# Using a Razor to Unravel Difficult LHC Signatures

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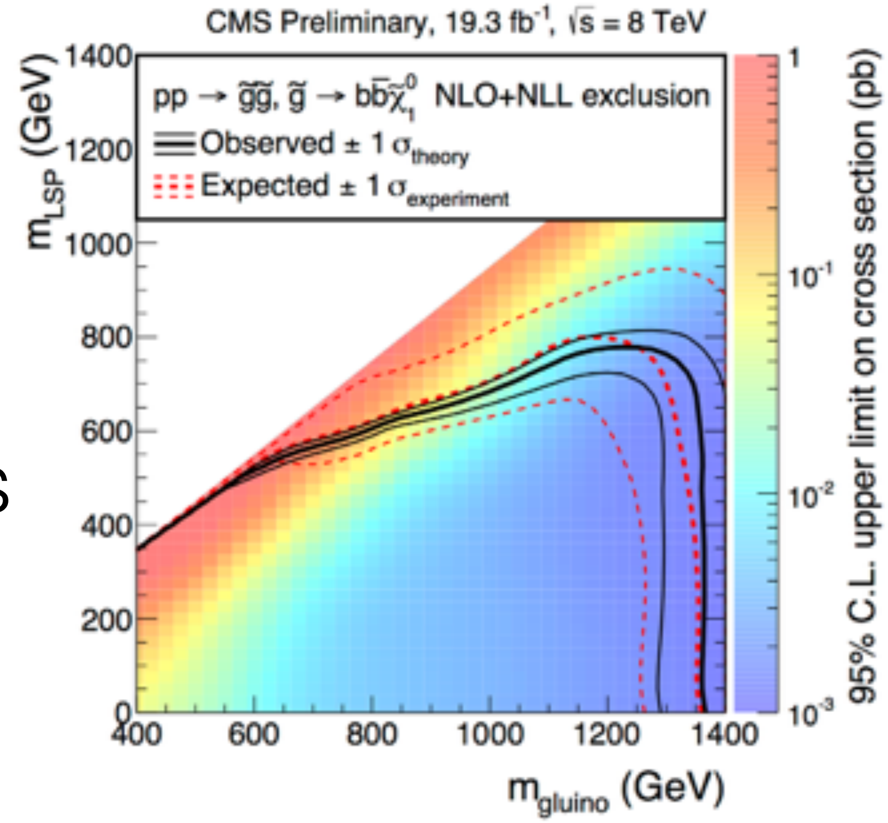
# What to look for next?

- We all know what the LHC didn't find.
  - No strongly interacting particles decaying to jets and large MET
  - No evidence of non-Standard Higgs




- The parameter space ruled out by the LHC covers much of the "Standard" MSSM.
  - One thing the LHC appears to be telling us to be that the new physics looks nothing like this.

# What to look for next?

- Things that we are not yet as sensitive to:
  - 3rd generation partners
  - Degenerate spectra
  - Direct electroweak production
  - Displaced vertices
  - Things I haven't thought of yet

- Many of these can be well-motivated by theory, and many can be searched with even in the 8 TeV data

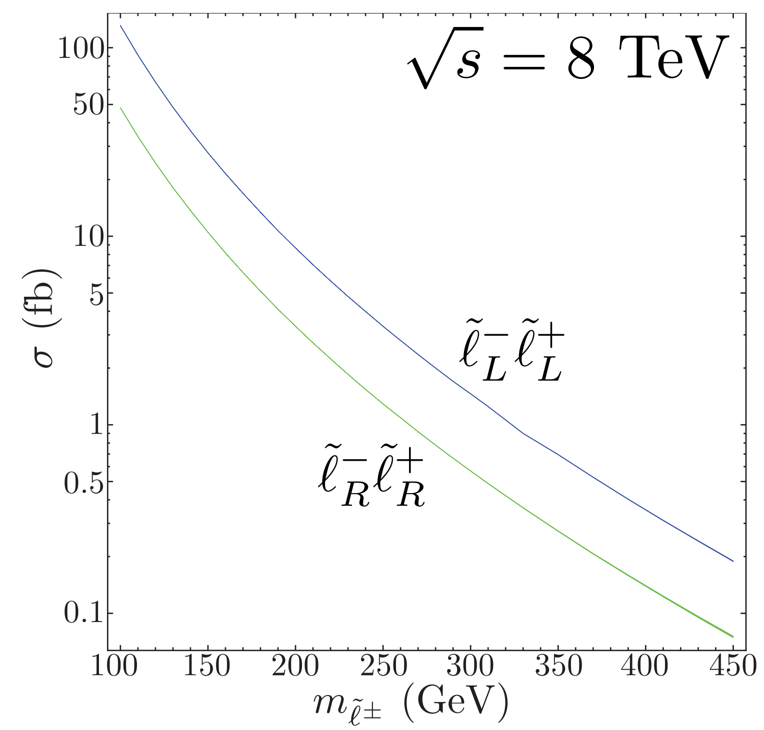
# Sleptons and Charginos

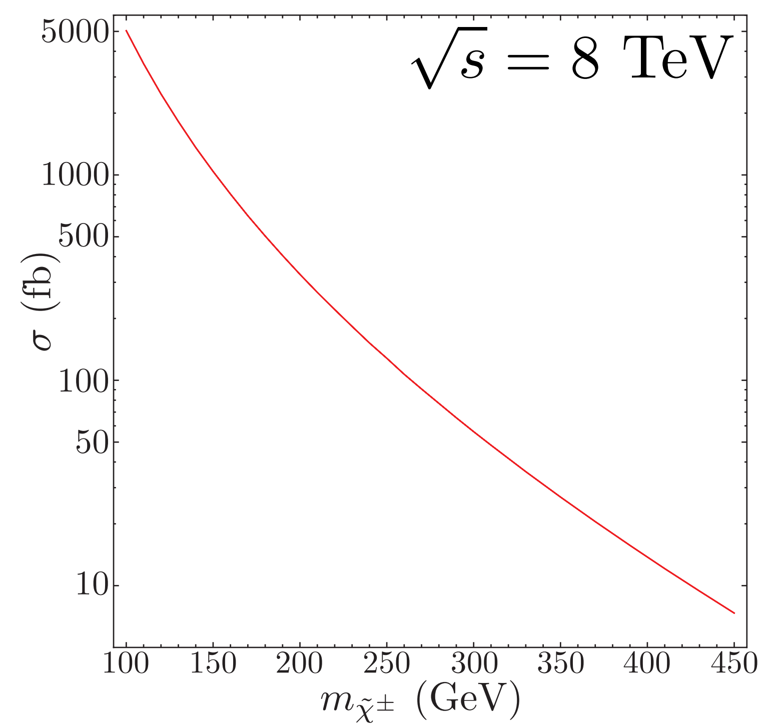
- Very difficult signatures at the LHC

$$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to (W^+ \tilde{\chi}_1^0)(W^- \tilde{\chi}_1^0) \to (\ell^+ \nu \tilde{\chi}_1^0)(\ell^- \bar{\nu} \tilde{\chi}_1^0)$$

$$pp \to \tilde{\ell}^+ \tilde{\ell}^- \to (\ell^+ \tilde{\chi}_1^0)(\ell^- \tilde{\chi}_1^0)$$

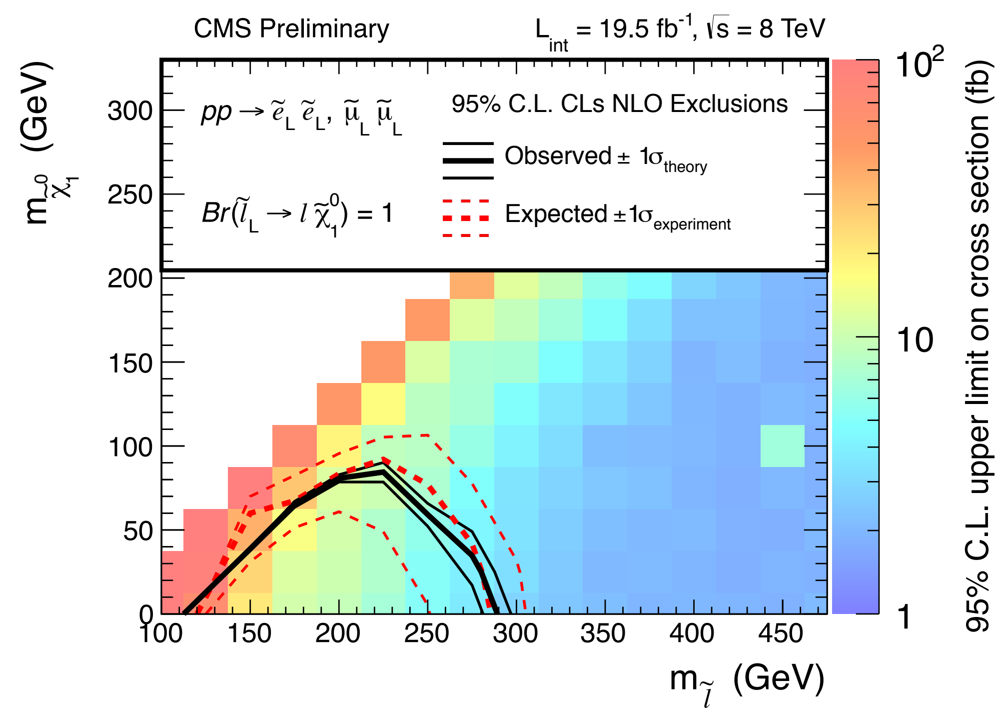
- Low rates, high backgrounds which have very similar kinematics to signal.

