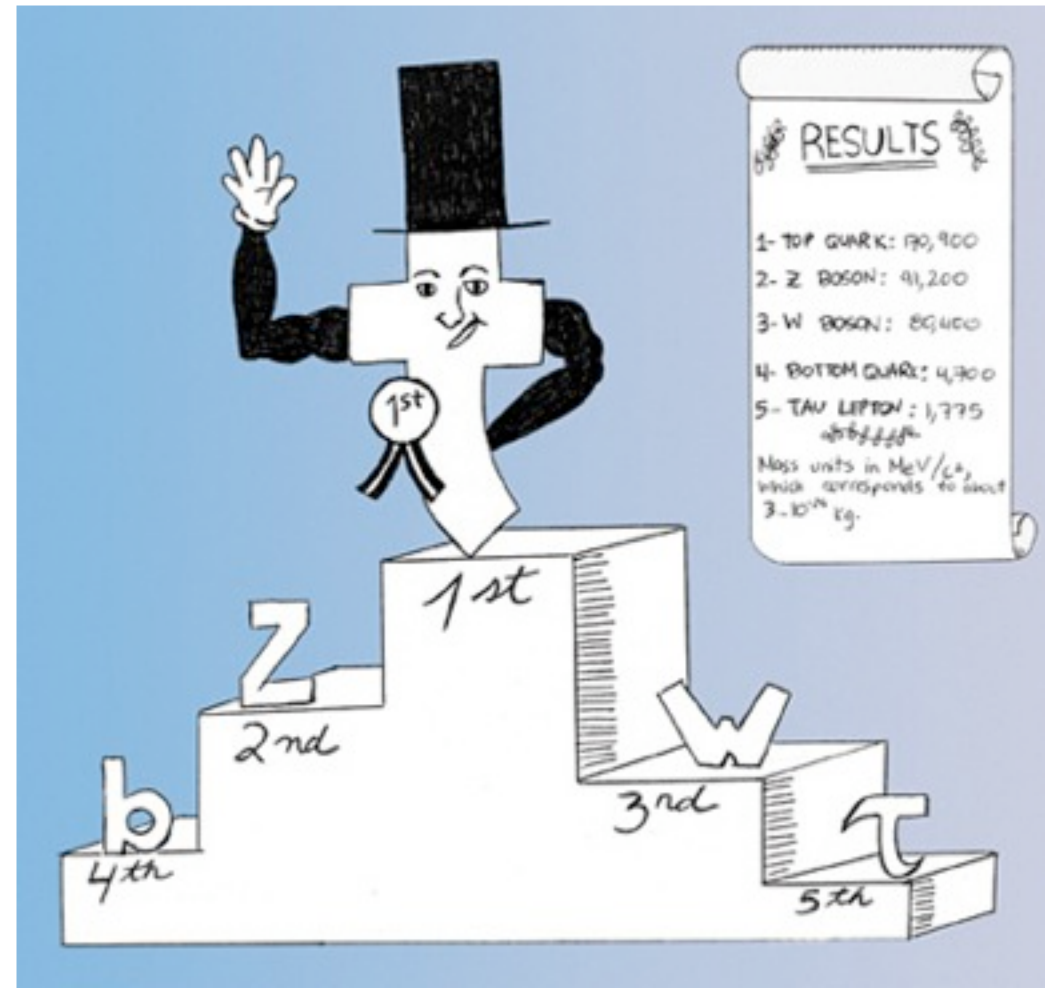
Top Signatures of New Physics



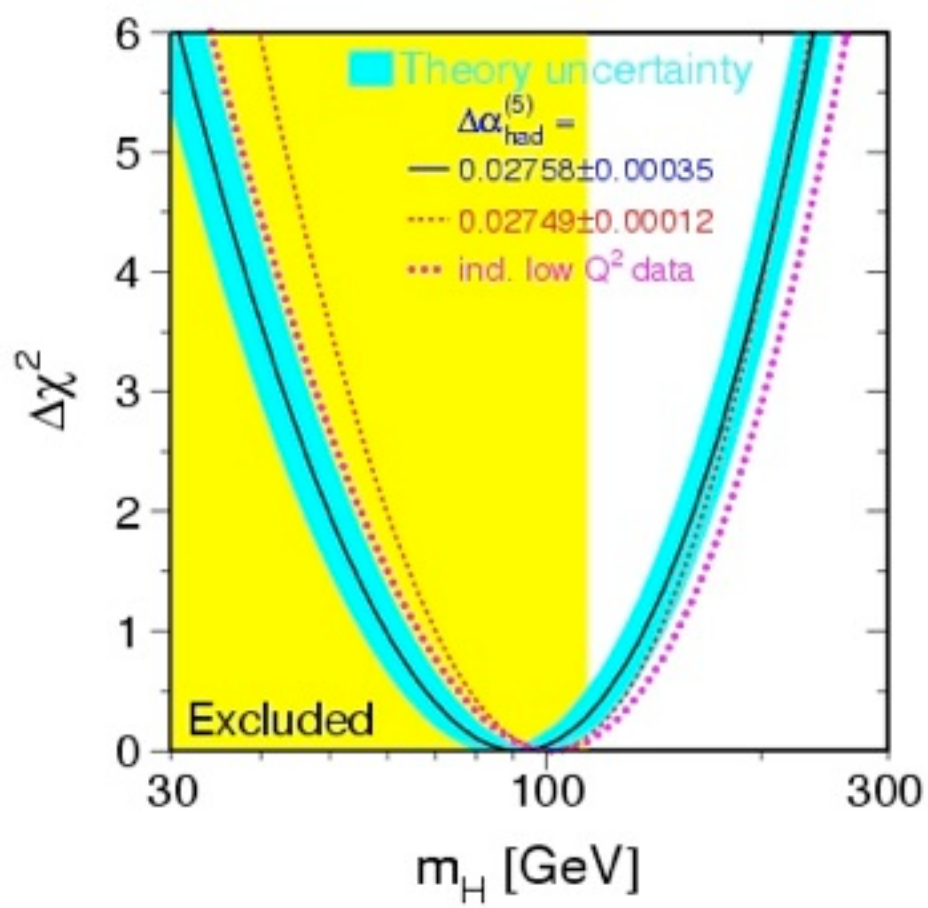
Maxim Perelstein, Cornell/LEPP

LEPP Journal Club, February 12, 2012

Cornell University
Laboratory for Elementary-Particle Physics

Evidence for (Light) Higgs

Exhibit A: Precision Electroweak Observables



$$m_h < 160 \text{ GeV}, 95\% \text{ c.l.}$$

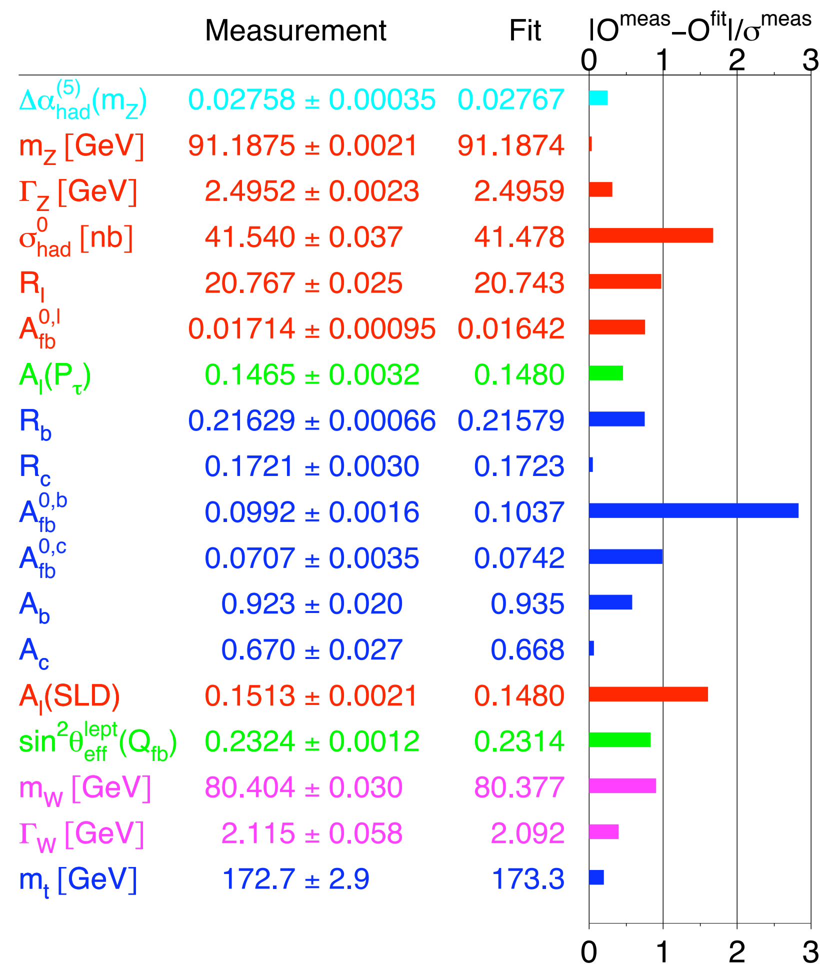
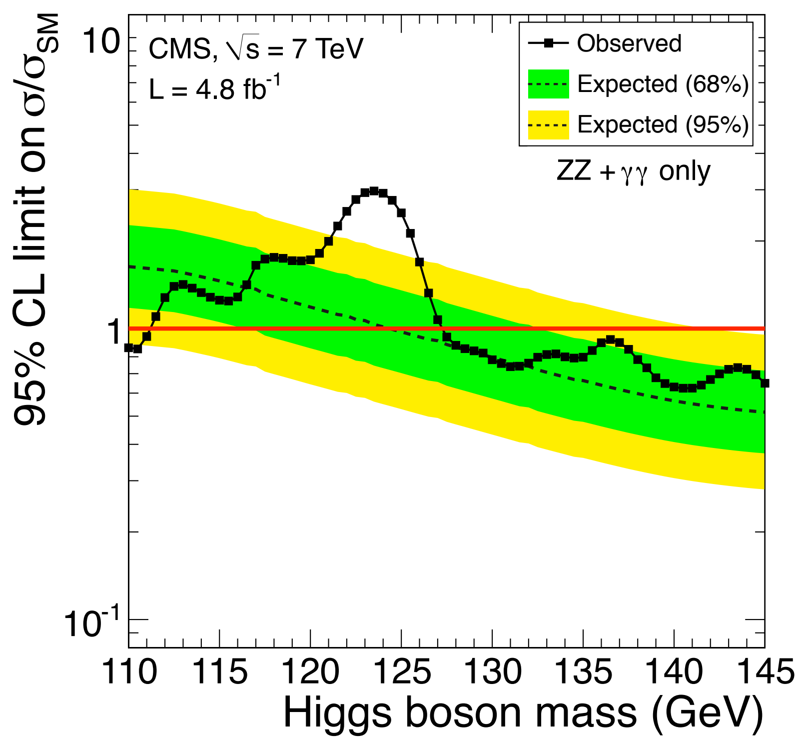
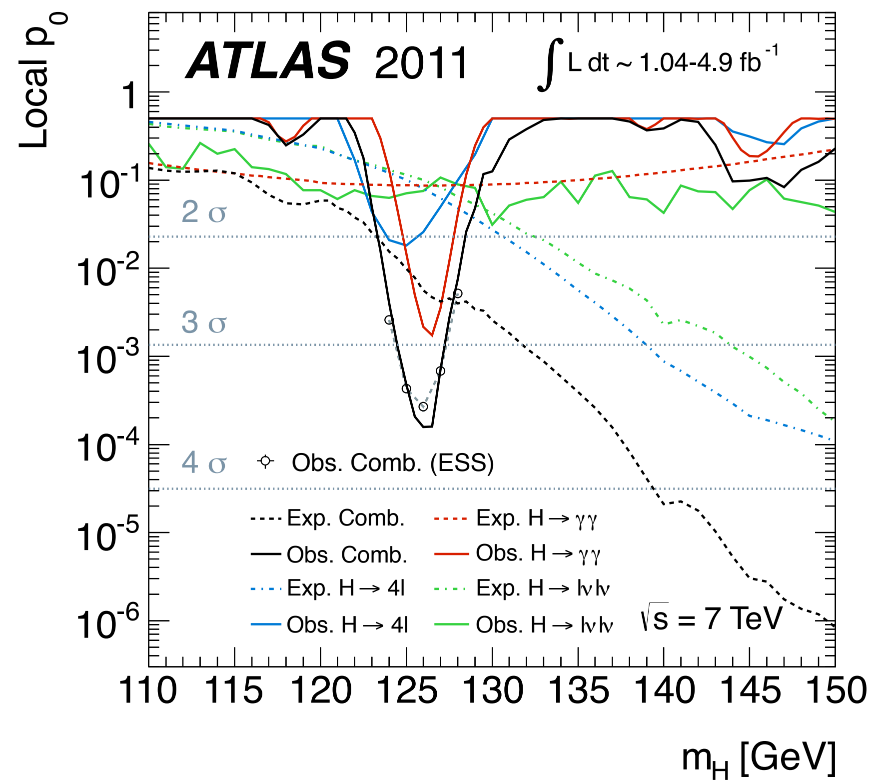


Exhibit B: CMS and ATLAS 5 fb-1 Searches





A fairly strong hint of SM-like Higgs at $m_h \approx 125\ \mathrm{GeV}$

* Almost all statements in this talk will not depend on exhibit B being right

SM Higgs: Lagrangian and Physical Parameters

- The SM Higgs potential has two terms → two parameters:

$$V = -\frac{\mu^2}{2} h^2 + \frac{\lambda}{4} h^4$$

- Higgs gets a vacuum expectation value, known from e.g. the W mass:

$$v = \frac{\mu}{\sqrt{\lambda}} \qquad M_W = \frac{gv}{2} = 80.4 \text{ GeV} \to v = 246 \text{ GeV}$$

- The physical Higgs boson mass is

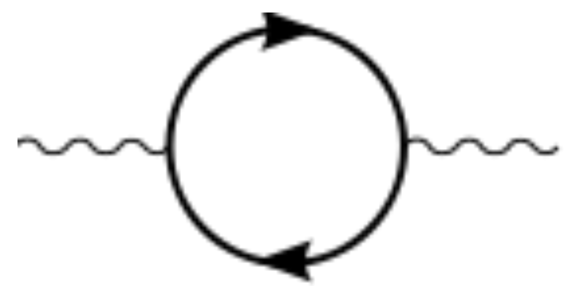
$$m_h = \sqrt{2}\,\mu$$

- If we believe the 125 GeV Higgs, we know the whole potential!

