The Search for New Particles and Forces

GGI - 2009

M. E. Peskin
October 2009

Donatello

Rafaello

There are many problems in high-energy physics: The origin of gauge symmetry, the question of grand unification, the origin of CP violation, the origin of flavor and the values of quark and lepton masses, the orgin of inflation, the unification of particle physics interactions with gravity.

Among these, there are two problems for which we are likely to find solutions in the next few years:

What is the origin of electroweak symmetry breaking ?

What particles are responsible for cosmic dark matter ?

The special relevance of these problems comes from the likelihood that they are solved at the TeV energy scale, which we will now begin to probe at the LHC.

So, the most important news of the meeting is:

There is beam in the LHC again, and we are moving into the LHC experimental era.

Roberto Tenchini: "Don't get discouraged, the die hard are always rewarded ..."

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Roberto Tenchini: "Don't get discouraged, the die hard are always rewarded ..."

Silicon Valley lore: (thanks to Elliott Bloom)

The Six Stages of a Project

1. Enthusiasm
2. Disillusionment
3. Panic
4. Search for the guilty
5. Punishment of the innocent
6. Praise and honor for the non-participants

I will not review this conference systematically.

The talks are available at:

http://ggi-www.fi.infn.it//index.php?p=schedule.inc&idev=62

Some of these talks -- in particular, the very pedagogical explanation by Alessandro Nisati of the Higgs search in ATLAS -- contain much interesting material and merit serious off-line study.

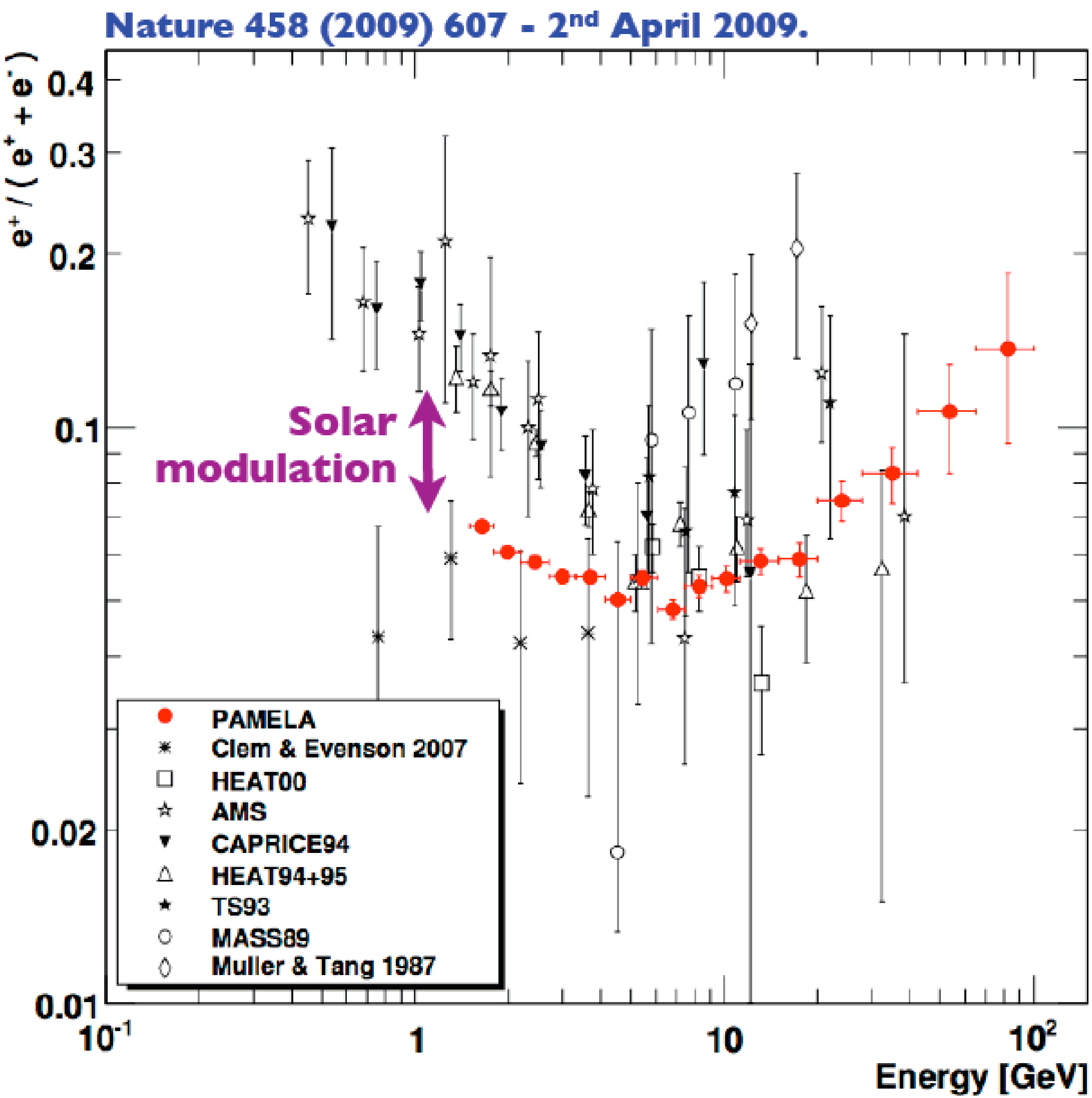
I will concentrate on two topics:

New perspectives on dark matter

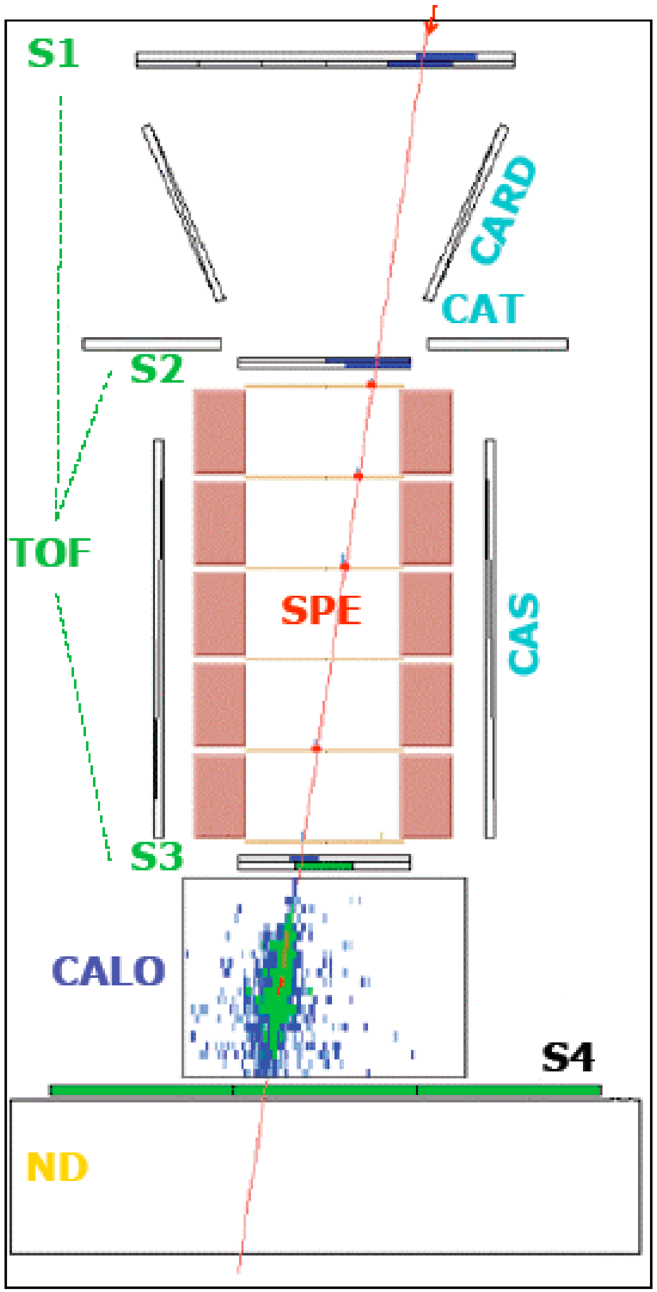
Possibility of discoveries at the LHC in 2010

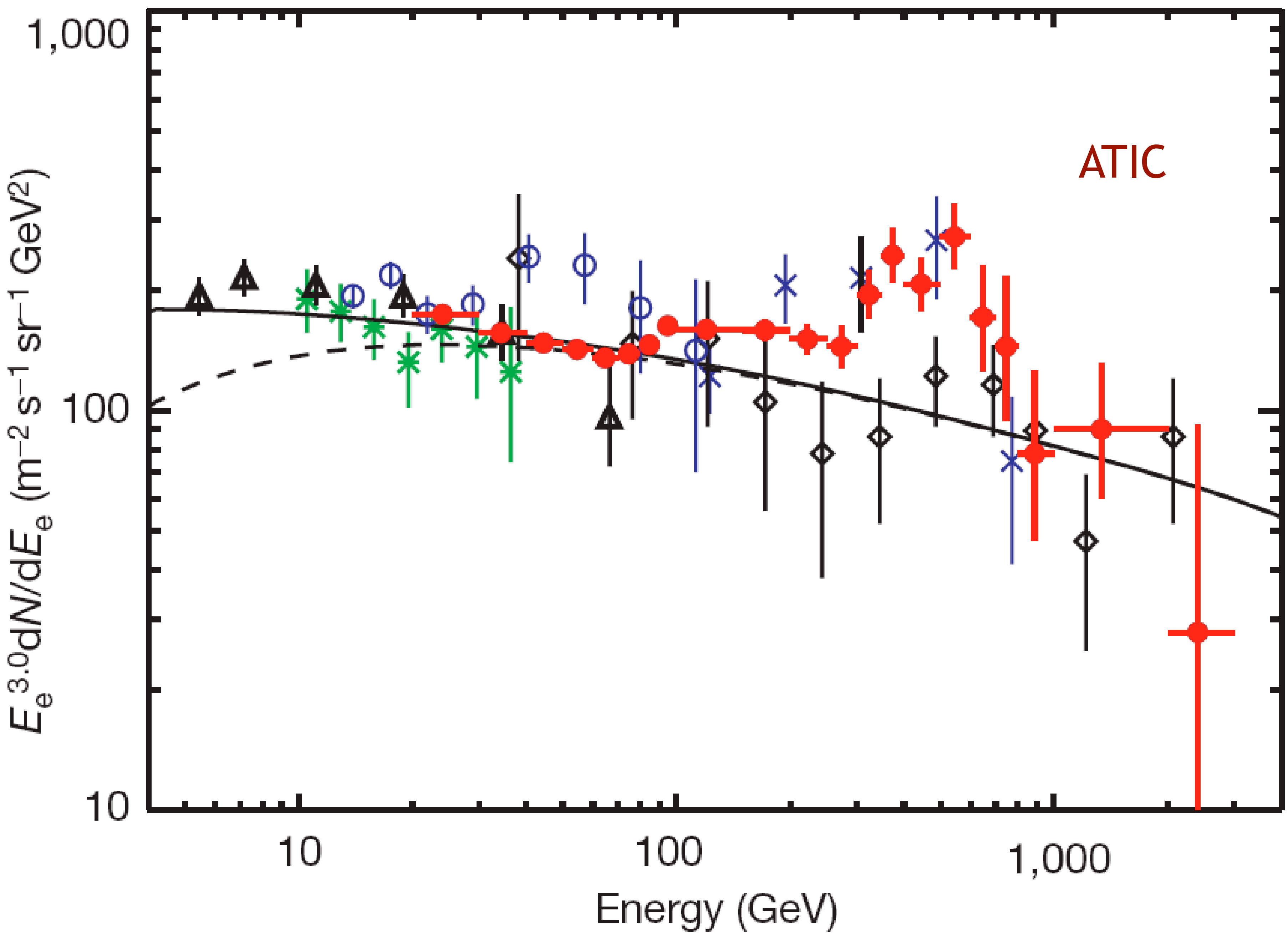
The most important discovery of the past year is that there is a new source of high-energy electrons and positrons in the galaxy, not accounted for by conventional (hadronic) cosmic-ray production mechanisms. This might be evidence for dark matter annihilation.

Dan Hooper gave us a beautiful talk on the topic.

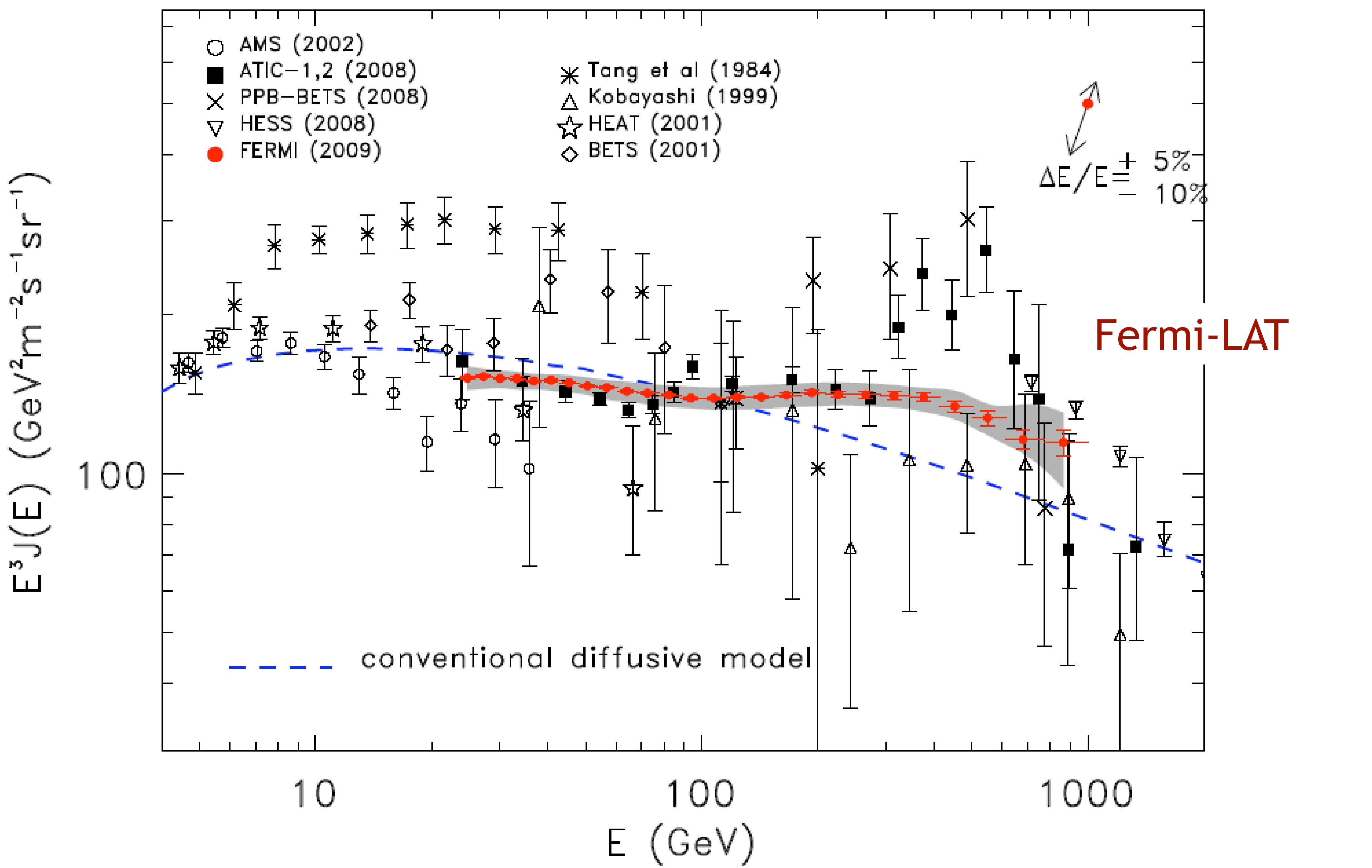

Nature 458 (2009) 607 - 2nd April 2009.
e+ / (e+ + e-)
0.4
0.3
0.2
0.1
0.02
0.01
10-1
1
10
10²
Energy [GeV]
Solar
modulation
PAMELA
Clem & Evenson 2007
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987

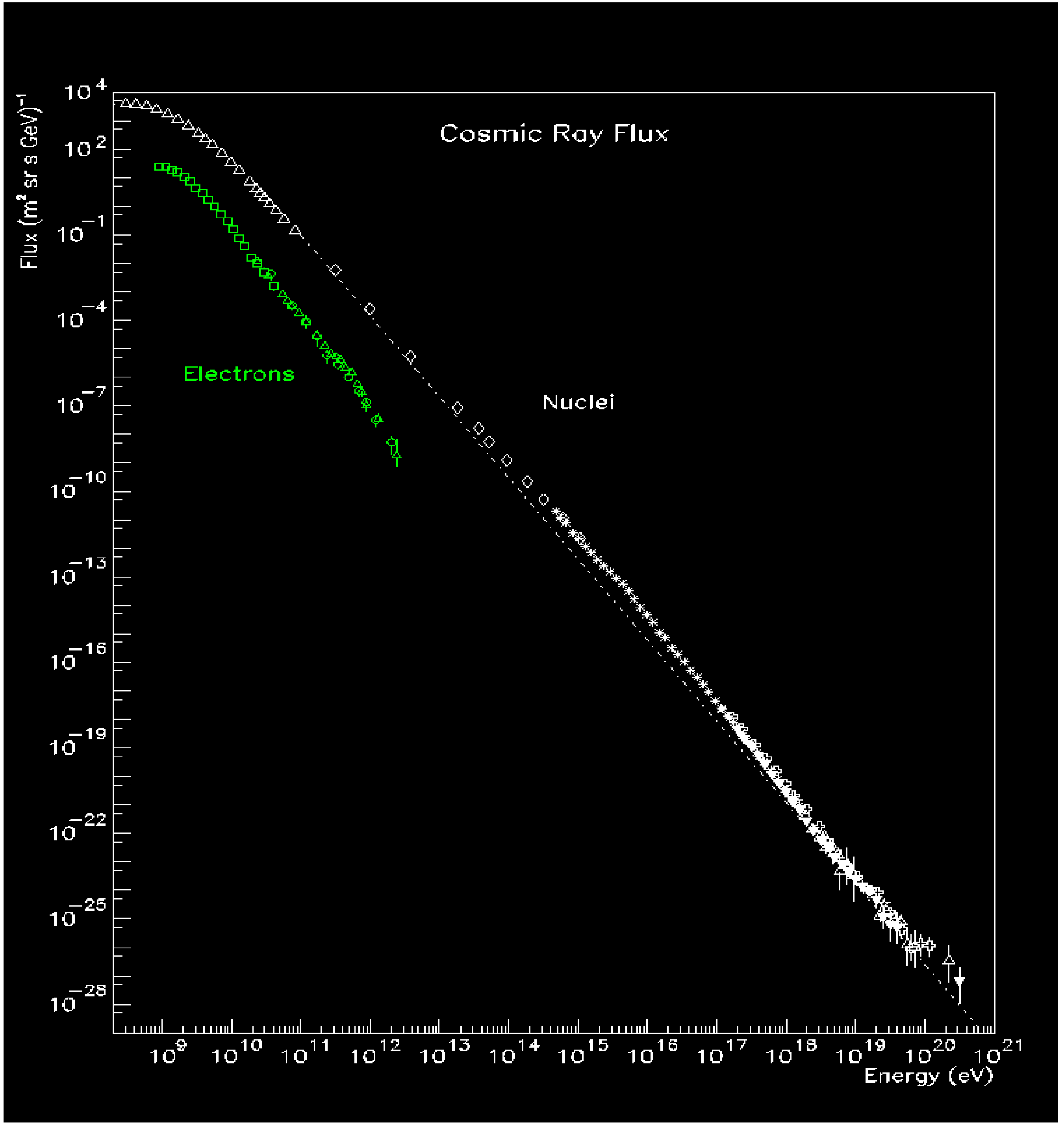
PAMELA
e+/(e+ + e-)


