Three Tales of Two Tops

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BROWN UNIVERSITY

Fermilab Wine and Cheese Seminar

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Big Questions

Can we combine QM and G. Relativity?

Dark energy?
Cosmological constant?

Unification of forces?

Beginning of universe(s)?

Correct interpretation of QM?

Dark matter?

Arrow of time

Where is antimatter?

Black hole information paradox?

Why three generations of matter?

Extra dimensions?

Magnetic monopoles?

Inflation?

Are there many universes?

Mechanism of symmetry breaking, Higgs, origin of mass, mecanism for meutrino masses?

End of universe(s)?

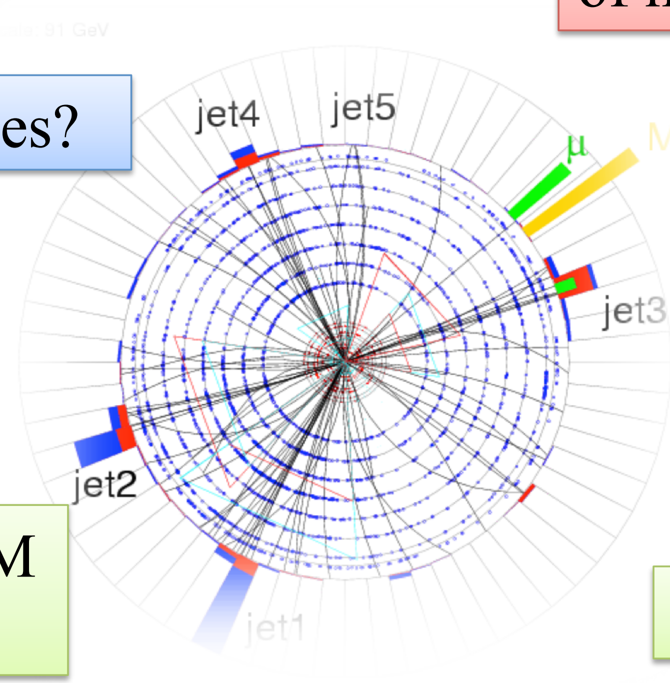
Locality in QM (Quantum entanglement)?

Clues from p-$\overline{p}$(p) Collisions?

Higgs

Why three generations of matter?

Unification of forces?



Mechanism of symmetry breaking, origin of mass

Dark matter?

Extra dimensions?

Can we combine QM and G. Relativity?

Where is antimatter?

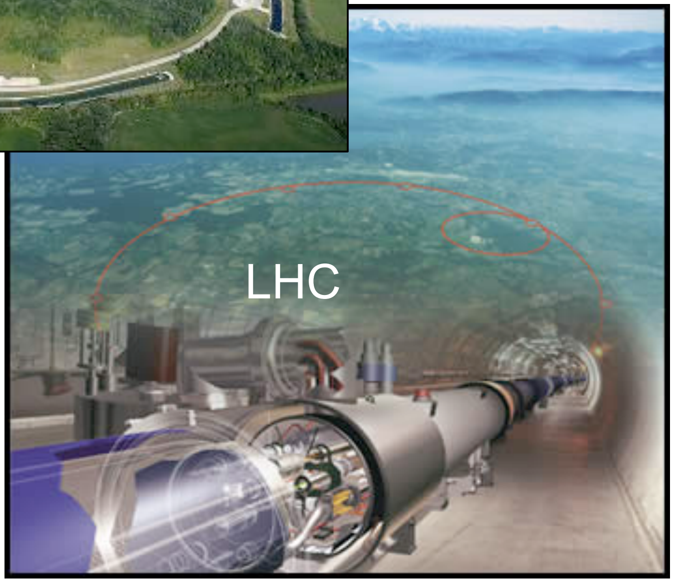
Arrow of time

Unknown unknowns?

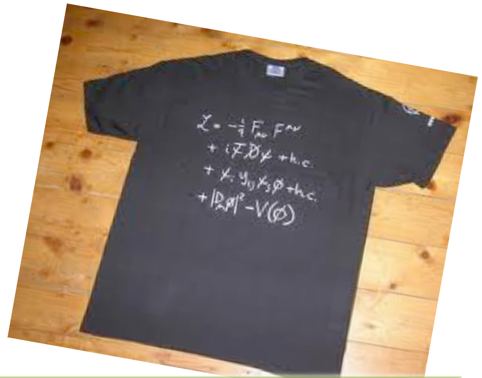
QCD	B Physics	Electroweak	Top Quark	Higgs	New Phenomenon

Chicago and Geneva

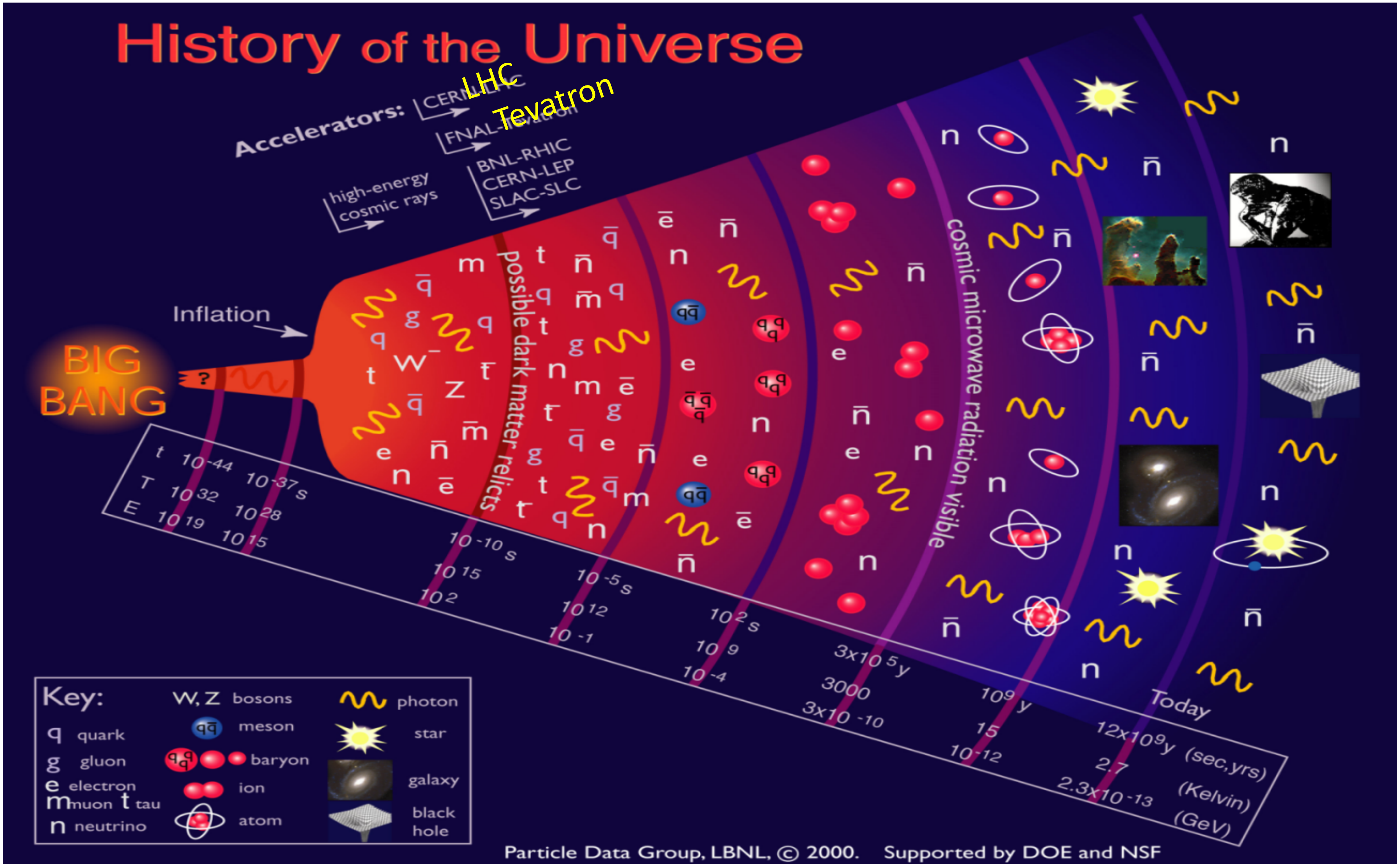
Theorists and experimentalists have been busy for the last couple of decades



Our Ideas are sooo Popular…



……… that today we have our own line of plush toys, clothing, and household merchandise (magnets, coffee cups …..)



History of the Universe
Accelerators:
CERN-LHC
LHC
FNAL-Tevatron
Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

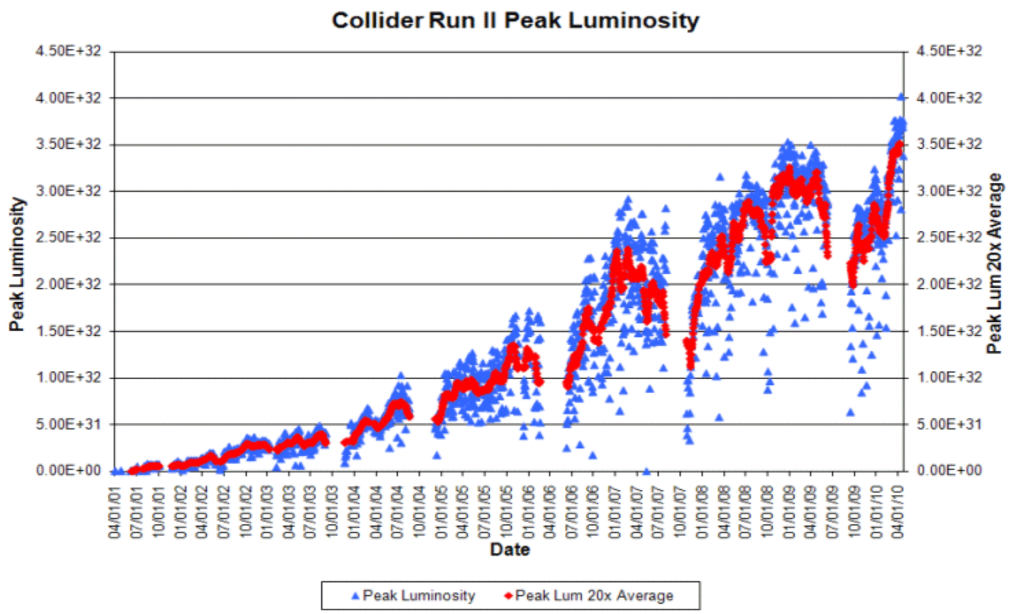
The Tevatron

25years ago, first Tevatron collisions in 1985

Tevatron's design luminosity 3x10^{30} cm^{-2}s^{-1}

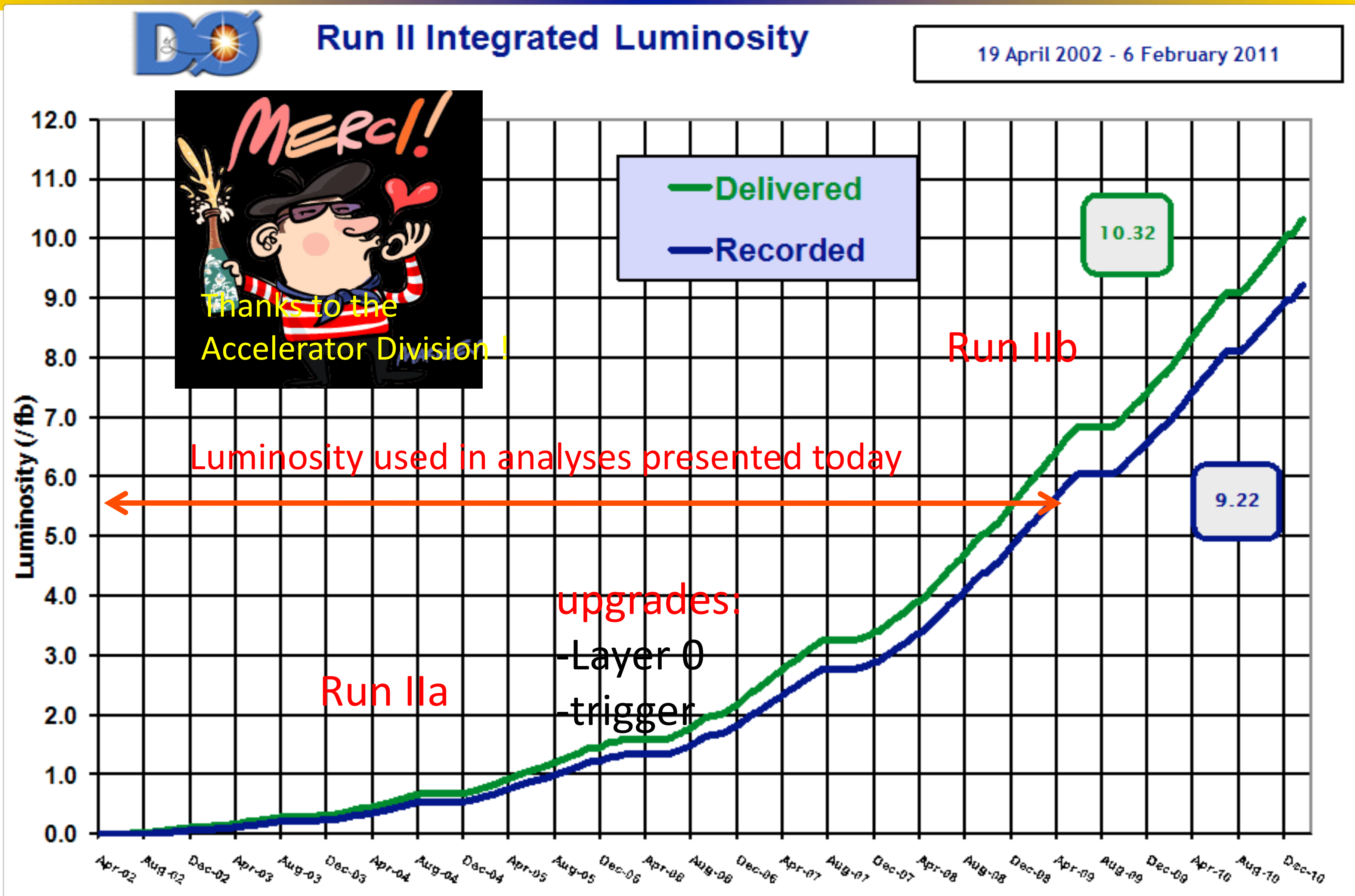
Now running at 3x10^{32} cm^{-2}s^{-1} routinely!

