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

The first year at the Large Hadron Collider

Cornell Physics Colloquium
September 19th, 2011
Julia Thom

The Large Hadron Collider

- 14 TeV proton-proton collider (currently at 7 TeV)
  - 1 TeV = 10^{12} eV, factor of 7 more energy than the Tevatron
  - probe length scale ~ 10^{-19}m, around 1/10000 of the proton radius

- 9300 superconducting magnets (1232 dipoles)
  - 60 tons of liquid helium, 11,000 tons of liquid nitrogen
  - energy stored in magnets = 10 GJ

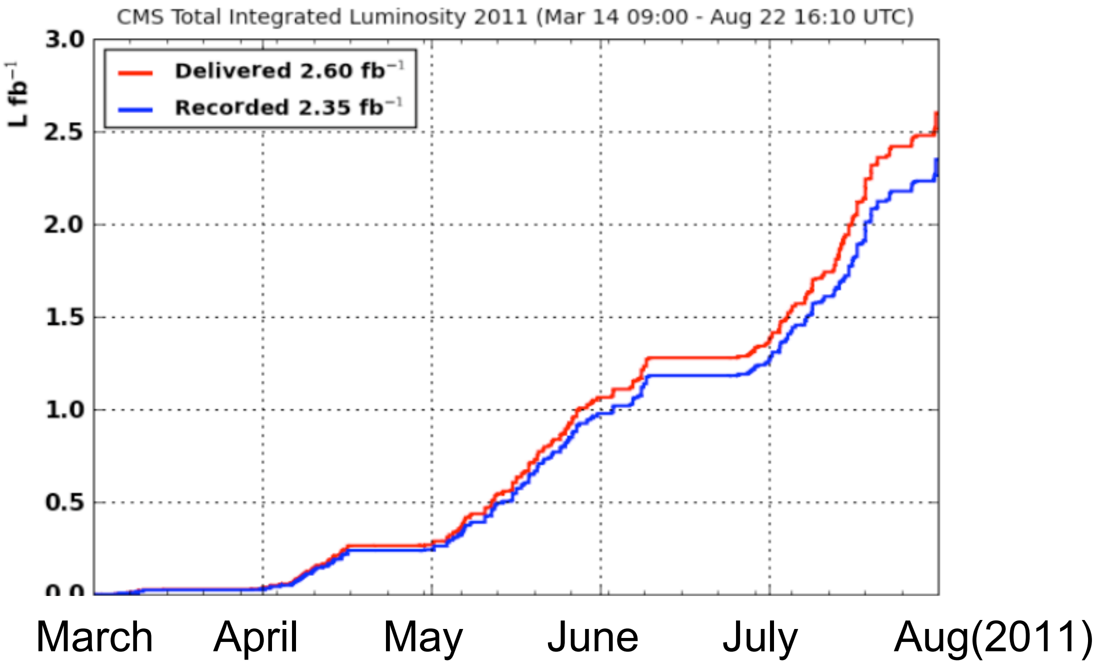
- There are 2808 "bunches" of protons in each beam, (currently 1380)
  - 10^{11} protons per bunch

- When brought into collision the transverse size of the bunches is of order 10 μm (currently ~18μm)
  - O(10) collisions per crossing
  - crossing occurs every 50ns (20 MHz)

LHC performance

The LHC performance is exceeding all expectations!

- measured in "integrated luminosity" (= number of collisions per unit area per unit time)
- Have ~3 fb^{-1} (~half of the Tevatron data set)
- The sensitivity of most LHC studies is now far superior to the Tevatron



LHC: the Superconducting
Proton Accelerator and Collider
installed in a 27km circumference underground
tunnel (tunnel cross-section diameter 4m) at
CERN

LHC Physics

Results from the LHC have been eagerly awaited for decades, because it allows us to probe a new energy scale. Exciting for many reasons:

- The Higgs mechanism, which breaks electroweak symmetry in our currently accepted model, implies the existence of a Higgs boson with mass < 1TeV

- A big problem ("Hierarchy Problem"): Higgs mass receives radiative corrections due to quantum loops, proportional to the largest scale in the theory (Planck Mass, 10^{19} GeV)

- "New Physics" must exist at the TeV scale to solve this problem

The "New Physics"

Among the suggested solutions to the Hierarchy problem:

- new weakly interacting particles and symmetries that cancel quadratic loops
- introduction of extra spacial dimensions
- and more…

all of them predict a spectrum of new particles at the TeV-scale, including a dark matter candidate

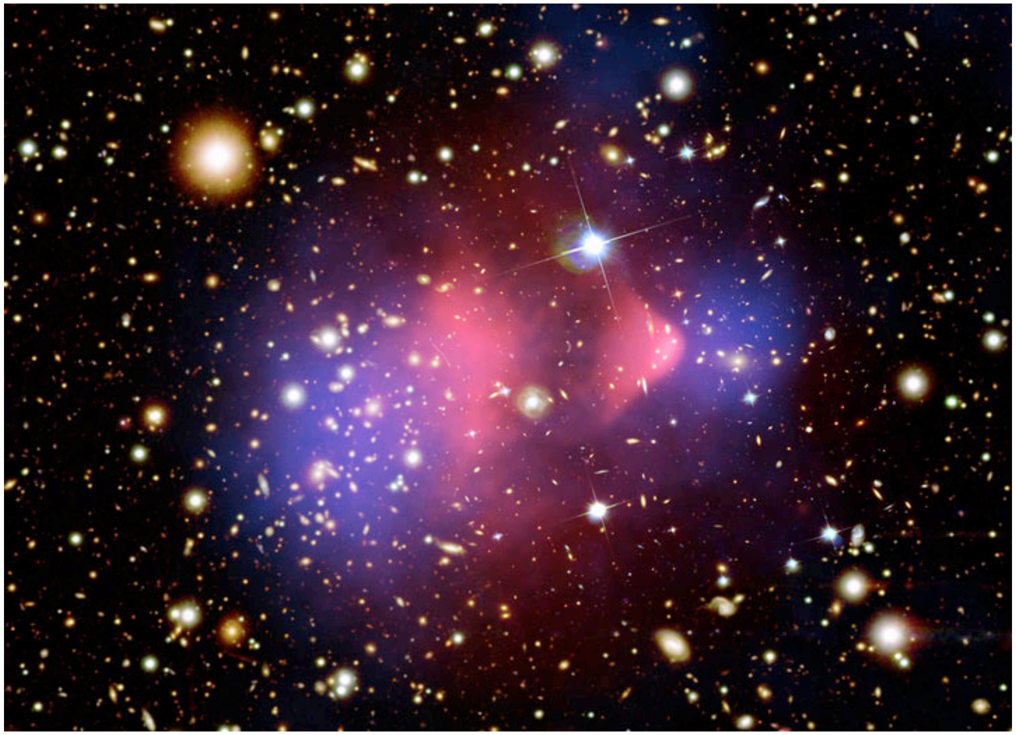
Study on how to distinguish them: Perelstein, JT, et al Phys.Rev.D79:075024,2009

More on Dark Matter

One more reason we believe in "New Physics": massive cold dark matter (DM) is implied by a host of data but cannot be explained by our current model.

A neutral, weakly interacting particle of mass ~100 GeV can account for the correct DM abundance

➔"WIMP miracle"

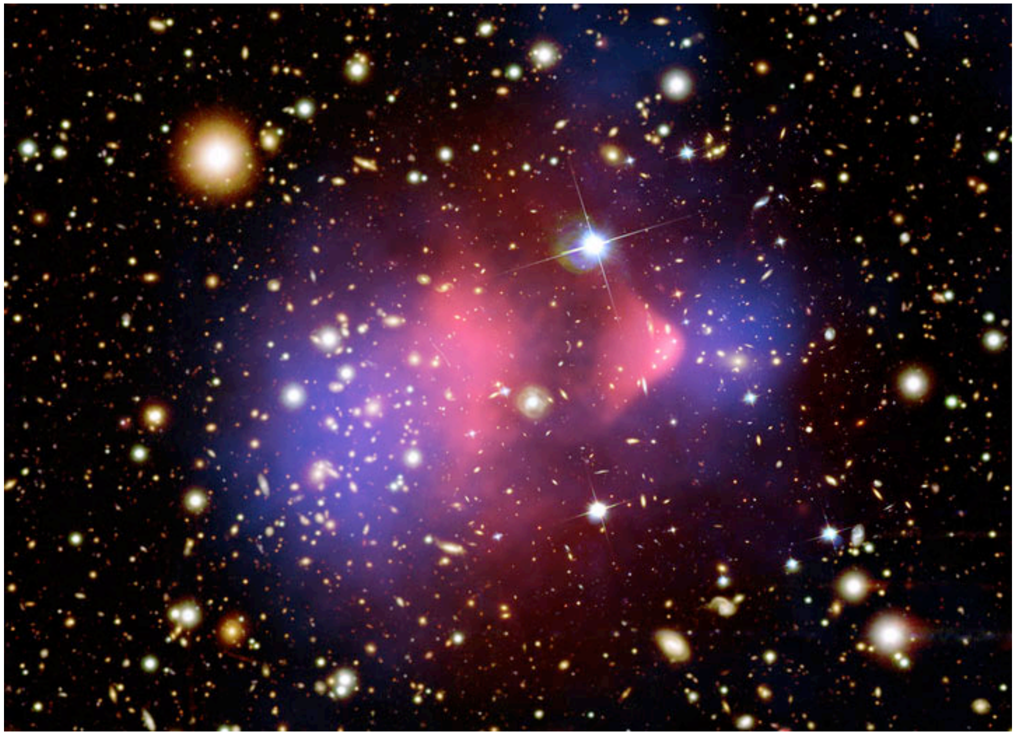


Bullet cluster, Chandra X-ray Observatory

More on Dark Matter

One more reason we believe in “New Physics”: massive cold dark matter (DM) is implied by a host of data but cannot be explained by our current model.

But DM could be much more complicated: many particles? Or non-WIMP, e.g. axions, ..



Bullet cluster, Chandra X-ray Observatory

Supersymmetry (SUSY)

- Symmetry between fermions and bosons
  - predicts partner particles for all known particles, with identical quantum numbers but different spin
- If this is true the superpartners must be heavier than the ordinary particles
  - But cannot be too heavy- expected at ~TeV scale
- Assume "matter parity"-
  - protects against proton decay
  - superpartners must be produced in pairs
  - if exact, lightest SUSY particle ("LSP") is stable
  - neutral LSP- perfect dark matter candidate!

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

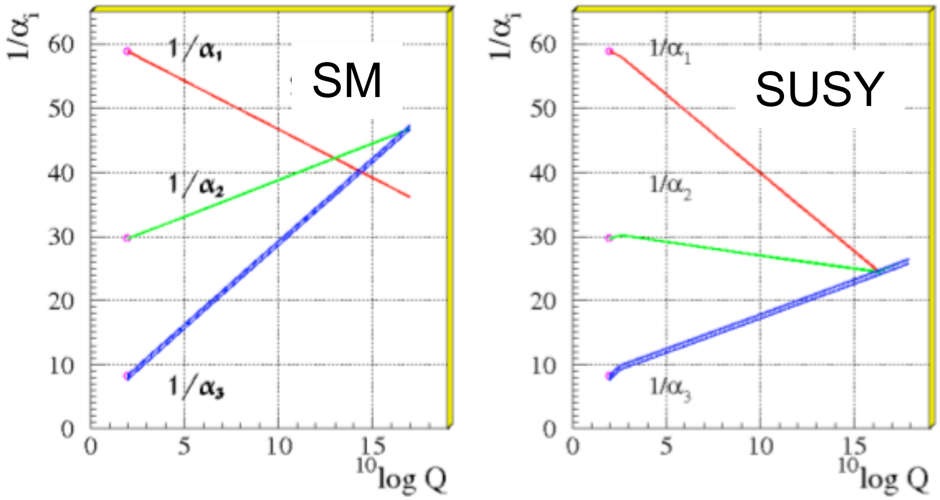
Matter Particles

A linear combination of several superpartners forms the neutralino χ^0, the lightest Superparticle (LSP) and Dark Matter candidate

Reasons to favor SUSY

many true believers in SUSY because it

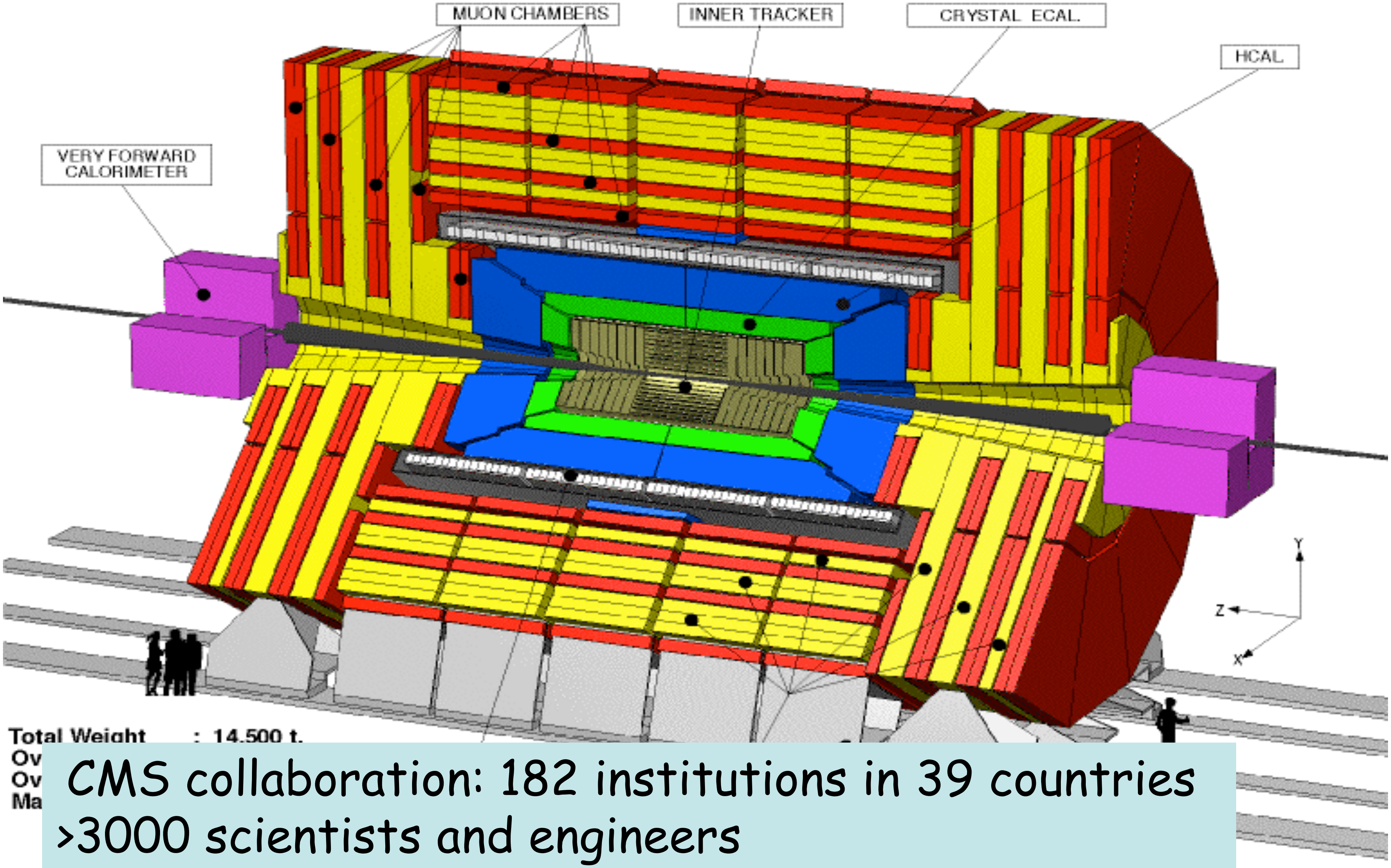
- unifies treatment of matter with force carriers
- tames divergences, allows for unification of gauge couplings
- provides a suitable WIMP
- making SUSY a local symmetry, one can obtain General Relativity (Supergravity)



"would be a shame if Nature didn't take advantage of it"

The Compact Muon Solenoid (CMS) and how we use it to detect particle decays

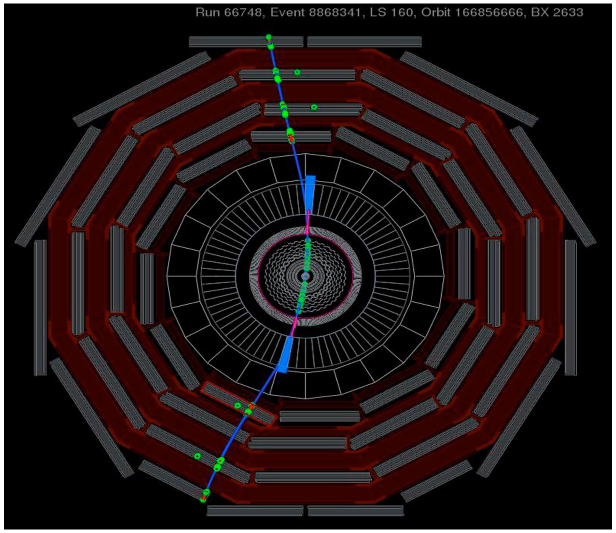
The Compact Muon Solenoid



CMS collaboration: 182 institutions in 39 countries
>3000 scientists and engineers
~ 2000 authors (including students)

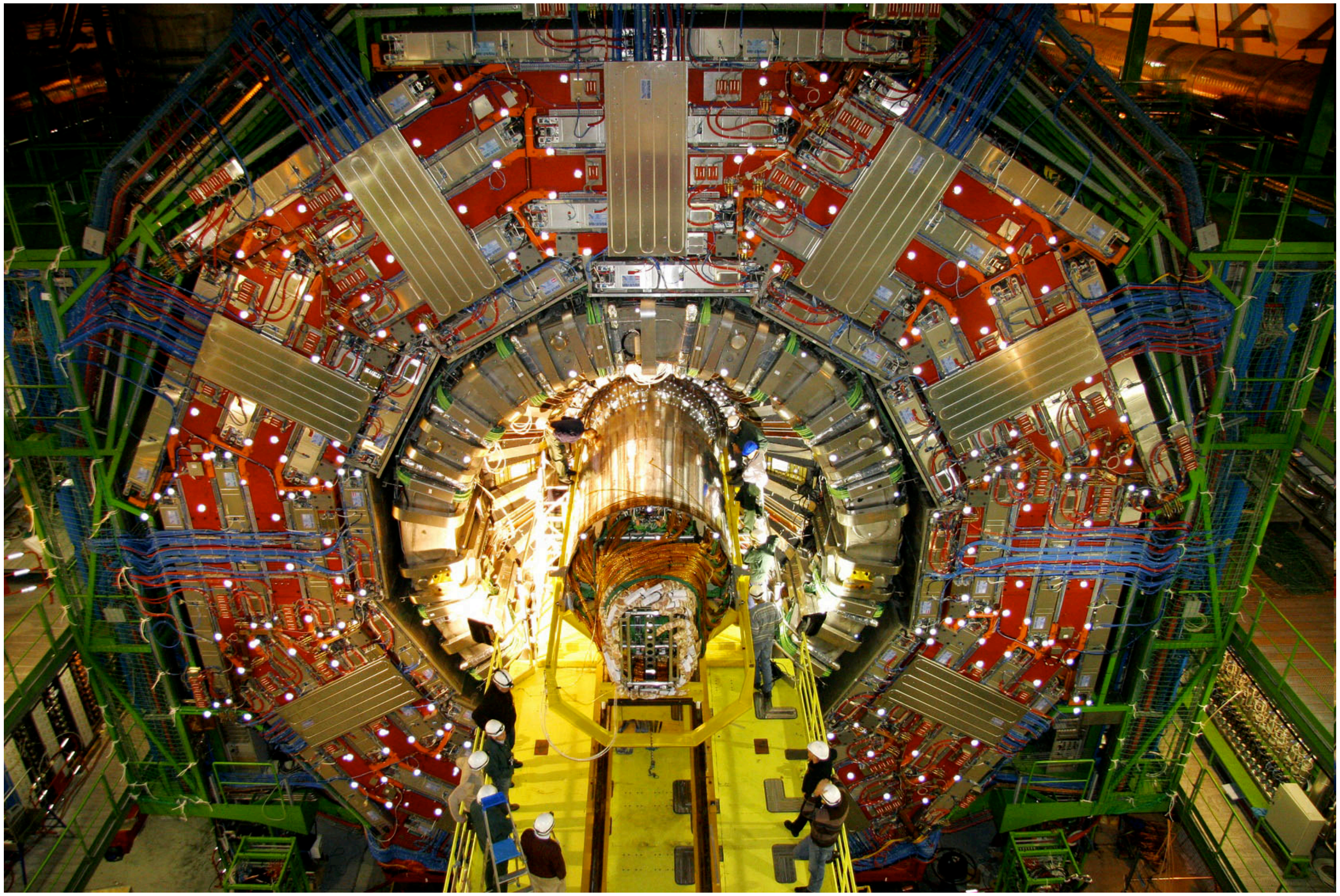
What does the detector do?

- The detector measures the 4-momenta of all particles produced in a pp collision
- 3-momenta of charged particles are inferred by reconstructing tracks as they bend in a 4T magnetic field
- Energy is measured by size of "shower" in instrumented material (calorimeter)
- The interaction patterns of particles with the detector elements allows to "identify" the particle species
  - *e.g.*, electron/muon/photon/proton



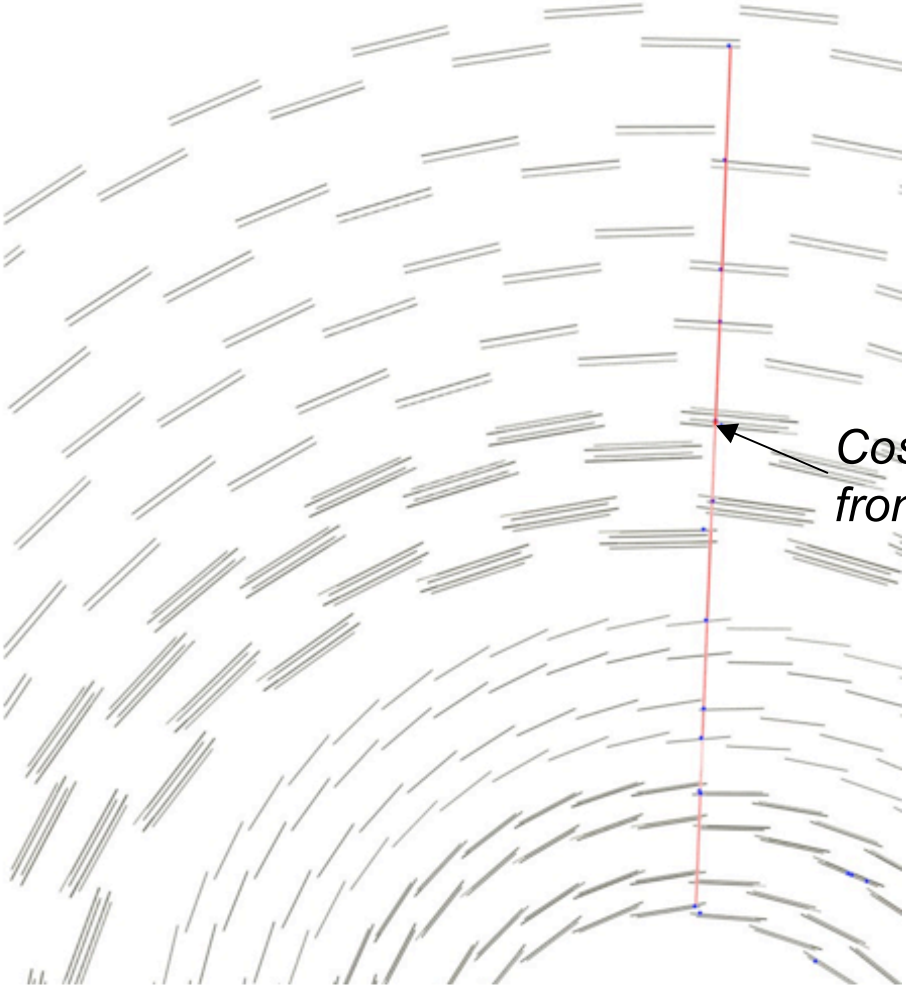
Cosmic muon

Bore of the superconducting solenoid (4T axial field) is outfitted with various particle detection systems. Among them: the silicon pixel and strip tracker which measures particle trajectories.



Insertion of the tracker.

