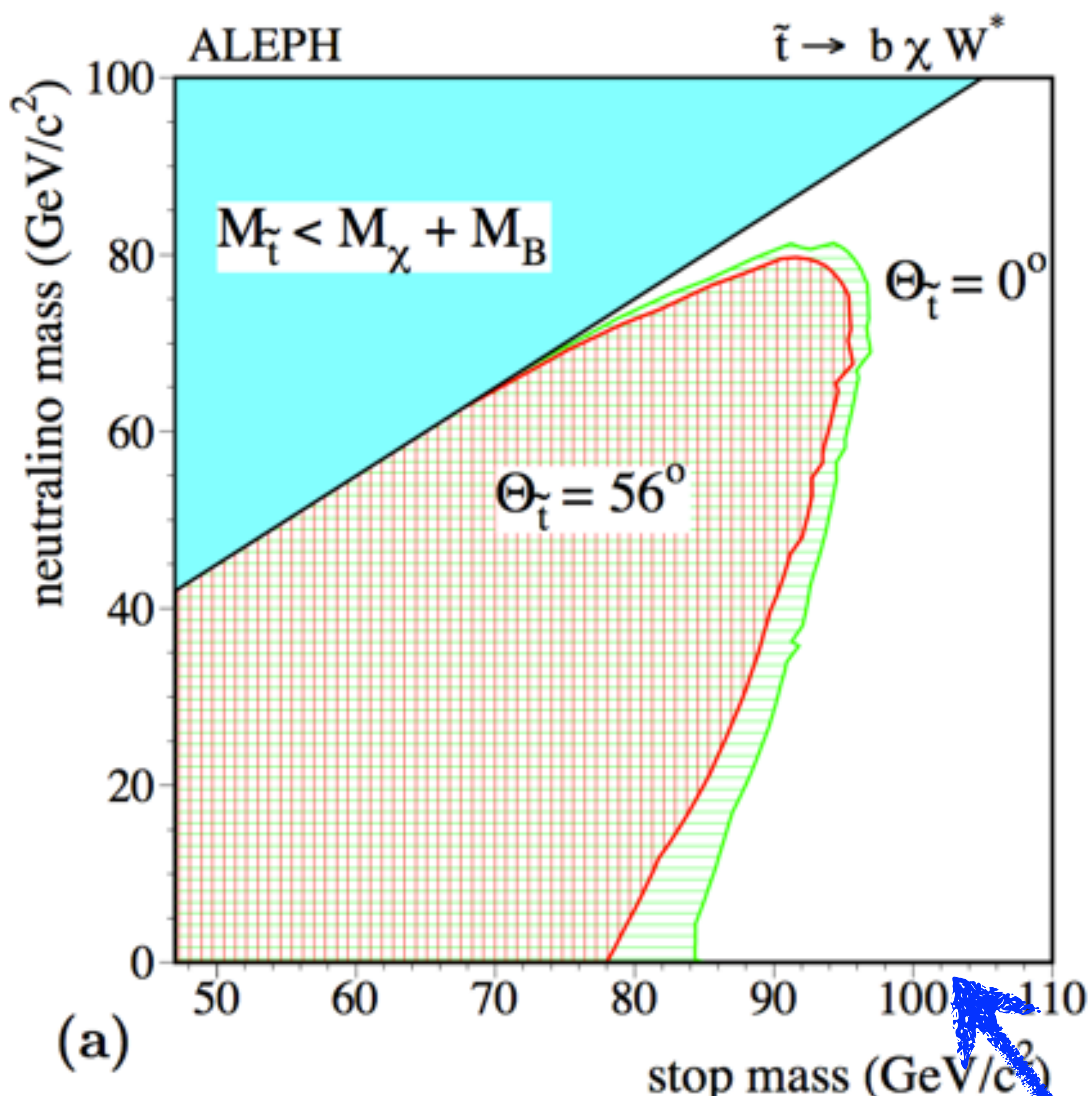


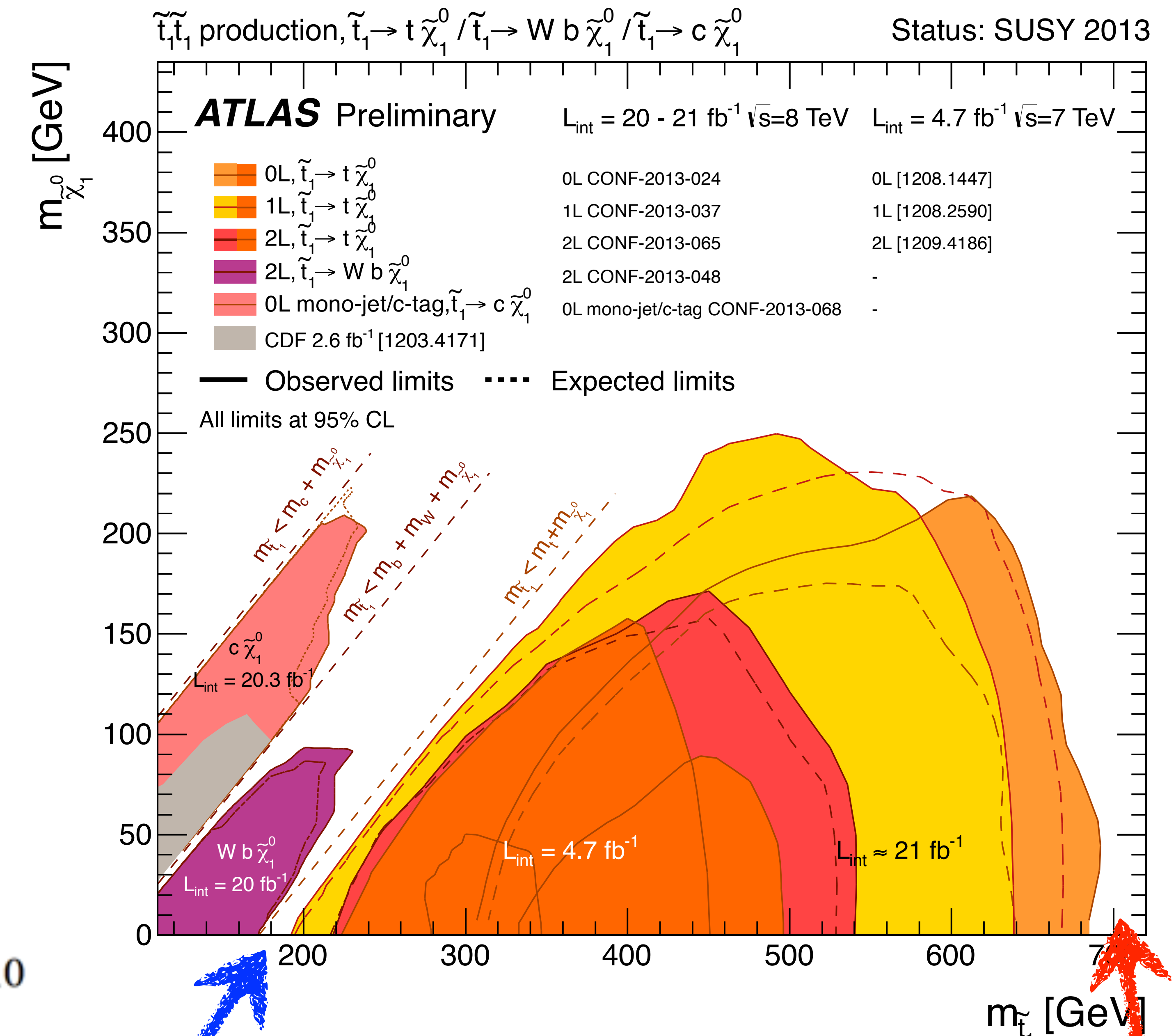




state of stops





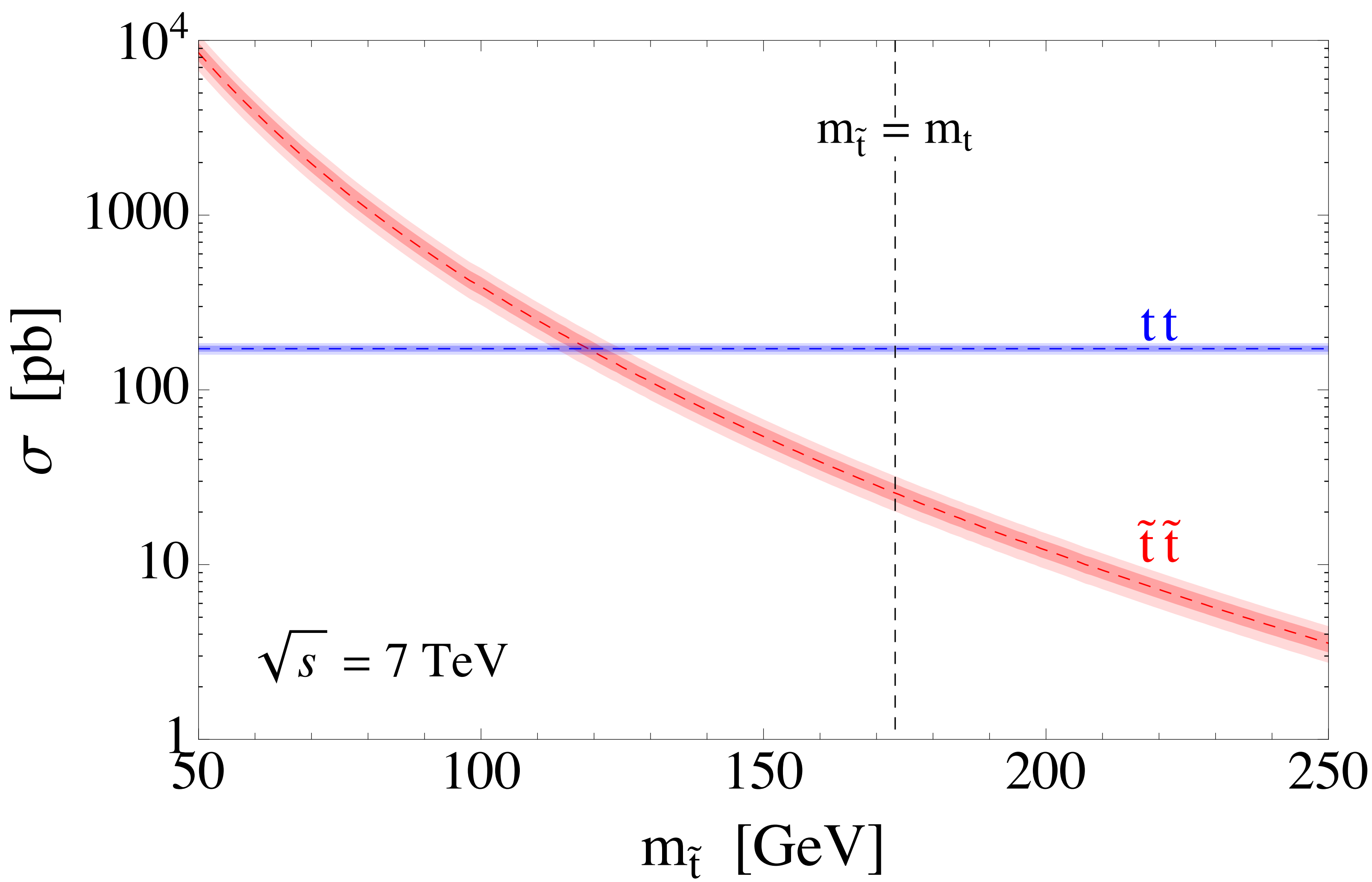


gaps

~10% tuning

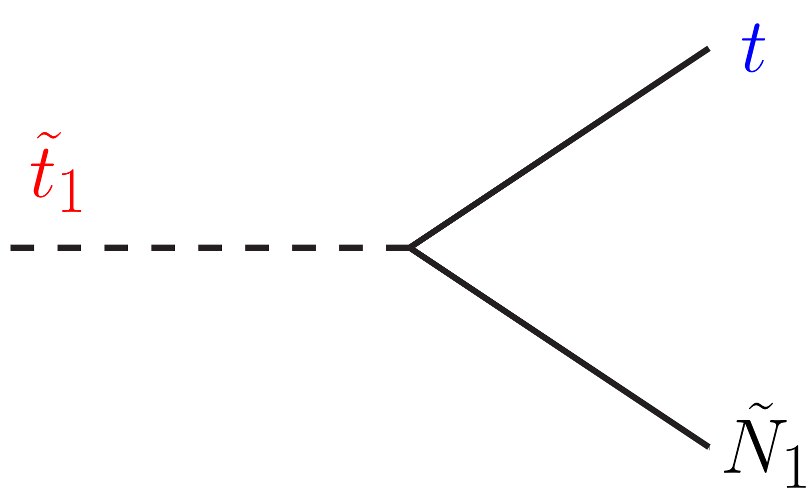
top background

why it is hard to look for light stops:



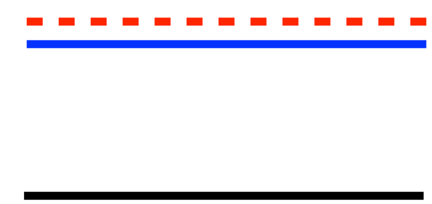
$$\frac{\sigma_{\tilde{t}\tilde{t}^*}}{\sigma_{t\bar{t}}}(m_{\tilde{t}} = m_t) \approx 0.15$$

