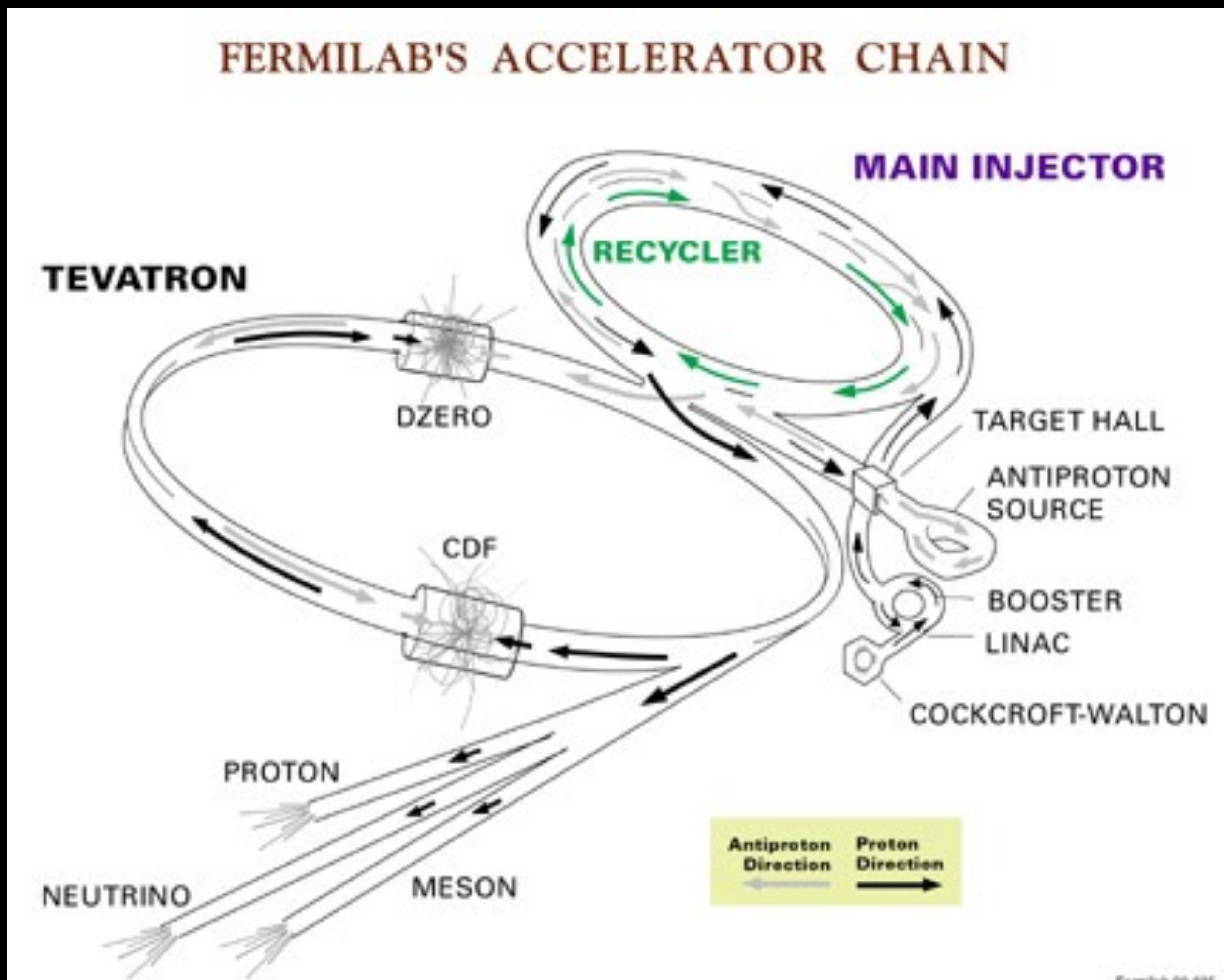
ANTONIO LIMOSANI ON BEHALF OF THE CDF AND D0
UNIVERSITY OF SYDNEY / CERN / VISITOR AT DUKE UNIVERSITY
@ 10TH ASIA-PACIFIC SYMPOSIUM ON COSMOLOGY AND PARTICLE ASTROPHYSICS

REVIEW OF RESULTS FROM THE TEVATRON

OVERVIEW

- CDF and D0 experiments are analysing data and publishing in the LHC era
- Focus on measurements with a long lasting legacy (competitive and complementary to the LHC)
- Expect ~30 papers by CDF and ~25 papers by D0 this year
- Here discuss results of some relevance to cosmology

THE TEVATRON

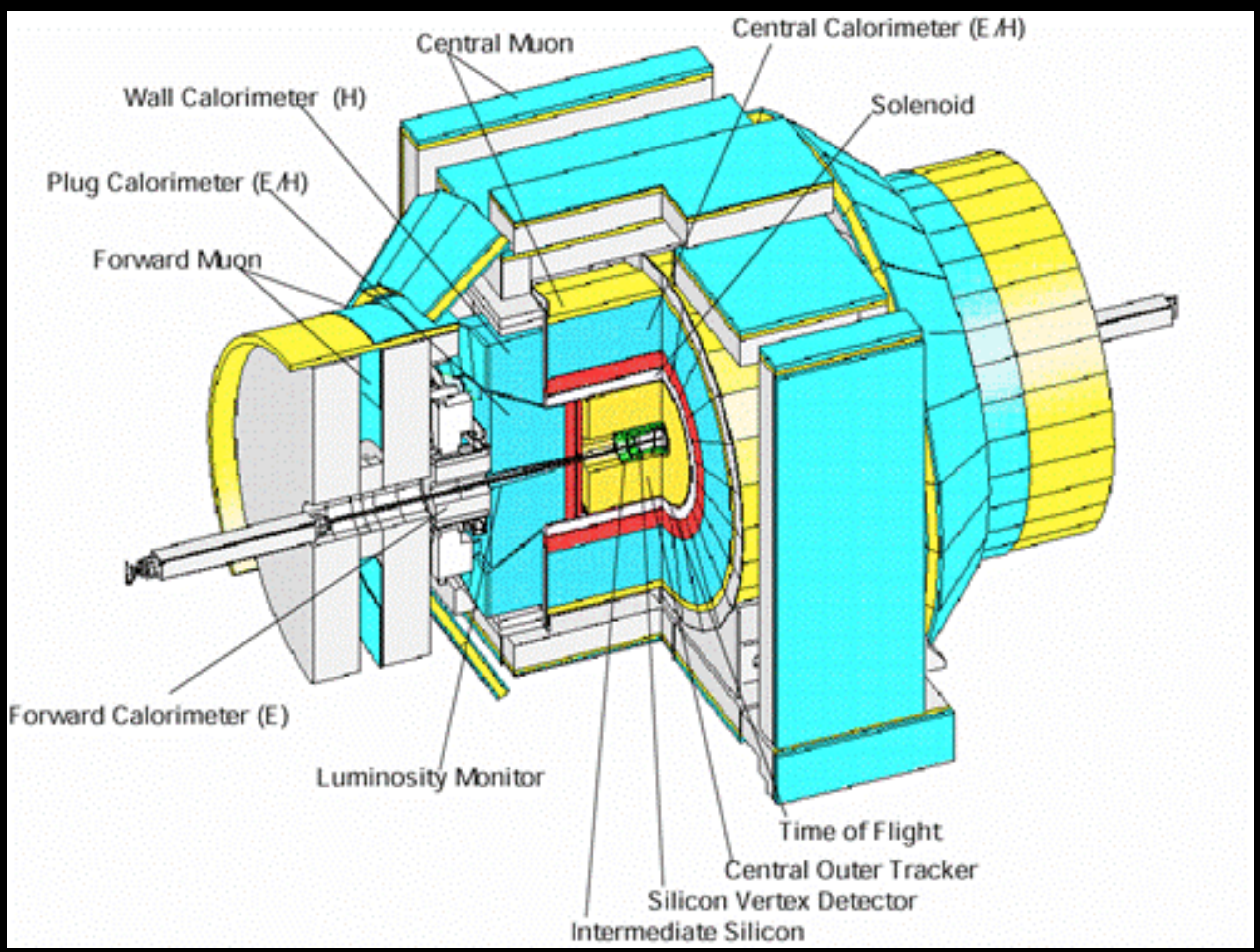


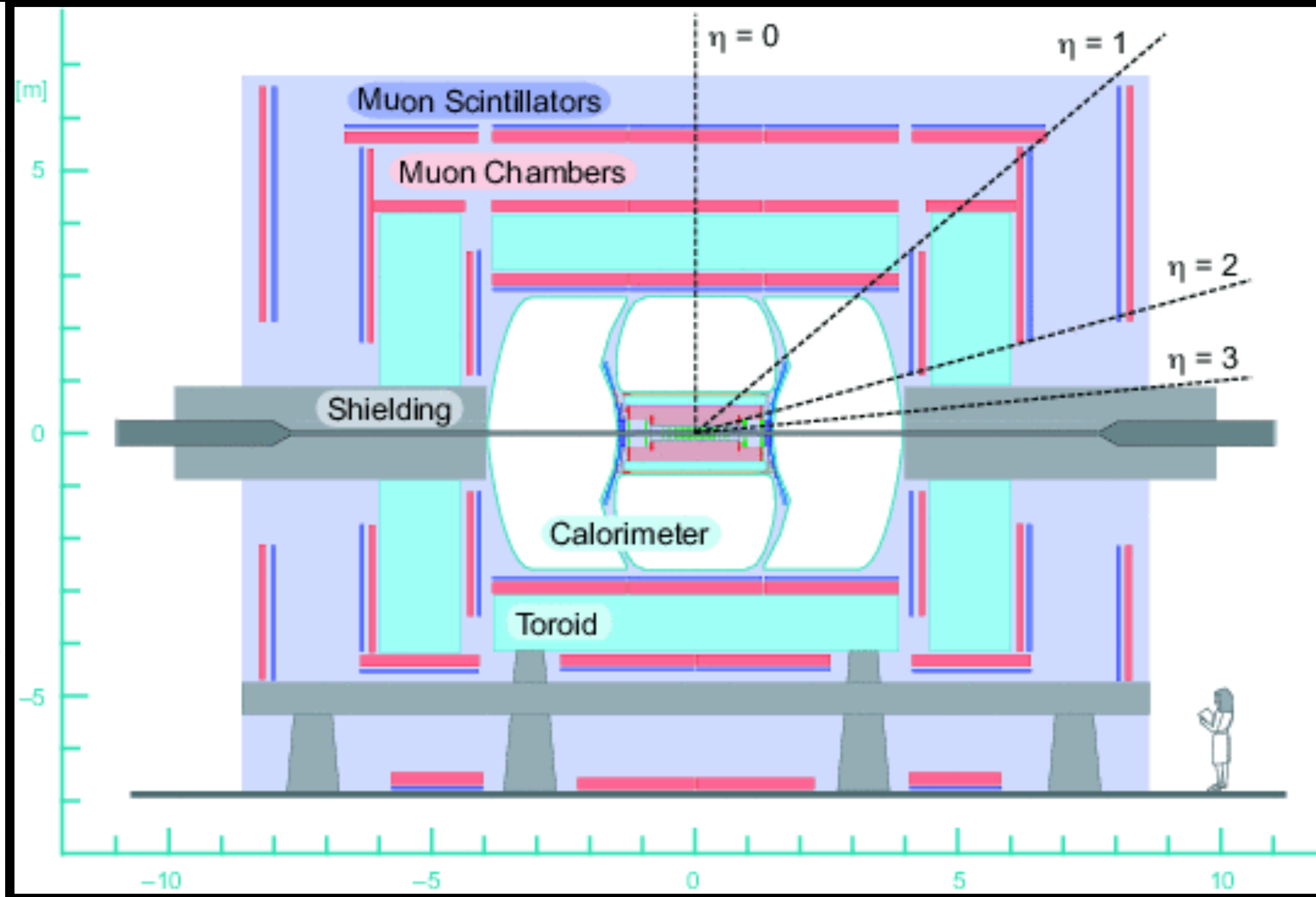
- Proton Anti-proton collider 1.96 TeV collision energy, 36 bunches, 396 ns bunch crossing
- July 3, 1983 - September 29, 2011

