Weakly-interacting particle kinematics at the LHC and the super-razor variables

Christopher Rogan

HARVARD UNIVERSITY

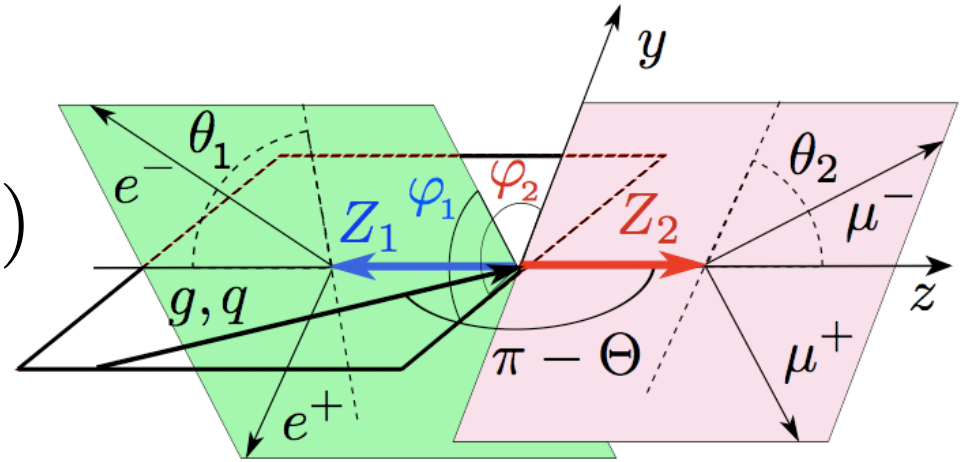
with M. Buckely, J. Lykken and M. Spiropulu

Dark Matter at the LHC, U. of Chicago – Sept. 20 2013

Talk Outline

- Open final states – what and why?
- Event reconstruction challenges
- Super-razor variables by example: slepton pair production and dark matter LSP's
- Outlook

Open vs. closed final states



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

Can calculate all masses, momenta, angles

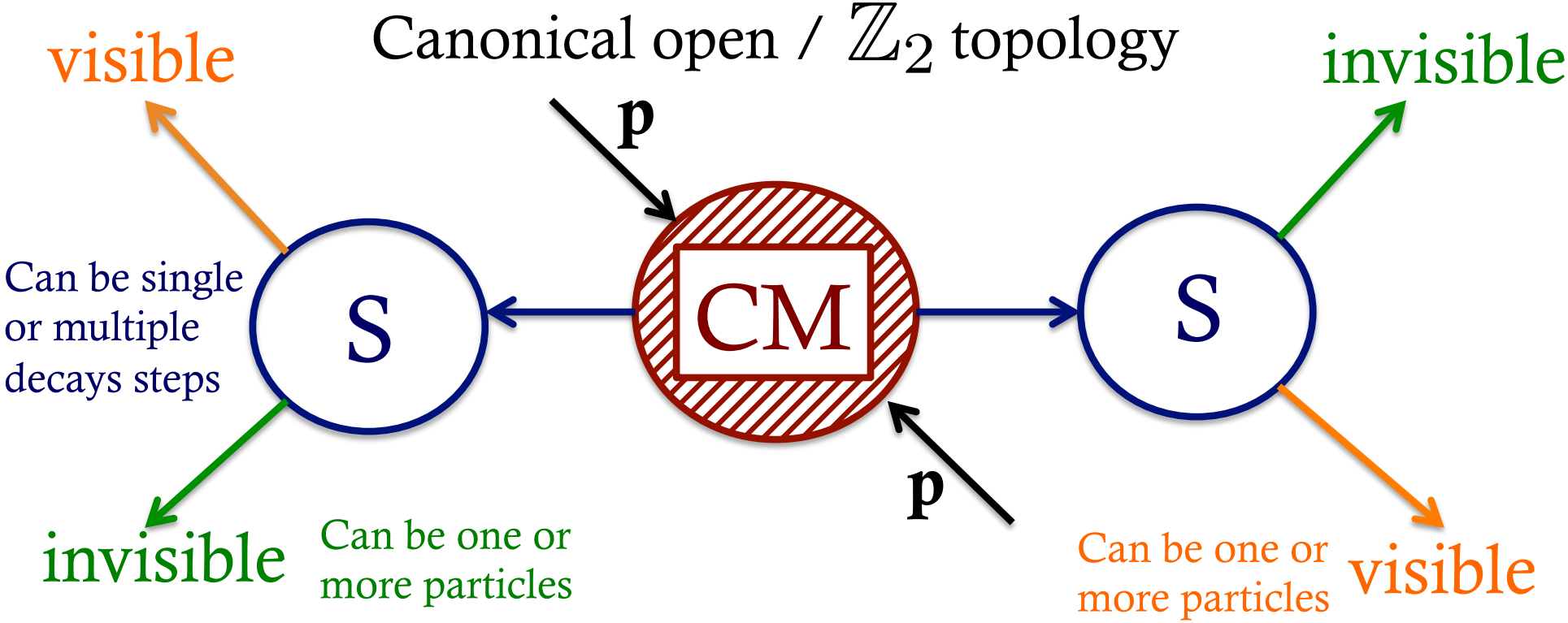
Can use masses for discovery, can use information to measure spin, CP, etc.

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

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?

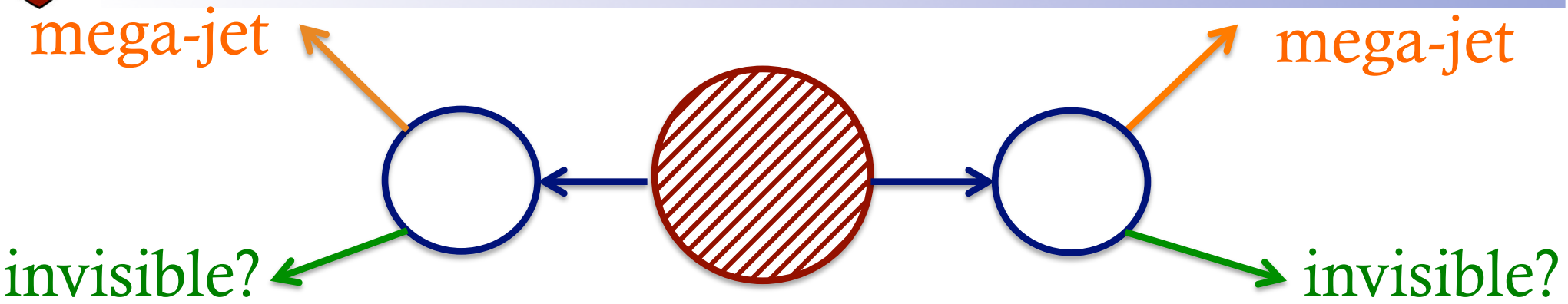
What/why open final states?



- Dark Matter
- Higgs quadratic divergences
- ....

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

Razor kinematic variables

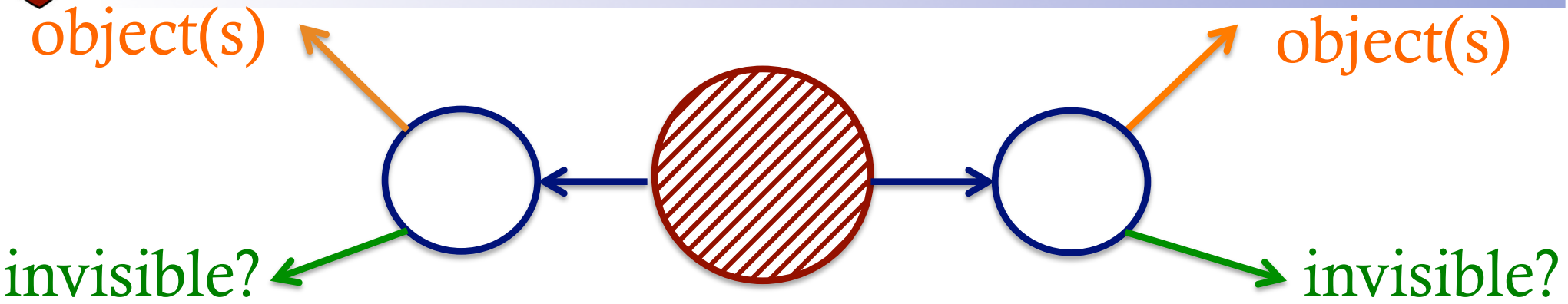


- Assign every reconstructed object to one of two mega-jets
- Analyze the event as a 'canonical' open final state:
  - two variables: M_R (mass scale) , R (scale-less event imbalance)
- An inclusive approach to searching for a large class of new physics possibilities with open final states

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

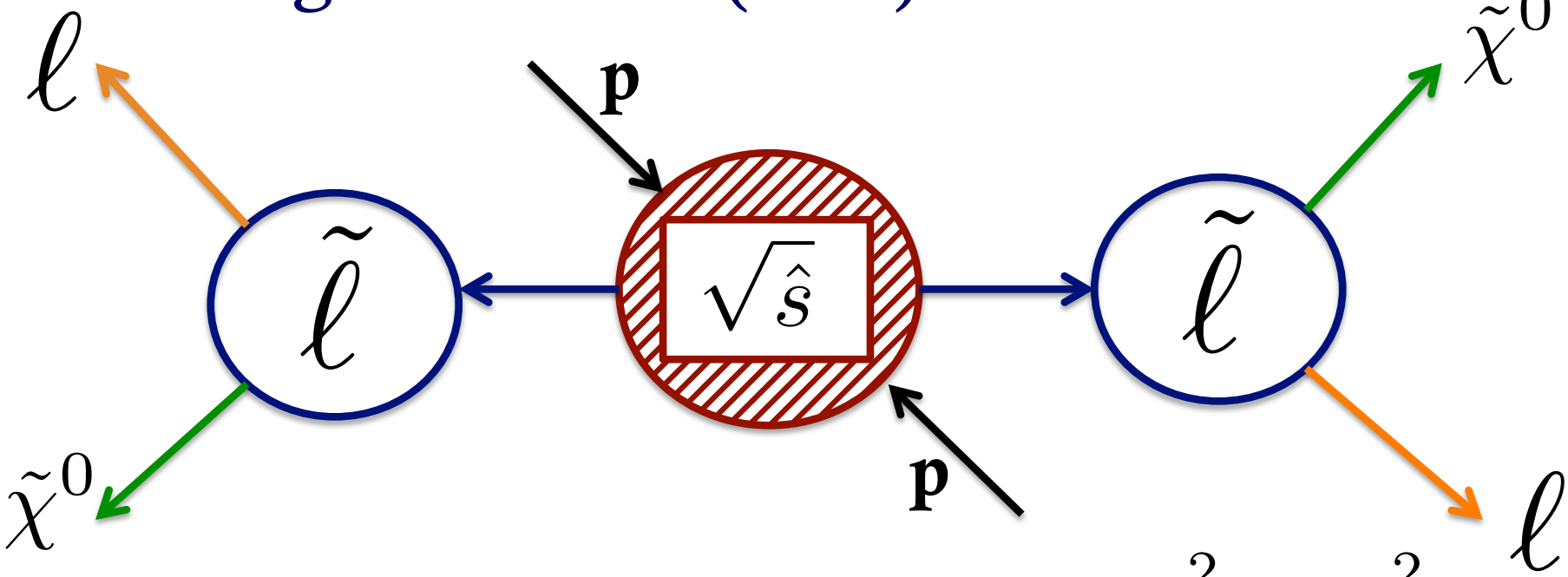
Beyond Razor



- Inclusive approach doesn't:
  - Distinguish between particles/objects coming from the hard scatter 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 glean from an event?

