Using the MET cone for mass measurement at the LHC

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arXiv:1009.1148 and in preparation

Mass measurement at Hadron colliders

- Many models, particularly those that could be responsible for providing dark matter provide only “incomplete” event information due to one or more missing particles in the event
- Reconstruction of such events is a priority, but a difficult task
- At the dawn of the LHC, much progress has been made, but more needs to be done

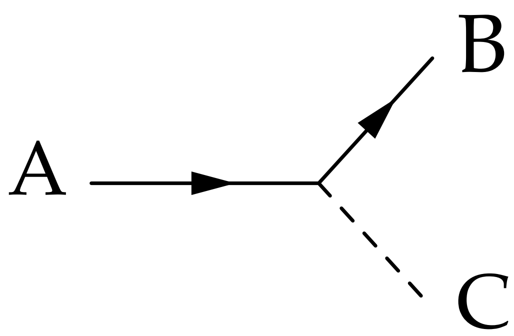
Model independence

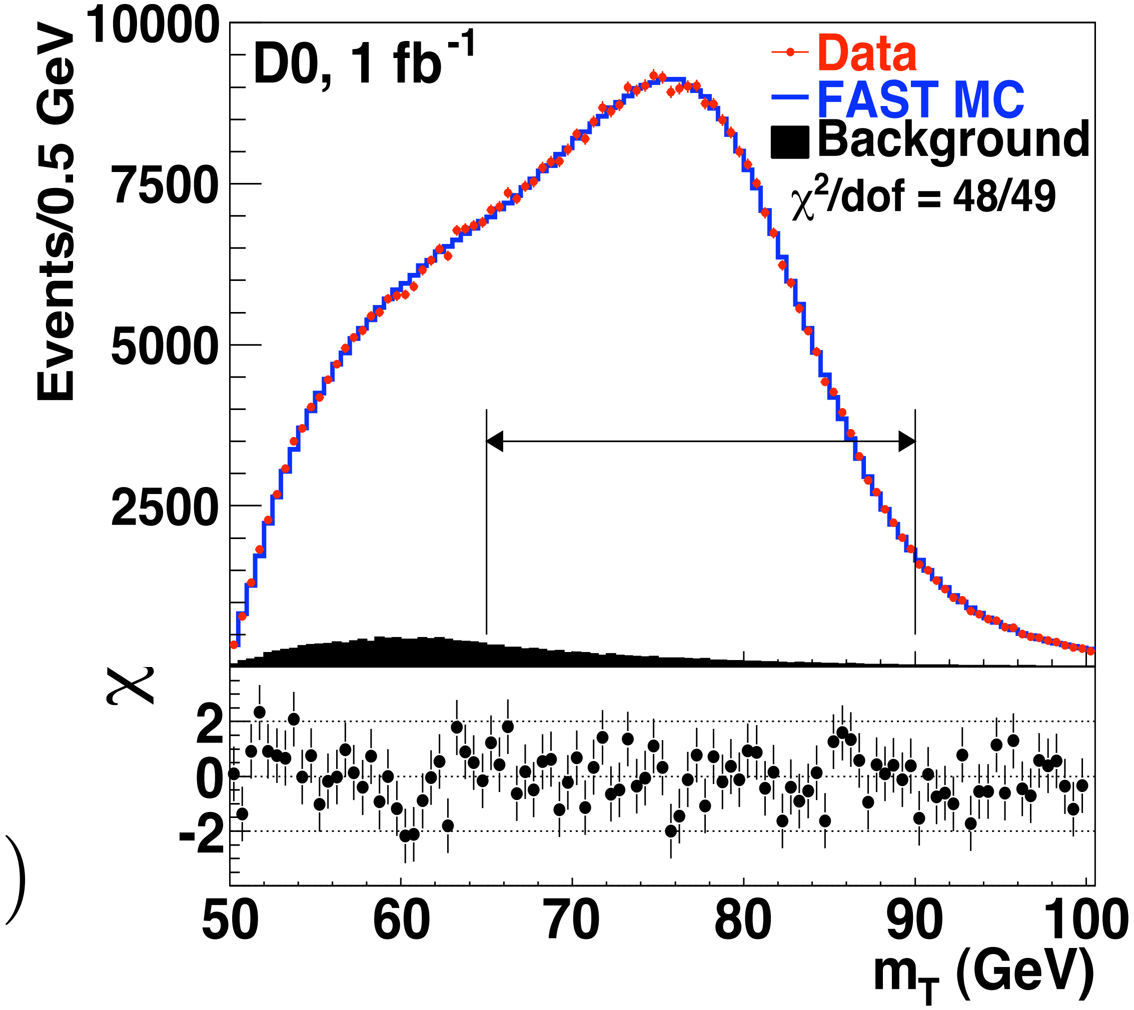
- Methods which are model independent, i.e. which exploit on-shell kinematic constraints are ideal
  - peaks, edges/endpoints, cusps
  - features of simplified models/topologies
- we should search for such features in events with missing transverse momentum
  - the more independent constraints we have, the better
    - nail down spectrum, quantum numbers, rule out topology hypotheses

Edges

D0 - 0908.0766

Transverse mass





$$M_T^2 \equiv m_B^2 + m_{\not{C}}^2 + 2\left(e_b e_{\not{c}} - \mathbf{b}_T \cdot \not{c}_T\right)$$

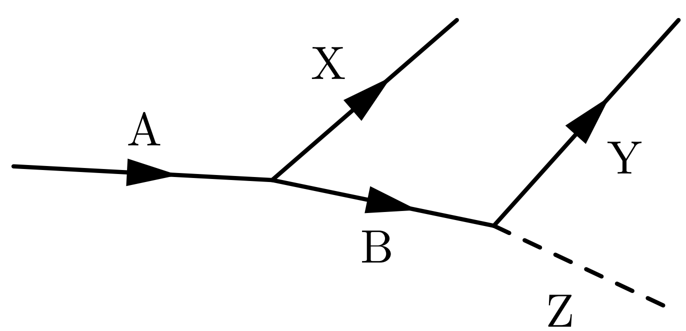
The transverse mass, for known daughter masses, has a kinematic edge

(here smeared by resolution effects, off-shell-ness and backgrounds)

Edges

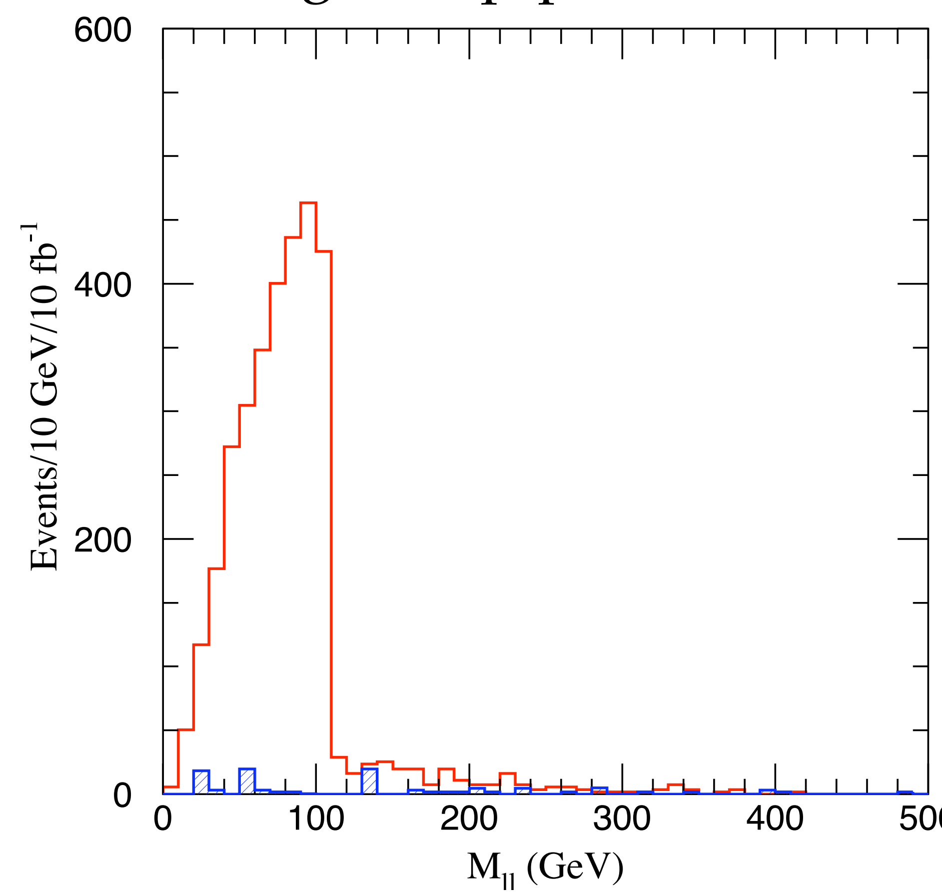
Invariant mass of visibles, X,Y (e.g. leptons)

- distribution sensitive to mass spectrum
- kinematic edge when angle between X,Y are back-to-back



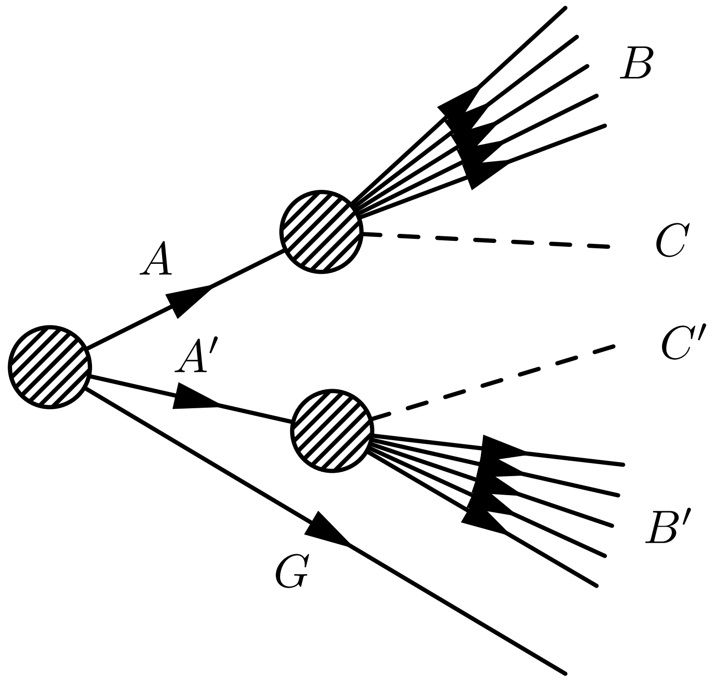
$$(m_{XY}^{\max})^2 = \frac{(m_A^2 - m_B^2)(m_B^2 - m_Z^2)}{m_B^2}$$

