Missing Energy ($\not\!\!E_T$) at the LHC:
The Dark matter Connection

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University of Wisconsin – Madison

at Cornell University (Sept. 25, 2009)

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Outline

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“Antler Decay” Kinematics

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Summary

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Pauli's "Neutron", Fermi's "Neutrino"

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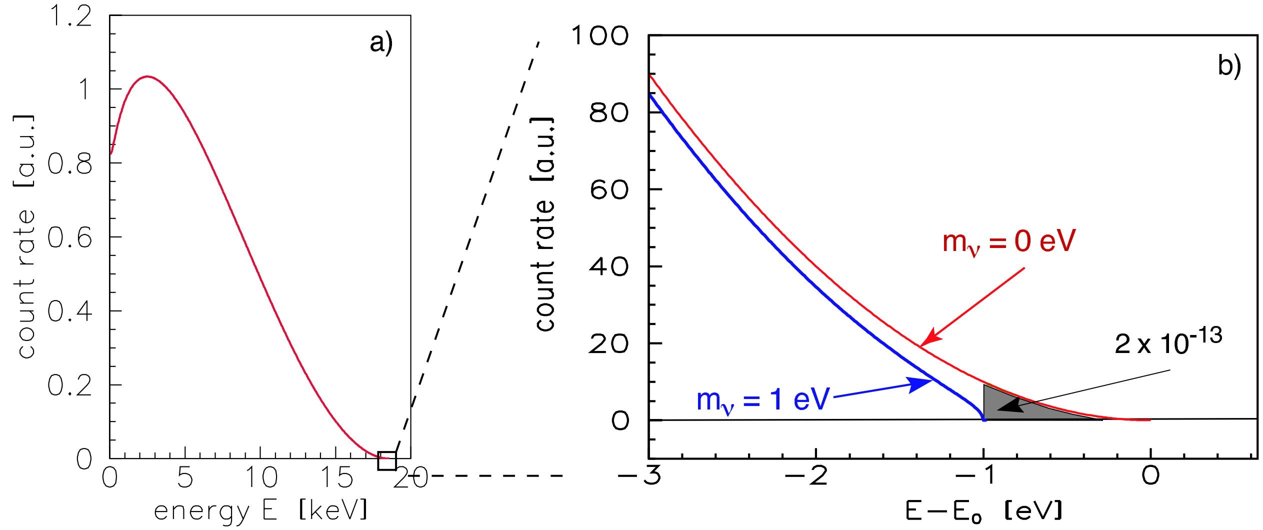

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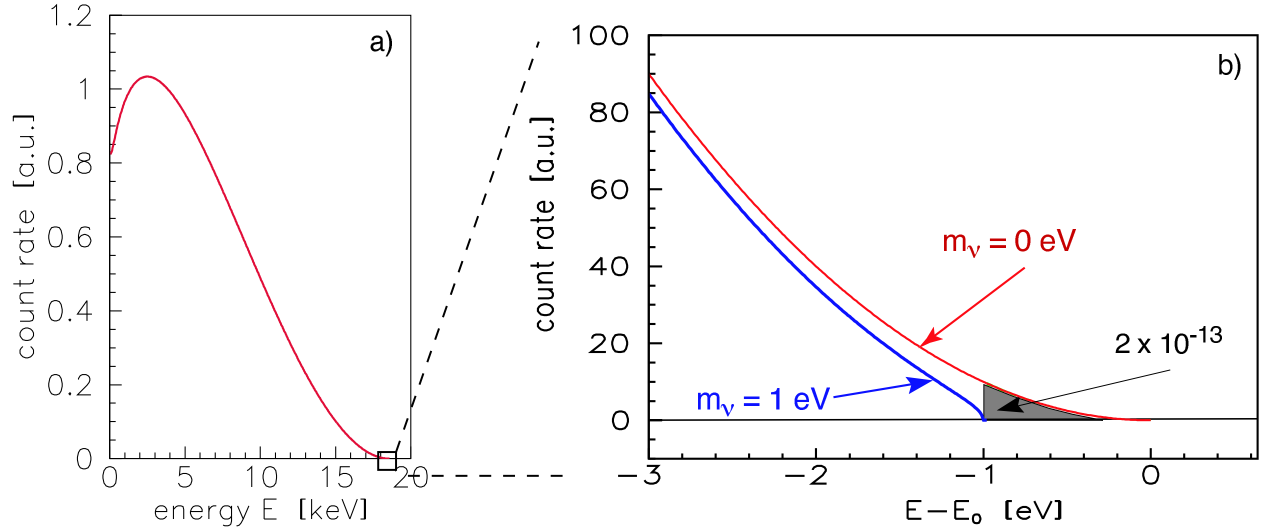

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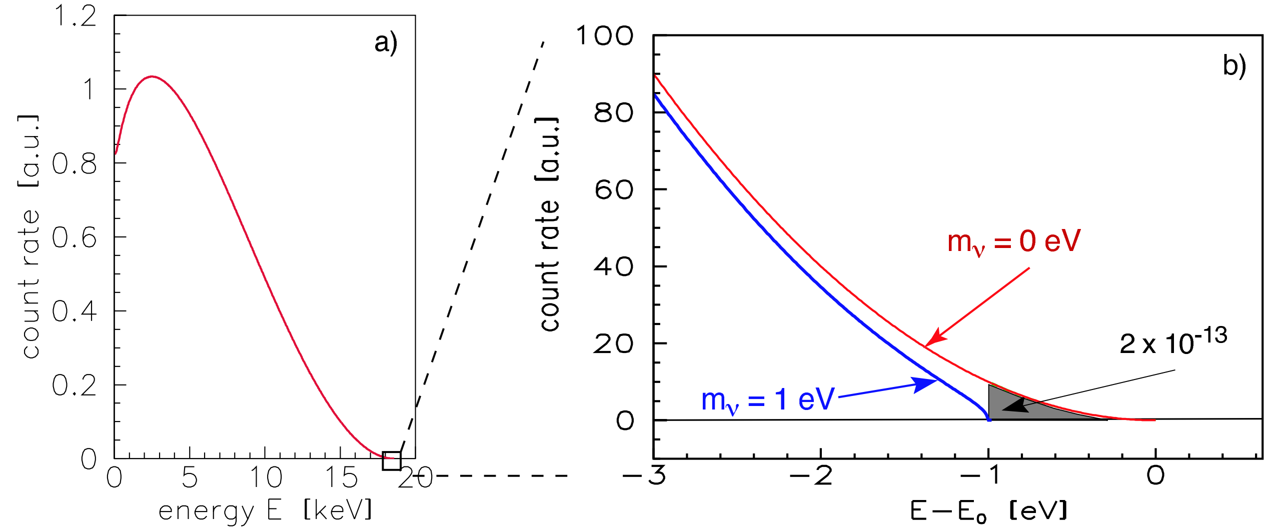

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For a 3-body decay, $M \to abc$, the kinetic energy of a:

$$0 \le K_a \le \frac{(M - m_a)^2 - (m_b + m_c)^2}{2M}.$$

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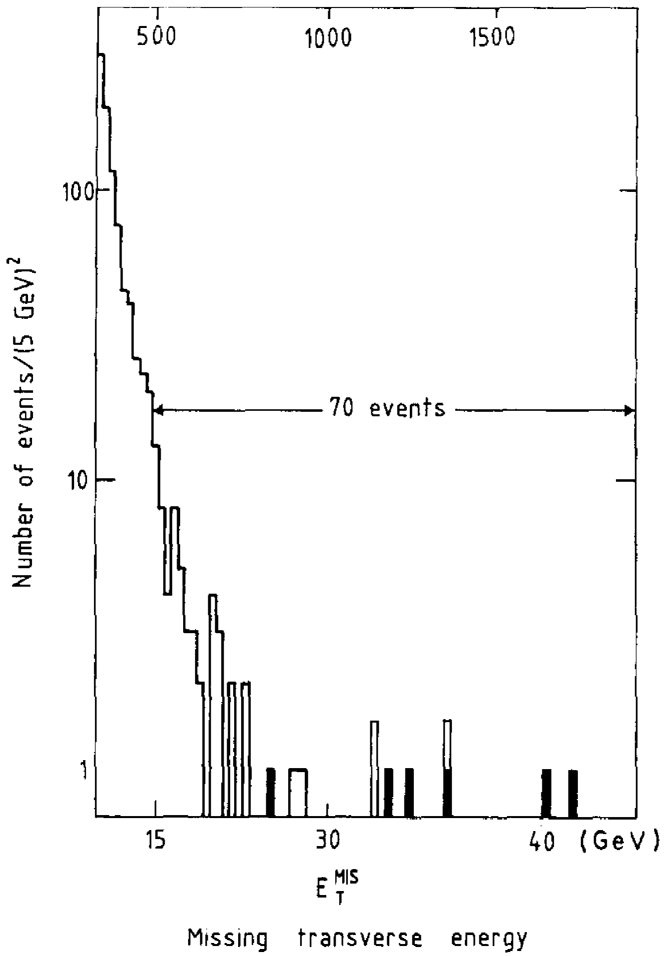
"Dark matter direct detection".

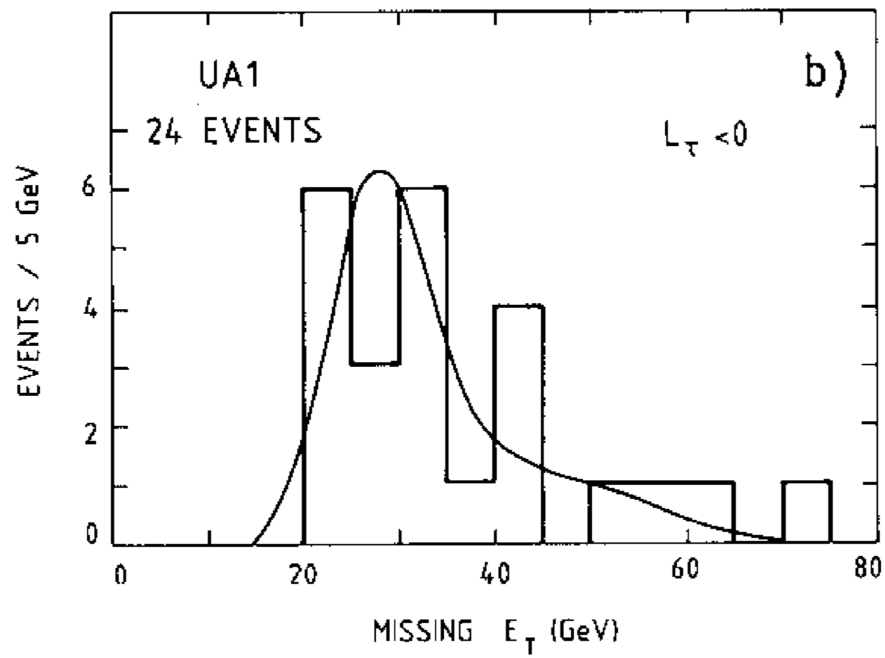
$W^{\pm}$ and Missing Energy

- The discovery of $W^{\pm} \to \ell \nu_{\ell}$ (UA1/UA2 in 1983):

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland





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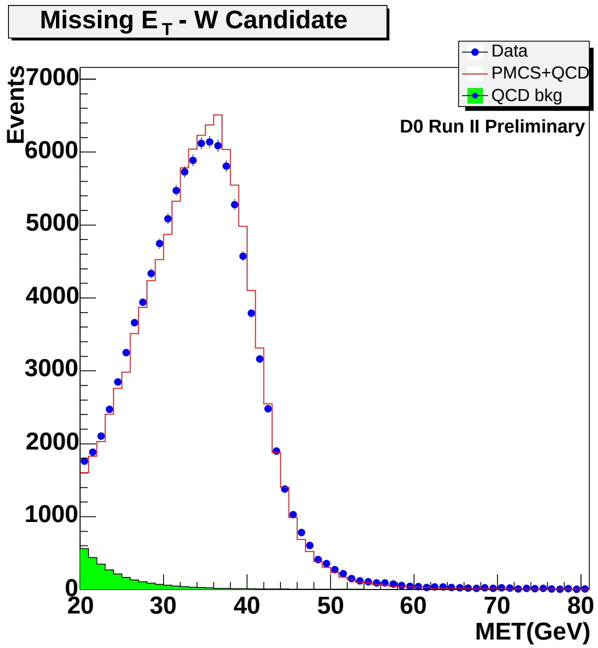

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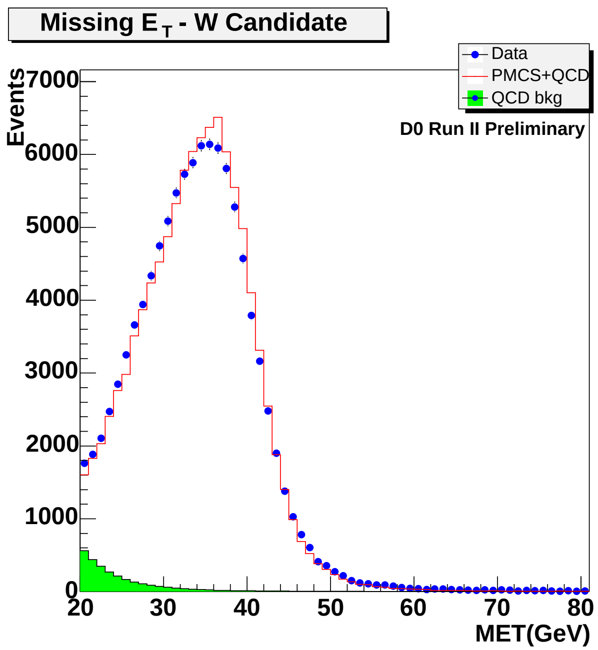


