Determining the Dark Matter particle's mass at the LHC

Are R. Raklev

Disclaimer

- We can't really measure the mass of THE DM @ LHC!
  - Massive invisible particle could be unstable.
    - Either decays to the real DM or has nothing to do with it.
  - Could be looking at a sub-dominant DM component.
  - Need to test consistency with direct and indirect detection.
- See talks by Roszkowski/Polesello for long-term program.
- Here, I will focus more on specific techniques for DM mass measurement in a pedagogical fashion.

Disclaimer

The story may be apocryphal, but it has been said that prior to the establishment of the quark model, new particles were being found at such an alarming rate that it was seriously proposed that a Nobel Prize ought to be awarded to the first physicist who *couldn't* discover a new particle.

In the 1950s and early 1960s particle physics may have been expanding into a theoretical vacuum driven by an excess of experimental results. In the case of mass measurement techniques for the LHC, however, the process seems to have been turned upside down. The earliest LHC specific techniques were proposed in 1996, or thereabouts, and in the course of the intervening 15 years they have been developed beyond all recognition. All of this has happened in an almost complete absence of data against which to test these techniques.

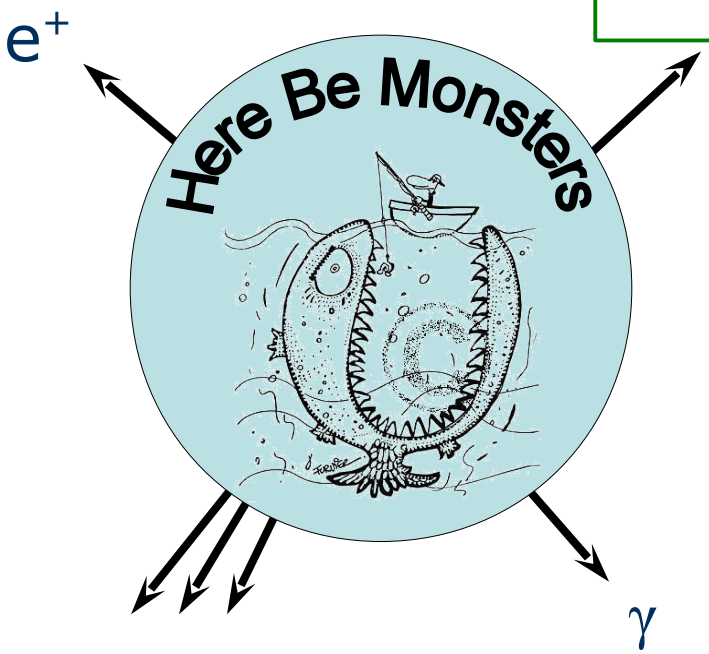
[Barr, Lester, arXiv:1004.2732]

Content

- Canonical missing energy signature @ the LHC
- An idea of the scale of New Physics
- Edges & shapes
- MT-something-or-other
- Mass shell method + some work in progress
- Conclusions