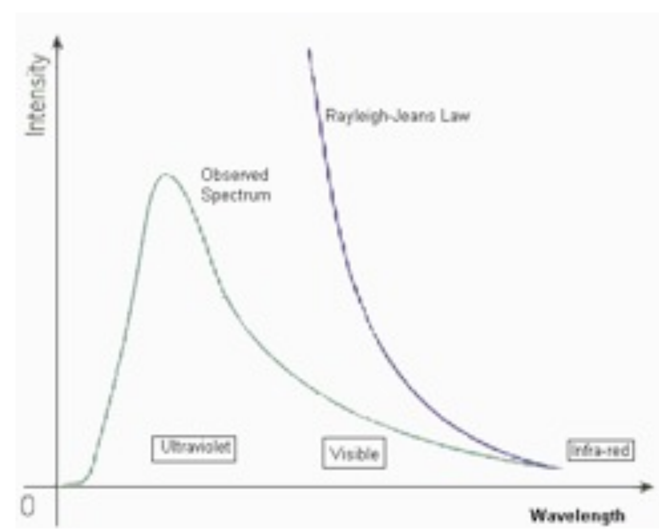
$$\mu = 88.4 \text{ GeV}, \quad \lambda = 0.13$$

100-200 GeV Higgs Needs NEW PHYSICS To Survive!

- The Higgs mass parameter $-\mu^2$ is renormalized by radiative corrections = loop diagrams:



- These loop integrals are divergent at high momentum (=short distance) ➡ new physics must come in and "regulate" them



- Uniquely among the SM loop diagrams, the divergence is quadratic

$$-\mu^2 = -\mu^2_{\text{tree}} + \frac{c^2}{16\pi^2}\Lambda^2 + \ldots$$

new physics scale

- Higgs mass parameter renormalization:

$$-\mu^2 = -\mu^2_{\text{tree}} + \frac{c^2}{16\pi^2}\Lambda^2 + \ldots$$

- Two options:
  - "Natural" Higgs with New Physics at $\Lambda < 4\pi\mu \approx 1\ \text{TeV}$
  - "Fine-Tuned Higgs" with $\Lambda > 1\ \text{TeV}$ and precise cancellation between the tree and loop terms
- First option is much more appealing ⇒ search for new physics @ LHC!
- Two possible sorts of new physics:
  - Strong coupling at Λ , perturbation theory breaks down!!!
  - Weak coupling, but new particles with masses $\approx \Lambda$, special couplings to the Higgs to cancel the quadratic divergence

Supersymmetry!!!

- SUSY is the undisputed queen among the weakly-coupled candidate models

- SYMMETRY ensures cancellation of quadratic divergence (valid to all loop orders, not just one-loop)

- “Minimal” supersymmetric SM (MSSM): superpartner for each SM d.o.f., plus 2nd Higgs doublet and its superpartners

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

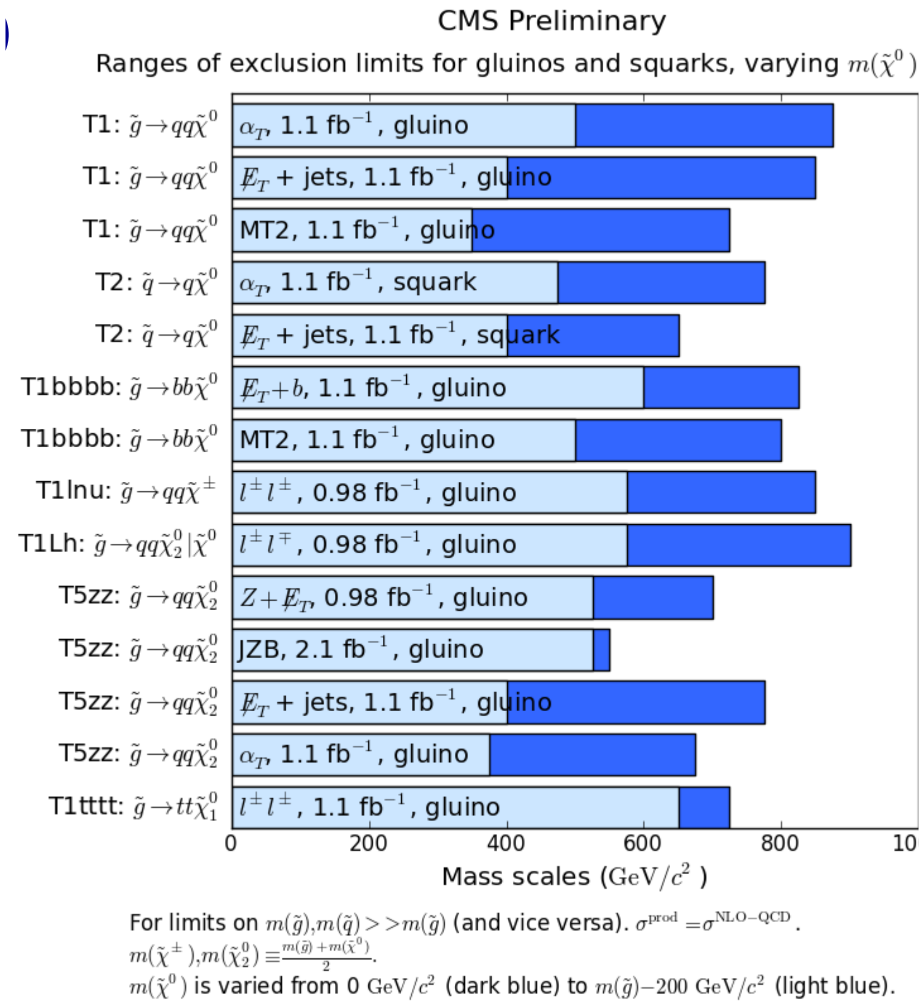
Table 7.1: The undiscovered particles in the Minimal Supersymmetric Standard Model (with sfermion mixing for the first two families assumed to be negligible).

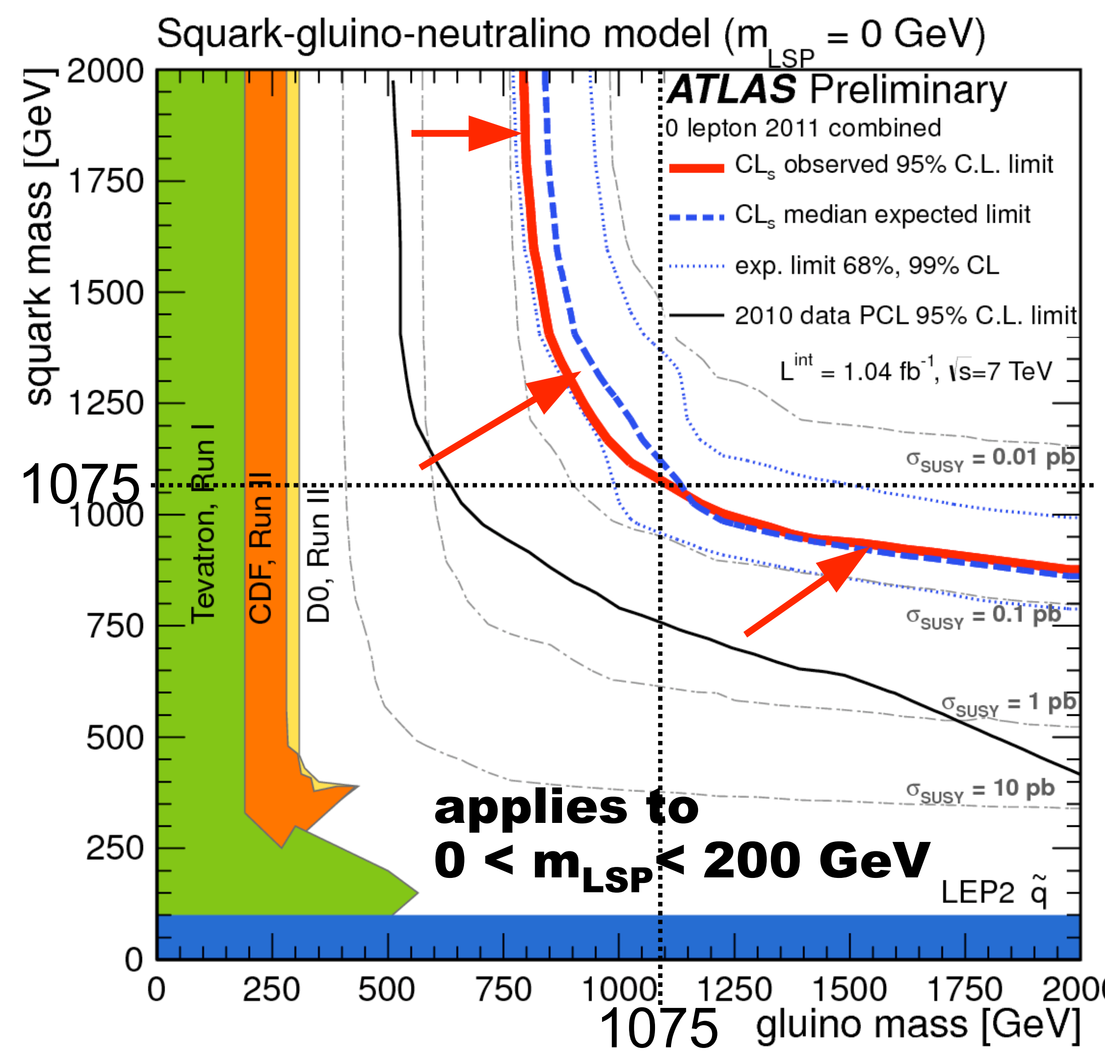
34 new particles waiting to be discovered!

[table: S. Martin, hep-ph/9709356]

Supersymmetry???

1 fb^{-1} summary





Bottom line: gluino/squark mass bounds are around 1 TeV

- Recall the "Two possibilities":
  - "Natural" Higgs with New Physics at $\Lambda < 4\pi\mu \approx 1\ \mathrm{TeV}$
  - "Fine-Tuned Higgs" with $\Lambda > 1\ \mathrm{TeV}$ and precise cancellation between the tree and loop terms
- Superparticle mass scale acts like the cutoff scale Λ
- Is SUSY already being pushed from "natural" into "fine-tuned" territory?

- Recall the “Two possibilities”:
  - “Natural” Higgs with New Physics at $\Lambda < 4\pi\mu \approx 1\ \mathrm{TeV}$
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- Superparticle mass scale acts like the cutoff scale Λ
- Is SUSY already being pushed from “natural” into “fine-tuned” territory?

BBC NEWS

SCIENCE & ENVIRONMENT

27 August 2011 Last updated at 02:41 ET

LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

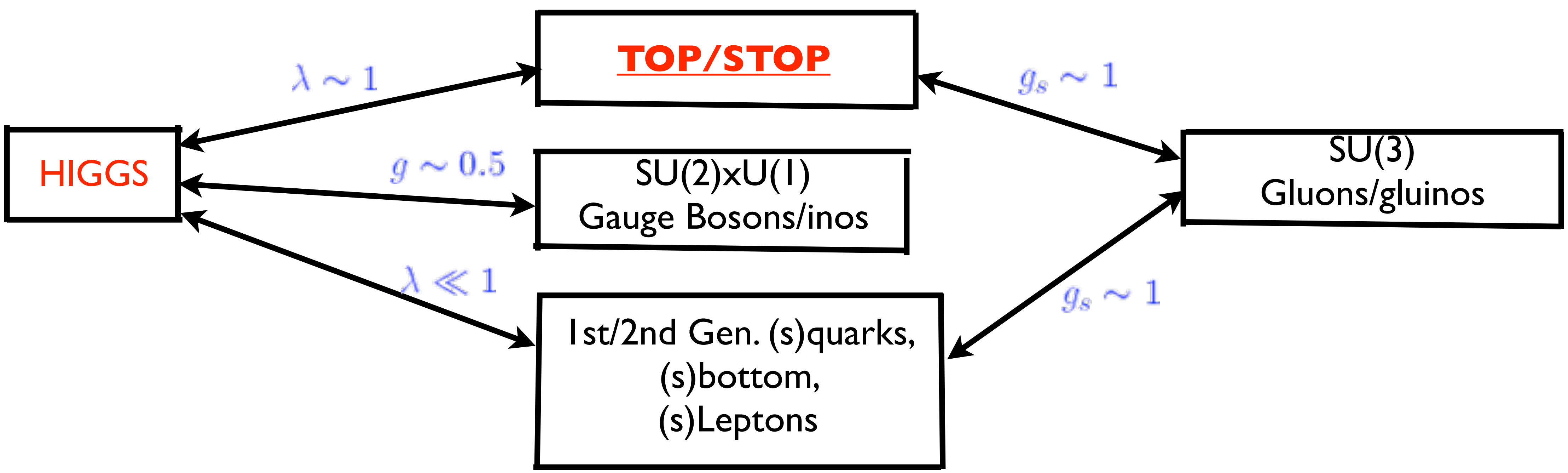
Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

- This argument is a bit too fast. Recall Higgs mass parameter renormalization formula:

$$-\mu^2 = -\mu_{\text{tree}}^2 + \frac{c^2}{16\pi^2}\Lambda^2 + \ldots \qquad c = \kappa_X^2 N_X$$

- κ_X = Higgs-X coupling constant, N_X = # of d.o.f. in X

- Most SM fields couple only very weakly, or not at all, to the Higgs!



