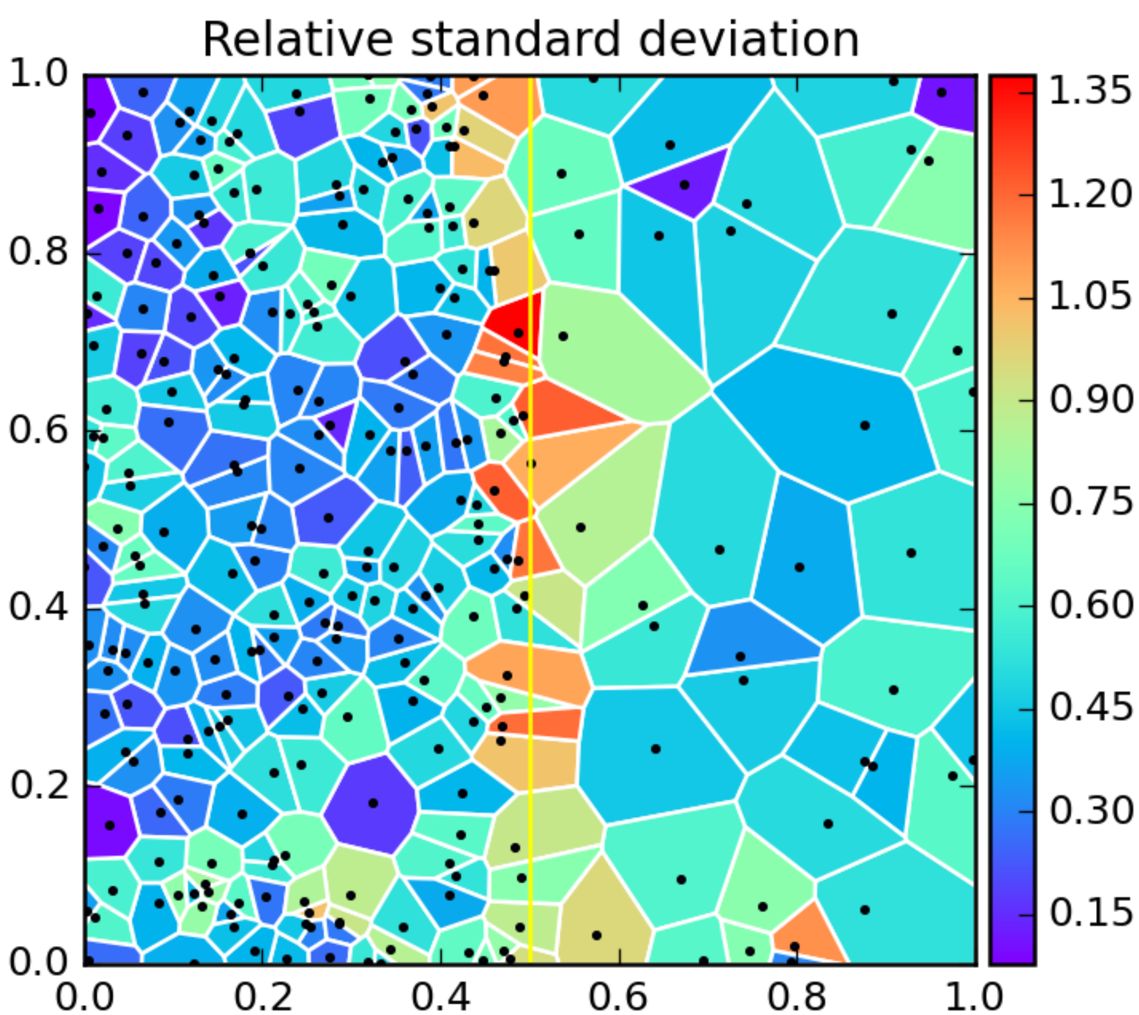
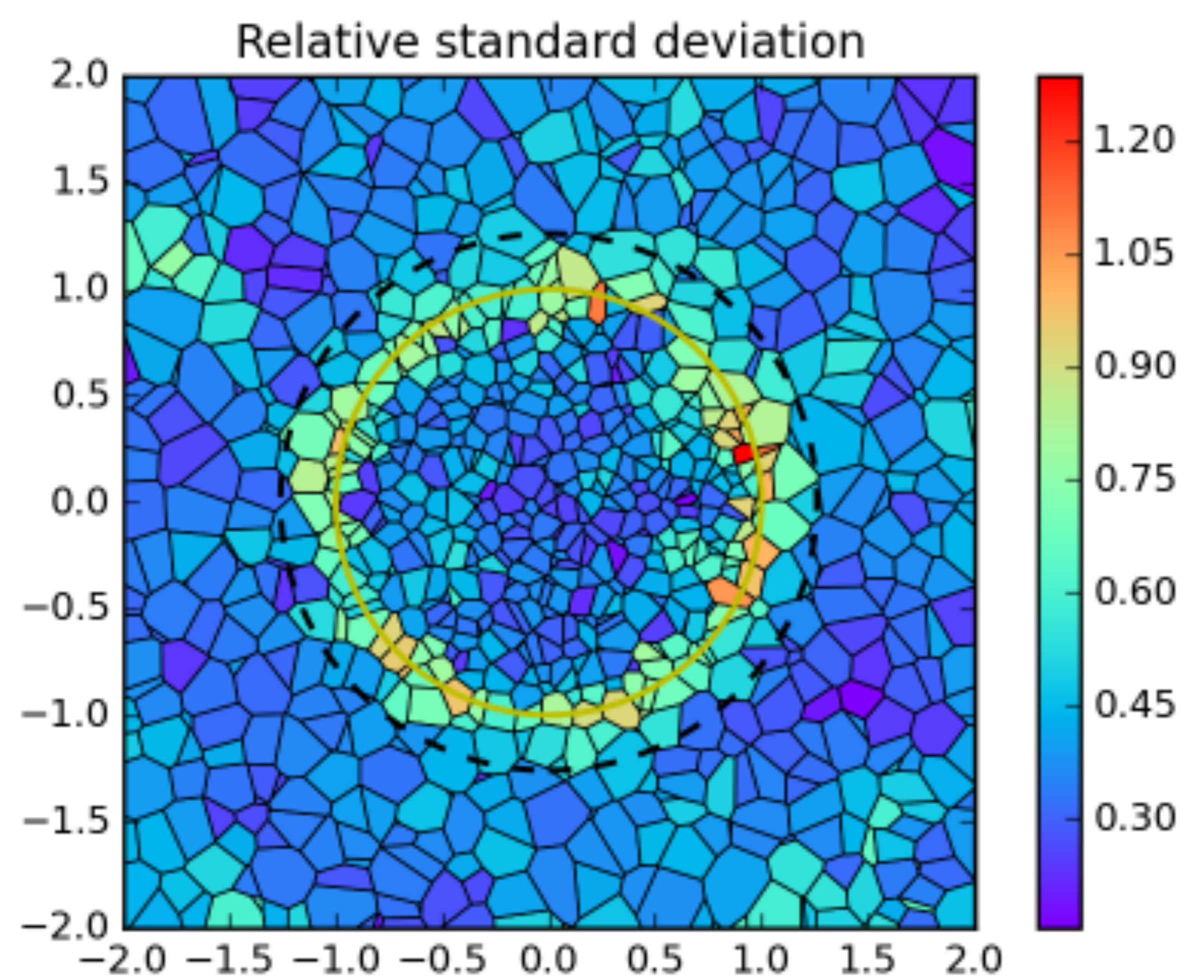

MARVEL
COMING SOON

VoronoiHEP


Relative standard deviation
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.35
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15


Relative standard deviation
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
1.20
1.05
0.90
0.75
0.60
0.45
0.30

VoronoiHEP

- It's MC4BSM, so I need to plug a physics tool
- Kinematic variables from Voronoi tessellations are an exciting new direction in the field!
    - Talk today from Yuan-Pao Yang
    - An important application of Voronoi methods is to finding structure in phase space: see Matt Klimek's talk today
- We plan on making our code public
    - builds on Voronoi class in scipy
    - tools for performing analyses
    - and visualization (building on matplotlib)

- All I'm going to say about Voronoi tessellations in this talk

Toward Kinematic Measurements of the Gluino Mass

Jamie Gainer
University of Hawaii at Manoa

May 12, 2017

MC4BSM 2017

- arXiv:1612.00795,
  Baer, Barger, JG, Huang, Savoy, Sengupta, Tata

- arXiv: 1702.06588,
  Baer, Barger, JG, Huang, Savoy, Sengupta, Serce, Tata

- Work in progress…

Kinematic Measurement of Gluino Mass

- Not a new topic
  - Cho, Choi, Kim, Park, 2007
  - Nojiri, Shimizu, Okada, Kawagoe, 2008
  - Burns, Kong, Matchev, Park, 2008
  - Burns, Kong, Matchev, 2008
  - Cheng, Han, 2008
  - Curtin, 2011
  - Agashe, Franceschini, Kim, 2014
  - …
- What's changed?

The Context: Theory

- No SUSY yet + 125 GeV Higgs → we must consider models in which somewhat heavier sparticles are natural: Natural SUSY

- We work in a particular natural SUSY scenario: "Radiatively Natural SUSY" (Baer, Barger, Huang, Mickelson, Mustafayev, Sreethawong, and Tata, 2013)

  - NUHM2: small value of $-m^2_{H_u}$ at the SUSY scale

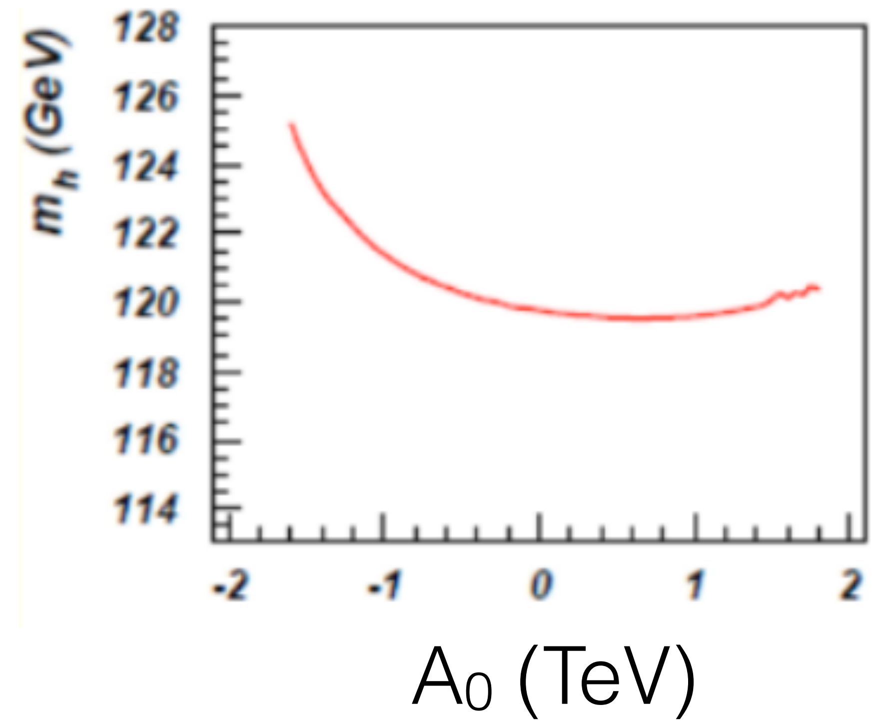
  - Large negative A_0 to enhance stop mixing