<u>…and this is not the only time when a Tevatron team exceeded its own expectations and projections</u>

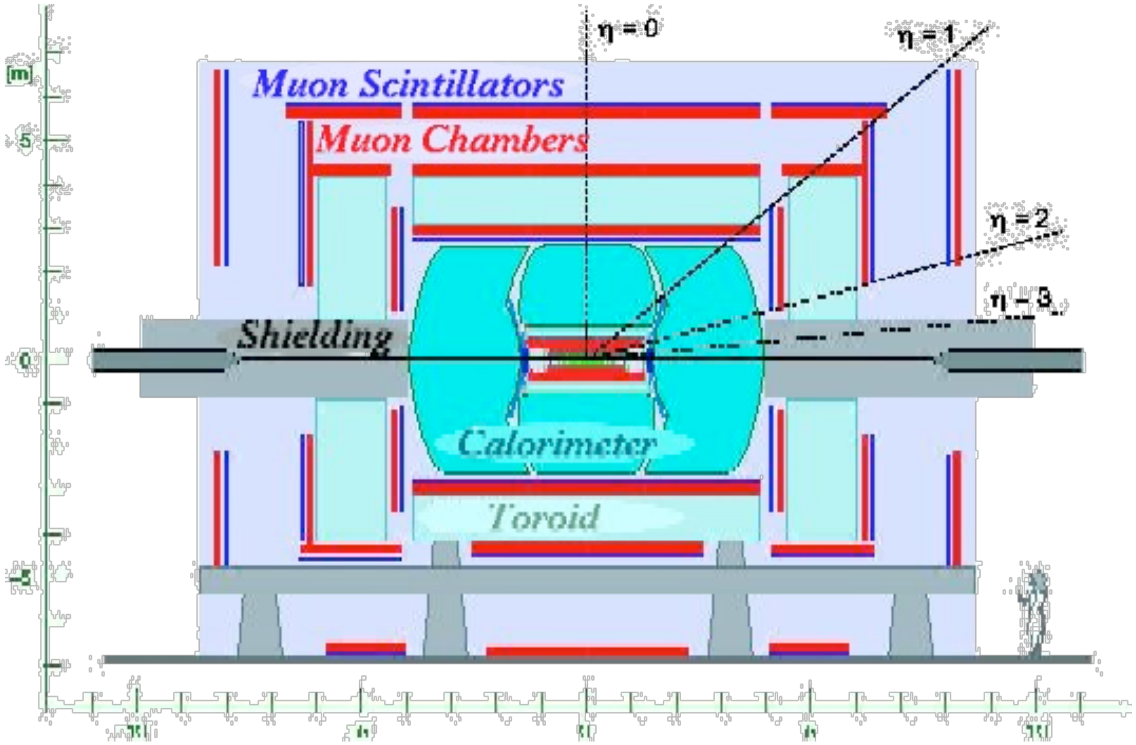


For many years, the Tevatron has been the only machine at the frontier… and has given us a lot to celebrate

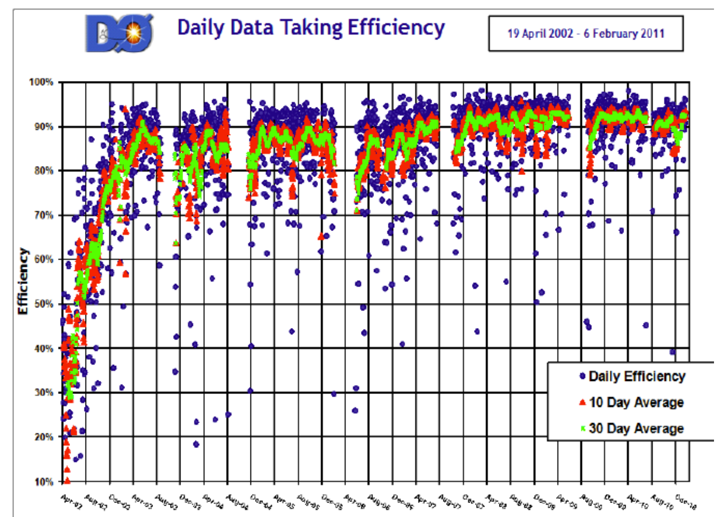
DØ Luminosity



Our Eyes – Our Detectors



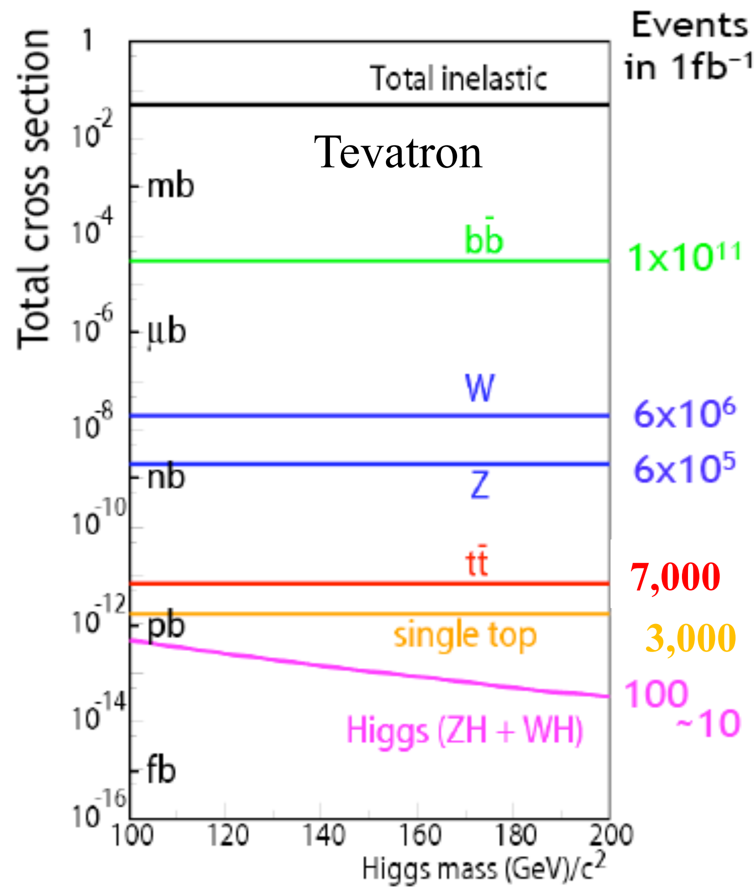
Institutions: 86 total, 37 US, 49 non-US



- Weighs 5000 tons, is about 12 meters in all three dimensions.
- All-purpose detector
  - Good resolution for all physics objects
  - >90% avg. data taking efficiency

Production of Fundamental Particles

- Cross section:
  Total inelastic cross section is huge
  ~10 trillion events in 1 fb^{-1}
- Translate it into rates
  bb:42 kHz
  Jets with ET>40 GeV: 300 Hz
  W: 3 Hz
  Top: 2-3 evt /hour
- Trigger needs to select the interesting events



The key is trigger – that is rejecting as much as we can while keeping as many interesting events as possible on tape

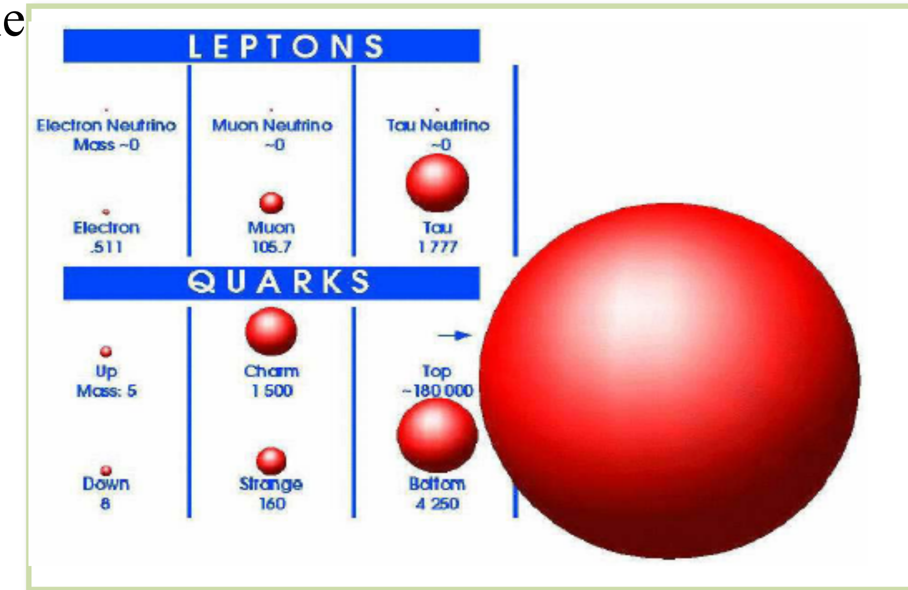
Why Look at the Top Quark?

- **Was discovered at Fermilab in1995**
- The heaviest known fundamental particle
  - m_t = 173.3 ±1.1 GeV (<1% precision)

    Close to a gold atom

  $\tau = 5\times10^{-25}$ s $<<\Lambda_{QCD}^{-1}$

  Decays before hadronization



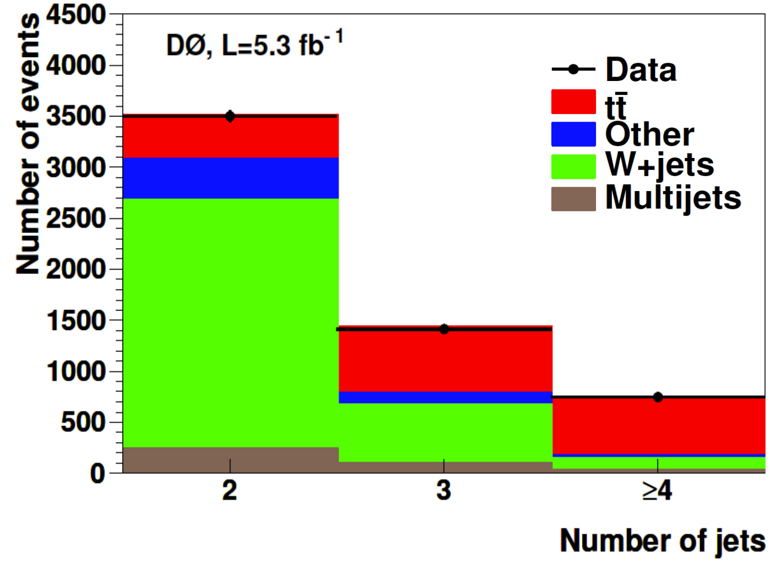
- Mass close to scale of electroweak symmetry breaking
  - Only quark for which coupling to Higgs is significant
  - May shed light on EWSB mechanism
- Top quark plays special role in many of the new physics models

Why Keep Looking at the Top?

Even more than a decade after its discovery, our sample consists of few thousand top quark events

Many of the measurements of top quark properties are still statistics limited

ttbar events with 1 b jet identifed



Lot of room for surprises!

Why we Love to Talk about Top?

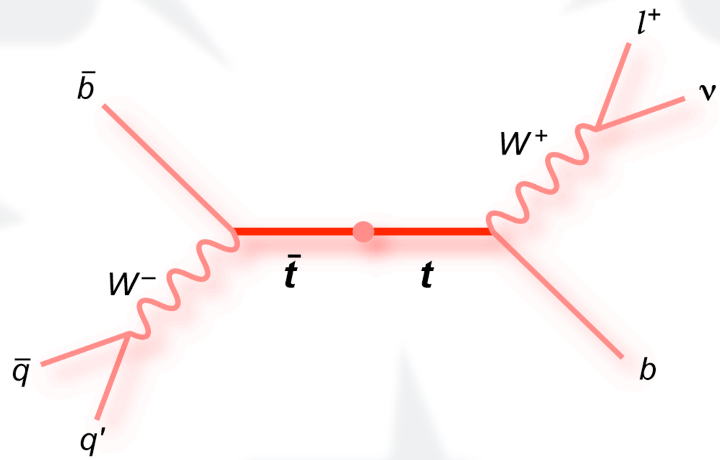
Top Mass
Width
Charge
Spin

W helicity
Anomalous couplings
CP violation
FCNC
$|V_{tb}|$

Production Cross-section

Resonant production

Charge asymmetry



Branching Ratios
Rare/non SM decays

Three Tales of Two Tops

5.3 fb^{-1}
Top Mass
Width
Charge
Spin Correlations
5.3 fb^{-1}

W helicity
Anomalous couplings
CP violation
FCNC 4.1 fb^{-1}
$|V_{tb}|$

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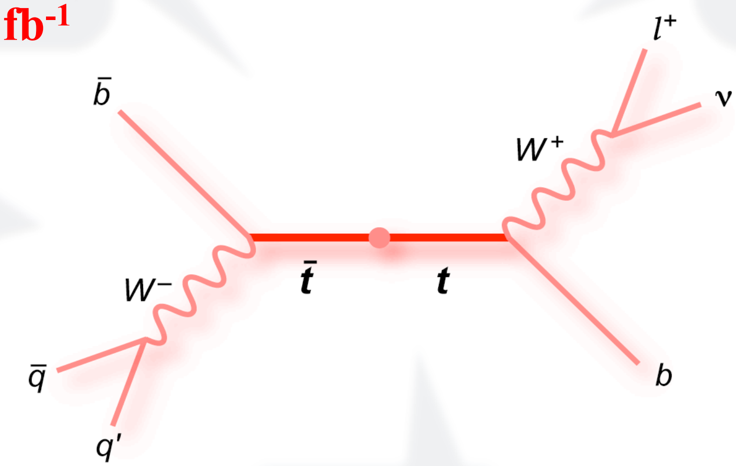


