Tevatron Legacy Measurements
or
The Tevatron Collider Legacy

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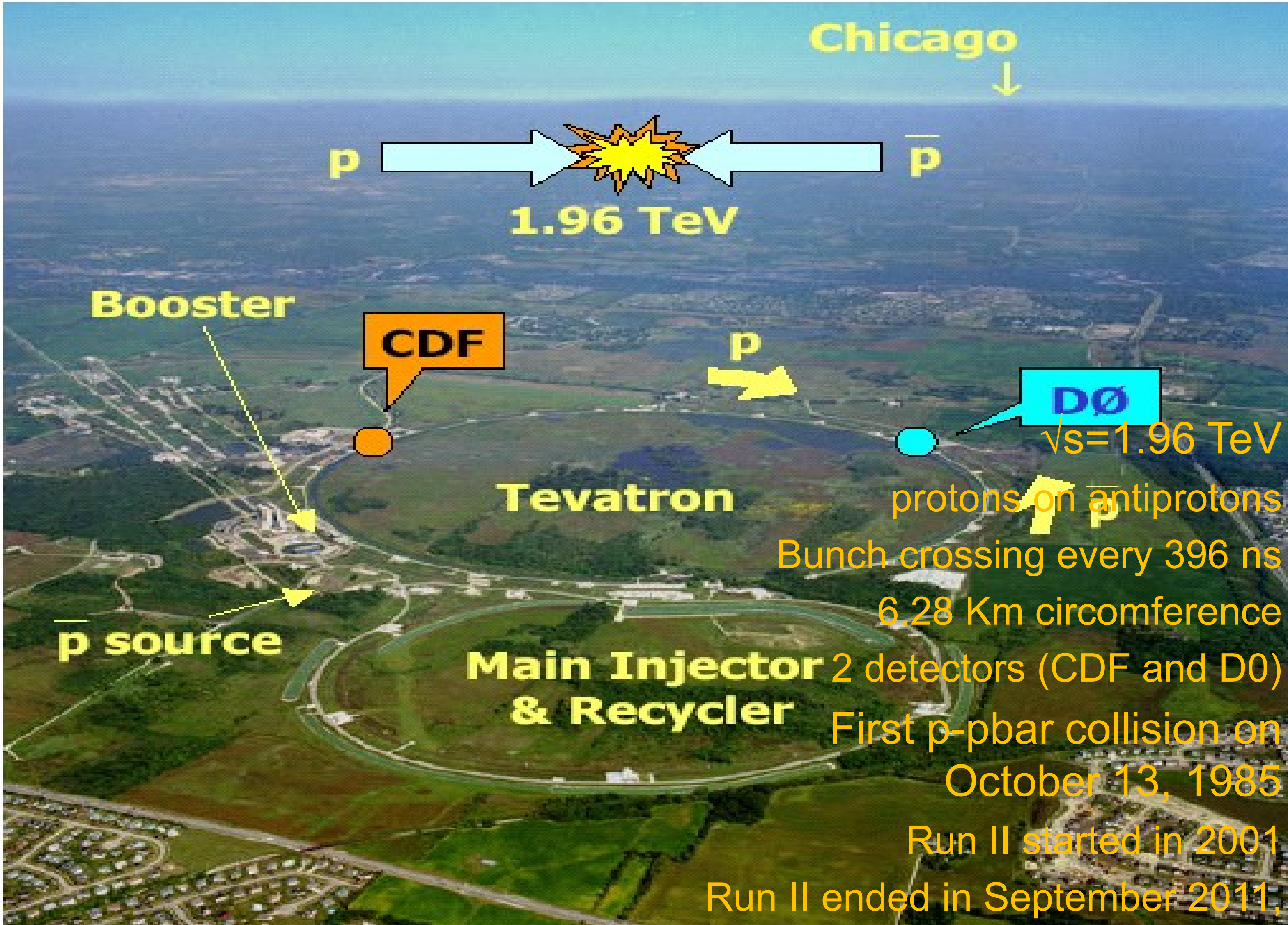
>25 years of operation



$\sqrt{s}$=1.96 TeV

protons on antiprotons

Bunch crossing every 396 ns

6.28 Km circumference

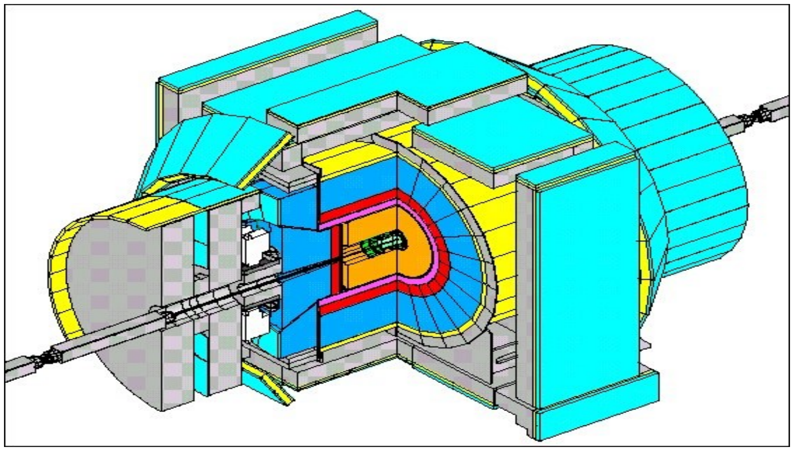
2 detectors (CDF and D0)

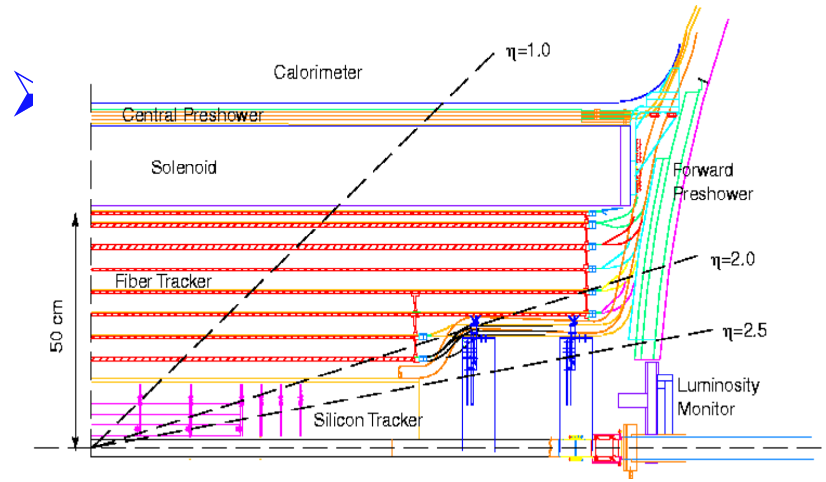
First p-pbar collision on October 13, 1985

