

Missing Energy (\cancel{E}_T) at the LHC: The Dark matter Connection

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Joint-seminar at UMD/Hopkins (Sept. 30, 2009)

(Collaborators: Ian-Woo Kim, J.H. Song)

Outline

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Missing Energy and New Physics at the LHC

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Determining the Dark Matter Mass

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“Antler Decay” Kinematics

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Summary

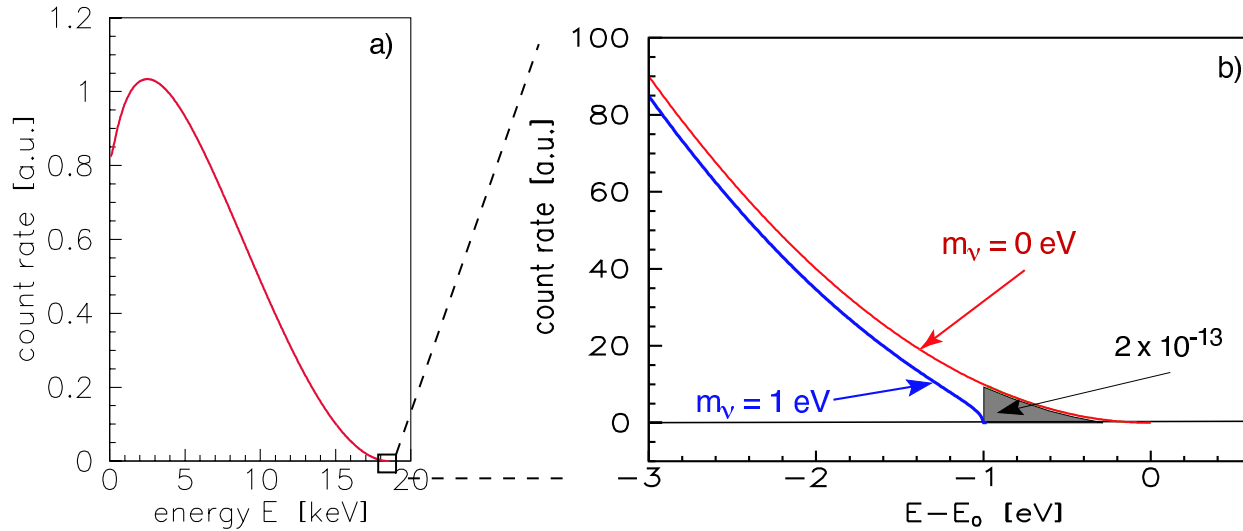
Missing Energy Events

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

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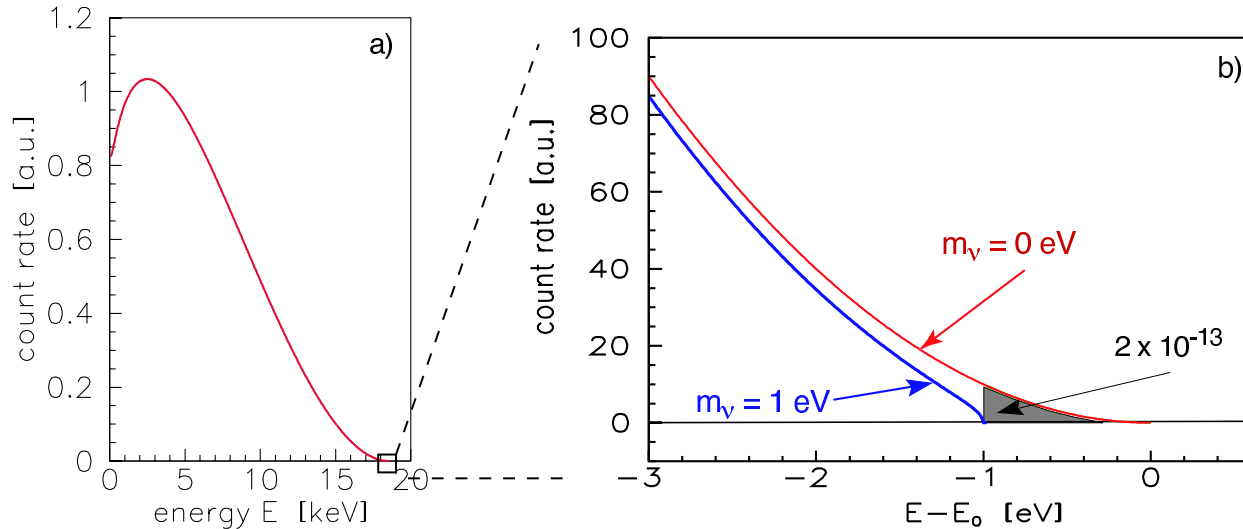


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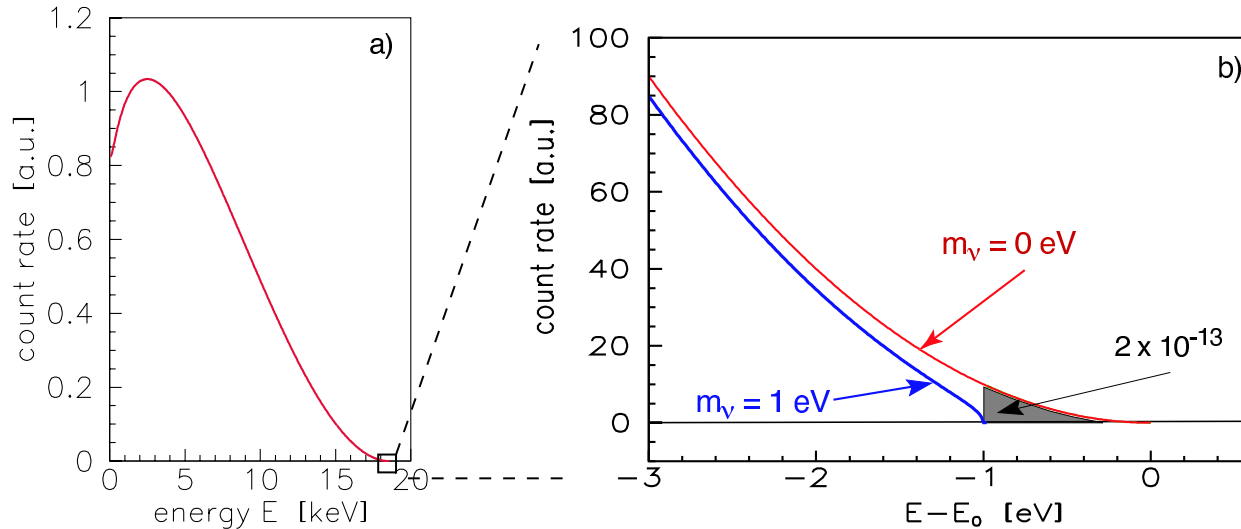
$$K_a = \frac{(M - m_a)^2 - m_b^2}{2M}.$$

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

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

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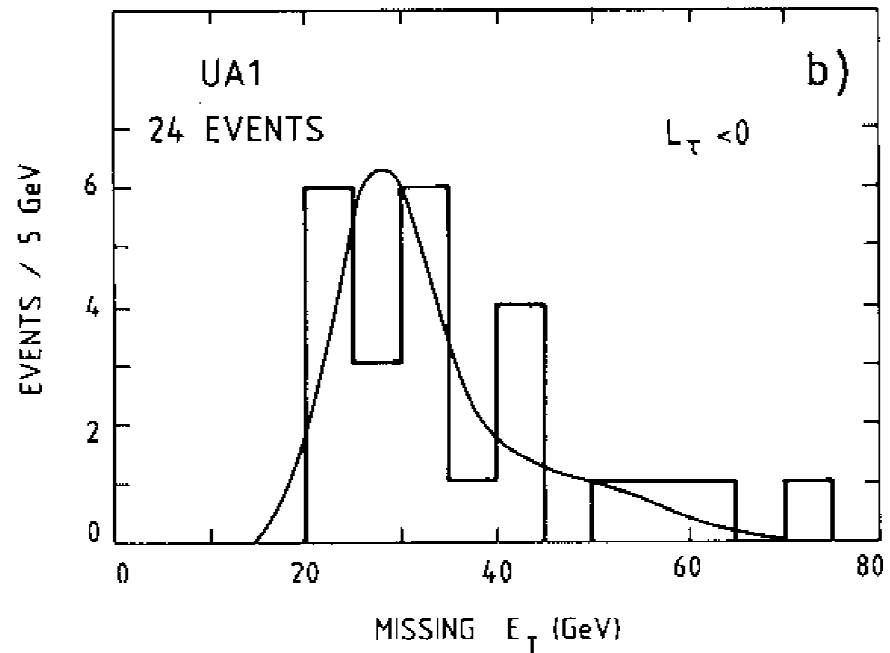
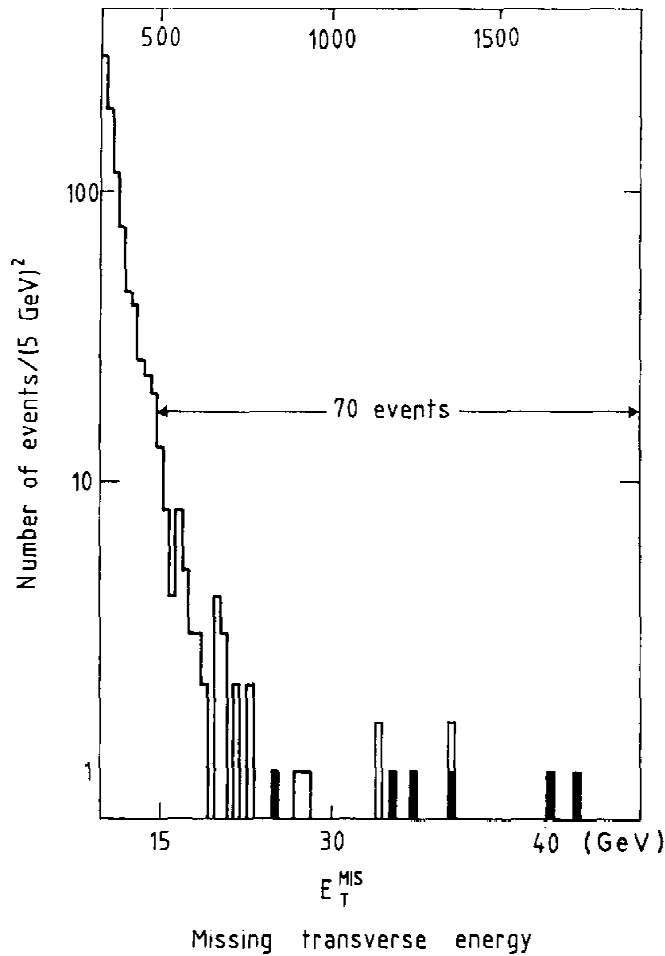
“Dark matter direct detection”.

W^\pm and Missing Energy

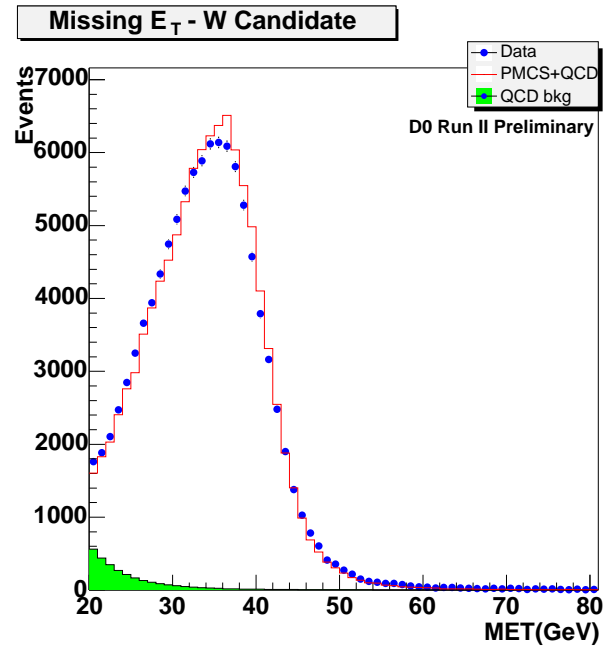
- The discovery of $W^\pm \rightarrow l\nu_l$ (UA1/UA2 in 1983):

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

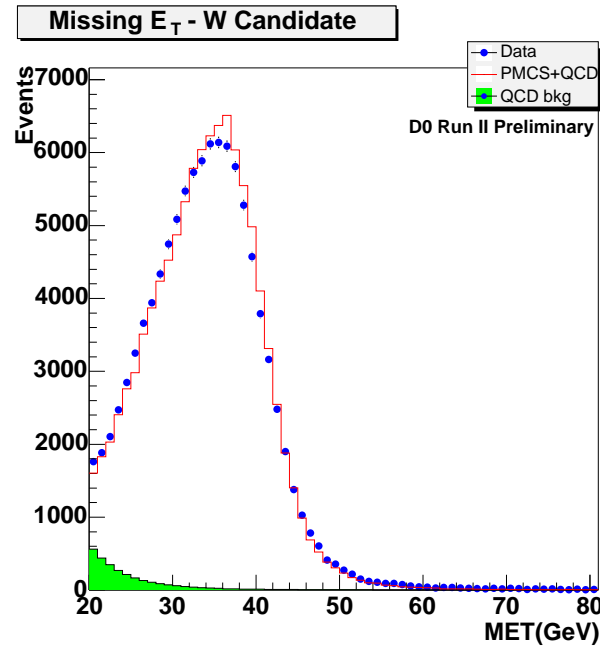
UA1 Collaboration, CERN, Geneva, Switzerland



