New Physics Searches with Boosted Tops

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Introduction

- Large top mass ⇒ Strong coupling of the EWSB sector to tops ⇒ Many new physics scenarios produce top-rich signatures, e.g. new particles decaying preferentially to tops

- Energy scales probed at the LHC are already $\gg m_t$ in many cases ⇒ tops from such decays likely move with relativistic velocities

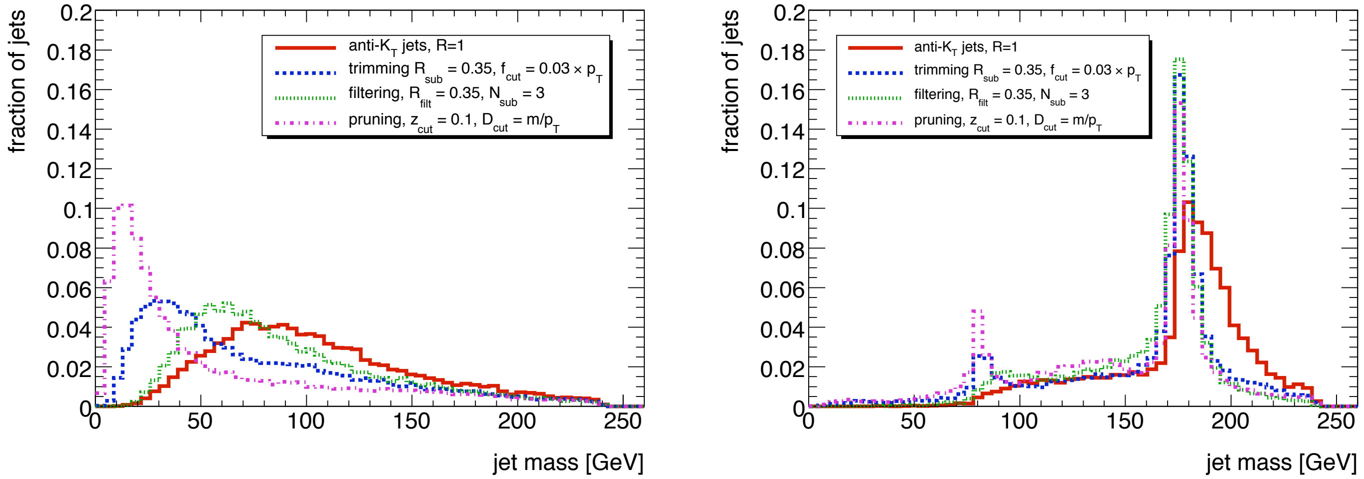
- Top decay products are boosted ⇒ hadronic top will show up as a single jet, instead of three, but with properties different from a typical QCD jet (for example, jet invariant mass $\approx m_t$)

- "Top-tagging" such jets was proposed in 2008, as a way to search for KK gluon in Randall-Sundrum models [Kaplan, Rehermann, Schwartz, Tweedie; Thaler, Wang; ...]

- Top-tagging is becoming a mature experimental technique, tested with data [see Raz Alon's talk yesterday]

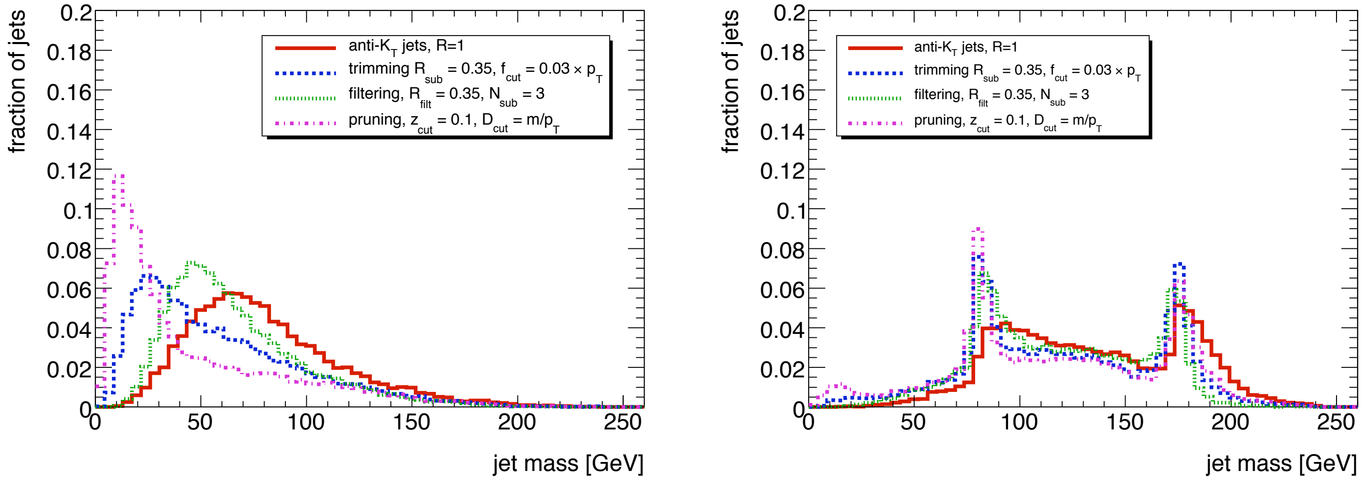
- Should be useful for much more than just the RS KK gluon search!

Top-Jet Tagging: Jet Mass



(a) dijets, 500–600 GeV

(b) $t\bar{t}$, 500–600 GeV



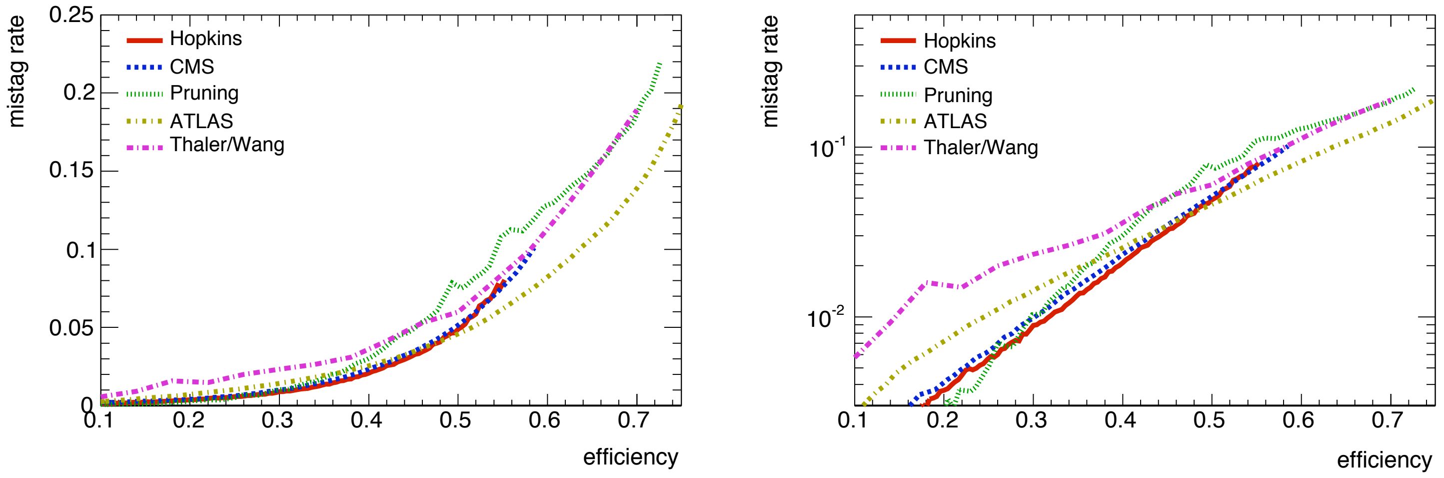
(c) dijets, 300–400 GeV

(d) $t\bar{t}$, 300–400 GeV

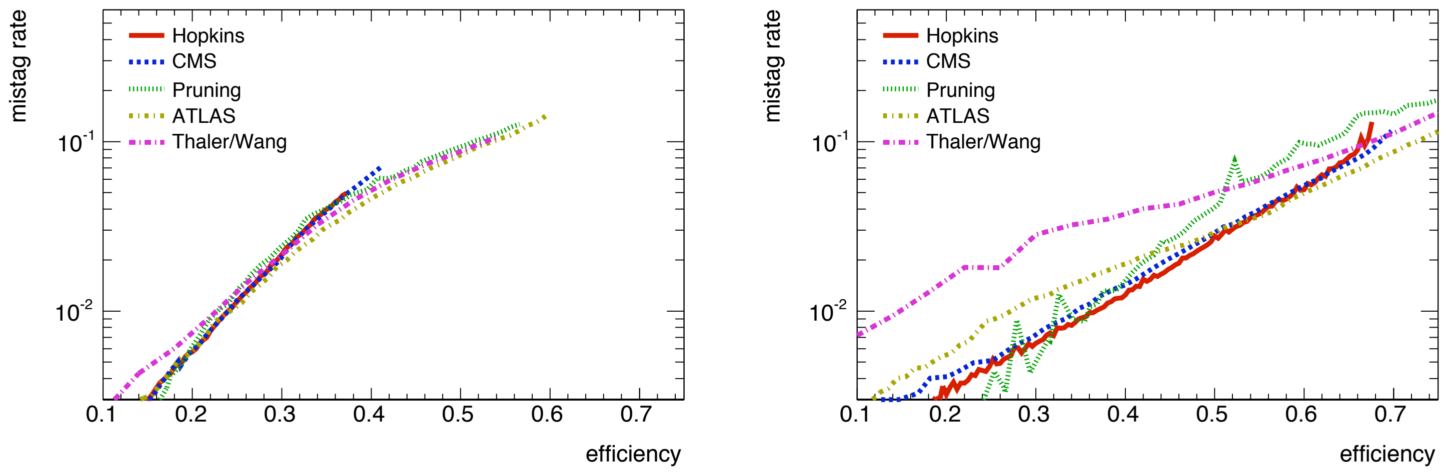
Fig. 1. Jet invariant mass m_j for $t\bar{t}$ (a,c) and dijet (b,d) events, for three grooming methods. Each groomed analysis begins with anti-k_T jets with $R = 1.0$. The solid curve (red in the online version) represents these jets without grooming. The distributions correspond to $t\bar{t}$ or di-jet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



