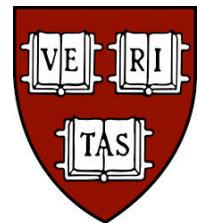




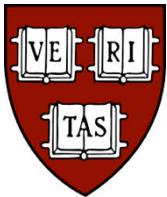
# Kinematic Variables for New Physics Searches at the LHC

Christopher Rogan



HARVARD  
UNIVERSITY

SUSY at the Near Energy Frontier  
Fermilab – Nov. 13, 2013



# Talk Outline

- New physics in open final states: what, why?
- Kinematic variables for open final states
- Towards a kinematic basis for open final states
- Outlook

Disclaimer: This talk does not cover an exhaustive list of interesting variables – see some of the other talks in this workshop for examples not discussed here



# Open vs. closed final states

CLOSED

constrained





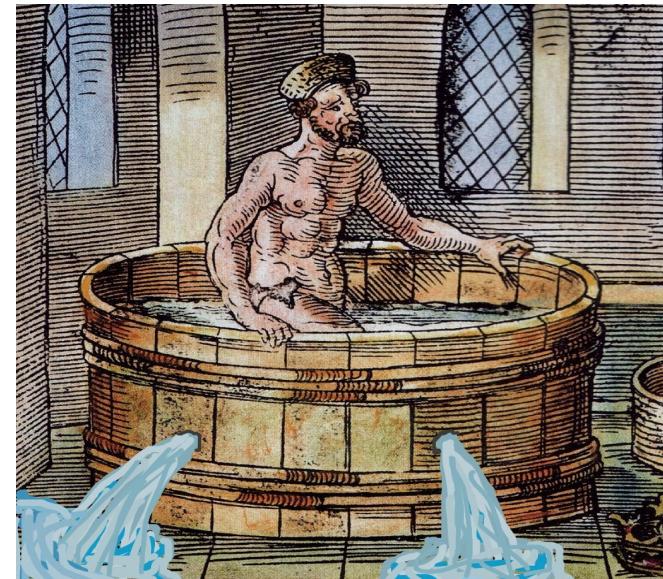
# Open vs. closed final states

CLOSED

constrained

OPEN

Under-constrained

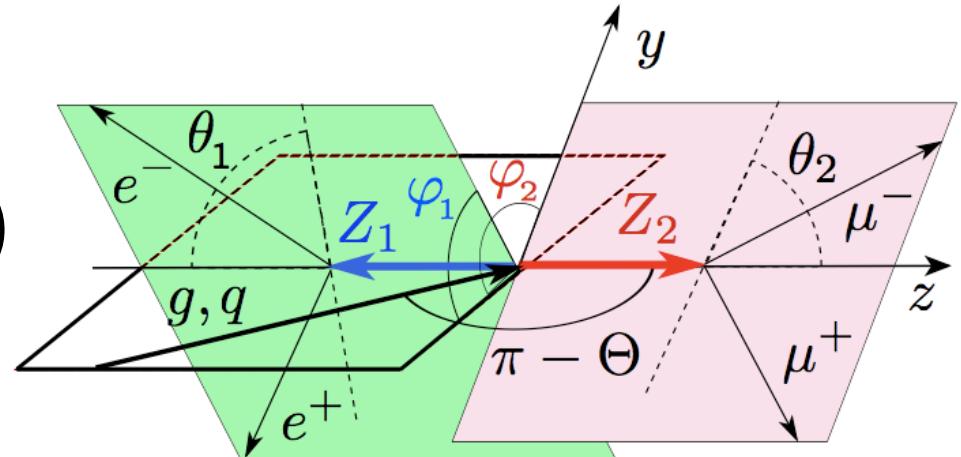




# Open vs. closed final states

CLOSED  $H \rightarrow Z(\ell\ell)Z(\ell\ell)$

Can calculate all masses,  
momenta, angles



Can use masses for discovery, can use  
information to measure spin, CP, etc.

OPEN  $H \rightarrow W(\ell\nu)W(\ell\nu)$

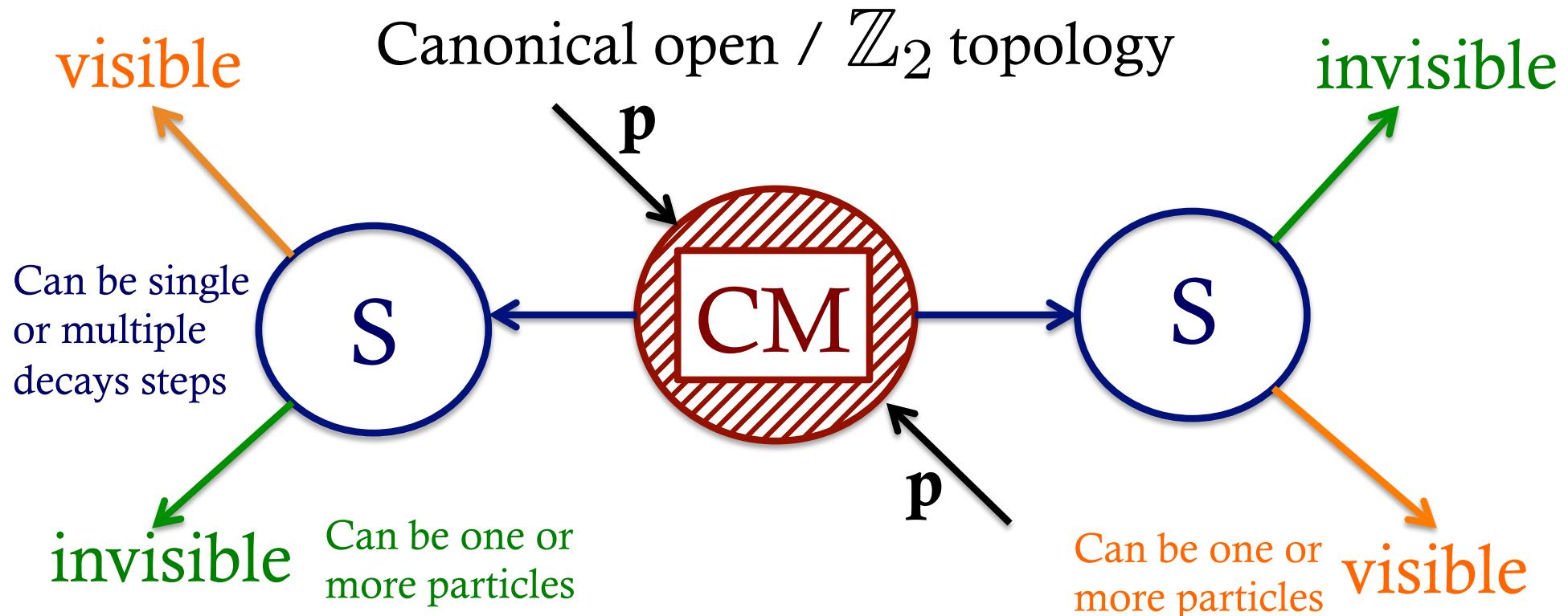
Under-constrained system with multiple weakly interacting  
particles – can't calculate all the kinematic information

What useful information can we calculate?

What can we measure?



# What/why open final states?



- Dark Matter
- Higgs quadratic divergences

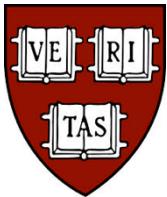


Theory  
SUSY  
Little Higgs  
UED

...

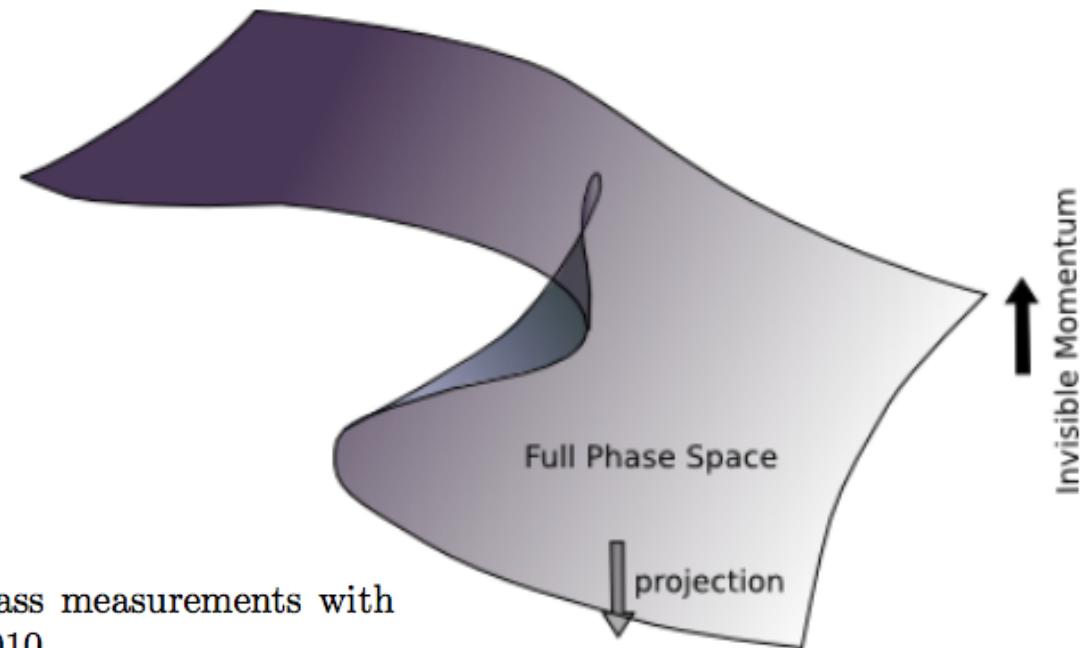
$\mathbb{Z}_2$   
R-parity  
T-parity  
KK-parity

...



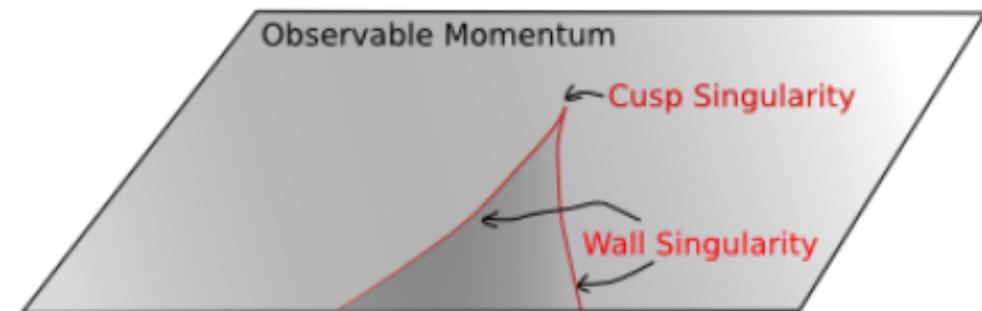
# Singularity variables

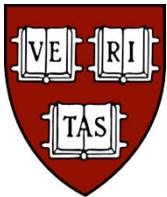
Kinematic Singularities. A singularity is a point where the local tangent space cannot be defined as a plane, or has a different dimension than the tangent spaces at non-singular points.



**From:**

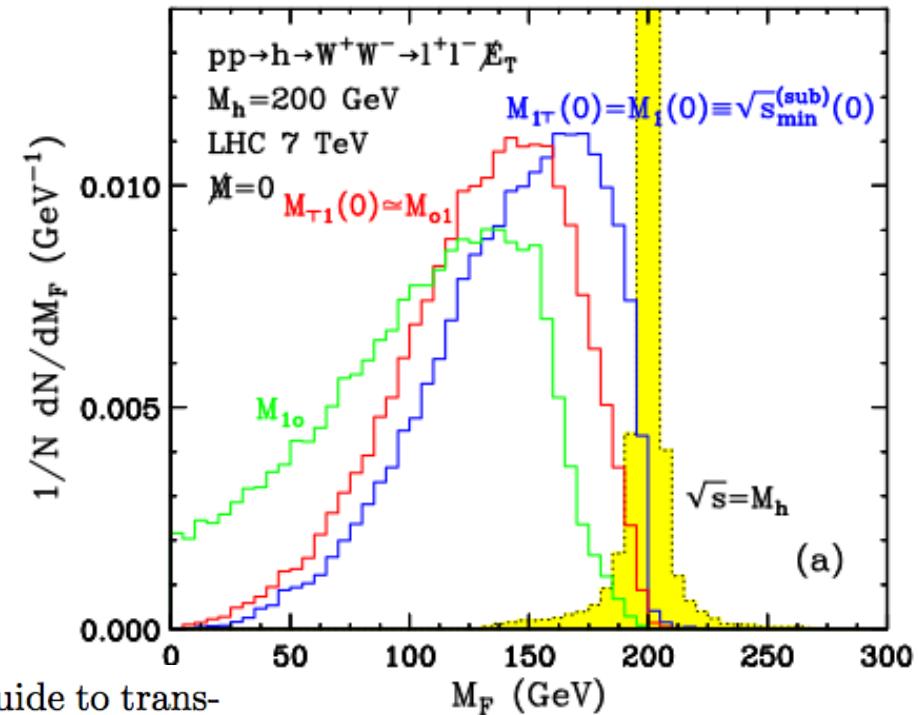
Ian-Woo Kim. Algebraic singularity method for mass measurements with missing energy. *Phys. Rev. Lett.*, 104:081601, Feb 2010.





# Singularity variables

The guiding principle we employ for creating useful hadron-collider event variables, is that: *we should place the best possible bounds on any Lorentz invariants of interest, such as parent masses or the center-of-mass energy  $\hat{s}^{1/2}$ , in any cases where it is not possible to determine the actual values of those Lorentz invariants due to incomplete event information.*



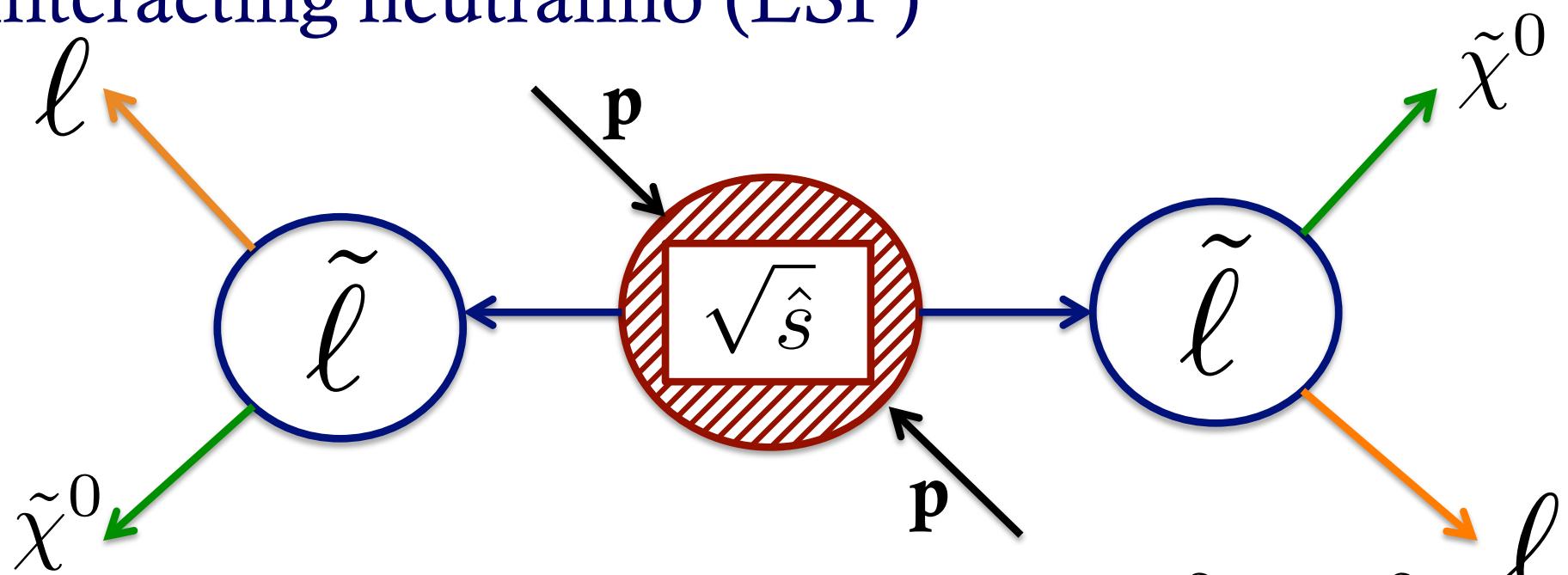
**From:**

A.J. Barr, T.J. Khoo, P. Konar, K. Kong, C.G. Lester, et al. Guide to transverse projections and mass-constraining variables. *Phys. Rev.*, D84:095031, 2011.