At the Tevatron Run II:



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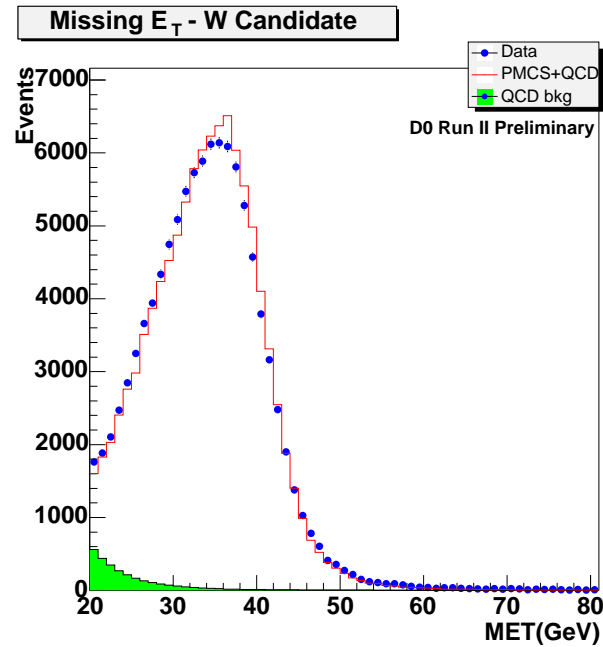
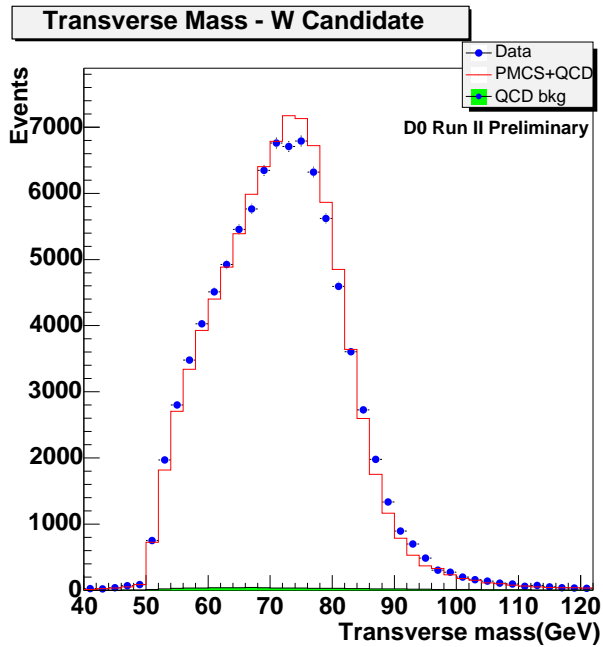
The transverse momentum of ν or e has a Jacobian peak:

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

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

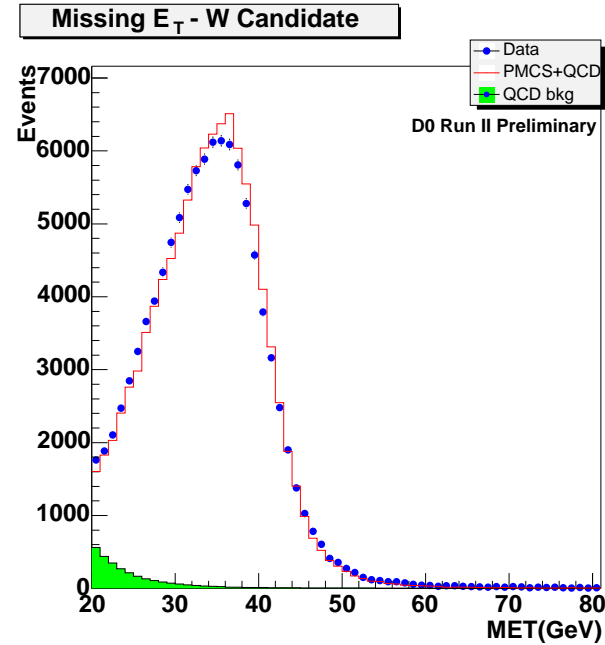
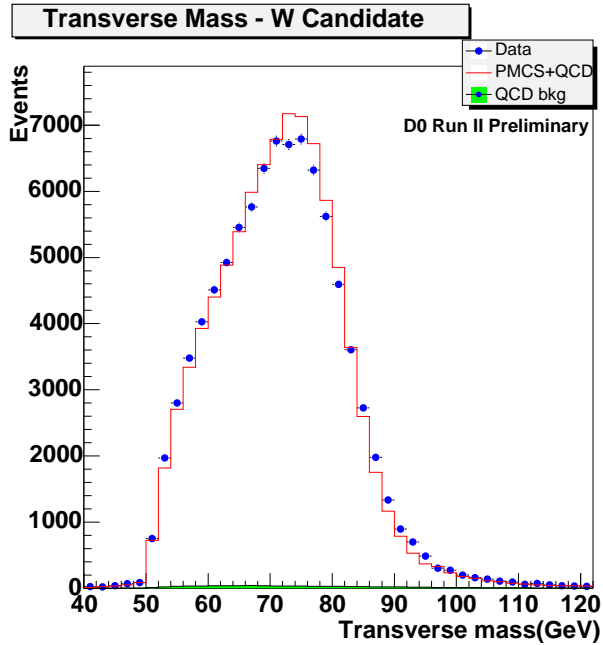
Transverse mass variable $W \rightarrow e\nu$:

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



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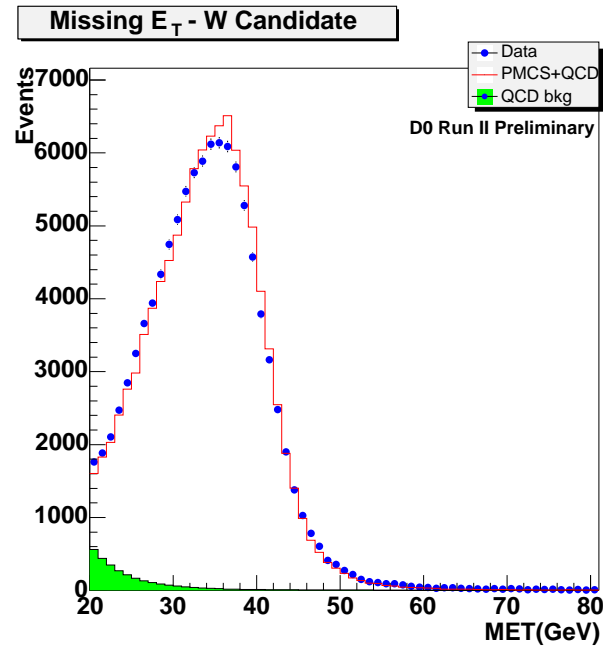
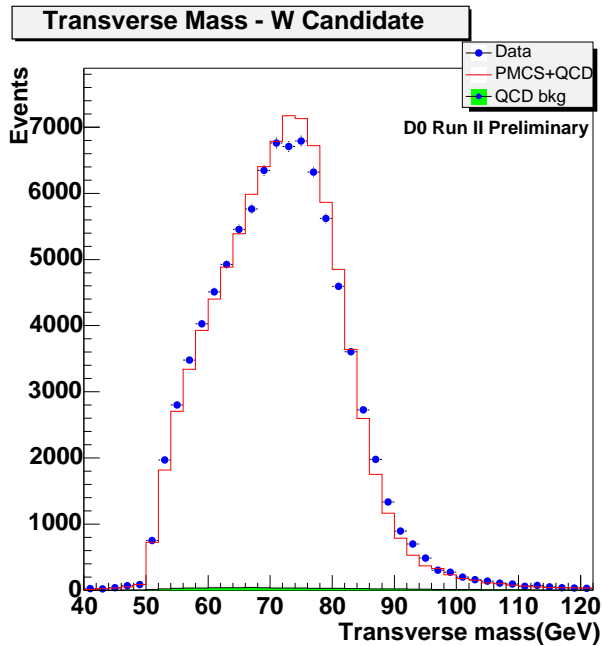
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⇒ If $p_T(W) = 0$, then: $m_{e\nu T} = 2E_{eT} = 2E_T^{miss}$.

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

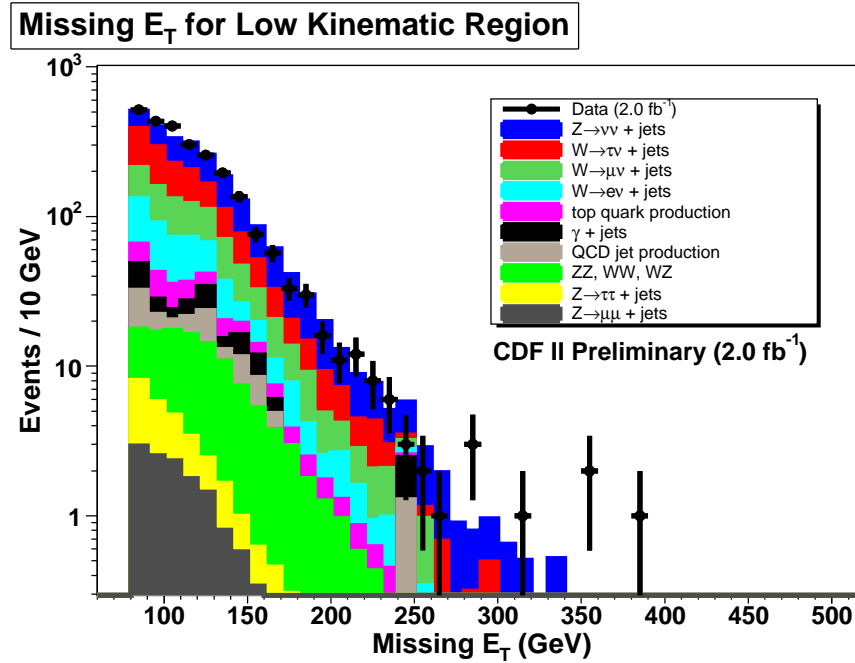
$$p'_{eT} \sim p_{eT} [1 + \delta P_V/M_V],$$

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

$$m^2_{e\nu} = m^2_{e\nu}.$$

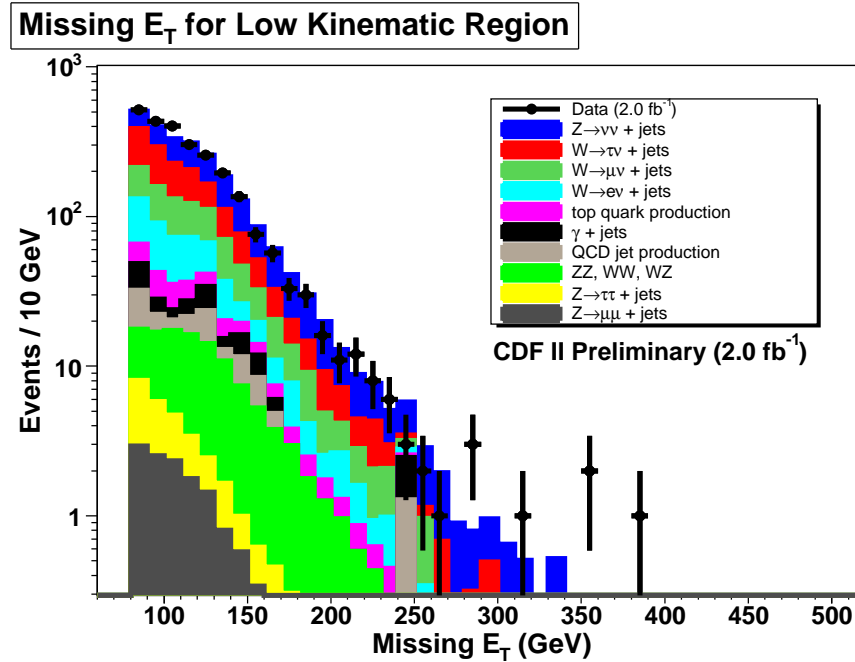
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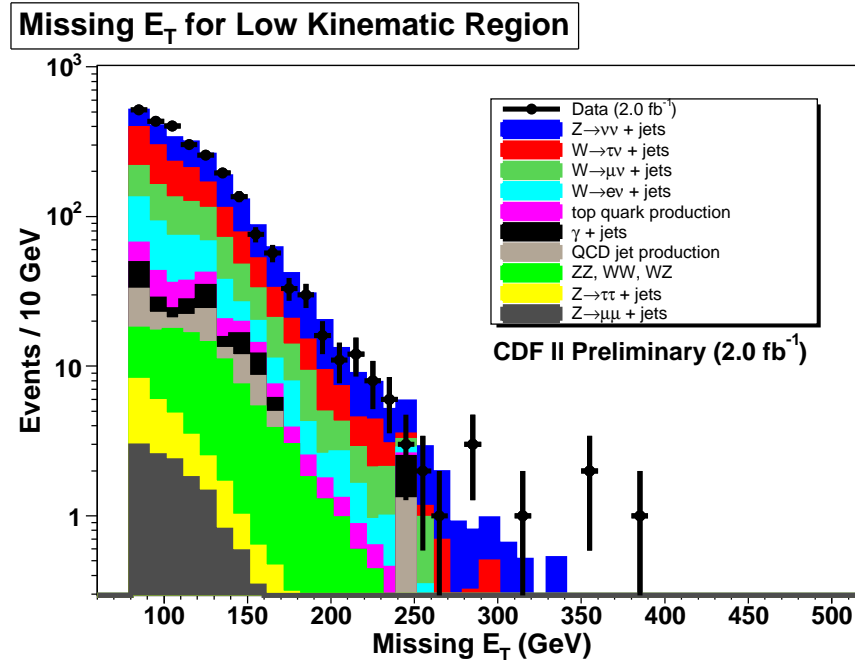