S1
CARD
CAT
S2
TOF
SPE
CAS
S3
CALO
S4
ND



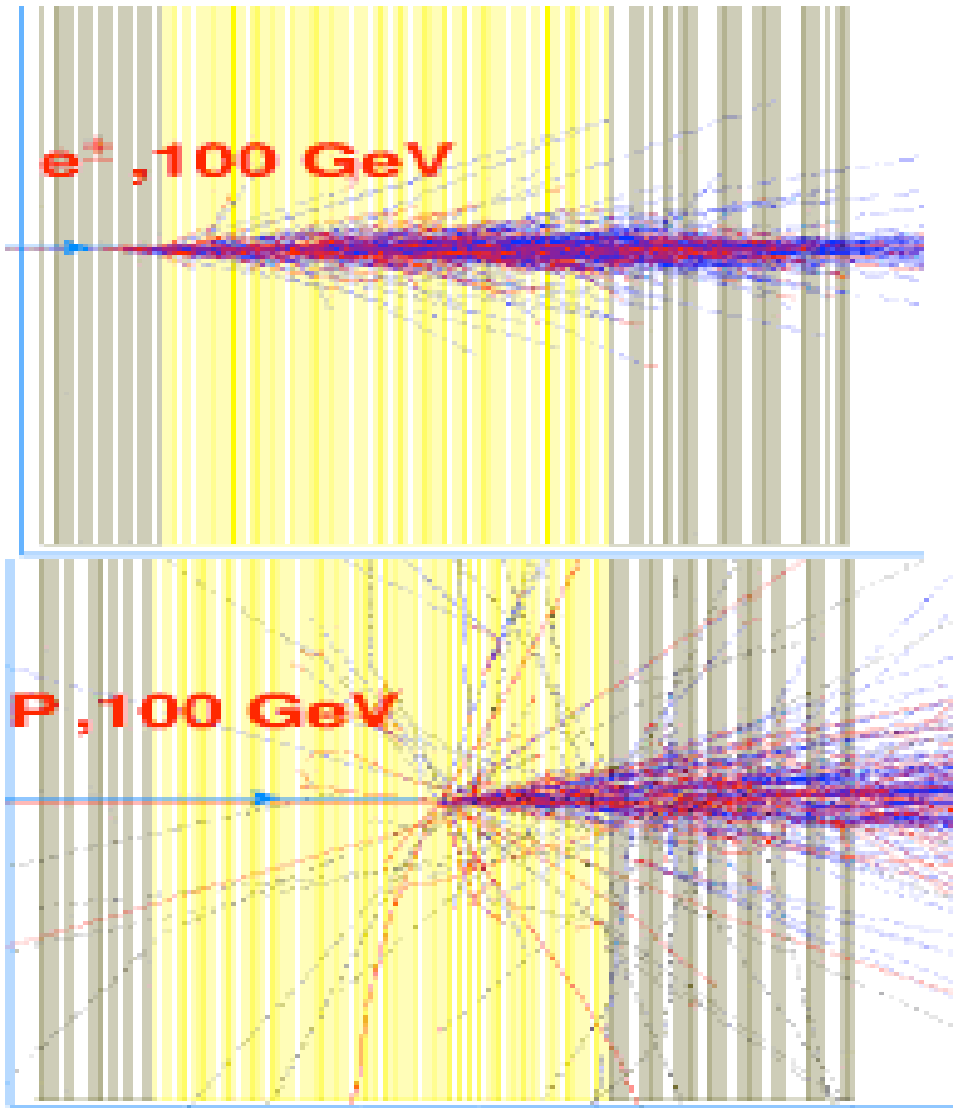
ATIC
1,000
100
10
10
100
1,000
Energy (GeV)
$E_e^{3.0}dN/dE_e$ (m^{-2} s^{-1} sr^{-1} GeV^2)


AMS (2002)
ATIC−1,2 (2008)
PPB−BETS (2008)
HESS (2008)
FERMI (2009)
Tang et al (1984)
Kobayashi (1999)
HEAT (2001)
BETS (2001)
ΔE/E = + 5% − 10%
Fermi-LAT
conventional diffusive model
100
10
1000
E (GeV)
$E^3J(E)$ $(GeV^2m^{-2}s^{-1}sr^{-1})$

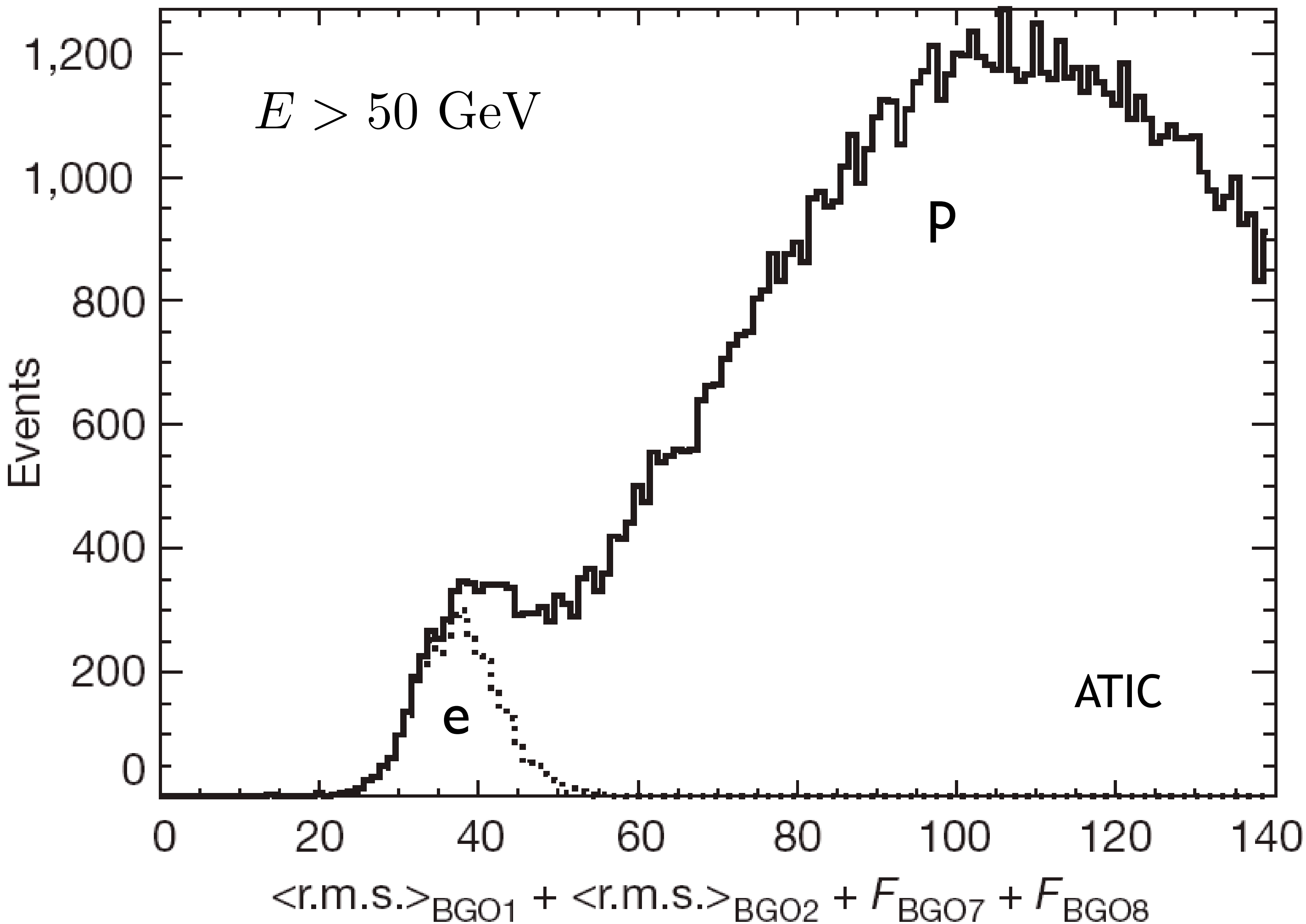

Cosmic Ray Flux
Flux (m² sr s GeV)⁻¹
Electrons
Nuclei
Energy (eV)
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
10¹⁵
10¹⁶
10¹⁷
10¹⁸
10¹⁹
10²⁰
10²¹

J. Conrad

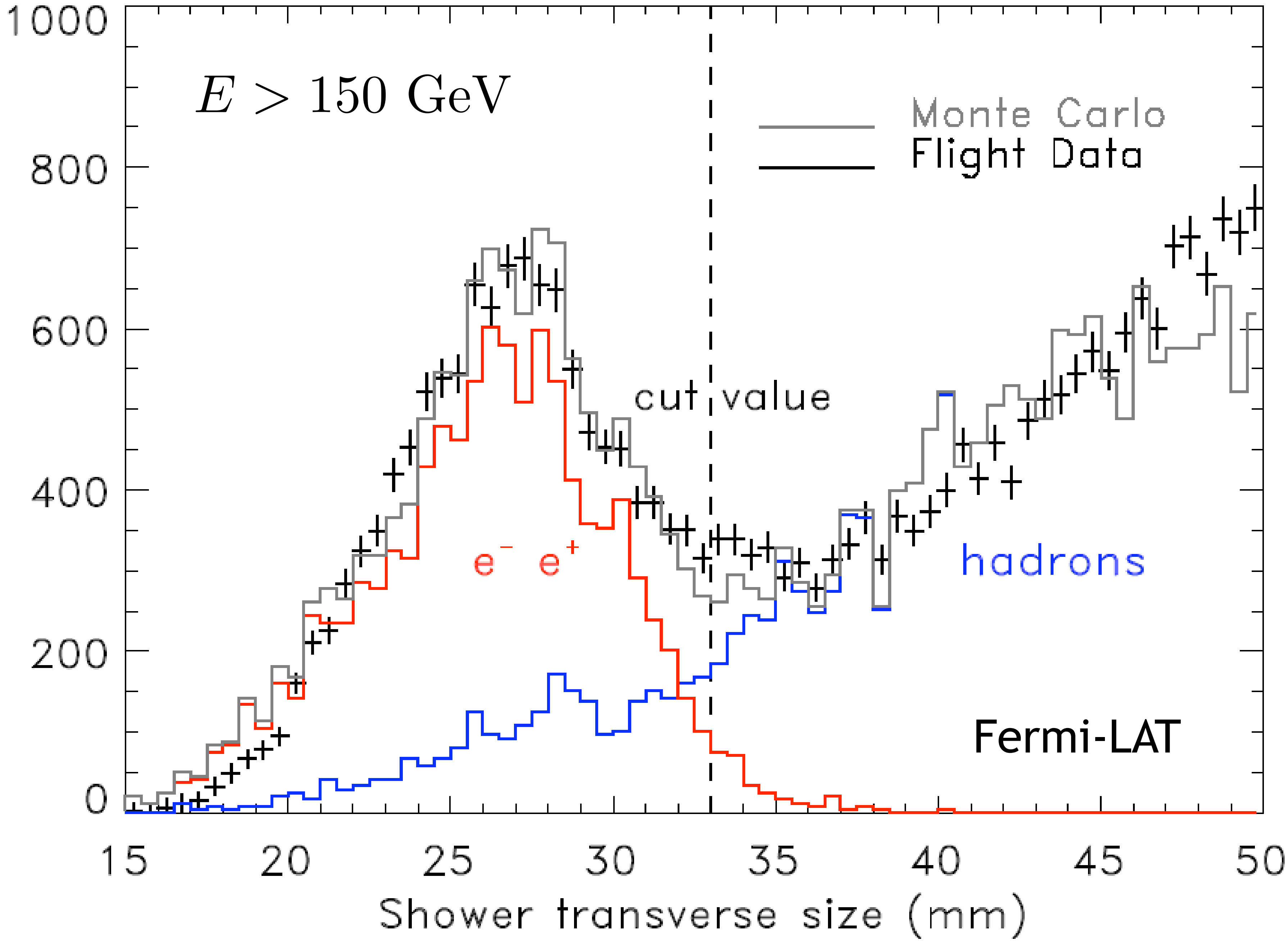
Hadron/electron discrimination



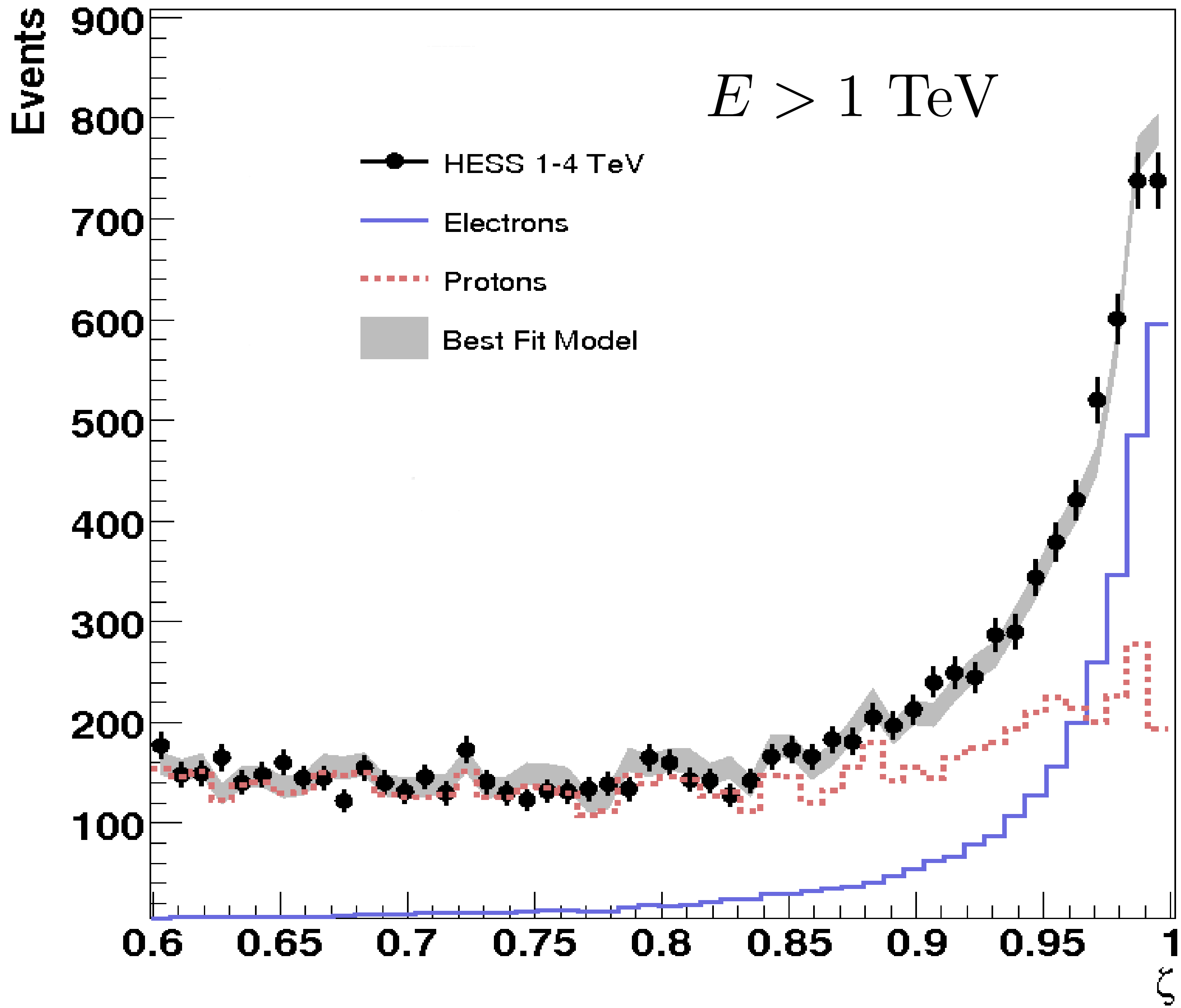
- Main idea:
  - Veto detectors (Anti-coincidence)
  - difference in shower shape for em/hadronic showers in calorimeter
  - Background rejection gets harder with rising energy
  - Full analyses apply combined information of several detectors in multivariate classification (Neural networks …)



