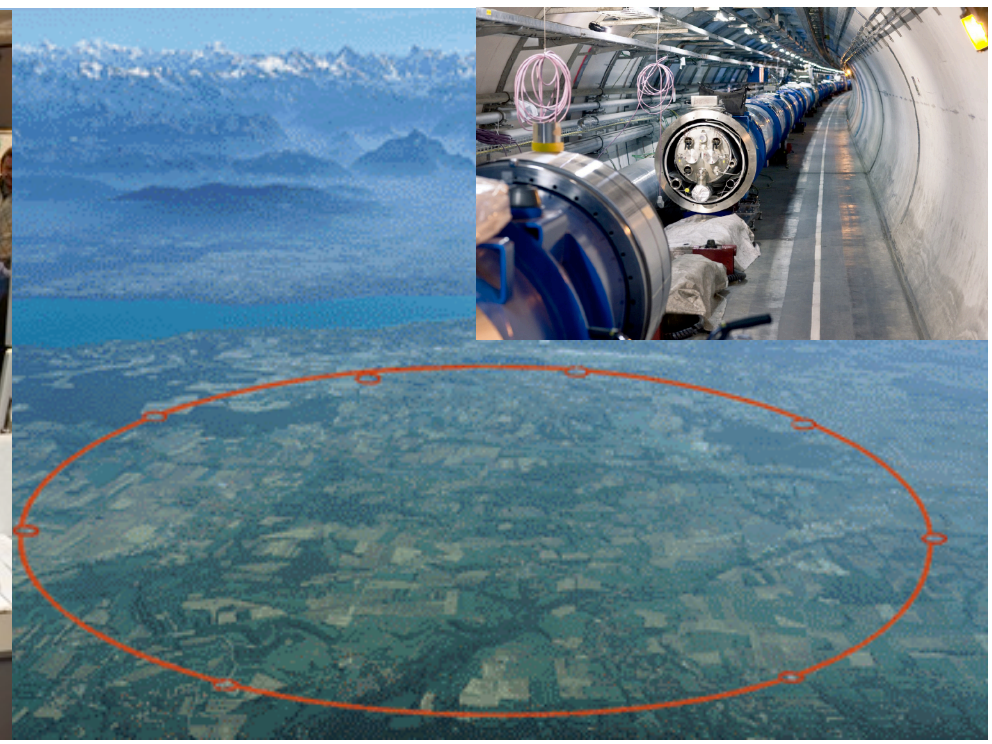
Cornell University
Floyd R. Newman Laboratory for
Elementary-Particle Physics

First Results from the CMS experiment at the Large Hadron Collider

University of Rochester
Physics Colloquium
November 17th, 2010
Julia Thom, Cornell University

Proton Collisions at 7 TeV

- Colliding two beams of 3.5 TeV protons at the LHC as of March 2010
  - 1 TeV=10^{12}eV
  - Factor 3.5 more energy than Tevatron p-anti-p collider
- First run ended last week: most of the data taken in 2 weeks before. ~1% of current Tevatron data set (40/pb)



Overview

- Which questions do we want to answer with the Large Hadron Collider (LHC)? What is the LHC?
- A collider detector (CMS) at the LHC, and how we do physics with it.
- How do we search for New Physics, and first results from the early data.

The "Standard Model"

- Over the last 4 decades we have developed a model that explains all known phenomena and has extraordinarily successful prediction power
  - Quantum Chromo Dynamics + Unified Electroweak Theory

- We have tested it to energies O(100 GeV)
  - ~10^{-18}m

The Standard Model (SM)

The Matter Particles (Fermions):

				Electric charge
6 leptons	e	μ	τ	Q= -1
	ν_e	ν_μ	ν_τ	Q=0
quarks 6 "flavors"	u	c	t	Q=+2/3
	d	s	b	Q=-1/3

..plus antiparticles of opposite charge:

e^+, μ^+, $\tau+$, $\bar{u}$, $\bar{d}$, $\bar{c}$, $\bar{s}$, $\bar{t}$, $\bar{b}$

The Masses

- electron: $M_e \approx 0.0005\ GeV/c^2$ ($\approx 10^{-30}$kg)
- u-Quark: $M_u \approx 0.005\ GeV/c^2$
- c-Quark: $M_c \approx 1.2\ GeV/c^2$

- t-Quark: $M_t = 173.3 \pm 1.1\ GeV/c^2$

→almost as heavy as an atom of gold!!

These are experimental observations--
masses cannot be predicted in the SM

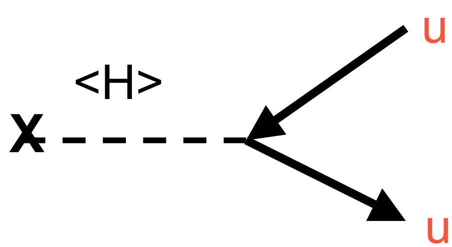
The Forces

transmitted by exchange of Spin 1 Gauge-Bosons
between the Spin ½ Fermions

Force	Boson	Mass	Couples to
Strong (nucl.binding)	Gluons g	0	Quarks, gluons Strongly charged
Electro-magnetic	Photons γ	0	Leptons, … Electr. charged
Weak (nucl.decay)	W^{+-} Z^0	91 GeV 80 GeV	Quarks, leptons W,Z Weakly charged

EWK symmetry breaking in the SM: the "Higgs Mechanism"

- W, Z and the fermions acquire mass by interaction with the Higgs field



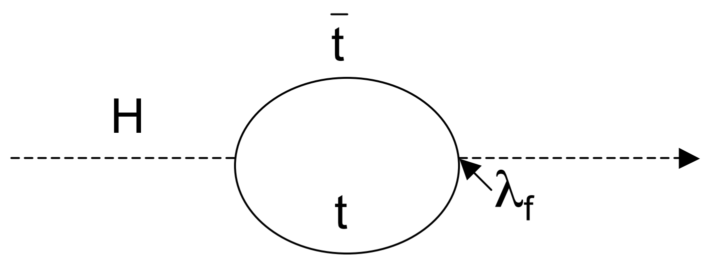
Analogy: effective mass of electron moving through crystal lattice

- Photon doesn't interact with Higgs, remains mass-less (and long-range)
- Large Fermion mass hierarchy put in by hand via appropriate coupling constants spanning 5 orders of magnitude
- Higgs not (yet) observed. It would be observable at the TeV scale.

"Hierarchy"-Problem

- As the Higgs propagates, it interacts virtually with all particles it can couple to, e.g. Fermions

- this would contribute to the Higgs mass ("radiative corrections")



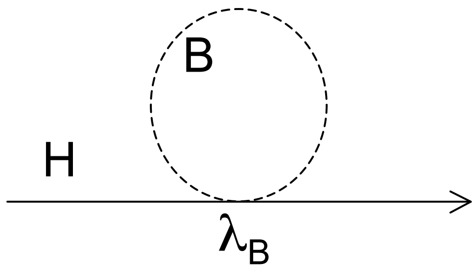
- Higgs mass can receive enormous corrections proportional to the largest scale in the theory ("Planck Mass", 10^{19} GeV)

$$\Delta m_H{}^2 = \frac{|\lambda_t|^2}{16\pi^2}(-\Lambda_{UV}{}^2 + \ldots)$$

One plausible solution:

Many theories suggested, one of them is Supersymmetry (SUSY)

- We know that a boson loop would contribute to Δm_H with opposite sign



$$\Delta m_H^{\ 2} = \frac{\lambda_B}{16\pi^2}(\Lambda_{UV}^{\ 2} + \ldots)$$

- Supersymmetry allows for systematic cancellation between Fermion and Boson loop contributions

Supersymmetry

- Implies that for every known Fermion there exists a new "superpartner" boson and vice-versa.

- If this is true, the superpartners must be heavier than the ordinary particles, and they exist at the TeV scale.

- The lightest superpartner (e.g. neutralino) is neutral and stable and would be an ideal candidate for dark matter

Superpartners

name	spin	Super partner	spin
photon	1	photino	1/2
gluon	1	gluino	1/2
W+-	1	Wino	1/2
Z	1	Zino	1/2
Higgs	0	Higgsino	1/2

Transmission of forces

name	spin	Super partner	spin
lepton	1/2	slepton	0
quark	1/2	squark	0

Matter Particles

Summary: Part 1

- The fundamental questions we are trying to answer with experiments at the TeV scale:
  - Does the Higgs boson exist? If not, something else must be at work at the TeV scale.
  - What is the complete picture? SUSY? Is the lightest Superpartner = Dark Matter?
- The LHC is the machine that allows us to explore the TeV energy regime

Summary: Part 1

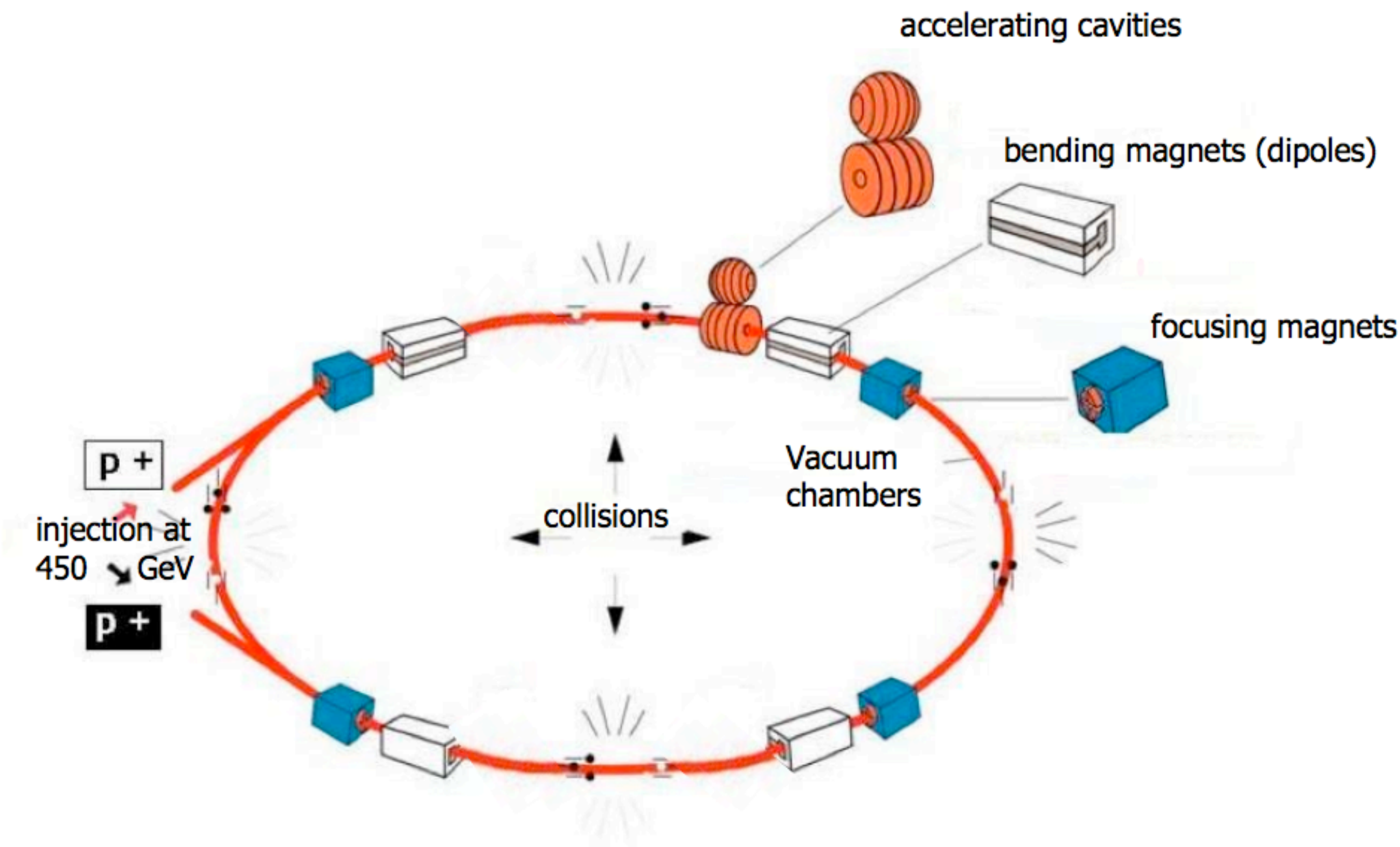
- The fundamental questions we are trying to answer with experiments at the TeV scale:
  - Does the Higgs boson exist? If not, something else must be at work at the TeV scale.

    this talk
  - What is the complete picture? SUSY? Is the lightest Superpartner = Dark Matter?
- The LHC is the machine that allows us to explore the TeV energy regime

What is the Large Hadron Collider (LHC)?

- A 14 TeV proton-proton collider (currently at 7TeV)
  - 1 TeV = 10^{12} eV
  - A factor of 7 more energy than the Tevatron
- 27 Km long tunnel, 100 m below ground
- 9300 superconducting magnets (1232 dipoles)
  - 60 tons of liquid helium
  - 11,000 tons of liquid nitrogen
- Energy stored in magnets = 10 GJ

The LHC collider basic layout



- Each of the 1232 dipoles....
  - is 15 m long
  - carries 11.8 kA of current
  - provides a field of 8.3 T
- There are 2808 "bunches" of protons in each beam
  - 10^{11} protons per bunch
- When brought into collision the transverse size of the bunches is of order 10 μm
  - O(20) collisions per crossing
  - Crossing occurs every 25ns

Where do the protons come from?

Picture of the tunnel

Overview

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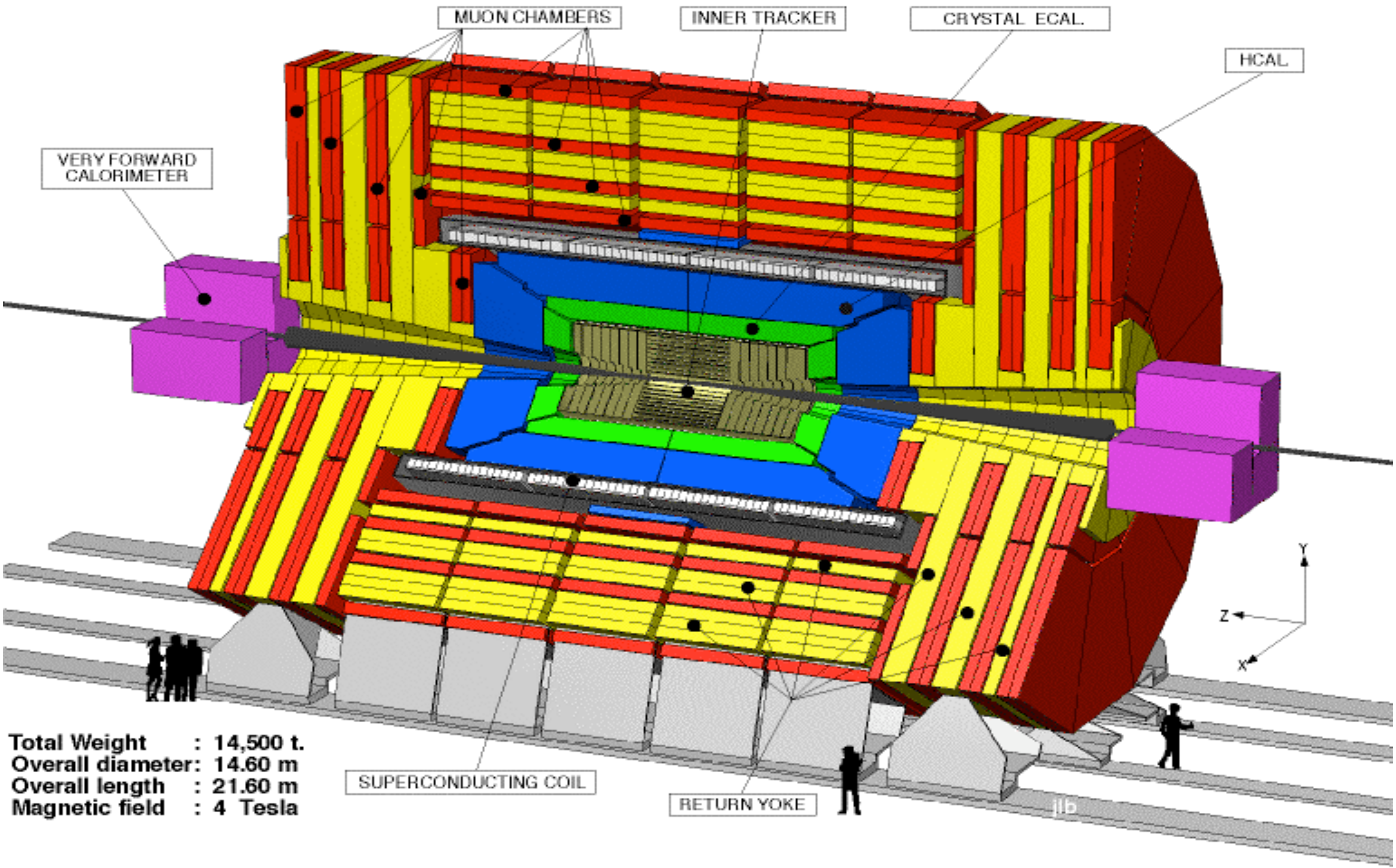
- A collider detector (CMS) at the LHC, and how we do physics with it.
- How do we search for New Physics, and first results from the early data.

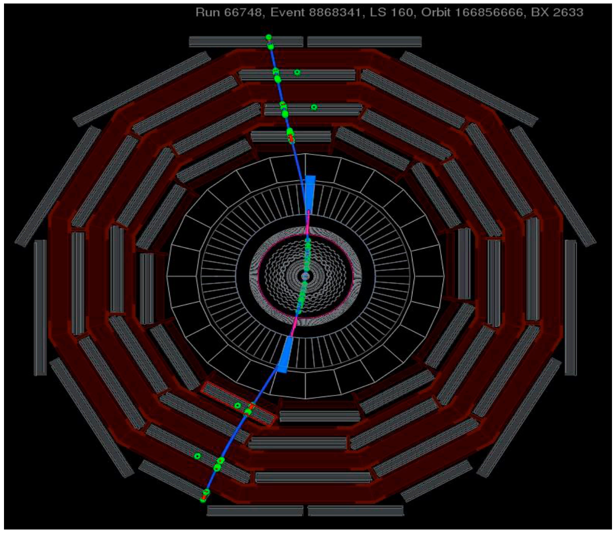


Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

The CMS collaboration:
3170 scientists and engineers (incl.800 students) from 169 institutes and 39 countries

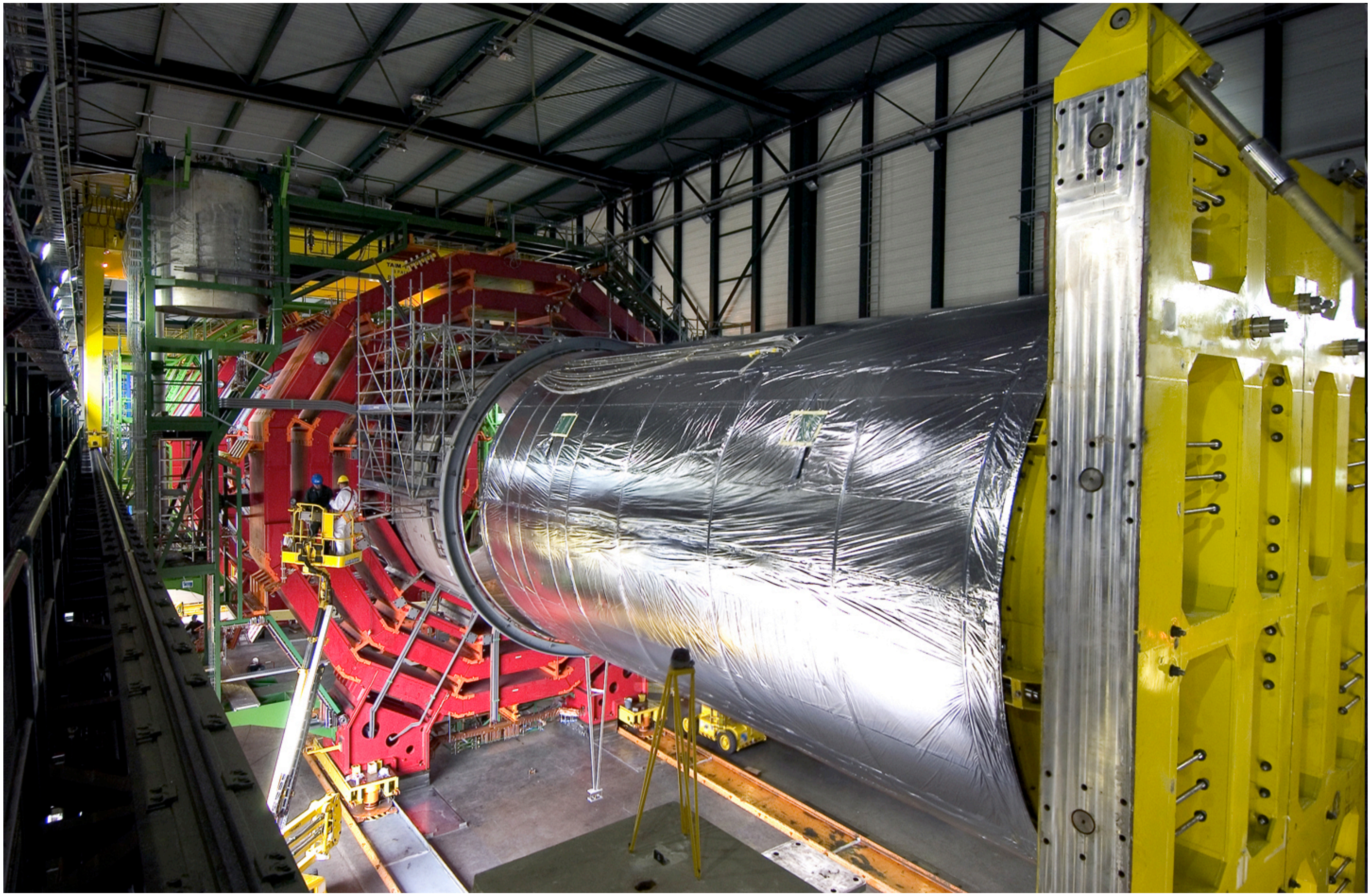
What does the detector do?