- The real "one-loop naturalness upper bound" on the mass of SUSY partner of particle X is not 1 TeV, but

$$\frac{1\ \text{TeV}}{c_X^2}$$

- For 1st, 2nd gen. squarks, sbottom, sleptons, this bound is 10 TeV or more.

- For stop, it's in fact lower: $c_t = 6\lambda_t^2 \approx 6$ ⇒ $m_t < 400\ \text{GeV}$ is required for (complete) naturalness

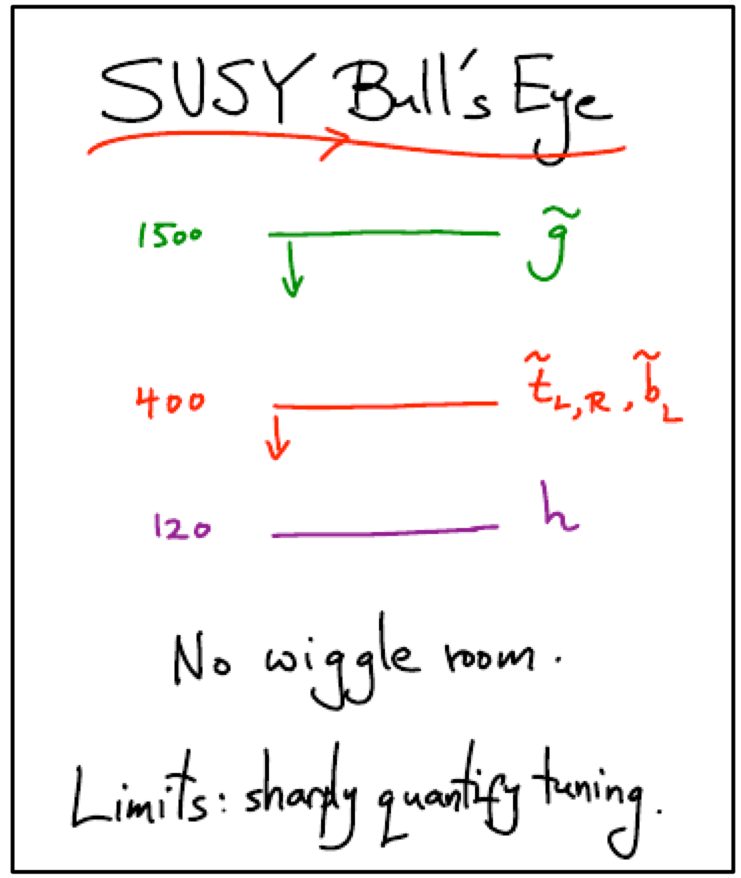
- NB: since left-handed top and bottom are in the same SU(2) doublet, their superpartners must be close in mass ⇒ one light bottom is required.

- There's no one-loop upper bound on gluino mass: $c_g = 0$

- However two-loop naturalness requires $m_g < 2m_t$ (Majorana gluinos)

  $m_g < 4m_t$ (Dirac gluinos)

- This suggests the minimal SUSY spectrum consistent with naturalness:



Arkani-Hamed - LPCC workshop 10/31/2011

- Disclaimer: We've been treating each superparticle mass as a free parameter. "SUSY breaking models" relate them, and in models constructed pre-LHC the three generations of squarks typically have roughly equal masses. All the more reason to not take these models seriously.

- Explicit light-stop models exist: e.g. Csaki, Randall, Terning, 1201.1293.

- Flavor constraints are easy to satisfy (see e.g. Brust, Katz, Lawrence, Sundrum, 1110.6670)

- LHC currently has no published bounds on direct stop production (much work is in progress - more from Julia next week)

- Theorists' estimate of the LHC bounds from published searches in 1 fb-1 (Papucci, Ruderman, Weiler, 1110.6926): not yet constraining naturalness!

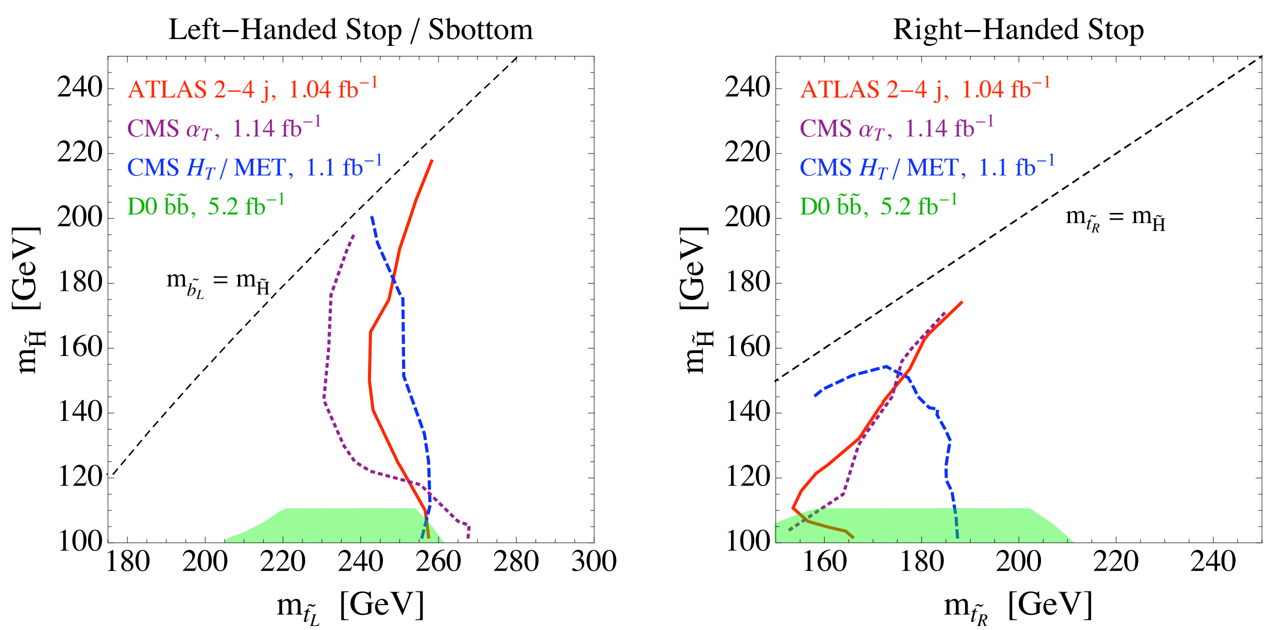
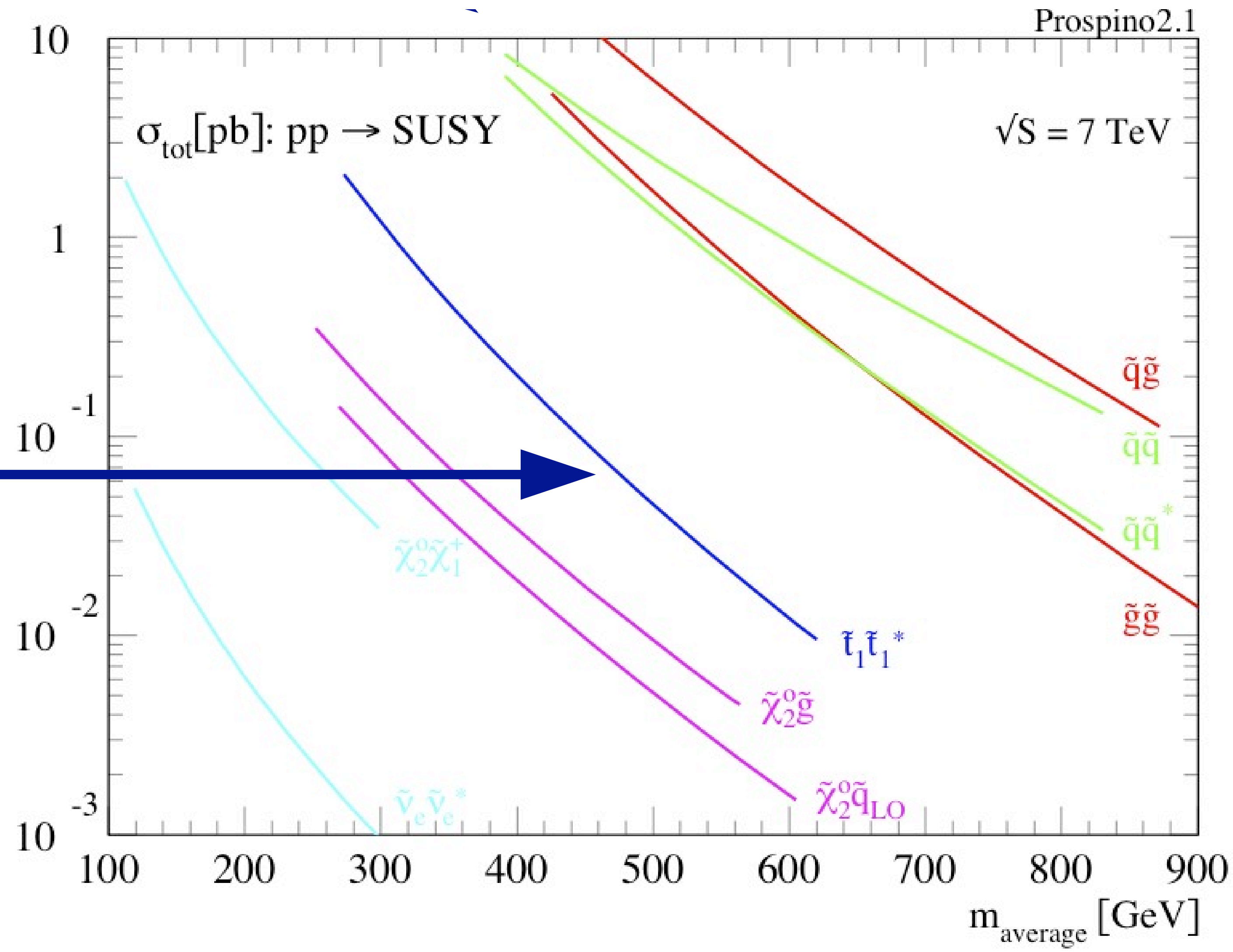


FIG. 3: The LHC limits on the left-handed stop/sbottom (*left*) and right-handed stop (*right*), with a higgsino LSP. The axes correspond to the stop pole mass and the higgsino mass. We find that the strongest limits on this scenario come from searches for jets plus missing energy. For comparison, we show the $D0$ limit with 5.2 fb^{-1} (green), which only applies for $m_{\tilde{N}_1} \lesssim 110$ GeV, and has been surpassed by the LHC limits.

Why are Stops Hard



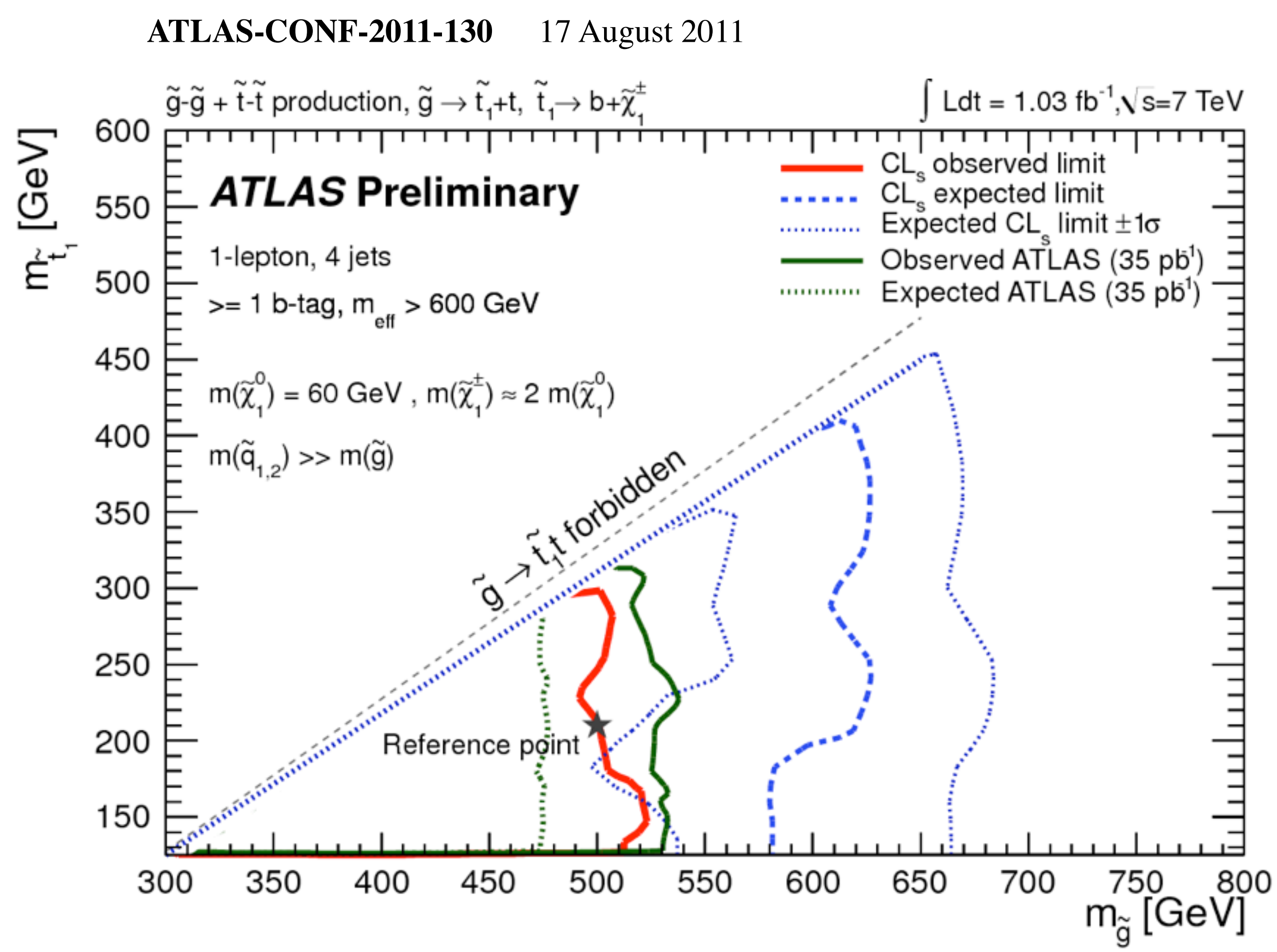
Stops have small cross sections:

$\sigma(\tilde{t}\tilde{t}^*) \approx 30$ fb

at 500 GeV mass

+ more complicated final states (decayed tops → high multiplicity → combinatoric issues, soft jets)

Gluinos Decaying to Stops



$m_{\tilde g} \gtrsim 500\,\mathrm{GeV} \qquad m_{\tilde t} \gtrsim\ ?$

- Bound about 100 GeV weaker than expected - what's going on?
- Not-quite-minimal spectrum assumed: light chargino gives more leptons

Boosted Tops from Gluino Decays

Berger, MP, Saelim, Spray, 1111.6594

- Assume minimal spectrum as described above (but ignore $\tilde{b}$ for simplicity)

- Focus on gluino pair-production to get higher cross sections, and consider the decay chain $\tilde{g} \to \tilde{t} + \bar{t}, \quad \tilde{t} \to t\tilde{\chi}^0$

- (First) top energy in the gluino rest frame: $E_t = \dfrac{m_{\tilde{g}}^2 + m_t^2 - m_{\tilde{t}}^2}{2m_{\tilde{g}}}$

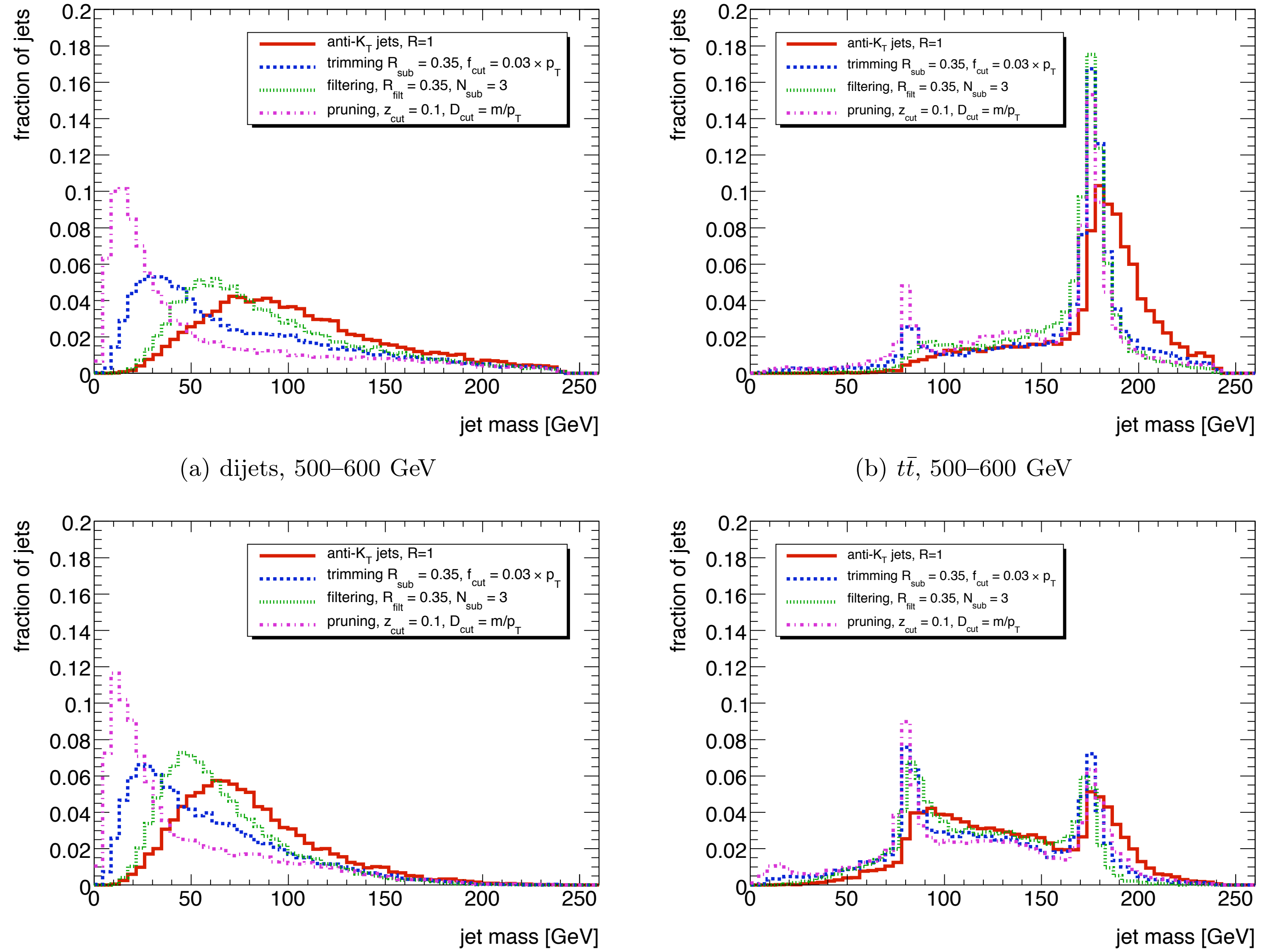
- For example: $m_{\tilde{g}} = 800 \text{ GeV}, \ m_{\tilde{t}} = 400 \text{ GeV}$ ⟹ $\boxed{\gamma_t \approx 1.8}$

- Gluino velocity in lab frame: on average, about 0.5-0.7 in the relevant mass range

- In large part of parameter space, the tops are typically relativistic in the lab frame!

- Top decay products are boosted ⟹ hadronic top will show up as a single jet, instead of three! ⟹ Simpler final states (but potentially higher background)

Top-Jet Tagging: Jet Mass



(a) dijets, 500–600 GeV

(b) $t\bar{t}$, 500–600 GeV

(c) dijets, 300–400 GeV

(d) $t\bar{t}$, 300–400 GeV

Fig. 1. Jet invariant mass m_j for $t\bar{t}$ (a,c) and dijet (b,d) events, for three grooming methods. Each groomed analysis begins with anti-k_T jets with $R = 1.0$. The solid curve (red in the online version) represents these jets without grooming. The distributions correspond to $t\bar{t}$ or di-jet quarks or dijet samples with parton-level p_T of 500–600 GeV (a,b) and 300–400 GeV (c,d).

[plots: BOOST-2010 report, 1012.5412]

Top-Jet Tagging: Eff vs. Mistag

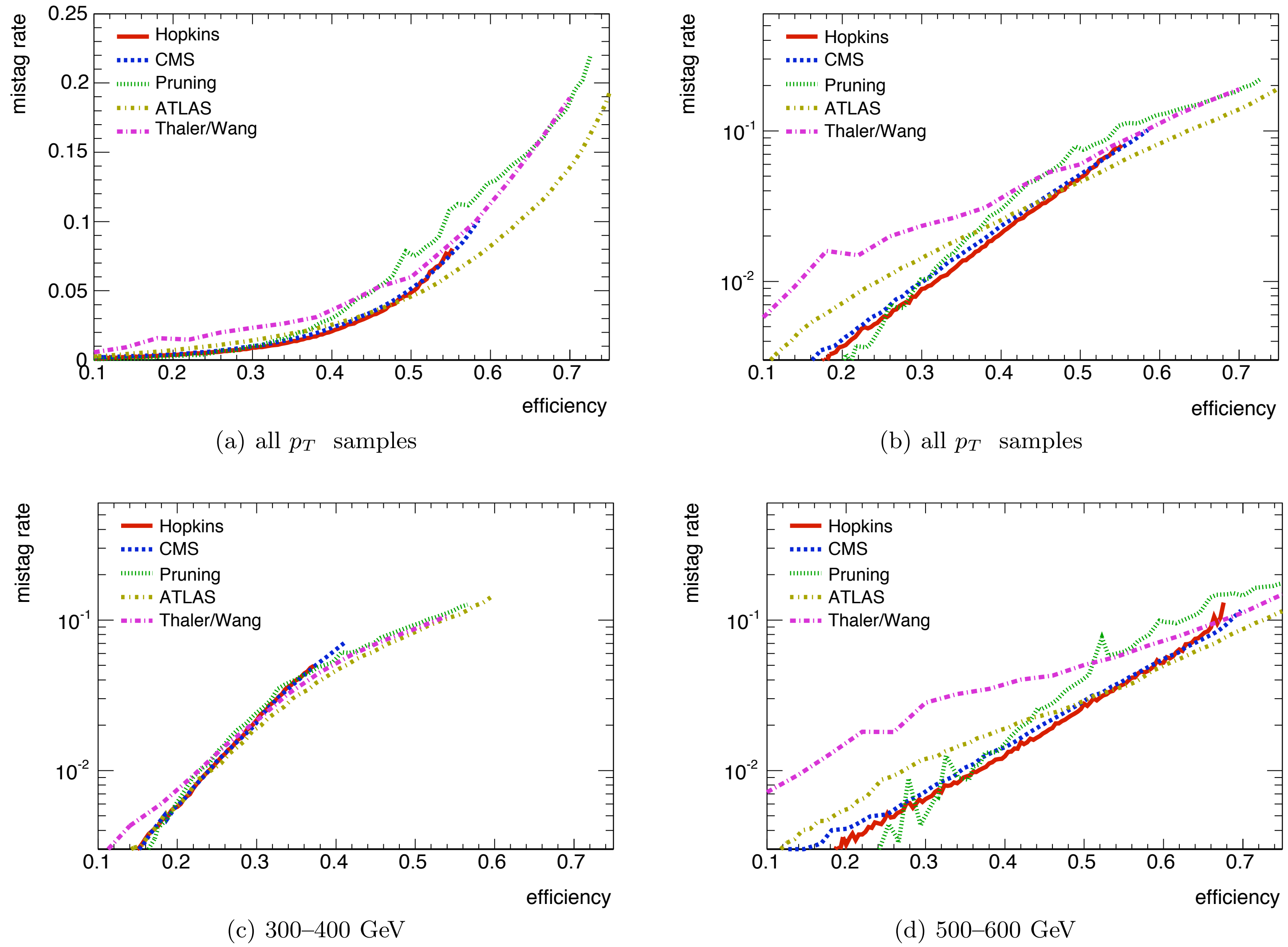


Fig. 3. Mistag rate versus efficiency after optimisation for the studied top-taggers in linear scale (a) and logarithmic scale (b). Tag rates were computed averaging over all p_T subsamples (a,b) and for the subsample containing jet with p_T range 300–400 GeV (c) and 500–600 GeV (d)

[plots: BOOST-2010 report, 1012.5412]