http://www.fnal.gov/pub/tevatron/tevatron-accelerator.html

CDF & D0

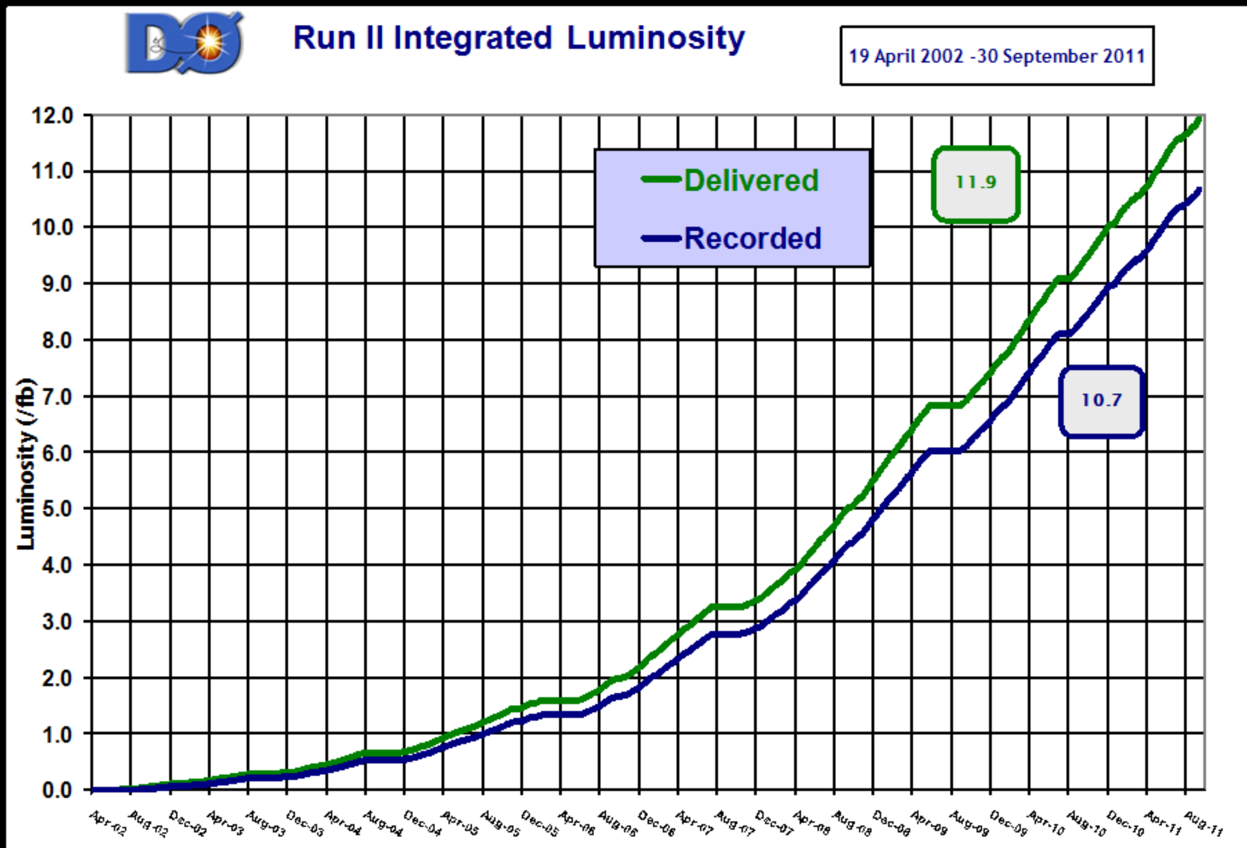
- Hermetic detectors to capture the products of the collisions

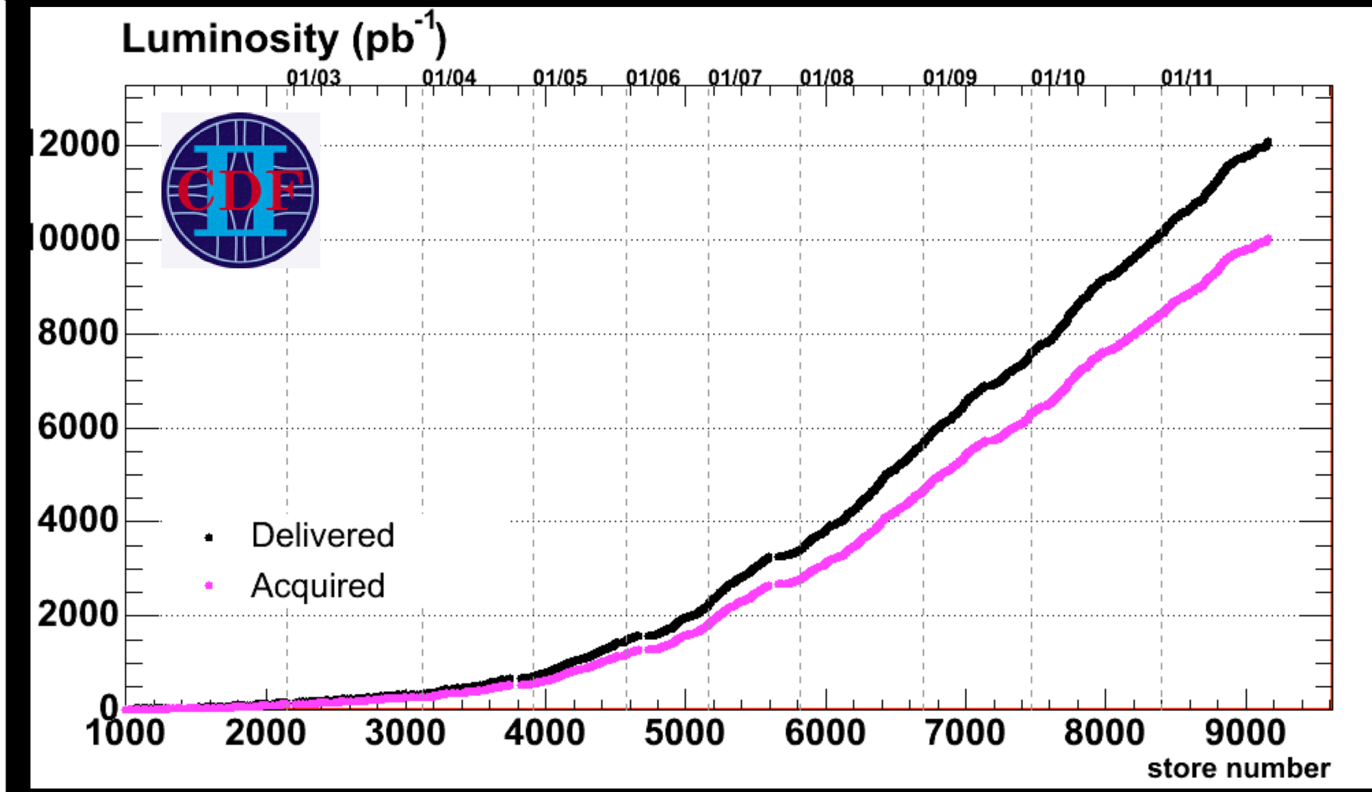




- CDF - 600 physicists / 60 universities and labs / 13 countries
- D0 - 550 physicists / 89 universities and labs / 18 countries

