Milestones of the Tevatron Run

Young-Kee Kim
Fermilab and the University of Chicago

Hadron Collider Physics Symposium 2011
November 14, 2011
Paris, France

U.S. DEPARTMENT OF ENERGY

Fermilab

“Long live the Tevatron”
Chris Quigg, Fermilab
CERN Courier Sep. 23, 2011
http://cerncourier.com/cws/article/cern/47206

“Farewell to the Tevatron”
Roger Dixon, Fermilab
CERN Courier Oct. 25, 2011
http://cerncourier.com/cws/article/cern/47505

For this presentation, special thanks to
Chris Quigg (HEPAP presentation)
Paul Grannis (APS/DPF presentation)
CDF/DØ spokespersons

Tevatron shut down at ~2:30 pm, September 30, 2011 after 28 years of operations

CDF and DØ Collaborations on September 30, 2011

Tevatron Symposium, June 11, 2012

The Tevatron: 1983 – 2011

First high-energy superconducting synchrotron

Model for HERA (ep) proton ring

Key milestone toward Large Hadron Collider

Lyn Evans (Science: September 23, 2011): *“The Tevatron is where I learned about building superconducting machines”, “If you like, it was a prototype for the LHC.”*

> 5 APS Wilson Prizes

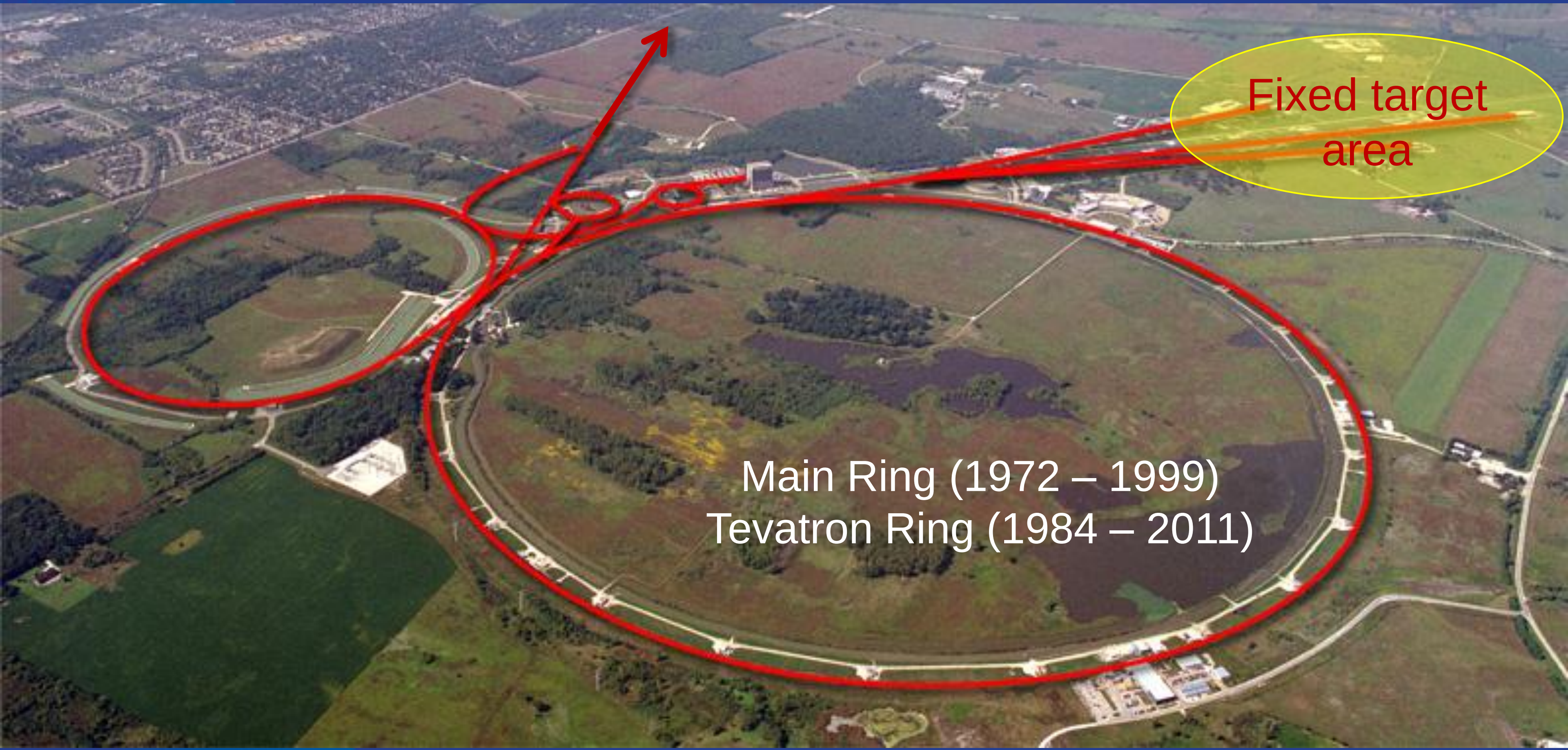
National Medals of Technology to 4 people

The beam was injected for the first time on June 2, 1983.

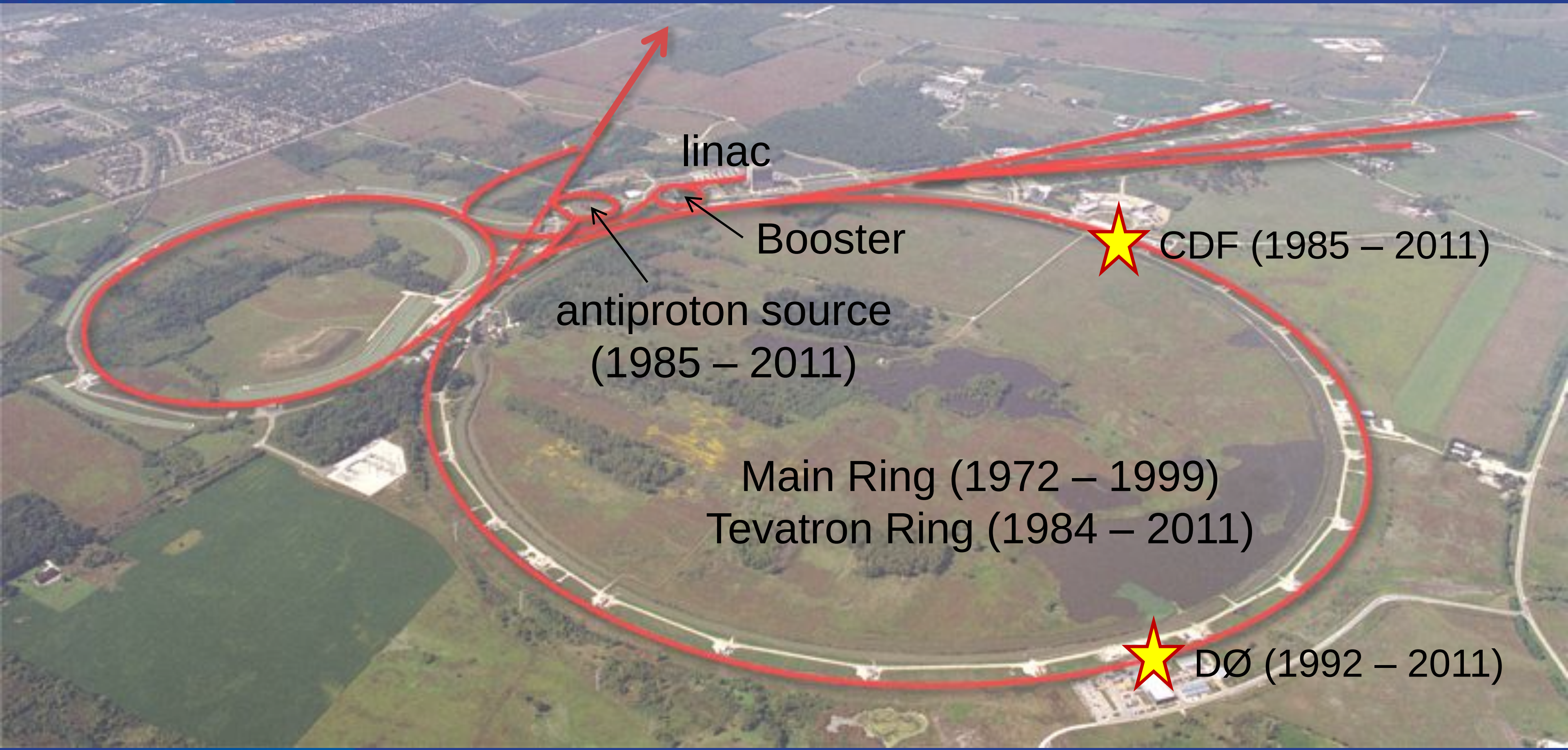
On July 3, the Tevatron (then called “the Energy Doubler”) reached 512 GeV.

By 1984, the energy reached 800 GeV and the Energy Doubler was renamed the Tevatron.

800 GeV Tevatron Fixed Target Program (1984 – 2000)



The Tevatron Collider (1985 – 2011)



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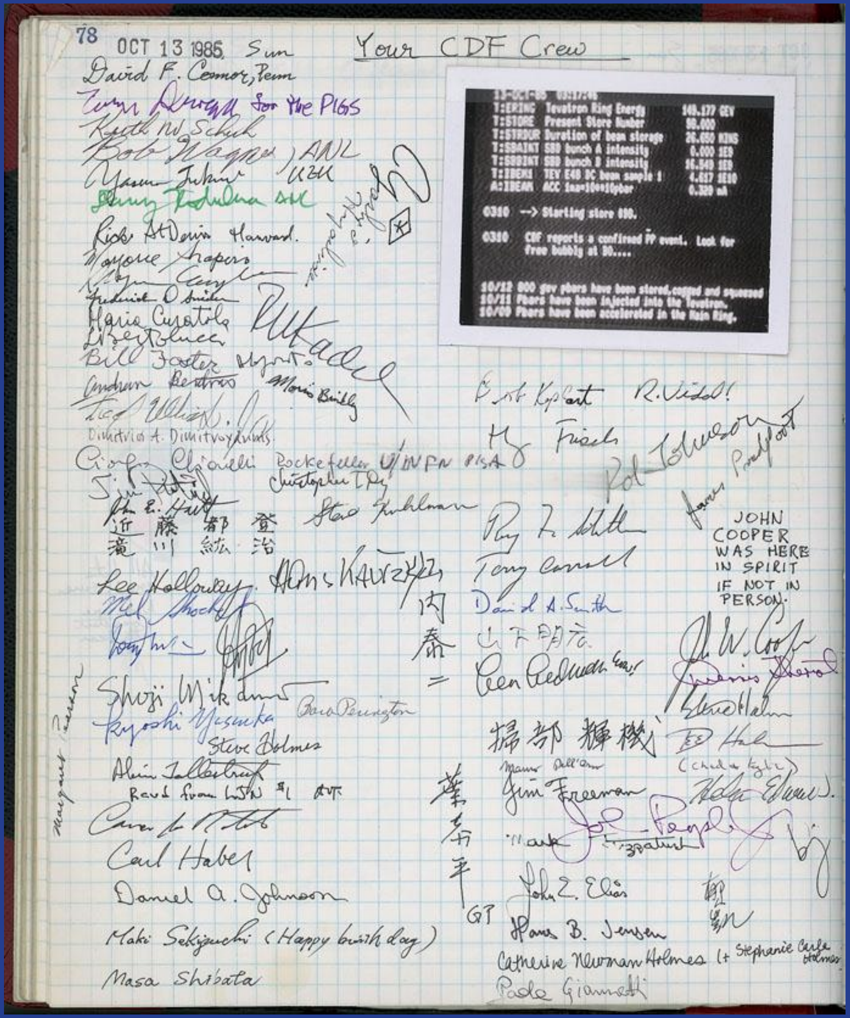
Antiproton source
(1985 – 2011)


Main Ring (1972 – 1999)
Tevatron Ring (1984 – 2011)

