Tevatron

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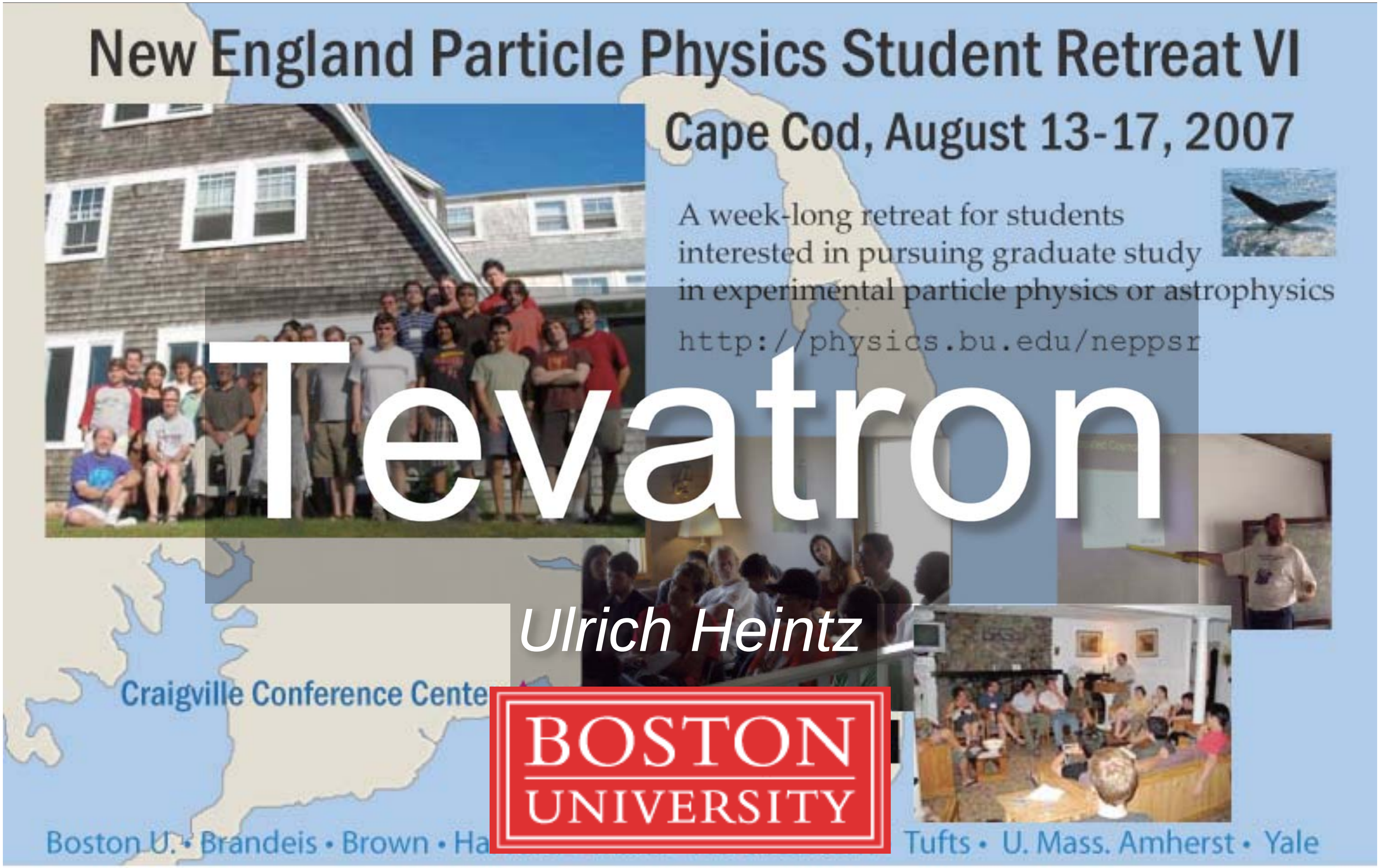
BOSTON UNIVERSITY



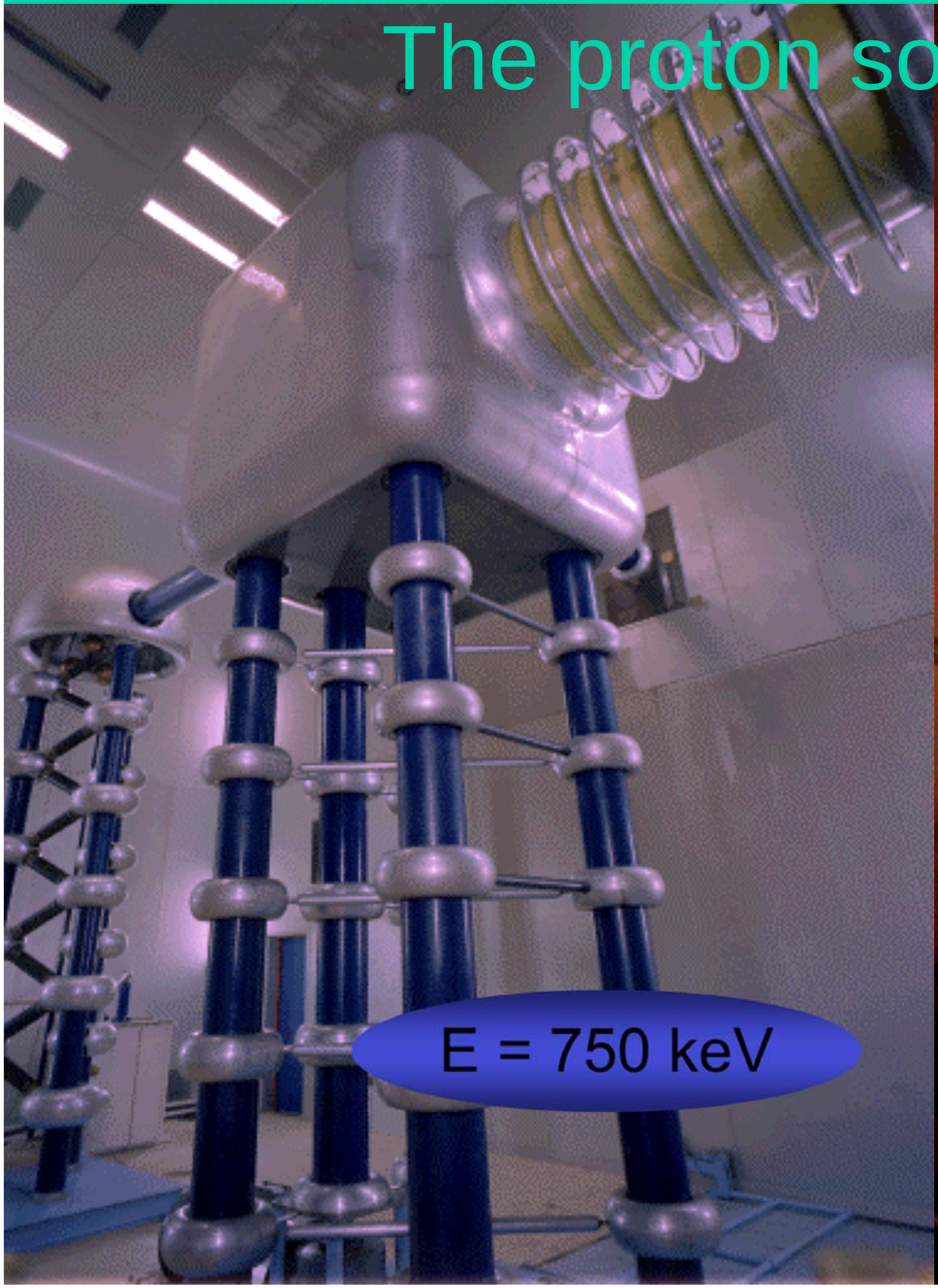
Outline

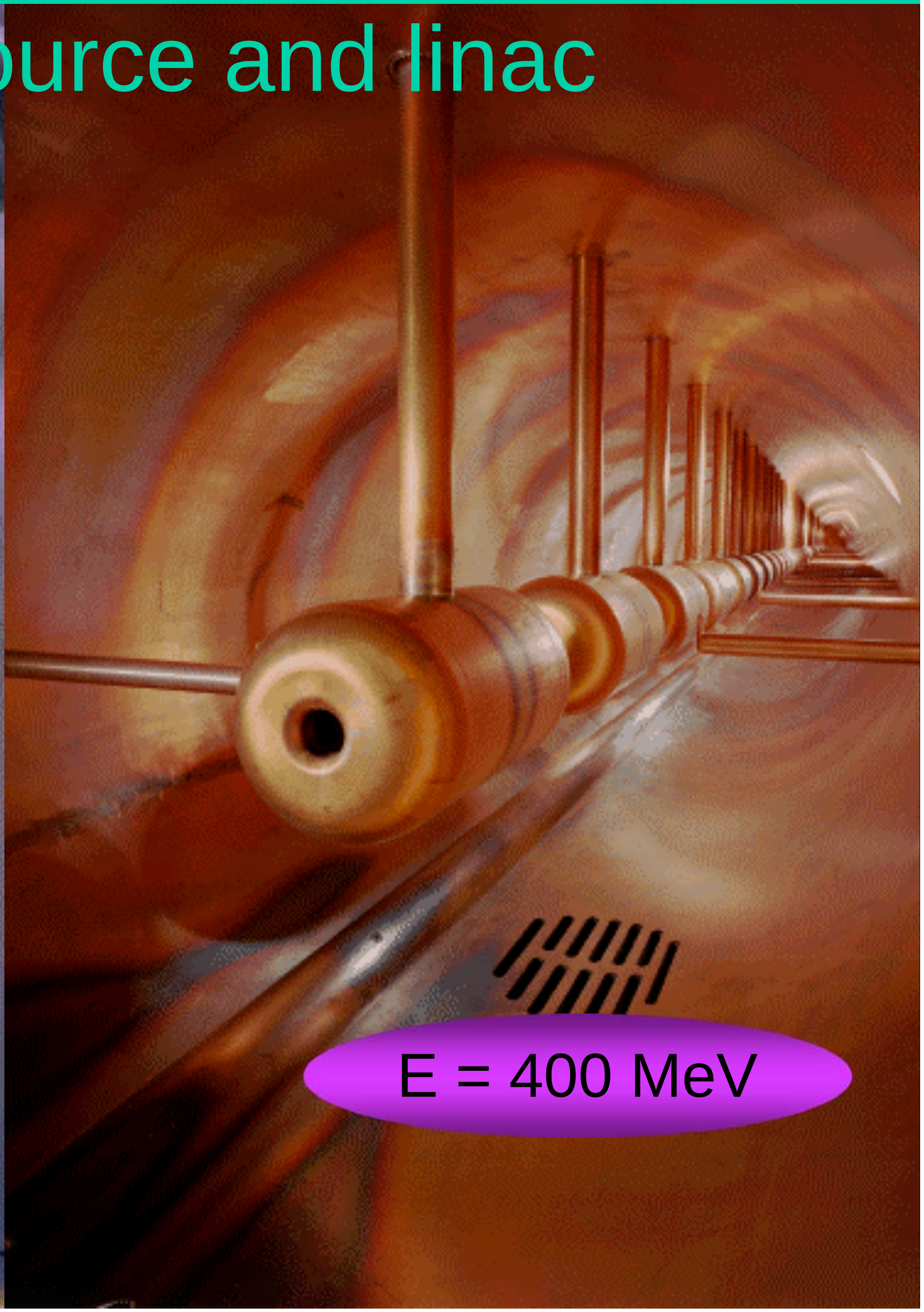
- Fermilab
- QCD
- b-quark physics
- electroweak physics
- top quark physics
- the Higgs boson
- new physics
- summary