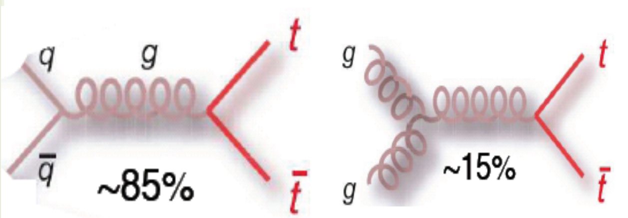
Branching Ratios
Rare/non SM decays

Top Quark at the Tevatron

Production

Top quark pair production

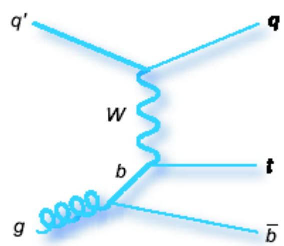
σ_{tt} ~7.5 pb



Single Top quark production

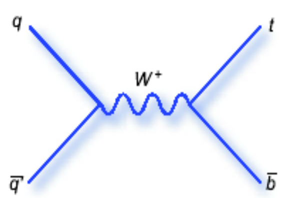
***t*-channel**

σ ~2 pb



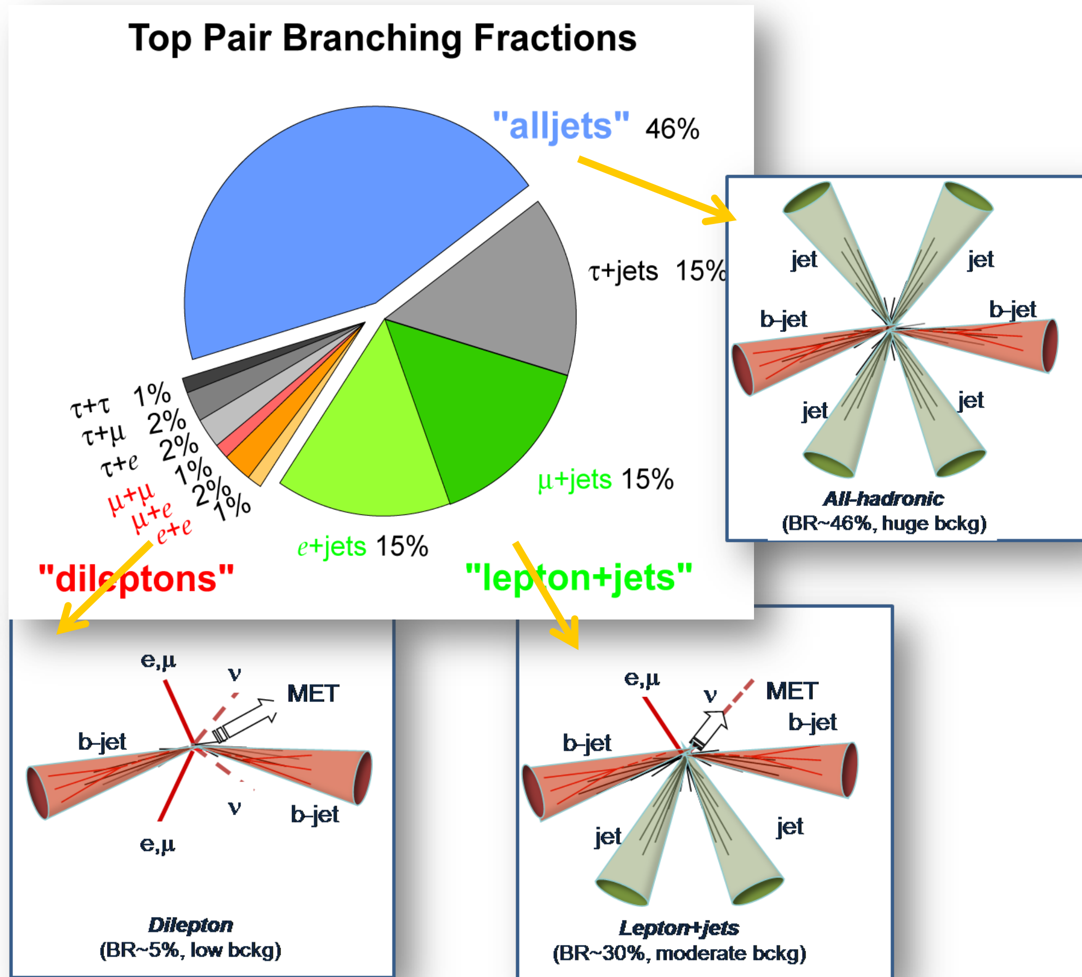
***s*-channel**

σ ~1 pb



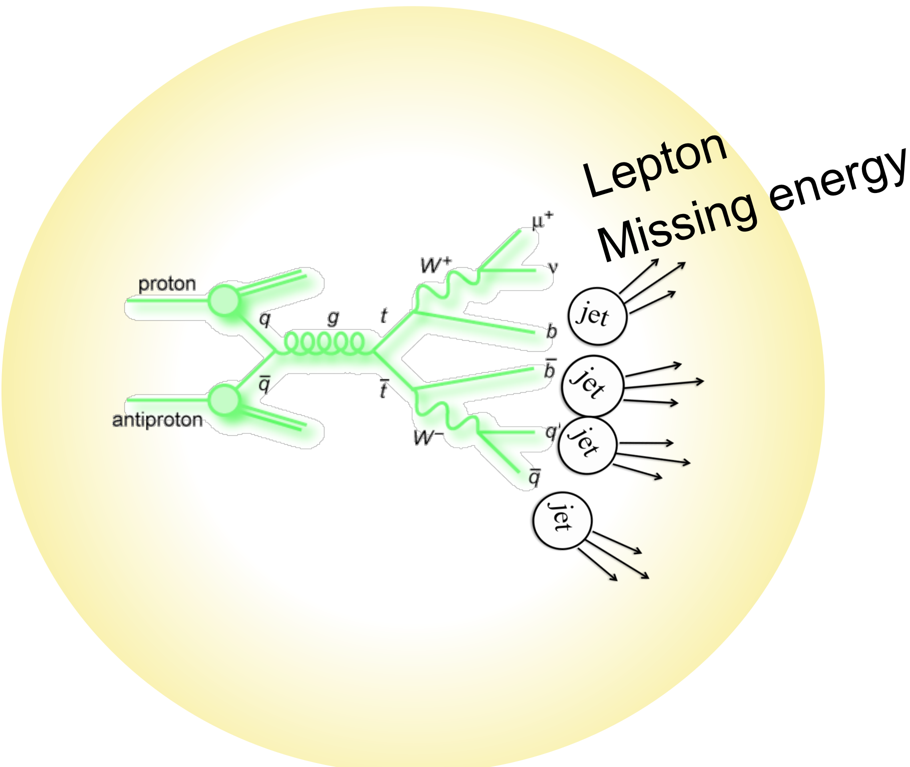
Decay

Within Standard Model t→Wb ~ 100%

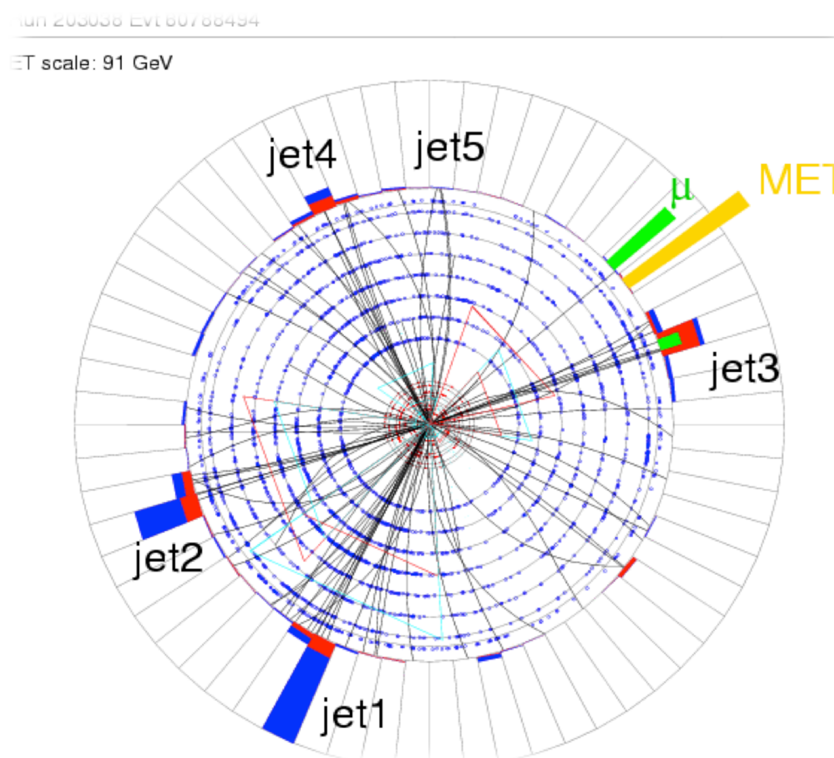


What our "Eyes" See

In theory



In detector



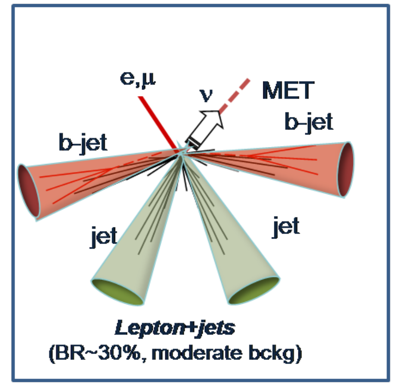
- Dominant Backgrounds

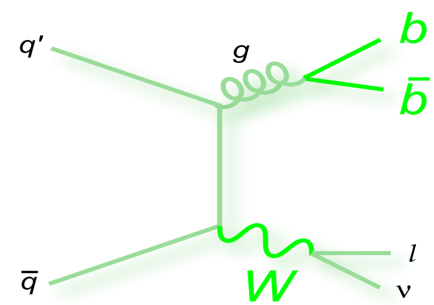
  Arise from W+jets and multijet production (for ℓ+jets channel) and Z+jets, WW+jets (for dilepton channel)

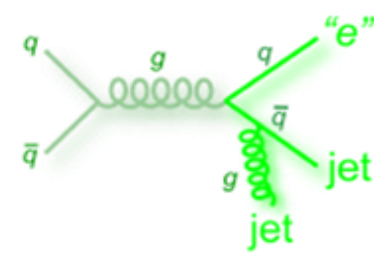
- Signal Modeling

  The SM top-antitop samples are generated with ALPGEN or MC@NLO for matrix elements interfaced with PYTHIA or HERWIG, respectively, for parton showering and hadronization

- Background Modeling
  - Some modeled using ALPGEN or PYTHIA
  - For some others use both MC and data, e.g, W+jets
  - Some purely determined from data , e.g, multijet background







The First Tale

5.3 fb^{-1}
Top Mass
Width
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5.4 fb^{-1}

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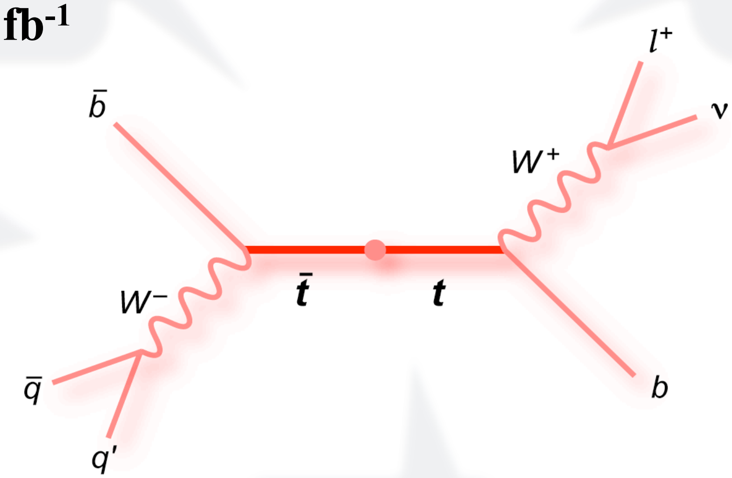
Production Cross-section mechanism,

Resonant production,

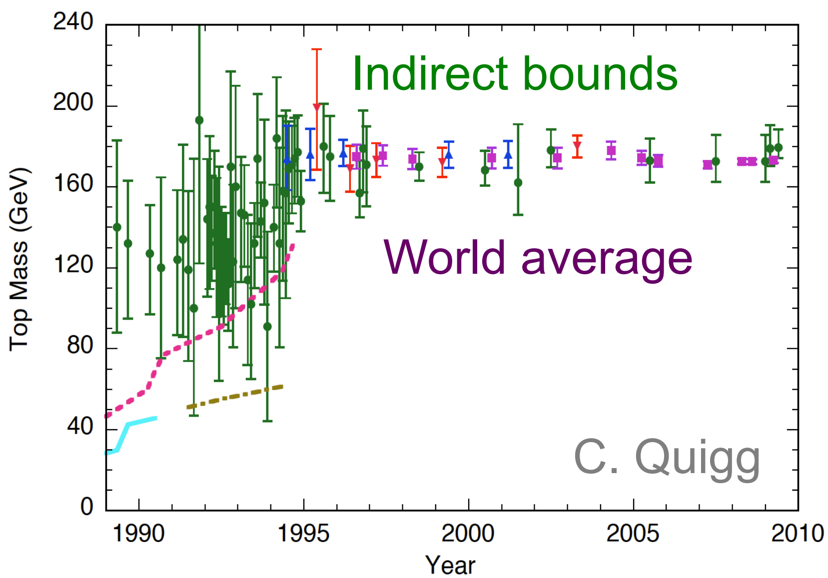
Charge asymmetry

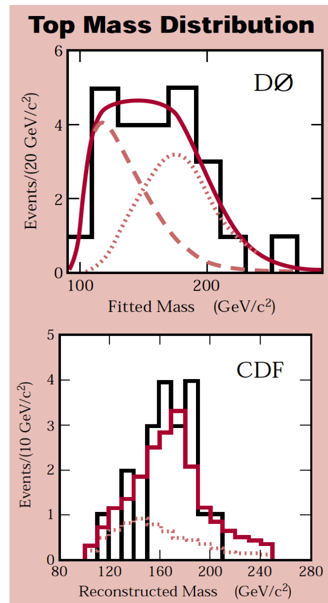


Branching Ratios
Rare/non SM decays

Top Quark Mass Over the Years

…indeed a very long tale






NEWS AND VIEWS

CERN comes out again on top

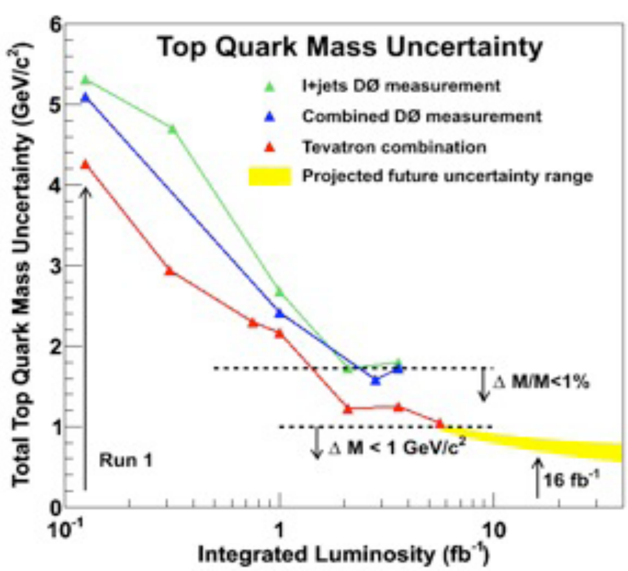
With the discovery of the electroweak bosons (W± and Z⁰) in the bag, CERN now announces the discovery of the quark called top. What will come next?