First SUSY bound: CDF with 25.3 nb^{-1} (!) (1989)

No events found with $\cancel{E}_T > 40 \text{ GeV} \Rightarrow \sigma_{MSSM} < 0.1 \text{ nb}$
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Current SUSY bound: CDF with 2 fb^{-1}

$\Rightarrow \sigma_{MSSM} < 0.1 \text{ pb}$
 $\Rightarrow m_{\tilde{g}} > 320 \text{ GeV}, m_{\tilde{q}} > 390 \text{ GeV}.$

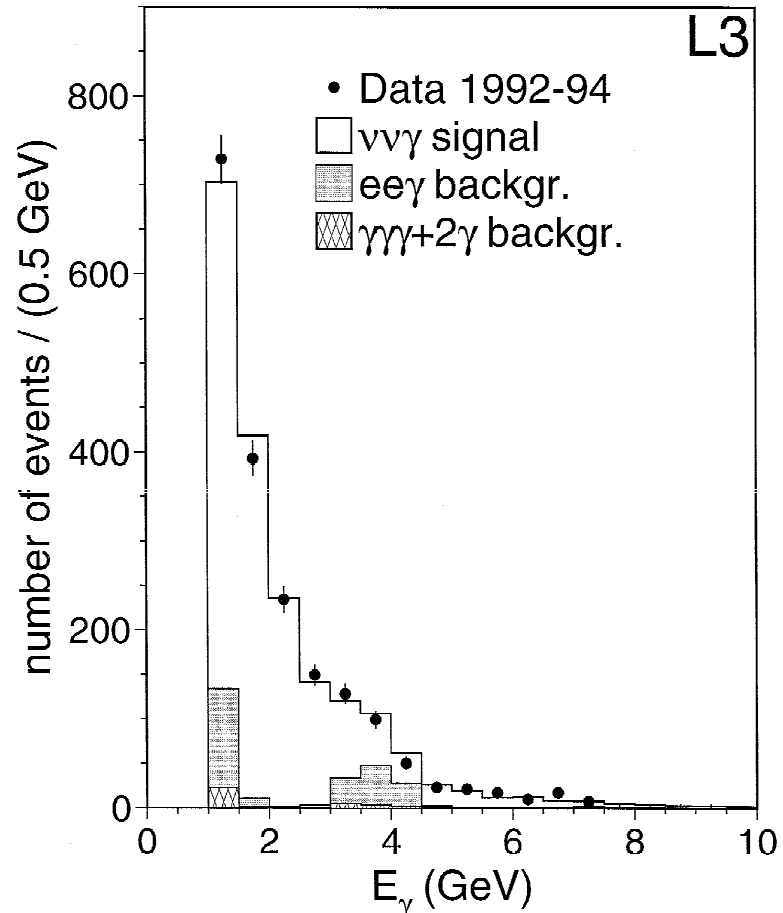
Missing energy events in e^+e^- collisions

At LEP I (L3):

Neutrino counting:

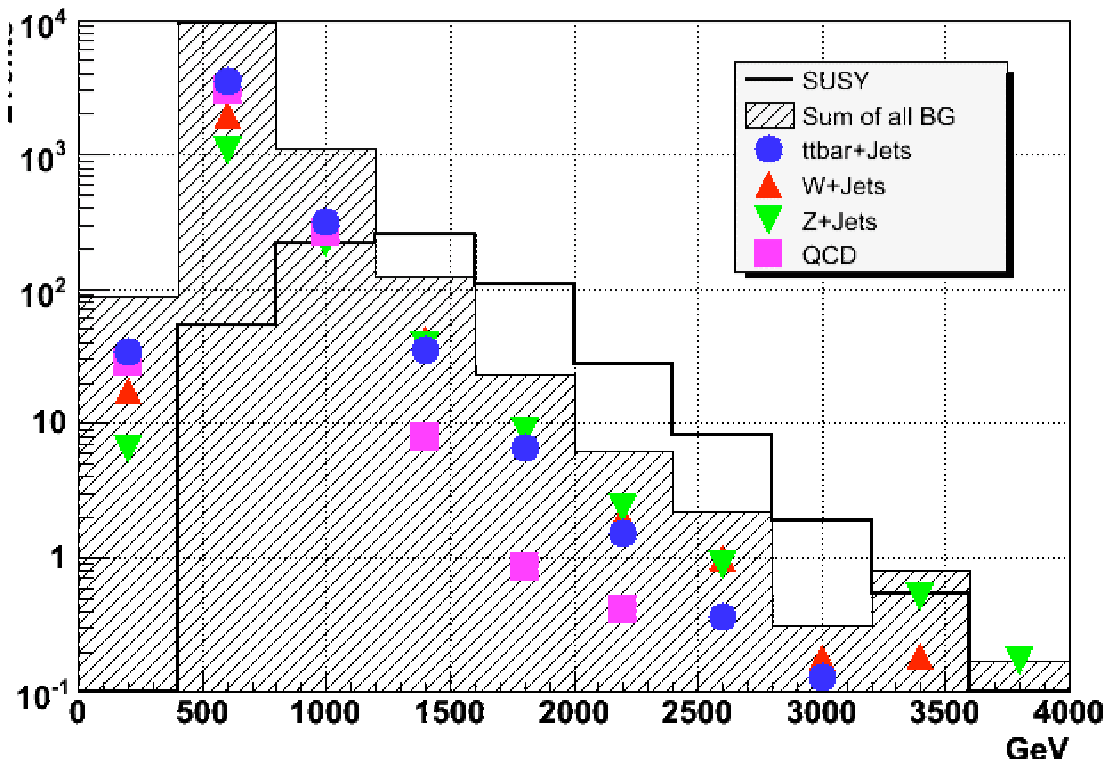
$$e^+e^- \rightarrow \gamma + \nu_i \bar{\nu}_i$$

$$N_\nu \approx 3.$$



Missing Energy and New Physics at LHC

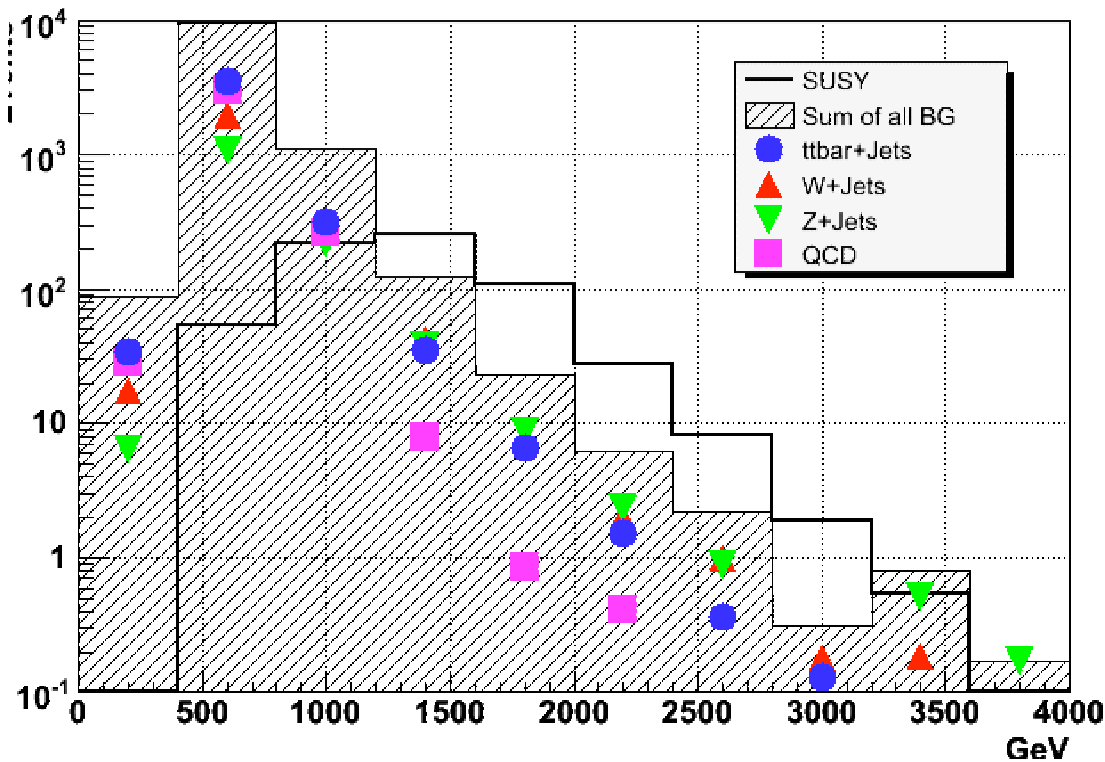
New Physics Expectation in \cancel{E}_T : †



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

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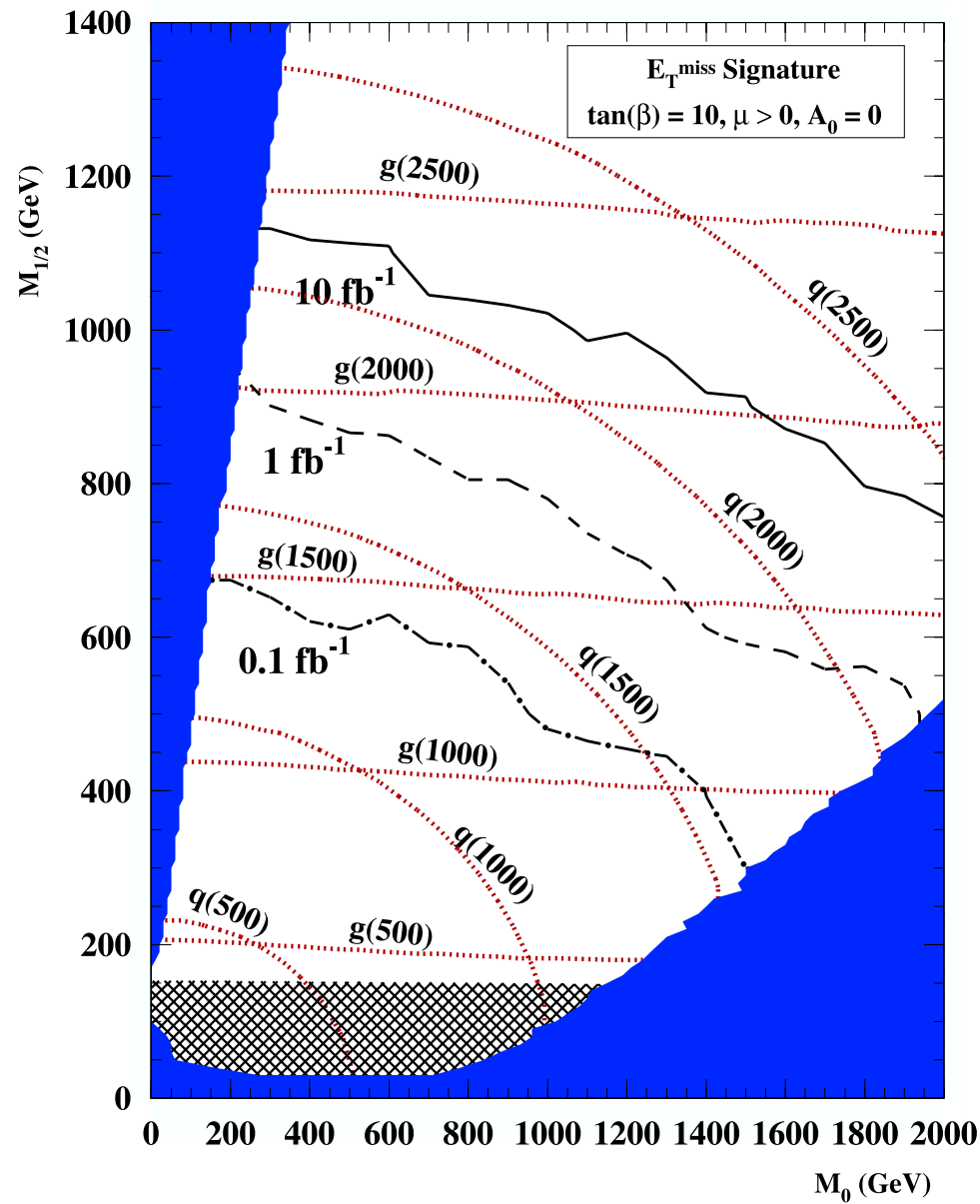
New Physics Expectation in \cancel{E}_T : †