Fermilab

- accelerator
- experiments
  - D0
  - CDF

The proton source and linac





Fermilab

The main injector

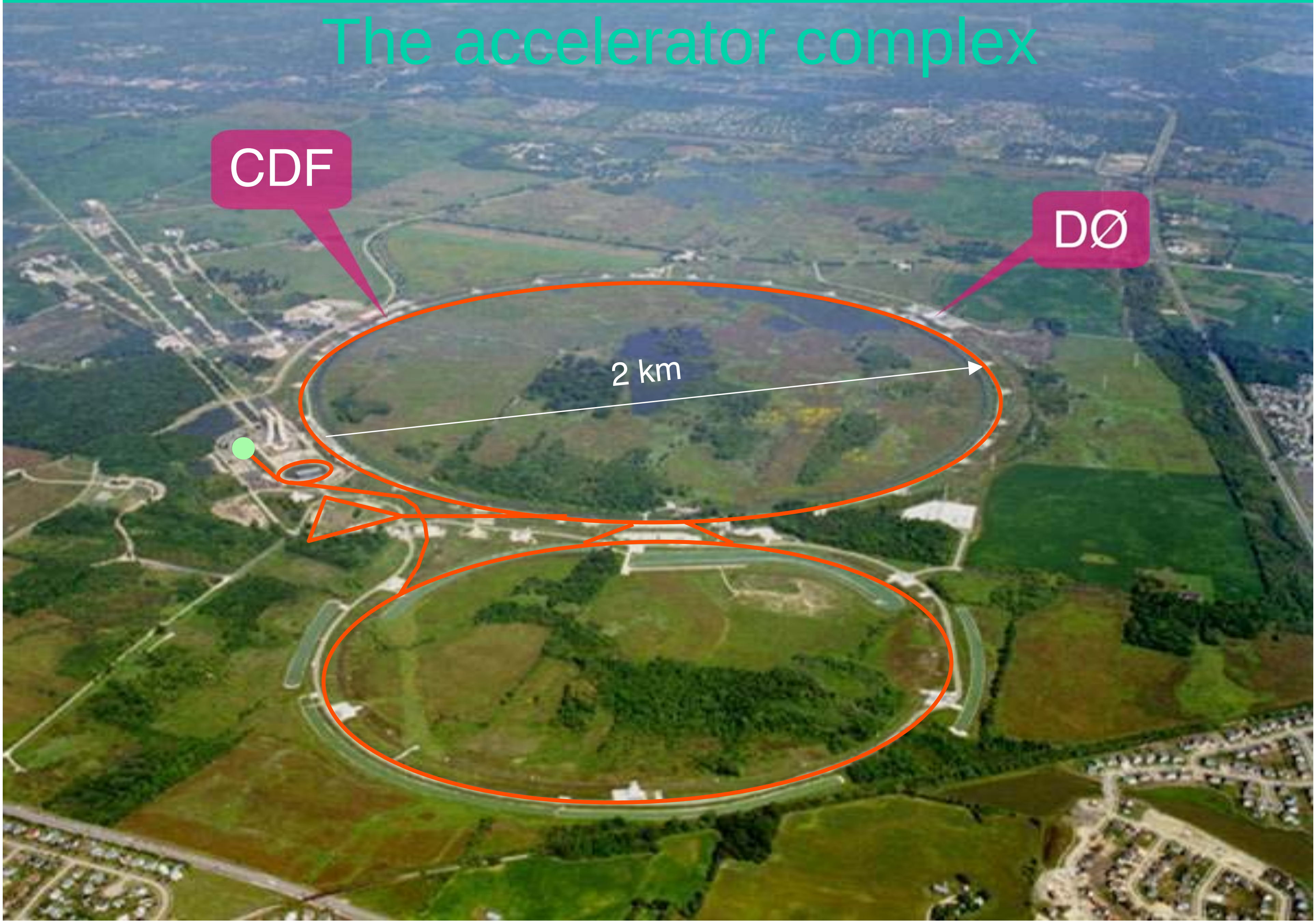
Fermilab

The Tevatron

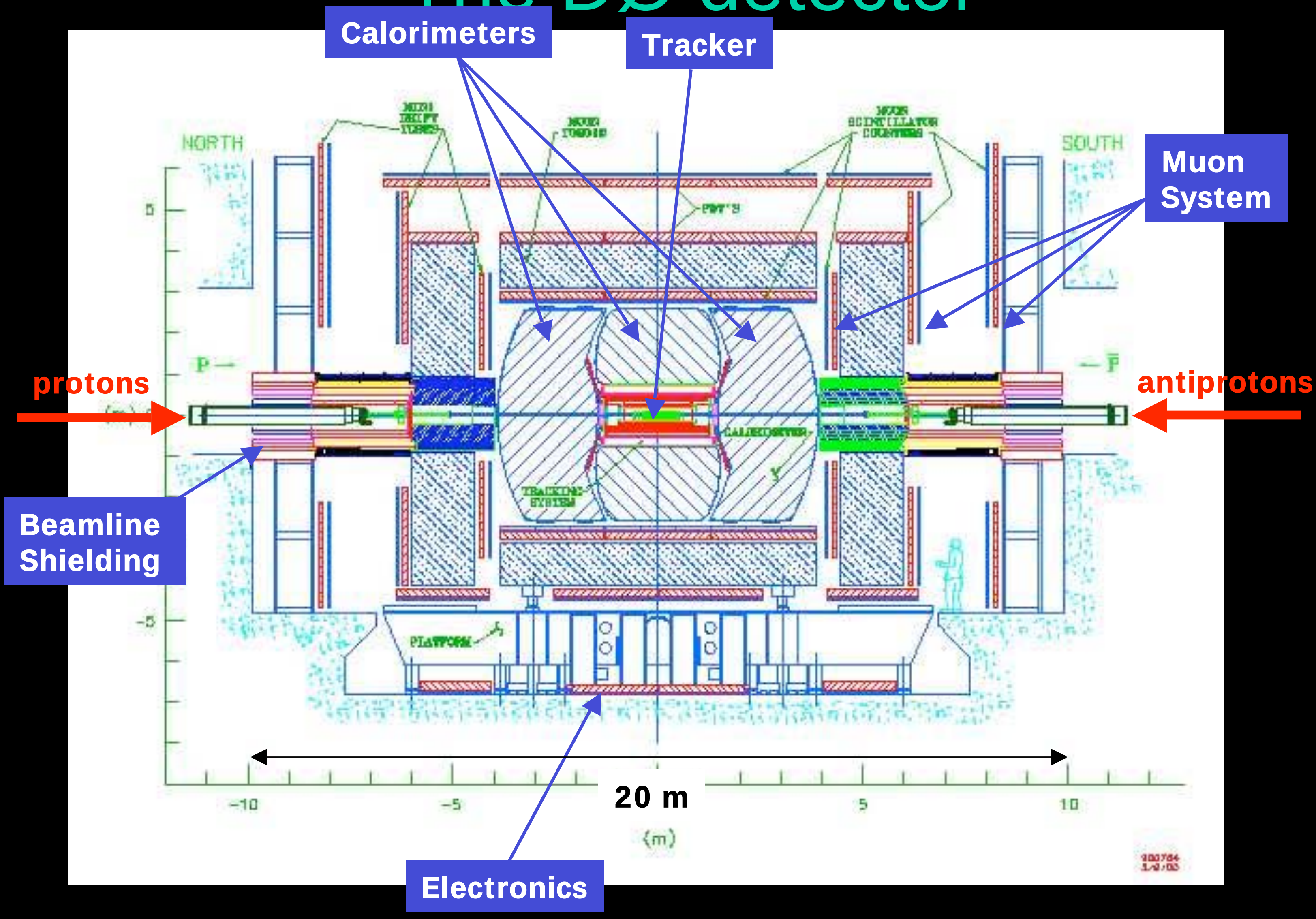
- collides beams of protons and antiprotons
- beam energy = 980 GeV
- 2×10^{11} protons in 36 bunches
- 2×10^{10} antiprotons in 36 bunches
- time between collisions = 396 ns