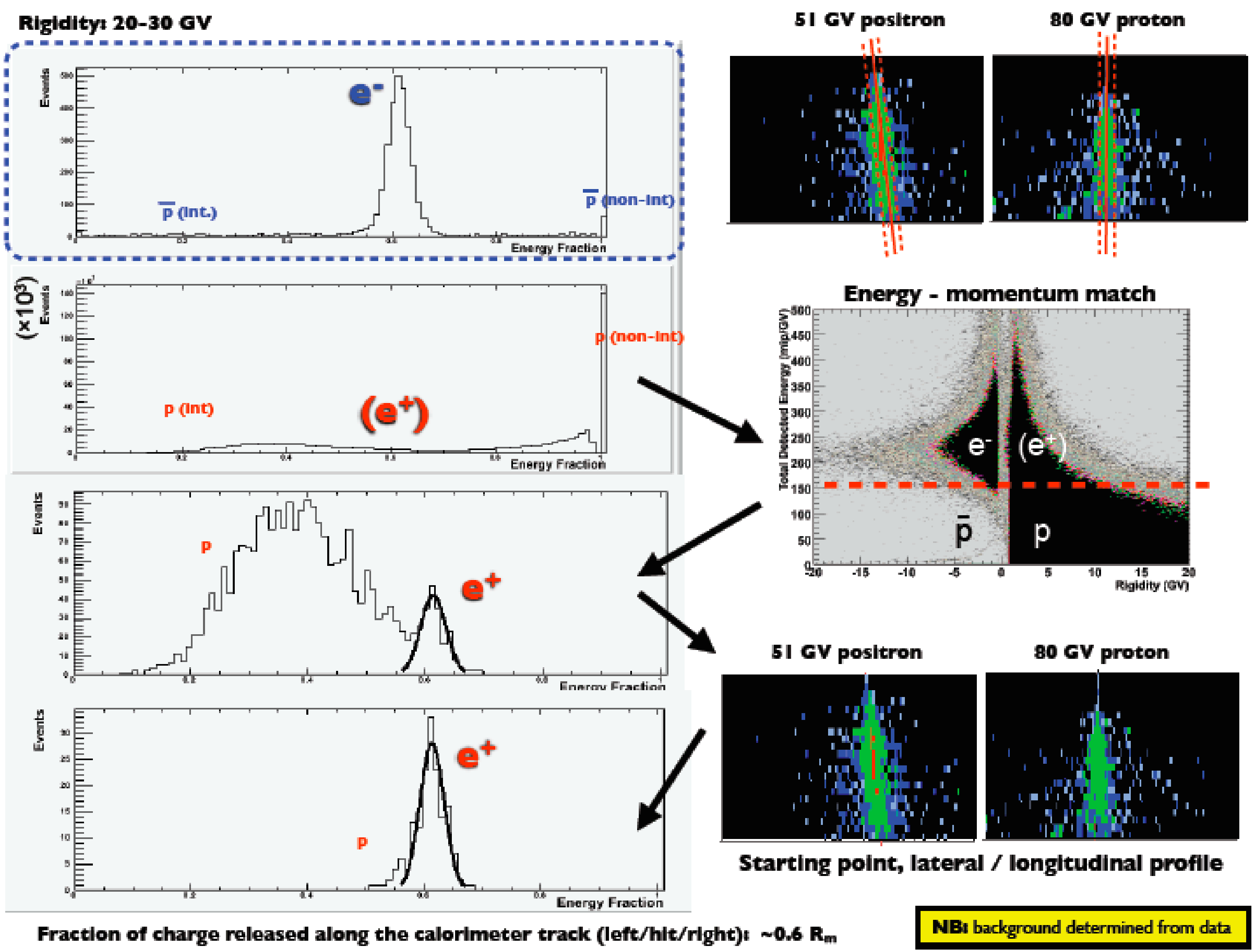
$E > 50$ GeV
1,200
1,000
800
600
400
200
0
Events
p
e
ATIC
0
20
40
60
80
100
120
140
$\langle$r.m.s.$\rangle_{BGO1}$ + $\langle$r.m.s.$\rangle_{BGO2}$ + F_{BGO7} + F_{BGO8}



$E > 150$ GeV
Monte Carlo
Flight Data
cut value
e^- e^+
hadrons
Fermi-LAT
1000
800
600
400
200
0
15
20
25
30
35
40
45
50
Shower transverse size (mm)


Events
900
800
700
600
500
400
300
200
100
$E > 1$ TeV
HESS 1-4 TeV
Electrons
Protons
Best Fit Model
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
ζ

HESS

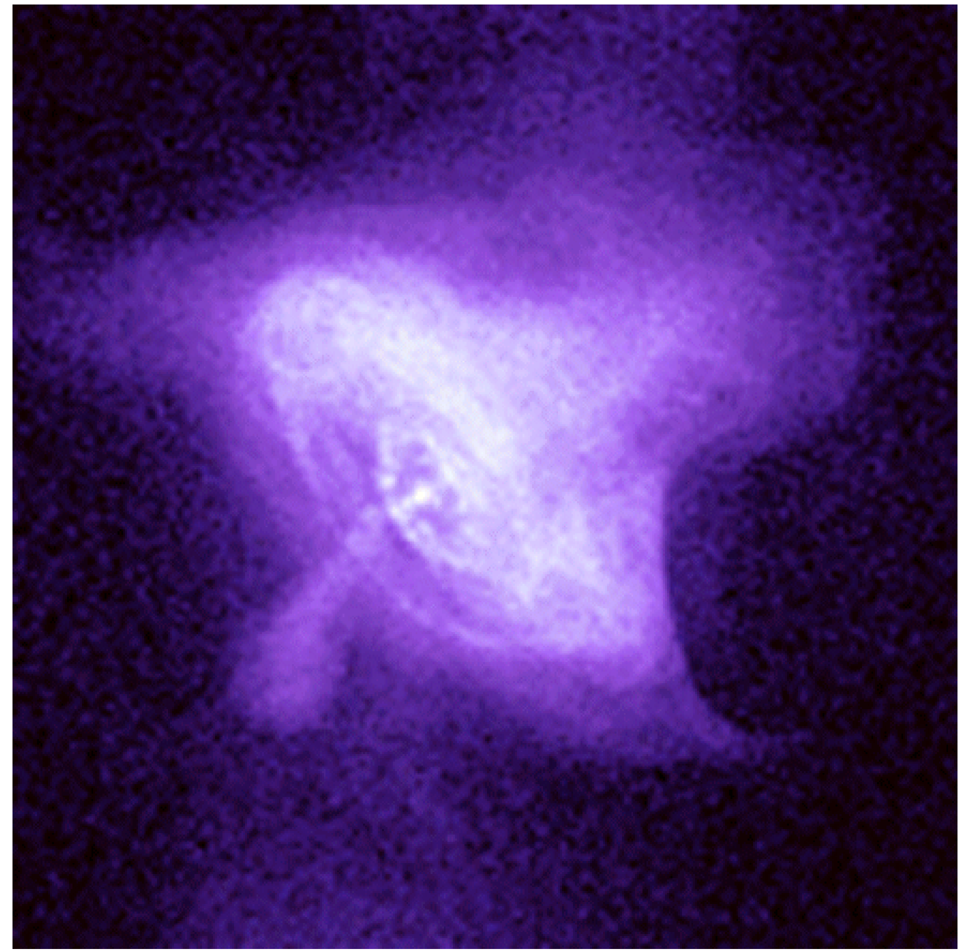


PAMELA

The ability to discriminate e+ from p eventually limits the ability of PAMELA to observe an endpoint in the e+ spectrum. Hopefully, next year, AMS2 will do better.

Is it dark matter annihilation ?

A plausible alternative: e+ and e- release from a nearby Pulsar Wind Nebula.



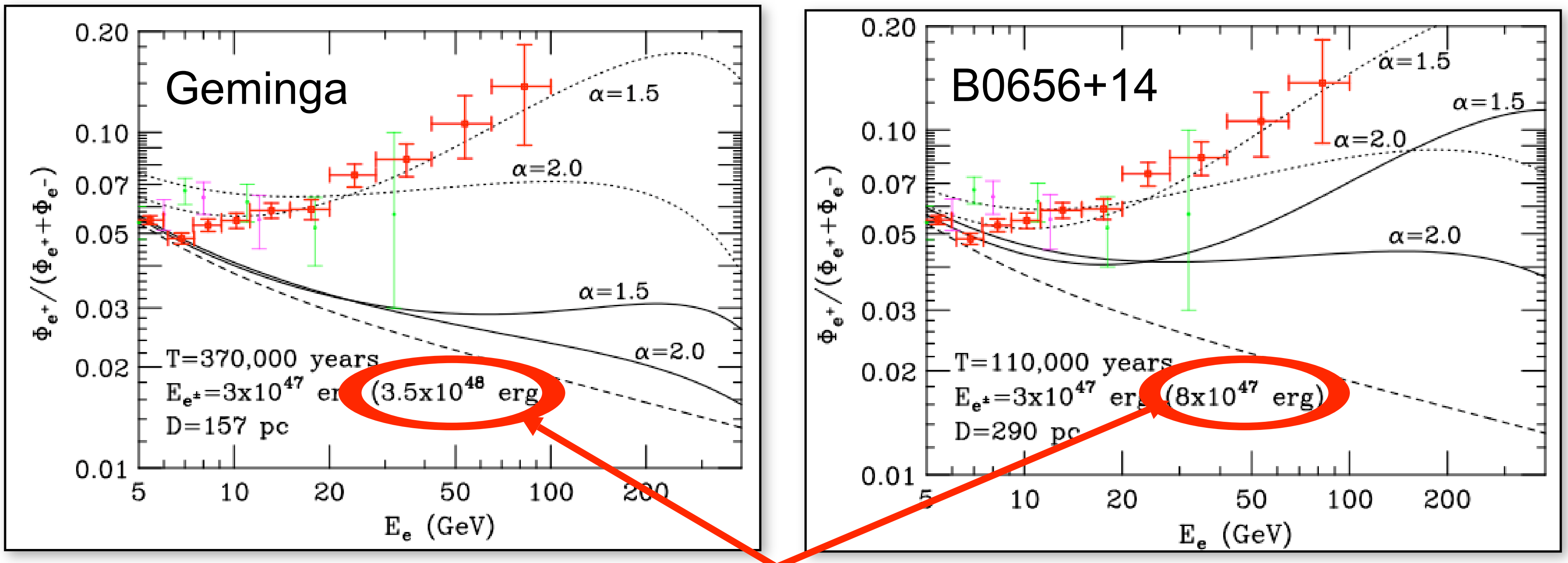
ESO

Crab Nebula

Chandra X ray ST

High-Energy Positrons From Nearby Pulsars

Two promising candidates:
Geminga (157 pc away, 370,000 years old)
B0656+14 (290 pc, 110,000 years)



Tens of percent of the total spindown energy is needed in high energy e^+e^- pairs!

Hooper, P. Blasi, P. Serpico, JCAP arXiv:0810.1527

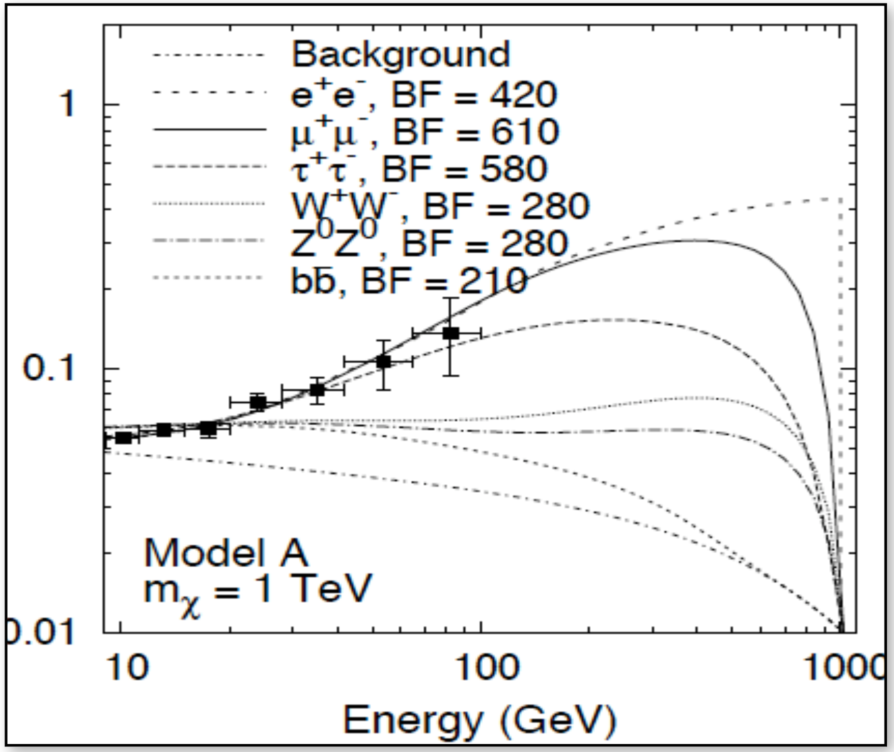
"The [Crab] pulsar has steadily released about a third of its total reservoir of ~ 5×10^{49} ergs of rotational energy into its surrounding nebula over the last 950 years."   --

Gaensler and Slane, Ann. Rev. Astron. Astro. 44, 17 (2006)

The pulsar that emitted the high energy positrons seen by PAMELA must be nearby (within a few kps) and its PWN must have collapsed recently (within less than 100,000 yr).

It might not be visible to us either in radio or in gamma rays.

A different pulsar or pulsars, close to the galactic center, must be invoked to explain the WMAP haze.



Dark matter explanations require

- a very heavy primary WIMP
- decay into leptons only
- enhancement of $\sigma_{\chi\chi}$

The needed WIMPs are not easily produced or observed at the LHC.

Can we gain confidence that dark matter, rather than high energy astrophysics, is the explanation?

Search Technique	advantages	challenges
Galactic center	Good Statistics	Source confusion/ Diffuse background
Subhalos Dwarf galaxies	Low background, Good source id	Low statistics
Milky Way halo	Large statistics	Galactic diffuse background
Extra-galactic	Large Statistics	Astrophysics, galactic diffuse background
Spectral lines	No astrophysical uncertainties, good source id	Low statistics

Dark matter sources should be:

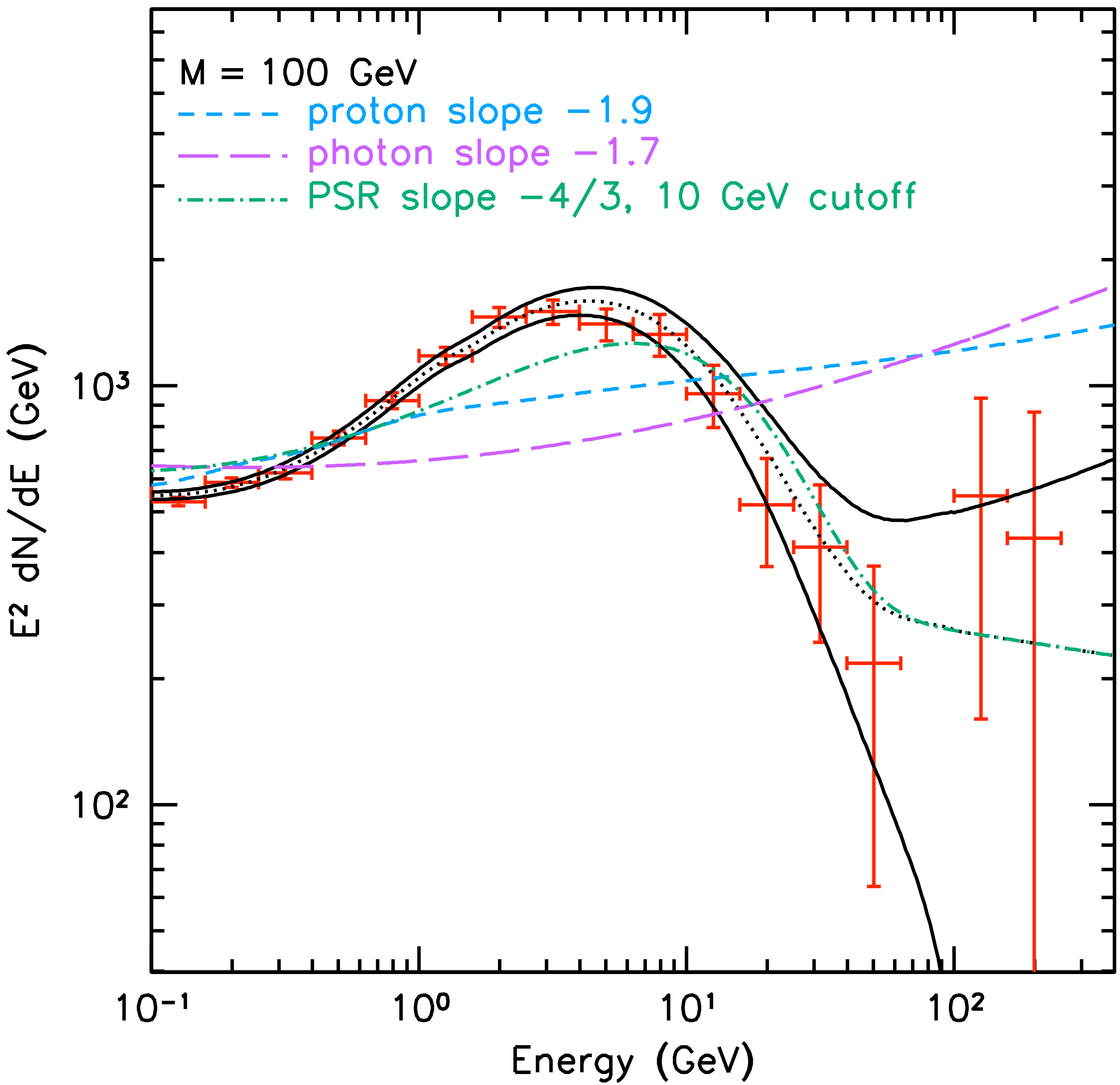
	Energy cutoff	Extended	Non-variable	High latitude	No counterparts
Subhalos	X	X	X	X	X
Molec. clouds		X	X	X	
Pulsars	?			?	
Plerions		X	X		
SNR		X	X		
Blazars				X	

J. Conrad

gamma ray spectrum, including extragalactic background. The error bars correspond to a 5 year GLAST observation of a dark matter subhalo clump of mass

$$2 \times 10^6 M_\circ$$

at 3 kpc.

