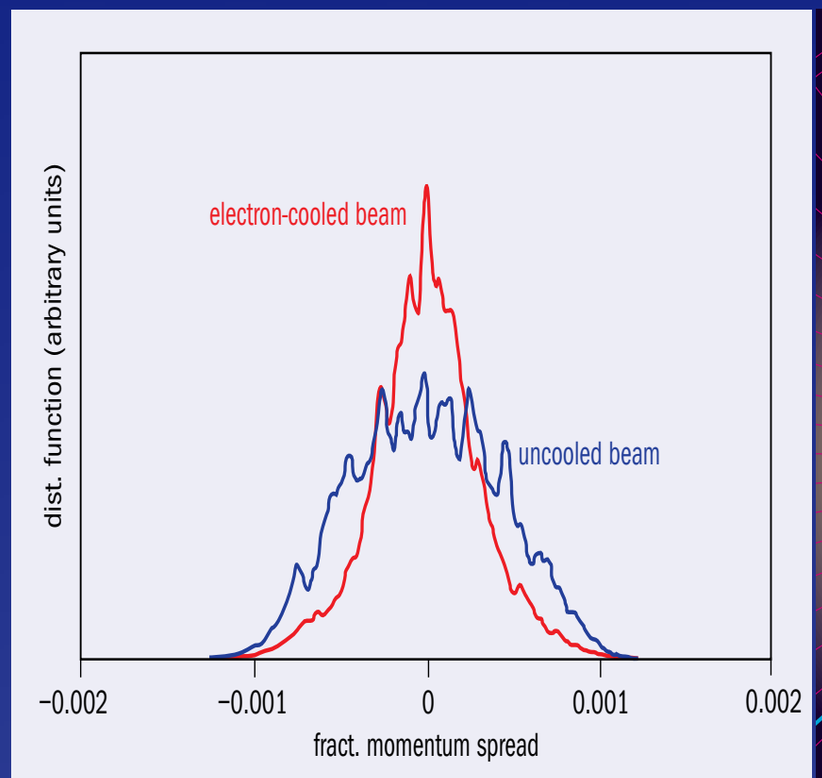
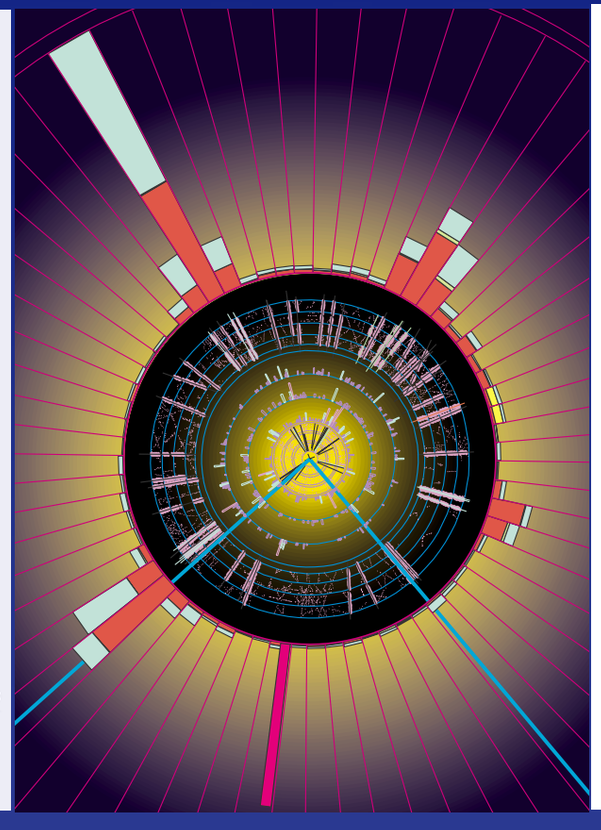
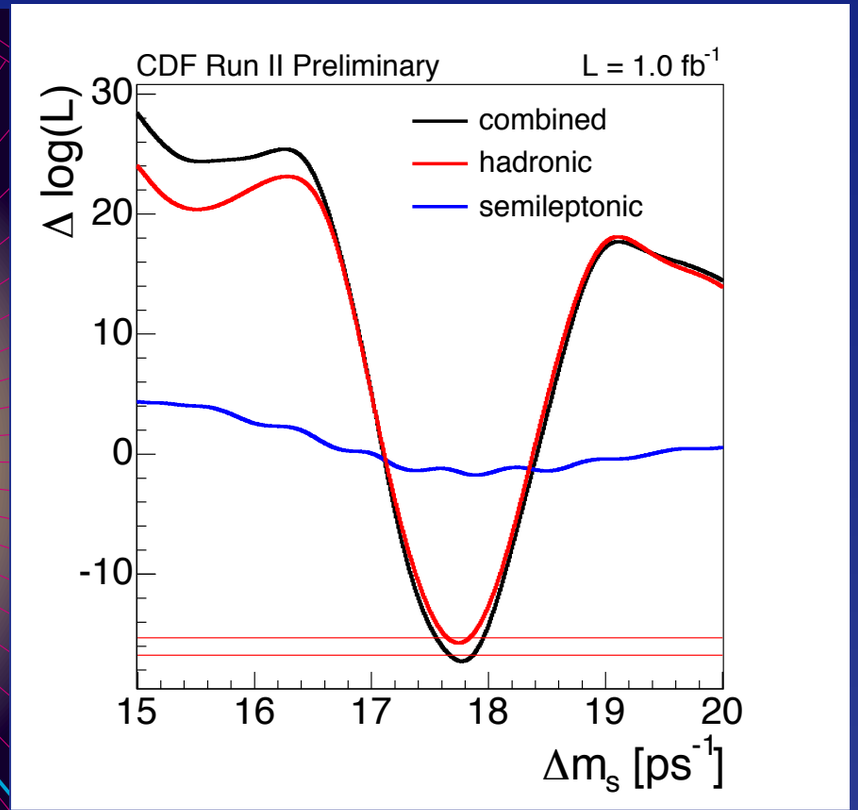
A Tevatron Collider Retrospective

Chris Quigg

Fermi National Accelerator Laboratory







HEPAP · Washington · 27 October 2011

Fermilab Tevatron · 1983–2011

First high-energy superconducting synchrotron
Model for HERA ($e^{\pm}p$) proton ring
Key milestone toward Large Hadron Collider

>5 Wilson Prizes

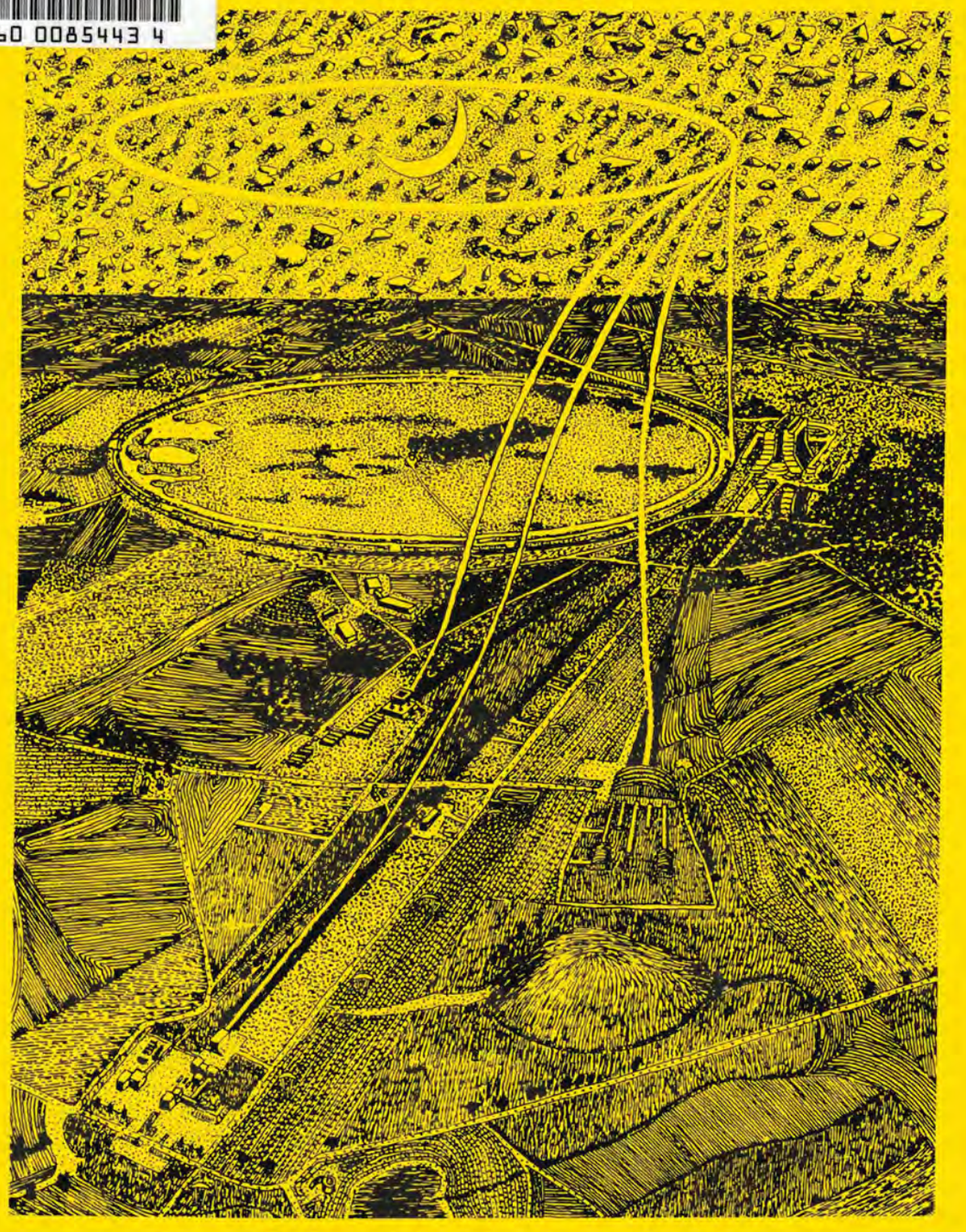
4 National Medals of Technology

2 July 1983: 512-GeV protons

800-GeV Fixed-target experiments, 1984–2000

Symposium in Celebration of the

Fixed Target Program with the Tevatron



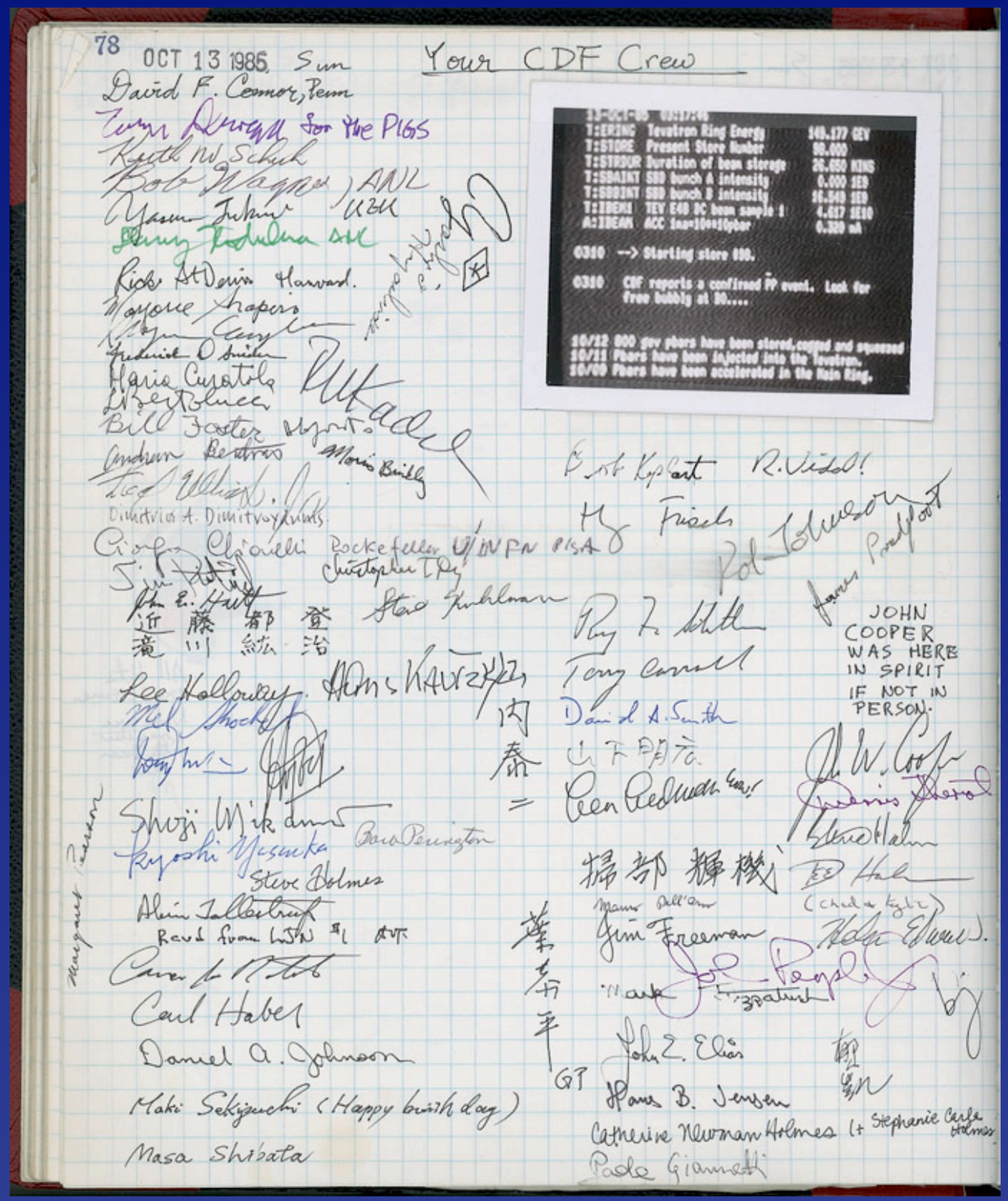
Fermi National Accelerator Laboratory

June 2, 2000

Tevatron proton-antiproton collider

Antiproton source

First 1.6-TeV collisions · 13 October 1985, 02:32



$$\mathcal{L} \approx 2 \times 10^{25}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Run 493 Event 11 FILE NONE 13-OCT-1985 02:32

