Dark Matter and Missing Energy Signals at Tevatron and the LHC

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Outline

- Introduction: Dark Matter
- The Hierarchy Problem
- New Physics Scenarios
- Hadron Collider Signatures
- Mass Determination with Missing Energy
- WIMPless Dark Matter at Tevatron and the LHC

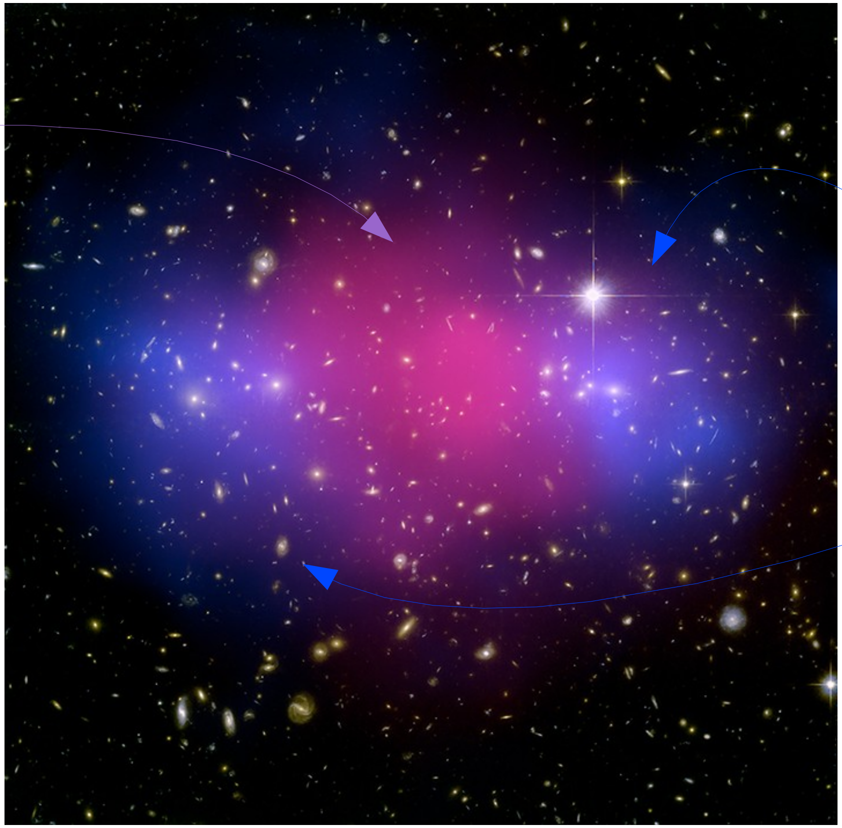
Introduction - Dark Matter

- Only strong empirical evidence for new physics
- Host of astronomical/cosmological observations indicate non-baryonic, non-relativistic, weakly or non-interacting dark matter
  - Galactical rotation curves
  - Gravitational micro-lensing
  - Galaxy structure formation
  - Cosmic microwave background data favouring 73% Dark energy – 22% Dark matter – 4.7% atoms

Introduction - Dark Matter

Most exciting observation (Bradac et al):
The MACS J0025.4-1222 cluster collision

Luminous (X-ray-emitting) gas (stopped by collision)



Dark matter (deduced by graviational lensing) (unaffected by collision)

Introduction - Dark Matter

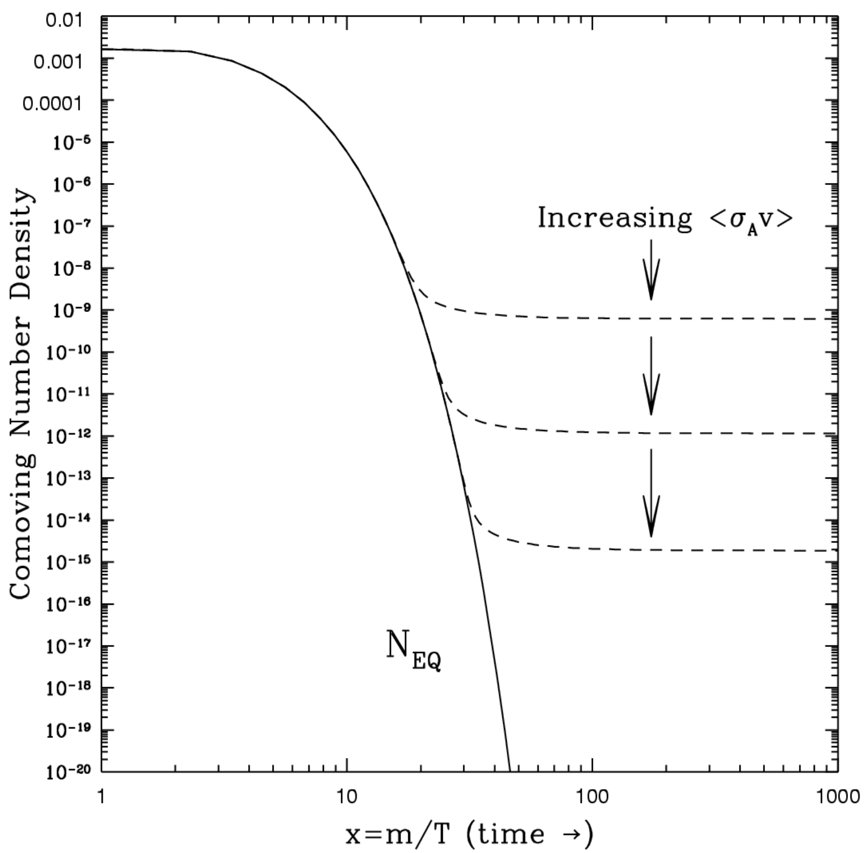
Relic density of particles in the universe:

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$m_X \simeq m_W \sim 100\text{GeV}$$

$$g_X \simeq g_{\text{Weak}} \sim 0.6$$

$$\Rightarrow \Omega_X \sim 0.1$$



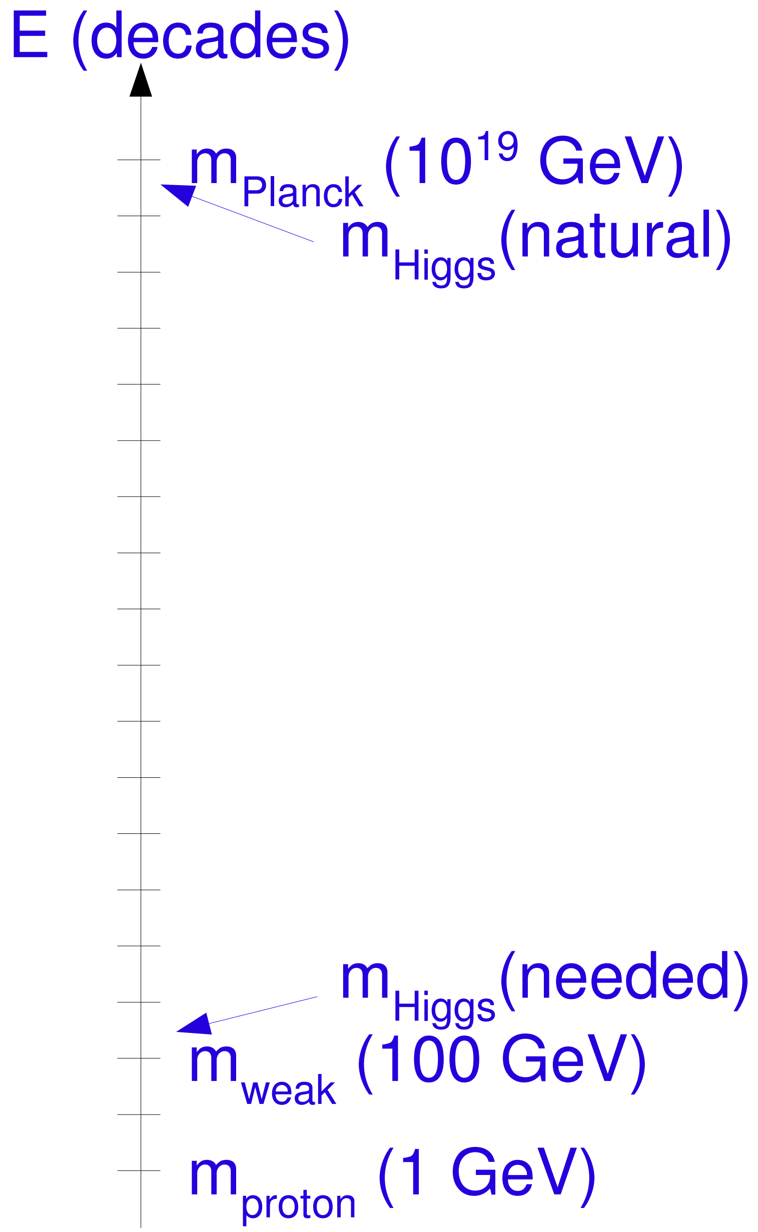
Weakly Interacting Massive Particle

The "WIMP miracle" - Particle with weak-scale mass and coupling gives right relic density!

Stabilizing Dark Matter

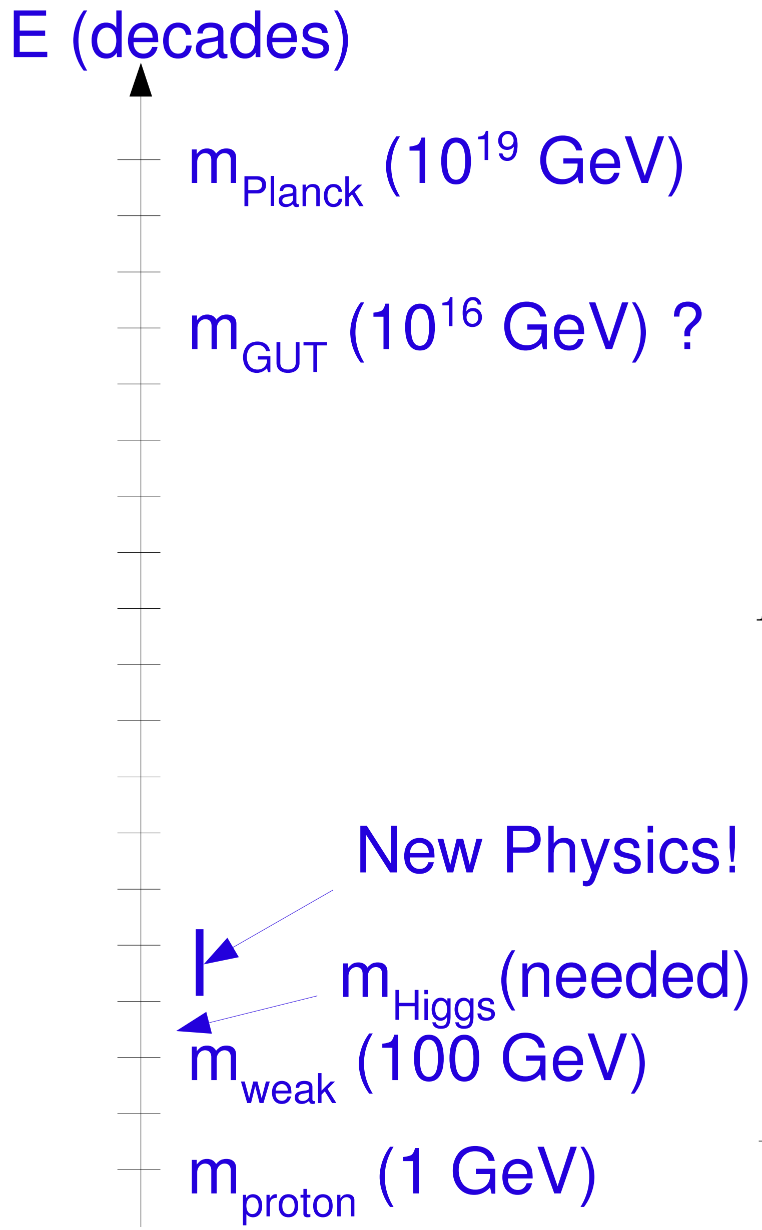
- For dark matter to be stable (on cosmological time scales) it must be charged under some new (approximately) unbroken symmetry
- Possibilities:
  - New gauge symmetry
  - New continuous global symmetry
  - New discrete symmetry
- Simplest possibility: $\mathbb{Z}_2$ symmetry ("parity")

The Hierarchy Problem

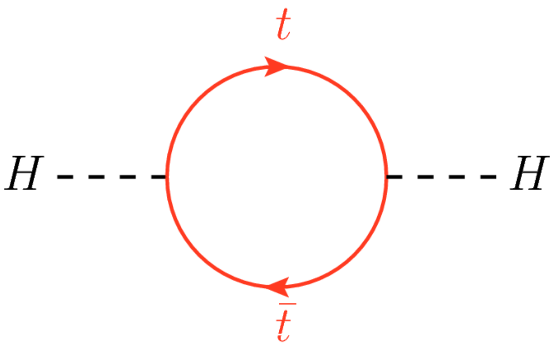


- Standard Model Higgs boson mass naturally at the scale of new physics (only known: Planck scale, 10^{18} GeV)
- Standard Model only works if the Higgs mass below ~800 GeV
- New physics scale communicated through quantum loops of top quarks, W bosons and H

