BOOST 2018

# Jet Observables and Stops at 100 TeV Collider

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# Motivation for a new collider

Once HL-LHC is done. What's next? Discovery Machine: **100 TeV Collider**

- Give the final verdict on fine-tuning in SM, down to $10^{-3}$–$10^{-4}$.
- An exploratory machine. For generic physics involving high mass states, a large centre of mass energy provides the most direct access to new physics!

[Arkani-Hamed, Han, Mangano, Wang, 1511.06495]

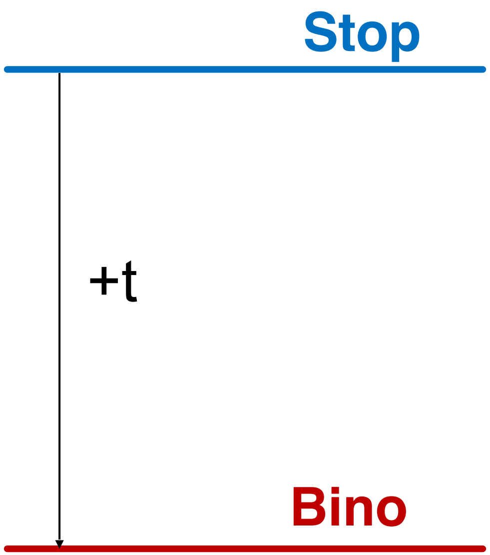
In a $\sqrt{s} = 100$ TeV hadron collider,

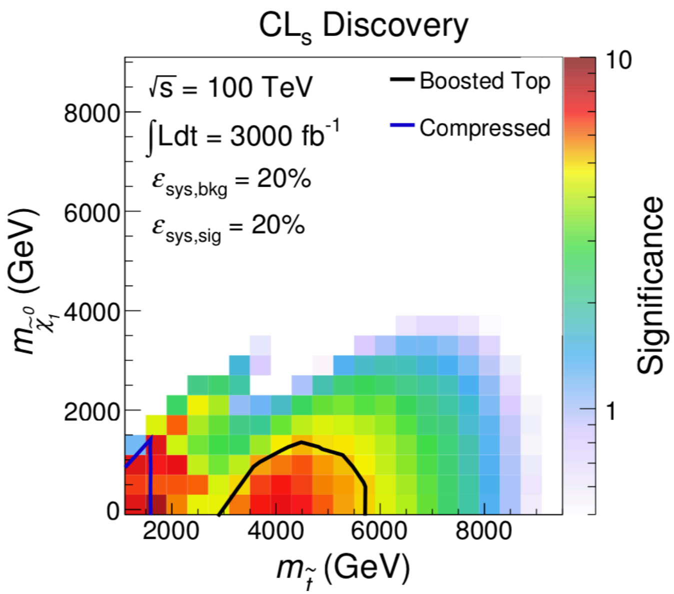
Very hadronic environment;

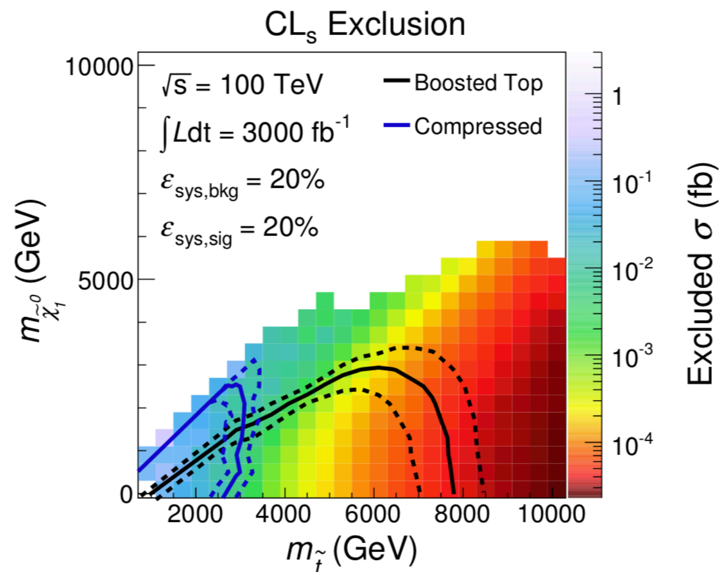
SM objects are boosted and collimated.

→ Jet substructure techniques are needed to extract physics!

# Previous work



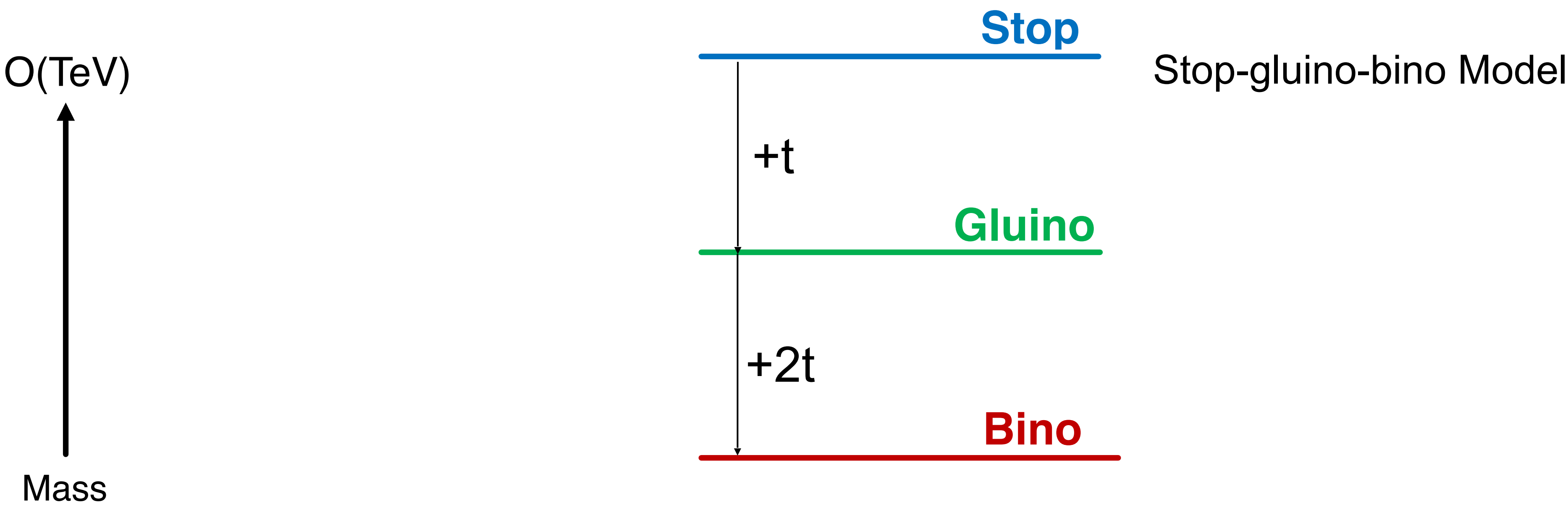



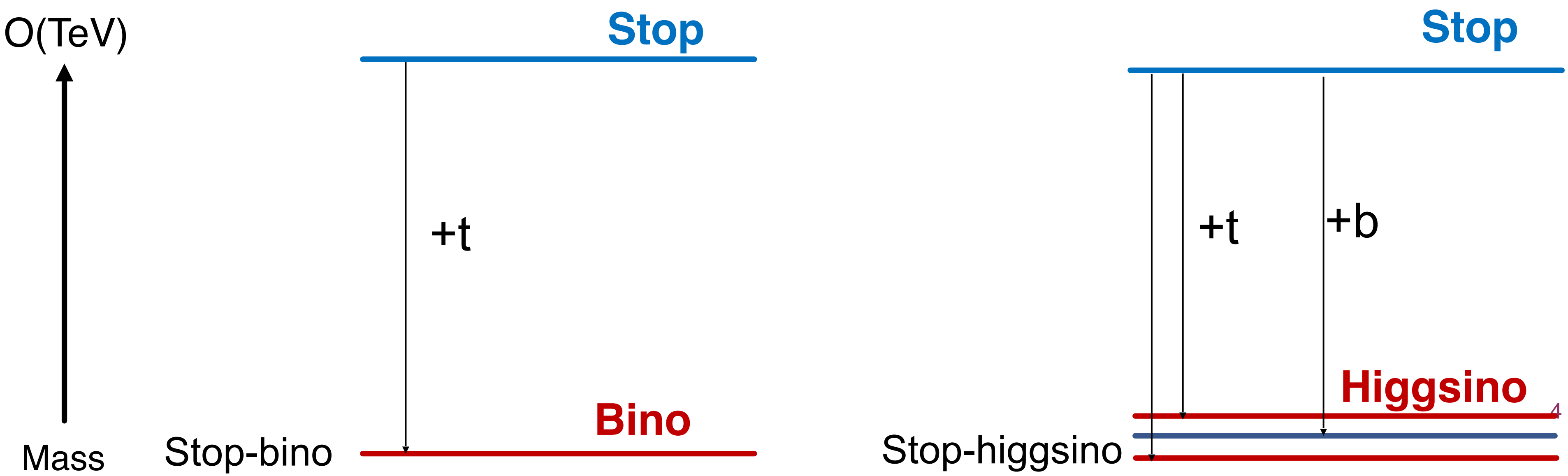

Previous study investigated simple stop-LSP model in $\sqrt{s} = 100$ TeV collider using mostly kinematics variables.