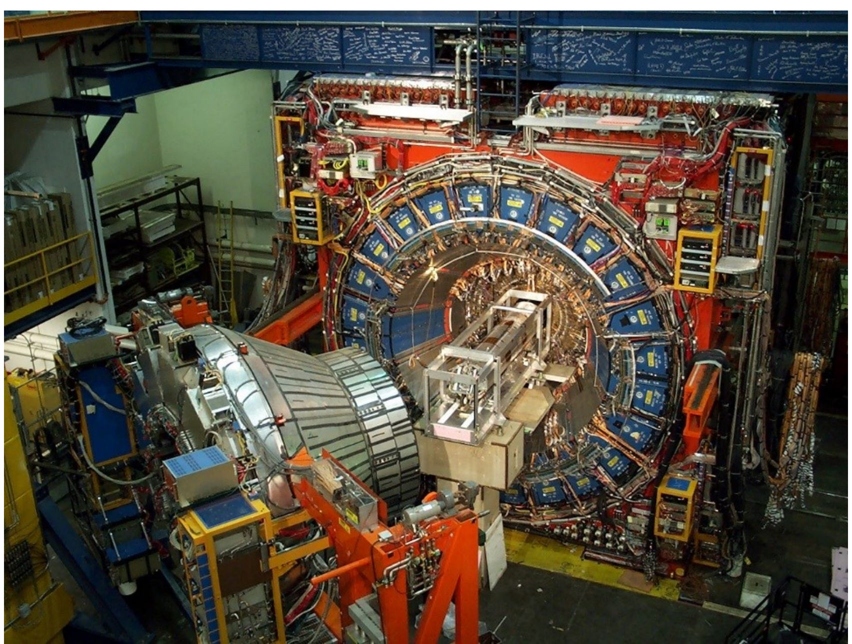
Run II started in 2001

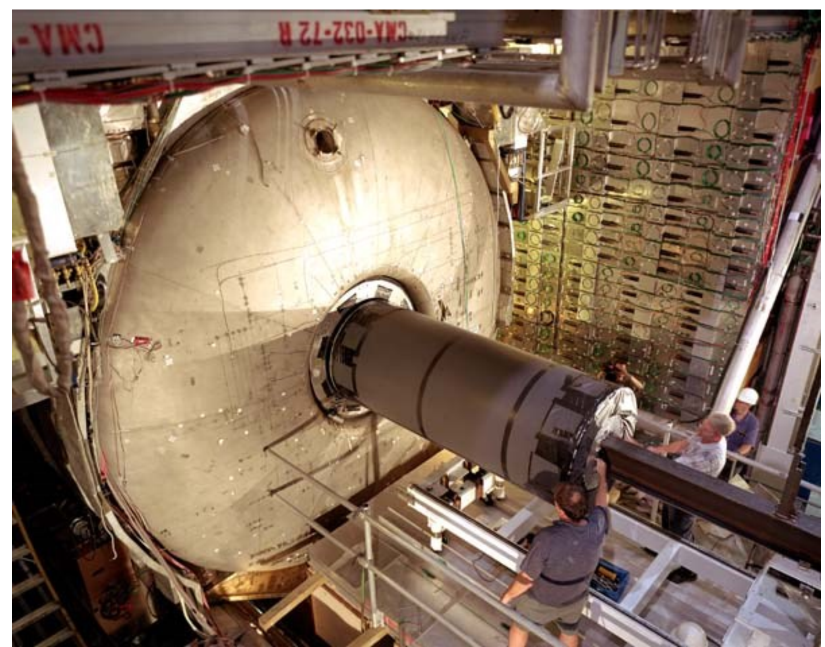
Run II ended in September 2011, when Tevatron stopped operation

Two detectors









Two experiments that invented hadron collider physics

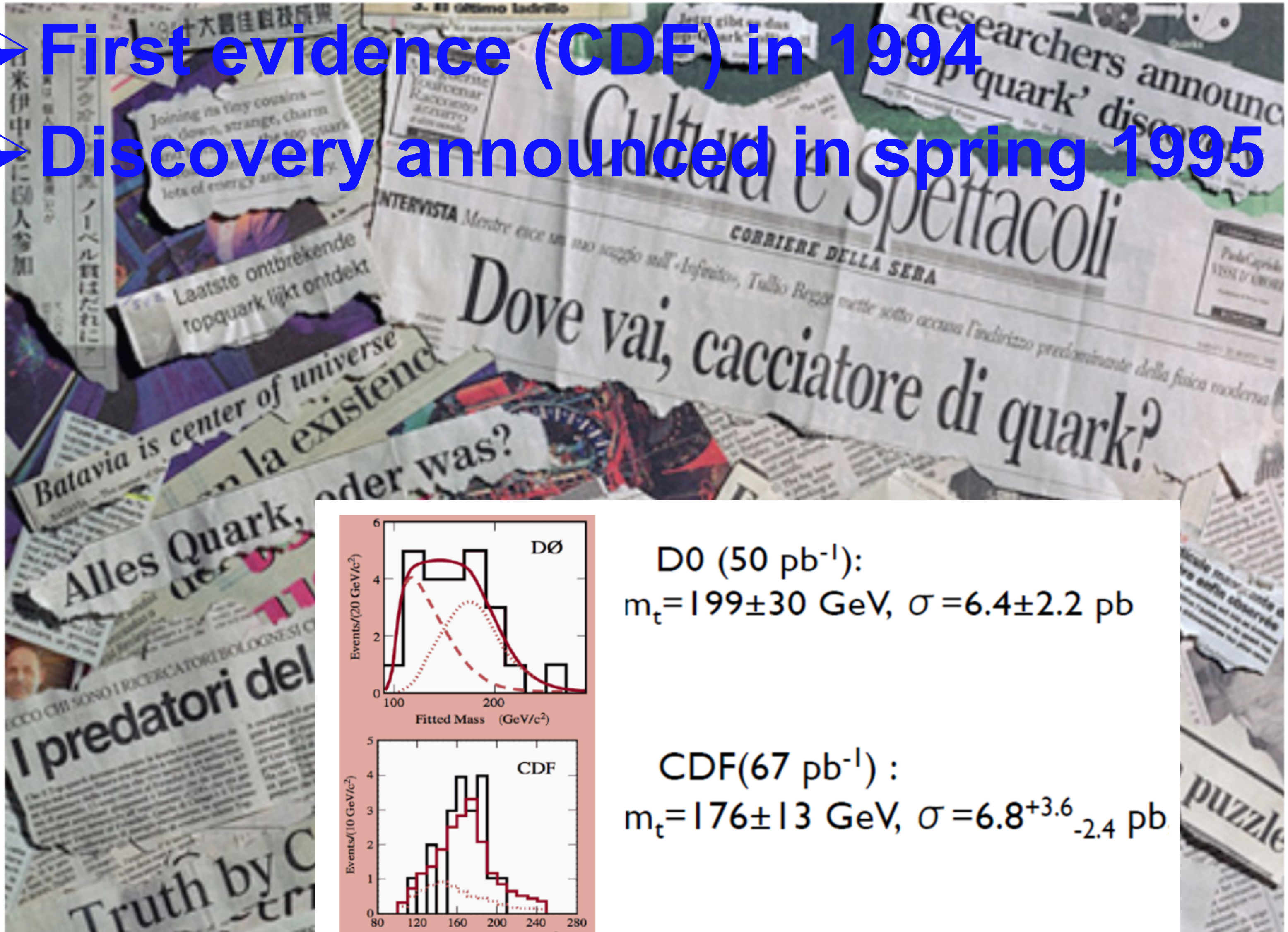
Remember: collider physics in 1989 (Run-0) was at its infancy

- An handful of Z and W from UA1/UA2
- «physics objects» (a.k.a. Electrons, jets, muons etc) in experimental apparatus not yet standardized
- Secondary vertexing at Hadron Collider was for the brave (and a little crazy)
- B physics was not yet part of hadron colliders physics programs