The first collision: 2:32 am, October 13, 1985



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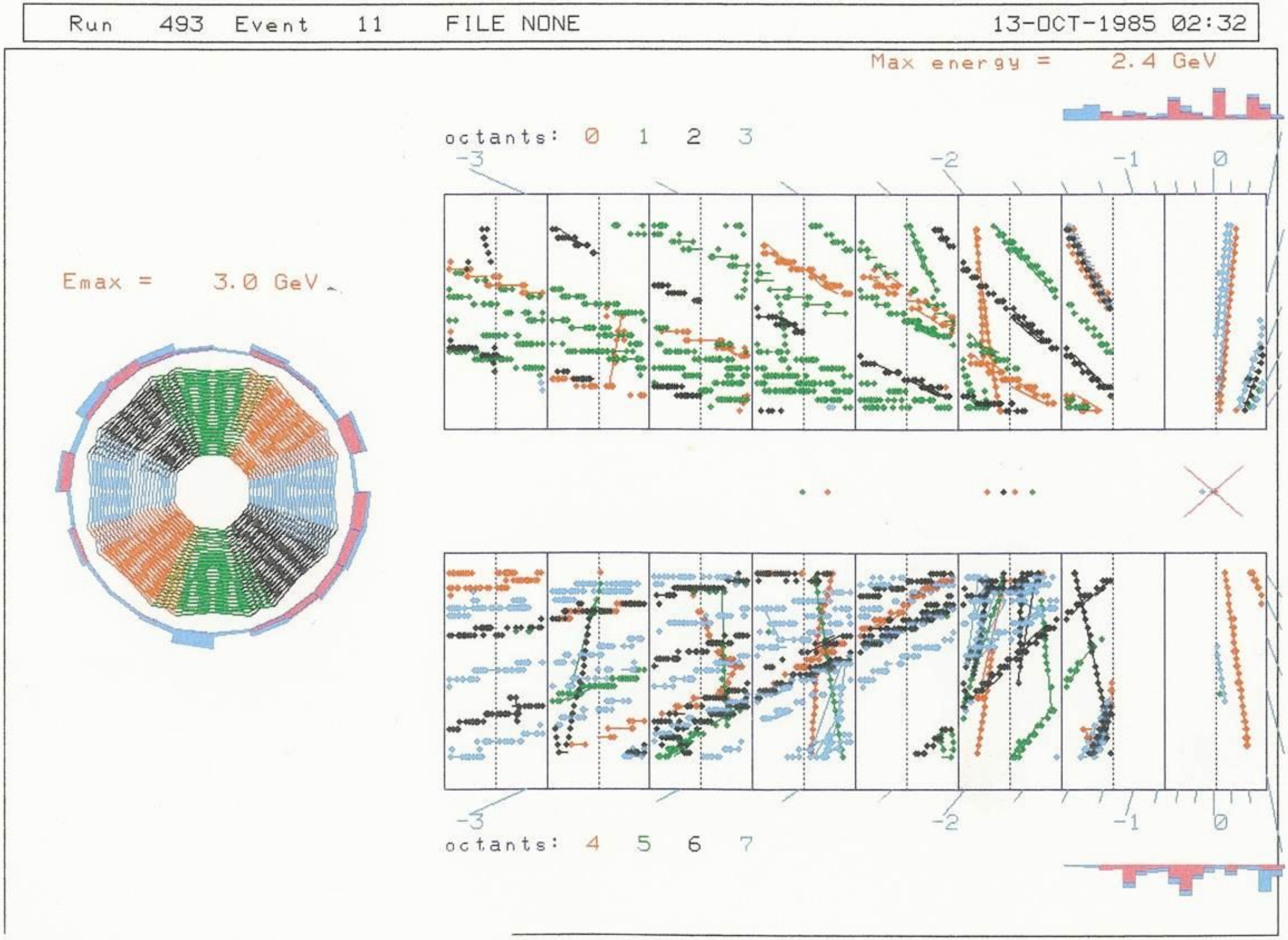
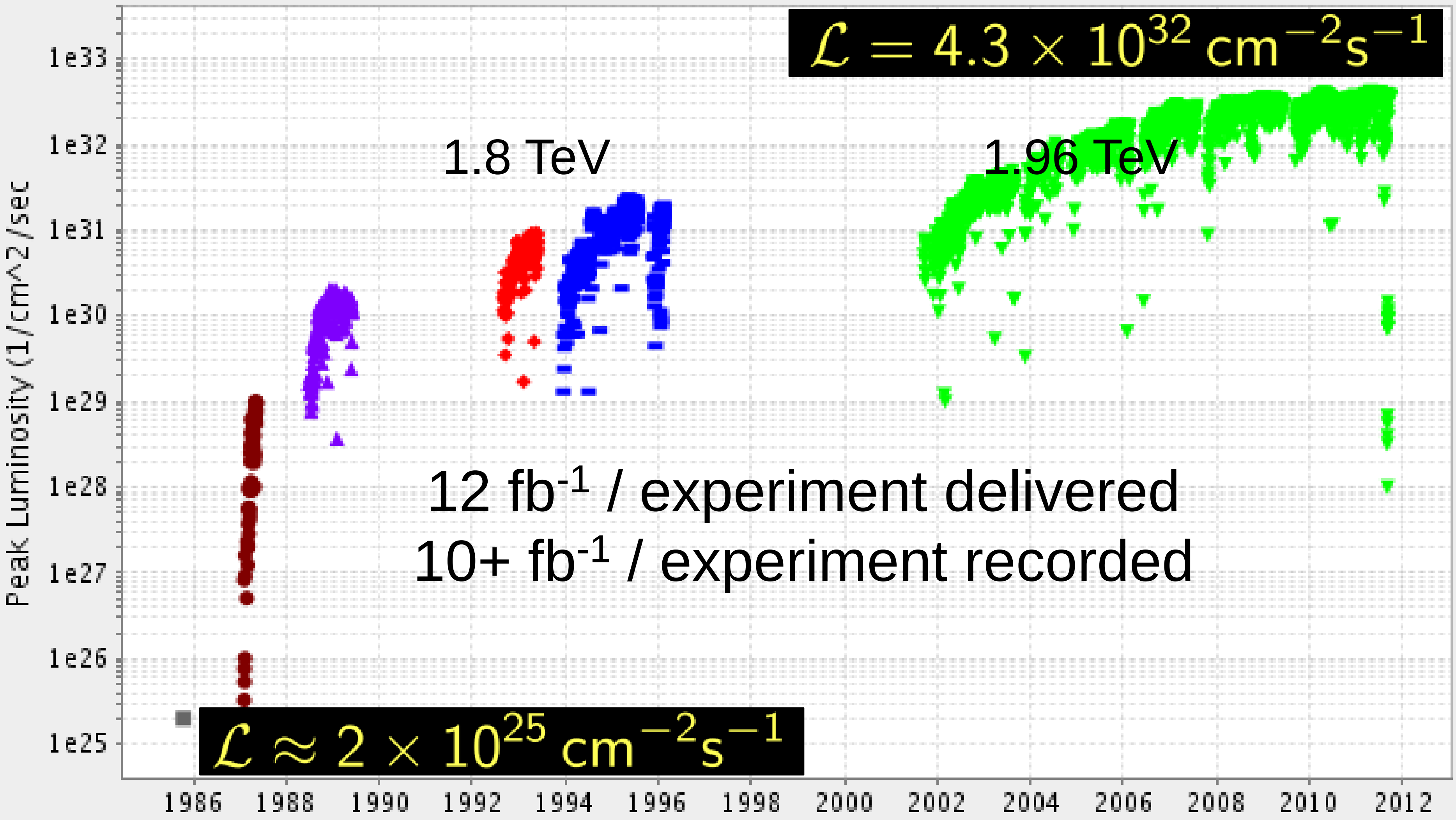
CDF



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

Tevatron Collider Luminosity



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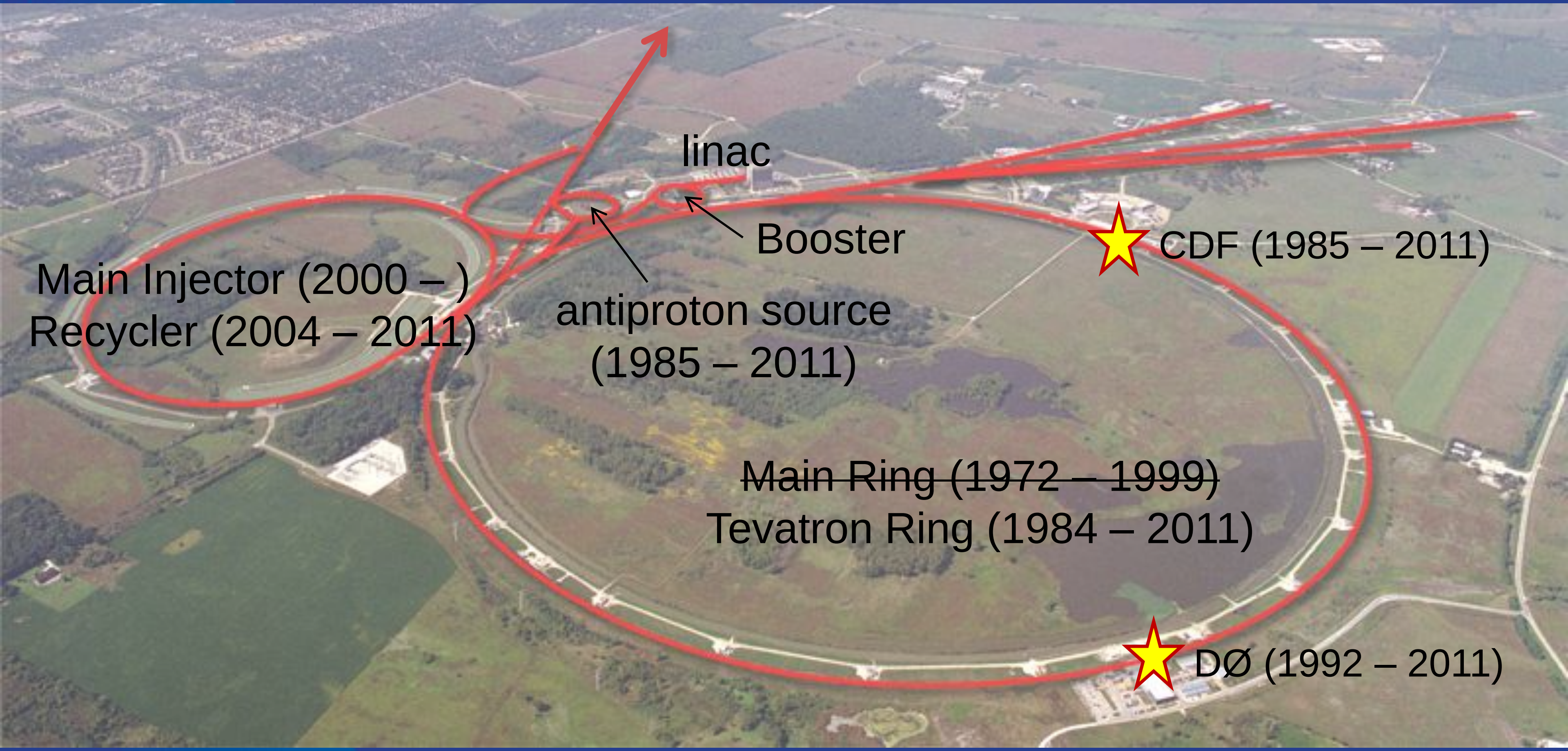
The Tevatron Collider (1985 – 2011)



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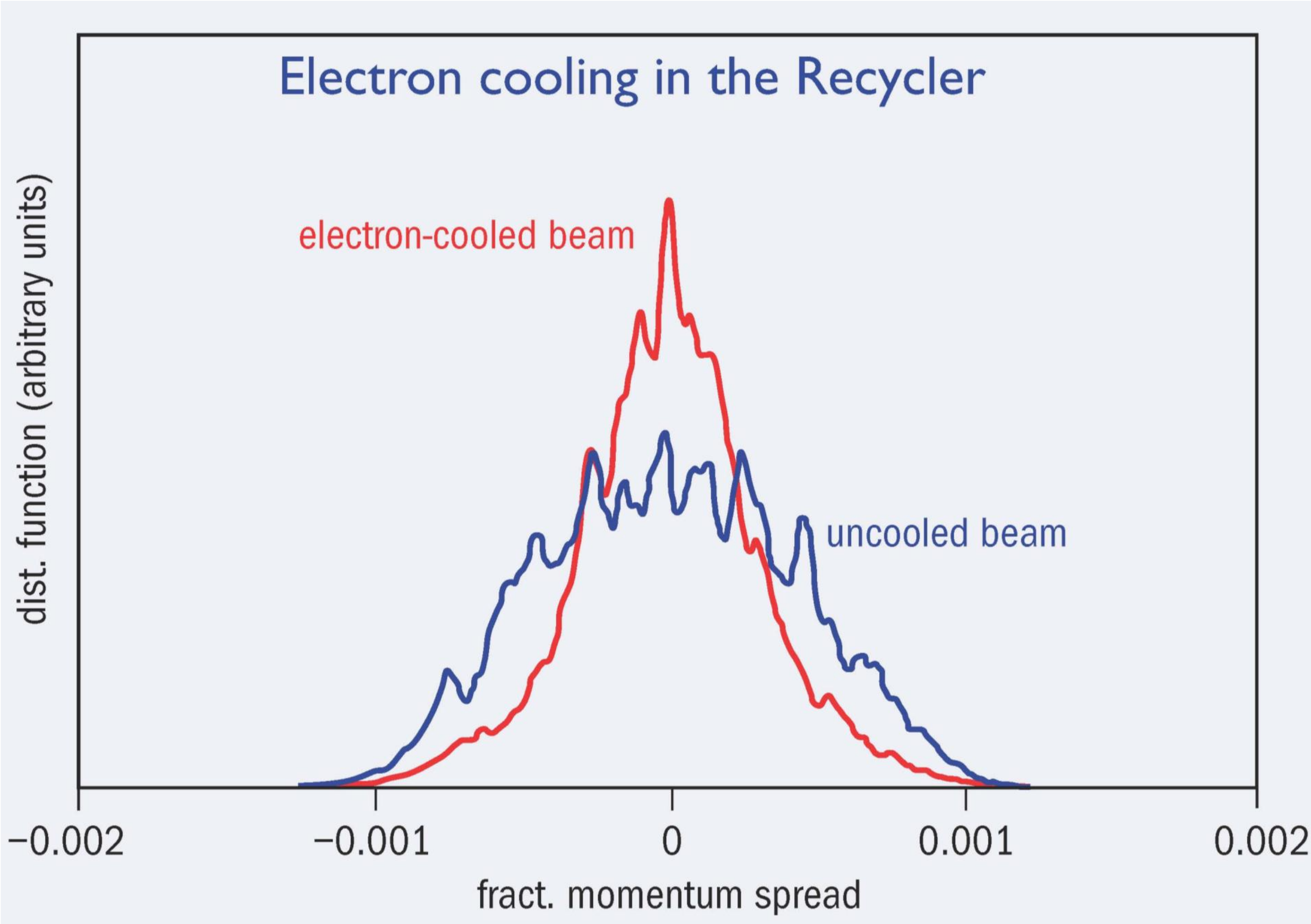
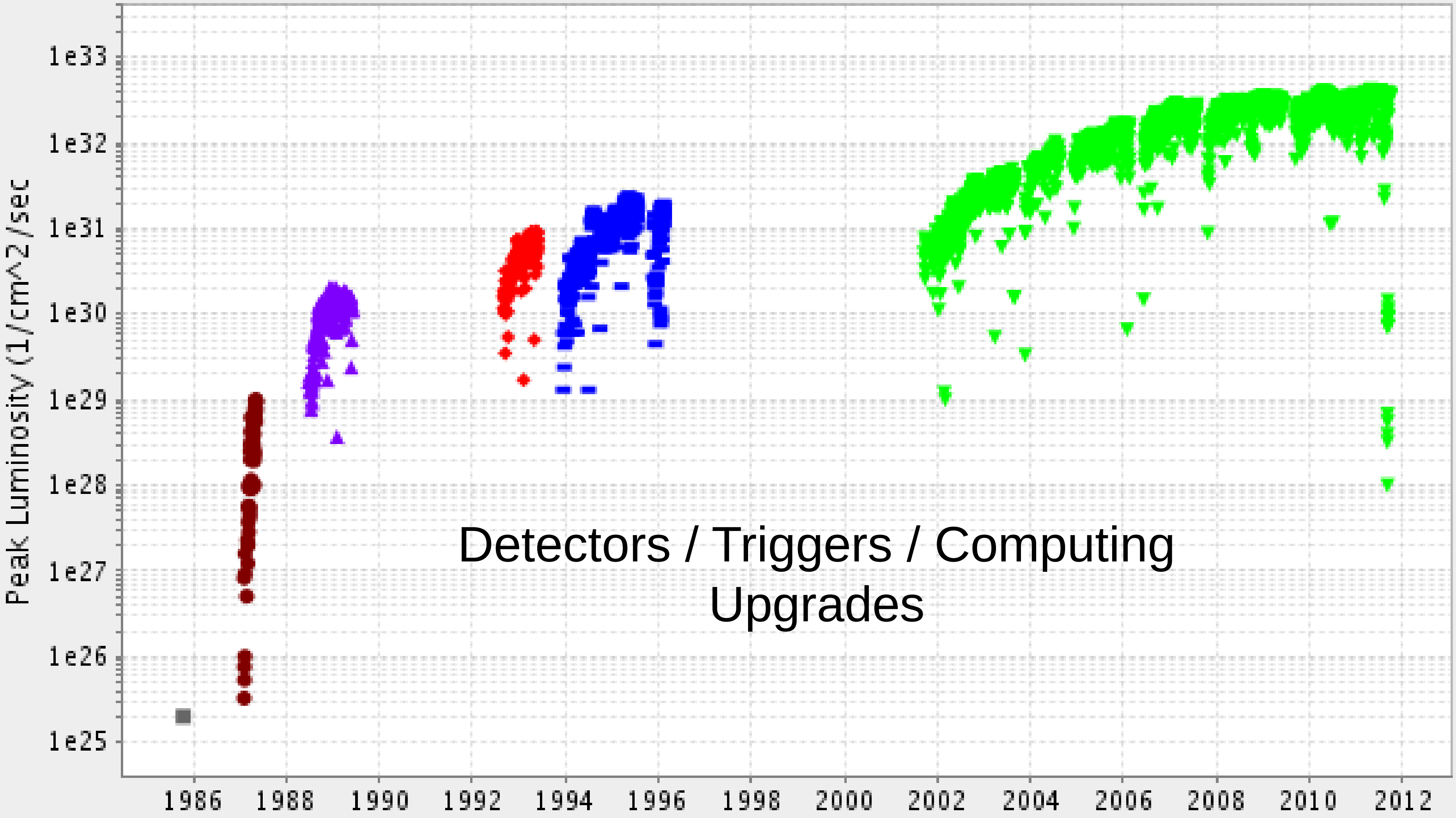
Recycler
Main Injector