[1406.4512, Cohen, D'Agnolo, Hance, Lou, Wacker]

We will investigate the reach of more complicated models with stop-gluino-LSP and higgsino LSP scenario.

# Simplified model's mass spectrum



# Method

**Cross-section:**

SUSY process $\rightarrow$ NLO + NNLL

SM process $\rightarrow$ Madgraph LO

**Event generation:**

Madgraph5 $\rightarrow$ Parton-level event

Pythia8 $\rightarrow$ parton-shower and hadronization

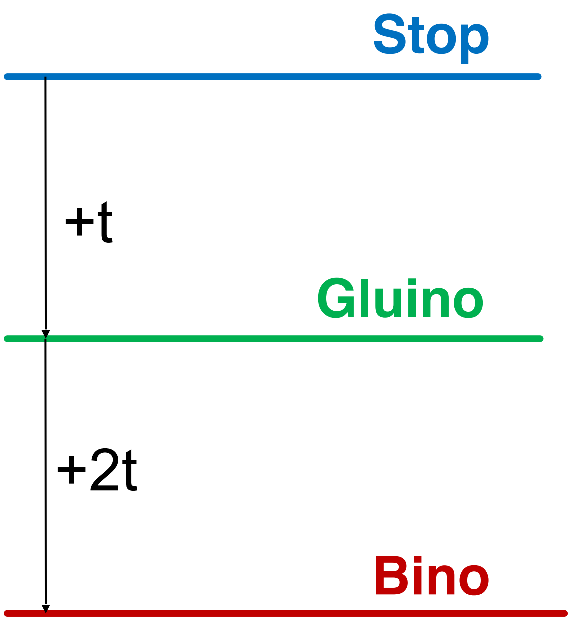
Delphes $\rightarrow$ Detector

**SM Background:**

QCD, $t\bar{t}$, $W/Z + \text{jets}$, $t + W/Z$ +2 jets

$t\bar{t} + W/Z$ +1 jet

# $\tilde{t} - \tilde{g} - \tilde{\chi}^0$ Models



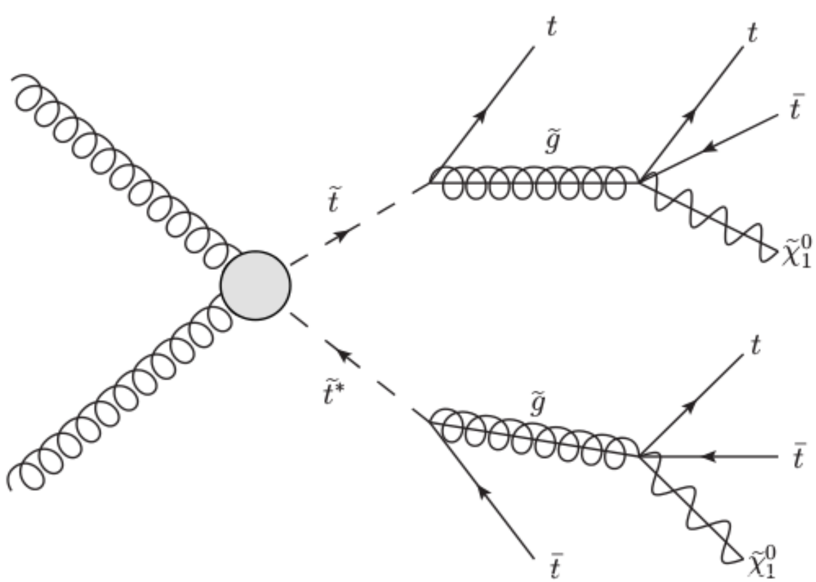

Stop-gluino-bino Model

# stop-gluino-LSP model

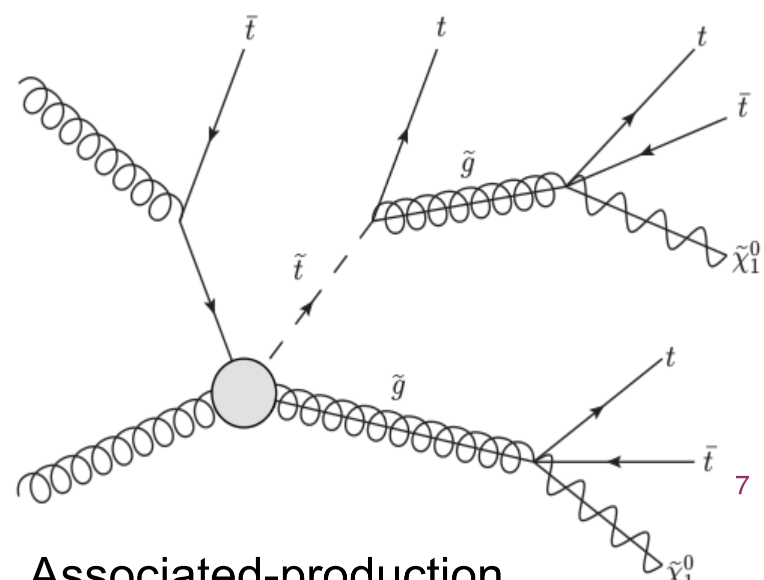
Two production channels (stop-pair and stop-gluino associated)

Final states: 6t + MET

The busy jet environment makes hard MET cut difficult




Pair-production




Associated-production

# Cut Flow

**Kinematic cuts**

$H_T > 4$ TeV, MET > 250 GeV

No $p_T > 35$ GeV isolated lepton

200 GeV jets > 6 and ISRs ($p_T$ hierachy < 0.2, $|\eta| > 2$) < 2

$|\Delta\phi(j, \not{E}_T)|$ > 0.5 for any jet with $p_T > 500$ GeV

↓

$\tilde{t}\tilde{t}^* + \tilde{t}\tilde{g}$ = 6.5k events

QCD = $10^7$ events + other SM background!

Top-tagging ($m_j$, $\tau_{3,2}$, $x_u$)

Need hadronic top tag.
Cannot sacrifice leptonic branching ratio

↓

Refined HT and MET cut

# Top-tagger and Jet clustering algorithm

[1503.03347, Larkoski, Maltoni, Selvaggi]

1. Cluster a C/A fat jet with R=1.0 and $p_T$ > 200 GeV

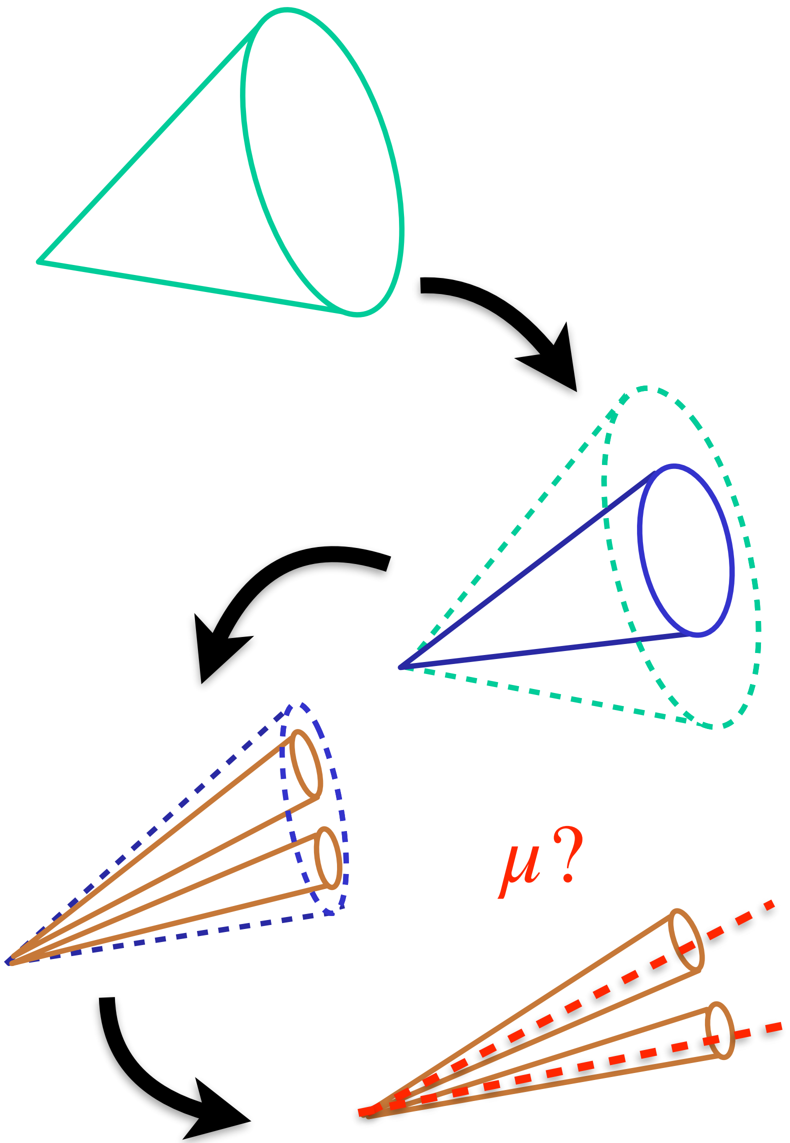
2. Scale down the jet by reclustering anti-$k_T$ jet with dynamical jet radius and a $p_T$ cut

$$R(p_T) = \frac{Cm_t}{p_T} \qquad C \sim O(1)\,\text{constant}$$

3. Repeat (2.) with smaller C's to isolate individual tops

4. The scaled-down anti-$k_T$ jets becomes candidate top jet

5. Look for $p_T$ > 200 GeV muon within the jet radius.
   If so, → leptonic top tagger
   else, → hadronic top tagger




Candidate top jets

# Jet mass ($m_j$) discriminant

Reconstructing the top mass from the track-based jet mass:

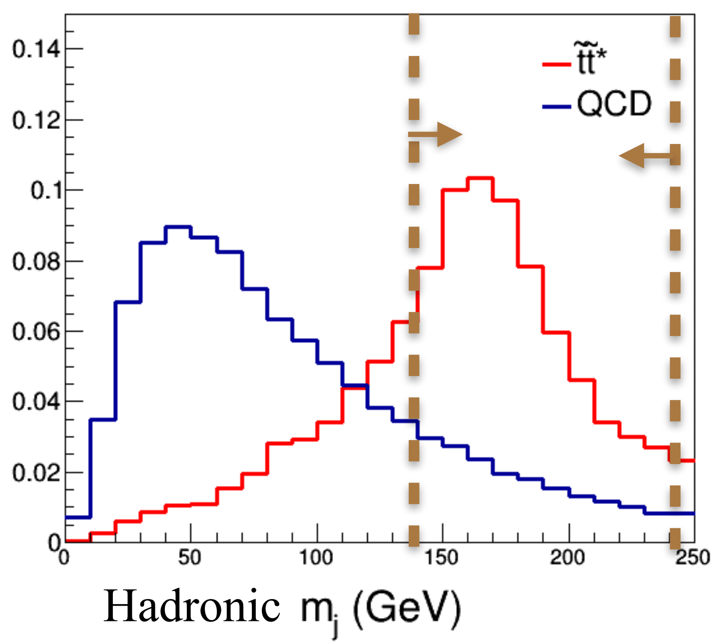
$$m_j = m_j^{(\text{track})} \frac{p_T^{(\text{total})}}{p_T^{(\text{track})}}$$

(Calorimeter jet resolution too low to resolve $m_j$)

$m_j \approx m_{top}$ for a top jet

**Hadronic top tagger**

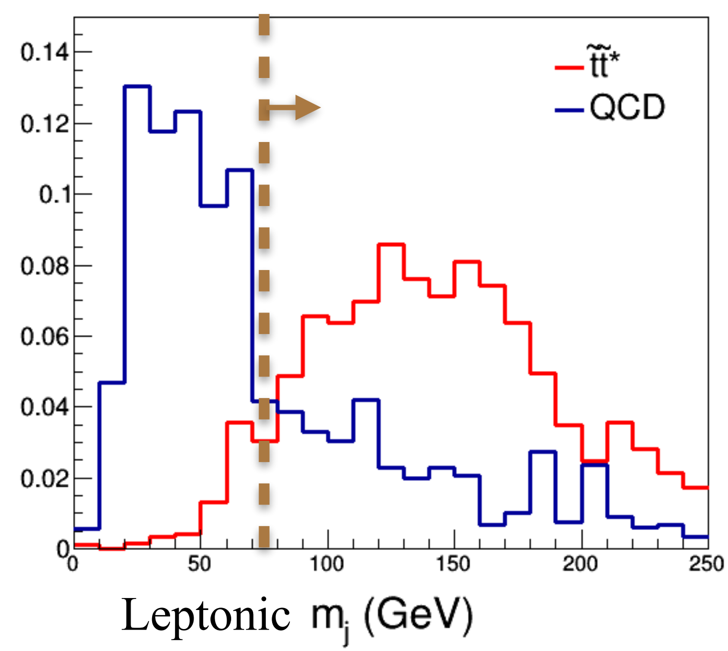
140 GeV < $m_j$ < 240 GeV




**Leptonic top tagger**

MET from neutrino forbid complete mass reconstruction

$m_j$ > 75 GeV



# Hadronic top-tagger: N-subjettiness ($\tau_N$)

N-subjettiness is a measure of how much a jet is an N-prong object. We recluster a jet to N subjets and find the distance of the $i^{th}$ particle from the nearest subjet:

$$\tau_N^{(\beta)} = \frac{1}{R_0} \sum_i p_{T,i} \min( \Delta R_{1,i}^{\beta}, \Delta R_{2,i}^{\beta}, \ldots, \Delta R_{N,i}^{\beta})$$

$p_{T,i}$ — transverse momentum of $i^{th}$ jet constituent

$\Delta R_{k,i}$ — distance between $k^{th}$ subjet and $i^{th}$ constituent

We use $\beta=1$ in our analysis.

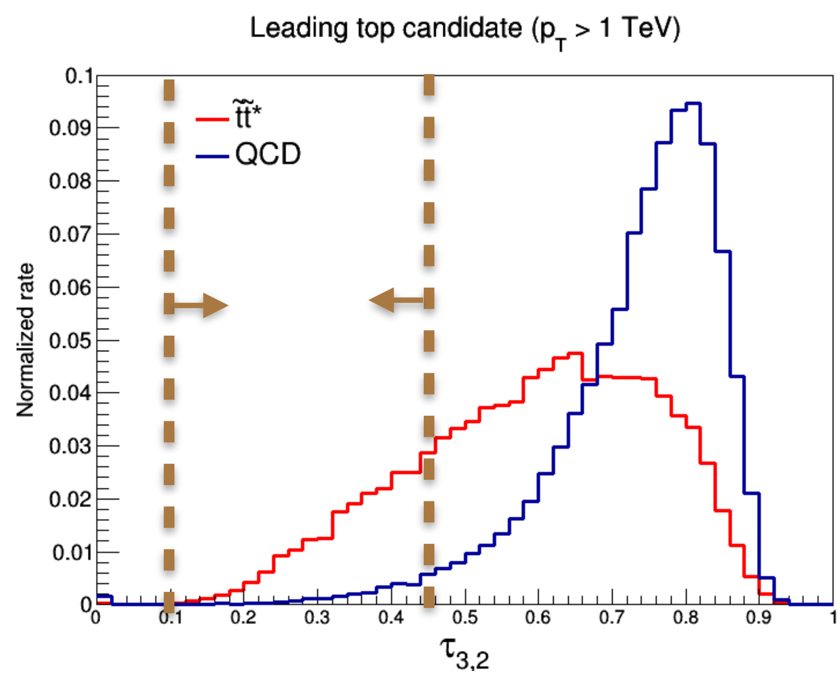
Hadronic top is a 3-prong object

$$t \rightarrow Wb \rightarrow q\bar{q}b$$

Top-jet will have small $\tau_3$ and large $\tau_2$.

QCD jet will have evenly distributed $\tau_3$ and $\tau_2$.

$\tau_3/\tau_2$ is a good discriminant variable.
$0.1 < \tau_3/\tau_2 < 0.45$ is the top-tag window.




QCD vs hadronic top

# Leptonic top-tagger: Mass-drop ($x_\mu$)

Leptonic top decays with a hard muon carrying a significant portion of energy-momentum $t \to b\mu\nu$. Mass-drop looks at the portion of muon contribution to jet-mass:

$$x_\mu = 1 - \frac{m_{j\not\mu}^2}{m_j^2}$$

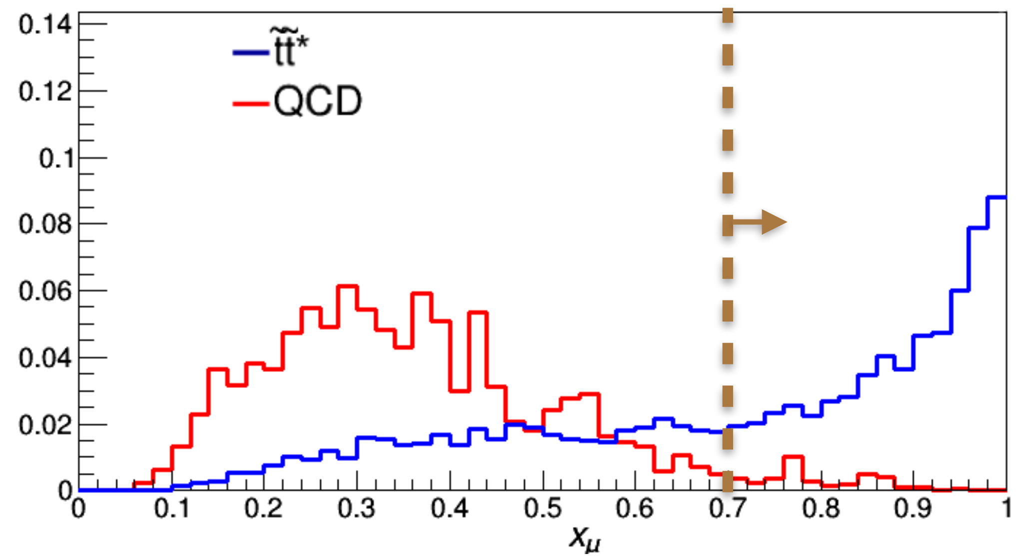
$m_j$ — full jet mass

$m_{j\not\mu}$ — jet mass without muon

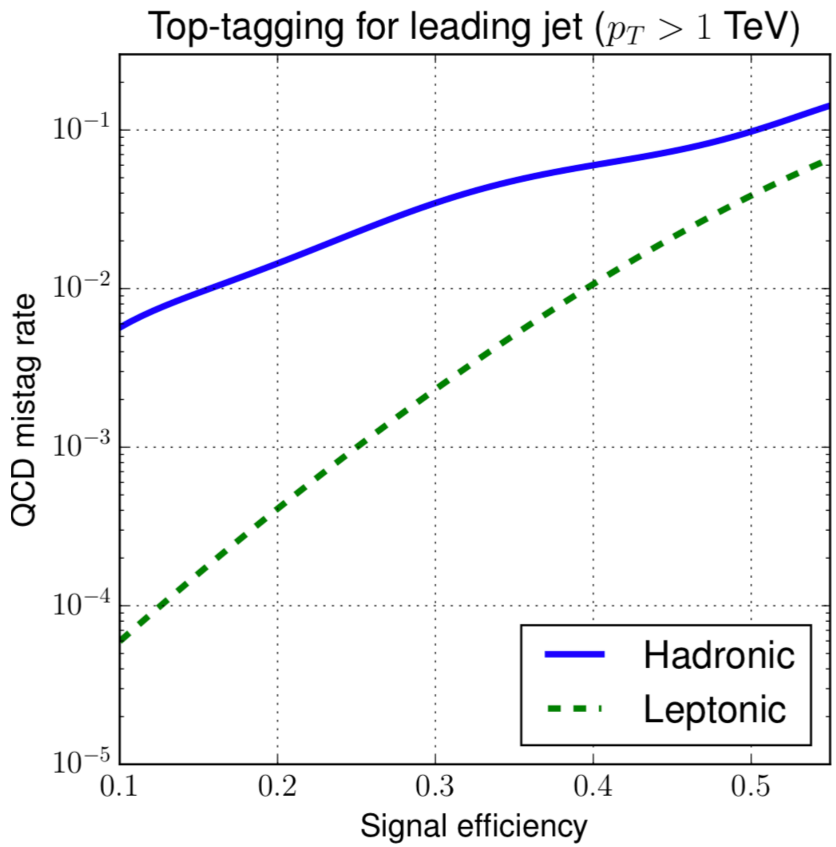
Leptonic top will fail to reconstruct mass once muon is removed: $x_\mu \to 1$.

QCD jet mass does not tend to change since the muon is just a part of radiation.

Acceptance is $x_\mu > 0.7$



# Tagging Efficiency




QCD mistag vs signal efficiency

# Cut Flow Recap

$H_T > 4$ TeV, MET $> 250$ GeV

No $p_T > 35$ GeV isolated lepton

Number of jet and ISR cut

$|\Delta\phi(j, \not{E}_T)| > 0.5$ for any jet with $p_T > 500$ GeV

**Kinematic cuts**

Jet recluster

Leptonic: Jet mass cut → mass-drop cut

Hadronic: Jet mass cut → $\tau_3/\tau_2$ subjettiness cut

**Top-tagger X 3**

Refined HT and MET cut

# Stop mass reach

| $m_{\tilde{t}}$ (TeV) | S | B | σ |
|---|---|---|---|
| 5.5 | 10.7 | 1.7 | 6.3 |
| 6.0 | 10.0 | 6.7 | 3.5 |

10% systematics

3σ can be reached for the benchmark point of 6 TeV stop and 2.75 TeV of gluino at L = 30 $ab^{-1}$.

An increased L is needed due to high the high SUSY background.

# Gluino mass Reach

A gluino mass reach to 11 TeV at L = 3 $ab^{-1}$ (pair-production channel).

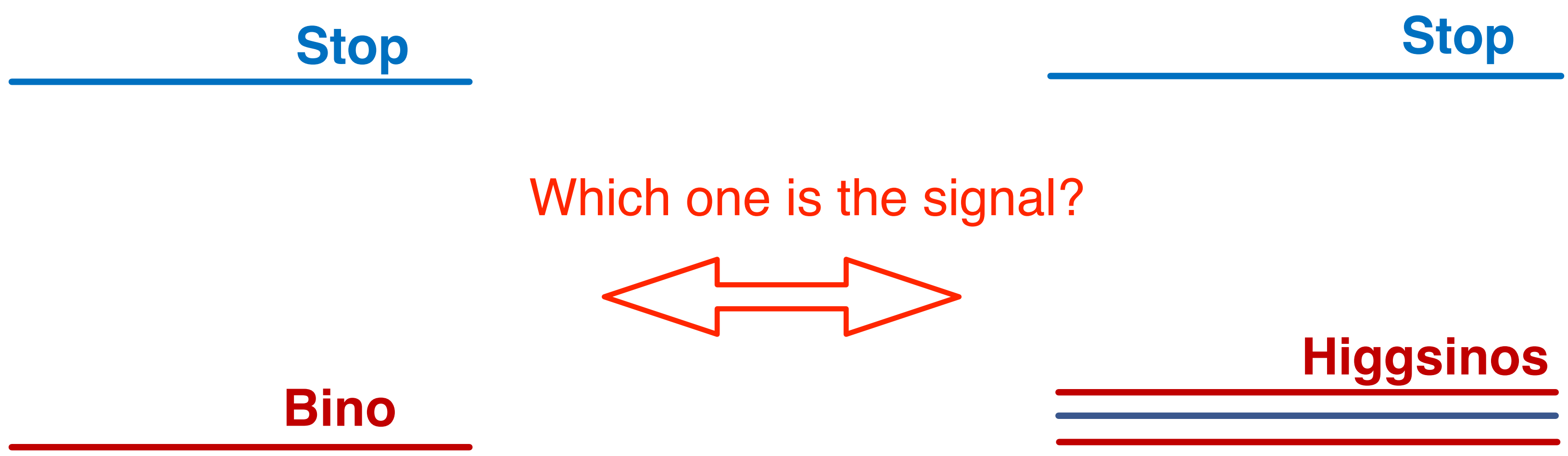
| $m_{\tilde{g}}$ (TeV) | Top tags | S | B | σ |
|---|---|---|---|---|
| 10.0 | 2 | 12.4 | 0.8 | 8.1 |
| 11.0 | 1 | 13.8 | 9.5 | 3.9 |

10% systematics

~2 TeV improvement compared to the same sign Di-lepton gluino search in [1311.6480].

# $\tilde{t}-\tilde{B}$ Model and $\tilde{t}-\tilde{H}$ Model

# Search Strategy Stop-Bino/Higgsino




$$\tilde{t} \longrightarrow b\tilde{\chi}^{\pm} \longrightarrow b\tilde{\chi}_1^0 j^{(\text{soft})}$$

$$\tilde{t} \longrightarrow t\tilde{\chi}_1^0$$

$$\tilde{t} \longrightarrow t\tilde{\chi}_2^0 \longrightarrow t\tilde{\chi}_1^0 j^{(\text{soft})}$$

$$\tilde{t} \longrightarrow t\tilde{\chi}_1^0$$

- The environment is clean. Hard MET cut is possible.
- Stop-bino model always decay to top.
- Stop-higgsino model decay 50% of time to top and 50% to bottom

# Search Strategy Stop-Bino/Higgsino

Two anti-$k_T$ jets with $p_T > 1$ TeV;

No isolated lepton with $p_T > 1$ TeV;

$|\Delta\phi(j, \not{E}_T)| > 0.5$ for any jet with $p_T > 500$ GeV;

MET > 3 TeV

**Kinematic cuts**

Muon $p_T > 200$ GeV inside one of the jets

Muon-in-jet does not select leptonic top.
Boosted b-jet also contains hard muons!

Further selection on hadronic jets needed!

Boosted top / b-jet tagger

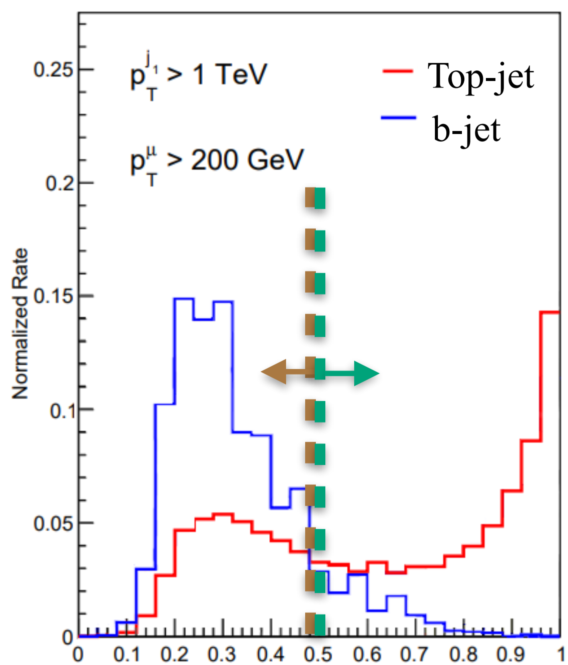
# Search Strategy Stop-Gluino-LSP

After passing through the muon-in-jet requirement. We partition the events into two possibilities using jet mass and mass-drop:

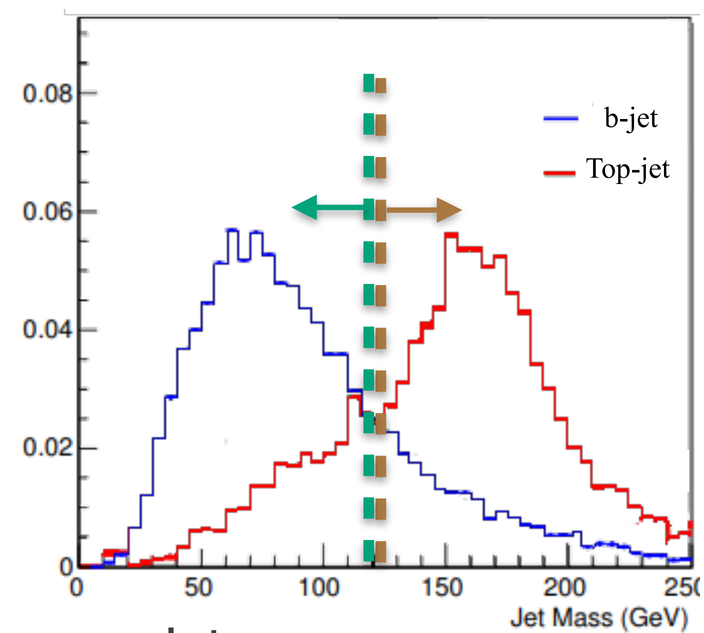
Hadronic top jet

Boosted top jet ( $\tilde{t} \longrightarrow t\tilde{\chi}^0$): $m_j > 120$ GeV **OR** $x_u > 0.5$ ← Leptonic top jet

