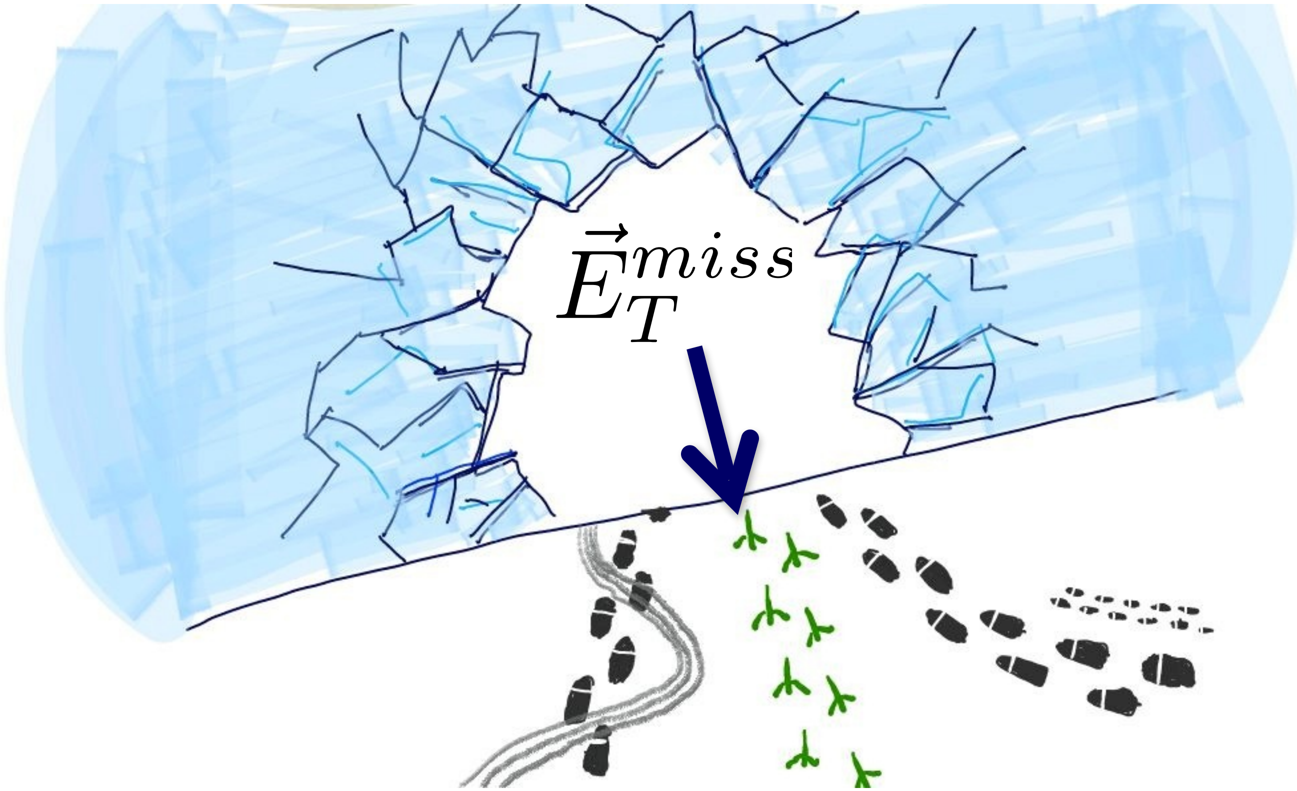


Kinematic variables for weakly-interacting particle final state reconstruction at the LHC

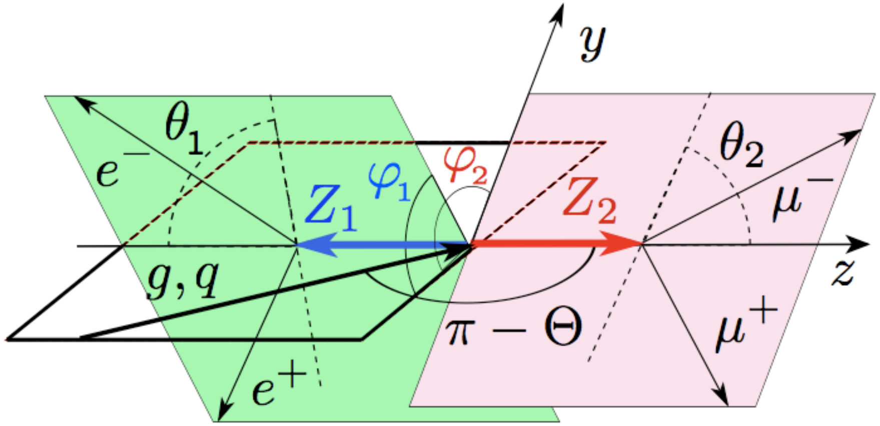
Christopher Rogan

HARVARD UNIVERSITY

SUSY14 - University of Manchester – July 22, 2014

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.

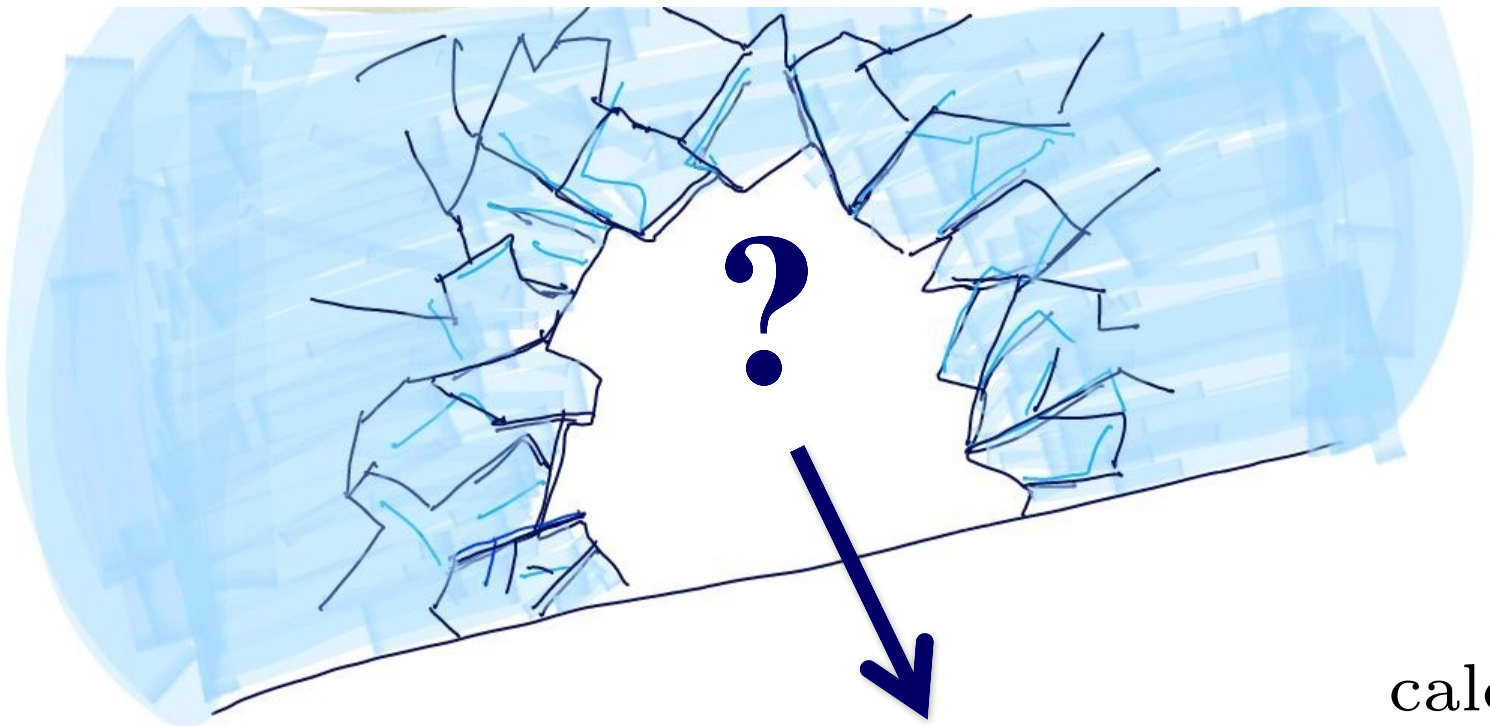
OPEN $H \rightarrow W(\ell\nu)W(\ell\nu)$

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?

Missing transverse energy

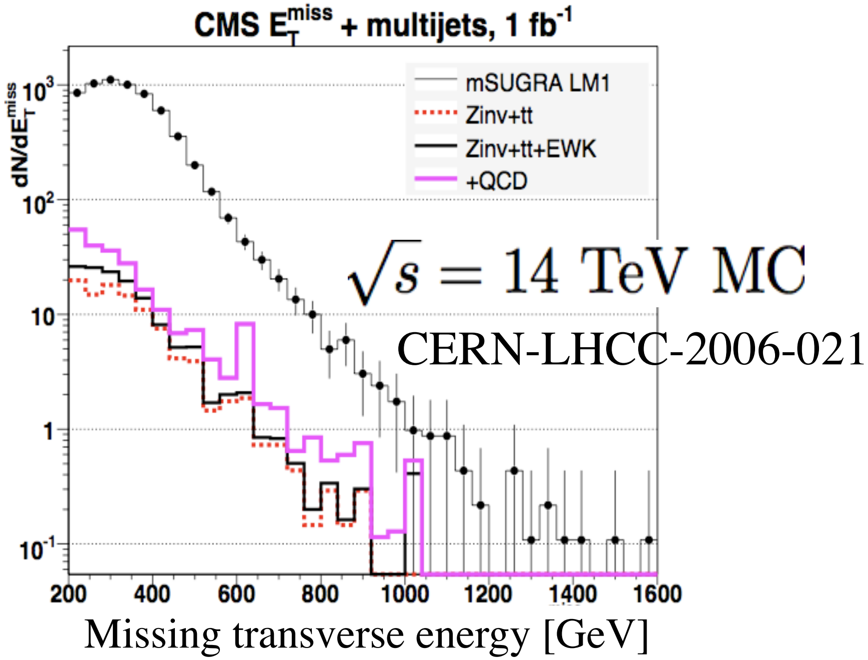


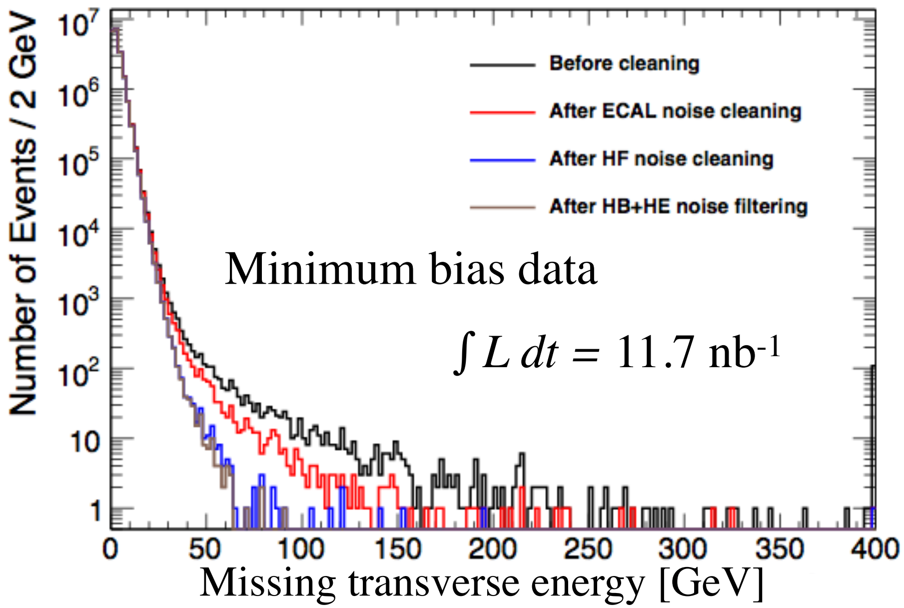
$$\vec{E}_T^{miss} \equiv -\sum_i^{\text{calo}} \vec{E}_T^i$$

We can infer the presence of weakly interacting particles in LHC events by looking for missing transverse energy

Missing transverse energy

Figures from SUSY10 conference talk:

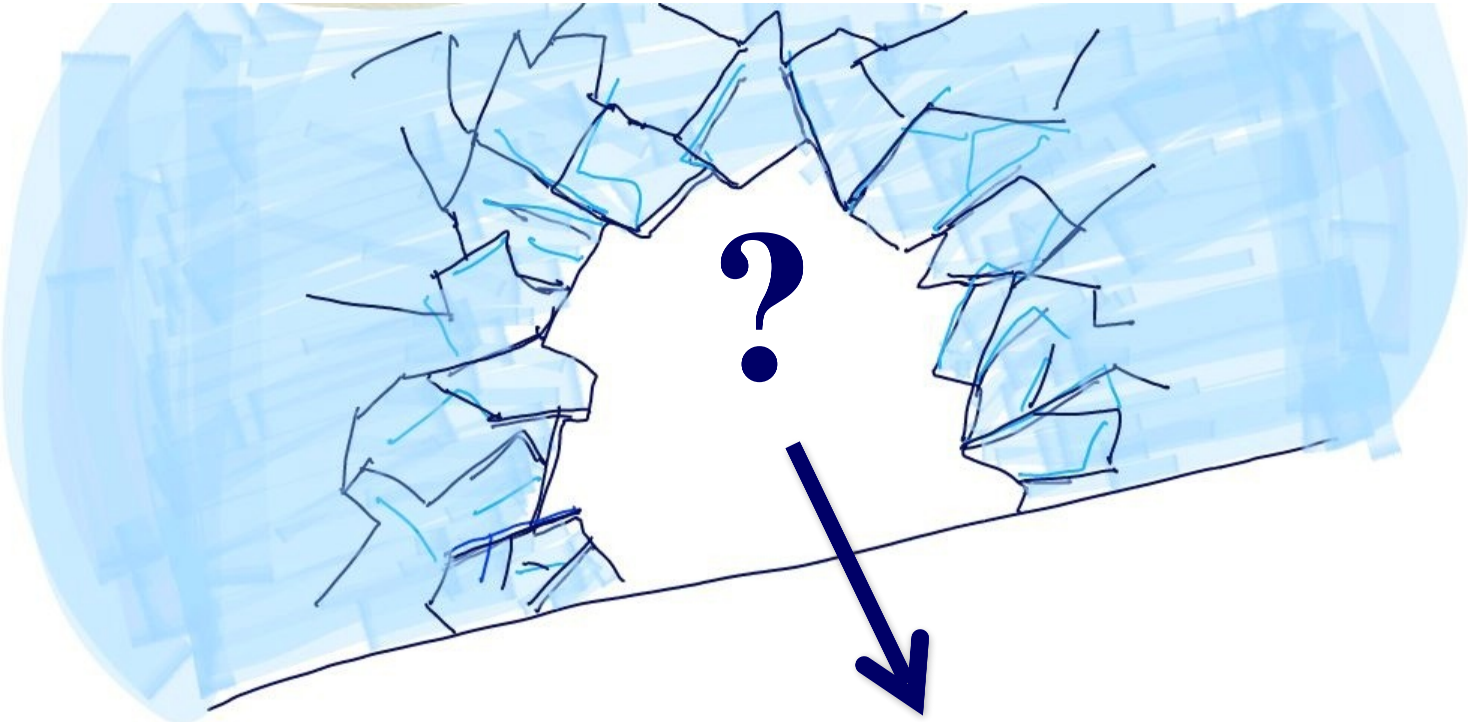




Missing transverse energy is a powerful observable for inferring the presence of weakly interacting particles

But, it only tells us about their transverse momenta – often we can better resolve quantities of interest by using additional information

Missing transverse energy



$\vec{E}_T^{miss}$

Missing transverse energy only tells us about the momentum of weakly interacting particles in an event…

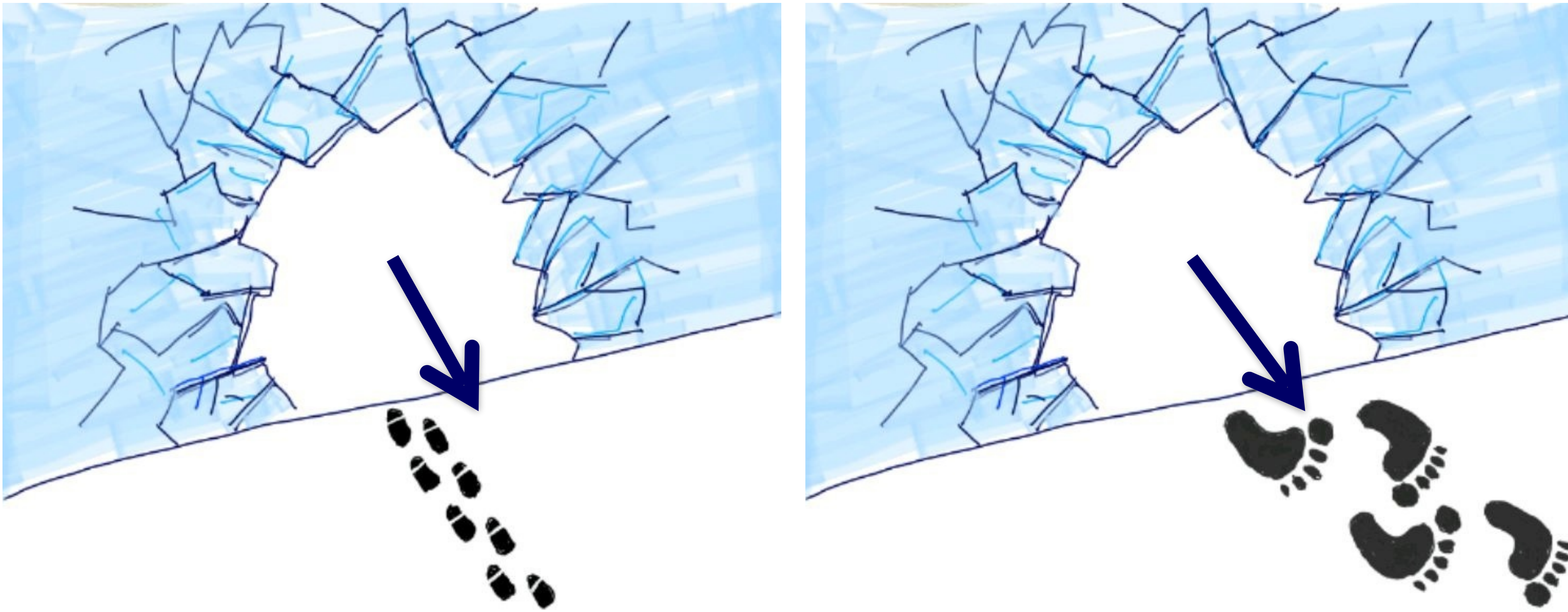
Missing transverse energy

…not about the identity or mass of weakly interacting particles

Missing transverse energy

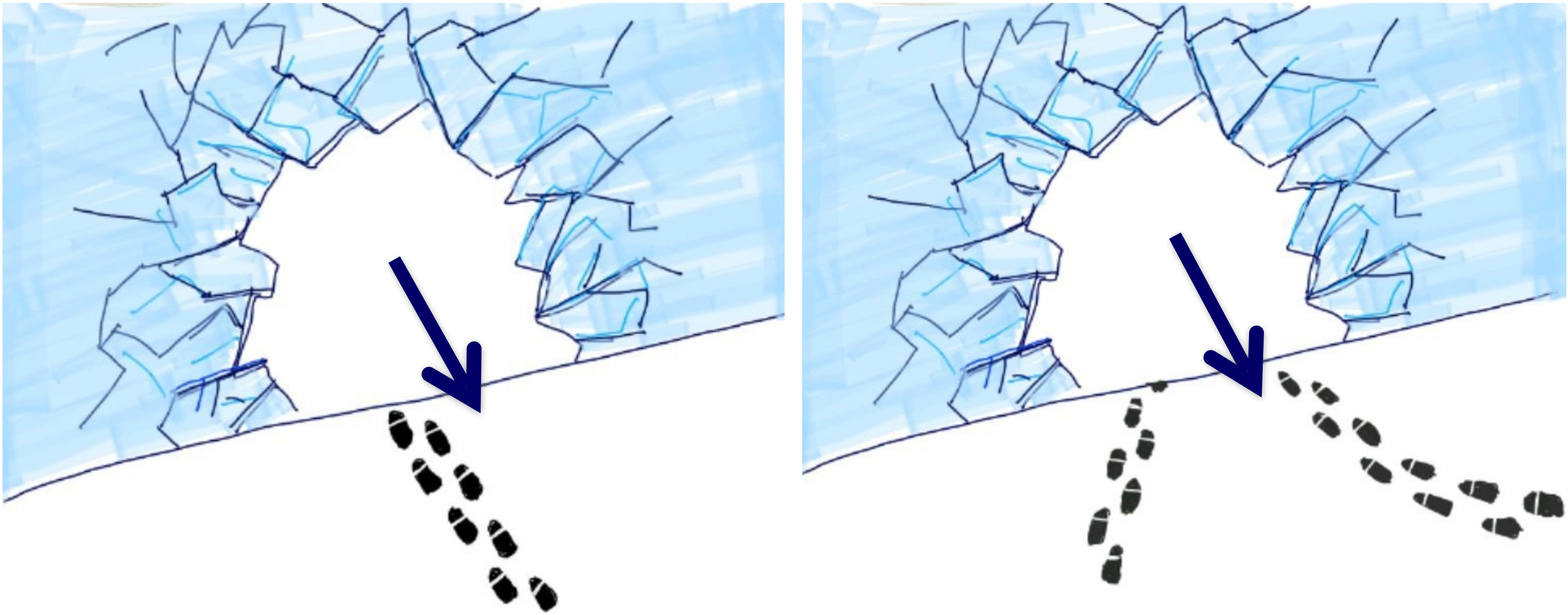
…not about the identity or mass of weakly interacting particles

