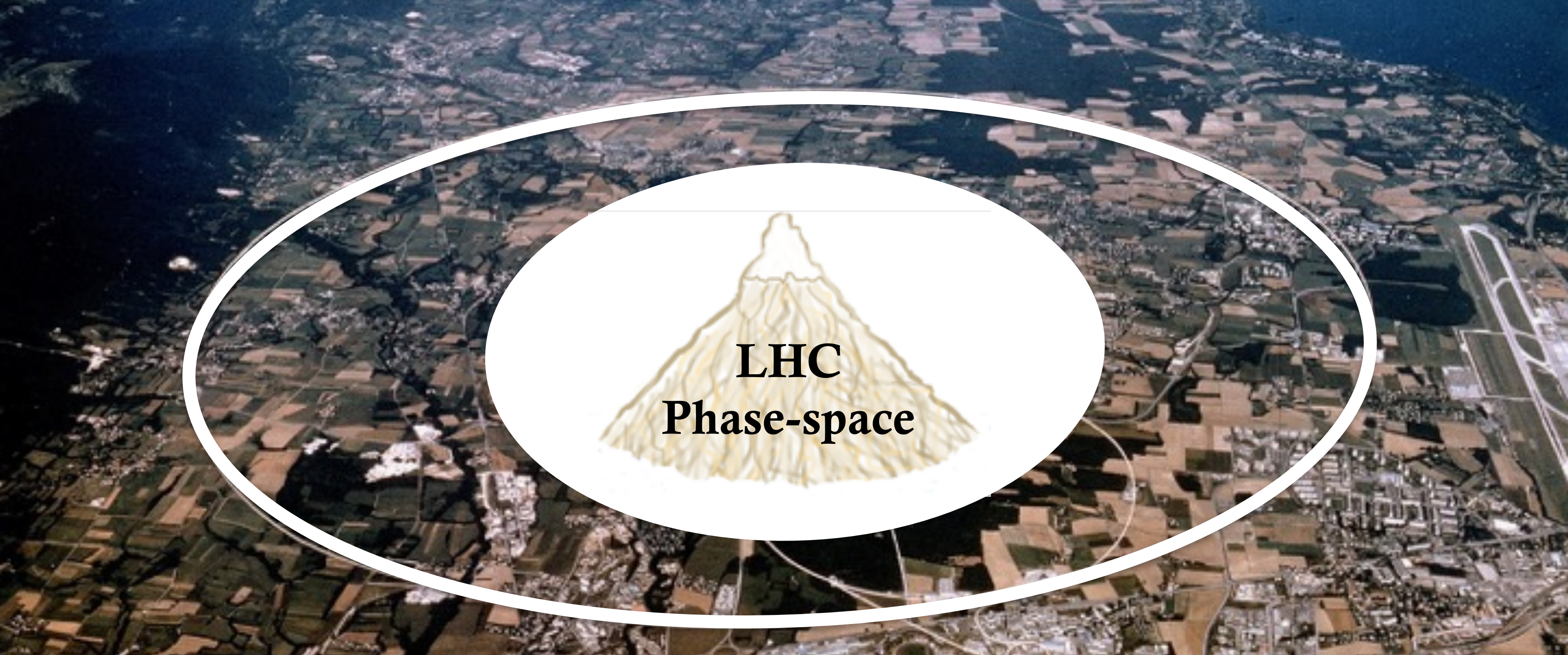


Techniques for Probing SUSY at Colliders

Christopher Rogan

HARVARD UNIVERSITY

SUSY16 - University of Melbourne - July 6, 2016

Entering the next phase of our **fantastic journey**…

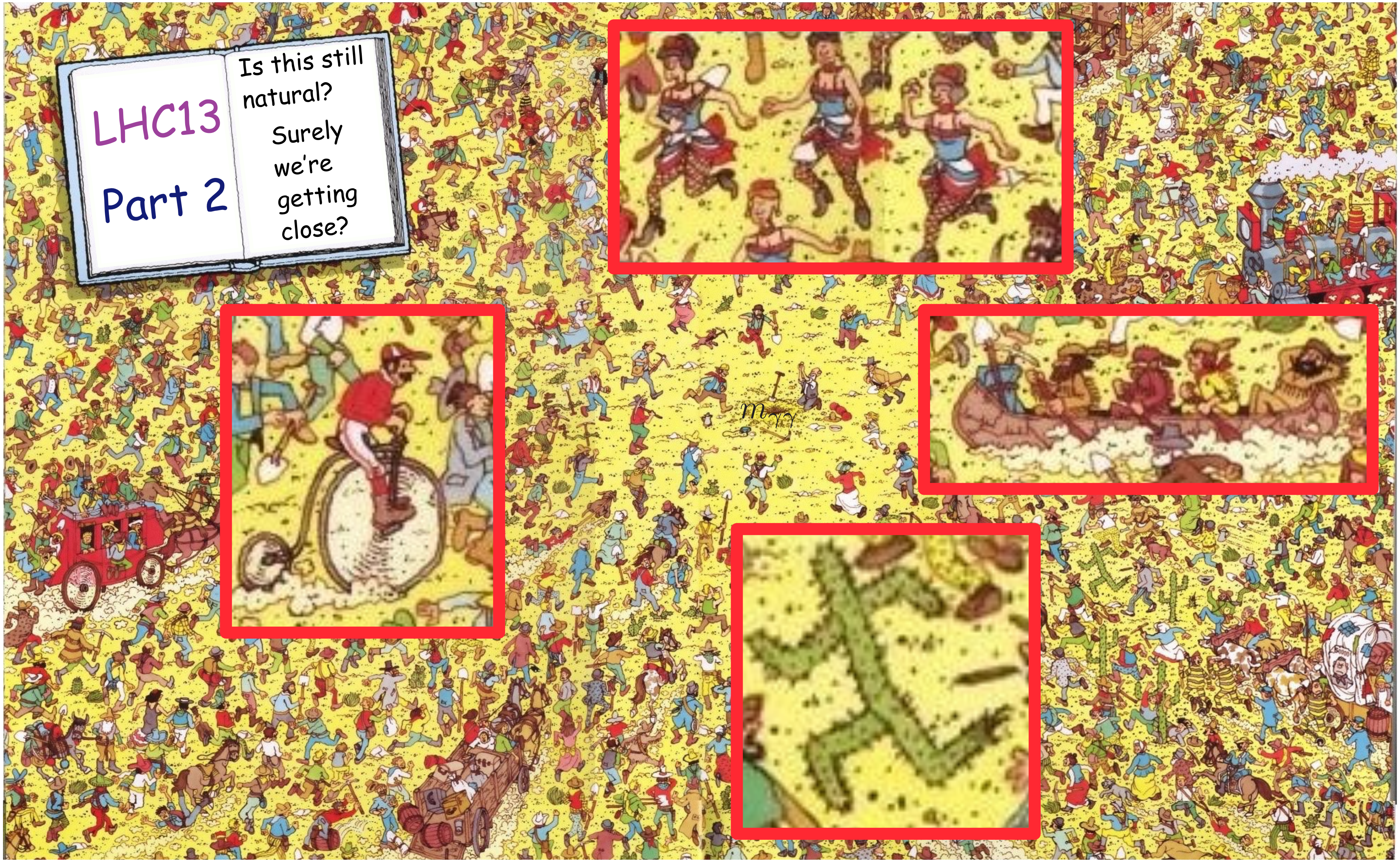
Entering the next phase of our **fantastic journey**…

Not quite the right analogy…

…"SUSY" isn't one signature that we simply look for

Rather: Is this what LHC13 is supposed to look like?…

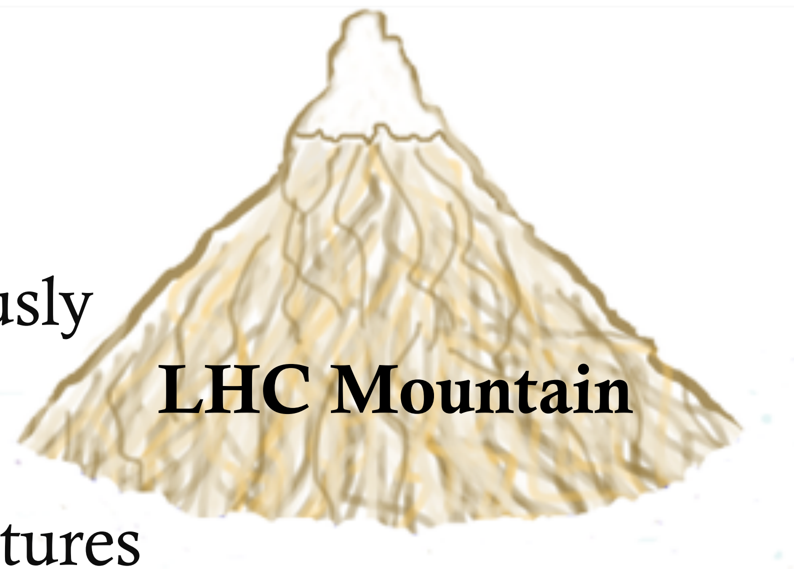
…Are our observations consistent with the SM?



Searching Collider Phase Space for **SUSY**

Less like searching for a single person

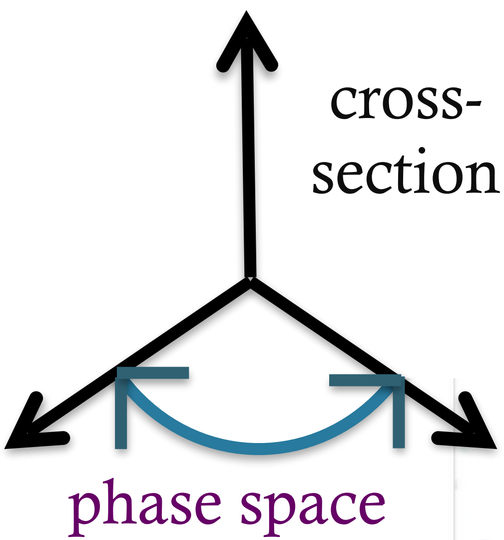
More like exploring a previously unvisited landscape, searching for new flora/fauna/geographical features

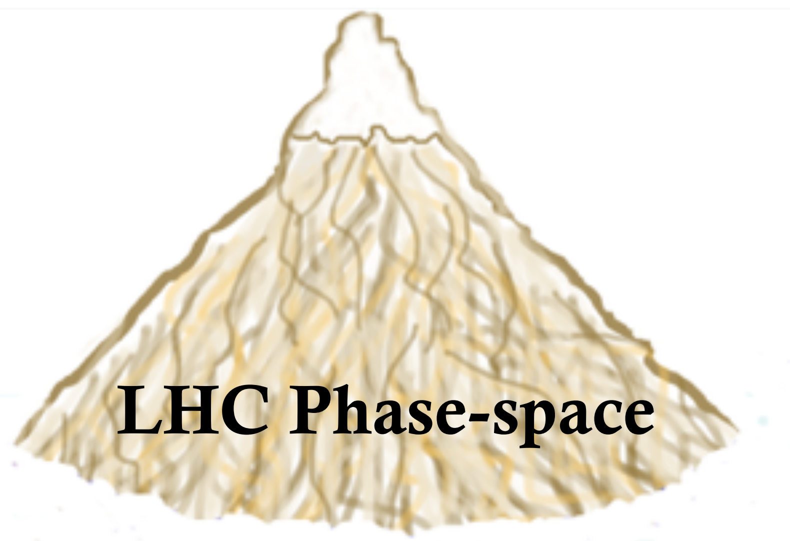


Searching Collider Phase Space for **SUSY**

The elevation represents the rate of production of different types of collision events

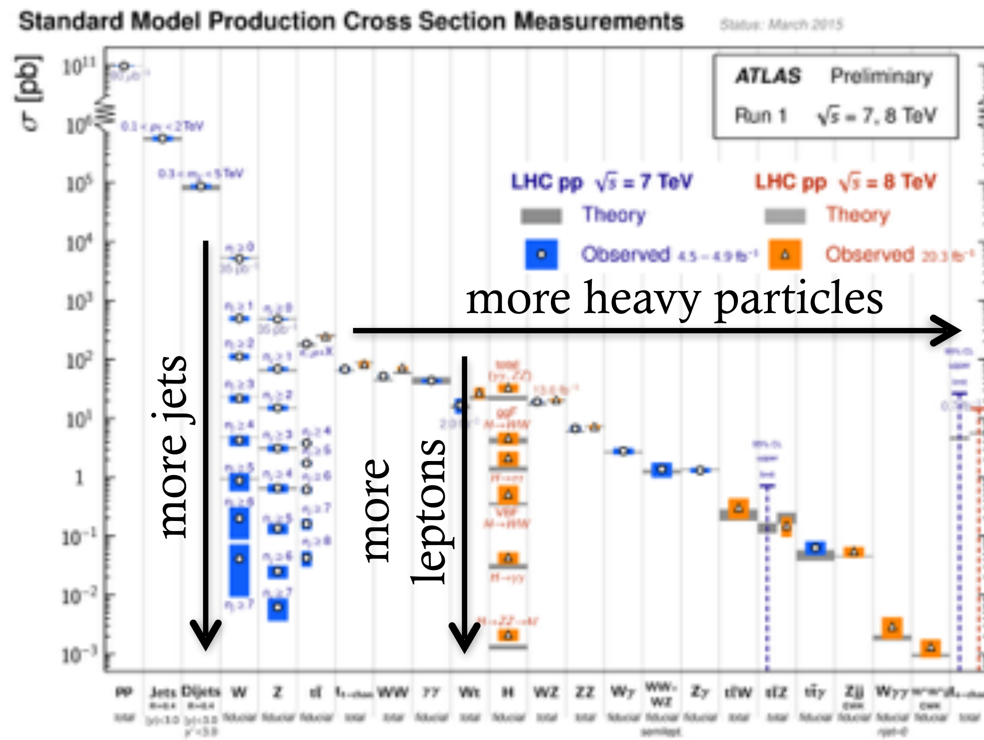
The lateral distance from the center of the mountain represents what's in those collision events, i.e. how rare they are

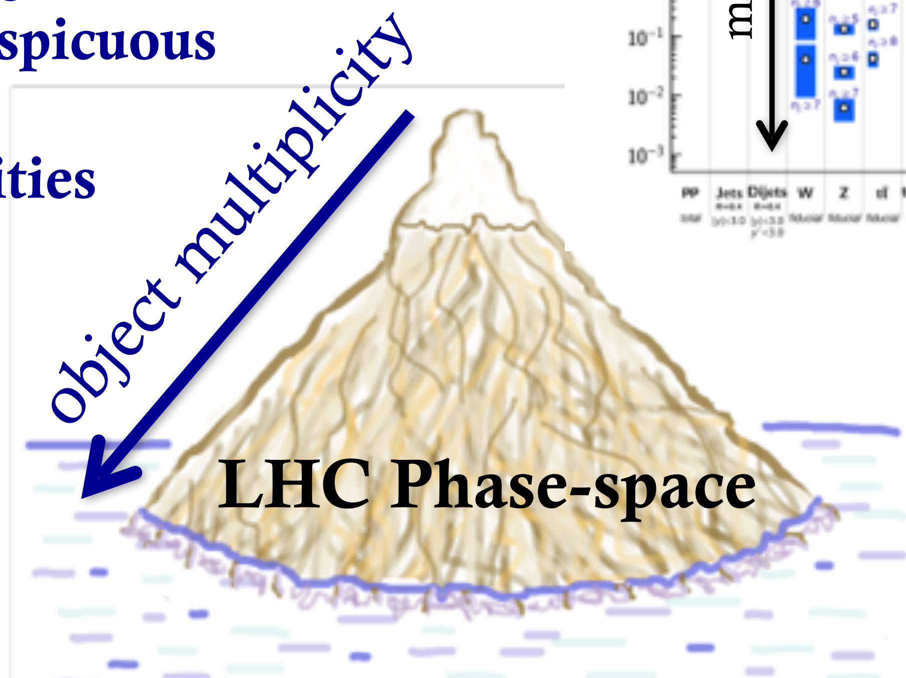




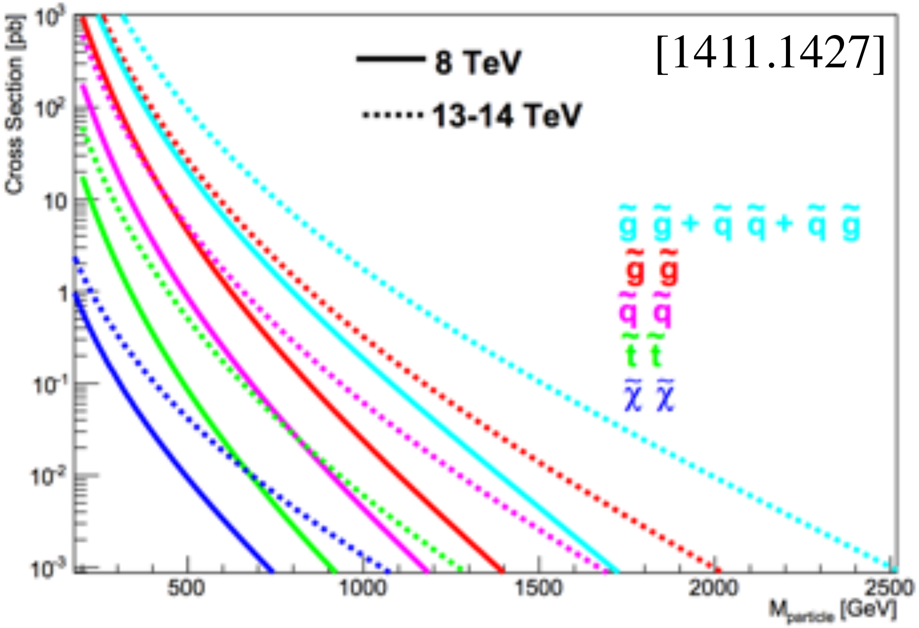
Searching Collider Phase Space for **SUSY**

- Particles decaying to **W/Z/γ/leptons/ top quarks/b-jets**
- Cascading decays through SM spectrum (BSM?) can lead to **high/conspicuous object multiplicities**



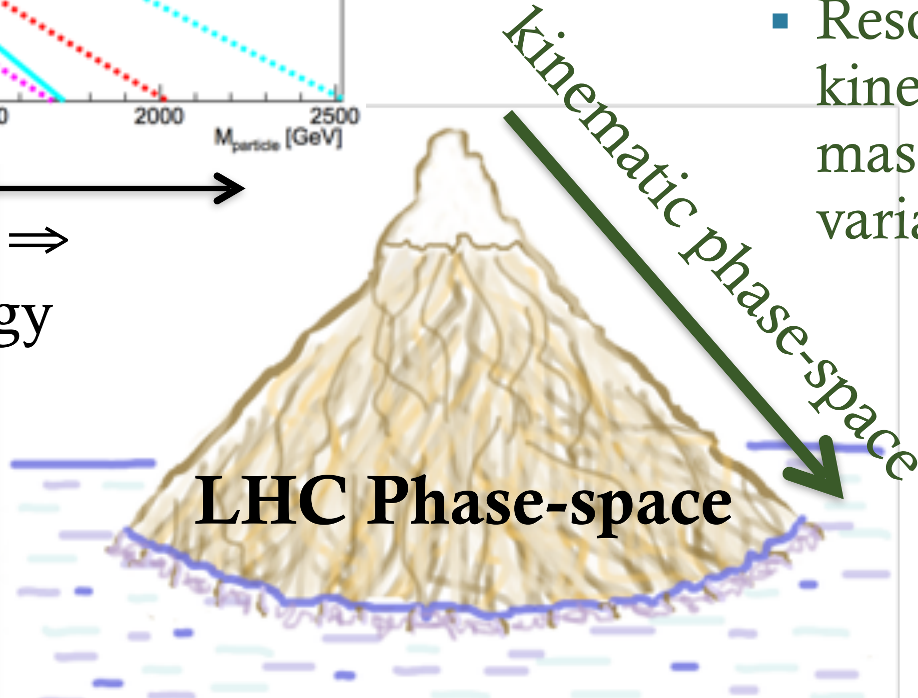


Searching Collider Phase Space for **SUSY**



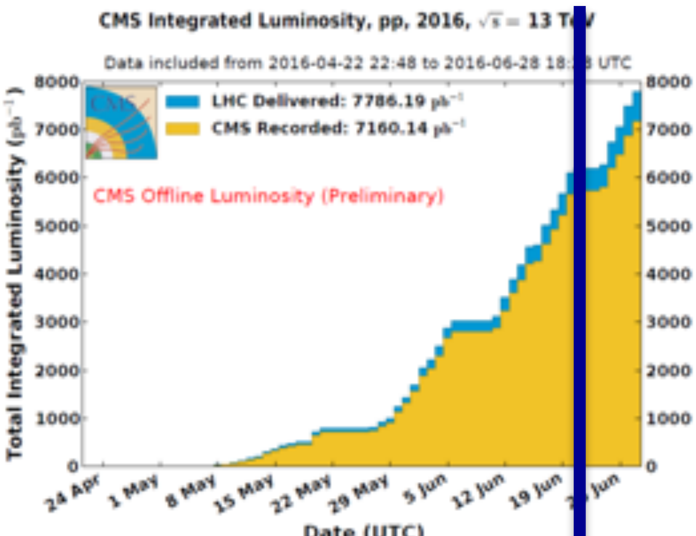
more mass ⇒
more energy

- Heavy BSM particles decaying to SM particles
  ➔ **large visible momenta**
- New symmetry conservation
  ➔ **large missing momenta**
  - Resonances, kinematic edges, mass sensitive variables…

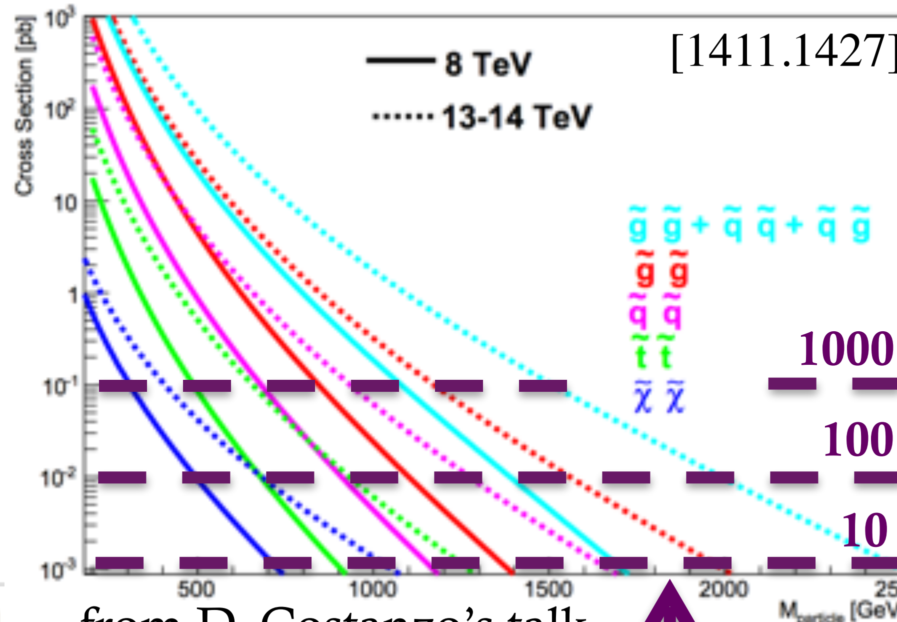


Searching Collider Phase Space for **SUSY**

more integrated luminosity (more data) reveals more of the phase-space

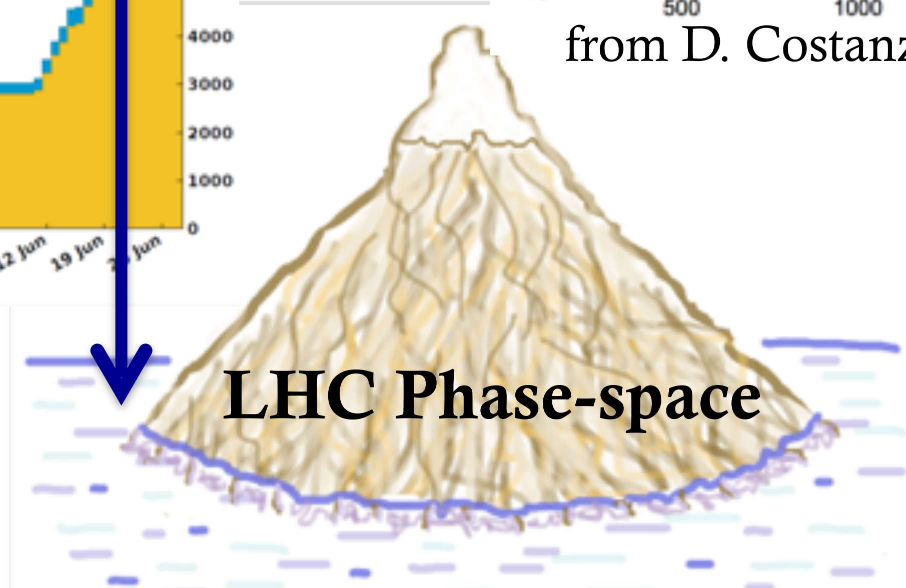


from A. Askew's talk



from D. Costanzo's talk

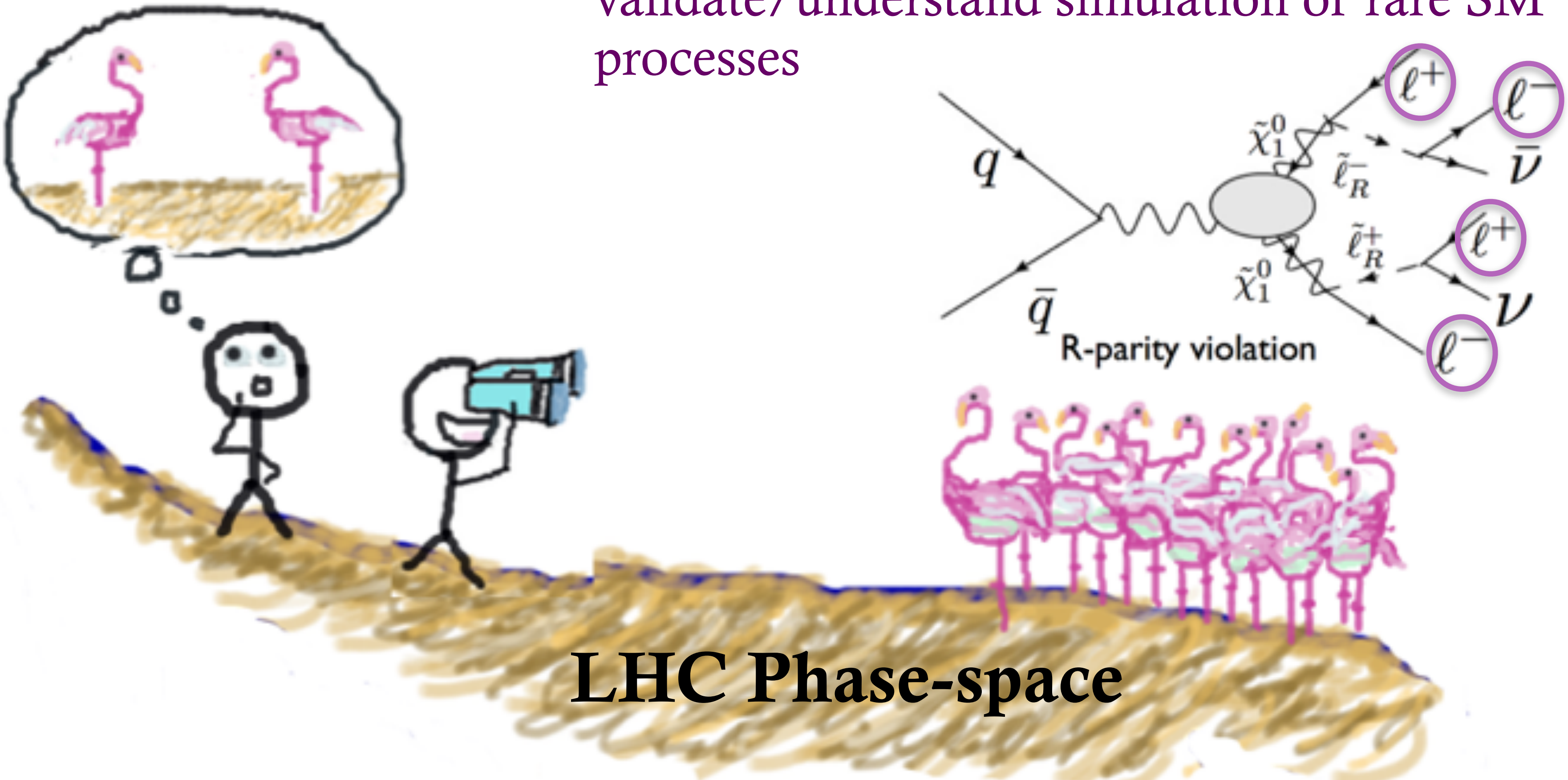
10 events produced / 10 fb^{-1}



Searching for rare events

- BSM physics can potentially produce event topologies rarely seen in the SM
- Must control/measure object fake-rates and validate/understand simulation of rare SM processes