This and much more was achieved by CDF and D0 people

The home of the top quark

- First evidence (CDF) in 1994
- Discovery announced in spring 1995



D0 (50 pb^{-1}):
m_t=199±30 GeV, σ =6.4±2.2 pb

CDF(67 pb^{-1}) :
m_t=176±13 GeV, σ =$6.8^{+3.6}_{-2.4}$ pb

Exploring the frontier

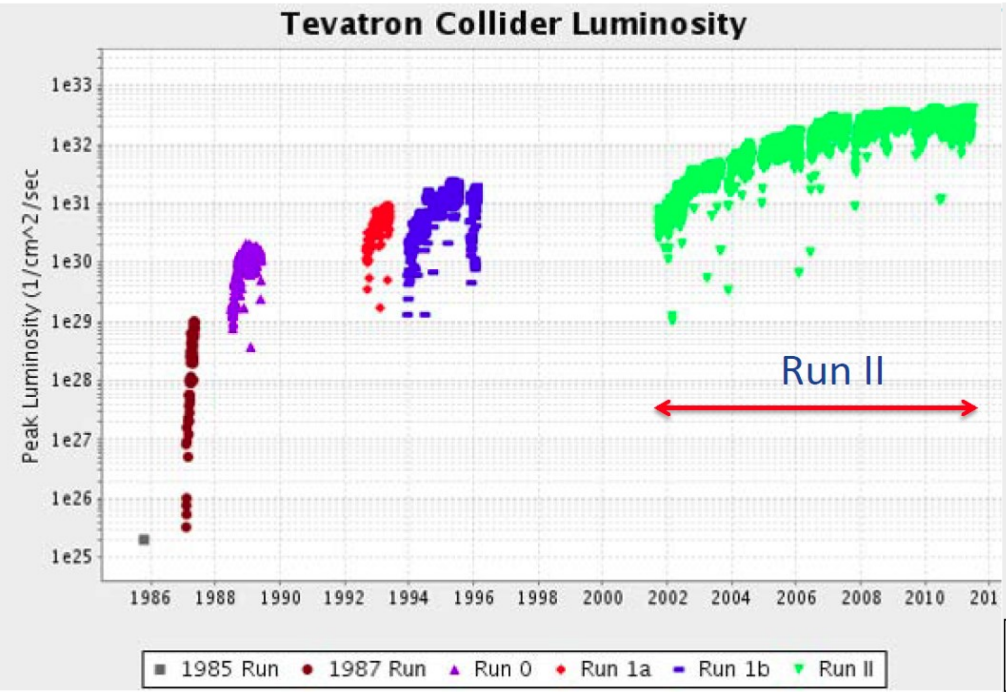
Energy from

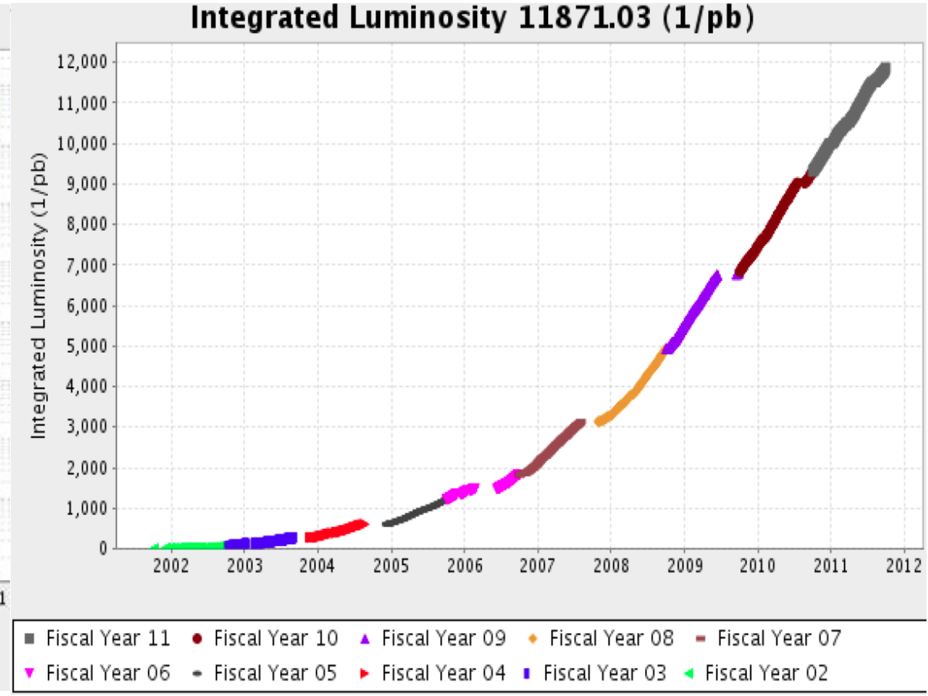
- 1.8 TeV (Run-0) to 1.96 TeV (Run 1)
  - Highest energy available until LHC started operation
- Explored the energy frontier
  - Looking for unknown
  - Confirming SM expectation
    - Top Quark, search for the Higgs Boson

Design luminosity: 10^{30} $cm^{-2}s^{-1}$.

- Run 2 $>10^{32}$ $cm^{-2}s^{-1}$: study of rare processes with unprecedented accuracy
  - B Physics (Bs oscillations)
  - W mass
  - Top Mass

The Machine





Record peak luminosity: 4.14 x 10^{32} cm^{-2} s^{-1}

After a slow start in Run 2, a reliable machine operated for years and shutdown by DOE (i.e. unbroken)

How many measurements?

- CDF> 700 papers, D0 similar figure
- >1000 PhDs between the two
  - CDF: 15 countries, 600 physicists, 63 institutions
  - D0: 18 countries, 650 physicists, 90 institutions

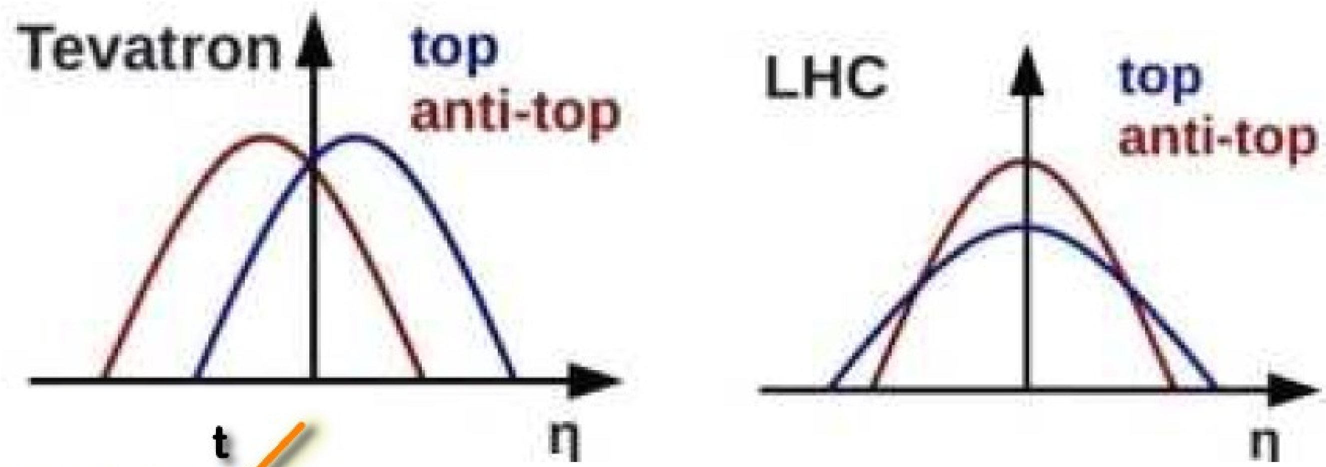
No way I can summarize in 25’

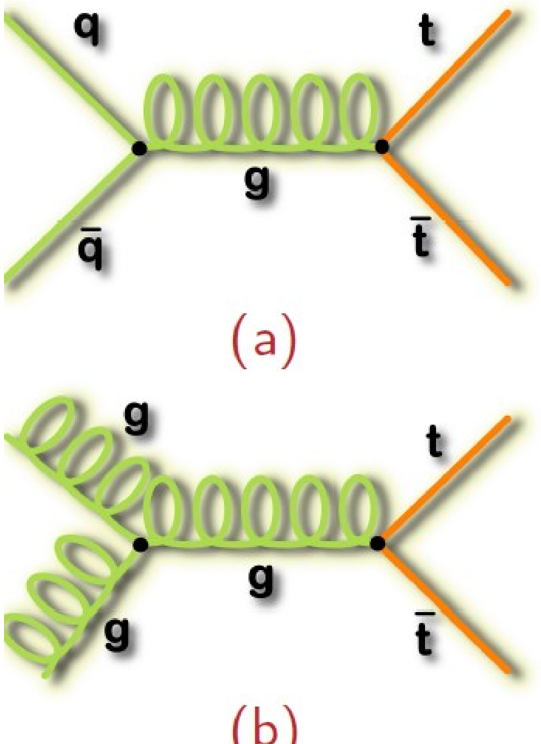
- I made some choices
  - Exploring the SM
  - The immaterial legacy
  - My own (arbitrary) selection..