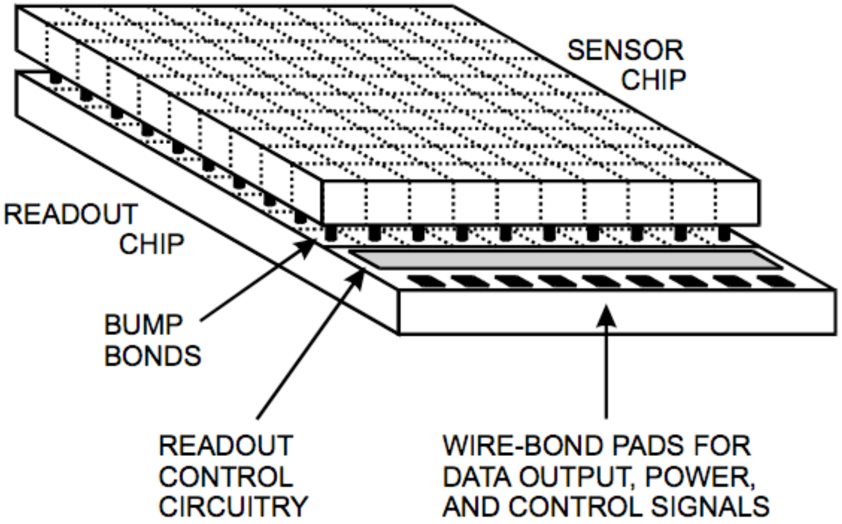
CMS silicon strip tracker

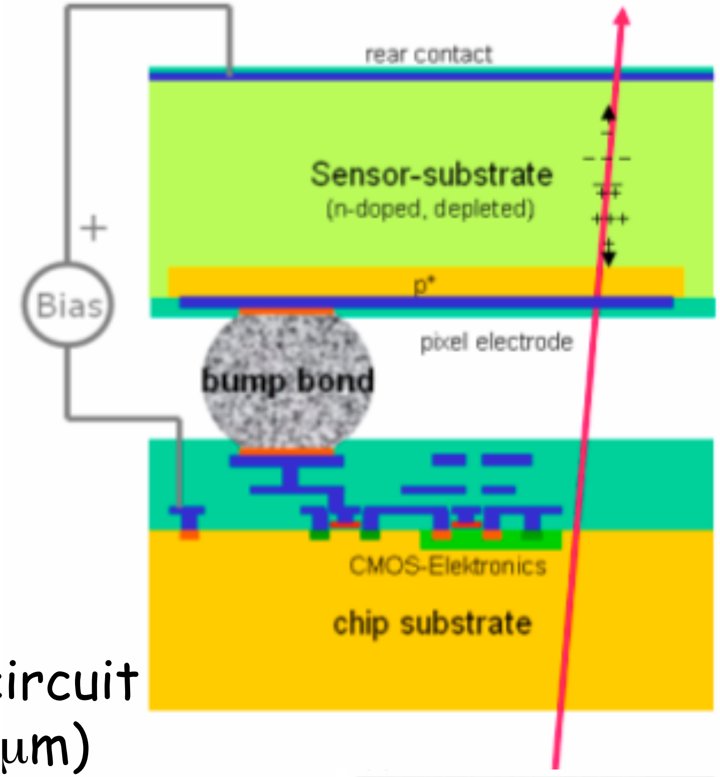


Cosmic muon track, reconstructed from charge deposition on Si strips

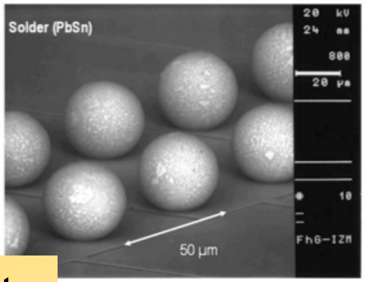
Silicon pixel detector

Adds crucial tracking resolution in the area closest to the beam





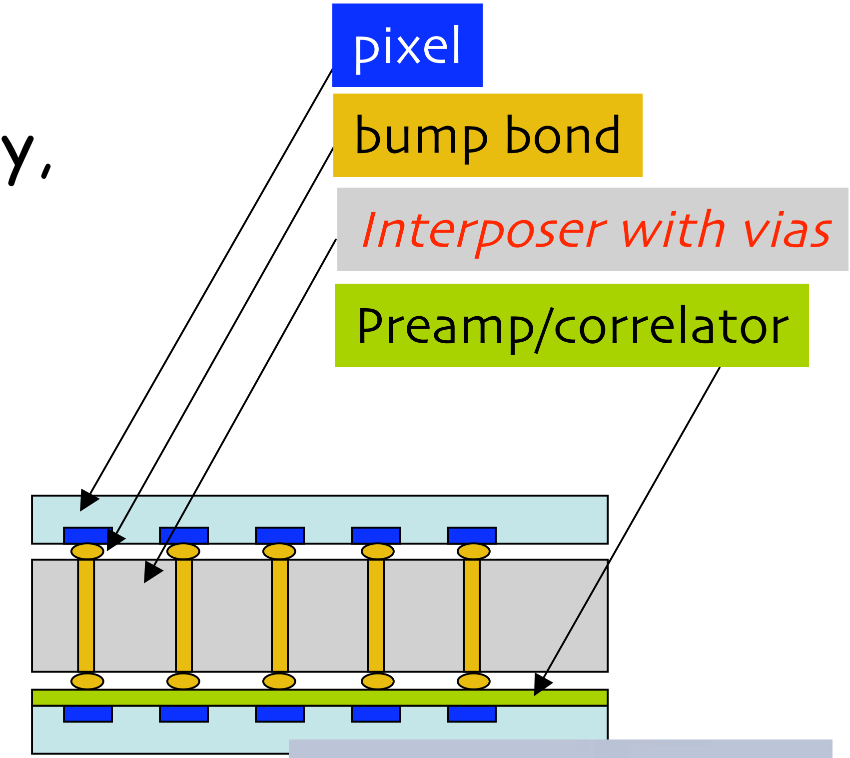
- 3 layers + 2 forward disks
- 66 Million Pixels, size limited by readout circuit and heat/power dissipation limit (150x150µm)
- Time to read out 1 hit: 6 bunch crossings
- Charge deposition threshold on a pixel ~2500e



Significant contribution of the Cornell group to DAQ, commissioning, etc

An aside: silicon detector development for the Super-LHC

- Upgrade of the LHC to reach higher luminosities, originally planned for 2016
- To preserve detector capability, need a new tracker, R&D ongoing at Cornell
  - 3D integrated circuit to process information at detector level
  - Prototype development at CNF

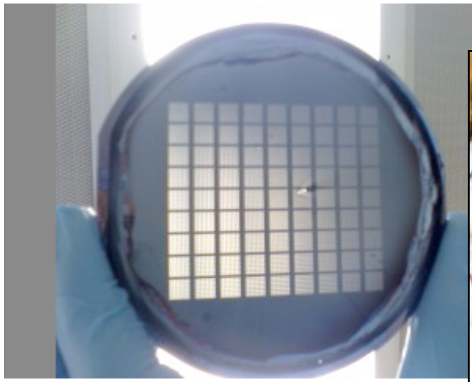


pixel

bump bond

Interposer with vias

Preamp/correlator

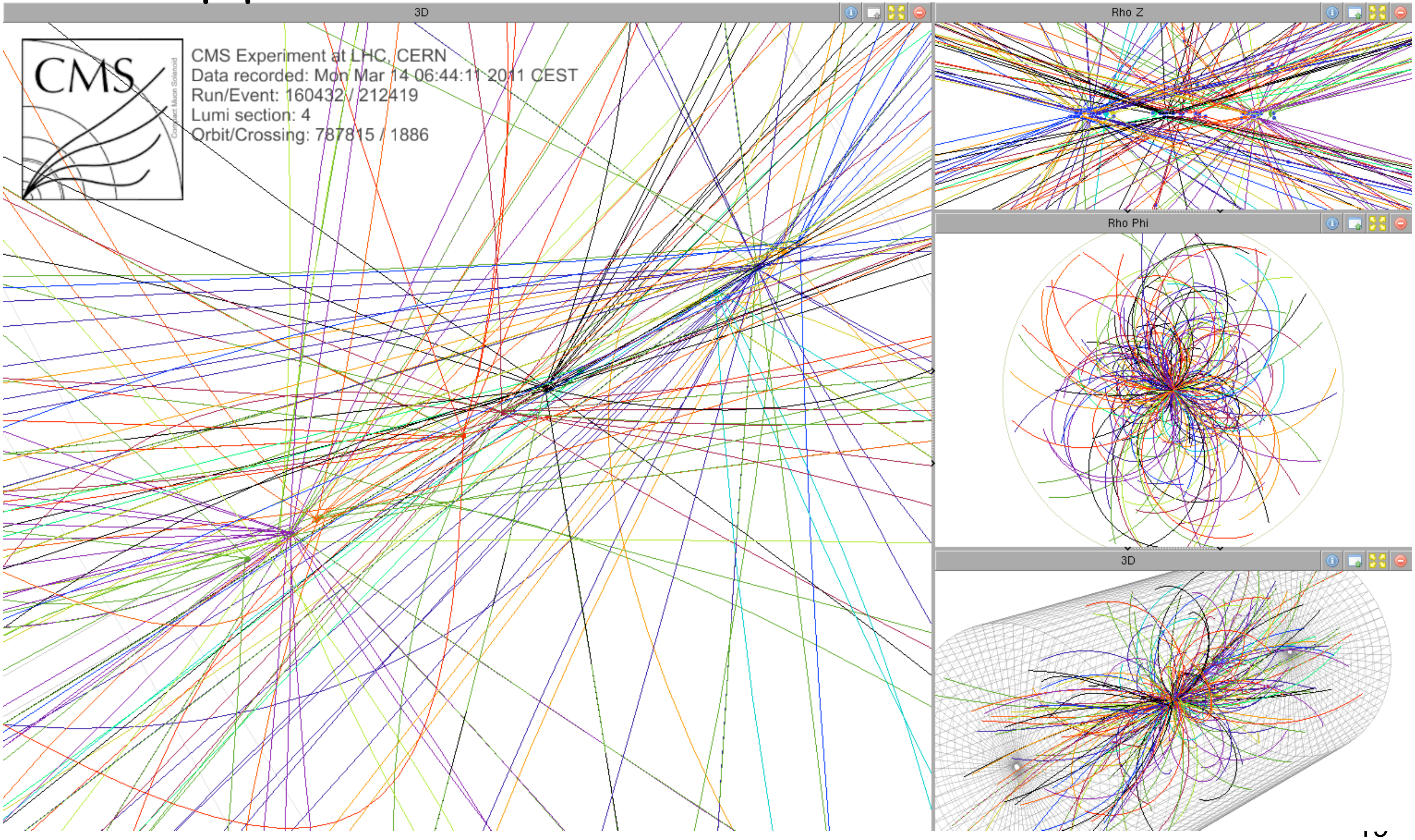


CNF Cornell NanoScale Science and Technology Facility

JT, J.Alexander, undergrads Suri, Lutz,…

Particle tracks in 3D

Si Tracker allows us to reconstruct particle tracks in 3D, with micrometer precision and extrapolate to their origin within the beam pipe



CMS Experiment at LHC, CERN
Data recorded: Mon Mar 14 06:44:11 2011 CEST
Run/Event: 160432 / 212419
Lumi section: 4
Orbit/Crossing: 787815 / 1886

What are the objects we can reconstruct with this detector?

1. Jets
2. Missing Transverse Energy
3. Individual electrons, muons, photons, …

What are the objects we can reconstruct with this detector?

Some details in the following slides

1. Jets
2. Missing Transverse Energy
3. Individual electrons, muons, photons, …

1. Jets

Gluons and quarks do not directly show up in the detector. They form "Jets".

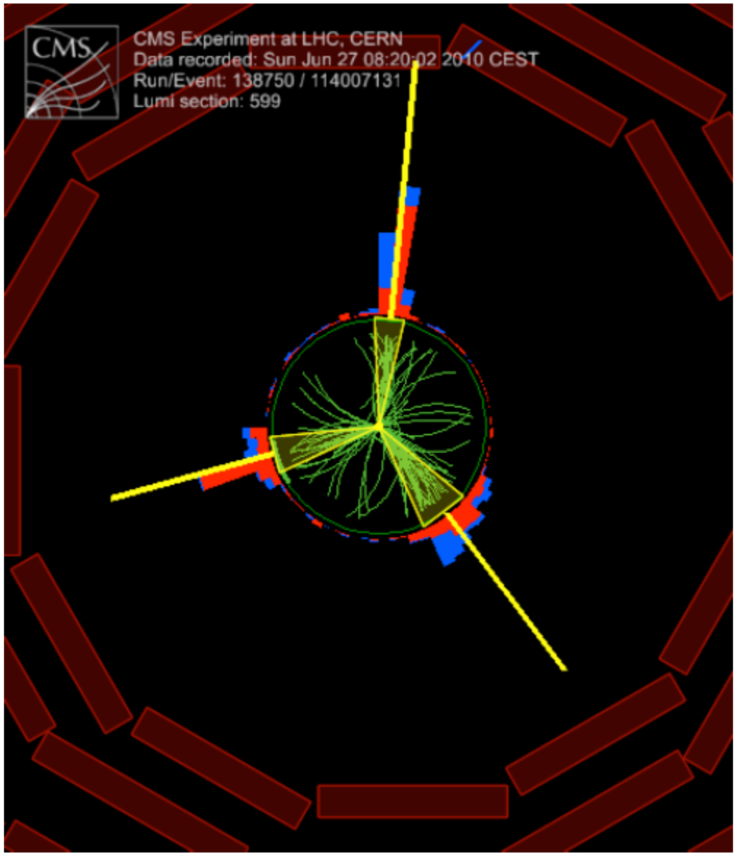
- Quarks and antiquarks are pulled from the vacuum and bound states are formed (eg, pions, kaons, protons, etc)
- If the original gluon or quark is energetic enough, the result is a spray of hadrons **(=jet)** that preserves the direction and energy of the original gluon or quark (more or less)

Jet reconstruction

Reconstruct all particles using all sub-detectors, then cluster them into Jets and sum up the energy

Calorimeter response is non-linear and non-uniform, so observed energy needs to be corrected:

- –depending on algorithm, jet momentum and direction: correction up to factor 2!
- –correction done using simulation, checked in data, e.g. with energy balance in di-jet and γ+jet events

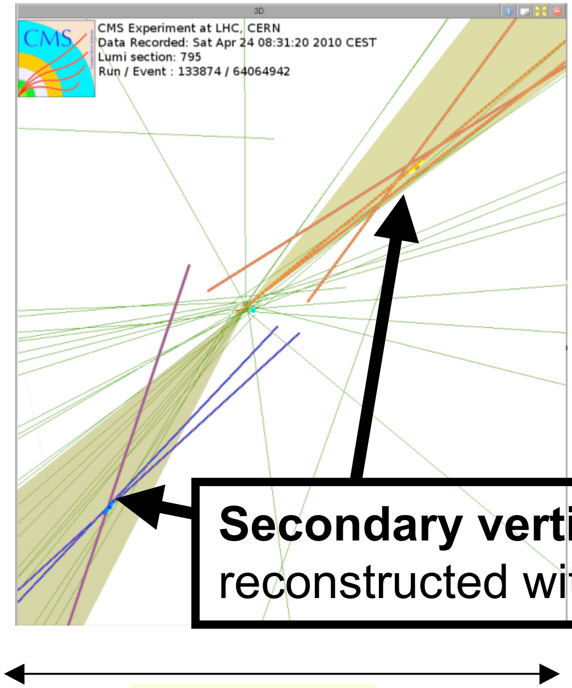


~5% difference between data/MC jet energy scale measurements (=systematic uncertainty)

B tagging of jets

- Identify jets originating from b quark by long lifetime of B hadrons
  - causes a decay vertex clearly separated from the interaction point
- Example algorithm:
  - reconstruct secondary vertices based on track impact parameter

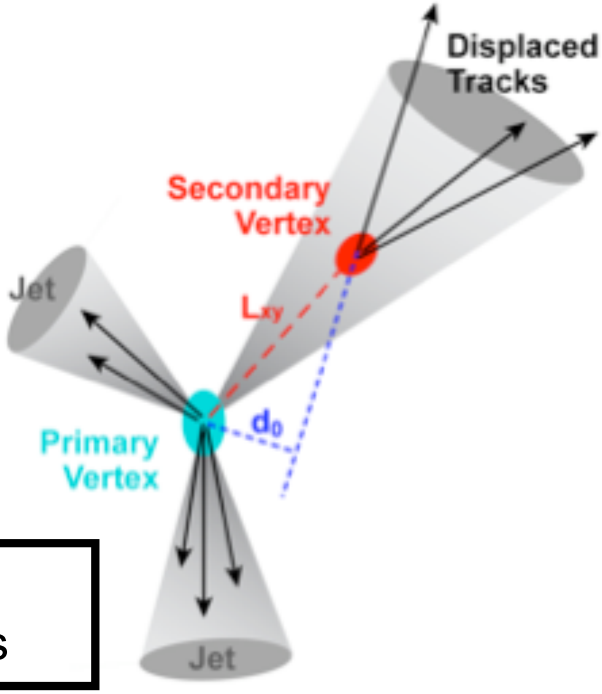
typical jet from a top decay is tagged as coming from a b quark with ~50% efficiency and ~1% mistag rate



CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
Run / Event : 133874 / 64064942

Secondary vertices
reconstructed within jets

Few mm

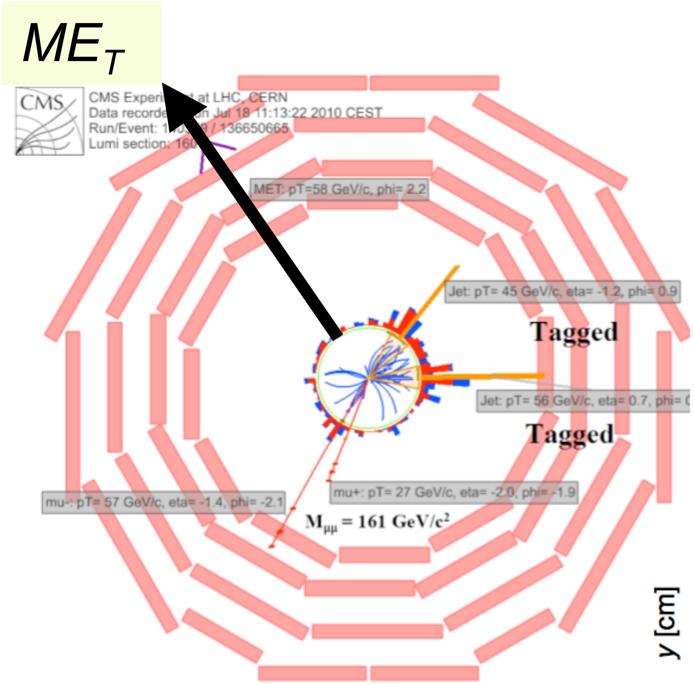


2. Missing Transverse Energy ME_T

- Missing transverse momentum is defined as the apparent imbalance of the component of the momentum in the plane perpendicular to the beam direction
  - particles escaping down the beampipe are not measured

- magnitude is referred to as missing transverse energy ME_T

- Allows for (indirect) detection of neutrinos, WIMPS,.. which cause imbalance in the transverse vector sum
  - e.g. most SUSY models predict ME_T>150 GeV



Outline of the rest of the talk

Can only show a small selection of many interesting topics:

1. A top quark cross section measurement, representative of how we go about measuring decay rates

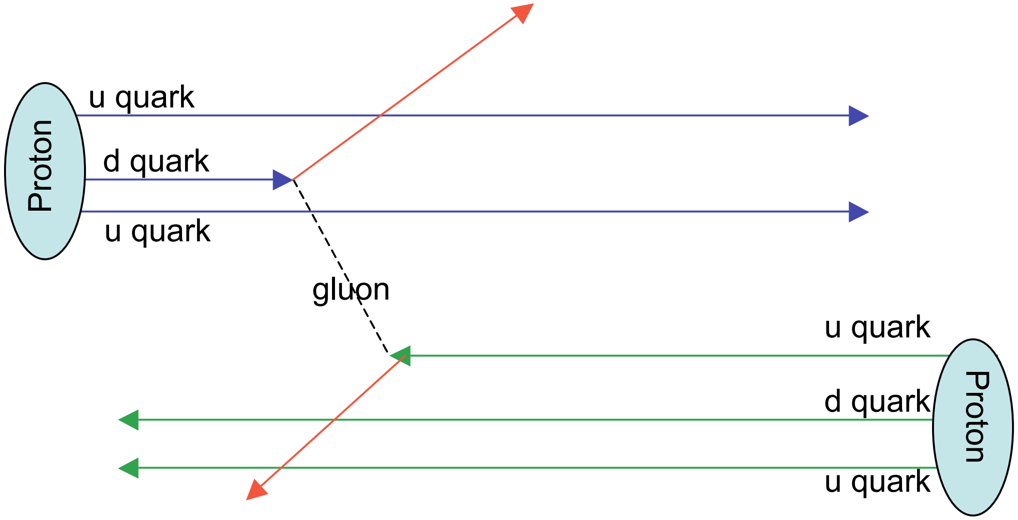
2. Searches for New Physics, in particular: Supersymmetric particle production

3. Briefly: the latest results on the Higgs Boson search

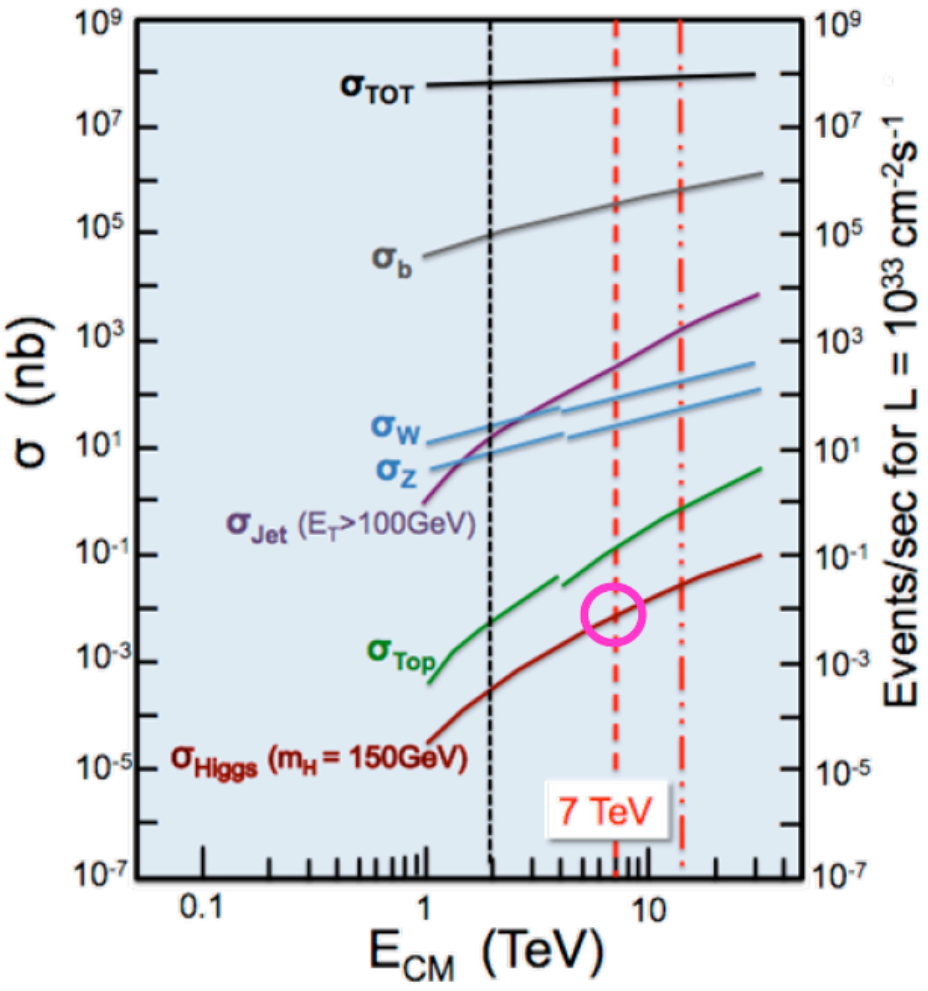
How top quarks (and Higgs, Superpartners,..) are produced

- 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 and many many gluons).
  - Note: their momentum is unknown
  - Represent only a tiny fraction of the total inelastic cross section



Hard scatters: production cross sections as calculated in our current model

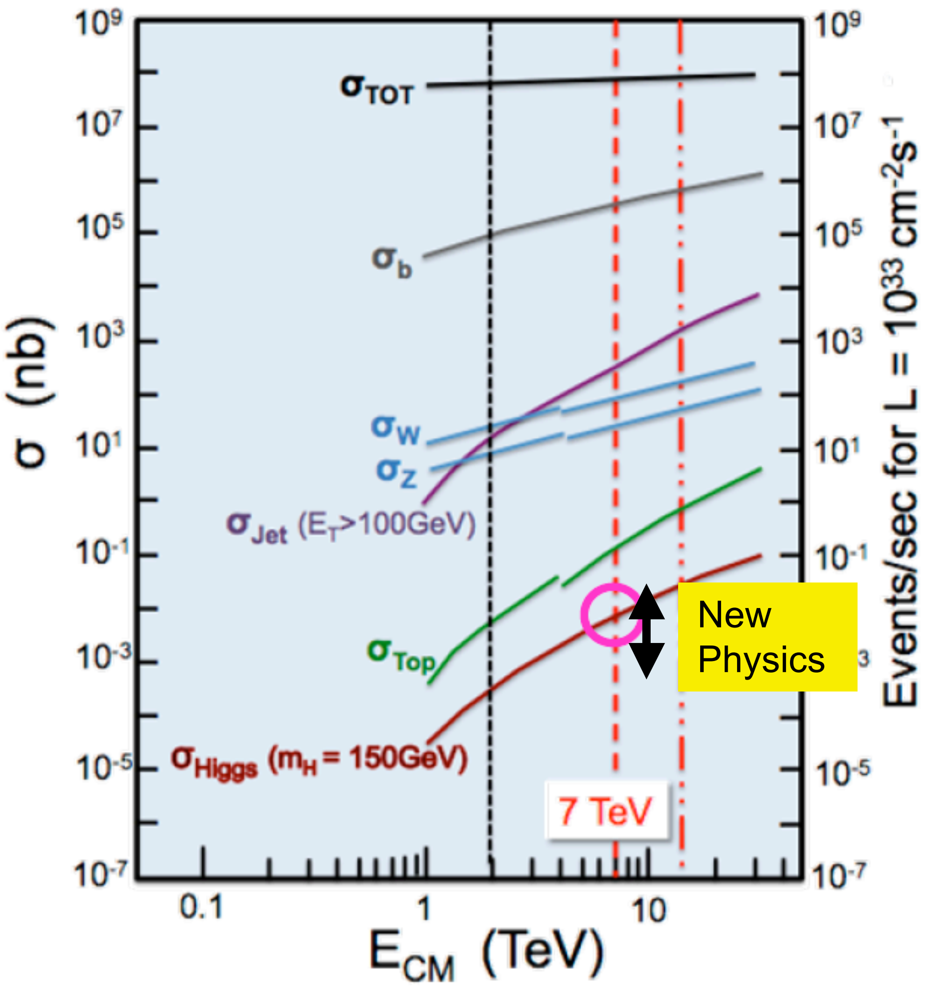


Rate = σ x Luminosity

so we (currently) produce approximately

- "any" event: 10^8 / second
- W boson: 100 / s
- Top quark: 1 / s
- Higgs: 0.01 / s

production cross sections



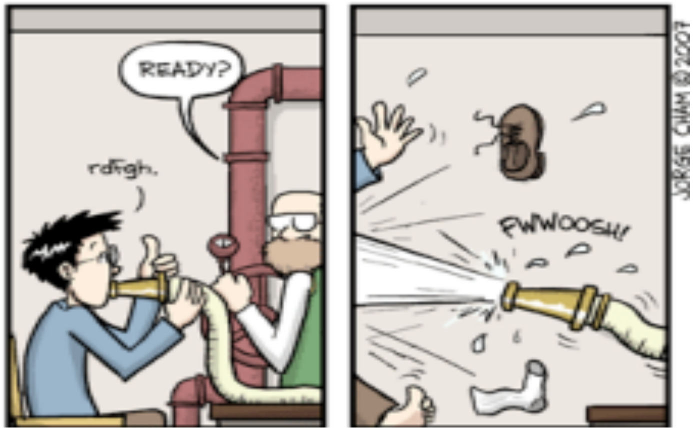
at LHC, production of superpartners or other NP processes expected ~10pb

with large data set collected in the 1st year we are starting to be sensitive to these rare processes

Cross sections will increase once we are at 14 TeV

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

- Total cross section yields an "event rate" O(100) MHz
- Each event is ~ 250 kb, corresponds to 250 kb x 100 MHz = 25 Tbytes/second



- Trigger is the system that selects the ~ 200 events/sec that are saved for further study
- Most of the events are thrown away!
- Trigger selects events based on the reconstructed objects, (e, μ, ME_T, jets..) or combinations thereof

- Currently have O(100) triggers, and are severely tightening thresholds to deal with the ever increasing luminosity
  - Have to make tough decisions! Don't want to compromise our ability to observe unexpected physics..