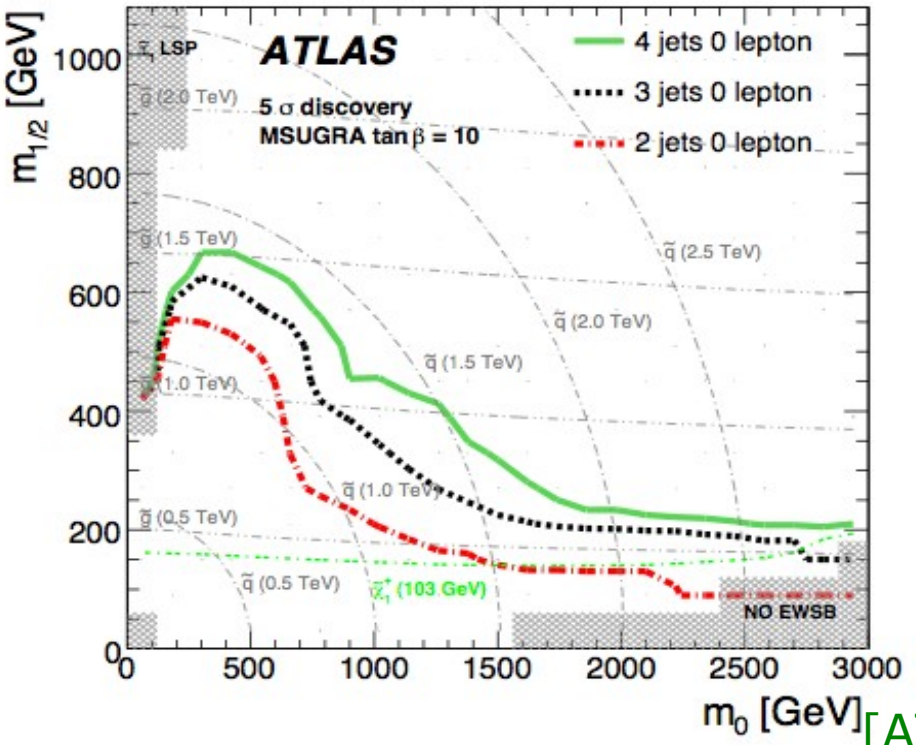
The LHC for theorists

Average **transverse** direction of invisible stuff



(also called missing energy)

Missing energy (ETmiss) discovery



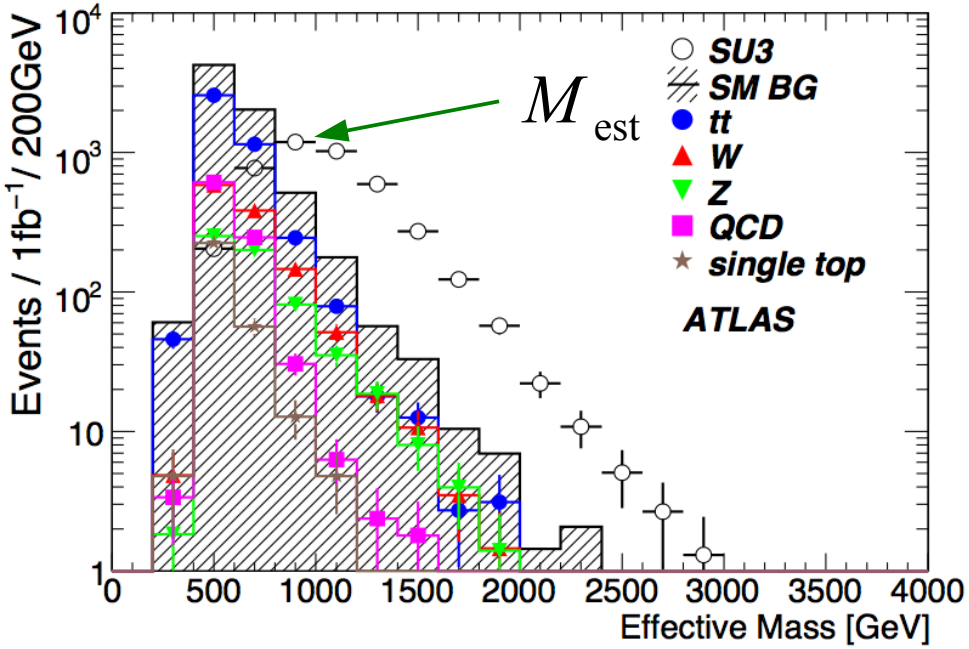
Experimental issues:

- Fakes.
- Data driven estimate of SM backgrounds.

Good reach already with 1 fb^{-1} of **understood** data at 14 TeV.

[ATLAS Collaboration, arXiv:0901.0512]

New Physics scale (Effective mass)



$$M_{\text{eff}} = E_T^{\text{miss}} + \sum p_T^{\text{jet}}$$

Use, say, maximum of M_{eff} as an estimator M_{est}.