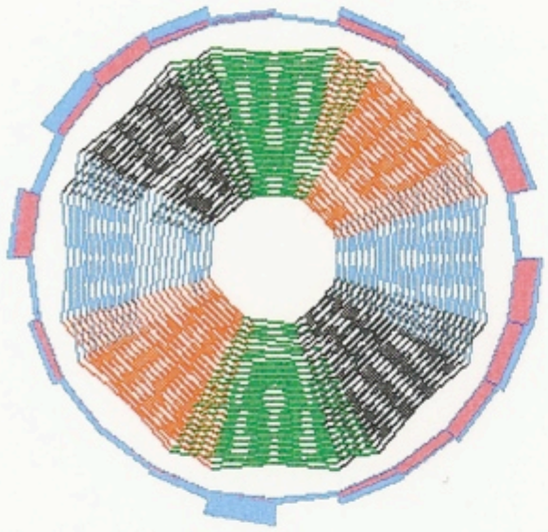
CDF

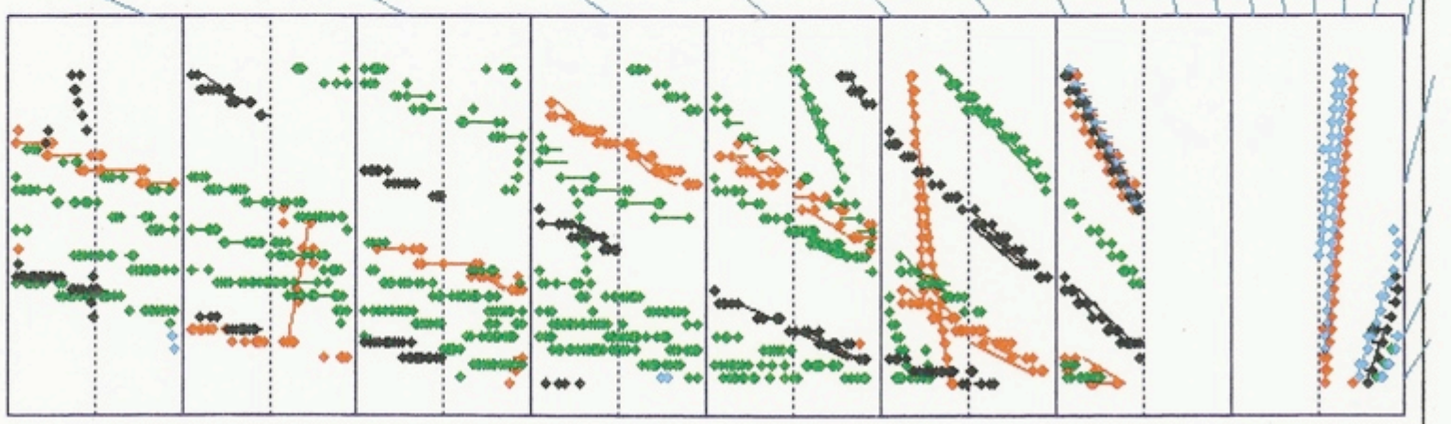
Max energy = 2.4 GeV

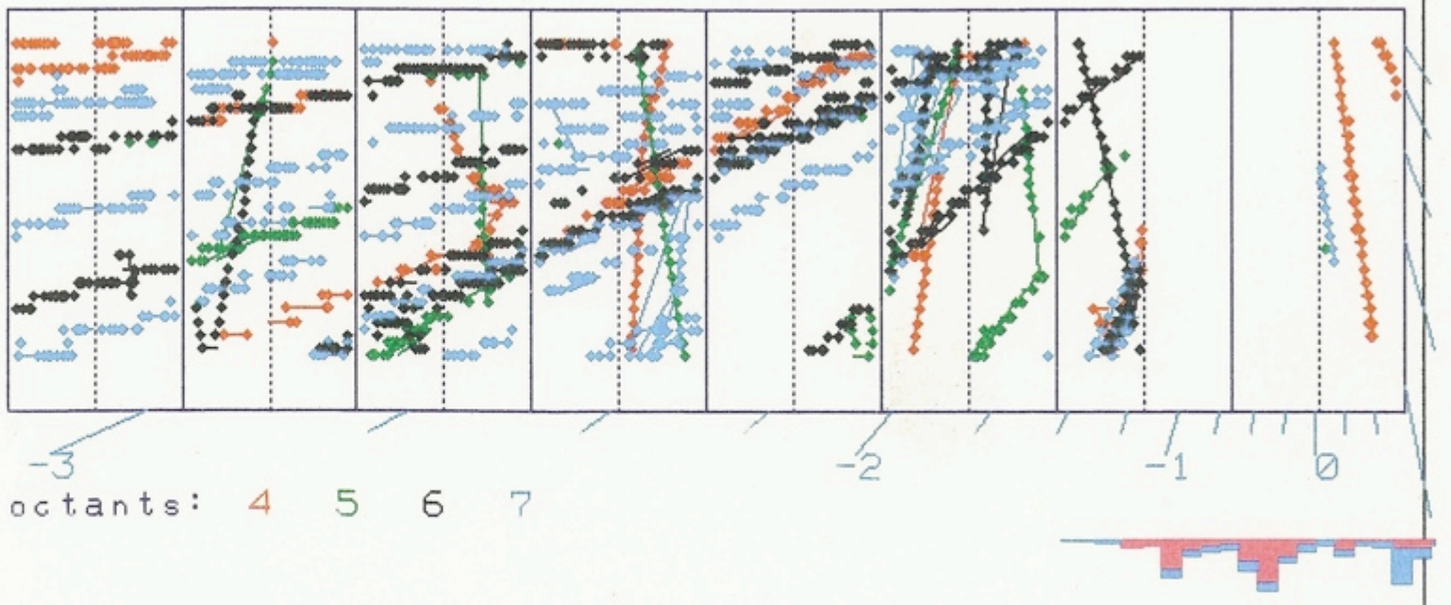
octants: 0 1 2 3

-3 -2 -1 0

Emax = 3.0 GeV







-3 -2 -1 0

octants: 4 5 6 7

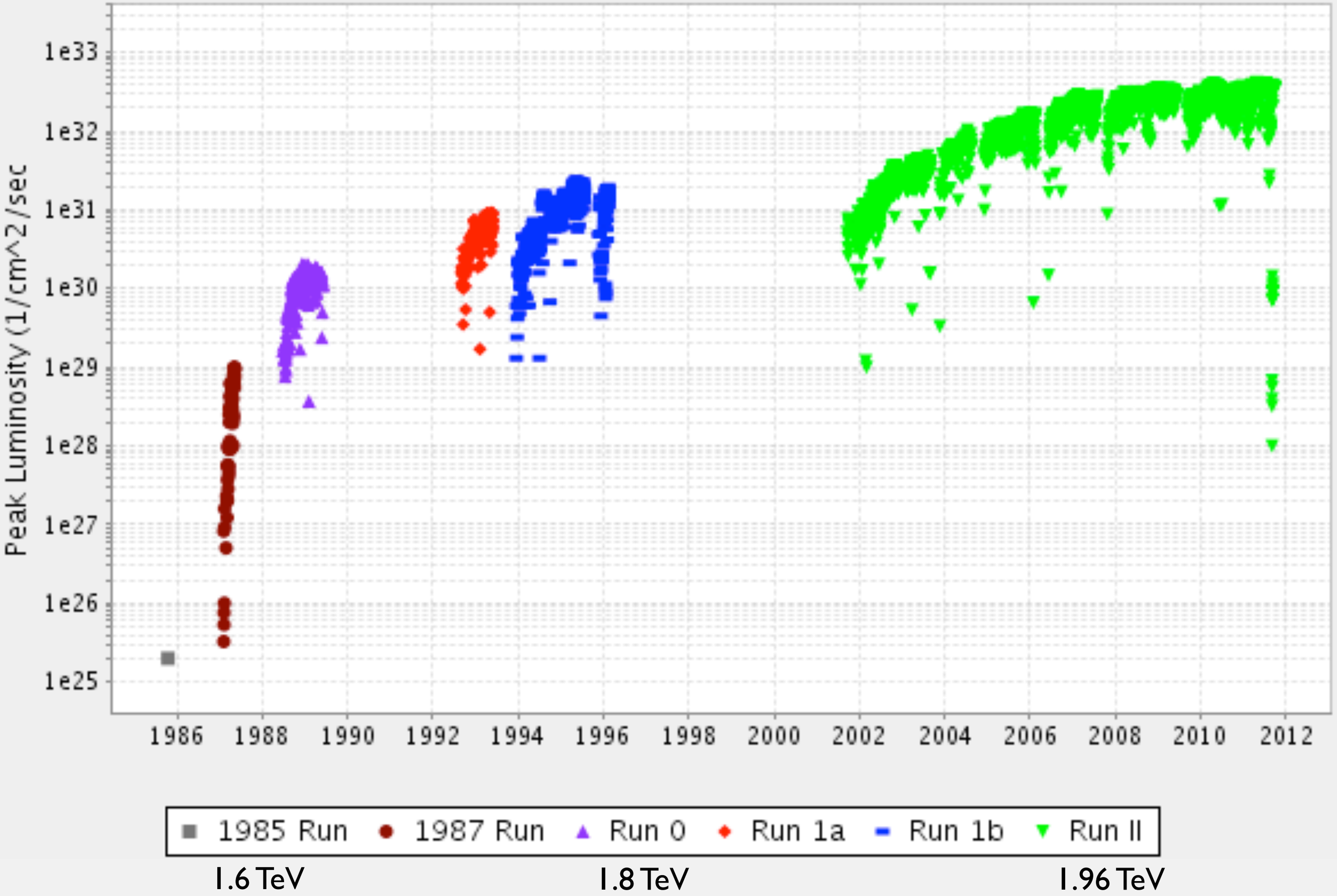
During final months of operation at 1.96 TeV

Typical $\mathcal{L} > 3.5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Peak $\mathcal{L} = 4.3 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

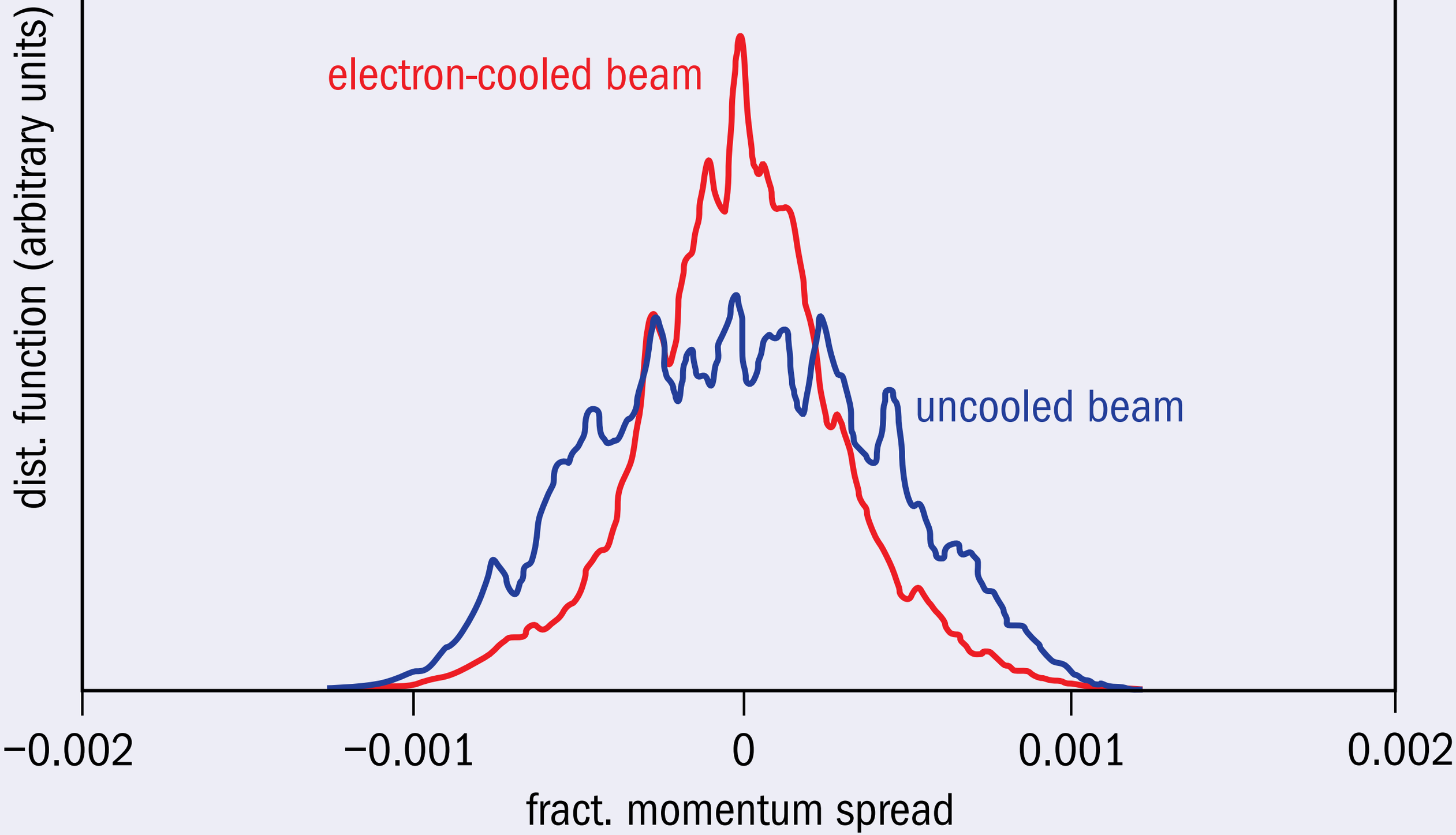
12 fb^{-1} delivered, 10+ fb^{-1} recorded