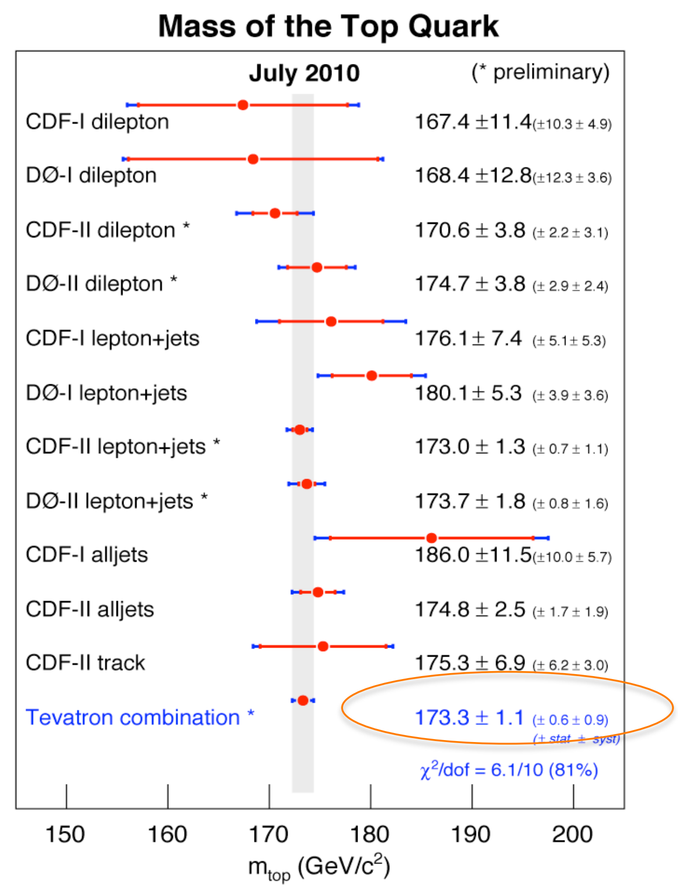
John Maddox

Top Quark Mass

- Top quark mass is measured directly
  - in different channels

    Dilepton, lepton+jets, all jets channels
  - using a variety of techniques by both CDF and DØ
- Both experiments are in agreement





Measured top mass = 173.3±1.1 GeV

We have long exceeded the Tevatron goal of **δ**M=2 GeV

But which Mass do we Measure?

Theoretically

- At LO top mass is a free parameter but at NLO it depends on renormalization scale and scheme
- Two popular cases are pole mass scheme and MS-bar mass scheme

$$m_t^{Pole} = m_t^{\overline{MS}}(m_t^{\overline{MS}})[1 + \frac{4}{3}\frac{\overline{\alpha}_s(m_t^{\overline{MS}})}{\pi} + ...] + O(\Lambda_{QCD})$$

Difference between top quark mass in these two schemes can be ~10 GeV

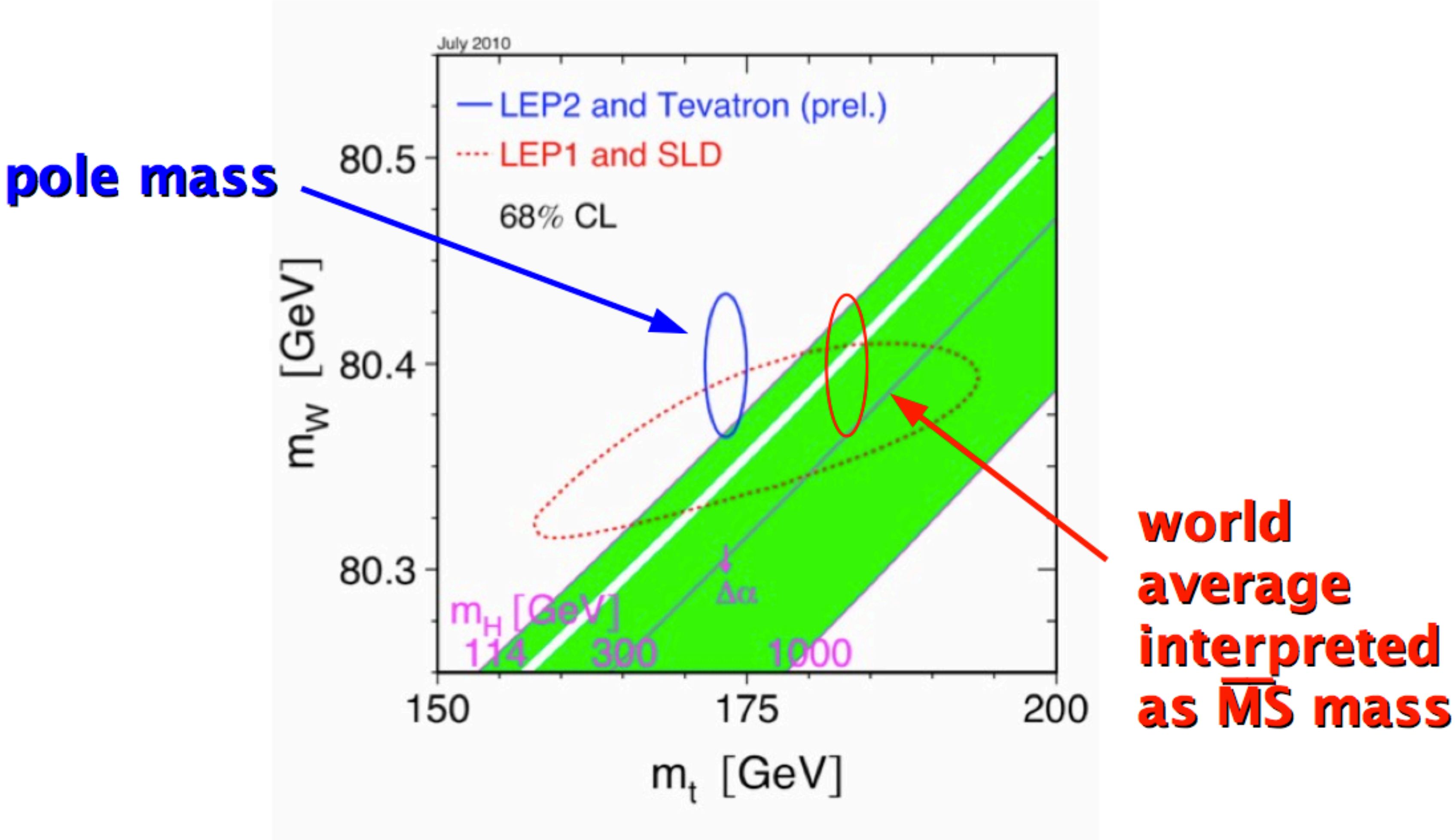
Experimentally

- Direct measurements of top quark mass depend on details of Monte Carlo simulations.

- But MC simulations used today are LO

Higher orders are simulated through parton showers at Leading Logarithm (LL)

SM Self Consistency

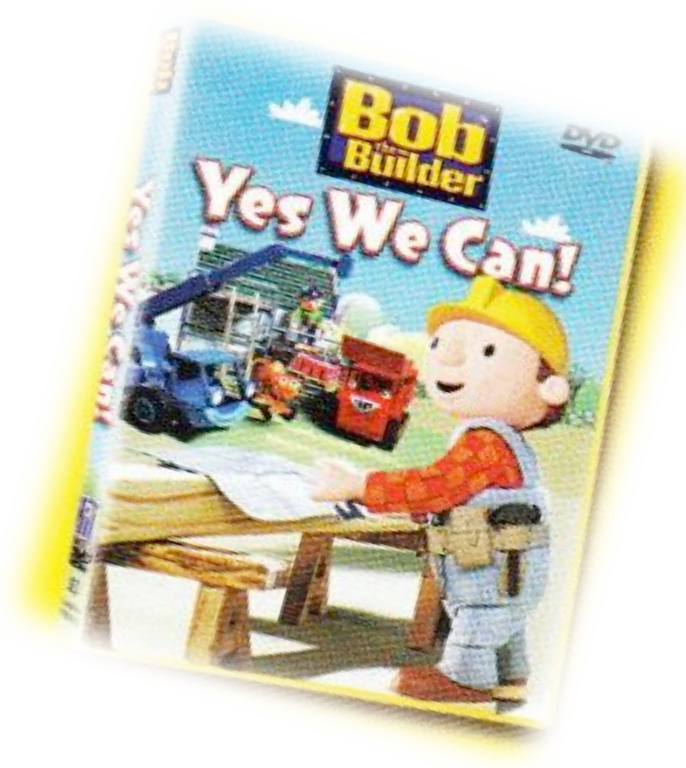


The top mass depends on M_H through loop diagrams ($m_t \sim \log m_H$).

Can we do Anything about it?

Can we do Anything about it?

Yes we can!

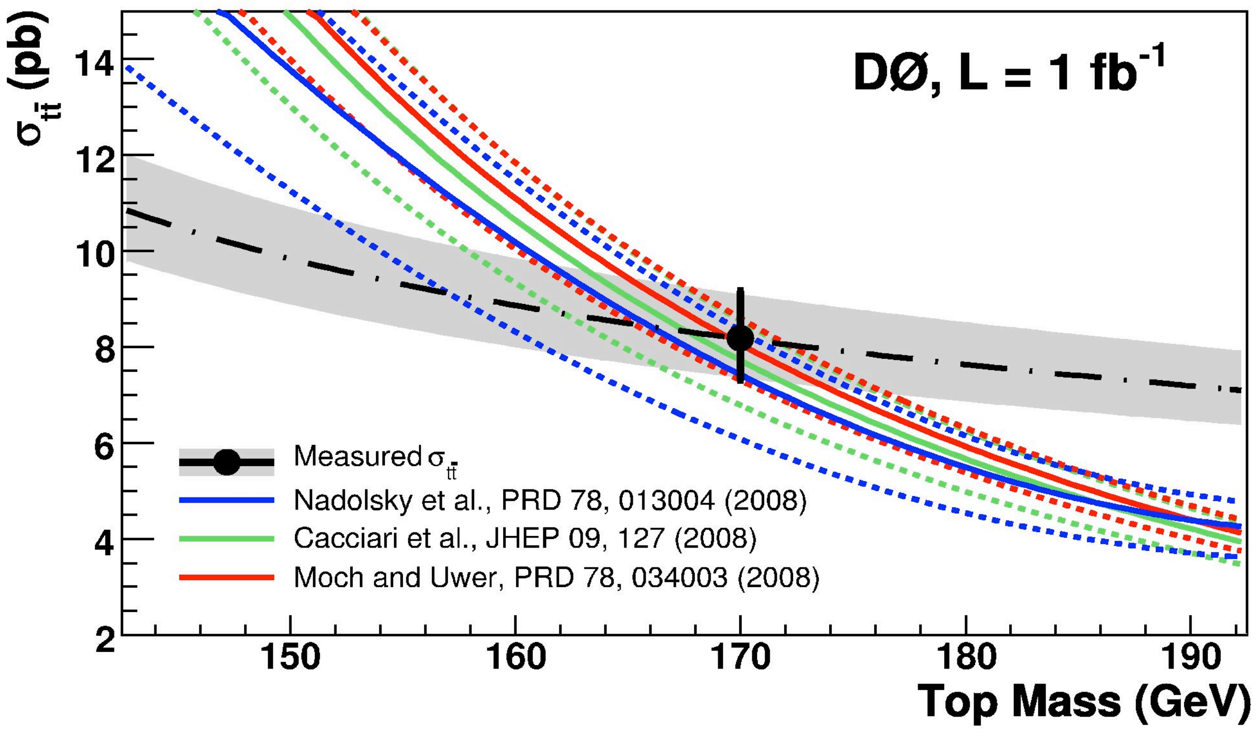


No! it's not Obama….