# Example: slepton pair-production

- Each slepton decays to a lepton and a weakly interacting neutralino (LSP)



$$\sqrt{\hat{s}} = 2\gamma^{decay} m_{\tilde{\ell}}$$

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

- Signature: di-leptons+MET
- Main backgrounds: WW, ttbar, Z+jets



# Example: $M_{T2}$

assuming  $\sim$ mass-less leptons

Extremization of unknown degrees of freedom

LSP ‘test mass’

$$M_{T2}^2(m_\chi) = \min_{\vec{p}_T^{\chi_1} + \vec{p}_T^{\chi_2} = \vec{E}_T^{miss}} \max \left[ m_T^2(\vec{p}_T^{\ell_1}, \vec{p}_T^{\chi_1}, m_\chi), m_T^2(\vec{p}_T^{\ell_2}, \vec{p}_T^{\chi_2}, m_\chi) \right]$$

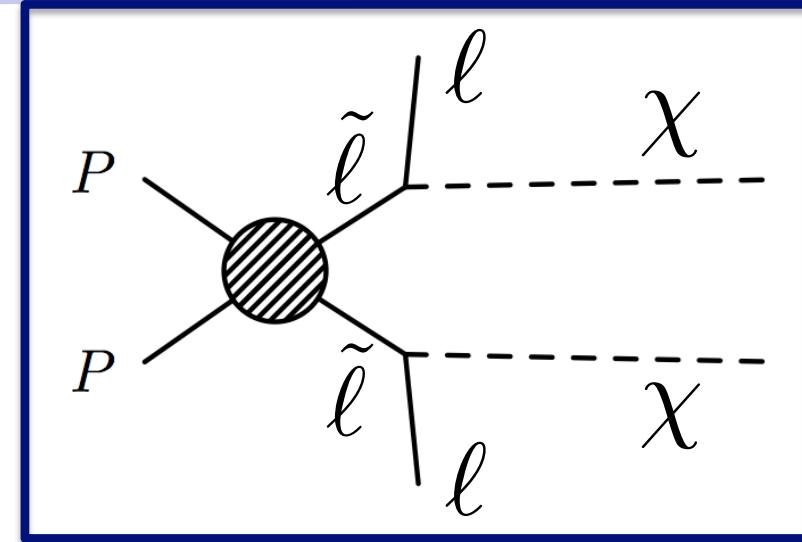
Subject to constraints

$$\text{with: } m_T^2(\vec{p}_T^{\ell_i}, \vec{p}_T^{\chi_i}, m_\chi) = m_\chi^2 + 2 \left( E_T^{\ell_i} E_T^{\chi_i} - \vec{p}_T^{\ell_i} \cdot \vec{p}_T^{\chi_i} \right)$$

Constructed to have a kinematic endpoint (with the right test mass) at:  $M_{T2}^{\max}(m_\chi) = m_{\tilde{\ell}}$

From:

C.G. Lester and D.J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders. *Phys.Lett.*, B463:99–103, 1999.



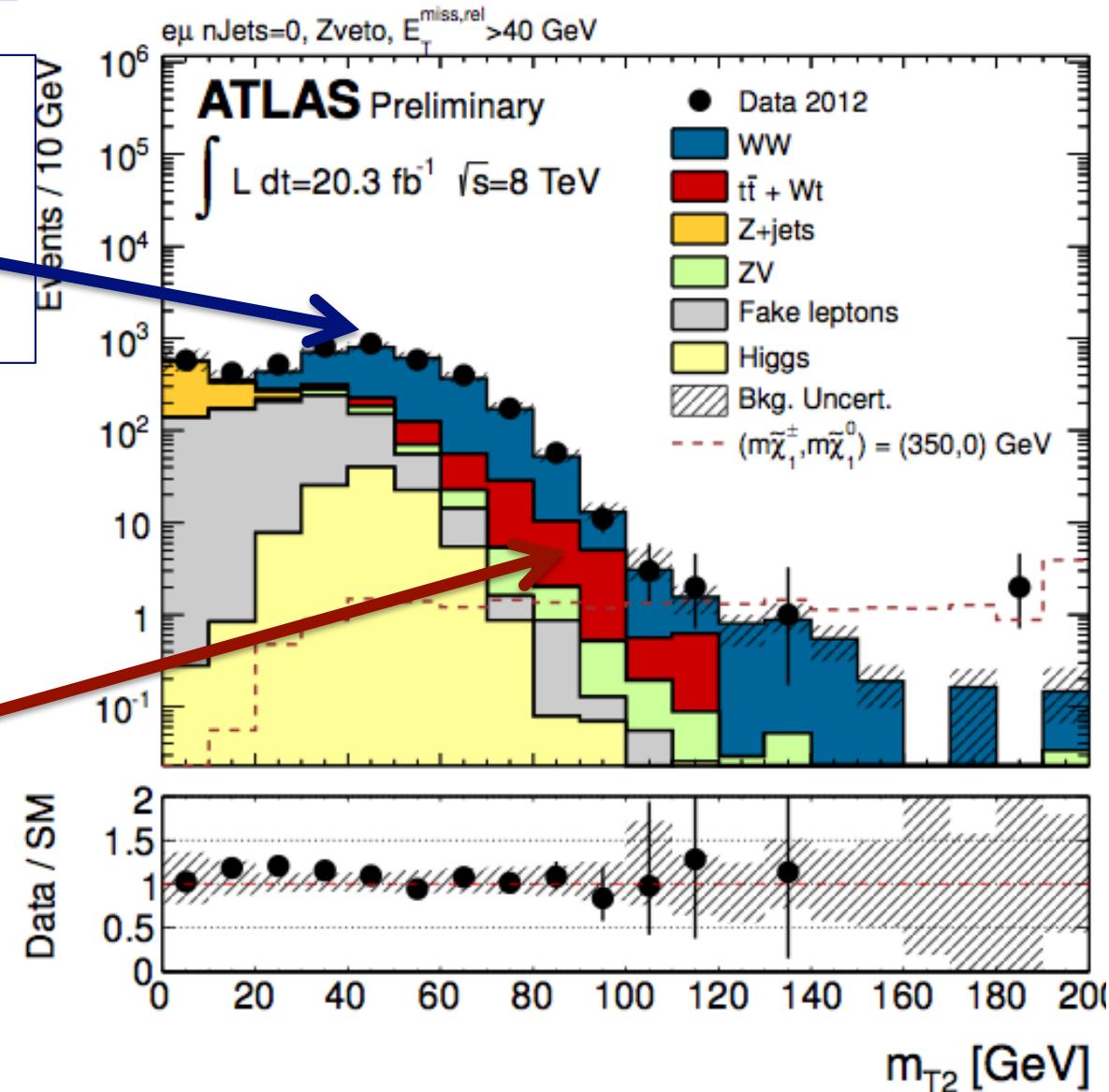


# $M_{T2}$ in practice

'peak position' of signal and backgrounds due to other cuts ( $p_T$ , MET) and only weakly sensitive to sparticle masses

From:  
ATLAS-CONF-2013-049

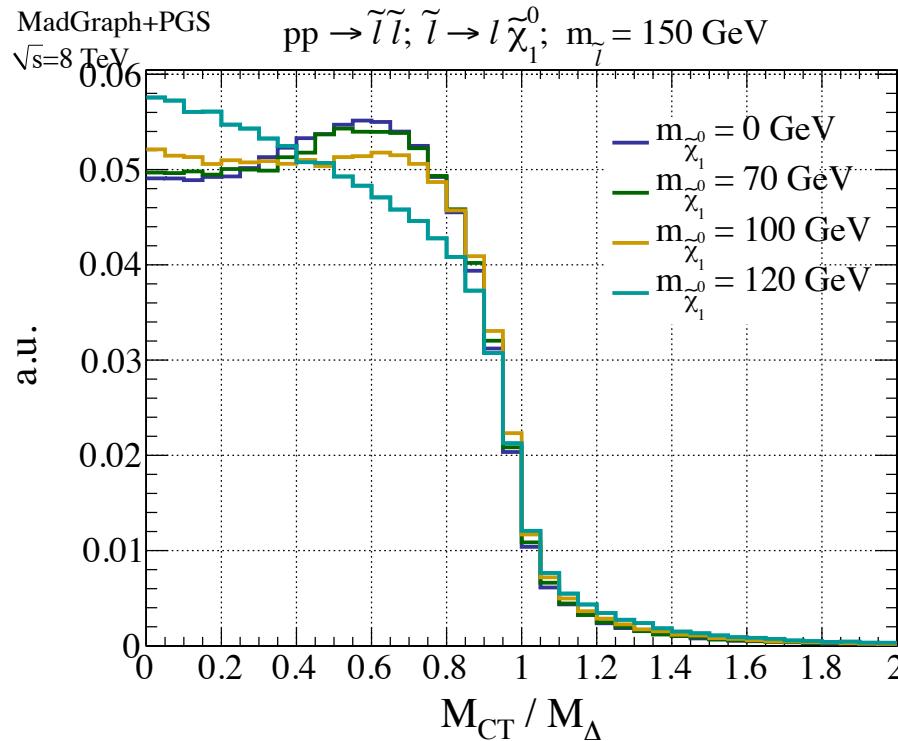
'endpoint' behavior degraded  
due to resolution effects,  
incorrect test mass, ISR, + ....





# Example: $M_{CT}$

assuming  $\sim$ mass-less leptons



$$M_{CT}^2 = 2 \left( p_T^{\ell_1} p_T^{\ell_2} + \vec{p}_T^{\ell_1} \cdot \vec{p}_T^{\ell_2} \right)$$

Constructed to have a kinematic endpoint at:

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

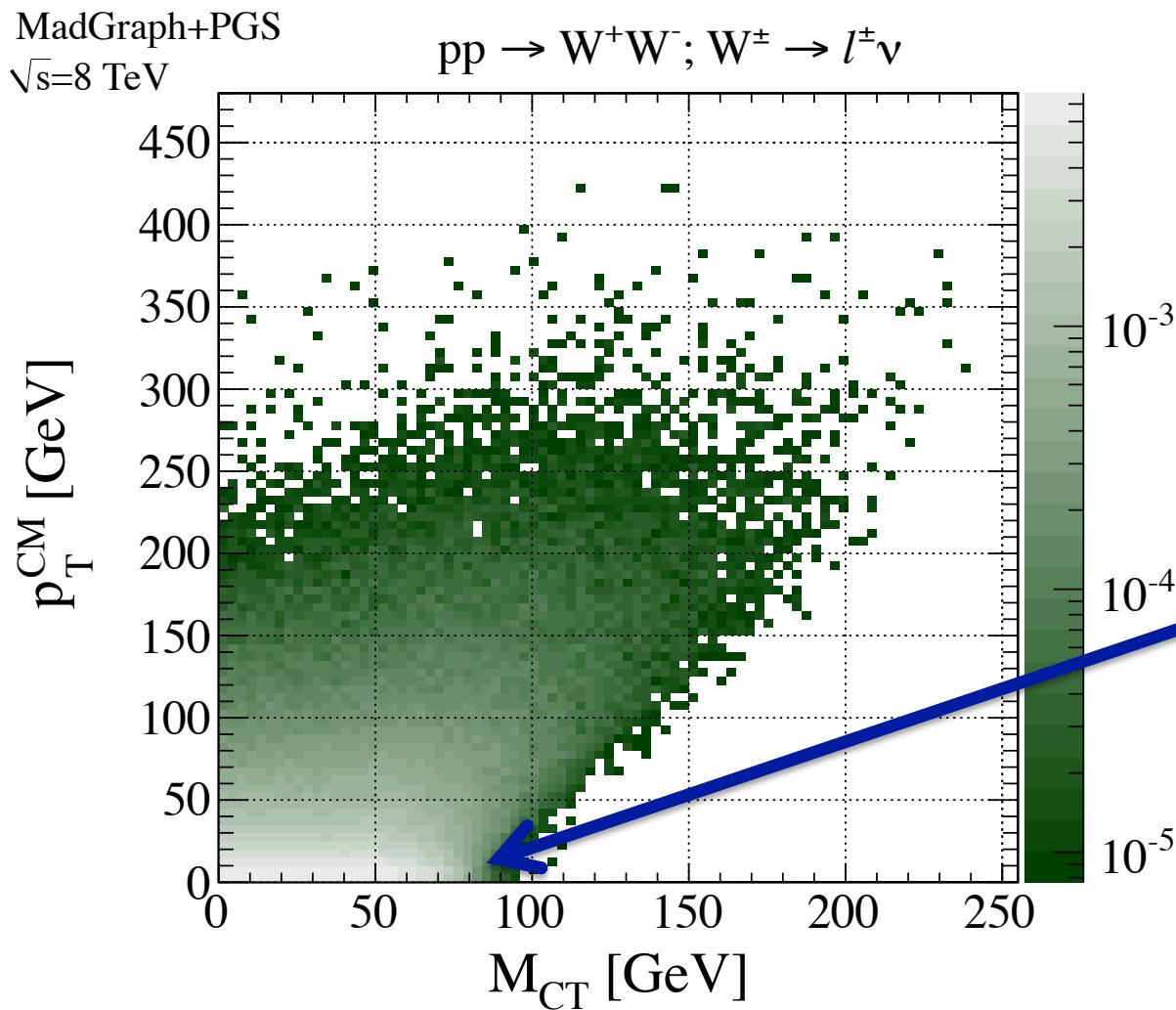
From:

Daniel R. Tovey. On measuring the masses of pair-produced semi-invisibly decaying particles at hadron colliders. *JHEP*, 0804:034, 2008.



# $M_{\text{CT}}$ in practice

Singularity variables (like  $M_{\text{CT}}$ ) can be sensitive to quantities that can vary dramatically event-by-event



Kinematic endpoint  
'moves' with nonzero  
CM system  $p_T$

a.u.



# The mass challenge

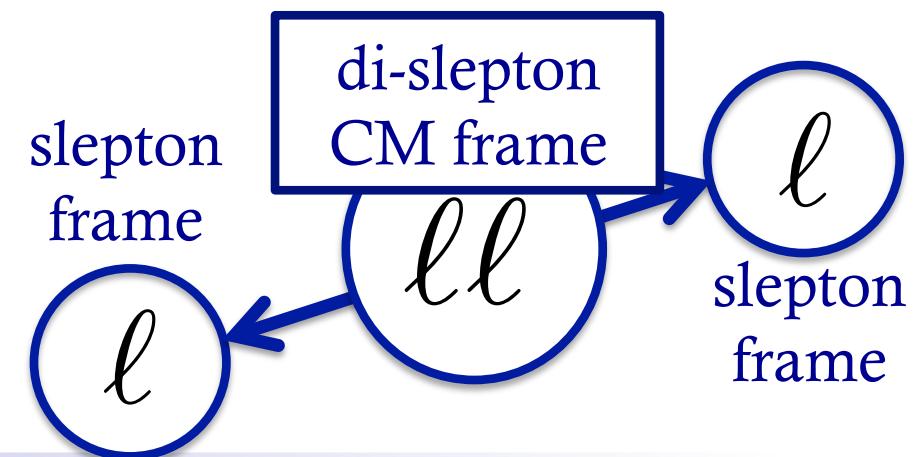
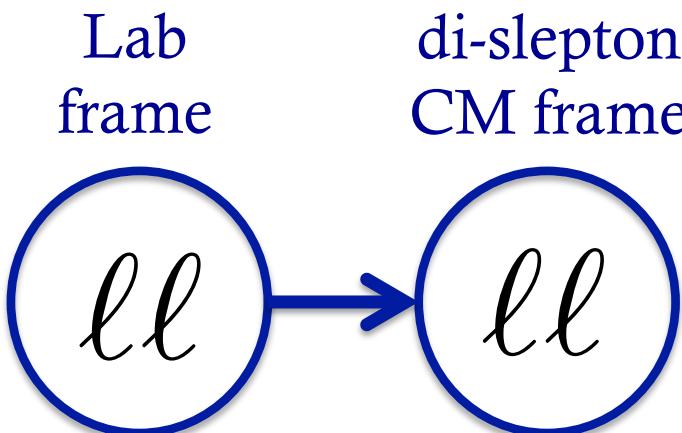
The invariant mass is invariant under coherent Lorentz transformations of two particles

$$m_{inv}^2(p_1, p_2) = m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

The Euclidean mass (or contra-variant mass) is invariant under anti-symmetric Lorentz transformations of two particles

$$m_{eucl}^2(p_1, p_2) = m_1^2 + m_2^2 + 2(E_1 E_2 + \vec{p}_1 \cdot \vec{p}_2)$$

Even the simplest case requires variables with both properties!





