Searching for the Particles of the Early Universe

David Toback

Texas A&M University

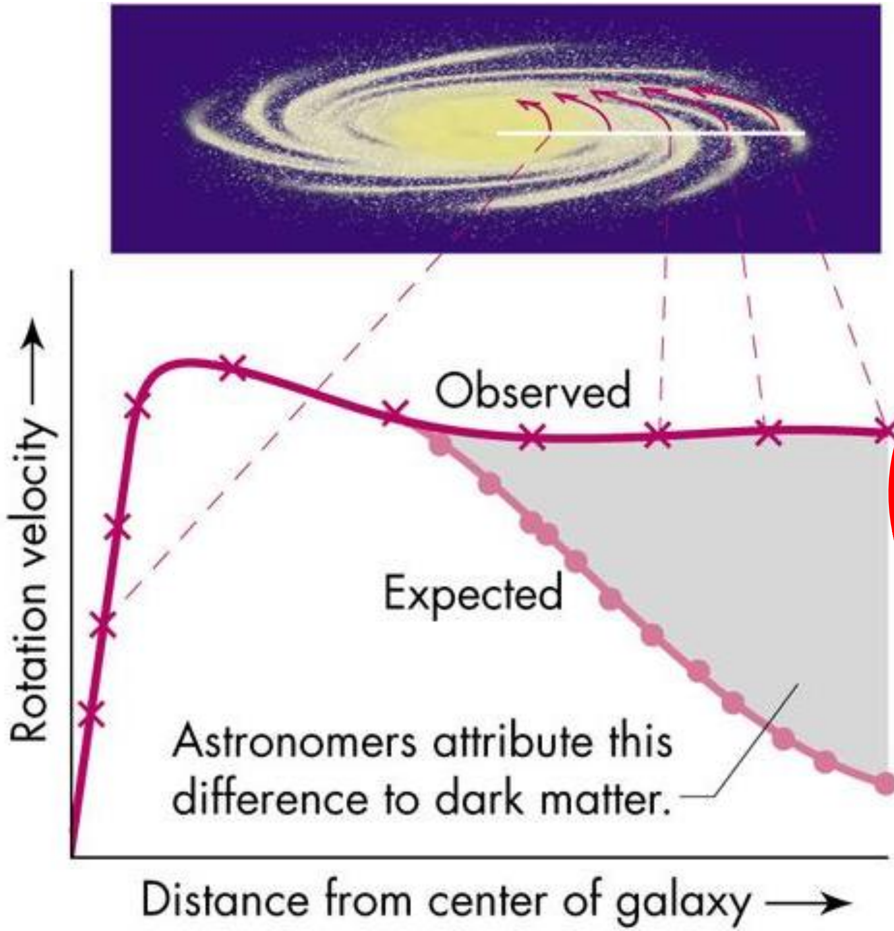
1876

Outline

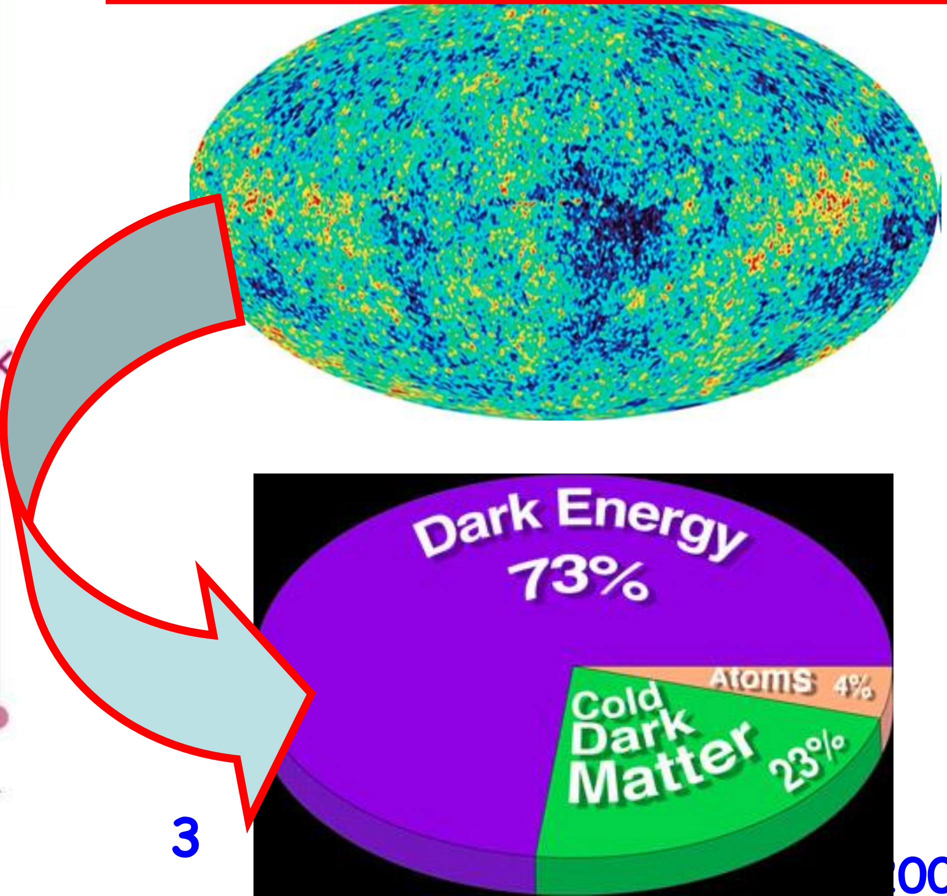
- Dark Matter in Astronomy, Cosmology and Particle Physics
- Supersymmetry and How it Could Help
- Searching for New Particles in Collider Physics Experiments
  - Recreating and Studying the Conditions of the Early Universe
- Looking towards the Future with the LHC

Dark Matter in Astronomy and Cosmology

Galaxy Rotation Data

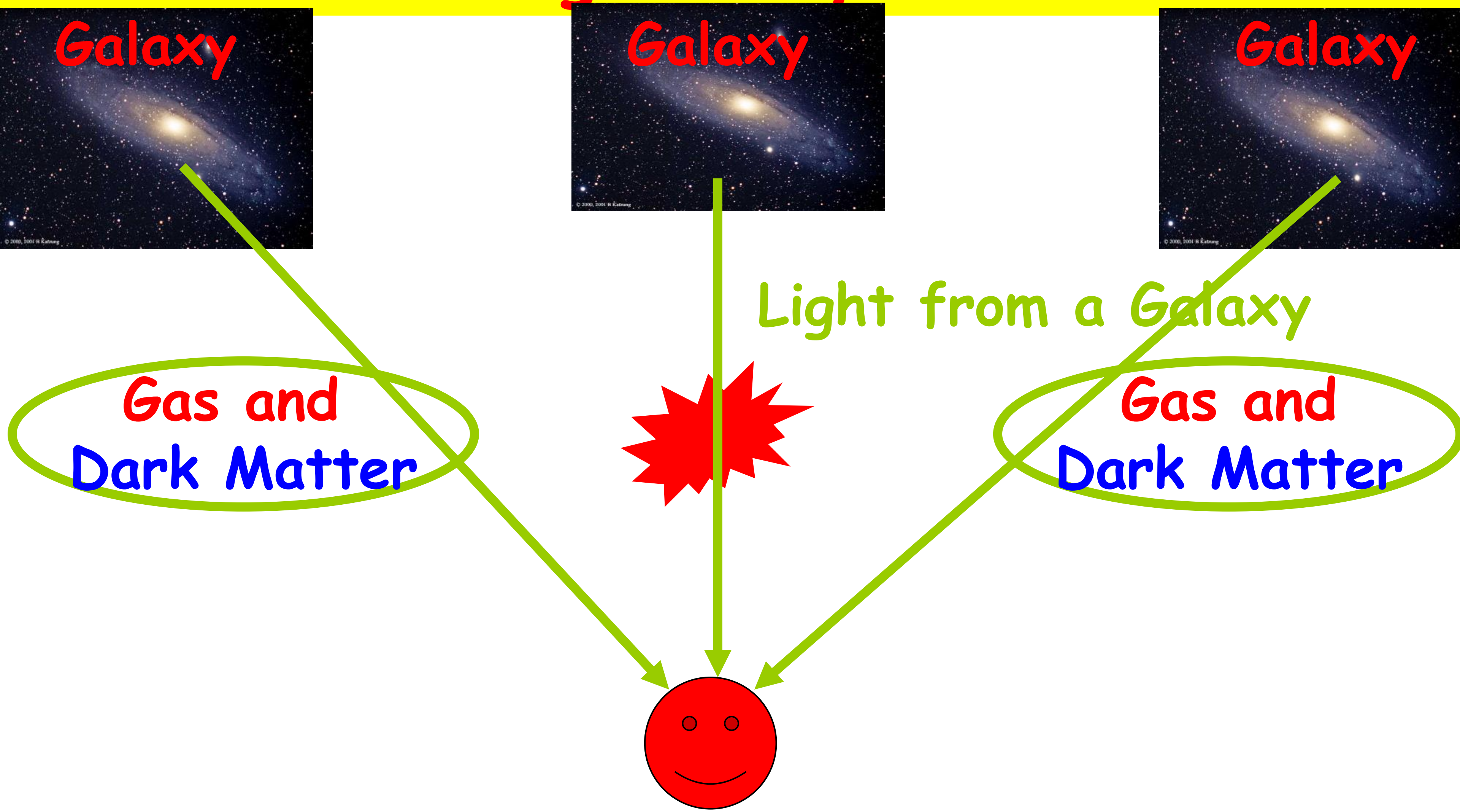


Cosmic Microwave Background Data from WMAP



Evidence for Dark Matter as Particles

Colliding Galaxy Cluster



Galaxy

Galaxy

Galaxy

Light from a Galaxy

Gas and Dark Matter

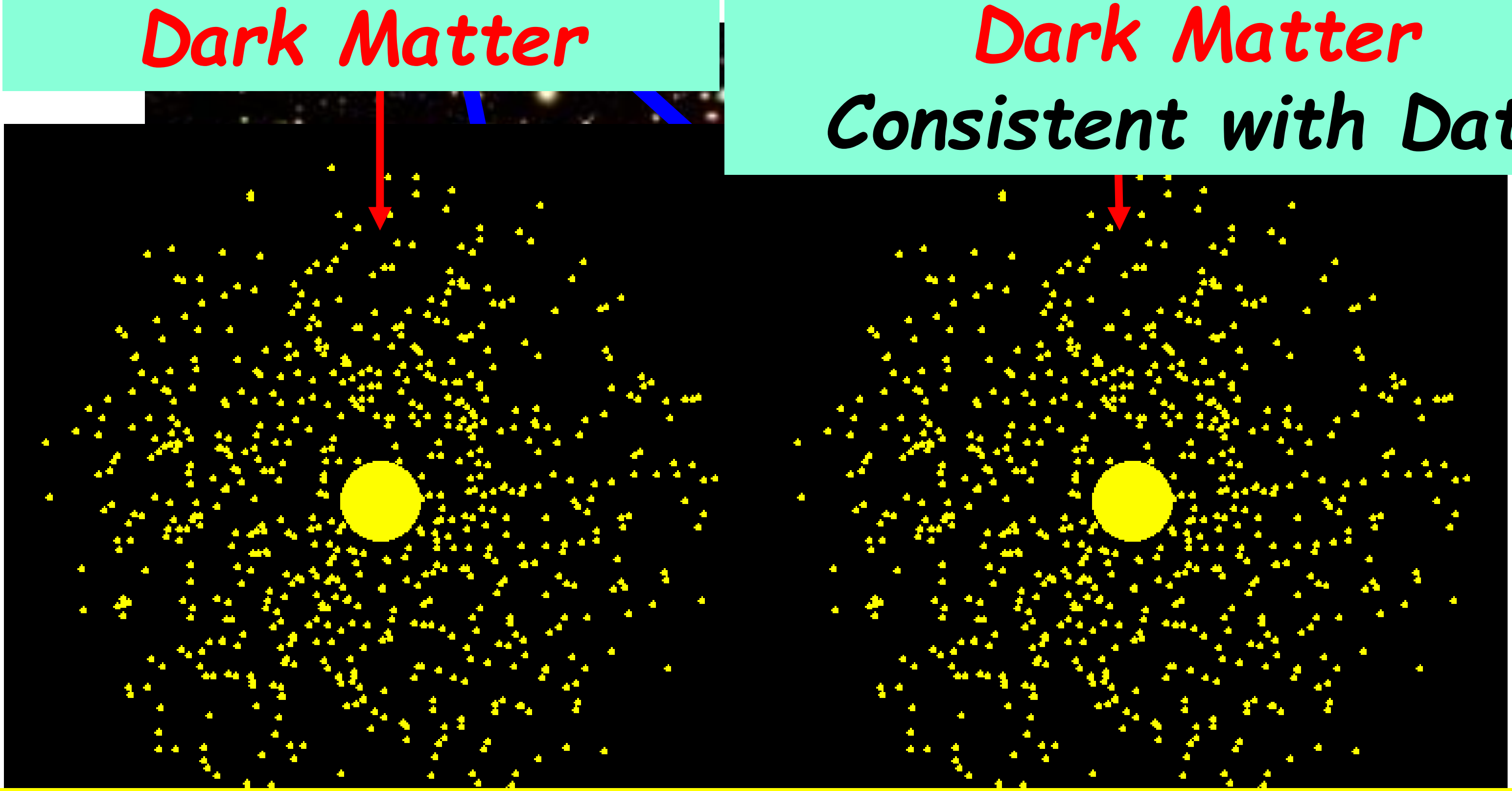
Gas and Dark Matter

Blue (Dark Matter) is the mass as measured by gravitational lensing:
Pass through → Weakly
I

Red part from x-ray observations
Slowed→Particles
with Standard Model

Simulation without Dark Matter

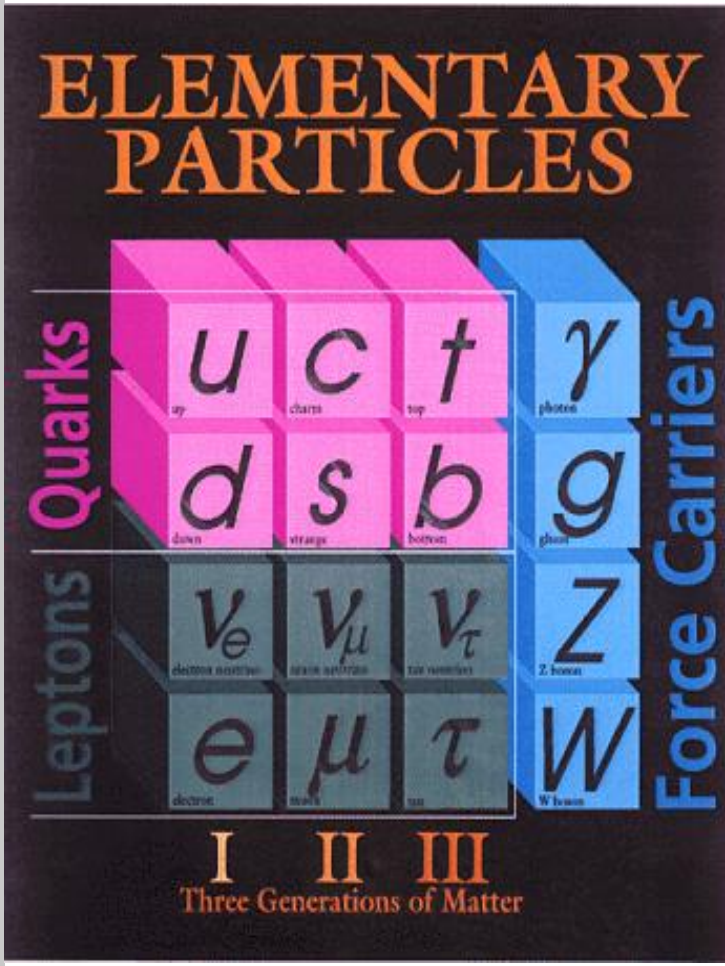
Simulation with Dark Matter
Consistent with Data



Galaxy Rotation Simulation with and without Dark Matter

The Known Particles

- No known particles have the properties of Dark Matter
- Other credible reasons to believe there are new fundamental particles to be discovered
- None experimentally verified, but lets take a look at our best bet



Why Focus on Supersymmetry?

