



# APPLICATIONS FOR THE RECURSIVE JIGSAW TECHNIQUE

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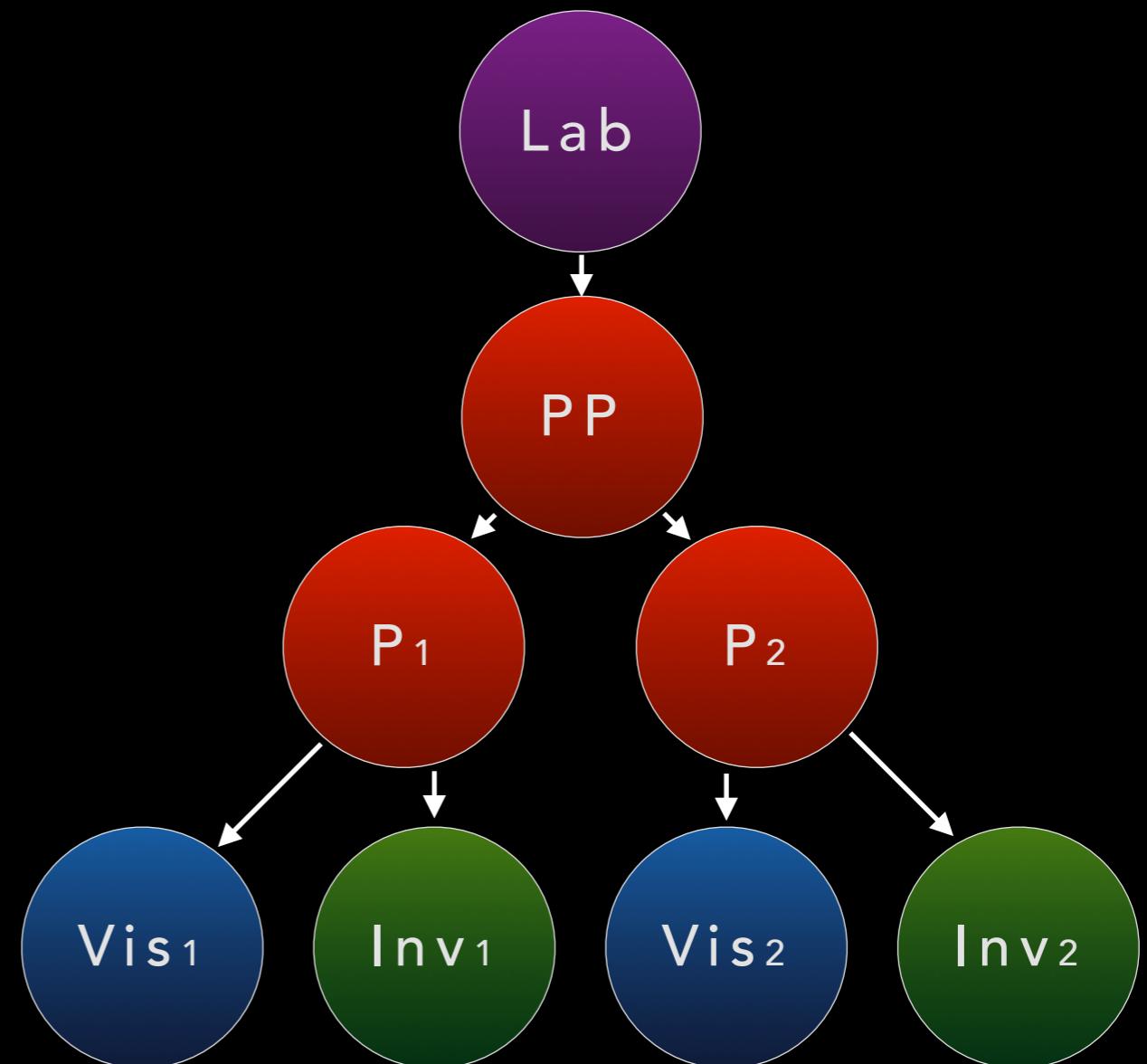
LAWRENCE LEE

WITH PAUL JACKSON, CHRIS ROGAN, MARCO SANTONI

- P PARENT FRAME
- v VISIBLE SYSTEM
- I INVISIBLE SYSTEM

# RECURSIVE JIGSAW

A GENERALIZED WAY TO GUESS  
MOMENTA IN EVENTS WITH  
MISSING TRANSVERSE ENERGY

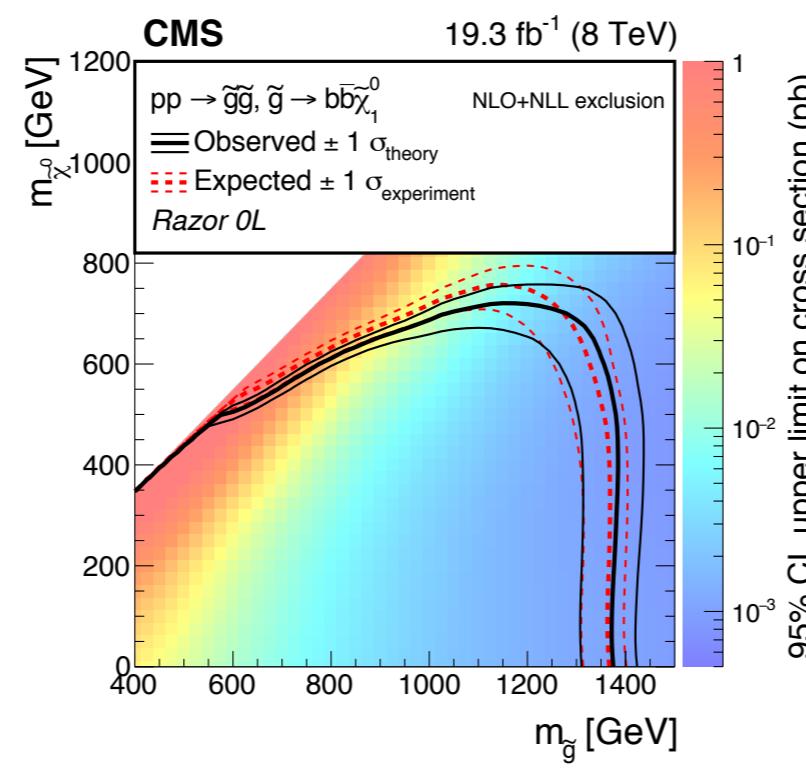
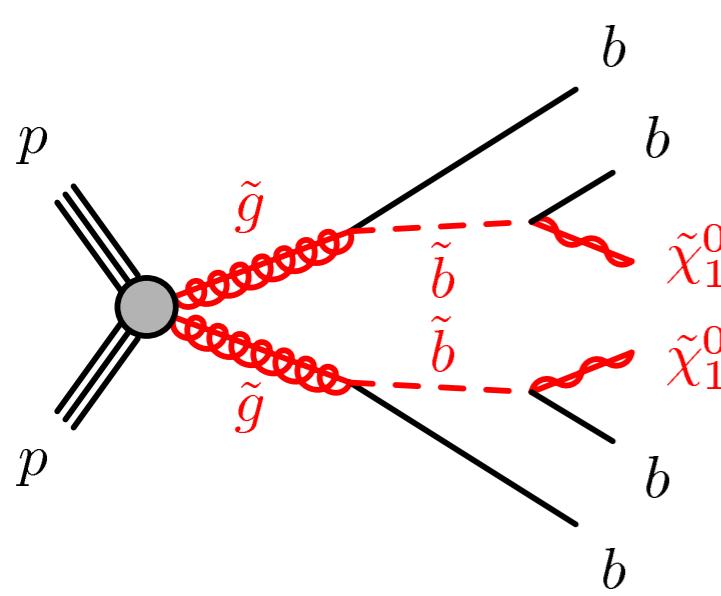


# A PARTICULARLY ILLUSTRATIVE SUSY EXAMPLE

GLUINO-MEDIATED SBOTTOM PRODUCTION

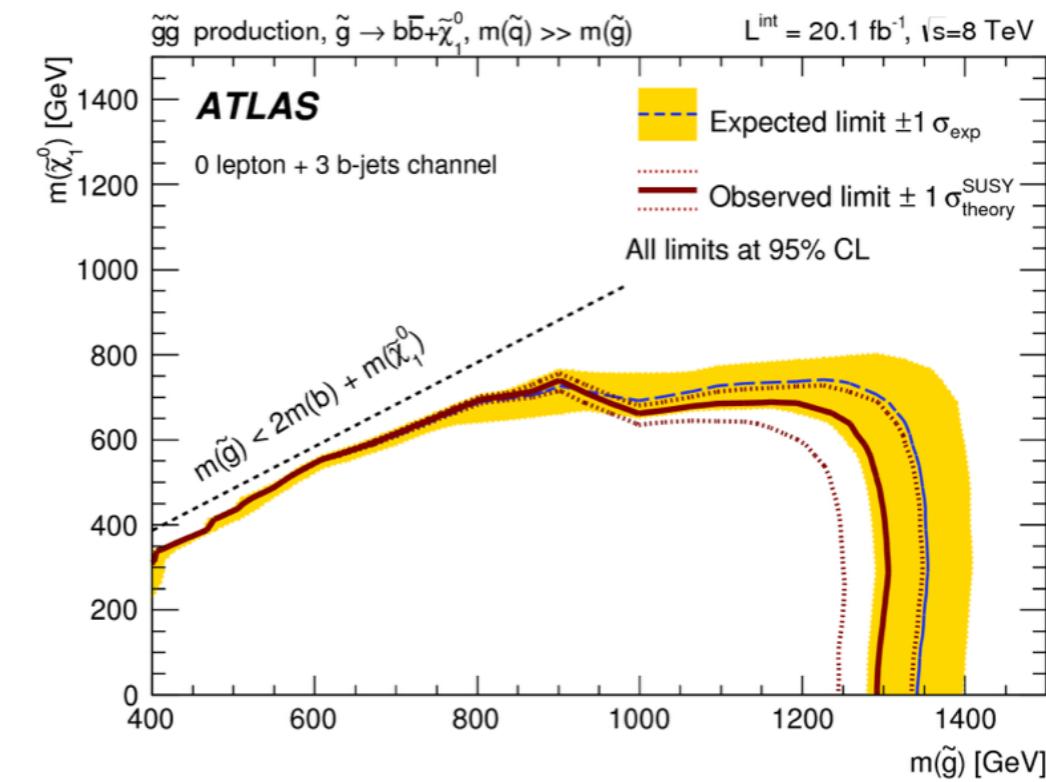
FINAL STATES WITH FOUR B-JETS LEAD TO ADDITIONAL HANDLES OVER OTHER HADRONIC  
MET-BASED SUSY SEARCHES

