JET OBSERVABLES AND STOPS AT A 100 TEV COLLIDER

JiJi Fan

Brown University

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based on work with Prerit Jaiswal and Shing Chau Leung, 1704.03014 (Phys.Rev. D96 (2017), 036017)

One classic target at a hadron collider is the top partner, whether it's fermionic (composite Higgs) or bosonic (stops in SUSY).

The mass scale of top partner $\rightarrow$ degree of electroweak fine-tuning

Testing fine-tuning will continue to be one of the main physics goals at FCC-hh.

Challenge at FCC: super-boosted SM objects from decays of massive new particles

$$p_T \sim \mathcal{O}(\mathrm{TeV})$$

$$\Delta R \sim \frac{m_{\mathrm{top}}}{p_T} \sim 0.08 \left(\frac{2\,\mathrm{TeV}}{p_T} \right)$$

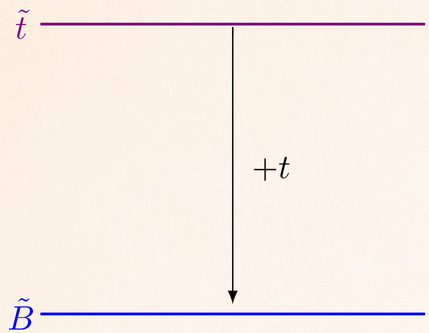
	CMS	FCC
$\sigma(E)/E$ (ECAL)	$7\%/\sqrt{E} \oplus 0.7\%$	$3\%/\sqrt{E} \oplus 0.3\%$
$\sigma(E)/E$ (HCAL)	$150\%/\sqrt{E} \oplus 5\%$	$50\%/\sqrt{E} \oplus 1\%$
$\eta \times \phi$ cell size (ECAL)	(0.02×0.02)	(0.01×0.01)
$\eta \times \phi$ cell size (HCAL)	(0.1×0.1)	(0.05×0.05)

Table 3: Calorimeter parameters for the CMS and FCC setup in Delphes.

Decay products of SM particles collimated into a single cell of calorimeter. Standard tagging procedure may not work.

Larkoski, Maltoni and Selvaggi 2015

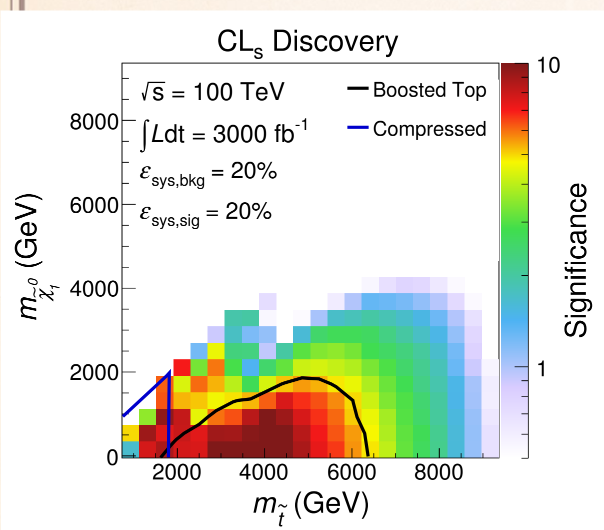
A possible simple strategy

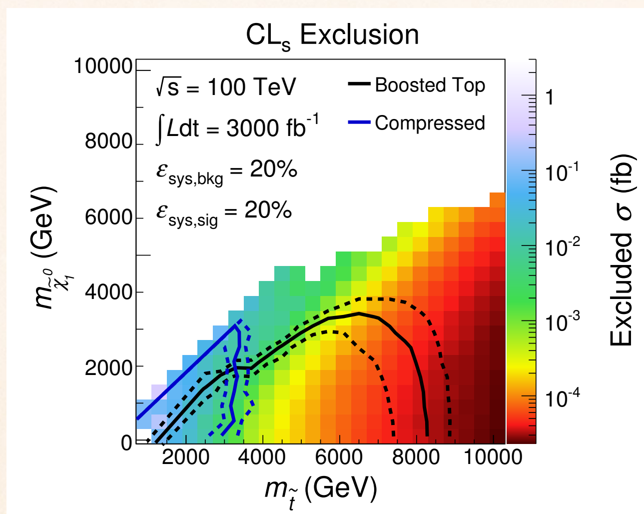


(b) Bino LSP

a hard muon (pT > 200 GeV)
inside a jet (ΔR < 0.5) + MET
(MET > 3 - 4 TeV)

Cohen, D'Agnolo, Hance, Lou, Wacker 2014





Dramatic Discovery Reach ~ 6 TeV stop!
Exclude 8 TeV stops.
Probe tuning ~ 3000.
(But need to improve compressed spectrum reach!)