Missing transverse energy



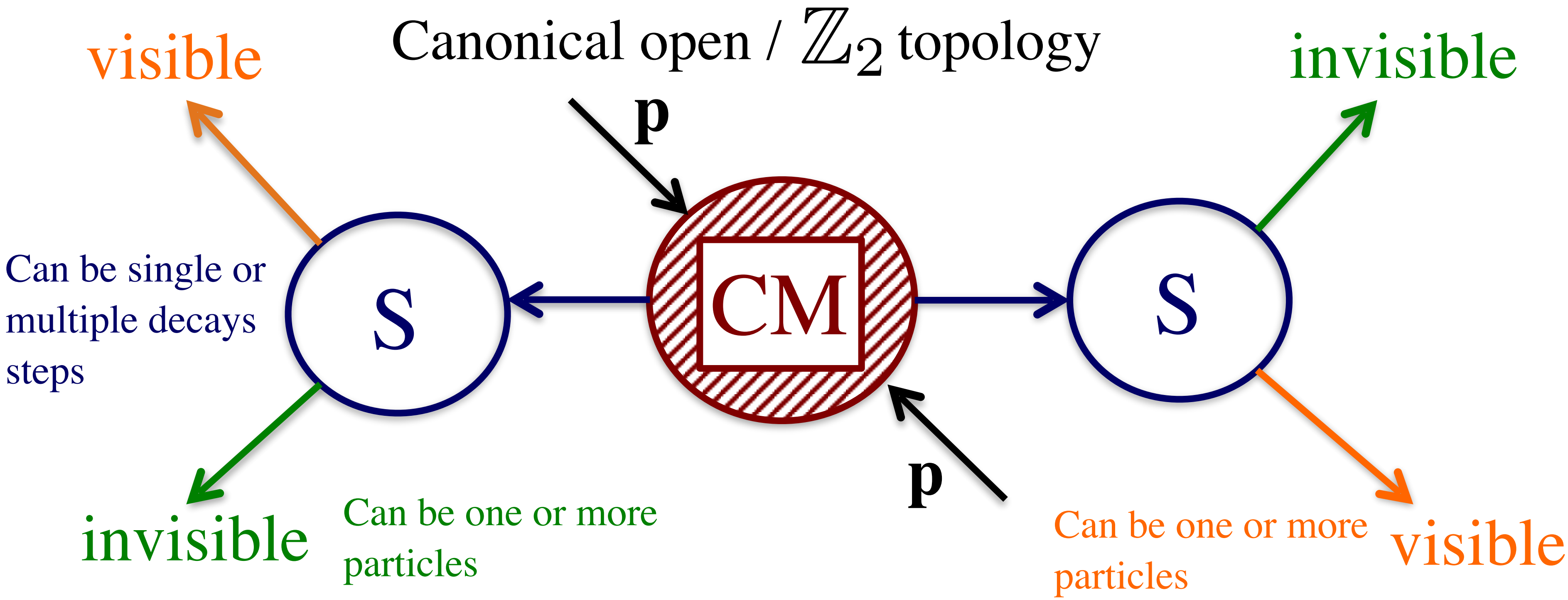
We can learn more by using other information in an event to contextualize the missing transverse energy

Missing transverse energy



We can learn more by using other information in an event to contextualize the missing transverse energy ⇒
multiple weakly interacting particles?

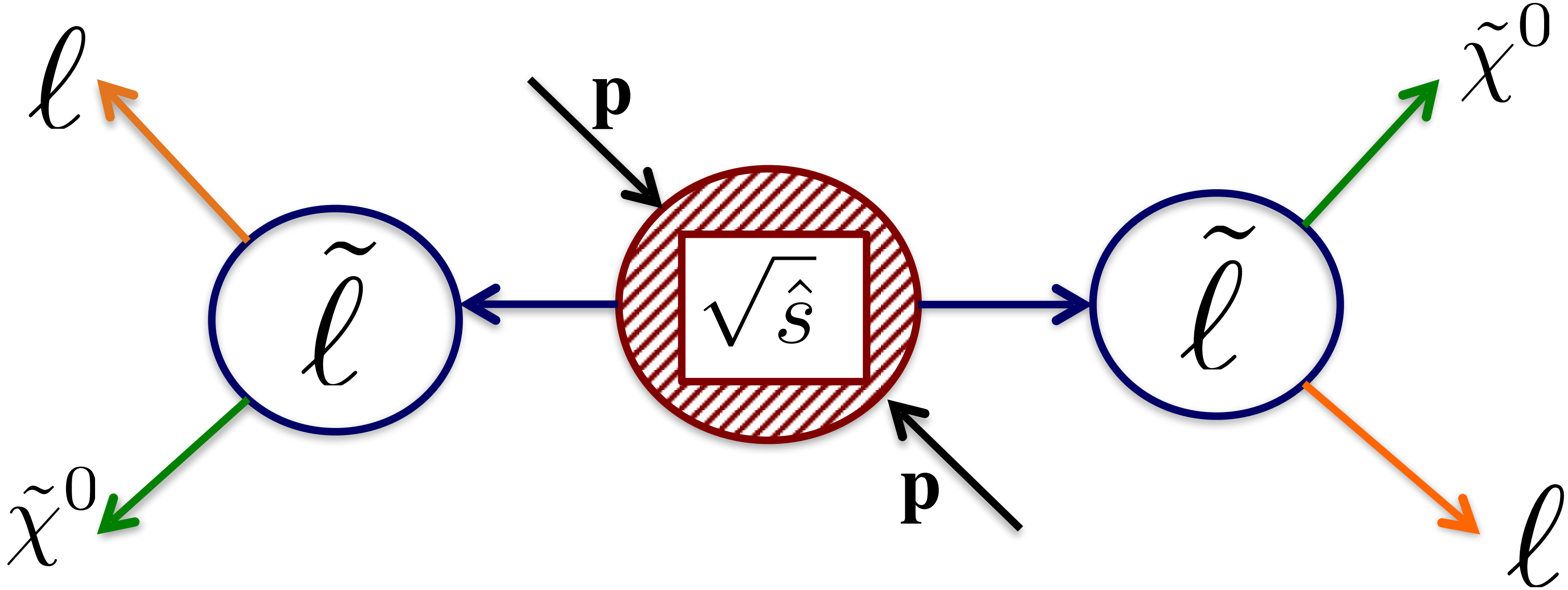
Multiple weakly interacting particles?



- Dark Matter
- Higgs quadratic divergences
- ….

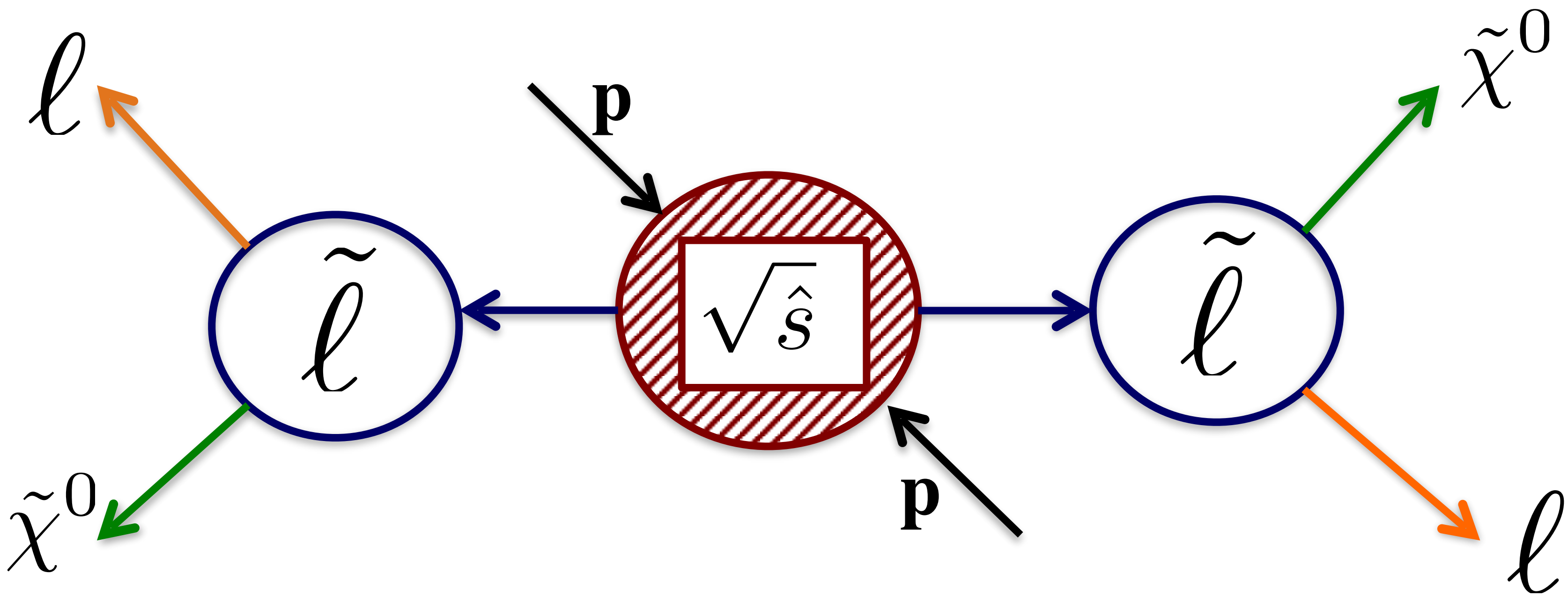
Theory	$\mathbb{Z}_2$
SUSY	R-parity
Little Higgs	T-parity
UED	KK-parity

Example: slepton pair-production

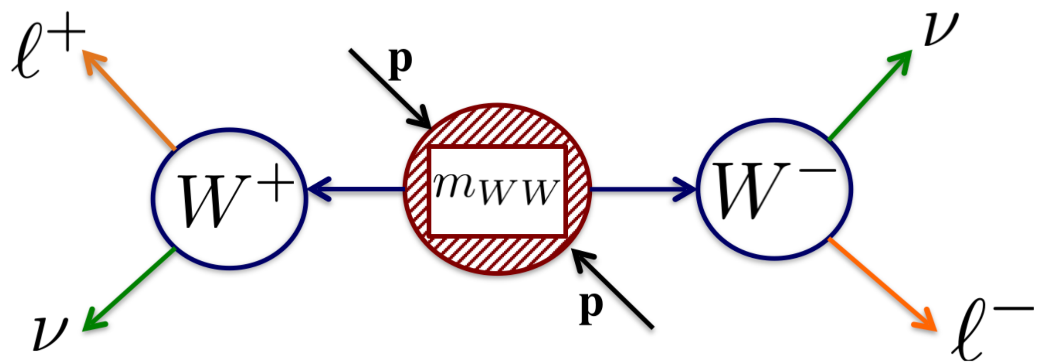


Experimental signature: di-leptons final states with missing transverse momentum

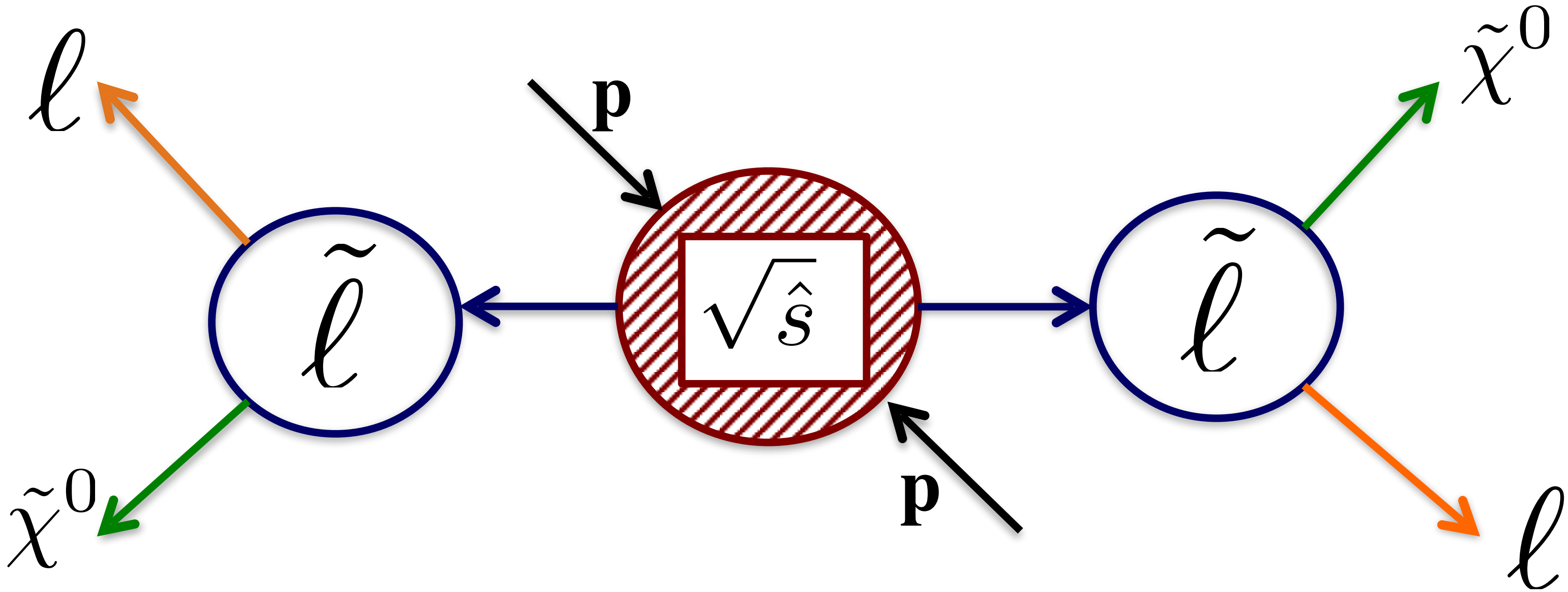
Example: slepton pair-production



Main background:



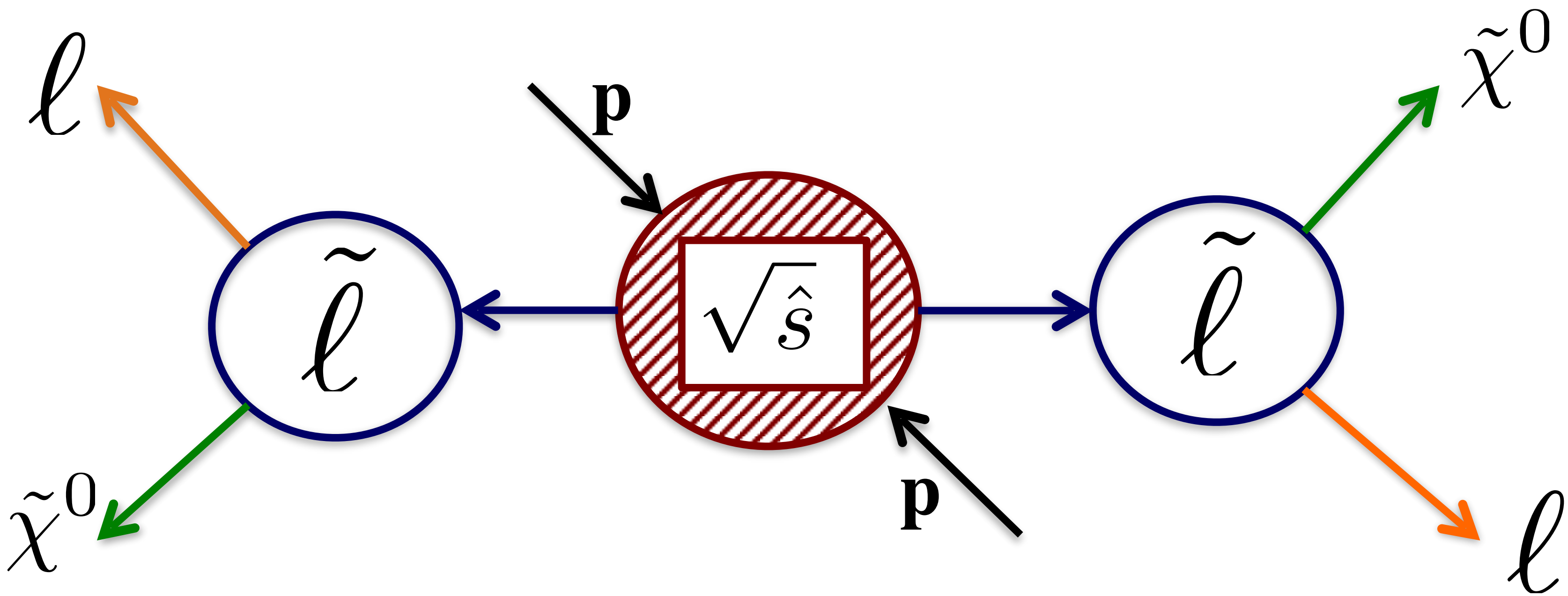
Example: slepton pair-production



What quantities, if we could calculate them, could help us distinguish between signal and background events?

$$\sqrt{\hat{s}} = 2\gamma^{decay} m_{\tilde{\ell}} \qquad M_{\Delta} \equiv \frac{m_{\tilde{l}}^2 - m_{\tilde{\chi}^0}^2}{m_{\tilde{l}}}$$

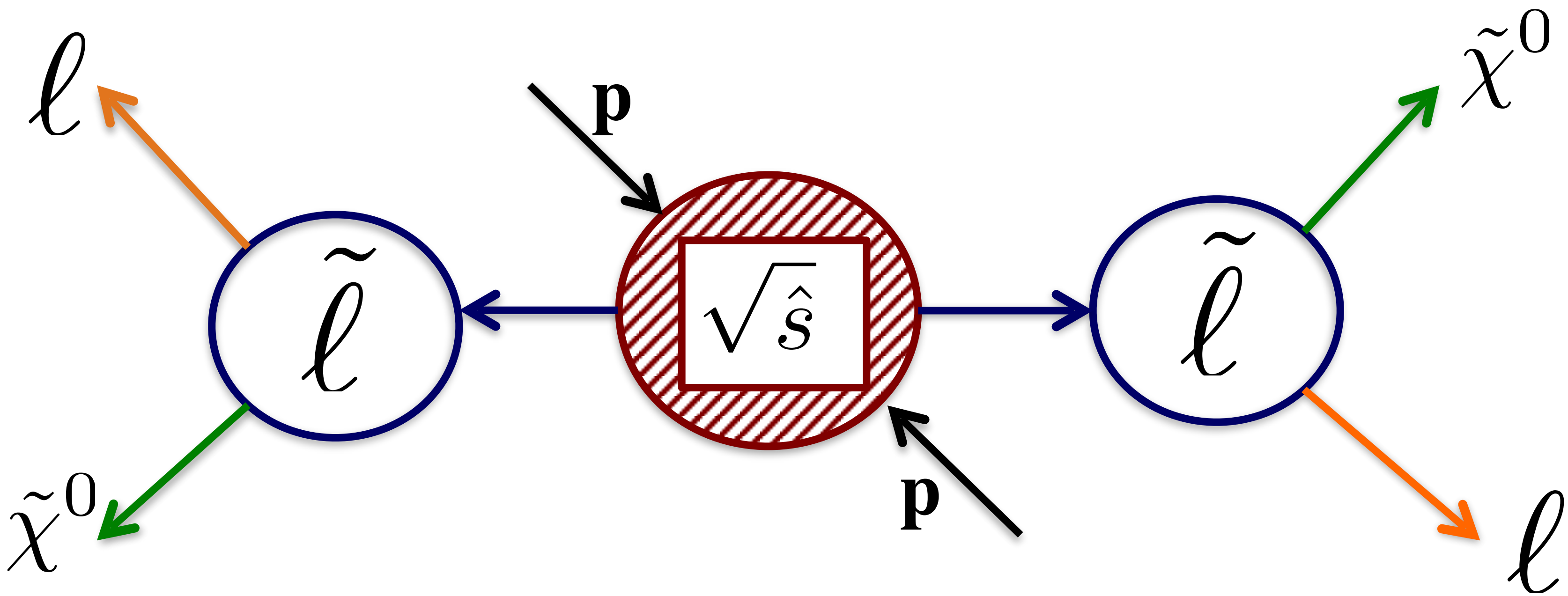
Example: slepton pair-production



What information are we missing?

We don't observe the weakly interacting particles in the event. We can't measure their momentum or masses.