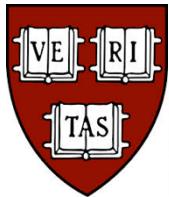
# Correcting for CM $p_T$

- Want to boost from lab-frame to CM-frame
- We know the transverse momentum of the CM-frame:

$$\vec{p}_T^{CM} = \vec{p}_T^{\ell_1} + \vec{p}_T^{\ell_2} + \vec{E}_T^{\text{miss}}$$

- But we don't know the energy, or mass, of the CM-frame:

$$\beta_{lab \rightarrow CM} = \frac{\vec{p}_T^{CM}}{\sqrt{|\vec{p}_T^{CM}|^2 + \hat{s}}}$$



# $p_T$ corrections for $M_{CT}$

Attempts have been made to mitigate this problem:

- (i) ‘Guess’ the lab  $\rightarrow$  CM frame boost:

$$M_{CT(\text{corr})} = \begin{cases} M_{CT} & \text{after boosting by } \beta = p_b/E_{\text{cm}} \quad \text{if } A_{x(\text{lab})} \geq 0 \text{ or } A'_{x(\text{lo})} \geq 0 \\ M_{CT} & \text{after boosting by } \beta = p_b/\hat{E} \quad \text{if } A'_{x(\text{hi})} < 0 \\ M_{Cy} & \text{if } A'_{x(\text{hi})} \geq 0 \end{cases}$$

x – parallel to boost

y – perp. to boost

with:

$$A_x = p_x[q_1]E_y[q_2] + p_x[q_2]E_y[q_1]$$

$$M_{Cy}^2 = (E_y[q_1] + E_y[q_2])^2 - (p_y[q_1] - p_y[q_2])^2$$

Giacomo Polesello and Daniel R. Tovey. Supersymmetric particle mass measurement with the boost-corrected contransverse mass. *JHEP*, 1003:030, 2010.

- (ii) Only look at event along axis perpendicular to boost:

$M_{CT\perp}$

Konstantin T. Matchev and Myeonghun Park. A General method for determining the masses of semi-invisibly decaying particles at hadron colliders. *Phys.Rev.Lett.*, 107:061801, 2011.

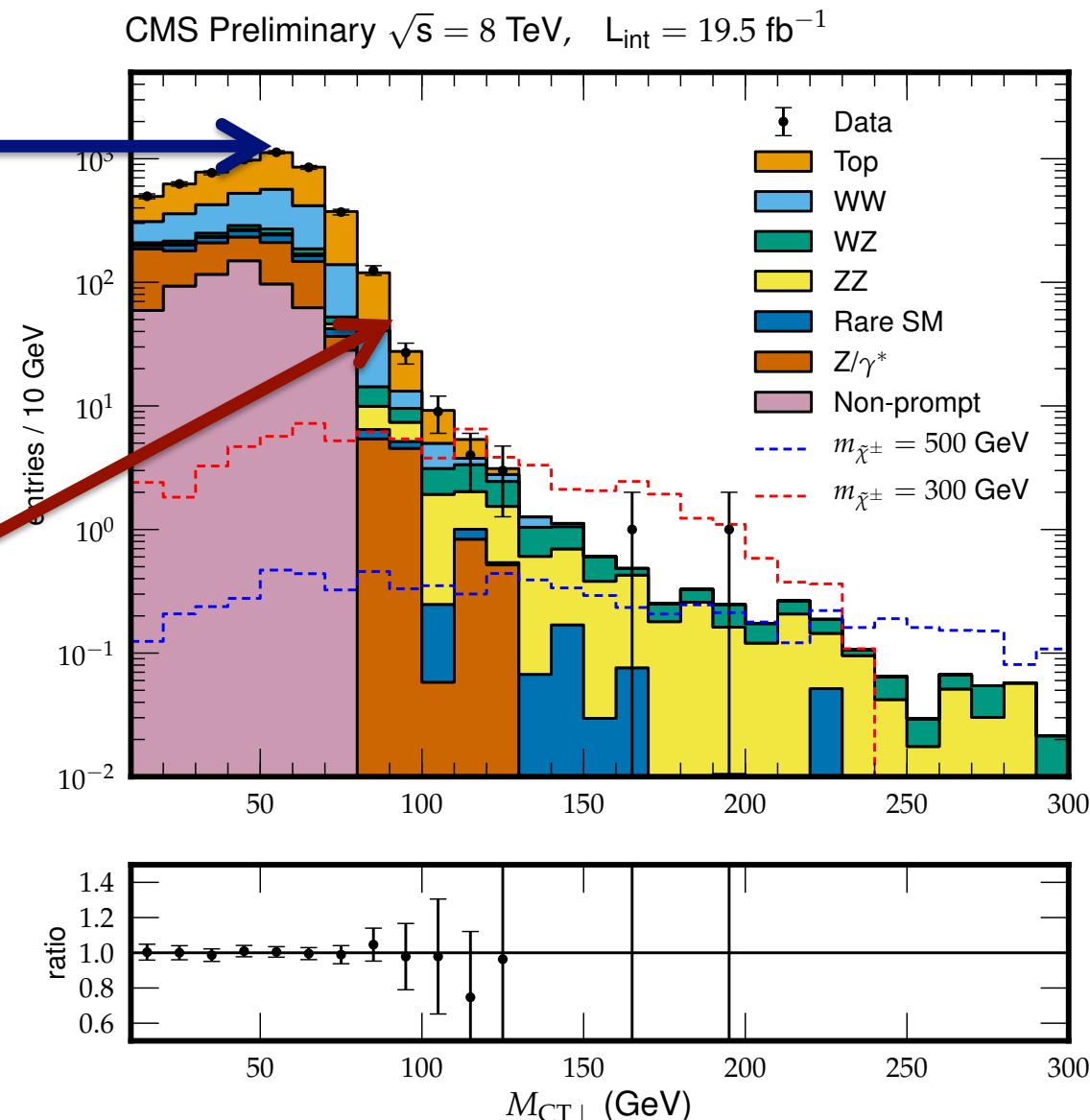


# $M_{CT\perp}$ in practice

'peak position' of signal and backgrounds due to other cuts ( $p_T$ , MET) and only weakly sensitive to sparticle masses

From:  
SUS-PAS-13-006

'endpoint' behavior lost due to resolution effects, incorrect test mass, ISR, + ....

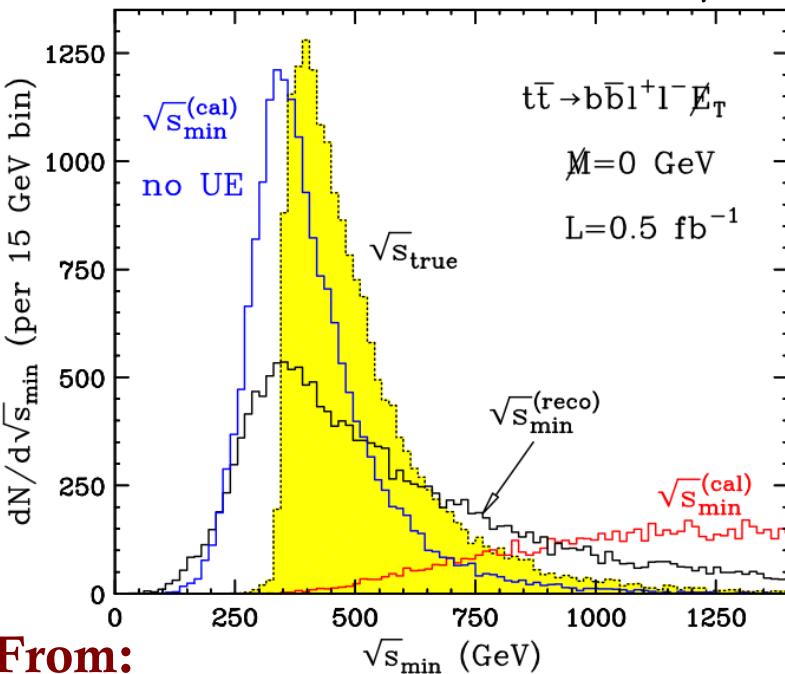




# Example: $\sqrt{s}_{\min}$

Weakly interacting system ‘test mass’

$$\begin{aligned}\sqrt{s}_{\min}(M_{\text{miss}}) &= \sqrt{M_{\text{vis}}^2 + P_{T,\text{vis}}^2} + \sqrt{M_{\text{miss}}^2 + P_{T,\text{miss}}^2} \\ &= \sqrt{m_{\ell\ell}^2 + P_{T,\ell\ell}^2} + \sqrt{M_{\text{miss}}^2 + E_{T,\text{miss}}^2}\end{aligned}$$



Constructed to have a kinematic endpoint at the true event invariant mass (for the correct test mass)

$$\sqrt{s}_{\min}^{\max}(M_{\text{miss}}) = \sqrt{\hat{s}}$$

From:

Partha Konar, Kyoungchul Kong, Konstantin T. Matchev, and Myeonghun Park. RECO level  $\sqrt{s}_{\min}$  and subsystem  $\sqrt{s}_{\min}$ : Improved global inclusive variables for measuring the new physics mass scale in MET events at hadron colliders. *JHEP*, 1106:041, 2011.



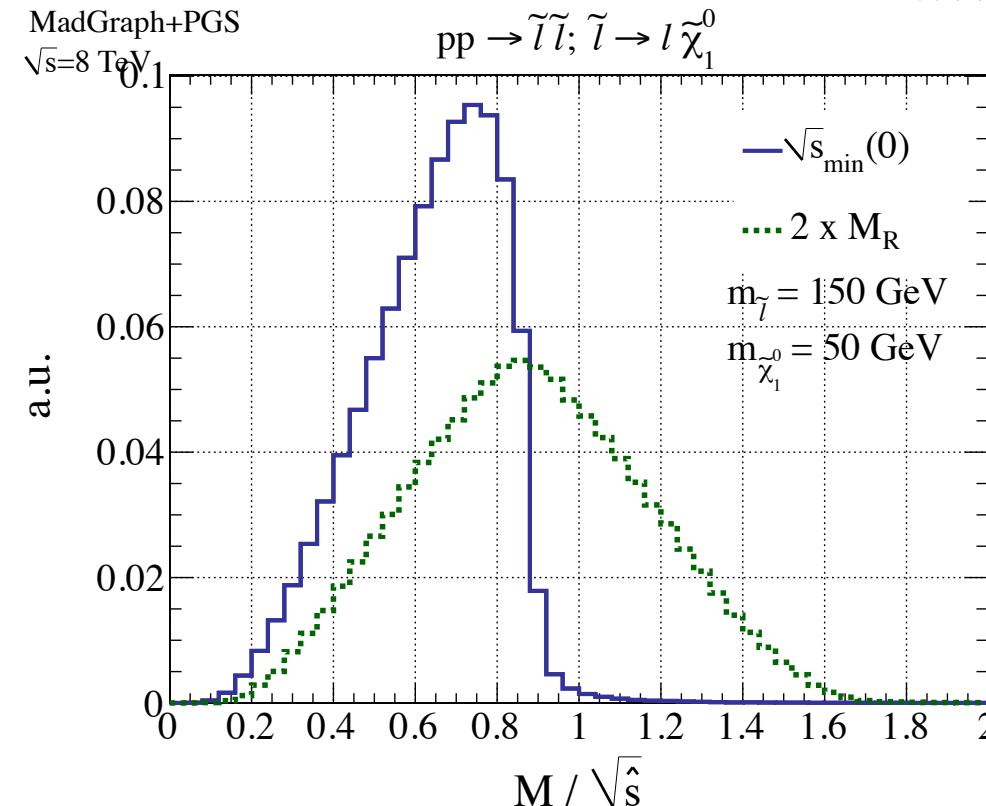
# Edge or Peak?

Don't know  $M_{\text{miss}}$

$$\sqrt{s}_{\min}(M_{\text{miss}}) = \sqrt{m_{\ell\ell}^2 + P_{T,\ell\ell}^2} + \sqrt{M_{\text{miss}}^2 + E_{T,\text{miss}}^2}$$

Minimize w.r.t.  $M_{\text{miss}}$

$$\sqrt{s}_{\min}(0) = \sqrt{m_{\ell\ell}^2 + P_{T,\ell\ell}^2 + E_{T,\text{miss}}^2}$$



Can make a peaking variable

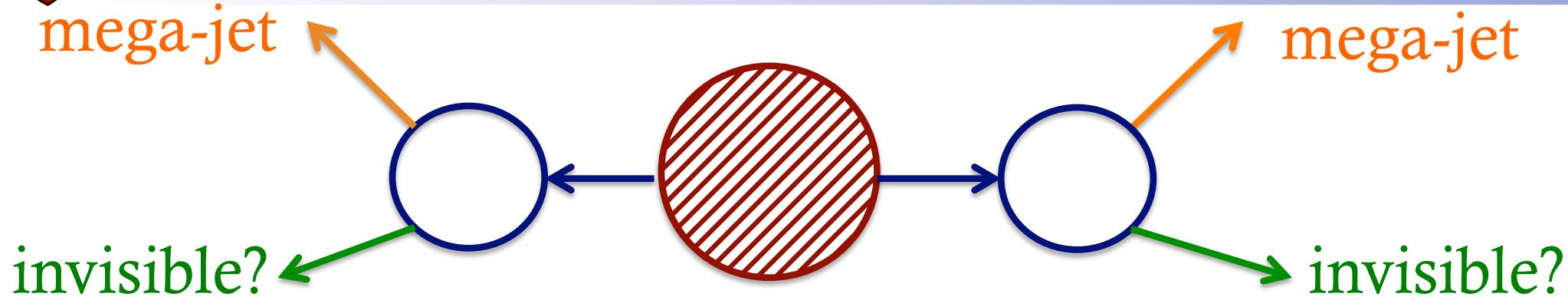
$$M_R = \sqrt{m_{\ell\ell}^2 + P_{T,\ell\ell}^2}$$

Razor mass,  $M_R$

Doesn't use all available information



# Razor kinematic variables



- Assign every reconstructed object to one of two **mega-jets**
- Analyze the event as a ‘canonical’ open final state:
  - two variables:  $M_R$  (mass scale) ,  $R$  (scale-less event imbalance)
- An inclusive approach to searching for a large class of new physics possibilities with open final states

Razor variables

arXiv:1006.2727v1 [hep-ph]

PRD 85, 012004 (2012)

EPJC 73, 2362 (2013)

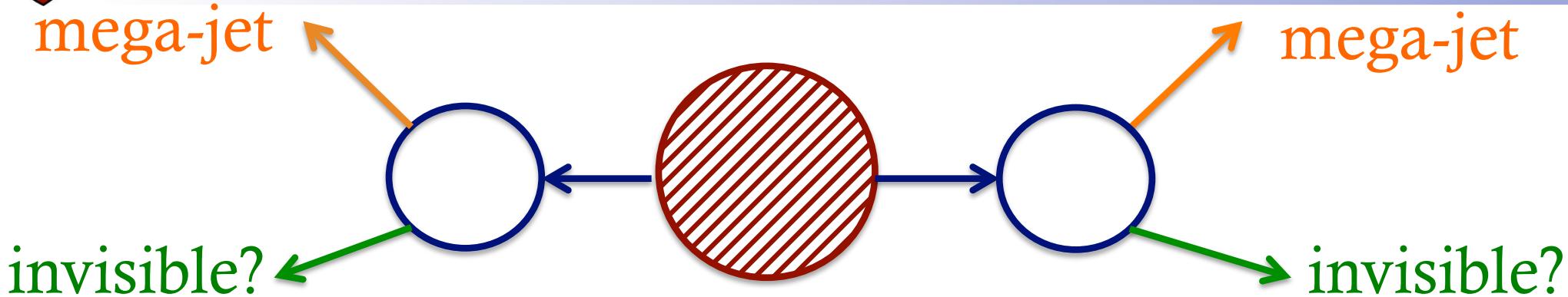
PRL 111, 081802 (2013)

CMS-PAS-SUS-13-004

CMS+ATLAS  
analyses



# Razor kinematic variables



- Assign every reconstructed object to one of two **mega-jets**
- Analyze the event as a ‘canonical’ open final state:
  - two variables:  $M_R$  (mass scale) ,  $R$  (scale-less event imbalance)

$$M_R \sim \sqrt{\hat{s}}$$

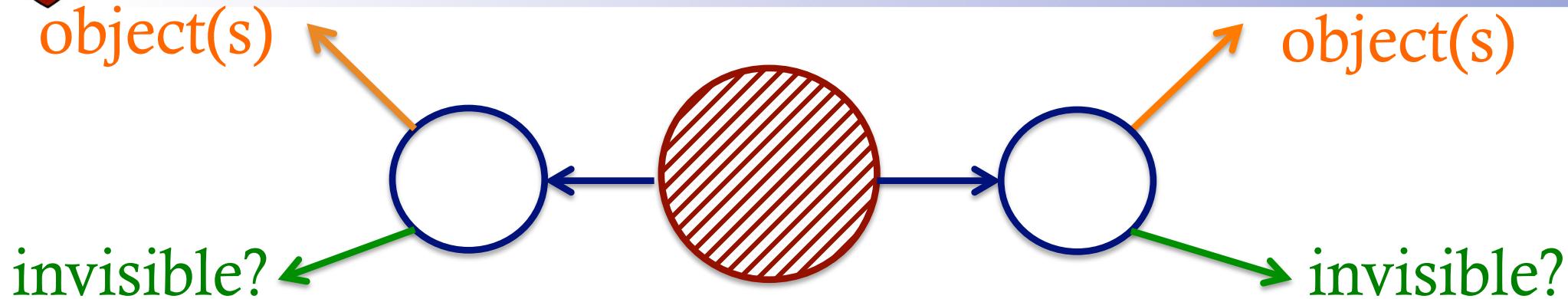
$$R = \frac{M_T^R}{M_R} \sim \frac{M_\Delta}{\sqrt{\hat{s}}}$$

Two distinct mass scales in event

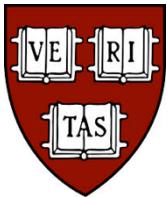
Two pieces of complementary information



# Beyond Razor



- Inclusive approach doesn't
  - distinguish between particles/objects coming from the CM system of interest and ex. ISR, underlying event etc.
  - make assumptions about signals to assign objects to mega-jets or interpret event
- For cases where we assume a specific decay topology, what other information can we extract from an event?



