Pheno 2017 Symposium

JET OBSERVABLES AND STOPS AT 100 TEV COLLIDER
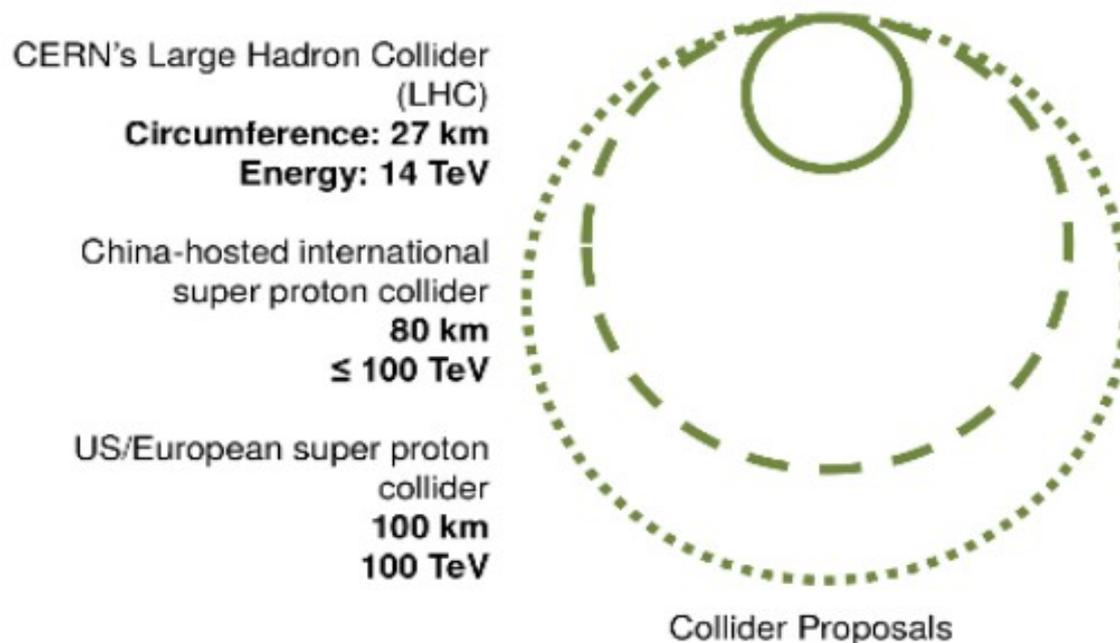## [JIJI FAN, PRERIT JAISWAL, SHING CHAU LEUNG, ARXIV: 1704.03014]

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Brown University
May 9, 2017

MOTIVATION

Once LHC@14 TeV is done. What's next?

- Pin down the naturalness of SM.

- 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, 16]

CERN's Large Hadron Collider
(LHC)
Circumference: 27 km
Energy: 14 TeV

China-hosted international
super proton collider
80 km
≤ 100 TeV

US/European super proton
collider
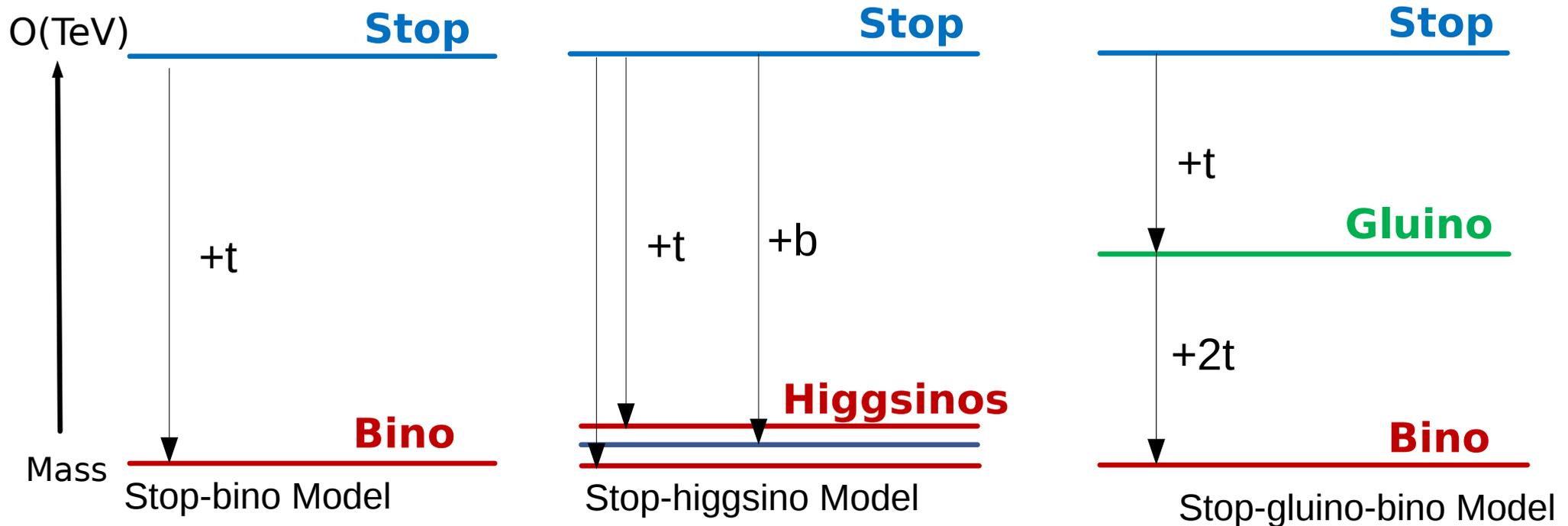**100 km**
100 TeV

Collider Proposals

OUR PAPER

- Studies the mass reach for three simplified SUSY models.

- Addresses challenges involving hyper-boosted SM objects from generic heavy states in 100 TeV collider

- Implements jet substructure techniques to improve the analysis sensitivity

SUSY MODELS

SIMPLIFIED MODELS

O(TeV)

Stop

+t

Bino

Mass

Stop-bino Model

Stop

+t   +b

Higgsinos

Stop-higgsino Model

Stop

+t

Gluino

+2t

Bino

Stop-gluino-bino Model

- Model 1 – LSP Bino   (decay channel: t + MET)

- Model 2 – LSP Higgsino   (t + MET /   b + MET)

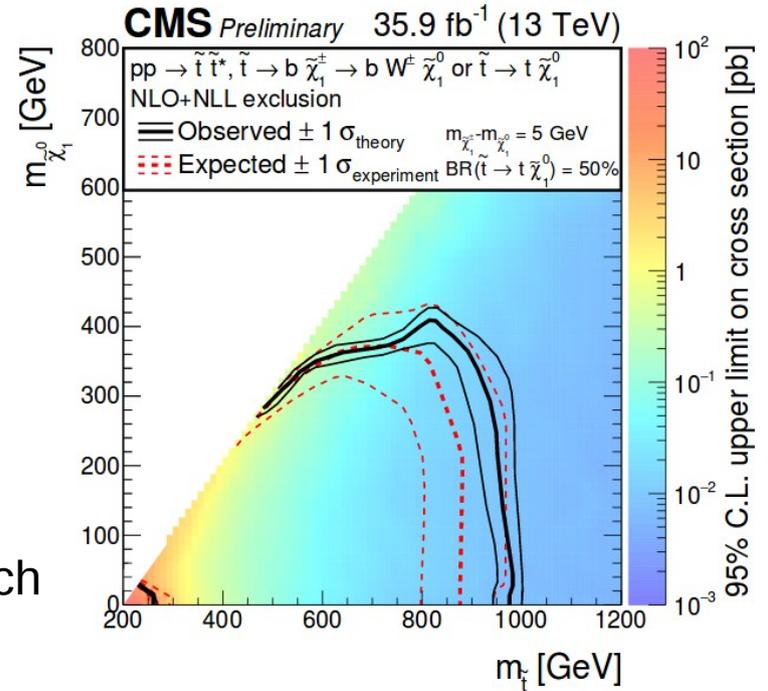- Model 3 – LSP Bino, a gluino between LSP and stop (3t + MET)