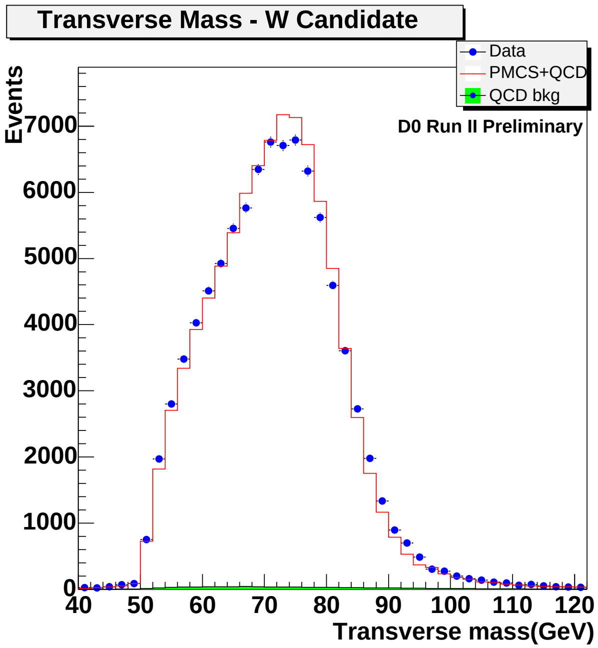
The transverse momentum of ν or e has a Jacobian peak:

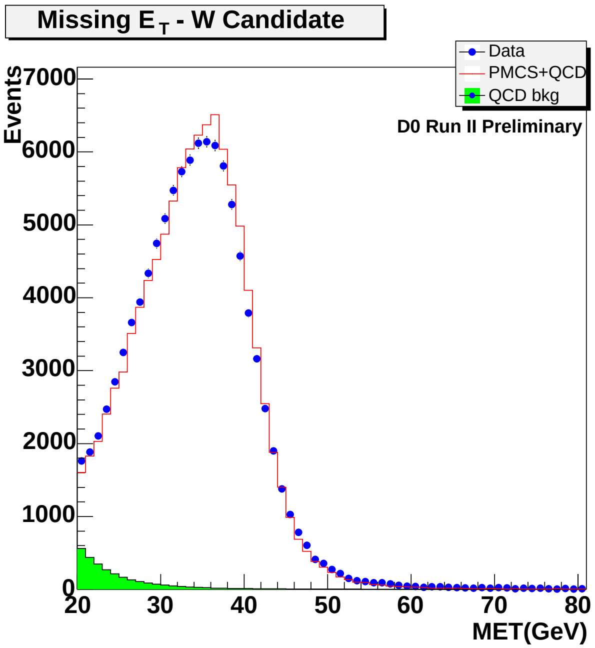
$$p_T = E \sin\theta ,$$

$$\frac{d\hat{\sigma}}{dm_{e\nu}^2 \, dp_{eT}^2} \propto \frac{\Gamma_W M_W}{(m_{e\nu}^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \frac{1}{m_{e\nu}^2 \sqrt{1 - 4p_{eT}^2/m_{e\nu}^2}} .$$

Transverse mass variable $W \to e\nu$:

$$m_{e\nu\ T}^2 = (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2$$
$$= 2E_{eT}E_T^{miss}(1 - \cos\phi) \leq m_{e\nu}^2.$$





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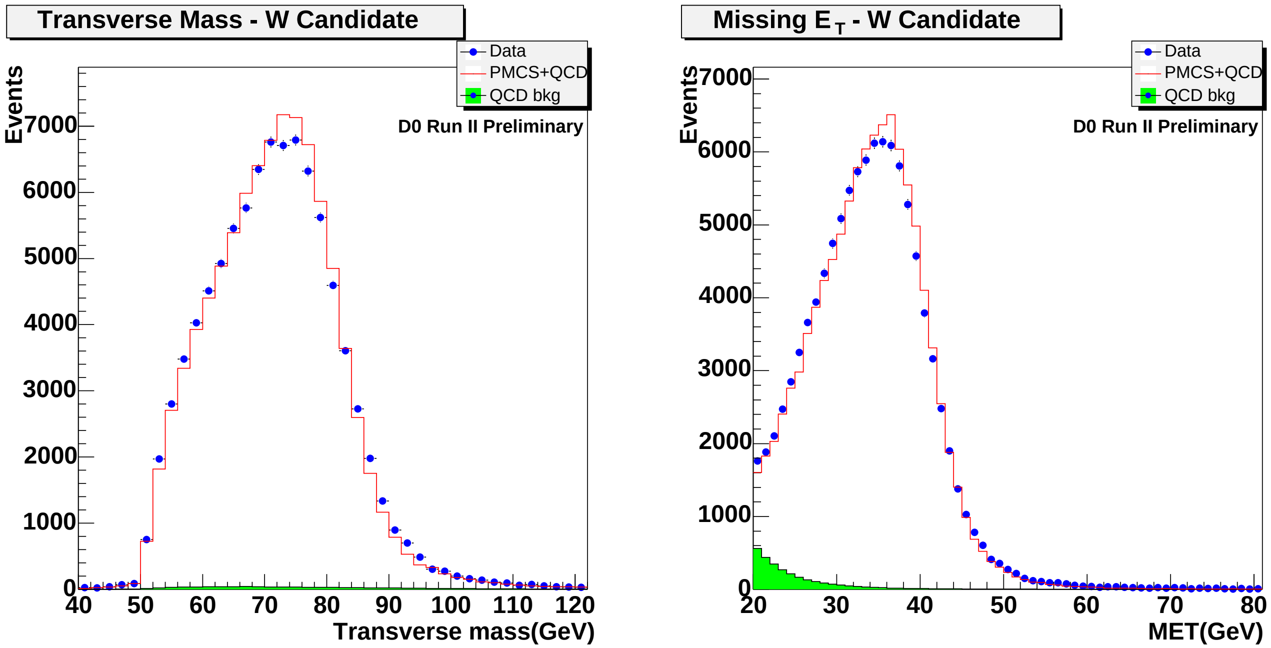

$\Rightarrow$ If $p_T(W) = 0$, then: $m_{e\nu\ T} = 2E_{eT} = 2E_T^{miss}$.

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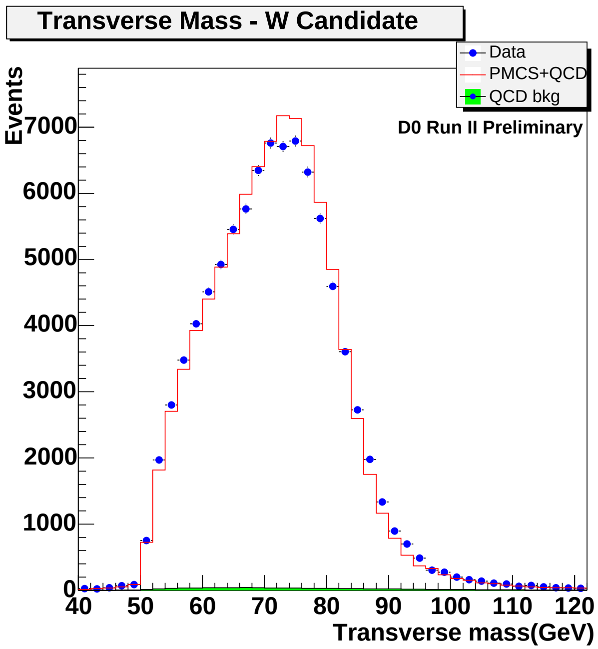
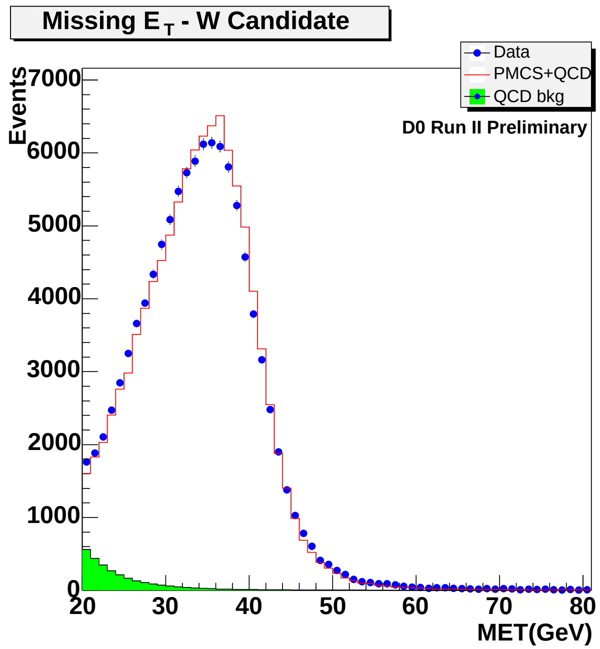




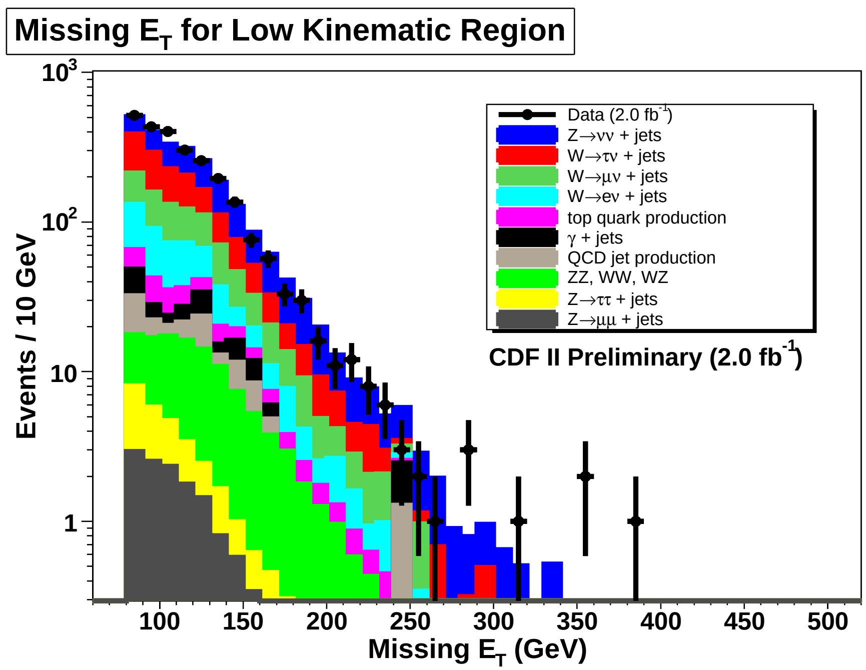
$\Rightarrow$ If $p_T(W) = 0$, then: $m_{e\nu\ T} = 2E_{eT} = 2E_T^{miss}$.

$\Rightarrow$ If $p_T(W) \neq 0$ (some transverse motion δP_V), then:

$$p'_{eT} \sim p_{eT}\ [1 + \delta P_V/M_V],$$
$$m'^2_{e\nu\ T} \sim m^2_{e\nu\ T}\ [1 - (\delta P_V/M_V)^2],$$
$$m'^2_{e\nu} = m^2_{e\nu}.$$

Large(r) missing energy events at the Tevatron:

SM prediction:



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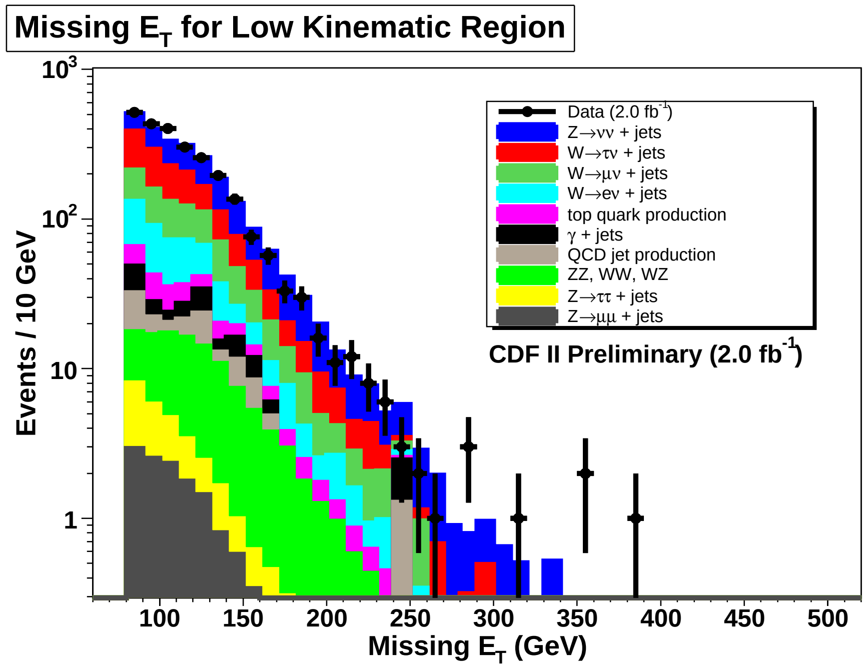

First SUSY bound: CDF with 25.3 nb^{-1} (!) (1989)

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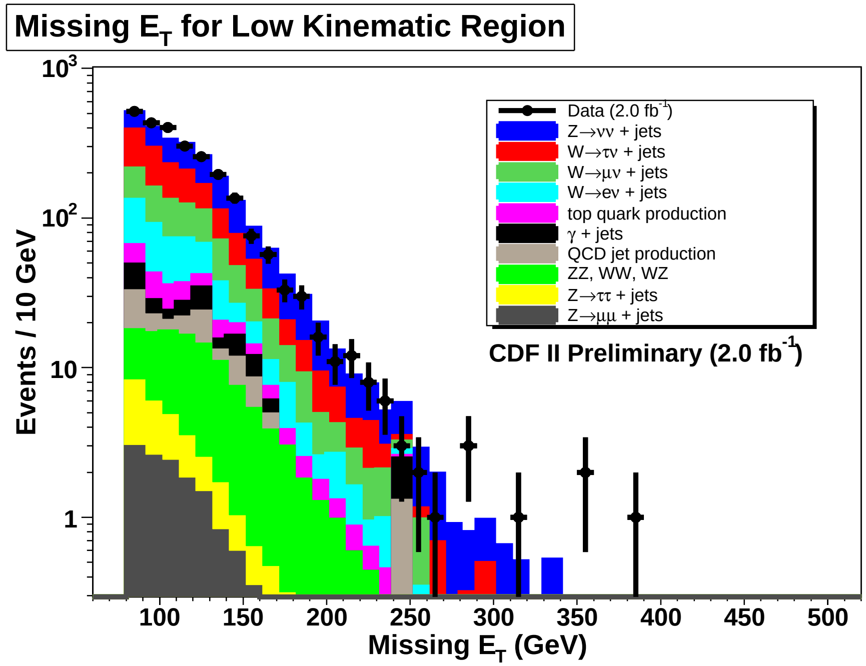

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Current SUSY bound: CDF with 2 fb^{-1}

$\Rightarrow \sigma_{MSSM} < 0.1$ pb

$\Rightarrow m_{\tilde{g}} > 320$ GeV, $m_{\tilde{q}} > 390$ GeV.

