Observing Dark Matter and its Heavy Partners at the CERN Large Hadron Collider

M. E. Peskin
January 2007

For many years, elementary particle physics centered on the questions:

What are the basic forces of Nature responsible for the nuclear strong and weak interactions ?

Today, we regard these as solved problems. These forces are well described by ‘Yang-Mills gauge theories’, theories that generalize Maxwell’s electrodynamics. Particle physicists call this theory ‘the Standard Model’.

This level of understanding lets us focus on new questions. Two major questions argue for new particles and forces at the energy scale of 100 GeV.

These arguments will be soon be tested. I would like to tell you how.

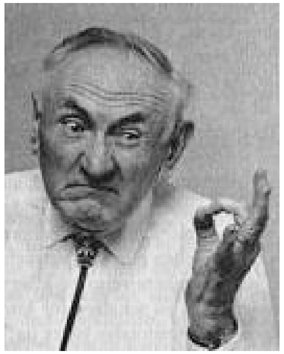
The first question is:

What is the nature of cosmic dark matter ?

Dark matter is a weakly-interacting neutral substance that is a major component of the mass of the universe.

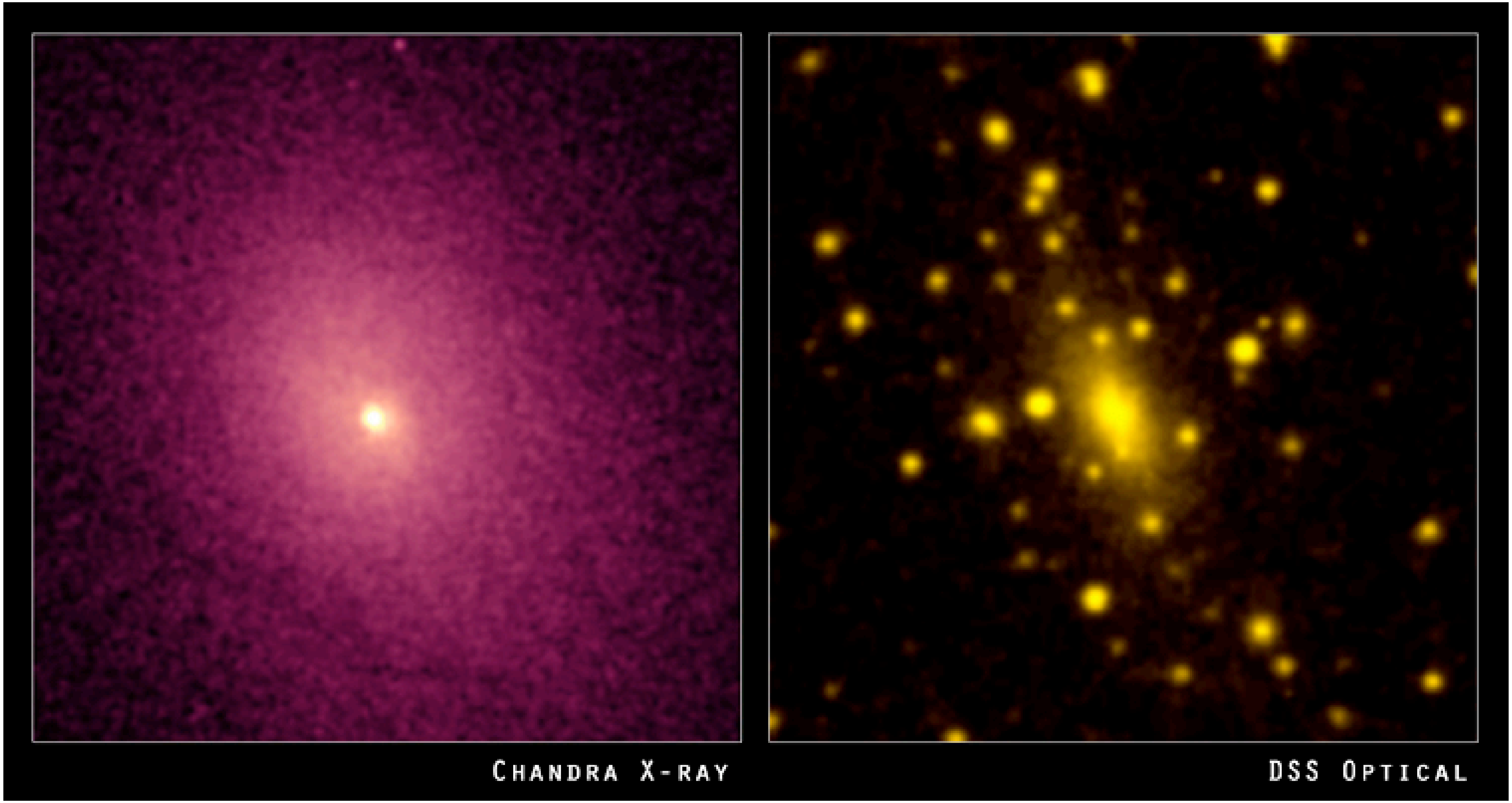
The story of dark matter began in 1933, when Fritz Zwicky measured the mass of the Coma cluster of galaxies.

He found a result 400 times larger than the mass of the stars in the galaxies.



O. Lopez-Cruz and I. K. Sheldon - Kitt Peak

We now know that much of this mass takes the form of hot gas radiating X-rays:



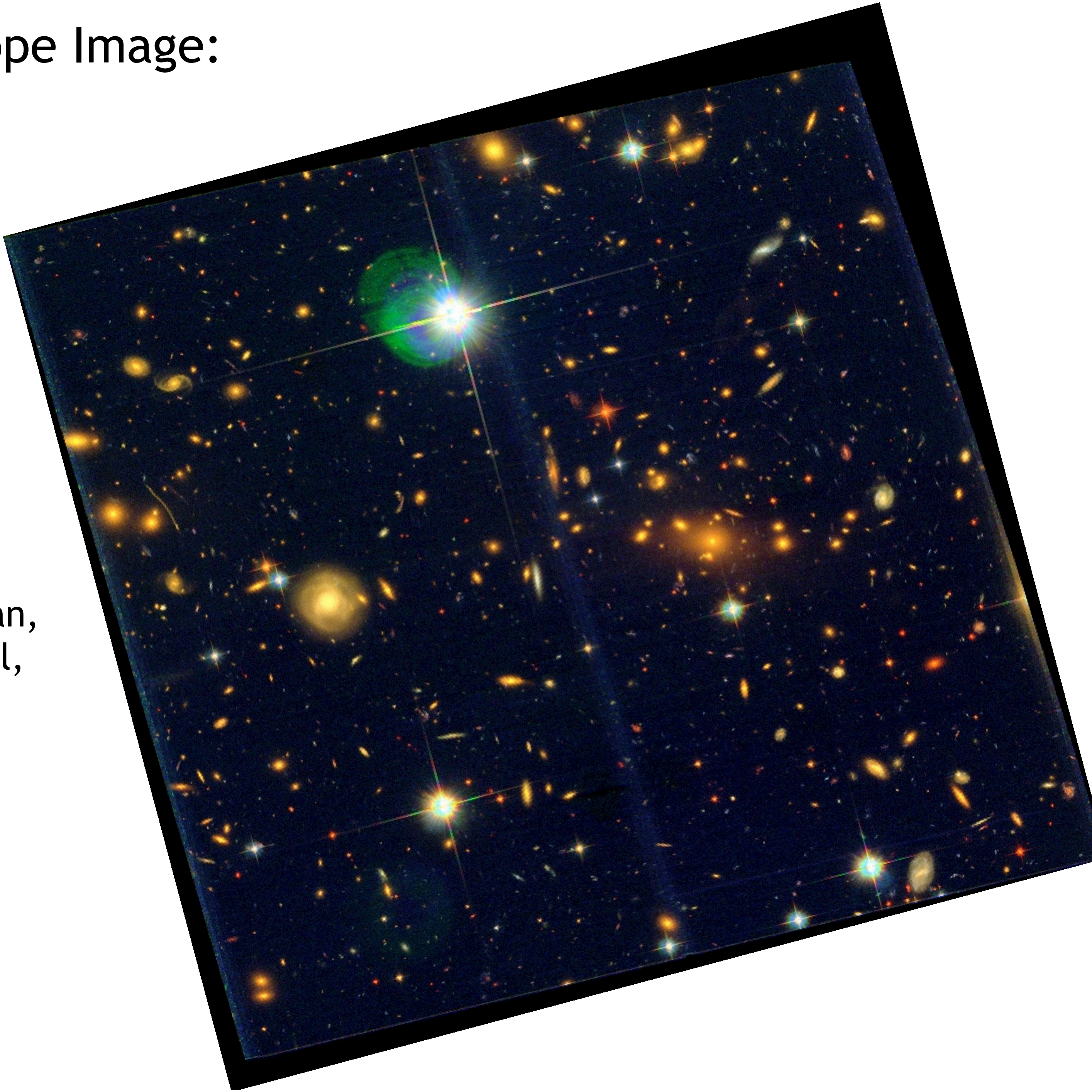
Abell 2029

but still only 15% of the mass is accounted for.

Let me show you a modern analysis of a cluster of galaxies, done in 2006, that gives striking evidence for the existence of dark matter.

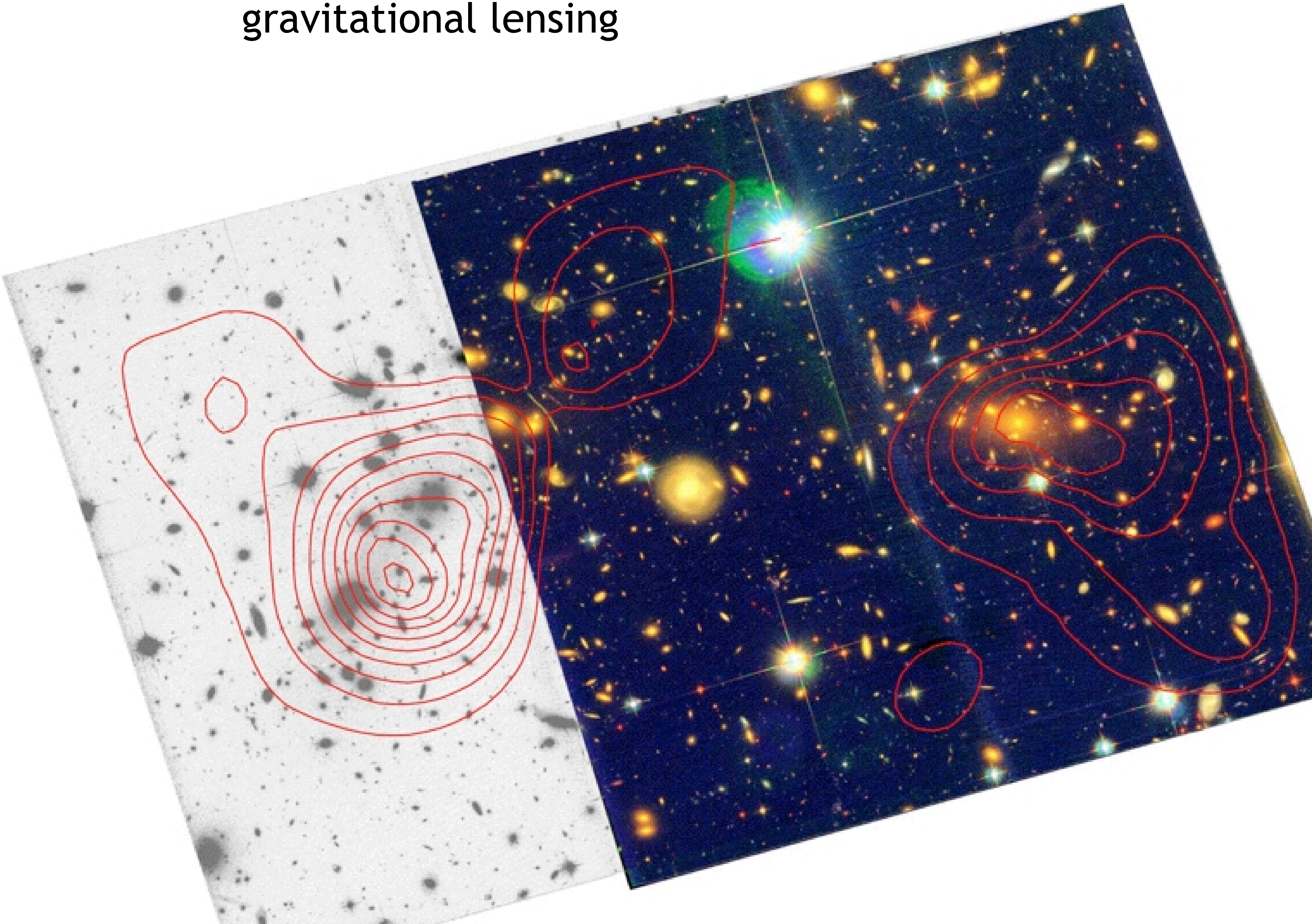
The object I will discuss is the ‘bullet cluster’ (1E0657-56).

Here is the Hubble Space Telescope Image:

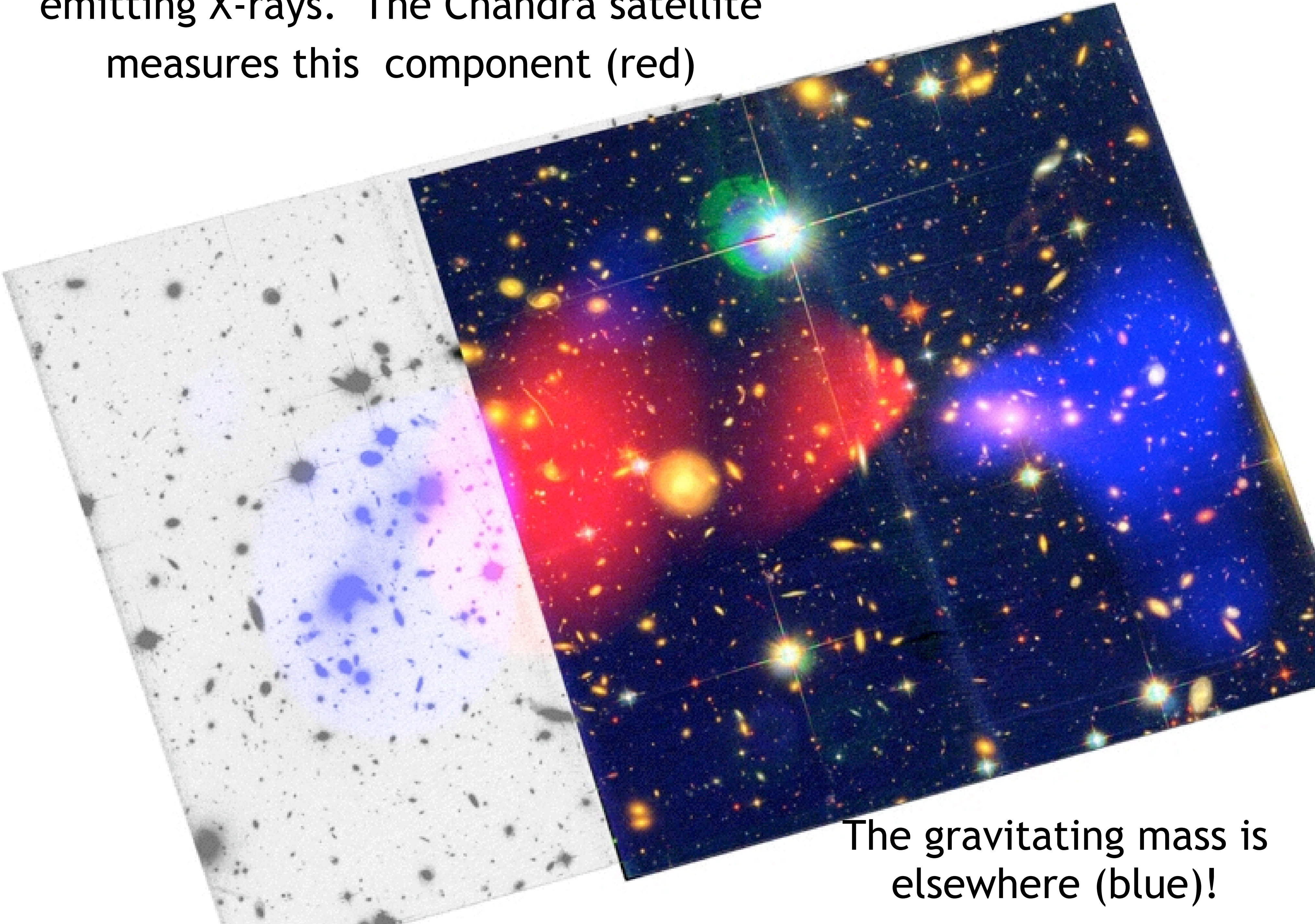


analysis of Bradac, Clowe, Gonzalez, Marshall, Forman, Jones, Markevitch, Randall, and Schrabback

Here is the mass distribution reconstructed from gravitational lensing



The atomic matter is mainly in hot gas, emitting X-rays. The Chandra satellite measures this component (red)



The gravitating mass is elsewhere (blue)!

Additional evidence for dark matter comes from measurements of the mass distribution in our galaxy and in other galaxies, and from measurements of the primordial equation of state at T = 1 eV as reflected in the cosmic microwave background. These last experiments measure the overall densities in the universe:

$\Omega_b = \rho_b/\rho_c = 4.2\%$ atoms

$\Omega_d = \rho_d/\rho_c = 20.\%$ dark matter

$\Omega_\Lambda = \rho_\lambda/\rho_c = 76\%$ dark energy

WMAP 2006

Dark matter cannot be made of quarks, leptons, or any other known particle.

A simple model of dark matter is that it is composed of a neutral, stable, weakly-interacting massive particle (WIMP).

Let’s assume also that WIMPs can be pair-produced at a rate such that they would be in thermal equilibrium in the early universe. From this assumption, one can compute the cosmic density:

$$\Omega_N = \frac{s_0}{\rho_c} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{1}{\xi_f m_{\rm Pl}} \frac{1}{\langle \sigma v \rangle}$$

Putting in the numbers, we can solve for the annihilation cross section:

$$\langle \sigma v \rangle = 1 \text{ pb}$$

How big is this ? Parametrize:

$$\langle \sigma v \rangle = \frac{\pi \alpha^2}{8 m^2} \quad , \quad \text{then} \quad m = 100 \text{ GeV} \ .$$

There are other reasons also to believe that there are new fundamental interactions that act at energies of order 100 GeV. These come from a continuing mystery in particle physics.

The Standard model of weak interactions is based on Yang-Mills theory, which requires an exact underlying symmetry. To give mass to W and Z bosons and to the quarks and leptons, this symmetry must be spontaneously broken.

The underlying symmetry makes specific predictions for the couplings of W and Z bosons to fermions. These are dramatically confirmed.

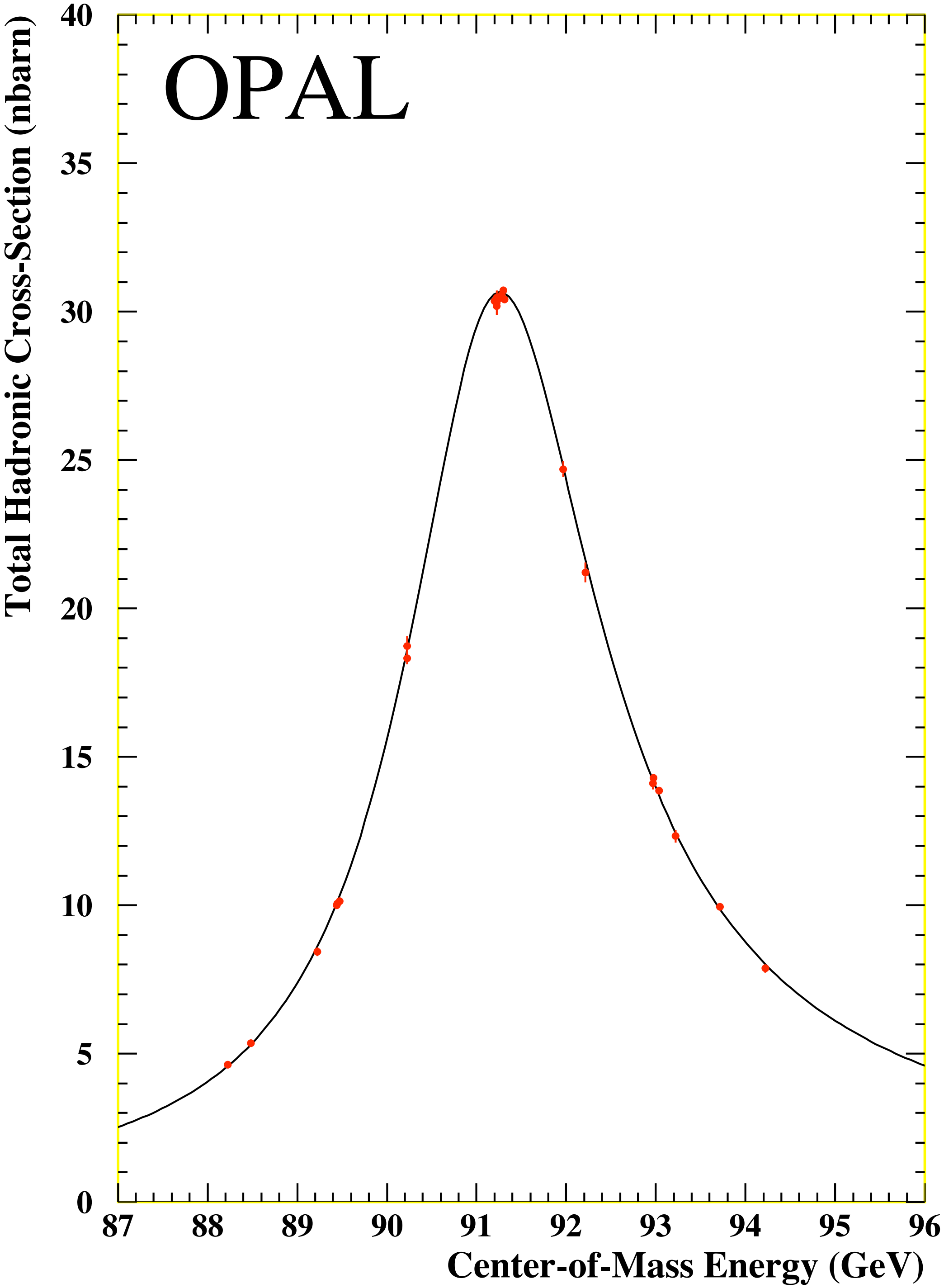
But, we still need a mechanism of symmetry breaking. This requires new forces and particles.

I would like to show you two results from the campaign of precision meaurements of the weak interactions carried out in the 1990's.

Here is the resonance lineshape for the reaction

$$e^+e^- \rightarrow Z^0$$

The theory, which includes contributions from strong, weak, and electromagnetic interactions, is confirmed to parts per mil accuracy.