Boosted b-jet ( $\tilde{t} \longrightarrow b\tilde{\chi}^{\pm}$ ): $m_j < 120$ GeV **AND** $x_u < 0.5$



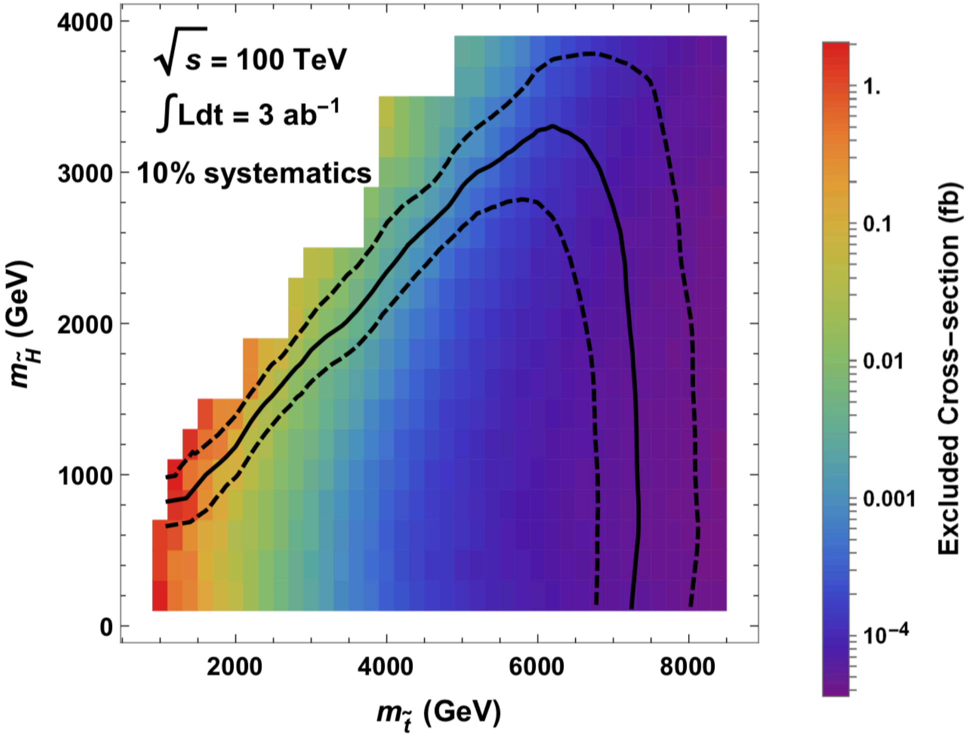

Mass-drop $x_u$

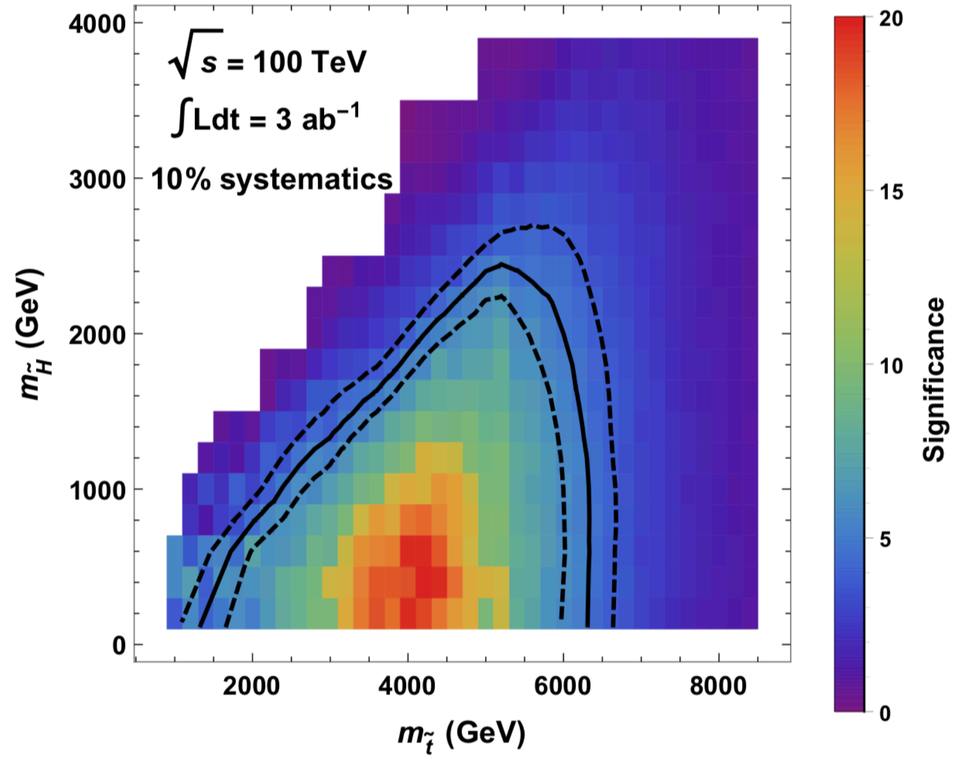



Jet mass $m_j$

# Stop-higgsino Mass Reach

The discovery/exclusion contours for stop-higgsino model with an integrated luminosity L = 3 $ab^{-1}$.




The solid lines are 5σ discovery contour (left) and exclusion at 95% C.L.(right). The dashed lines are the ±1σ boundaries.

The stop-bino and stop-higgsino model signature differs in the b-jet signature.

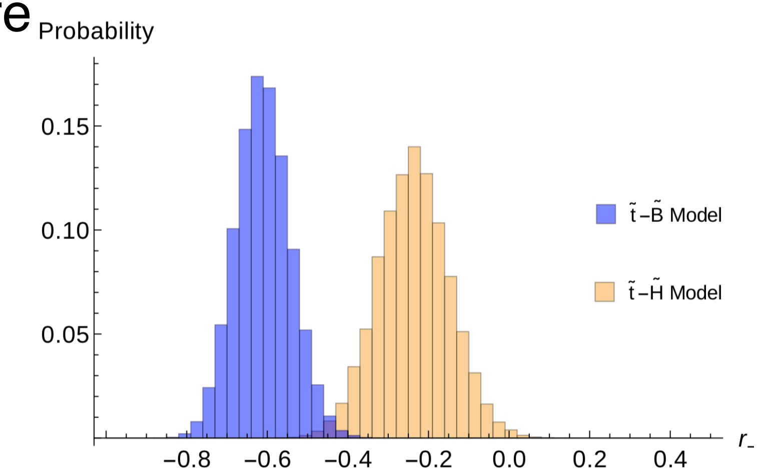
We define the variable

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

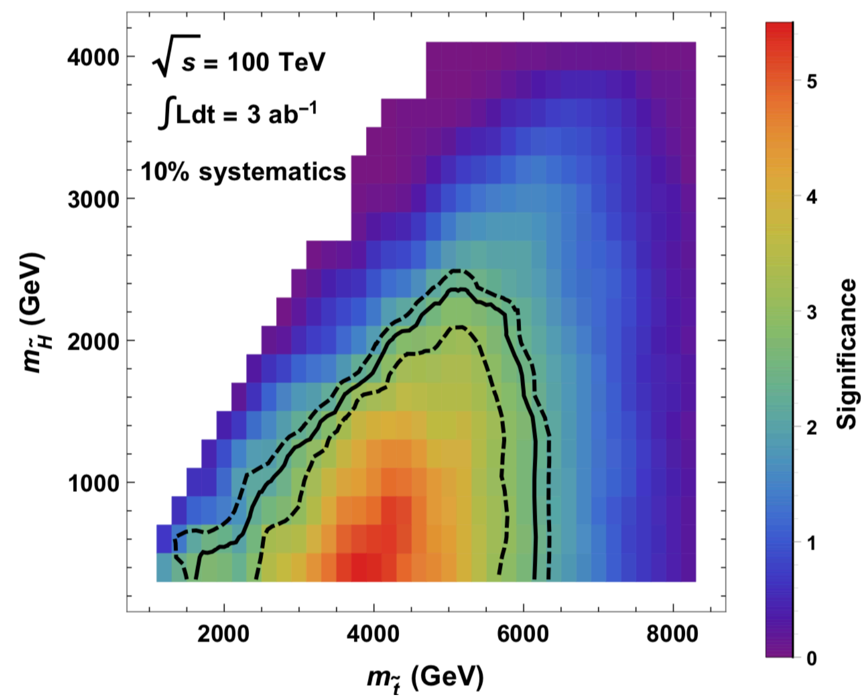
$N_b$ = # of boosted b-tagged events
$N_t$ = # of boosted top-tagged events

Stop-higgsino has 50% b-jet and 50% top jet. $r_- \sim 0$
Stop-bino 100% top jet. Hence $r_- \sim -1$

Model-distinguishability Reach:
$\{m_{\tilde{t}} \sim 6 \text{ TeV}, m_{\tilde{\chi}} \sim 2 \text{ TeV}\}$




$r_-$ distribution over the life time of the experiment




95% confident level

# Summary and future work

- Stop-Gluino-LSP model mass reach 6 TeV ($L = 30\ ab^{-1}$). Gluino mass reach 11 TeV ($L = 3\ ab^{-1}$). Stop-Bino/Higgsino discovery mass reach at 7 TeV, model identification reach at 6 TeV ($L = 3\ ab^{-1}$). Yet to be improved by BDT or NN!