- Setting a bound for mass scale may not be too hard.
- Establishing \cancel{E}_T signal would be challenging,
⇒ 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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$$\Omega_\chi h^2 \propto \frac{1}{\langle\sigma v\rangle} \sim \frac{m_\chi^2}{\alpha^2}.$$

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

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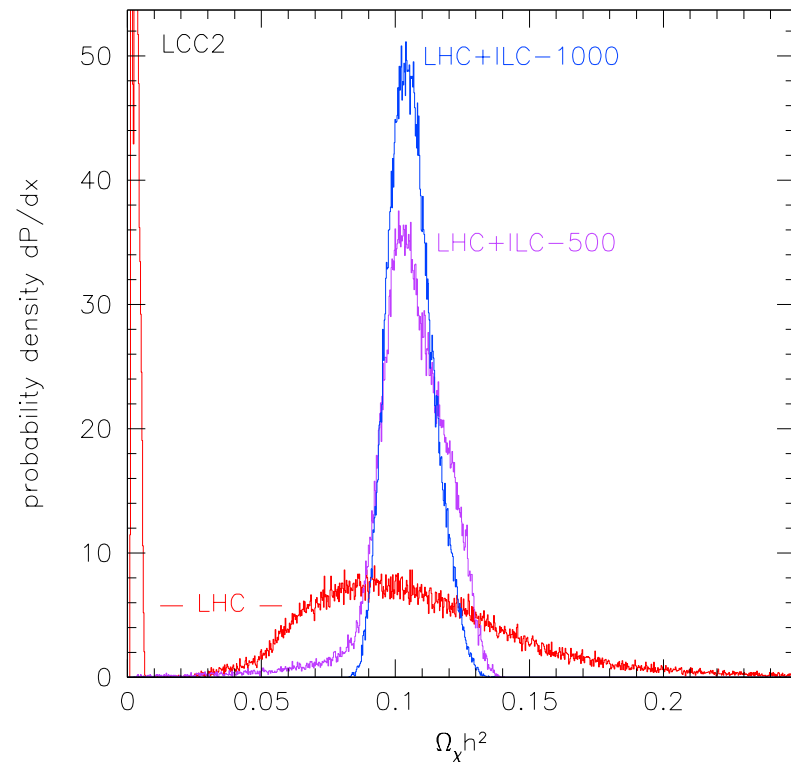
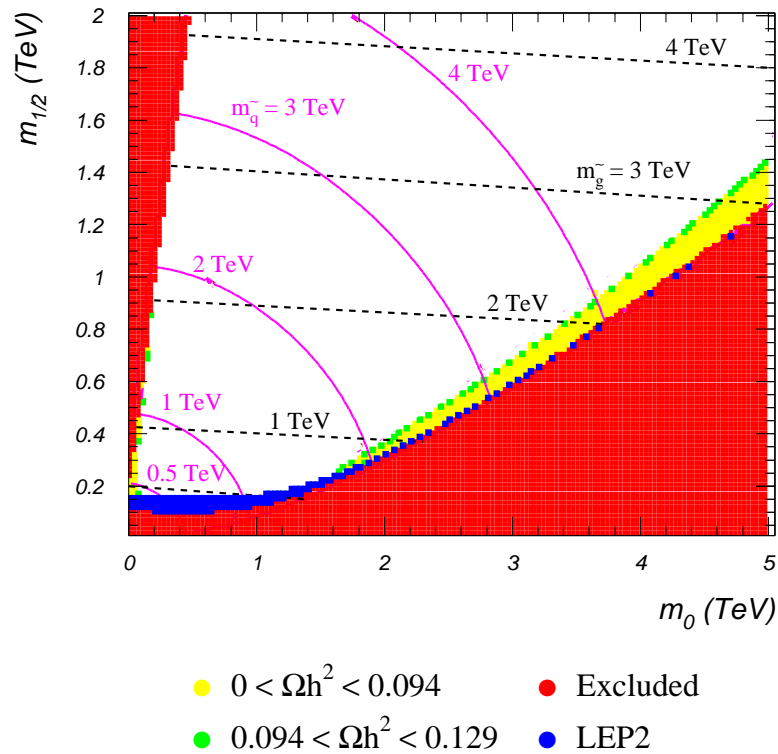
After that,

- 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 : $\tan\beta=10$, $A_0=0$, $\mu>0$, $m_t=171.4$ GeV

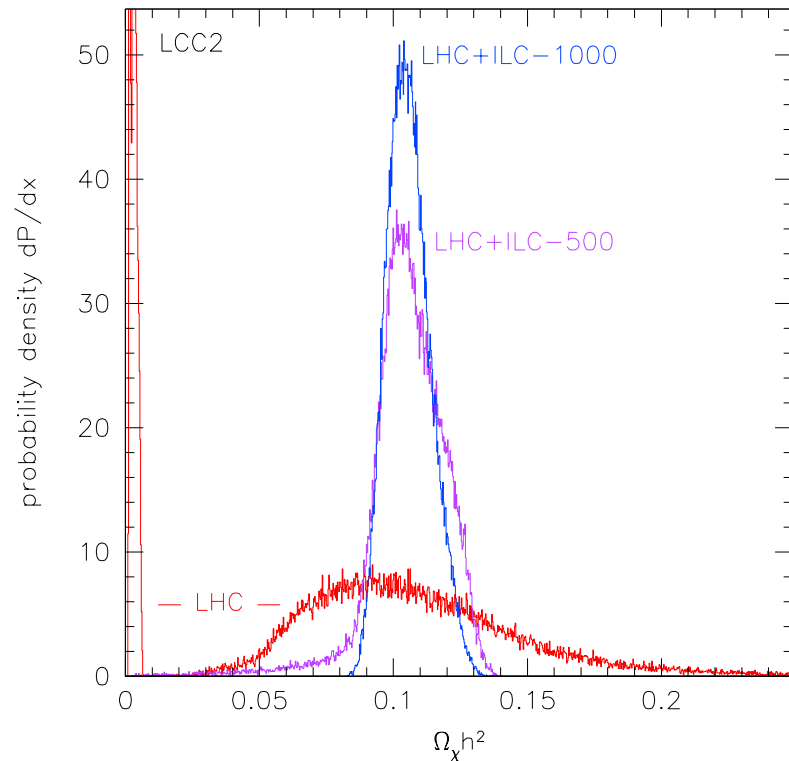
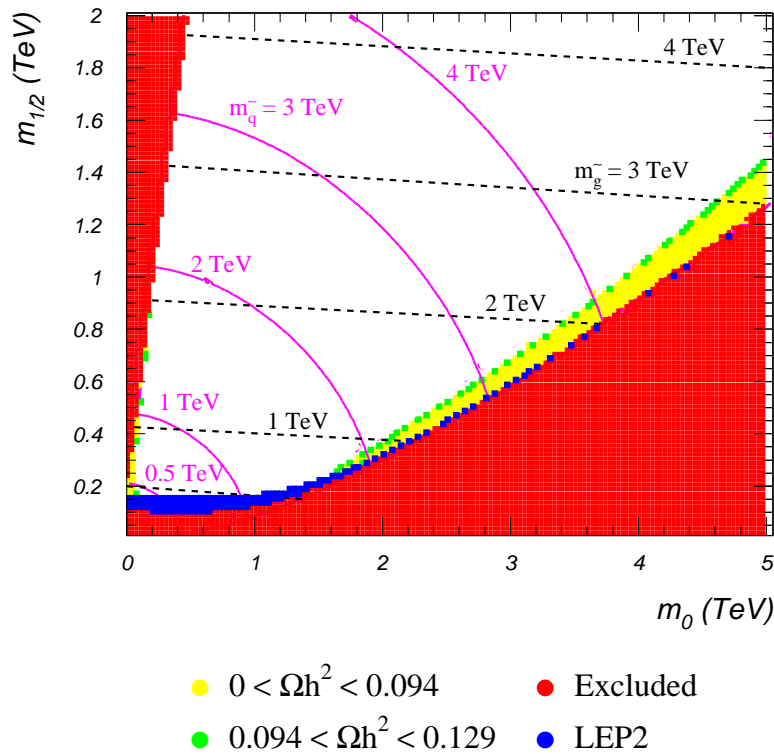


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For most general cases, situations may be much more complex:**

The “LHC inverse problem”: Data \Rightarrow many possible solutions!

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

Determining the Dark Matter Mass

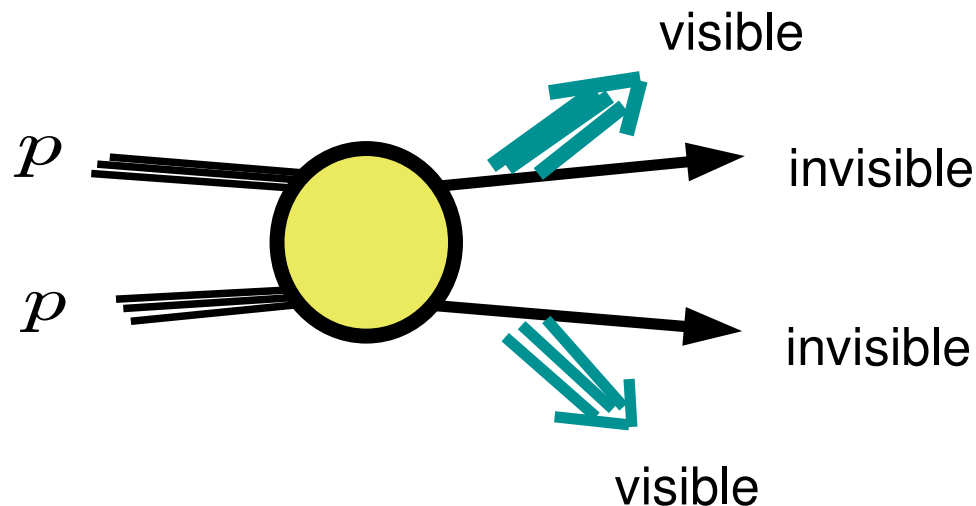
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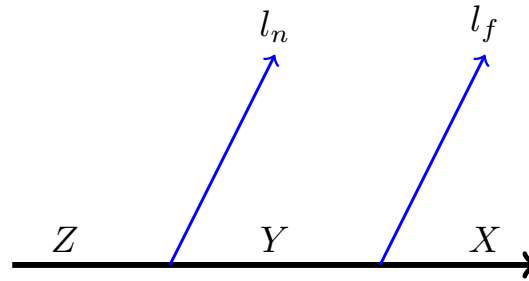
The difficulties:

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



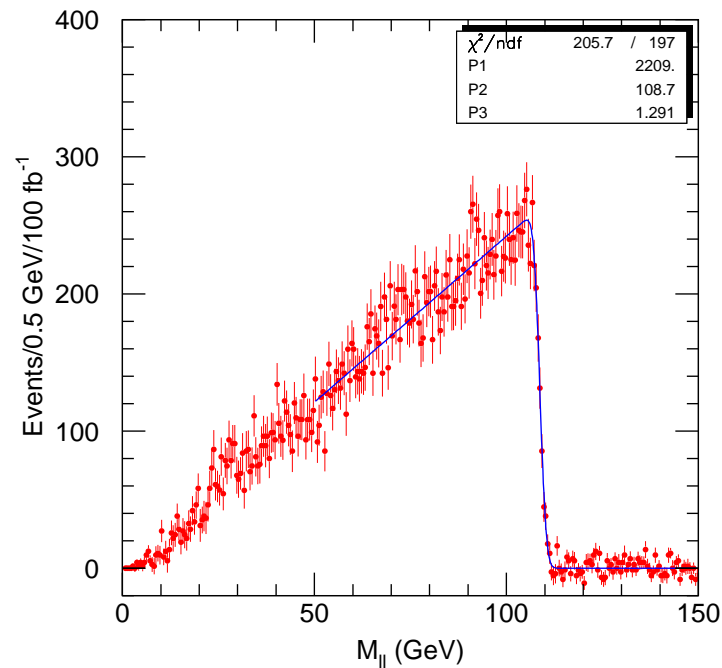
Edges, End-points etc.

- Simple decay chain:††



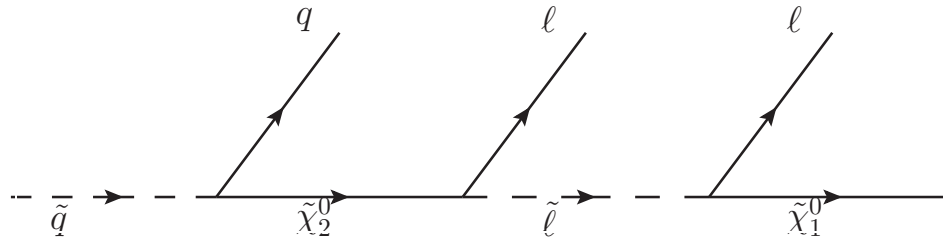
In general, $m_{ll}^{max} = M_Z - M_X$ (gives mass difference).