- The detector tries to measure the 4-momenta of all particles in a pp collisions
- 3-momenta of charged particles are inferred by reconstructing tracks as they bend in a 4T magnetic field
- For neutrals (γ, neutrons), energy is measured by size of "shower" in instrumented material (calorimeter)
- The interactions patterns of particles with the detector elements allows to "identify" the particle species
  - *e.g.,* electron vs muon vs proton



Cosmic muon

Central feature of detector is
superconducting solenoid with 4T axial field:



Magnet insertion, 12,000 tons. Stores enough energy to melt 18 tons of gold.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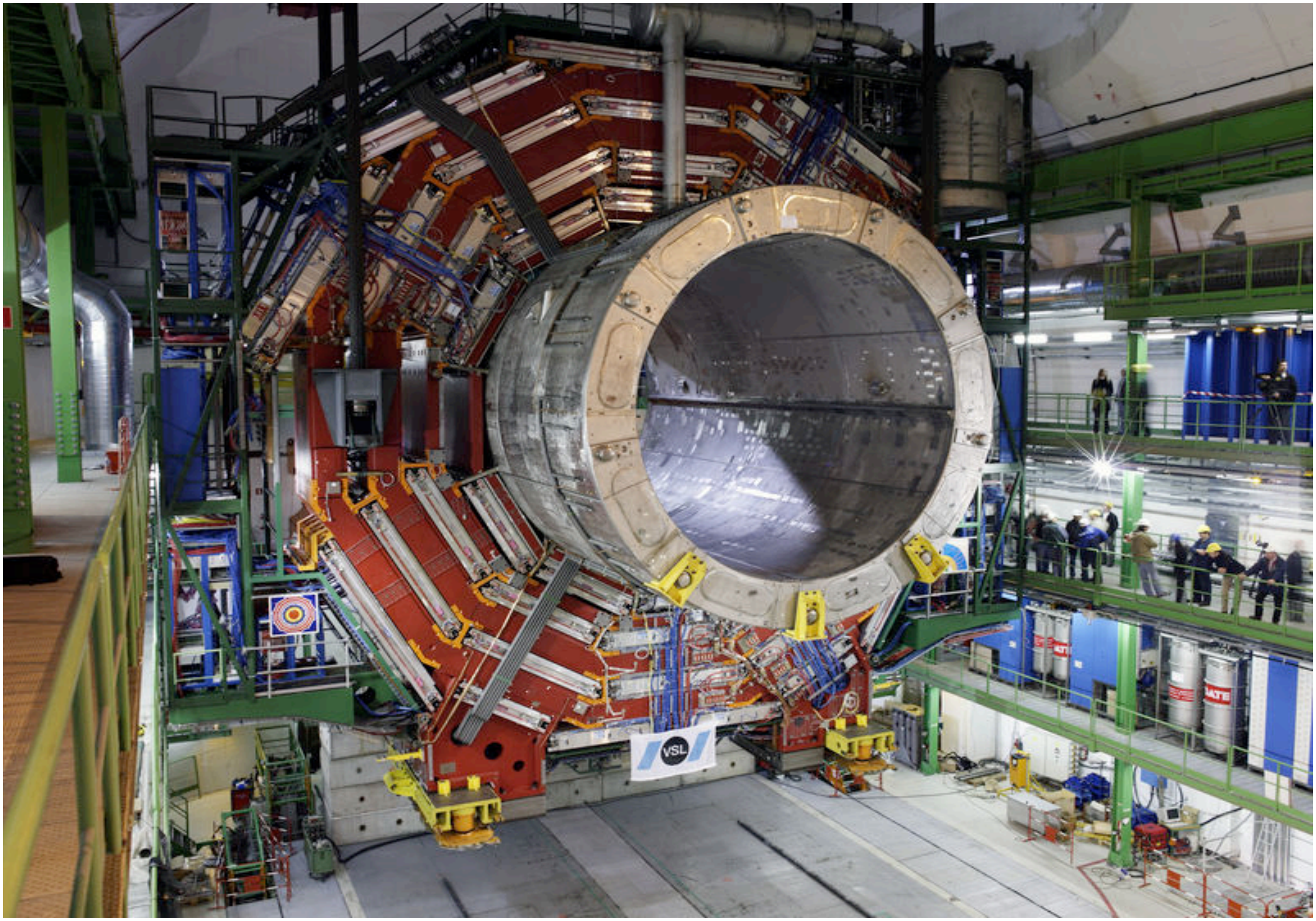
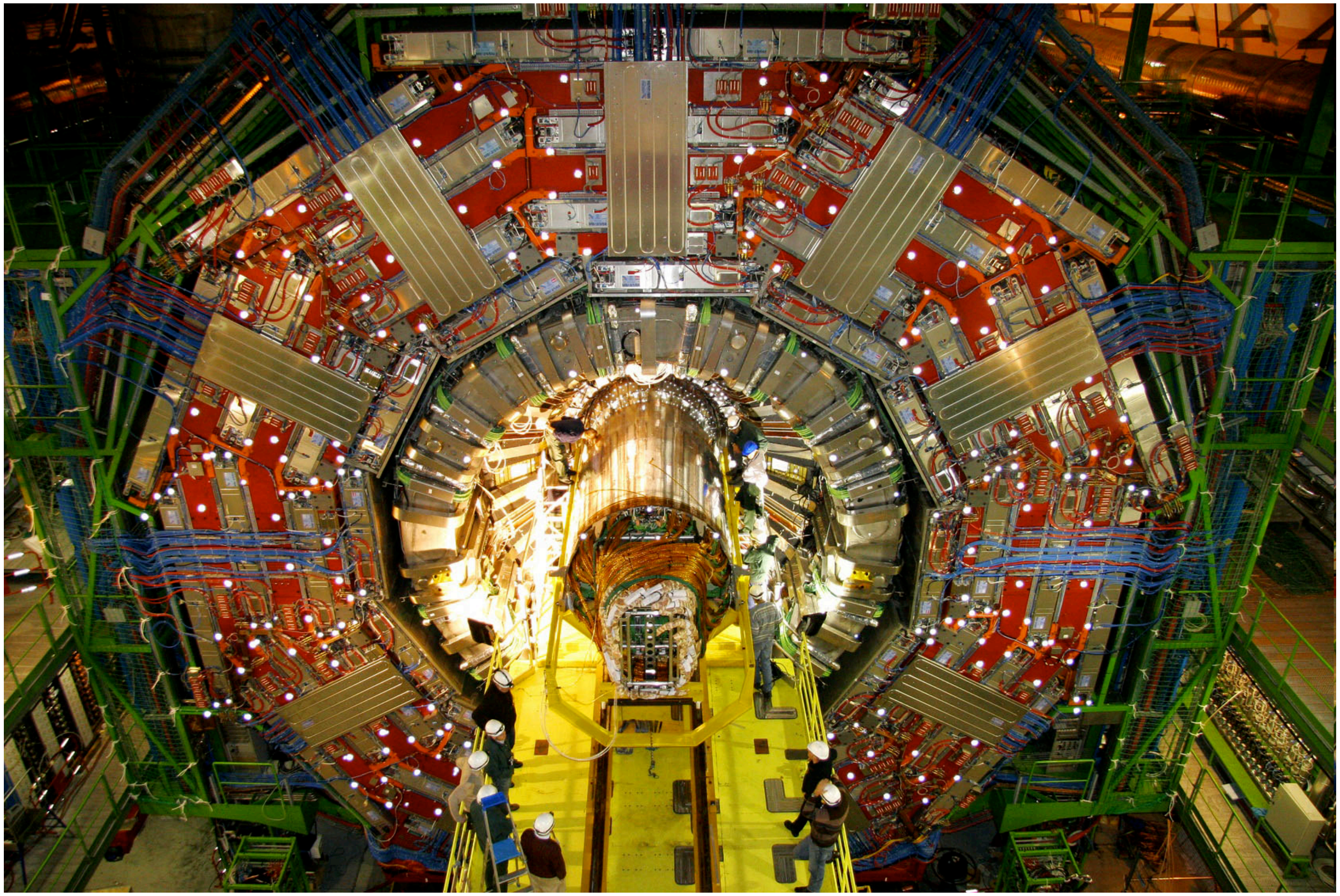

VSL

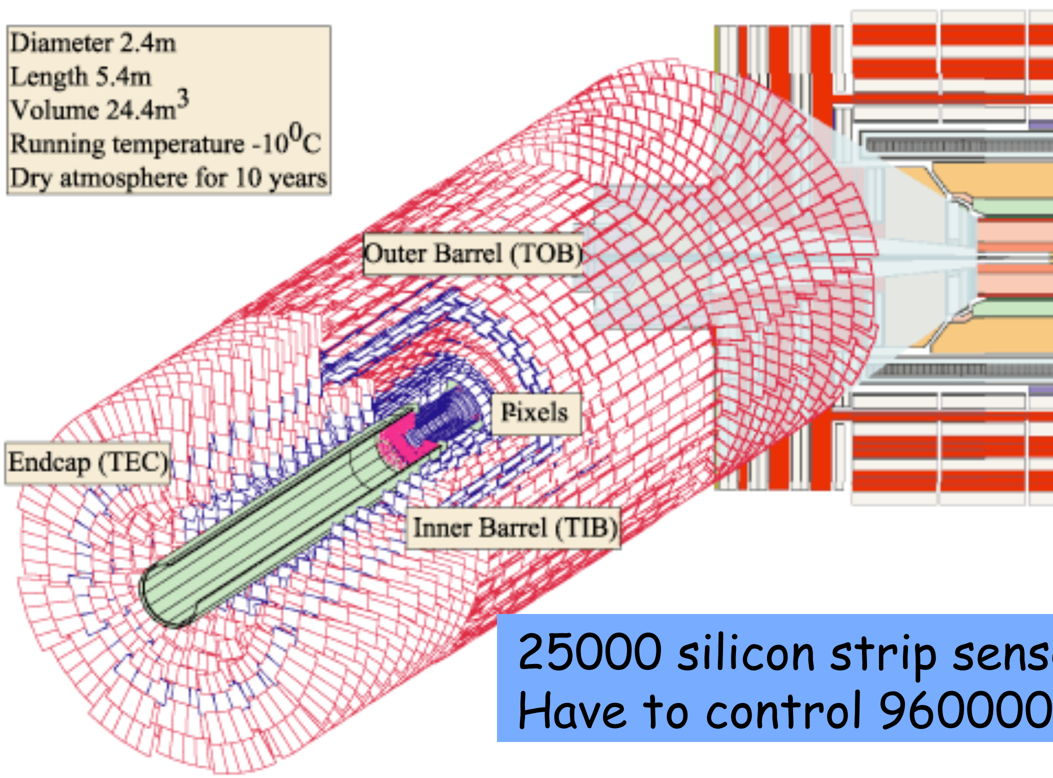
Bore of the solenoid is outfitted with various particle detection systems. Among them: the silicon pixel and strip tracker which measures particle trajectories.



Insertion of the tracker.

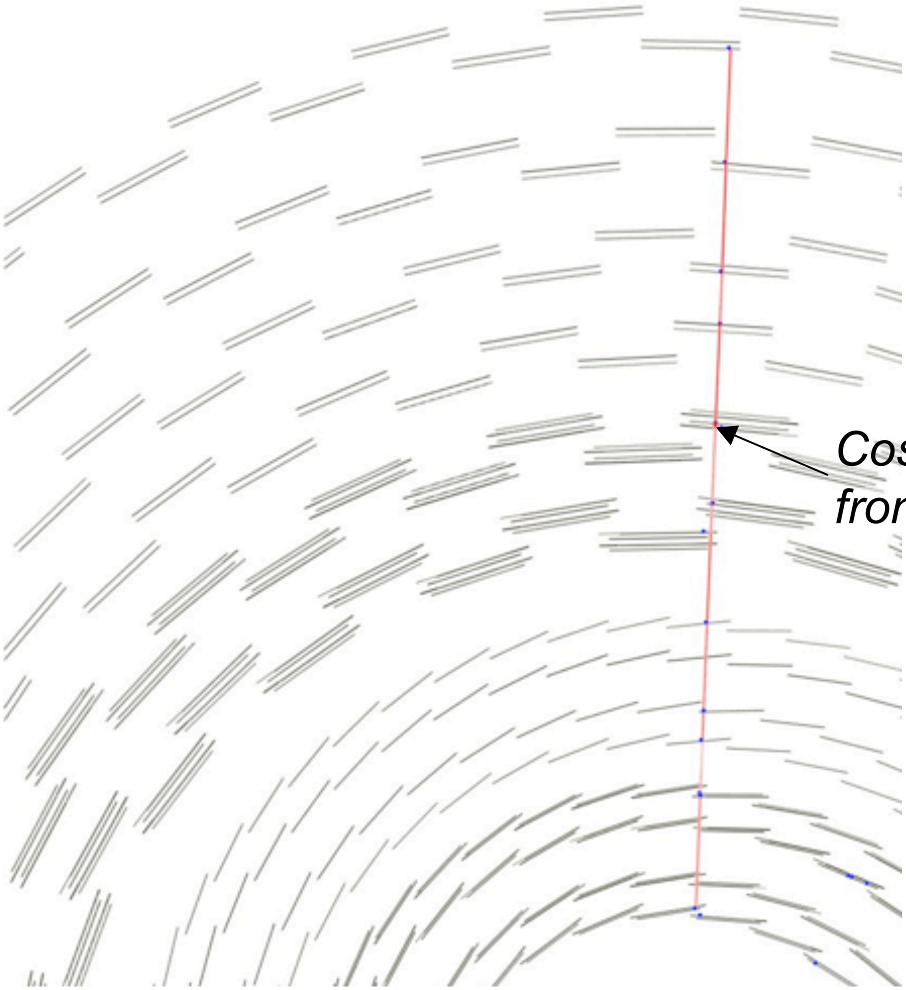
CMS silicon strip tracker

- Single-sided p-type strips on n-type bulk
- Thickness: 320-500 μm, strip pitches: 80-200 μm
- Small angle stereo angle of 100 mrad



25000 silicon strip sensors covering an area of 210 m^2.
Have to control 9600000 electronic readout channels

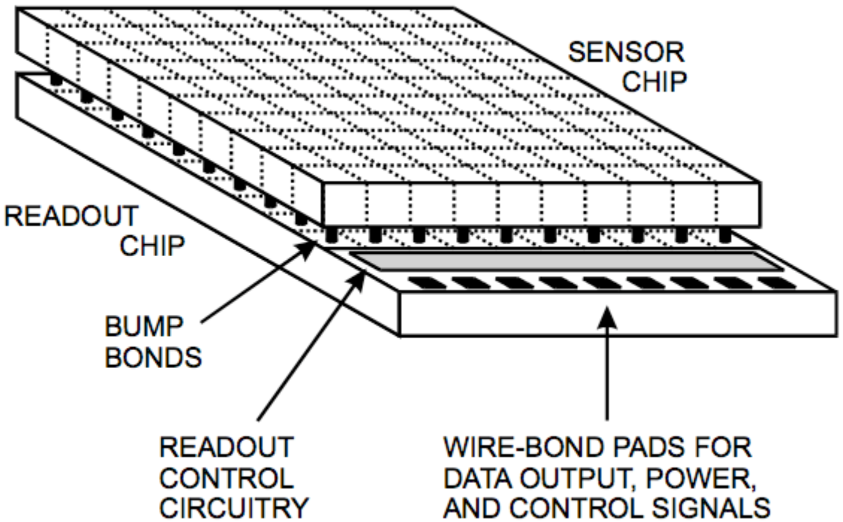
CMS silicon strip tracker

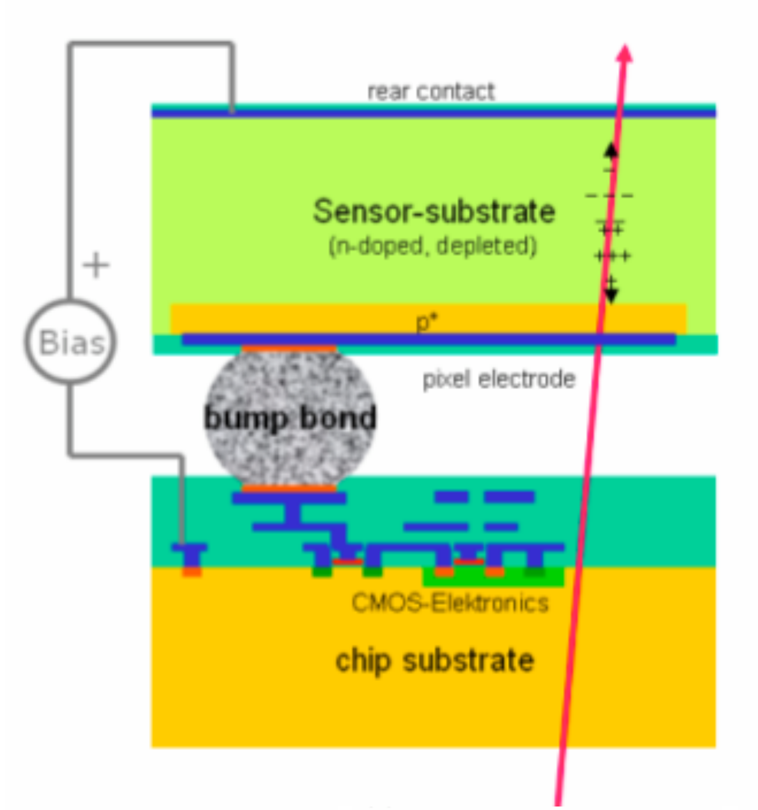


Cosmic muon track, reconstructed from charge deposition on Si strips

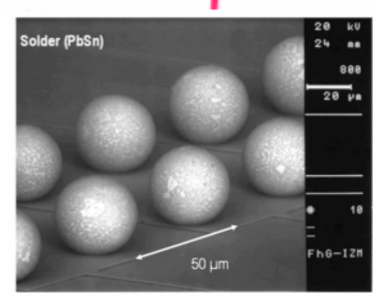
Silicon pixel detector

Adds crucial tracking resolution in the area closest to the beam

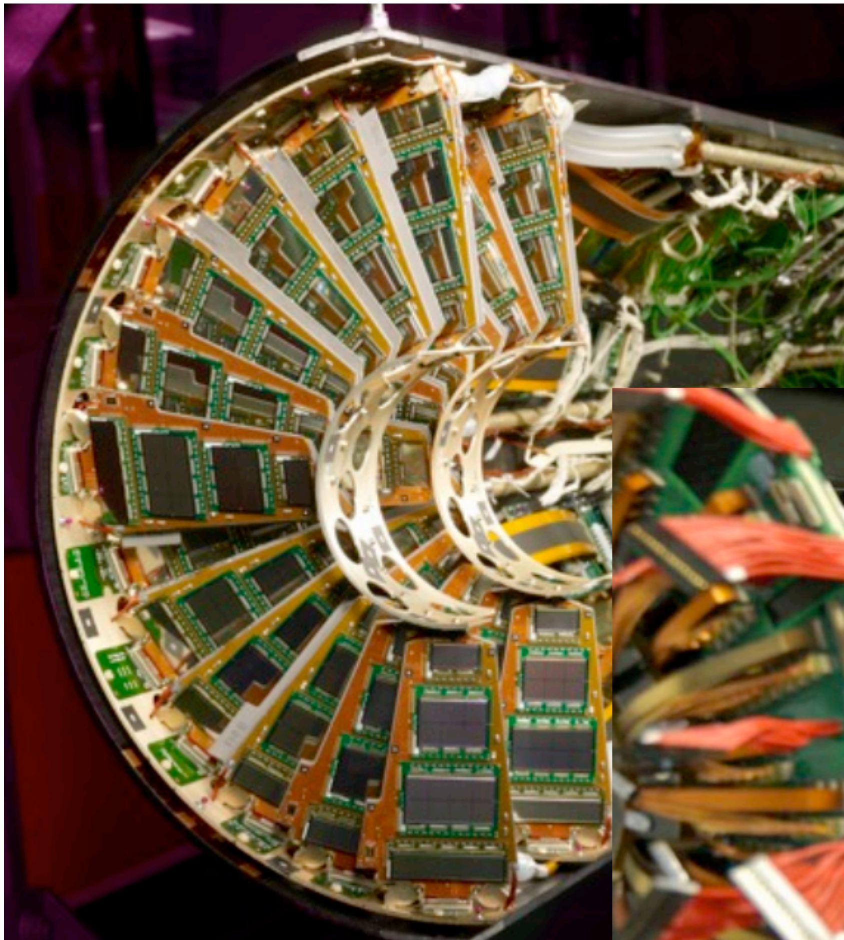


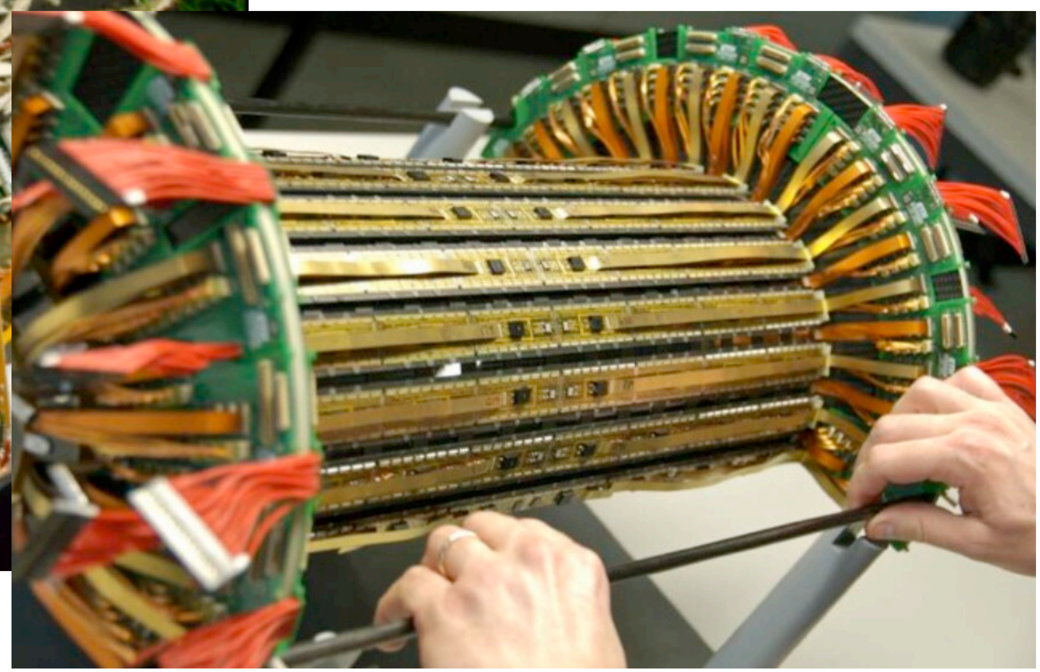


- 3 layers + 2 forward disks
- 66 Million Pixels, $1m^2$ of silicon
- pixel size limited by readout circuit and heat/power dissipation limit (150x150μm)
- Time to read out 1 hit: 6 bunch crossings
- Charge deposition threshold on a pixel ~2500e