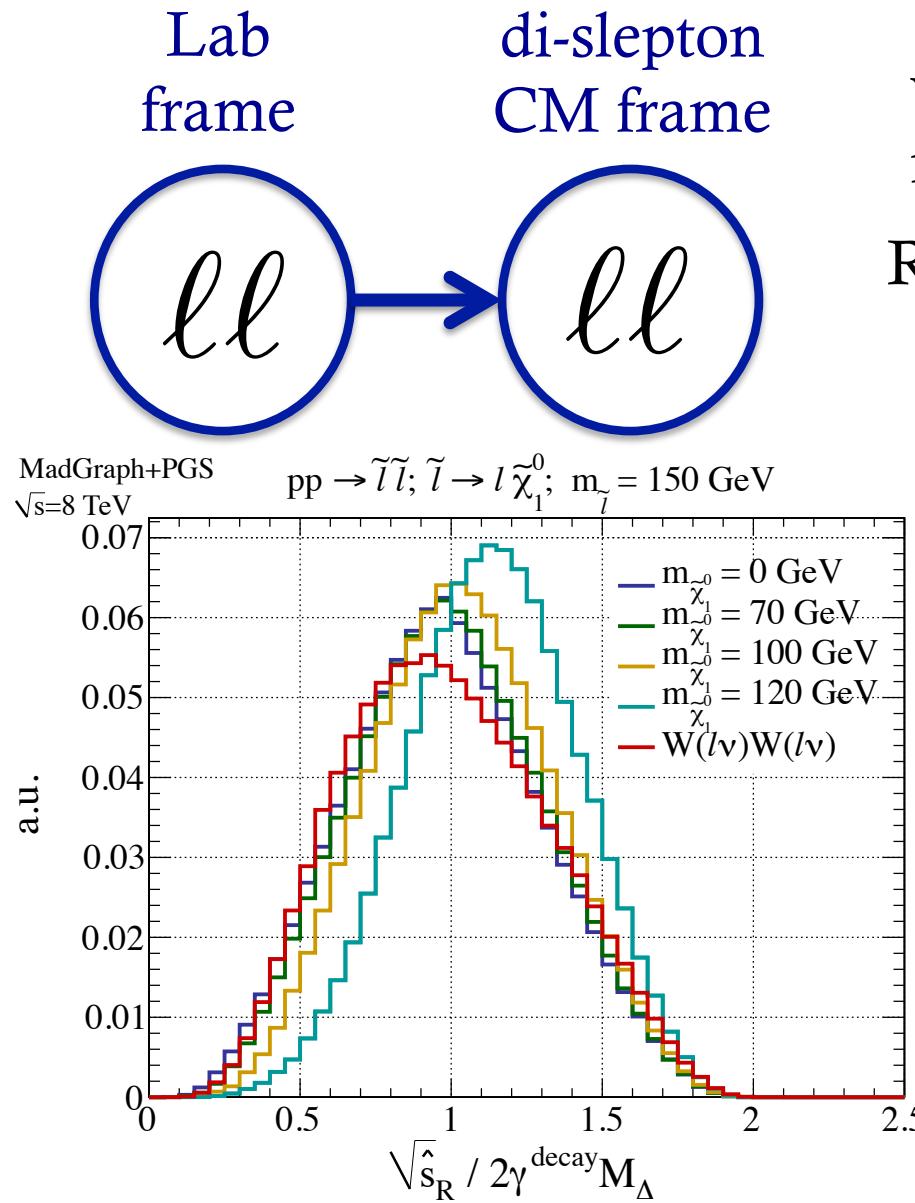
# Super-razor variables

M. Buckley, J. Lykken, CR, M. Spiropulu, arXiv:1310.4827 [hep-ph]

- Systematic approach for deriving a *kinematic basis of variables*
- The strategy is to transform observable momenta iteratively *reference-frame to reference-frame*, traveling backwards through each of the decay reference frames relevant to the topology
- At each step, determine the next transformation by making *boost/contra-boost invariant* guesses for unknown parameters

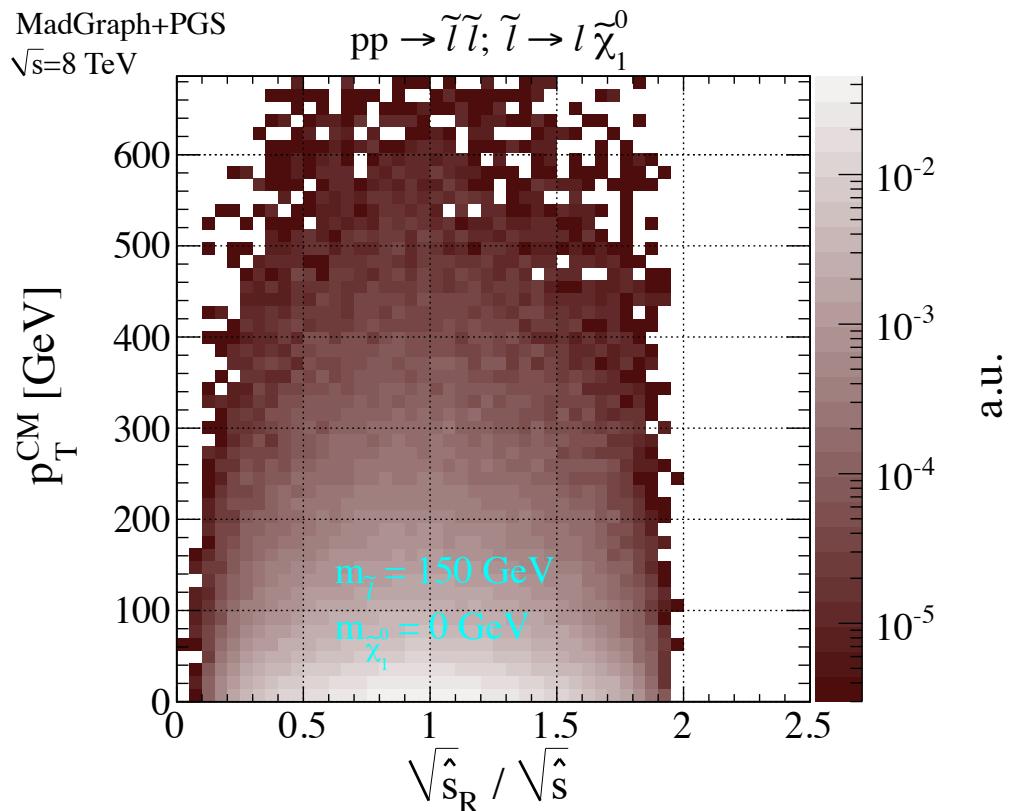


# Super-razor variables



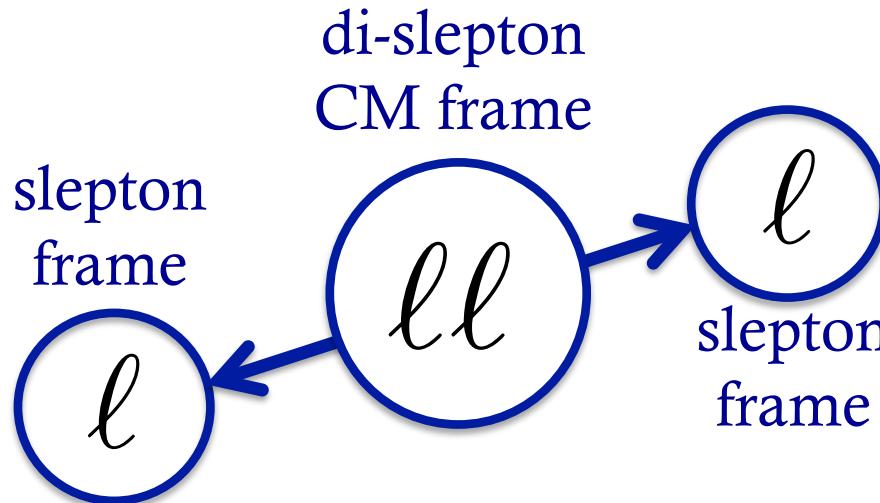
1<sup>st</sup> transformation: extract variable sensitive to invariant mass of total event:  $\sqrt{\hat{s}_R}$

Resulting variable is invariant under  $p_T$  of CM system:  $p_T\text{-corrected } M_R$





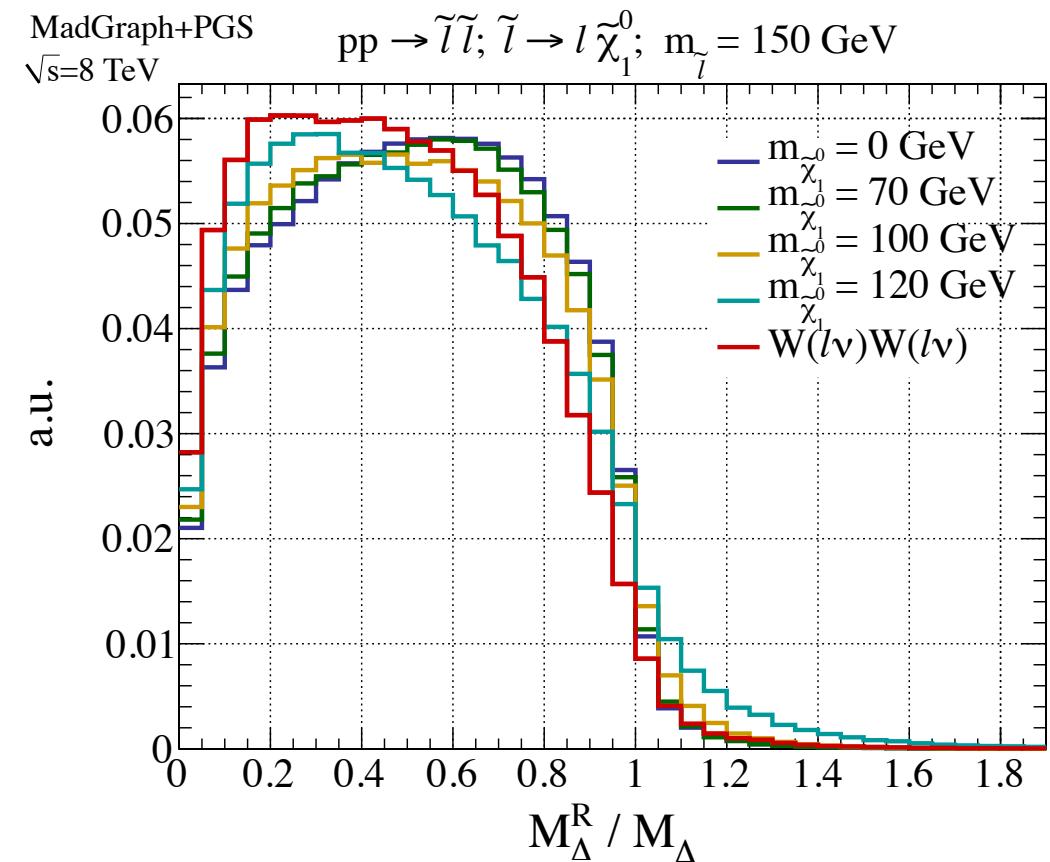
# Super-razor variables



Resulting variable has kinematic endpoint at:

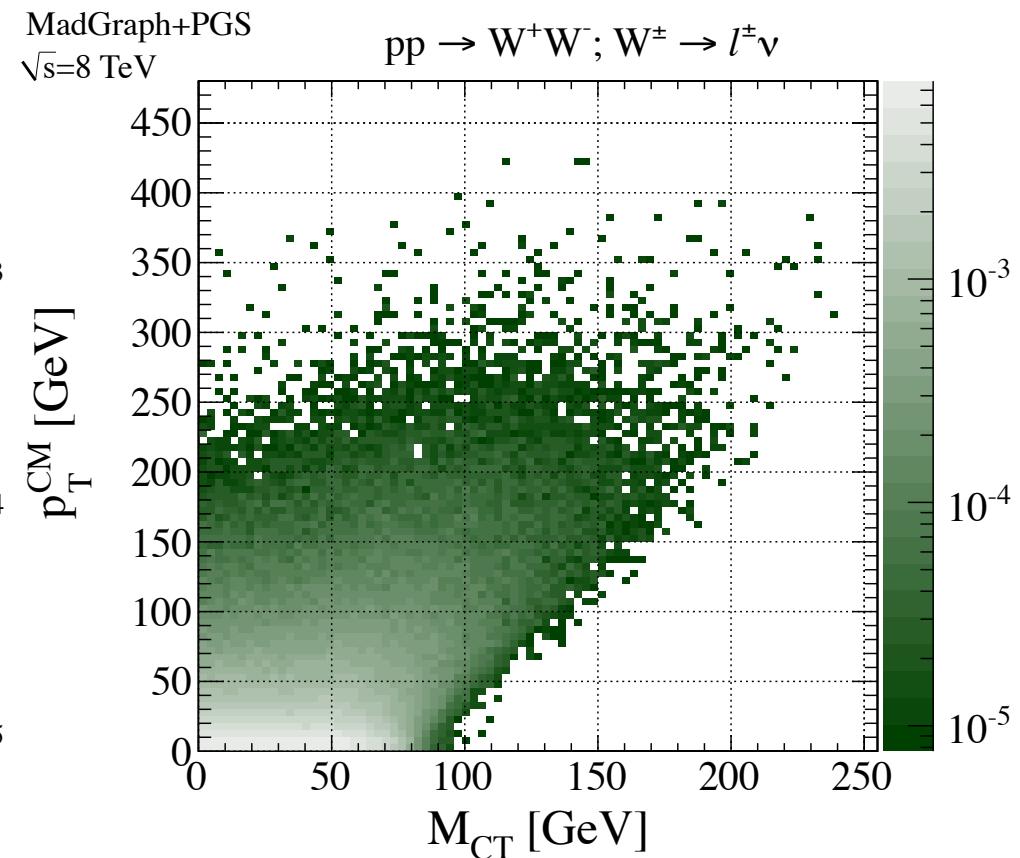
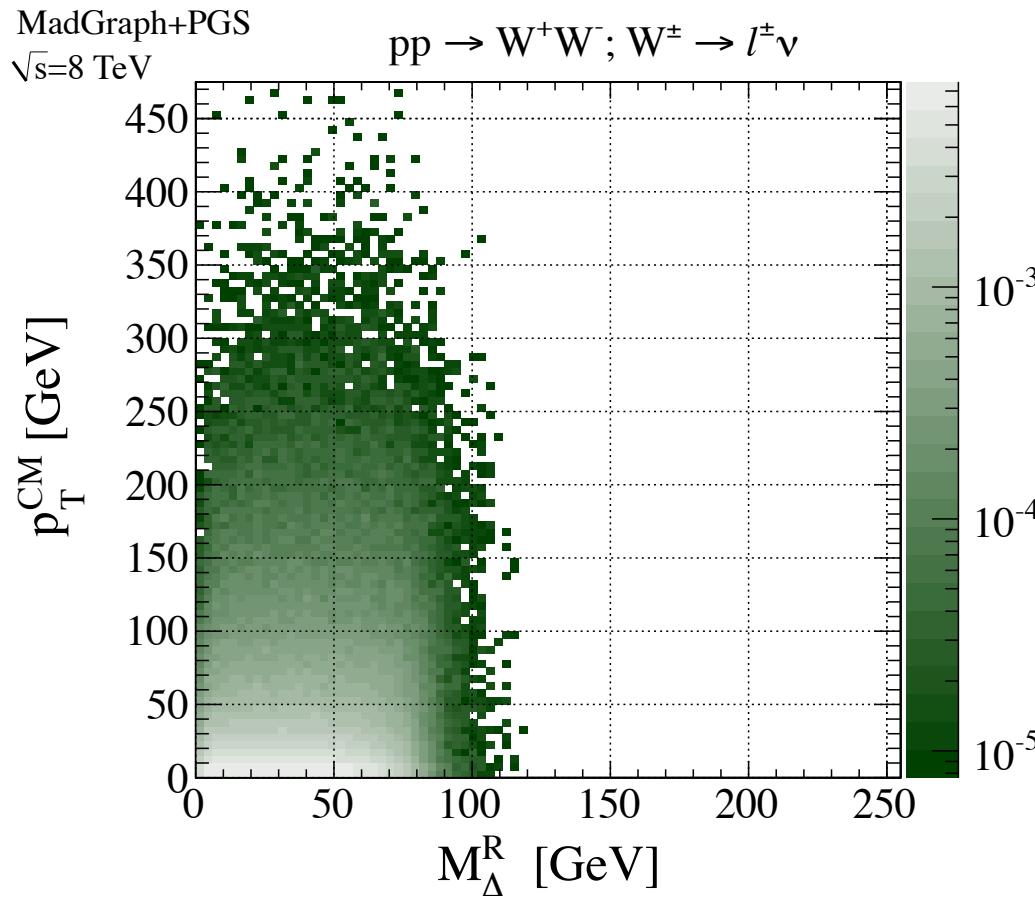
$$M_\Delta \equiv \frac{m_{\tilde{l}}^2 - m_{\tilde{\chi}^0}^2}{m_{\tilde{l}}}$$

