Clearcutting the Energy Frontier

February 1, 2012

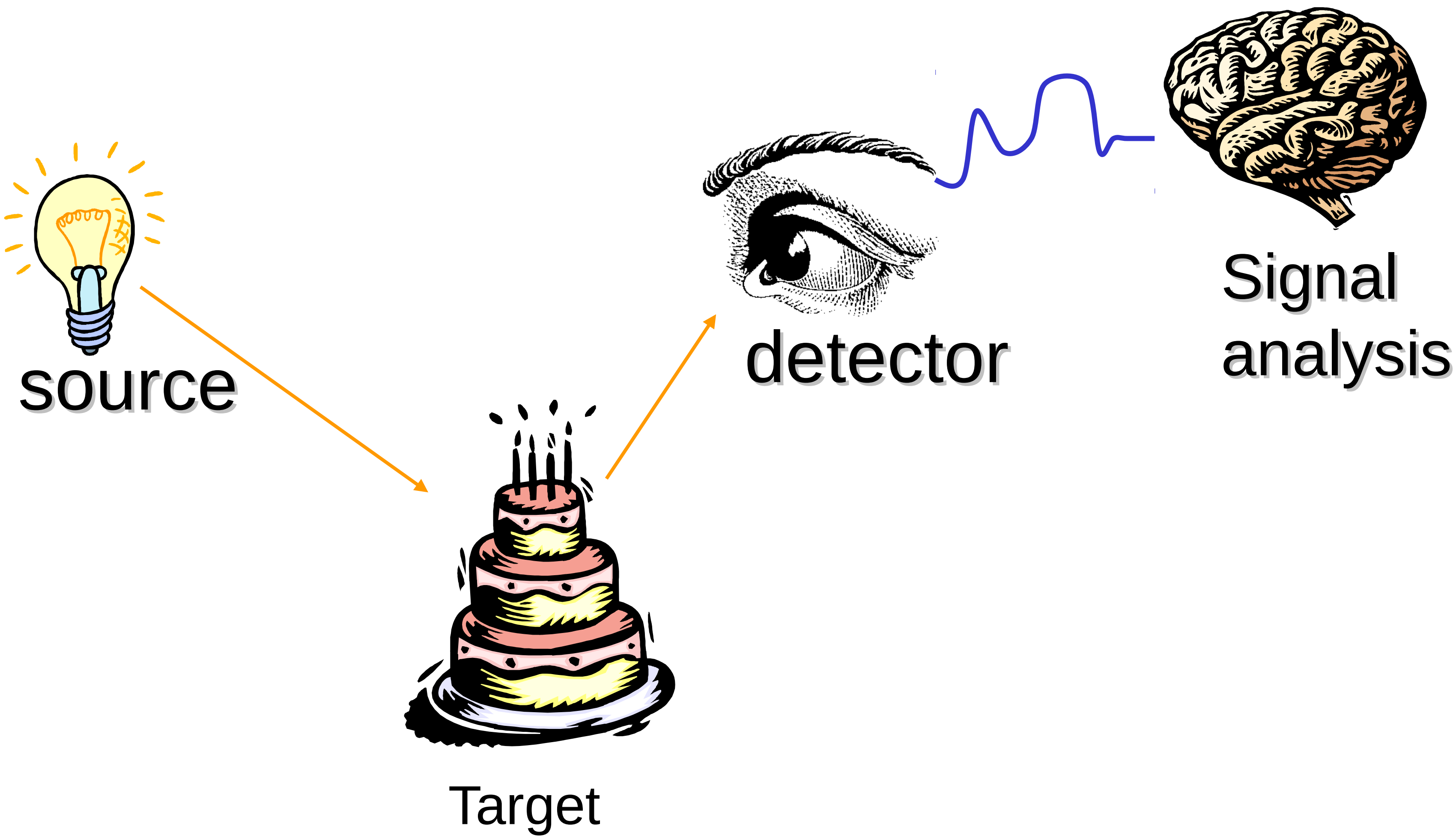
Amitabh Lath
Rutgers, The State University of New Jersey

Richard Plano
1929 - 2012

What is the Energy Frontier?

And why do we want to be there?

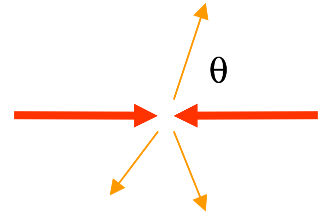
- How do we see anything?

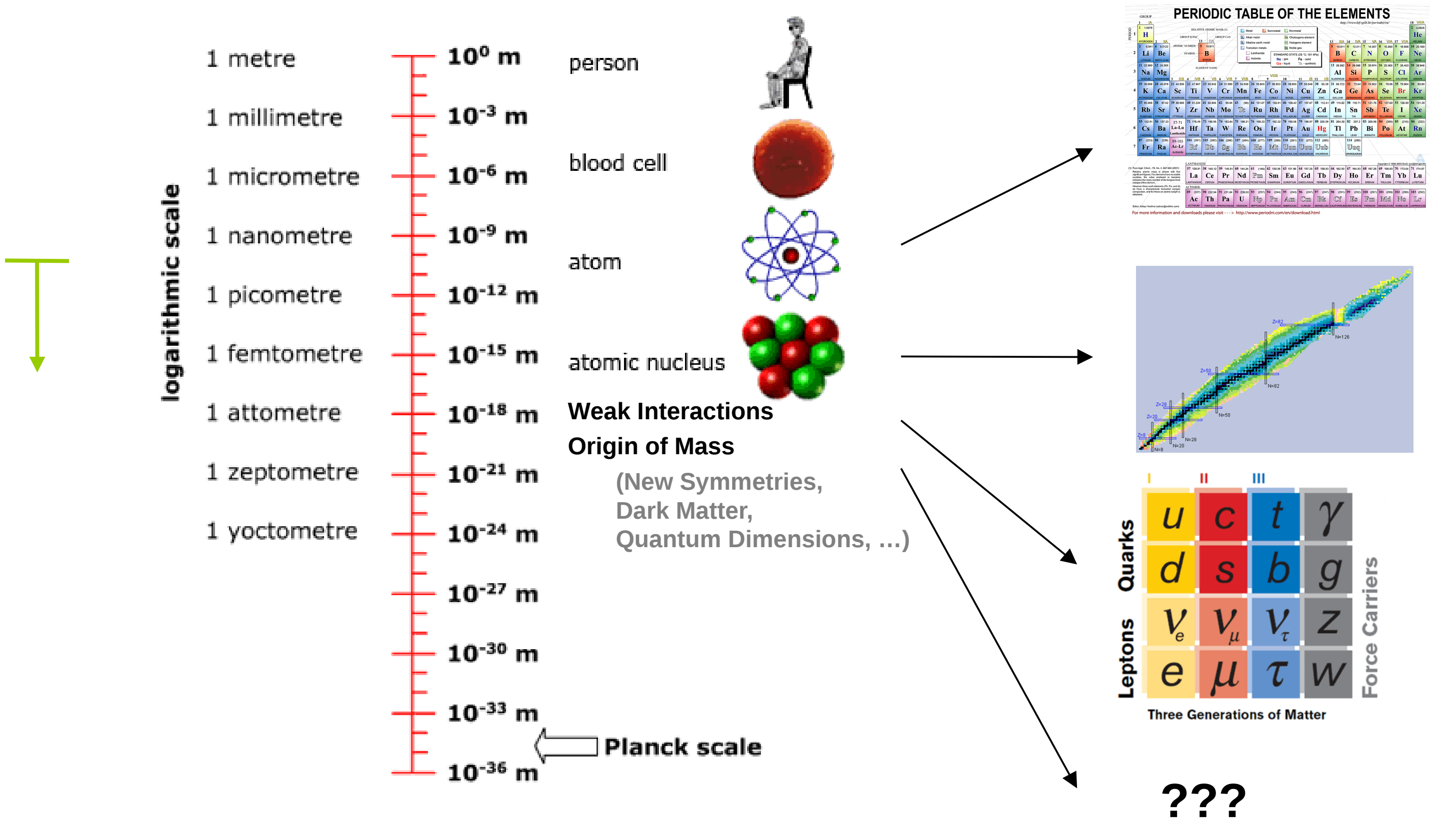


Scattering Experiments

High Energy Collisions of Particles

- Microscope to Short Distances
- New Substructure and Forces

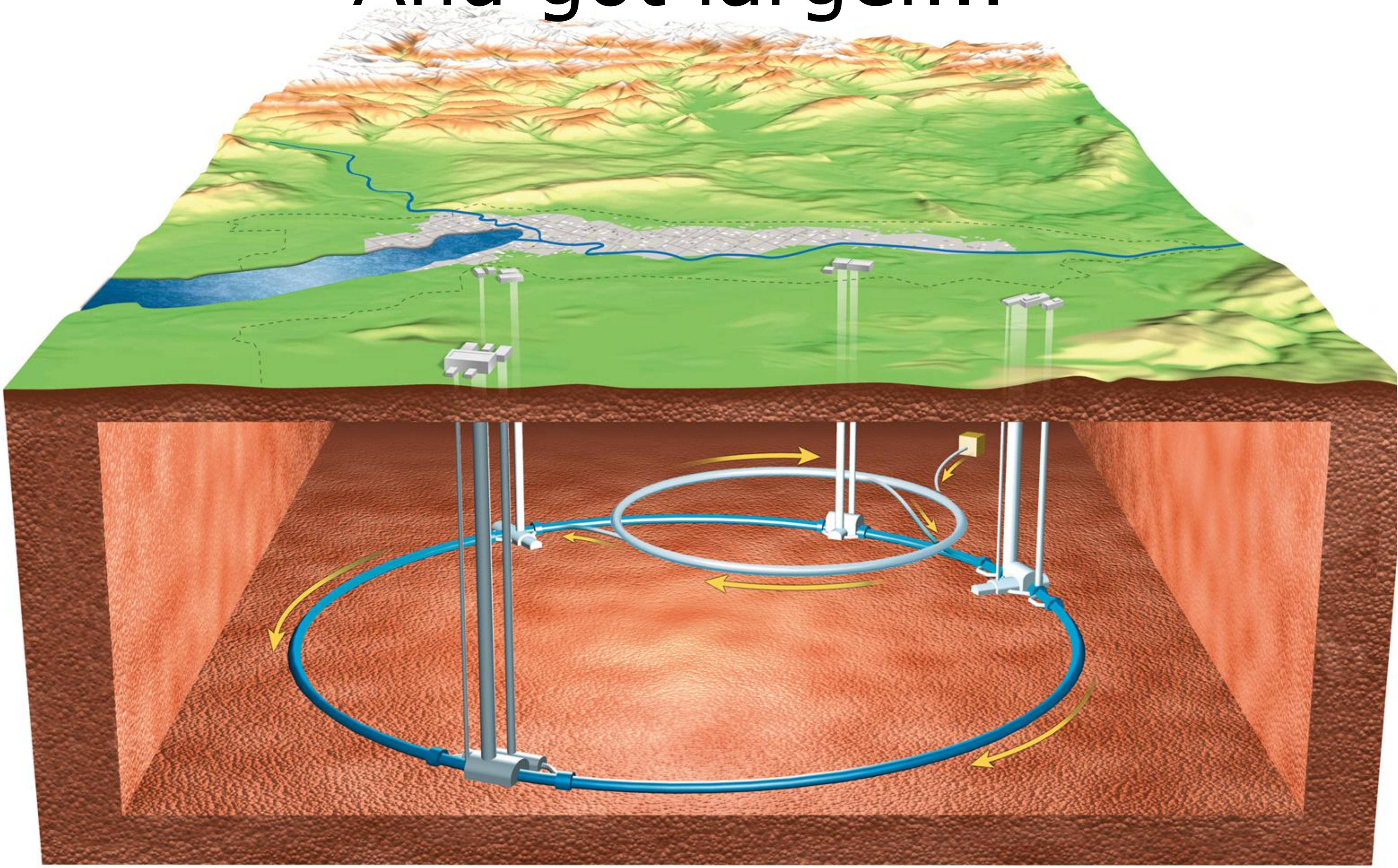




Things started small...

The first cyclotron…

And got larger...