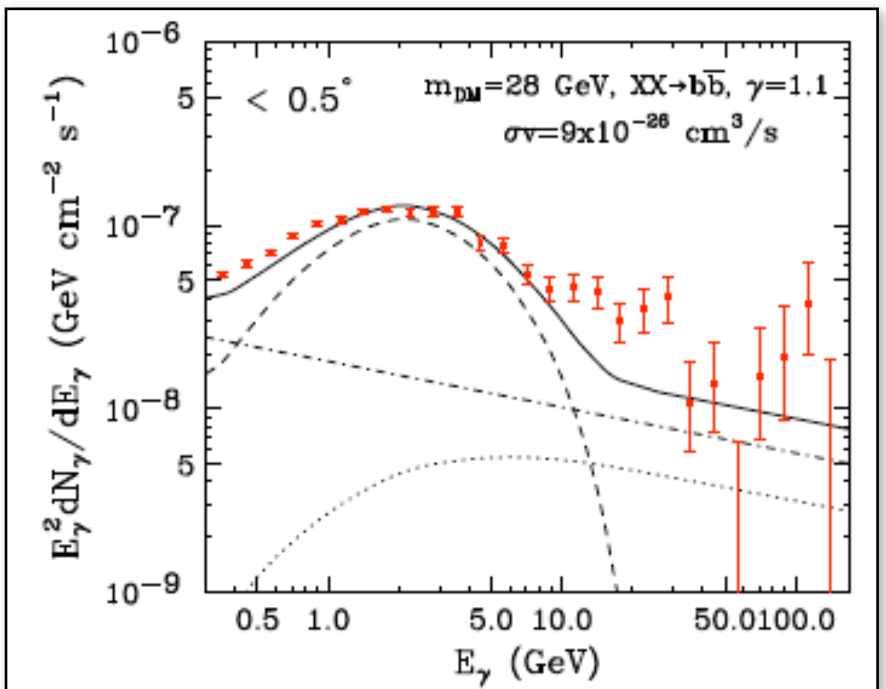


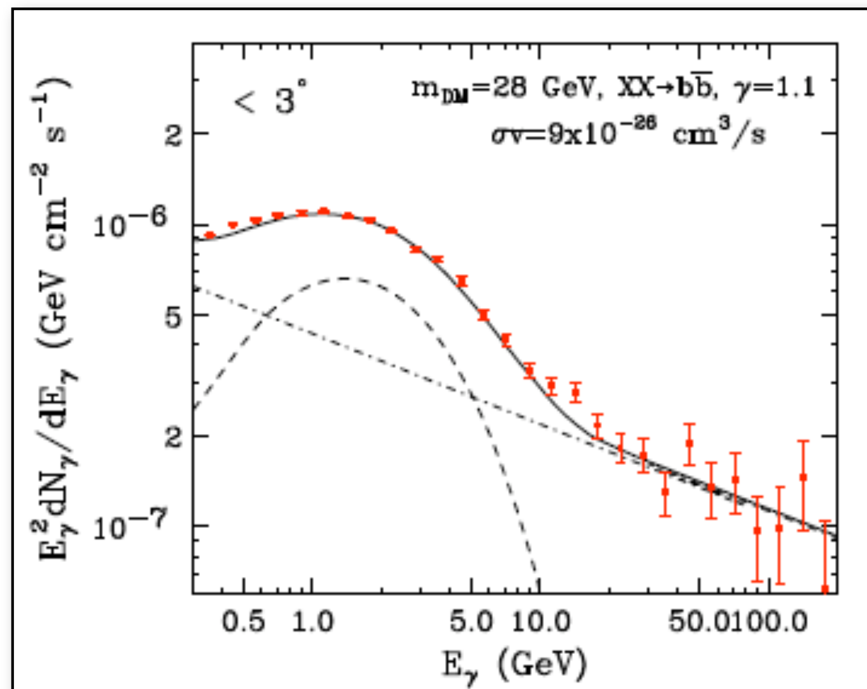
Baltz, Taylor, and Wai

first step: a new analysis of Fermi GST gamma rays from the galactic center - Goodenough and Hooper

§ The spectrum of the non-disk, non-HESS source emission contains a “bump-like” feature at ~1-5 GeV

§ Can be fit quite well by a simple 25-30 GeV dark matter particle, in a cusped distribution (γ~1.1), annihilating to bb with $\sigma\bar{v}$ ~ 9 x 10^{-26} cm^3/s





L. Goodenough, D. Hooper, arXiv:0910.2998

The unusual features of the needed WIMP call for an explanation from particle physics model building. A proposal that fills the requirements is:

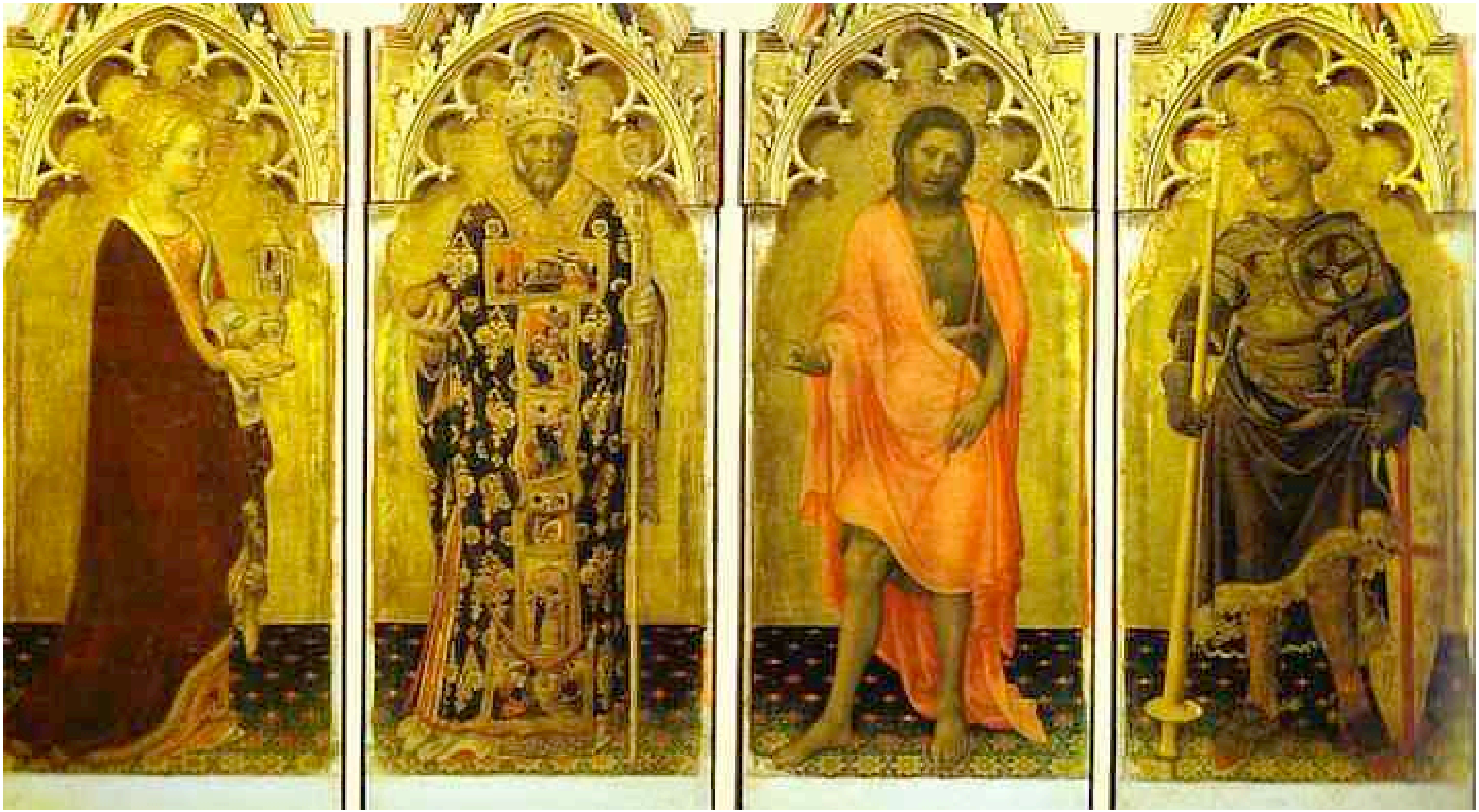
"A Theory of Dark Matter", arXiv:0810.0713
- Arkani-Hamed, Finkbeiner, Slatyer, and Weiner

This model calls for

a heavy (1 TeV) primary WIMP
GeV mass vector interactions
weak kinetic mixing with the SM U(1) $$-\frac{1}{4}\epsilon F^Y_{\mu\nu} F^{D\mu\nu}$$

Its nontrivial virtues are

essentially QED interaction with, decay to visible particles
Sommmerfeld enhancement of $\sigma_{\chi\chi}$
inelastic WIMP - matter interaction, can explain DAMA result

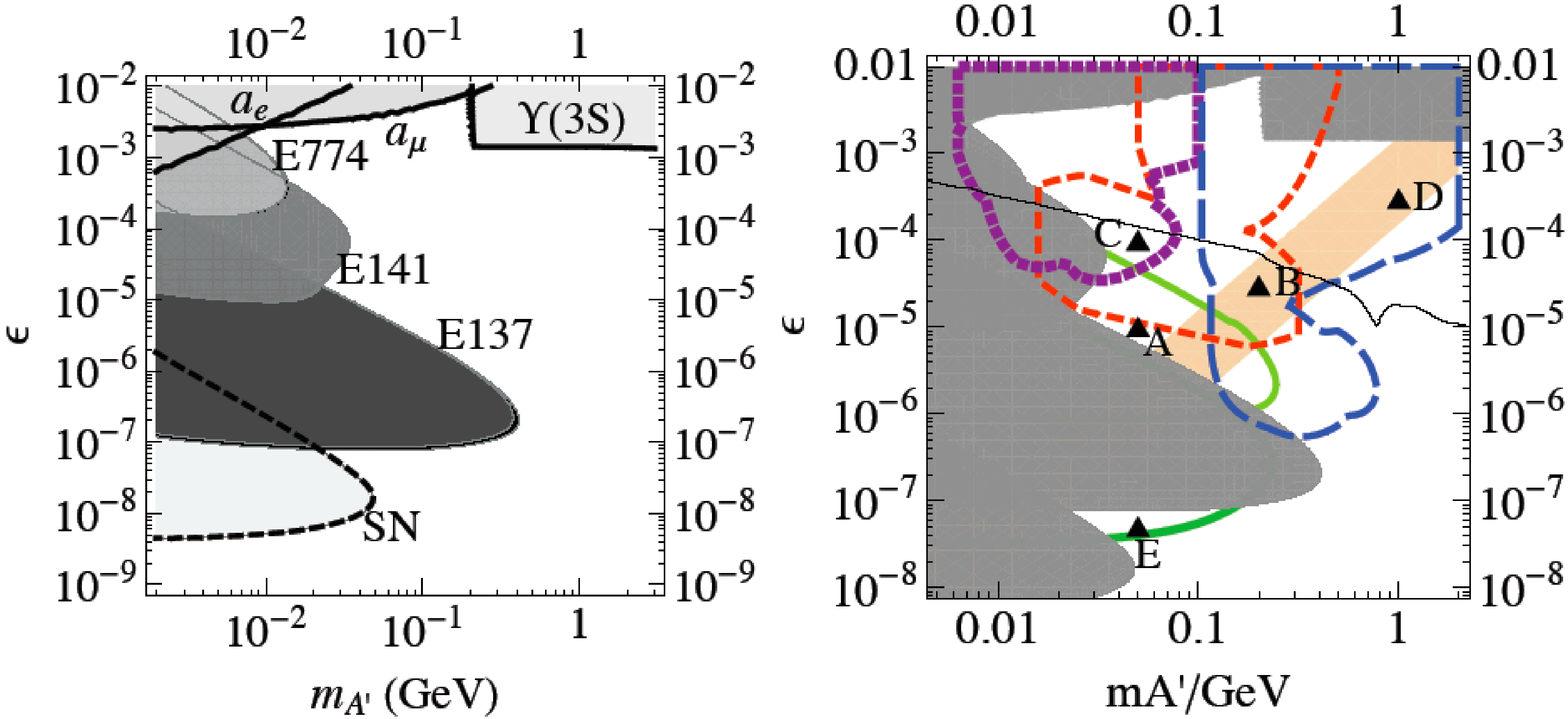


Gentile da Fabriano

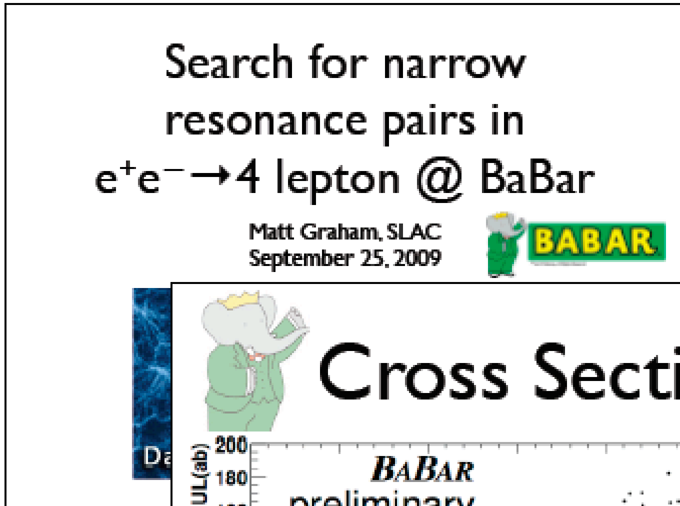
This theory has been discussed extensively at this meeting. I would only like to review two features:

First, this model predicts new QED-like processes at GeV energies whose rates are suppressed by ϵ^2. It is possible to search for these effects in current high-luminosity experiments and thus to confirm or exclude the model.

Philip Schuster gave us a very interesting talk on this topic.

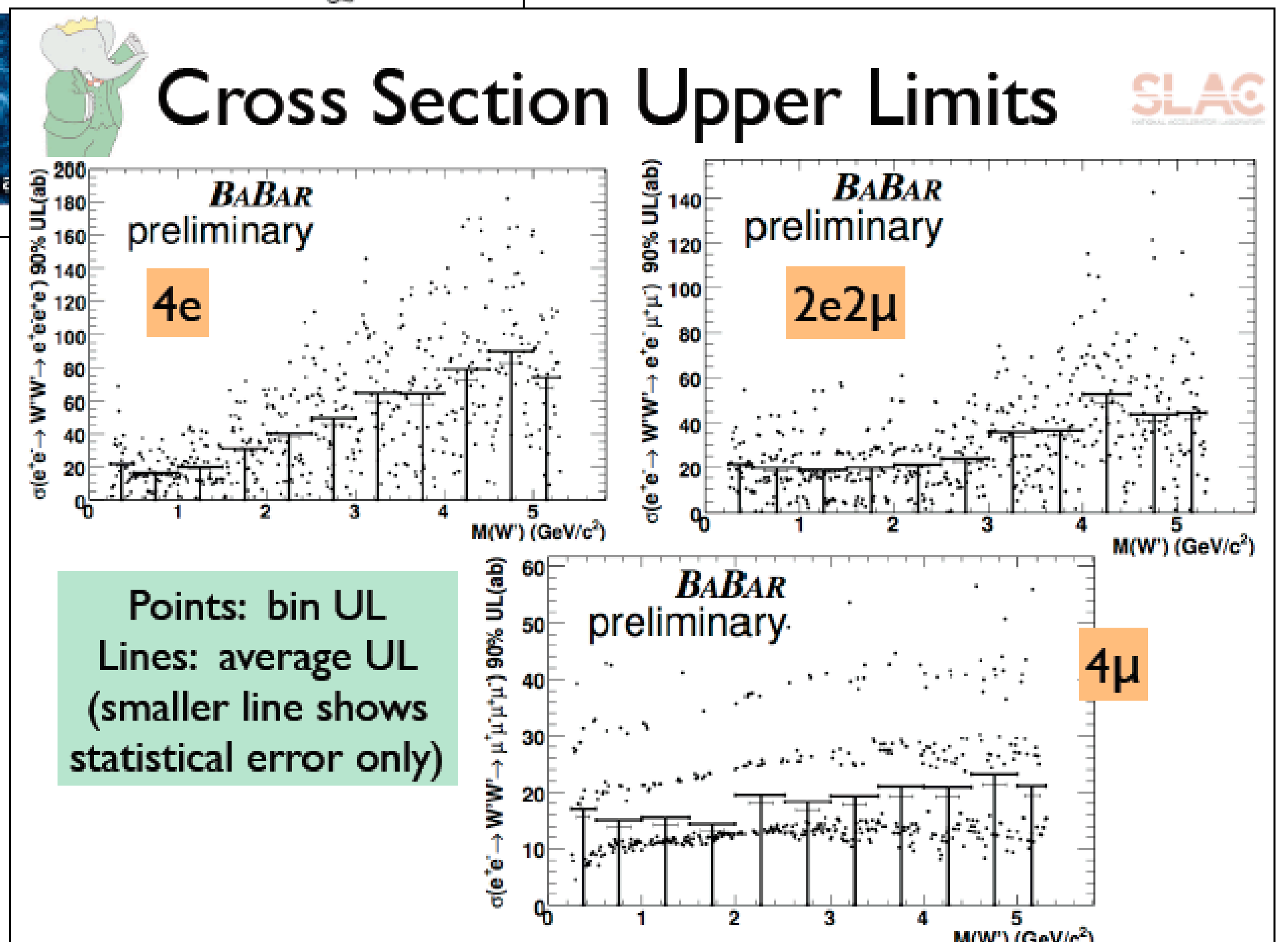


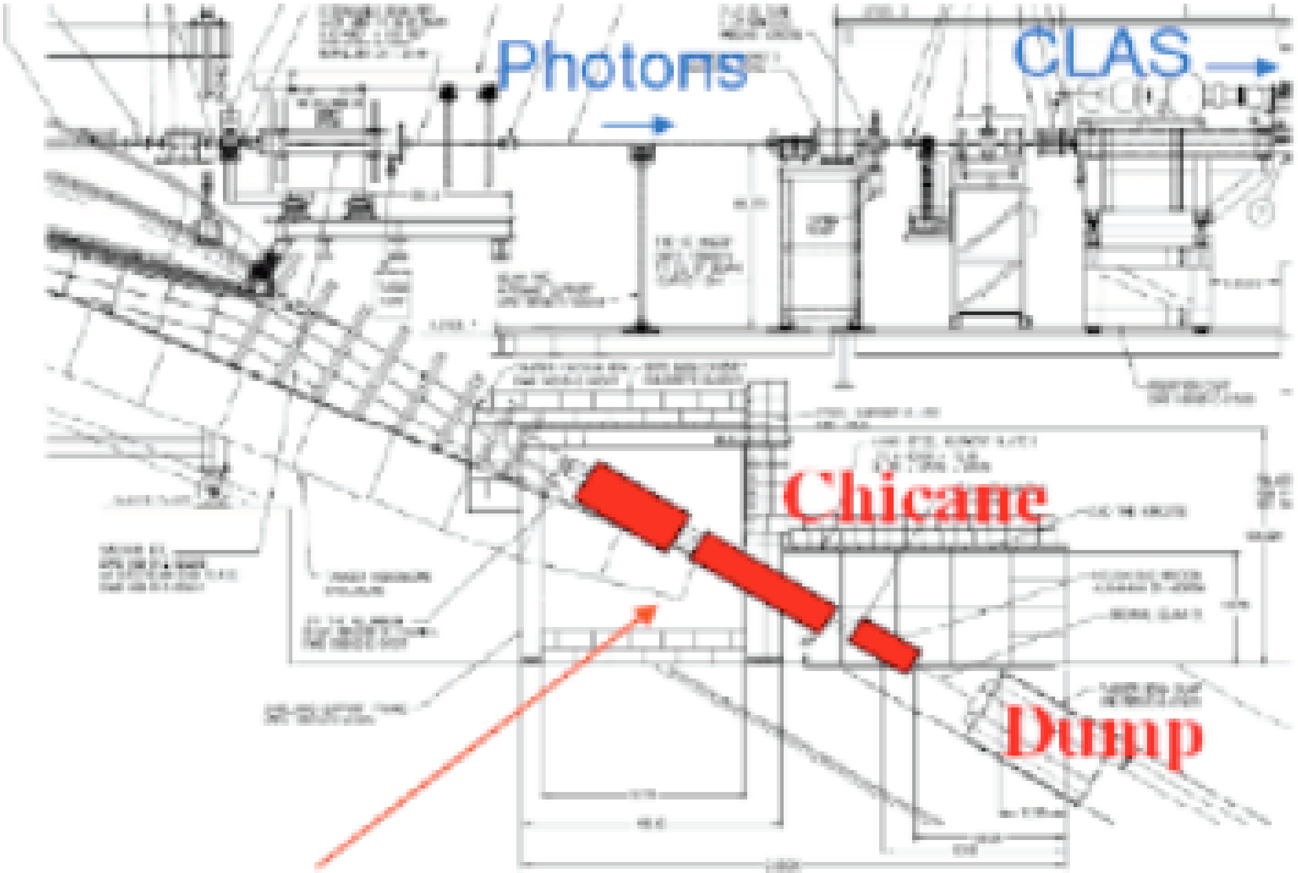
Bjorken, Essig, Schuster, Toro, arXiv:0906.0580