(a) all p_T samples (b) all p_T samples



(c) 300–400 GeV (d) 500–600 GeV

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]

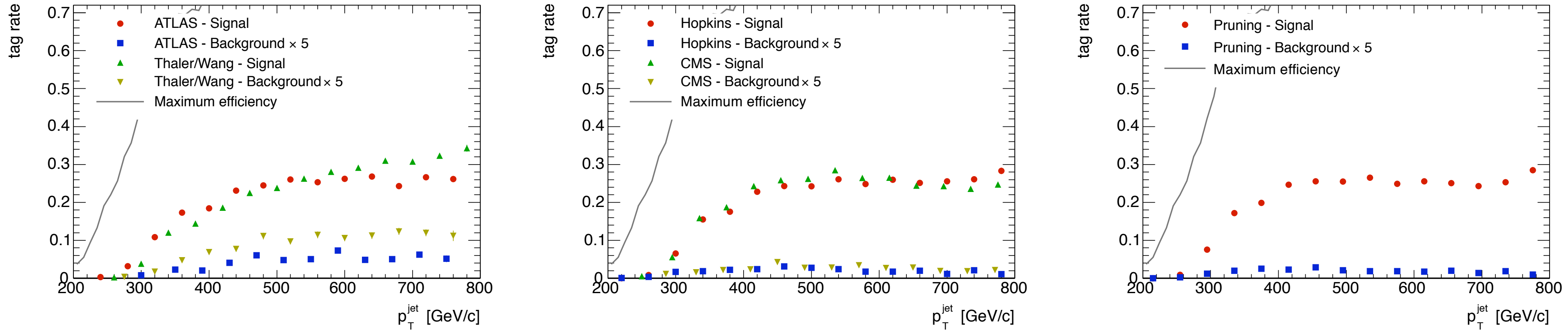
Sample "Working Points":

tight tag:
Eff=20%, Mistag=0.3%

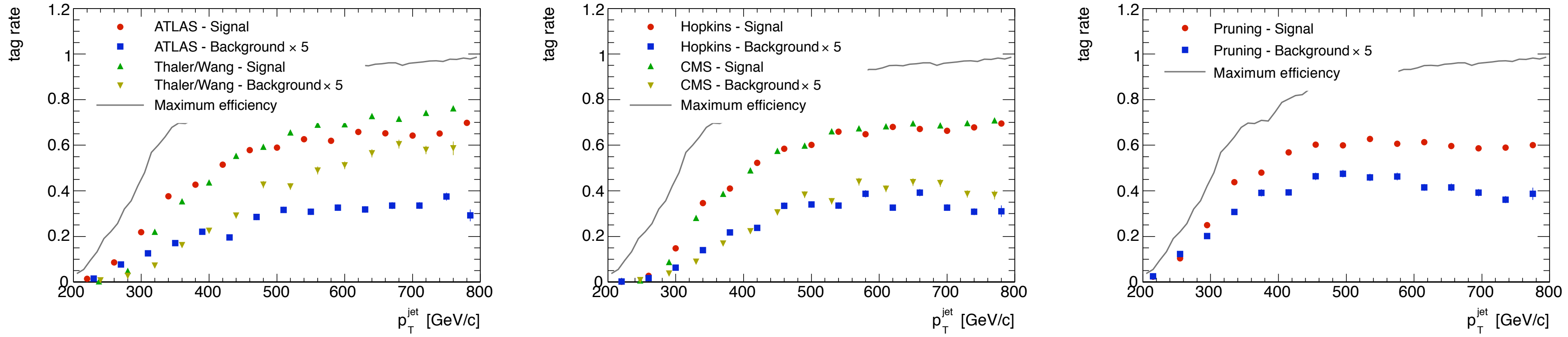
loose tag:
Eff=50%, Mistag=4%

[All results MC;
Eff from t tbar
Mistag from dijets]

Top-Jet Tagging: pT Dependence



(a) ATLAS, Thaler/Wang, $\epsilon = 20$ % (b) CMS, Hopkins, $\epsilon = 20$ % (c) pruning, $\epsilon = 20$ %



(d) ATLAS, Thaler/Wang, $\epsilon = 50$ % (e) CMS, Hopkins, $\epsilon = 50$ % (f) pruning, $\epsilon = 50$ %

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.

Eff rises linearly for top pT between 250 and 400 GeV, roughly constant above 400 GeV

[plots: BOOST-2010 report, 1012.5412]

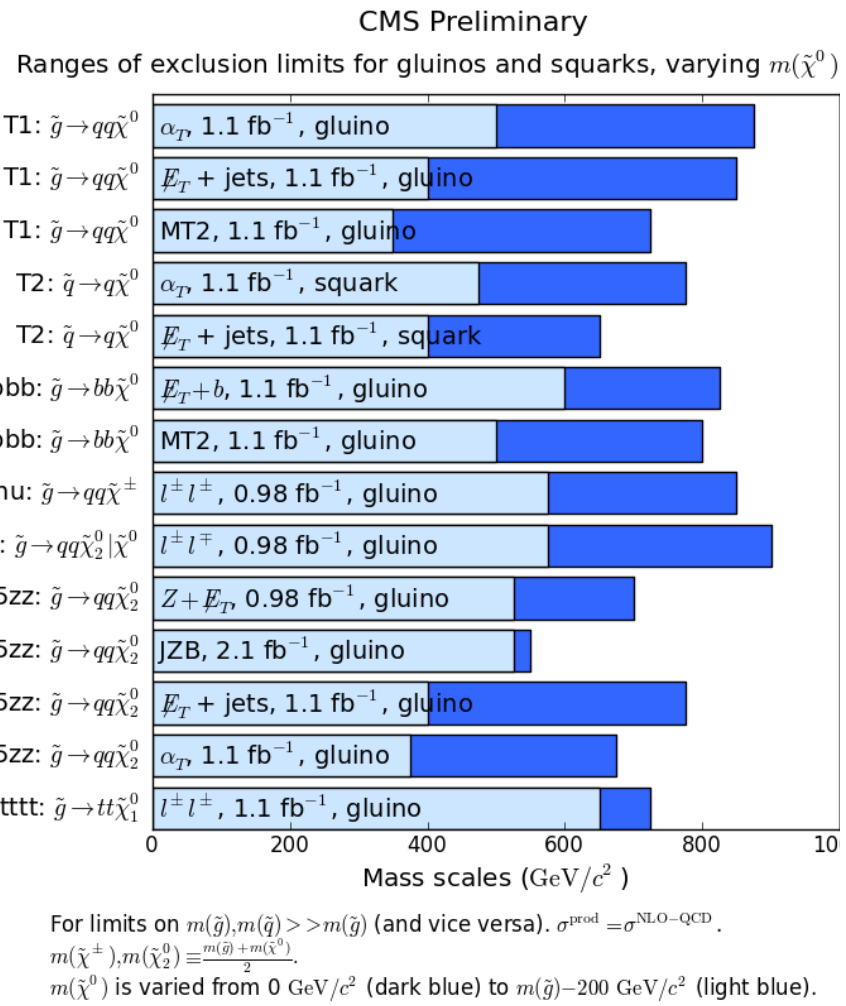
AGENDA:

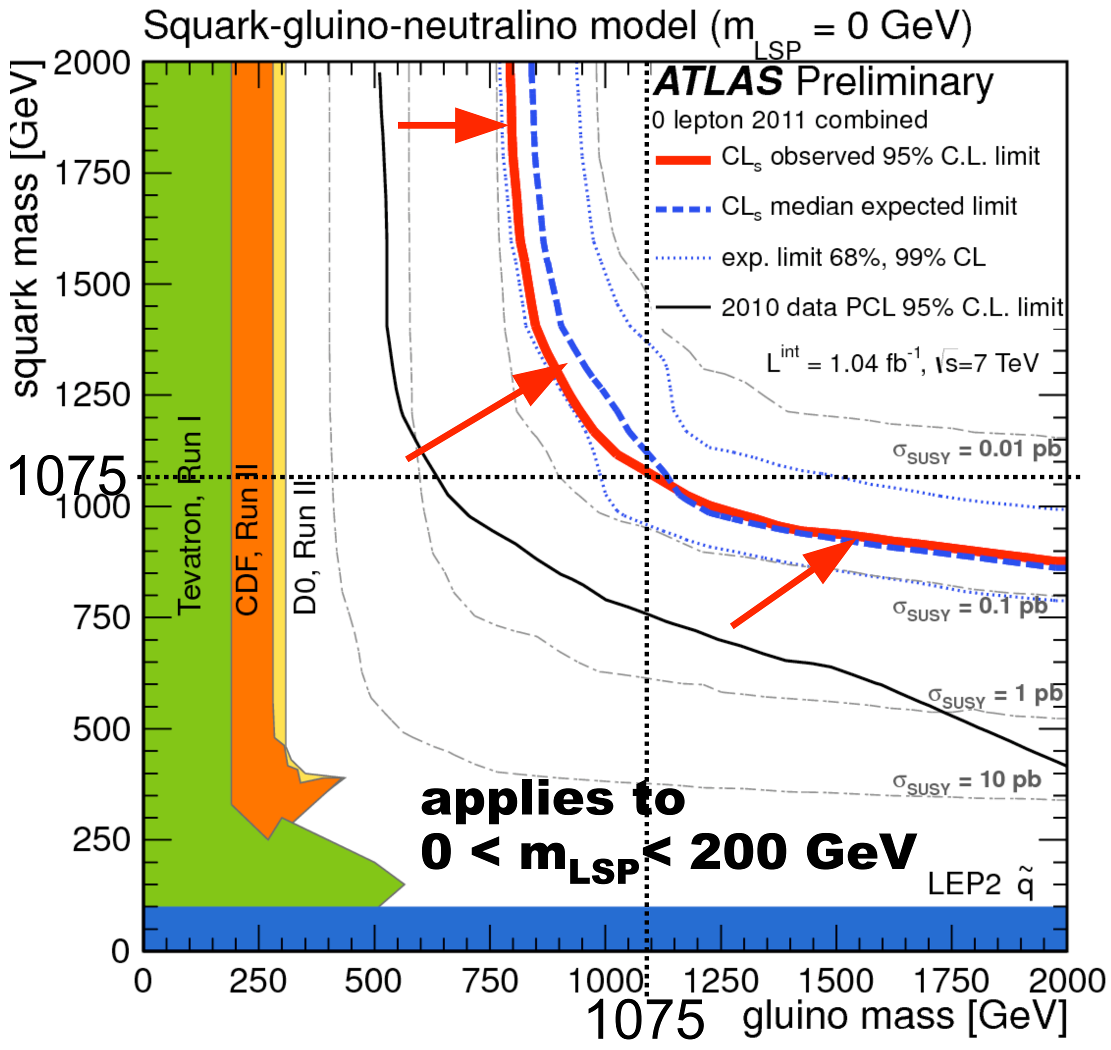
1. Boosted Tops from Gluino Decays in SUSY
[Berger, MP, Saelim, Spray, 1111.6594]

2. Boosted Tops from Reggeons in Randall-Sundrum Models
[MP, Spray, 0907.3496; 1106.2171]

I. Supersymmetry?

1 fb^{-1} summary





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

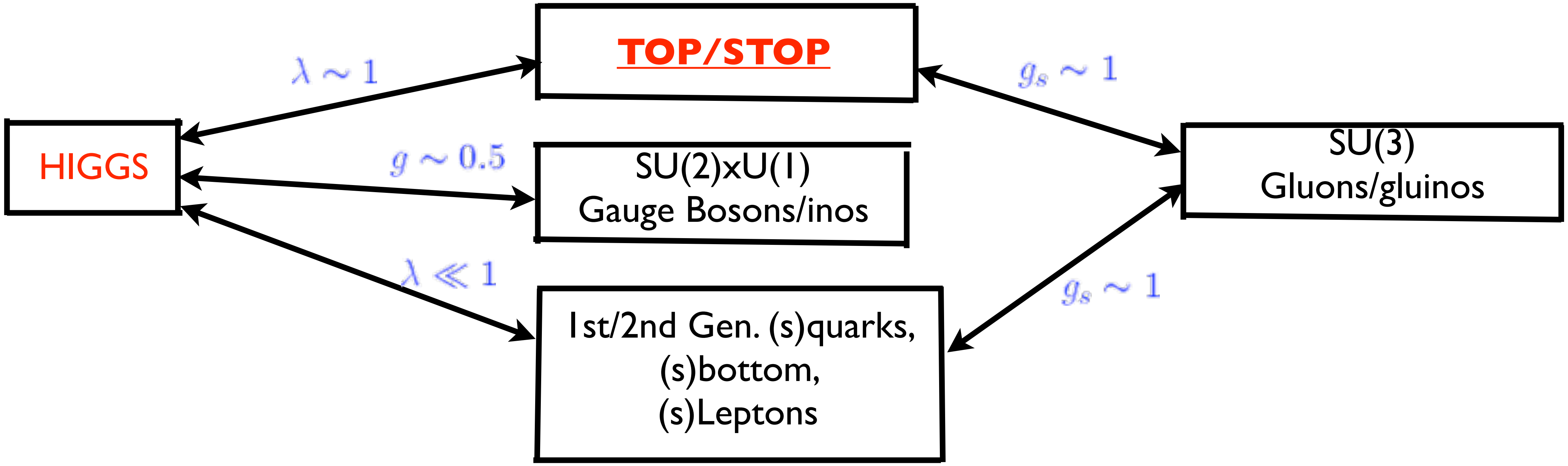
Is SUSY already being pushed from “natural” into “fine-tuned” territory?

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

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

- 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!



HIGGS

TOP/STOP

SU(2)xU(1)
Gauge Bosons/inos

1st/2nd Gen. (s)quarks,
(s)bottom,
(s)Leptons

SU(3)
Gluons/gluinos

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

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

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

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

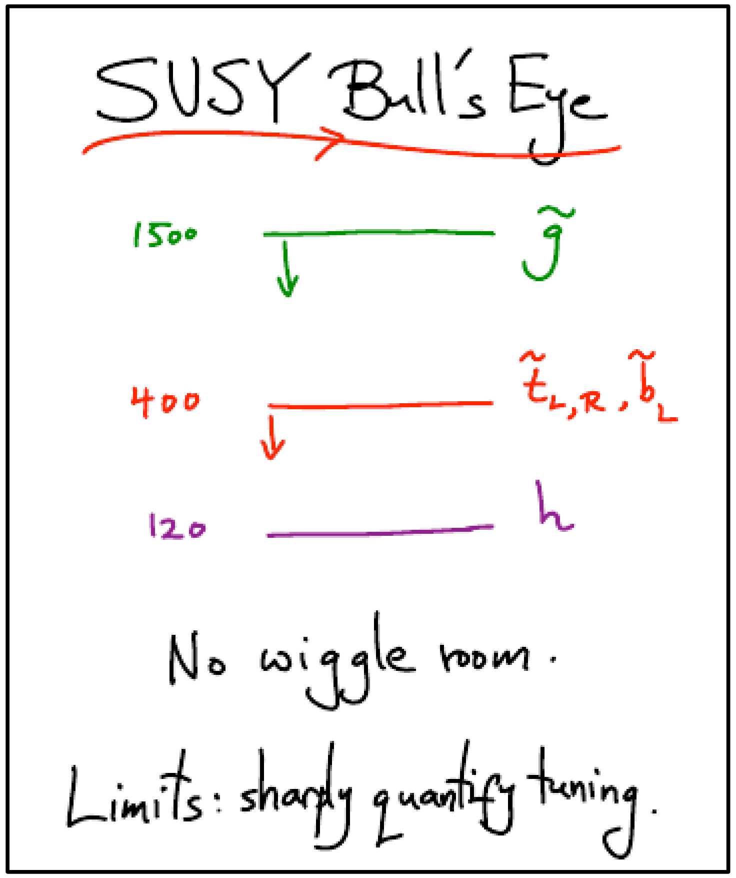
- NB: since left-handed top and bottom are in the same SU(2) doublet, their superpartners must be close in mass ⇒ one light bottom is required.