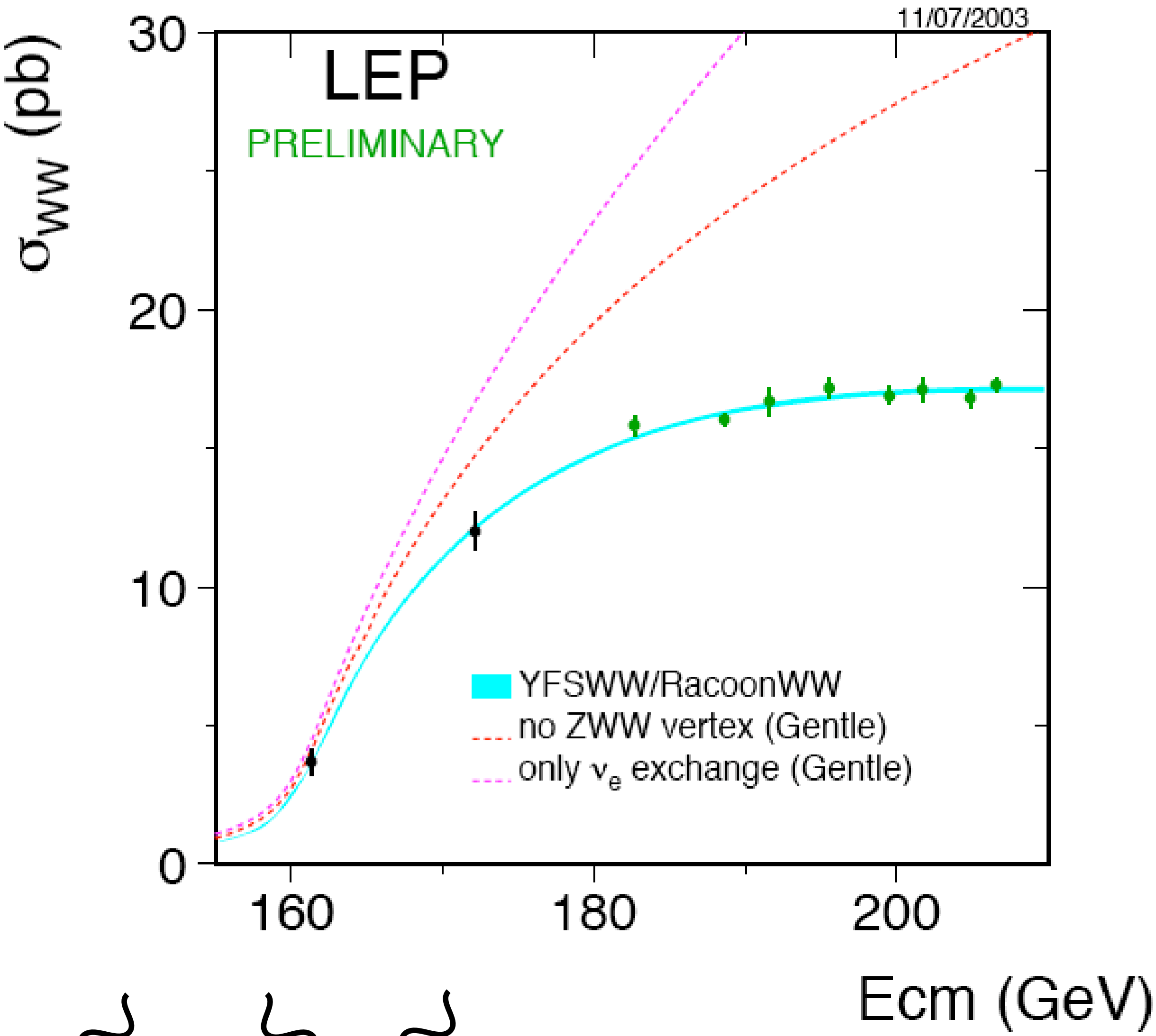


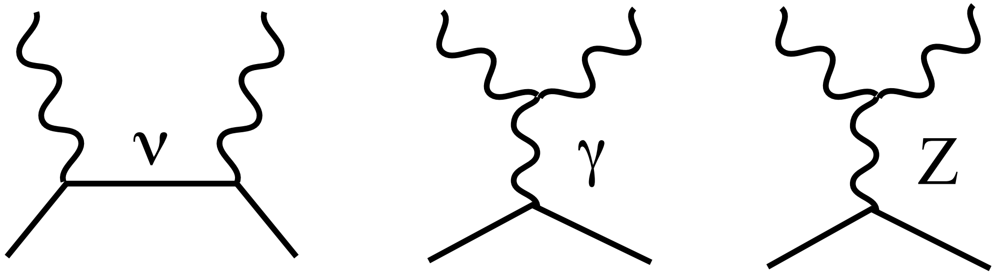
Here is the measured cross section for the reaction

$$e^+e^- \to W^+W^-$$

The Standard Model has a delicate cancellation among 3 Feynman diagrams.

This cancellation requires that the 3 boson vertex is precisely that of Yang-Mills theory.





In fact, almost all explicit models of symmetry-breaking mechanisms for the electroweak interactions contain heavy neutral particles with only weak interactions.

These particles are stable if the new particles in the model carry a conserved discrete symmetry. Usually, such a discrete symmetry is required for other reasons, e.g., to prevent rapid proton decay.

One such model is supersymmetry - the idea that all bosons and fermions in Nature have partners with the opposite statistics. In supersymmetry, the fermionic photon is a plausible candidate for the particle of dark matter.

In the past few years, many new models based on extra space dimensions have been studied. All have candidates for WIMP dark matter.

John Ellis

Steven Weinberg

In 2008, a new high-energy particle accelerator, the Large Hadron Collider (LHC) at CERN, will give us the energy to produce new particles beyond 1000 GeV in mass.

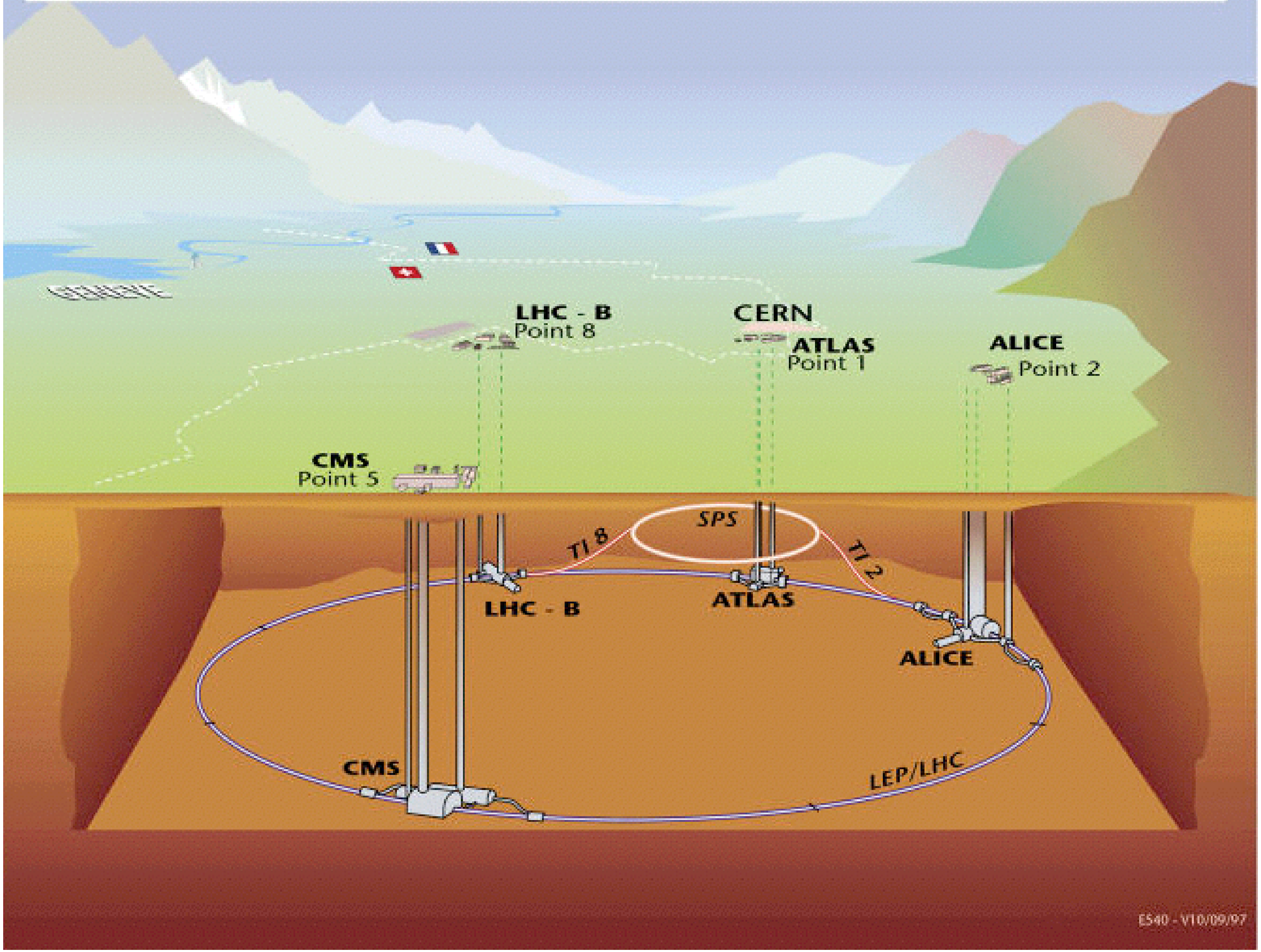
But, there is a price. The LHC is a proton-proton collider with CM energy 14 TeV. Proton-proton collisions lead to very complex events that are difficult to interpret. All but a tiny fraction of these events come from ordinary strong interaction quark-gluon collisions.

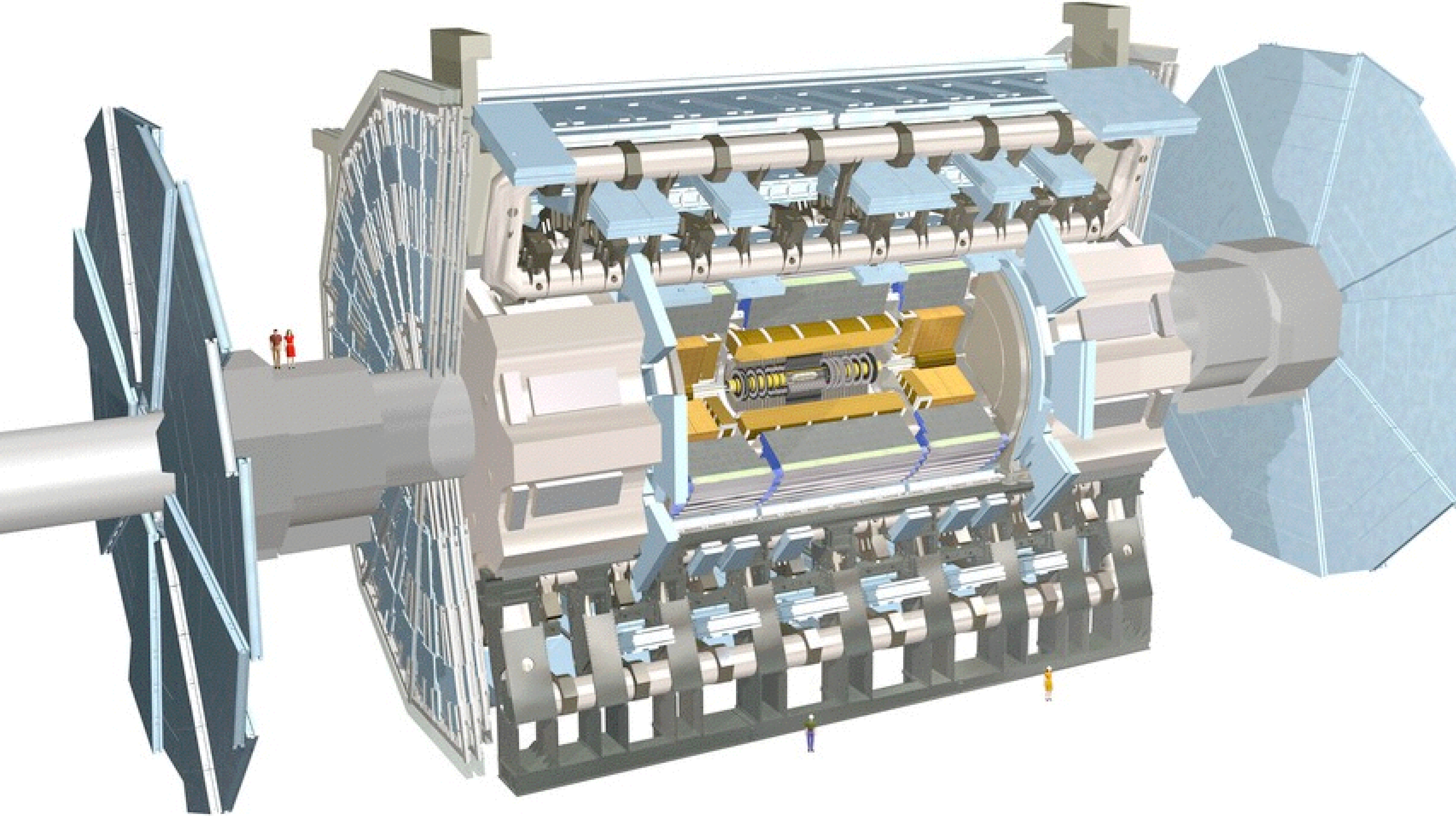
Can we find the new particles ? And, if we can find them, can we measure their properties ?

the Geneva region

with the CERN Large Hadron Collider

Overall view of the LHC experiments.

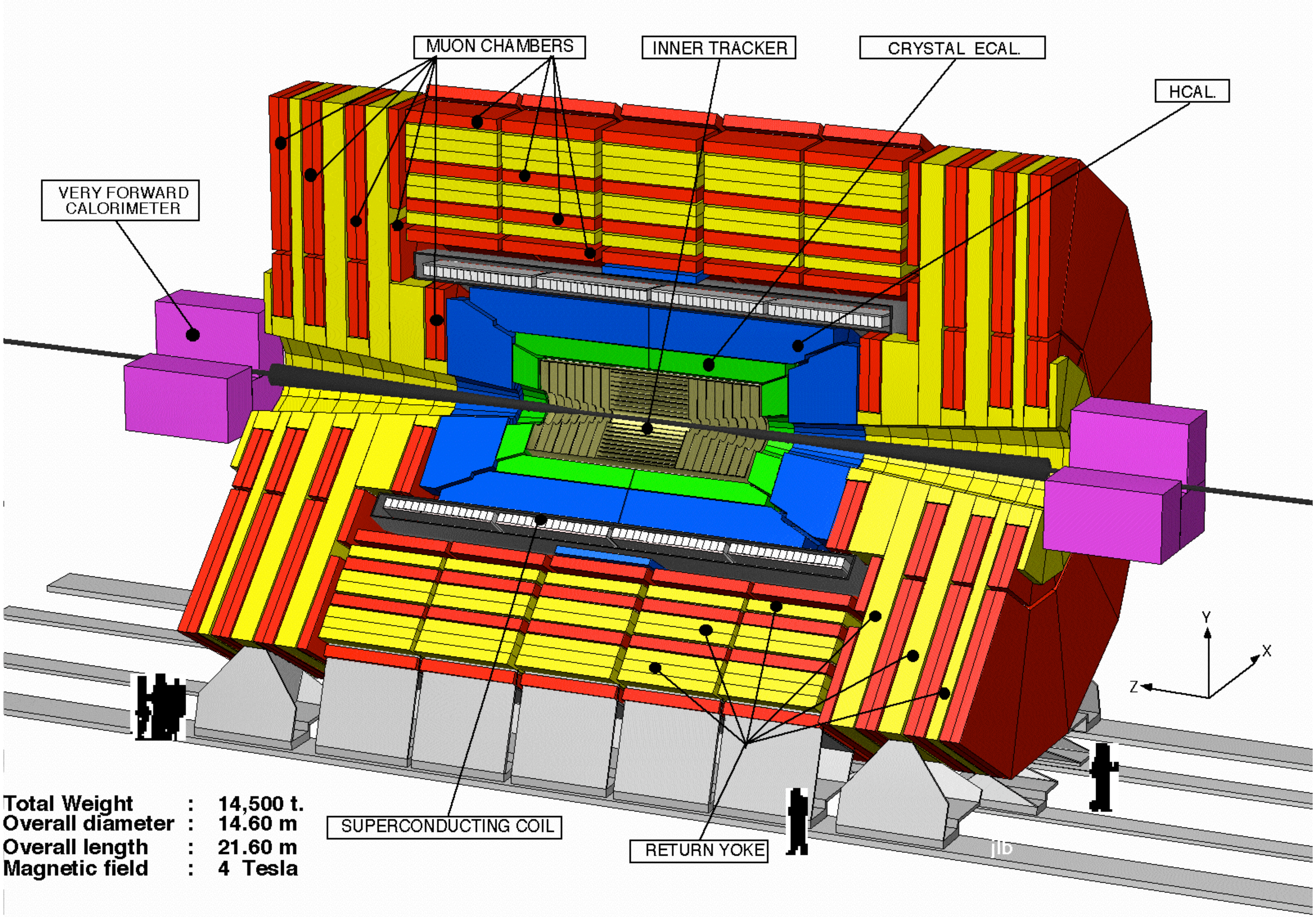




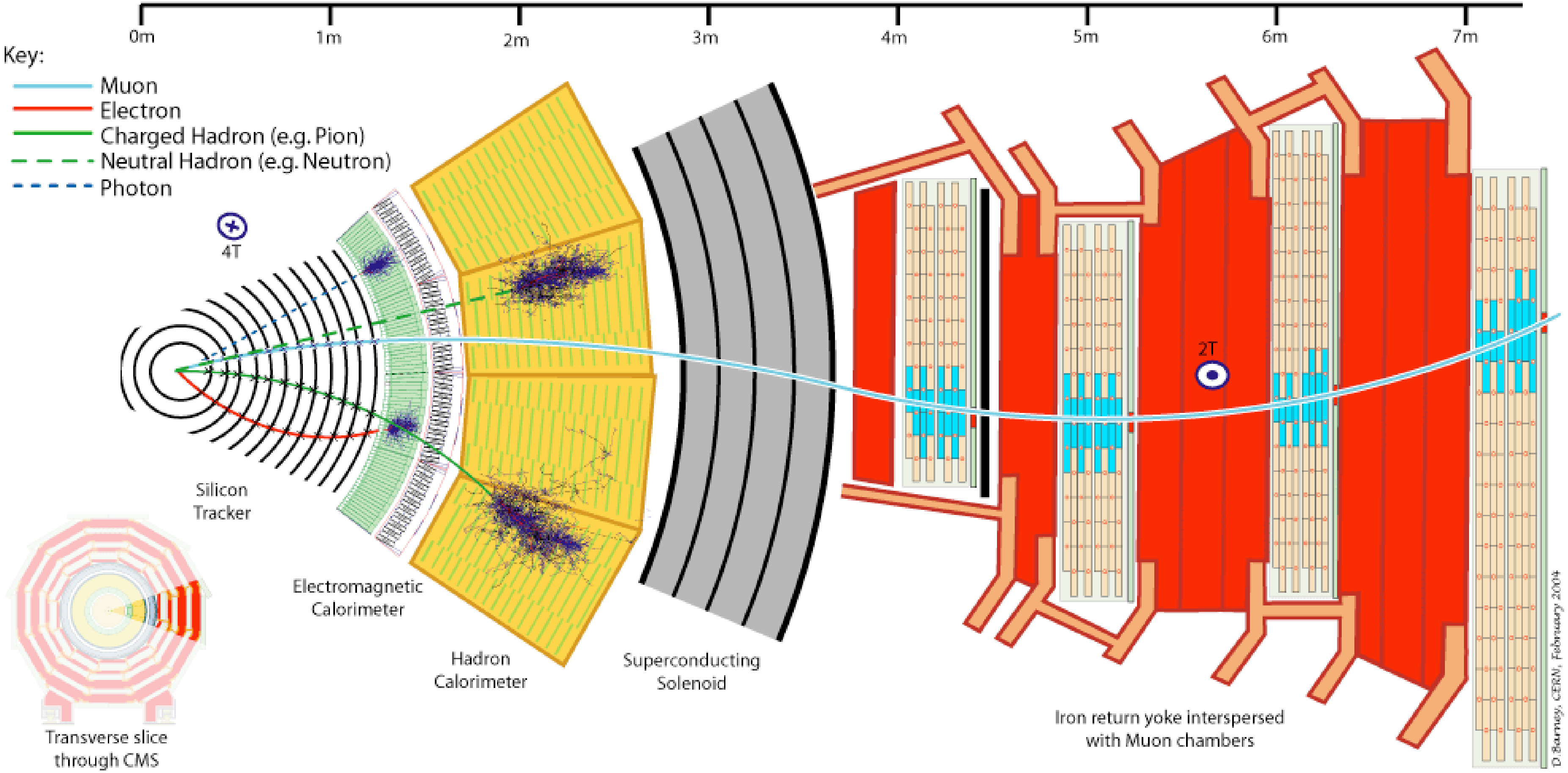
the ATLAS experiment

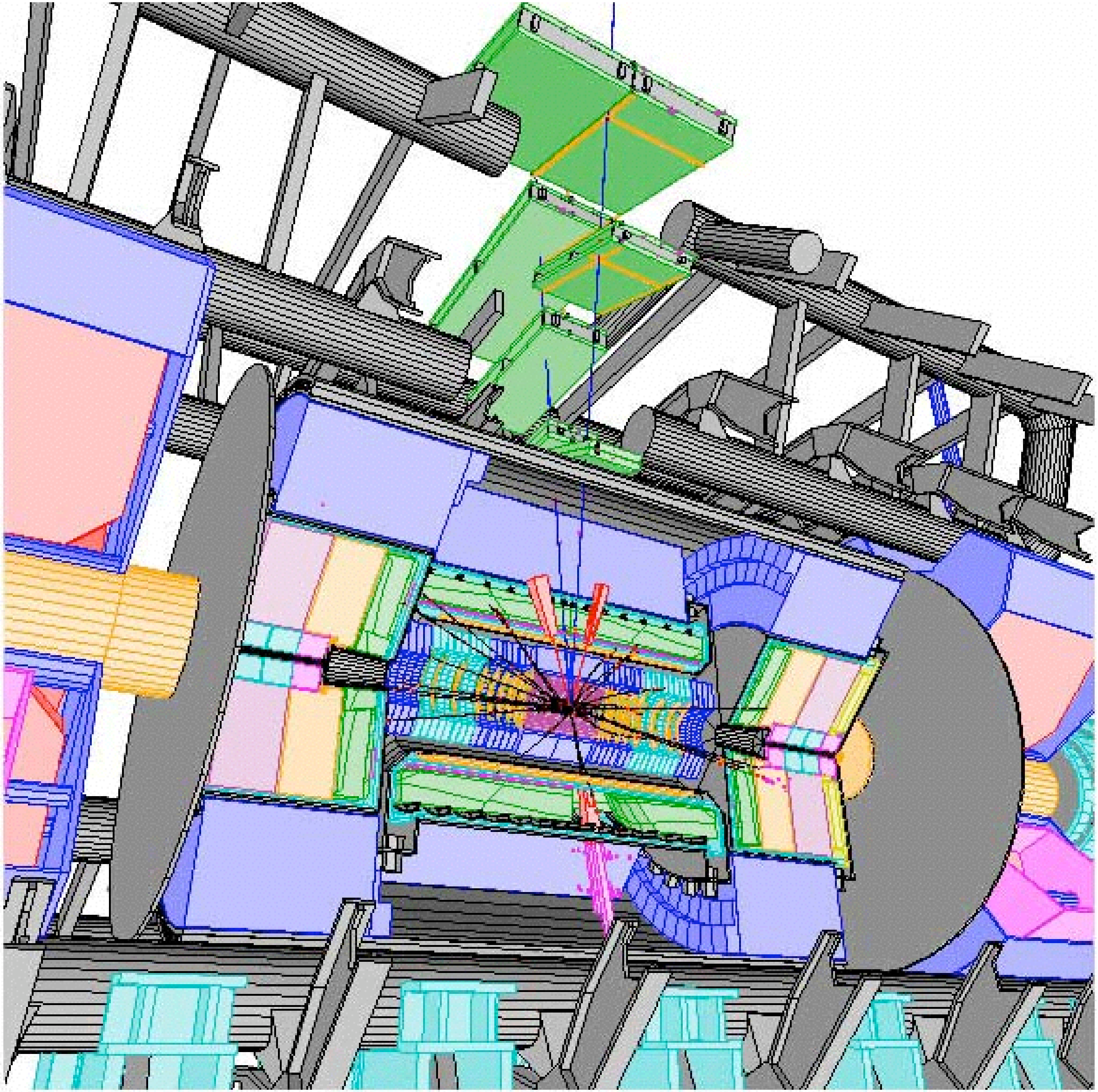
arrival of a superconducting muon toroid at CERN

A Compact Solenoidal Detector for LHC



Total Weight	:	**14,500 t.**
Overall diameter	:	**14.60 m**
Overall length	:	**21.60 m**
Magnetic field	:	**4 Tesla**