LHC LIMITS

[CMS-PAS-SUS-16-051, CMS-PAS-
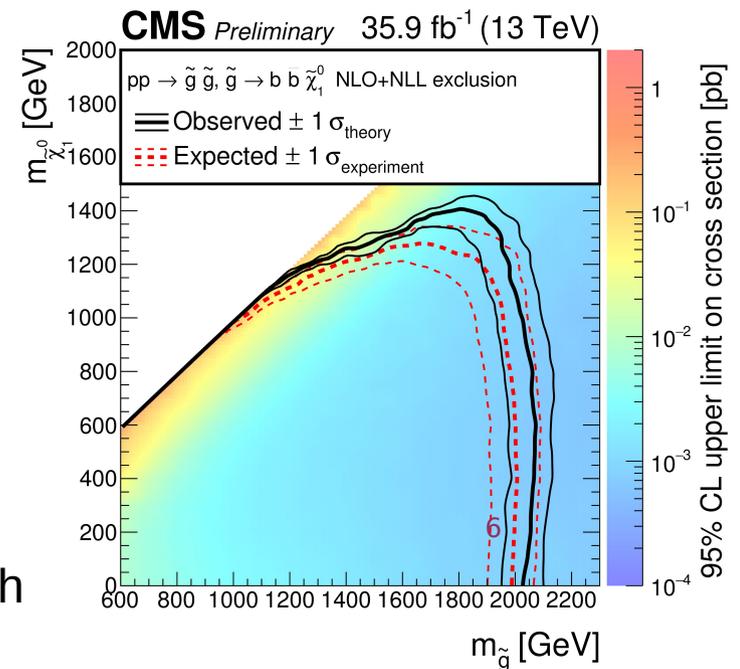SUS-16-036, CMS COLLABORATION]

$\sqrt{s}=13$ TeV LHC constraint

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

Single lepton search

→ In a $\sqrt{s}=100$ TeV collider, more jets at higher energy.

→ SM objects are boosted and collimated.

→ Jet substructure techniques are needed!
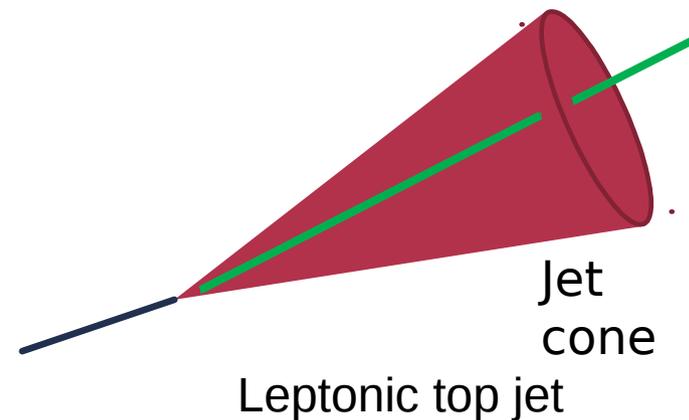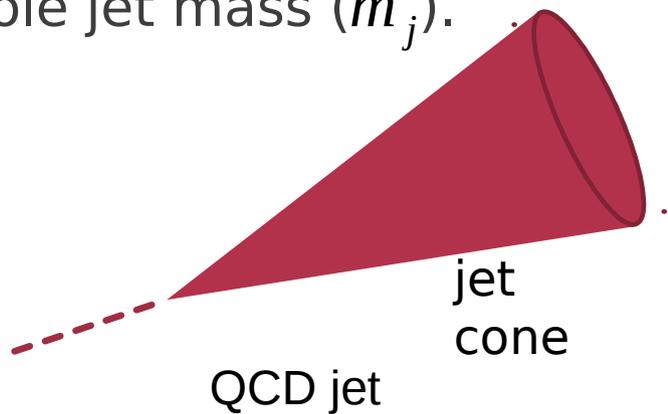
MT2 search

JET SUBSTRUCTURE TOOLS:
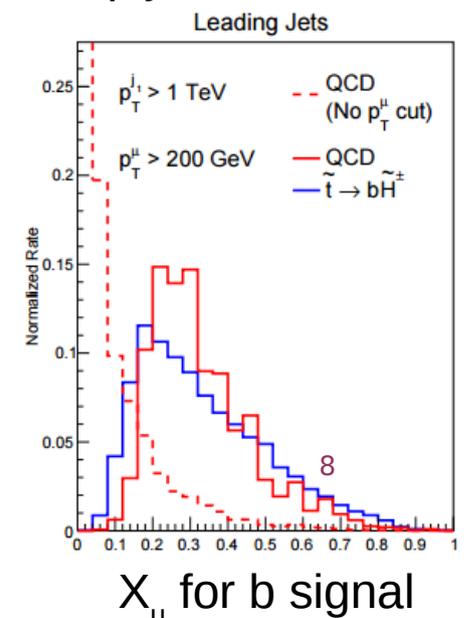# MASS DROP x_μ
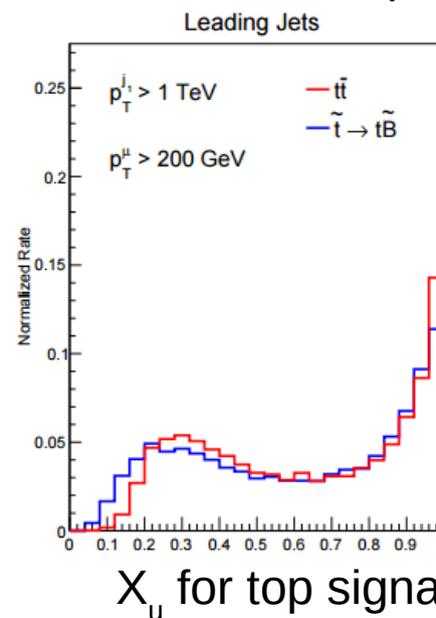
[THALER AND WANG, 08; REHERMANN AND TWEEDIE, 11]

A variable to distinguish between boosted leptonic top jet and QCD jets

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

which is the one minus ratio between jet mass without muons ($m_{j\not\mu}$) and whole jet mass (m_j).

jet
cone

QCD jet

Jet
cone

Leptonic top jet

- ■ for leptonic top jet 1
  - • m_j = mass of top
  - • $m_{j\not\mu}$ = mass of b
- ■ x_μ for b-jet has a broad spectrum since $m_j \approx m_{j\not\mu}$.