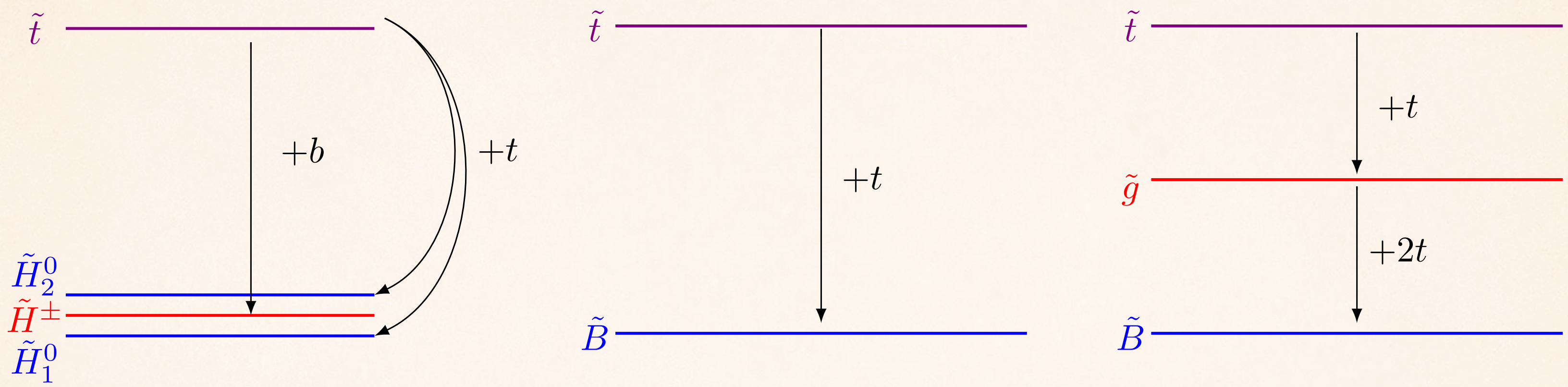
The simple muon tagging is nice yet it

- pays the price of top leptonic decaying branching fraction
- does not distinguish boosted top or bottom jet
- works for simple final states yet not for long cascades with complicated final states

We want to also tag hadronic-decaying tops and improve lepton-decaying top tagging as well.

The study is on stops in SUSY yet the strategies could be carried over to fermionic top partner searches and other types of new physics.

Stop simplified models



(a) Higgsino LSP (b) Bino LSP (c) Bino LSP with gluino NLSP

A mixture of boosted top/bottom

Two boosted tops

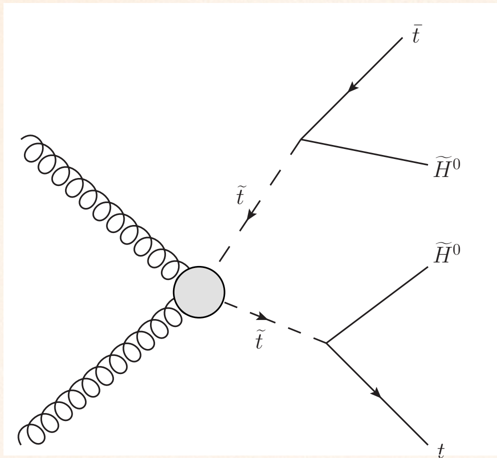
Multiple boosted tops

(in this case, gluino will be discovered first)

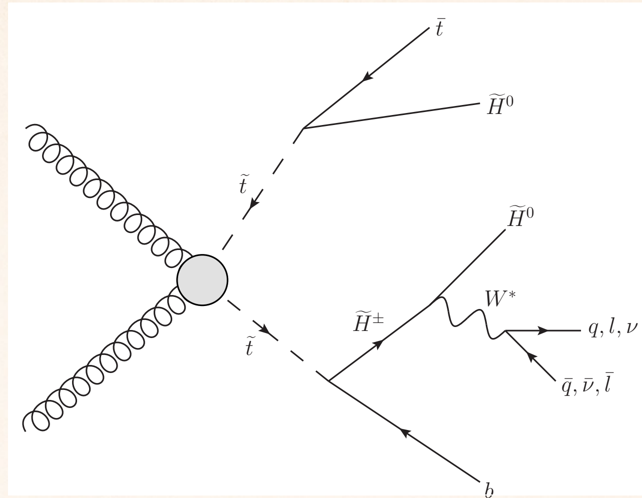
Try to develop a strategy to distinguish different LSPs

Boosted top(bottom)-rich final states

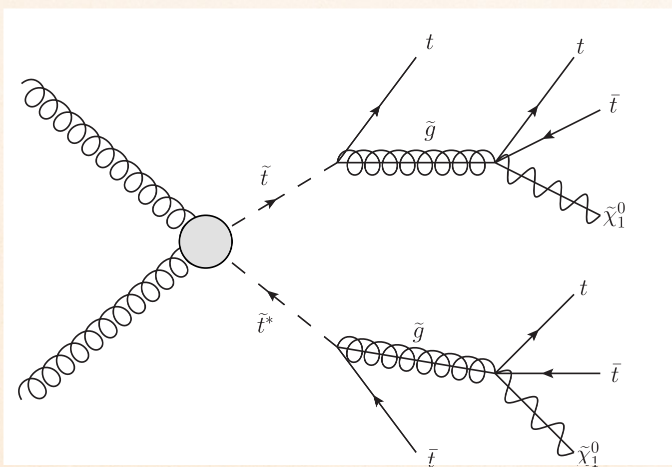
A hard muon inside a jet is not sufficient: distinguish a bottom and a top jet;
also need to tag hadronic decaying tops!



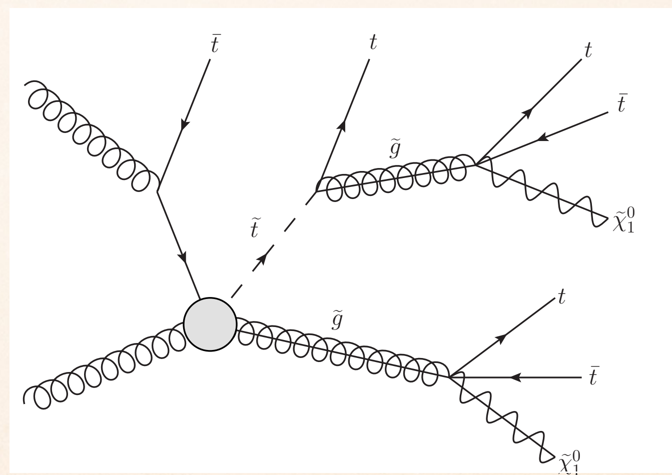
(a) Stops decaying to $\tilde{H}^0$



(b) Stops decaying to either $\tilde{H}^0$ or $\tilde{H}^\pm$



(a) Stop-pair production



(b) Stop-gluino associated production

In addition to the standard cuts, $H_T > 2$ TeV and $\not{E}_T > 200$ GeV we will use track-based jet observables for jets with pT > 1 TeV.