There are some theories that are so compelling that it's worth doing a comprehensive and systematically deep set of searches to see if they are realized in nature

- →Supersymmetry is such a theory

Also predicts Dark Matter

First things First: *What is Supersymmetry and why do we care?*

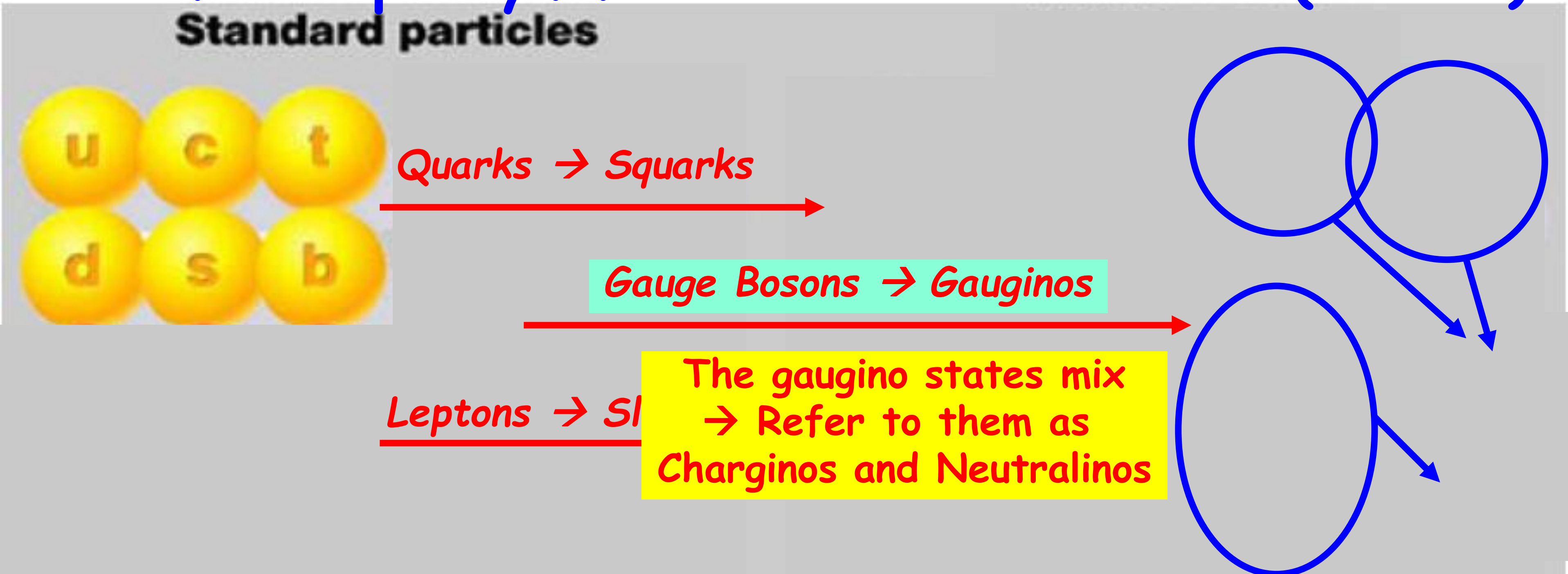
What is Supersymmetry?

Supersymmetry (SUSY) is a theory that postulates a symmetry between fermions and bosons

Q|Boson> = |Fermion>

Q|Fermion> = |Boson>

Minimal Supersymmetric Standard Model (MSSM)



Quarks → Squarks

Gauge Bosons → Gauginos

Leptons → Sl

The gaugino states mix
→ Refer to them as
Charginos and Neutralinos

Advantages and Disadvantages of SUSY

- There is no unique explanation of the origin of the sparticle masses or couplings
- With all these new couplings and particles it's possible we could have our known SM particles decaying through loops
  - Any version that predicts/allows a quick proton decay is clearly wrong
  - Any version that has the same mass for the particles and the sparticles must be wrong
    - Haven't observed any bosonic electrons in nature

    → $m_{positron} = m_{electron} \neq m_{selectron}$

→SUSY is broken somehow

Different Ways to Proceed

- There is no unique explanation of the symmetry breaking → need to make some assumptions
- Can put in masses and couplings by hand
  - General SUSY has over 100 new parameters
- Use experimental constraints and theoretical prejudices to further restrict the parameter space
  - To protect the proton lifetime can define R-parity = $(-1)^{3(B-L)+2s}$ and assert that it's conserved

  →R = 1 for SM particles

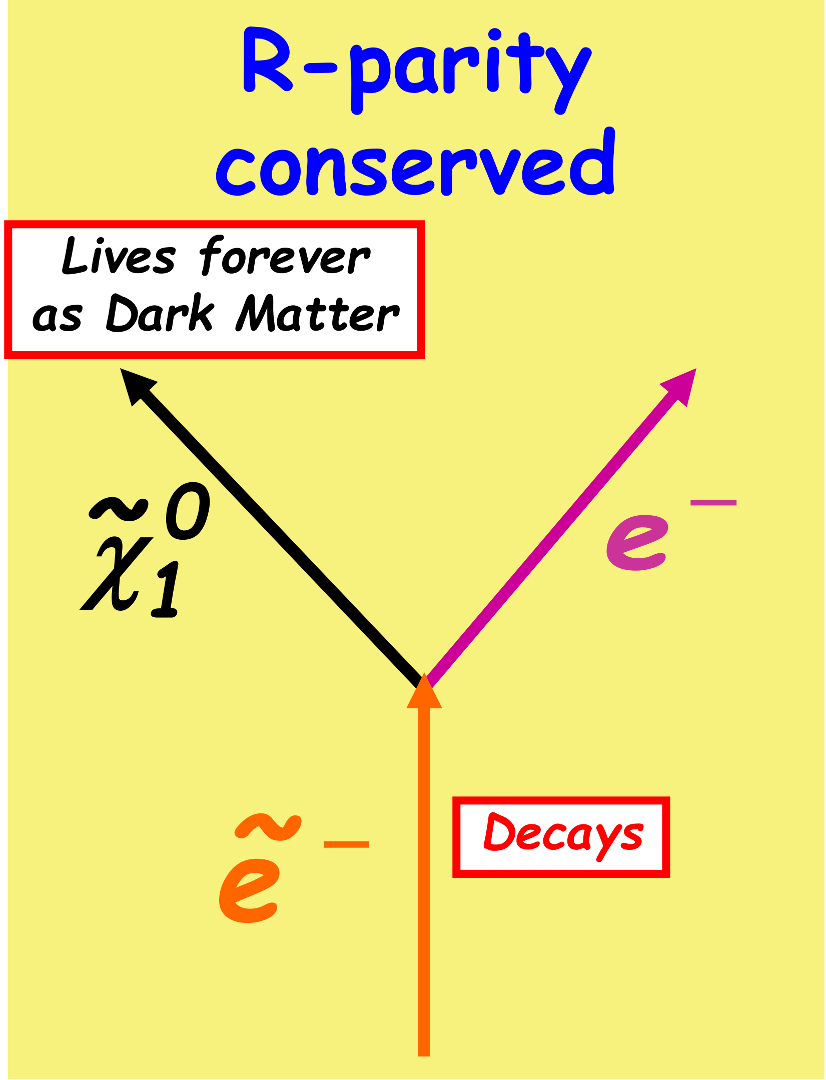
  →R = -1 for MSSM partners
- R-Parity violating terms would also have to be small for lepton number violation and still allow neutrino mixing

SUSY can provide a Dark Matter Candidate

If R-Parity is conserved then the lightest SUSY Particle can't decay and, if neutral

→Provides an excellent dark matter candidate

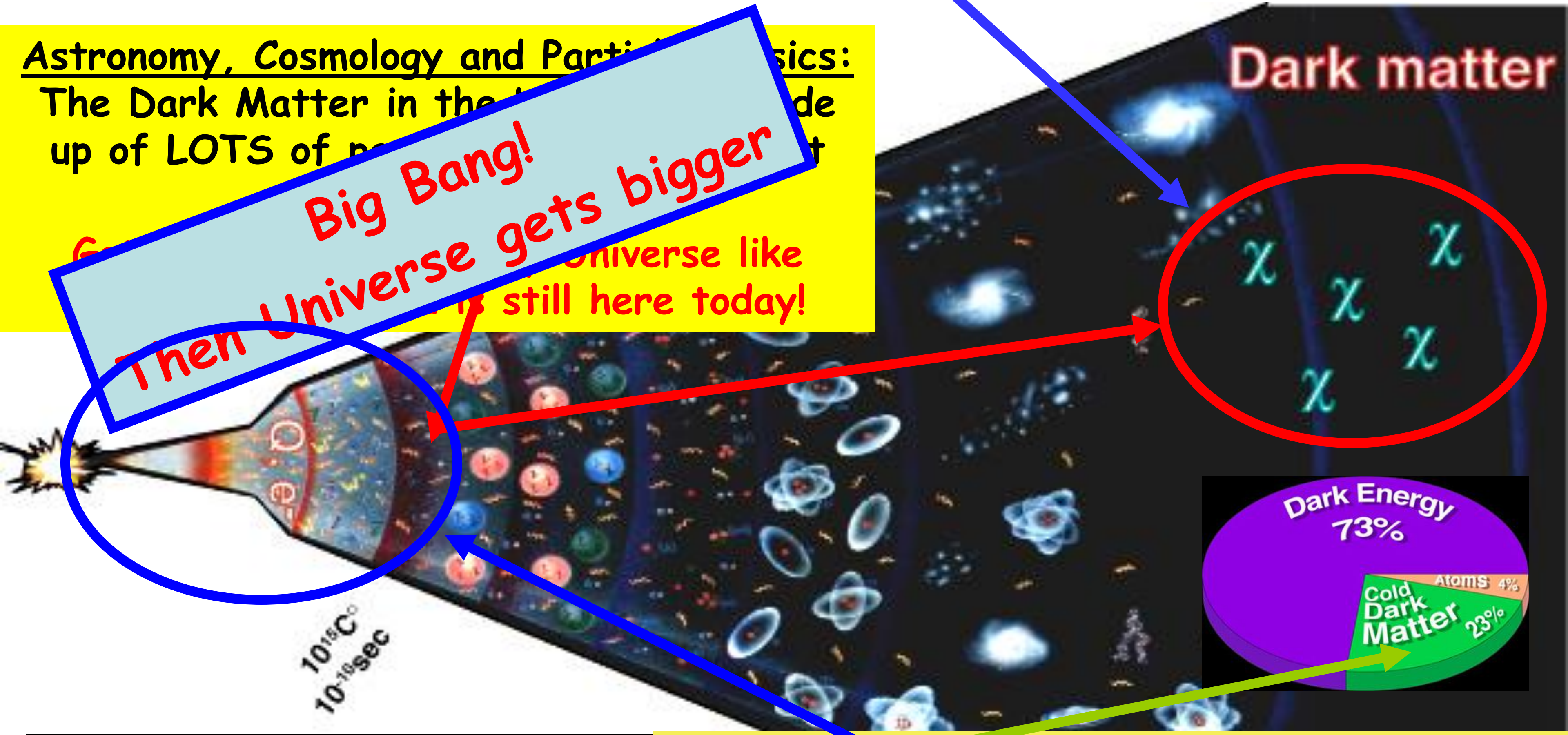
Provides the tie between Dark Matter, Cosmology and Particle Physics?



Particle Physics solution to an Astronomy/Cosmology problem?

- **Good:** Predict massive stable particles that explain Dark Matter effects
- **Better:** Provide both a model of particle physics and cosmology that is consistent with Early Universe Physics and evolves into the observed amount of Dark Matter today

Dark Matter = Supersymetric Particles?



Astronomy, Cosmology and Parti sics:
The Dark Matter in the de
up of LOTS of ne t

Go Universe like
is still here today!

Big Bang!
Then Universe gets bigger

SUSY provides a
a full calculation

Not good enough to simply provide a candidate, need to describe early Universe physics and correctly predict the Dark Matter relic density

Different Types of SUSY Solutions

Cold Dark matter
(~100 GeV)
Produced in the Early Universe

Warm Dark matter
(~1 keV)
Produced later in time

Sparticle Masses and Lifetimes deeply affect the particles in the Early Universe and Today

Collider Physics

How does Collider Physics Help us Answer These Questions?

Tevatron at
Fermilab

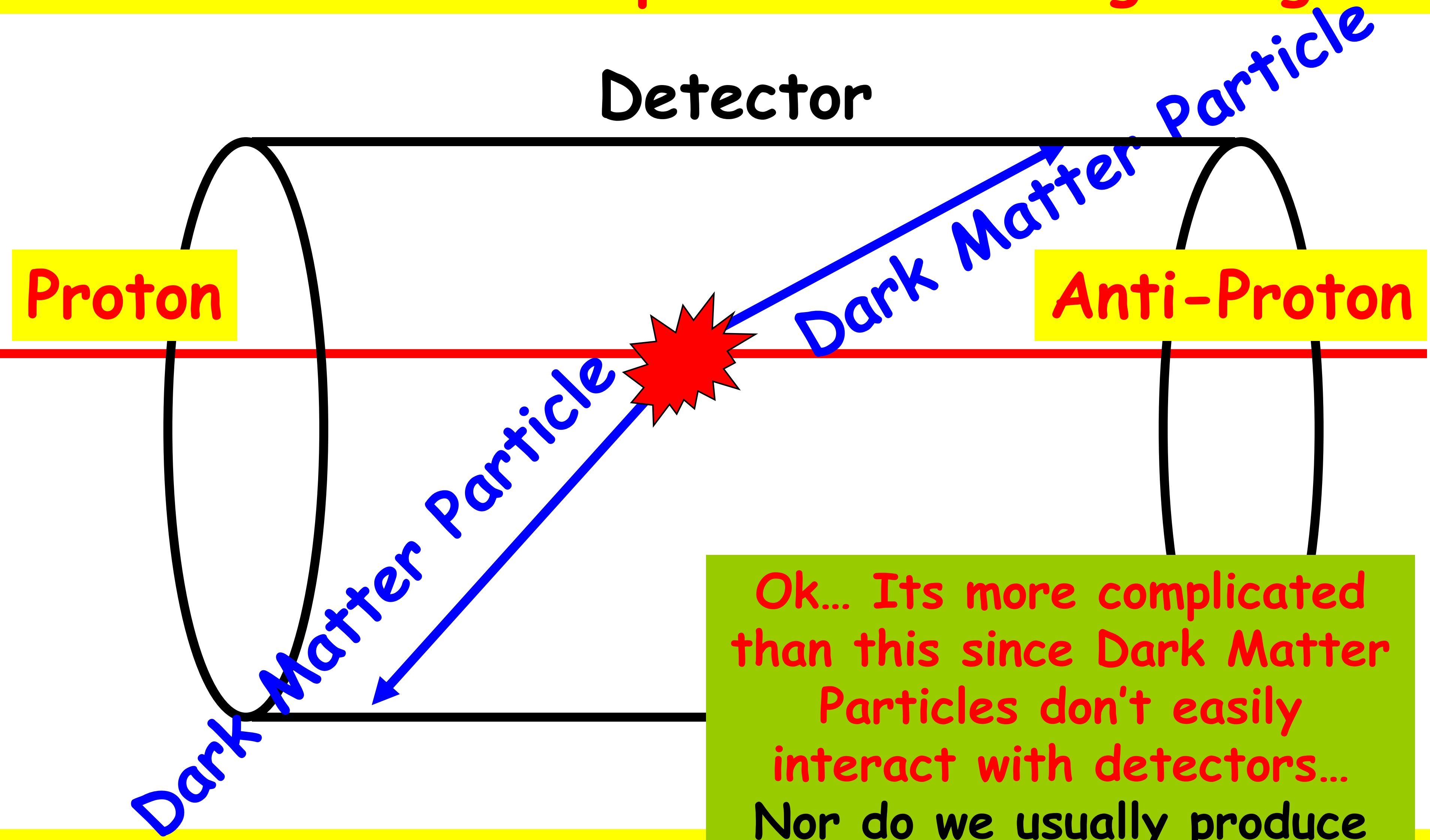
LHC at
CERN

Can we Make and Discover Dark Matter?

- High energy collisions between particles in the Early Universe
- Recreate the conditions like they were RIGHT AFTER the Big Bang
- If we can produce Dark Matter in a collision then we can STUDY it

High Energy Collisions → New particles

Tevatron→ ≈10 ps after the Big Bang



Ok… Its more complicated than this since Dark Matter Particles don't easily interact with detectors…