Look at correlation with some NP quantity, say,

$$M_{\text{eff}}^{\text{susy}} = M_{susy} - \frac{M_{\tilde{\chi}_0^1}^2}{M_{\text{susy}}}$$

[ATLAS Collaboration, arXiv:0901.0512]

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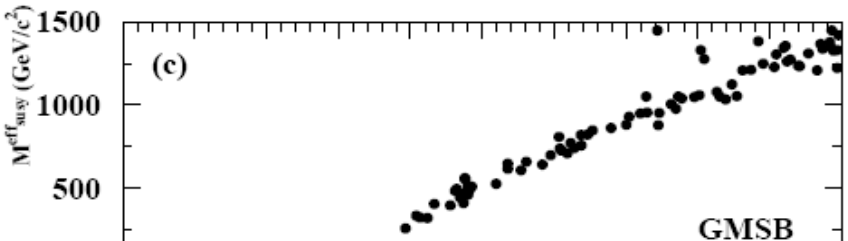
[Tovey, hep-ph/0006276]



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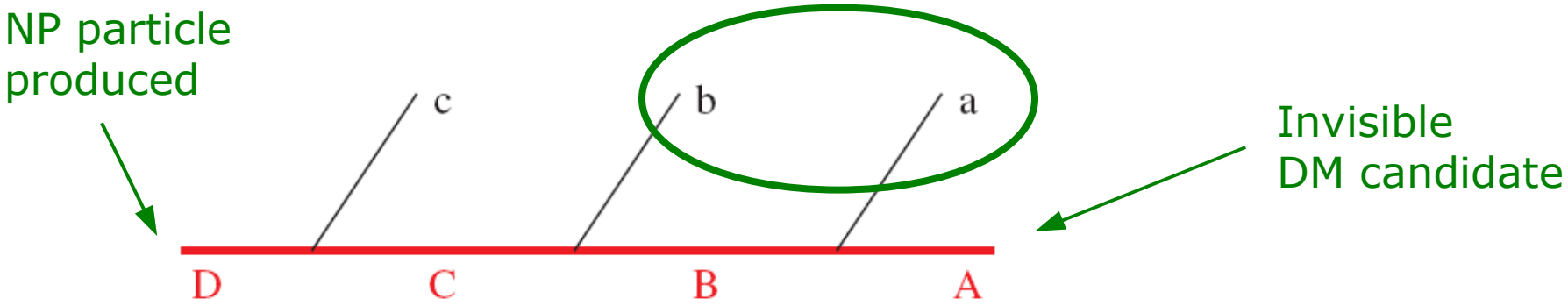
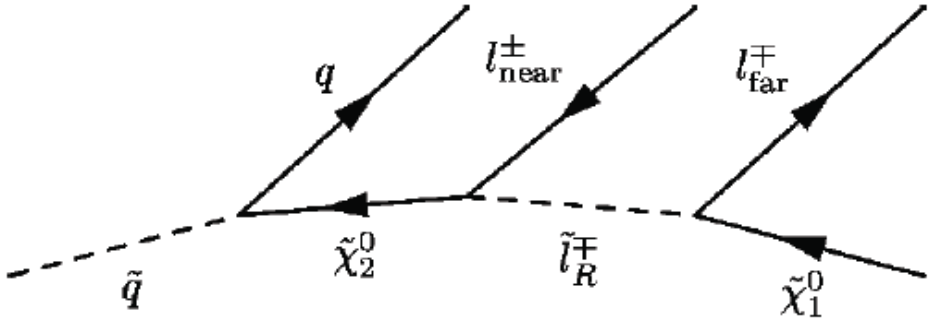
Endpoint technique

- It is, in principle, possible to reconstruct the DM mass by looking at the kinematics of cascade decays:

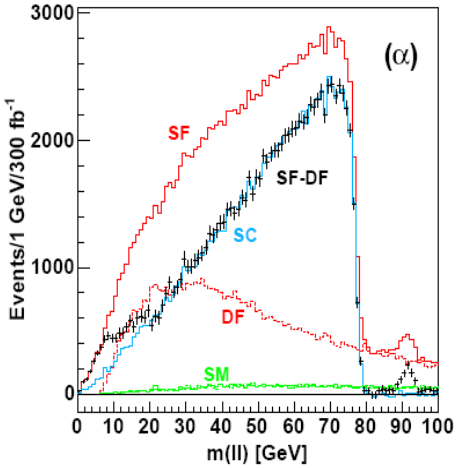


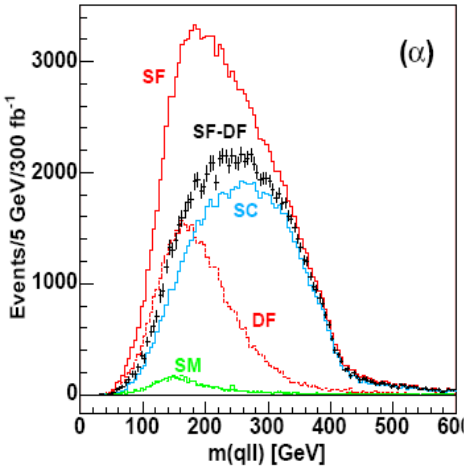
$$\left(m_{ab}^{\max}\right)^2 = \frac{\left(m_C^2 - m_B^2\right)\left(m_B^2 - m_A^2\right)}{m_B^2}$$

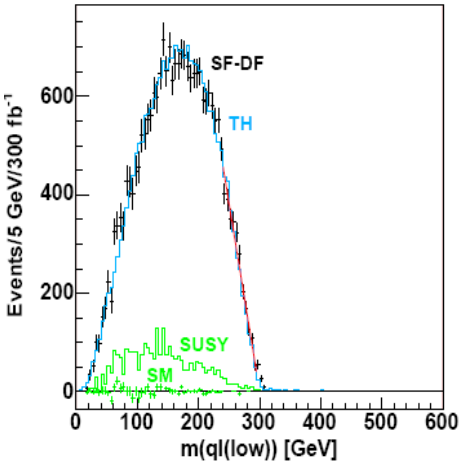
Endpoint technique

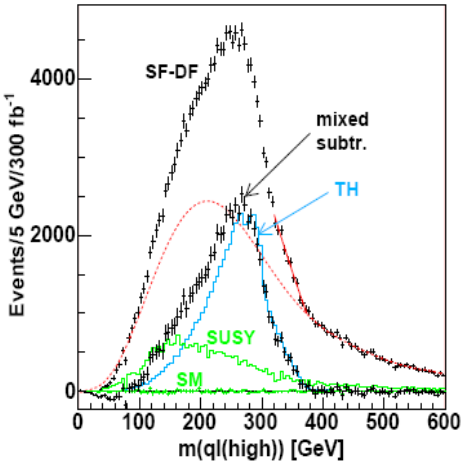


Four unknown masses need four endpoints.