Top Quarks

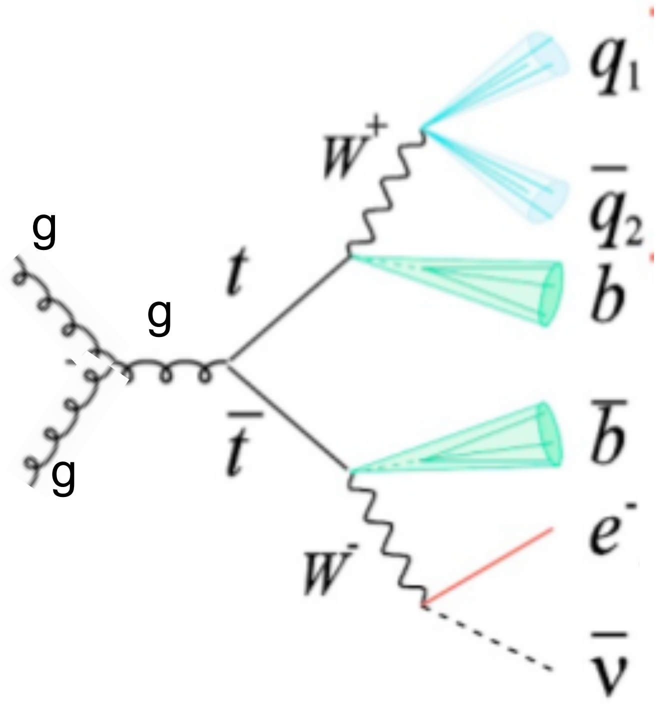
t-Quark: $M_t = 173.3 \pm 1.1$ GeV/c^2

almost as heavy as an atom of gold!

(=79 protons + 118 neutrons + 79 electrons)

- the mass is suspiciously close to the scale of electroweak symmetry breaking (EWSB)
- we have recently observed some unexplained phenomena in top decays at the Tevatron

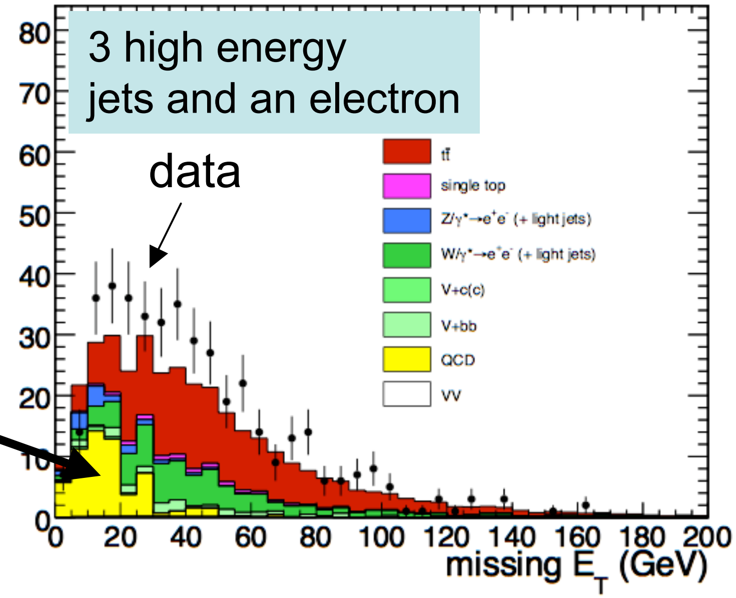
Example top- anti-top decay event



- Decays rapidly through the weak interaction without forming a quark bound state first
- Experimental signature: 4 energetic jets (2 from b), one electron, and ME_T from neutrinos
  - cuts are chosen to select a sample rich in top quarks, and backgrounds are subtracted to calculate a top production cross section

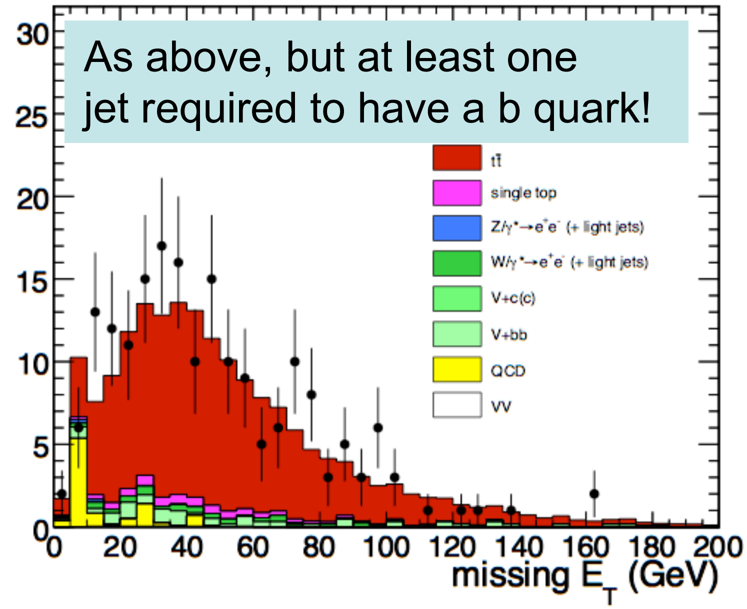
b tagging suppresses non-top background

- ME_T distribution of selected events
  - Red: simulation of top quarks
  - Disagreement due to imperfect simulation of backgrounds. More on this later!


3 high energy jets and an electron

data

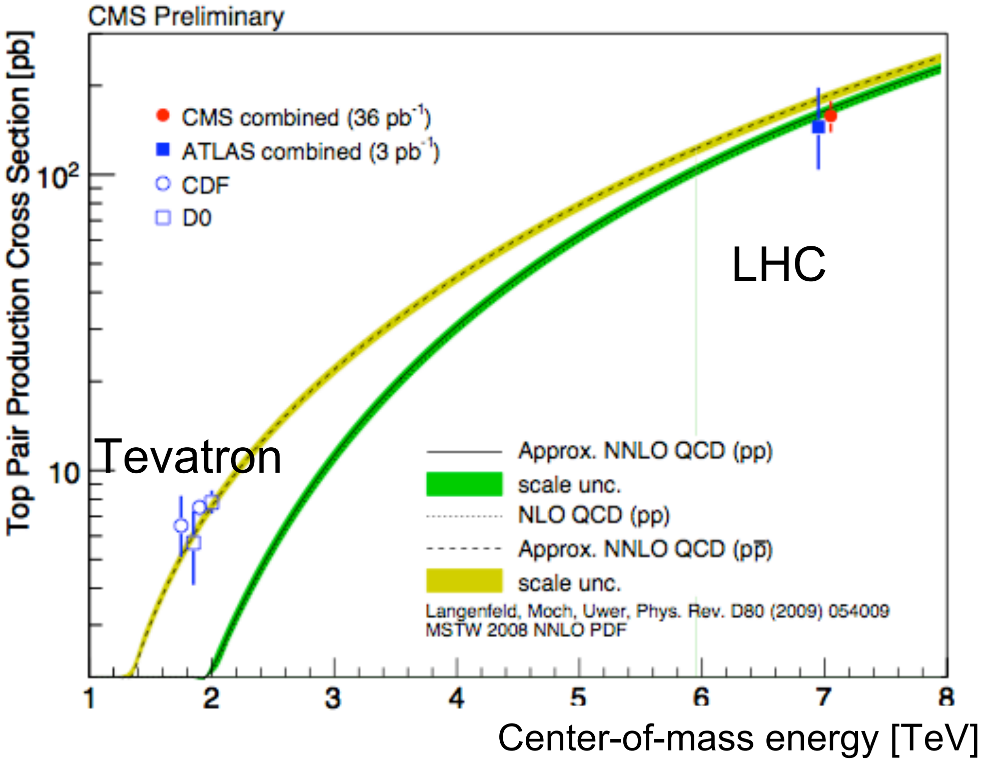
- In addition, require at least one b jet. Suppresses backgrounds to the top signal


As above, but at least one jet required to have a b quark!

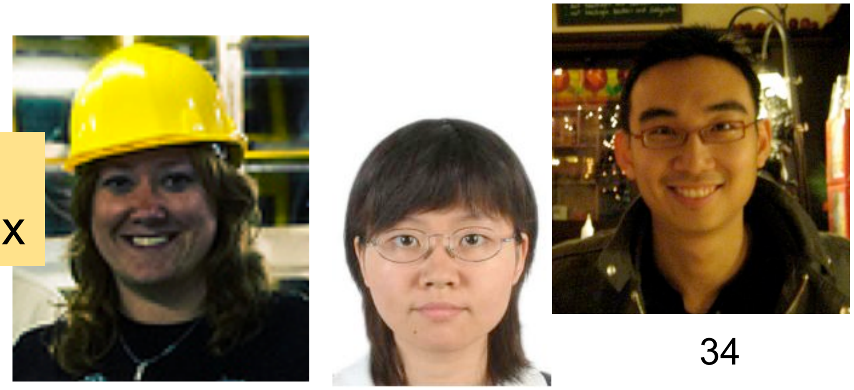
No surprises (so far)

Top Production Cross section measurements with 2010 data:

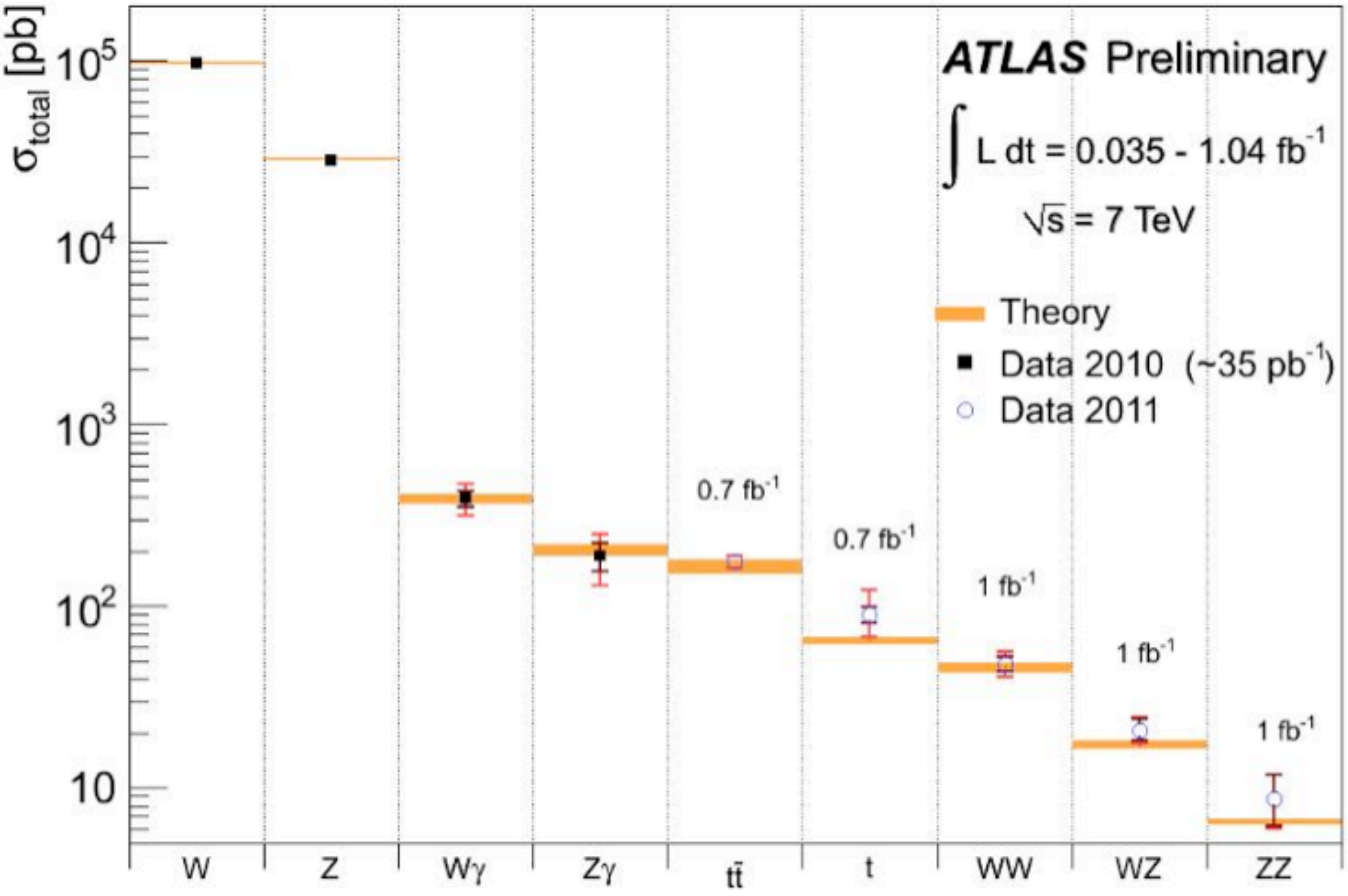
good agreement between the observed and predicted (NNLO) top production cross section calculation at the highest energies ever observed..



JT, Yao Weng, Freya Blekman,Hongwan Liu, CMS, Submitted to PRD, arXiv:1108.3773 hep-ex



beautiful agreement with calculations, not just in top physics



Search for Superpartners

What we knew a year ago:

light superpartners (gluinos and squark masses ~0.6 TeV) yielded the “best fit” to all measurements available at that time.

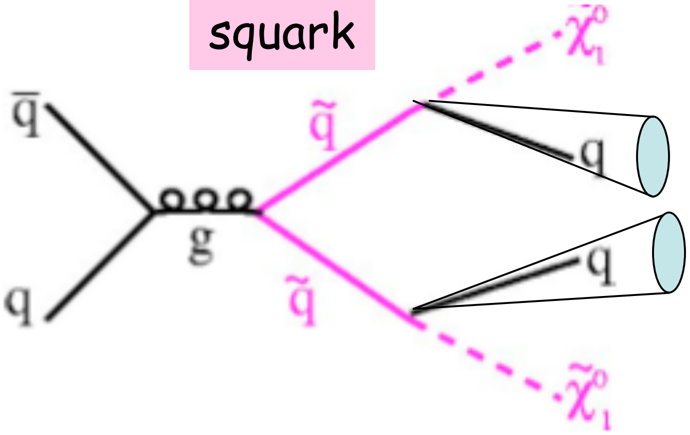
Many of us expected an early discovery.

Search Strategy

Reminder: we expect that

- Superpartners are produced in pairs
  - at hadron colliders, mainly squarks and gluinos
- decays end with lightest stable particle (LSP)

Simple example:



LSP, results in ME_T

squark

quarks, result in high energetic jets

→more generally, the signature of all SUSY decays is large energy release and high ME_T

Distinguishing SUSY from background

- SUSY cross sections are small, so need to know background rates and distributions with high precision

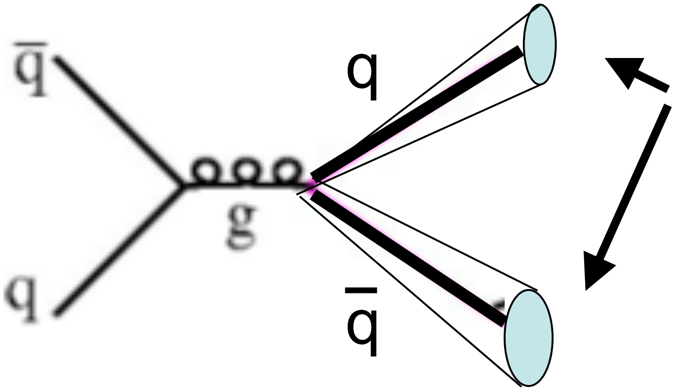
- our SM calculations give well-tested predictions for many processes, but some are difficult to calculate:
  - -instrumental effects
  - -fraction of transverse momentum carried by the proton constituents unknown
  - -non-perturbative calculations

➔Certain processes are unknown to O(2) or more

- -have to estimate background from data itself, using clever tricks
- -this is where 95% of the work goes!

One example of a poorly known background:

“QCD production” of quarks and gluons:

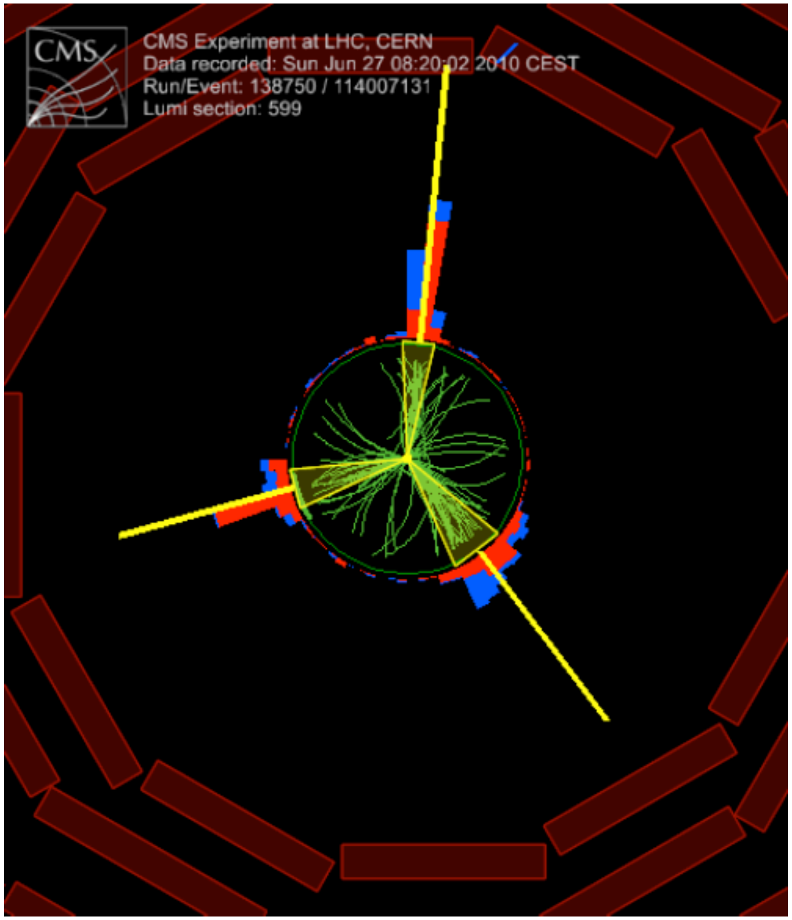


2 highly energetic jets, plus additional jets from strong processes

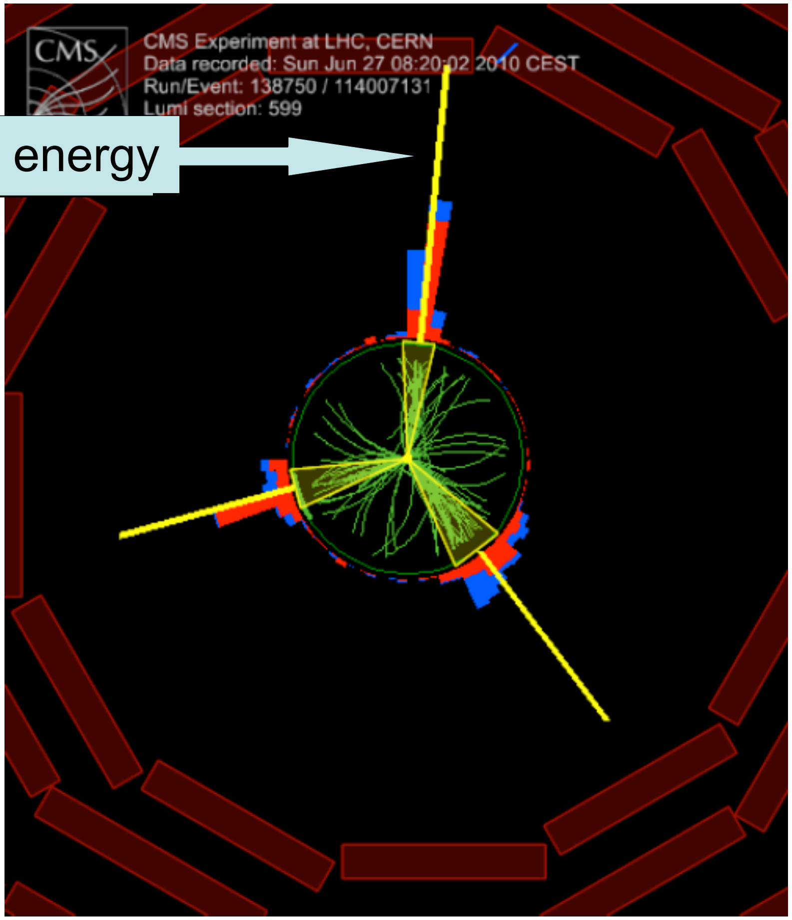
Problems:

- enormous cross section
- exact rates and distributions hard to calculate (strong interaction, unknown parameters)
- fake missing energy due to mis-measurement of jet energy in detector hard to calibrate