Jets: use a dynamical jet radius

$$R = \frac{3.5 m_{\rm top}}{p_T} = \frac{600\,\mathrm{GeV}}{p_T}$$

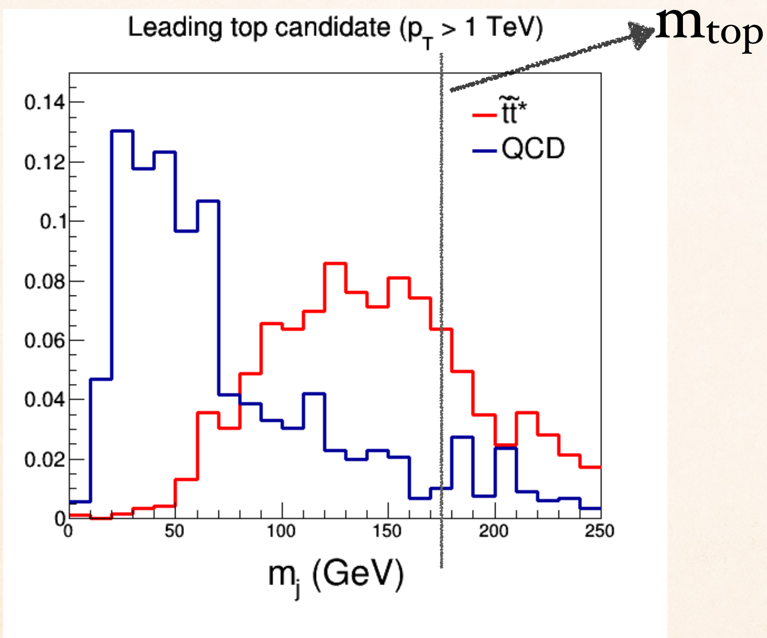
to mitigate the issue of ISR/FSR/underlying events.

Larkoski, Maltoni and Selvaggi 2015

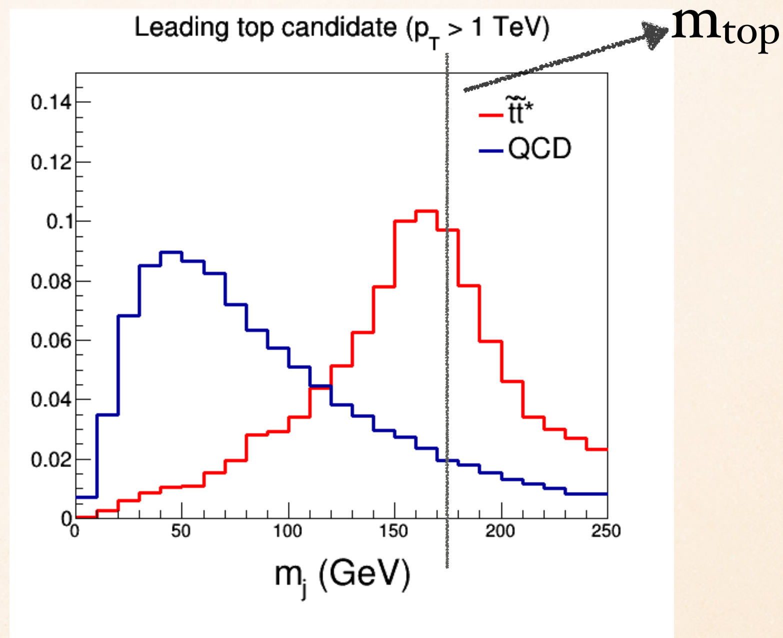
Track-based jet observable 1: jet mass

pT > 1 TeV: $m_j = m_j^{(\text{track})} \dfrac{p_T^{(\text{track+calorimeter})}}{p_T^{(\text{track})}}$

Larkoski, Maltoni and Selvaggi 2015



(a) Leptonically decaying top candidate



(b) Hadronically decaying top candidate

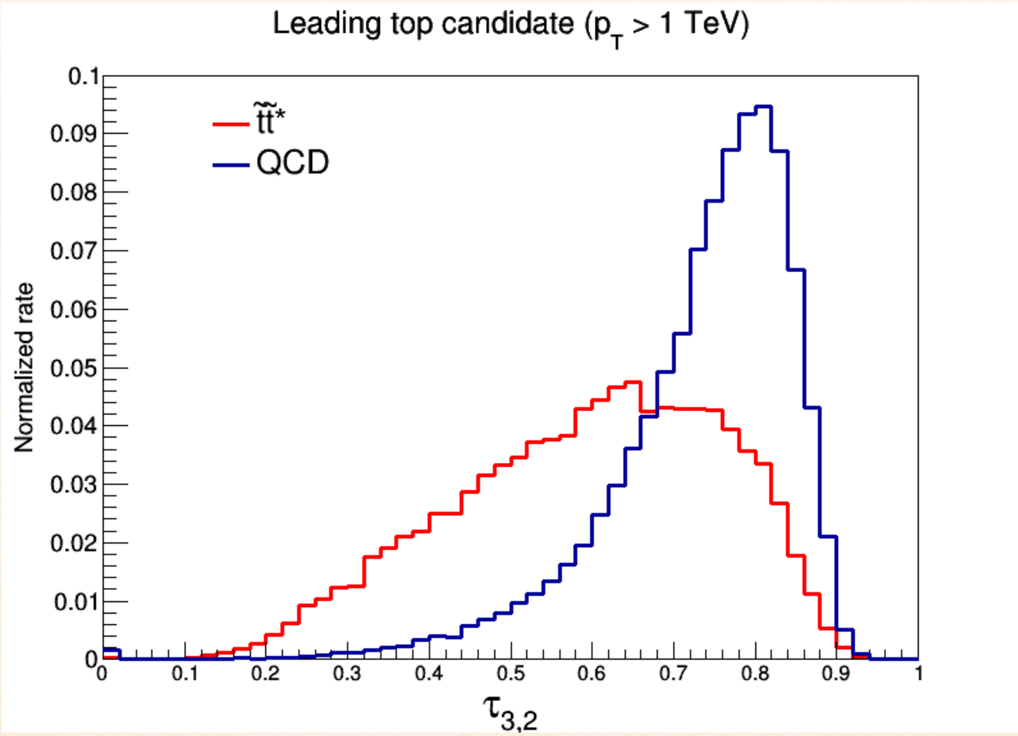
Track-based jet observable 2: N-subjettiness