stealth stop

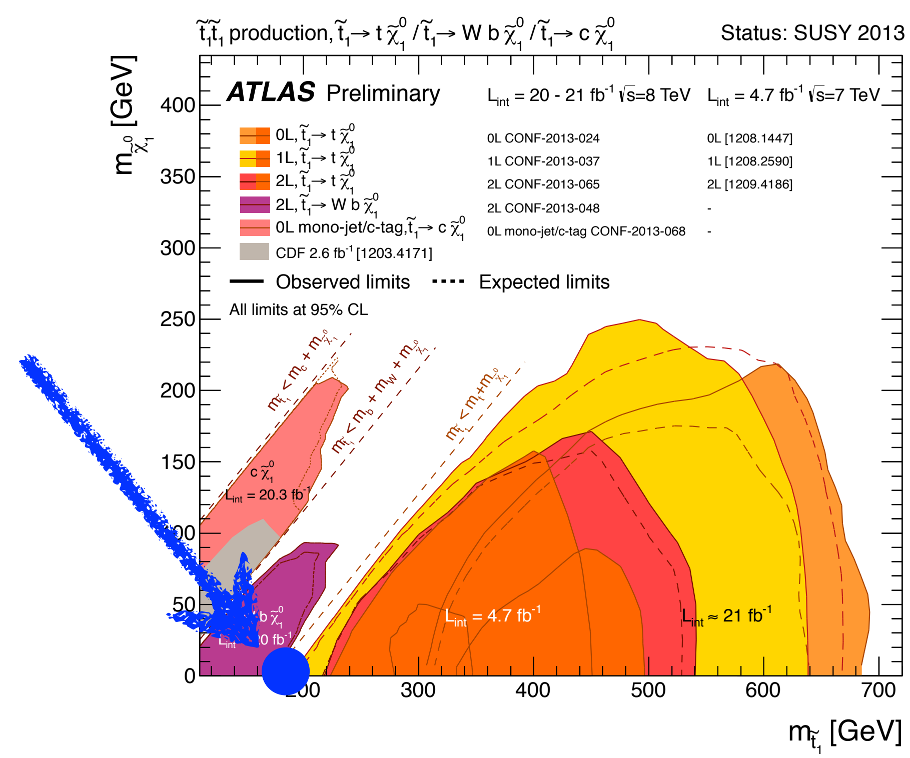


$$m_{\tilde{t}_R} \approx m_t$$

$$m_{LSP} \approx 0$$



$$\tilde{N}_1 = \tilde{B},\ \tilde{S},\ \tilde{G},\ \ldots$$

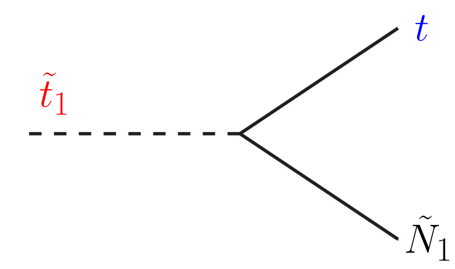


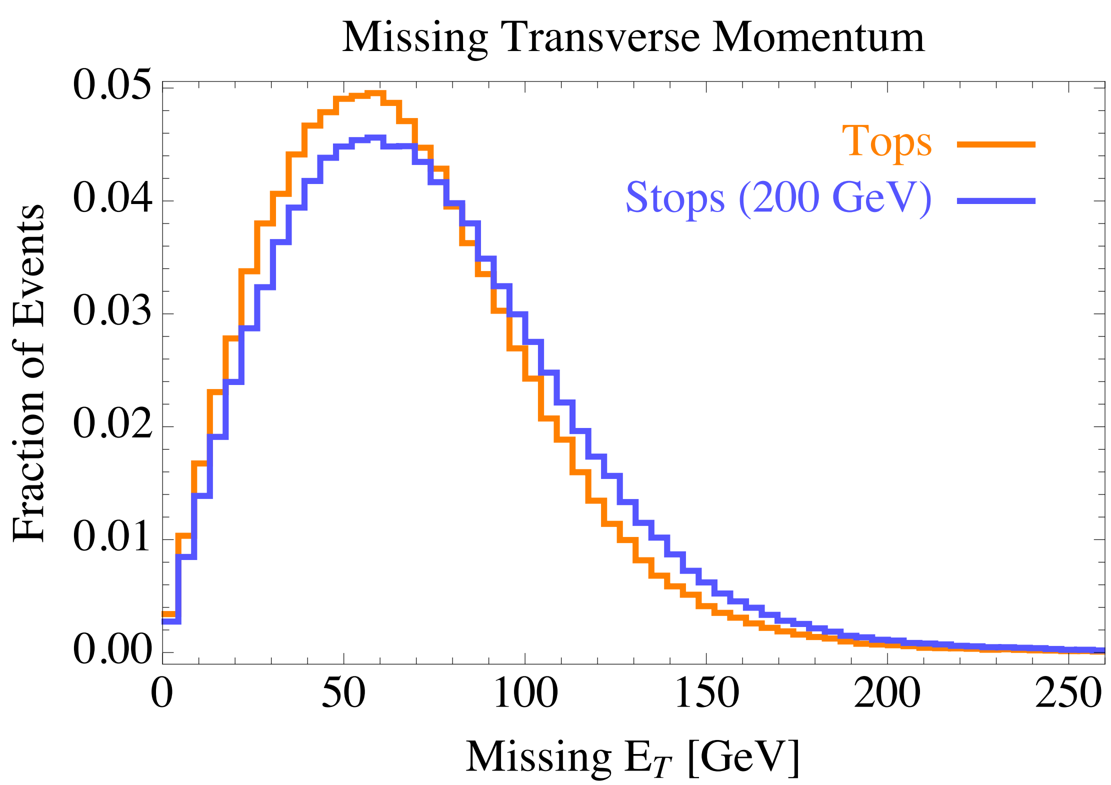
JiJi Fan, Matt Reece, JTR, 1105.5135

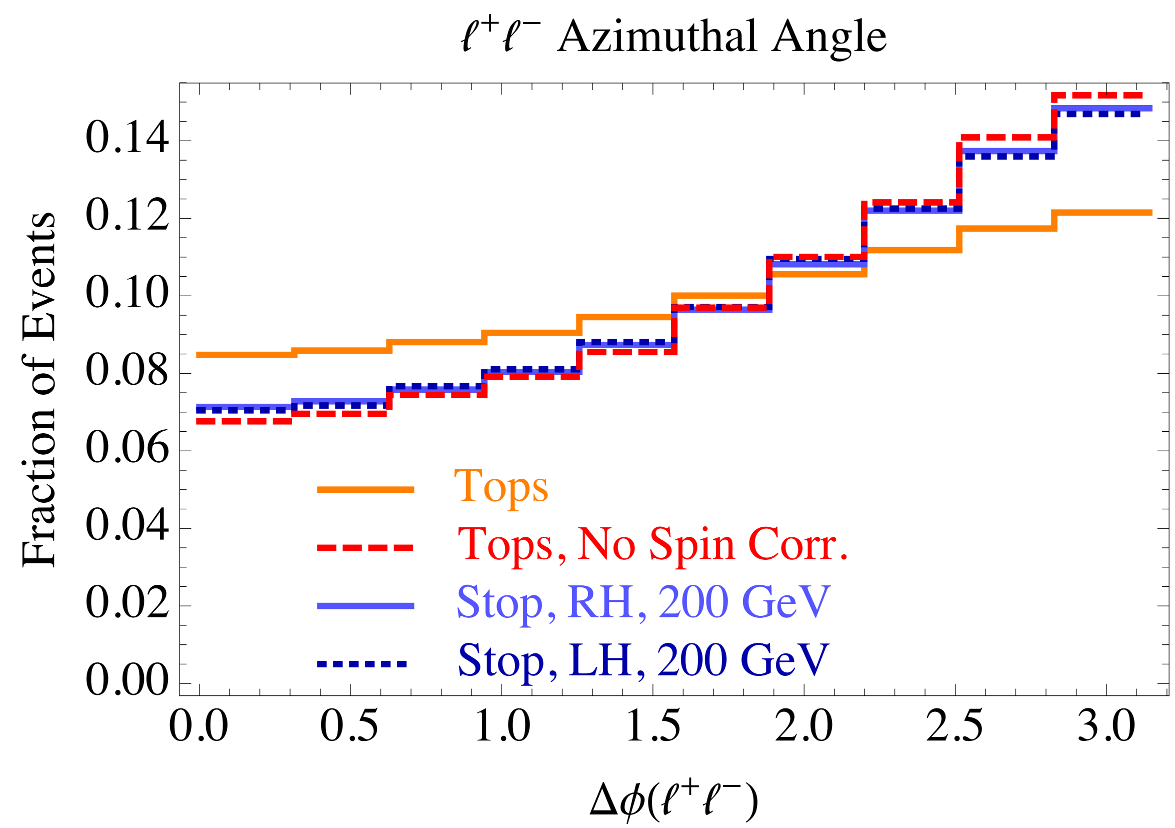
stealth stop

$m_{\tilde{t}_R} \approx m_t$

$m_{LSP} \approx 0$







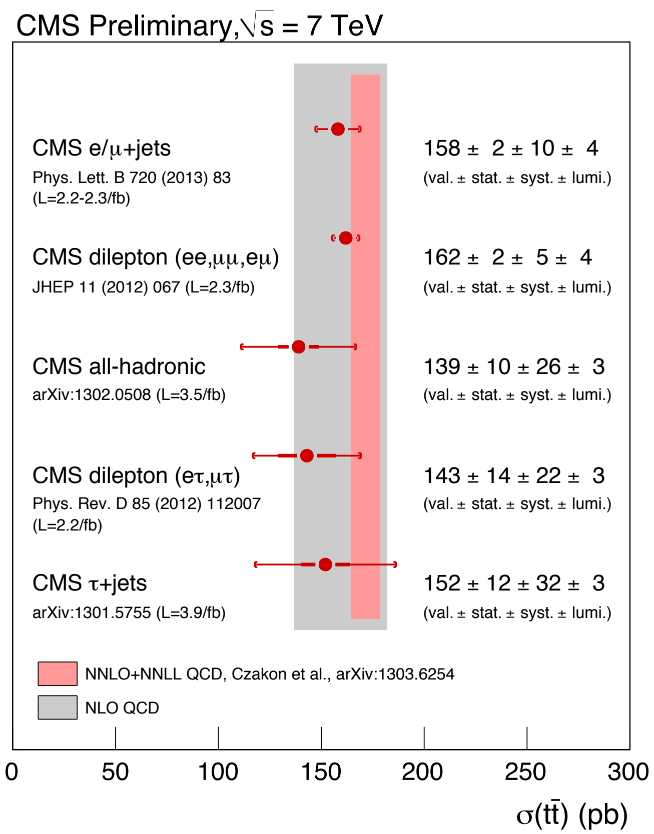
Han, Katz, Krohn, Reece 1205.5808

where is SUSY?

- we usually look for SUSY by separating signal from background (MET/H_T tails, ...)

- instead, what about using precision SM measurements?

top σ


CMS Preliminary, √s = 7 TeV
CMS e/μ+jets
Phys. Lett. B 720 (2013) 83
(L=2.2-2.3/fb)
158 ± 2 ± 10 ± 4
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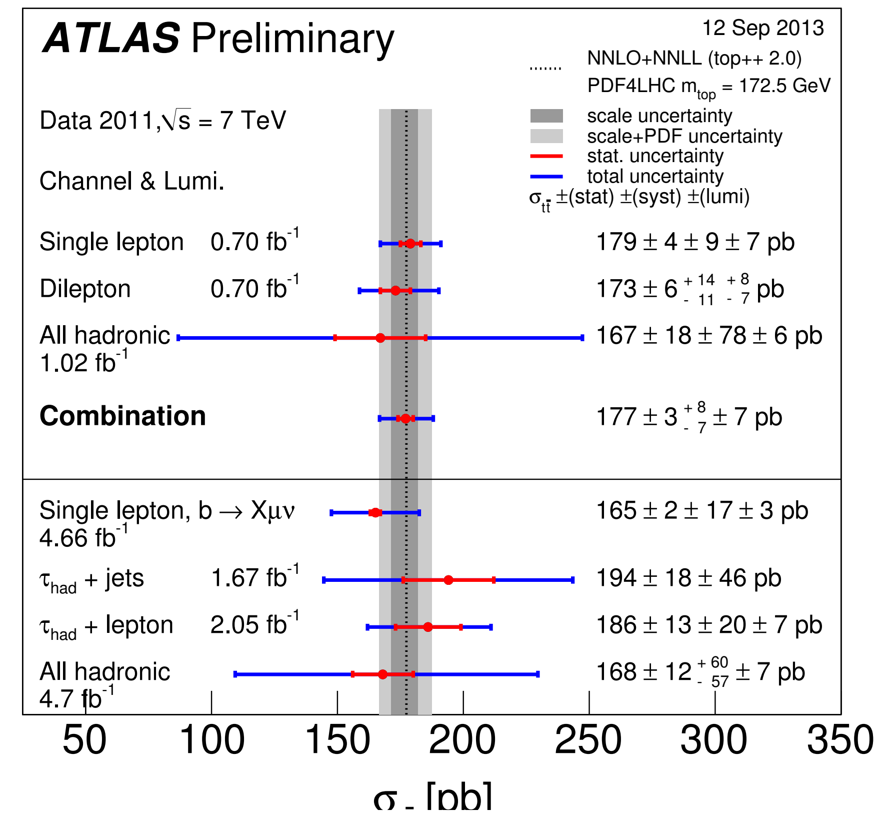
NNLO+NNLL QCD, Czakon et al., arXiv:1303.6254
NLO QCD
0
50
100
150
200
250
300
σ(tt̄) (pb)


ATLAS Preliminary
12 Sep 2013
NNLO+NNLL (top++ 2.0)
PDF4LHC m_top = 172.5 GeV
scale uncertainty
scale+PDF uncertainty
stat. uncertainty
total uncertainty
σ_tt̄ ±(stat) ±(syst) ±(lumi)
Data 2011, √s = 7 TeV
Channel & Lumi.
Single lepton 0.70 fb⁻¹
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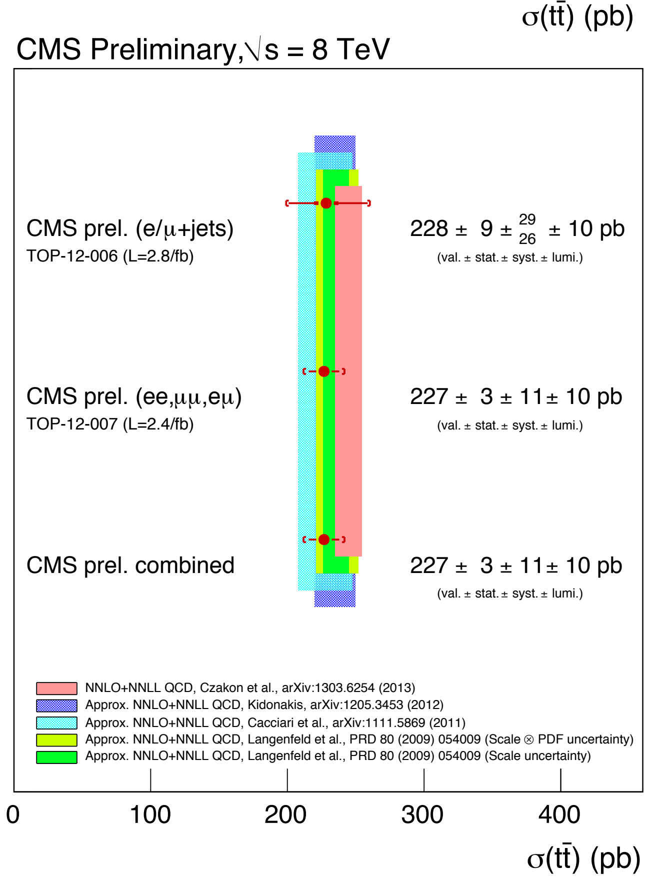
σ_tt̄ [pb]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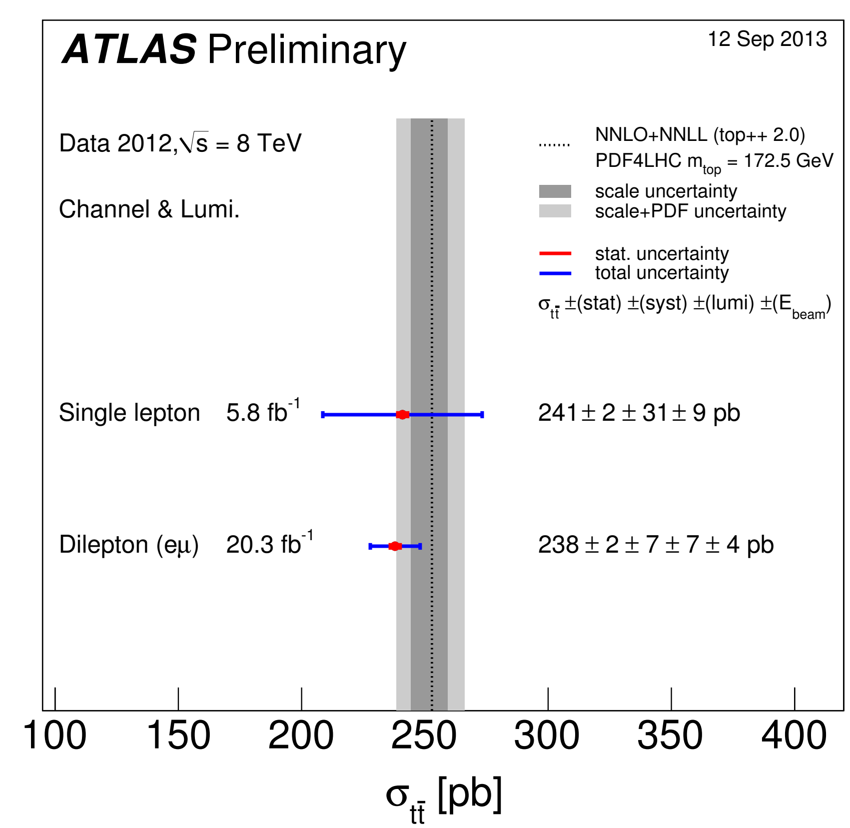
400
σ(tt̄) (pb)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σ_tt̄ [pb]

top σ

7 TeV

σ

$$\sigma_{t\bar{t}} \approx 172 \text{ pb} \qquad \sigma_{\tilde{t}\tilde{t}^*}(m_{\tilde{t}} = m_t) \approx 26 \text{ pb}$$

theory error

NLO:

$$\delta\sigma_{\rm th} \approx 20 \text{ pb}$$

experimental error

$$\delta\sigma_{\rm exp} \approx 7 \text{ pb}$$

top σ

7 TeV

σ

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

$\sigma_{t\bar{t}} \approx 172$ pb

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Alexander Mitov
Theory Division, CERN, CH-1211 Geneva 23, Switzerland

(Dated: March 26, 2013)

$\sigma_{t\bar{t}^*}(m_{t^*} = m_t) \approx 26$ pb

theory error

NLO:

$\delta\sigma_{\rm th} \approx 20$ pb

NNLO+NNLL

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

experimental error

$\delta\sigma_{\rm exp} \approx 7$ pb

top σ

7 TeV

σ

$$\sigma_{t\bar{t}} \approx 172 \text{ pb} \qquad \sigma_{\tilde{t}\tilde{t}^*}(m_{\tilde{t}} = m_t) \approx 26 \text{ pb}$$

theory error

NLO:

$$\delta\sigma_{\rm th} \approx 20 \text{ pb}$$

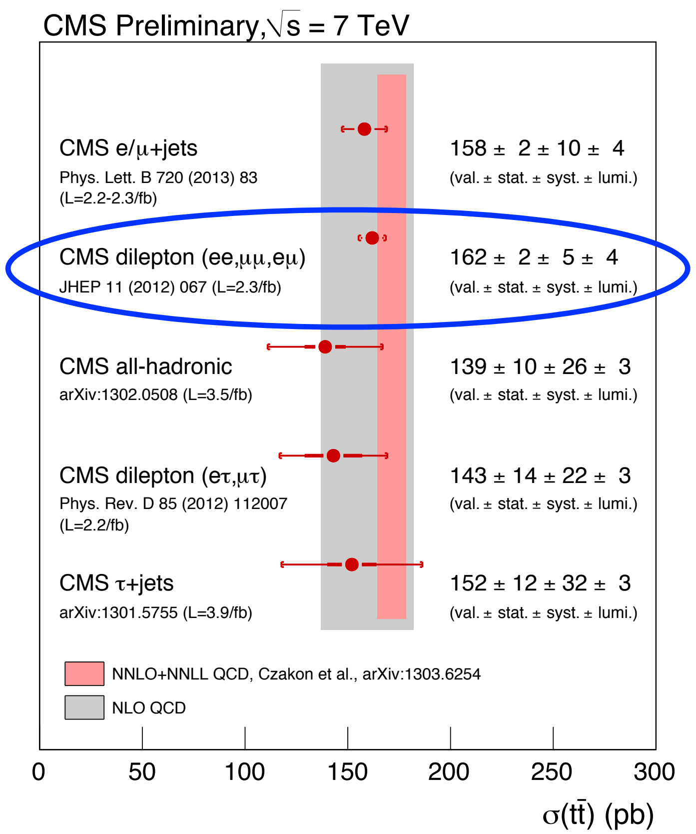
NNLO:

$$\delta\sigma_{\rm th} \approx 8 \text{ pb}$$

experimental error

$$\delta\sigma_{\rm exp} \approx 7 \text{ pb}$$

top σ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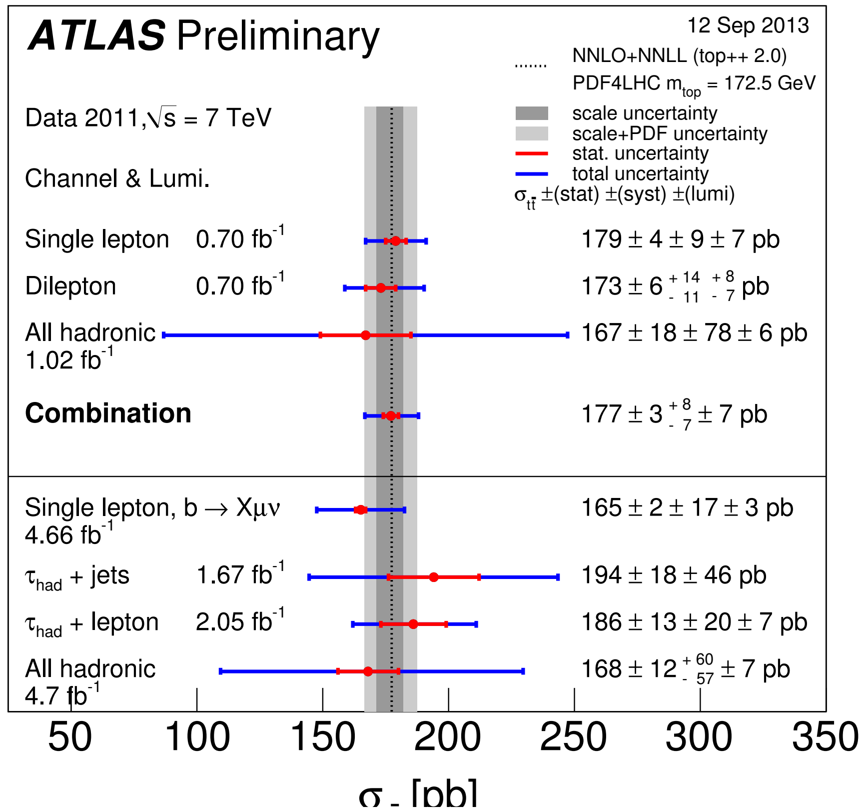
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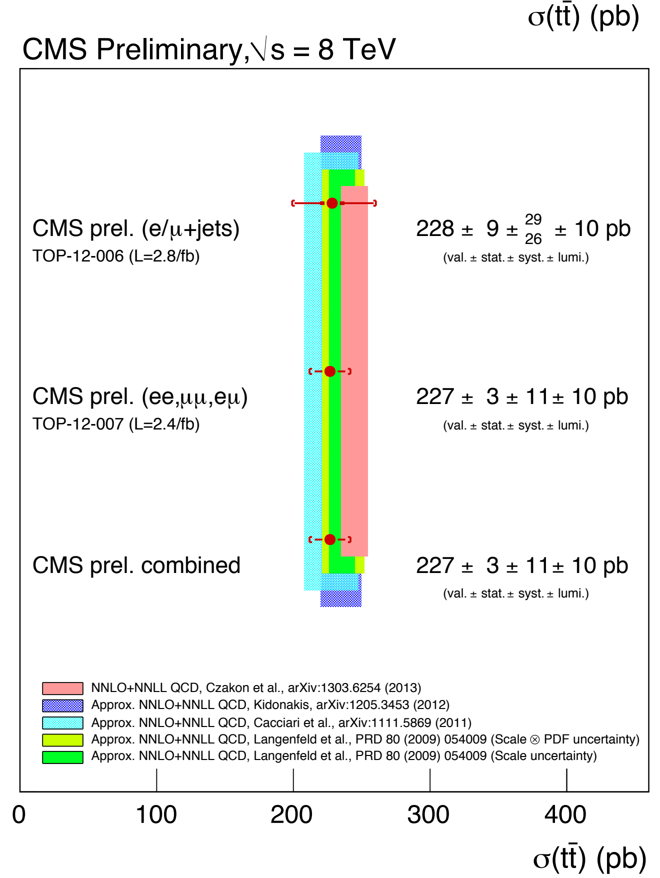
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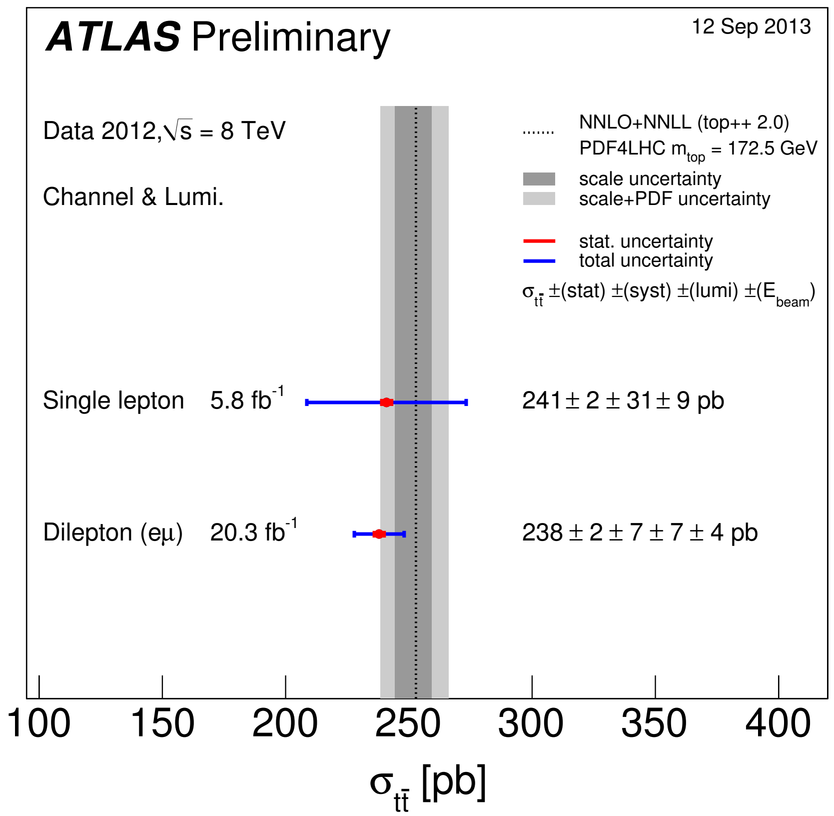
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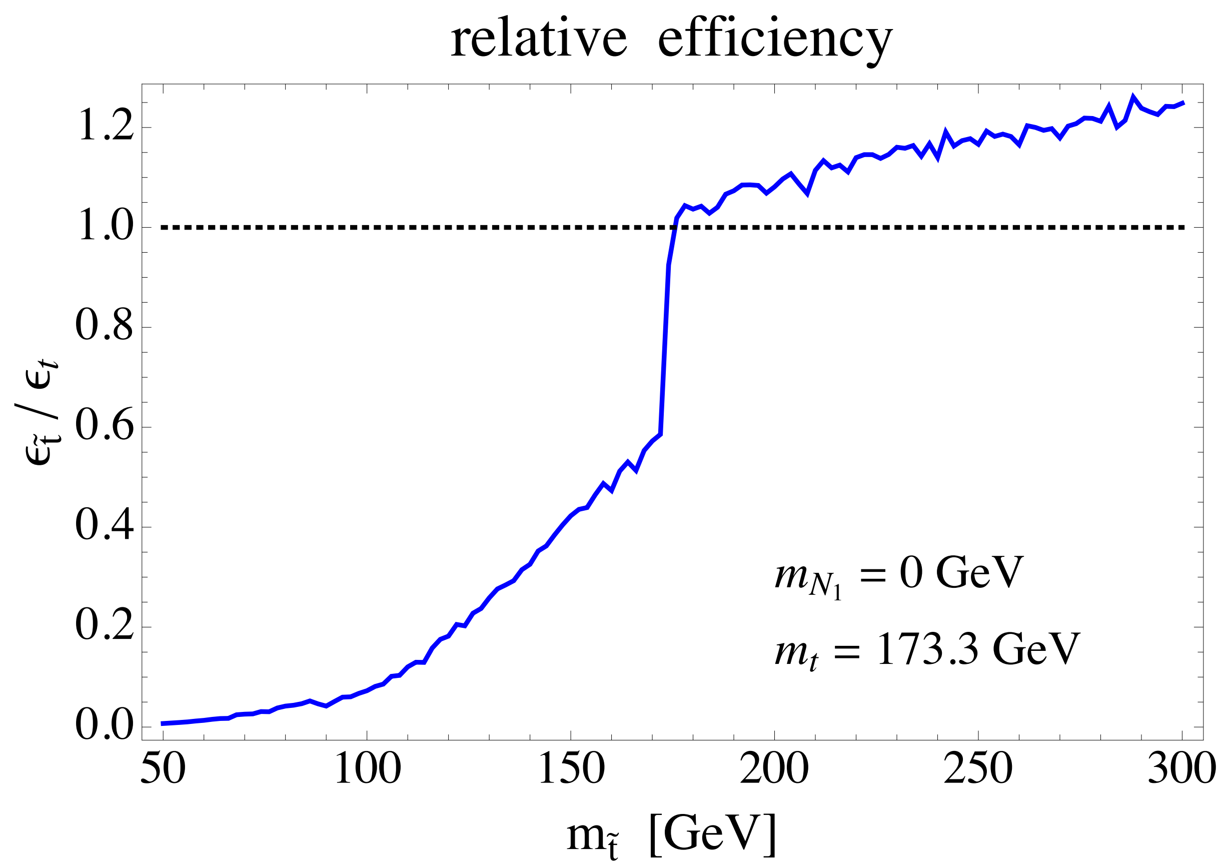
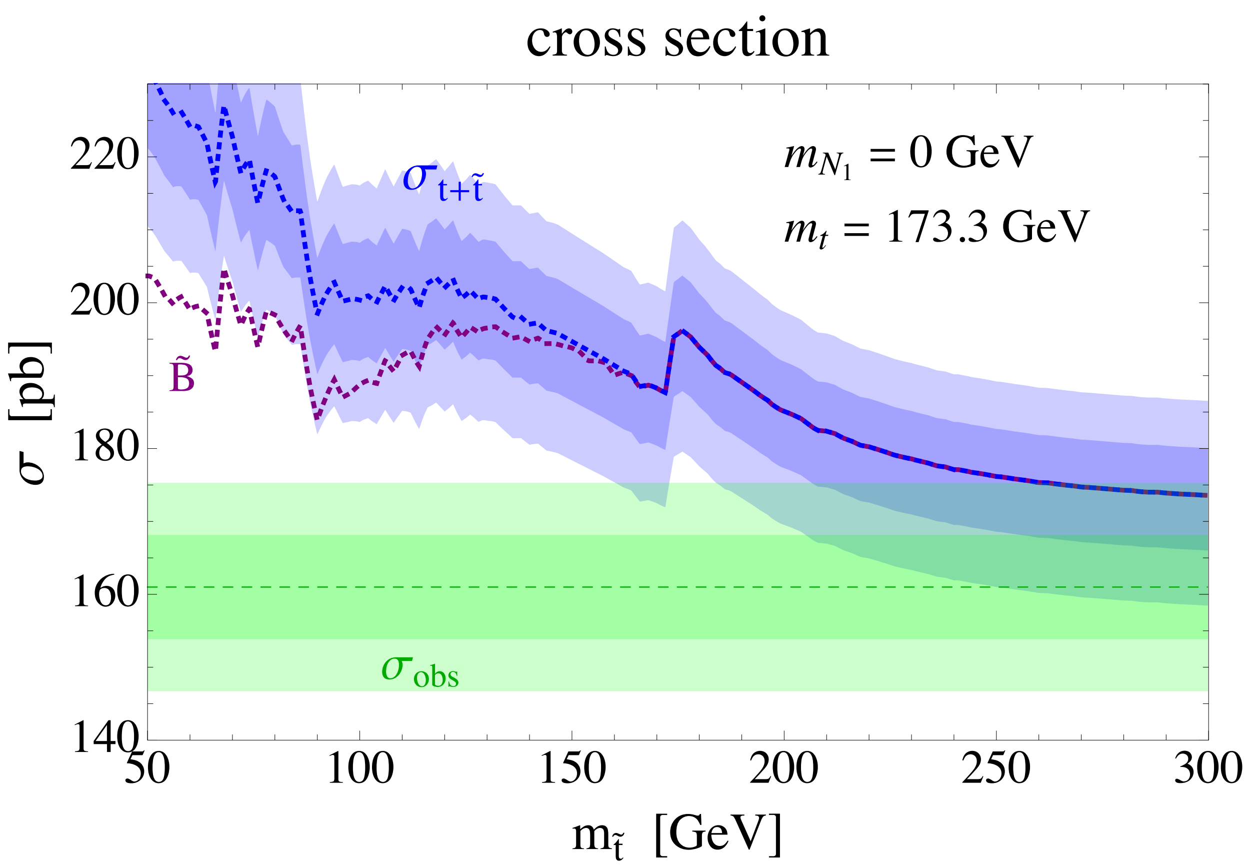
100 150 200 250 300 350 400
σ_tt̄ [pb]