E = 1 TeV

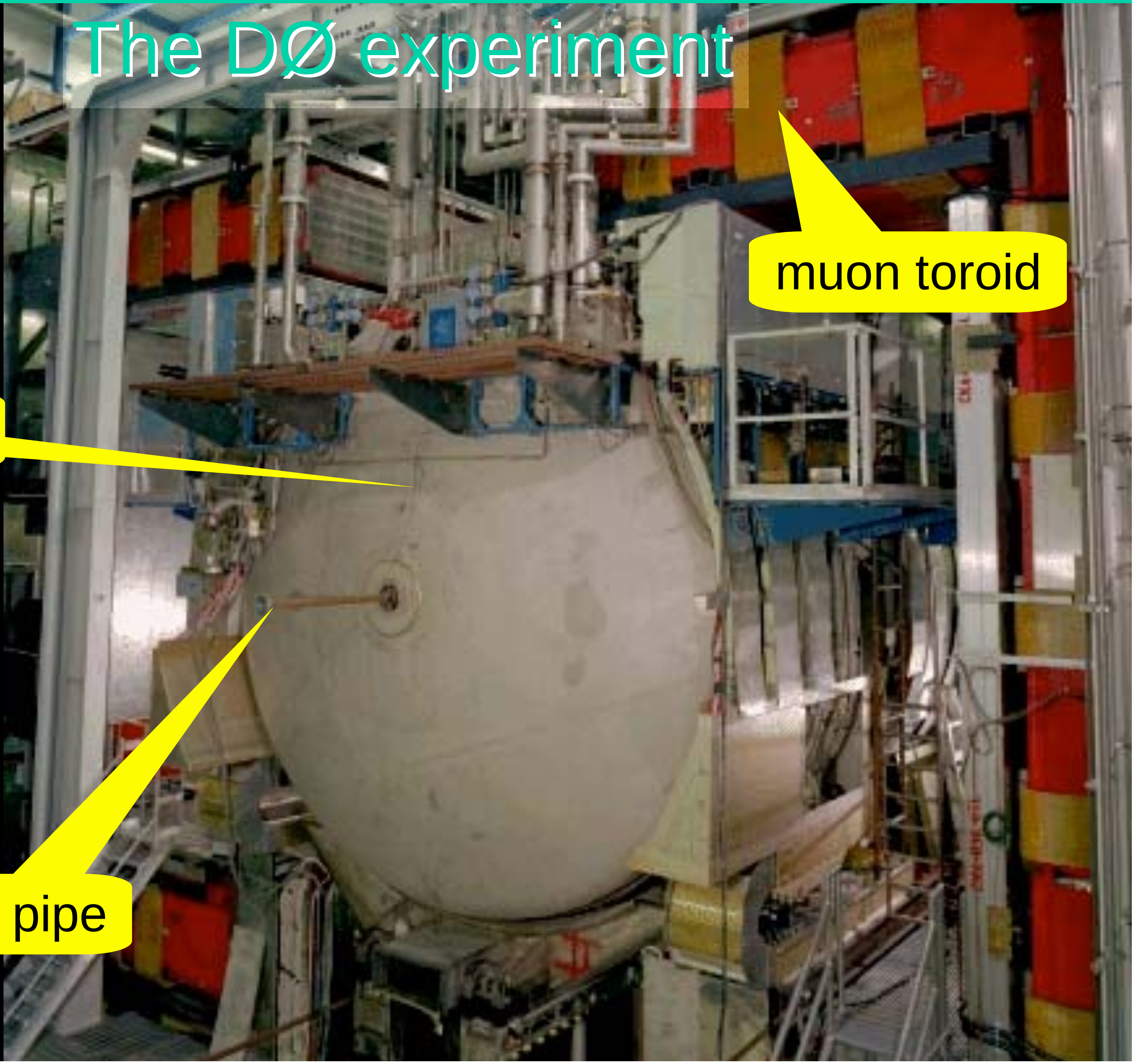
The accelerator complex



The DØ detector



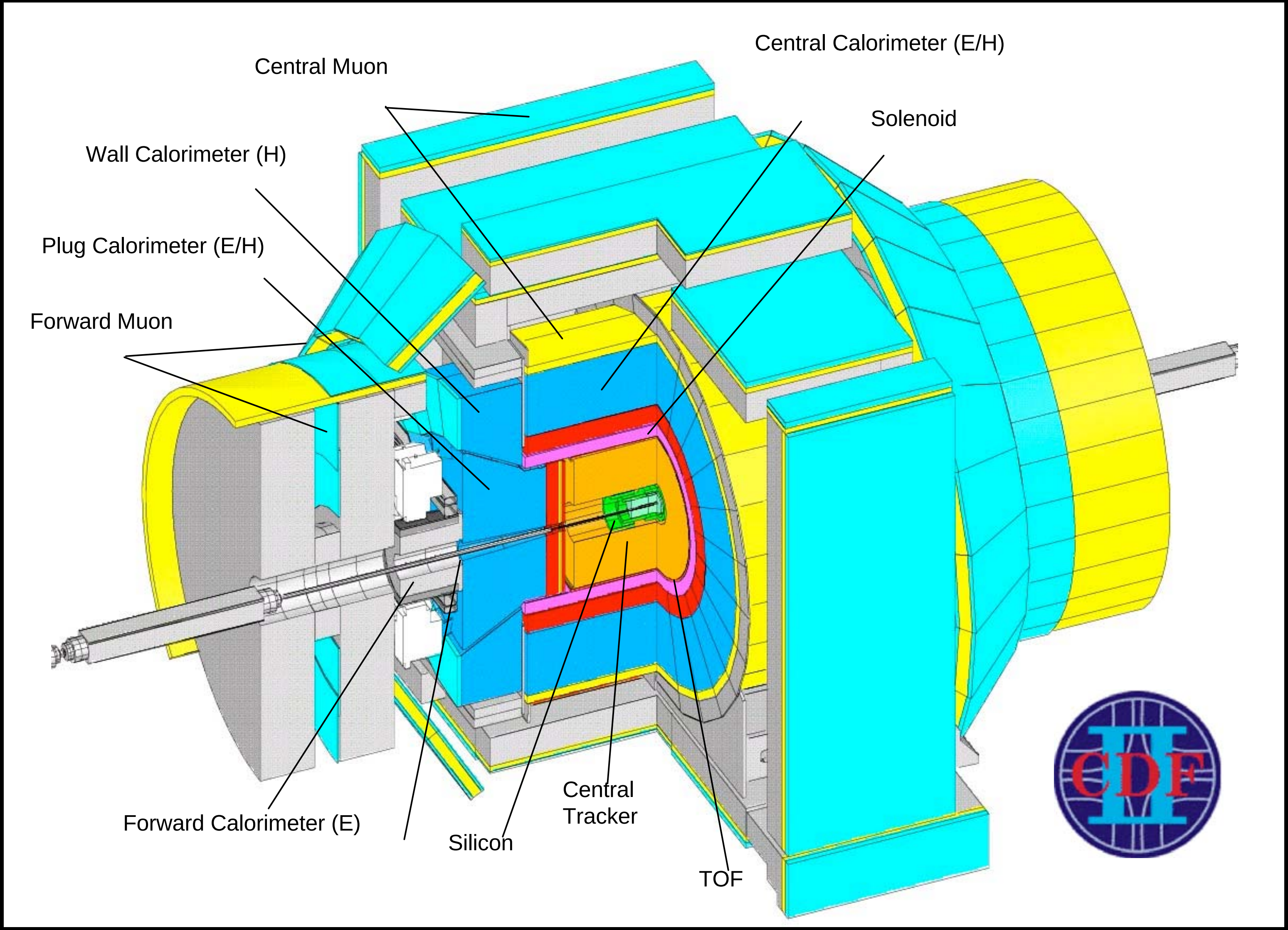
The DØ experiment



Fermilab

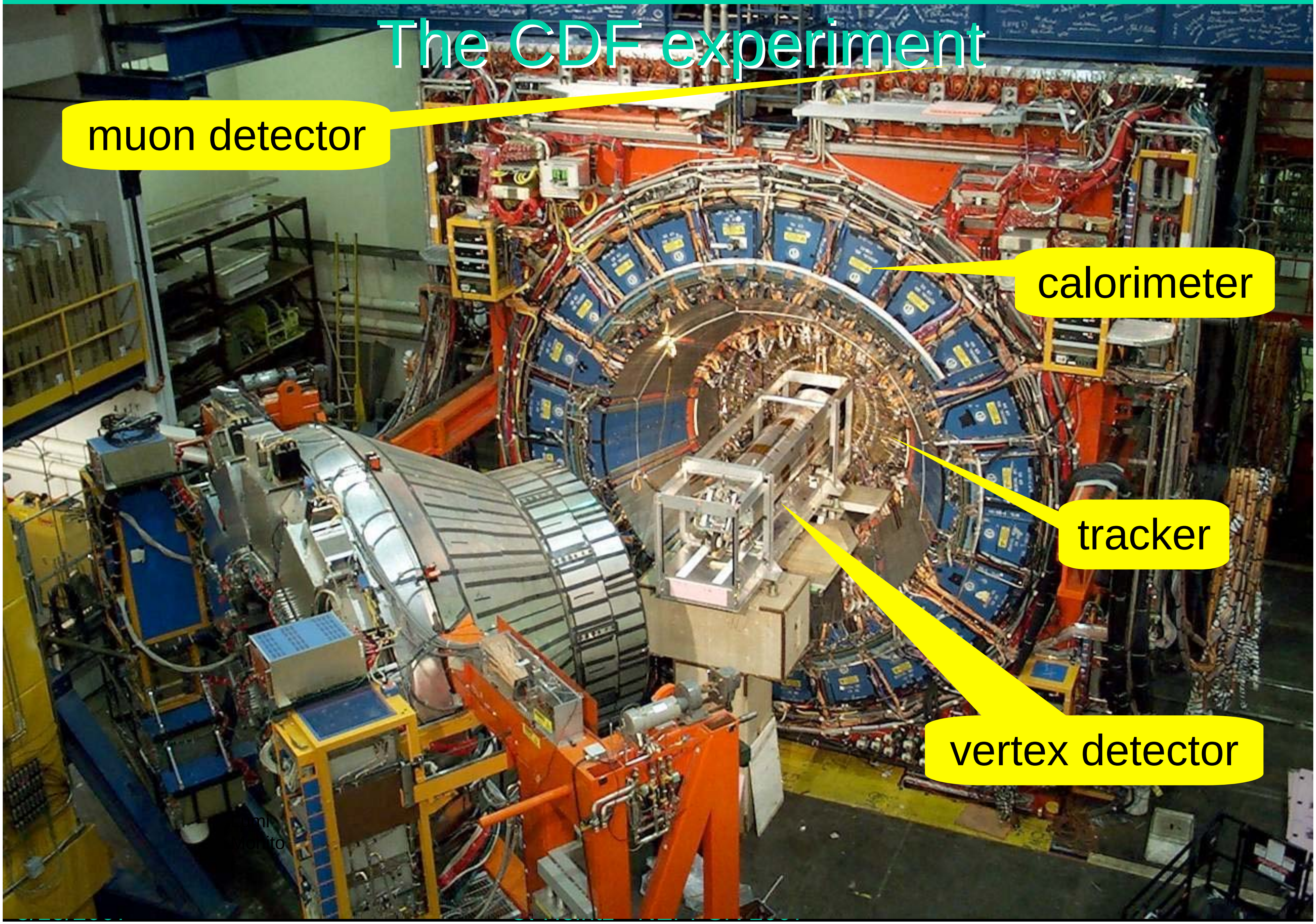
The DØ muon spectrometer

The CDF experiment



Fermilab

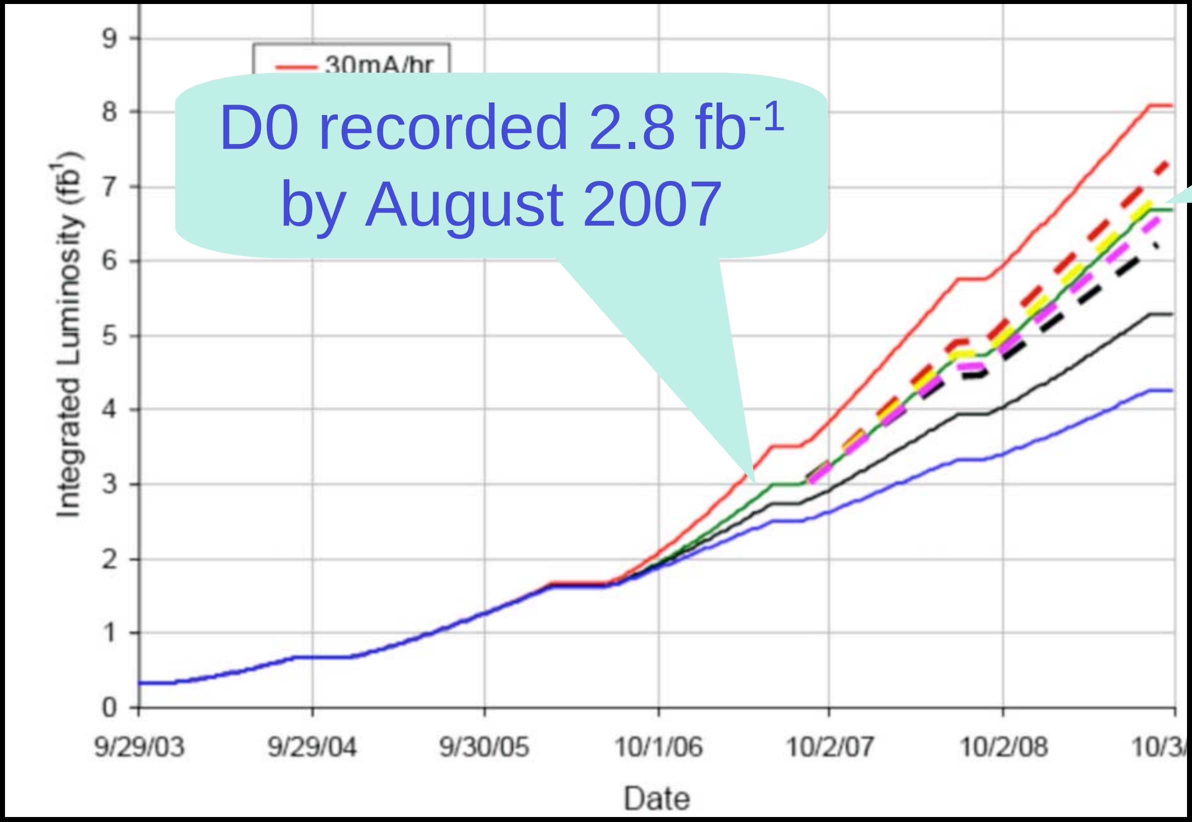
The CDF experiment



Tevatron performance

peak luminosity = $2.8 \times 10^{32} cm^{-2} s^{-1}$

most luminous hadron collider ever



D0 recorded 2.8 fb^{-1} by August 2007

expect 6-7 fb^{-1} by 2009

why is the Tevatron interesting?

we have data
at the highest
com energy