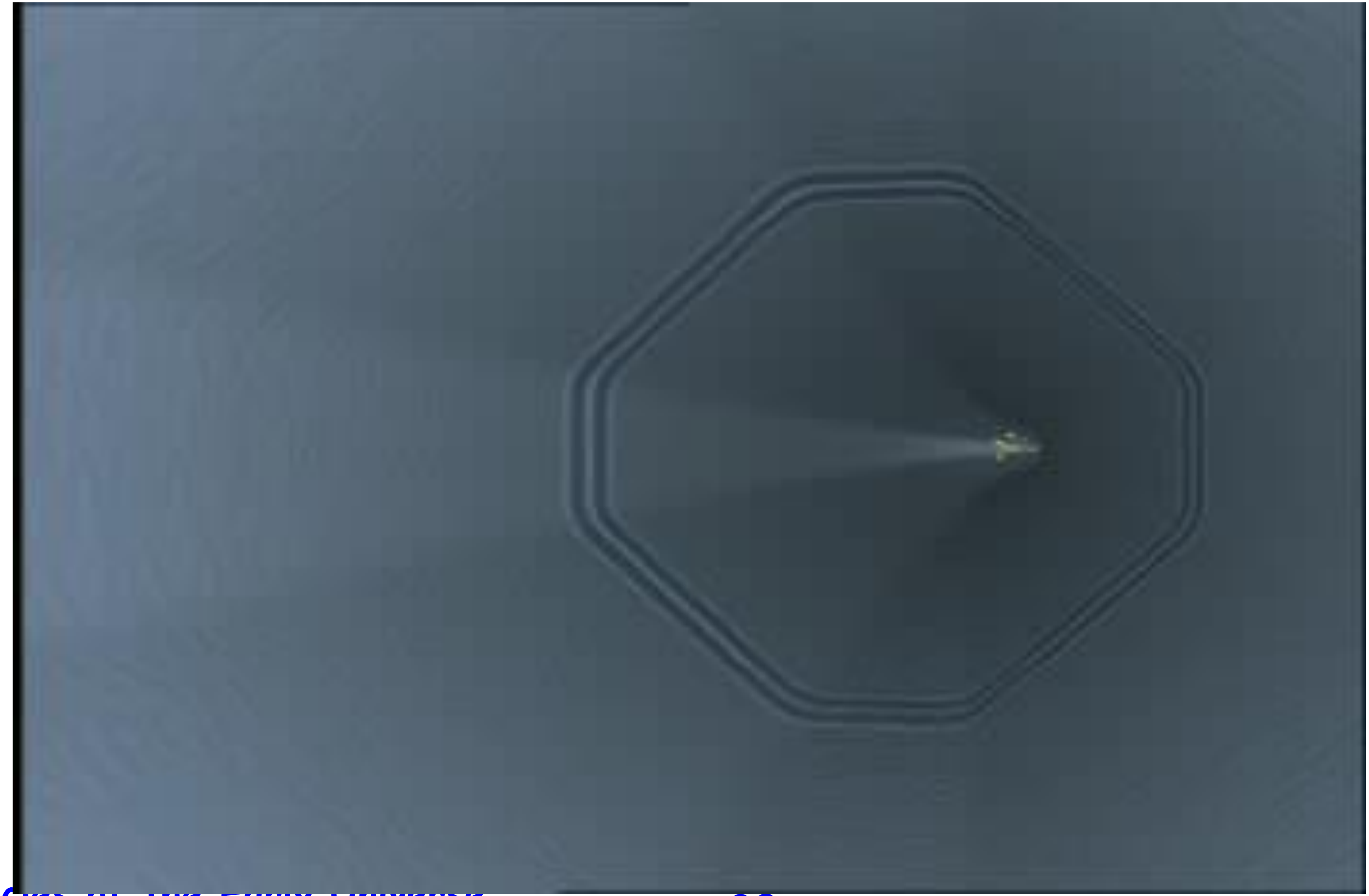
Nor do we usually produce them directly

Today: Fermilab

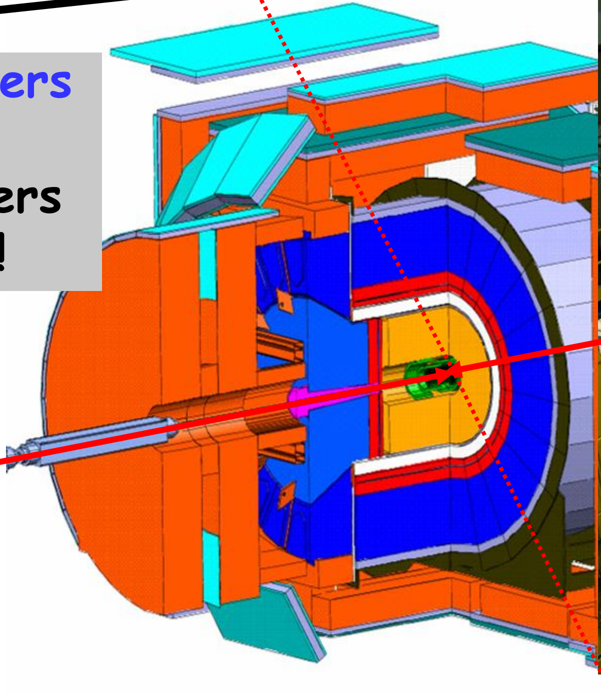
Today: Fermilab Tevatron

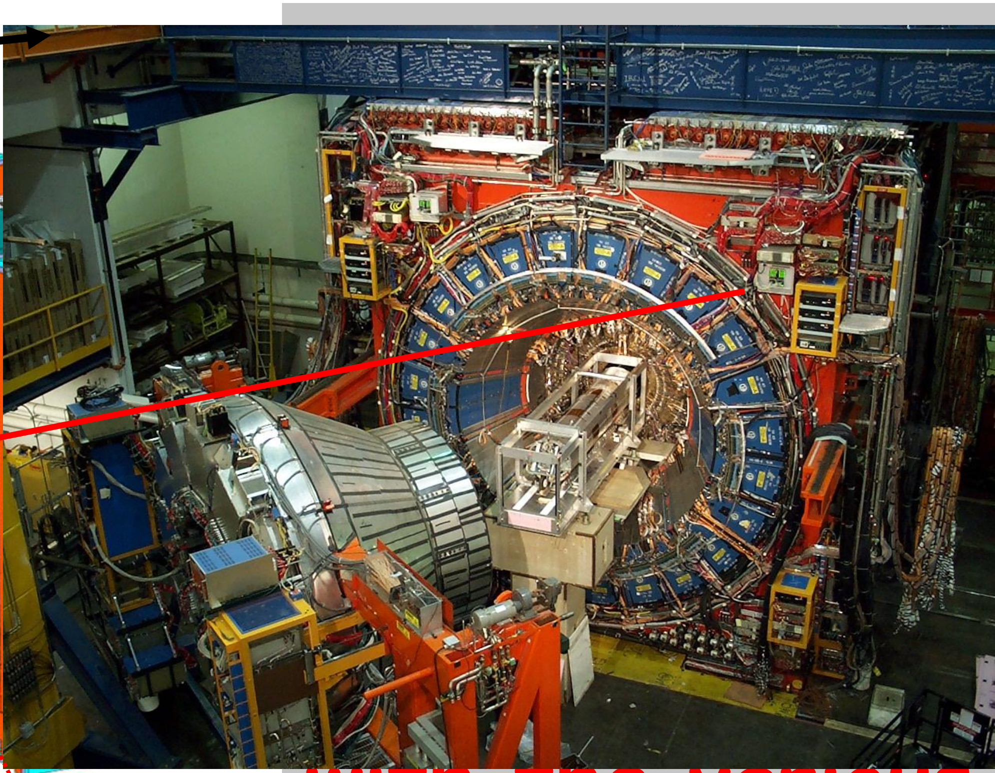
- The Tevatron is the high Energy Frontier until LHC turn-on
  - Proton anti-proton collisions
  - 2.5 million collisions per second
- Rumours of running until 2012 depending on the LHC schedule

Inside the Accelerator



The CDF Detector





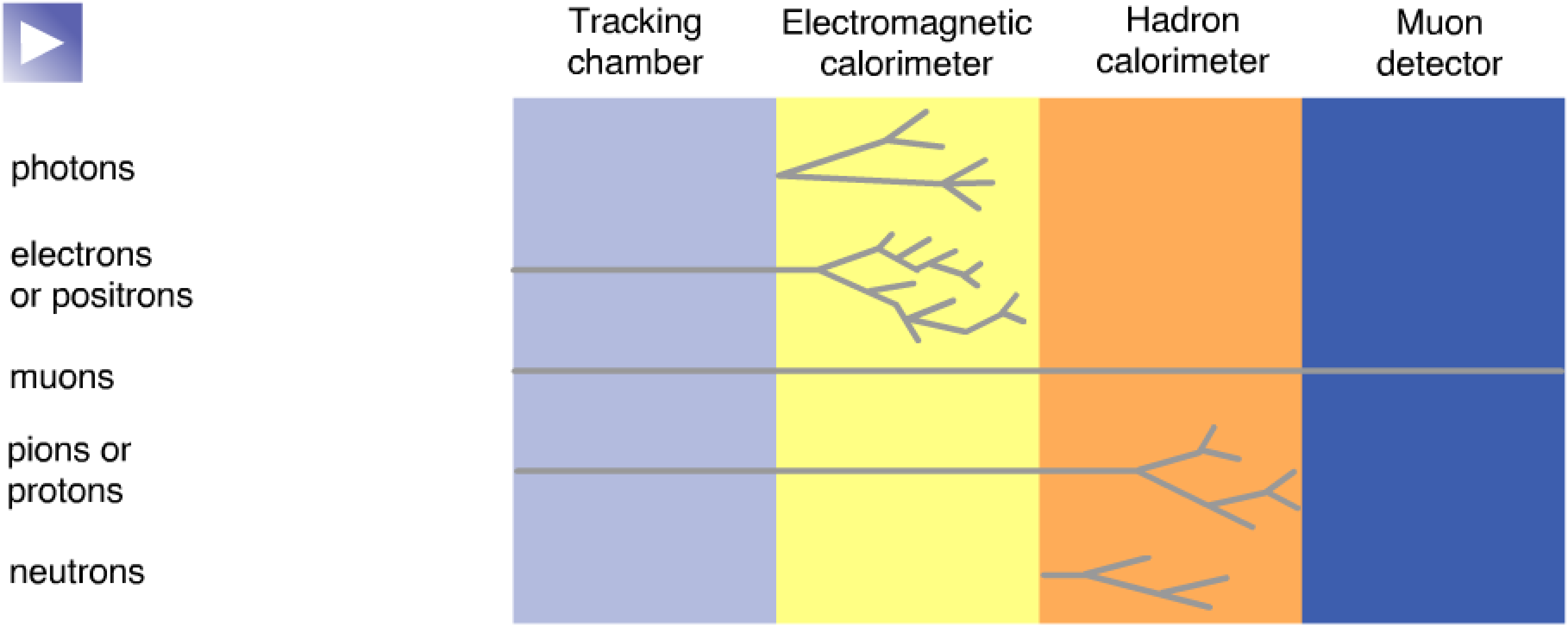
10 Meters Tall!

30 Meters Long!

with the various

Powerful multi-purpose detector

High quality identification of all the Standard Model particles



Tracking chamber

Electromagnetic calorimeter

Hadron calorimeter

Muon detector

photons

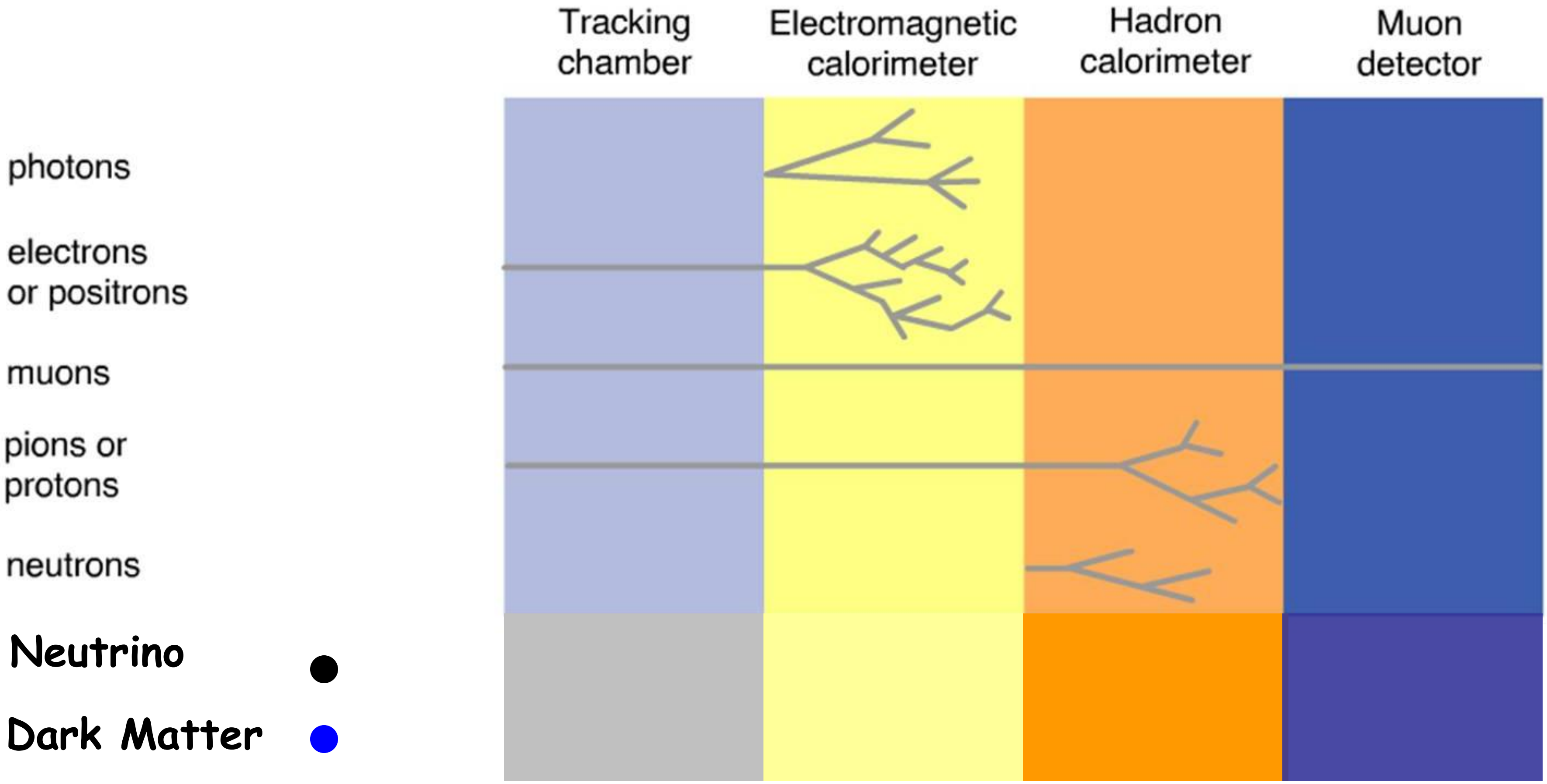
electrons or positrons

muons

pions or protons

neutrons

Neutrinos and Dark Matter Don't Interact with the Detectors



Tracking chamber

Electromagnetic calorimeter

Hadron calorimeter

Muon detector

photons

electrons or positrons

muons

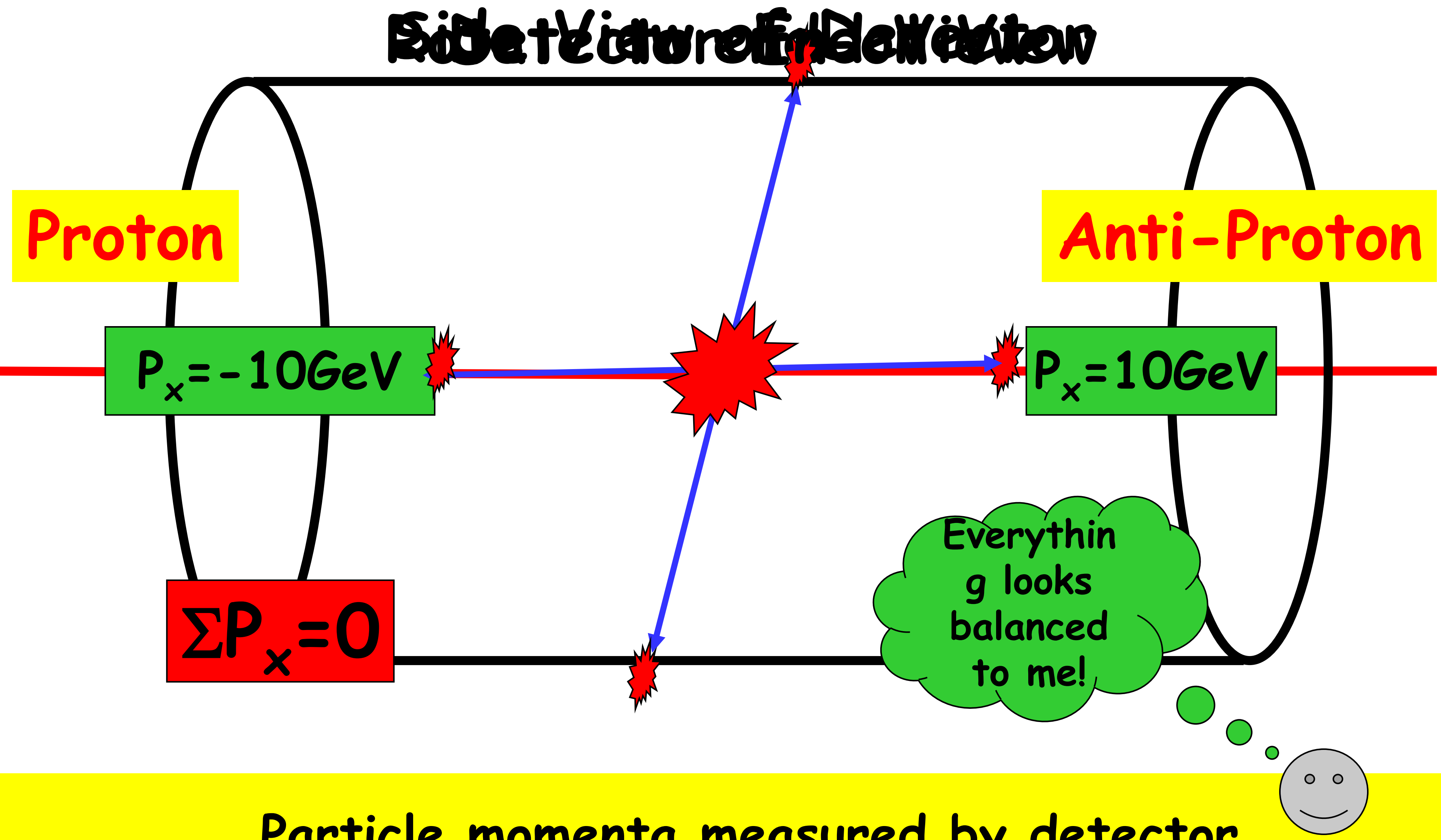
pions or protons

neutrons

Neutrino ●

Dark Matter ●

High Energy Collisions → Standard Model Particles



Particle momenta measured by detector

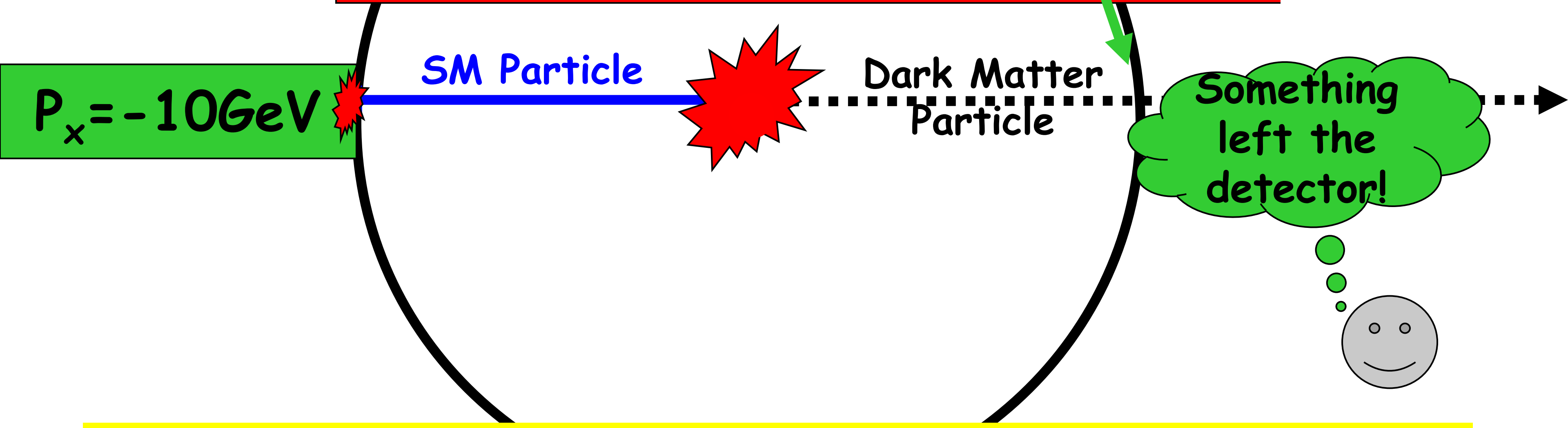
A Dark Matter and a SM particle at the same time?