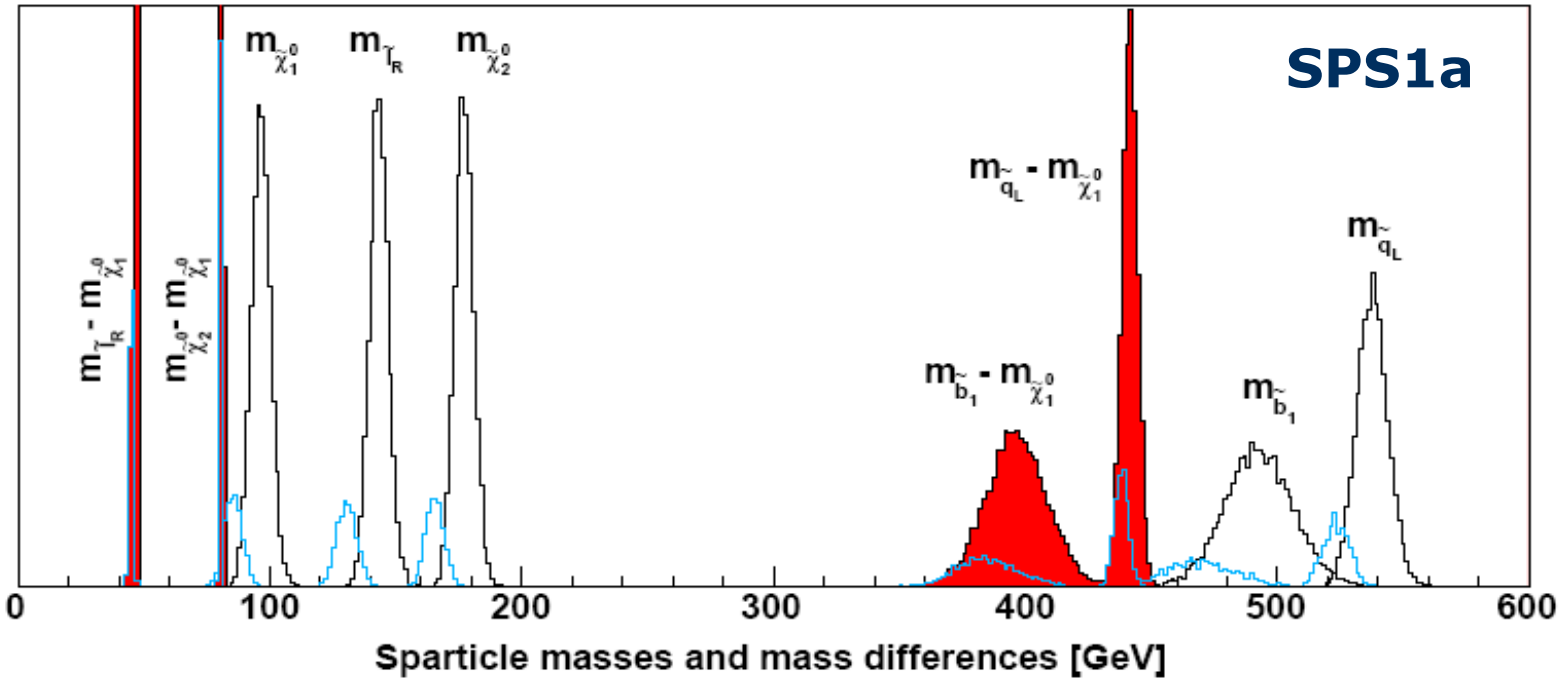


Endpoint technique - issues

- Identity of event what is the **true** signal topology?
- Combinatorics mapping detector objects to particles.
- Mass reach & statistics.
- Multiple solutions.
- Finite width & other NLO effects.
- Endpoint structures & more missing information.
- Absolute mass scale.