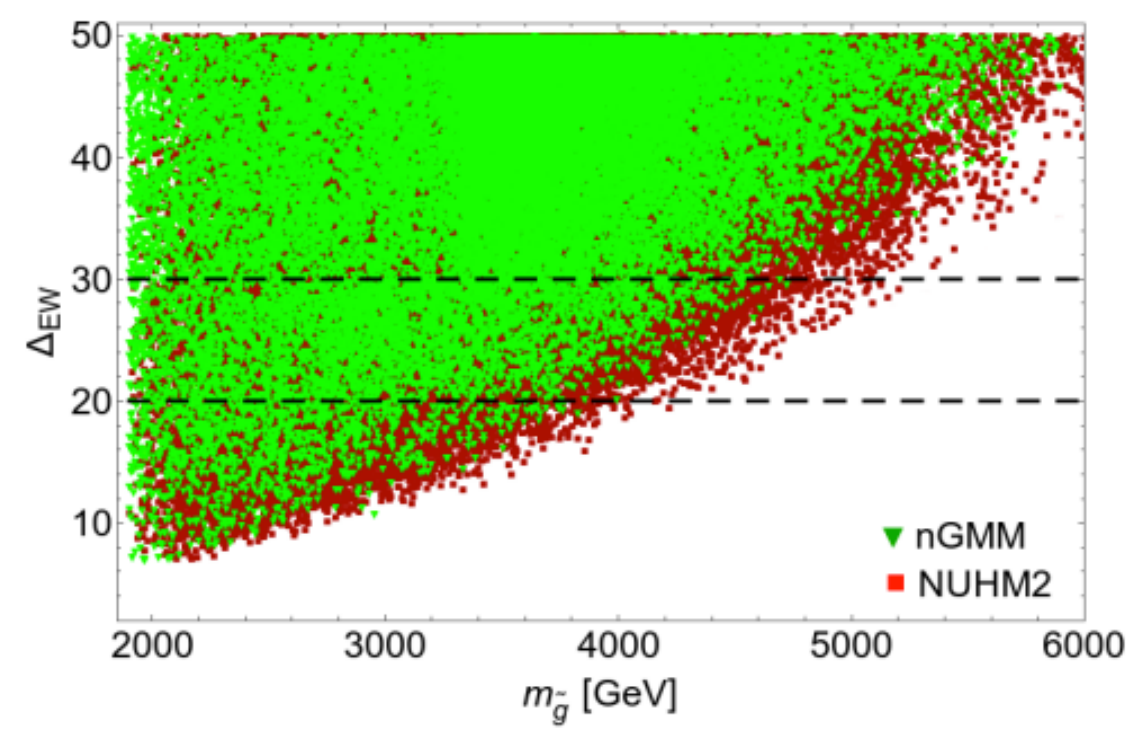
  - Higgsinos are light (the LSP in models we consider)

- Interesting on general grounds to look for models with gluinos in 2-3 TeV range, stops in 1-2 TeV range

- Just beyond current limits

- Stop and gluino cross sections fall fast





1702.06588

Big Questions

- **What is the gluino reach in RNS models?**

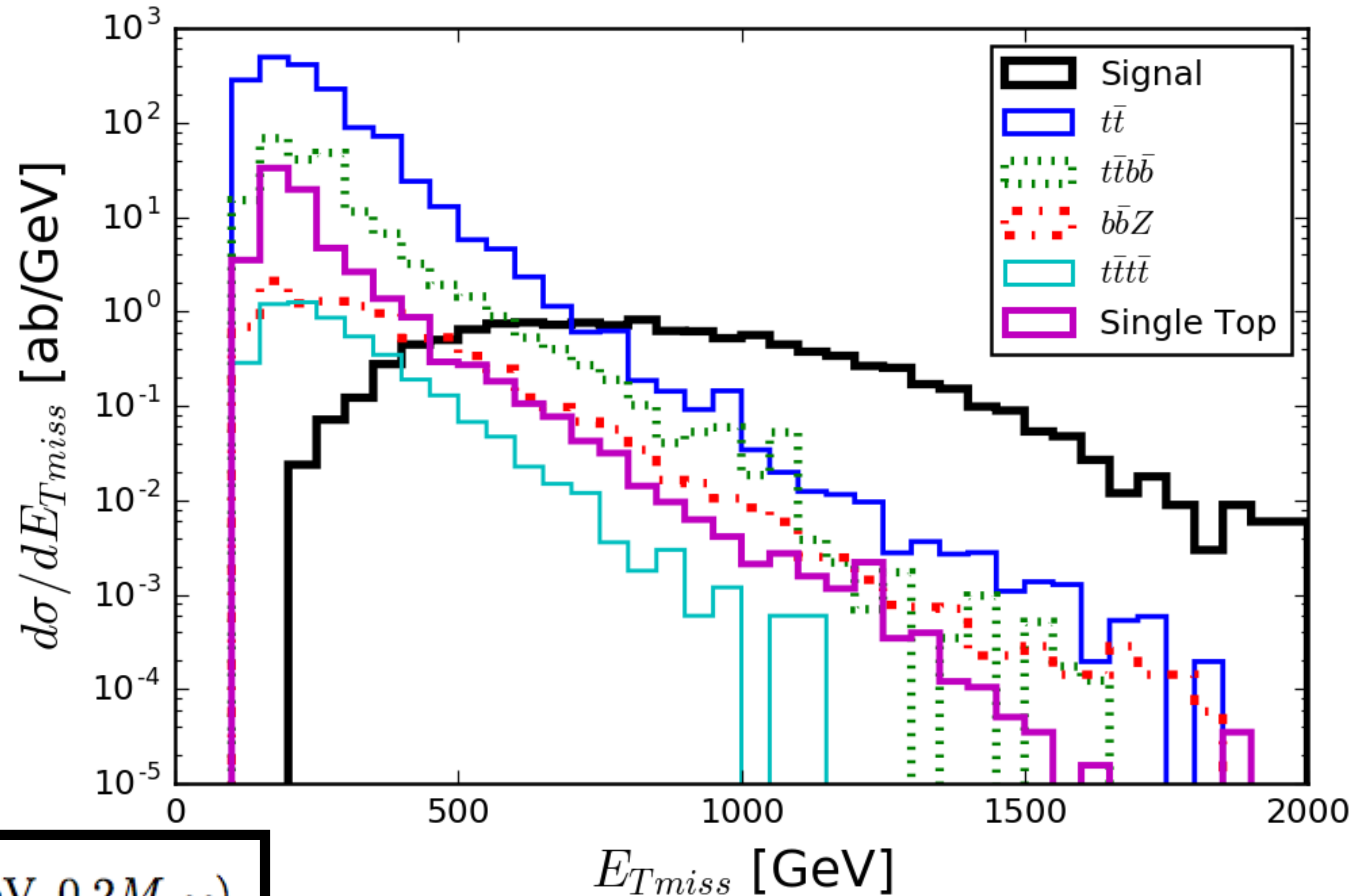
- **How well can we measure the gluino mass?**

Signal and Background

- Our benchmark model for developing our analysis will be a RNS model with m_0 = 5000 GeV, $m_{1/2}$ = 800 GeV, A_0 -8000 GeV, tan β = 10, μ = 150 GeV, mA = 1000 GeV
- **Gluino mass ≈ 2000 GeV, light stop mass ≈ 1500 GeV, Higgsinos ≈ 140 - 160 GeV**
- I will start with a conservative **cut-based analysis**.
- We lose sensitivity with respect to MVAs, but we gain robustness to inaccuracies in simulation
- The signal is gluino pair production with gluinos decaying to on shell stops and tops, and the stops decaying to light higgsinos (charginos or neutralinos)
- The backgrounds* are **tt**, ttbb, tttt, single top, Zbb**
- ***** Other backgrounds at zero event level in our MC
- ** We veto tt events with more than 2 truth b's to avoid double counting with ttbb

Preliminary Cuts

- We start by imposing some basic cuts.
- We use anti-kT jets with $\Delta R = 0.4$, $p_T > 50.$, $|\eta| < 3.$



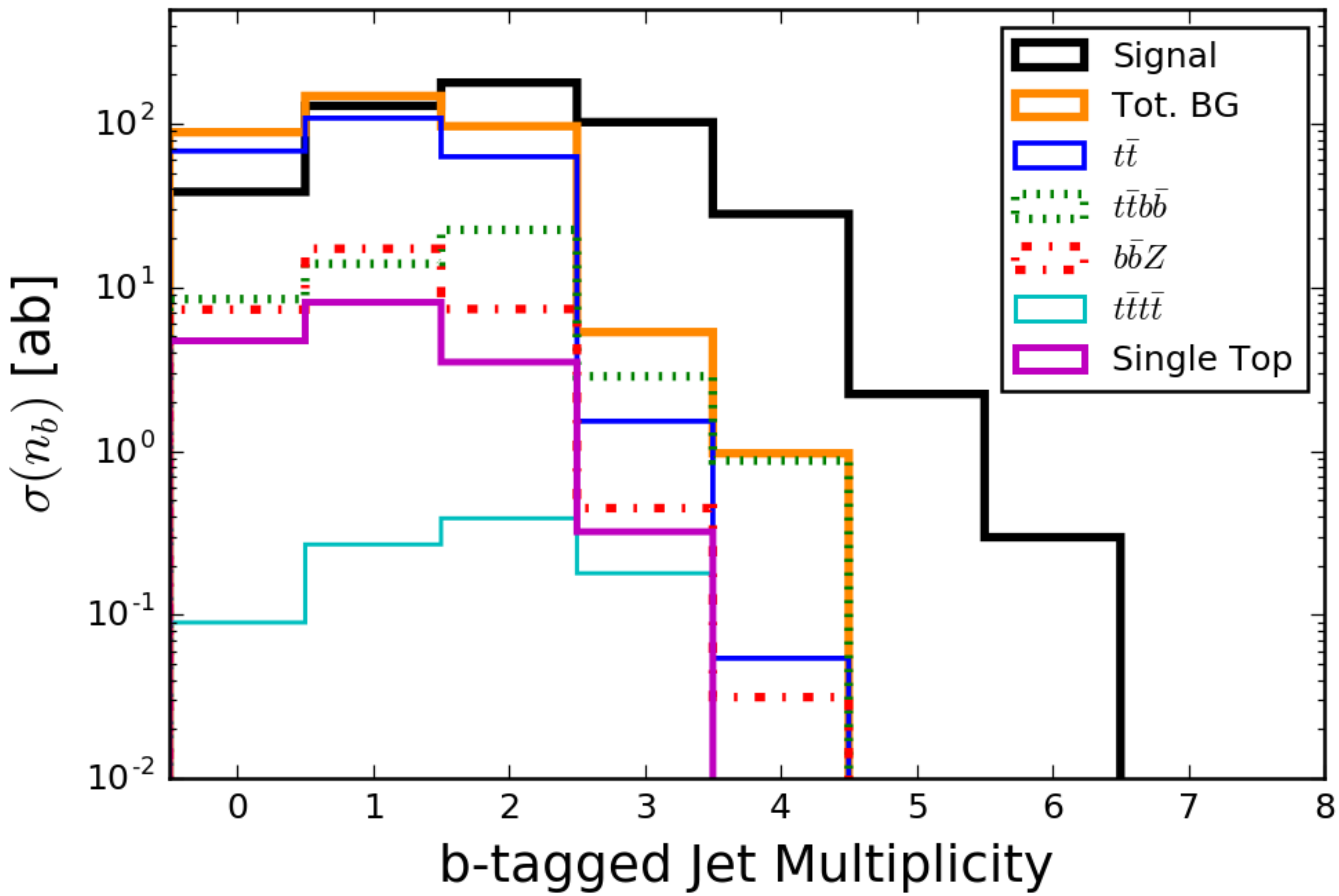
$$
\begin{aligned}
\not{E}_T &> \max(100\text{ GeV}, 0.2M_{eff}),\\
n(jets) &\geq 4,\\
E_T(j_1, j_2, j_3, j_4) &> 100\text{ GeV},\\
S_T &> 0.2,\\
m_T(\ell, \not{E}_T) &> 150\text{ GeV},\ \text{if } n_{lep} = 1.
\end{aligned}
$$