Top-Jet Tagging: pT Dependence

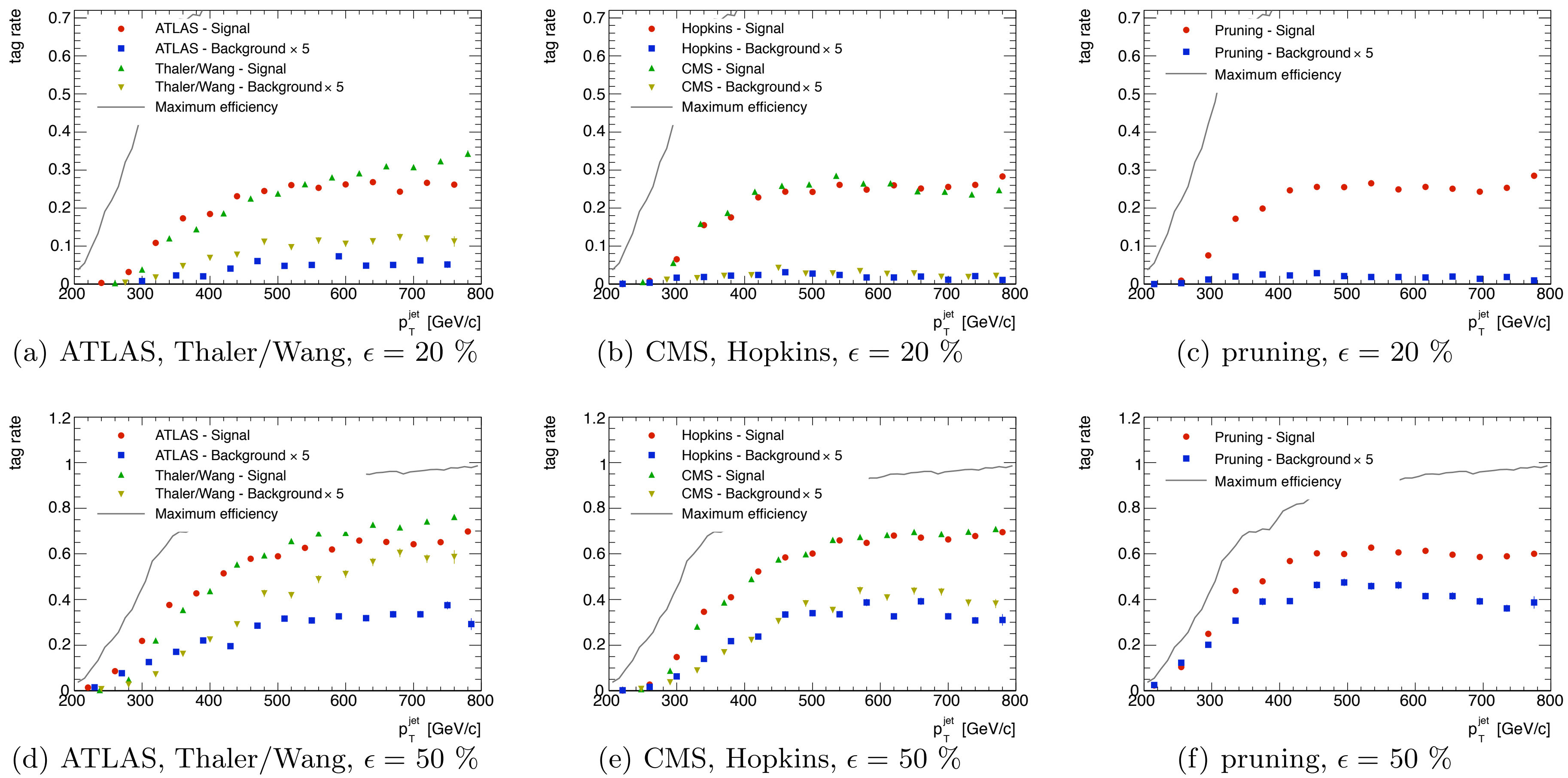


Fig. 4. Efficiency and mistag rate as function of jet p_T for working points with overall efficiency of 20% (uppermost row) and 50% (lowermost row). Results correspond to the ATLAS and Thaler/Wang taggers (a,d), the Hopkins and CMS taggers (b,e) and the pruning tagger (c,f). The mistag rate has been multiplied by a factor 5 to make it visible on the same scale.

[plots: BOOST-2010 report, 1012.5412]

Top-Tag Gluino Search: Benchmark Analysis

Process	σ_{tot}	Eff(p_T)	Eff(tag)	σ_{tag}	Eff($\not{E}_T$)	$\sigma_{\text{all cuts}}$
signal	61.5	37	6	1.31	81	1.06
$Z+4j$	2×10^5	0.2	0.1	0.44	66	0.29
$2t+2j$	5×10^4	3	0.3	5.7	2	0.10
$W+4j$	2×10^5	0.2	0.03	0.12	29	0.04
$Z+2t+2j$	50	4	1	0.02	72	0.02

TABLE I: Signal and background cross sections (in fb) and cut efficiencies (in %) at the 7 TeV LHC. Acceptance cuts of $p_T > 20$ GeV, $|\eta| < 5$ for all jets are included in the total cross sections. The cuts are labelled as follows: "p_T": requiring 4 jets with $p_T > 100$ GeV; "tag": requiring 2 jets to be tagged as tops with "loose" parameters; "$\not{E}_T$": requiring $\not{E}_T > 100$ GeV. The signal is at the benchmark point, $(m(\tilde{g}), m(\tilde{t})) = (800, 400)$ GeV. Backgrounds not listed here are negligible.

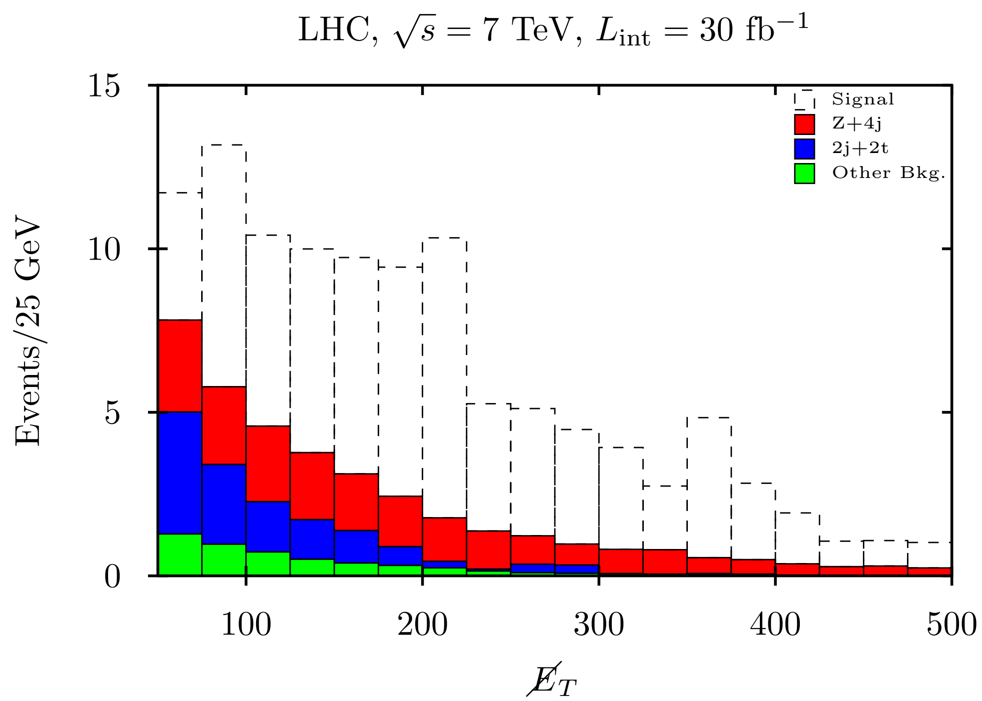


FIG. 1: Signal at the benchmark point, $(m(\tilde{g}), m(\tilde{t})) = (800, 400)$ GeV, and background rates as a function of MET, at 7 TeV LHC. Four jets with $p_T > 100$ GeV and two top-tagged jets are required.

Simulation: MadGraph → Pythia → FastJet (anti-kT jets)+Hopkins Top-Tagger

No detector effects are included, physical BGs only (except mis-top-tags)

Top-Tag Gluino Search: Reach Estimates

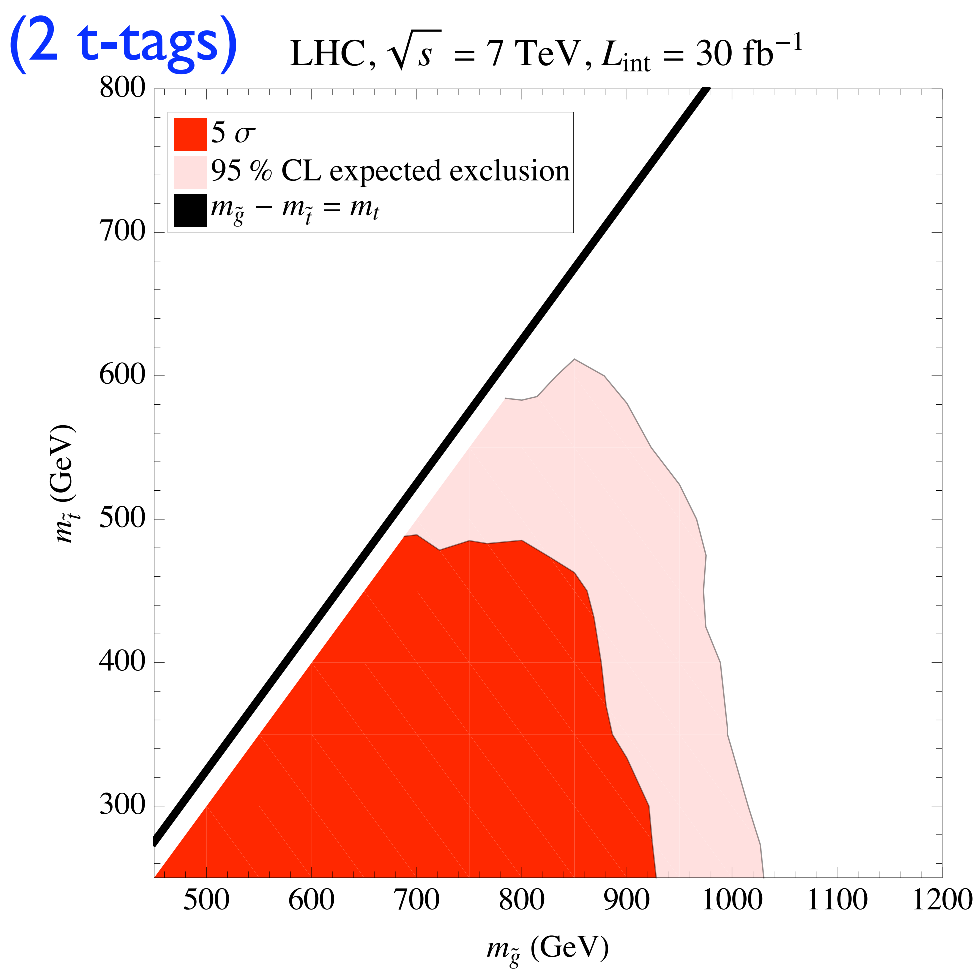


FIG. 2: The 95% c.l. expected exclusion and 5-sigma discovery reach of the proposed search at the 7 TeV LHC run with 30 fb^{-1} integrated luminosity.

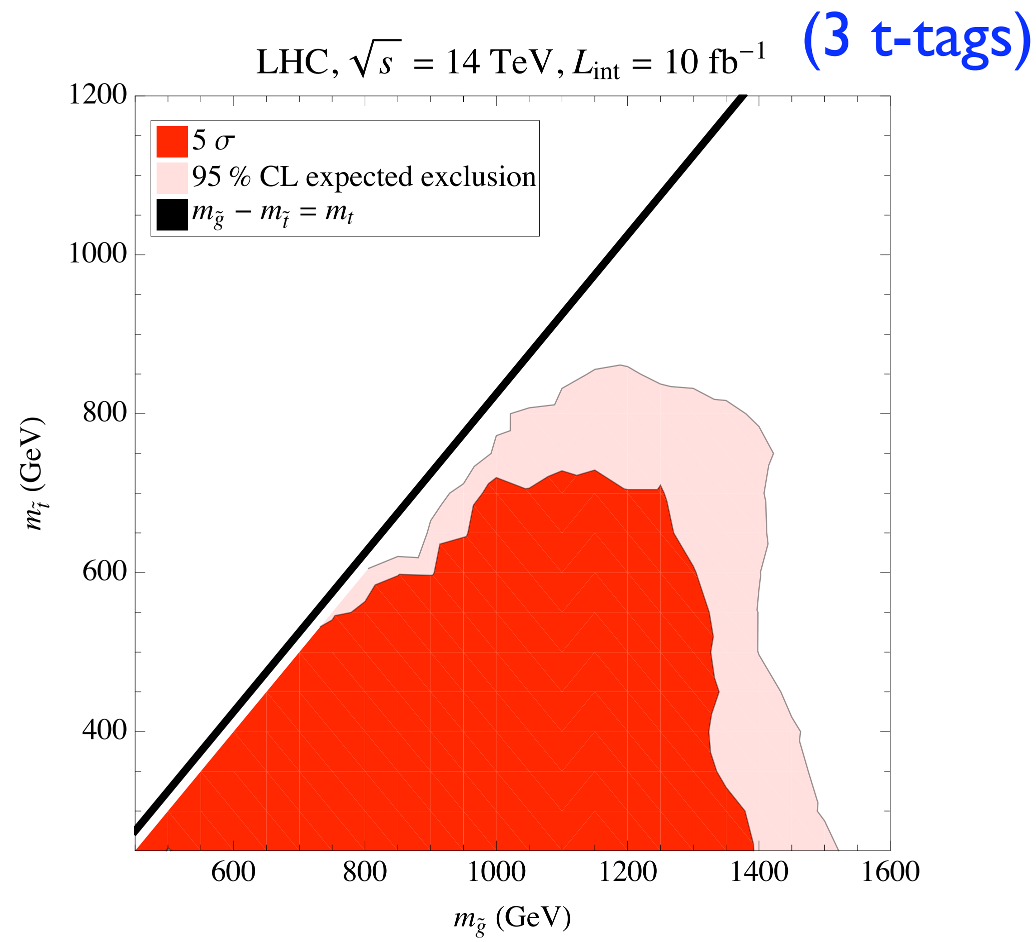


FIG. 3: The 95% c.l. expected exclusion and 5-sigma discovery reach of the proposed search at the 14 TeV LHC run with 10 fb^{-1} integrated luminosity.