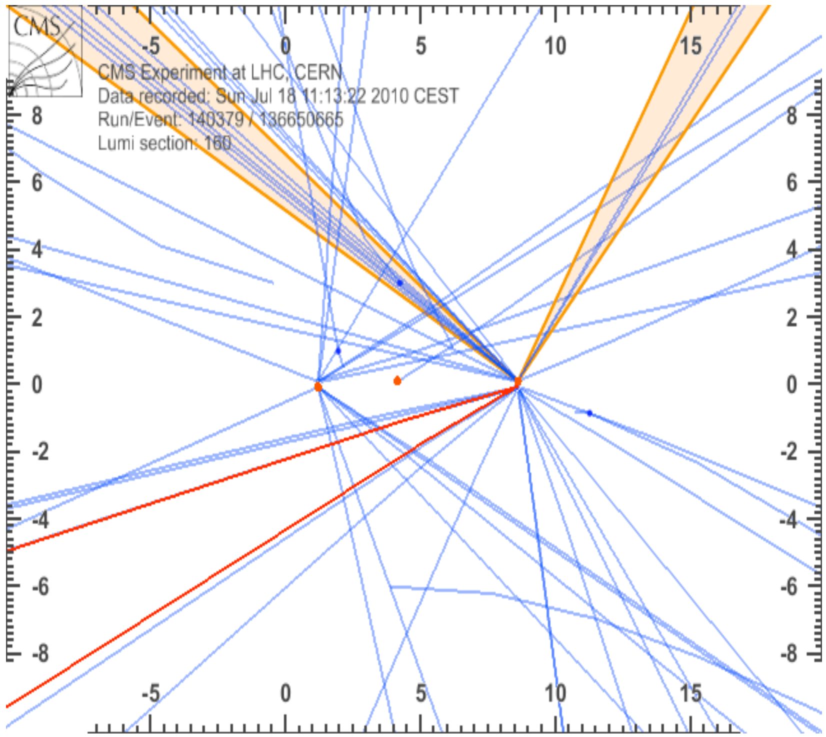
Silicon pixel detector





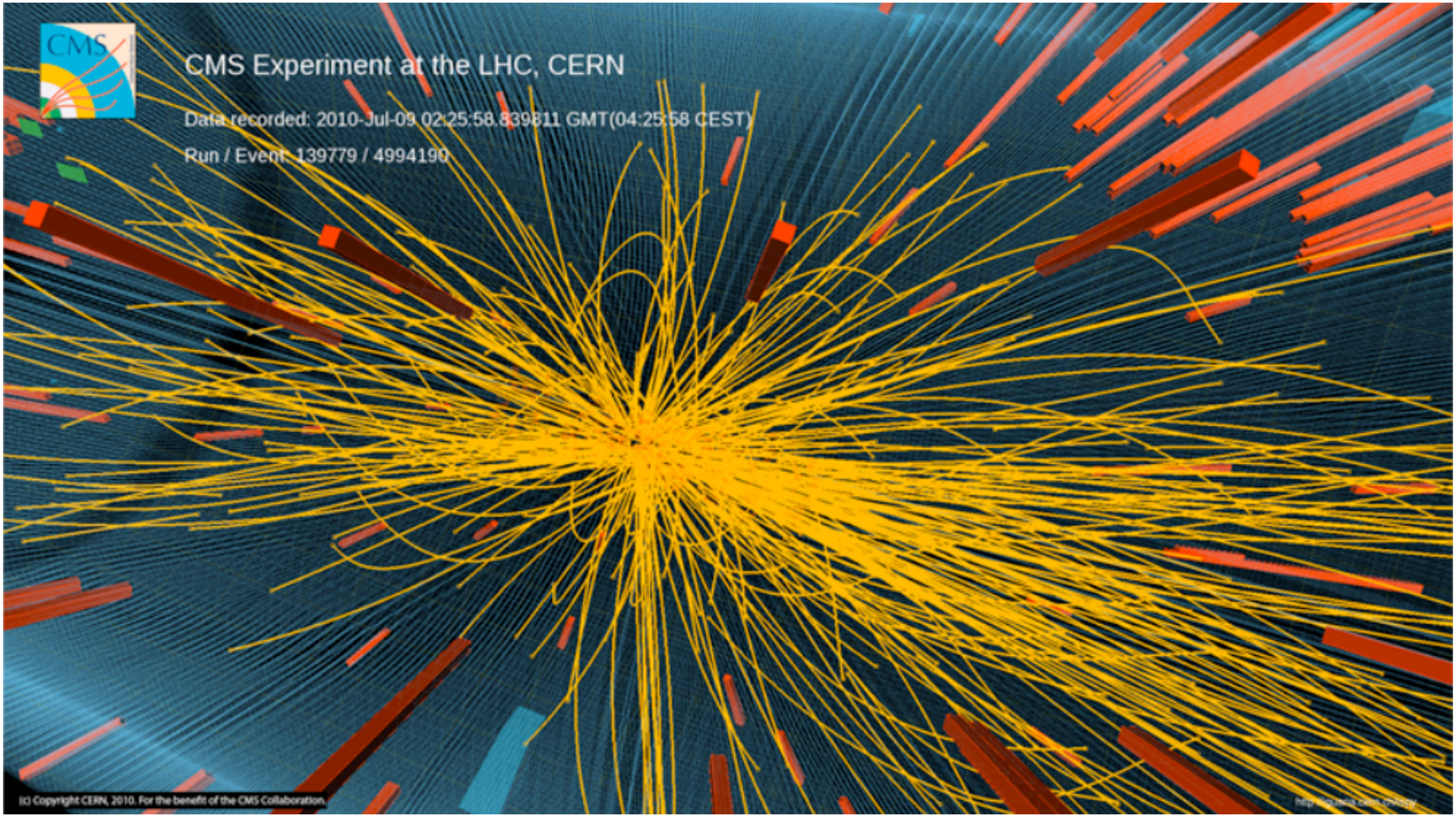
The Silicon tracker..

…allows us to reconstruct particle tracks with micrometer precision and extrapolate to their origin within the beam pipe



Data event display, zoomed into first few cm. Observe 2 events ("Pile-up")

Collision recorded at CMS, 2010

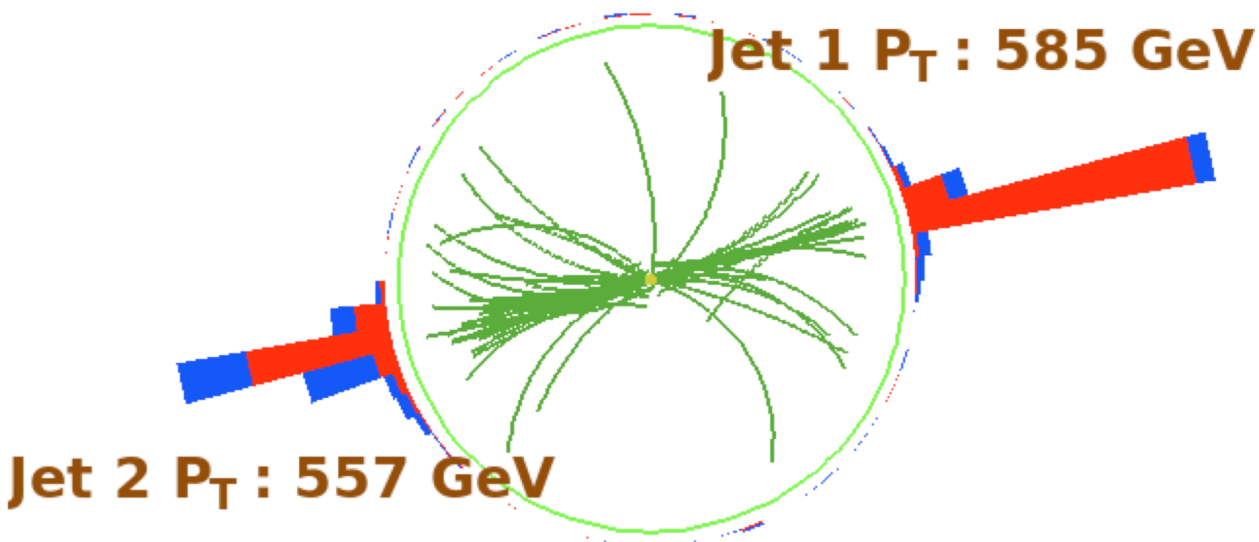


What are the objects we can reconstruct with this detector?

1) Gluons and quarks do not directly show up in the detector. They form "Jets".
   - Quarks and antiquarks are pulled from the vacuum and bound states are formed (hadrons, eg, pions, protons, etc)
   - If the original gluon or quark is energetic enough, the result is a spray of hadrons **(="jet")** that preserves the direction and energy of the original gluon or quark (more or less)

Example: production of 2 gluons results in 2 jets (back to back) in the detector

- Can reconstruct the 4-vector of each jet and determine the invariant mass
- Here: a di-jet data event with m_{jj}=2.13 TeV

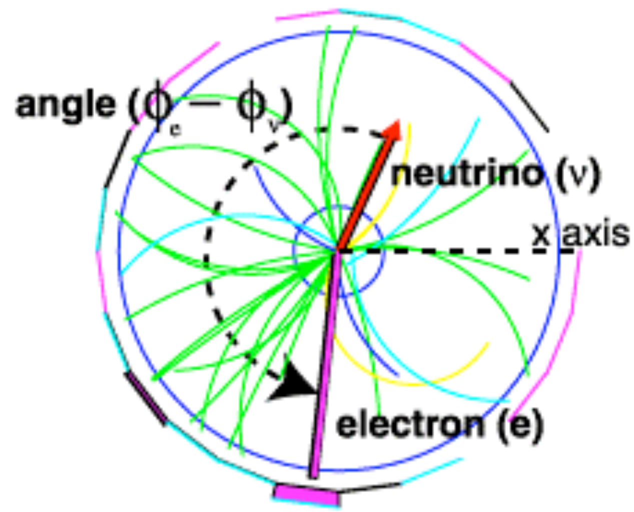


2) Neutrinos (or dark matter particles)

- They do not interact
- Their presence is inferred by conservation of momentum $\sum \vec{P}_{\nu} = -\sum \vec{P}_{\text{visible}}$

In practice this can only be done in the plane transverse to the beam direction, since particles escaping down the beampipe are not measured

-called "Missing Transverse Energy" MET

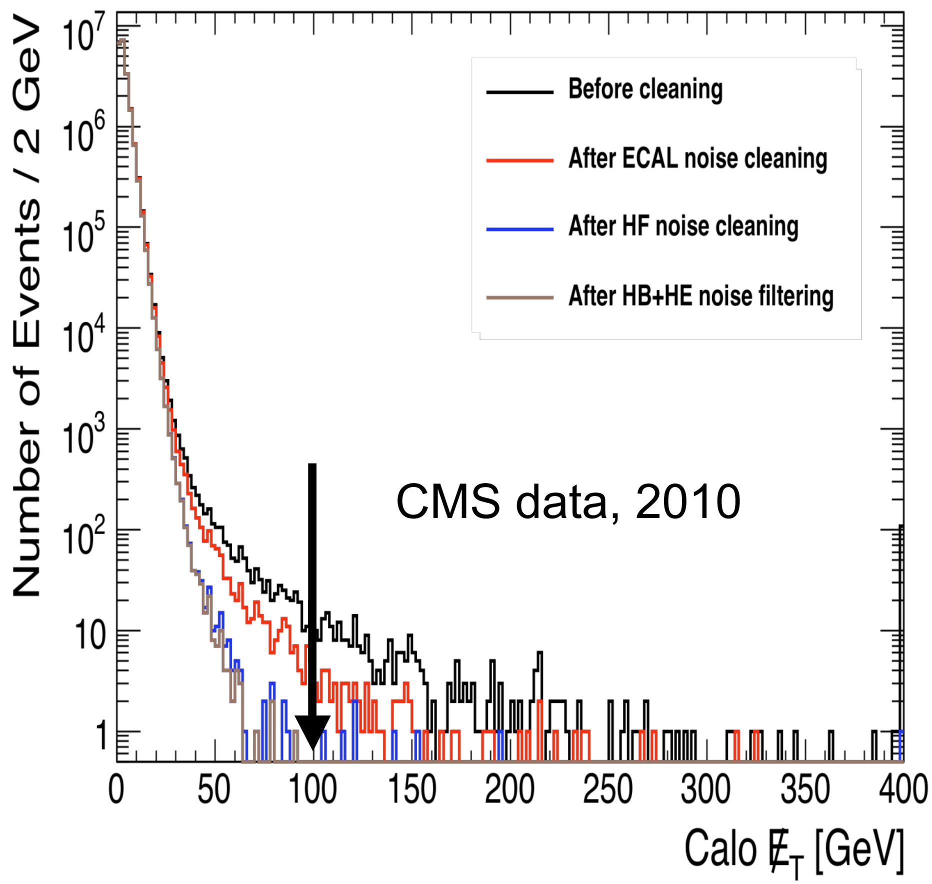


$W \rightarrow e + \nu$

- Most SUSY models predict that dark matter particles (LSPs) produce MET of at least 100 GeV

MET: Experimental Challenge

- False MET can be created by instrumental noise and other effects
  - a "hot" channel in the calorimeter mimics MET in the opposite direction
  - cosmics, beam halo,..
- Great care has to be taken to clean reconstructed MET of these effects



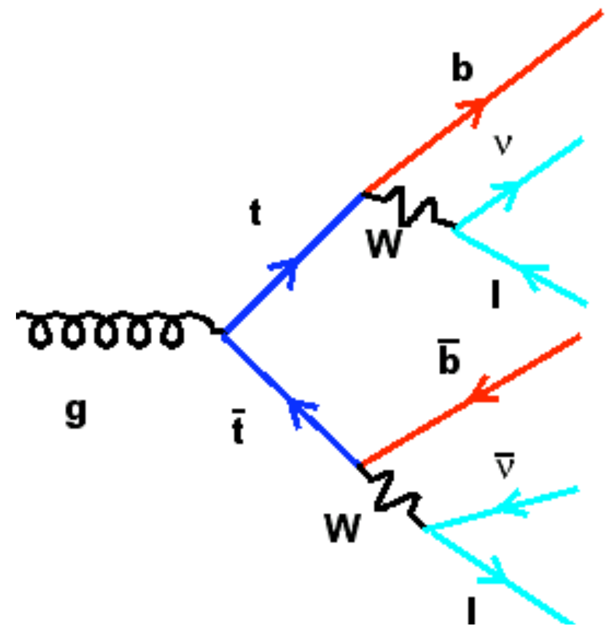
An example of the detector response to a complex decay: top quarks

Heaviest known quark, discovered in 1995 at the Tevatron

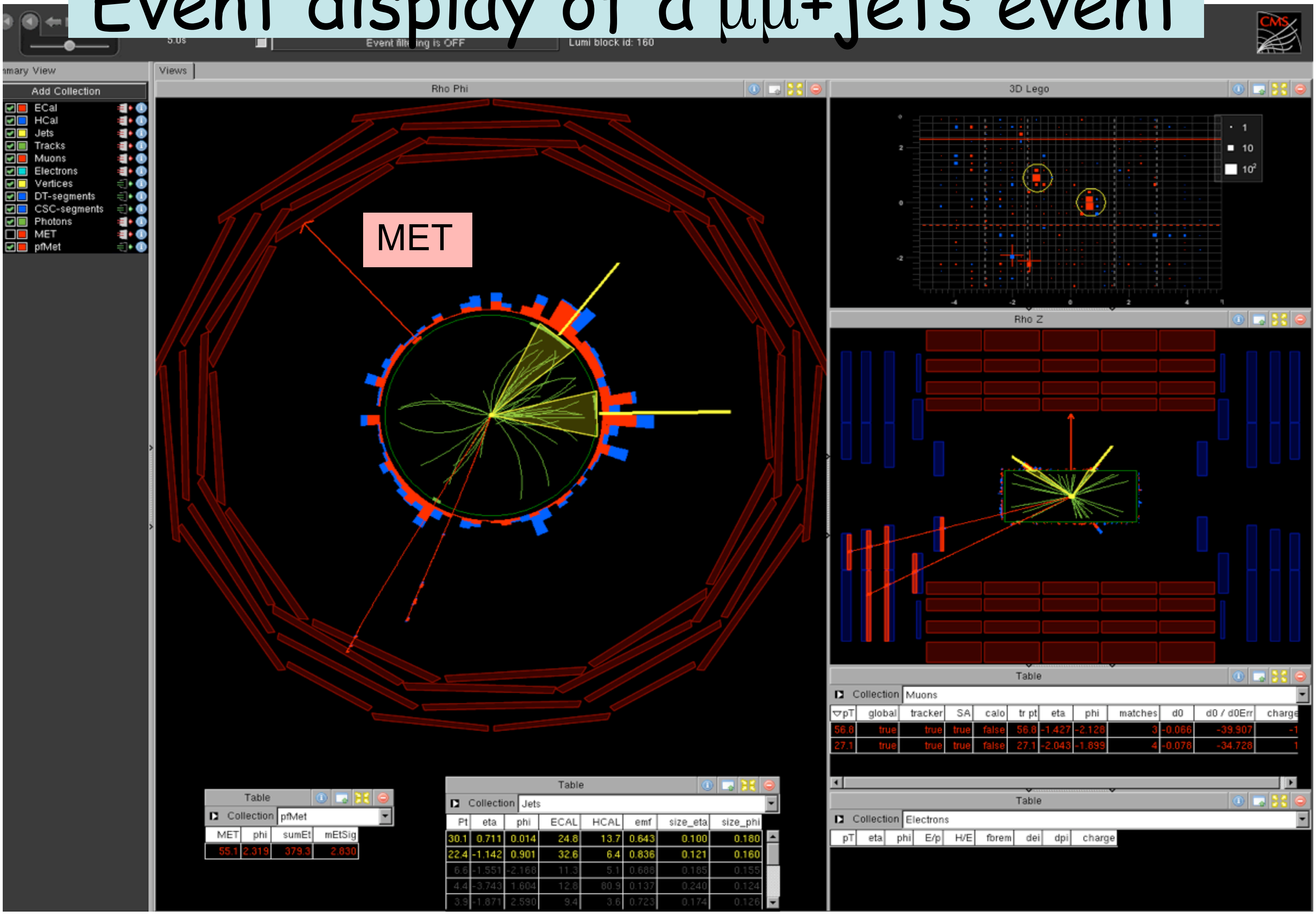
Top pairs are produced at the LHC as well. In the SM, each top quark decays to a W boson and a b quark.