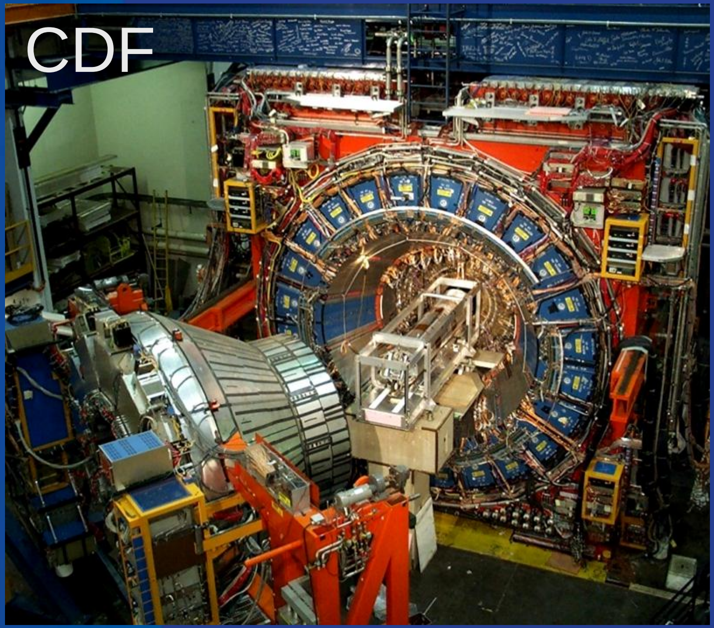
Electron cooling in the Recycler
electron-cooled beam
uncooled beam
dist. function (arbitrary units)
−0.002
−0.001
0
0.001
0.002
fract. momentum spread

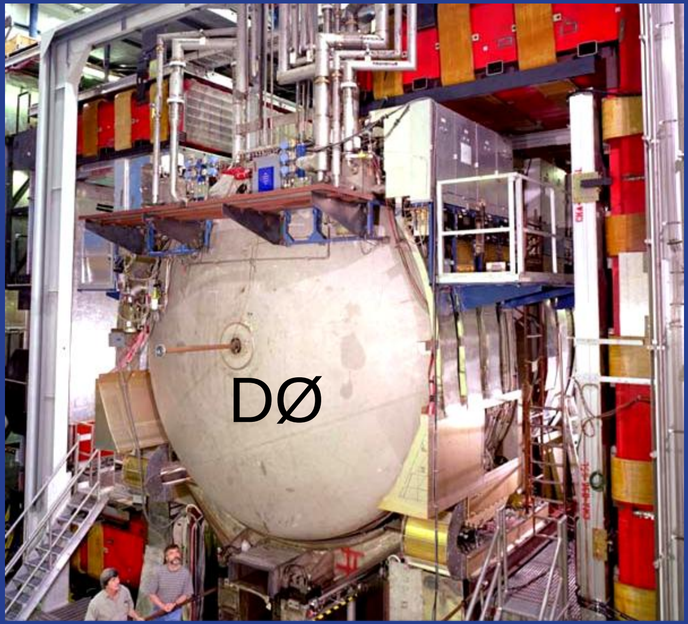
Tevatron Collider Luminosity



Detectors / Triggers / Computing Upgrades

The Experiments: Major Upgrades





CDF: new tracker, new Si vertex, upgraded forward cal and muons

DØ: add solenoid, fiber tracker, Si vertex, preshower, new forward muon

The upgraded experiments looked more like each other!
But have complementary strengths

Innovations at the Tevatron Experiments

CDF pioneered the silicon vertex detector in the hadron collider environment and pioneered the silicon vertex trigger separating *b*-hadrons

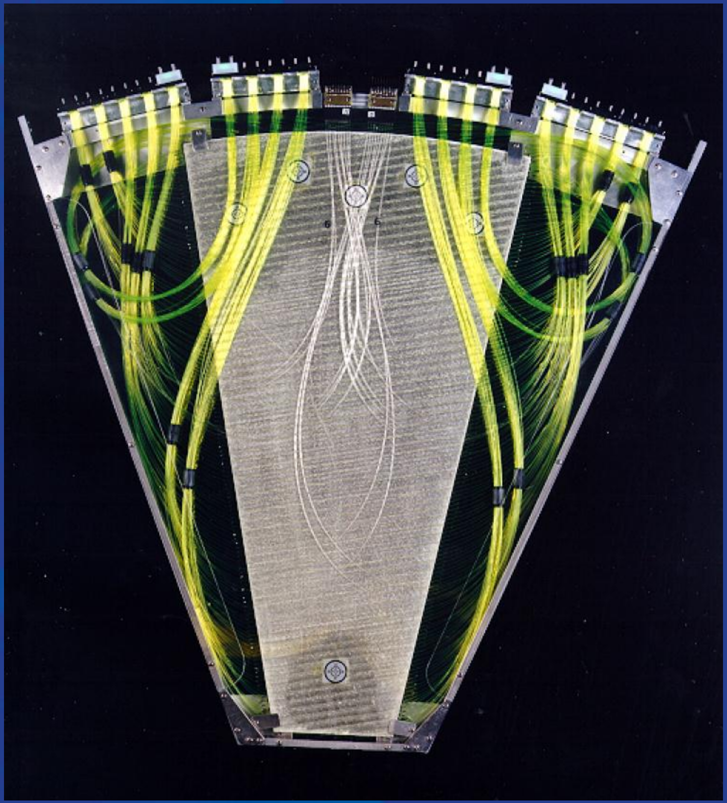
DØ demonstrated that sparse, high resolution trackers could stand up to the hadron collider environment, and its 4π U-LAr detector paved the way for the next generation of calorimeters

CDF and DØ developed multi-level triggering with fast microprocessor farms to give incisive selection of interesting events.

CDF and DØ pioneered multivariate analysis techniques for extracting signals in the face of huge backgrounds.

These advances are now adopted by LHC or future detectors

Detectors as Art



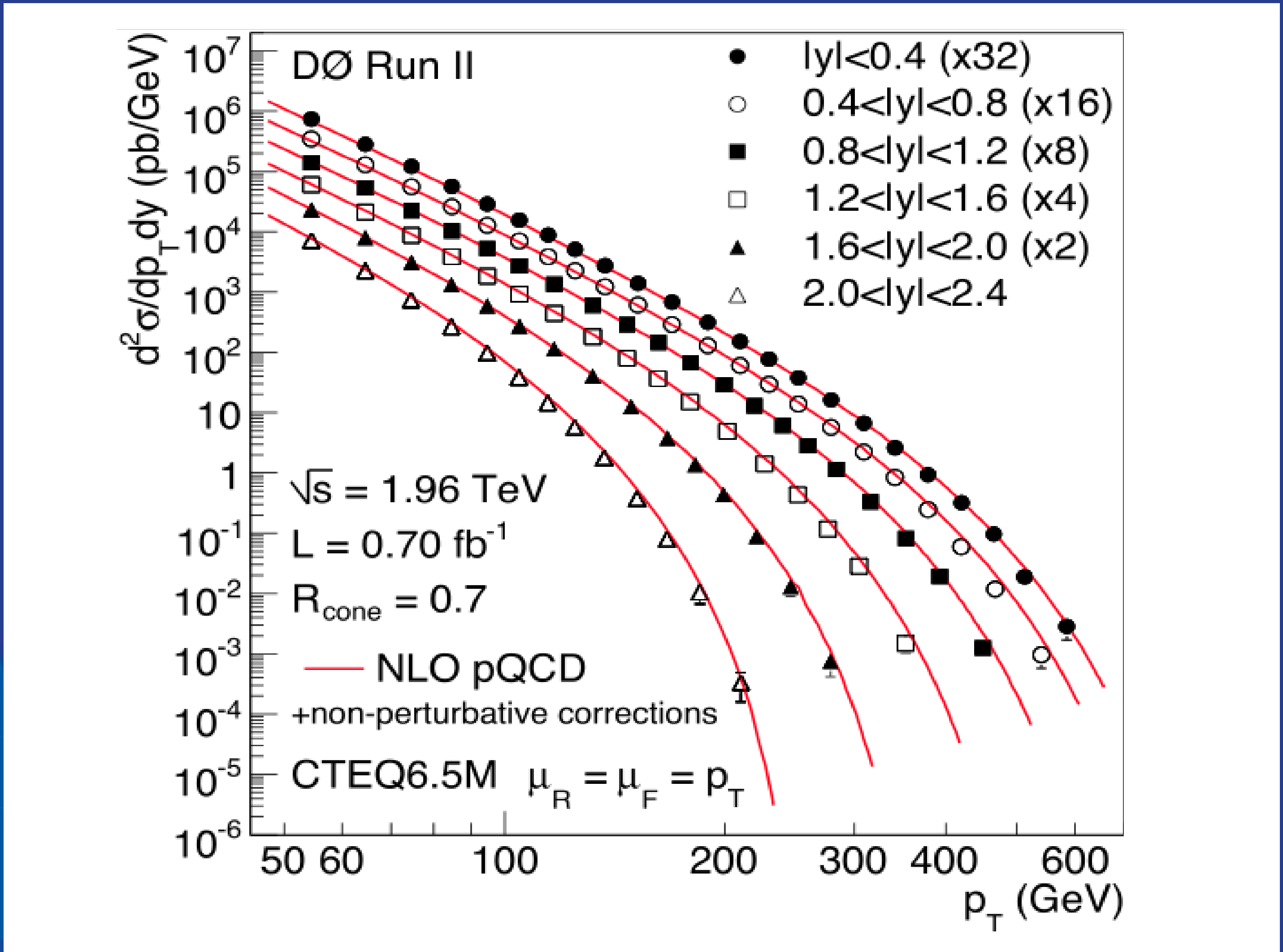
DØ Forward Preshower module at the Museum of Modern Art, New York

CDF’s first Silicon Vertex Detector at the Smithsonian Museum, Washington

Interests and capabilities continually evolved
Many results not anticipated

> 900 publications so far
(~100 to come)