The Hierarchy Problem

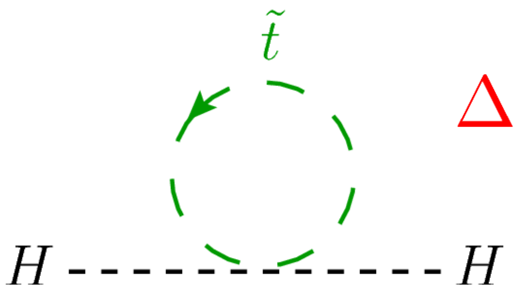


- New physics with masses around 1 TeV (e.g. SUSY) can cancel loop contributions by introducing new particles, e.g. top partner



$$\Delta M^2_{H\,\mathrm{top}} \sim M^2_{\mathrm{new\,physics}}$$

M_{Pl}~10^{38} GeV^2



$$\Delta M^2_{H\,(\mathrm{top+stop})} \sim M^2_{\mathrm{stop}}$$

~10^6 GeV^2

New Physics Scenarios

New physics which simultaneously addresses the hierarchy problem and dark matter predicts:

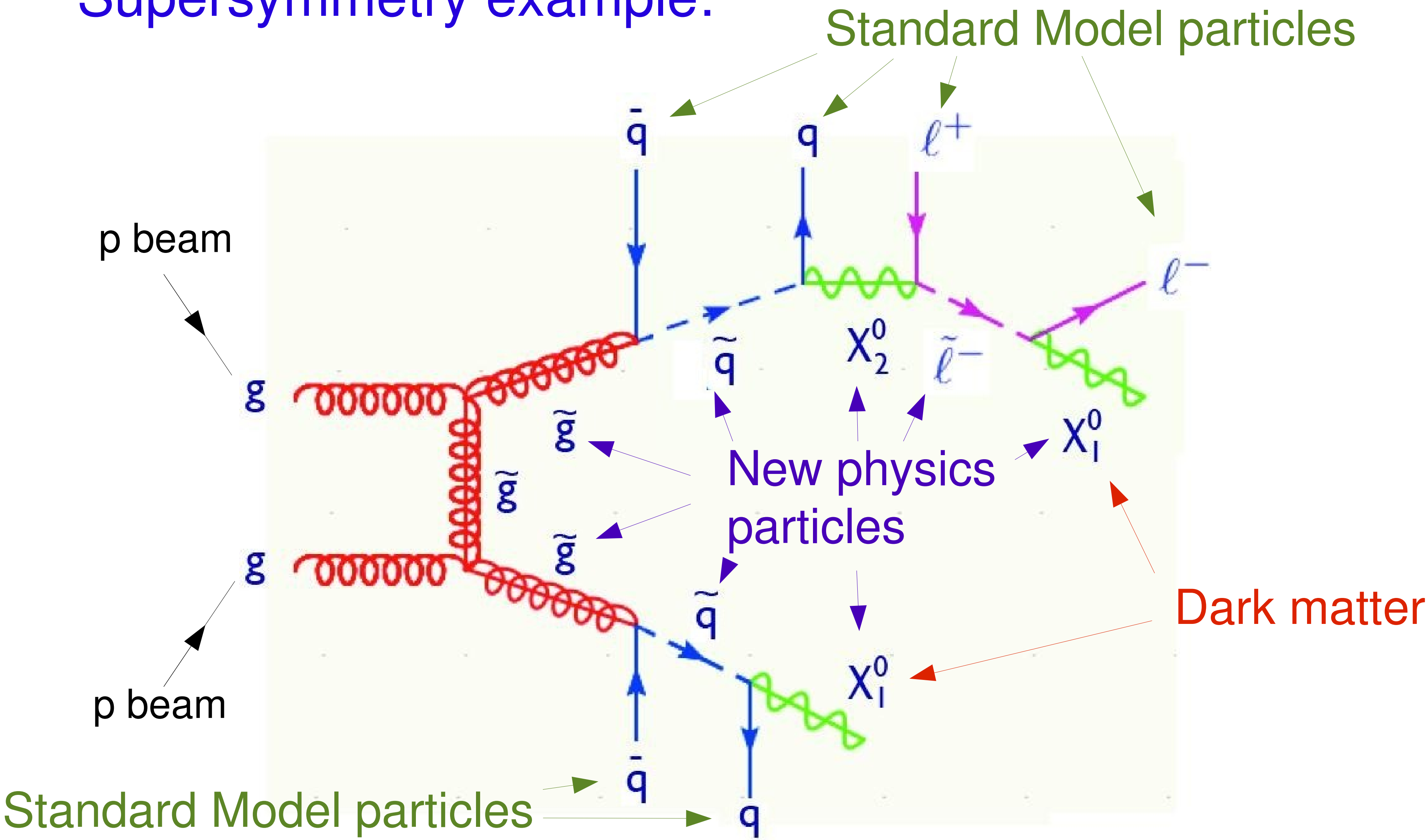
- A sector of new particles, probably some charged under QCD (at least top partners)
- At least some of the new particles charged under a new symmetry (SM particles uncharged)
- The lightest new particle electrically neutral color singlet
- New particle masses ~ 1 TeV

New Physics Scenarios

- Very general scenario for collider studies:
  - New physics particles pair produced, some with strong interaction cross sections
  - Decay to SM particles and dark matter
  - Typically cascade decays, if complex spectrum
- Examples:
  - Supersymmetry with R-parity
  - Little Higgs models with T-parity
  - Extra Dimensions with KK-parity

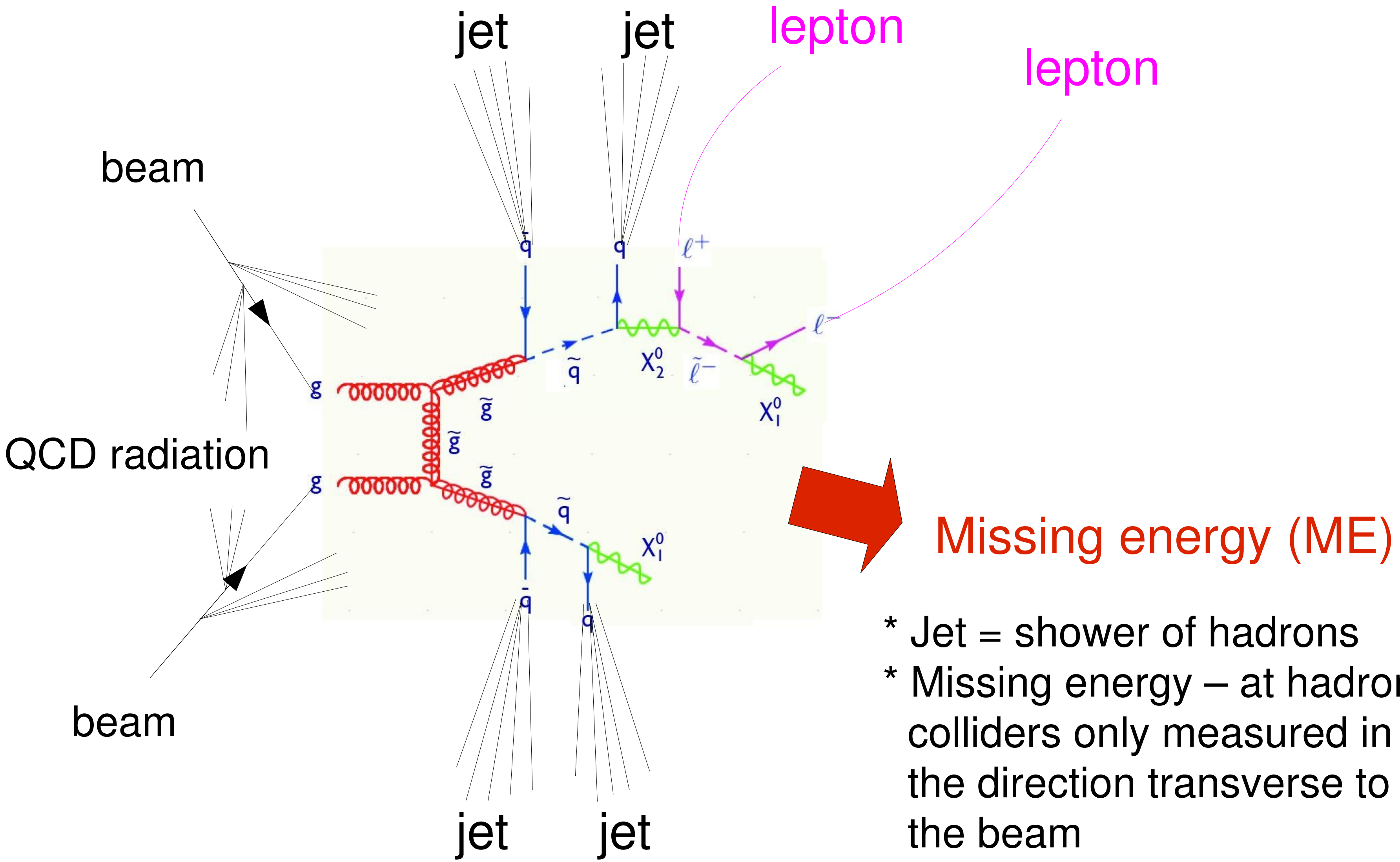
LHC signatures

Supersymmetry example:



LHC signatures

Supersymmetry example:



* Jet = shower of hadrons
* Missing energy – at hadron colliders only measured in the direction transverse to the beam

How to simulate New Physics

Steltzer, Maltoni [1994, 2003], J.A. et al [arXiv:0706.2334]

- MadGraph/MadEvent – an automatized Matrix Element and event generator
- On-demand simulation of (almost) any process in the SM or beyond (at tree level)
- Web-based or local simulation
- Interfaces to parton showers and detector simulations – full simulation chain!
- Completely new, super hot: MadGraph 5

Over 1500 registered users!

Welcome to visit us at
http://madgraph.hep.uiuc.edu !

Difficulties with ME signatures

Double-sided missing energy (pair-production plus decay to invisible particles) one of the most complicated signatures at hadron colliders. In general:

- No clear resonance features over background
- No way to reconstruct complete event
- Small kinematic sensitivity to mass of invisible particle
- Difficult to measure absolute masses – only mass differences directly reflected in kinematic distributions
- Jet signatures complicated by QCD radiation

Difficulties with ME signatures

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This talk

- Small kinematic sensitivity to mass of invisible particle
- Difficult to measure absolute masses – only mass differences directly reflected in kinematic distributions

- Jet signatures complicated by QCD radiation

Seminar

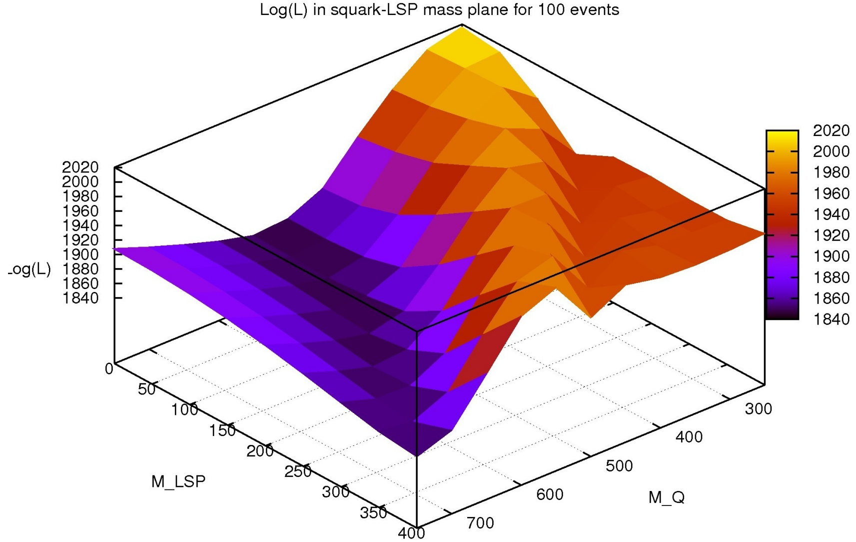
Mass determination with ME

- Mass reconstruction in double-sided ME events a major challenge
- Easier the longer the decay chains (more mass constraints)
- Requires large event statistics
- How to use information from experimental events most efficiently?