Fake ME_T from jet mis-measurement

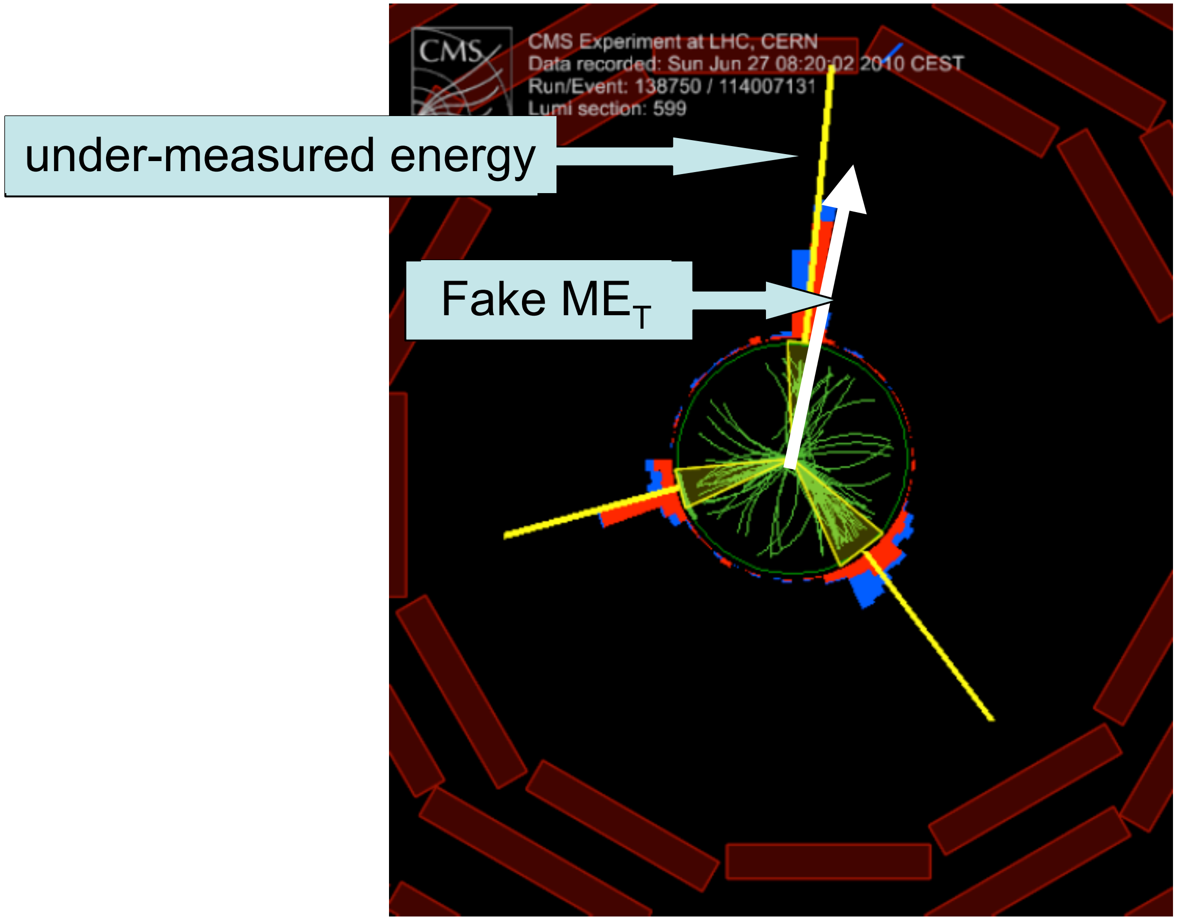


Fake ME_T from jet mis-measurement



Under-measured energy

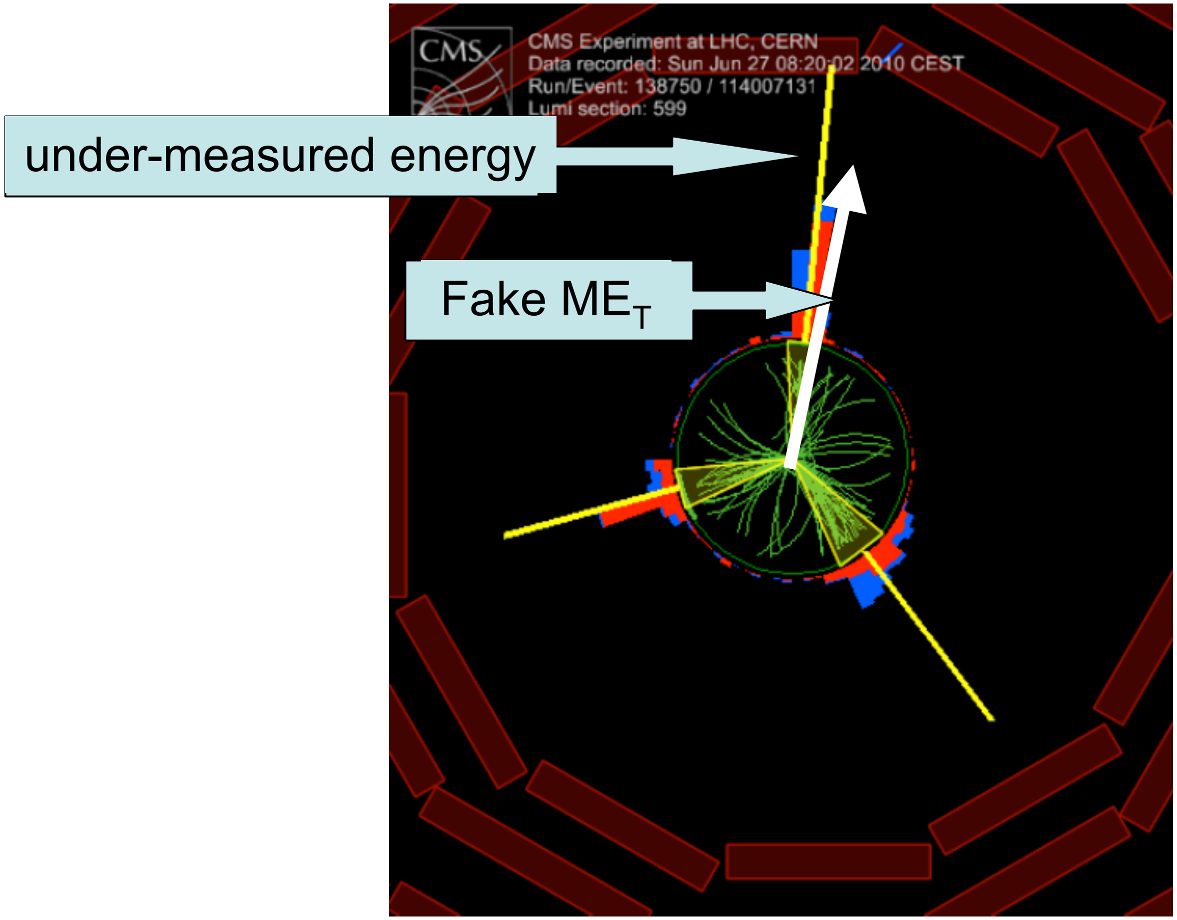
Fake ME_T from jet mis-measurement



under-measured energy

Fake ME_T

Fake ME_T from jet mis-measurement



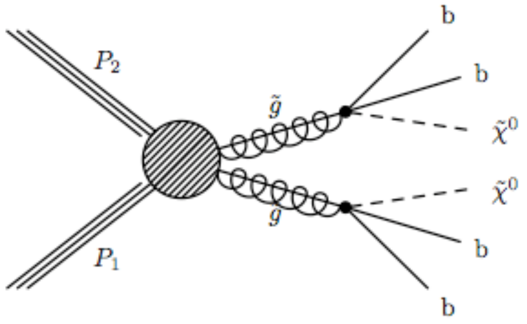
under-measured energy

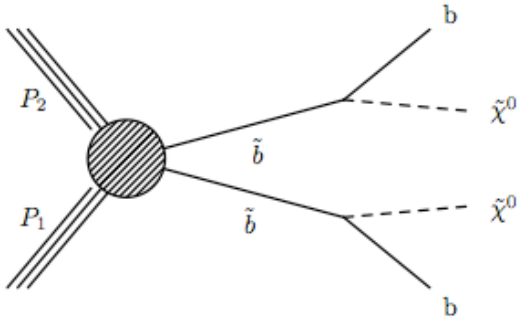
Fake ME_T

➔ Cut on the minimal angle between ME_T and jets to suppress this background

SUSY signatures with b jets and ME_T

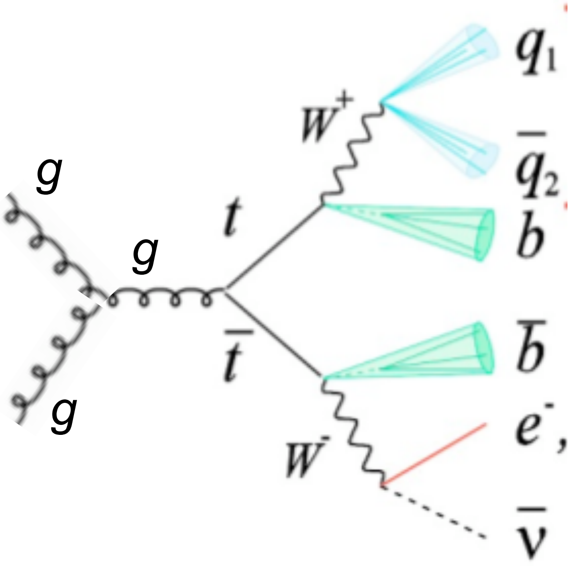
- Several good reasons to expect a large cross section for sbottom and stop production and thus many heavy quarks (bottom, top) in the final state
  - sbottoms and stops may be significantly lighter than the other squarks, since mixing to form the mass eigenstates is proportional to the corresponding fermion masses
  - for SUSY to work, sbottom and stops need to be below ~1 TeV, but NOT the other quarks. They could be much heavier (and thus inaccessible) *e.g.Cohen, Kaplan, Nelson, Phys.Lett.B388(1996)*
- Therefore it is interesting to narrow searches to signatures like this:





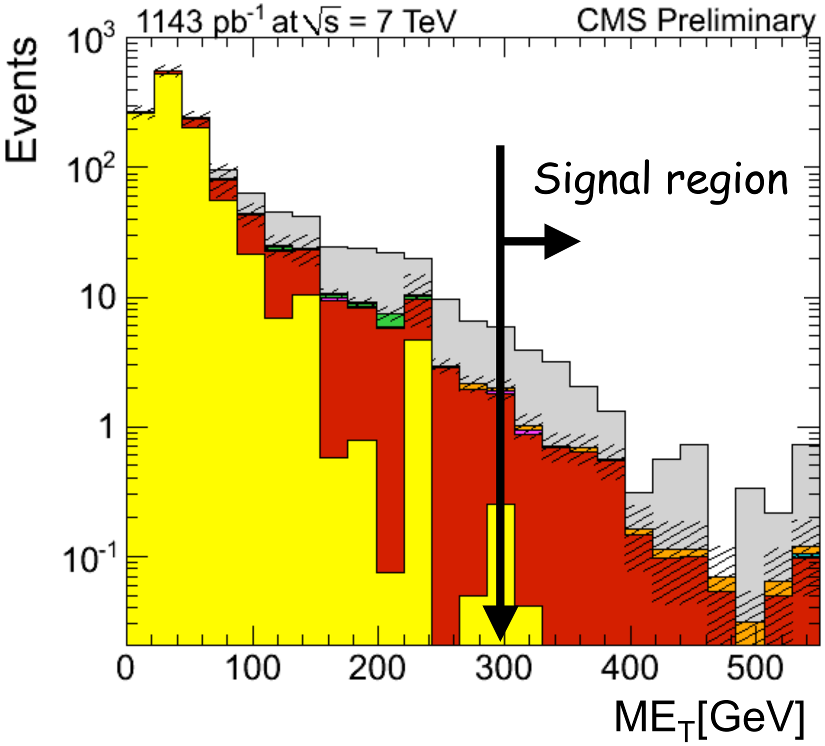
SUSY signatures with b jets and ME_T

- we look for an excess in events with 2 b-tagged jets, zero leptons, and large ME_T
  - luckily, the QCD background is highly suppressed here, since heavier quarks are less likely to be produced than lighter ones
  - the dominant background is from top decays, where the lepton has escaped detection



Expected signal and background shapes

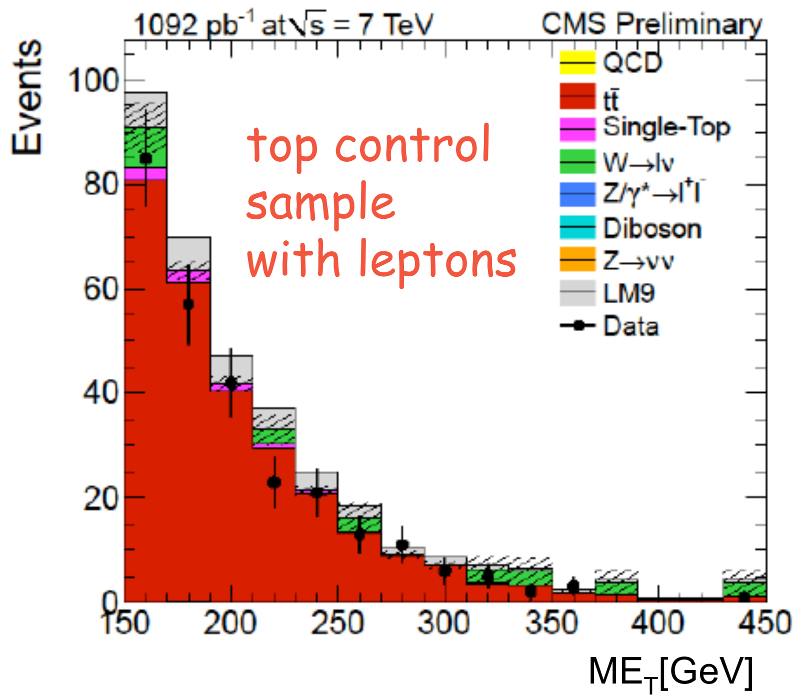
- In grey: simulated SUSY signal (assumptions:MSSM)
- In red: simulated background from top decays
- Yellow: simulated background from "QCD"



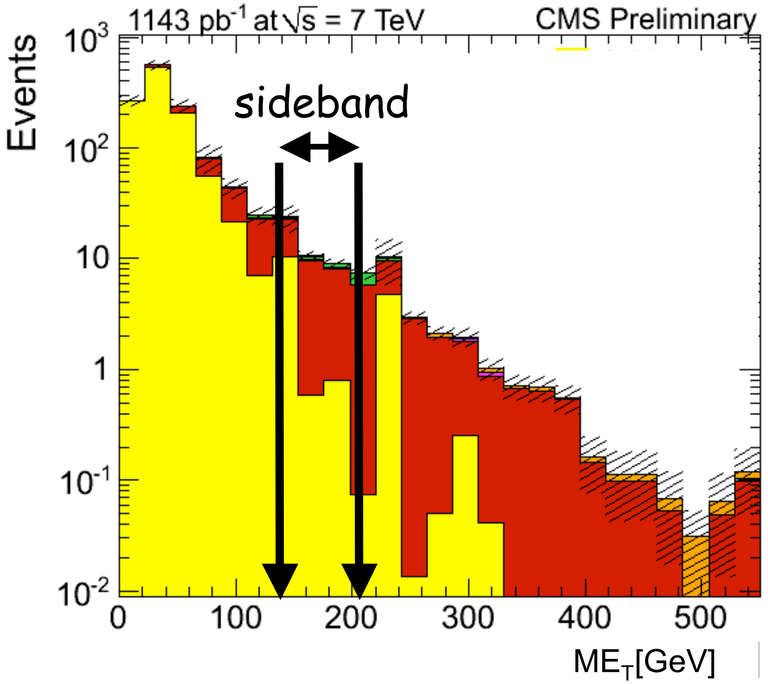
note: the background and signal ME_T shape is the same,
so we need to get the absolute rate of the background right!

Example of using data sidebands and control samples to estimate background

- We get the shape of the ME_T distribution of top decays from a top control sample with leptons (ME_T shapes match)
- We get the normalization using the low-ME_T sideband of our zero lepton signal sample (dominated by top decays)



top control sample with leptons



sideband

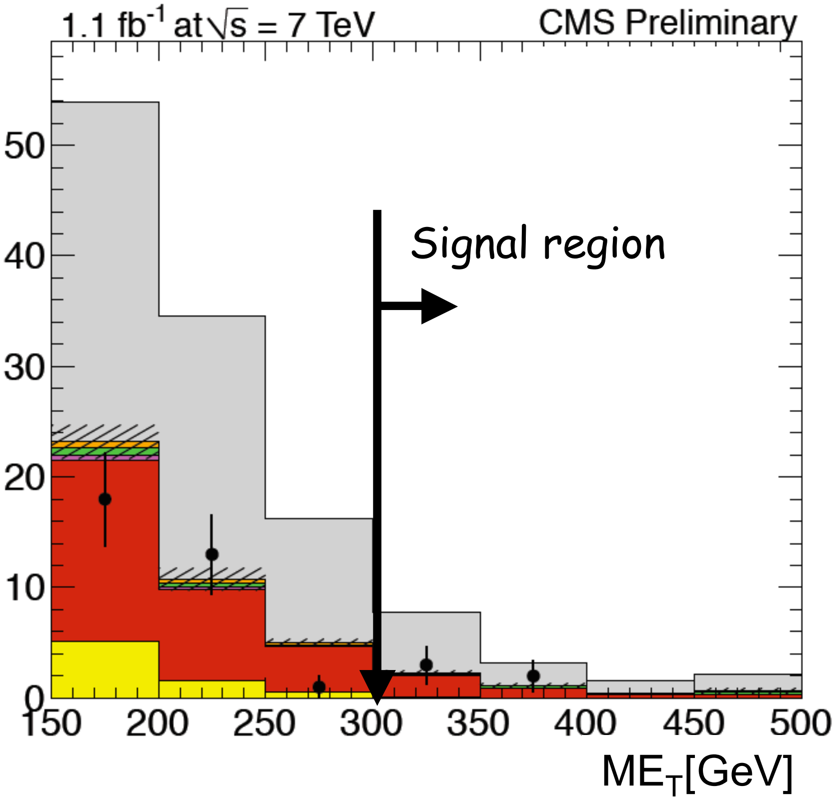
SUSY signatures with b jets and ME_T

Once all backgrounds are understood, we compare the data in the signal region with the background:

signatures with b jets and large ME_T

Once all backgrounds are understood, we compare the data in the signal region with the background:

The data agrees with the background-only hypothesis…

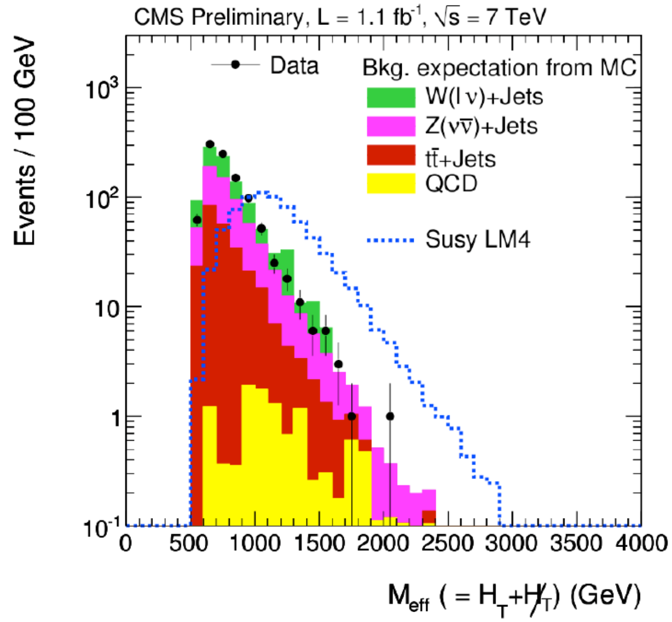


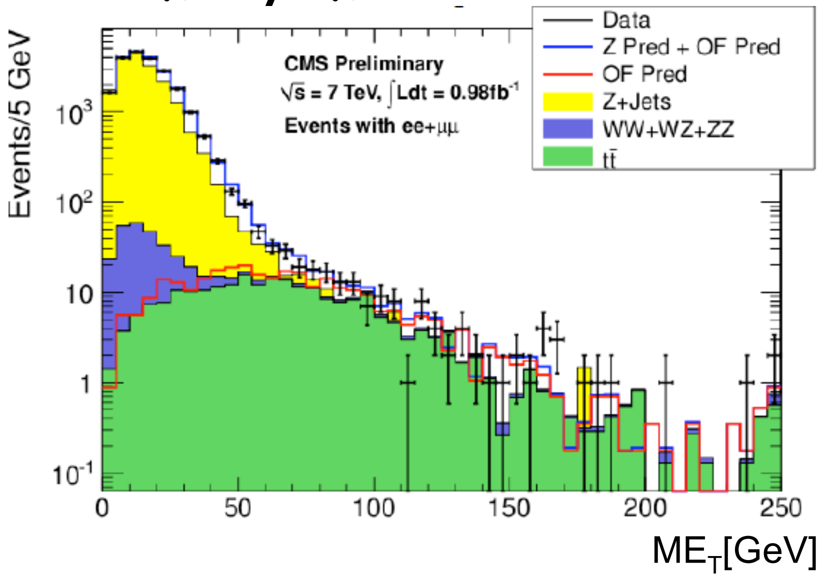
What does this tell us about SUSY?

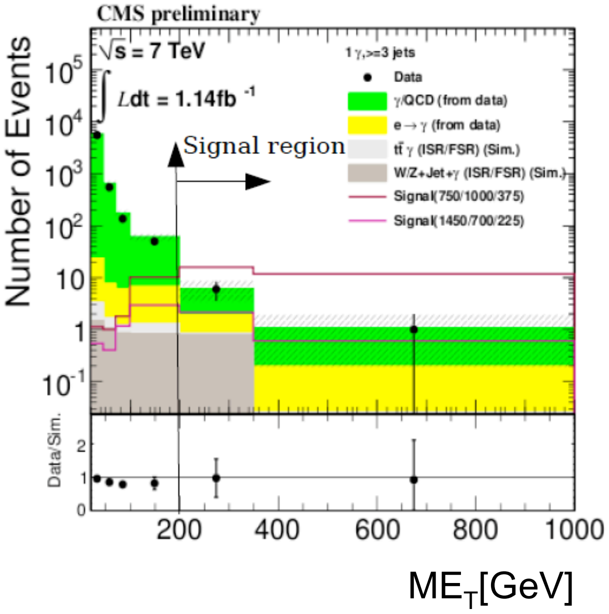
- Can turn the data-background agreement into exclusion limits, for example:
  - Cross sections for gluino pair production with subsequent production of b quarks is excluded above ~few pb
  - For heavy gluinos we exclude values above ~0.01 pb
- Cornell postdocs and students working on this:

Other SUSY searches

- Searches for jets and ME_T
  - much higher background from QCD
- Searches for leptons, jets and ME_T
- Searches for photons and ME_T
- And many more



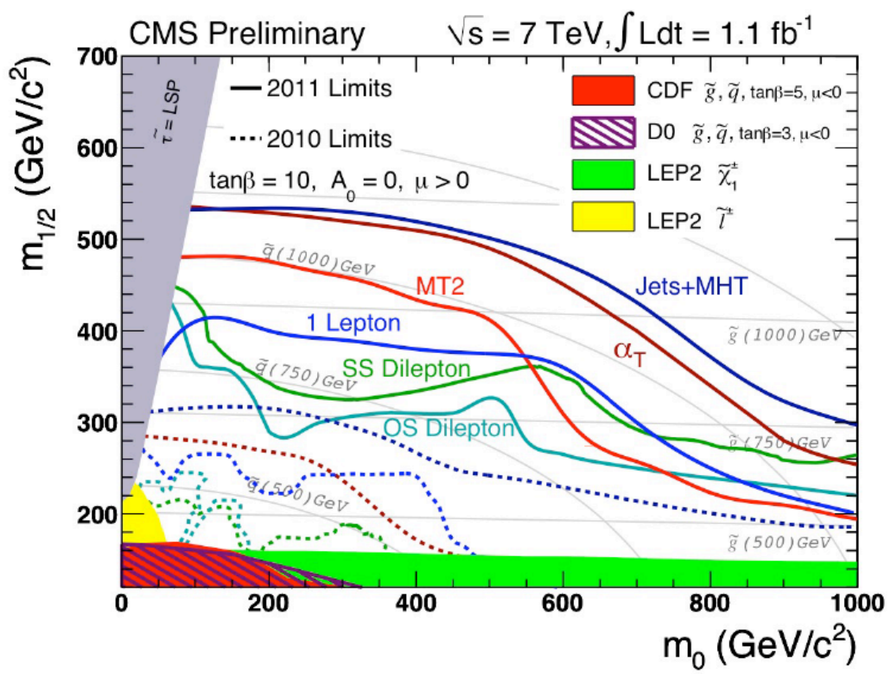




➔ No excess anywhere.

Exclusion limits

- turn the data-background agreement into an exclusion limit for superpartner masses
- using certain assumptions and simplifications ("constrained Minimal Supersymmetric Standard Model"): squarks and gluinos are excluded up to ~1 TeV



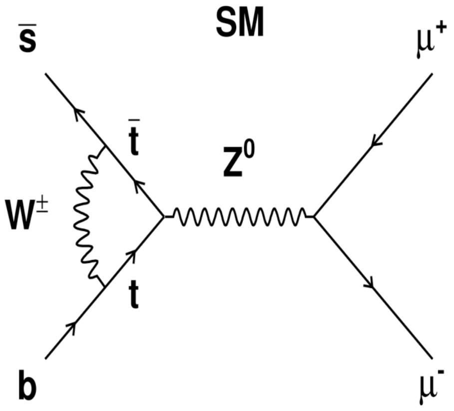
Is SUSY dead?

- The results are surprising: many of us expected Supersymmetry at lower energy (for good reasons)
- most of the parameter space of certain constrained SUSY models (e.g. cMSSM) is now excluded
- but those models are only one of the possibilities
  - albeit one of our favorite possibilities…

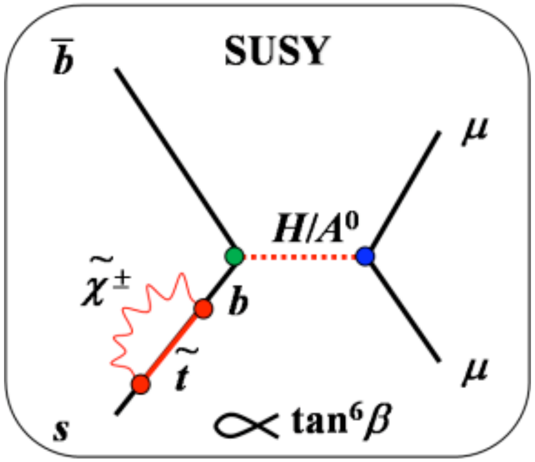
- The direct searches I just showed are a big part of the SUSY program, but also important: "indirect searches"
  - look for quantum loop effects: contribution of SUSY (or other NP particles) can alter known decay rates
  - note that the energy scales accessible through loops are much larger than those probed by the direct searches

An "indirect search" for NP: $B_s \rightarrow \mu^+\mu^-$

- This particular decay is, in the Standard Model, extremely rare.
  - flavor changing neutral current
  - accessible only through higher order ewk diagrams



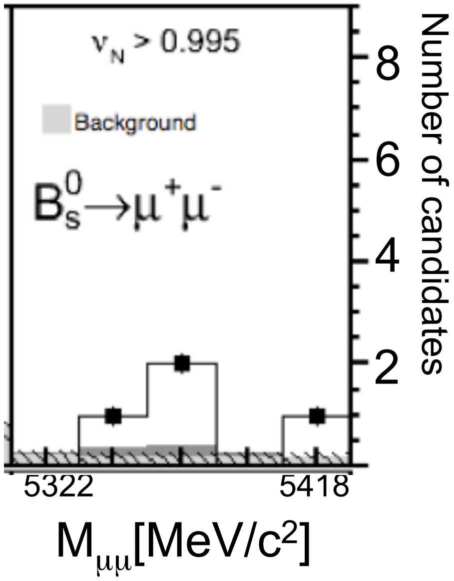
- But the rate can be enhanced by orders of magnitude due to new particles mediating this decay, such as supersymmetric particles
  - MSSM, MSUGRA



- search for these decays are a top priority at the LHC and Tevatron

Results for $B_s \to \mu^+\mu^-$ from the Tevatron

- Using 7 fb^{-1} at the Tevatron/CDF experiment, we observed ~4 such decays, where only about 1 was expected
  - for the event selection with highest signal efficiency: 1 event expected from background and SM signal
- Small numbers, so significance is only moderate
  - 2.8σ discrepancy with the background-only hypothesis: could be a fluctuation, but has generated some cautious excitement
- Results from the LHC (CMS and LHCb) do not confirm an excess, but do not exclude it either- need more data.



JT, Walter Hopkins, CDF collab.
Accepted PRL, arXiv:1107.2304

SUSY summary

Have launched broad program of SUSY searches at LHC

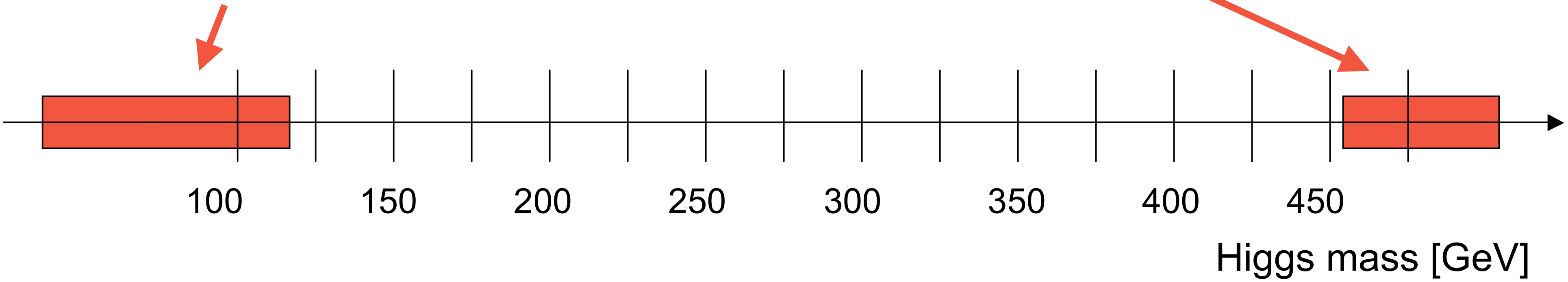
- direct searches have good sensitivity to the lower mass spectrum of superpartners already
    - have not found any signs of superpartners so far.
- indirect searches can probe different energy scales
    - maybe the hint of an excess seen in $B_s \rightarrow \mu^+\mu^-$ at the Tevatron
    - many others being investigated

The Higgs Chase

What we knew a year ago:

Existence of a Higgs with Mass < 115 GeV had been excluded in e+e- experiments (LEP)

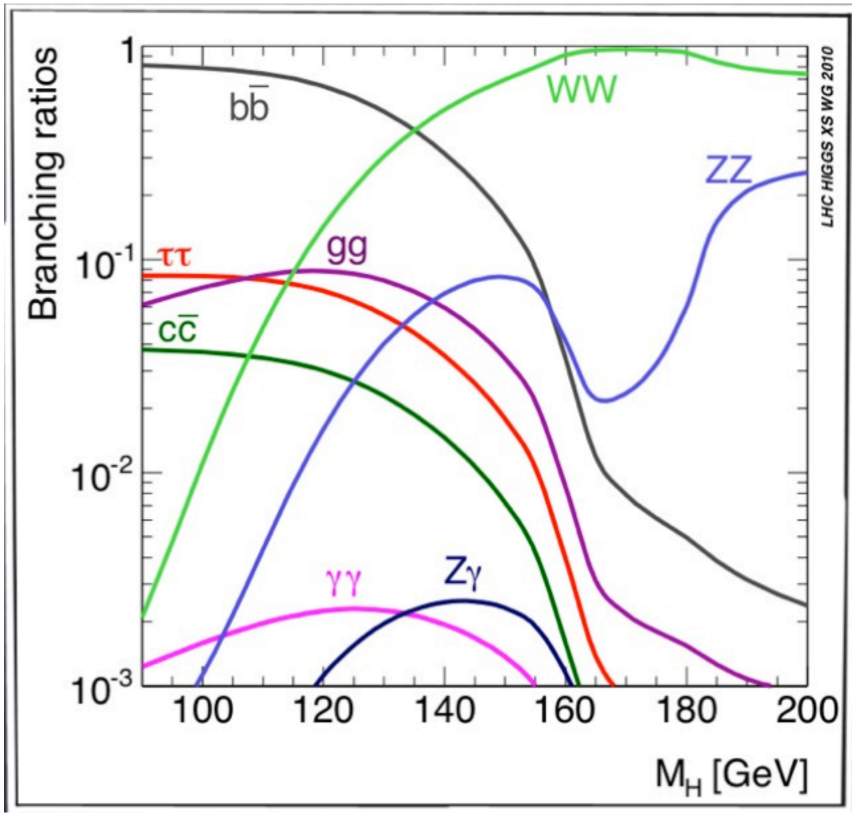
Mass > 466 GeV excluded
by precision measurements
of W and Z mass, to which
the Higgs contributes at quantum level



The Higgs Chase

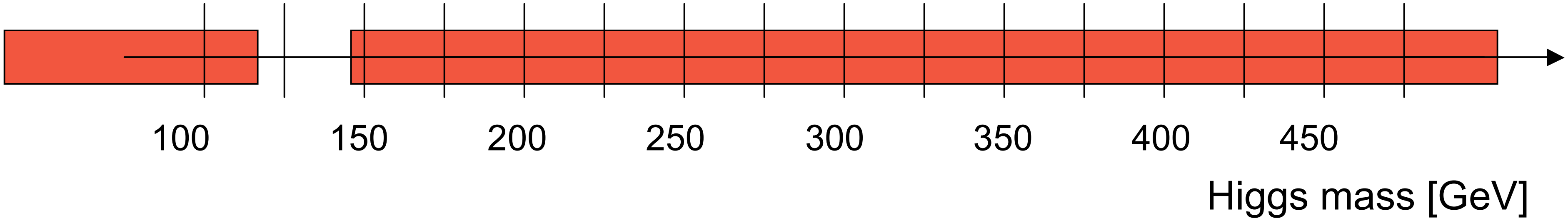
Given the expected decay chain of the Higgs boson, look for an excess over background

- dominant decays: H->b$\bar{b}$ and H->WW
- a lighter Higgs is harder to detect because of enormous backgrounds from non-Higgs bb production



Latest search results

The Higgs boson is now excluded by at least one LHC experiment in the mass range 145-466 GeV (very small gaps)



- This leaves 115-145 GeV as the most likely hiding place (and the hardest to detect)
  - incidentally, data from ewk precision measurements points to a light Higgs..
  - earlier this summer, a suggestive excess was seen around 140 GeV, but disappeared with more data
- will have to wait for more data (~end of the year) to exclude or discover the SM Higgs. It's hard to be patient.

