Cornell University
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Elementary-Particle Physics

Top Quark Physics at the Large Hadron Collider

MIT

Physics Colloquium

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Top quarks: an uninteresting species?

- Top quarks were finally discovered at Fermilab in '95 and completed the 3 generation structure of the Standard Model (SM)
- Production:

- Decay rapidly through the weak interaction without forming a quark bound state first, almost exclusively through t->bW

The Standard Model (SM)

The Matter Particles (Fermions):

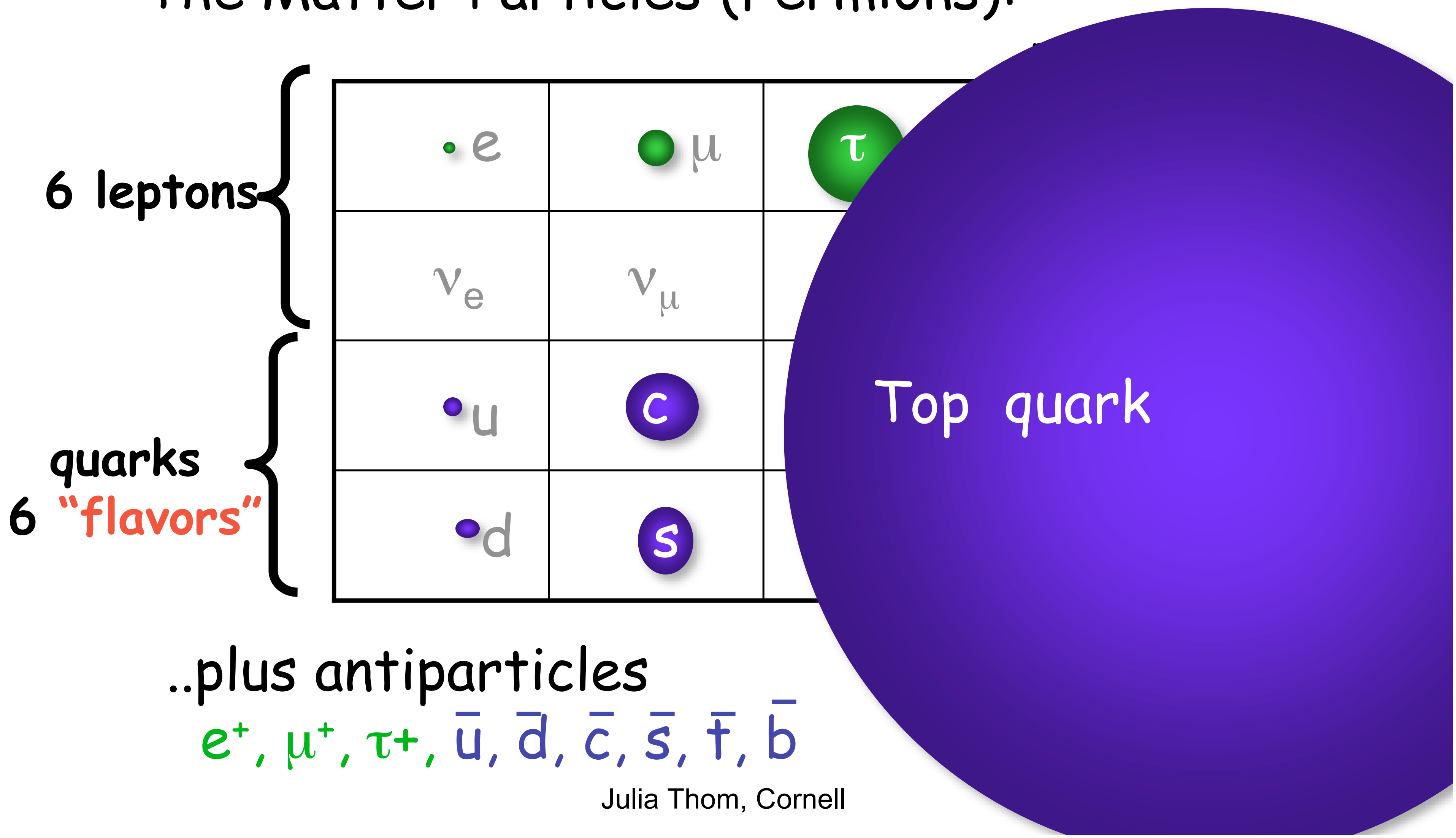
				Electric charge
6 leptons	e	μ	τ	Q= -1
	ν_e	ν_μ	ν_τ	Q=0
quarks 6 "flavors"	u	c		Q=+2/3
	d	s	b	Q=-1/3

..plus antiparticles of opposite charge:

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

The Standard Model (SM)

The Matter Particles (Fermions):



..plus antiparticles

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

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

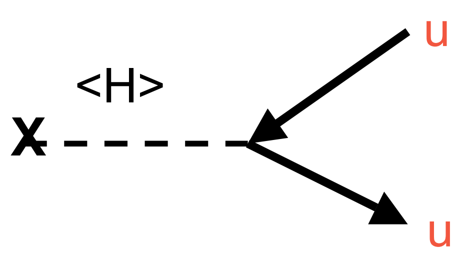
These are experimental observations-- masses cannot be predicted in the SM

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

- Does the top quark play a more fundamental role in EWSB? E.g.
  - several models predict that a top condensate breaks electroweak symmetry, not the Higgs field, analogy: cooper pair in superconductivity
  - Does it have unexpected decay or production mechanisms?
- If there are new particles lighter than the top (e.g. superpartners), does the top decay into them?
- If there are unknown heavy objects, for example a forth generation, they would decay into top quarks- do we see resonances?

Top Quark Physics tries to answer these questions.

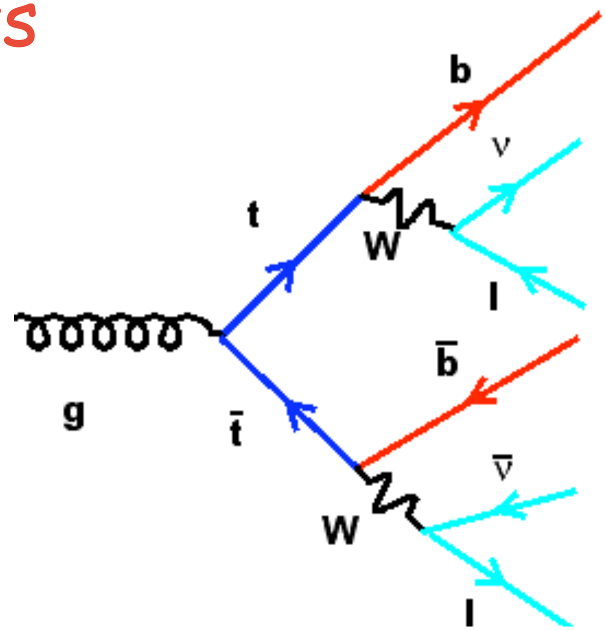
Experimental study of top quarks

top quarks are produced predominantly in pairs, in hadron collisions at the Tevatron and the Large Hadron Collider at CERN

In the SM, each top quark decays to a W boson and a b quark.

Final state (for pair production):

- 2 b quarks
- decay products of 2 W bosons: neutrinos, e/μ/τ, or quark pairs

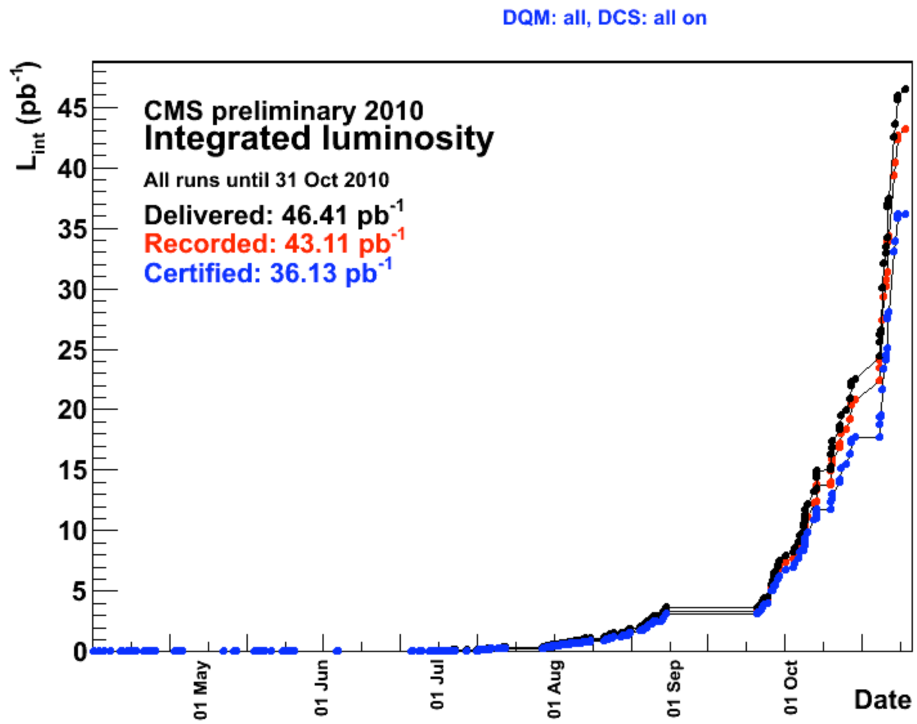


The Large Hadron Collider

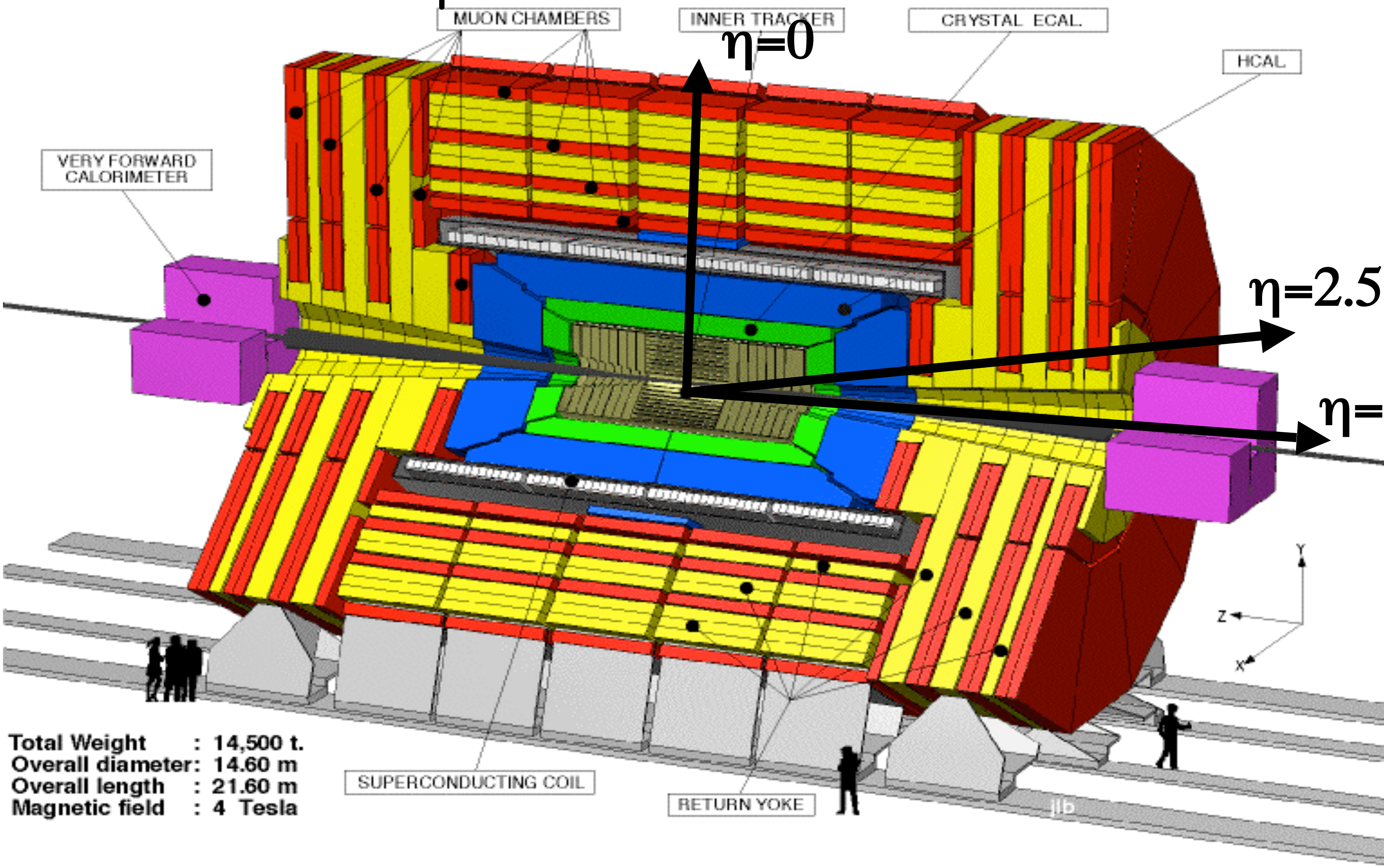
- 14 TeV proton-proton collider (currently at 7TeV)
  - 1 TeV = 10^{12} eV, factor of 7 more energy than the Tevatron
- 9300 superconducting magnets (1232 dipoles)
  - 60 tons of liquid helium, 11,000 tons of liquid nitrogen
  - Energy stored in magnets = 10 GJ
- There are 2808 "bunches" of protons in each beam, (currently 364)
  - 10^{11} protons per bunch
- When brought into collision the transverse size of the bunches is of order 10 μm (currently ~50μm)
  - O(20) collisions per crossing
  - Crossing occurs every 25ns (40 MHz)

The Large Hadron Collider

- 2010 data set is basis of my talk today
  - measured in "integrated luminosity" (=number of collisions per unit area per unit time)
  - 40pb^{-1} (~1% of the Tevatron data set)
- Luminosity increased exponentially over 5 orders of magnitude
- Plan to add another factor of ~100 of data this year

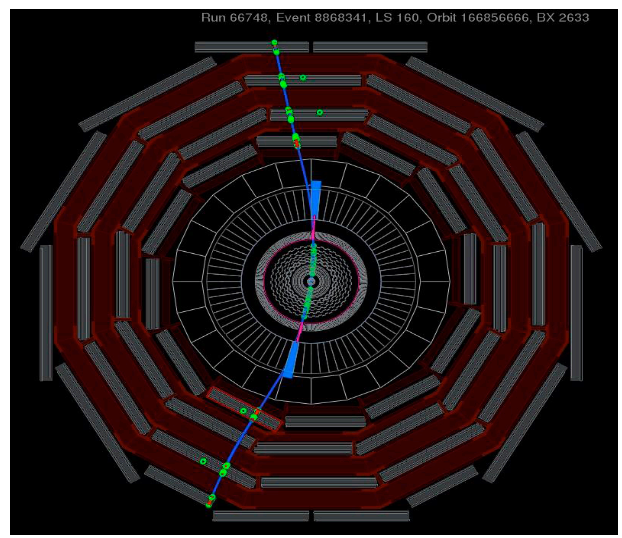


A collider detector at the LHC: The Compact Muon Solenoid



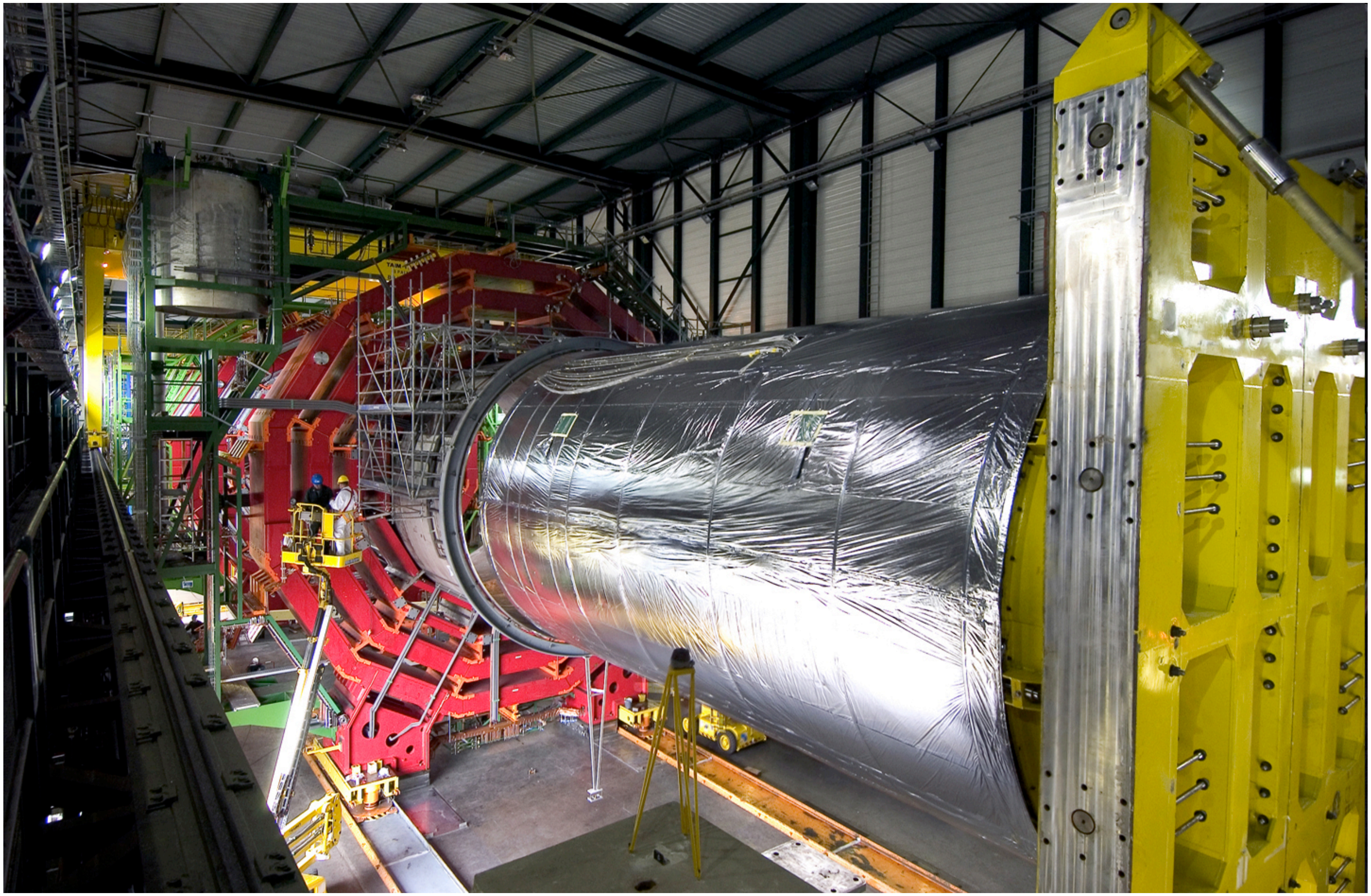
What does the detector do?

- The detector tries to measure the 4-momenta of all particles in a pp collision
- 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



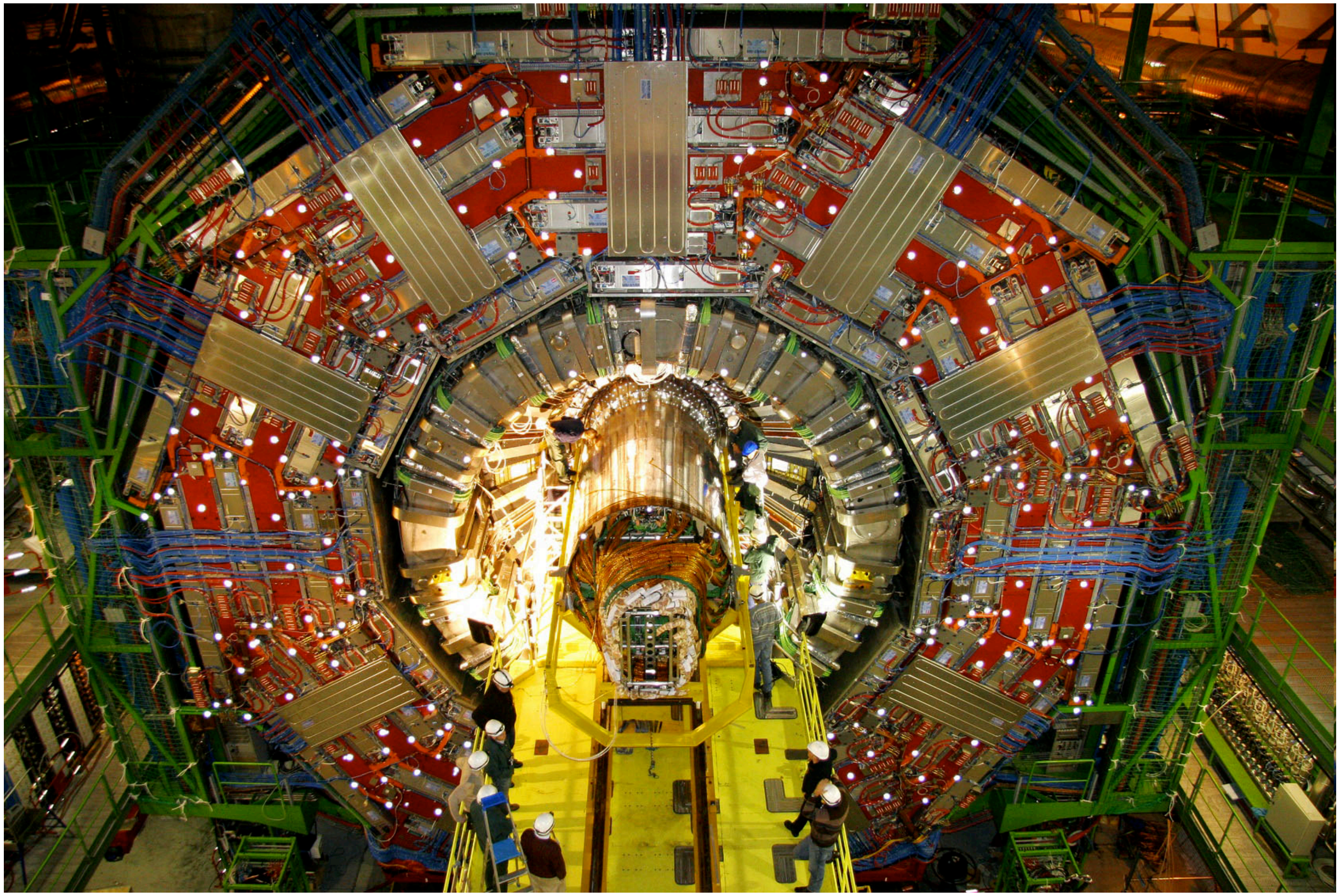
Cosmic muon

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.