BUT B-JET COMBINATORICS AND MULTIPLE INVISIBLE PARTICLES CREATE A CHALLENGE



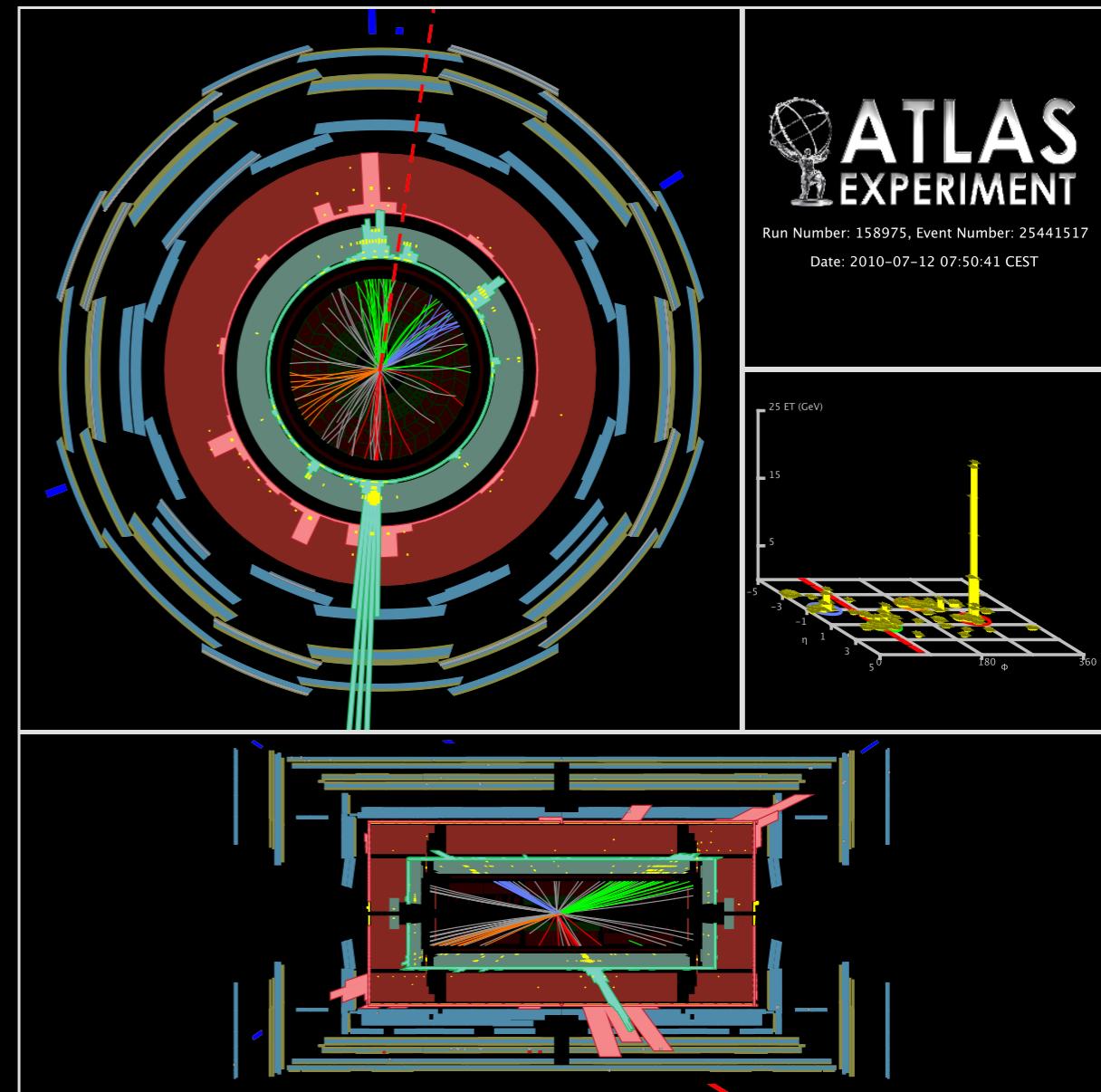
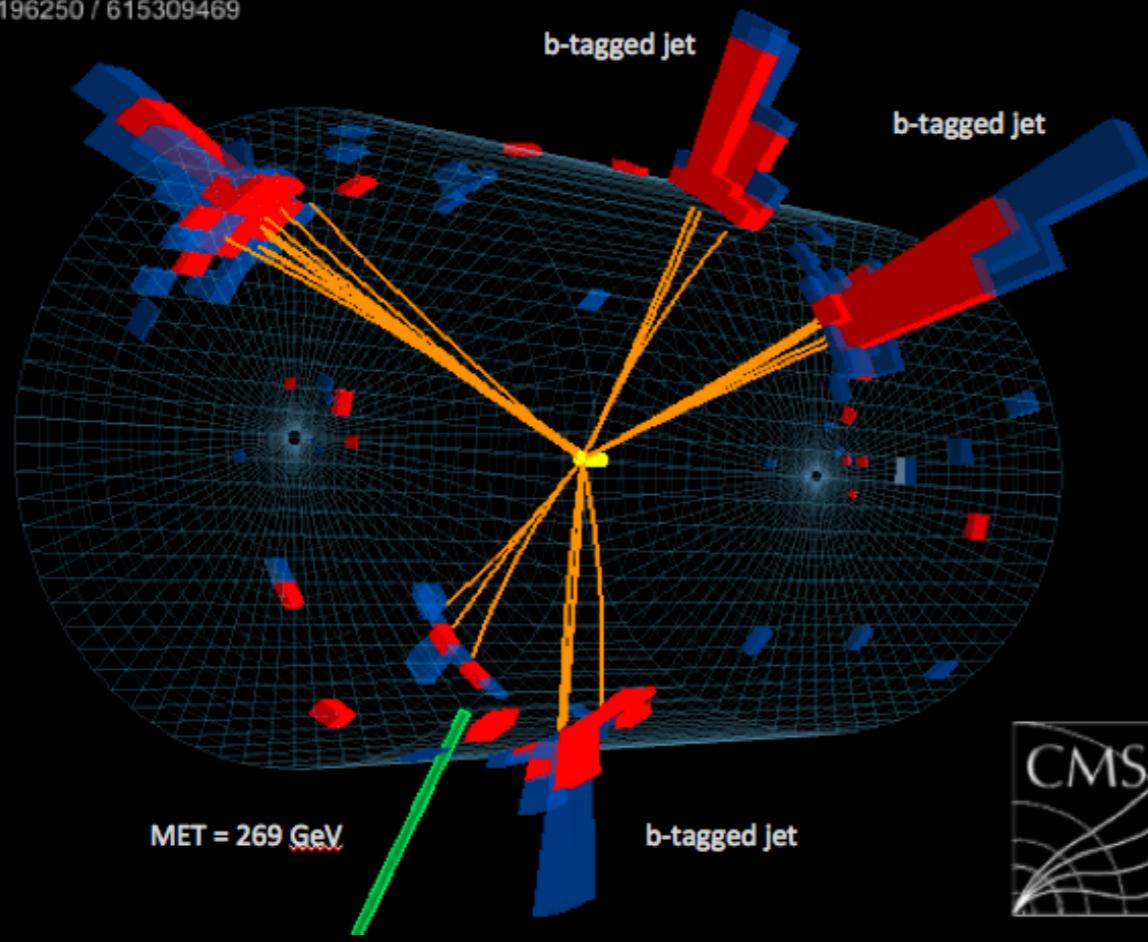
<http://arxiv.org/abs/1407.0600>

<http://arxiv.org/abs/1502.00300v1>



<http://arxiv.org/abs/1407.0600>

CMS Experiment at LHC, CERN  
Data recorded: Wed Jun 13 21:51:54 2012 PDT  
Run/Event: 196250 / 615309469