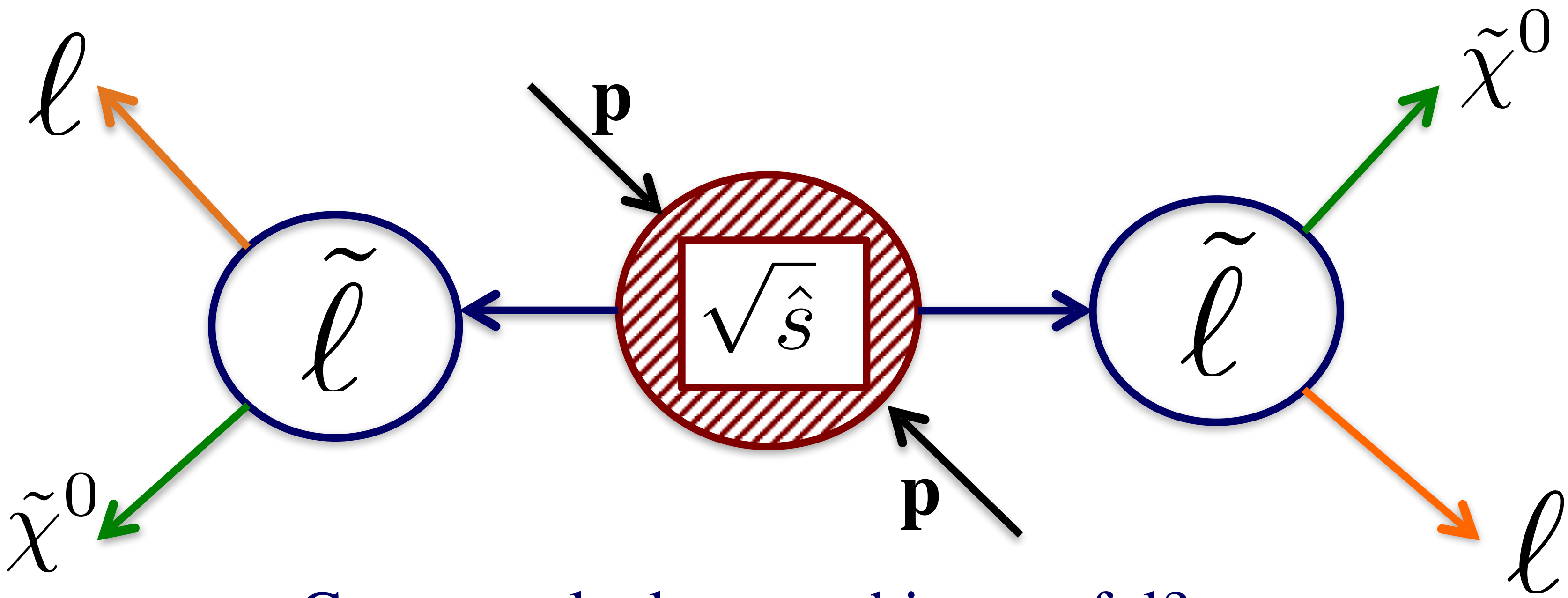
Example: slepton pair-production



What do we know?

We can reconstruct the 4-vectors of the two leptons and the transverse momentum in the event

Example: slepton pair-production



Can we calculate anything useful?

With a number of simplifying assumptions…

$$\vec{E}_T^{miss} = \sum \vec{p}_T^{\,\tilde{\chi}^0} \qquad m_{\tilde{\chi}^0} = 0 \qquad m_{\tilde{\ell}1} = m_{\tilde{\ell}2}$$

…we are still 4 d.o.f. short of reconstructing any masses of interest

Recursive Jigsaw Reconstruction

New approach to reconstructing final states with weakly interacting particles:

- The strategy is to transform observable momenta iteratively ***reference-frame to reference-frame***, traveling through each of the reference frames relevant to the topology
- At each step, ***extremize only the relevant d.o.f. related to that transformation***
- Repeat procedure recursively according to particular rules defined for each topology (the topology relevant to each reference frame)
- Rather than obtaining one observable, get a complete basis of useful observables for each event

See Paul Jackson's talk on Friday in this session

Recursive rest-frame reconstruction

For two lepton case, these are the 'super-razor variables':

M. Buckley, J. Lykken, CR, M. Spiropulu, PRD 89, 055020 (2014)

$\ell_1^{lab}, \ell_2^{lab}$ Begin with reconstructed lepton 4-vectors in lab frame

Recursive rest-frame reconstruction

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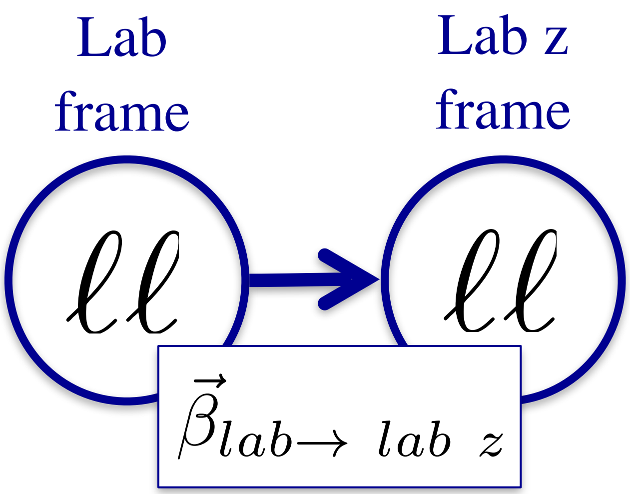
$\ell_1^{lab}, \ell_2^{lab}$ Begin with reconstructed lepton 4-vectors in lab frame

$$\frac{\partial(E_{\ell_1}^{lab\ z} + E_{\ell_2}^{lab\ z})}{\partial\beta_z} = 0 \rightarrow \beta_z$$

Remove dependence on unknown longitudinal boost by moving from 'lab' to 'lab z' frames



Recursive rest-frame reconstruction

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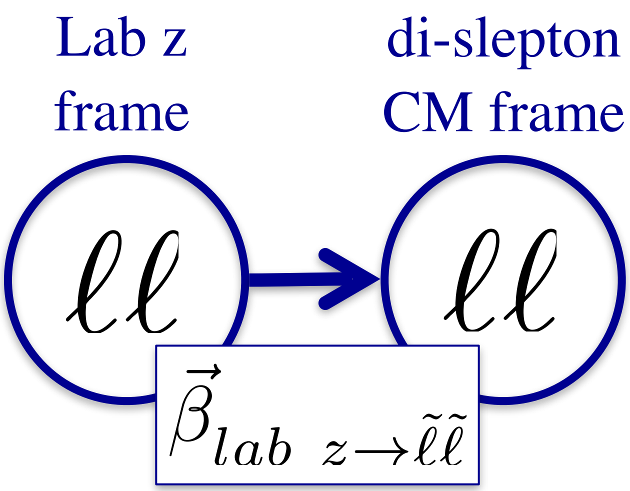
M. Buckley, J. Lykken, CR, M. Spiropulu, PRD 89, 055020 (2014)

$$(\tilde{\chi}_1 + \tilde{\chi}_2)^2 = (\ell_1 + \ell_2)^2$$

Determine boost from 'lab z' to 'CM ($\tilde{\ell}\tilde{\ell}$)' frame by specifying Lorentz-invariant choice for invisible system mass



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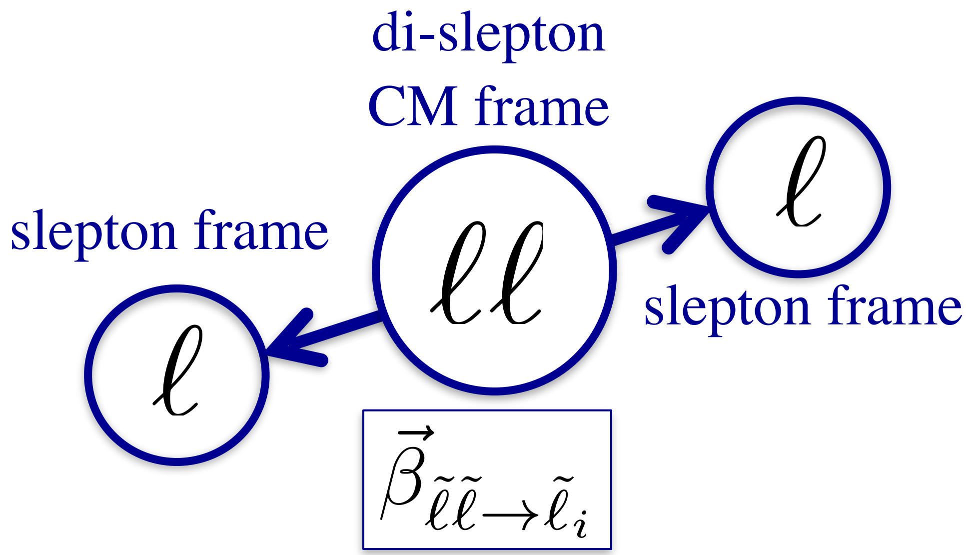
M. Buckley, J. Lykken, CR, M. Spiropulu, PRD 89, 055020 (2014)



$$\frac{\partial(E_{\ell_1}^{\tilde{\ell}_1}+E_{\ell_2}^{\tilde{\ell}_2})}{\partial\vec{\beta}_{\tilde{\ell}\tilde{\ell}\to\tilde{\ell}_i}} = 0 \to \vec{\beta}_{\tilde{\ell}\tilde{\ell}\to\tilde{\ell}_i}$$

Determine asymmetric boost from CM to slepton rest frames by minimizing lepton energies in those frames

Recursive rest-frame reconstruction

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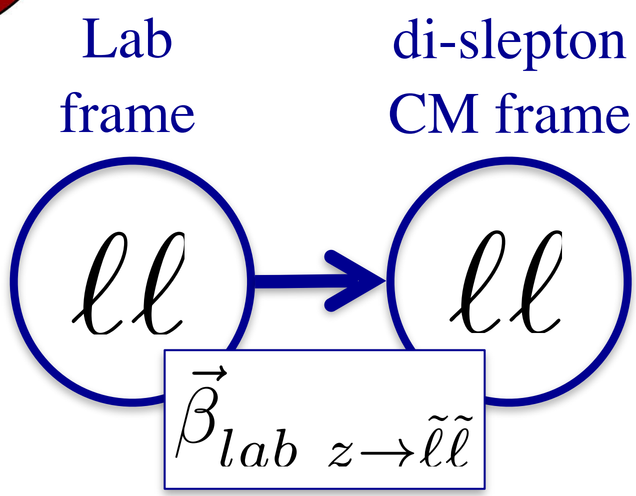
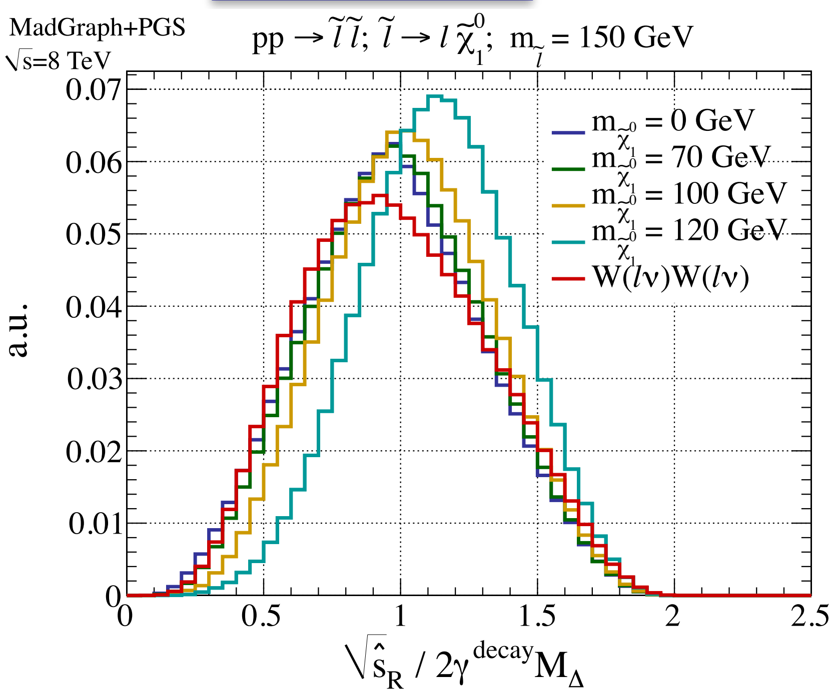
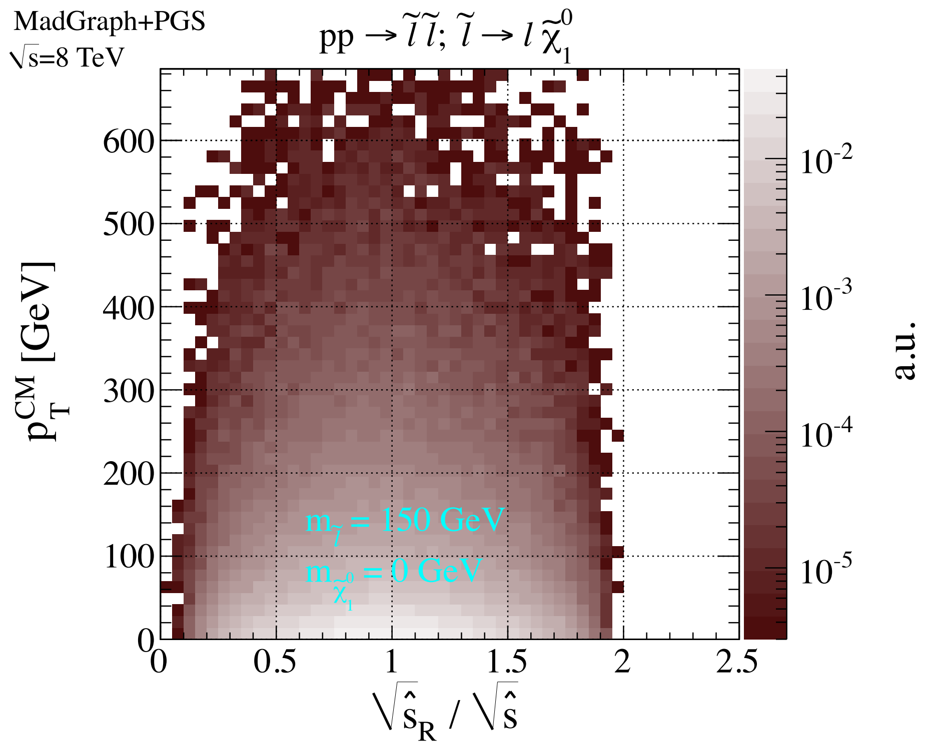
Recursive rest-frame reconstruction



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

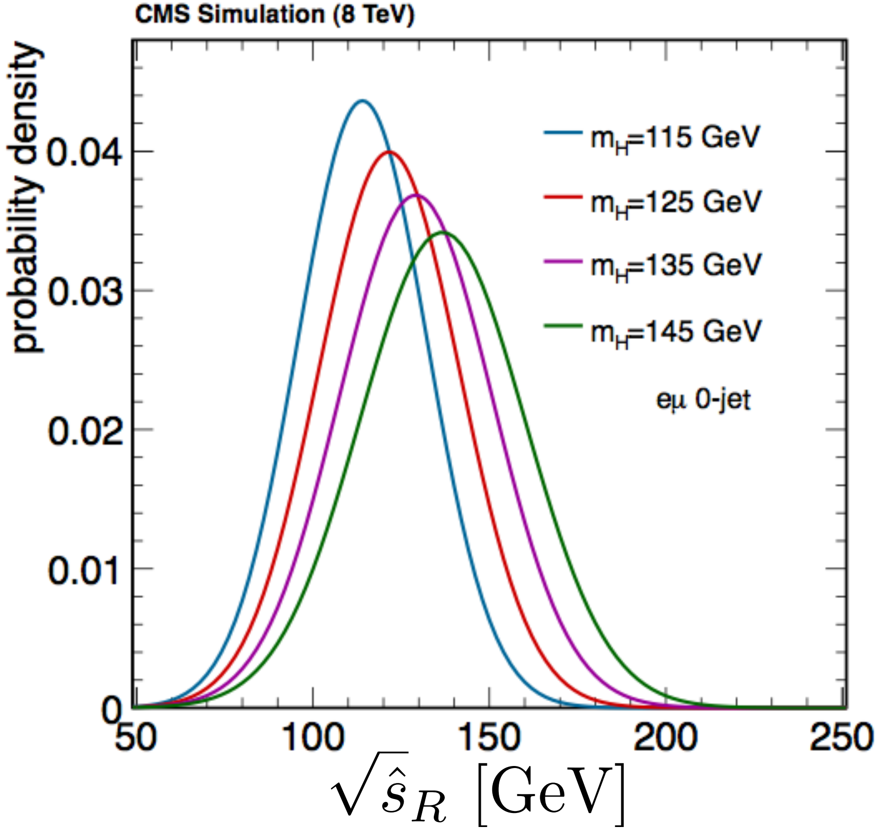
Resulting variable is invariant under p_T of di-slepton system





Resonant Higgs production

$$H \to WW^* \to 2\ell 2\nu$$

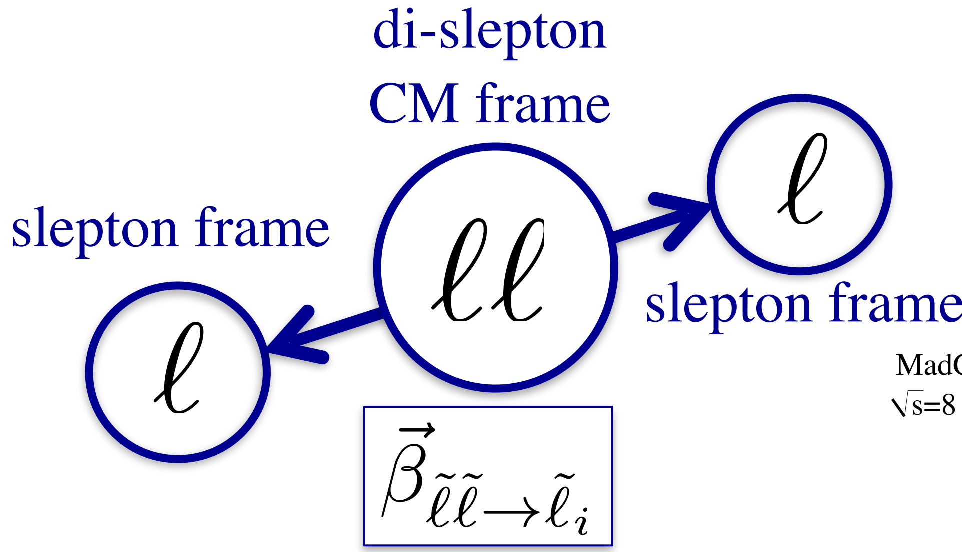


Using information from the two leptons, and the missing transverse momentum, the observable $\sqrt{\hat{s}_R}$ is directly sensitive to the Higgs mass

From:

CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, arXiv:1312.1129v1 [hep-ex]

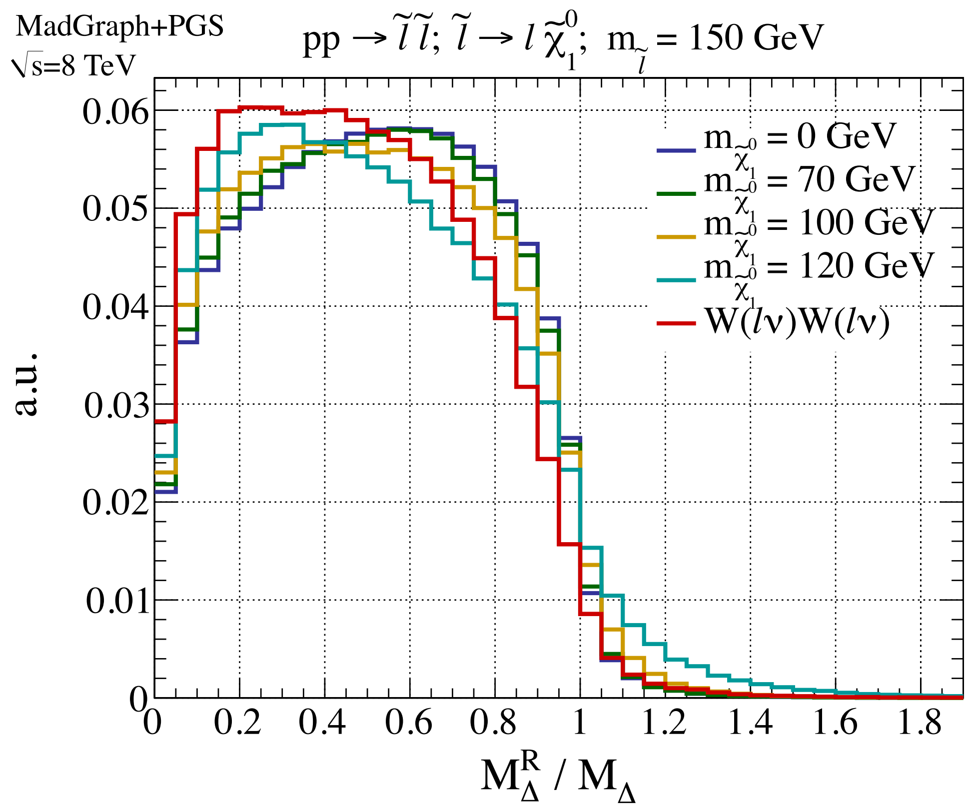
Recursive rest-frame reconstruction



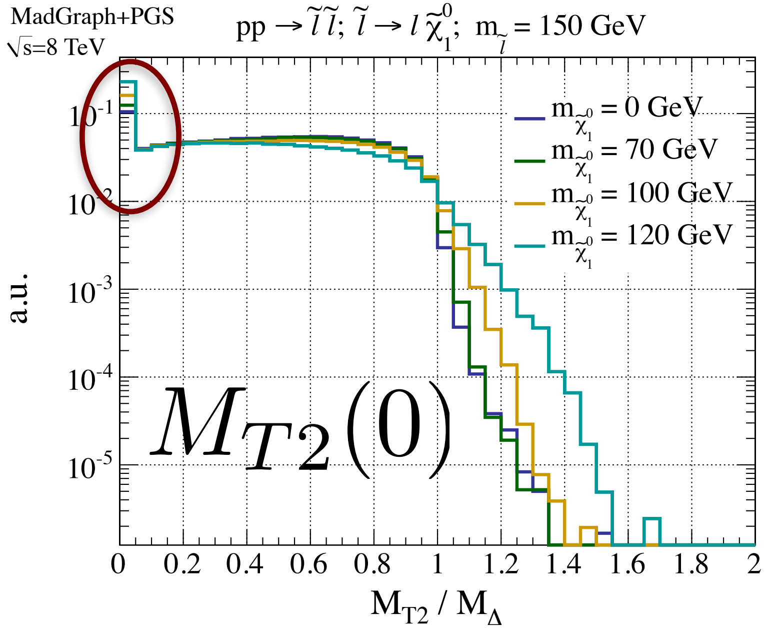
2nd transformation(s): extract variable sensitive to invariant mass of squark: M_{Δ}^{R}