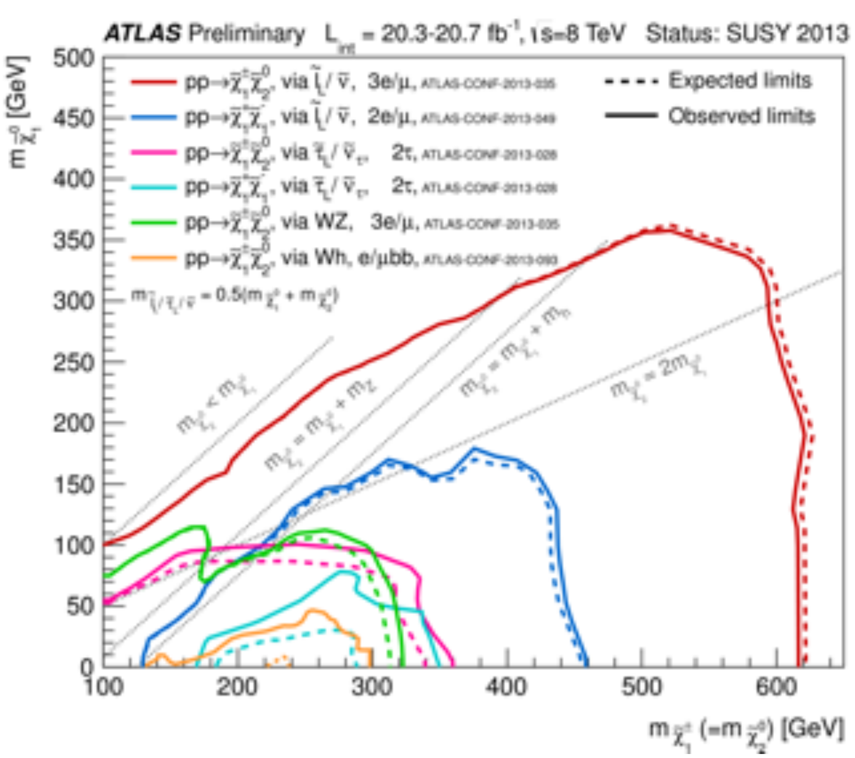


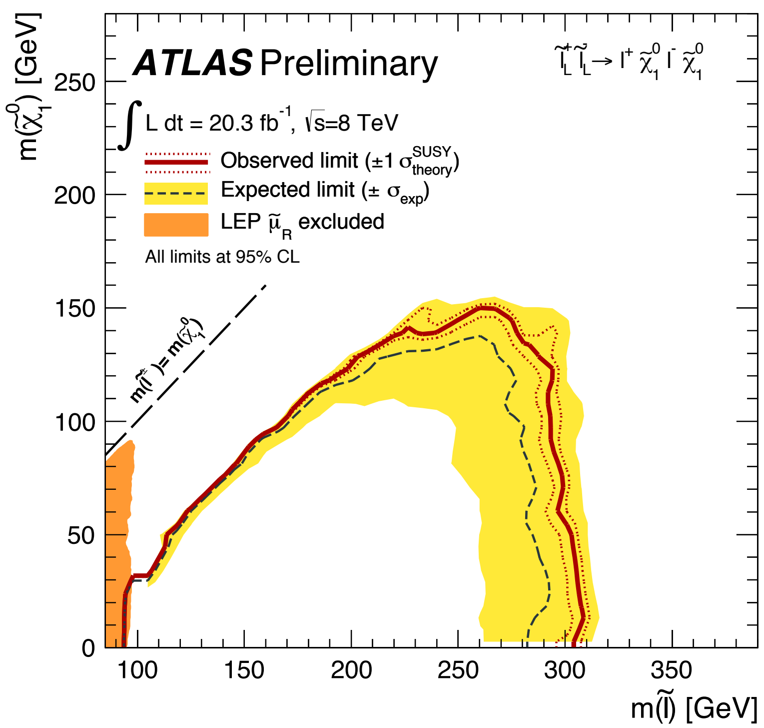



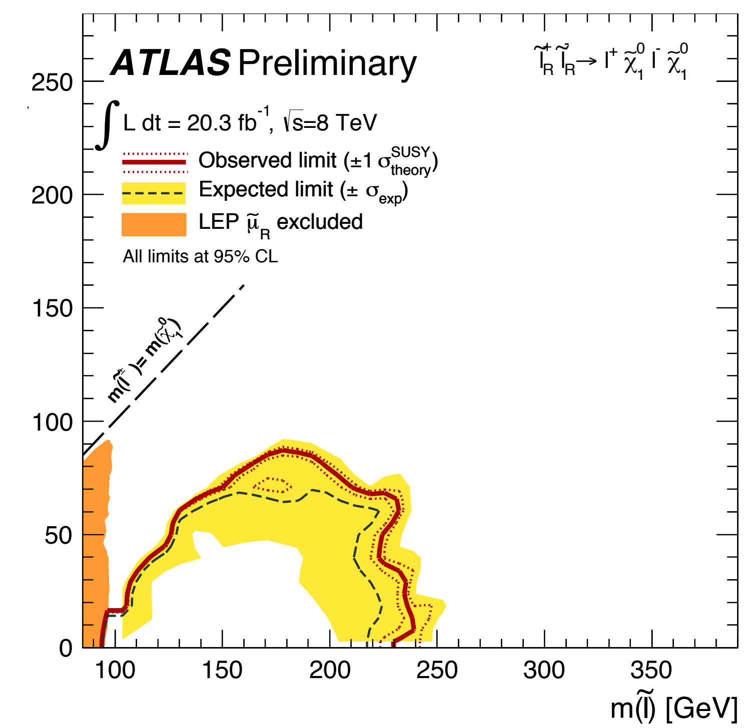
# ATLAS and CMS searches

- Note that many of these searches set leptonic BR of charginos to 1.
- Or look for several new particles in a cascade decay.



# ATLAS and CMS searches

- Searches for events like $pp \to \tilde{\ell}^+ \tilde{\ell}^- \to (\ell^+ \tilde{\chi}_1^0)(\ell^- \tilde{\chi}_1^0)$ typically use variables sensitive to the mass difference

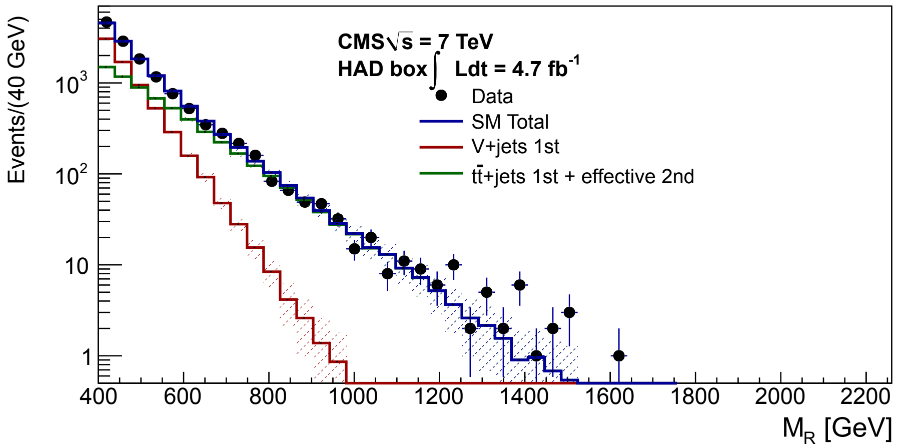
$$M_\Delta \equiv \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^0}}$$

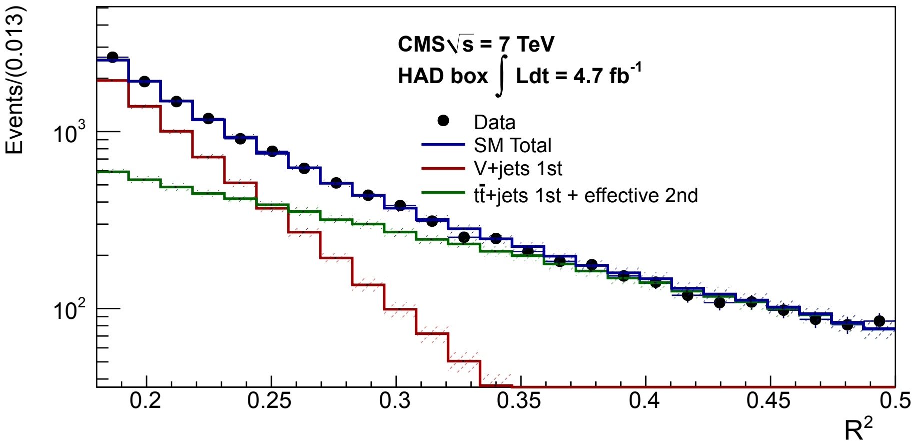
- Can attempt to correct for ISR jets which presumably don't have connection to the new physics.
  - *e.g.* the variable used by CMS, $M_{CT\perp}$, is $M_{CT}$ calculated along the direction perpendicular to the system recoiling against ISR jets.
  - Look for endpoints at $M_{CT\perp}, M_{T2} \sim M_\Delta$