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004



simulated high-energy event in ATLAS

To discover dark matter particles at the LHC, we have to pass through four levels of difficulty:

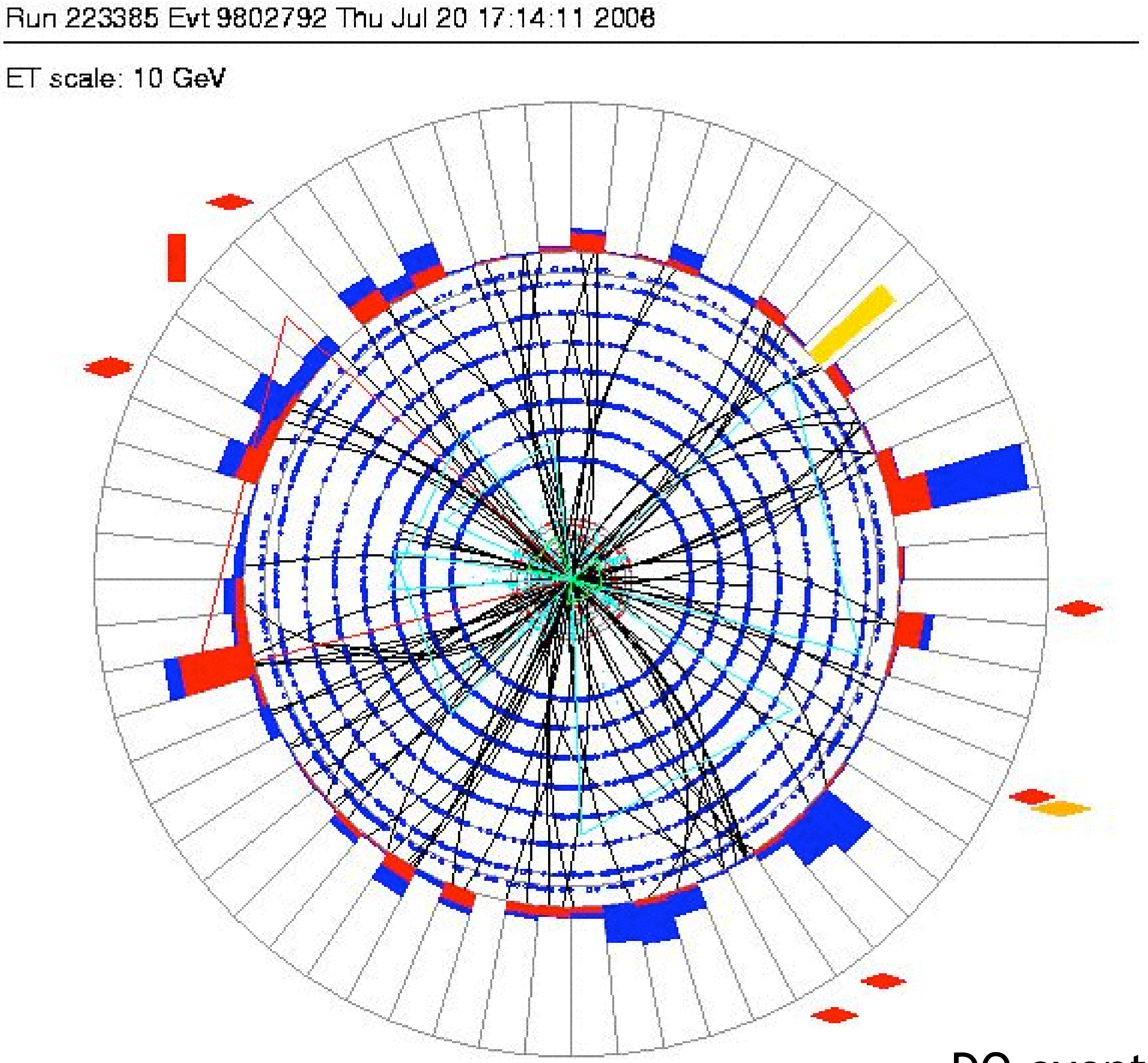
1. Typical events at the LHC are very complex. We need the right perspective to analyze them.

2. Dark matter particles are invisible to the LHC detectors. We need to know how to identify their production.

3. Events with new particles are expected to be rare, 10^{-10} of the total cross section. We need to know how to suppress or understand the background.

4. Much kinematic information is missing. But still we would like to measure the mass of the WIMP.

The first problem is that, even if we can image LHC events, they contain a huge amount of information. Even at current energies, at the Fermilab Tevatron, these events contain about 50 charged particles and a similar number of photons from π^0 decay.



D0 event

Most of these particles come from the soft interactions in which the two protons disrupt one another.

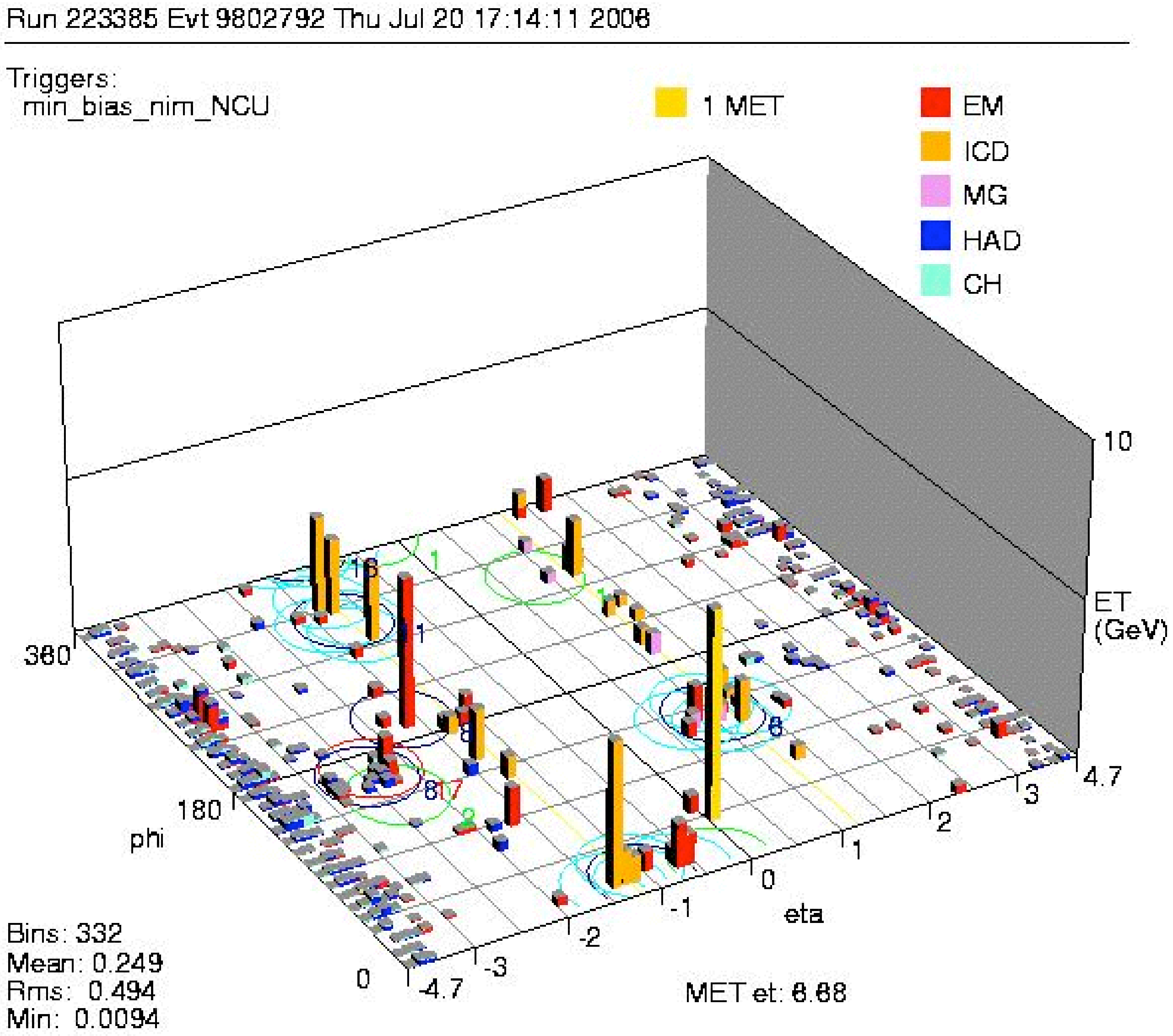
We can see the hard reaction much better by concentrating on particles produced at with large momentum transverse to the collision axis.

Some useful coordinates are (y, ϕ, p_T)

where y is rapidity, defined by

$$E = \mathcal{P}_T \cosh y \quad p^z = \mathcal{P}_T \sinh y \quad \mathcal{P}_T = \sqrt{p_T^2 + m^2}$$

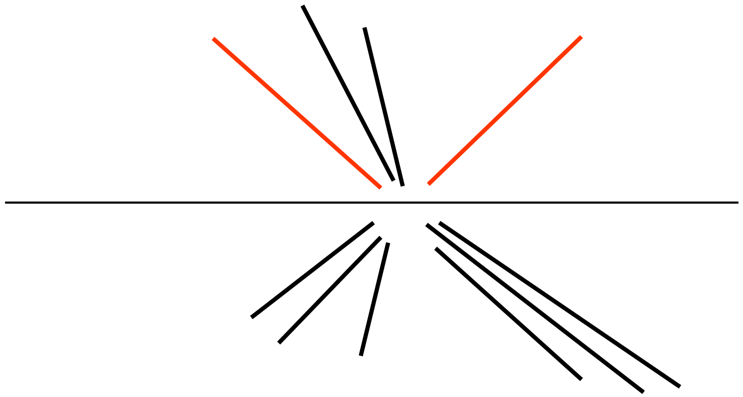
The three-dimensional plot of p_T over the (y, ϕ) plane is called the lego plot.



lego plot of DO event

Now we come to the second question: Dark matter particles are invisible to an LHC detector.

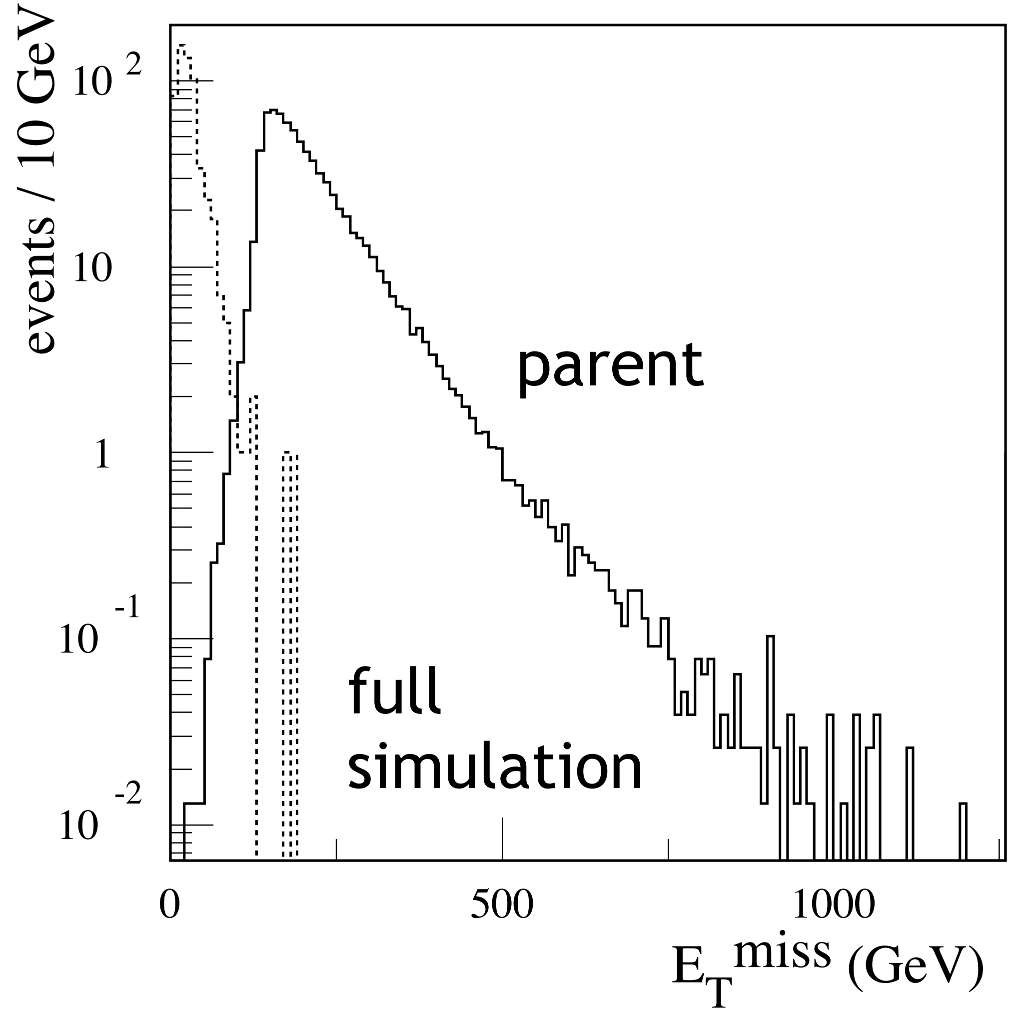
Fortunately, if dark matter is part of a new sector of particles, some of which have strong interactions, there is expected to be plenty of other activity in these events. The events are characteristic in that they have large deposited energy and apparently unbalanced pT.

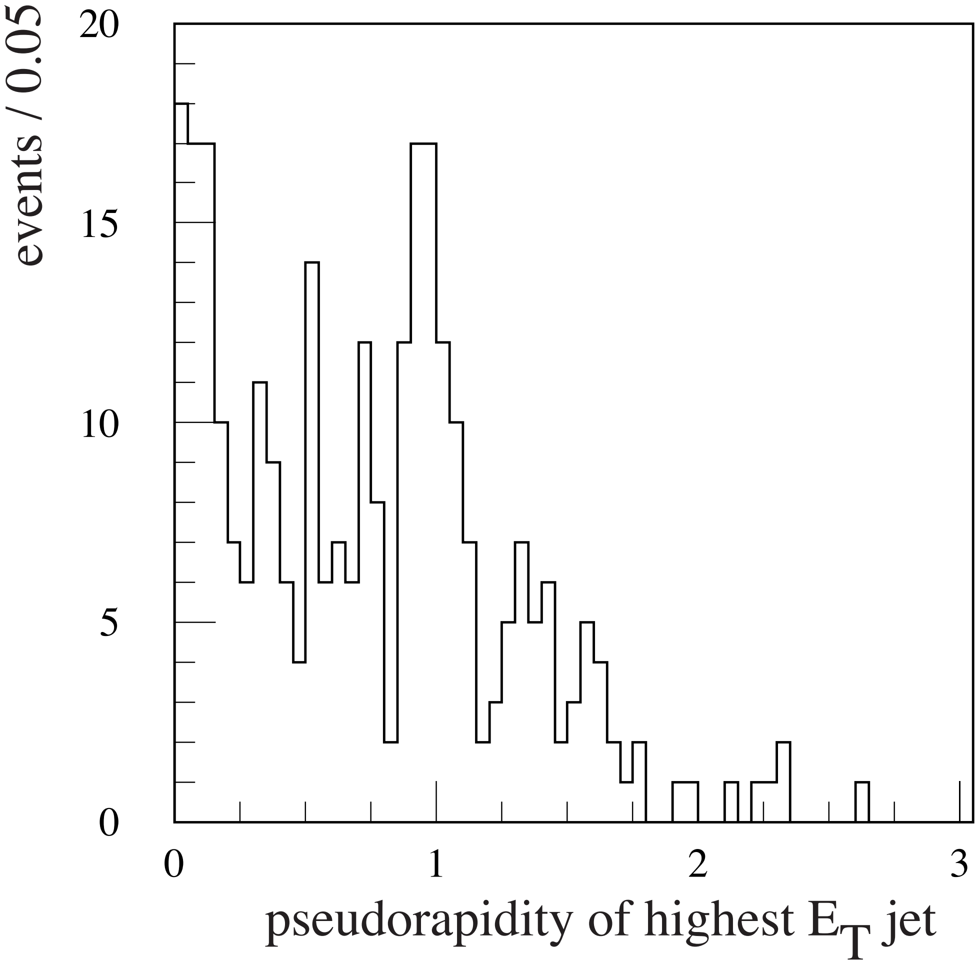


We have to identify these events from transverse energy flow only. Crucial variables are:

$$\not{E}_T \qquad H_T = \not{E}_T + \sum_i E_{Ti}$$

The LHC detectors are designed to accurately measure ET and to verify ET balance.





ATLAS simulation of missing ET in $Z(\rightarrow \mu^+\mu^-) + jet$

η of the jet w. the highest ET in events w. ET > 50

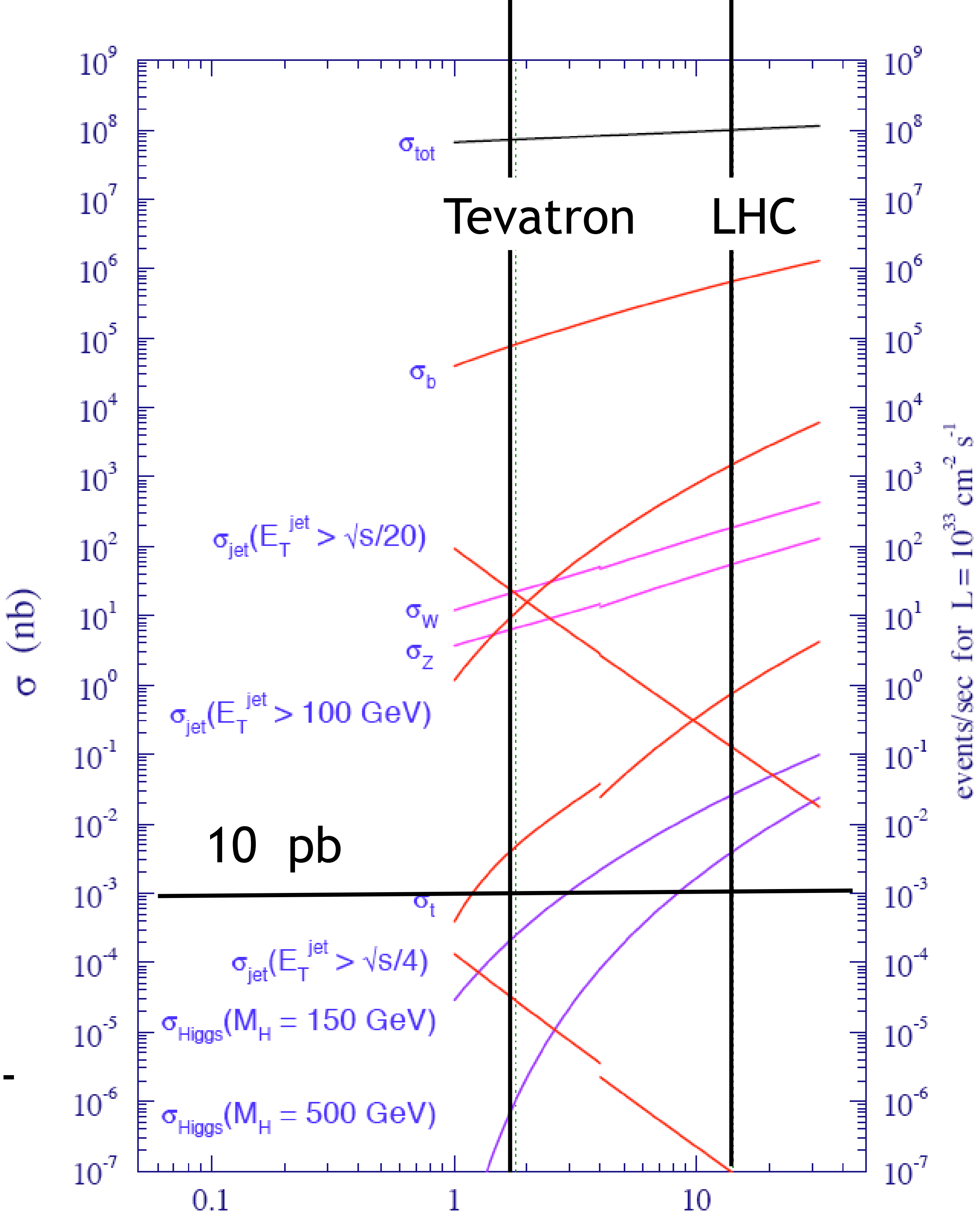
Thus, the ordinary events of quark and gluon scattering are not expected to be important backgrounds in the search for dark matter production.

The most troubling backgrounds are expected to come from heavy particle production within the current Standard Model, production of W and Z bosons and top quarks. Through

$$W^+ \to \ell^+ \nu \qquad Z^0 \to \nu \overline{\nu} \qquad t \to W^+ b \to \ell^+ \nu b$$

these particles can produce missing ET, leptons, and other exotic effects by perfectly conventional reactions.

Here is a plot of some representative pp collider cross sections

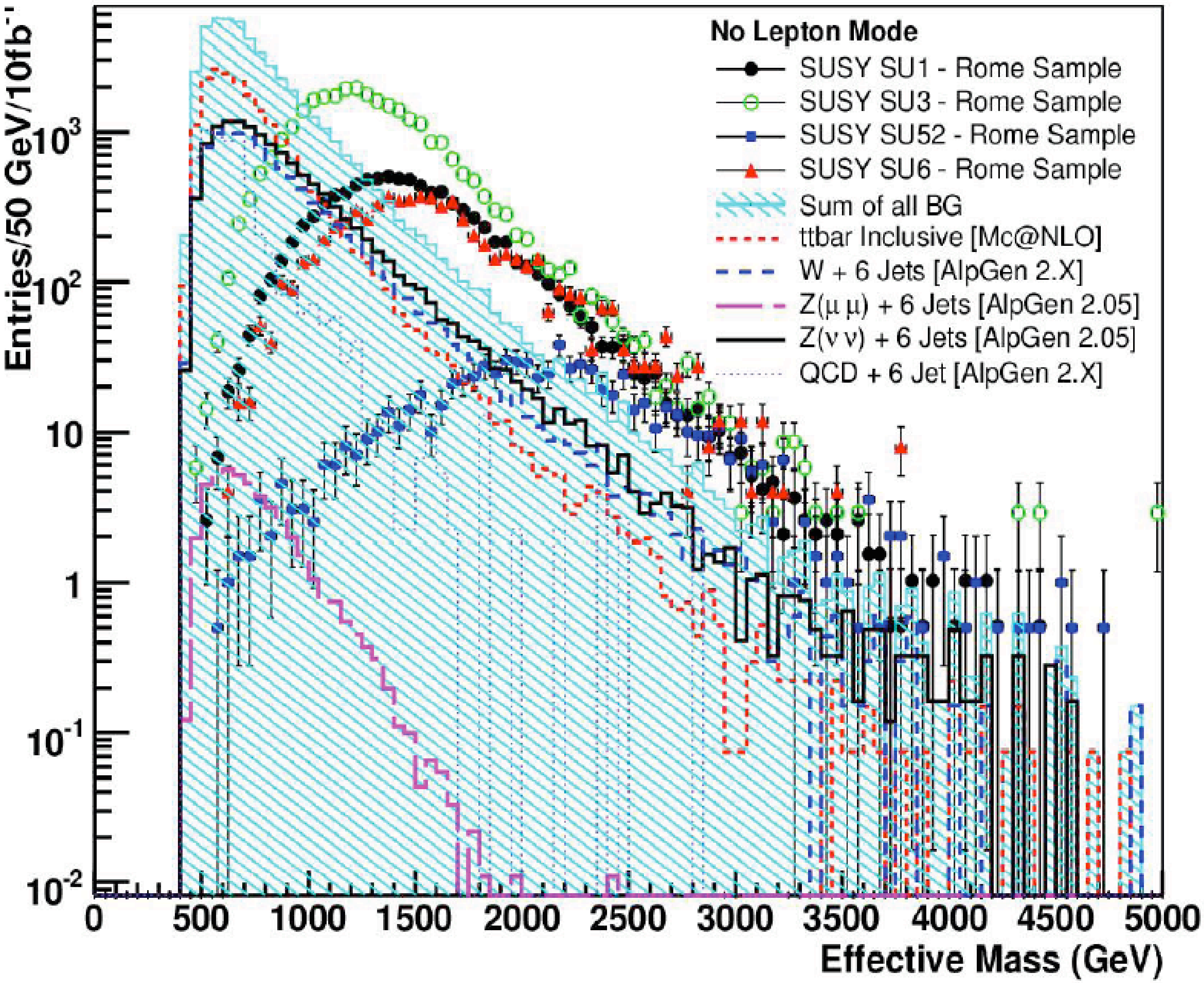


Campbell-Huston-Stirling

To discover these new physics events, we must make a vertiginous descent into this Standard Model background. There is a tremendous gain in concentrating on events with large HT and large missing ET. Still, we must pass through the levels:

σ_{tot}	100 mb
jet w. $p_T > 100$	1 μb
Drell-Yan	100 nb
$t\bar{t}$	800 pb
Dark Matter ($M < 1$ TeV)	1-10 pb

Sanjay Padhi recently made the following projection of the contributions of the various processes to the SM backgrounds.