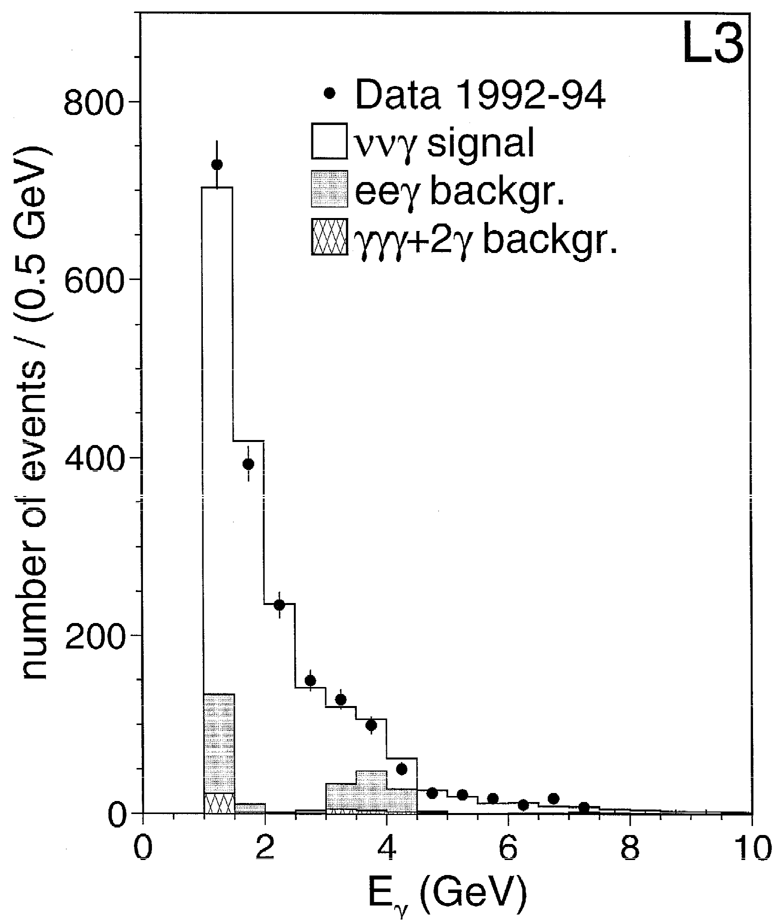
Missing energy events in e^+e^- collisions

At LEP I (L3):

Neutrino counting:

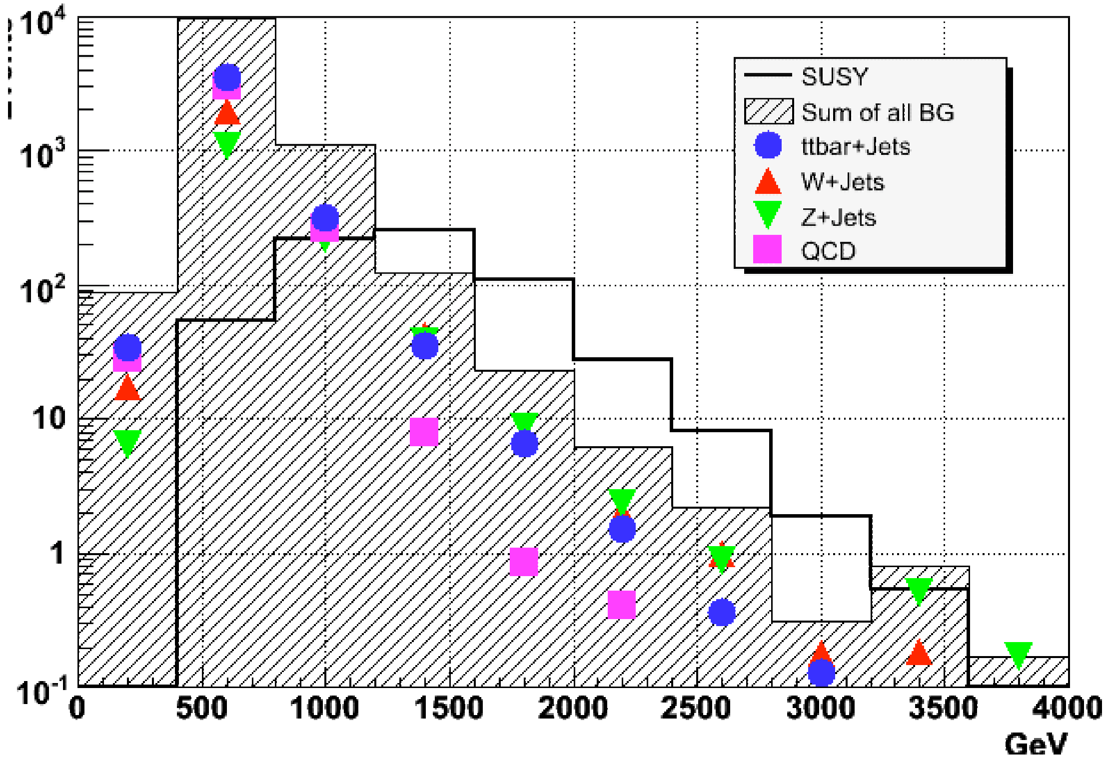
$e^+e^- \to \gamma + \nu_i \bar{\nu}_i$

$N_\nu \approx 3.$



Missing Energy and New Physics at LHC

New Physics Expectation in $\not{E}_T$: †



†M. Mangano, arXiv:0809.1567 [hep-ph].

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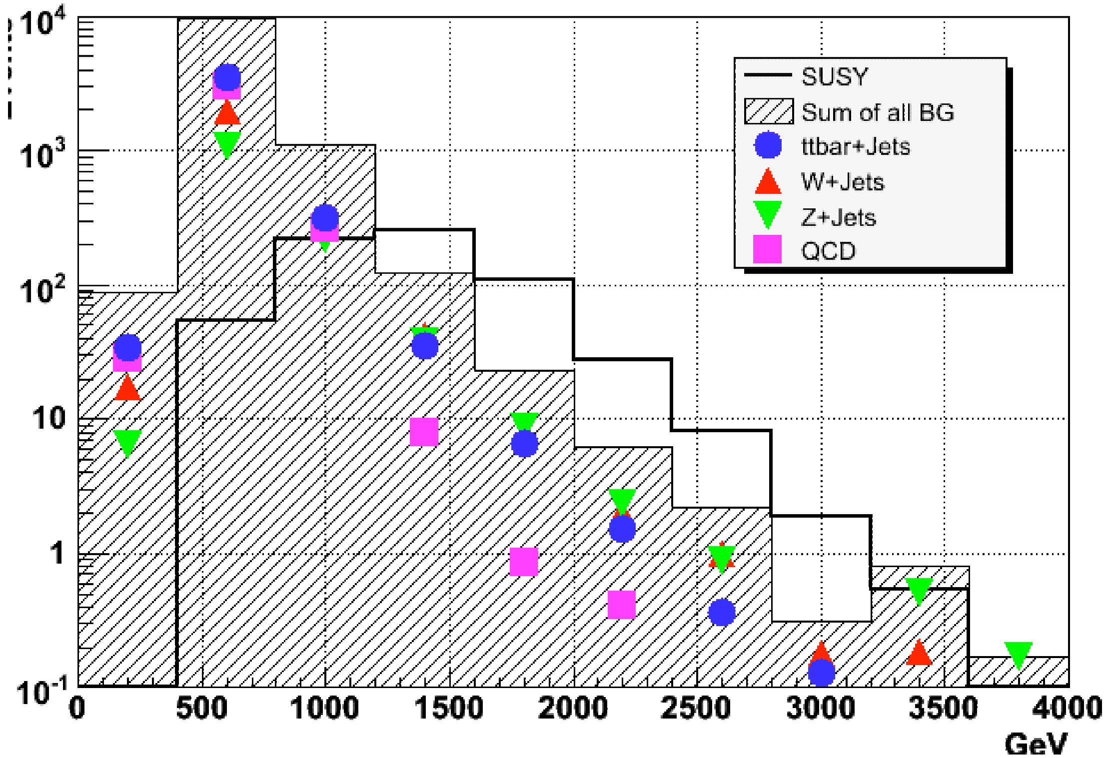
New Physics Expectation in $\not{E}_T$: [†]

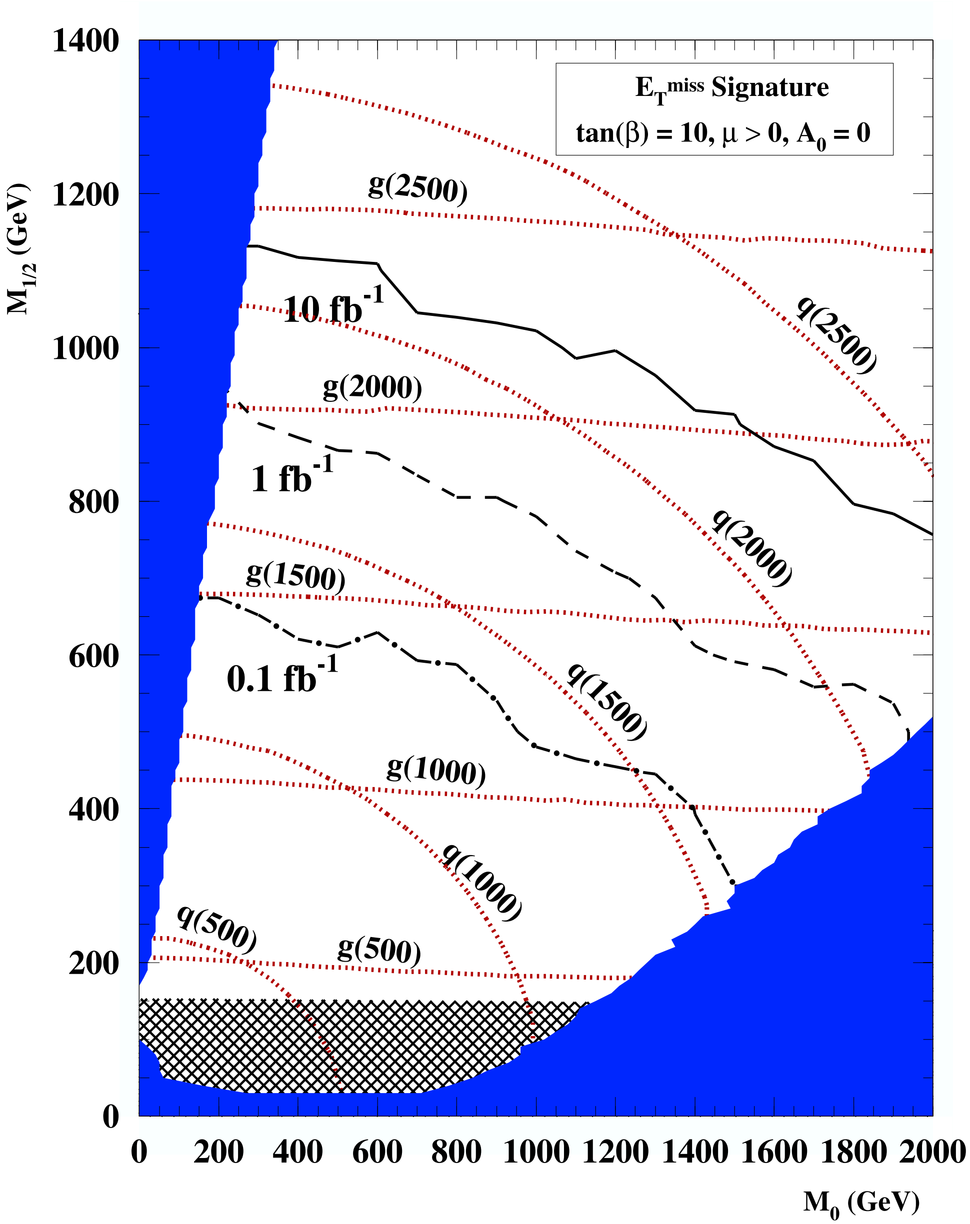


- Setting a bound for mass scale may not be too hard.
- Establishing $\not{E}_T$ signal would be challenging,

  $\Rightarrow$ that would be a revolutionary discovery for BSM physics!

[†]M. Mangano, arXiv:0809.1567 [hep-ph].

It has been shown quite promising (mSUGRA at ATLAS[‡])



[‡]D. R. Tovey, Eur. Phys. J. **C4**, N4 (2002).

Dark matter connection: LHC vs. Cosmology

Steps to follow:[§]

- Discover missing-energy events at a collider and estimate the mass of the WIMP.
- Observe dark matter particles in direct detection experiments and determine whether their mass is the same as that observed in collider experiments.

[§]Baltz, Battaglia, Peskin and Wizansky, hep-ph/0602187.

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Cosmic relic density:

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_\chi^2}{\alpha^2}.$$

By crossing, $\chi\chi$ annihilation is related to scattering.