Summary

- The LHC is running- and running well. The detectors work better than expected

- At the LHC no signs of the Higgs or SUSY or other New Physics….. YET!
  - first year of a 20y program, still at half design energy…
  - Have ~twice the data reported on today on tape already, news of evidence for New Physics could still come at any time

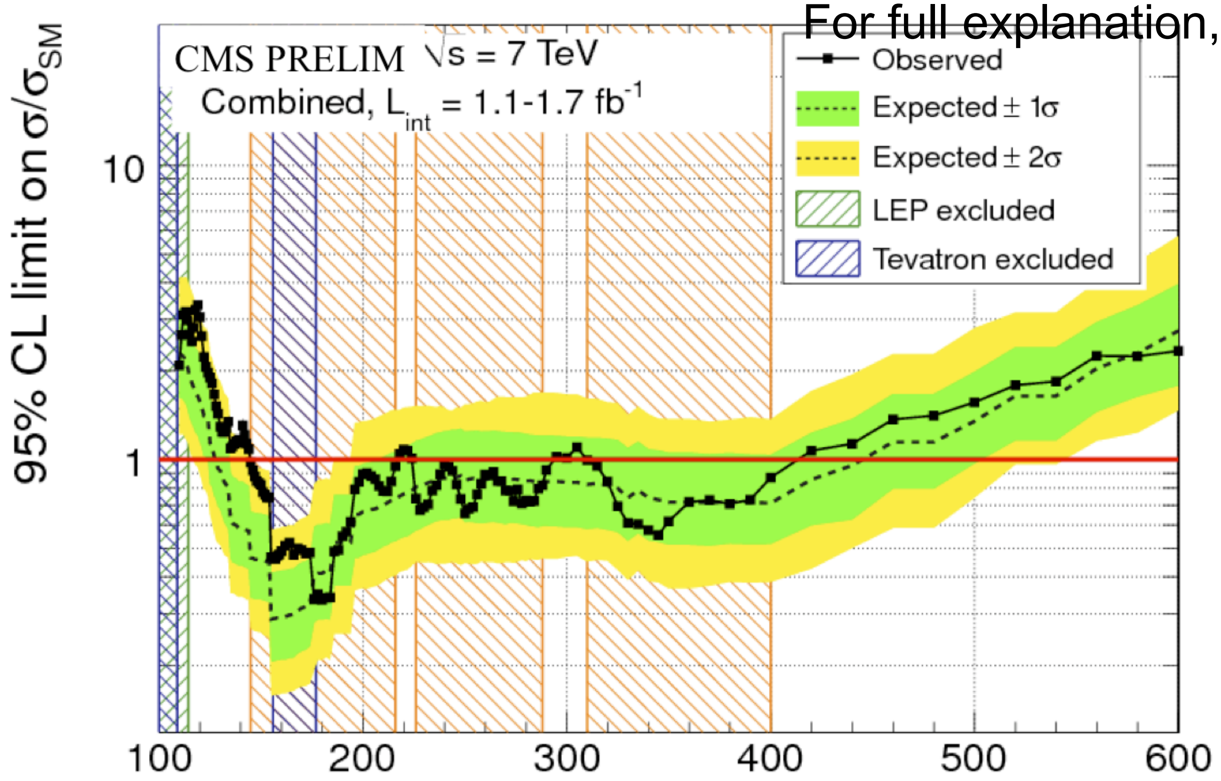
- New Physics could be at ~2TeV, or more complicated than the simplest scenarios we are investigating

We are deep into the most interesting
time in High Energy Physics in ~60 years.
Stay tuned.

Backup Slides

Higgs Exclusion Plots

In a nutshell: masses with the observation below the line at 1 is excluded, within the Standard Model, at 95% C.L.



For full explanation, see backup

Note: in New Physics scenarios the Higgs have different cross sections, invisible decays, etc .

➔Exclusion limits shown here become invalid!

More on Dark Matter

The "WIMP miracle":
Dark matter abundance is given by

$$\Omega_{\rm DM} \propto 1/\left\langle \sigma_{\rm ann} v \right\rangle \propto M_{\rm DM}^2/\alpha_{\rm DM}^2$$

Take M_{DM}~ 100 GeV and α_{DM} ~weak coupling
→right abundance

$$\Omega_{DM}h^2 \sim 0.1$$

- LHC has established its first set of basic top quark measurements using only a few hundred top candidates
  - First measurements of top at a radically higher energy scale!
  - with the current precision the production cross sections are in agreement with the calculations. Important validation of QCD tools

- Are there any "smoking guns" in the large Tevatron top data set- things that the LHC will investigate soon?

Anomalous Forward Backward Asymmetry

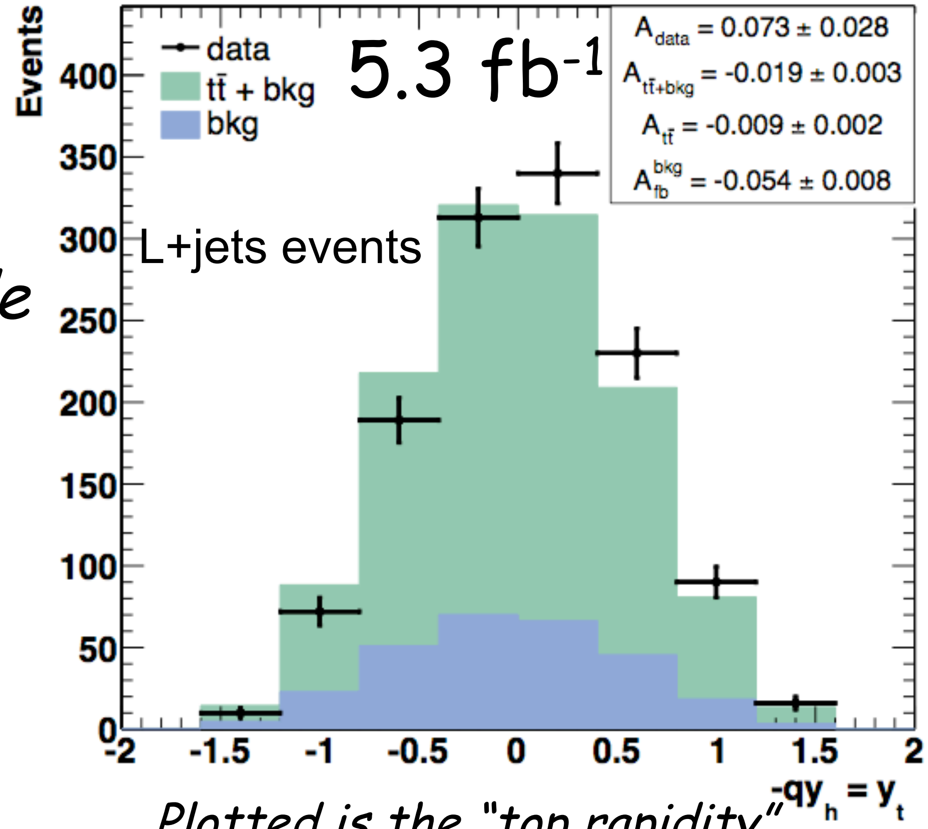
- Tevatron measures the "charge asymmetry": compare number of top and anti-top produced with momentum in a given direction, in $p\bar{p}$ lab frame or in $t\bar{t}$ rest frame

$$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

- Observable measures the tendency of the top quark to move forward along the same direction as the incoming quark. In the SM, this asymmetry is zero at LO.
  - At NLO: ~5% net positive asymmetry due to interference between ttj states (ISR, FSR)

Results, A_{FB}

In l+jets+btag channel: tag t vs $\bar{t}$ with lepton charge, use hadronic side to measure top rapidity



Plotted is the "top rapidity" (product of lepton charge and hadronic rapidity) in lab frame

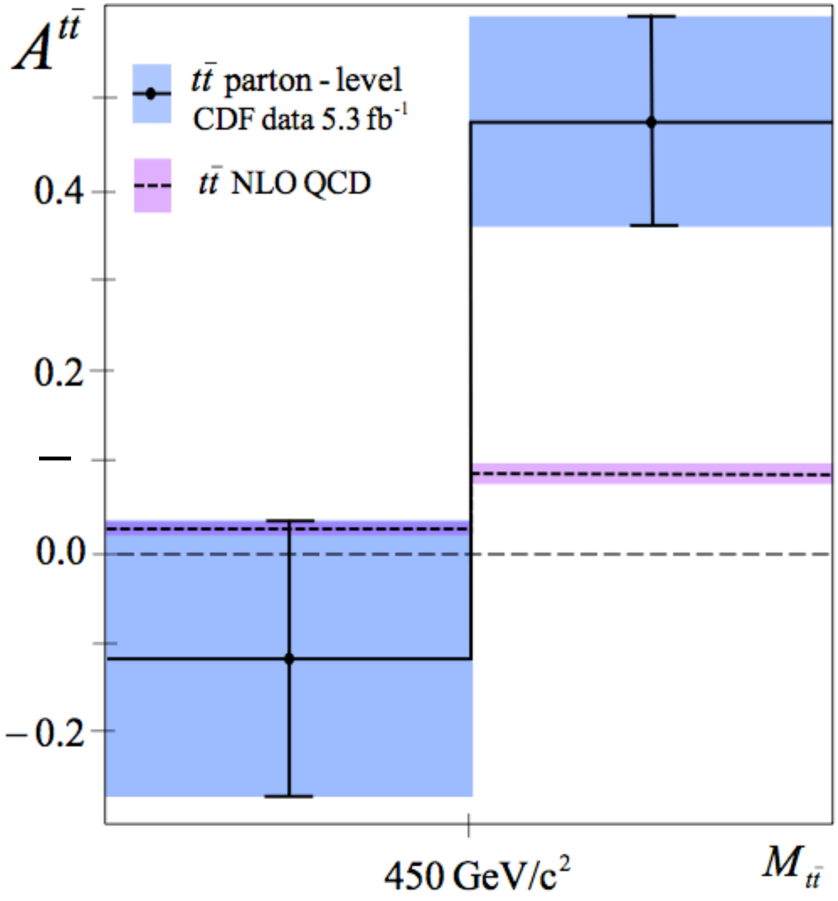
At parton level:

A_{fb}= 15.0% ± 5%

In rough agreement with SM at NLO (5%±1%), a ~2 σ discrepancy

A_{FB} at low and high mass of the $t\bar{t}$ system

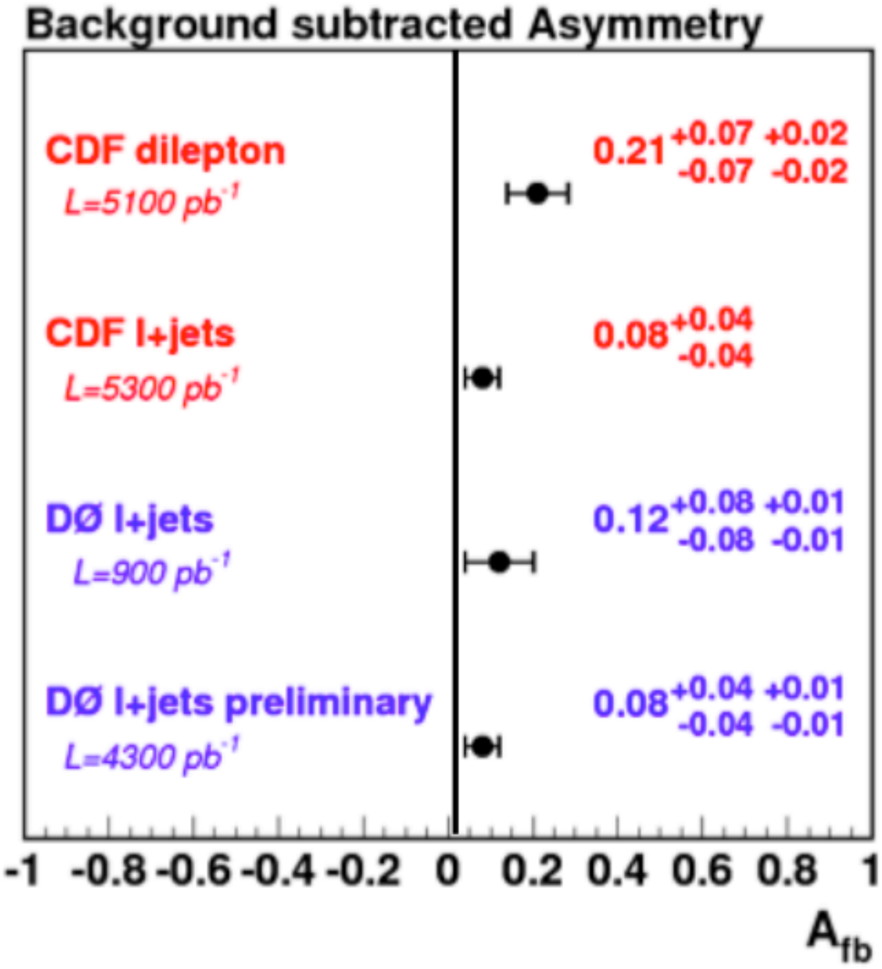
Note: at higher m_{tt}, we are more sensitive to possible new physics processes coupling to top quarks.



- for m_{tt}>450 GeV/c^2
  A_{fb}= 47.5% ±11% (parton level)

>3 σ discrepancy
hep-ex/1101.0034

comparisons



Other implications for the LHC?

- Which new processes could enhance A_{FB}, and can we observe them at the LHC?
  - Axigluons (V-A structure), e.g. Bai, Hewett, Kaplan et al, arXiv:0911.2955, would result in a di-jet resonance
  - production of a new scalar top partner (~200 GeV) that decays to a top quark (and invisible particle), e.g. Isidori, Kamenik, arXiv:1103.0016
  - Z' with flavor changing couplings between u and t quarks. Murayama et al, arXiv:0907.4112v1, would result in a same-sign top signature

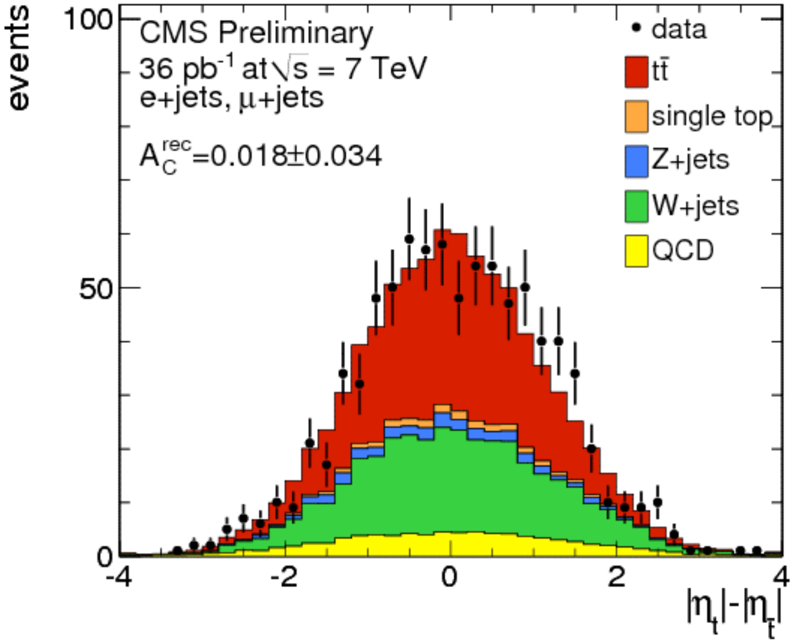
not an easy measurement at the LHC

- LHC collides protons, mainly produced in gluon-gluon interactions, so measurement of A_{FB} is very subtle. The SM asymmetry is much more diluted.
- Have checked for possible asymmetry using $\eta(t, \bar{t})$

$$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

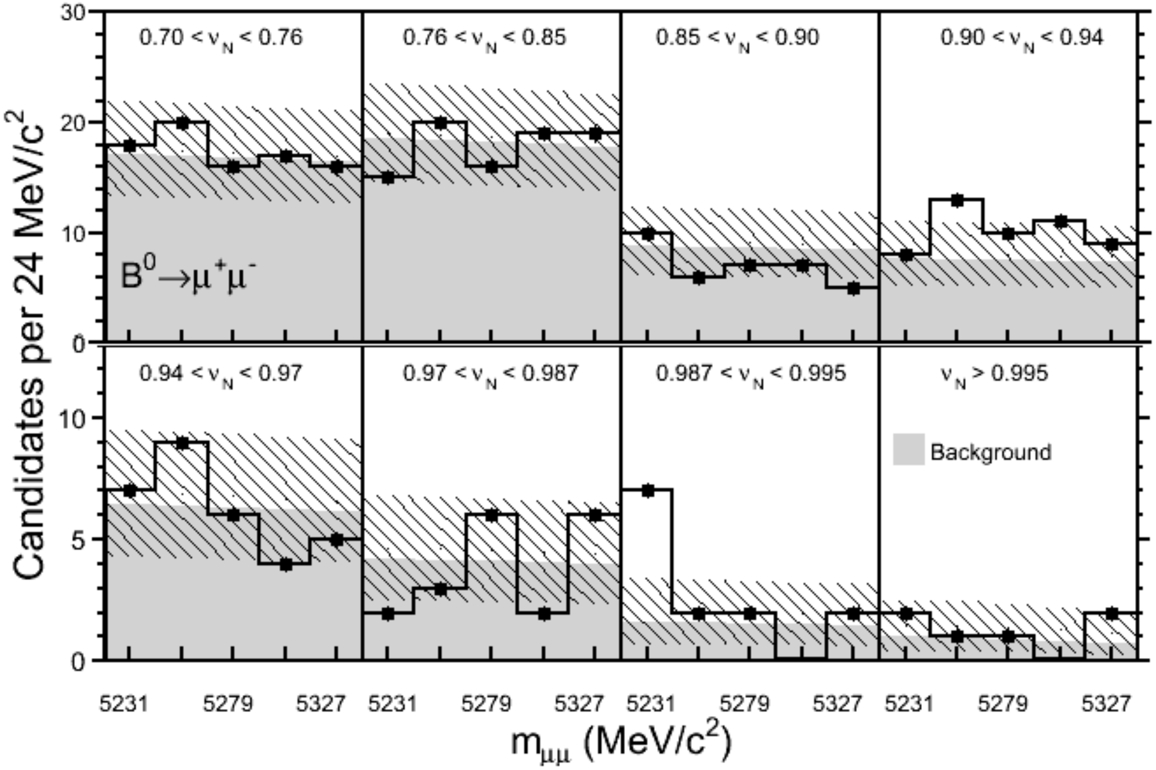
+,- determined from sign of $|\eta(t)| - |\eta(\bar{t})|$

Raw charge asymmetry is consistent with zero.



B^0 signal window, comparison of observation and background prediction

CC, CF combined

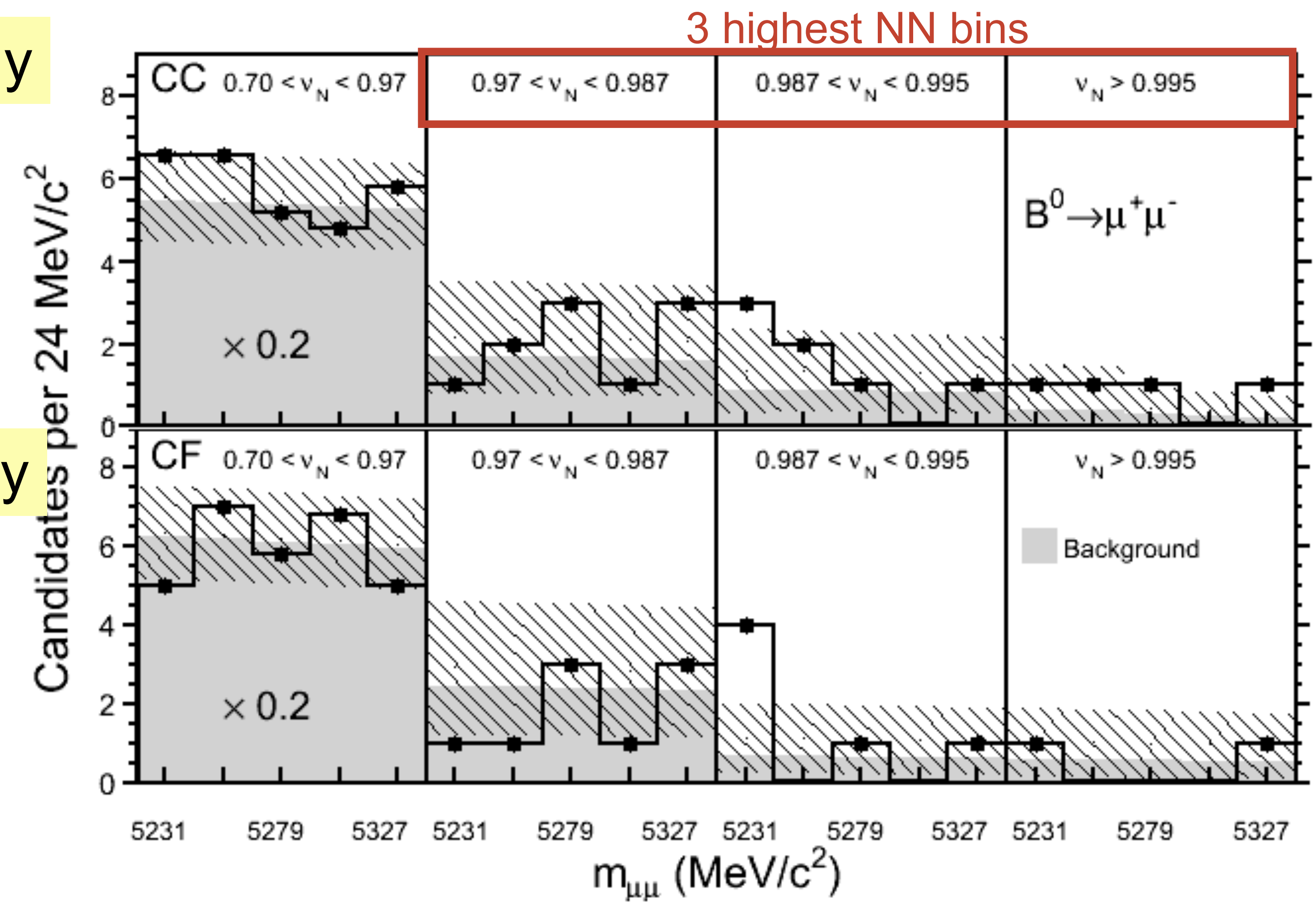


Dark hatched band shows the total uncertainty on the background estimate calculated by adding in quadrature the systematic uncertainty on the mean expected background in each bin with the associated poisson uncertainty.