ACCUMULATED DATA

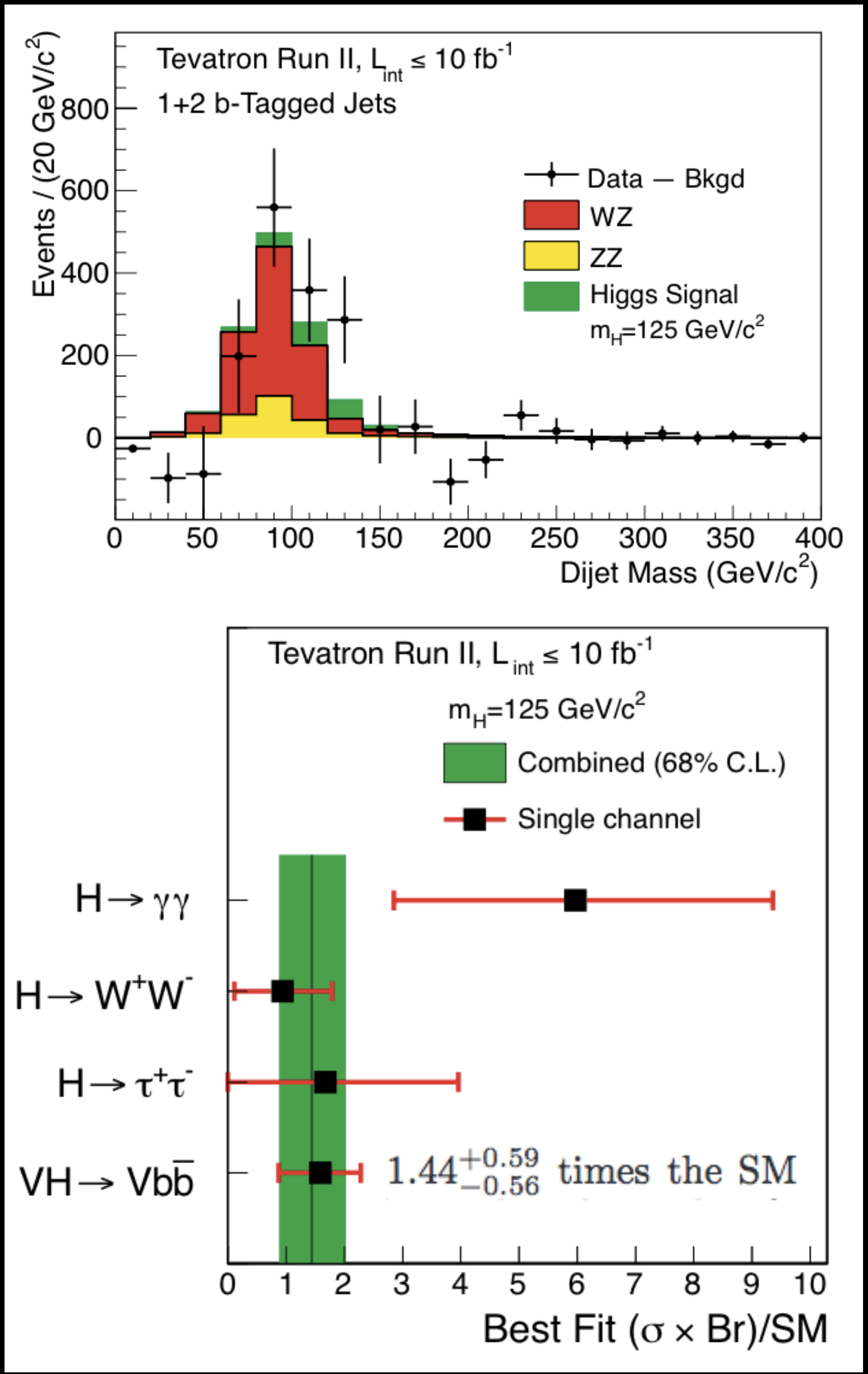




- ~10.7 / fb D0
- ~10.0 /fb CDF

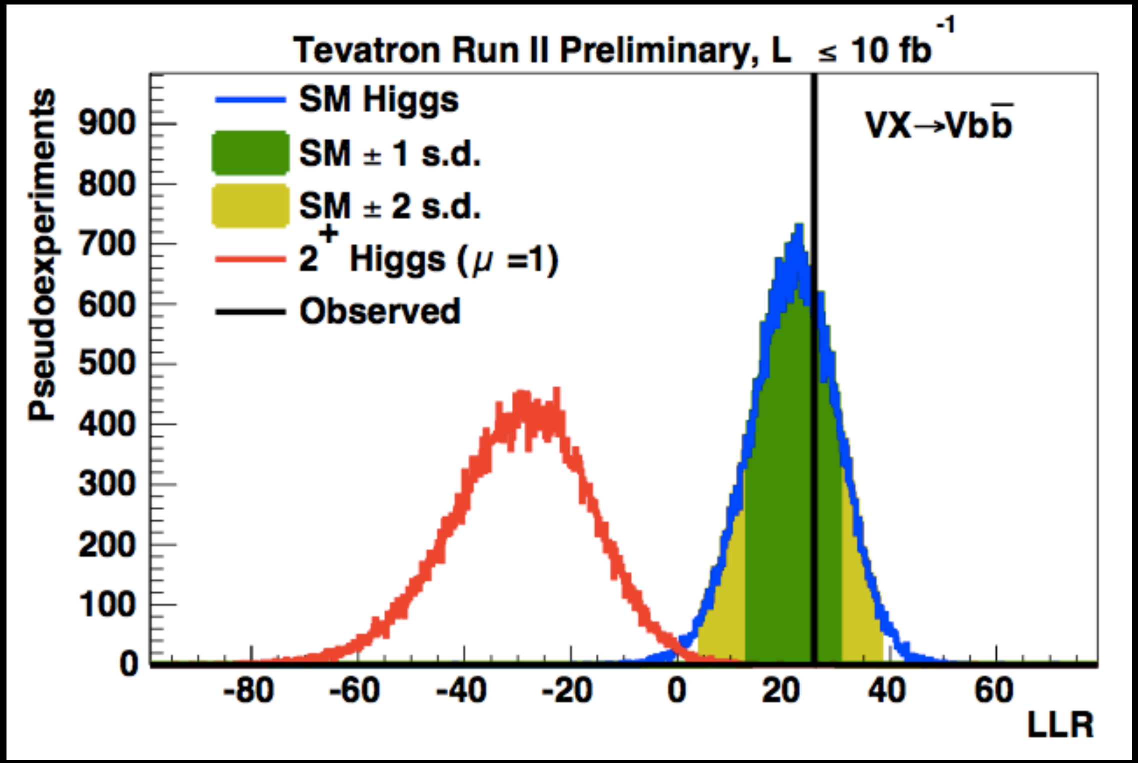
FINAL HIGGS COMBINATION

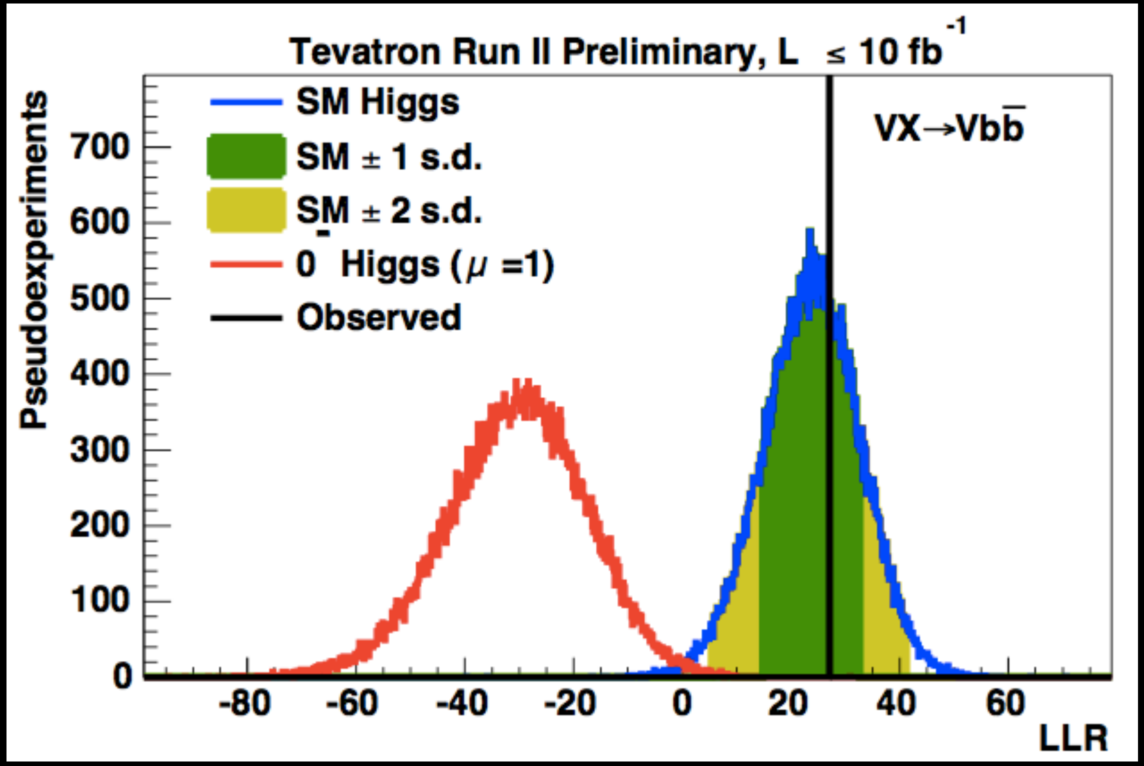
- Search is finished
- Decay of Higgs to b-quark pairs detected with significance of 3.0σ at a Higgs mass of 125 GeV
- Tevatron combination published PRD88 052014 (2013)



HIGGS PROPERTIES

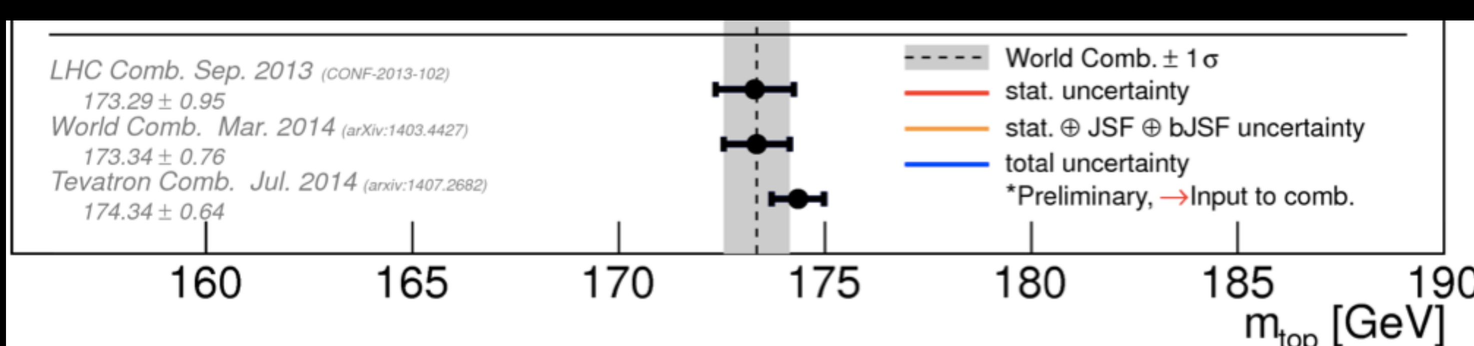
- Is it the Higgs predicted by the standard model?
- Spin and parity tests (SM $J^P=0^+$) in VH→Vbb
- Higgs at LHC may not be the same as that from the Tevatron
- Exotic models with $J^P=2^+$ (graviton like) and 0^- excluded at 5σ significance
- FERMILAB-CONF-14-265-E (Sep 10, 2014)

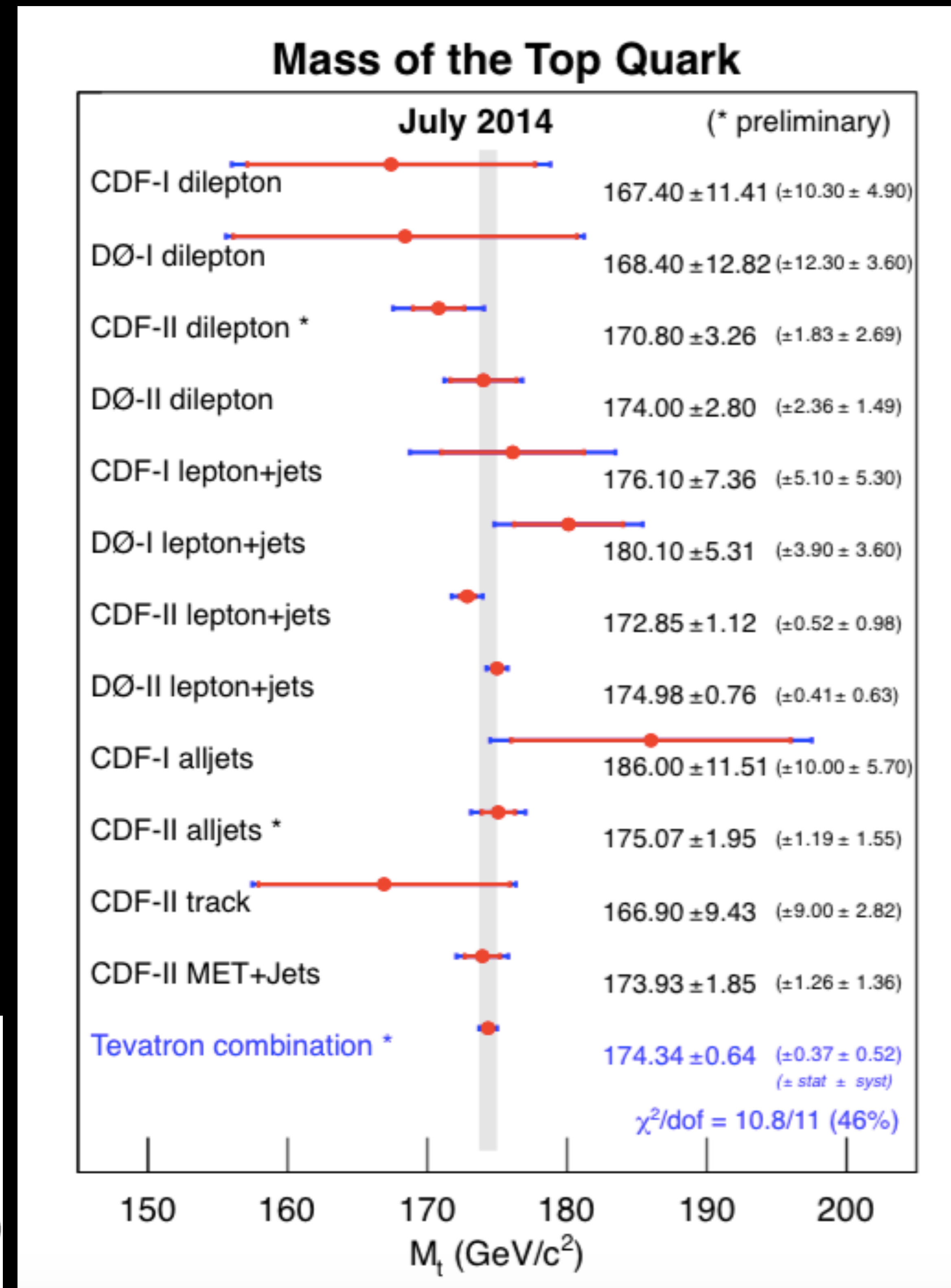




TOP QUARK MASS

- Top discovered at the Tevatron in 1995
- Analysis using Run 1 and and Run 2 datasets
- World's best determination