Quantum Chromodynamics



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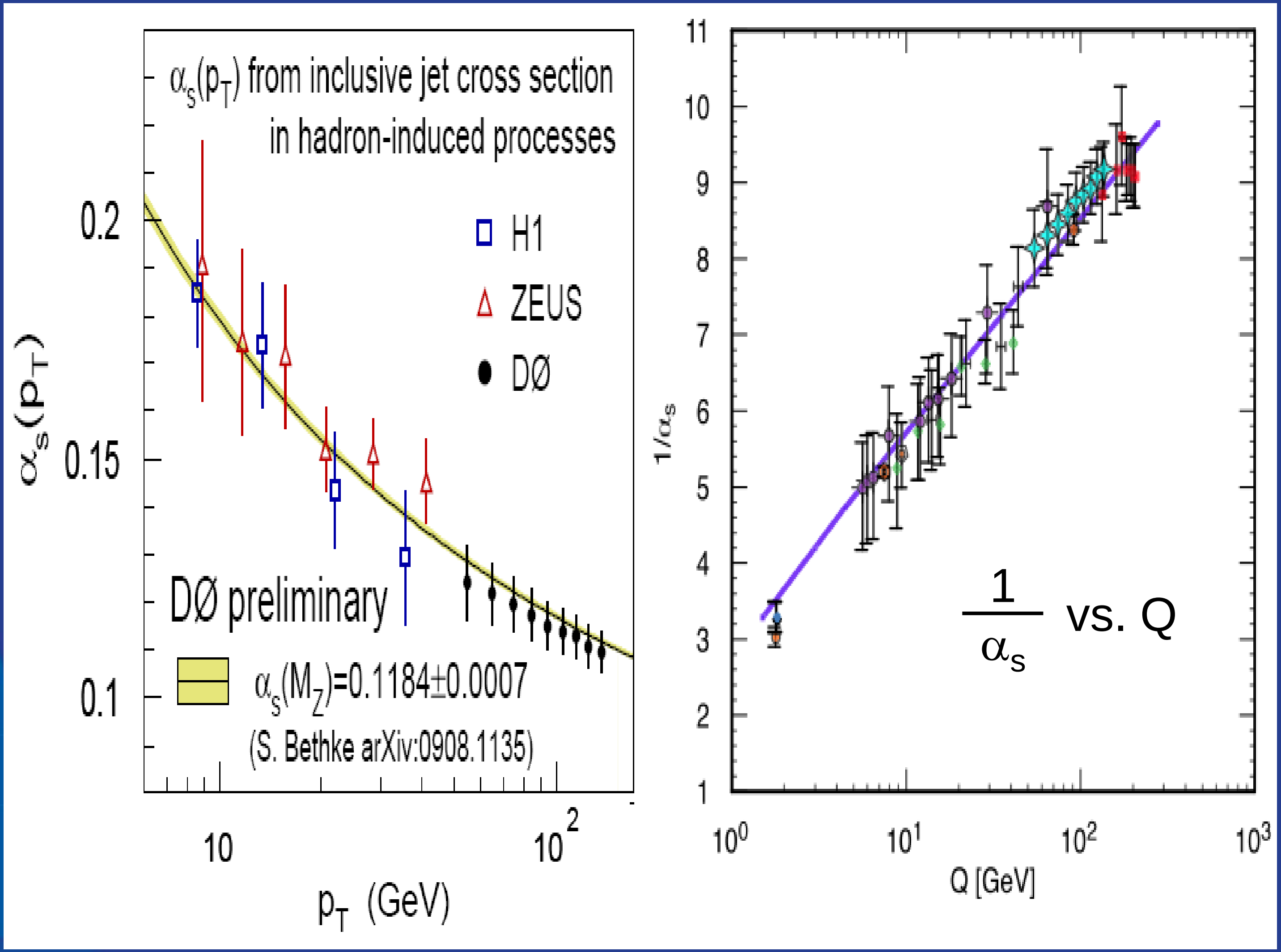
Quantum Chromodynamics



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

Quarks are pointlike and structureless at resolution of nearly 1/(3 TeV) or 0.3 attometer

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

Heavy Flavor Physics (bottom & charm)

Conventional wisdom held that hadron colliders could not compete with e^+e^- colliders

Production and decay of quarkonium states

Measurements of *b*-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

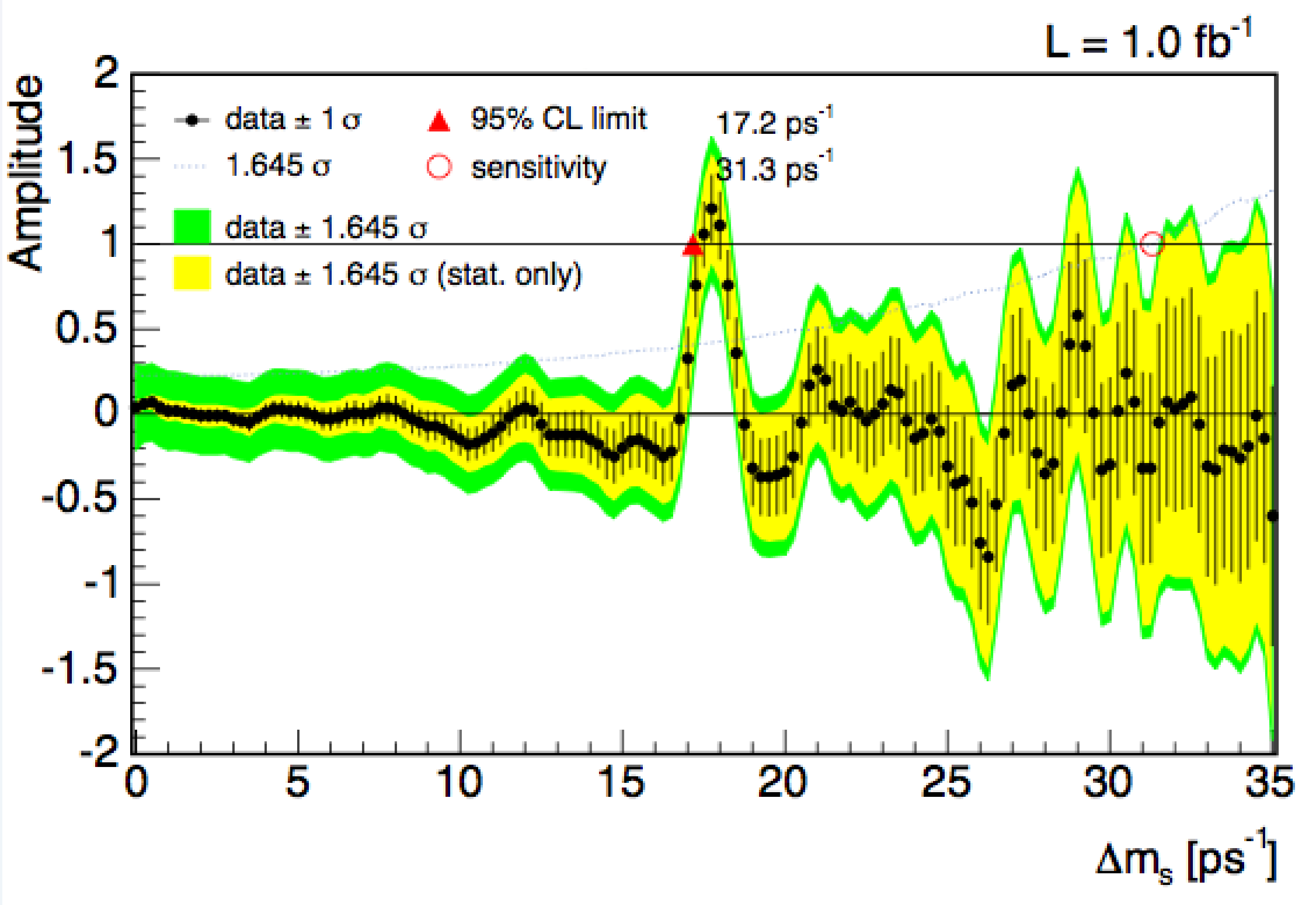
Important evidence on D^0 mixing

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

High-sensitivity searches for rare dimuon decays

Frequency of B_s Oscillations

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



Young-Kee Kim, Hadron Collider Physics Symposium 2011, Paris

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Electroweak Physics

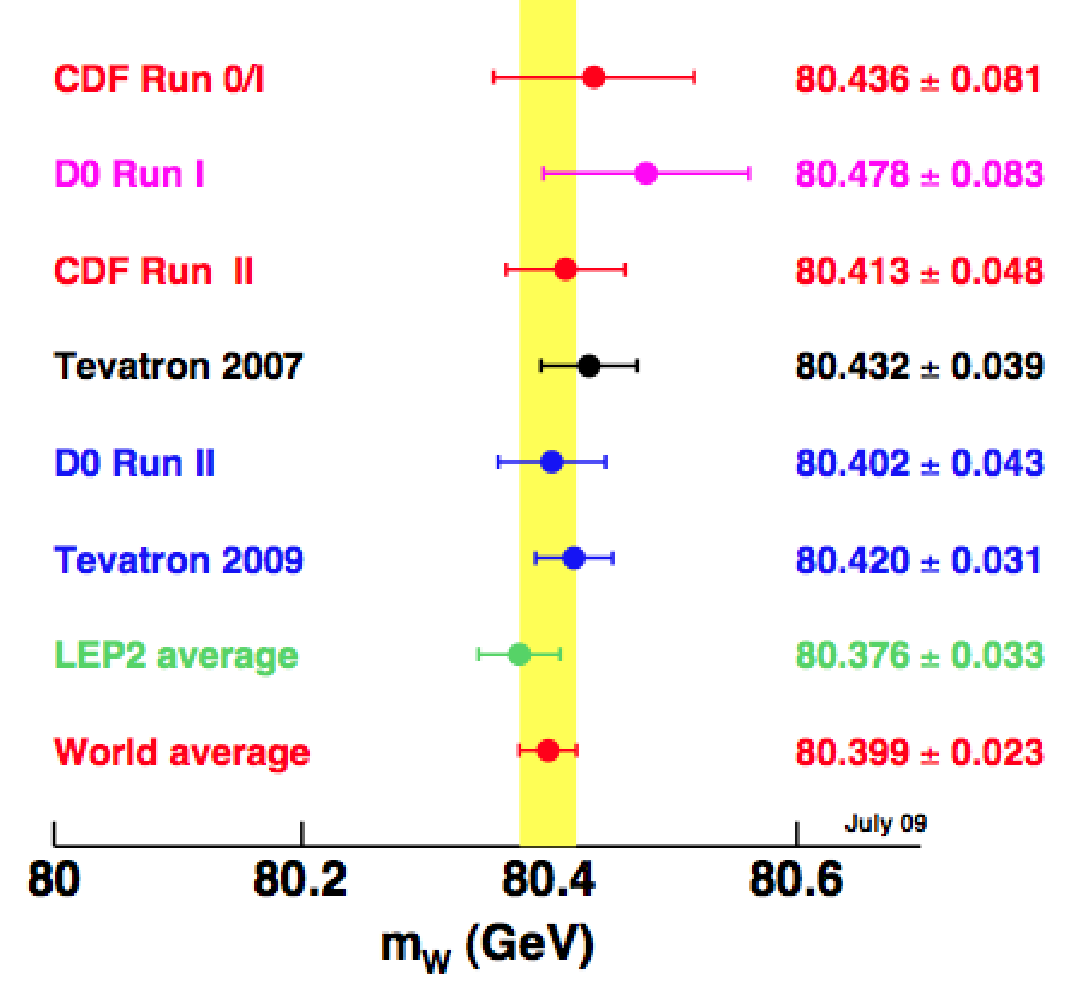
Each experiment expects ~10M *W* bosons and 400K *Z* bosons in each leptonic decay mode

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

Z (+ jets) production tests standard-model simulations

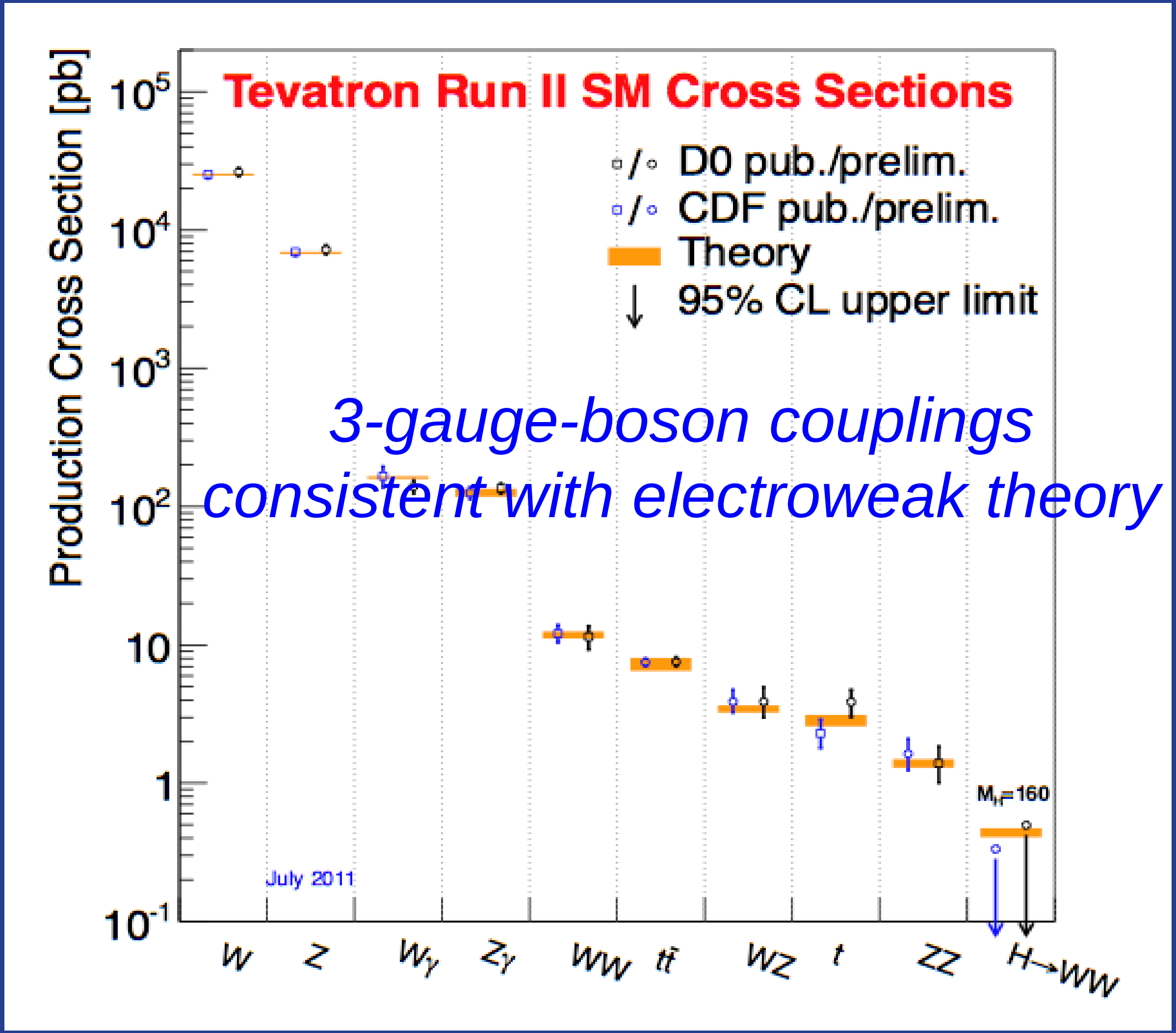
Forward-backward asymmetry of leptons from *W* decay provides important information about the up- and down-quark parton distribution functions