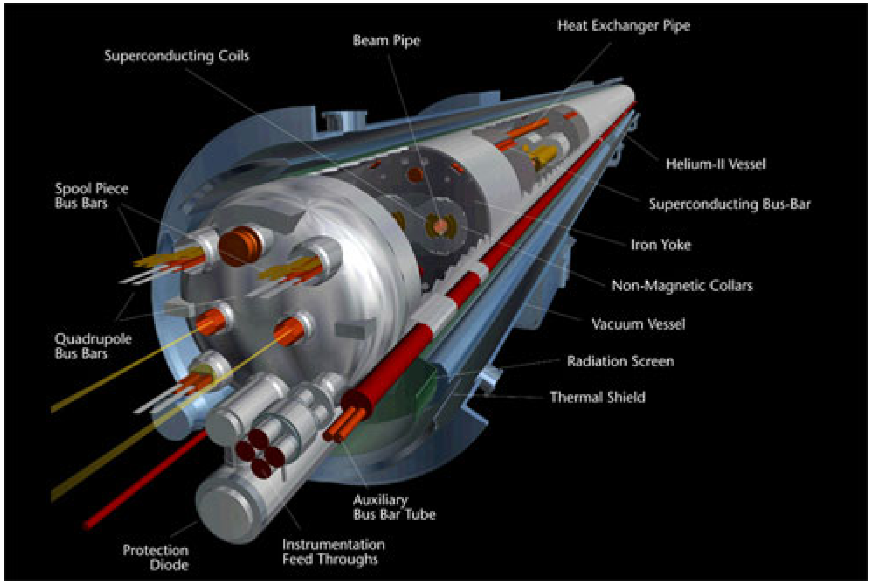



LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

Large Hadron Collider

Radio Frequency Klystron Cavities

1232 Super Conducting Dipole Magnets



T = 1.9 K   I = 12000 Amps

B = 8.3 Tesla   E = 7 MJ / Dipole

½ nanogram in Beam –

Kinetic Energy of 100,000 Ton
Aircraft Carrier at Cruising Speed

High Energy Collider Detectors

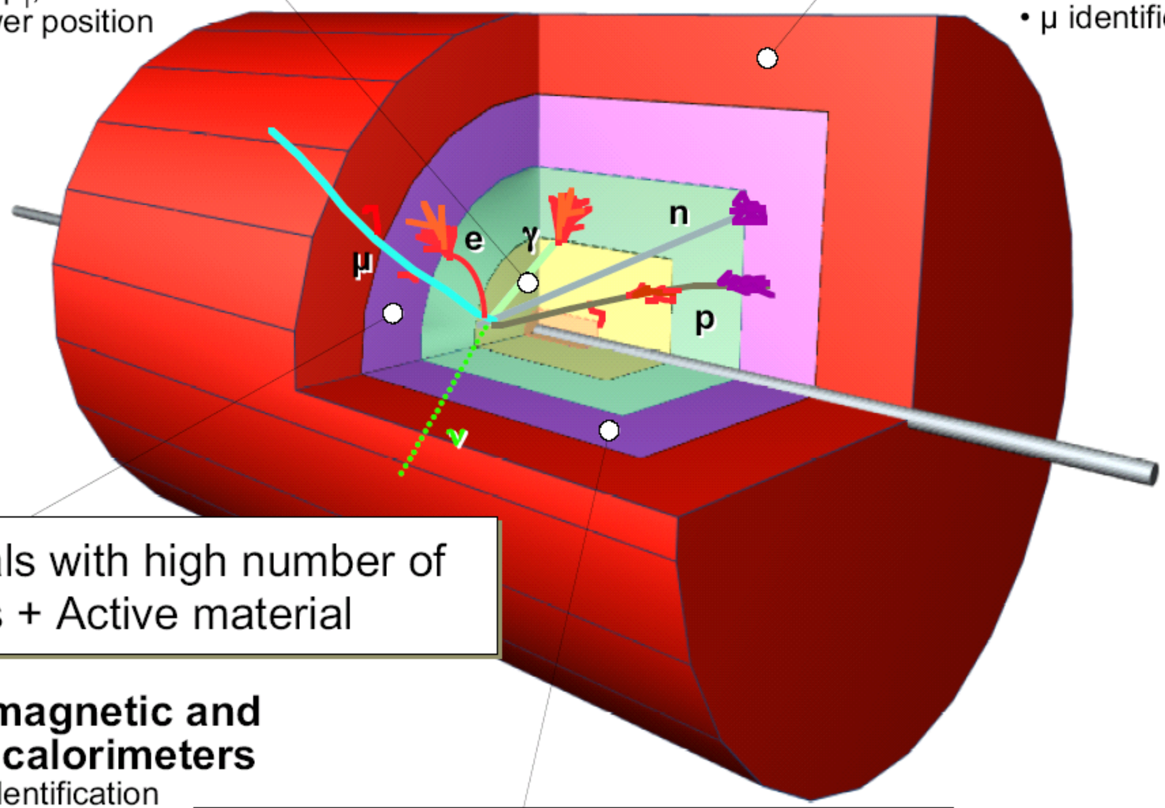
Light materials

Central detector
- Tracking, p_T, MIP
- Em. shower position
- Topology
- Vertex

Hermetic calorimetry
- Missing Et measurements

Heavy materials

Muon detector
- μ identification

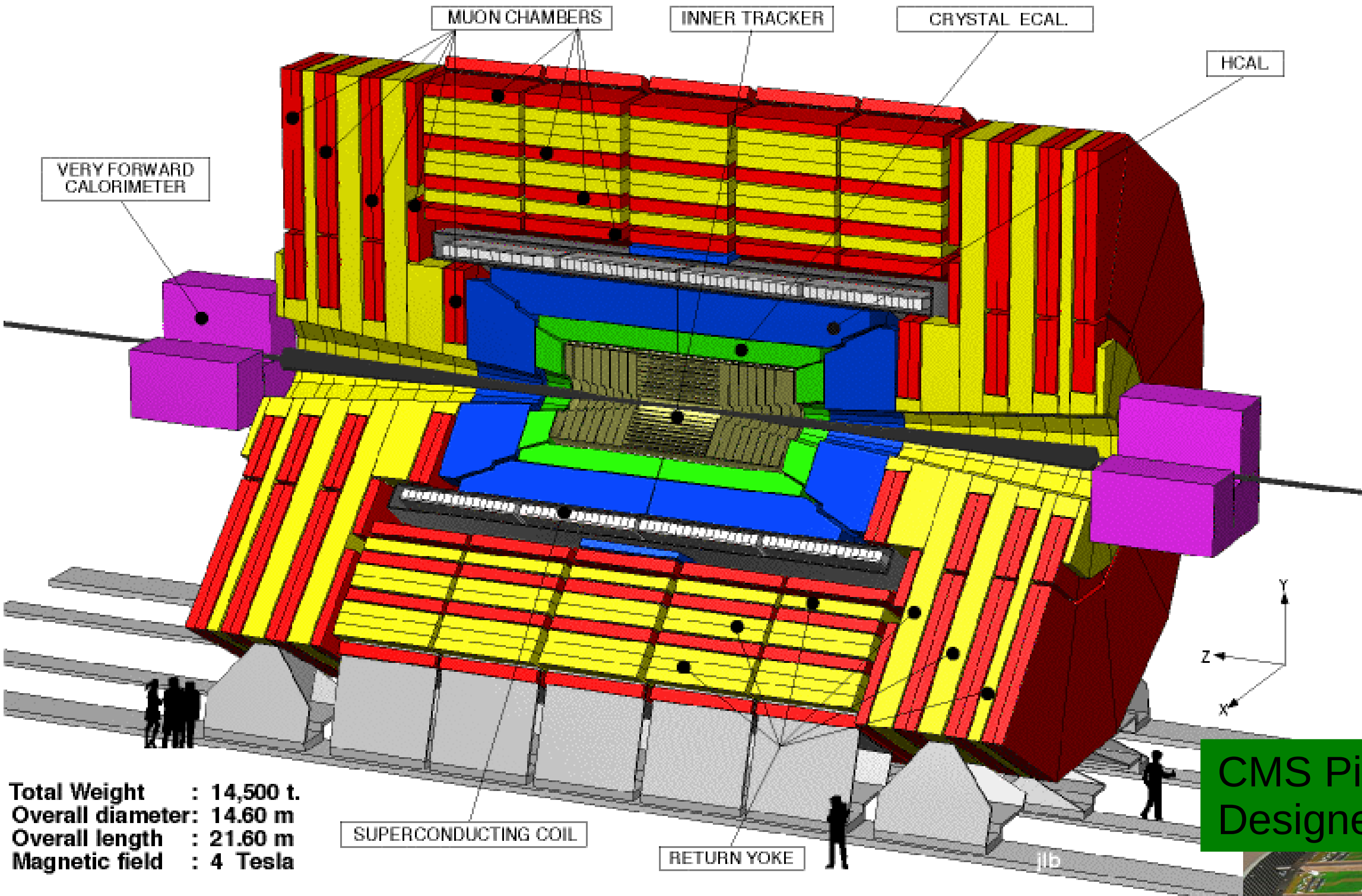


Materials with high number of protons + Active material

Electromagnetic and Hadron calorimeters
- Particle identification (e, γ Jets, Missing E_T)
- Energy measurement

Heavy materials
(Iron or Copper + Active material)

CMS Detector
(pretty close to the ideal)



CMS Pixels Electronics Designed at Rutgers

PLT Luminosity Monitor in CMS

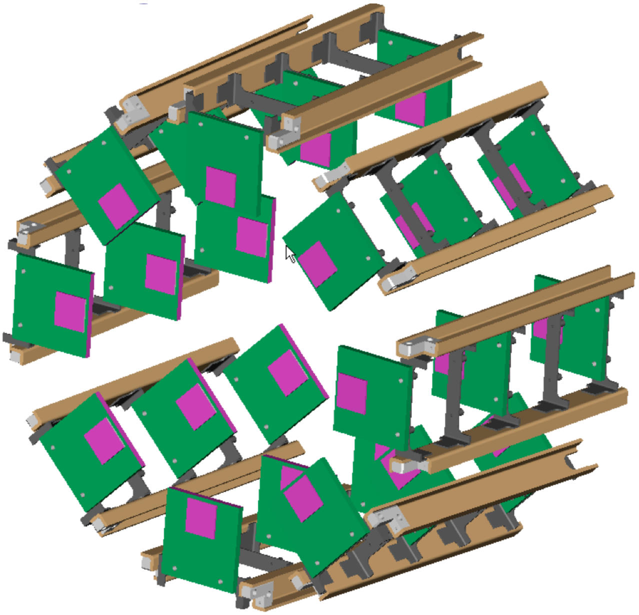
Rutgers designed and built detector for CMS

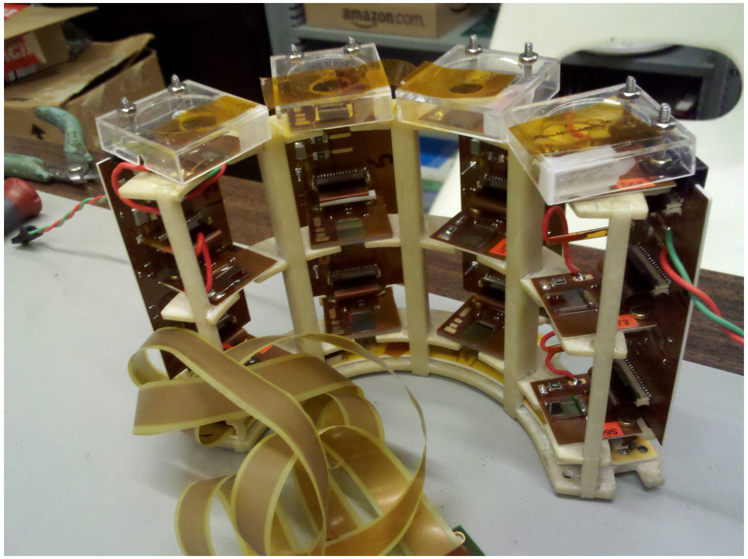
Dedicated, stand–alone luminosity monitor

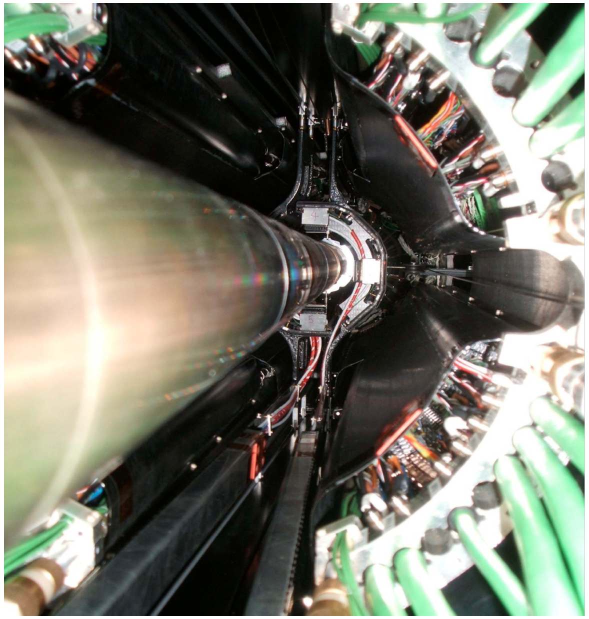
Eight 3-plane telescopes each end of CMS

Diamond pixel sensors pixel area: 3.9 mm x 3.9 mm

Stable 1% precision on bunch-by-bunch relative luminosity







So what is everything made of?

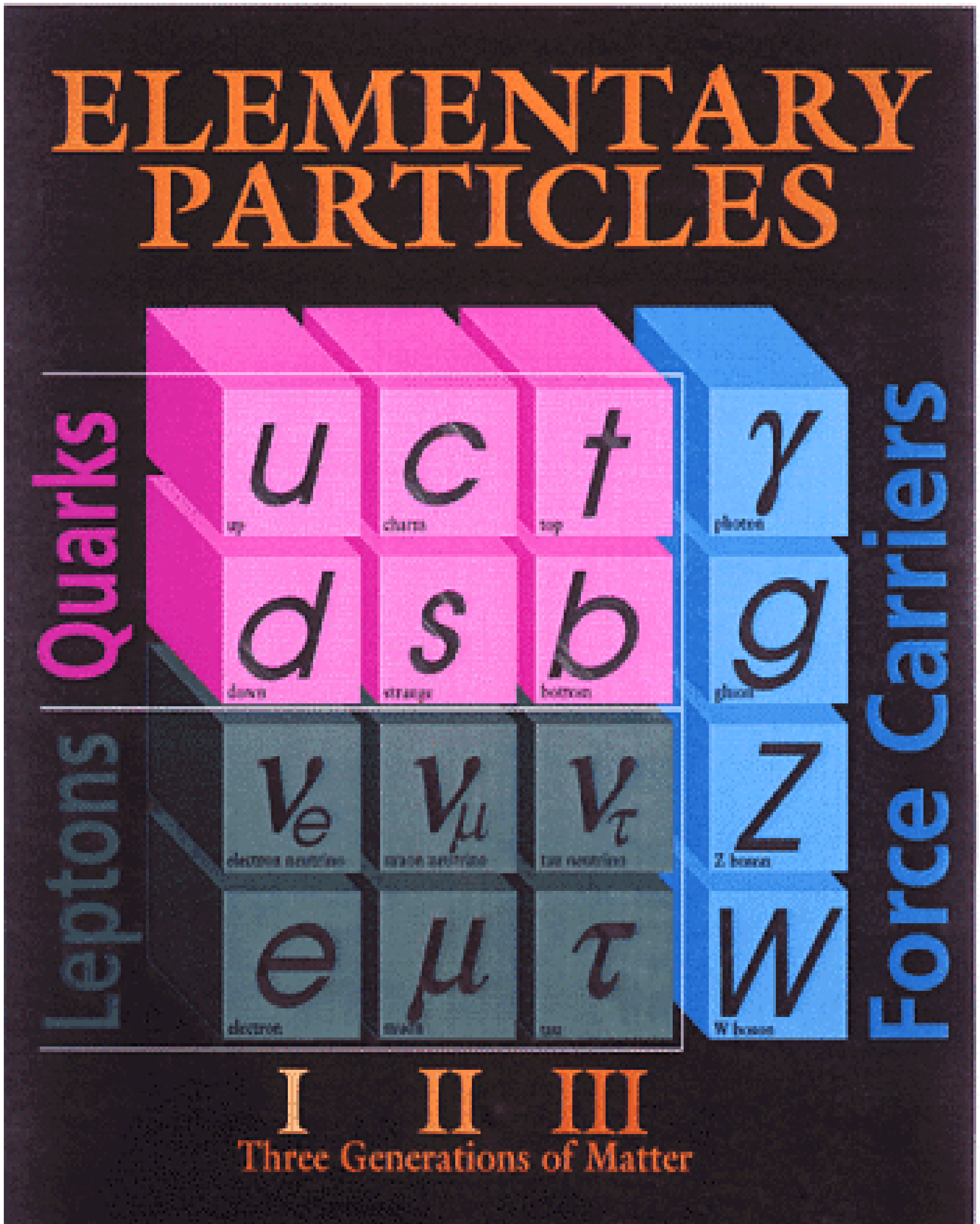
Status as of 2012

	Particles			Forces they feel: EM	Strong nuclear	Weak nuclear
Quarks	Up	Charm	Top	+2/3	yes!	yes
	Down	Strange	Bottom	-1/3	yes!	yes
Leptons	Electron	Muon	Tau	-1	no	yes
	e-neutrino	μ-neutrino	τ-neutrino	0	no	yes

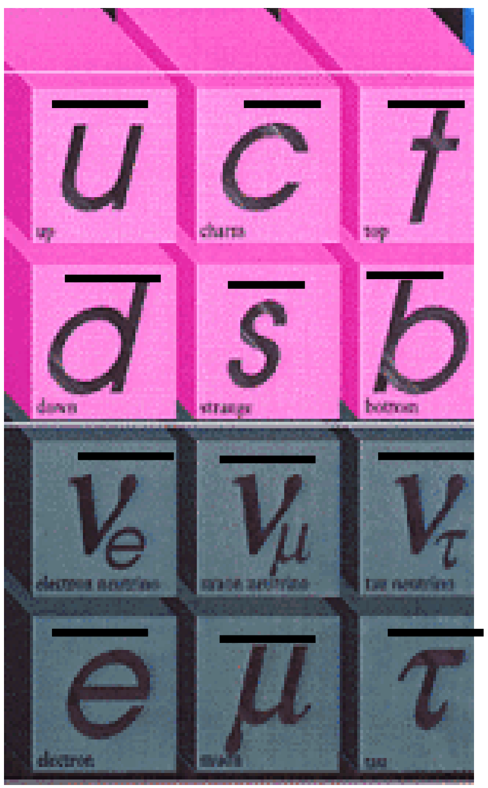
Everything* in the universe is made of the 1st generation particles.

Quarks bind together with the strong force to make familiar particles such as protons and neutrons.

So why isn't this good enough?

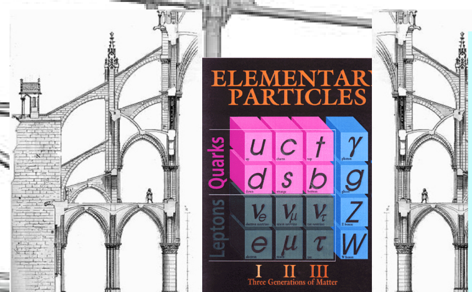


+



antimatter

Because it is not viable by itself



Everything we are made of, observe and interact with (baryonic matter) is made possible (stable) by some unknown set of forces/interactions/particles.

This happens at various scales: microscopic, galactic, cosmological.

We know *nothing* about this part of nature, except what we infer from our observations:

Inflation happened,
Antimatter got swept away,
Galaxies are not falling apart,
Matter has mass,
Gravity is very weak,
Weak interactions will violate unitarity...

The unknown part is probably larger, more complex and more interesting that the known.

What do you need to find new physics?