2<sup>nd</sup> transformation(s): extract variable sensitive to invariant mass of squark:  $M_\Delta^R$





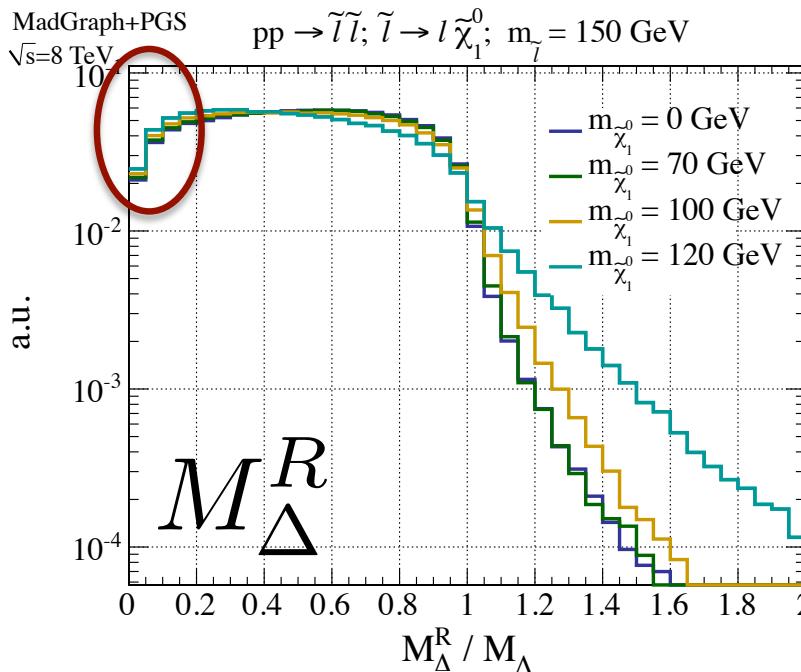
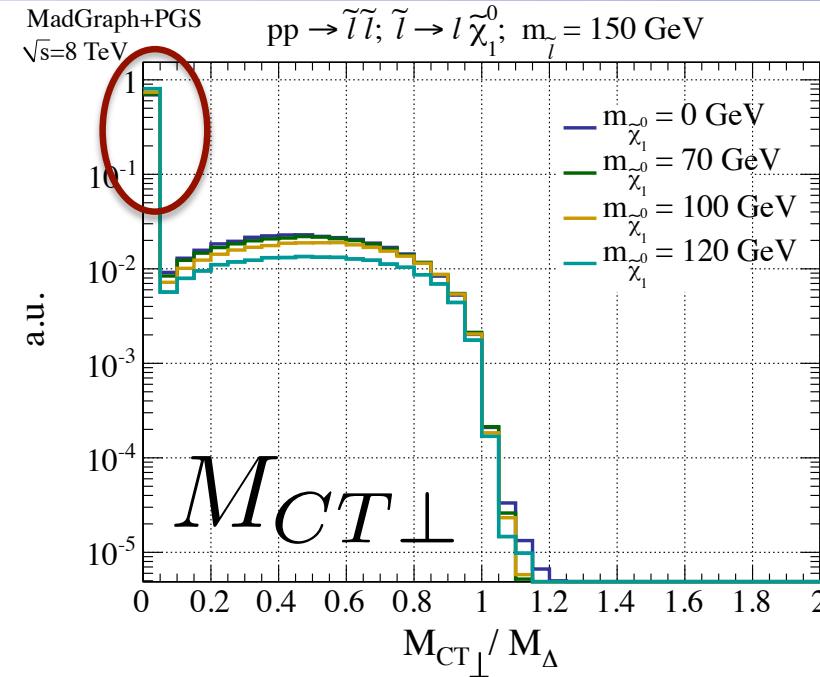
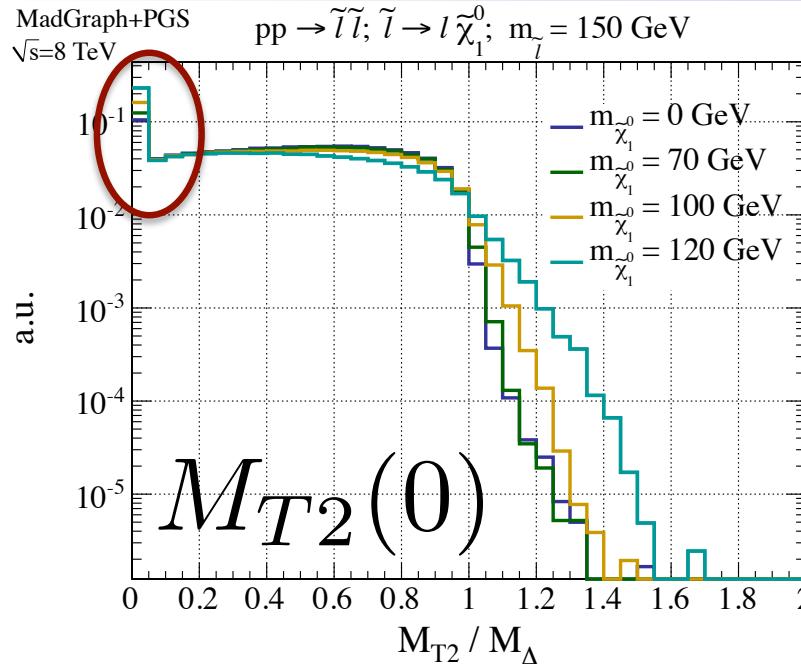
# Super-razor variables



$M_{\Delta}^R$  is a singularity variable – in fact it is essentially identical to  $M_{\text{CT}}$  but evaluated *in a different reference frame*. Boost procedure ensures that new variable is invariant under the previous transformations



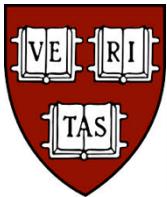
# Variable comparison



Three different singularity variables, all attempting to measure the same thing

$$M_\Delta^R \geq M_{T2}(0) \geq M_{CT\perp}$$

More details about variable comparisons in arXiv:1310.4827 and backup slides

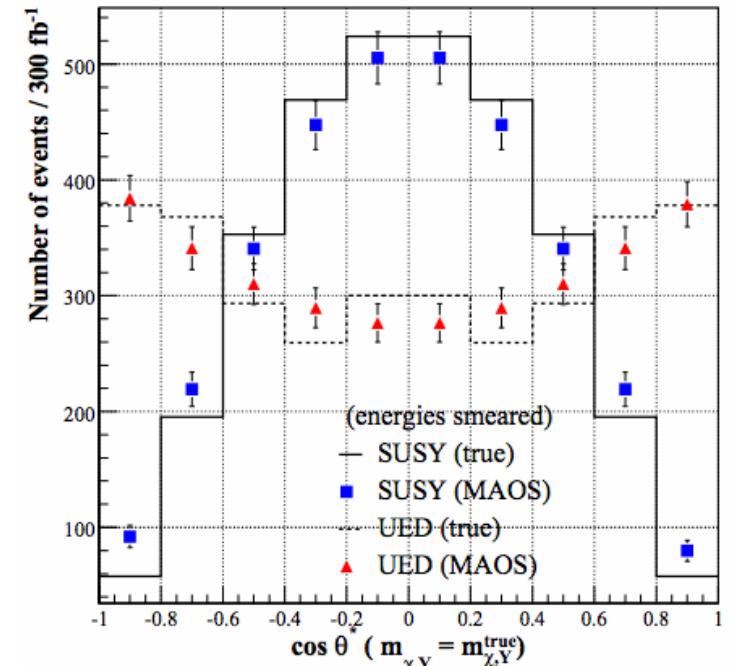


# What other info can we extract?

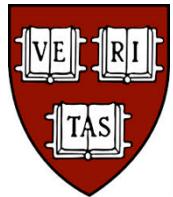
Ex.  $M_{T2}$  extremization assigns values to missing degrees of freedom – if one takes these assignments literally, can we calculate other useful variables?

From:

Mass and Spin Measurement with  $M(T2)$  and MAOS Momentum - Cho, Won Sang et al.  
Nucl.Phys.Proc.Suppl. 200-202 (2010) 103-112 arXiv:0909.4853 [hep-ph]

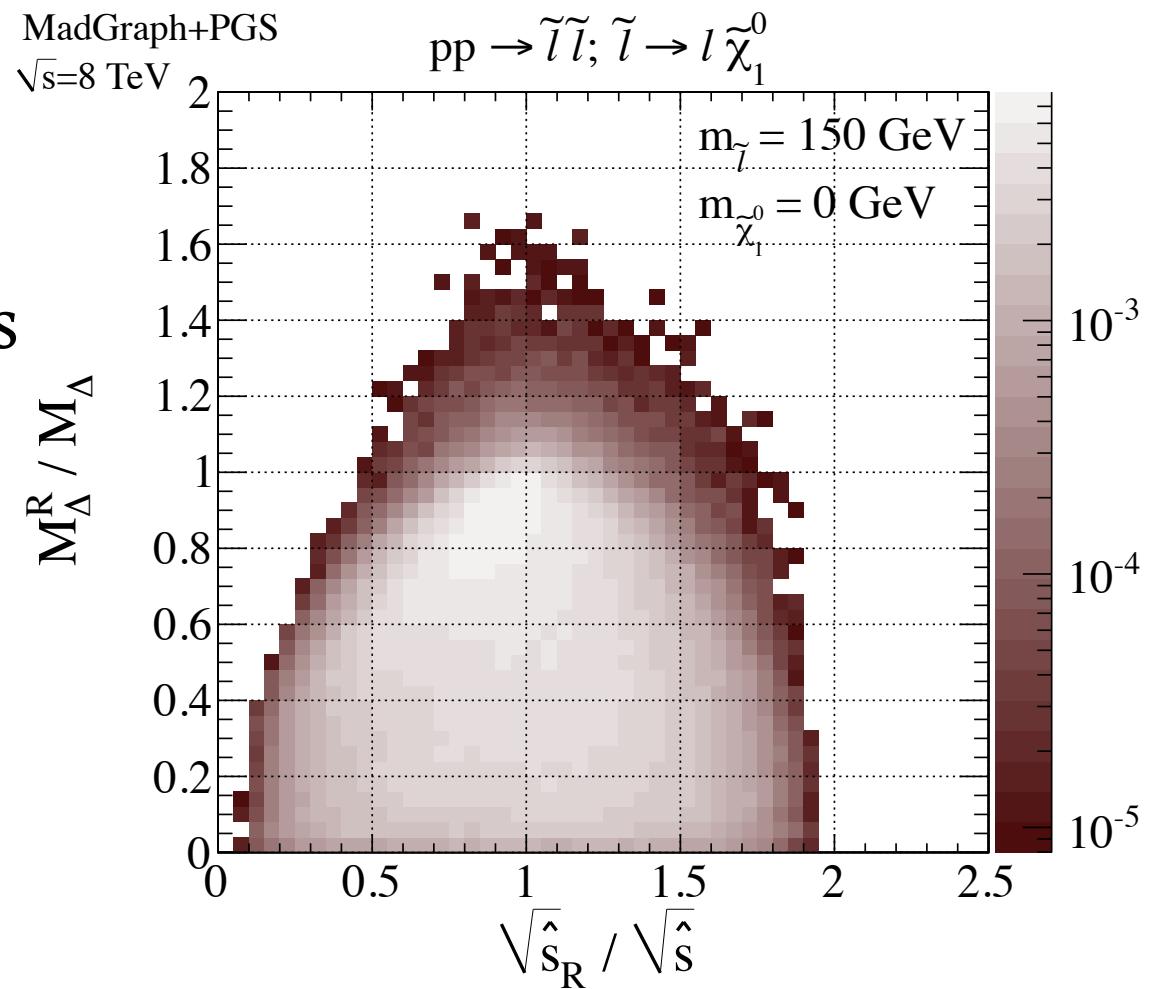


When we assign unconstrained d.o.f. by extremizing one quantity, what are the general properties of other variables we calculate? What are the correlations among them?



# Towards a kinematic basis

Can extract the two mass scales  $\sqrt{\hat{s}}_R$  and  $M_\Delta^R$  almost completely independently



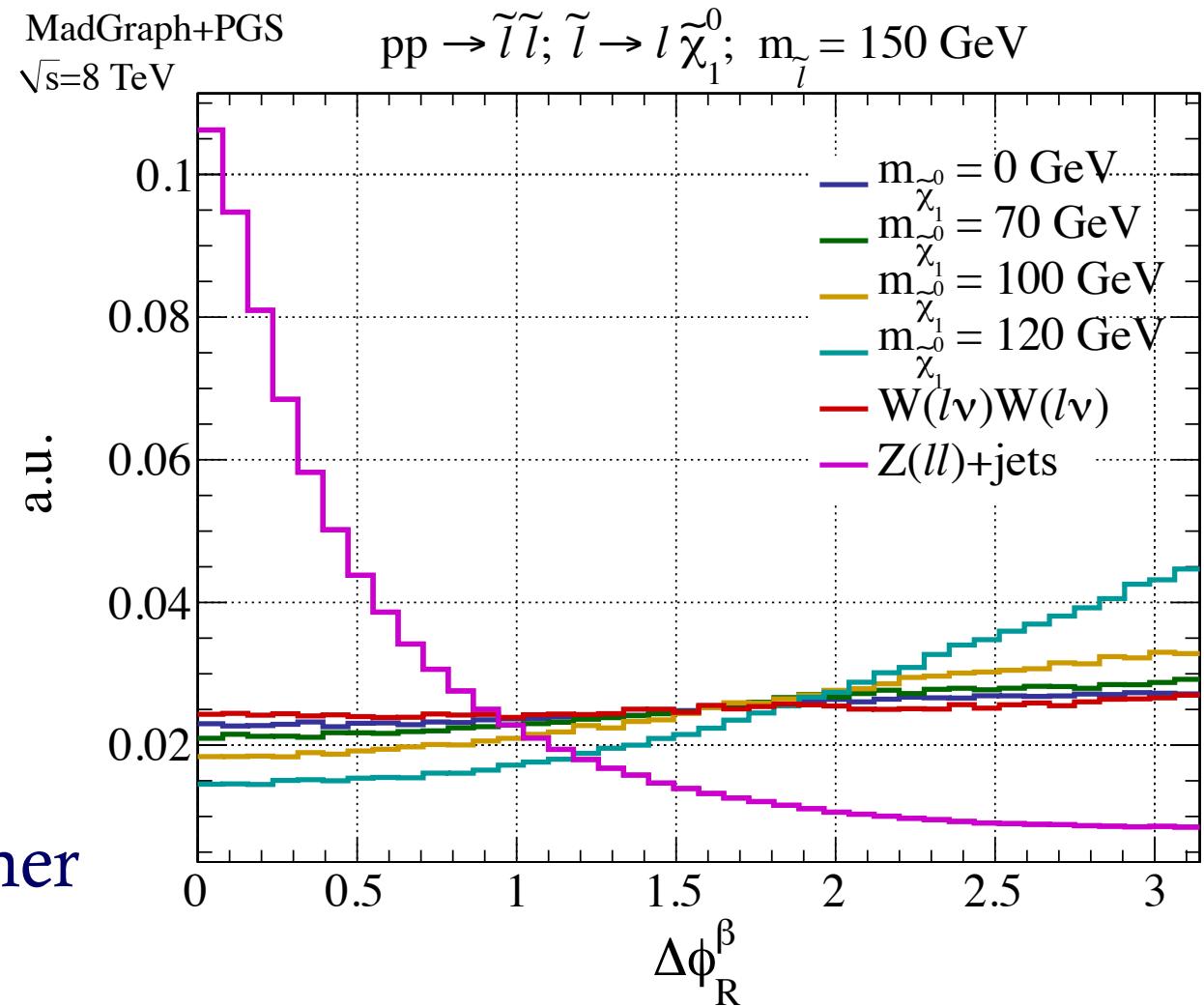


# Angular Variables

Angle between  
lab  $\rightarrow$  CM frame boost  
and di-leptons in CM  
frame is sensitive to