W Mass Measurements



aim for ±15 MeV

Bosons: Cross sections



3-gauge-boson couplings consistent with electroweak theory

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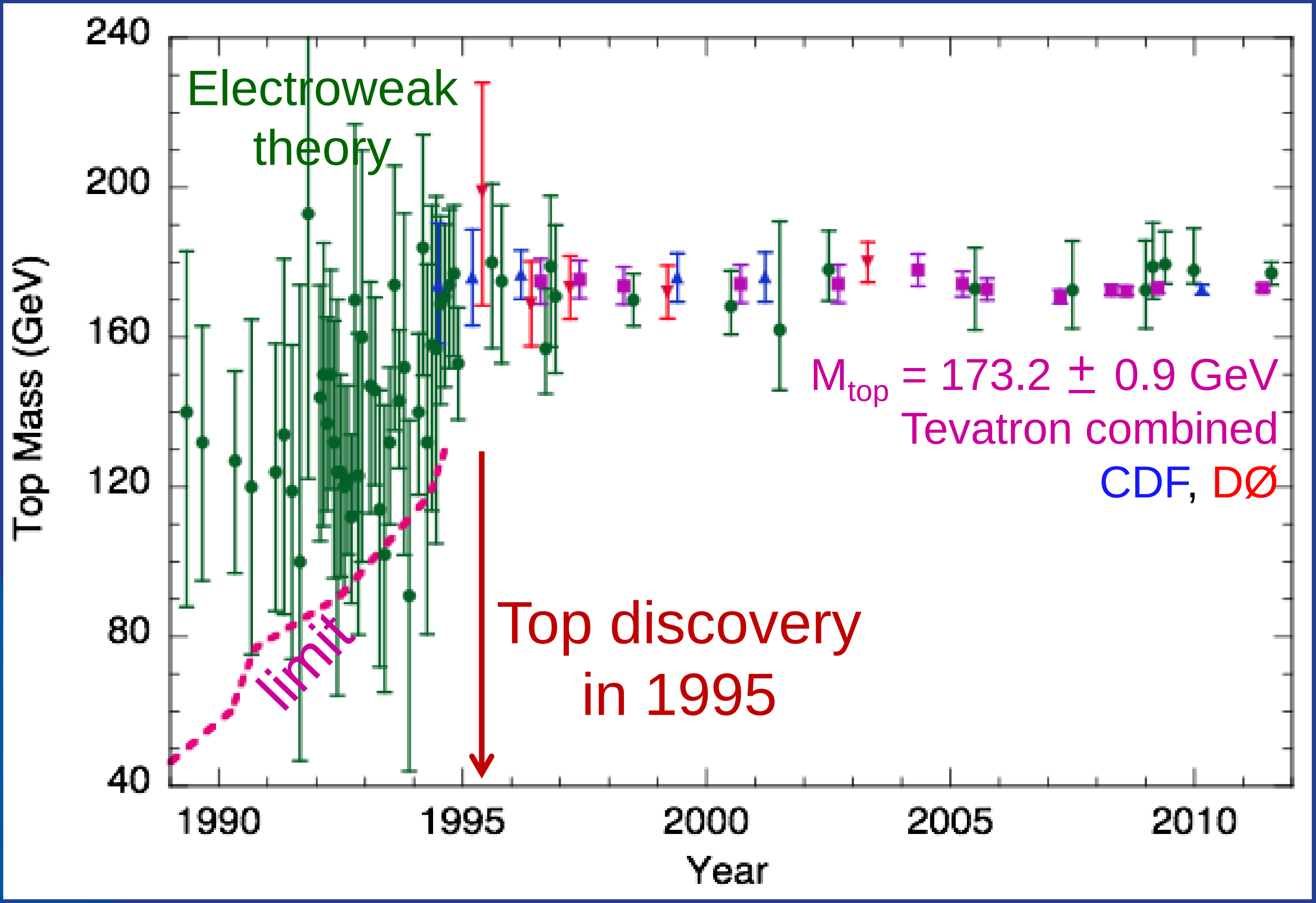
Top mass in the electroweak theory

(W and Z)

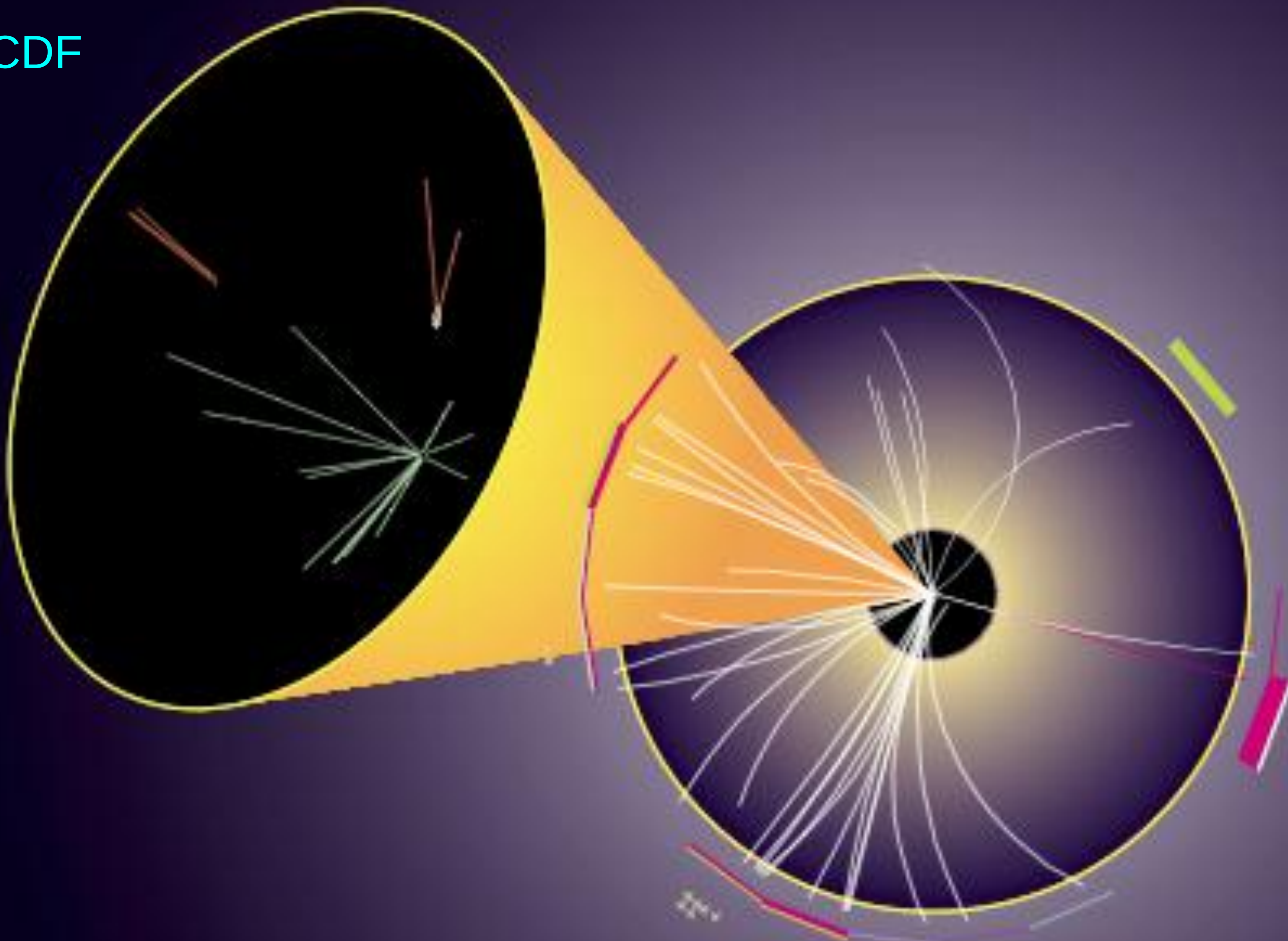


1995


Researchers announce 'top quark' discovery
Cultura e Spettacoli
Dove vai, cacciatore di quark?
Batavia is center of universe
... la existence
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
The Quark Is a Porker
Physicists Weigh In
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


DØ

CDF



Top as a tool to probe new physics

Top pair production in agreement with QCD

No top pair resonances seen

Top-quark charge = +2/3

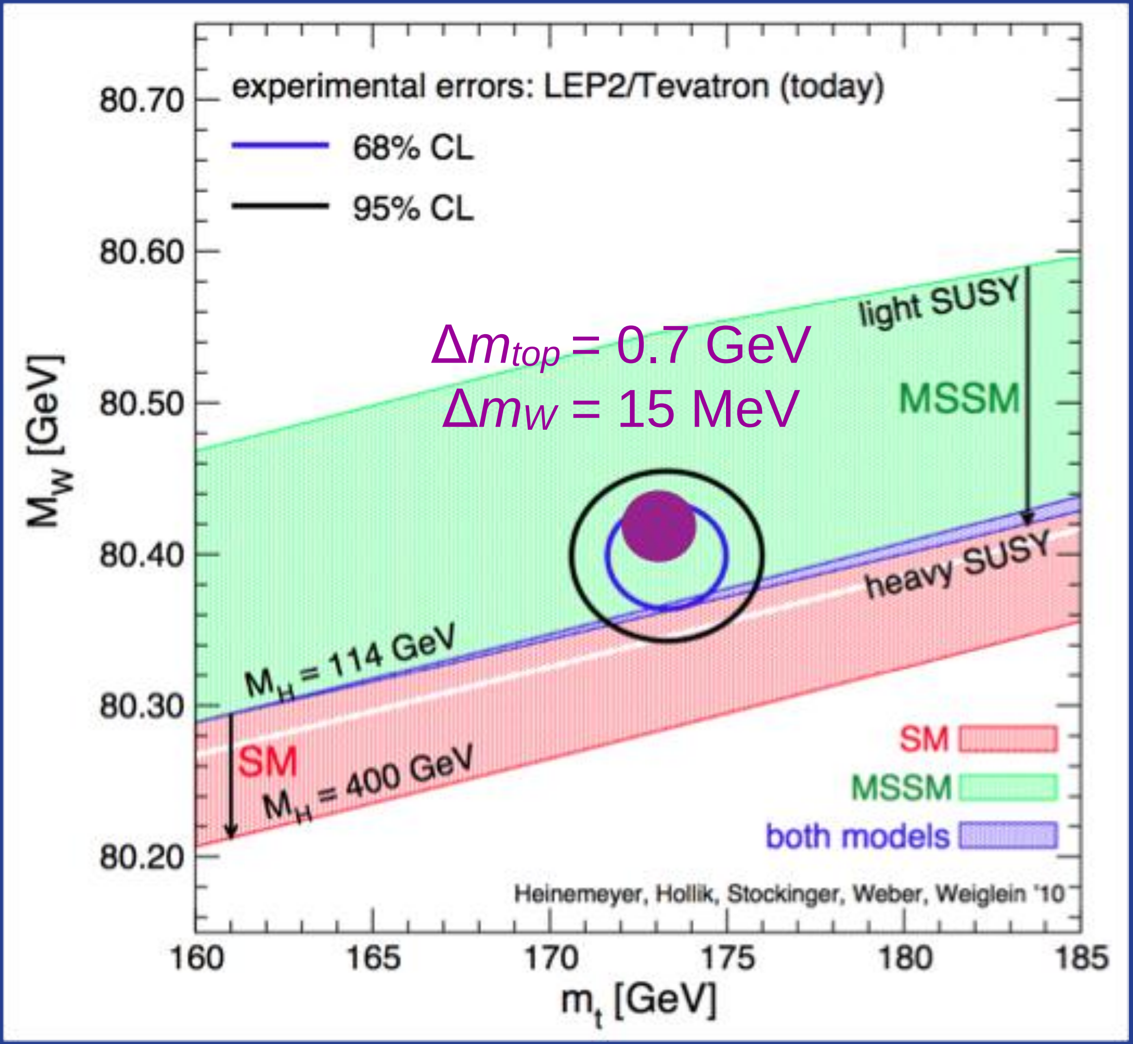
70% of the *W* bosons emitted in top decay are longitudinally polarized, rest left-handed