the physics landscape in 1984

1974: J/Ψ discovery (BNL/SPEAR)
1975: SPEAR jets observed
1976: Open charm, tau discoveries (SPEAR)
1977: Upsilon discovery (FNAL)
1982: Open beauty meson discovery (CLEO)
1983: W/Z discoveries (CERN)
1984: High p_T jets seen at UA2
UA1: Monojets (jets with large missing E_T) ??
UA1/UA2: anomalous $Z \rightarrow \ell^+ \ell^- \gamma$??
UA1: $W \rightarrow t\, b$ top evidence ??

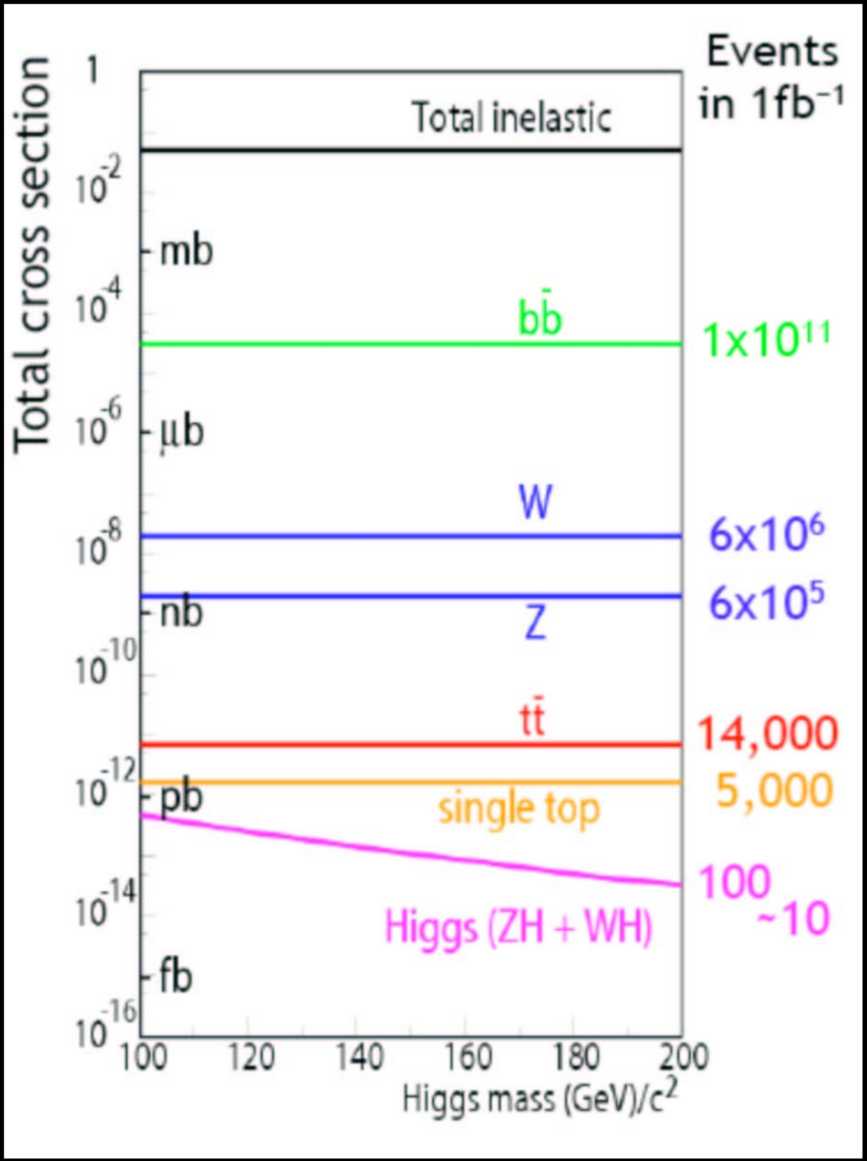
A decade of discovery!

There was a sense of excitement and discovery in the air - skepticism about tantalizing fluctuations was suspended.