Example final state:

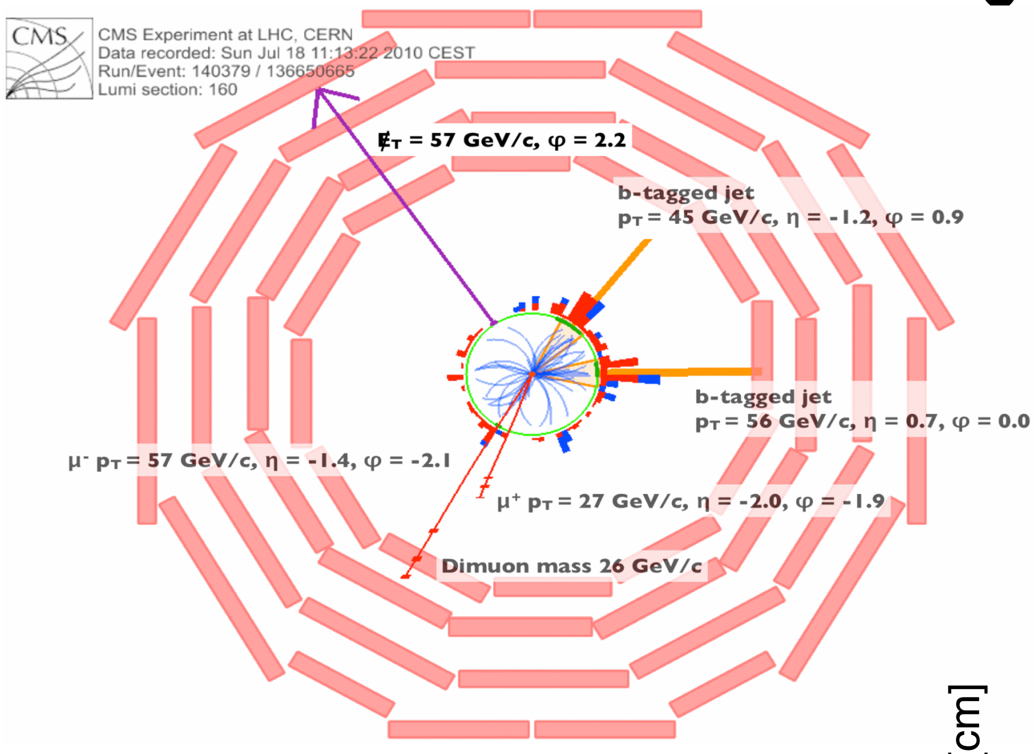
- at least 2 jets (from b quarks)
- missing E_T from the two ν's
- two leptons



Event display of a μμ+jets event



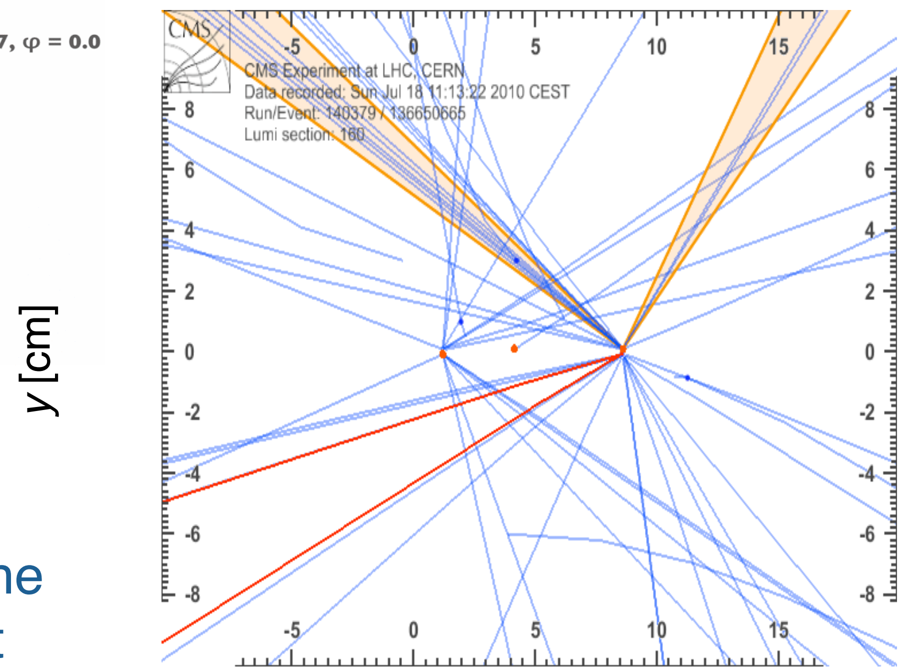
details: μμ+jets event



$m(\mu\mu) = 26\ \mathrm{GeV/c^2}$

Multiple primary vertices → multiple *pp* collisions ("pile-up")

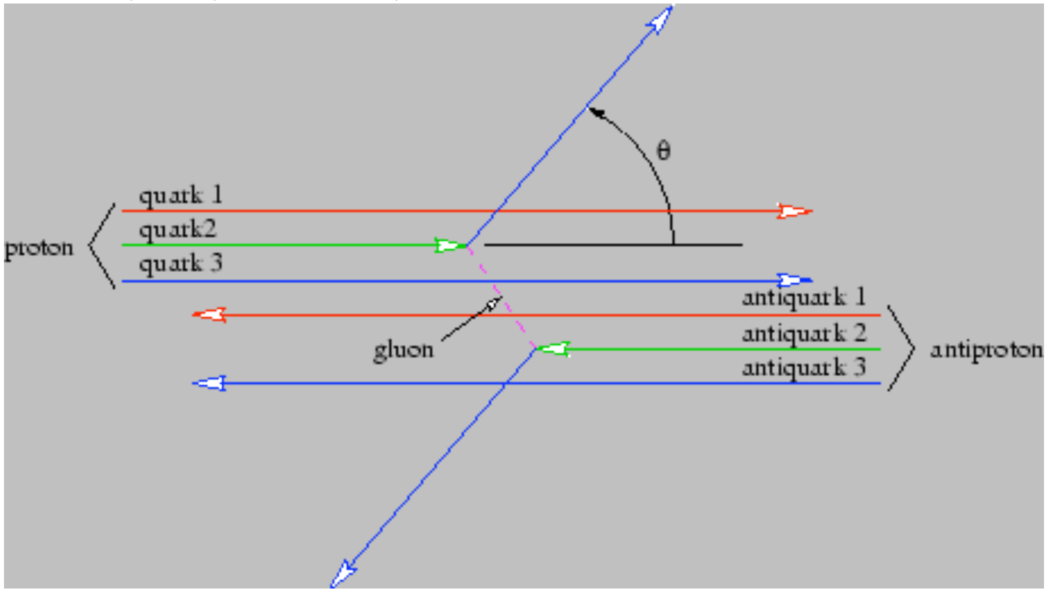
Jets & muons originate from same primary vertex



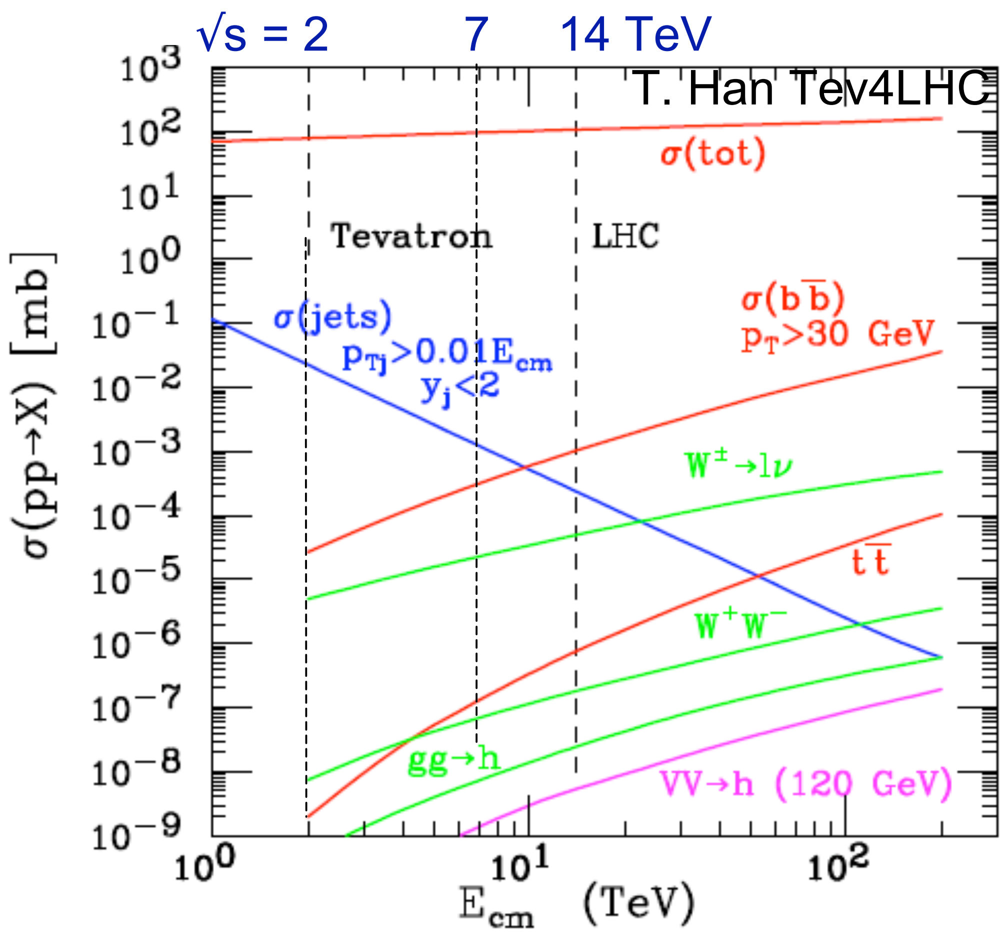
Preliminarily reconstr. mass is in the range 160–220 GeV/c² (consistent with m_{top})

How top quark pairs (or W,Higgs,SUSY etc) are produced

- The interesting collisions are the "violent" collisions where a lot of transverse momentum is exchanged
- Here we can think of collisions between the components of the proton (quarks, many many gluons).
  - Note: their momentum is unknown!



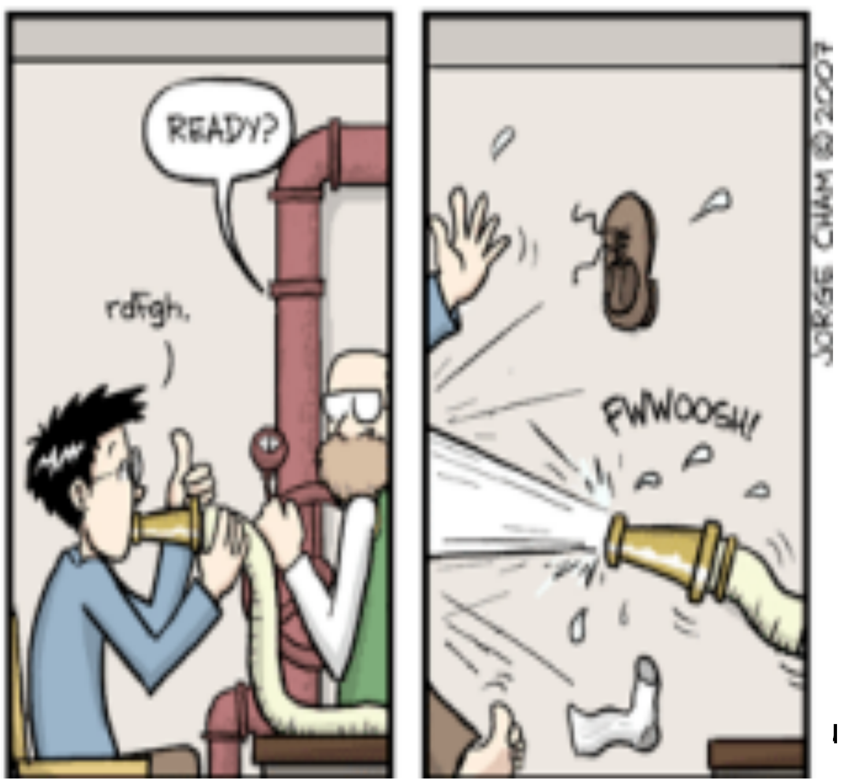
The hard scatters: the production cross sections as calculated in the SM



- Jet production is so large because it is a strong process, e.g. *gg->gg*
- Top quark pair production (and other interesting physics) is suppressed by many orders of magnitude
- SUSY particle production of order 10^{-9}mb

How we beat down 9 orders of magnitude of background: the "Trigger"

- $\sigma(pp)$ ~ 100 mb
- Gives an "event rate" of order 100 MHz
- Each event is ~ 250 kb
- 250 kb x 100 MHz = 25 Tbytes/second



- Trigger is the system that selects the ~ 200 events/second that are saved for further study

- Most of the events are thrown away!!!!

Trigger (2)

- The decision on what to trigger on has enormous impact on the physics that we can do

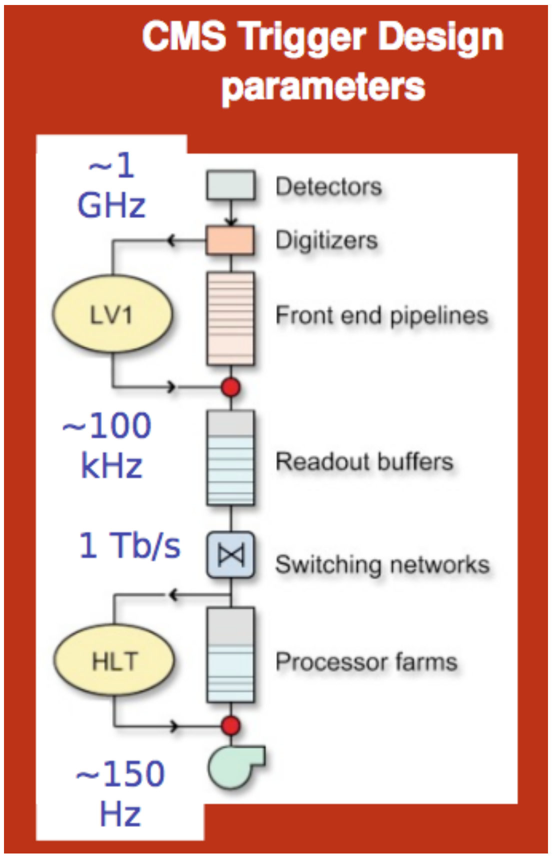
- Trigger selects objects (e, μ, MET, jets..) or combinations thereof
  - Currently have O(100) triggers

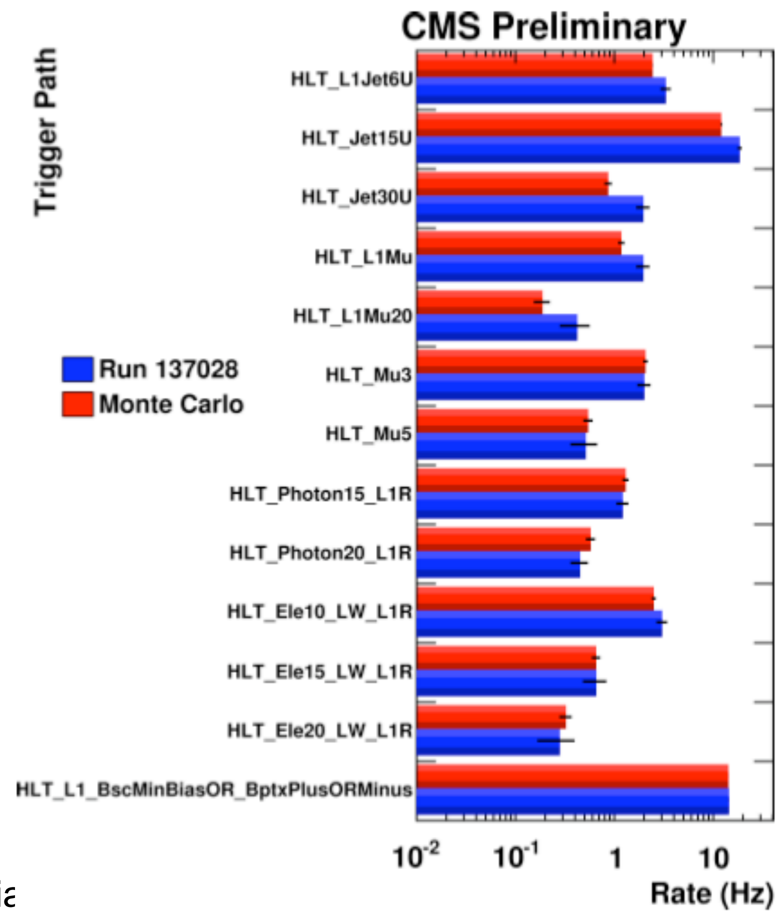
- All kinematical distributions fall steeply with P_T → trigger selects objects above a threshold
  - compromise between competing priorities
  - A source of great debate in the collaboration

- If you want to search for a particular NP signature:
  1. Check that your events have been triggered on
  2. If not, try to convince people to devote bandwidth to your idea

Trigger (3)

- First decision (1GHz to 100 kHz) is made at detector level
- Second decision (100 kHz to 150 Hz) is made with software
- Current total trigger processing time per event: <50 ms





Summary: Part 2

- Physics objects we observe in the detector are:
  - Jets
  - MET
  - electrons, muons, photons,…
- They are the stable decay products of hard scatters of the proton constituents
  - Main process in hard pp scatters: jet production. Higgs, top, SUSY, etc are very rare
- A trigger selects ~1 out of each million of events to be saved for further study

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- How do we search for New Physics (NP), and first results from the early data.

how we plan to "discover NP"

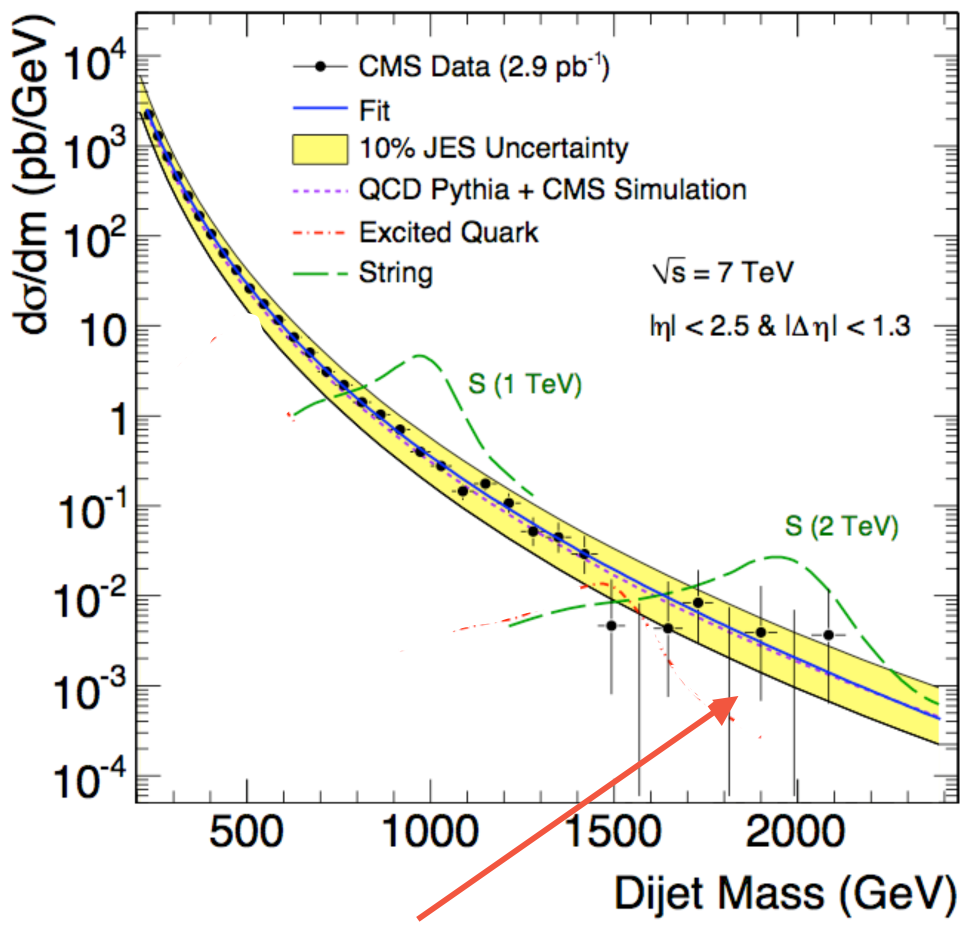
1. Most dramatic: signals that stand out, e.g. mass peak of di-jets
   - E.g. a mass peak
     - X→AB, measure the 4-momenta of A & B, then, $(P_A+P_B)^2=M_X^2$

2. Less dramatic, but just as important: compare counts of events of a given type with the SM expectations,
   - e.g. if we select top quark decays, do we get the number of events we expect?

3. compare distributions with the SM expectation,
   - for example the MET in jet events.

Example for a search for resonances: the di-jet mass spectrum

- Many NP models predict new massive objects coupling to q,g, resulting in resonances
- Starting to exclude certain NP ranges, e.g.
  - string resonances with m<2.6 TeV decaying to qg
  - Composite excited quark mass m<1.6 TeV
  - Many others..