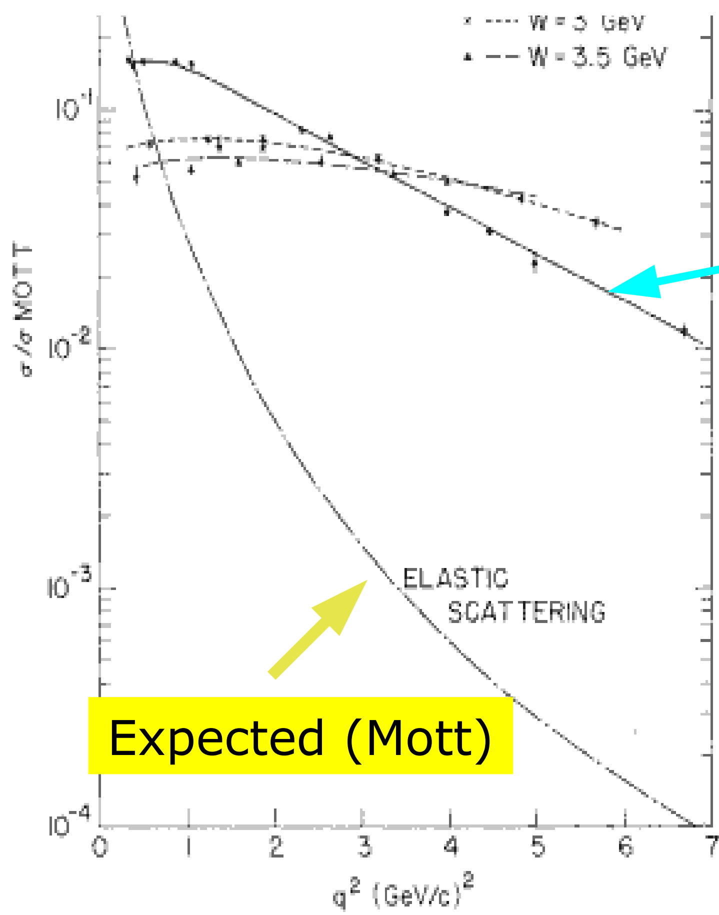
- Even more important than highest energy colliders and cutting-edge detectors...
- Need to know what new physics will look like when it shows up.
- Experimental and Theoretical workers have to collaborate closely.
  - Unique feature of Rutgers physics.

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)



SLAC theorist

Seen
(Bjorken scaling, aka scattering off quarks)

FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{\mathrm{Mott}}$, in GeV^{-1}, vs q^2 for $W = 2$, 3, and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by σ_{Mott}, $(d\sigma/d\Omega)/\sigma_{\mathrm{Mott}}$, calculated for $\theta = 10°$, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

PRL Vol 23, No 16, (1969)

Around the same time at BNL…

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini
CERN Laboratory, Geneva, Switzerland

(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7\ \mathrm{GeV}/c^2$ have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}{}^5\ \mathrm{cm}^2\ (\mathrm{GeV}/c)^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

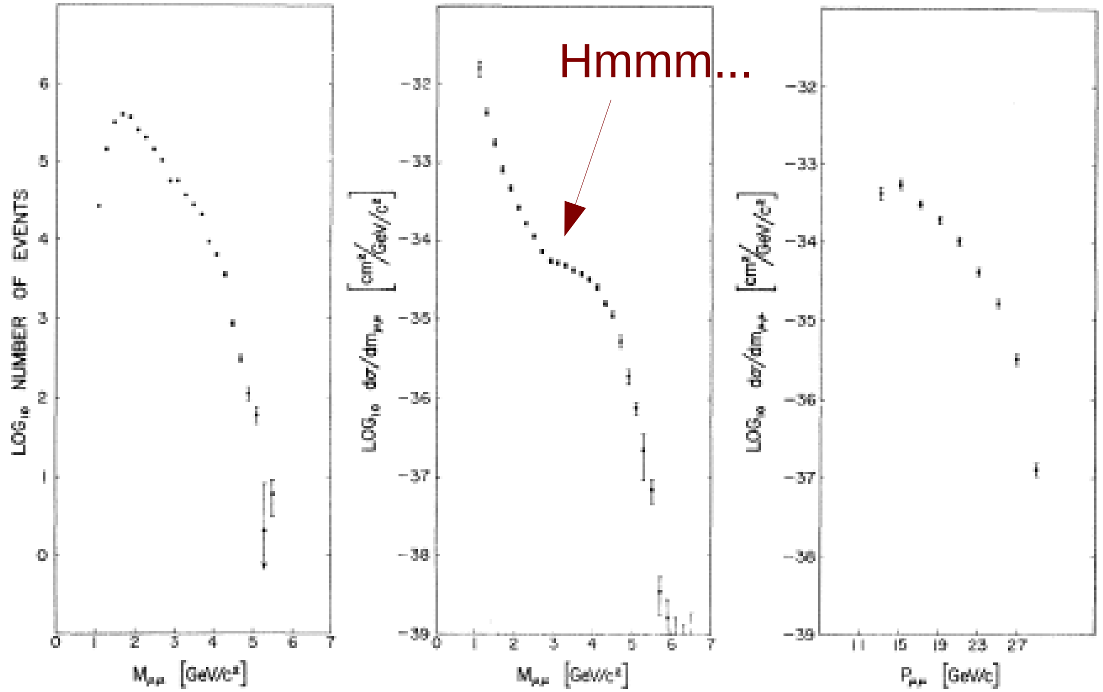
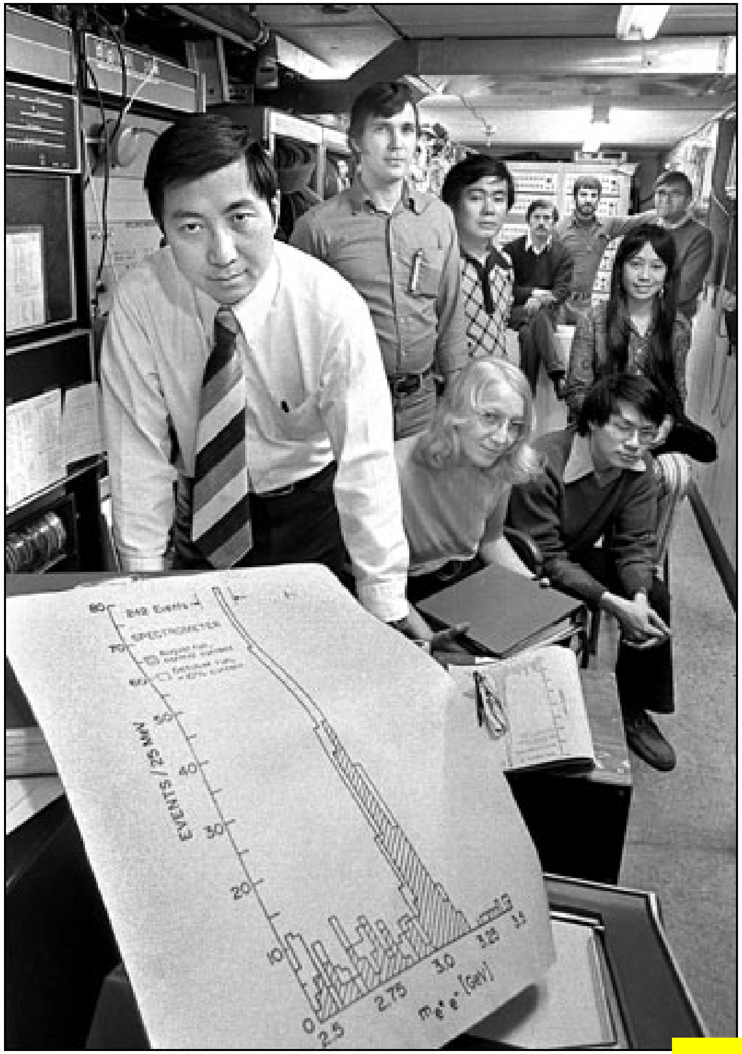
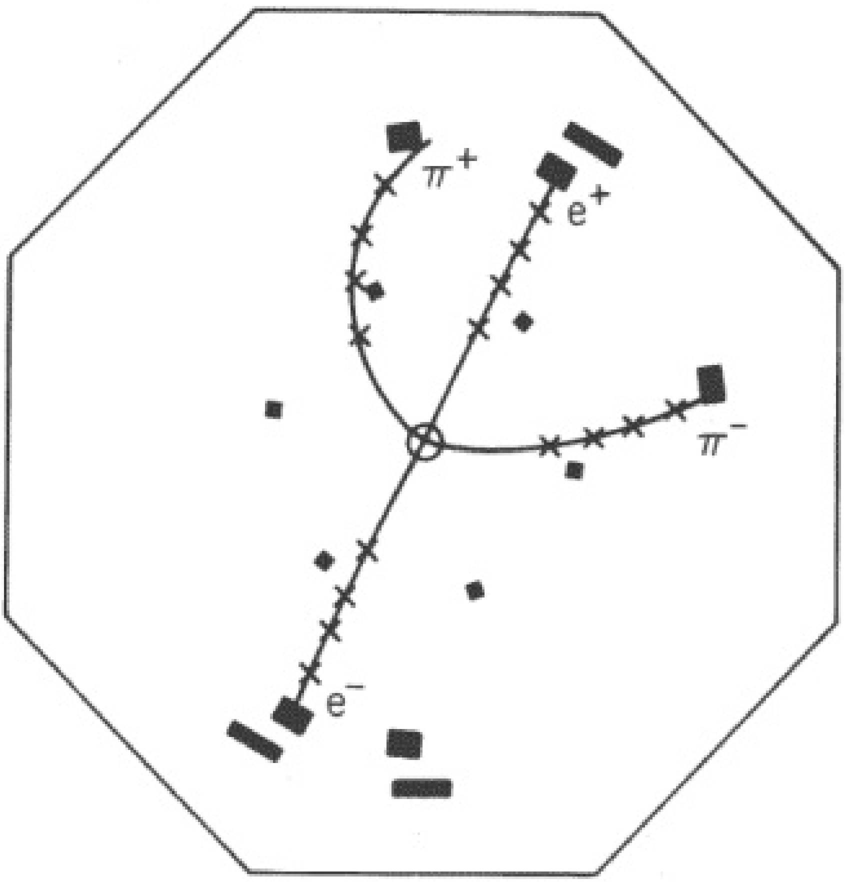


FIG. 2. (a) Observed events as a function of the effective mass of the muon pair. (b) Cross section as a function of the effective mass of the muon pair (these data include the wide-angle counters). (c) Cross section as a function of the laboratory momentum of the muon pair.

Four years later...

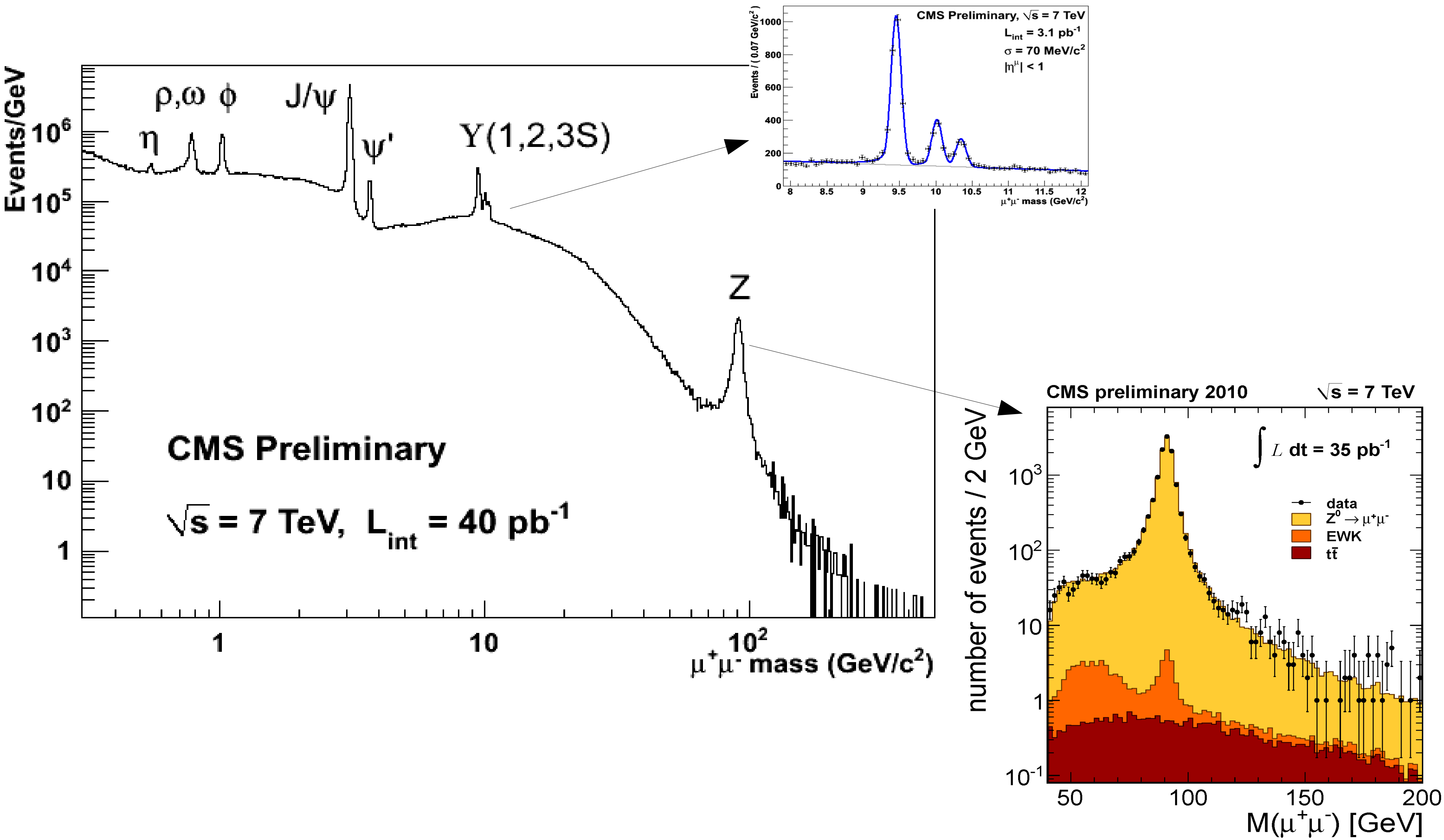
1974 Nobel Prize awarded for Charm quark discovery





Could a proto-theory of charm have motivated the BNL Drell-Yan group to investigate further?

CMS in the first few months after turning on (2010)

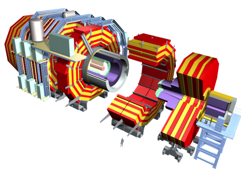


The Rutgers LHC Group

Collider Experiment:



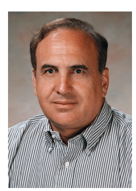
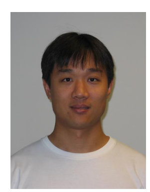


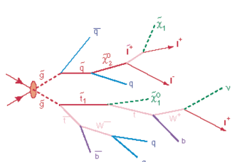



John Paul Chou, Yuri Gershtein, Eva Halkiadakis, Amit Lath, Steve Schnetzer, Sunil Somalwar

+ undergrad students + grad students + postdocs

New High Energy Theory Center:



Tom Banks, David Shih, Matthew Strassler, Scott Thomas,

+ undergrad students + grad students + postdocs

The New Physics is hiding somewhere

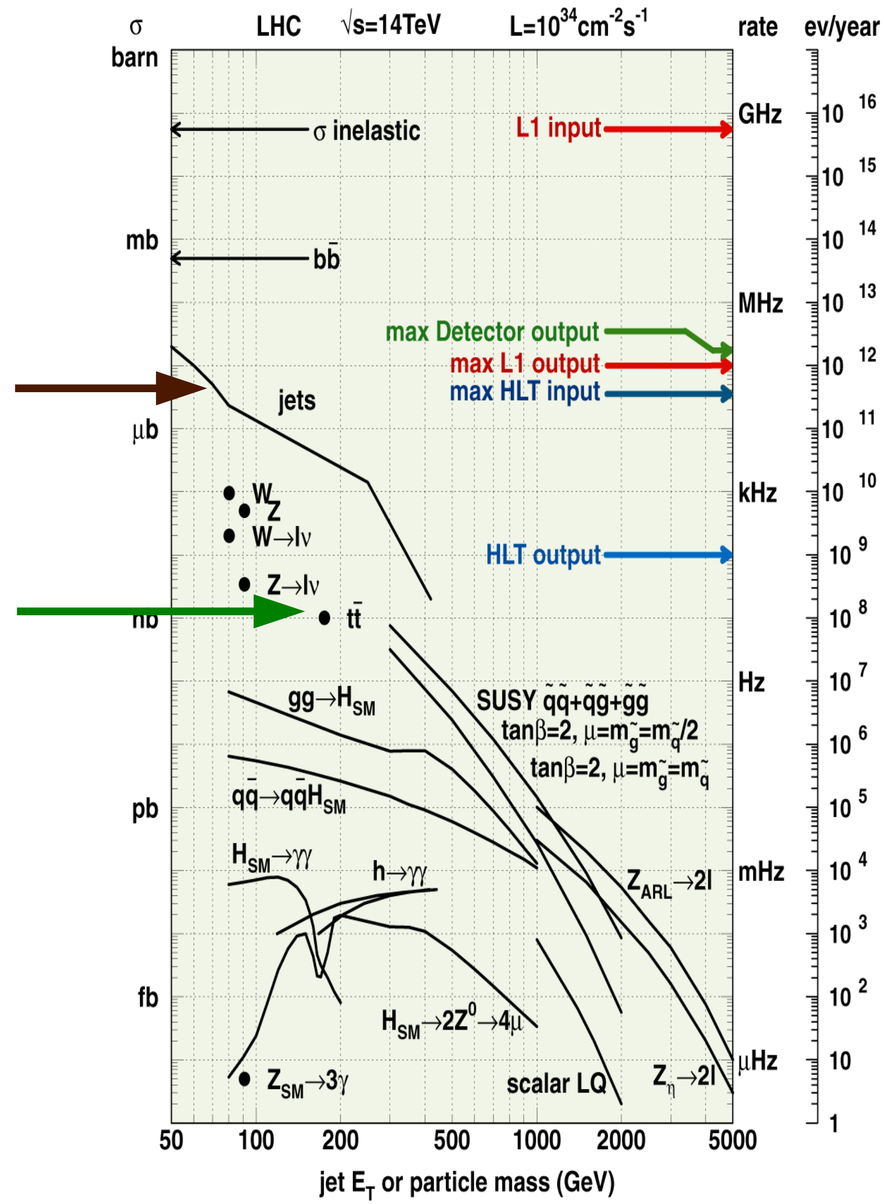
New physics has not shown up in easy to harvest areas.