14 TeV LHC

all subsequent figures in this part of the talk from 1612.00795

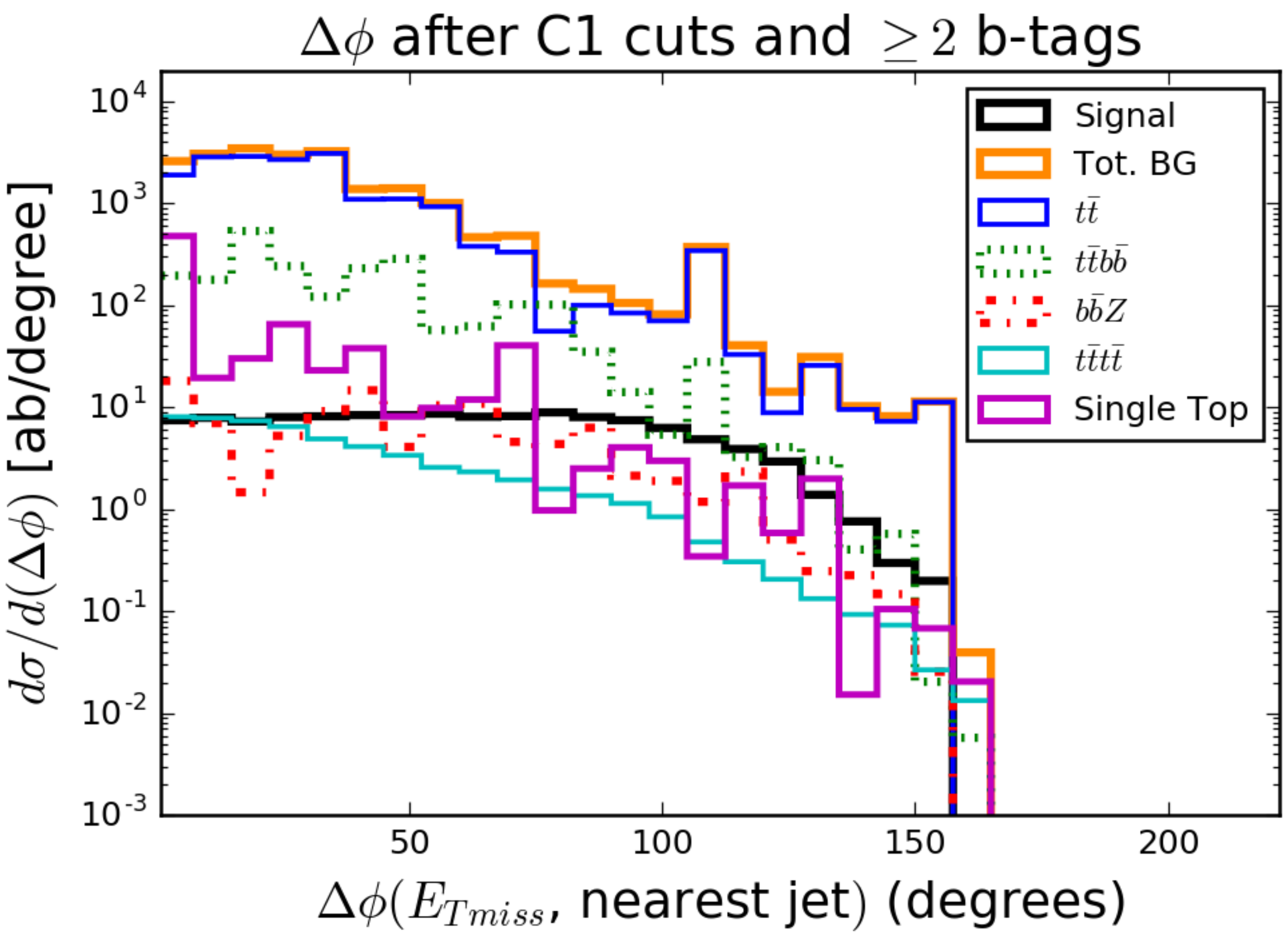
B-Jet Multiplicity

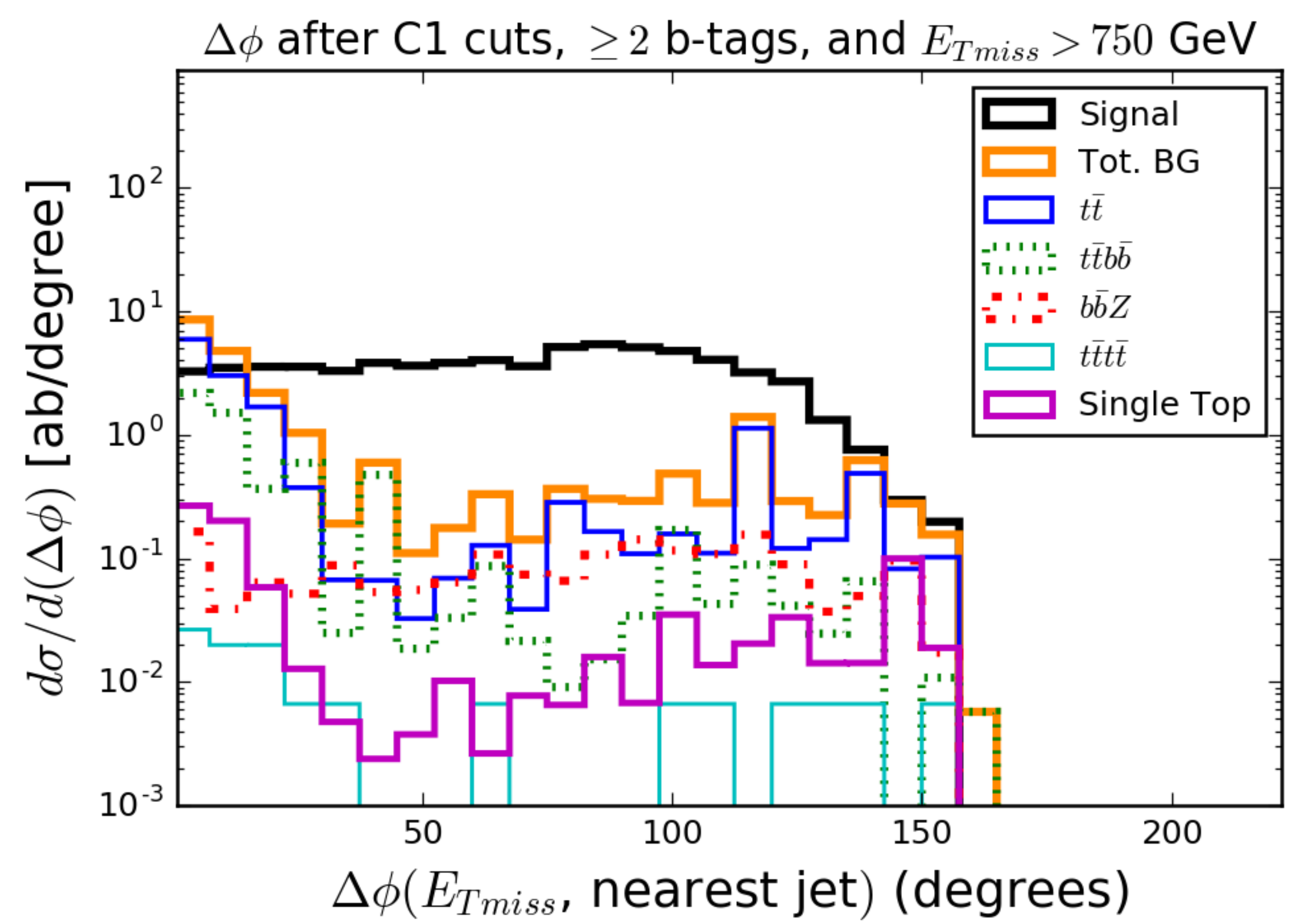
- Signals are b-enriched
- b-tagging and preliminary cuts remove QCD backgrounds
- tt is the main remaining background



- Demanding 2 b-tags is essential, demanding 3 is better for S/B but worse in terms of S.