- Implement more sophisticated top-tagging and boosted b-tagged technologies. [1707.06741, Han, Son, Tweedie], [1511.05990, Pedersen and Sullivan]

- A 100 TeV collider will extend our understanding to the naturalness of Standard Model and help exploring new physics.

- Jet substructure technique is a necessary and powerful tool to extract physics from a 100 TeV collider. Help make the case for future colliders.

# Back-up Slides

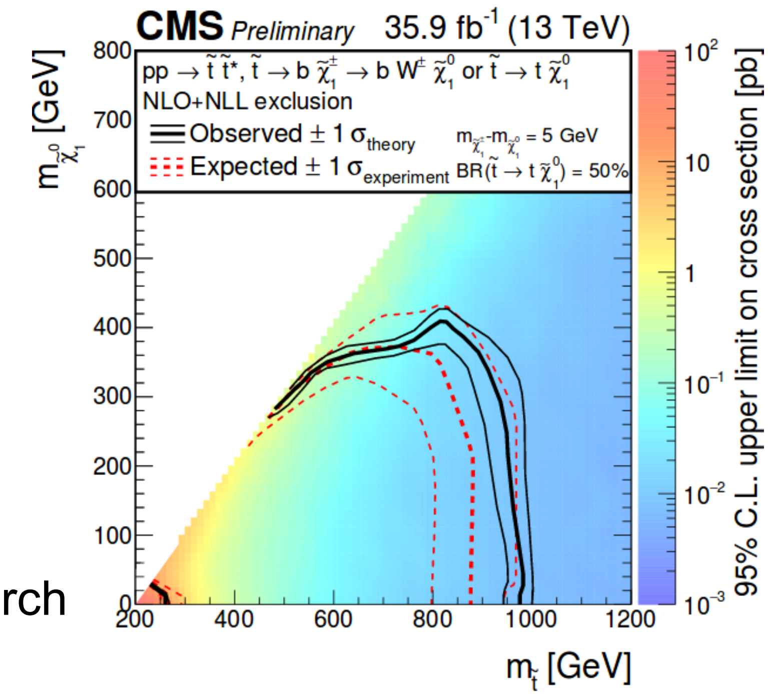
# LHC limits

[SUS-16-050, CMS collaboration]

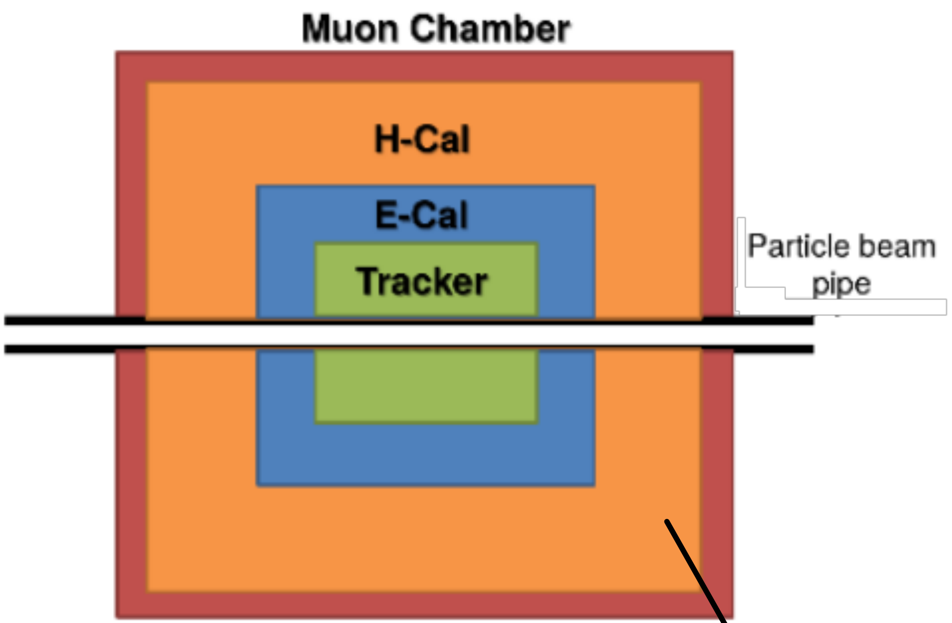
$\sqrt{s} = 3$ TeV LHC constraint

- Stop ~ 1 TeV
- Weak LSP ~ 500 GeV
- Gluino ~ 2 TeV

MT2, top, 0L search



# Detector design

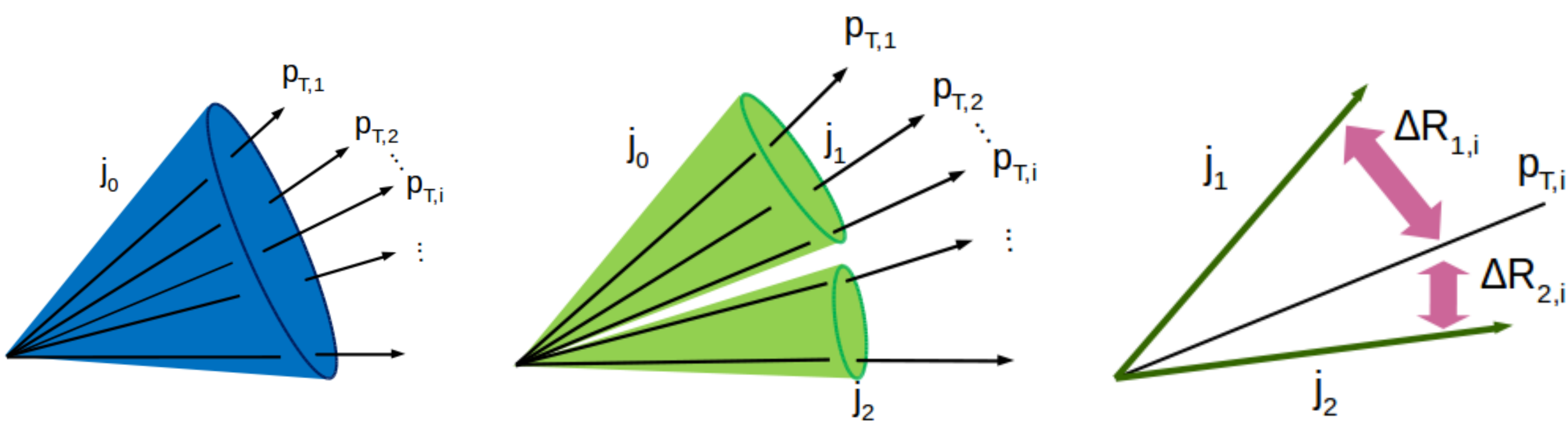



A common design for a particle detector

30 cells in |η|<2.5, 5-10 deg per cell

How much does jet “looks like” from a N-body decay?

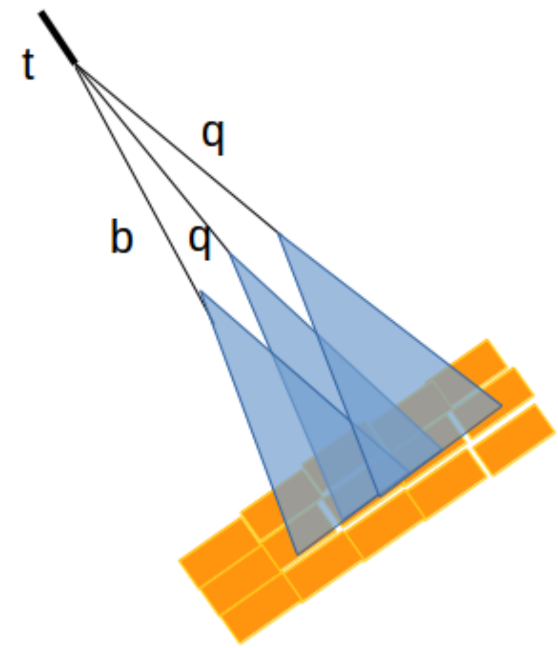
N-subjetiness ($\tau_N$) → how close are the jet constituents are from N sub-jet axes in the jet cone.