Sensitivity to $\epsilon \sim 10^{-4}$

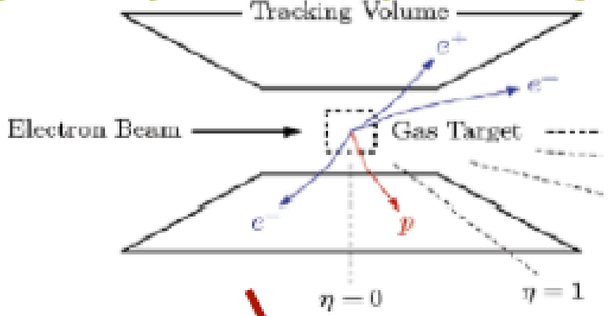
[M. Graham, arXiv:0908.2821]



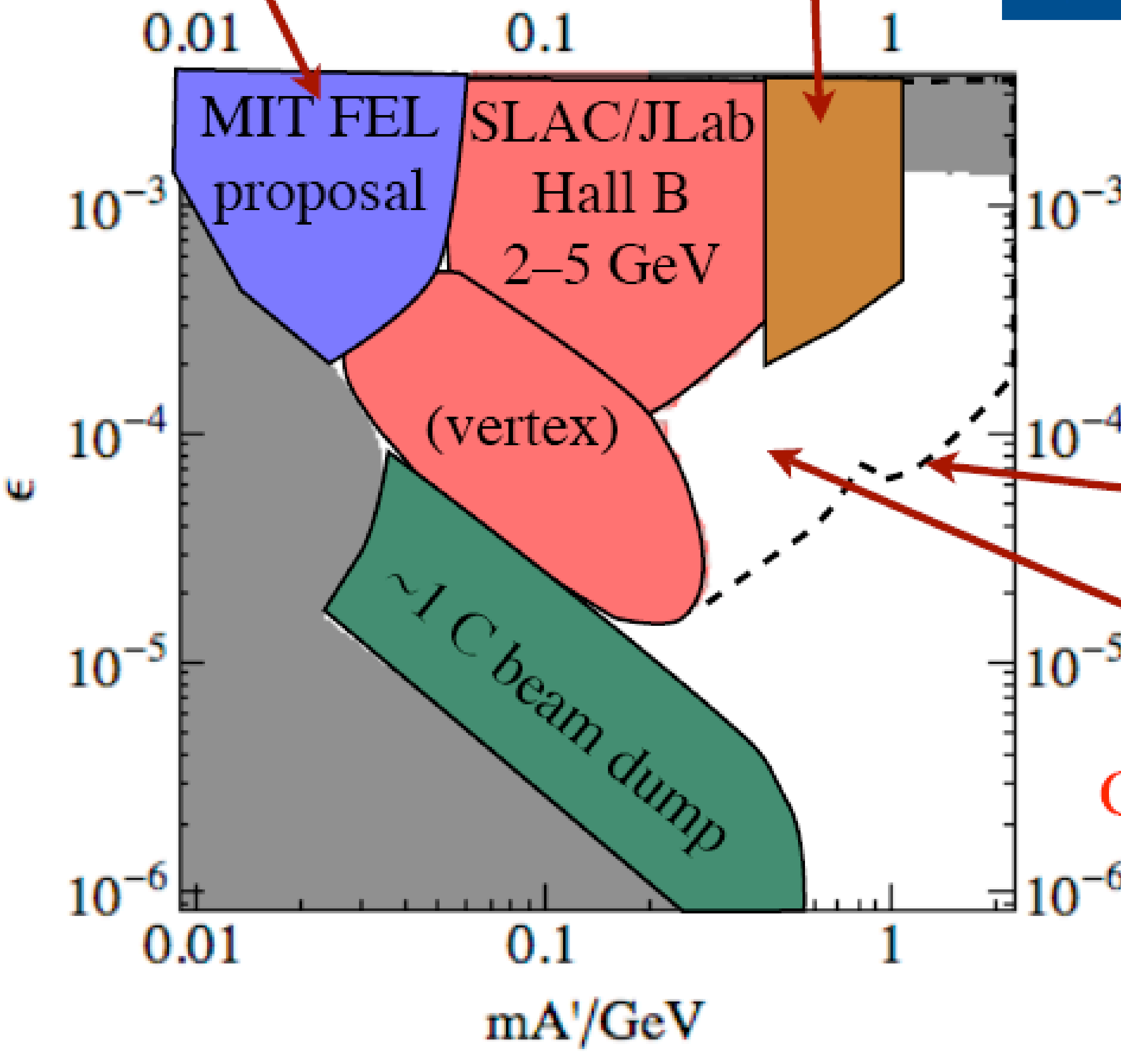


Photons
CLAS
Chicane
Dump

[see: Freytsis, Ovanesyan, Thaler]



JLab
Hall A
(20 days)



Sensitivity and Improvements:

Sensitivity with existing beams but better acceptance

Pixel tracking extends reach

Complementary coverage from B-factories: higher mass, multi-lepton channels

The second aspect, emphasized in the talk of Itay Yavin, is the possibility that high energy collider events could contain collimated bundles of leptons -- lepton jets.

The signature of isolated lepton pairs, possibly with an observable vertex displacement, has also been discussed in models of other types:

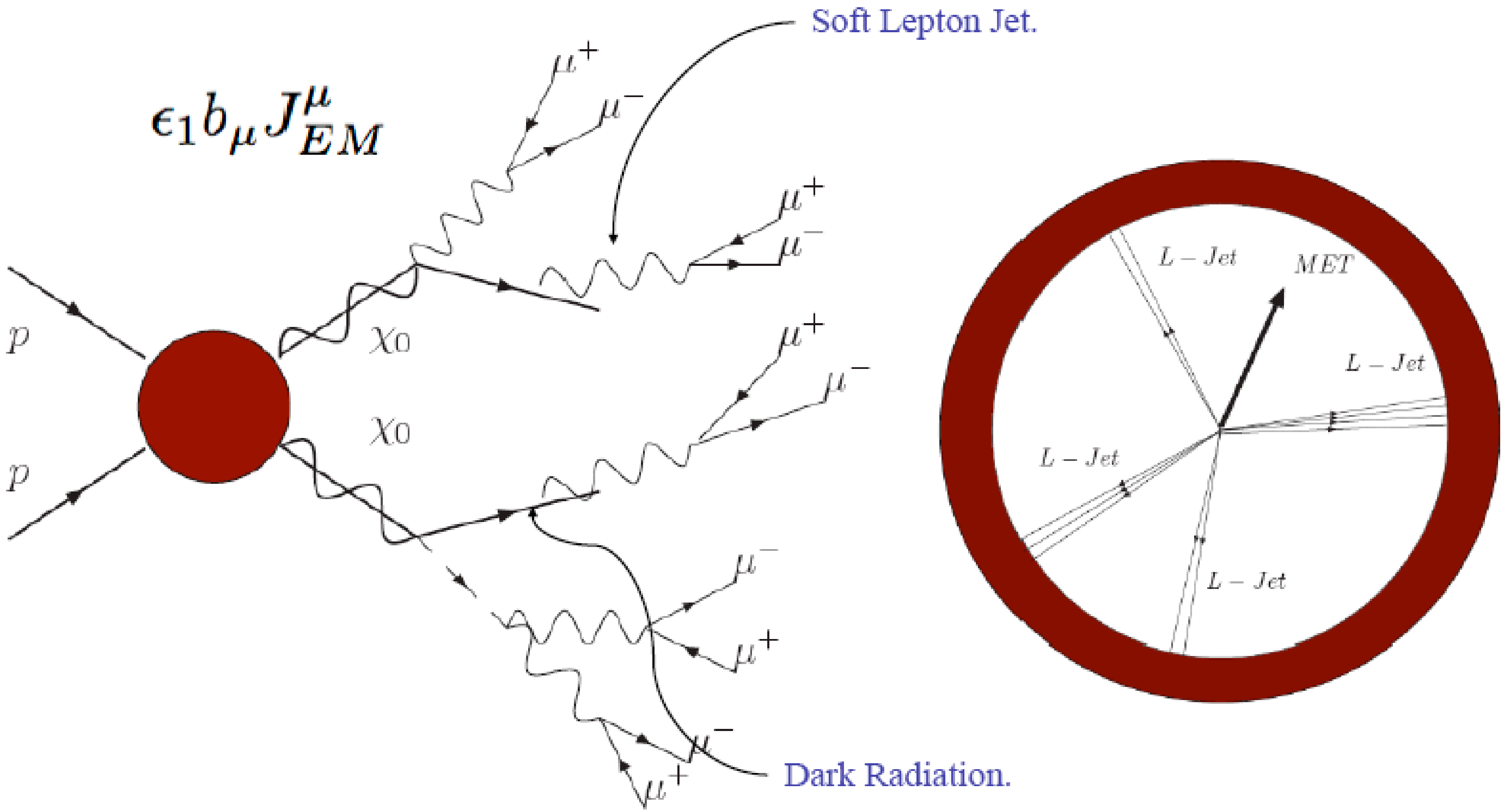
Goh and Ibe, arXiv:0810.5773 : R-axion

Lisanti and Wacker, arXiv:0903.1377 : $a^0 \to \mu^+\mu^-$
and search in DO data by Haas

Thus, low-mass lepton bundles are interesting even independently of dark-matter considerations and need to be added to the catalogue of BSM signatures for LHC.

Goh and Ibe: detailed assessment of heavy meson backgrounds to dimuon jets

process	$Br_{\mu\mu}^{(X)}$	$P_{\rm geo}$	$\sigma_{X\to\mu\mu}$(fb)
$B^0 \to K^{*0}\mu^+\mu^-$	1.3×10^{-6} [44]	$(m_a/m_B)^3$	10^{-4}
$B^0 \to J/\psi + X \to \mu^+\mu^- + X$	$\simeq 5.9\times10^{-5}$	$\lesssim 10^{-6}$	10^{-5}
$B^0 \to D^0 + X \to D^0 + \mu^+\mu^-$	$< 10^{-8}$	(m_a/m_B)	10^{-4}
$B^0 \to D^\pm + \mu^\mp + \nu \to \mu^+\mu^- + X$	10^{-2}	$(m_a/m_B)^3$	1
$B^0 \to \pi^-\mu^+\nu$	3×10^{-8}	$(m_a/m_B)^3$	10^{-5}
$D^0 \to \rho^0 + \mu^+\mu^-$	1.5×10^{-7} [46]	$(m_a/m_D)^3$	10^{-3}
$D^0 \to \omega + K_S^0 \to \mu\mu + K_S^0$	10^{-6}	(m_a/m_D)	1
$D^0 \to \rho^0 + \pi^0 \to \mu\mu + \pi^0$	10^{-7}	(m_a/m_D)	10^{-1}
$D^0 \to K^\pm + \mu^\mp + \nu$	10^{-5}	$(m_a/m_D)^3$	10^{-1}
$D^0 \to \pi^\pm + \mu^\mp + \nu$	6×10^{-7}	$(m_a/m_D)^3$	10^{-2}


$\epsilon_1 b_\mu J^\mu_{EM}$
Soft Lepton Jet.
Dark Radiation.
p
p
χ_0
χ_0
μ^+
μ^-
$L - Jet$
MET

If SUSY particles or particles of some other new particle spectroscopy decay to lepton jets, it is possible that the cross sections for lepton jets can be fb at the Tevatron but tens of pb at a higher energy above the new particle thresholds.

Lepton jets could be a qualitative feature of all new physics events at the LHC.

Now I turn to a more specific discussion of the capabilities of the LHC, in particular, in the first run.

There is a conventional picture of discovery at the LHC, a measured, essentially hierarchial march toward the ultimate confirmation of the Standard Model and Higgs boson.

Botticelli

Our real experience could be very different.

My prediction is that, by the time the Higgs boson is discovered at the LHC, that discovery will no longer be considered interesting.

Instead, we will be immersed in the discovery and clarification of a new spectrum of elementary particles associated with the generation of the energetics of electroweak symmetry breaking.

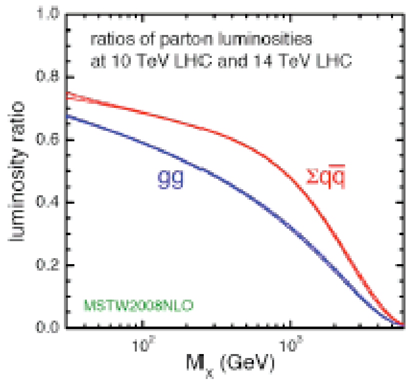
This refers to the ultimate LHC program. The program for 2010 will be much more limited. Maybe

~ 200 pb -1 at ECM = 7 -10 TeV

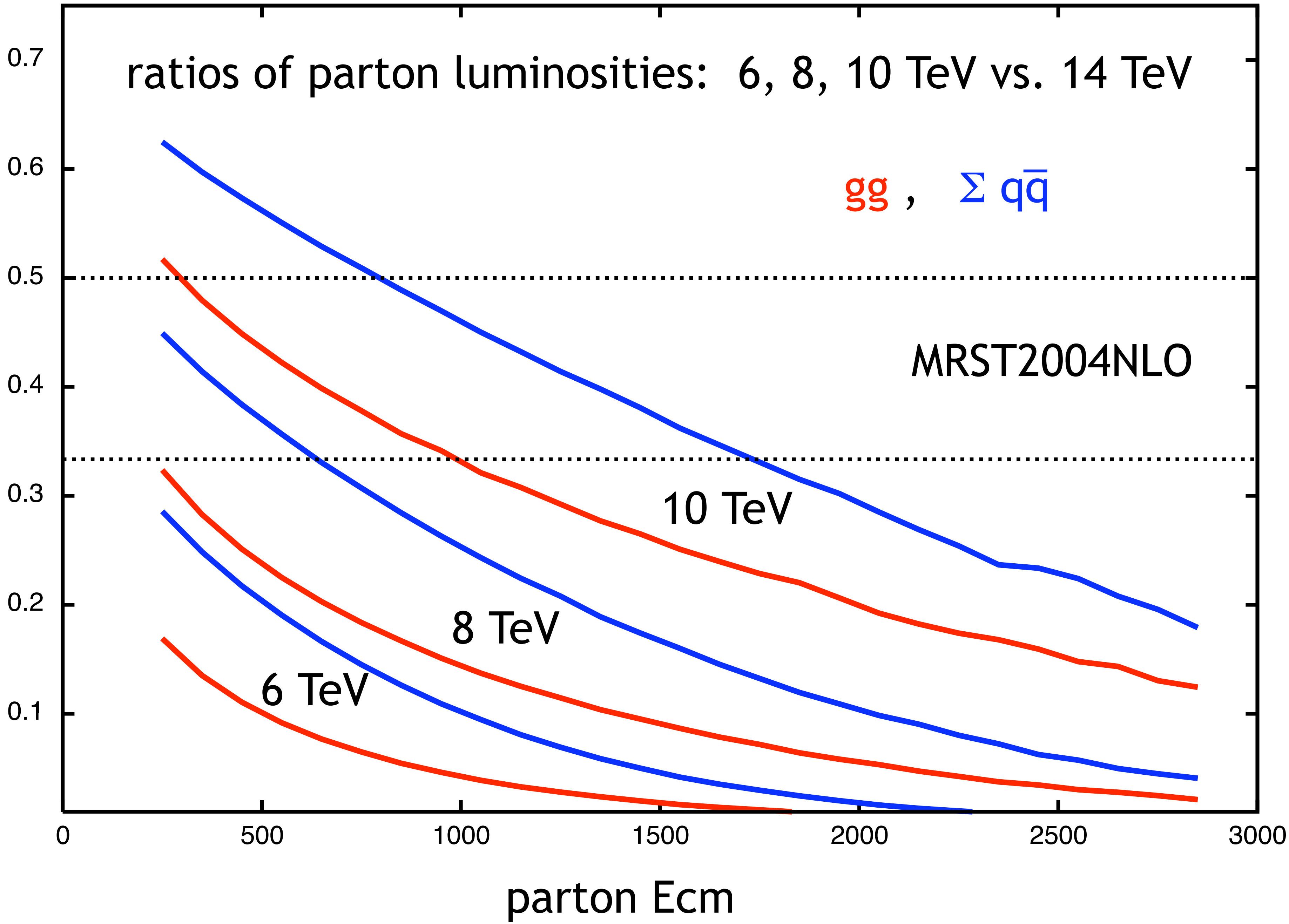
Can we make discoveries with this energy and luminosity? What should we concentrate on ?