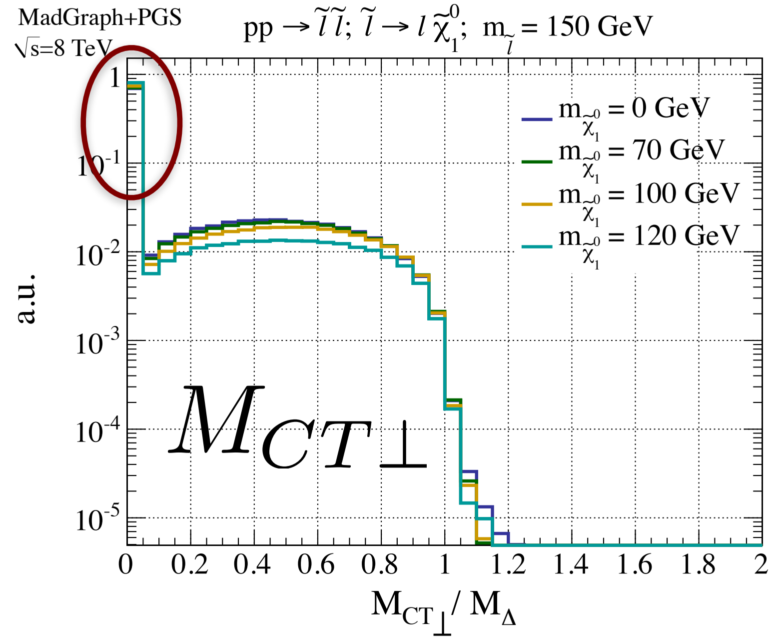
Resulting variable has kinematic endpoint at:

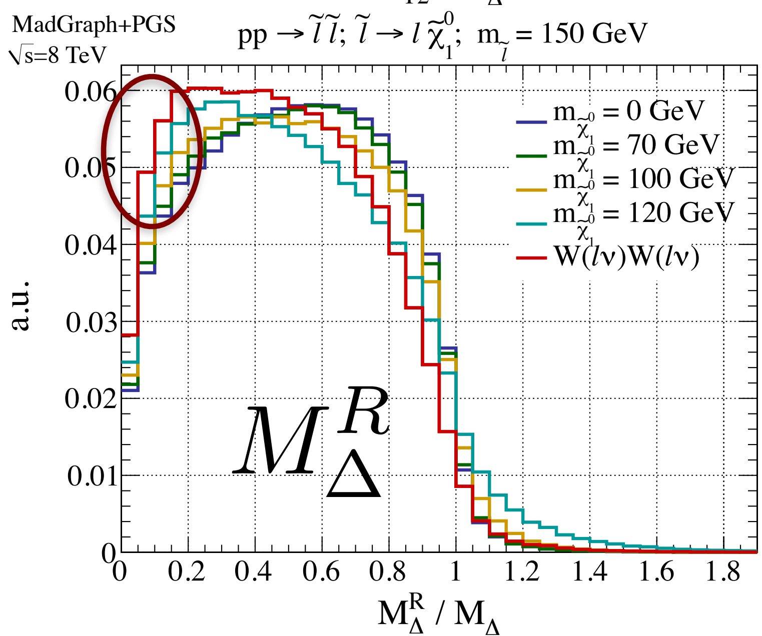
$$M_{\Delta} \equiv \frac{m_{\tilde{l}}^2 - m_{\tilde{\chi}^0}^2}{m_{\tilde{l}}}$$



Variable comparison







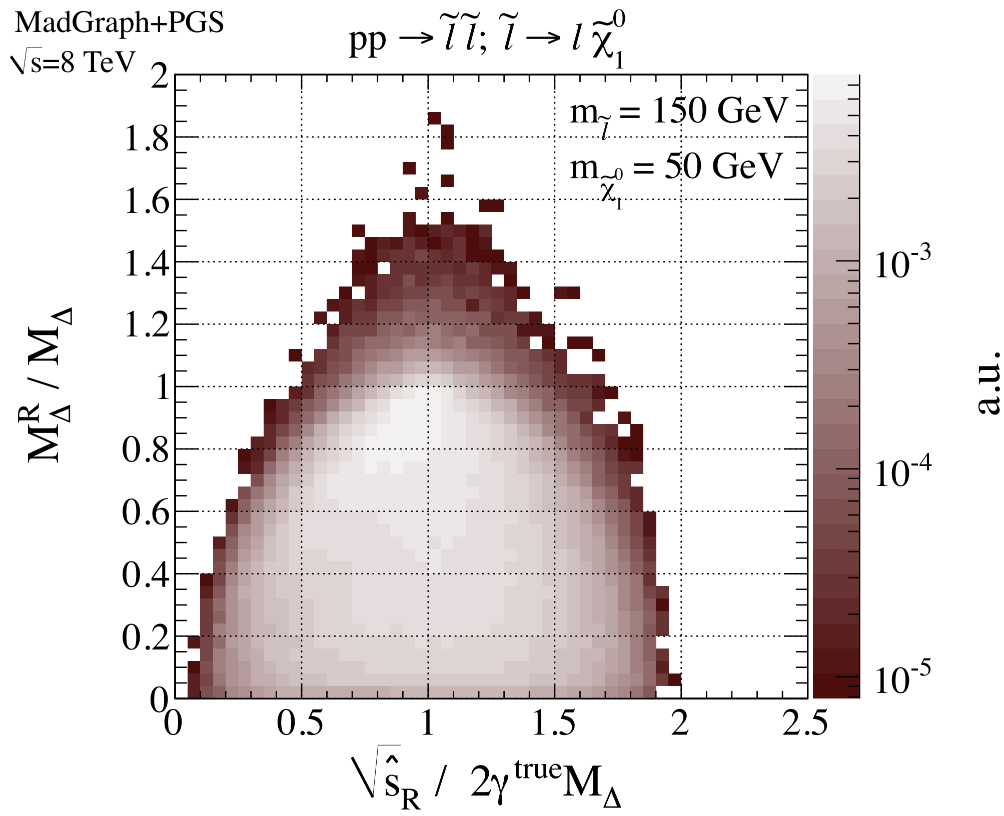
Three different singularity variables, all attempting to measure the same thing

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

More details about variable comparisons in PRD 89, 055020 (arXiv:1310.4827) and backup slides

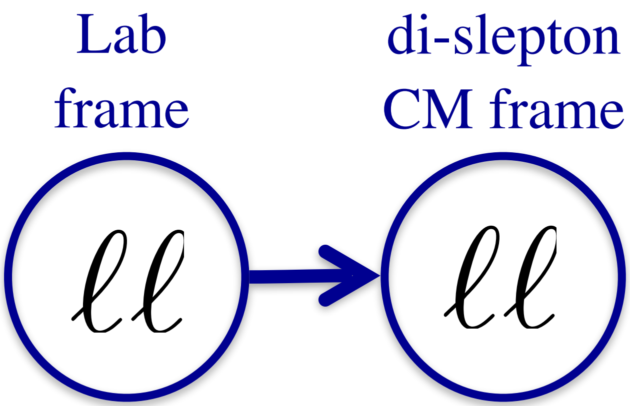
But what else can we calculate?

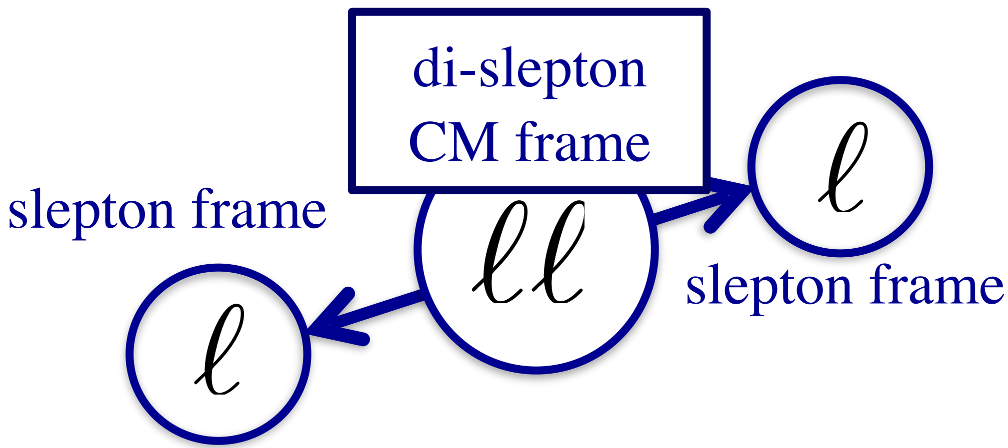
With recursive scheme can extract the two mass scales $\sqrt{\hat{s}_R}$ and M_{Δ}^{R} almost completely independently



Angles, angles, angles…

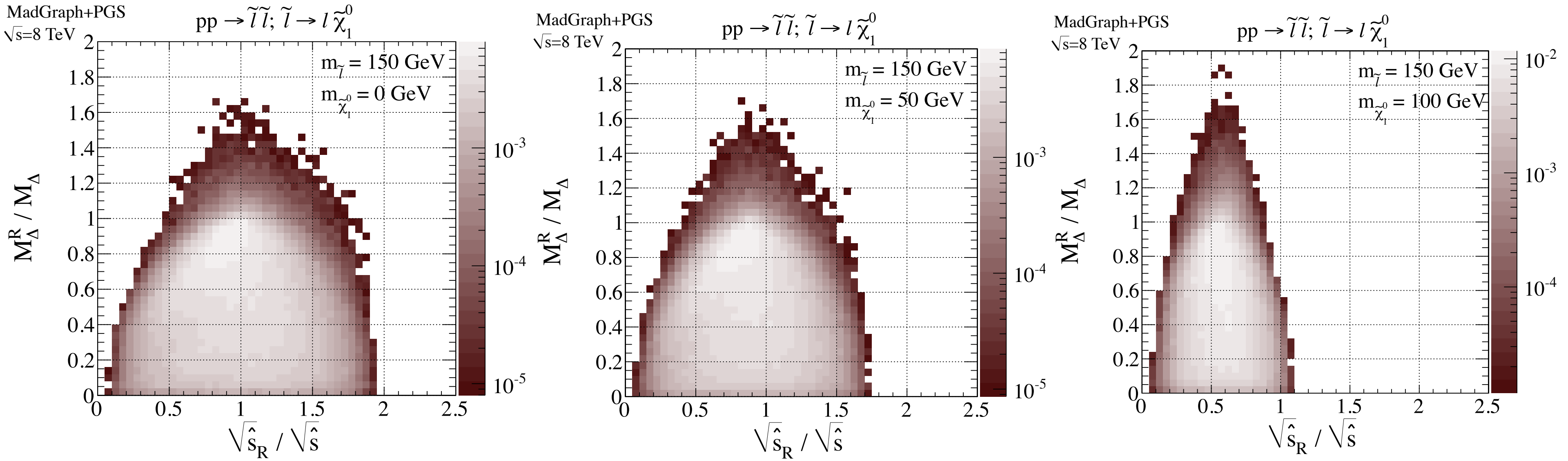
Recursive scheme fully specifies approximate event decay chain, also yielding angular observables





Two transformations mean at least two independent angles of interest (essentially the decay angle of the state whose rest-frame you are in)

Towards a kinematic basis



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

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

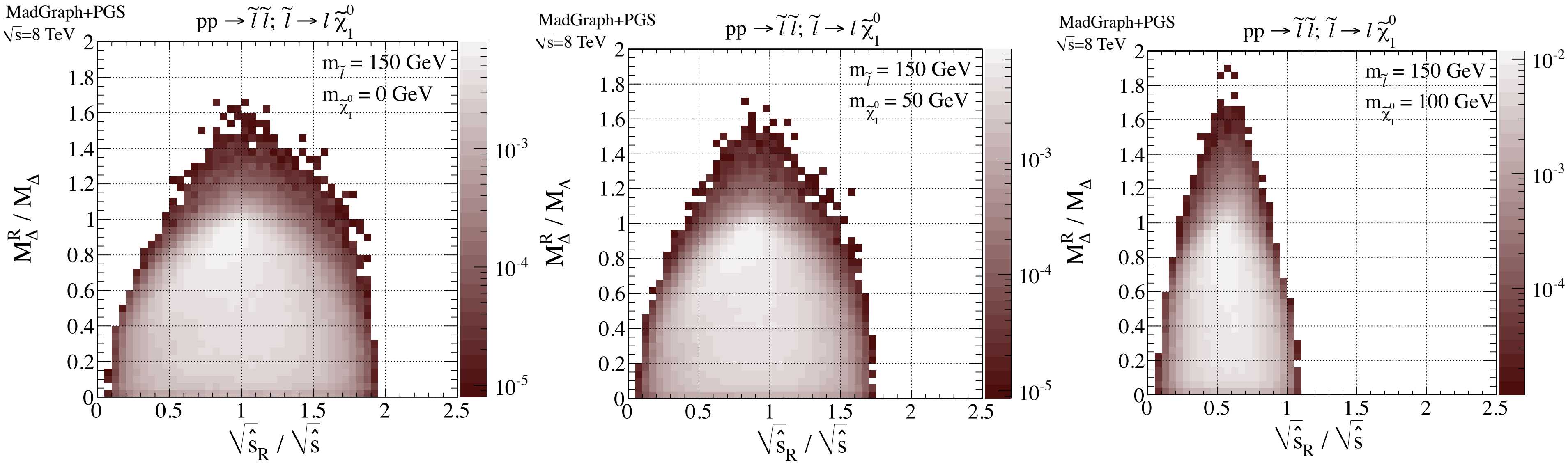
$$\vec{p}_T^{\,CM} = \vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{E}_T^{\,\text{miss}}$$

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

$$\vec{\beta}_{lab \to CM} = \frac{\vec{p}_T^{\,CM}}{\sqrt{|\vec{p}_T^{\,CM}|^2 + \hat{s}}}$$

From PRD 89, 055020 (2014)

Towards a kinematic basis



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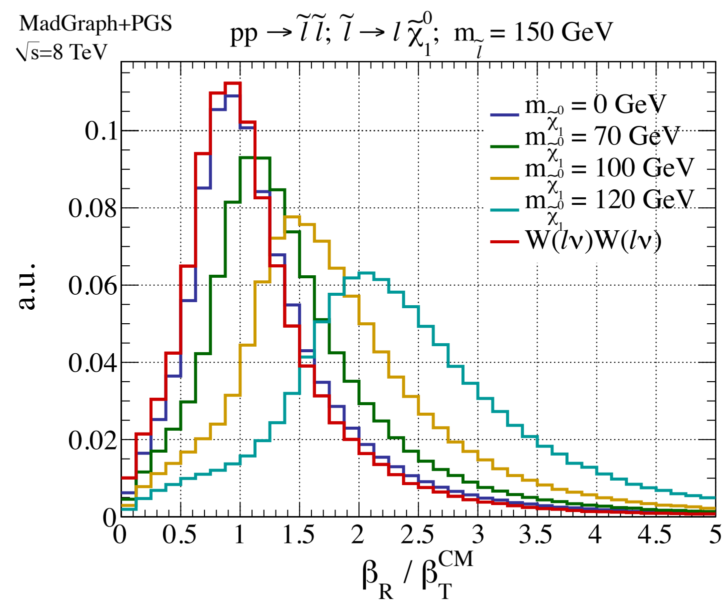


Underestimating the real mass means over-estimating the boost magnitude:

From PRD 89, 055020 (2014)

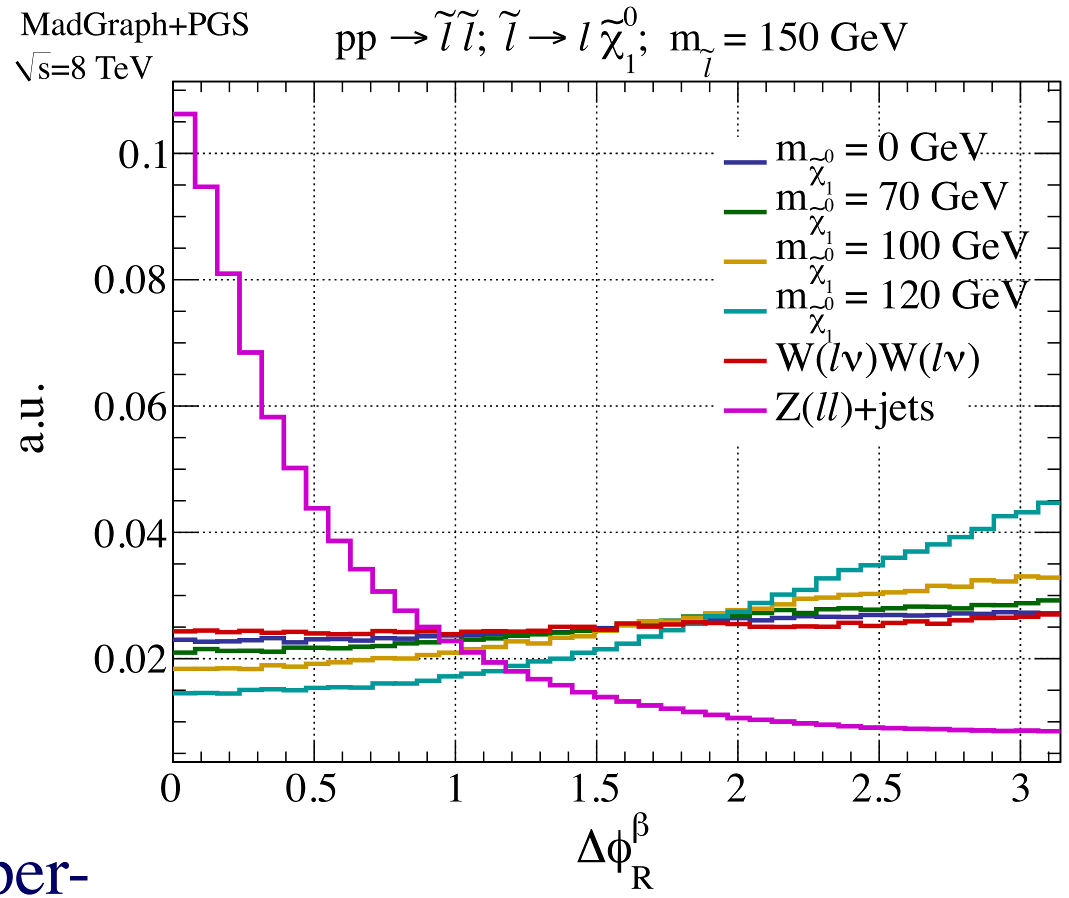
Angular Variables

Incorrect boost magnitude
induces correlation

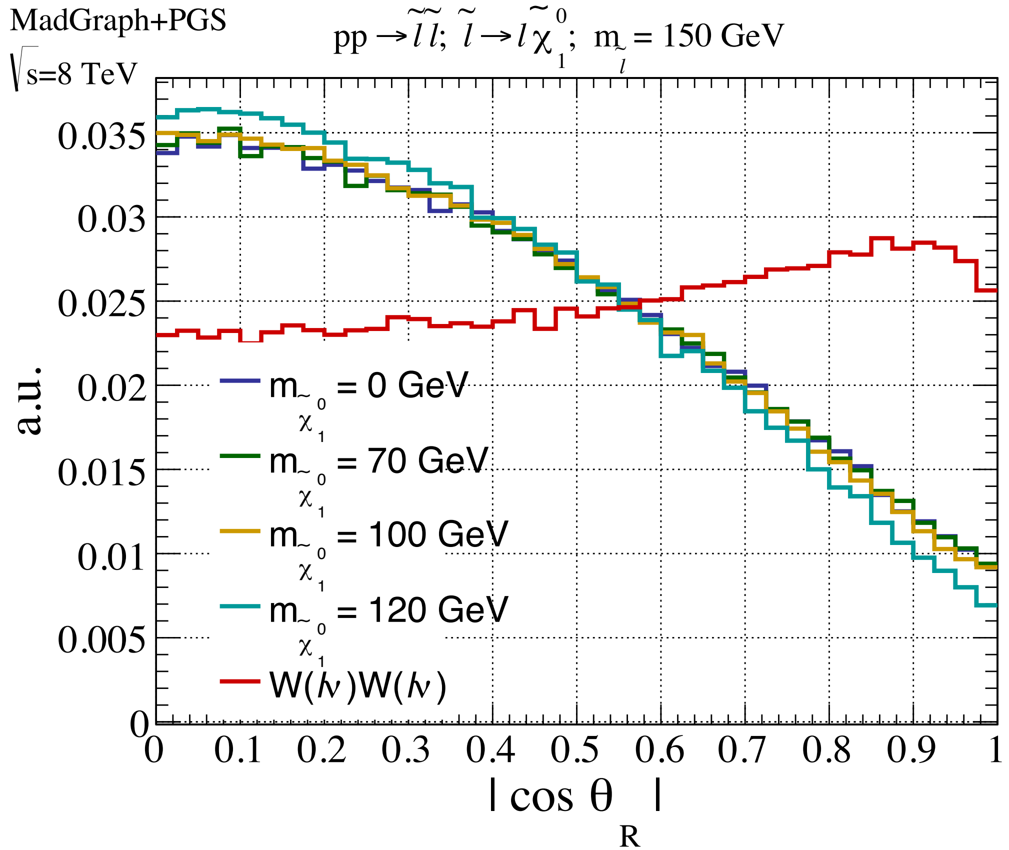
Angle between
lab ➔ CM frame boost and
di-leptons in CM frame is
sensitive to