$\Sigma P = -10$ GeV

in the *x*-direction

→Missing Energy!

Smoking Gun for Dark Matter



$P_x = -10$GeV

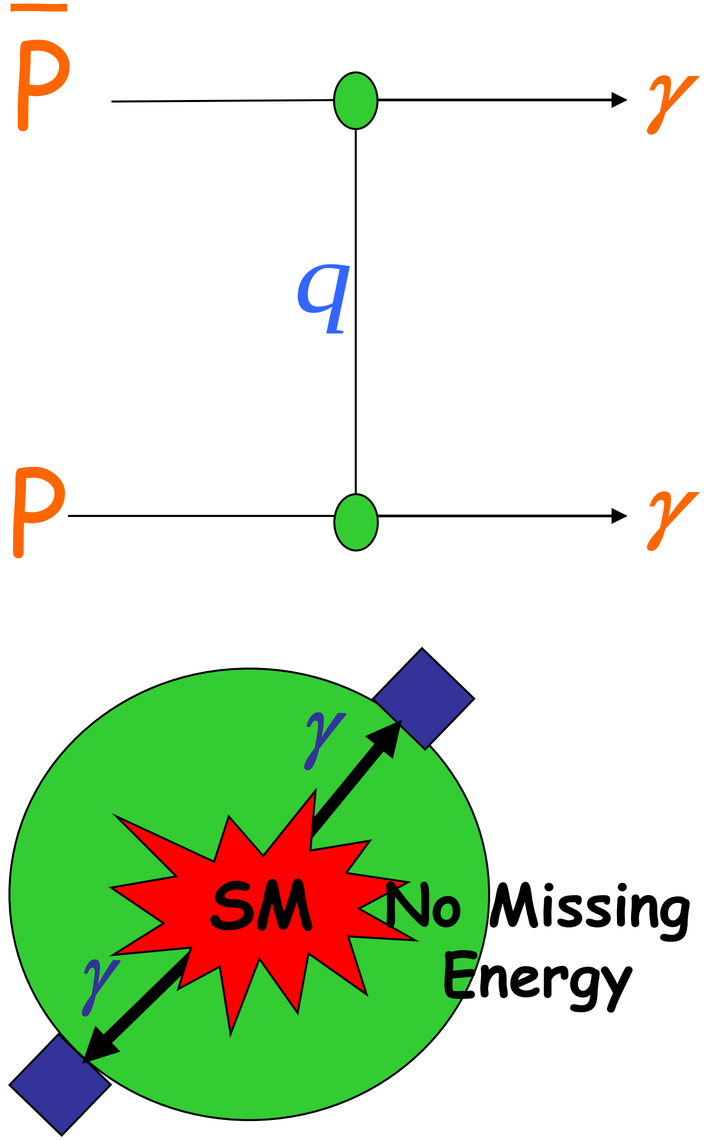
SM Particle

Dark Matter Particle

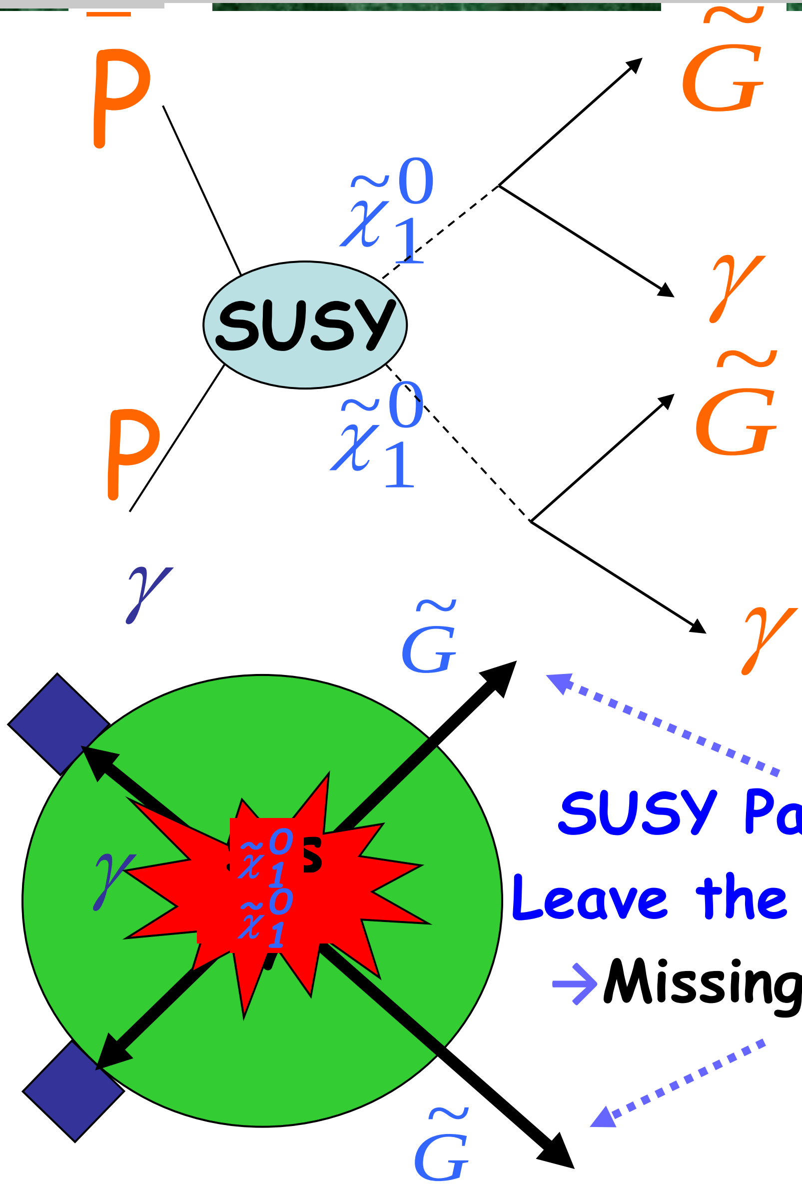
Something left the detector!

SM Particle Deposits energy, but Dark Matter particle doesn't interact with the detector and leaves

Standard Model: Supersymmetry:



No Missing Energy



SUSY Particles
Leave the detector
→Missing Energy

Going from Collisions to experimental results

Look at lots of collisions (call them events) and identify the ones that pass the “Dark matter Identification Requirements”

$$N_{events} = \text{Luminosity} \times \sigma_{production} \times \text{Acceptance}$$

How many collisions (events) pass all our requirements

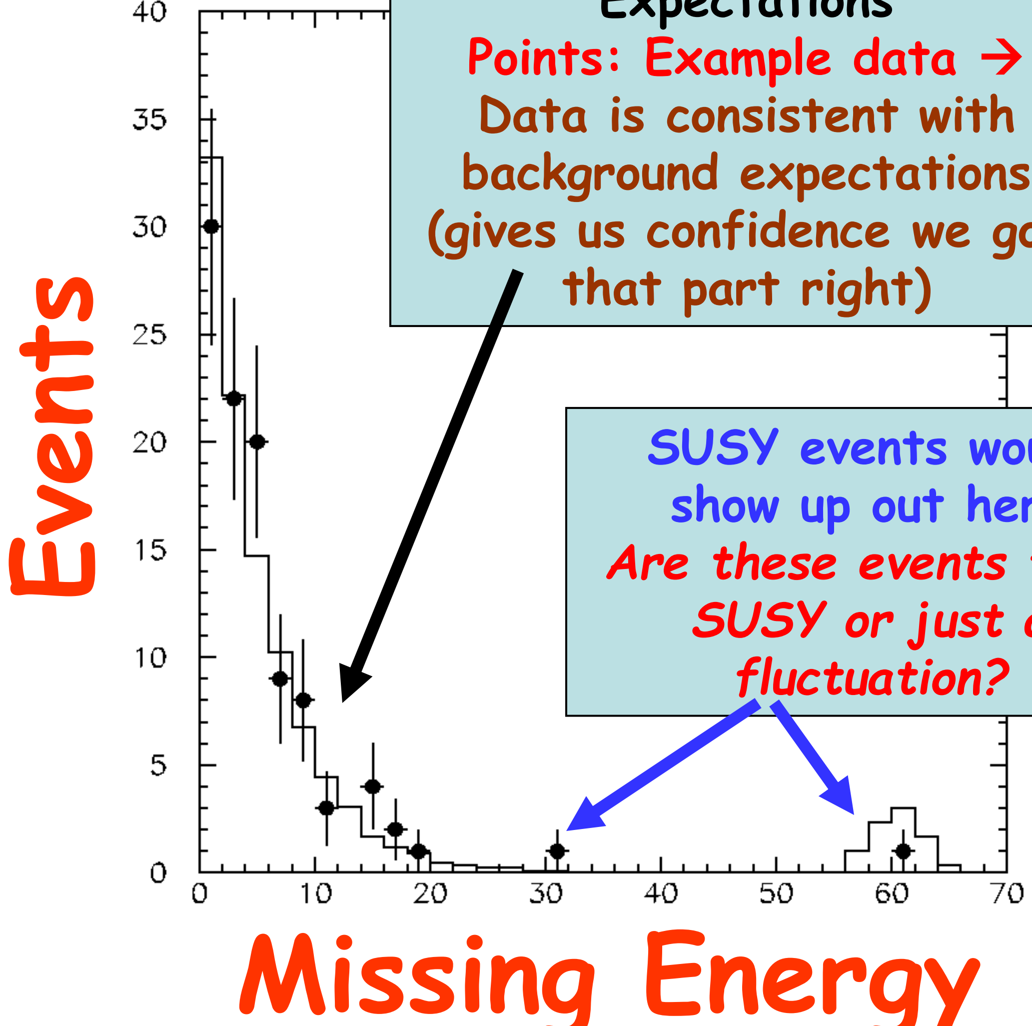
How many proton anti-proton collisions happened

How often a proton anti-proton collision produces a SUSY event

How well the detector does at detecting SUSY events

Number of background events from Standard Model Sources follows the same procedure

Signal Vs. Background



Solid line: Background Expectations

Points: Example data →

Data is consistent with background expectations (gives us confidence we got that part right)

SUSY events would show up out here

Are these events from SUSY or just a fluctuation?

- Look at each event
- Put the measured missing energy in a histogram
- Compare the expected predictions from Standard Model and from SUSY

Outline of the Searches

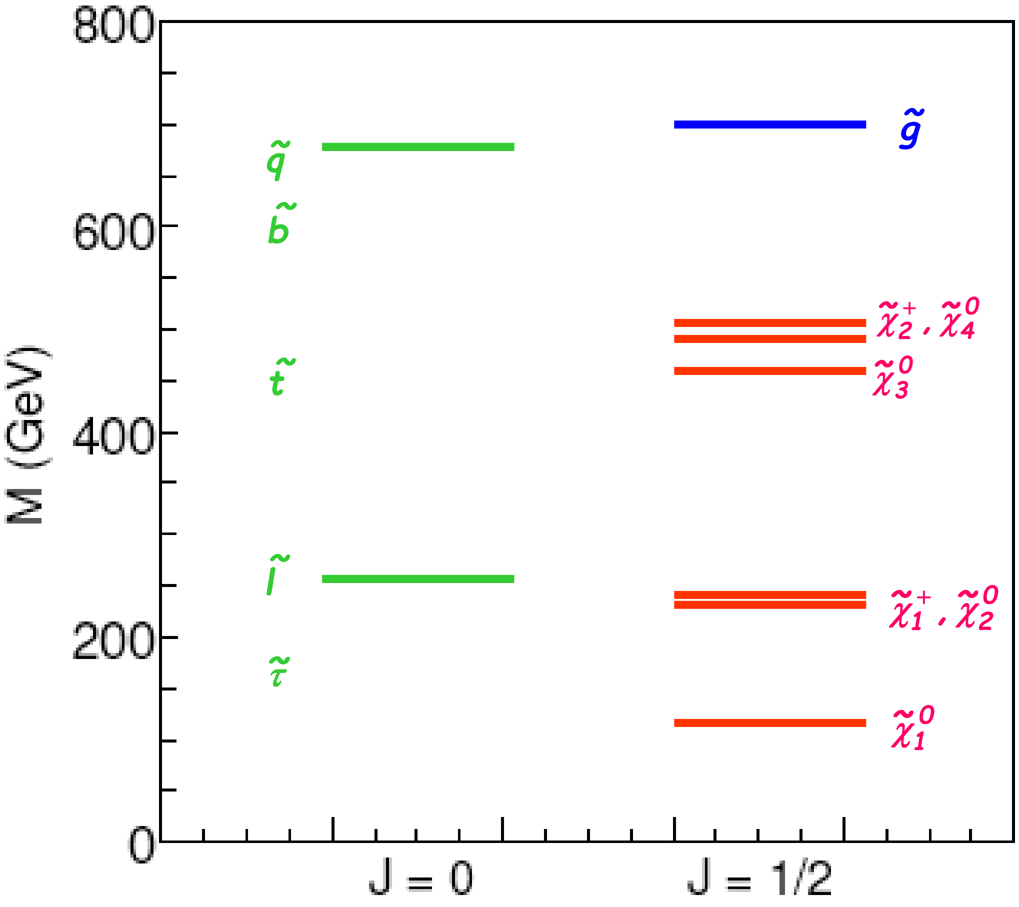
- Cold Dark Matter Searches
  - Squarks & Gluinos
  - Gaugino Pair Production
- Warm Dark Matter Searches
  - Short and long-lifetimes

The Sparticle Masses in Cold Dark Matter Scenarios

In a typical Cold Dark Matter type scenario

- Squarks and gluinos are heavy
- 1st and 2nd generation squarks are mass degenerate
- The lightest neutralino is the LSP
  - Dark Matter candidate

In some important versions the Stop, Sbottom and Stau can get much lighter

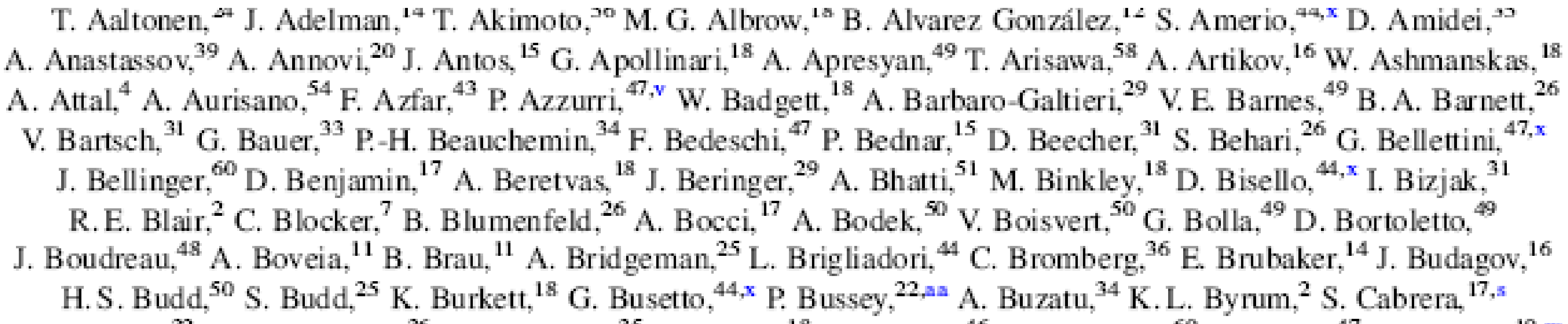


Golden Search Channels

Three main ways to look for minimal models with Cold Dark Matter Models

- Direct production of Squarks and Gluinos
  - Heavy, but strong production cross sections
- Direct production of the Gauginos
  - Lighter, but electroweak production cross sections, also leptonic final states have smaller backgrounds
- Indirect search via sparticles in loops
  - Affect branching ratios

Move on to the results from me and about 700 of my closest friends at Fermilab…



T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] M. G. Albrow,[18] B. Alvarez González,[12] S. Amerio,[44,x] D. Amidei,[35]
A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18]
A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] P. Azzurri,[47,v] W. Badgett,[18] A. Barbaro-Galtieri,[29] V. E. Barnes,[49] B. A. Barnett,[26]
V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47] P. Bednar,[15] D. Beecher,[31] S. Behari,[26] G. Bellettini,[47,x]
J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello,[44,x] I. Bizjak,[31]
R. E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49]
J. Boudreau,[48] A. Boveia,[11] B. Brau,[11] A. Bridgeman,[25] L. Brigliadori,[44] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16]
H. S. Budd,[50] S. Budd,[25] K. Burkett,[18] G. Busetto,[44,x] P. Bussey,[22,aa] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera,[17,s]

Aside before we begin…

- Most analyses will look like they were easy
- Noto Bene: It's 2009 and we're 8 years into running
- This is a lot harder than it looks and it takes a lot longer than it should
- I'll try to comment periodically on lessons for LHC