Top quark physics

- CDF and D0 measured
  - Production cross section
    - Both QCD (ttbar) and EWK (single top)
  - Couplings & branching fractions
  - Properties: angular correlation, asymmetry, Mass
- Mass measurement is challenging
  - «we will never be able to see a top quark mass peak» (circa 1994, a famous CDF colleague)...
  - re-discovered old techinques
    - First CDF measurement partly based on code developed for bubble chambes
  - Developed entirely new techinques
    - Matrix Element (D0, Run I)
    - Constrain Jet Energy Scale (CDF, D0 Run 2) during fitting exploiting W→jj decay
    - ...

Asymmetry in ttbar events:





Asymmetry from qqbar annihilation:
Tevatron production is dominated (85%) by qqbar annihilation (a),

LHC is dominated (90%) by gluon fusion(b)

Asymmetry sizeable in ppbar collisions, limited to central-forward effects in pp at LHC

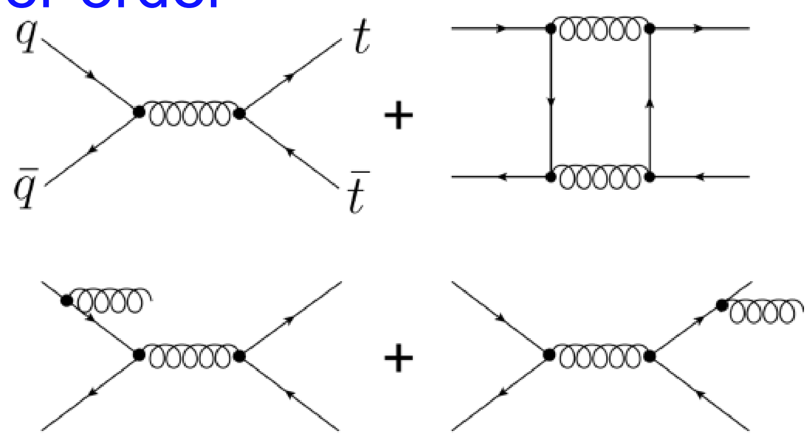
Precision check of SM:

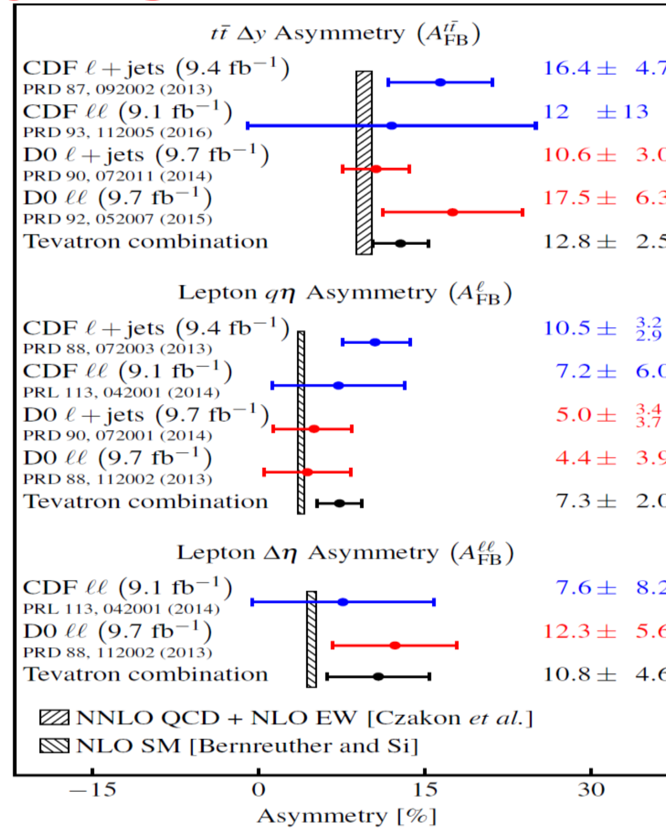
Asymmetry zero at LO

Check of higher order predictions:

NLO,

NNLO





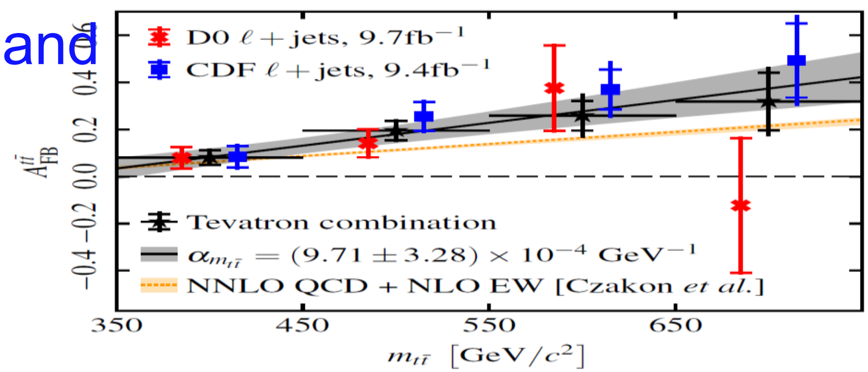
Early indications of deviations from SM

Improvements on both exp.

(more data and more robust analyses) and theoretical calculations

(higher order, more effects)

..Final results show reasonable agreement with SM



Top quark studies in one slide

Top quark mass: m_t = 174.3±0.6 GeV (0.3% accuracy)

Are top and antitop masses the same? Test of CPT

Δm=0.8± 1.9 GeV (equal to 1%)

Top quark lifetime

Γ_t=1.99(+0.69/-0.55) GeV agrees with SM

Top charge |q|=2/3e to 95% C.L.

W helicity in top decay expect 70% longitudinal, 30% left-handed

SM looks good

Asymmetry of top quark in p vs pbar direction expected to be a few %

Anomalous asymmetry of ~12% - requires theory improvements?

Correlations of spins of top and anti-top are consistent with SM

No flavor changing neutral currents

$<2\times10^{-4}$ (t→ gu); $<4\times10^{-3}$ (t → gc)

No evidence for SUSY $H^\pm$ in top decays

Anomalous top vector/tensor couplings?

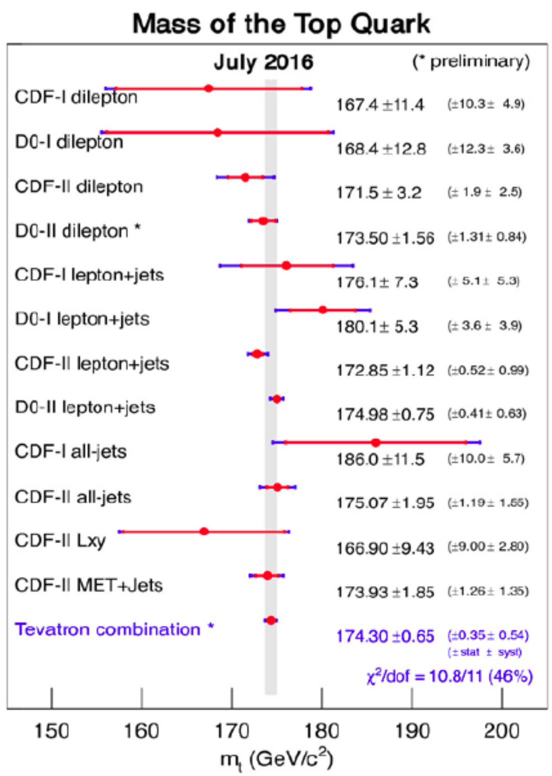
Combination of W helicity & single top is in good agreement with SM V-A