Tevatron Collider Luminosity




EXIT

Electron cooling in the Recycler



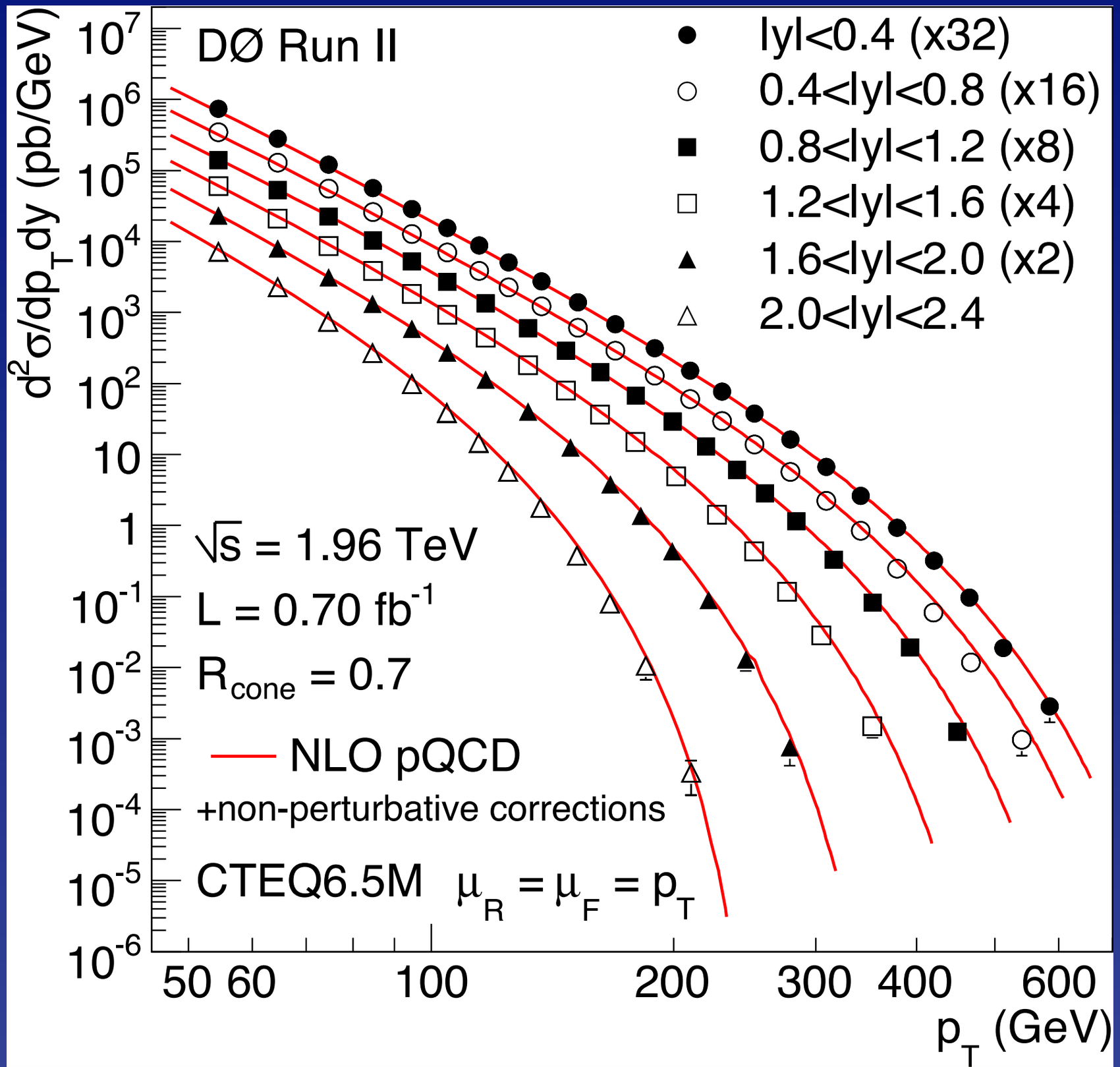
CDF & D0 Highlights

Top quark discovery
Exacting measurements: m_t, M_W, B_s oscillations

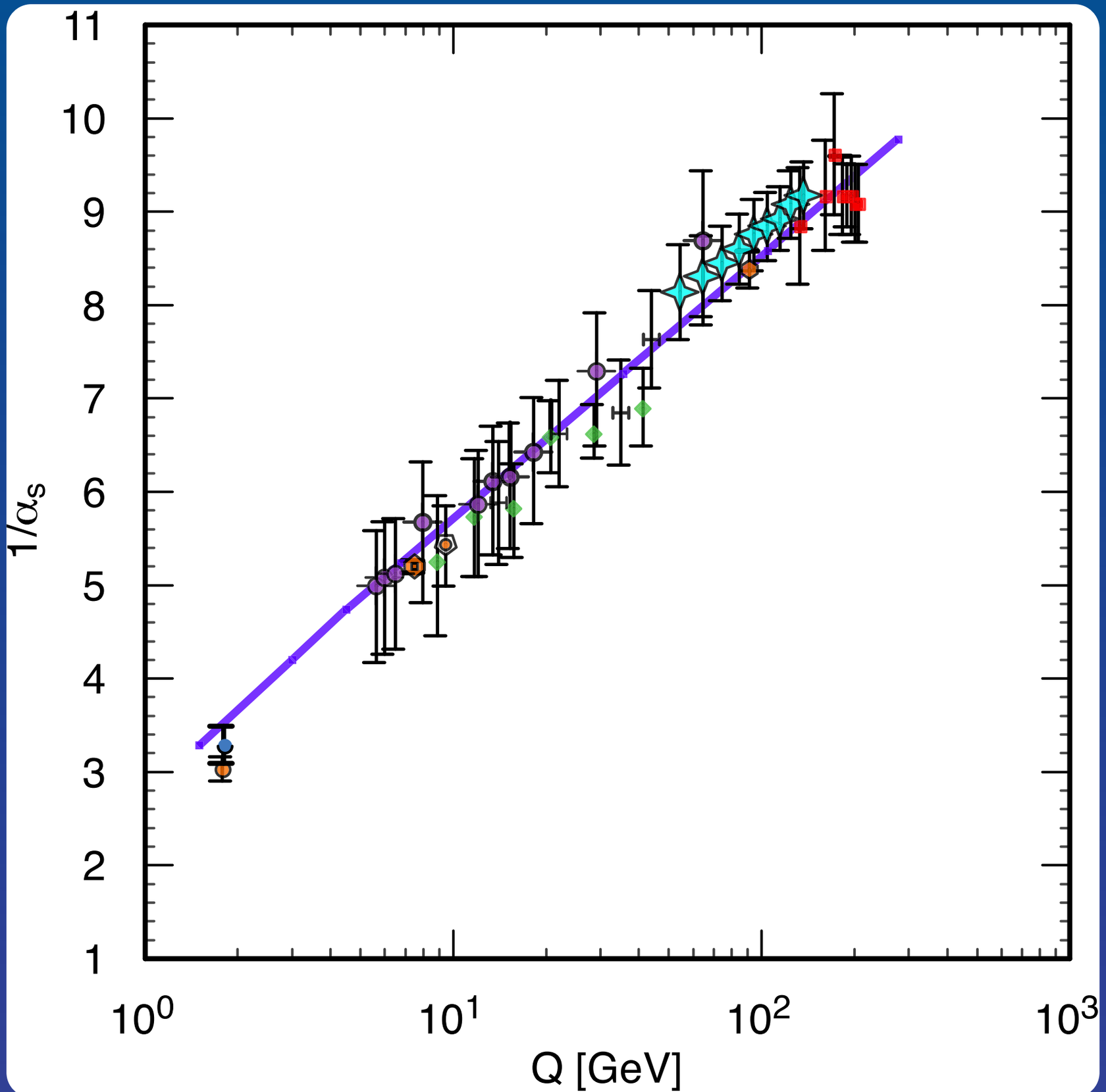
Innovations in technique
Silicon vertex detector in hadron collider
LAr-^{238}U calorimetry
Secondary vertex trigger · multilevel triggering
Multivariate analysis techniques
Mining petabyte data sets

Scientific interests and capabilities expand and deepen
respond to new opportunities
deliver a harvest of results not imagined at the start

Quantum Chromodynamics



Evolution of the strong coupling



Angular distribution of dijet production confirms Rutherford-scattering-like expectation of QCD

Quarks are pointlike and structureless at resolution of nearly 1/(3 TeV)

Dijet mass spectrum extends beyond 1.2 TeV with no evidence for unexpected resonances

Electroweak Physics

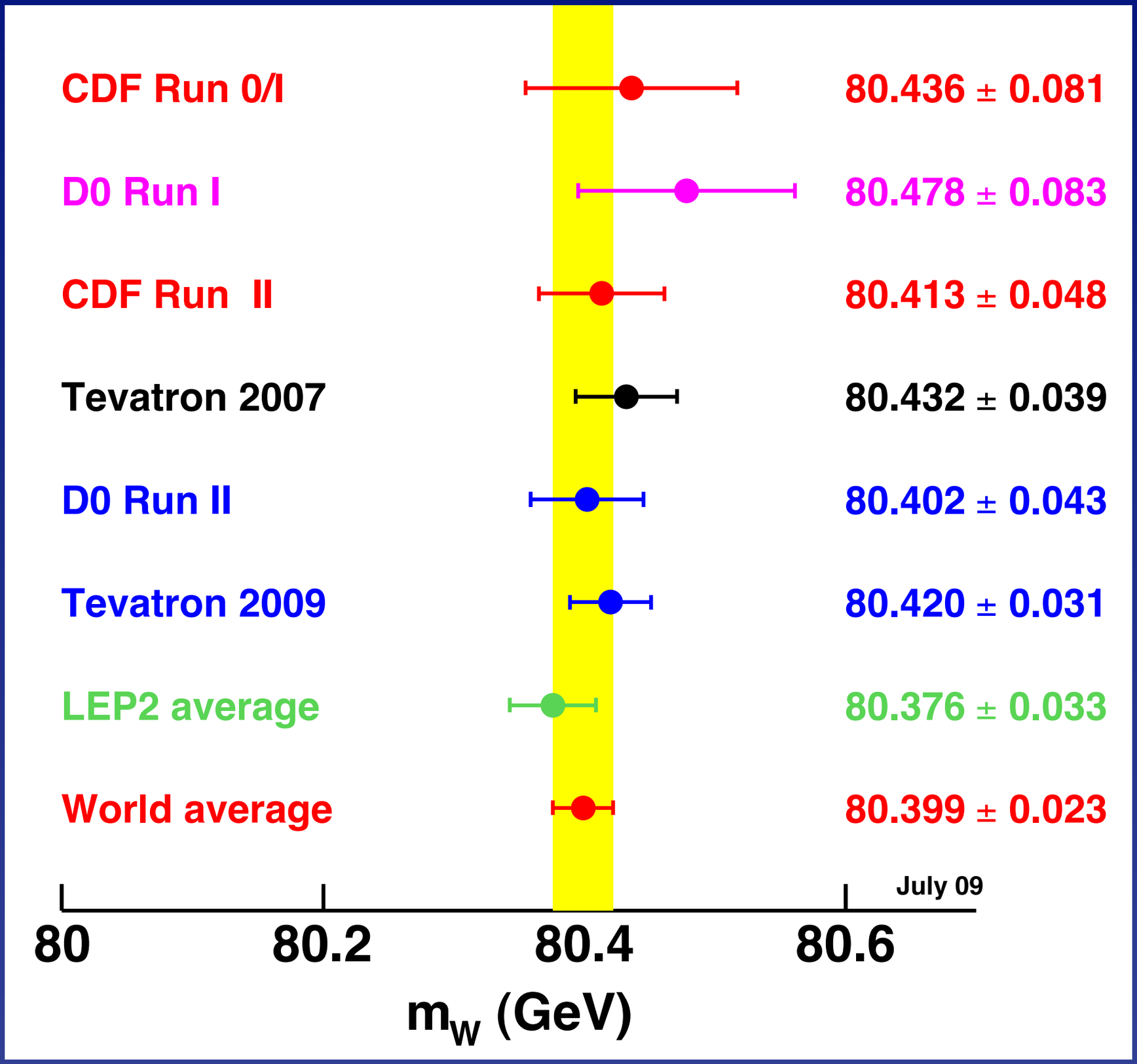
Each experiment expects $O(10^7)$ W bosons and 400K Z bosons in each leptonic decay channel.

Production cross sections agree with QCD; possible primary luminosity monitor for LHC experiments.

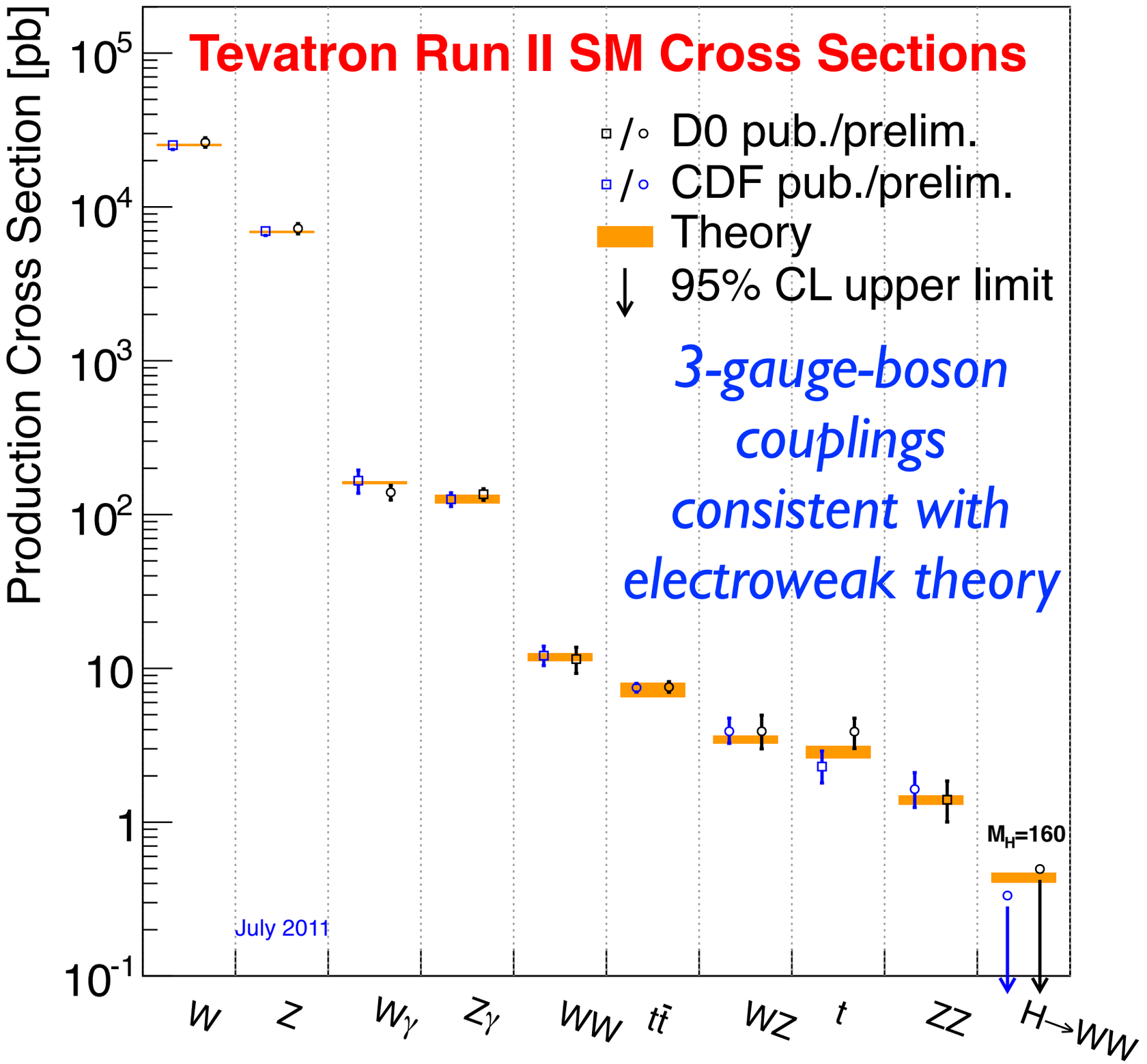
Z (+ jets) production tests standard-model simulations.

Forward-backward asymmetry of leptons produced in W decay provides important information about the up-quark and down-quark parton distribution functions.