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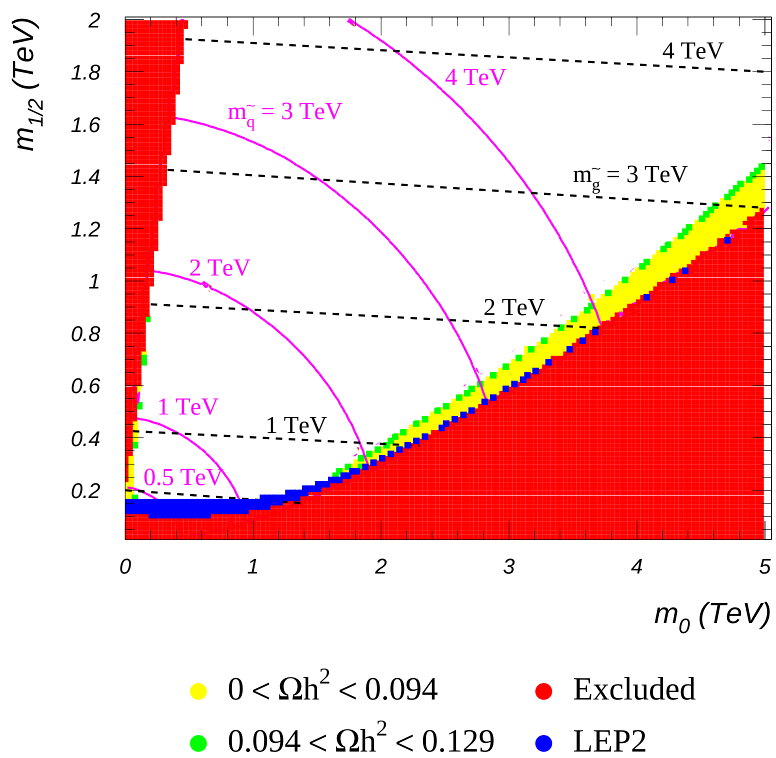
After that,

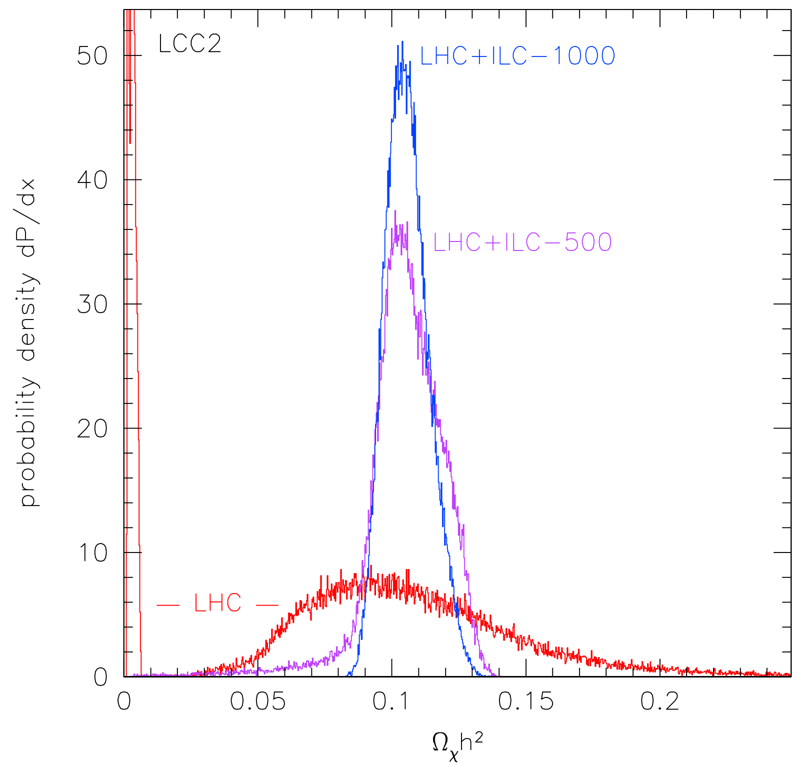
- Determine the qualitative physics model that leads to missing-energy events.
- Determine the parameters of this model that predict the relic density.
- Determine the parameters of this model that predict the direct and indirect detection cross sections.
- Measure products of cross sections and densities from astrophysical observations to reconstruct the density distribution of dark matter.

§Baltz, Battaglia, Peskin and Wizansky, hep-ph/0602187.

Optimistic conclusions were obtained for mSUGRA¶ and for MSSM parameter-determinations:‖

mSUGRA : tanβ=10, A_0=0, μ>0, m_t=171.4 GeV





¶For a review: Baer and Tata, arXiv:0805.1905.

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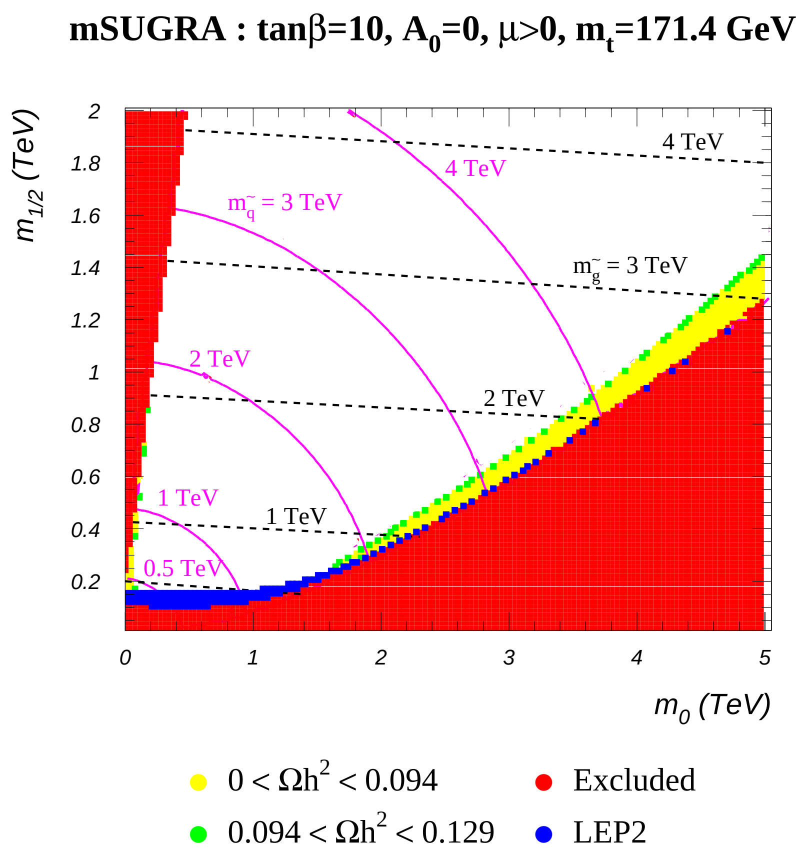

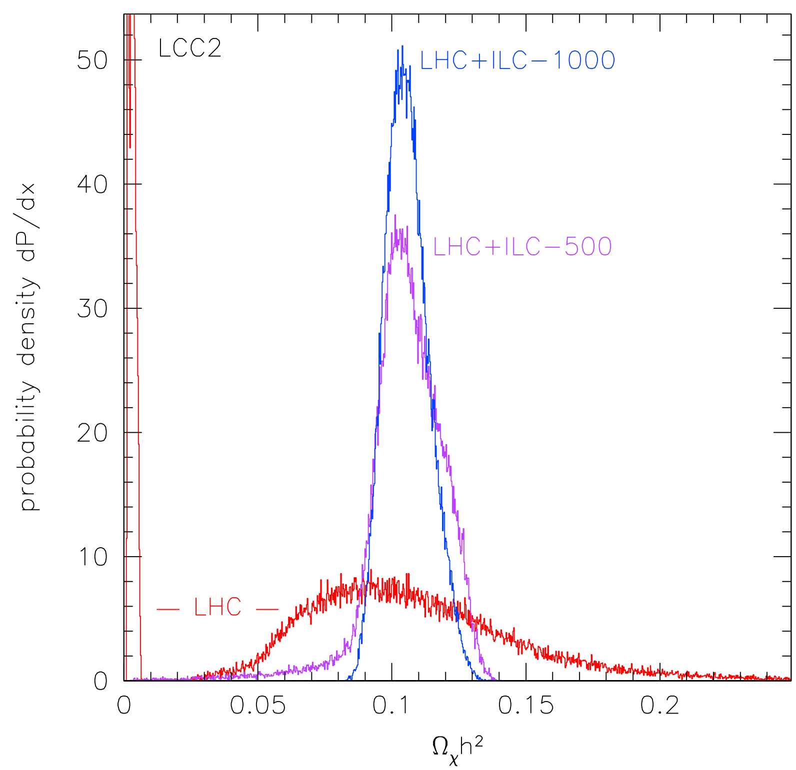

For most general cases, situations may be much more complex:**
The "LHC inverse problem": Data ⇒ many possible solutions!

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**Akani-Hamed, Kane, Thaler and Wang, hep-ph/0512190.

Determining the Dark Matter Mass

– Model-independent approaches at colliders

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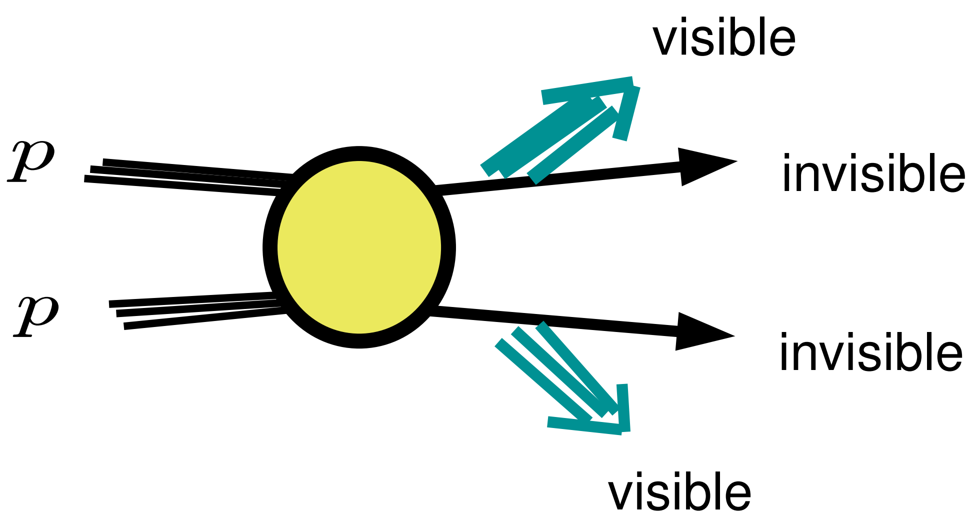
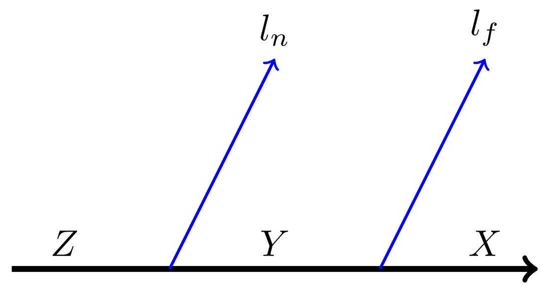
The difficulties:

- Two missing particles in each event;
- Unknown parton frame leads to less constrained kinematics.



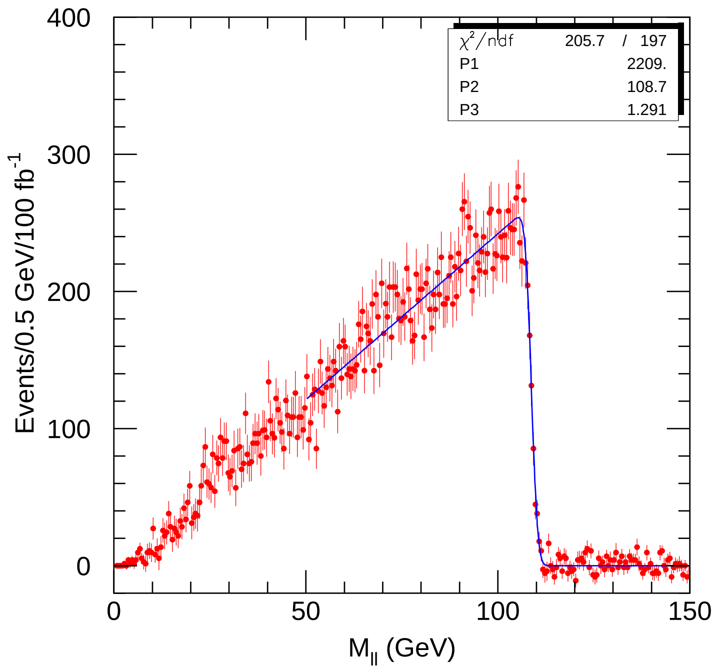
Edges, End-points etc.

- Simple decay chain:[††]



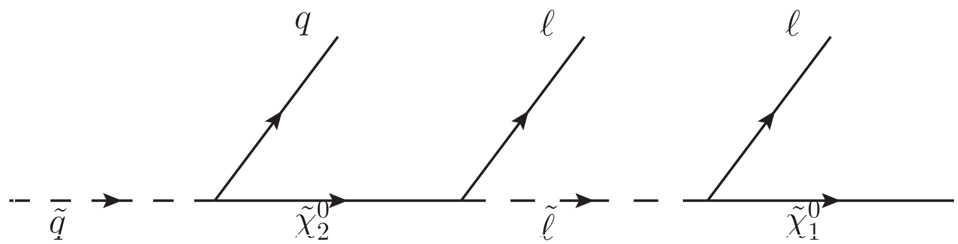
In general, $m_{\ell\ell}^{max} = M_Z - M_X$ (gives mass difference).

If Y is also on-shell, $m_{\ell\ell}^{max} = \sqrt{(M_Z^2 - M_Y^2)(M_Y^2 - M_X^2)/M_Y}$.

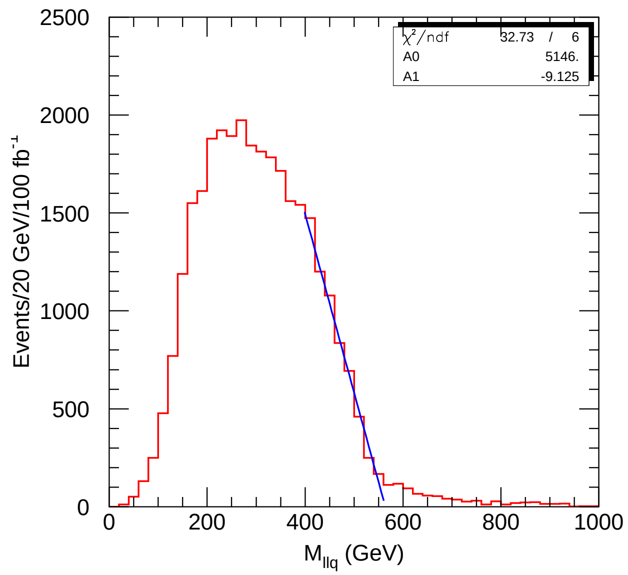


[††]Bachacou, Hinchliffe and Paige, arXiv:hep-ph/9907518.