# Can the Razor do better?

- Original Razor variables designed to look for new physics in jets+MET
  - Divide events into two “mega-jets” and make an attempt to boost into a frame that approximates the pair-production frame.
  - If these approximations hold, then Razor variables approximate $M_\Delta$

$$M_R^2 = (E_1 + E_2)^2 - (q_1^z + q_2^z)^2, \ (M_T^R)^2 = \frac{1}{2}\left[\not{E}_T (q_{1T} + q_{2T}) - \vec{\not{E}}_T \cdot (\vec{q}_{1T} + \vec{q}_{2T})\right]$$



# The Super Razor

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## [illegible] Everything, We're Doing Five Blades

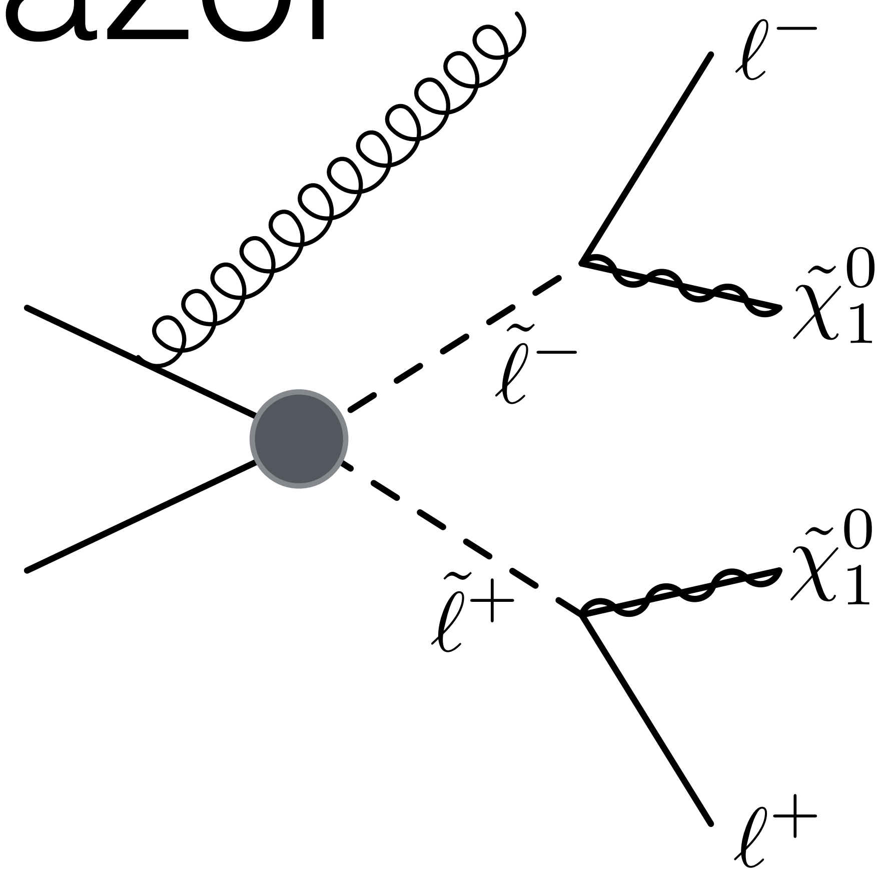
**COMMENTARY · Opinion · Business · ISSUE 40·07** · Feb 18, 2004

**By James M. Kilts, CEO And President, <Br>The Gillette Company**

James M. Kilts

Would someone tell me how this happened? We were the [illegible] vanguard of shaving in this country. The Gillette Mach3 was *the* razor to own. Then the other guy came out with a three-blade razor. Were we scared? Hell, no. Because we hit back with a little thing called the Mach3Turbo. That's three blades *and* an aloe strip. For moisture. But you know what happened next? Shut up, I'm telling you what happened—the bastards went to four blades. Now we're standing around with our

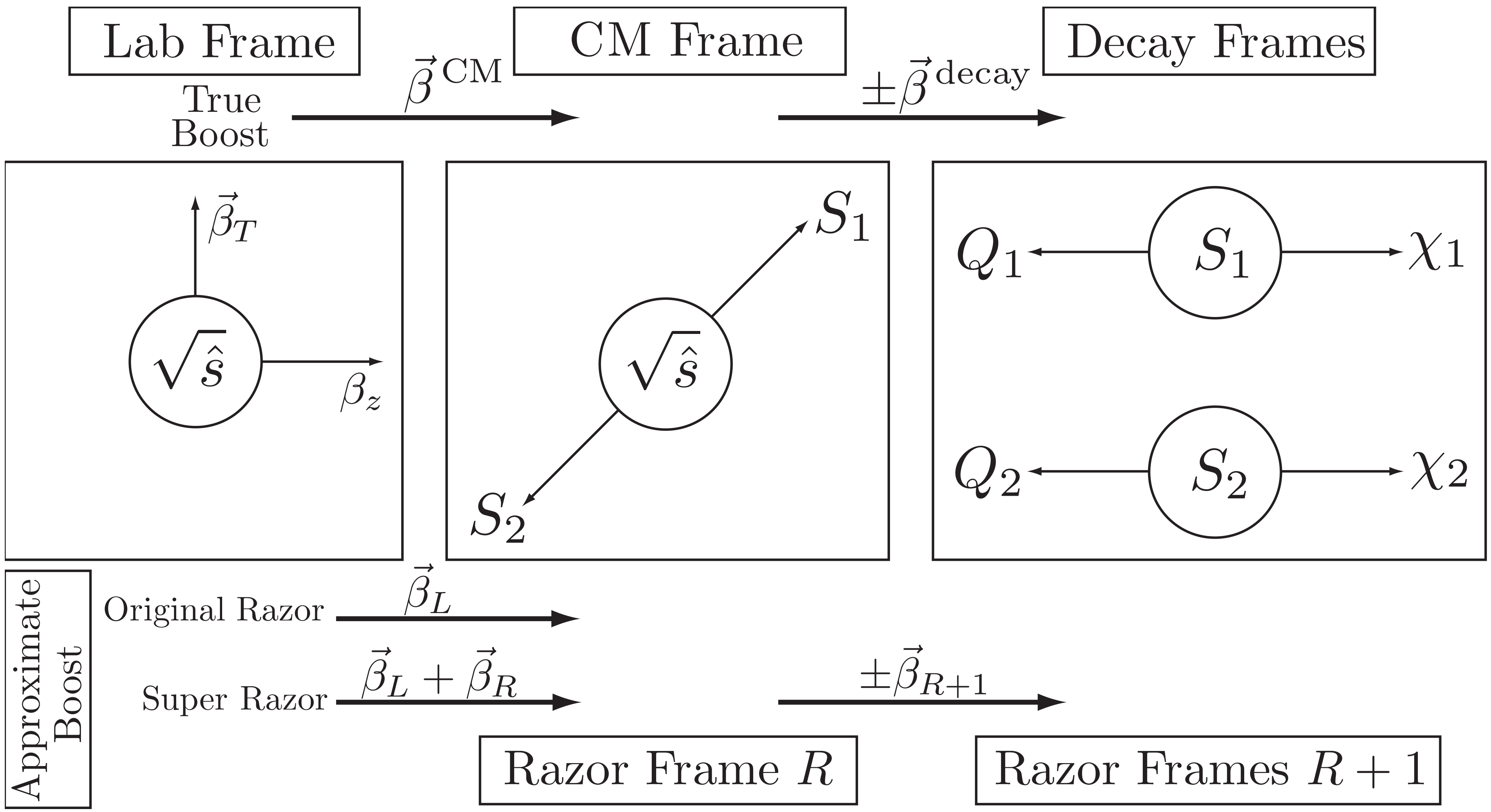
# The Super Razor




- Not enough information to reconstruct the event.
  - Make a series of approximations:
    - Invisible invariant mass = visible invariant mass
    - Results independent of unknown CM $z$-momentum
    - All jets unrelated to physics of interest

# The Super Razor

- Construct a series of boosts that approximate the true boosts from the lab, to the CM frame, to the decay frames



# Constructing the CM frame

- Boost against the extra jets in the event

$$\vec{J}_T = \sum_j \vec{p}_j = -\vec{E}_T^{\text{miss}} - \vec{q}_{1T} - \vec{q}_{2T}$$