Leading Jets

$p^{j_1}_T > 1$ TeV   — $t\bar{t}$
                        — $\tilde{t} \to t\tilde{B}$
$p^\mu_T > 200$ GeV

Normalized Rate

0.25
0.2
0.15
0.1
0.05
0

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

X_u for top signal

Leading Jets

$p^{j_1}_T > 1$ TeV   -- QCD
                           (No p^μ_T cut)
$p^\mu_T > 200$ GeV   — QCD
                        — $\tilde{t} \to b\tilde{H}^\pm$

Normalized Rate

0.25
0.2
0.15
0.1
0.05
0

8

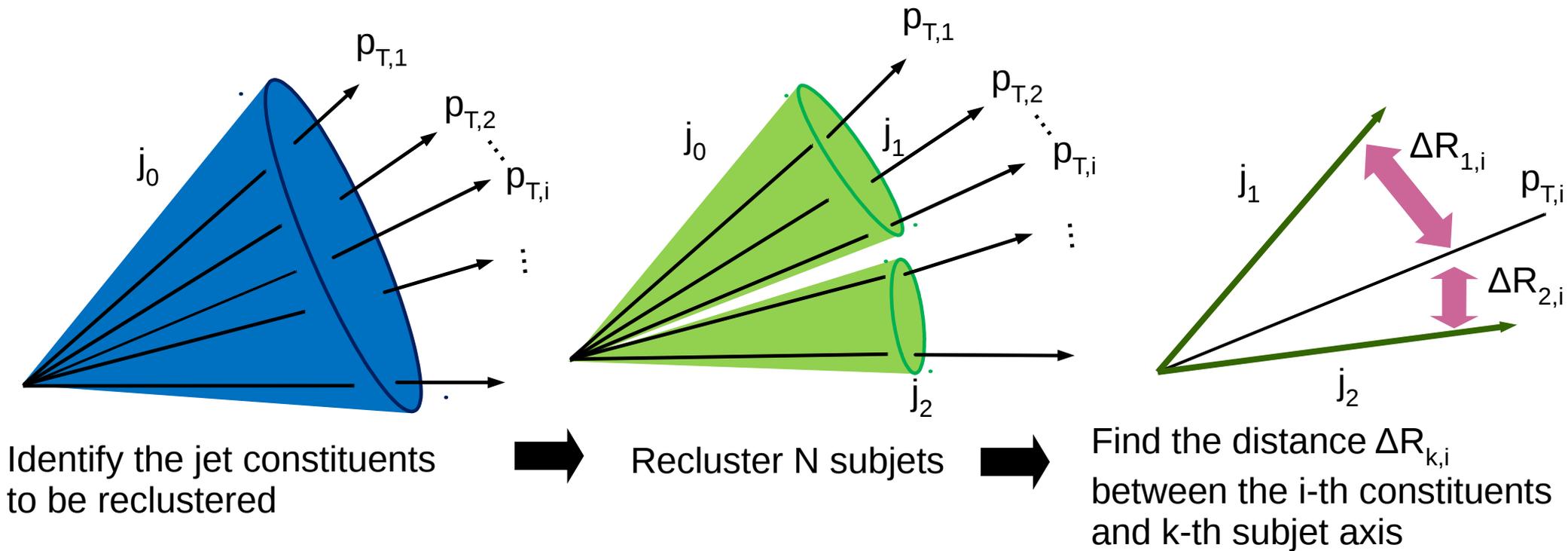0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

X_u for b signal

# SUBSTRUCTURE TOOLS: N-SUBJETINESS τ_N

[J. THALER AND K. VAN TILBURG, 11]

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

N-subjetiness (τ_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

$$\tau_N^{(\beta)} = \frac{1}{R_0} \sum_i p_{T,i} \, min\left\{ \Delta R_{1,i}^{\beta}, \Delta R_{1,i}^{\beta}, ..., \Delta R_{1,i}^{\beta} \right\}$$

- When a jet looks like a 3-prong object, τ_3 will be small but τ_2 will be large.

  e.g. a hadronic top jet (t → Wb → qqb)

- A spread-out QCD jet can have a small τ_N, but τ_{N-1} is small as well!

- τ_3/τ_2 is a good variable to distinguish a hadronic top jet from QCD jet.

Leading top candidate (p_T > 1 TeV)
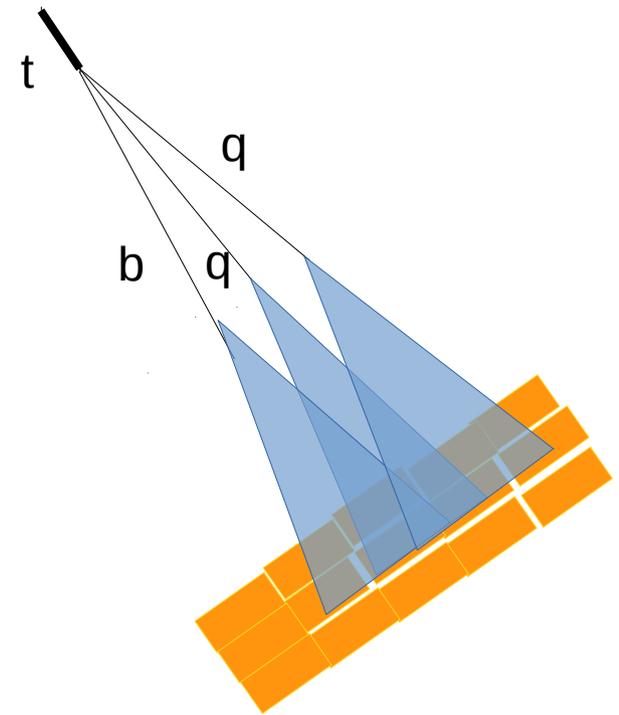
QCD vs hadronic top
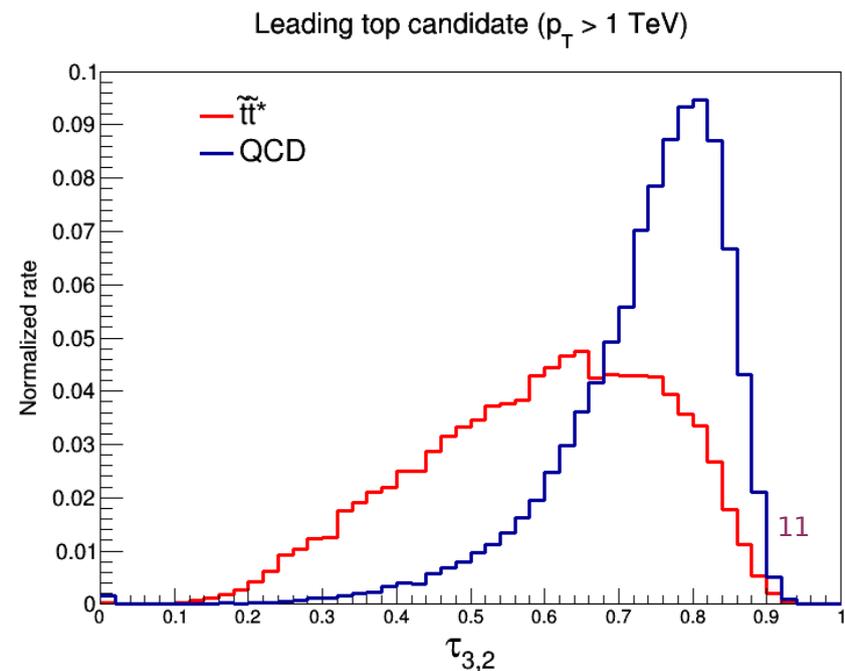
ANALYSIS STRATEGY AND RESULT

SEARCH STRATEGY STOP-BINO/HIGGSINO

- Two jets with p_T > 1 TeV;

- No isolated lepton with p_T > 1 TeV;

- MET > 3 TeV

- Muon-in-jet (> 200 GeV) requirement

  → high p_T muons are either from leptonic W decay or from B-meson decay.