4th generation t'? None below ~450 GeV

tt resonances? None below ~800 GeV

Is W in top quark decay color singlet? Singlet preferred

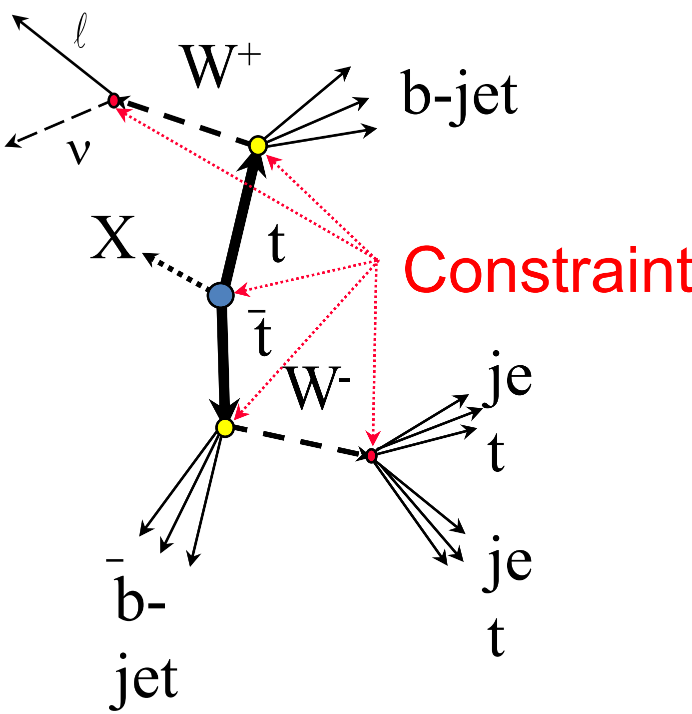
Electroweak single top quark production observed: $|V_{tb}|$ > 0.92 @ 95% C.L.



Stolen to D. Denisov

M_{Top}. How do we measure?

- Top Mass cannot be measured directly
  - One or two neutrinos in final state
- Use observables sensitive to Mtop
  - Wide possibiliy of choices
- Link observables back to partons
- Constrains:
  $M_{W+}=M_{W-}$
  $M_t=M_{tbar}$
- Identify b-jets (reduce combinatorial)
- Exploits W→jj to fix Jet Enrgy scale during fitting



Compare data and MC: template method

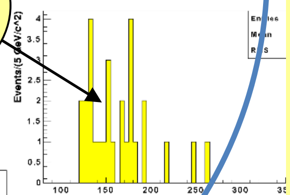
Datasets

Data

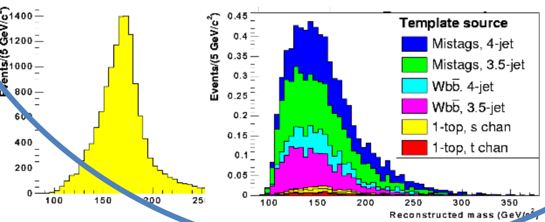
Wbb MC (backg)

tt MC

$\chi 2$ mass fitter



Templates



χ^2 mass fitter:

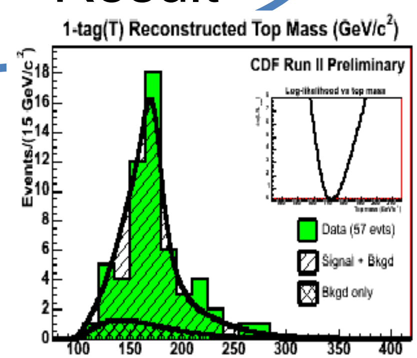
- Finds top mass that fits event best
- All event info into one number
- 12 parton/jet matching assignments possible, 2 longit. neutrino possible, use b-tag to reduce permutations
- test for consistency with top using kinematic constraints
- choose combination with lowest χ^2

Likelihood fit

Likelihood fit:

- fit resulting mass distribution to MC background + top signal templates at different values of M_{top}
- Best template to fit data gives mass
- Constraint on background normalization

Result



..or you can add kinematics

- D0 first (successfully) attempted to include known kinematics and dynamics:
  - Matrix Element Method
    - Assign each event a probability to be either top or background depending upon the top mass

$$L = \frac{1}{N(m_t)} \frac{1}{A(m_t, \mathrm{JES})} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{FF} \, \mathrm{TF}(\vec{y} \cdot \mathrm{JES} \mid \vec{x}) \, |M_{t\bar{t}}(m_t, \vec{x})|^2 \, d\Phi(\vec{x})$$

with $L = L(\vec{x} \mid m_t, \mathrm{JES})$

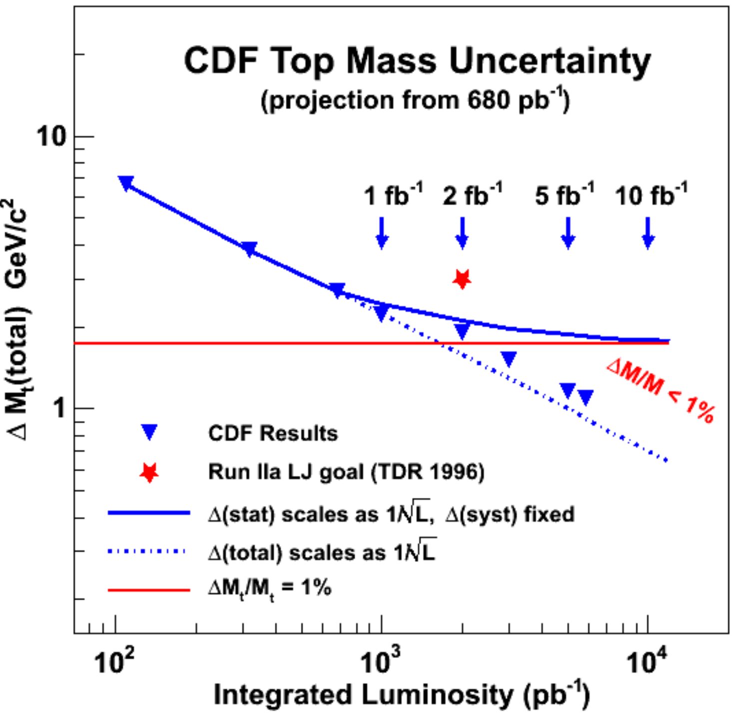
Differential cross section: LO ME (qq->tt) only

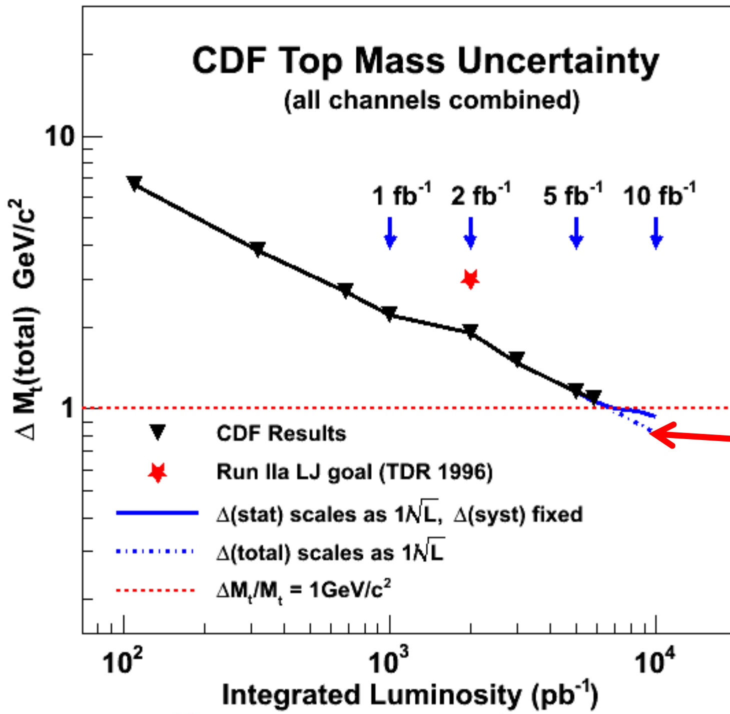
Transfer function: probability to measure x when parton-level y was produced

$$L(f_{top}, M_{top}, JES) \propto \prod_{i}^{Nevents} \left(f_{top} \, P_{top,i}(M_{top}, JES) + (1 - f_{top}) \, P_{bkgd,i}(JES) \right)$$