Paige - hep-ph/9609363



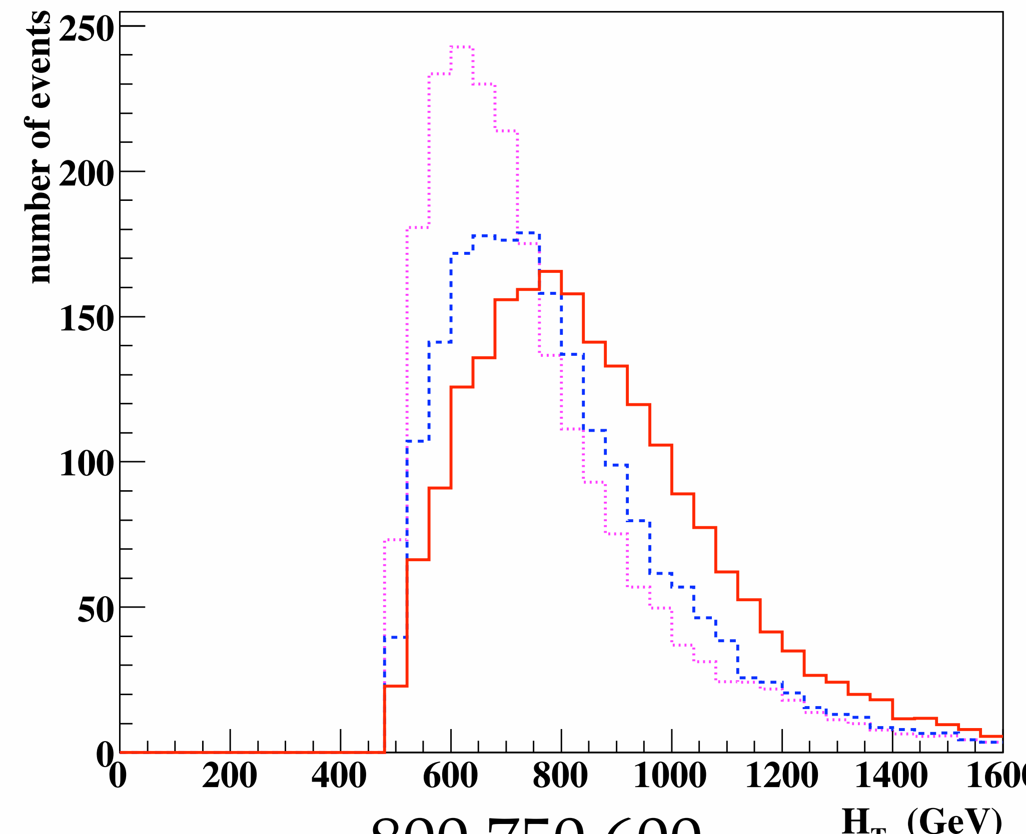
“Dilepton” edge - sensitive to mass differences

Early Mass Measurement



$$M_{\mathrm{eff}} \backslash M_{\mathrm{est}} \backslash H_T = \sum_{i=j}^{n} \not{E}_T + E_{T,i}^{\mathrm{jets}}$$

JH, Lykken, Pierini, Spiropulu 0805.2398

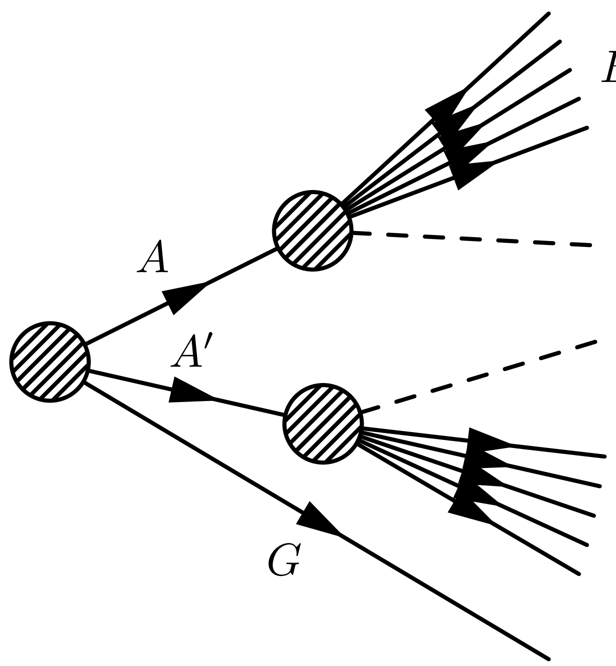


800,750,600

constructed to give an approximation to mass of strongly coupled exotica - gluinos/squarks - Tovey (hep-ph/0006276)

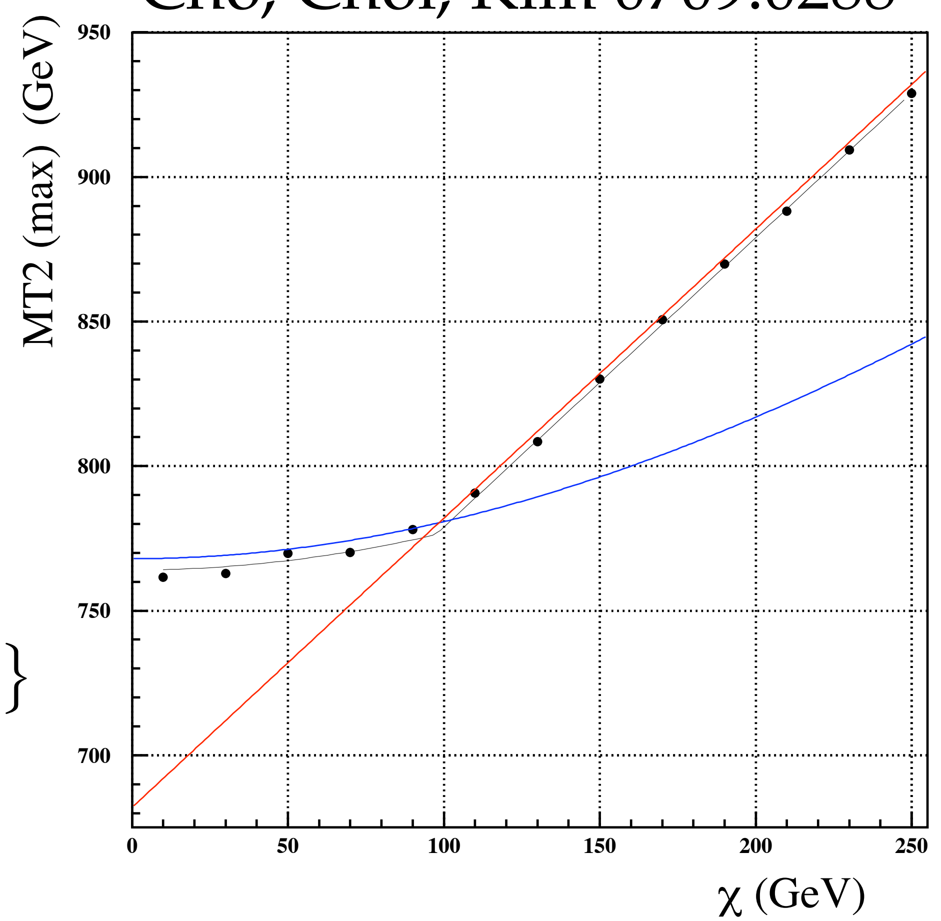
Peak position sensitive to (unknown) LSP mass

Cusps



$$M_{T2}(m_B, m_{B'}, \mathbf{b}_T, \mathbf{b}'_T, \not{\mathbf{p}}_T; \chi) \equiv \min_{\not{\mathbf{c}}_T + \not{\mathbf{c}}'_T = \not{\mathbf{p}}_T} \left\{ \max\left(M_T, M'_T \right) \right\}$$