Data and background expectation are in good agreement

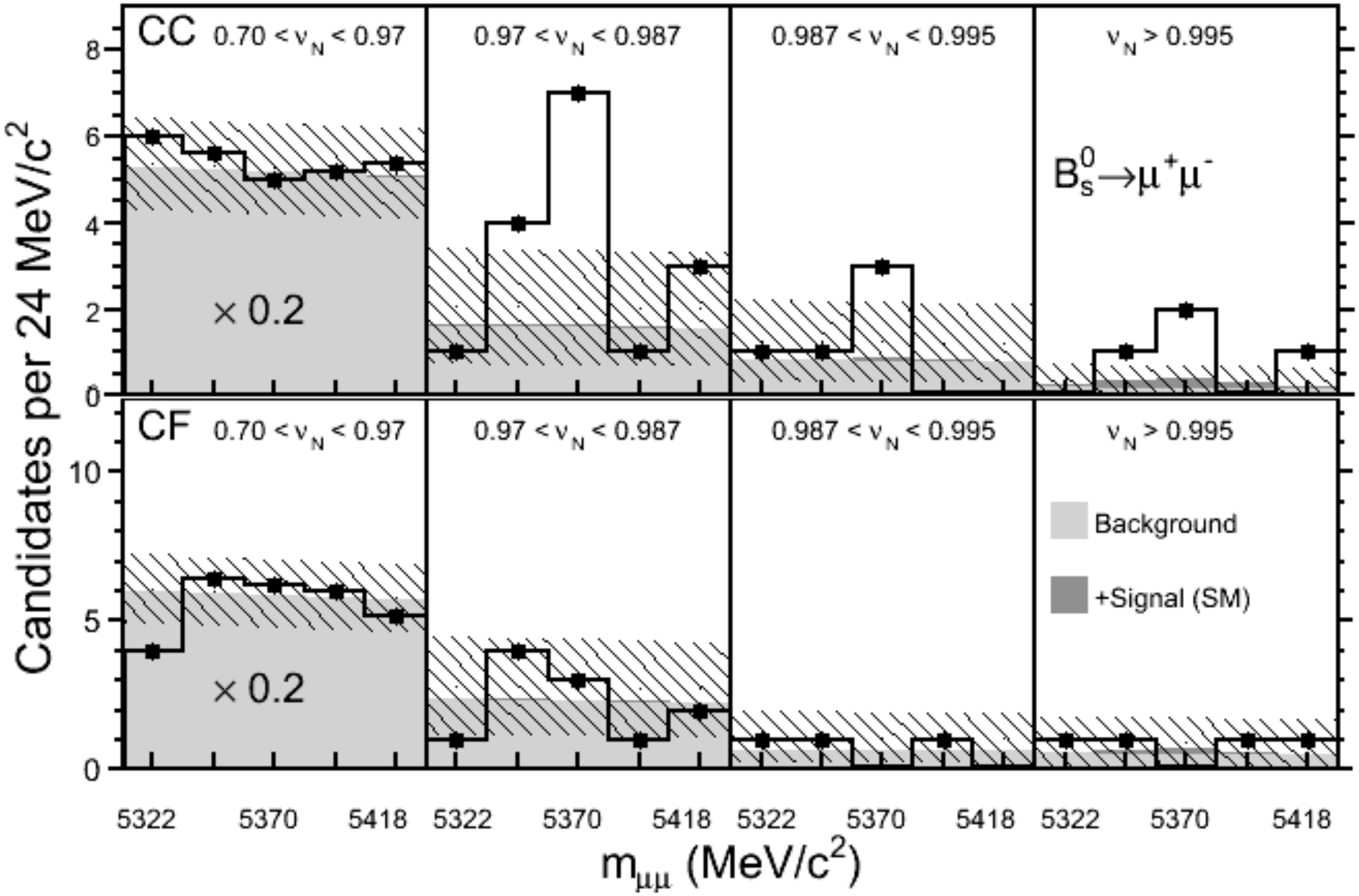
B^0 signal window, comparison of observation and background prediction

CC only


3 highest NN bins

CF only

Data in B_s signal window

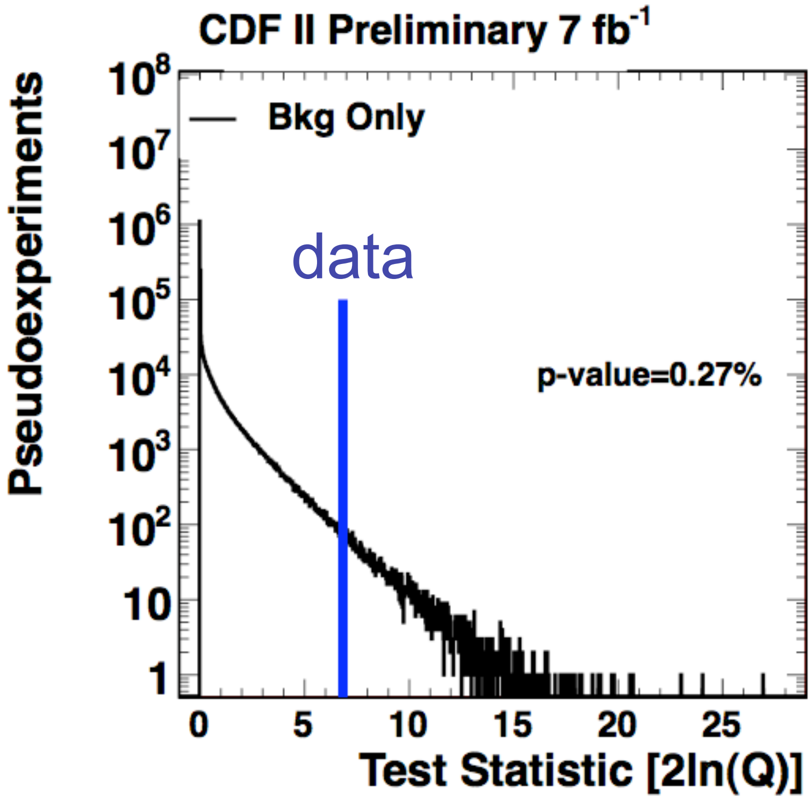


P value for background-only hypothesis

Log Likelihood Distribution of pseudo-experiments for background hypothesis

Observed p-value: 0.27%.

This corresponds to a 2.8σ discrepancy with a background-only null hypothesis (one-sided gaussian)



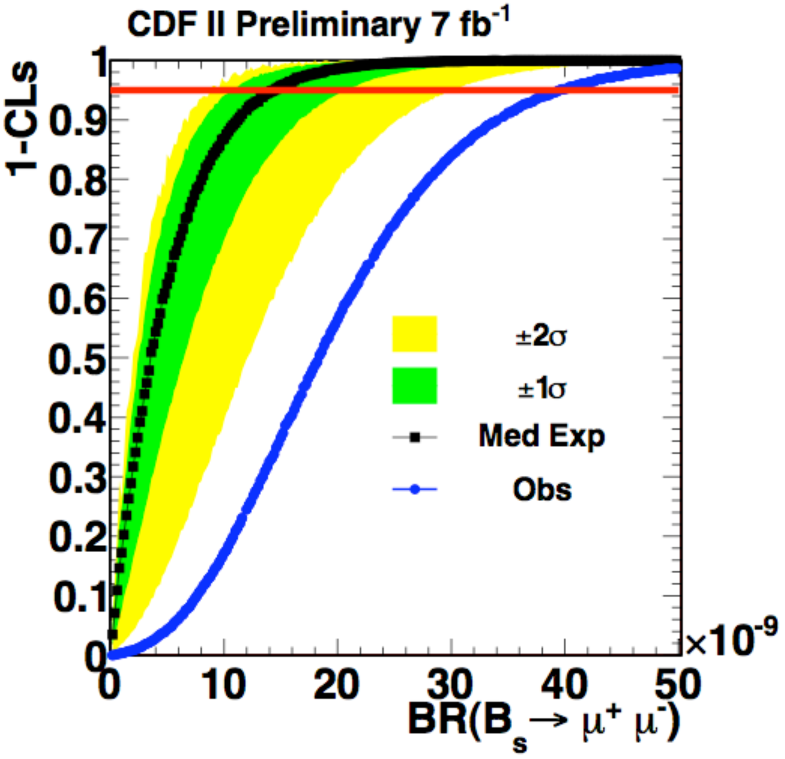
$B_s \rightarrow \mu^+\mu^-$ search, observed limit

assuming that all observed events come from background only:

$BR(B_s \rightarrow \mu^+\mu^-) < 4.0\times10^{-8}$

at 95% C.L.

- Compare to the expected limit $BR(B^0 \rightarrow \mu^+\mu^-) < 1.5\times10^{-8}$
- outside the 2σ consistency band



Need statistical interpretation of the observed excess:

- what does a fit to the data in the B_s search window yield?

Fit to the data in the B_s search window

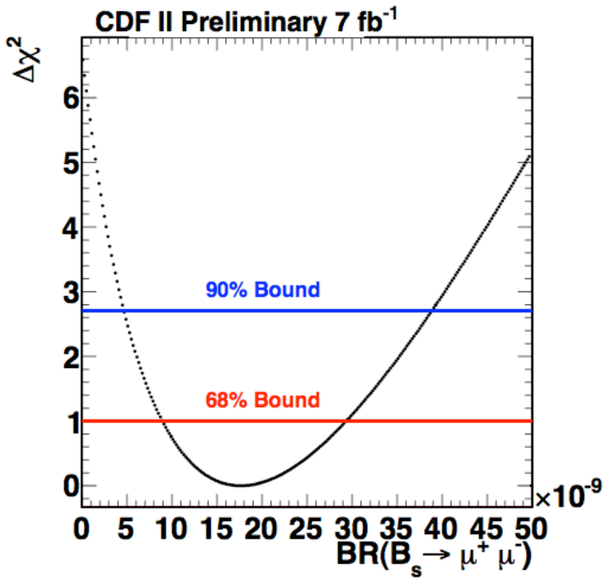
Assuming that the observed events have a significant contribution from either SM or NP source of $B_s \to \mu^+\mu^-$:

first two-sided limit of $B_s \to \mu^+\mu^-$ decay

$$4.6\times10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.9\times10^{-8}$$

@90% C.L.

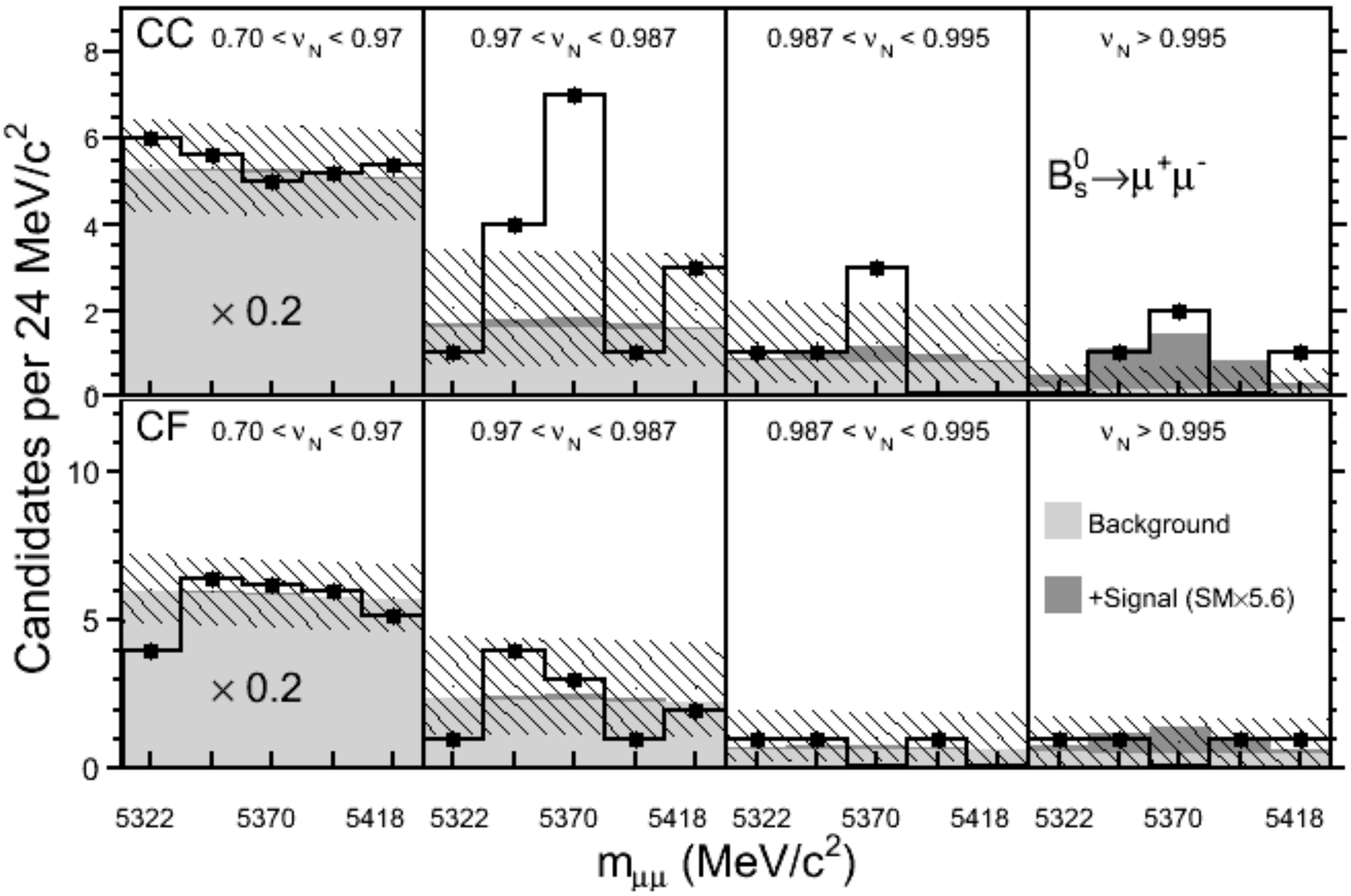
$$BR(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9}\times10^{-8}$$



Compare to SM calculation of

$$BR(B_s \to \mu^+\mu^-) = (3.2\pm0.2)\times10^{-9}$$

Data in B_s signal window

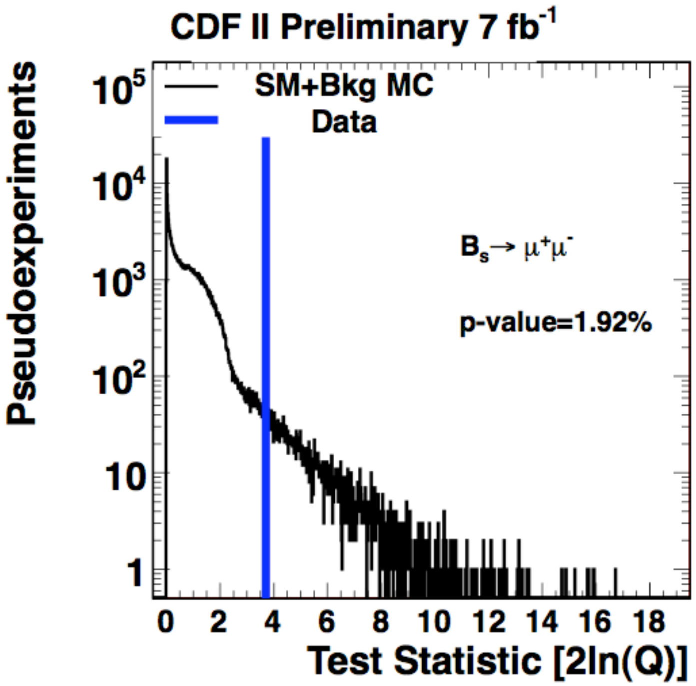


Consistency with the SM prediction of $B_s \to \mu^+\mu^-$ decays

reminder: SM prediction: BR($B_s \to \mu^+\mu^-$)=$(3.2\pm0.2)\times10^{-9}$

A. J. Buras et al., JHEP 1010:009,2010

If we include the SM BR($B_s \to \mu^+\mu^-$) in the background hypothesis, we observe a p-value of 1.9%



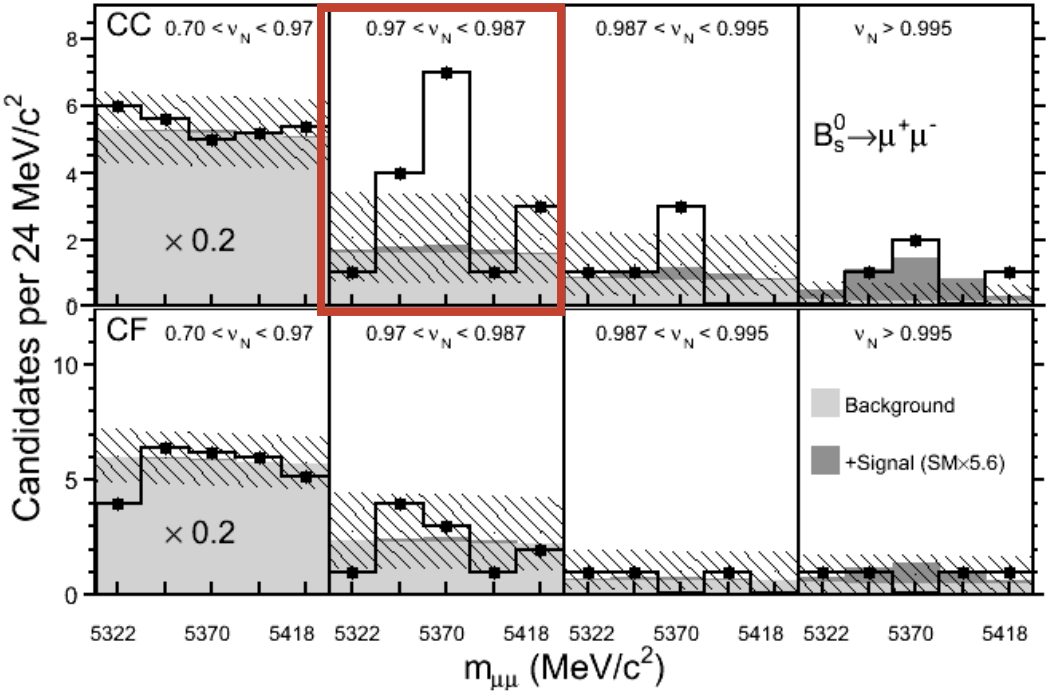
taking into account the small theoretical uncertainty on the SM prediction by assuming +1σ: p-value: 2.1%

A closer look at the data

- in most sensitive NN bin: data looks signal-like

- see a fluctuation in 0.97<NN<0.987- little signal sensitivity in this bin.

B_s signal window, CC and CF separate
Showing only the most sensitive 4 highest NN bins



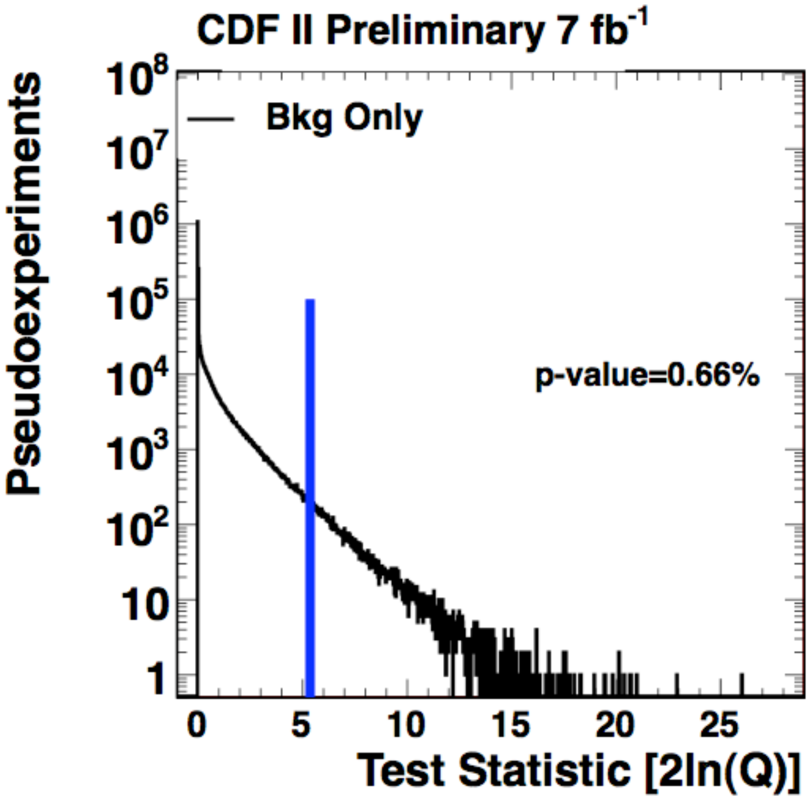
Does this bin drive the result?
Check how the answer changes if we only look at the two highest NN bins..

Fit to the data, only considering the 2 highest NN bins

- Background-only hypothesis:
  Observed p-value: 0.66%
  (compare to 0.27%)

- Background + SM hypothesis:
  Observed p-value: 4.1%
  (compare to 1.9%)

- Conclusion: “fluctuation” in the lower sensitivity bin adds to the observed discrepancy, but is not the driving contribution



- Limits and central value:

$$BR(B_s \to \mu^+\mu^-) = 1.4^{+1.0}_{-0.8} \times 10^{-8}$$

$$3.3\times10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.3\times10^{-8}$$

All Experiments

LHCb: $BR(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}\, at \cdot 95\% \cdot C.L.$ 0.34 fb^{-1}

CMS: $BR(B_s \to \mu^+\mu^-) < 4 \times 10^{-8}\, at \cdot 95\% \cdot C.L.$ 1.1 fb^{-1}

LHC combination: $BR(B_s \to \mu^+\mu^-) < 1.08 \times 10^{-8}\, at \cdot 95\% \cdot C.L.$

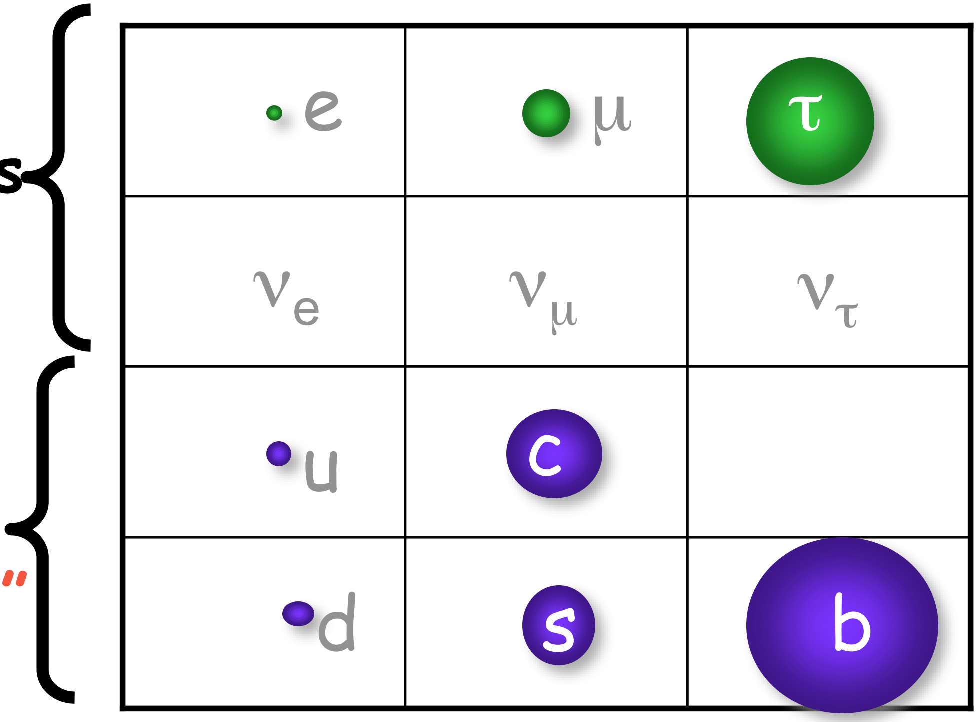
CDF: $4.6 \times 10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}$ at 90% C.L.

$$BR(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

- LHC 95% C.L. combination limit compatible with the 1σ CDF error
- both experiments see low significance excess compatible with the SM expectation (combined p value: 8%)
- some tension between the CDF and LHC results. Need more data

The Standard Model (SM)

The Matter Particles (Fermions):



6 leptons

quarks
6 "flavors"

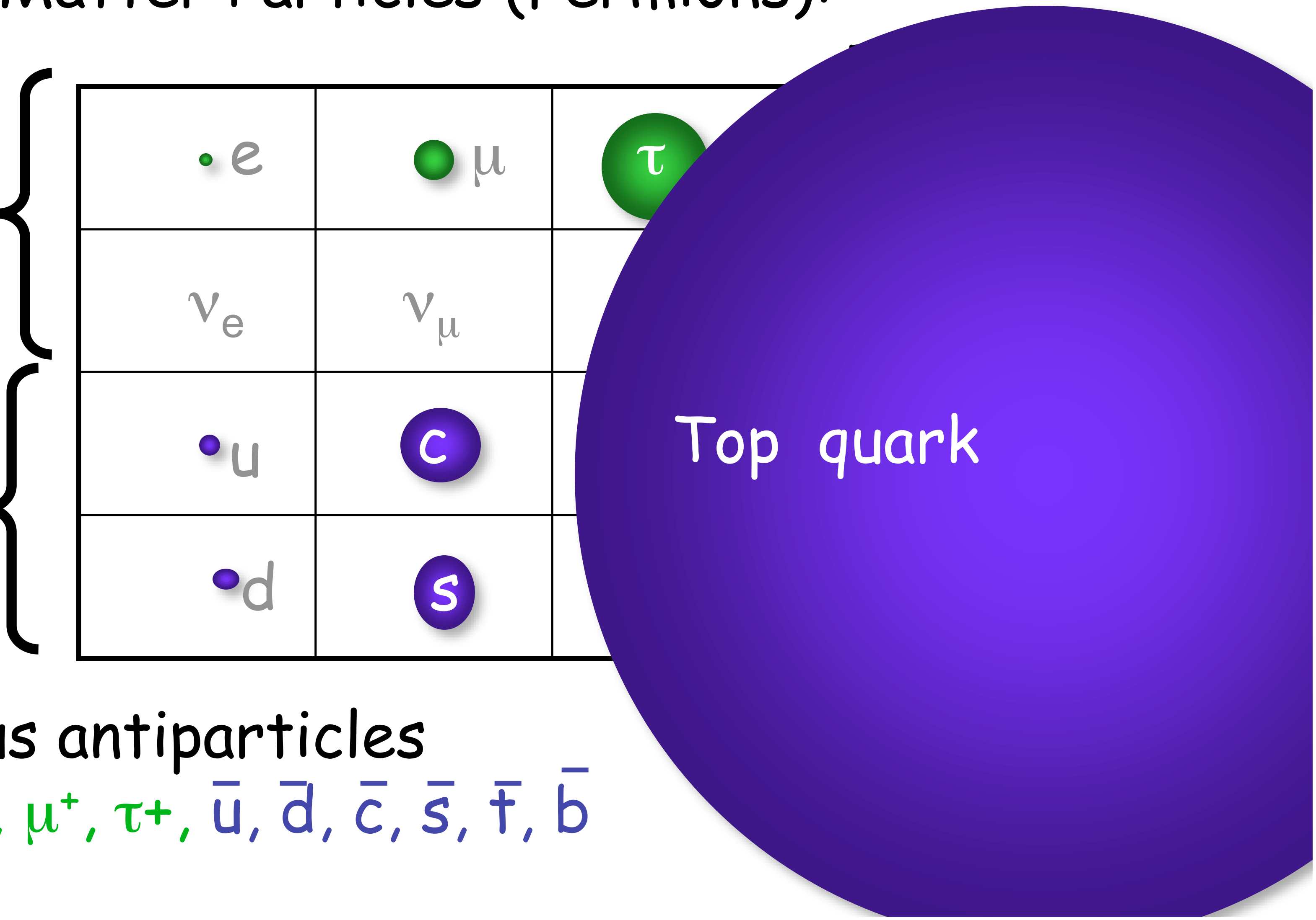
			Electric charge
e	μ	τ	Q= -1
ν_e	ν_μ	ν_τ	Q=0
u	c		Q=+2/3
d	s	b	Q=-1/3

..plus antiparticles of opposite charge:

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

The Standard Model (SM)

The Matter Particles (Fermions):



6 leptons

quarks
6 "flavors"

e	μ	τ
ν_e	ν_μ	
u	c	
d	s	

..plus antiparticles

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

The Masses

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

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

Surprise →almost as heavy as an atom of gold = 79 protons + 118 neutrons + 79 electrons.