Roberto Tenchini explained to us the debate about the energy to be chosen for the initial LHC run.

14, 10, 7 TeV cross section ratios



Process	σ(10TeV)/σ(14TeV)	σ(7TeV)/σ(10TeV)
H (m=160)	0.54	0.50
WW, ZZ, WZ	0.65	0.62
tt	0.45	0.39
tW	0.45	0.39
W, Z	0.68	0.66


ratios of parton luminosities: 6, 8, 10 TeV vs. 14 TeV
gg , Σ q$\bar{q}$
MRST2004NLO
10 TeV
8 TeV
6 TeV
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
1000
1500
2000
2500
3000
parton Ecm

We need a flexible plan that takes into account the three problems with attaining useable luminosity at the LHC:

1. poorly constructed interconnections and shunts for superconducting dipoles

2. complex optics of the LHC

3. difficulties in training magnets for their design field

#3 is an issue only above 12 TeV; irrelevant for 2010.

My understanding is that the CERN accelerator group is well equipped to deal with problem #2, less so with problem #1.

I suspect there is a better hope for 300 pb-1 at 8 TeV than for 150 pb-1 at 10 TeV.

What can we discover with this luminosity and energy ?

This depends strongly on the model of new physics:

weakly coupled ?

strongly coupled ?

For weakly-coupled models, we are looking for pair-production of particles of a new spectroscopy.

The largest cross sections are for quark and gluon partners.

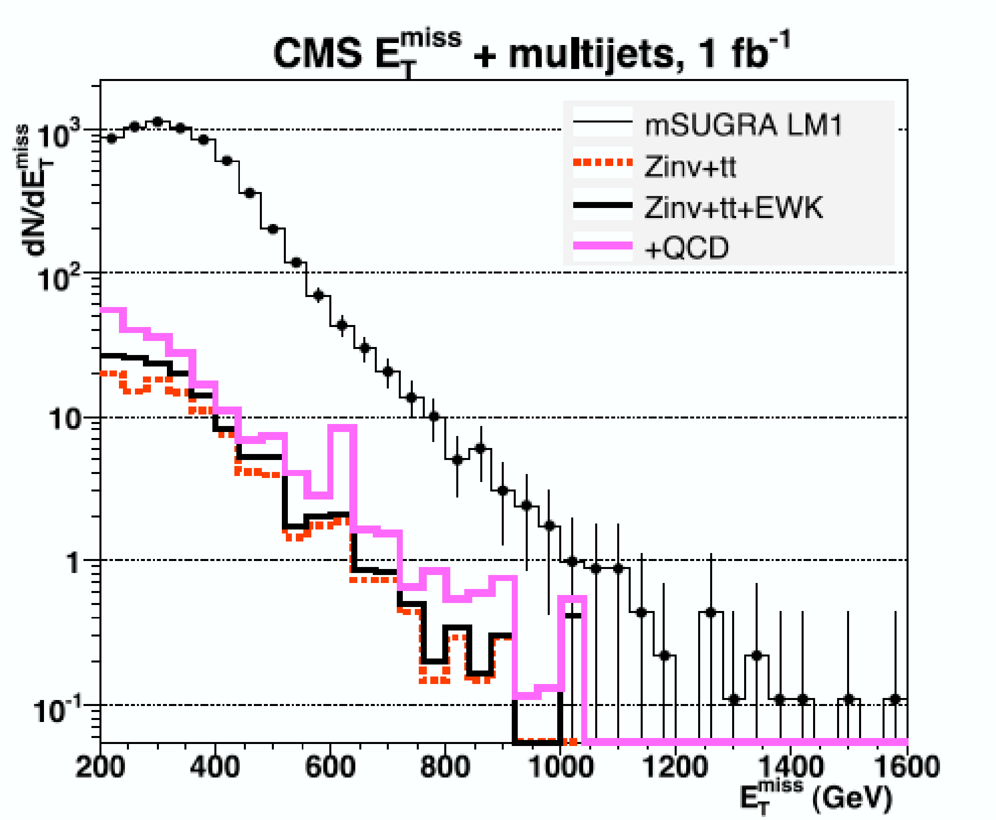
There is a slice of phase space for discovery ;

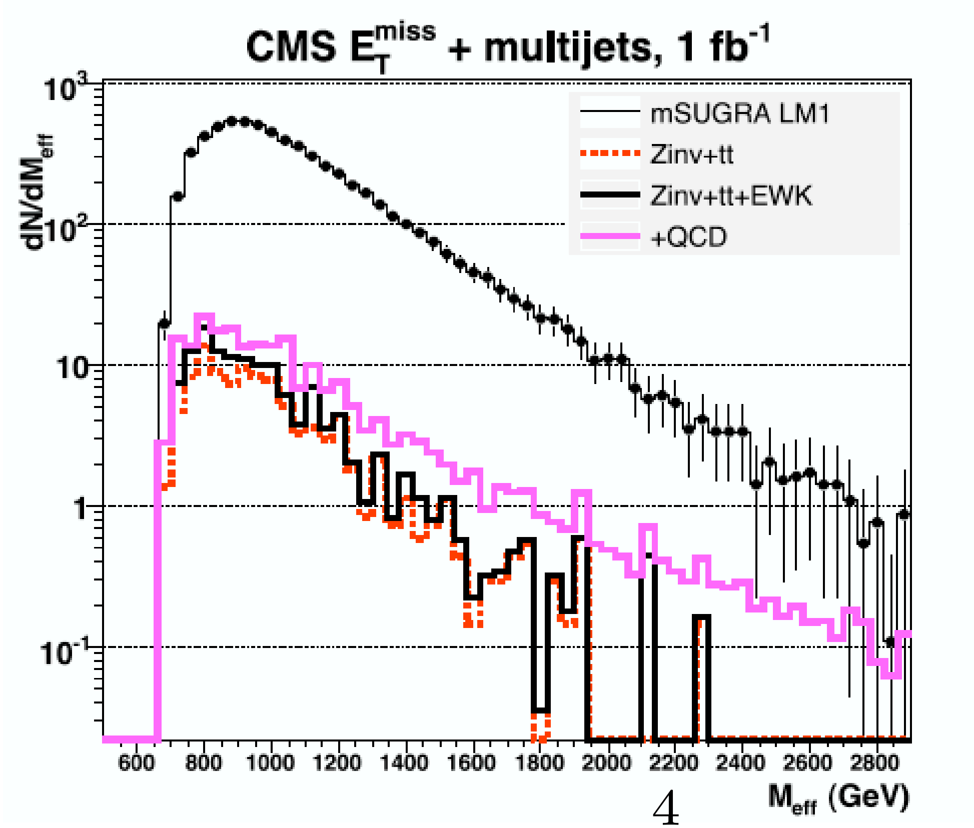
in SUSY (mSUGRA), we might explore the region between 400 GeV and 600 GeV for squark and gluino masses

SUSY masses just beyond the current limits are always the ones favored by naturalness.

The nicest solution to the "little hierarchy problem" is that we have not been sufficiently patient.

$$m(\widetilde{g}) = 600\ \mathrm{GeV}$$





$$\not{E}_T$$

$$M_{\mathrm{eff}} = \not{E} + \sum_i^4 E_{Ti}$$

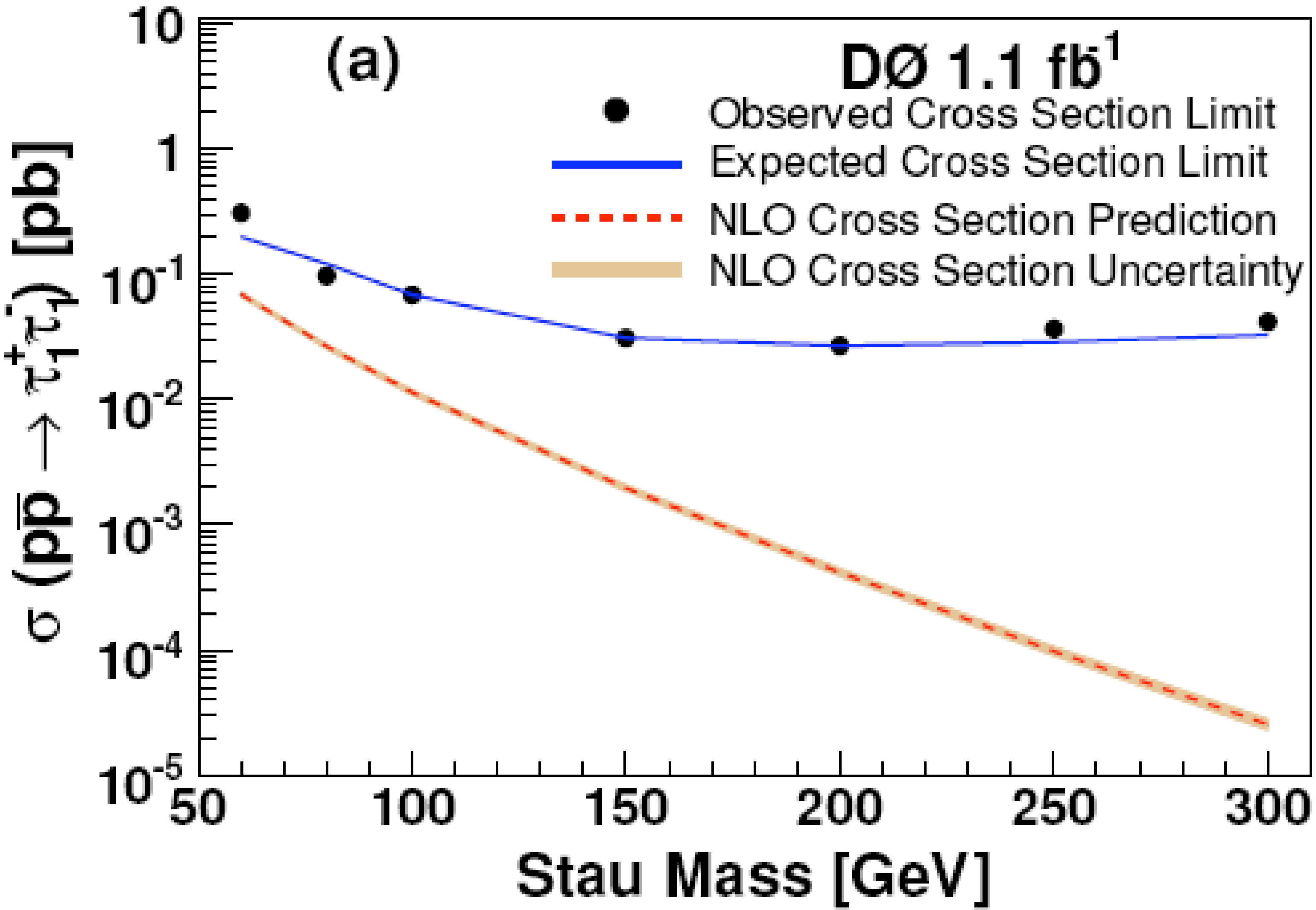
Yetkin and Spiropulu

There is an important exception to this generally pessimistic appraisal:

In models of gauge-mediated SUSY breaking, the lightest SM SUSY partner can be a stau that is stable on collider experiment timescales. It eventually decays to a “superWIMP”.   Other weakly coupled models can have a similar phenomenology.

(Feng, Rajaraman, Takayama)

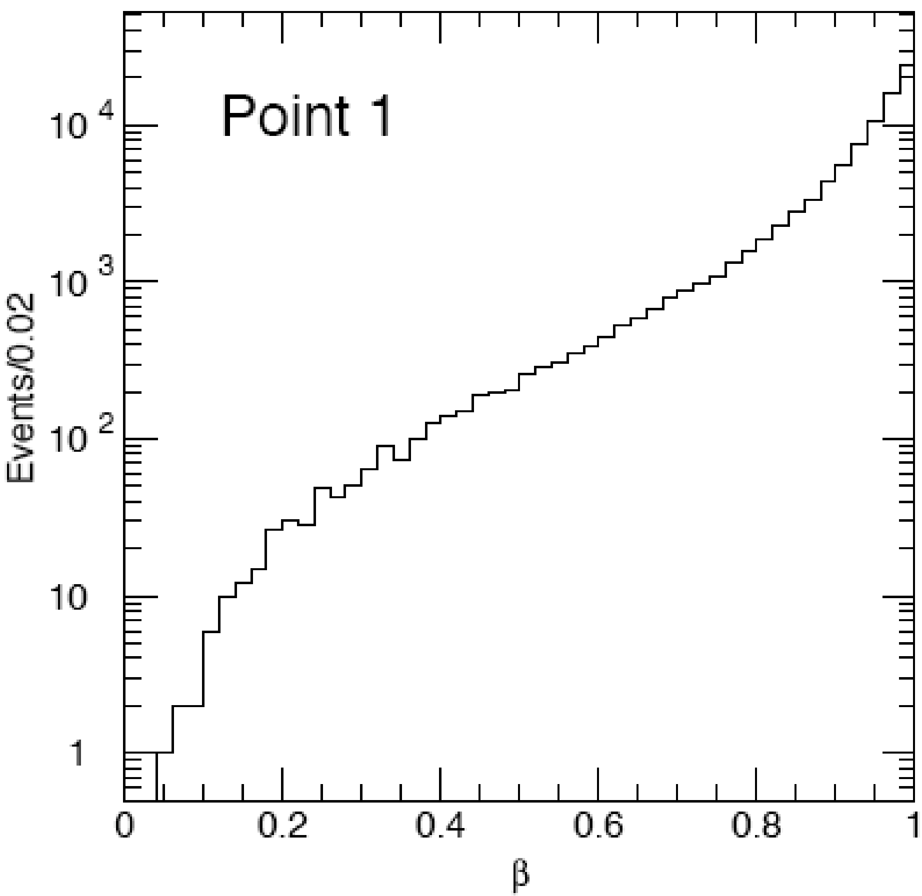
This this scenario, as soon as our hadron collider is above threshold for SUSY production, the signal is very easy to discover.

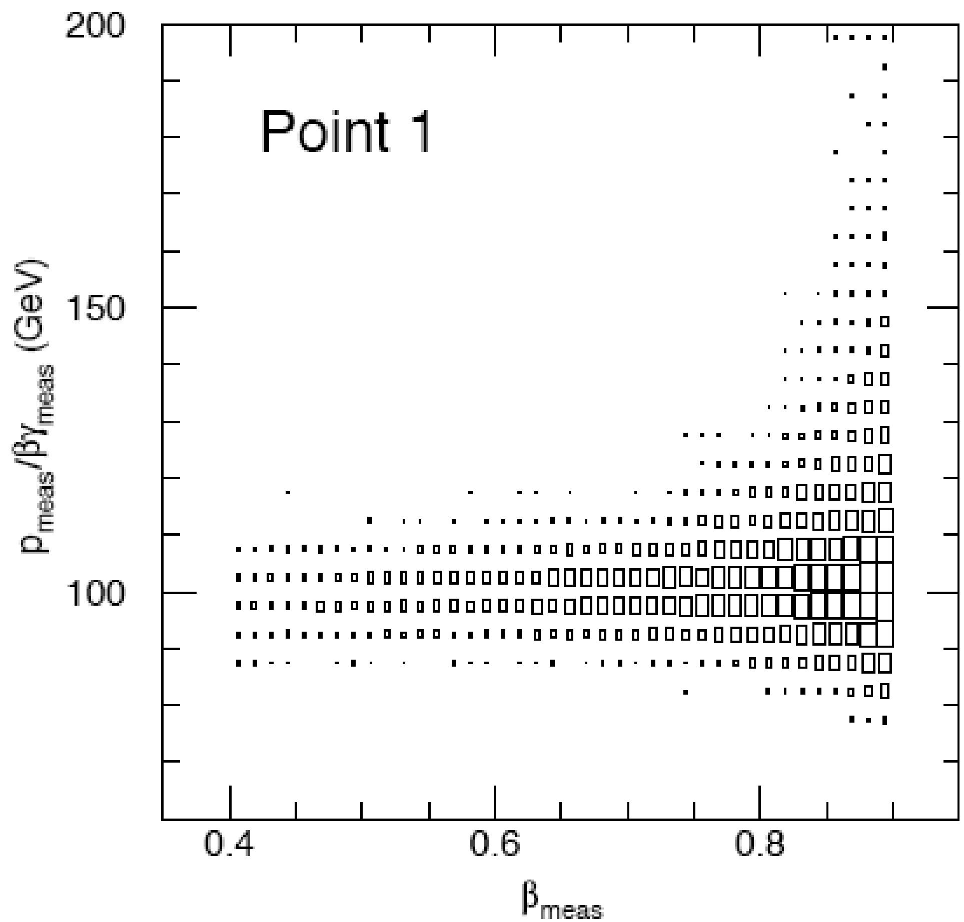


(a)
DØ 1.1 fb-1
Observed Cross Section Limit
Expected Cross Section Limit
NLO Cross Section Prediction
NLO Cross Section Uncertainty
σ (pp̄ → τ̃1+τ̃1-) [pb]
Stau Mass [GeV]
10
1
10-1
10-2
10-3
10-4
10-5
50
100
150
200
250
300

Heavy stable particles appear as muons which are slow but can still be within the time bucket of the muon system.

Using $\beta \ vs. \ p$, it is possible to measure the mass to 0.1%.