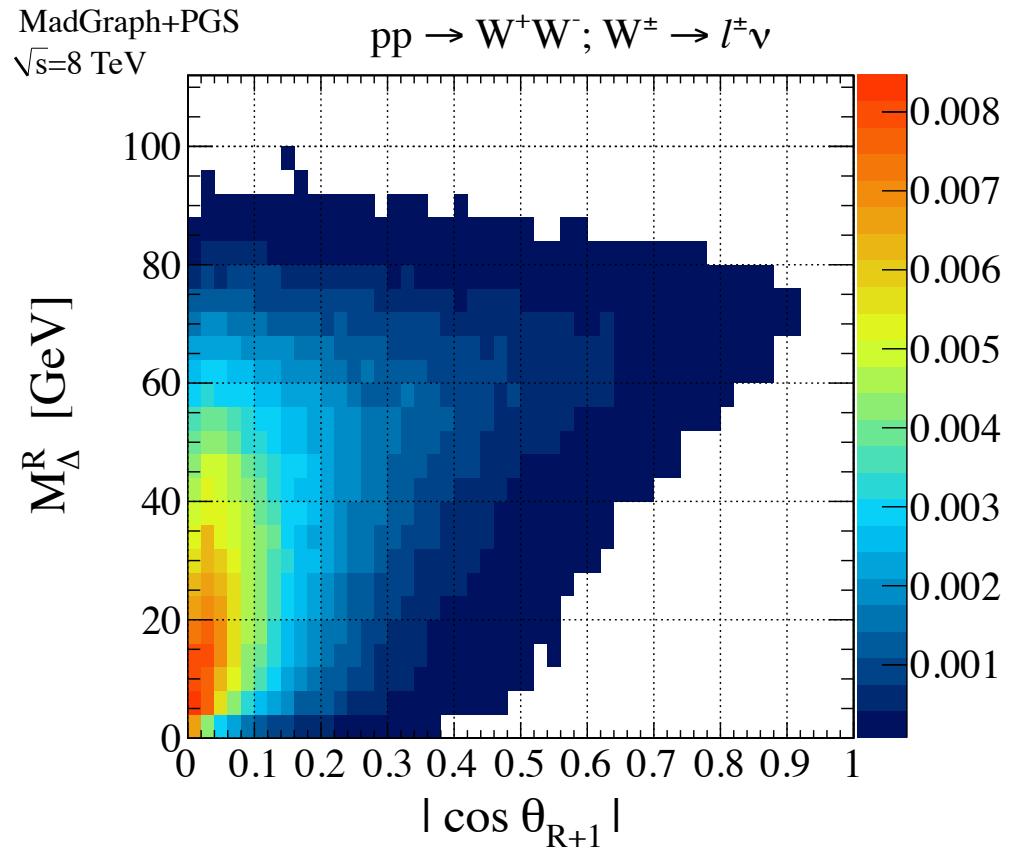
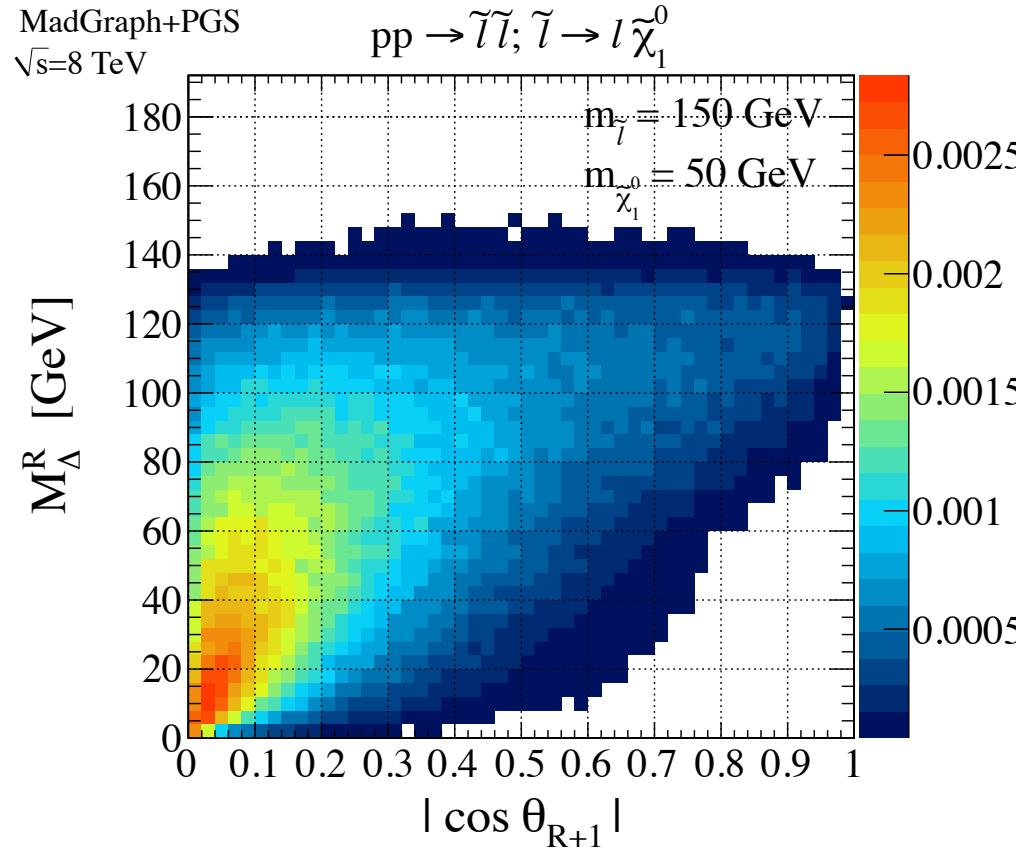
$\frac{m_\chi}{m_{\tilde{\ell}}}$  rather than  $M_\Delta$

$\sim$ Uncorrelated with other  
super-razor variables





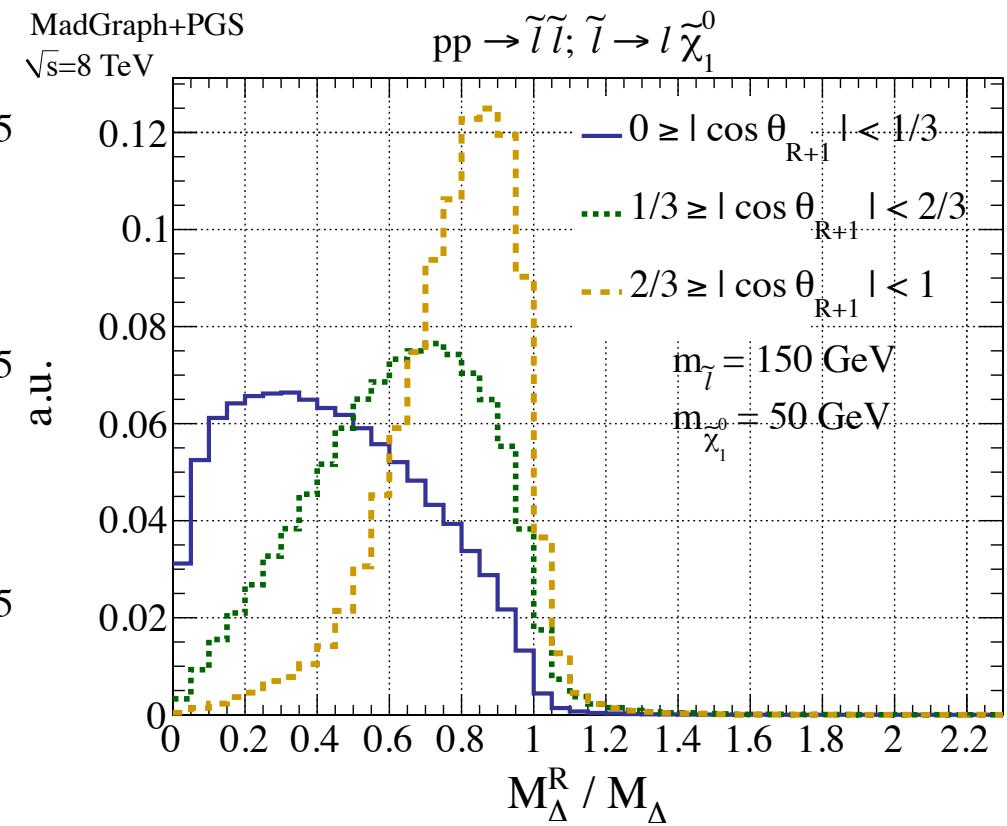
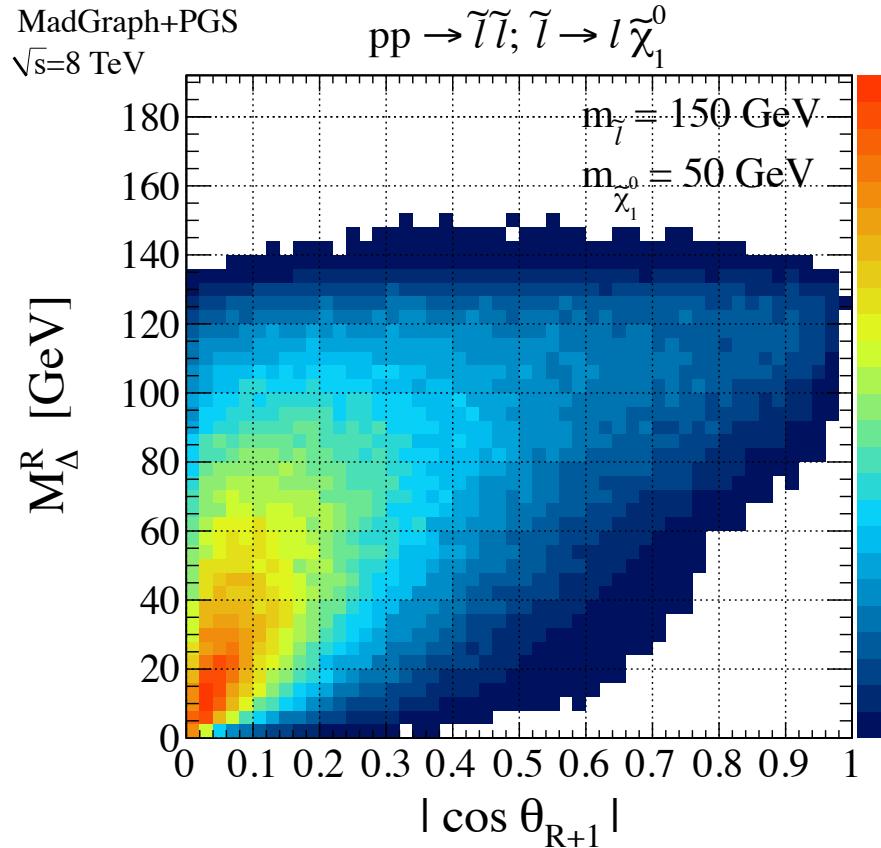
# Angular Variables



In the approximate slepton rest frames,  
reconstructed slepton decay angle sensitive  
to particle spin correlations



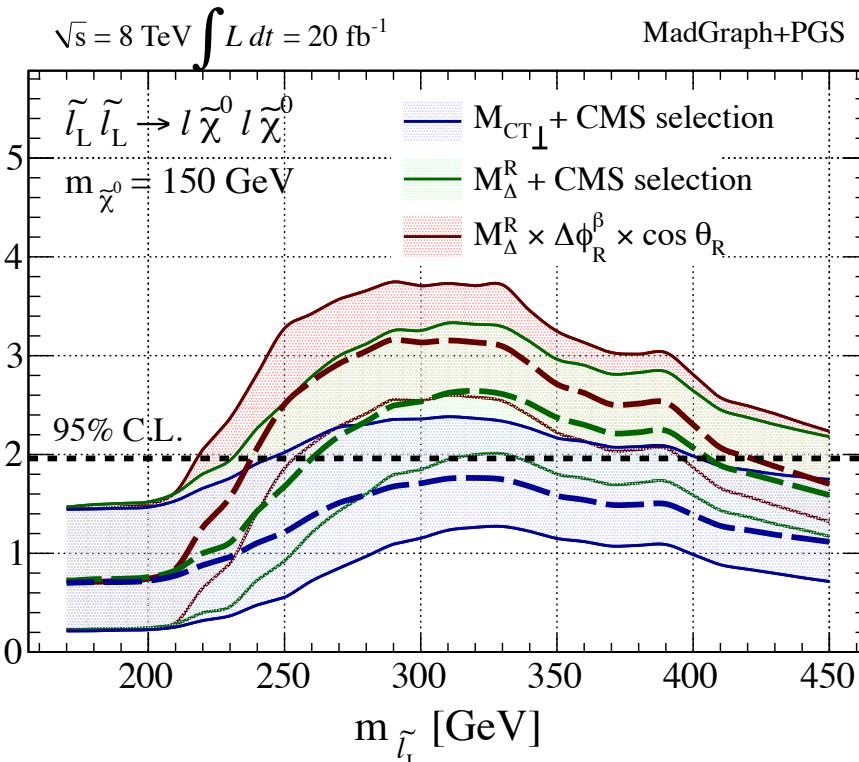
# Angular Variables



Also allows us to better resolve the kinematic endpoint of interest



# Super-razor variable basis



$\sqrt{\hat{s}}_R$  Sensitive to mass of CM  
Good for resonant prod.

Can re-imagine a di-lepton analysis in new basis of variables

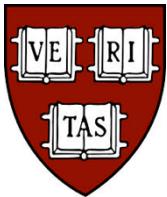
Can improve sensitivity while removing MET cuts!

$$\Delta\phi_R^\beta$$

Ratio of invisible and visible masses

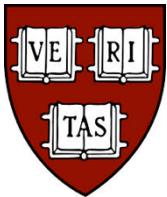
$M_\Delta^R$  Mass-squared difference resonant/non-resonant prod.

$|\cos\theta_{R+1}|$  Spin correlations, better resolution of mass edge



# Outlook

- Many different kinematic variables for physics searches—many variations of singularity variables w/ more complexity or constraints not discussed here
- Trade-off between inclusivity and specificity but generally: What characteristics are different between signal and background? Which observables best resolve those differences?
- Unfortunately, mass scale and object multiplicity may not be enough – new physics events may look like old physics. What other properties can we exploit? Are we using all the kinematic information we have? What is the basis of variables that best captures this information?