HT distribution subject to

$\not{E}_T > 100$

4 jets, 2 w.

$E_T > 100$

ATLAS full simulation

In the real experiment, we would like to measure the background levels using data. there is a first level of this analysis that is very straightforward. Identify events of

$$pp \to Z + \text{jets} \ , \quad Z \to \ell^+\ell^-$$

with no missing energy. These events are unlikely to be contaminated by SUSY production. Remove the leptons; this is a model for $pp \to Z + \text{jets} \ , \quad Z \to \nu\bar{\nu}$ the single most important background shown above.

However, this simple analysis is rate-limited, since

$$\frac{\Gamma(Z \to e^+e^-, \mu^+\mu^-)}{\Gamma(Z \to \nu\overline{\nu})} = \frac{1}{3}$$

It would be better to build a complete model of

$$pp \to (W, Z) + \text{jets}$$

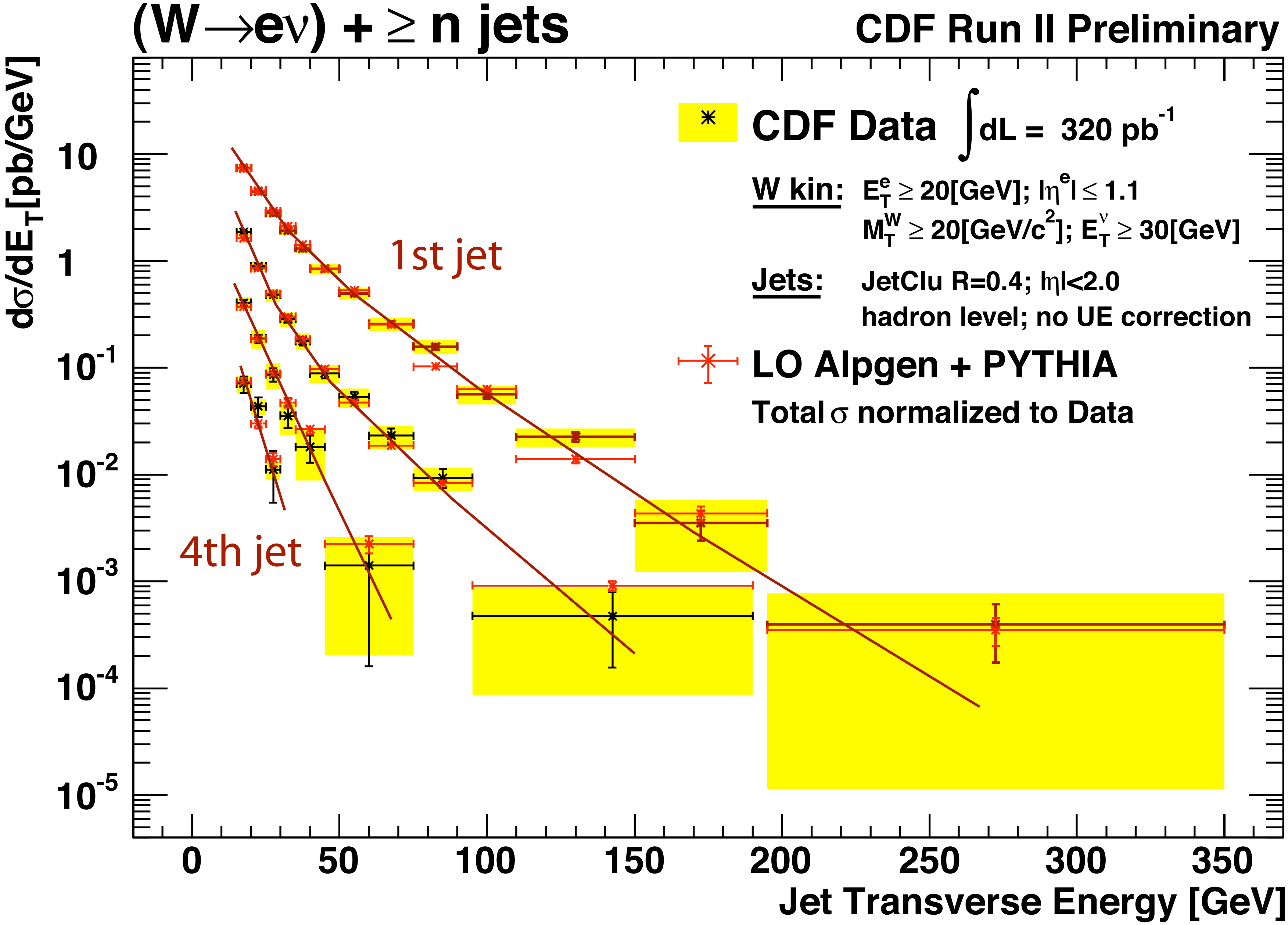
that uses data from both Z and W production.

There is a methodology for this that has been used successfully in the CDF and DO analyses of top quark production at the Tevatron.

Use the fact that new particles appear in events with large numbers of jets and large HT.

Compute systematically the SM rates for n jet production. The results for fewer jets can be validated against data, both in a general setting and also with the experimental cuts that define the new physics search. Now extrapolate to large numbers of jets and large HT.

I like to call this method the Berends-Giele staircase.


(W→eν) + ≥ n jets
CDF Run II Preliminary
CDF Data ∫dL = 320 pb^-1
W kin: E_T^e ≥ 20[GeV]; |η^e| ≤ 1.1
M_T^W ≥ 20[GeV/c^2]; E_T^ν ≥ 30[GeV]
Jets: JetClu R=0.4; |η|<2.0
hadron level; no UE correction
LO Alpgen + PYTHIA
Total σ normalized to Data
1st jet
4th jet
dσ/dE_T [pb/GeV]
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
0
50
100
150
200
250
300
350
Jet Transverse Energy [GeV]

Let me show you how this technique was used in the search for the top quark at the Fermilab Tevatron. For top quark production at the Tevatron

$$\sigma(t\bar{t}) = 7 \text{ pb} \qquad \sigma_{tot} = 100 \text{ mb}$$

so the problem has similar difficulty to identifying dark matter events at the LHC. The top quark decays via

$$t \to bW^+ \to b\bar{q}q \text{ or } b\ell^+\nu$$

so, in this case also, W + quarks, gluons events provide the dominant background.

The quarks and gluons are observed as jets of pions and kaons with large ET.

e + 4 jet event

40758_44414

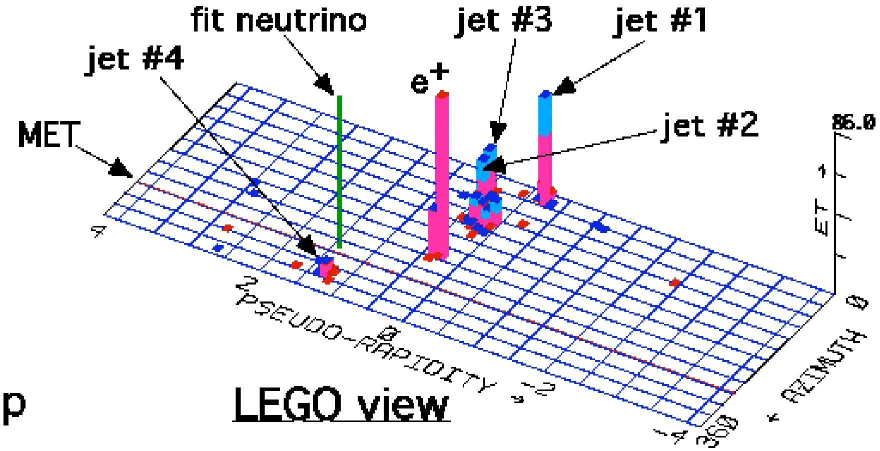
24-September, 1992

TWO jets tagged by SVX

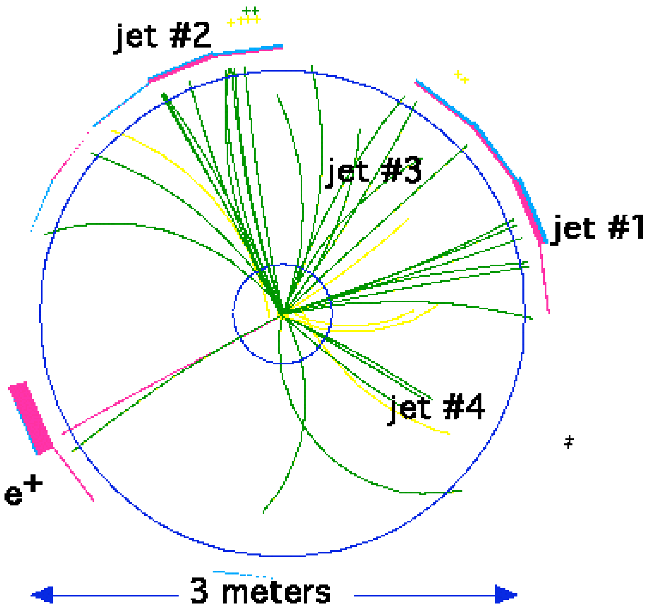
fit top mass is 170 +- 10 GeV

e$^+$, Missing E$_t$, jet #4 from top

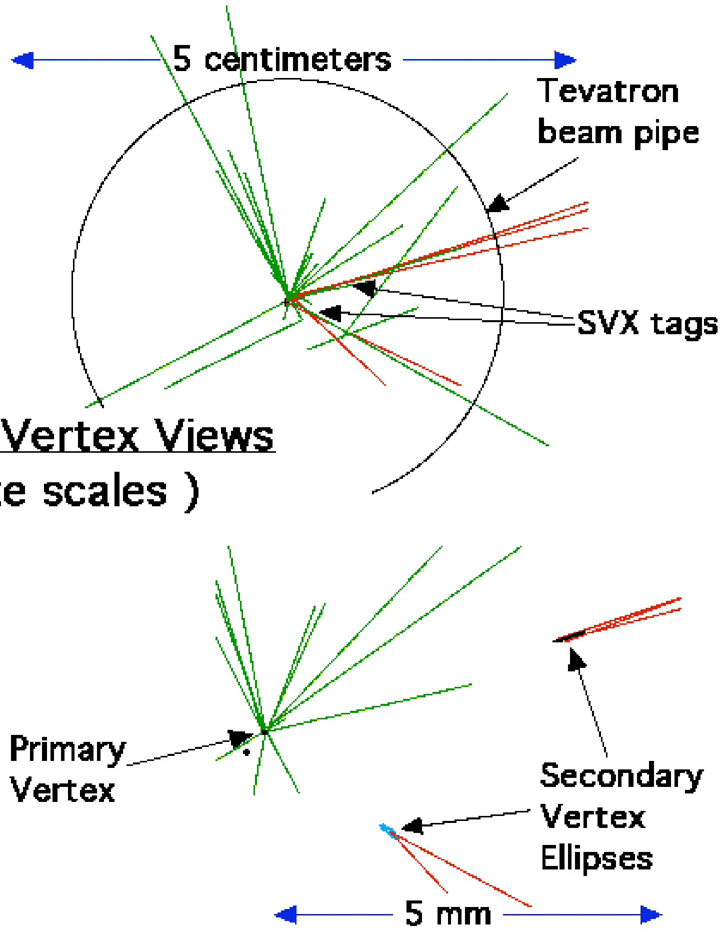
jets 1,2,3 from top (2&3 from W)



LEGO view



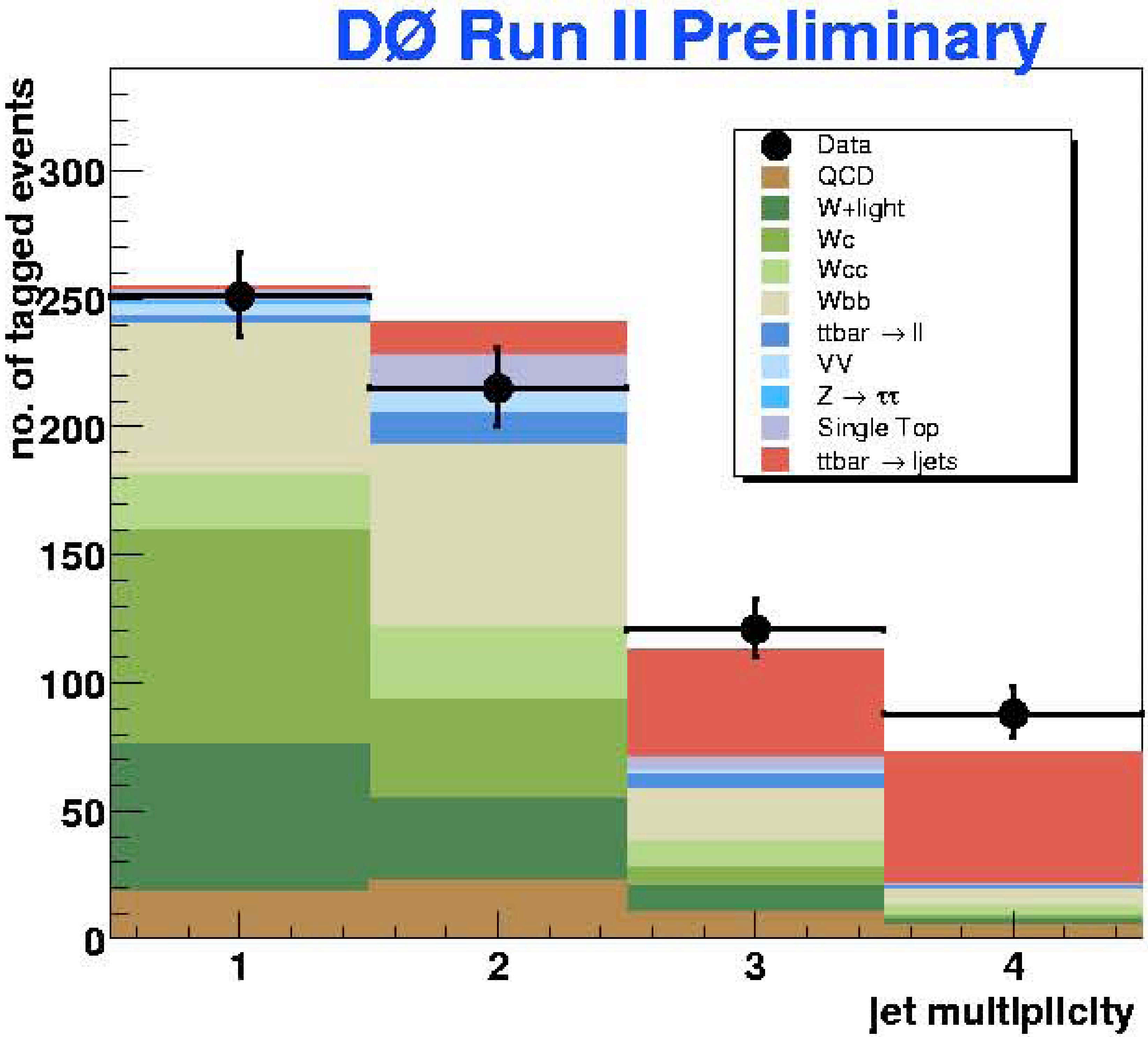
Tracking View



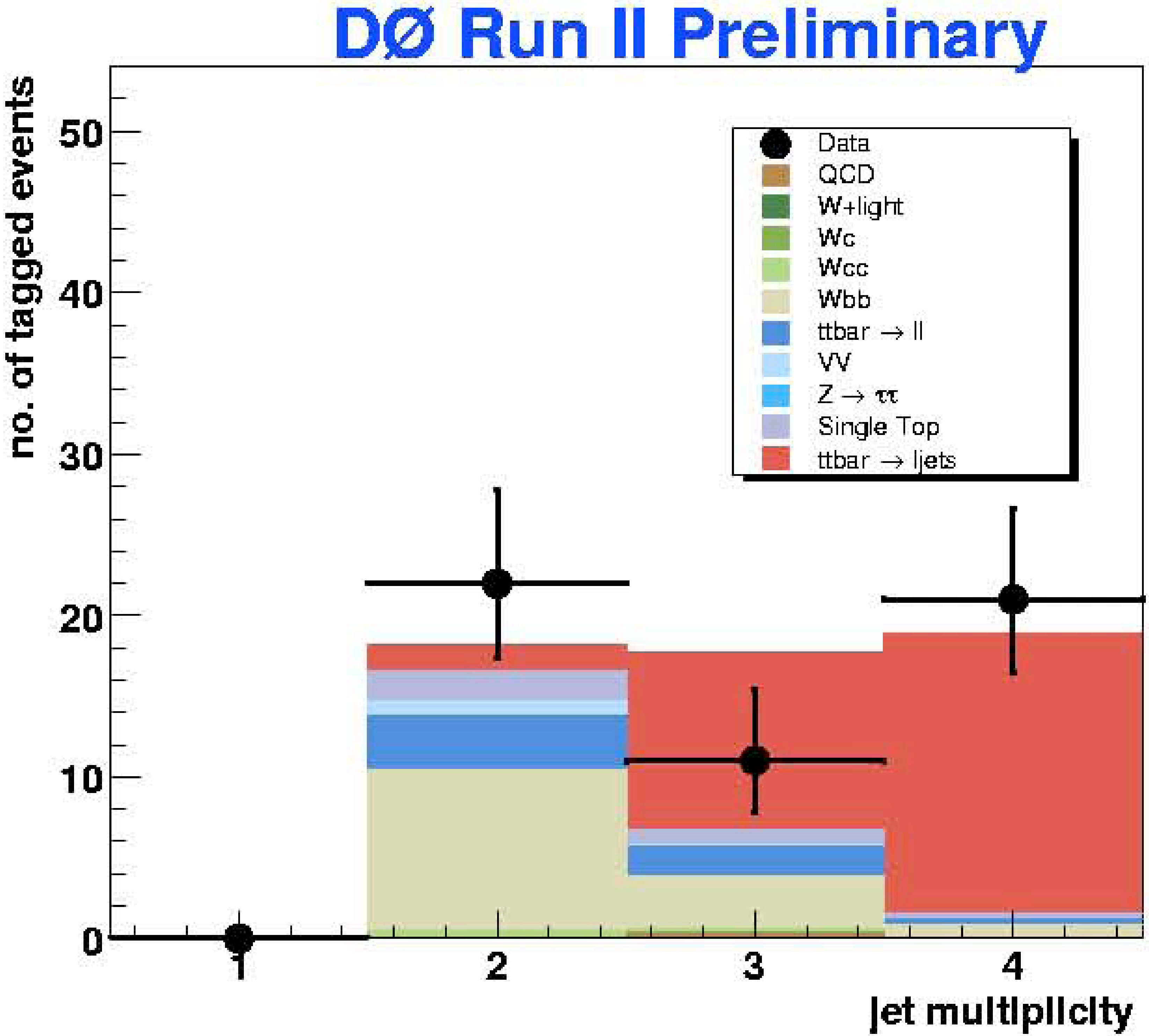
Two Vertex Views

(note scales)

CDF

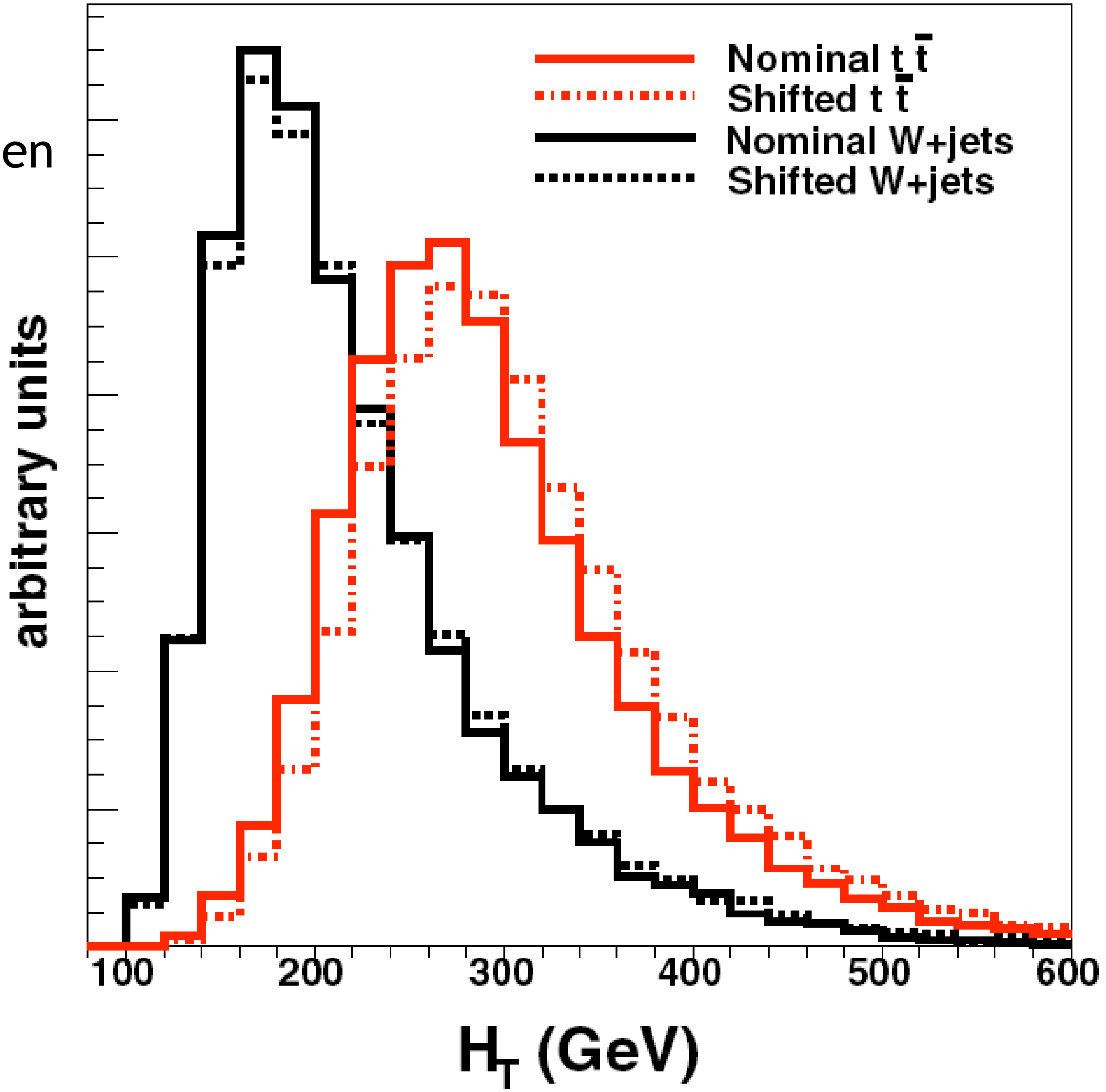

DØ Run II Preliminary
no. of tagged events
0
50
100
150
200
250
300
1
2
3
4
jet multiplicity
Data
QCD
W+light
Wc
Wcc
Wbb
ttbar → ll
VV
Z → ττ
Single Top
ttbar → ljets

The analysis can run in more than one dimension.
Add a second b tag or a constraint on H_T .