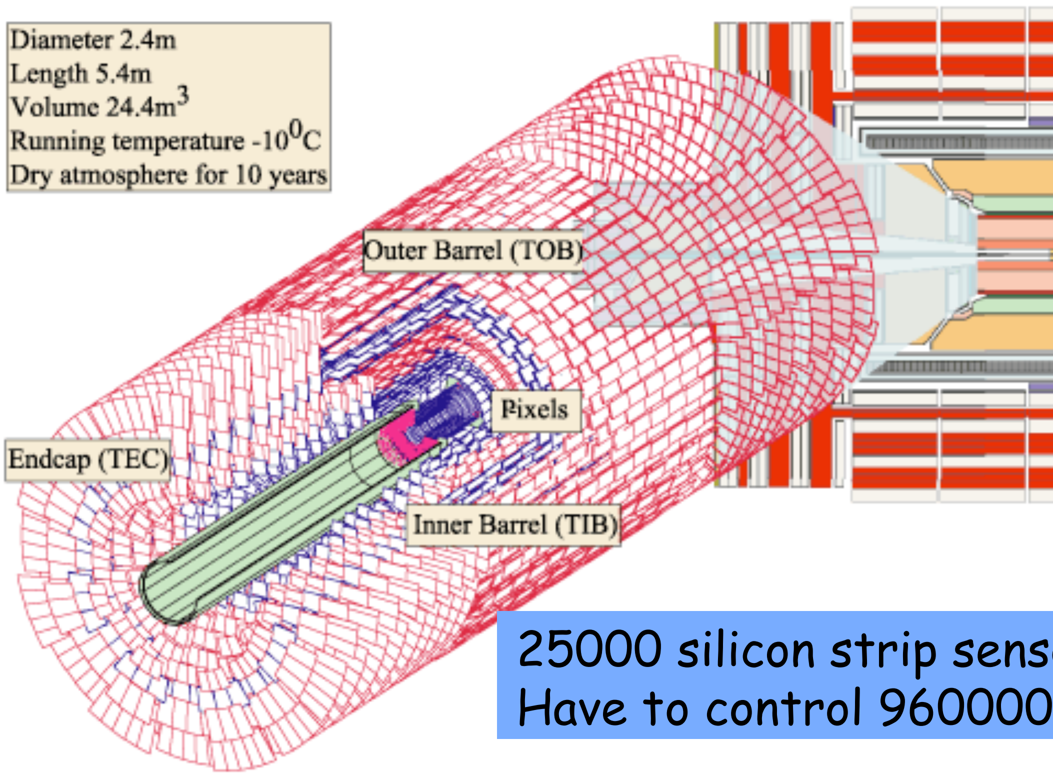
Bore of the solenoid is outfitted with various particle detection systems. Among them: the silicon pixel and strip tracker which measures particle trajectories.



Insertion of the tracker.

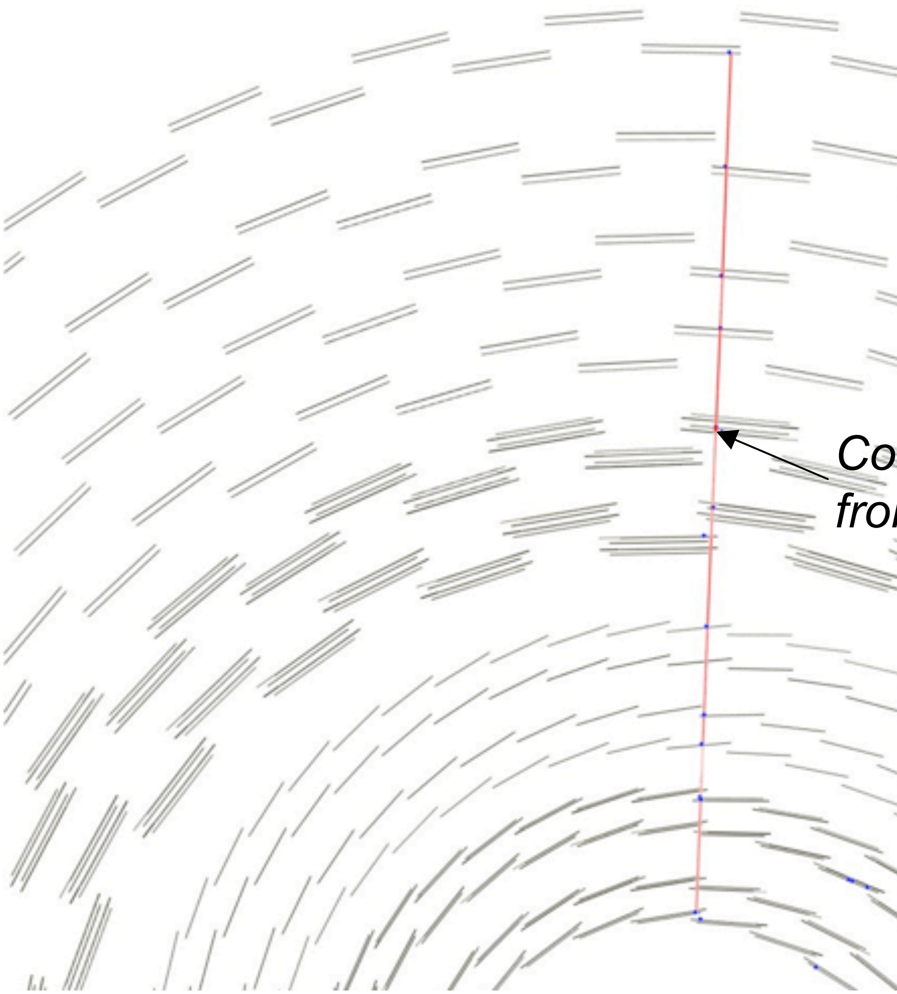
CMS silicon strip tracker

- 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

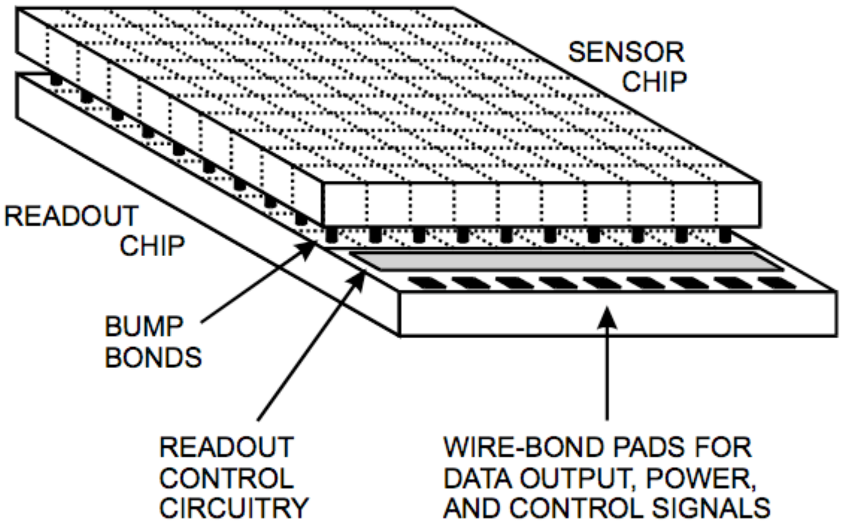
CMS silicon strip tracker

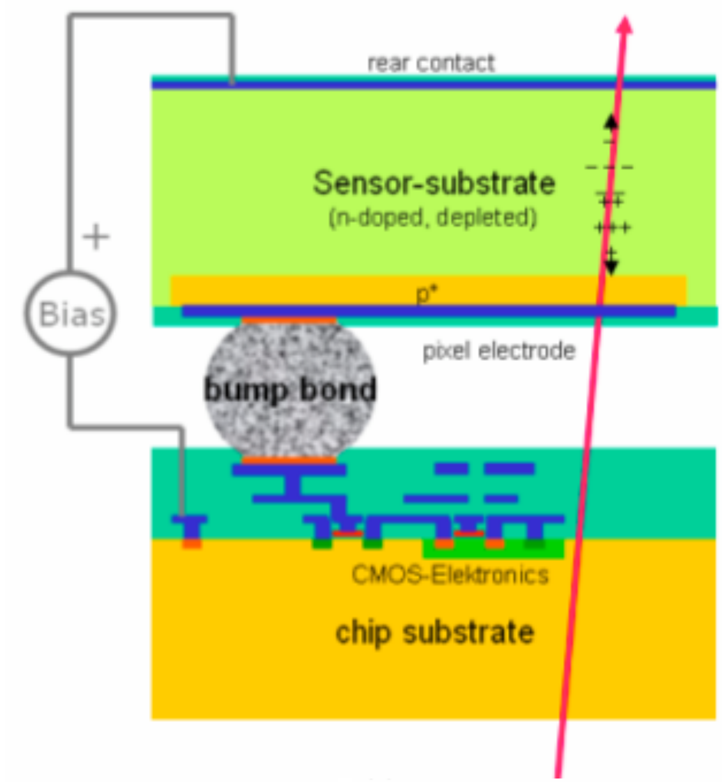


Cosmic muon track, reconstructed from charge deposition on Si strips

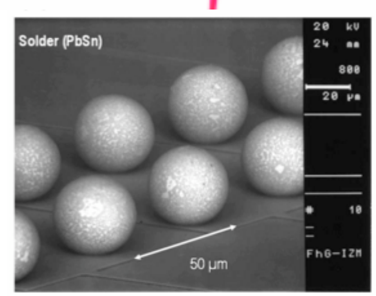
Silicon pixel detector

Adds crucial tracking resolution in the area closest to the beam

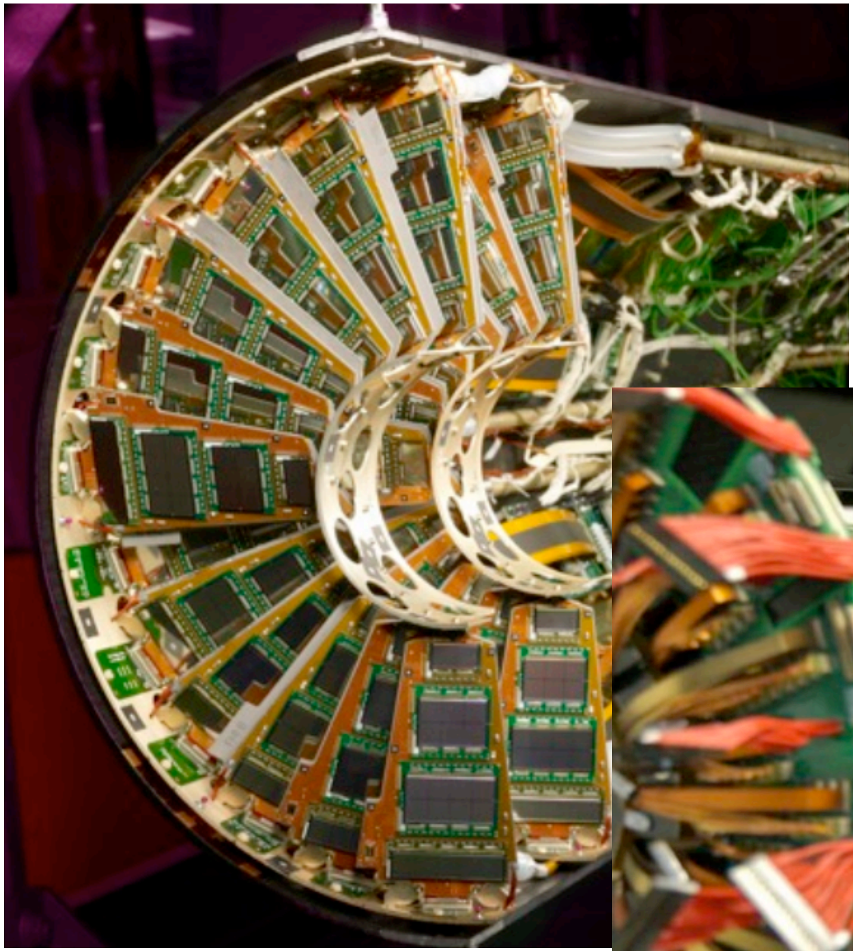


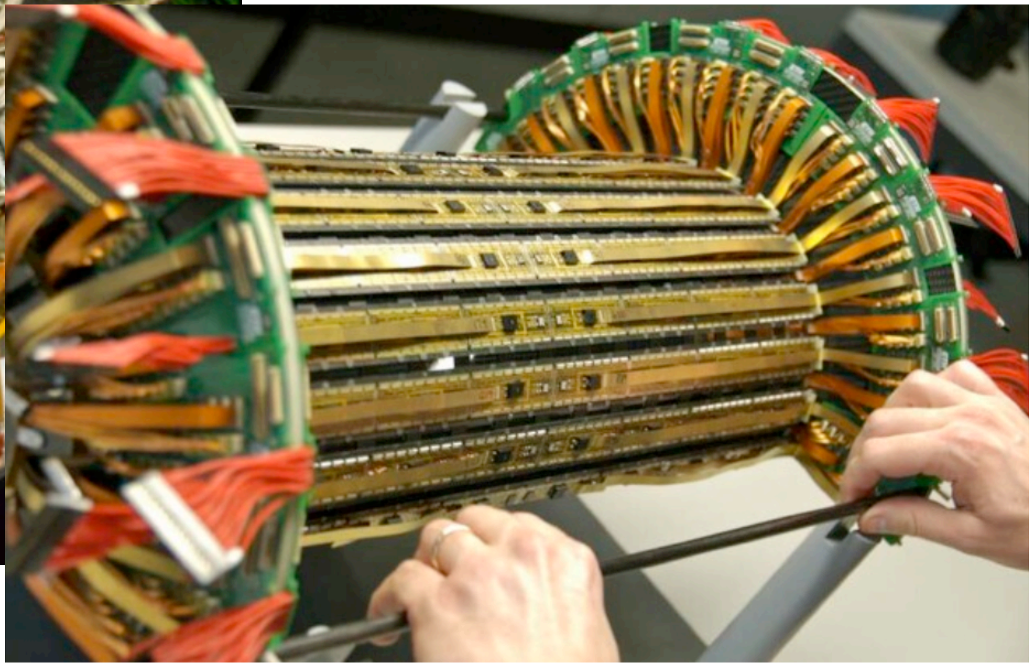


- 3 layers + 2 forward disks
- 66 Million Pixels, 1m^2 of silicon
- pixel size limited by readout circuit and heat/power dissipation limit (150x150μm)
- Time to read out 1 hit: 6 bunch crossings
- Charge deposition threshold on a pixel ~2500e



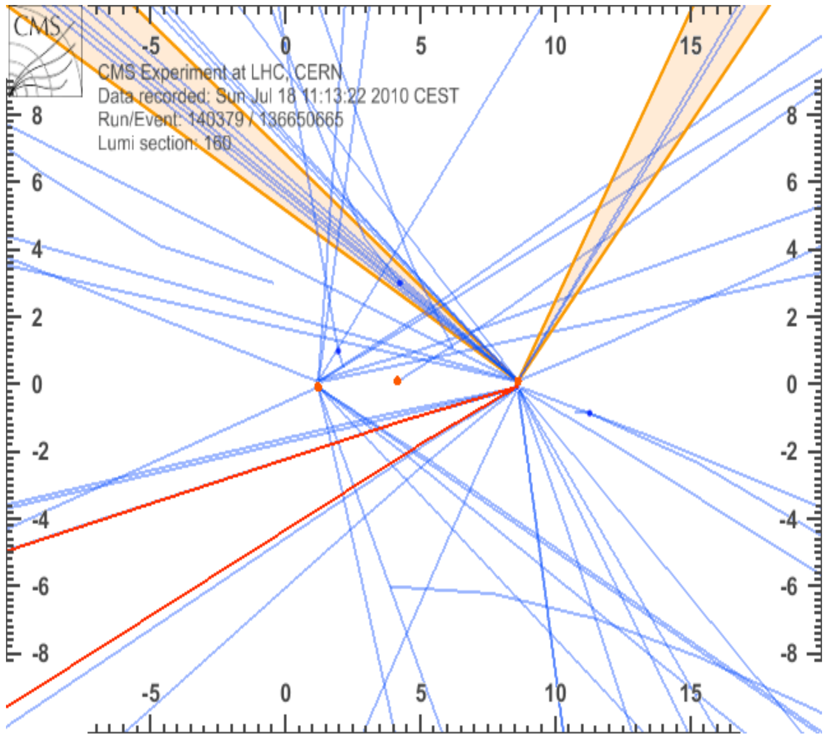
Silicon pixel detector





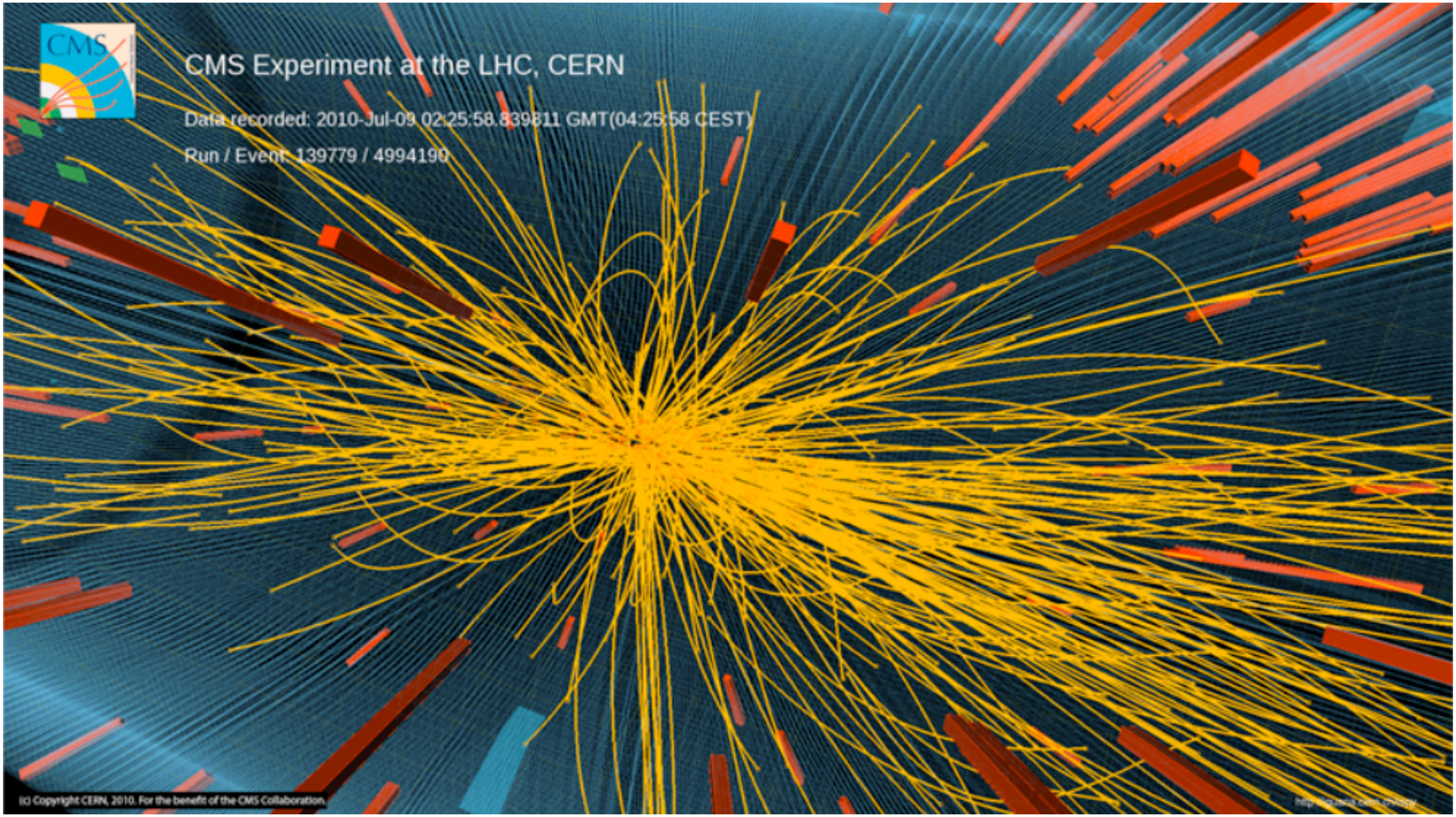
The Silicon tracker..

…allows us to reconstruct particle tracks in 3D, 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



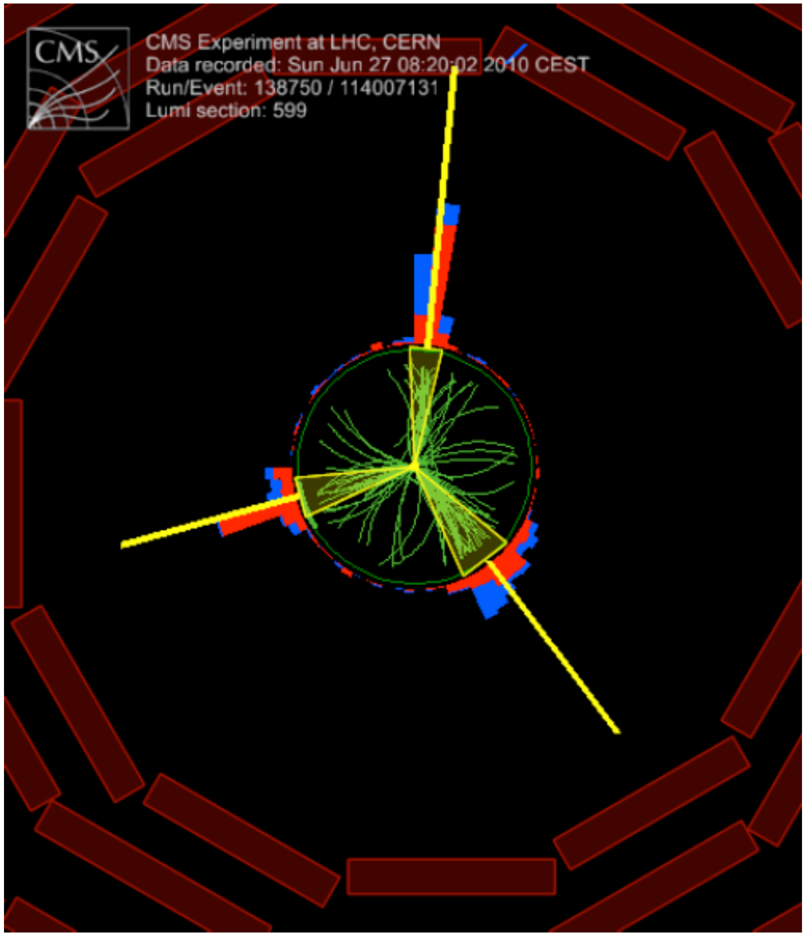
What are the objects we can reconstruct with this detector?