Paul Grannis

QCD

QCD allows to calculate production cross sections

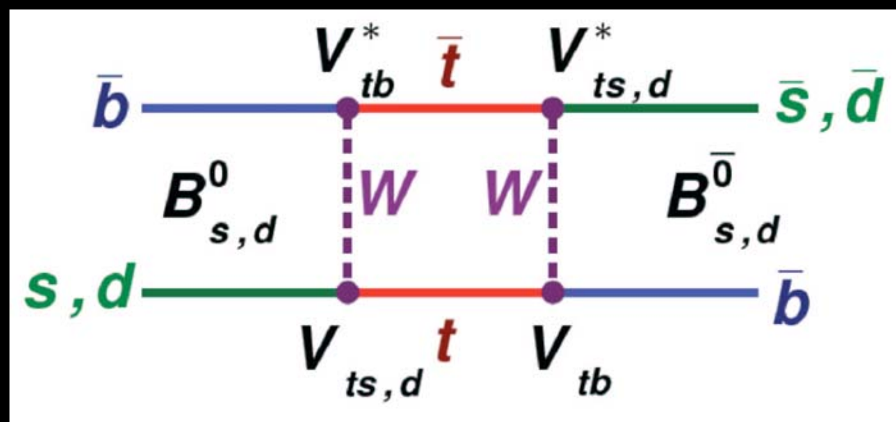


b-quark physics

- B_s mixing
- new states

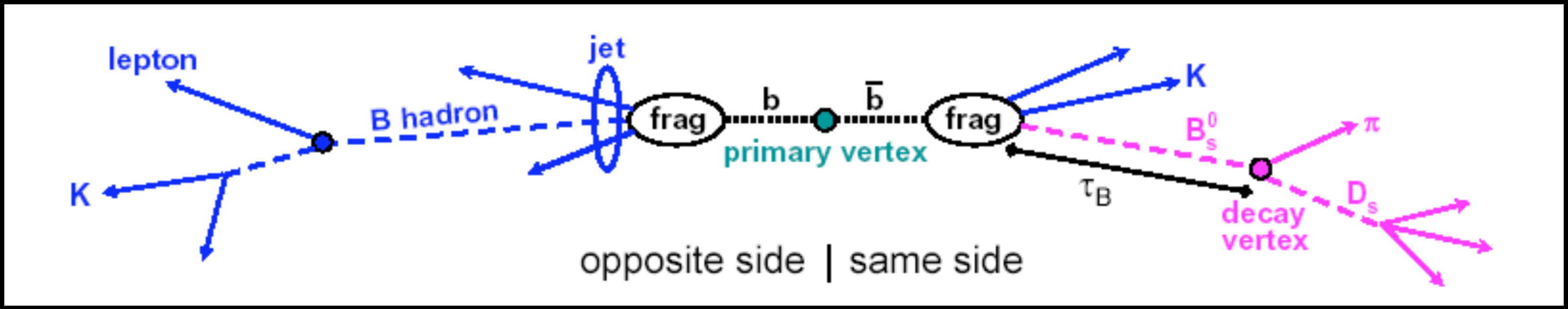
B_s mixing

mixing measurements in B_d and B_s systems allow access to CKM elements



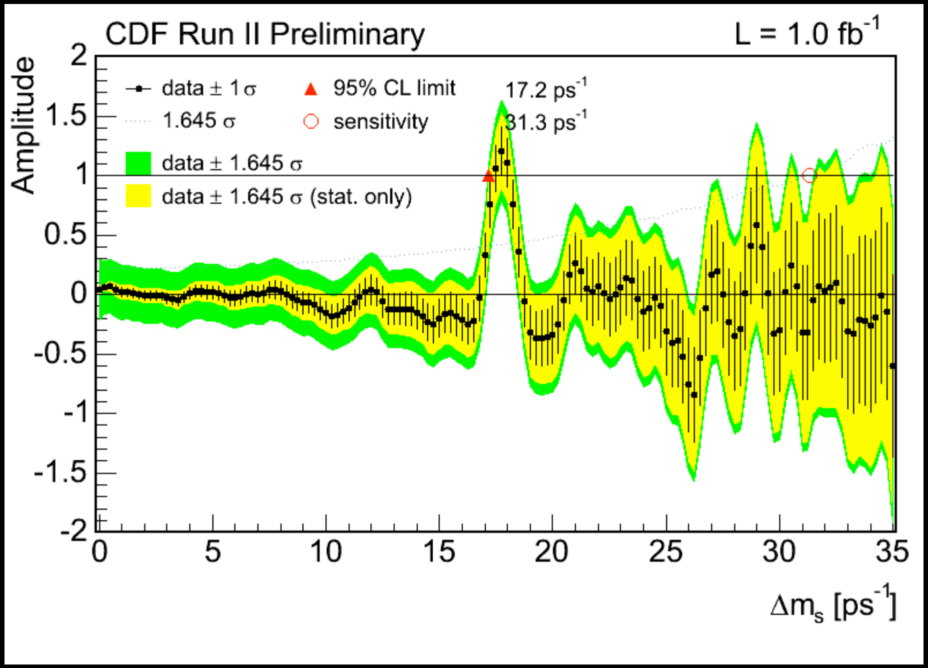
Δm_d is well measured
0.509§0.004 ps^{-1}

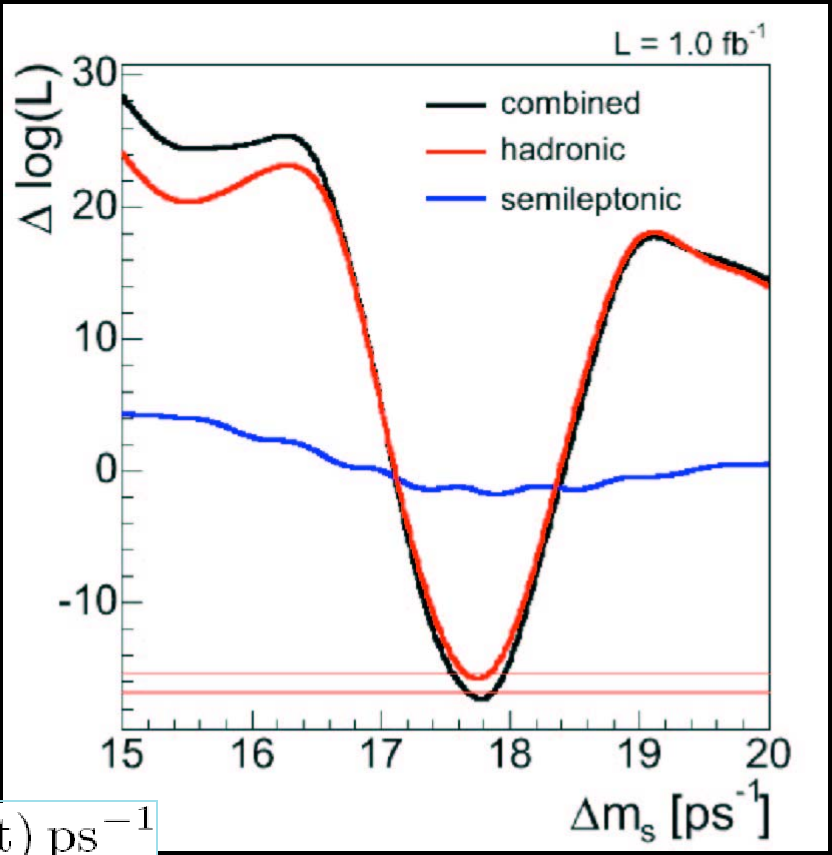
B_s mixing



- measurement of production flavor
  - OS kaon charge b!c!K^-
  - SS kaon charge
  - lepton charge b!X l^- but b!c!X^+
  - jet charge
- measurement of decay flavor
  - reconstruct specific decay mode
- measurement of proper decay time
  - $\tau = m_B\, L_T/p_T$

B_s mixing

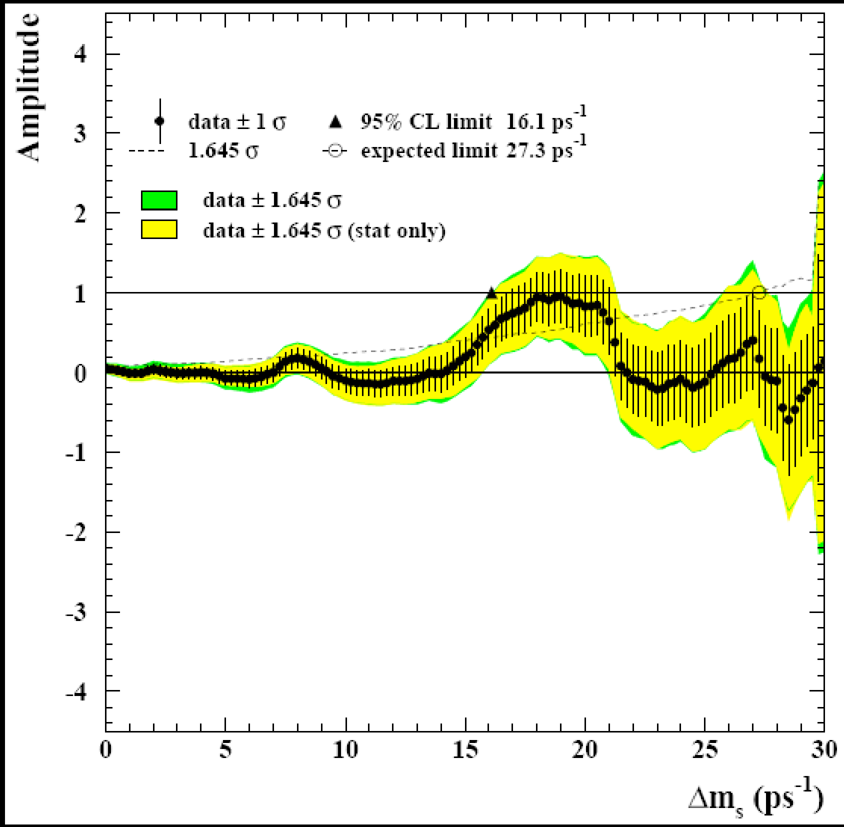


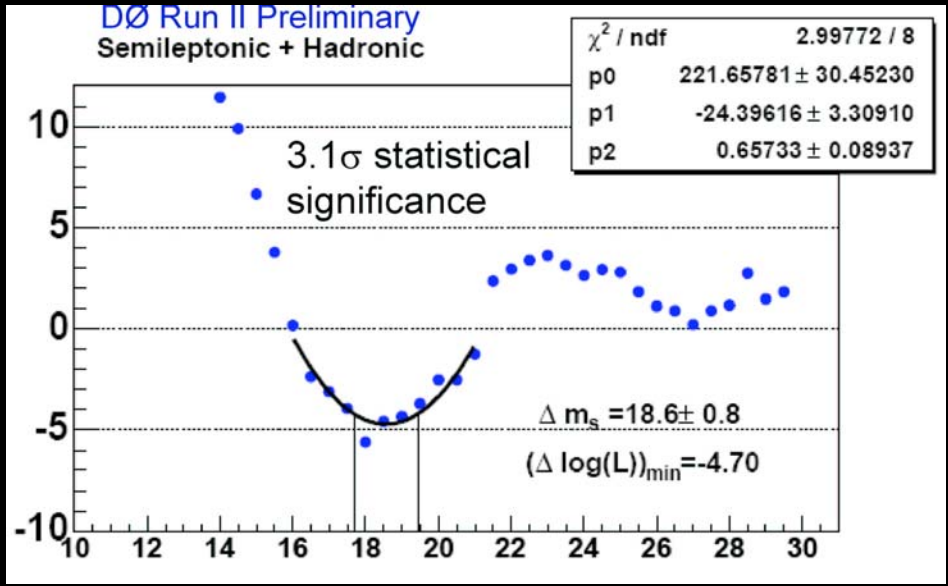


$$\Delta m_s = 17.77 \ \pm 0.10 \ (\text{stat}) \ \pm 0.07 \ (\text{syst}) \ \text{ps}^{-1}$$

$$|V_{td}/V_{ts}| = 0.2060 \ \pm 0.0007 \ (\text{exp}) \ ^{+0.0081}_{-0.0060} \ (\text{theor})$$