We need better tools, since new physics is hiding in hard to reach areas.

First example of Rutgers LHC innovation

- No new* physics since 1974!
- What are we missing?
  - Strong couplings?
- Typical* searches require electrons/ muons/ missing momentum.
  - **Blind** to strongly coupled signals.

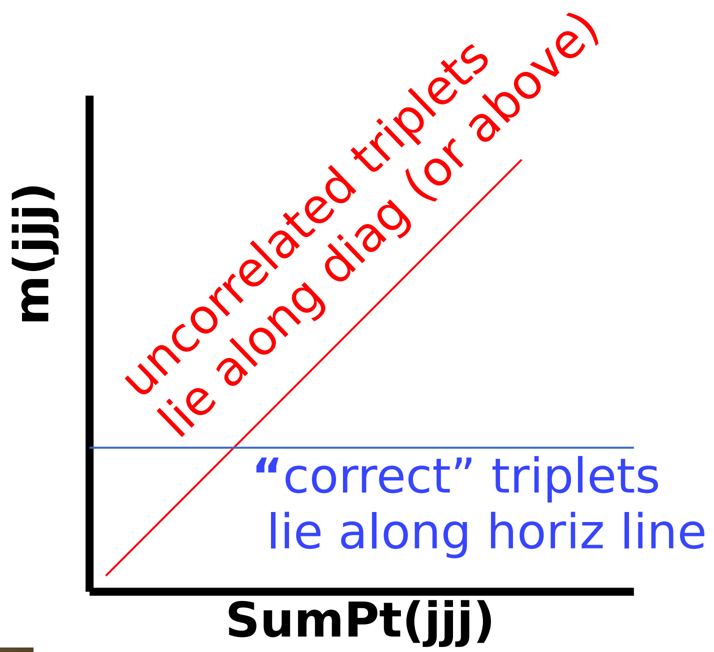
- We designed a technique to find these signals amid horrible backgrounds.



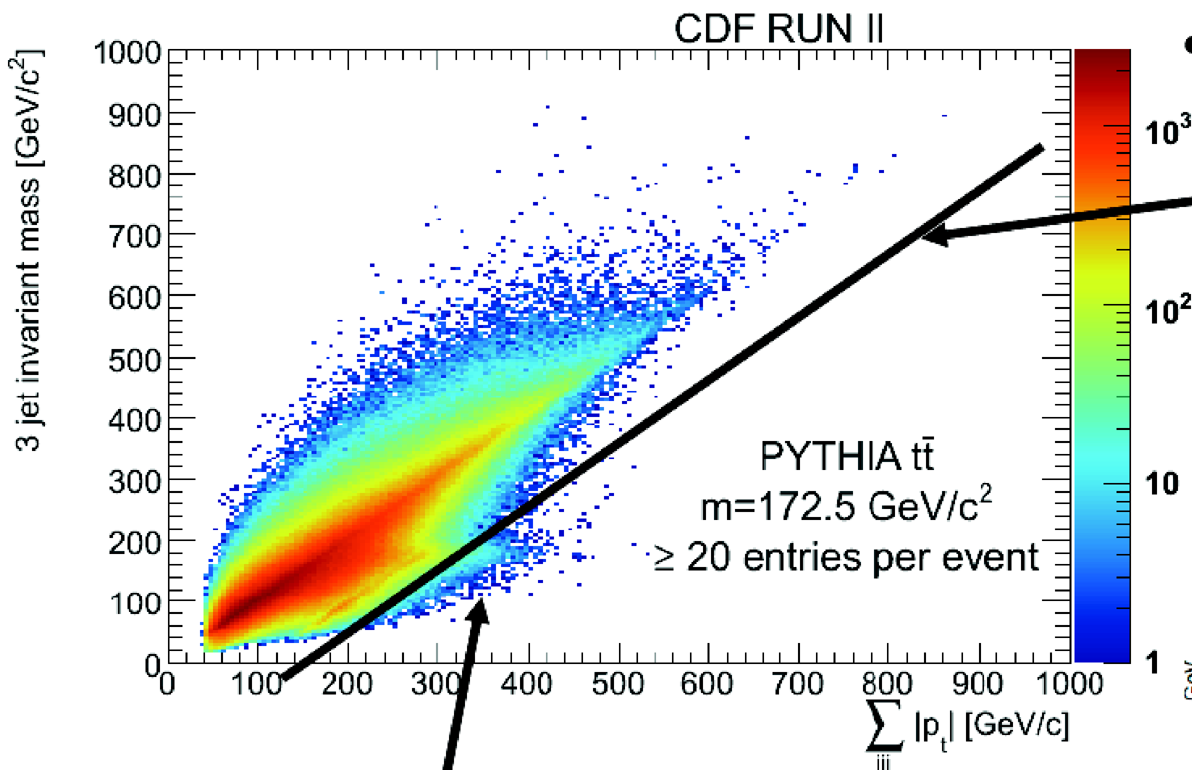
In a multiple-jet event,
how do you know which triplet of jets belong together?
Our technique: Look at them all

- *Ensemble* method
- There are several jet triplets in a multi-jet event.
- Plot the invariant mass

  m_{jjj} vs ΣPt_{jjj}
- We look at them all (multiple entry plot).



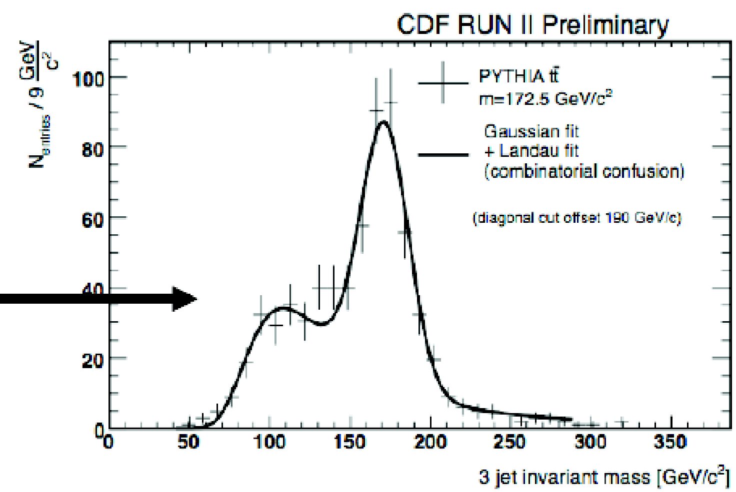
Simulated new physics



- Diagonal cut:
  - For any triplet require: $M_{jjj} < \Sigma|p_T|_{jjj}$ – diagonal offset
  - Reduces background from combinatorial confusion and QCD

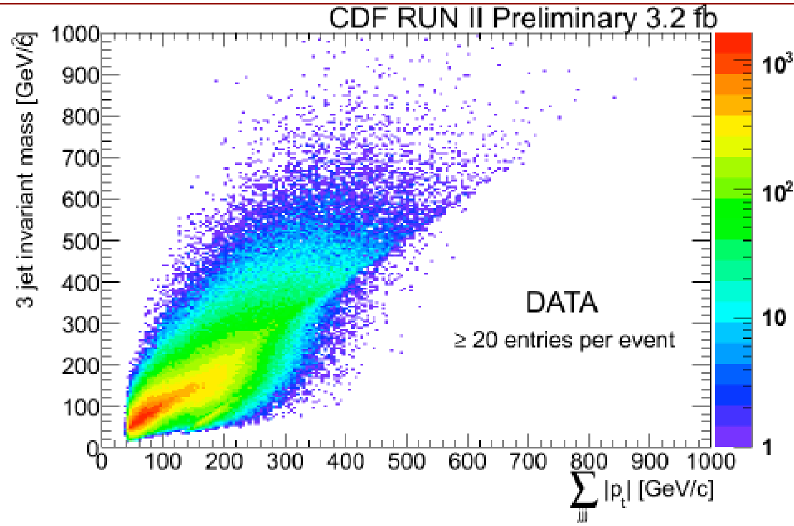
- Projection on to mass axis
  - Signal still contains jet combinatorial confusion
  - QCD has a similar shape

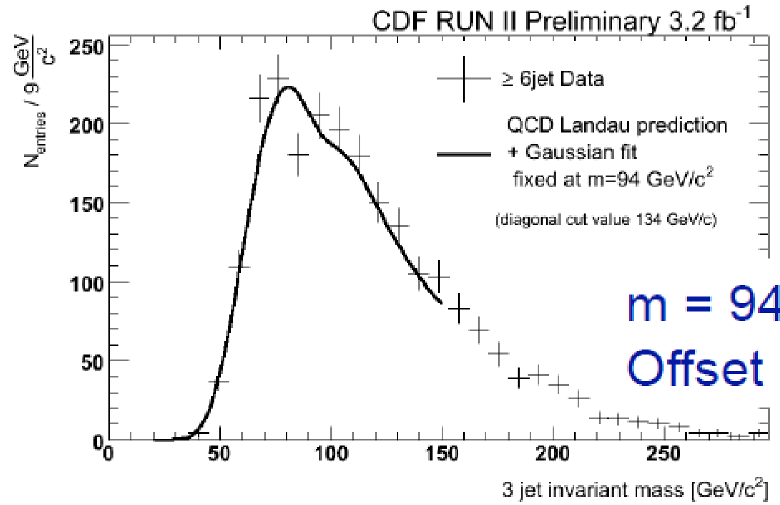
Offset 190 GeV



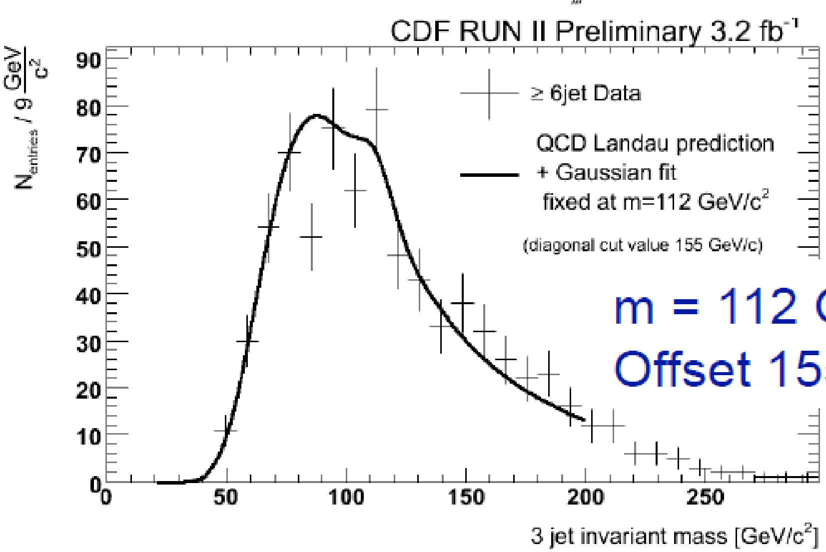
Fitting for signal in data

Search in the range of 77 – 240 GeV

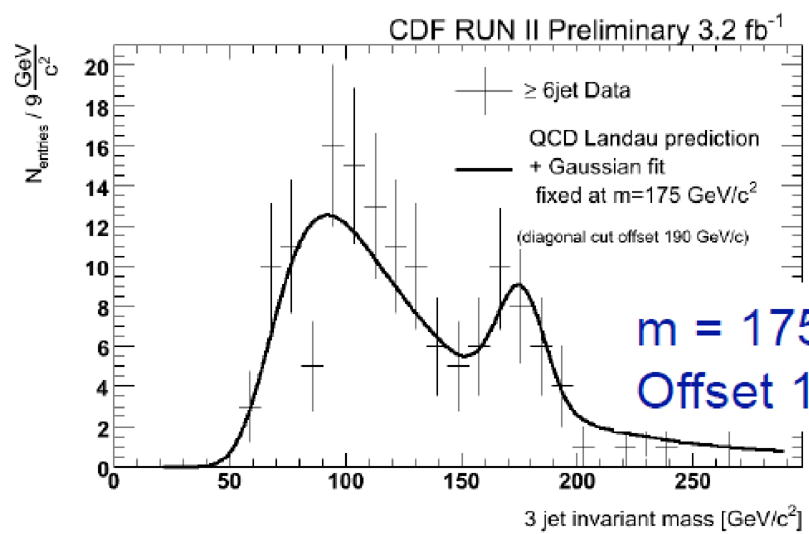




m = 94 GeV
Offset 134 GeV



m = 112 GeV
Offset 155 GeV



m = 175 GeV
Offset 190 GeV

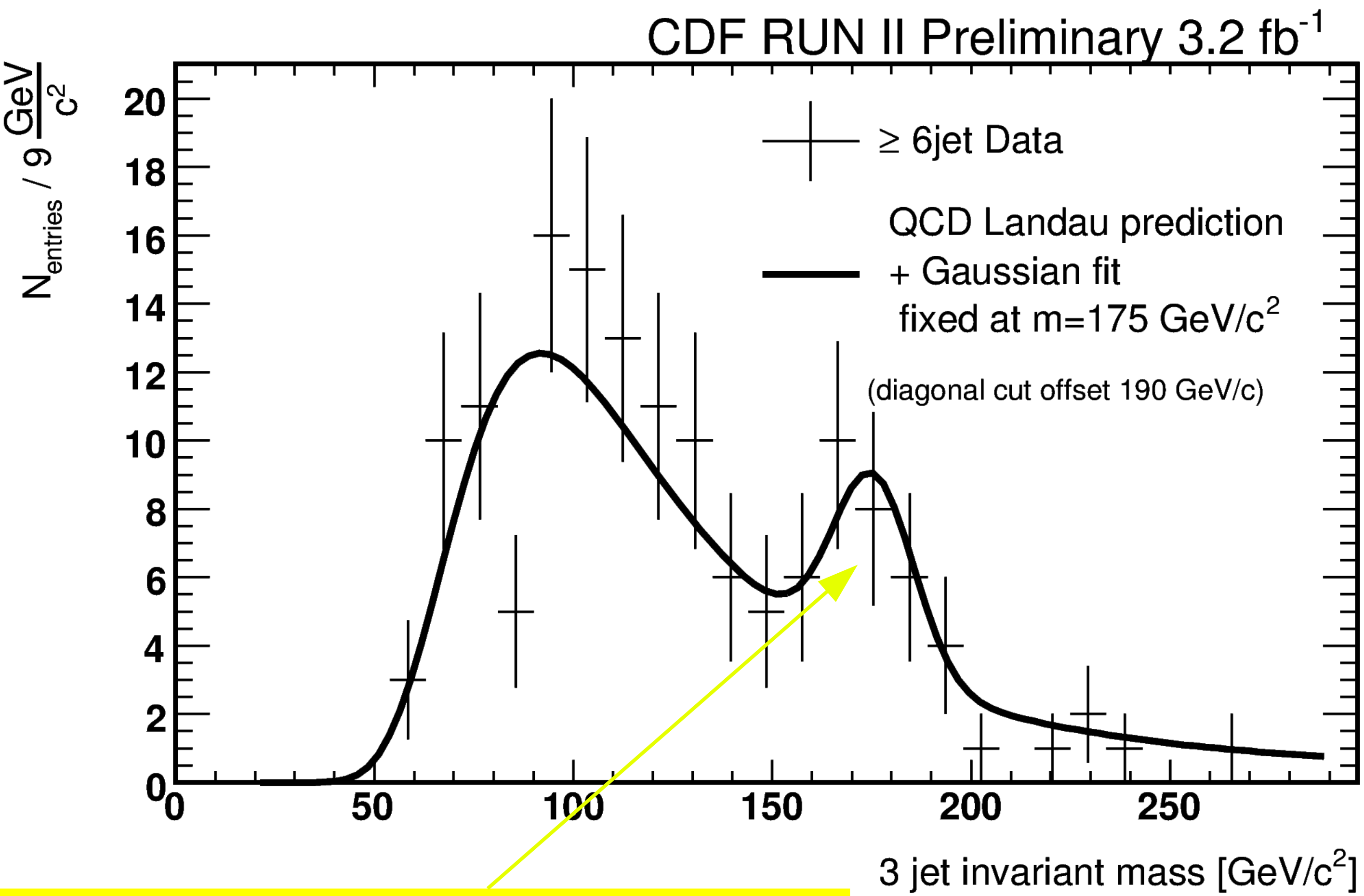
Largest excess near m_{top}: 2 σ

More on this later.