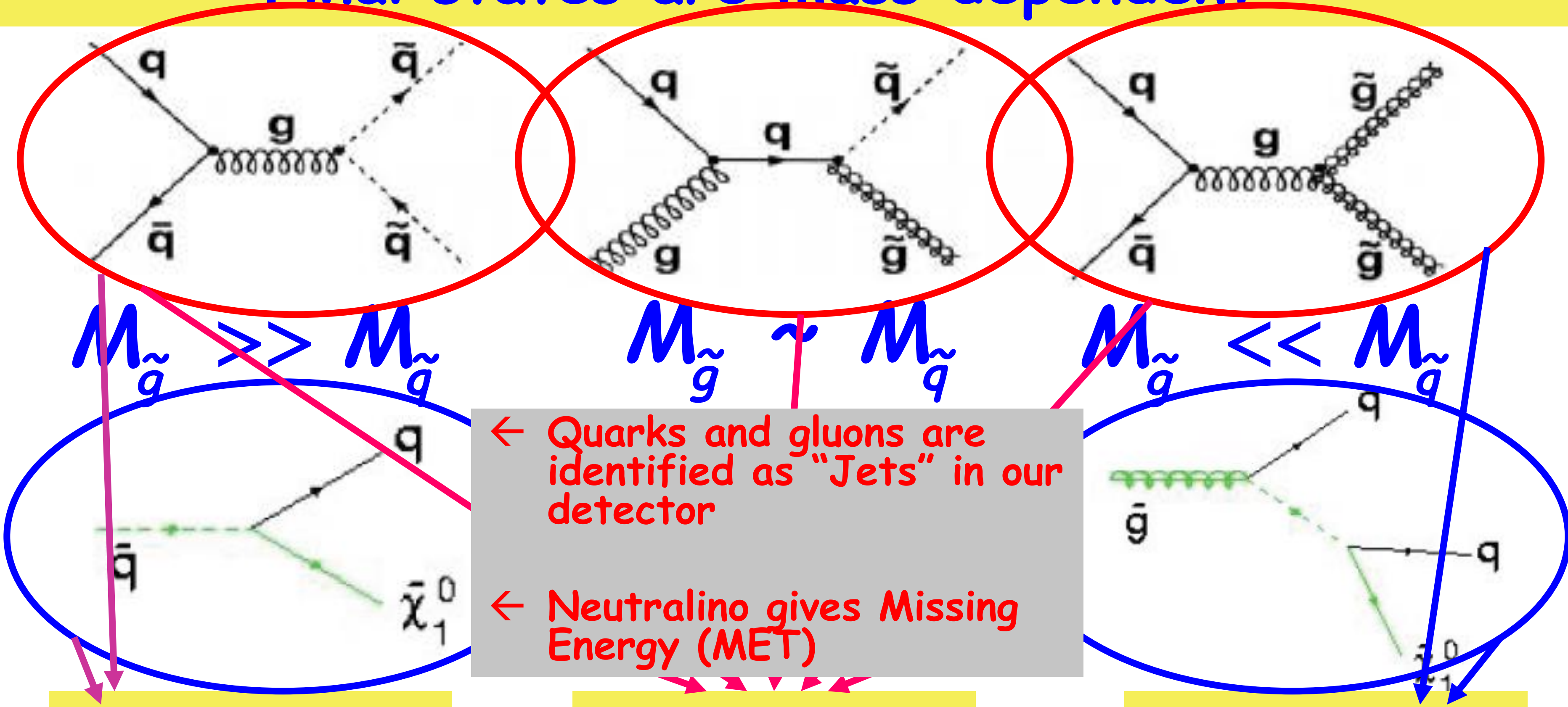
"It's a lot of work to make it look this easy"
– Joe DiMaggio

– Yogi Berra

Squark and Gluino Searches in Multijet + Met

Three main production diagrams

Final states are mass dependent



$M_{\tilde g} \gg M_{\tilde q}$ $M_{\tilde g} \sim M_{\tilde q}$ $M_{\tilde g} \ll M_{\tilde q}$

← Quarks and gluons are identified as "Jets" in our detector

← Neutralino gives Missing Energy (MET)

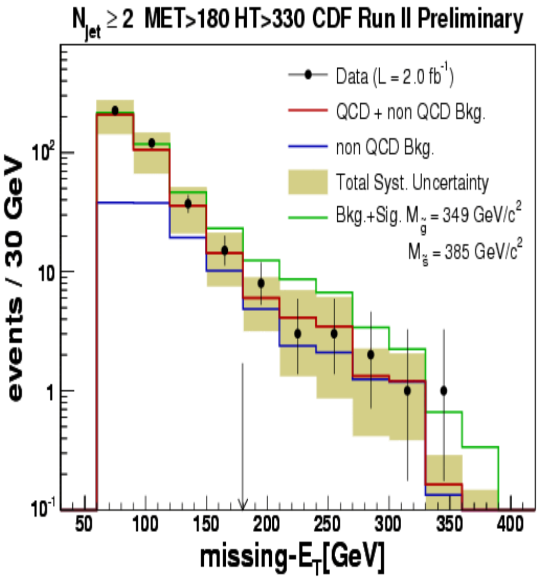
2 jets + MET

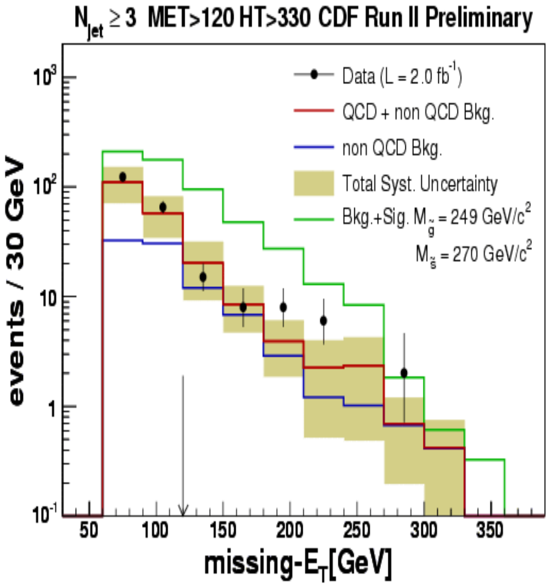
3 jets + MET

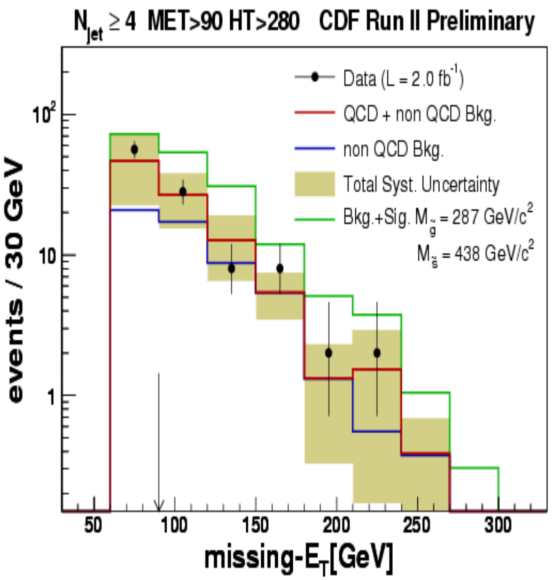
4 jets + MET

Multiple final states + Unified Analysis → best coverage

Unified Squark/Gluino Search







2 jets + MET

3 jets + MET

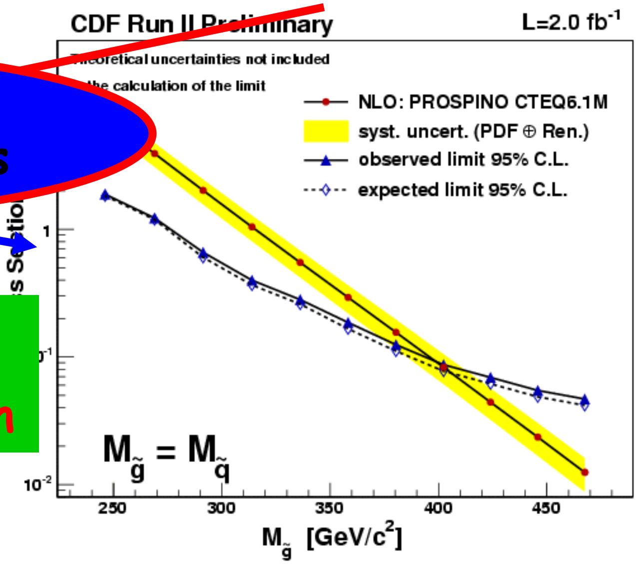
4 jets + MET

SUSY Interpreter

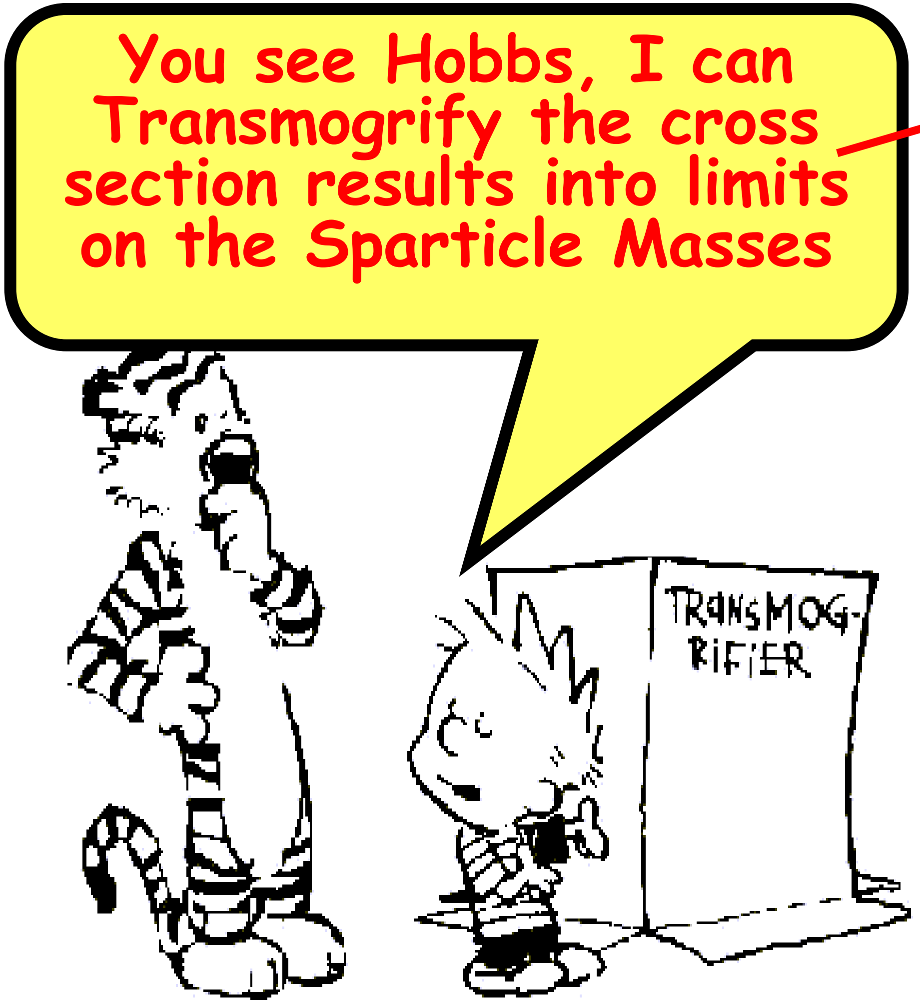
Set Cross Section Limits

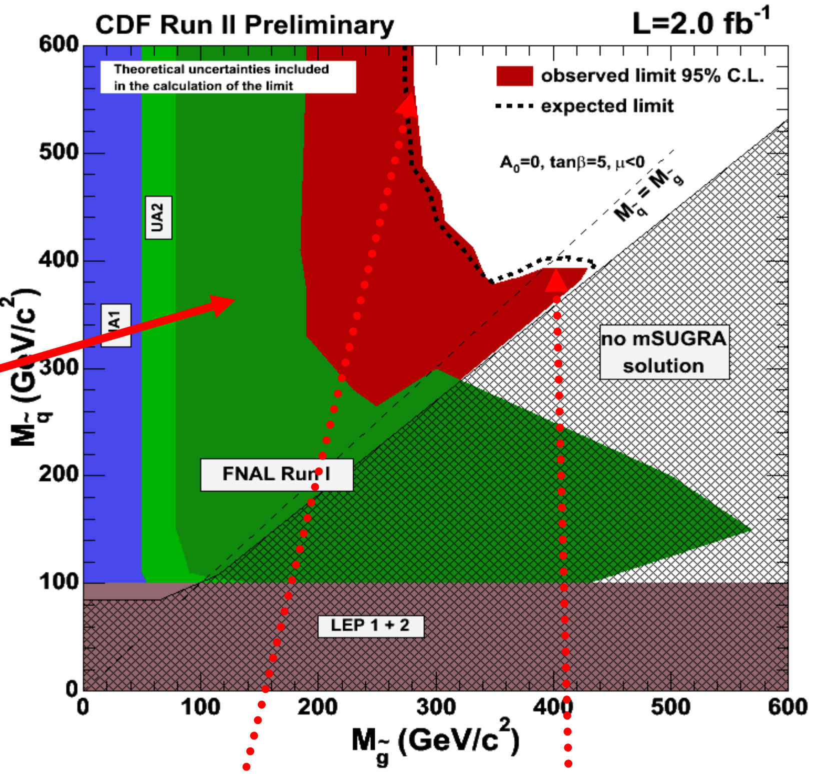
No evidence for new physics

As with most CDF results, there are comparable DØ results which I won't touch on



More limits…





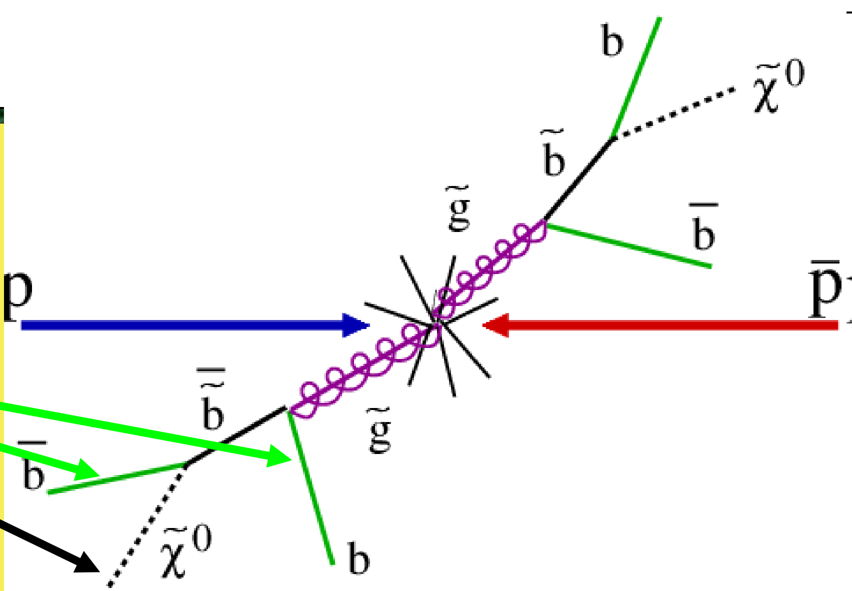
$M_g < 280$ GeV always excluded
$M > 392$ GeV when $M_g=M_q$

CDF, PRL 102, 121801 (2009)

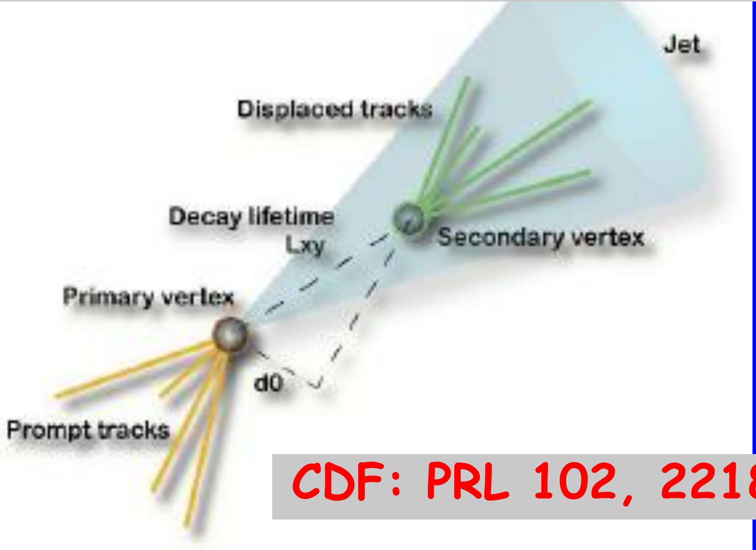
Sbottom Searches

Two primary Sbottom searches in *b*+jets+Met

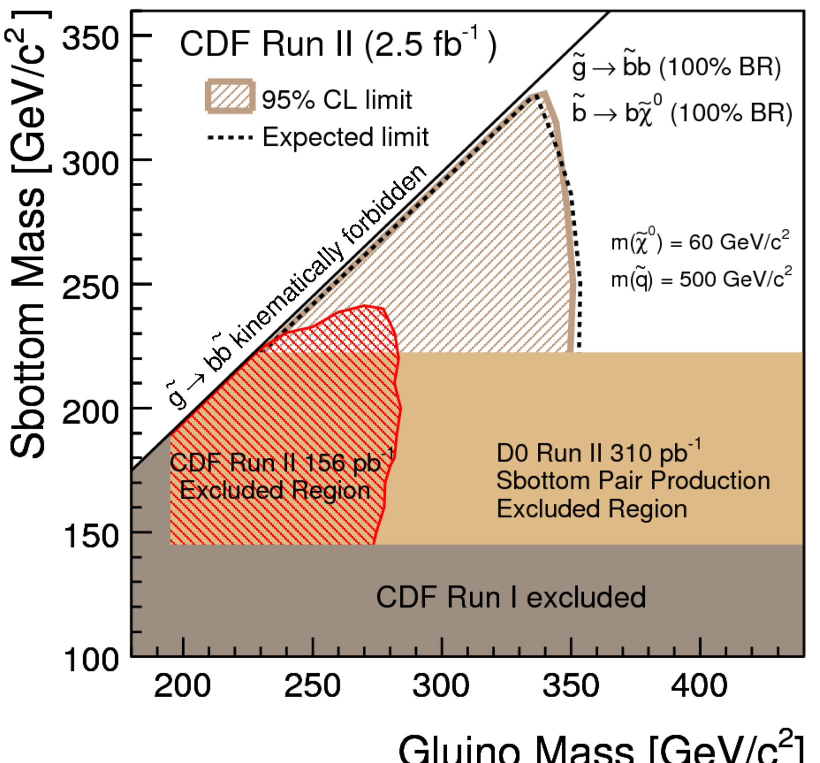
1. Sbottoms from gluinos
2. Direct sbottom pair production