Ambrosanio, Mele, Petrarca, Polesello, Rimoldi

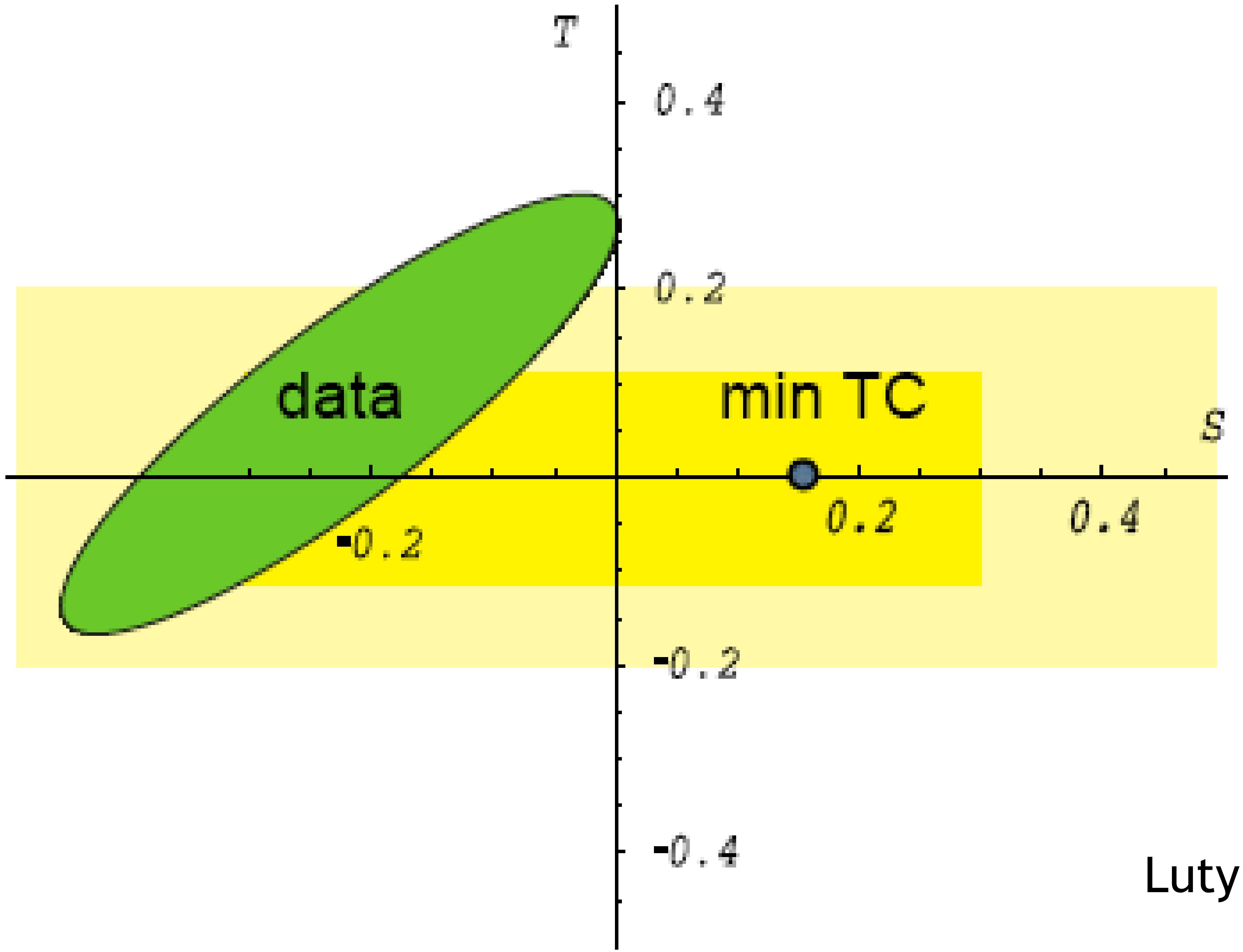
For strongly-coupled models of electroweak symmetry breaking, we have more opportunity, but also and more constraints.

The opportunity comes from the fact that the models predict resonances and other exotic states.

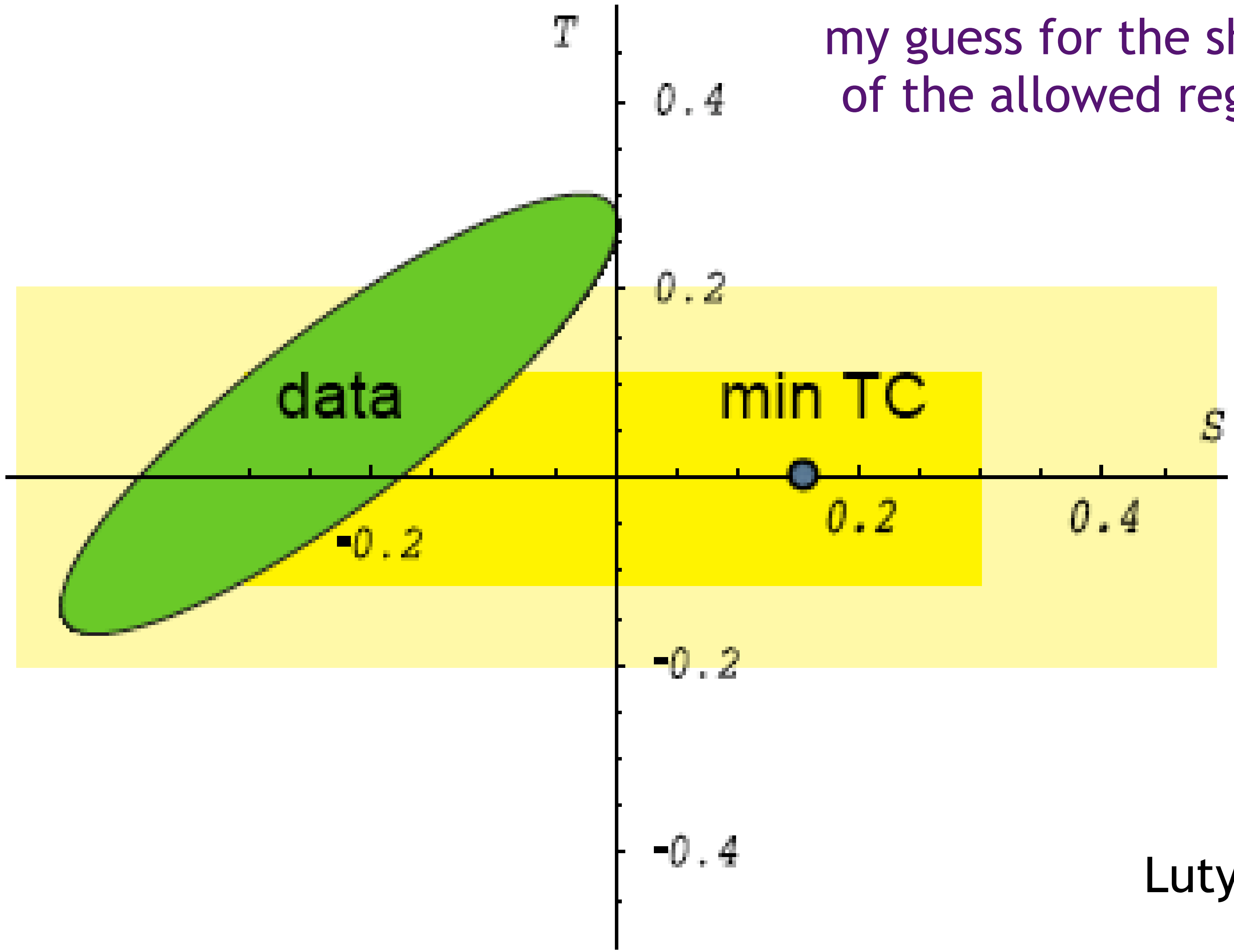
The problems come from the fact that the coefficients of higher-dimension operators that affect precision electroweak and flavor physics can be large.

Rattazzi

Markus Luty gave us his estimation of the precision electroweak constraints.

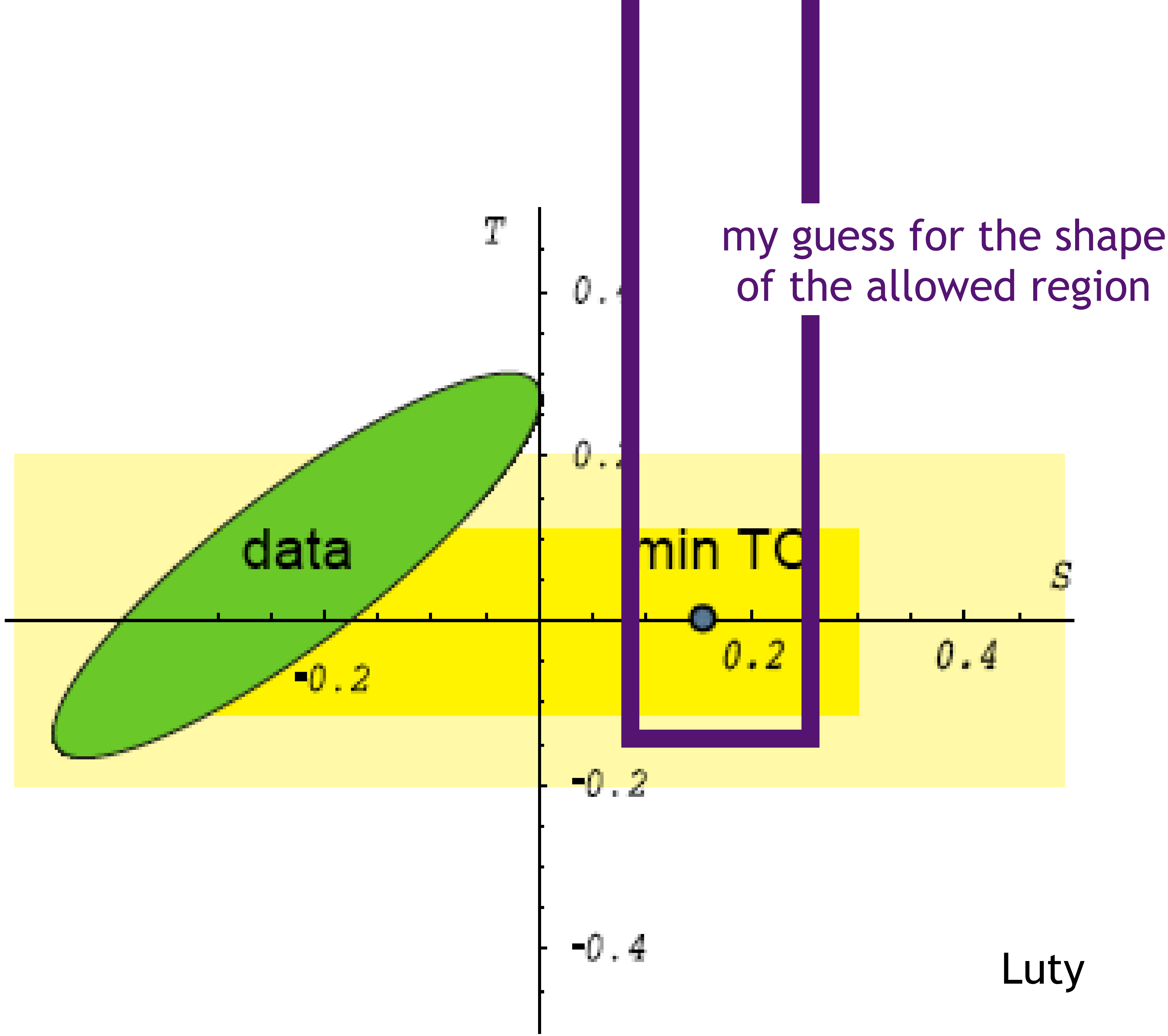


Luty



my guess for the shape of the allowed region

Luty


my guess for the shape
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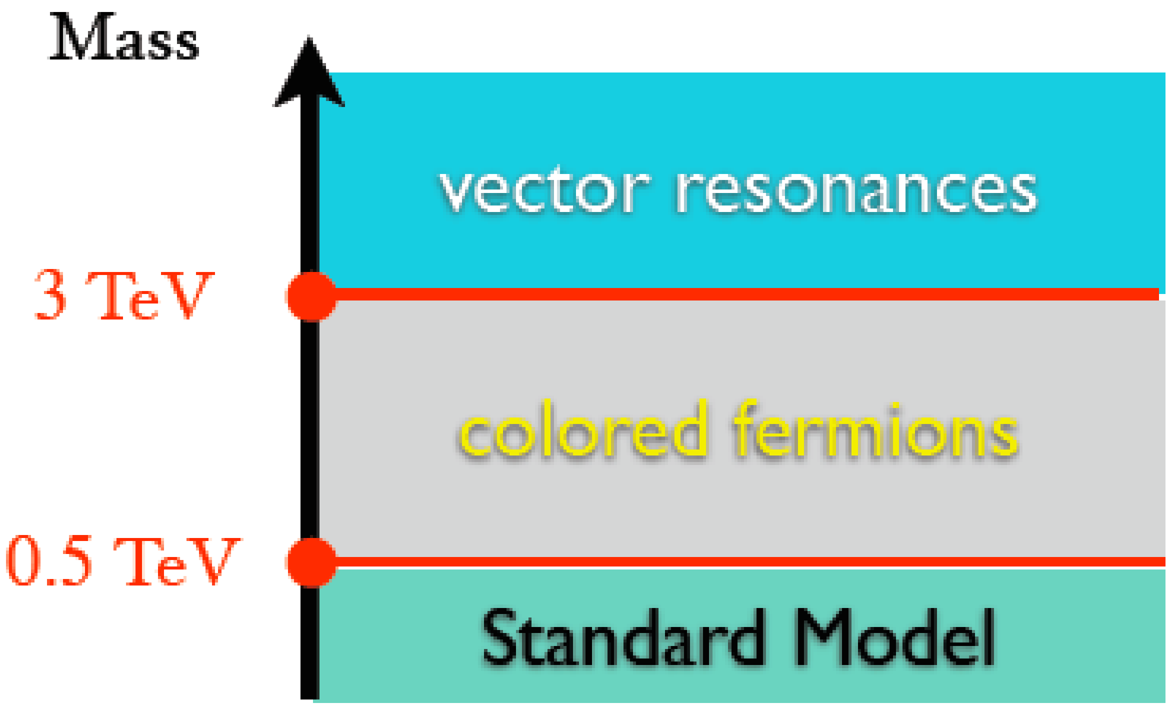
Luty

Nevertheless, we have an opportunity to search; let's hope for the best and go forward.

We can look for new physics of a strongly interacting electroweak sector either as pair-production of new particles or as resonances.

Here is the advice that we received from Riccardo Rattazzi:



especially,
top partners !

There is a particularly exciting proposal of a new pair-produced particle.

The precision electroweak constraint on $\Gamma(Z^0 \to b\bar{b})$ is an important constraint on top compositeness, since bL is in the same SM multiplet as tL.

Agashe, Contino, da Rold, Pomarol proposed that, if there is an unbroken (not strongly broken) custodial SU(2) which contains $\bar{b}_L \gamma^\mu b_L$, the nonrenormalization of that current can protect $\Gamma(Z^0 \to b\bar{b})$.

The simplest structure with this property is:

$$Q = (\mathbf{2}, \mathbf{2})_{2/3} = \begin{bmatrix} T & T_{5/3} \\ B & T_{2/3} \end{bmatrix}, \quad \tilde{T} = (\mathbf{1}, \mathbf{1})_{2/3}$$

The Q = 5/3 quark has a beautiful like-sign dilepton signal. Andrea Wulzer gave us a detailed analysis of this search. (see also work of Contino and Servant). Unfortunately, there is only a small window in which this can be discovered in the first year.

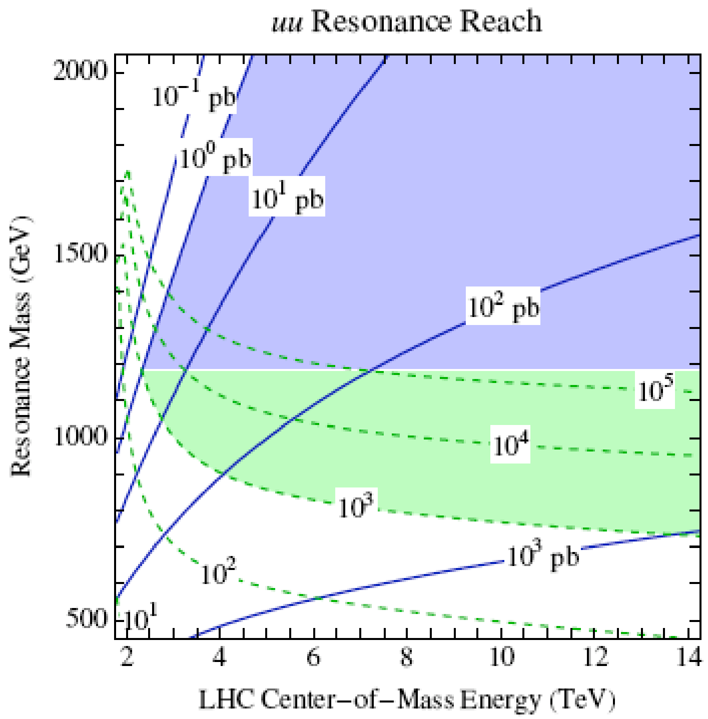
LHC @ 10 TeV:

Mass, [TeV]	$L_{\text{discovery}}$, [fb^{-1}]	# signal	# background
0.5	0.072	5	0
1.0	5.5	9	3
1.5	210	22	19

Another example was given by Martin Schmaltz:

(Bauer, Ligeti, Schmaltz, Thaler, Walker, arXiv:0909.5213)

Supermodels with diquark resonances that can be discovered at LHC with 10 pb-1 of data a 10 TeV.



Unfortunately, the defining property of supermodels is that they are unattainable...

So, much attention must be given to searches for s-channel resonances associated with strongly interacting electroweak sectors, and other possible s-channel resonances.

New strong interactions should contain prominent resonances. These will be weakly coupled to Standard Model particles, but the couplings to quarks and gluons could be as strong as α_s .

It is a high priority of the first year of the LHC to search for and exclude or discover resonances in all possible channels, and most especially:

$$jj \ , \quad t\bar{t} \ , \quad \ell^+\ell^-$$

copy by Rubens of the lost “Battle of Anghiari” by Leonardo di Vinci

There are also many weakly-coupled models with TeV resonances.

Extended gauge groups:

SU(2) x U(1) is broken at 250 GeV. This could be a subgroup of a larger gauge group that is broken at 1-2 TeV.