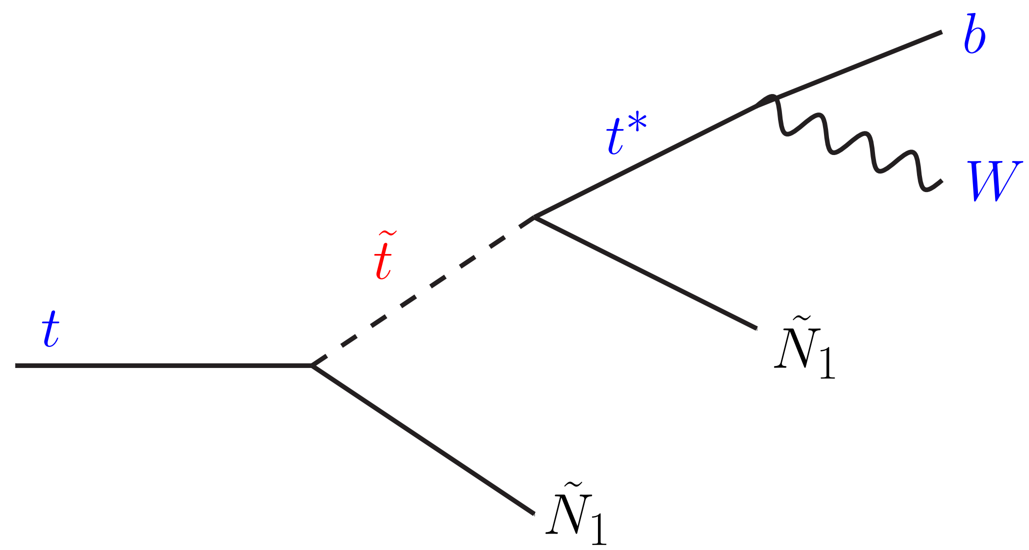
stop + top

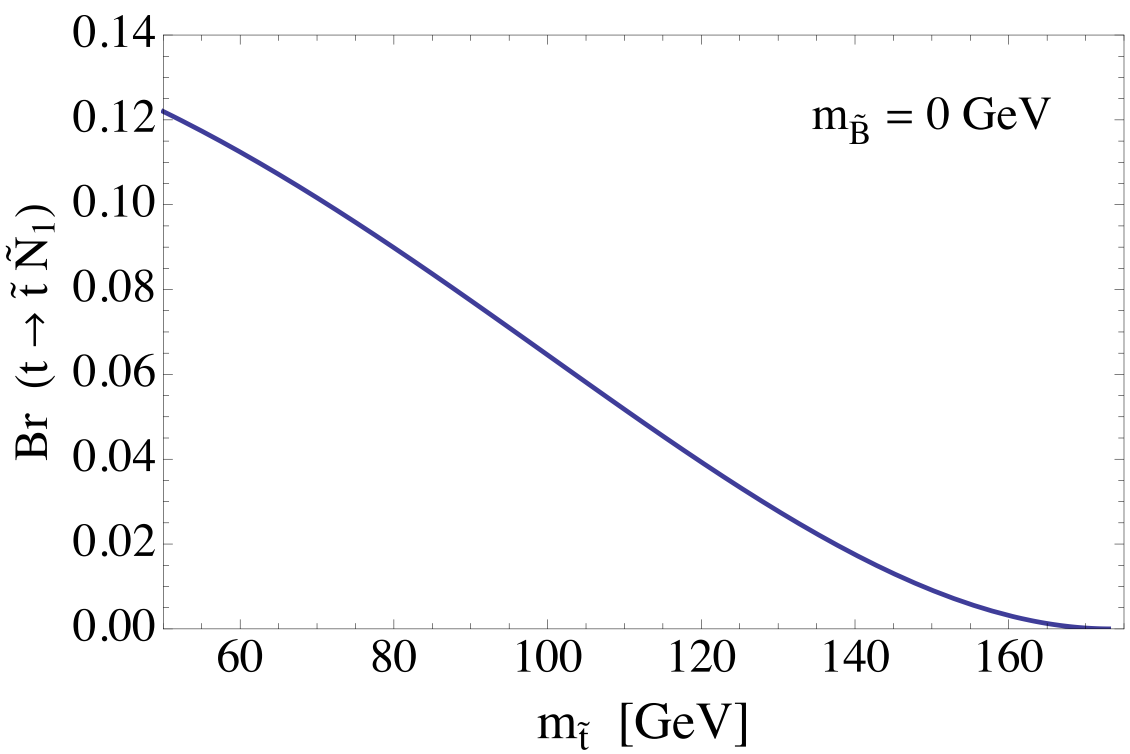
CMS dilepton @7TeV:

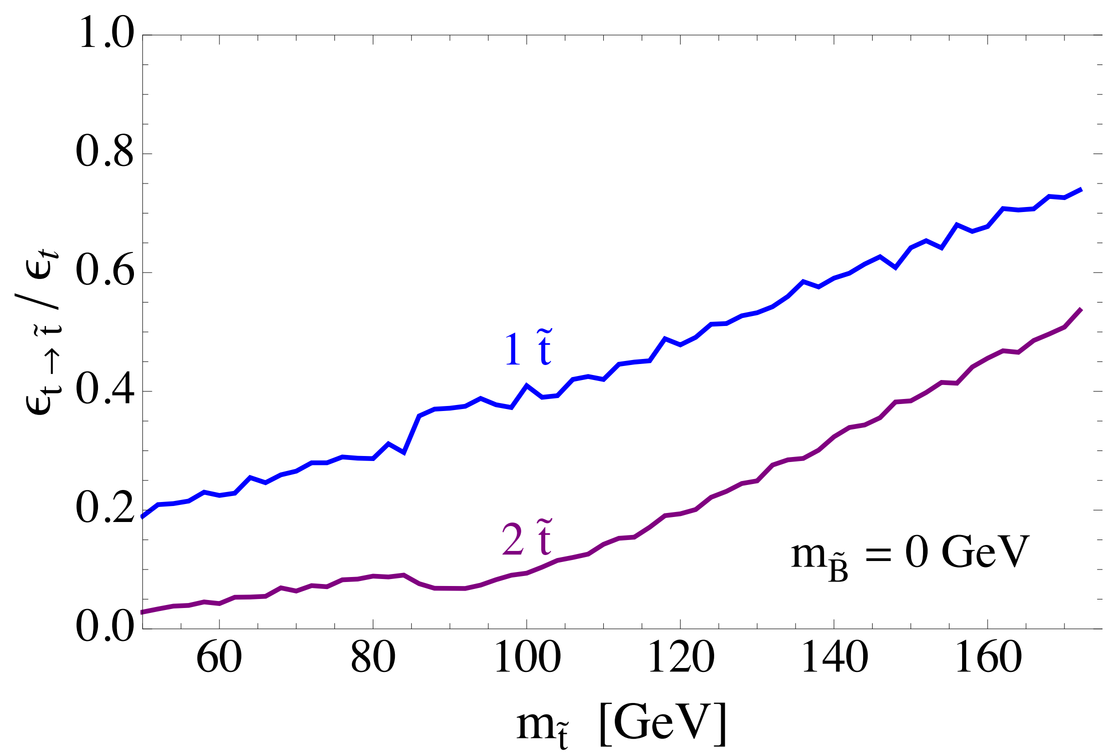




top to stop

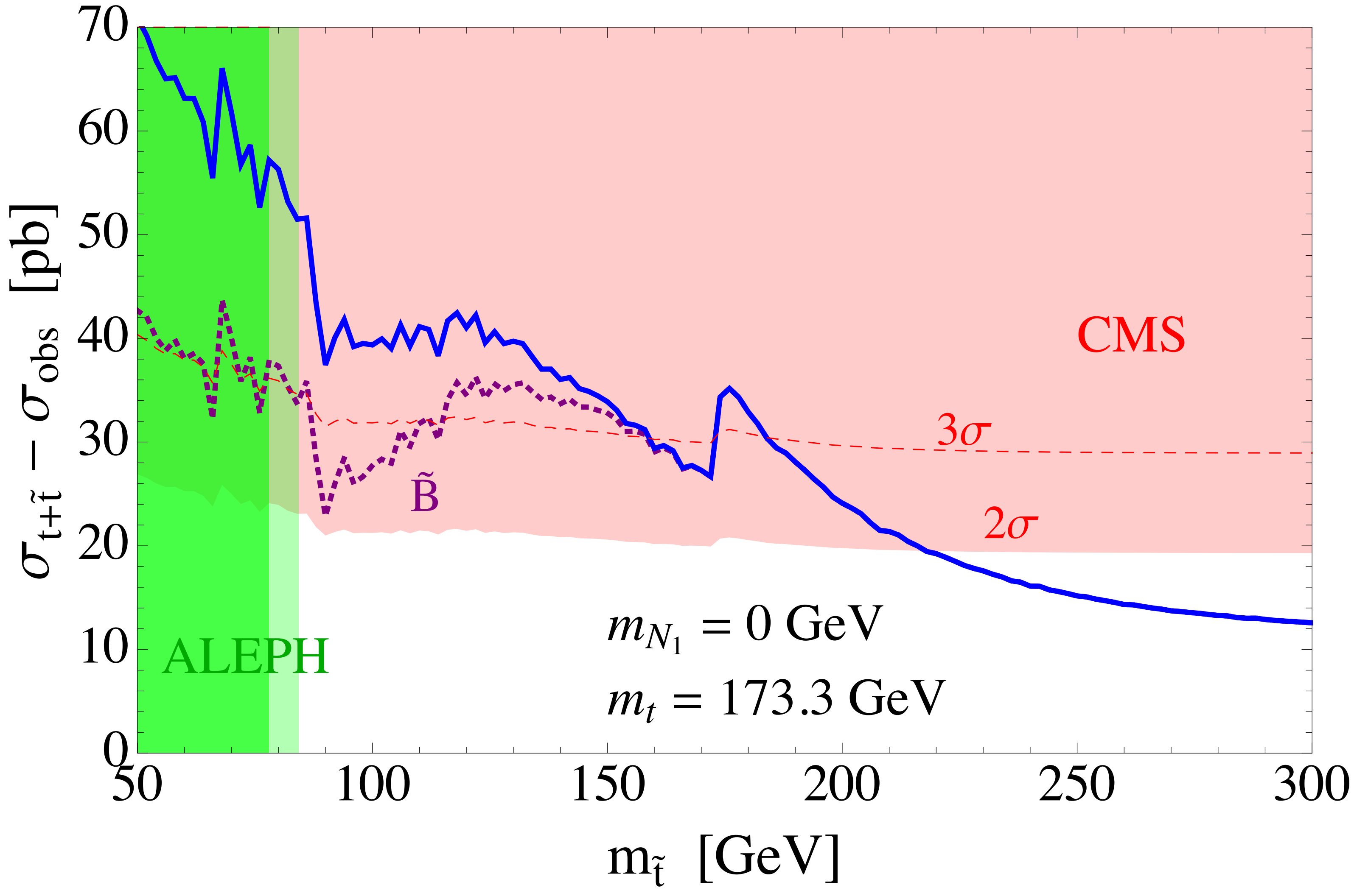




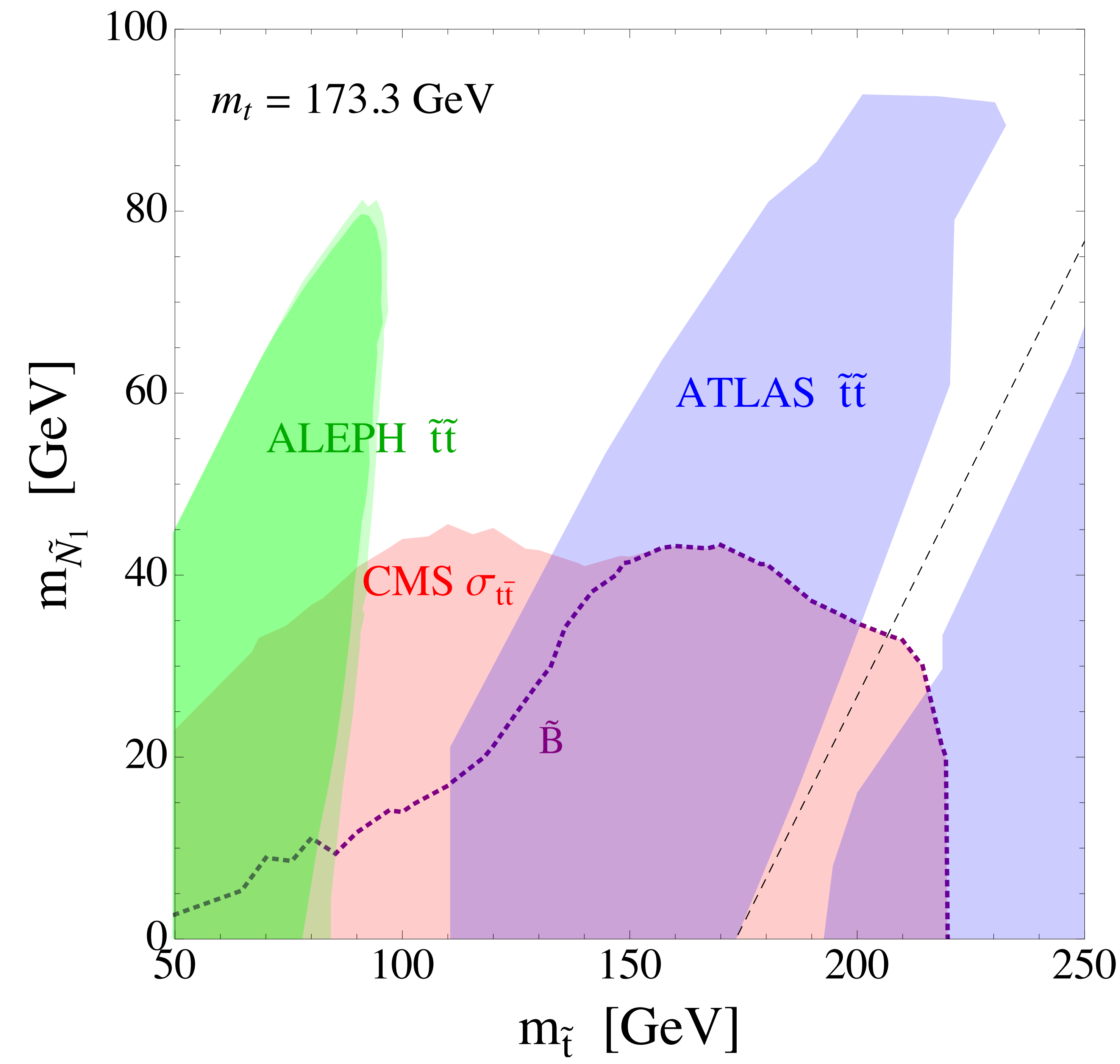


stop + top

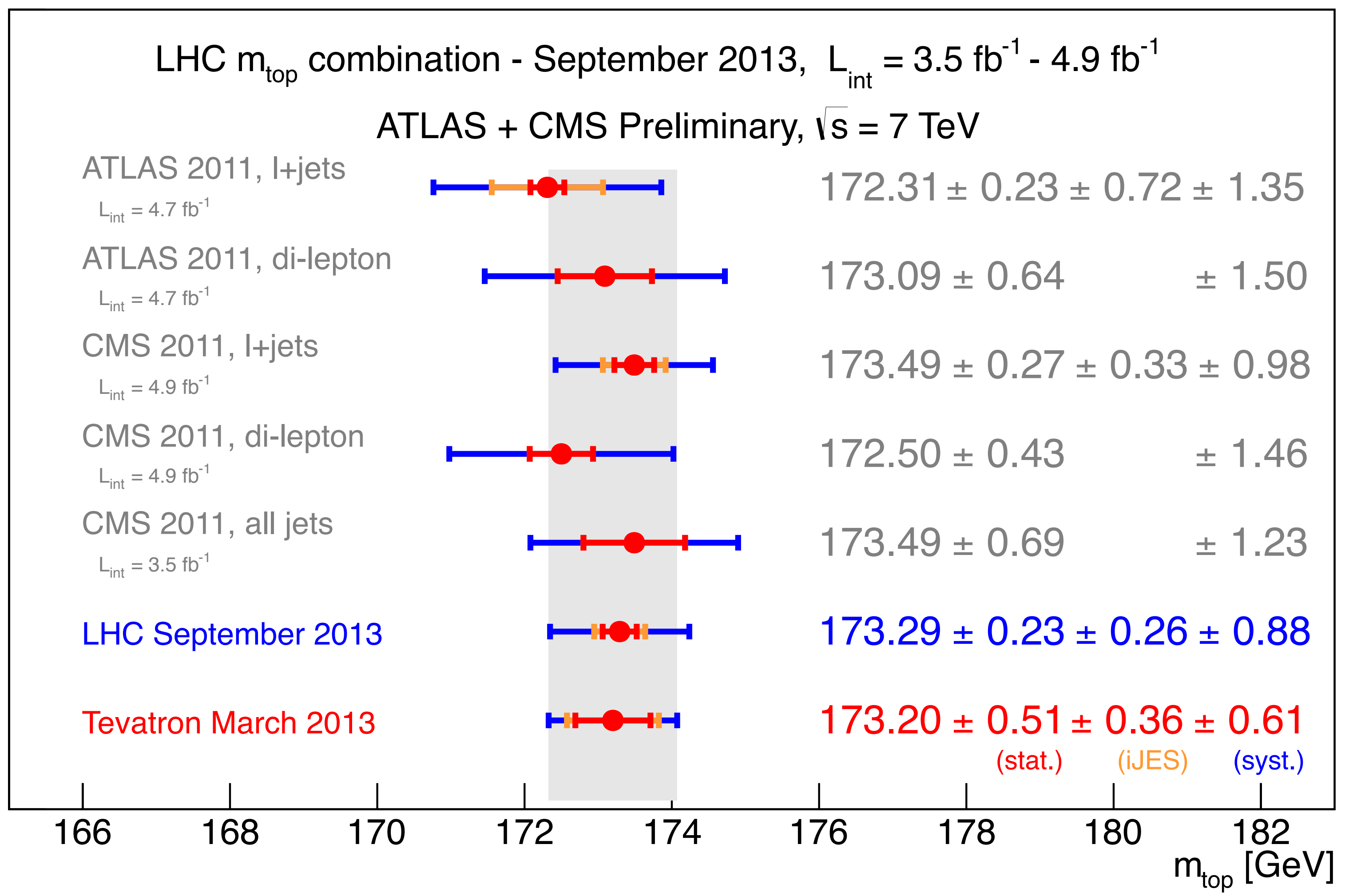
CMS dilepton @7TeV:



neutralino mass dependence



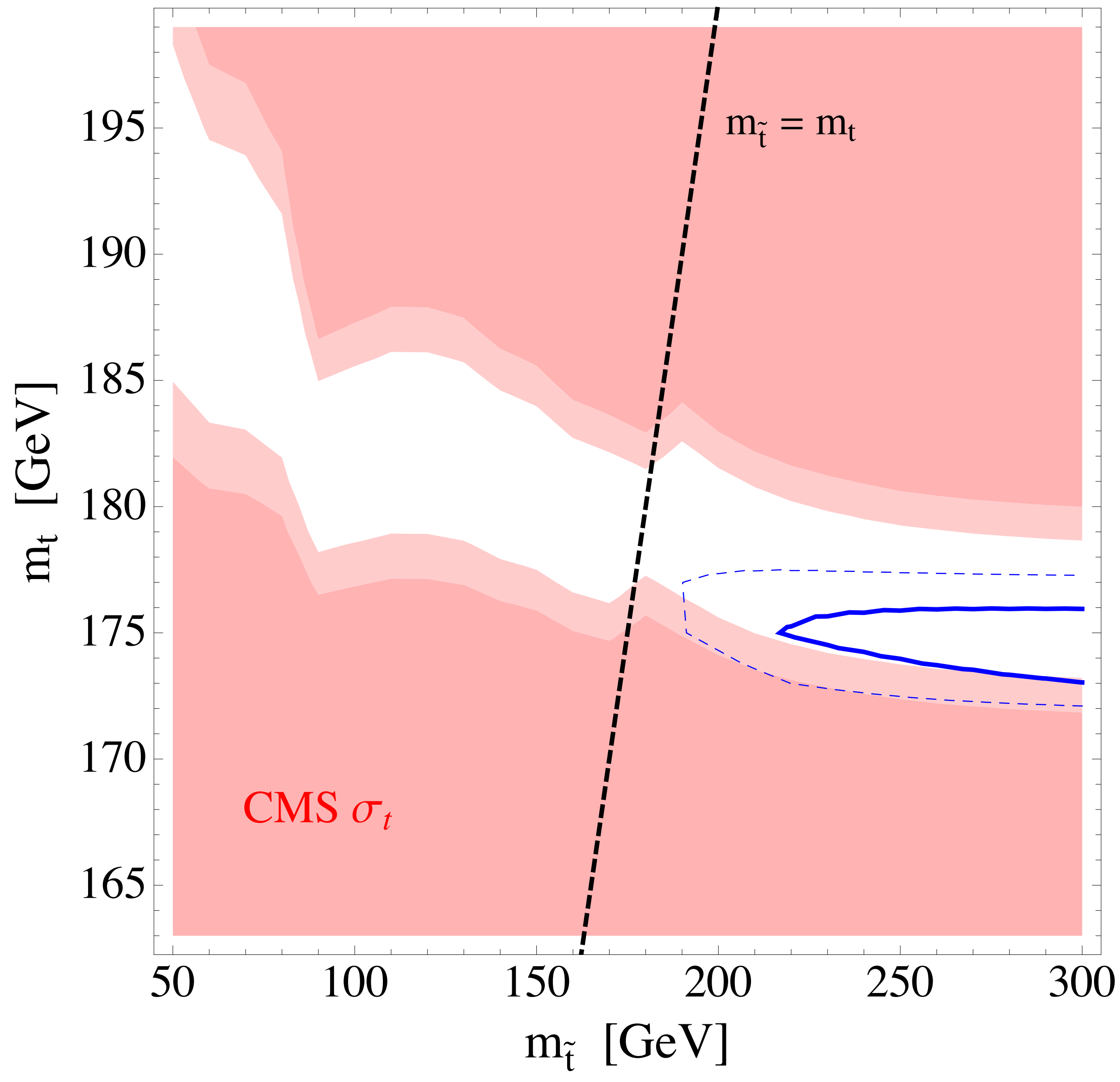
top mass



all measurements of the top mass assume the SM, what if there are an O(1) fraction of stops events?

stop + top

varying the top mass:



LHC top mass
(5/fb)

$173.3 \pm 0.5 \pm 1.3$ GeV

(assuming stops have no effect)

$$m_h \approx 125 \text{ GeV}$$

natural

$\tilde{m} \approx m_h$

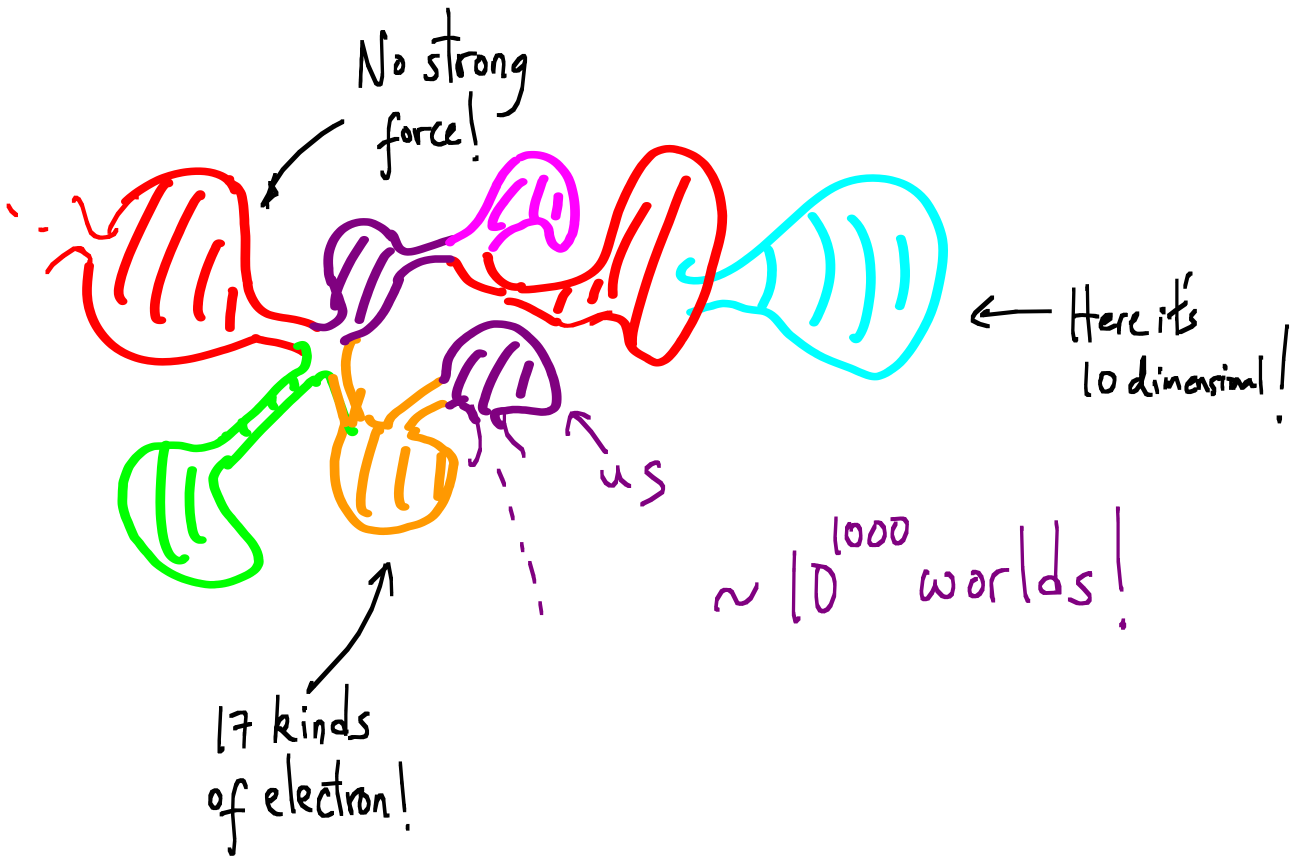
where are the stops?

fine-tuned

$\tilde{m} \gg m_h$

multiverse?

2. the weak scale from BBN

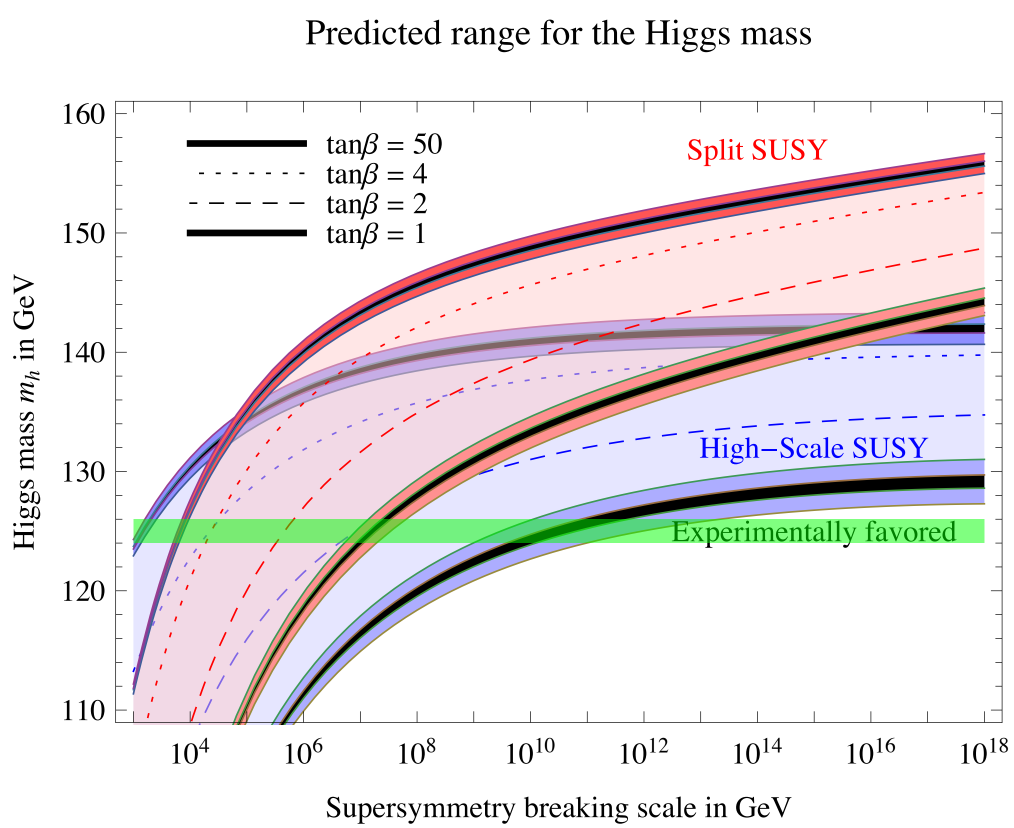


Lawrence Hall, David Pinner, JTR, *to appear.*

is SUSY split?

$$\tilde{m}_s \gg \tilde{m}_f \sim m_h$$

- flavor/CP ✓
- gauge coupling unification ✓
- dark matter ✓
- natural EWSB ✗



Giudice and Strumia, 1108.6077

Wells 0306127
Arkani-Hamed, Dimopoulos 0405159

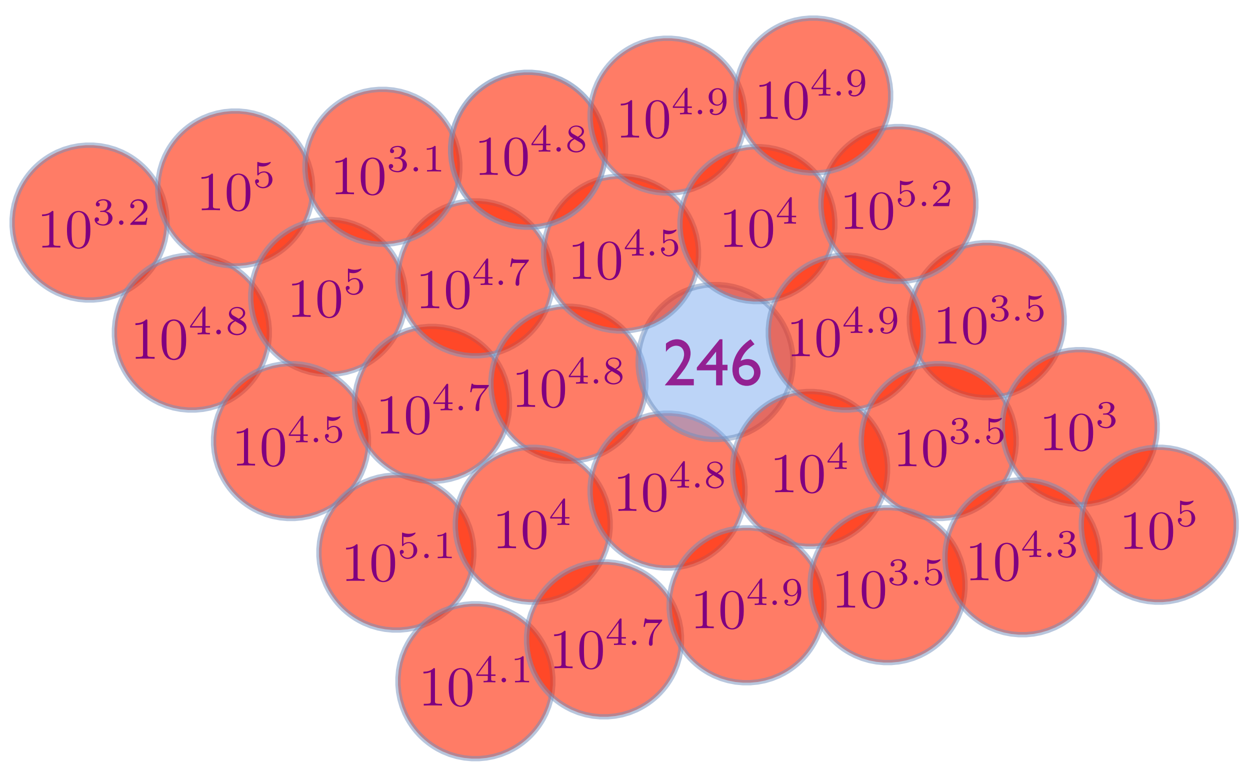
lots of recent attention:

spread, pure gravity mediation, mini-split, simply unnatural, ...

is SUSY split?

how can we understand the failure of technical naturalness to describe m_h?

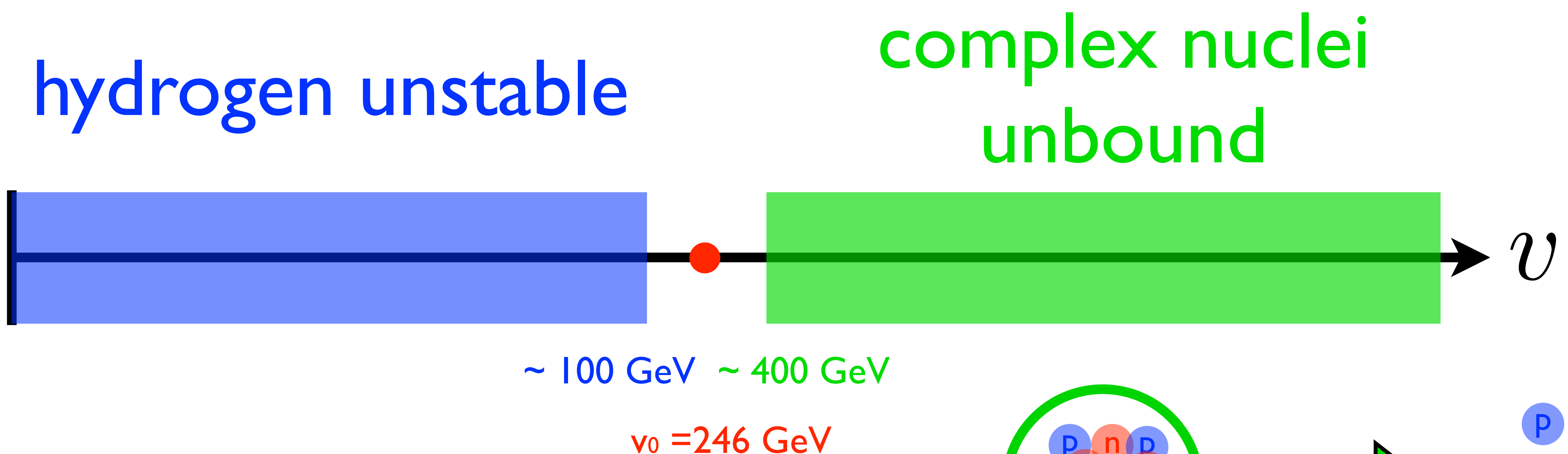
an alternative:
anthropic selection in the multiverse



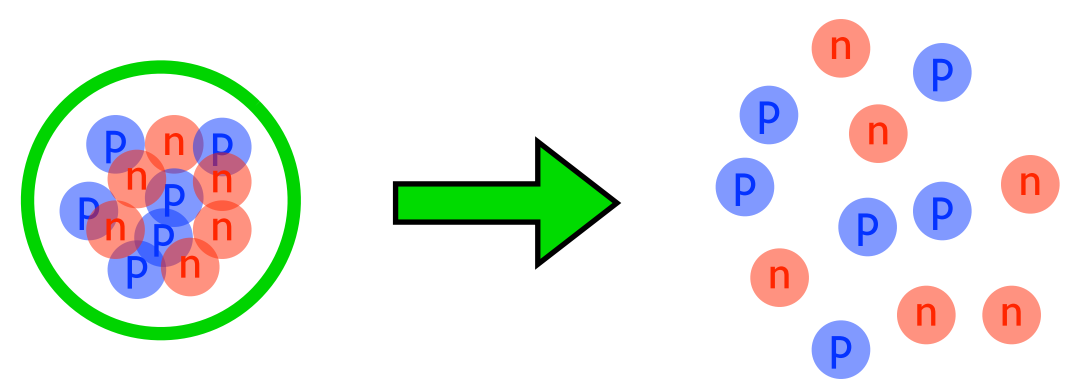
dangers of a variable weak scale

$$m_u = y_u \, v$$

$$m_d = y_d \, v$$



$$p + e^- \to n + \nu_e$$



- Agrawal, Barr, Donoghue, Seckel 9707380
- Damour, Donoghue 0712.2968

unknown structure of the multiverse

- which parameters scan? $v, \ldots$
- what are their distributions? $\int dp_i \, f(p_i)$

  $f(v) \propto v^2$?