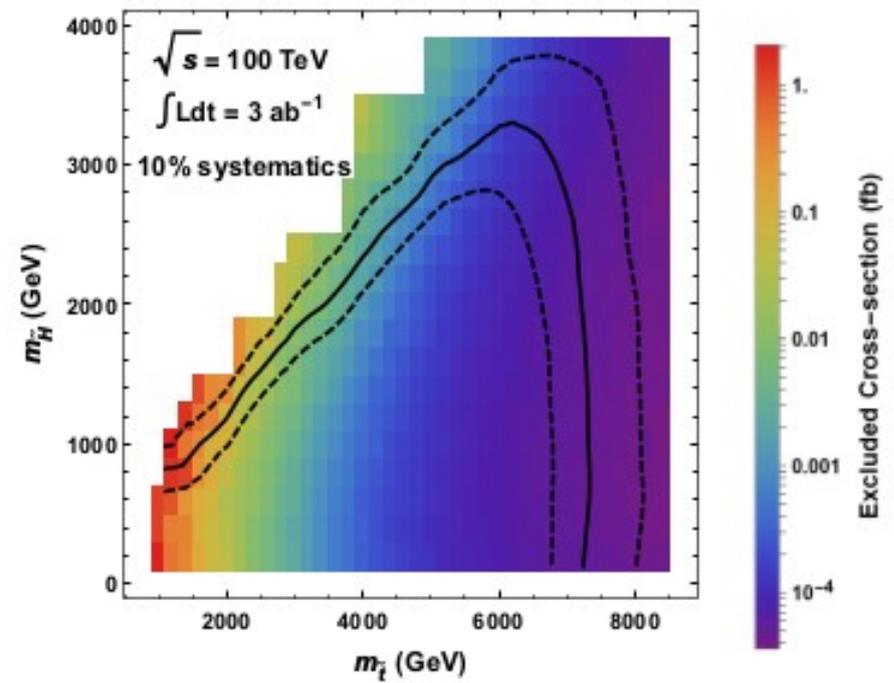 → muon is in jet due to the boosted t / b quarks.

Stop

Stop

Which one is the signal?

Bino
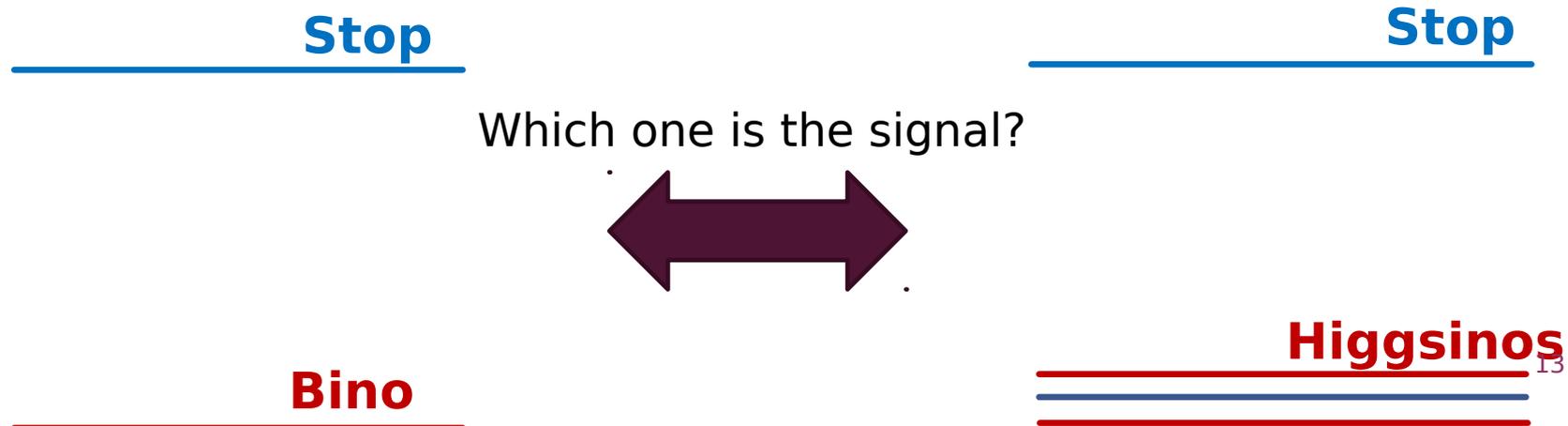
Higgsinos

STOP-HIGGSINO MASS REACH

The discovery/exclusion contours for stop-higgsino model with an integrated luminosity L = 3 ab^{-1}.
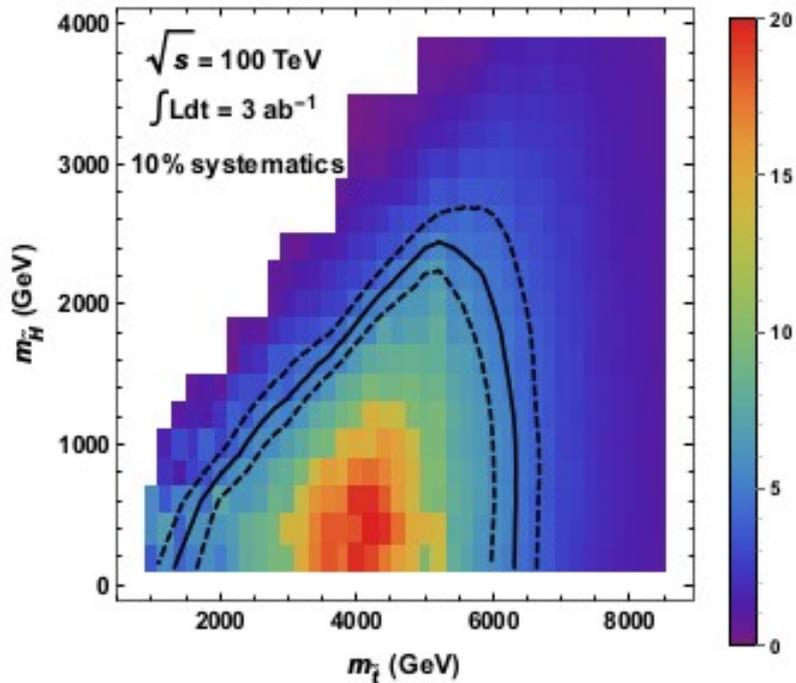
(a) Discovery (b) Exclusion

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.
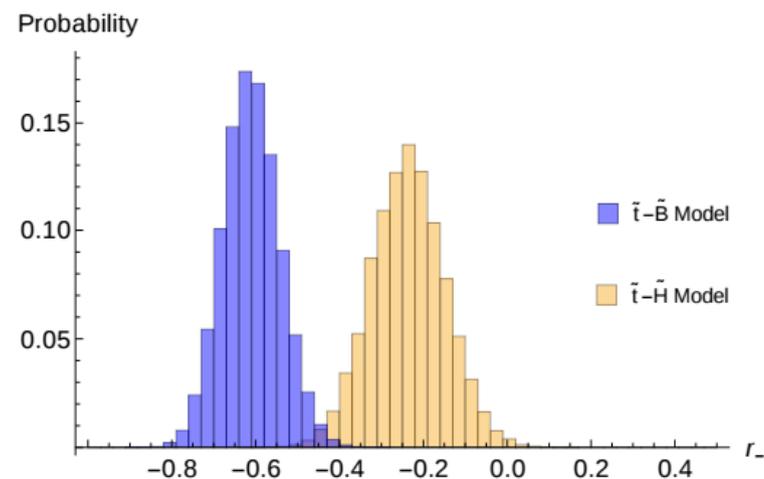
We define the variable r_-

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

N_b = # of B-jet defined by $m_j < 120$ GeV and $x_u < 0.5$;

N_t = # of top-jet defined by $m_j > 120$ GeV or $x_u > 0.5$.