Reach extending beyond the Tevatron

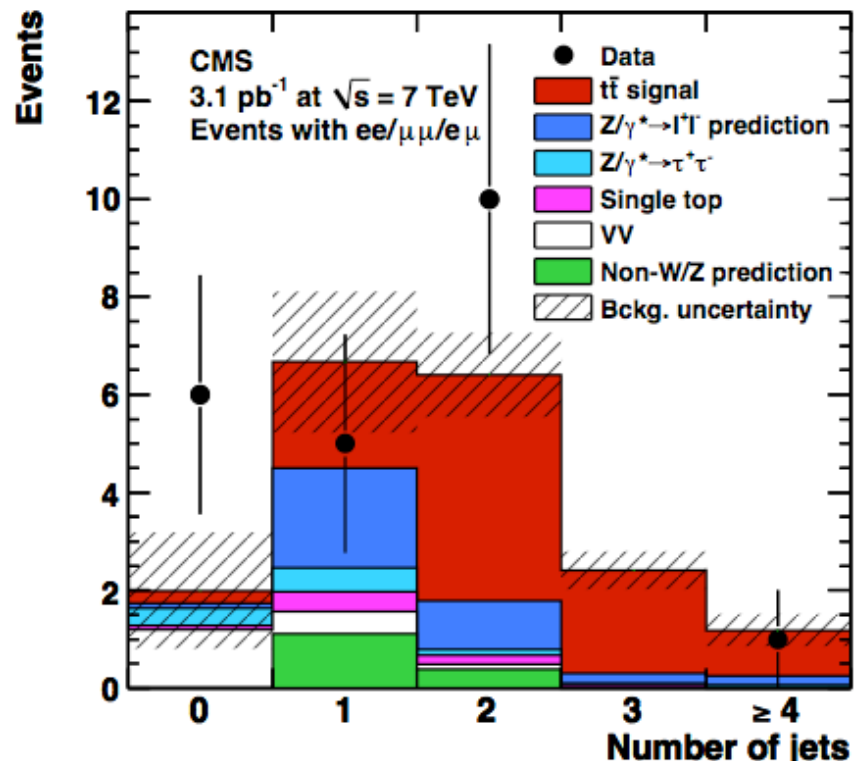
Less dramatic "signal" search: check if number of events passing event selection larger than SM expectation

arXiv:1010.5994 ; CERN-PH-EP-2010-039

- Select events with 2 leptons (e,μ) and high energetic jets, significant missing energy (MET>30 GeV)

- Milestone for CMS: We have "rediscovered" the top quark

- note: backgrounds are measured from the data in control samples



$$\sigma(t\bar{t}) = 194 \pm 72(stat) \pm 24(syst) \pm 21(\mathrm{lum})\ \mathrm{pb}$$

SM calculation: NLO: σ(tt)=157±23 pb at m_t=172.5GeV/c². 25x bigger than at Tevatron!

Less dramatic "signal" search: check if number of events passing event selection larger than SM expectation

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- Select events with 2 leptons (e,μ) and high energetic jets, significant missing energy (MET>30 GeV)

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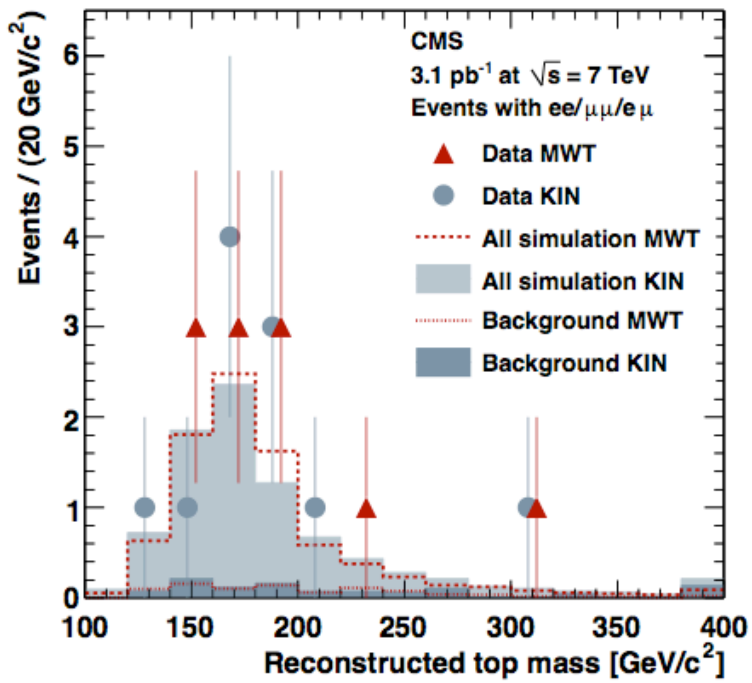
- Checking for consistency with the top mass hypothesis



$$\sigma(t\bar{t}) = 194 \pm 72(stat) \pm 24(syst) \pm 21(\mathrm{lum})\ \mathrm{pb}$$

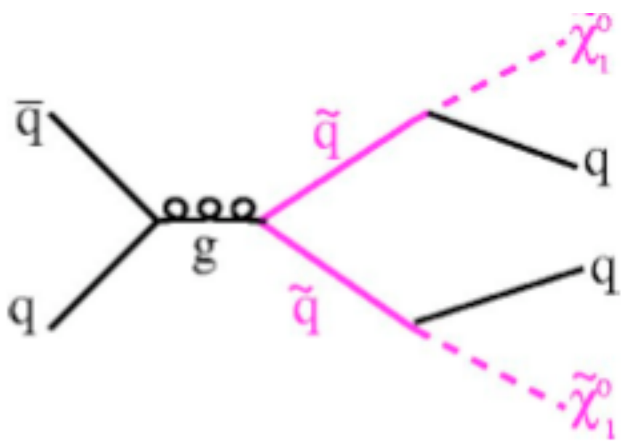
SM calculation: NLO: σ(tt)=157±23 pb at m_t=172.5GeV/c^2

How well can we predict the backgrounds?

- Our SM calculations give well-tested predictions for many processes
- But some background processes are difficult to calculate, due to
  - instrumental effects in the detector
  - We don't know the fraction of transverse momentum carried by the proton constituents
  - Non-perturbative calculations
- Certain processes are unknown to O(2) or more
  - Crucial to have a good estimate! Have to estimate background from data itself, using clever tricks
  - This is where 90% of the work goes!

Example

- pp → jets + MET is a generic signature of SUSY:



1. Squark pairs are produced.
2. Each squark decays to a quark and a Neutralino (Dark Matter particle).
3. We would "see" 2 jets and MET (~60GeV or more)

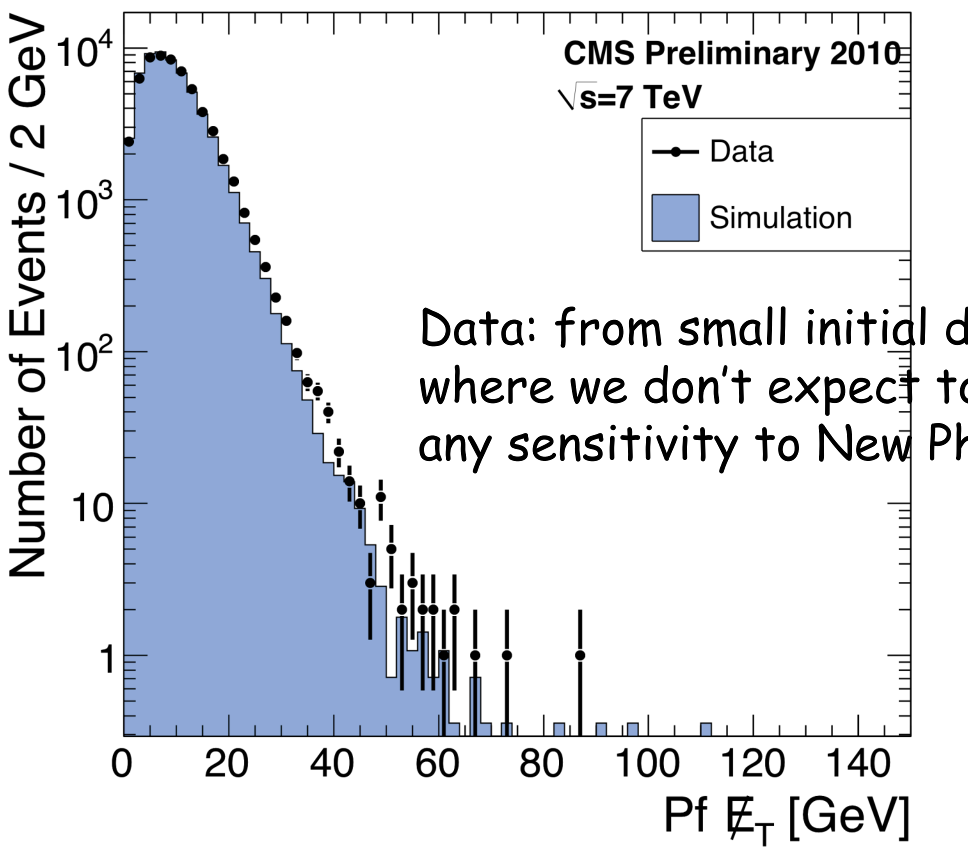
$$\vec{P}_T(\text{Dark1}) + \vec{P}_T(\text{Dark2}) = -\sum \vec{P}_T(\text{visible})$$

- Not trivial to distinguish it from a di-jet event with instrumental (fake) MET.

  Can we rely on calculations and detector simulations?

How well we can predict the tail of the MET distribution?

- Example: di-jet events



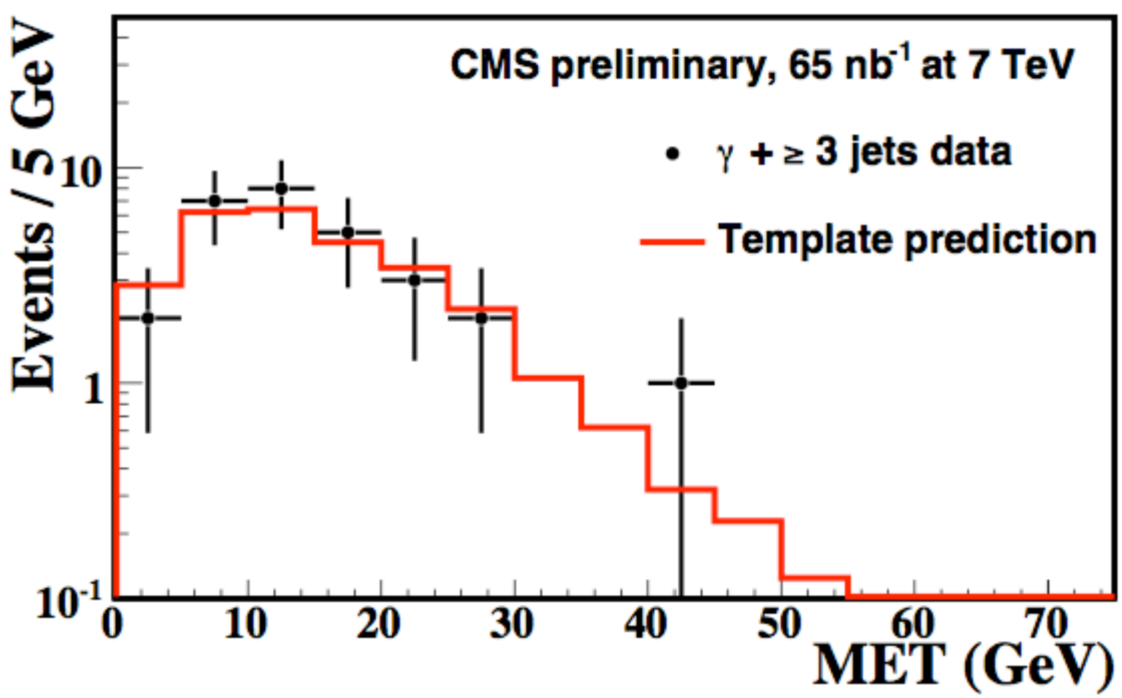
Data: from small initial data set, where we don't expect to have any sensitivity to New Physics

Simulation includes known detector effects. Agreement not too bad, but even small deviations in the tail are important!

Example: MET shape prediction from the data

Form templates from data to model (true and fake) MET, using Jet and γ+jet triggers

- Test template prediction in region relevant for SUSY searches

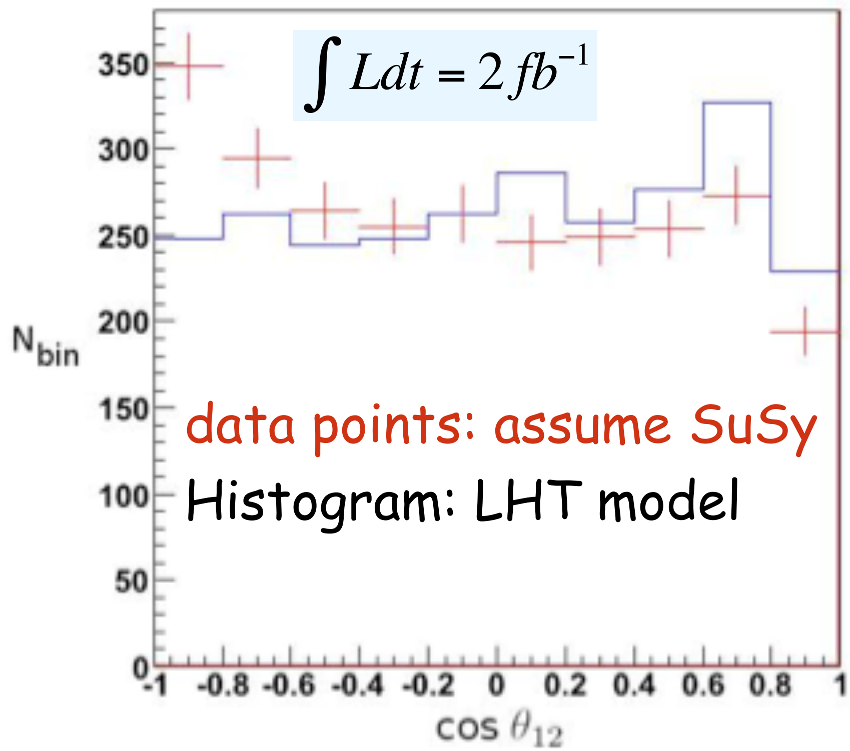


Model Discrimination

Perelstein, JT, et al Phys.Rev.D79:075024,2009

- How much data is needed to distinguish between two look-alike New Physics models?
  - For example: SuSy and Little Higgs
  - Same signature in the CMS detector, but different spin
  - jet angular correlations carry information
- using full detector simulation: at least 2 fb^{-1} needed to exclude wrong hypothesis

Example Distribution: cos Θ between 2 most energetic jets



Summary: Part 3

- We have begun to search for New Physics in all ways we can think of
  - Looking for mass peaks
  - Looking for disagreement with SM prediction, e.g. in MET shape
- Crucial: solid calibration of backgrounds using data

Outlook

- Our initial data sample, taken at half the design COM energy of 7 TeV, is large enough to gain a very solid understanding of the detector effects and response to Standard Candles
  - we are measuring top, W, Z cross sections, and much more
  - All detector components are working well

- We may even see first discrepancies with the SM, but will become much more sensitive with the next run and higher energy.

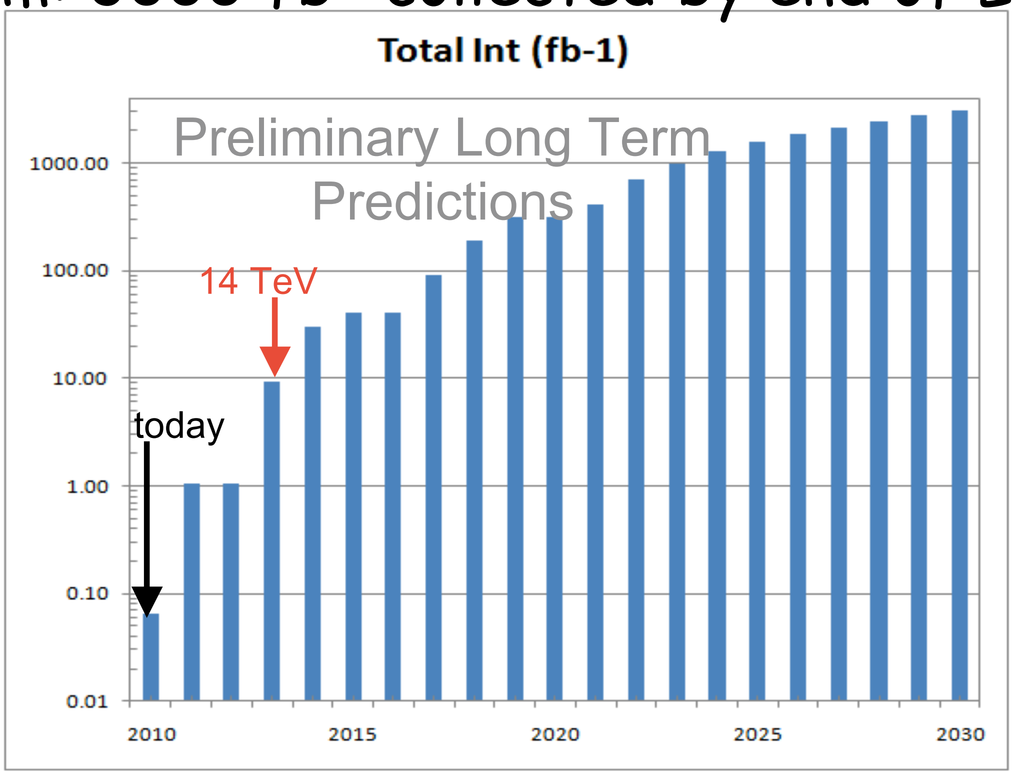
- Stay tuned for results to come out this winter!

LHC operations: the future

Short term: at least 1 fb^{-1} delivered by end of 2011

- Will go back to pp collisions early next year
- Energy will increase slightly next year, and will increase to 14 TeV in 2013

Longer Term: 3000 fb^{-1} collected by end of LHC life

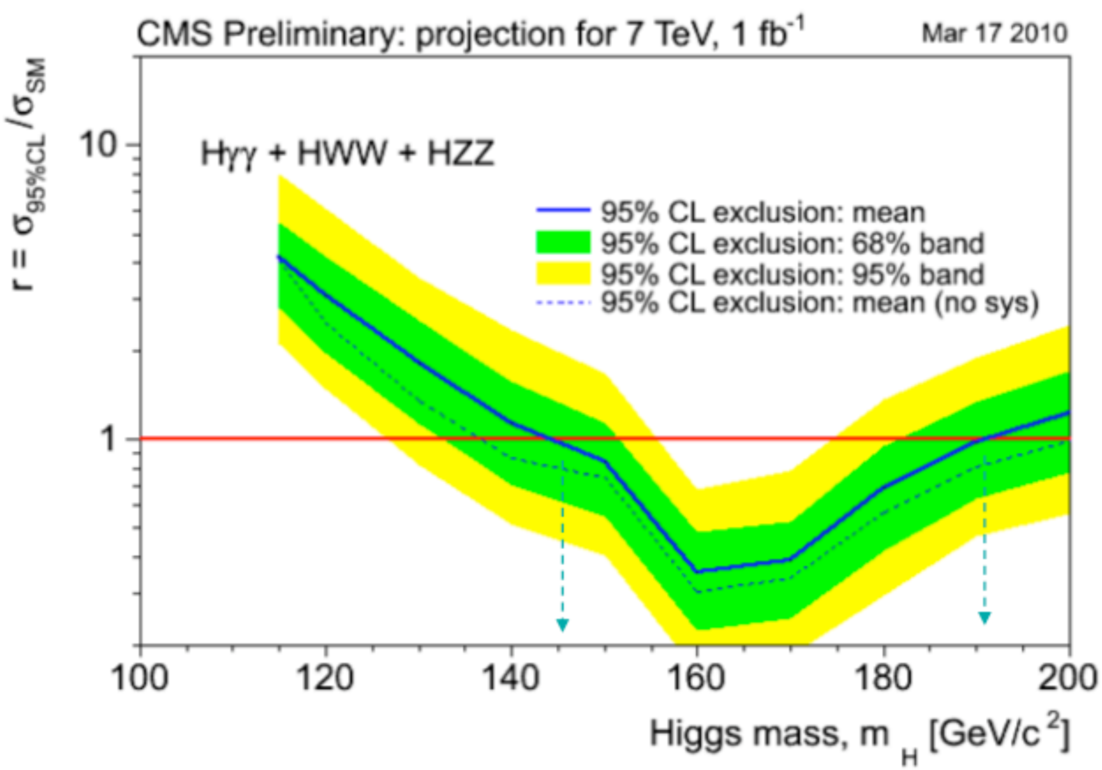


From S.Meyers, ICHEP

Backup Material

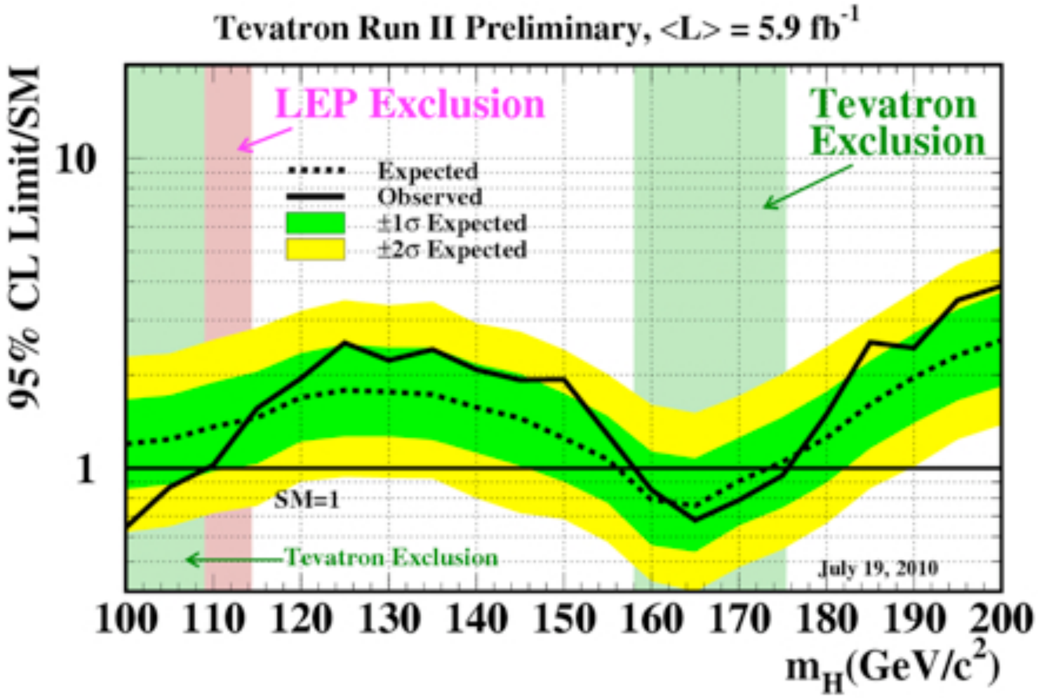
SM Higgs Prospects

- SM Higgs: combination of $\gamma\gamma$+WW+ZZ search channels
- With 7TeV, $1fb^{-1}$ by end of 2011
  - expected 95% CL exclusion range: 145-190 GeV
  - Conservative estimate, based on $\gamma\gamma$+WW+ZZ channels only