Example: slepton pair-production

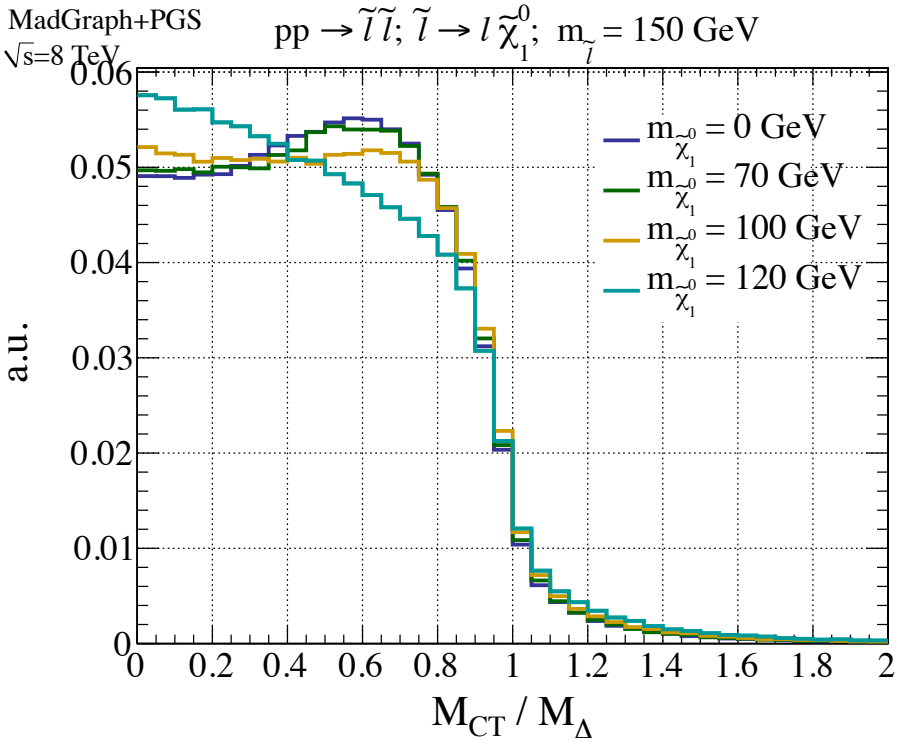
- Each slepton decays to a lepton and a weakly interacting neutralino (LSP)



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

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

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:

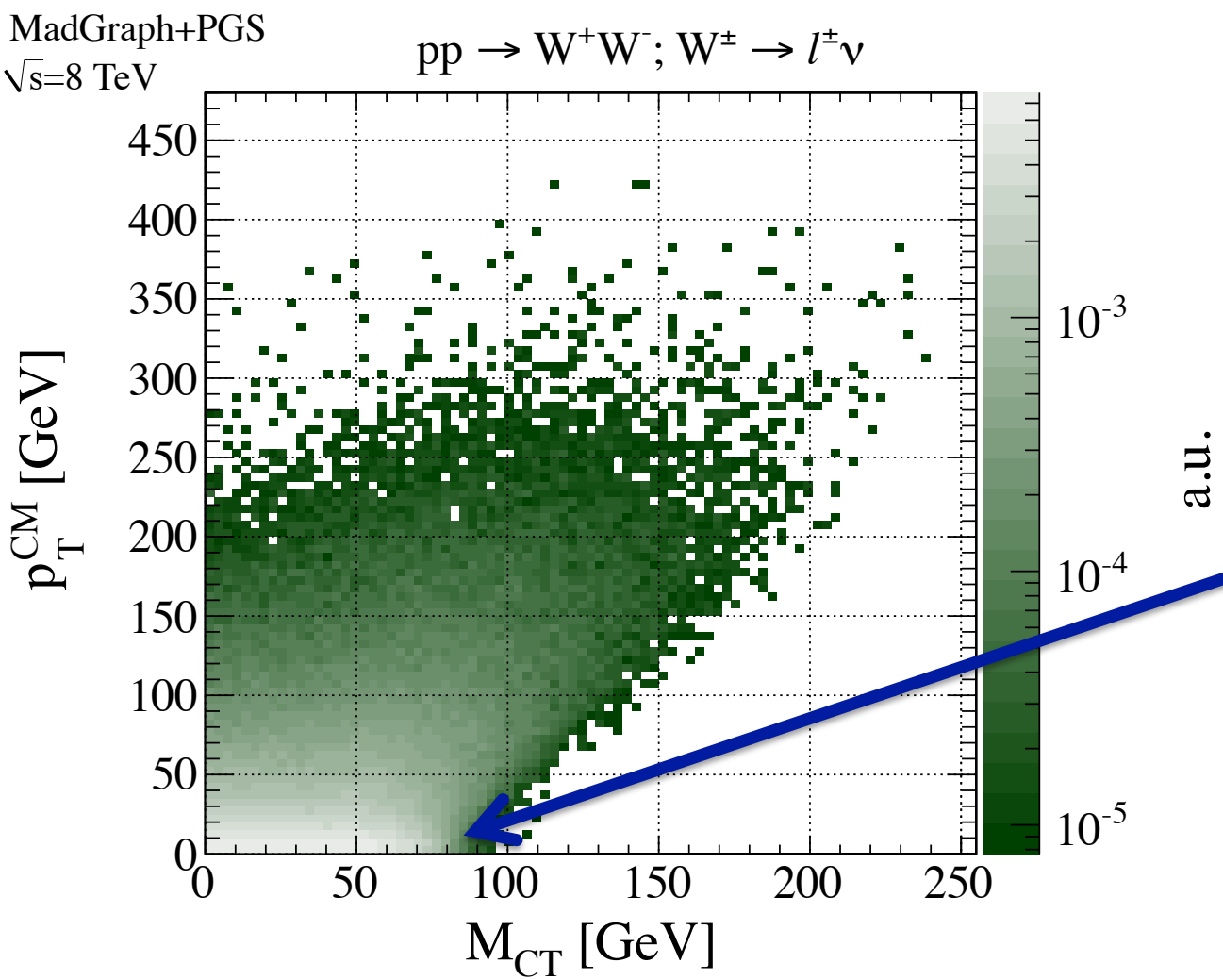
$$M_{CT}^{\max} = \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^0}} = M_\Delta$$

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

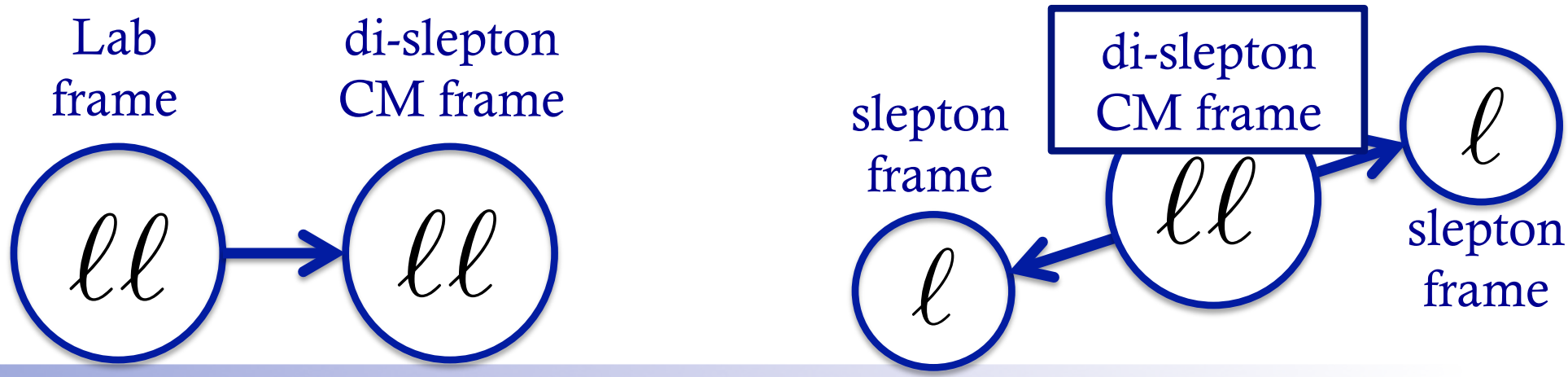
The invariant mass is invariant under coherent Lorentz transformations of two particles

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

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:

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

- 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:

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

x – parallel to boost

y – perp. to boost

with:

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

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

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

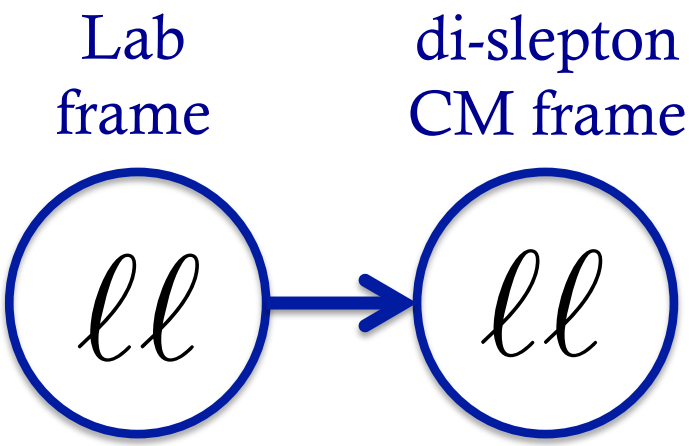
(ii) Only look at event along axis perpendicular to boost: $M_{CT\perp}$

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.

Super-razor variables

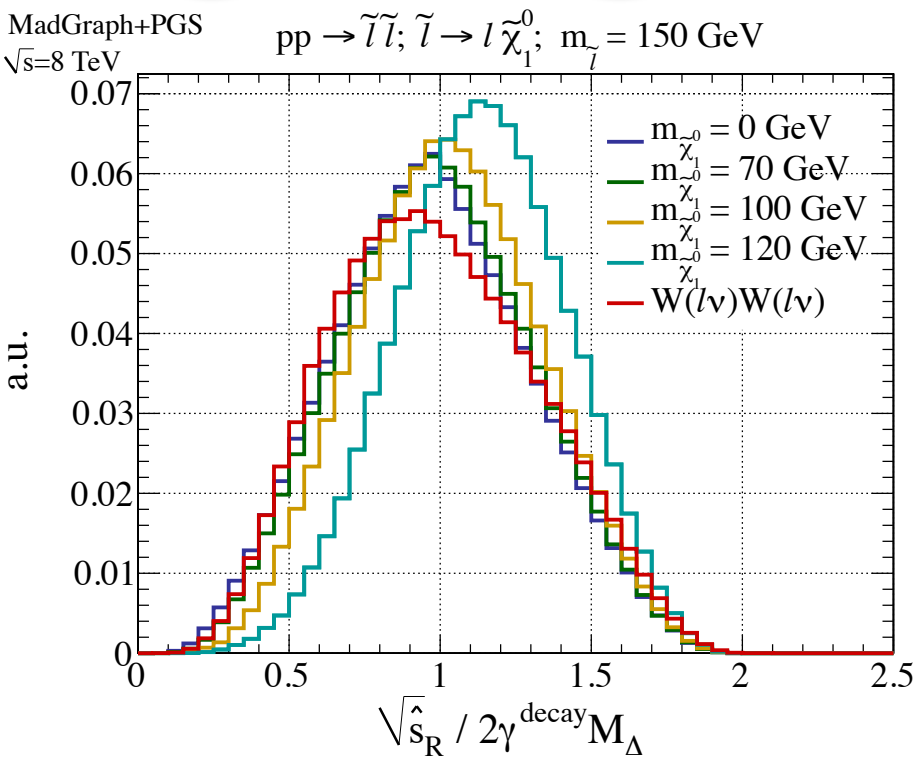
- The strategy is to transform observable momenta iteratively ***reference-frame to reference-frame***, traveling through each of the reference frames relevant to the topology
- At each step, determine the next transformation by making ***boost/contra-boost invariant*** guesses for unknown parameters