EXPERIMENTAL LIMITATIONS OF TOP QUARK MASS MEASUREMENT

	Tevatron combined values (GeV/c^2)
M_t	174.34
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.10
Model for b jets (bJES)	0.10
Out-of-cone correction (cJES)	0.02
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.13
Lepton modeling (LepPt)	0.07
Signal modeling (Signal)	0.34
Jet modeling (DetMod)	0.03
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.08
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.52
Statistical uncertainty (stat)	0.37
Total uncertainty	0.64

Further improvement to come when all analysis channels from CDF and D0 use the all Run II data and are optimised to reduce systematic uncertainties

FORWARD BACKWARD ASYMMETRY IN TOP QUARK PAIR PRODUCTION

- Over the past seven years CDF and D0 have been measuring this asymmetry and finding disagreement with the SM prediction.
- Many new physics scenarios proposed to account for this discrepancy, heavy resonances e.g parity violating strong interactions from Frampton and Glashow in Phys. Lett. B190, 157 (1987), or heavy axial color gluon octet or a flavor-changing Z'
- Proton / anti-proton collisions, top pair are produced from valence quark and anti-quark annihilation
- Direction of the proton coincides with the direction of the incoming quark
- Phys.Rev. D90 (2014) , 072011

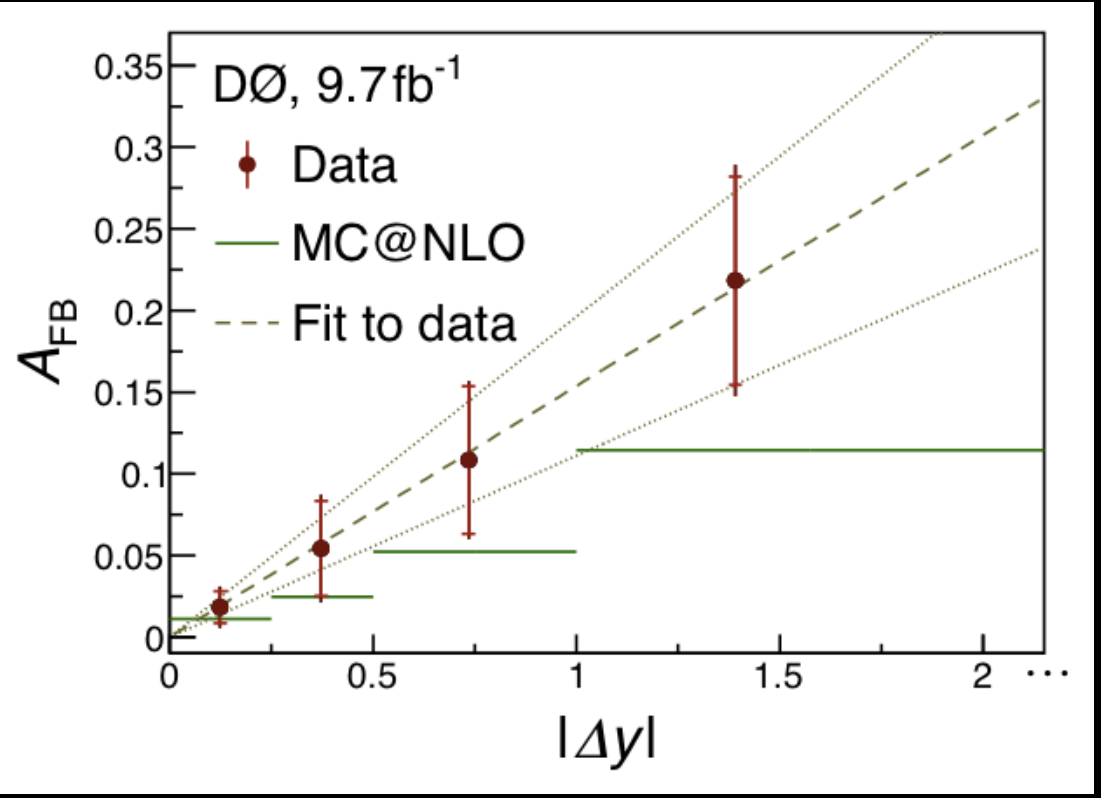
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

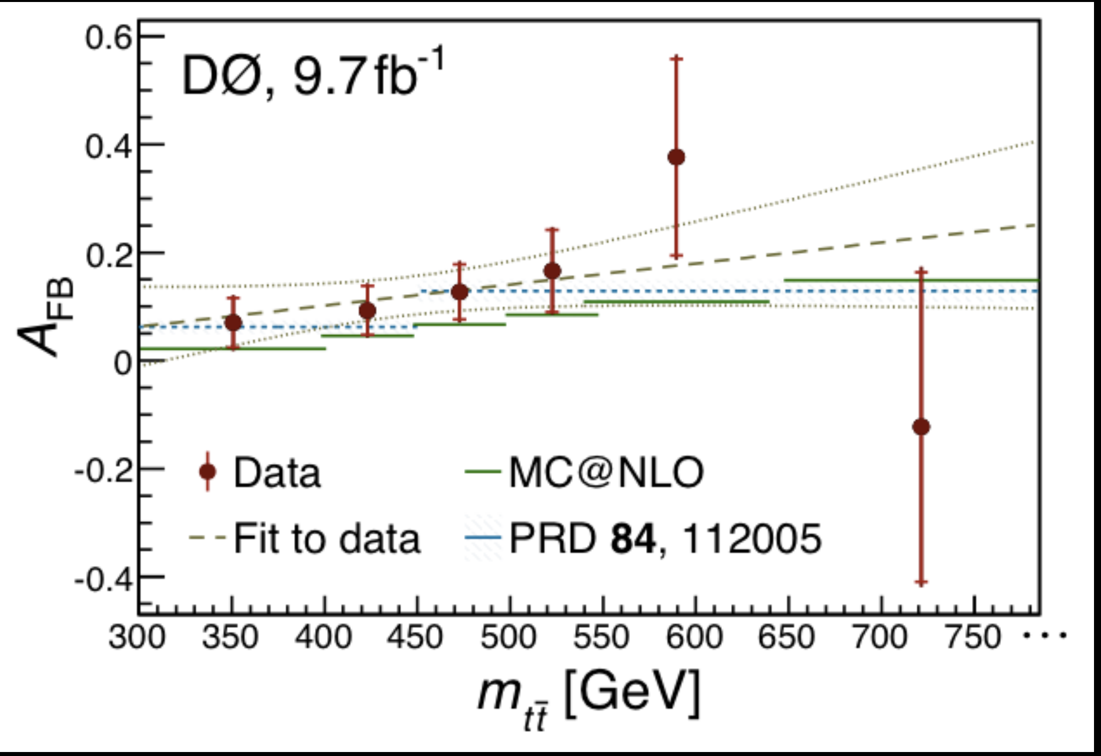
$$\Delta y = y_t - y_{\bar{t}}.$$

$$\Delta y > 0 \text{ as “forward”}$$

$$\Delta y < 0 \text{ as “backward”}$$

$$A_{\mathrm{FB}} = \frac{N_f - N_b}{N_f + N_b}$$





FORWARD BACKWARD ASYMMETRY IN TOP QUARK PAIR PRODUCTION

Lepton+jets	**Charge Asymmetry A_{FB}**	$A_{FB} = 0.150 \pm 0.050(stat) \pm 0.024(syst)$ in ppbar rest frame $A_{FB} = 0.158 \pm 0.072(stat) \pm 0.017(syst)$ in ttbar rest frame $A_{FB} = 0.475 \pm 0.114$ in the parton level. Compare to $A_{FB} = 0.088 \pm 0.013$ from QCD.	5.3 fb^{-1}	5.3 fb^{-1} 6/8/2011 **PRD 83 112003** 3.2 fb^{-1} **Conf. Note 9724** 1.9 fb^{-1} **PRL 101 202001**
Dilepton	**Charge Asymmetry A_{FB}**	$A_{FB} = 0.21 \pm 0.07(stat) \pm 0.02$(bkg-shape) in ttbar rest frame $A_{FB} = 0.42 \pm 0.15(stat) \pm 0.05(syst)$ in the ttbar rest frame; in the parton level. To be compared to $A_{FB} = 0.06 \pm 0.01$ from QCD.	5.1 fb^{-1}	03/01/2011 **Conf. Note 10436**
Lepton+jets	**Charge Asymmetry A_{FB}**	Inclusive parton-level $A_{FB} = 0.164 \pm 0.045(stat + syst)$ Compare to 0.066 ± 0.020 from NLO SM	9.4 fb^{-1}	10/31/2012 **PRD 87 092002** **arXiv:1211.1003** **Conf Note 10807**

- Latest D0 measurement consistent with SM predictions yet still do not disfavour larger asymmetries previously measured

Lepton+jets	Charge Asymmetry A_{FB}	$A_{FB} = 0.106 \pm 0.030$ Compare to 0.05 (MC@NLO)	9.7 /fb	PRD90 072011 (2014)

FORWARD BACKWARD ASYMMETRY IN TOP QUARK PAIR PRODUCTION

- CAVENDISH-HEP-14-10”   arXiv:1411.3007

Resolving the Tevatron top quark forward-backward asymmetry puzzle

Michal Czakon,[1] Paul Fiedler,[1] and Alexander Mitov[2]

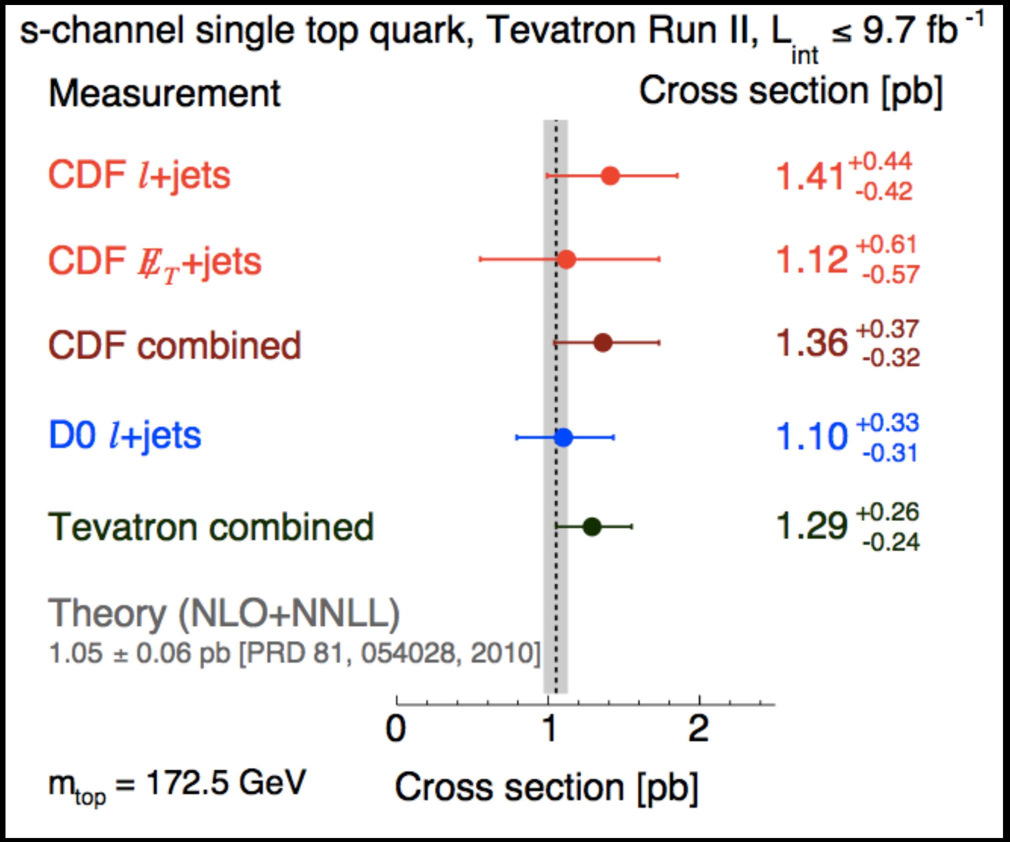
[1] *Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany*