Identify the jet constituents to be reclustered ➡ Recluster N subjets ➡ Find the distance $\Delta R_{k,i}$ between the i-th constituents and k-th subjet axis

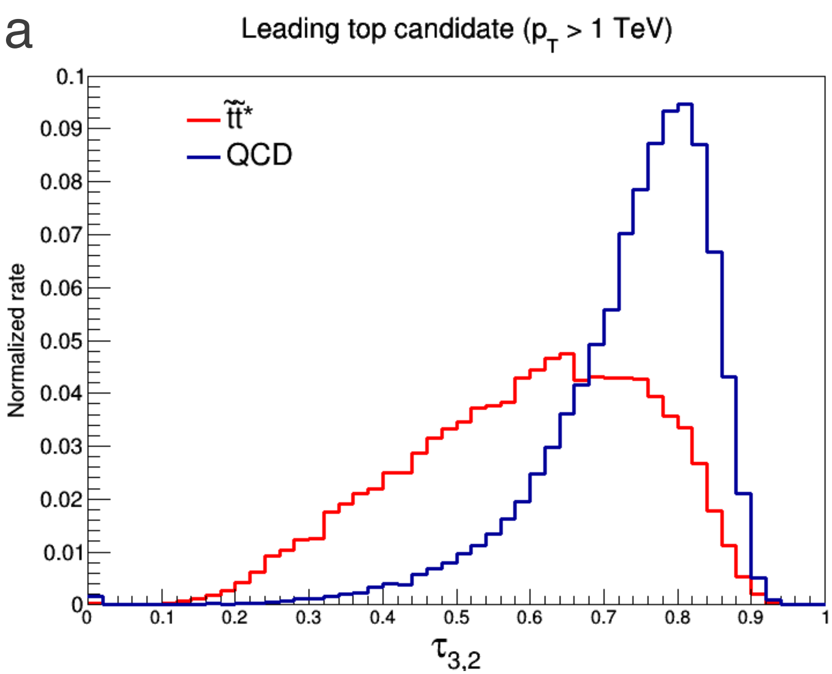
$$\tau_N^{(\beta)} = \frac{1}{R_0} \sum_i p_{T,i} \min( \Delta R^{\beta}_{1,i}, \Delta R^{\beta}_{2,i}, \ldots, \Delta R^{\beta}_{N,i} )$$

- When a jet looks like a 3-prong object, $\tau_3$ will be small but $\tau_2$ will be large.
  e.g. a hadronic top jet ($t \rightarrow Wb \rightarrow qqb$)




- A spread-out QCD jet can have a small $\tau_N$, but $\tau_{N-1}$ is small as well!

- $\tau_3/\tau_2$ is a good variable to distinguish a hadronic top jet from QCD jet.




QCD vs hadronic top

# Reason for mass spectrum

Why do we have light stop?

- The need for cancelation of Higgs renormalization.
- Large renormalization and $t_R$-$t_L$ mixing pull the down to the foot of the scalar spectrum. [Pierce, Bagger, Matchev, Zhang, 97]

Why the Scalar-Gaugino mass splitting? [Arkani-Hamed, Dimopoulos, Giudice, Romanino, 04]

Suppose there is no gauge singlet in an underlying SUSY theory. SUSY breaking from a hidden sector is mediated by a messenger with a group index .

- Scalar mass is generated at tree-level in the Kähler potential

$$\int d^4\theta \frac{S_a^\dagger S_a}{M_*^2}\Phi^\dagger\Phi = m_{soft}^2\Phi^\dagger\Phi$$

- Tree-level gaugino mass is forbidden by symmetry mass suppression!