B_s mixing



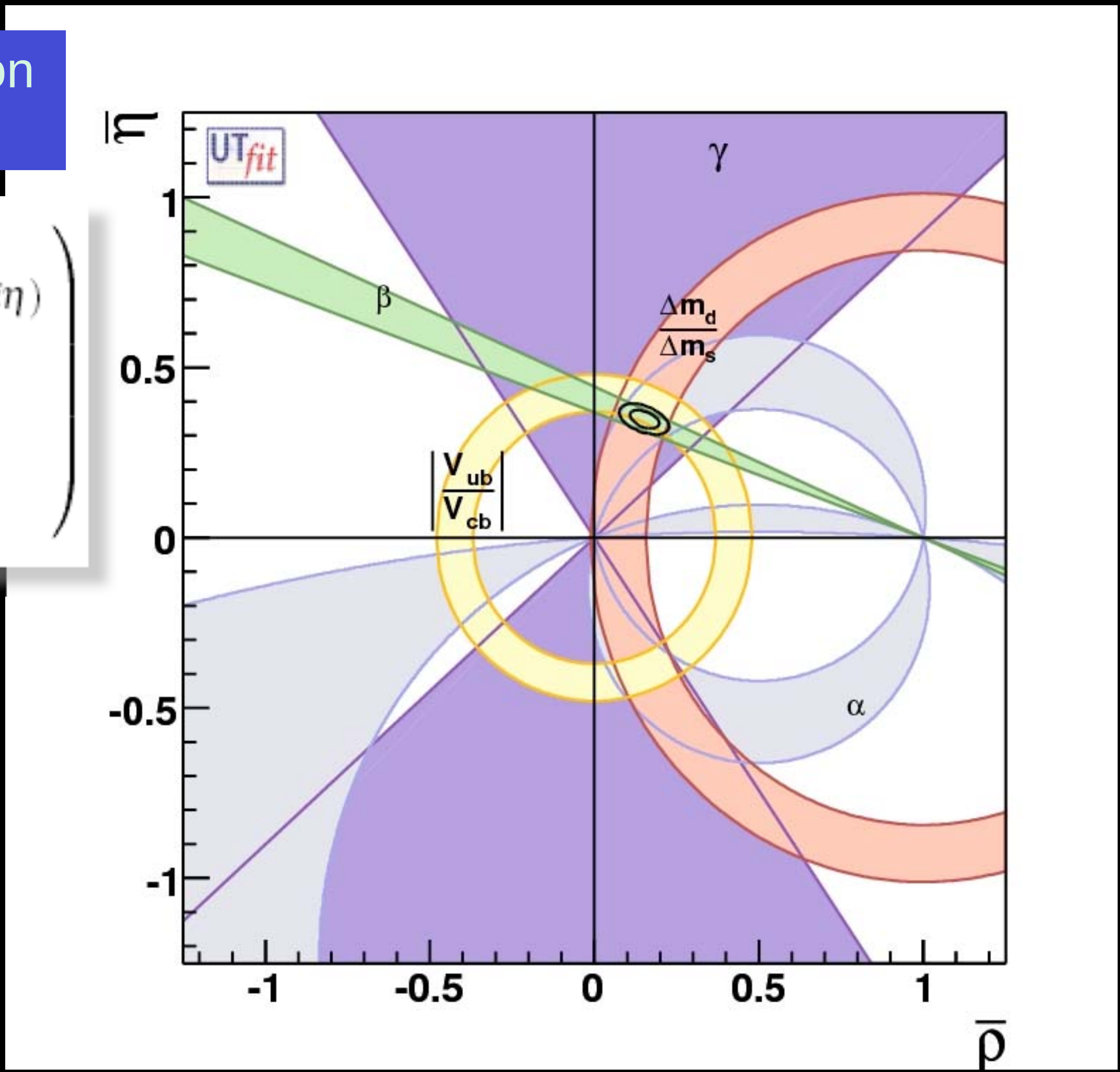


$$\Delta m_s = 18.56 \pm 0.87 \text{ ps}^{-1}$$

B_s mixing

Wolfenstein parametrization of CKM matrix

$$\begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



discovery of the Ξ_b baryon

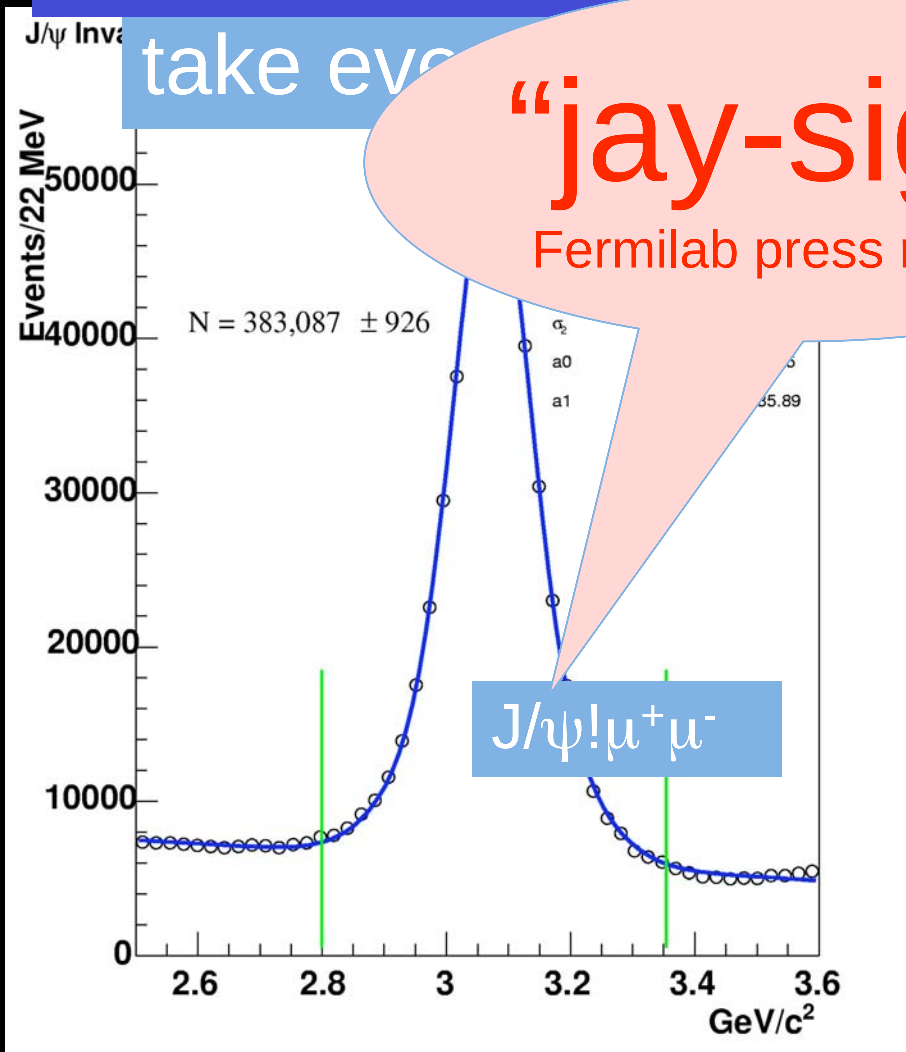
how to discover a new particle?

take eve

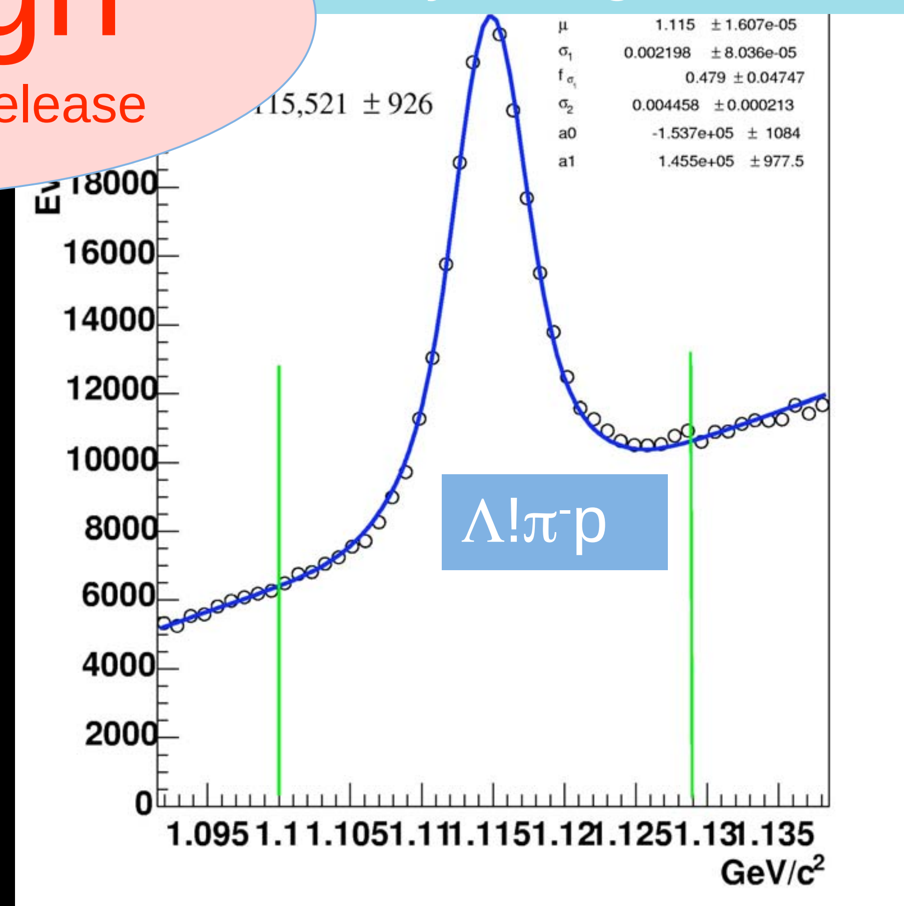
combine any other two
sitely charged tracks