$\Delta\phi$



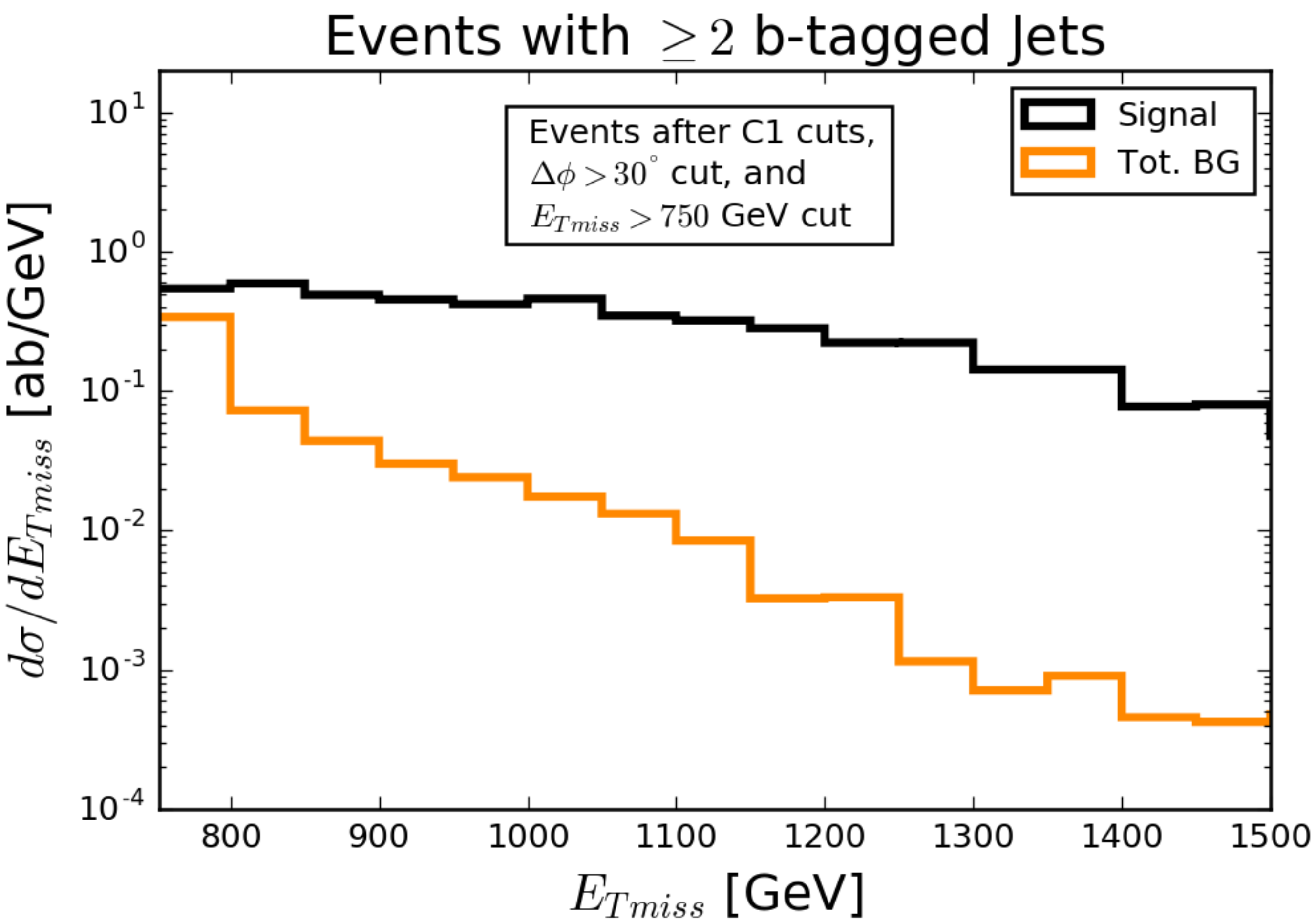


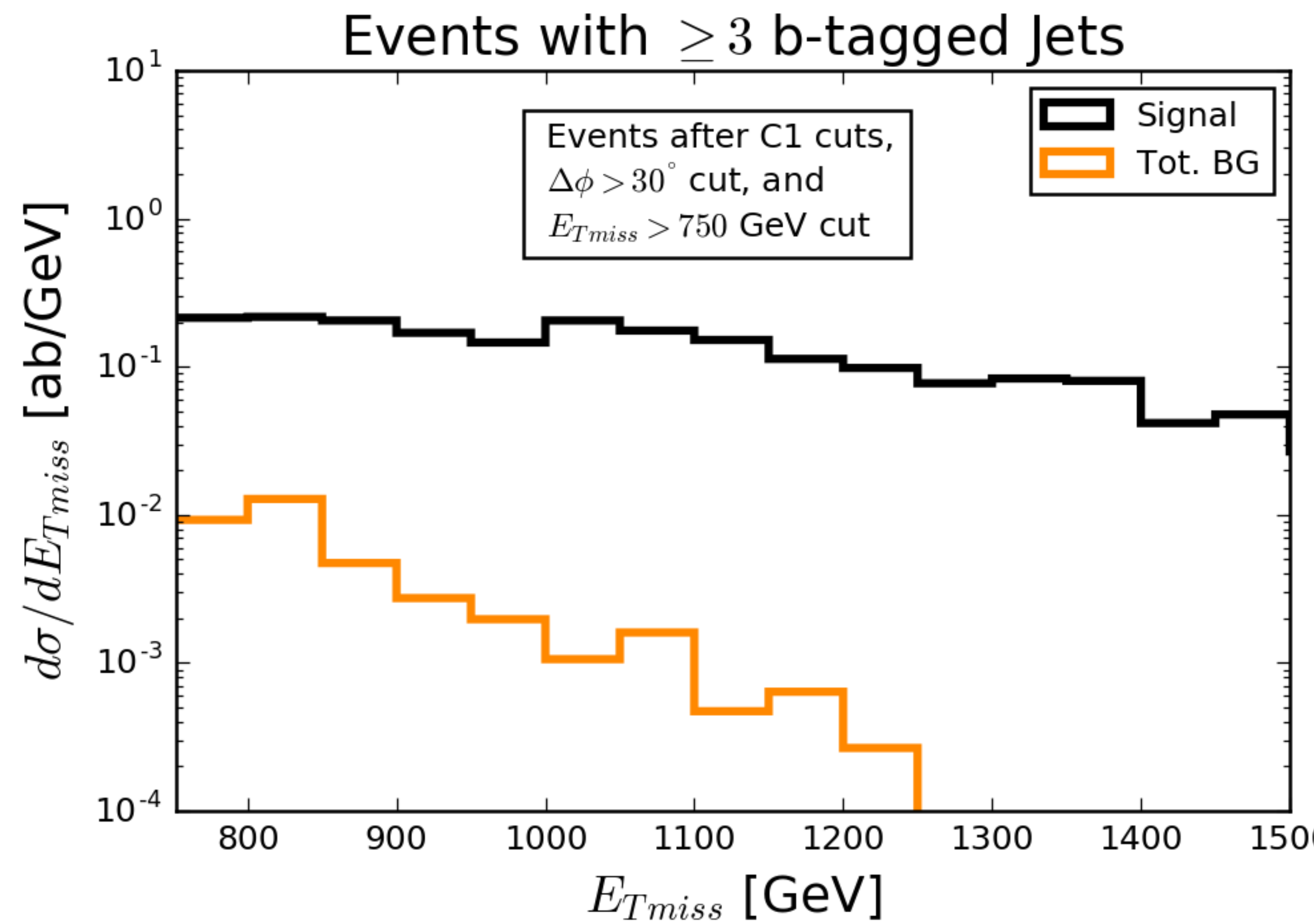
- In tt events with MET from leptonic decay of top, should be a b-jet close to the MET

- Especially true with large missing ET → boosted tops

- So we impose a cut of $\Delta\phi > 30^{o}$

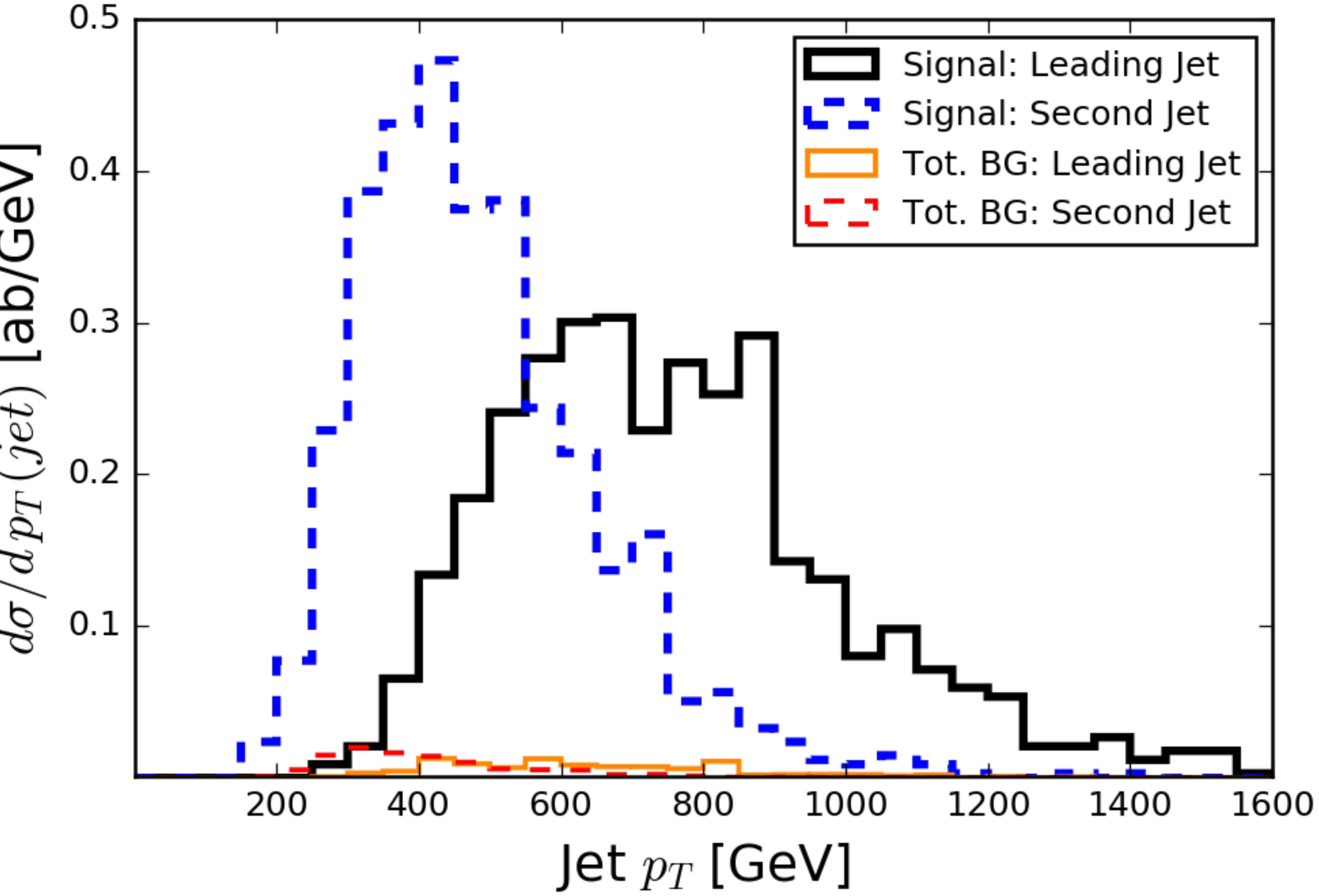
Final MET Cut

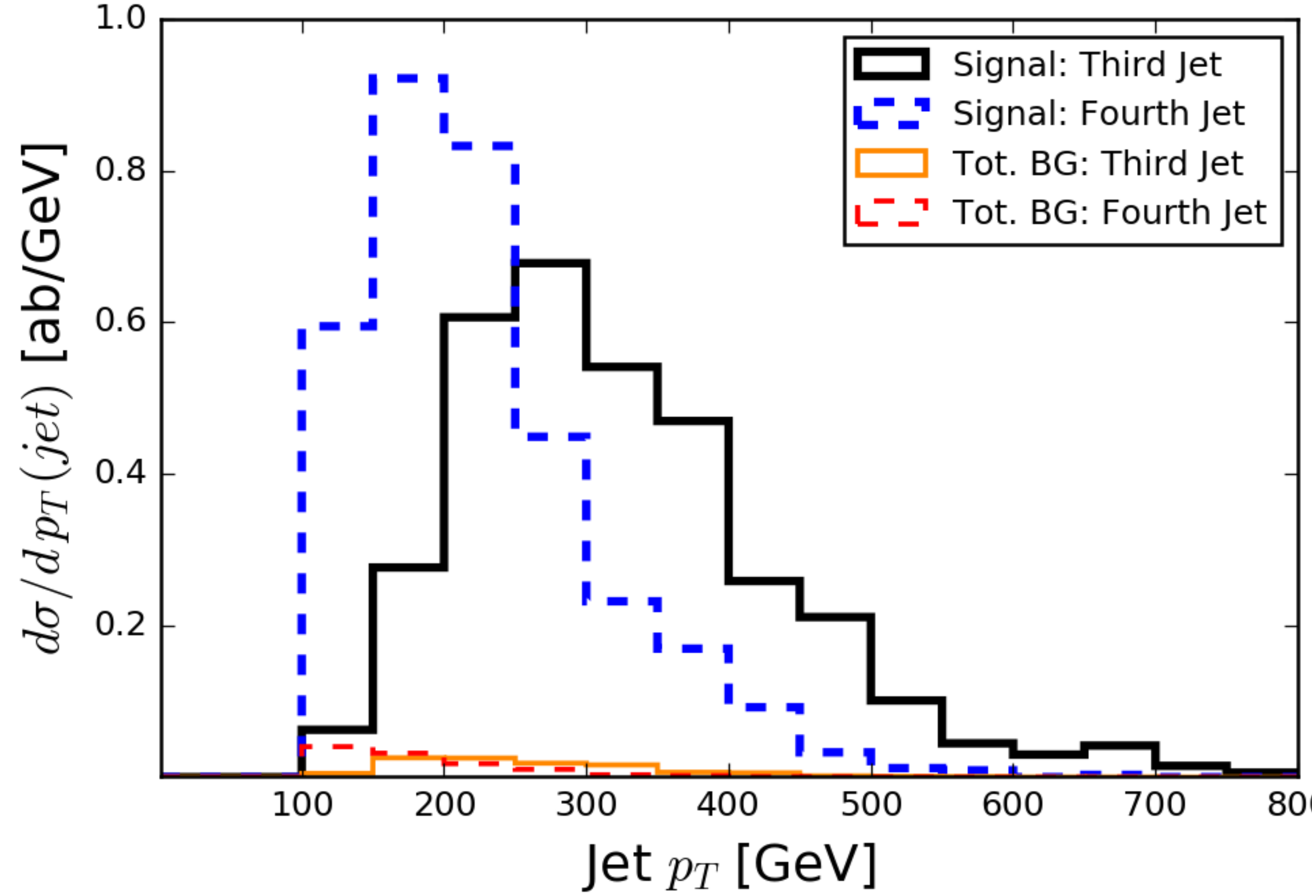


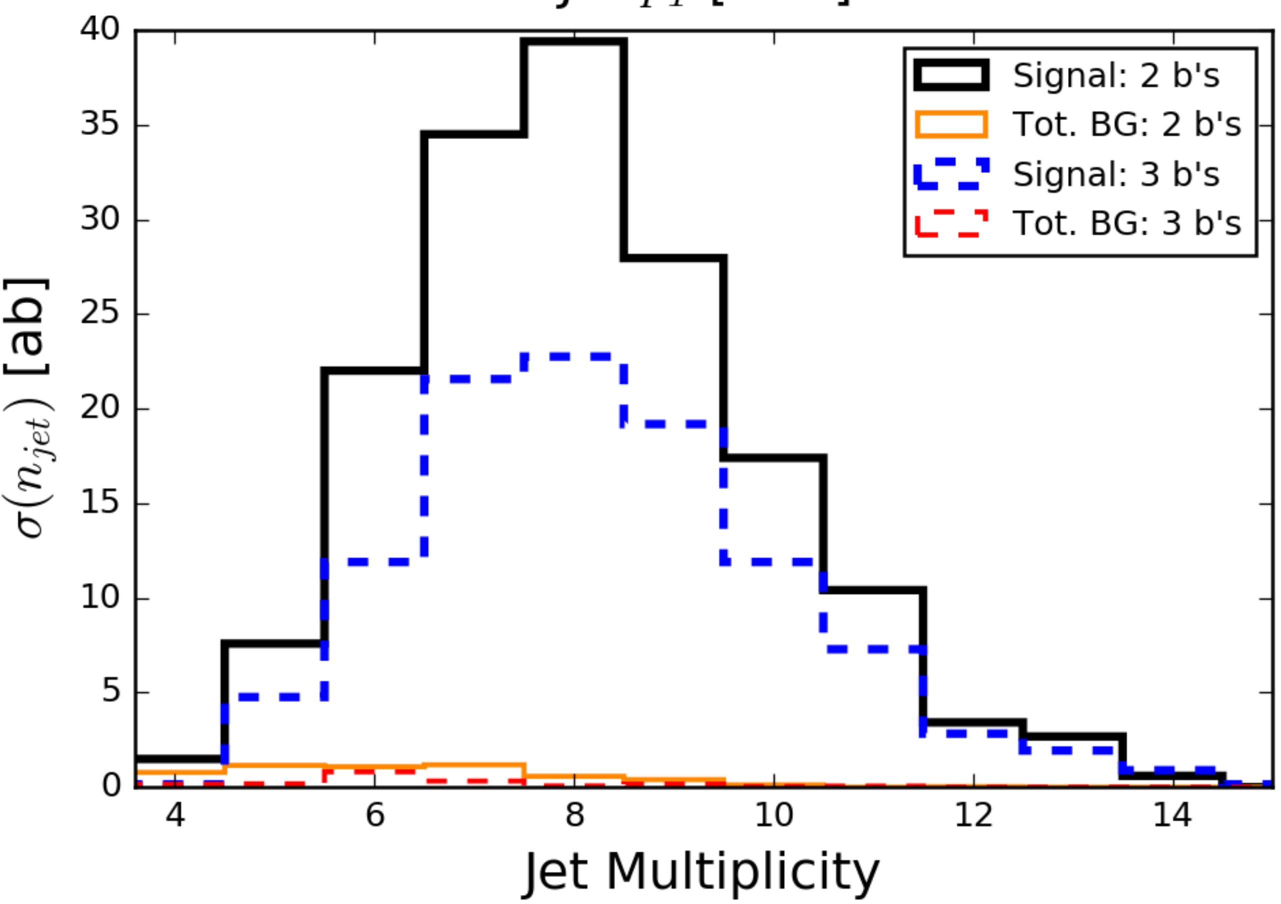


- We note that S/B is dramatically better when we demand 3 b-tags
- But much of the 2 b-tag background is at relatively low MET
- So we consider both approaches, i.e., we have one set of cuts with >= 3 tags and no further cuts and one set of cuts with >= 2 b-tags where we demand MET > 900 GeV