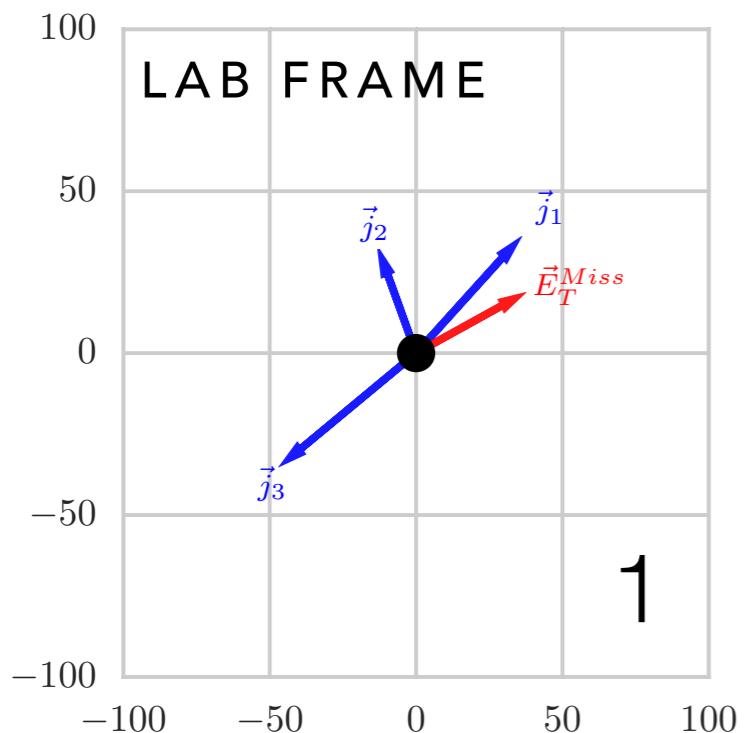


BUT THE CHALLENGE IS: THIS IS ALL WE SEE

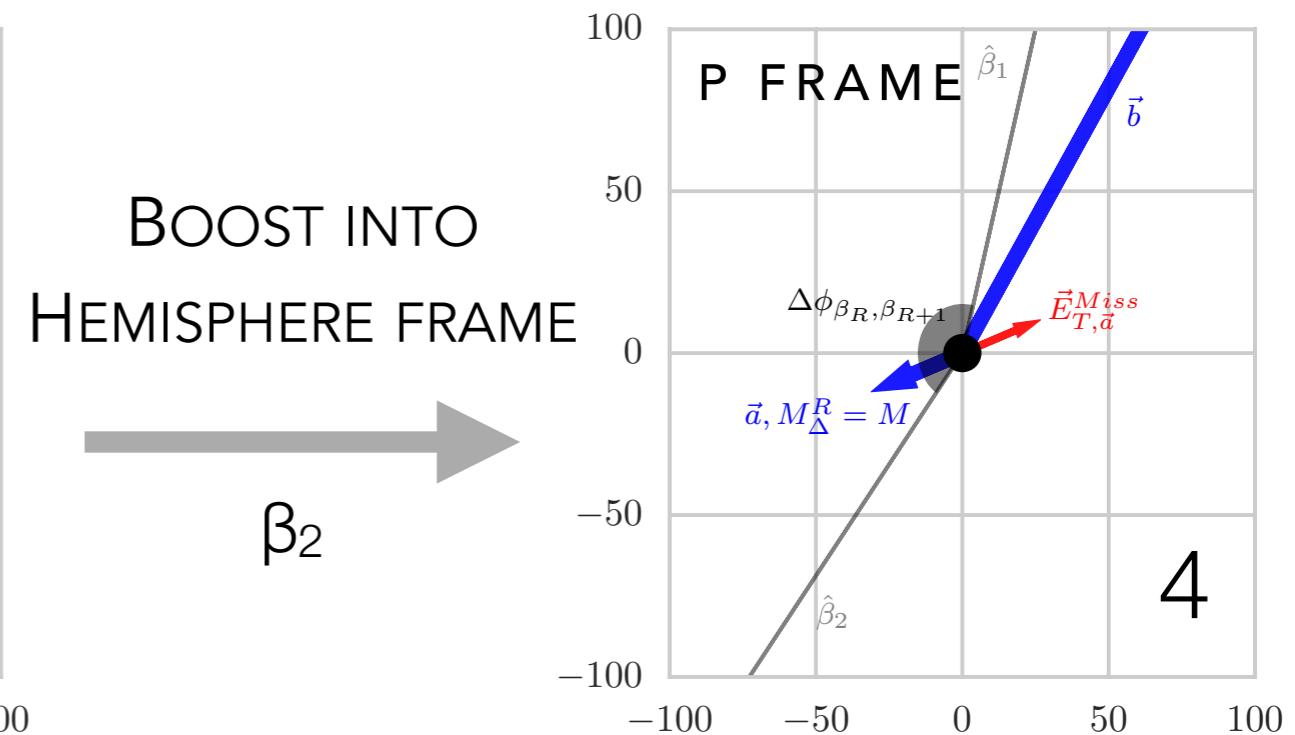
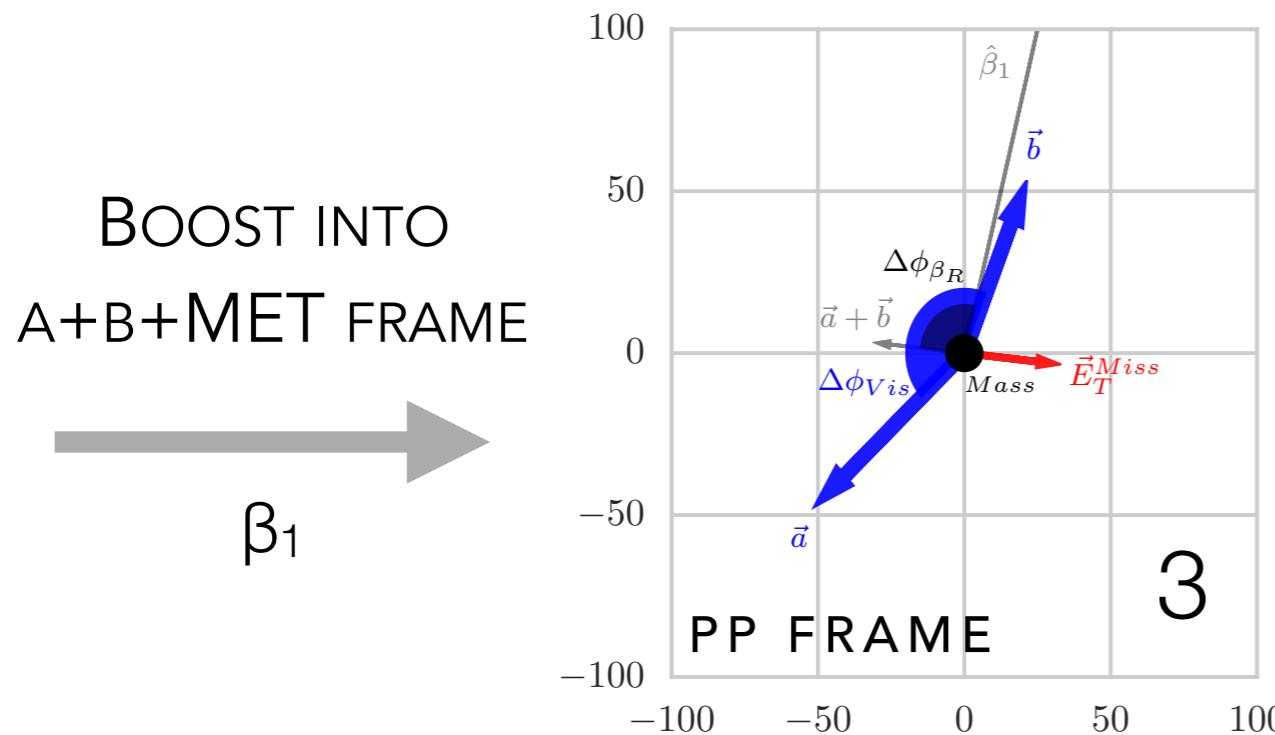
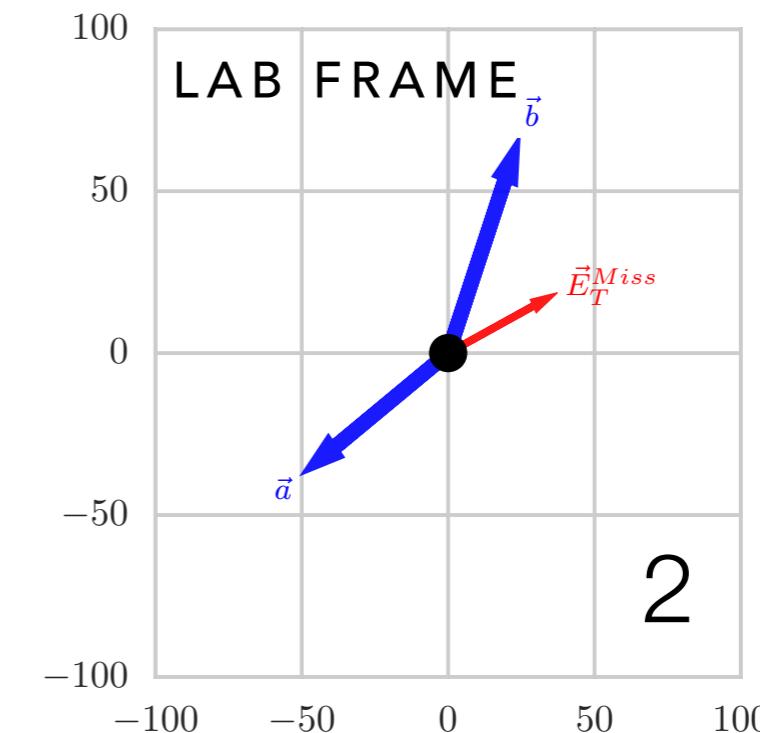
WE'VE LOST **SIX** DEGREES OF FREEDOM  
(2 INVISIBLE 4-VECTORS  $\rightarrow$  MET 2-VECTOR)

# KINEMATIC VARIABLES

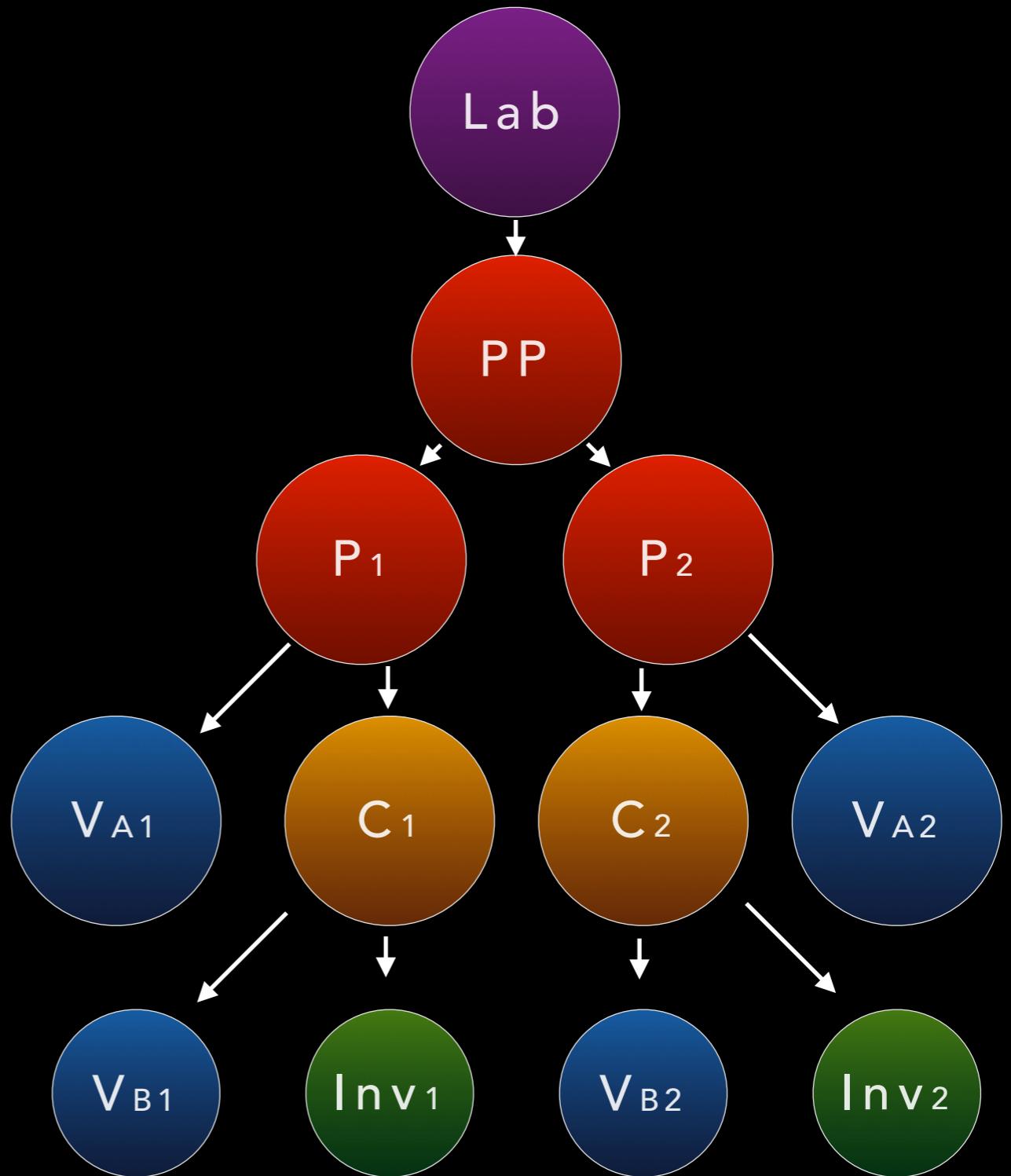
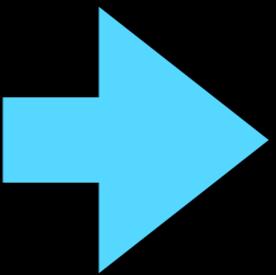
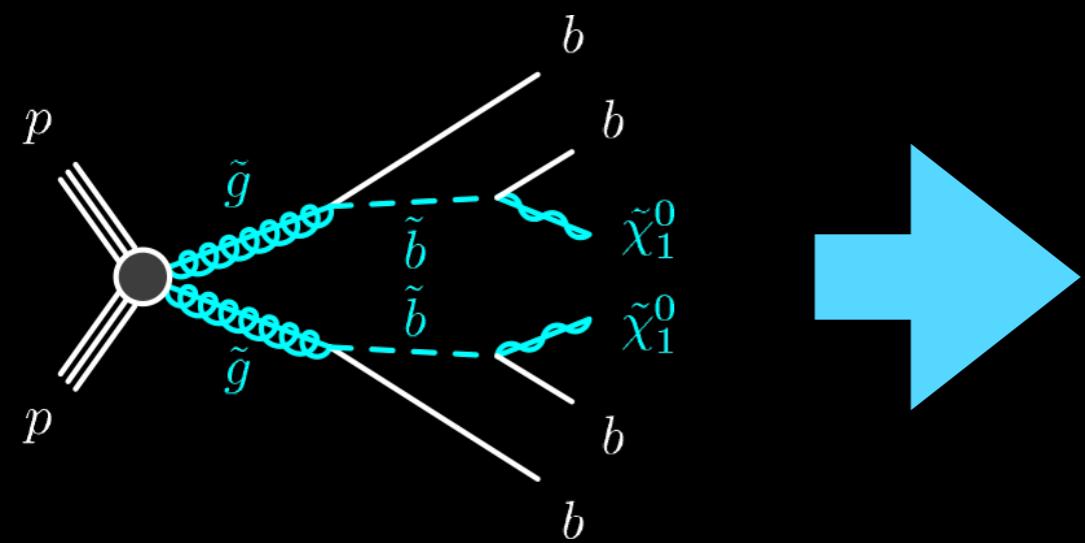
- Growing industry of constraining this under-constrained system with very powerful observables
  - e.g.  $M_{T2}$ ,  $M_{CT}$ , Razor Variables
  - Huge BSM programs from ATLAS and CMS using these techniques
  - Extremize on a global view of event
- Recursive Jigsaw Reconstruction (RJR): a recipe for assigning 4-vectors to the invisible particles to constrain system at each step of decay
  - To build a suite of **complementary variables**
  - A significant extension of Super-Razor
  - **See Paul Jackson's talk for more info on RJR basis construction**