- 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: I'm 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)

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

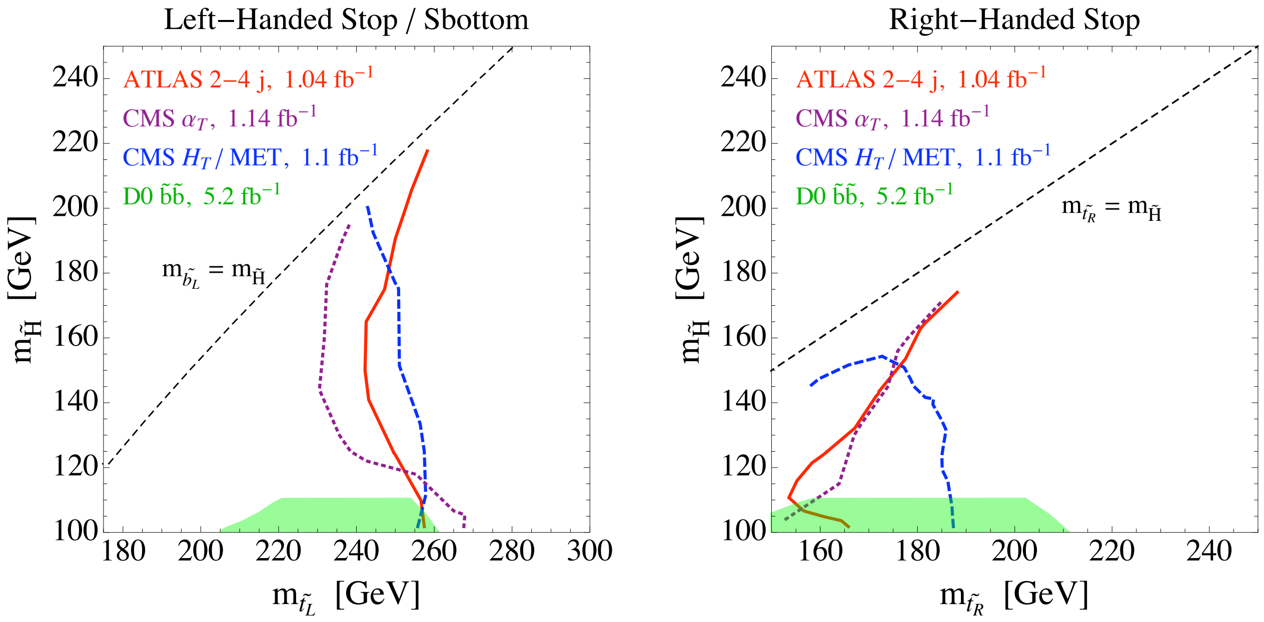


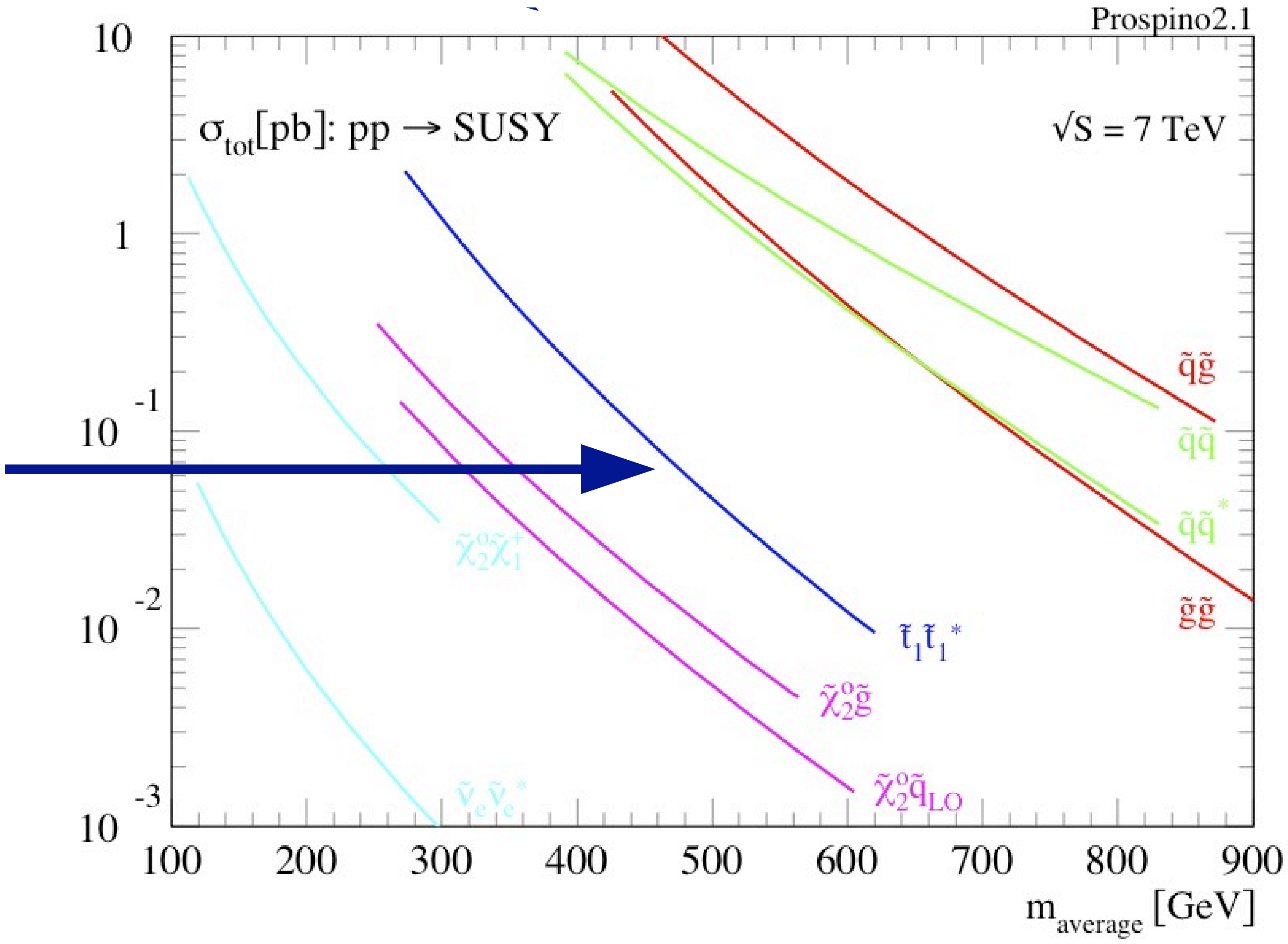
FIG. 3: The LHC limits on the left-handed stop/sbottom (*left*) and right-handed stop (*right*), with a higgsino LSP. The axes correspond to the stop pole mass and the higgsino mass. We find that the strongest limits on this scenario come from searches for jets plus missing energy. For comparison, we show the *D*0 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.

Direct Stops vs. Gluinos

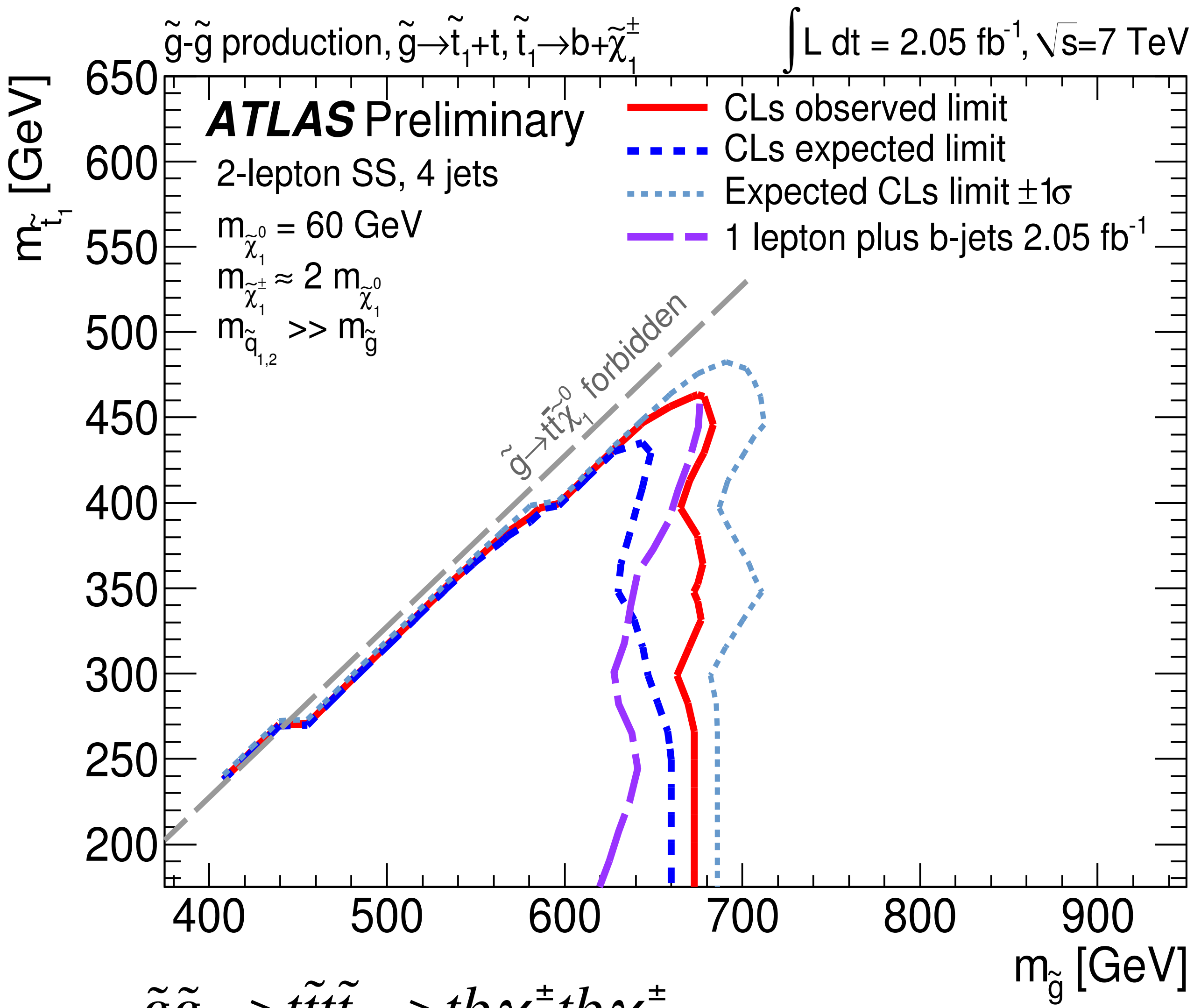
Stops have small cross sections:

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

at 500 GeV mass



Gluinos Decaying to Stops



$\tilde{g}\tilde{g} \rightarrow t\tilde{t}t\tilde{t} \rightarrow tb\chi^{\pm}tb\chi^{\pm}$

$m(\tilde{g}) > 650\ \mathrm{GeV}$

- Note: Not-quite-minimal spectrum assumed: light chargino gives more leptons

Top-Tag Gluino Search

- Consider a minimal "simplified model": $\tilde{g}, \tilde{t}, \tilde{\chi}^0$
- All gluinos decay via $\tilde{g} \to \tilde{t} + \bar{t}, \qquad \tilde{t} \to t\tilde{\chi}^0$
- If $\tilde{b}_L$ is included, this chain generically has branching ratio of 2/3.
- (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: $m_{\tilde{g}} = 800\ \mathrm{GeV},\ m_{\tilde{t}} = 400\ \mathrm{GeV} \Longrightarrow \boxed{\gamma_t \approx 1.8}$
- Gluino velocity in lab frame: on average, about 0.5-0.7 in the relevant mass range
- A sizable fraction of tops are relativistic in the lab frame!

Monte Carlo Study

- Signal Simulation: MadGraph → Pythia → FastJet (anti-kT jets)+Hopkins Top-Tagger
- Cross section rescaled to NLO [Prospino]
- Backgrounds: $nt + (4-n)j, n = 0 \dots 4$ [MET from leptonic top]

  $Z/W + nt + (4-n)j, n = 0, 2, 4$ [invisible Z/leptonic W]
- Instrumental backgrounds (other than mis-top-tags) not included
- Due to small mis-tag rate and limited statistics, we do not simulate top-tagger action on backgrounds directly; instead, apply pT-dependent mis-tag probabilities measured in dijet Monte Carlo (assumed to be independent of environment)
- Use LO cross section for backgrounds
- Dominant backgrounds have K-factors < 1: $K = 0.73, \quad 2t + 2j$

  $K = 0.95, \quad Z + 4j$

[Bevilacqua, Czakon, Papadopoulos, Worek; Ita, Bern, Dixon, Cordero, Kosower, Maitre]

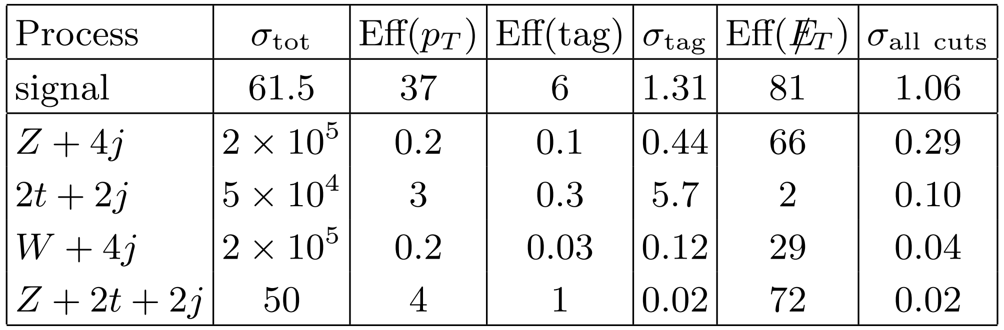
Cut Optimization

- Require 4 jets with pT>100 GeV
- Optimize at the benchmark SUSY point:

$$m_{\tilde{g}} = 800\ \mathrm{GeV},\ \ m_{\tilde{t}} = 400\ \mathrm{GeV}$$

- Top-tag options: can demand between 0 and 4 tags, each loose or tight
- More tags ⇨ better S/B, pay price in statistics
- Two (hopelessly outdated) scenarios: 7 TeV, 30 fb-1 and 14 TeV, 10 fb-1
- Find that 2 loose tags are optimal at 7 TeV, 3 loose tags optimal at 14 TeV
- Need MET cut to get rid of very large QCD background (even with 4 tags); require MET>100 GeV at 7 TeV and MET>175 GeV at 14 TeV.

Benchmark Point Results: 7 TeV



Process	$\sigma_{\rm tot}$	Eff(p_T)	Eff(tag)	$\sigma_{\rm tag}$	Eff($\not\!\!E_T$)	$\sigma_{\rm all\ cuts}$
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.

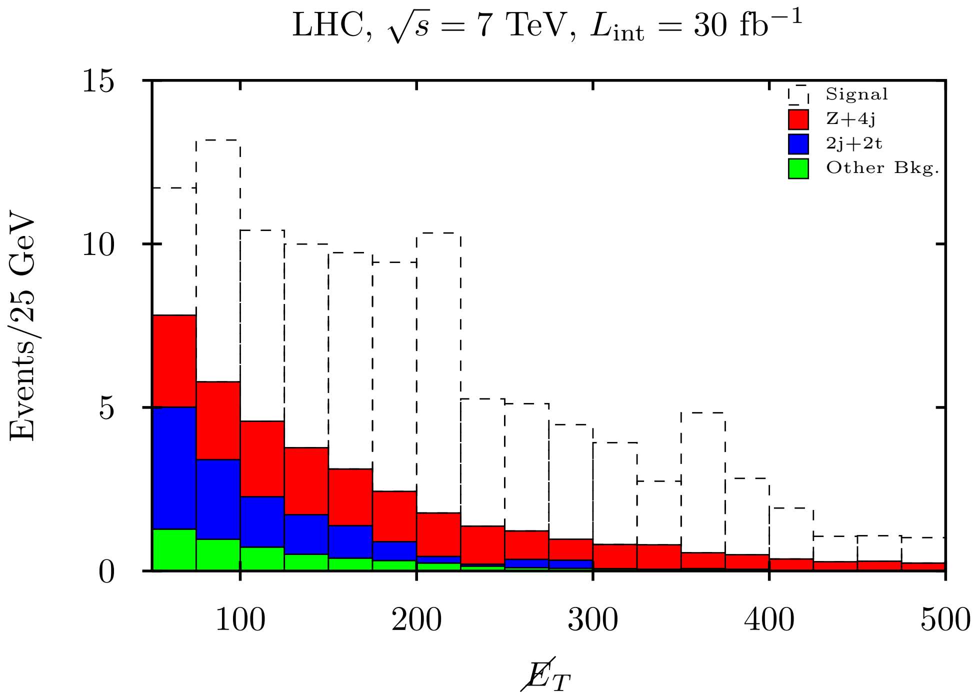


FIG. 1: Signal at the benchmark point, $(m(\tilde{g}), m(\tilde{t})) = (800, 400)$ GeV, and background rates as a function of MET, at 7 TeV LHC. Four jets with $p_T > 100$ GeV and two top-tagged jets are required.