W mass: aim for ±15 MeV Tevatron combined



$\sigma B < 0.1$ pb


Tevatron Run II SM Cross Sections
Production Cross Section [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
D0 pub./prelim.
CDF pub./prelim.
Theory
95% CL upper limit
3-gauge-boson couplings consistent with electroweak theory
M_H=160
July 2011
W
Z
$W\gamma$
$Z\gamma$
WW
$t\bar{t}$
WZ
t
ZZ
$H\rightarrow WW$

Heavy flavors

Production and decay of quarkonium states

Measurements of *b*- and *t*-quark production

B_c mass and lifetime

Masses and lifetimes of *B* mesons and baryons

Unique source of information on many *B*-baryons

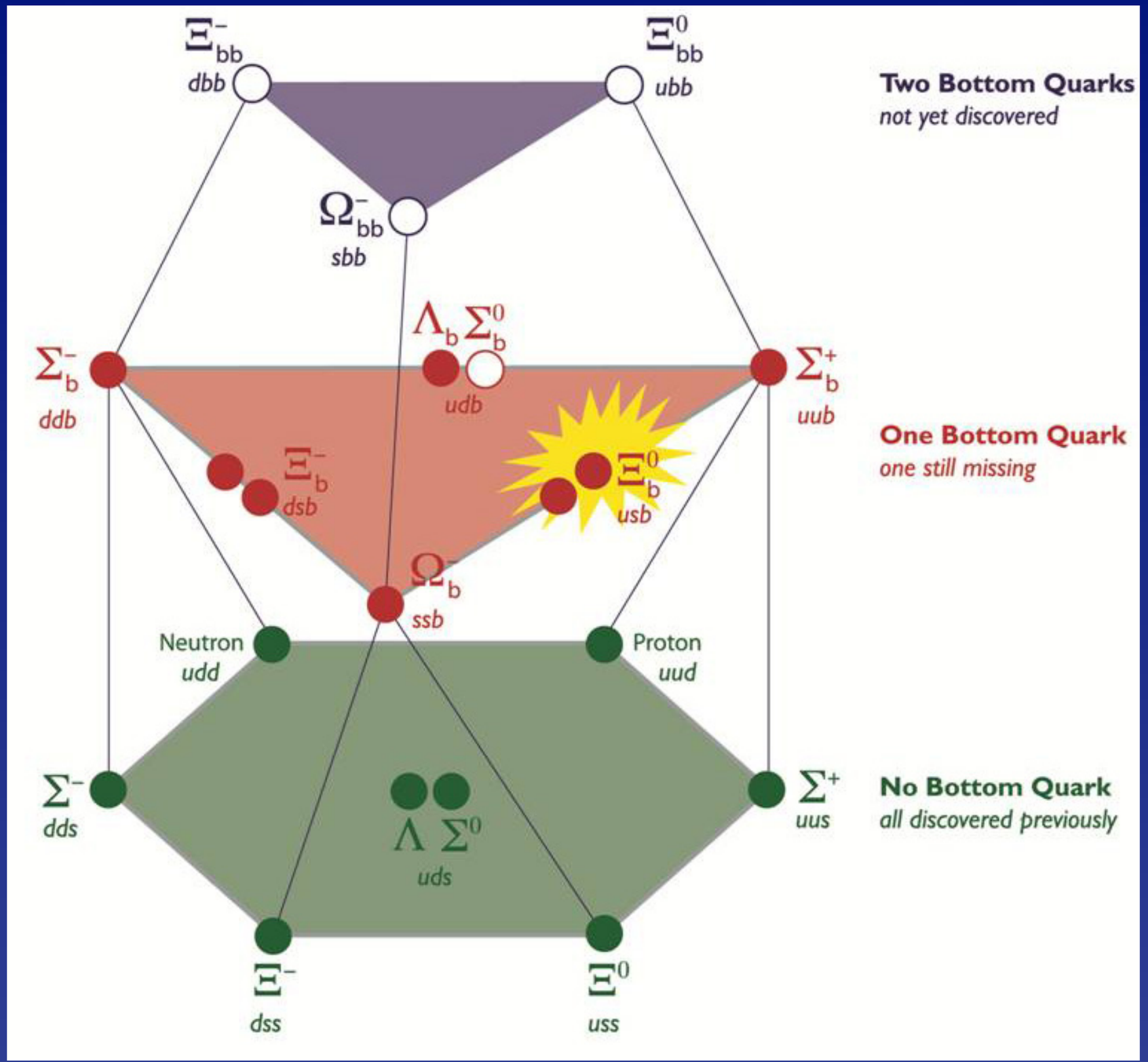
Orbitally excited *B* and B_s mesons

X(3872) mass and quantum numbers

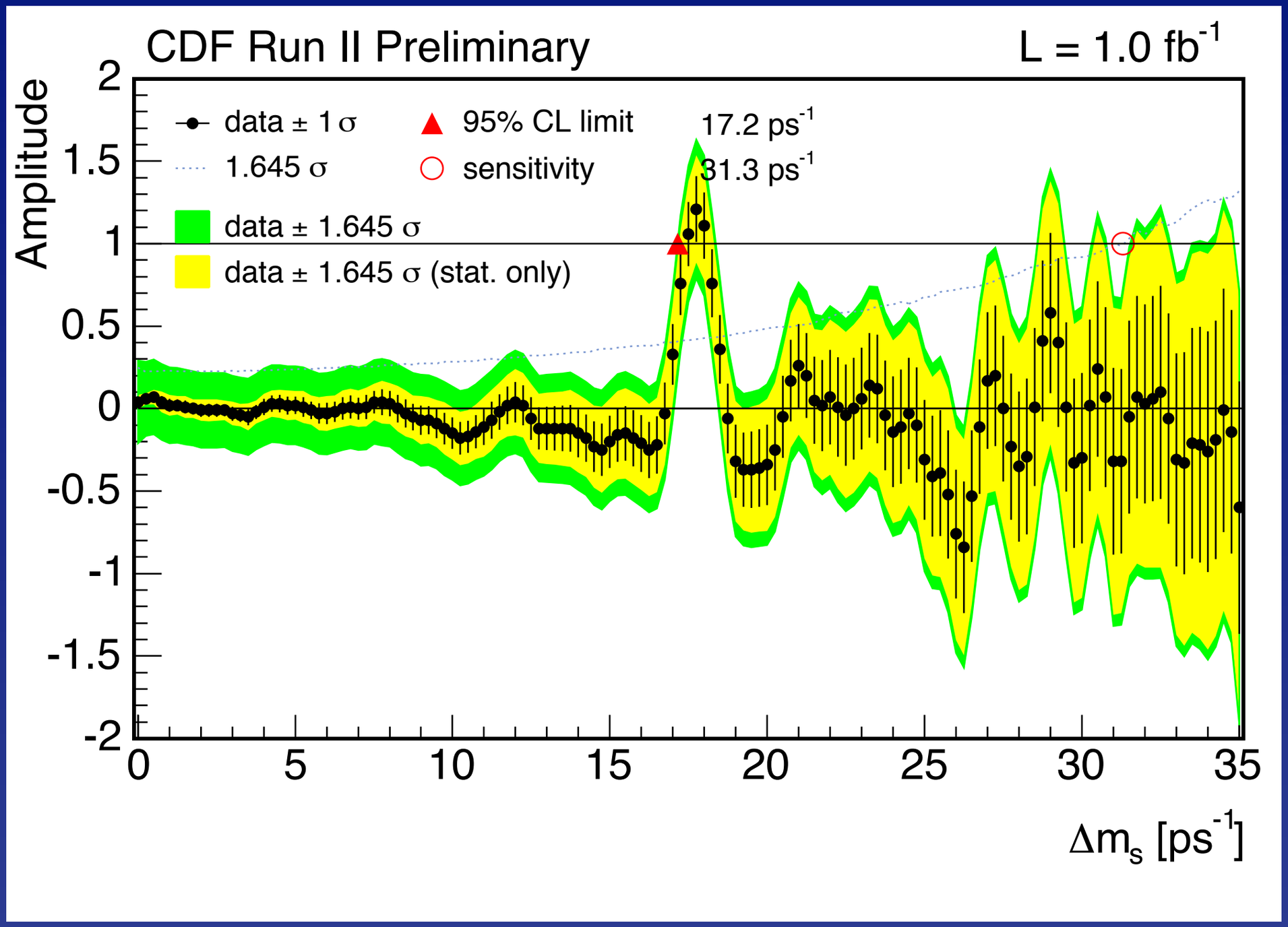
Important evidence on D^0 mixing

Precise CP asymmetries for $D^0 \to \pi^+\pi^-$, $B^+ \to J/\psi K^+$

High-sensitivity searches for rare dimuon decays


Ξ_{bb}^{-}
dbb
Ξ_{bb}^{0}
ubb
Ω_{bb}^{-}
sbb
Λ_b Σ_b^0
udb
Σ_b^{-}
ddb
Σ_b^{+}
uub
Ξ_b^{-}
dsb
Ξ_b^{0}
usb
Ω_b^{-}
ssb
Neutron
udd
Proton
uud
Σ^{-}
dds
Λ Σ^0
uds
Σ^{+}
uus
Ξ^{-}
dss
Ξ^{0}
uss
Two Bottom Quarks
not yet discovered
One Bottom Quark
one still missing
No Bottom Quark
all discovered previously