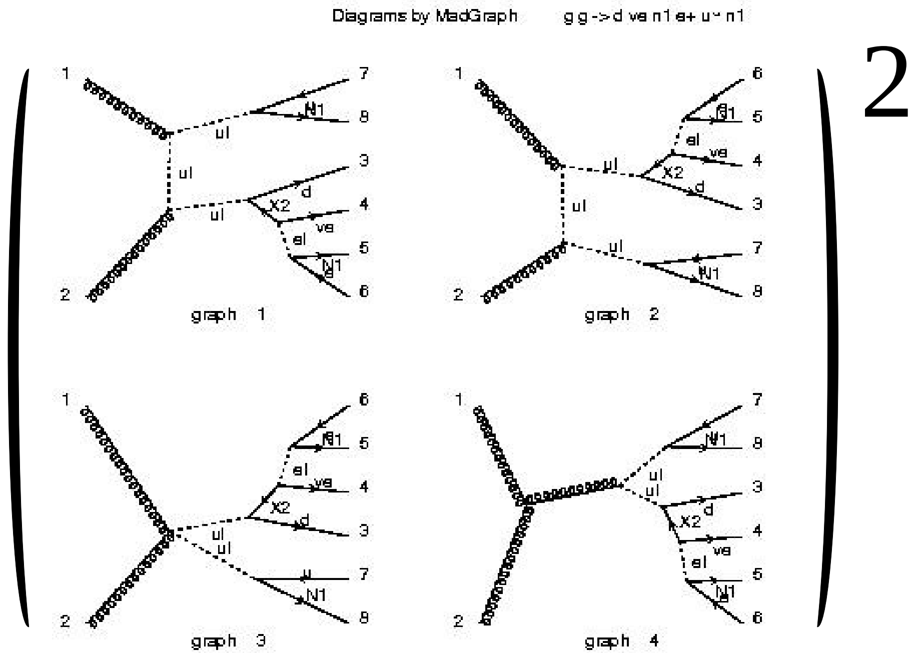
The Matrix Element Method

[Canelli et al [DØ], 1999;
Artoisenet et al, in preparation]

- Method to extract maximum information from all experimental events of given type
- Can be used for mass/parameter reconstruction, distinction between signal and background, distinction between models



The Matrix Element Method



Feynman diagrams by MadGraph for process

$$gg \rightarrow \tilde{\bar{q}}\tilde{q} \rightarrow q\chi_2^+ \bar{q}\chi_1^0$$

$$\chi_2^+ \rightarrow \nu\tilde{l} \rightarrow \nu l^+ \chi_1^0$$

- The matrix element for a process encodes all information about the model: Masses, spins, couplings, structure of interactions
- Usually used to simulate the process and generate events/kinematical distributions

The Matrix Element Method

- Invert this idea: Calculate the matrix element using 4-vectors of experimental event
  $\rightarrow$ measure of probability that event was generated by this matrix element
- Combine information from many events in likelihood
  $\rightarrow$ can distinguish properties of the events

$$P(\boldsymbol{x}, \alpha) = \qquad |M_\alpha|^2(\boldsymbol{x})$$

Prob
for event
x given α

Squared
matrix
element

The Matrix Element Method

- Invert this idea: Calculate the matrix element using 4-vectors of experimental event
  $\rightarrow$ measure of probability that event was generated by this matrix element
- Combine information from many events in likelihood
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$$P(\boldsymbol{x}, \alpha) = \frac{1}{\sigma} \int d\phi(\boldsymbol{y}) |M_\alpha|^2(\boldsymbol{y}) W(\boldsymbol{x}, \boldsymbol{y})$$

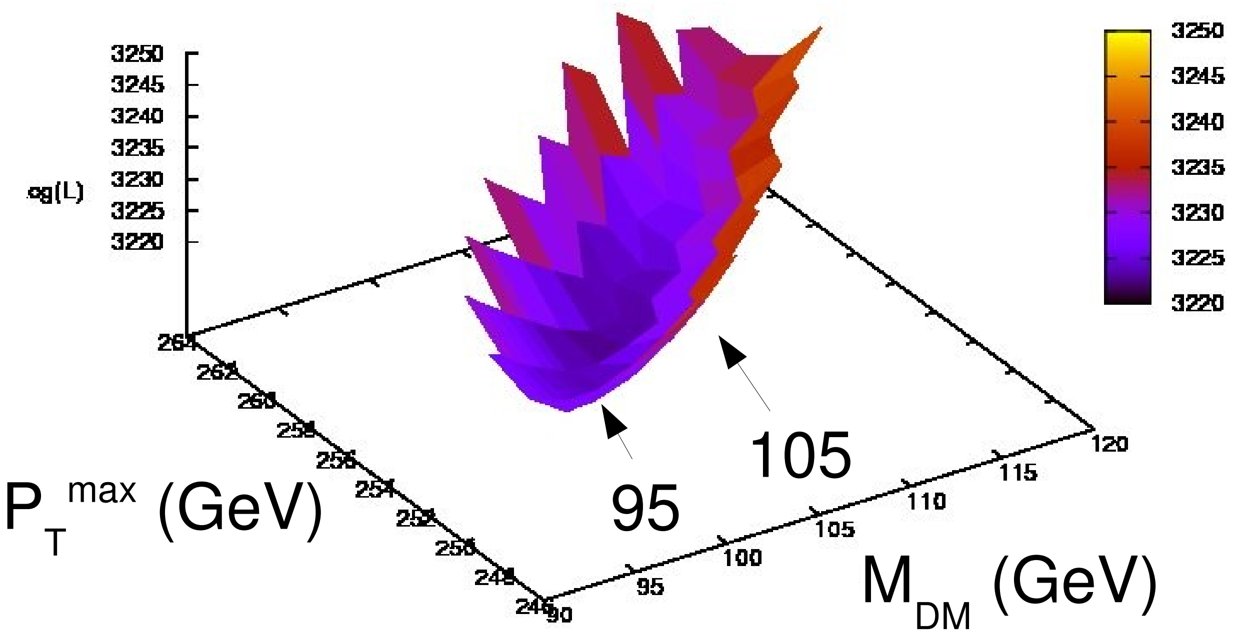
Prob for event x given α | Normalization | Phase space integral | Squared matrix element | Transfer function

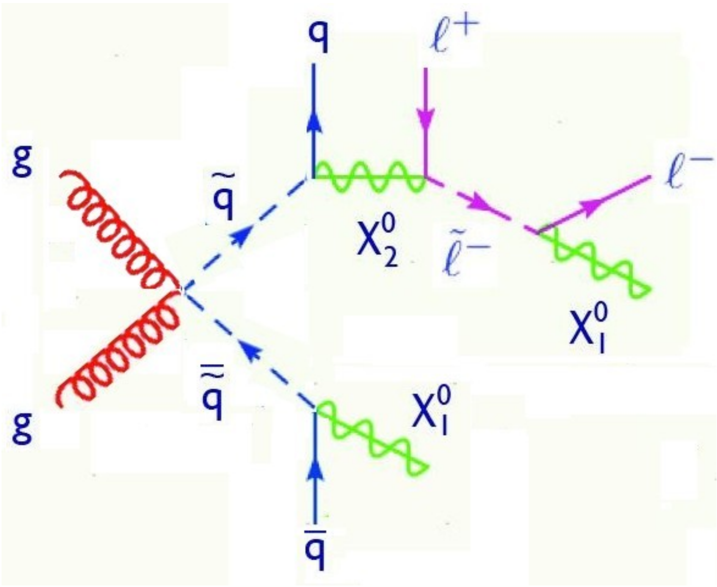
The Matrix Element Method

[JA, Freitas, Mattelaer, in progress]

- By using maximum information from the events, we can accurately determine masses already with very small event samples

-Log(L) for 100 events



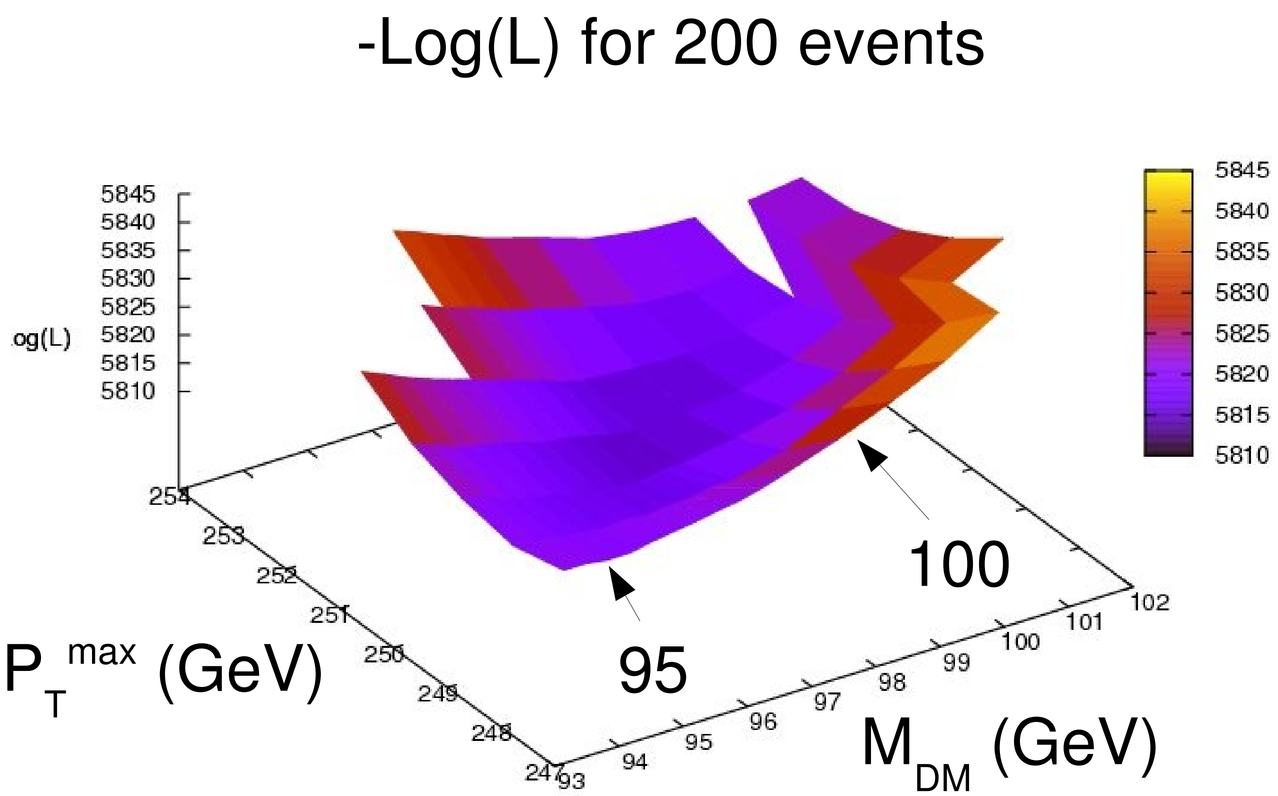


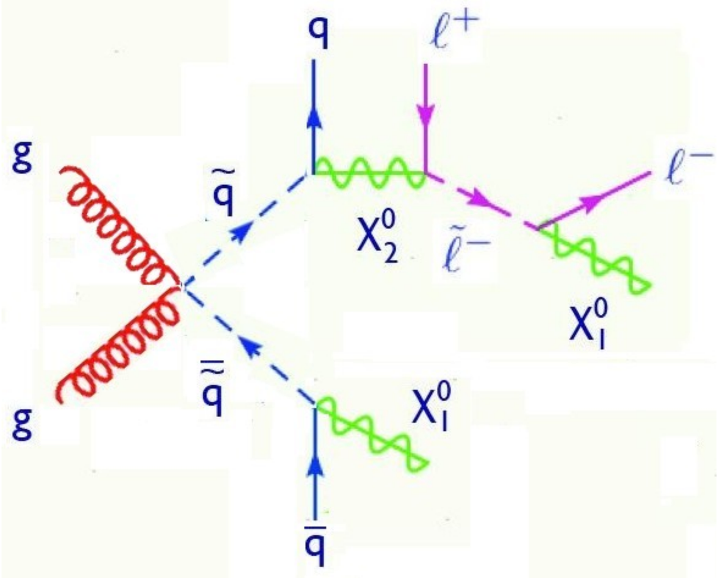
~ 100 clean events

→ ΔM_{LSP} ~ 10 %

The Matrix Element Method

- By using maximum information from the events, we can accurately determine masses already with very small event samples