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

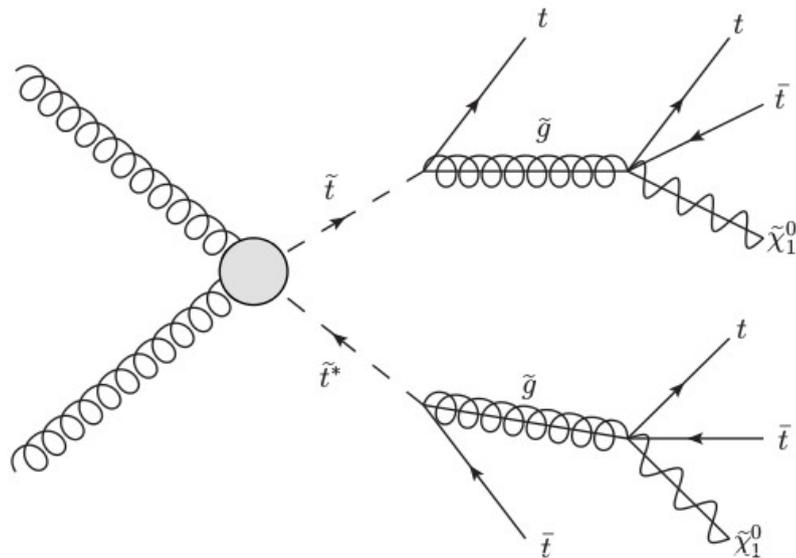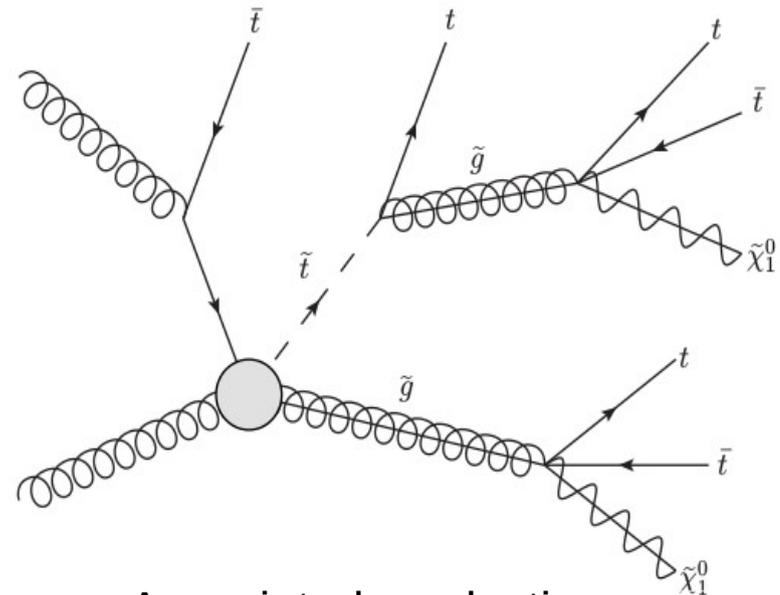r_- distribution
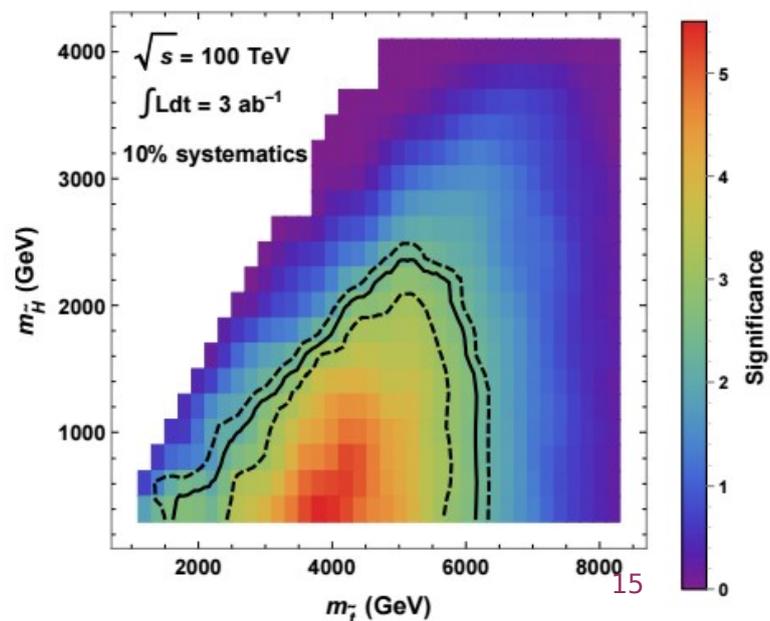
95% confident level

SEARCH STRATEGY STOP-GLUINO-LSP

Pair-production

Associated-production

- Kinematic cuts
- 3 Top-tagging. Definition of top tagging for jets in events passing kinematic cuts
    - → Leptonic top jets (jets with $p_T > 200$ GeV muon): $x_u > 0.7$
    - → Hardronic top jets (jets without tagged muon): $0.1 < \tau_3/\tau_2 < 0.45$

      (jet mass window: 140 GeV $< m_j <$ 240 GeV)

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

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

Using the same set of jet substructure techniques:

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

~2 TeV improvement compared to the same sign Di-lepton gluino search in [Cohen, et al., 14].

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

SUMMARY

- A 100 TeV collider will extend our understanding to the naturalness of Standard Model and explore new physics in general.

- We need jet substructure technique to effectively extract physics from a 100 TeV collider.

- Stop-Bino/Higgsino discovery mass reach at 7 TeV, model identification reach at 6 TeV (L = 3 ab^{-1})

- Stop-Gluino-LSP model mass reach 6 TeV (L = 30 ab^{-1}). Gluino mass reach 11 TeV (L = 3 ab^{-1}).

BACK-UP SLIDES

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!

Uncontracted group index

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

Mass term   An extra factor of suppression
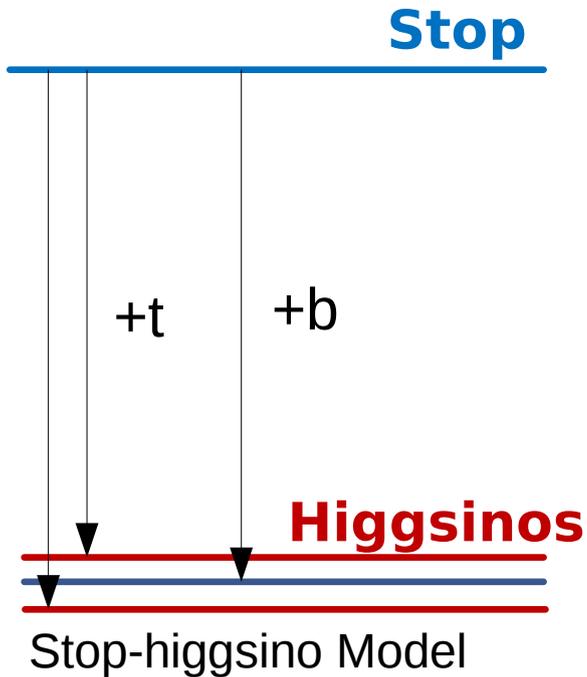
STOP-BINO MODEL