HEMISPHERE  
CONSTRUCTION



- P PARENT FRAME ~ GLUINO FRAME
- c CHILD SYSTEM ~ SBOTTOM FRAME
- v VISIBLE SYSTEM ~ B JETS
- i INVISIBLE SYSTEM ~ LSP

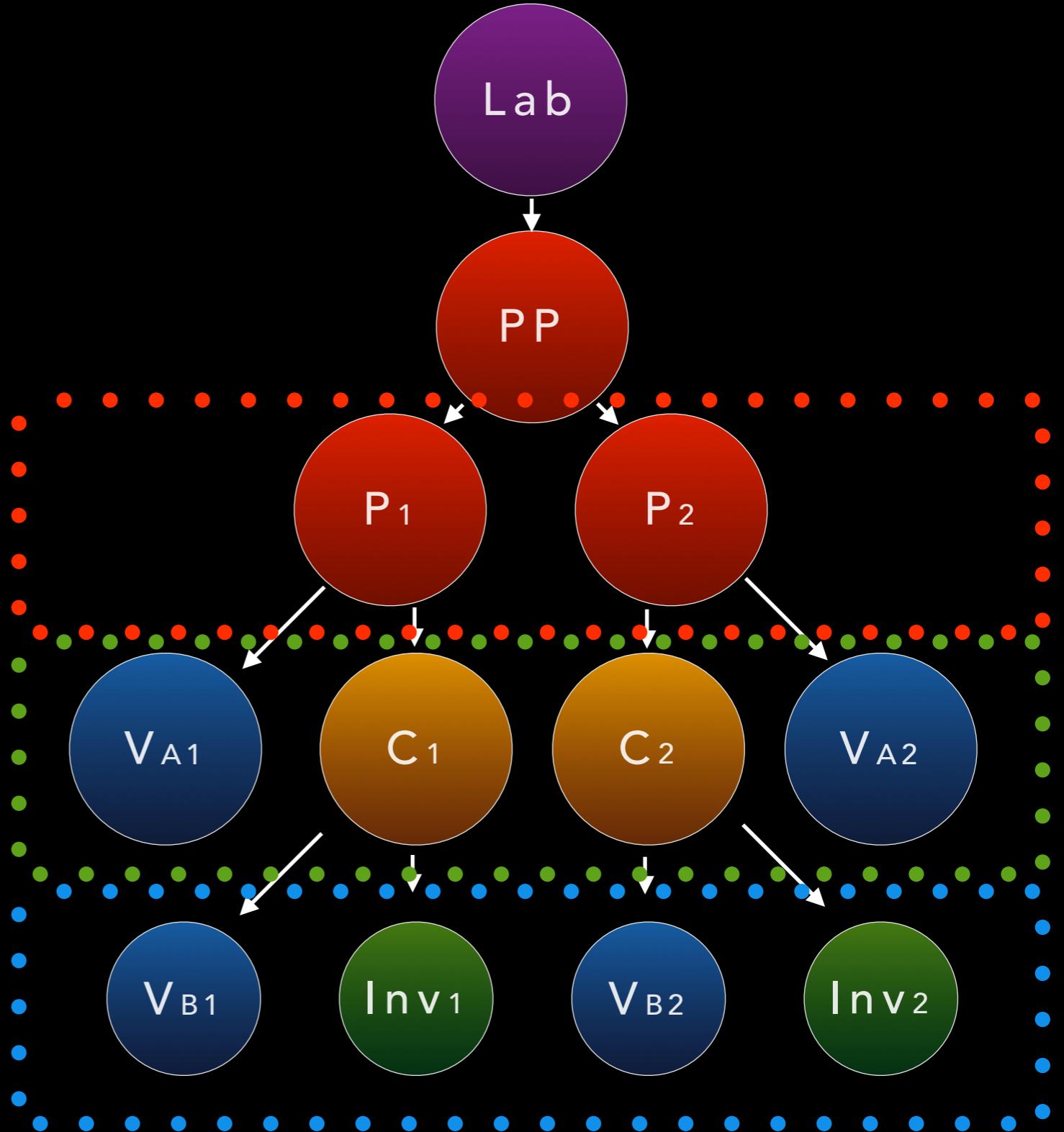


- P PARENT FRAME ~ GLUINO FRAME
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E.g. can look in these frames

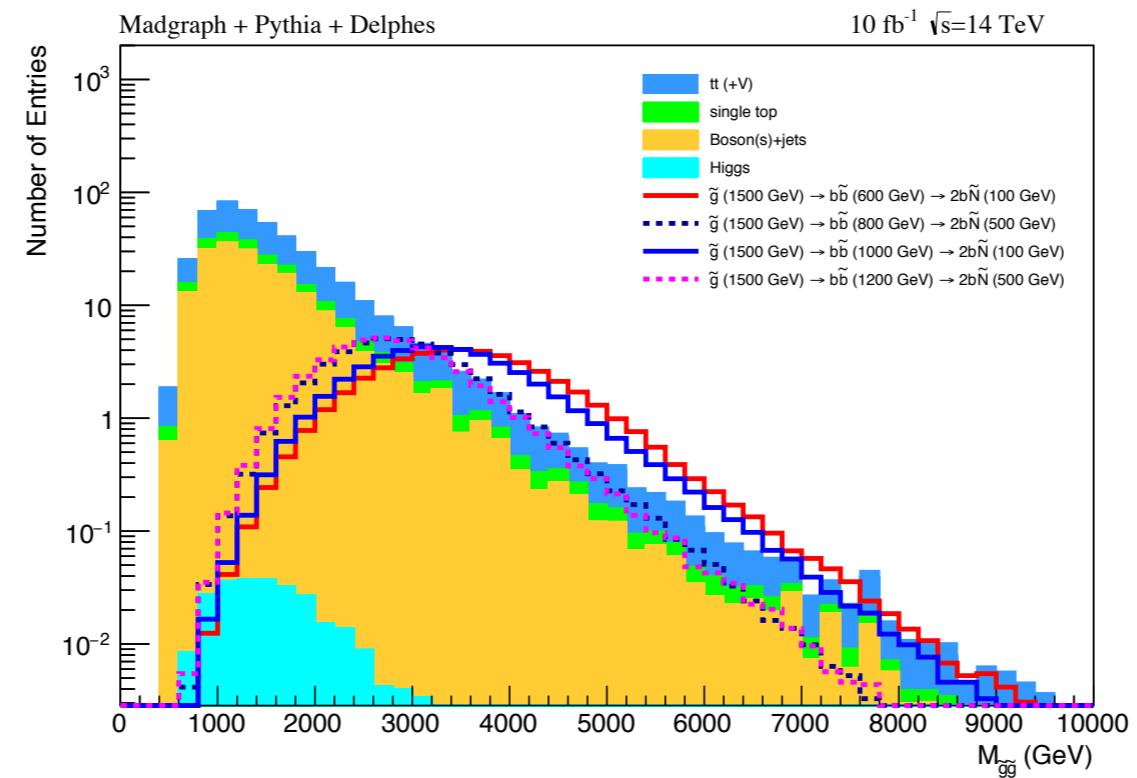
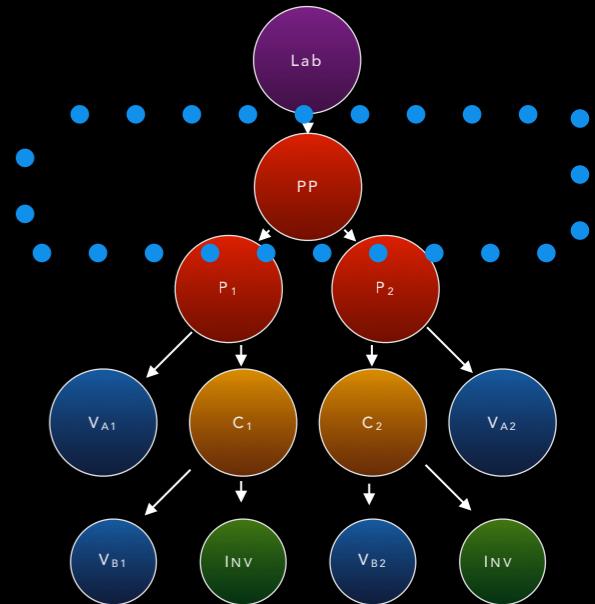
and only use this information