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 (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

Jet reconstruction algorithms:

1. Calorimeter only
2. Calorimeter, corrected using associated track measurements
3. "Particle flow": reconstruct all particles using all sub-detectors prior to jet clustering
4. Track jets (independent)

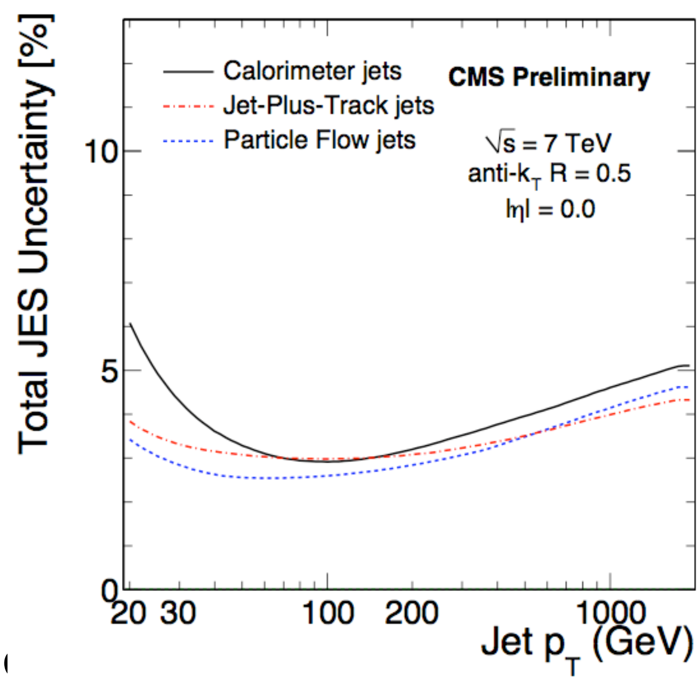


Jet Energy Calibration

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

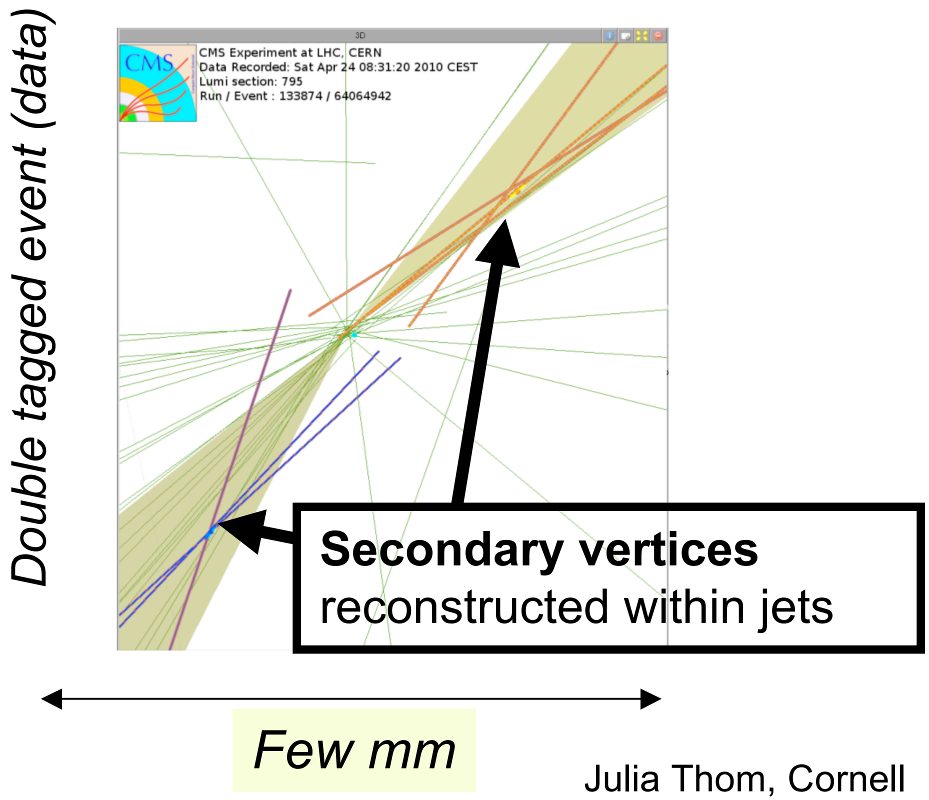
- depending on algorithm, jet p_T and η: correction up to factor 2!
- Correction done using simulation, checked in data, e.g. with energy balance in di-jet and γ+jet events

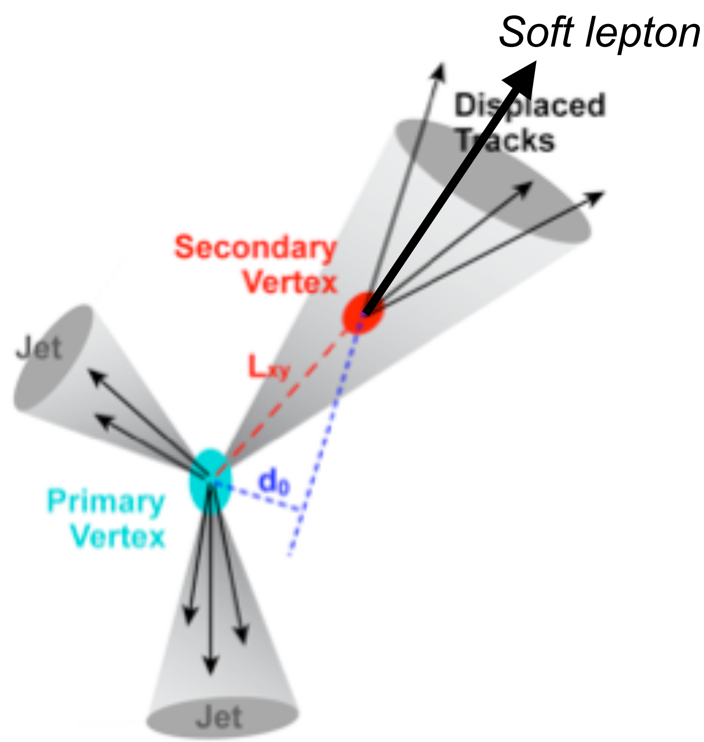
~5% difference between data/MC jet energy scale measurements (=systematic uncertainty)



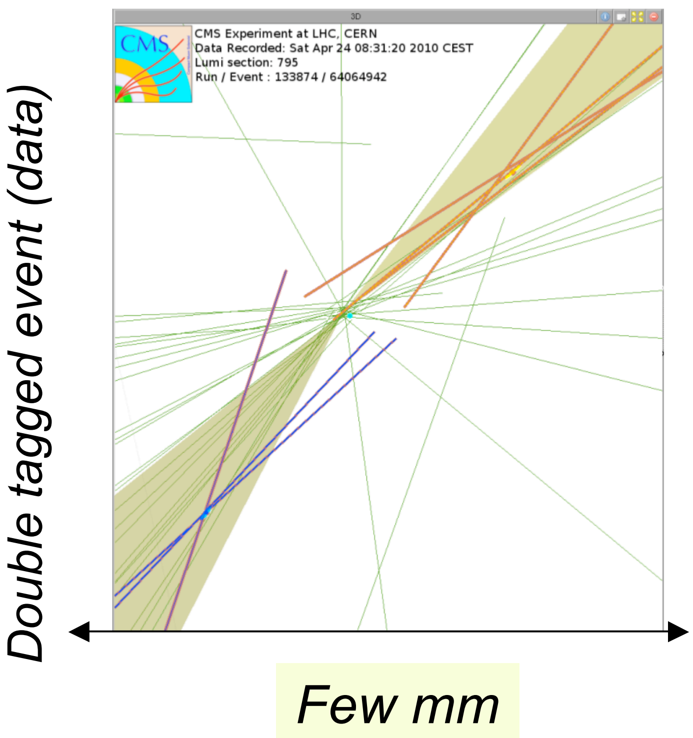
B tagging of jets

- 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





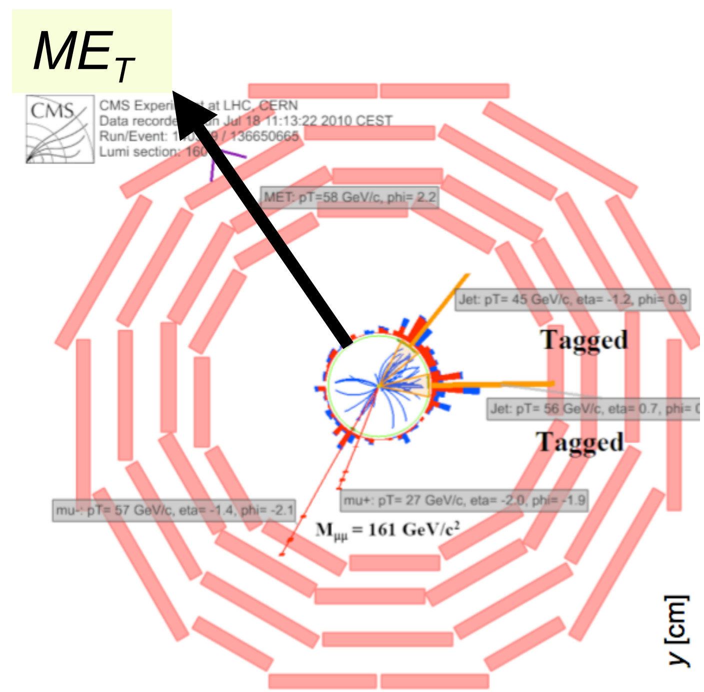
B tagging of jets



Example performance of a track impact parameter b-tagger: typical jet from a top decay is tagged as coming from a b quark with ~50% efficiency and ~1% mistag rate. Modeling in the simulation correct to ~10%

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



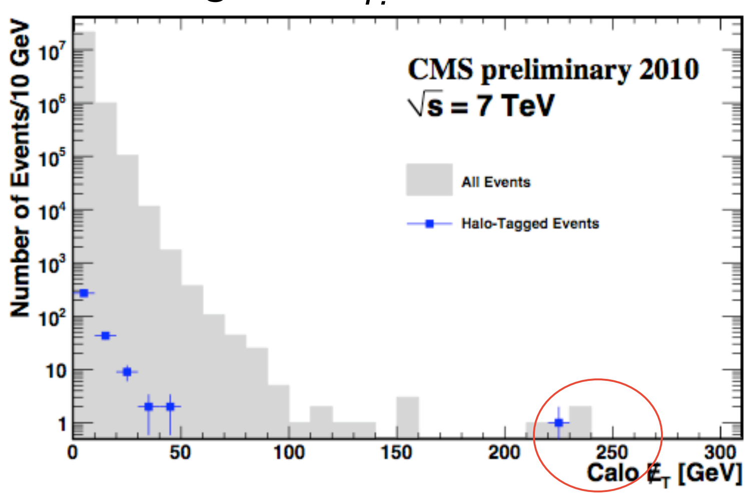
- magnitude is referred to as missing transverse energy ME_T
- Allows for (indirect) detection of neutrinos, WIMPS,.. which cause imbalance in the transverse vector sum
  - E.g. most SUSY models predict ME_T>150 GeV

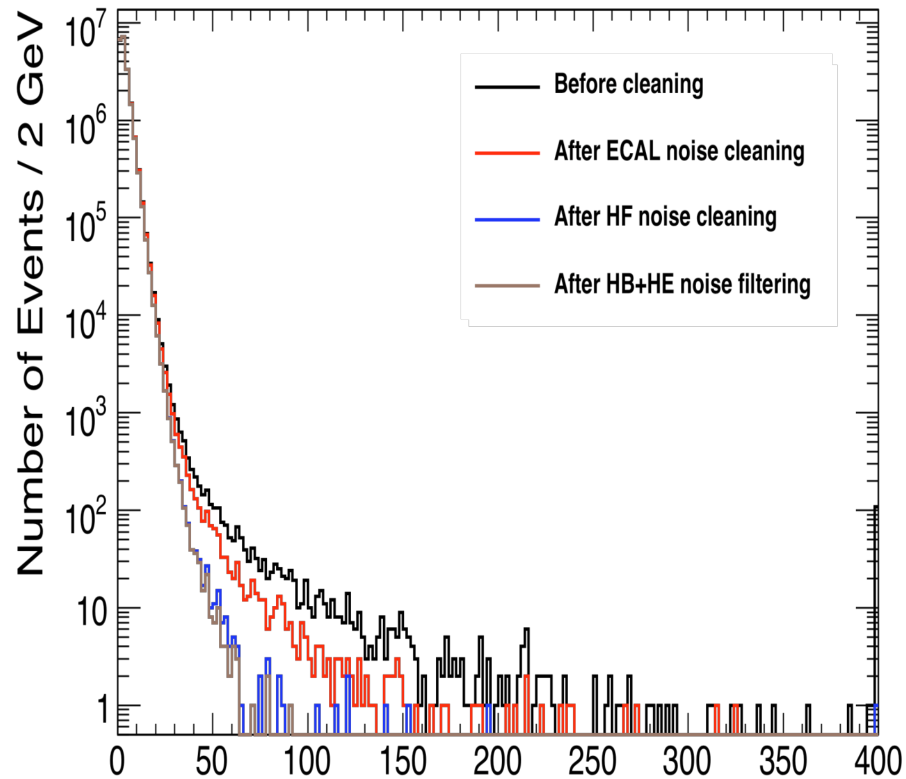
ME_T: Experimental Challenge

Reconstructed ME_T has to be cleaned of effects due to

- instrumental noise
- cosmics, beam halo,..

Beam halo tagged events at high $ME_{T:}$

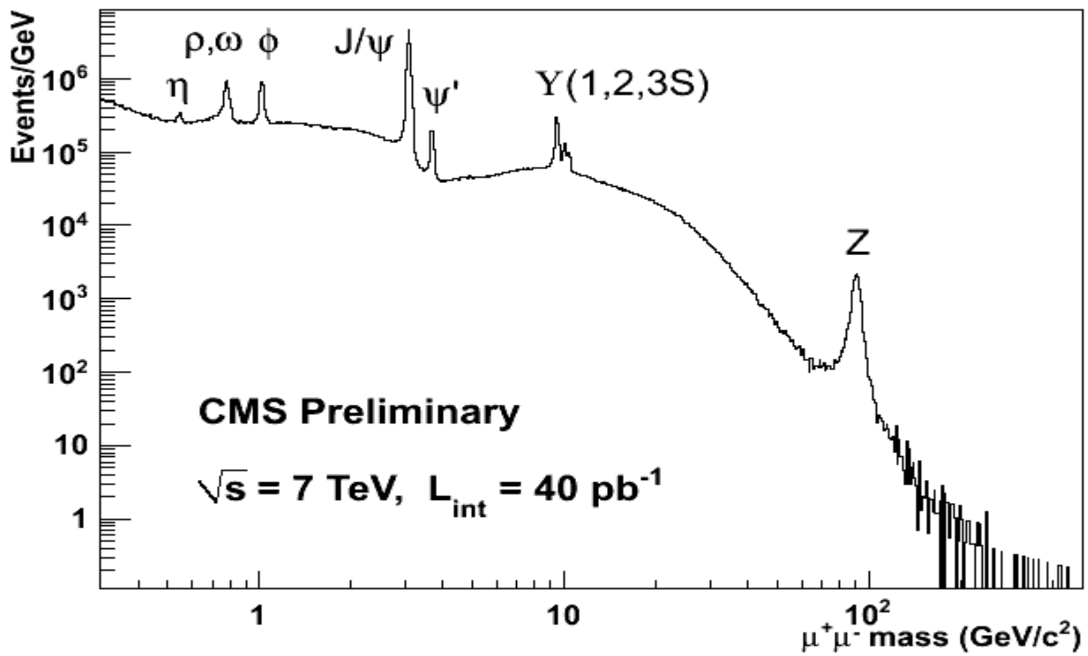




Reconstructed ME_T

3) Muons, electrons, photons,..

- Photons, electrons and muons identified using characteristic signatures in the detector. Tracking information is combined with information from muon chambers and calorimeter.

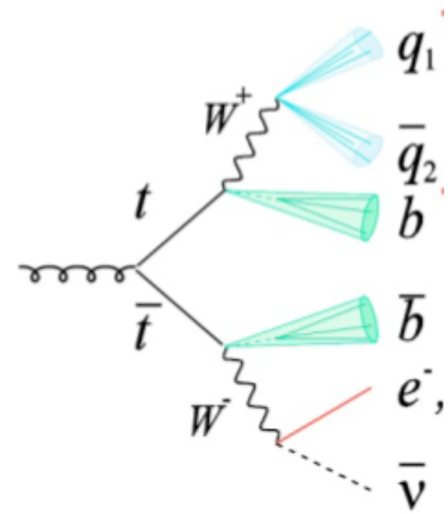


Example plot: reconstructed invariant mass of muon pairs

All objects mentioned so far are needed to identify top events

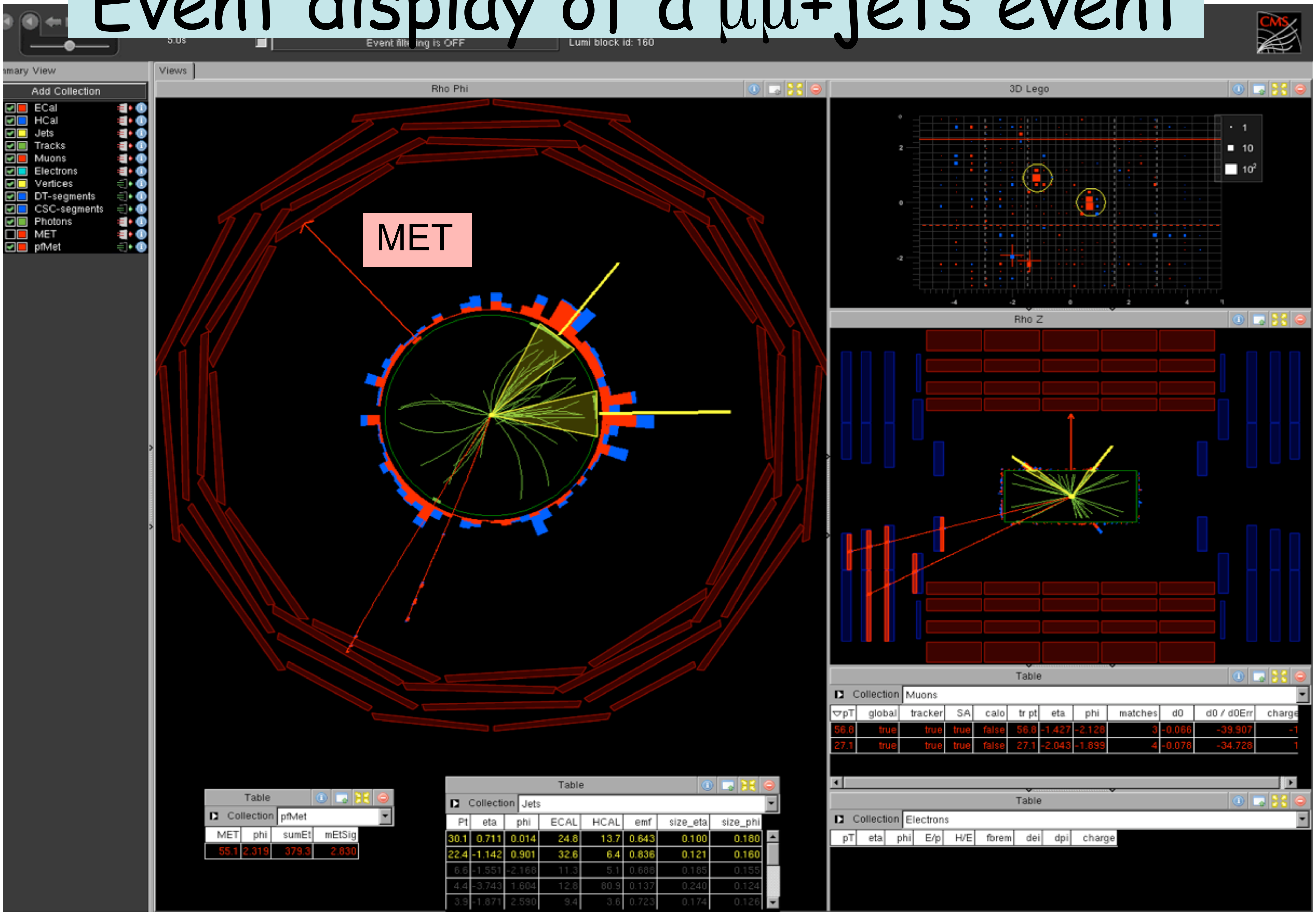
Events classified by decays of the two W bosons:

- "lepton+jets": 4 jets (2 from b) and ME_T from ν
  - BF=24/81, but significant background from W+jet production. Can suppress with b tagging!