Stop

+t

Bino
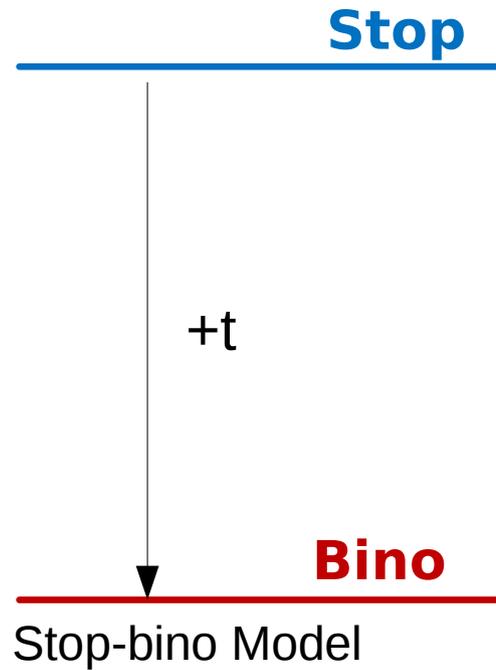
Stop-bino Model

Final state: tt + MET
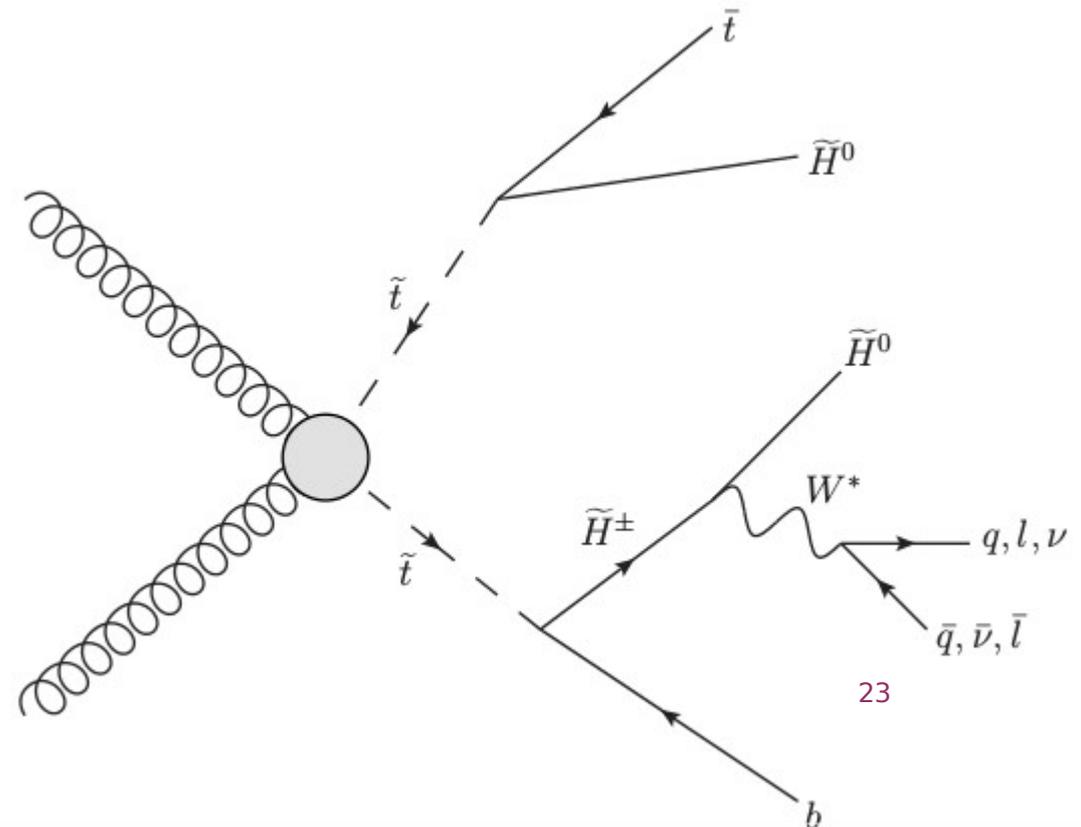
STOP-HIGGSINO MODEL

Stop

+t   +b
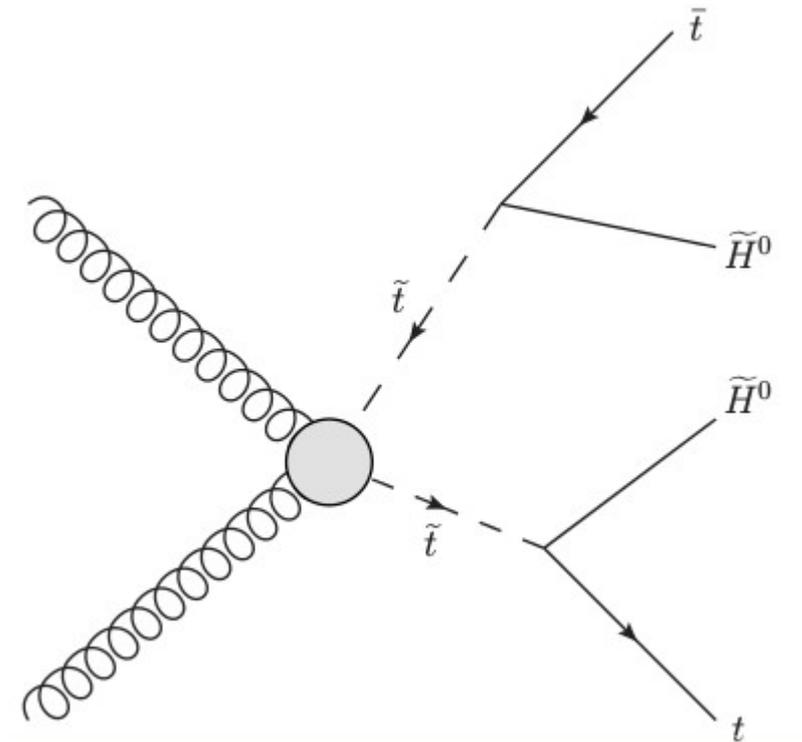
Higgsinos

Stop-higgsino Model

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

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

Final states: combinatoric of both

23

STOP-GLUINO-LSP MODEL

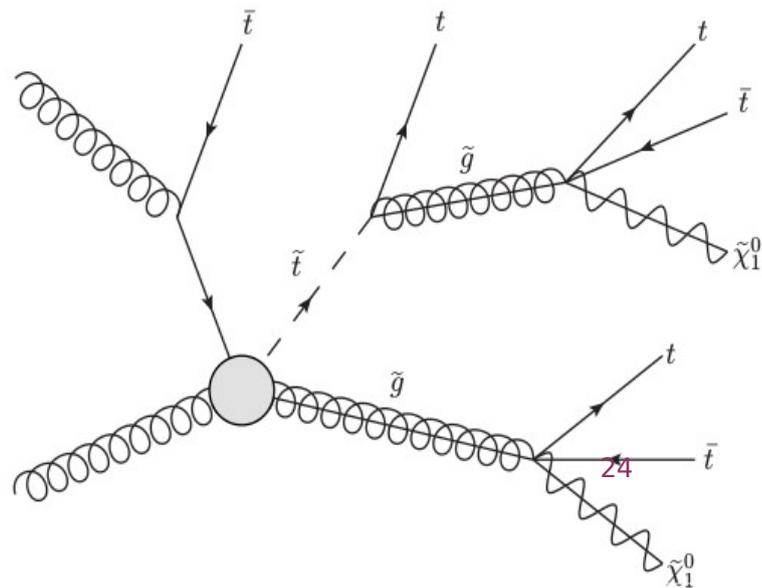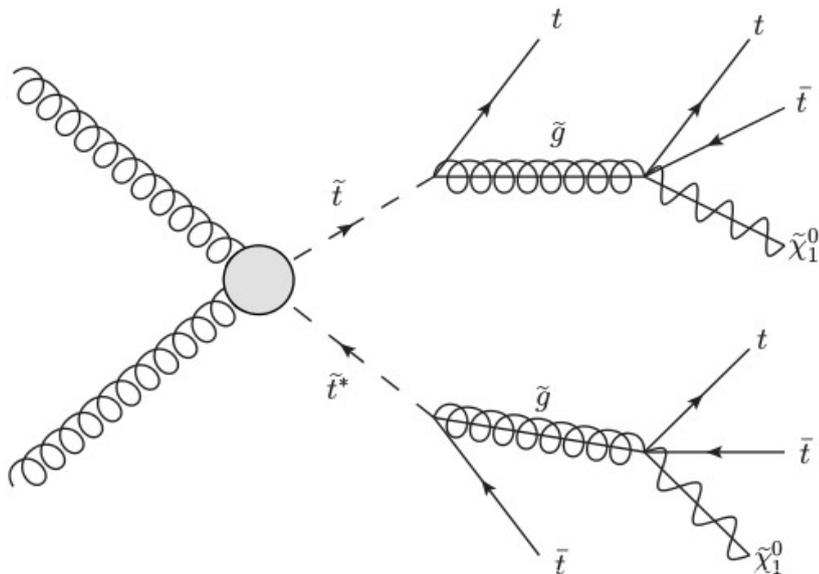Stop-gluino-bino Model