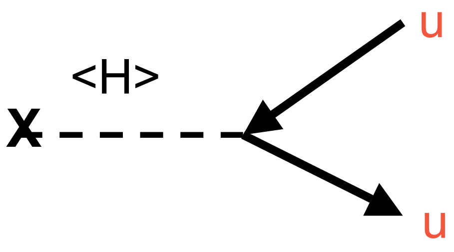
These are experimental observations-- masses cannot be predicted in the SM

How masses are generated in the SM: the "Higgs Mechanism"

- 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
  - Causes "Spontaneous symmetry breaking"

Coupling to the Higgs field

- In this theory, the fermions acquire mass by interaction with the Higgs field



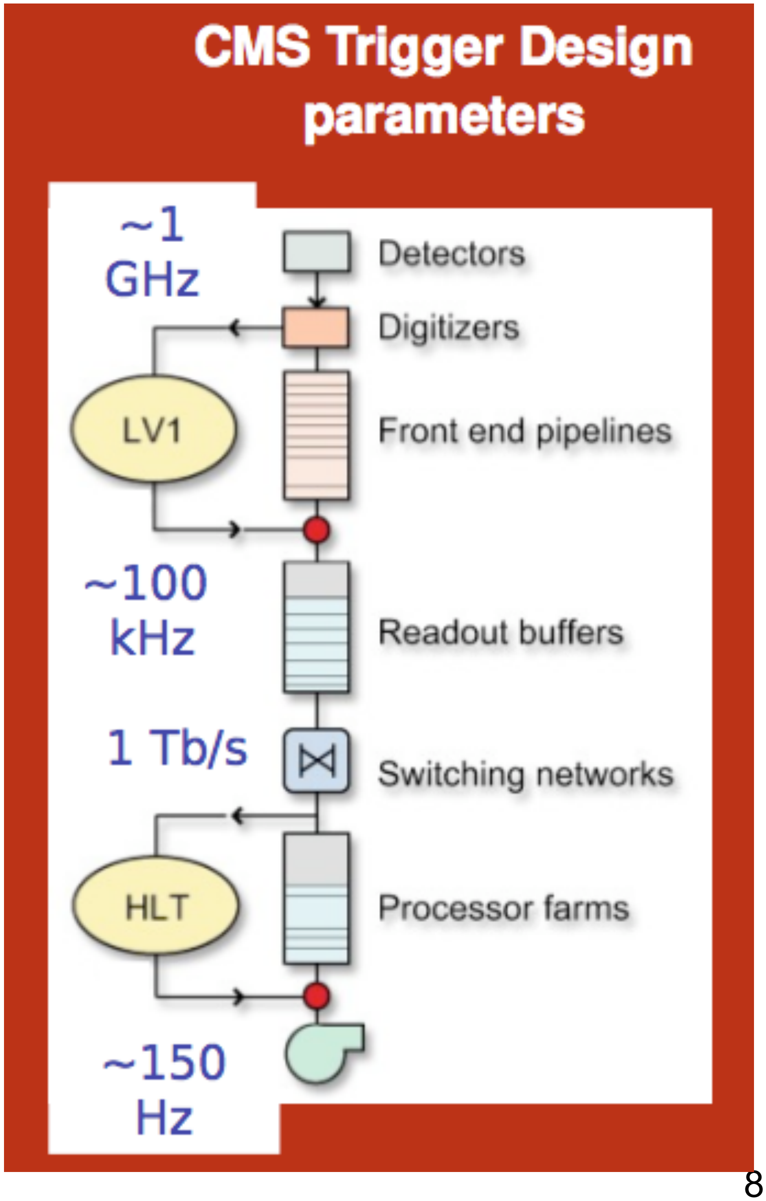
Analogy: effective mass of electron moving through crystal lattice

- Large fermion mass hierarchy is put in by hand via appropriate coupling constants spanning 5 orders of magnitude
  - The coupling constant for the top quark is ~1, all others are much smaller

➡ The top mass is suspiciously close to the scale of electroweak symmetry breaking (EWSB). This unique property raises a number of interesting questions

Trigger

- First decision (reduction 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



CMS Trigger Design parameters

The CMS detector

Tracker coverage $|\eta| < 2.5$

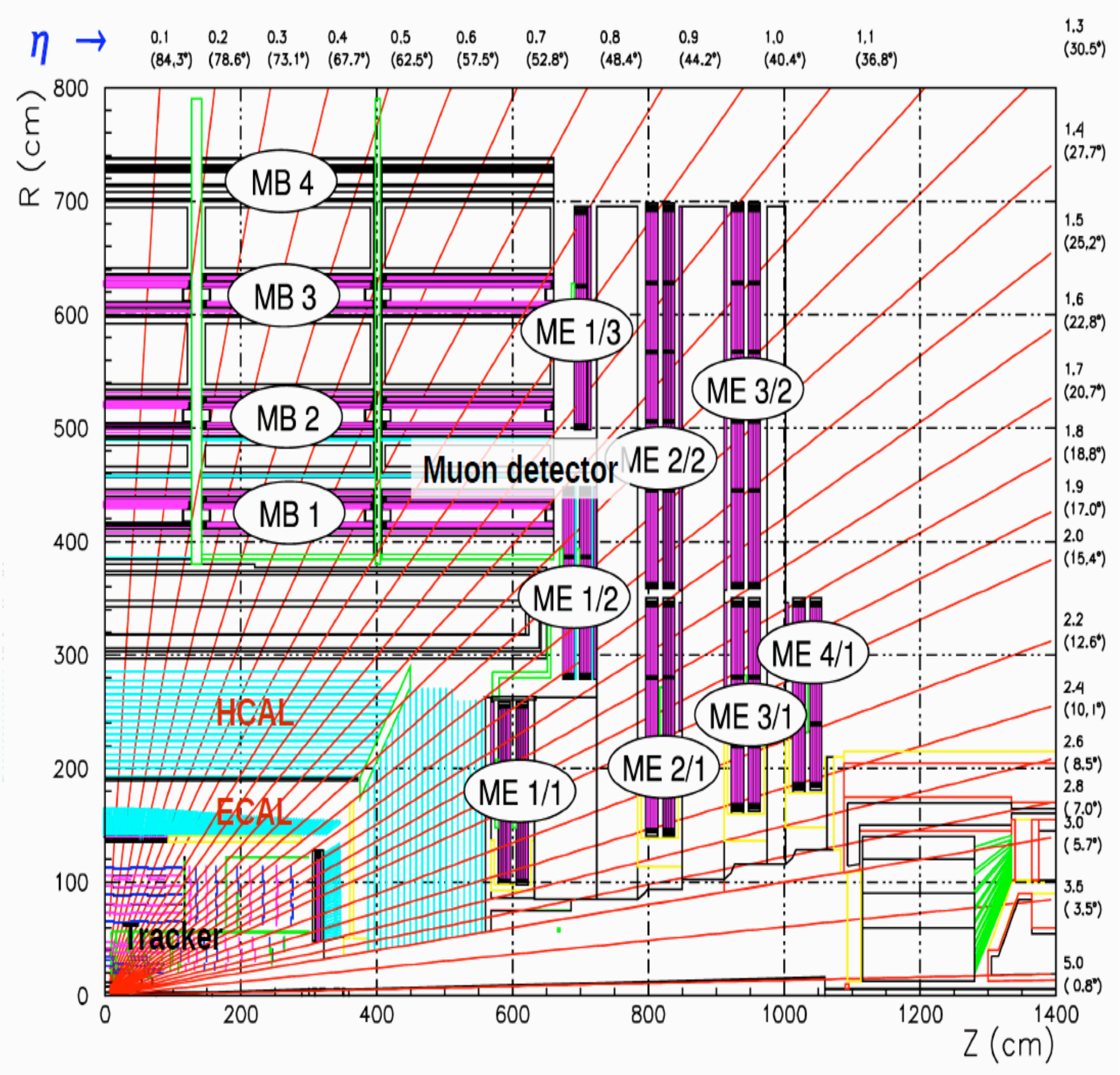
Electron coverage $|\eta| < 2.5$

Muon coverage $|\eta| < 2.4$

Efficient muon (electron) triggering down to 9 (17) GeV at L = 2E32

3.8 T solenoid + 76000 crystal ECAL + 200 m^2 silicon = percent level lepton momentum resolution at high PT

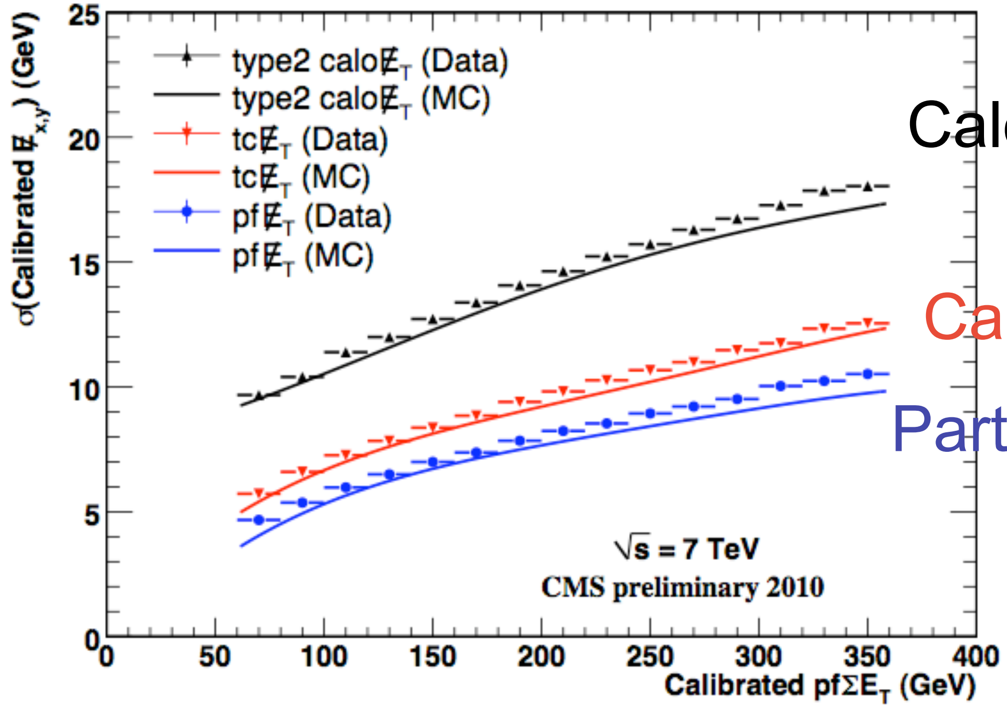
HCAL/HF coverage $|\eta| < 5.0$



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



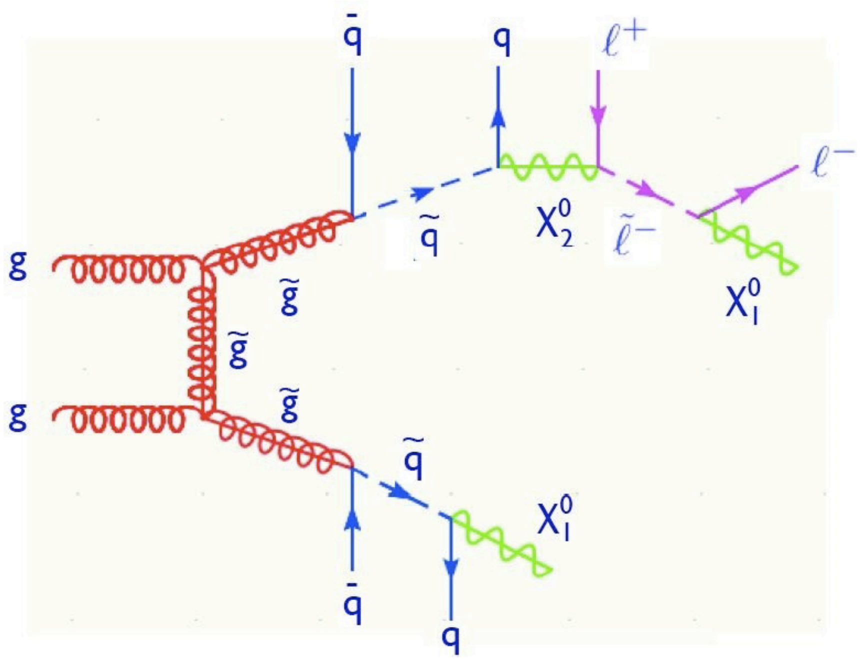
Calorimeter only

Calo+tracks

Particle flow

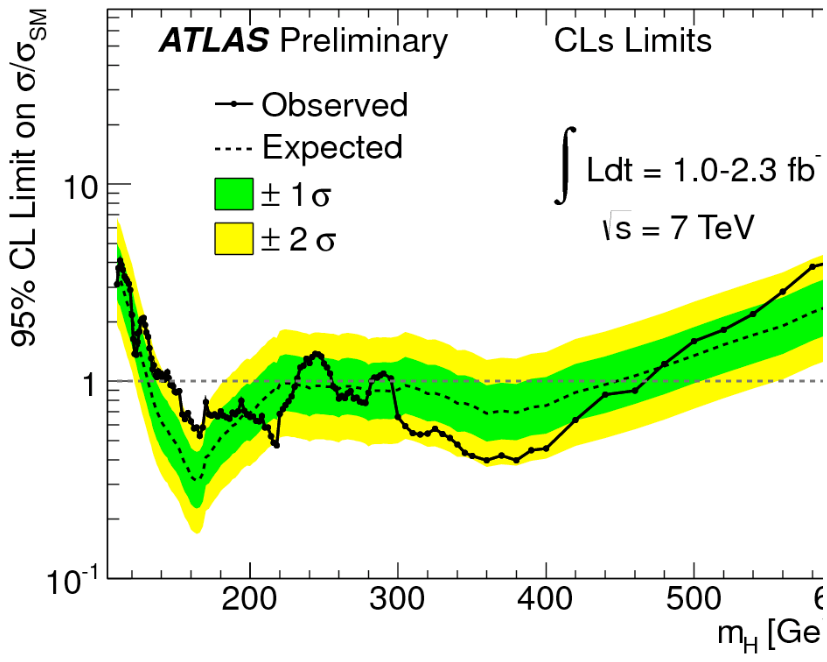
Search for Supersymmetry

Many other variations are possible, for example leptons in addition to jets and MET in the final state.
Subject of many searches at the LHC..

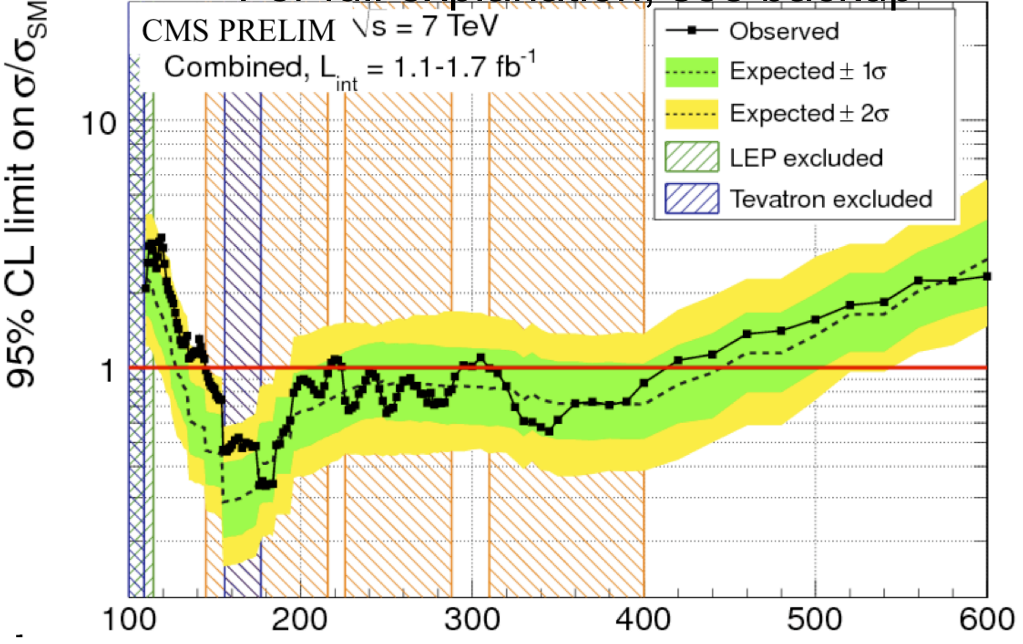


Higgs CMS vs Atlas

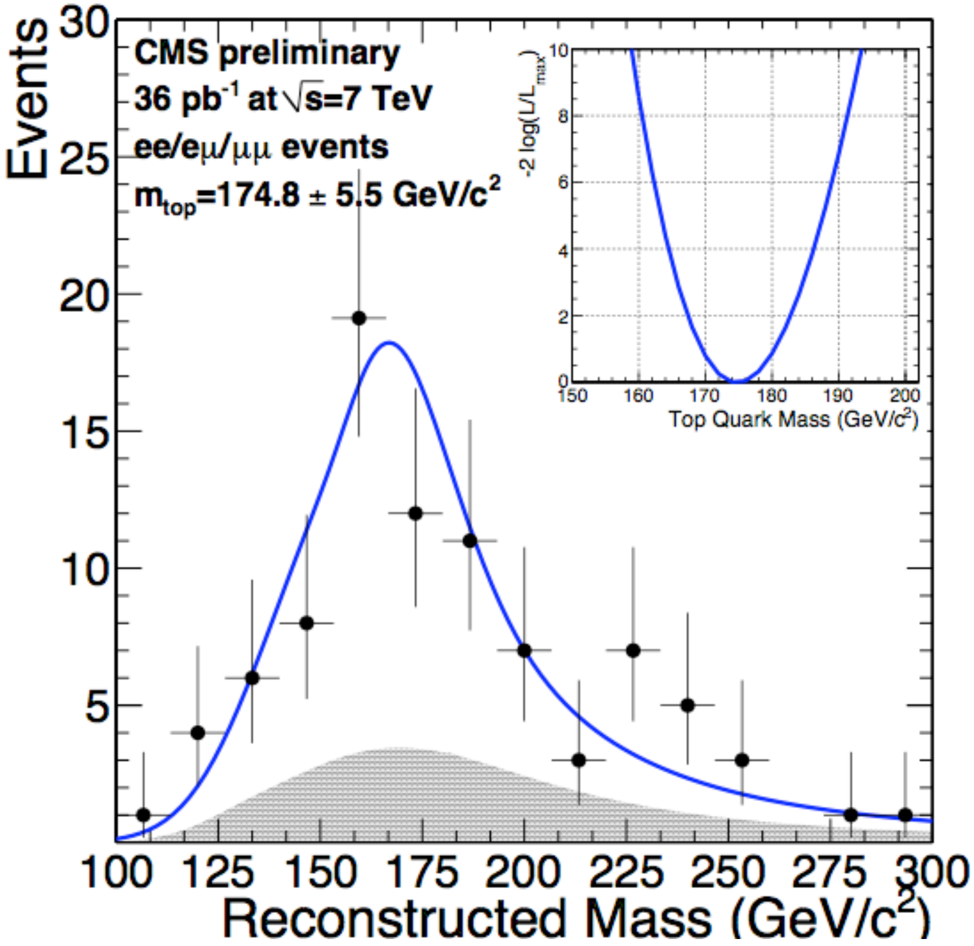
In a nutshell: masses with the observation below the line at 1 is excluded, within the Standard Model, at 95% C.L.



For full explanation, see backup



First top mass measurements with 2010 data



reconstruction method: pick lepton-jet comb. based on solutions upon variation of jet p_T, ME_T direction, $p_z(tt)$, and their resolutions.

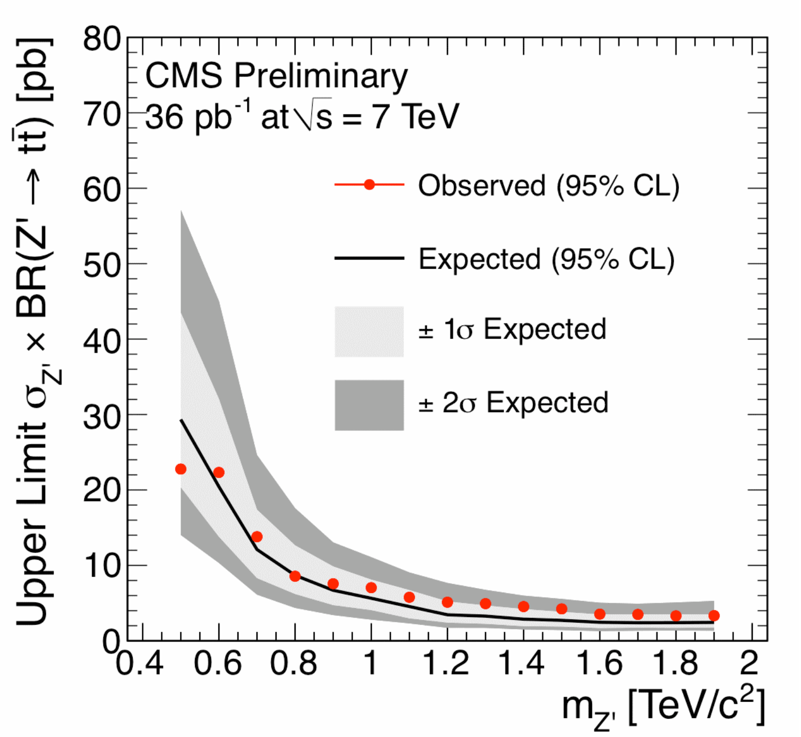
CMS dilepton channel (highest purity): m_t=175.5 ±4.6 (stat)± 4.6 (sys) GeV/c^2

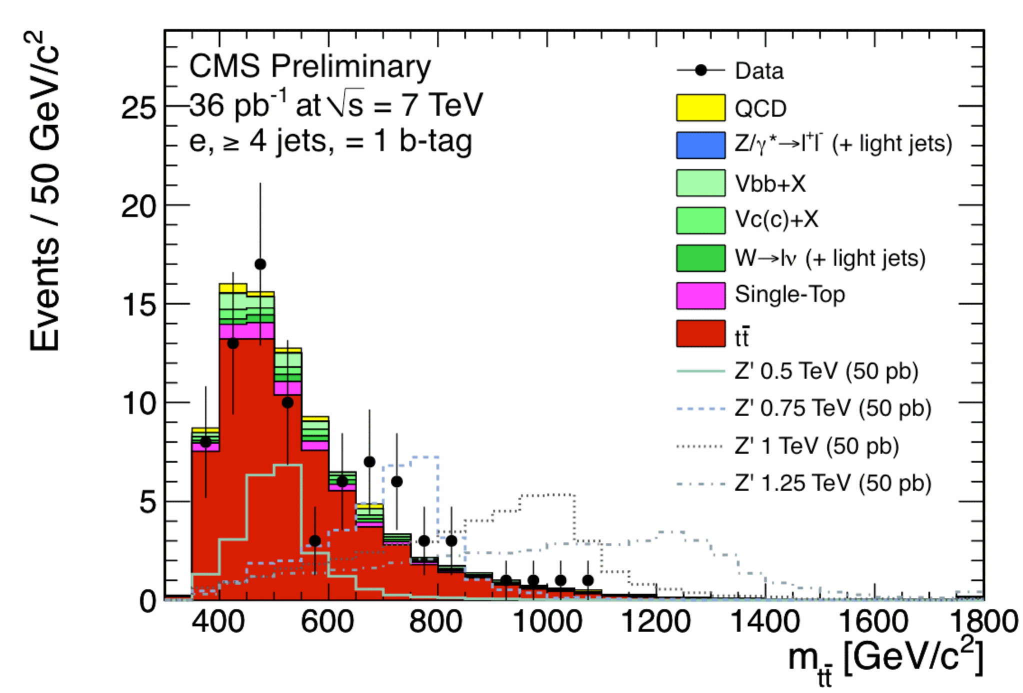
Compare to CDF, D0 combined: 173.1 ± 1.1

Very soon precision will increase and put very tight constraints on m_H

Search for top resonances at CMS

- Z′ decaying to a top quark pair? Look for resonances in the invariant mass spectrum
  - Tevatron reach will be extended at the LHC





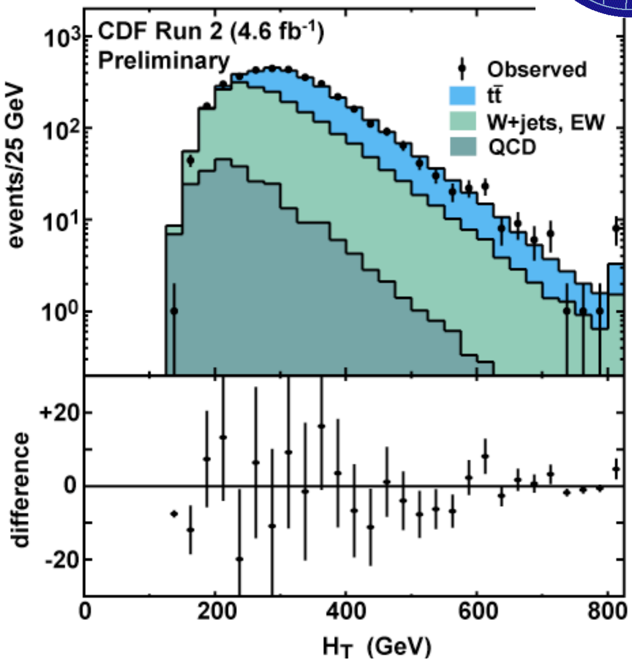
Example plot: Reconstructed m(tt) after kinematic fit (4-jet events with 1 b tag) in the electron + jets channel