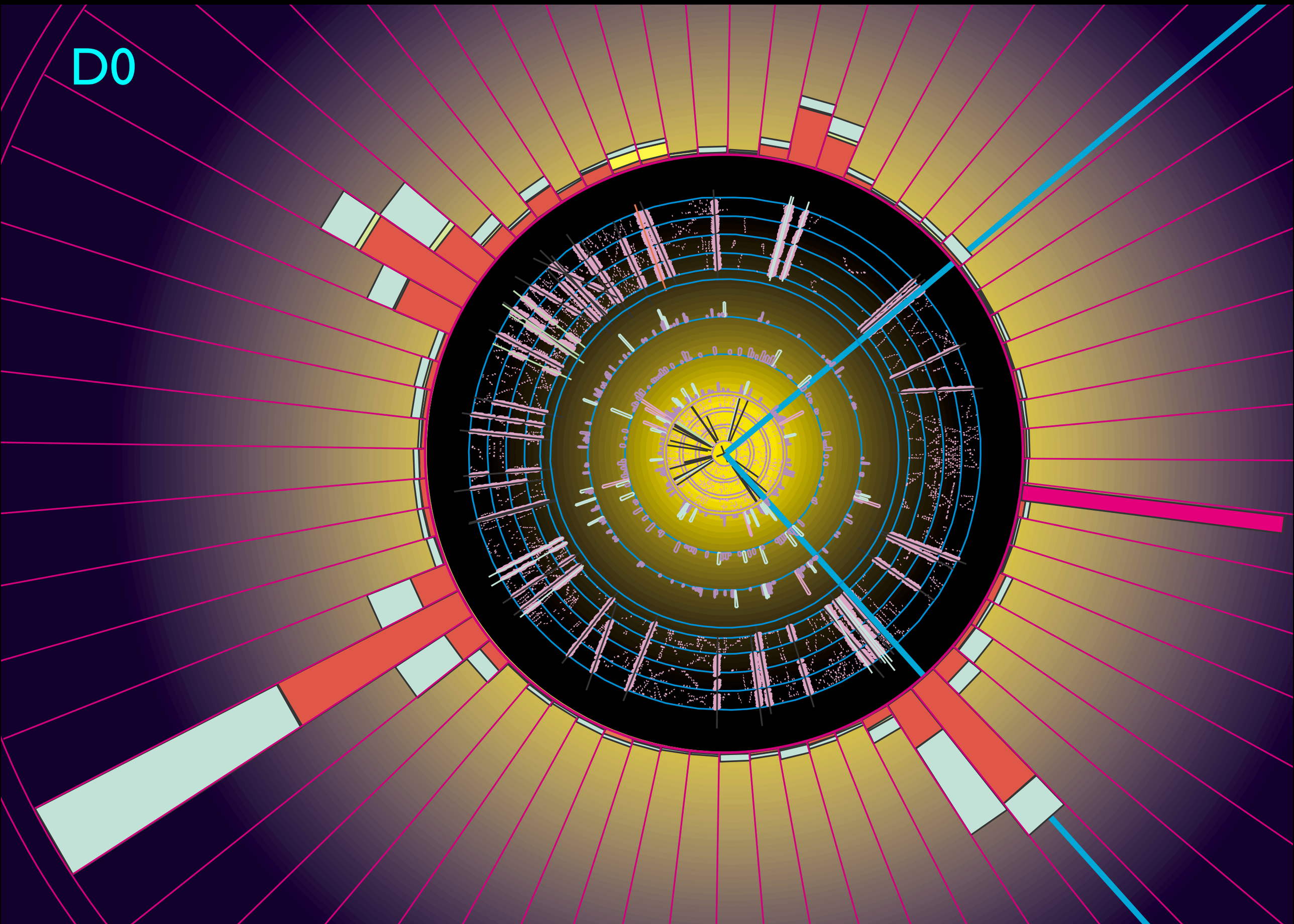
Frequency of B_s oscillations

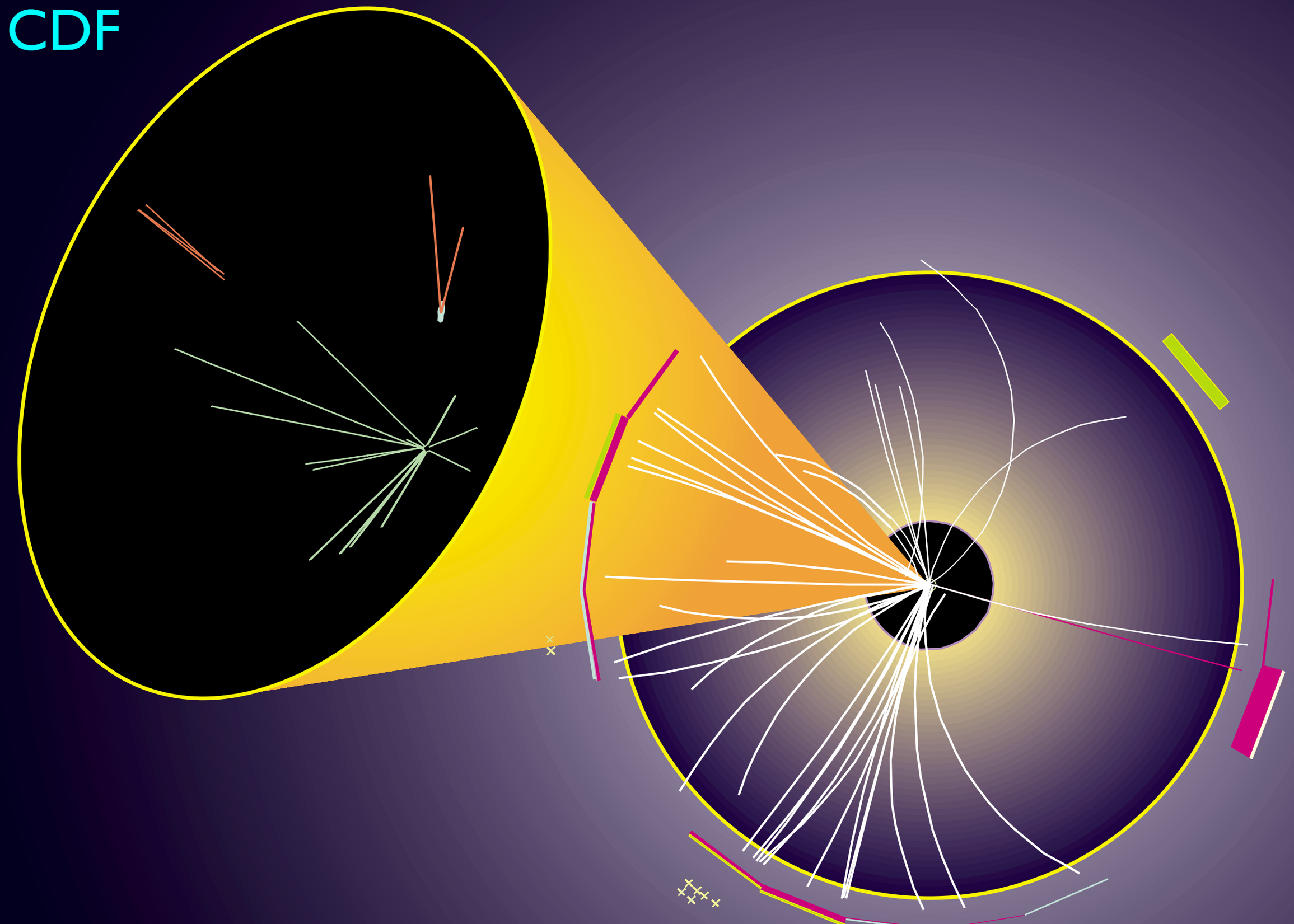


$\Delta m_s = 17.77 \pm 0.13\ \text{ps}^{-1}$

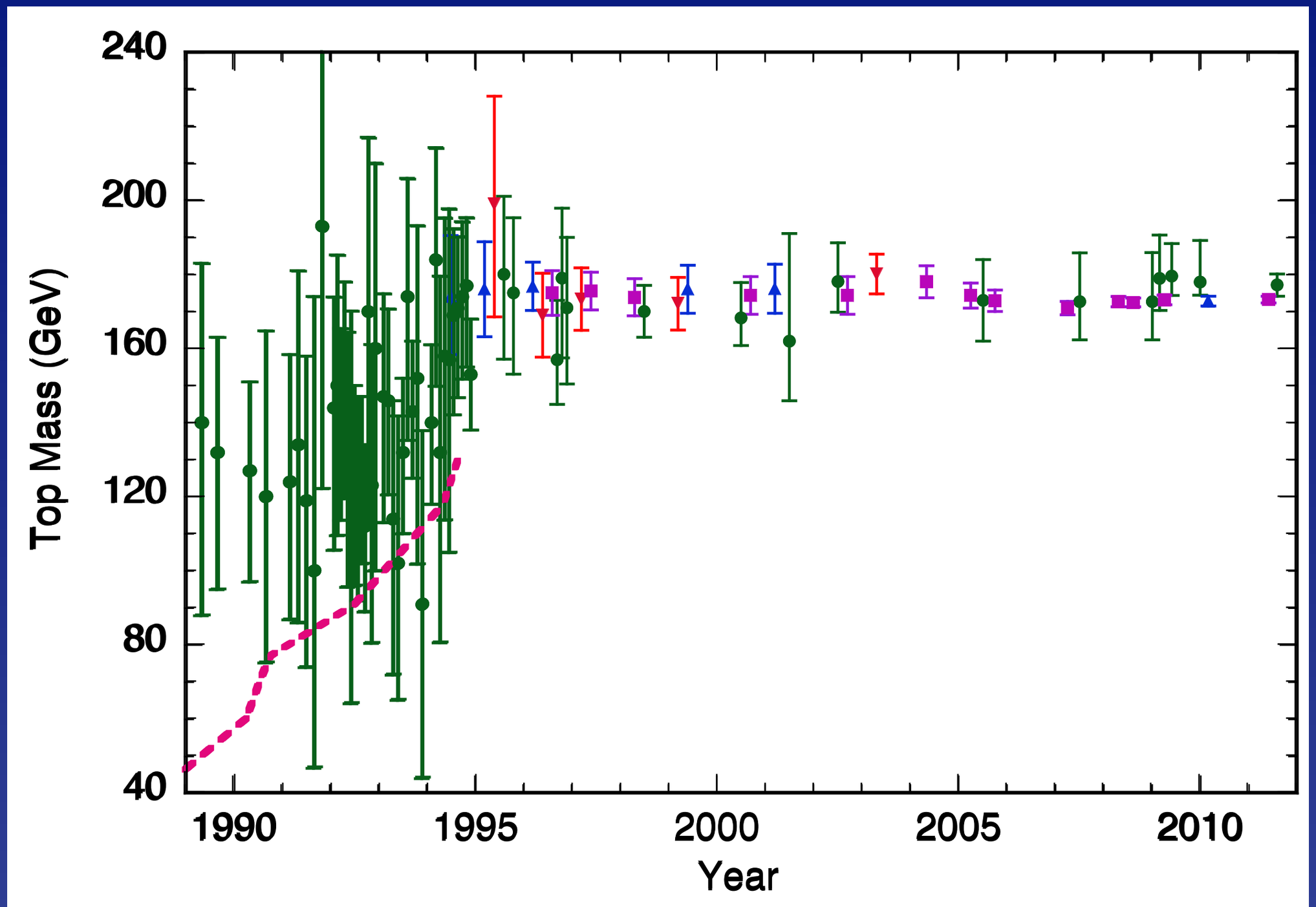
1995


Researchers announce 'top quark' discovery
Cultura e Spettacoli
Dove vai, cacciatore di quark?
Batavia is center of universe
Alles Quark, oder was?
I predatori del quark perduto
For physicists, last piece of a puzzle
Nation
RICERCA ITALIANA
EPPUR SI MUOVE
Truth by Consensus
Tajemniczy szósty kwark
AUJOURD'HUI
Quand les particules livreront leur dernier secret
Physicists Weigh In: The Quark Is a Porker
Kwark T – najdziwniejszy z osobliwej rodziny
tuttoscienze
LES BRICOLAGES DE LA VIE
Ora la fisica è al Top
Fine del viaggio al centro della materia
Topquark-jagers eindigen ex aequo

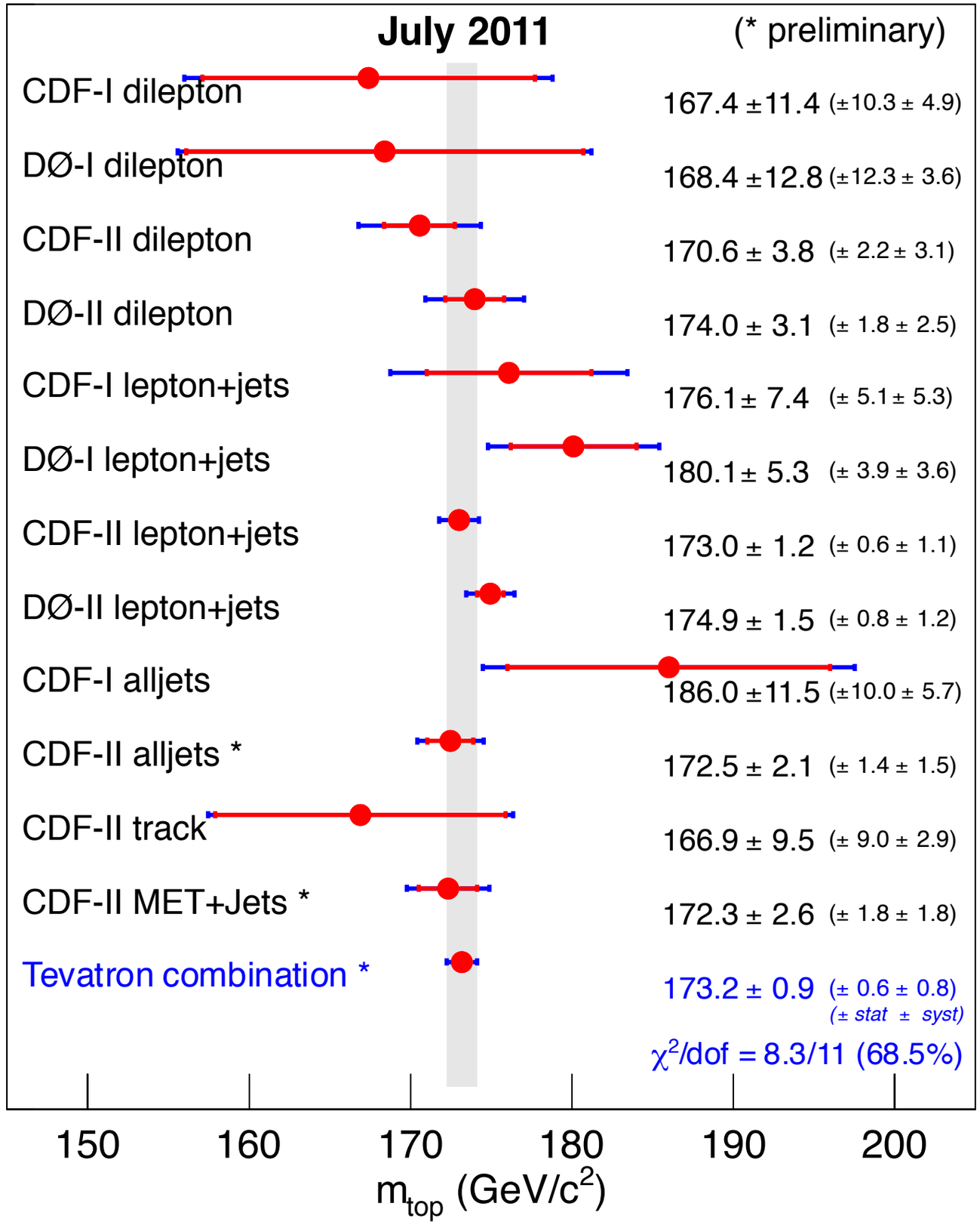

D0

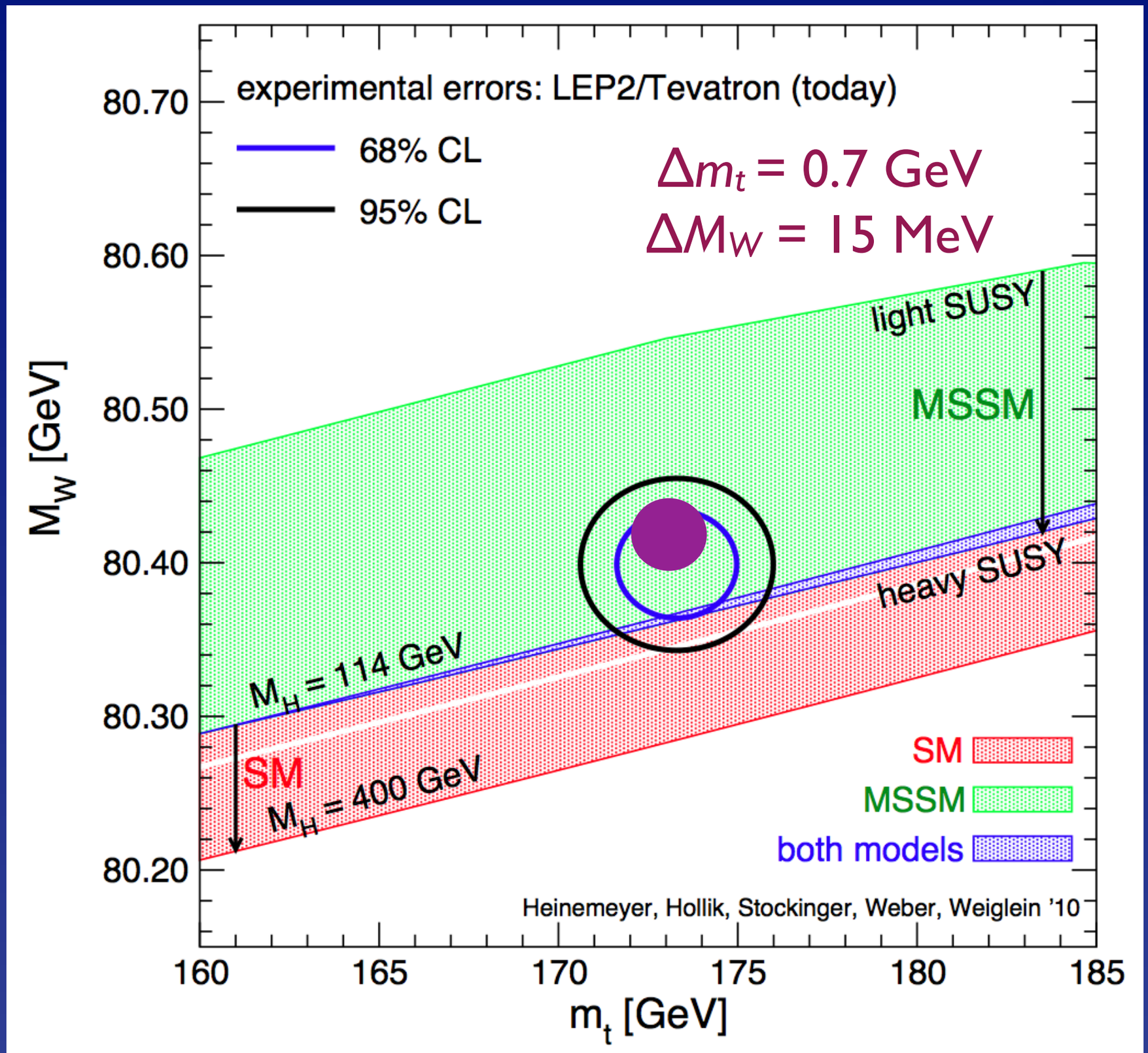

CDF

Top mass in the electroweak theory



Mass of the Top Quark




experimental errors: LEP2/Tevatron (today)
68% CL
95% CL
Δm_t = 0.7 GeV
ΔM_W = 15 MeV
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
M_H = 400 GeV
SM
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '10
M_W [GeV]
m_t [GeV]
80.70
80.60
80.50
80.40
80.30
80.20
160
165
170
175
180
185

Top as a tool

Top pair production in agreement with QCD

No top pair resonances seen

Top-quark charge = +2/3

70% of the *W* bosons emitted in top decay are longitudinally polarized, rest left-handed