Nowadays one of the many ways to measure top mass

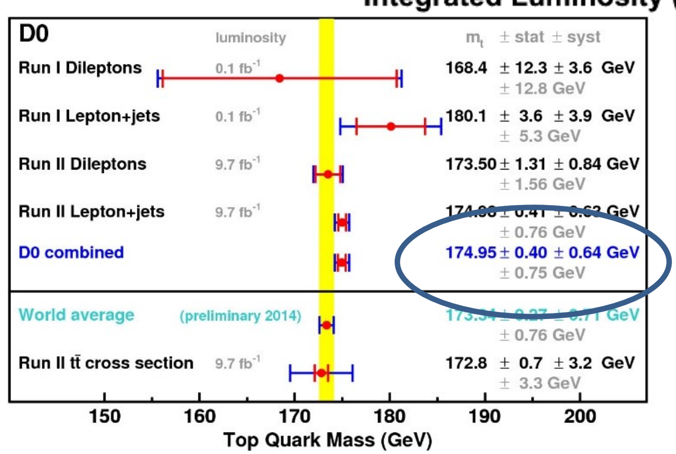
Expectations for top mass measurement were fulfilled





Current D0 combination (2017): 174.95±0.75 GeV/c^2

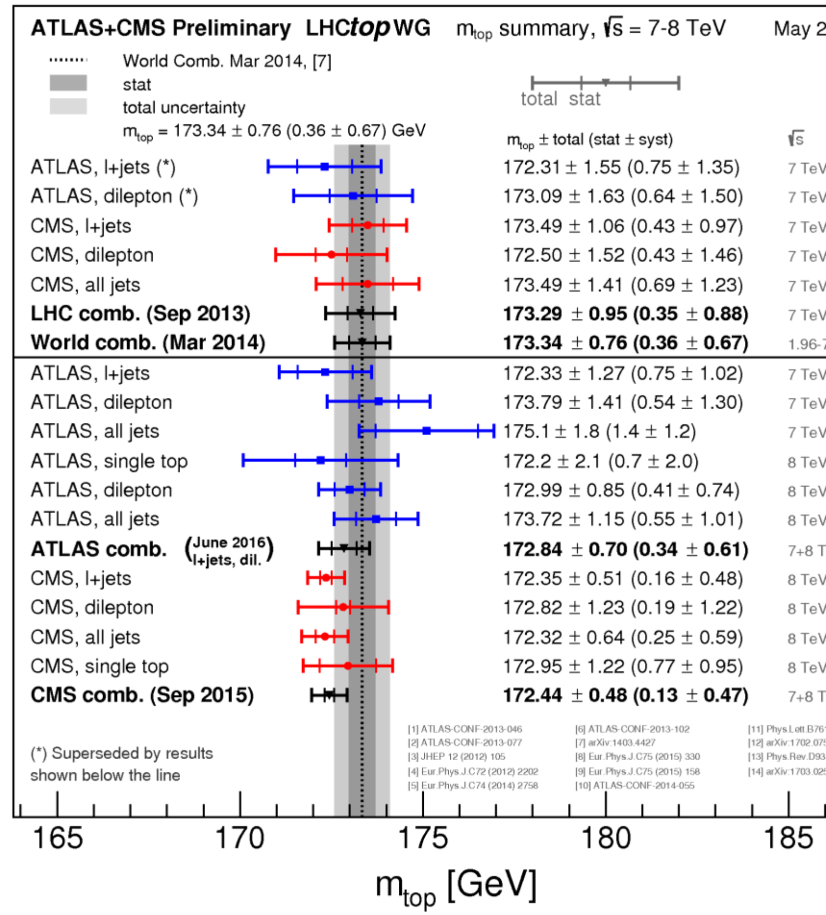
(Run I+ Run 2)



Current CDF combination (2014): 173.16±0.93 GeV/c^2

World role of the Tevatron

- Top mass from the Tevatron: 174.3±0.35±0.54 GeV/c^2
- World combination is 173.34±0.36±0.67 GeV/c^2 **[2014]**
  - Despite the much larger statistics available at the LHC, Tevatron input is still important



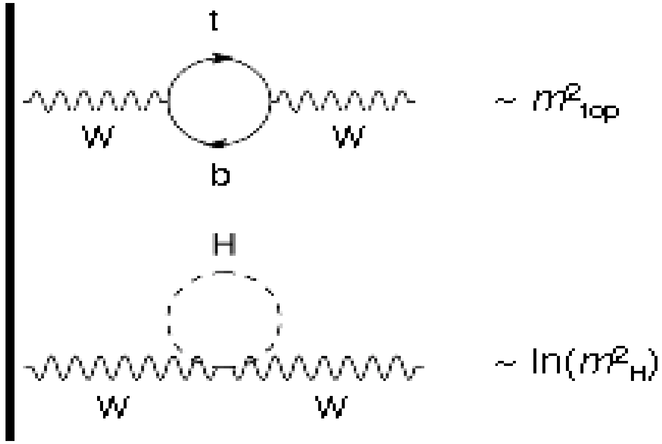
	Individual comb. [GeV]	Parameter value [GeV]	Correlations m^{TEV}	m^{LHC}	χ^2/ndf (χ^2 probability) m^{TEV}	m^{LHC}
m^{TEV}	173.58 ± 0.94	173.41 ± 0.91	1.00		–	
m^{LHC}	173.28 ± 0.94	173.26 ± 0.94	0.36	1.00	0.02/1 (0.89)	–

Top physics-ongoing

- CDF still working on top mass:
  - ME in l+jets with full dataset
    - CDF result on Mtop, driven by measurement in l+jets channel at ~70%
  - New CDF combination
  - New Tev combination!
- F-B asymmetry combination in ttbar event
  - Published soon
    - The latest word?
- Other properties
  - Spin and polarization

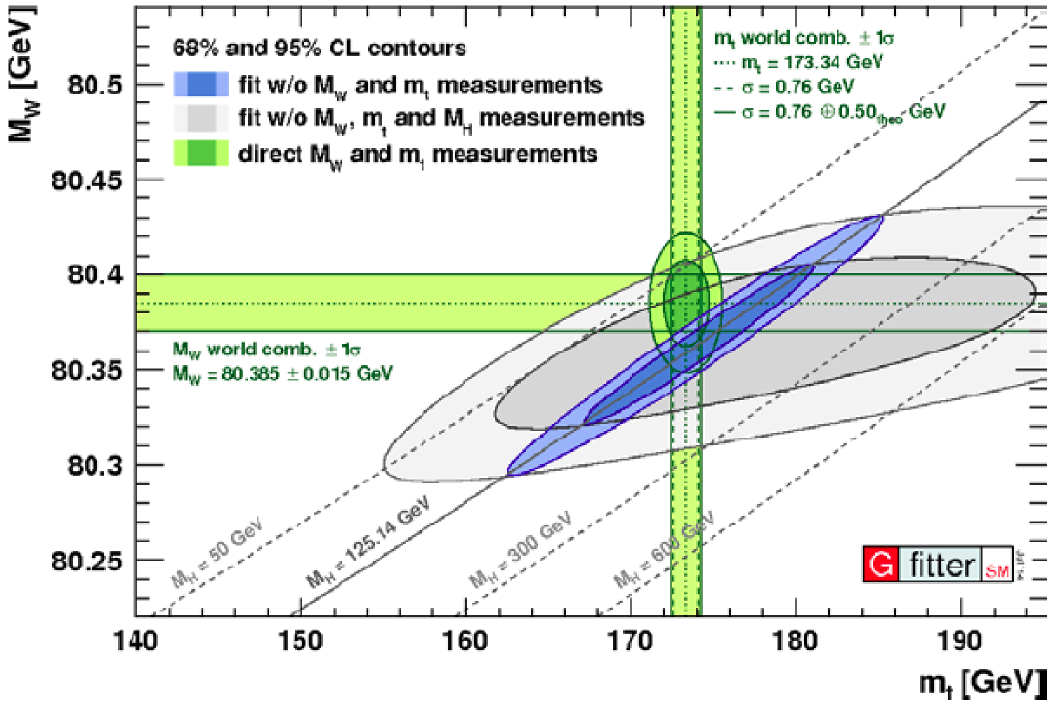
Truth is in the masses (cit.)