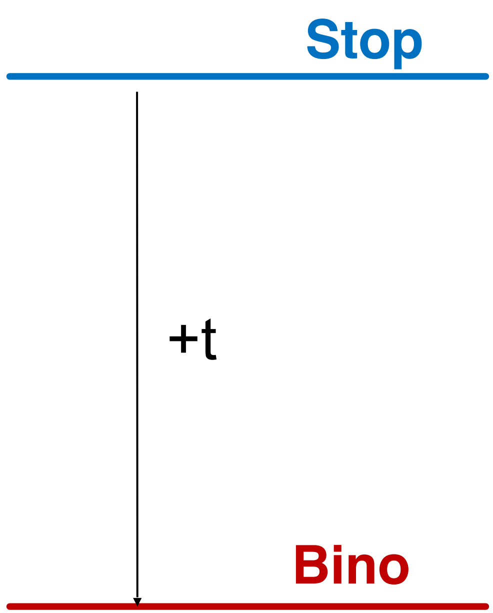
$$\int d^2\theta \frac{S_a}{M_*^2}WW$$

Uncontracted group index

Mass term

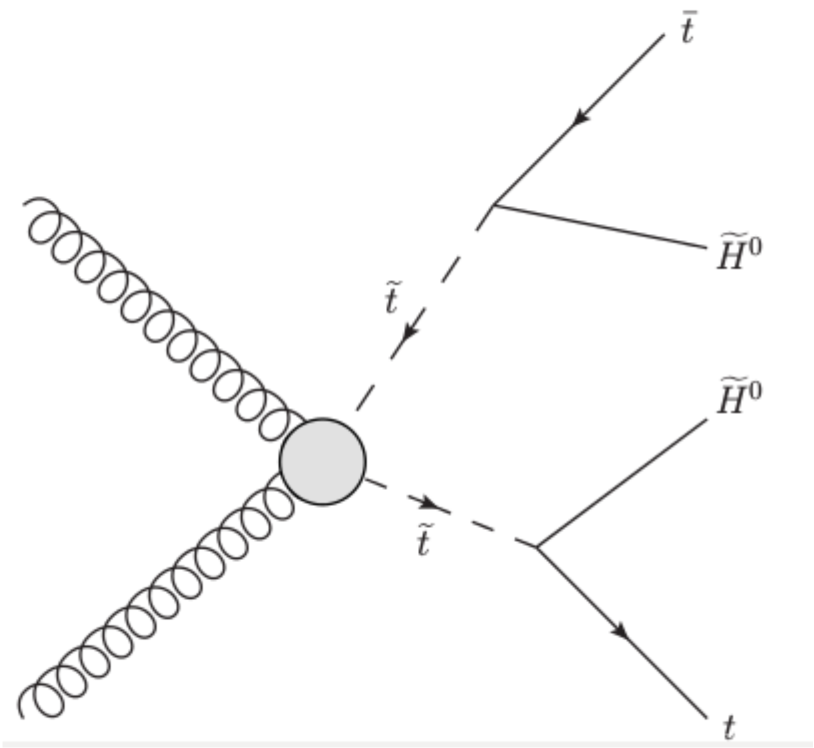
An extra factor of suppression

# stop-bino model

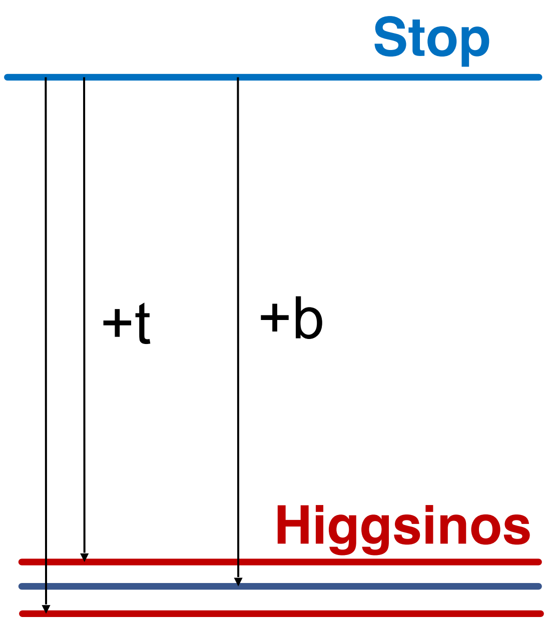


Stop-bino Model

Final state: tt + MET



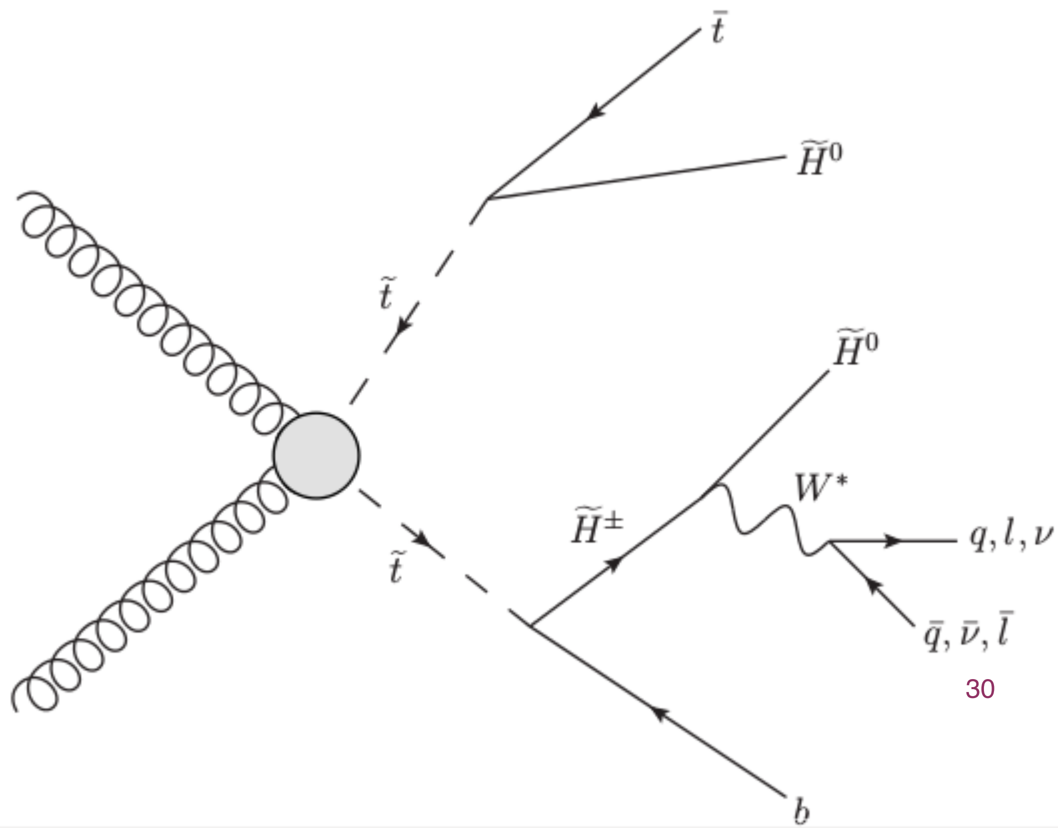
# stop-higgsino model




Stop-higgsino Model

- $\tilde{t}$ 50% decay to t + MET
- $\tilde{t}$ 50% decay to b + MET

Final states: combinatoric of both



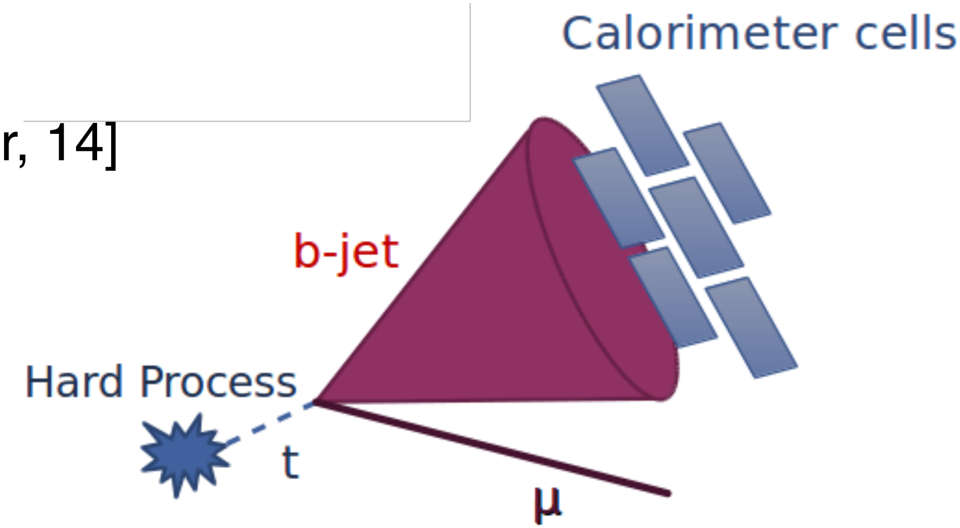
# Boosted Object Challenges

[Cohen, D’Agnolo, Hance, Lou, and Wacker, 14]

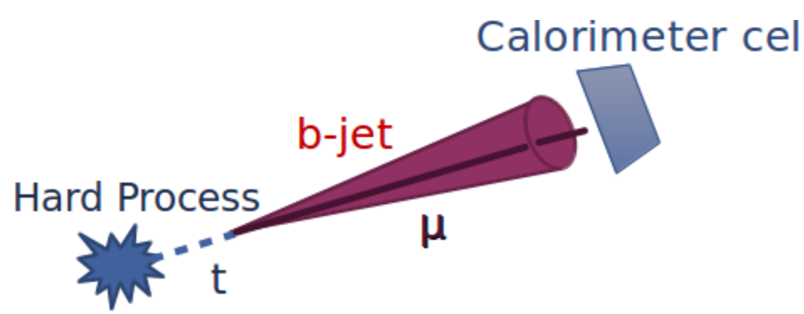
- At high luminosity, the high Standard Model event rate can conceal new physics.

- At high energy, SM objects are boosted. Different objects are collimated along the boost direction, to a point they are smaller than a colorimeter cell.

- New jet substructure techniques are needed.

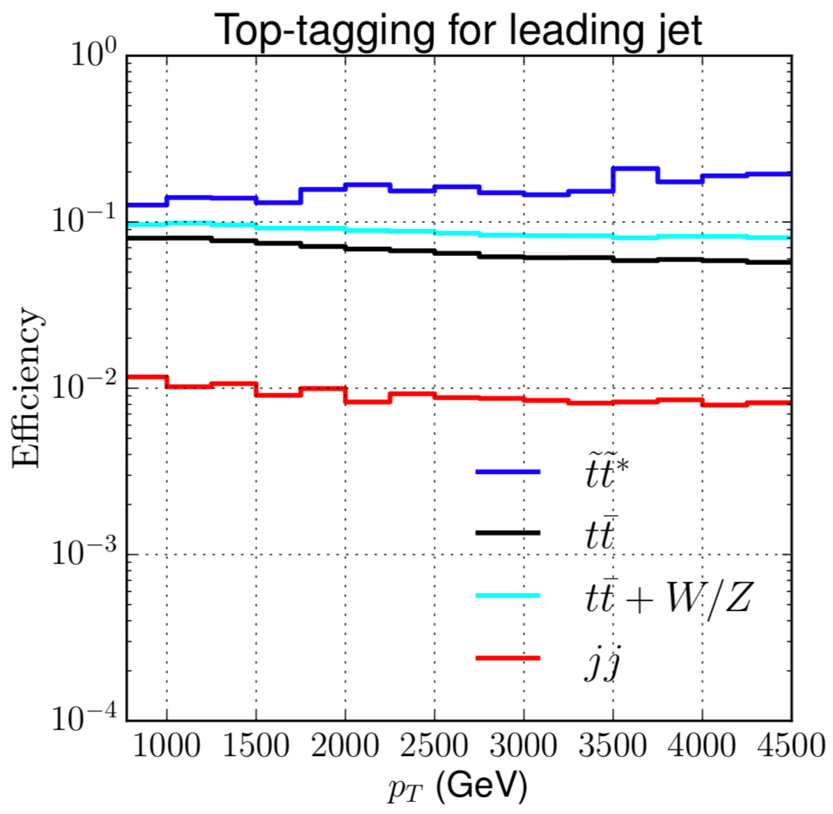



A top quark decaying in the LHC



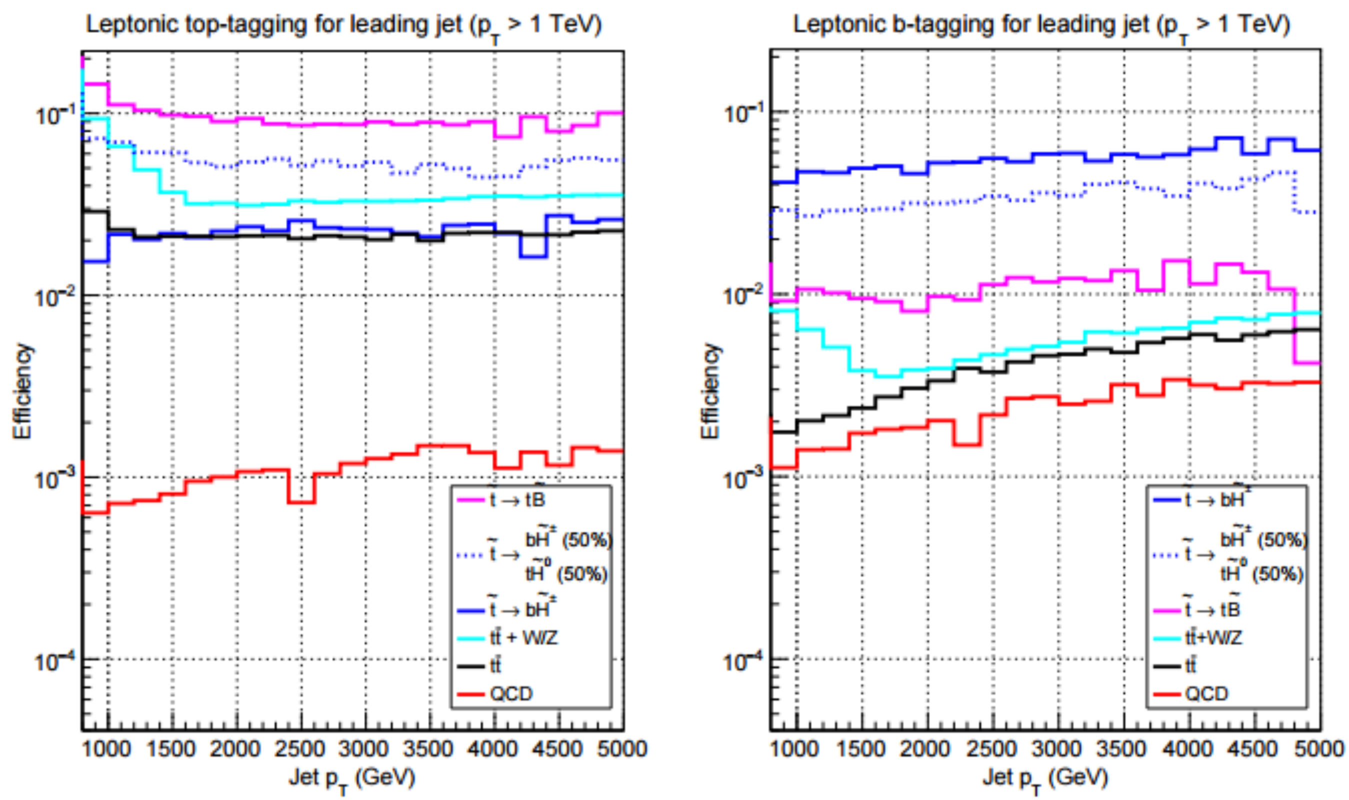

A boosted top in a 100 TeV collider

# Tagging Efficiency




Signal/background efficiencies top-tagging

# Efficiency




Signal/background efficiencies for stop-higgsino cut