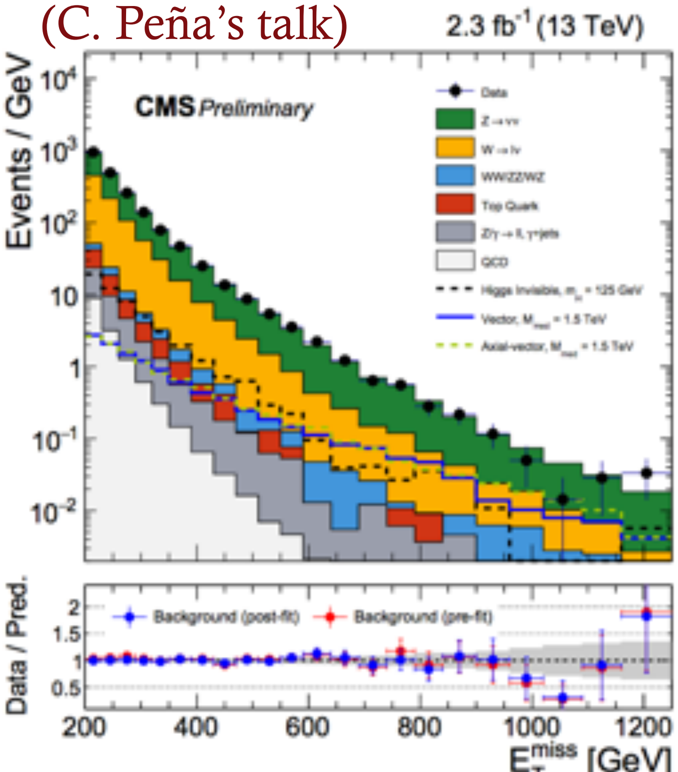
$Z + \text{jets}, ZZ, Z\gamma, WZ, \cdots$

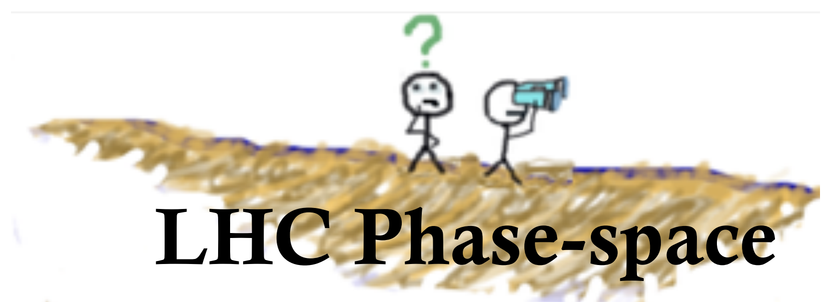


Searching for general excesses

- BSM can produce an excess of events with interesting kinematic features (large missing transverse energy, momentum, mass)
- Final states with weakly interacting particles can lead to 'broad' excesses in the tails of these kinematic distributions

CMS-EXO-16-013
(C. Peña's talk)





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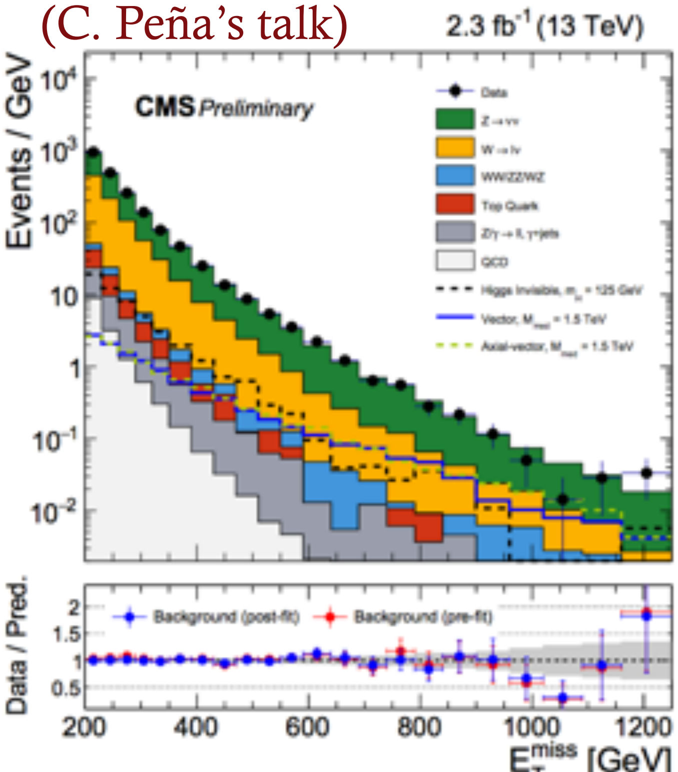
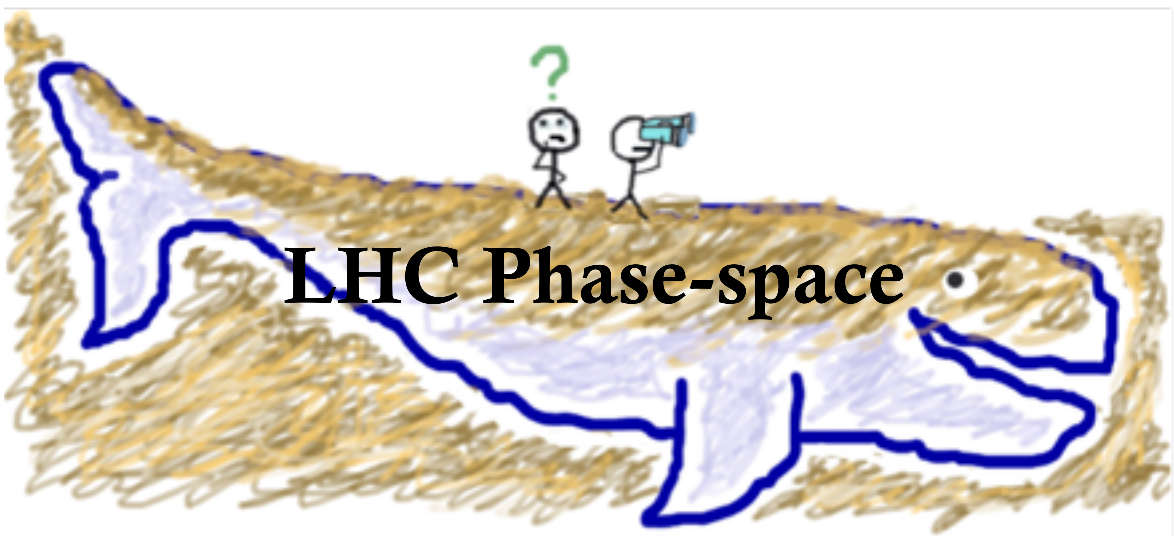
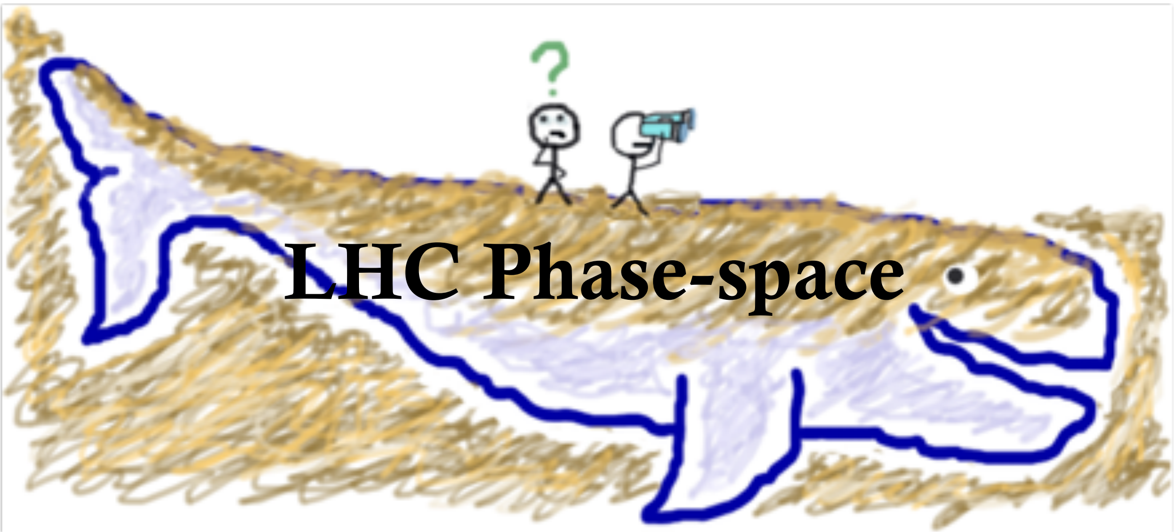


- Must have an accurate reference expectation for the SM to see subtle features!



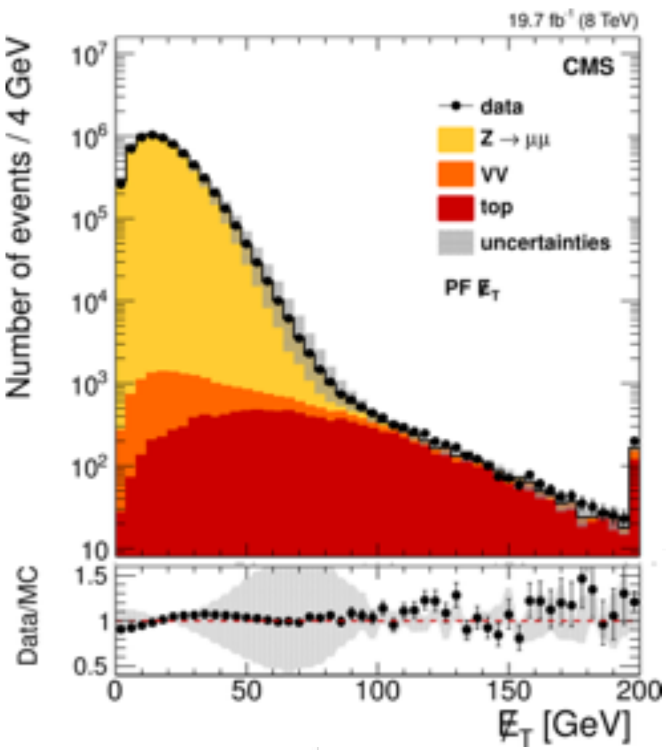
Searching for general excesses

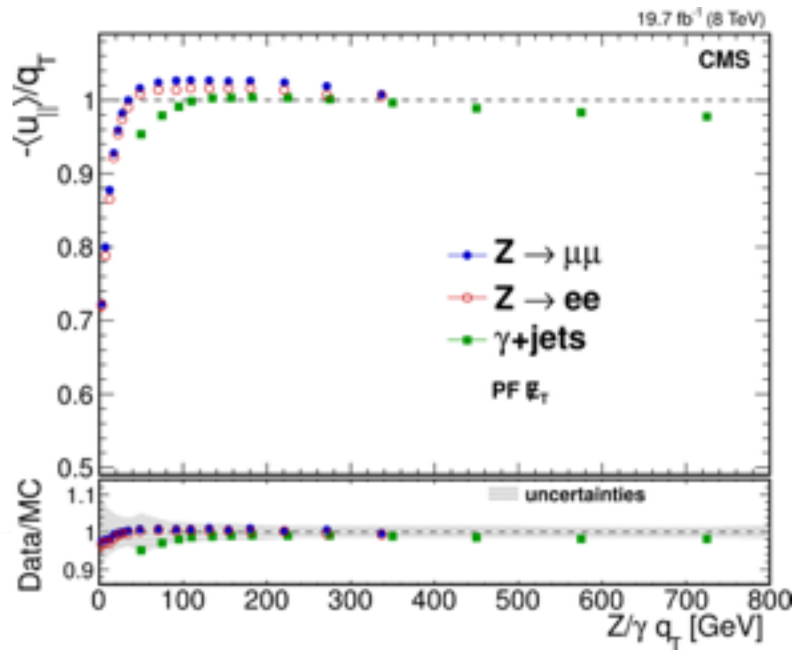
Nearby regions of phase space are often necessary to contextualize our observations in signal sensitive regions
sidebands, control regions, …



The view from the pole(s)

- SUSY searches begin at **'the pole'**: W/Z bosons, tops, quarkonia candles
- Used to: select control samples of leptons, photons, b-jets, …
  calibrate/measure object reconstruction performance, fake-rates, energy scales
  validate our understanding of the SM in new phase-space

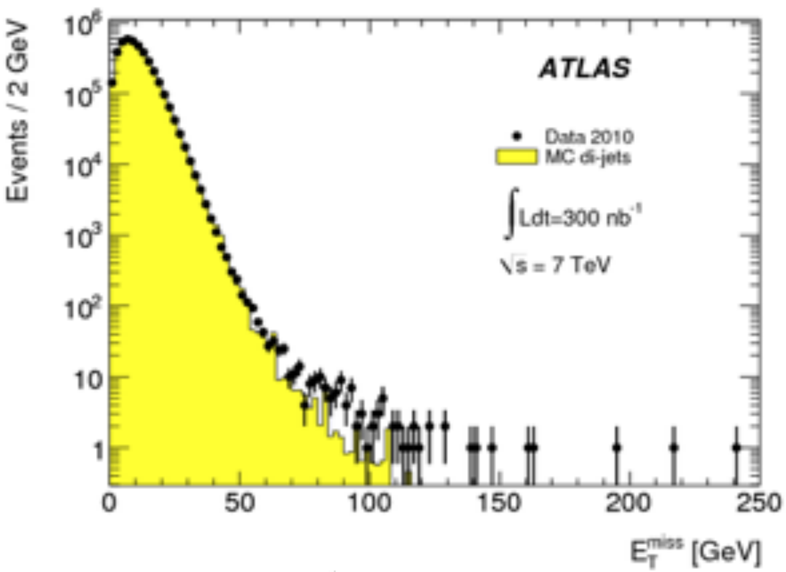


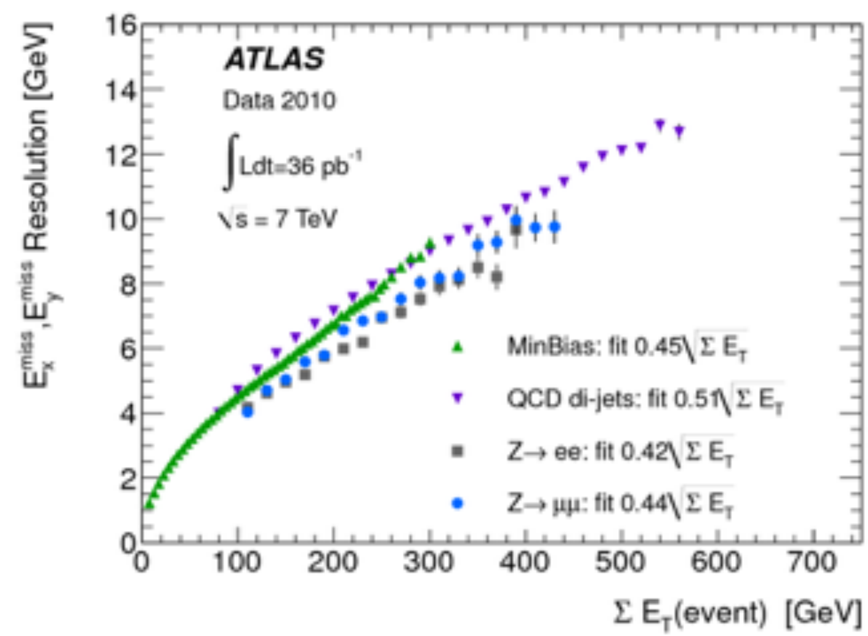


JINST 10 (2015) P02006

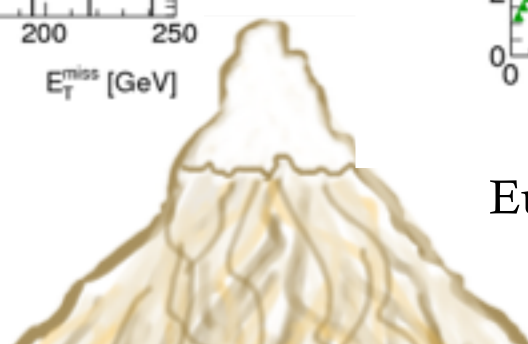
The view from the peak

- BSM searches begin at **'the rate peak'**: **QCD mult-ijets**
- Used to:
  - select control samples of leptons, photons, b-jets, …
  - calibrate/measure object reconstruction performance, fake-rates, energy scales
  - **validate our understanding of the SM in new phase-space**





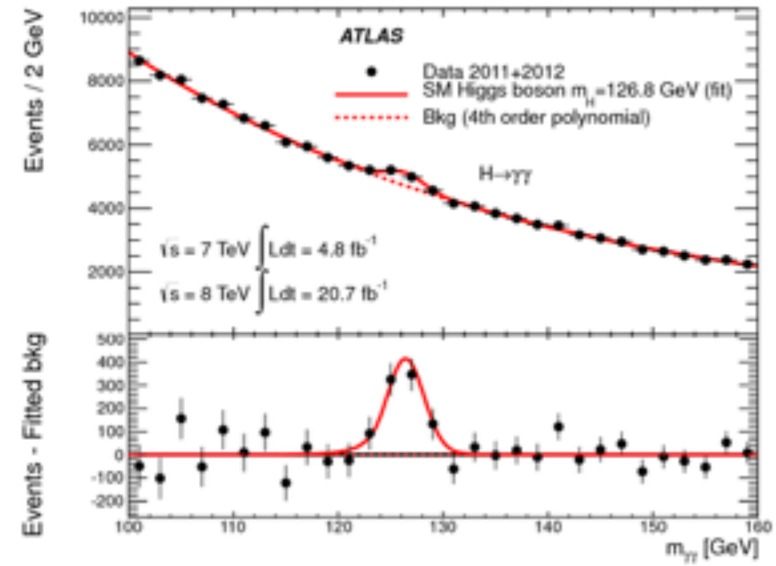
Eur.Phys.J. C72 (2012) 1844

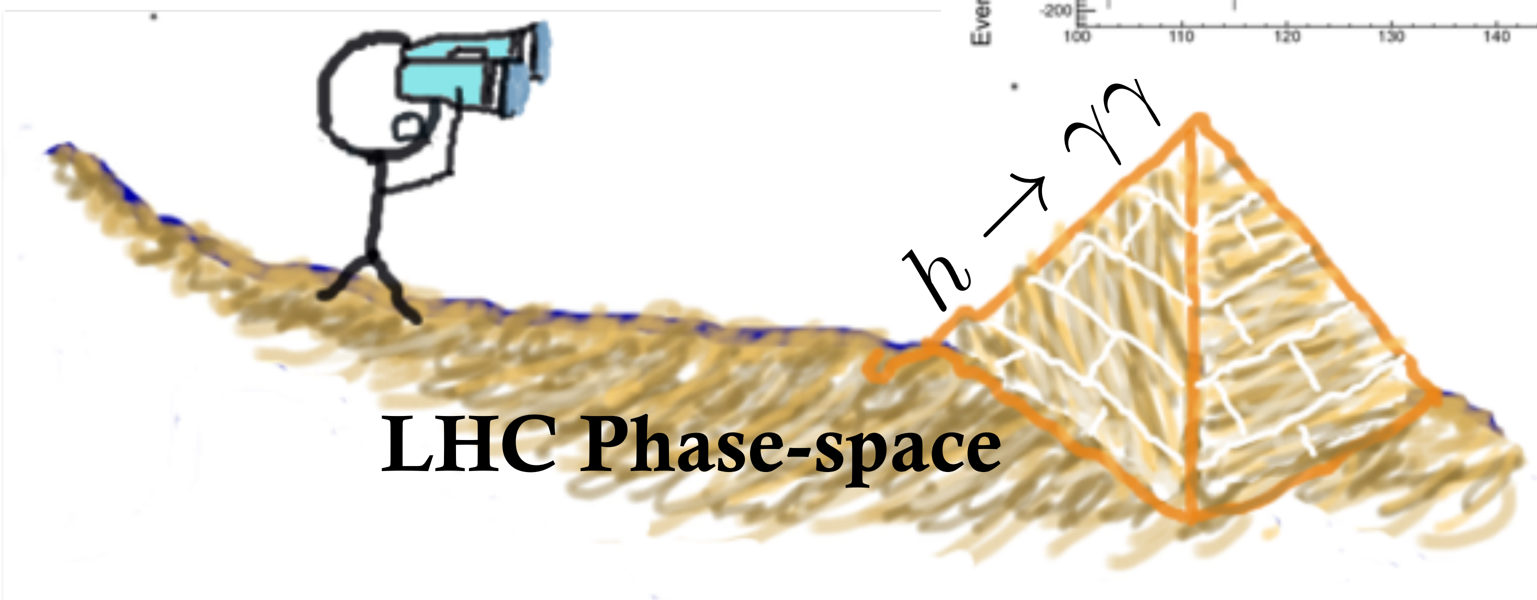


Searching for kinematic features

- New physics can produce kinematic features that are not expected in the SM – bumps, edges…
- Understanding/measuring/improving physics object reconstruction essential for being able to resolve these features