No evidence for new physics above SM background

We see the top quark!

first time without any special aids



At the top mass, we **expect ~1** event,
But **see 11** events (+-1 σ integral of Gaussian)

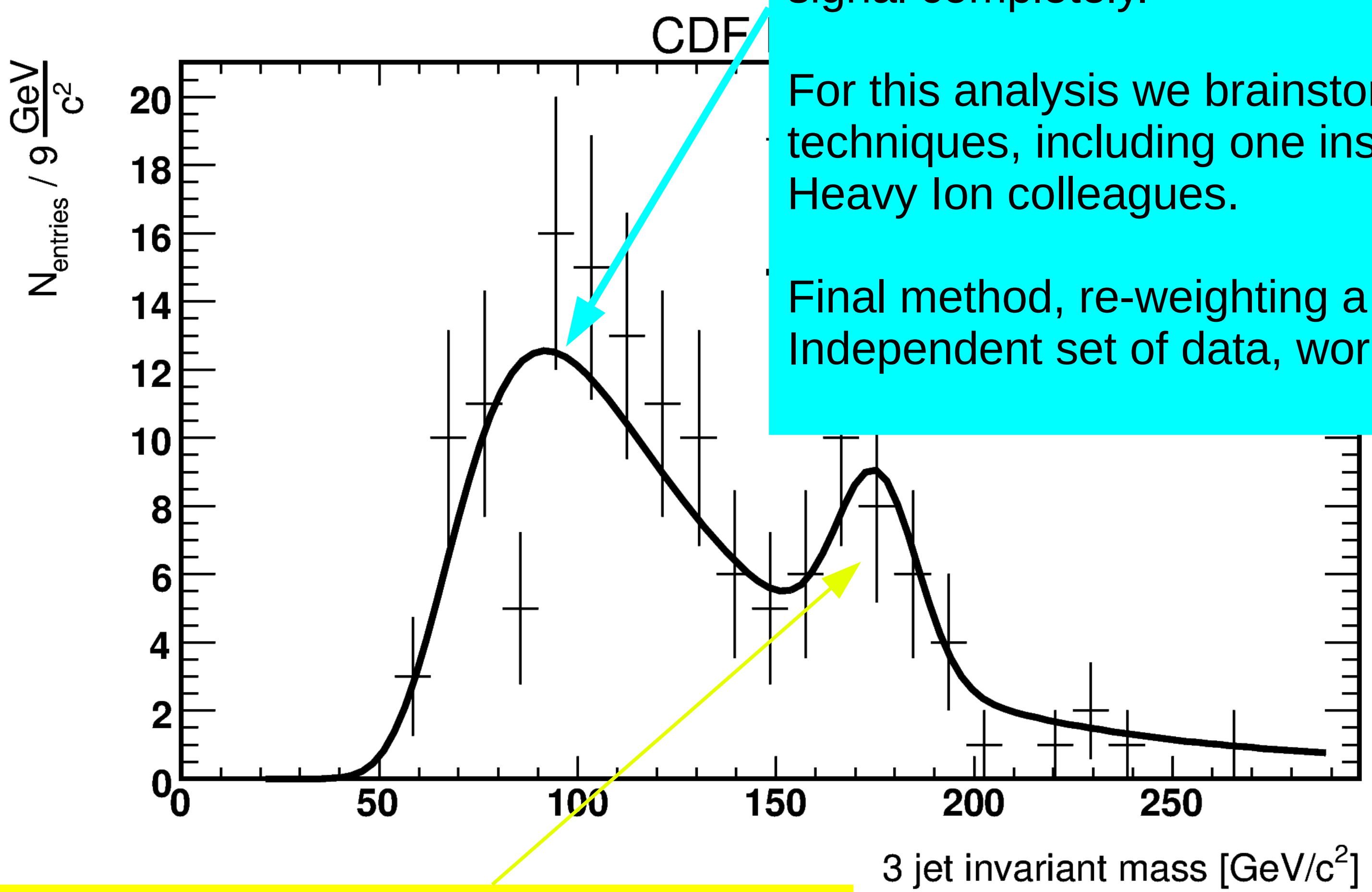
We see the [...] first time without [...]

Aside: Understanding Backgrounds.
Crucial to all searches for new phenomena.

One can easily introduce a bias, turning fluctuations into signal, or missing a real signal completely.

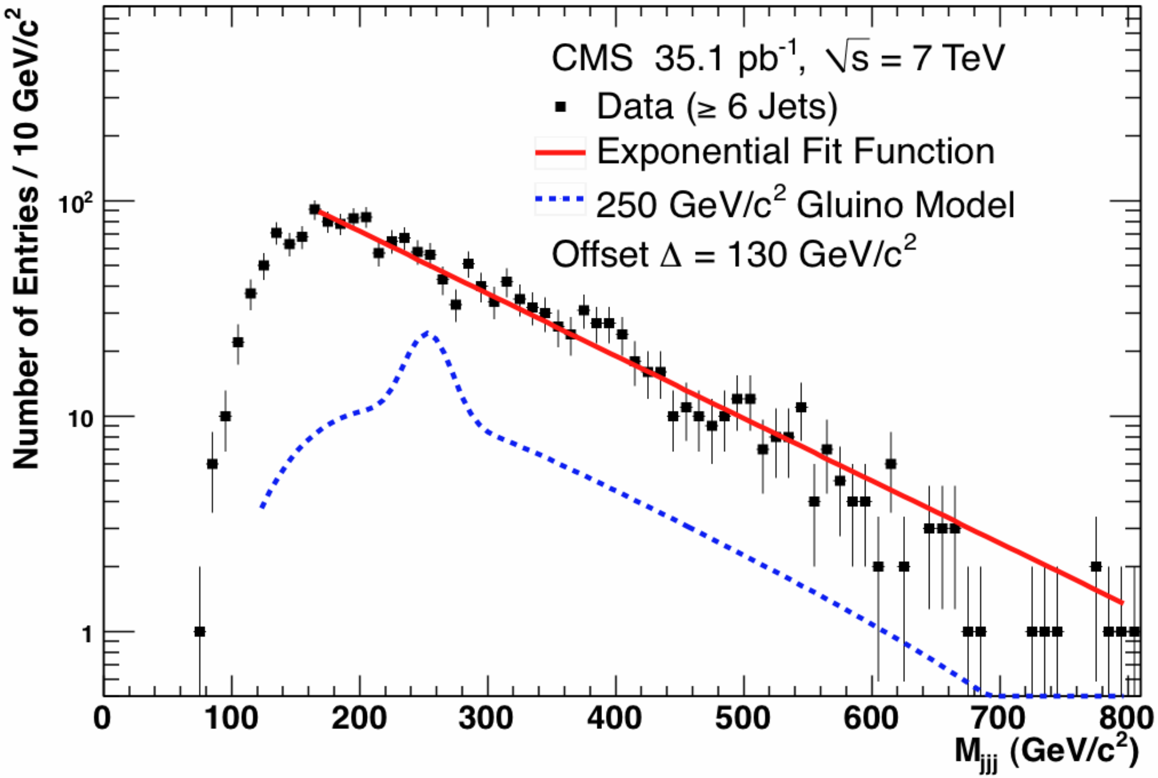
For this analysis we brainstormed several techniques, including one inspired by RU Heavy Ion colleagues.

Final method, re-weighting a statistically Independent set of data, works beautifully.



At the top mass, we **expect ~1** event,
But **see 11** events (+-1 σ integral of Gaussian)

Similarly on CMS (2010 data)



First ever 3-jet resonances search.

Multijet resonances were not considered possible for searches.

A new analysis technique invented and executed by Rutgers LHC group.

Need tools to get to harder to reach areas.

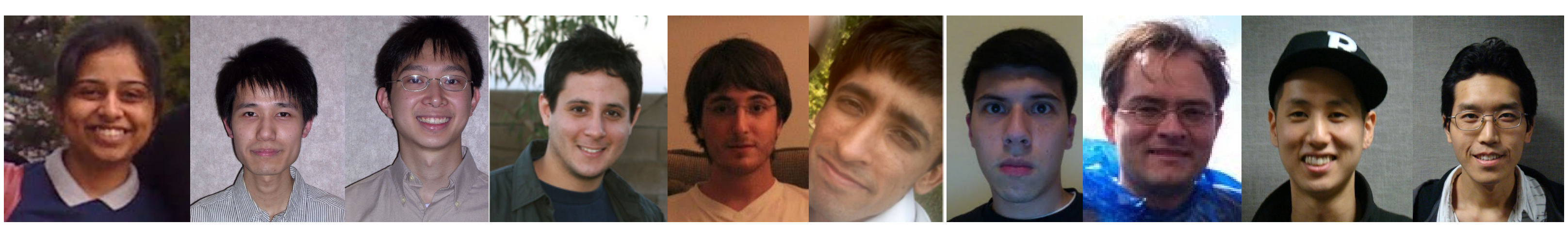
Four-jet, Eight-jet analyses are also ongoing.
We are systematically tackling physics with jets.

Another example: Multileptons

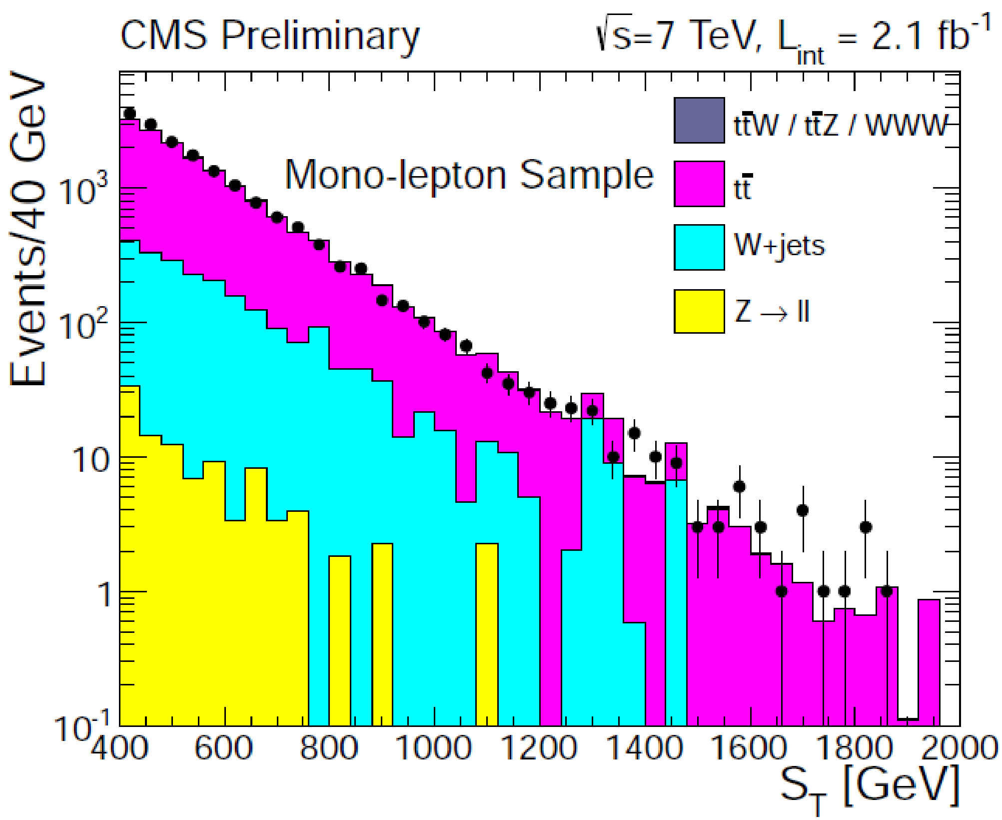
- Leptons (electrons, muon, taus*) are interesting.
  - Indicate something Weak happened.
- Good tools for new physics searches
- Standard Procedure:
  - Find a model of new physics that produces leptons.
  - Now look for it...
    - Z-primes: two opposite signed, same type leptons
    - Supersymmetry: Three leptons, missing momentum
    - Leptoquarks: Some leptons, some jets
    - Fourth generation, Extra dimensions, &c...
- Rutgers approach to multileptons:
  - Do it all.

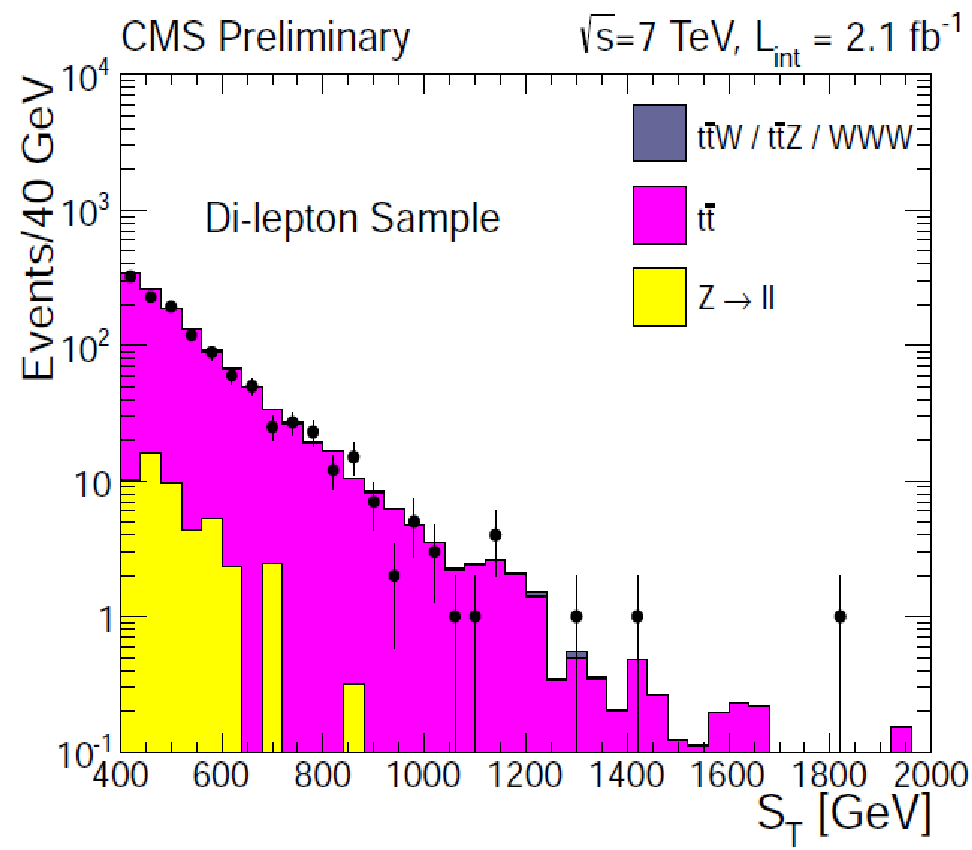
Rutgers Multileptons

- Instead of piecemeal approach, look at all interesting events with 3 or more leptons.
  - Difficult for the Standard Model to produce
- Bin them in #leptons, missing momentum, total energy in event, is there a Z-boson present...
  - Lots of bins.
  - Some bins will have lots of events from SM.
  - Some will have few/none.
- Need to understand all ways SM can make leptons!