and save this information for  
constructing other variables



$$2x \sim g \rightarrow b\bar{b}X^0$$

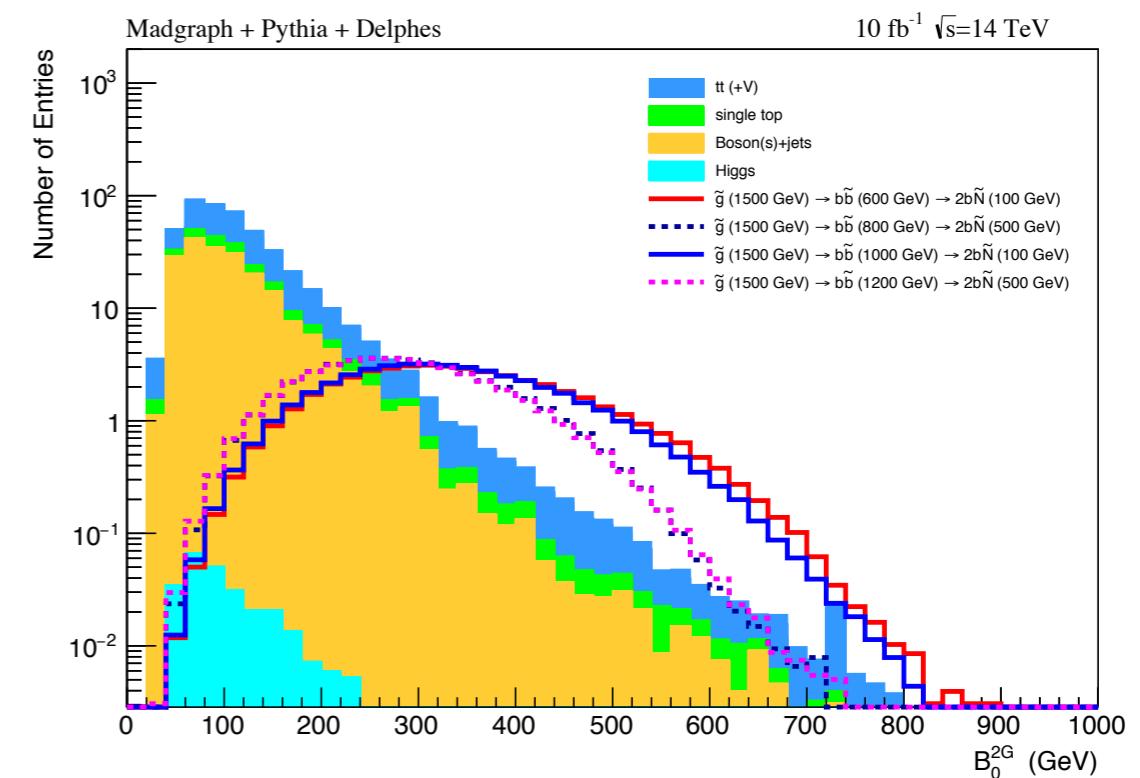
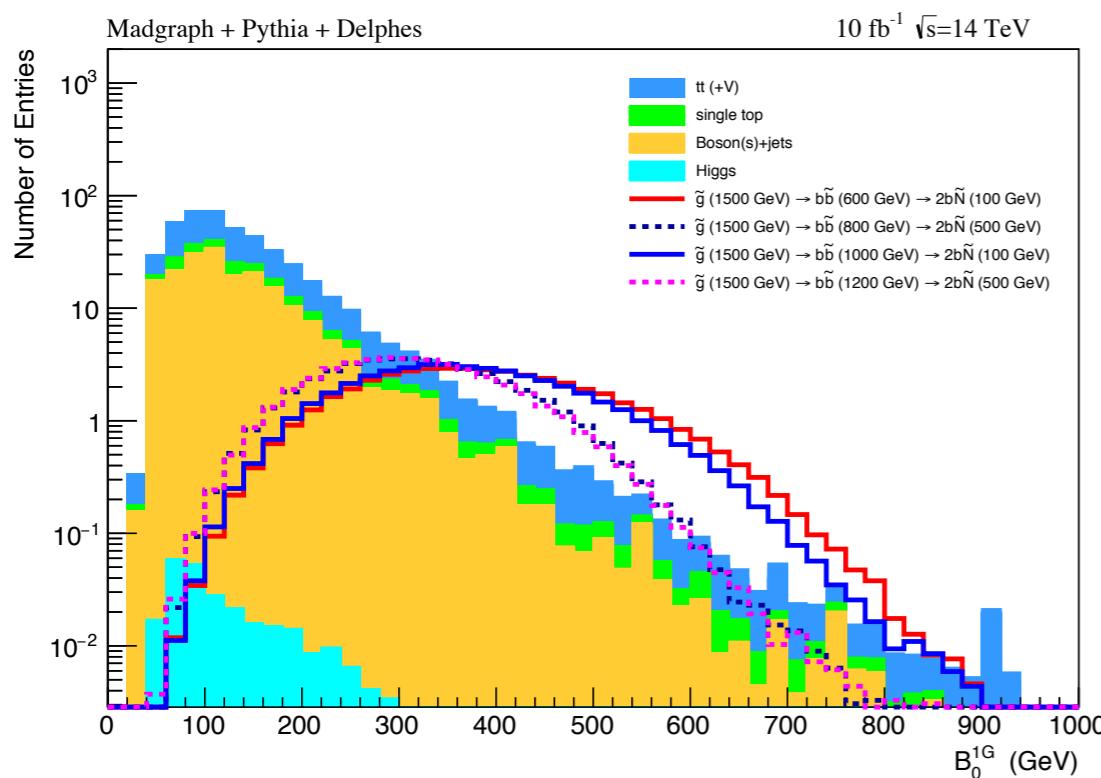
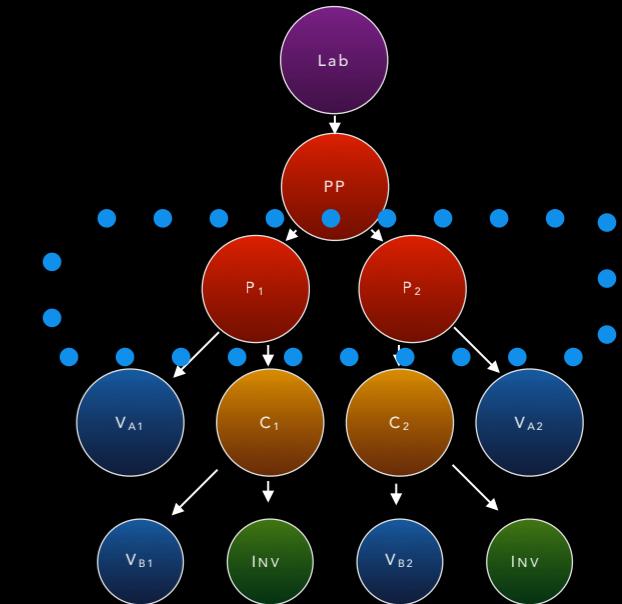
- Define observables using only information from each step
  - e.g. Zero-th level variables only look at  $(bb)_1 + (bb)_2 + \text{Invisible frame}$
  - Calculate vars from broad information about  $P_1$  and  $P_2$