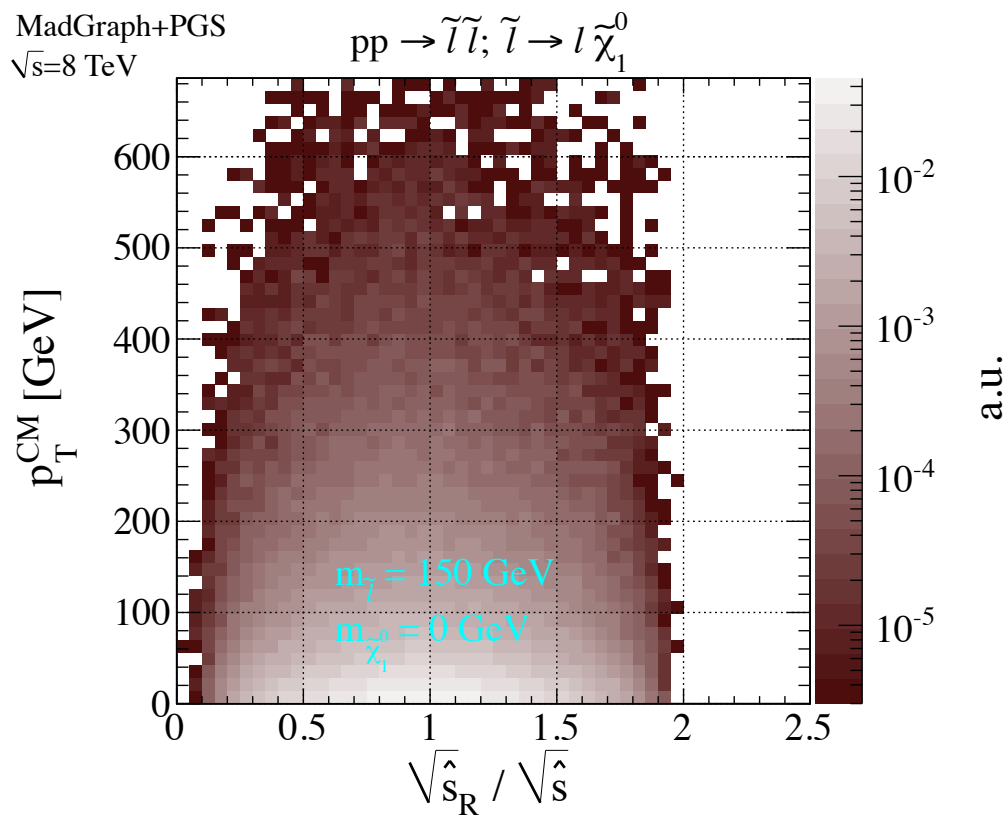
Super-razor variables



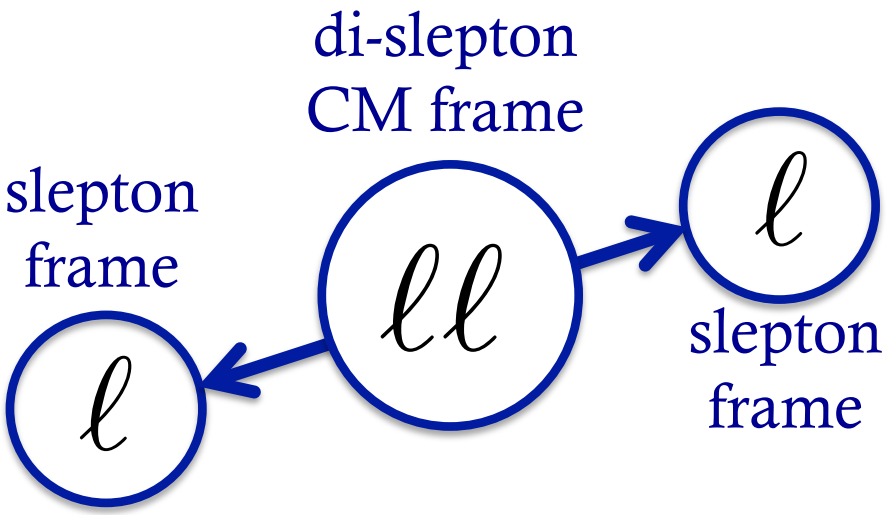
1st transformation: extract variable sensitive to invariant mass of total event: $\sqrt{\hat{s}_R}$

Resulting variable is invariant under pT of CM system!

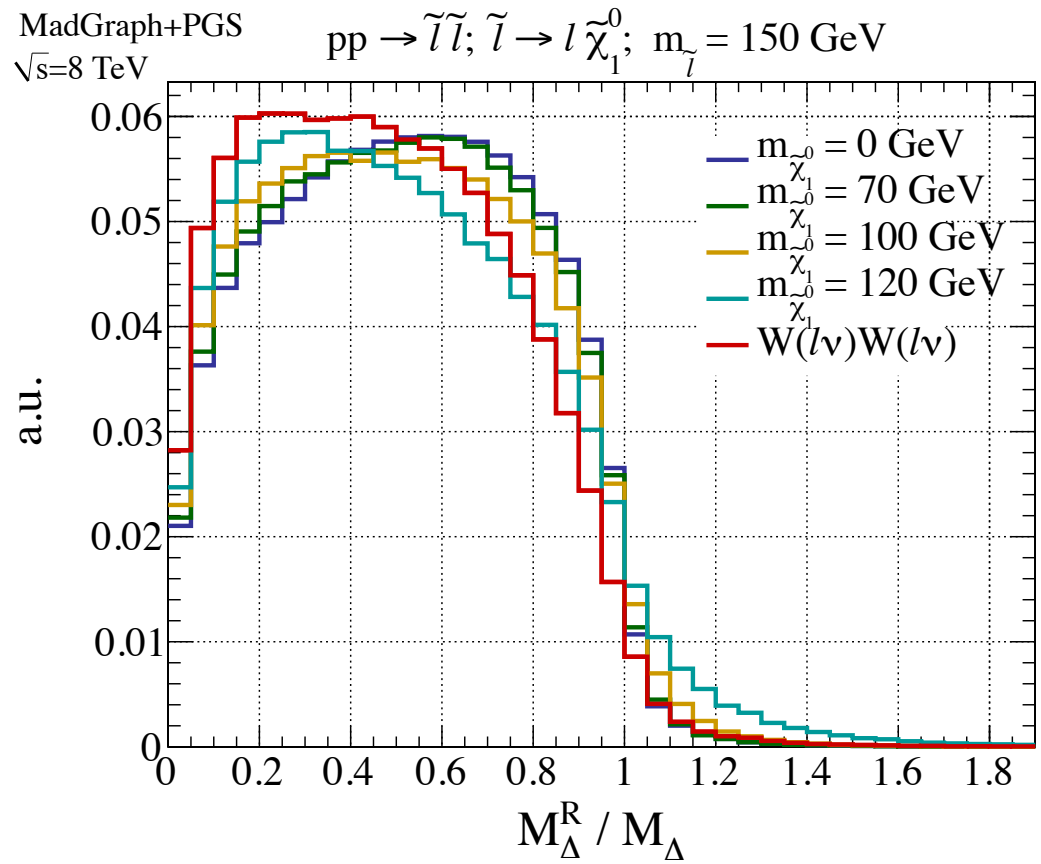




Super-razor variables



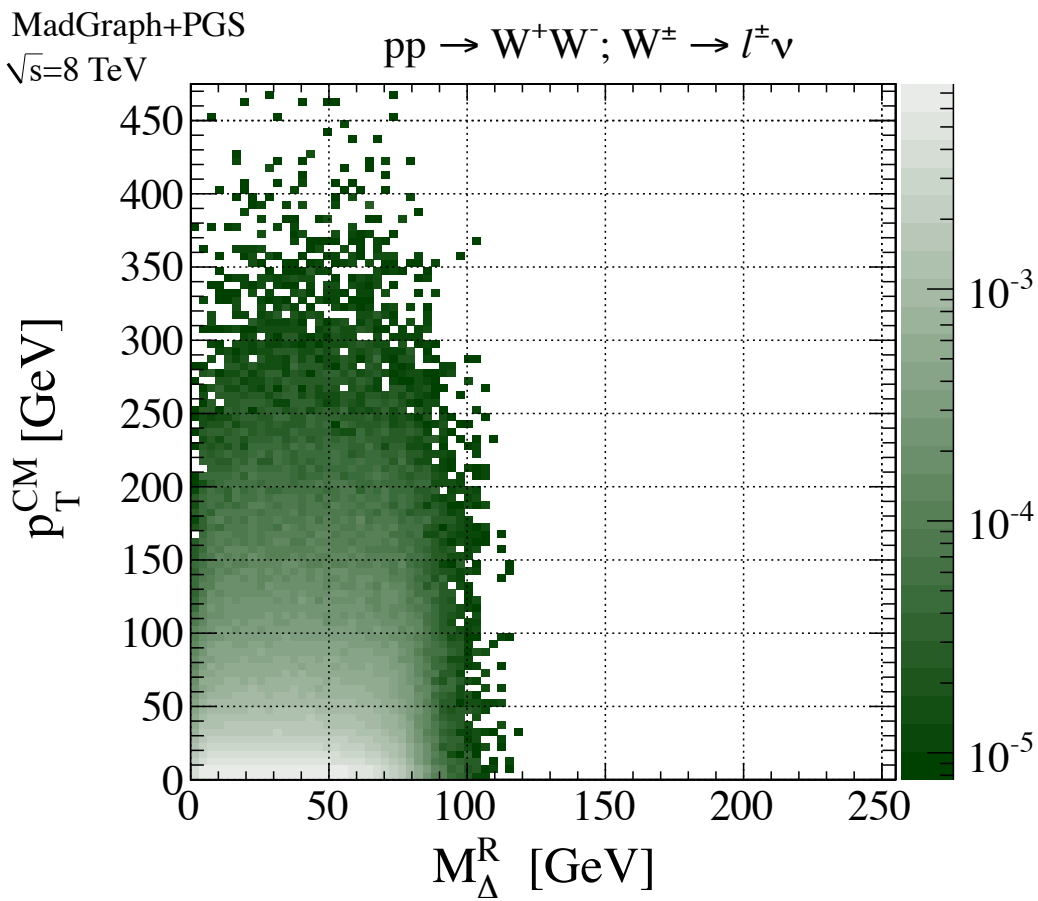
2nd transformation(s): extract variable sensitive to invariant mass of squark: M_Δ^R

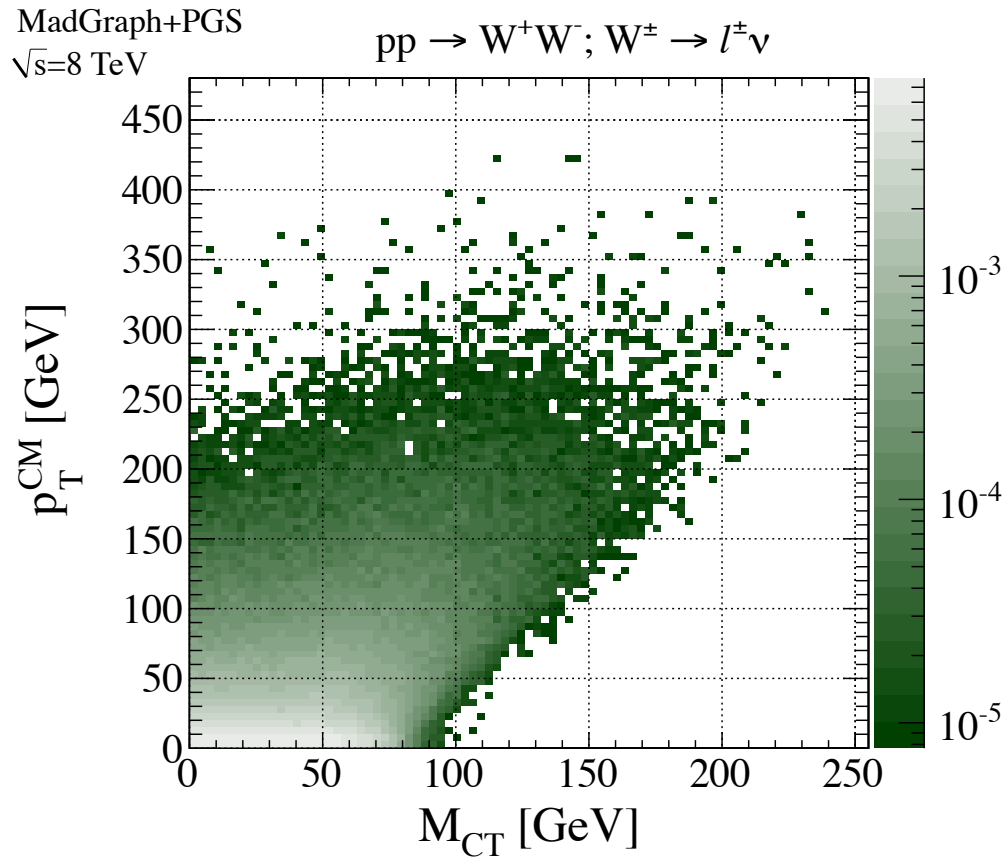


Resulting variable has kinematic endpoint at:

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

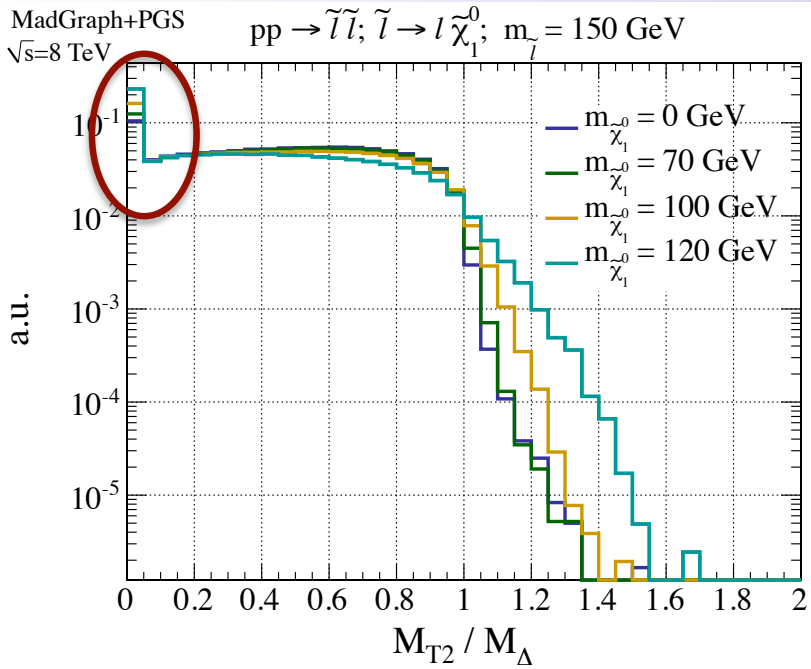
Super-razor variables

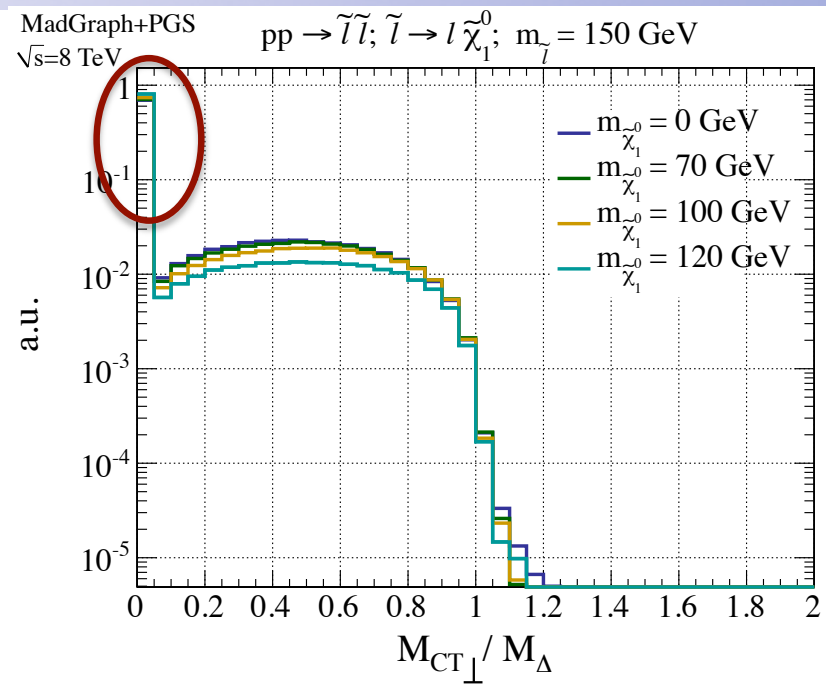


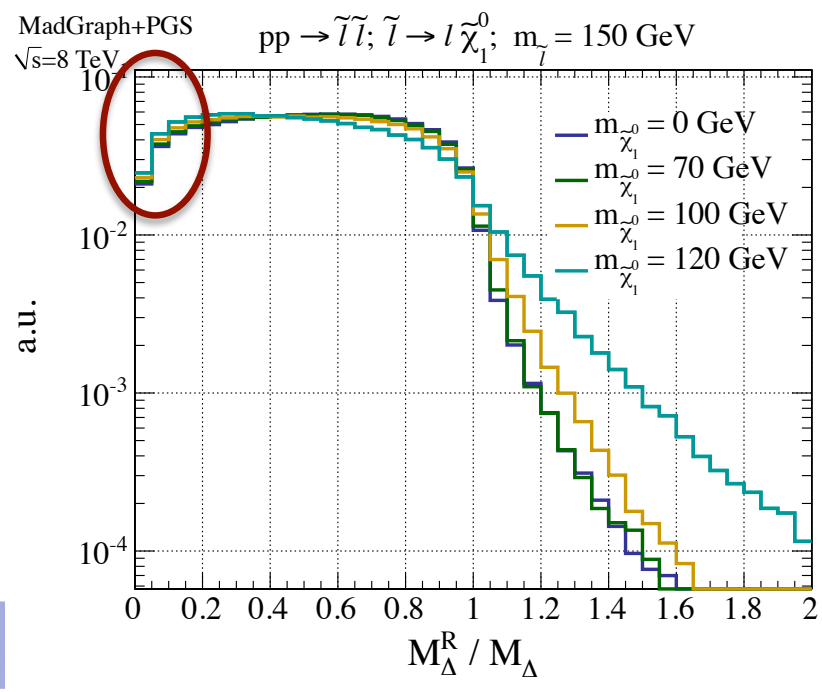


M_Δ^R is a singularity variable – in fact it is essentially identical to M_{CT} but evaluated ***in a different reference frame***. The result is that the new variable is invariant under the previous transformations!

Variable comparison



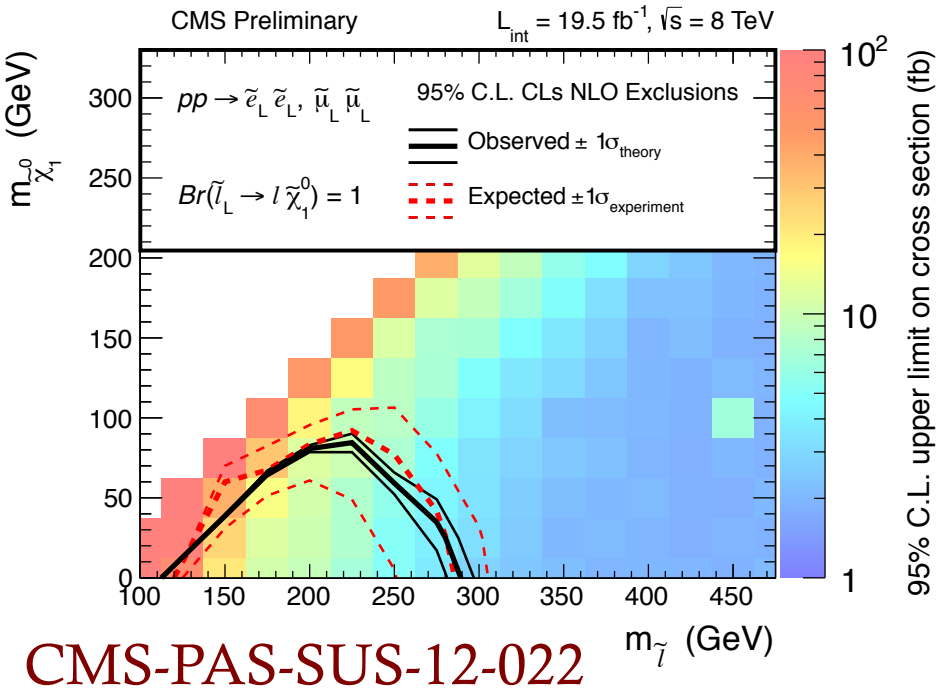




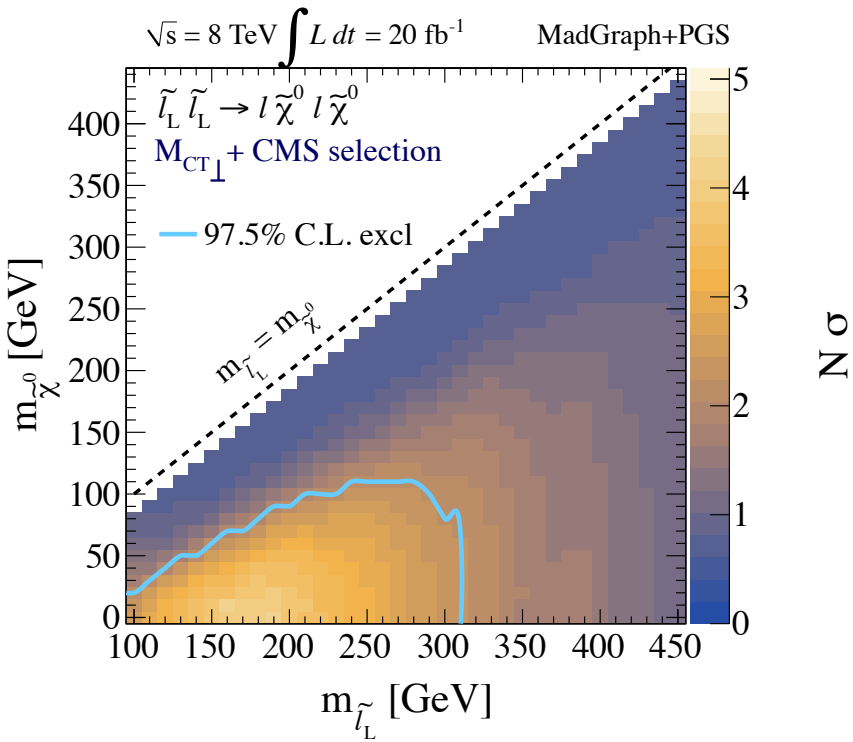
Three different singularity variables, all attempting to measure the same thing
Which is the best? Why?

MC analysis implemented with ATLAS and CMS-like selections to compare variables (see backup)