Distributions

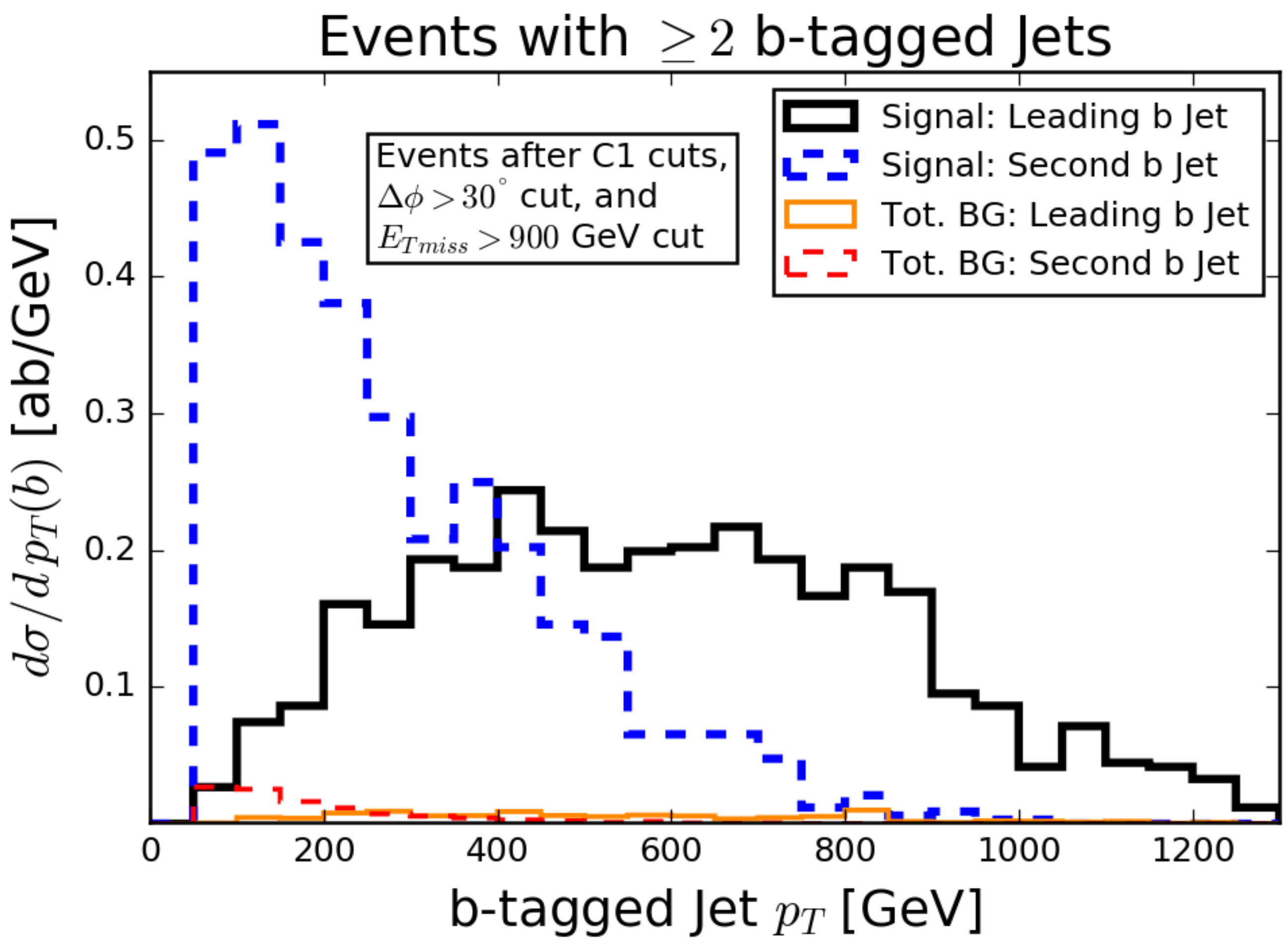


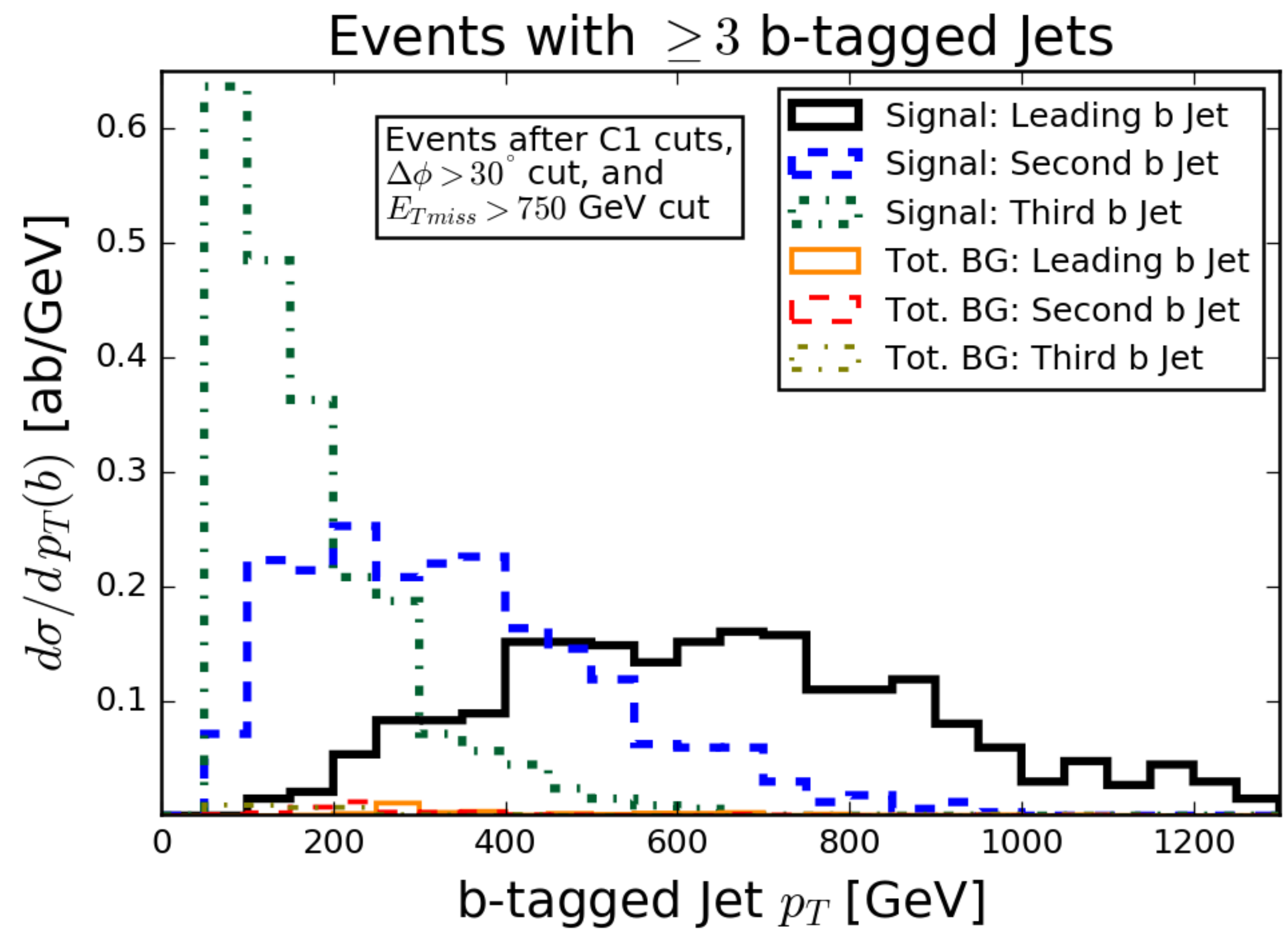




- Peak of j_1, j_2, j_3, j_4 distributions at p_T's of ~ 700, 400, 300, 200 GeV
- Signal after cuts is relatively jetty

Distributions





- Signal distributions of b-jets broader, and somewhat softer
- Signal events generally have ~4 hard truth b's, but b-tagging efficiency is finite, so sometimes one of these truth b-jets isn't tagged
- Also distributions of hardest jets on previous slides receives contributions from ISR, etc.

Cross Sections after Cuts

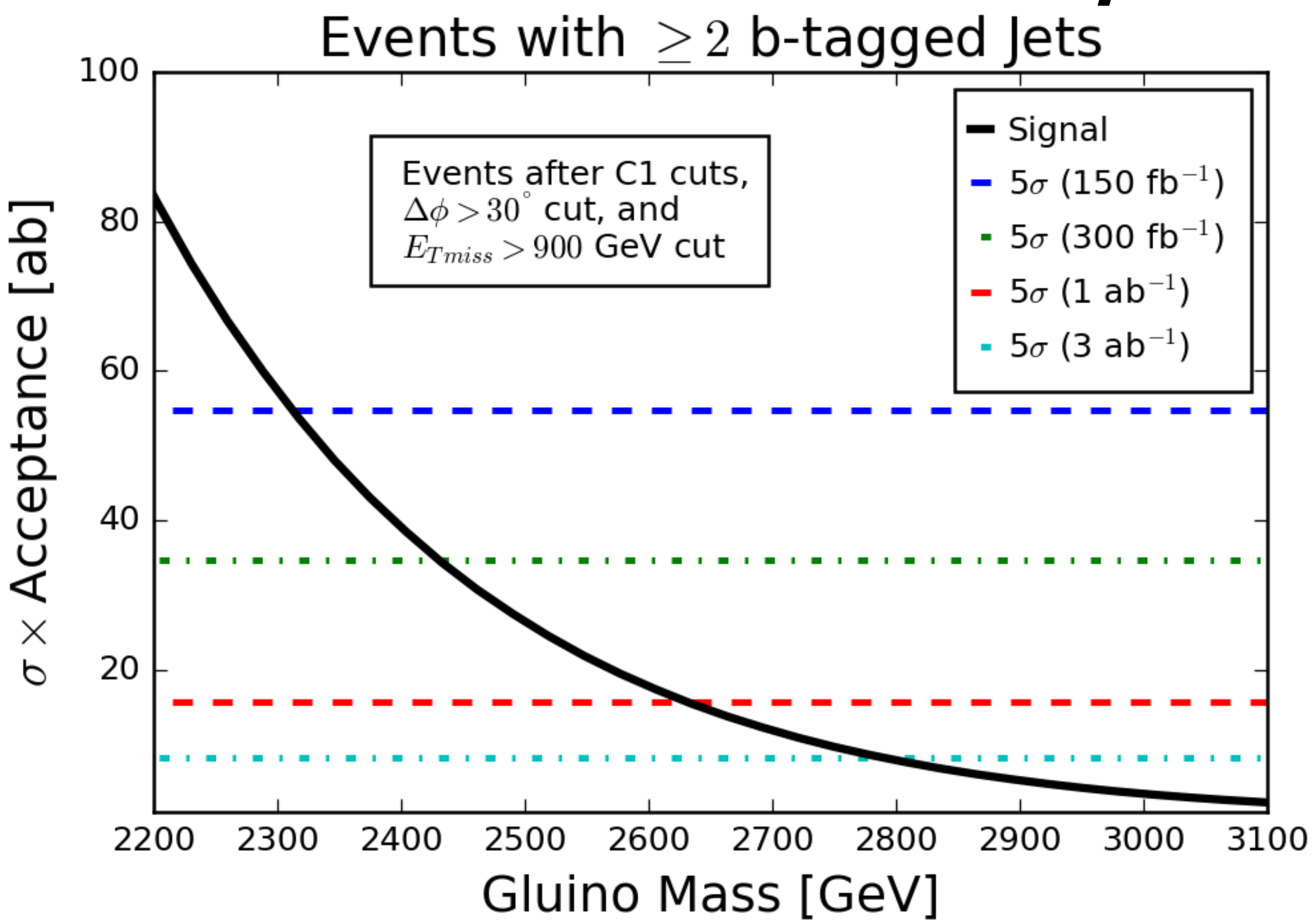
Cut	$2b$ Sig.	$2b$ BG	$3b$ Sig.	$3b$ BG
C1	872	5.14×10^5	872	5.14×10^5
$\not{E}_T > 750$ GeV	479	340	479	340
b-tagging	311	103	133	6.31
$\Delta\phi > 30°$	249	28.1	105	1.78
Final $\not{E}_T$ cut	167	5.31	105	1.78