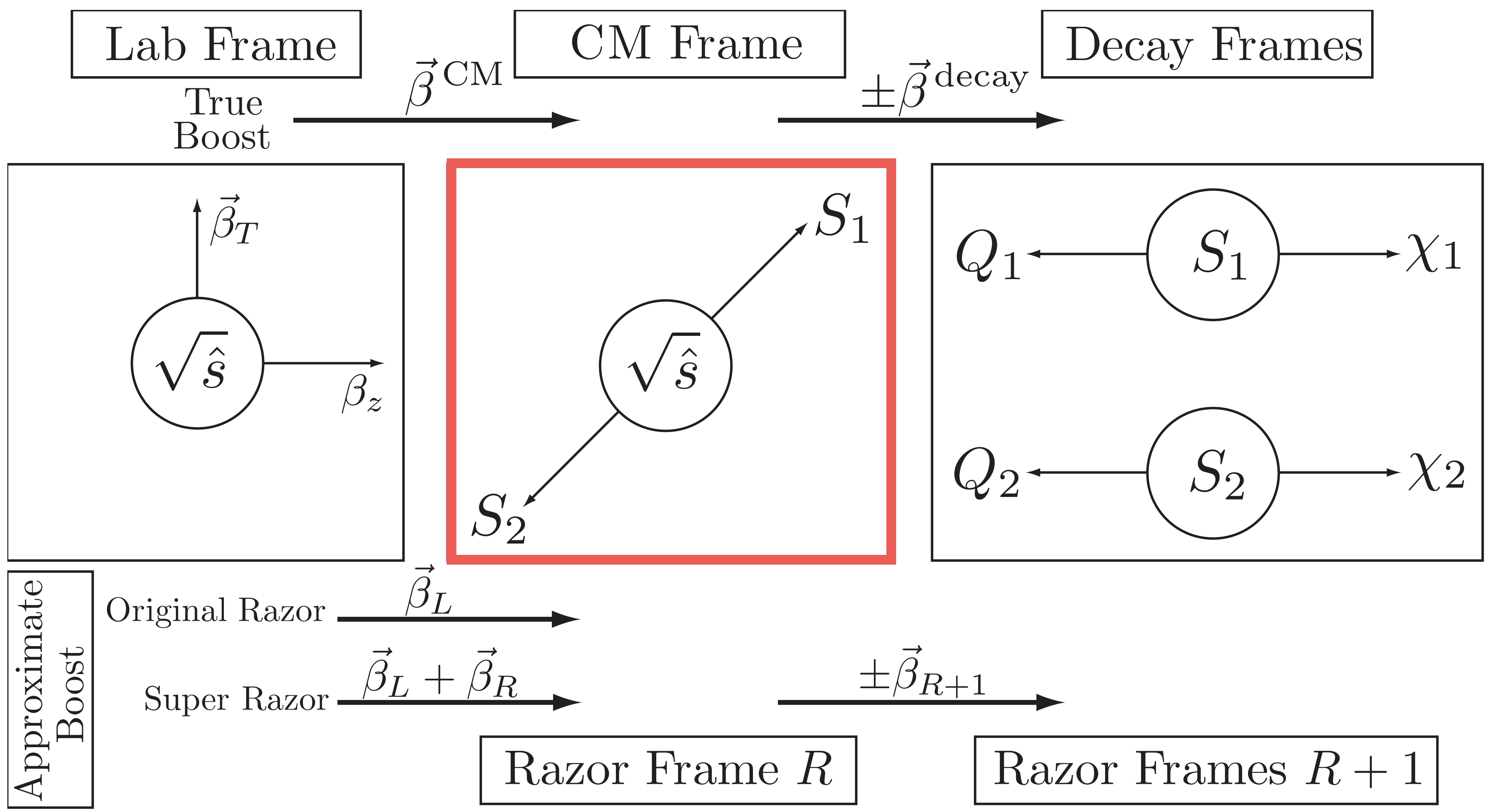
- Approximating the correct boost from lab to CM frame requires a guess as to the CM invariant mass. There's a unique choice:

$$\frac{\hat{s}_R}{4} = \frac{1}{2}\left( M_R^2 + \vec{J}_T \cdot (\vec{q}_1 + \vec{q}_2) + M_R \sqrt{M_R^2 + |\vec{J}_T|^2 + 2\vec{J}_T \cdot (\vec{q}_1 + \vec{q}_2)} \right)$$

  - This is a "jet-corrected" razor variable.
  - Now can also construct our approximate boost $\vec{\beta}_R$

$$\vec{\beta}_R = \frac{\{-\vec{J}_T, p_z^R\}}{\sqrt{|\vec{J}_T|^2 + |p_z^R|^2 + \hat{s}_R}}$$

# The Super Razor



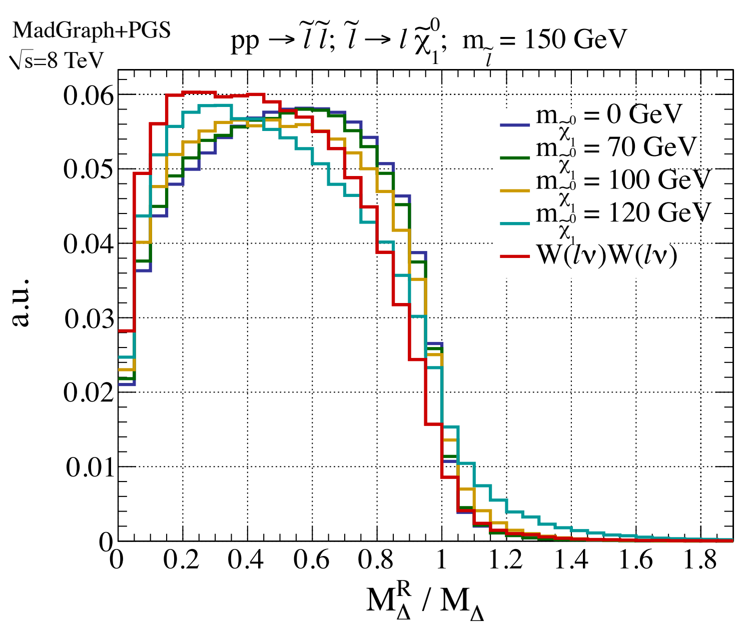
# Getting to the decays

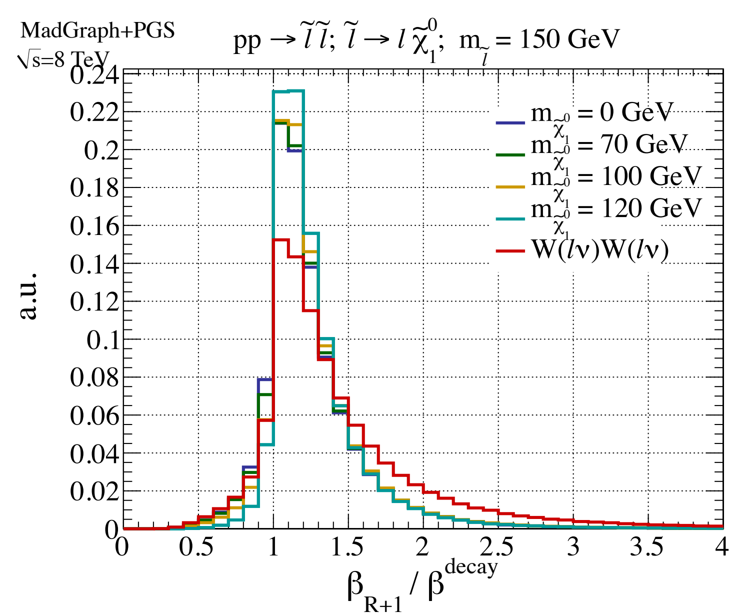
- From the approximate CM frame, only one choice of boost that has the right symmetries to approximate $\pm\vec{\beta}^{\,\mathrm{decay}}$

$$\vec{\beta}_{R+1} = \frac{\vec{q}_{R1} - \vec{q}_{R2}}{E_{R1} + E_{R2}}$$

- Correct boosts give $\sqrt{\hat{s}} = 2\gamma^{\mathrm{decay}} m_{\tilde{\ell}}$ , so define