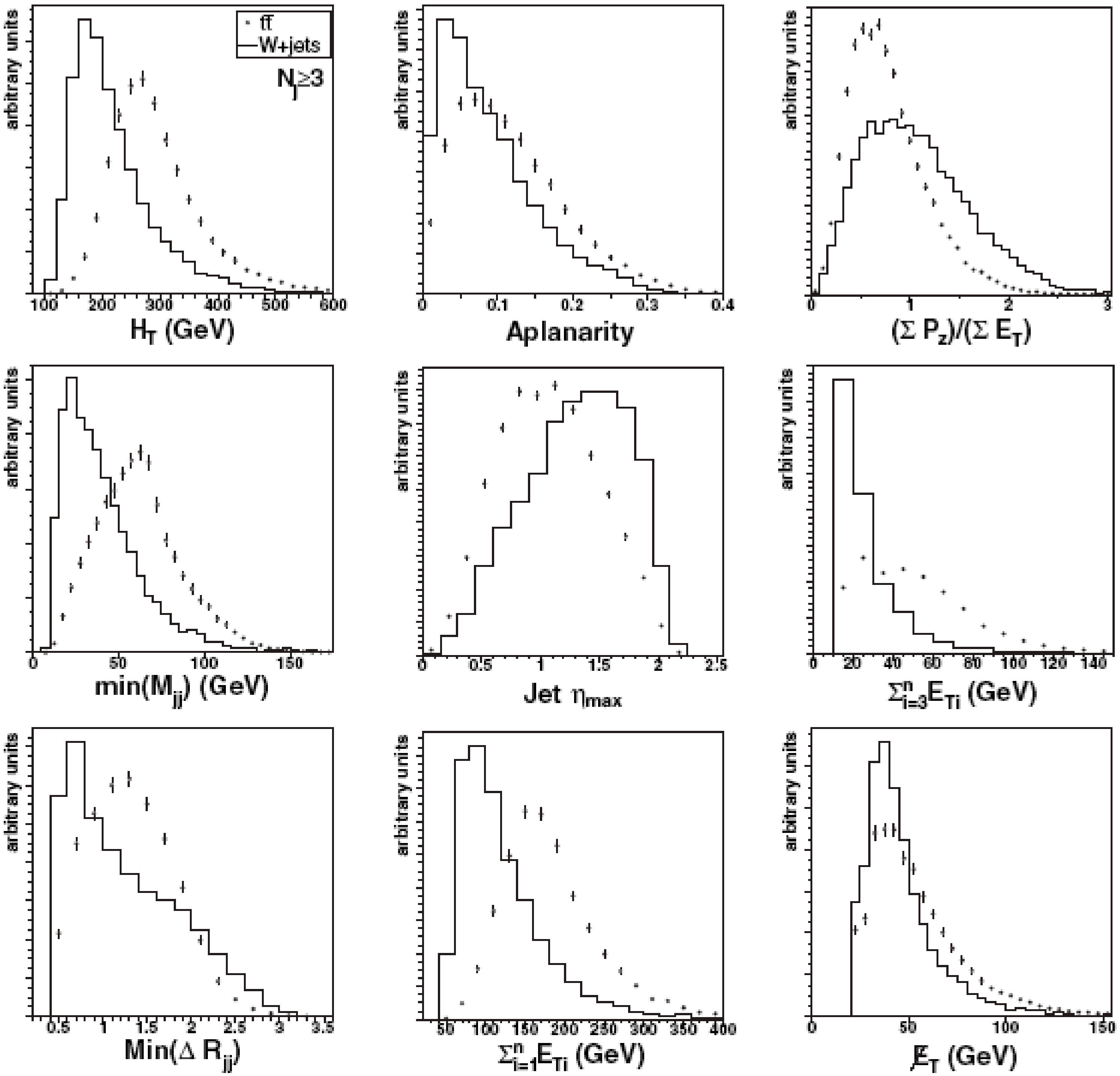

DØ Run II Preliminary
no. of tagged events
0
10
20
30
40
50
1
2
3
4
jet multiplicity
● Data
QCD
W+light
Wc
Wcc
Wbb
ttbar → ll
VV
Z → ττ
Single Top
ttbar → ljets

CDF

Comparison of HT distributions between ttbar and W + jets events



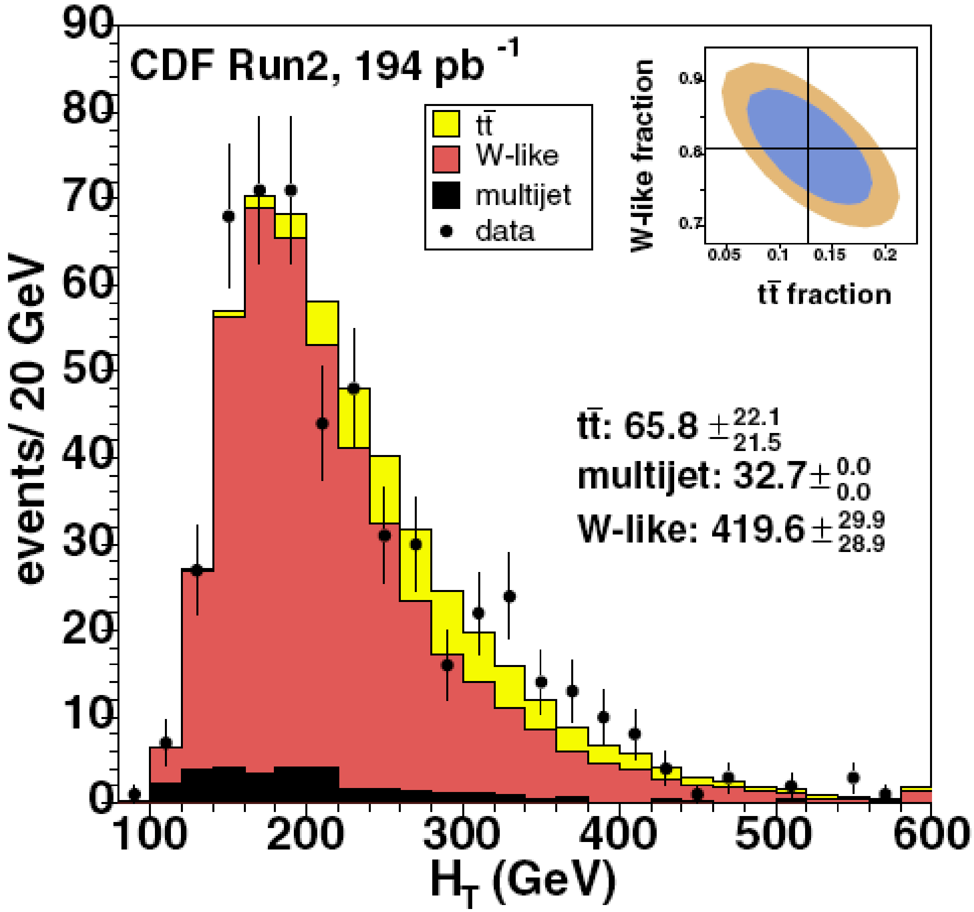
ttbar/W+jets shape comparisons for 9 kinematic observables.



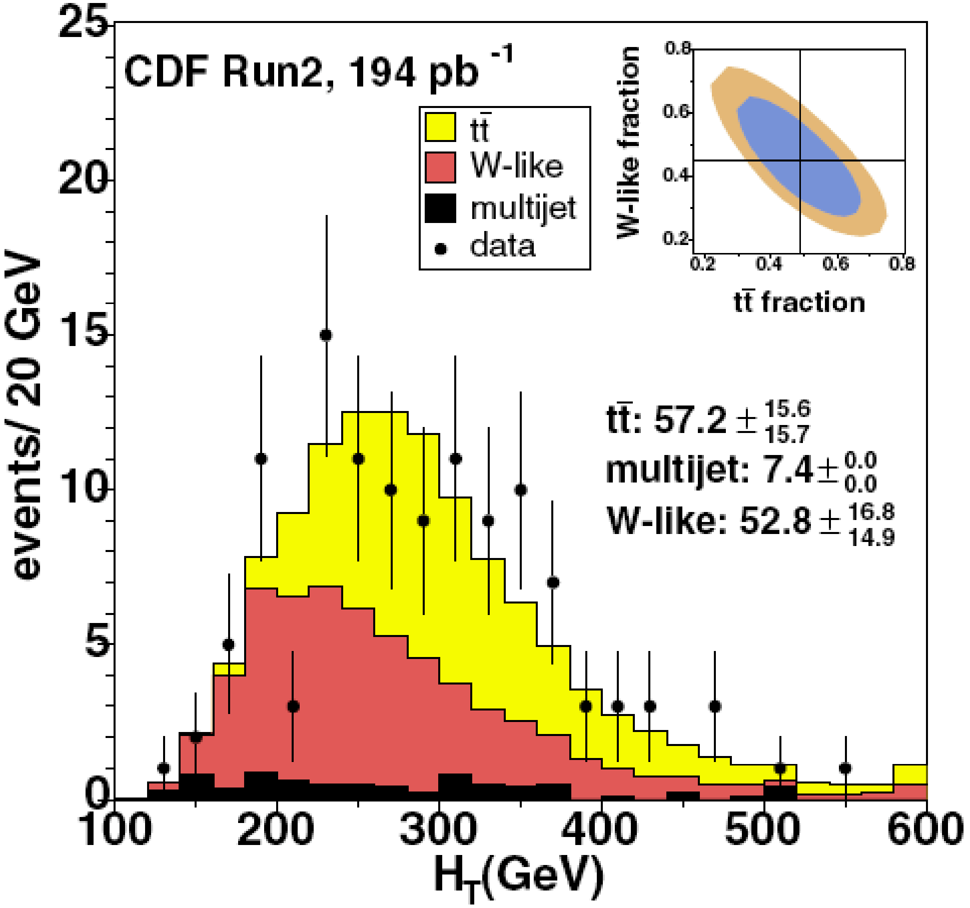
CDF

Using these and 10 more variables input to a neural network classfier, CDF has demonstrated the ability to observe $t\bar{t}$ events without b-tagging. Here are the last two steps in the staircase in that analysis.

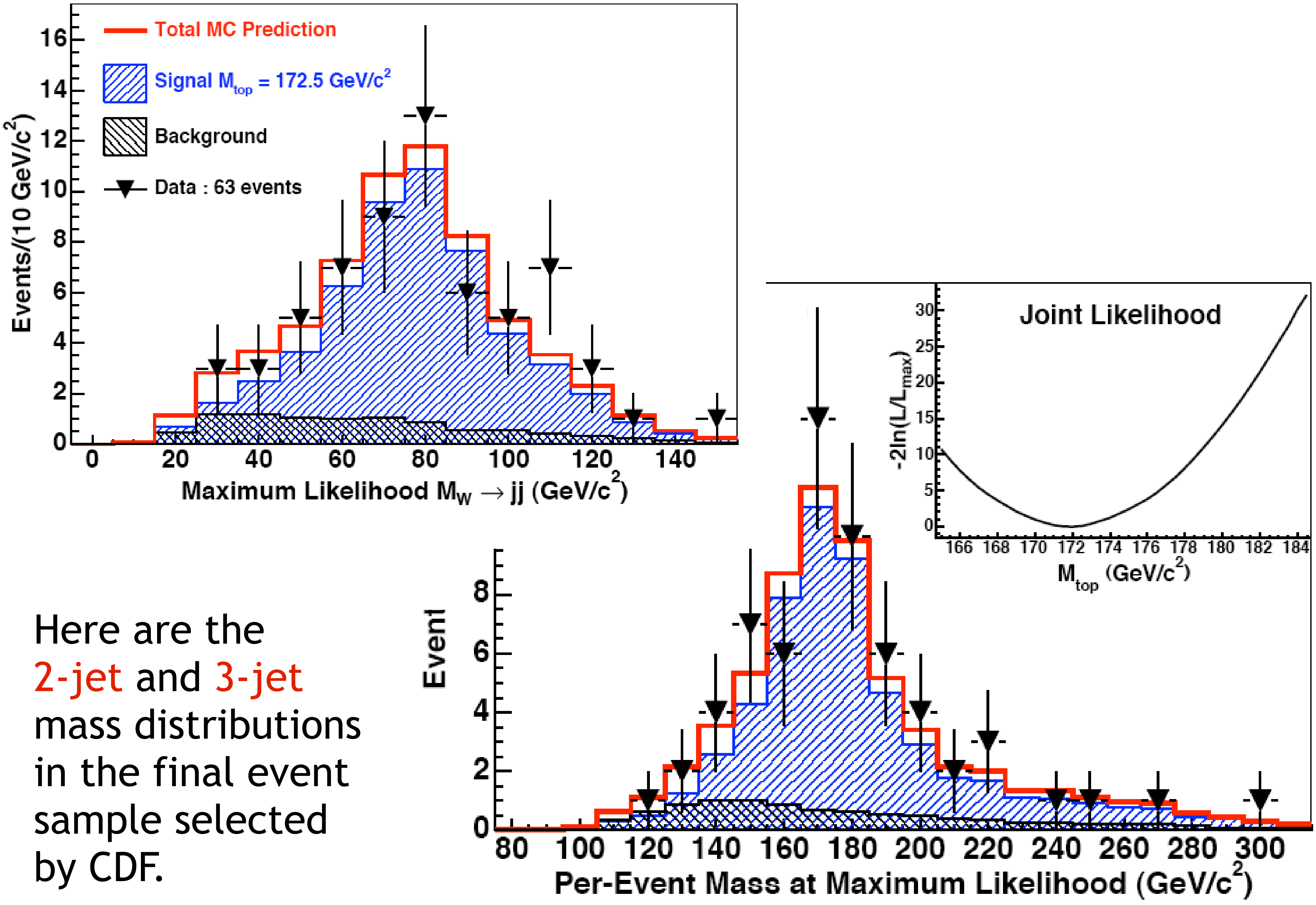
W+3 jets



W + 4 jets



$$H_T = \not{E}_T + E_{T\ell} + \sum_i E_{Ti}$$



Here are the 2-jet and 3-jet mass distributions in the final event sample selected by CDF.

We can also move in the direction of multilepton signatures. Here there is another staircase, the Baer-Tata staircase.

Many new physics models such as supersymmetry predict 2, 3, 4 - lepton events in a steadily decreasing progression.

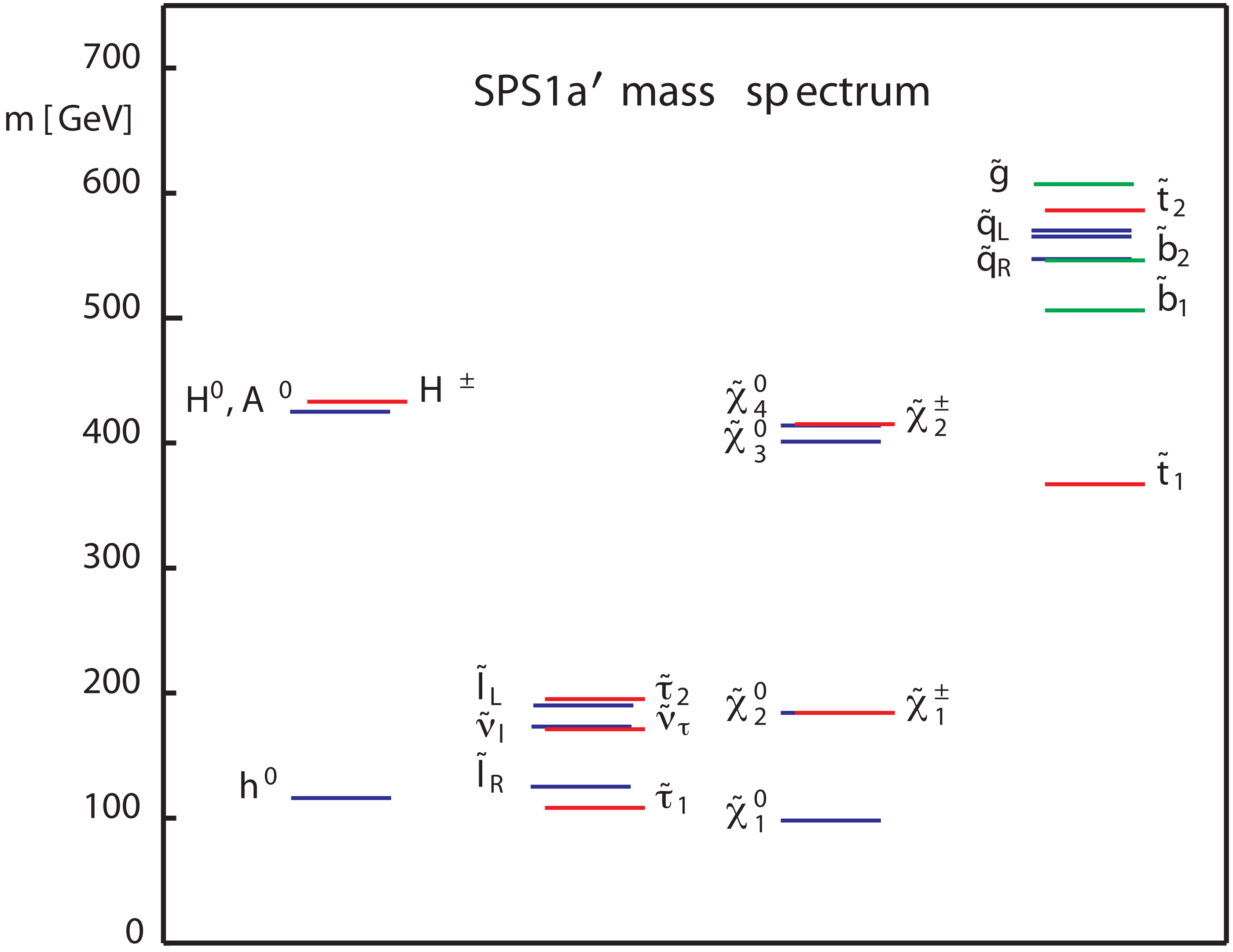
The Standard Model also produces such events, from multiple heavy-quark decays and jets faking leptons.

Fortunately, these come from the same W, Z, $t\bar{t}$ + jets processes that we have already been discussing.

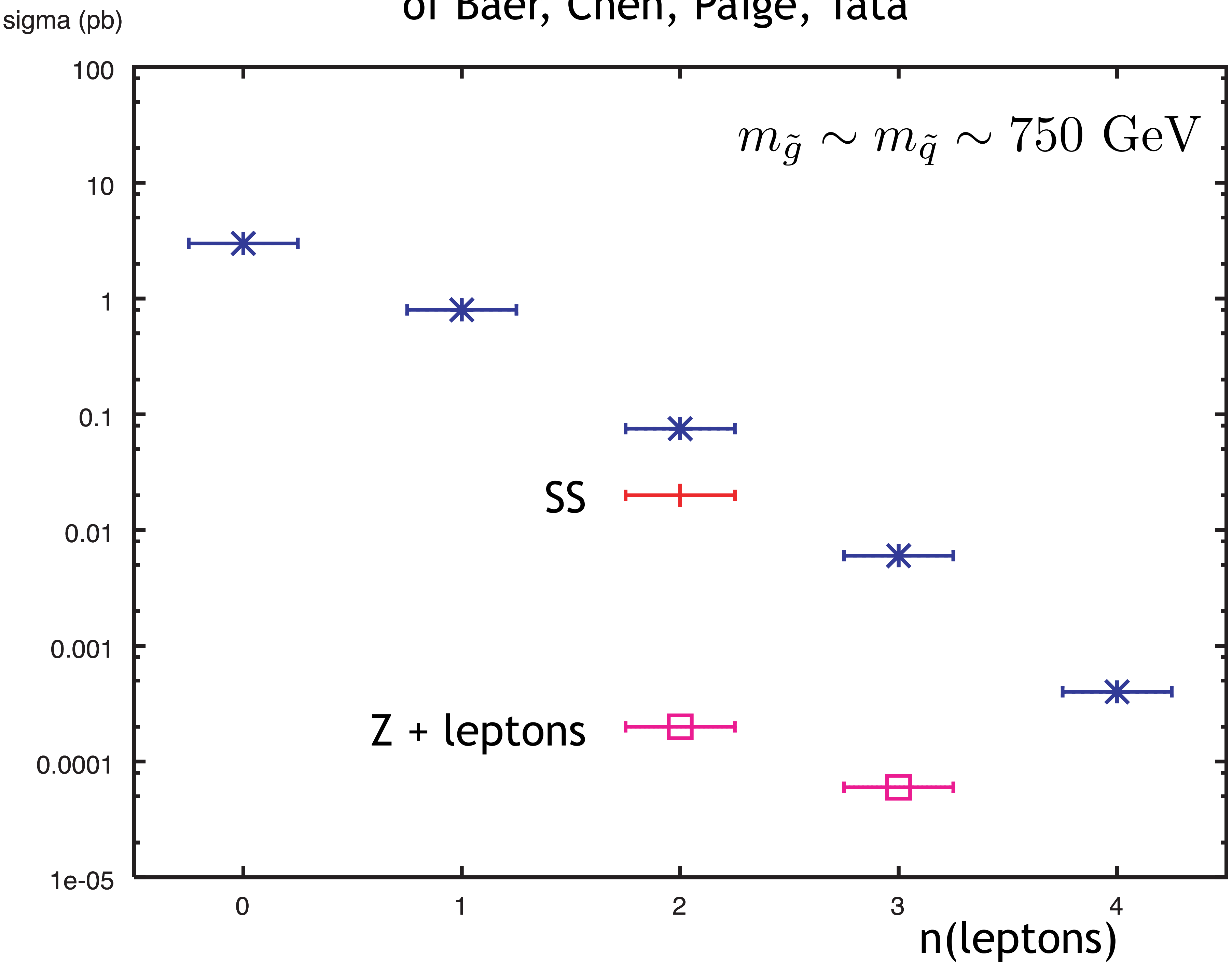
Electroweak backgrounds, e.g. $pp \to W^+W^+ \to \ell^+\ell^- + \mathrm{jets}$ are at the fb level.

Here is the mass spectrum of new particles in one example of a model with supersymmetry.