“jay-sigh”

Fermilab press release



J/ψ!$\mu^+\mu^-$



Λ!π^-p

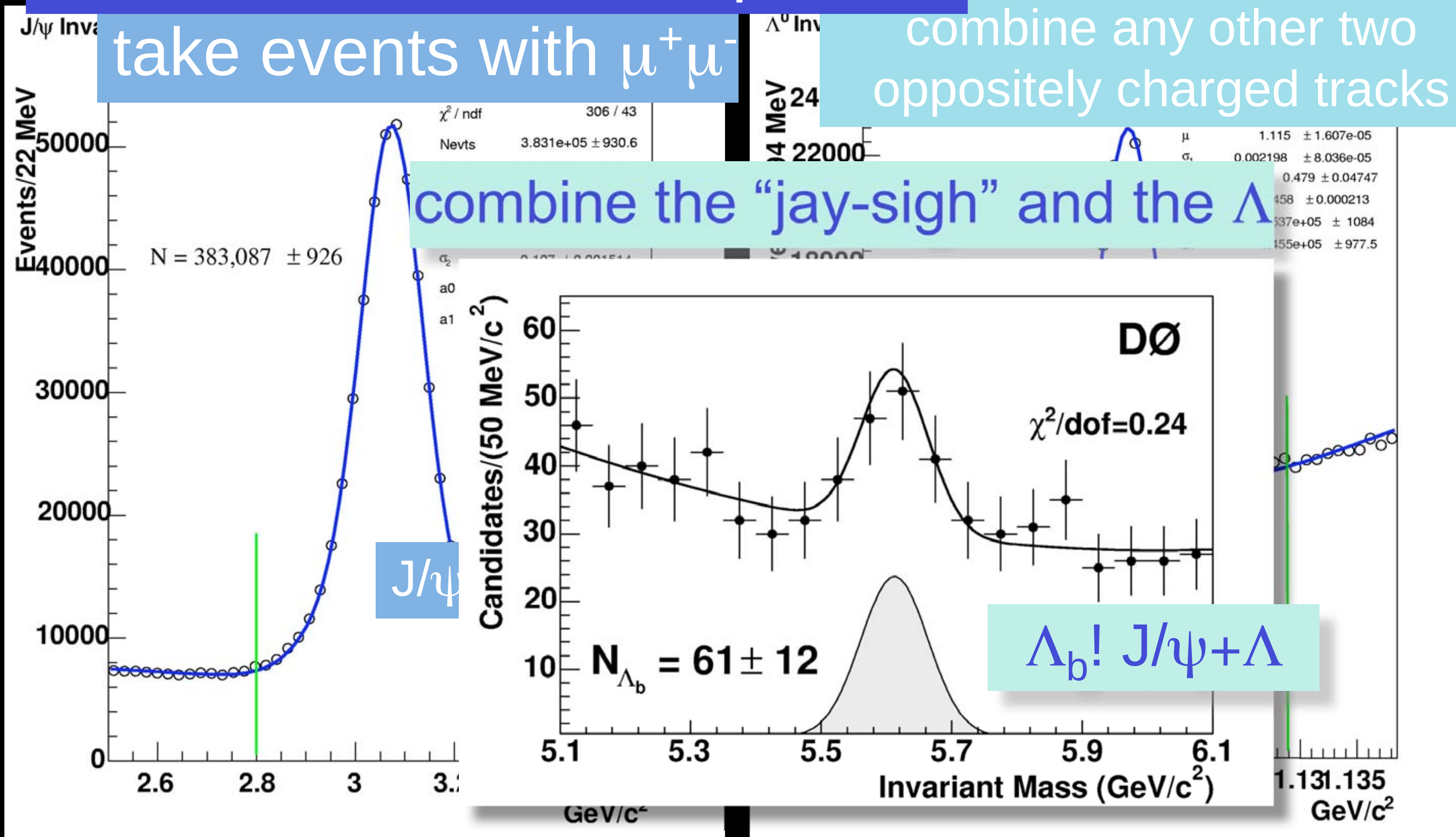
discovery of the Ξ_b baryon

how to discover a new particle?

take events with $\mu^+\mu^-$

combine any other two oppositely charged tracks

combine the “jay-sigh” and the Λ



J/ψ

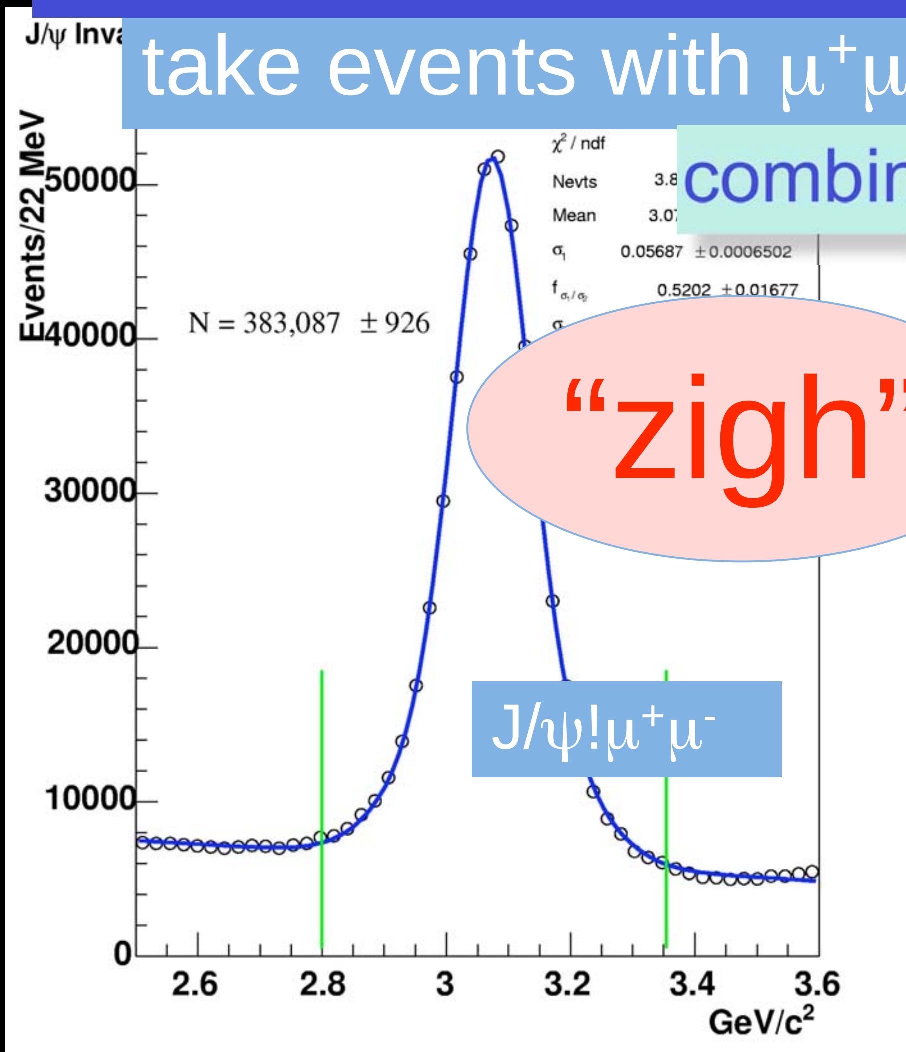
Λ_b! $J/\psi+\Lambda$

$N_{\Lambda_b} = 61 \pm 12$

discovery of the Ξ_b baryon

how to discover a new particle?

take events with $\mu^+\mu^-$

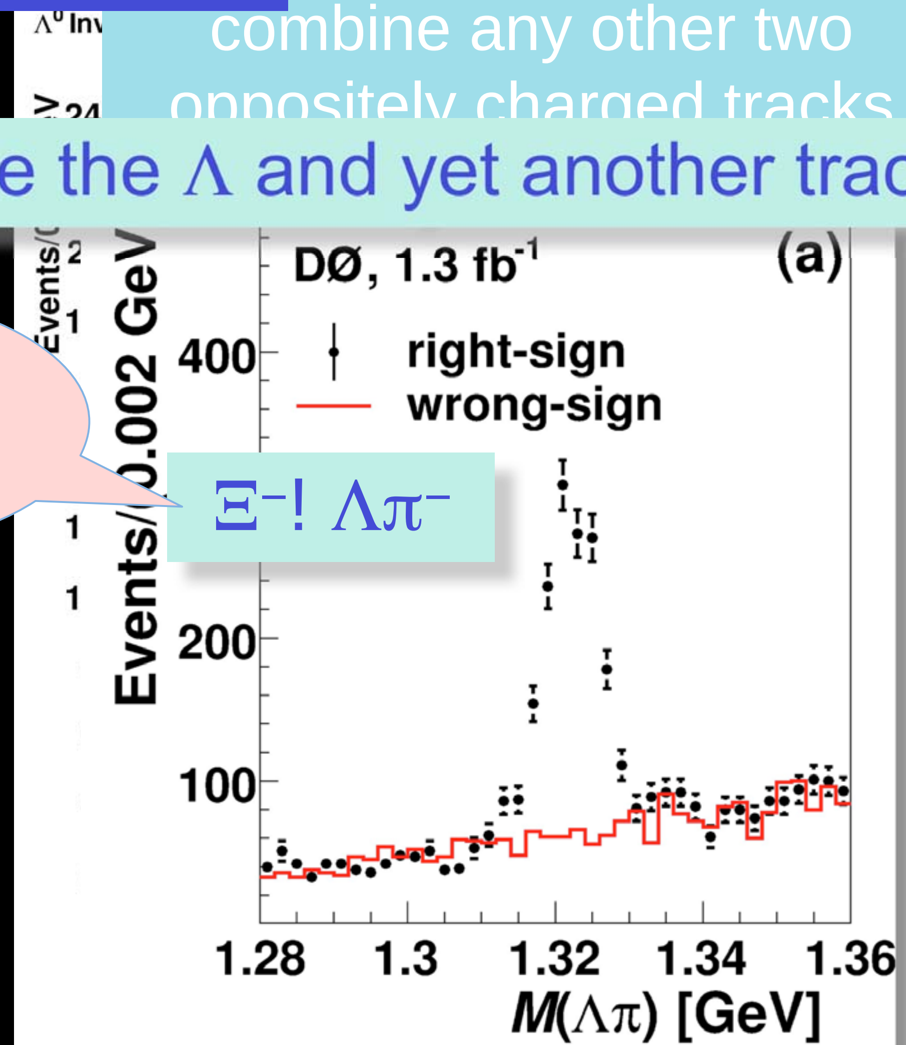


$J/\psi ! \mu^+\mu^-$

“zigh”