$$\boxed{\sqrt{\hat{s}_R} = 2\gamma_{R+1} M_\Delta^R}$$



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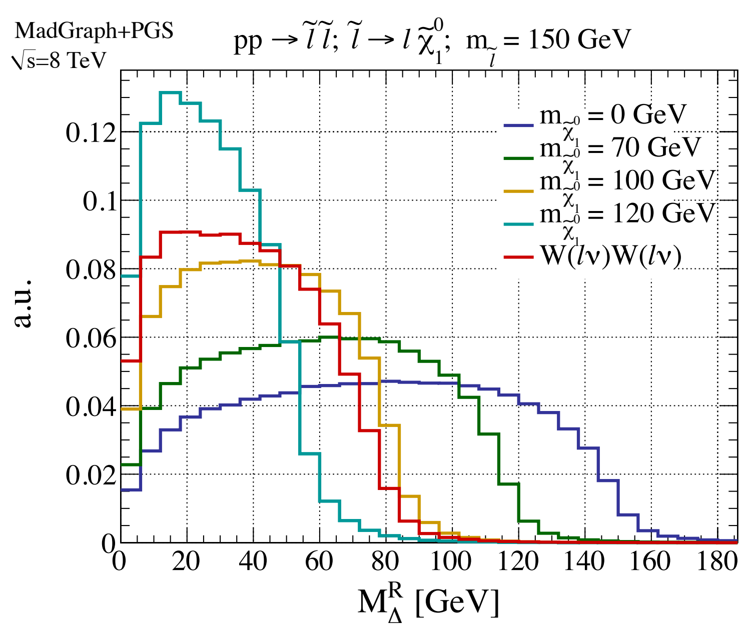
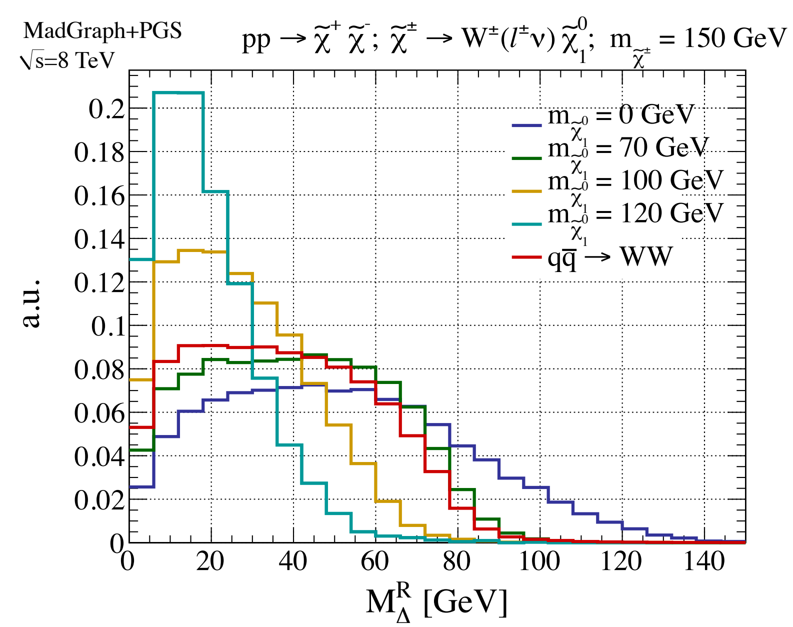
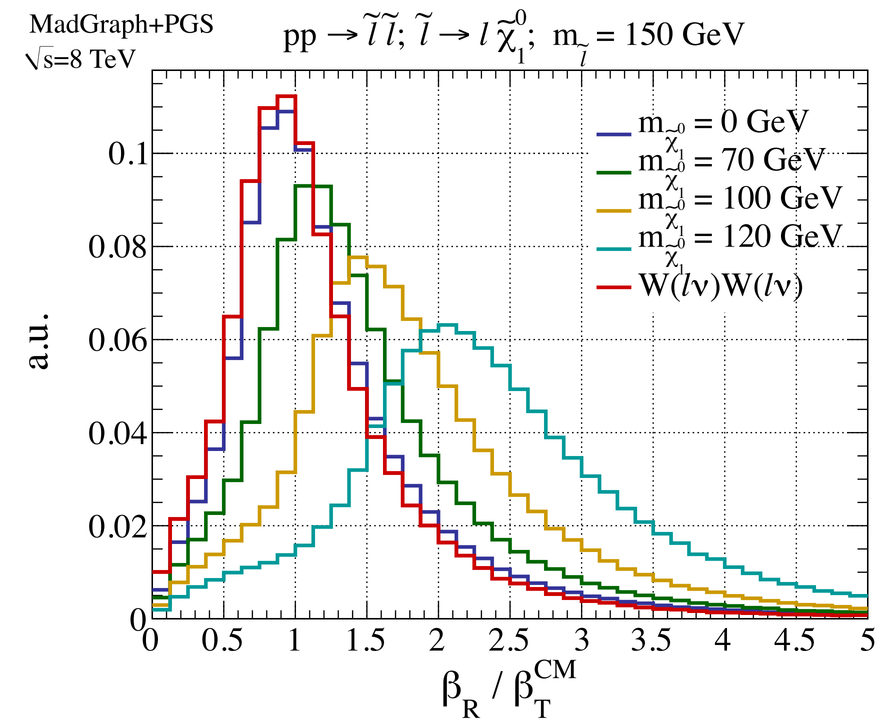
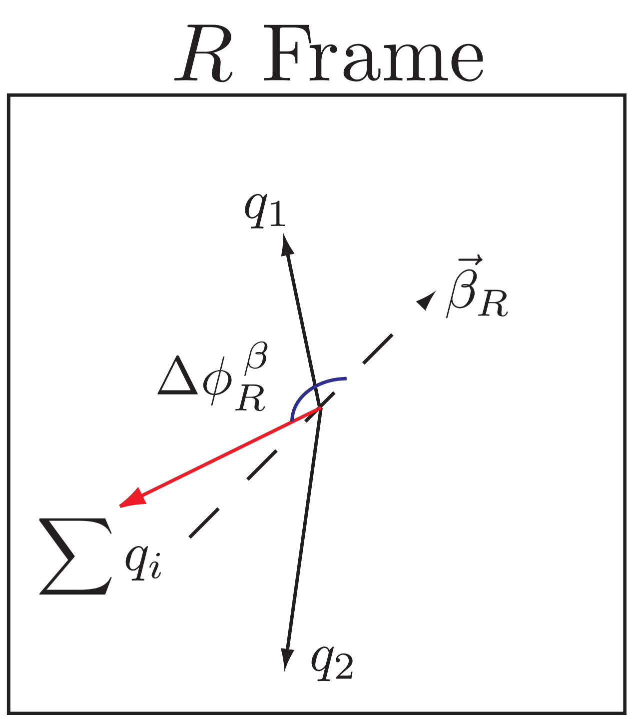


# A New Angle

- So far, these are "jet-corrected" versions of the original razor variables. Sensitive to $M_\Delta$
  - Not good when $M_\Delta \to m_W$
- But we also have the approximations of the boosts.
- Notice that, as $m_{\tilde{\chi}_1^0}/m_{\tilde{\ell}} \to 1$, we overestimate the boost $\beta_R$
- Can define an $\Delta\phi_R^\beta$ angle between the boost direction and *R*-frame $q_1 + q_2$



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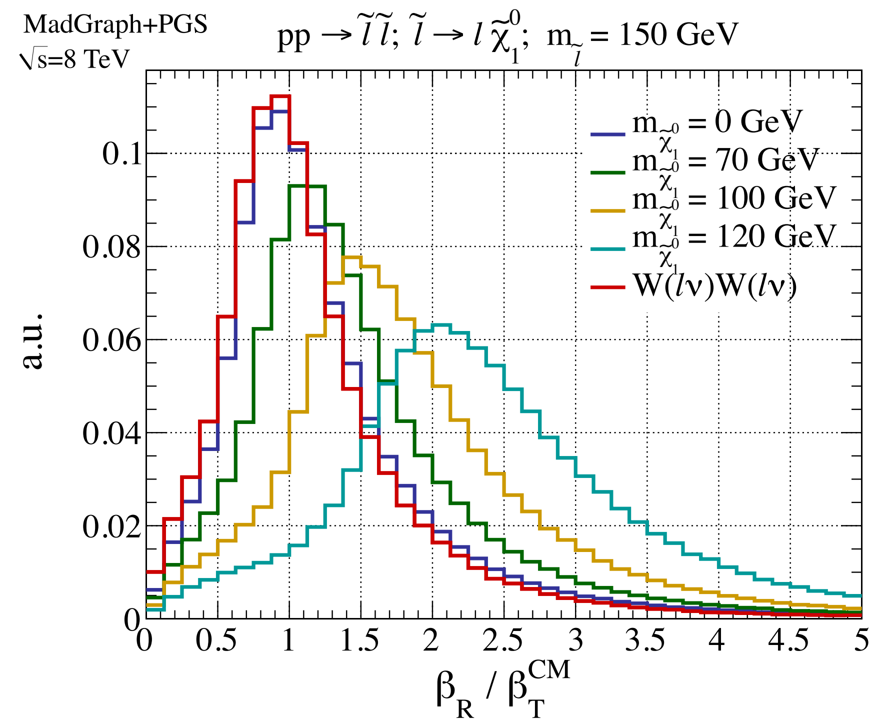


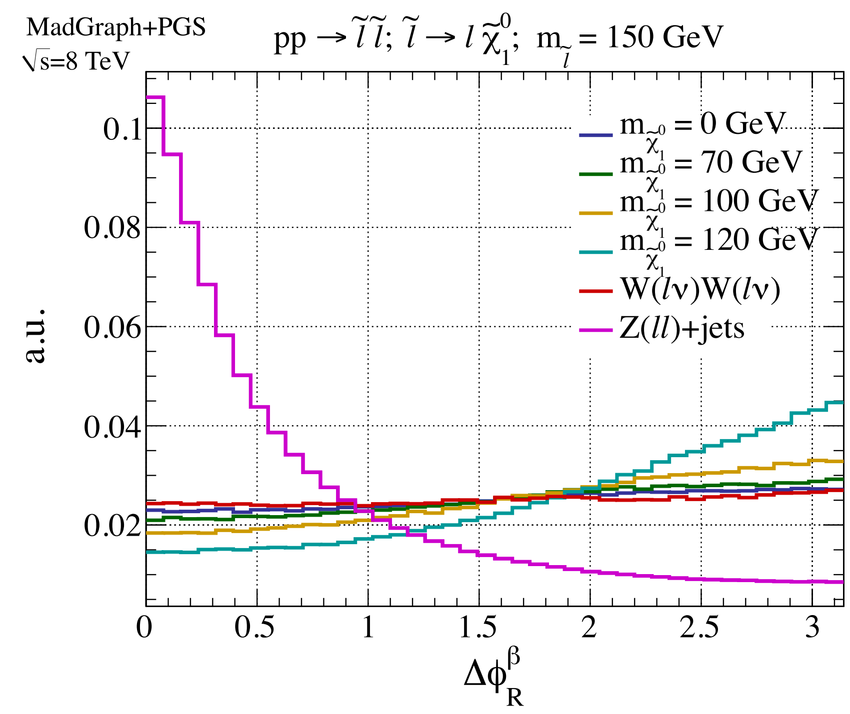

# One Last Angle

- Last piece of information we haven't used is $(E_1 - E_2)^2$
  - Define an "angle"

$$|\cos\theta_{R+1}| = \frac{(E_{1R} - E_{2R})^2}{\hat{s}_R/4 - (M_\Delta^R)^2}$$

- Thought of as an angle, it is the opening angle between boost $\vec{\beta}_{R+1}$ and the momentum of the lepton $q_1$ in the approximate decay frame $R+1$.
  - Perhaps easier to think of it as the energy difference of the two visible leptons in the $R$ frame.