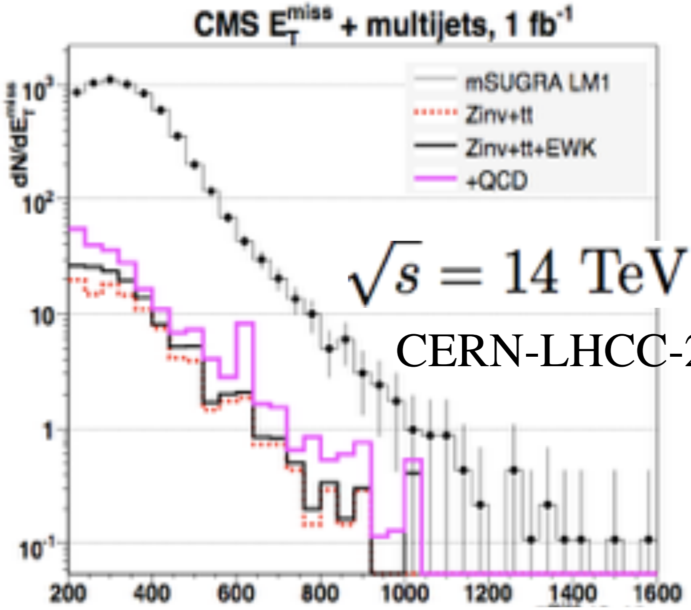
Phys. Lett. B 726 (2013), pp. 88-119





Missing transverse energy

Two plots from my SUSY10 conference talk…



$\sqrt{s} = 14$ TeV MC

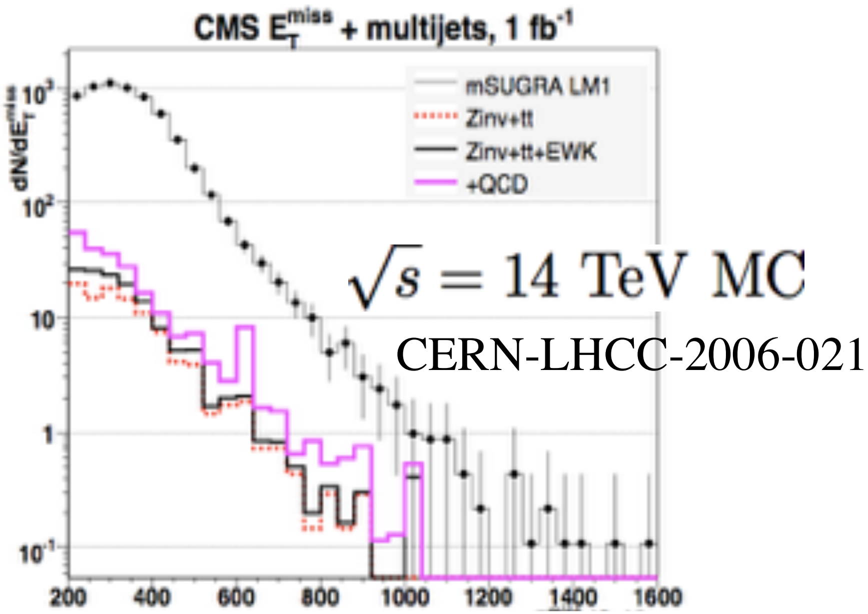
CERN-LHCC-2006-021

Missing transverse energy [GeV]

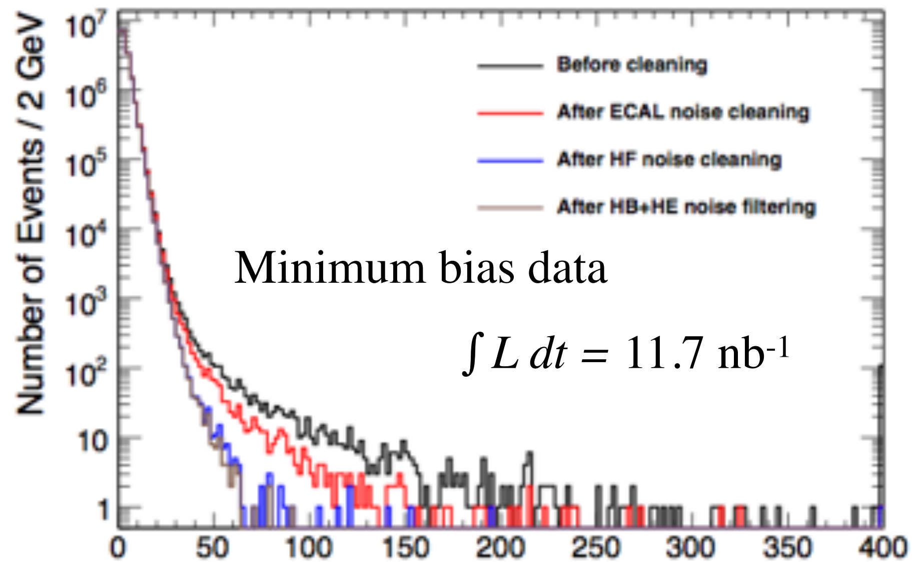
we turned the LHC on in 2010 hoping to see this…

Missing transverse energy

Two plots from my SUSY10 conference talk…



Missing transverse energy [GeV]

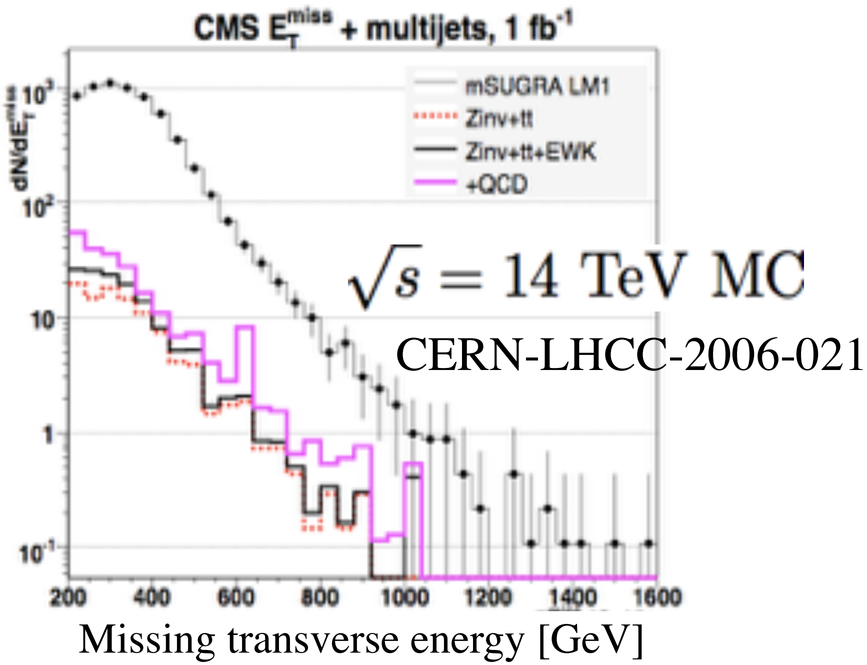


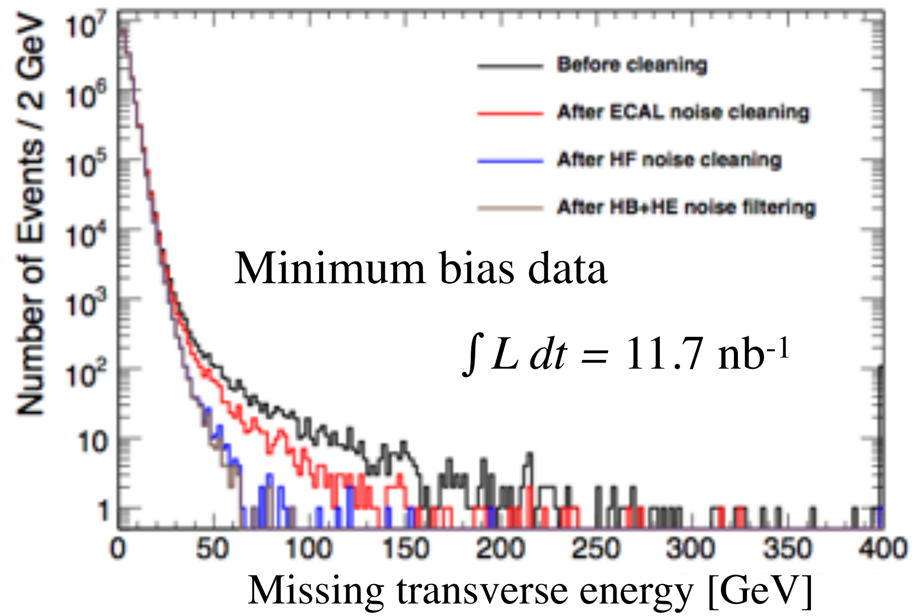
Missing transverse energy [GeV]

…and we got this

Missing transverse energy

Two plots from my SUSY10 conference talk…

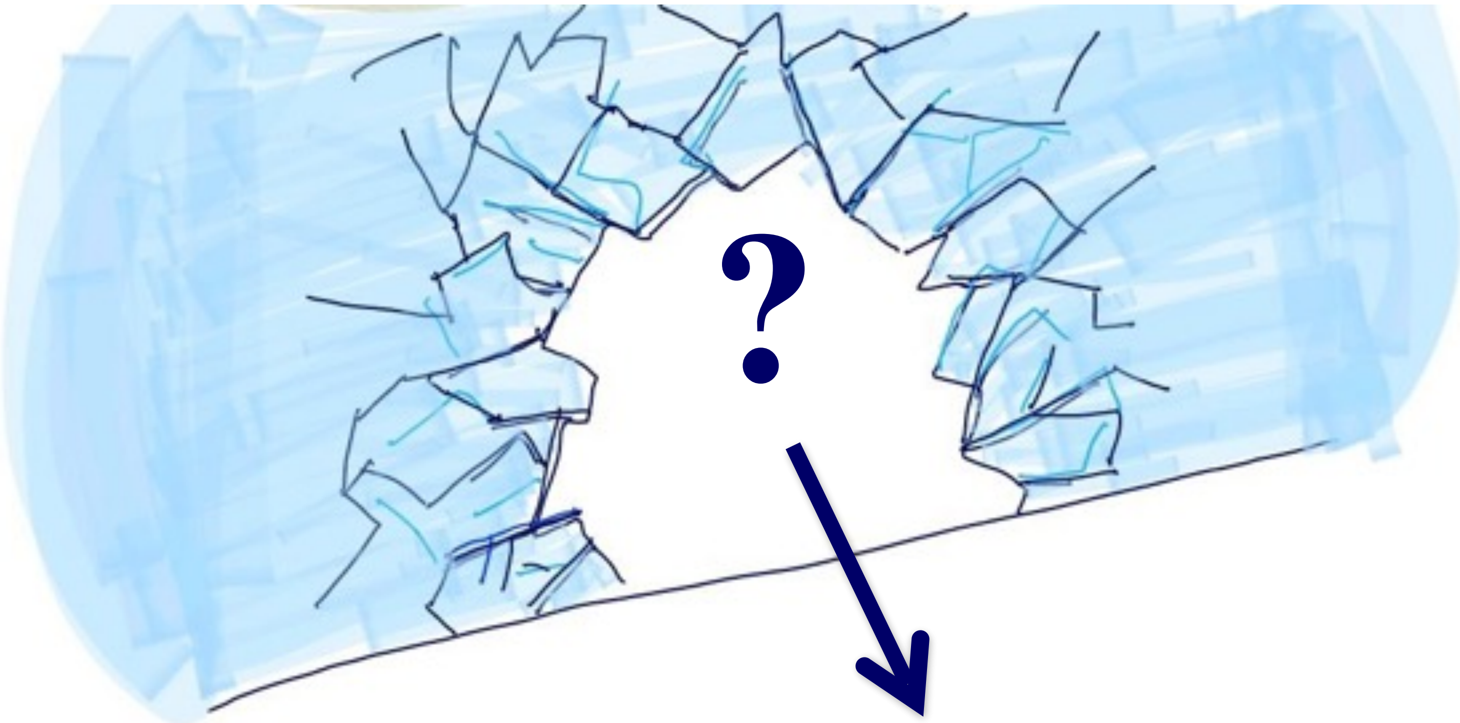




Missing transverse energy is a powerful observable for inferring the presence of weakly interacting particles in events…

…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…

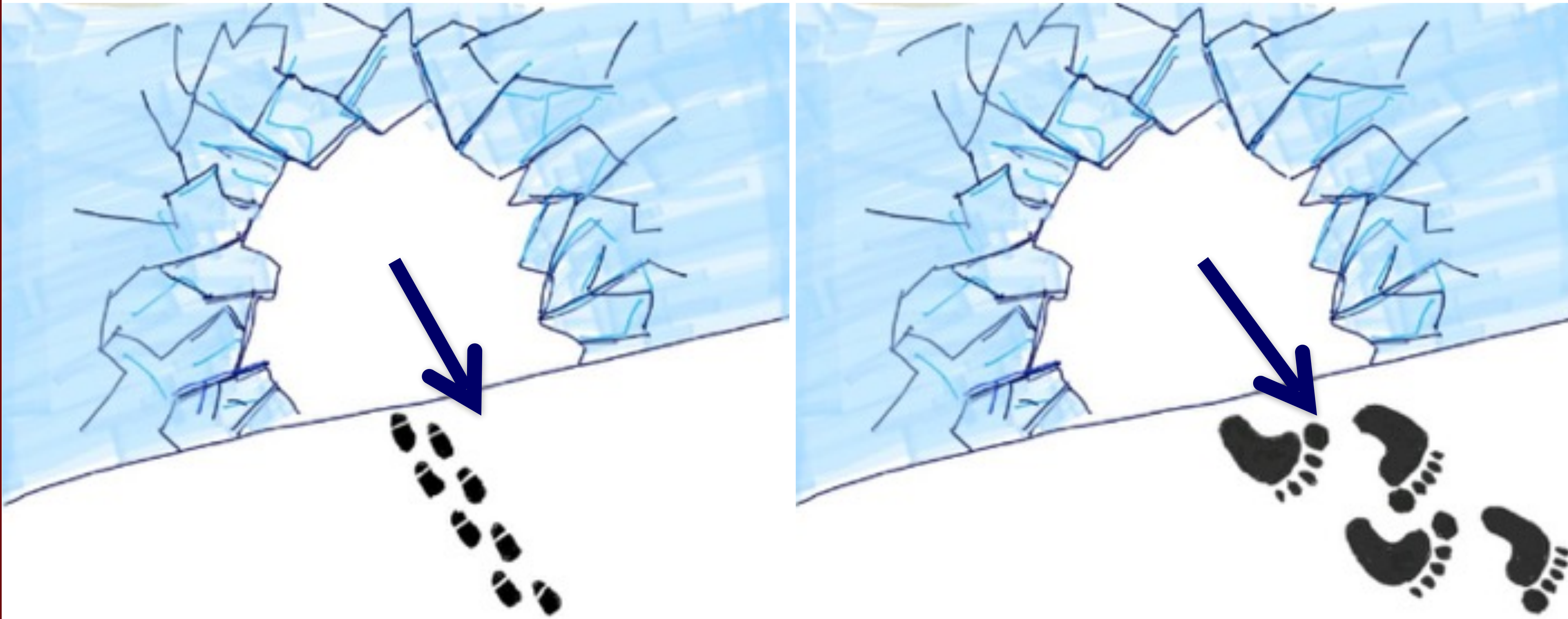
Missing Transverse Energy

…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…

Missing Transverse Energy

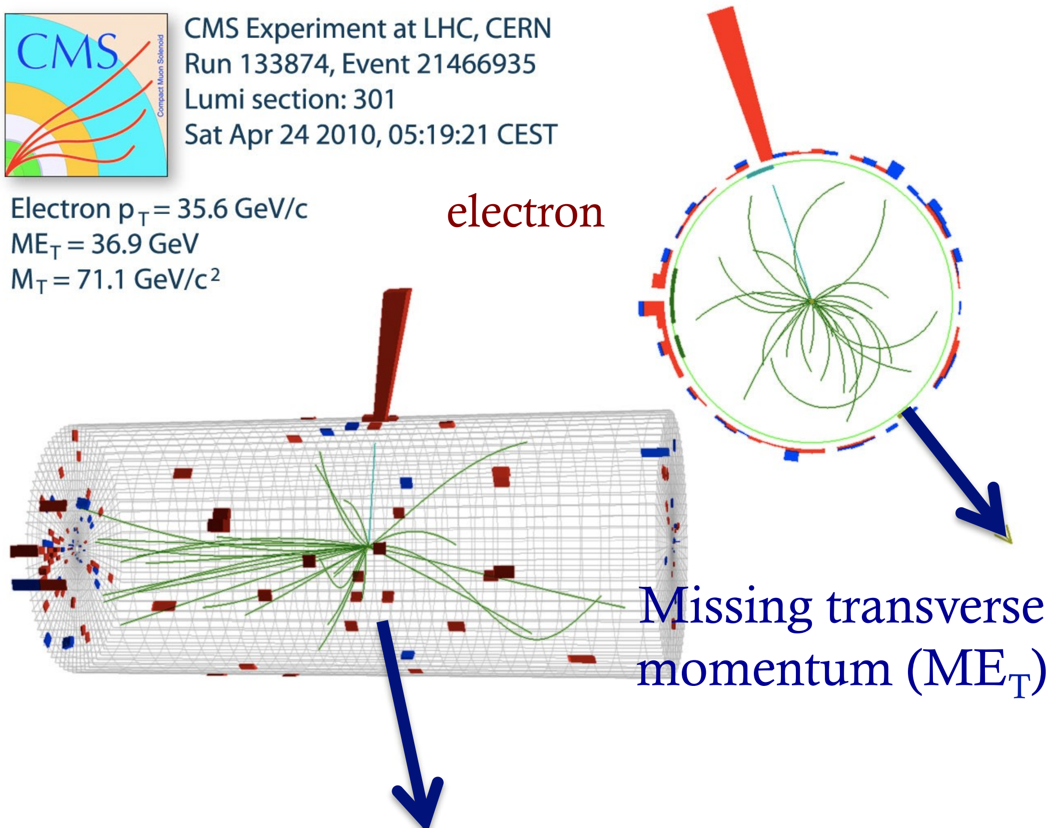
…not about the identity or mass of weakly interacting particles, or about the particle(s) they may decay from…

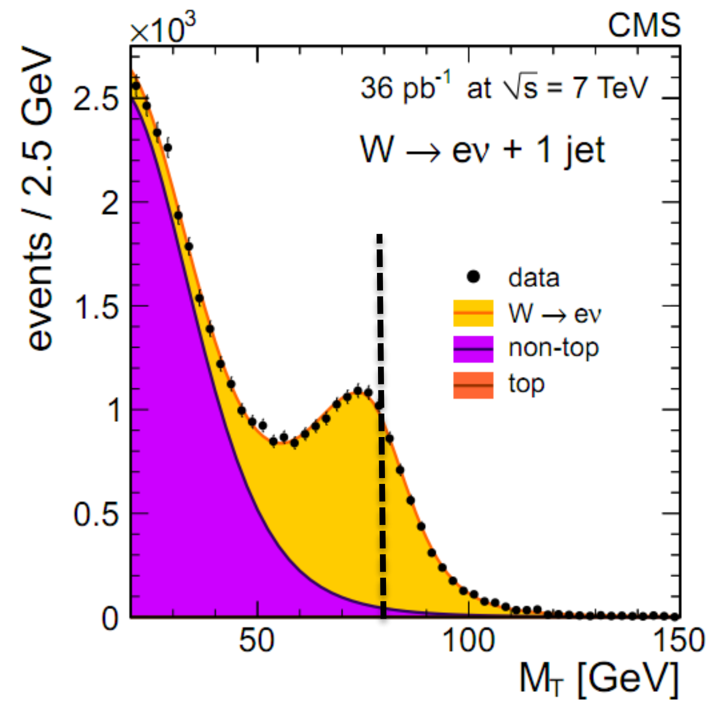
Missing Transverse Energy



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

Resolving the invisible $W(e\nu)$



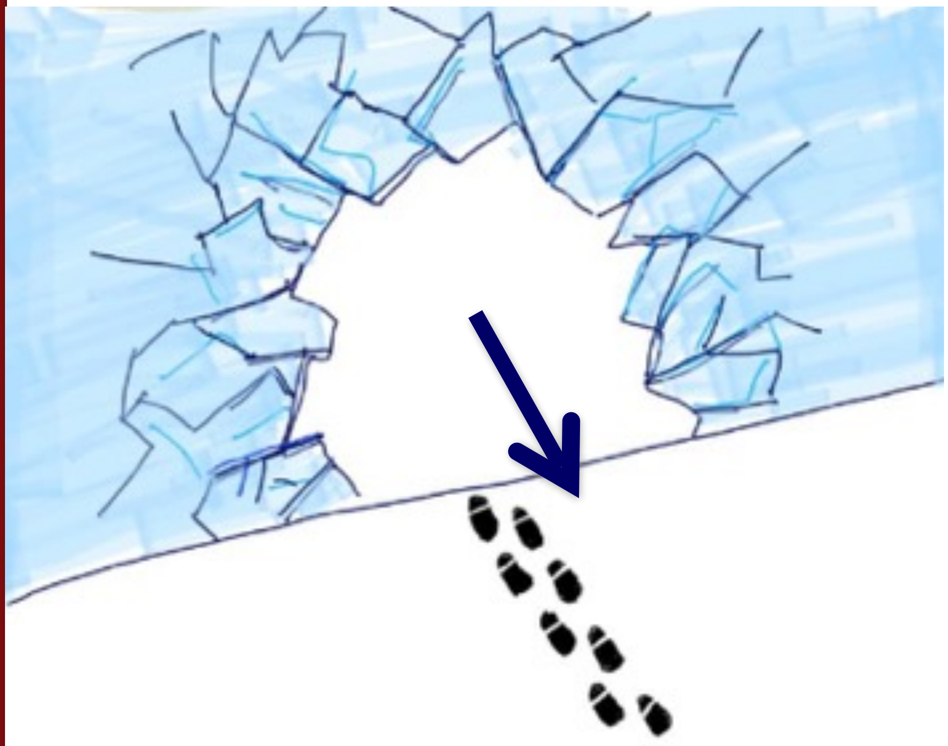


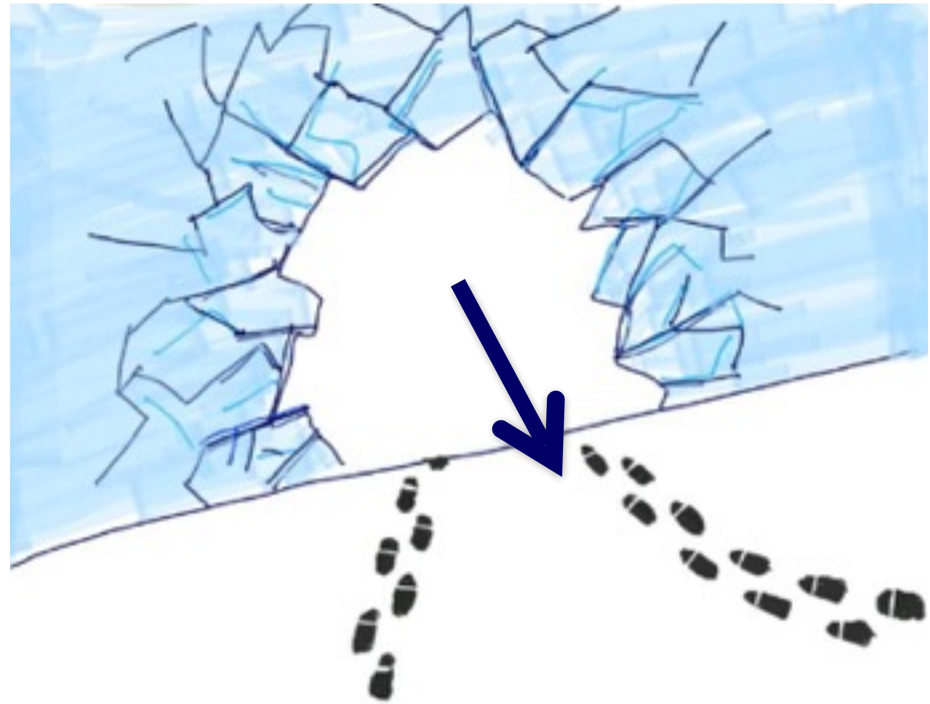
$$\boxed{m_T = \sqrt{2p_T^e p_T^\nu (1 - \cos\phi)}}$$

$m_T(\ell\nu)$ has kinematic *edge* at $m_W \sim 80$ GeV

Can use visible particles in events to contextualize missing transverse energy and better resolve mass scales