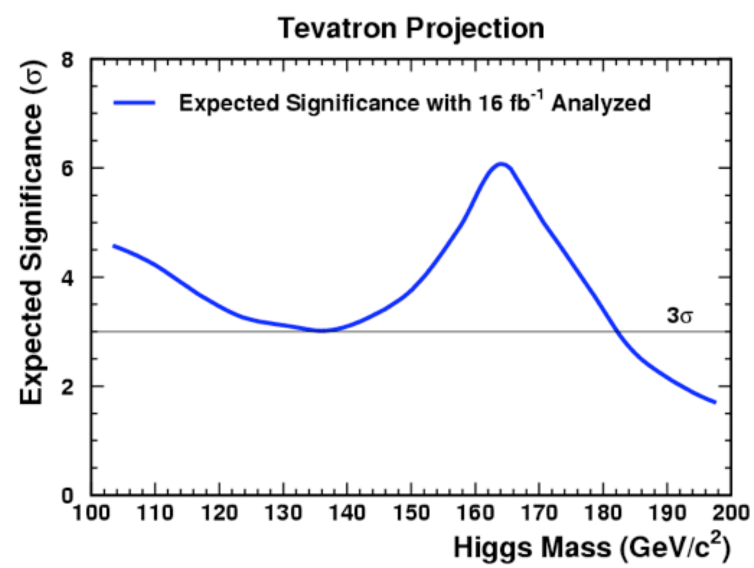


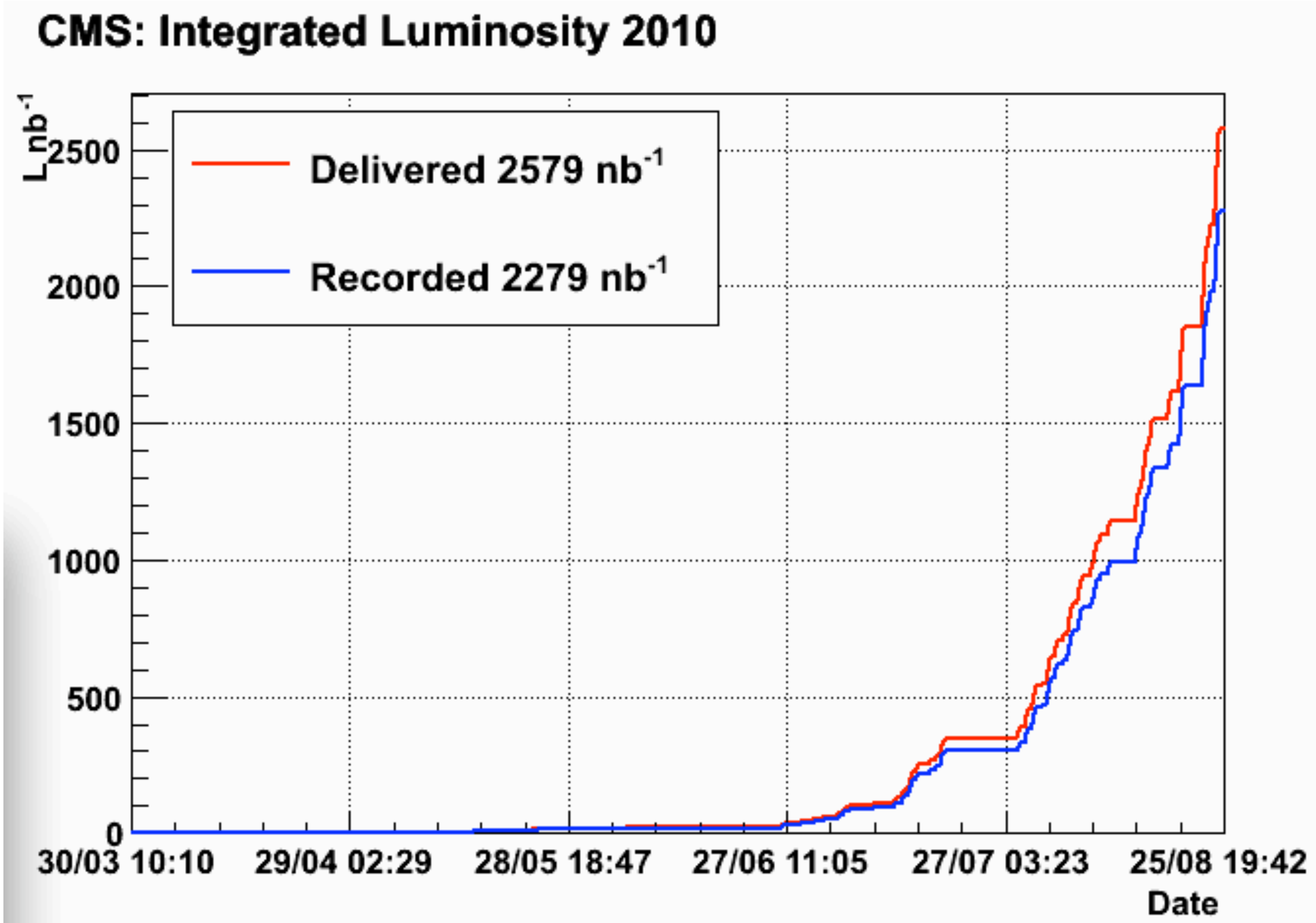
SM Higgs: Tevatron

Status as of Summer 2010 (have 2x more data)

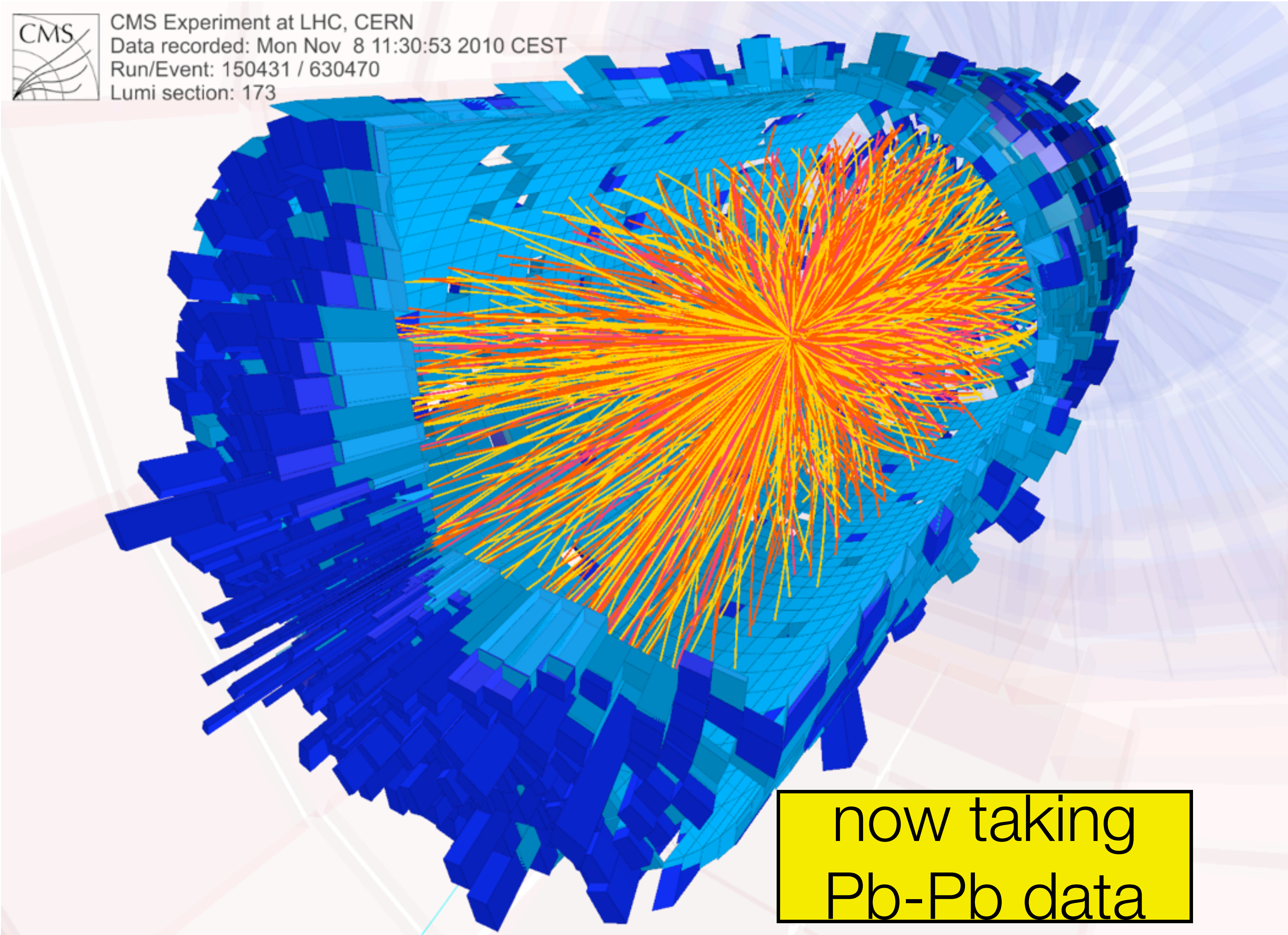


Tevatron extension through 2014:





CMS: Integrated Luminosity 2010
L nb-1
2500
2000
1500
1000
500
0
Delivered 2579 nb-1
Recorded 2279 nb-1
30/03 10:10
29/04 02:29
28/05 18:47
27/06 11:05
27/07 03:23
25/08 19:42
Date


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173
now taking
Pb-Pb data

What happens when two protons collide?

- Most of the times: not very much
- The protons might break up with most daughter particles going down the beampipe. *A* few (~50-100) particles with small transverse momentum (P_T) show up in the detector

Elements of Particle Detectors

- Momentum measurement of charged particles
  - path radius of charged particles in Magnetic Field
- Measure tracks of charged particles through charge deposition on silicon microstrips and silicon pixels (3D)
- Measure Energy (Calorimeters)
  - Through electromagnetic and hadronic interactions
- Identify muons from tracks and hits in muon drift chambers

Experimental Challenges

- High Interaction rate
  - data for only ~10 out of 1 million bunch crossings can be recorded.
  - Need to make quick decision if event should be recorded ("Trigger")
- 20 superimposed proton collisions in each bunch crossing
  - ~1000 tracks stream into detector every 25 ns
  - need high granularity of detector -> large number of readout channels
- High radiation levels

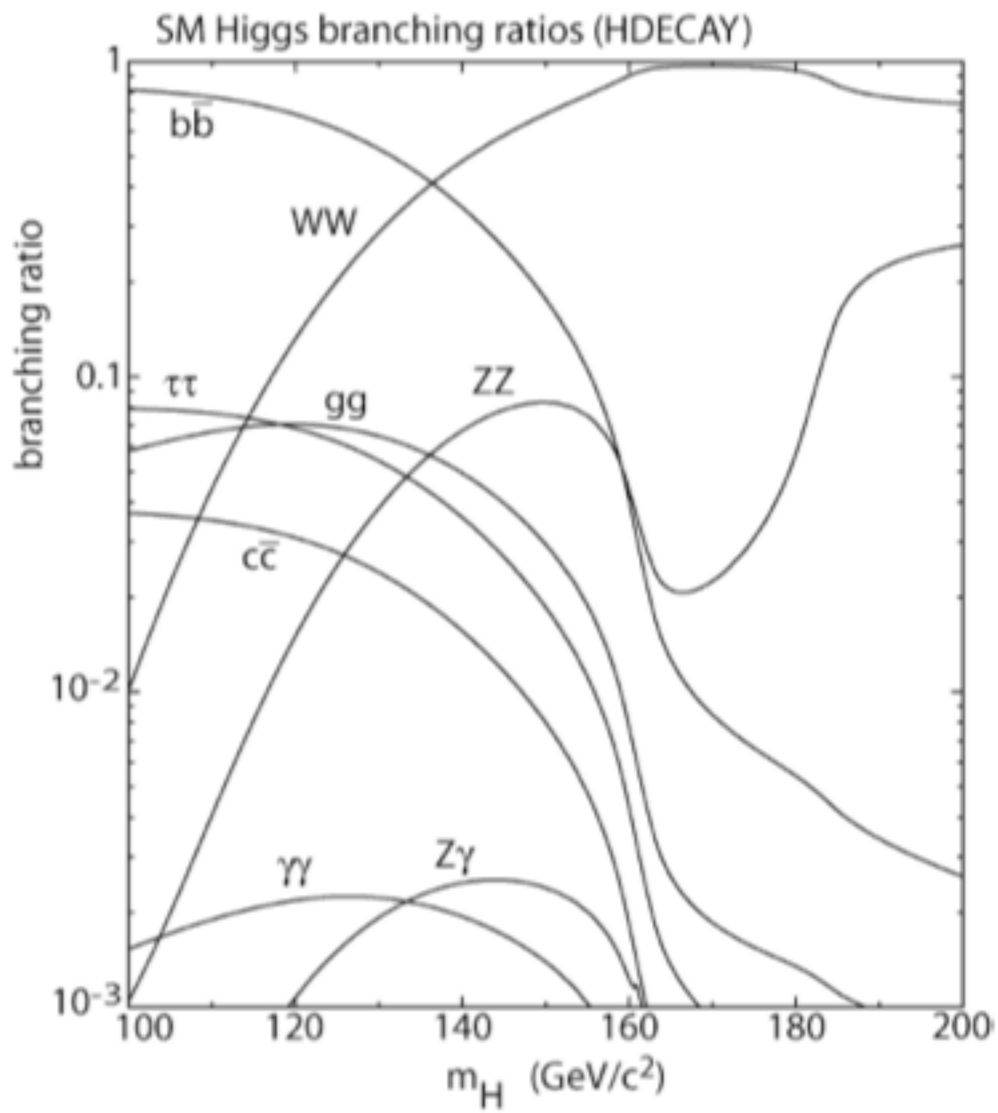
Higgs Production at LHC

- Proton Collision Center of Mass Energy is 7 TeV
- Probability to produce Higgs is ~1 in 10^{13}

- That's ~100 Higgs Bosons per day*
- detect them through their (stable) decay products

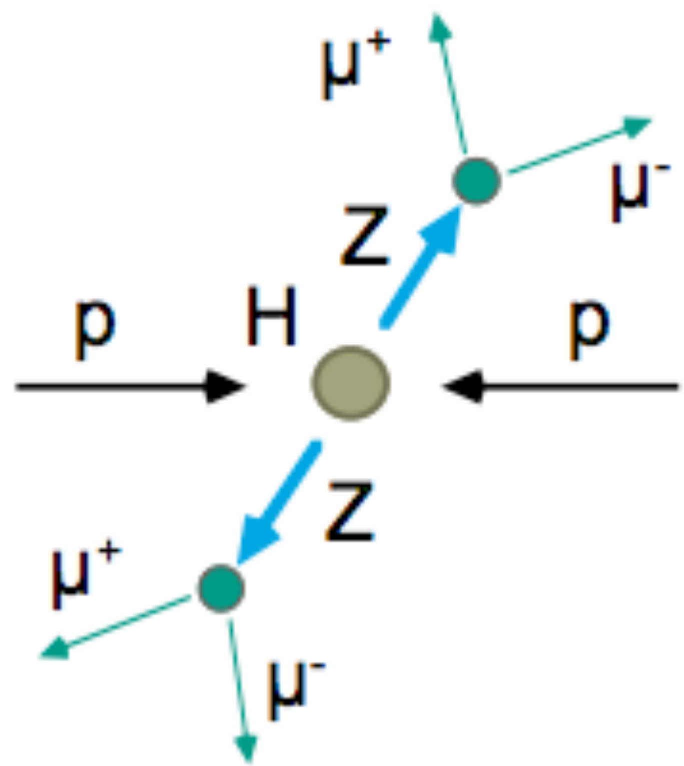
* Not necessarily recorded!

Higgs Decay Modes



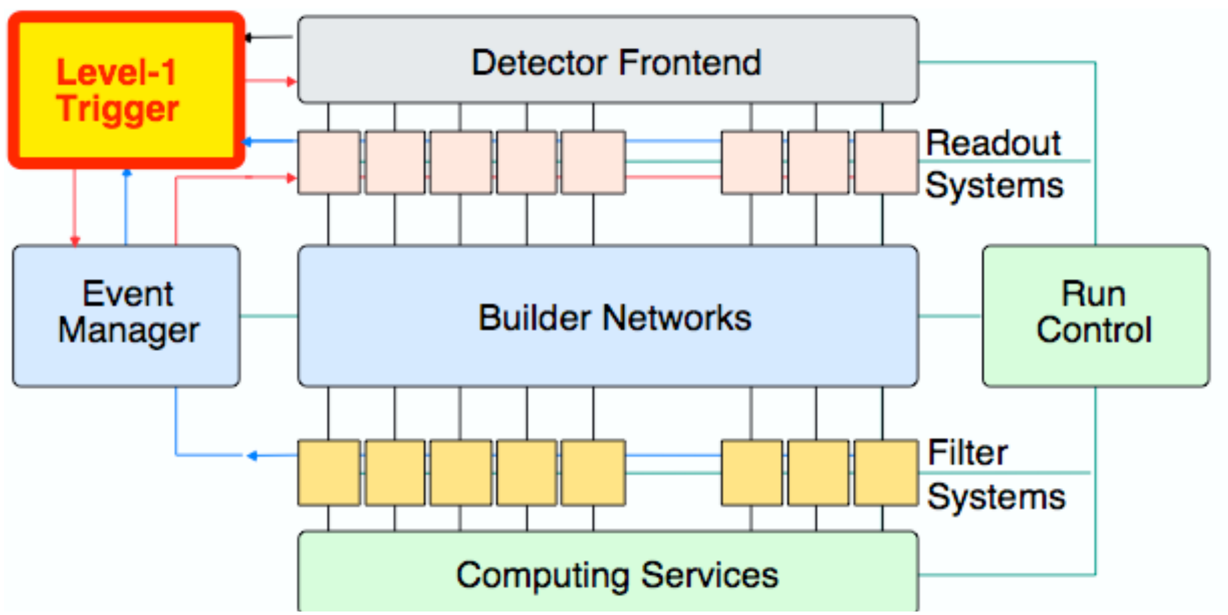
Higgs decays

- assuming m_H~ 200 GeV
- Can decay into two Z bosons, each of which decay into 2 muons,
- Final State: 4 muons



Computing Power

- Average event size 1Mbyte
- Data production: 1TByte/day
- 300 readout crates, 10000 electronics boards

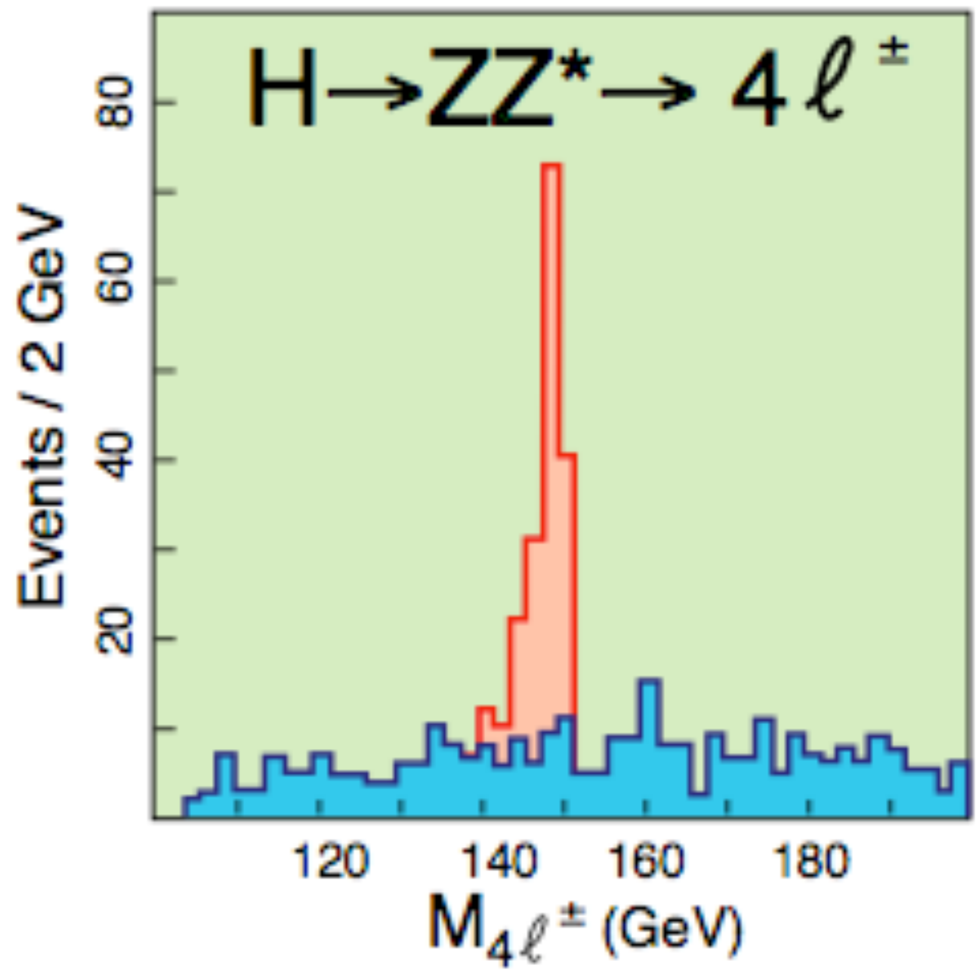


Have found 4 muons..are we done?