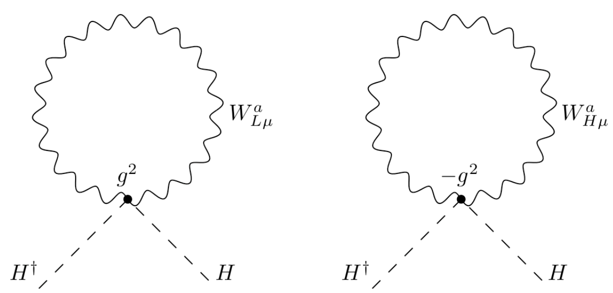
Errors Stat.-only; S/B>1 @ 7 TeV, >10 @ 14 TeV

Alternative to SUSY: Same-Spin Top Partner

[MP, Peskin, Pierce, hep-ph/0310039;
Hubisz, Meade, Noble, MP, hep-ph/0506042;
Berger, Hubisz, MP, in progress]

Gauge-Higgs Unification

- A zero-mass photon does not require fine-tuning - mass is protected by gauge symmetry
- In a 5D theory, the gauge field $A_M(x) \to A_\mu(x), A_5(x)$
- If the 5th dimension is infinite, A_5 is naturally massless!
- After compactification, $m(A_5) \sim 1/R$ ⇨ good if $1/R \sim M_W \sim M(W')$
- Higgs mass quadratic divergences are canceled by KK modes:



- Quadratic divergence cancellation by same-spin states can also occur in a purely 4D theory - Little Higgs (~ effective theory of the lowest-lying modes in GHU)

Top Loop Cancellation in LH

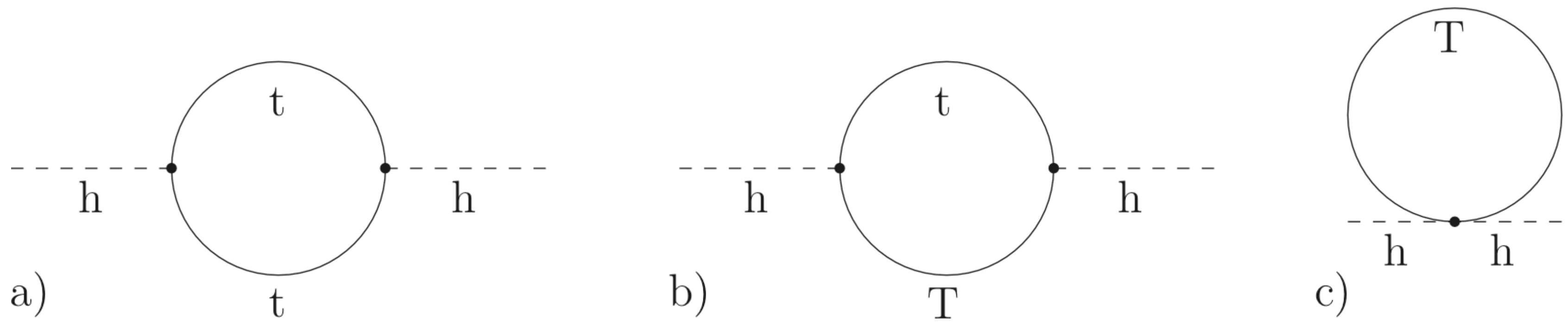


Figure 1. One-loop Higgs mass renormalization in a model with a same-spin top partner, such as the Littlest Higgs.

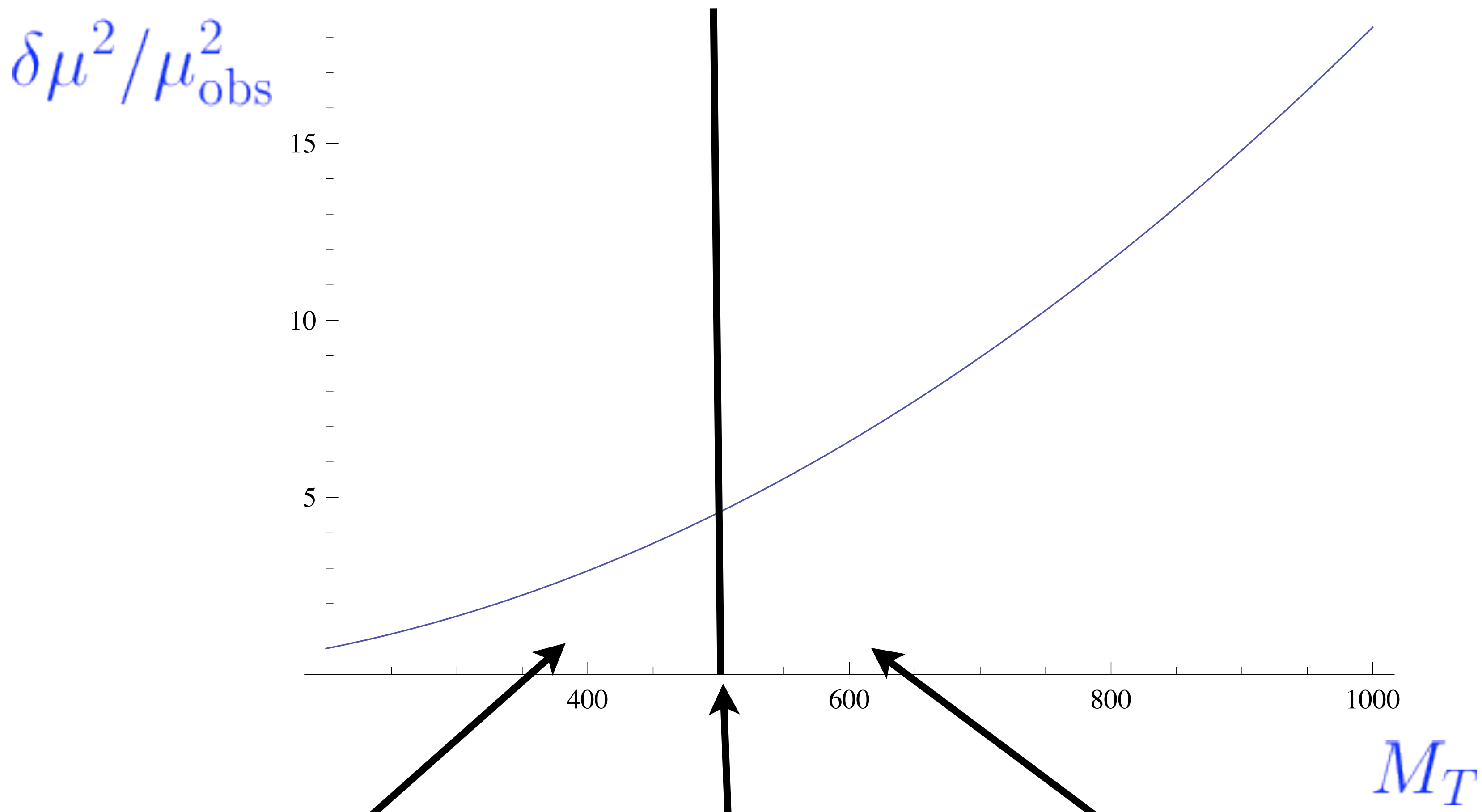
- Cancellation is due to a relation between couplings, which can be traced back to the global symmetries of the theory
- Cancellation only works at one-loop, but theory becomes non-perturbative at ~10 TeV ⇨ sufficient to restore naturalness
- For same reasons as in SUSY, only top partner is required below TeV

EWSB and Higgs Mass in LH

- Higgs mass parameter is ZERO at tree level, due to global symmetry
- At one-loop, the Higgs mass parameter induced by top loops is

$$-\delta\mu^2 = -\frac{3\lambda_t^2 M_T^2}{8\pi^2}\log\frac{\Lambda^2}{M_T^2}$$

- This automatically has the right sign to trigger ElectroWeak Symmetry Breaking!
- If $\delta\mu^2/m_h^2 \gg 1$, fine-tuning (accidental cancellation) in the Higgs sector is required
- If we assume 125 GeV Higgs, we can compute how much fine-tuning is needed for a given top-partner mass

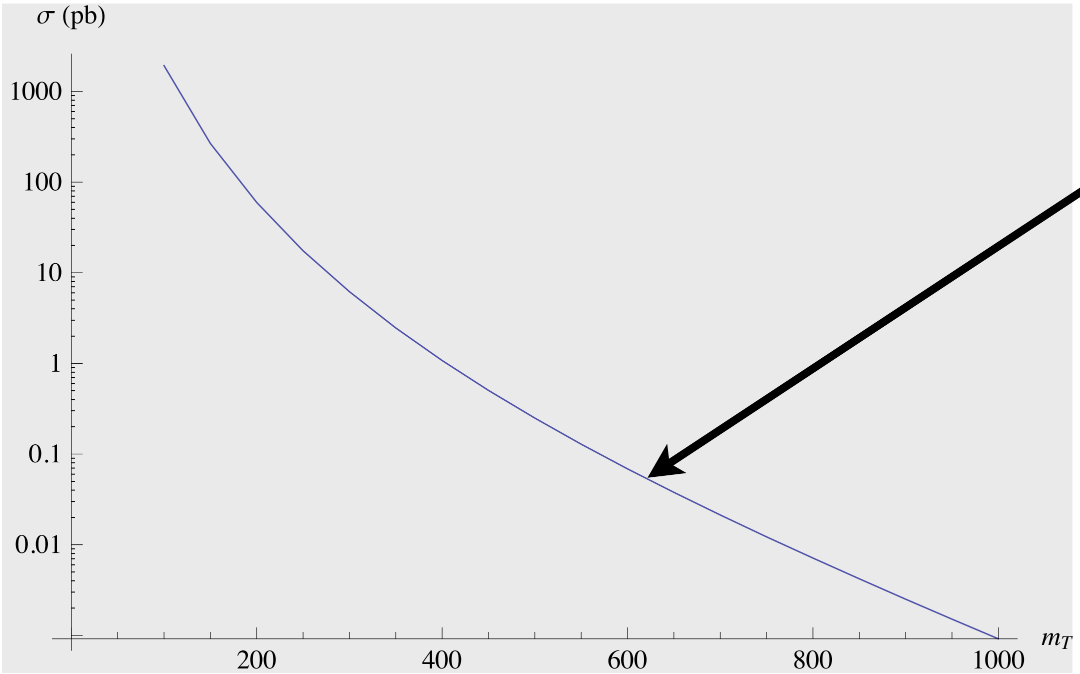


Ruled out by Precision EW Constraints and theoretical consistency

Open for LHC Searches

Minimal fine-tuning about 25%

Top-Partner Phenomenology



~100 fb at
600 GeV mass

Pair-production cross section @ 7 TeV

Decays:

$$T \to Wb, \quad 50\%$$
$$T \to Zt, \quad 25\%$$
$$T \to ht, \quad 25\%$$

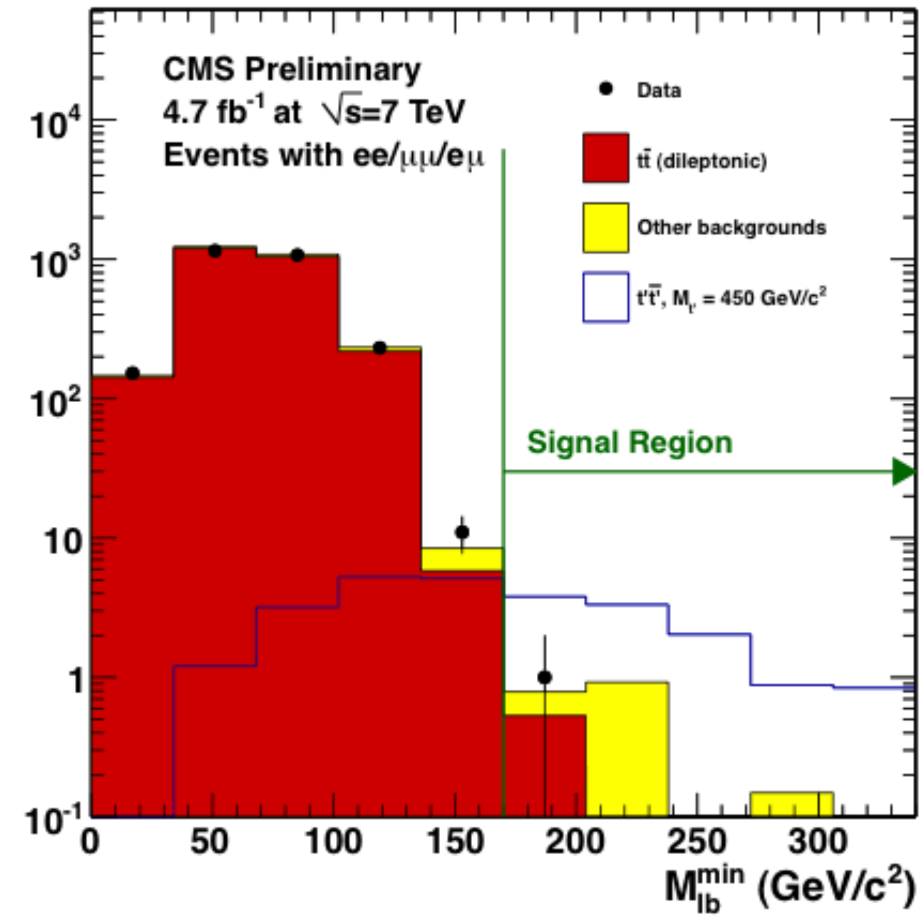
[The BRs are in the limit MT >> mt; corrections easily calculated]

Search for production of: $t'\bar{t}' \rightarrow bW^+\bar{b}W^-$

In dilepton channels: ee, eμ, μμ with opposite sign

Use M_{lb}(min): minimum value of four possible combinations

Select events with M_{lb}(min) > 170 GeV to reduce ttbar background



Backgrounds:

Sample	Yield
Category I (data-driven)	0.74 ± 0.79
Category II (data-driven)	$0^{+0.4}_{-0.0}$
Category III (simulated)	0.99 ± 0.69
Total prediction	1.73 ± 1.12
Data	1