$$\tau_N^{(\beta)} = \sum_i p_{T,i} \min\left\{(\Delta R_{1,i})^\beta, (\Delta R_{2,i})^\beta, \cdots, (\Delta R_{N,i})^\beta\right\}$$

$$\tau_{3,2}^{(\beta)} = \frac{\tau_3^{(\beta)}}{\tau_2^{(\beta)}}$$

ΔR: Angular separation between ith constituent and subjet axis

Thaler, Van Tilburg 2010



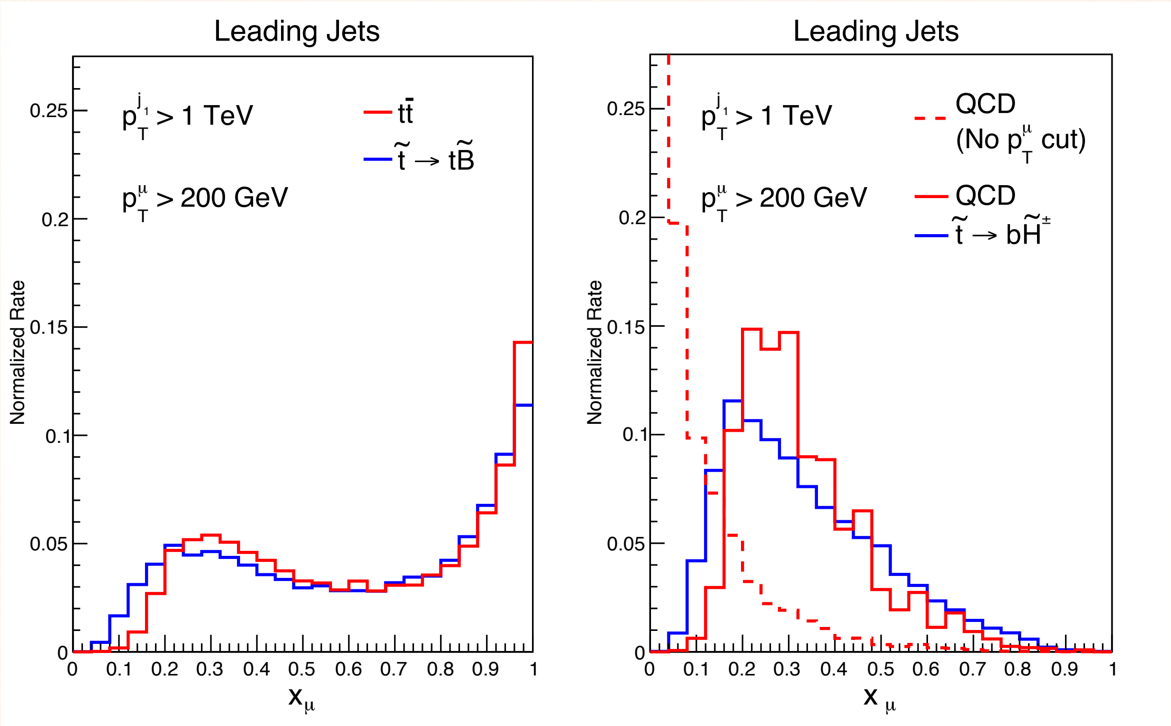
Track-based jet observable 3: mass drop for leptonic tops

$$x_\mu \equiv 1 - \frac{m^2_{j\not{\mu}}}{m^2_j},$$

Thaler, Wang 2008;
Rehermann and Tweedie 2010;

Leptonic top: $m_{j\not{\mu}} \sim m_b \quad m_j \sim m_{\text{top}} \quad x_\mu \sim 1$

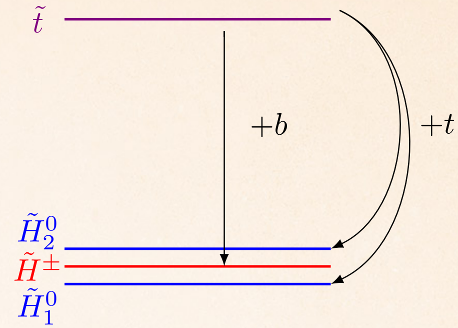
QCD: $m_{j\not{\mu}} \sim m_j \quad x_\mu \sim 0$