Electroweak single top production observed

Lifetime close to 0.3 yoctosecond

Spin correlations accord with standard model

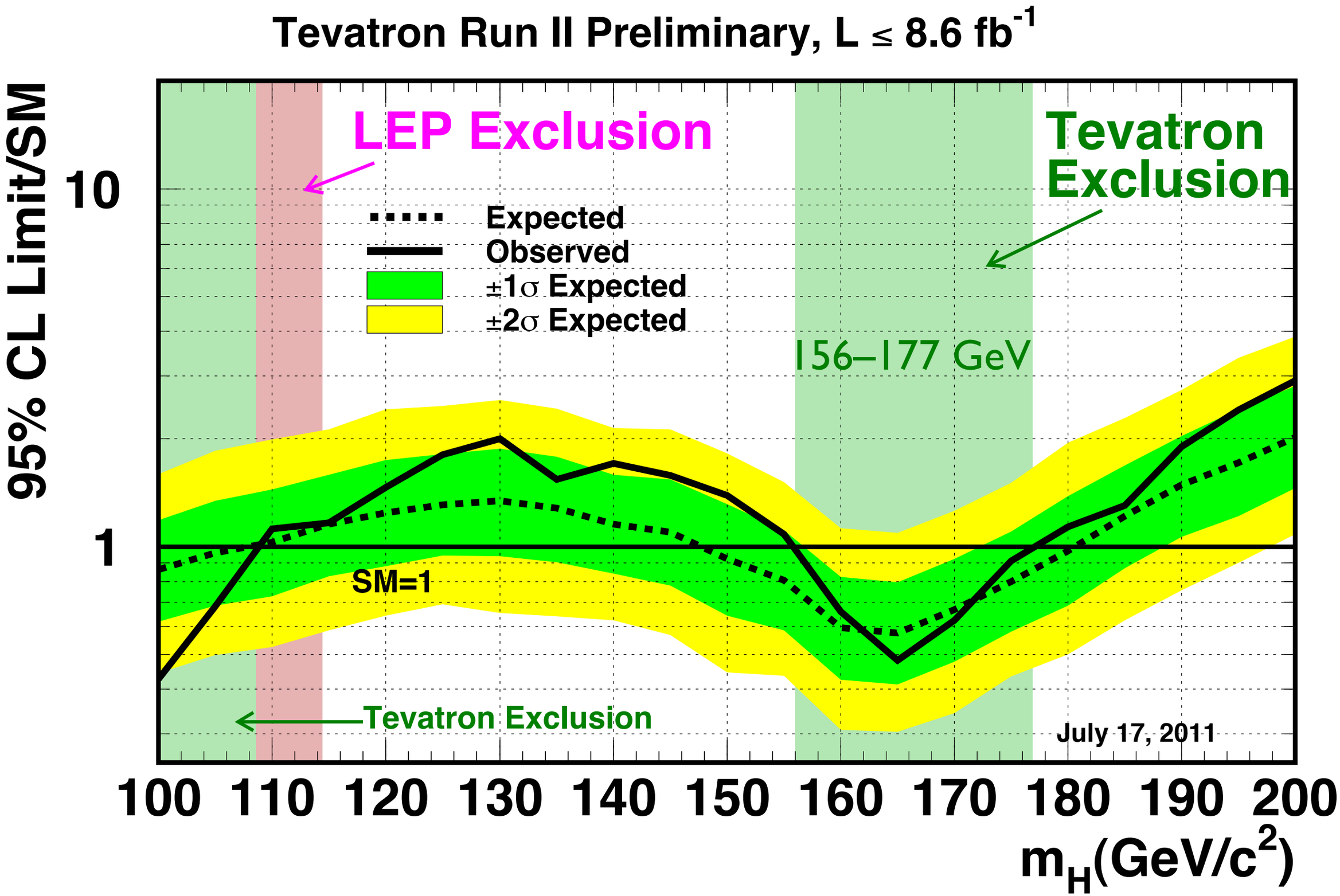
Standard-model Higgs boson search

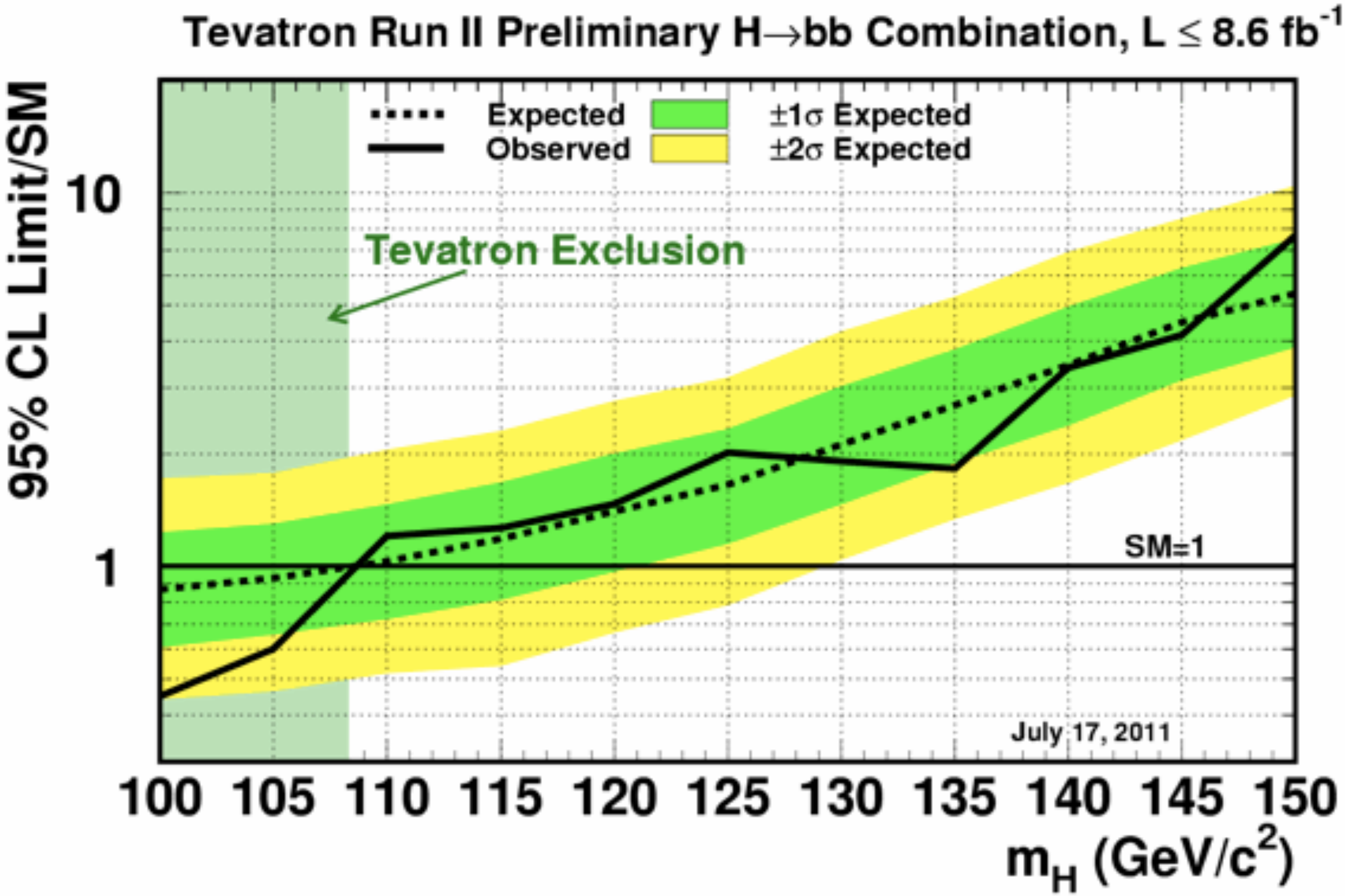
The ultimate challenge for the Tevatron

$gg \rightarrow H \cdot H(W \text{ or } Z) \cdot W \rightarrow H$

dozens of distinct final states

Search for standard-model Higgs boson




Tevatron Run II Preliminary H→bb Combination, L ≤ 8.6 fb-1
95% CL Limit/SM
10
1
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron Exclusion
SM=1
July 17, 2011
100 105 110 115 120 125 130 135 140 145 150
mH (GeV/c2)

Higgs boson: 10 fb^{-1} projections

95% CL exclusion for $M_H < 185$ GeV

3σ "evidence" possible for

$M_H < 120$ GeV

$150 \text{ GeV} < M_H < 175$ GeV

Diverse searches for new phenomena

Limits on

supersymmetric particles

extra spatial dimensions

signs of new strong dynamics

leptoquarks

new gauge bosons

magnetic monopoles

…

Tevatron experiments did not find what is not there

Some observations do not match expectations

Forward-backward asymmetry in top pairs (CDF+D0)

Anomalous like-sign charge asymmetry in b pairs (D0)

Excess of jet pairs + W (CDF–D0)

Work in progress at Tevatron and LHC

One week of special runs at 300 and 900 GeV

Primary physics goals include

Min Bias: multiplicity distributions, charged particle pseudorapidity densities, mean p_t, …

Central exclusive hadron production

Underlying event studies

Collected

300 GeV: 12M min bias, 9.2M diffractive, 1.8M zero-bias events. *D0: 2.2M events*

900 GeV: 54M min bias, 21M diffractive, 8M zero-bias events. *D0: 20M events*

Still to come …

- Higgs
  - Searches in all channels
  - Exclusion in the full 115-185 GeV mass range, if Higgs does not exist
  - Results of precision measurements of backgrounds, including W+jets(including b-jets), ttbar cross sections, di-boson production, etc.
- Top quark
  - Precision measurement of top quark mass with below 1 GeV precision
  - Precision measurement of top/anti-top quarks mass difference
  - Measurements of top quark production properties, including cross sections
  - Measurements of top quark decay properties
  - Measurements of s- and t-channels single top quark production
- Electroweak
  - W boson mass measurement with ~20 MeV precision
  - Production and decay properties of di-bosons: WW, WZ, ZZ, $W\gamma$, $Z\gamma$, etc.
  - Precision measurement of $\sin(\theta_W)$
- B physics
  - Studies of di-muon production asymmetry and CP violation
  - Measurements of b-baryons and b-mesons production, properties and lifetimes
- QCD
  - Precision measurements of single, double and triple jets cross sections
  - Precision measurement of angular correlations in jets production
  - Extraction of α_{QCD} and PDFs
- New Phenomena
  - Model independent search for new physics
  - Supersymmetry searches, including MSSM Higgs
- Detectors performance over 10 years and 10 fb^{-1} of data

CDF Collaboration

D0 Collaboration

Thanks to CDF and D0 collaborators not only for the results they have put in the books, but also for the demands they have placed on theorists to calculate more processes ever more accurately, to make more reliable simulations, and to think in new ways.

Reserve

Resource needs

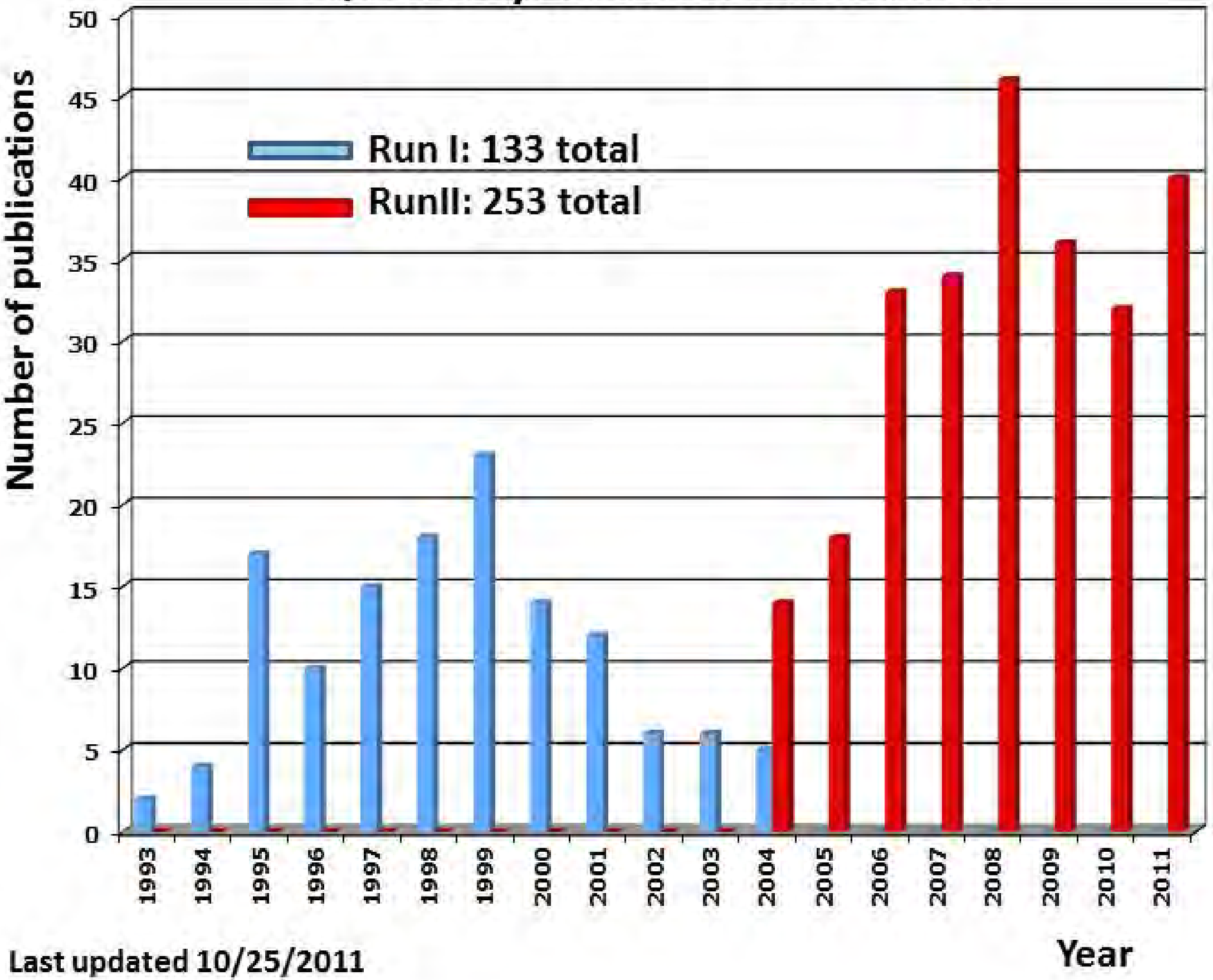
2012 guest and visitor budget comparable to 2011 level to bring people to Fermilab for offline and physics leadership/analysis.

Computing resources at 2011 level.

Continued support to university postdocs and graduate students.

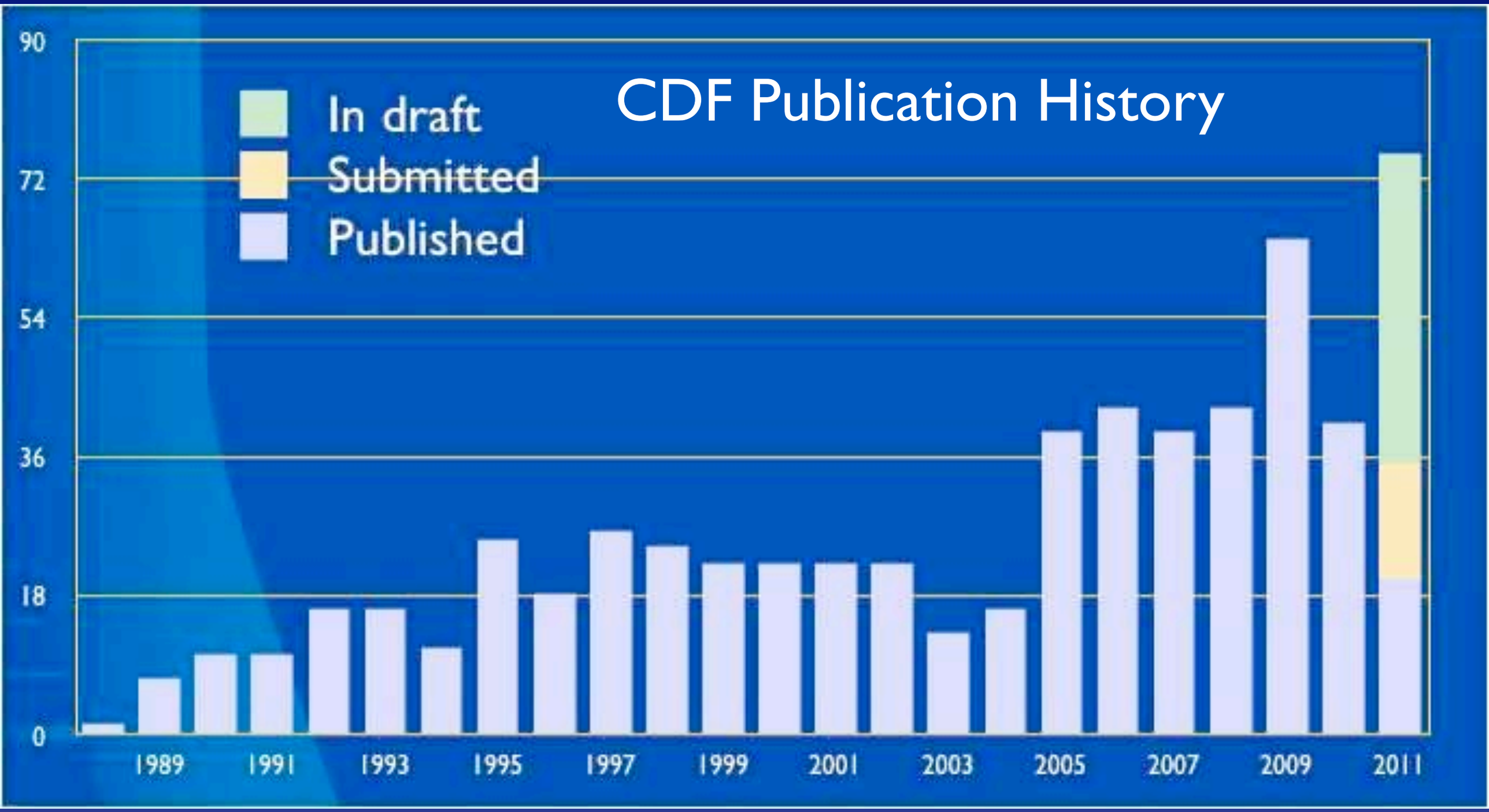
Most international collaborators
wish to participate in analysis to completion