- Background from
  - 4 unrelated muons from other decays
  - Particles that look like muons

- Need other characteristics of $H\text{->}ZZ\text{->}4\mu$ to reject these and estimate remaining background events

- use energy measurement of the muons: they have to add up to to a Higgs mass

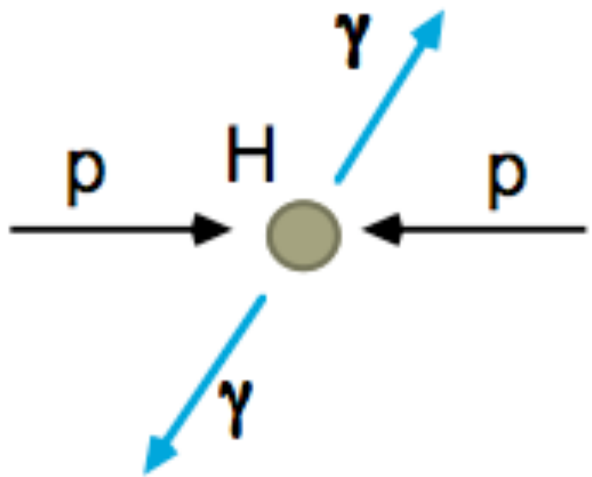


Red: simulated muons from Higgs
Blue: backgrounds from b, cosmics, …

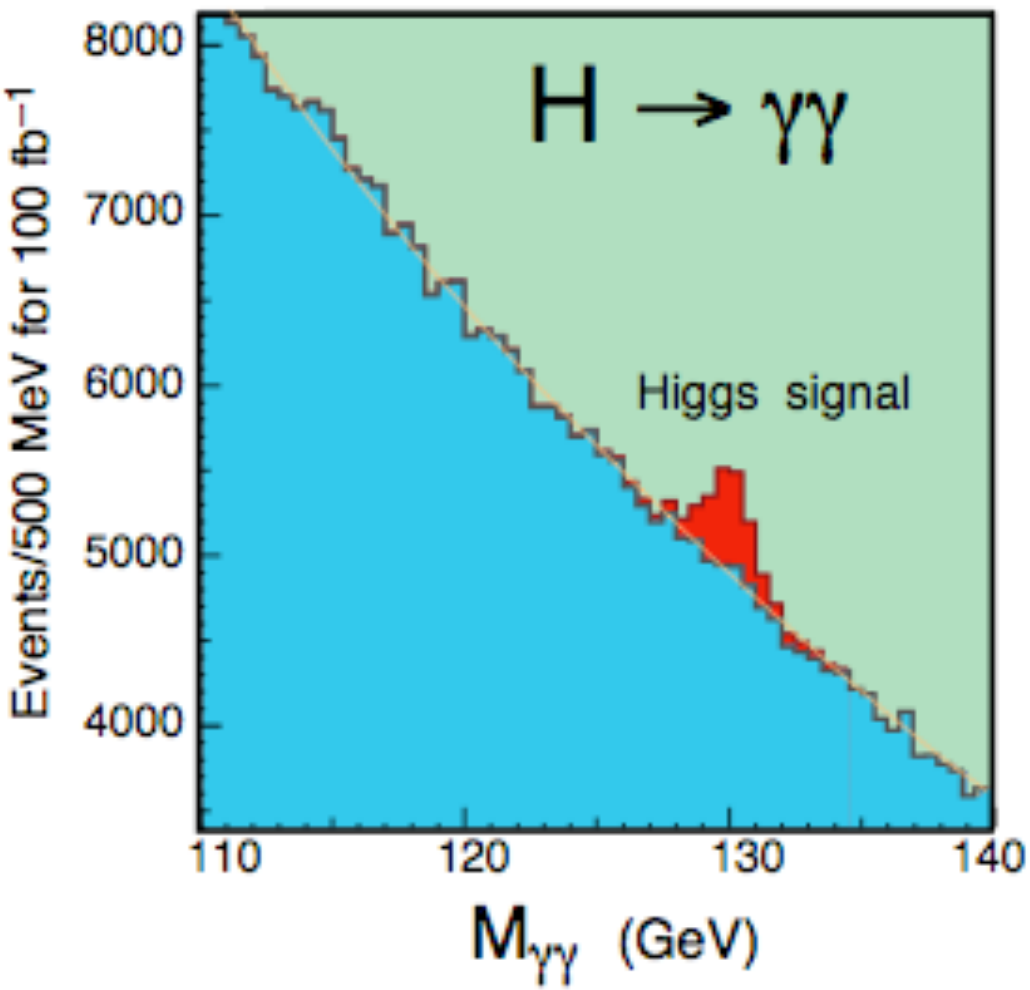
More realistically..

We know that Higgs mass is <200GeV

Most probable detection mode is H->$\gamma\gamma$



Very difficult measurement..

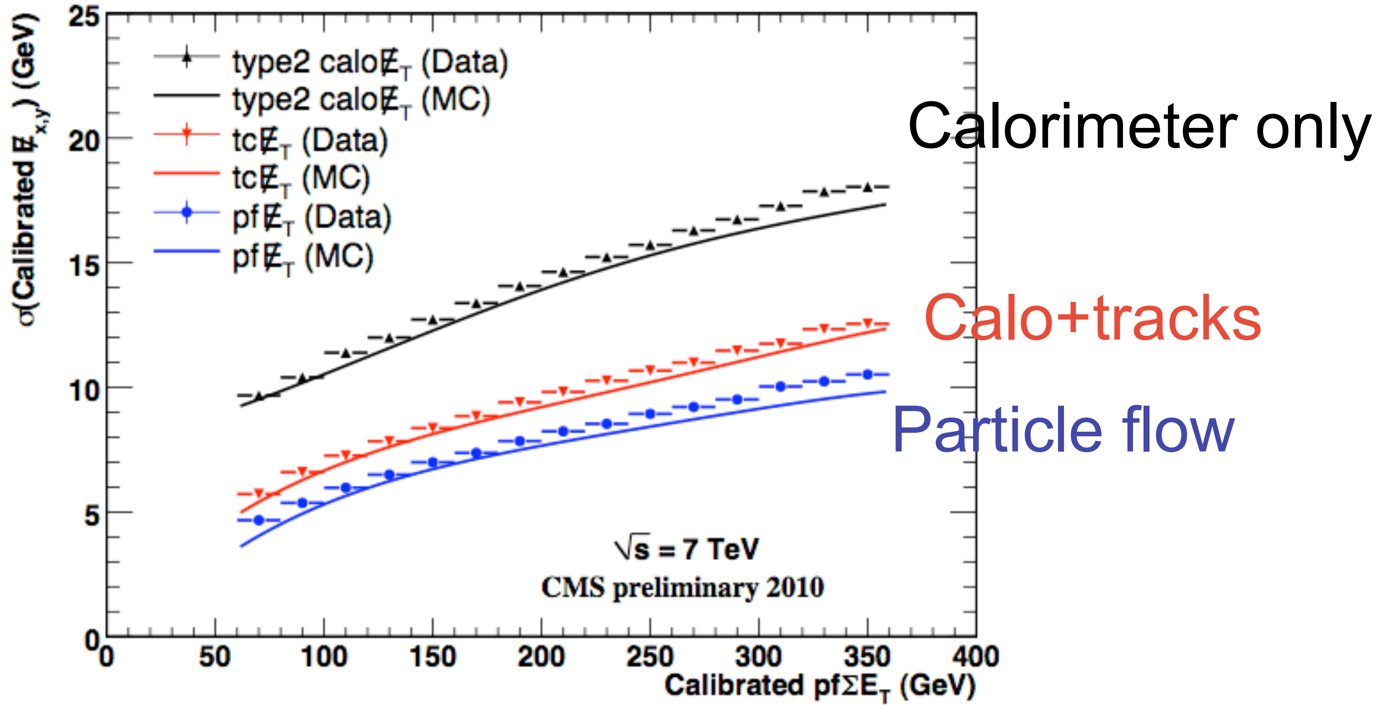


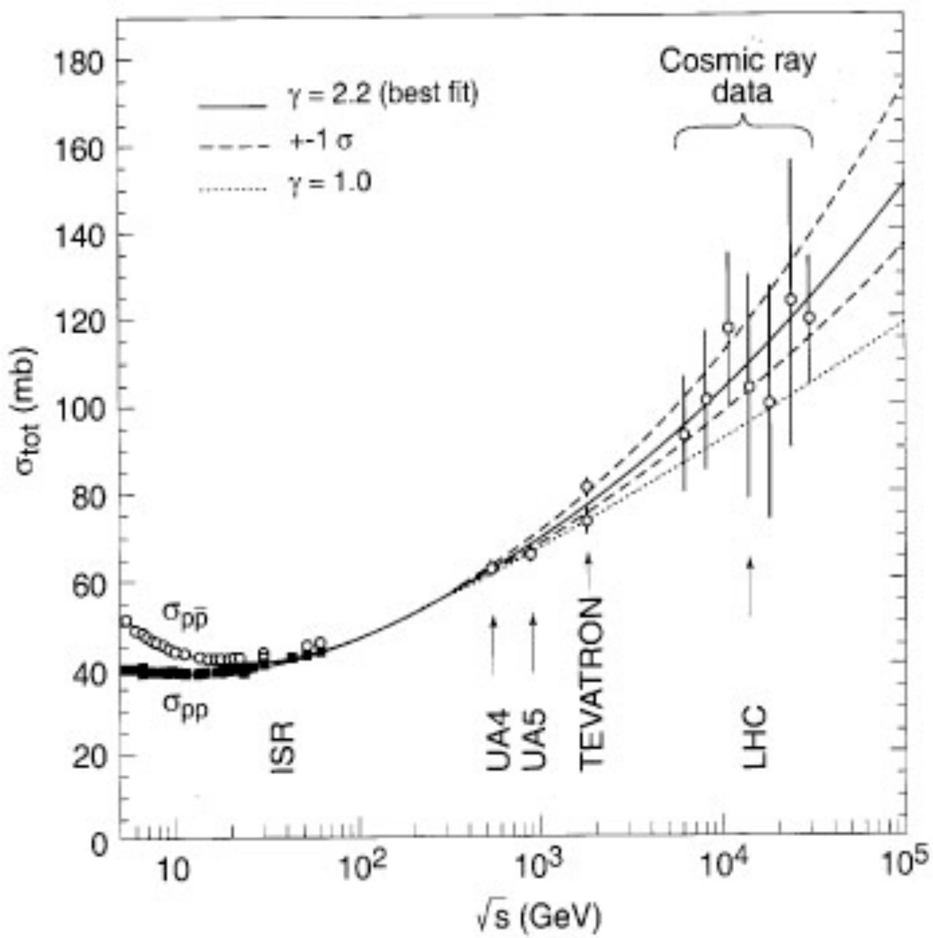
Summary

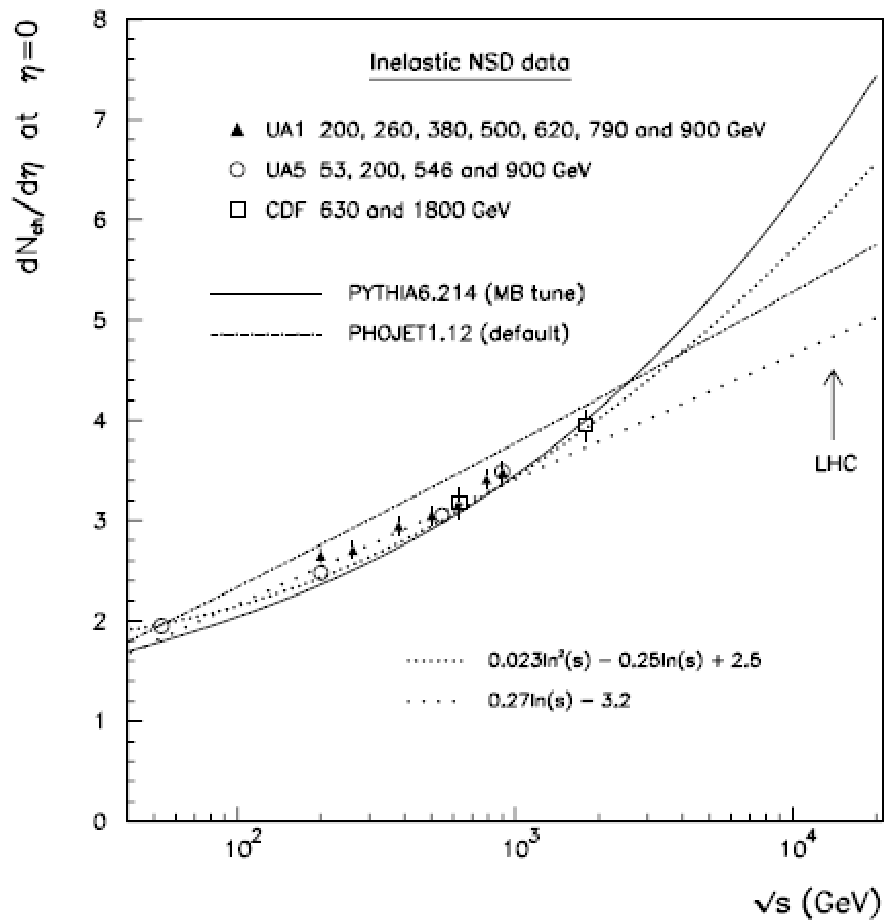
- We believe that we're just around the corner of a revolution in particle physics- the LHC is our tool for the next decades of experiments
- LHC has started taking data and is reaching the critical point where we could make discoveries any day now. Stay tuned!

ME_T resolution

- ME_T resolution due to noise, calorimeter response etc strongly depends on the associated sum of transverse energy, ΣE_T
- Very good (5-10 %) ME_T resolution, esp. for particle flow and track-corrected ME_T, as measured in minimum-bias data





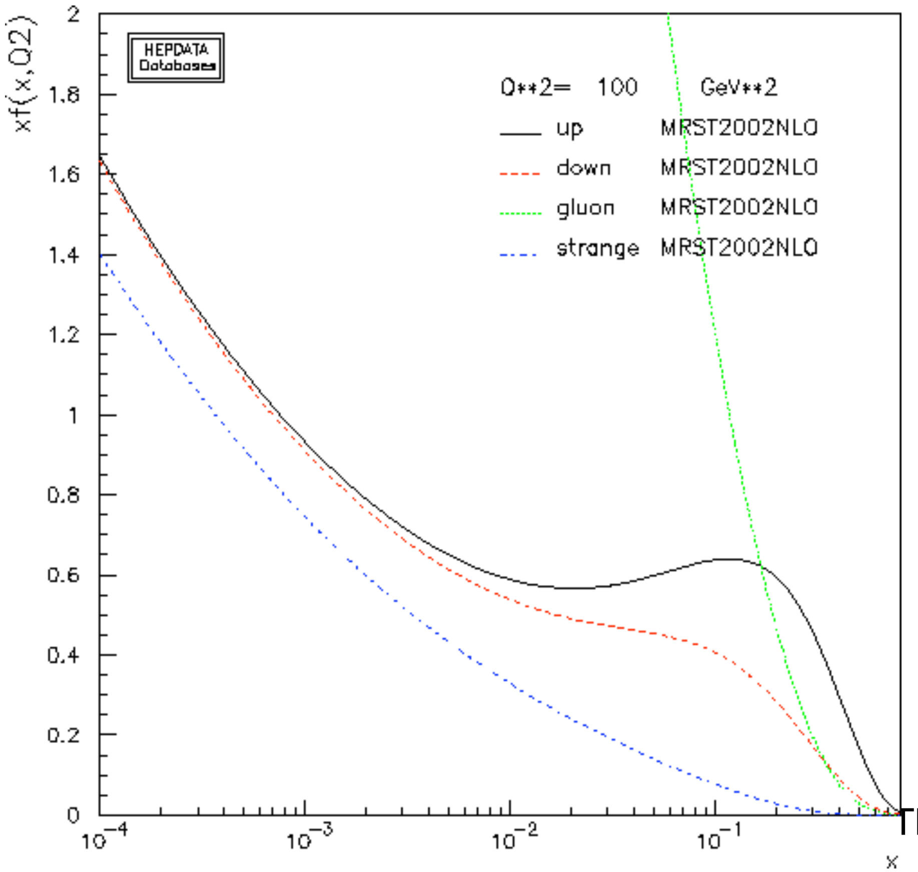


Physics 105B: Billiard ball scattering:

$\sigma=4\pi R^2$

$R_{proton} \sim 10^{-15}$ m → $\sigma(pp) \sim 10^{-29}$ m^2=100 mb

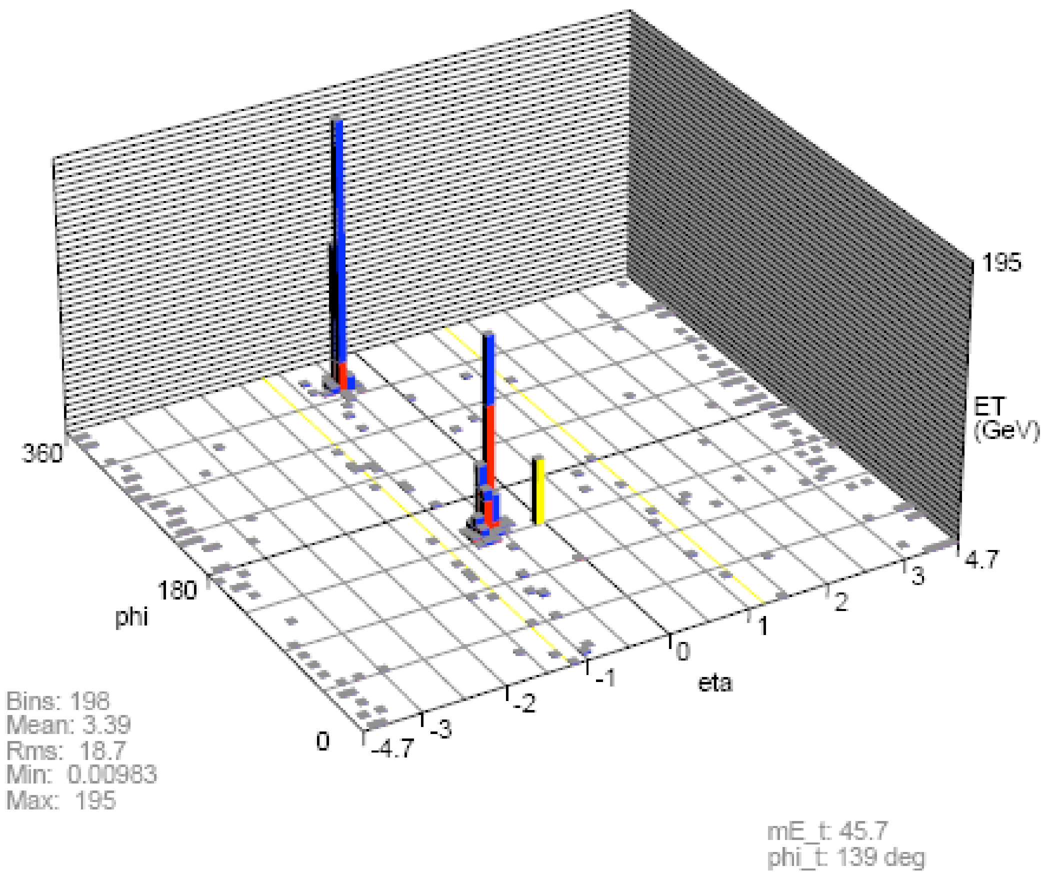
- Think of the LHC as a parton-parton collider
- <u>Broadband</u> collider. Partons in the proton can take any fraction of the proton momentum.
- In a probabilistic way, that we cannot calculate from first principles → measure it