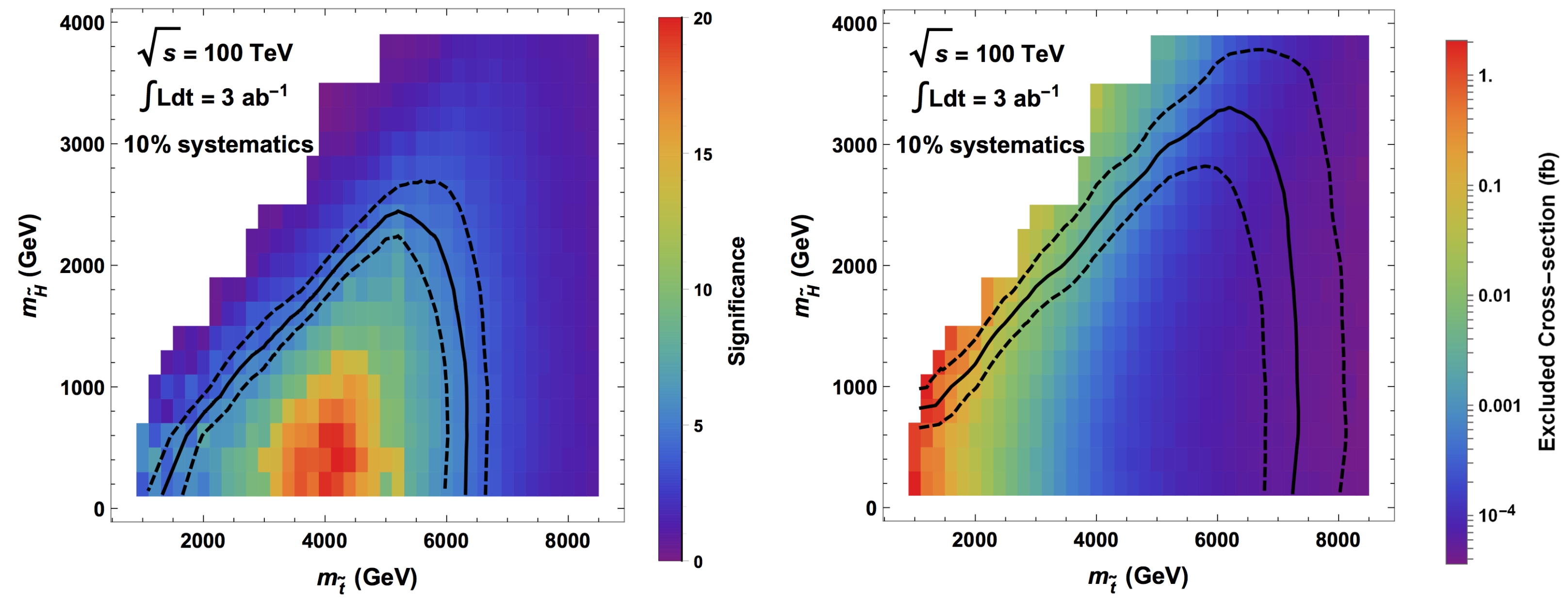
Results: stop-higgsino simplified model

b jet: $x_\mu < 0.5$ **and** $m_j < 120$ GeV

top jet: $x_\mu > 0.5$ **or** $m_j > 120$ GeV



(a) Higgsino LSP

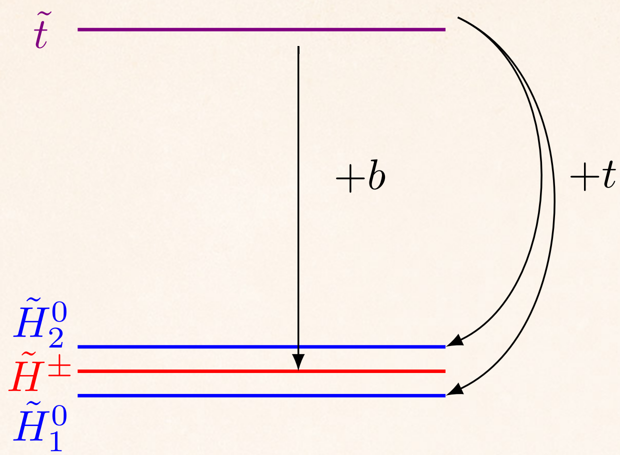


(a) Discovery (b) Exclusion

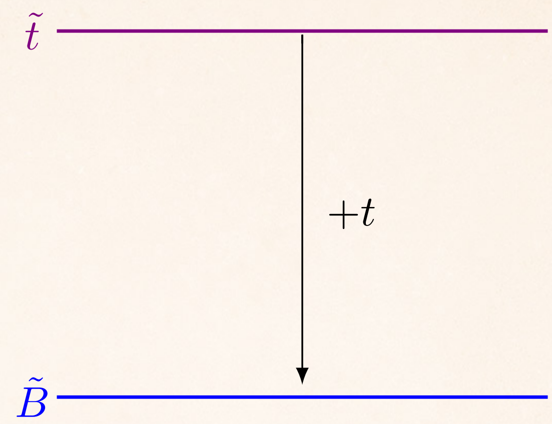
Discovery Reach ~ 6 TeV. Exclude 7 TeV stops.

Probe tuning ~ 3000.