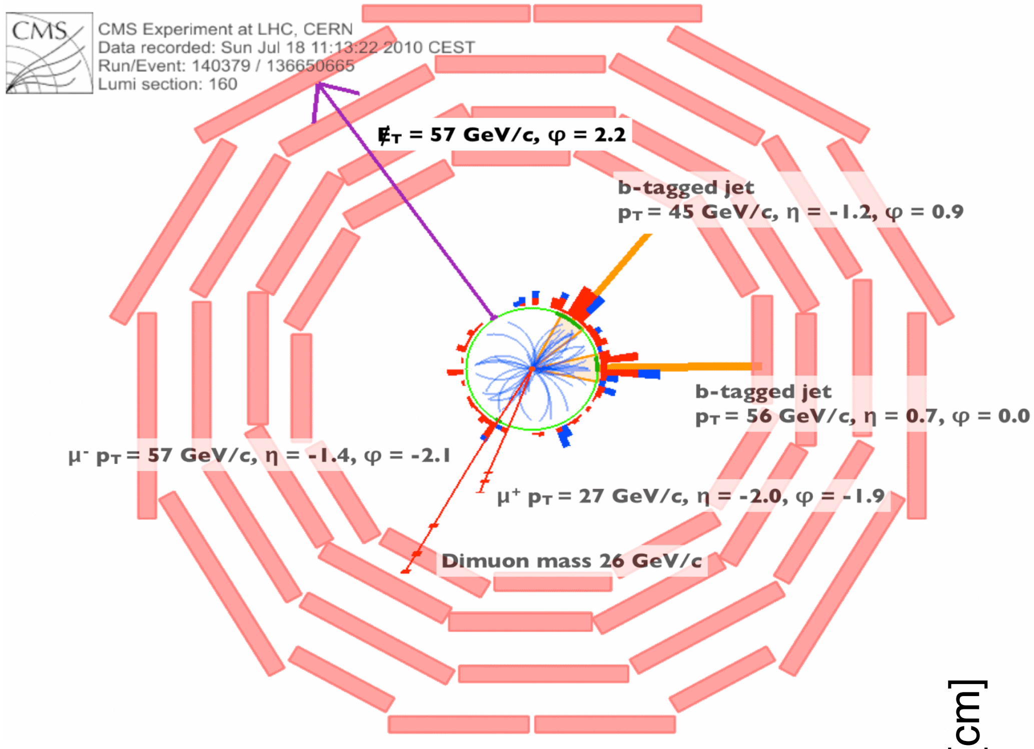


- "dilepton": 2 jets and ME_T from 2 ν's
  - Clean, but low stat. BF=4/81
- "hadronic": 6 or more jets
  - BF=36/81, but large QCD multijet background
  - Jet energy scale uncertainty, combinatorics

Event display of a μμ+jets event



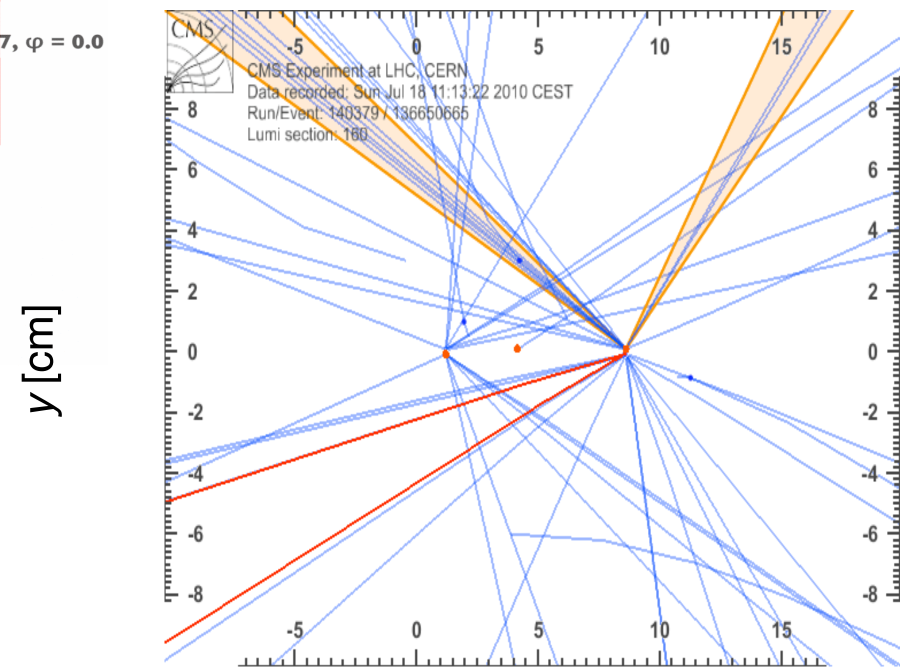
details: μμ+jets event



m(μμ) = 26 GeV/c²

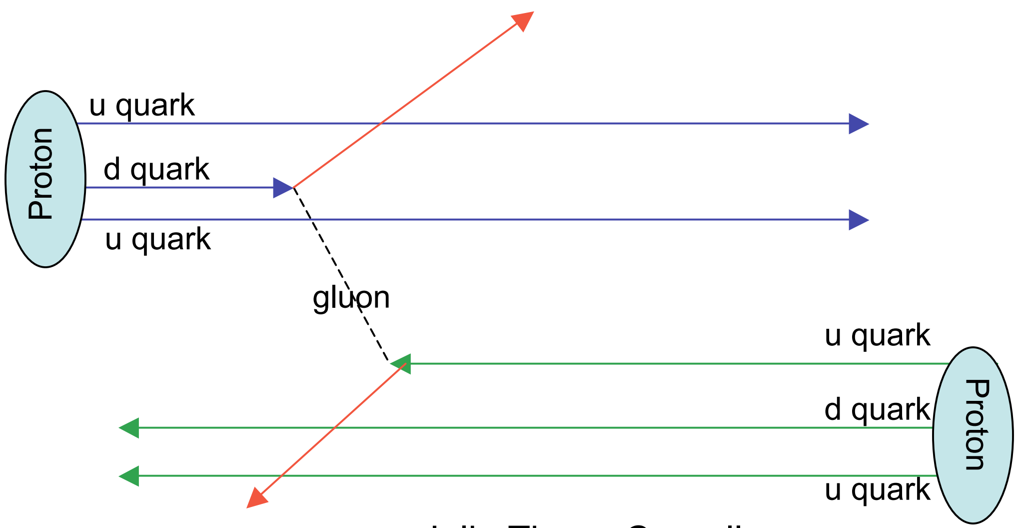
Multiple primary vertices from multiple pp collisions ("pile-up")

Jets & muons originate from same primary vertex

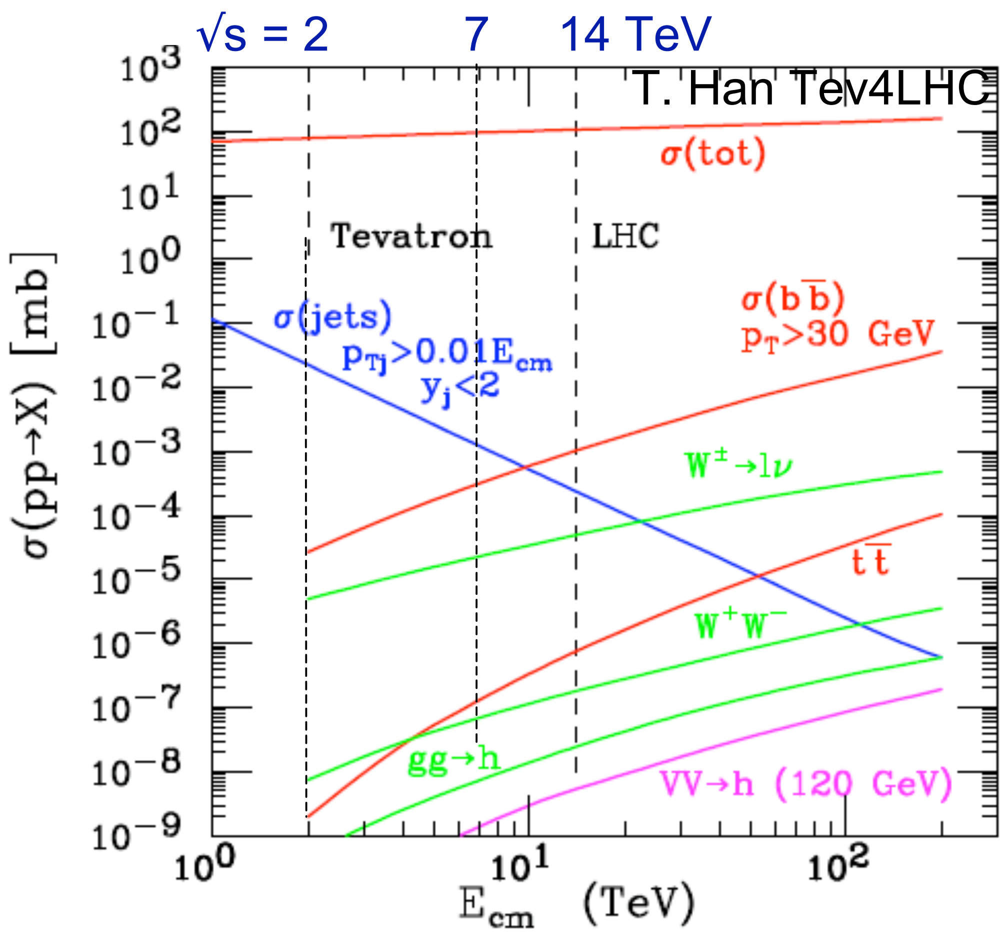


How top quark pairs (or W,Higgs,SUSY etc) are produced

- 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 and many many gluons).
  - Note: their momentum is unknown!



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



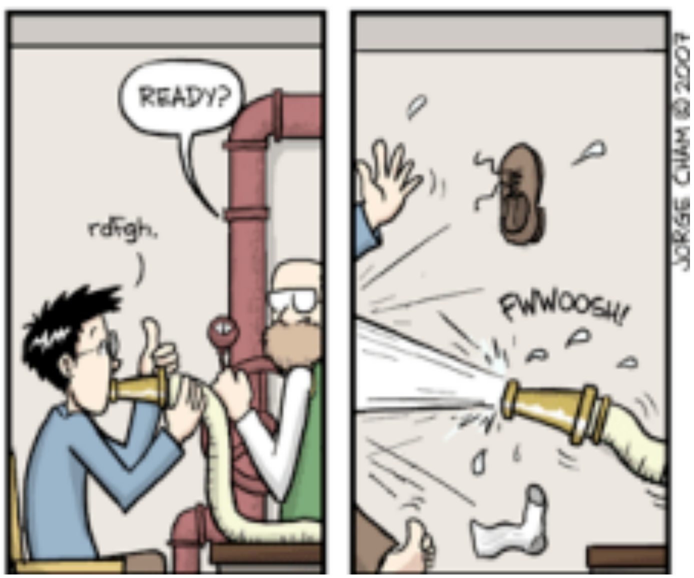
At LHC, production of

- "Any" event: 10^9 / second
- W boson: 150 / s
- Top quark: 8 / s
- Higgs: 0.2 / s

(for $L=10^{34}$ $cm^{-2}s^{-1}$)

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

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

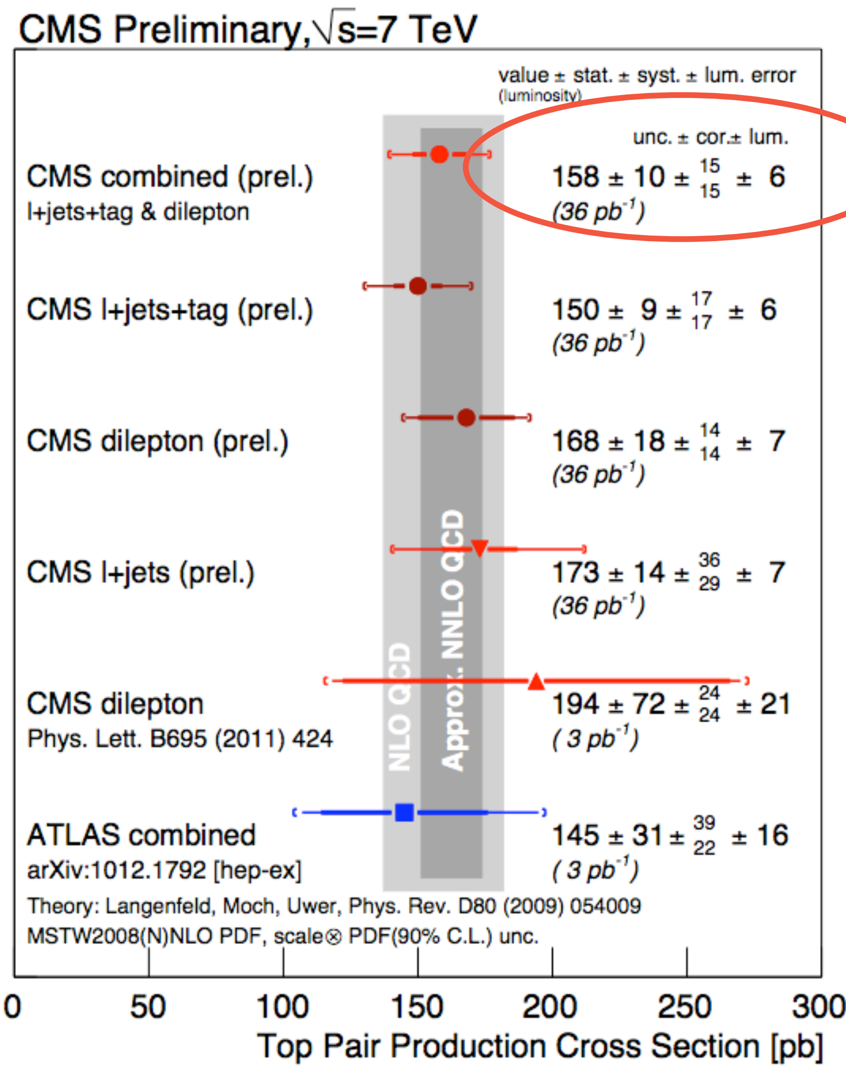


- Trigger is the system that selects the ~ 200 events/second that are saved for further study
  - select objects (e, μ, MET, jets..) or combinations thereof
  - Currently have O(100) triggers
- Most of the events are thrown away!

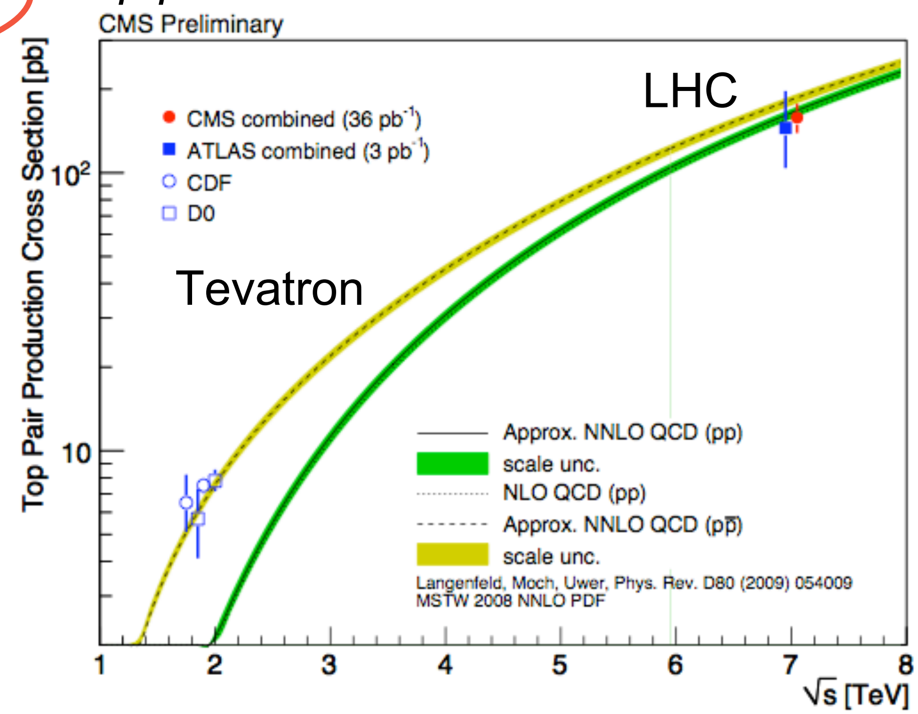
Summary so far

- Physics objects we observe in the detector are:
  - Jets
  - ME_T
  - 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
- Now: some of the first top physics results from the LHC (CMS experiment)

Summary of Top Production Cross section measurements with 2010 data



We see good agreement between the Observed and SM predicted (NNLO) top production cross section calculation:

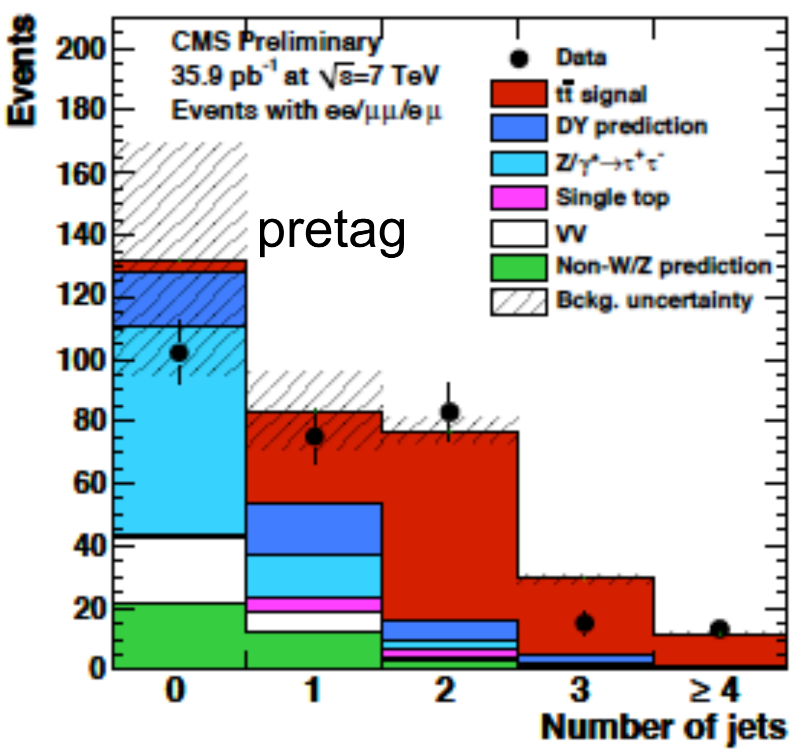


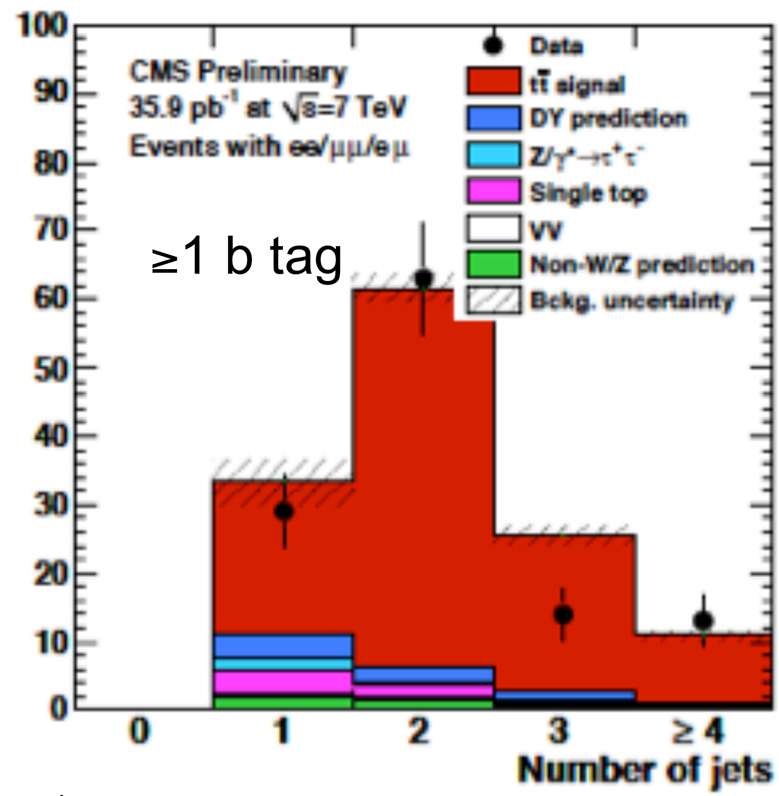
Comparison to Tevatron top cross section Measurements done with ~5fb^{-1}(more than 100 times more data):

σ_{tt} = 7.50 ± 0.31(stat) ± 0.34(syst)±0.15(Lumi) pb

Dilepton Channel

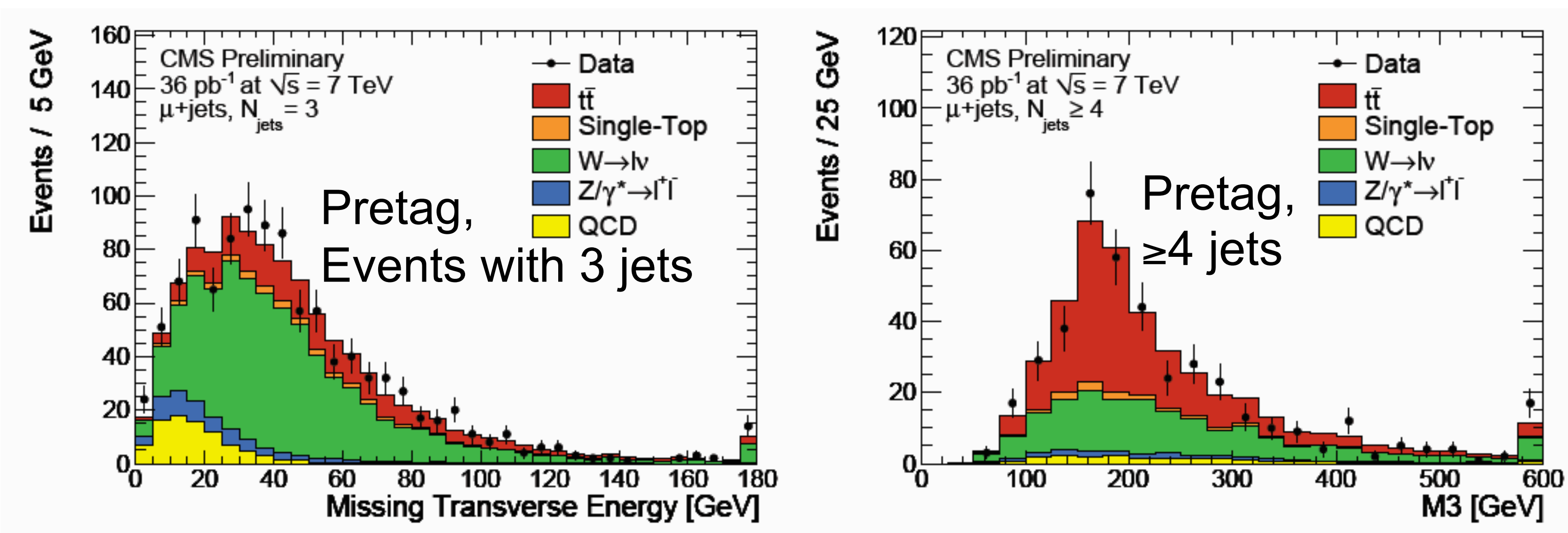
- Event selection:
  - 2 isolated, oppositely charged, central muons or electrons p_T>20 GeV, ME_T>30 GeV, at least 2 central jets p_T>20 GeV, at least one of them with a b-tag, Z veto
  - Simple counting experiment performed to calculate top production cross section