Results validation



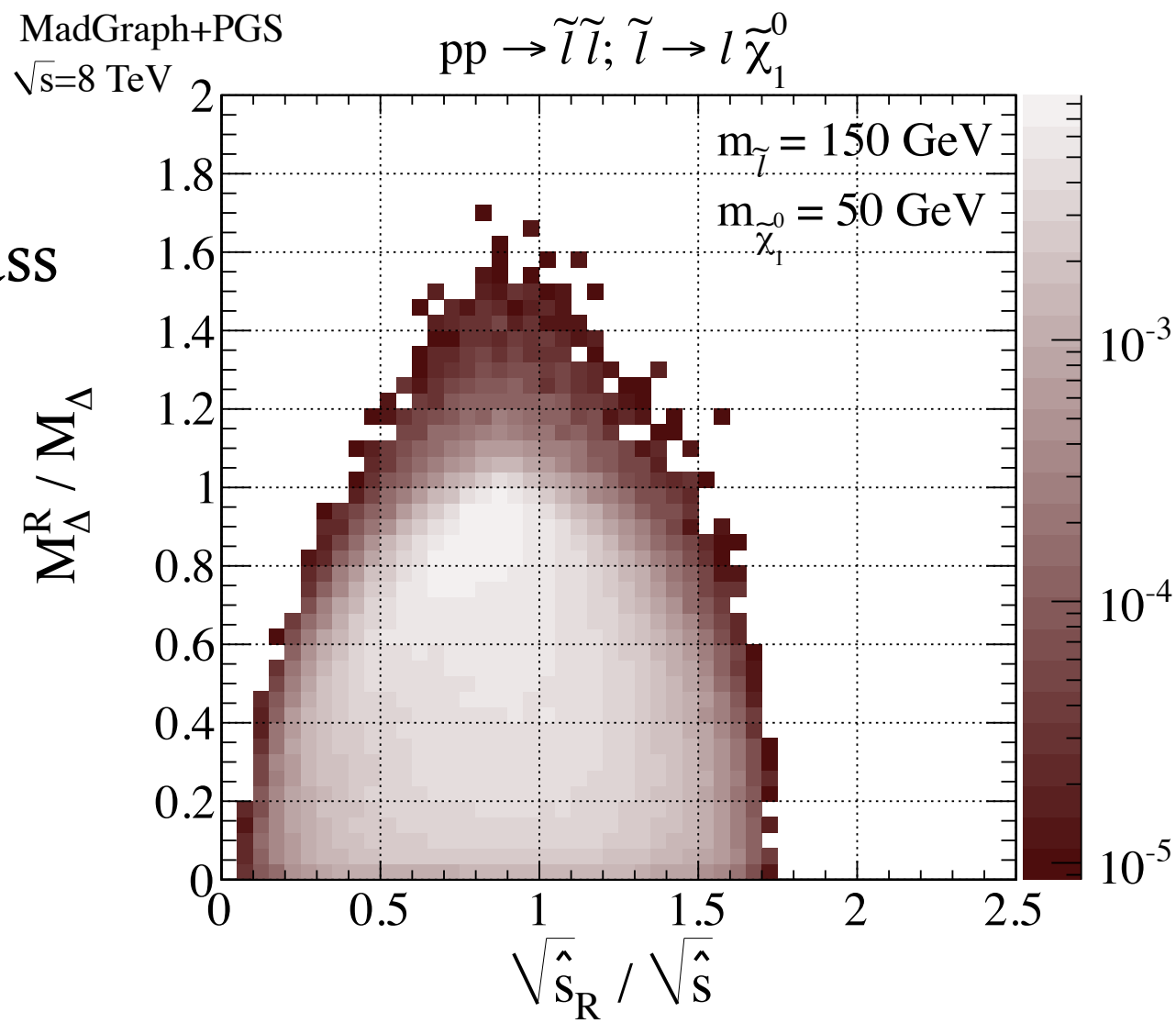
CMS-PAS-SUS-12-022



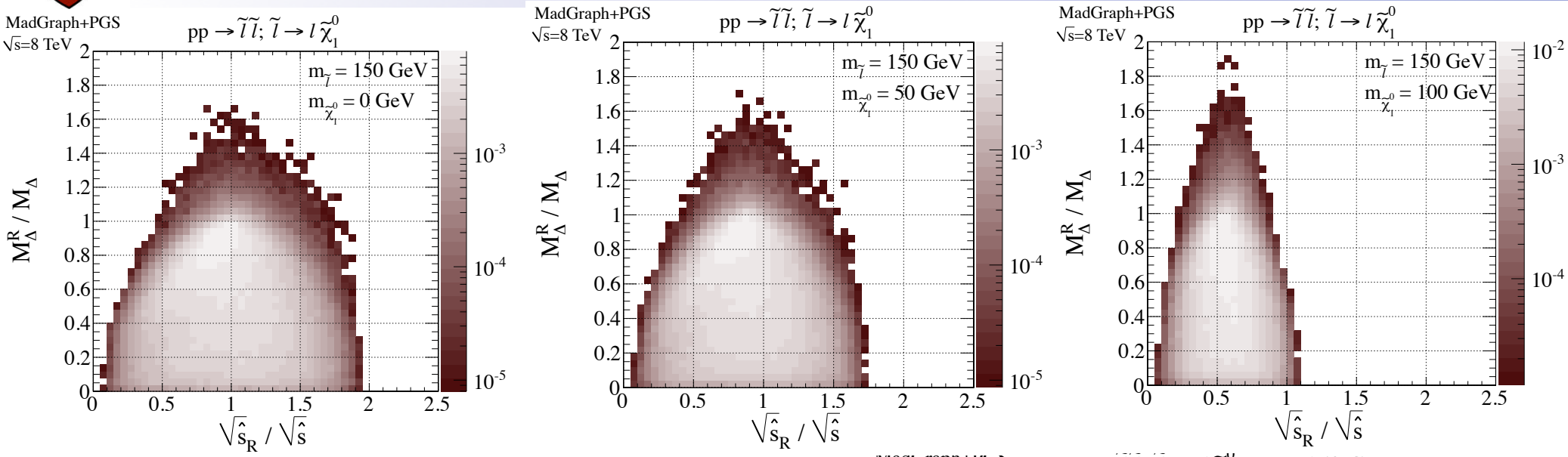
See Matt Buckley's talk (next) for results of this variable comparison for both slepton and chargino pair-production!

But what else can we calculate?

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



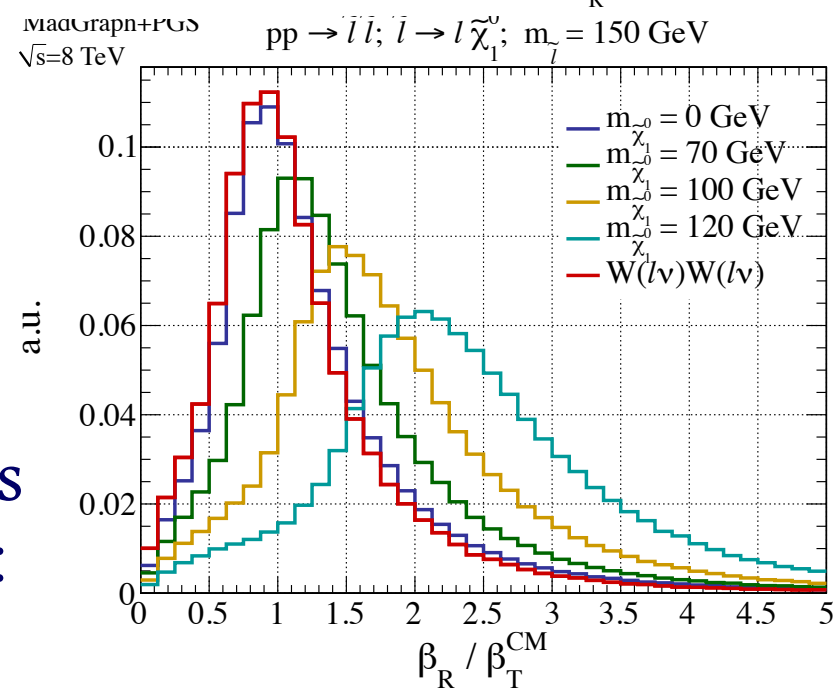
But what else can we calculate?



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

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

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

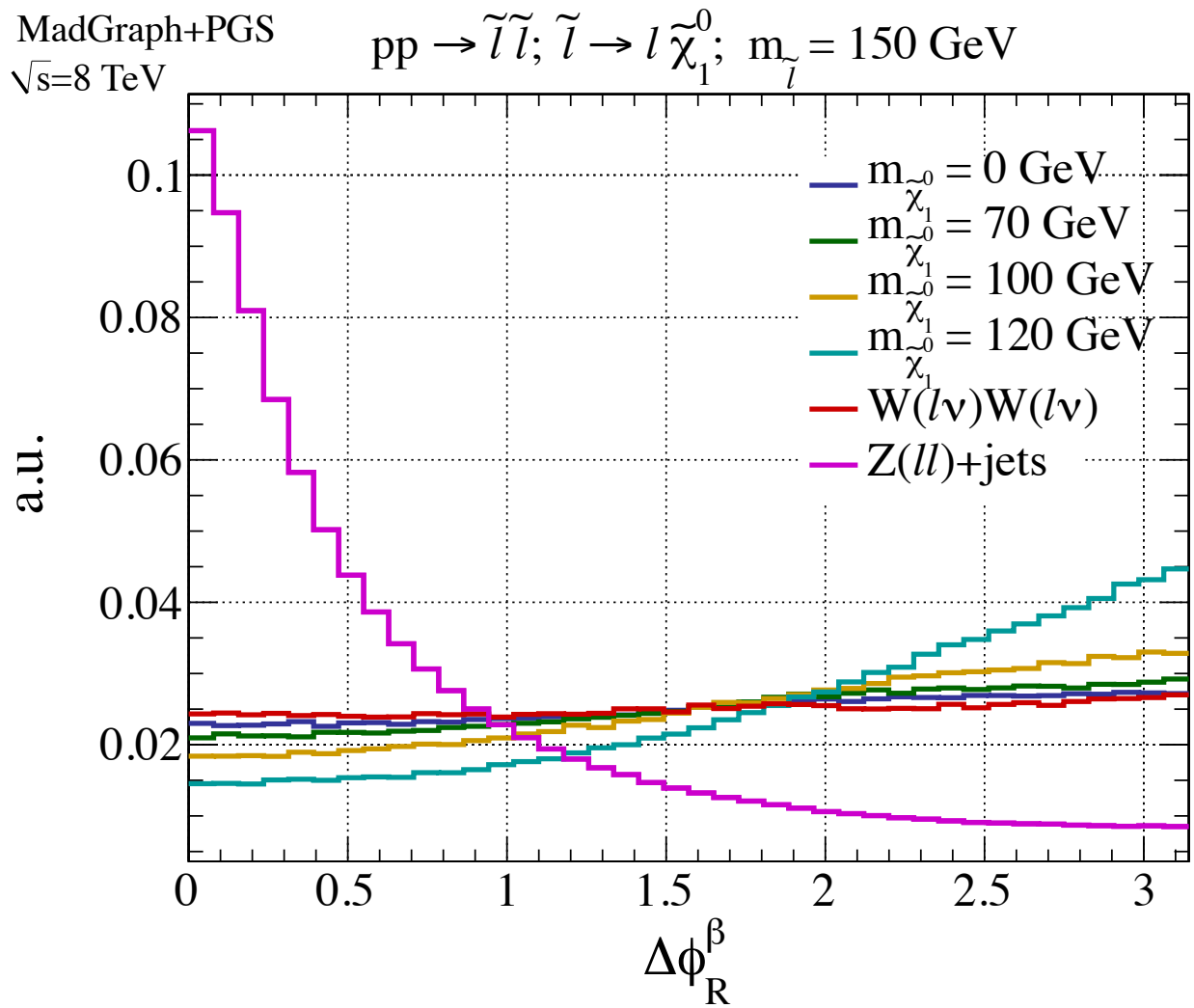


Angles, angles, angles…

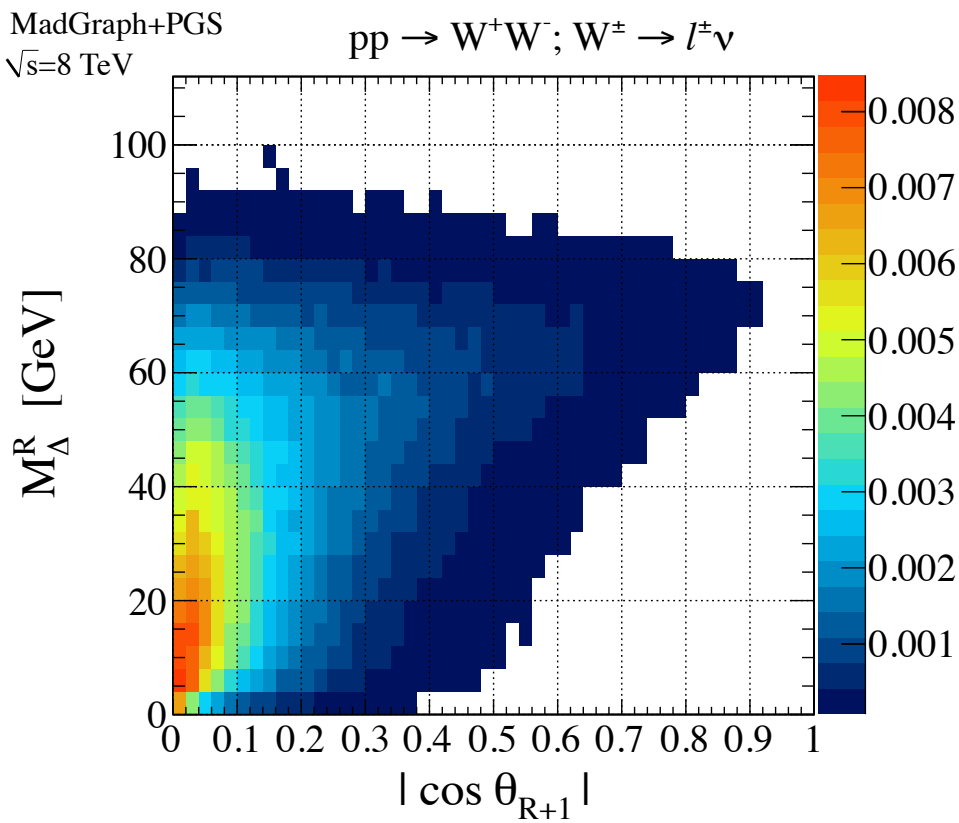
Angle between lab ➔ CM frame boost and di-leptons in CM frame is sensitive to