Distinguish different LSPs



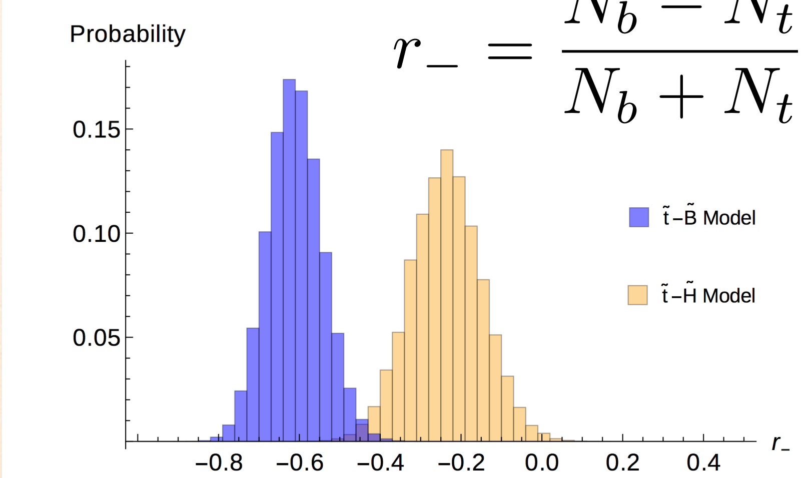
(a) Higgsino LSP



(b) Bino LSP

A mixture of bottoms and tops

Only tops

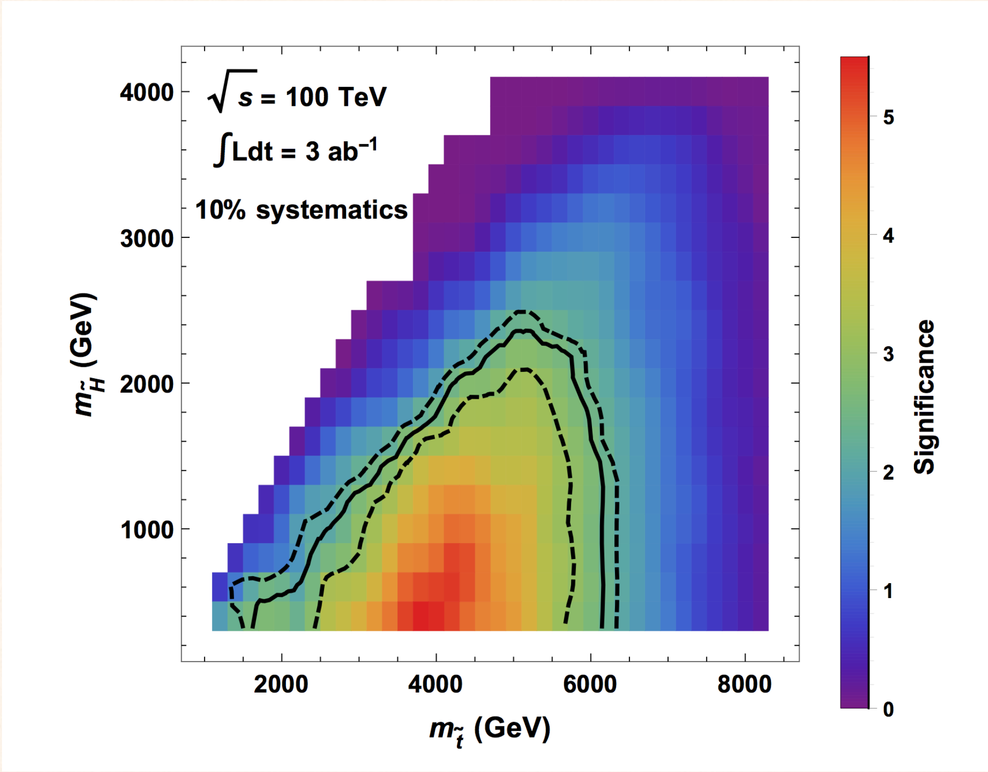


$$r_- = \frac{N_b - N_t}{N_b + N_t}.$$

b jet: $x_\mu < 0.5$ **and** $m_j < 120$ GeV

top jet: $x_\mu > 0.5$ **or** $m_j > 120$ GeV

Distinguishing LSPs



We could not only discover stops up to 6 TeV but also distinguish the LSPs up to 6 TeV.

Results: stop-gluino-LSP simplified model

Challenges: More complicated final states with more tops; a huge new physics background (gluino pair production)

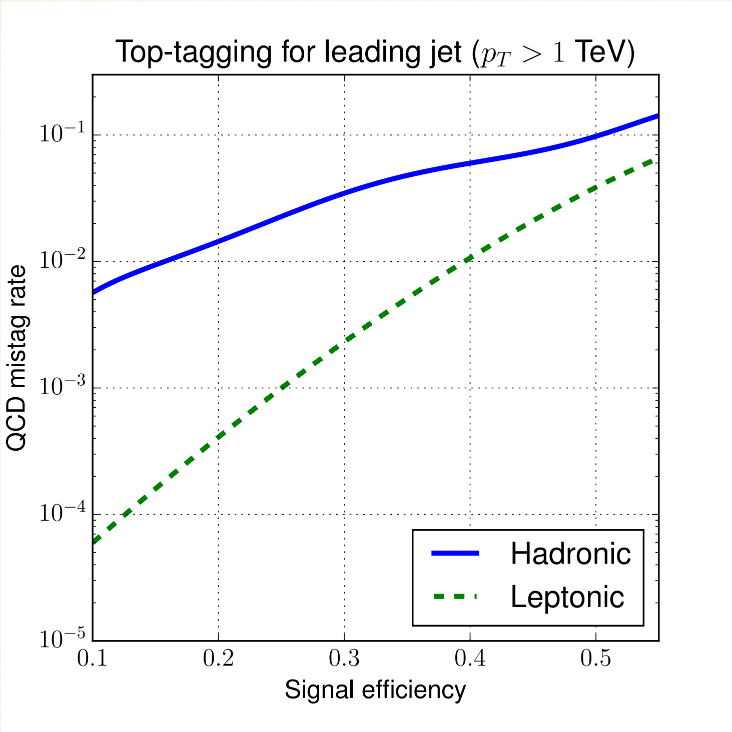
Hadronic top tagging must be included:

$$140 \text{ GeV} < m_j < 240 \text{ GeV}$$

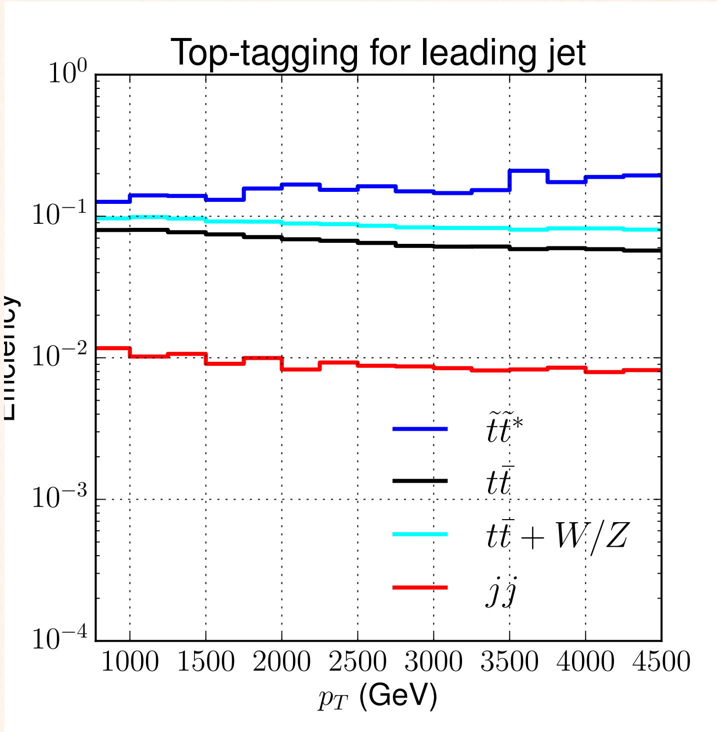
$$\tau_{3,2} < 0.45$$

- $H_T > 4$ TeV and $\not{E}_T > 250$ GeV;
- No isolated leptons with $p_T > 50$ GeV;
- At least 7 jets (anti-k_T with $R = 0.5$ and $p_T > 200$ GeV);
- At most one ISR jet among the leading 6 jets (see below);
- $|\Delta\phi(j, \not{E}_T)| > 0.5$ for the leading two jets;
- At least 3 top tagged jets with the top tagging described in Section 5.1;
- Optimized H_T and $\not{E}_T$ cuts (see below).

Efficiencies for top tagging



(a)



(b)

Combined signal efficiency: 10 - 20%

QCD: 1%

Results: stop-gluino-LSP simplified model

$m_{\tilde{t}}$ (TeV)	$\sigma^{\mathrm{NLO+NLL}}_{pp\to\tilde{t}\tilde{t}^*}$ (fb)	S	B	σ
5.5	0.40	10.7	1.7	6.3
6.0	0.23	10.0	6.7	3.5

30 ab^{-1}

- $H_T > 4$ TeV and $\not{E}_T > 250$ GeV;
- No isolated leptons with $p_T > 50$ GeV;
- At least 7 jets (anti-k_T with $R = 0.5$ and $p_T > 200$ GeV);
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Improve the gluino reach

In the snowmass study (1311.6480), gluino reach is 9 TeV in the **di-leptonic** channel at a 100 TeV with 3 ab^{-1} data.

Using **hadronic** top tagging, one could get close to **11 TeV** gluino (requiring one or two top tags)

$m_{\tilde{g}}$ (TeV)	$\sigma^{\mathrm{NLO+NLL}}_{pp\to\tilde{g}\tilde{g}}$ (fb)	Top tags	S	B	σ
10.0	0.31	2	12.4	0.8	8.1
11.0	0.13	1	13.8	9.5	3.9

Conclusion and future directions

New physics searches at a 100 TeV collider will **not** just be trivial extensions of those at the LHC.

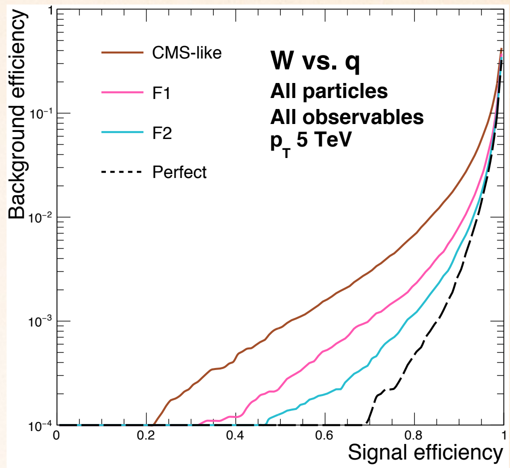
Jet tools could be a key player.
The substructure provides a powerful way to discriminate intricate new physics final states containing many hyper-boosted objects from messy SM and new physics backgrounds.
It also helps us distinguish between different new physics models and improve their reach significantly.

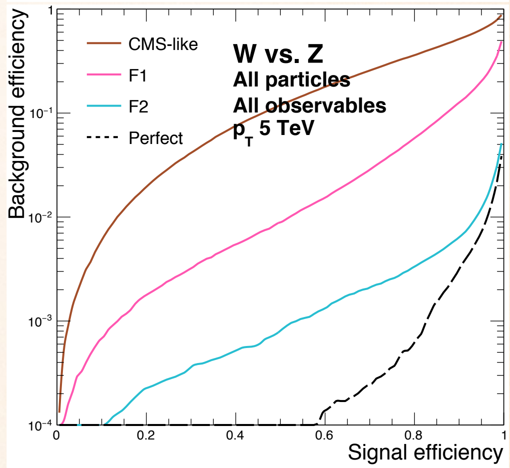
More sophisticated top tagger at a 100 TeV collider:
Han, Son, Tweedie 1707.06741

Improved calorimetry

Scenario:	Perfect	CMS-like	Future 1	Future 2
$\sigma^{\eta}_{\mathrm{HCAL}}/E = \sigma^{\phi}_{\mathrm{HCAL}}/E$	0	0.022	0.01	0.002
$\sigma^{\eta}_{\mathrm{ECAL}}/E = \sigma^{\phi}_{\mathrm{ECAL}}/E$	0	0.0175	0.005	0.001
$\sigma^{E}_{\text{charged particles}}/E$	0	$0.00025\, p_{\mathrm{T}} \oplus 0.015$	$\times \frac{1}{2}$	$\times \frac{1}{2}$
$\sigma^{E}_{\text{photons}}/E$	0	$0.021/\sqrt{E} \oplus 0.094/E \oplus 0.005$	$\times \frac{1}{2}$	$\times \frac{1}{2}$
$\sigma^{E}_{\text{neutral hadrons}}/E$	0	$0.45/\sqrt{E} \oplus 0.05$	$\times \frac{1}{2}$	$\times \frac{1}{2}$
$E^{\max}_{\text{track}}$	∞	220 GeV	220 GeV	220 GeV

Table 2: Smearing resolutions and calorimeter granularities for the detector components in each hypothetical detector scenario. Unless otherwise specified, all quantities are dimensionless. Resolutions which depend on p_{T} and E are scaled with coefficients measured in GeV^{a}, for appropriate a.