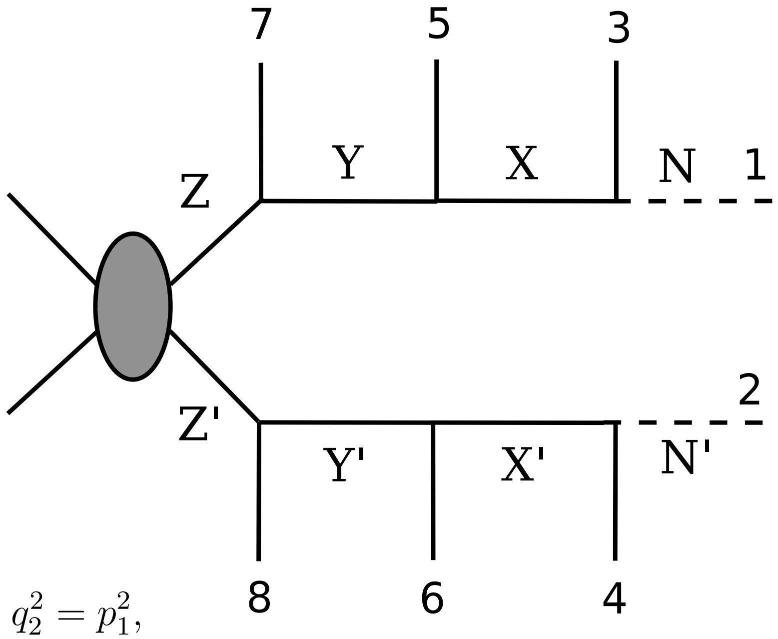
Cho, Choi, Kim 0709.0288



Eg. gluino 3 body decays

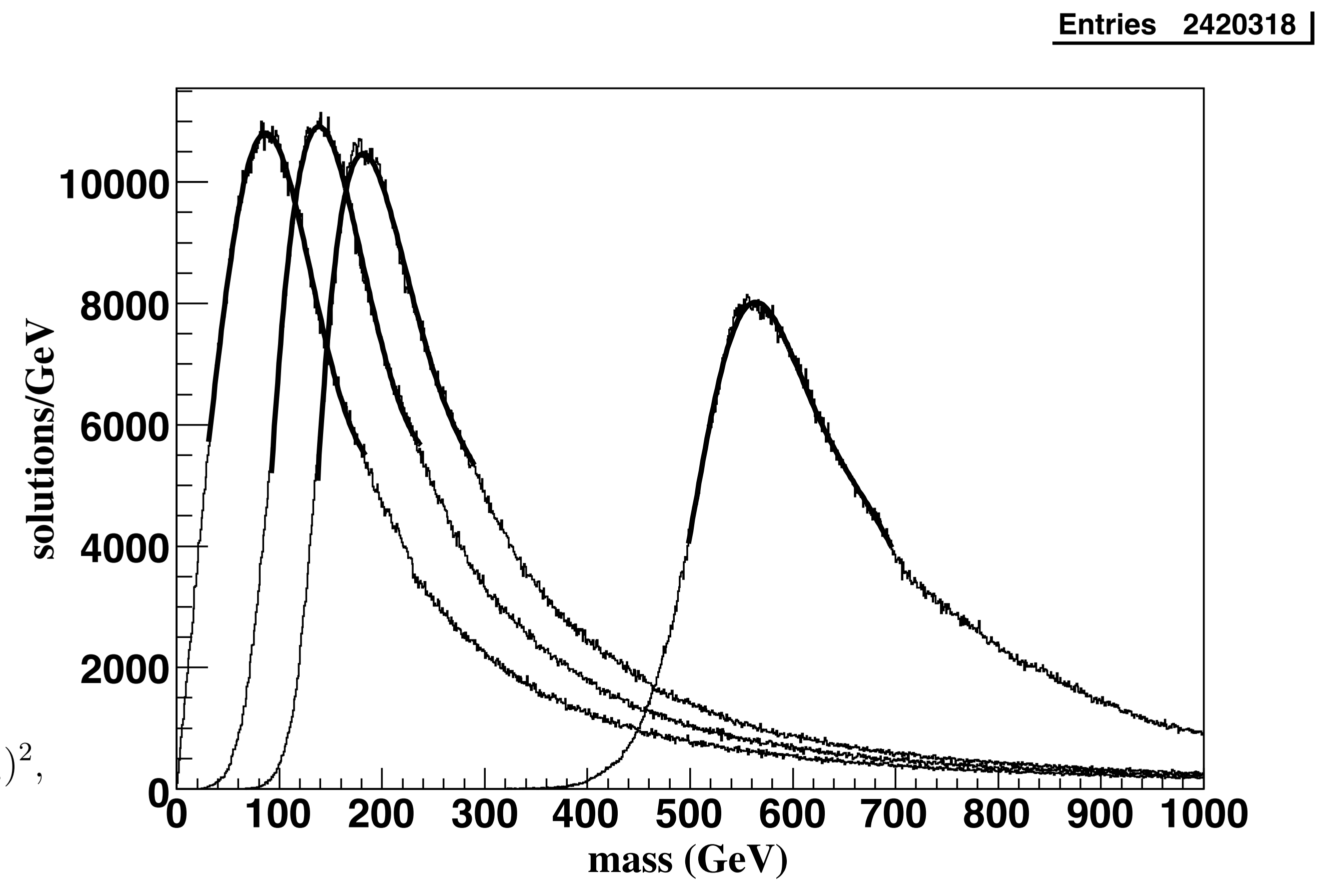
Hemisphere selection and combinatorics

Peaks



$$q_1^2 = q_2^2 = p_1^2,$$
$$(q_1 + q_3)^2 = (q_2 + q_4)^2 = (p_2 + p_4)^2,$$
$$(q_1 + q_3 + q_5)^2 = (q_2 + q_4 + q_6)^2 = (p_2 + p_4 + p_6)^2,$$
$$(q_1 + q_3 + q_5 + q_7)^2 = (q_2 + q_4 + q_6 + q_8)^2 = (p_2 + p_4 + p_6 + p_8)^2,$$
$$q_1^x + q_2^x = q_{miss}^x, \quad q_1^y + q_2^y = q_{miss}^y.$$

Cheng, Gunion, Han, McElrath 0905.1344



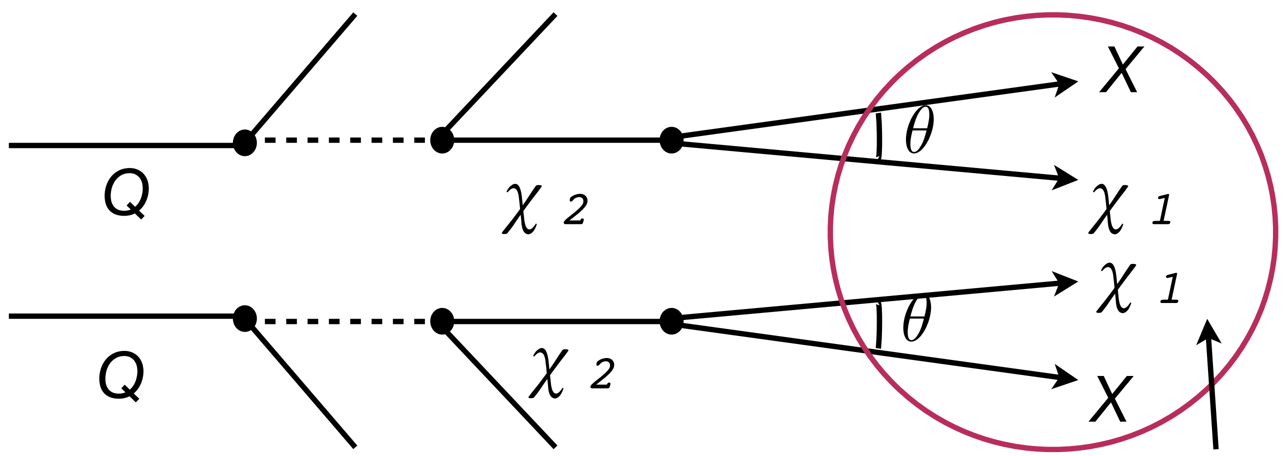
Uses pairings of events with identical topology to completely constrain kinematics

And more...

- Co-transverse mass
  - Tovey 0802.2879
- M_{T2} endpoints - subsystem M_{T2}
  - Burns, Kong, Matchev, Park 0810.5576
- Hybrids of methods (Barr, Ross, Serna, Pinder)
- These methods all exploit singularities in computation of variables at truth masses
  - Kim 0910.1149
- Review of Techniques: Barr, Lester 1004.2732

What’s(re) my topology(ies) and disentanglement method?

MET-Cones
Event-by event endpoints

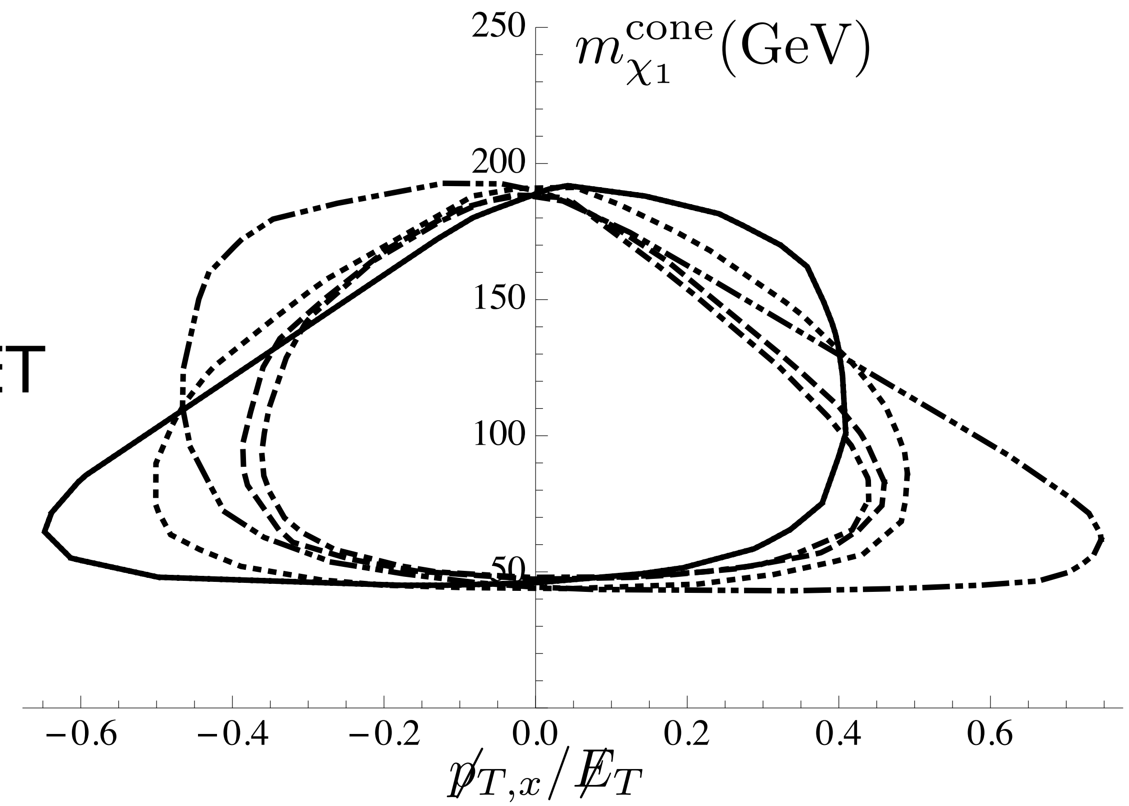


Only use the information of X and MET

$$\vec{p}^{\,a}_{\chi_1}(\vec{p}^{\,a}_X|\theta^a_0,\phi^a|m_{\chi_1},m_{\chi_2})$$

$$\vec{p}^{\,b}_{\chi_1}(\vec{p}^{\,b}_X|\theta^b_0,\phi^b|m_{\chi_1},m_{\chi_2})$$