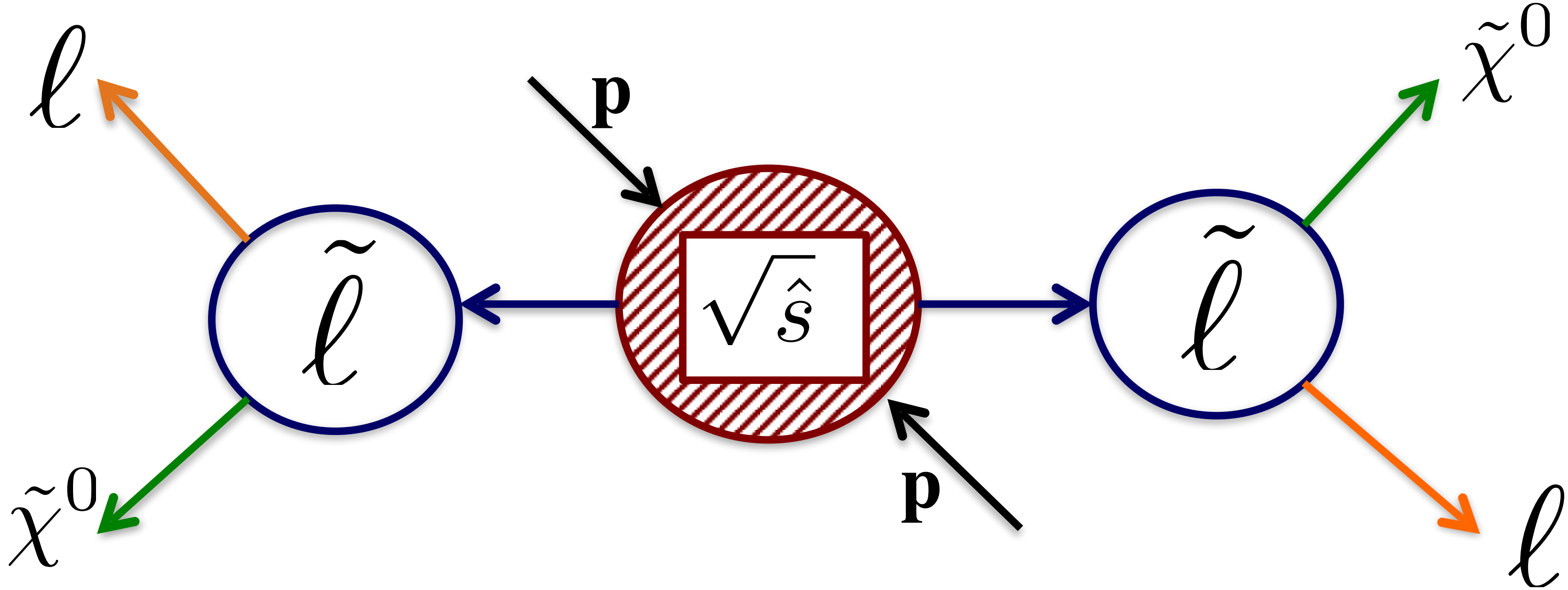
Missing Transverse Energy





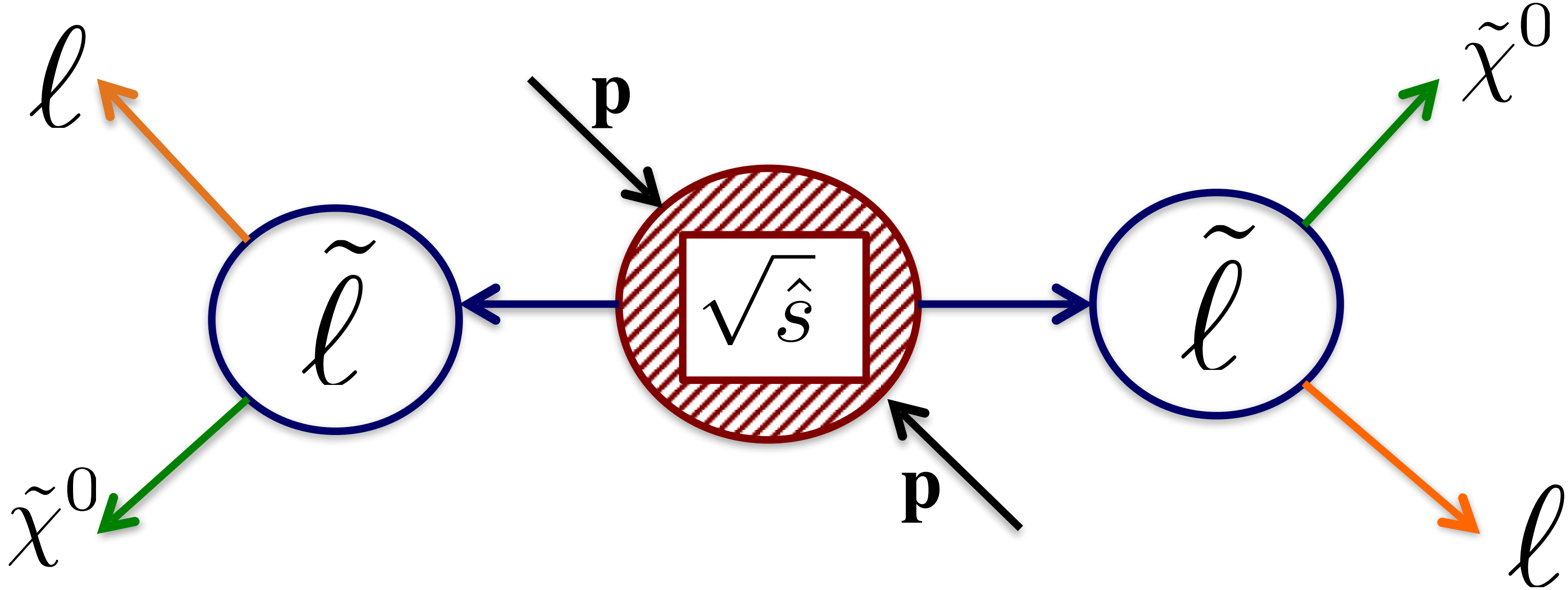
We can learn more by using other information in an event to contextualize the missing transverse energy $\Rightarrow$
what about multiple weakly interacting particles?

Example: slepton pair-production

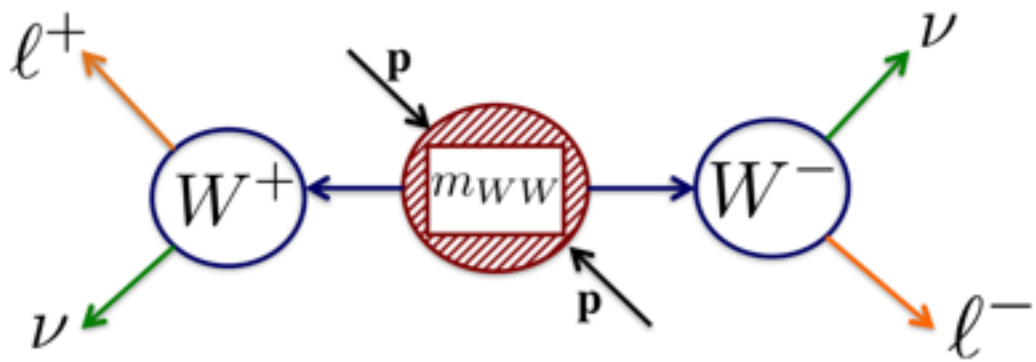


Experimental signature: di-lepton final states with missing transverse momentum

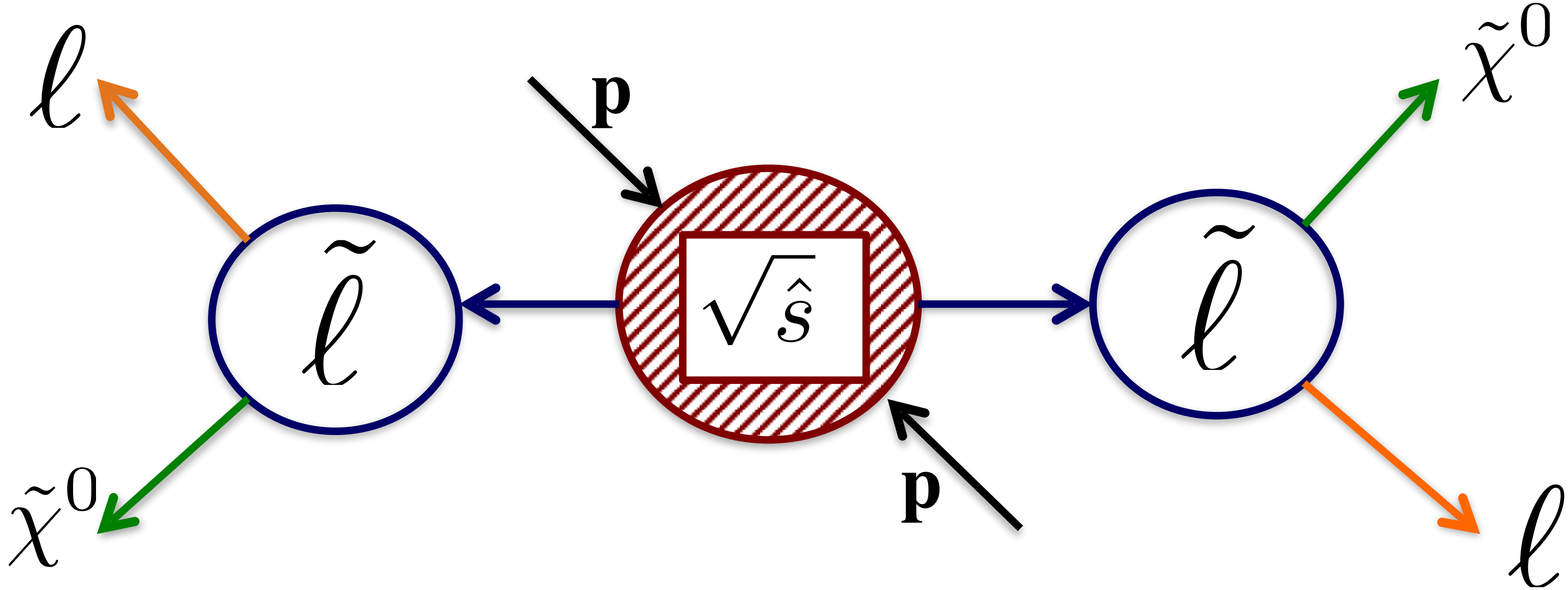
Example: slepton pair-production



Main background:



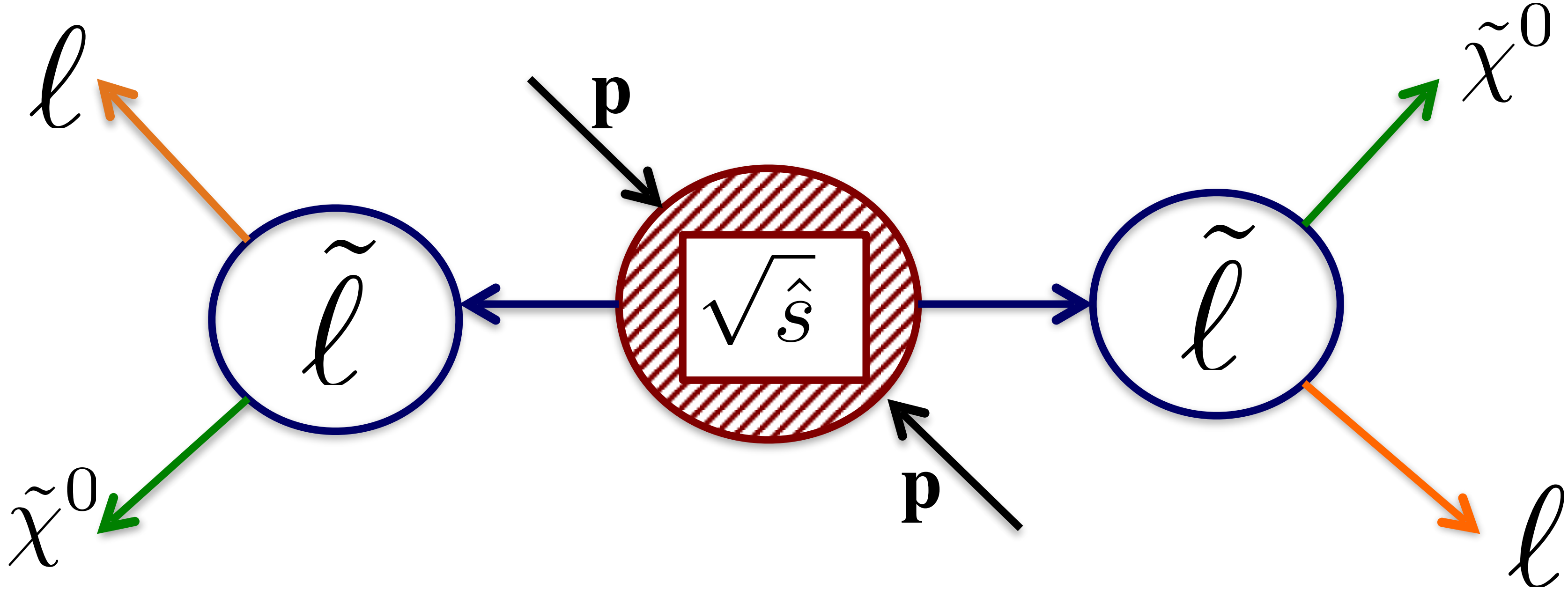
Example: slepton pair-production



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

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

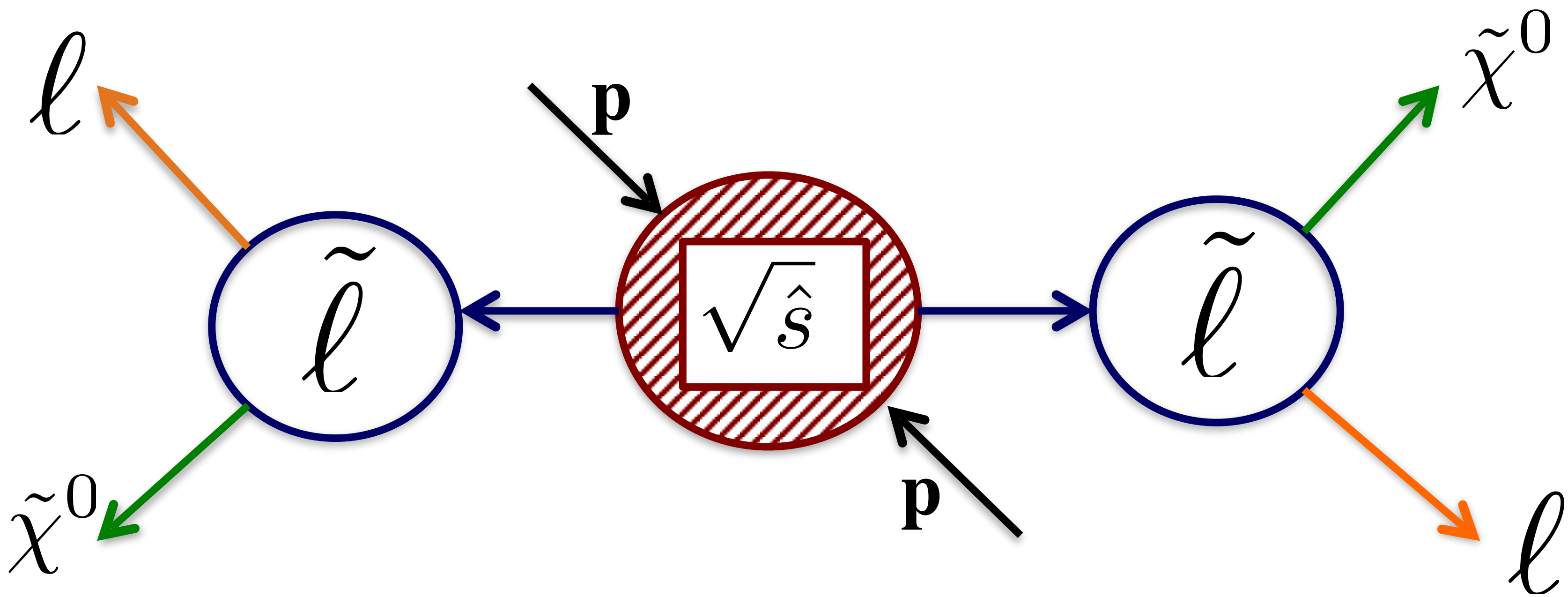
Example: slepton pair-production



What information are we missing?

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

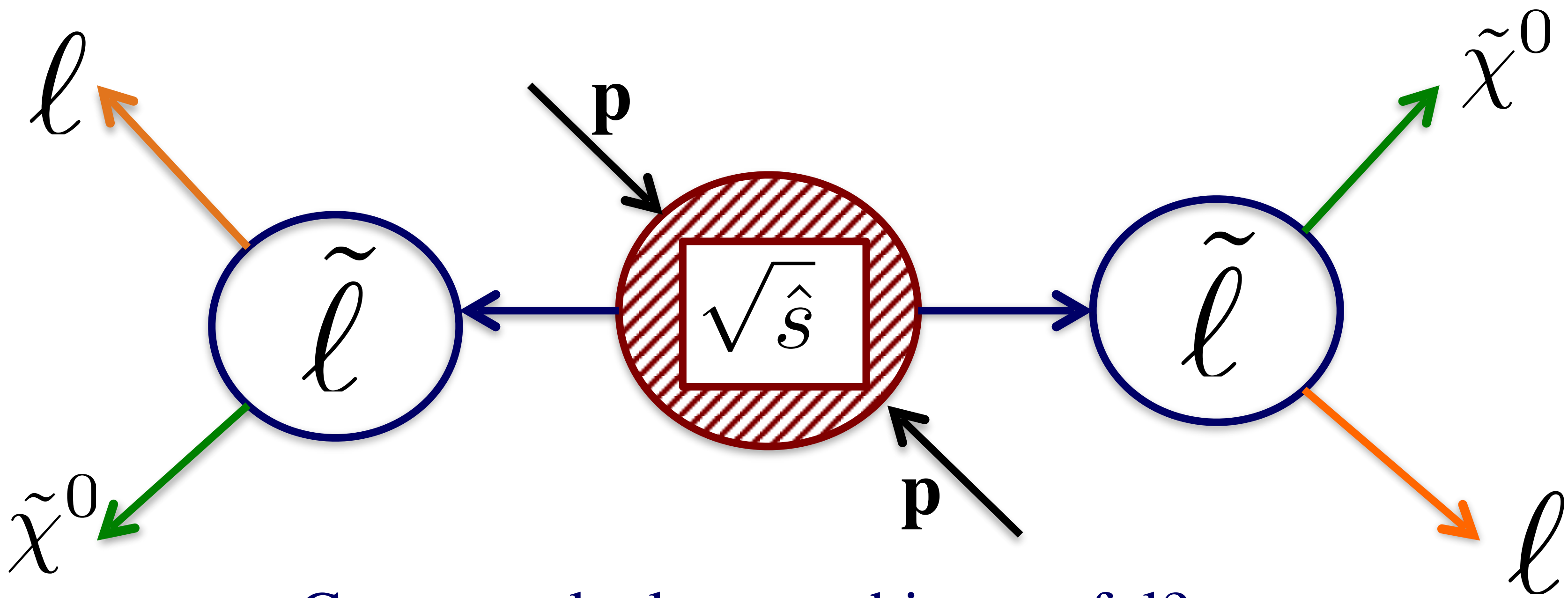
Example: slepton pair-production



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…

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

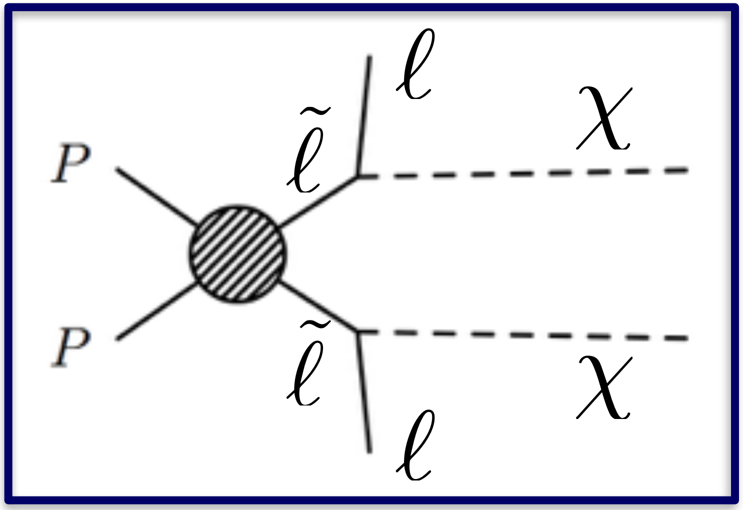
…we are still 4 d.o.f. short of reconstructing any masses of interest

‘Singularity’ Mass 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



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

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

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.

Singularity Variable Example: M_{T2}

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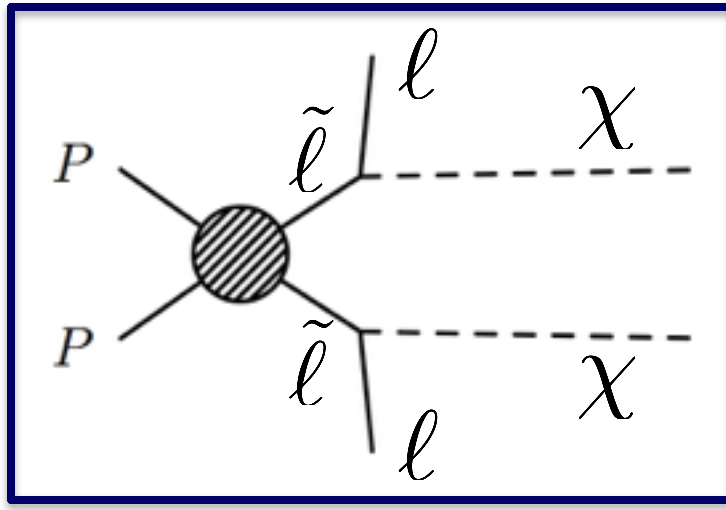

LSP 'test mass'

Extremization over under-constrained d.o.f.

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

Subject to constraints

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

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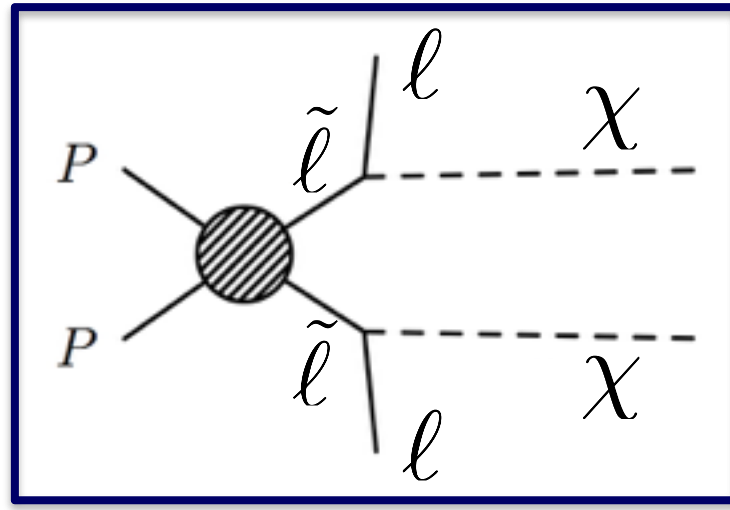

Extremization over under-constrained d.o.f.

LSP 'test mass'

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

From:

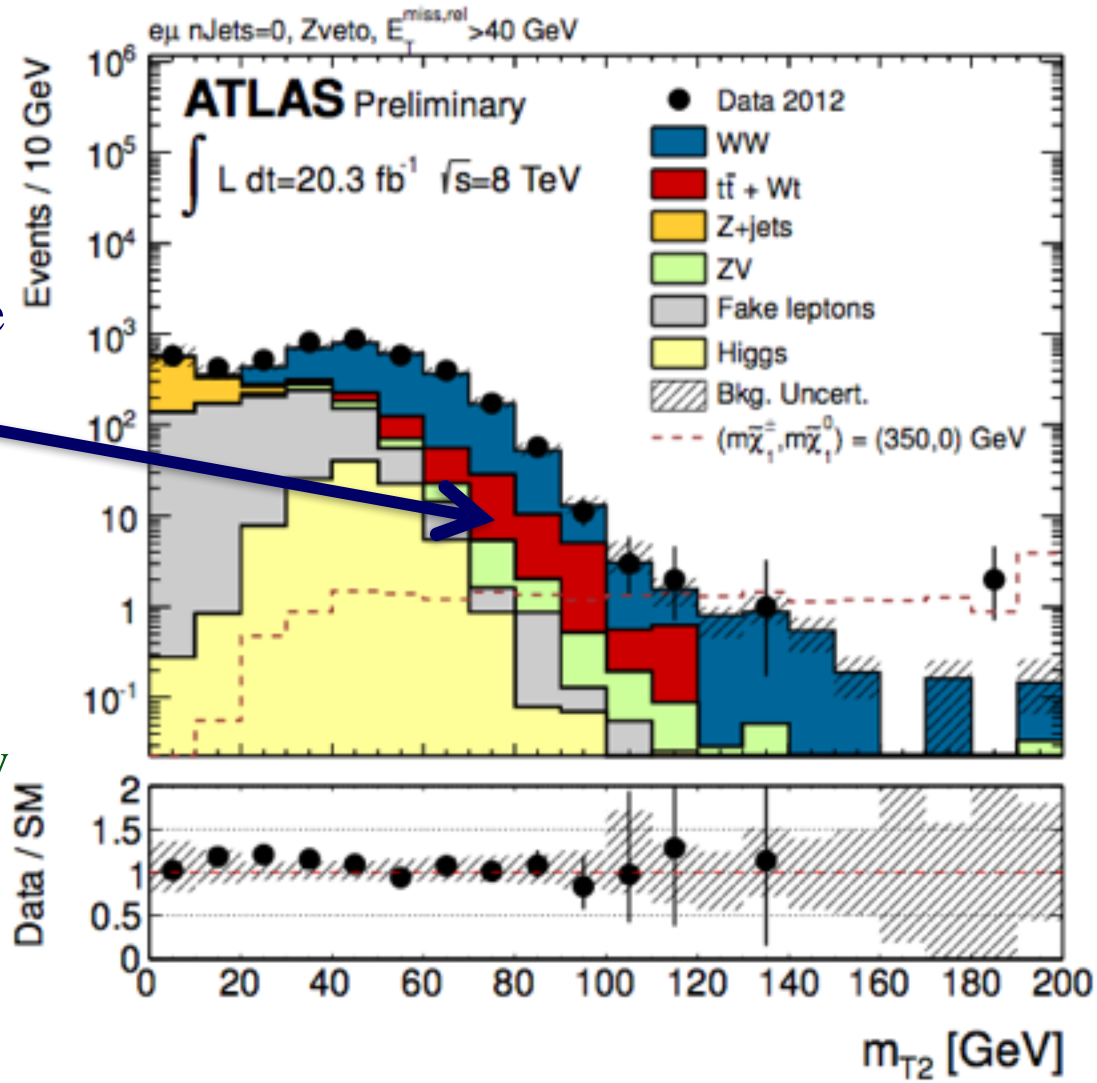
C.G. Lester and D.J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders. *Phys.Lett.*, B463:99–103, 1999.