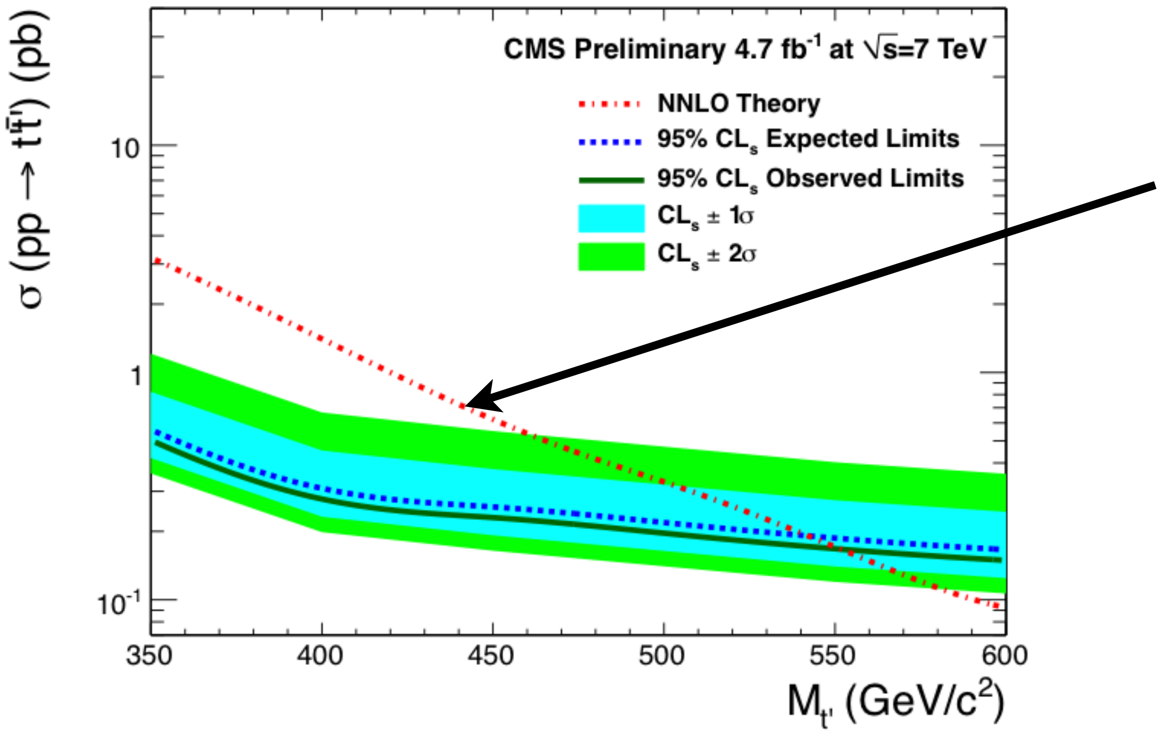
- Category I: events with mistagged b(s) and 2 real leptons
- Category II: events with misidentified lepton(s) and 2 real bs
- Category III: events with 2 real bs and 2 real leptons
- Category IV: events with mistagged b(s) and misidentified lepton(s). ← negligible

CMS PAS-EXO-11-050

Limits on Heavy Top-like Quark Production

t' excluded below 552 GeV

$4.7\ fb^{-1}$



But this assumes
$BR(T \to Wb) = 100\%$

$M_{t'}$	350 GeV/c^2	400 GeV/c^2	450 GeV/c^2	500 GeV/c^2	550 GeV/c^2	600 GeV/c^2
Theory (pb)	3.200	1.406	0.622	0.330	0.171	0.092
Expected (pb)	0.560	0.309	0.256	0.219	0.187	0.166
Observed (pb)	0.503	0.278	0.230	0.196	0.168	0.149

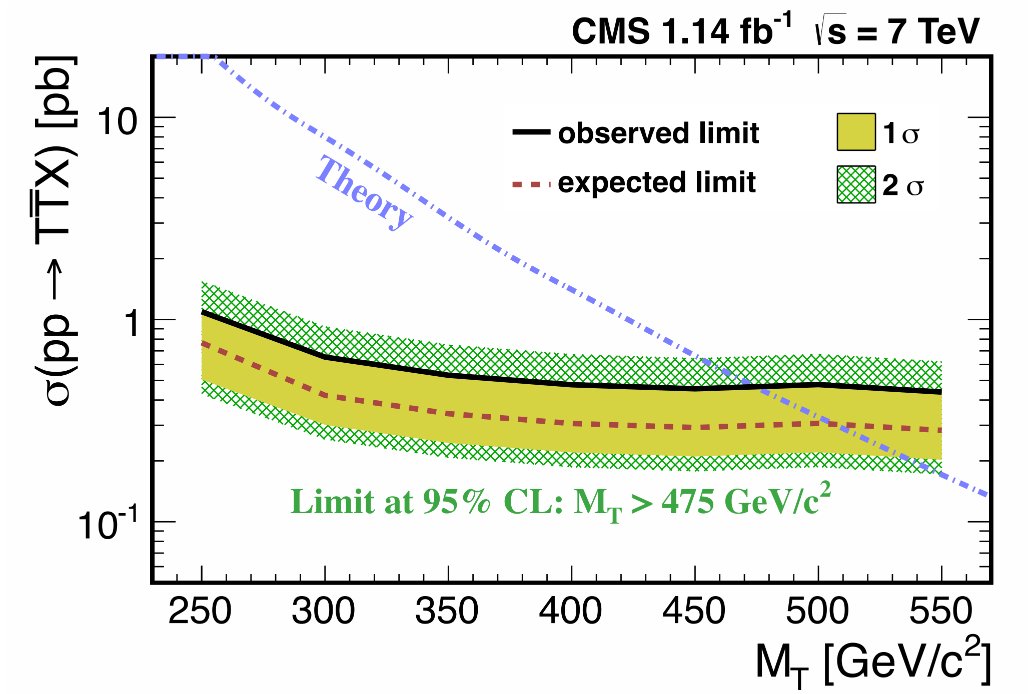
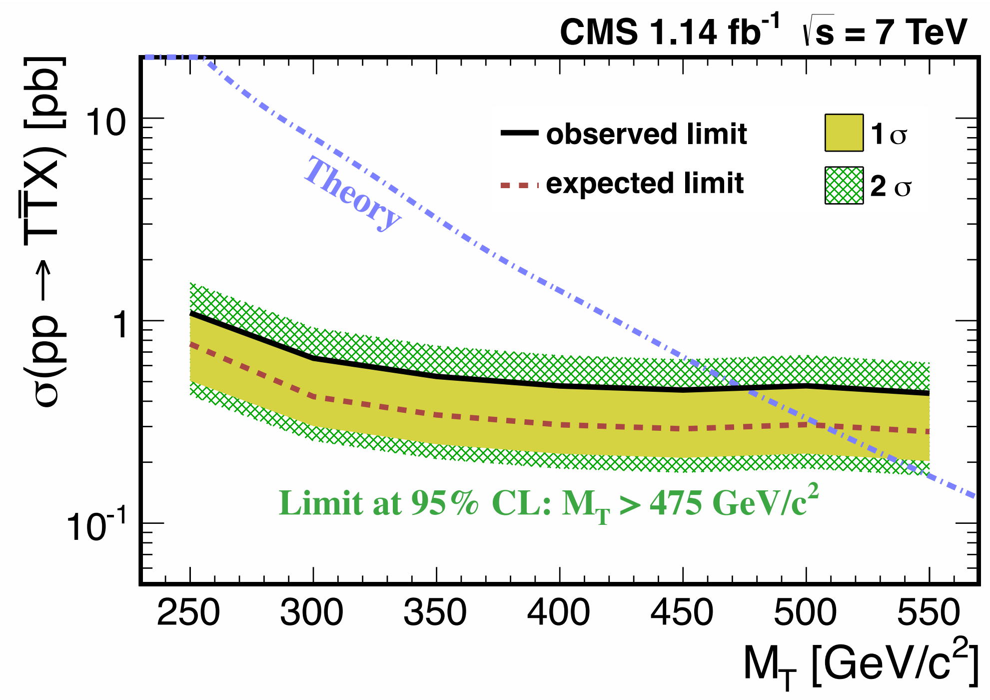


Figure 2: The 95% confidence level (CL) upper limit on the cross section of the pp $\to$ T$\bar{\text{T}}X$ process, as a function of the T-quark mass. The branching fraction of T $\to$ tZ is assumed to be 100%. The solid line shows the observed limit. The dotted line corresponds to the expected limit under a background-only hypothesis. The solid (hatched) area shows the ± 1 (± 2) standard deviation uncertainties on the expected limit. The dot-dash line shows the value of the theoretical cross section [27] for the T$\bar{\text{T}}$ process.

[CMS, 1109.4985]



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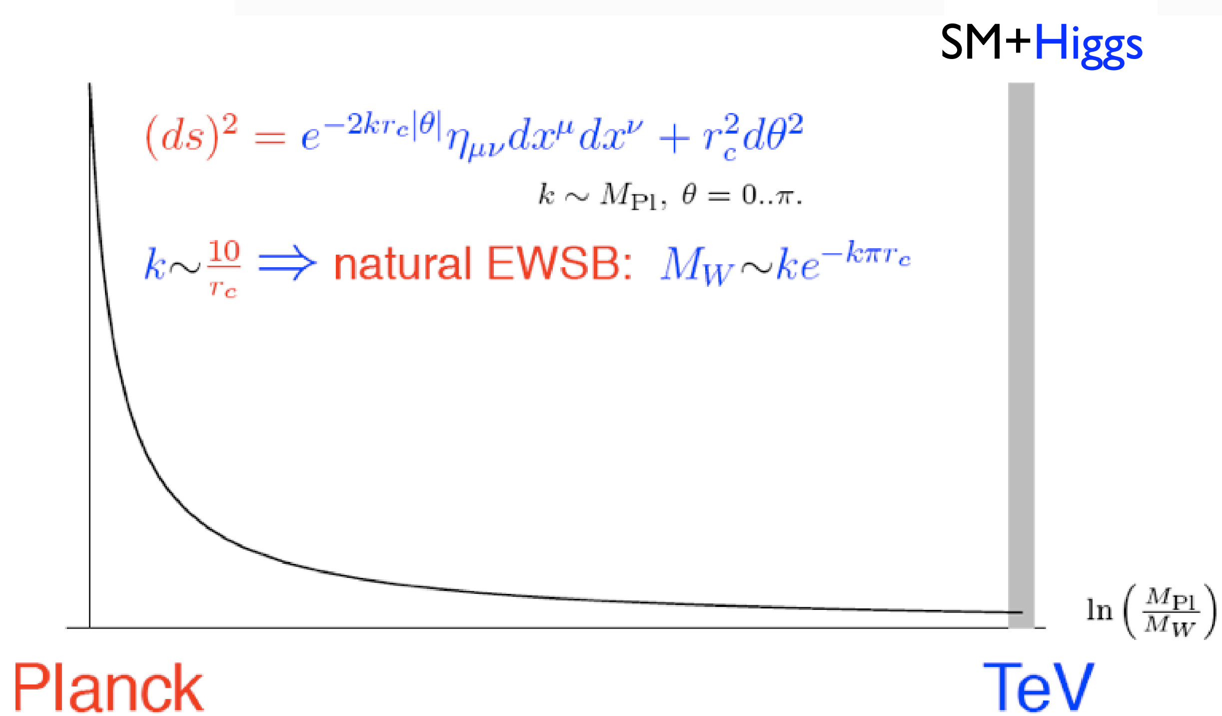
Some Open Questions:

Can this search at MT>>mt be improved by applying top-tagging techniques?

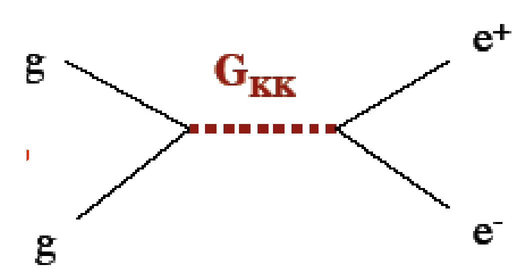
Can a search for T -> th with top-tagging and Higgs-tagging be feasible?