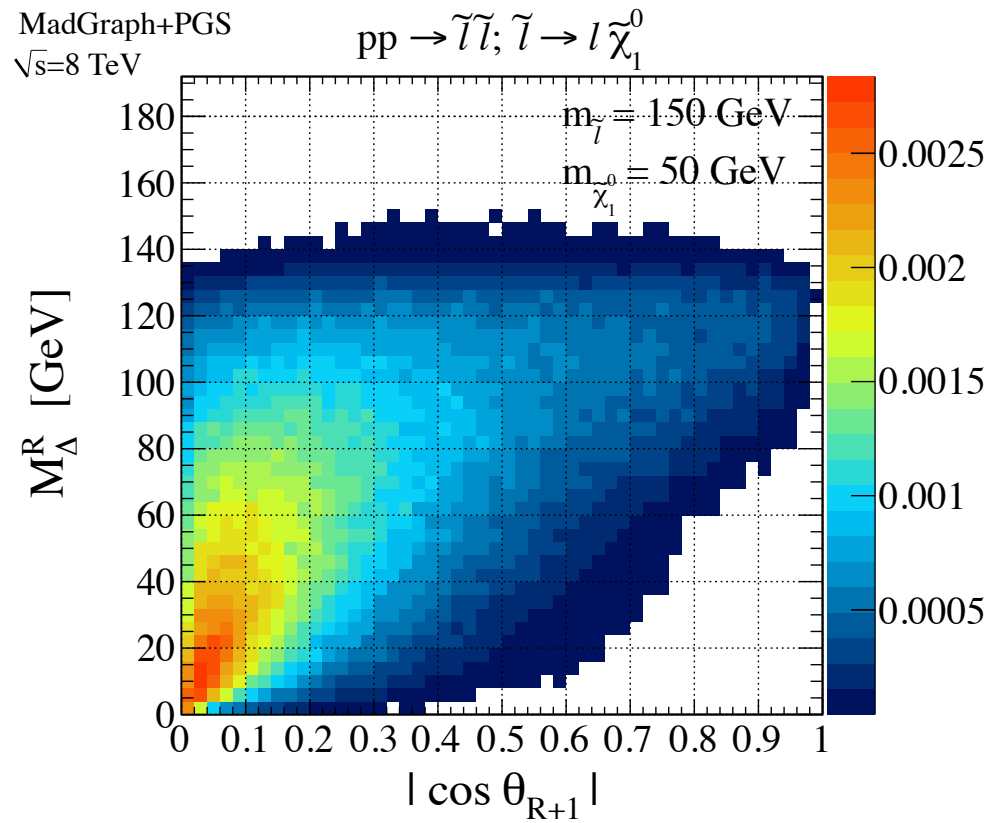
$$\frac{m_\chi}{m_{\tilde{\ell}}} \text{ rather than } M_\Delta$$

~Uncorrelated with other kinematic variables!



Angles, angles, angles…

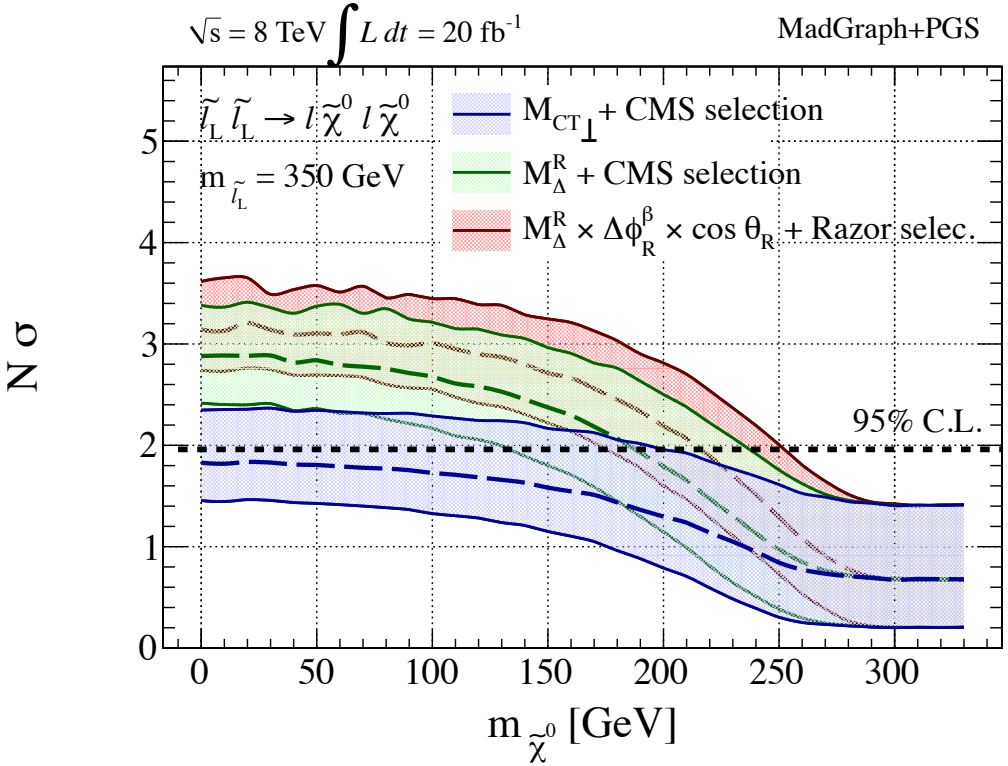




Approximation of slepton helicity angle sensitive to particle spin!

Also allows us to better resolve the kinematic endpoint of interest

Super-razor variables



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

Can improve sensitivity while removing MET cuts!

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

$\Delta\phi^\beta_R$ Ratio of invis. to vis. masses

M^R_Δ Mass-squared difference
resonant/non-resonant prod.

$|\cos\theta_R|$ spin correlations, better
resolution of mass edge

Summary

- not only develop 'good' mass estimator variables, but to decompose each event into a ***basis of kinematic variables***
- Through iterative 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***
- Applicable to a wide range of signals

BACKUP SLIDES

A Monte Carlo analysis to compare

- Baseline Selection
  - 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

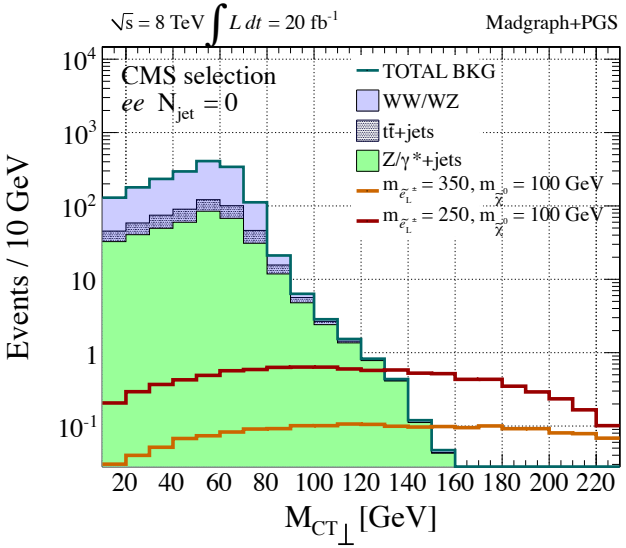
'ATLAS selection'

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

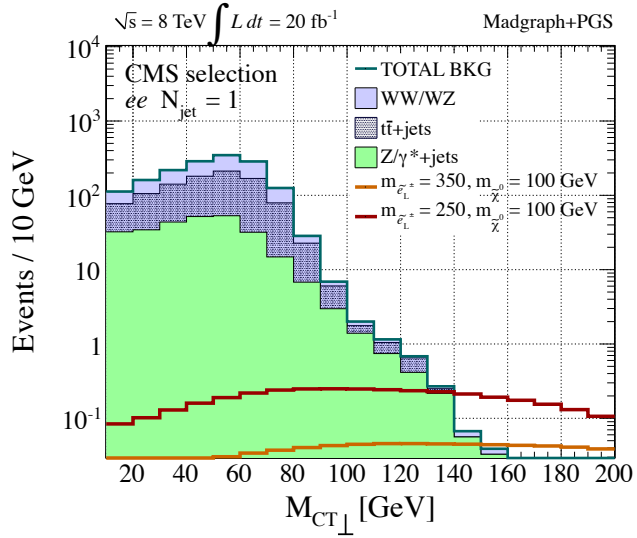
$$E_{\mathrm{T}}^{\mathrm{miss,rel.}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases} > 40 \text{ GeV}$$

ATLAS-CONF-2013-049

1D Shape Analysis



+



+ Other jet multiplicity and lepton flavor categories

- 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

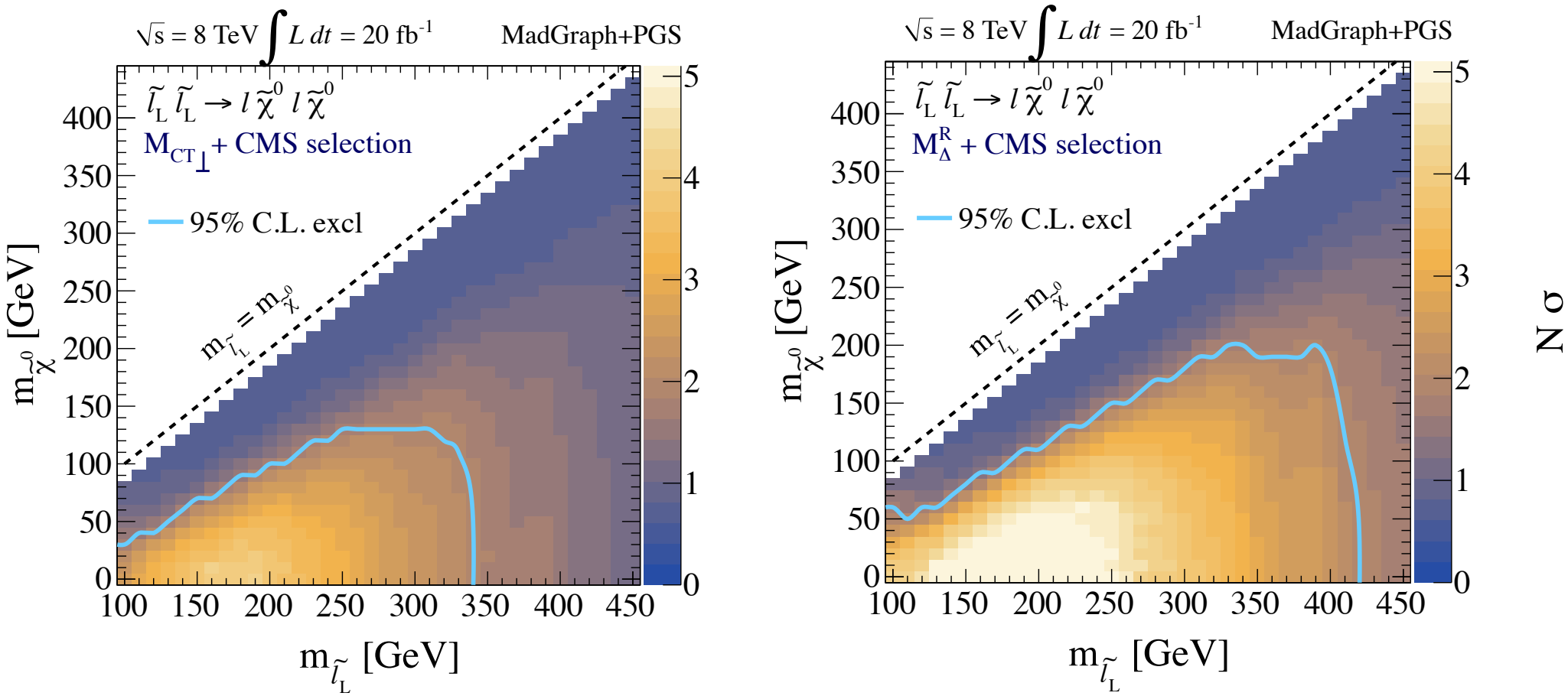
$$(ee, \mu\mu, e\mu) \times (0, 1, \geq 2 \text{ jets}) \quad \text{with } p_T^{jet} > 30 \text{ GeV}/c, \ |\eta^{jet}| < 3$$