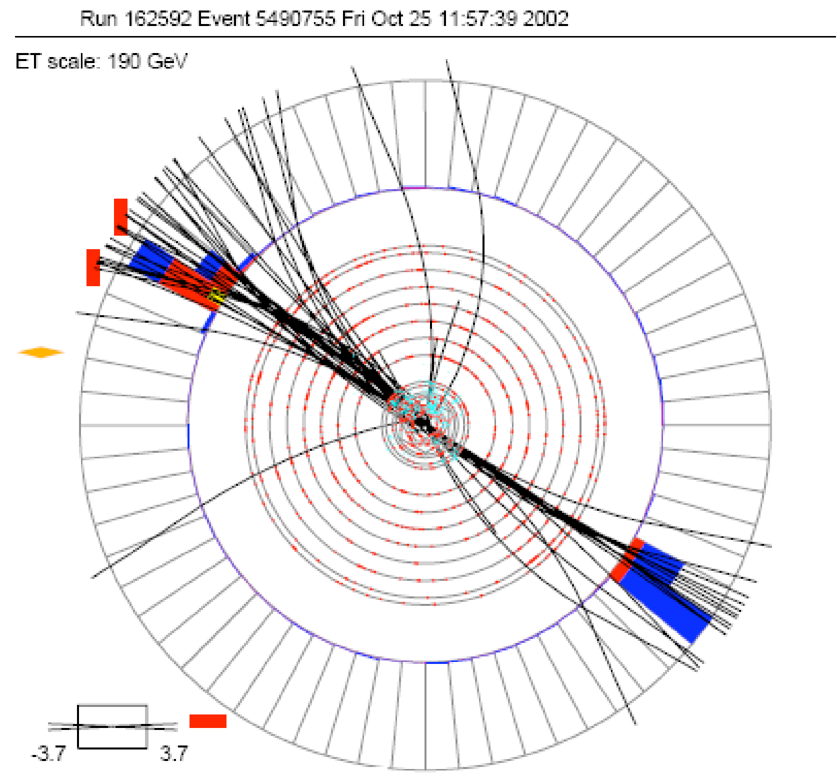


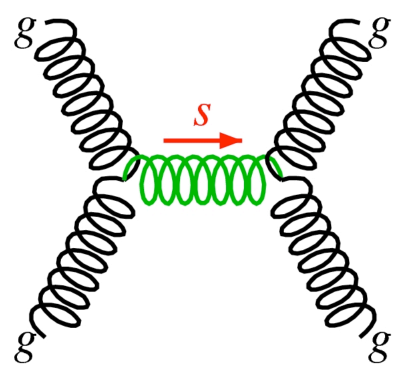
- $f_i(x)$ = prob of parton i having momentum $x*P_{proton}$
- Parton Distribution Function (pdf)

- Note that there are many many many gluons.
- LHC = gluon collider

A two jet event from D0:



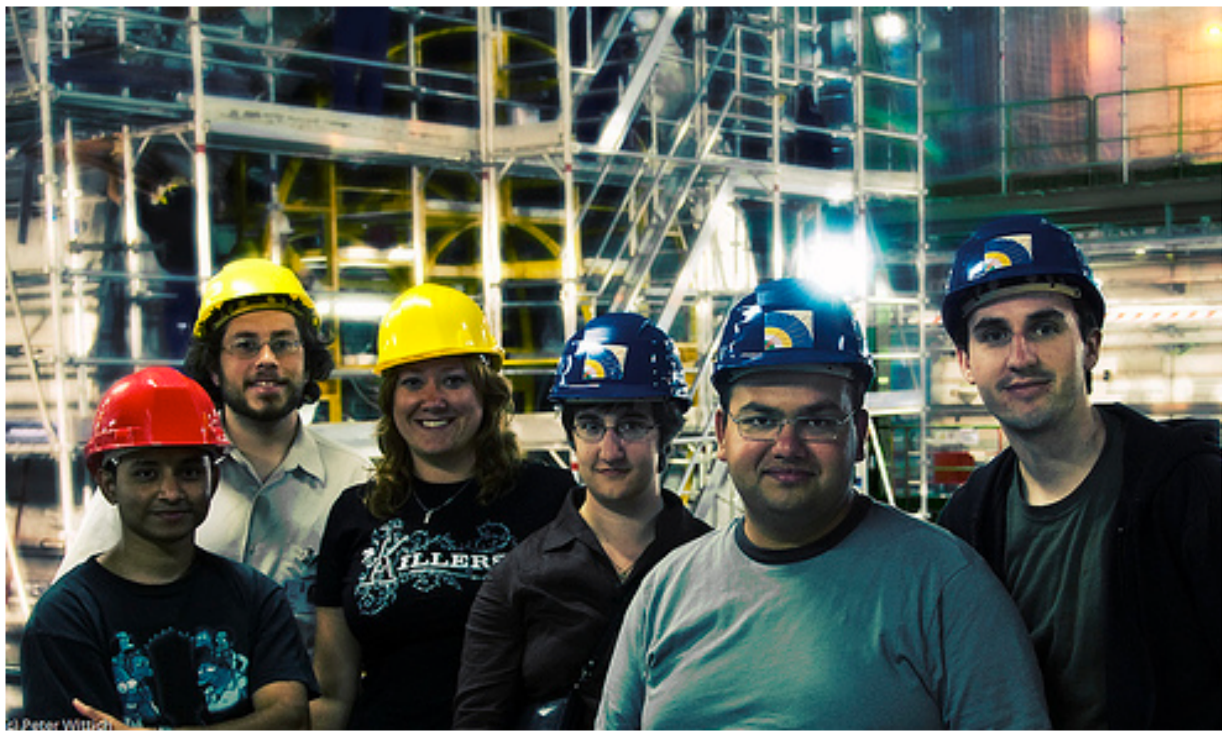




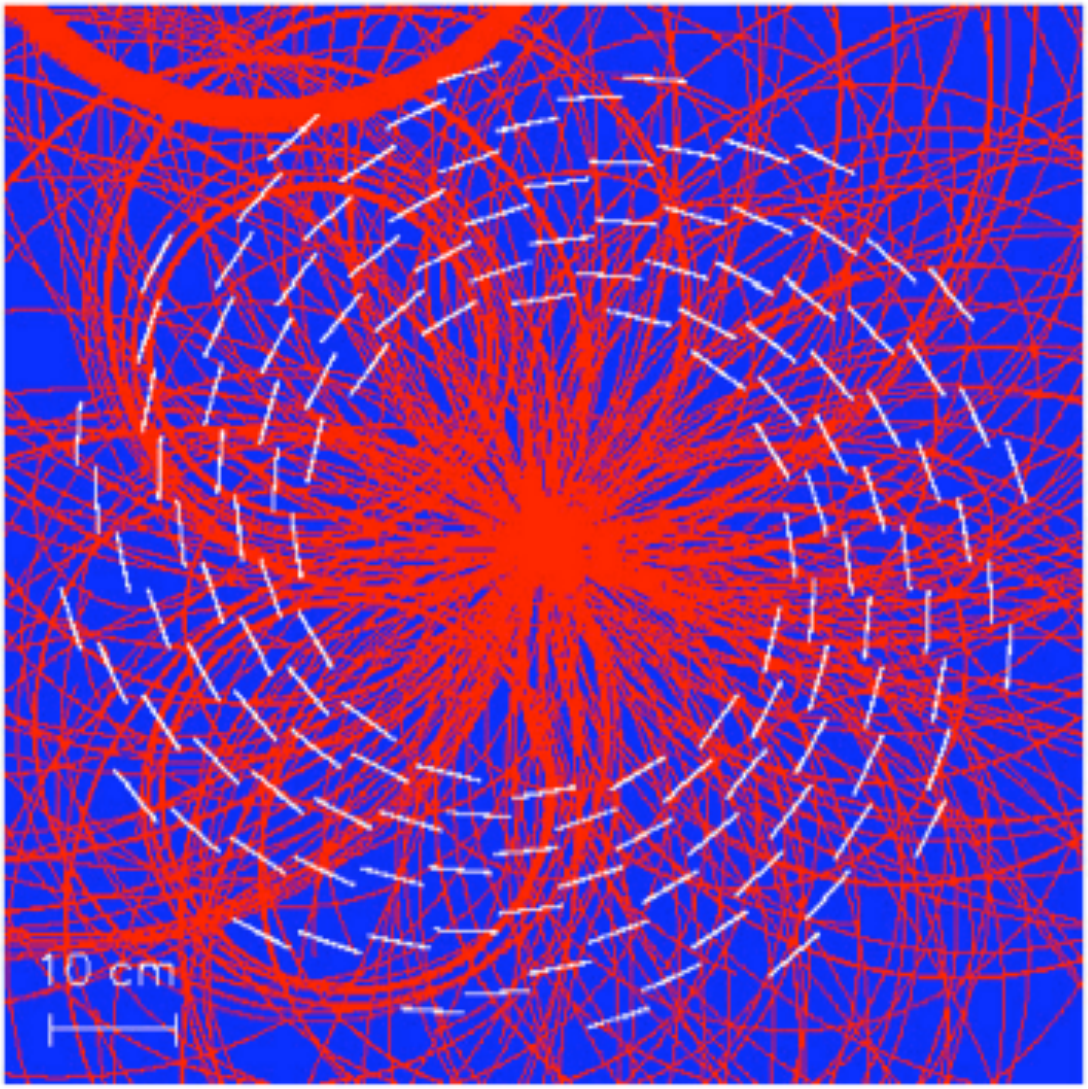
Two jets back-to-back in ϕ
Note: 45 GeV of MET

Cornell's experimental HEP group at the Large Hadron Collider

- 7 faculty, 7 postdocs, 8 graduate students and 10 undergraduate students, working at CERN and CU
- Our contribution to the Compact Muon Solenoid (CMS) Experiment
  - Software
  - Pixel Detector
  - Trigger
  - Calorimeter
  - Physics analysis
  - Tracker Upgrade

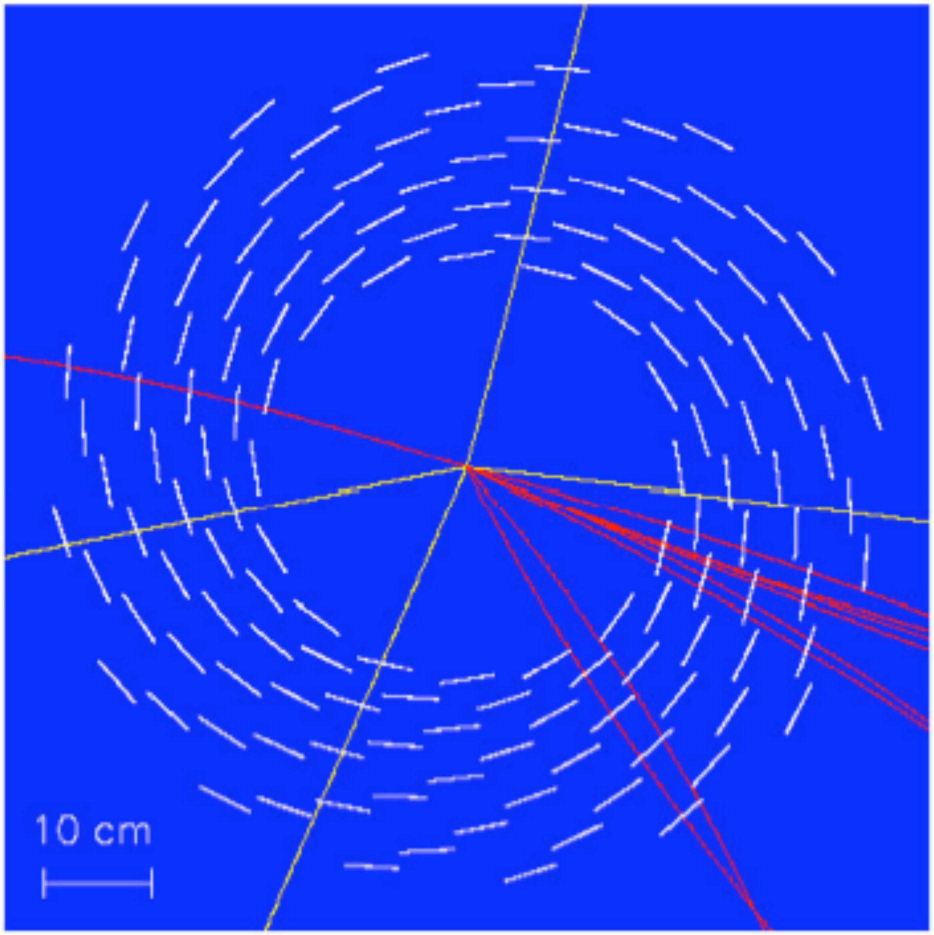


18 superimposed pp collisions,
as seen by internal part of CMS silicon central tracker.
Among them 4 muons from a higgs decay.



Reconstructed tracks of $p_t > 2$ GeV.

Among them well visible 4 muons from the higgs decay.

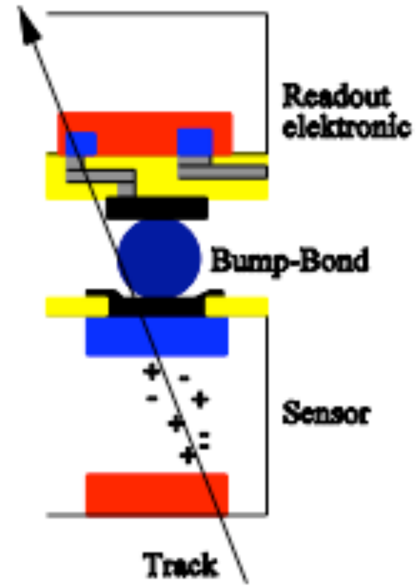


The solution is possible if detector occupancy ~1%

→ microstrip area ~1mm^2

→ >10^7 readout channels

CMS pixel detector

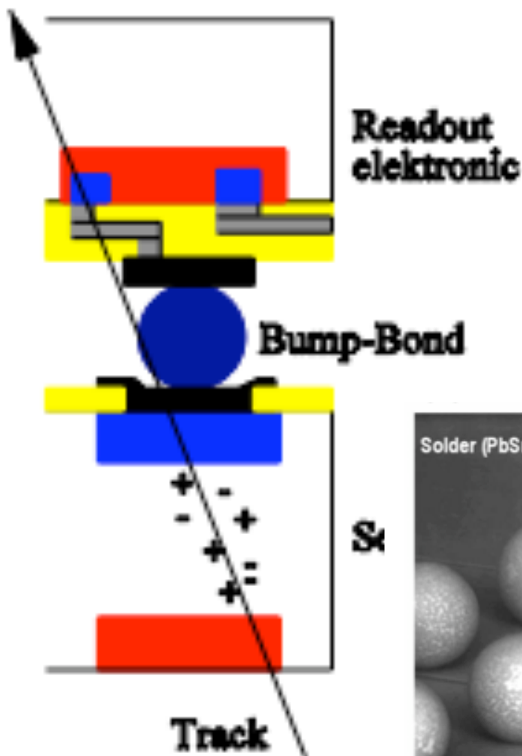


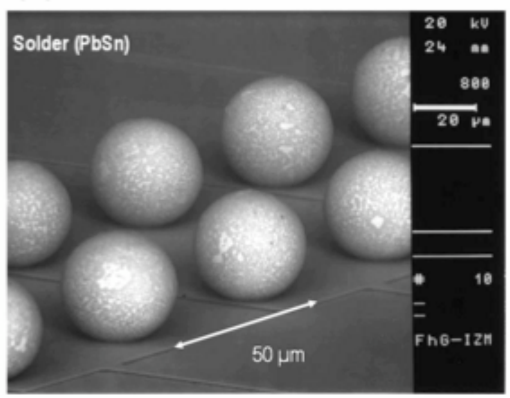
- "Hybrid active pixels". Presently only technology for LHC application
- Need pixels because of huge track multiplicity
  - Readout chip has same pixelation as sensor, bump-bonded onto sensor
  - pixel size limited by readout circuit and heat/power dissipation limit (150x150μm)
  - 2% X0 per layer (3 pixel layers 4, 7, 11cm, material budget driven by COOLING)
  - Readout chip:0.25μ CMOS technology
    - rad hard "Complemetary metal oxide semiconductor", Field effect Transistor circuit (fast)

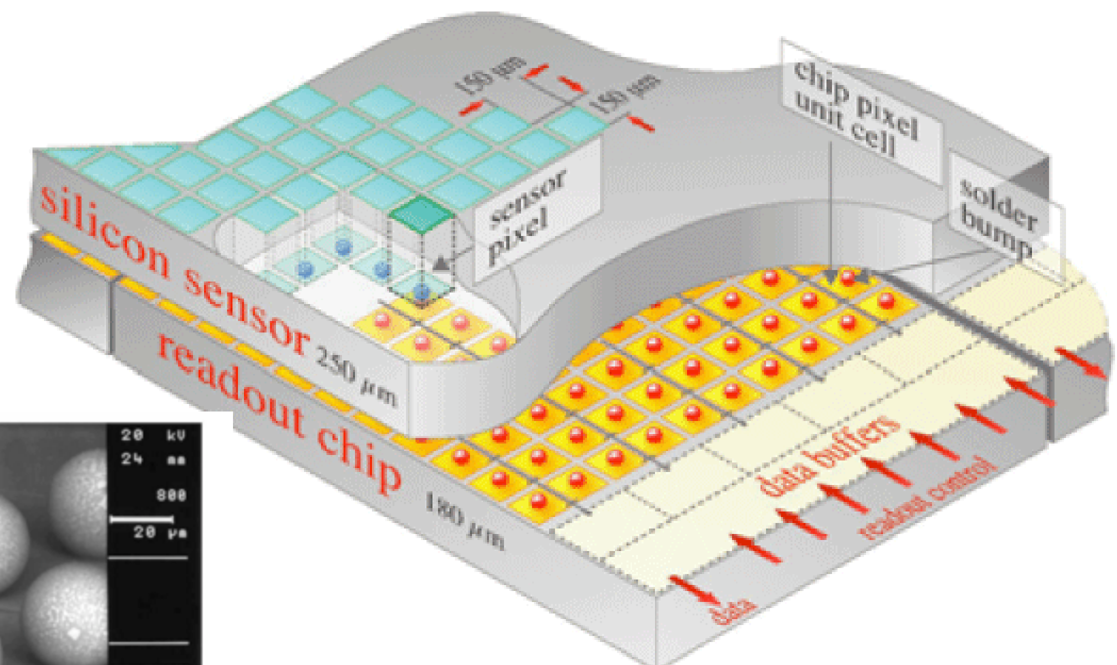
- Vertexing and track reconstruction in a harsh environment!
  - Radiation:
    - dose: $3x10^{14}pcm^{-2}yr$
  - Rate
    - up to $20MHz/cm^2$ of particles
- For b-tagging, vertex reconstruction: 100GeV B jet, flight path ~100μ
  - need ~20 μ resolution, 3D space point
  - All hit information has to be stored until L1 decision
  - Trigger latency: 3μs, 10Tbit/sec stored and transferred by ROC
- Also want low cost, easy cooling & cabling, low material budget

CMS pixel detector

- 66 Million Pixels, 1m^2 of silicon
- pixel size limited by readout circuit and heat/power dissipation limit (150x150μm)







Higgs Mechanism

- Introduce weak doublet spin 0 "higgs field" H with classical potential

$$V = m_H^2 \,|\, H \,|^2 + \lambda \,|\, H \,|^4$$

- H acquires non-vanishing vacuum-expectation value if Higgs mass $m_H^2 < 0$

$$\langle H \rangle = \sqrt{\frac{-m_H^2}{2\lambda}}$$

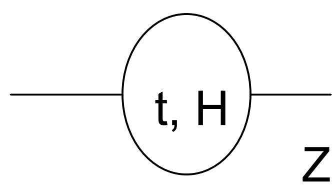
- If superpartners too heavy introduce a mini-hierarchy problem (Δm_H proportional to m_S^2)

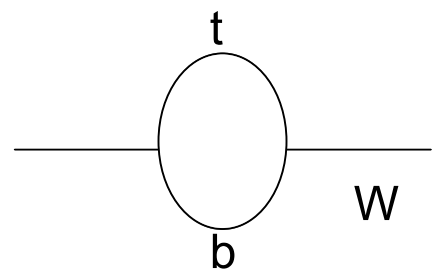
$$\Delta m_H = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

Higgs mass constraints

"Indirect":

- Top and Higgs loops contribute to W and Z mass





- We have measured W and Z masses with high precision, can indirectly constrain Higgs mass

$m_H^{SM} < 200$ GeV

Direct searches in current experiments:

$m_H^{SM} > 115$ GeV

How are the masses generated: Electroweak Symmetry Breaking

- High energy: electromagnetic and weak forces are unified, i.e. equal couplings; gauge bosons mass-less
- Observation: M_γ=0 but M_Z,M_W ~100 GeV
- How does this difference arise?

The Higgs Field

- Introduce Spin 0 Higgs field
- Introduce classical potential for Higgs field such that at minimum Higgs acquires "vacuum expectation value" $\langle H \rangle \neq 0$
- Higgs is electrically neutral (doesn't couple to photons) but weakly charged
- "Spontaneous symmetry breaking"