M_{T2} in practice

From:

ATLAS-CONF-2013-049

Backgrounds with di-leptonic W's fall steeply once M_{T2} exceeds the W mass Jacobian edge



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

The Family of Singularity Variables

- Transverse mass-bounding variables

$M_{2\top}, M_{\top 2}, M_{\circ 2}$ and $M_{2\circ}$ PRD 84, 095031 [1108.5182]

- 3D (3+1) generalizations, possibly with constraints

JHEP 1408 070 [1401.1449]

Example:

test masses

$$M_{2CC} \equiv \min_{\vec{q}_1, \vec{q}_2} \{\max [M_{P_1}(\vec{q}_1, \tilde{m}), \; M_{P_2}(\vec{q}_2, \tilde{m})]\}$$

Extremization over 3D momenta

$$\begin{aligned} \vec{q}_{1T} + \vec{q}_{2T} &= \vec{\not{P}}_T \\ M_{P_1} &= M_{P_2} \\ M^2_{R_1} &= M^2_{R_2} \end{aligned}$$

subject to constraints

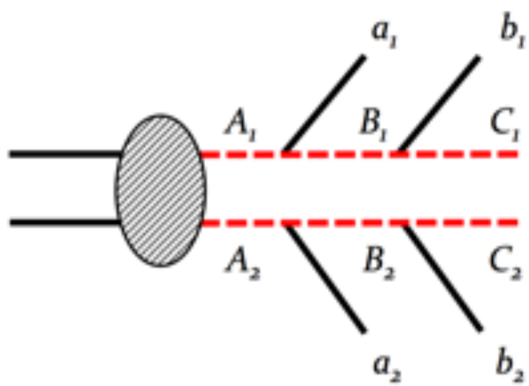
The Family of Singularity Variables

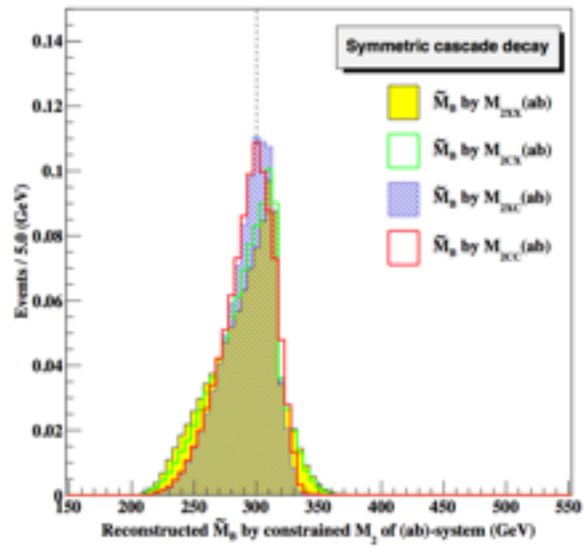
- Transverse mass-bounding variables

  $M_{2\top}, M_{\top 2}, M_{\circ 2}$ and $M_{2\circ}$ PRD 84, 095031 [1108.5182]

- 3D (3+1) generalizations, possibly with constraints

  JHEP 1408 070 [1401.1449]





See talks from Partha Konar and Abhaya Kumar Swain at SUSY16

SUSY Search Variables

- A list (incomplete) of observables used in the collider searches described at SUSY16:

$$E_T^{\text{miss}},\ H_T^{\text{miss}},\ H_T,\ S_T,\ L_T,\ M_{eff},\ \frac{E_T^{\text{miss}}}{M_{eff}}$$

$$\frac{E_T^{\text{miss}}}{\sqrt{H_T}},\ M_{T2},\ M_{CT},\ M_{CT\perp},\ M_R,\ R$$

$$L_p,\ \ \min\Delta\phi_{\text{jet},\ E_T{}^{miss}},\ \alpha_T,\ dE/dx,\ \beta$$

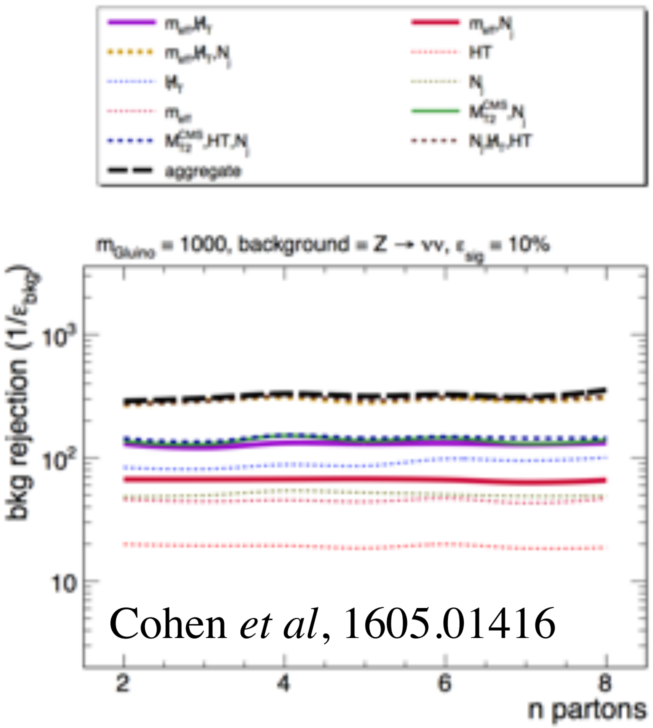
$$M_{jj},\ \Sigma M_{\text{jet}},\ \bar{M}_{\text{jet}},\ M_{\text{fat jet}},\ M_{\gamma\gamma},\ M_{\ell\ell}$$

$$N_{\text{jet}},\ N_{\text{b}-\text{tag}},\ N_{\ell},\ N_{\gamma},\ \cdots$$

- See the many experimental/pheno talks in this conference for descriptions/explanations

SUSY Search Variables

- Which variables is/are the best?
  - Depends on final state, background composition, sparticle/particle masses, instantaneous luminosity, integrated luminosity, …



[1605.01416]

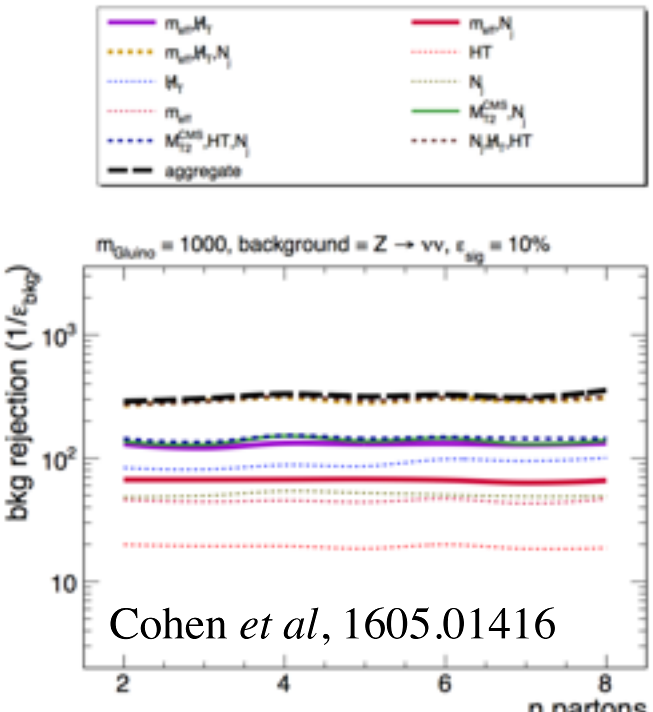
Study of Jets and MET searches for n-parton simplified models

Varying n, sparticle masses, compression and comparing different variables/combinations

See Matt Dolen's SUSY16 talk for more details

SUSY Search Variables

- ~~Which variable is/are the best?~~ **wrong question**
  - Depends on final state, background composition, sparticle/particle masses, instantaneous luminosity, integrated luminosity, …



Cohen *et al*, 1605.01416

[1605.01416]
Study of Jets and MET searches for *n*-parton simplified models

Varying *n*, sparticle masses, compression and comparing different variables/combinations

See Matt Dolen's SUSY16 talk for more details

- Which combination/basis is the best?

SUSY Search Variable Basis “wish-list”

- Complete
  - contains all the event information that’s useful
- Always well-defined
  - not over-constrained as to prevent real solutions
- Orthogonal/~uncorrelated
  - as little redundant information as possible (“minimal”)
- “Diagonalized”
  - Ideally, matched to the particle masses, decay angles, etc. that we hope to study/discover

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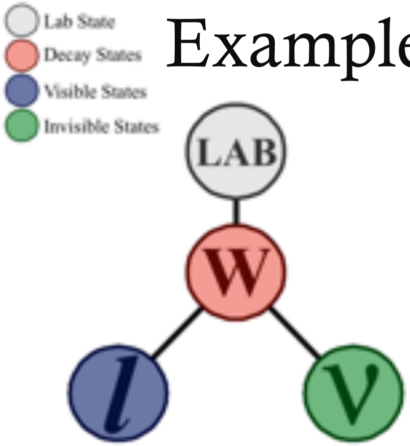
- "Diagonalized"
  - Ideally, matched to the particle masses, decay angles, etc. that we hope to study/discover
- Recursive Jigsaw Reconstruction [P. Jackson, CR,1607.xxxx] is a systematic prescription for deriving such a basis

Recursive Jigsaw Reconstruction

Example: single W production



four unknown d.o.f. associated with neutrino

$$(\vec{p}_{\nu,T},\ p_{\nu,z},\ m_{\nu})$$

subject to three constraints

$$\vec{E}_T^{\text{miss}} = \vec{p}_{\nu,\,T} \qquad m_{\nu} = 0$$

Recursive Jigsaw Reconstruction

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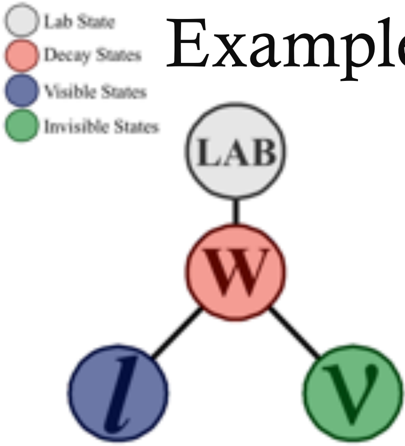

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subject to three constraints

$$\vec{E}_T^{\text{miss}} = \vec{p}_{\nu,\ T} \qquad m_{\nu} = 0$$

re-express under-constrained d.o.f.
in terms of unknown velocity
along beam-line to W rest frame

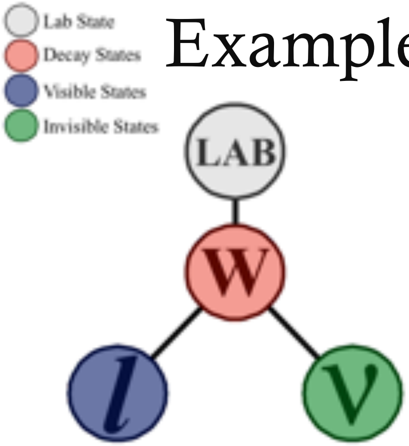
$$p_{\nu,z} \to \beta_z^{\text{LAB}\to W}$$

choose β_z such that

$$\frac{\partial M_W(\beta_z)}{\partial \beta_z} = 0$$

equivalent to setting the nu
rapidity equal to the lepton's

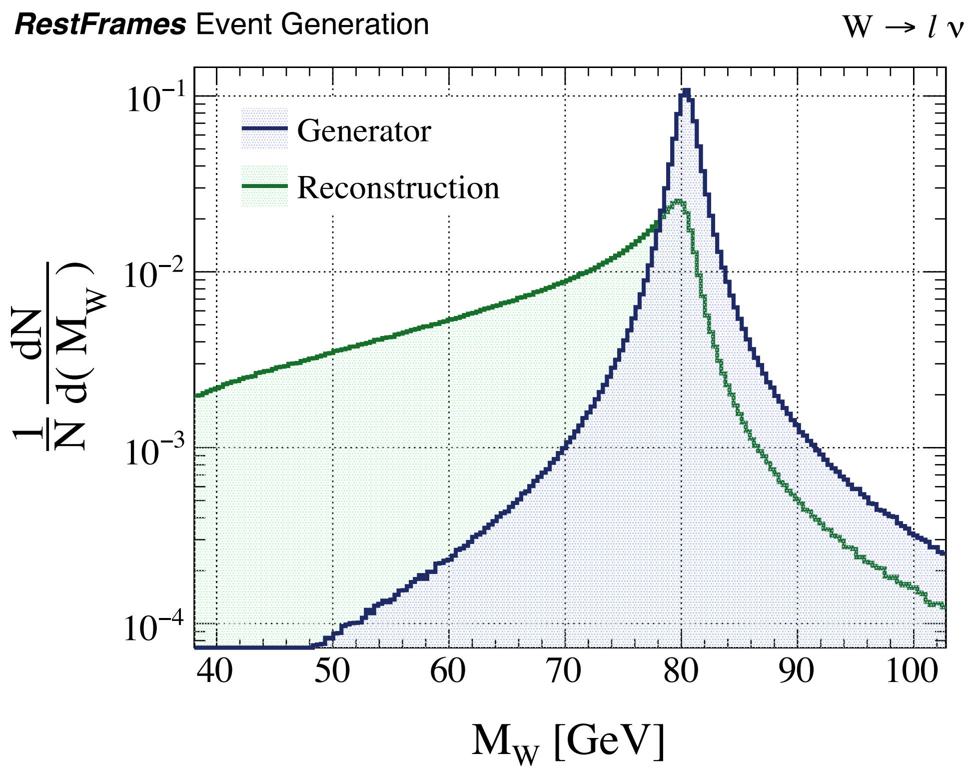
Recursive Jigsaw Reconstruction



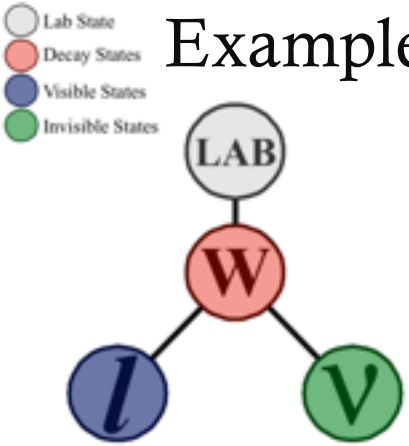
Example: single W production

choosing $$\frac{\partial M_W(\beta_z)}{\partial \beta_z} = 0$$

we have essentially re-derived the W transverse mass



Recursive Jigsaw Reconstruction

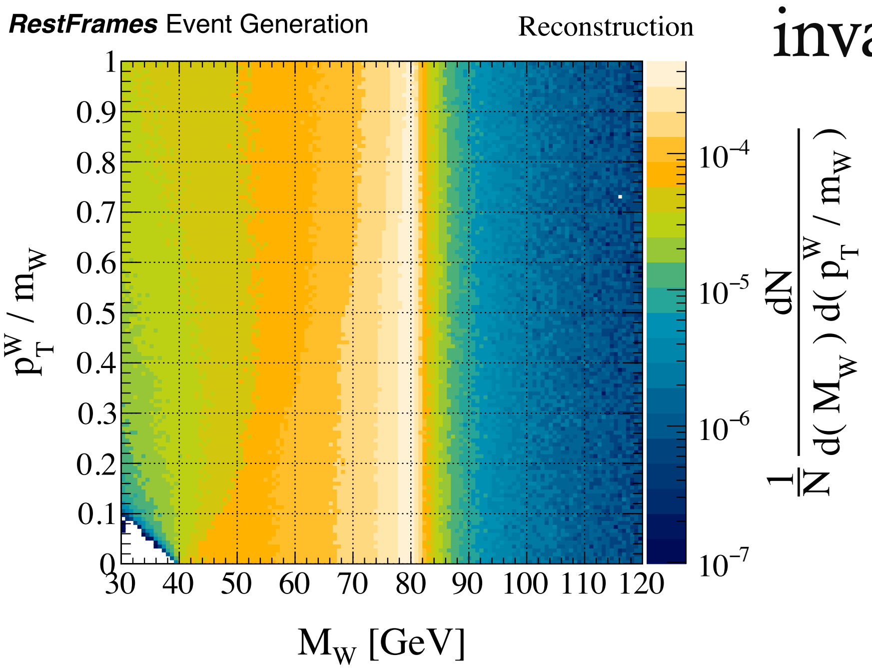


Example: single W production

energy of lepton after boost

subtlety: $\dfrac{\partial M_W(\beta_z)}{\partial \beta_z} \propto \dfrac{\partial (\Lambda_{\beta_z} \mathbf{p}_\ell)_0}{\partial \beta_z}$

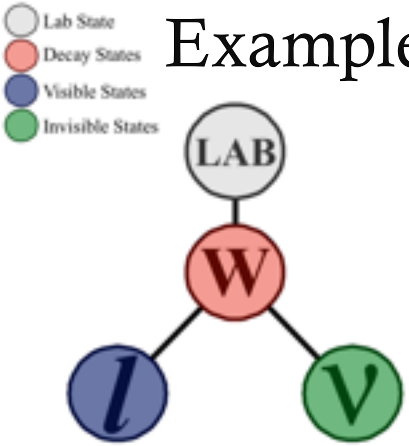
our W mass variable is (manifestly) invariant under longitudinal boosts



it is also invariant to order β_T^2 to transverse boosts

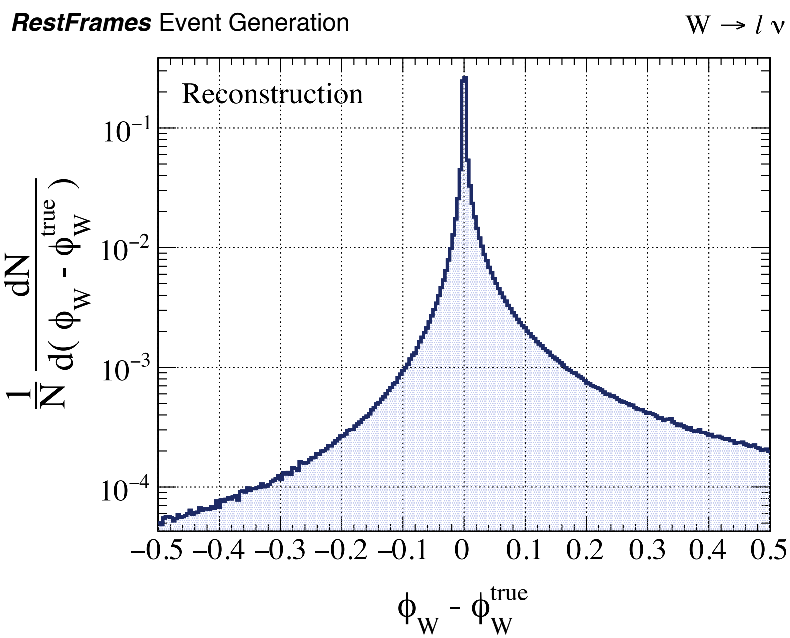
our approximation of the W rest frame has these same properties

Recursive Jigsaw Reconstruction

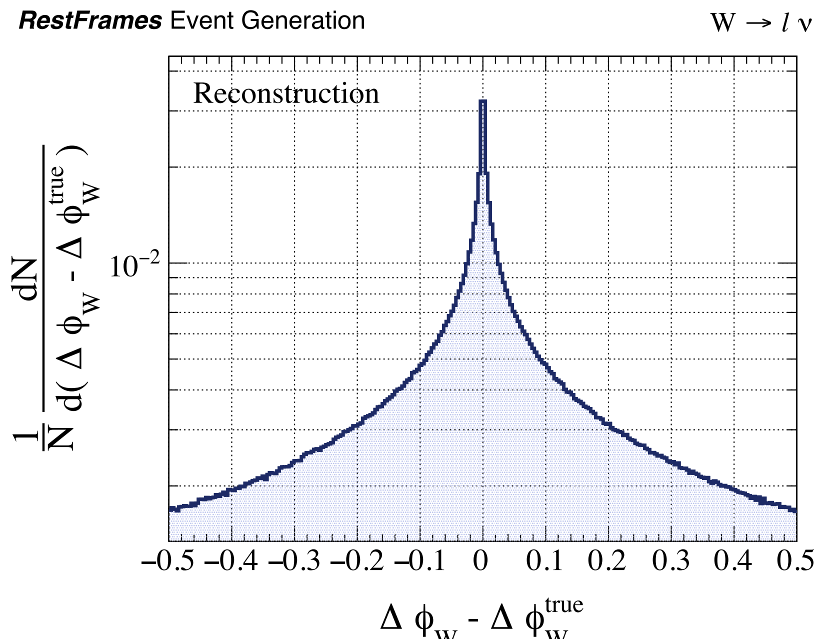


Example: single W production

with approximations of all the velocities relating the reference frames in our event, we can calculate a complete basis of observables



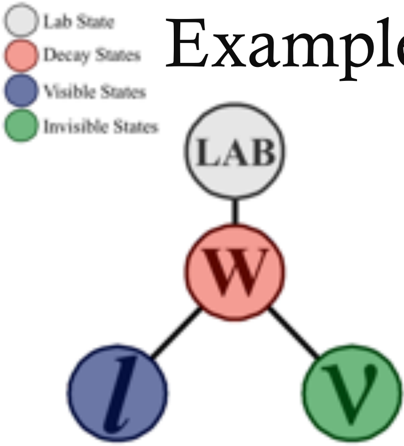
transverse part of W decay angle



azimuthal angle between W decay plane and $\vec{p}_{W,T}/\hat{n}_z$ plane

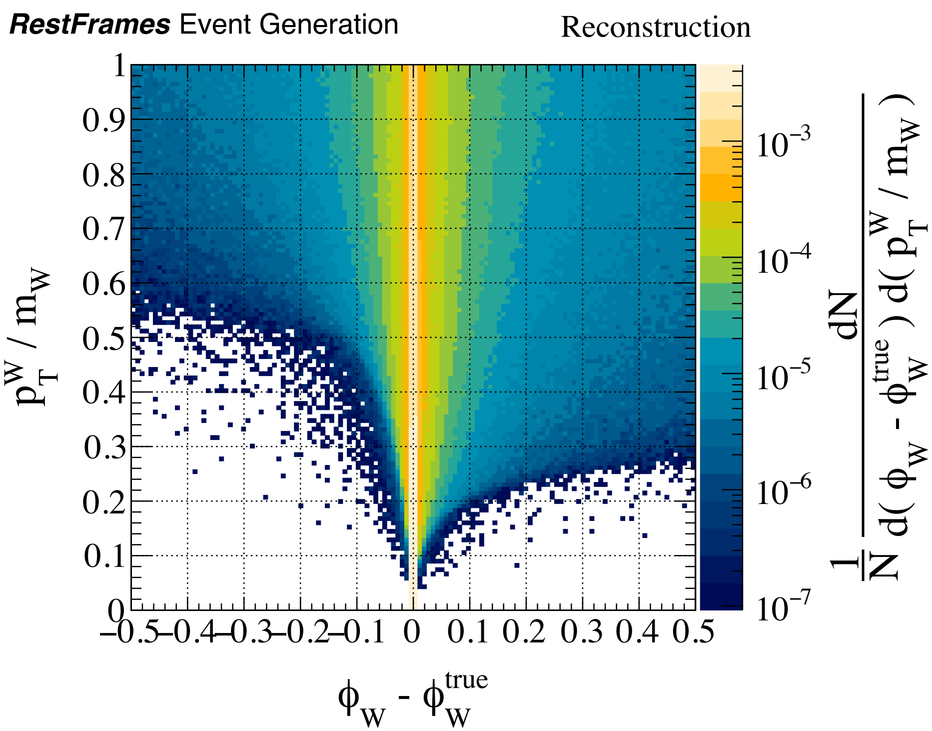
Recursive Jigsaw Reconstruction

Example: single W production



with approximations of all the velocities relating the reference frames in our event, we can calculate a complete basis of observables

$$\vec{p}_{W,T}\,,\ \ M_W\,,\ \ \phi_W\,,\ \ \Delta\phi_W$$

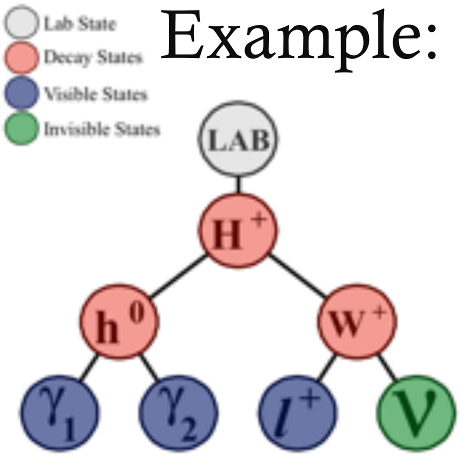


Observables defined in a particular reference frame inherit derived properties of that frame

ϕ_W is invariant under longitudinal boosts and up to order β_T^2 in transverse ones