30 fb-1 @ 7 TeV: $S = 32,\ S/\sqrt{B} = 6.8,\ S/B = 2.4$

Reach Estimates

(2 t-tags)

(3 t-tags)

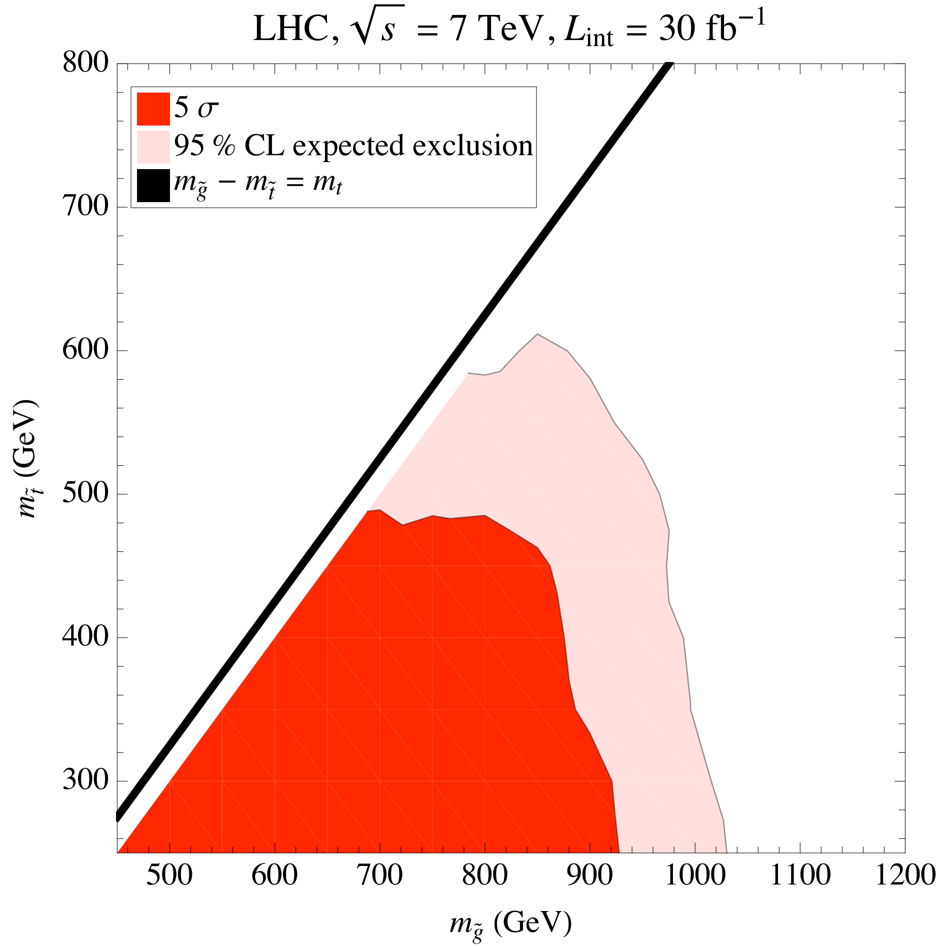


FIG. 2: The 95% c.l. expected exclusion and 5-sigma discovery reach of the proposed search at the 7 TeV LHC run with 30 fb^{-1} integrated luminosity.

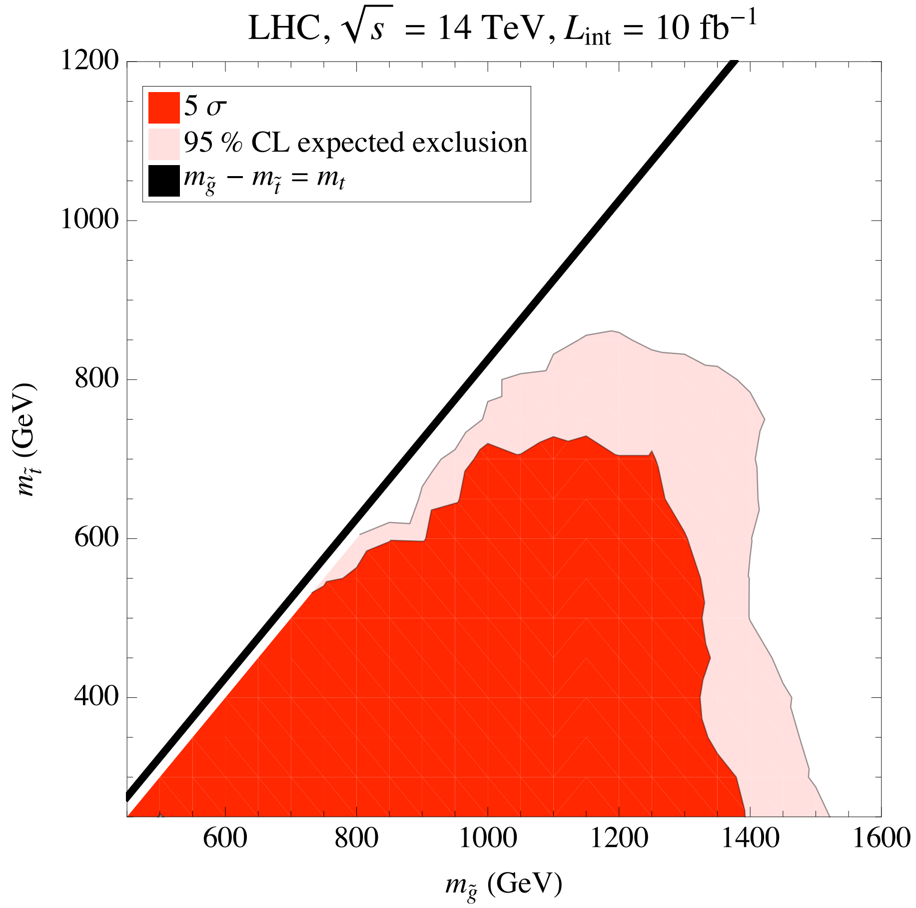


FIG. 3: The 95% c.l. expected exclusion and 5-sigma discovery reach of the proposed search at the 14 TeV LHC run with 10 fb^{-1} integrated luminosity.

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

Comments

- Comparison with other channels? Could not find sufficient information for direct comparison.
- Other searches rely on leptons (e.g. same-sign dilepton)
- Probing gluinos above ~TeV requires dealing with mostly relativistic tops
- Lepton from a decay of a relativistic top is not isolated from the (b-)jet from the same top decay - may complicate life
- A more detailed study is needed

II. Regge Excitations

- String theory: SM particles are zero-modes of strings
- 4-pt Veneziano Scattering amplitude (in flat background space)

$$\mathcal{S}(s,t) = \frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)}$$

- Poles at $s = n/\alpha'$ - “Regge excitations”
- Reggeons have higher spins $S = S_0 + n$, with $M_n = \sqrt{n} M_S$
- May be accessible to the LHC in models with string scale $\sim \mathrm{TeV}$, eg. ADD

  [Cullen, MP, Peskin, ’00; Goldberg, Lust, Taylor, et.al. ’08-’11]

- For example, spin-2 Regge gluon shows up as a dijet resonance

Reggeons in Randall-Sundrum

- In RS model (with all SM fields in 5D), the Reggeon masses should be set by the "warped-down" string scale

$$M_S e^{-k\pi R} \sim \mathrm{TeV}$$

[MP, Spray, '09; March-Russell et.al., '09; Reece, Wang, '10]

- From AdS/CFT point of view, Reggeons are just higher-spin bound states of the 4D strong dynamics - like the original Regge states in QCD
- May be accessible to the LHC. Phenomenology?
- Generalization of the Veneziano amplitude for AdS background is unknown
- A bottom-up, field-theory approach:
  - Start with flat space Veneziano amplitudes
  - Construct a Lagrangian for low-lying Regge states that reproduces V.amp.
  - Extend to AdS in a minimally generally-covariant way

Example: RS Regge Gluon

- 4-gluon scattering in flat space:

[MP, Spray, '09]

$$\begin{aligned}\mathcal{A}(1,2,3,4) \;=\; & g^2 A(1,2,3,4)\,\mathcal{S}(s,t)\,\mathrm{tr}[t^1t^2t^3t^4+t^4t^3t^2t^1]\\ & + g^2 A(1,3,2,4)\,\mathcal{S}(u,t)\,\mathrm{tr}[t^1t^3t^2t^4+t^4t^2t^3t^1]\\ & + g^2 A(1,2,4,3)\,\mathcal{S}(s,u)\,\mathrm{tr}[t^1t^2t^4t^3+t^3t^4t^2t^1]\,,\end{aligned}$$

$$A(1^+,2^-,3^-,4^+) = -4\frac{t}{s}\,,\qquad A(1^+,2^-,3^+,4^-) = -4\frac{u^2}{st}$$

- Factorize at the first Regge pole:

$$\mathcal{A}(g^+g^+\rightarrow g^+g^+) = -2\,g^2\frac{s}{s-M_S^2}\cdot\mathcal{C}^{1234}\,,$$

$$\mathcal{A}(g^+g^-\rightarrow g^+g^-) = -2\,g^2\frac{u^2}{s^2}\,\frac{s}{s-M_S^2}\cdot\mathcal{C}^{1234}$$