$\frac{m_\chi}{m_{\tilde{\ell}}}$ rather than M_Δ

~Uncorrelated with other super-razor variables

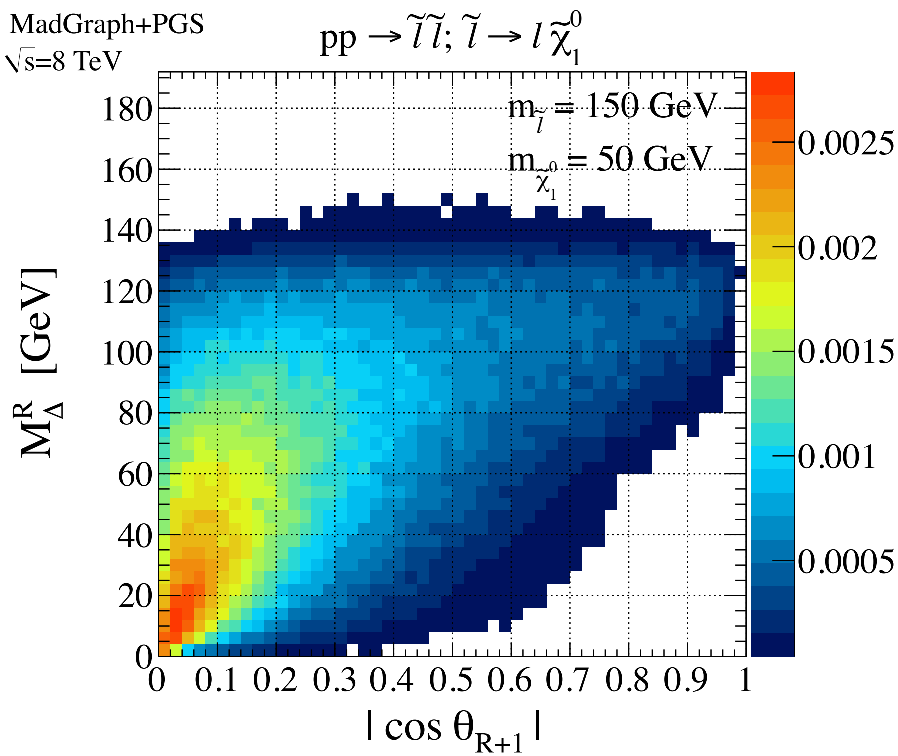


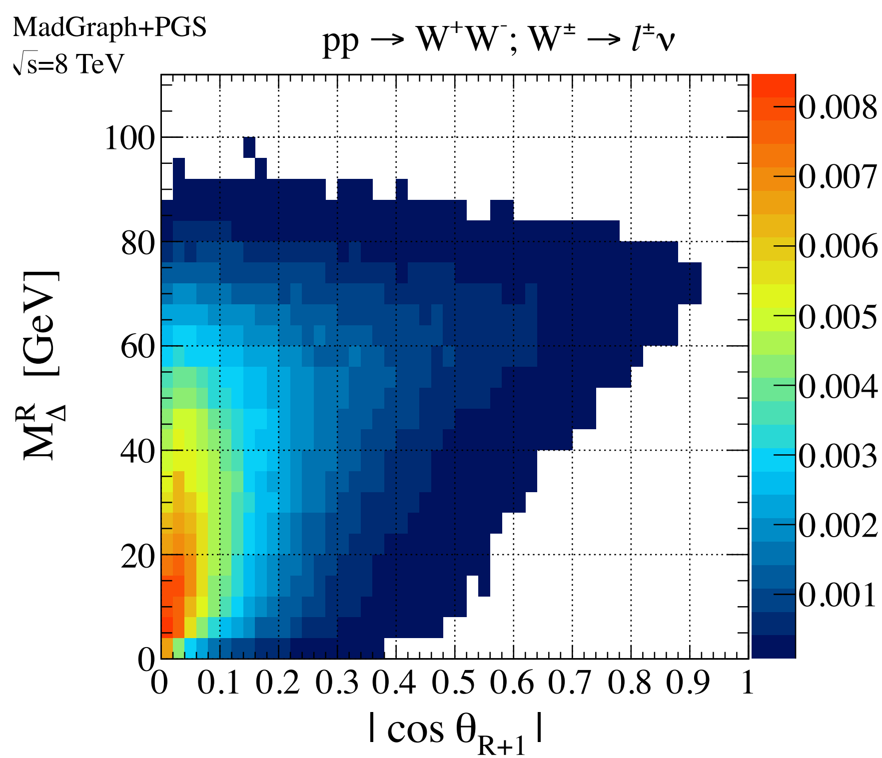
Angular Variables



In the approximate di-slepton rest frame, reconstructed decay angle sensitive to particle spin and production

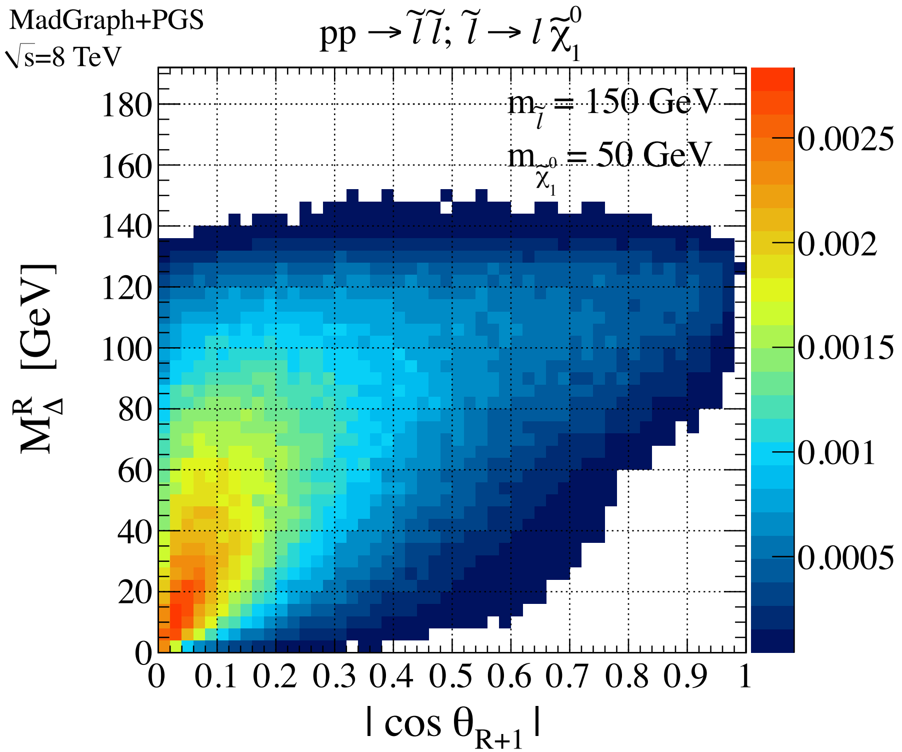
Angular Variables

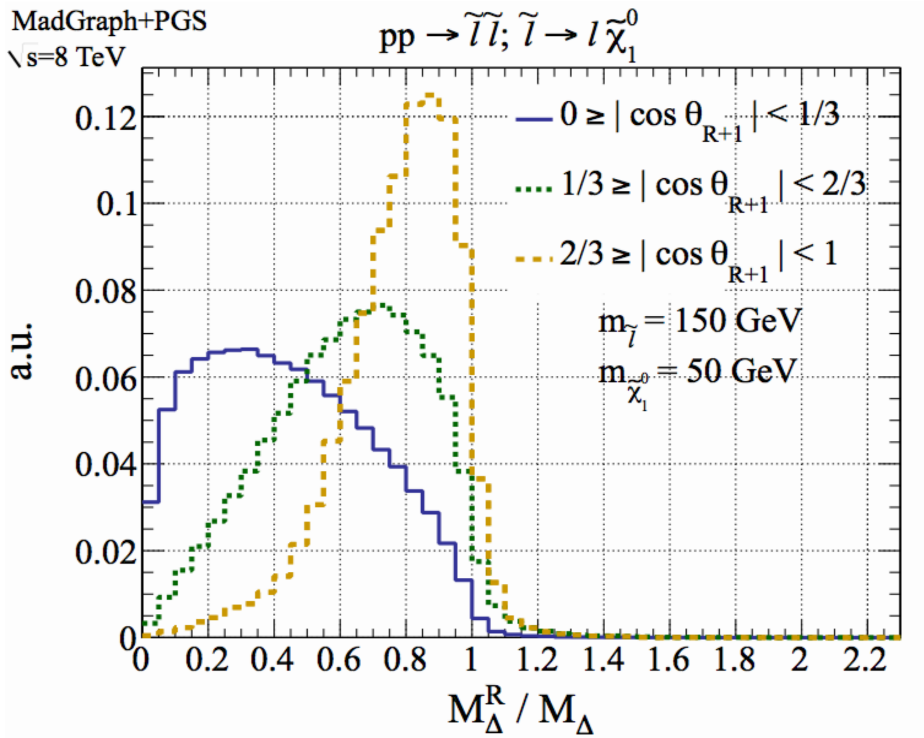




In the approximate slepton rest frames, reconstructed slepton decay angle sensitive to particle spin correlations

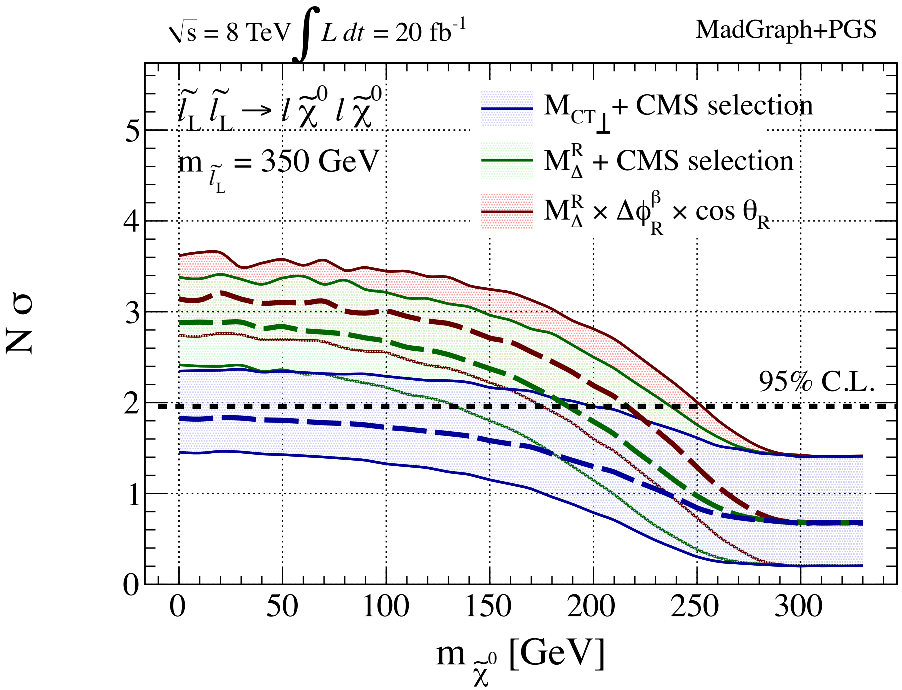
Angular Variables





Also allows us to better resolve the kinematic endpoint of interest

Super-razor variable basis



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

Can improve sensitivity while removing MET cuts!

$\Delta\phi_R^\beta$ Sensitive to ratio of invisible and visible masses

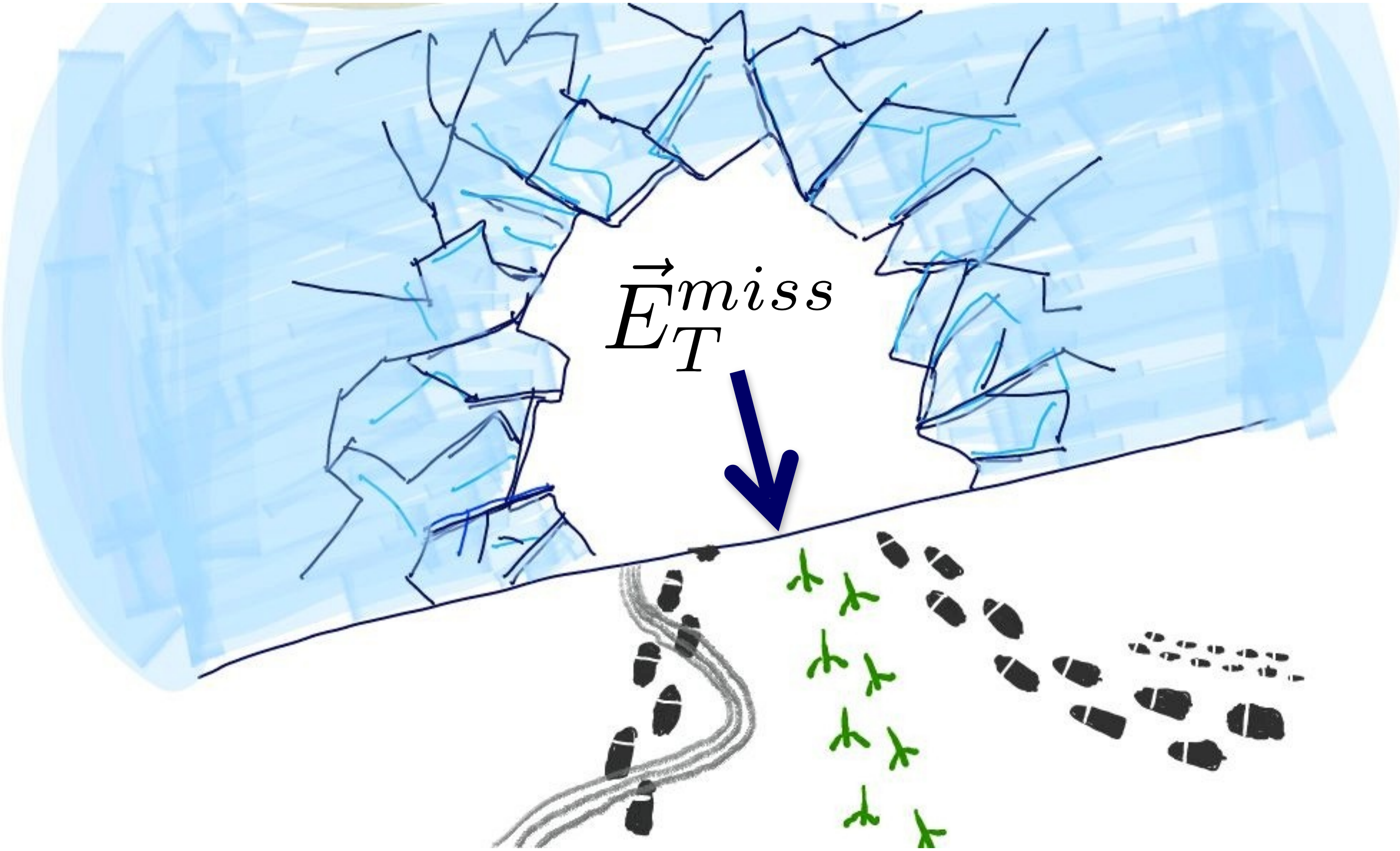
$\sqrt{\hat{s}}_R$ Sensitive to mass of CM. Good for resonant production of heavy parents

$|\cos\theta_R|$ Spin and production

M_Δ^R Mass-squared difference resonant/non-resonant prod.

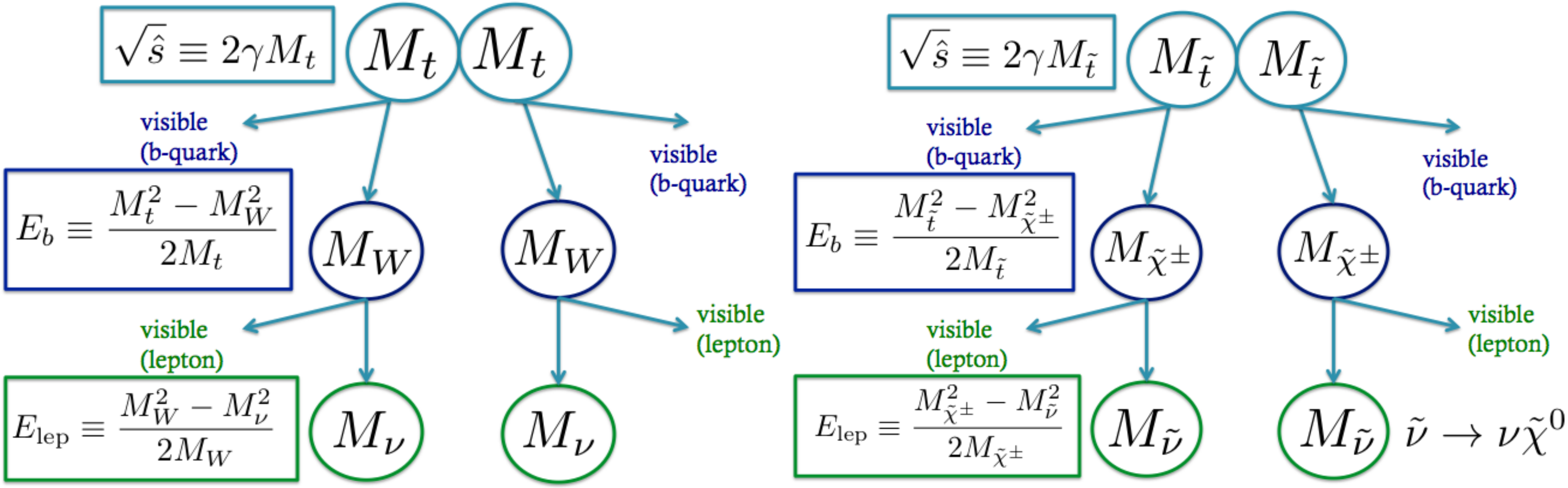
$|\cos\theta_{R+1}|$ Spin correlations, better resolution of mass edge

Generalizing further



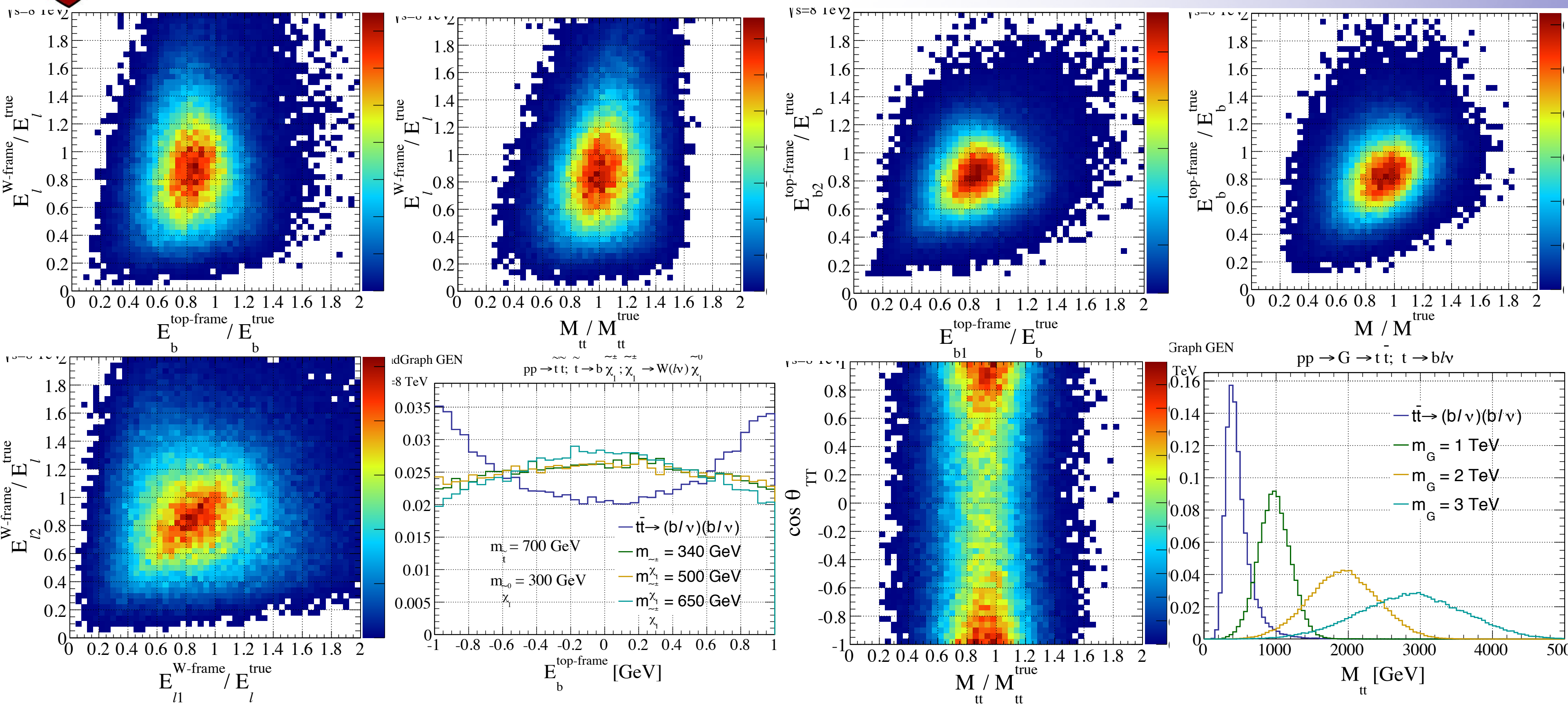
Recursive Jigsaw approach can be generalized to arbitrarily complex final states with weakly interacting particles