bbbbXX Mass Proxy

$\dots \sim g \rightarrow b\bar{b}X^0$

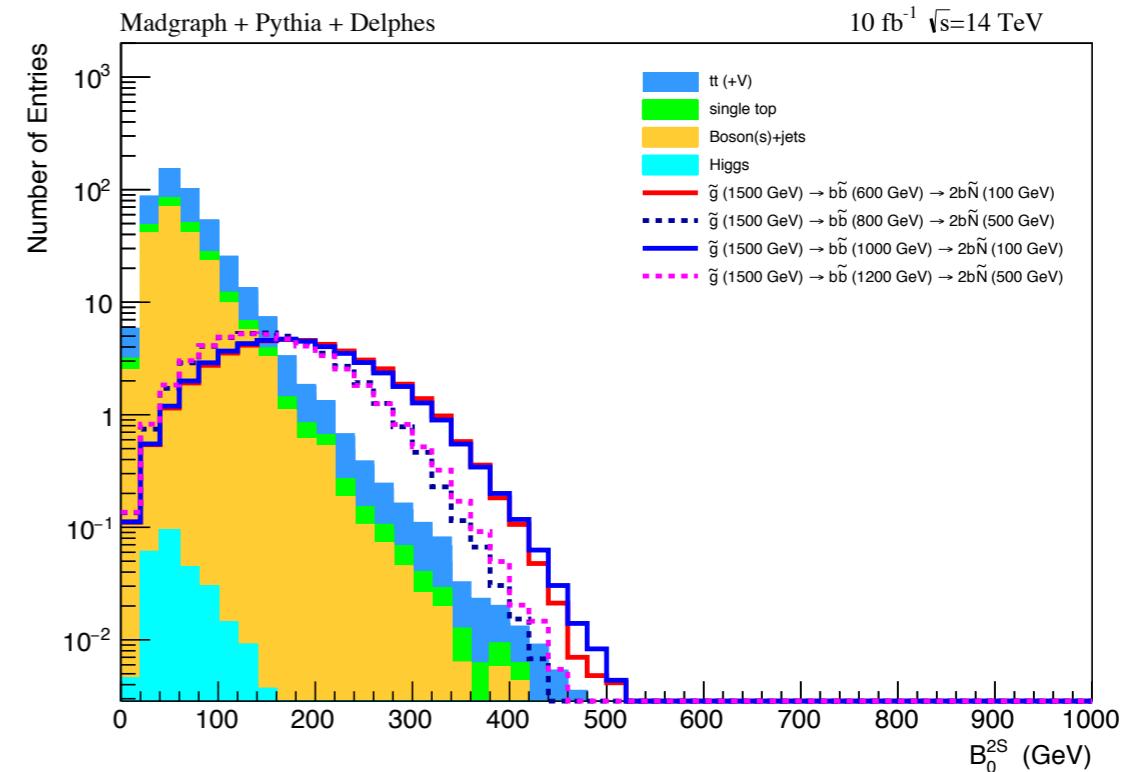
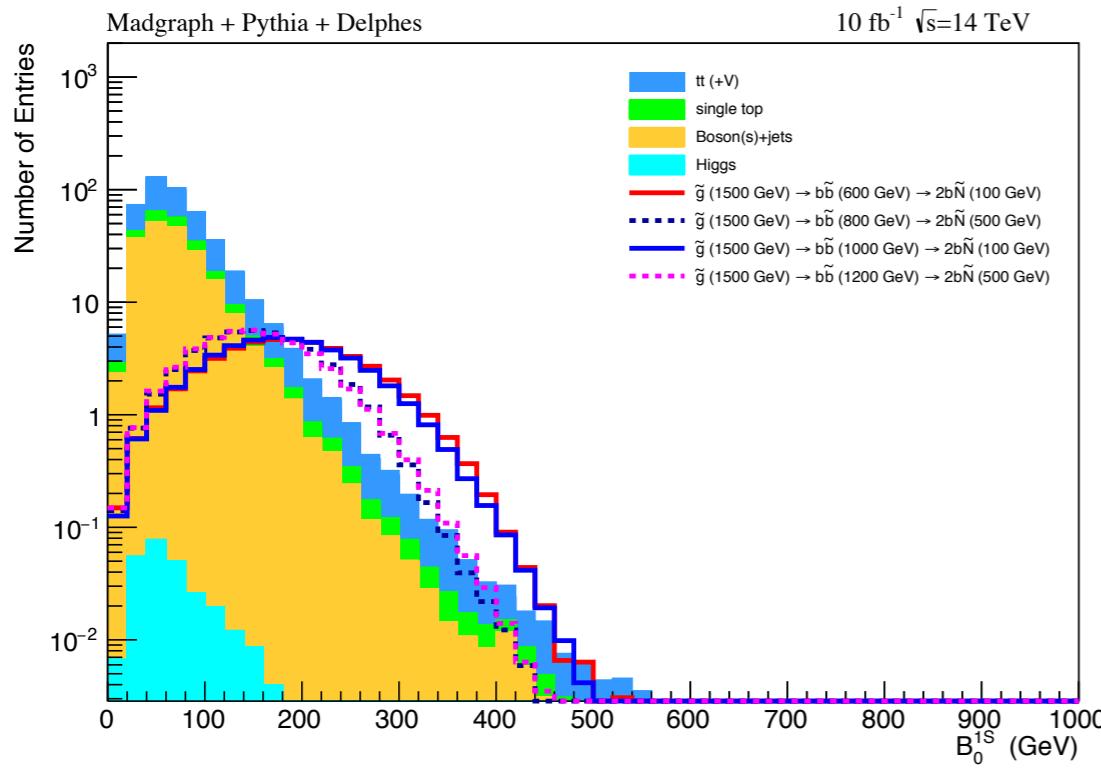
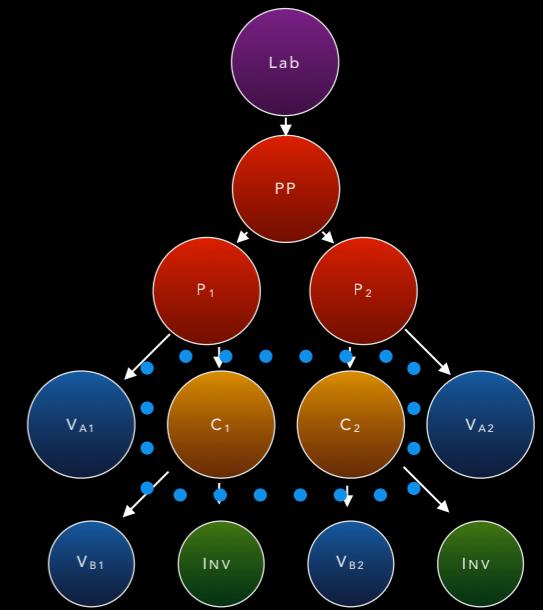
- First level variables only look at  $(bb)_i + Inv_i$
- These are calculated from aggregate info from V and C
- Not yet using structure of the “child”~“sbottom” system!



$bbX$  Mass Proxy

$$\dots \sim b \rightarrow b X^0$$

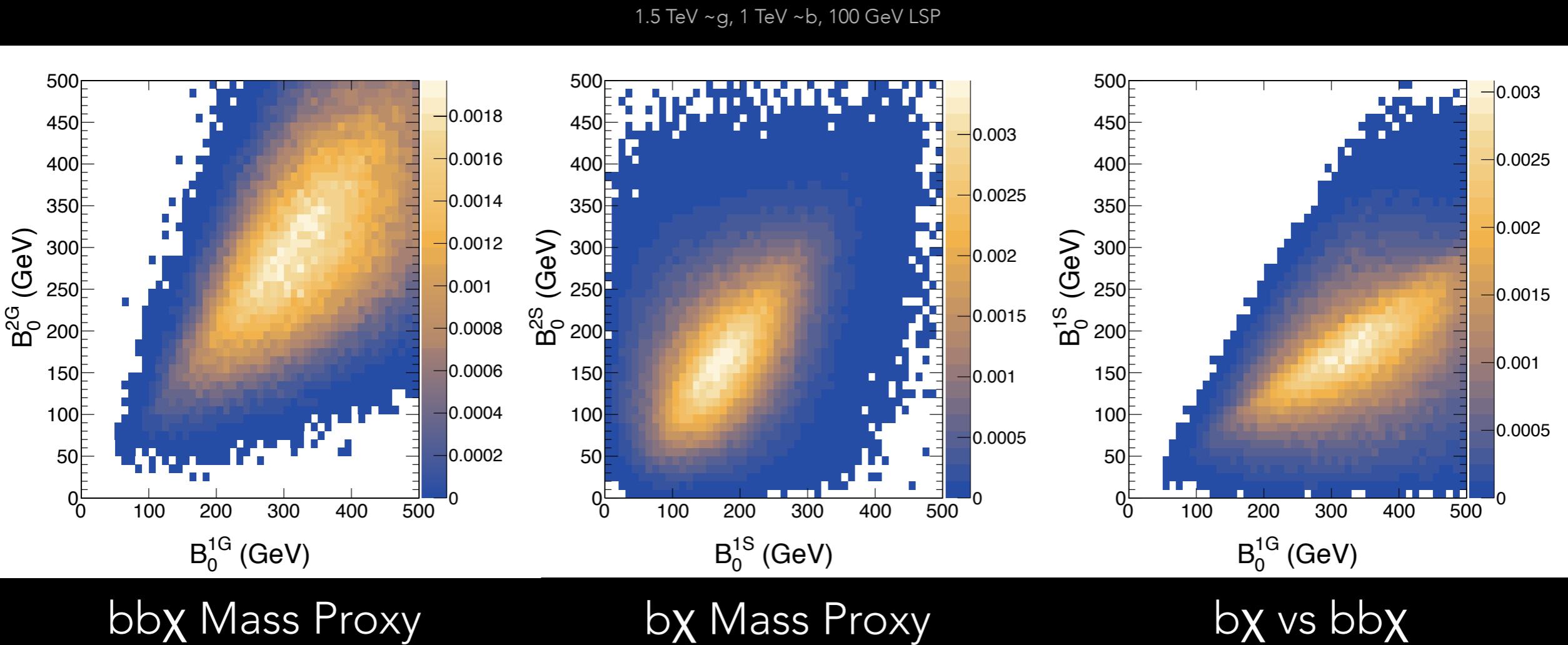
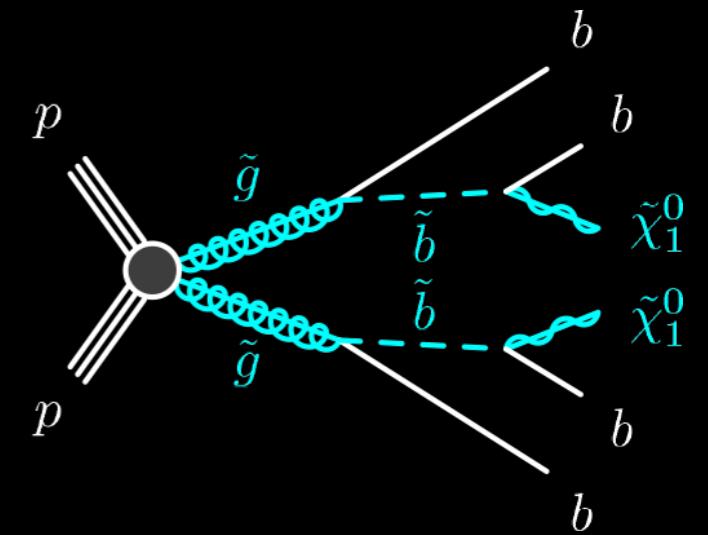
- Break up  $(bb)_i + \text{Inv} \rightarrow b_{i1} + (b_{i2} + \text{Inv})$  by similar mass minimization
- New mass scale of  $b_{i2} + \text{Inv}$  system
- Calculated in the  $bX$  proxy frame



$bX$  Mass Proxy

# CORRELATIONS

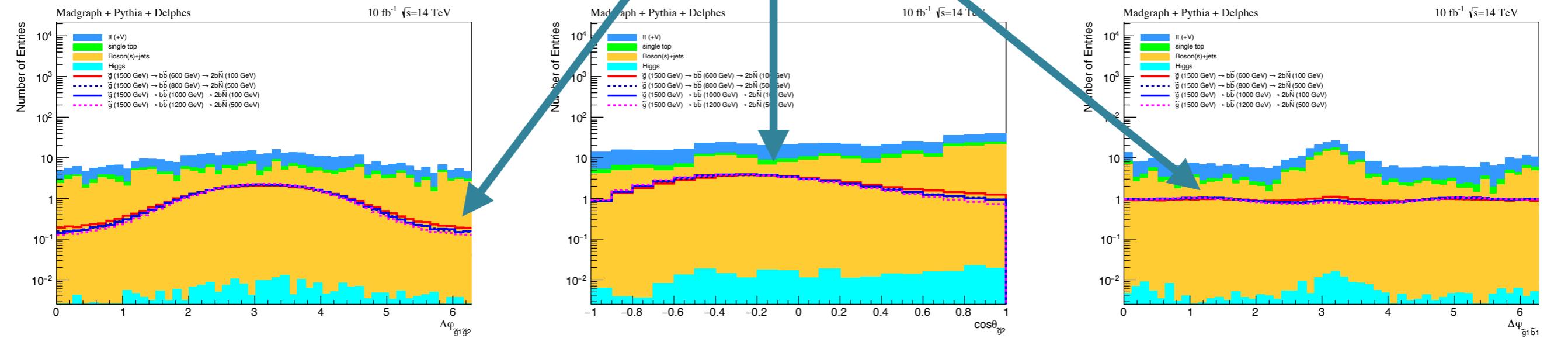
- But these are computed in different hemispheres and frames
- There is **new information** in each handle