DØ History of Journal Submissions



Last updated 10/25/2011

CDF Publication History



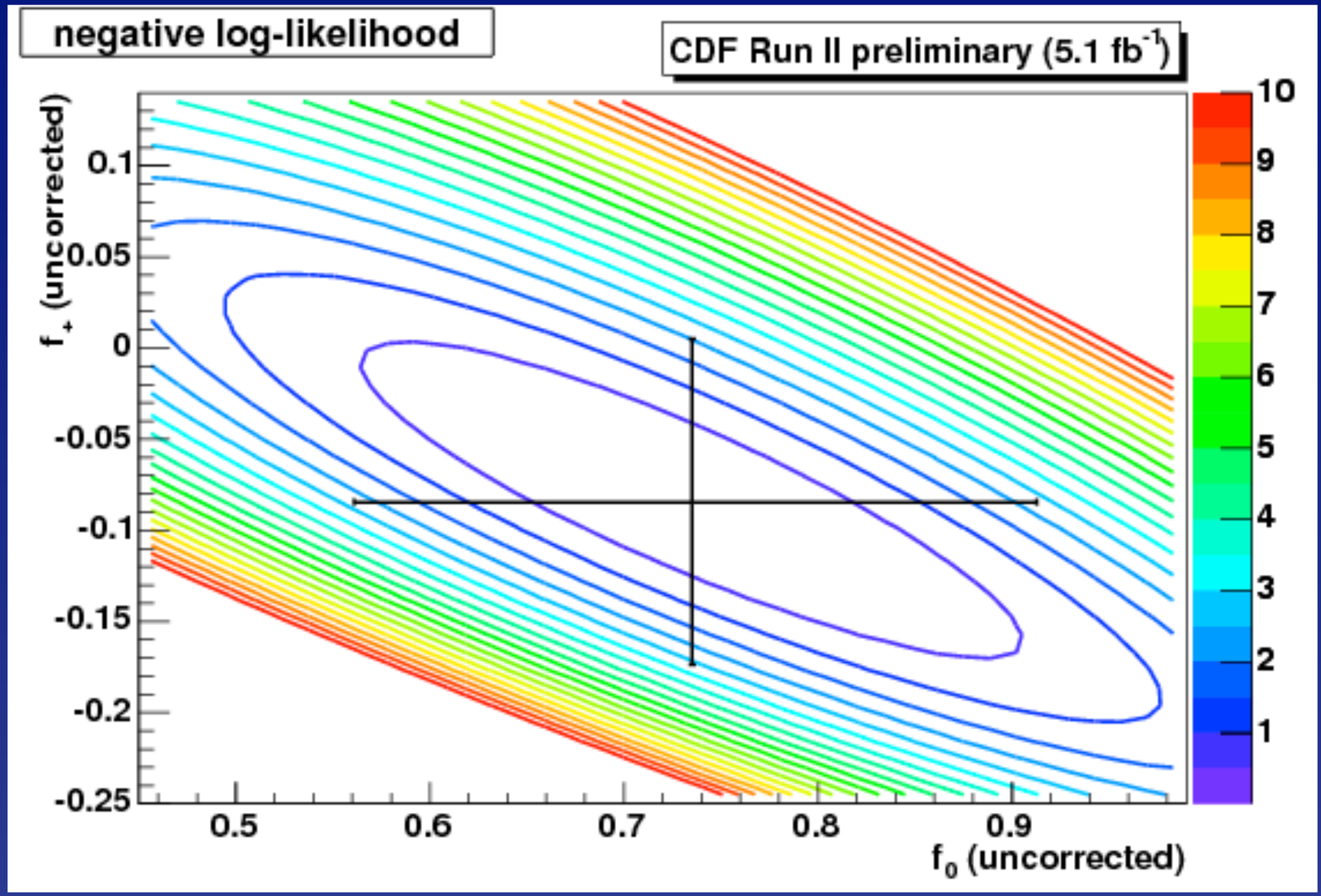
Early Tevatron history: H. Edwards, *Ann. Rev. Nucl. Part. Sci.* 35, 605 (1985).

Recent overview: S. Holmes, R. S. Moore, and V. Shiltsev, *JINST* 6, T08001 (2011).

Anecdotal accounts: V. Shiltsev, "Accelerator Breakthroughs, Achievements and Lessons from the Tevatron Collider," 2010 John Adams Lecture, http://j.mp/qndsb5; J. Peoples, Wilson Prize Lecture, "The Tevatron Collider: A Thirty Year Campaign," http://j.mp/ohzgjh. S. Holmes, DPF 2011 Lecture, "Celebrating the Tevatron: the Machine(s)," http://j.mp/mRCPsQ.

Two recent results

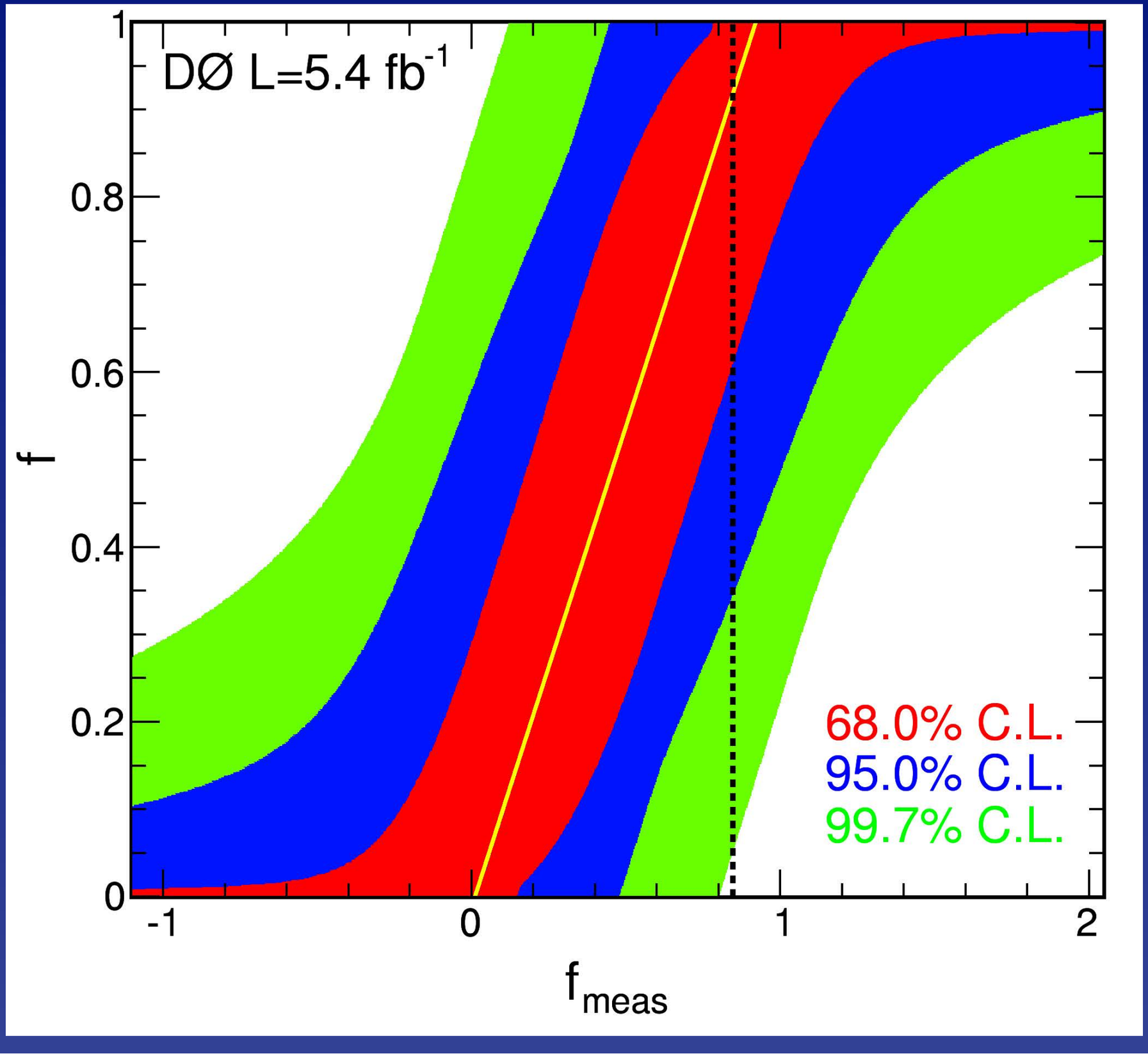
W helicity in top decays (dilepton events)



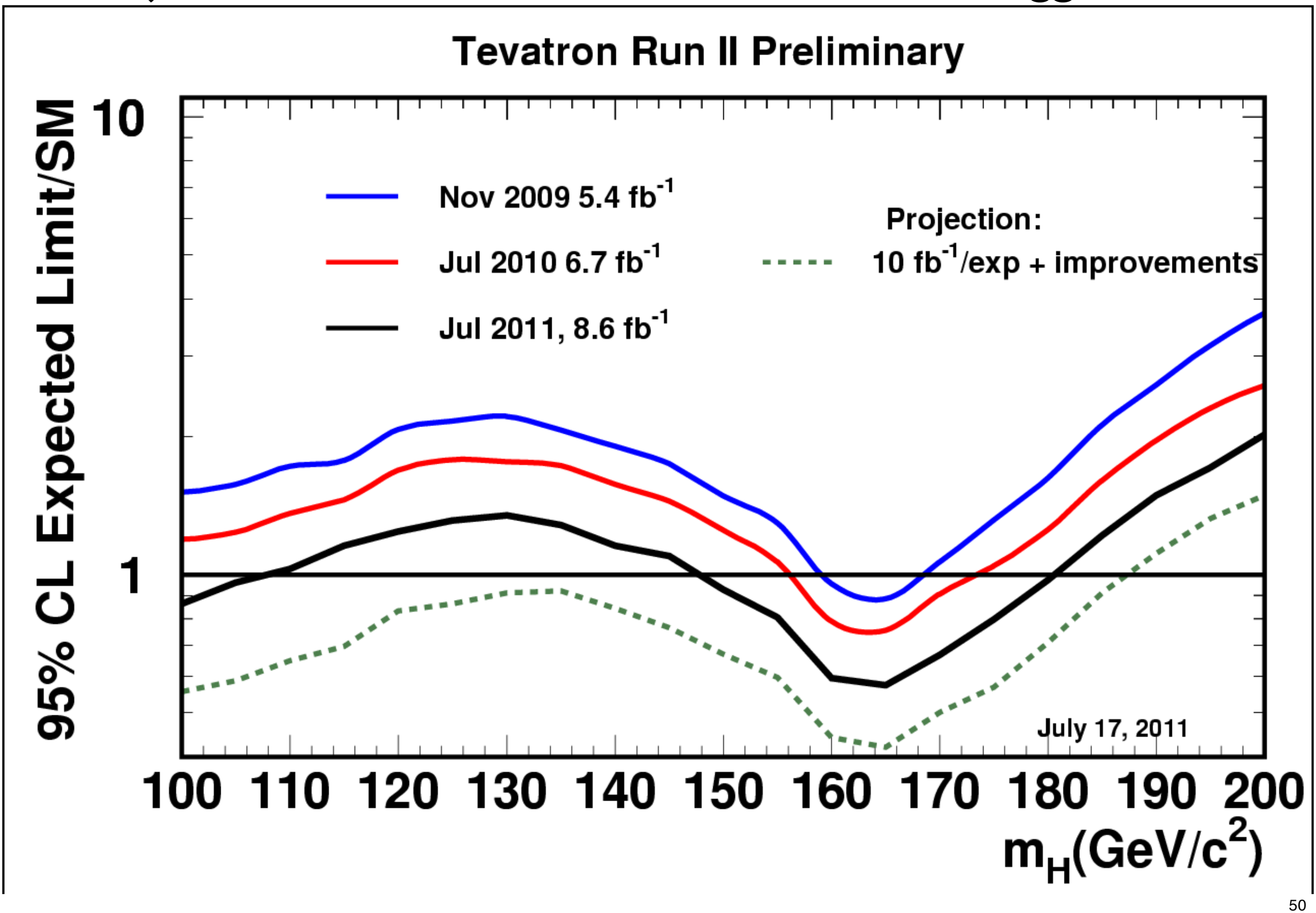
$$f_0 = 0.71^{+0.18}_{-0.17}\ (\text{stat.}) \pm 0.06\ (\text{syst.})$$