- Longer decay chain.‡‡



Similarly, $m_{q\ell\ell}^{max} = \sqrt{(M_{\tilde{q}}^2 - M_{\tilde{\chi}_2}^2)(M_{\tilde{\chi}_2}^2 - M_{\tilde{\chi}_1}^2)}/M_{\tilde{\chi}_2}$.



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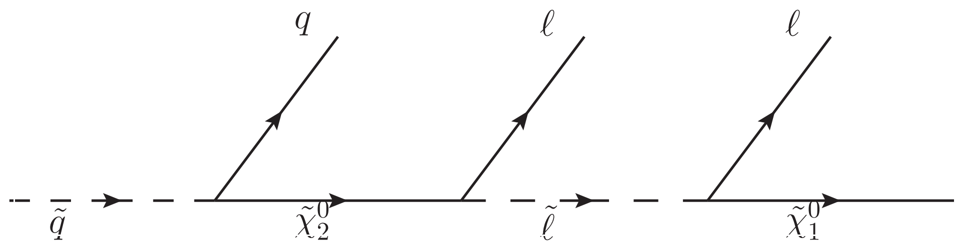

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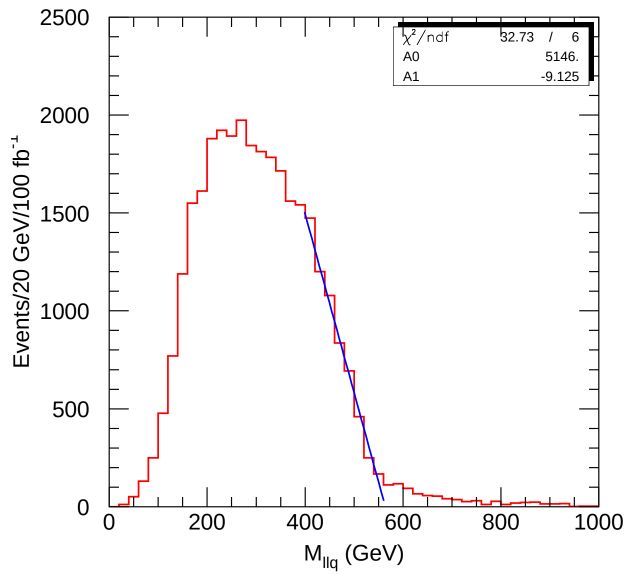

† Only probe mass differences.

† May encounter combinatoric ambiguities.

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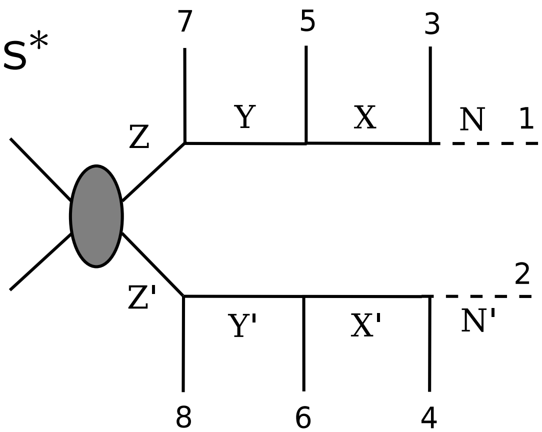
Fully Constructable Kinematics

Kinematical on-shell conditions*



*Cheng, Gunion, Z. Han and McElrath, arXiv:0905.1344.

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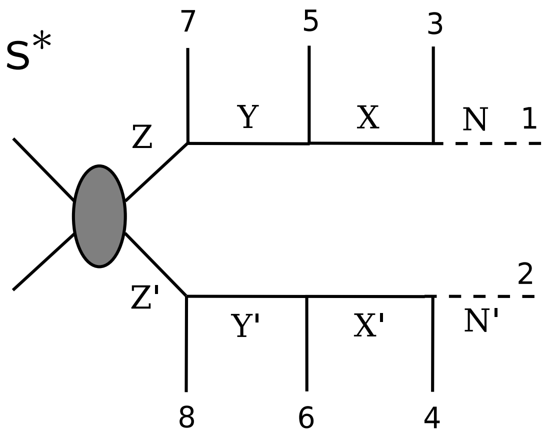

Assume:

- n signal events: particles 3,5,7; 4,6,8 observed; 1, 2 missing.
- Unknowns: masses N, X, Y, Z (4); 4-momenta of 1, 2 (8n) $\Rightarrow 4 + 8n$.

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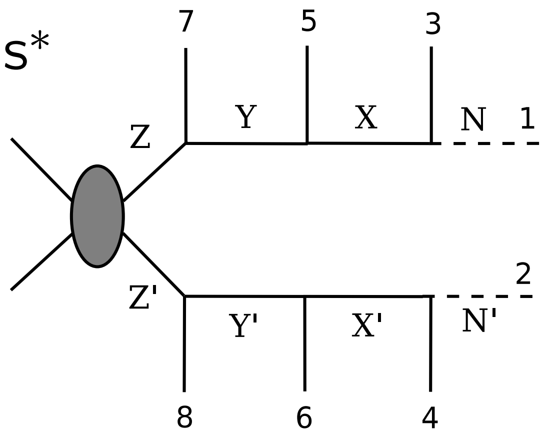

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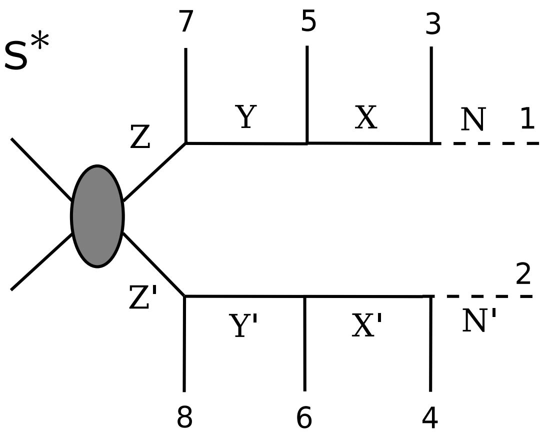

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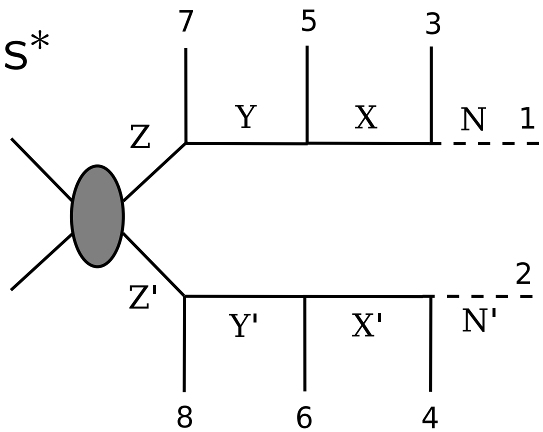
Let constraints $\geq$ unknowns $\Rightarrow$ $n \geq 2$.

*Cheng, Gunion, Z. Han and McElrath, arXiv:0905.1344.

Fully Constructable Kinematics

Kinematical on-shell conditions*



Assume:

- n signal events: particles 3,5,7; 4,6,8 observed; 1, 2 missing.
- Unknowns: masses N, X, Y, Z (4); 4-momenta of 1, 2 ($8n$) $\Rightarrow$ $4 + 8n$.
- Constraints: missing transverse momenta (x,y): $2n$.
  on-shell conditions (both chains) 8n. Total $\Rightarrow$ $10n$.

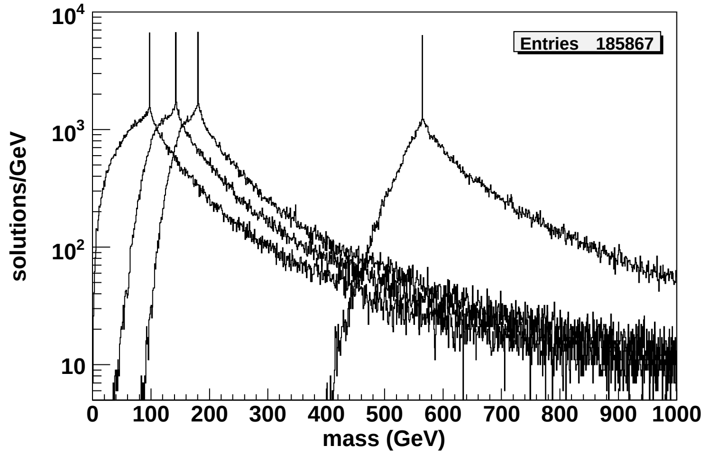
Let constraints $\geq$ unknowns $\Rightarrow$ $n \geq 2$.

† With many events (n), it's an over-constrained system.

† If only 3 on-shell particles in each chain,
there will be fewer constraints than unknowns.

*Cheng, Gunion, Z. Han and McElrath, arXiv:0905.1344.

Simulated results:*



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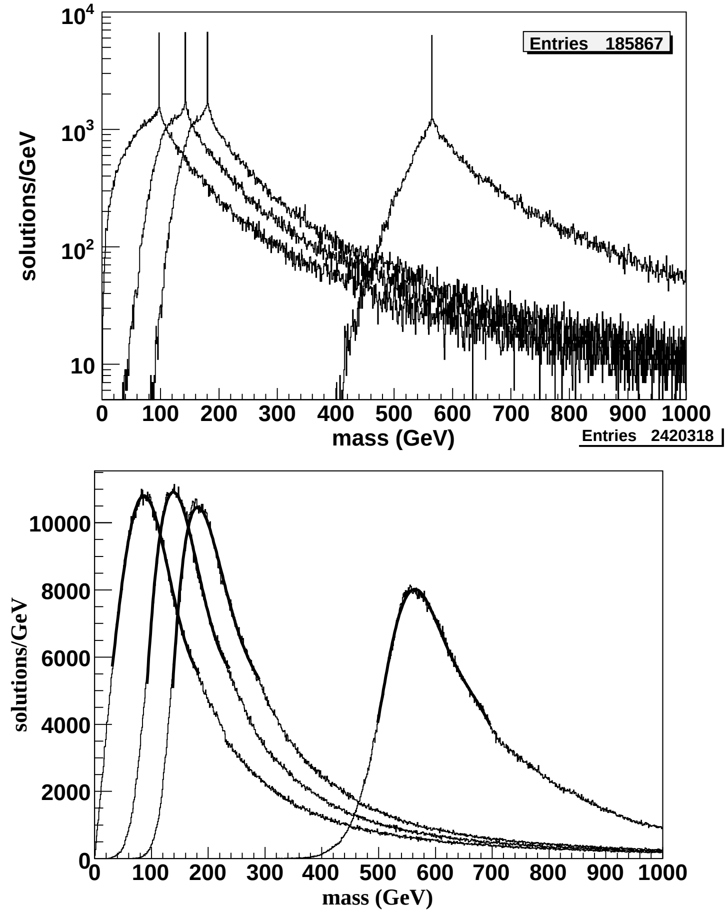

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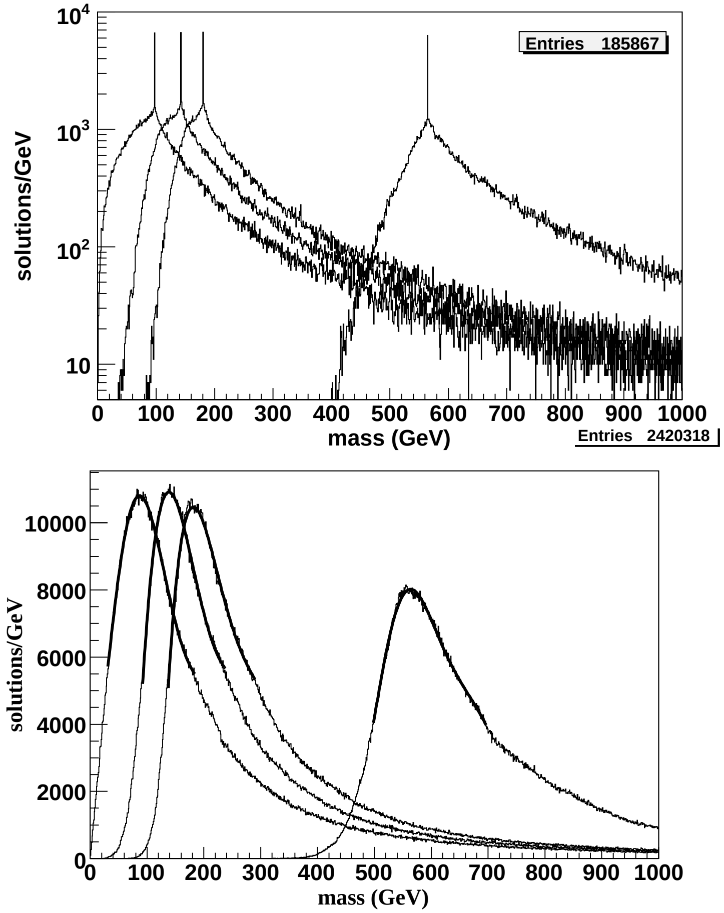

Remarks:

- Very selective channels.
- Very restrictive kinematics.
- Realistic experimental conditions will further dilute the solutions.

*Cheng, Gunion, Z. Han and McElrath, arXiv:0905.1344.

Transverse Mass Variables M_{T2}

In the attempt to determine the absolute masses (parent and missing one), without fully reconstructing the events, M_{T2} was introduced.*

*C. Lester and D. Summers, hep-ph/9906349.