Randall-Sundrum warped extra dimensions:

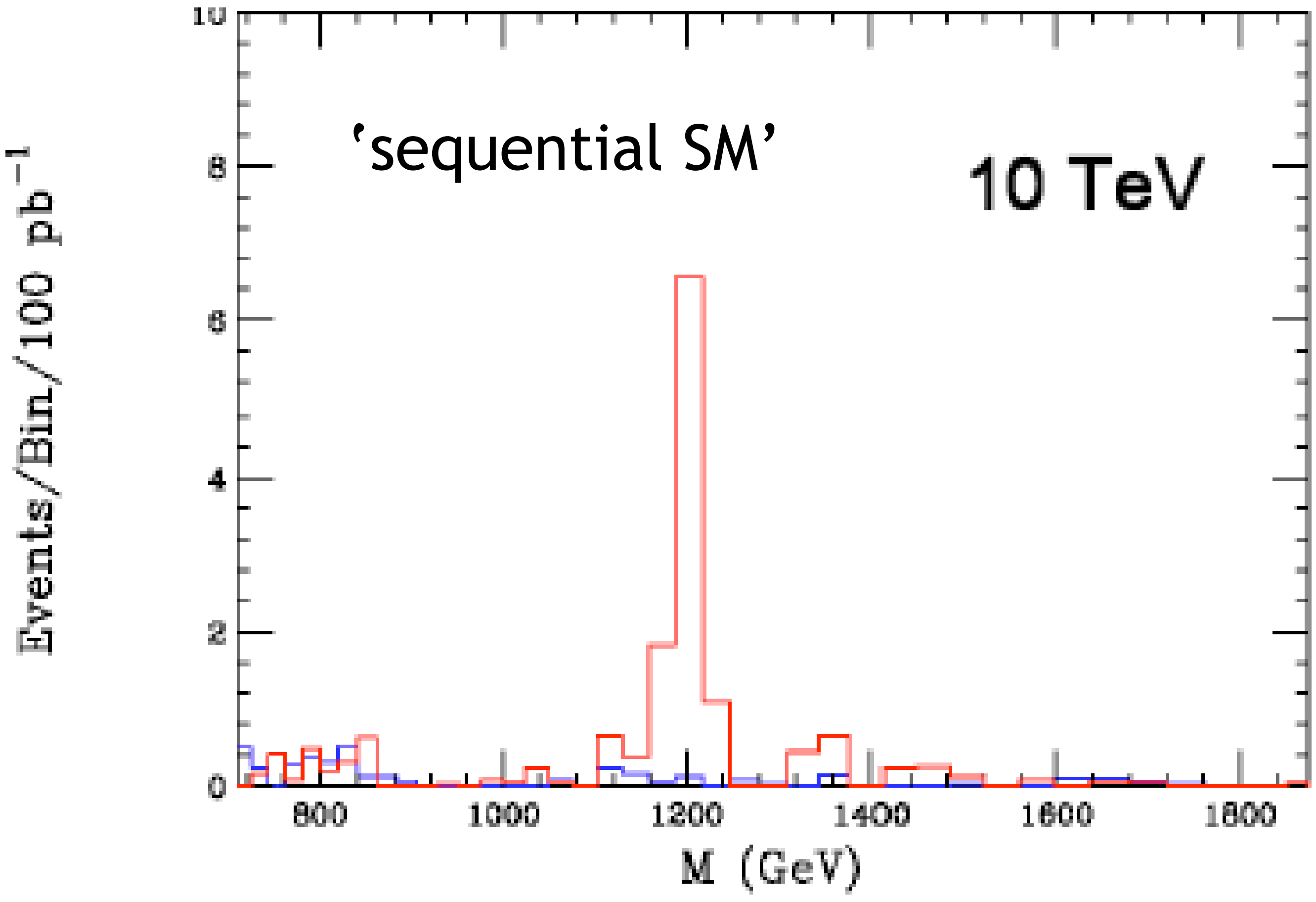
This theory is best thought of as a 'holographic dual' of a strongly coupled theory. A feature of RS theories is that the must be composite to generate a large enough top quark mass.

String theory with large extra dimensions:

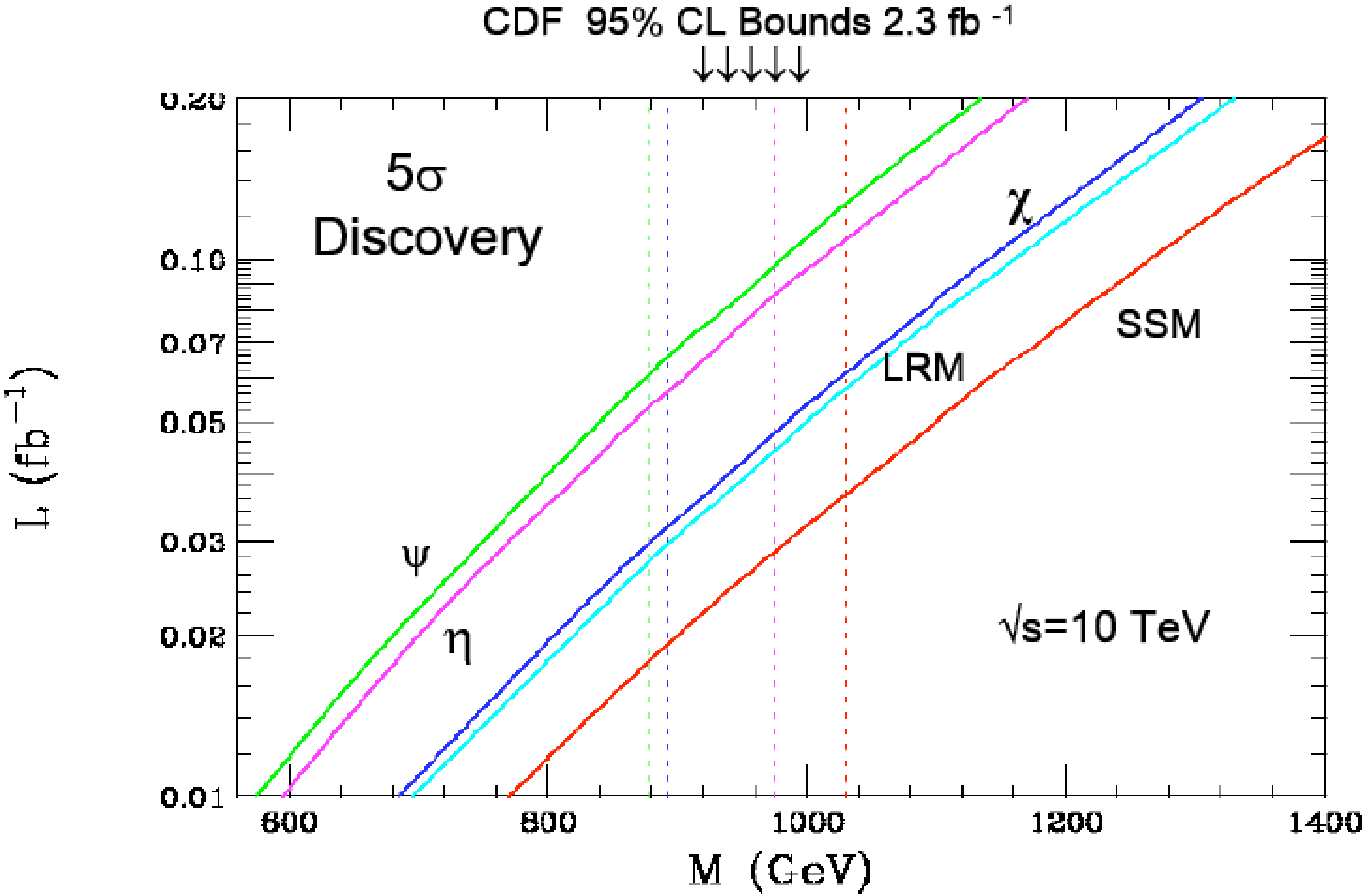
In models of extra dimensions where the Planck scale is brought down to the few-TeV scale, we expect string excited states of quarks and gluons at the TeV scale.

In the weakly-coupled cases, the resonances also couple to quarks and leptons with strength α_s or α_w, so these can be taken as concrete models illustrating the more general situation.

Extended gauge theories, especially, are very well studied.



Rizzo


CDF 95% CL Bounds 2.3 fb -1
5σ
Discovery
χ
SSM
LRM
ψ
η
√s=10 TeV
L (fb⁻¹)
M (GeV)
0.20
0.10
0.07
0.05
0.03
0.02
0.01
600
800
1000
1200
1400

Rizzo

Resonances could also appear in the jj and $t\bar{t}$ mass distributions.

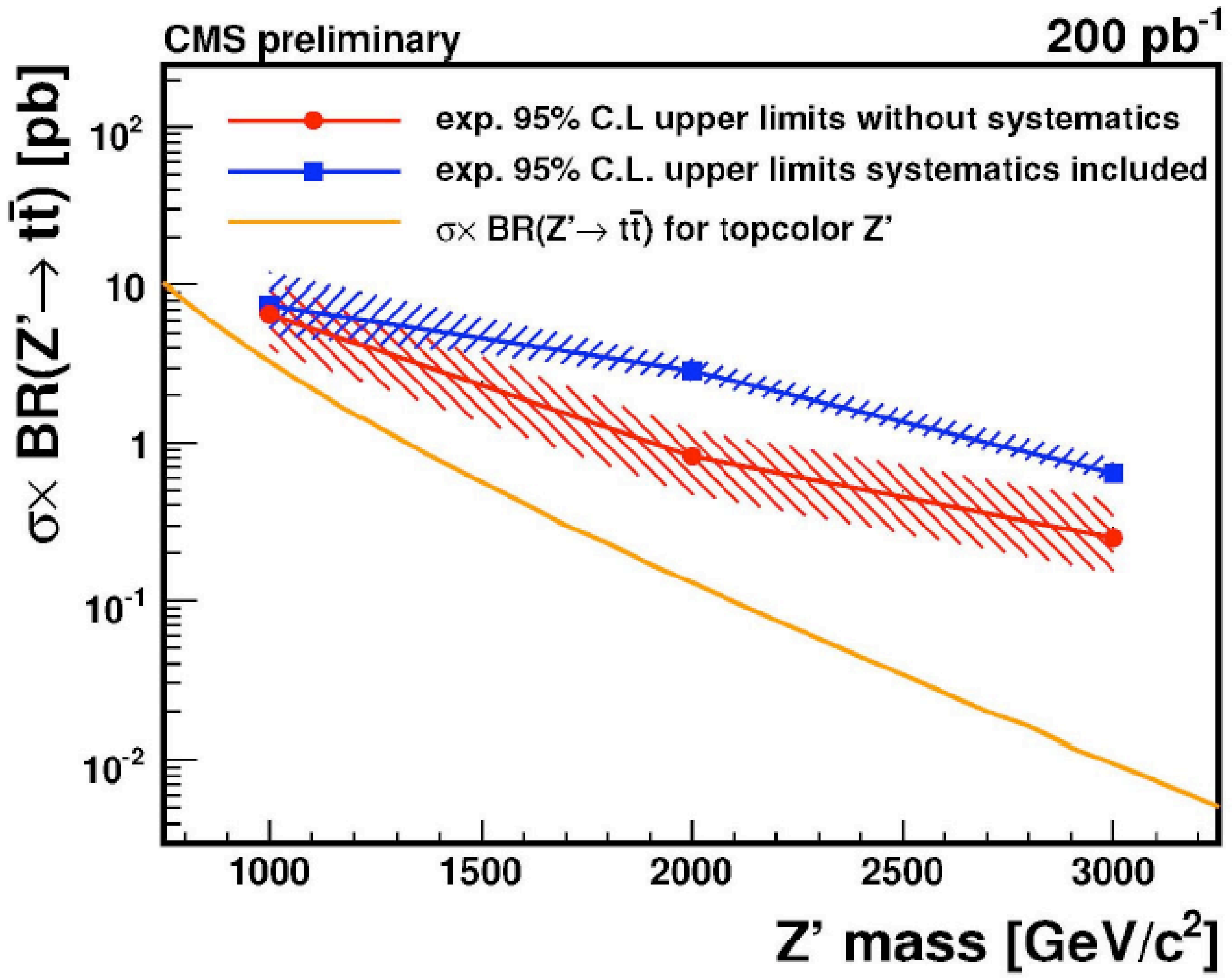
A jj resonances is sometimes called an 'axigluon'. CDF set a very strong limit on this particle already in Run 1 (250 pb-1 at 1.8 TeV):

$$m_A > 0.98 \text{ TeV} \quad\quad (95\% \ \ \text{conf.})$$

It is much easier to search for a resonance in the jj mass distribution than to search for a broad excess at high mass ('quark compositeness').

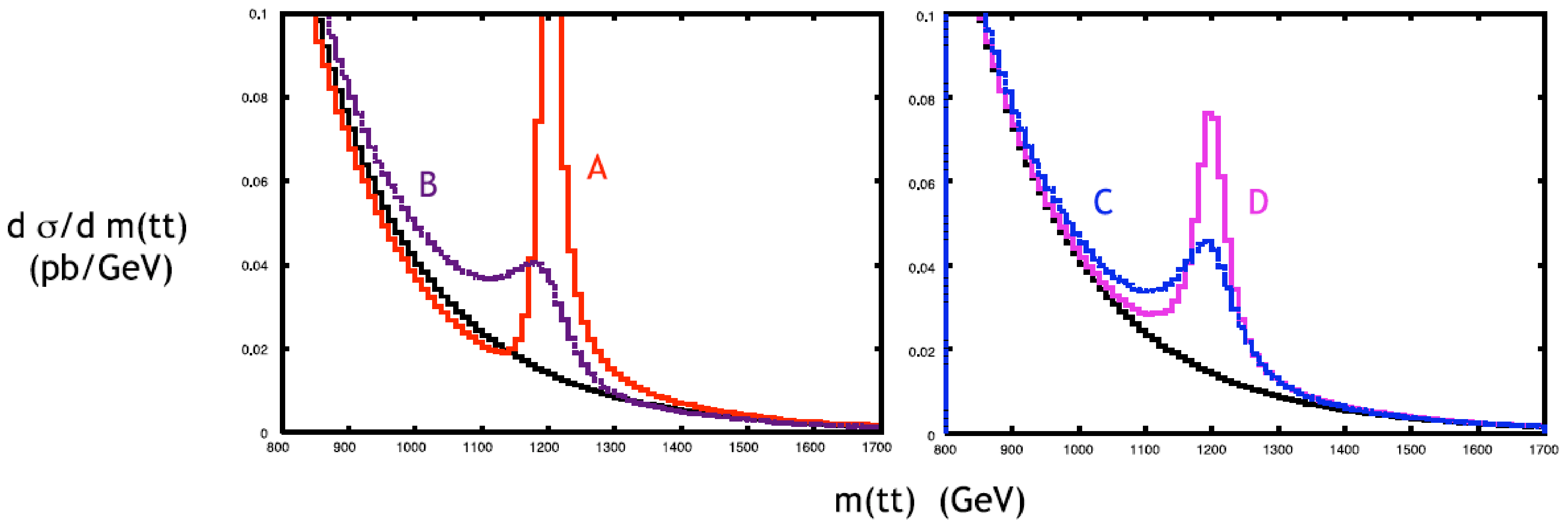
The search for $t\bar{t}$ resonances is complicated by the fact that $t\bar{t}$ pairs represent only 1% of the total QCD pair production rate at high energy. This search benefits from new techniques for boosted exotic jets that I will not have time to discuss.

The methodology for $t\bar{t}$ resonance searches is under active investigation (eg. by Brooijmans in ATLAS). Here is a current example from a lepton + jets analysis in CMS:



N. Hadley (Maryland/JHU) for CMS

Just to tempt you, here are some models of top quark resonances that are discoverable at LHC at 10 TeV and will not be excluded at the Tevatron:



(Please do not ask the rationale for these models.)

One last thought on the 2010 run of the LHC:

It is very likely that the results of the 2010 run will give many 2-3 sigma anomalies that might or might not be explained by improved understanding of the detectors and of rare QCD processes.

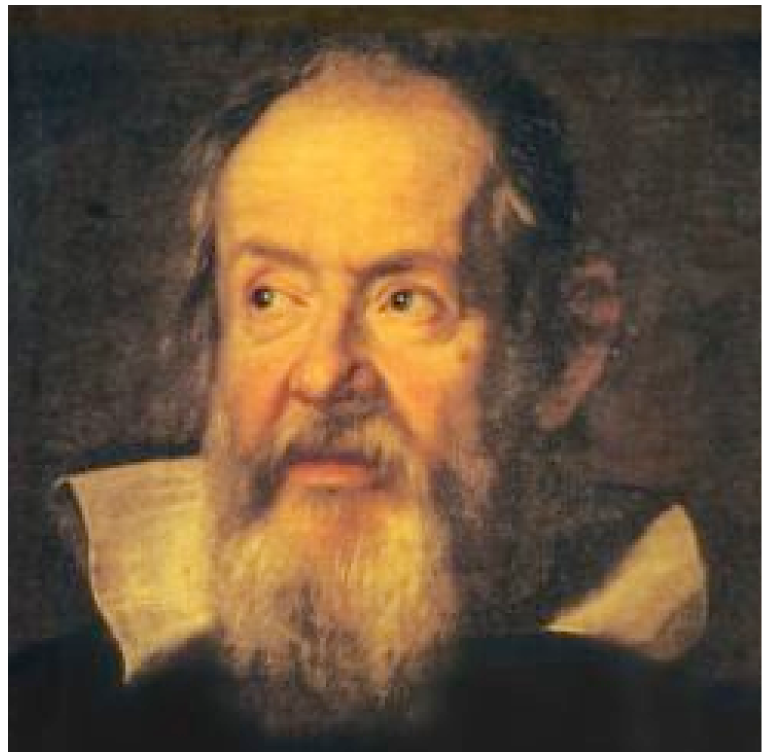
In 2011, LHC will have a long shutdown that might last as long as 1 year.

In this situation, it is important that ATLAS and CMS think about the best strategy to manage the release of information to the high energy physics community and to the world.

I feel that the only realistic strategy is to be open about the most prominent anomalies, giving clear physics reasons why these anomalies might be explainable within the Standard Model.

Everyone will benefit from having theorists involved in these issues.

FInally, I thank the organizers for this wonderful opportunity to visit Florence and to discuss the major issues of high energy physics in this very congenial environment.



Perhaps, in the next few years, our hopes for the discovery of new particles and new laws of physics will be realized.

Durer