Improvement in background rejection ~ 5 or larger due to improved calorimetry at pT = 5 TeV

Coleman, Freytsis, Hinzmann, Narain, Thaler, Tran, Vernieri 1709.08705

More detector studies are needed to optimize new physics reach!

Thank you!

Backup

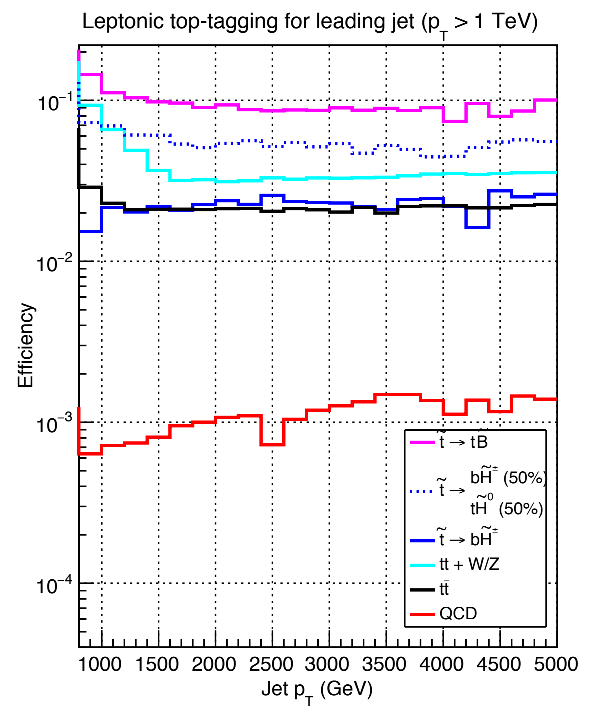
Dynamical jet radius

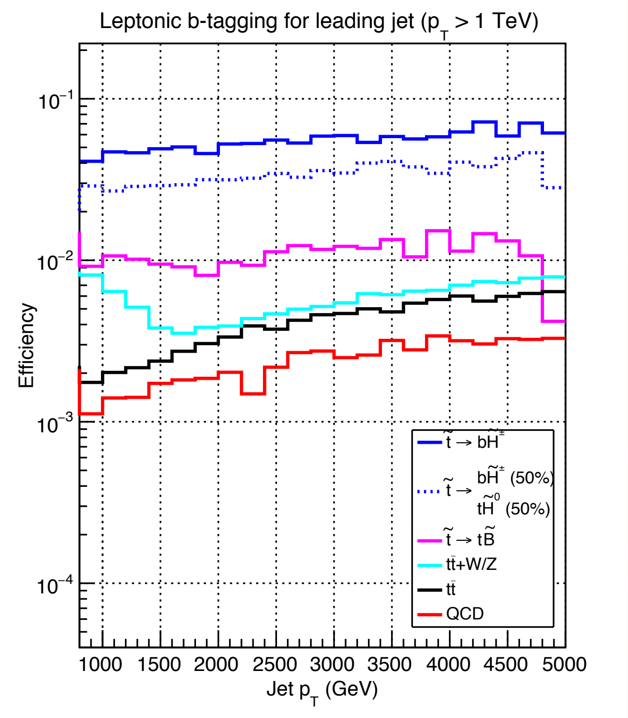
$$m^2 \simeq m_{\rm top}^2 + p_T\, p_T^{\rm ISR} R^2 \ .$$

$$R = C\frac{m_{\rm top}}{p_T} \ ,$$

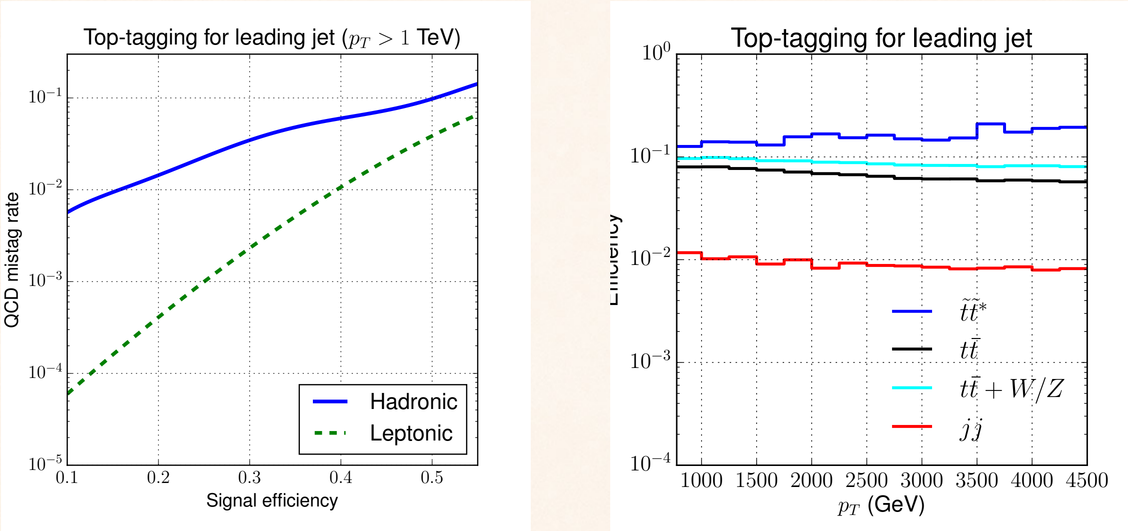
$$\begin{aligned} m^2 &\simeq m_{\rm top}^2 + p_T\, p_T^{\rm ISR} \left(\frac{C\, m_{\rm top}}{p_T}\right)^2 \\ &\simeq m_{\rm top}^2 \left(1 + C^2 \frac{p_T^{\rm ISR}}{p_T}\right) \ , \end{aligned}$$

Efficiencies for top tagging





Efficiencies for top tagging



(a) (b)