# One Last Angle

$$|\cos\theta_{R+1}| = \frac{(E_{1R} - E_{2R})^2}{\hat{s}_R/4 - (M_\Delta^R)^2}$$

- This picks up some helicity information:
  - Direction of leptons from scalar decay uncorrelated.
    - In *R*-frame, $E_{1R}, E_{2R}$ should be relatively uncorrelated.
    - Unless the scalars are highly boosted.
  - Vector boson decay products are correlated with momentum of parents.
    - Leptons correlated in *R*-frame, resulting in more events with $E_{1R}, E_{2R}$ similar, and $|\cos\theta_{R+1}|$ near zero.

# One Last Angle

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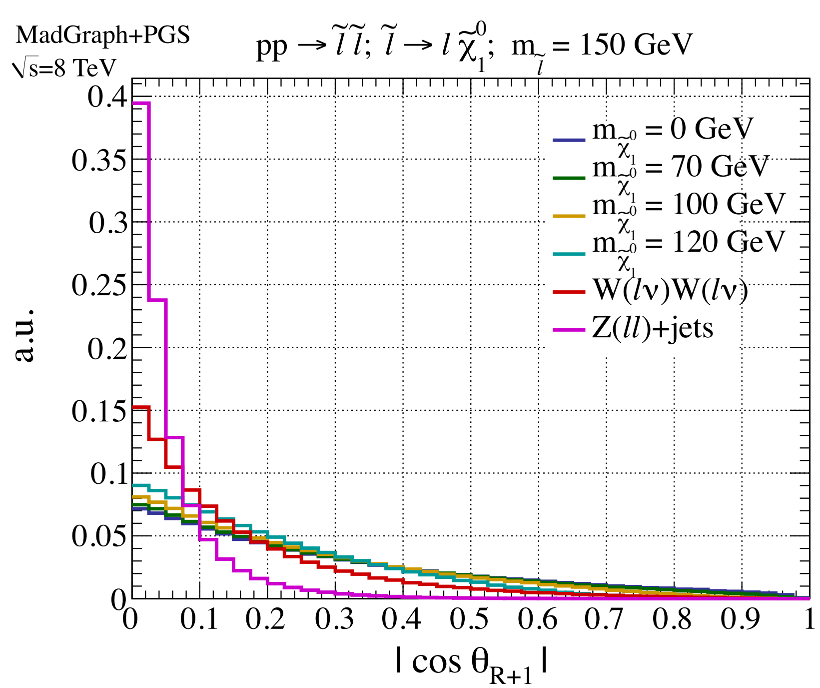
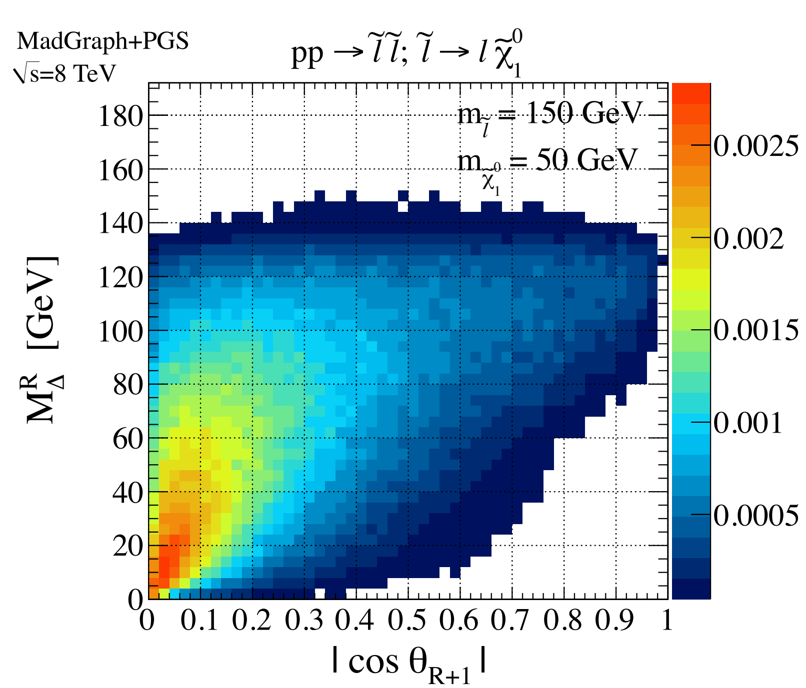
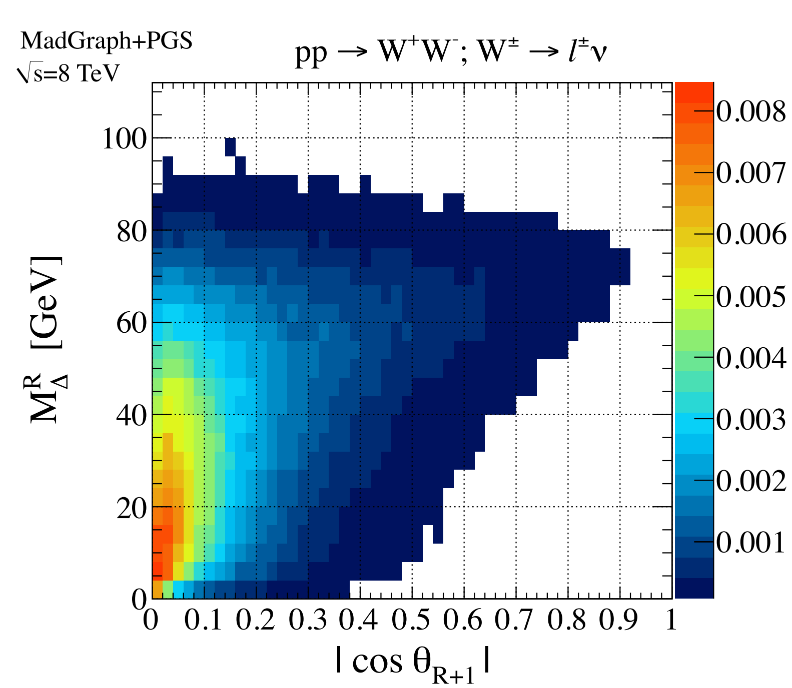


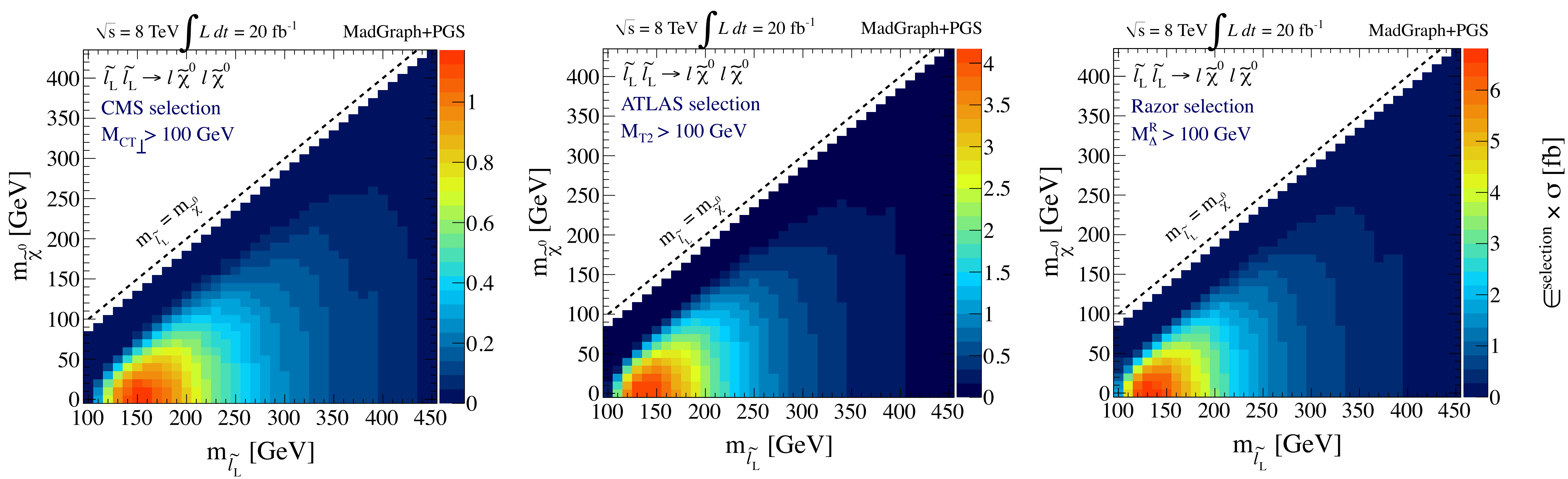



# A Recap

- Expand the original "Razor" concept to attempt to reconstruct the entire production and decay chain.
  - This gives us two variables sensitive to $M_\Delta$: $\hat{s}_R,\ M_\Delta^R$
    - (These are correlated, so we chose $M_\Delta^R$)
    - A variable sensitive to $m_{\tilde{\chi}_1^0}/m_{\tilde{\ell}}$: $\Delta\phi_R^\beta$
    - A variable that picks up some spin-related information: $|\cos\theta_{R+1}|$
  - Throw all this information in to a multi-dimensional analysis of di-lepton events, looking for slepton or chargino production.
    - Major backgrounds $WW,\ t\bar{t},\ Z/\gamma^*$