Measuring Mass from Cross Section

- The Top quark cross section measurement allows for an indirect measurement of the the top mass using the top-mass dependence of the cross section

- This dependence is different for different top mass schemes so we can investigate these differences experimentally

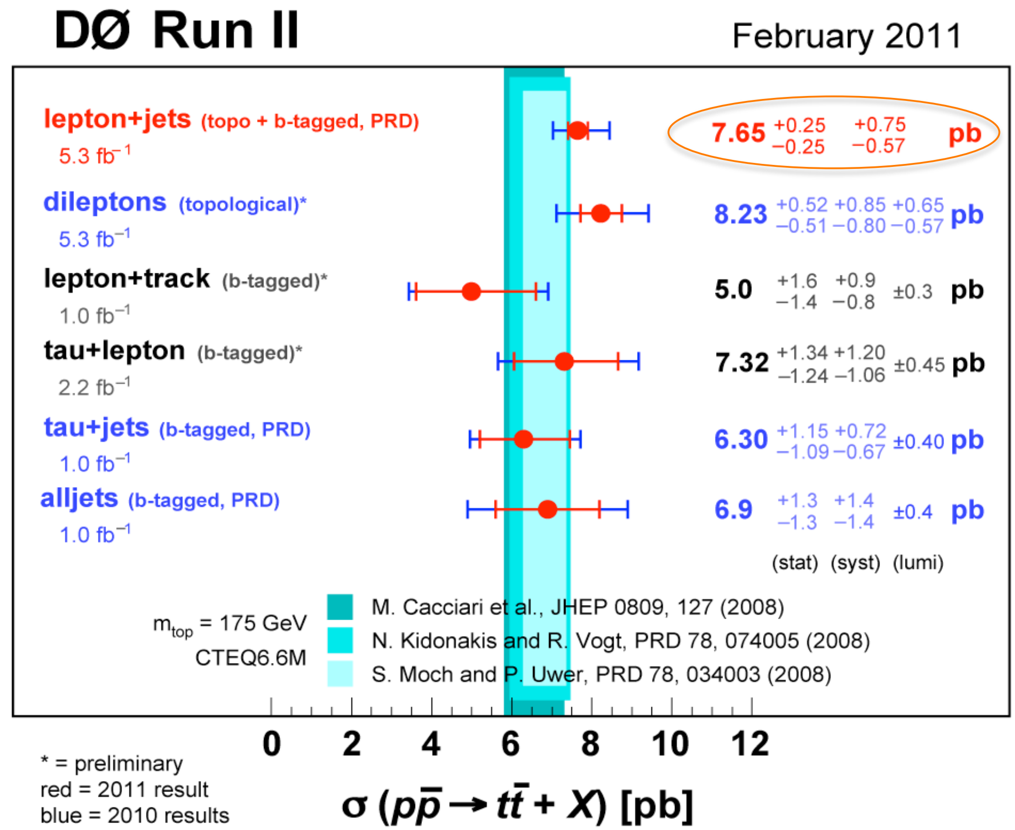


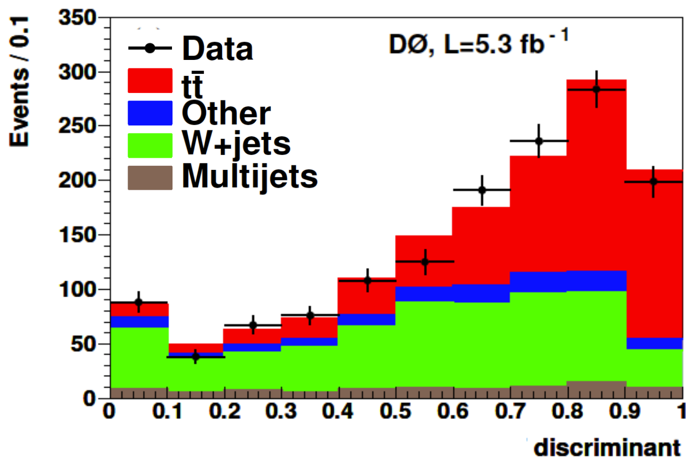
Measuring Top Quark Cross Section

- Measured in lepton+jets, dilepton and all jets channel
- Use different techniques to distinguish the signal from background

  Exploiting specific kinematic features of ttbar events

  Using b-jet identification



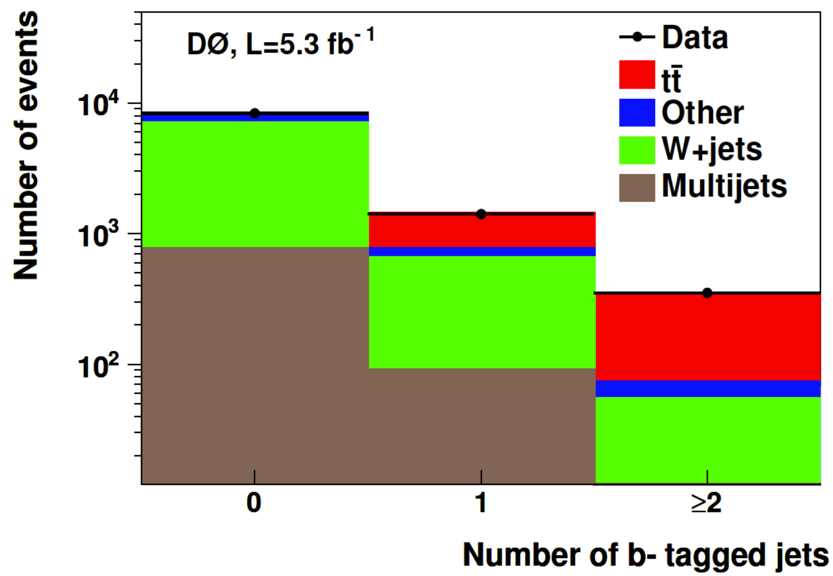


Latest measurement in lepton+jets combining both methods for a mass of 172.5GeV with 5.3 fb^{-1}

arXiv.org:1101.0124

Mass Dependence of Cross Section

- Selection efficiency depends on the input MC top quark mass
  → dependence of measured cross-section on the top quark mass



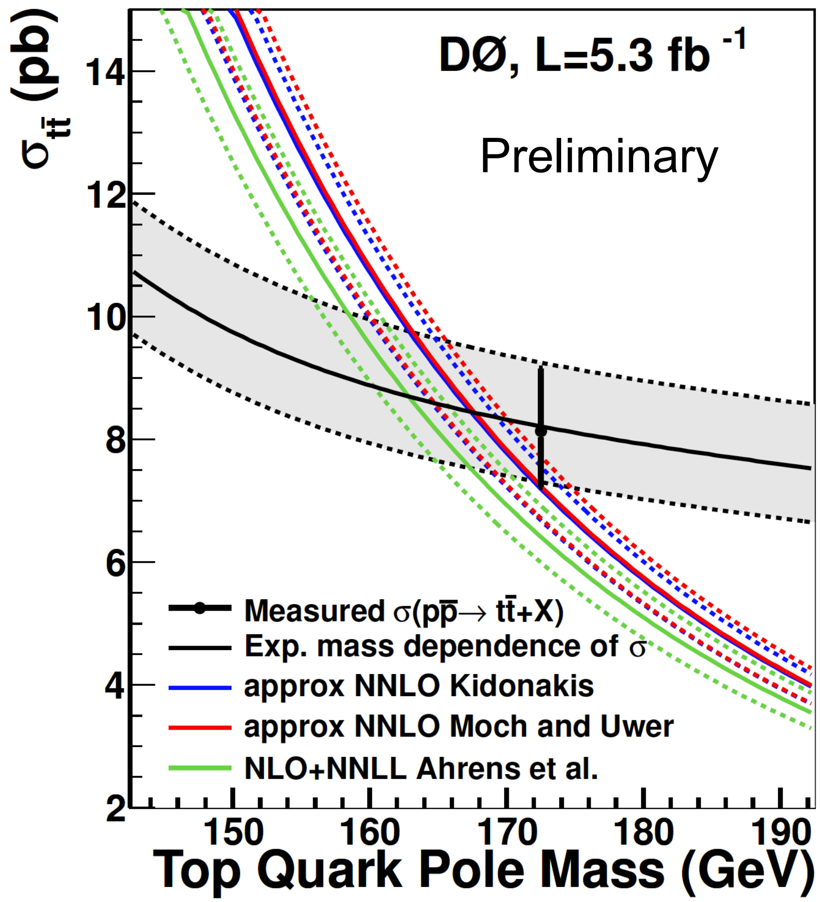
- For extraction of mass from cross section
  use b-jet identification for cross section measurement
  least dependence on input top quark mass

$$\sigma_{t\bar{t}} = 8.13 \pm 0.25^{+0.99}_{-0.86} \text{ (stat+syst) pb}$$

Top Quark Mass from Cross Section

- The experimental cross section is fitted as a function of the top quark mass

$$\sigma_{t\bar{t}}(m_t^{\rm MC}) = \frac{1}{(m_t^{\rm MC})^4}[a + b\,(m_t^{\rm MC} - m_0) + c\,(m_t^{\rm MC} - m_0)^2 + d\,(m_t^{\rm MC} - m_0)^3]$$



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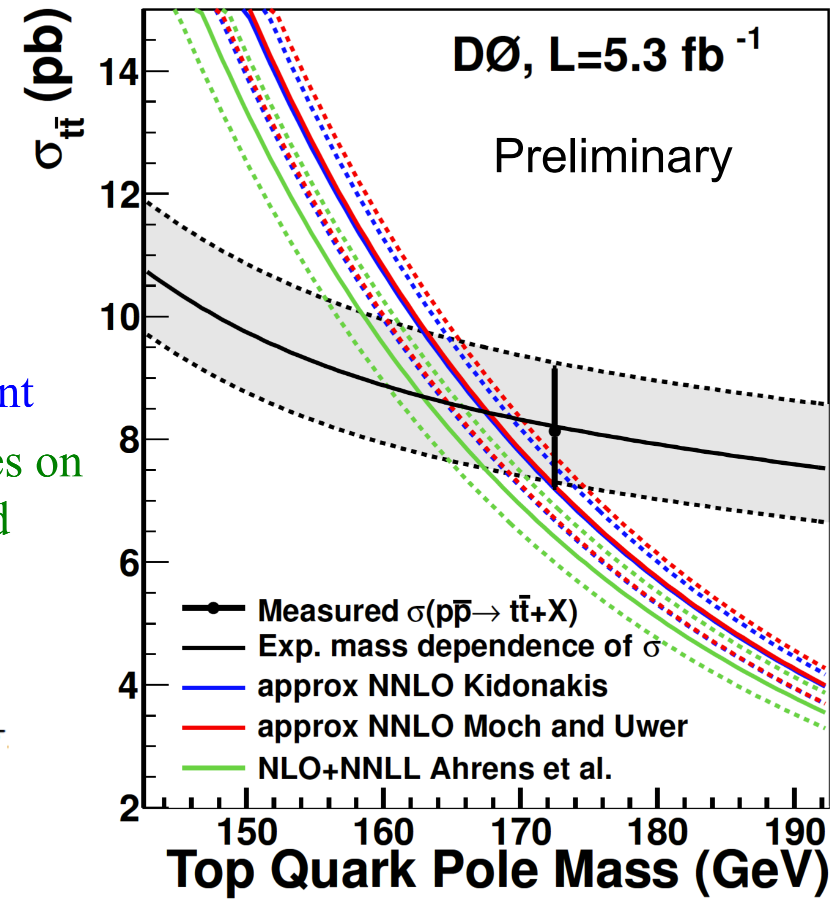
- A joint likelihood is calculated

  Gaussian uncertainties for experimental measurement

  Renormalization and factorization scale uncertainties on theory calculations are taken to be flat and changed from m_t to $m_t/2$ and $2m_t$

  PDF uncertainties are taken to be Gaussian

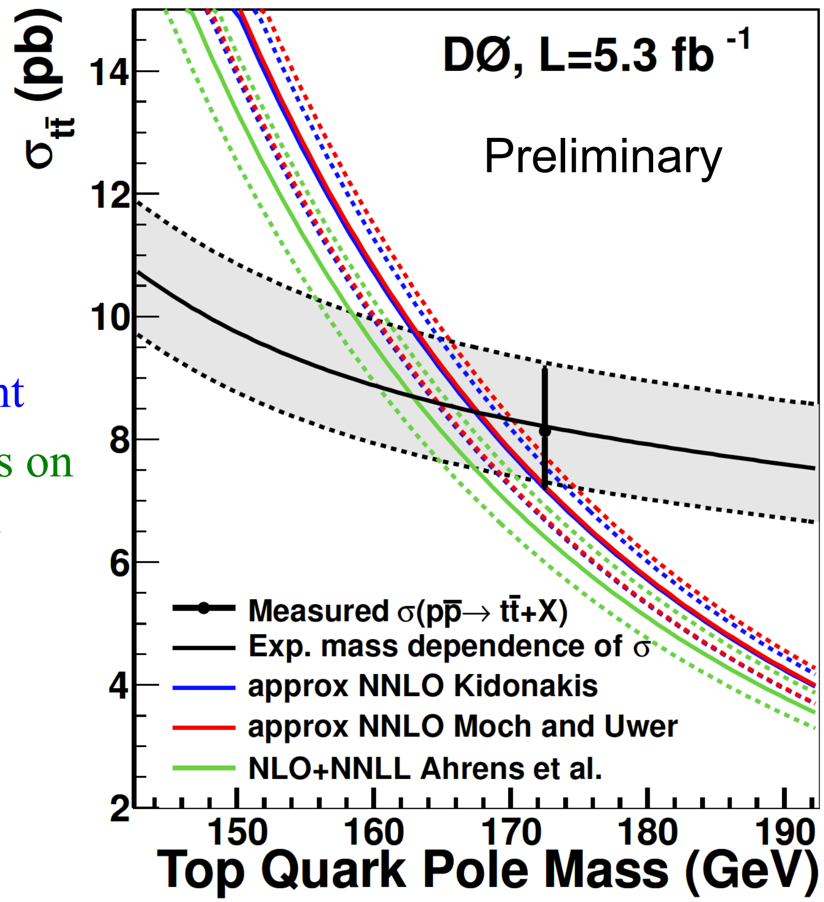
$$L(m_t) = \int f_{exp}(\sigma|m_t)(f_{\rm scale}(\sigma|m_t) \star f_{\rm PDF}(\sigma|m_t))d\sigma$$



Top Quark Mass from Cross Section

- The experimental cross section is fitted as a function of the top quark mass

$$\sigma_{t\bar{t}}(m_t^{MC}) = \frac{1}{(m_t^{MC})^4}[a + b\,(m_t^{MC} - m_0) + c\,(m_t^{MC} - m_0)^2 + d\,(m_t^{MC} - m_0)^3]$$