~ 200 clean events

$\rightarrow \Delta M_{LSP}$ ~ 5 %

The Matrix Element Method

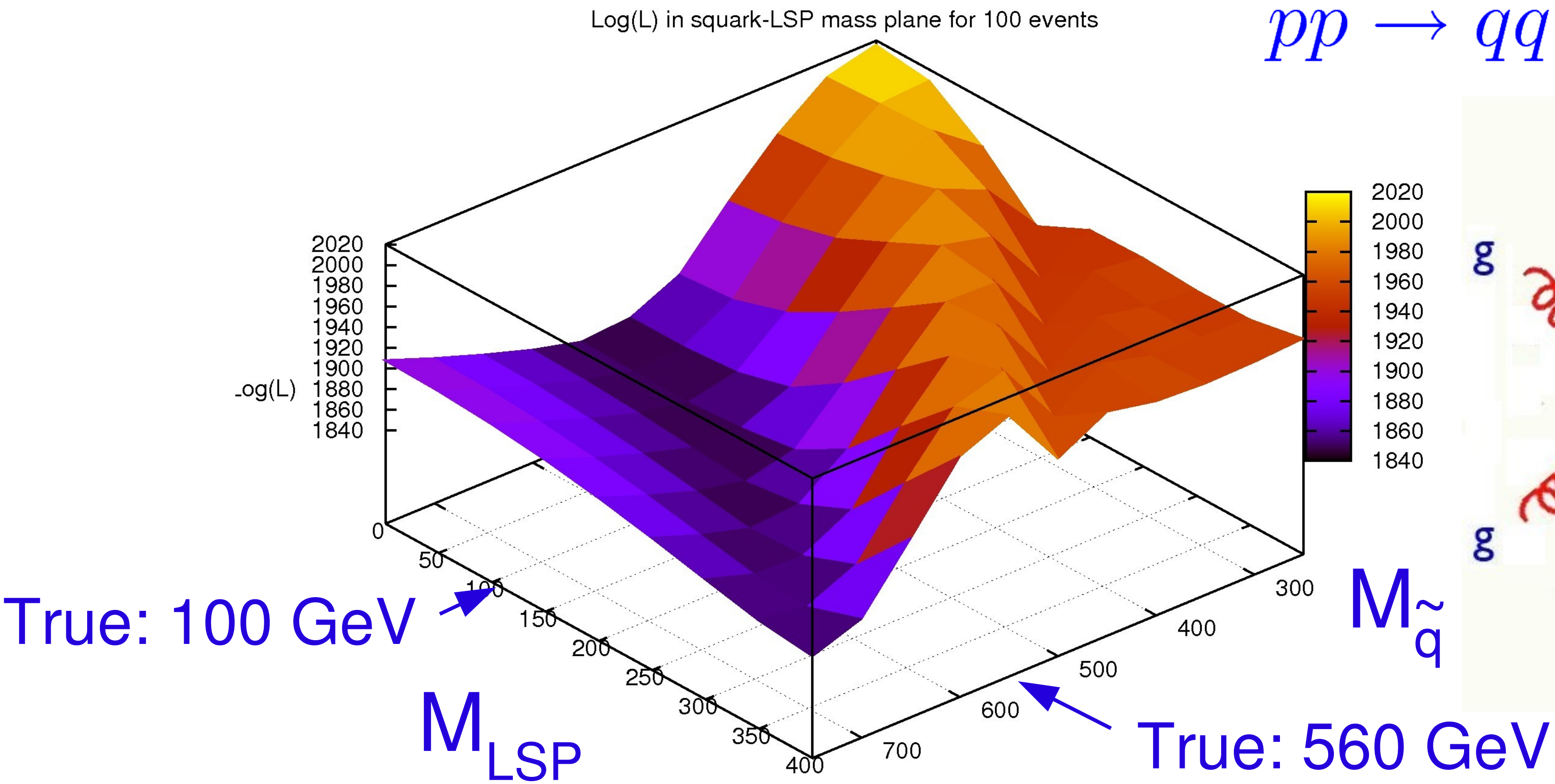
[JA, Freitas, Mattelaer, arXiv:0910.2522 & in progress]

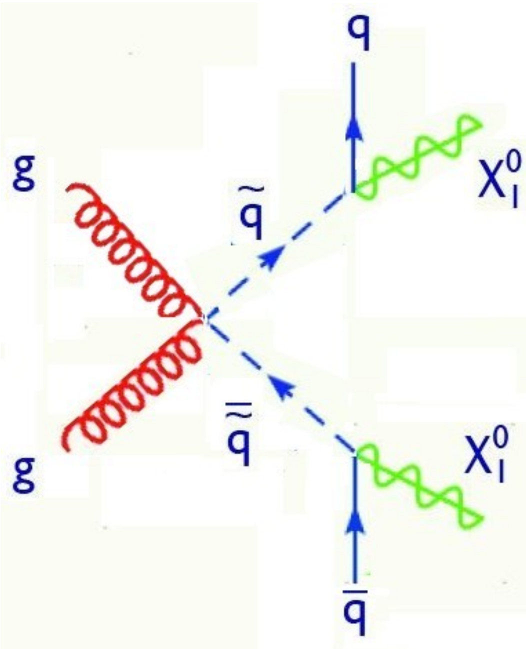
- Most difficult scenario:
  Pair production of particles decaying to only jets and dark matter
  - Ex: $pp \to \bar{\tilde{q}}\tilde{q} \to q\chi_1^0\bar{q}\chi_1^0$
  - No leptons (which are easier to measure than jets)
  - No long decay chain with multiple mass constraints
  - Impossible (or very difficult) to measure DM mass using endpoint analysis (need at least three masses in decay chains)
  - Matrix element method might be only possibility!

The Matrix Element Method

-Log(L) for 100 events (parton level only, no backgrounds)

$$pp \longrightarrow \bar{\tilde{q}}\tilde{q} \longrightarrow q\chi_1^0\bar{q}\chi_1^0$$





The Matrix Element Method

$$pp \to \bar{\tilde{q}}\tilde{q} \to q\chi_1^0\bar{q}\chi_1^0$$

Change variables: $M_{\tilde{q}} \to P_T^{\max} = (M_{\tilde{q}}^2 - M_{\mathrm{DM}}^2)/(2M_{\tilde{q}})$

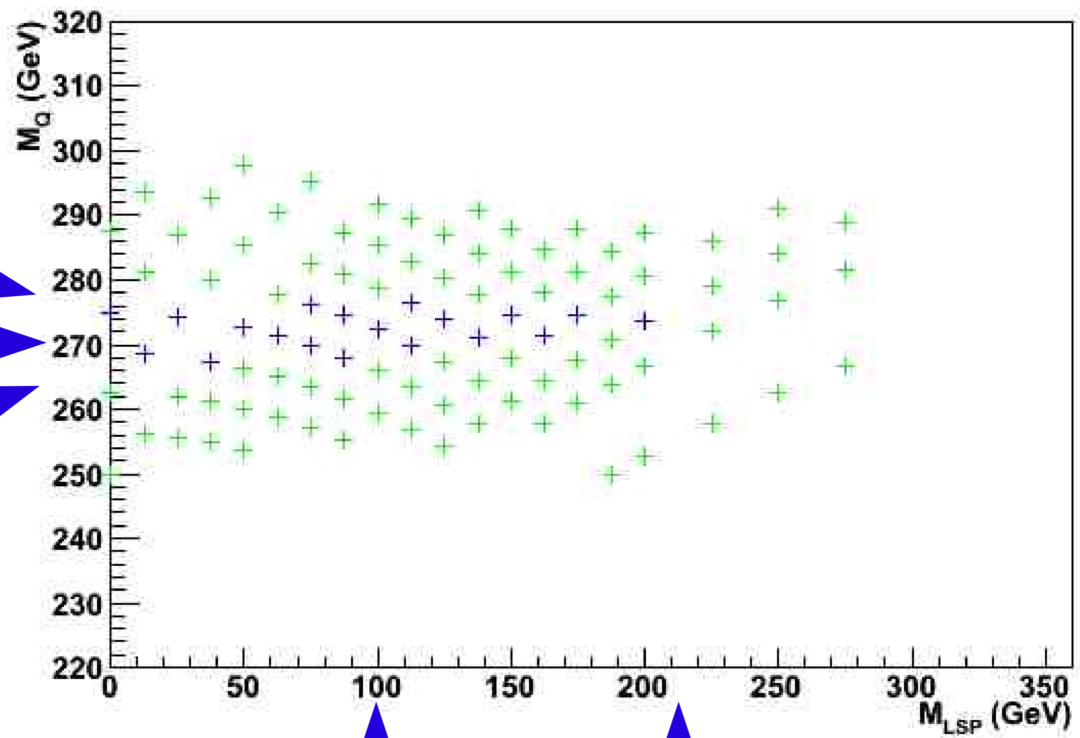
-Log(L) for 700 events – blue below min+4

p_{Tmax}

Max: 278 GeV

True: 272 GeV

Min: 265 GeV



M_{DM}

True: 97 GeV Max: 210 GeV

The Matrix Element Method

$$pp \rightarrow \bar{\tilde{q}}\tilde{q} \rightarrow q\chi_1^0\bar{q}\chi_1^0$$

Change variables: $M_{\tilde{q}} \rightarrow P_T^{\max} = (M_{\tilde{q}}^2 - M_{\rm DM}^2)/(2M_{\tilde{q}})$

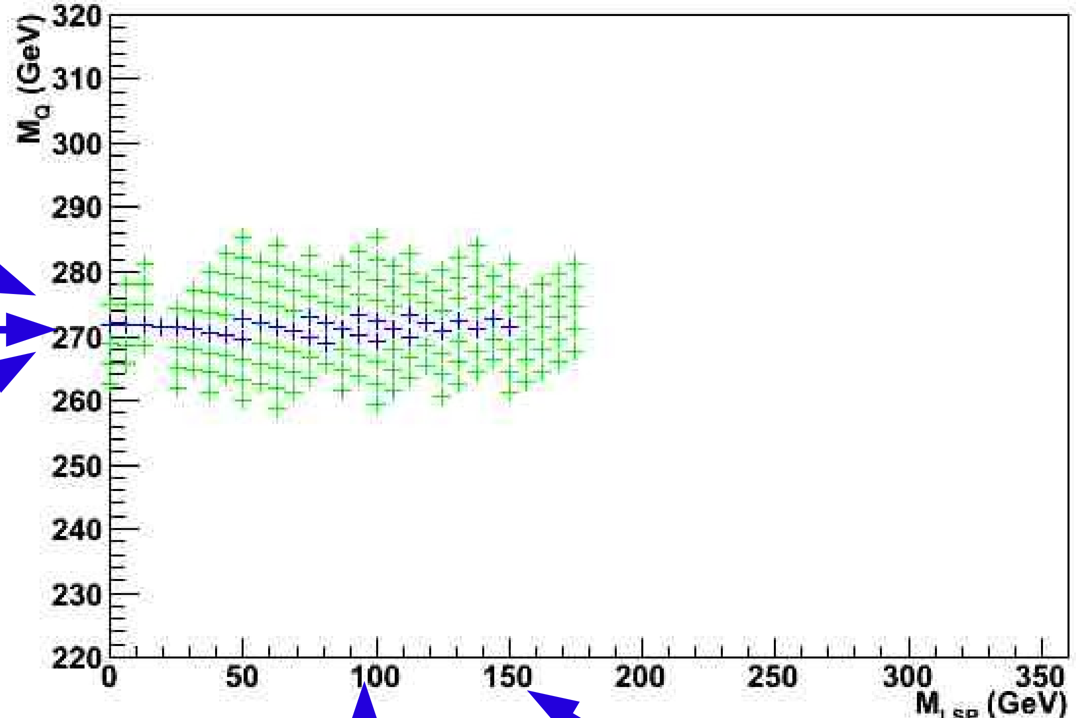
-Log(L) for 3000 events – blue below min+4

p_{Tmax}

Max: 275 GeV

True: 272 GeV

Min: 268 GeV



True: 97 GeV Max: 150 GeV

M_{DM}

The Matrix Element Method

$$pp \to \bar{\tilde{q}}\tilde{q} \to q\chi_1^0\bar{q}\chi_1^0$$

Change variables: $M_{\tilde{q}} \to P_T^{\max} = (M_{\tilde{q}}^2 - M_{\rm DM}^2)/(2M_{\tilde{q}})$

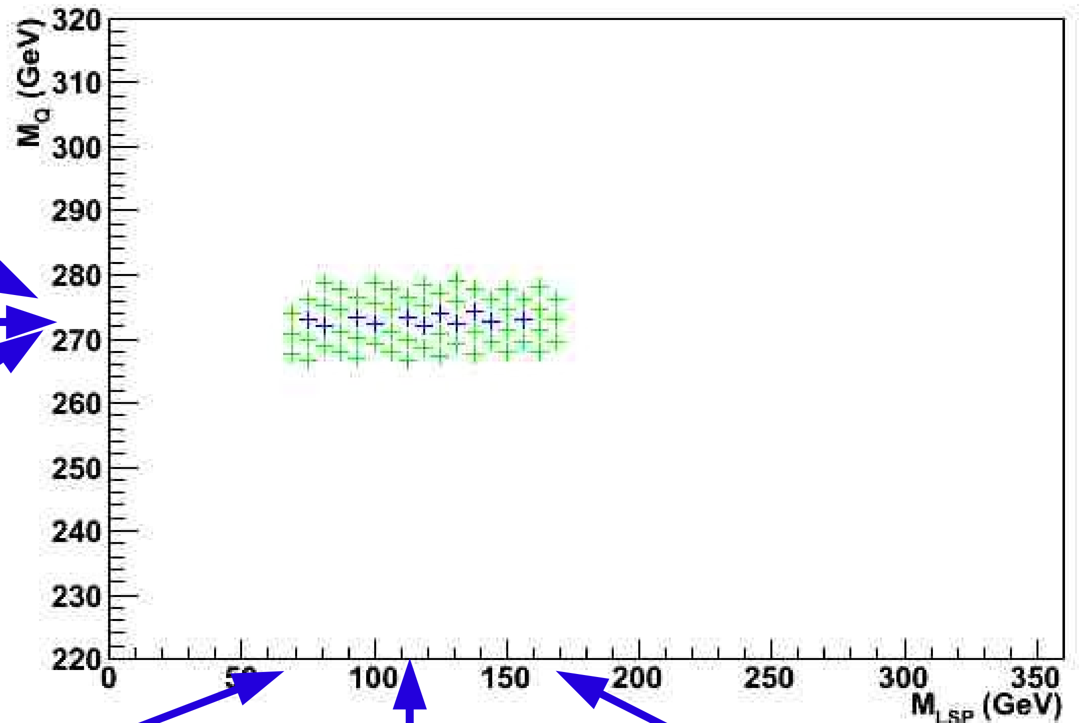
-Log(L) for 7500 events – blue below min+4

p_{Tmax}

Max: 275 GeV

True: 272 GeV

Min: 271 GeV



Min: 65 GeV True: 97 GeV Max: 160 GeV M_{DM}

Case study:
WIMPless dark matter

Remember:

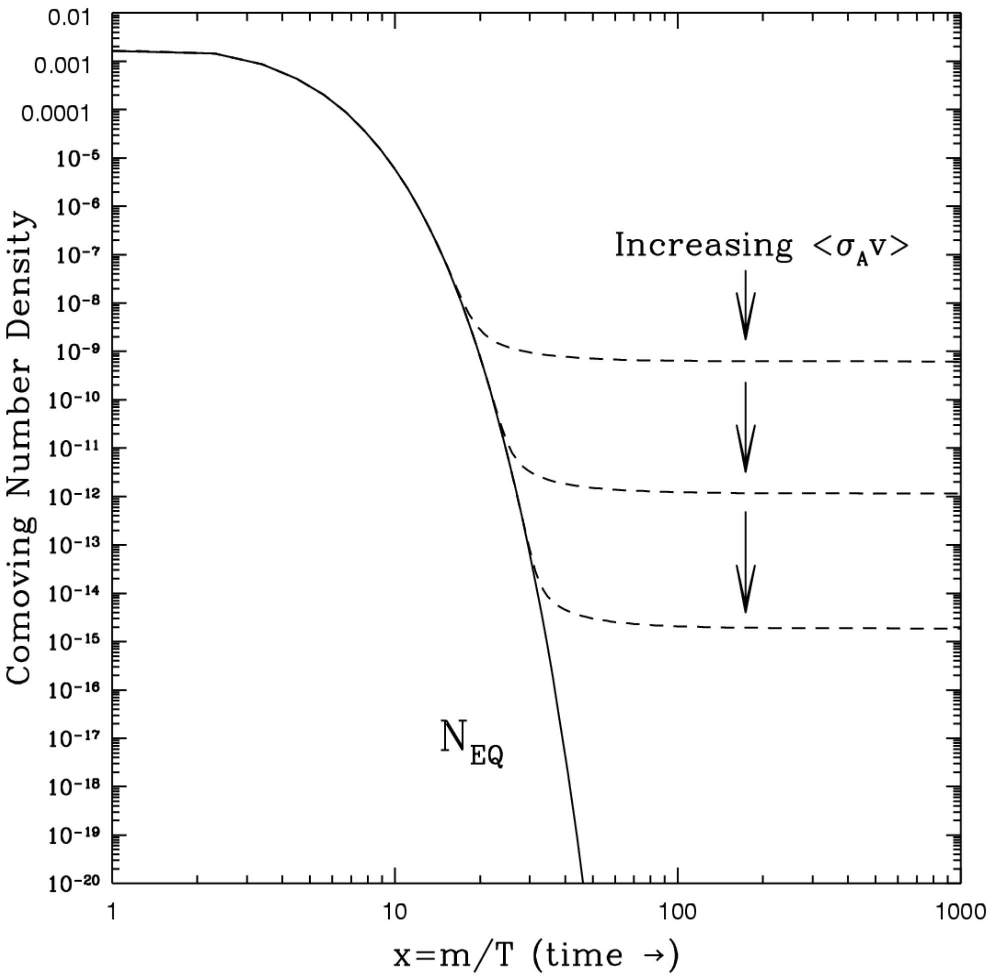
The WIMP miracle

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$m_X \simeq m_W \sim 100\mathrm{GeV}$$

$$g_X \simeq g_{\mathrm{Weak}} \sim 0.6$$

$$\Rightarrow \Omega_X \sim 0.1$$



But does it have to be WIMPs?

Gauge mediated SUSY breaking

- Gauge mediated supersymmetry breaking gives soft masses to SUSY partners according to

$$m_S^2 = -\frac{g^4 N_{mess}}{4\pi^4}\left(\frac{F}{M_{mess}}\right)^2$$

- So,

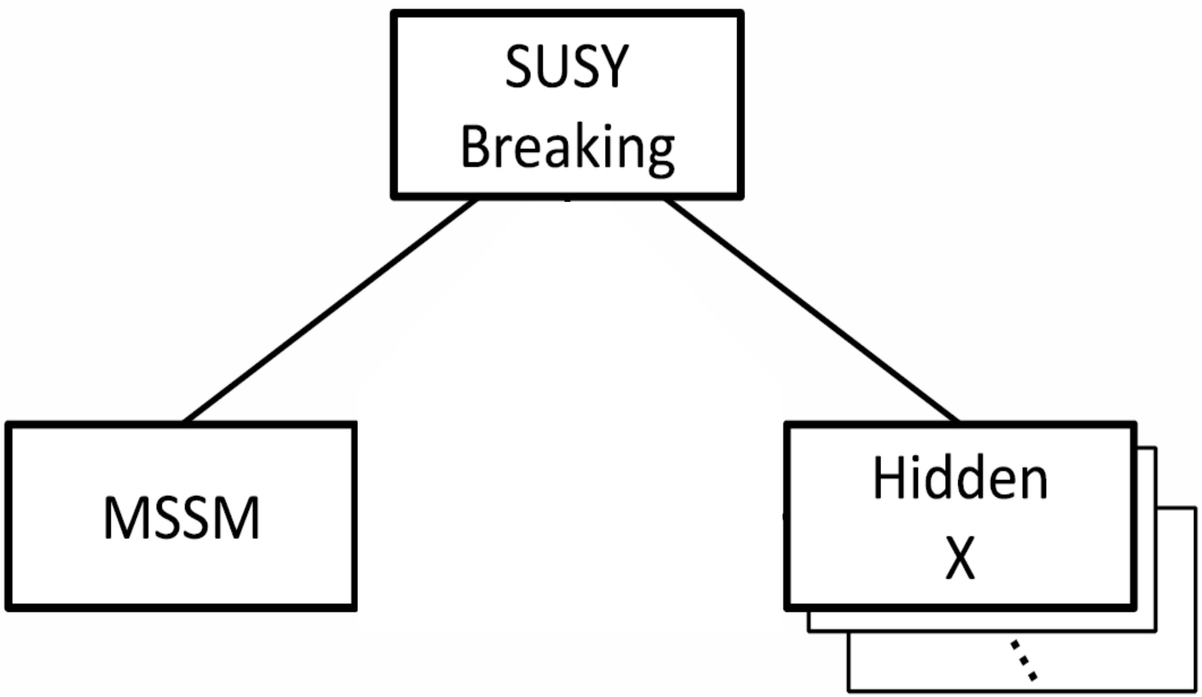
$$\frac{m_S}{g^2} \sim \frac{F}{M_{mess}} = \text{const}$$

- However, GMSB has light gravitino, so no stable WIMP dark matter candidate

The WIMPless miracle

[Feng, Kumar (2008)]

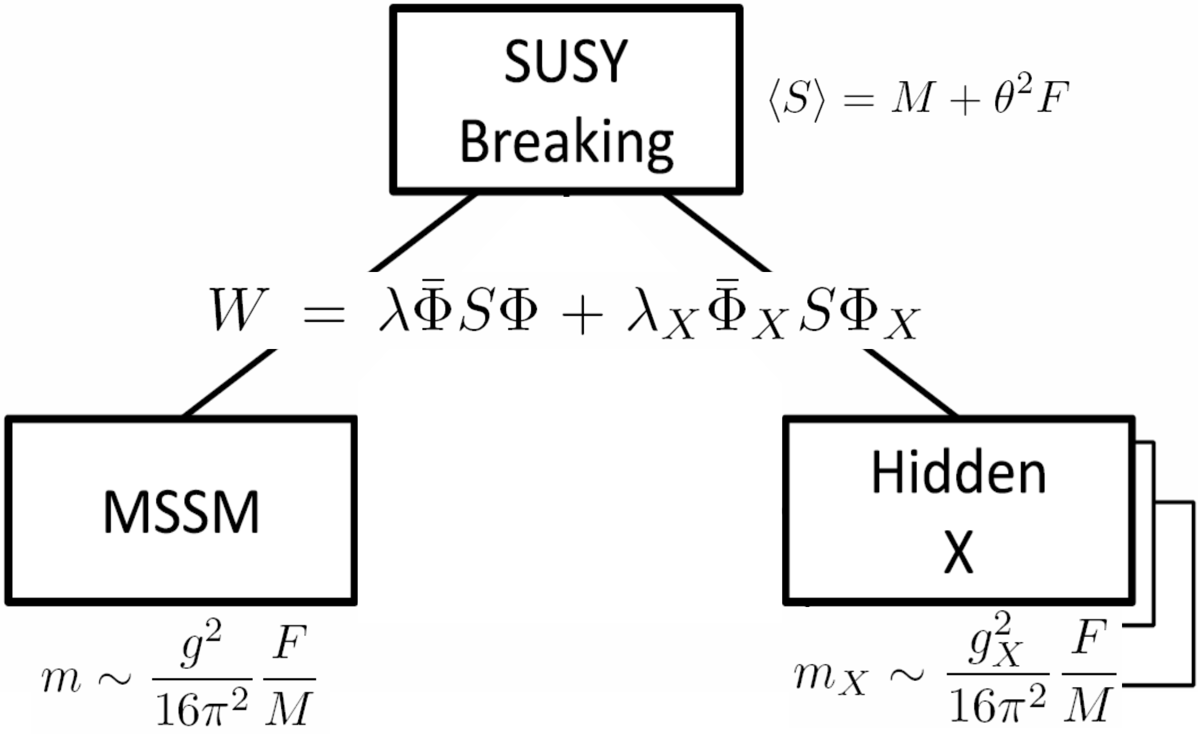
What if there are other, hidden, sectors?



Each sector has its own particle content, gauge groups, couplings, ...

The WIMPless miracle

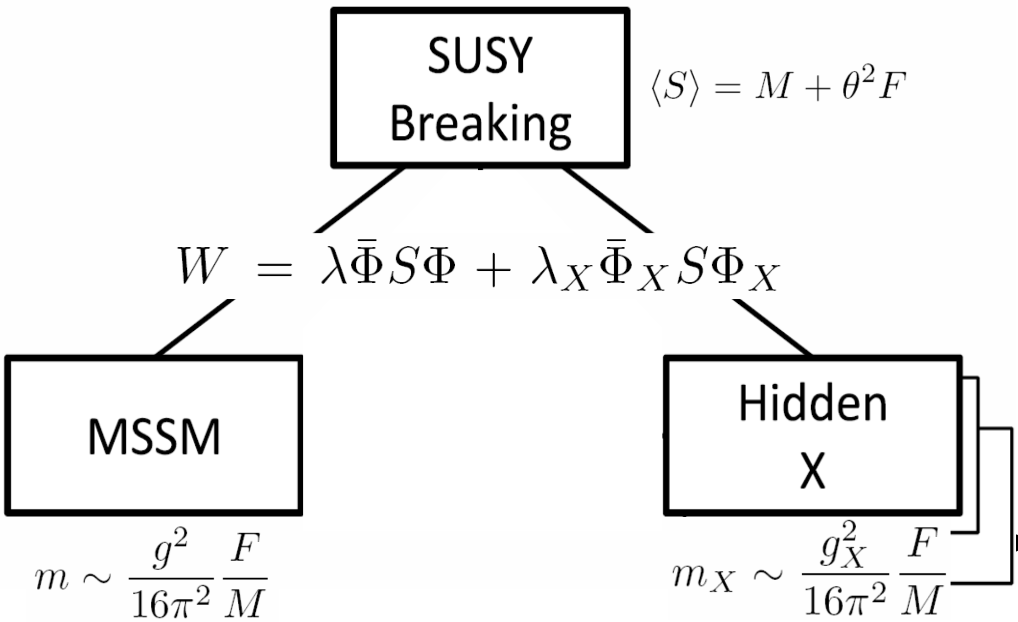
If Supersymmetry is broken by the same mechanism in all sectors:



- Superpartner masses depend on gauge couplings, with the same ratio in all sectors