JH, Jing Shao 1009.1148



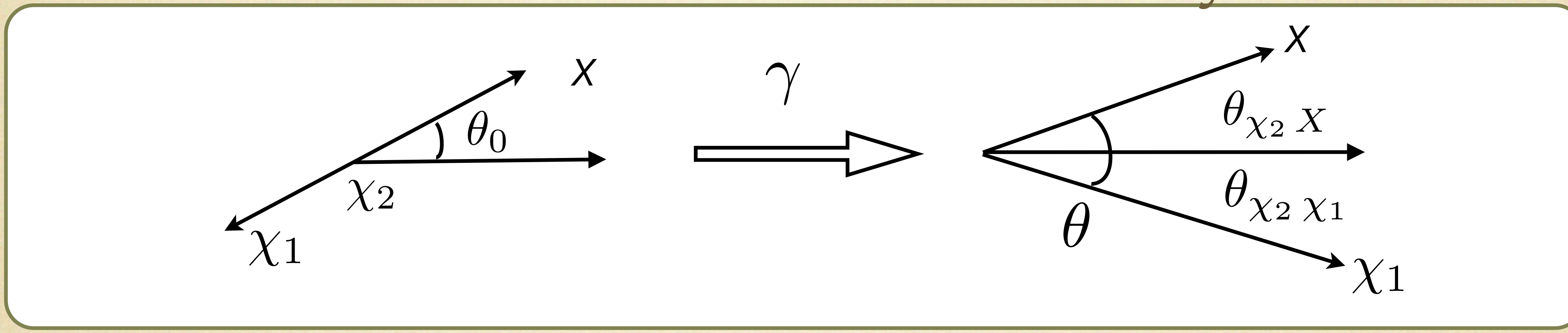
X is massive and fully reconstructed object (e.g. Z-boson)

Example: $pp \to \bar{\tilde{q}}\tilde{q} \to 2j + 2Z + \mathrm{MET}$

dual cascades could be asymmetric, up to last decay

Two 2-Body Decays

Consider kinematics of “NLSP” decay to X + LSP



Calculate kinematics in rest-frame of NLSP and boost

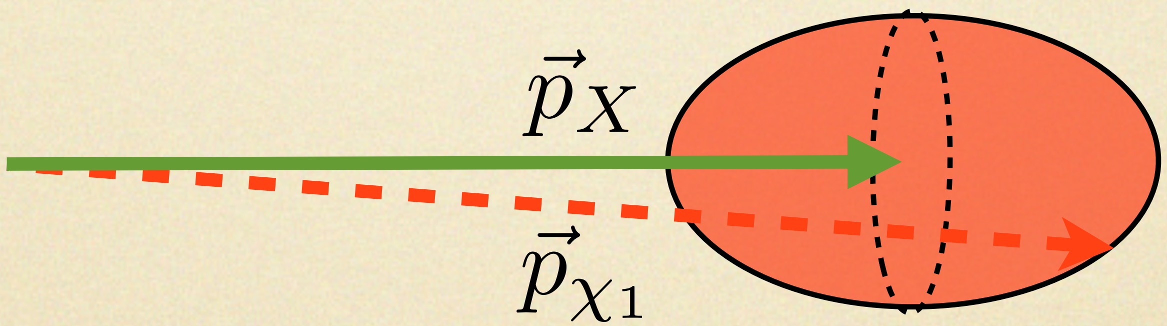
$$(\beta_0^X)^2 = \frac{\left(m_{\chi_2}^2 - (m_{\chi_1} + m_X)^2\right)\left(m_{\chi_2}^2 - (m_{\chi_1} - m_X)^2\right)}{\left(m_{\chi_2}^2 + (m_X^2 - m_{\chi_1}^2)\right)^2}$$

NLSP has boost/velocity γ, β

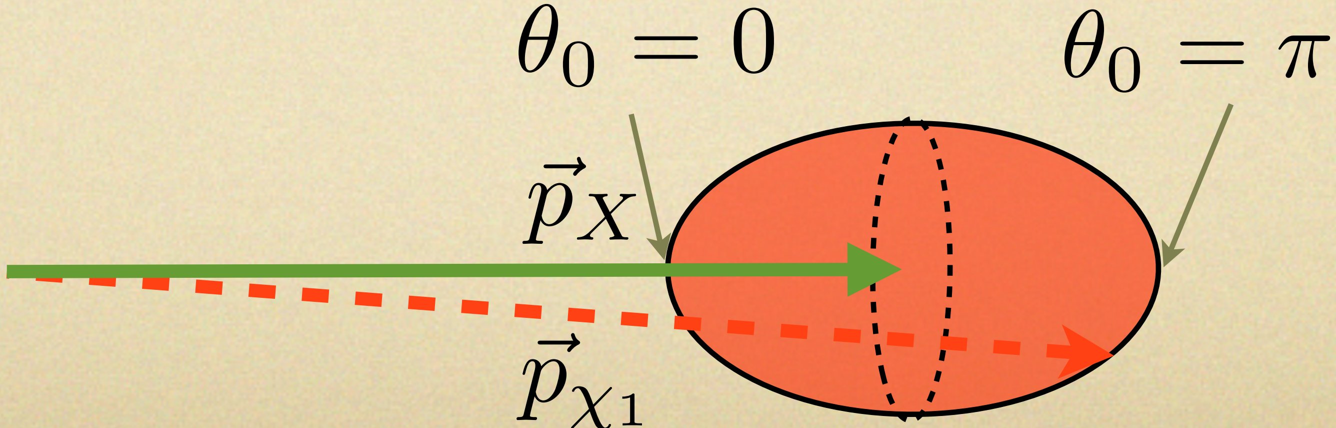
$$\tan\theta_{\chi_2 X} = \frac{\beta_0^X}{\gamma}\left(\frac{\sin\theta_0}{\beta_0^X\cos\theta_0 + \beta}\right)$$

Going backwards

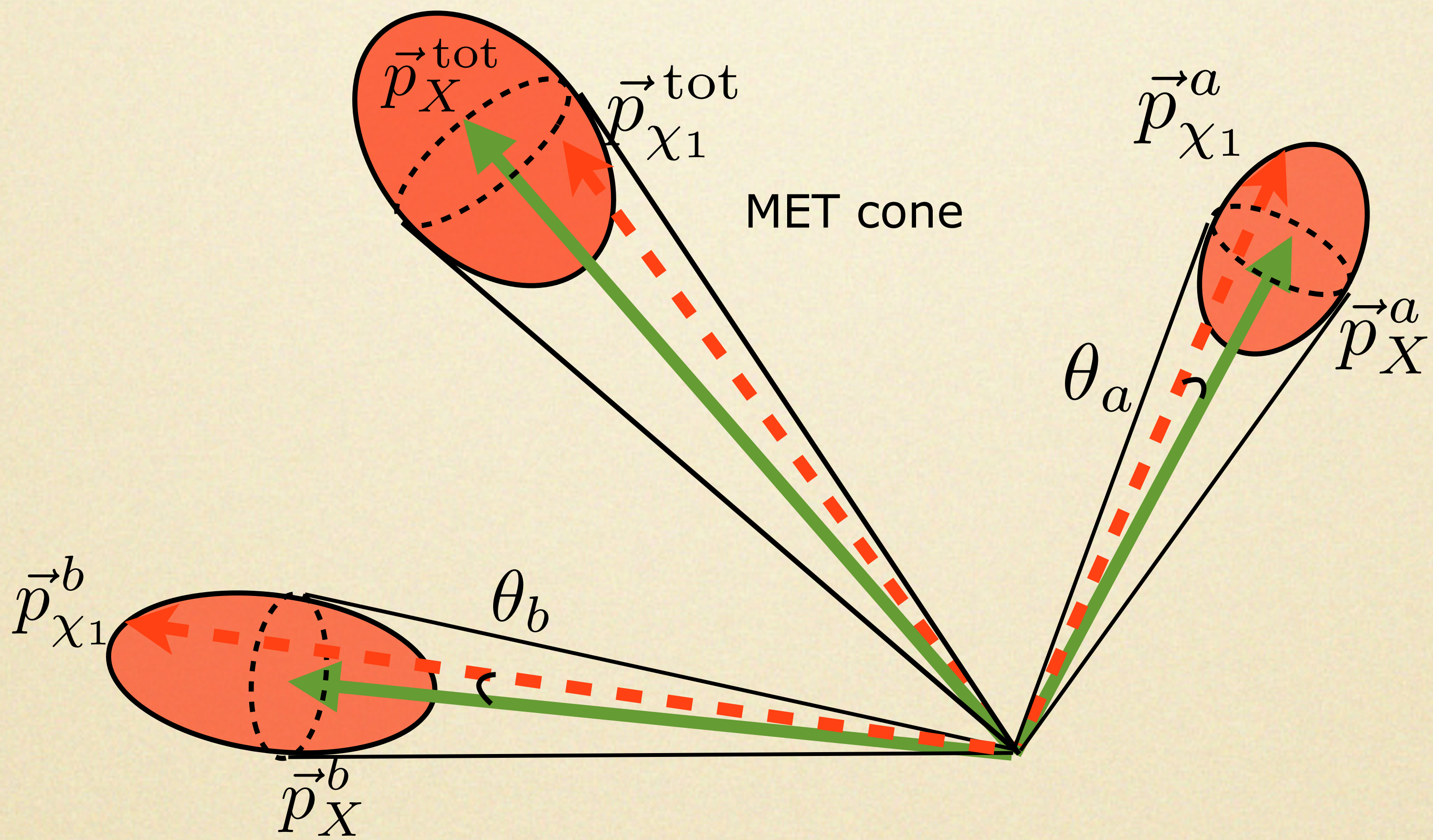
Can start with p_X for given NLSP, LSP masses, then find allowed range for LSP momentum