Example: the di-leptonic top basis



In more complicated decay topologies there can be many masses/mass-splittings, spin-sensitive angles and other observables of interest that can be used to distinguish between the SM and SUSY signals

Example: the di-leptonic top basis

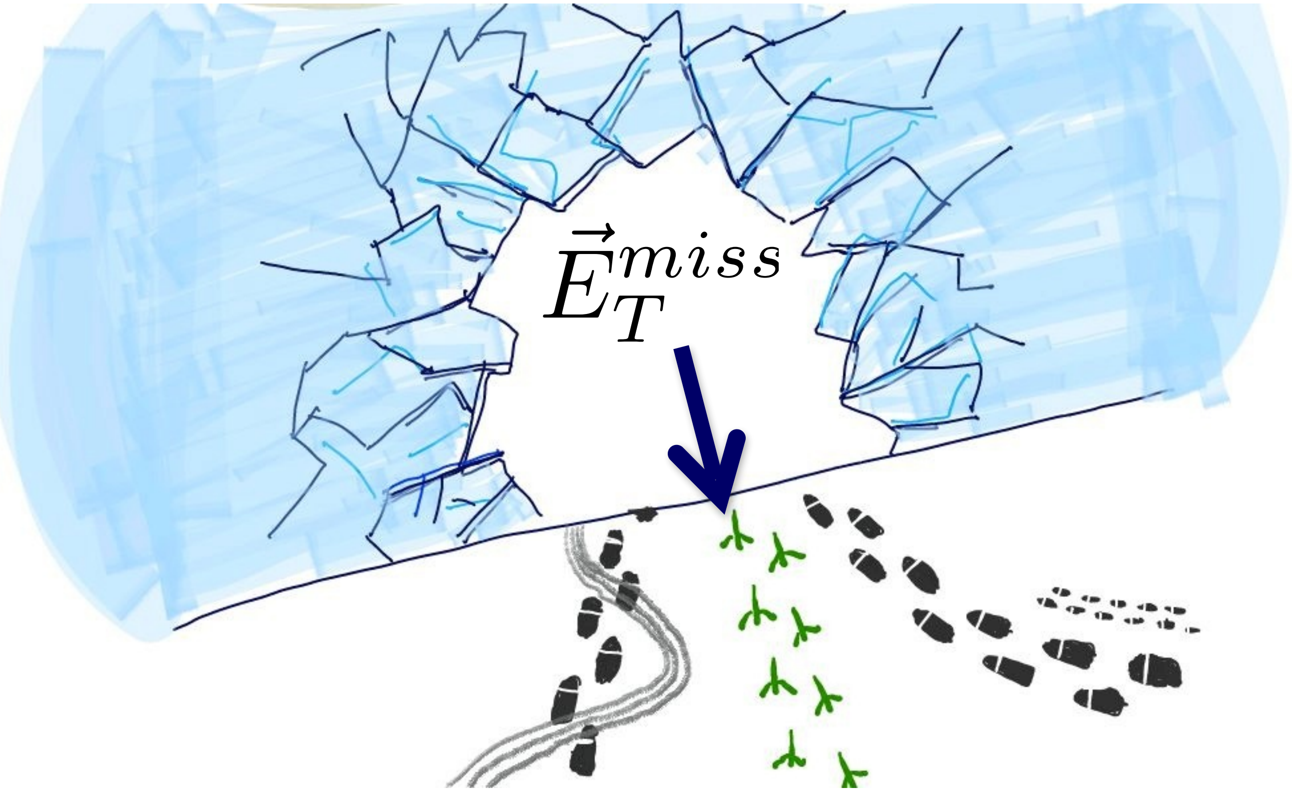


A rich basis of useful Recursive Jigsaw observables can be calculated, each with largely independent information

See Paul Jackson’s talk on Friday for more details!

Outlook

- The strategy of Recursive Jigsaw Reconstruction is to not only develop 'good' mass estimator variables, but to decompose each event into a ***basis of kinematic variables***
- Through the recursive procedure, each variable is (as much as possible) ***independent of the others***
- The interpretation of variables is straightforward; they each correspond to an ***actual, well-defined, quantity in the event***
- Can be generalized to arbitrarily complex final states with ***many weakly interacting particles***
- Stay tuned for documentation and code package to be released next month



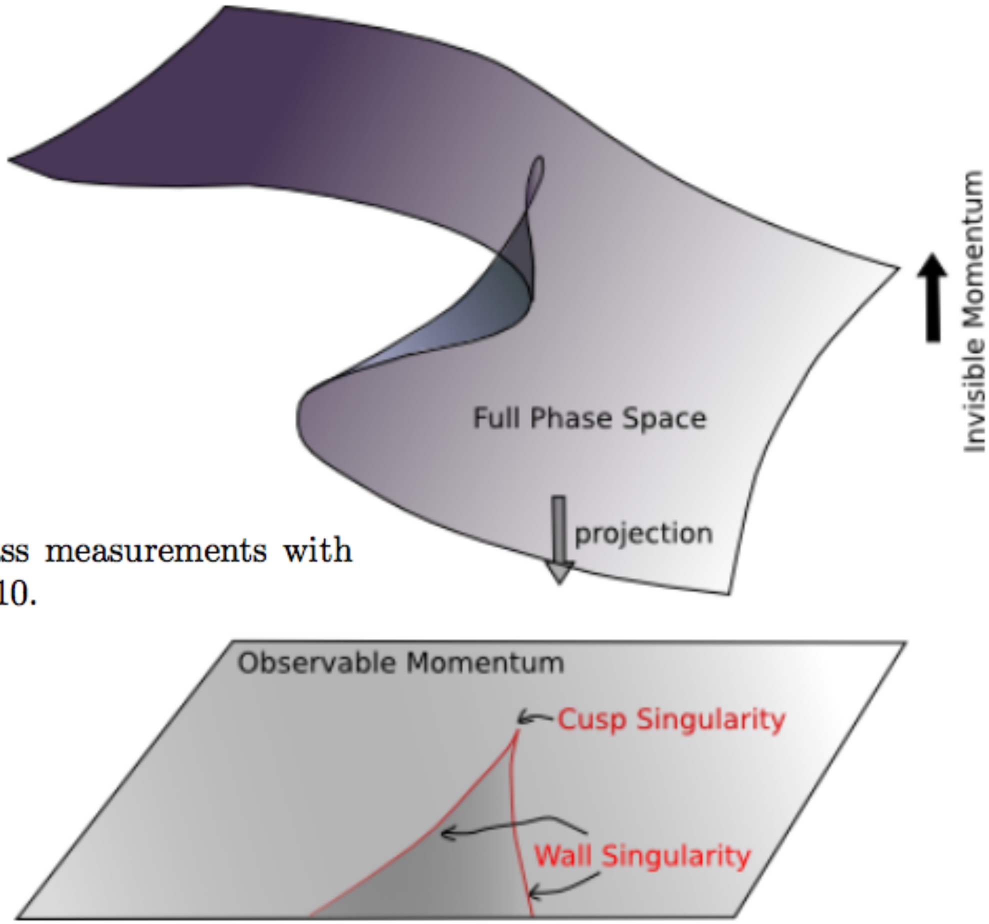
BACKUP SLIDES

Weakly interacting particles @ LHC

- Why are they interesting?
  - Electroweak bosons
    - Decays of W and Z often produce neutrinos
  - New symmetries
    - Discrete symmetries (ex. R-parity) make lightest new ‘charged’ particles stable
  - Dark Matter
    - It exists - but what is it? Would like to know if we’re producing these particles at the LHC
  - Natural SUSY
    - Present in both RPC and RPV scenarios
- How do we study them?
  - Can infer their presence through missing transverse energy
  - Hermetic design of LHC experiments allows us to infer ‘what’s missing’

Singularity variables

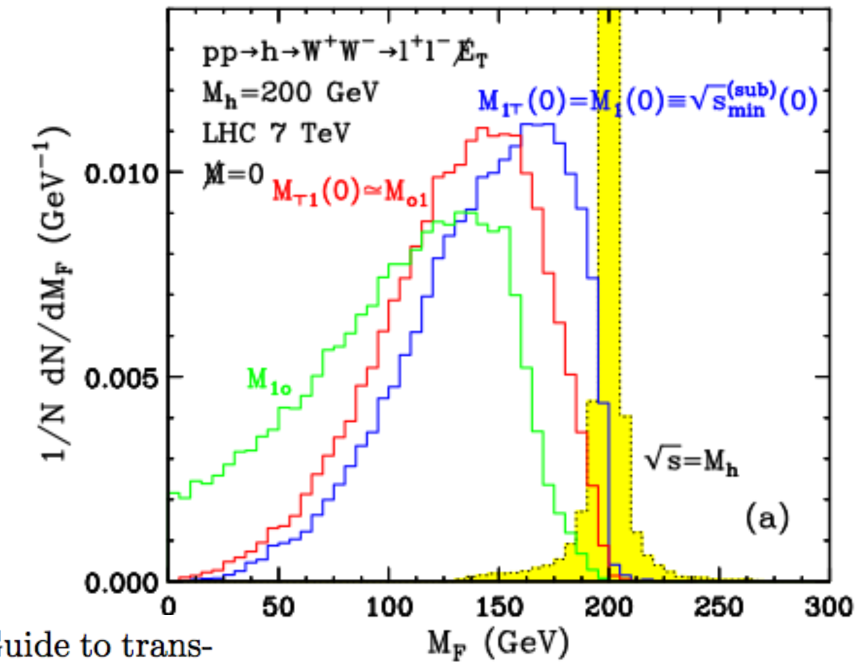
Kinematic Singularities. A singularity is a point where the local tangent space cannot be defined as a plane, or has a different dimension than the tangent spaces at non-singular points.



From:

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

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.

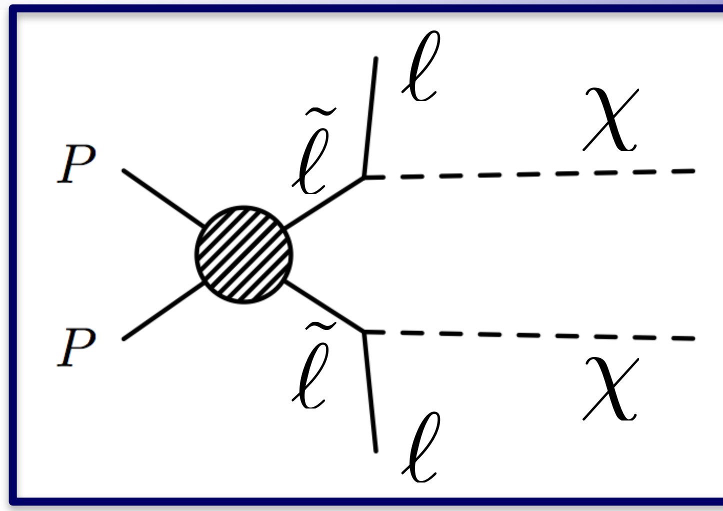
Singularity Variables

- State-of-the-art for LHC Run I was to use singularity variables as observables in searches

- Derive observables that bound a mass or mass-splitting of interest by
  - Assuming knowledge of event decay topology
  - Extremizing over under-constrained kinematic degrees of freedom associated with weakly interacting particles

Singularity Variable Example: M_{T2}

Generalization of transverse mass to two weakly interacting particle events



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

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: $M_{T2}^{\max}(m_\chi) = m_{\tilde{\ell}}$

$$M_{T2}^{\max}(0) = M_\Delta \equiv \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}}$$

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.

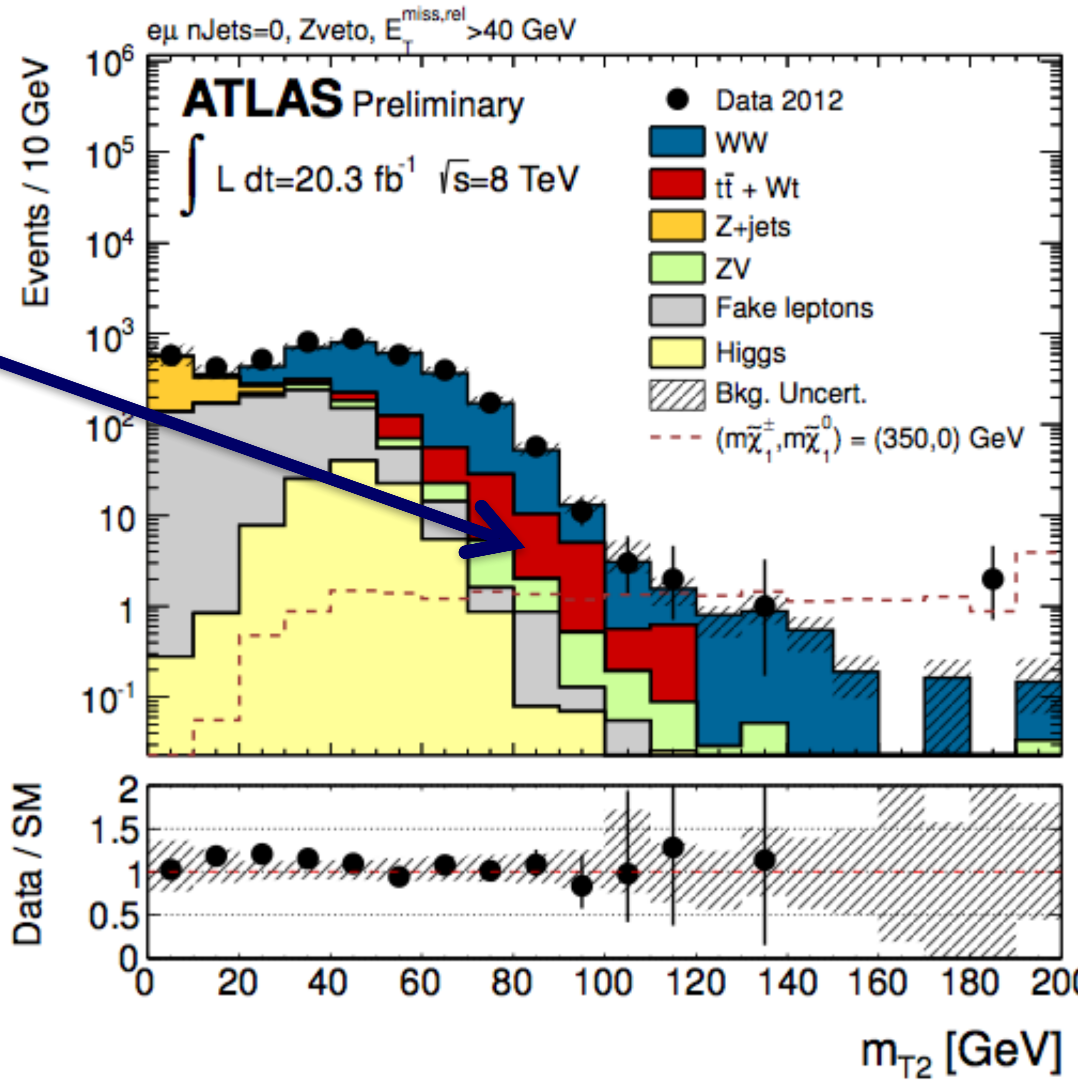
M_{T2} in practice

From:

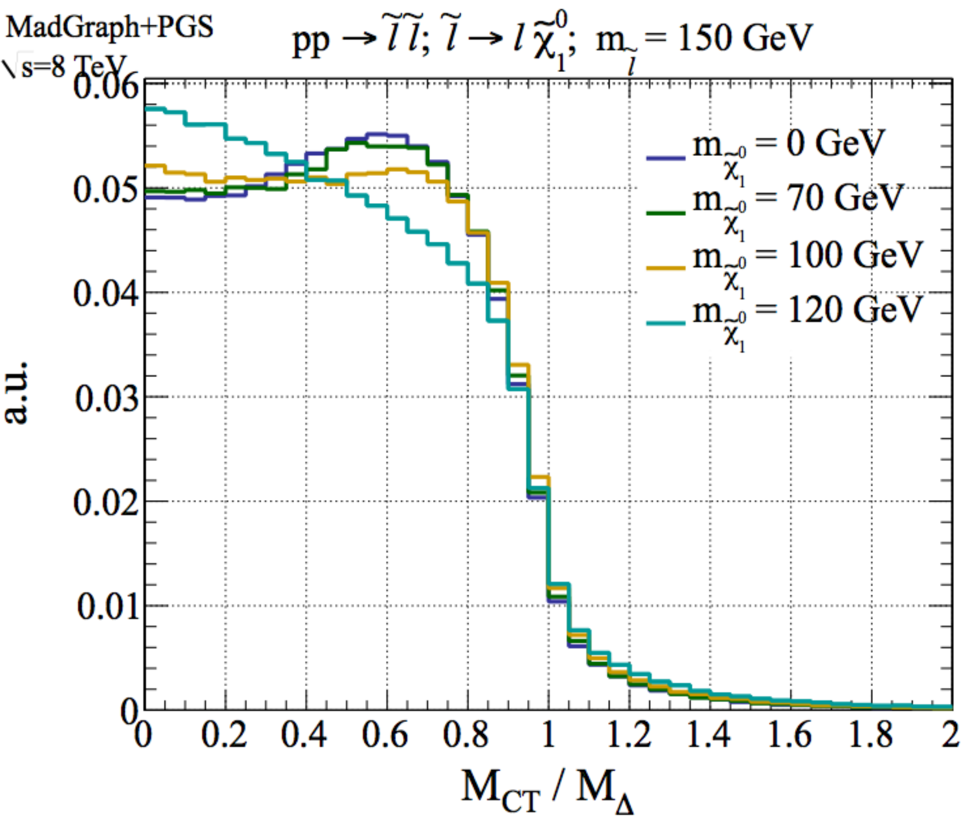
ATLAS-CONF-2013-049

Backgrounds with leptonic W decays fall steeply once M_{T2} exceeds the W mass

Searches based on singularity variables have sensitivity to new physics signatures with mass splittings larger than the analogous SM ones



Example: M_{CT}



assuming ~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:

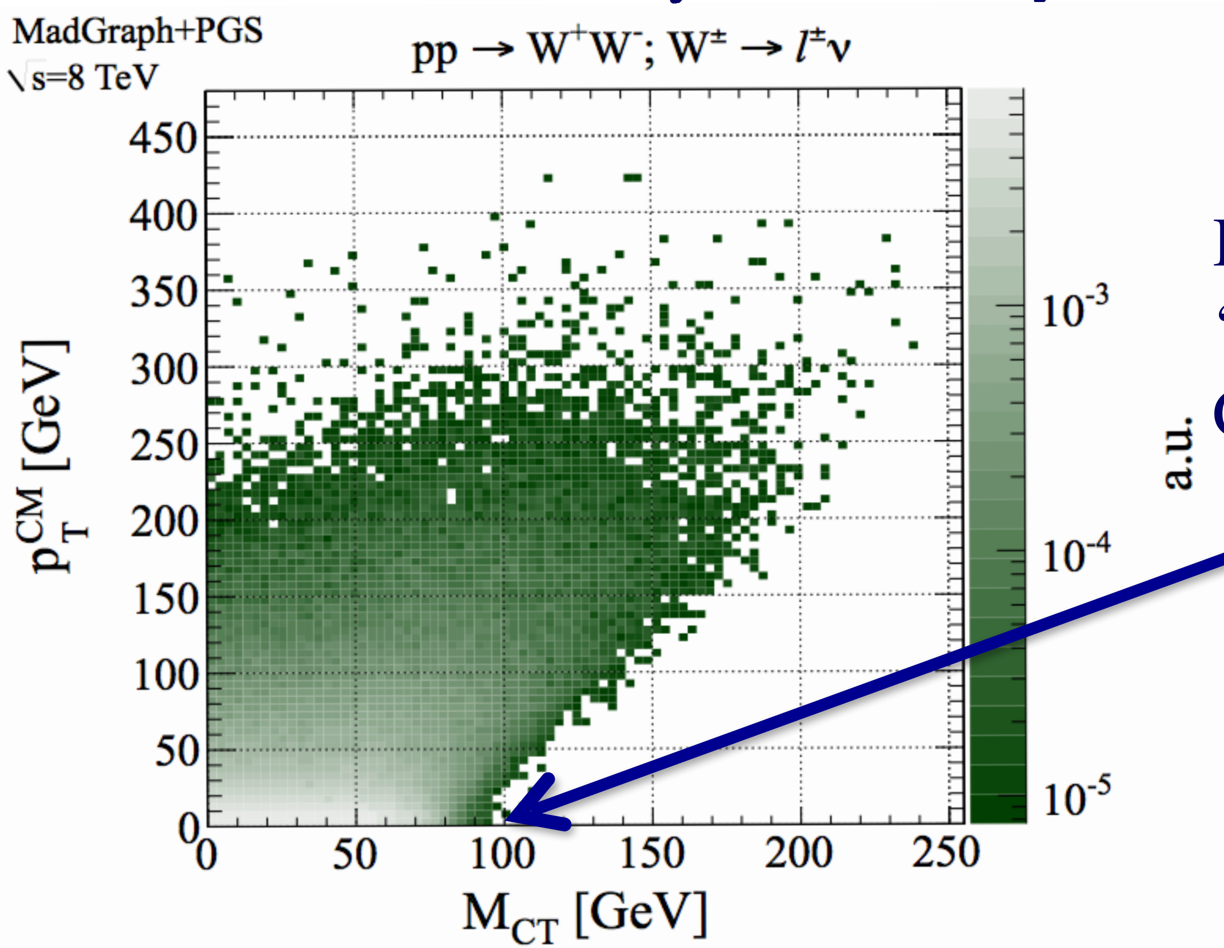
$$M_{CT}^{\max} = \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^0}} = M_\Delta$$