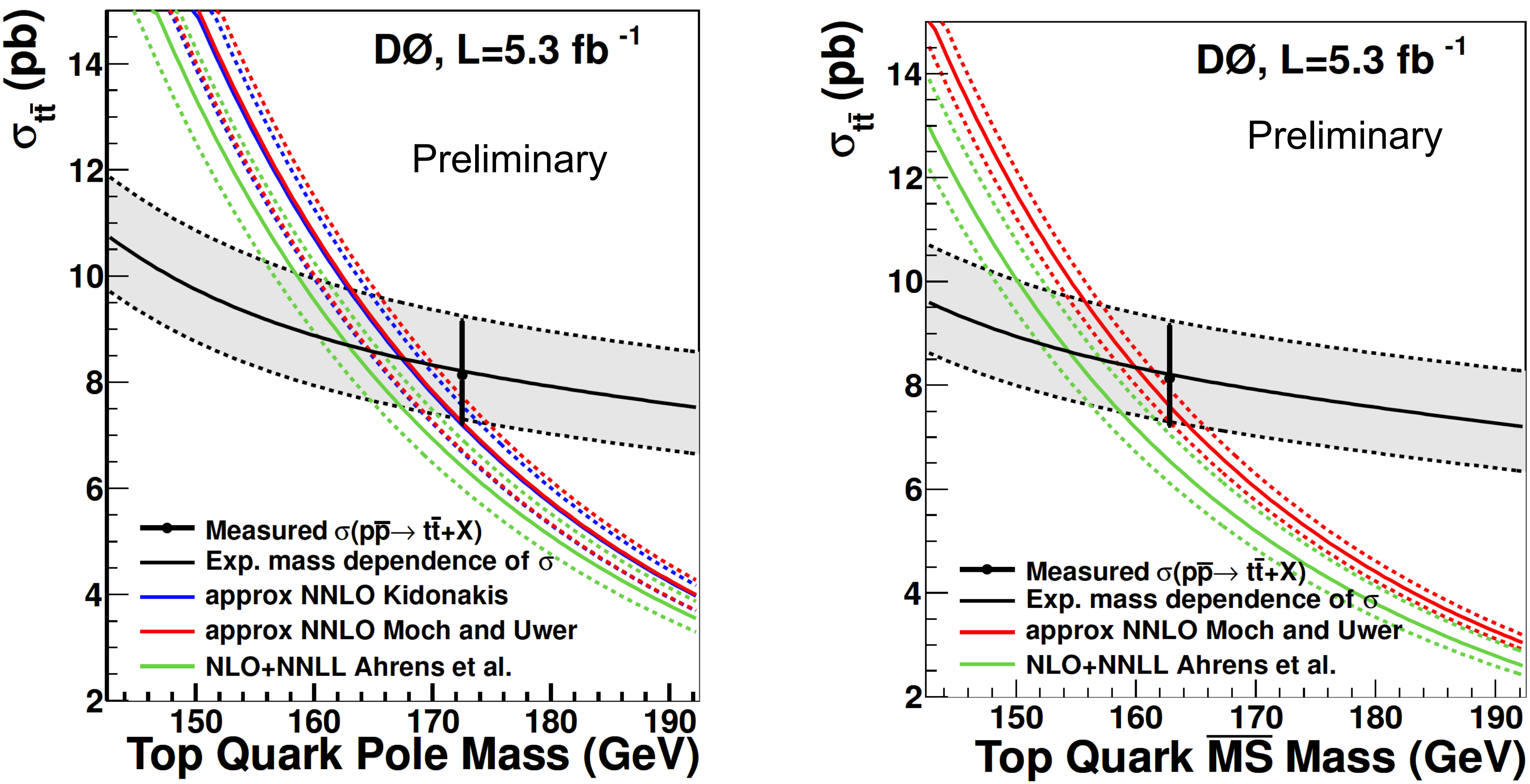
- A joint likelihood is calculated
  - Gaussian uncertainties for experimental measurement
  - Renormalization and factorization scale uncertainties on theory calculations are taken to be flat and changed from m_t to $m_t/2$ and $2m_t$
  - PDF uncertainties are taken to be Gaussian

$$L(m_t) = \int f_{exp}(\sigma|m_t)(f_{\rm scale}(\sigma|m_t) \star f_{\rm PDF}(\sigma|m_t))d\sigma$$

- Input MC mass is assumed to be pole mass
  - Measurement is repeated by assuming input MC mass is MS-bar mass instead
  - Difference is taken as additional uncertainty

Top Quark Mass from Cross Section

Compare the experimental value for cross-section as function of top mass with theoretical calculations in pole and MS-bar schemes



Top Quark Mass from Cross Section

- We extract the most probable top quark mass values in pole and MS-bar schemes and corresponding 68% CL bands

Theoretical Calculation	**Measured Mass**	
	Pole mass	MS-bar mass
NLO+NNLL	163.0+5.4 -4.9	154.4+5.2-4.5
Approx. NNLO	167.5+5.4-4.9	159.9+5.1-4.4

NNLO approx Moch and Uwer
NLO+NNLL Ahrens et al.

Directly measured top quark mass = 173.3±1.1 GeV

- For the first time the top quark MS-bar mass is extracted taking the mass dependence of the measured top-antitop cross section correctly into account

The Second Tale

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Production Cross-section mechanism,

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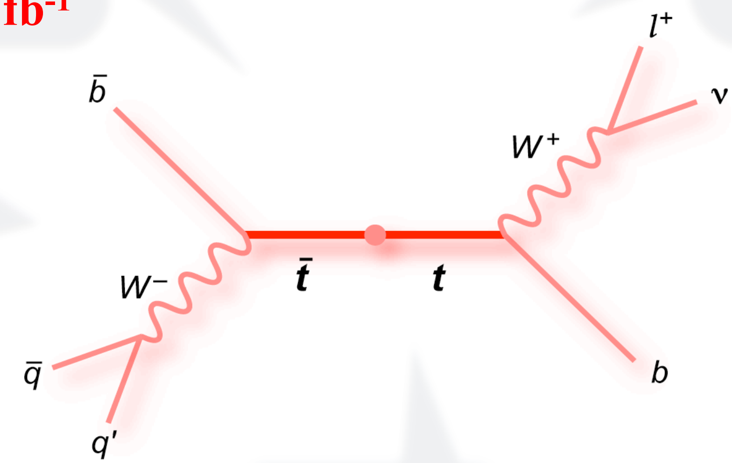
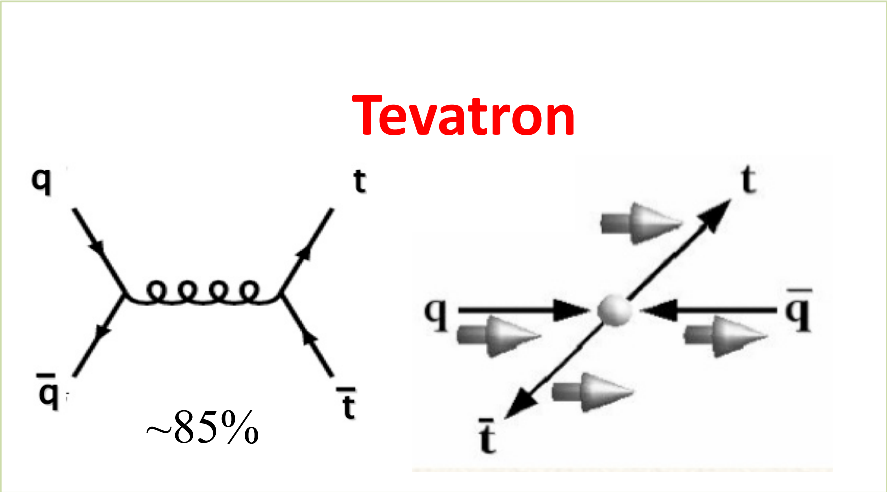
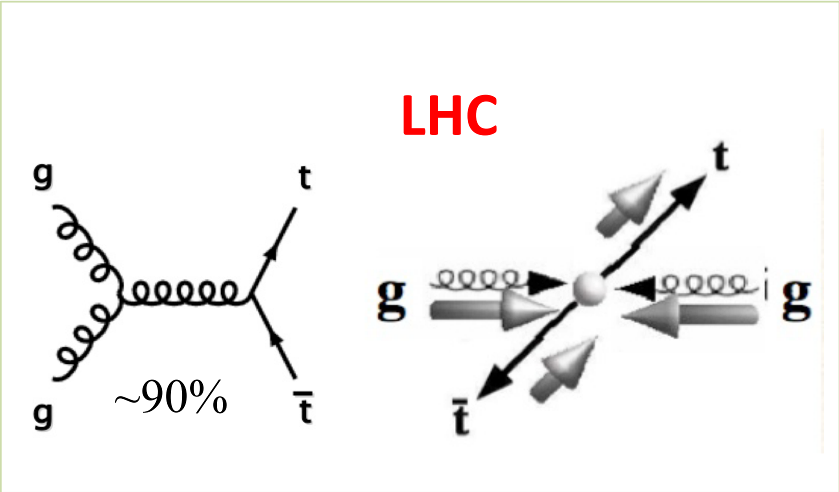


Branching Ratios
Rare/non SM decays

Spin Correlation in ttbar Events

- In top pair production at hadron colliders, their spins are expected to be correlated
- Observation of spin correlation will place upper limit on top quark life time
- Scenarios beyond the standard model predict changes in production and decay dynamics to change effect of spin correlation
- Complementary to LHC

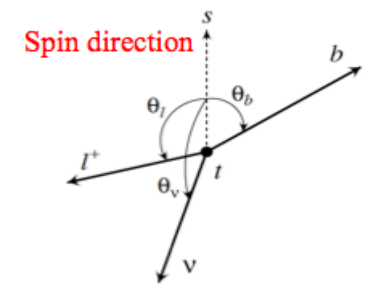




Measuring Spin Correlations

- Maximum correlation for charged lepton or down type quark
  - → Use dilepton decay channel

arXiv:hep-ph/9811219v1



Decay product	Correl Coeff.
b	-0.40
$\nu_\ell, u,$ or c	-0.33
$\bar{\ell}, \bar{d},$ or $\bar{s}$	1.00

Measuring Spin Correlations

- Maximum correlation for charged lepton or down type quark
  → Use dilepton decay channel
- The top-antitop spin correlation strength C is obtained from the distribution

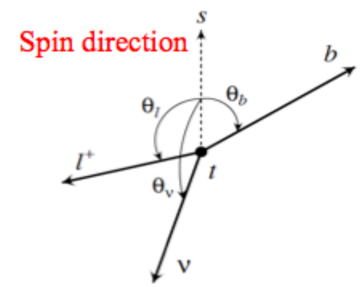
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

Cross section

Spin correlation strength

$$C = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

arXiv:hep-ph/9811219v1



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- Maximum correlation for charged lepton or down type quark
  → Use dilepton decay channel
- The top-antitop spin correlation strength C is obtained from the distribution

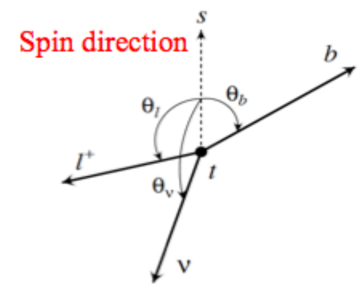
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

Cross section

Spin correlation strength

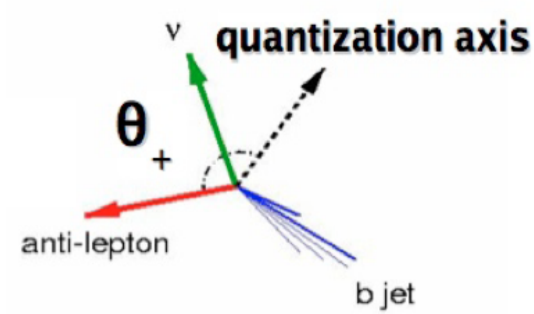
$$C = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

arXiv:hep-ph/9811219v1



Decay product	Correl Coeff.
b	-0.40
ν_ℓ, u, or c	-0.33
$\bar{\ell}$, $\bar{d}$, or $\bar{s}$	1.00

- C depends on the quantization axis used and determines the extent of the top pair spin correlation



- Choosing the beam momentum vector as the quantization axis the NLO QCD prediction

$$C = 0.777^{+0.027}_{-0.042}$$

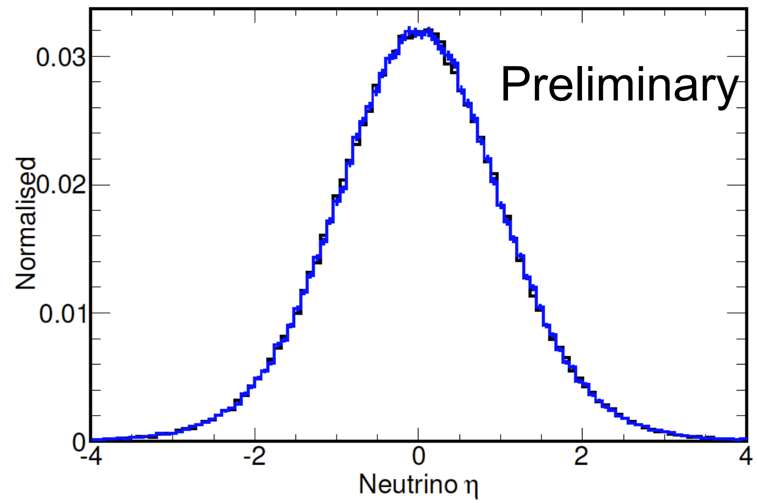
Event Reconstruction

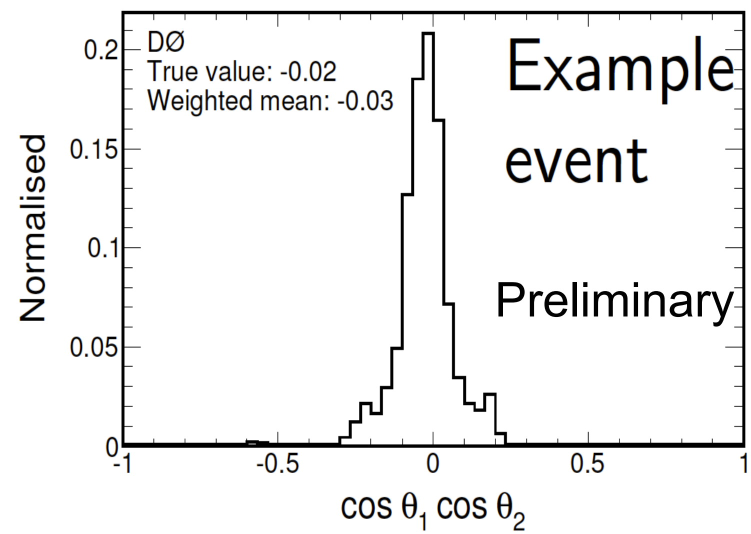
- Use W boson and top quark mass constraints

  To resolve ambiguity of two neutrinos test several assumptions for neutrino and antineutrino η.