[2] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*

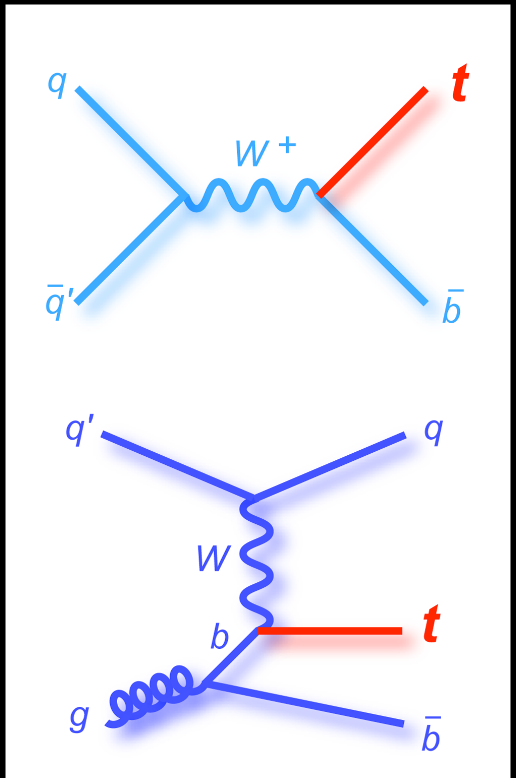
We determine the dominant missing Standard Model (SM) contribution to the top quark pair forward-backward asymmetry at the Tevatron. Contrary to past expectations, we find a large, around 27%, shift relative to the well-known value of the inclusive asymmetry in next–to–leading order (NLO) QCD. Combining all known Standard Model corrections, we find that $A_{FB}^{SM} = 0.095 \pm 0.007$. This value is in perfect agreement with the latest DØ measurement [1] $A_{FB}^{DØ} = 0.106 \pm 0.03$ and about 1.5σ below that of CDF [2] $A_{FB}^{CDF} = 0.164 \pm 0.047$. Our result is derived from a fully differential calculation of the next–to–next–to leading order (NNLO) QCD corrections to inclusive top pair production at hadron colliders and includes – without any approximation – all partonic channels contributing to this process. This is the first complete fully differential calculation in NNLO QCD of a two–to–two scattering process with all coloured partons.

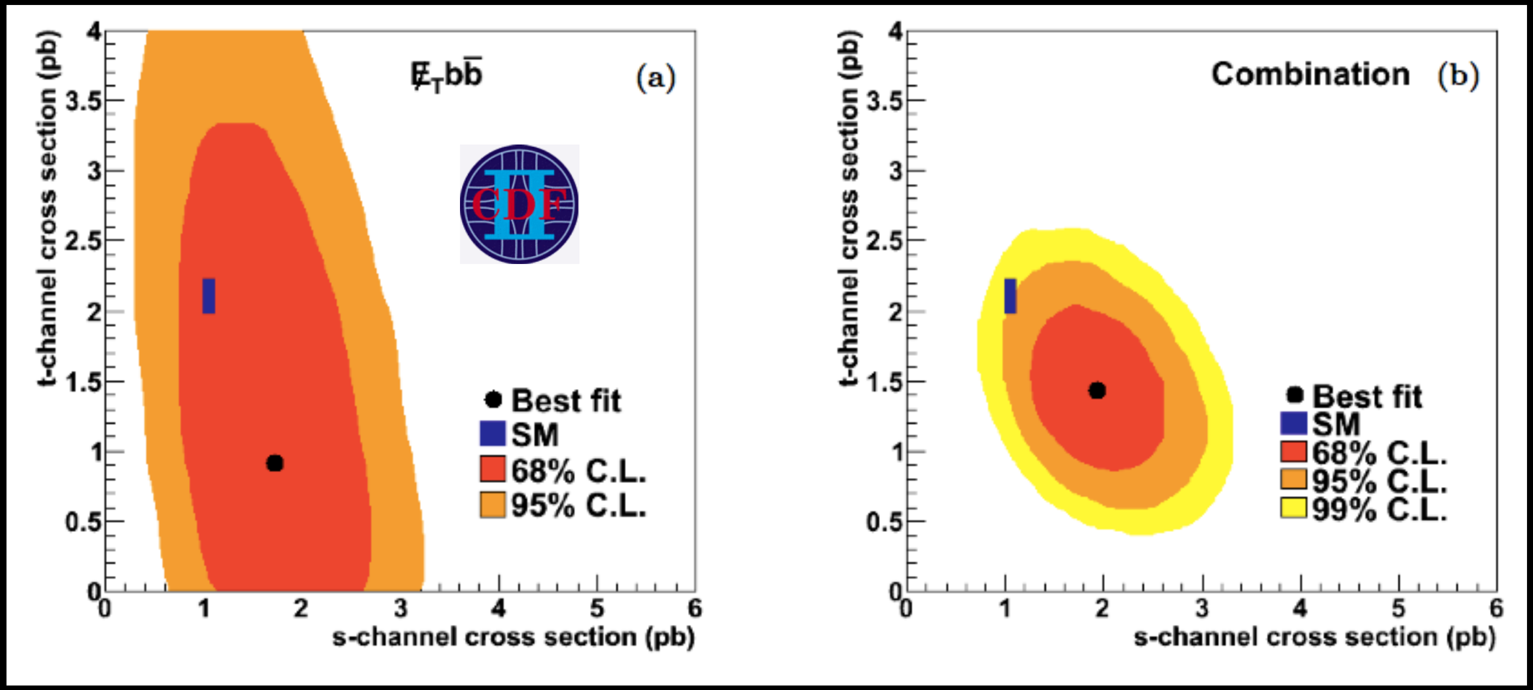
SINGLE TOP

- Observation of s-channel production of single top quarks at the Tevatron
- CKM V(tb), 4th generation quarks, Flavour Changing Neutral currents, anomalous top-quark couplings, heavy W bosons, 2HDM charged Higgs bosons etc.
- Tevatron is more sensitive to s-channel production than LHC owing to valence anti-quarks
- 6.2 σ observation (5.1 σ expected)
- Tevatron combination : Phys. Rev. Lett. 112, 231803 (2014), arXiv:1402.5126



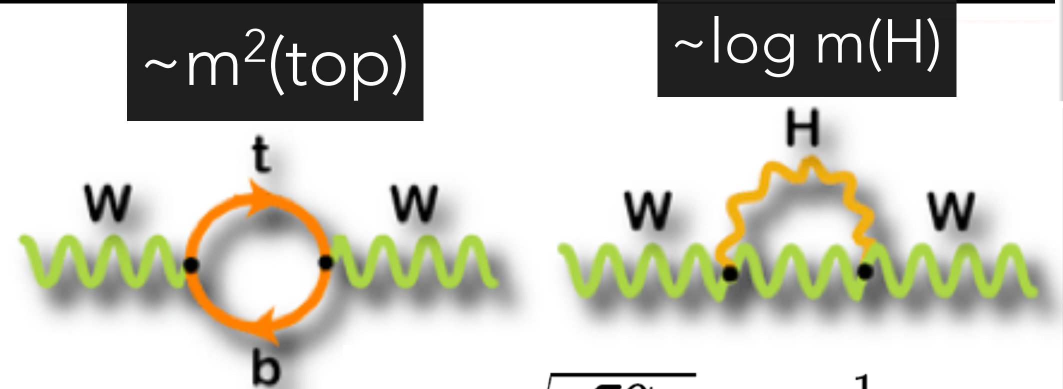
FERMILAB-PUB-14-398-E
arXiv:1410.4909
Recent update from CDF