$$f_+ = -0.07 \pm 0.04\ (\text{stat.}) \pm 0.03\ (\text{syst.})$$

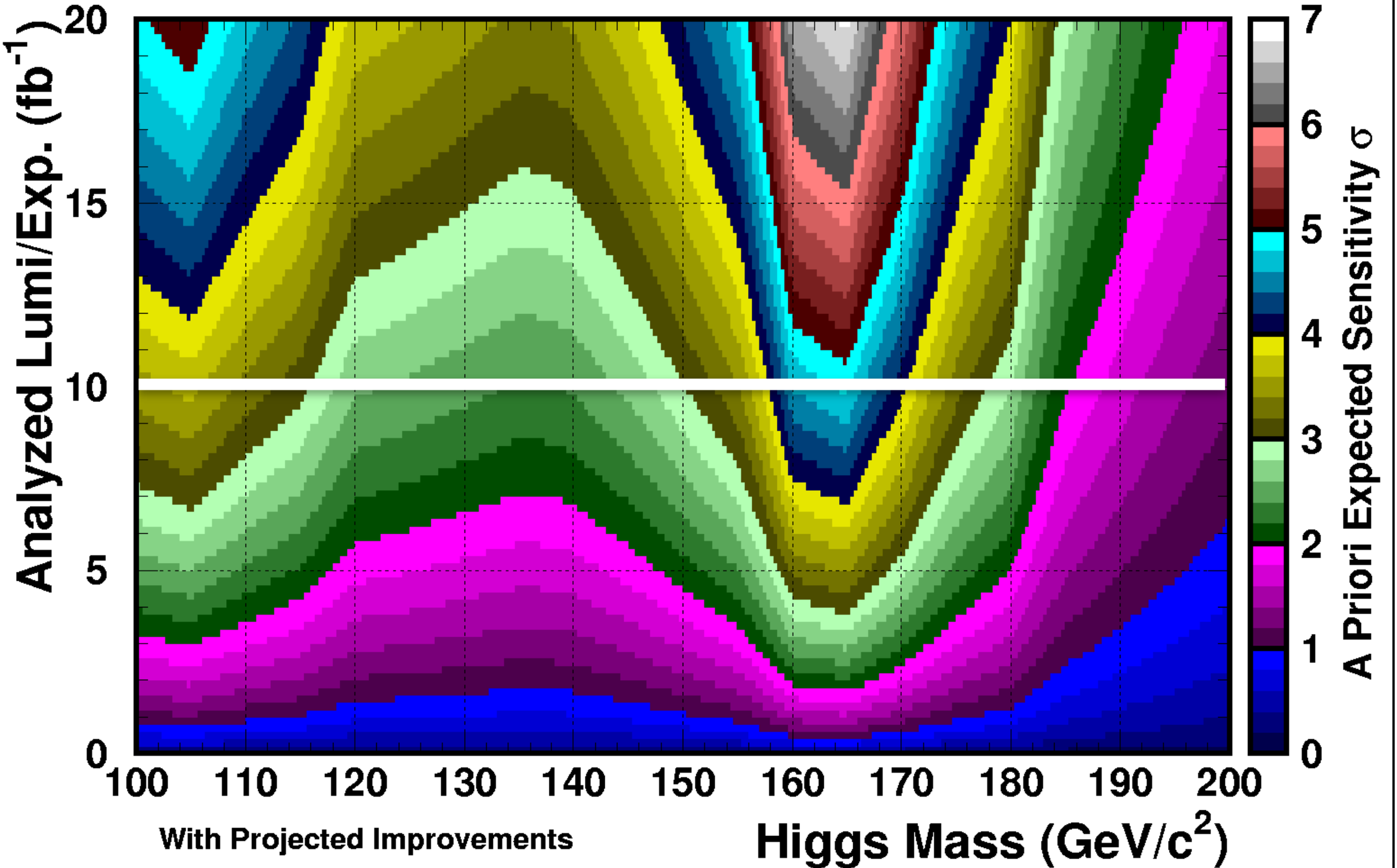
$t\bar{t}$ spin correlations

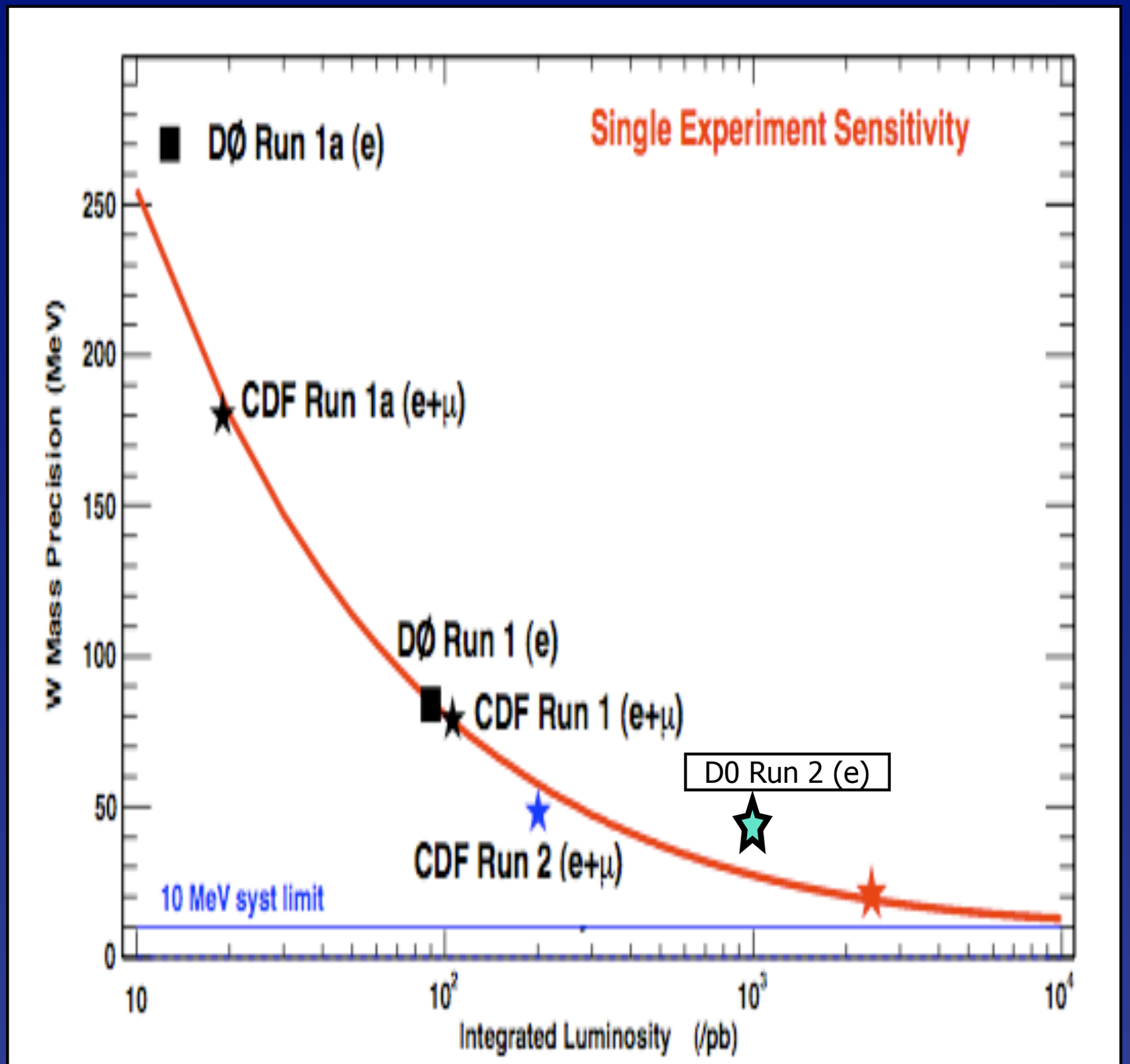


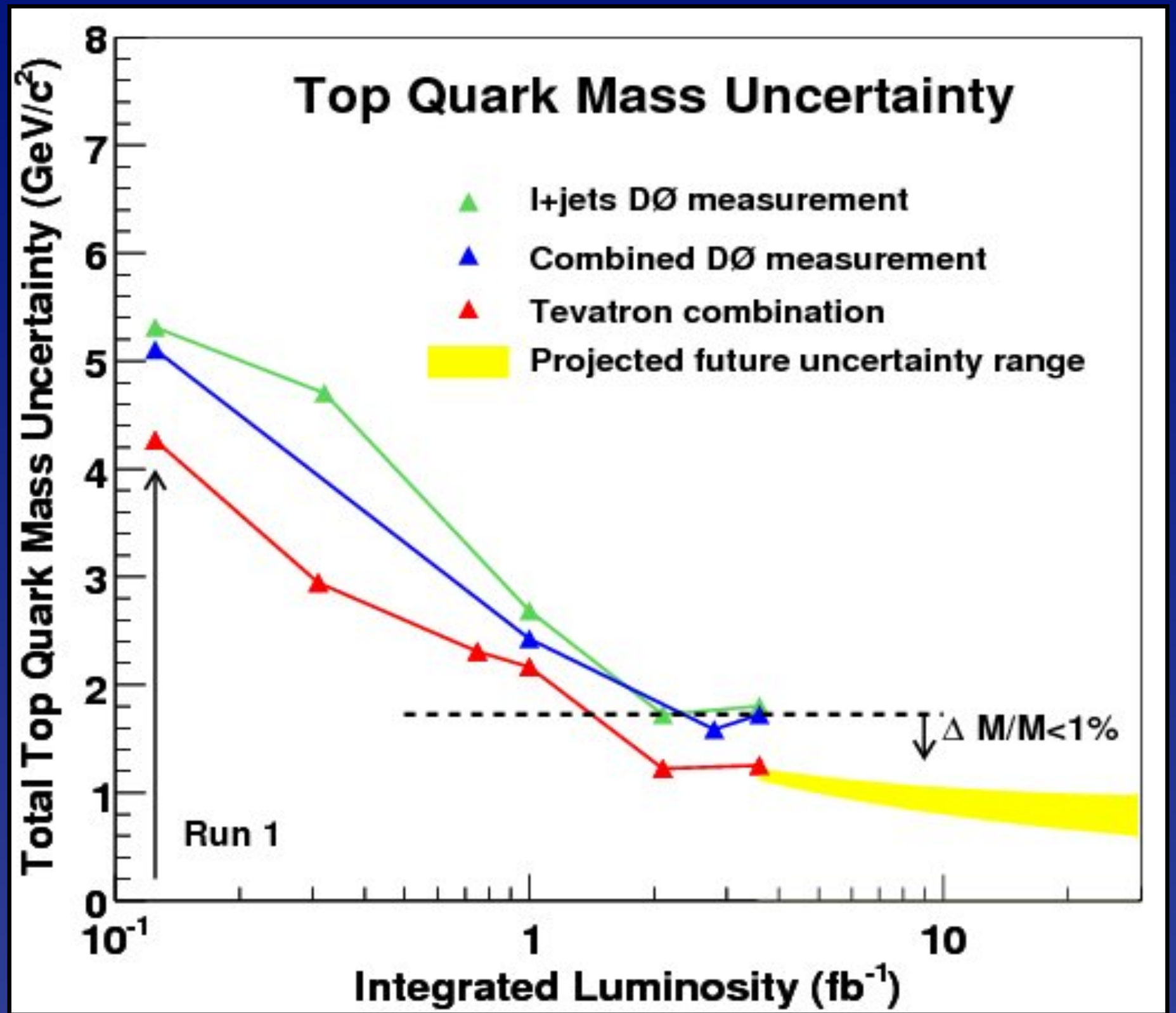
Projected sensitivities to standard-model Higgs boson

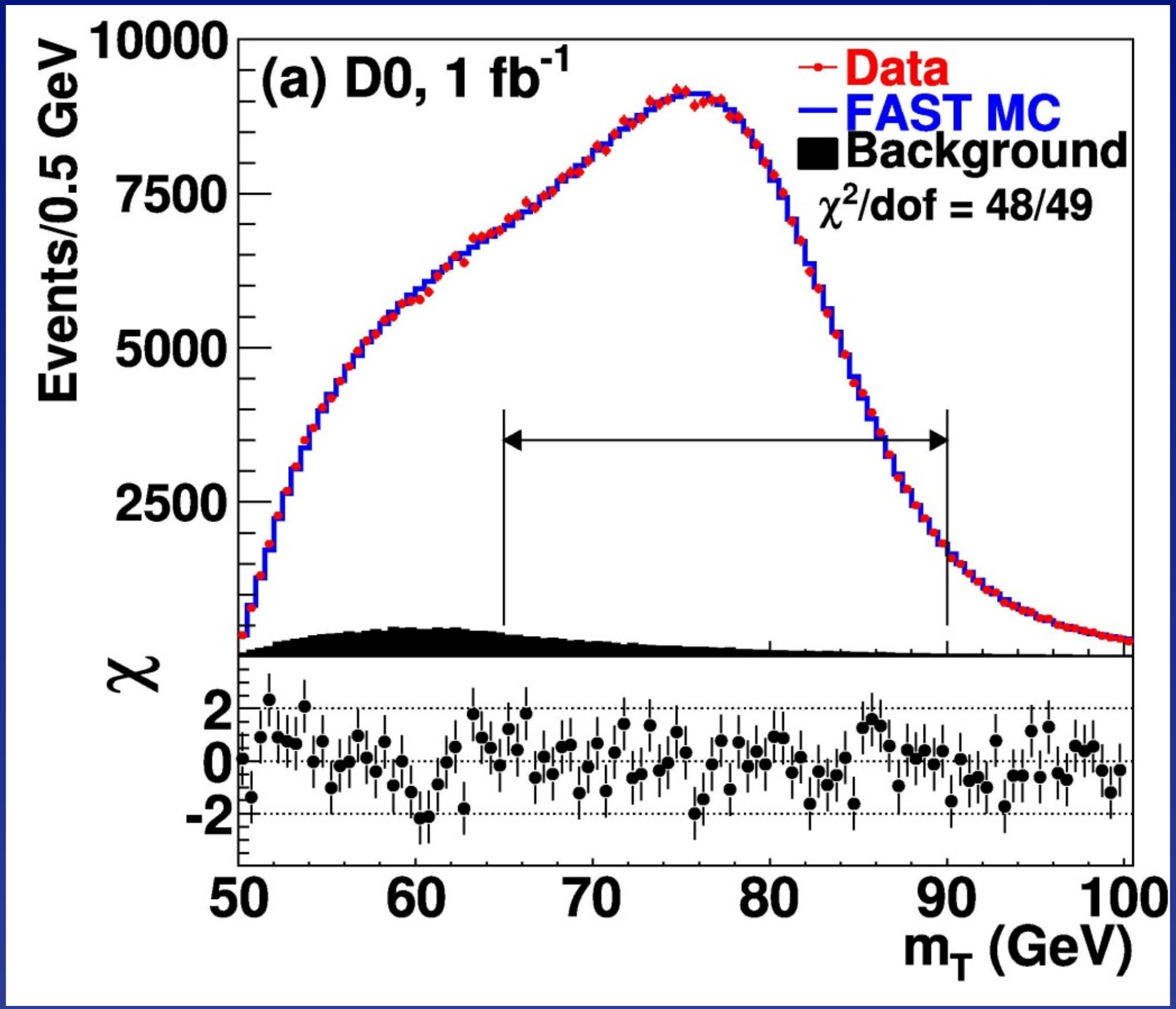


Tevatron Higgs Search Projection




Single Experiment Sensitivity
DØ Run 1a (e)
CDF Run 1a (e+μ)
DØ Run 1 (e)
CDF Run 1 (e+μ)
D0 Run 2 (e)
CDF Run 2 (e+μ)
10 MeV syst limit
W Mass Precision (MeV)
Integrated Luminosity (/pb)
250
200
150
100
50
0
10
10^2
10^3
10^4


Top Quark Mass Uncertainty
l+jets DØ measurement
Combined DØ measurement
Tevatron combination
Projected future uncertainty range
Δ M/M<1%
Run 1
Total Top Quark Mass Uncertainty (GeV/c²)
Integrated Luminosity (fb⁻¹)
0
1
2
3
4
5
6
7
8
10⁻¹
1
10


(a) D0, 1 fb-1
Data
FAST MC
Background
χ2/dof = 48/49
Events/0.5 GeV
10000
7500
5000
2500
χ
2
0
-2
50
60
70
80
90
100
mT (GeV)

D0

CDF