  Weight each solution by agreement with measured missing transverse energy

- Weighted mean of all solutions used as estimator for $\cos\theta_1 \cos\theta_2$ value



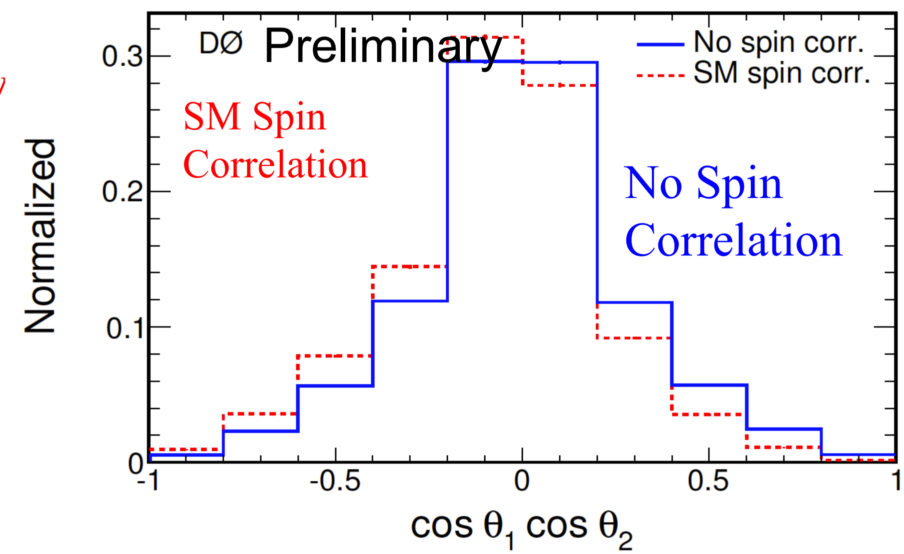


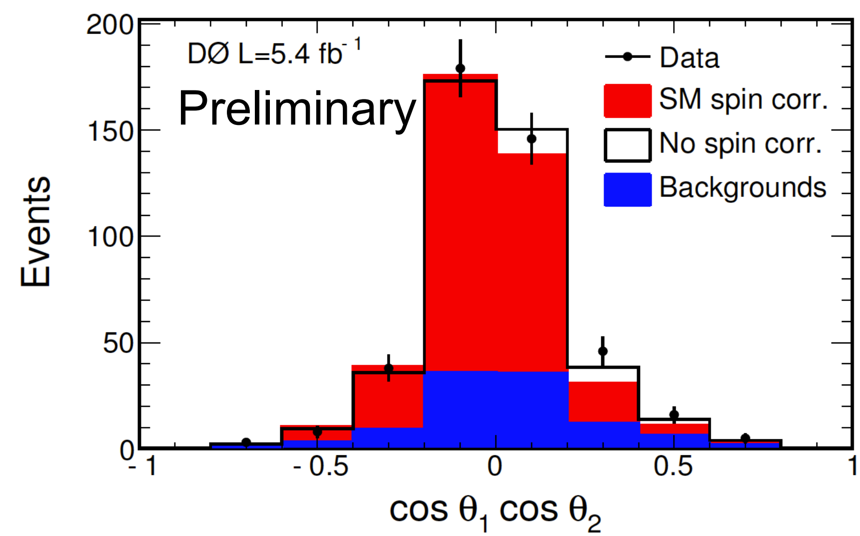
Measurement

- Distinguish between a hypothesis of no correlation and the correlation predicted by the SM

  Template for each background

  Mix signal templates for SM spin and no spin as function of C





- Fit the templates to data

  Simultaneous fit for C and top pair cross-section

- Main systematic uncertainties

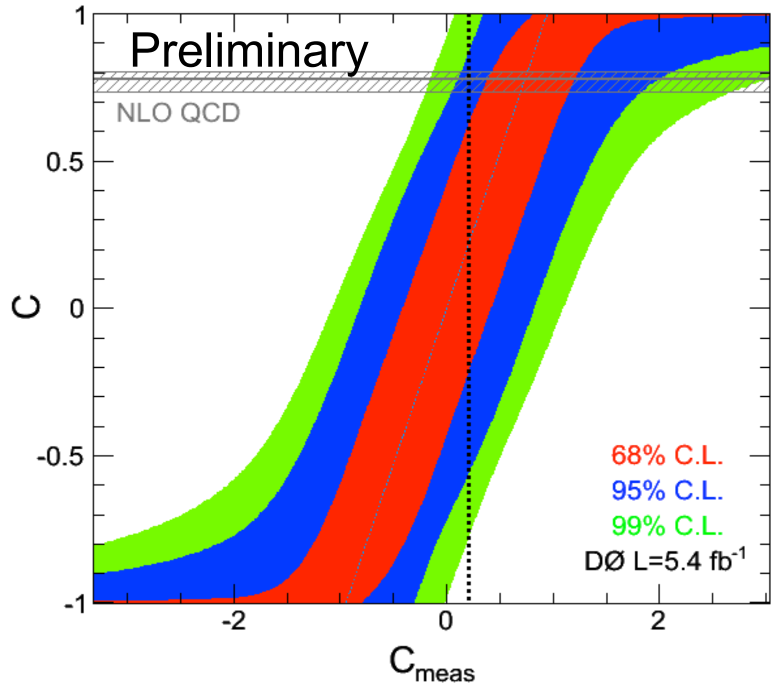
  MC template statistics, Jet identification and PDF

Spin Correlation: Result

- Extract the spin correlation simultaneously with the top pair production cross section.

$$C_{\mathrm{meas}} = 0.21^{+0.39}_{-0.41}\ (\mathrm{stat+syst})$$

Statistical uncertainty = +0.34,-0.39



- At the moment, within uncertainties, result is consistent with both SM correlation and no correlation hypotheses
  Agrees within 2 standard deviations with the SM prediction for a spin correlation

$$C = 0.777^{+0.027}_{-0.042}$$

- Combining CDF and D0 measurements for full RunII data we expect to be able to distinguish between no spin and spin correlations

The Third Tale

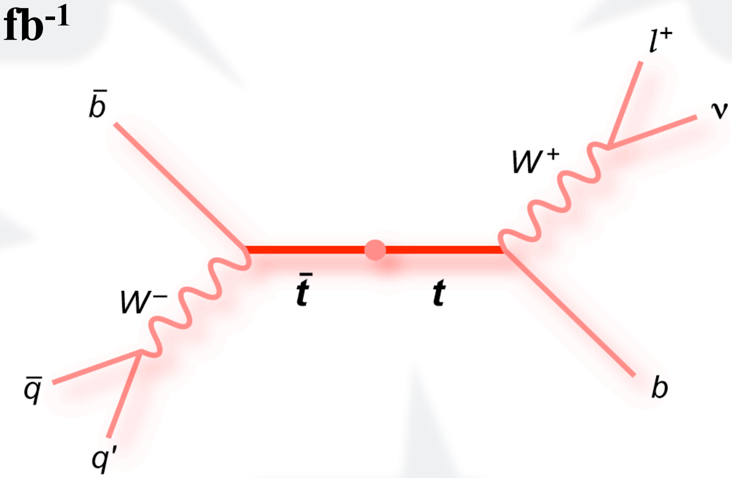
5.3 fb^{-1}
Top Mass
Width
Charge
Spin
5.4 fb^{-1}

W helicity
Anomalous couplings
CP violation
FCNC 4.1 fb^{-1}
$|V_{tb}|$

Production Cross-section mechanism,

Resonant production,

Charge asymmetry



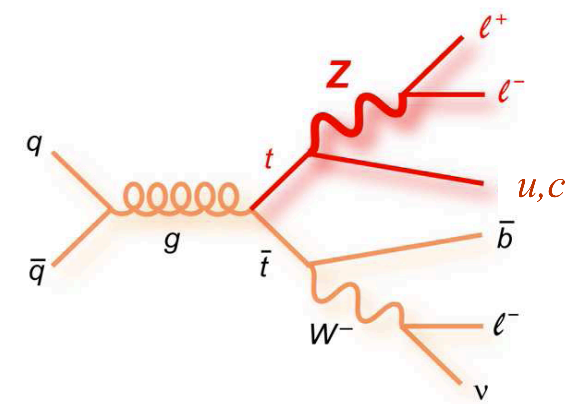
Branching Ratios
Rare/non SM decays

Search for FCNC (Flavor Changing Neutral Currents)

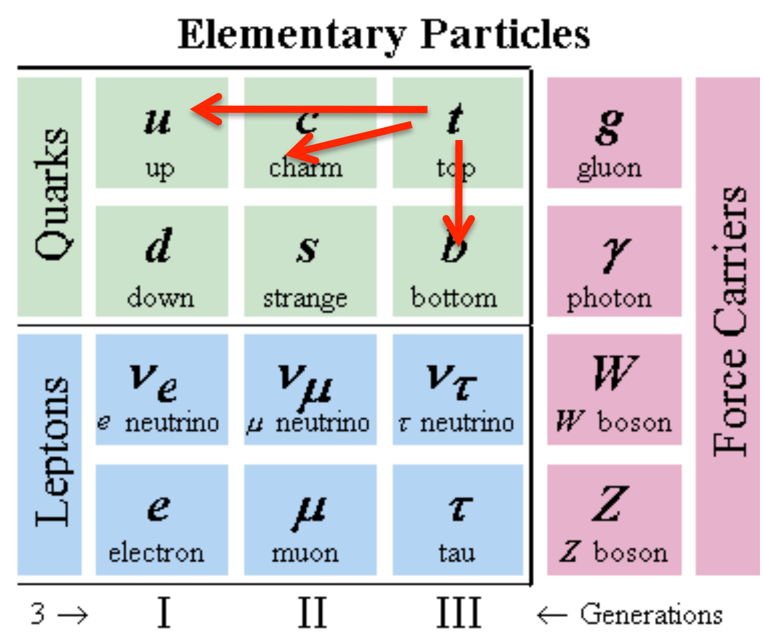
- In standard model no FCNC at tree level

  SM branching fraction for t →Zq (q = u, c quarks) is 10^{-14}

  Some scenarios beyond standard model predict fractions as high as 10^{-4}



Sensitive indicators of physics beyond the standard model



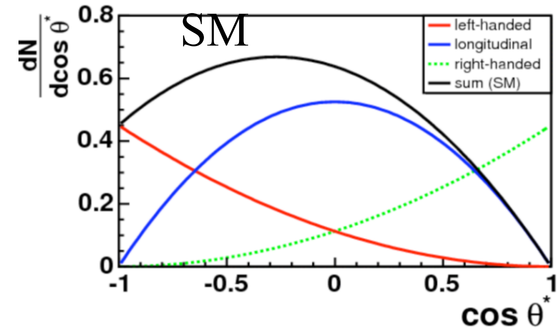
Search for FCNC

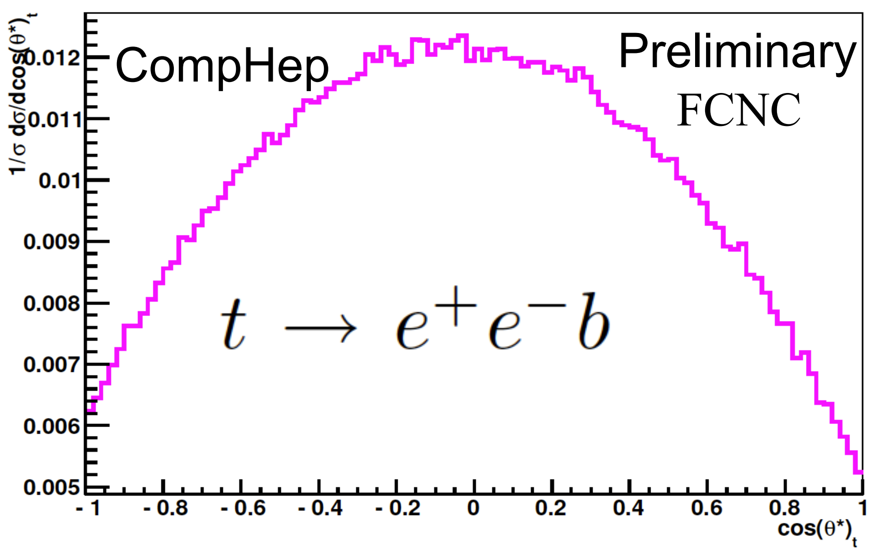
- Introduce dimension-4 vector and axial vector couplings v_{tqZ} and a_{tqZ}

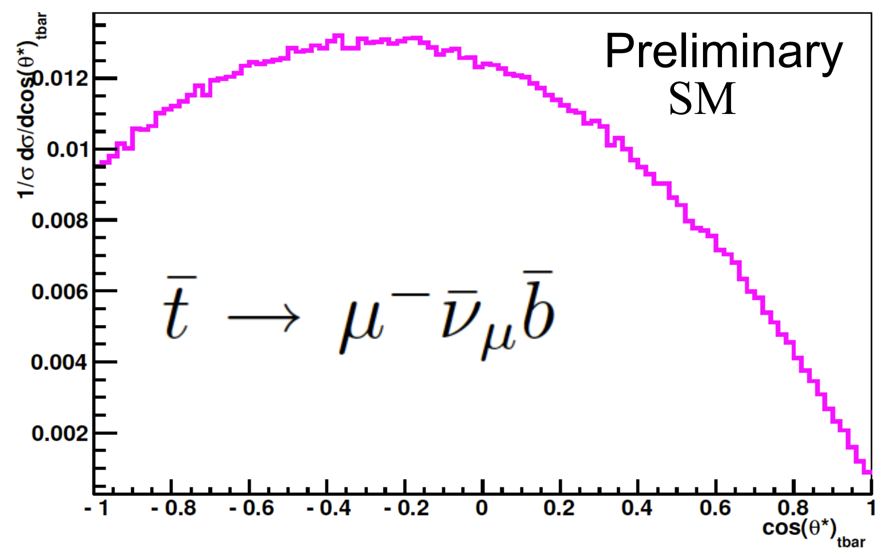
$$\mathcal{L}_{\rm FCNC} = \frac{e}{2\sin\theta_W\cos\theta_W}\,\bar{t}\,\gamma_\mu(v_{tqZ} - a_{tqZ}\gamma_5)\,q\,Z^\mu + h.c.$$

vector coupling

Axial vector coupling







Search for FCNC

- Search in events with three leptons

  2 Leptons from Z decay identified using Z mass constraint

- WZ, Z+jets, ZZ, and Zγ are the main backgrunds

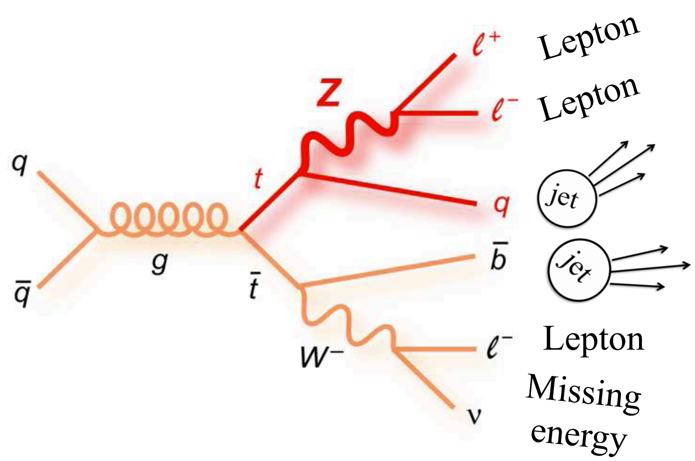
  Small contribution from W+jets and SM top pair