- Two production channels (stop-pair and stop-gluino associated)
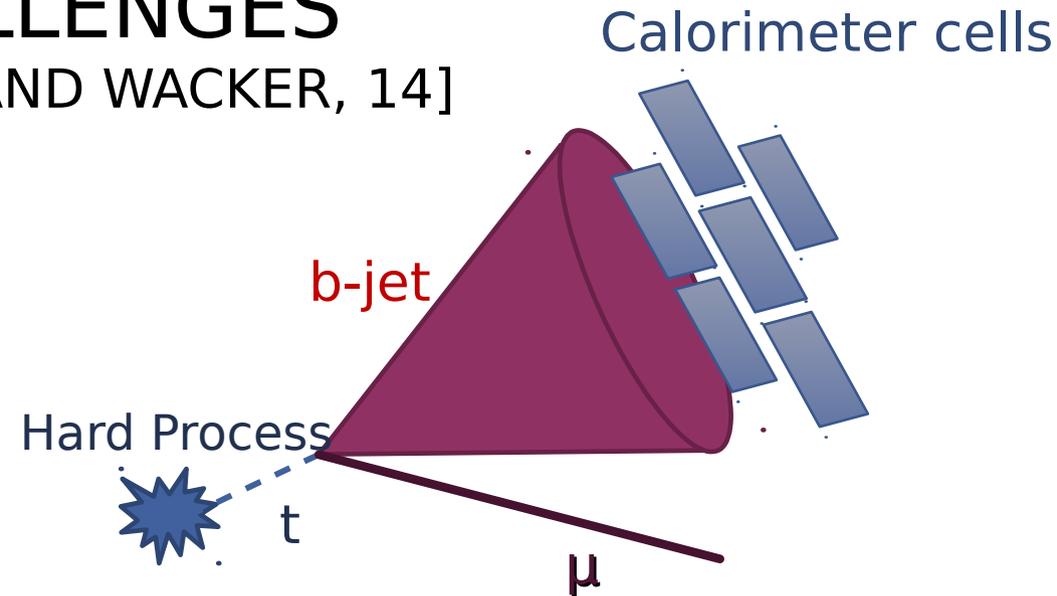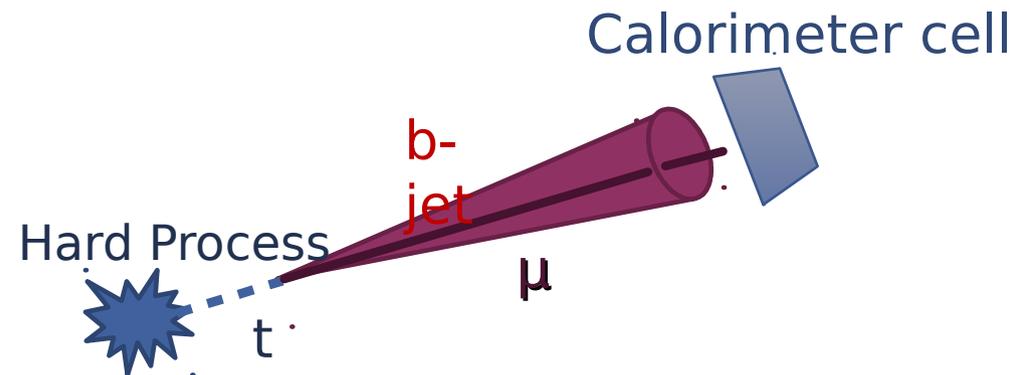
- Final states: 6t + MET

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.