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

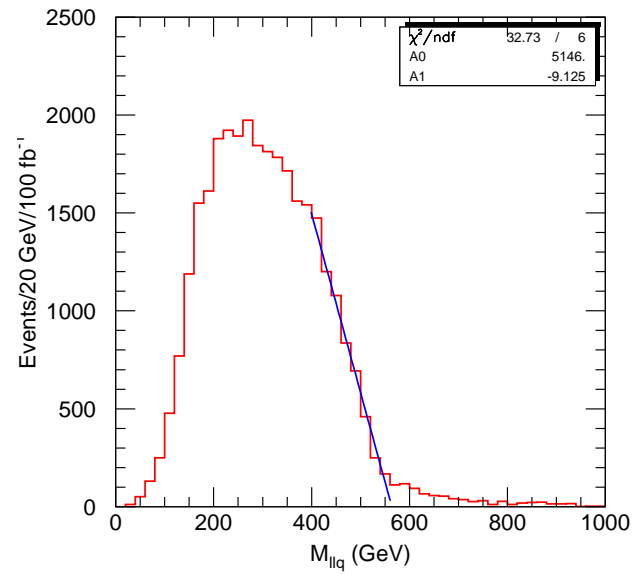


††Bachacou, Hinchliffe and Paige, arXiv:hep-ph/9907518.

- Longer decay chain^{††}

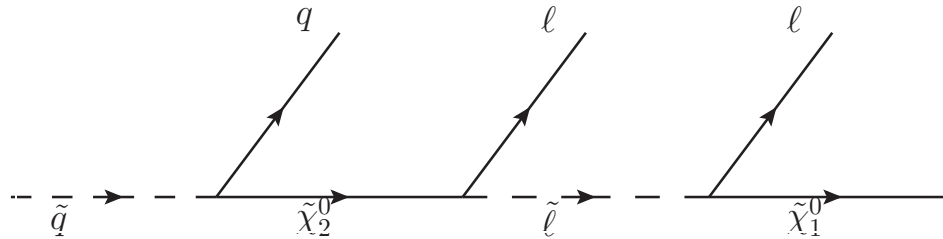


Similarly, $m_{qll}^{max} = \sqrt{(M_{\tilde{q}}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)} / M_{\tilde{\chi}_2^0}$.

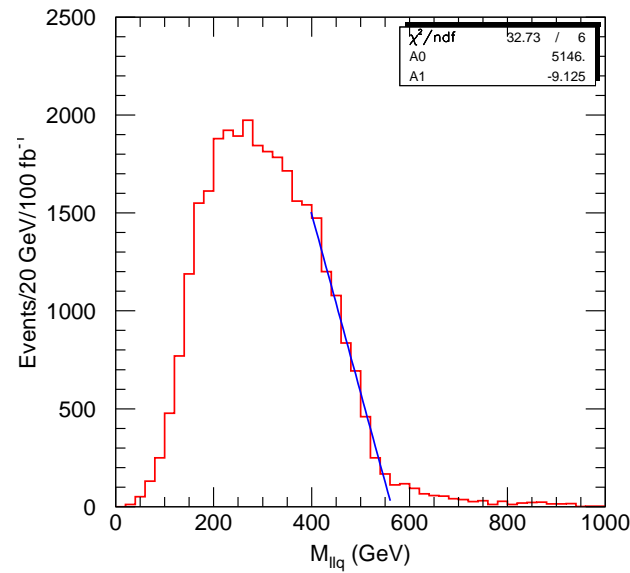


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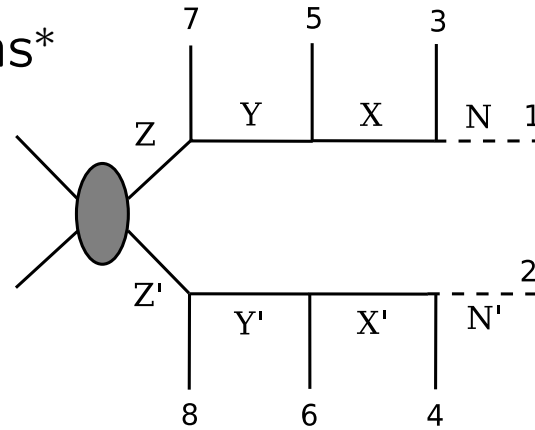


- † Only probe mass differences.
- † May encounter combinatoric ambiguities.

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Fully Constructable Kinematics

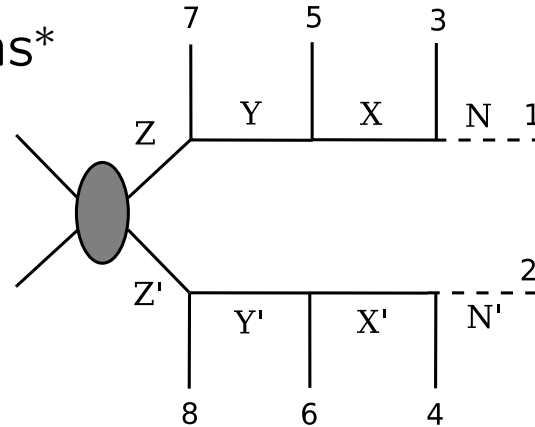
Kinematical on-shell conditions*



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

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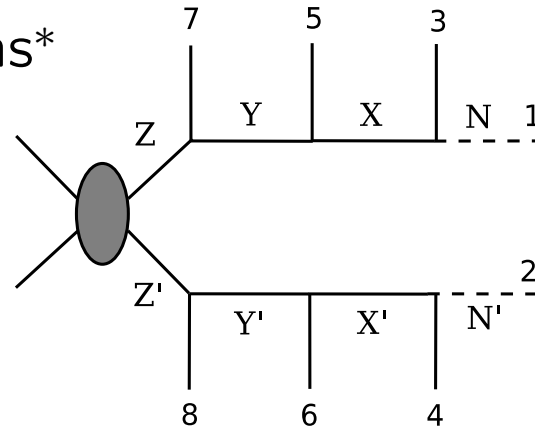
Assume:

- 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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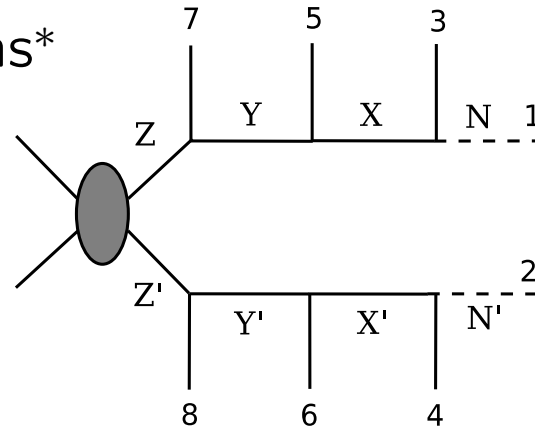
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on-shell conditions (both chains) $8n$. Total $\Rightarrow 10n$.

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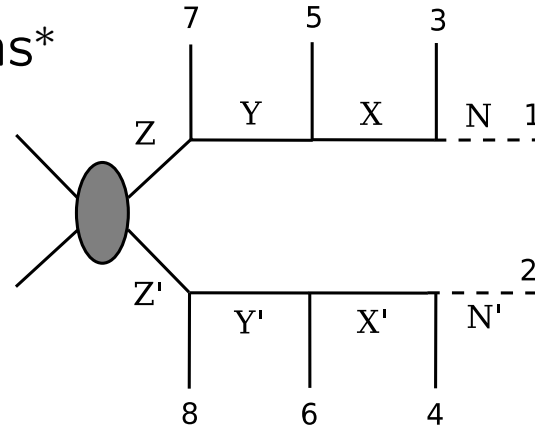
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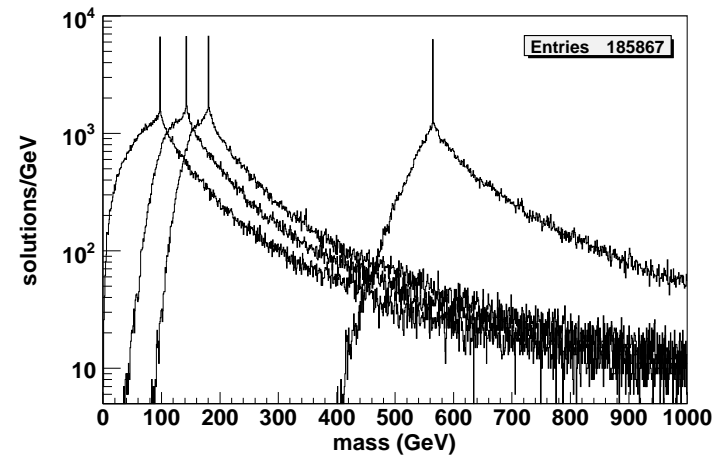
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- † With many events (n), it's an over-constrained system.
- † If only 3 on-shell particles in each chain,
there will be fewer constraints than unknowns.

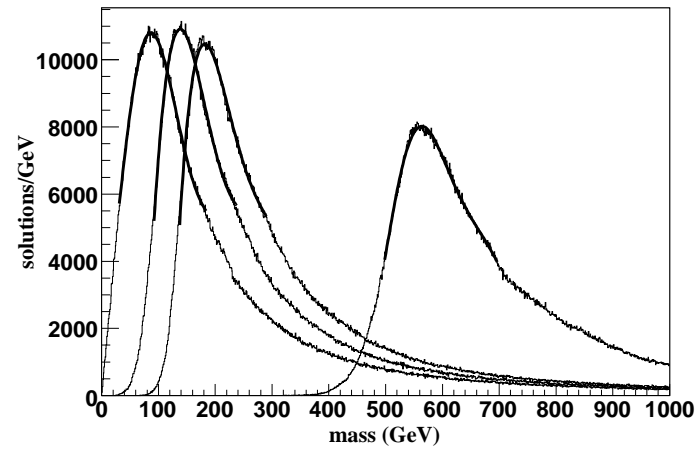
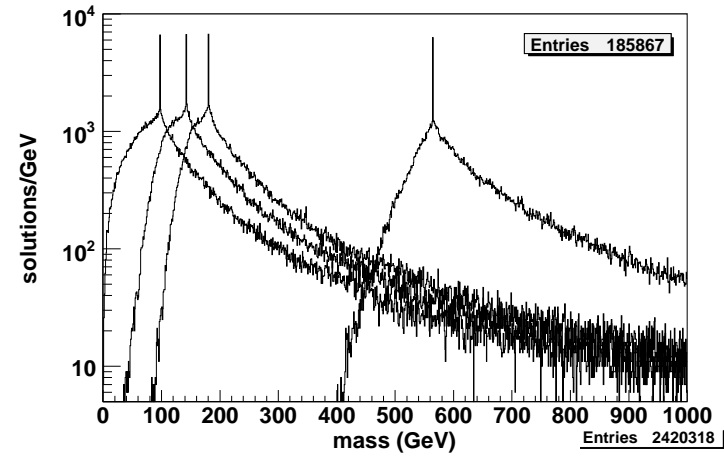
*Cheng, Gunion, Z. Han and McElrath, arXiv:0905.1344.

Simulated results:*



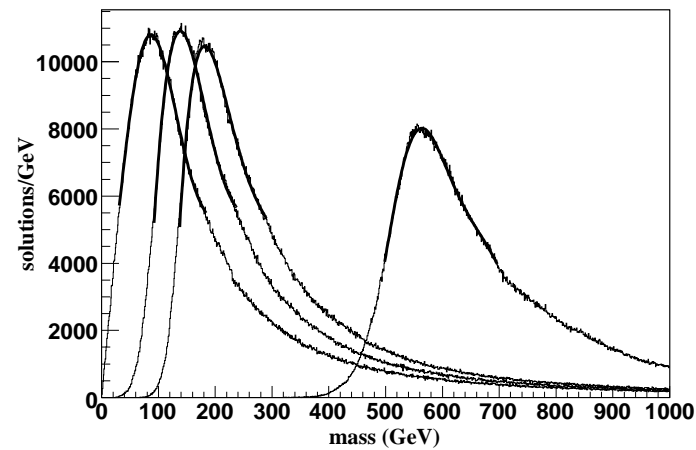
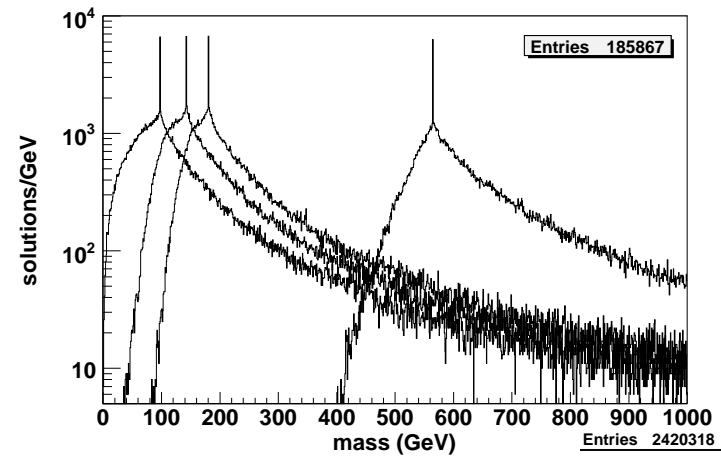
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Remarks:

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

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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.*

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This is a “functional”:

- † For each event (\cancel{E}_T), run through trial \vec{p}_{Tb1} and $\vec{p}_{Tb2} = \cancel{E}_T - \vec{p}_{Tb1}$:
- 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.