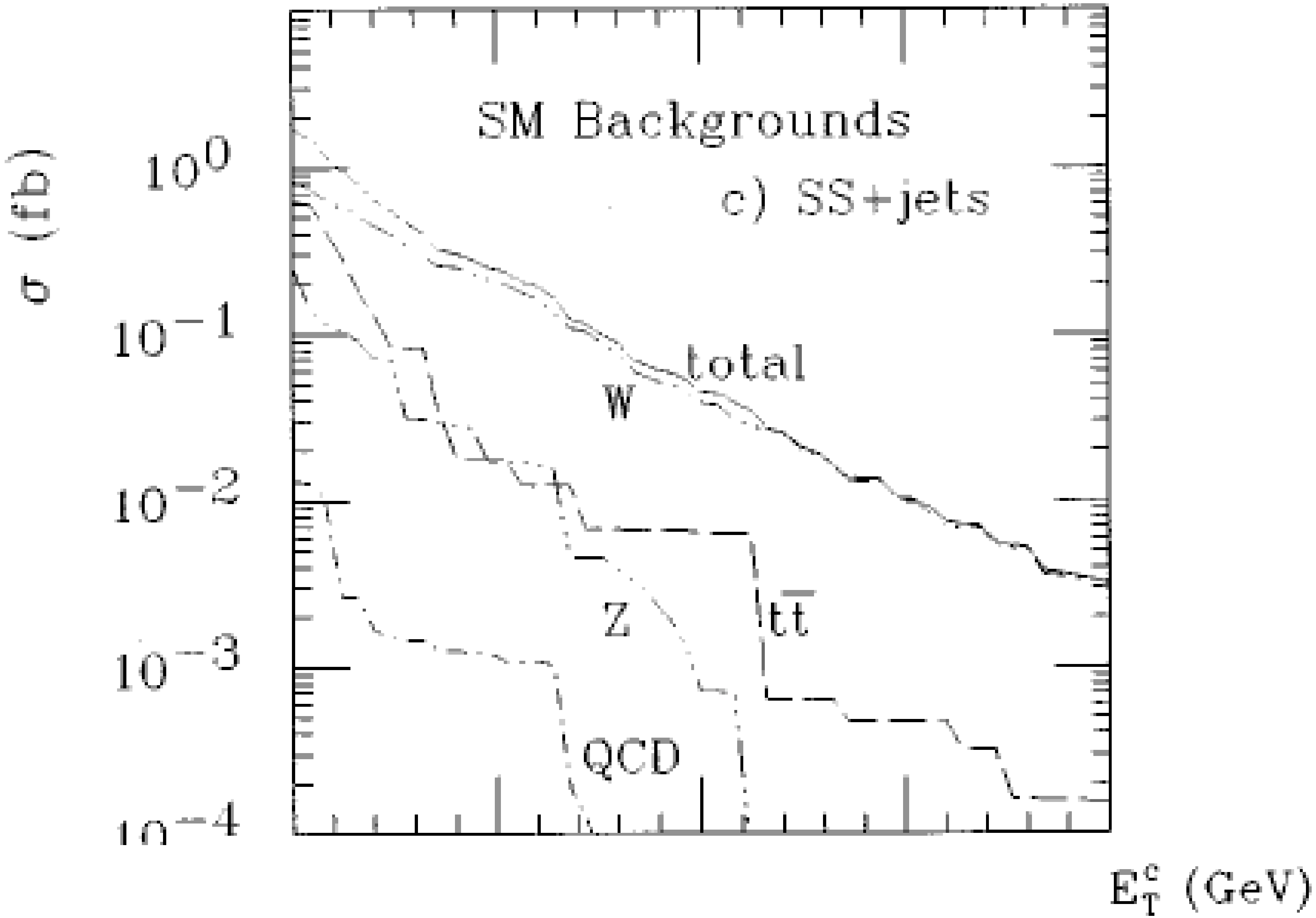
Note that there are many opportunties for isolated leptons to appear in heavy particle decays.



signal cross sections from one of the models of Baer, Chen, Paige, Tata



dissection of the Same Sign dilepton background from this paper



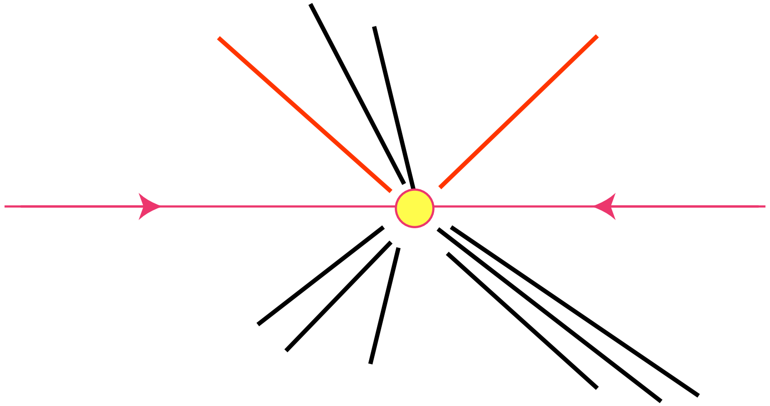
Now we come to the final question:

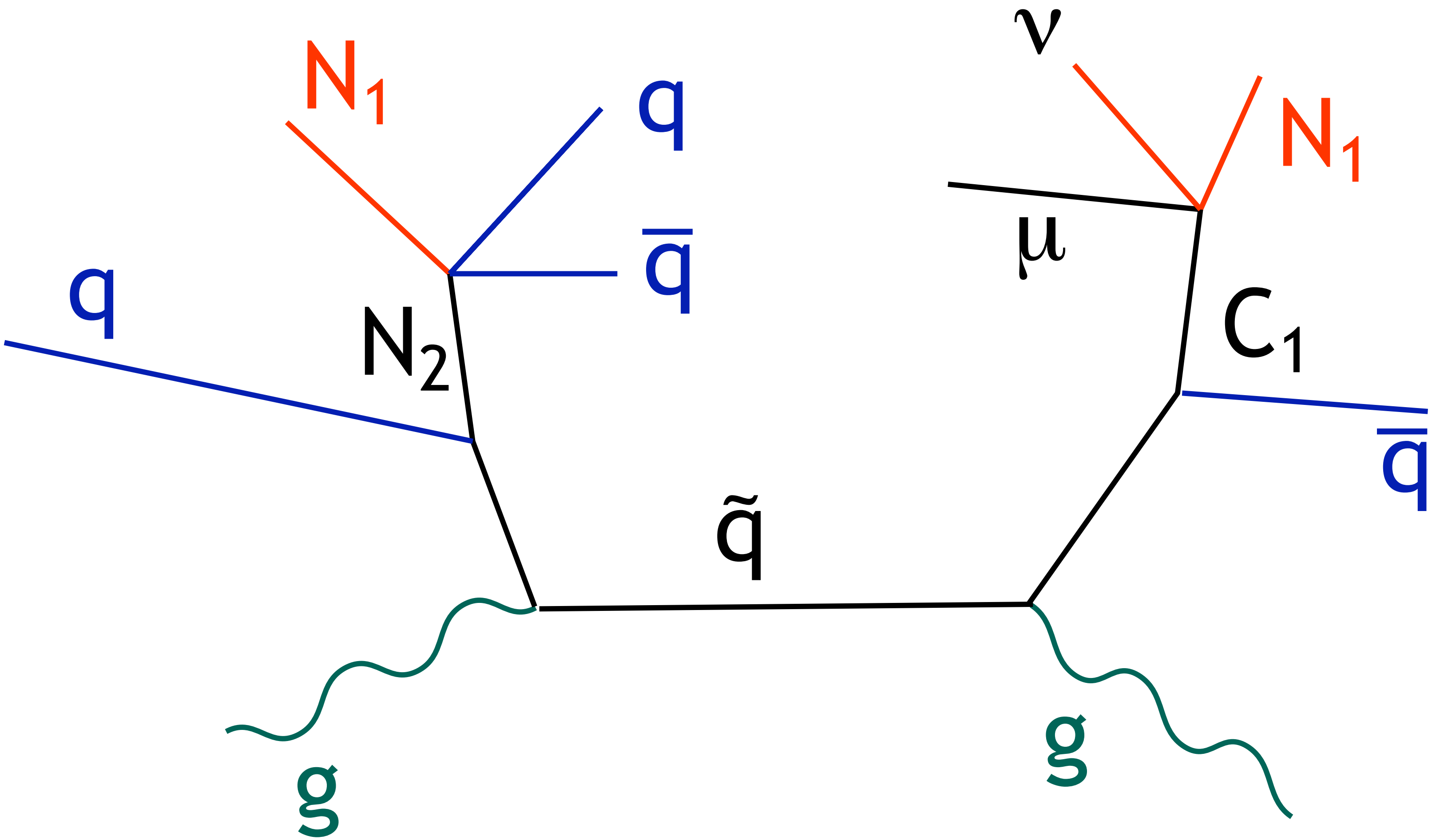
How do we measure the mass of the dark matter particle ?

There are significant difficulties in trying to measure new particle masses from resonances or bumps in particle distributions.

Any given process involves one quark or gluon colliding with another. We do not know the momenta of these individual particles. So we do not know the momentum of the initial state.

The final state contains two WIMPs. We do not observe these particles or measure their momentum. So we have incomplete information about the final state.




N1
q
ν
N1
q̄
μ
q
N2
C1
q̄
q̃
g
g

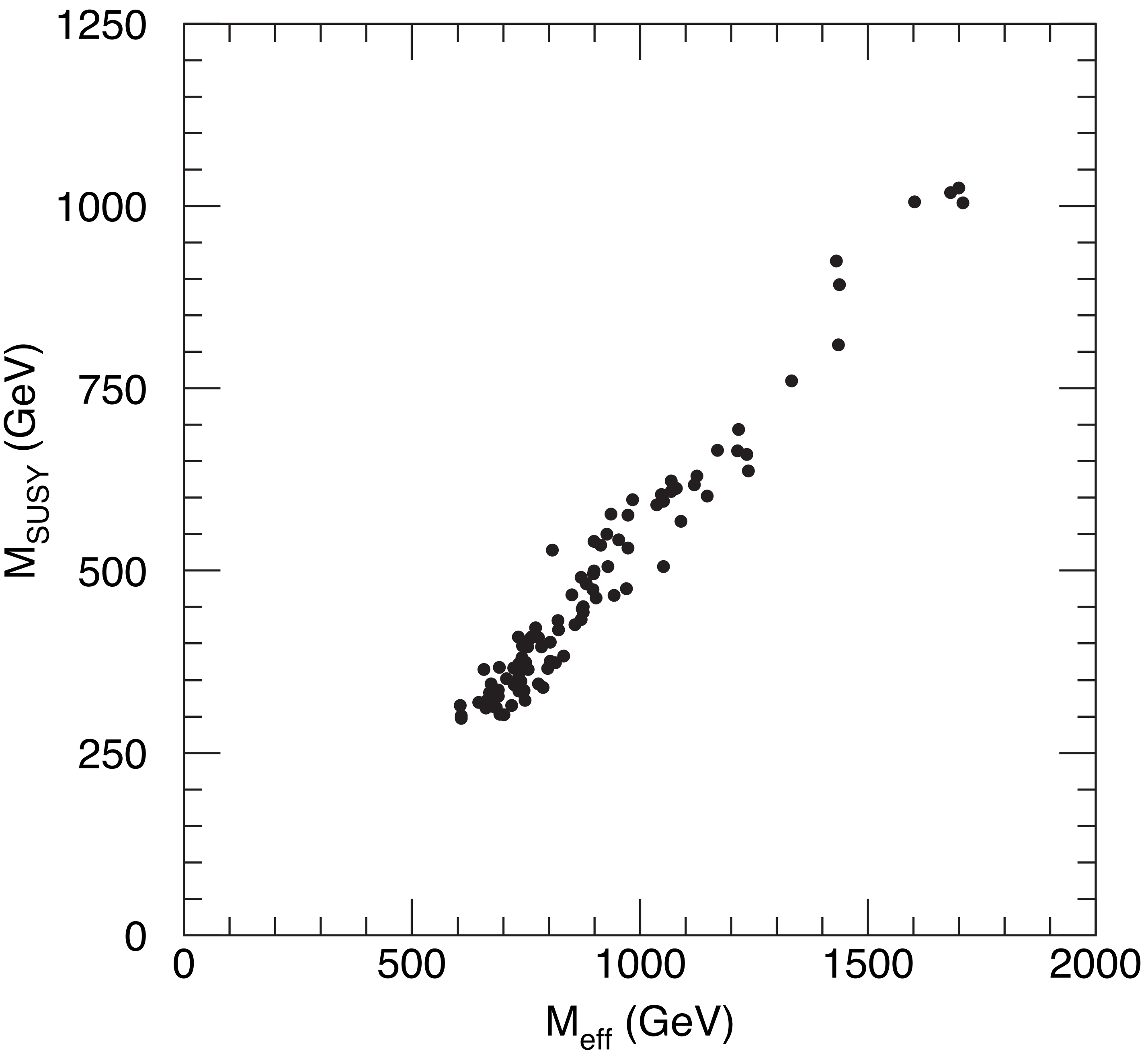
FIrst, we would like to have a general idea of the scale of the masses of the superparticles.

It seems likely that a measure of the total activity in the event would tell us this.

For example:

$$m_{eff} = \not{E}_T + \sum_{1}^{4} E_{Ti}$$

Use transverse projections of the measured energy deposition; these are insensitive to the momentum imbalance of the initial particles.



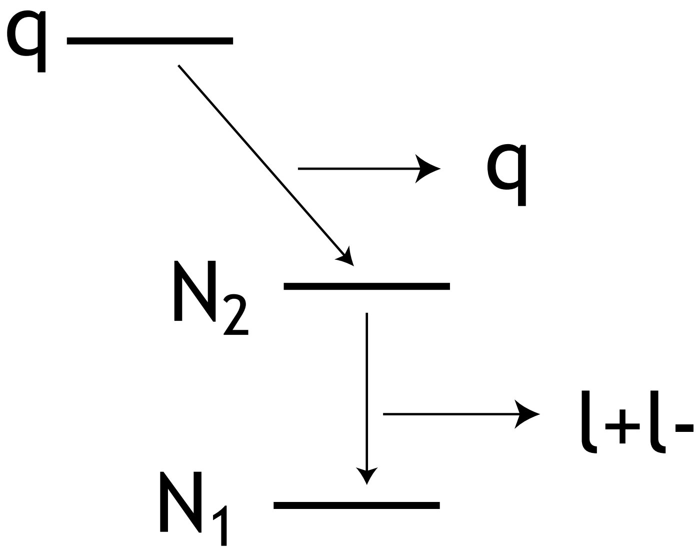
Hinchliffe-Paige-Shapiro-Soderqvist-Yao

Now focus in on the details of the spectrum.

Here we will use tricks that take advantage of special properties of each scenario.

Every spectrum has its own special features; we need to recognize and make use of them.

A feature of many supersymmetry spectra is the decay chain

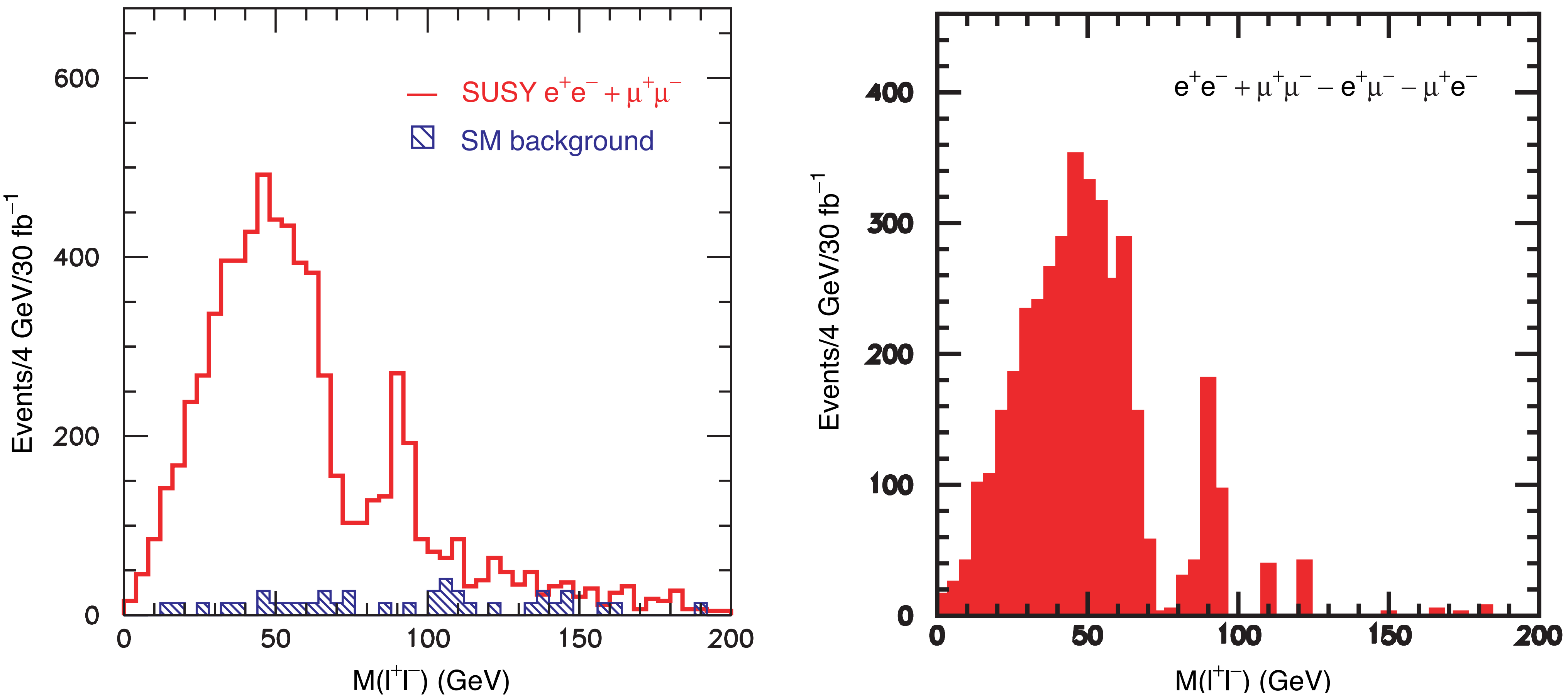


The lepton moment are measured completely, and we can construct their spectrum of invariant masses. If

$$m(N_2) - m(N_1) < m_Z$$

this spectrum terminates at

$$m(\ell^+\ell^-)_{max} = m(N_2) - m(N_1)$$

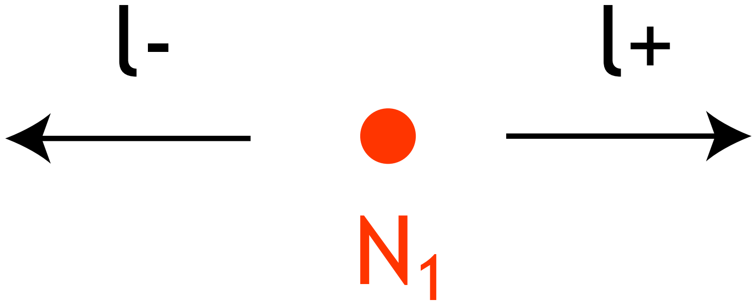


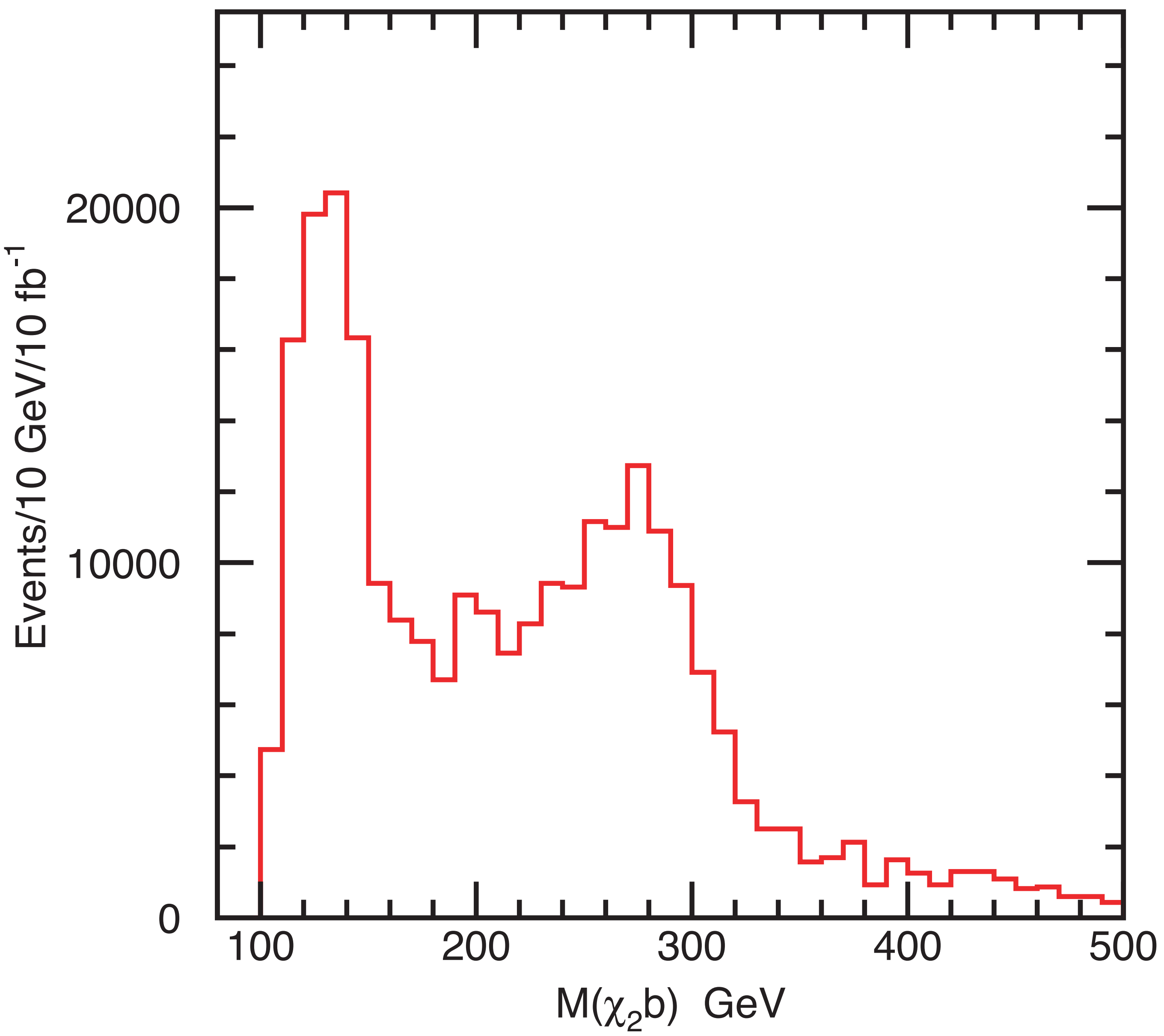
Hinchliffe et al.

Hinchliffe et al. noticed that one could go further.

At the endpoint, the unobserved WIMP is at rest in the frame of the l+l- pair. If we have an estimate of the mass of the WIMP, we can add back its 4-vector.

Now there is no more missing information. Add observed jets and reconstruct the parent squarks.

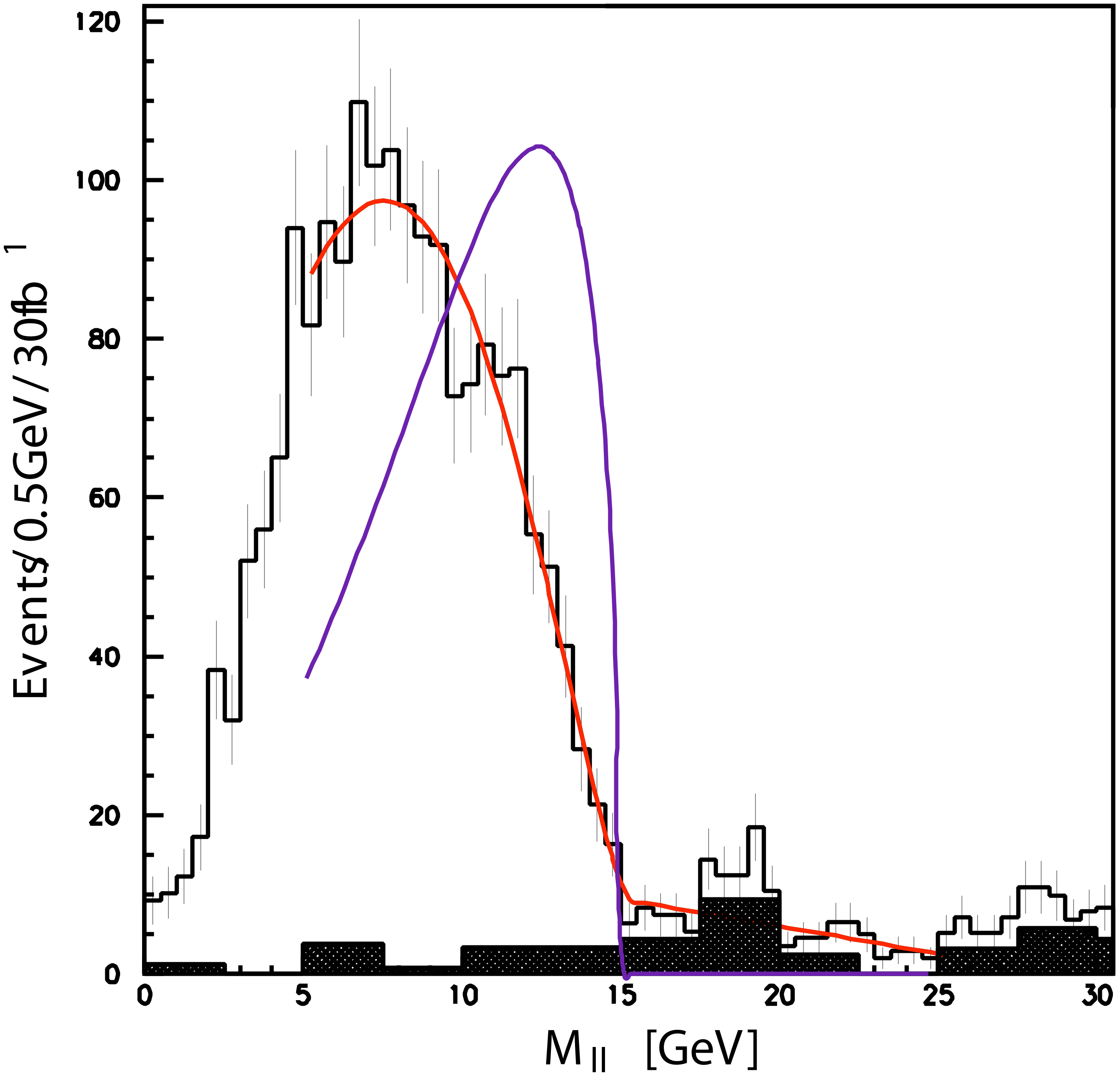




Hinchliffe et al.