Spheroid parametrized by rest-frame angles



The Shape of MET



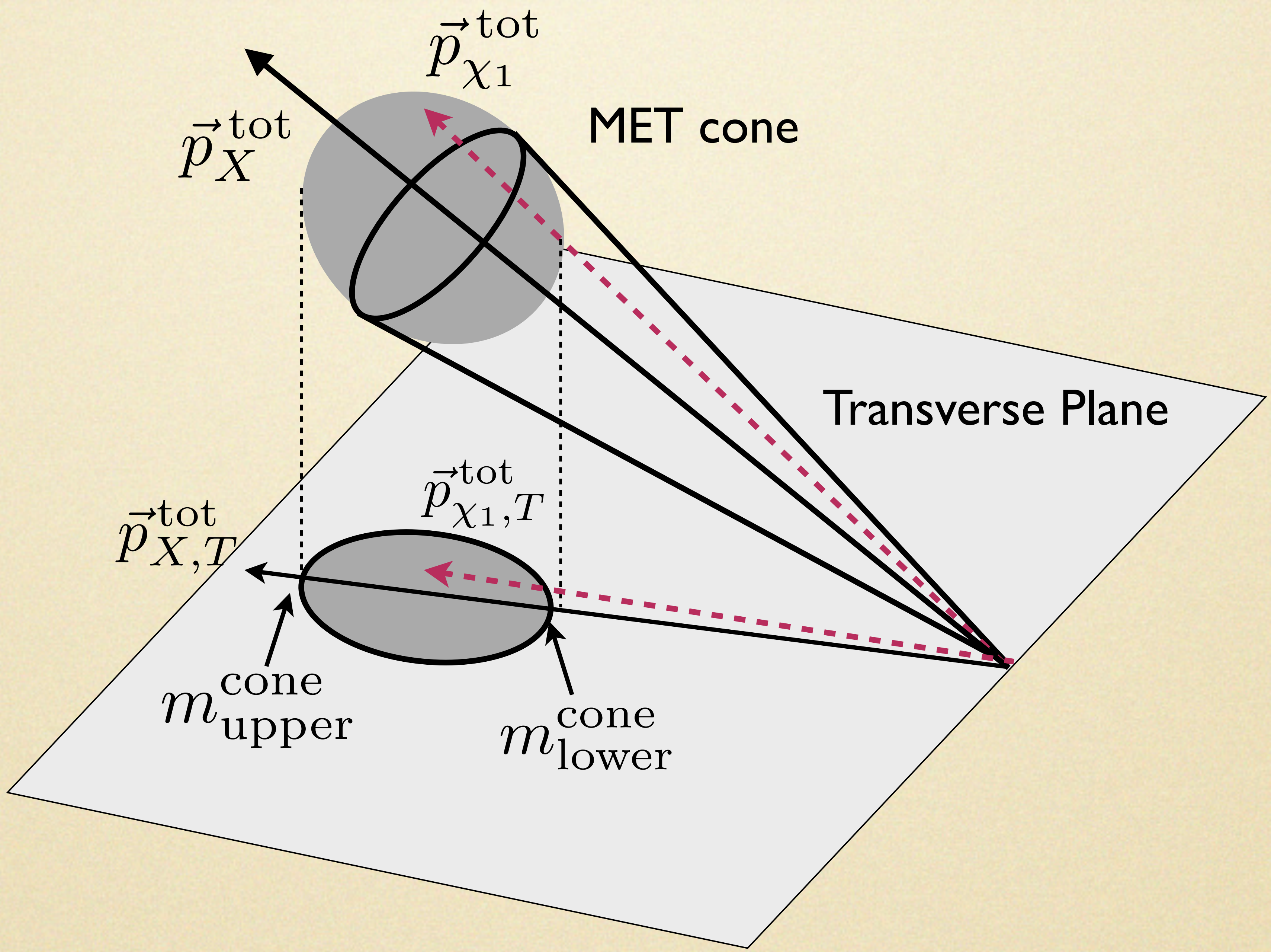
Each MET particle momentum resides on a surface

- shape determined by NLSP-LSP spectrum and corresponding X-momenta

Total MET particle momentum vector resides in blob

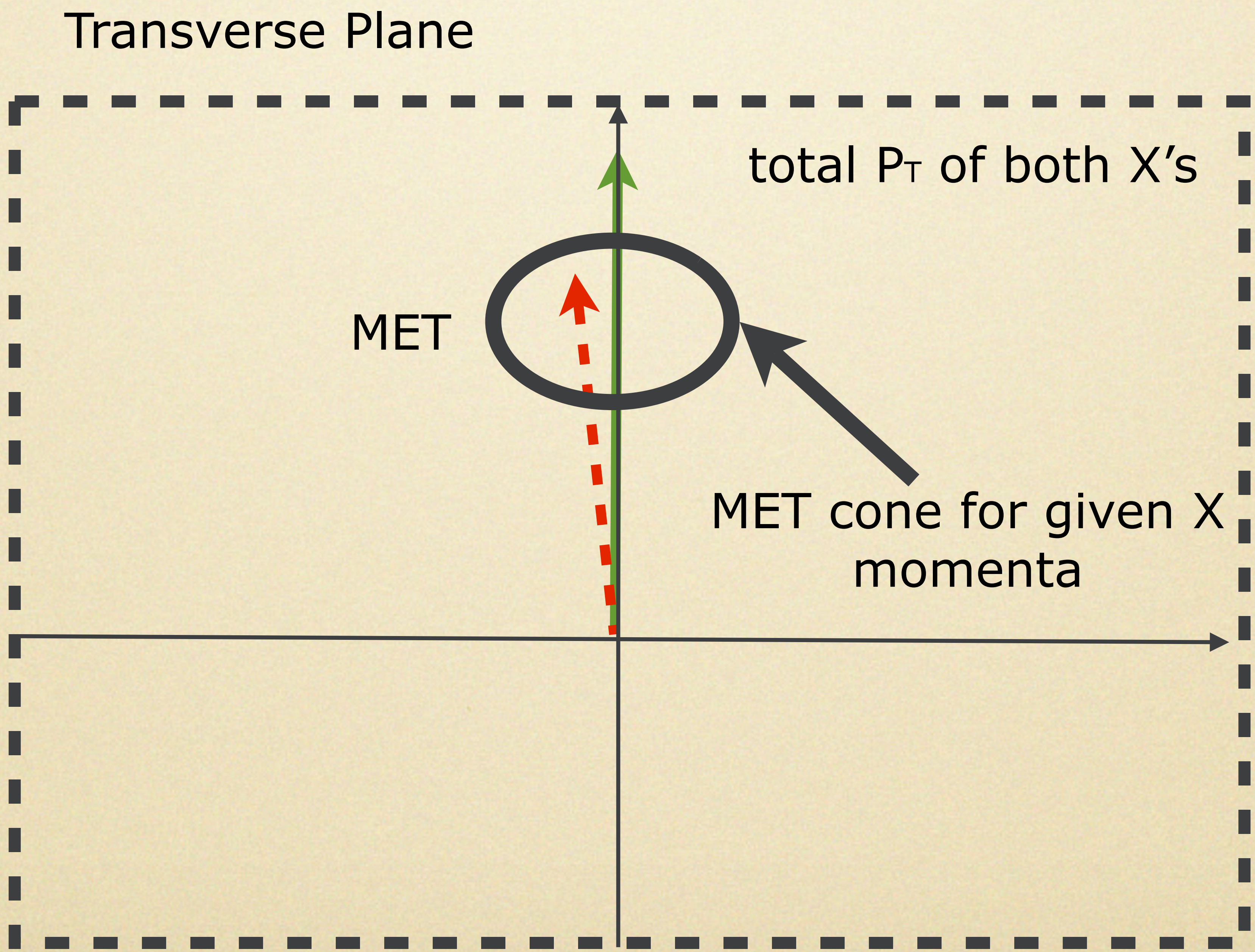
- total missing momentum resides in projection of blob onto transverse plane
- blob obtained by varying over 4 rest-frame angles
- boundaries determined purely by kinematics

The "MET-Cone"



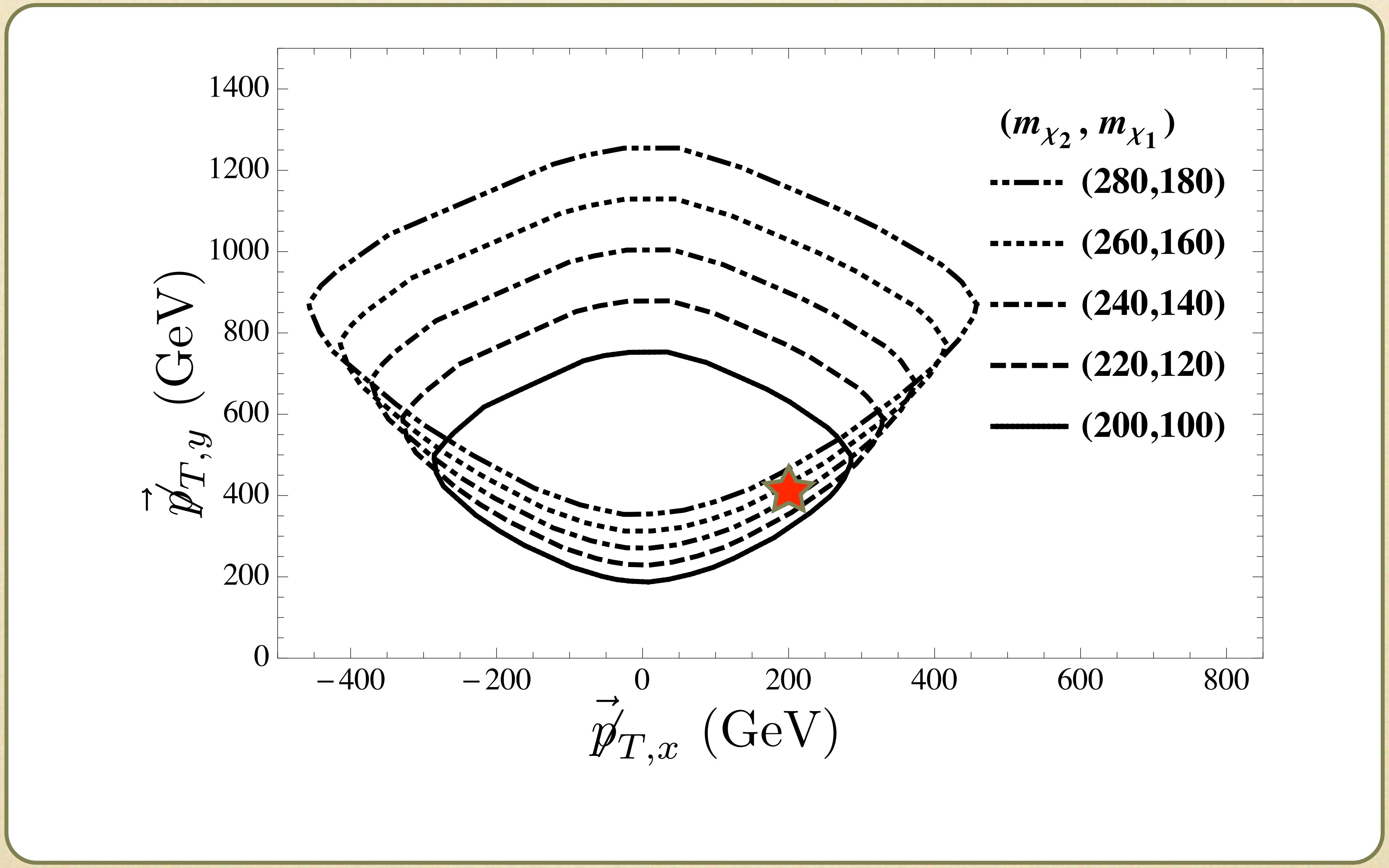
Projection of the blob onto the transverse plane