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Thus, one defines:*

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

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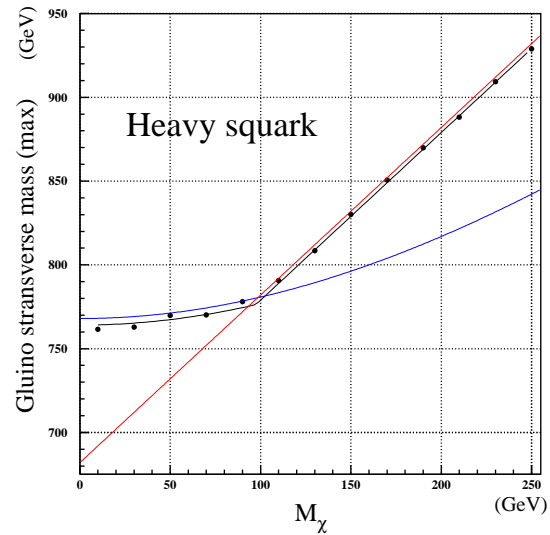
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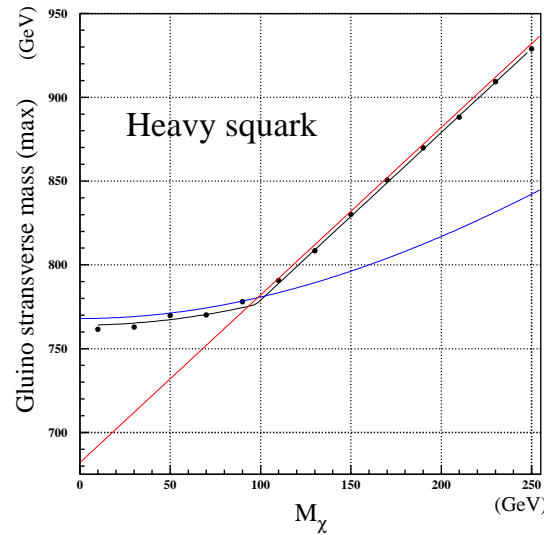
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† For simple 2-body decay, no clear kink;

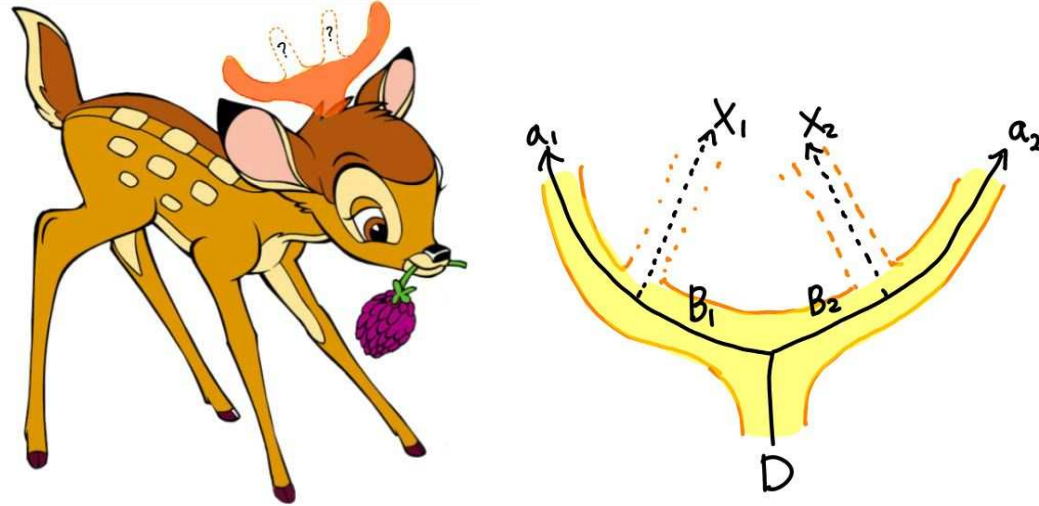
† For multi-body decays, combinatorics dilute the kink.

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“Antler Decay” Kinematics

The “Antler decay” †

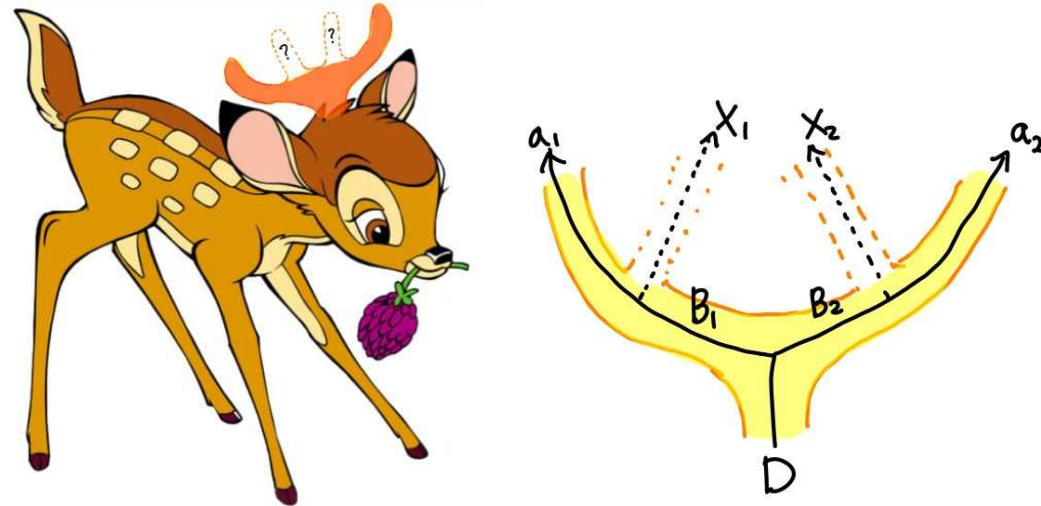


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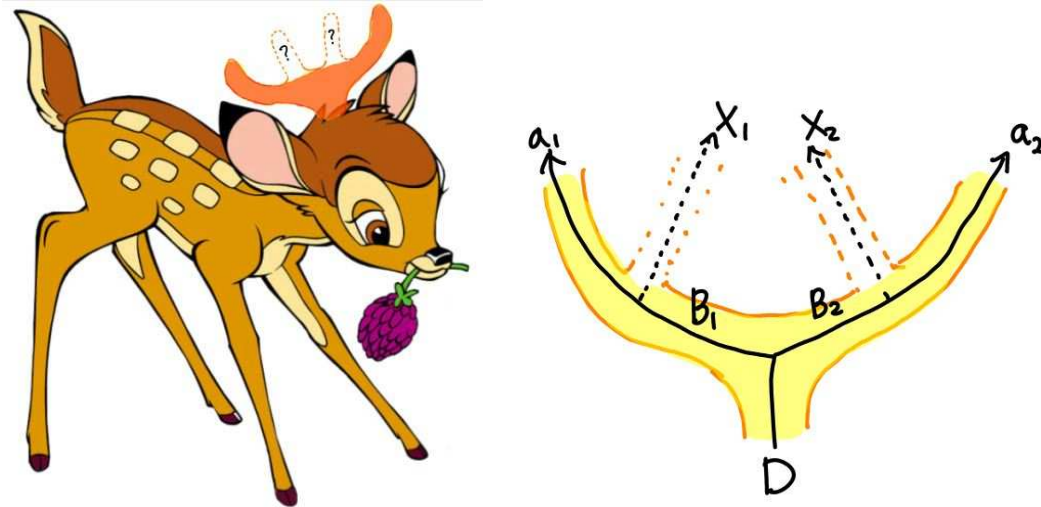
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- More constrained kinematics: M_D is known from other SM modes.

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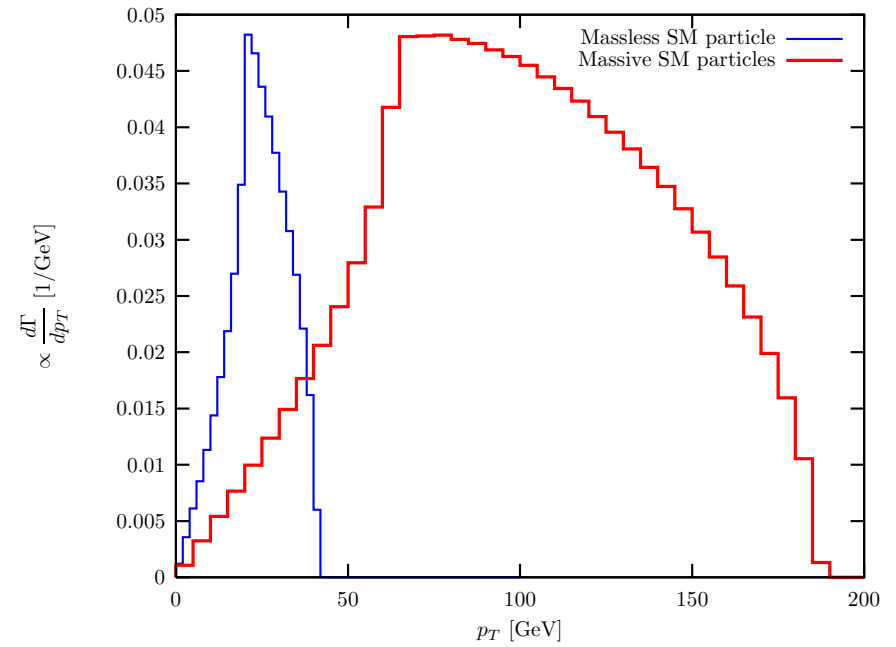
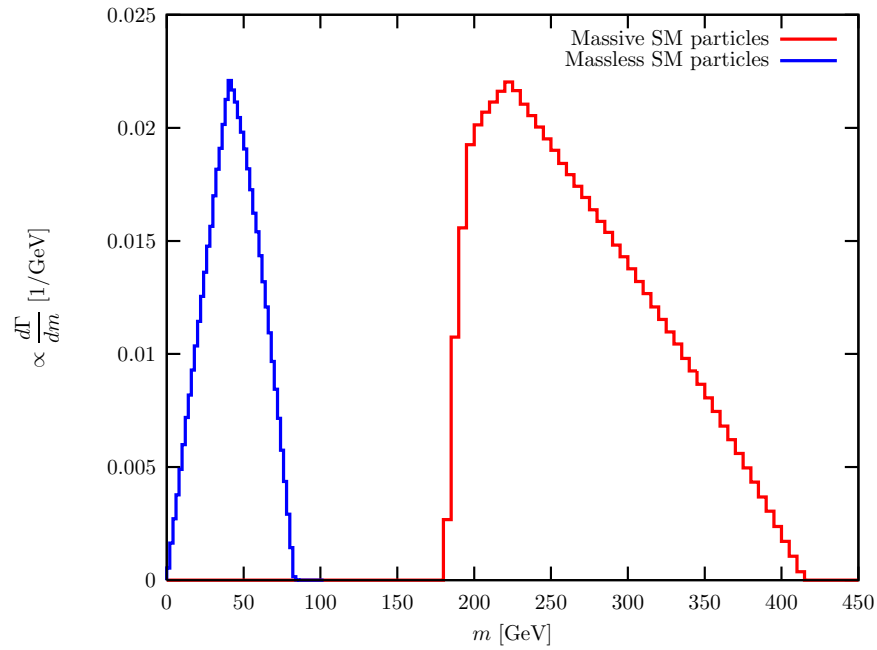
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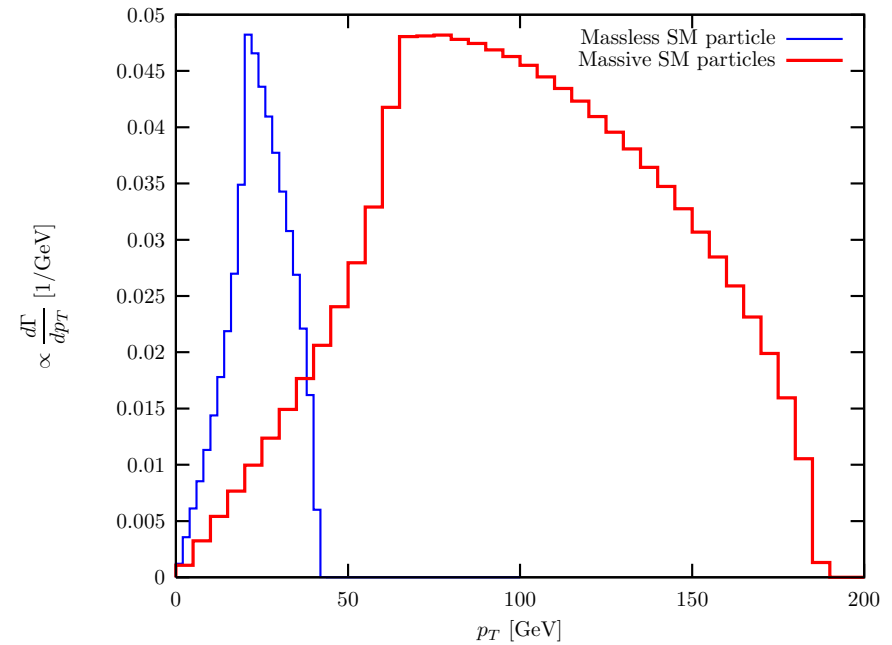
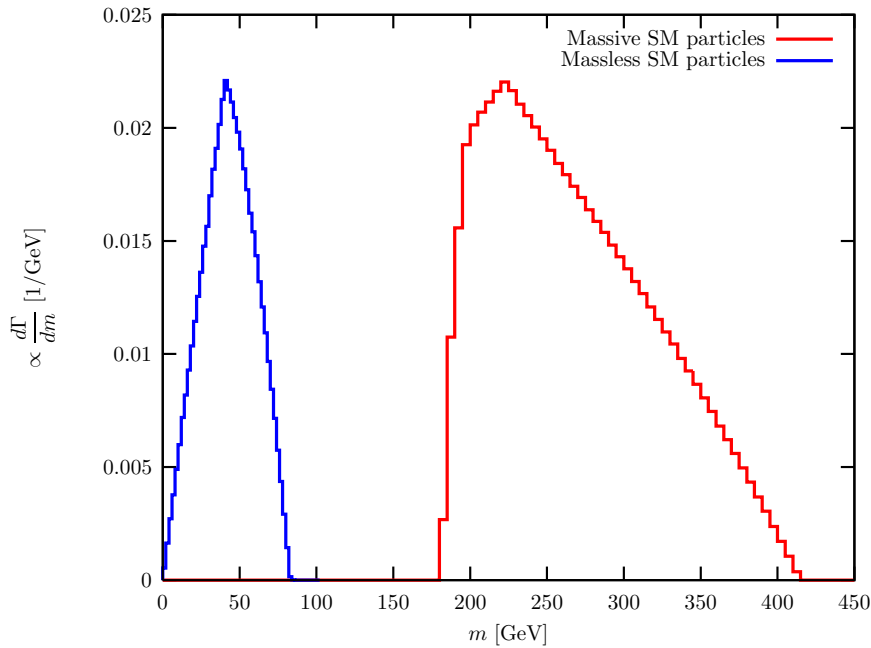
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A new kinematical feature: cuspy structures!