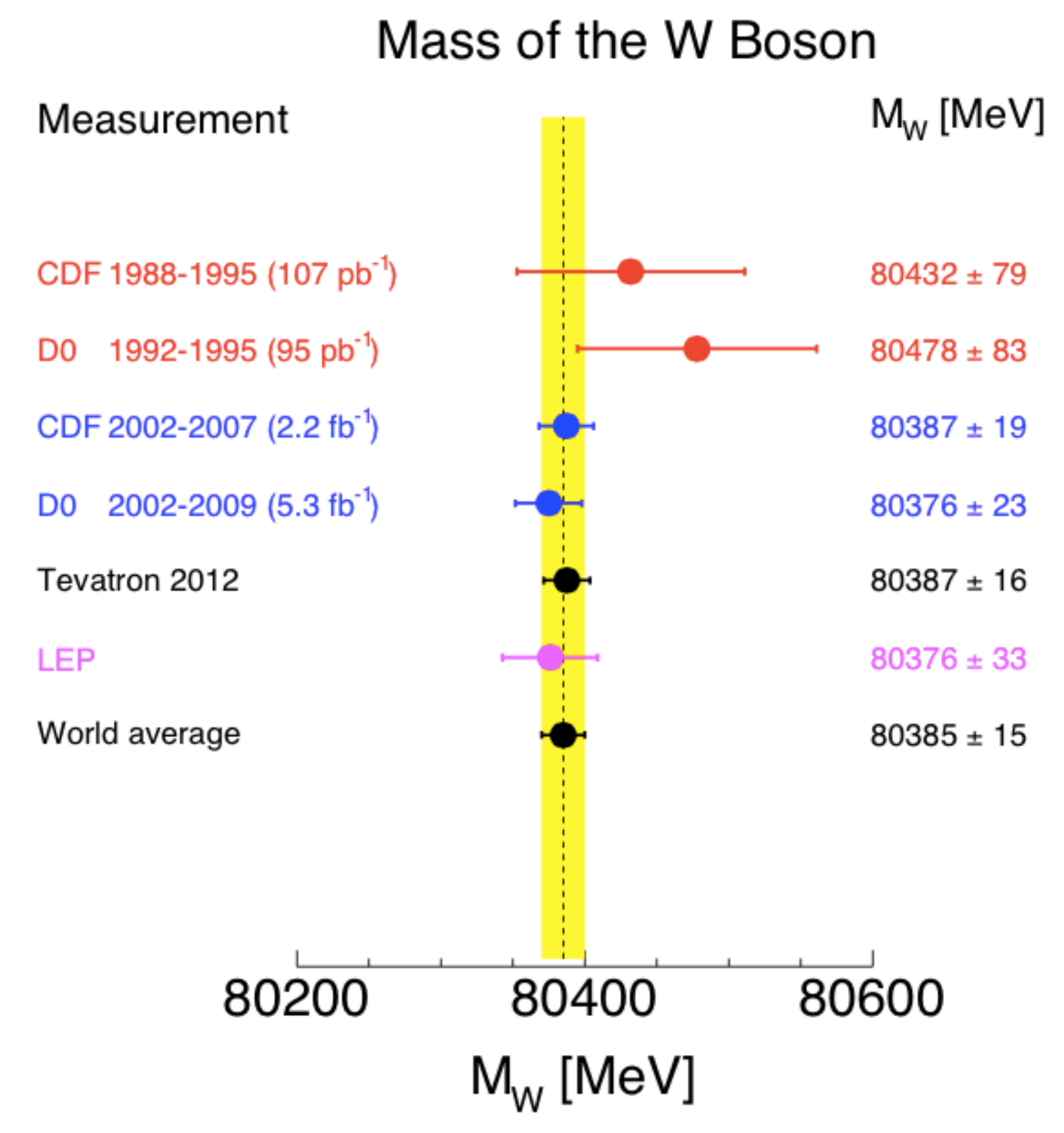


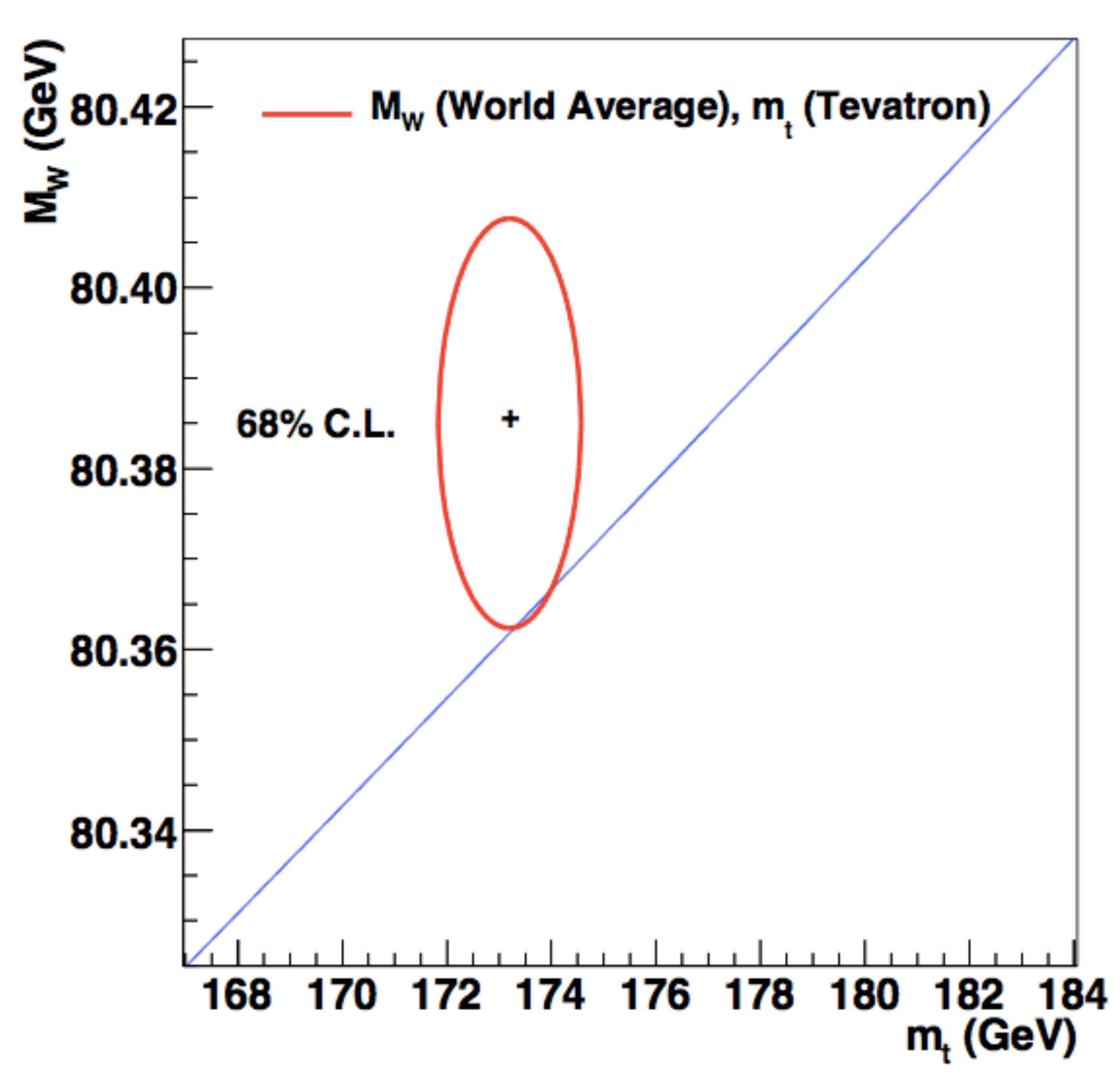
W BOSON MASS

- Quantum corrections to mass(W) dependent on mass(Top), mass(HIGGS) and α
- Powerful test of the SM
- Phys.Rev. D88 (2013) 052018



$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$





- Indirect prediction of m(W) given measured LHC Higgs mass (1.3σ agreement)

EXPERIMENTAL LIMITATIONS OF W MASS MEASUREMENT

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal from recoil	2
Backgrounds	3
Experimental subtotal	10
Parton distribution functions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson event yield	12
Total uncertainty	19

TABLE I: Uncertainties of the CDF (2012) M_W measurement determined from the combination of the six measurements.

Source	Uncertainty (MeV)
Electron energy calibration	16
Electron resolution model	2
Electron shower modeling	4
Electron energy loss model	4
Recoil energy scale and resolution	5
Electron efficiencies	2
Backgrounds	2
Experimental subtotal	18
Parton distribution functions	11
QED radiation	7
$p_T(W)$ model	2
Production subtotal	13
Total systematic uncertainty	22
W-boson event yield	13
Total uncertainty	26

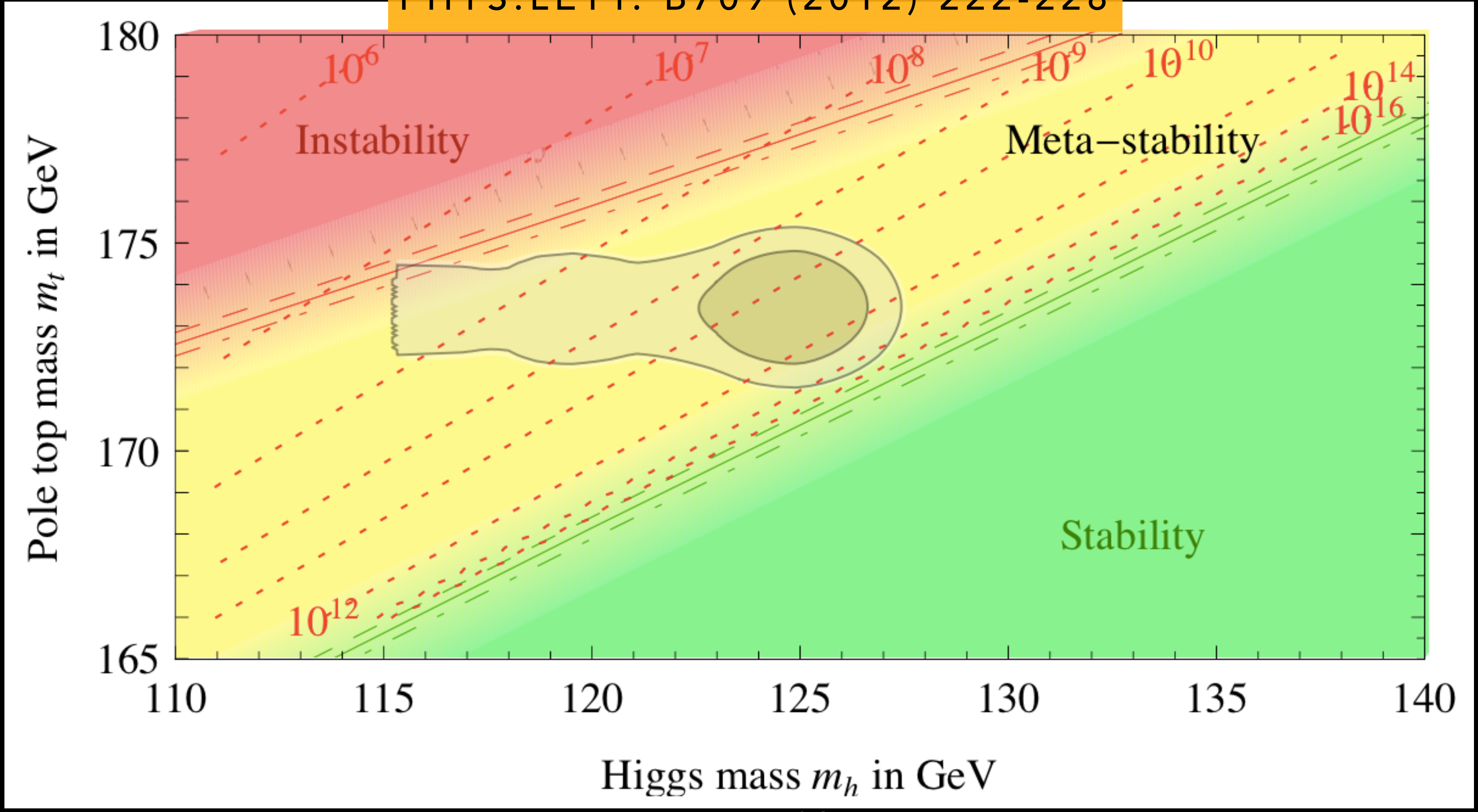
TABLE II: Uncertainties of the D0 (2012) M_W measurement determined from the combination of the two most sensitive observables m_T^e and p_T^e.

- Lepton energy scale - calibration of calorimeter response is a leading systematic uncertainty
- Theory and modelling uncertainties account for half of the uncertainty
- These measurements extend the limits of knowledge of our detector
- Analysis of full data set underway, 30% improvement possible!

IS THE UNIVERSE STABLE?