From:

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

M_{CT} in practice

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



Kinematic endpoint 'moves' with nonzero CM system p_T

The mass challenge

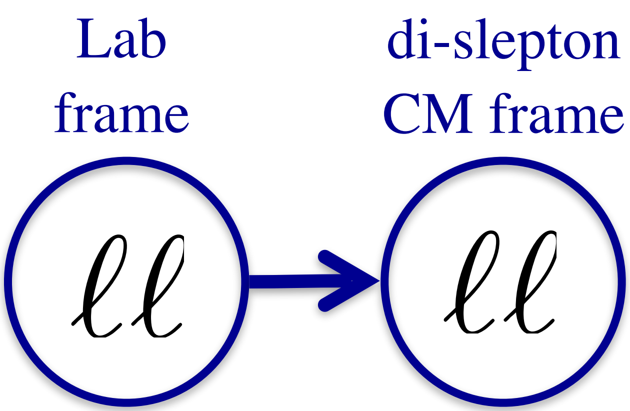
The invariant mass is invariant under coherent Lorentz transformations of two particles

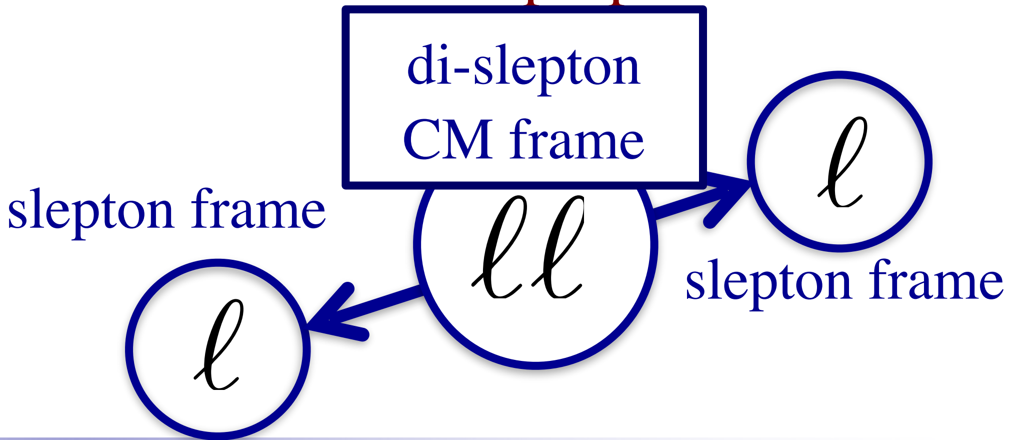
$$m^2_{inv}(p_1, p_2) = m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2)$$

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

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

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:

$$\vec{\beta}_{lab\to CM} = \frac{\vec{p}_T^{\,CM}}{\sqrt{|\vec{p}_T^{\,CM}|^2 + \hat{s}}}$$

p_T corrections for M_{CT}

Attempts have been made to mitigate this problem:

(i) 'Guess' the lab ➔ CM frame boost:

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

x – parallel to boost

y – perp. to boost

with:

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

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

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

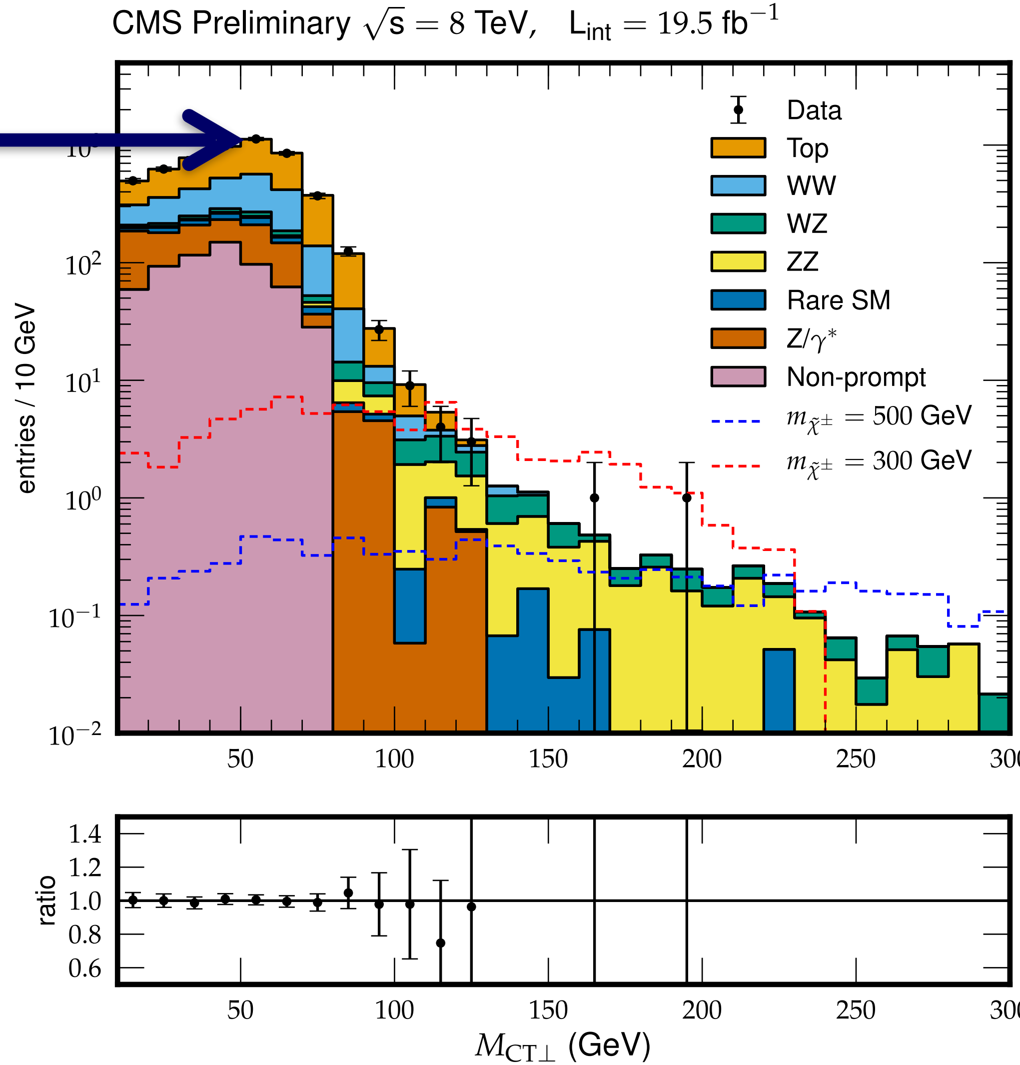
(ii) Only look at event along axis perpendicular to boost:

$M_{CT\perp}$

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_{CTperp} in practice

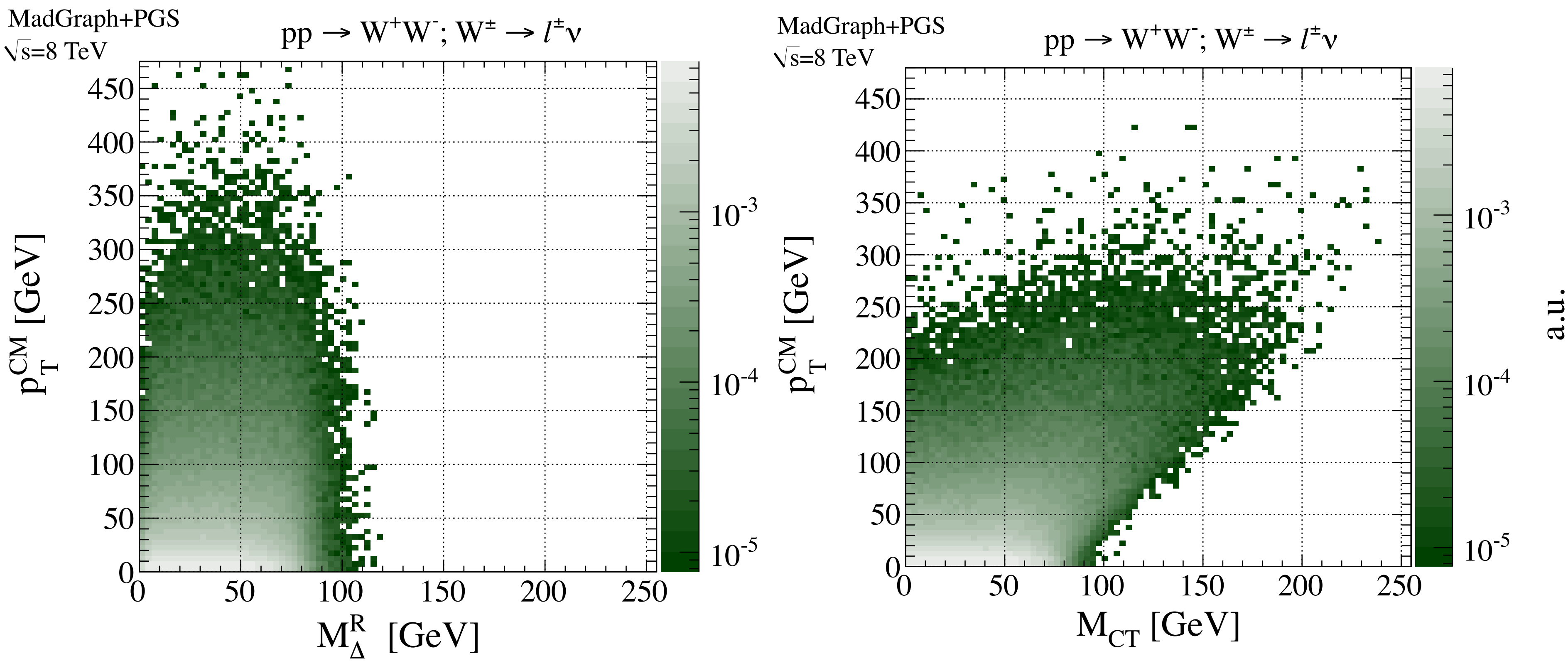
'peak position' of signal and backgrounds due to other cuts (p_T, MET) and only weakly sensitive to sparticle masses



From:

CMS-SUS-PAS-13-006

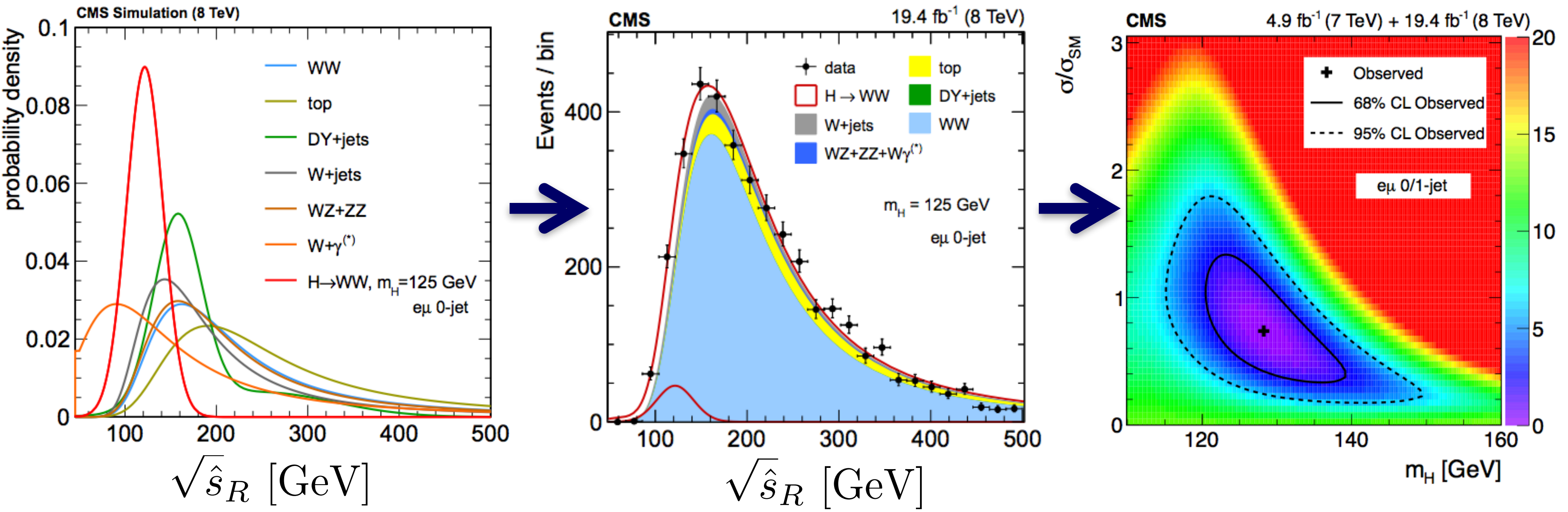
Recursive rest-frame reconstruction



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

Resonant Higgs production

$H \to WW^* \to 2\ell 2\nu$



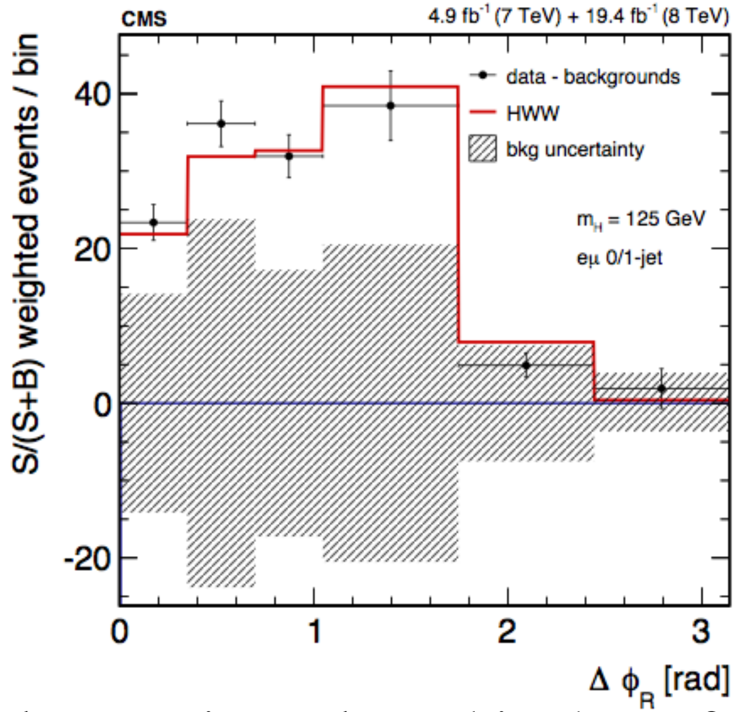
The shape of the $\sqrt{\hat{s}_R}$ distribution, for the Higgs signal and backgrounds, is used to extract both the Higgs mass and signal strength – even while information is lost with the two escaping neutrinos

From:

CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, arXiv:1312.1129v1 [hep-ex]

Resonant Higgs production

$H \to WW^* \to 2\ell 2\nu$



The $\Delta\phi$ between the leptons is evaluated in the R-frame, removing dependence on the p_T of the Higgs and correlation with $\sqrt{\hat{s}}_R$

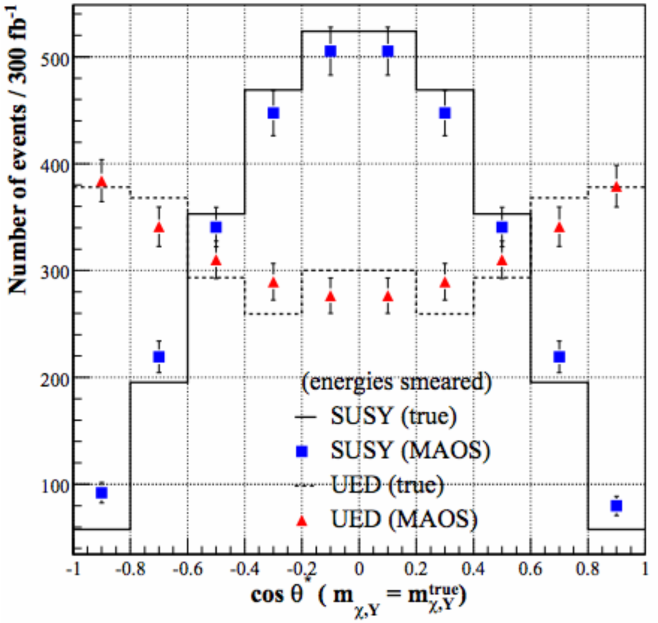
CMS uses 2D fit of variables to measure Higgs mass in this channel

From:

CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, arXiv:1312.1129v1 [hep-ex]

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?

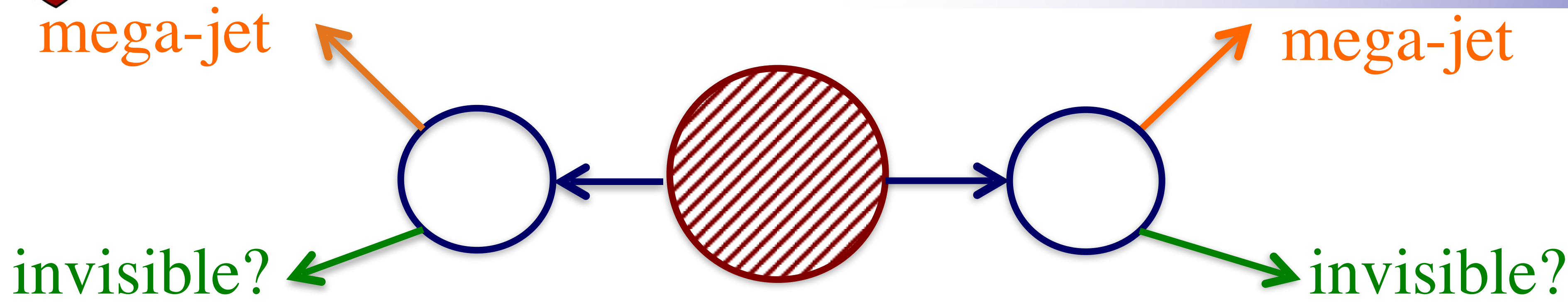


From:

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?

Razor kinematic variables

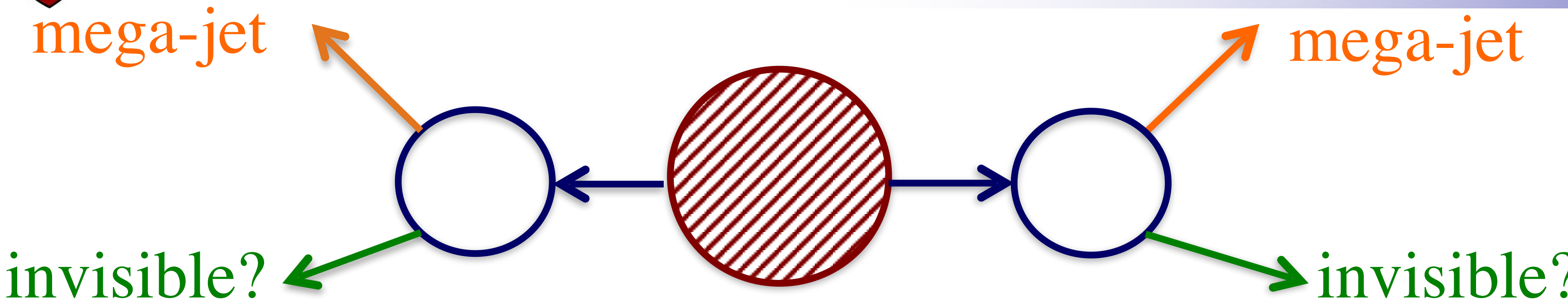


- Assign every reconstructed object to one of two mega-jets
- Analyze the event as a 'canonical' open final state:
  - two variables: M_R (mass scale) , R (scale-less event imbalance)
- An inclusive approach to searching for a large class of new physics possibilities with open final states

Razor variables — arXiv:1006.2727v1 [hep-ph]

CMS+ATLAS analyses — PRD 85, 012004 (2012)
EPJC 73, 2362 (2013)
PRL 111, 081802 (2013)
CMS-PAS-SUS-13-004

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)

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

Two distinct mass scales in event

Two pieces of complementary information

A Monte Carlo analysis to compare

- Baseline Selection — From PRD 89, 055020 (arXiv:1310.4827 [hep-ph])
  - Exactly two opposite sign leptons with $p_T > 20$ GeV/c and $|\eta| < 2.5$
  - If same flavor, $m(\ell\ell) > 15$ GeV/c2
  - ΔR between leptons and any jet (see below) > 0.4
  - veto event if b-tagged jet with $p_T > 25$ GeV/c and $|\eta| < 2.5$
- Kinematic Selection

'CMS selection'

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

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

CMS-PAS-SUS-12-022

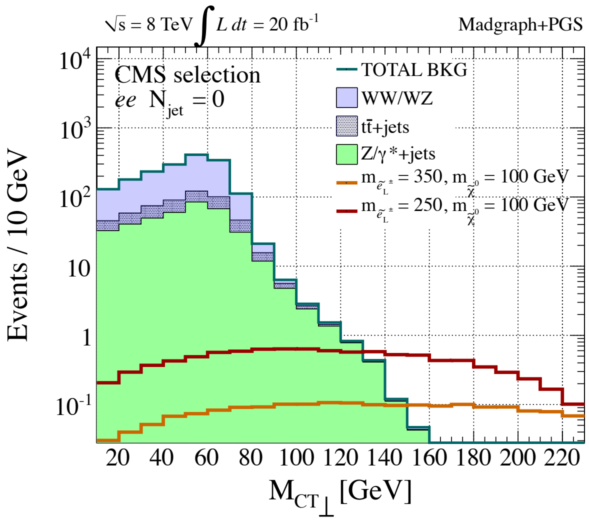
'ATLAS selection'