# BACKUP SLIDES



# A Monte Carlo analysis to compare

- Baseline Selection From arXiv:1310.4827 [hep-ph]

- Exactly two opposite sign leptons with  $p_T > 20 \text{ GeV}/c$  and  $|\eta| < 2.5$
- If same flavor,  $m(\ell\ell) > 15 \text{ GeV}/c^2$
- $\Delta R$  between leptons and any jet (see below)  $> 0.4$
- veto event if b-tagged jet with  $p_T > 25 \text{ GeV}/c$  and  $|\eta| < 2.5$

- Kinematic Selection

‘CMS selection’

$$|m(\ell\ell) - m_Z| > 15 \text{ GeV}$$

$$E_T^{miss} > 60 \text{ GeV}$$

$$E_T^{\text{miss,rel.}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_T^{\text{miss}} \times \sin \Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases} > 40 \text{ GeV}$$

CMS-PAS-SUS-12-022

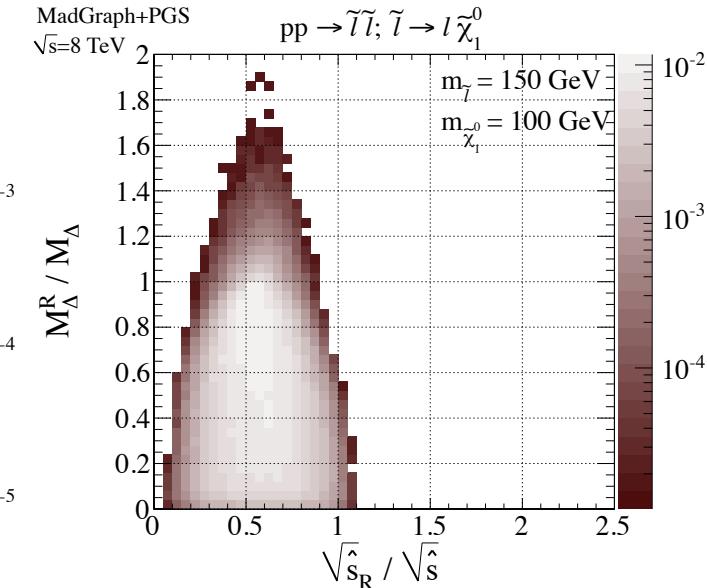
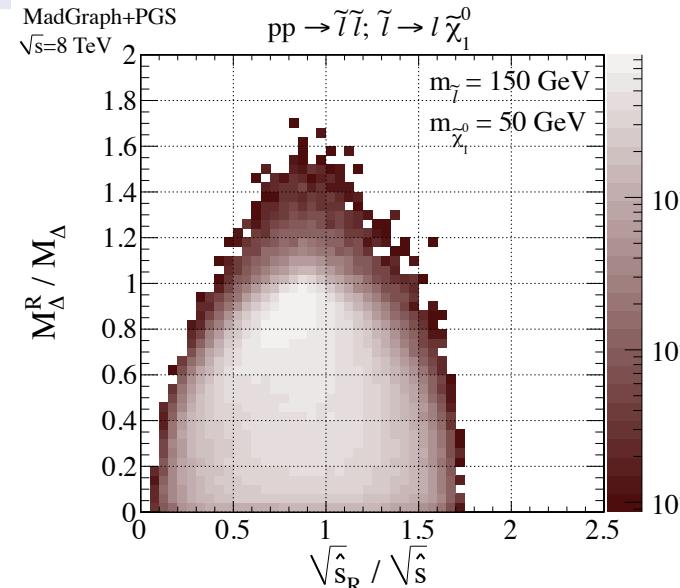
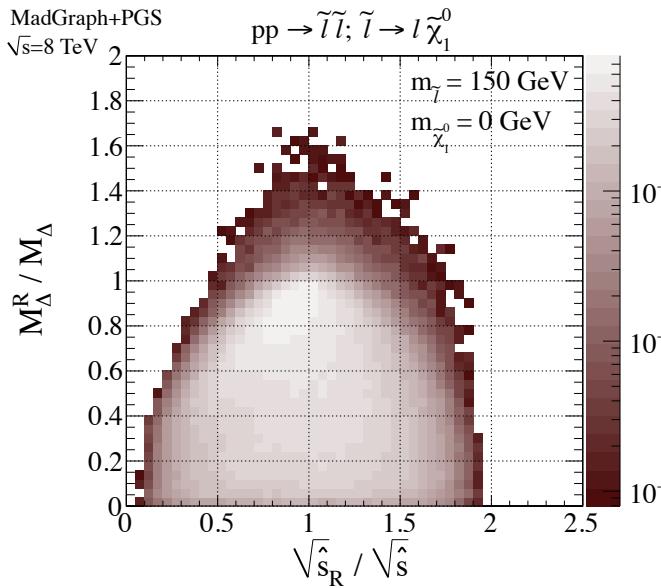
‘ATLAS selection’

$$|m(\ell\ell) - m_Z| > 10 \text{ GeV}$$

ATLAS-CONF-2013-049



# Towards a kinematic basis

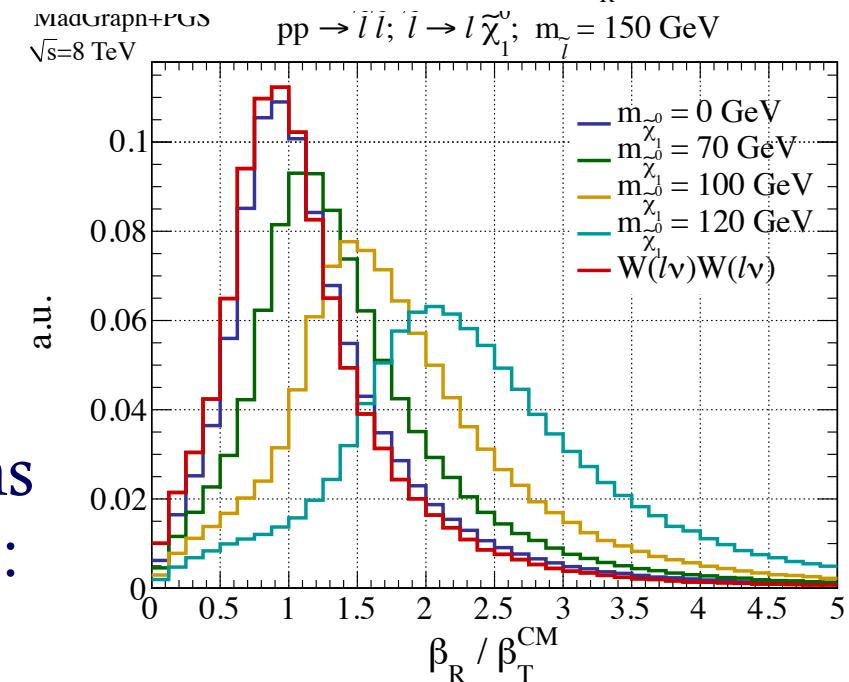


but  $\sqrt{\hat{s}_R} \sim 2\gamma^{\text{decay}} M_{\Delta}$

while  $\sqrt{\hat{s}} = 2\gamma^{\text{decay}} m_{\tilde{\ell}}$

Underestimating the real mass means  
over-estimating the boost magnitude:

From arXiv:1310.4827 [hep-ph]

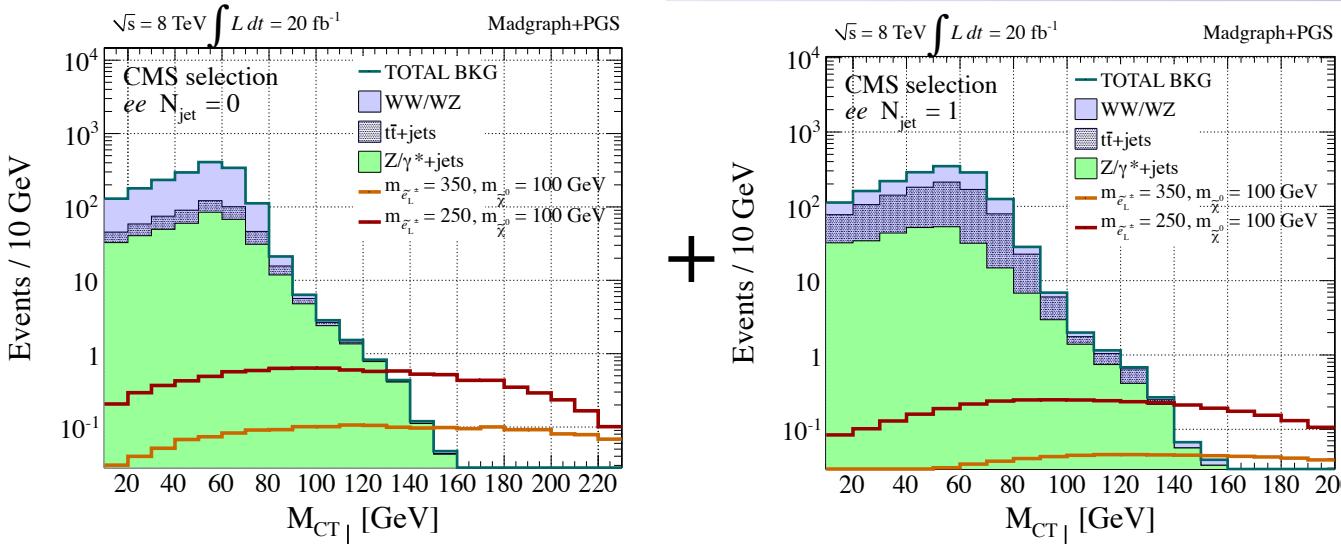




# 1D Shape Analysis

arXiv:1310.4827 [hep-ph]

Other jet  
+ multiplicity and  
lepton flavor  
categories



## Analysis Categories

- Consider final 9 different final states according to lepton flavor and jet multiplicity – simultaneous binned fit includes both high S/B and low S/B categories

$(ee, \mu\mu, e\mu) \times (0, 1, \geq 2 \text{ jets})$  with  $p_T^{jet} > 30 \text{ GeV}/c$ ,  $|\eta^{jet}| < 3$

Fit to kinematic distributions (in this case,  $M_{\Delta^R}$ ,  $M_{T2}$  or  $M_{CT\text{perp}}$  in 10 GeV bins), over all categories for  $WW$ ,  $t\bar{t}$  and  $Z/\gamma^* + \text{jets}$  yields



# Systematic uncertainties

From arXiv:1310.4827 [hep-ph]

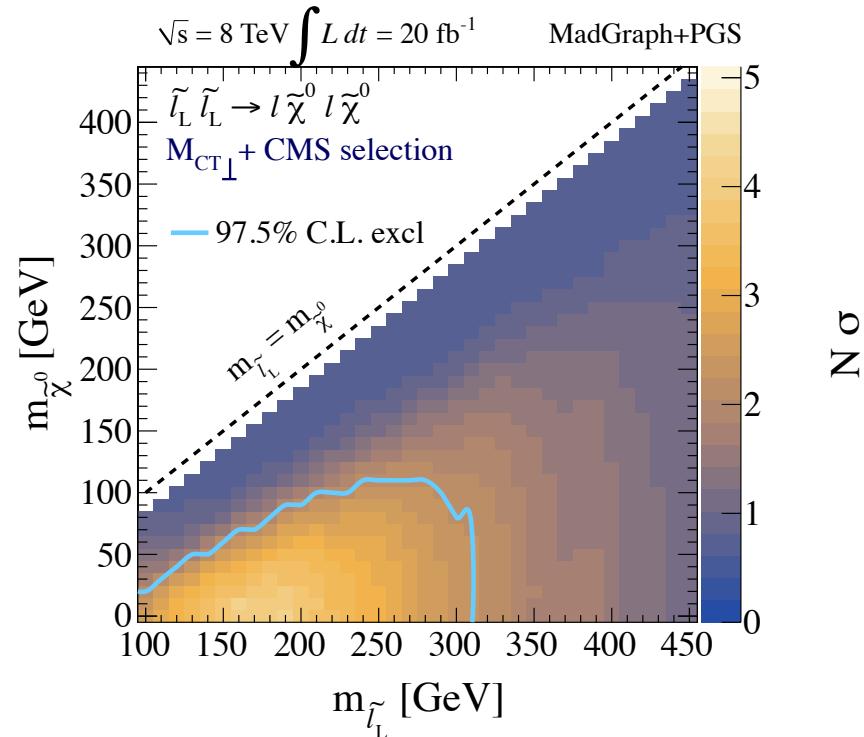
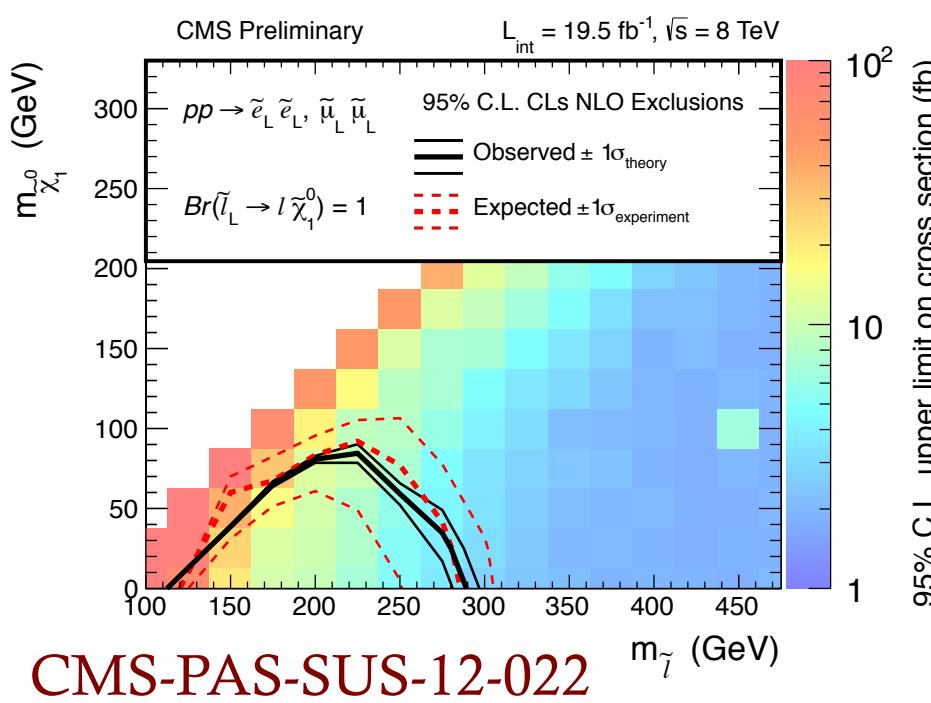
- 2% lepton ID (correlated btw bkgs, uncorrelated between lepton categories)
- 10% jet counting (per jet) (uncorrelated between all processes)
- 10% x-section uncertainty for backgrounds (uncorrelated) + theoretical x-section uncertainty for signal (small)
- ‘shape’ uncertainty derived by propagating effect of 10% jet energy scale shift up/down to MET and recalculating shapes templates of kinematic variables
- Uncertainties are introduced into toy pseudo-experiments through marginalization (pdfs fixed in likelihood evaluation but systematically varied in shape and normalization in toy pseudo-experiment generation)



# Compared to Reality

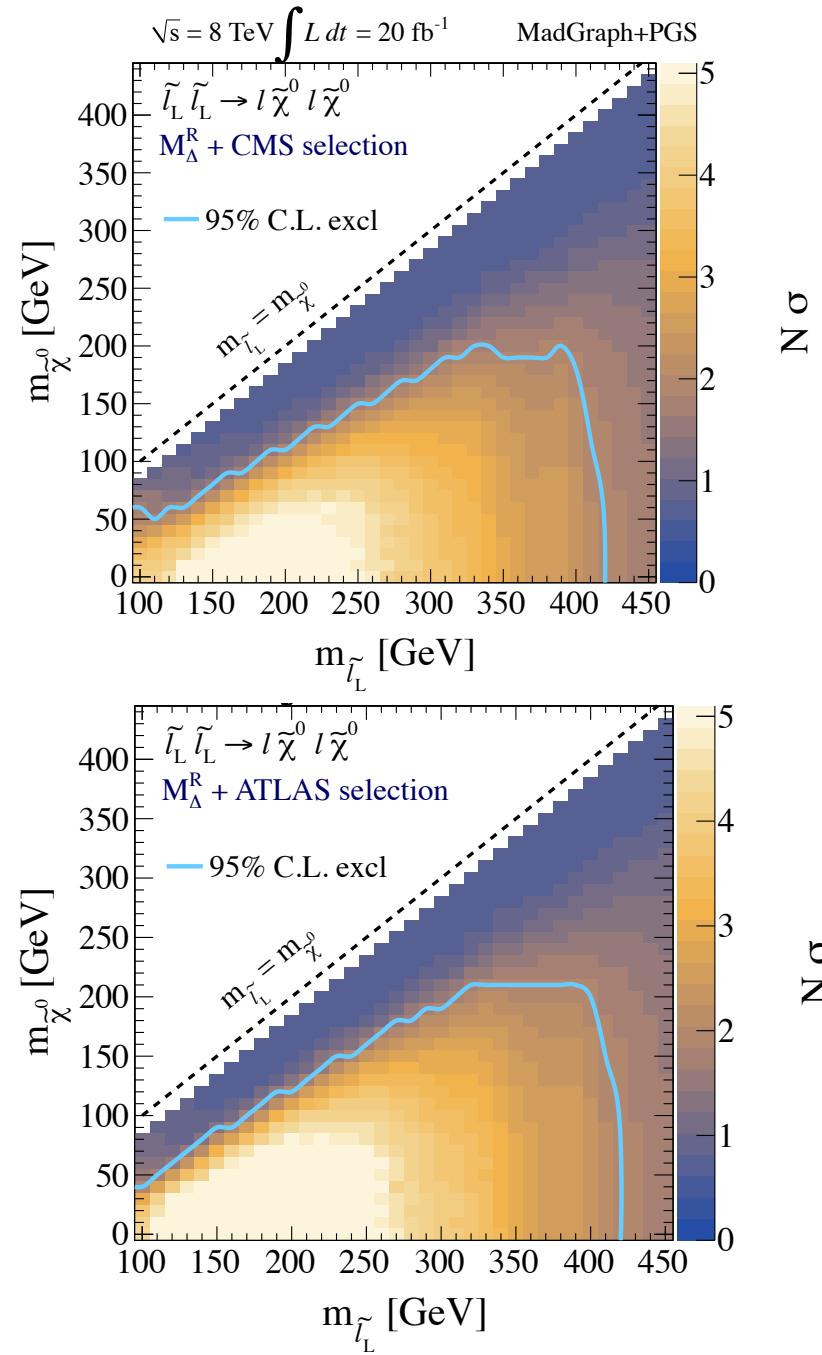
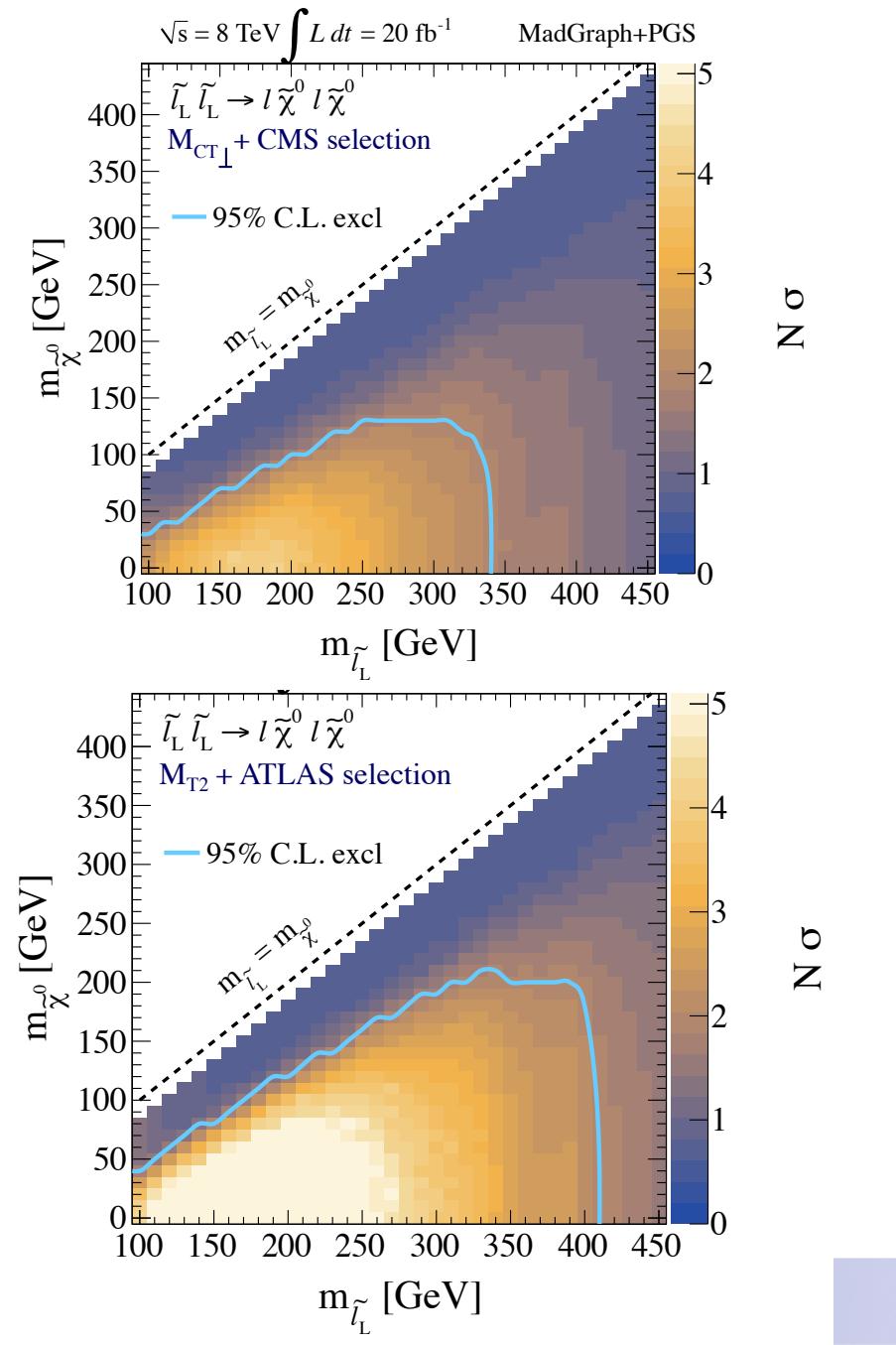
From arXiv:1310.4827 [hep-ph]