Lepton+jets channel

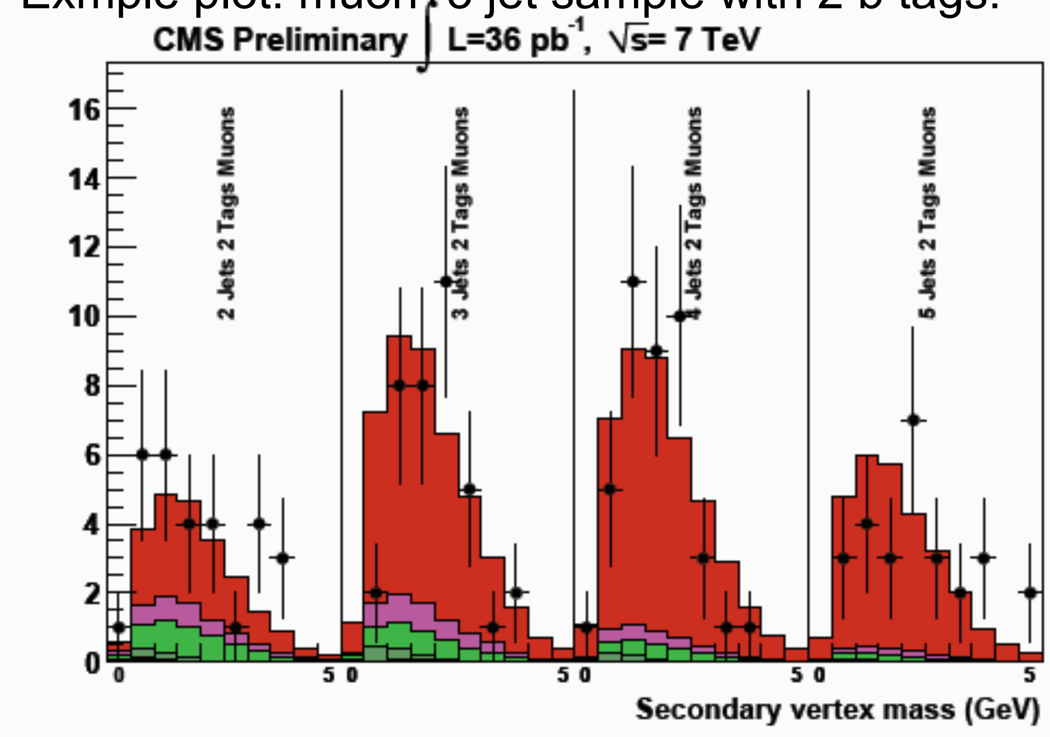
- Event selection:
  - Exactly one good isolated and central muon (electron) with pT>20(30) GeV, at least 3 central jets pT>30 GeV , no MET requirement (~700 top candidates expected)
  - 2D likelihood fit to MET and "M3"(=3-jet mass with highest momentum) extracts the cross section (separately for 3, 4 jets, e, μ)
  - Jet energy scale is largest uncertainty.

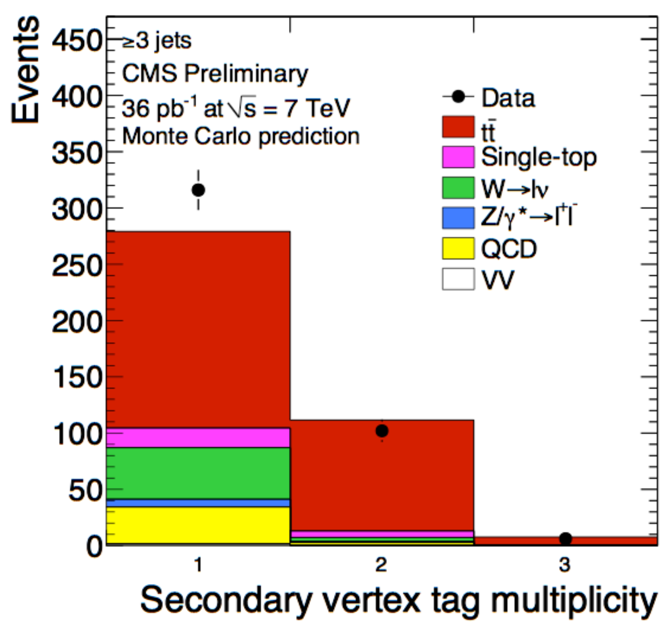


Lepton+jets channel

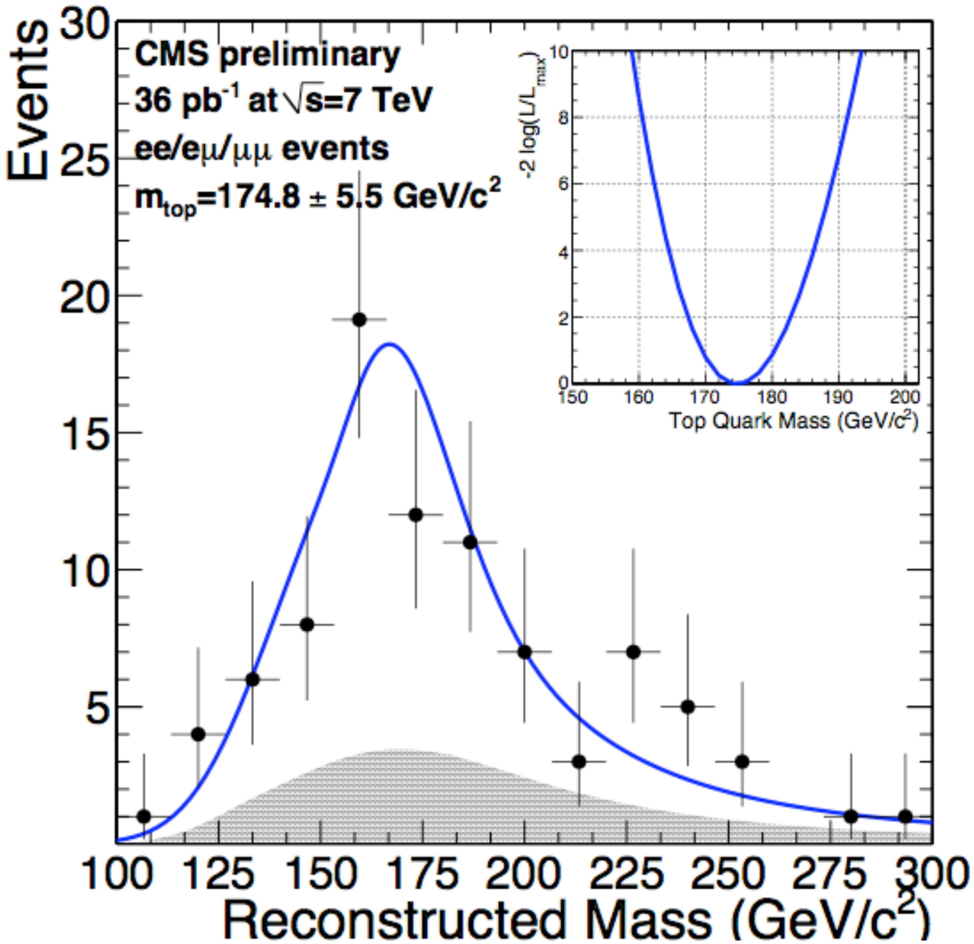
- Adding b-tags to suppress backgrounds:
  - 1D LH fit to the vertex mass, for 18 categories of events (1,2…5 jets, e,μ, 1 and more b tags separately)
  - All normalizations and nuisance parameters (JES, Q^2, btag eff., etc.) floating in the fit

Exmple plot: muon+3 jet sample with 2 b tags:





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.

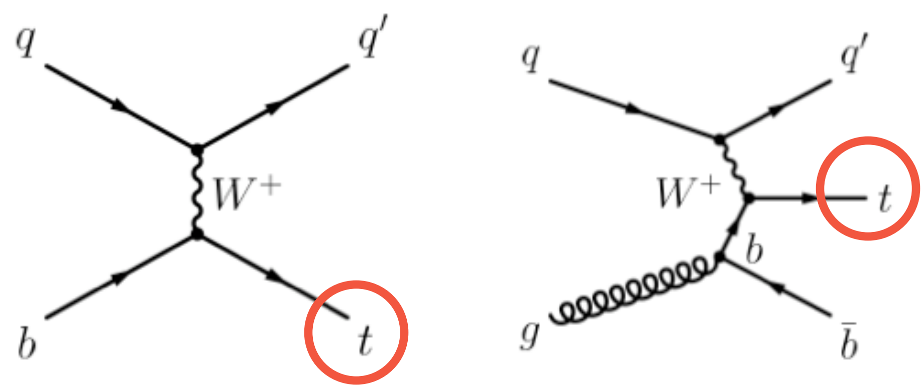
CMS dilepton channel (highest purity): m_t=175.5 ±4.6 (stat)± 4.6 (sys) GeV/c^2

Compare to CDF, D0 combined: 173.1 ± 1.1

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

Single Top

- Observation in 2009 (2.3-3.2 fb^{-1}) at Tevatron
  - Tiny cross section- at LHC it is 20x higher (60pb)
- Charged EWK production only, direct probe of top weak coupling
- Important background to Higgs searches
- Very difficult measurement- signal (t->Wb) looks like the (dominant) background from W+jets. Need sophisticated fits/tools to measure a cross section.

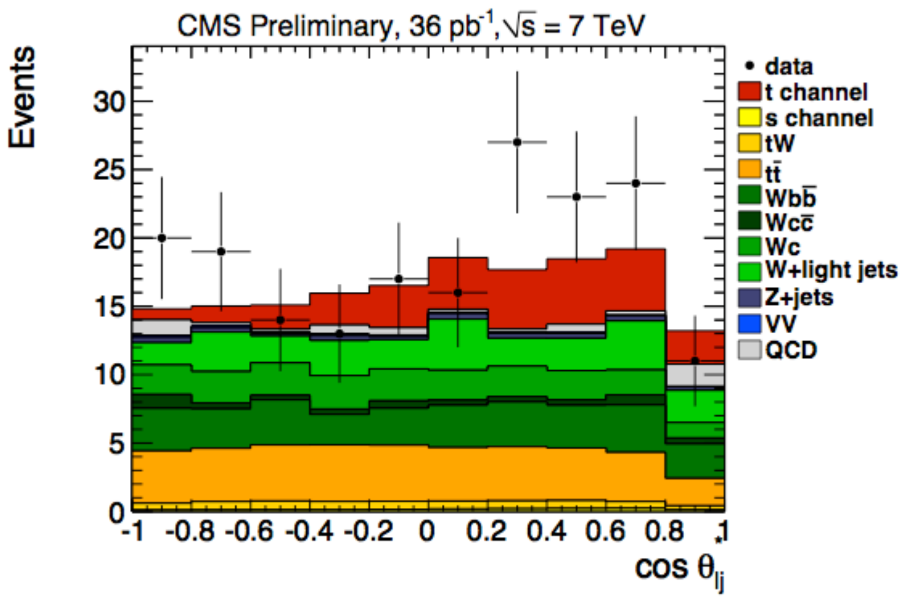


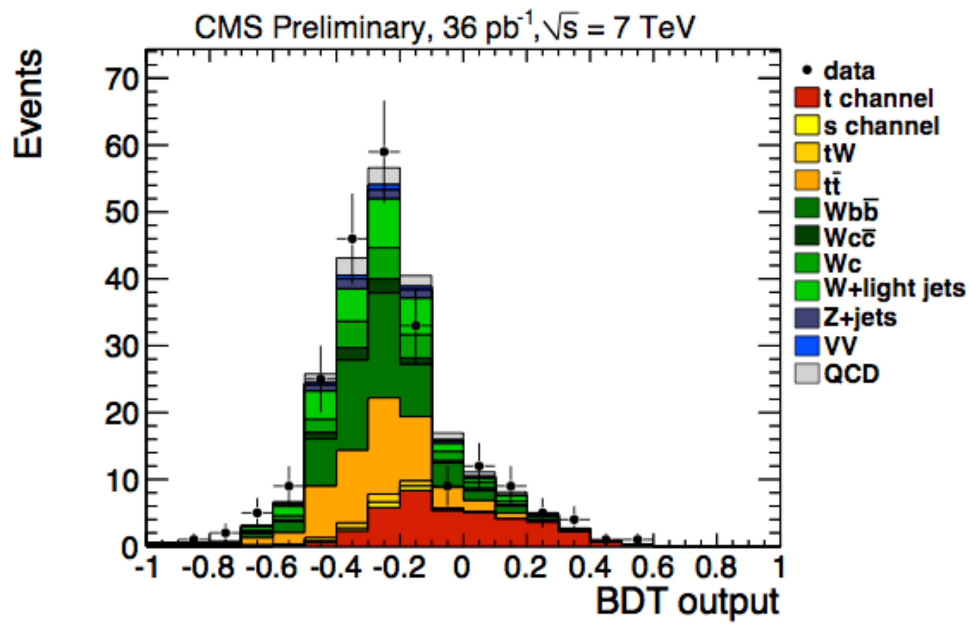
Single top production in the "t-channel"

Evidence for Single Top at LHC

2 complementary analyses are combined: a 2D fit to angular correlation variables, and a fit to a "boosted decision tree", based on SM single top expectation. Significance measured (expected):

2D: 3.7(2.1) σ BDT: 3.5(2.9) σ

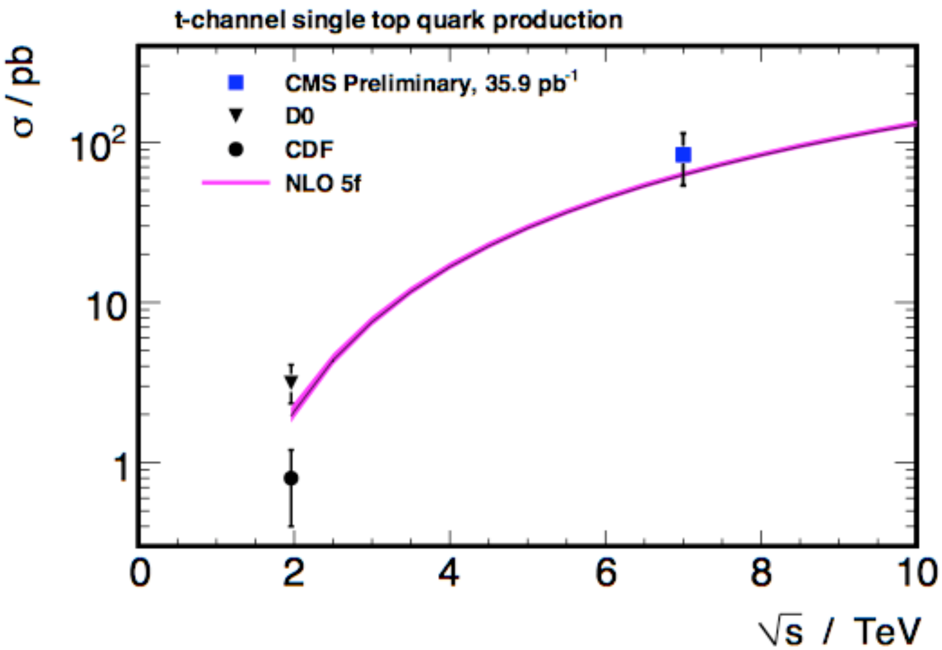


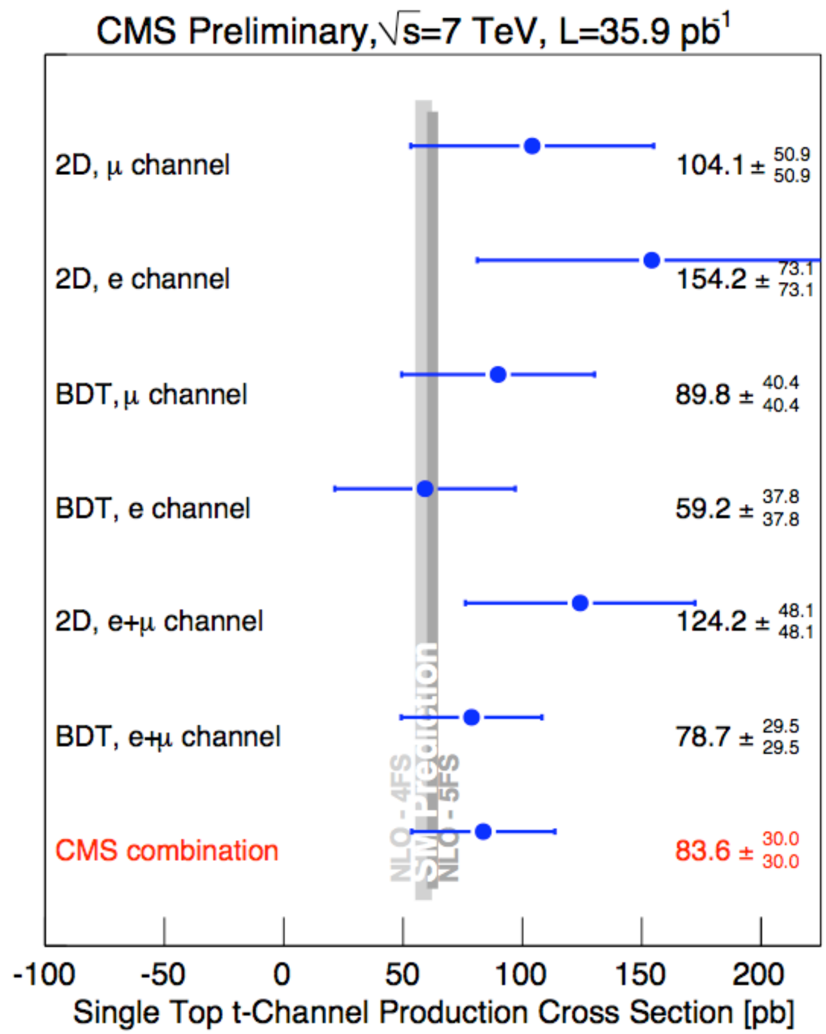


Plotted is the angle between the lepton and untagged jet. For single top, specific angular correlation due to top quark spin.