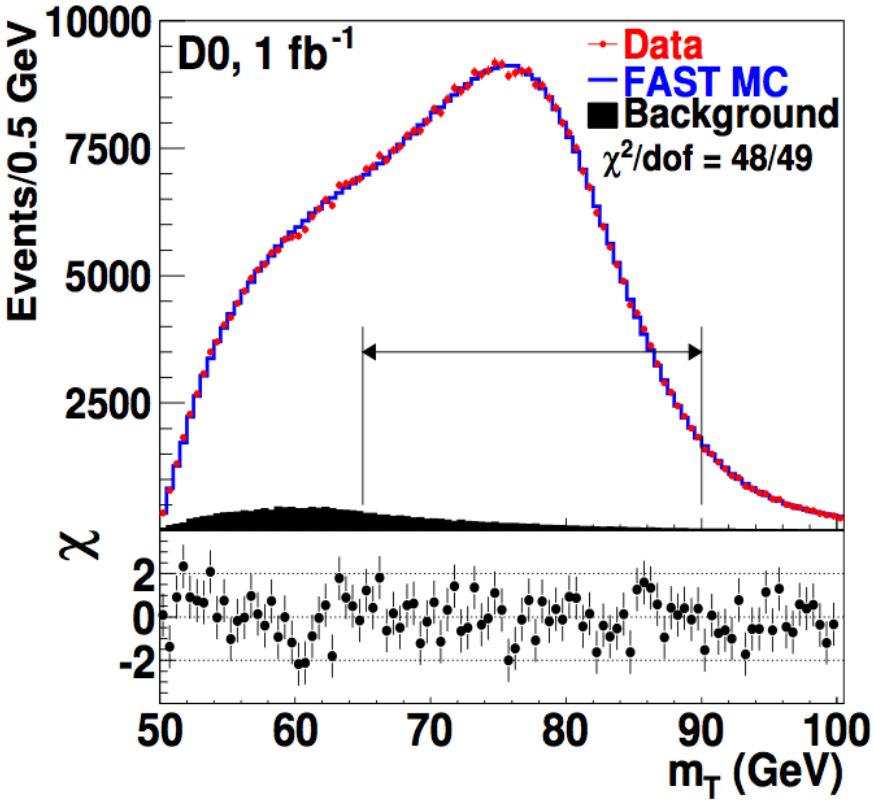
Distribution shapes may help

Endpoint technique - issues



[Gjelsten, Miller, Osland, hep-ph/0410303]

MT2



The W mass measurement uses **transverse mass** m_T:

$$m_T^2 = m_l^2 + m_\nu^2 + 2\left(E_{lT}E_{\nu T} - \vec{p}_{lT}\vec{p}_{\nu T}\right)$$

Relies on ETmiss from only one source (neutrino).

Symmetry responsible for DM stability often implies DM pair-production.

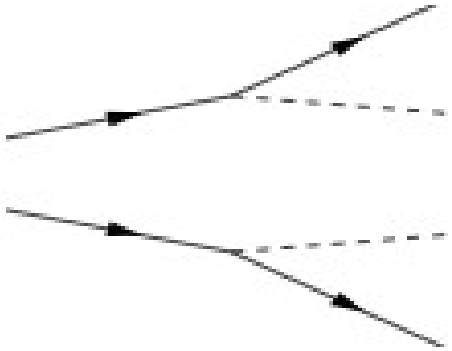
[D0 Collaboration, 0908.0766]

MT2

- Can generalize transverse mass to **stransverse mass**

$$M_{T2}^2 \equiv \min_{\not{\mathbf{p}}_{T1}+\not{\mathbf{p}}_{T2}=\not{\mathbf{p}}_T} \left[\max \left\{ m_T^2(\mathbf{p}_{Tl-}, \not{\mathbf{p}}_1), m_T^2(\mathbf{p}_{Tl+}, \not{\mathbf{p}}_2) \right\} \right]$$

[Lester, Summers, hep-ph/9906349]



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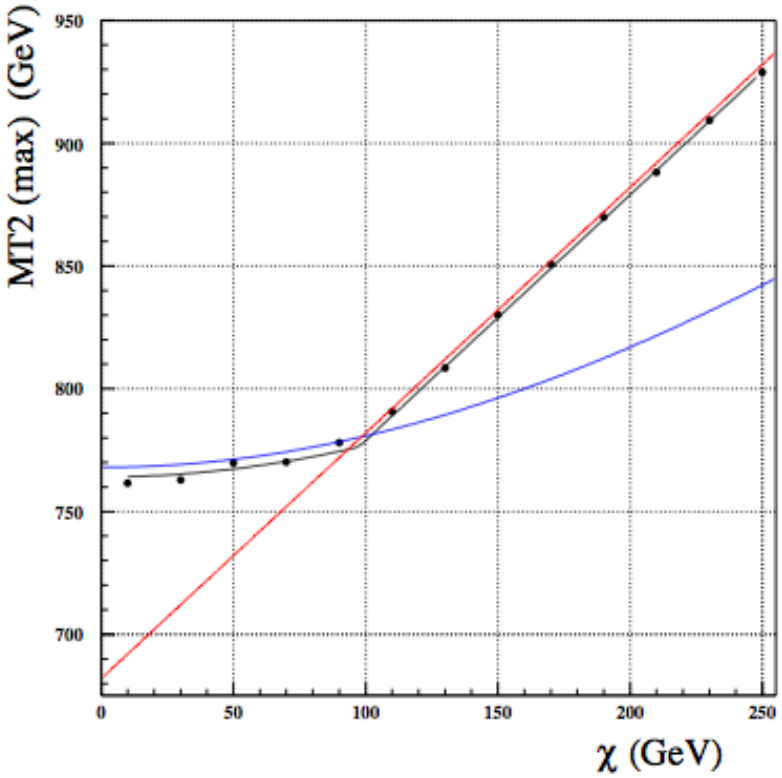
[Lester, Summers, hep-ph/9906349]