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Recall the invariant mass/transverse mass of ab (or $e\nu$):

$$m_{ab}^2 = m_a^2 + m_b^2 + 2(E_T^a E_T^b \cosh \Delta\eta - \vec{p}_T^{\,a} \cdot \vec{p}_T^{\,b}) \geq m_T^2.$$

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Consider a pair production/decay $D_1 \to a_1\ b_1$, $D_2 \to a_2\ b_2$:

$$m_D^2 \geq \max(m_{TD_1}^2,\ m_{TD_2}^2).$$

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Only knowing $|\vec{p}_{Tb1} + \vec{p}_{Tb2}| = \not{E}_T$, one defines:

$$M_{T2}^2(m_{a1}, m_{a2};\ m_b) = \min_{|\vec{p}_{Tb1}+\vec{p}_{Tb2}|=\not{E}_T}[\max(m_{T1}^2,\ m_{T2}^2)].$$

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This is a "functional":

† For each event $(\not{E}_T)$, run through trial $\vec{p}_{Tb1}$ and $\vec{p}_{Tb2} = \vec{\not{E}}_T - \vec{p}_{Tb1}$:

→ It is smaller than the true $\max(m_{TD_1}^2,\ m_{TD_2}^2)$;

→ With many events, it still doesn't go over it.

*C. Lester and D. Summers, hep-ph/9906349.

Thus, one defines:*

$$M_{T2}^{max}(m_b) = \text{max}_{(all\ \ events)} M_{T2}(m_{a1}, m_{a2};\ m_b).$$

a function of the trial missing mass m_b.

*W.S. Cho, K. Choi, Y.G. Kim, C.B. Park, arXiv:0709.0288.

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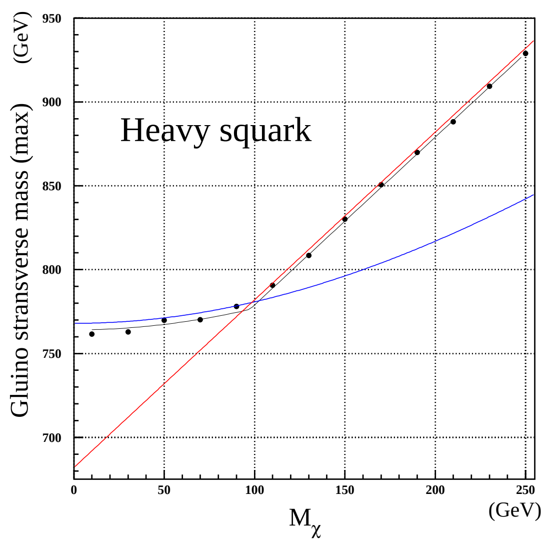
The kink structure: †

When varying the trial missing mass below to above the true value of m_b, the curve $M_{T2}^{max}(m_b)$ (for multi-body decay) changes the slope:



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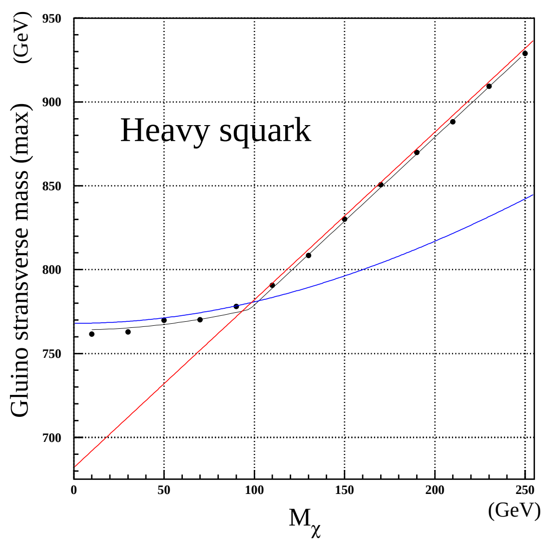

† For simple 2-body decay, no clear kink;

† For multi-body decays, combinatorics dilute the kink.

*W.S. Cho, K. Choi, Y.G. Kim, C.B. Park, arXiv:0709.0288.

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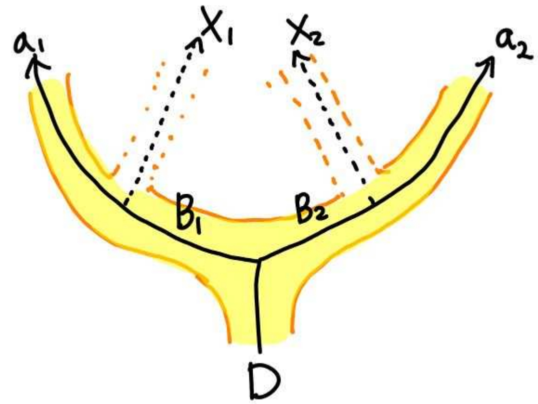
"Antler Decay" Kinematics

The "Antler decay" †



D, a SM-like particles; B, X carry a new quantum number.

†TH, I.-W. Kim and J. Song, arXiv:0906.5009.

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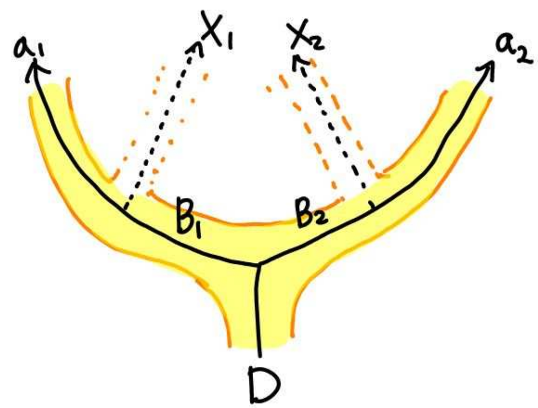

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Advantages:

- More constrained kinematics: M_D is known from other SM modes.

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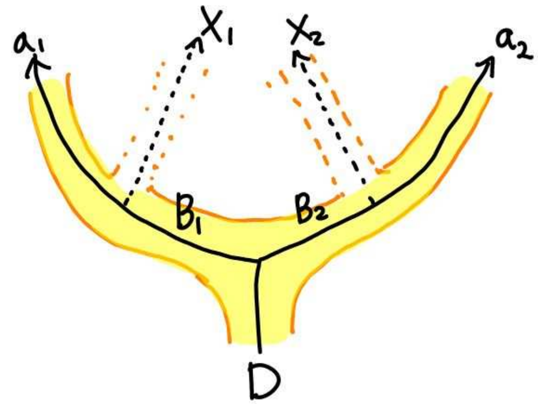

$D,\ a$ SM-like particles; B, X carry a new quantum number.

Advantages:

- More constrained kinematics: M_D is known from other SM modes.
- Many channels:

MSSM: $H \to \tilde{\chi}_2^0 + \tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0 + Z\tilde{\chi}_1^0;$

Z' SUSY: $Z' \to \tilde{\ell}^+ + \tilde{\ell}^- \to \ell^-\tilde{\chi}_1^0 + \ell^+\tilde{\chi}_1^0;$

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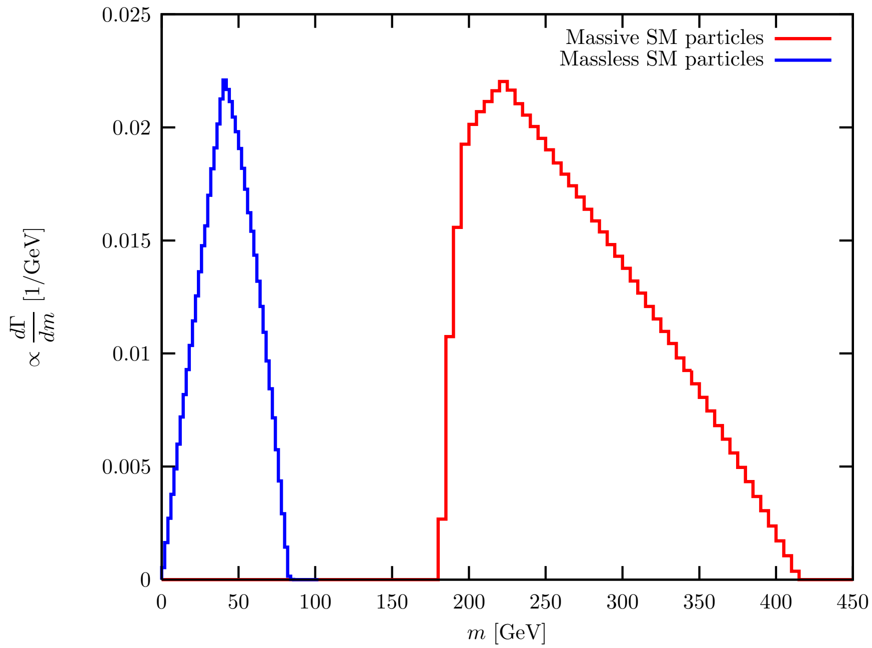
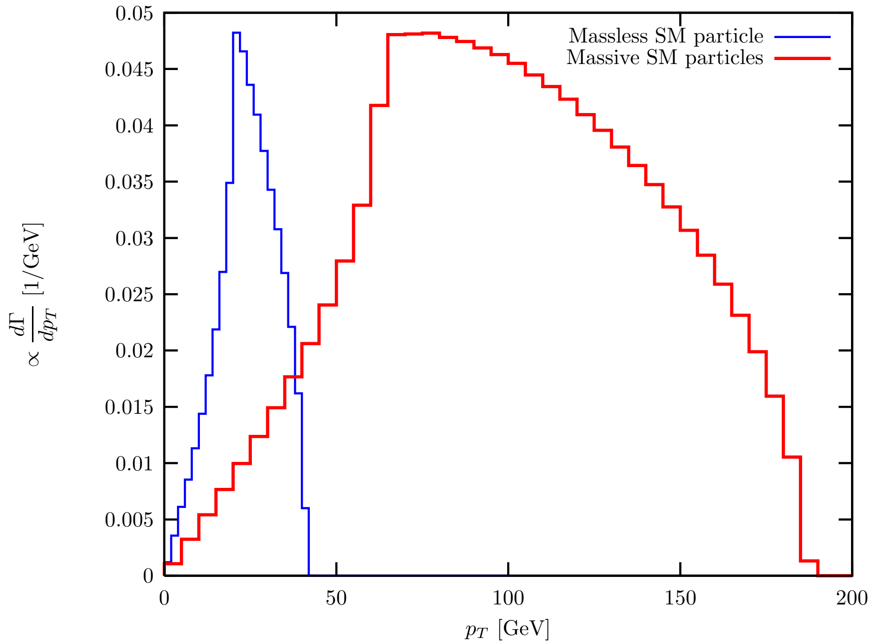
A new kinematical feature: cuspy structures!





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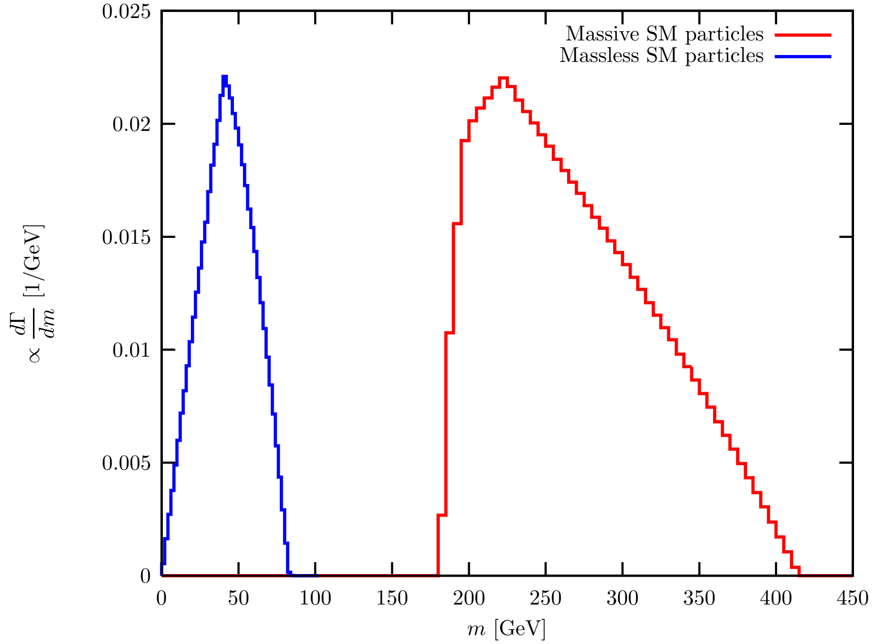
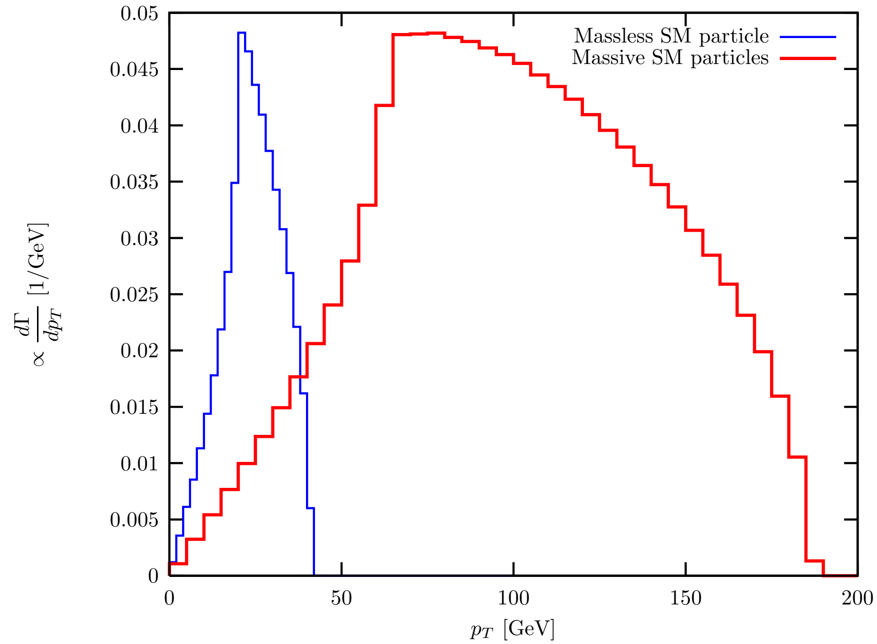
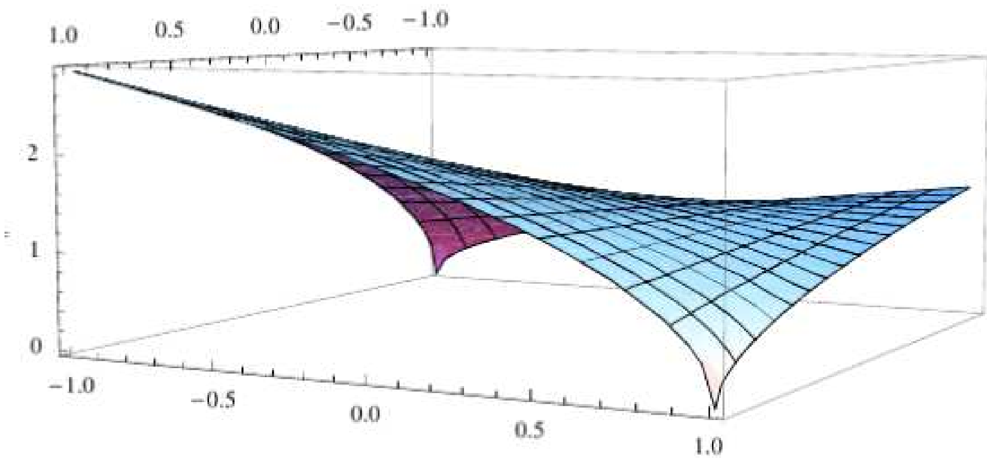
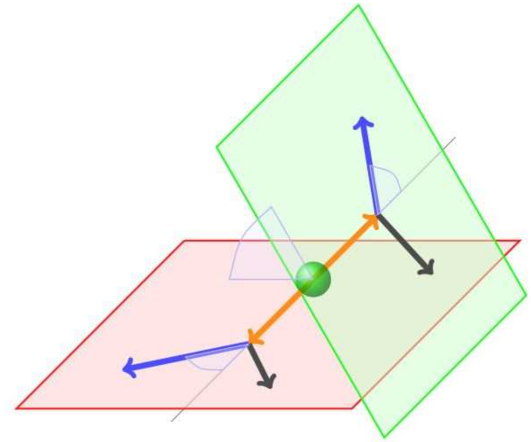