Information on the properties of the WIMP is also available.

In models with supersymmetry, the WIMP can in principle be the superpartner either of a gauge boson or of a Higgs boson. The shape of the lepton mass distribution can distinguish gaugino- and Higgsino-like WIMPs.



Kitano-Nomura

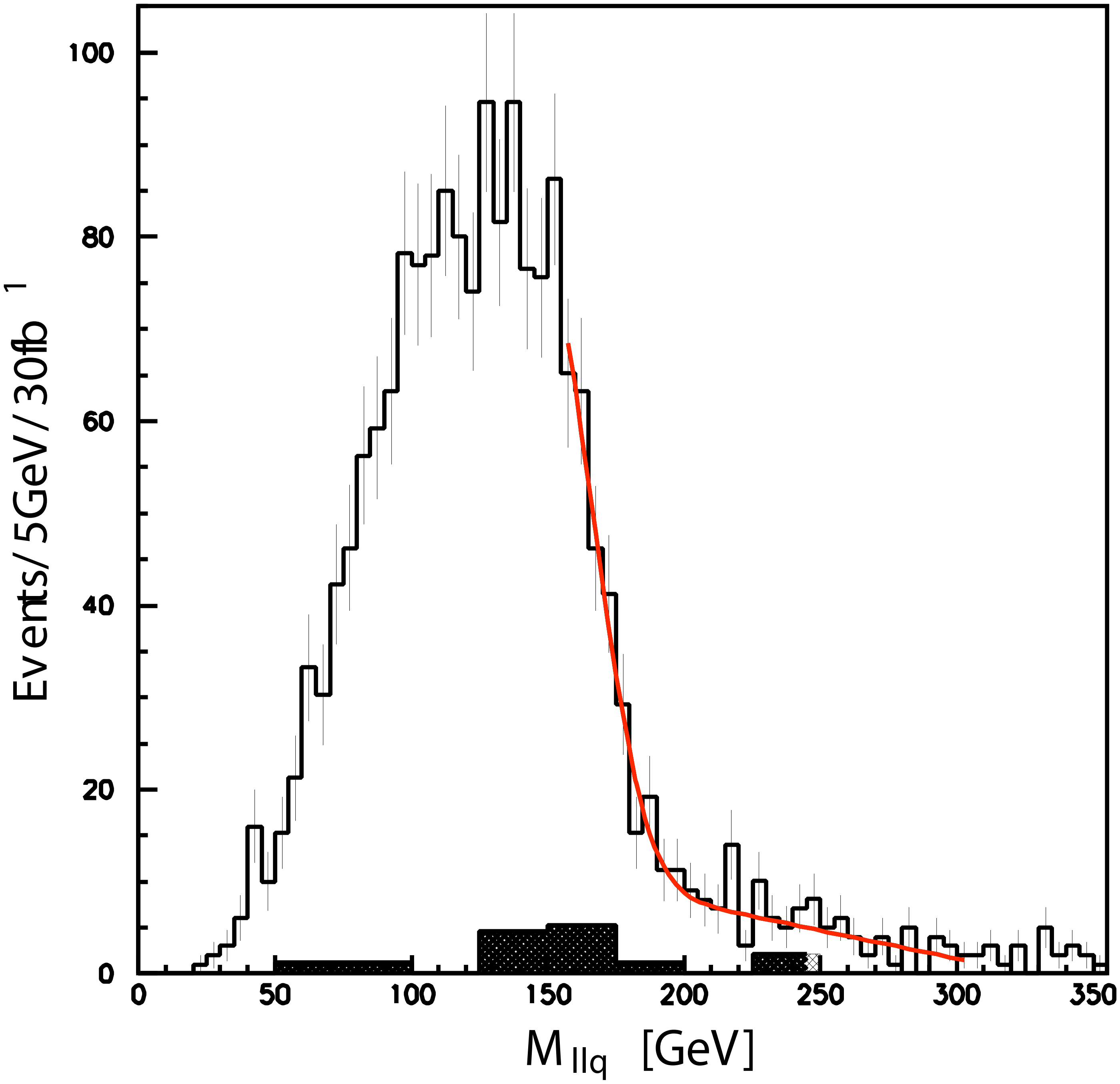
Again we can go further, following the analysis of Kitano and Nomura. Find the two hardest jets, and try to combine one with the lepton pair.

Some useful variables are:

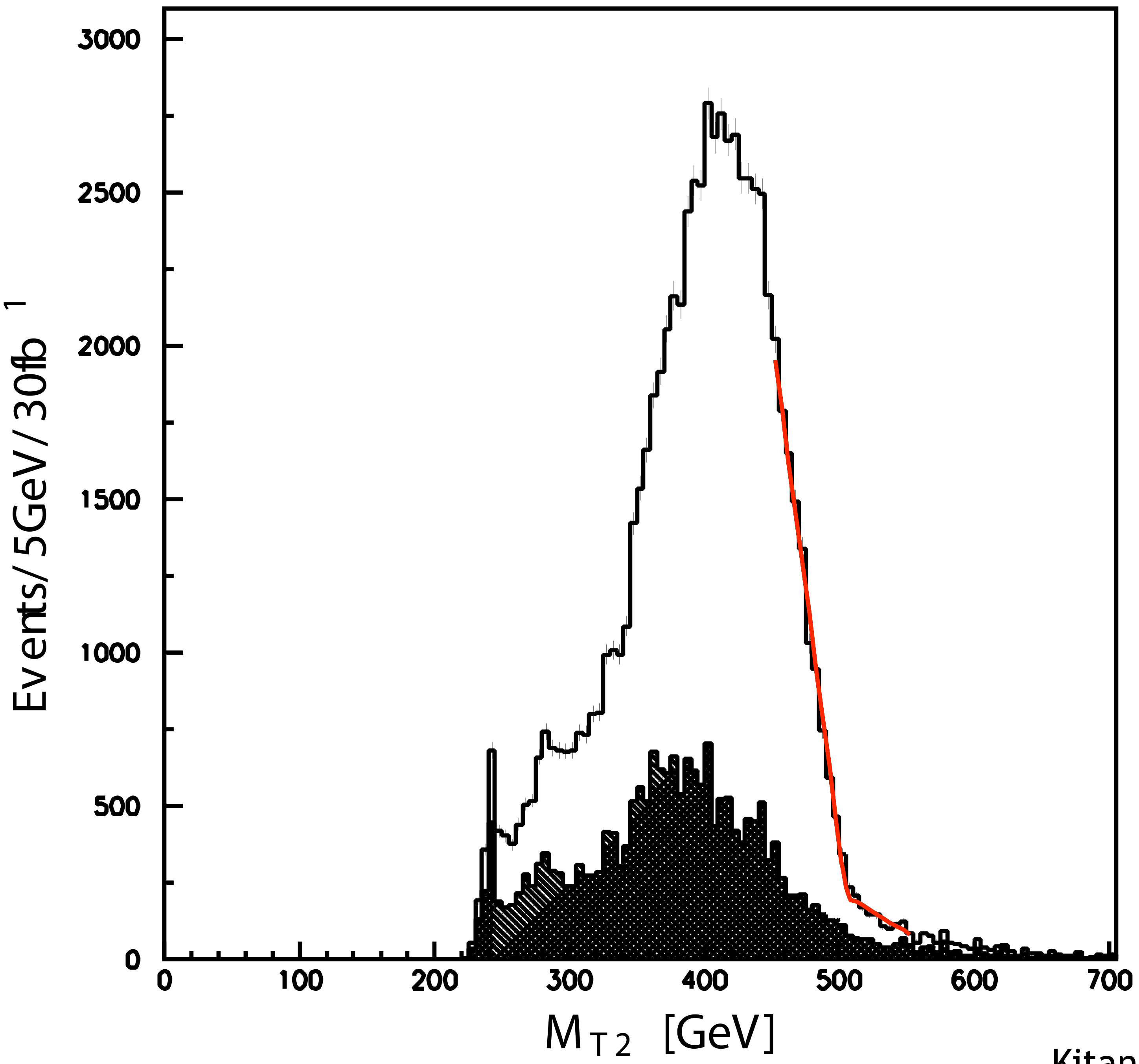
$$min_{1,2}\{m(\ell\ell j)\}$$

$$M_T^2 = min_{(\not{p}_{T1}+\not{p}_{T2}=\not{p}_T)}\ max\{m_T^2(p_1\ \not{p}_1), m_T^2(p_2\ \not{p}_2)\}$$

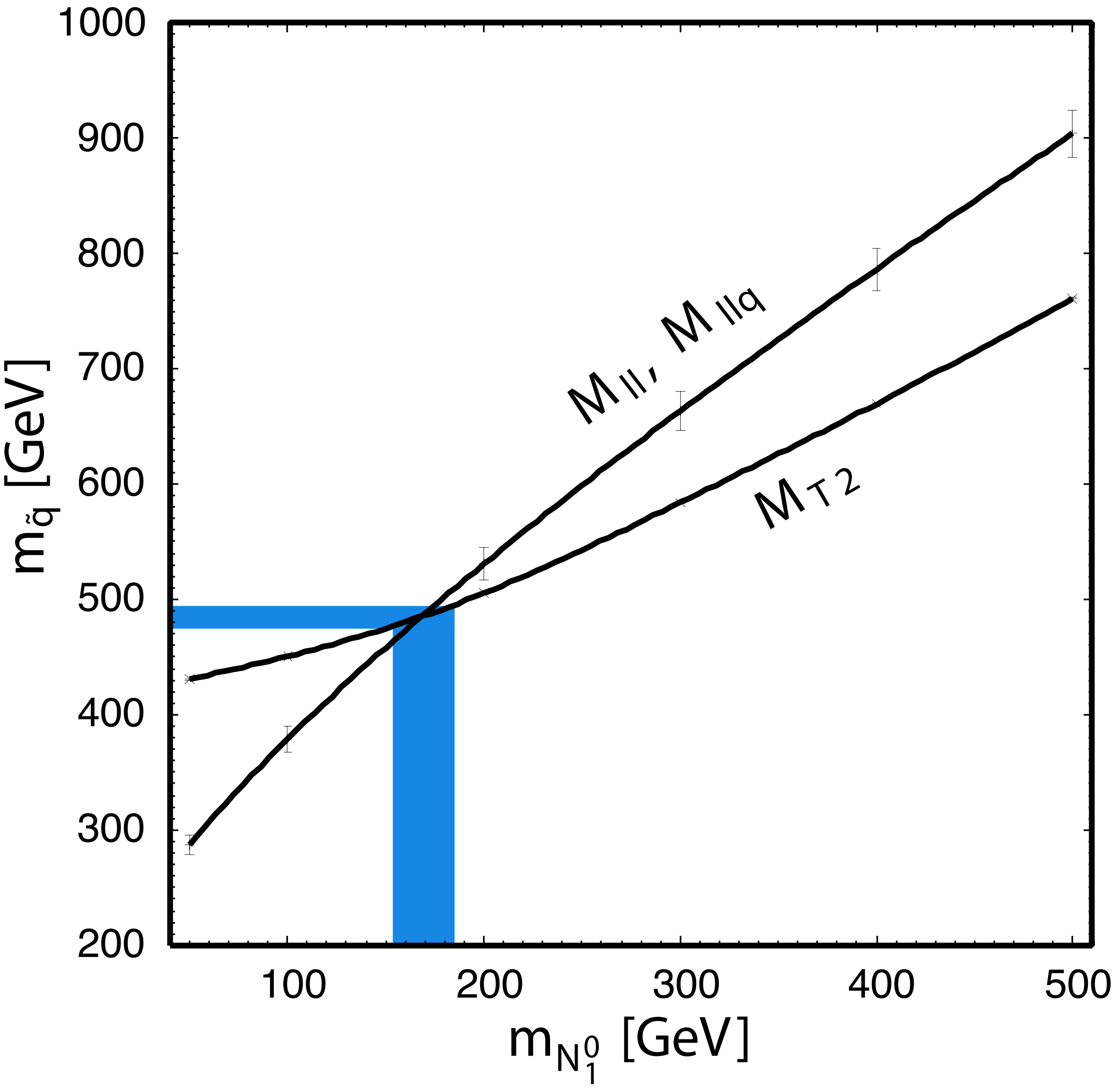
Lester and Summers



Kitano-Nomura



Kitano-Nomura



$$m_{N_1} = 169 \pm 17 \text{ GeV} \quad m_{\tilde{q}} = 486 \pm 11 \text{ GeV}$$

Kitano-Nomura

With these and other tricks, one can determine masses at the level of

10% or below for WIMP, squark, gluino masses

1% for mass differences in l+l- cascades

I cannot resist showing you a few glimpses from a further step into the future, in which new particles are also observed in e+e- collisions.

Here we know the kinematics of the initial states.

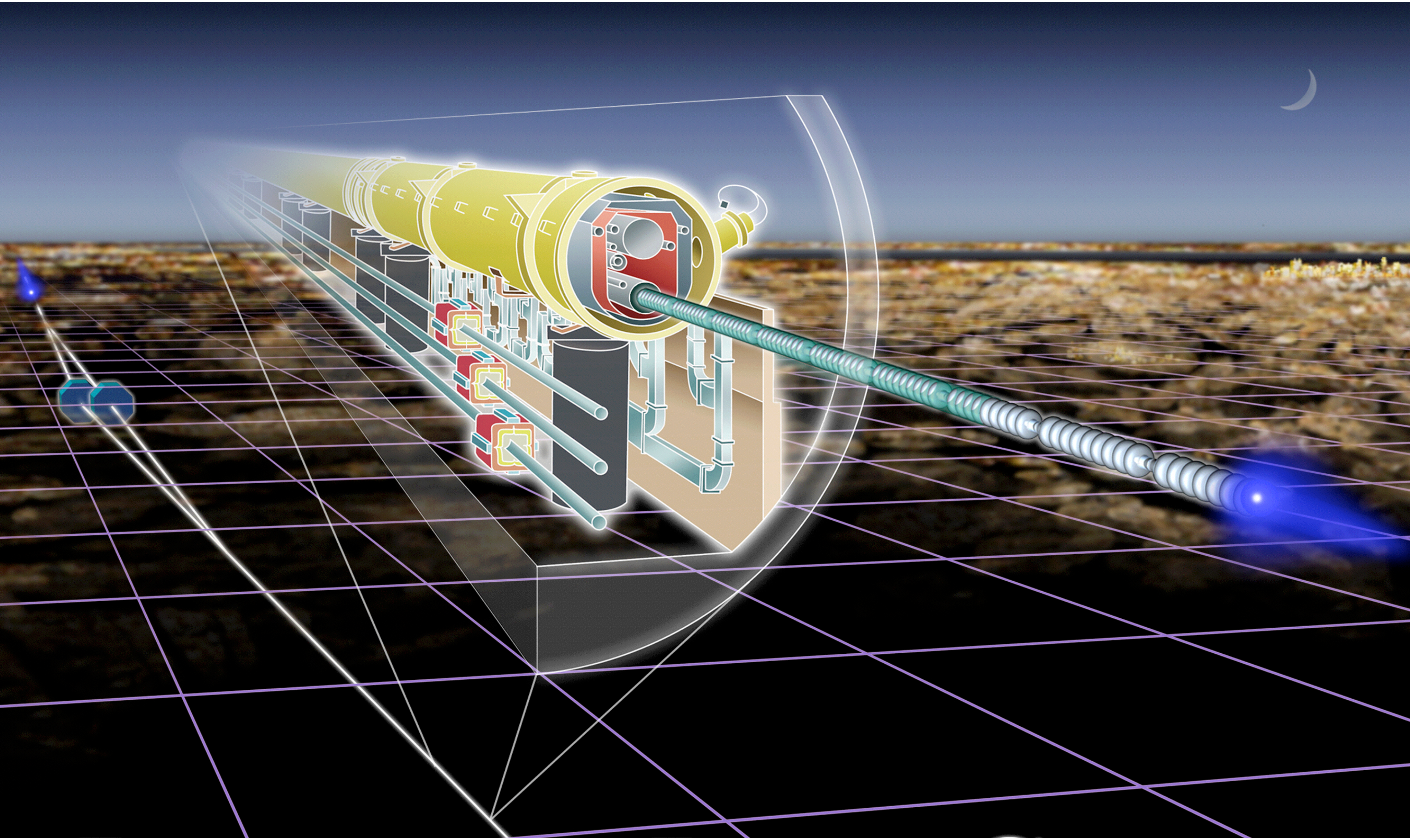
Also, since the colliding particles are leptons, the strong interactions need not become involved and the typical events are much simpler.

A major new e+e- collider is now under design.

the International Linear Collider (ILC)

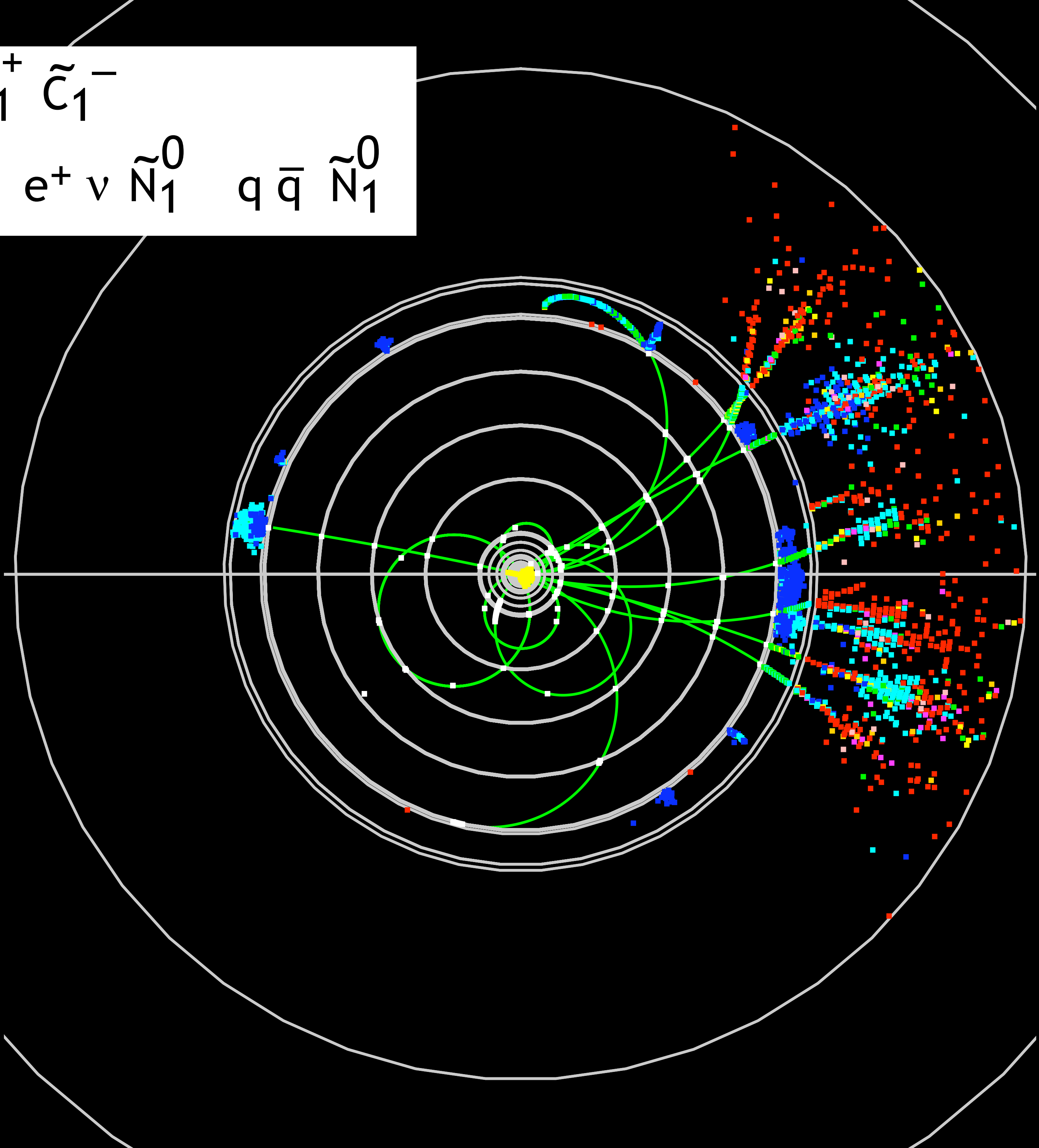
The design CM energy is 500 GeV, with the potential for upgrade to 1000 GeV.