- Properties:
  - M_{T2} is bounded above by decaying particle mass **assuming** the invisble particle mass is known, *i.e.* M_W - M_ν is known.
  - There exists a kinematics configuration that saturates bound.
- MCT, MCT2, MTGen, M2C, M3C, MT3,...

MT2 – the kinky stuff



Plot maximum of stransverse mass as a function of assumed invisible mass.

Functional form changes at correct mass.

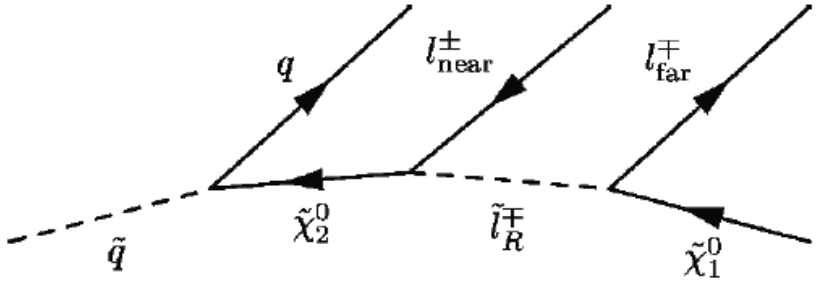
[Cho *et al.*, arXiv:0709.0288]

MT2 has now been used to measure top quark mass!

[CDF Collaboration, arXiv:0911.2956]

Mass shell methods

- Even single events can in principle be fully solved if they are complicated enough.



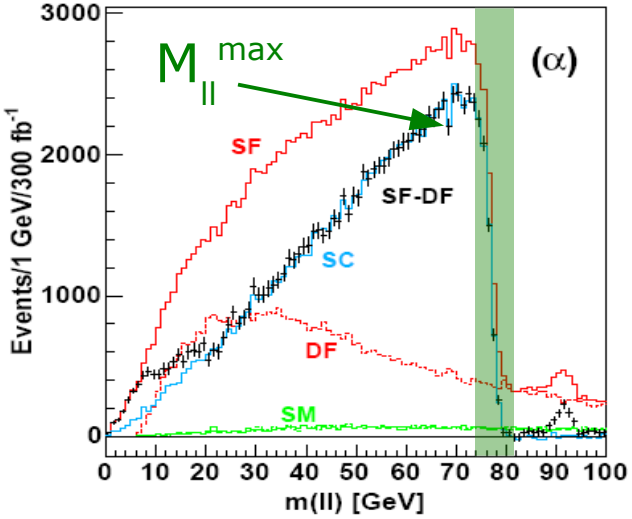
- In practice, we make some assumptions and/or use several events.

[Kawagoe, Nojiri, Polesello, hep-ph/0410160]
[Webber, arXiv:0907.5307]

Combining endpoints & mass shell

Events near endpoints, e.g. M_{ll}^{max}, have special properties:

- DM four-vector calculable, assuming values for all sparticle masses relative to LSP.
- No near/far ambiguity.