- EWK loops link top quark mass and W mass to Higgs mass (last unknown 'til 2012)



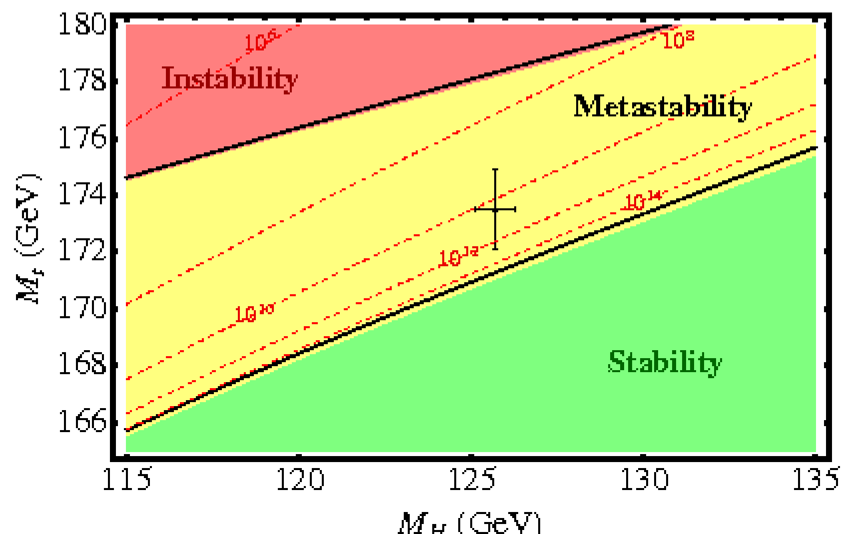
  - A precision measurement of both would constrain the Higgs (before discovery)
  - ...or check SM after discovery

What is at stake?



Very mportant to have an excellent understanding of the detector behaviour and of the underlying event structure

Precision (10^{-4} level) test of the SM at the EWSB scale!

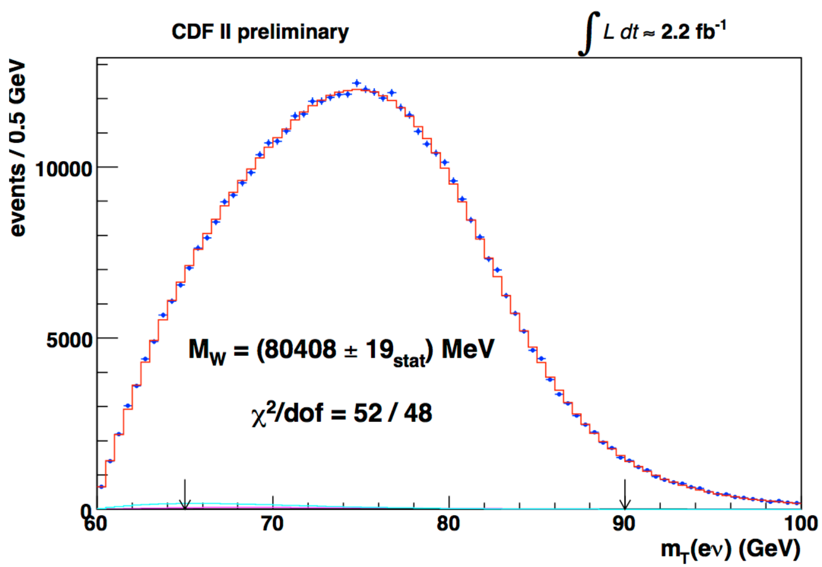


W mass

- $W \rightarrow l\nu$ ($l=e,\mu$) is the most important channel at Hadron Colliders
  - ν from missing transverse energy measurements
    - Essentially a sum of the energy measured in calorimetric cells
    - Keep under control both detector and «underlying event» effects
      - Latter: exploring the unknown, little theoretical input
- Mass from P_T of the leptons (l,ν) and from M_T (transverse mass)

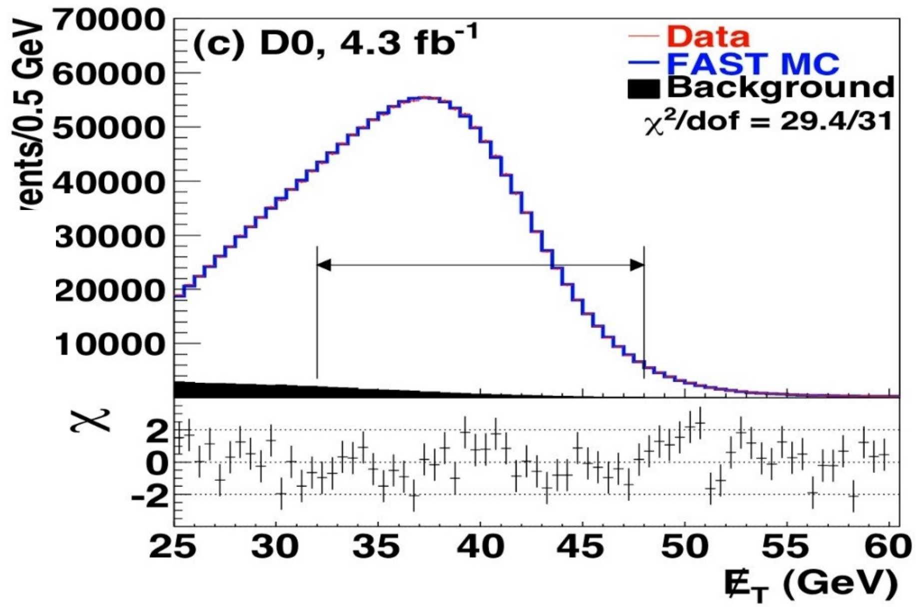
How do we measure it?

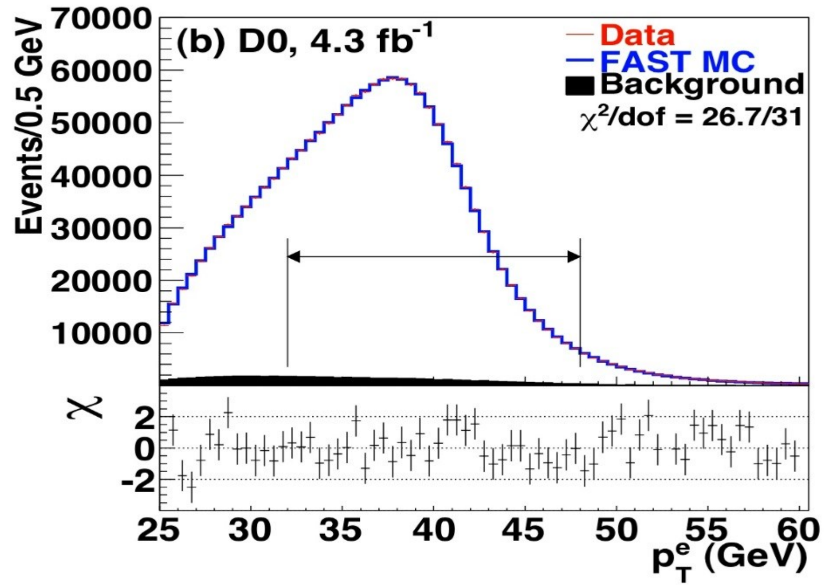
- Fit P_T l (e,μ,ν), M_T



- Quantities are correlated,

  Results: next slide





Status as of Summer 2017

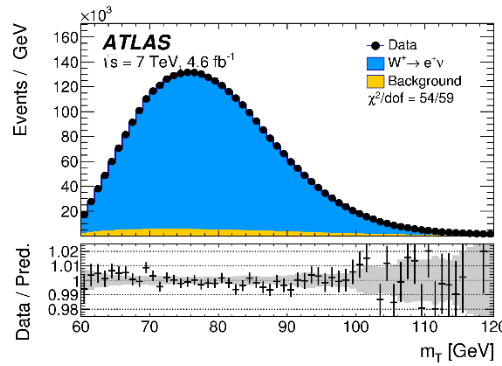
- Tevatron:
  - CDF (2.2 fb^{-1}): 80.387±0.019 GeV/c^2
    - 12 MeV/c^2 stat,
    - 15 MeV/c^2 syst.
  - D0 (4.3 fb^{-1}): 80.375±0.023 GeV/c^2
  - Combination: 80.387±0.016 GeV/c^2