Single Top

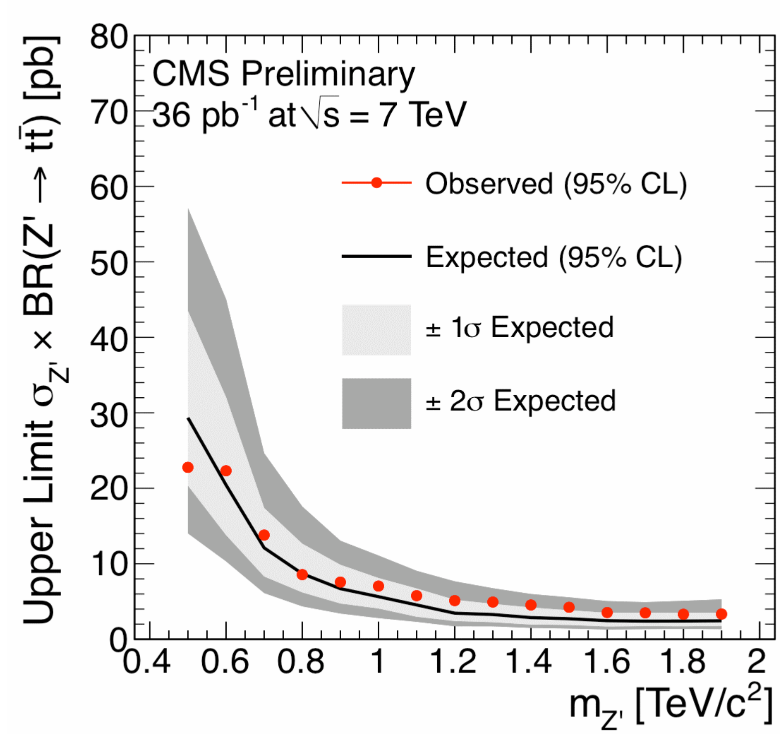
combined: σ_t=83.6±29.8 (stat.+syst.)±3.3 (lumi.) pb

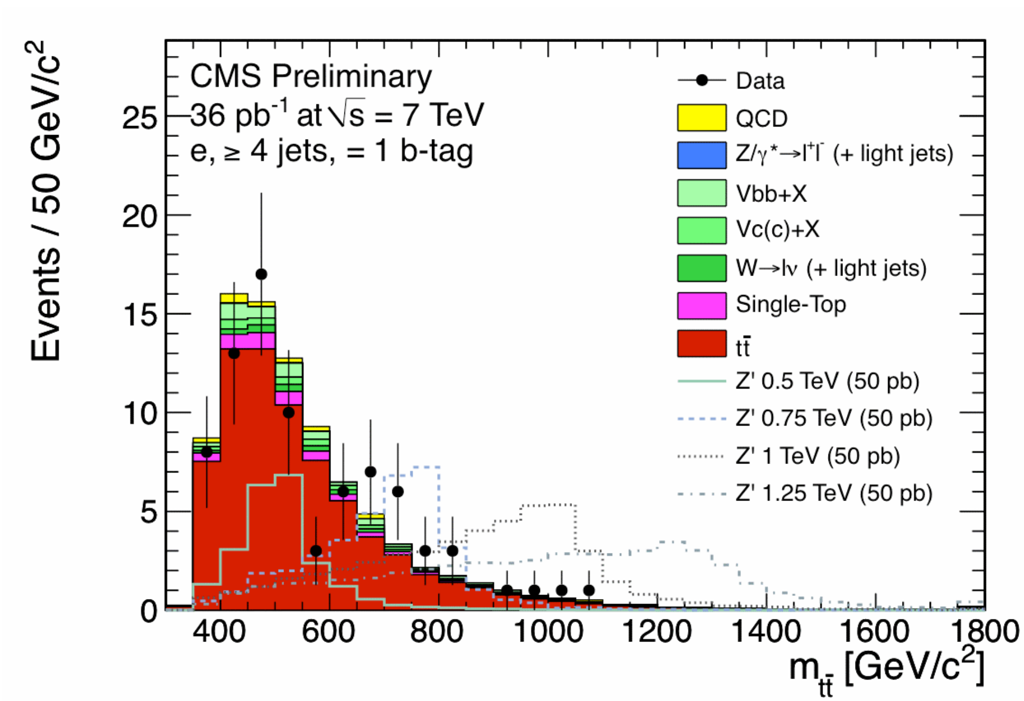




Search for top resonances at CMS

- 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

- 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

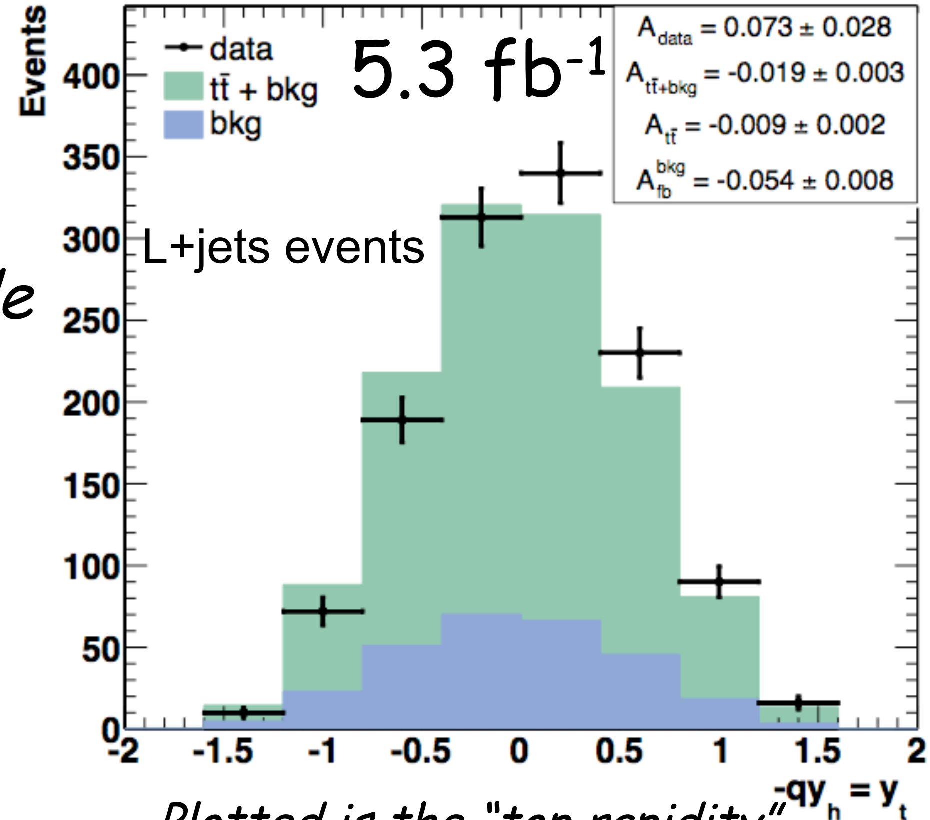
- Tevatron measures the "charge asymmetry": compare number of top and anti-top produced with momentum in a given direction, in $p\bar{p}$ lab frame or in $t\bar{t}$ rest frame

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

- 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

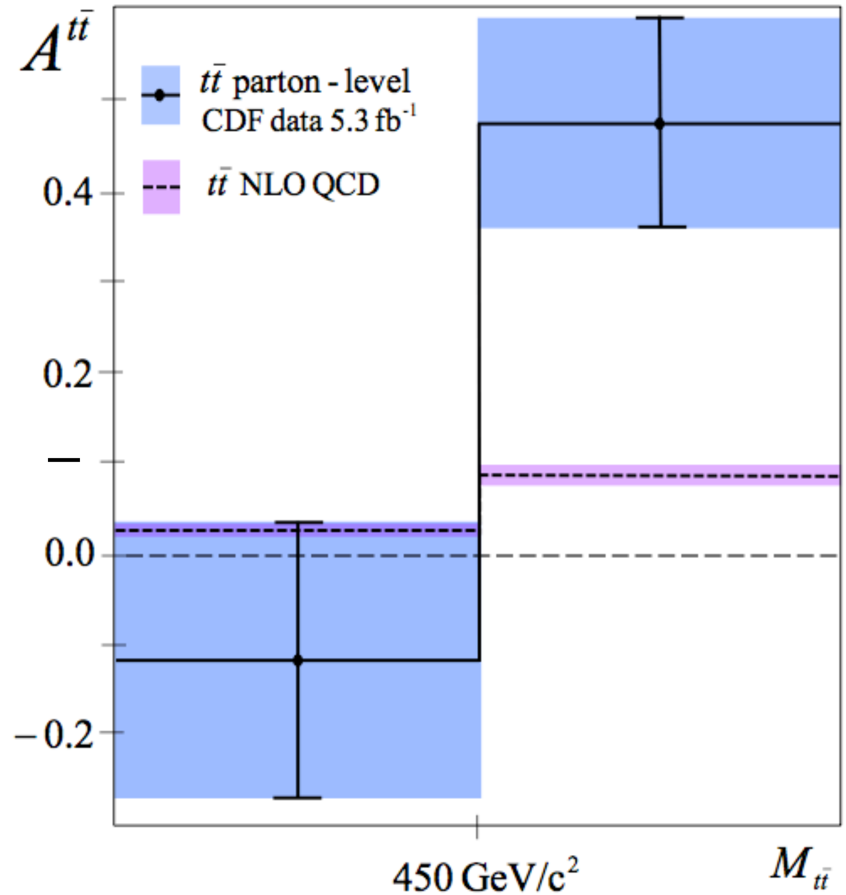
At parton level:

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

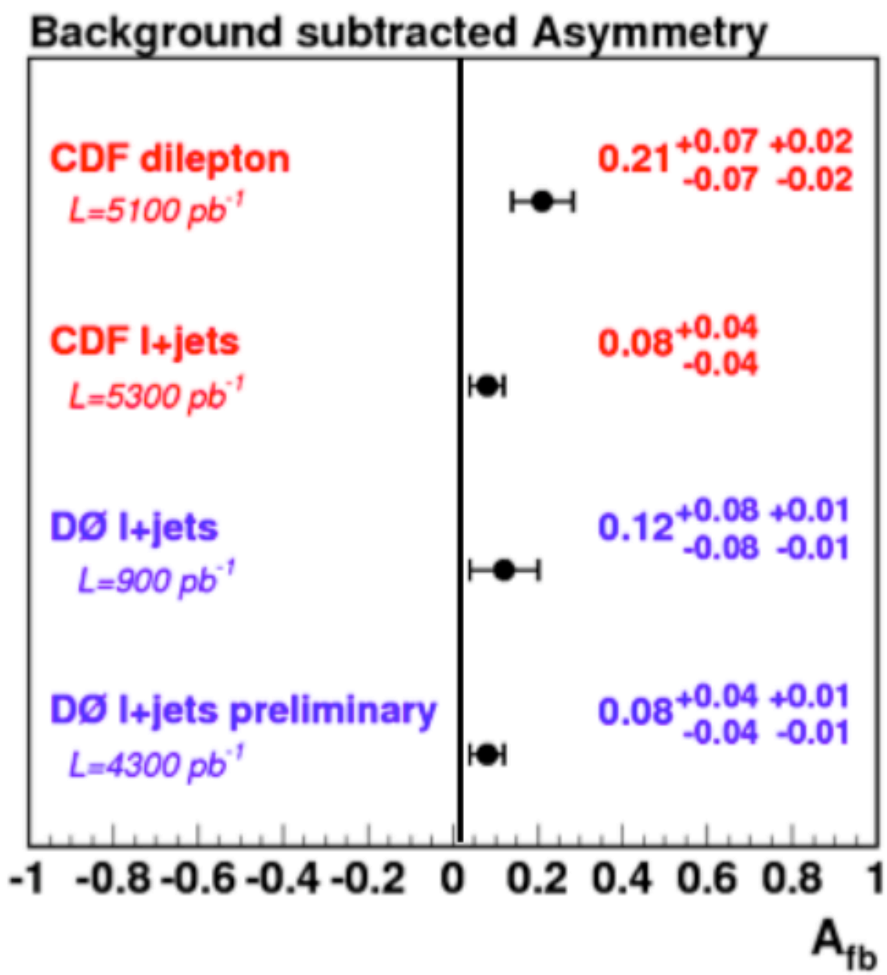
Note: at higher m_{tt}, we are more sensitive to possible new physics processes coupling to top quarks.



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

>3 σ discrepancy
hep-ex/1101.0034

comparisons



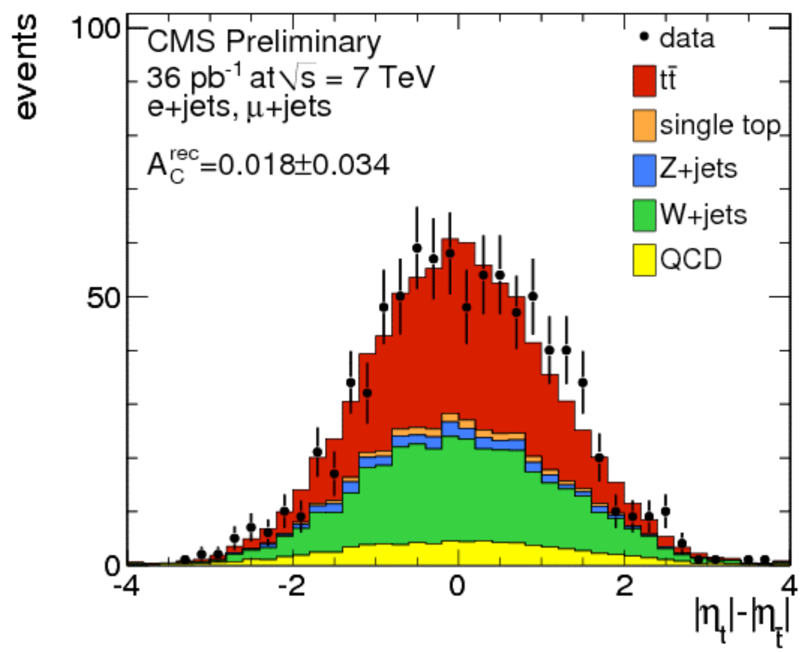
not an easy measurement at the LHC

- 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.



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

Summary

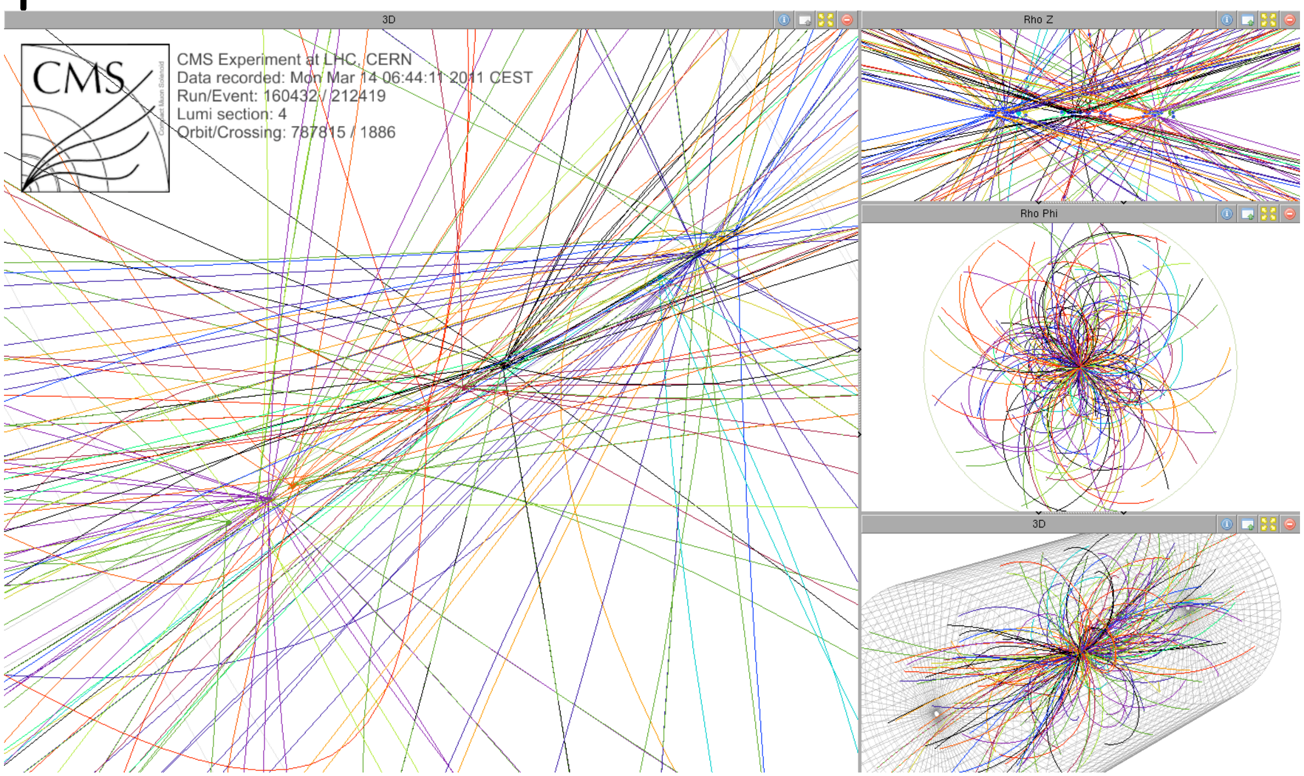
- Top quark physics could be the first place to see NP at the LHC
  - interesting Tevatron asymmetry results may be the first glimpse?

- The collider experiments at the LHC have produced first top quark measurements at the highest energies ever reached and will soon take the lead in the field of top physics

- Already in the last few weeks, a data set of comparable size has been recorded. By the end of the year we expect ~100 times more data. Stay tuned!

2011 run so far

- In just 7 days of warm-up we have recorded a data set half the size of the 2010 data set. Already surpassed the 2011 baseline lumi of L=2x10^{32}.Very impressive operation and detector performance
- One of the problems facing us now: "pile-up"
  Example: event with 13 reconstructed vertices:

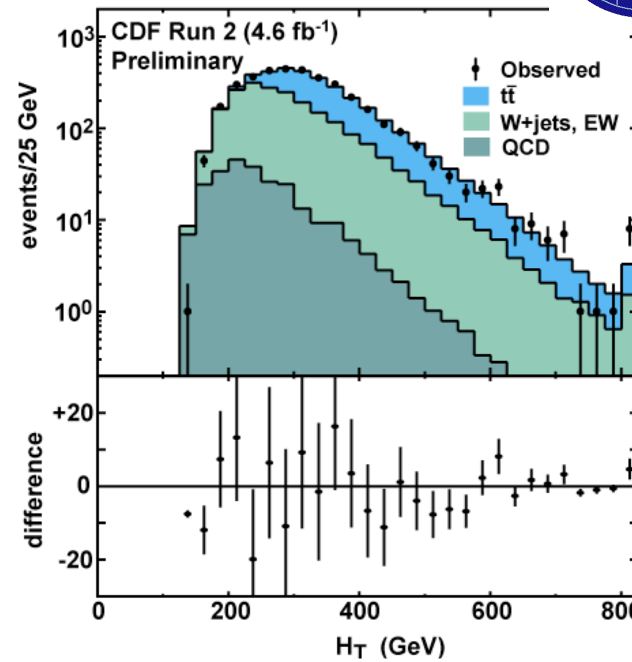


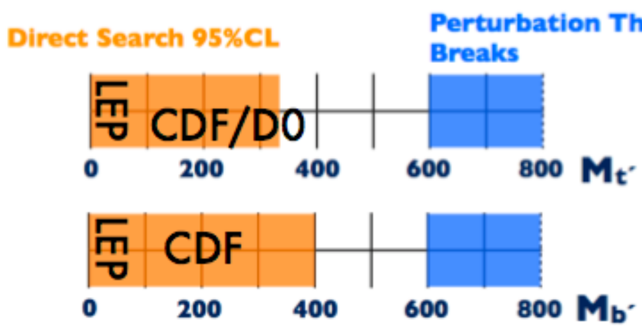
Search for Heavy Top t' → Wq

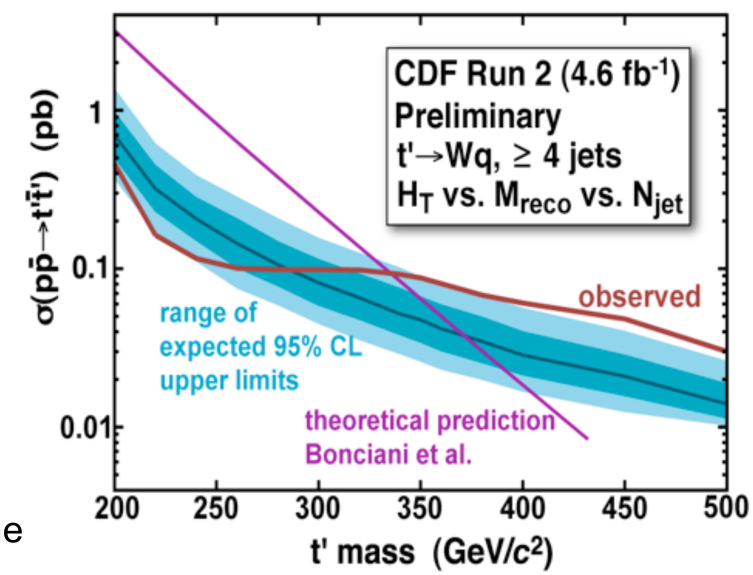
Search for heavy top decay to Wq final states (e.g.LHT)

- Use observed H_T and mass distribution to fit signal t' and background (top, W,...) distributions

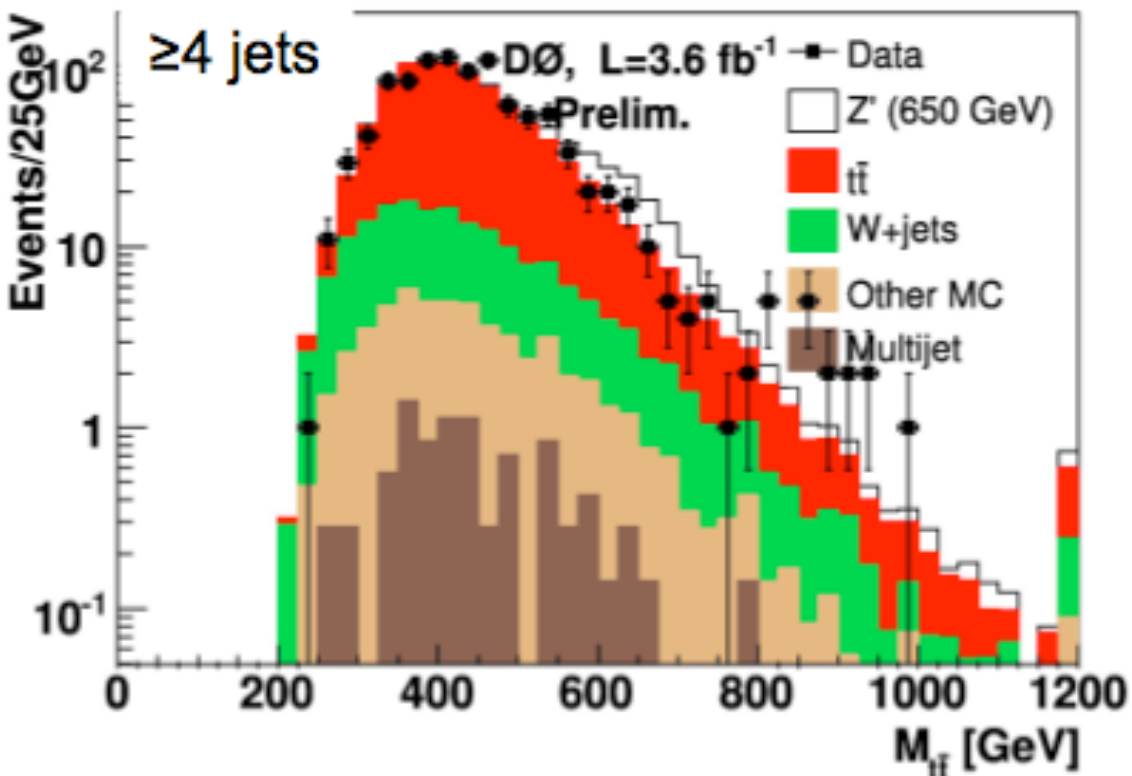
- exclude a standard model fourth-generation t' quark with mass below 335 GeV at 95% CL.