# SCALE-INDEPENDENCE

- 4-vectors defined in decay frames
- In addition to masses, there are many angles and ratios
  - Boosts factorize out mass-dependence
  - Sensitive to e.g. spin or compatibility with decay topology

NOTICE THESE SIGNALS LOOK THE SAME IN THESE VARIABLES



$\Delta\Phi(\sim g \sim g \text{ DecayPlanes})$

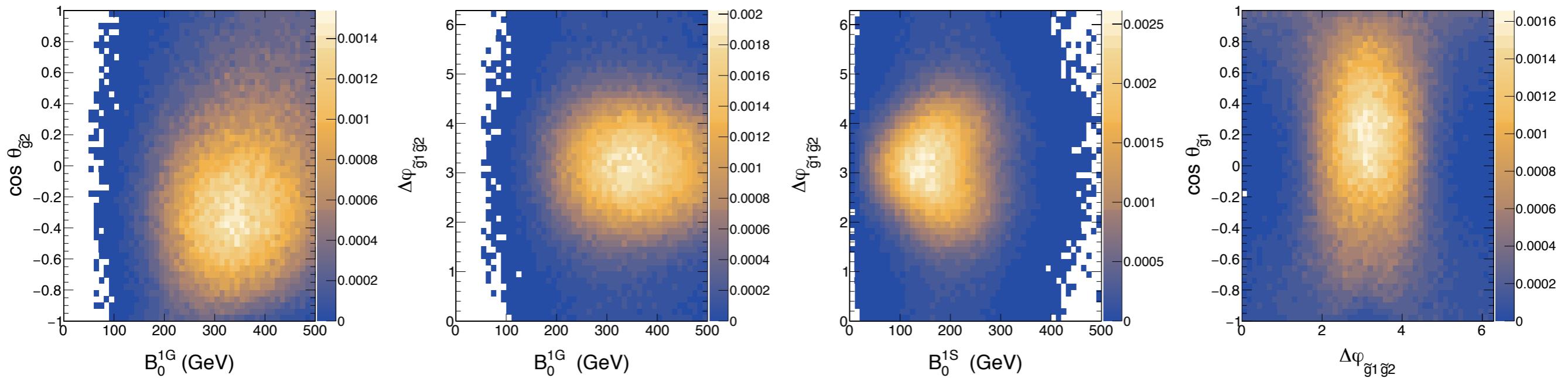
$\cos\Theta(\beta_i, B_i)$

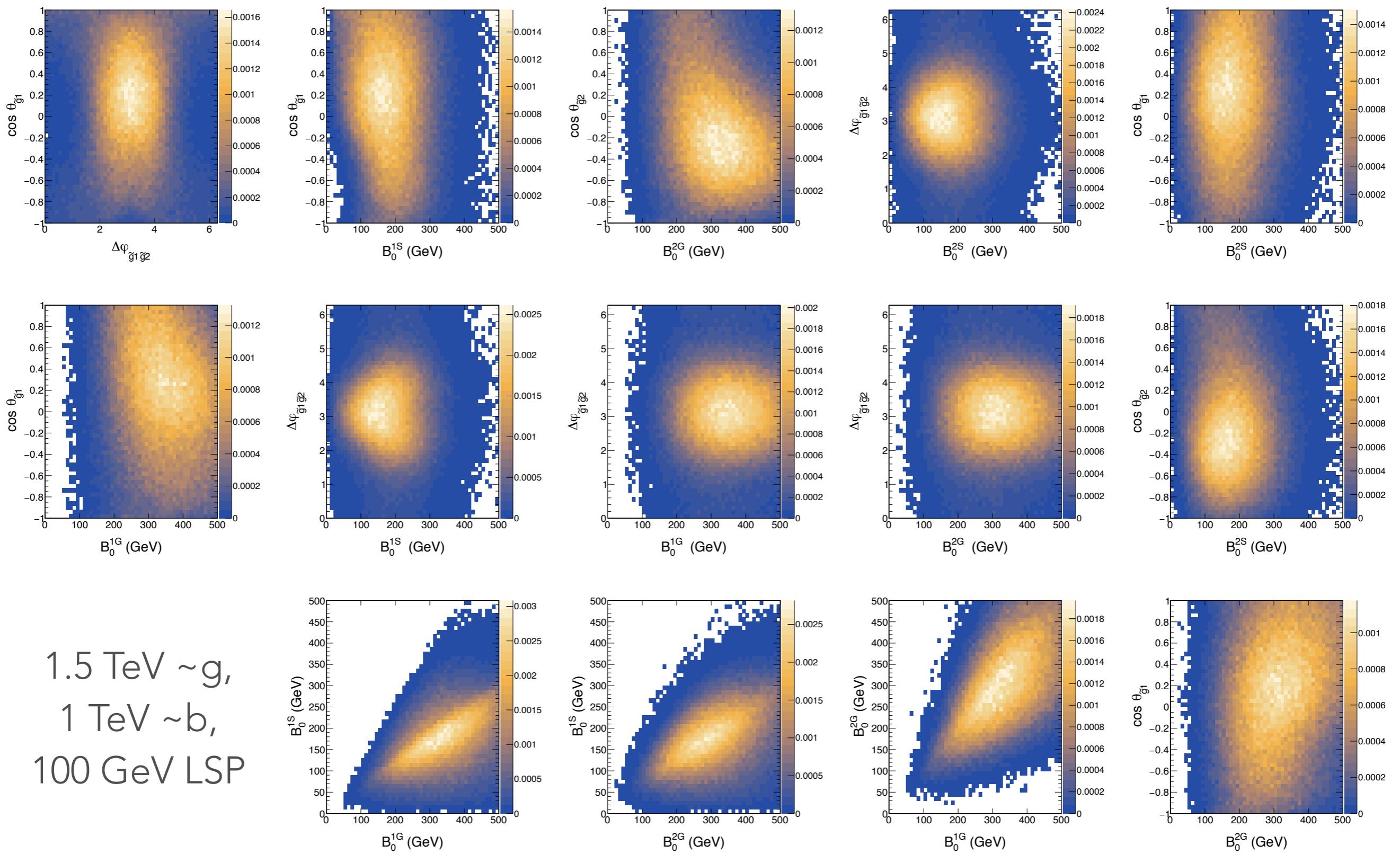
$\Delta\Phi(\sim g \sim b \text{ DecayPlanes})$

# SCALE-INDEPENDENCE

- To make a scale-independent analysis, let these variables do some of the heavy lifting
- This should then give sensitivity across a wide range of masses
- **By construction these are uncorrelated with the mass scales**

1.5 TeV  $\sim g$ , 1 TeV  $\sim b$ , 100 GeV LSP



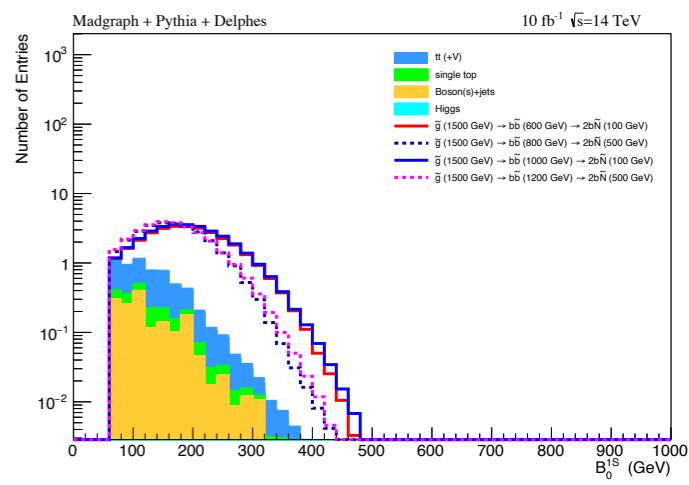
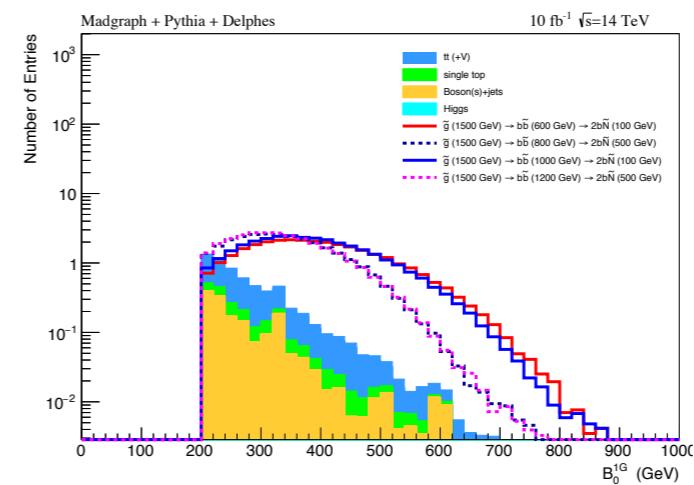
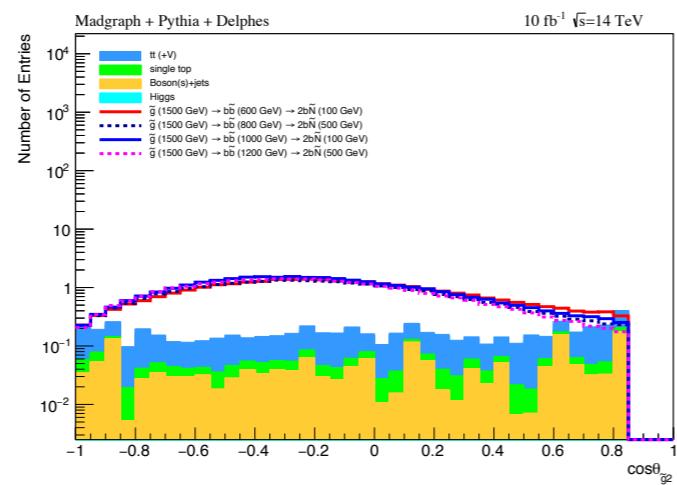
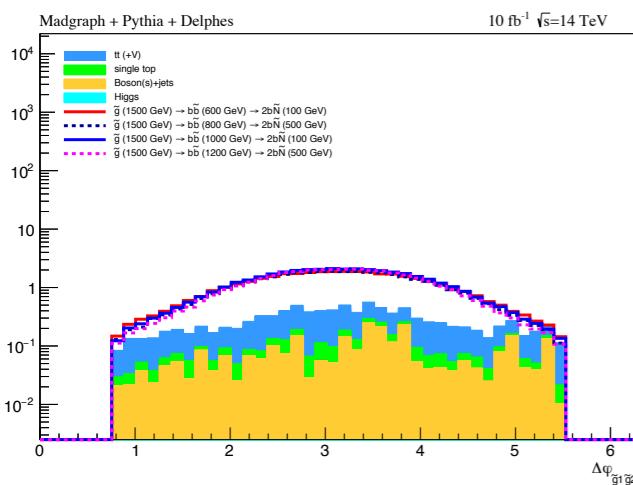
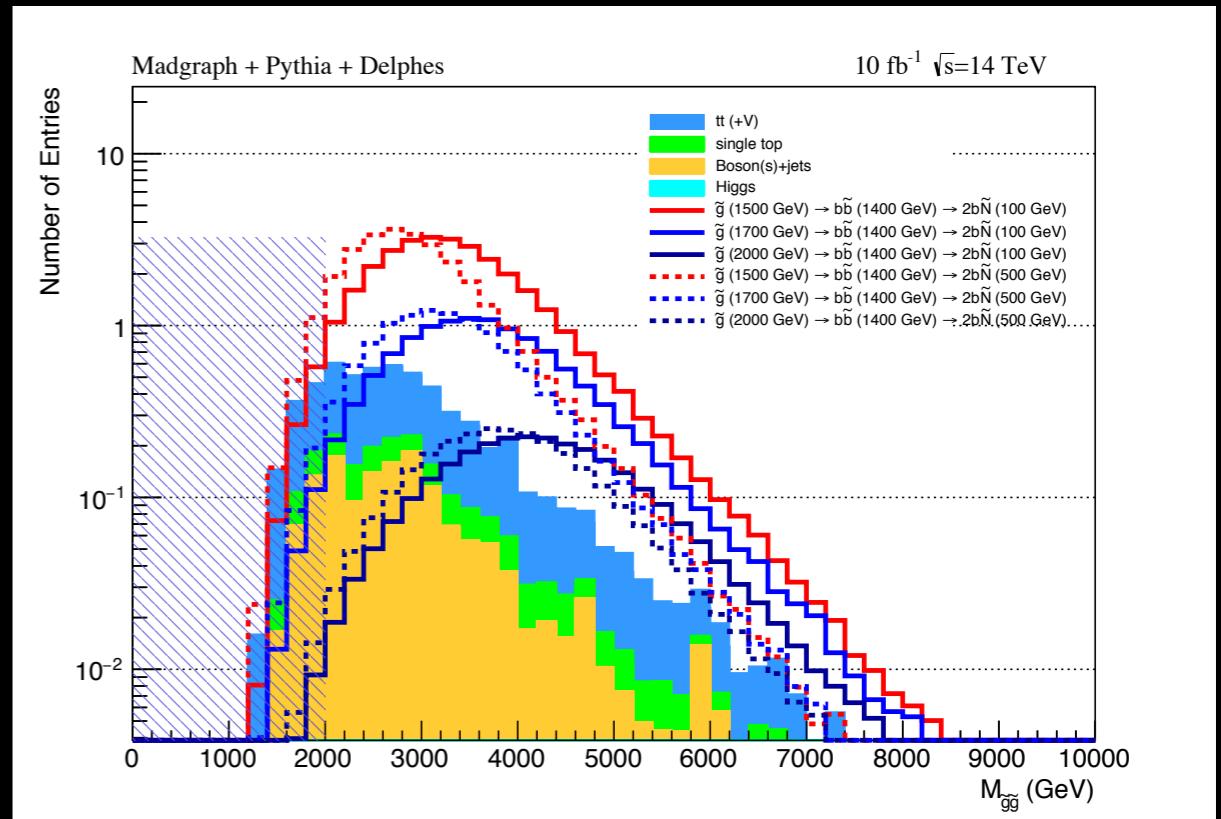