- Interpret as s-channel exchange of spin-2, 1, 0 particles ➡ gluon-Reggeon interaction Lagrangian:

$$\mathcal{L}_{ggg^*} = \frac{g}{\sqrt{2}M_S}\,C^{abc}\left(F^{a\rho\mu}F^{b\nu}_{\rho} - \frac{1}{4}F^{a\rho\sigma}F^{b}_{\rho\sigma}\eta^{\mu\nu}\right)B^c_{\mu\nu} + (\mathrm{vectors},\mathrm{scalars})$$

$$C^{abc} \;=\; 2\left(\mathrm{tr}[t^at^bt^c]+\mathrm{tr}[t^at^ct^b]\right)$$

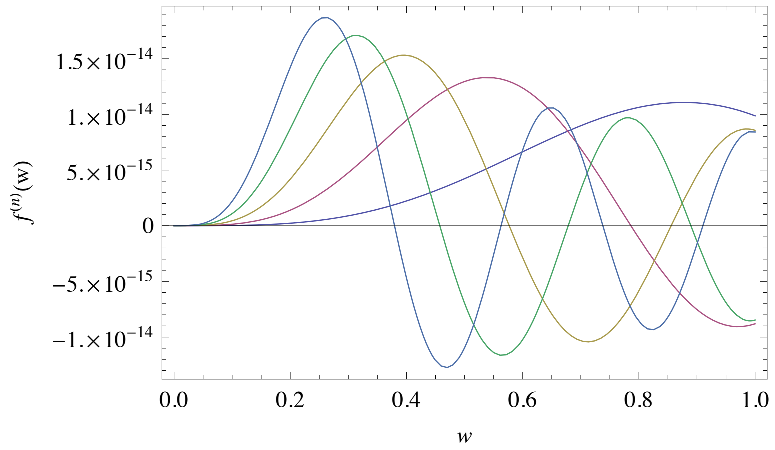
- Generalize to 5D, non-flat background (ensure 5D gen. covariance)

$$\mathcal{S}_{ggg^*} = \int d^5x\sqrt{-G}\,\frac{g_5}{\sqrt{2}M_S^*}\,C^{abc}\left(F^{aAC}F_C^{bB} - \frac{1}{4}F^{aCD}F^b_{CD}G^{AB}\right)B^c_{AB} \qquad g_5 = \sqrt{\pi R}\,g_s\,.$$

- KK-decompose all fields in RS background:

$$B_{\mu\nu}(x,y) = \frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty} B^{(n)}_{\mu\nu}(x) f^{(n)}(y).$$

$$f^{(n)}(y) = \frac{1}{N}\left\{J_\nu\left(\frac{\mu^{(n)}}{\Lambda_{\rm IR}}w\right) + c\,J_{-\nu}\left(\frac{\mu^{(n)}}{\Lambda_{\rm IR}}w\right)\right\}$$



- Interactions among zero-mode and KK gluons with the Reggeon:

$$\mathcal{L}_{ggg^*} = \sum_n \frac{g^{(n)}}{\sqrt{2}\tilde{M}_S}\mathcal{C}^{abc}\left(F^{a\alpha\gamma}F_\gamma^{b\ \beta} - \frac{1}{4}F^{a\gamma\delta}F^b_{\gamma\delta}\right)B^c_{\alpha\beta}\,, \qquad \tilde{M}_S = e^{-\pi kR}M_S^* \sim \text{a few TeV}$$

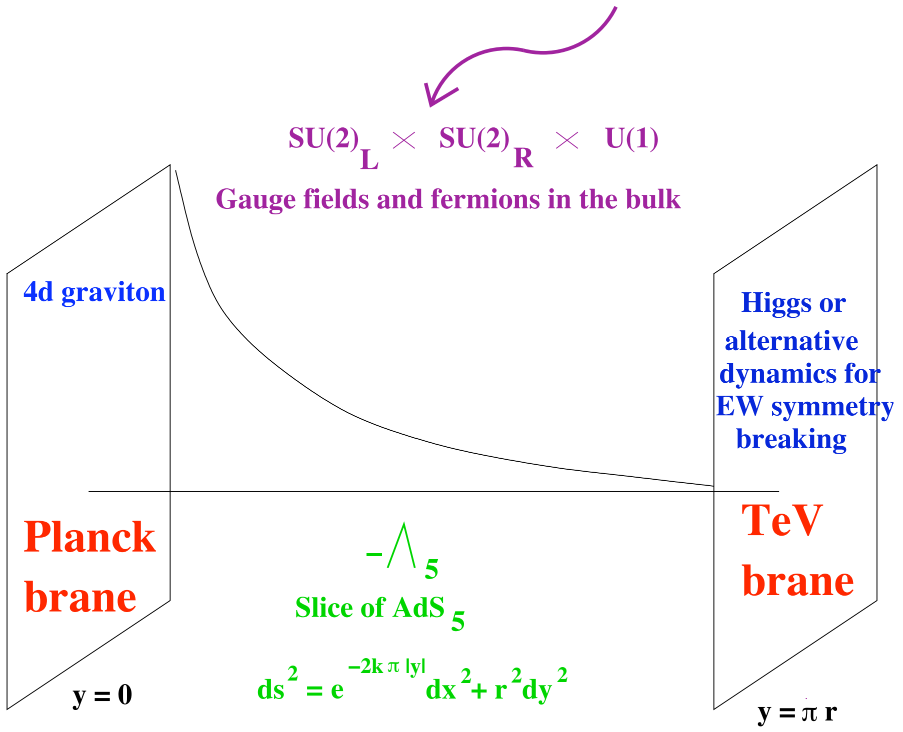
$$g^{(n)} = \frac{g_s\,e^{-\pi kR}}{\pi R}\int_0^{\pi R} dy\,e^{2ky}\,f^{(n)}(y)\,.$$

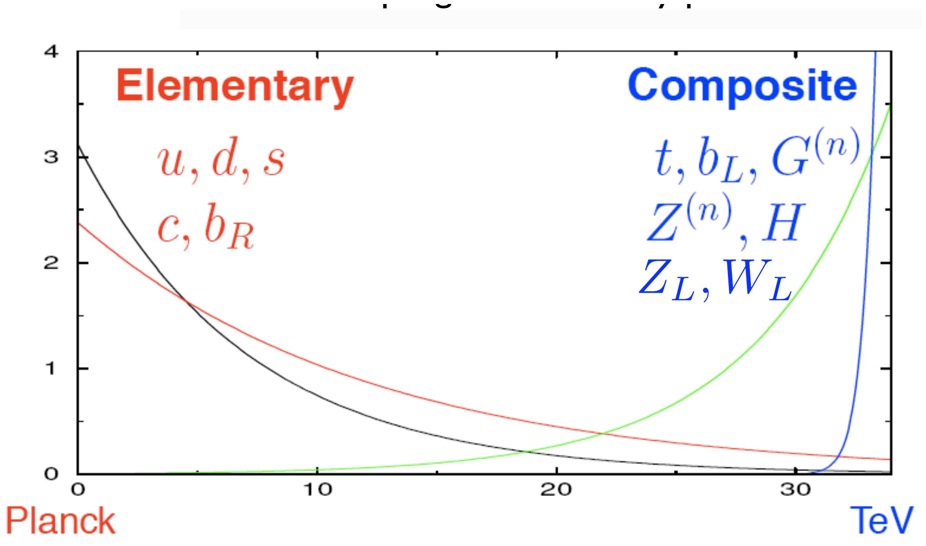
- SM+KK fermion couplings to the Reggeon derived in the same manner

Regge Gluon in RS: Pheno

[MP, Spray, ’11]

- Focus on spin-2 Regge gluon
- Describe as a spin-2 massive field propagating on RS background
- KK decompose and focus on the lowest-lying KK state
- Reggeon wavefunction localized near the TeV brane ⇒ dominantly couples to right-handed tops and KK quarks/gluons, subdominant coupling to SM gluon, very weak couplings to 1st and 2nd generation SM quarks





Regge Gluon Decays

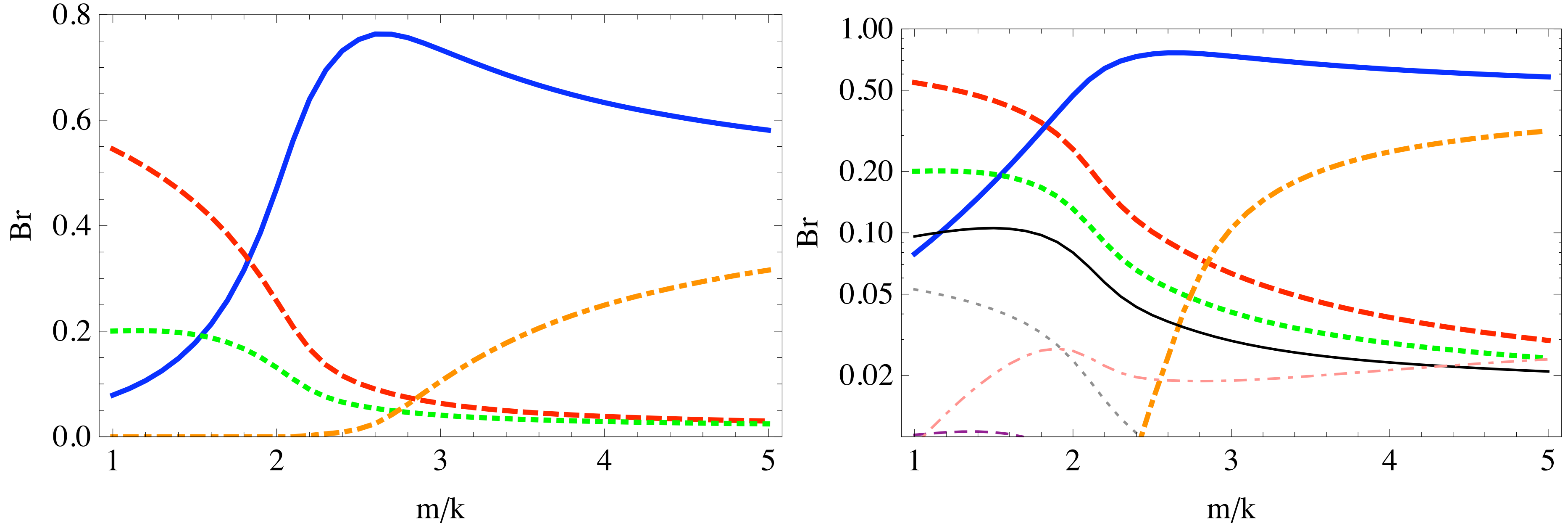


Figure 5. The Reggeon branching fractions in Model A: (left) The four leading decay channels; (right) All channels with branching ratio above 1%. On the left panel, the blue solid line corresponds to the $\underline{g^1 g^{1(*)}}$ final state; the red dashed line to the $\underline{t_R \bar{t}_R}$; the 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: $pp \rightarrow G^2 \rightarrow g^1 g^{1(*)} \rightarrow \underline{4t}$