Special tricks to identify *b*-quarks from their long lifetime

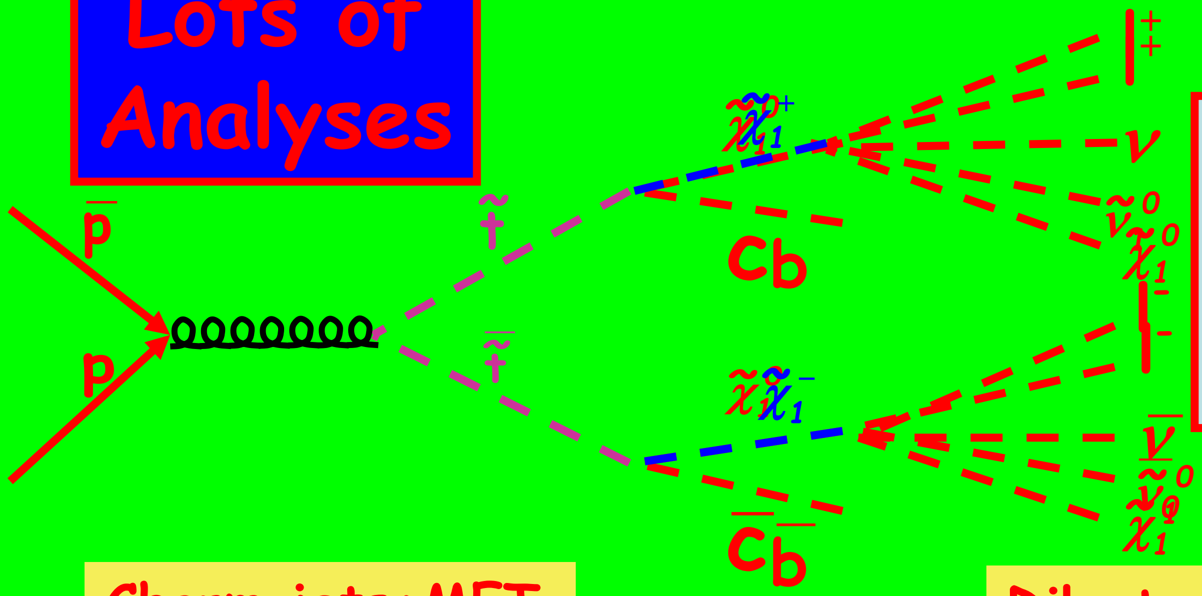


CDF: PRL 102, 221801 (2009)



Lightest Squark = Stop?

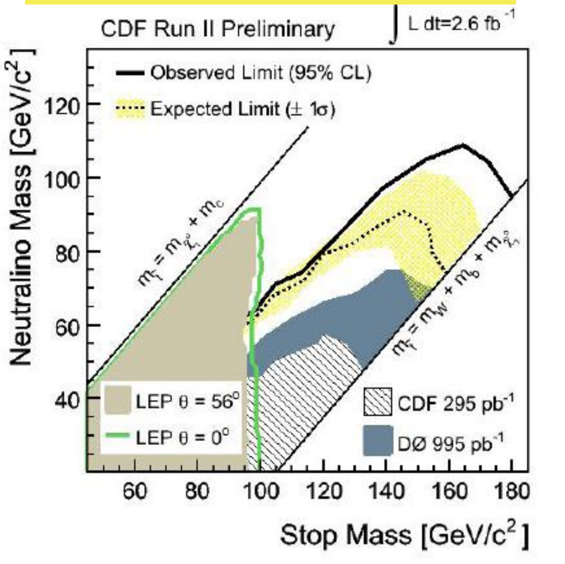
Lots of Analyses

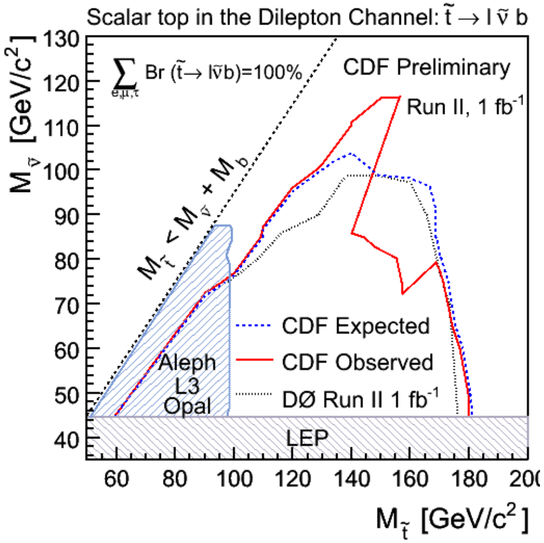


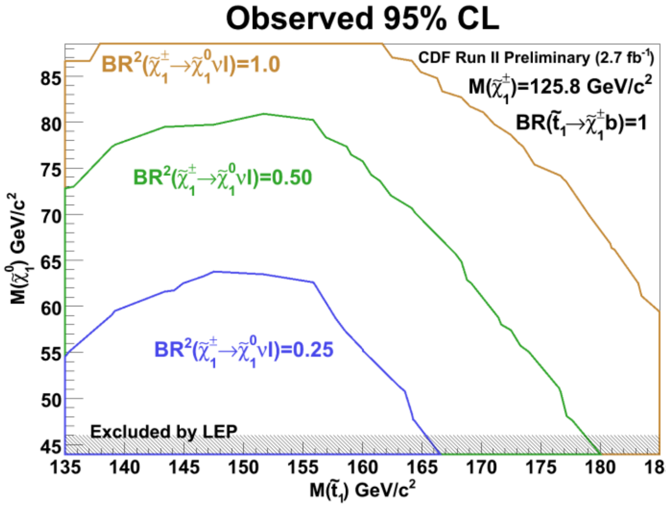
Direct Counting Experiments and Sophisticated Fitting Methods

Charm jets+MET

Dileptons+Jets+MET



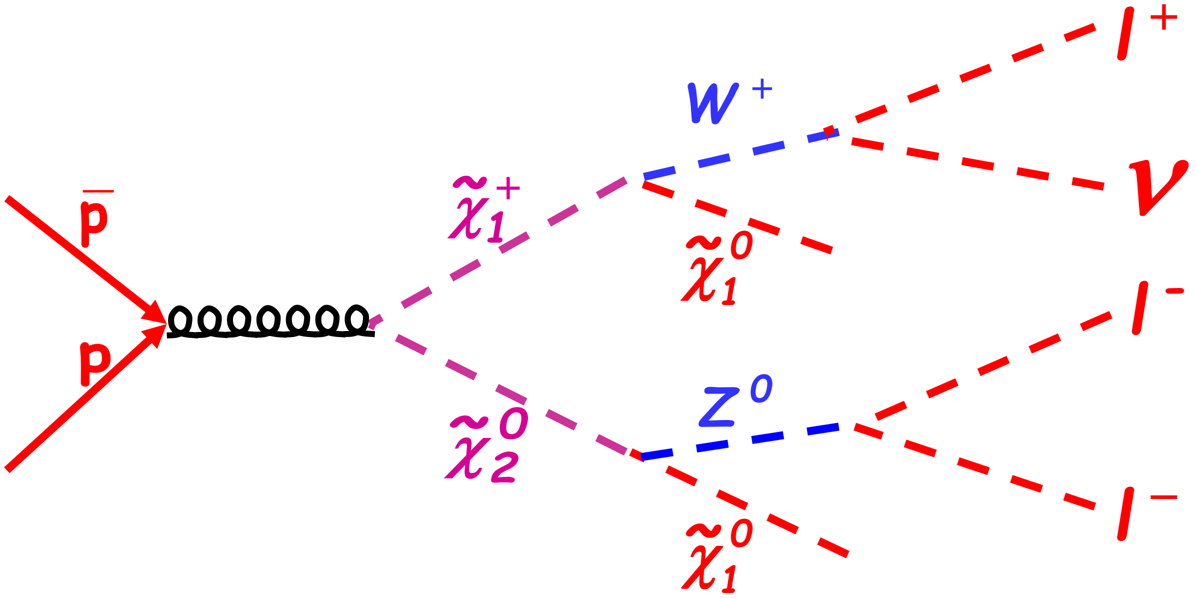




Gaugino Pair Production

Chargino-Neutralino gives three low energy leptons in the final state

Dominates the production cross section

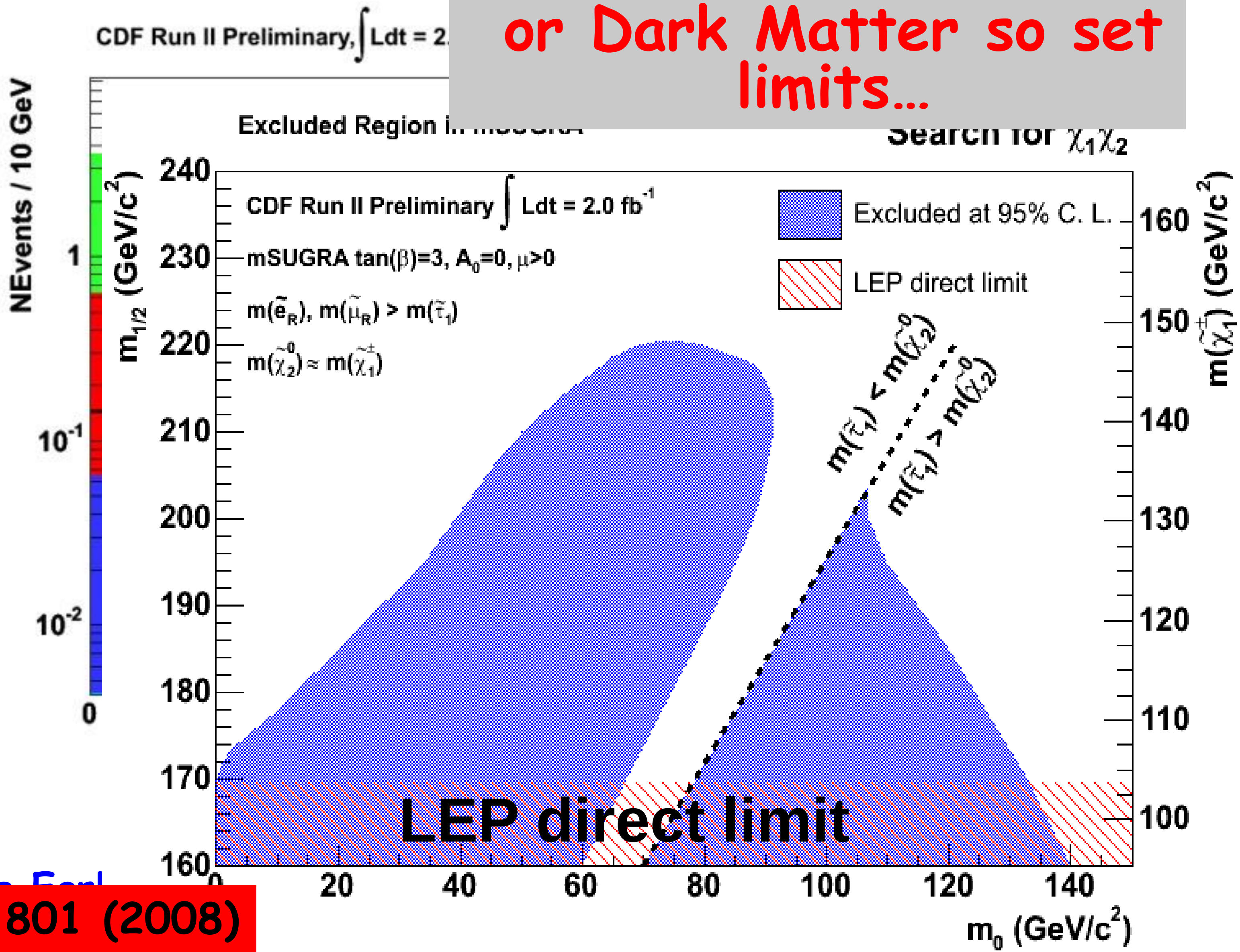


eee eeτ
eeμ μμτ
eμμ eμτ
μμμ

Lots separate final states + Unified Analysis → best coverage

SUSY in Trilepton Events?

No evidence for SUSY or Dark Matter so set limits…



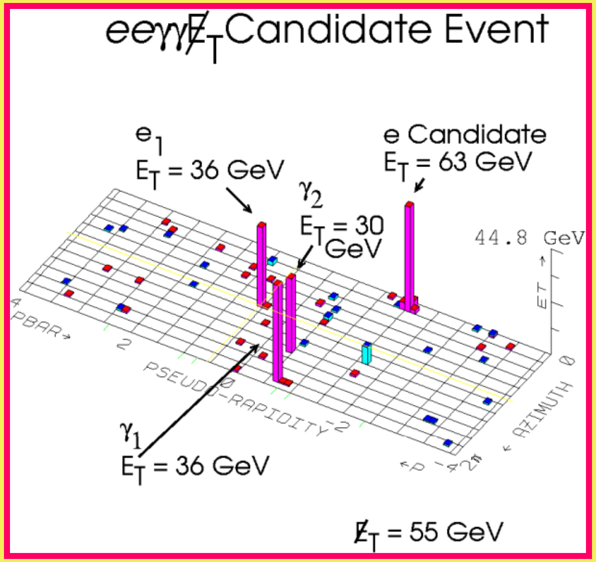
Particles of the Earl

PRL 101, 251801 (2008)

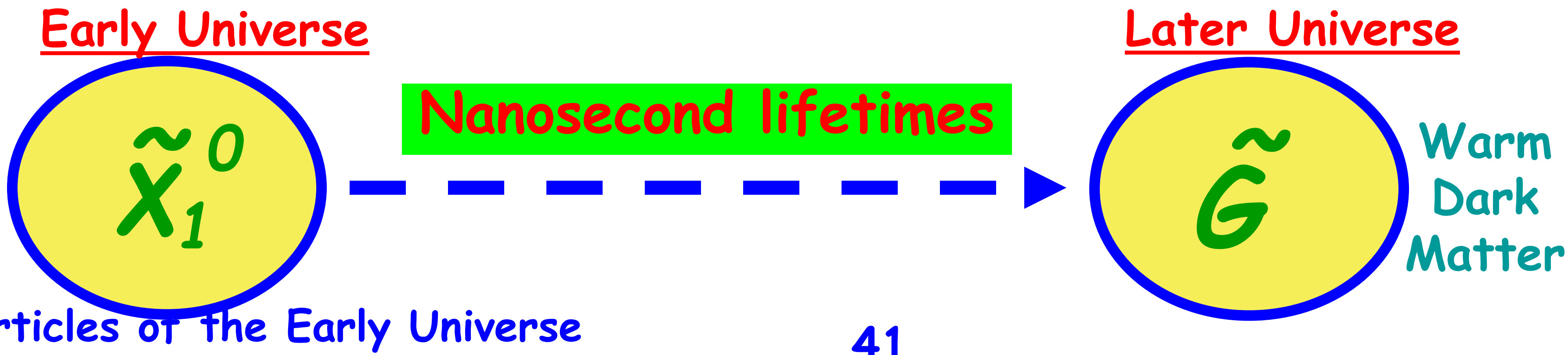
Warm Dark Matter Models

$\tilde{\chi}_1^0 \to \gamma\tilde{G}$ models provide a warm dark matter candidate Consistent with Astronomical observations and models of inflation