Electroweak single top production observed

Lifetime close to 0.3 yoctosecond

Spin correlations accord with standard model

Higgs mass in the electroweak theory



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Standard-model Higgs Search

The ultimate challenge for the Tevatron

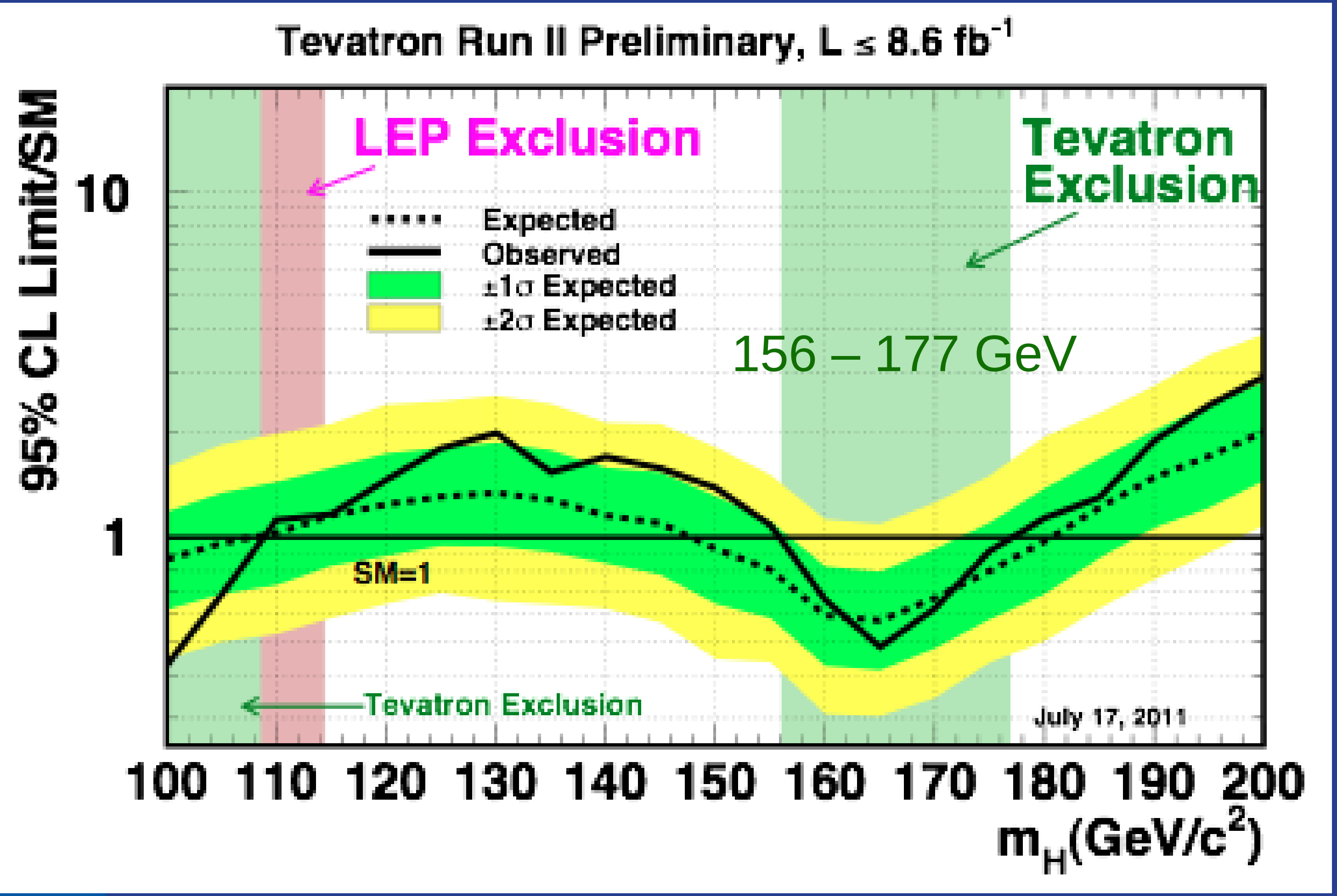
$gg \rightarrow H$

$qq \rightarrow WH$ or ZH

$VV \rightarrow H$

dozens of distinct final states

Standard-model Higgs search



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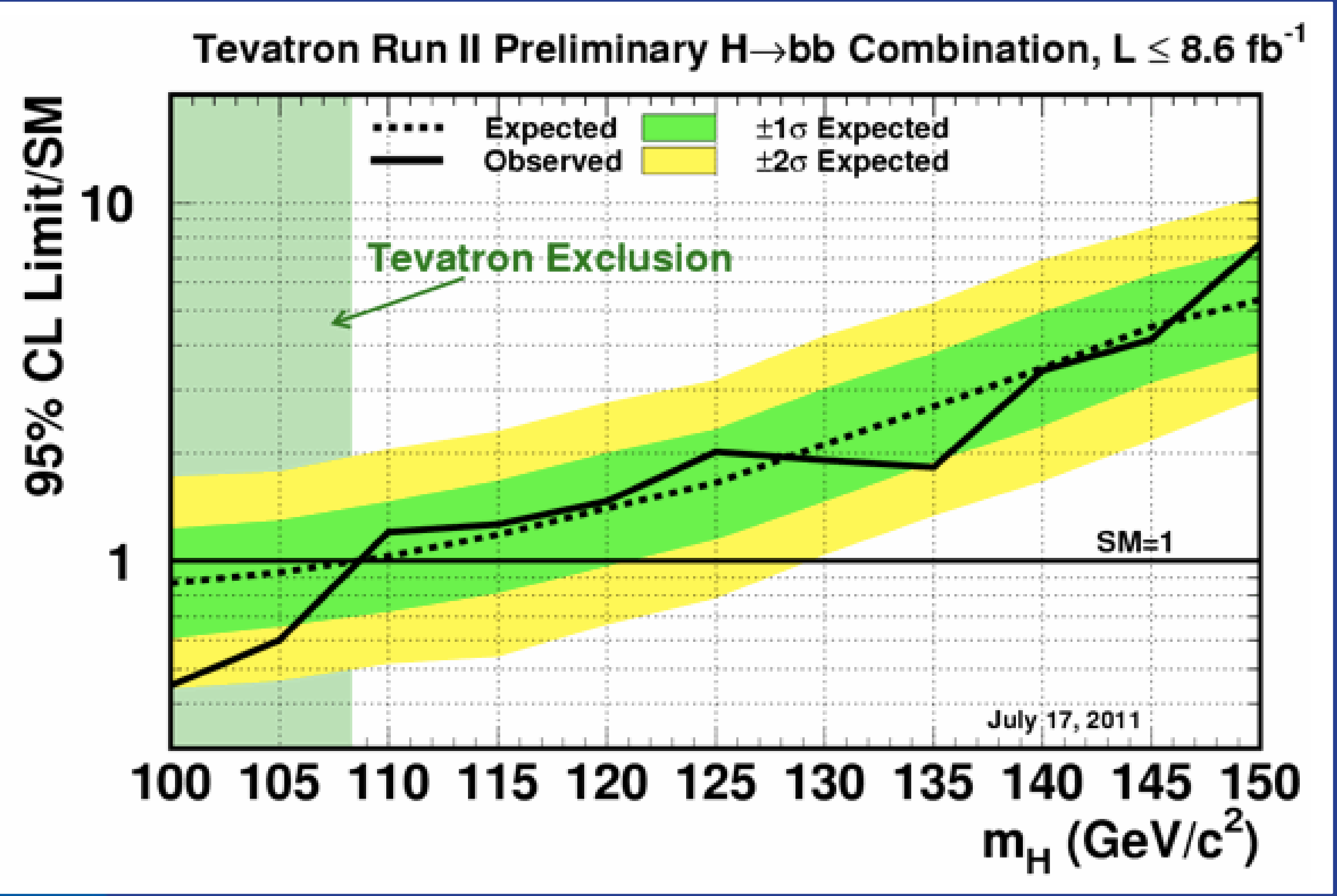
Standard-model Higgs → bb search



Higgs Boson: 10 fb^{-1} projections

95% CL exclusion for

M_H < 185 GeV

3σ “evidence” possible for

M_H < 120 GeV

150 < 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+DØ)

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

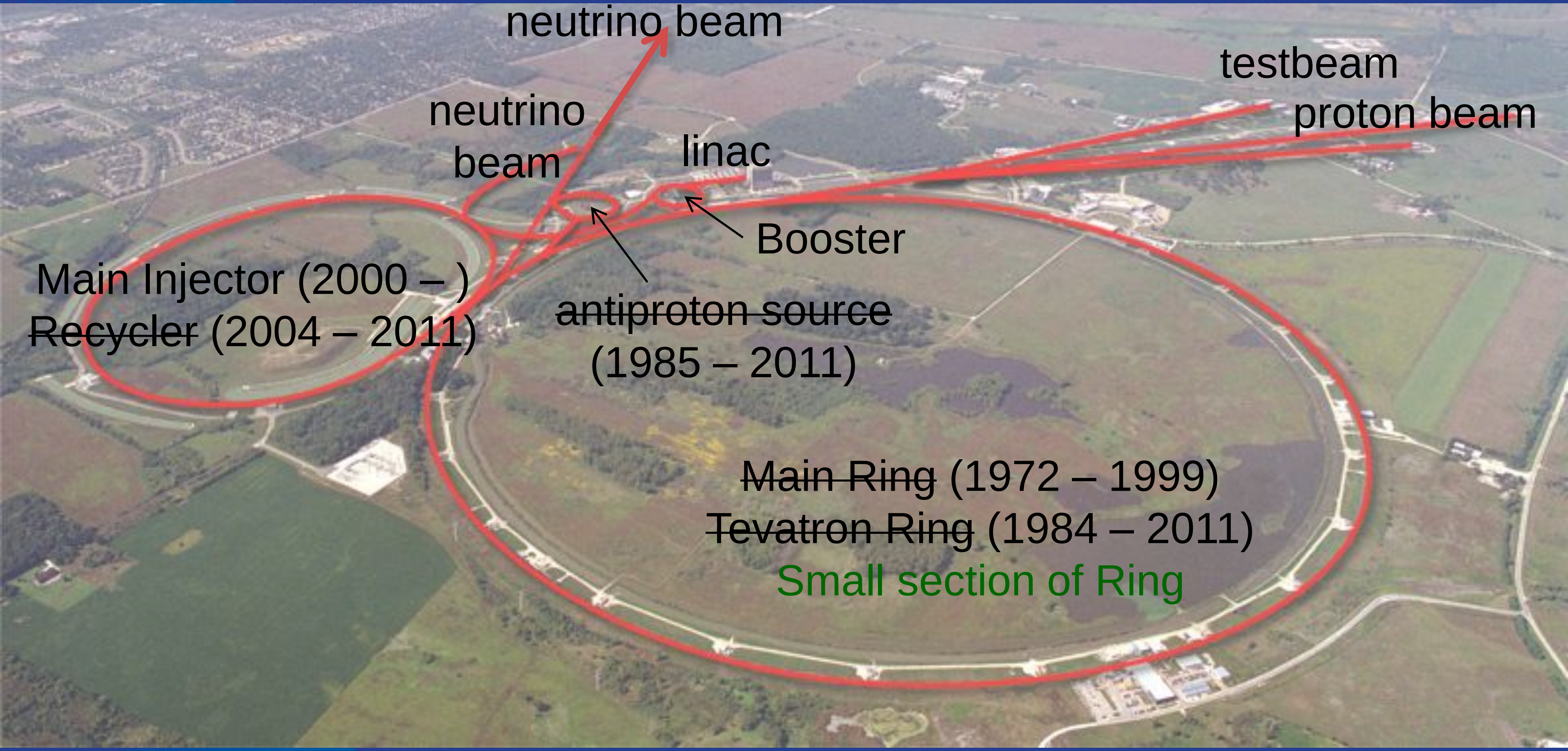
Excess of jet pairs + W
(CDF–DØ)

Work in progress at Tevatron and LHC

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

Fermilab Accelerator Complex (now)



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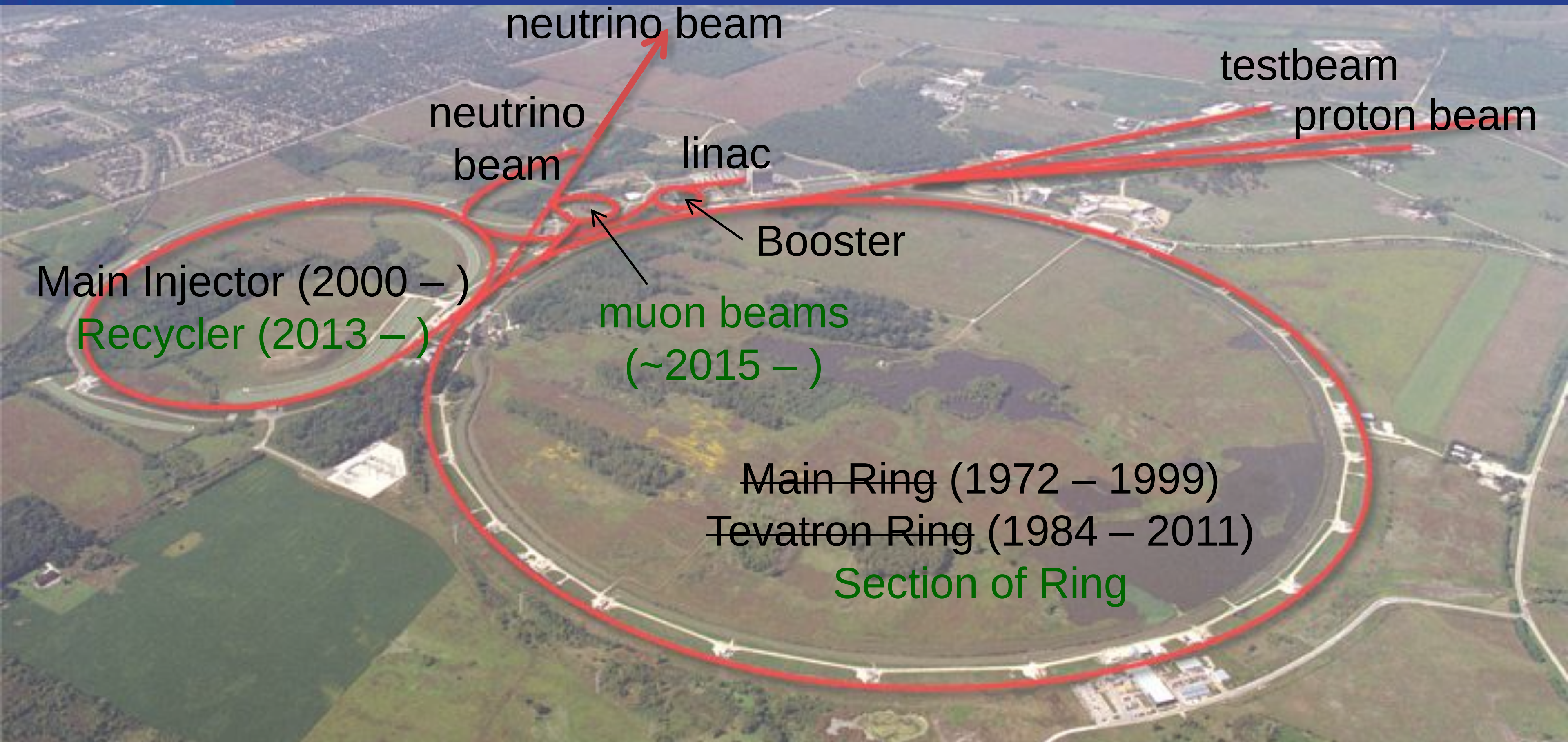
Accelerator Complex (in a couple of years)