Regge Gluon Production

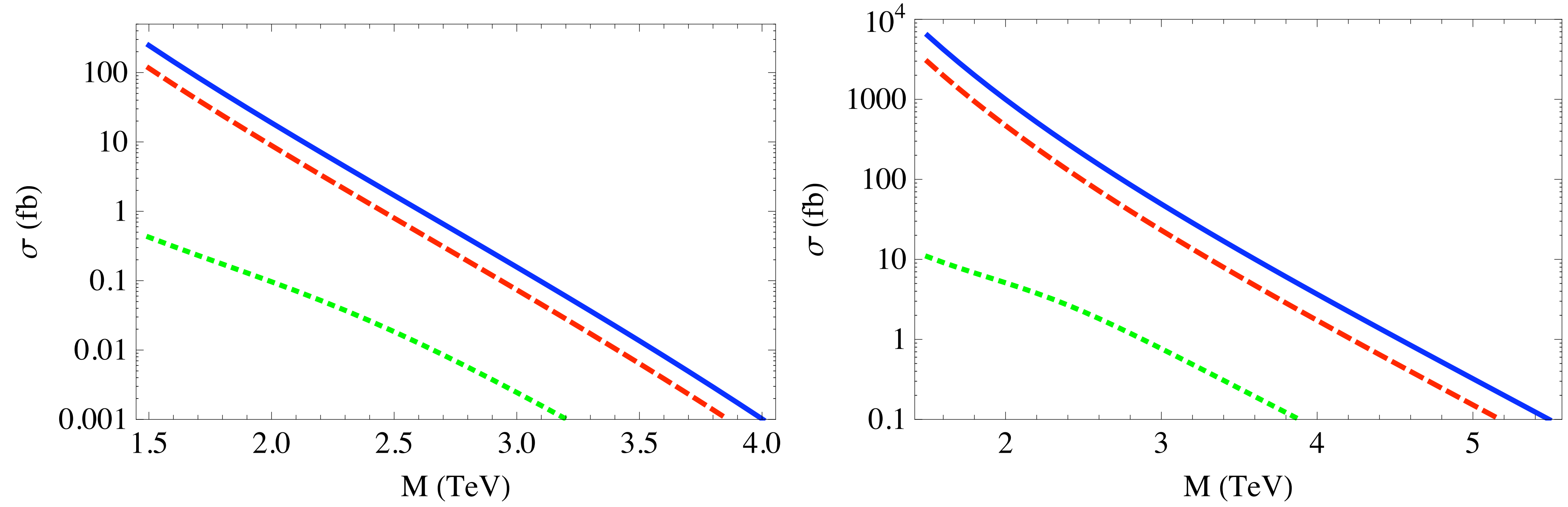
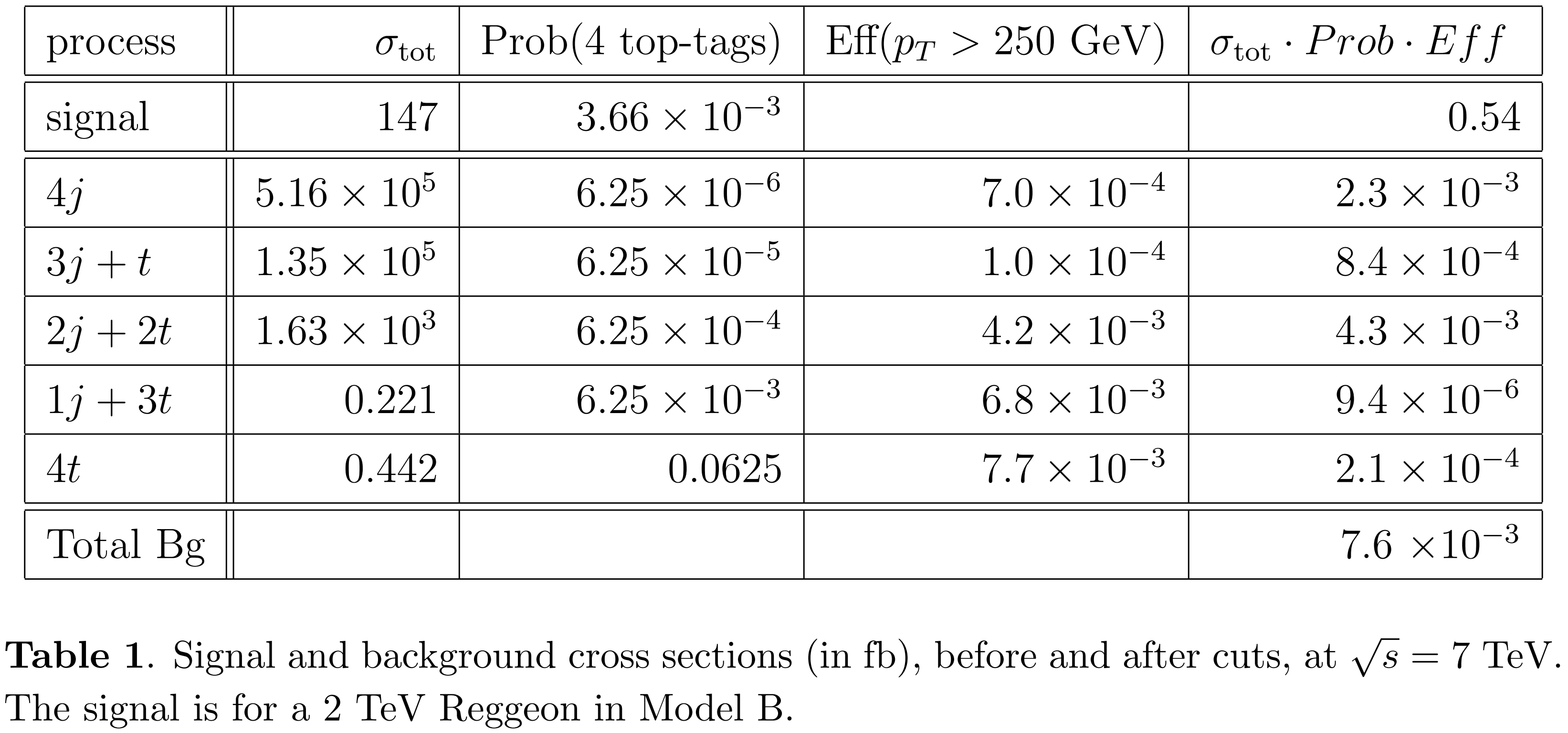


Figure 7. The Reggeon production cross section, as a function of its mass, in Model A: (left) $\sqrt{s} = 7$ TeV; (right) $\sqrt{s} = 14$ TeV. We used the MSTW 2008 [23] PDF set at next to leading order, with the factorization and renormalization scales set to the Reggeon mass. In both panels, blue/solid 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.

[Assume efficiencies from BOOST-2010 t tbar study]

Preliminary LHC Analysis



process	σ_{tot}	Prob(4 top-tags)	Eff($p_T > 250$ GeV)	$\sigma_{\text{tot}} \cdot Prob \cdot Eff$
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.

- Signal: no MC, use a rough model of phase space, top-tag efficiencies from t tbar MC
- Backgrounds: MadGraph only, no top-tagging MC, top mis-tag rates from dijet MC
- Looks promising: S/B~100 - a more rigorous analysis seems worthwhile

Conclusions

- Top quark plays a special role in EWSB, New physics with preferential couplings to tops is well motivated
- Decays of heavy new particles produce relativistic tops ⇨ top jets
- Top-jet tagging technology is maturing and becoming part of the standard experimentalist's toolbox
- Time to explore possible applications beyond just looking for ttbar resonance
- Two examples today: boosted tops + MET signature of SUSY, and 4-top resonance signature of Regge gluon in Randall-Sundrum models
- Pheno-level analyses look promising, searches should be pursued by ATLAS/CMS