The WIMPless miracle

- Particle Physics



Superpartner masses depend on gauge couplings

- Cosmology

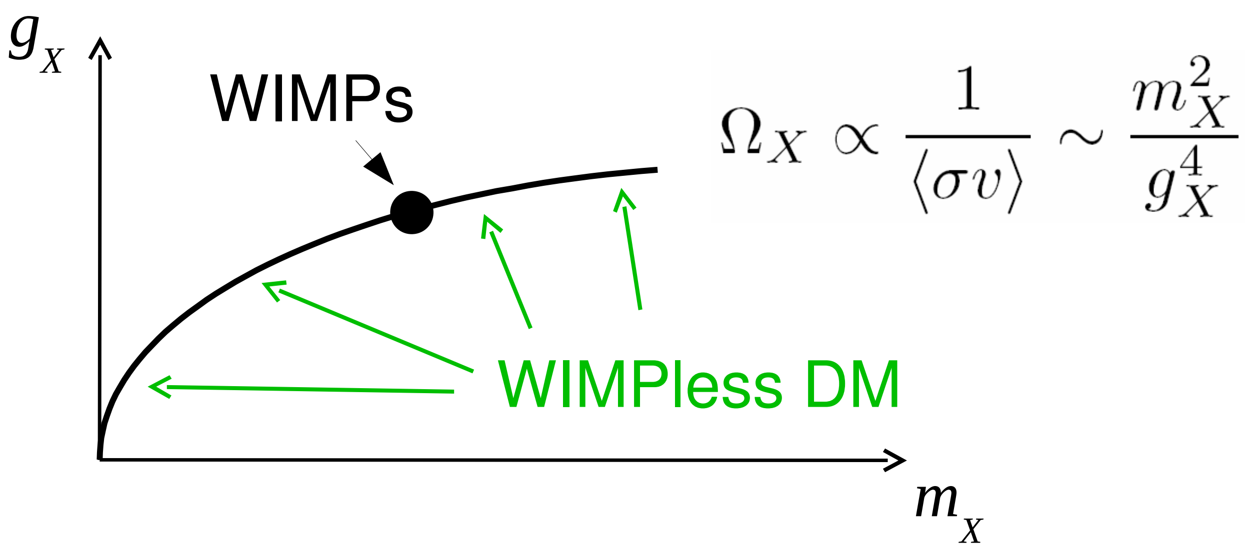
$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

Ω depends only on the SUSY breaking sector:

$$\Omega_X \sim \Omega_{\mathrm{WIMP}} \sim \Omega_{\mathrm{DM}}$$

Hidden sector lightest particle automatically has the right relic density!

The WIMPless miracle



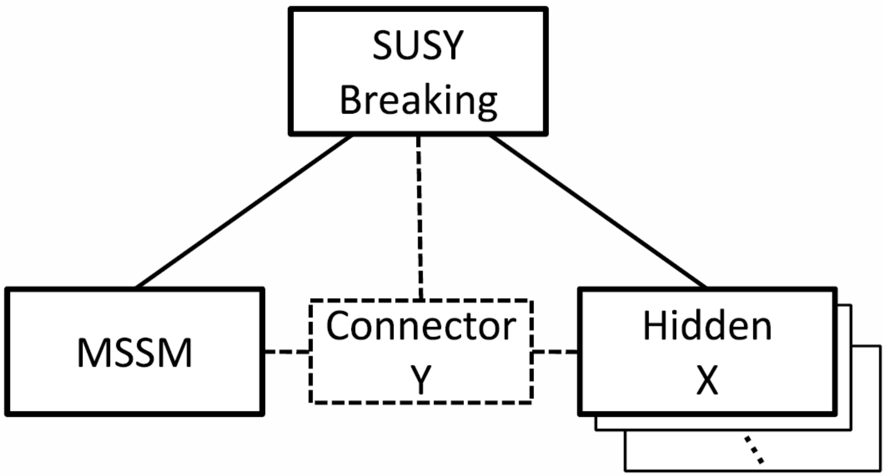
No longer necessarily WIMPs, but allow for a range of masses and couplings

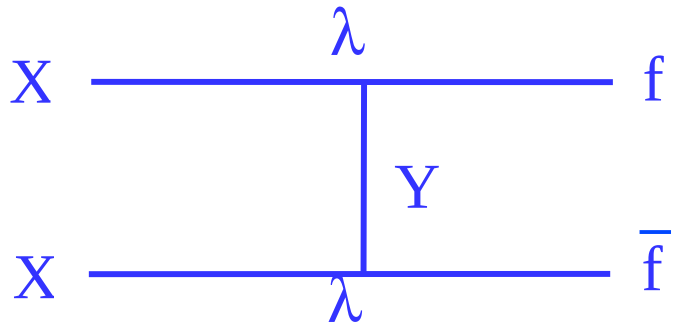
The "WIMPless miracle"!

Detecting WIMPless DM

[Feng, Kumar, Strigari (2008)]

- DM sector has no SM gauge charges, but might interact by connector Y with both SM and hidden charge
- Y particles will mediate both annihilation to, and scattering by, SM particles
- Natural solution for connector: Heavy quarks decaying to top or bottom quarks and dark matter





(Possible solution to the DAMA puzzle and Cogent results, avoids detection by other experiments)

Dark matter production

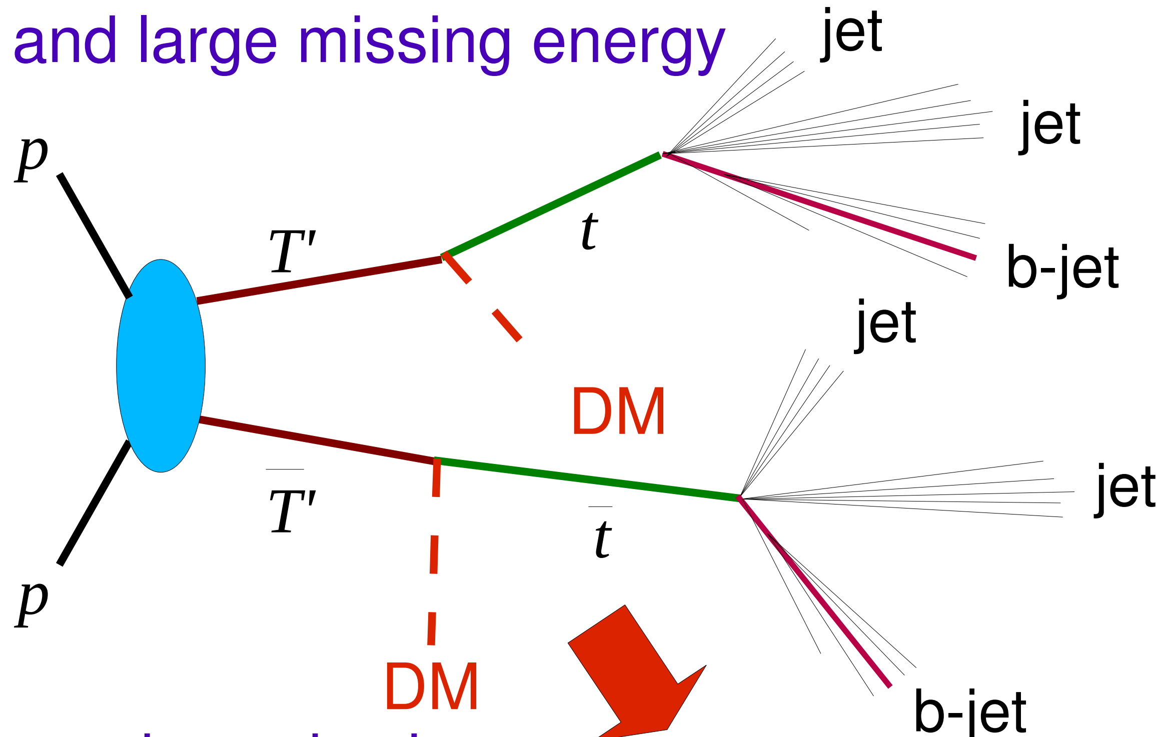
[J.A., Feng, Kumar, Su, arXiv:1002.3366]

Scenario:

- 4^{th} generation quarks, with QCD+Electroweak and "hidden" quantum numbers
  - Pair produced at the Tevatron or the LHC
  - Decay to top / bottom quarks and dark matter
- Have to obey constraints from precision measurements and unitarity
  - Masses $\lesssim$ 600 GeV, small mass difference T'-B'
- Low mass, large cross section: One of the most promising DM scenarios for Tevatron and early LHC!

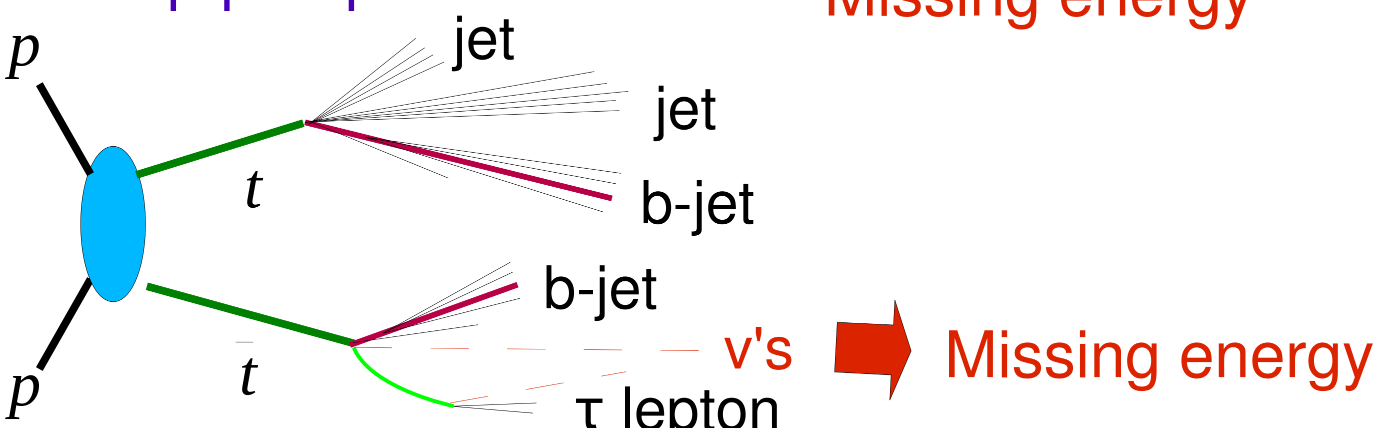
Dark matter production

Signal: Multiple jets and large missing energy



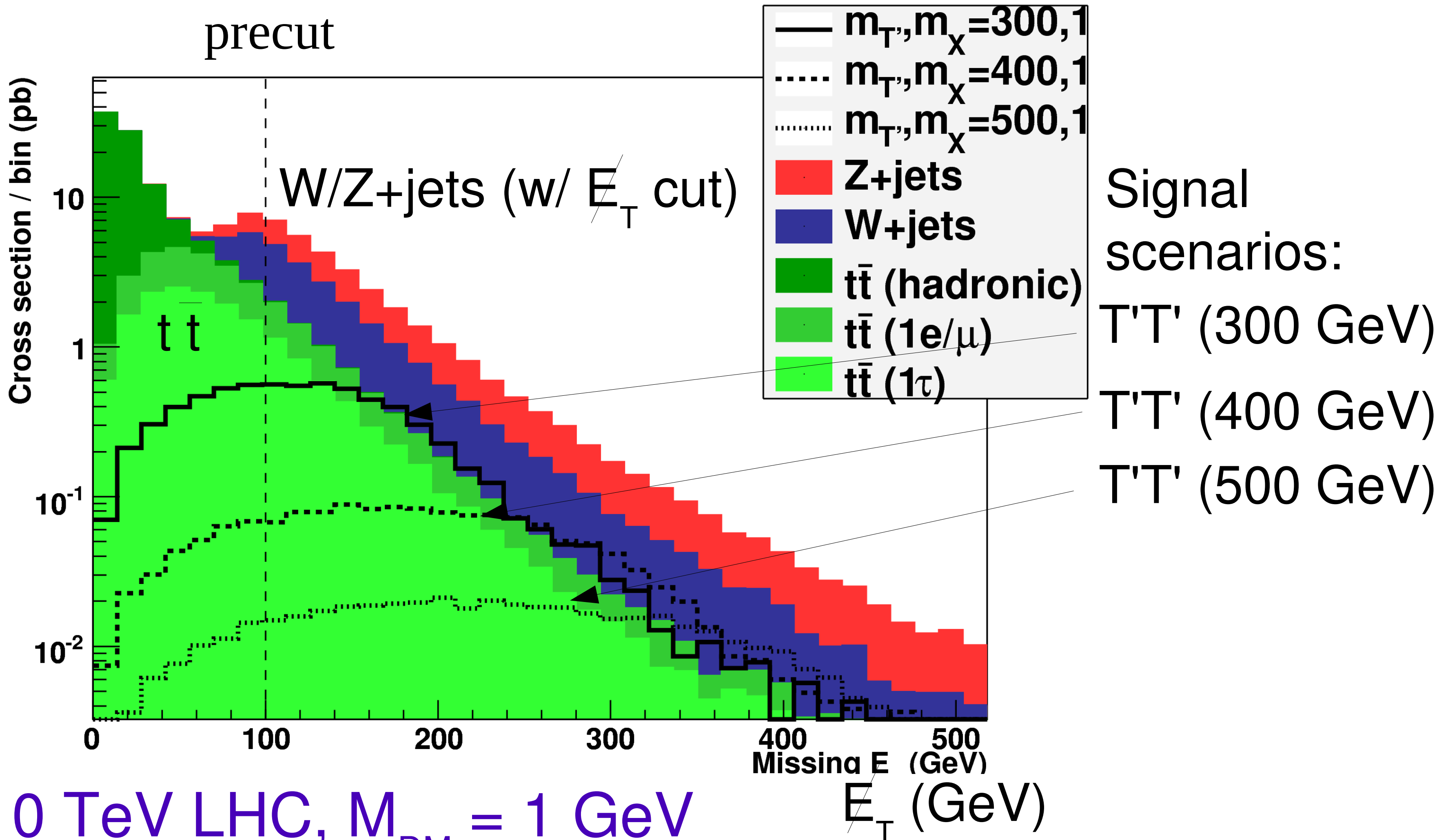
Missing energy

Main background: top pair production



How to dig out the signal?