Pronounced “peaks” appear, suitable for observation!

Origin of the cusps:





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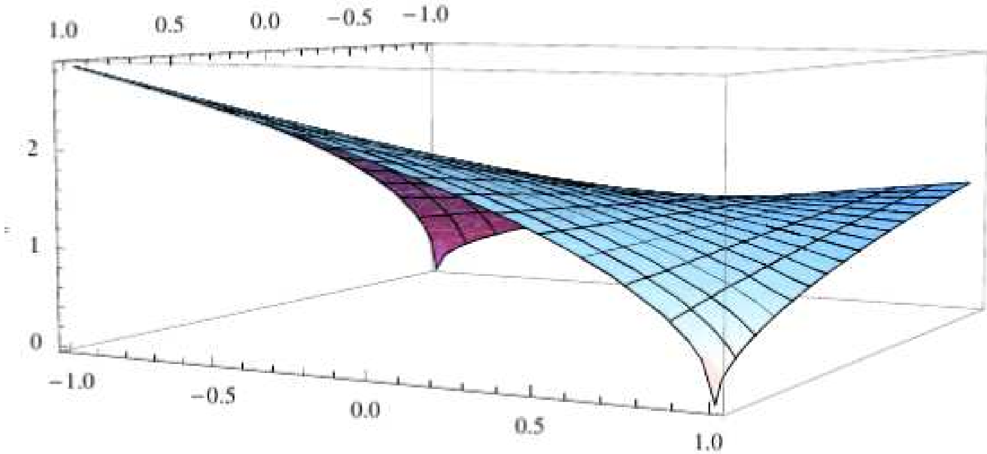

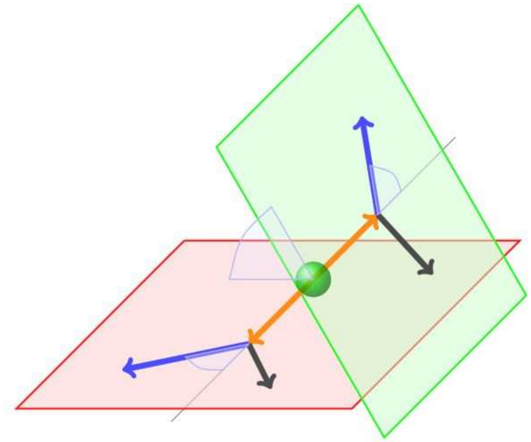

Limiting cases (at the corners)

$$a_2 X_2 \leftarrow B_2 \;\Leftarrow D \Rightarrow\; B_1 \rightarrow a_1 X_1$$

- Back-to-back: $(\cos\theta_1, \cos\theta_2) = (+1, -1)$ $\Leftarrow + \Rightarrow$

  Maximum M_{aa} configuration.
- Head-on: $(\cos\theta_1, \cos\theta_2) = (-1, +1)$ $\Rightarrow + \Leftarrow$

  Medium M_{aa} configuration.
- Parallel: $(\cos\theta_1, \cos\theta_2) = (\pm 1, \pm 1)$ $\Rightarrow + \Rightarrow, \quad \Leftarrow + \Leftarrow$

  Zero M_{aa} configurations.

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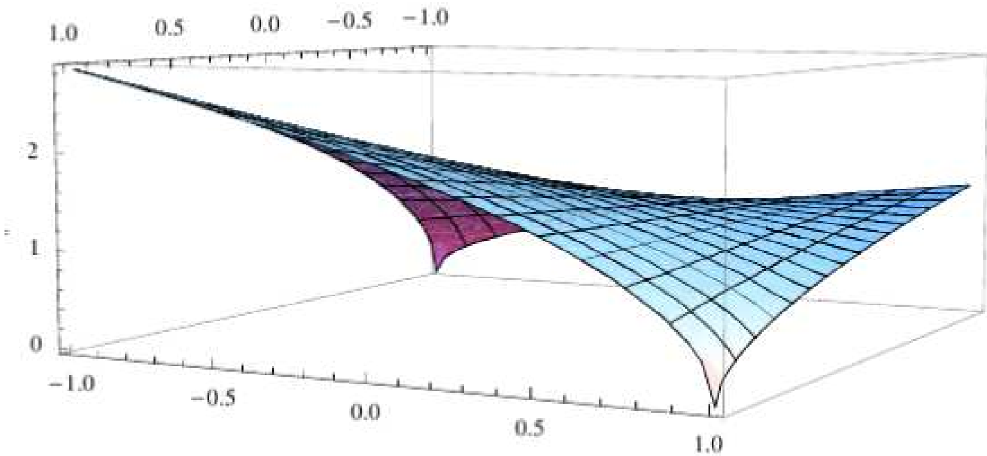

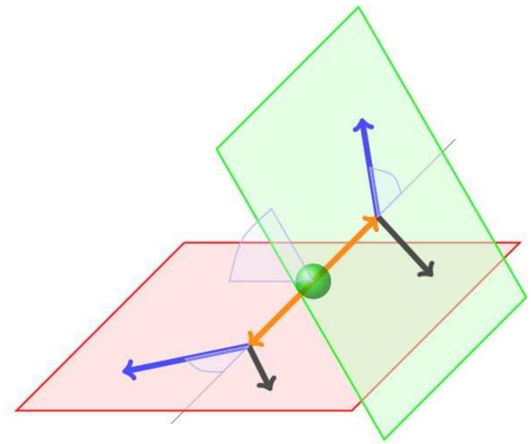

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  Zero M_{aa} configurations.
- Upon variable projection (losing info), singularities may be developed.
- It is purely kinematical, and new (rigorous singularity theorems in math).

The rapidities η and ζ in the parent-rest frame:

$$\cosh\eta = \frac{m_D}{2m_B} \equiv c_\eta, \quad \cosh\zeta = \frac{m_B^2 - m_X^2 + m_a^2}{2m_a m_B} \equiv c_\zeta,$$

$$\text{thus}: \quad \eta,\ \zeta \ (\text{plus } m_D) \implies m_B,\ m_a.$$

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- Cusp and Edge: ($M_a = 0$ case)

The end-point, instead of being $M_{aa}^{\text{max}} = m_D - 2m_X$, becomes

$$M_{aa}^{\text{max}} = m_B\left(1 - \frac{m_X^2}{m_B^2}\right)e^{\eta},$$

$$M_{aa}^{\text{cusp}} = m_B\left(1 - \frac{m_X^2}{m_B^2}\right)e^{-\eta}.$$

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Thus,

$$M_{aa}^{\text{max}}/M_{aa}^{\text{cusp}} = e^{2\eta}, \quad (D \to B)$$

$$M_{aa}^{\text{max}} M_{aa}^{\text{cusp}} = m_B^2 \left(1 - \frac{m_X^2}{m_B^2}\right)^2. \quad (B \to X)$$

Algebraically/graphically,

$$\frac{d\Gamma}{dM_{aa}} \propto \begin{cases} 2\eta M_{aa}, & \text{if } 0 \leq M_{aa} \leq M_{aa}^{\text{cusp}}; \\ M_{aa} \ln \frac{M_{aa}^{\text{max}}}{M_{aa}}, & \text{if } M_{aa}^{\text{cusp}} \leq M_{aa} \leq M_{aa}^{\text{max}}. \end{cases}$$

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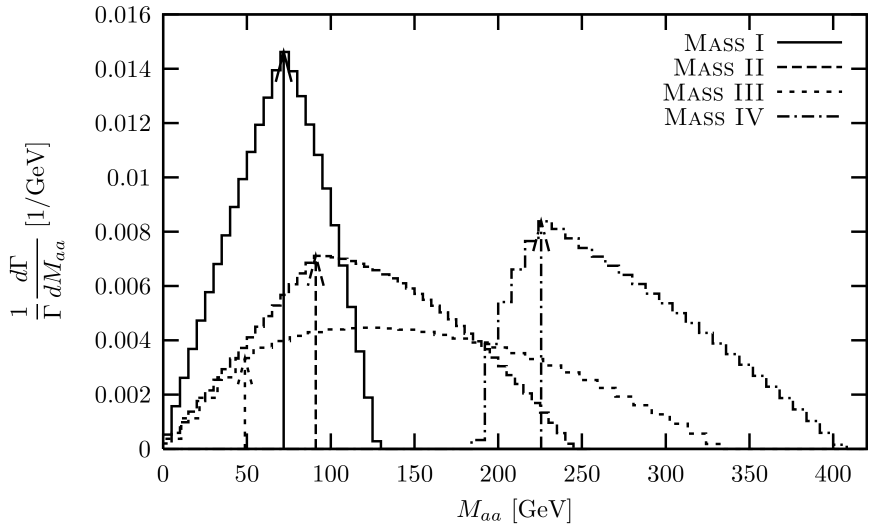


	m_D (GeV)	m_B (GeV)	m_a (GeV)	m_X (GeV)
Mass I	1250	600	0	550
Mass II	1000	440	0	300
Mass III	1000	350	0	200
Mass IV	600	250	m_Z	100

Mass I: "near threshold case" ($Z^{(2)}$ decay in the UED model).

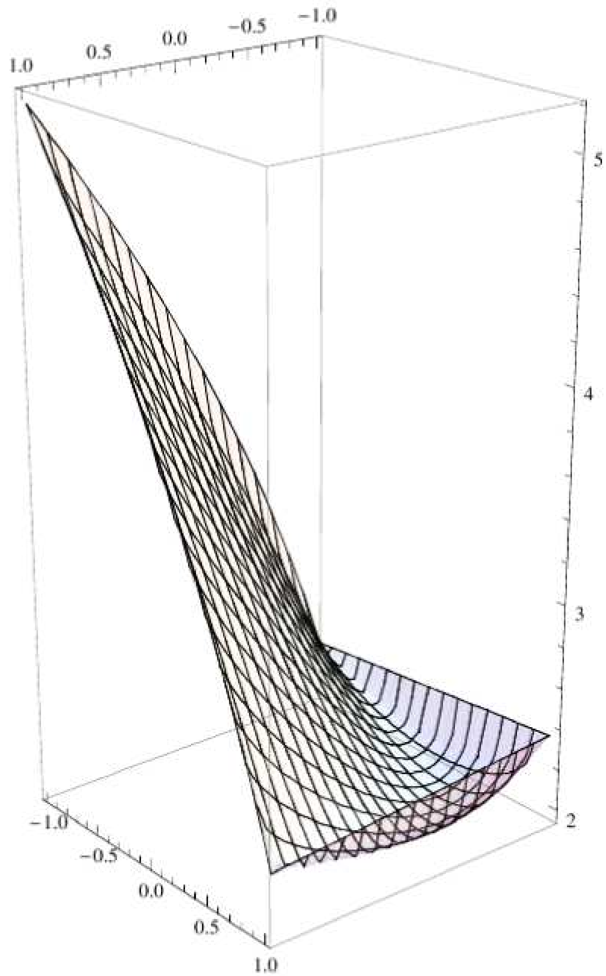
Mass II: "boundary case" ($m_B \approx 0.44 m_D$).