Recursive Jigsaw Reconstruction

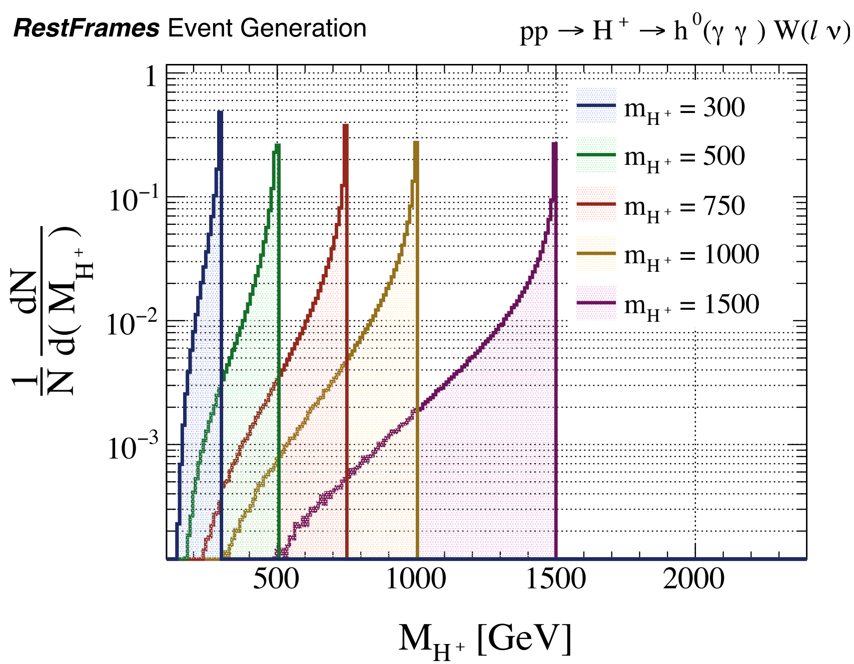
Example: charged Higgs production



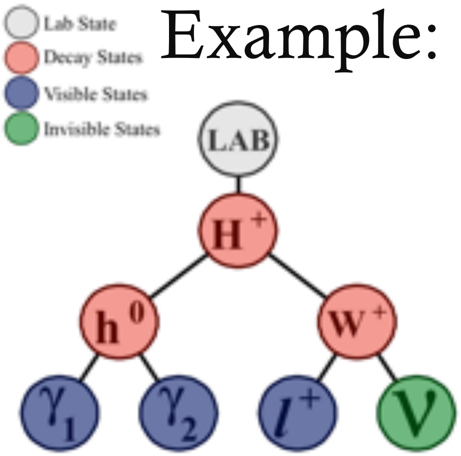
same unknown d.o.f. and constraints as W case

choose β_z such that the rapidity of the neutrino is the same as the $h^0(\gamma\gamma) + \ell$ system (minimizes M_{H^+})

procedure gives us our transverse mass…



Recursive Jigsaw Reconstruction



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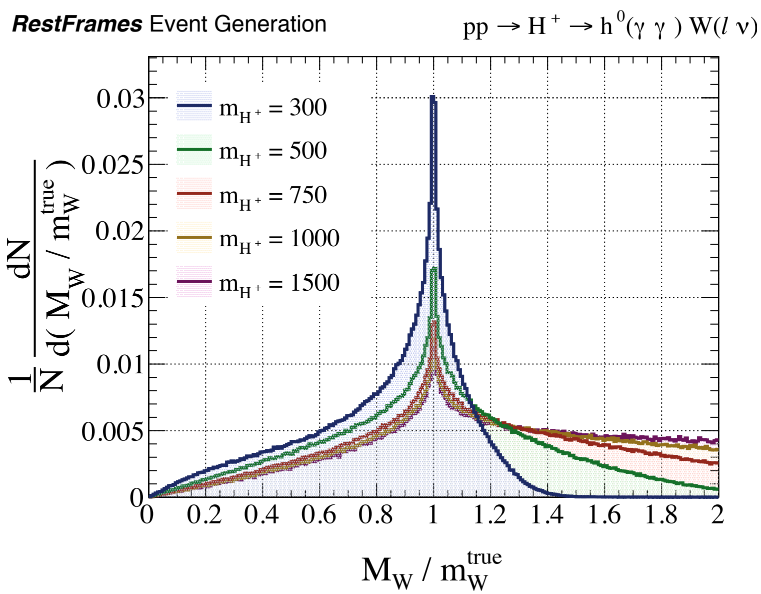
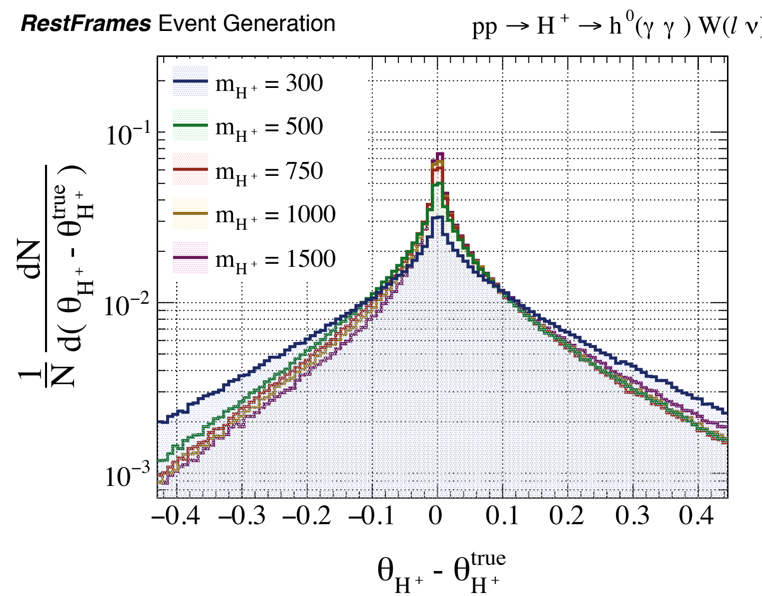
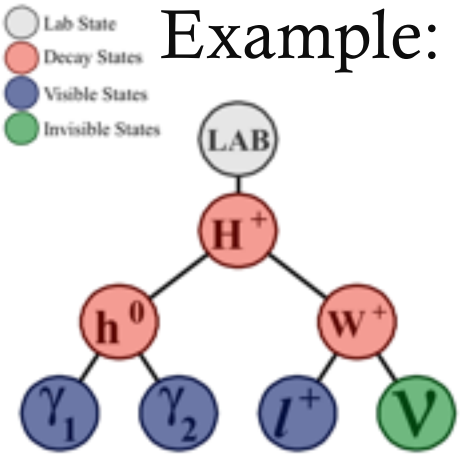




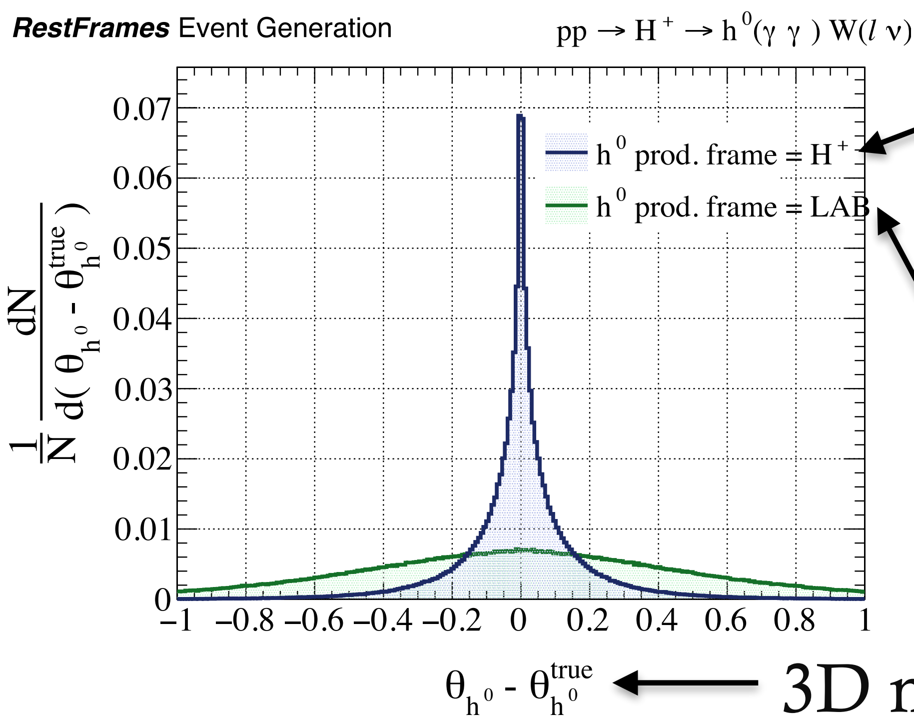
…and a full basis of ~uncorrelated observables

Recursive Jigsaw Reconstruction

Example: charged Higgs production



RJR procedure provides a complete, physics-motivated basis that improves resolution of kinematic features we are interested in



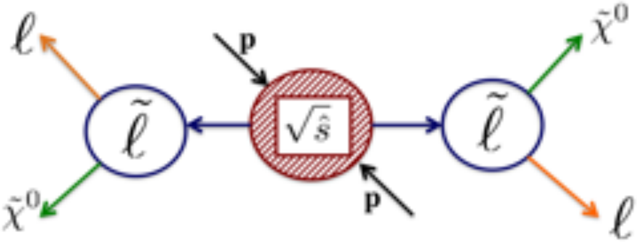
assumes h^0 production frame is our H^+ rest-frame approximation

assumes h^0 production frame is the lab frame

3D neutral Higgs decay angle

Recursive Jigsaw Reconstruction

Example: di-sleptons



eight unknown d.o.f. 2x
associated with LSP's $(\vec{p}_{\tilde{\chi},T},\ p_{\tilde{\chi},z}\ ,m_{\tilde{\chi}})$

four simplifying constraints

$$E_T^{\rm miss} = \vec{p}_{\tilde{\chi}_a,T} + \vec{p}_{\tilde{\chi}_b,T} \qquad m_{\tilde{\chi}} = 0$$

Recursive Jigsaw Reconstruction

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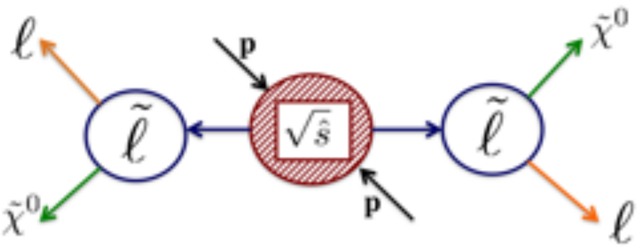

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$$E_T^{\text{miss}} = \vec{p}_{\tilde{\chi}_a,T} + \vec{p}_{\tilde{\chi}_b,T} \qquad m_{\tilde{\chi}} = 0$$

Tricky mass problem:

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

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

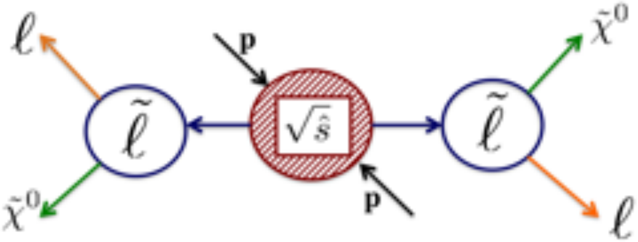
The Euclidean mass (or contra-variant mass) is invariant under anti-symmetric Lorentz transformations of two particles

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

For two mass observables ($\sqrt{\hat{s}}\ , m_{\tilde{\ell}}$) we want to capture both types of behavior…

di-sleptons

Example: di-sleptons

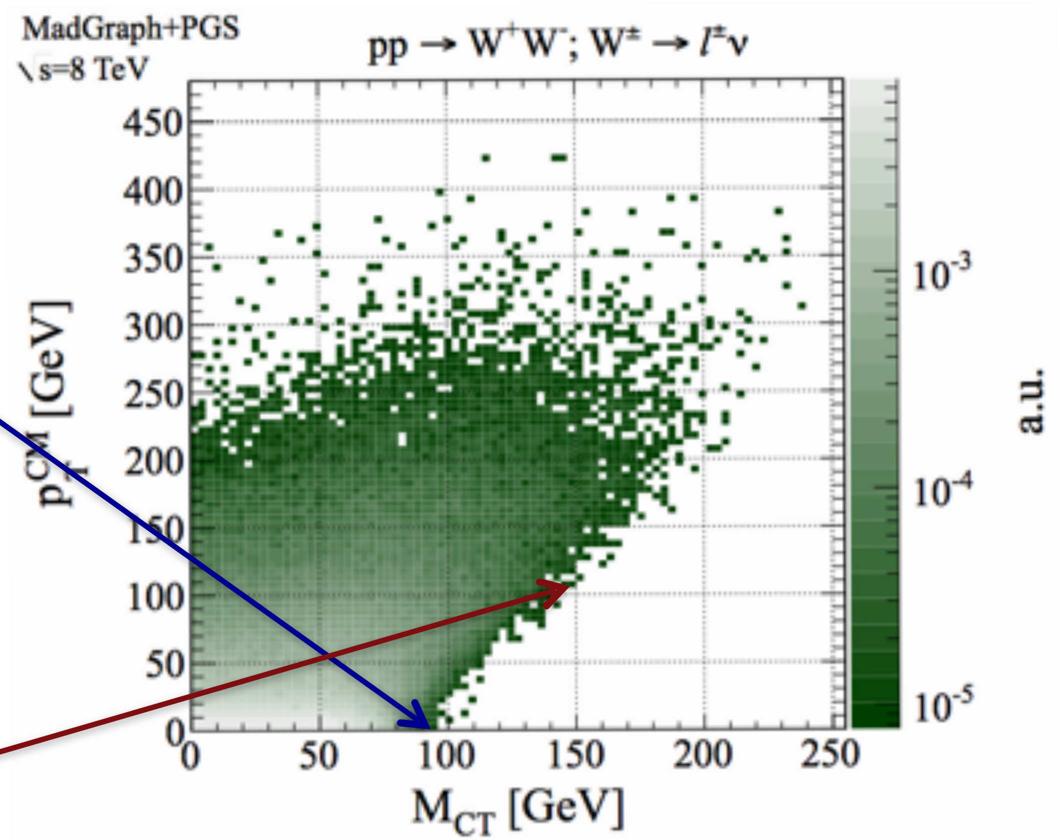


assuming ~mass-less leptons

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

JHEP 0804:034

contraboost invariant transverse mass has same $M_\Delta \equiv \dfrac{m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0}}{m_{\tilde{l}}}$ end-point, irrespective of $\sqrt{\hat{s}}$ …

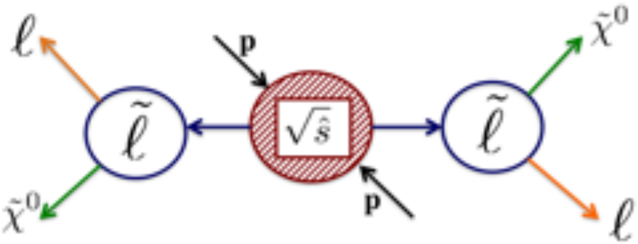


…but end-point is not invariant under Lorentz boost of CM system

PRD 89, 055020 (2014)

Recursive Jigsaw Reconstruction

Example: di-sleptons



In RJR, rather than determining all under-constrained d.o.f. in one go *a la* singularity variables, we factorize the problem:

Imagine we knew how to get to di-slepton rest-frame:

with the lepton four-vectors in this frame $\mathbf{p}_{\ell\ a}^{\tilde{\ell}\tilde{\ell}}$ $\mathbf{p}_{\ell\ b}^{\tilde{\ell}\tilde{\ell}}$

Recursive Jigsaw Reconstruction

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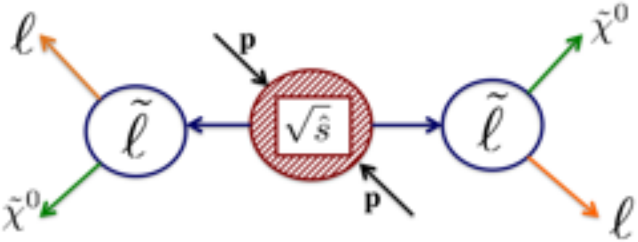

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we choose the velocity to get to the lepton frames $\vec{\beta}^{\ \tilde{\ell}\tilde{\ell}\to\tilde{\ell}_i}$

$$\frac{\partial(\Lambda_{\vec{\beta}}\ \mathbf{p}_{\ell\ a}^{\tilde{\ell}\tilde{\ell}} + \Lambda_{-\vec{\beta}}\ \mathbf{p}_{\ell\ b}^{\tilde{\ell}\tilde{\ell}})_0}{\partial\vec{\beta}} = \frac{\partial(E_{\ell\ a}^{\tilde{\ell}\ a} + E_{\ell\ b}^{\tilde{\ell}\ b})}{\partial\vec{\beta}} = 0$$

Recursive Jigsaw Reconstruction

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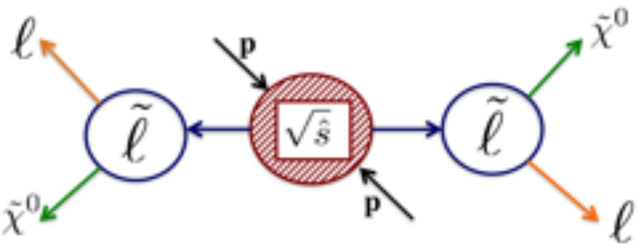

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Recursive Jigsaw Reconstruction

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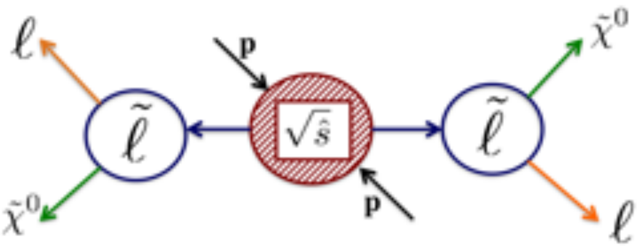

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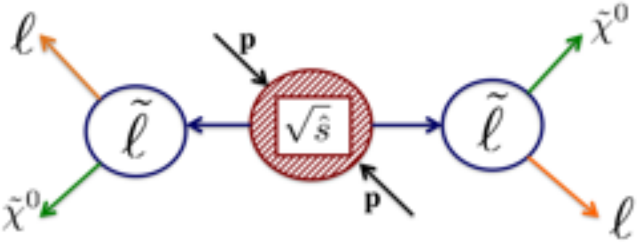
which also sets $M_{\tilde{\chi}\tilde{\chi}} = m_{\ell\ell}$

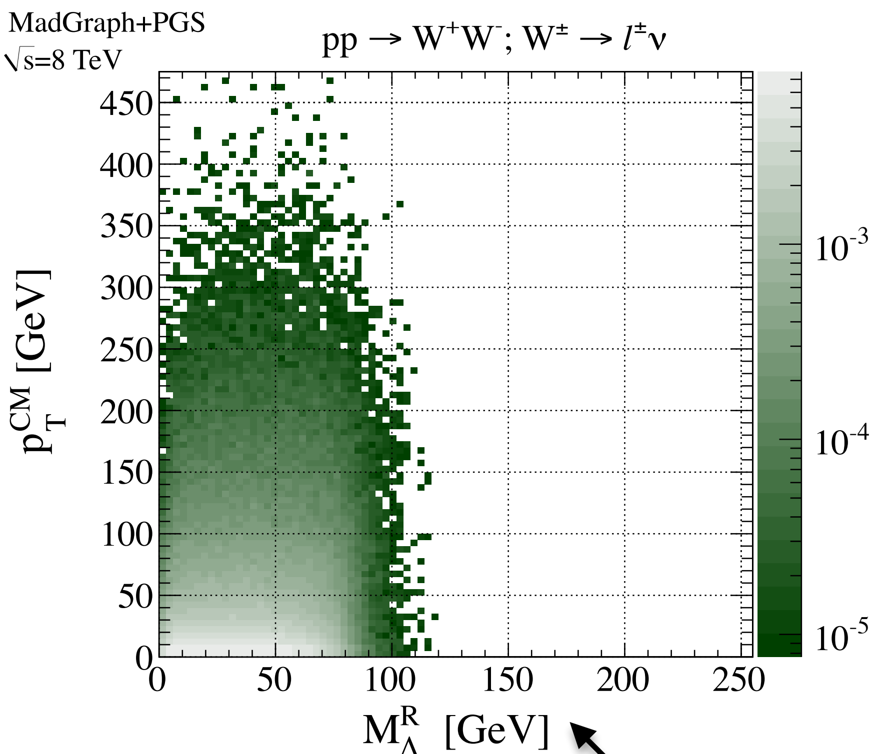
which allows us to determine longitudinal component of $\vec{\beta}^{\ \mathrm{LAB}\to\mathrm{CM}}$ by minimizing $\sqrt{\hat{s}}$, as in previous examples

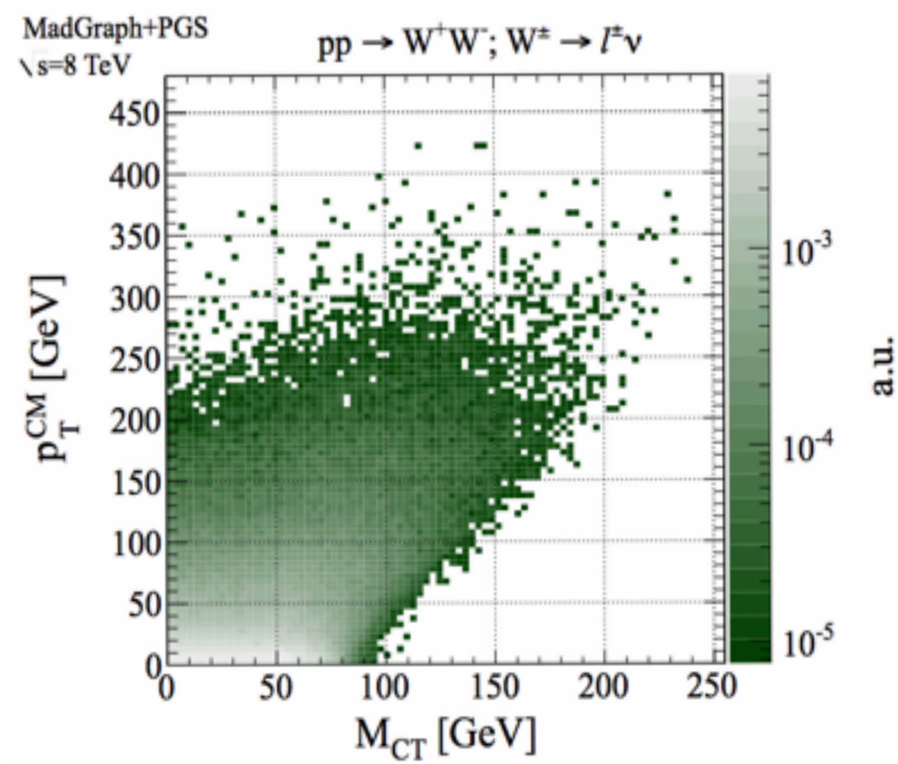
Recursive Jigsaw Reconstruction

Example: di-sleptons



Resulting basis of observables are the super-razor variables
[PRD 89, 055020 (2014)]