$$pp \rightarrow \tilde{\ell}_L \tilde{\ell}_L; \quad \tilde{\ell}_L \rightarrow \tilde{\chi}_1^0 \ell$$





# Expected Limit Comparison

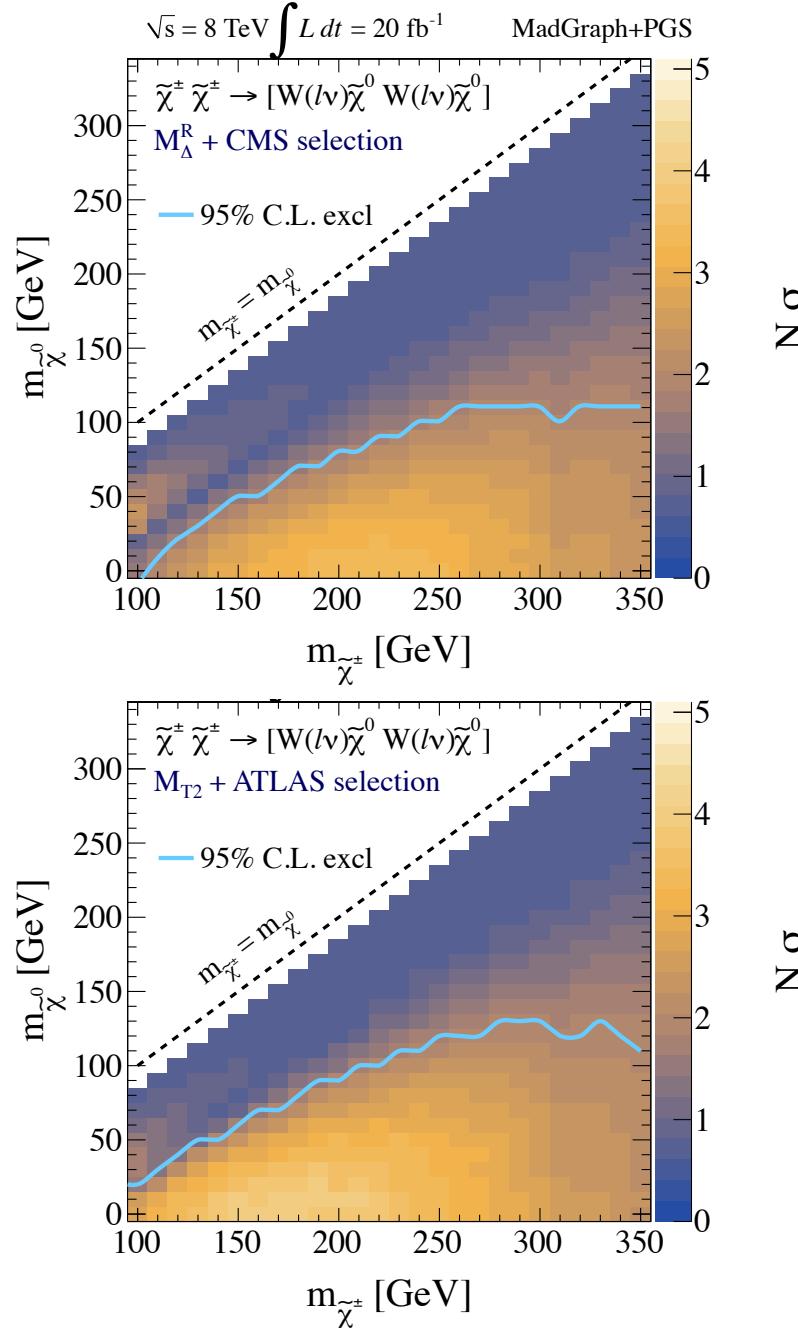
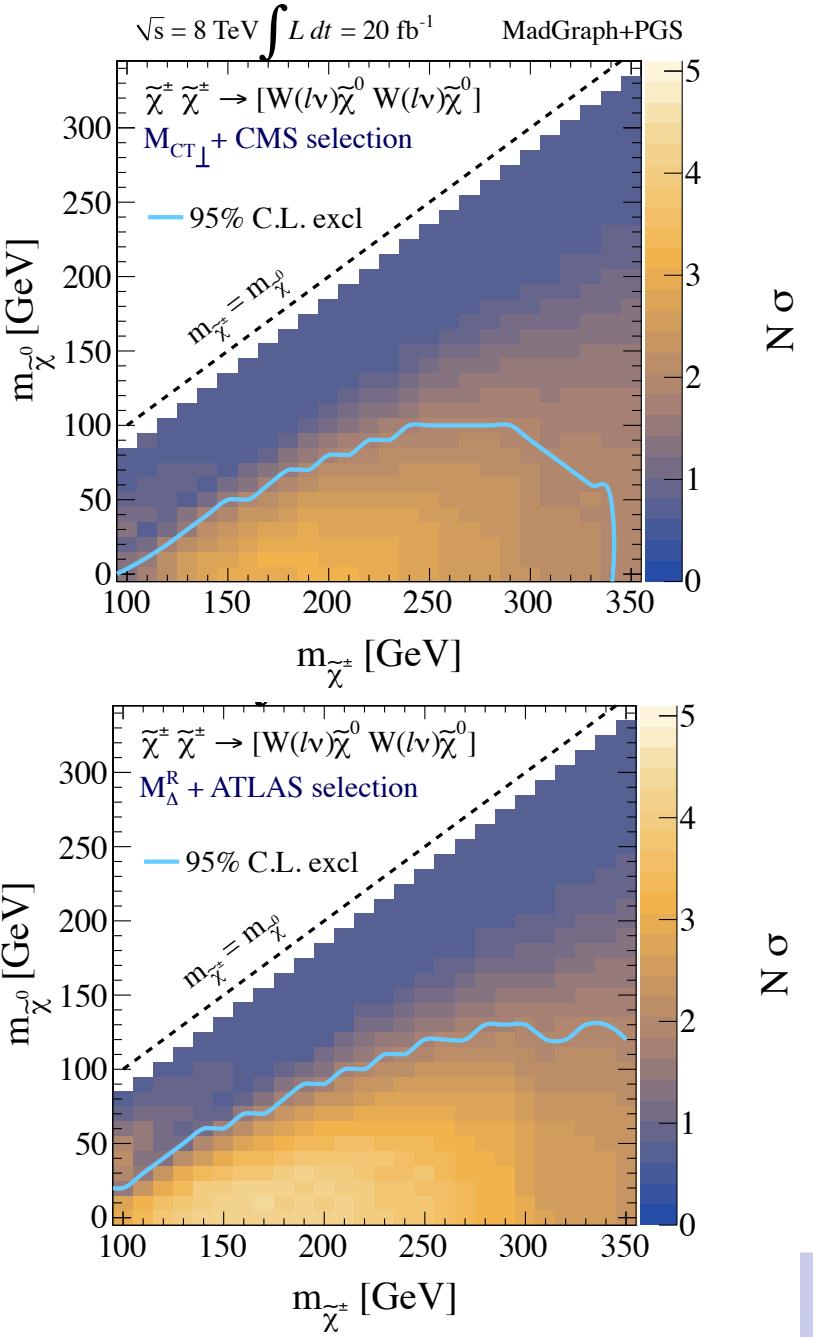


$p p \rightarrow \tilde{\ell}_L \tilde{\ell}_L; \tilde{\ell}_L \rightarrow \tilde{\chi}_1^0 \ell$

From arXiv:1310.4827 [hep-ph]



# Charginos



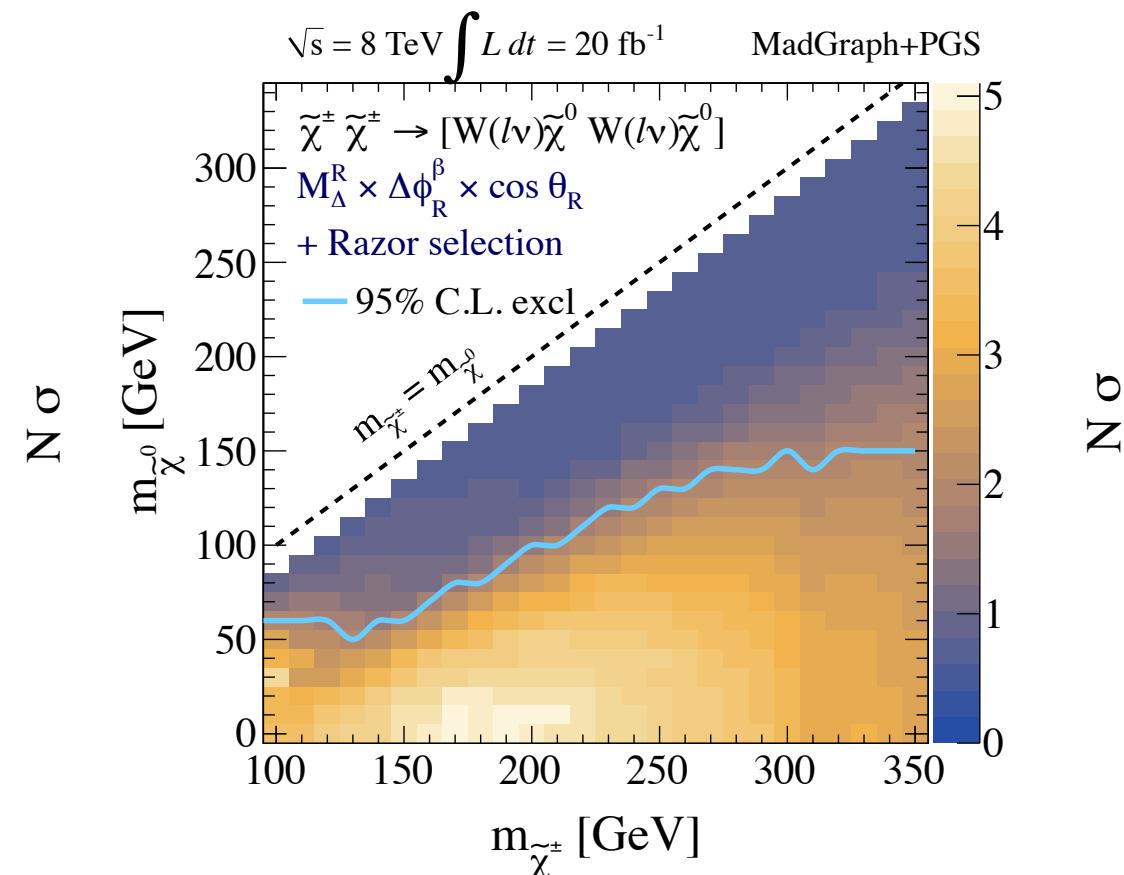
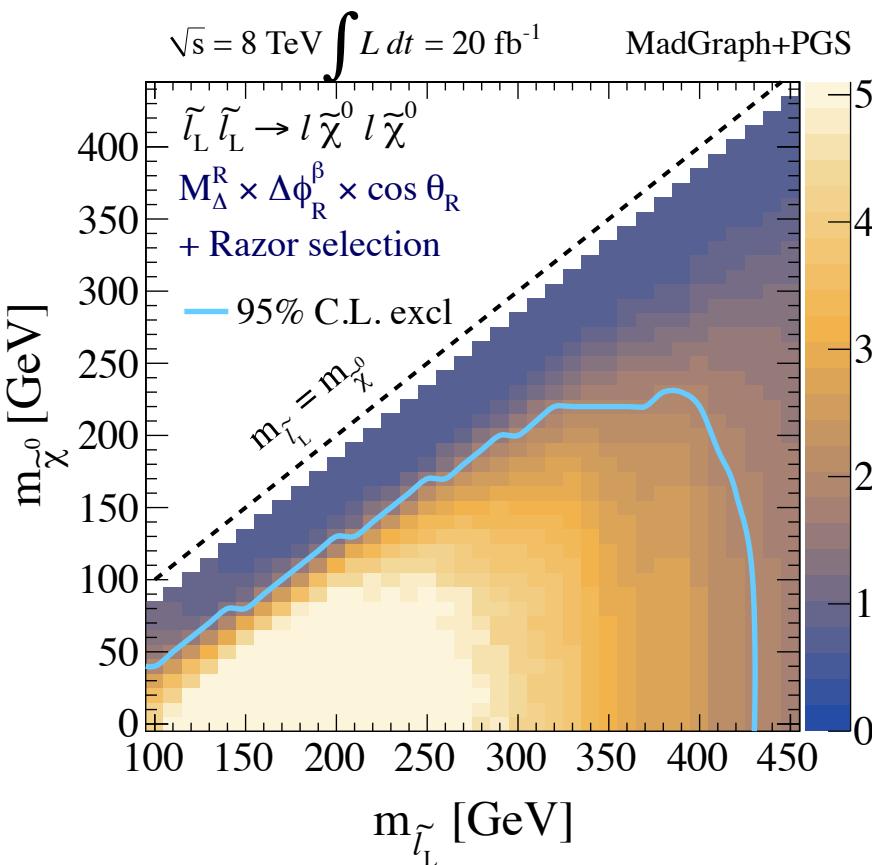
$p p \rightarrow \tilde{\chi}_1^\mp \tilde{\chi}_1^\pm ; \quad \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm (\ell^\pm \nu)$

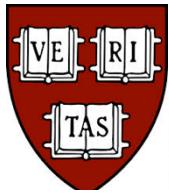
From arXiv:1310.4827 [hep-ph]



# Super-Razor Basis Selection

From arXiv:1310.4827 [hep-ph]





# Comparisons