Provides alternative solutions for other particle physics problems



CDF Run I eeγγ+Met candidate event



Early Universe

Later Universe

$\tilde{\chi}_1^0$

Nanosecond lifetimes

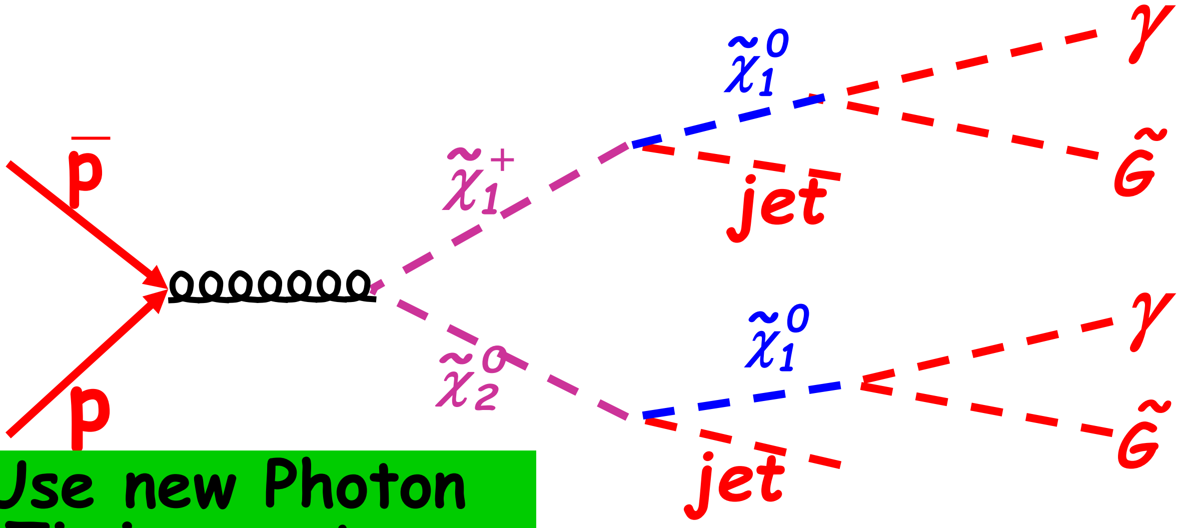
$\tilde{G}$

Warm Dark Matter

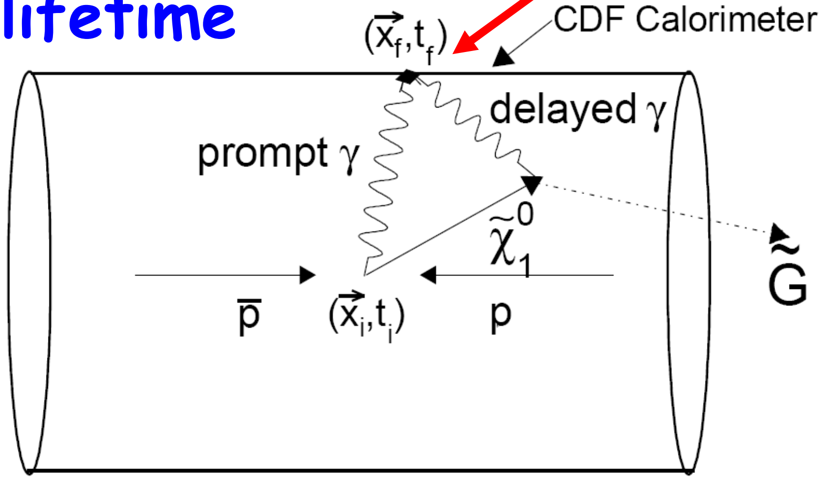
High and Low Lifetime Searches

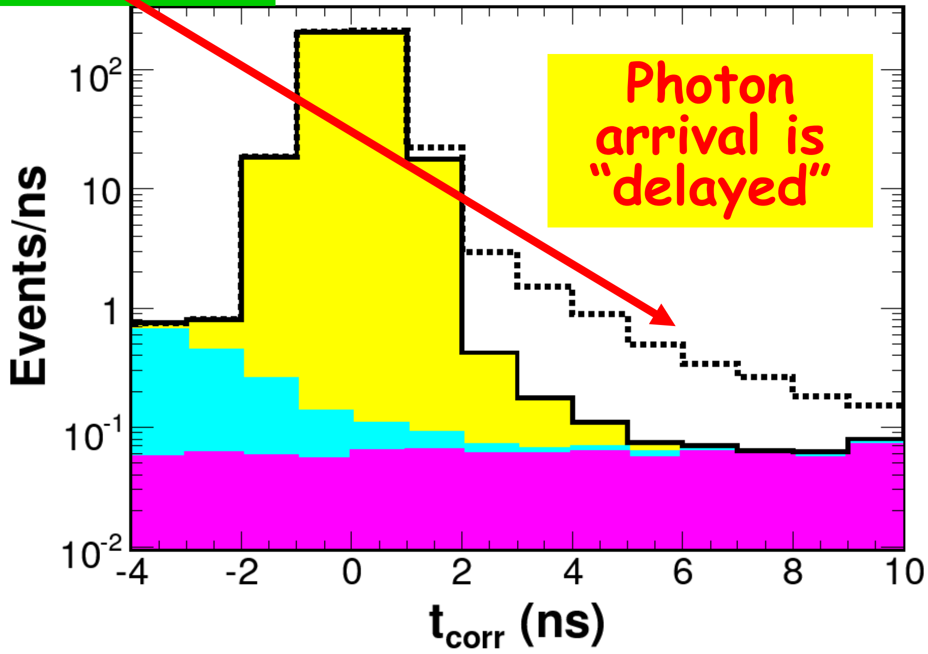
The lifetime and associated particle production dictate different final states

- $\gamma\gamma$+Met for small lifetime
- Delayed Photon +Met for large lifetime



Use new Photon Timing system





Photon arrival is "delayed"

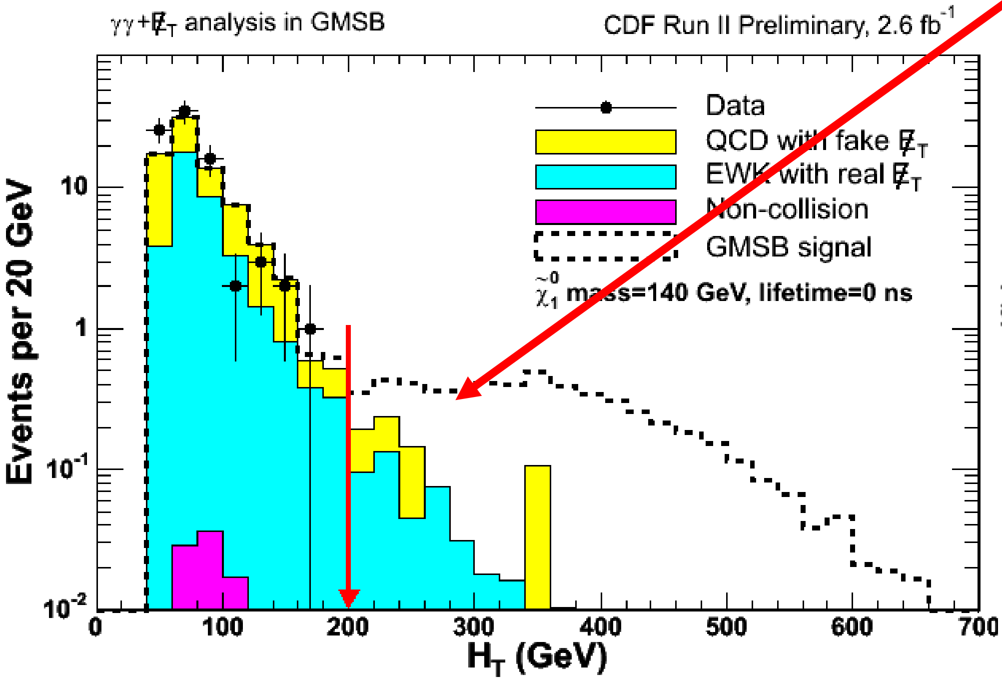
Low lifetime Neutralinos

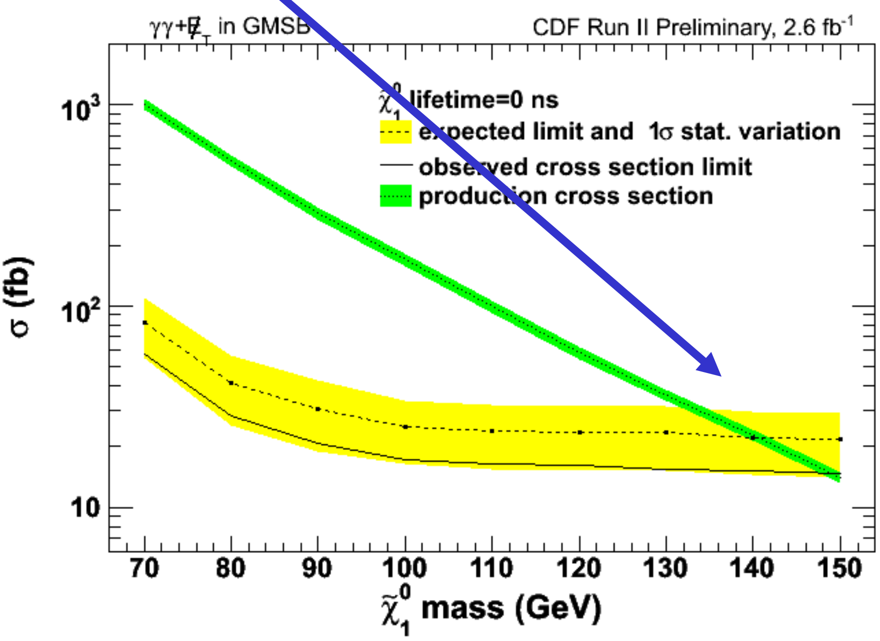
Optimize the γγ+Met analysis for 0 ns lifetime:

Significant Met and Large "other energy"

No evidence for new physics

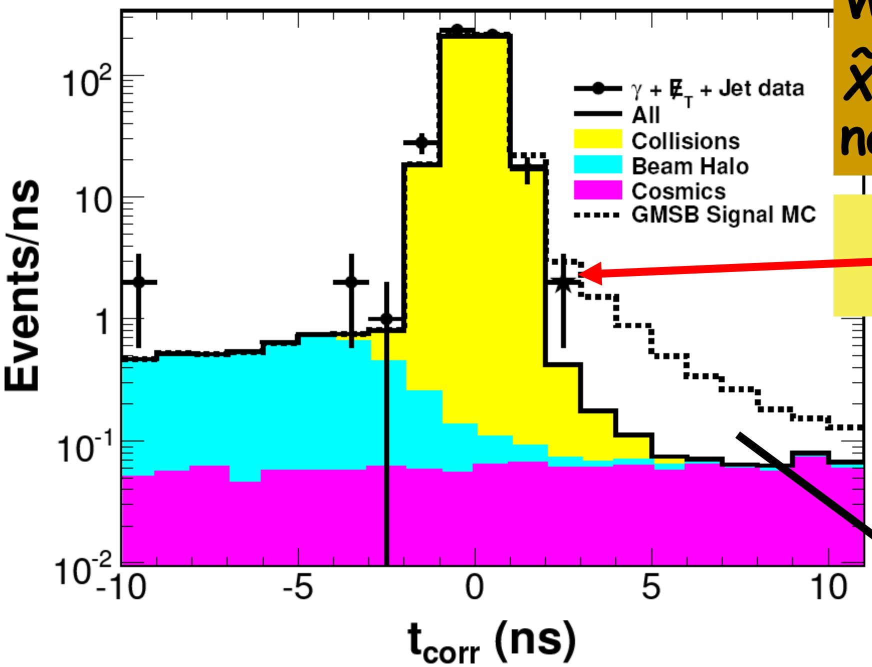
To be submitted to PRL next week





All Neutralino Lifetime Searches

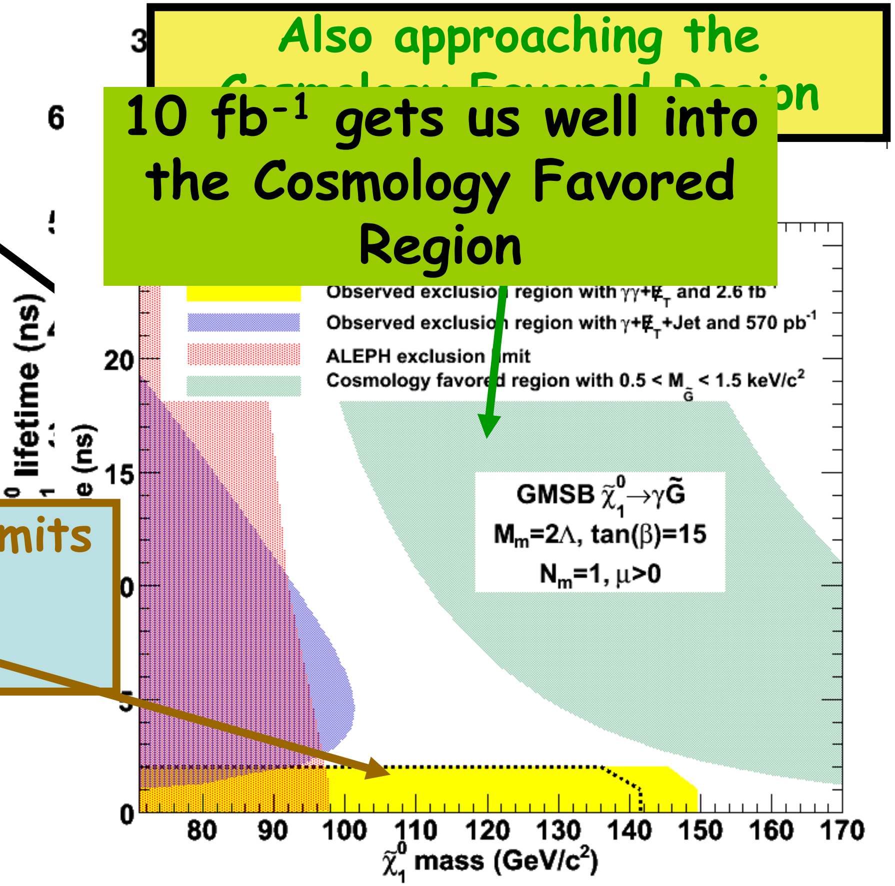
Warm dark matter models of GMSB with $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ favor keV $\tilde{G}$ masses and nanosecond $\tilde{\chi}_1^0$ lifetimes



Measure the time of arrival of photons in γ+Met+Jet events

Also approaching the Cosmology Favored Region

10 fb^{-1} gets us well into the Cosmology Favored Region



CDF, PRL 99, 121801 (2007)

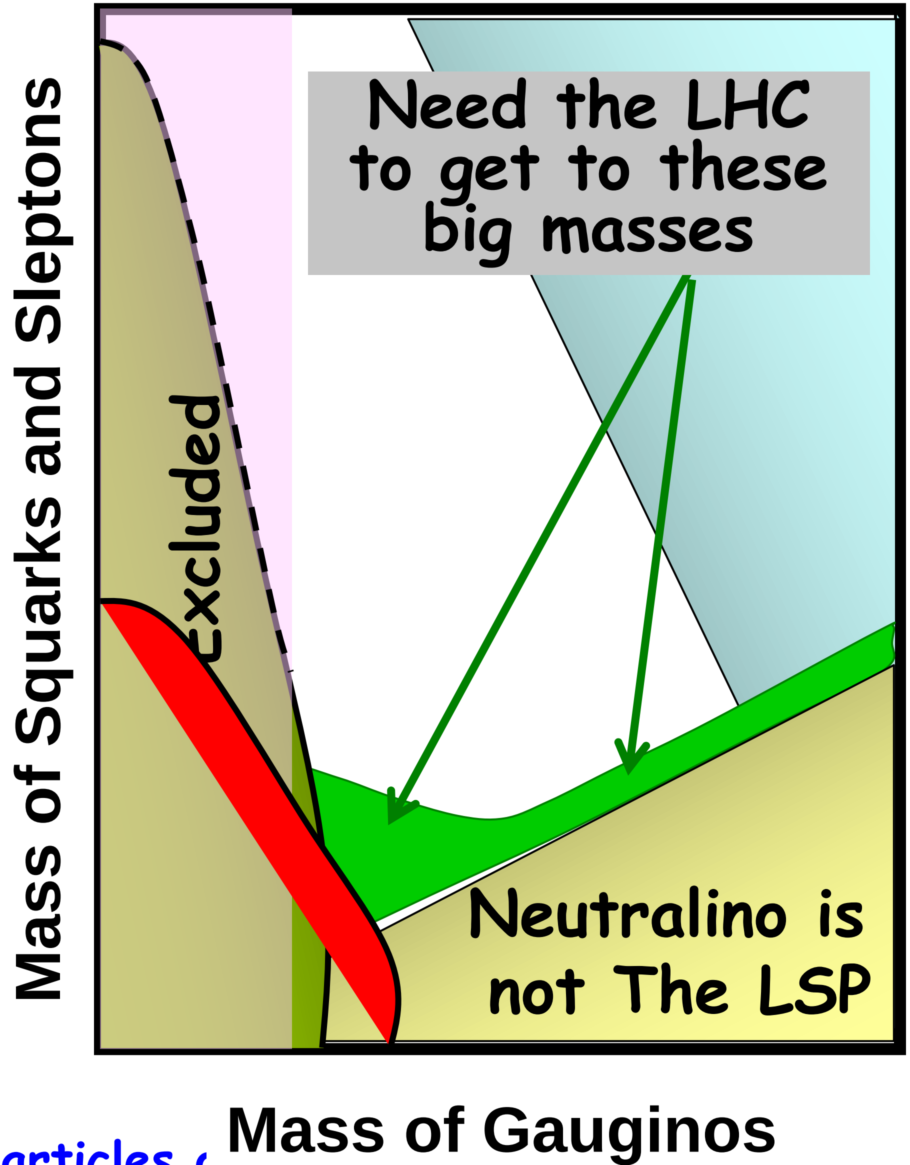
CDF, PRD 78, 0321015 (2008)

Combine γγ+Met and Delayed Photon Limits
Set limits for zero and
Non-zero lifetimes

Looking Back and Looking Forward

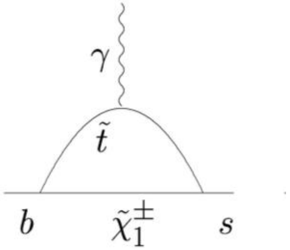
- Despite a broad and deep search there is no evidence for having produced Dark Matter in Collider Experiments
- Spend a few minutes on other techniques and a look to the future at the LHC

If you believe in minimal Cold Dark Matter Models

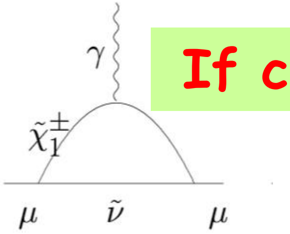


🟪 e^+e^- Collider Limits on the Higgs

🟩 **b-Colliders Indirect: Branching Ratio $b \to s\gamma$**



🟦 **g-2: Magnetic Moment of Muon**



If confirmed…

🟩 **WMAP Favored region**

🟥 **Tevatron Indirect: $B_s \to \mu\mu$ is most sensitive**

From the Tevatron to the LHC

- The Tevatron allows us to look at the conditions of the Early Universe about 1-10 ps after the Bang
  - 100 GeV particles
- The LHC allows us to go about a factor of 10 earlier
  - 1000 GeV particles

Moving to the LHC… Looking Forward

$$N_{events} = \text{Luminosity} \times \sigma_{production} \times \text{Acceptance}$$

We will get more data per year!