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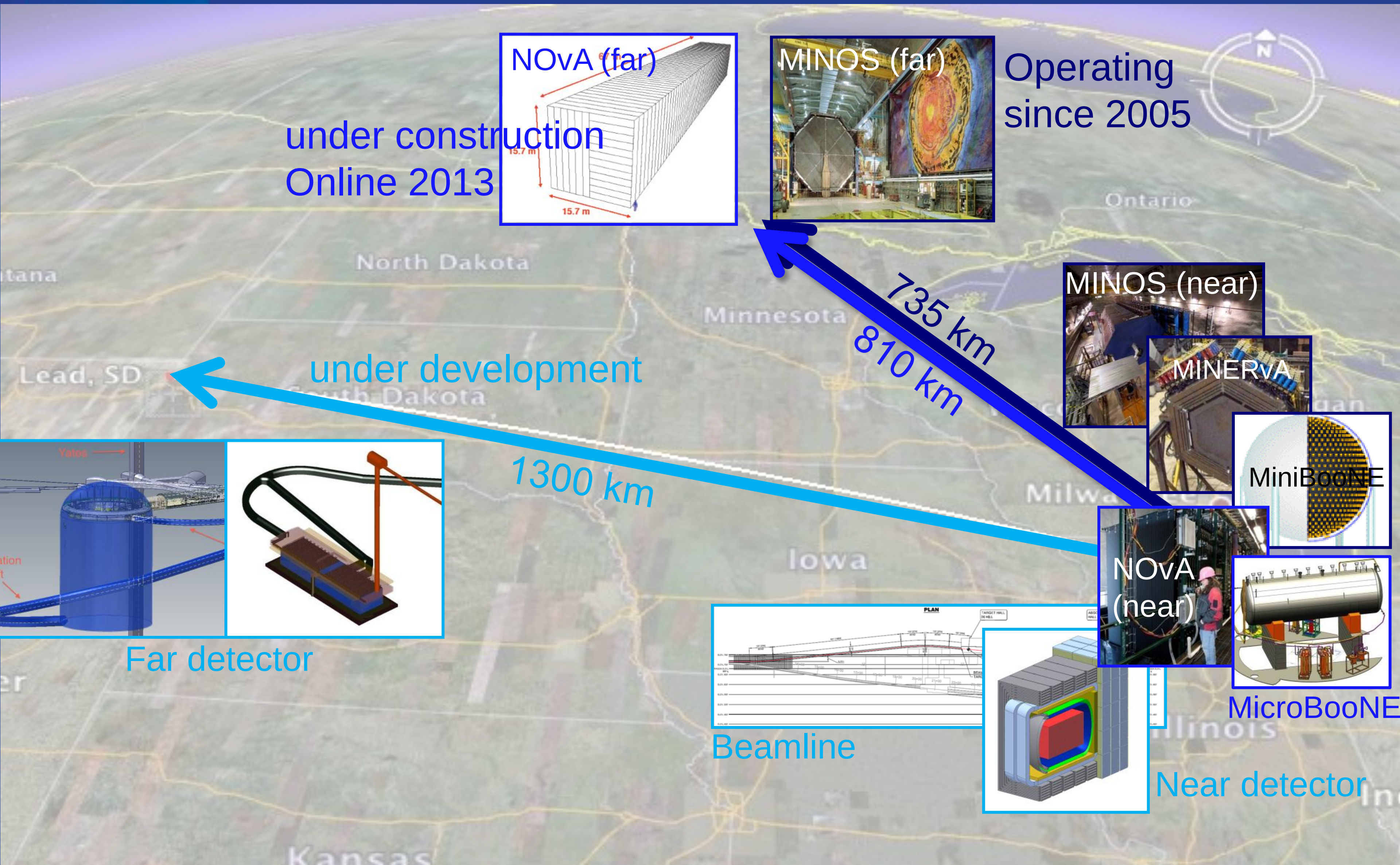
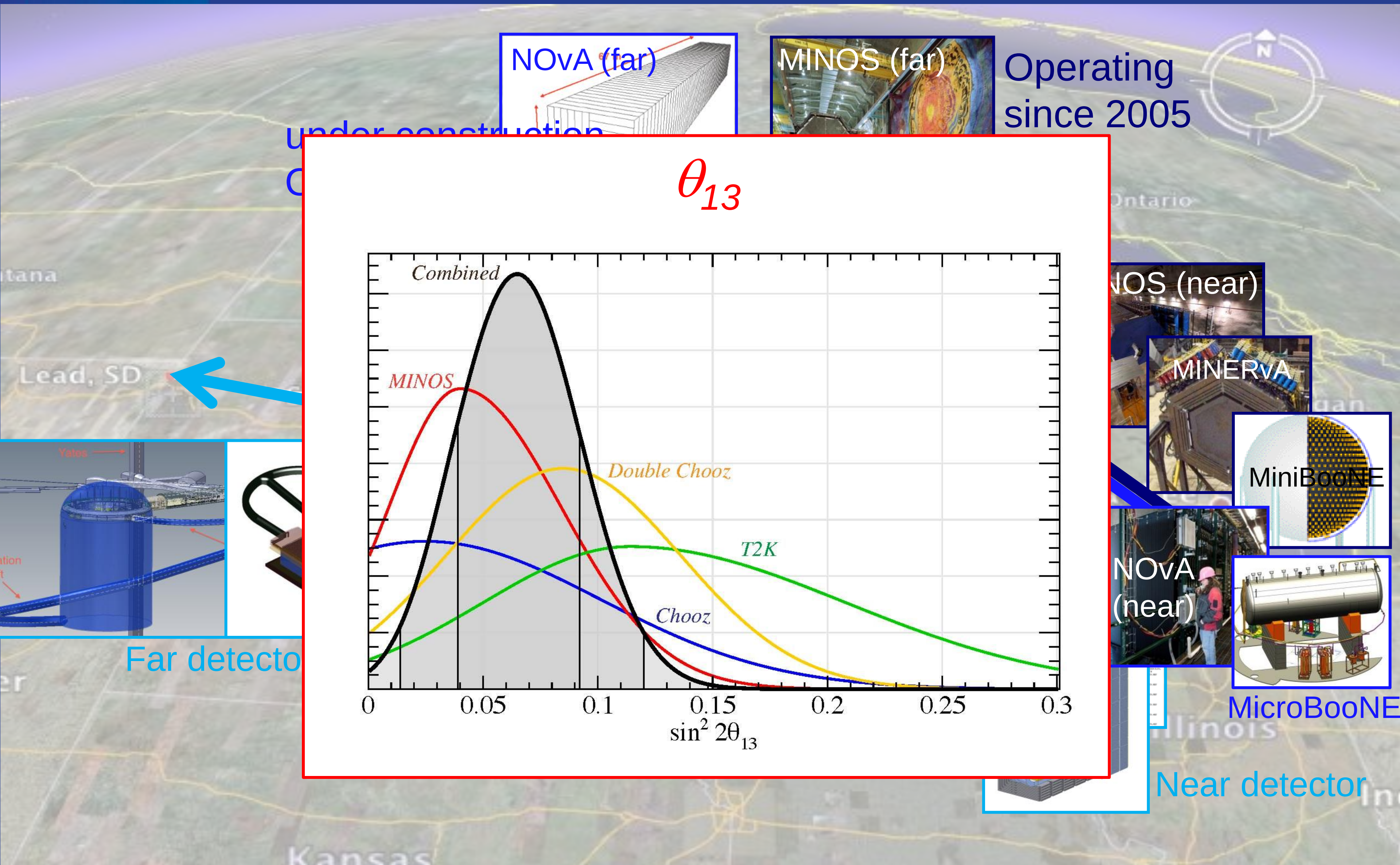
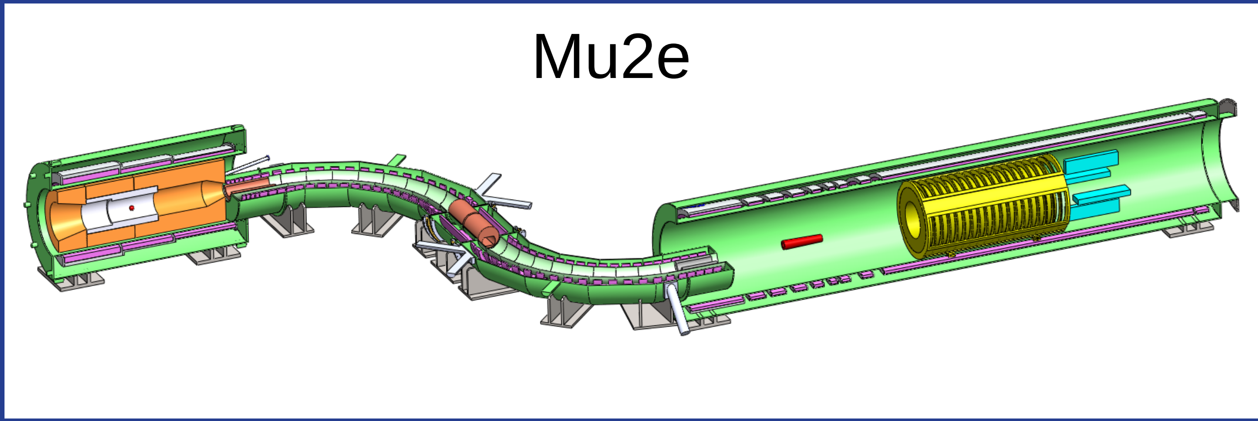
Neutrino Program

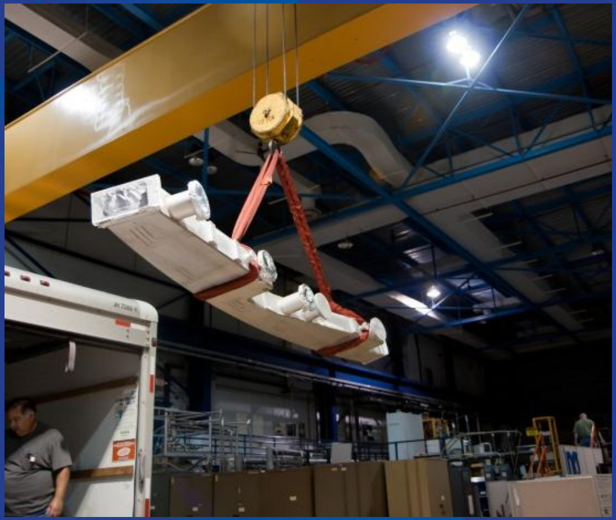


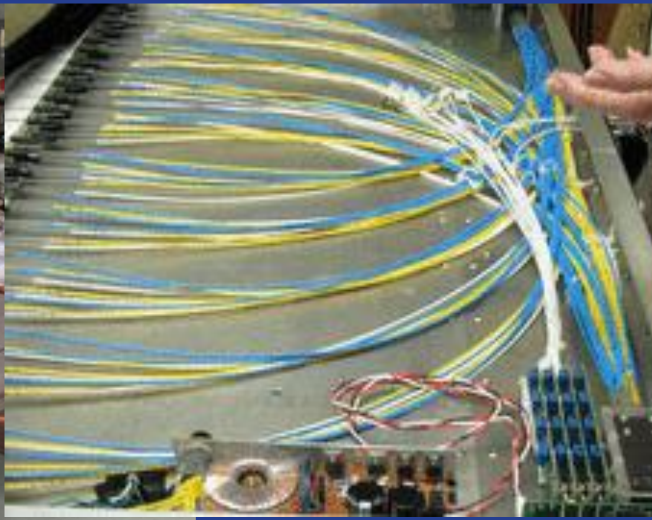
Neutrino Program



New Muon Program (this decade)







Project X

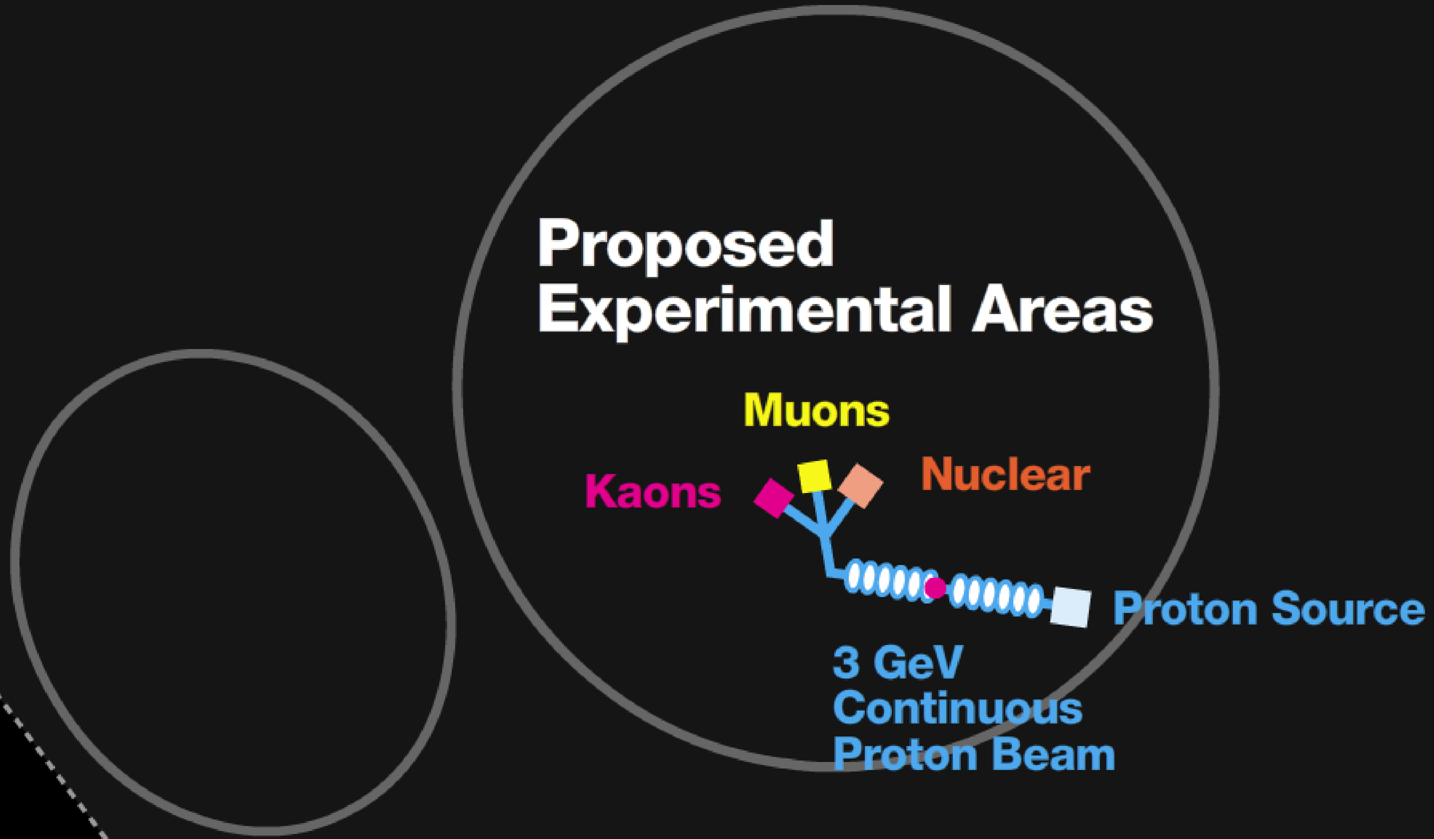
will be the world's most powerful proton source