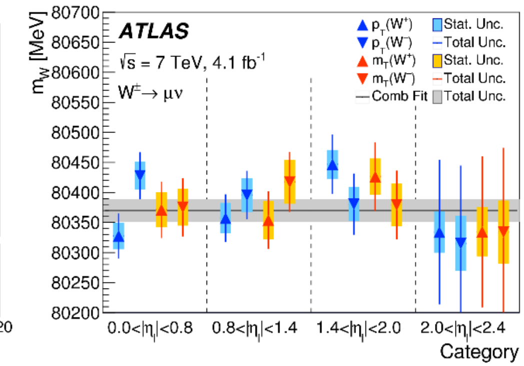
WA: 80.385±0.015 GeV/c^2

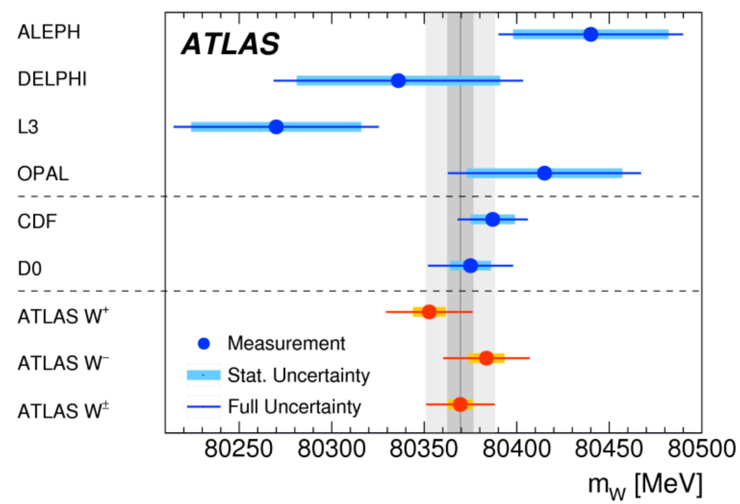
(Not including ATLAS new result)

- LHC
  - ATLAS @ 7 TeV

    80.370±0.019 GeV/c^2







Systematics uncertainties

One channel (electron)

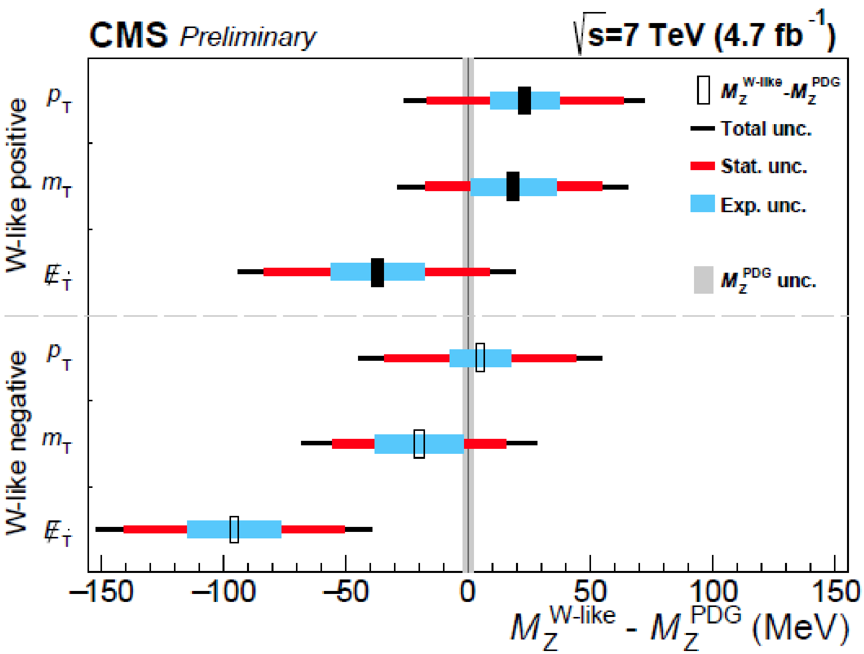
Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

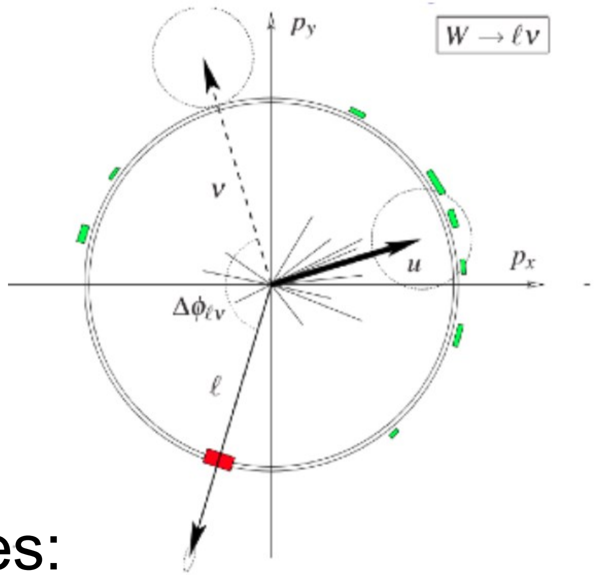
Both e and μ

Source	Uncertainty (MeV)	
Lepton energy scale and resolution	7	exp
Recoil energy scale and resolution	6	exp
Lepton removal	2	exp
Backgrounds	3	exp
$p_T(W)$ model	5	th
Parton distributions	10	th
QED radiation	4	th
W-boson statistics	12	stat
Total	19	

What is the issue at LHC?

- Systematics understanding of the underlying event and of the detector





- Challenges:
  - Higher Pile-up (calibration and recoil more difficult)
  - Potentially larger theoretical uncertainties
  - Charge of W relevant: split into W^+ and W^-

Future...

- Tevatron is still analyzing the full data set
  - Uncertainties below 15 MeV are reachable
    - Lower pileup than LHC
    - Symmetric inital state
      - No need for charge separation
- This M_W measurement will stay with us for a long time
  - It is likely to be a long standing legacy

The most important heritage

- Immaterial heritage (based on >30 years):
  - Accelerators deliver larger Luminosity than in TDR
    - Accelerator physicists are smart (in many ways...)
  - Hadron collider physics is changed
    - Magnetic spectrometers (UA1 vs UA2)
      - Definitively solved at the Tevatron
    - <u>Secondary vertexing</u>
    - Sofisticated multi-level trigger
      - <u>Real time triggers on secondary vertex</u>
    - <u>«precision physics» is now the realm of had-coll</u>.
  - Never say never
    - Somebody smarter than you is in this room
    - When you have data, brain works better

(*) Underlined: pioneering contributions

Conclusion

- Tevatron is still analyzing data
  - young and bright minds coming to us with new ideas
- The «immaterial» heritage is by far the most important
  - Tevatron established hadron collider physics
    - Paved the way to LHC and to the Higgs discovery

Thanks for your attention!