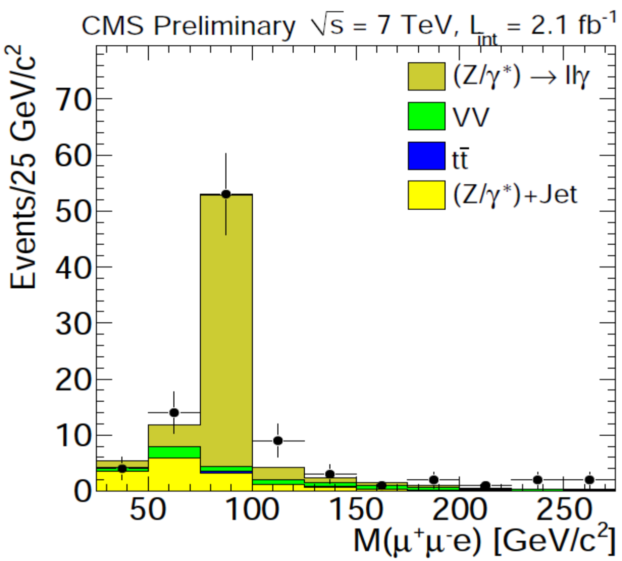
How do you get leptons? From top quark decays

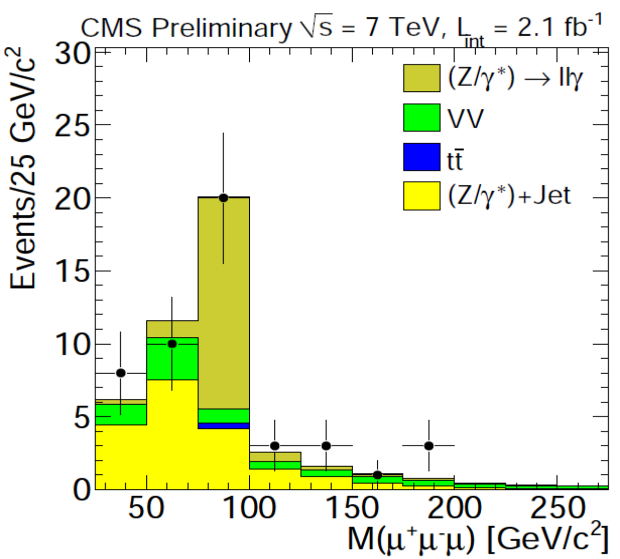




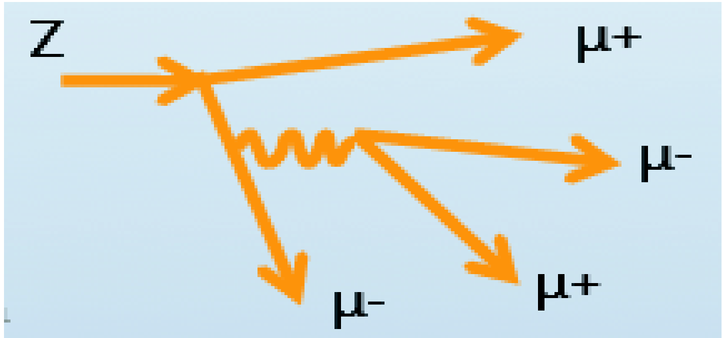
Superb understanding of leptons from top quark decays

How do you get leptons?
From “newly discovered” SM processes





- How can three leptons make a Z?
- Answer: Asymmetric conversions.
  - Internal conversion of emitted photon can give you a ee or μμ pair.



  - Conversions can be highly *asymmetric*, one of the pair carries of all the photon's momentum.
  - If simulation has a momentum cutoff for soft particles, will miss this important background.
- Background pollutes all lepton analyses.
- Discovered by Rutgers LHC group

... The totals at the bottom are for informational purposes.

# Bodies (Selection)	τ=0 obs	τ=0 SM	τ=0 sigA	τ=0 sigB	τ=1 obs	τ=1 SM	τ=1 sigA	τ=1 sigB	τ=2 obs	τ=2 SM	τ=2 sigA	τ=2 sigB
$\geq$ FOUR Lepton Results												
4 (DY0) S_T(High)	0	0.0000 ± 0.0007	2.9	0.3	0	0.00 ± 0.09	2.0	2.5	0	0.09 ± 0		
4 (DY0) S_T(Mid)	0	0.001 ± 0.002	0.0	0.0	0	0.11 ± 0.10	0.0	0.0	0	0.68 ± 0		
4 (DY0) S_T(Low)	0	0.02 ± 0.02	0.0	0.0	0	1.69 ± 0.27	0.0	0.0	4	1.34 ± 0		
4 (DY1,ZV) S_T(High)	1	0.002 ± 0.001	12.6	1.1	0	0.02 ± 0.07	6.1	5.5	0	0.10 ± 0		
4 (DY1) S_T(High)	1	0.010 ± 0.004	2.9	0.4	0	0.22 ± 0.10	1.6	1.8	0	0.15 ± 0		
4 (DY1,ZV) S_T(Mid)	0	0.008 ± 0.003	0.0	0.0	0	0.20 ± 0.09	0.0	0.0	0	0.45 ± 0		
4 (DY1) S_T(Mid)	0	0.27 ± 0.11	0.0	0.0	2	1.38 ± 0.38	0.0	0.0	2	1.52 ± 0.44	0.0	0.0
4 (DY1,ZV) S_T(Low)	0	0.03 ± 0.01	0.0	0.0	4	2.2 ± 1.4	0.0	0.0	10	10.0 ± 7.8	0.0	0.0
4 (DY1) S_T(Low)	0	0.37 ± 0.13	0.0	0.0	14	6.6 ± 1.5	0.0	0.0	56	30 ± 22	0.0	0.0
4 (DY2,ZV) S_T(High)	0	0.005 ± 0.002	7.7	0.8	–	–	–	–	–	–	–	–
4 (DY2) S_T(High)	0	0.33 ± 0.13	3.9	0.5	–	–	–	–	–	–	–	–
4 (DY2,ZV) S_T(Mid)	0	0.022 ± 0.009	0.0	0.0	–	–	–	–	–	–	–	–
4 (DY2) S_T(Mid)	1	2.2 ± 0.9	0.0	0.0								
4 (DY2,ZV) S_T(Low)	0	0.04 ± 0.02	0.0	0.0								
4 (DY2) S_T(Low)	10	7.2 ± 2.9	0.0	0.0								
THREE Lepton Results												
3 (DY0) S_T(High)	2	0.53 ± 0.25	6.3	3.2								
3 (DY0) S_T(Mid)	3	3.8 ± 1.5	0.0	0.0								
3 (DY0) S_T(Low)	9	6.4 ± 2.0	0.0	0.0								
3 (DY1,ZV) S_T(High)	4	1.34 ± 0.40	19.9	8.4								
3 (DY1) S_T(High)	8	7.9 ± 2.6	3.2	2.4								
3 (DY1,ZV) S_T(Mid)	20	10.2 ± 2.8	0.0	0.0								
3 (DY1) S_T(Mid)	31	43 ± 13	0.0	0.0								
3 (DY1,ZV) S_T(Low)	88	85 ± 21	0.0	0.0								
3 (DY1) S_T(Low)	368	381 ± 92	0.0	0.0								
Totals	546	549 ± 95	59.0	17.0	1							
Totals 4L	13	10.4 ± 3.1	29.9	3.1								
Totals 3L	533	539 ± 95	29.0	14.0	1							

Superb understanding of all backgrounds (sources of fake leptons) is the hallmark of this analysis.

Selection	N(τ)=0 obs	N(τ)=0 expected SM	N(τ)=1 obs	N(τ)=1 expected SM	N(τ)=2 obs	N(τ)=2 expected SM
$\geq$FOUR Lepton Results						
MET>50,H_T >200,noZ	0	0.003 ± 0.002	0	0.01 ± 0.05	0	0.30 ± 0.22
MET>50,H_T >200, Z	0	0.06 ± 0.04	0	0.13 ± 0.10	0	0.15 ± 0.23
MET>50,H_T <200,noZ	1	0.014 ± 0.005	0	0.22 ± 0.10	0	0.59 ± 0.25
MET>50,H_T <200, Z	0	0.43 ± 0.15	2	0.91 ± 0.28	0	0.34 ± 0.15
MET<50,H_T >200,noZ	0	0.0013 ± 0.0008	0	0.01 ± 0.05	0	0.18 ± 0.07
MET<50,H_T >200, Z	1	0.28 ± 0.11	0	0.13 ± 0.10	0	0.52 ± 0.19
MET<50,H_T <200,noZ	0	0.08 ± 0.03	4	0.73 ± 0.20	6	6.9 ± 3.8
MET<50,H_T <200, Z	11	9.5 ± 3.8	14	5.7 ± 1.4	39	21 ± 11
THREE Lepton Results						
MET>50,H_T >200,no-OSSF	2	0.87 ± 0.33	21	14.3 ± 4.8	12	10.4 ± 2.2
MET>50,H_T <200,no-OSSF	4	3.7 ± 1.2	88	68 ± 17	76	100 ± 17
MET<50,H_T >200,no-OSSF	1	0.50 ± 0.33	12	7.7 ± 2.3	22	24.7 ± 4.0
MET<50,H_T <200,no-OSSF	7	5.0 ± 1.7	245	208 ± 39	976	1157 ± 323
MET>50,H_T >200,noZ	5	1.9 ± 0.5	7	10.8 ± 3.3	–	–
MET>50,H_T >200, Z	8	8.1 ± 2.7	10	11.2 ± 2.5	–	–
MET>50,H_T <200,noZ	19	11.6 ± 3.2	64	52 ± 13	–	–
MET<50,H_T >200,noZ	5	2.0 ± 0.7	24	26.6 ± 3.3	–	–
MET>50,H_T <200, Z	58	57 ± 21	47	44.1 ± 7.0	–	–
MET<50,H_T >200, Z	6	8.2 ± 2.0	90	119 ± 14	–	–
MET<50,H_T <200,noZ	86	82 ± 21	2566	1965 ± 438	–	–
MET<50,H_T <200, Z	335	359 ± 89	9720	7740 ± 1698	–	–
				7.8 ± 1.5	45	30 ± 12
				10267 ± 1754	1086	1291 ± 324

Results binned several ways:

Total energy in event

Missing momenta in event

Possible Z in event

This technique is **the** way to get at new physics that produces leptons.
Does the work of several previous lepton analyses.

3(e/μ) Lepton Results

Selection			3(e/μ)	
ST	DYpairs	Z?	SM	Obs
>600	DY0		0.53 ± 0.25	2
300-600	DY0		3.8 ± 1.5	3
0-300	DY0		6.4 ± 2.0	9
>600	DY1		1.34 ± 0.40	4
>600	DY1	Z	7.9 ± 2.6	8
300-600	DY1		10.2 ± 2.8	20
300-600	DY1	Z	43 ± 13	31
0-300	DY1		85 ± 21	88
0-300	DY1	Z	381 ± 92	368
3-body			539 ± 95	533

High S_T Control Channel

Mid S_T Control Channel

Low S_T Control Channels

- Control channels have been highlighted. Other channels are potential signal channels.

Results first presented in public by RU Research Associate R.C. Gray

4(e/μ) Lepton Results

Selection			4(e/μ)	
ST	DYpairs	Z?	SM	Obs
> 600	DY0		0.0000 ± 0.0007	0
300-600	DY0		0.001 ± 0.002	0
0-300	DY0		0.02 ± 0.02	0
> 600	DY1		0.002 ± 0.001	1
>600	DY1	Z	0.010 ± 0.004	1
300-600	DY1		0.008 ± 0.003	0
300-600	DY1	Z	0.27 ± 0.11	0
0-300	DY1		0.03 ± 0.01	0
0-300	DY1	Z	0.37 ± 0.13	0
>600	DY2		0.005 ± 0.002	0
>600	DY2	Z	0.33 ± 0.13	0
300-600	DY2		0.022 ± 0.009	0
300-600	DY2	Z	2.2 ± 0.9	1
0-300	DY2		0.04 ± 0.02	0
0-300	DY2	Z	7.2 ± 2.9	10
4-body			10.4 ± 3.1	13

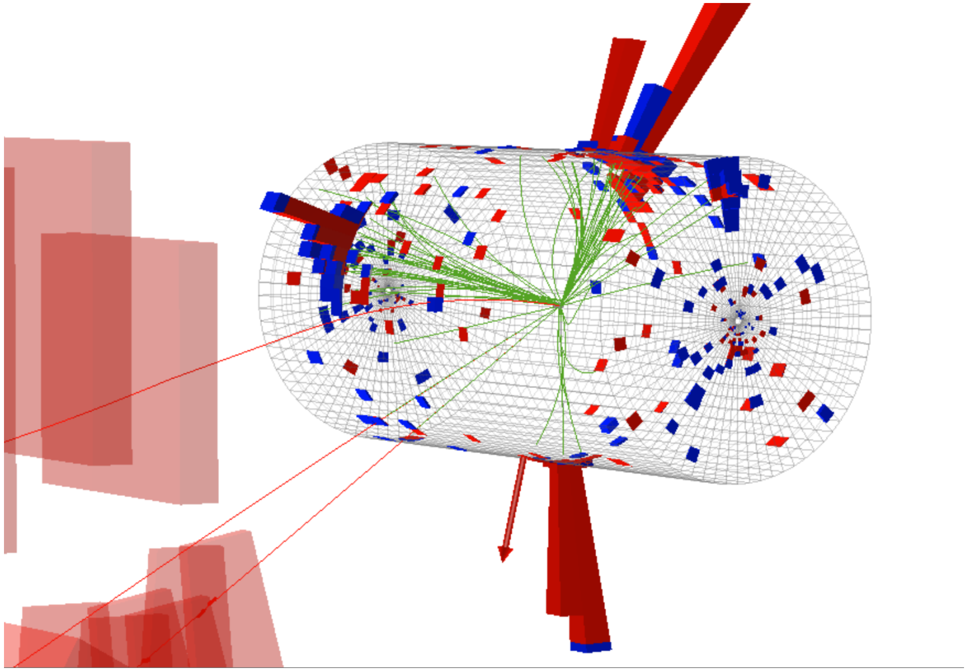
High S_T Control Channel

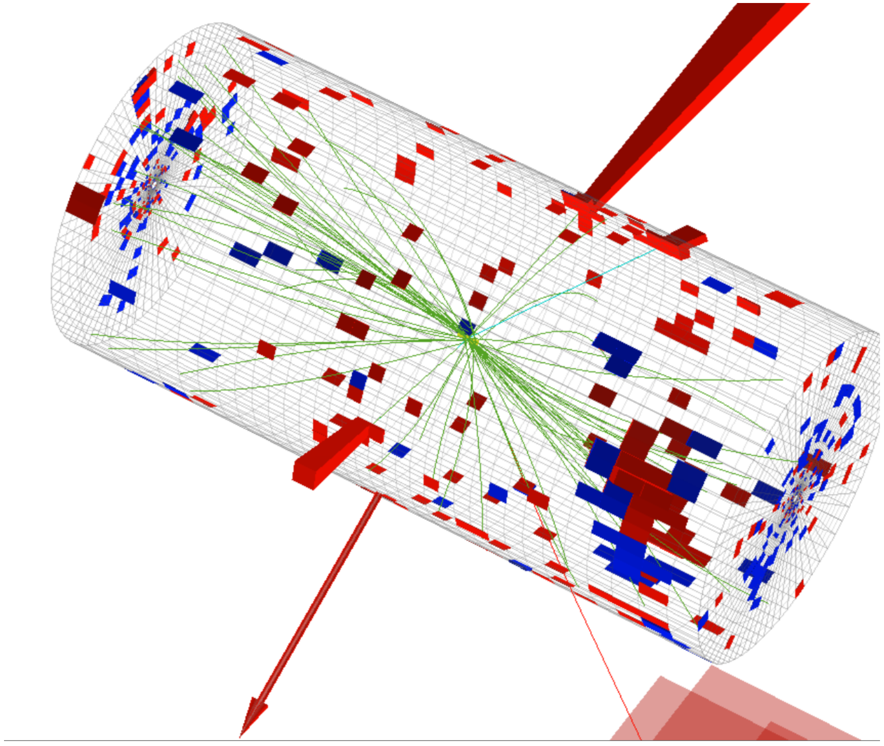
Mid S_T Control Channel

Low S_T Control Channels

- A few events in very low background channels.
- These could become interesting if we see more with additional data.