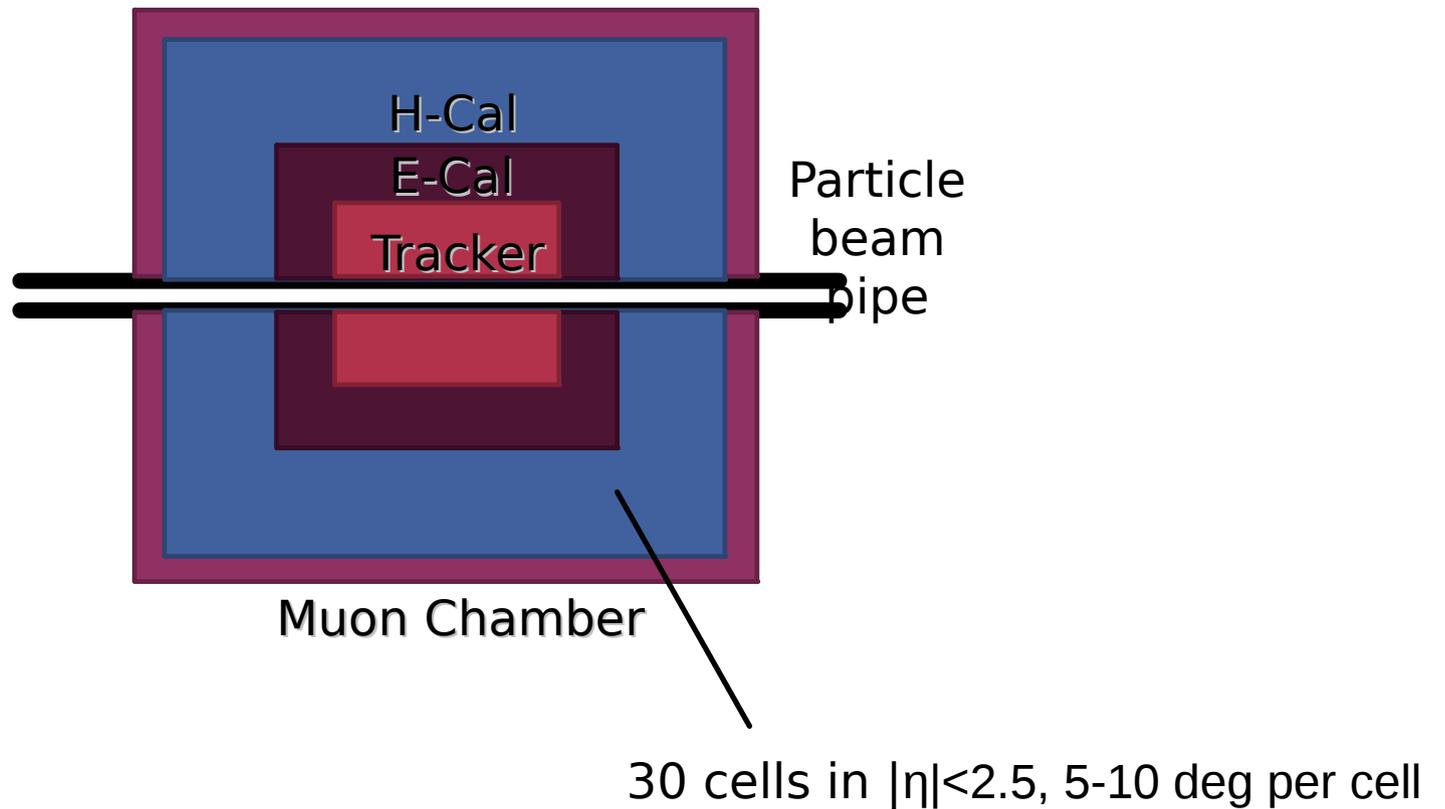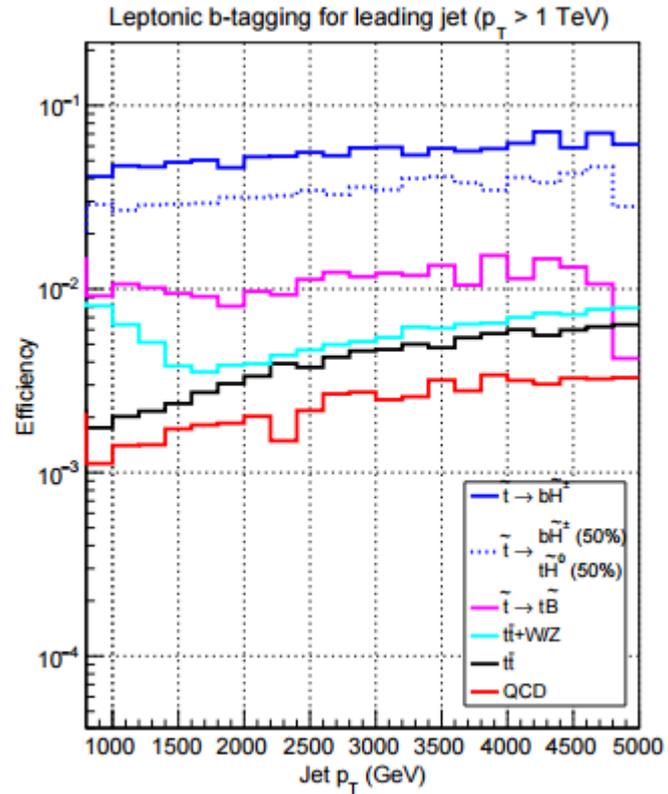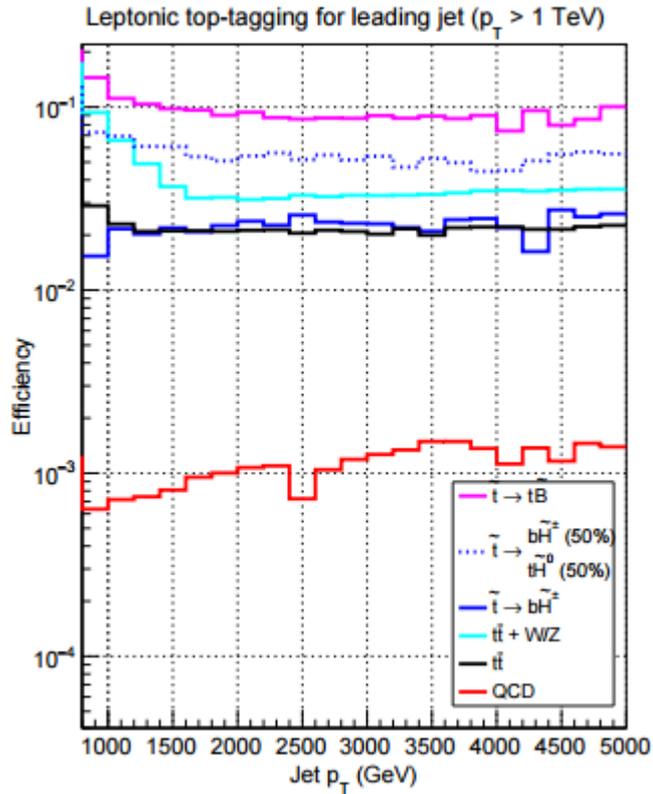- New jet substructure techniques are needed.

Calorimeter cells

b-jet

Hard Process

t

μ

A top quark decaying in the LHC

Calorimeter cell

b-jet

Hard Process

t

μ

A boosted top in a 100 TeV collider

DETECTOR DESIGN

H-Cal

E-Cal

Tracker

Particle beam pipe

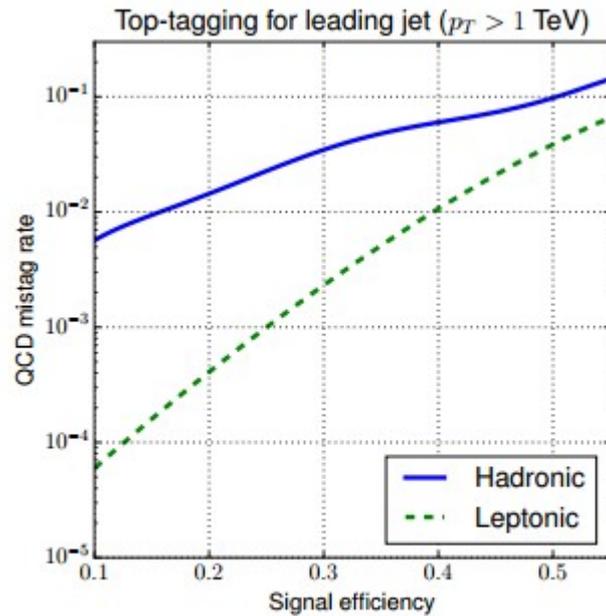Muon Chamber

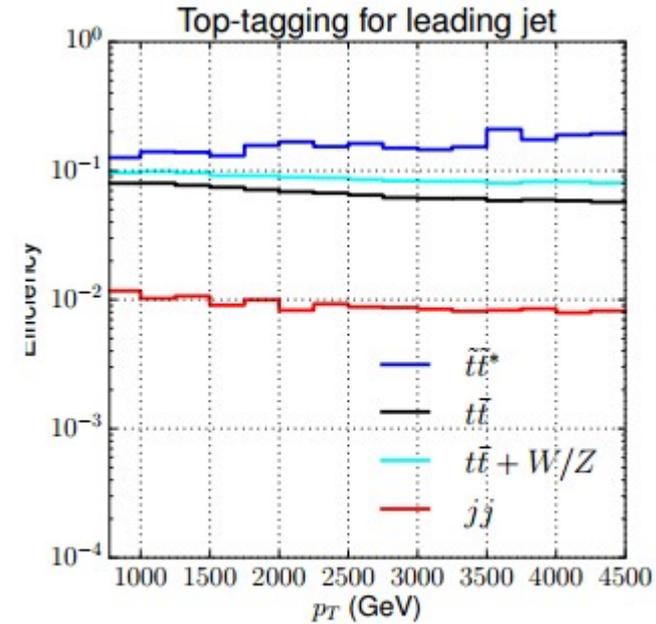30 cells in |η|<2.5, 5-10 deg per cell

EFFICIENCY

Signal/background efficiencies for stop-higgsino cut

EFFICIENCY

QCD mistag vs signal efficiency   Signal/background efficiencies top-tagging