Warped (RS) Extra Dimension

- Original model had the SM on the TeV brane, solves the hierarchy problem

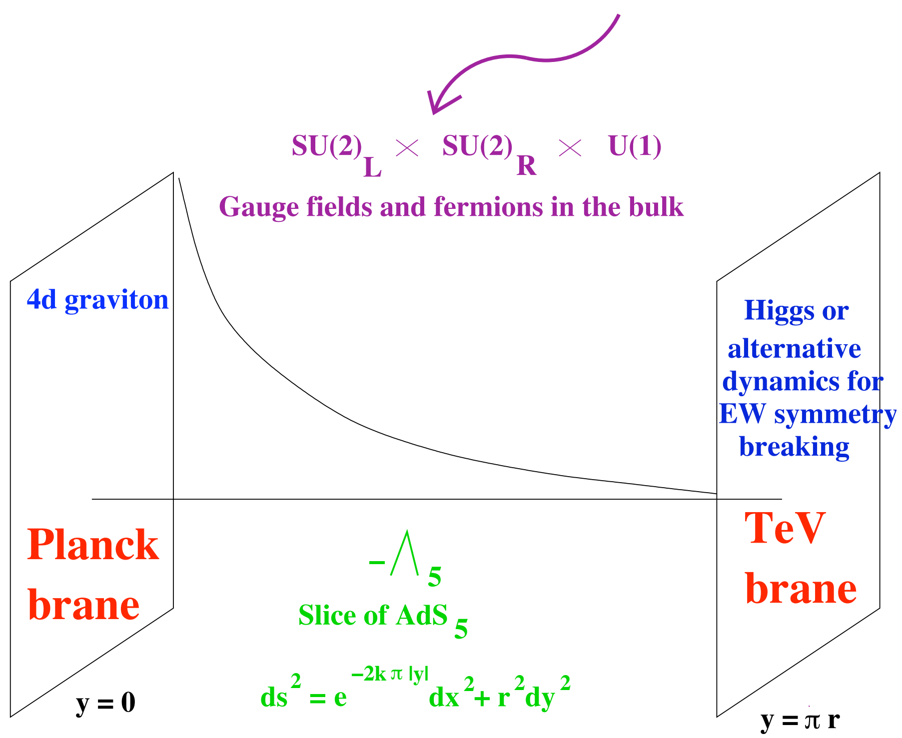


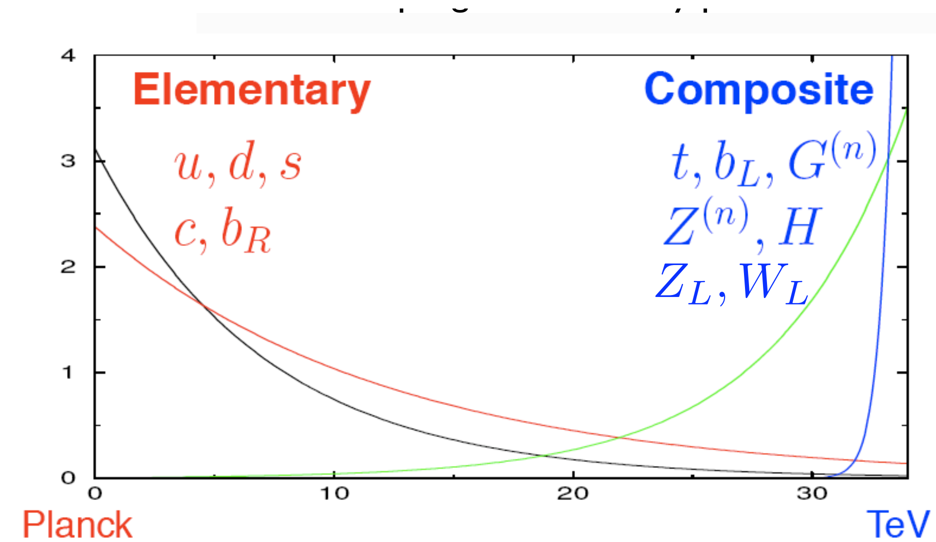
- New states: KK gravitons at the TeV scale
- Couplings: $\mathcal{L} \sim \frac{1}{(\mathrm{TeV})^2} T_{\mu\nu} G^{\mu\nu}_{\mathrm{KK}}$



RS with Bulk Matter

- It was subsequently realized that models with SM gauge fields and fermions in the “bulk” are more interesting:





- natural solution to fermion mass hierarchy problem

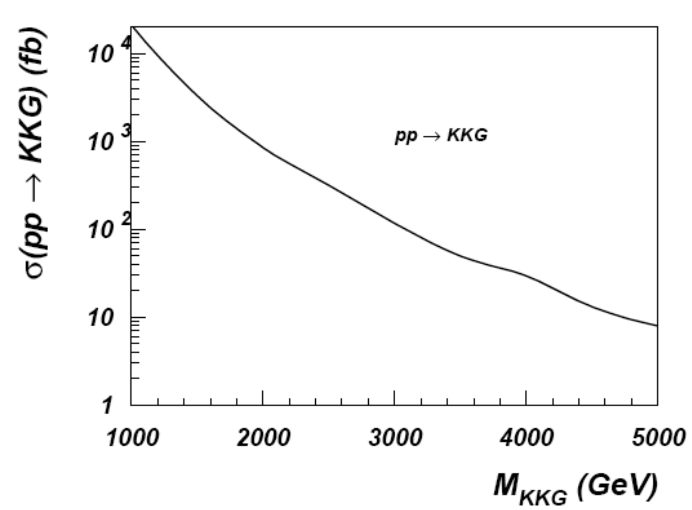
- natural suppression of flavor-changing neutral currents

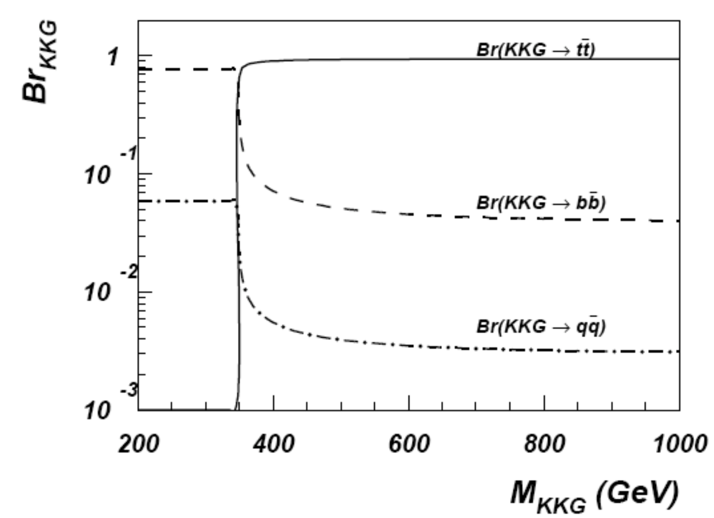
- possibility of gauge coupling unification, as in the MSSM

figure credits: G. Perez, G. Servant

RS with Bulk Matter: Pheno

- Good: all SM states now have KK modes!
- Bad: the KKs do not couple to light quarks and leptons much...
- Worse: PEW constraints force KK masses > 3 TeV or so
- KK gluon is probably the easiest target at the LHC





Agashe et. al., hep-ph/0612015; Lillie et.al., hep-ph/0701166

Final state: A pair of highly-boosted tops

"Regge Excitations" in RS

[MP, Spray, 0907.3496; 1106.2171]

- "Regge excitations" are particles of same quantum numbers but varying spin: s0, s0+1, s0+2, ..., with higher-spin states being heavier: $M^2 \propto S$
- Regge excitations at GeV scale have been observed in QCD bound state spectra
- Regge excitations at the string scale are predicted by string theory
- In the RS model with 5D matter, expect all SM particles to have Regge excitations, with ~TeV masses ⇨ possibly within the reach of the LHC
- As an example, we focus on spin-2 "Regge gluon"
- Constructed a 5D field-theory model for this particle

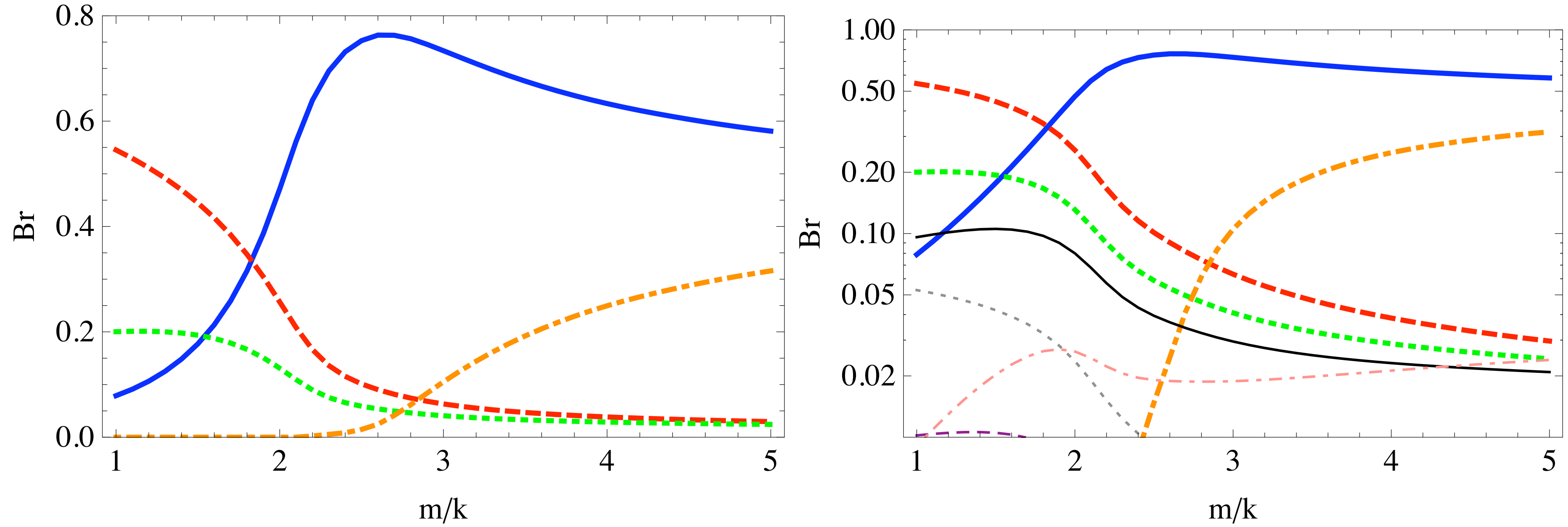


Figure 5. The Reggeon branching fractions in Model A: (left) The four leading decay channels; (right) All channels with branching ratio above 1%. On the left panel, the blue solid line corresponds to the $g^1 g^{1(*)}$ final state; the red dashed line to the $t_R \bar{t}_R$; the green dotted line to $g^1 g$; and the orange dot-dashed line to two KK quarks (all flavors). The additional thin lines on the right panel are: $t_L \bar{t}^1_L + b_L \bar{b}^1_L + t^1_L \bar{t}_L + b^1_L \bar{b}_L$ (solid); quark + KK quark summed over first two generations + b_R (dashed); $t_L \bar{t}_L + b_L \bar{b}_L$ (dotted); and $t_R \bar{t}^1_R + t^1_R \bar{t}_R$ (dot-dashed).

Signature: $pp \to G^2 \to g^1 g^{1(*)} \to \underline{4t}$

Four Tagged Jets Search

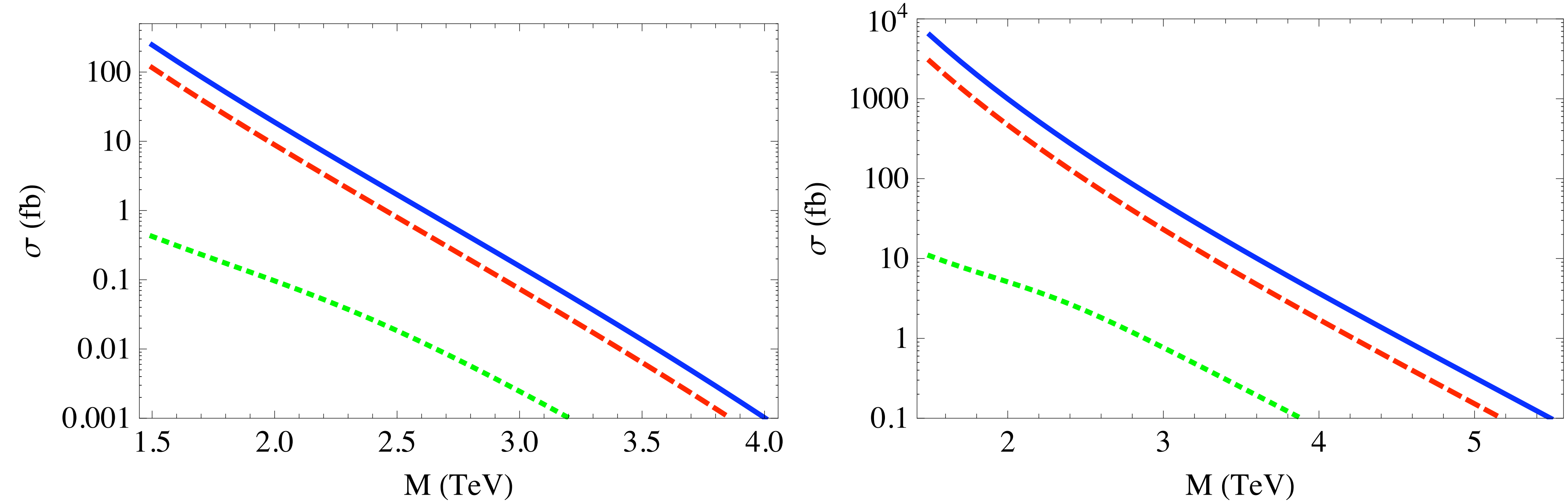


Figure 7. The Reggeon production cross section, as a function of its mass, in Model A: (left) $\sqrt{s} = 7$ TeV; (right) $\sqrt{s} = 14$ TeV. We used the MSTW 2008 [23] PDF set at next to leading order, with the factorization and renormalization scales set to the Reggeon mass. In both panels, blue/solid line corresponds to the total production cross section; red/dashed lines show the total rate of the four-top events; and green/dotted lines show the rate of events for which all four top-jets are tagged.

process	$\sigma_{\rm tot}$	Prob(4 top-tags)	Eff($p_T > 250$ GeV)	$\sigma_{\rm tot} \cdot Prob \cdot Eff$
signal	147	3.66×10^{-3}		0.54
$4j$	5.16×10^5	6.25×10^{-6}	7.0×10^{-4}	2.3×10^{-3}
$3j + t$	1.35×10^5	6.25×10^{-5}	1.0×10^{-4}	8.4×10^{-4}
$2j + 2t$	1.63×10^3	6.25×10^{-4}	4.2×10^{-3}	4.3×10^{-3}
$1j + 3t$	0.221	6.25×10^{-3}	6.8×10^{-3}	9.4×10^{-6}
$4t$	0.442	0.0625	7.7×10^{-3}	2.1×10^{-4}
Total Bg				7.6×10^{-3}

Table 1. Signal and background cross sections (in fb), before and after cuts, at $\sqrt{s} = 7$ TeV. The signal is for a 2 TeV Reggeon in Model B.

- Many disclaimers: No MC for the signal, use a rough model of phase space for this estimates; No top-tagging MC, extrapolate efficiencies from other studies; etc.

- However S/B is almost 100 - a more rigorous analysis seems worthwhile