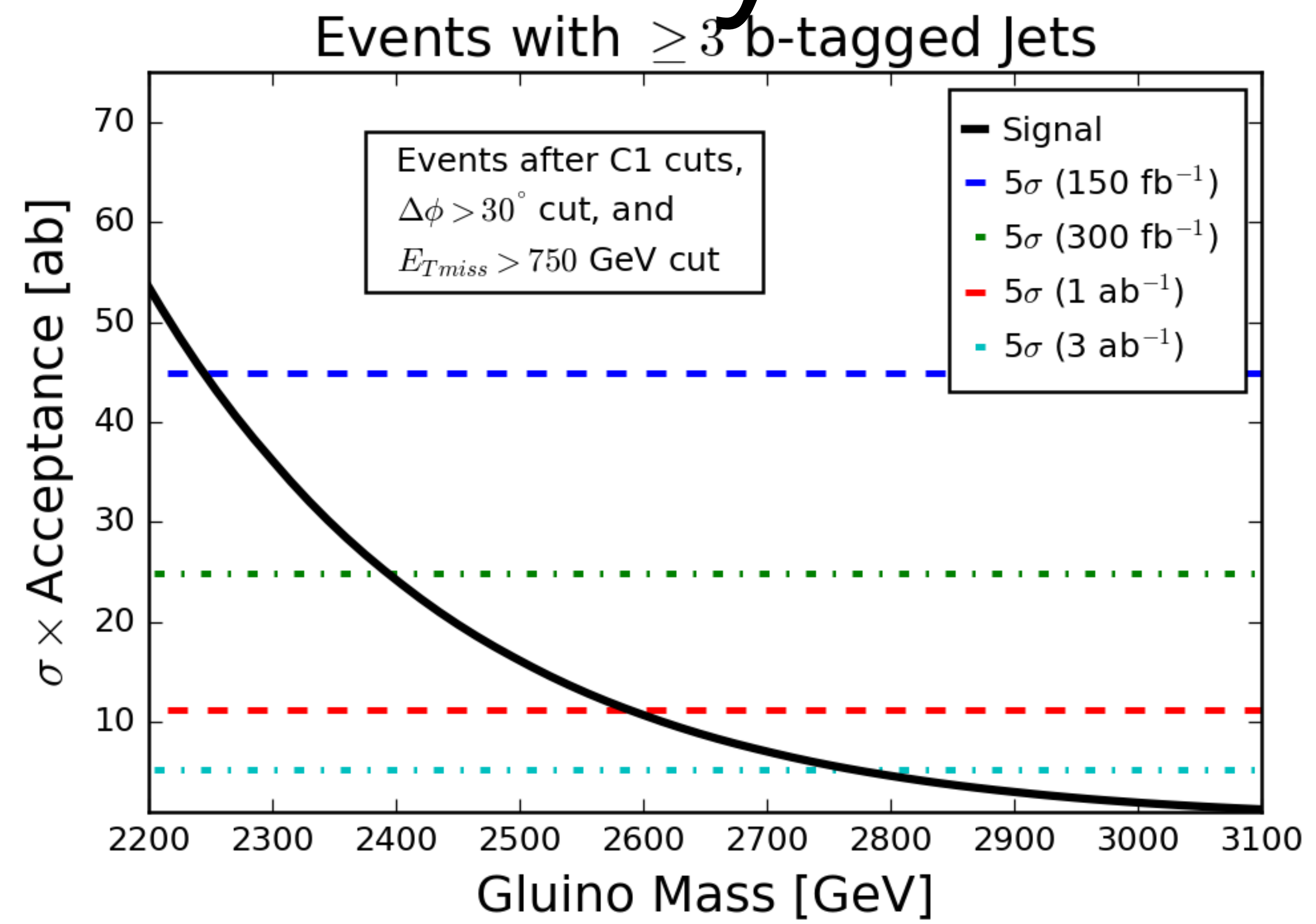
- Cut table for signals and backgrounds
- End up with 100-200 ab signal, large S/B

	Isajet	CMS Medium	CMS Tight
≥ 2 tagged b jets, $\not{E}_T > 900$ GeV	167 (32)	207 (25)	121 (39)
≥ 3 tagged b jets, $\not{E}_T > 750$ GeV	105 (59)	182 (47)	61.1 (78)

- Results relatively robust to choice of b-tagging algorithm

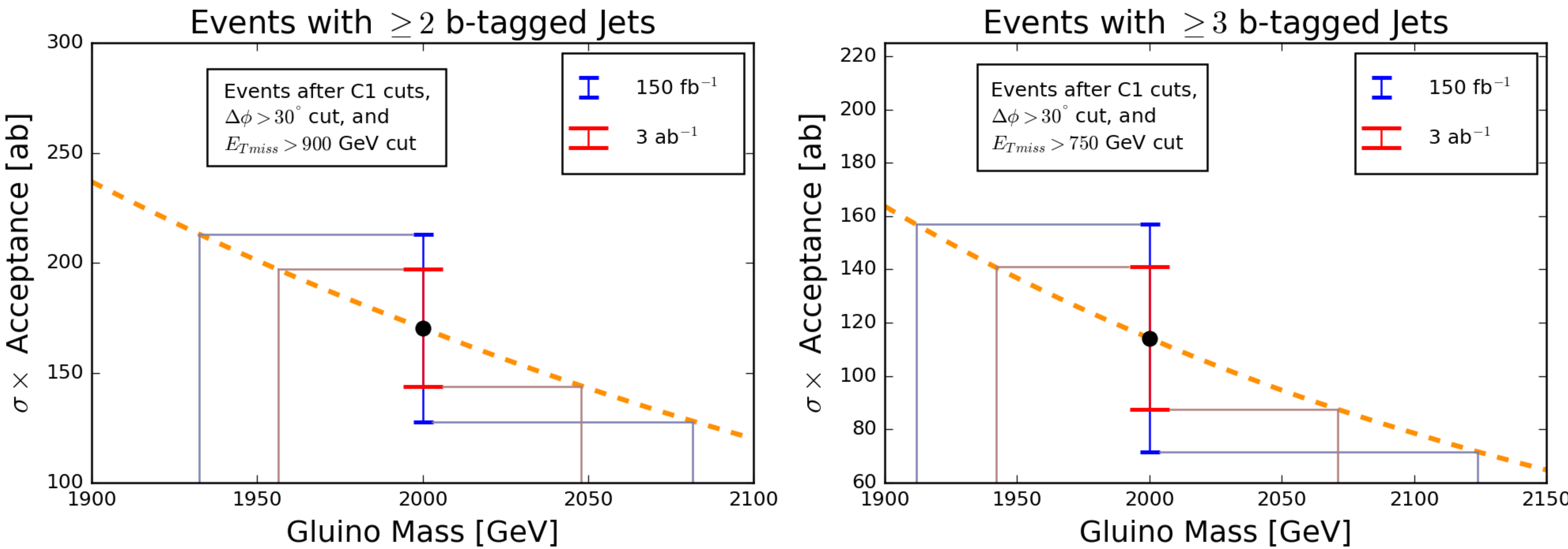
Reach/ Discovery





- Using signal cross sections x efficiency along model line (varying $m_{1/2}$)
- Background cross sections x efficiency from previous slide
- Determine signal cross section for which Poission p-value for background only hypothesis drops below 5σ if the expected number of (S+B) events observed
- Ultimate reach ~2800 GeV for high luminosity LHC