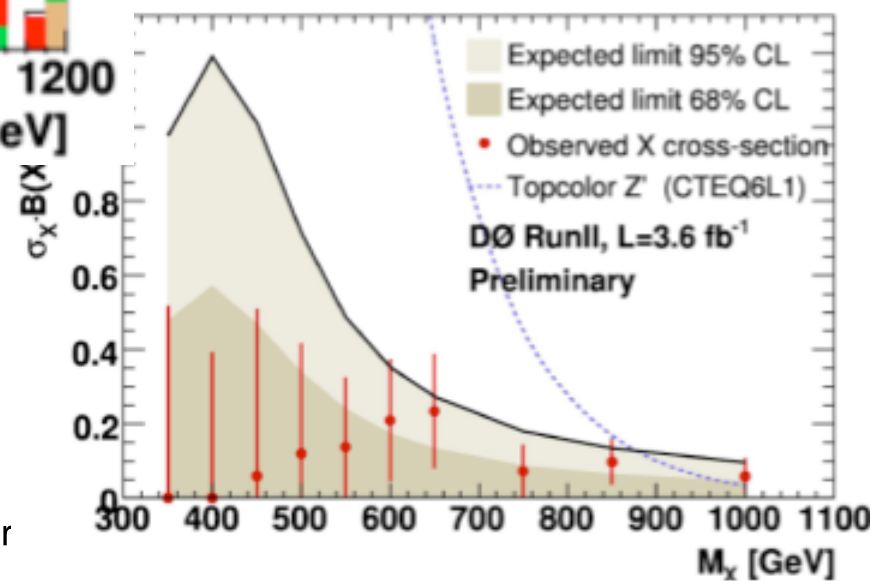




Search for top resonance at D0



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



More top physics, not mentioned in this talk

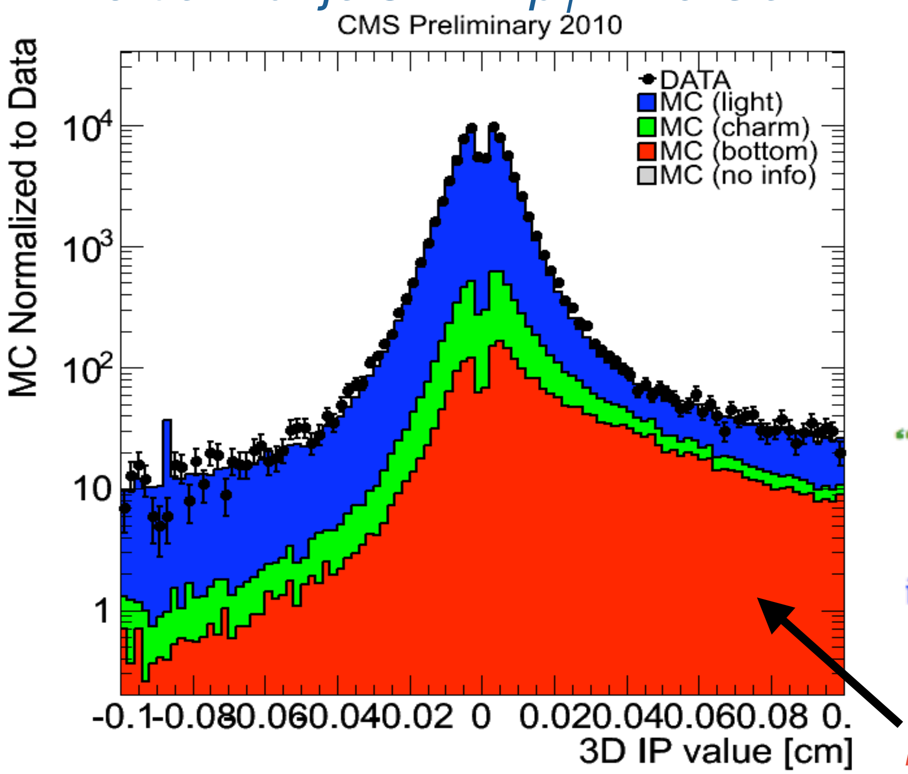
- role of precision top mass measurements
- role of Httbar production
- Investigation of W helicity in t->Wb
- Measurements of top spin, charge, width, etc

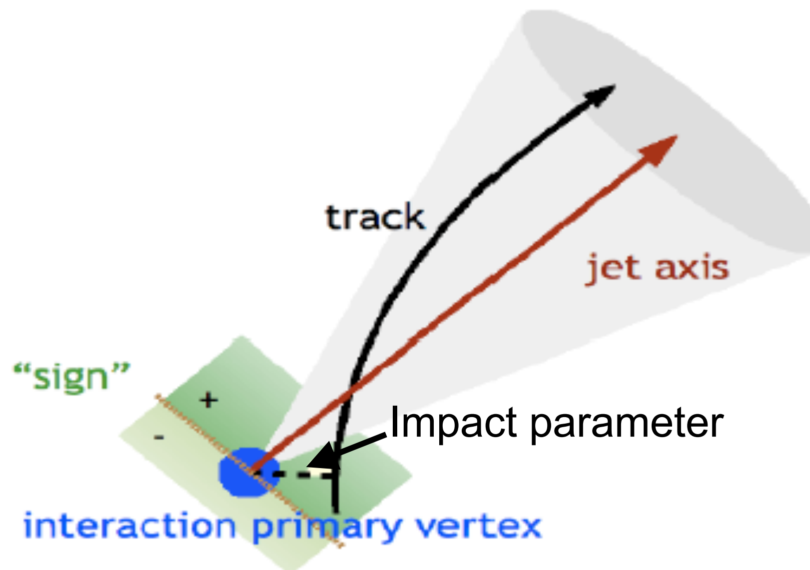
B tagging: 3D impact parameter

Measure the 3D impact parameter of tracks within jets:

- Large impact parameter value: track points to secondary vertex
- Need excellent alignment and general tracking performance

For tracks with p_T>1GeV belonging to central jets with p_T > 40 GeV:

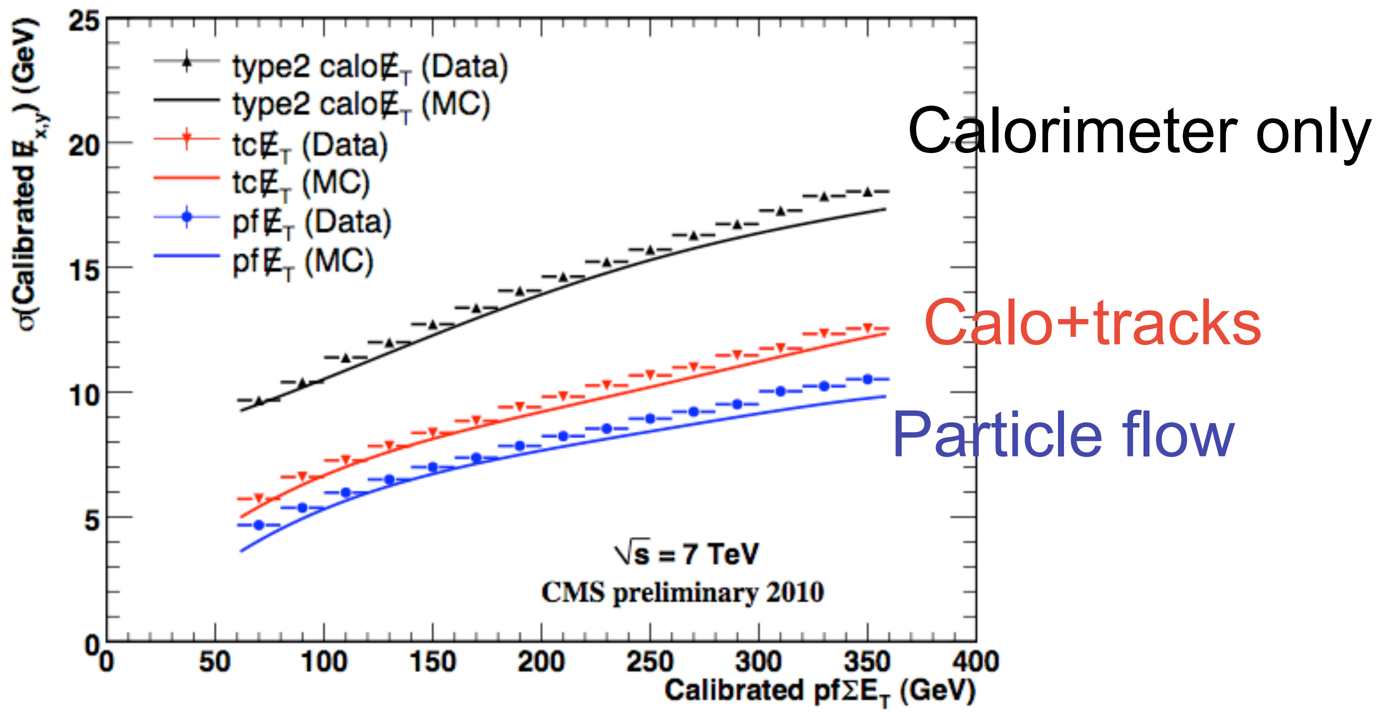




Long-lived b (and c)

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



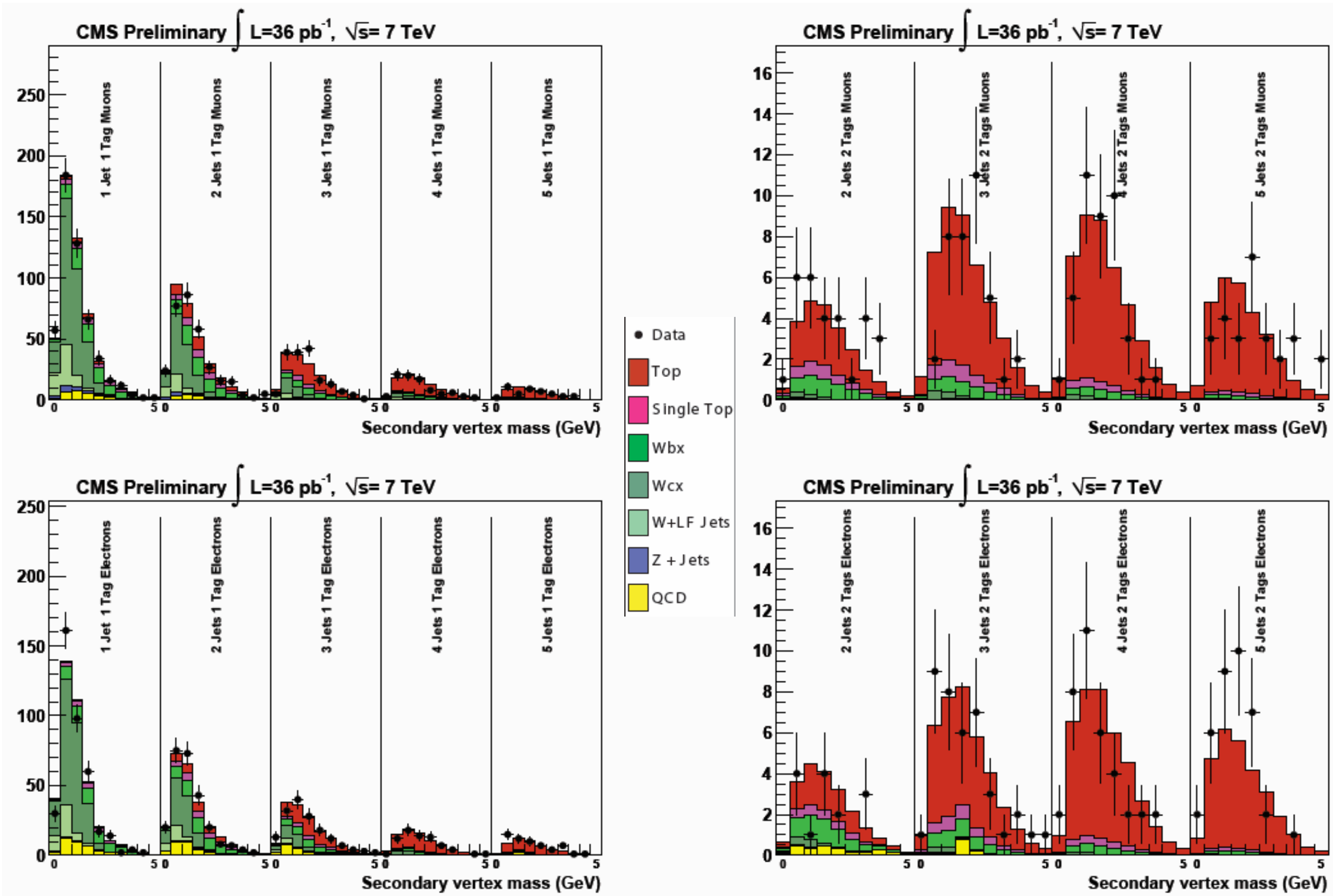
Top Lepton+Jets (tagged) Fit

>= 4 jet
>= 1 tag

80% purity

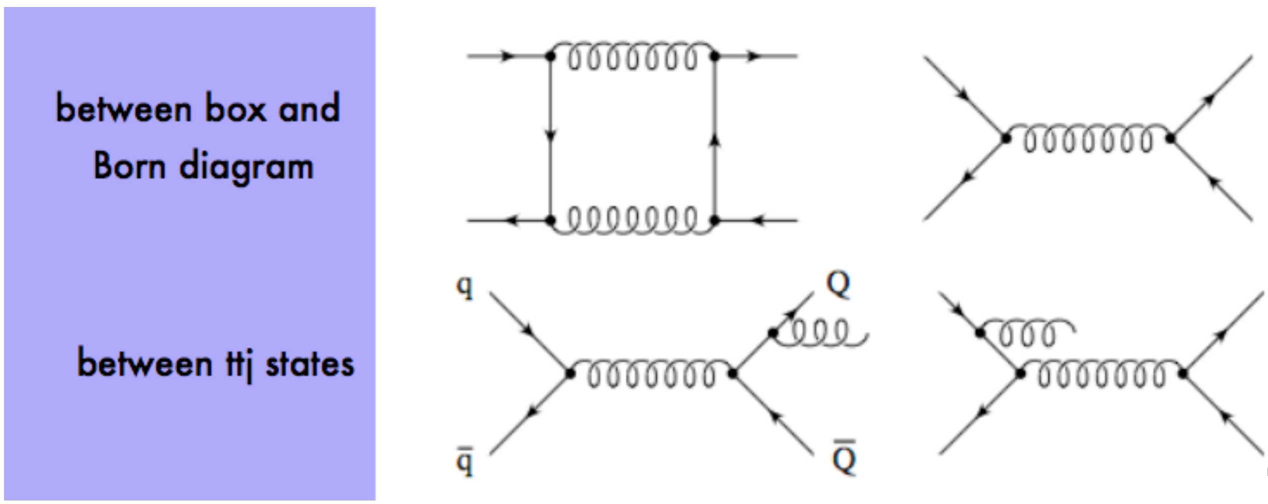
>= 4 jet
>= 2 tag

90% purity



Anomalous Forward Backward Asymmetry

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



tt frame asymmetries:

A_{FB} ~ +10-12 % NLO

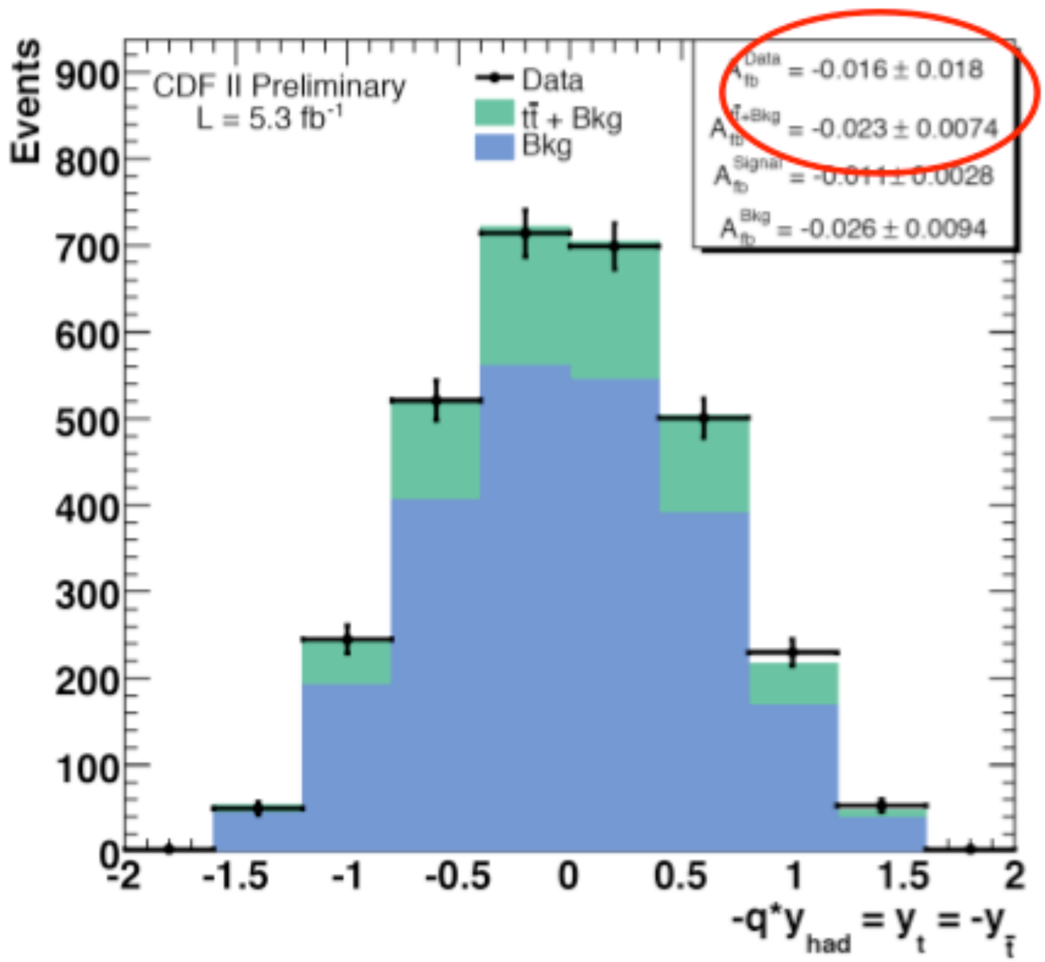
A_{FB} ~ -7 % NLO

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

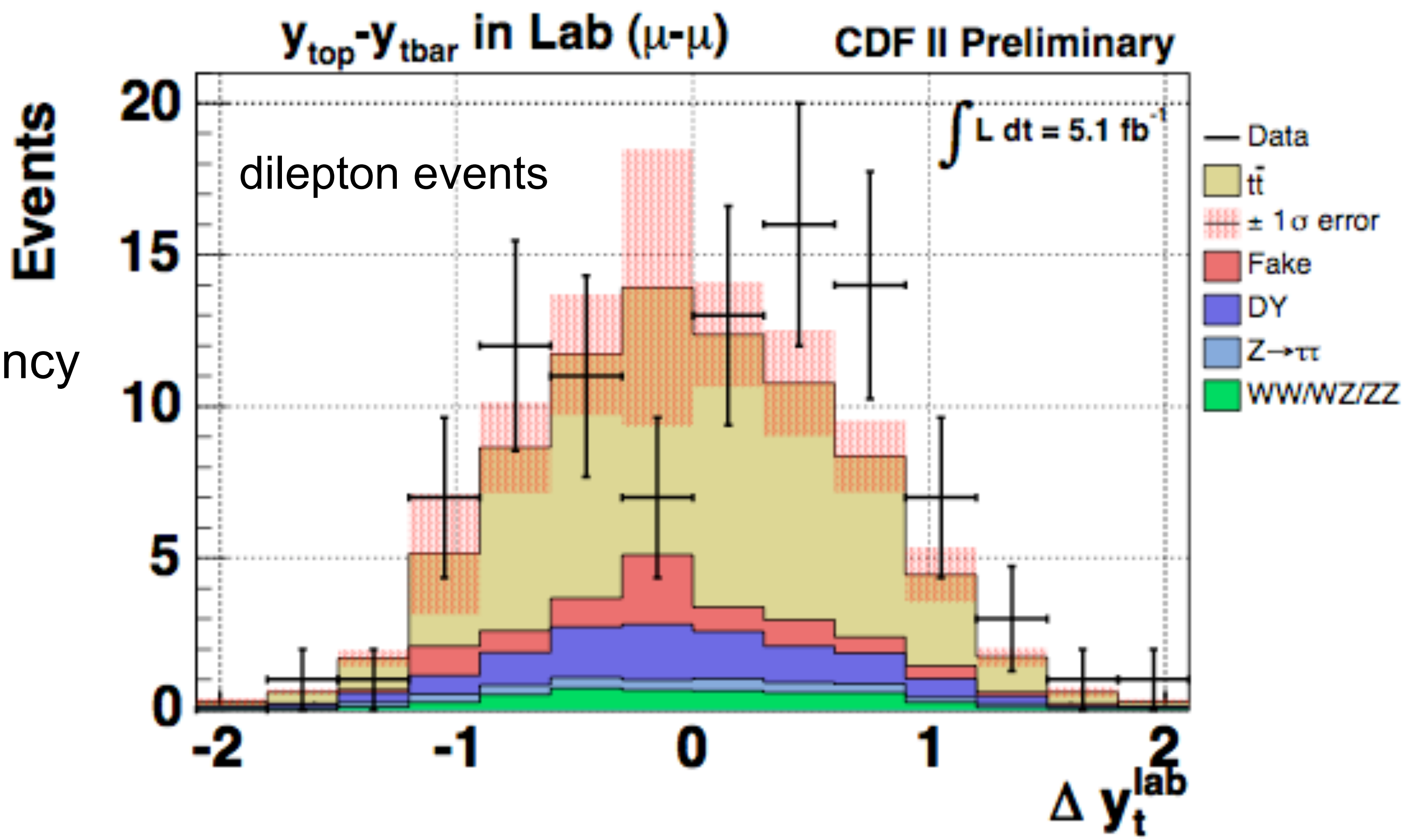


A_{FB} in the dilepton channel

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

A_{fb}= 42.0% ±16%

2.3 σ discrepancy

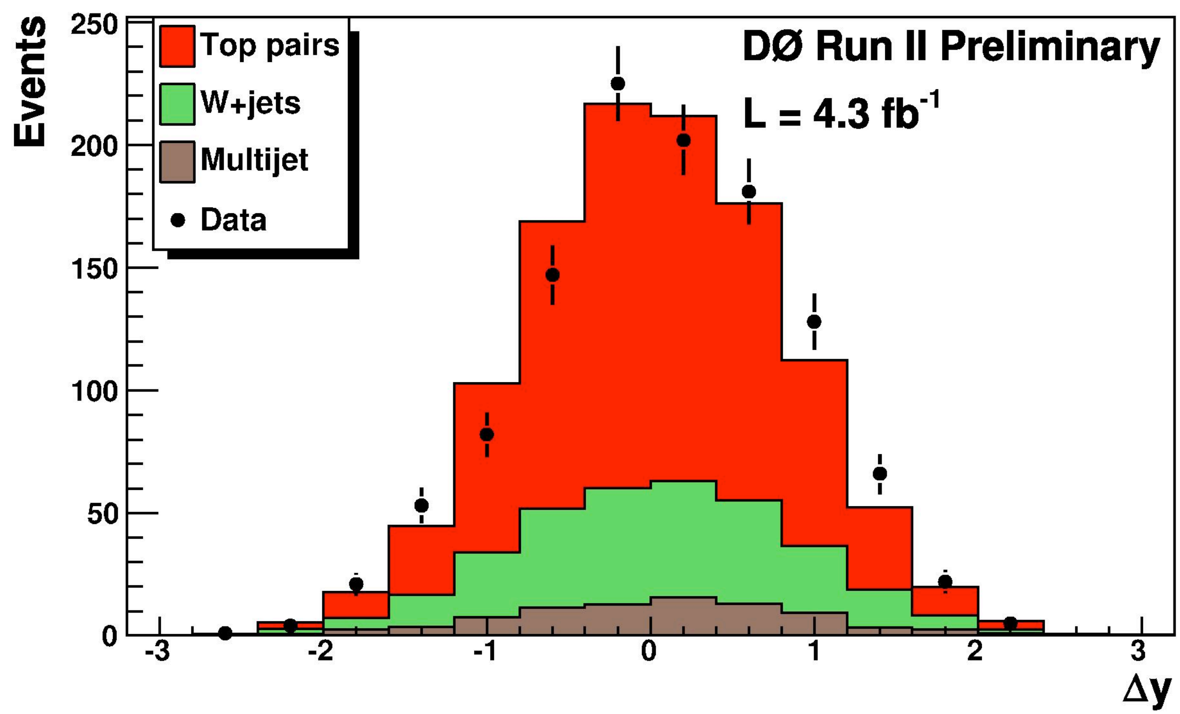


consistent with D0 results

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

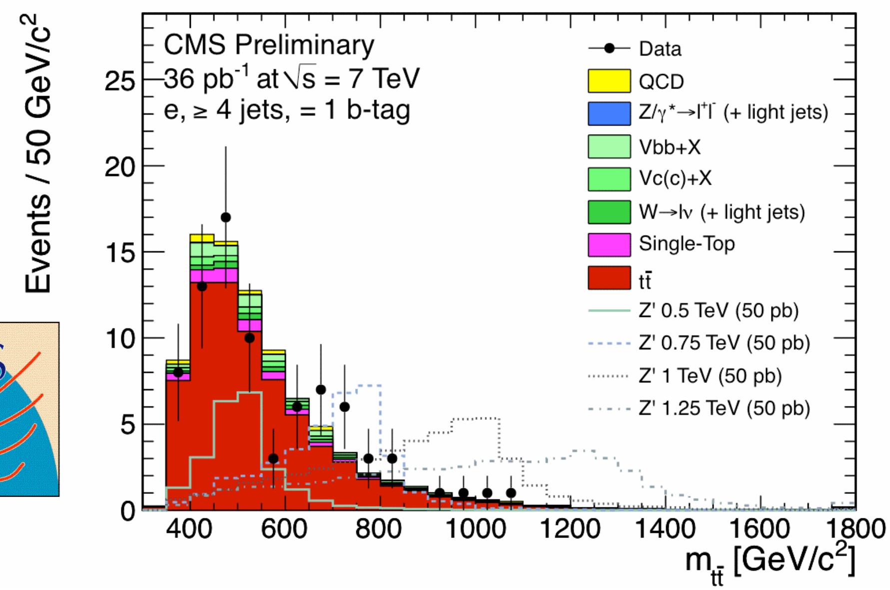
  A_{fb}= 8.0% ±4%

2 σ discrepancy

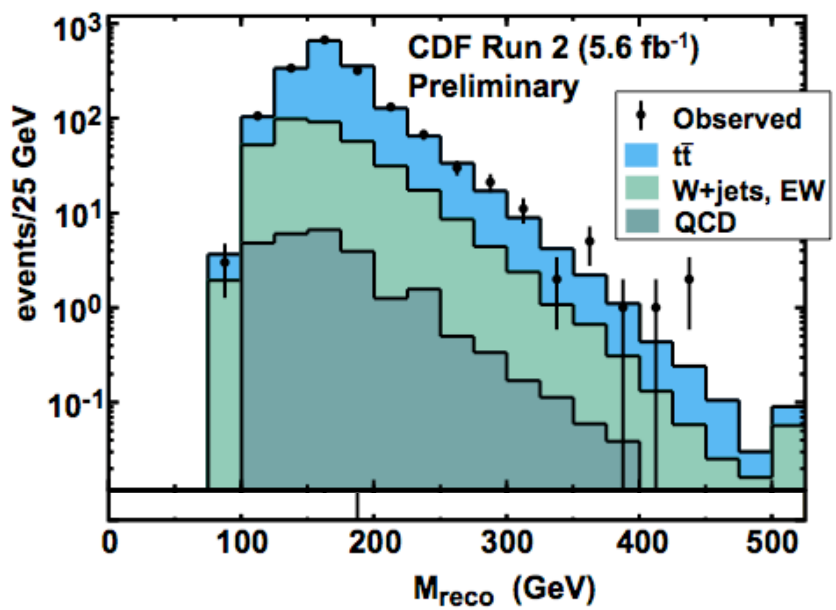


Other interesting searches

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



- Searches for 4th generation quarks (t′->Wq)
  - Still not ruled out- possible mass = few 100 GeV



Julia Thom, C

Top Lepton+Jets (tagged) Results

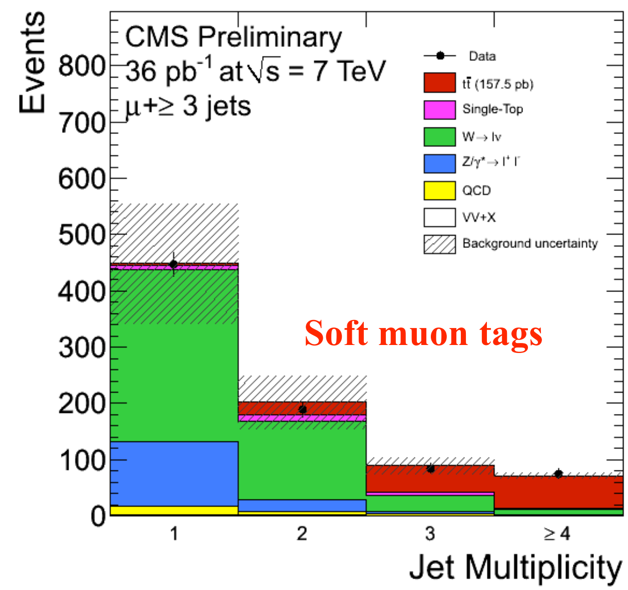
Interesting best fit nuisance parameters

B-tag efficiency scale factor: 0.975±0.045
Jet energy scale shift: +0.6±0.6 σ
W + jets Q^2 scale shift: -0.25±0.45 σ

W+bx scale factor: 1.9±0.6 X "SM"
W+cx scale factor: 1.4±0.2 X "SM"
"SM" = MadGraph scaled to W+jets NLO

Source	Uncertainty (%)
Systematic uncertainties	
Lepton ID/reco/trigger	3
Unclustered E_T^{miss} resolution	< 1
$t\bar{t}$+ Jets Q^2-scale	2
ISR/FSR	2
ME to PS matching	2
PDF	3.4
Profile likelihood parameters	
Jet energy scale and resolution	7.0
b tag efficiency	7.5
W+Jets Q^2-scale	9.1
Combined	11.6

Cross-checked by 4 other analyses which use explicit **IP** and **soft muon** b-tagging



Mu $\sigma_{t\bar{t}} = 145 \pm 12\,(\text{stat.}) \pm 18\,(\text{syst.}) \pm 6\,(\text{lum.})$ pb;
Ele $\sigma_{t\bar{t}} = 158 \pm 14\,(\text{stat.}) \pm 19\,(\text{syst.}) \pm 6\,(\text{lum.})$ pb

Combined result

$$\sigma_{t\bar{t}} = 150 \pm 9\,(\text{stat.}) \pm 17\,(\text{syst.}) \pm 6\,(\text{lum.})\ \text{pb.}$$

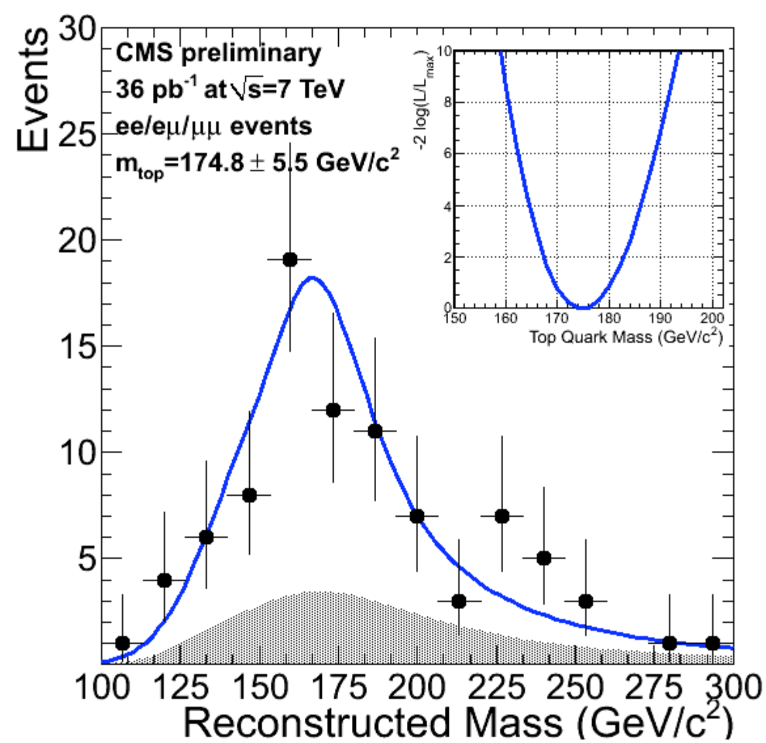
13% precision, largest systematics reducible

First LHC top mass measurement

Use top dilepton events first:
highest purity,
least number of jets,
cross section and event selection established six months ago

Based on improved versions of Tevatron methods
CDF MWT doi:10.1103/PhysRevD.73.112006
D0 KIN doi:10.1103/PhysRevLett.80.2063

KINb method:
•many solutions per lepton-jet pairing upon variation of jet PT, MET direction, Pz(tt), and their resolutions.
•B-tagging used for jet-lepton assignment wherever possible
•Choose combination with the largest number of solutions (75% success).
•1D Likelihood fit to reconstructed top mass



First LHC top mass measurement

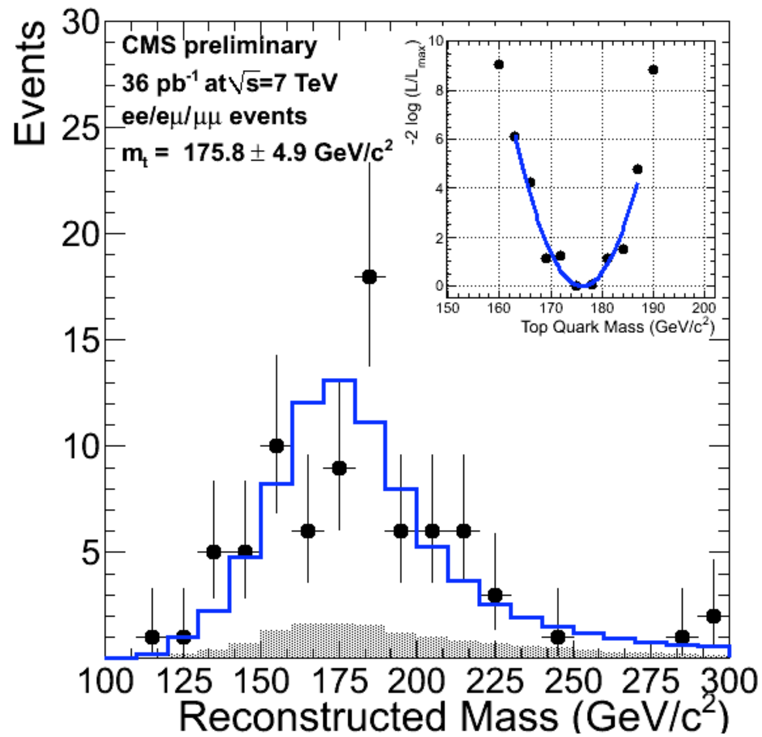
AMWT method:

•many solutions per lepton-jet pairing upon variation of jet PT, MET direction, Pz(tt), and their resolutions, Each assigned a weight

$$w = \{\sum F(x_1)F(\bar{x_2})\}\, p(E^*_{\ell+}|m_t)p(E^*_{\ell-}|m_t)$$

•M_{AMWT} is Mtop hypothesis with largest average weight

•1D LH fit to M_{AMWT} over 3 b-tagging categories



Method	Measured m_{top} (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9(stat) \pm 4.5(syst)$	0.65
KINb	$174.8 \pm 5.5(stat)^{+4.5}_{-5.0}(syst)$	0.35
combined	$175.5 \pm 4.6(stat) \pm 4.6(syst)$	χ^2/dof=0.040 (p-value=0.84)

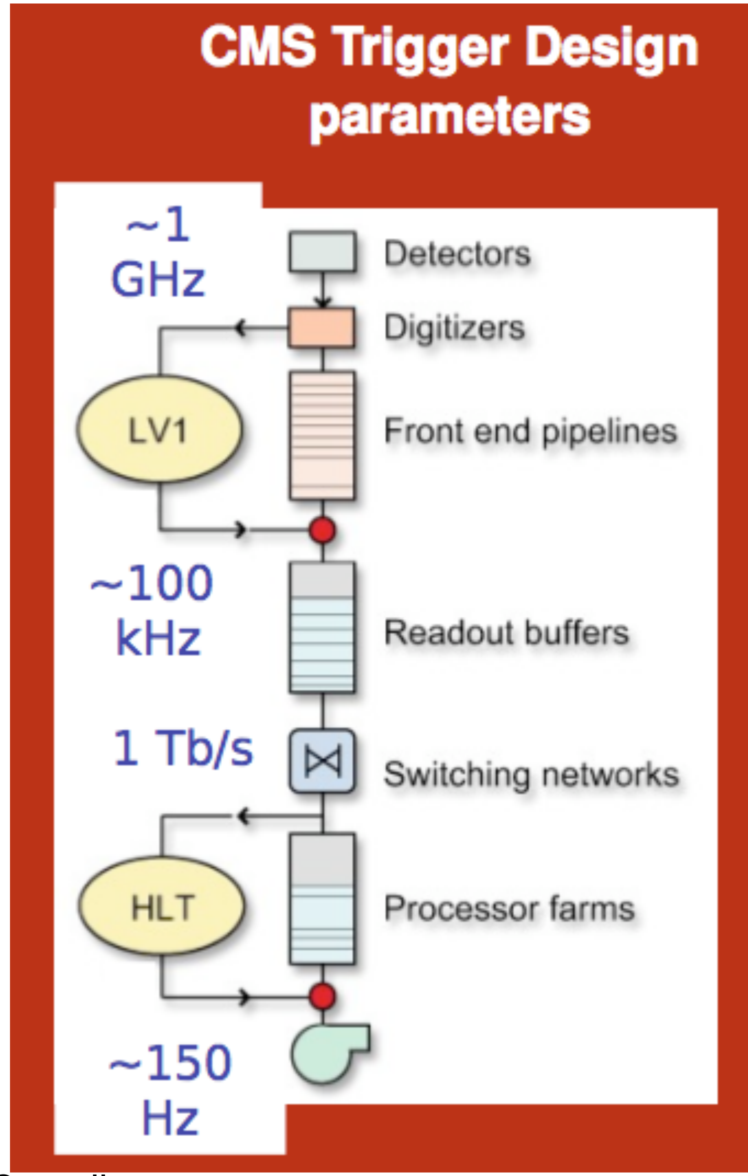
Dominant systematics are **JES** and **b-JES**

Agrees with world average top mass

ATLAS l+jets preliminary : 169.3±4.0±4.9

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



The CMS detector

Tracker coverage |η| < 2.5

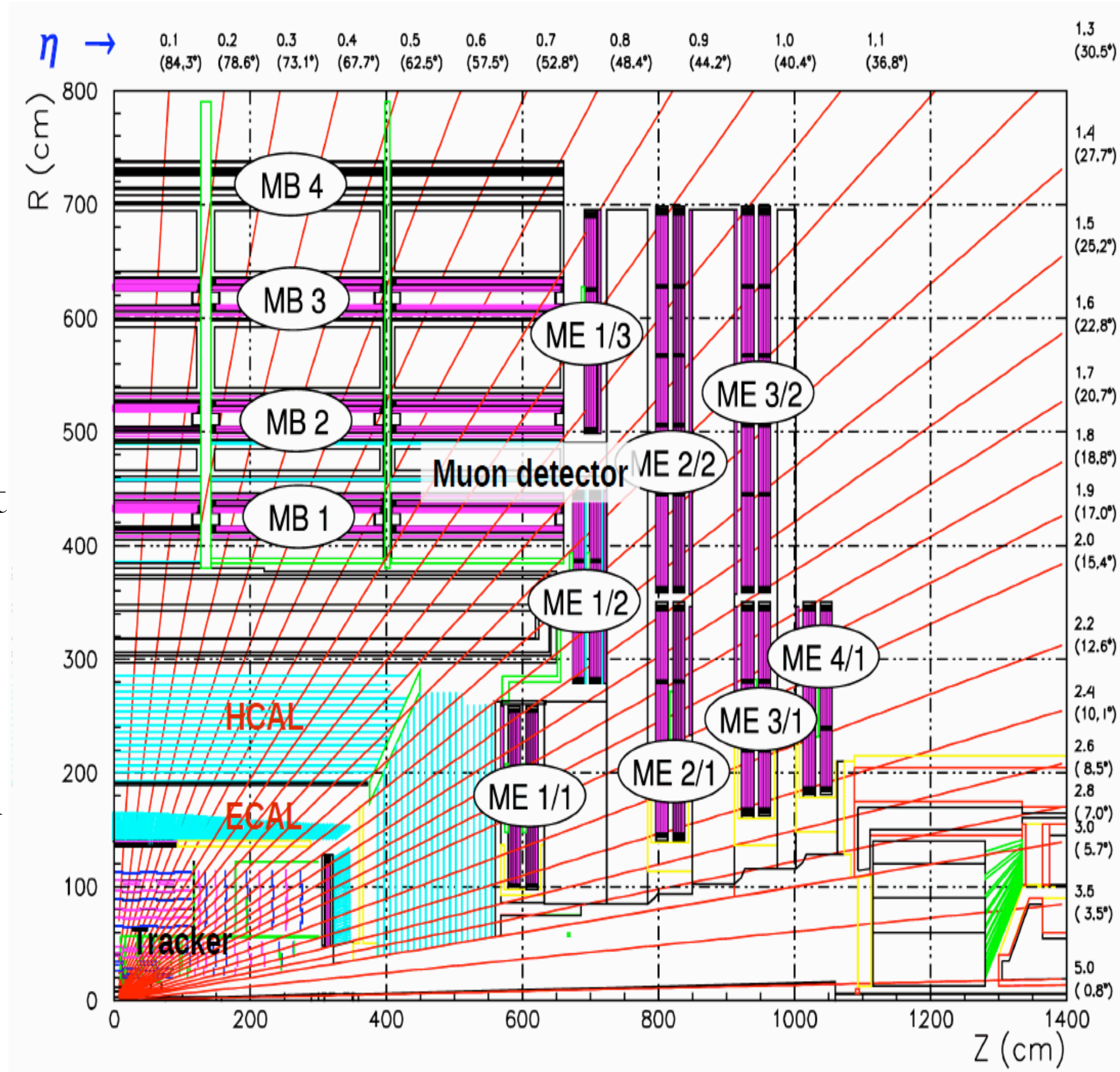
Electron coverage |η| < 2.5

Muon coverage |η| < 2.4

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

3.8 T solenoid + 76000 crystal ECAL + 200 m² silicon = percent level lepton momentum resolution at high PT

HCAL/HF coverage |η| < 5.0



Top Dilepton

Cross section systematic uncertainties (%), by channel

Combine nine categories:

ee/mumu/emu in three jet/tag categories:

= 1 jet >= 0 tag
>= 2 jet >= 0 tag
>= 1 jet >= 1 tag

	$N_{jet} = 1$		$N_{jet} \geq 2$	
Source	$e^+e^- + \mu^+\mu^-$	$e^\pm\mu^\mp$	$e^+e^- + \mu^+\mu^-$	$e^\pm\mu^\mp$
Lepton selection	1.91/1.30	1.11	1.91/1.30	1.11
Energy scale	−3.0	−5.5	3.8	2.8
Lepton selection model	4.0	4.0	4.0	4.0
Branching ratio	1.7	1.7	1.7	1.7
Decay model	2.0	2.0	2.0	2.0
Event Q^2 scale	8.2	10	−2.3	−1.7
Top-quark mass	−2.9	−1.0	2.6	1.5
Jet and $\not{E}_T$ model	−3.0	−1.0	3.2	0.4
Shower model	1.0	3.3	−0.7	−0.7
Pileup	−2.0	−2.0	0.8	0.8
Subtotal (before tags)	11.2/11.1	13.1	8.0/7.9	6.2
b tagging ($\geq$ 1 b tag)			5.0	5.0
Subtotal with tags			9.5/9.4	8.0
Luminosity	4	4	4	4

Combined cross section: $168 \pm 18(\text{stat}) \pm 14(\text{syst}) \pm 7(\text{lum})$ pb.

14% precision with no dominant systematic ingredient

b-tag efficiency inferred from double-tag/single-tag ratio →