# Predicted Reach

- We compare to ATLAS and CMS search strategies.
  - Can also use our new razor variables to relax certain selection cuts without sacrificing $S/B$
  - Replace a cut on $\not{E}_T$ with cuts on razor boosts and $\Delta\phi_R^\beta$



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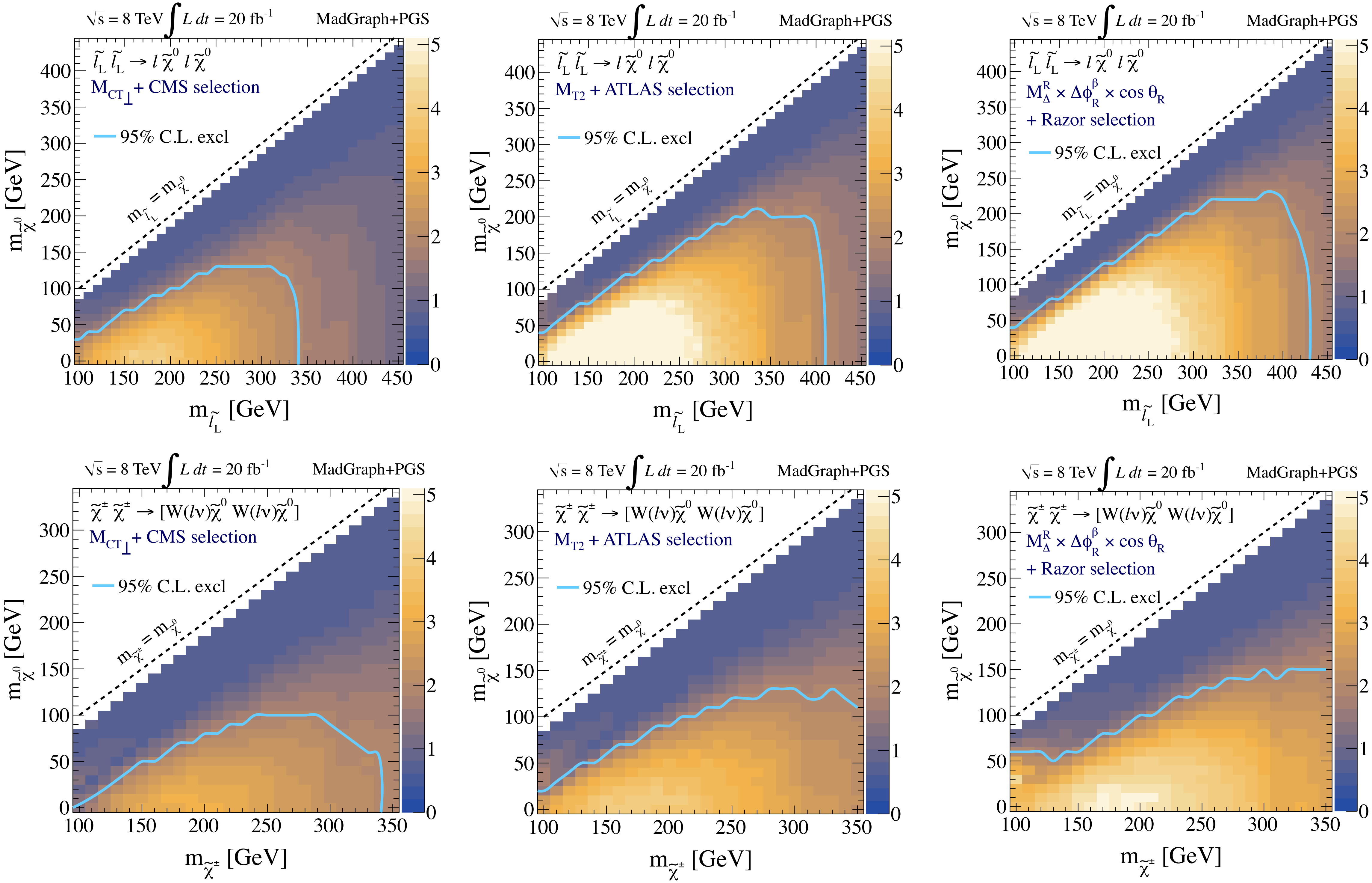
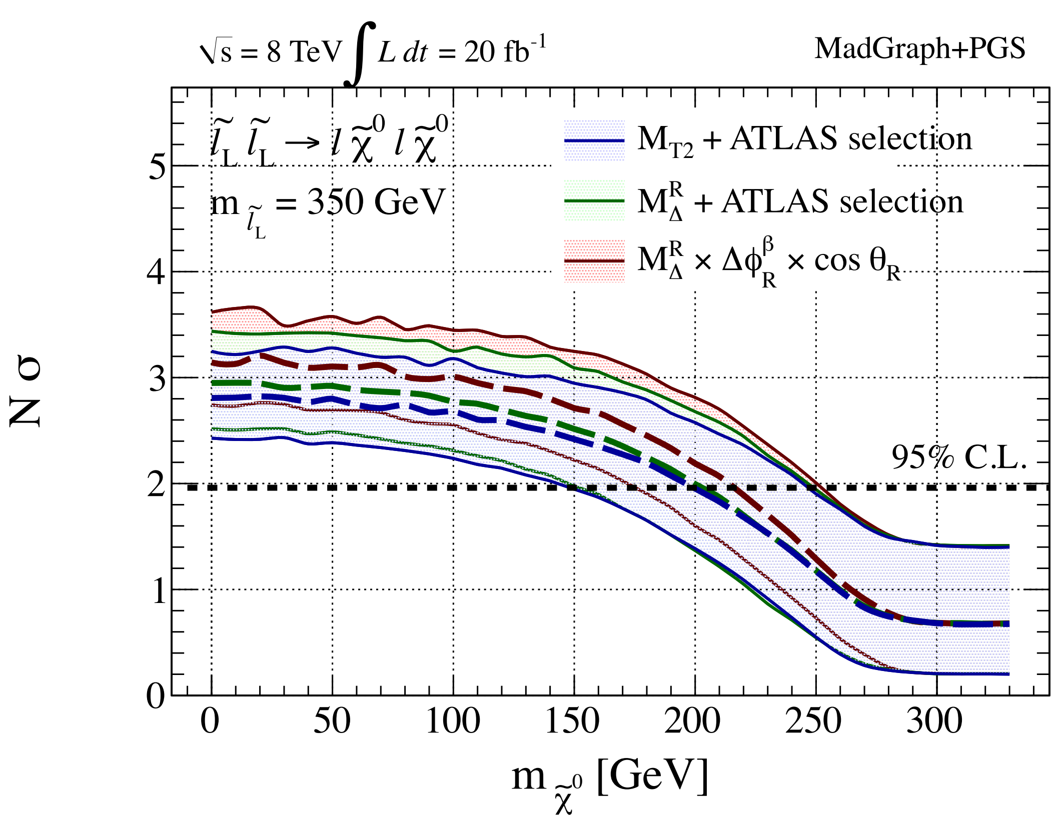
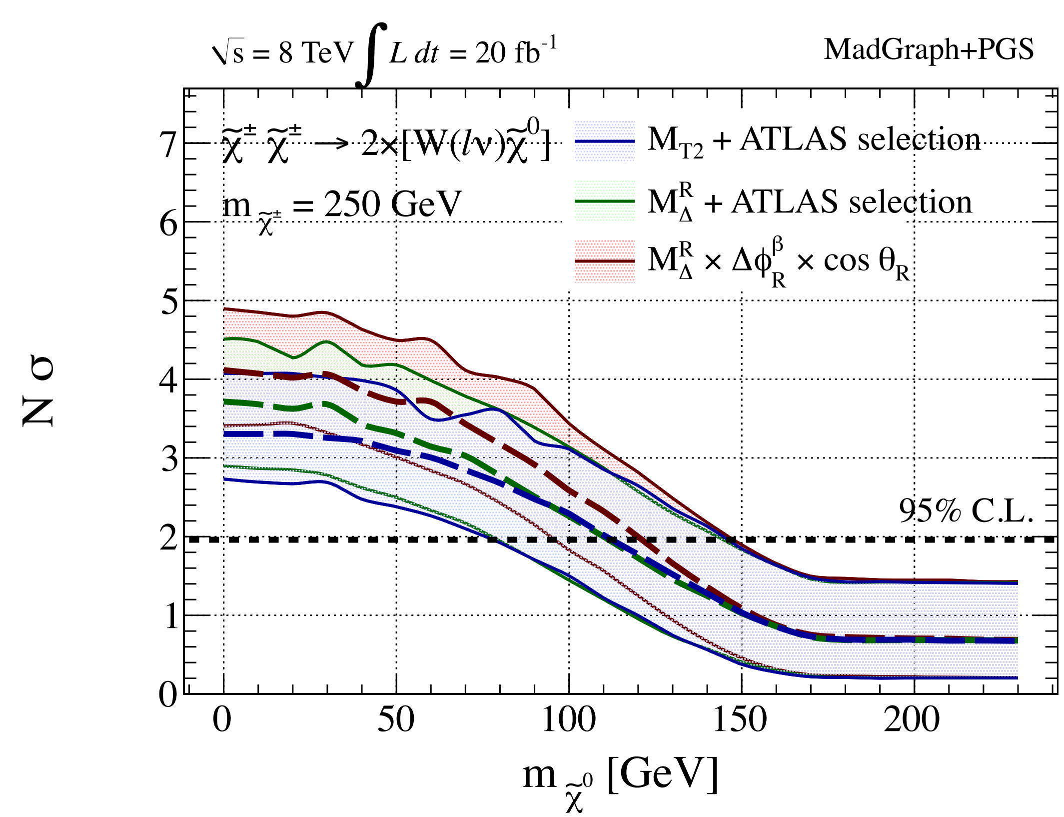