Two spectacular events





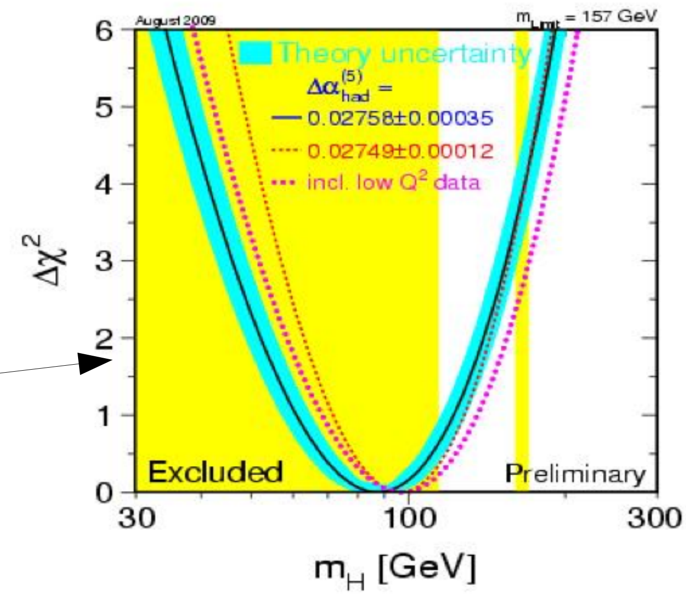
We are using this technique to go after *any* physics with leptons:

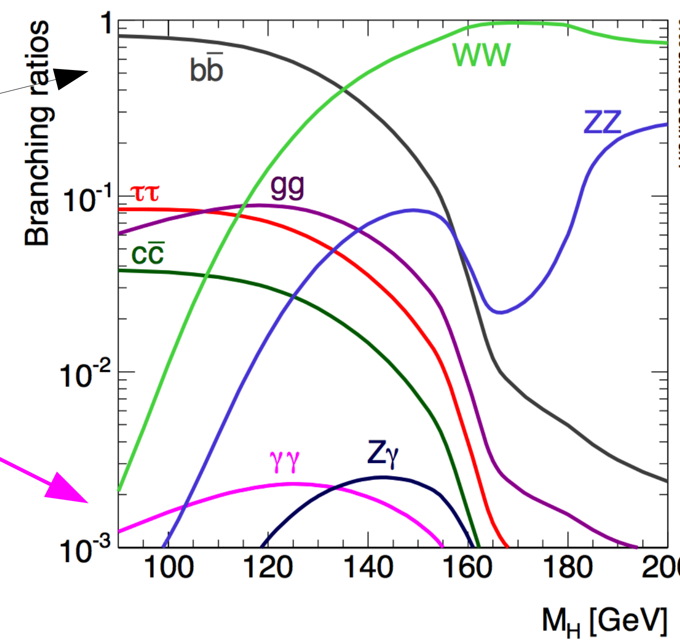
* Supersymmetry with and without missing momentum.
* fourth generation quarks.
* Higgs produced with top quarks

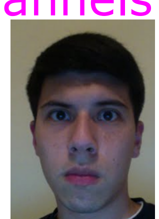
...

Search for the Higgs Boson

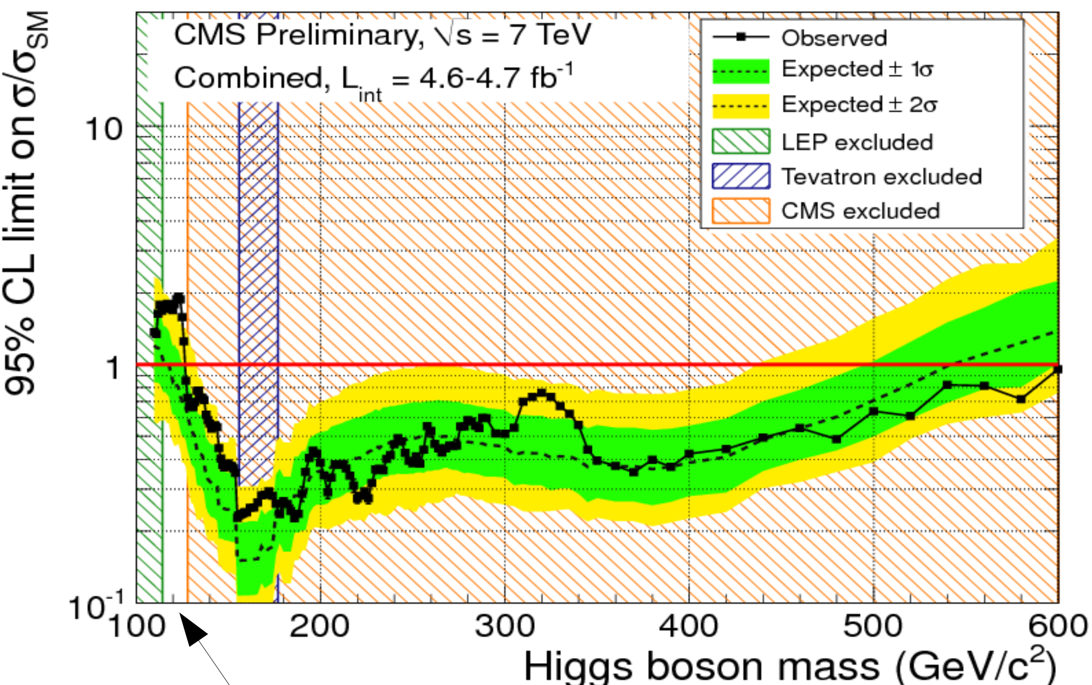
- Higgs field permeates all space.
- Interactions with this field "gives" a particle its mass
- Field → particle, so there has to be a Higgs particle.
  - Indirect indications are that it is light (low mass).
- Couples to mass, so decays to heaviest things allowed.
  - In most probable mass range, most common decay channels swamped by SM.
  - We focus on rare but more fruitful channels

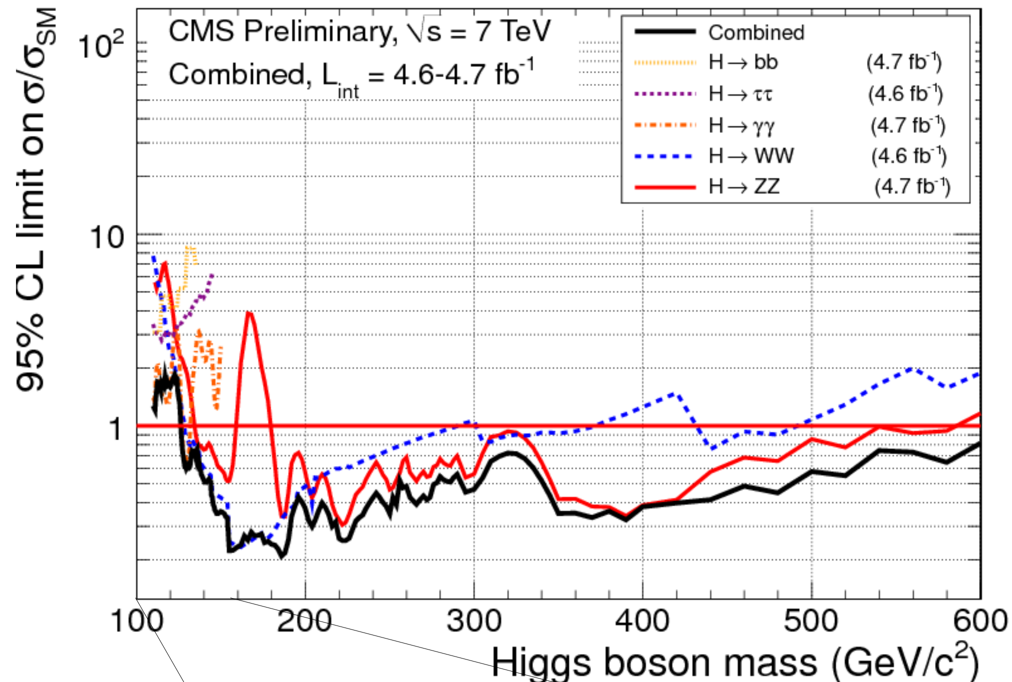


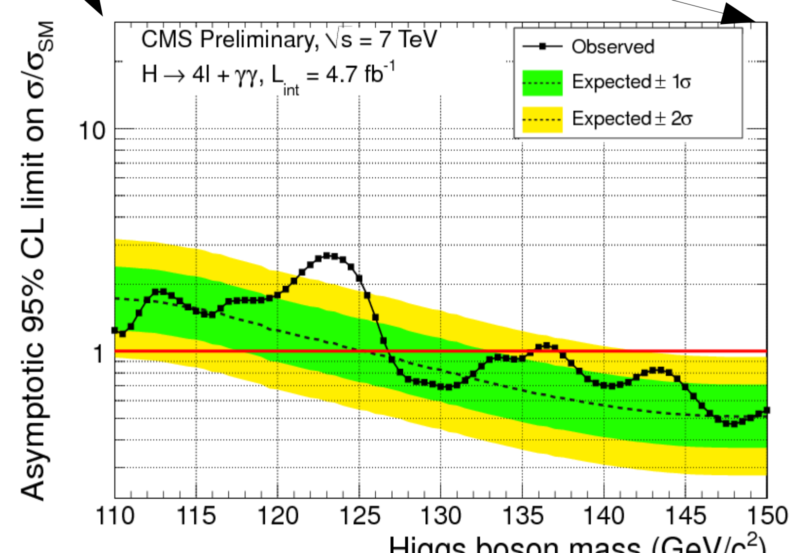




Current Higgs result (Dec 2011)



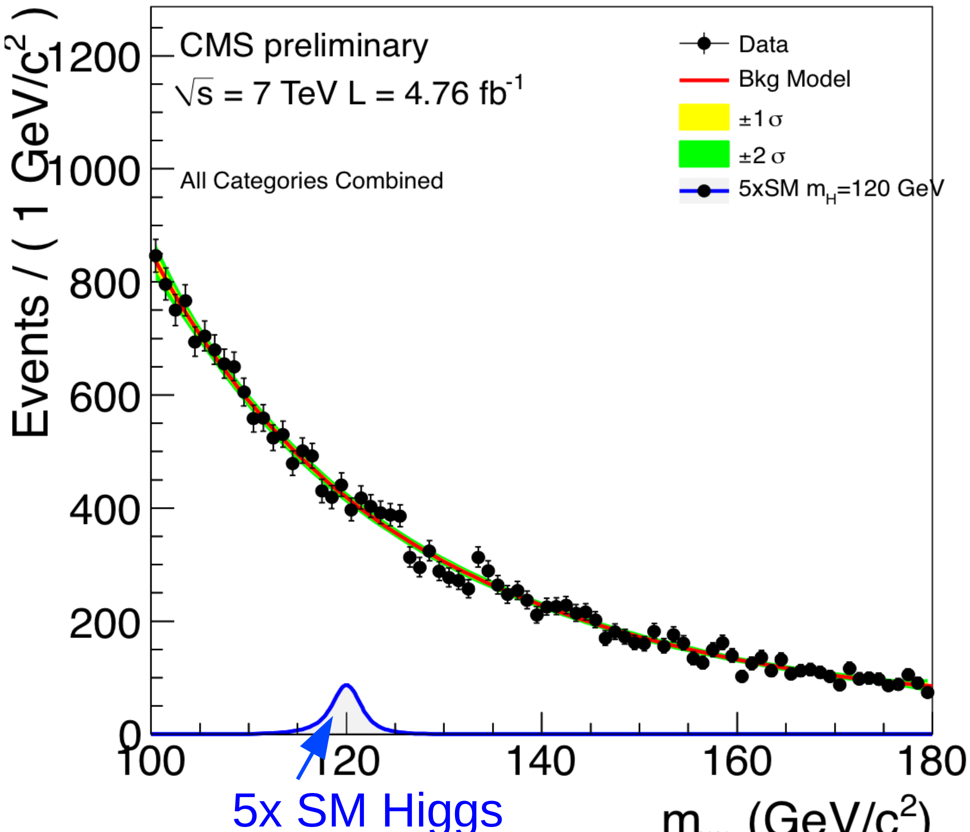




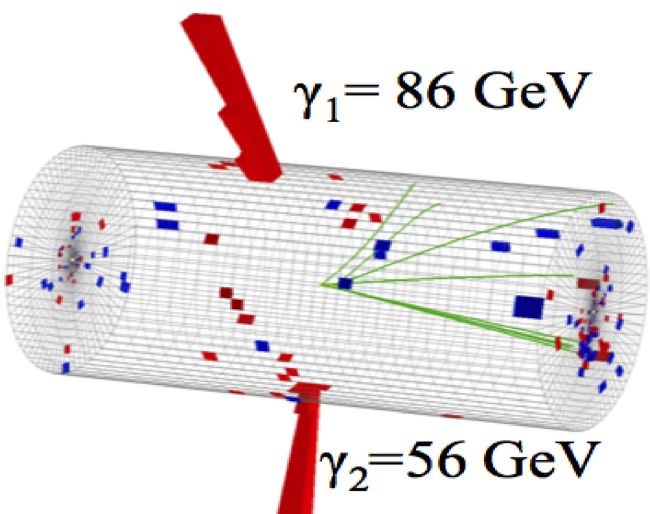
Small window left for light Higgs.
RU working on $\gamma\gamma$ mode.

Higgs to two photons

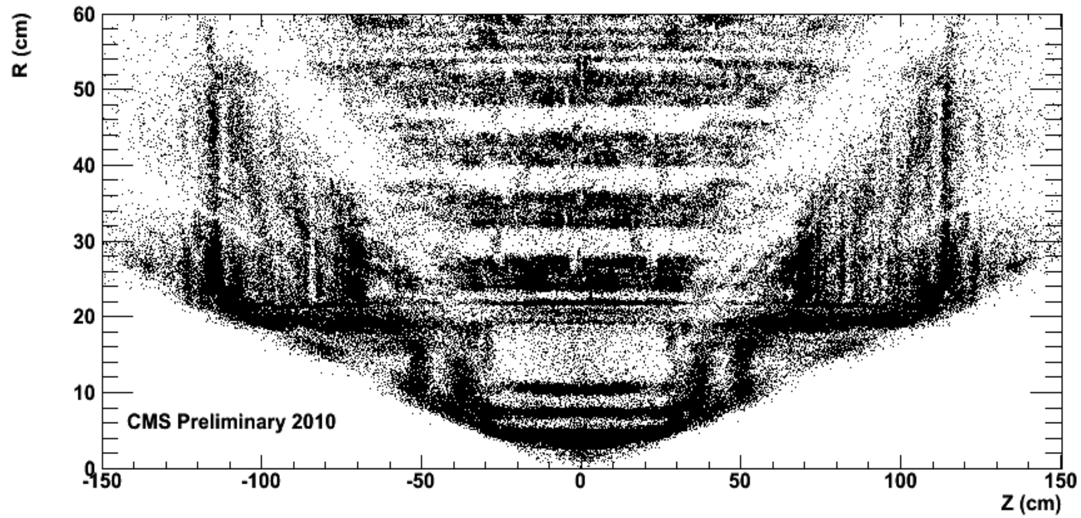
rare, but SM background is featureless



- Looking for tiny bump on smooth background.
- To increase sensitivity:
  - Don't throw away less than perfect photons
  - Use kinematic information (other than mass!) that separates signal from background



Understand photons in the detector



Photons convert to e+e- pair
in presence of material

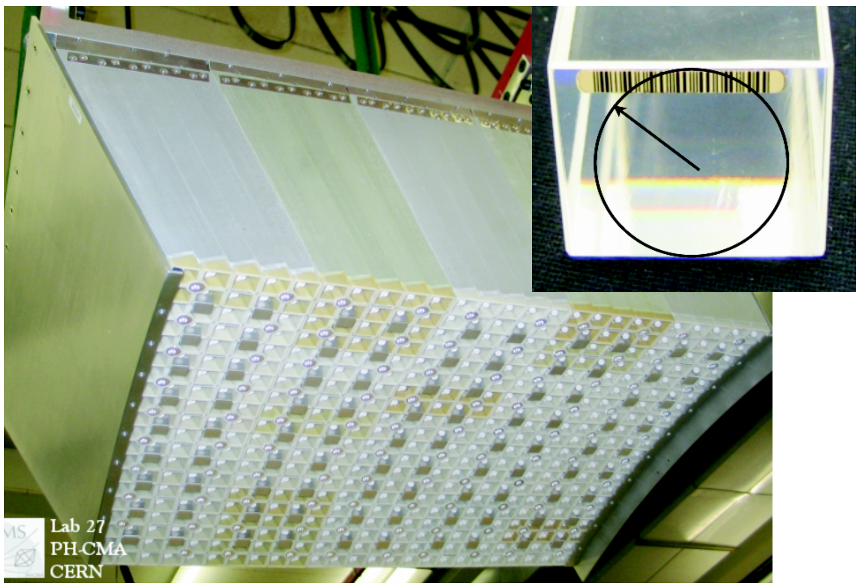
Use information about material that photon had to swim through in photon energy calculation.