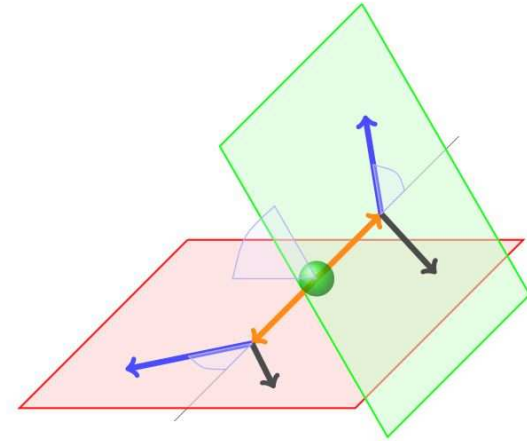
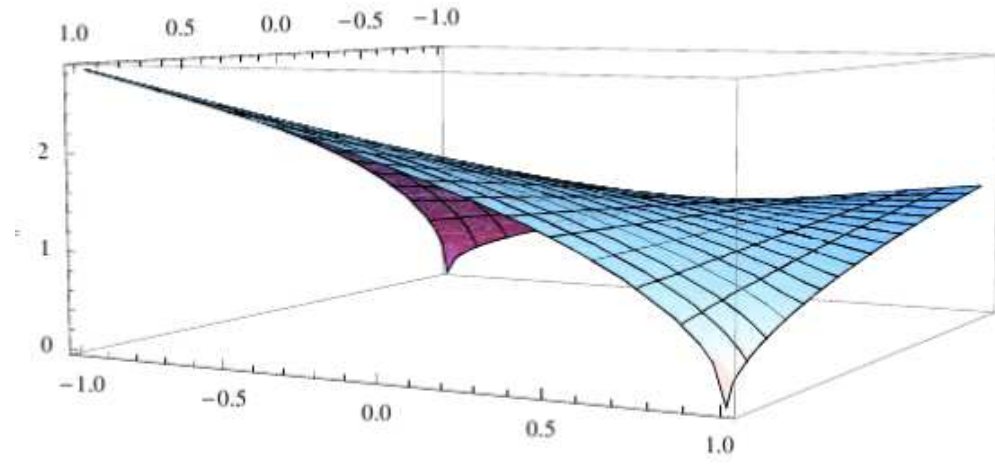


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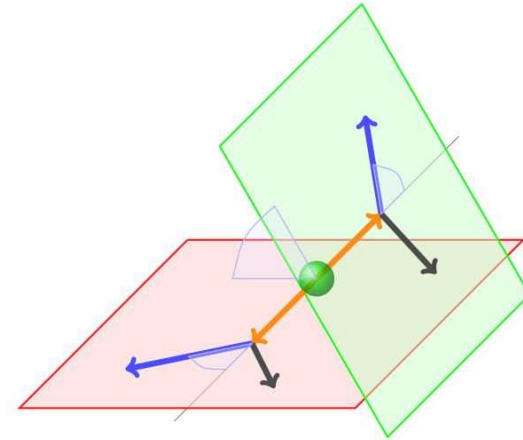
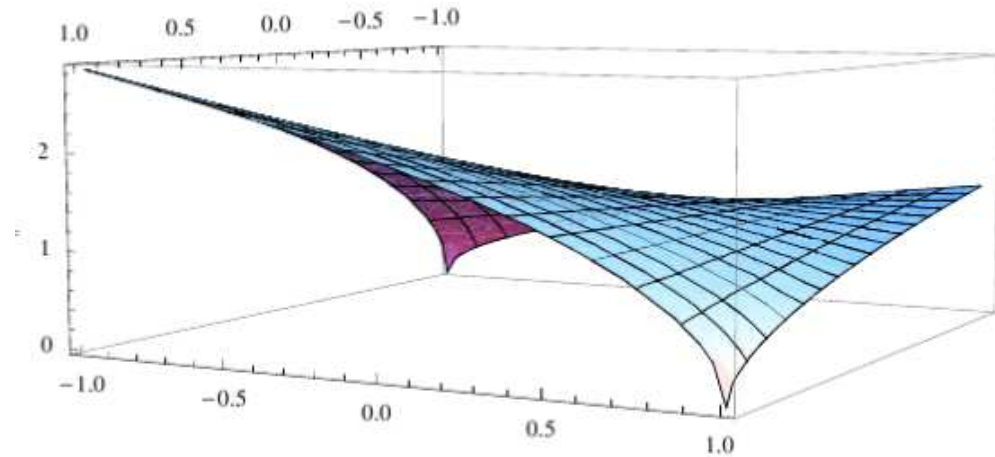


Pronounced “peaks” appear, suitable for observation!

Origin of the cusps:



Origin of the cusps:

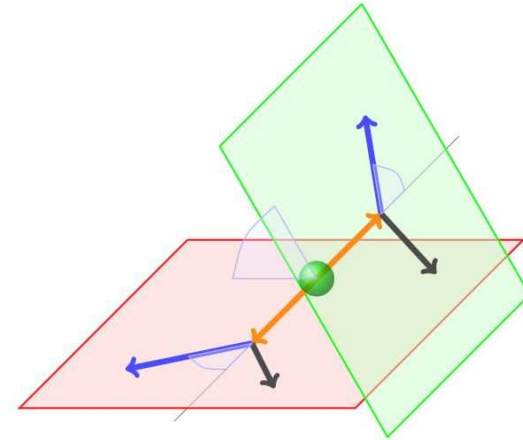
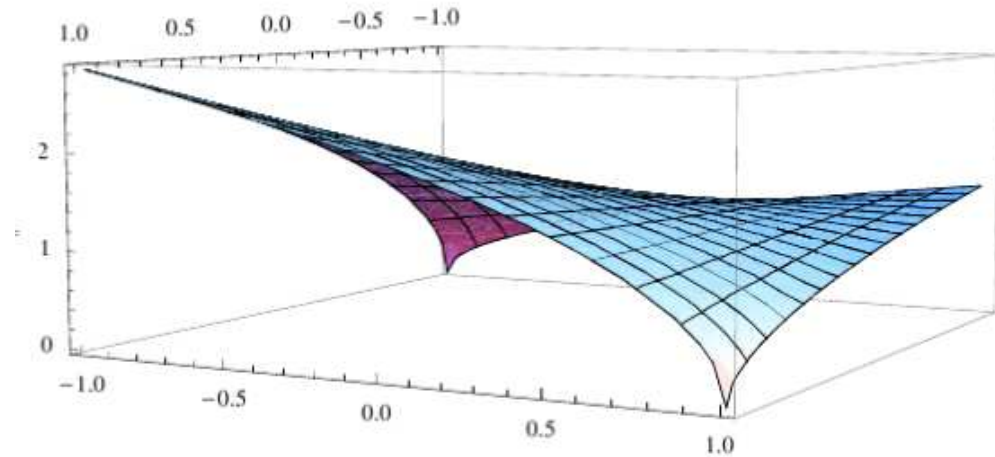


Limiting cases (at the corners)

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

- 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.
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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:

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

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

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

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

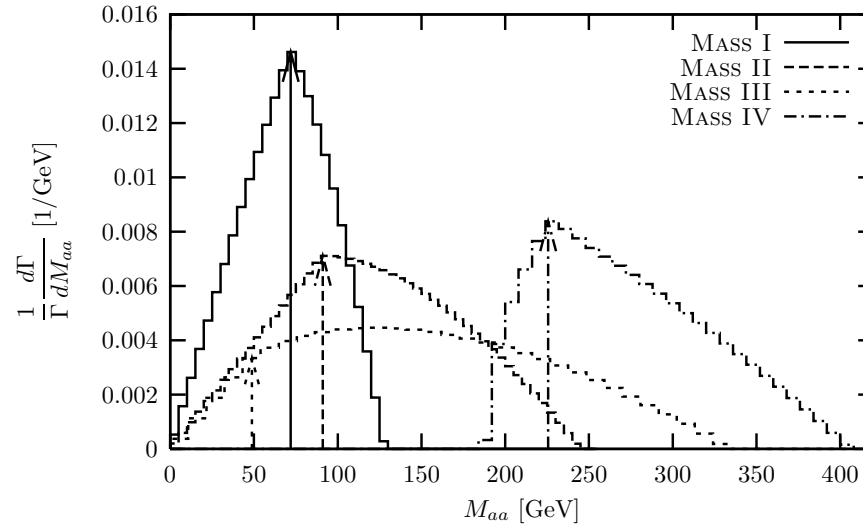
$$M_{aa}^{\max} M_{aa}^{\text{cusp}} = m_B^2 \left(1 - \frac{m_X^2}{m_B^2} \right)^2. \quad (B \rightarrow X)$$

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).