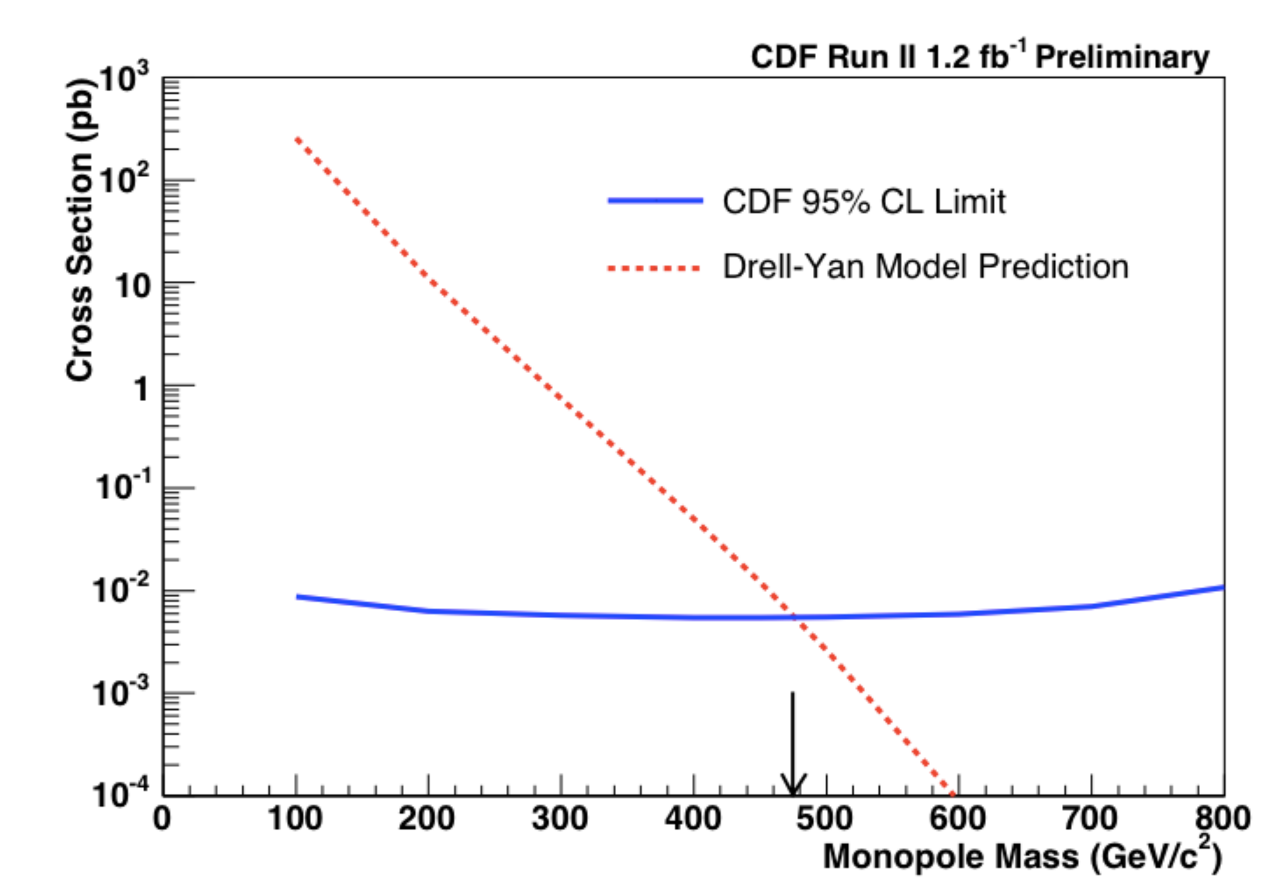
- Stability of the universe is intimately connected to the Higgs boson and top quark masses and α_s (Phys.Lett. B709 (2012) 222-228, Phys.Lett. B716 (2012) 214-219)
- Extrapolate the SM to the Planck scale (M$_{Higgs}$ ≥ 129.8 ± 5.6 GeV c.f. M$_{Higgs}$ = 125.2 ± 0.3 GeV)
- Precise test : determine "pole" mass(top) with 0.2 GeV accuracy
- Analysis provides information about the early stages of the universe (RH neutrinoes, leptogenesis and baryon asymmetry)
- Search for new physics between the Fermi and the Planck scale

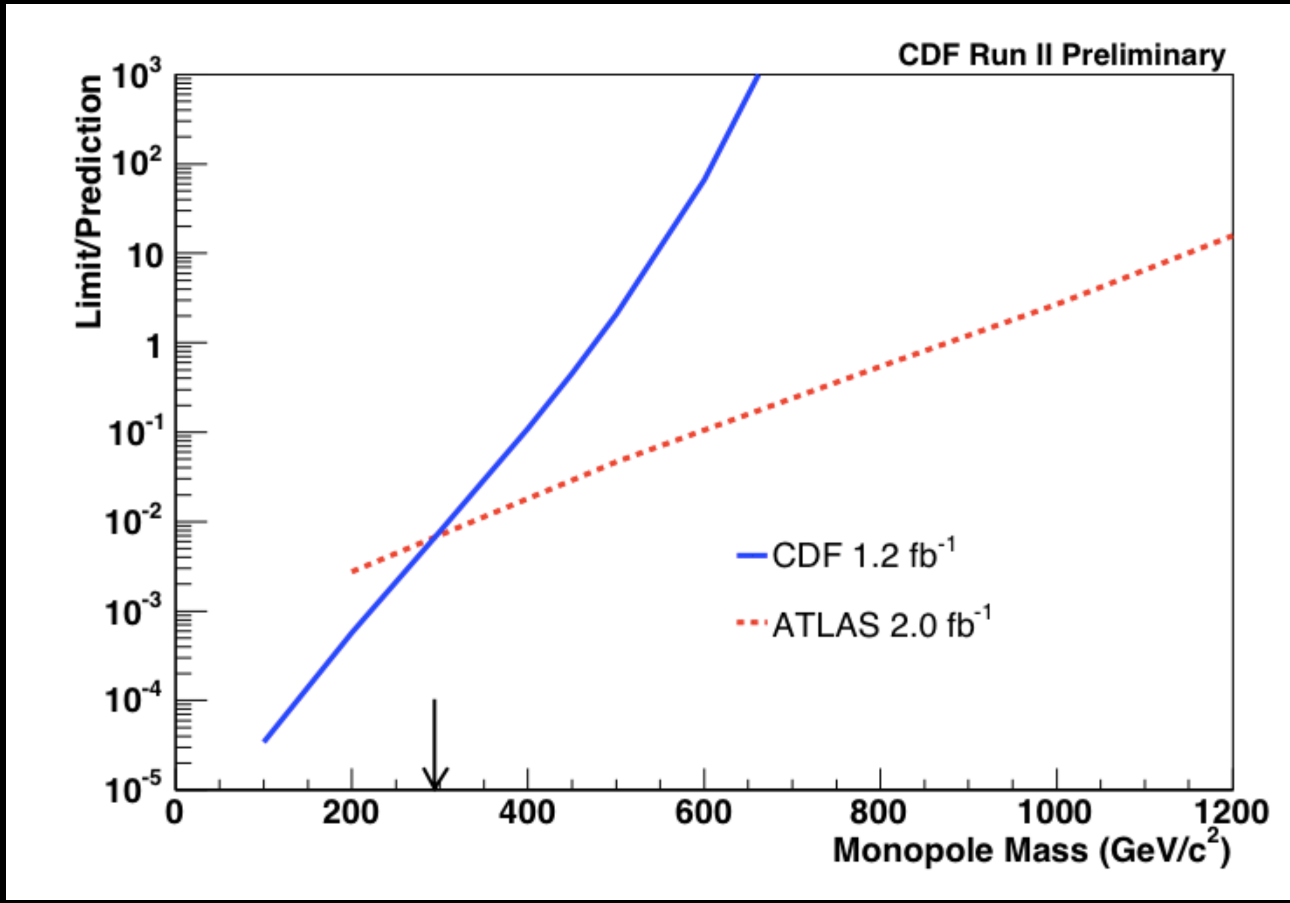
PHYS.LETT. B709 (2012) 222-228



MONOPOLE SEARCH

- Dirac magnetic monopoles
- Charge quantisation consequence of angular momentum quantisation
- GUTs monopole masses 10^{17} TeV
- Lack thereof one of the original motivations for the theory of inflation
- Specialised trigger relying on large light pulses in the scintillators of the Time-of-flight
- Produced in a similar way to Drell-Yan production
- Highly ionising, naturally feel force parallel to the magnetic field
- Upper limit for Mpl mass 476 GeV
- No events observed





http://www-cdf.fnal.gov/physics/exotic/r2a/20140619.monopole/index.html

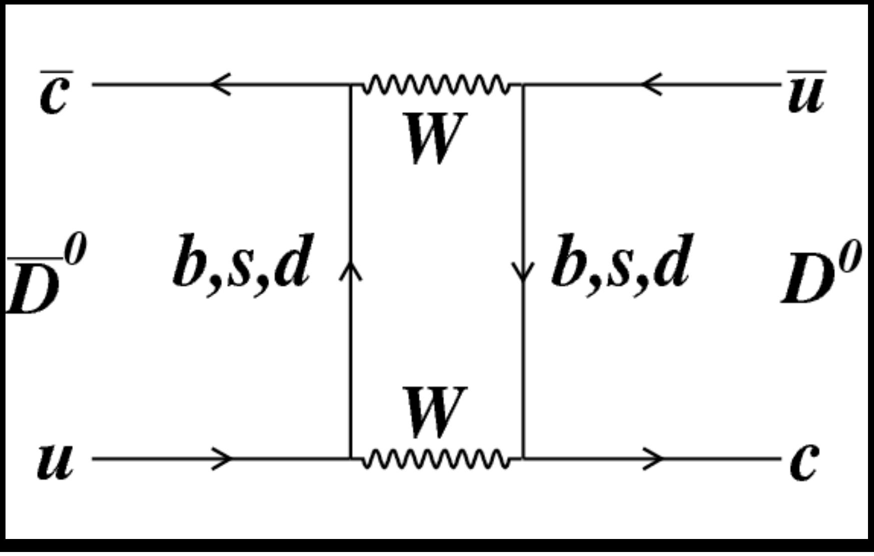
MYSTERY OF MATTER DOMINANCE

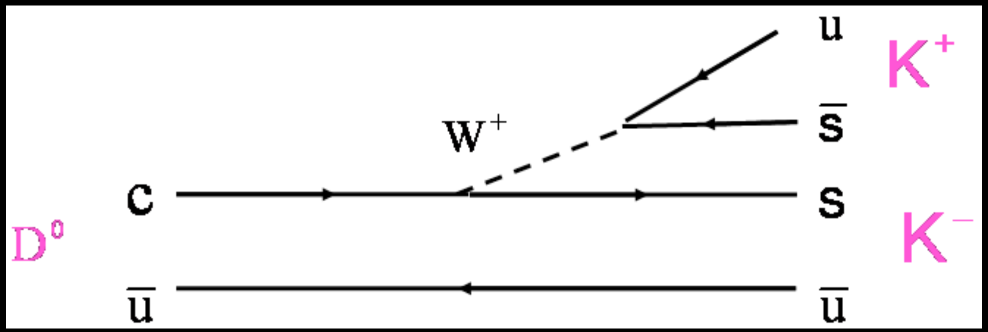
- Sakharov conditions for a baryon generating interaction to produce a matter anti-matter asymmetry
  - Baryon number violation
  - C-symmetry and CP-symmetry violation
  - interactions out of thermal interactions (rate of reaction of B violation is less than expansion rate of the universe)
- The standard model has CP violation in the quark mixing matrix through an irreducible complex phase, orders of magnitude less than needed to explain baryogenesis

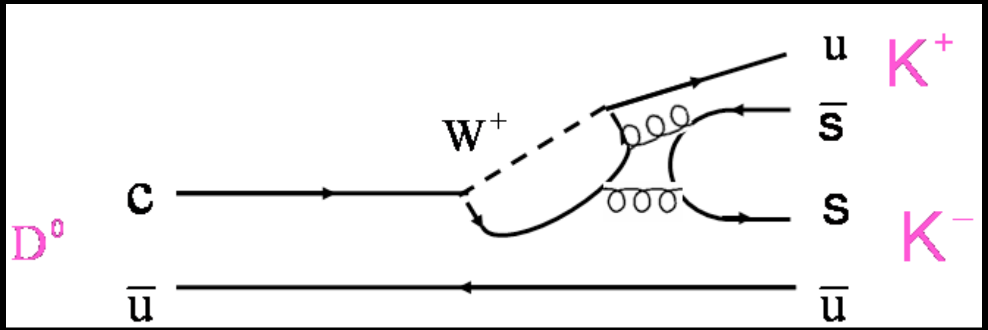
Measurement of indirect CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