Then again, none yet…

With higher energy collisions, processes that weren't available before may now be accessible

Backgrounds to the interesting physics will get bigger also

Simulations of both will take awhile to get right

With bigger detectors and better technology we should have better sensitivity to interesting events

Understanding how well the detectors will respond to collisions will take awhile

Simulations of signal and background also not vetted

Tevatron:

- Not as high energy, but there is lots of data with a beautifully working detector

LHC will be great, but not quick

- Important to search today and prepare for tomorrow

Hypothetical Timeline

With the world's most experienced SUSY-Collider Search Team and a clear vision* let's look in our crystal ball

- 2010-12: First evidence for SUSY particles at LHC
- 2013-15: Establish that we live in a Supersymmetric world
- 2015-2020: Precision measurements of the particle masses → compare Dark Matter relic density predictions to those from WMAP
- 20?? Compare to Direct Detection methods → *Does the SUSY LSP have the same properties as the Dark Matter in the Milky Way?*

Combining Particle Physics with Cosmology

$$\Omega_{\mathrm{SUSY\ DM}} \overset{?}{=} \Omega_{\mathrm{CDM}}$$

---

*Arnowitt, Dutta, Kamon, D.T., *et al.*, PRL100 (2008) 231802, PLB 649 (2007) 73 , PLB 639 (2006) 46

Conclusions

- The Tevatron has performed a broad and deep set of searches for Dark Matter in the context of Supersymmetry
  - Unfortunately, no sign of new physics
- Tevatron experiments are performing great and the LHC should enter the race this year
- If our understanding of Cosmology and Particle Physics are correct, a major discovery may be just around the corner!


BU-URRP!

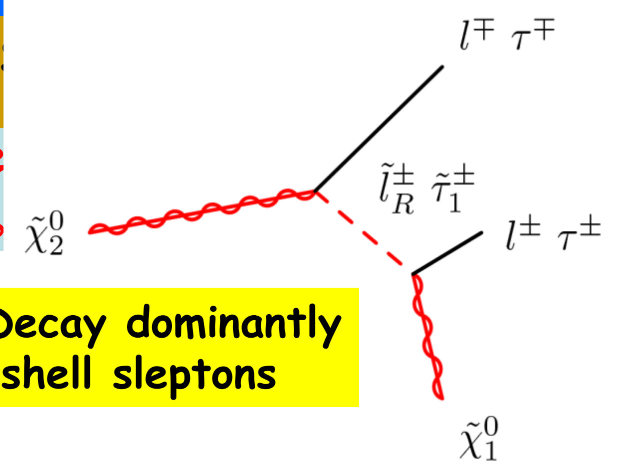
Gaugino Pair Production in Events with Three leptons + Met

Dominates the production cross section

Lots tes + Unified Analysis → best coverage

eee, e

eeτ,

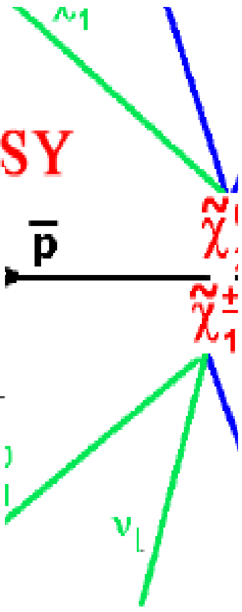


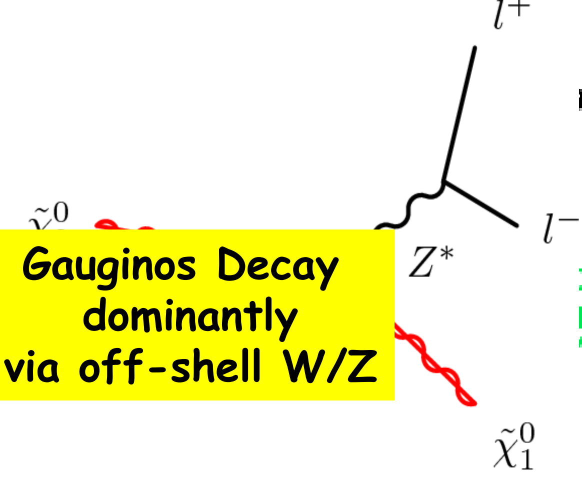
eee, eeμ, eμμ & μμμ

3 Tight Leptons + MET

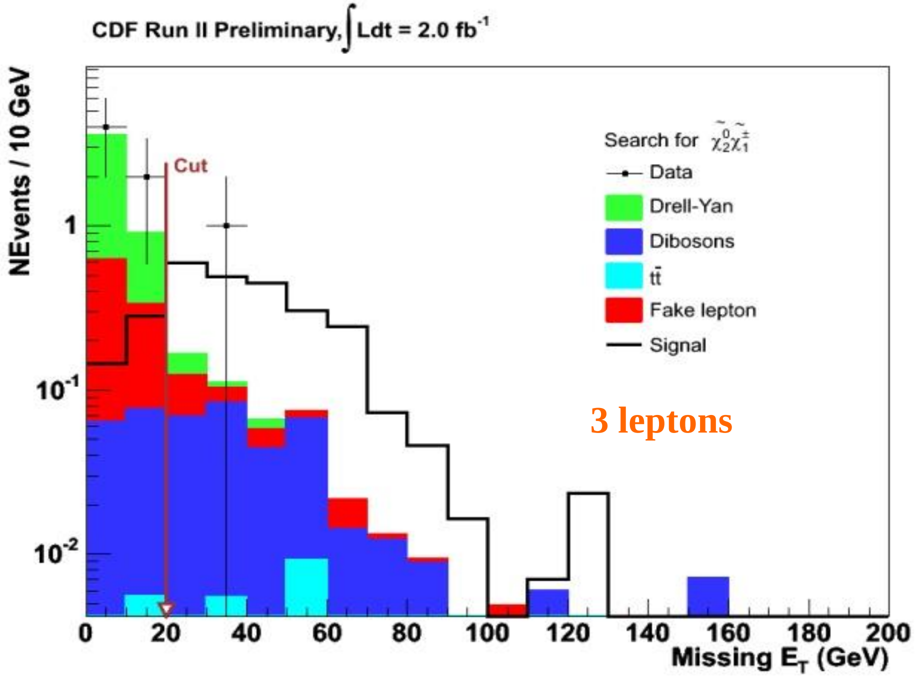
Gauginos Decay dominantly via on-shell sleptons

ic Trilepton Event





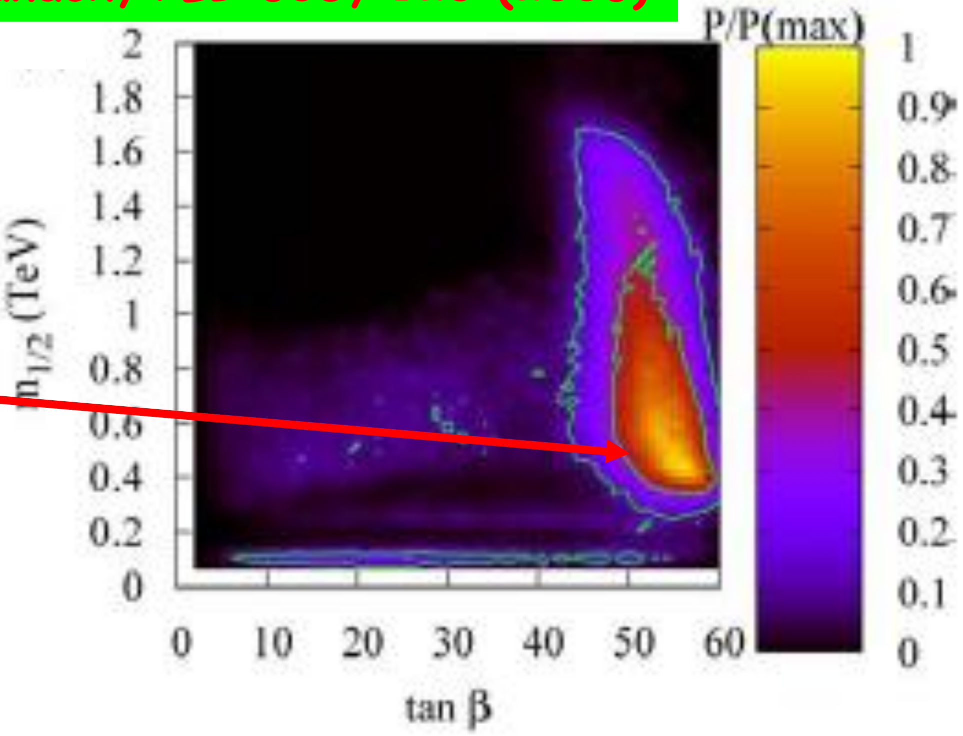
Gauginos Decay dominantly via off-shell W/Z



High Tanβ

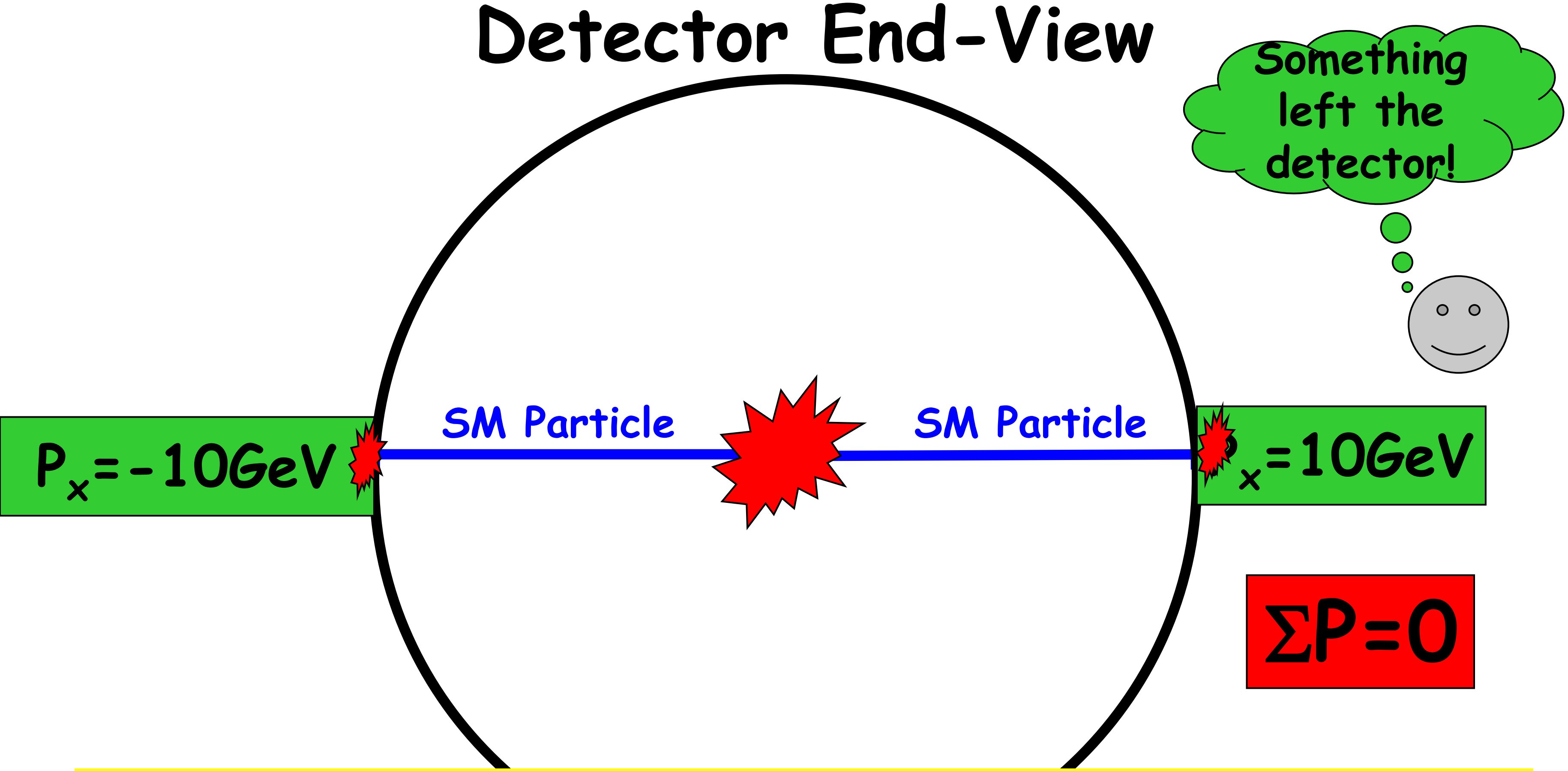
- Likelihood fits including Higgs mass limits, *g*-2, and other experimental data to the MSSM in the plane of $m_{1/2}$ and tanβ
  - Prefers high tanβ
- Stop and Sbottom masses can be very different than the other squark masses
- Gaugino branching fractions to τ's can rise to 100% as the stau gets light…

Allanach, PLB 635, 123 (2006)



The Tevatron has moved towards having a full suite of high tanβ targeted searches

Now look at the head-on view of particles coming out



Proton and Anti-Proton Collide in the middle and produce SM particles

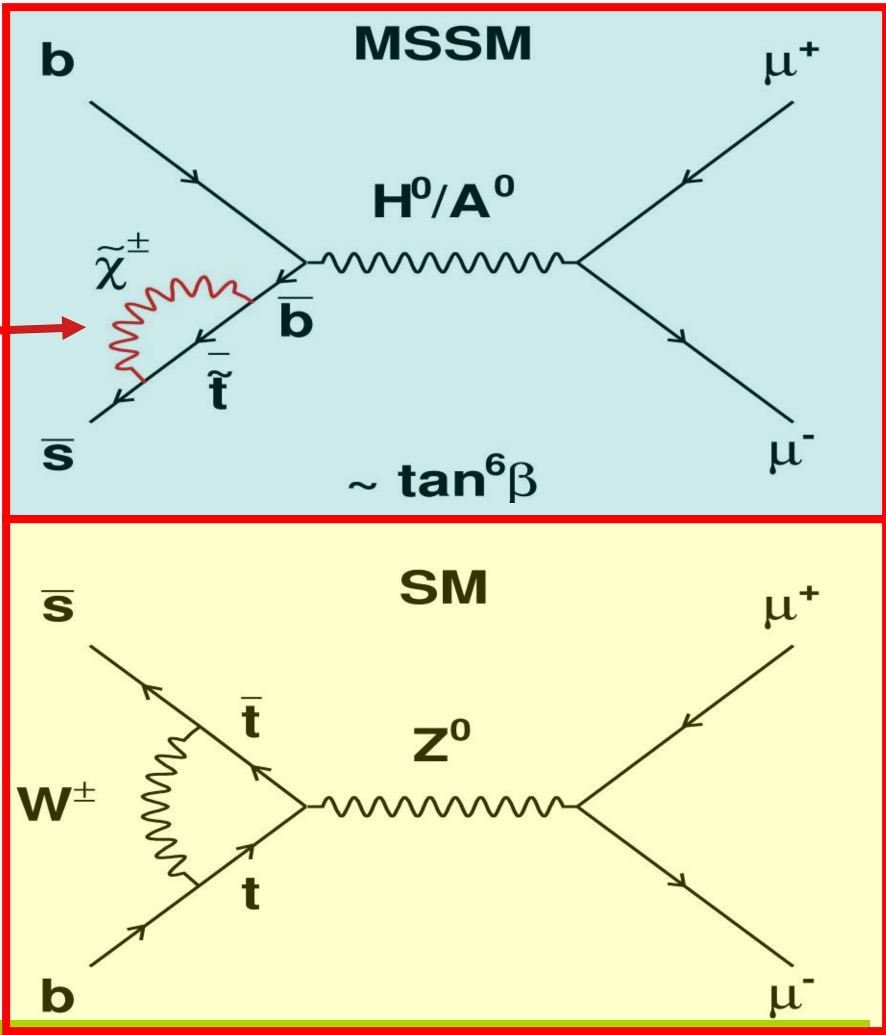
Particle momenta measured by detector

Ideas:

- Lots of different ways of looking, use the general principles and look at the high energy frontier.
- If we incorporate more info then perhaps we zoom in to be more sensitive
- One in the hand is sometimes worth two in the bush. Then again if you fail to plan, you are planning to fail.
- Looking to the future, what's the plan?
- Will do the same types of experiments I've shown (I could tell you numbers of masses we would have sensitivity to, but that wouldn't tell you much). In some sense either

1. Its there to be found or it isn't
2. If it isn't… well… There it is…
3. If its there
    1. Either we can find it with the general techniques we have now, or
    2. We need to make more assumptions, try new models and create other dedicated searches that rely more on our assumptions. Semi-infinite?
4. Let's do an example…
    1. General principle… at the LHC with 14 TeV of energy we should have sensitivity to larger masses. There is good reason to believe that if the squarks are about a TeV then we should have enough energybe able to produce them directly. Strong production cross sections should make them much easier to observe whereas at the Tevatron we have gotten so sensitive to SUSY if it were there that only the things that could be allowed to exist are, in general, too heavy to be made.

Indirect Search: $B_s \rightarrow \mu\mu$



The search for $B_s \rightarrow \mu\mu$ is perhaps the most sensitive to SUSY since sparticles show up in loops

Especially sensitive at high tanβ (Br $\propto \tan\beta^6$)

The Standard Model decay of $B_s \rightarrow \mu^+\mu^-$ is heavily suppressed

$$BR_{SM}(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

- How do I incorporate B_S→mm?
- How do I transition to LHC?
- How do I do the incorporation of the other experiments to constrain which CDM model to focus on?
- How much time do I spend on the Pheno PRL?
- How much do I praise LHC and at the same time pat myself on the back for having stayed on Tevatron?