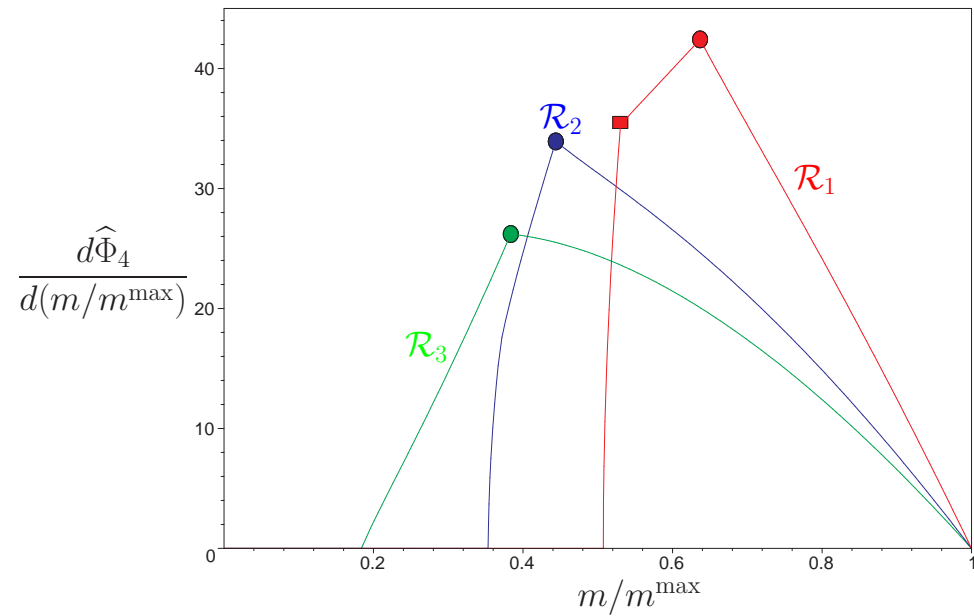
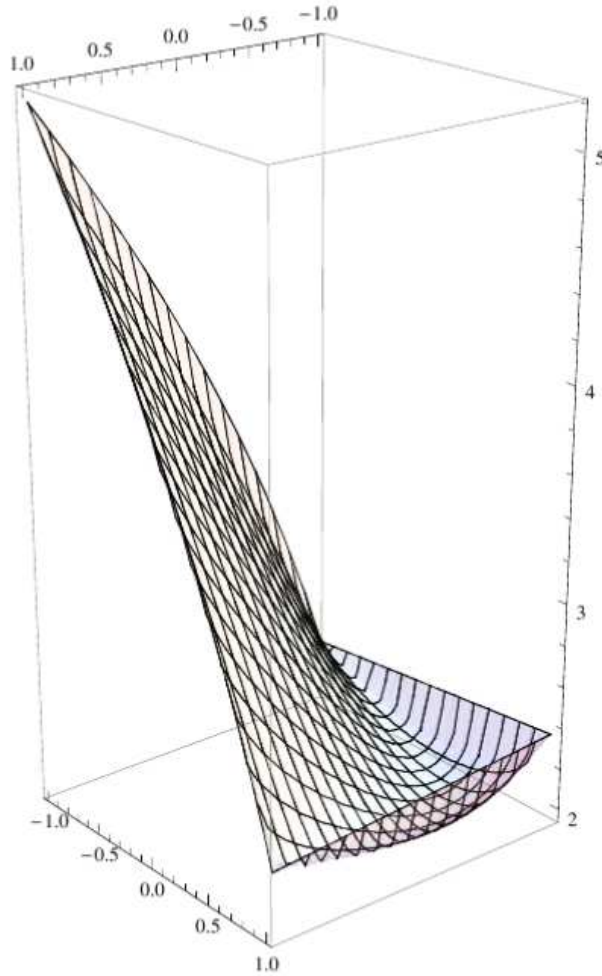
Mass II: “boundary case” ($m_B \approx 0.44m_D$).

Mass III: “large mass gap case”.

Mass IV: “massive case” (Z, t, \dots in the final state).

- Massive SM final state: ($M_a \neq 0$)

For a massive case $a = Z, t, \dots$, $d\Gamma/dM_{aa}$ 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

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

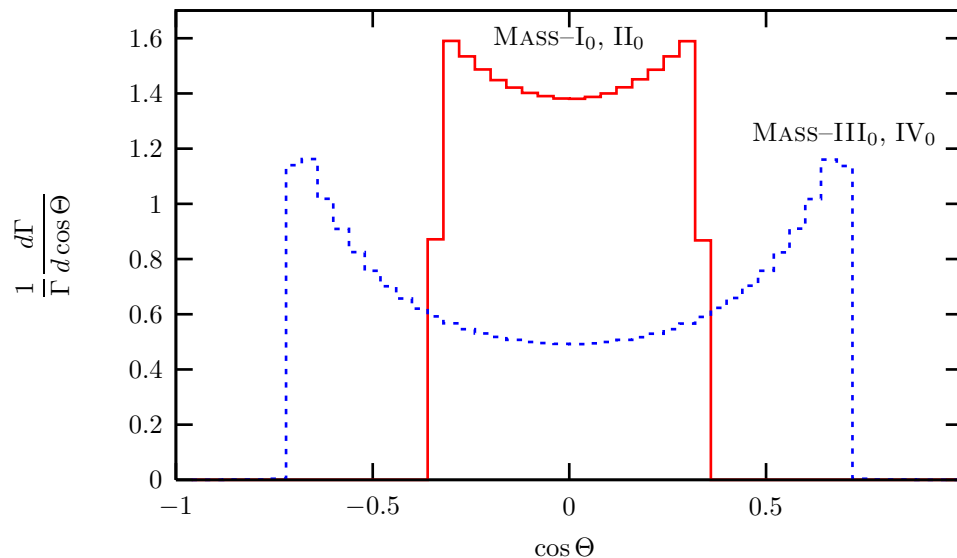
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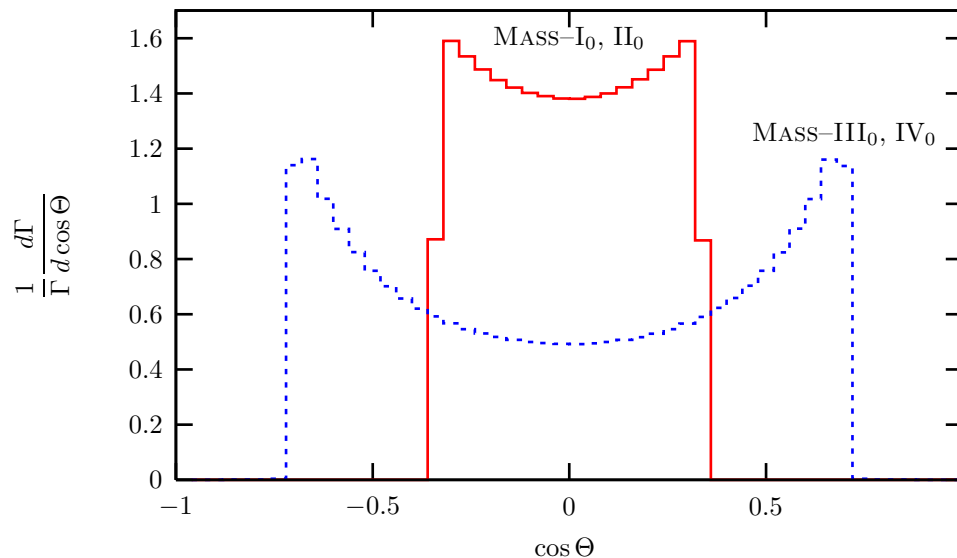
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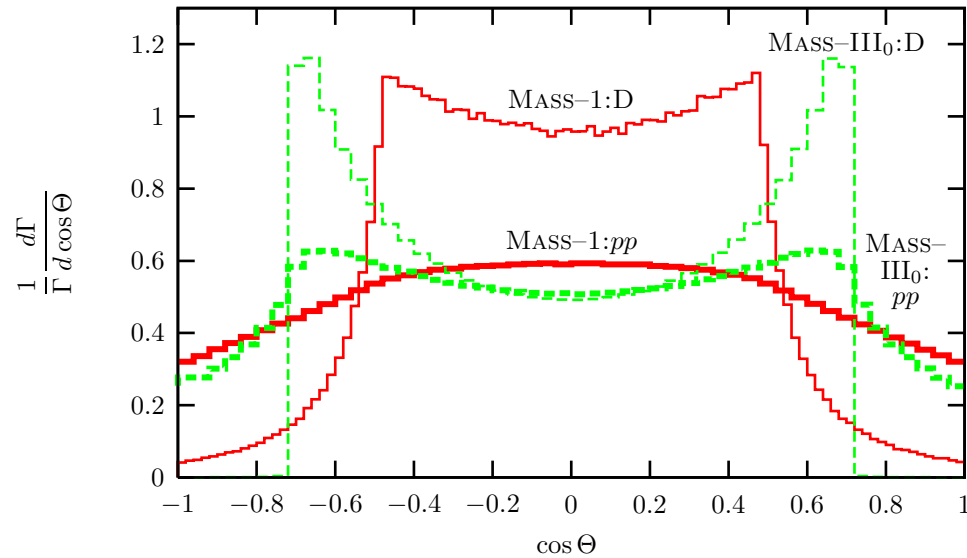


Complementarity: Large-mass gap worse for M_{aa} , better for $\cos\Theta$.

- “Robustness” of the proposal

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

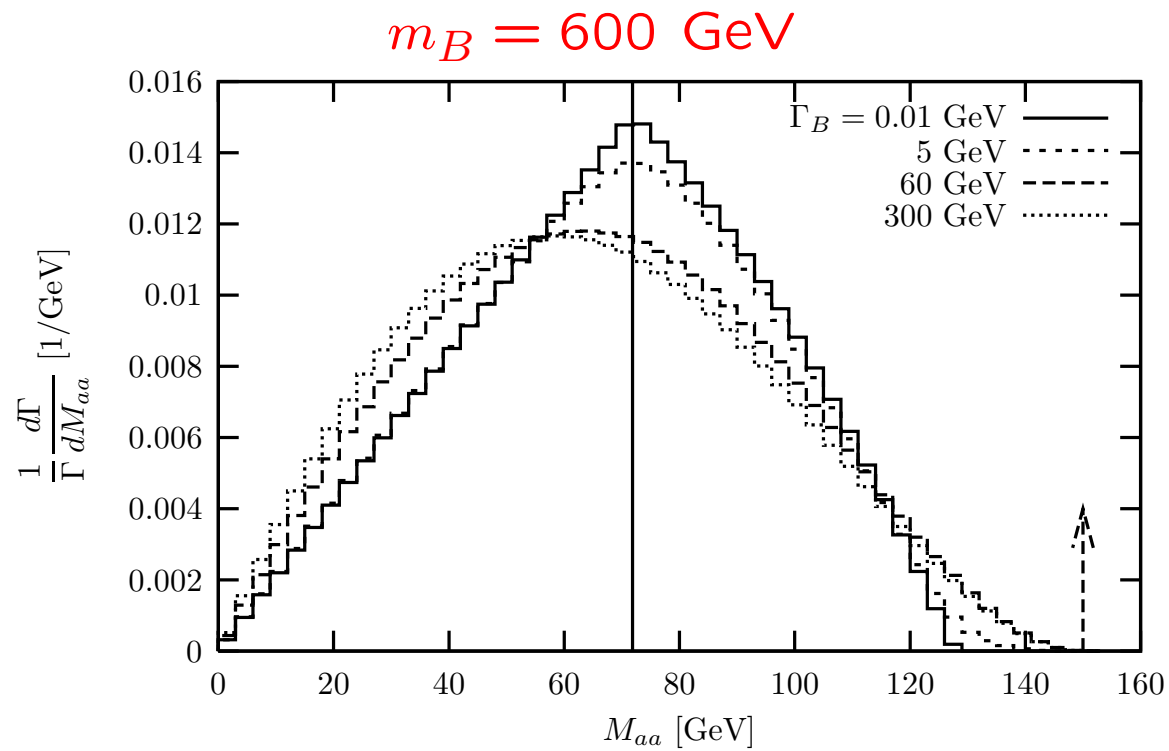
⇒ M_{aa} not effected, $\cos \Theta$ peaks diluted:



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

⇒ M_{aa} , $\cos \Theta$ not appreciably effected,

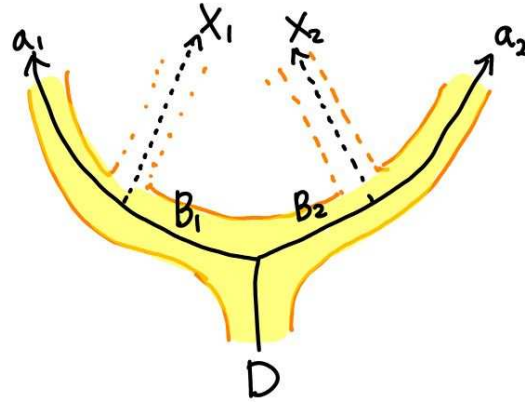
(c). Off-shell decays: finite width effects



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

On-going studies: †

- Reconstruct the antler kinematics:

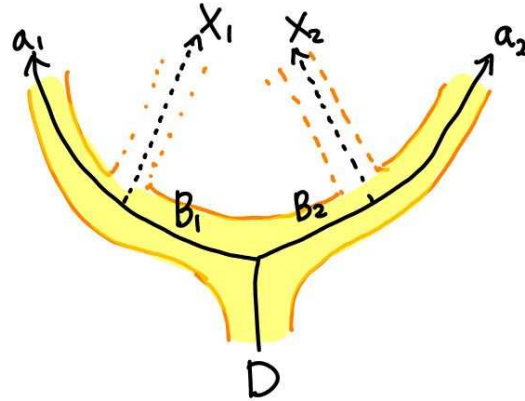


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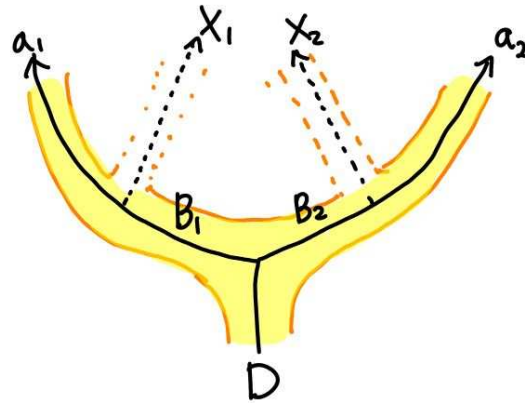
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- Other channels with cusps:

† 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.

Summary

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