The ILC will be a global project. An international design team, drawn from laboratories in the US, Europe, and Japan, is already at work.



the International Linear Collider (ILC)

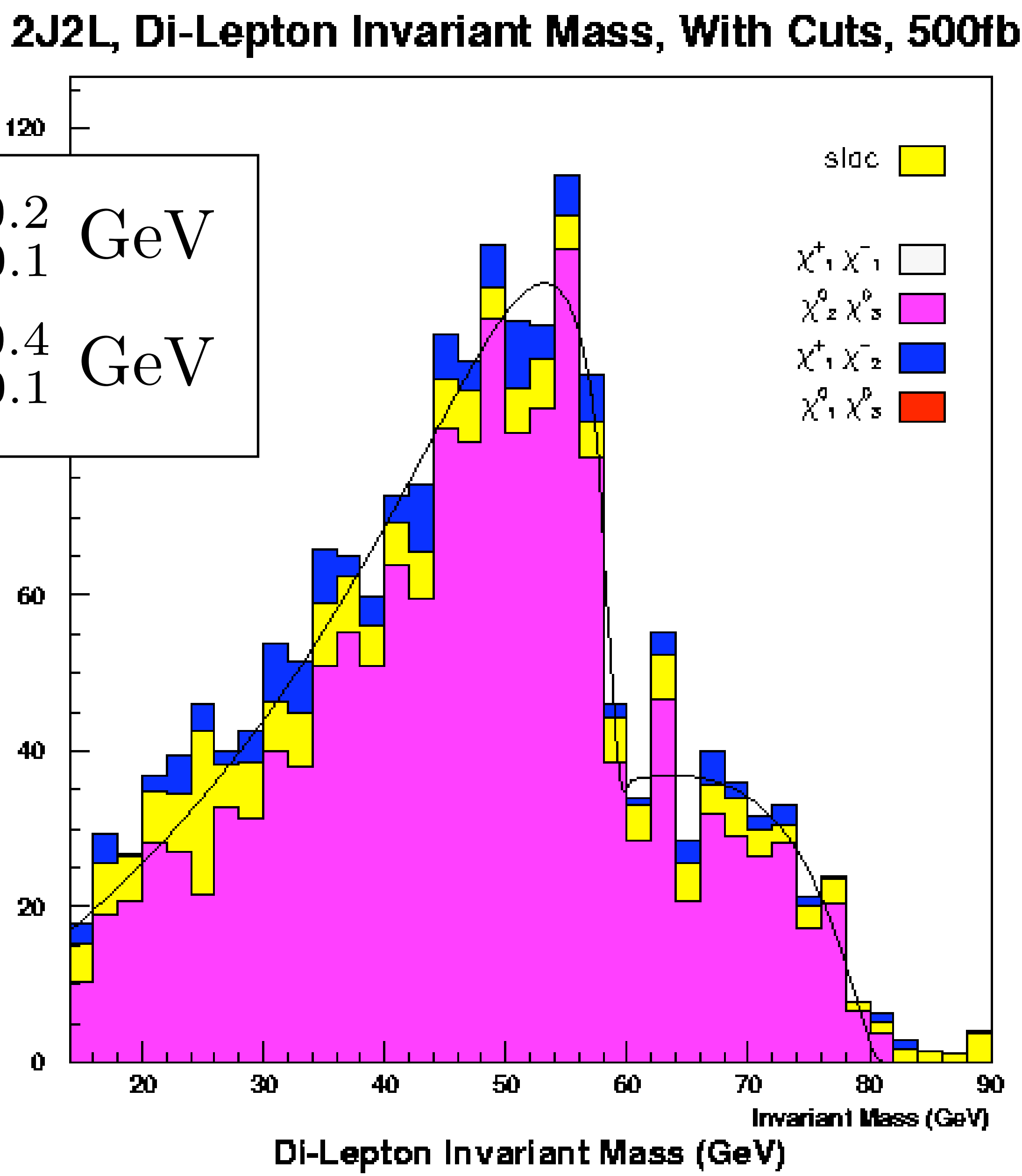
$$e^+e^- \to \tilde{C}_1^+ \, \tilde{C}_1^-$$
$$\to \quad e^+ \nu \, \tilde{N}_1^0 \quad q \, \bar{q} \, \tilde{N}_1^0$$



$$m(\widetilde{N}_2) - m(\widetilde{N}_1) = 58.7^{+0.2}_{-0.1}\ \mathrm{GeV}$$

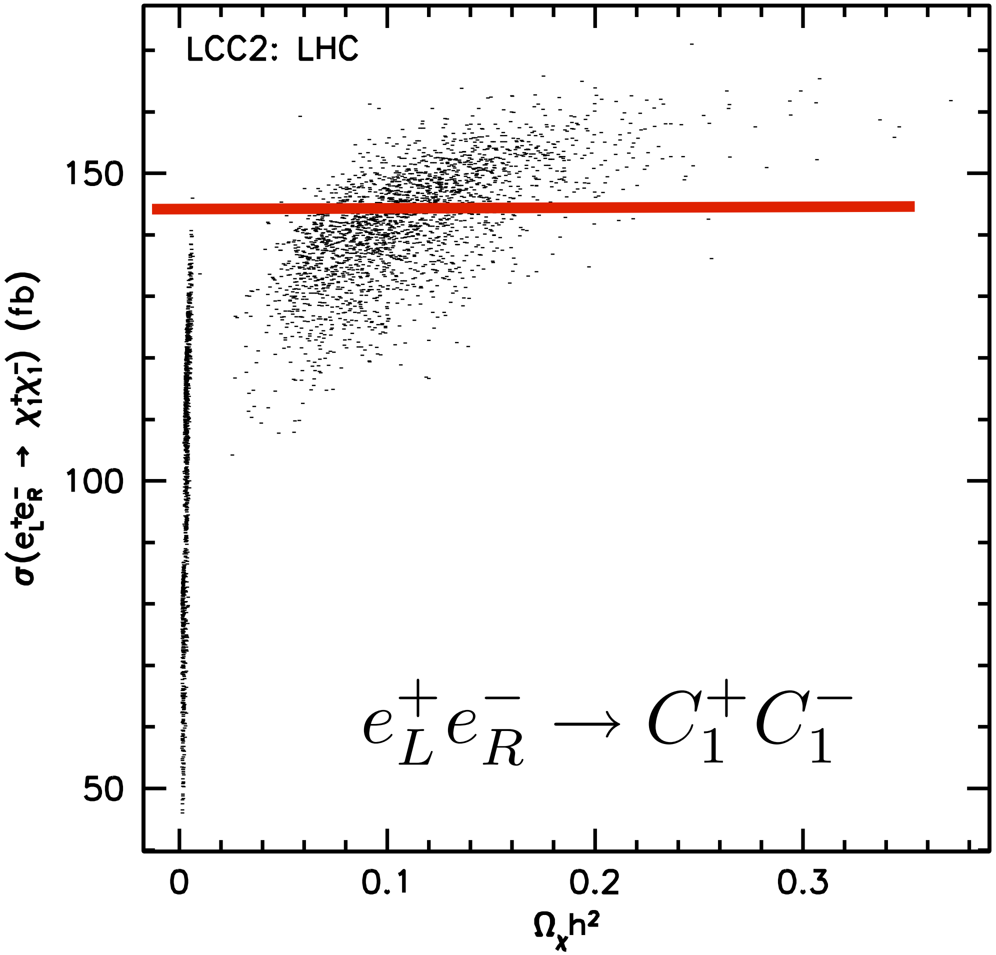
$$m(\widetilde{N}_3) - m(\widetilde{N}_1) = 82.0^{+0.4}_{-0.1}\ \mathrm{GeV}$$

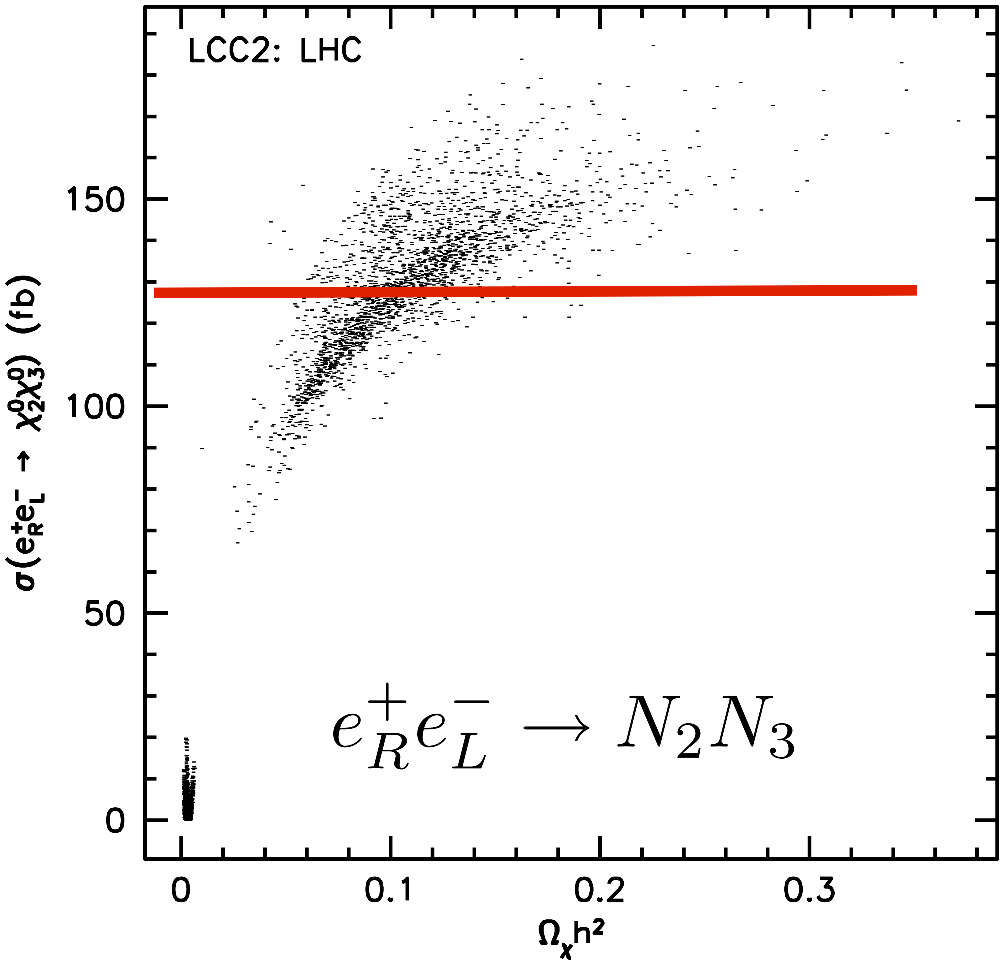
Here is an example from the ILC studies in which two dilepton endpoints are determined to parts per mil.



J. Alexander, et al.

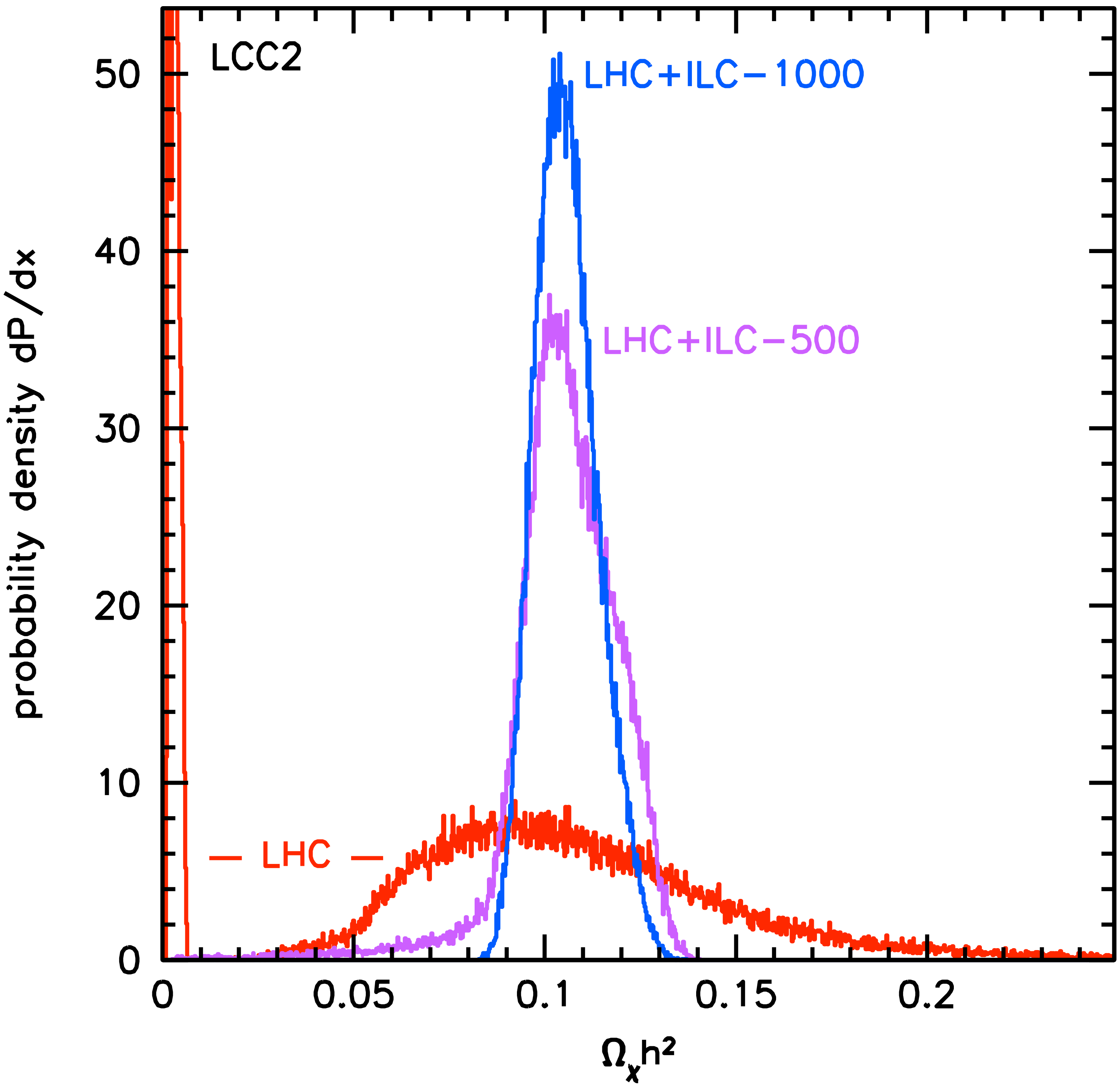
It is difficult at the LHC to measure mixing angles in the new particle sector. This analysis concerns a supersymmetry model in which there are two possible assignments of the WIMP as gauge boson partners. The ambiguity is resolved by measuring polarization-dependent production cross sections at the ILC:





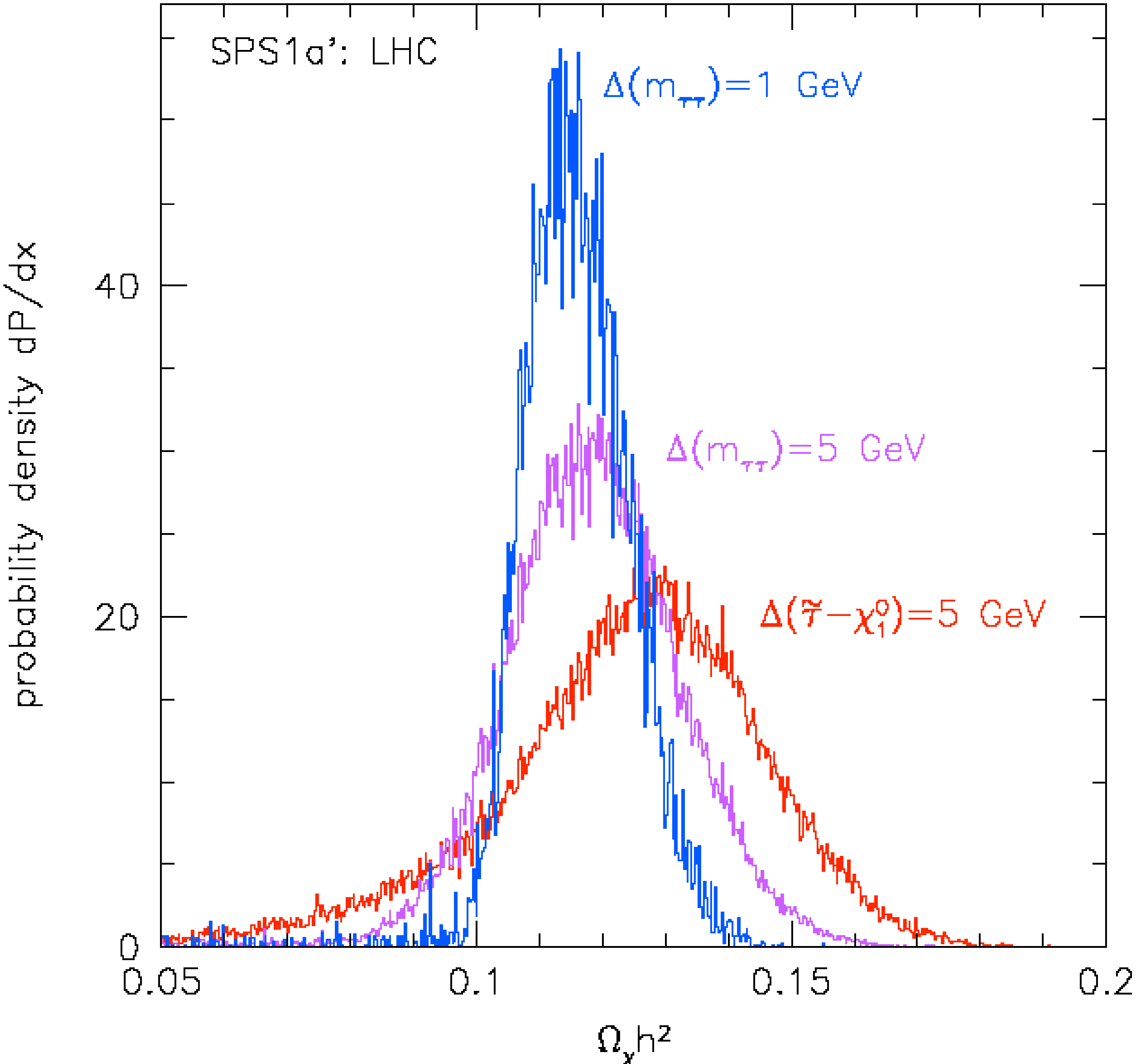
For example, based on the information from LHC and ILC, which is the likelihood function for the dark matter relic density ?

This depends on the specific spectrum of the model and its measurability.

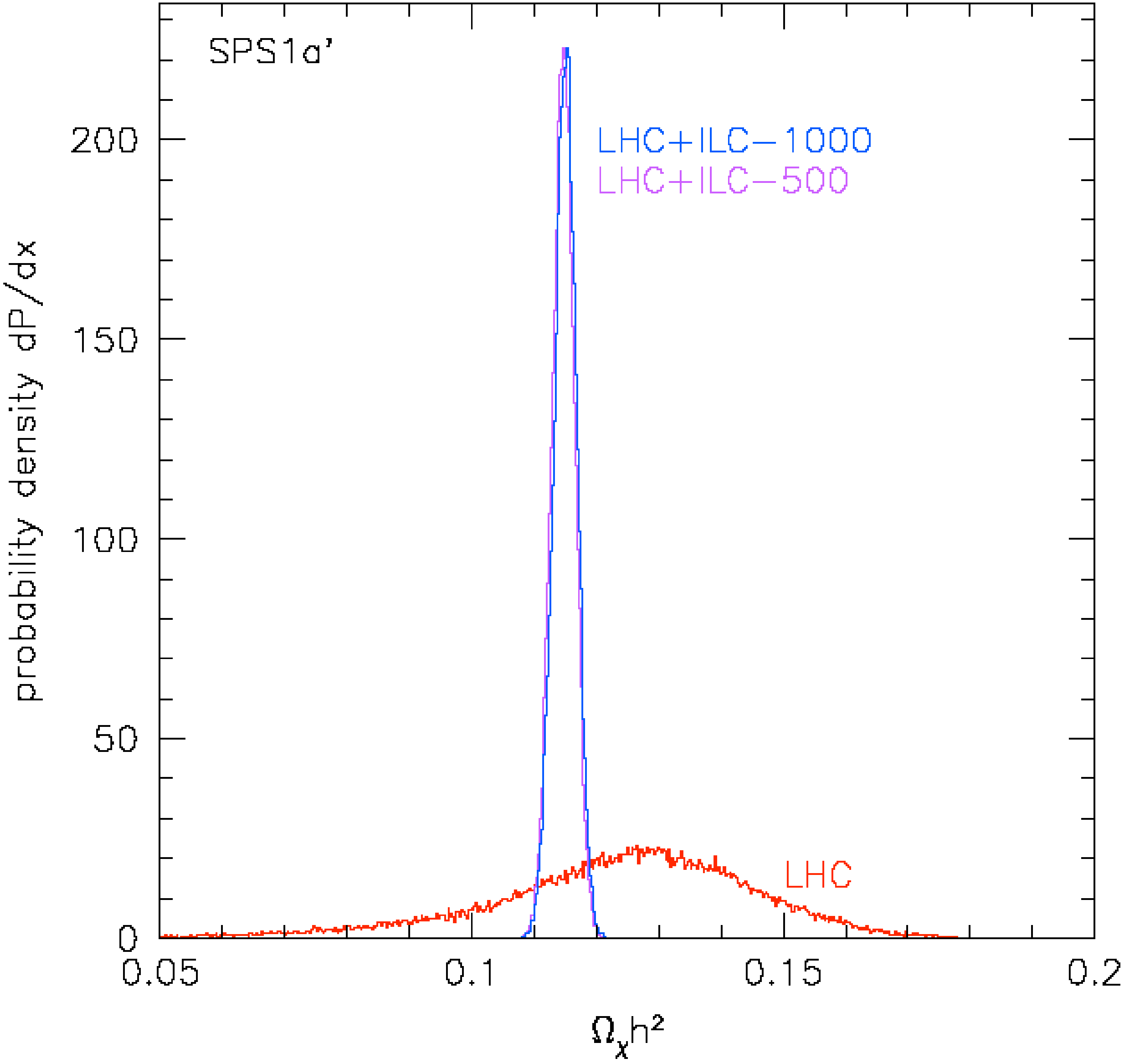


In this second model, it is much easier to collect all of the relevant information.

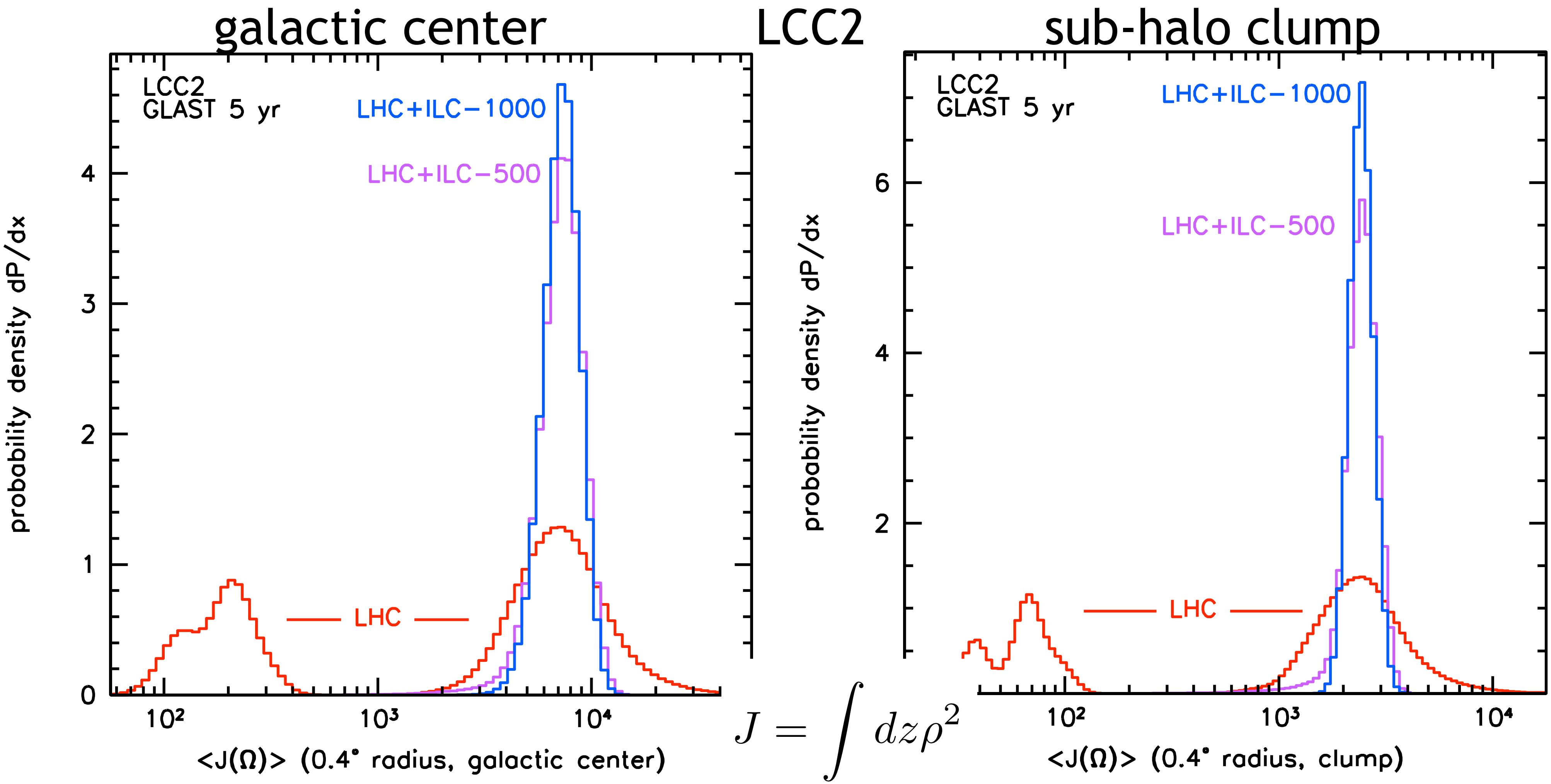
The final answer from LHC data depends on the ability to detect soft tau leptons at the LHC.



Adding ILC data, we can, in this model, reach part per mil precision, comparable to what the CMB experiments will have in this era.



The microscopic data also allows us to compute dark matter detection cross sections. If we could compute the dark matter annihilation cross section, we could convert observations of gamma rays from dark matter annihilation into absolute measurements of the dark matter density inside sources in the galaxy. Here is the result of combining LHC/ILC with GLAST.



$$J = \int dz \rho^2$$

The experiments at the next generation of high-energy particle colliders should give precision data on the spectrum of new particles that is in its own right important information about the fundamental interactions.

In addition, these data constrain the WIMP properties so that astrophysicists can use these to determine the distribution of WIMPs in the galaxy.

In the next 5 - 10 years I expect major developments both in elementary particle physics and in the astrophysics of dark matter. It will be exciting to see this program realized.