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

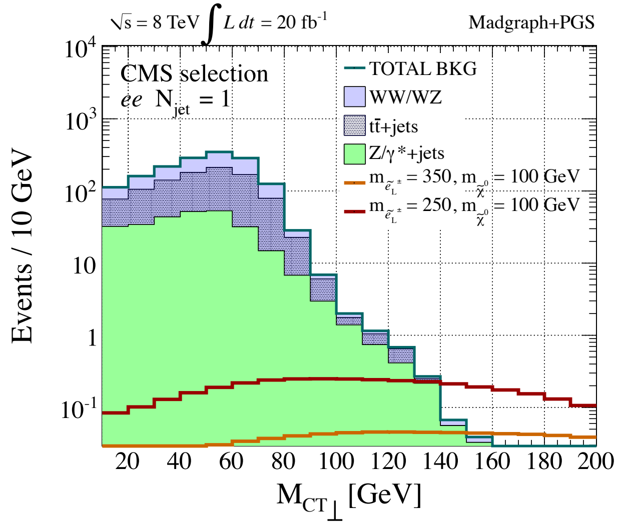
$$E_{\mathrm{T}}^{\mathrm{miss,rel.}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases} > 40 \text{ GeV}$$

ATLAS-CONF-2013-049

1D Shape Analysis



+



+ Other jet multiplicity and lepton flavor categories

From PRD 89, 055020

- 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

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

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

Systematic uncertainties

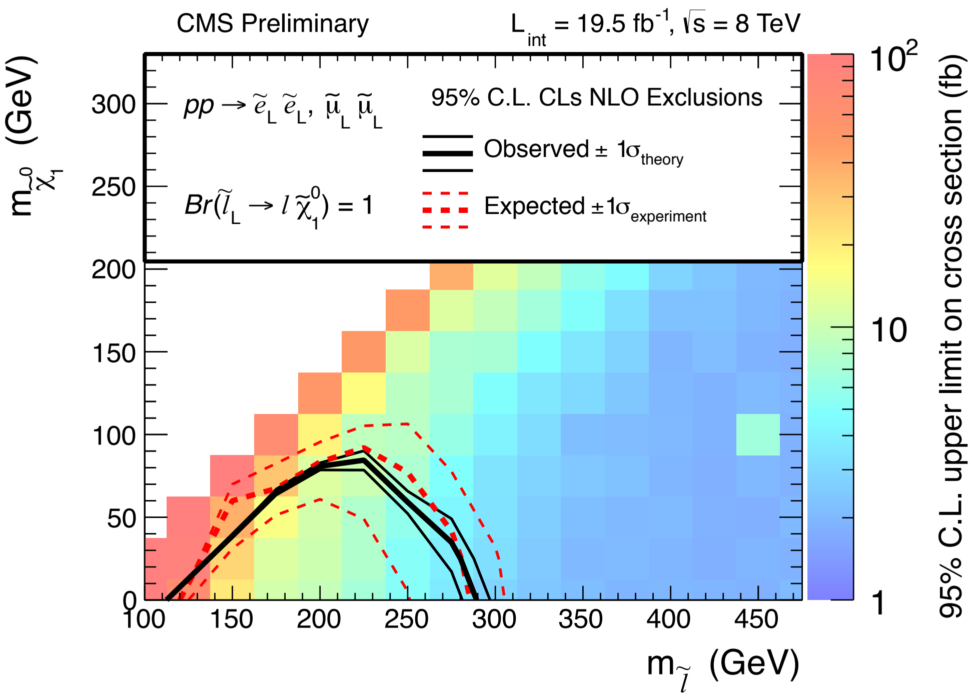
From PRD 89, 055020 (arXiv:1310.4827 [hep-ph])

- 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 PRD 89, 055020 (arXiv:1310.4827 [hep-ph])

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



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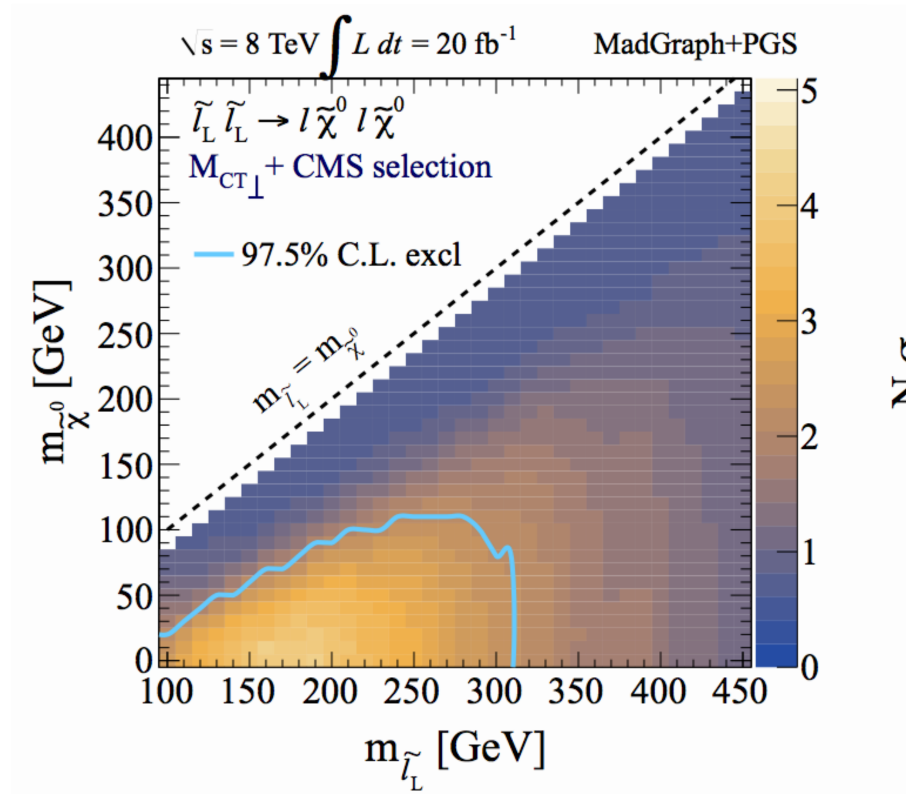
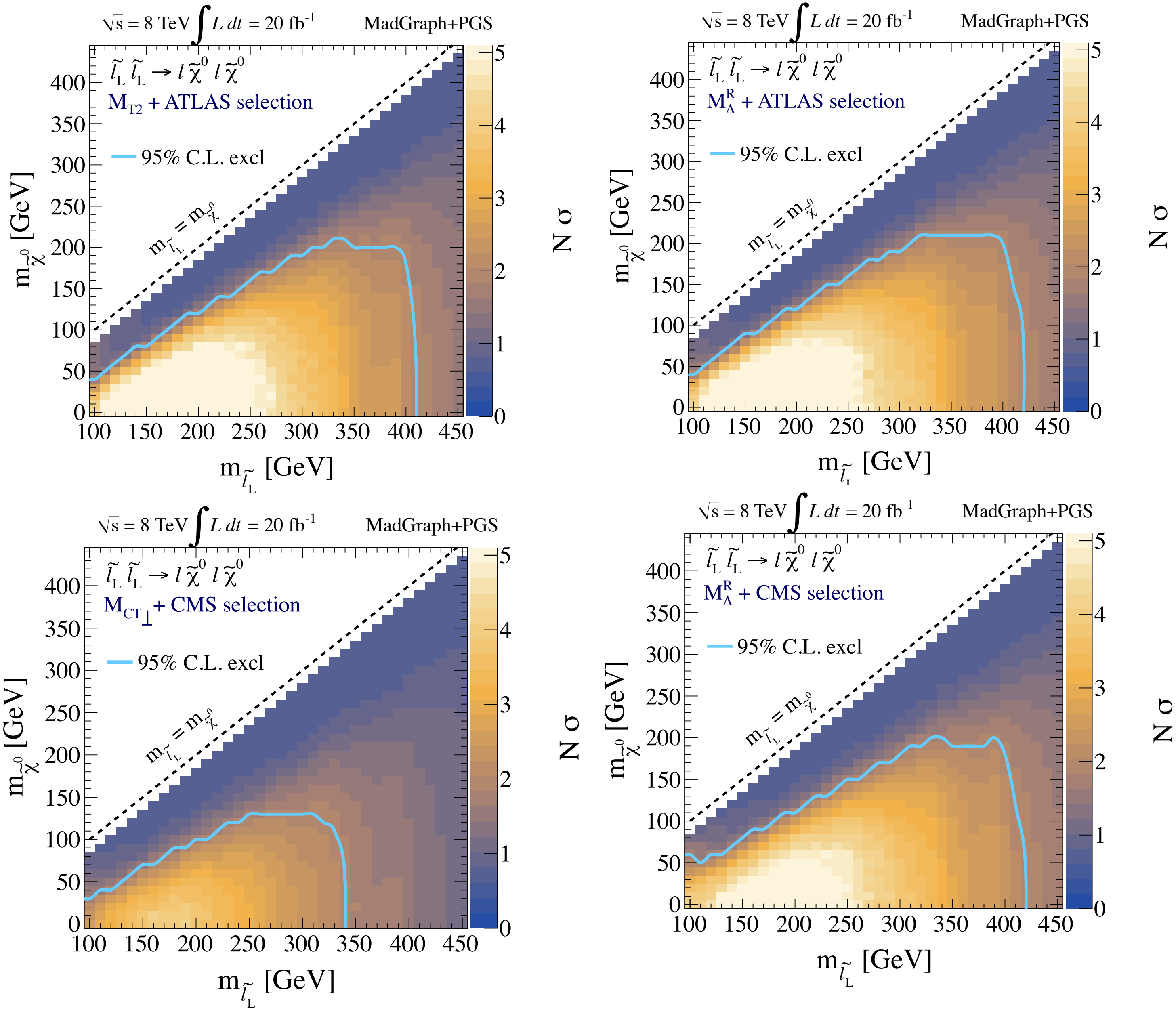


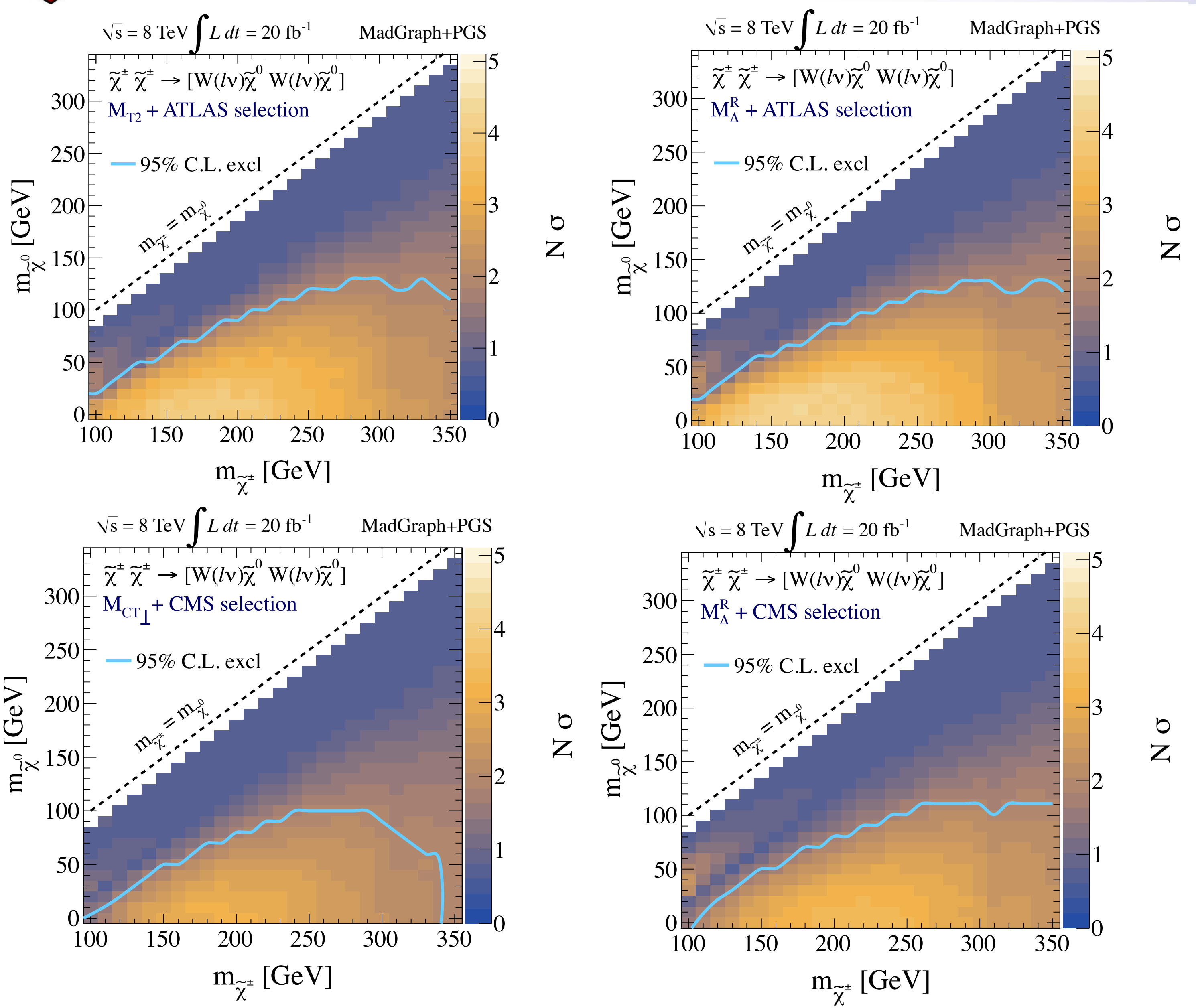
Expected Limit Comparison



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

From PRD 89, 055020 (arXiv:1310.4827)

Charginos

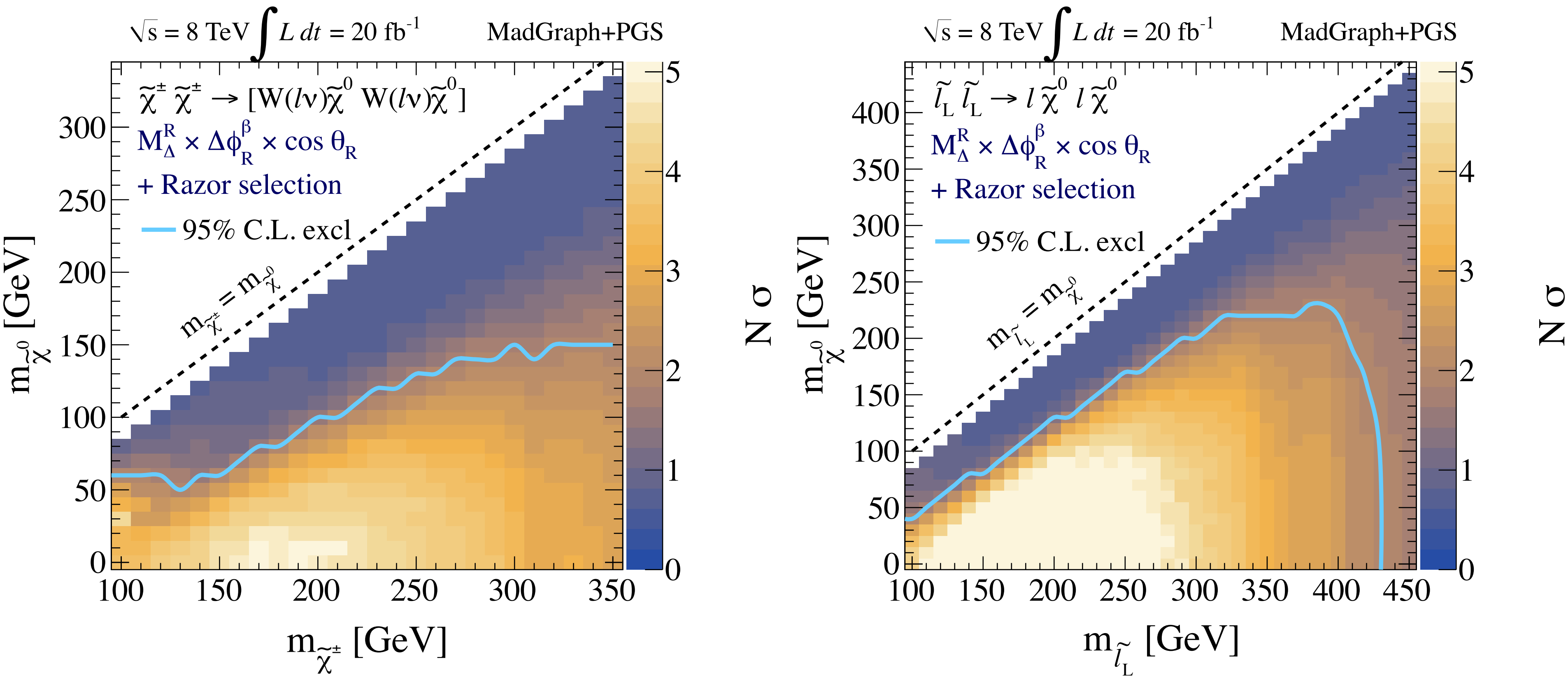


$pp \rightarrow \tilde{\chi}_1^{\mp}\tilde{\chi}_1^{\pm};\ \ \tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^{0} W^{\pm}(\ell^{\pm}\nu)$

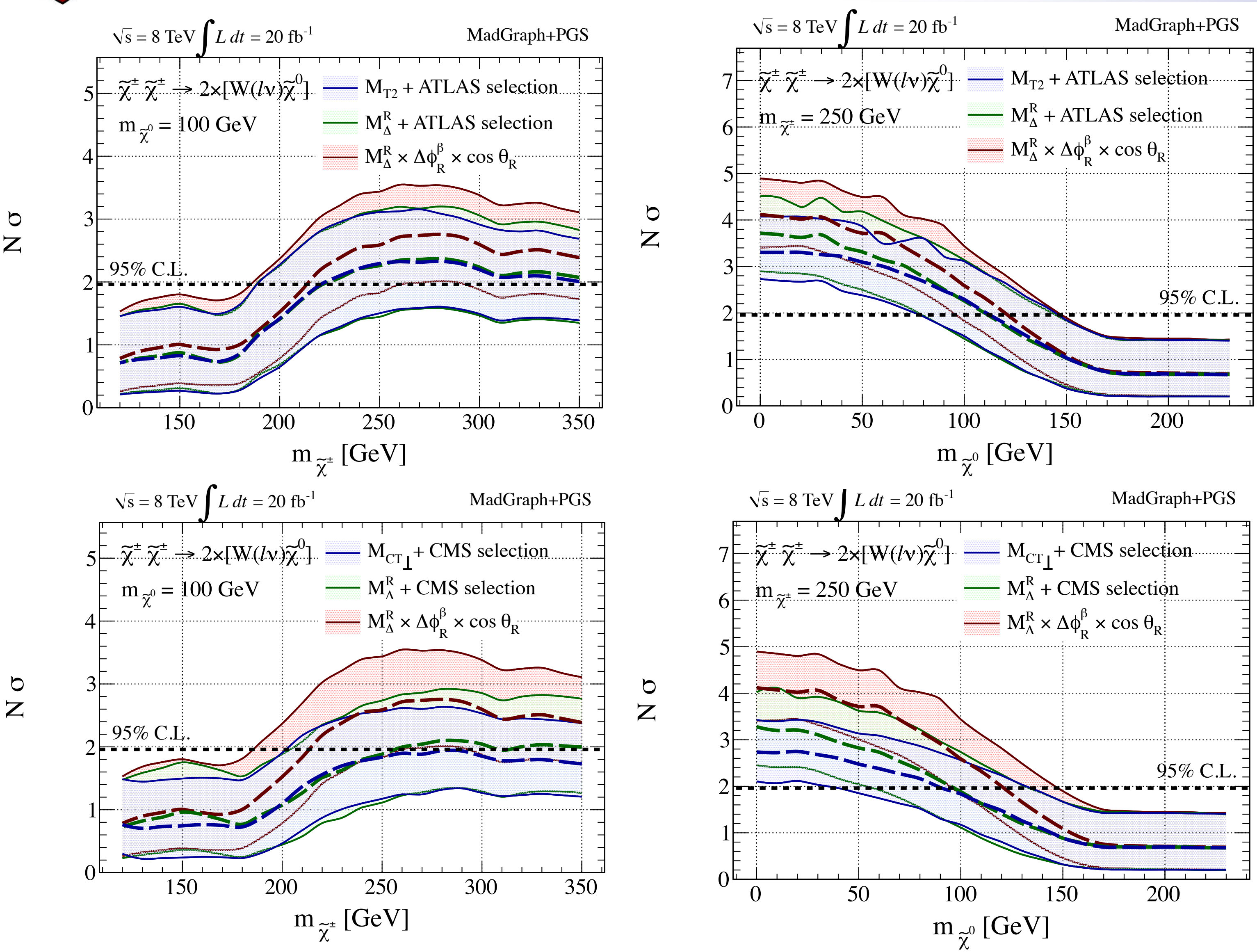
From PRD 89, 055020 (arXiv:1310.4827)

Super-Razor Basis Selection

From PRD 89, 055020 (arXiv:1310.4827 [hep-ph])



Comparisons



From PRD 89, 055020 (arXiv:1310.4827)