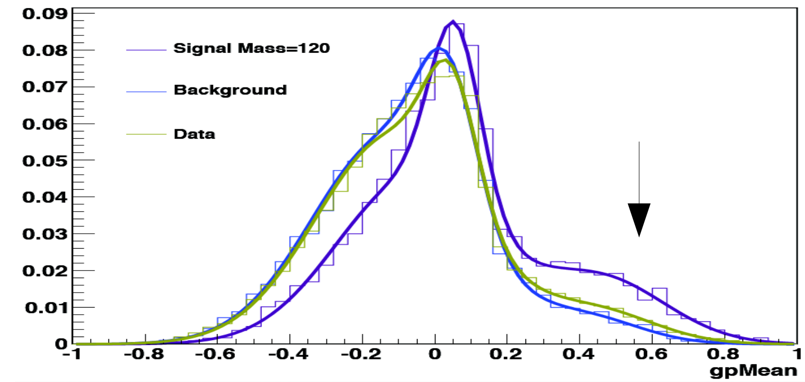
Correct photon energy for where on face of crystal it hit.

Use kinematic information about photon Pair to distinguish from background.

All of these (and other) improvements give few% each. But together they are substantial.

Rutgers one of the best positioned groups for 2012 Higgs to γγ effort.





Various ways to look for Higgs

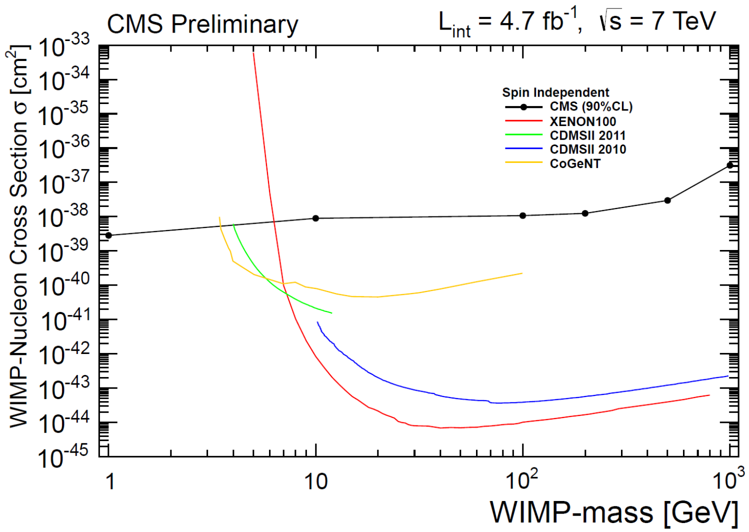
		Production				
		Inclusive h	Wh	Zh	$q\bar{q}h$	$t\bar{t}h$
	WW	OS+MET	SS+$[jj]$+MET			SS+$[jj][jj]b(j)$+MET 3L+$[jj]b(j)$+MET 4L+$b(j)$+MET
	$\gamma\gamma$	$[\gamma\gamma]$	$[\gamma\gamma]$+L+MET	$[\gamma\gamma]$+MET	$[\gamma\gamma]+jj$	$[\gamma\gamma]+[[jj]b]jj(j)$
Decay	ZZ	[[OSSF]·[OSSF]]				
	$\tau\tau$	OSτF			OSτF$+jj$	
	$b\bar{b}$		L+$\{bb\}$+MET	[OSSF]+$\{bb\}$ $\{bb\}$+MET		
	$\mu\mu$	[OSμF]				

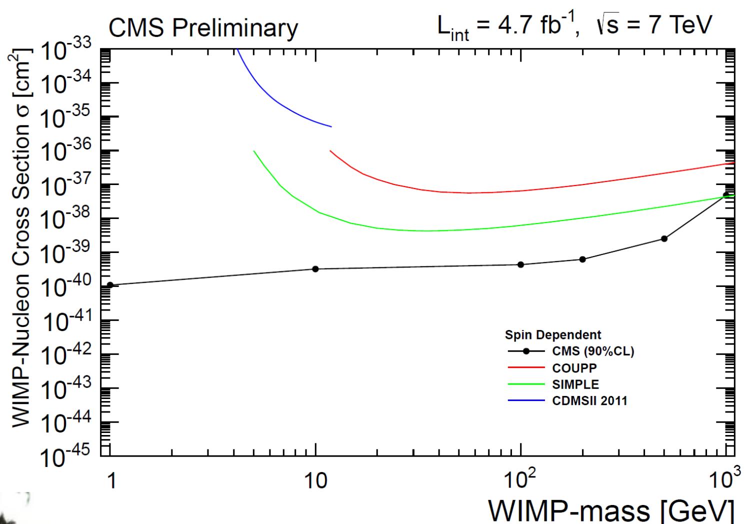
Various ways to look for Higgs*

		Production				
		Inclusive h	Wh	Zh	$q\bar{q}h$	$t\bar{t}h$
	WW	OS+MET	SS+ … IET			SS+[jj … +MET 3L+[jj … j)+MET 4L+$b(j)$+MET
	$\gamma\gamma$	…]	[$\gamma\gamma$ … ET	… ET	… j	[$\gamma\gamma$]+[[jj]b]$jj(j)$
Decay	ZZ	[[OSSF]·[OSSF]]				
	$\tau\tau$	OSτF			OSτF+jj	
	$b\bar{b}$		L+{bb}+MET	[OSSF]+{bb} { … }+MET		
	$\mu\mu$	[OSμF]				

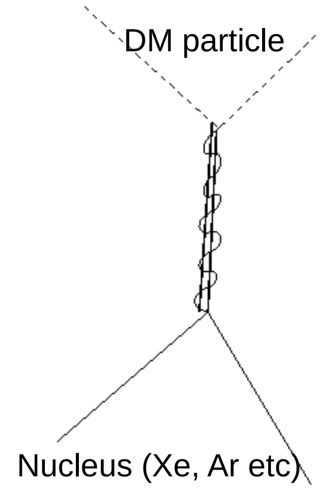
*not all searches optimized for Higgs like γγ, but sensitive especially in case of non-standard Higgs.

Competing with dedicated Dark Matter searches!

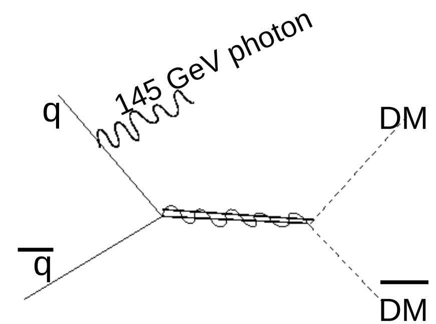




- Direct search:
  - Acoustic technique
  - DM particle hits nucleus



- Collider:
  - Production of DM pairs that go undetected
  - Initial quark radiates hard photon (QED).
  - Analysis is:
    - γ + missing momentum



Spin Independent: competetive at low mass.
Spin Dependent: better at all masses.
Not dependent on relic density of DM. We make our own!

Summary

- Many other analyses ongoing that I was not able to present:
  - Search for a heavy W boson (W')
  - Black Holes (completely independent of decay model!)
  - High mass di-photon resonances
  - Extra dimensions with photons and missing momentum
  - Production of 3 heavy objects (ttW, ttZ)

- Close cooperation between experiment and theory is the ideal way in the LHC era. Recalls dawn of quark era.
  - New physics may not announce itself unambiguously. Will need excellent understanding of possible signals and backgrounds.

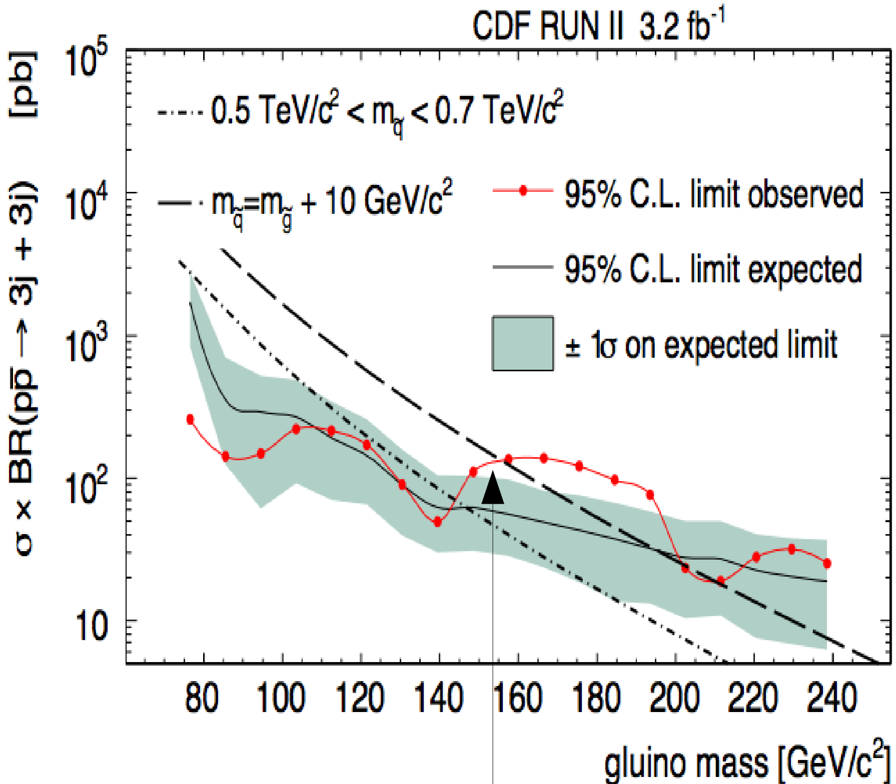
  - Rutgers is at the forefront. Helps us attract the best people, at all levels.

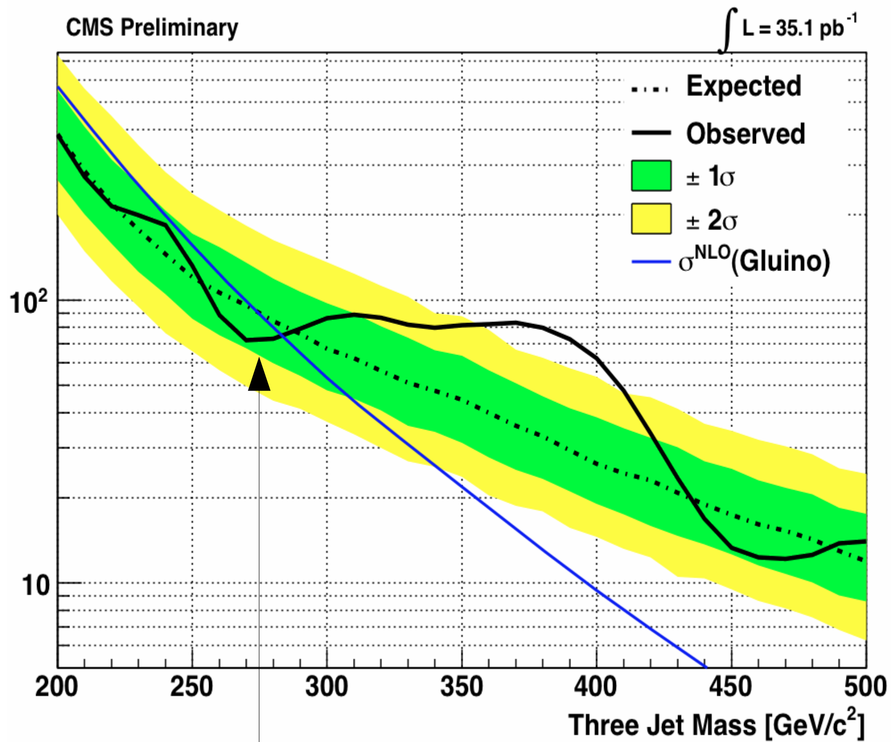
- **2012 will be a very exciting year!**
  - Will get x4 the data (at higher CM energy).
  - Are covering new physics with jets, b-quarks, leptons, photons.
    - RU(+friends) search for Higgs → $\gamma\gamma$ is well positioned to find it (if it is indeed there).
    - Watch this space.

backup

CDF + CMS Limits

3 jet resonances

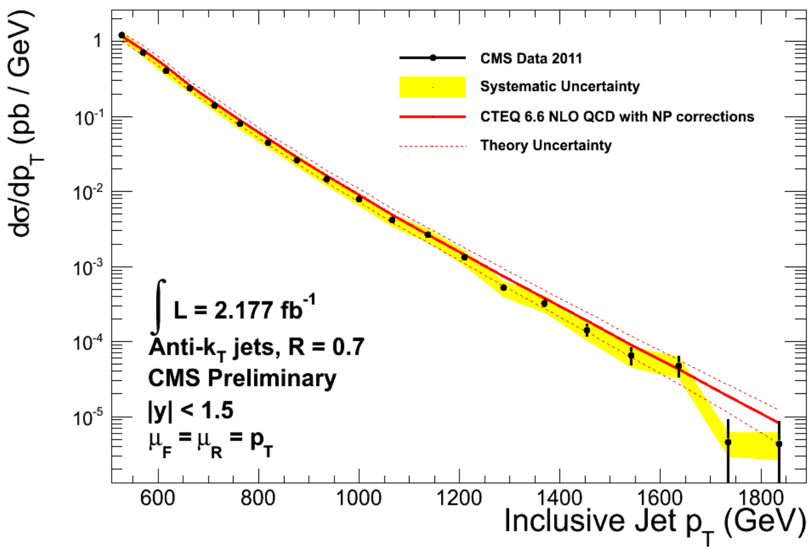


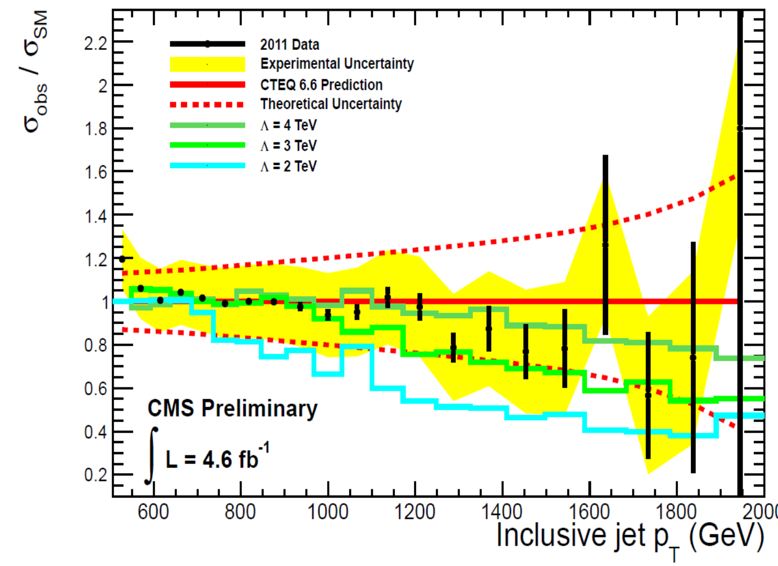


Excluded:
RPV gluino mass < 144 GeV

Excluded:
RPV gluino mass < 280 GeV

Jet Extinction (black holes)

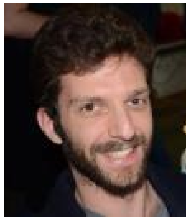




If black holes are made at LHC, then all other processes have to turn off completely.

This will be obvious at the highest rate processes first.
This is inclusive jet production.

We look for extinction of jet production
This way of looking at black holes does not assume anything about their decay process



First ZZ event (2010)

found by Richard Gray