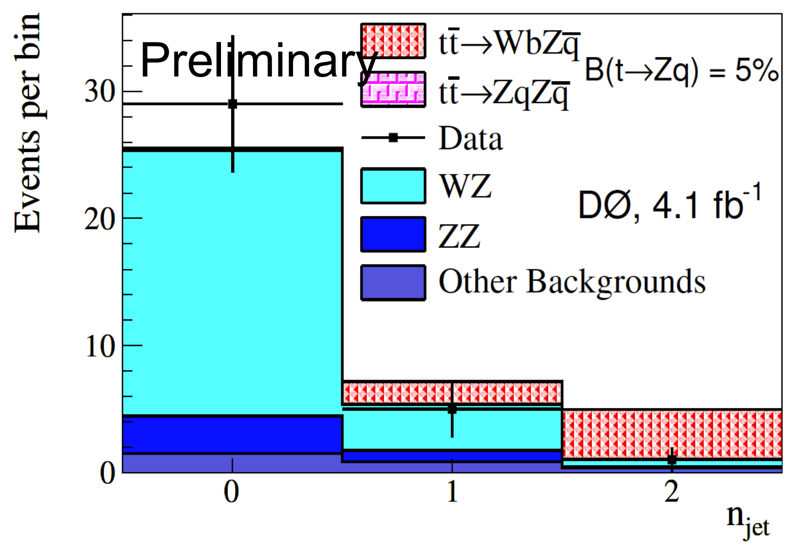
  – The WZ, ZZ, and ttbar backgrounds from MC

  – W,Z+jet background from data

  Misidentification rate is calculated in multi jet events

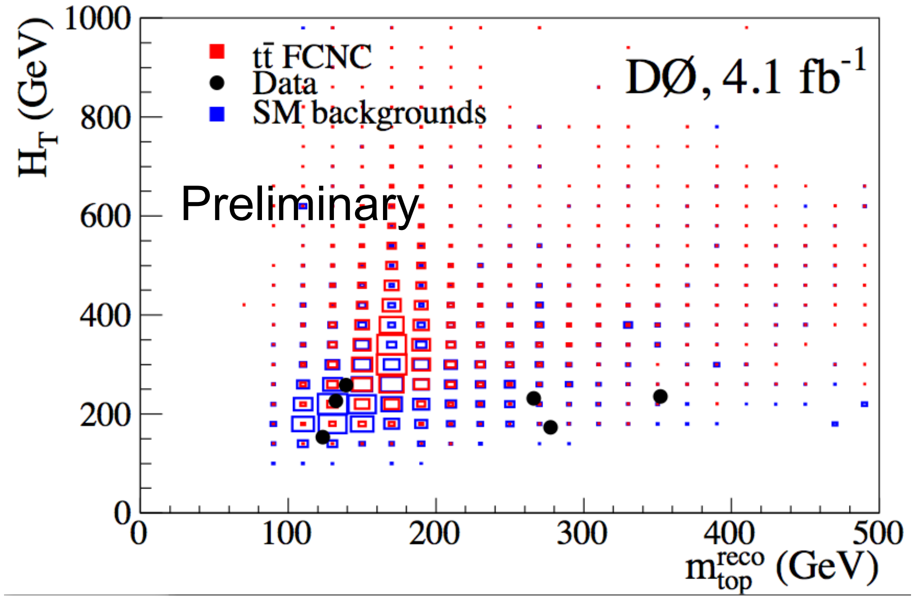
  W,Z+jets background is estimated by scaling a sample of Z+”false” events

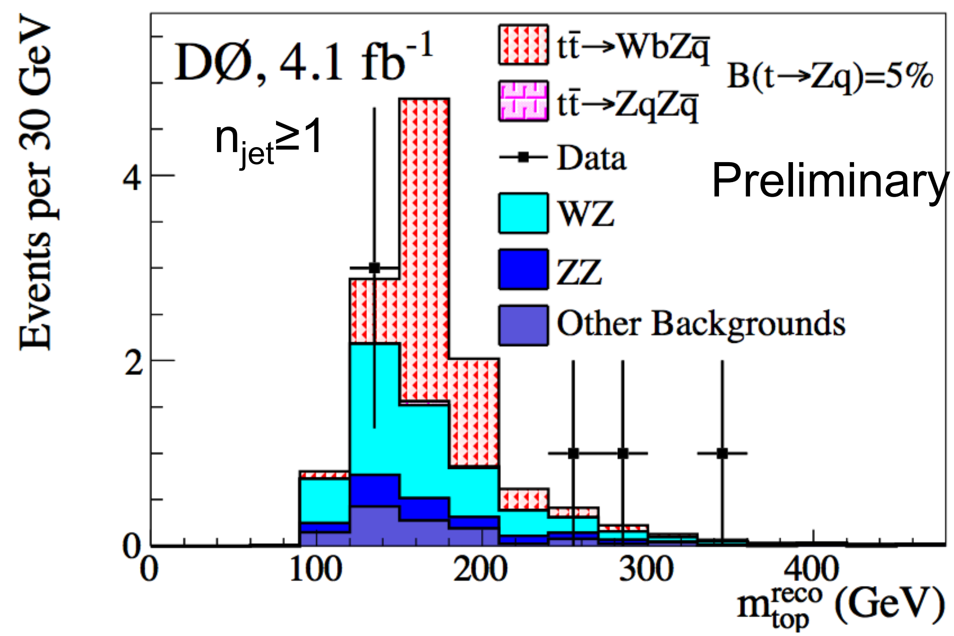




Search for FCNC

- To separate signal and background analyze the n_{jet}, H_T distributions and the reconstructed mass of the top quark decaying via $t \rightarrow Zq$





- Increase sensitivity by calculating limit in bins of jet multiplicity, H_T and reconstructed mass $t \rightarrow Zq$

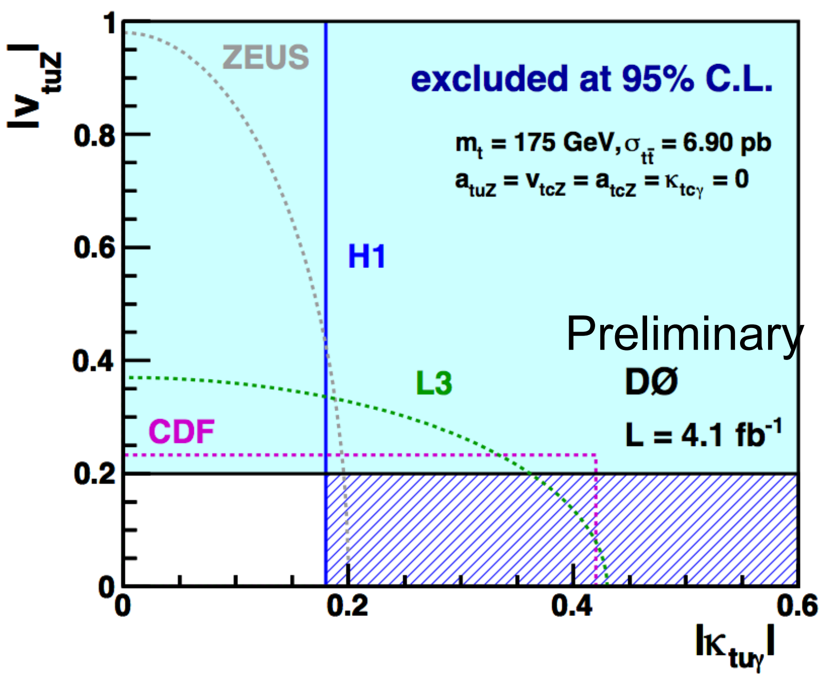
- Main systematic uncertainties from lepton identification, PDF, theoretical cross section for ZZ,WZ and ttbar and background modeling

Search for FCNC: Results

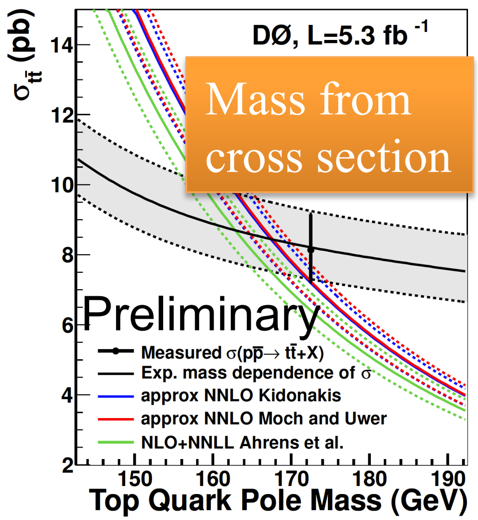
- We determine an observed limit of B($t \rightarrow Zq$) < 3.3% at 95% CL

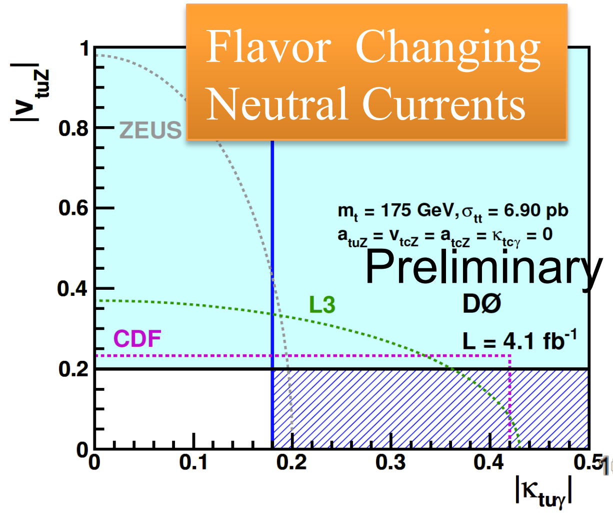
currently the world's best limit

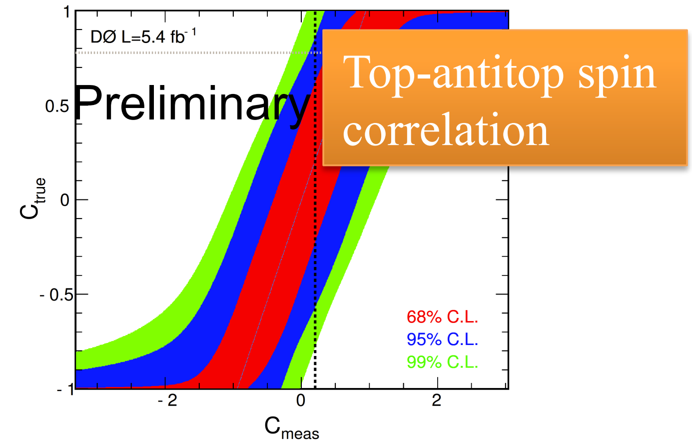
- This limit on of B($t \rightarrow Zq$) can be converted to limit on coulings v_{tqZ} and a_{tqZ}
- This is the first search for FCNC ttbar decays with trilepton +missing transverse energy final states and provides a measurement complementary to other searches

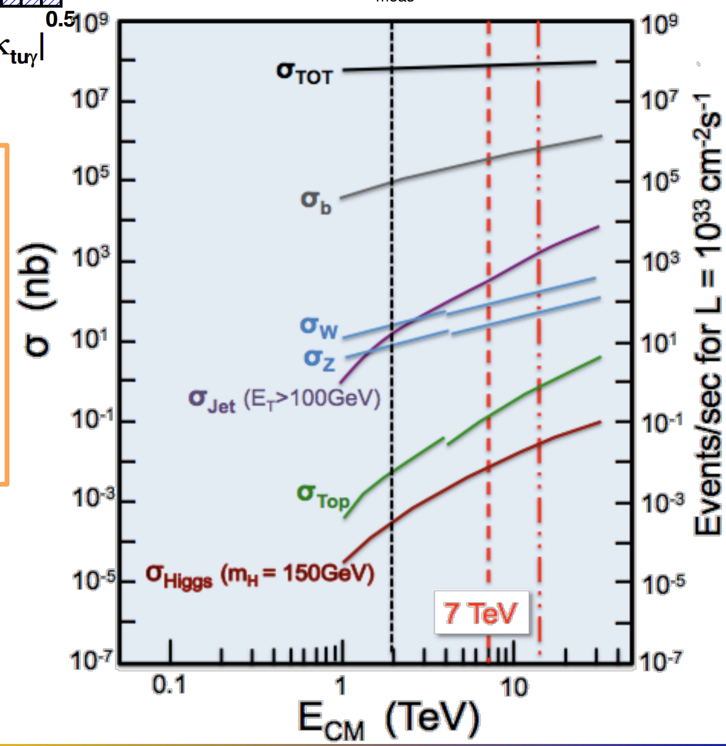


Three Tales of Two Tops









These three analyses are part of a large program to explore the mysterious top quark and with largest dataset available in the history of proton colliders

the fun has just started

[Link to D0 top public results]

Conclusion

- Tevatron has given us an enormous wealth of data

- CDF and D0 has published more than 300 papers each

  many of which include words like EVIDENCE, OBSERVATION and FIRST including top quark observation in 1995 to most recent observation of same sign dimuon charge asymmetry and forward backward in top-anti top quark events

- Tevatron's legacy is still being written and with half the data left to explore, the most interesting chapter of this story is perhaps just beginning

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- **After all another great discovery is just a handful of events away**