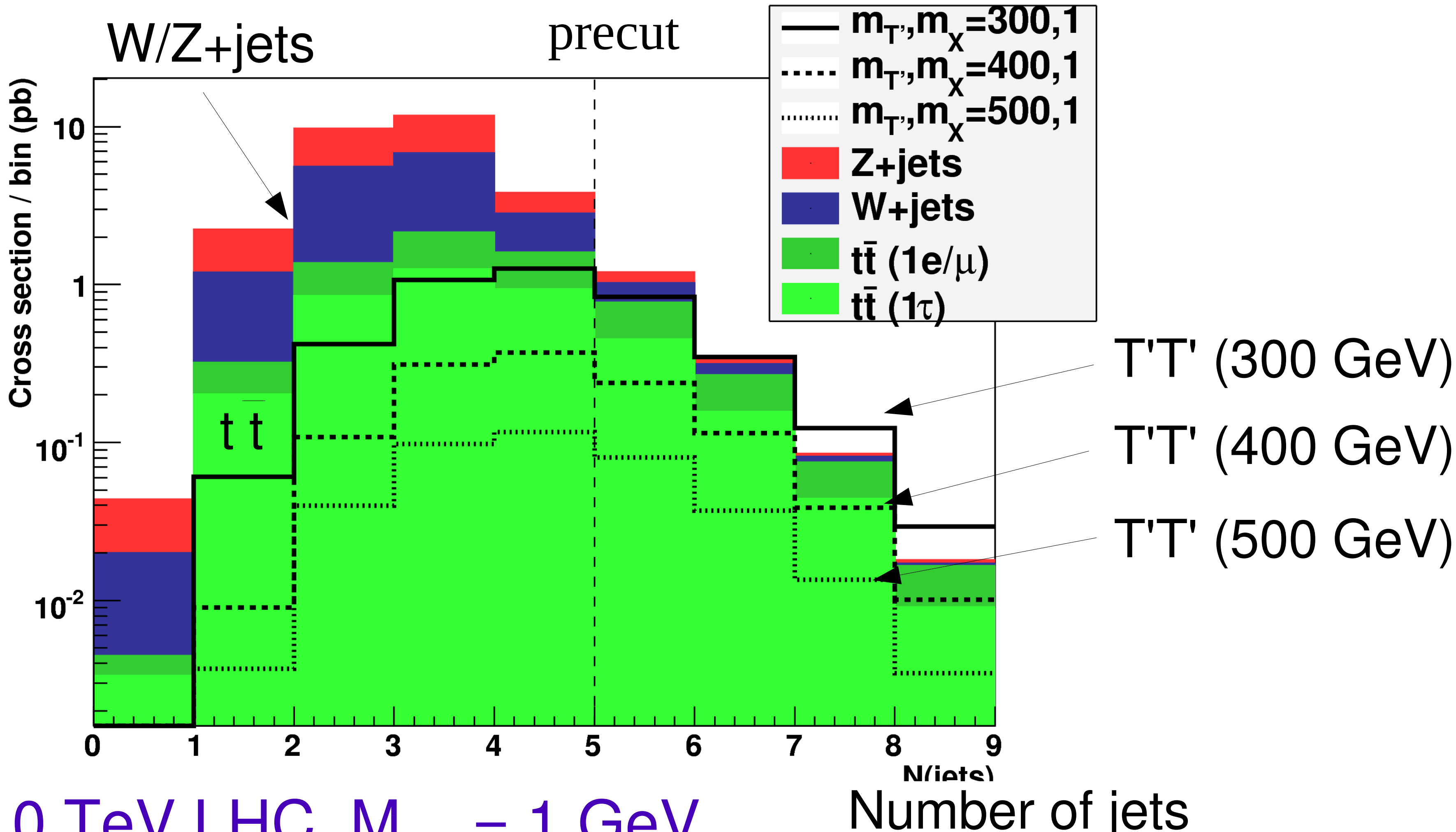
After 0-lepton cut



10 TeV LHC, M_{DM} = 1 GeV

How to dig out the signal?

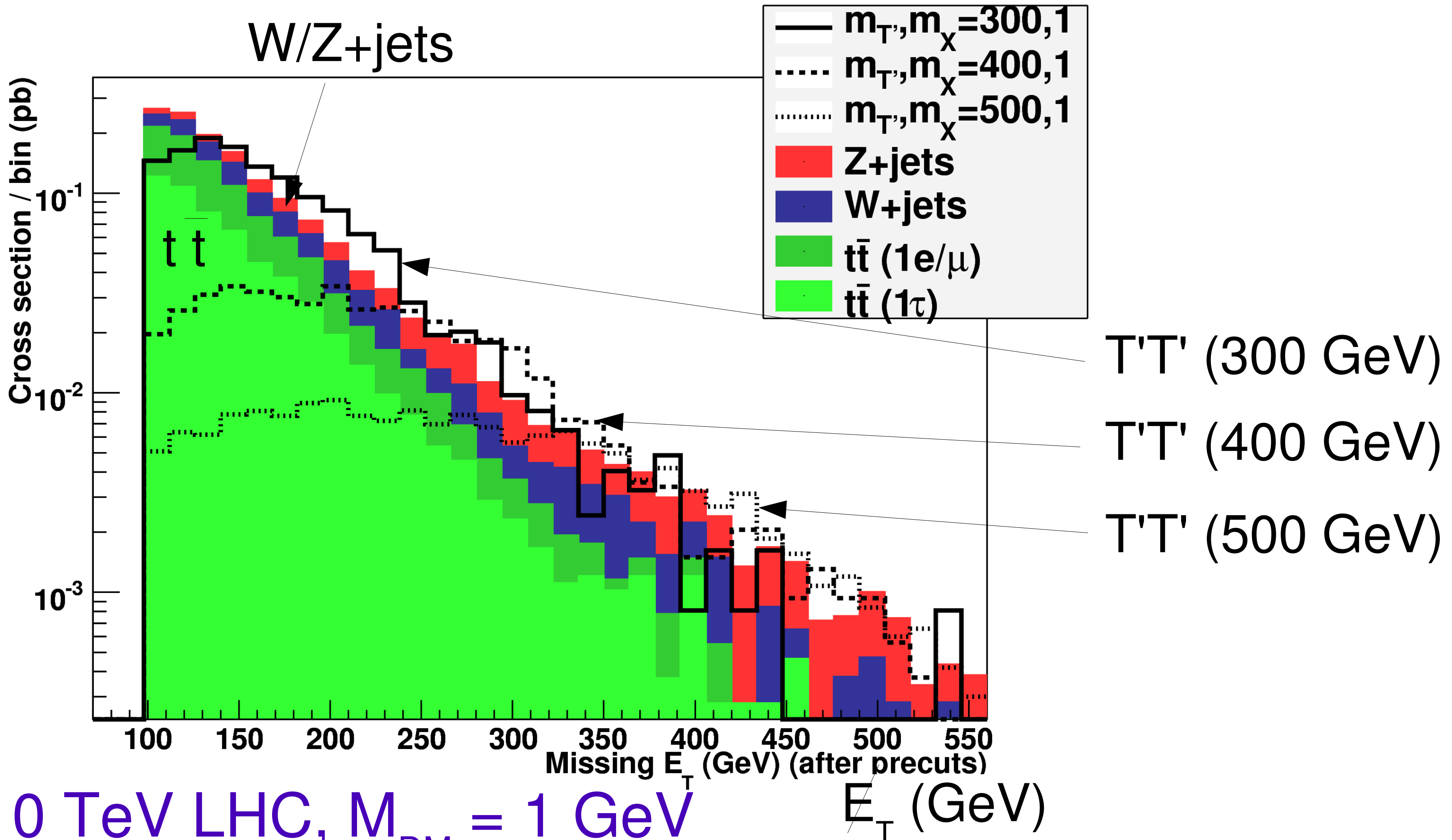
After 0-lepton + missing ET cut



10 TeV LHC, M_{DM} = 1 GeV

How to dig out the signal?

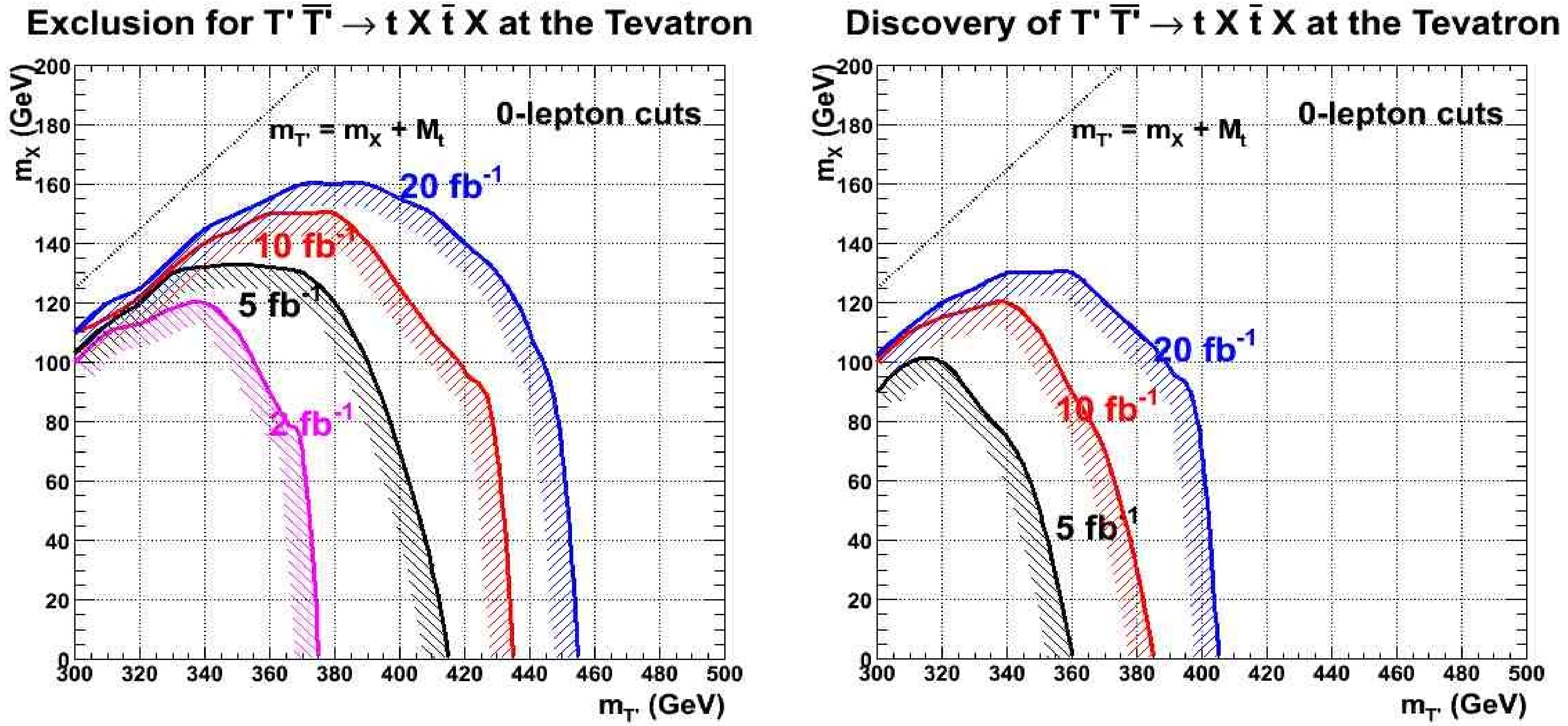
After all precuts



10 TeV LHC, M_{DM} = 1 GeV

Production at the Tevatron

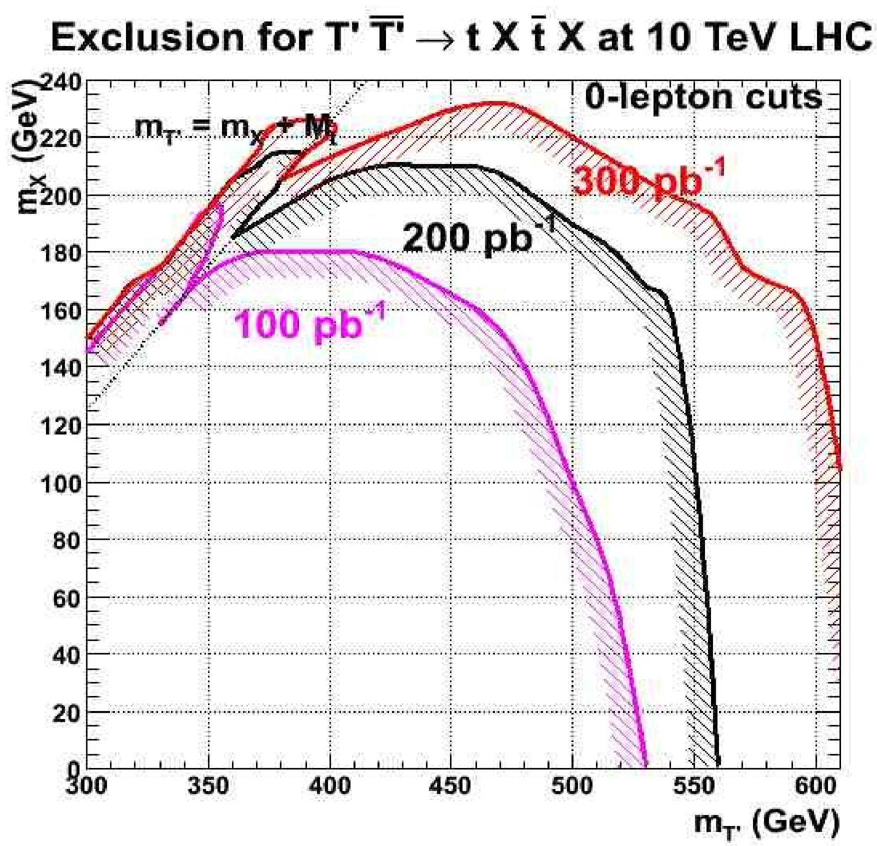
Might be discovered already at the Tevatron!