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

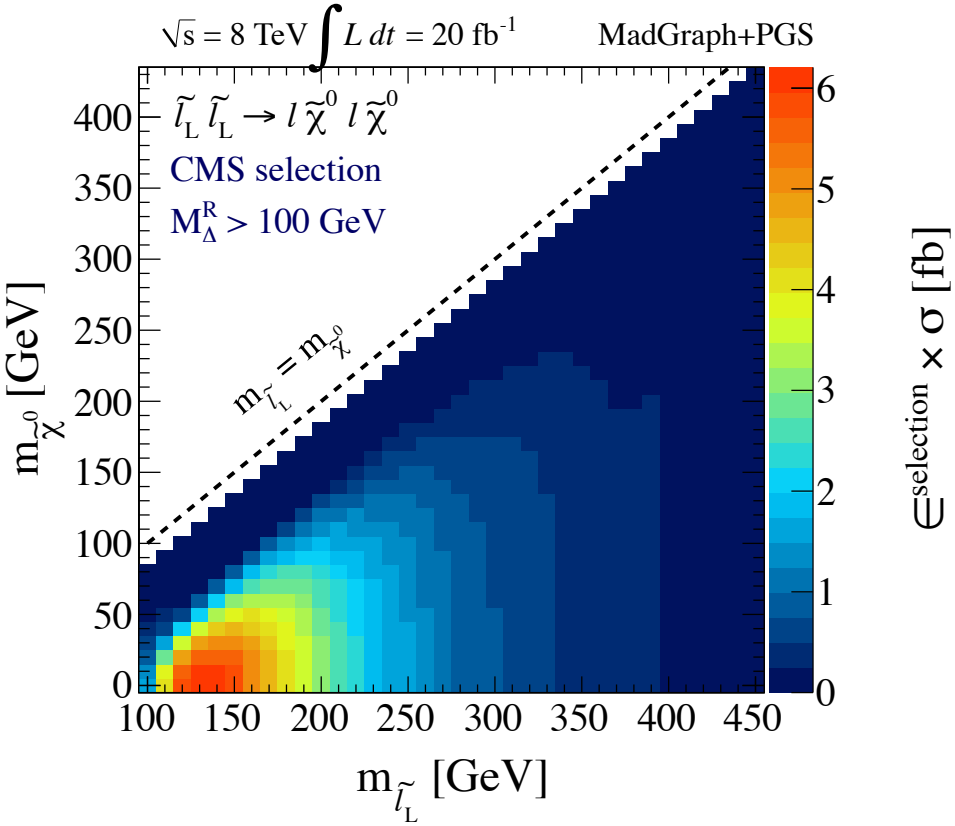
Systematic uncertainties

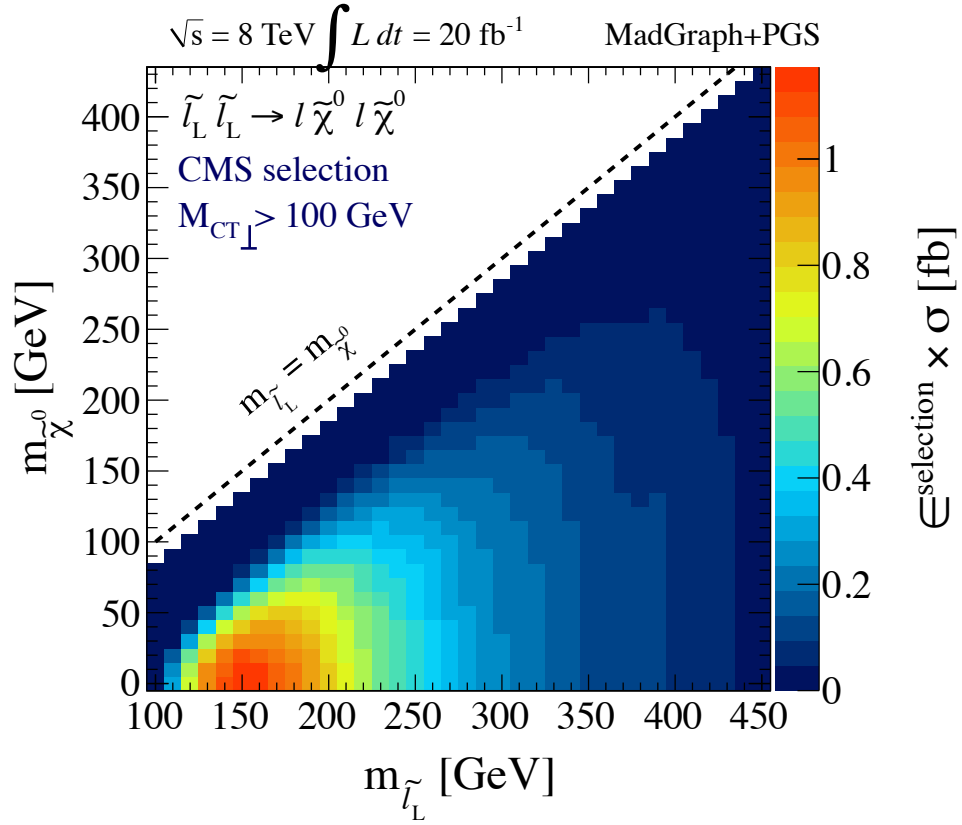
- 2% lepton ID (correlated btw bkgs, uncorrelated between lepton categories)
- 10% jet counting (per jet) (uncorrelated between all processes)
- 10% x-section uncertainty for backgrounds (uncorrelated) + theoretical x-section uncertainty for signal (small)
- 'shape' uncertainty derived by propagating 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)

Expected Limit Comparison



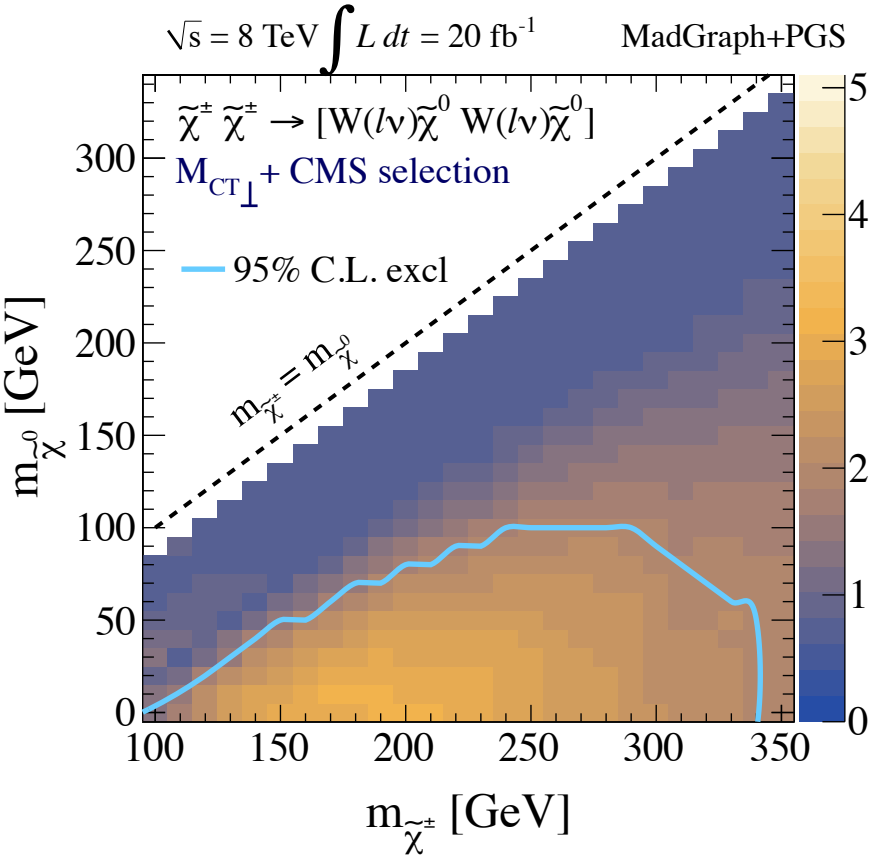
Where does improvement come from?

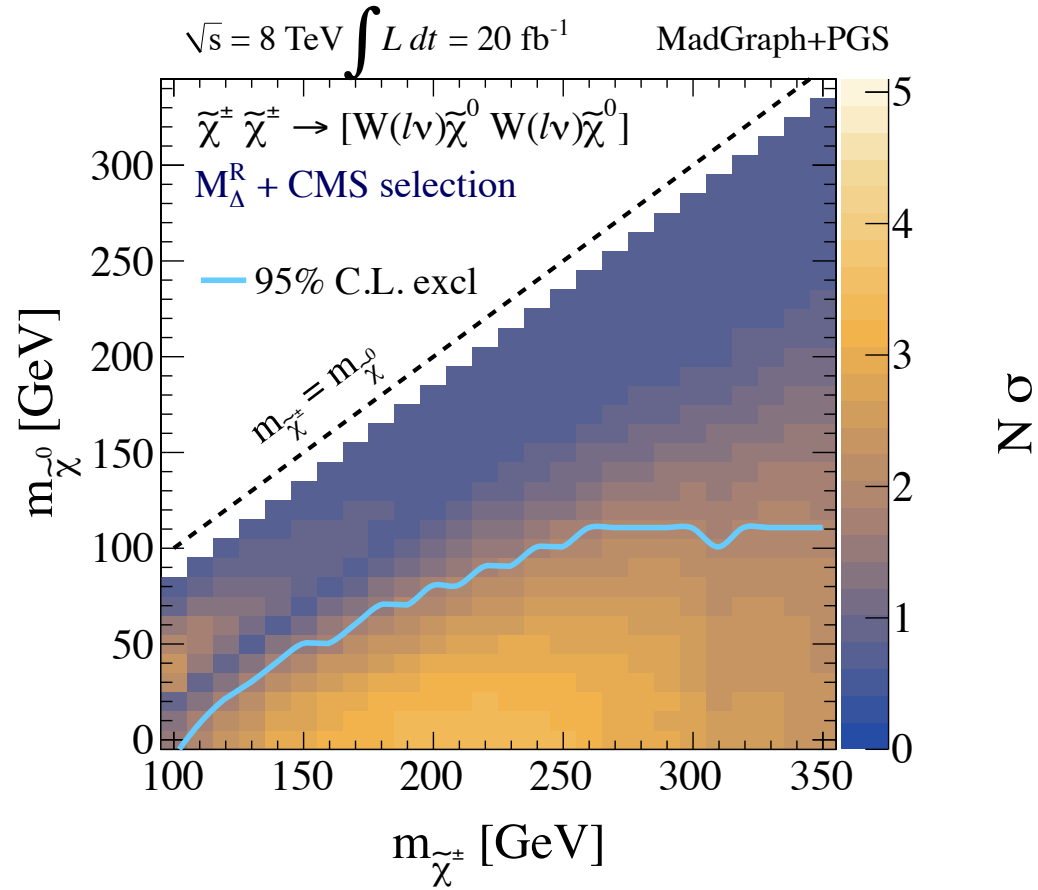




No accumulation of events in 'zero' bin ➔ large increase in signal efficiency in small background region of phase-space