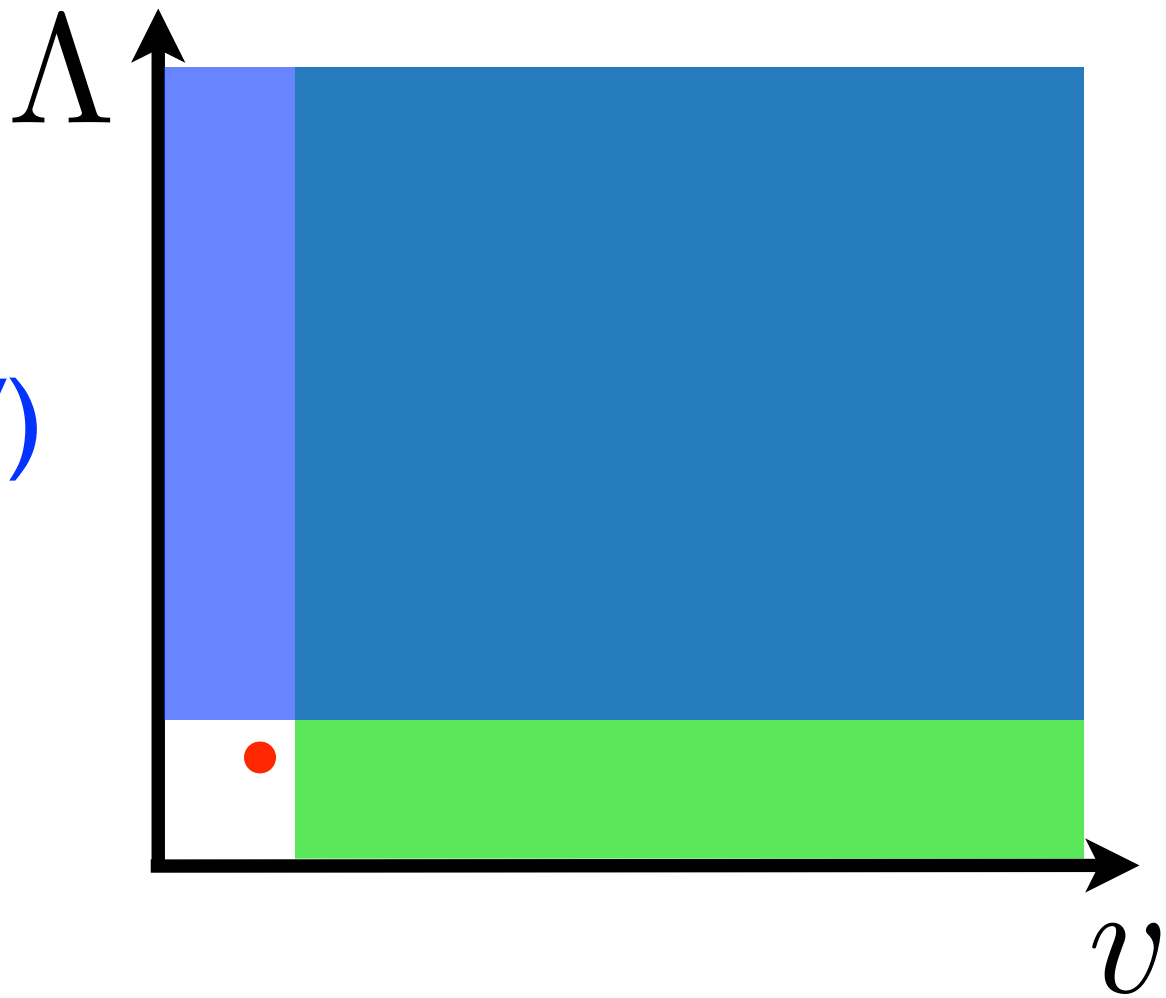
- what are the dangerous wall in parameter space?

  no atoms, ...

- models are refutable $P_{v<v_{\rm obs}} = \frac{\int_0^{v_{\rm obs}} dv\, f(v)\, w(v)}{\int_0^{\Lambda} dv\, f(v)\, w(v)}$

which parameters scan?

assuming only dimensionful parameters scan,

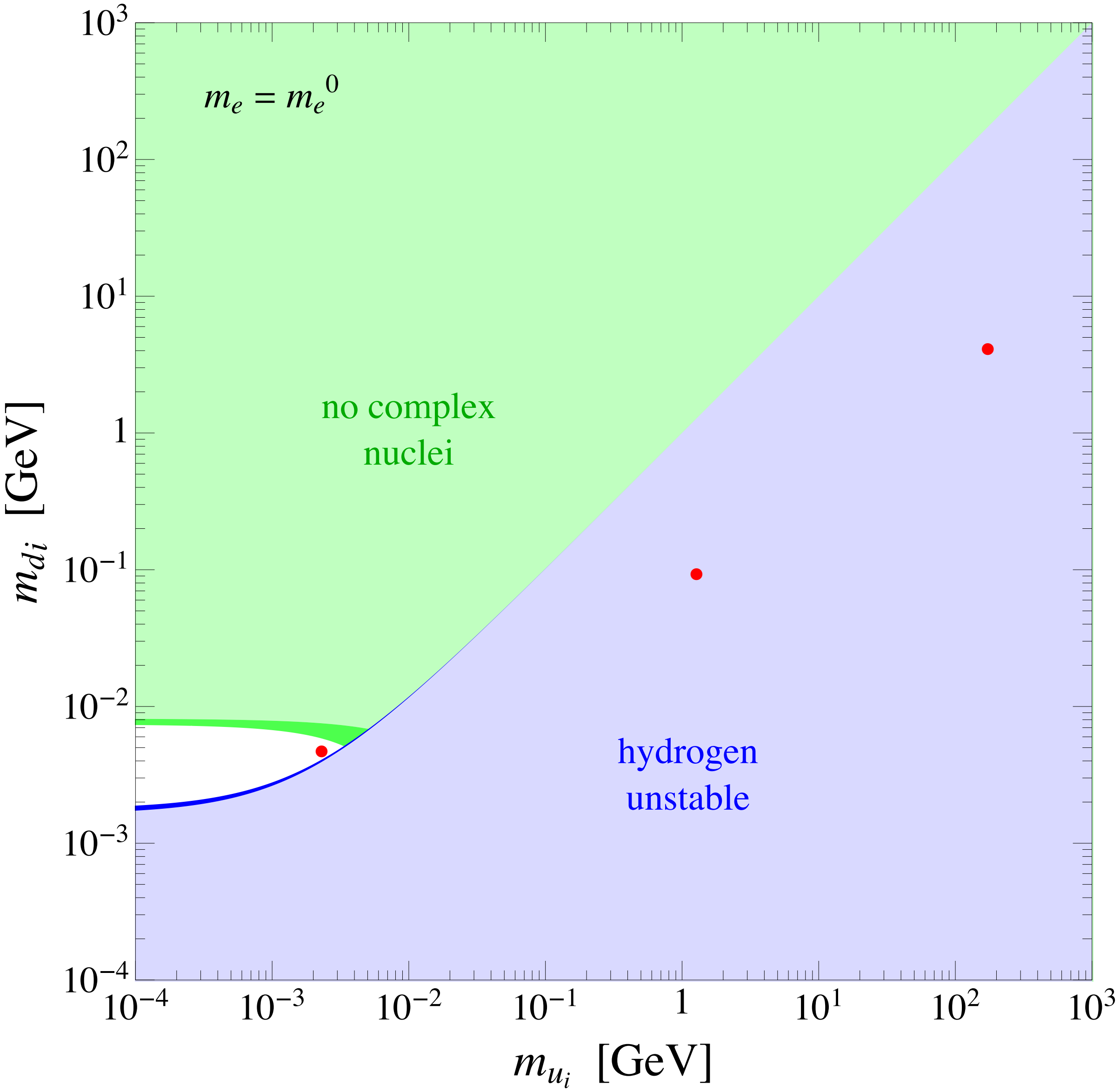


no structure
(Weinberg 1987)

no complex
nuclei

Arkani-Hamed, Dimopoulos, Kachru 0501082

scanning (y_u, y_d, v)



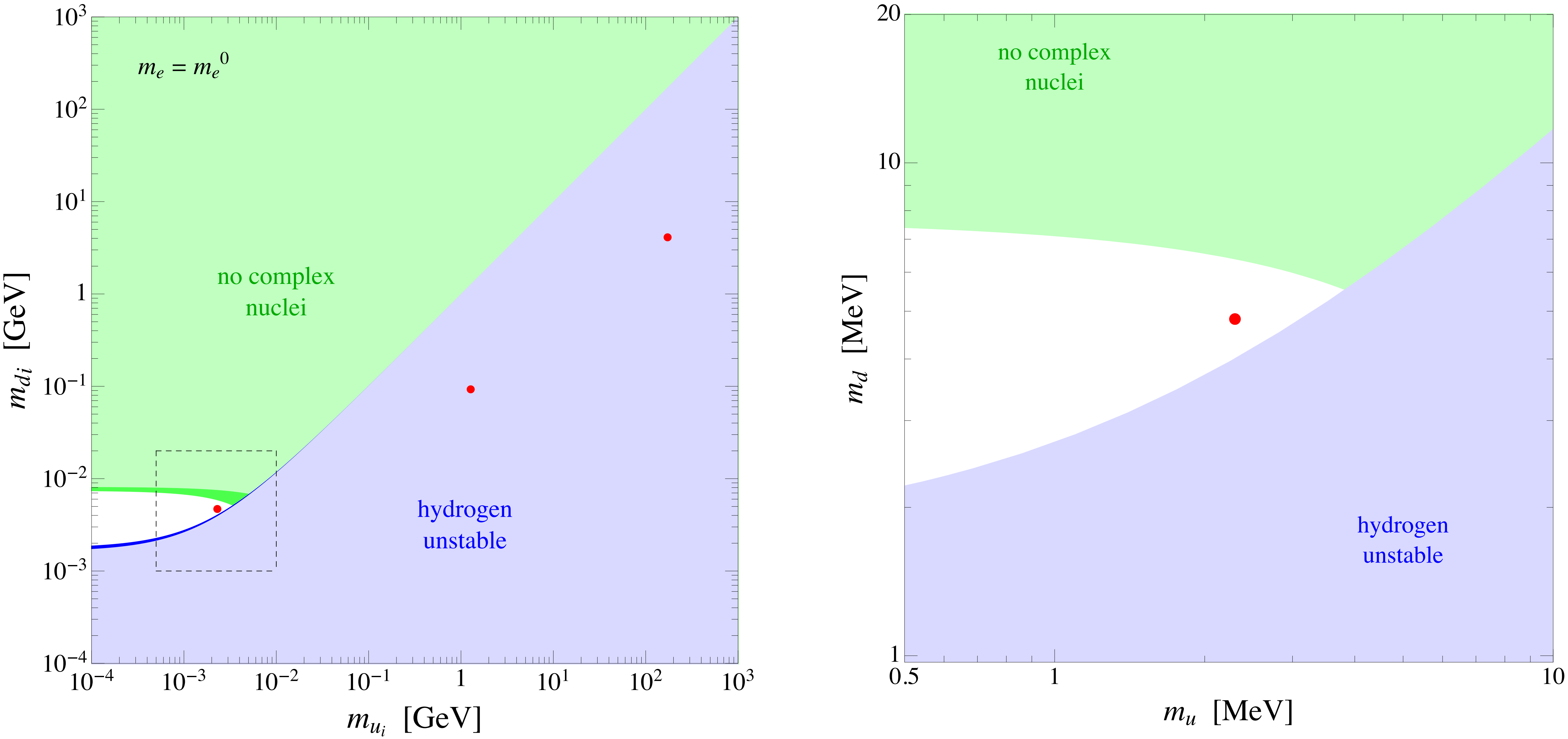
$$n \to p + e + \bar{\nu}$$

$$m_n - \left|\frac{B}{A}\right| = m_p + m_e$$

$$p + e \to n + \nu$$

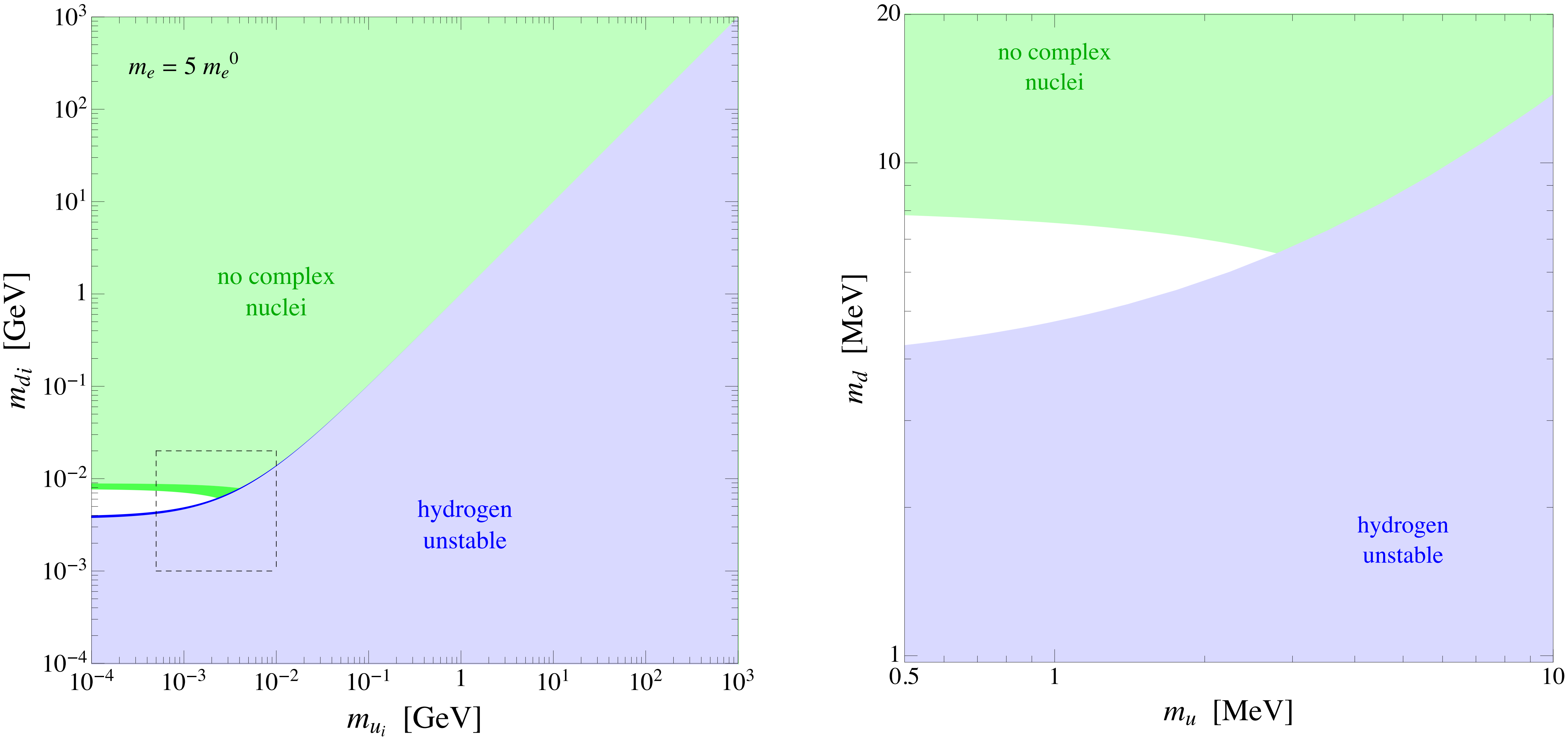
$$m_p + m_e = m_n$$

scanning (y_u, y_d, v)