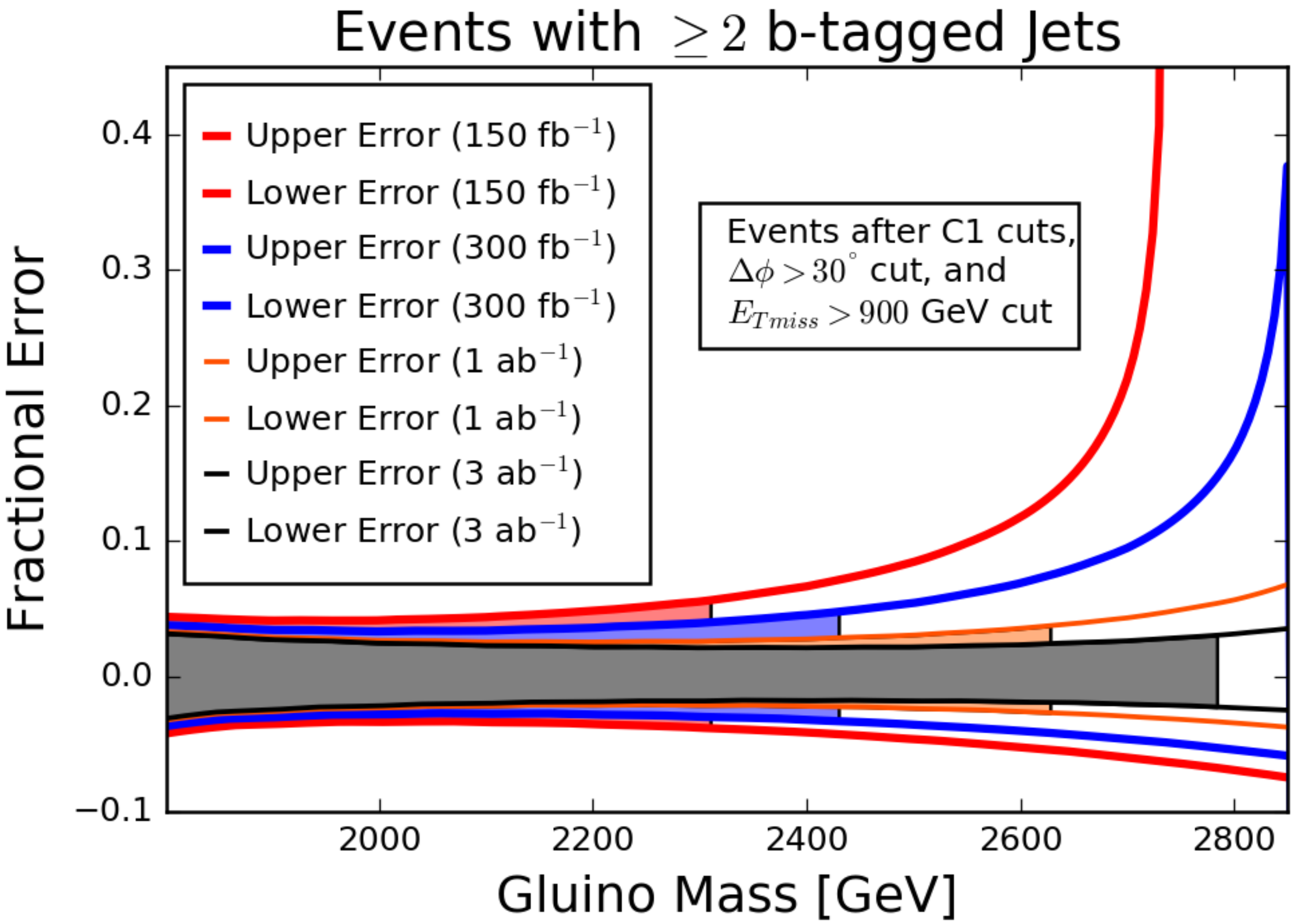
Mass Measurement

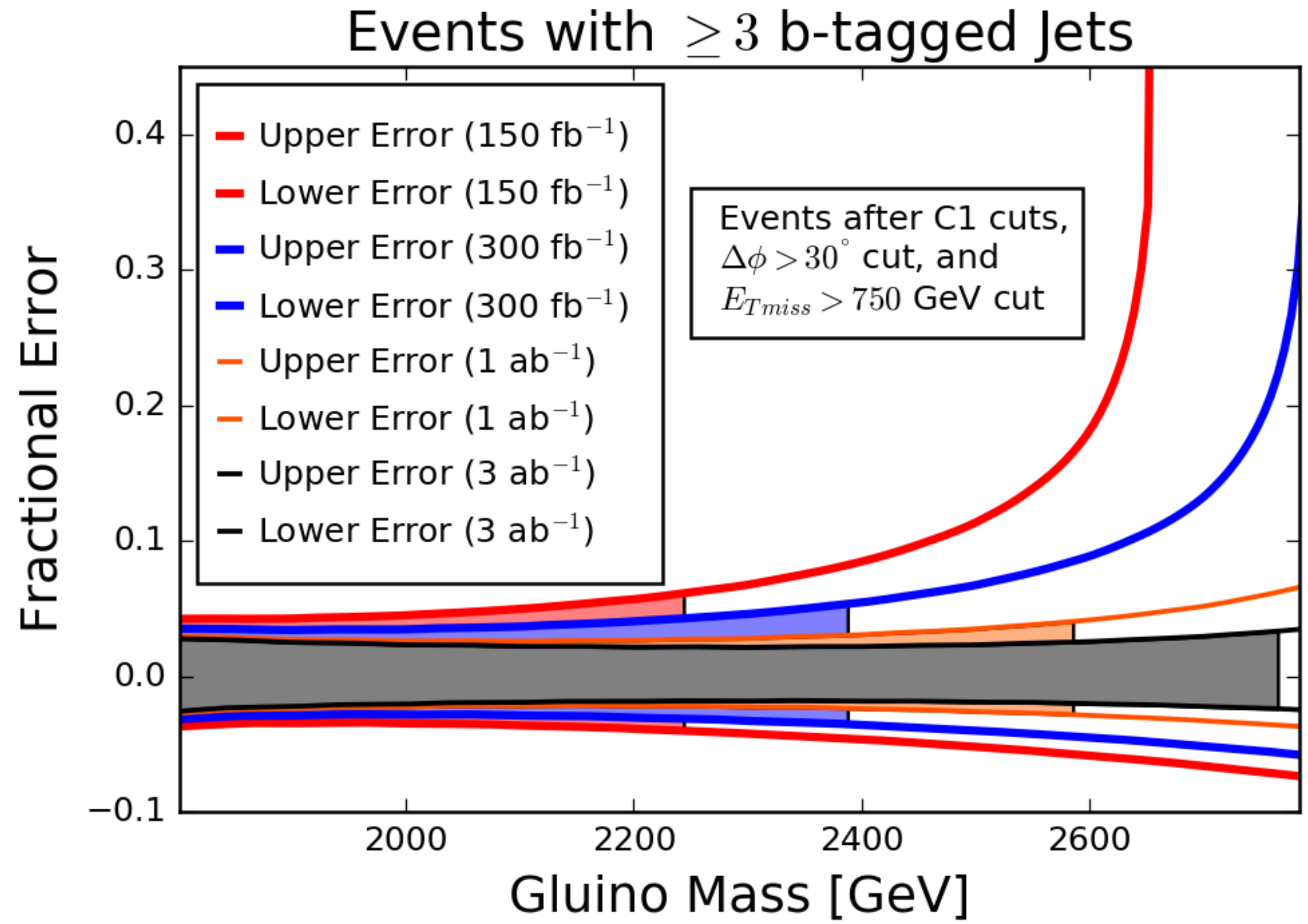


Error bars include systematics and statistical errors

- To perform a mass measurement we use the observed number of events to infer a gluino mass
- We assume symmetric 15% uncertainty on the theory cross sections times efficiency
- Currently theory cross section errors are ~30-40%, but much of this comes from uncertainties in the gluon pdf, so should drop significantly by the time these measurements could be made
- Errors on our efficiencies harder to estimate, cuts were conservative to reduce these errors

Mass Measurement



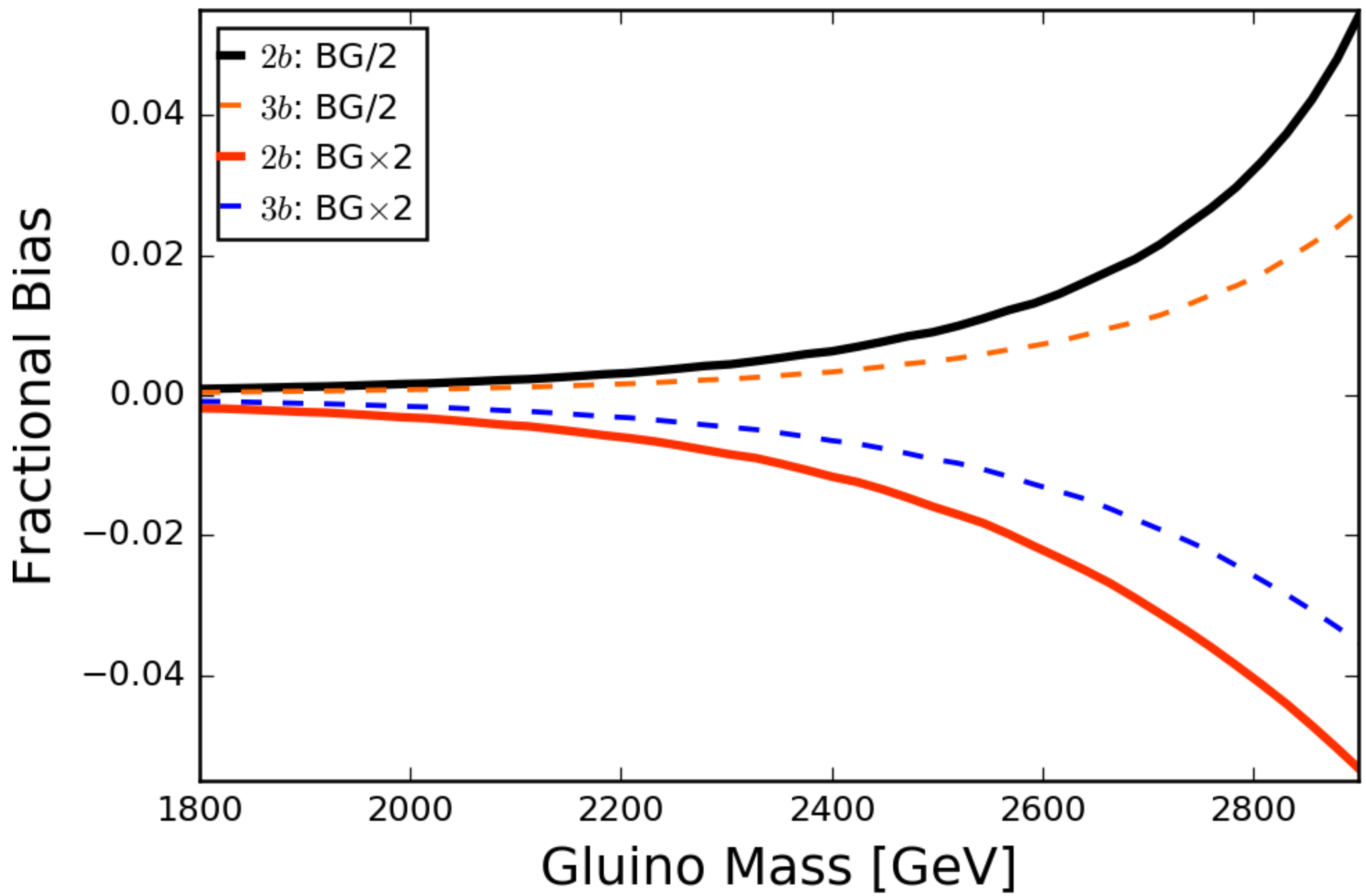


- Expressed as a percent error on the gluino mass, we find 2-5% measurements are possible for all discoverable gluino masses
- Relatively precise measurements for lower luminosities as well
- (Roughly) systematics limited in the left half of plots, statistics limited in the right half

Bias

- Errors on our background cross sections x efficiency can bias our measurement

- Factor of 2 errors have a modest effect on our results



- This relative robustness to background errors is the result of our conservative strategy of emphasizing low background rates

- Looser cuts would have reduced statistical errors

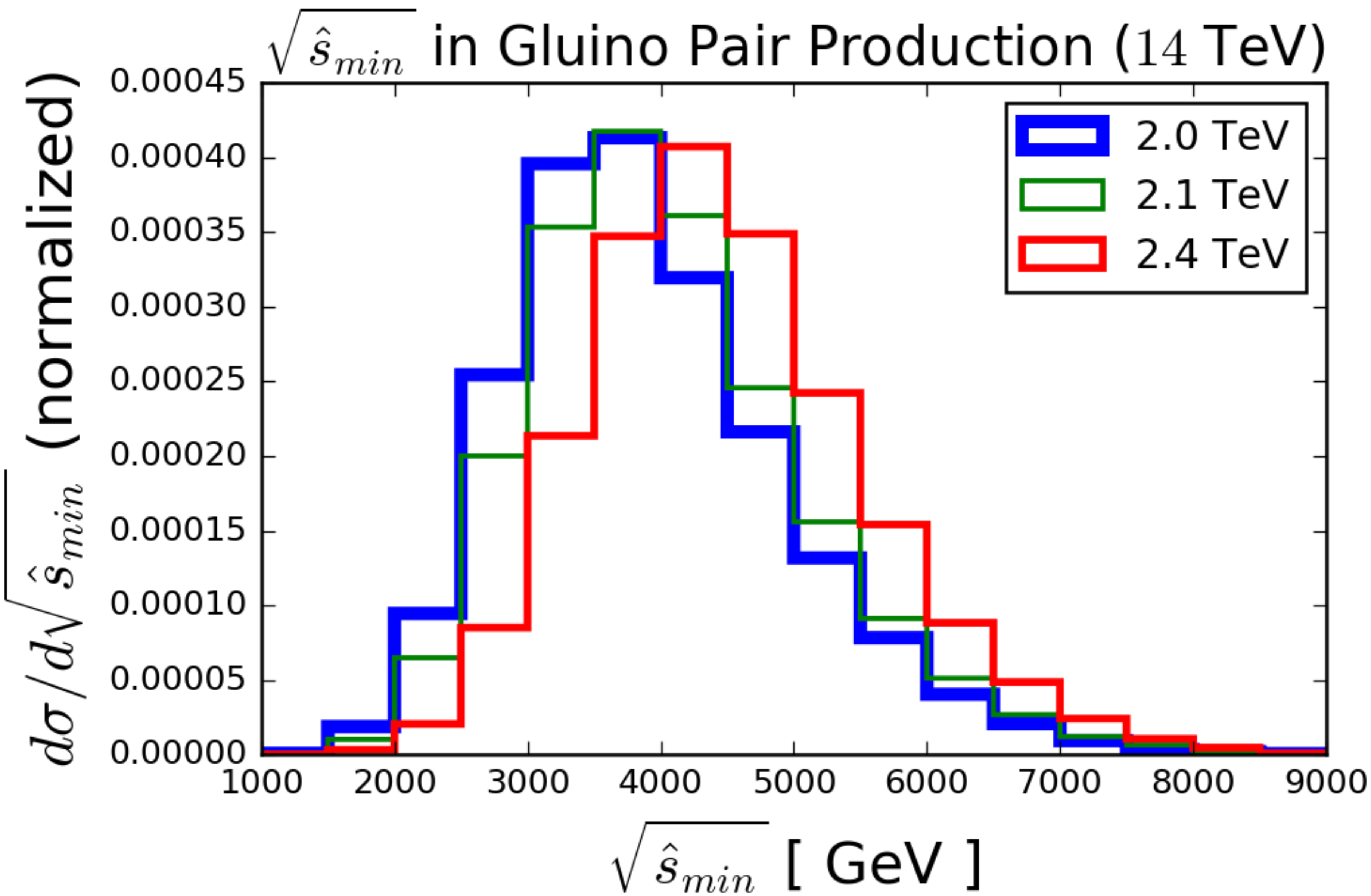
Kinematic Measurement of Gluino Mass

- We do pretty well with only rate information, why bother with kinematic variables?
- **Complementary systematics**
  - Theory error on total signal cross section irrelevant for kinematic variables
  - Jet energy scale, etc. not very relevant for rate measurement
  - Errors on the shapes of distributions affect both, we will try to be conservative— start with simple variables
- **In general more information = better**