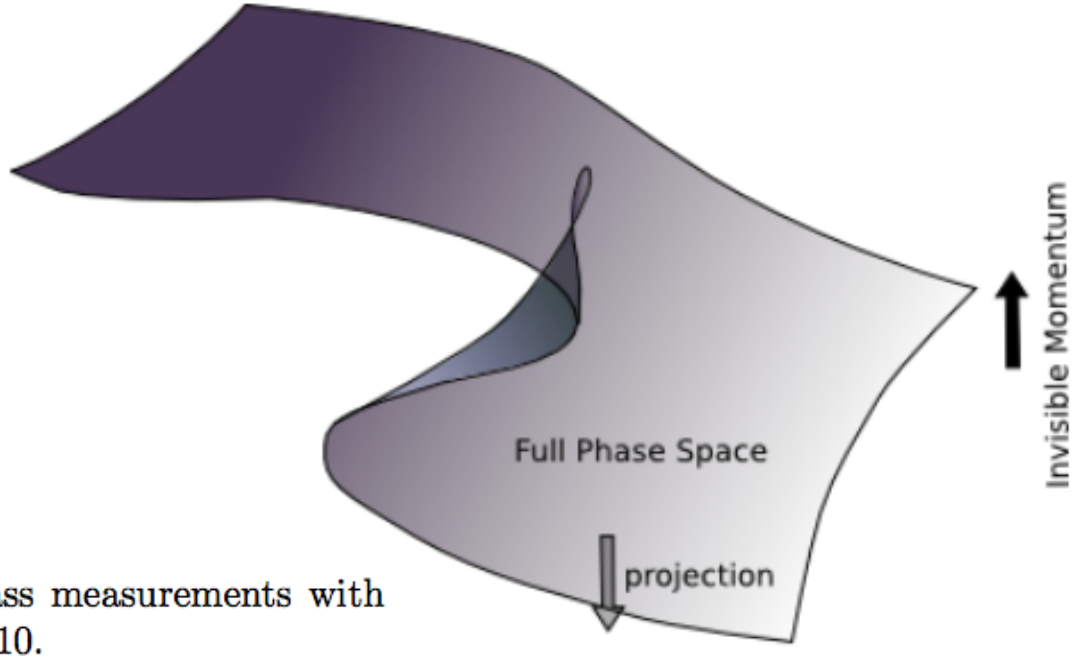
Charginos


$\sqrt{s}$ = 8 TeV $\int L\,dt$ = 20 fb^{-1}
MadGraph+PGS
$\tilde{\chi}^{\pm}\tilde{\chi}^{\pm} \rightarrow [W(l\nu)\tilde{\chi}^{0}\ W(l\nu)\tilde{\chi}^{0}]$
$M_{CT\perp}$ + CMS selection
95% C.L. excl
$m_{\tilde{\chi}^{\pm}} = m_{\tilde{\chi}^{0}}$
$m_{\tilde{\chi}^{0}}$ [GeV]
$m_{\tilde{\chi}^{\pm}}$ [GeV]
N σ


$\sqrt{s}$ = 8 TeV $\int L\,dt$ = 20 fb^{-1}
MadGraph+PGS
$\tilde{\chi}^{\pm}\tilde{\chi}^{\pm} \rightarrow [W(l\nu)\tilde{\chi}^{0}\ W(l\nu)\tilde{\chi}^{0}]$
M_{Δ}^{R} + CMS selection
95% C.L. excl
$m_{\tilde{\chi}^{\pm}} = m_{\tilde{\chi}^{0}}$
$m_{\tilde{\chi}^{0}}$ [GeV]
$m_{\tilde{\chi}^{\pm}}$ [GeV]
N σ

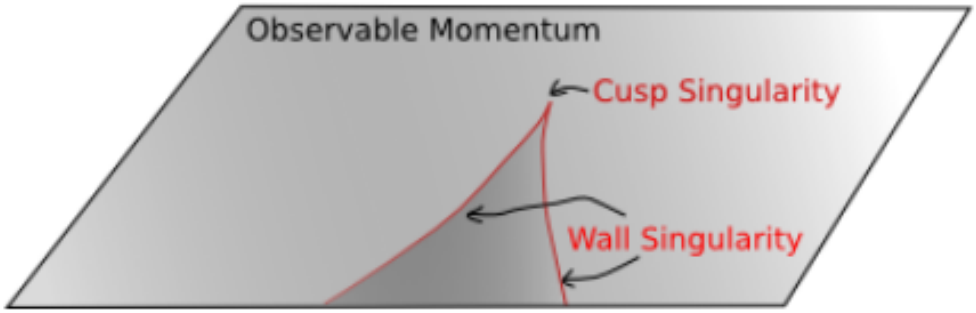
Singularity variables

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.



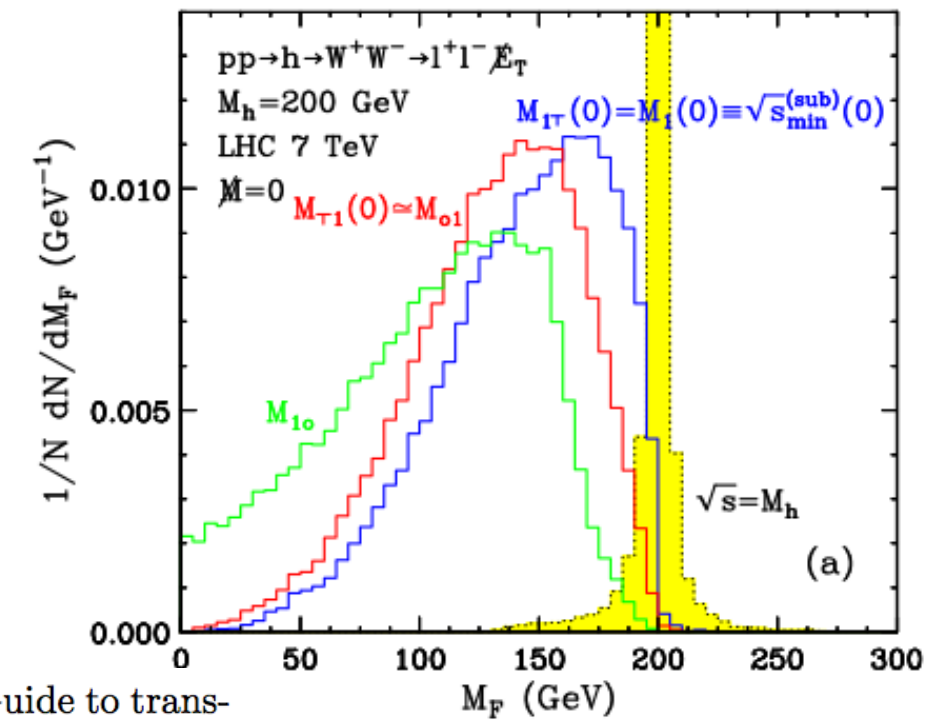
From:

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



Singularity variables

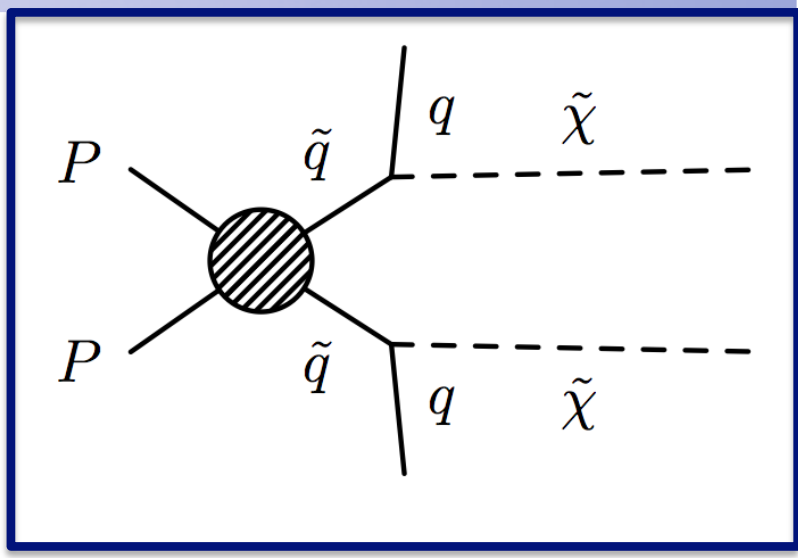
The guiding principle we employ for creating useful hadron-collider event variables, is that: *we should place the best possible bounds on any Lorentz invariants of interest, such as parent masses or the center-of-mass energy $\hat{s}^{1/2}$, in any cases where it is not possible to determine the actual 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: M_{T2}



Extremization of unknown degrees of freedom

LSP 'test mass'

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

Subject to constraints

with: $m_T^2(\vec{p}_T[q_1],\vec{p}_T[\chi_1],\mu_\chi) = m_q^2 + \mu_\chi^2 + 2\left(E_T[q_1]E_T[\chi_1] - \vec{p}_T[q_1]\cdot\vec{p}_T[\chi_1]\right)$

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

From:

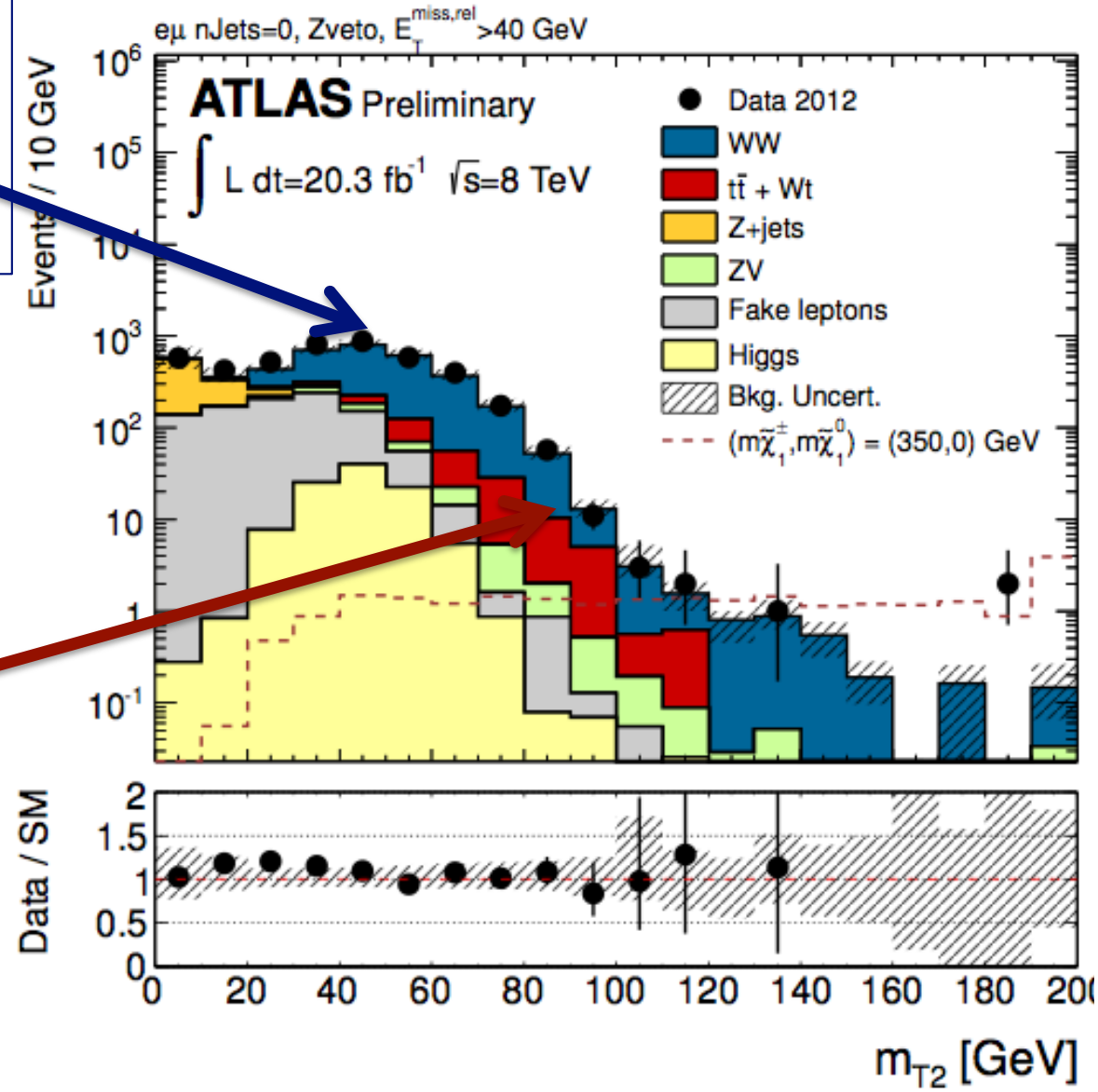
C.G. Lester and D.J. Summers. Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders. *Phys.Lett.*, B463:99–103, 1999.

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 lost due to resolution effects, incorrect test mass, ISR, + many other effects….