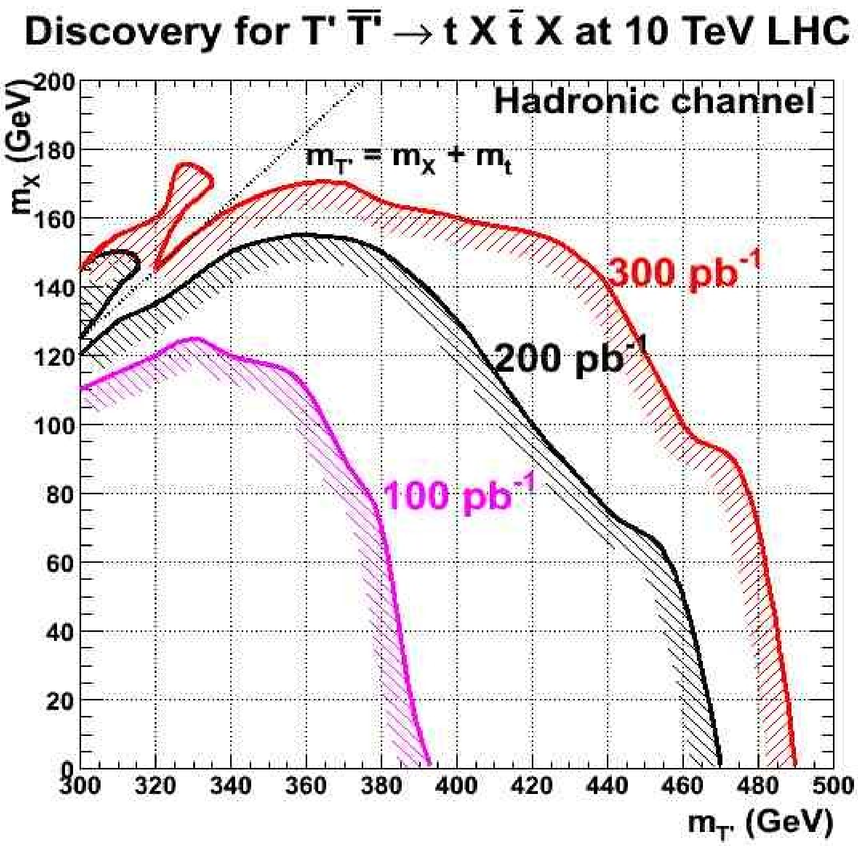


2 σ exclusion and 3 σ discovery reach for the Tevatron, with 2/5/10/20 fb^{-1} integrated luminocity

Production at early LHC

Full relevant parameter space covered by early LHC!





2 σ exclusion and 3 σ production reach for 10 TeV LHC, with 100/200/300 pb^{-1} integrated luminocity (corresponding to ~ 300/600/900 pb^{-1} with 7 TeV CM energy)

Summary

- Dark matter well established by observations
- If dark matter is related to the Electroweak symmetry breaking and the hierarchy problem
  - Possible to produce at colliders, in particular LHC
  - Infered from missing energy signals
- Mass reconstruction for invisible particle a challenge
  - Powerful methods (e.g. the "Matrix Element method") under study
- Light "WIMPless" dark matter one of most promising for Tevatron and early LHC
  - Full parameter space covered (exclusion or discovery) within 2 years!

Backup slides

Cuts for Tevatron

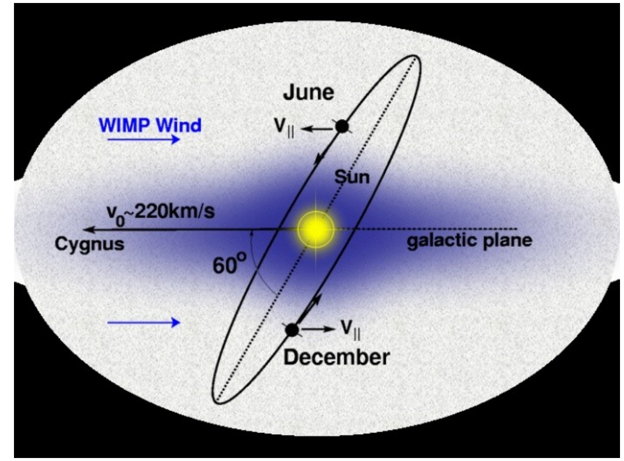
- Precuts (0-lepton channel):
  - No lepton or tau-tagged jet with pT > 2 GeV
  - MET > 100
  - At least 5 jets with pT > 20 GeV
  - Cuts on $\Delta\varphi$(jet, MET) for 2 hardest jets
- Final cuts:
  - MET > 150, 200, 250 GeV
  - HT > 250, 300, 350 GeV
  - N(jets) > 6, and combinations of these cuts

Cuts for LHC

- Precuts (0-lepton channel):
  - No lepton or tau-tagged jet with pT > 2 GeV
  - MET > 100
  - At least 5 jets with pT > 40 GeV
  - Cuts on $\Delta\varphi$(jet, MET) for 3 hardest jets
- Final cuts:
  - MET > 150, 200, 250, 300 GeV
  - HT > 400, 500 GeV
  - N(jets) > 6, and combinations of these cuts

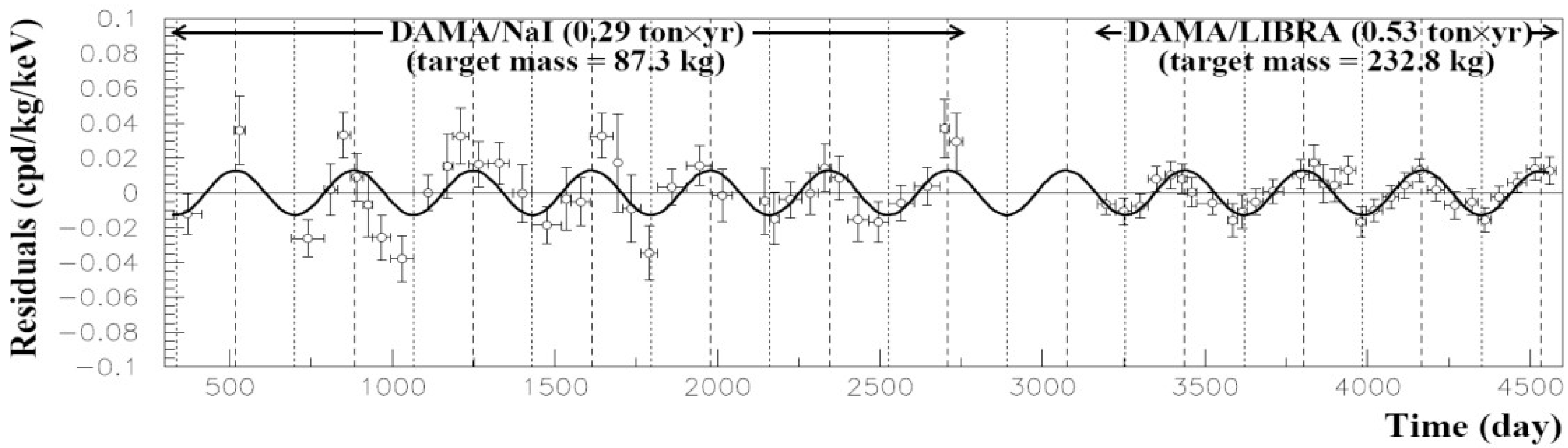
DAMA

Collision rate of dark matter with a detector should change as Earth's velocity adds constructively/ destructively with the Sun's



Drukier, Freese, Spergel (1986)

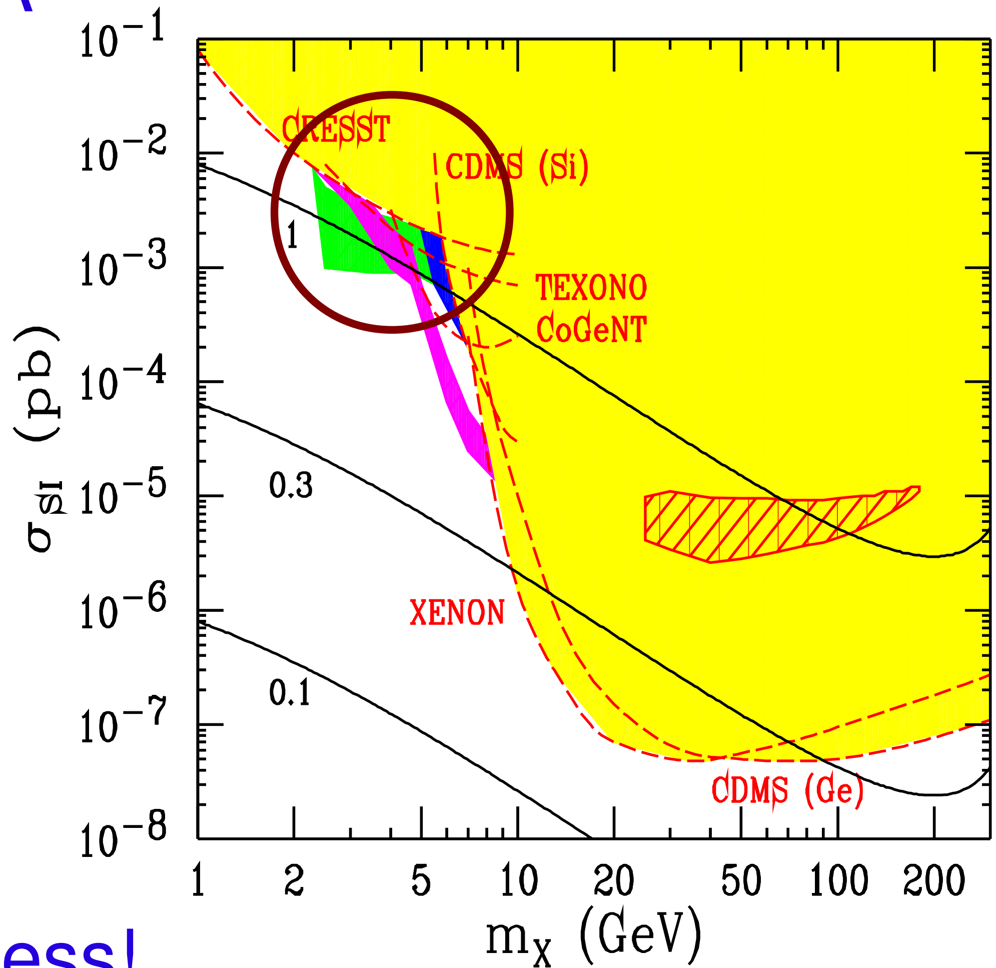
DAMA: 8σ signal with T ~ 1 year, max ~ June 2



DAMA (2008)

DAMA

- Most of the allowed DAMA region has been ruled out by other direct detection experiments
- One corner still possible: Very small DM masses (~ 1 GeV) "invisible" for other experiments
- Awkward for WIMPS, but no problem for WIMPless!



MadGraph 5

- Completely new matrix element generation implementation
- Alpha version 0.3.0 already out – capabilities corresponding to MG4 + more and faster/more efficient
- Allows for
  - Output in any language / for any event simulator
  - Effective theories, non-renormalizable multiparticle vertices
  - No restrictions in number of diagrams or decay lengths
  - Implementation of recursion relations/efficient simultation of multiparton amplitudes
  - Next-to-leading order matrix element generation
  - Much more – the sky (and our imagination) is the limit!