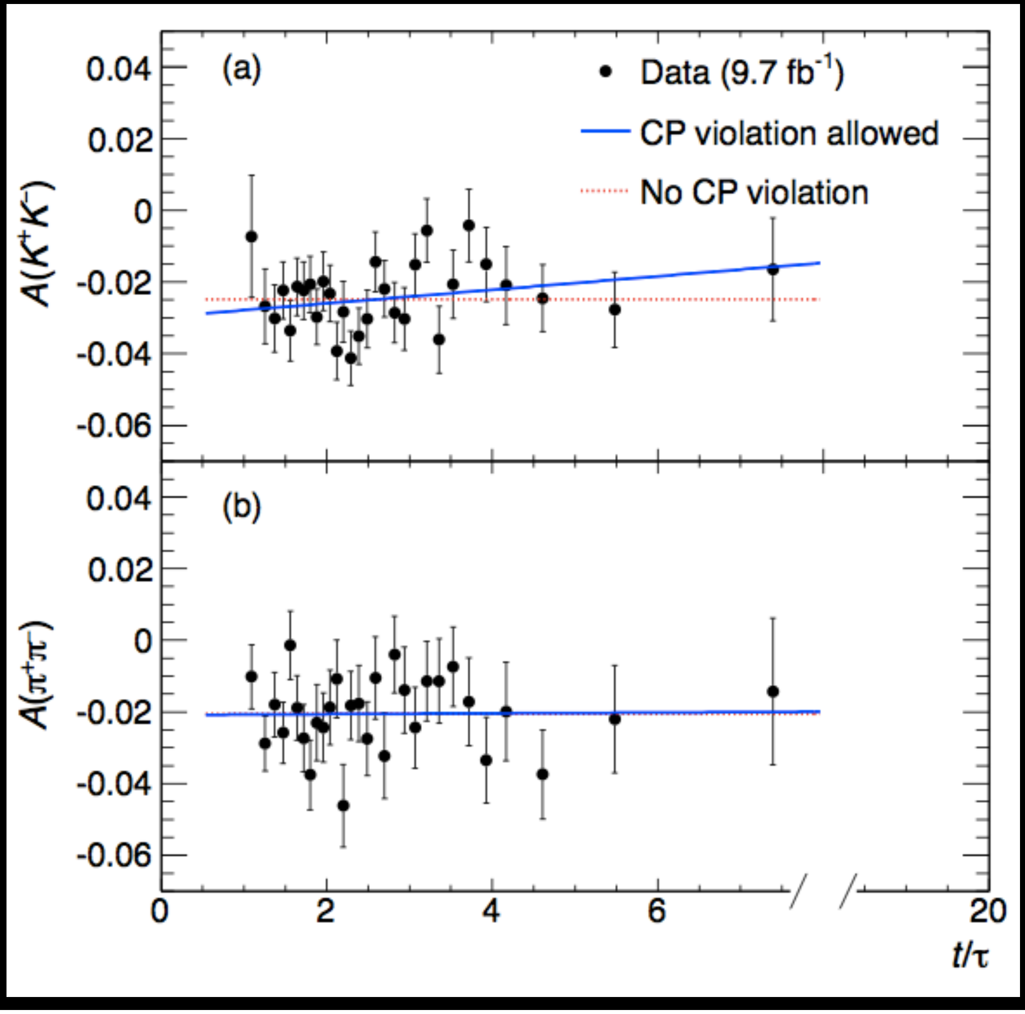
Submitted to: Phys.Rev.Lett.
FERMILAB-PUB-14-429-PPD

- CPV heavily suppressed in charm system
- yet to be observed. Null test of the SM
- Amplitudes can suffer interference from non-SM particles in the loops of mixing and penguin diagrams









$$\mathcal{A}_{CP}(t) = \frac{d\Gamma(D^0 \to h^+h^-)/dt - d\Gamma(\overline{D}^0 \to h^+h^-)/dt}{d\Gamma(D^0 \to h^+h^-)/dt + d\Gamma(\overline{D}^0 \to h^+h^-)/dt}$$

$$\mathcal{A}_{CP}(t) \approx \mathcal{A}_{CP}^{\text{dir}}(h^+h^-) - \frac{t}{\tau}\, A_\Gamma(h^+h^-)$$

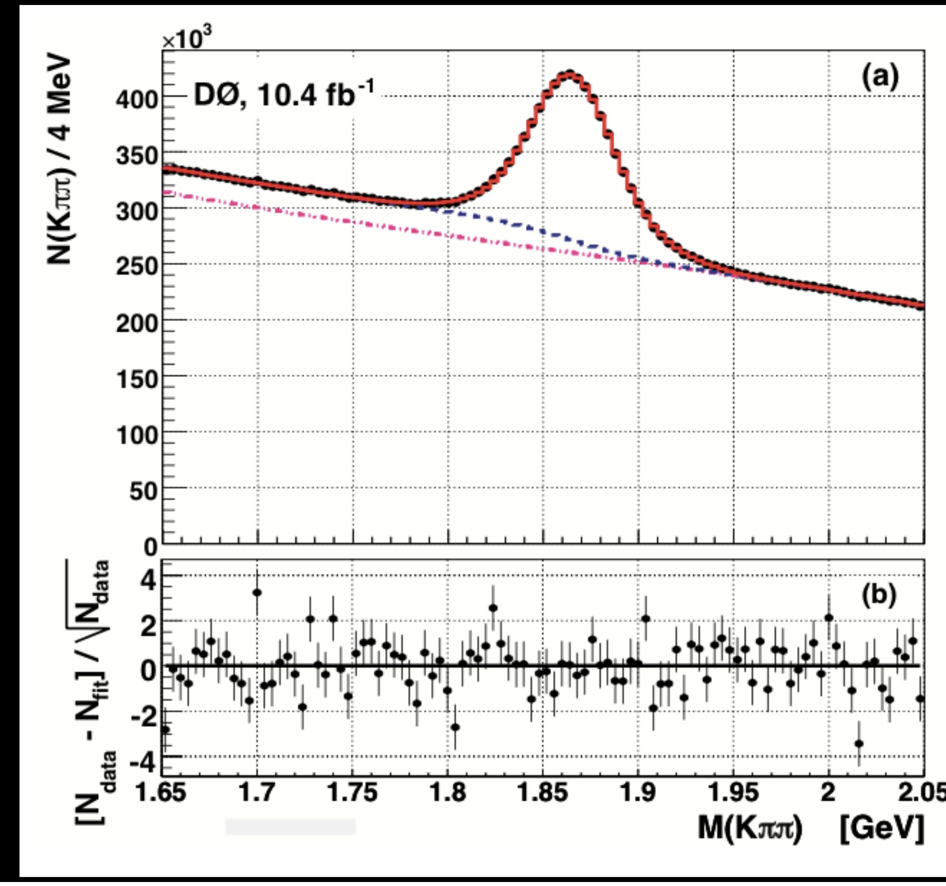
$$A_\Gamma(K^+K^-) = (-0.19 \pm 0.15\ (\text{stat}) \pm 0.04\ (\text{syst}))\%$$
$$A_\Gamma(\pi^+\pi^-) = (-0.01 \pm 0.18\ (\text{stat}) \pm 0.03\ (\text{syst}))\%$$

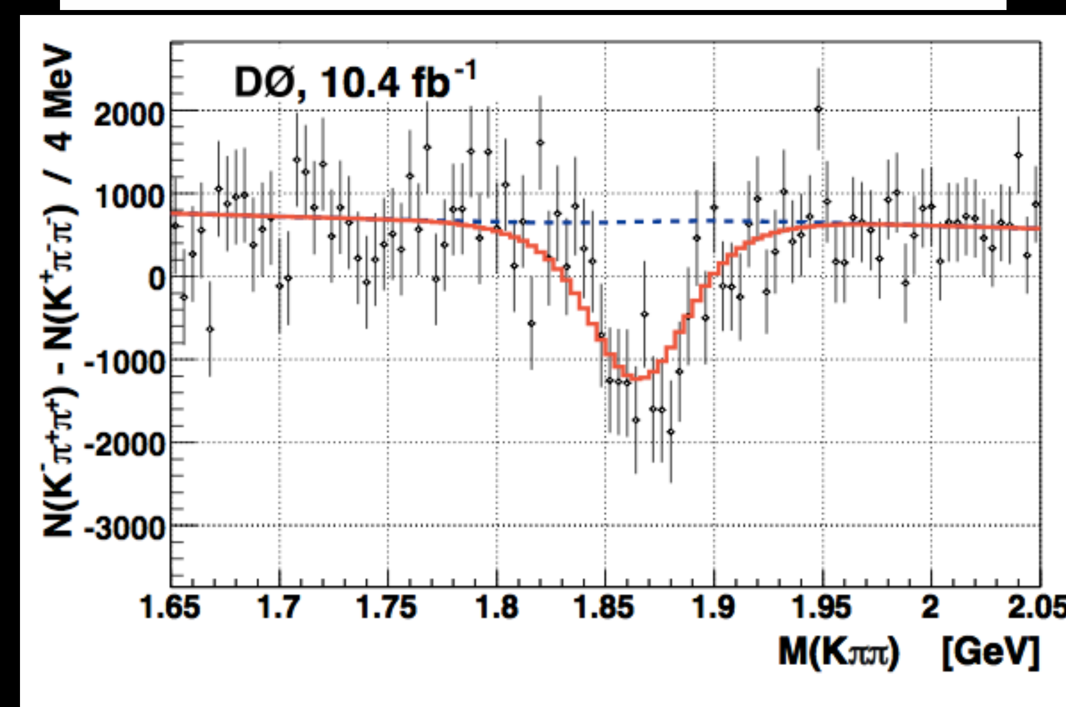
Measurement of the direct CP-violating parameter $A_{CP}(D^+ \to K^-\pi^+\pi^+)$

- Search for direct CP Violation
- SM expectation is 0.

$$A_{CP}(D^+ \to K^-\pi^+\pi^+) = \frac{\Gamma(D^+ \to K^-\pi^+\pi^+) - \Gamma(D^- \to K^+\pi^-\pi^-)}{\Gamma(D^+ \to K^-\pi^+\pi^+) + \Gamma(D^- \to K^+\pi^-\pi^-)}$$

Source	$\sigma_{\mathrm{syst.}}(A_{\mathrm{CP}})$ (%)
Fit range (A)	0.017
Fit model (A)	0.005
Bin width (A)	0.005
Polarity weighting method (A)	0.001
Kaon asymmetry statistics (A_{det})	0.040
Kaon asymmetry method (A_{det})	0.053
Muon asymmetry statistics (A_{det})	0.011
Muon asymmetry method (A_{det})	0.004
Pion asymmetry (A_{det})	0.050
a_{sl}^q (dominates A_{phys})	0.023
Total	0.089





$$A_{CP}(D^+ \to K^-\pi^+\pi^+) = [-0.16 \pm 0.15\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})]\%$$

arXiv:1408.6848, accepted PRD-RC

SUMMARY

- CDF and D0 physicists focus on measurements and are doing exciting physics and publishing at a strong rate
- Precision measurements are leaving of long lasting legacy, e.g. mass of W boson and top quark, are world's best.
- Top pair forward backward asymmetry uniquely probed at the Tevatron.

SEARCH FOR INVISIBLE HIGGS DECAYS

- How does dark matter get its mass? Does it interact with the Higgs boson ?
- Simplest H→invisible is highly suppressed in the SM
- Beyond SM scenarios allow for enhanced rates
- Search in ZH→Z + invisible channel using opposite sign di-muon and di-electron events
- Exclude cross-section values of H→invisible, produced in association with Z→ll, smaller than 90 fb (Mass(Higgs) = 125 GeV)
- CDF/PUB/TOP/PUBLIC/11068

$ZH \to l^+l^-$ + **invisible** (signal region) CDF Run II Preliminary, $\mathcal{L}$=9.1fb^{-1}	
ZZ	27.2 ± 2.9
WW	19.2 ± 1.8
WZ	13.7 ± 1.5
Z+jets	7.1 ± 3.1
W+jets	3.8 ± 0.6
$t\bar{t}$	5.5 ± 0.9
$W\gamma$	0.5 ± 0.1
Total prediction	76.9 ± 7.2
Data	78
ZH ($m_H = 125$ GeV/c^2)	8.2 ± 1.3