# TEST SIGNAL REGION

- Selection

- 4 "medium" b-tags, 3 "tight" b-tags
- $\pi/4 < \Delta\phi(\sim g \sim g \text{ DecayPlanes}) < (2-1/4)\pi$
- $\cos\theta_{g1} > -0.95, \cos\theta_{g2} < 0.85$
- $\cos\theta_{b1,2} < 0.975$
- Gluino 1 mass scale  $> 200 \text{ GeV}$ , Gluino 2 mass scale  $> 180 \text{ GeV}$
- Sbottom 1 mass scale  $> 60 \text{ GeV}$
- Gluino+Gluino mass scale  $> 2 \text{ TeV}$
- No requirement on MET**

$bbbbXX$  Mass Proxy



$\Delta\Phi(\sim g \sim g \text{ DecayPlanes})$

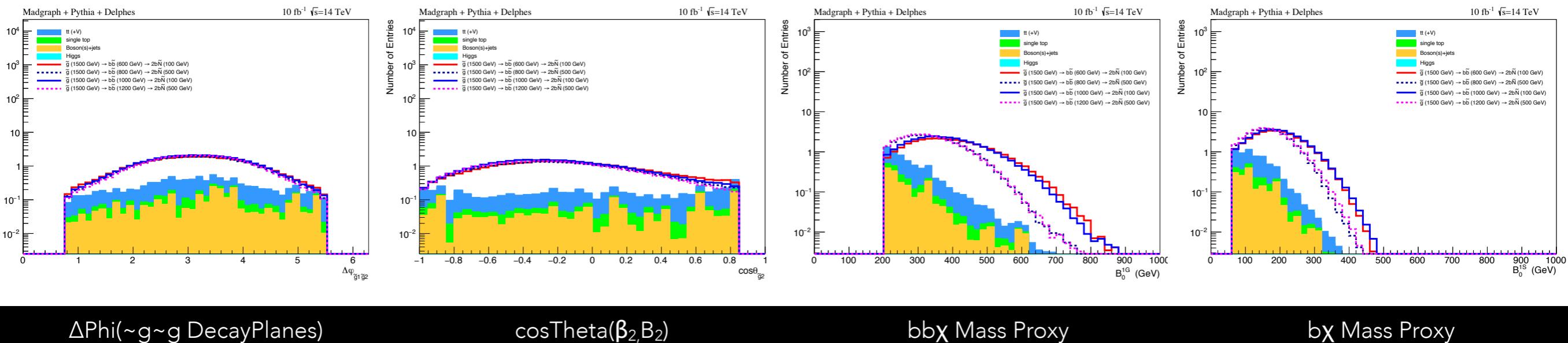
$\cos\Theta(\beta_1, B_1)$

$bbX$  Mass Proxy

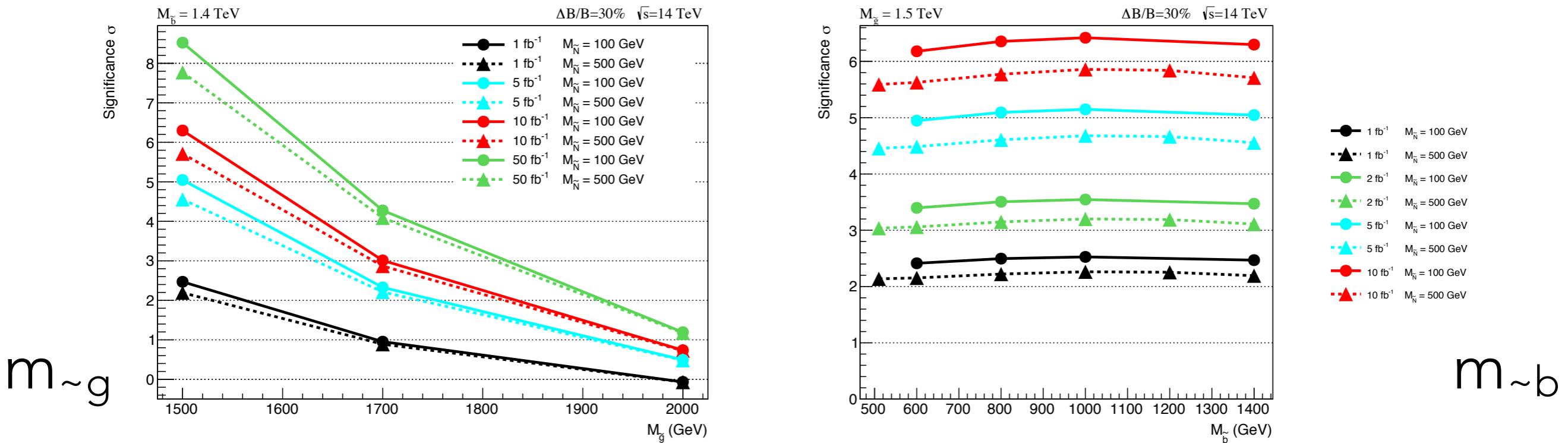
$bX$  Mass Proxy

# TEST SIGNAL REGION

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- $\left\{ \begin{array}{l} \cdot \text{Gluino 1 mass scale} > 200 \text{ GeV}, \text{Gluino 2 mass scale} > 180 \text{ GeV} \\ \cdot \text{Sbottom 1 mass scale} > 60 \text{ GeV} \\ \cdot \text{Gluino+Gluino mass scale} > 2 \text{ TeV} \end{array} \right.$
- **No requirement on MET**
  - **No explicit MET cut**
    - Instead, use MET information to build other discriminators
    - But is a super-rough region that could benefit much from optimization
    - Could benefit from e.g. shape fit in Gluino+Gluino mass scale



# DISCOVERY POTENTIAL



- Sensitivity decreases with gluino-production cross section as expected
- But it's **pretty independent** of LSP mass
- And **very independent** of sbottom mass
  - Cutting hard on e.g. jet pTs or MET would have killed sensitivity for small mass splittings
  - Instead, after  $5 \text{ fb}^{-1}$  of LHC14,  $>4\sigma$  sensitivity to a  $1.5 \text{ TeV}$  gluino for low gluino-sbottom **and** sbottom-LSP mass splittings

# CONCLUSIONS

- Preliminary results for a preliminary technique
- A new method of starting from scratch to get at all of the kinematic information available in these signatures
- A few papers forthcoming for technique and applications
- **See Paul Jackson's talk Thursday for more background on this technique**
- Hopefully these techniques will help find SUSY in LHC Run 2

THANKS FOR YOUR ATTENTION

# ANALYSIS SAMPLES

- Using Snowmass background samples
- Privately generated signal samples
  - SoftSUSY-Sdecay for spectrum
  - MG5 + PYTHIA6 + Delphes 3
  - PYTHIA+Delphes config to match Snowmass samples
  - In agreement with LHC SUSY XS Working Group:
    - 1.5 TeV Gluino Pair Production  $\text{XS} = 0.0219 \text{ pb}$
    - 1.7 TeV Gluino Pair Production  $\text{XS} = 0.00757 \text{ pb}$
    - 2.0 TeV Gluino Pair Production  $\text{XS} = 0.00170 \text{ pb}$

# PRESELECTION

- Event Preselection
  - No MET Cut
  - $\geq 4$  jets
  - Jet pTs:  $(pT1, pT2, pT3) > (120, 100, 60)$  GeV
  - Exactly 0 Leptons
  - 4 Medium BTags, 2 Tight BTags