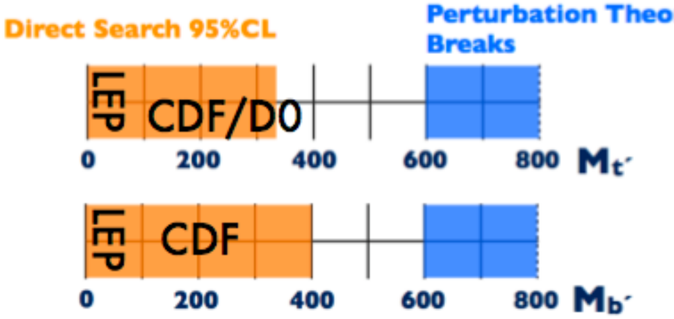
Search for Heavy Top t′ → Wq

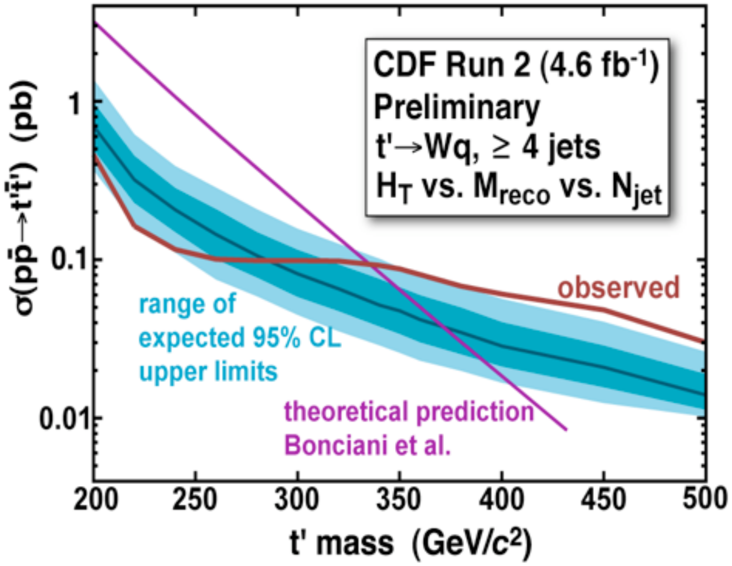
Search for heavy top decay to Wq final states (e.g.LHT)

- Use observed H_T and mass distribution to fit signal t′ and background (top, W,…) distributions

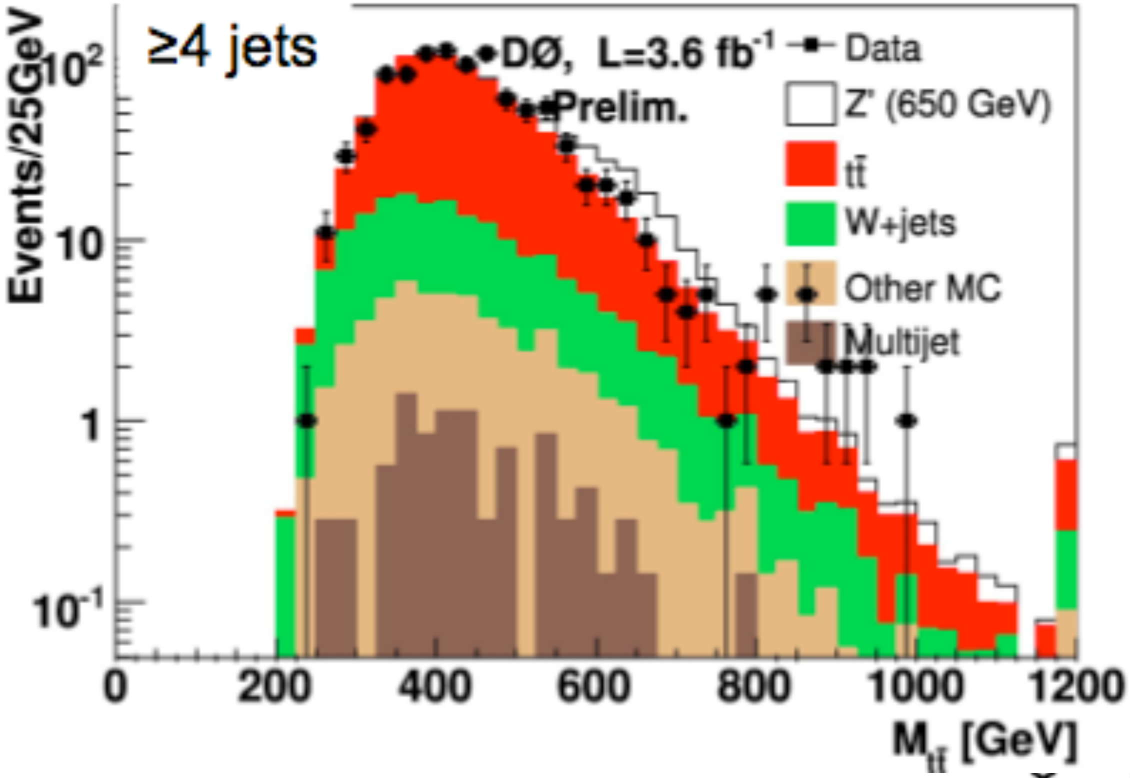
- exclude a standard model fourth-generation t' quark with mass below 335 GeV at 95% CL.



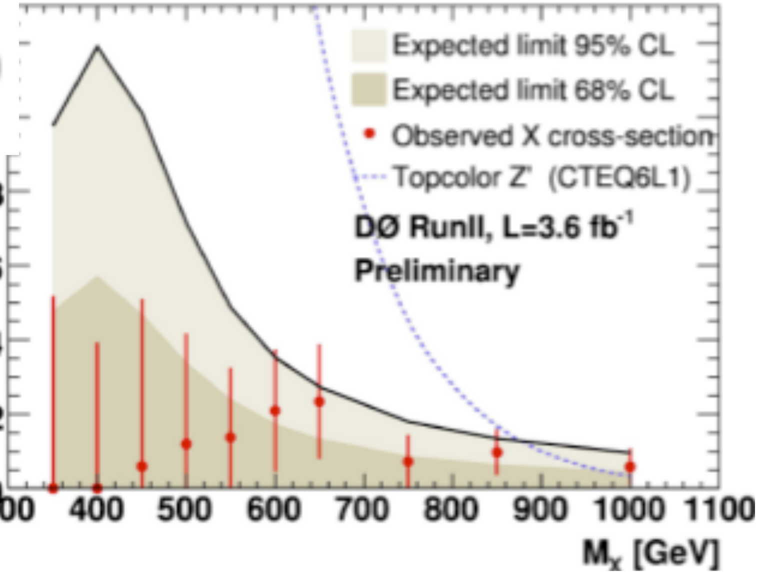




Search for top resonance at D0



Reconstructed m(ttbar) after kinematic fit (4-jet events with 1 b tag) in the electron + jets channel

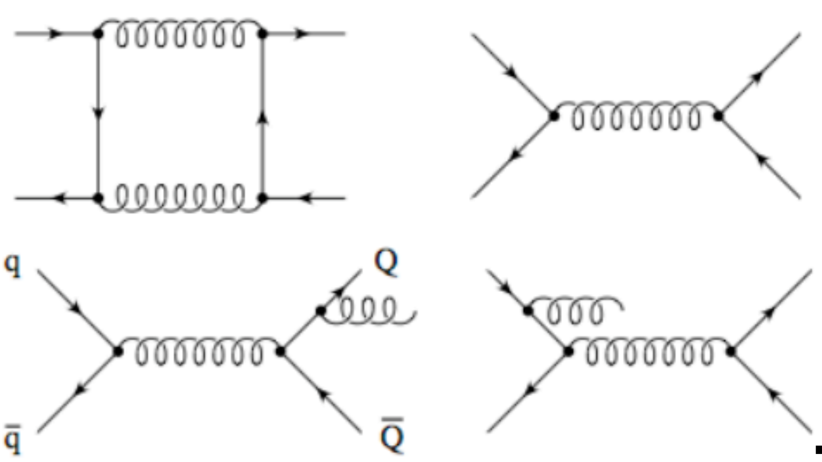


Anomalous Forward Backward Asymmetry

- NLO produces a positive asymmetry (A_{fb}=5%±1%) through interference:

between box and Born diagram

between ttj states



tt frame asymmetries:

A_{FB} ~ +10-12 % NLO

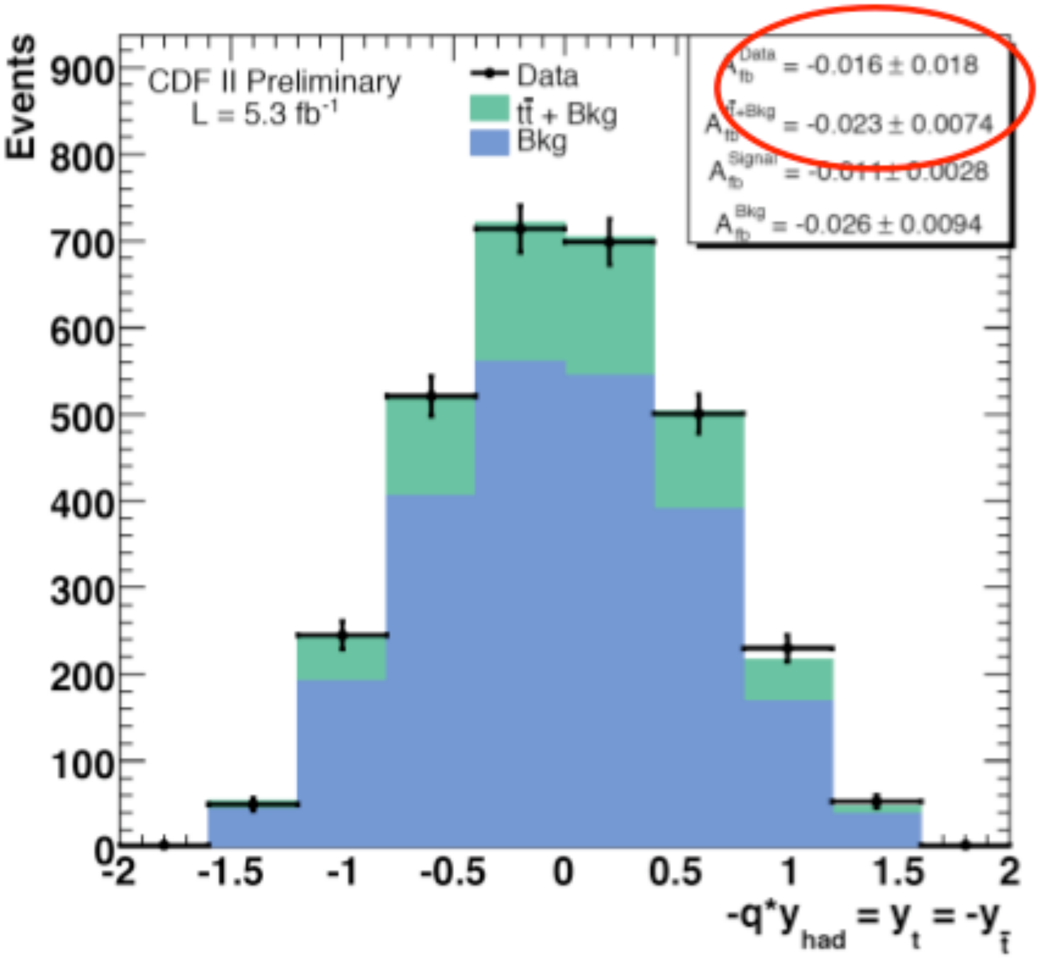
A_{FB} ~ -7 % NLO

Net: ~ 6 +- 1.0 %

Halzen, Hoyer, Kim; Brown, Sadhev, Mikaelian; Kuhn, Rodrigo; Ellis, Dawson, Nason; Almeida, Sterman, Vogelsang; Bowen, Ellis, Rainwater

Cross-check: background dominated asymmetry

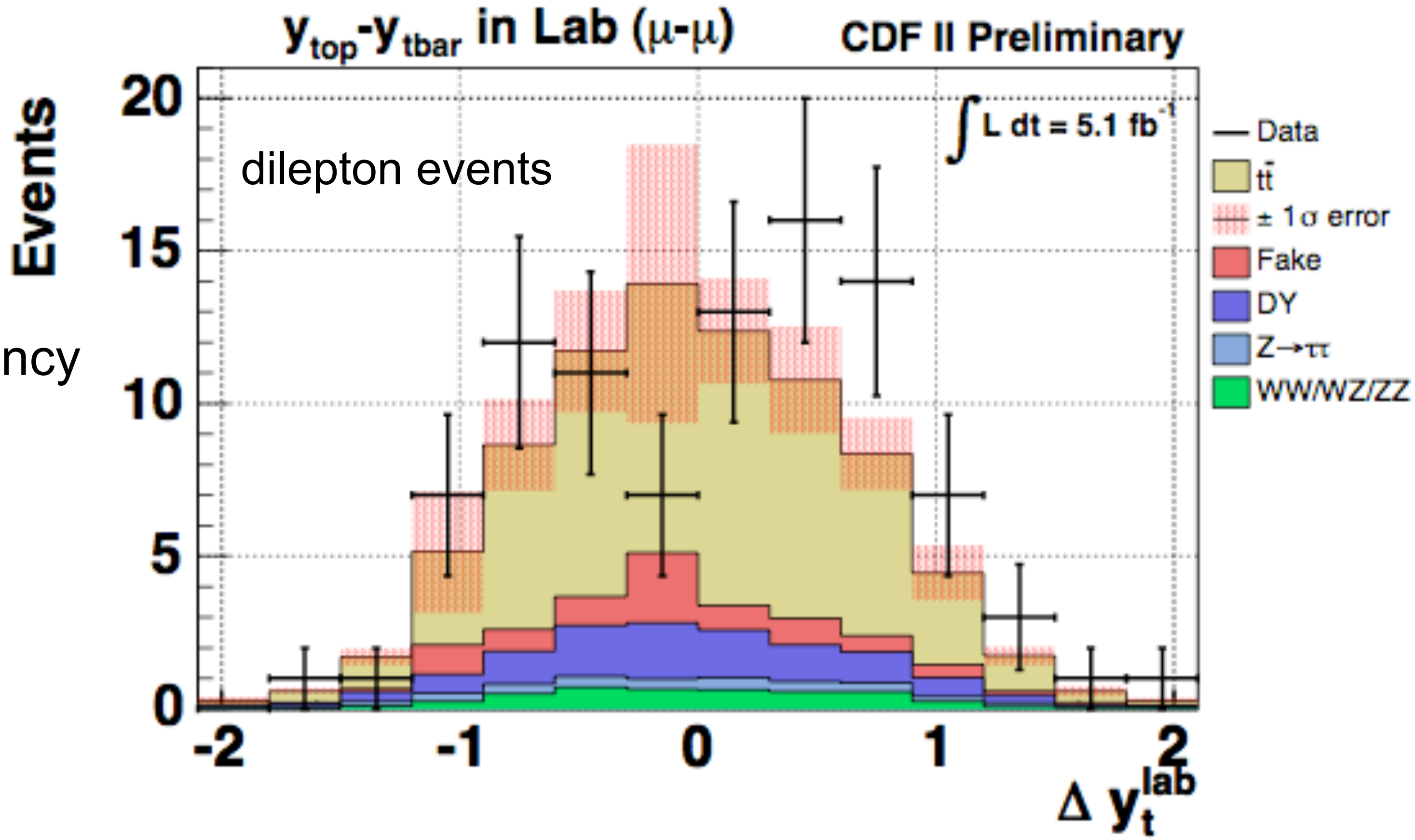
lab frame



A_{FB} in the dilepton channel

- at NLO: A_{fb} = 5%±1.5%
- Observed:

A_{fb}= 42.0% ±16%



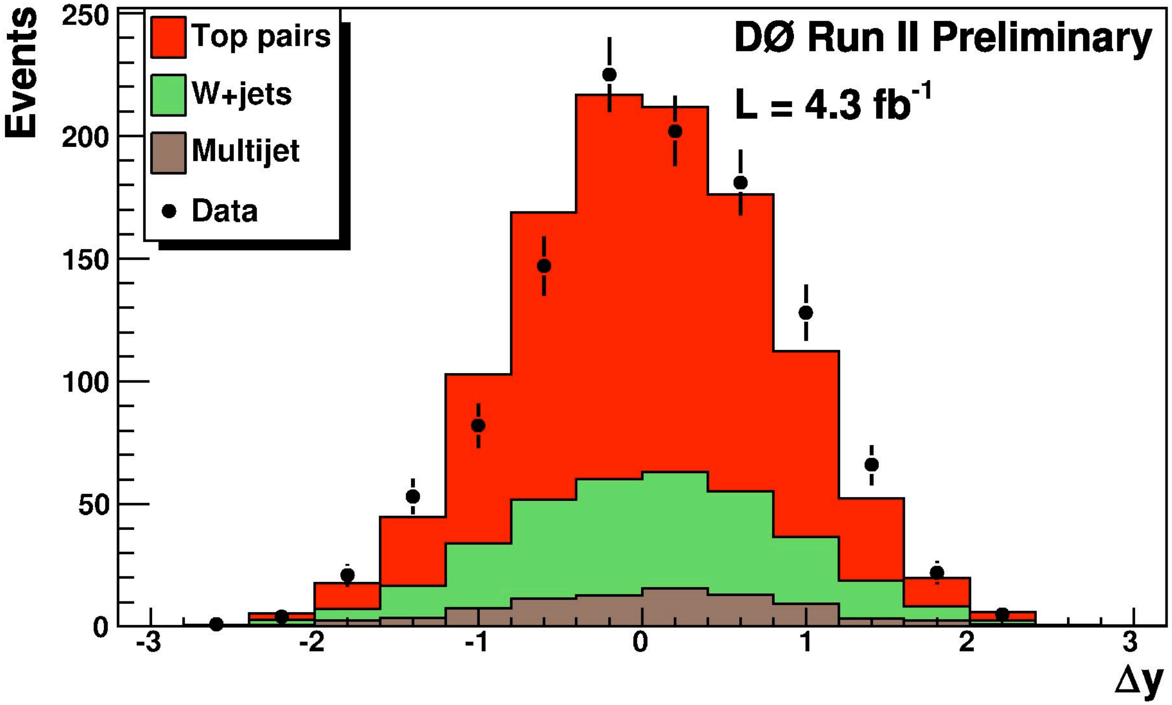
2.3 σ discrepancy

consistent with D0 results

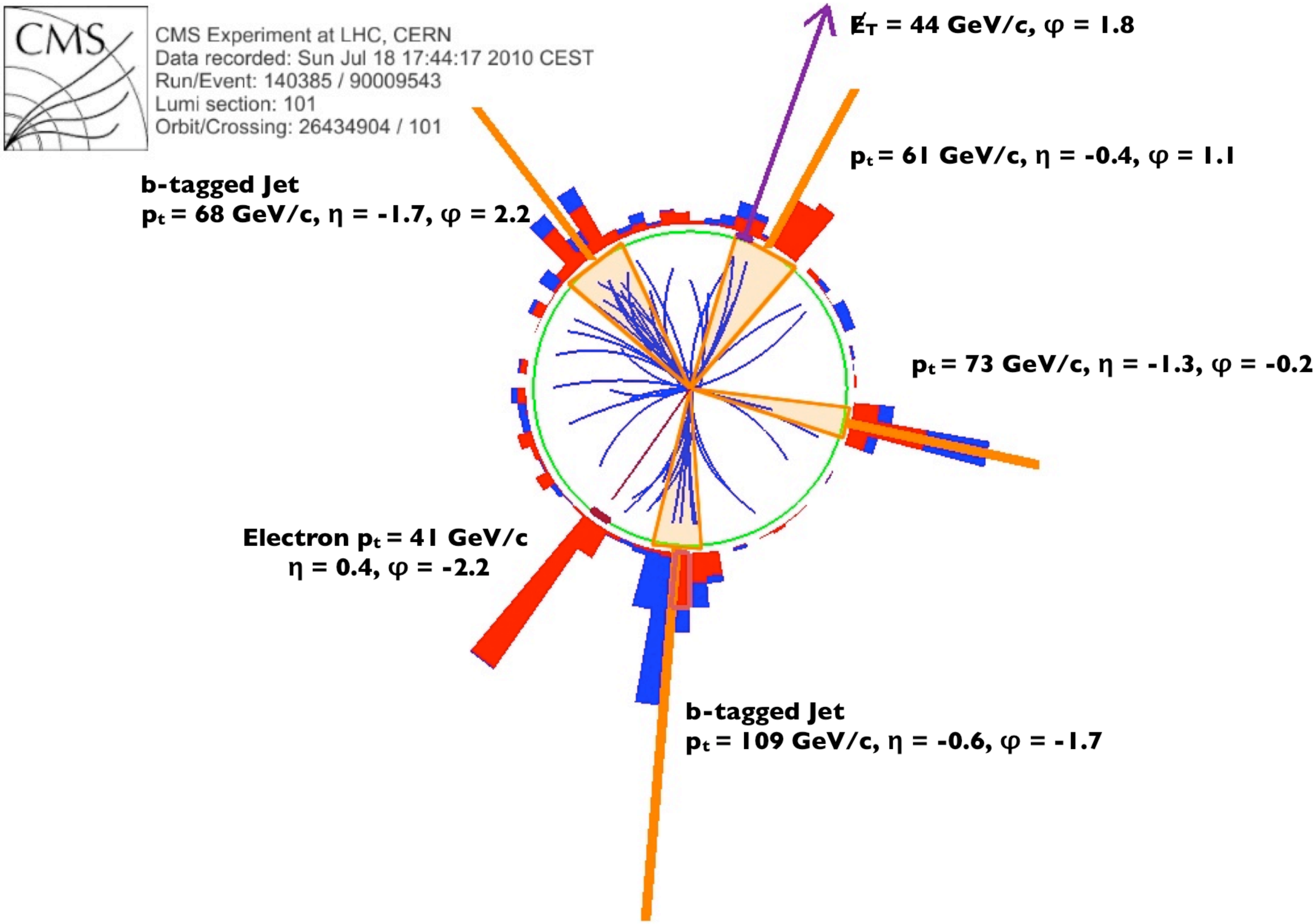
- at NLO: A_{fb} = 1%±1.5%
- Observed:

  A_{fb}= 8.0% ±4%

2 σ discrepancy

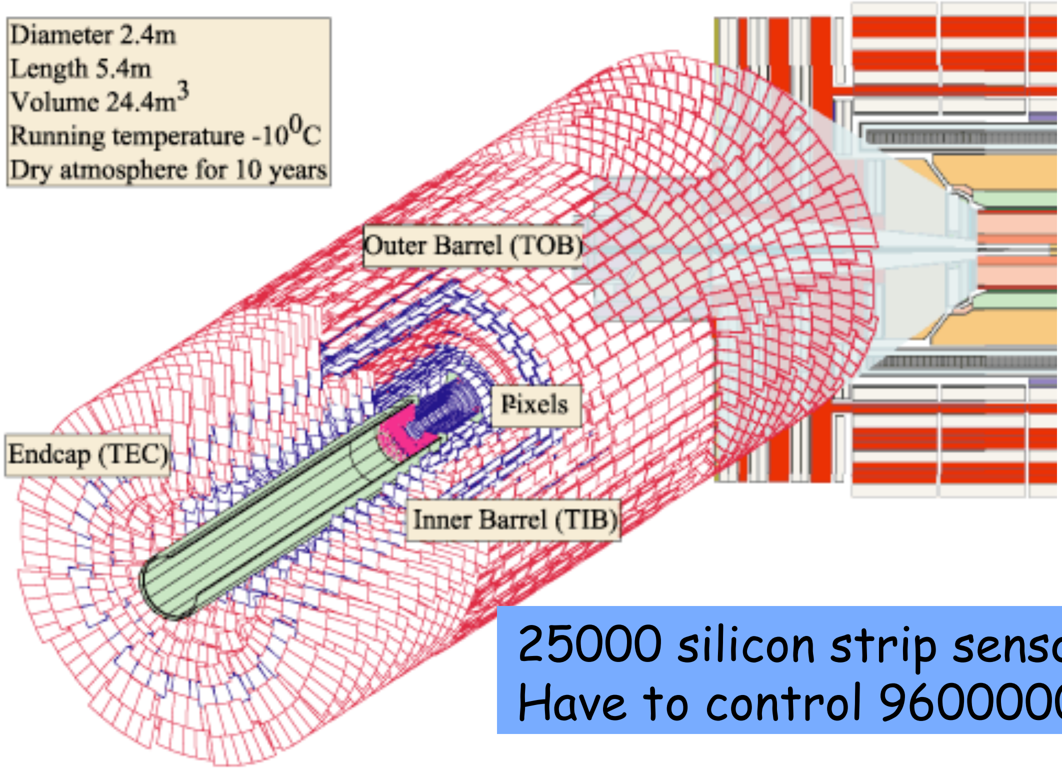


Detector event display of a top decay



CMS silicon strip tracker

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

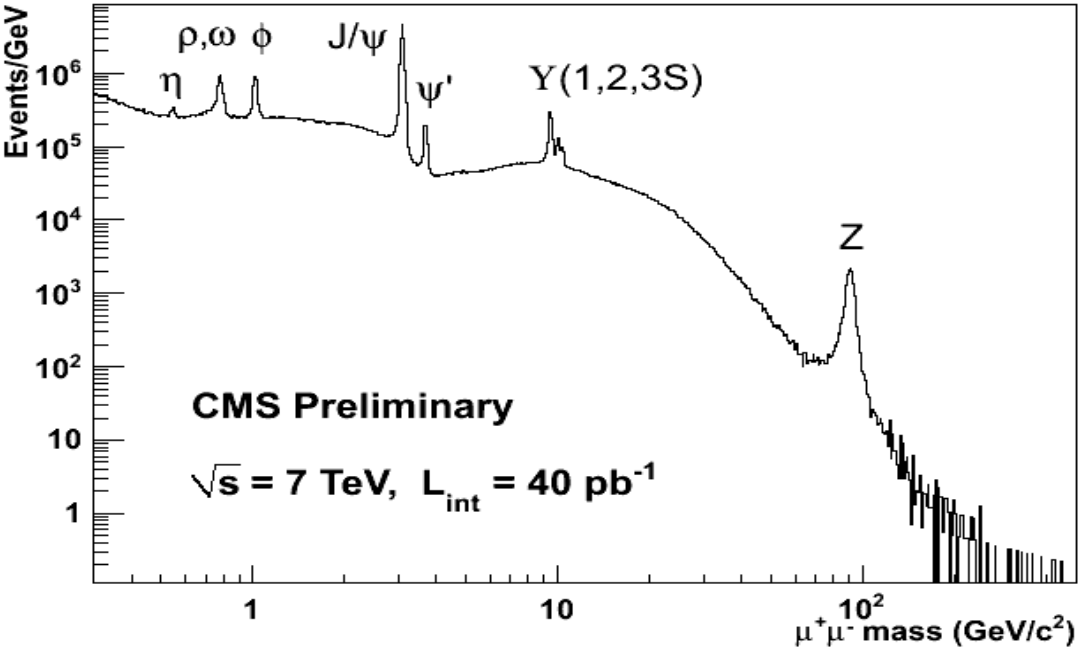


25000 silicon strip sensors covering an area of 210 m^2.
Have to control 9600000 electronic readout channels

3) Muons, electrons, photons,..

Photons, electrons and muons are identified using characteristic signatures in the detector.

Tracking information is combined with information from muon chambers and calorimeter.



Example plot: reconstructed invariant mass of muon pairs