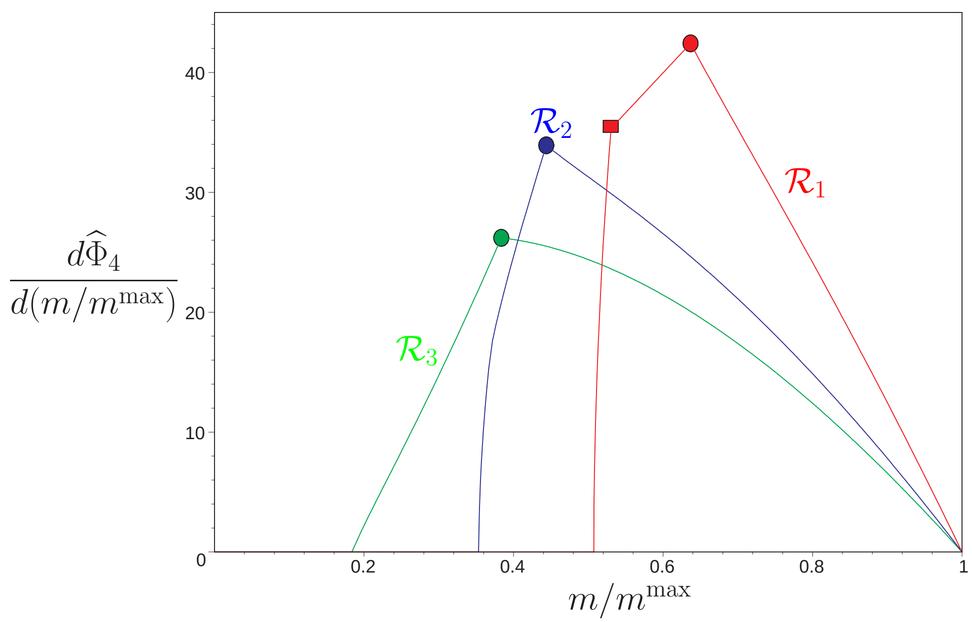
Mass III: "large mass gap case".

Mass IV: "massive case" ($Z, t, \ldots$ in the final state).

- <u>Massive SM final state: ($M_a \neq 0$)</u>

For a massive case $a = Z,\ t,\ \ldots\ ,\ d\Gamma/dM_{aa}$ may develop two cusps:





- Cusp in Angular Distribution: ($M_a = 0$)

Θ is the angle of a visible particle (a_1) in the $a_1 a_2$ c.m. frame with respect to the c.m. moving direction. Then

$$\frac{d\Gamma}{d\cos\Theta} \propto \begin{cases} \sin^{-3}\Theta, & \text{if } |\cos\Theta| \le \tanh\eta, \\ 0, & \text{otherwise.} \end{cases}$$

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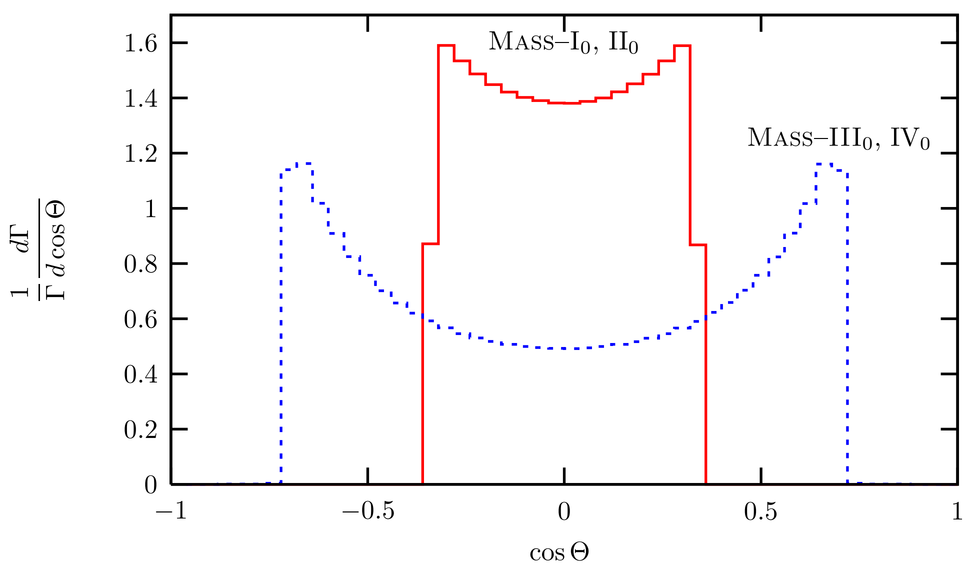
$\Rightarrow$ a sharp end-point (another cusp) at the boundary:

$$|\cos\Theta|_{\max} = \tanh\eta = \sqrt{1 - 4m_B^2/m_D^2}\ .$$



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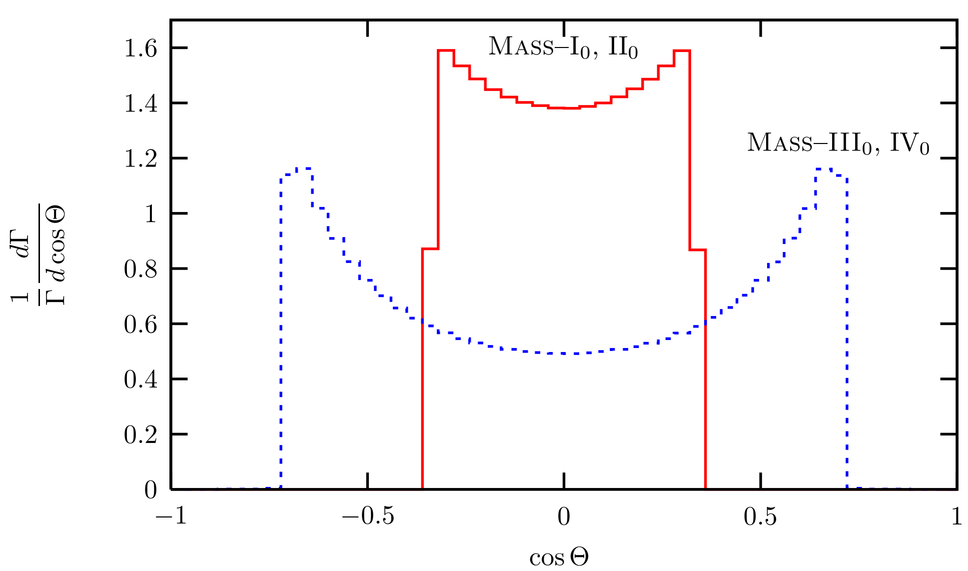
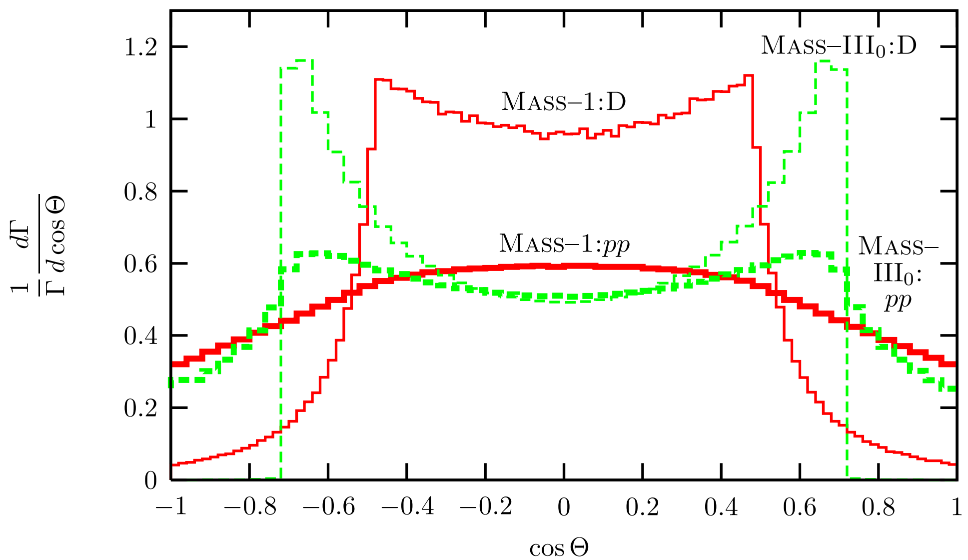


Complementarity: Large-mass gap worse for M_{aa}, better for $\cos\Theta$.

• "Robustness" of the proposal

(a). Back to the lab-frame: Lorentz boost

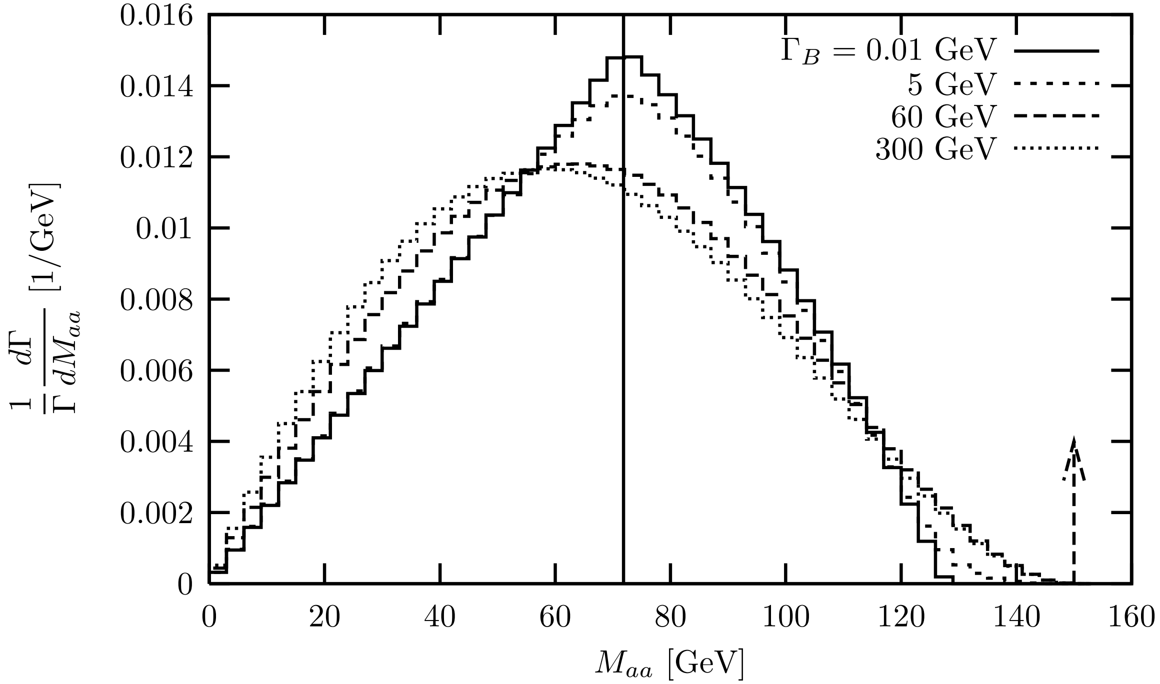
$\Rightarrow$ M_{aa} not effected, cos Θ peaks diluted:



(b). Dynamical effects: matrix elements, spin-correlations etc.

$\Rightarrow$ M_{aa}, cos Θ not appreciably effected, (c). Off-shell decays: finite width effects

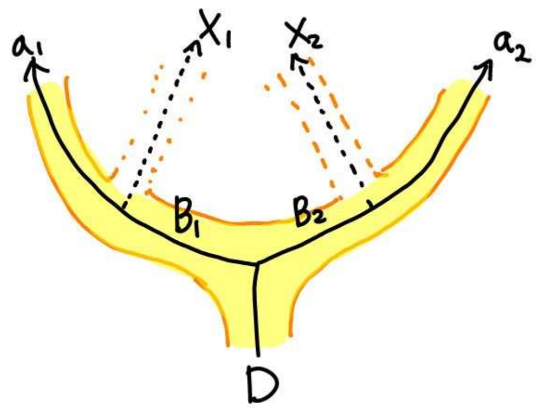
$m_B = 600$ GeV



$\Rightarrow$ $\Gamma_B \approx 10\%$ not good anymore.

On-going studies: †

- Reconstruct the antler kinematics:



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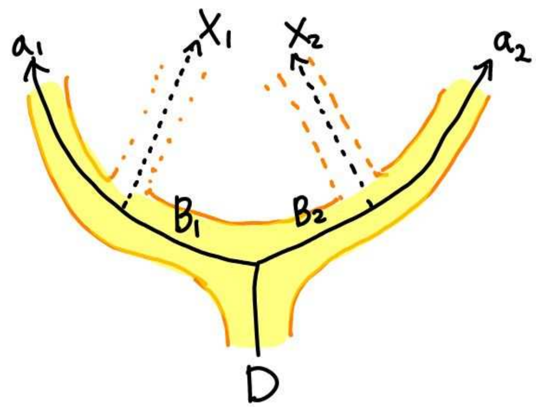

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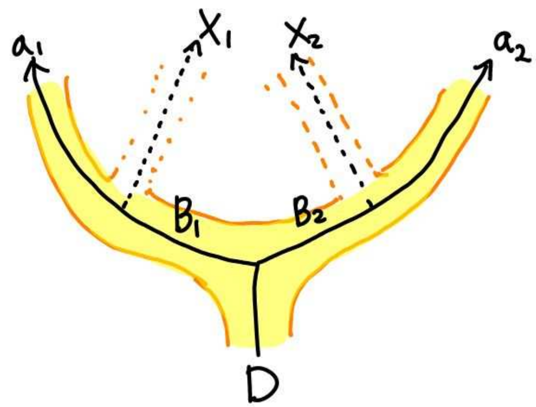
- Reconstruct the antler kinematics:



D, a SM-like particles; B (on-shell) and X (missing).

MSSM:	$H \to \tilde{\chi}_2^0 + \tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0 + Z\tilde{\chi}_1^0$;
Z' SUSY:	$Z' \to \tilde{\ell}^+ + \tilde{\ell}^- \to \ell^-\tilde{\chi}_1^0 + \ell^+\tilde{\chi}_1^0$;
UED:	$Z^{(2)} \to L^{(1)} + L^{(1)} \to \ell^+\gamma^{(1)} + \ell^-\gamma^{(1)}$;
LHT:	$H \to t_- + \bar{t}_- \to tA_H + \bar{t}A_H$.
ILC:	$e^+e^- \to B_1 + \bar{B}_2 \to a_1X_1 + a_2X_2$.

- Other channels with cusps:

† Decay chain kinematics: cusps as well. ‡

† Multi-particle final states: some dilution.

† TH, I.-W. Kim and J. Song, in progress.

‡ A. Agashe, M. Toharia et al.; P. Osland, Miller et al.

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We are all eagerly waiting for the excitement from the LHC!