$\sqrt{\hat{s}}_{min}$

- Konar, Kong, Matchev 2008.
- Calculate the minimum partonic center of mass energy consistent with
- No event reconstruction needed
- Peak of distribution represents mass scale of events

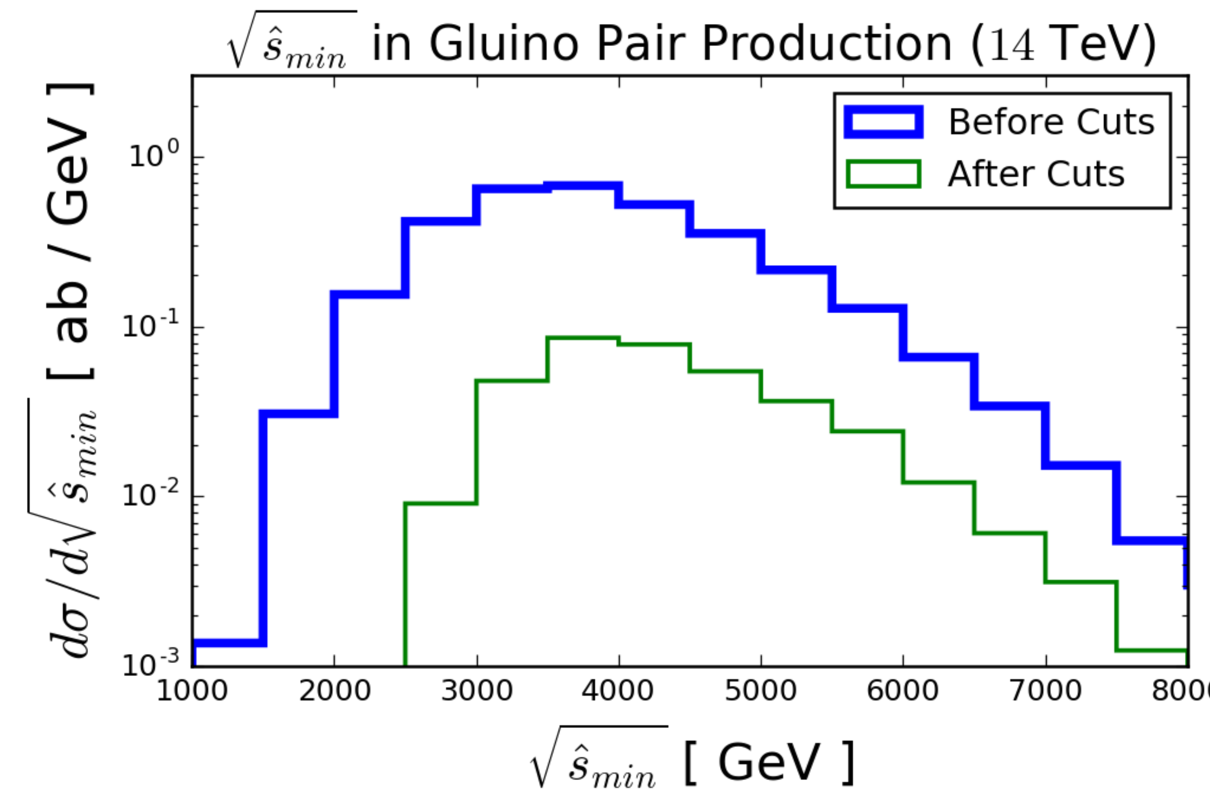
$\sqrt{\hat{s}_{min}}$ Results

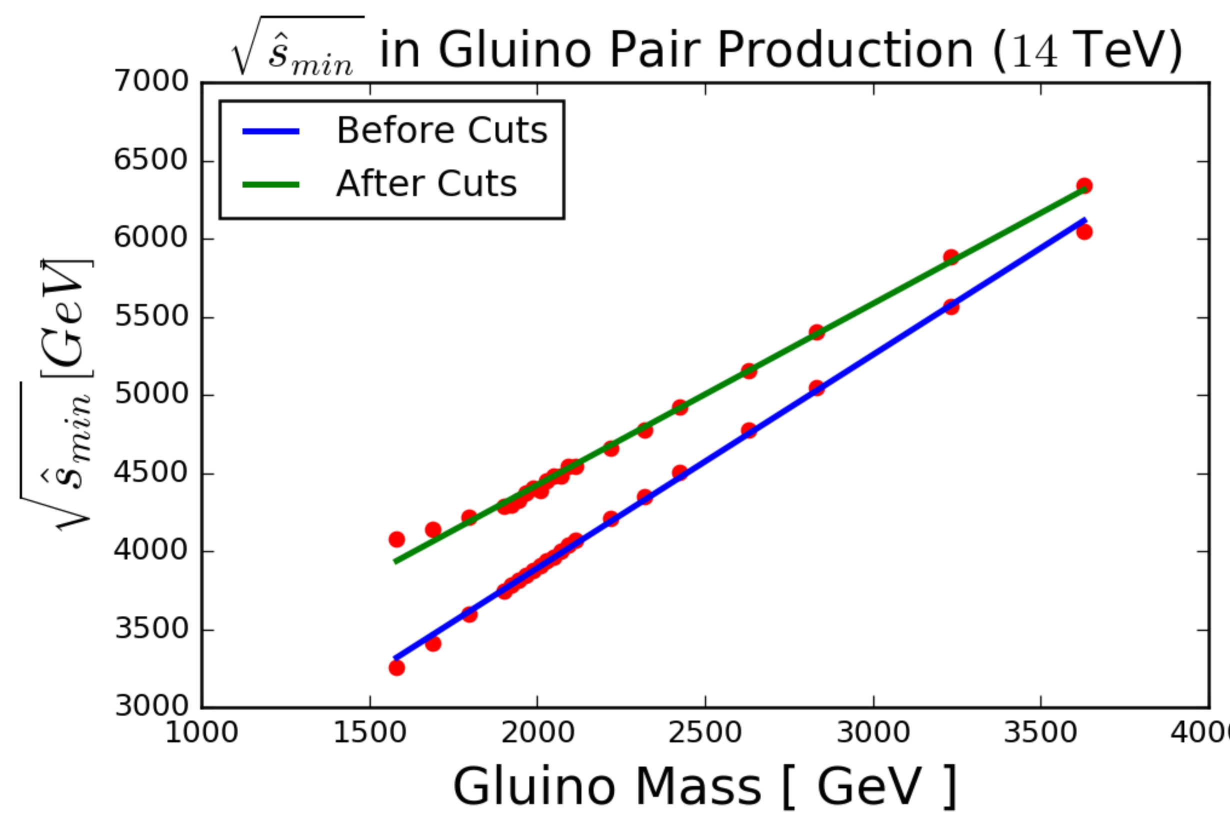


$\sqrt{\hat{s}_{min}}$ (with invisible particle mass set to zero) for all gluino events for various gluino masses along our model line

$\sqrt{\hat{s}_{min}}$ Results

- You might worry that the distribution of this variable would be sculpted by cuts
- You would be right, though the effect on the gluino mass measurement is relatively small.
- Slope of $\sqrt{\hat{s}_{min}}$ vs. gluino mass line reduced from 1.4 to 1.2
- Standard deviation / slope 830 GeV: "1 event error*"
- ~550 events (2 TeV) → 35 GeV error on gluino mass
- 50 GeV error with 300 events (2.1 TeV)
- 100 GeV error with 70 events (2.4 TeV)
- Better than our rate measurement at 2 TeV, worse but comparable at 2.4 TeV

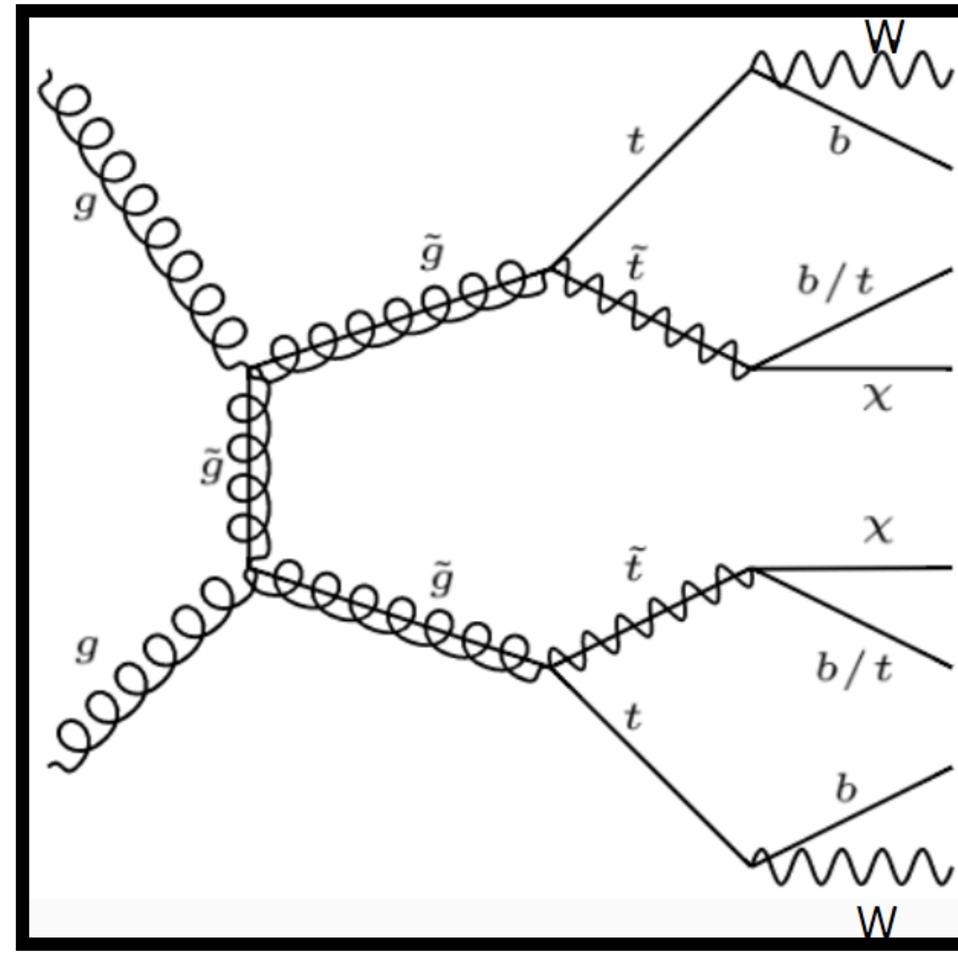




Constrained Subsystem M_2

- More sophisticated kinematic variables may improve upon $\sqrt{\hat{s}_{min}}$ the cost of combinatoric backgrounds, etc.

- A particularly interesting direction involves constrained subsystem M2 variables



- **Constrained**: demand gluino mass, stop mass mass equal in both decay chains

- **Subsystem**: Consider various reconstructed (3 + 1 dimensional) masses, not just the parent mass

- Burns, Kong, Matchev, Park, 2008; Cho, JG, Kim, Matchev, Moortgat, Pape, Park, 2014; Cho, JG, Kim, Matchev, Moortgat, Pape, Park, 2014

- **OPTIMASS**: Tool for calculating these variables (constrained optimization is hard!) Cho, JG, Kim, Lim, Matchev, Moortgat, Pape, Park, 2015

Conclusions

- After a SUSY discovery in HL-LHC running or at a future collider, it will be important to measure masses and other parameters
    - Likewise if new particles are from a non-SUSY BSM model
- Especially if this is an HL-LHC discovery we may have a relatively small event sample
- Gluino mass measurements using event rate obtain a precision of a few percent over the entire mass range where the gluino can be discovered
- We can obtain a ~5% measurement using a simple kinematic variable out to ~2.3 TeV at HL-LHC
- 33 TeV (or higher!) will let us do much better
- Combining rate and kinematic variables will make the measurement robust with respect to systematics
- Stay tuned!