Convenient Coordinates



Example

$$\chi_2 \to \chi_1 Z$$



Two Z's in transverse plane, relative angle of pi/2, both with boost factor of 5

Cone boundaries shown for identical mass splittings, different overall mass scale

MET vector inconsistent with some mass hypotheses

What SHOULD we do

- For every event, find the allowed region in the NLSP-LSP mass plane.
- Choose the point in this plane which minimally encloses every MET vector with a MET-cone
  - like shrink-wrap
- This is doable, but rather time consuming and computationally intensive
  - we (for now) study a quick and dirty way to access the MET cone information

The m$^{\text{cone}}$ variable

Consider the zero-splitting limit

-tiny phase space for NLSP decay

-far collinear limit (MET cones shrink to points)

$$\vec{p}_{\chi_1}^{\;a,b} = \vec{p}_X^{\;a,b}\frac{m_{\chi_1}}{m_X} \quad\Longrightarrow\quad \vec{p}_{\chi_1}^{\;\text{tot}} = \vec{p}_X^{\;\text{tot}}\frac{m_{\chi_1}}{m_X}$$

Define a “test MET” as function of new variable

$$\vec{p}_{\chi_1}^{\;i,\,\text{test}} \equiv \vec{p}_X^{\;i}\; m_{\chi_1}^{\text{cone}}/m_X \qquad \Delta \not{E}_T(m_{\chi_1}^{\text{cone}}) \equiv \left| \sum_{i=a,b} \left(\vec{p}_{\chi_1,T}^{\;i,\,\text{test}} \right) - \vec{\not{p}}_T^{\;\text{exp}} \right|$$

Minimize this and get

$$m_{\chi_1}^{\text{cone}} = \not{p}_{T,y}\frac{m_X}{|\vec{p}_{X,T}^{\;\text{tot}}|}$$

m^{cone} endpoints

$$m^{\text{cone}} \approx m_{\chi_1} \frac{\gamma_0^{\chi_1}}{\gamma_0^X} \frac{1+\beta^a\,\beta_0^{\chi_1}\cos\theta_0^a}{1-\beta^a\,\beta_0^X\cos\theta_0^a} \left(1 - \cot\theta_{ab}^X \cos\phi^a\theta^a + \csc\theta_{ab}^X \cos\phi^b\theta^b\right)$$

Deviations from collinearity

lab frame velocity of NLSP

For relativistic NLSP this has endpoints at extremal values of rest-frame angle:

$$m^{\text{cone}}_{\text{lower}} \approx m_{\chi_1} \frac{\gamma_0^{\chi_1}}{\gamma_0^X} \frac{1-\beta_0^{\chi_1}}{1+\beta_0^X}$$

$$m^{\text{cone}}_{\text{upper}} \approx m_{\chi_1} \frac{\gamma_0^{\chi_1}}{\gamma_0^X} \frac{1+\beta_0^{\chi_1}}{1-\beta_0^X}$$

Bounds LSP mass

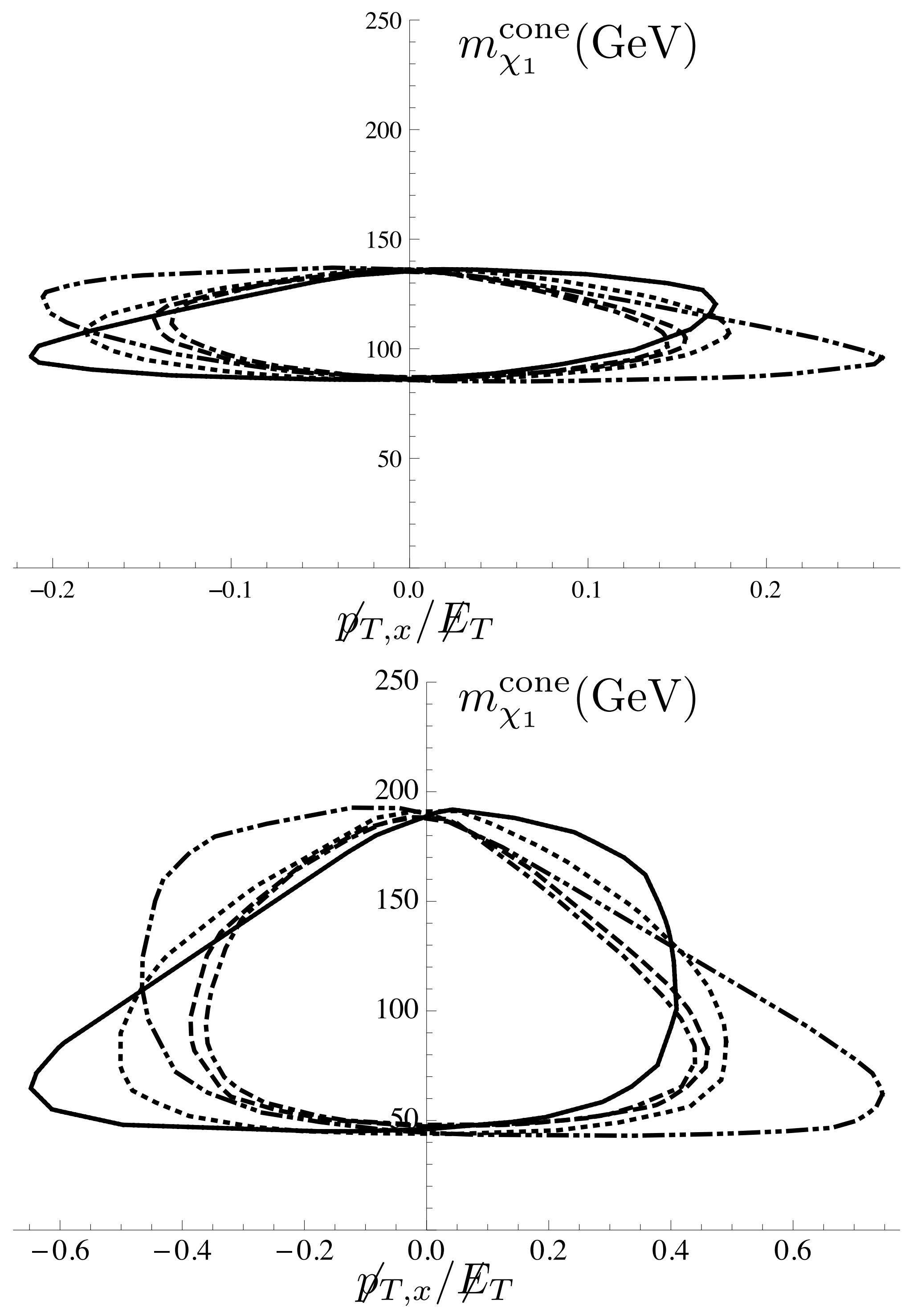
End points are functions of NLSP , LSP and X masses