# Predicted Reach

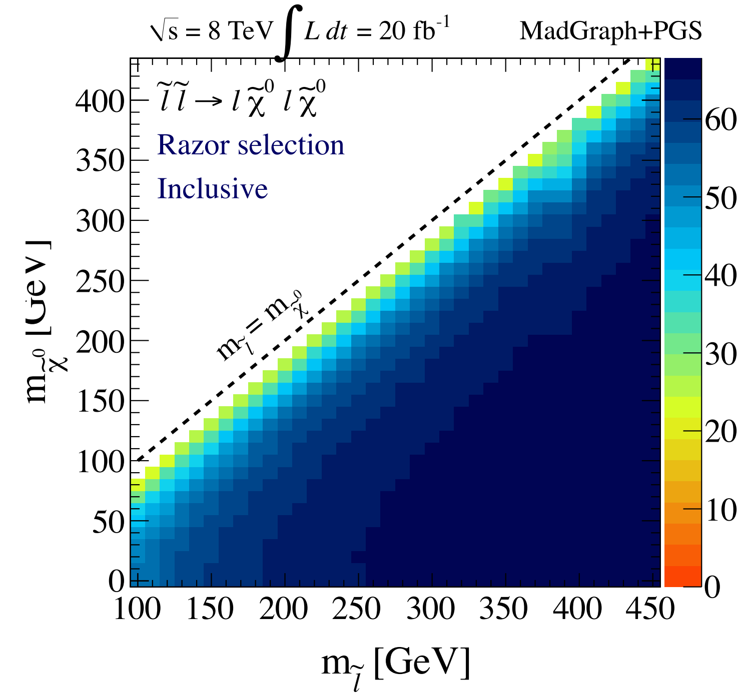
- Take a slice of constant $m_{\tilde{\ell}}/m_{\tilde{\chi}_1^\pm}$
- Biggest advances are due to inclusions of variables that are not sensitive to $M_\Delta$



# What's Next?

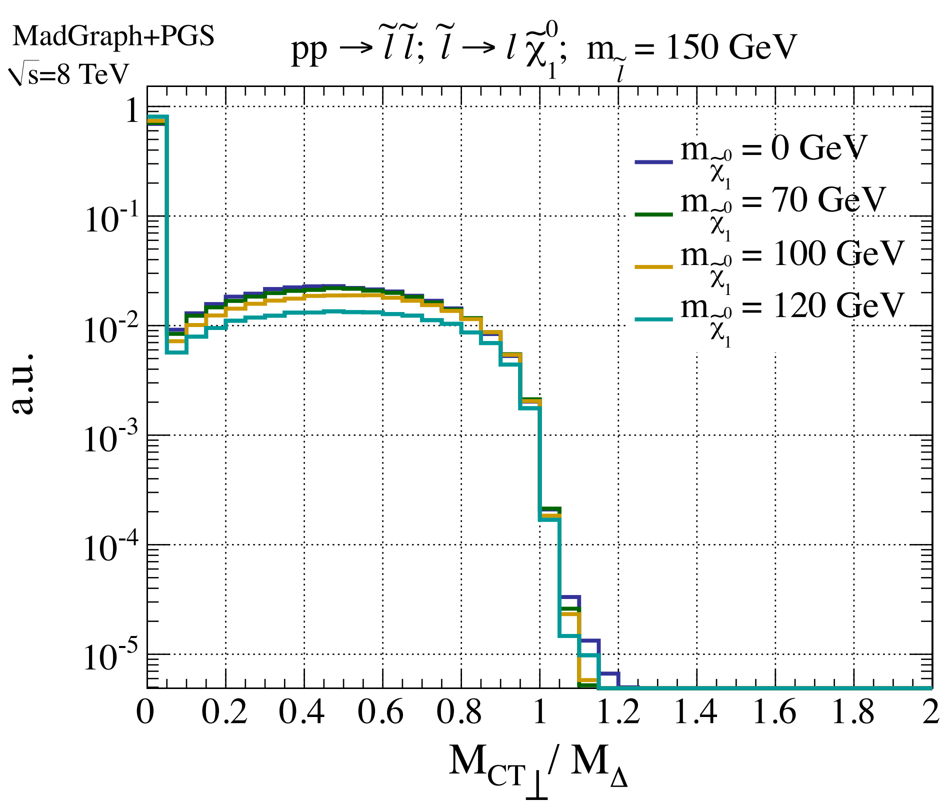
- As you can see, moderate improvements over the ATLAS variable $M_{T2}$, assuming a shape-analysis.
- Near degeneracy line, we're mostly limited by trigger efficiencies.
    - Since $\Delta\phi_R^\beta$ depends on $m_{\tilde{\chi}_1^0}/m_{\tilde{\ell}}$, not $M_\Delta$, this is the region we'd expect it to do the most good.
    - Adopt mono-jet searches for dark matter for triggering? Use low $p_T$ leptons in super-razor search?
- Apply super-razor to other final states $\tilde{\tau}^+\tilde{\tau}^-$

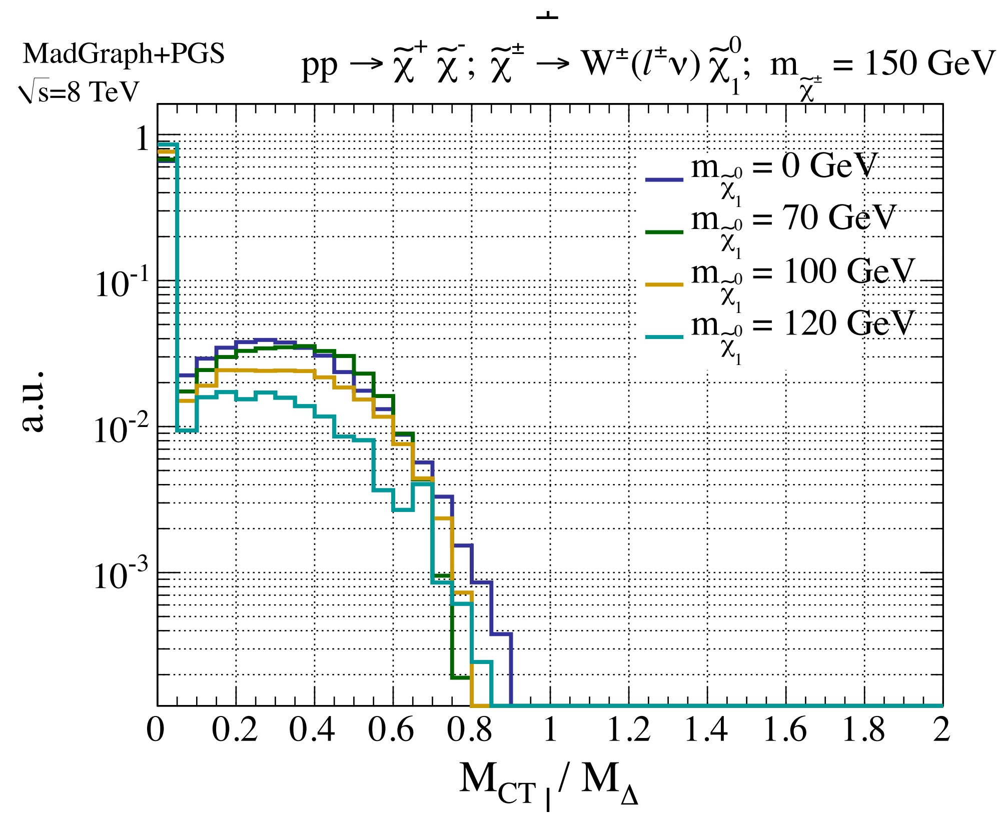


# $M_{T2}$

$$m_{T2}^2(\mu_\chi) = \min_{\vec{p}_T[\chi_1]+\vec{p}_T[\chi_2]=\not{E}_T} \max\left\{m_T^2(\vec{p}_T[q_1],\vec{p}_T[\chi_1],\mu_\chi), m_T^2(\vec{p}_T[q_2],\vec{p}_T[\chi_2],\mu_\chi)\right\}$$

- Pick a test mass, run over possible missing momentum configurations.



# $M_{CT\perp}$

- "Contra-transverse" mass $M_{CT}^2 = 2(p_{T1}p_{T2} - \vec{p}_{T1} \cdot \vec{p}_{T2})$
- From the jet boost direction $-\vec{J} = \vec{p}_{T1} + \vec{p}_{T2} + \vec{\not{E}}_T$ define the $M_{CT}$ variable using only momentum components perpendicular to $\vec{J}$