Scan over masses/edges minimizing

$$\xi = \sum_{n=1}^{N} \left| \sqrt{p^2_{\tilde{\chi}_1^0}} - m_{\tilde{\chi}_1^0} \right|$$

for N > 200 events gives competitive mass determination (no ETmiss used!)

[Kersting, Kraml, ARR, White]

Conclusions

- Even if we can't be sure it's THE DM, finding and measuring the mass of an invisible particle at the LHC will have a huge impact on the DM search program.
- We are armed with a multitude of techniques, now there will be data, and hopefully something to use them on.
- Combining methods can give surprisingly robust results with low statistics.

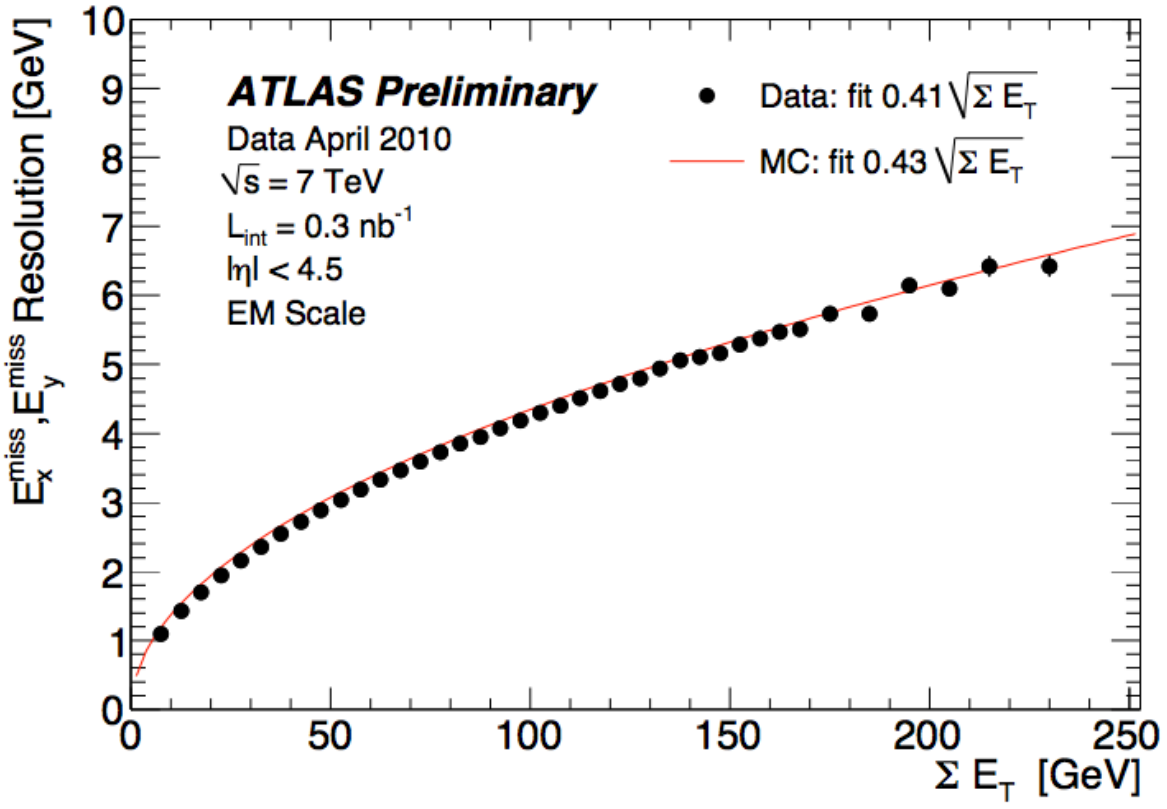
Conclusions

While writing this review, nothing was more disheartening than finding the words "We propose a new variable ..." in one of the abstracts circulated in the daily arXiv digest for hep-ph. We are pleased to be able to confirm that we, ourselves, have managed to create no new variables during the course of this review.

[Barr, Lester, arXiv:1004.2732]

Back-ups

ATLAS ETmiss resolution



[ATLAS Collaboration, PLHC 2010]