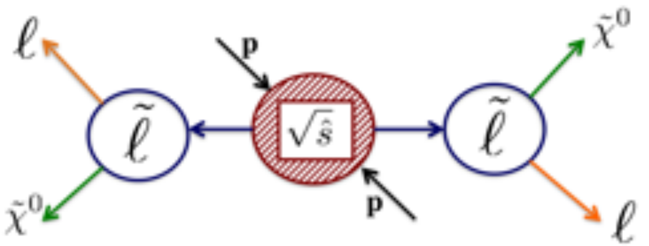




new mass-estimator acts like pT-corrected M_{CT}

Recursive Jigsaw Reconstruction

Example: di-sleptons



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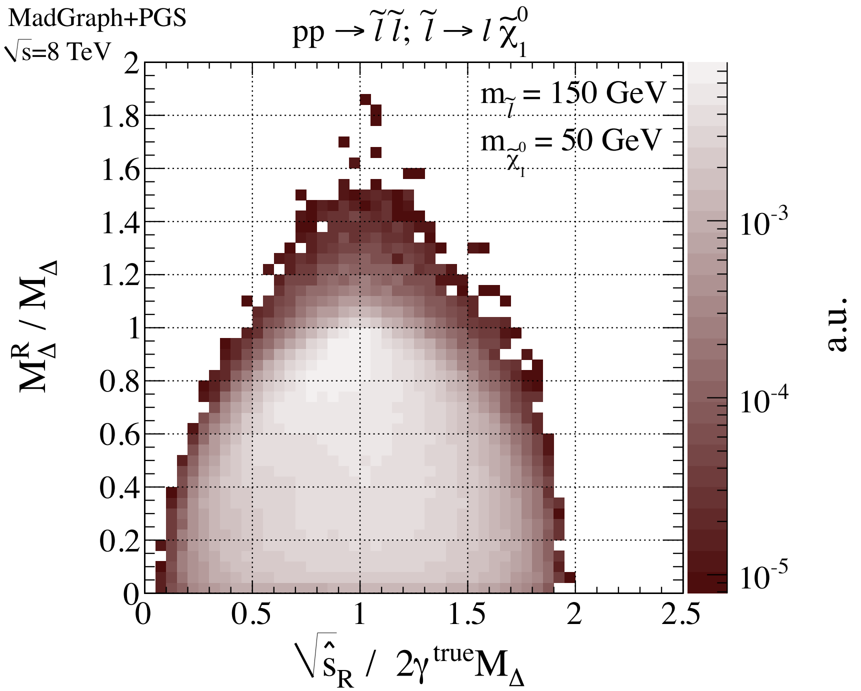
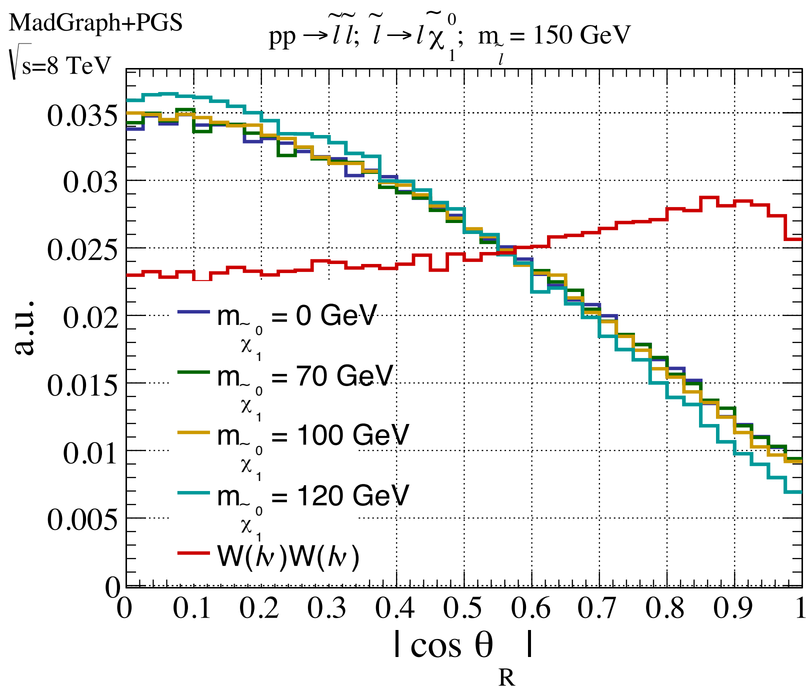
[PRD 89, 055020 (2014)]





extracts ~uncorrelated estimators for both mass scales

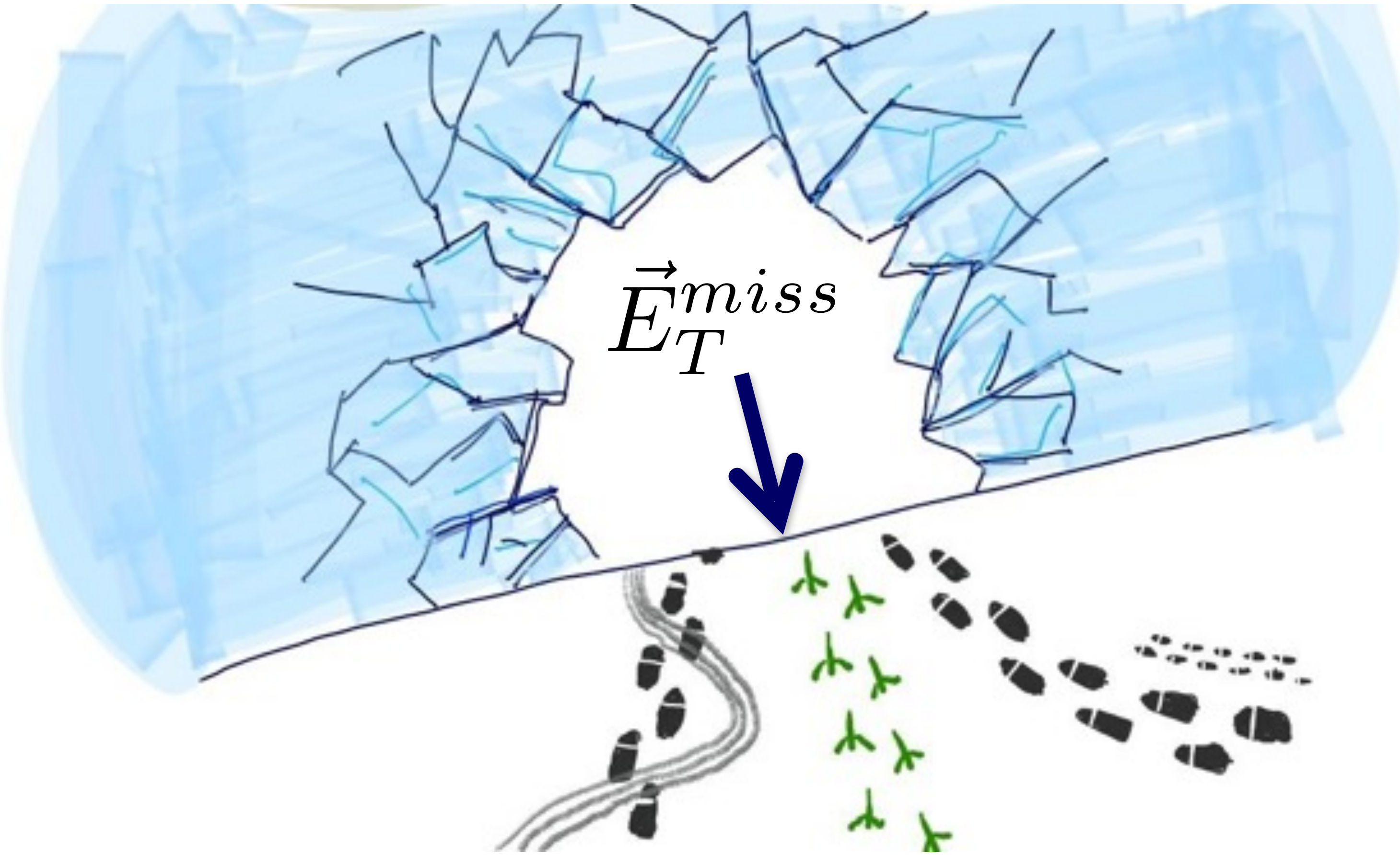
along with complete basis of other observables

Recursive Jigsaw Reconstruction

New approach to reconstructing final states with weakly interacting particles: ***Recursive Jigsaw Reconstruction***

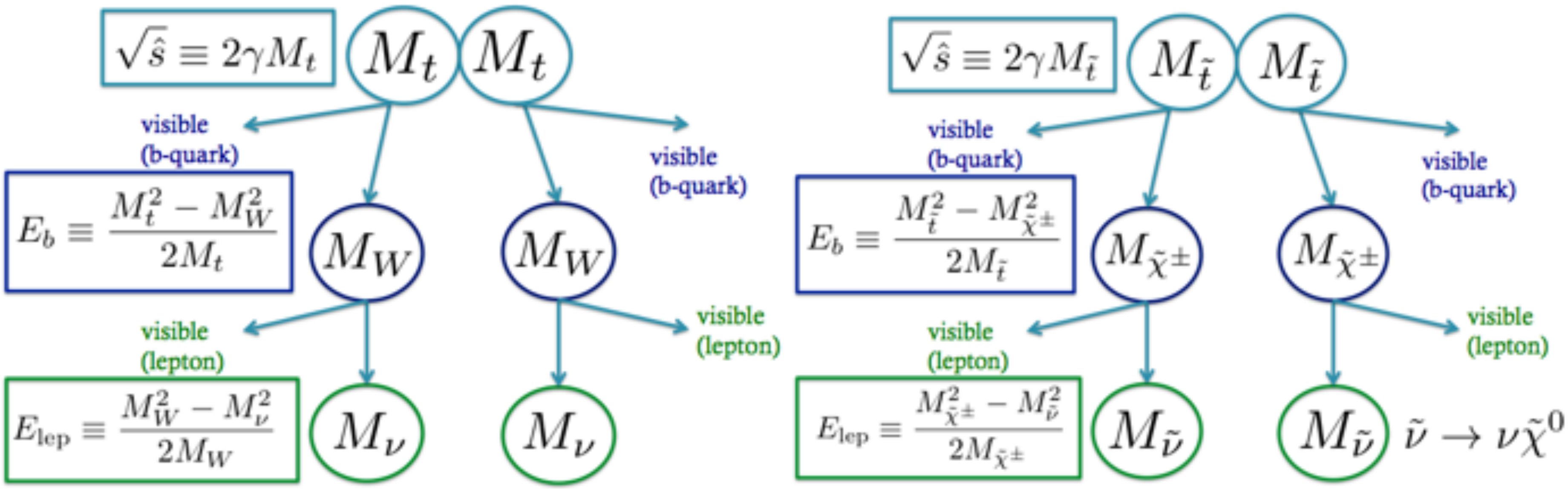
- The strategy is to transform observable momenta iteratively ***reference-frame to reference-frame***, traveling through each of the reference frames relevant to the topology
- **Recursive:** At each step, specify ***only the relevant d.o.f. related to that transformation*** ⇒ ***apply a Jigsaw Rule***
  Repeat procedure recursively, using the visible momenta encountered in each reference frame
- **Jigsaw:** each of these rules is factorizable/customizable/ interchangeable like a (strange) jigsaw puzzle pieces
- **Rather than obtaining one observable, get a *complete basis* of useful observables for each event**
- See P. Jackson and L. Lee's talks for additional applications

Generalizing Further…



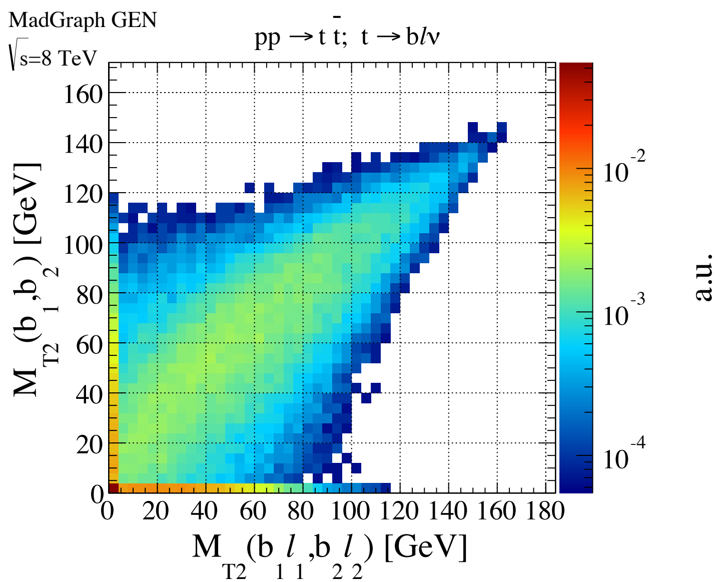
Recursive Jigsaw approach can be generalized to arbitrarily complex final states with weakly interacting particles

Example: the di-leptonic top basis

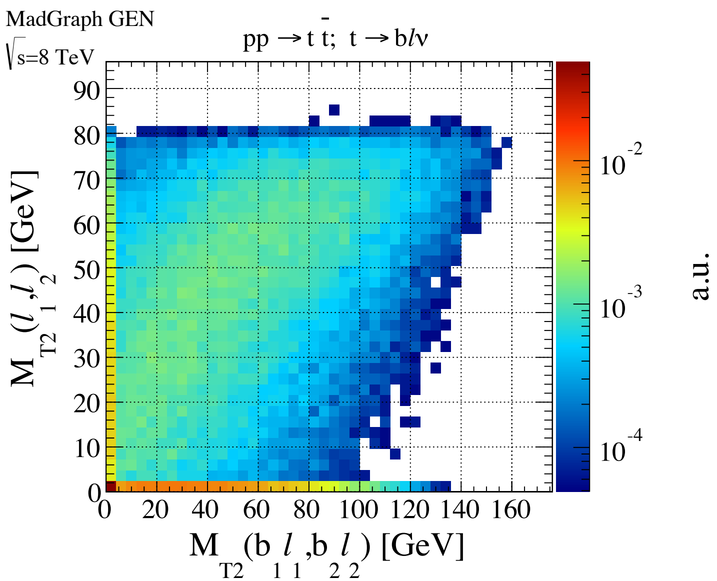


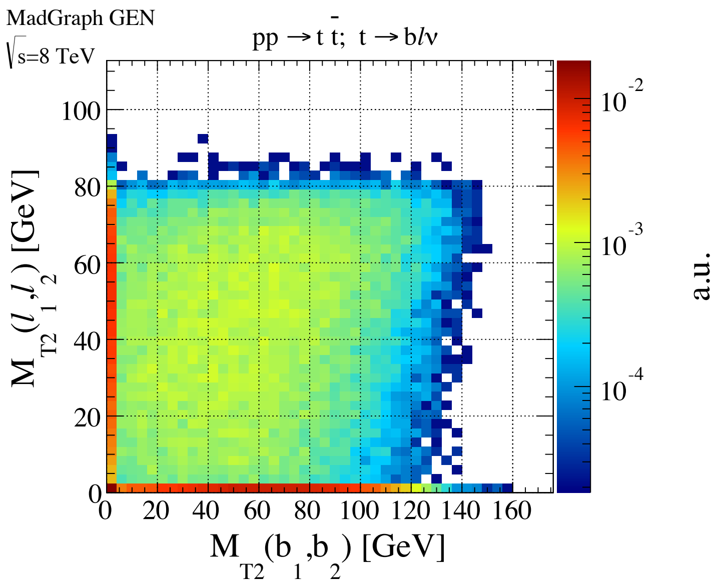
In more complicated decay topologies there can be many masses/mass-splittings, spin-sensitive angles and other observables of interest that can be used to distinguish between the SM and SUSY signals

Example: the di-leptonic top basis

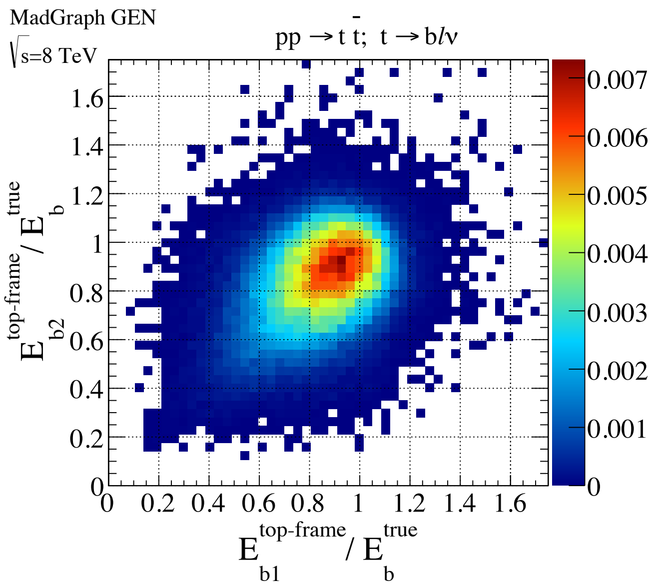


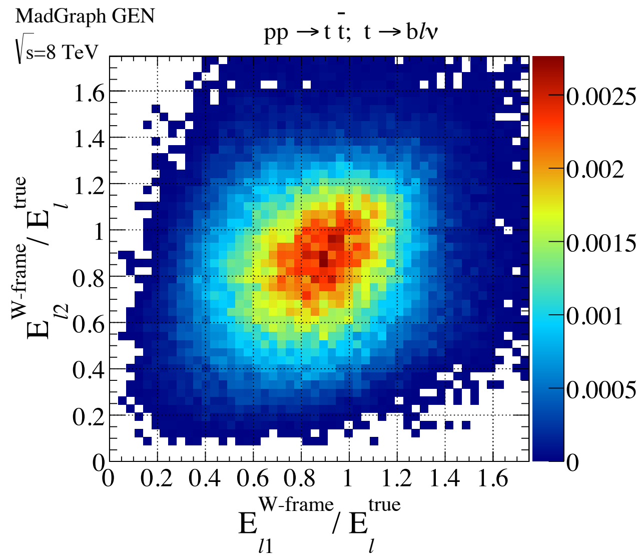
Mass-sensitive singularity variables are sensitive to mass splittings through end-points, but are not necessarily independent



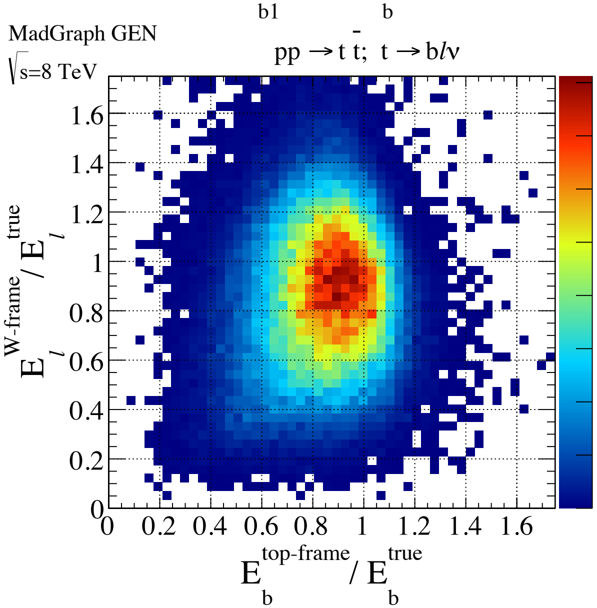


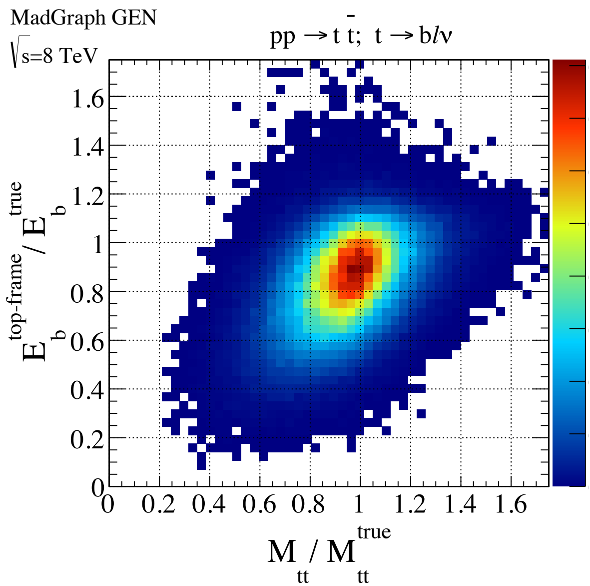
The di-leptonic top basis

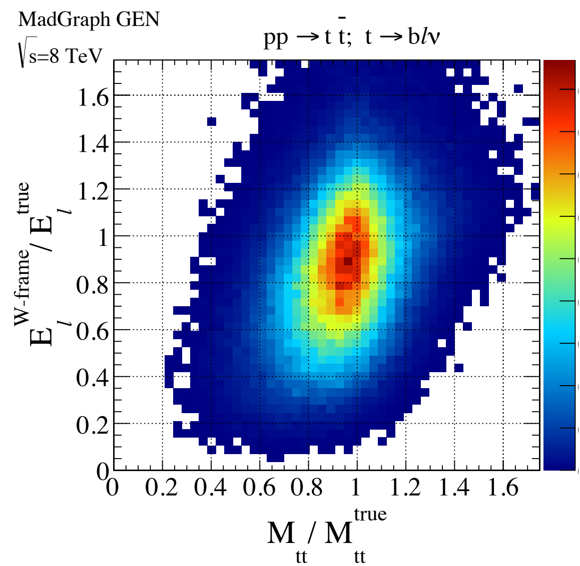




~independent information about five different masses, and decay angles

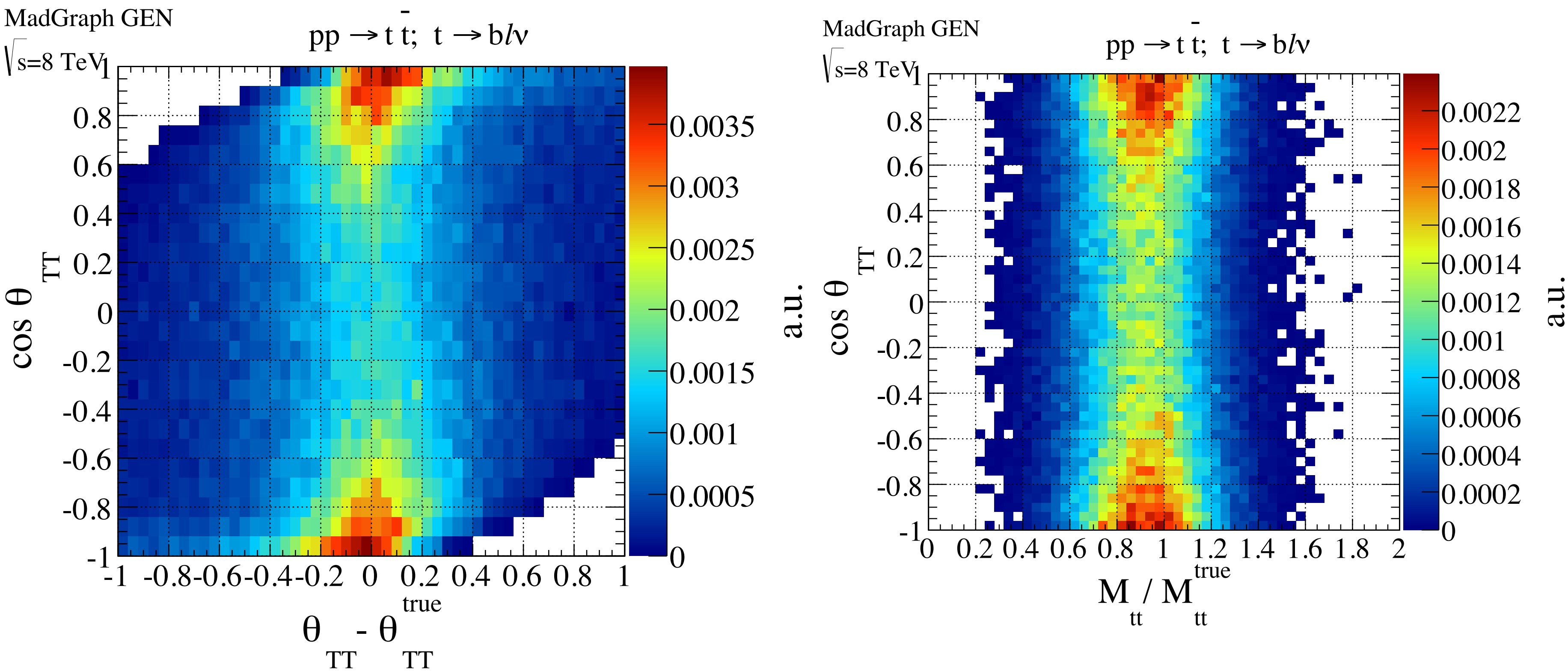






The di-leptonic top basis

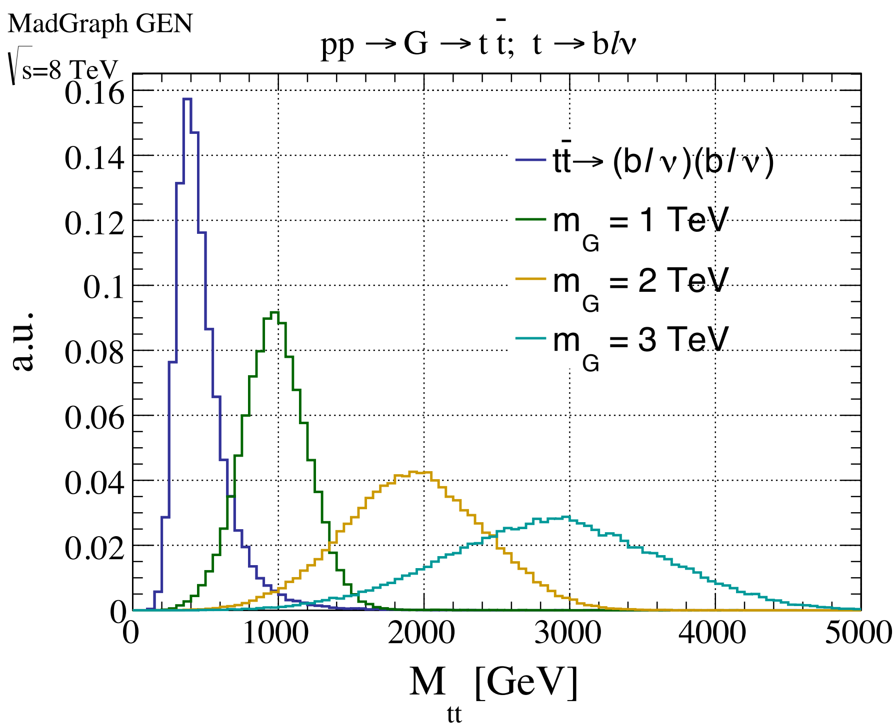
largely independent information about decay angles

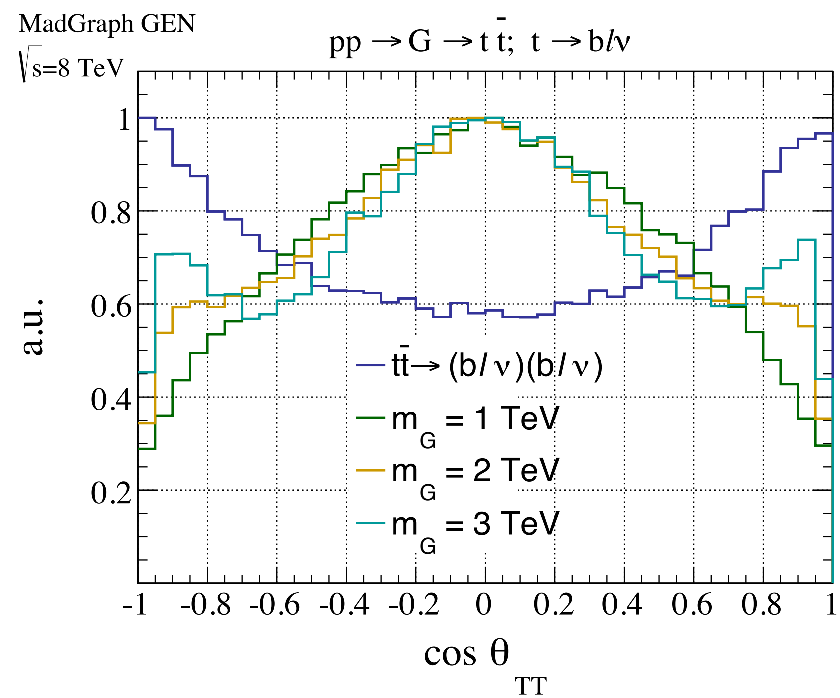


Here, the decay angle of the top/anti-top system can be used to study resonance structure, along with di-top mass