will make the world's most powerful beams of neutrinos, muons, kaons and nuclei to explore new physics in unprecedented breadth and depth

will establish a versatile technical foundation for future accelerators

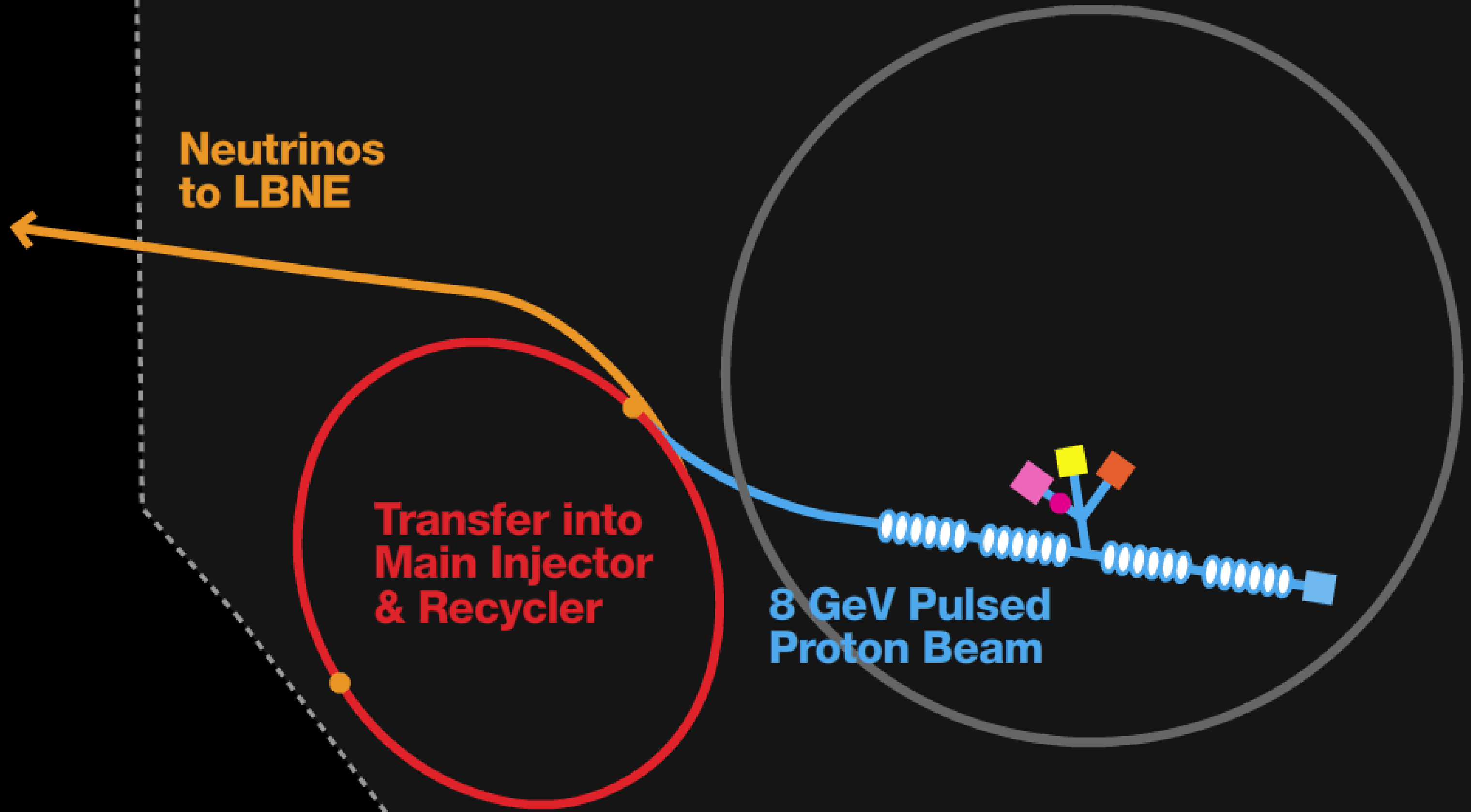
Project X: Low-energy Program

Highest-intensity proton accelerator in the world



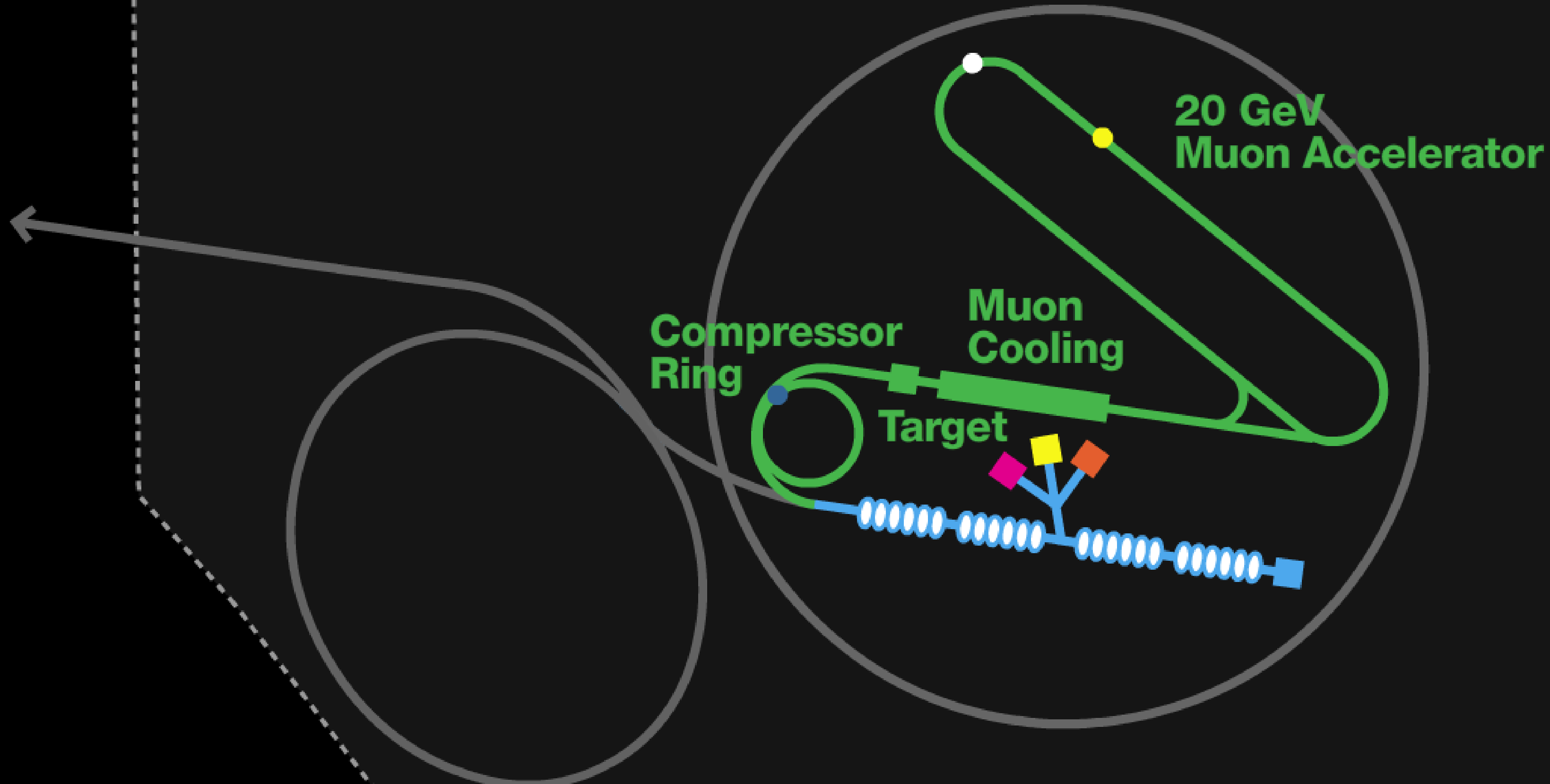
Project X: High-energy Program

More beam for high-intensity neutrino experiments



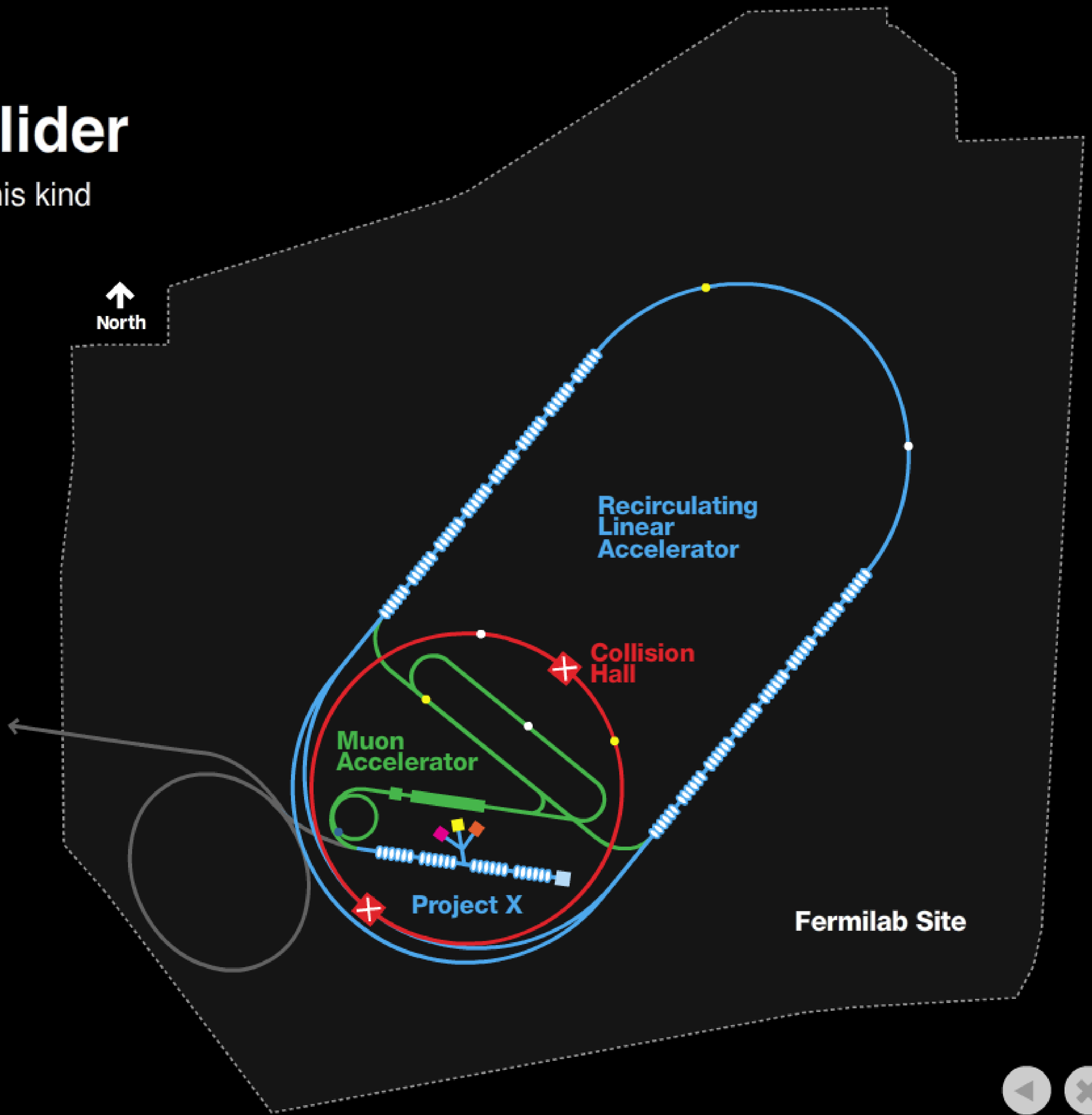
Muon Beamline & Neutrino Factory

Highest-intensity muon and neutrino source in the world



Muon Collider

The first collider of this kind



Fermilab Program

NuMI (120 GeV): 350 kW
Booster (8GeV): 35 kW

NuMI (120GeV): 700 kW
Booster (8GeV): 80 kW

Project X:
>2MW @ 120 GeV
3MW @ 3 GeV
150 kW @ 8 GeV

Neutrino Factory

LHC
Tevatron

LHC Upgrades in luminosity and energy

Lepton Colliders

Dark Matter, Dark Energy, Ultra High Energy Cosmic Particles

Accelerator/Detector/Computing Technology Development

Completion of an era: Tevatron Collider

Accelerator Innovations

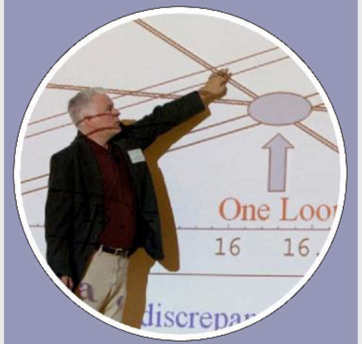
- First major SC synchrotron
- Industrial production of SC cable (MRI)
- Electron cooling
- New RF manipulation techniques

Detector innovations

- Silicon vertex detectors in hadron environment
- LAr-U238 hadron calorimetry
- Advanced triggering

Analysis Innovations

- Data mining from Petabytes of data
- Use of neural networks, boosted decision trees
- Major impact on LHC planning and developing
- GRID pioneers



Major discoveries

- Top quark
- B_s mixing
- Precision W and Top mass → Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica
- >1,000 publications

The next generation

- Fantastic training ground for next generation
- More than 500 Ph.D.s
- Produced critical personnel for the next steps, especially LHC

We look forward to
watching our new programs grow