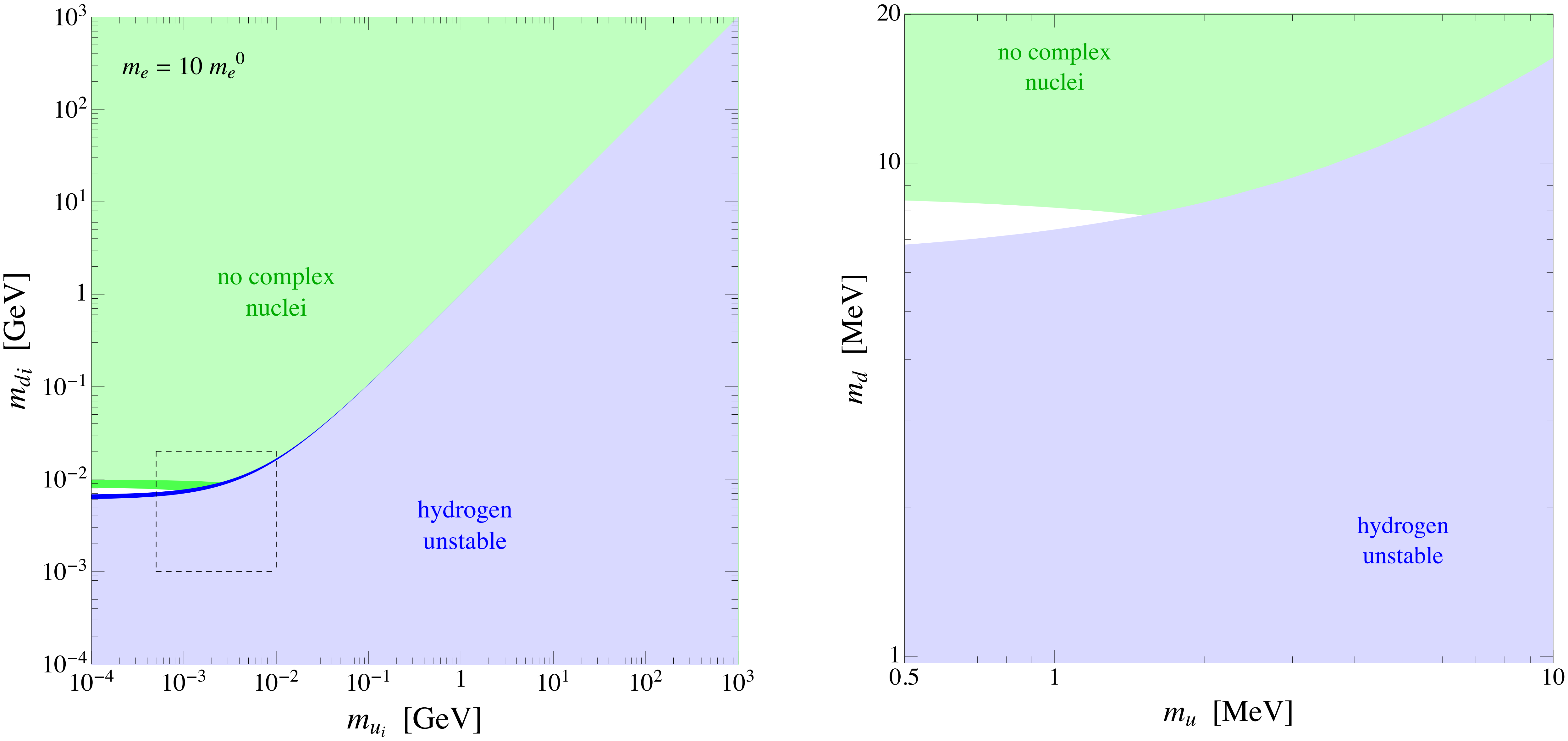
scanning (y_u, y_d, v)

$$m_e = 5\, m_e^0$$



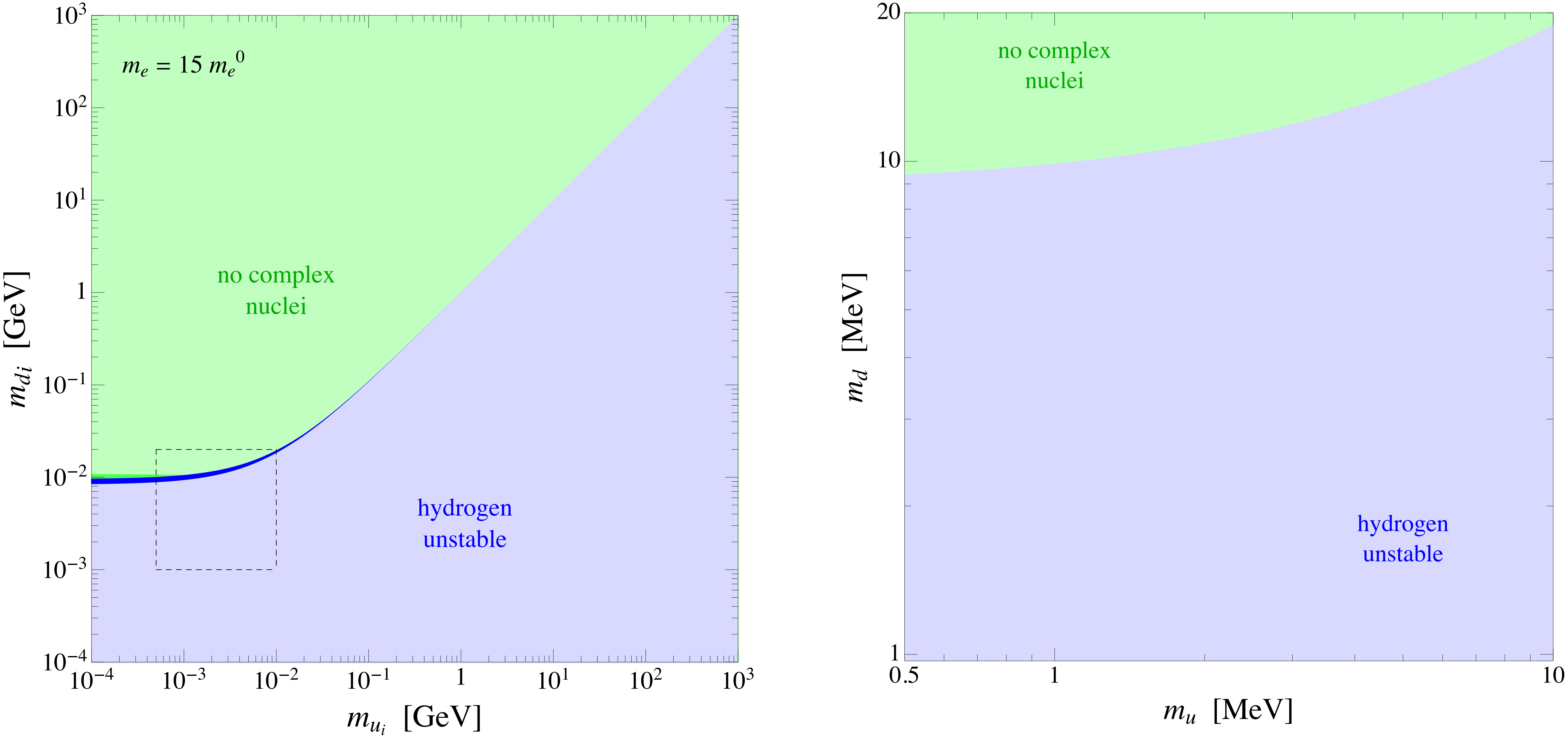
scanning (y_u, y_d, v)

$$m_e = 10\, m_e^0$$



scanning (y_u, y_d, v)

$$m_e = 15\, m_e^0$$



runaway to large v?

scan:

(y_u, y_d, v)

- nuclear physics depends on the quark masses

- runaway: increase v, fixing quark masses,

$$y_{u,d} \to \frac{m_{u,d}}{v}$$

“Weakless Universe,” Harnik, Kribs, Perez 0604027

weak-scale physics in our Universe

1. BBN

$$p + \bar{\nu}_e \rightarrow n + e^+$$

2. pp chain in stars

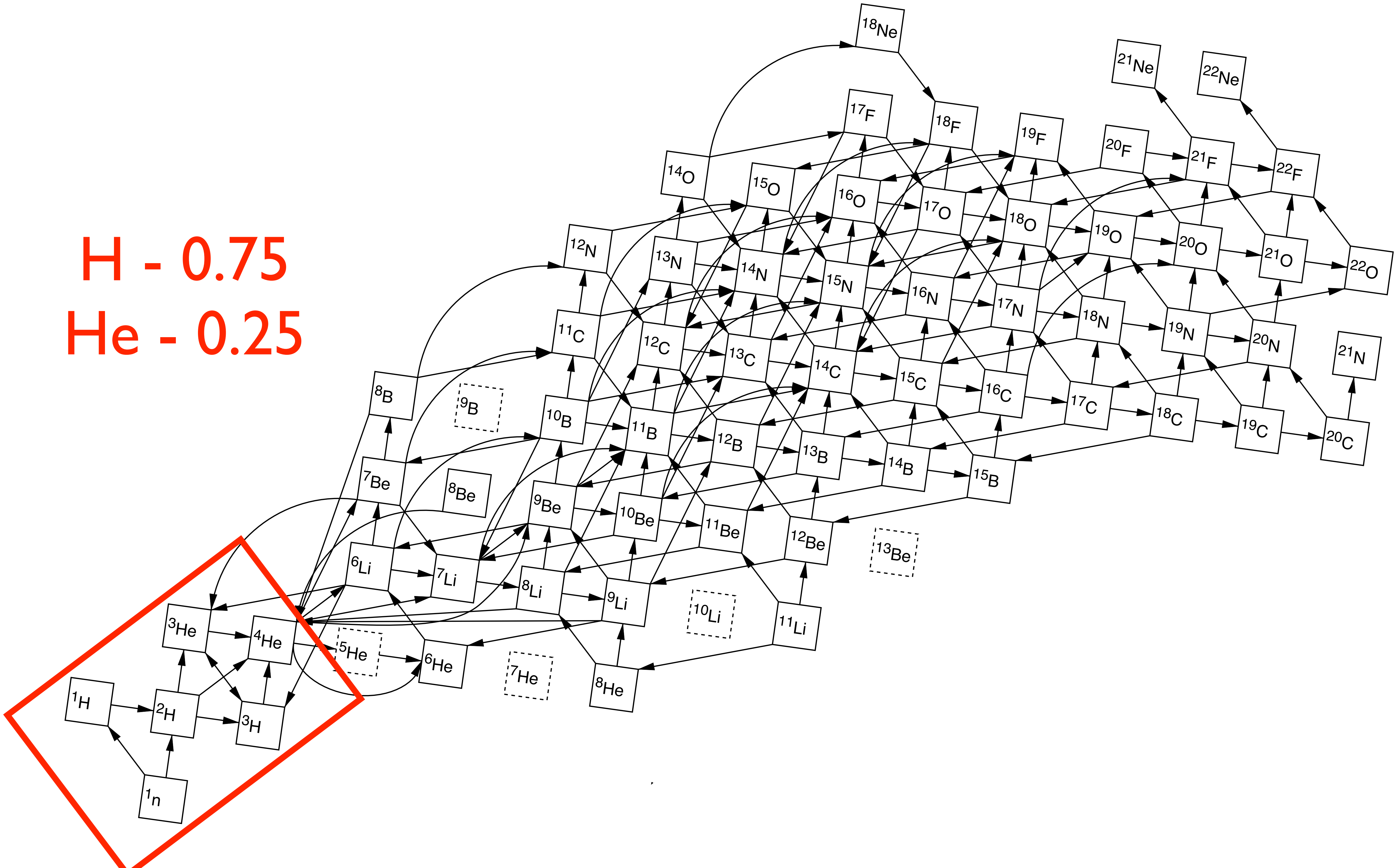
$$p + p \rightarrow d + e^+ + \nu_e$$

3. supernovae

$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$

$$\bar{\nu} + p \rightarrow n + e^+$$

BBN



H - 0.75

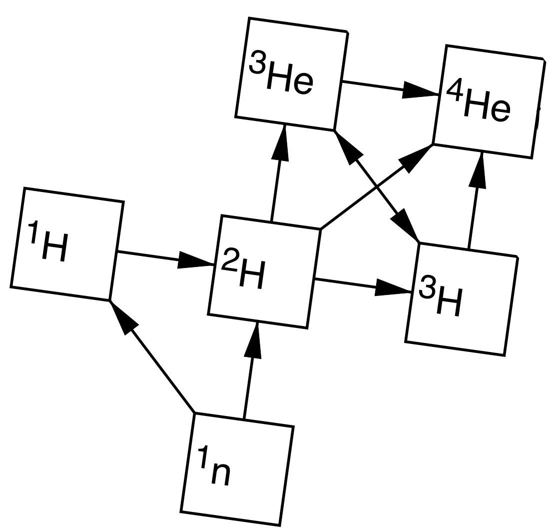
He - 0.25

BBN and He4

$$p + \bar{\nu}_e \longleftrightarrow n + e^+$$

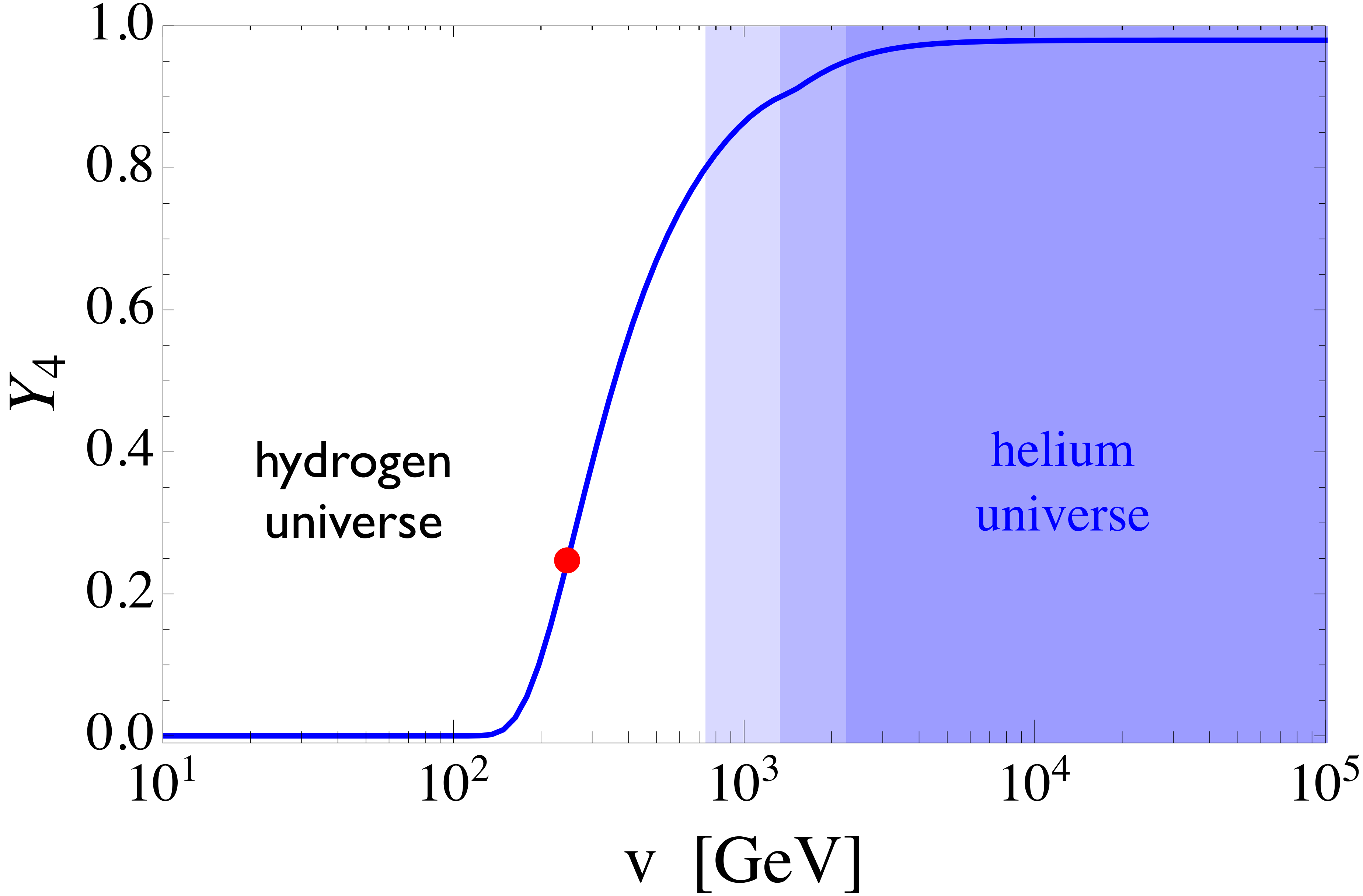
decouples: $$T_{\rm fr} \sim \frac{v^{4/3}}{M_p^{1/3}} \approx 1 \text{ MeV}$$

$$\frac{n}{p} = e^{-(m_N - m_P)/T_{\rm fr}} \qquad m_N - m_P \approx 1.3 \text{ MeV}$$



$$Y_4 \approx \frac{2(n/p)}{1 + n/p} \approx 0.25$$

BBN and He4



$$m_N - m_P \sim T_{\rm fr} \quad \Longleftrightarrow \quad (m_N - m_P)^3 M_p \sim v^4$$

dangers of a helium universe

primordial hydrogen is important for:

- galactic halo cooling
- stars powered by pp chain
- water

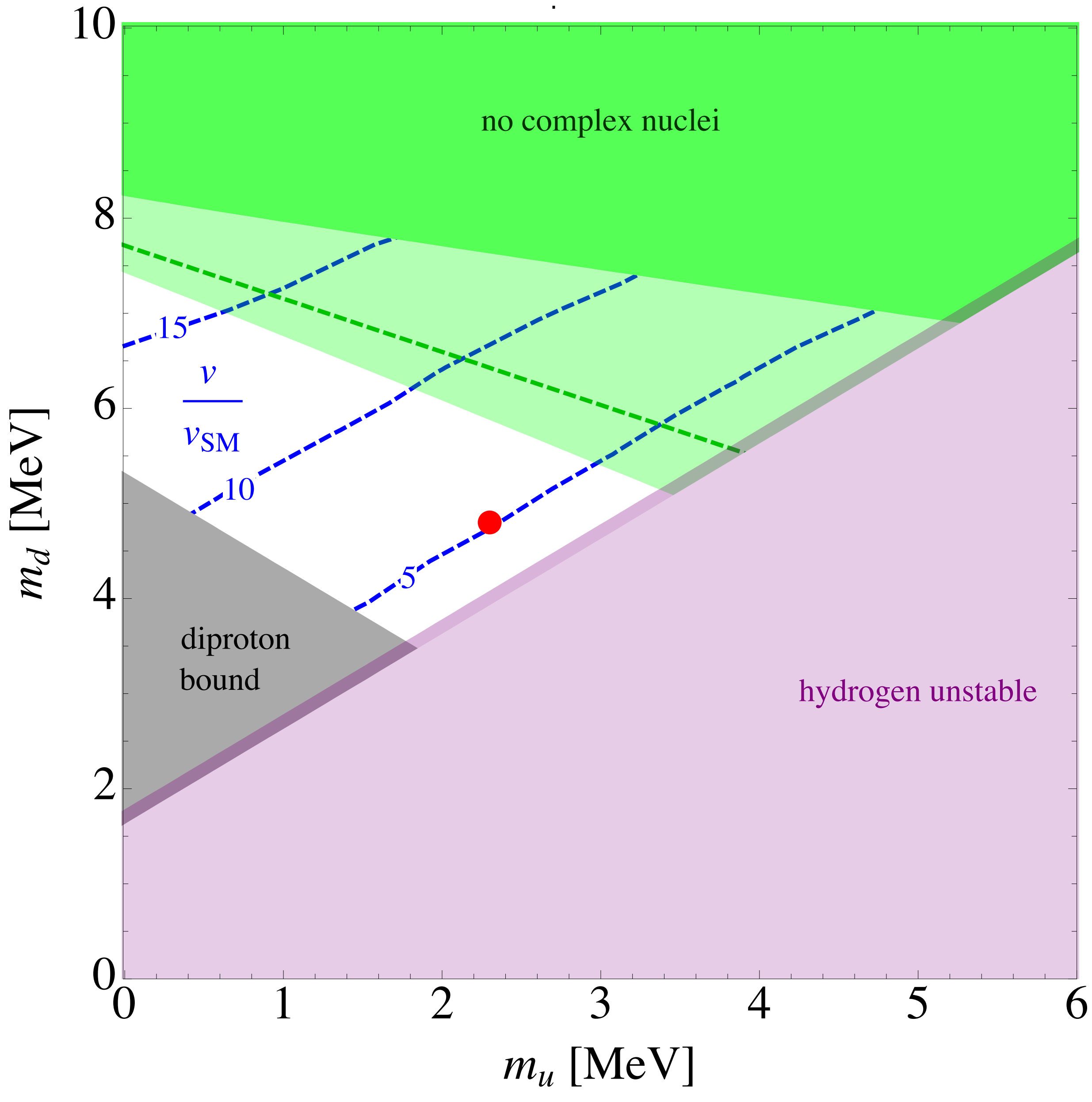
quantifying how much hydrogen is needed for observers is hard and we leave it for future work...

BBN and the weak scale

scan:

$$(y_u, y_d, v)$$

$$Y_4 < 0.9$$



- in a multiverse where (y_u, y_d, v) scan, all three parameters are bounded by requiring stable Hydrogen, complex nuclei, and not too much Helium from BBN

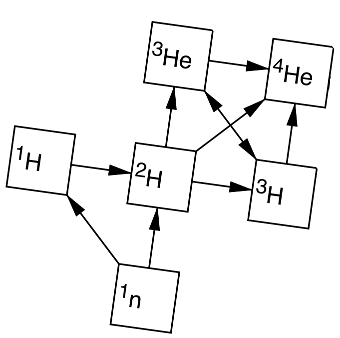
- but what if other parameters scan too?

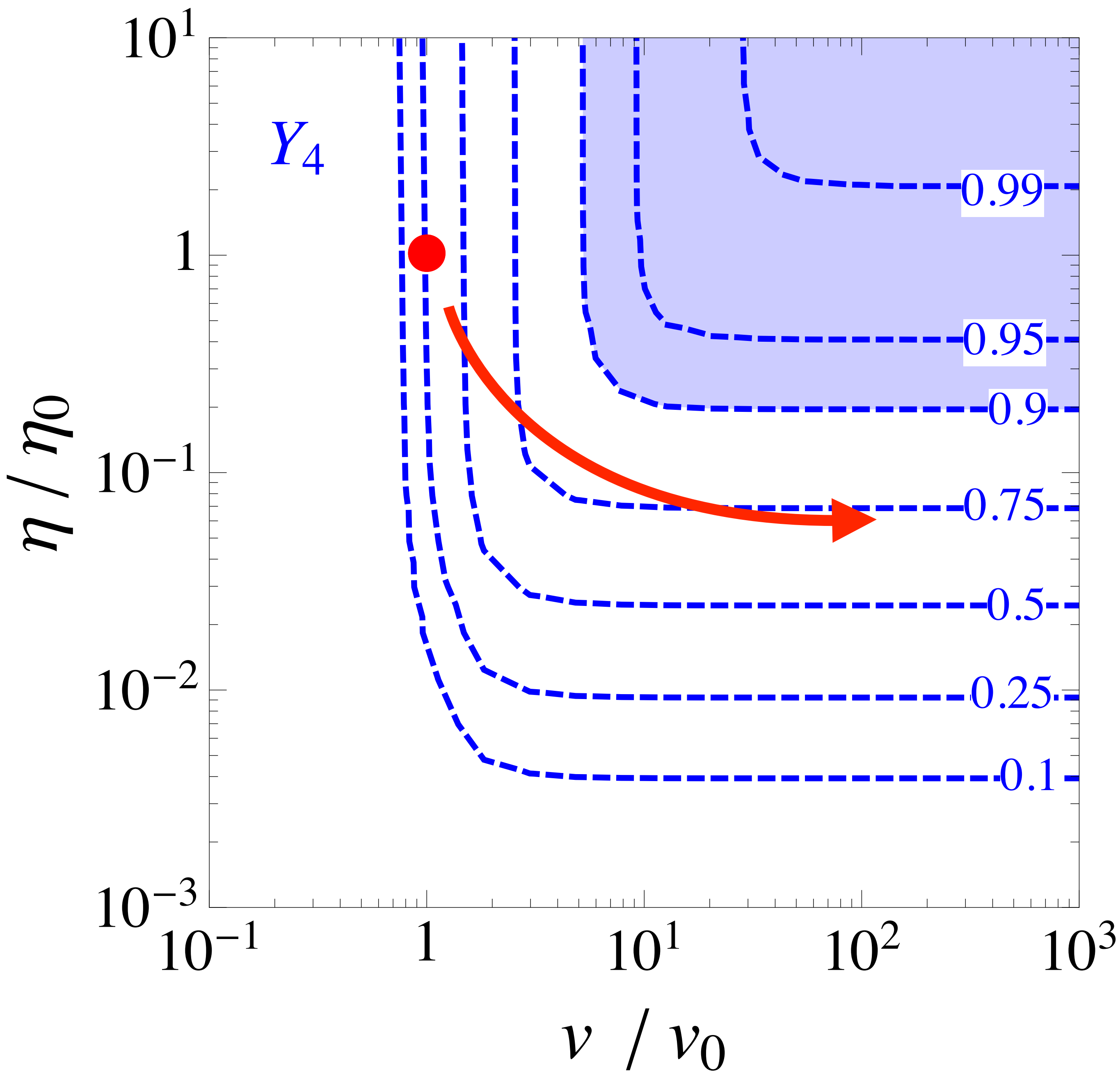
varying the baryon density

scan:
(v, η)

$$p + n \to d + \gamma$$

freezes out





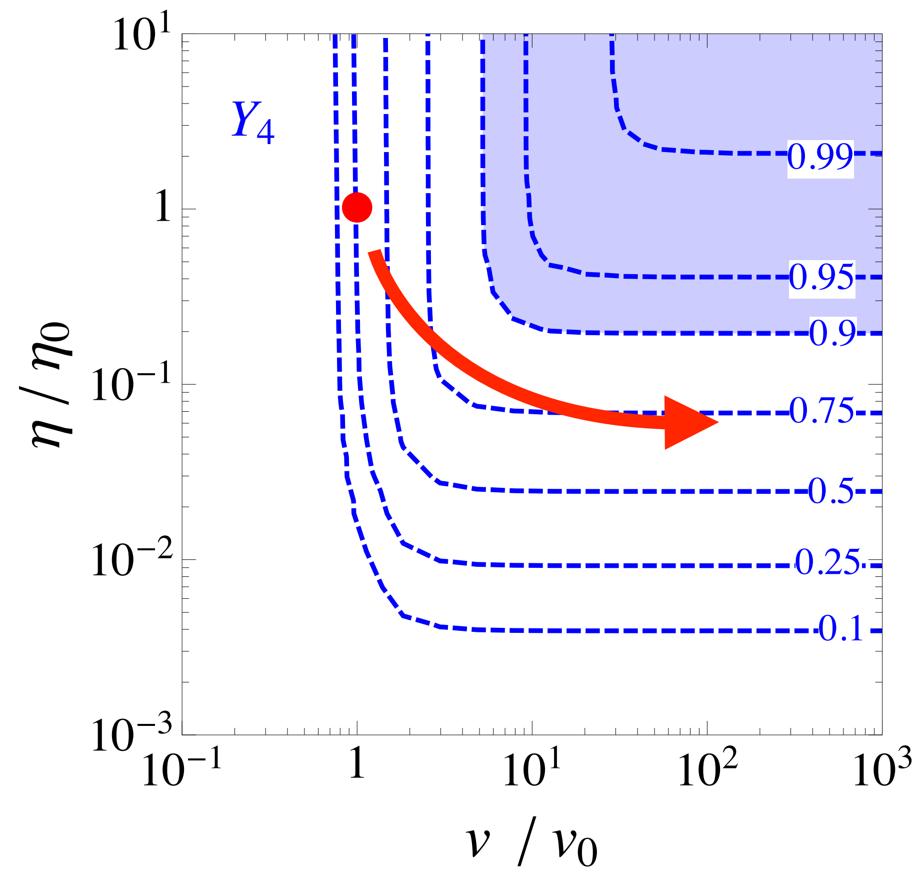
runaway
to large v

varying the baryon density

possible implications:

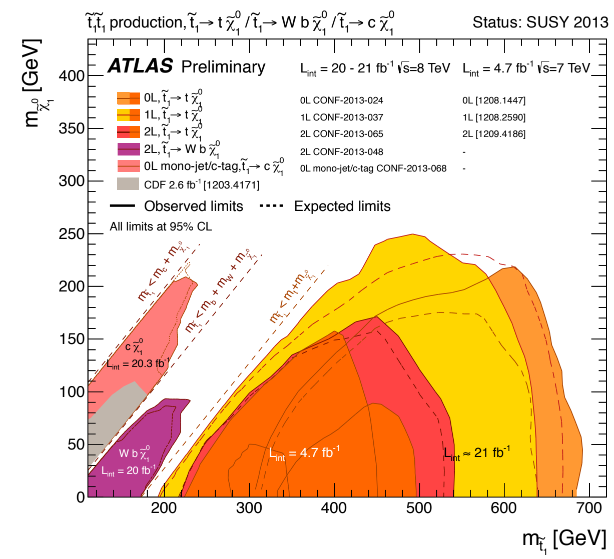
1. the baryon density does not scan

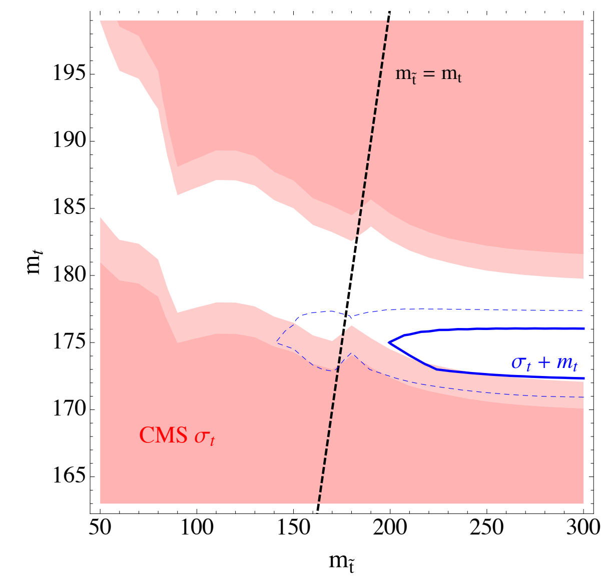
2. other dangerous walls are important and depend on the baryon density



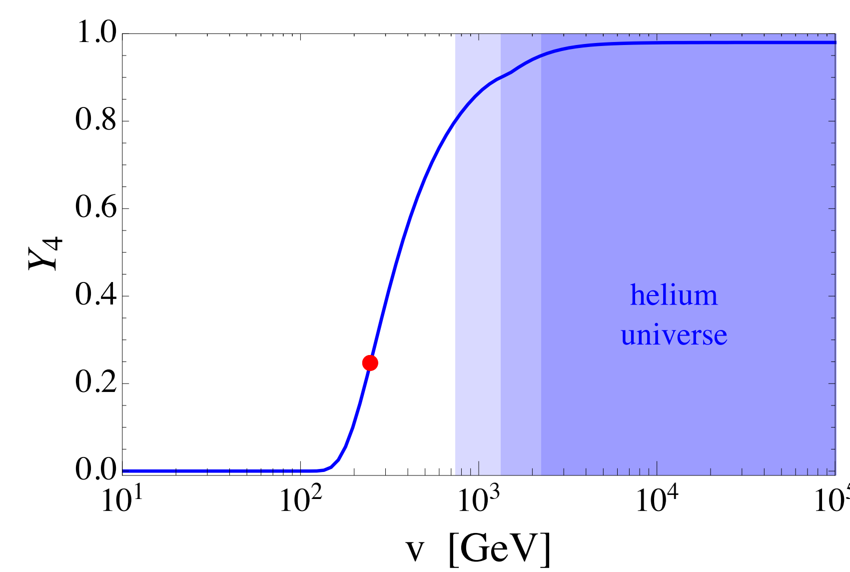
take away

1. the stealth stop window can be probed using the top σ and mass





2. BBN may determine the weak-scale in the multiverse



$$m_h \approx 125\ \text{GeV}$$

natural

$\tilde{m} \approx m_h$

fine-tuned

$\tilde{m} \gg m_h$

13 TeV awaits!