The di-leptonic top basis

largely independent information about decay angles

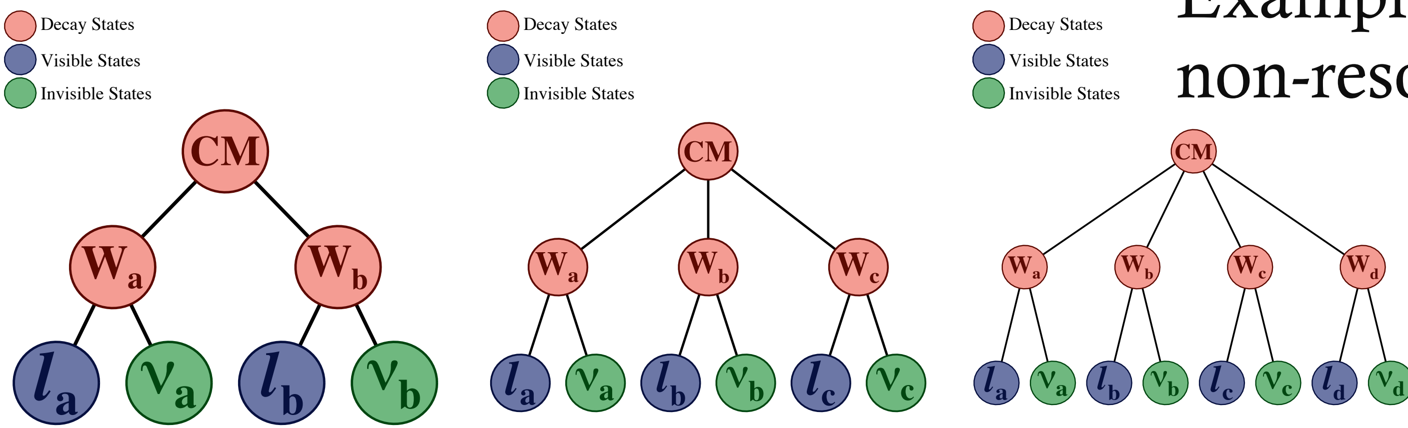


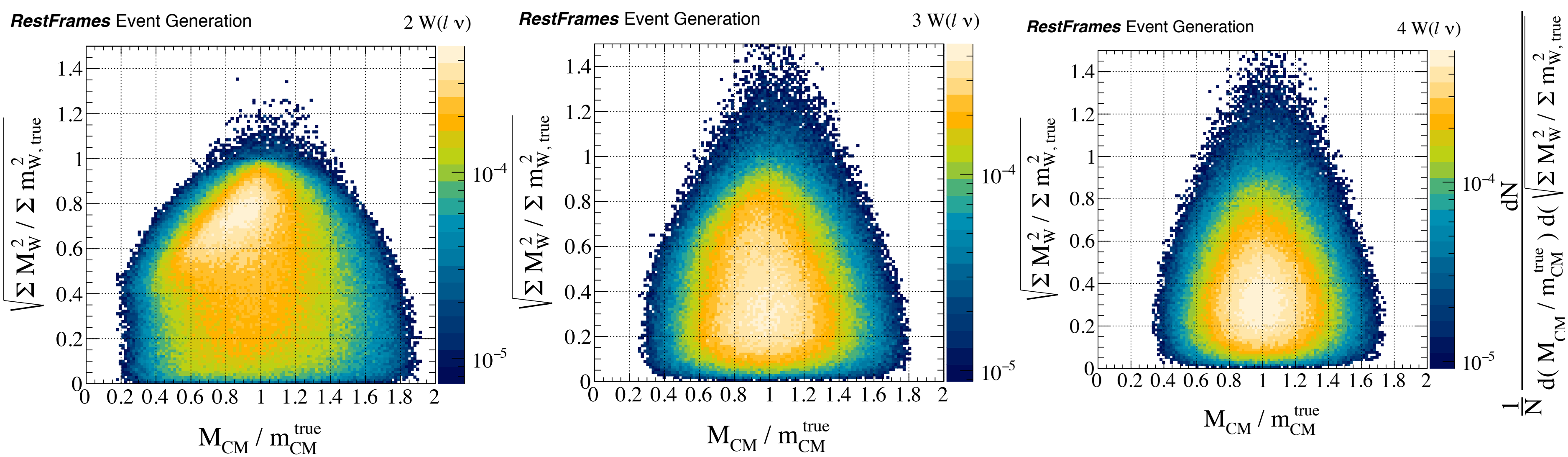


Here, the decay angle of the top/anti-top system can be used to study resonance structure, along with di-top mass

Recursive Jigsaw Reconstruction

Example:
non-resonant N $W(\ell\nu)$

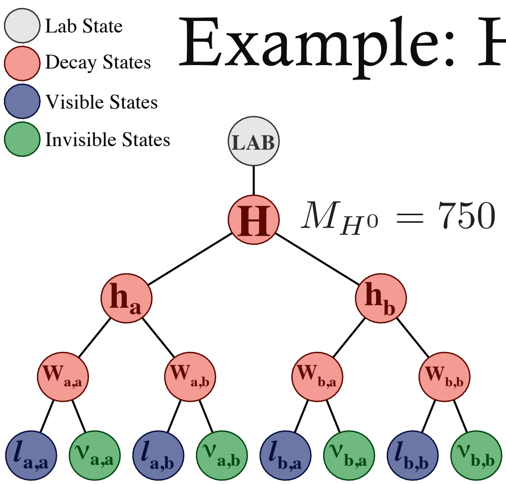


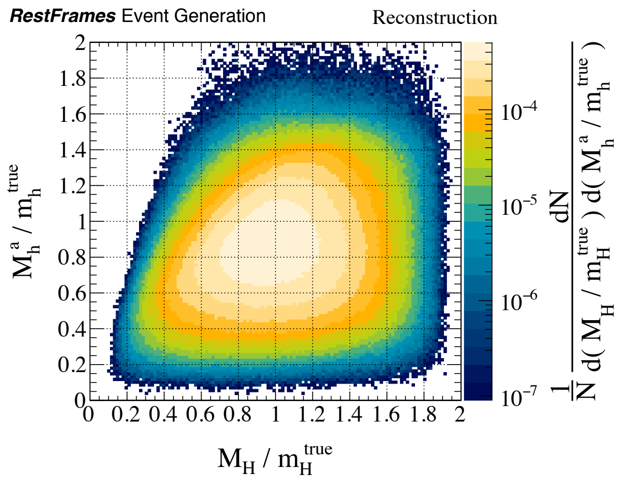


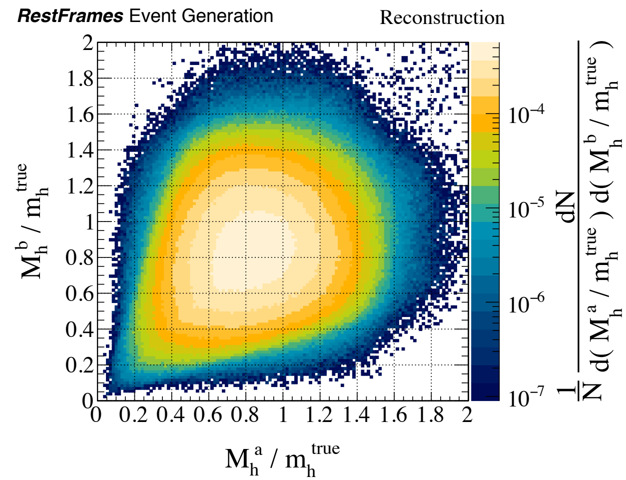
Christopher Rogan - SUSY16 - University of Melbourne, July 6, 2016

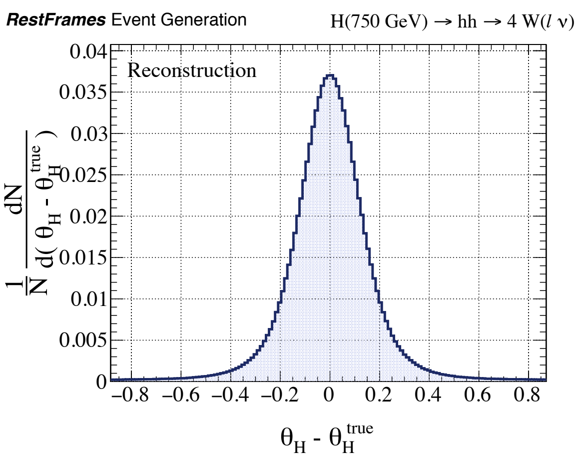
Recursive Jigsaw Reconstruction

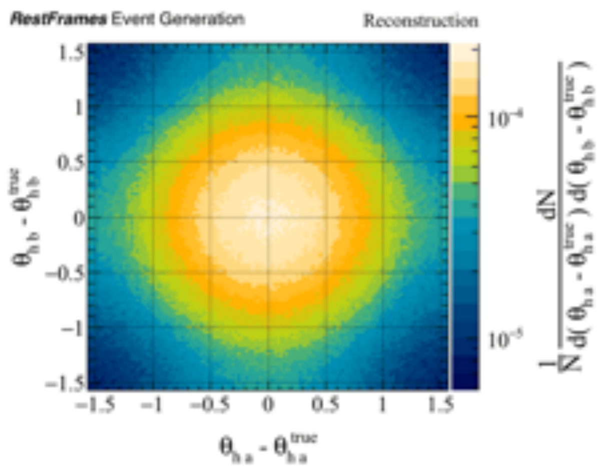
Example: Heavy Higgs to light Higgs to $4W(\ell\nu)$

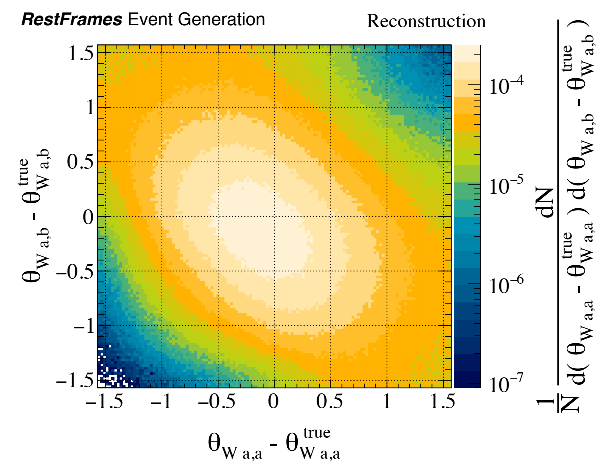








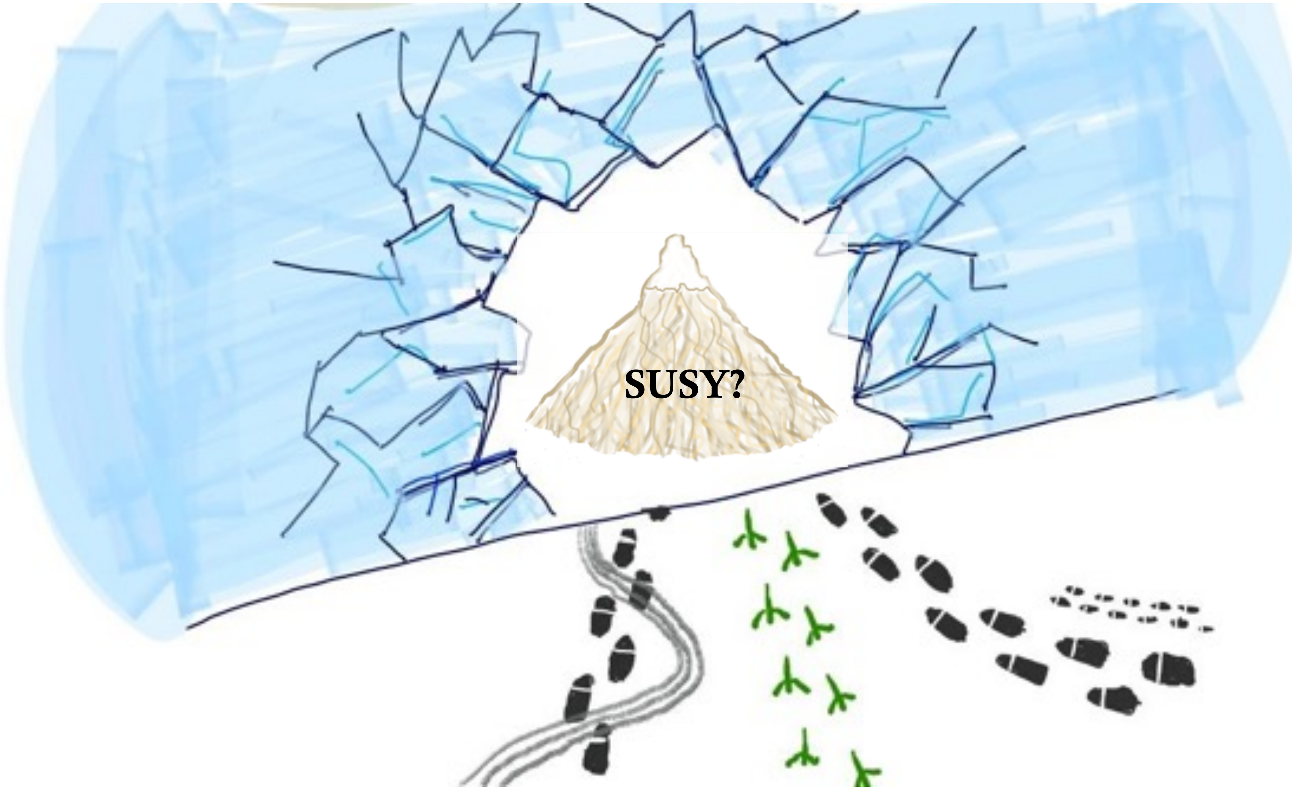




Implementations of the examples shown in this talk are available in the public software **RestFrames** (www.RestFrames.com)

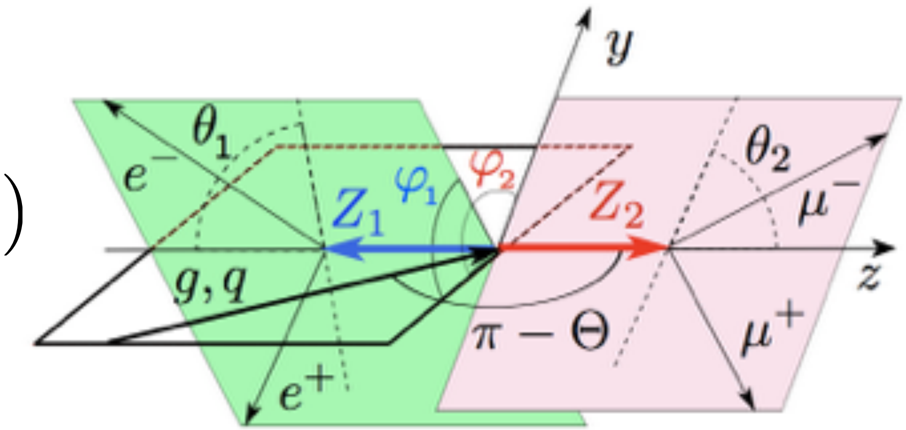
Summary

- Probing SUSY at colliders (here LHC13) involves understanding a large, new, phase-space
  - Boot-strapping our understanding of the SM and detectors from the poles to the regions where we're searching for evidence of BSM physics
- Many different way to partition that phase-space
  - Observables designed for every final state, every kinematic feature we hope to exploit. Enormous breadth of techniques/strategies/signatures
- We're getting closer to a discovery, SUSY or other
  - More data reveals more phase-space, increasingly detailed analyses probing more thoroughly.
  - No stone left unexamined - maybe SUSY17?



BACKUP SLIDES

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

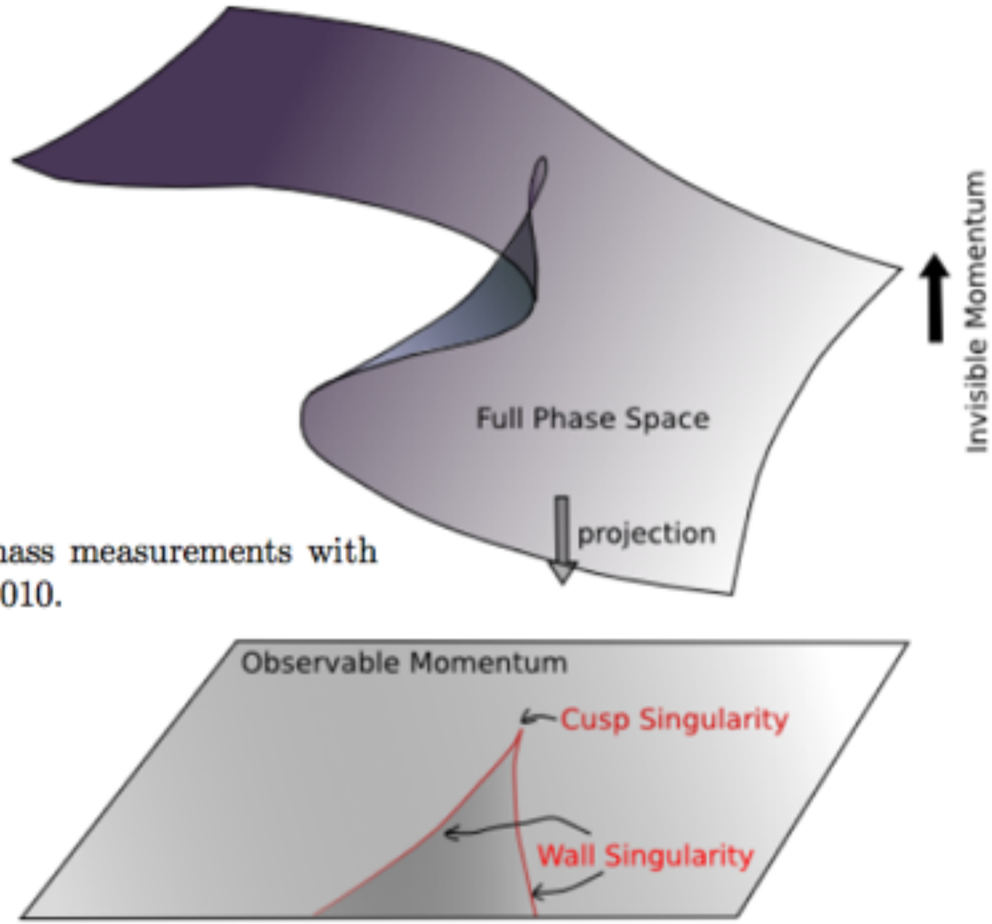
Under-constrained system with multiple weakly interacting particles – can't calculate all the kinematic information

What useful information can we calculate?

What can we measure?

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.

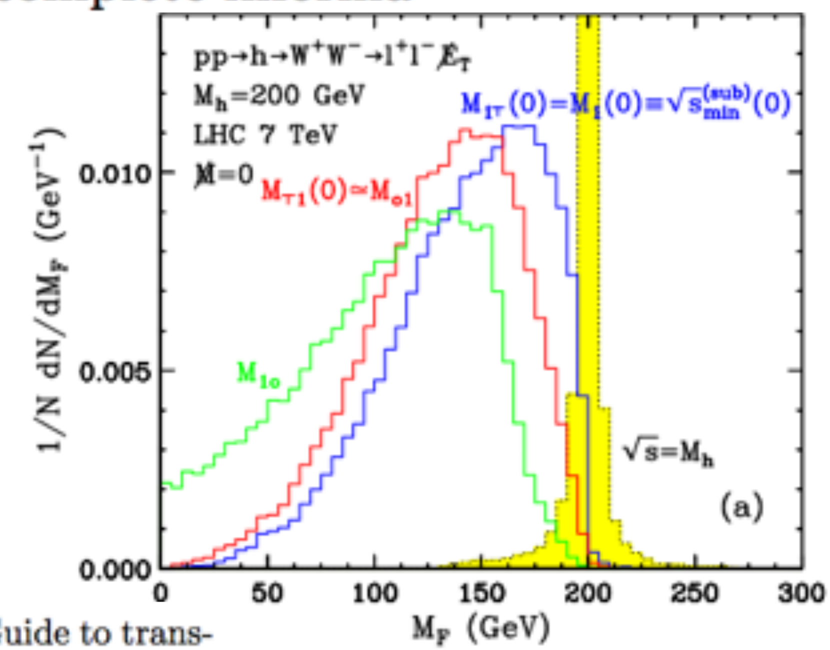


From:

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.* Such incomplete informa-



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.

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:

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

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

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:

$$\boxed{M_{CT\perp}}$$

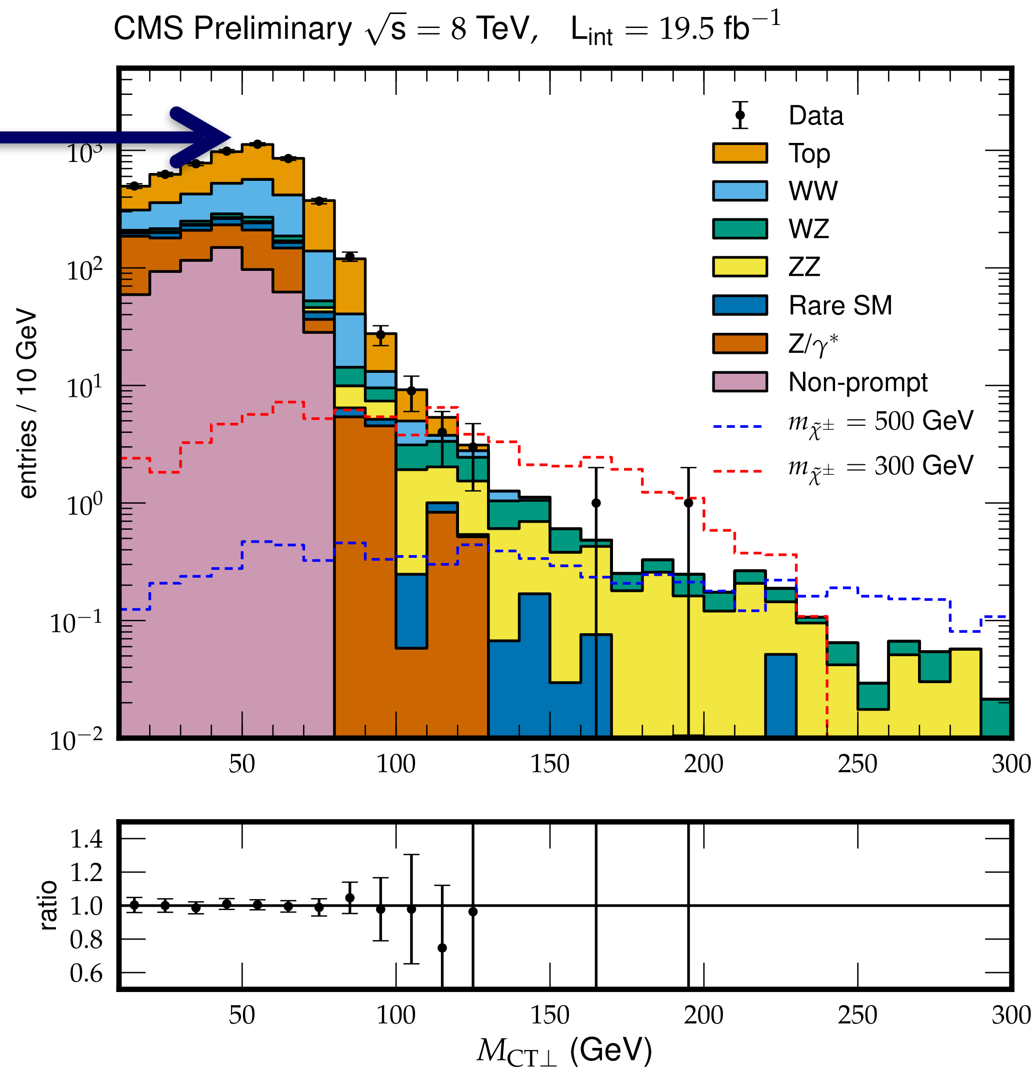
Konstantin T. Matchev and Myeonghun Park. A General method for determining the masses of semi-invisibly decaying particles at hadron colliders. *Phys.Rev.Lett.*, 107:061801, 2011.

M_{CTperp} in practice

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

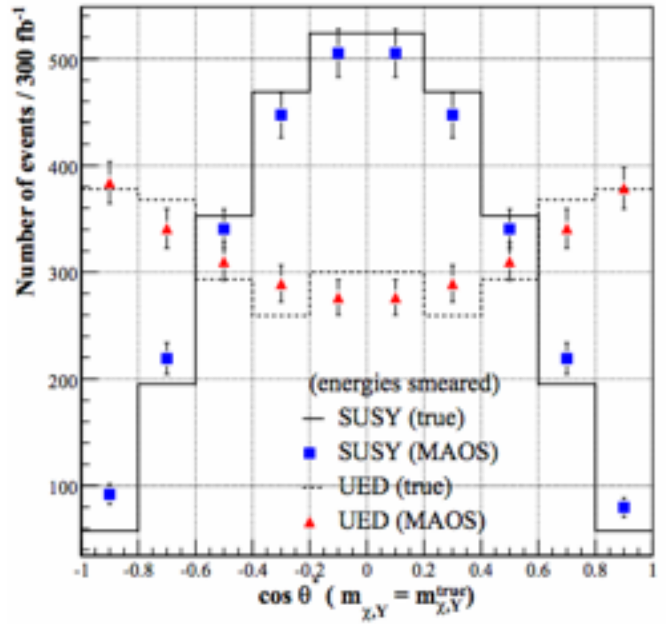
From:

CMS-SUS-PAS-13-006



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?