m^{cone} endpoints

small and smaller mass splittings shown

cones intersect at same points on m^{cone} axis

have also rescaled y-component by total MET



Simulation

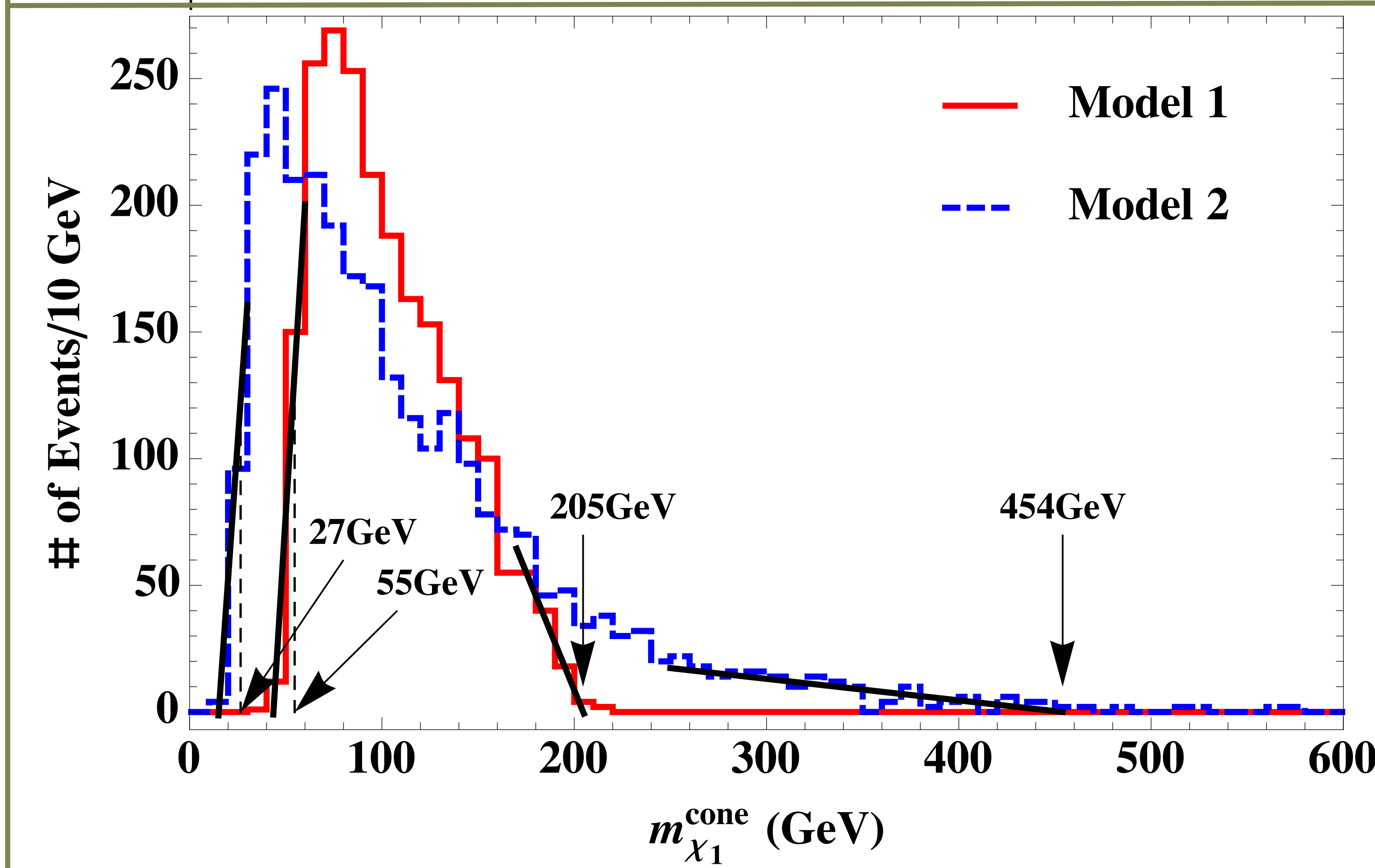
$$pp \to \bar{\tilde{q}}\tilde{q} \to 2j + 2Z + \mathrm{MET}$$

Parton level - Madgraph

20k before cuts

- at least two Z bosons with $p_T > 50$ GeV and $|\eta| < 3$
- missing energy $\not{E}_T > 200$ GeV
- η of total Z three-momentum $|\eta^{Z,\mathrm{tot}}| < 1$
- opening angle of two Z bosons $60^\circ < \theta^Z_{ab} < 120^\circ$
- $|\not{p}_{T,x}/\not{E}_T| < 0.15$

Model	$m_{\chi 1}$	$m_{\chi 2}$	$m_{\tilde{q}_L}$	$(m^{\mathrm{cone}}_{\mathrm{lower}})^{\mathrm{theo}}$	$(m^{\mathrm{cone}}_{\mathrm{upper}})^{\mathrm{theo}}$
1	100	200	1000	54.6	183.2
2	100	250	1250	21.6	463.0

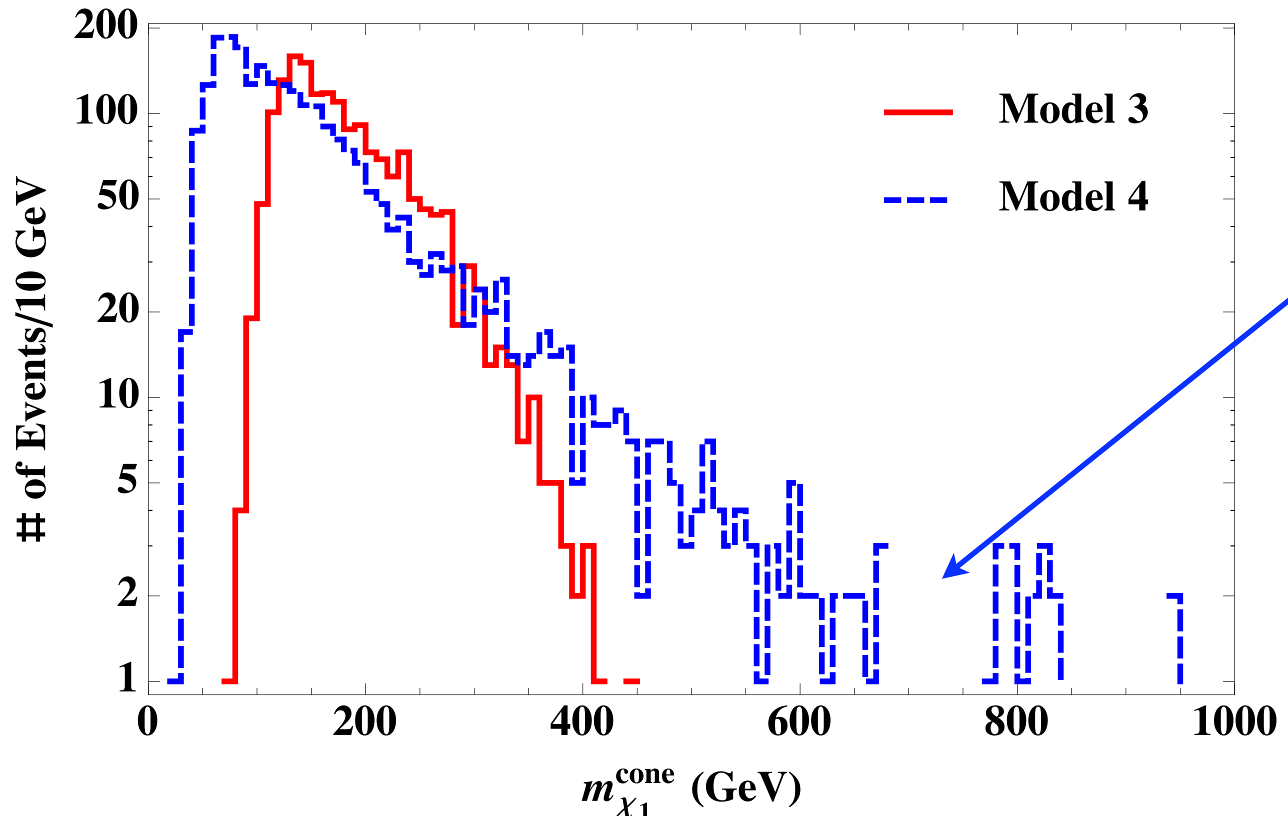


Model	$m_{\chi 1}$	$m_{\chi 2}$	$m^{\mathrm{test}}_{\mathrm{lower}}$	$m^{\mathrm{test}}_{\mathrm{upper}}$	$m^{meas}_{\chi 1}$	$m^{meas}_{\chi 2}$
1	100	200	55 ± 2	205 ± 3	106 ± 2	208 ± 3
2	100	250	27 ± 2	454 ± 20	110 ± 5	253 ± 5

Statistics can be tough

Model	m_{χ_1}	m_{χ_2}	$m_{\tilde{q}_L}$	$(m^{\text{cone}}_{\text{lower}})^{\text{theo}}$	$(m^{\text{cone}}_{\text{upper}})^{\text{theo}}$
3	200	300	1000	117.9	339.2
4	200	350	1250	52.6	761.0

Heavier overall scale



model 4 is running out of gas on the tail

Model	m_{χ_1}	m_{χ_2}	$m^{\text{test}}_{\text{lower}}$	$m^{\text{test}}_{\text{upper}}$	$m^{meas}_{\chi_1}$	$m^{meas}_{\chi_2}$
3	200	300	112 ± 5	342 ± 10	195 ± 5	296 ± 5
4	200	350	49 ± 2	682 ± 16	183 ± 5	329 ± 5

Model 3 does well
Model 4 does so-so

lower endpoint still provides **constraint**

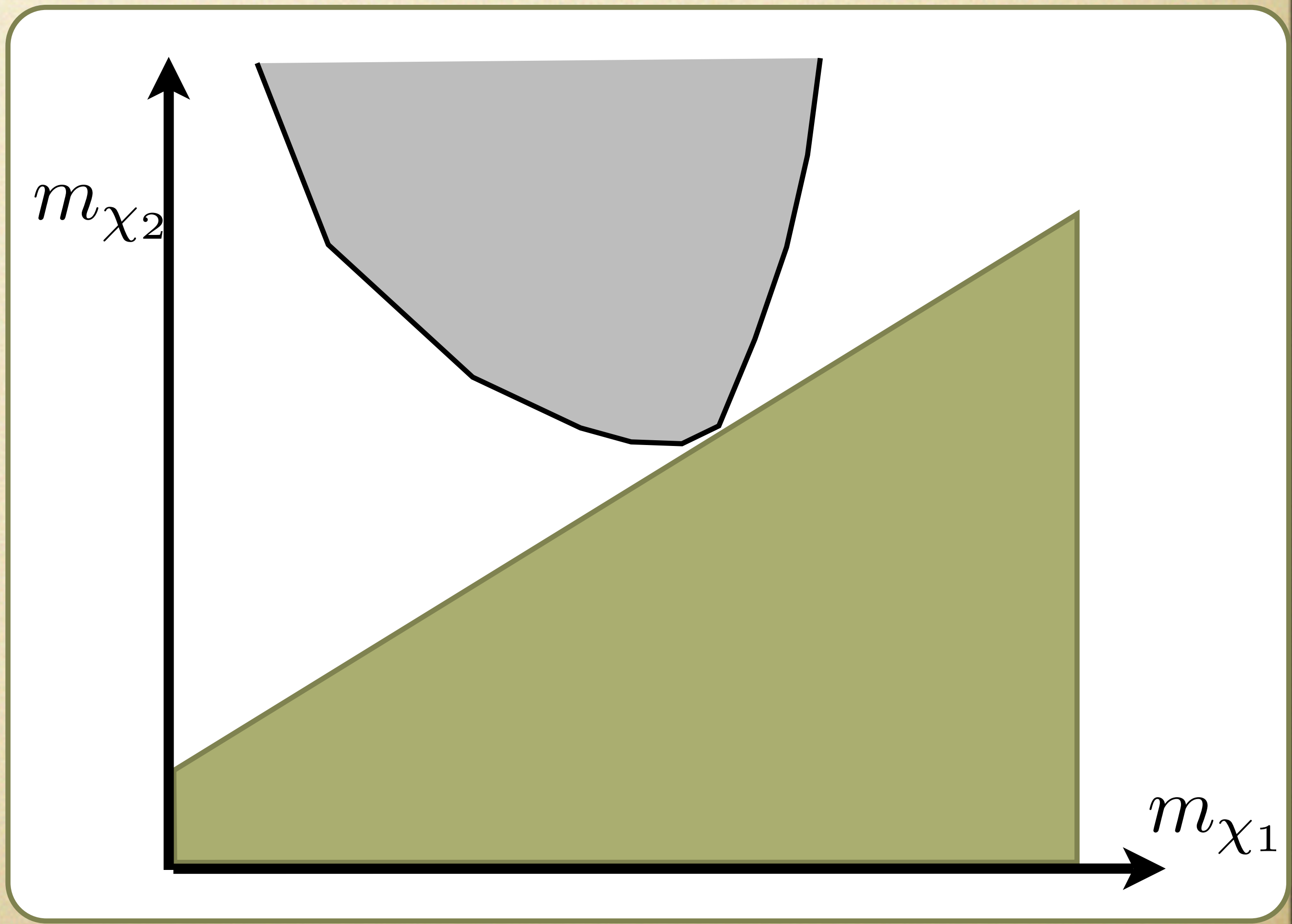
Sketch of the goal

Here is what we "know" in an event:

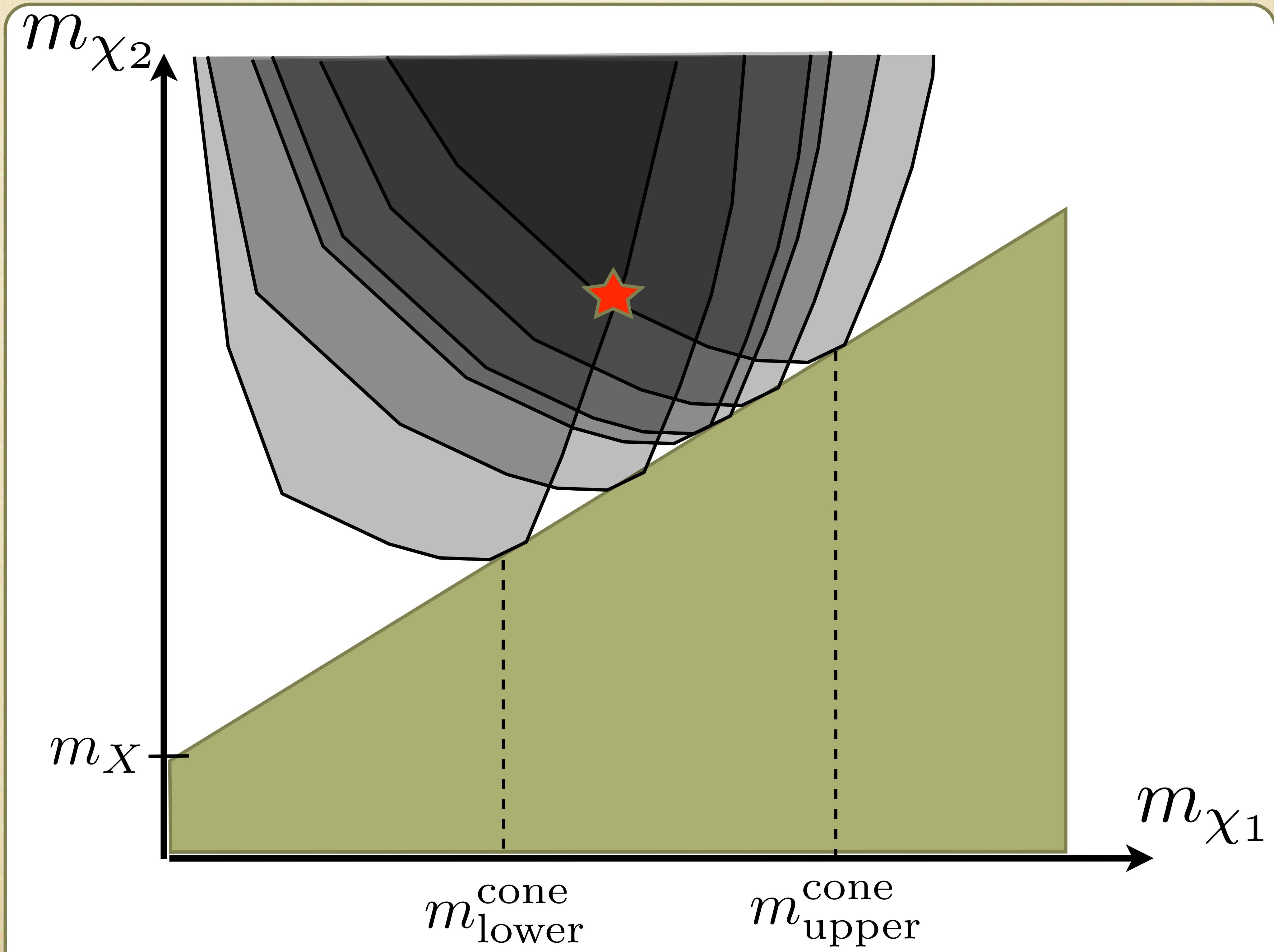
$$\vec{p}_X^{\,a}, \quad \vec{p}_X^{\,b}, \quad (\vec{p}_{\chi_1}^{\,a} + \vec{p}_{\chi_1}^{\,a})_T$$

For each event, we can calculate "mass-funnel"

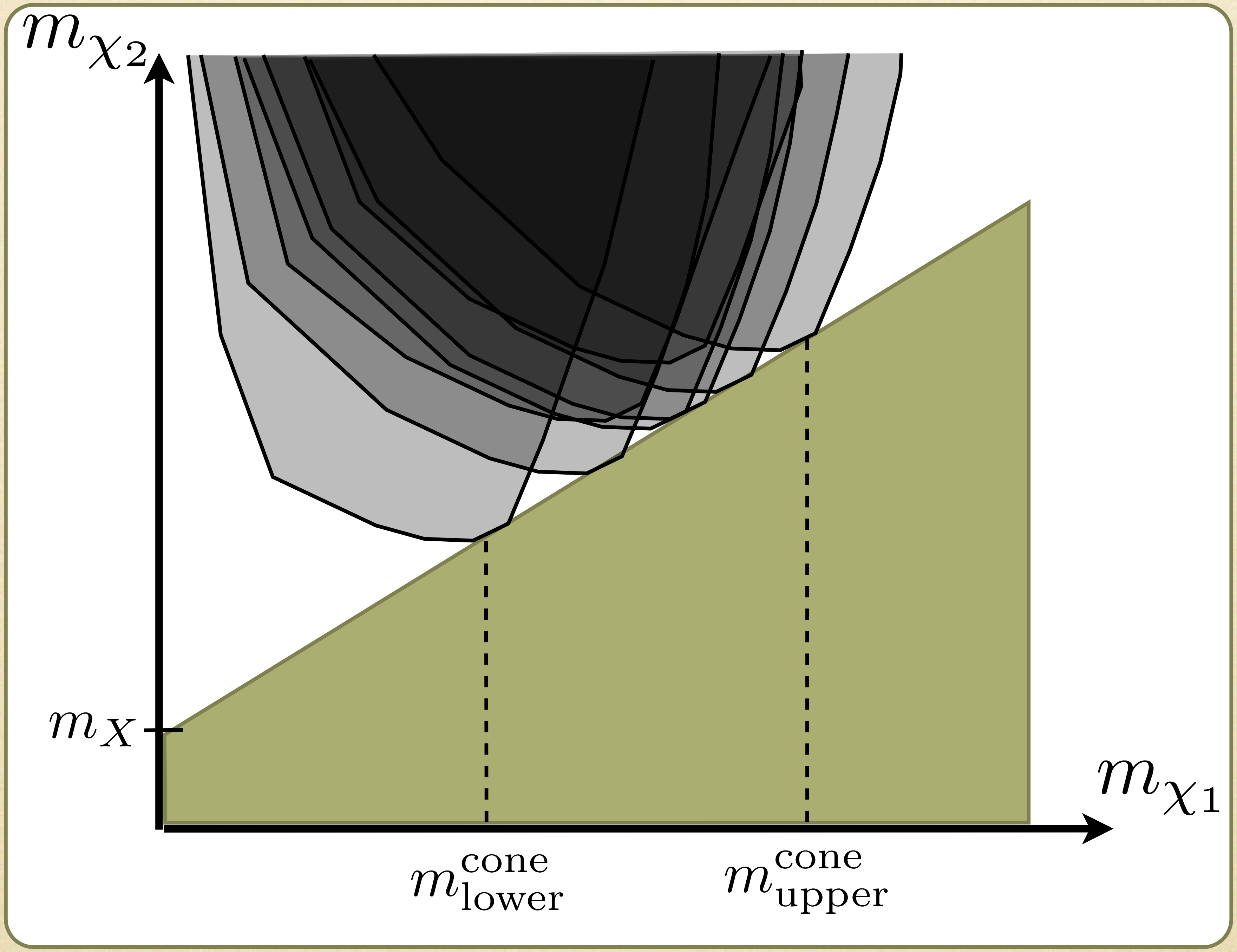
$$\vec{p}_{\chi_1}^{\,a}(\vec{p}_X^{\,a}|\theta_0^a, \phi^a|m_{\chi_1}, m_{\chi_2})$$
$$\vec{p}_{\chi_1}^{\,b}(\vec{p}_X^{\,b}|\theta_0^b, \phi^b|m_{\chi_1}, m_{\chi_2})$$



Another view of m^{cone}



Bring back the lost events



re-populate the region off the y-axis of the MET cone

improved statistics

Conclusions

- We offer a conceptually new method of mass measurement in dual-cascade decay chain events with missing energy
- Useful in topologies that end with decays of "NLSP" to "LSP" + massive visible
- Well suited to "simplified model" analysis
- Outlook:
    - take full advantage of event-by-event constraints
    - getting away from parton level