combine any other two oppositely charged tracks

combine the Λ and yet another track

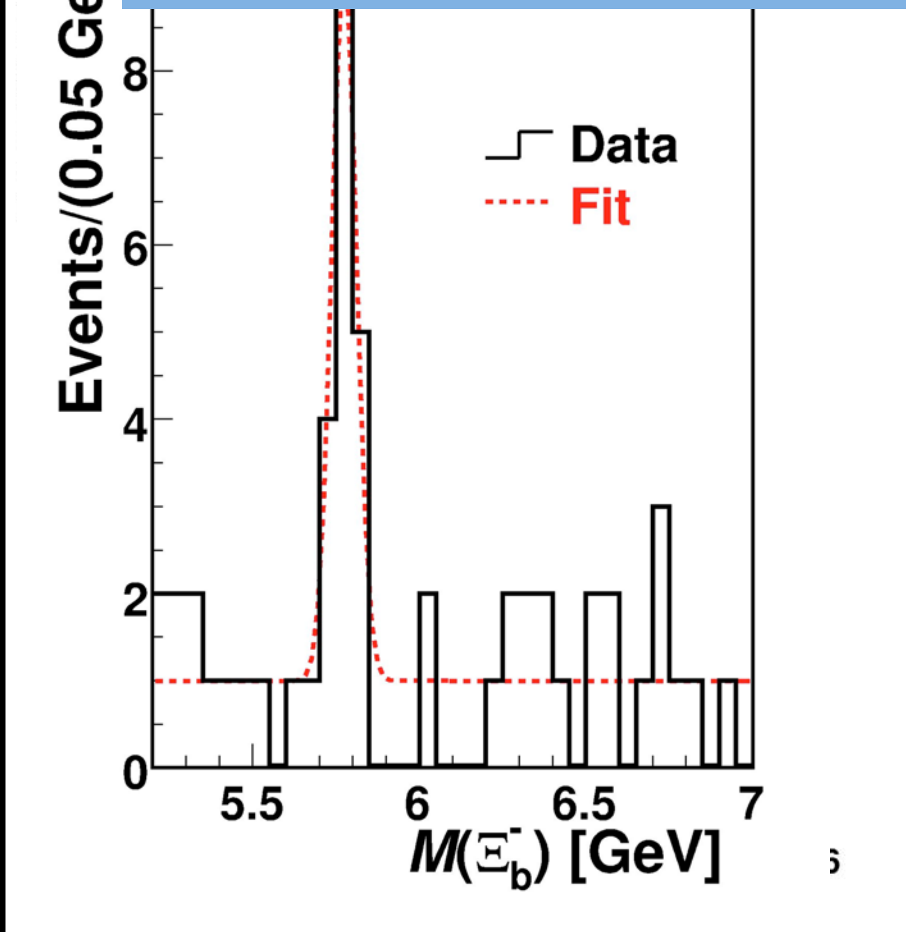


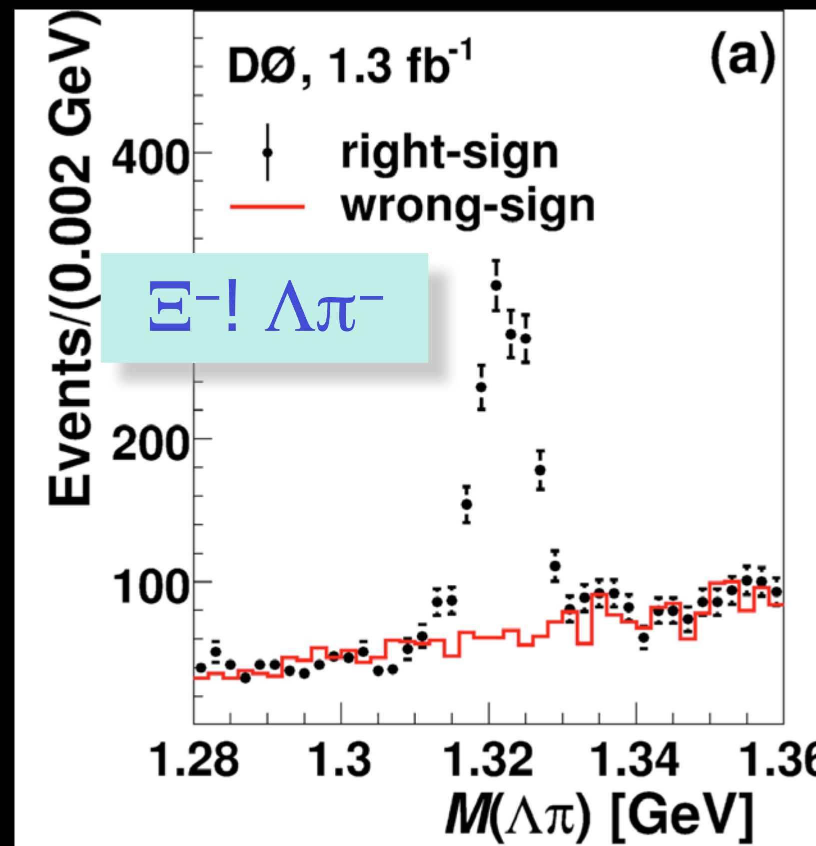
$\Xi^- ! \Lambda\pi^-$

discovery of the Ξ_b baryon

how to discover a new particle?

now take events with a jay-sigh and a zigh

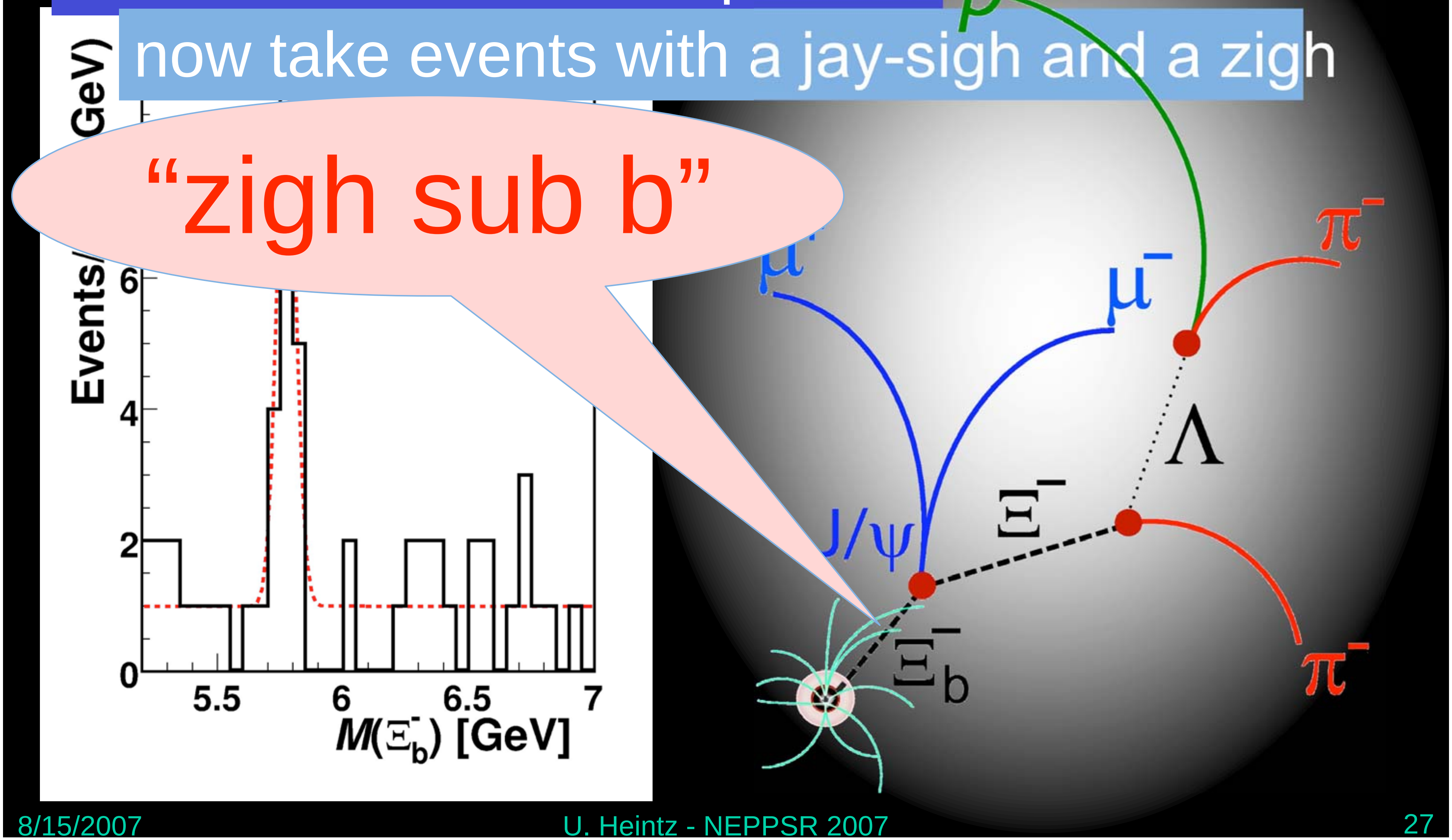




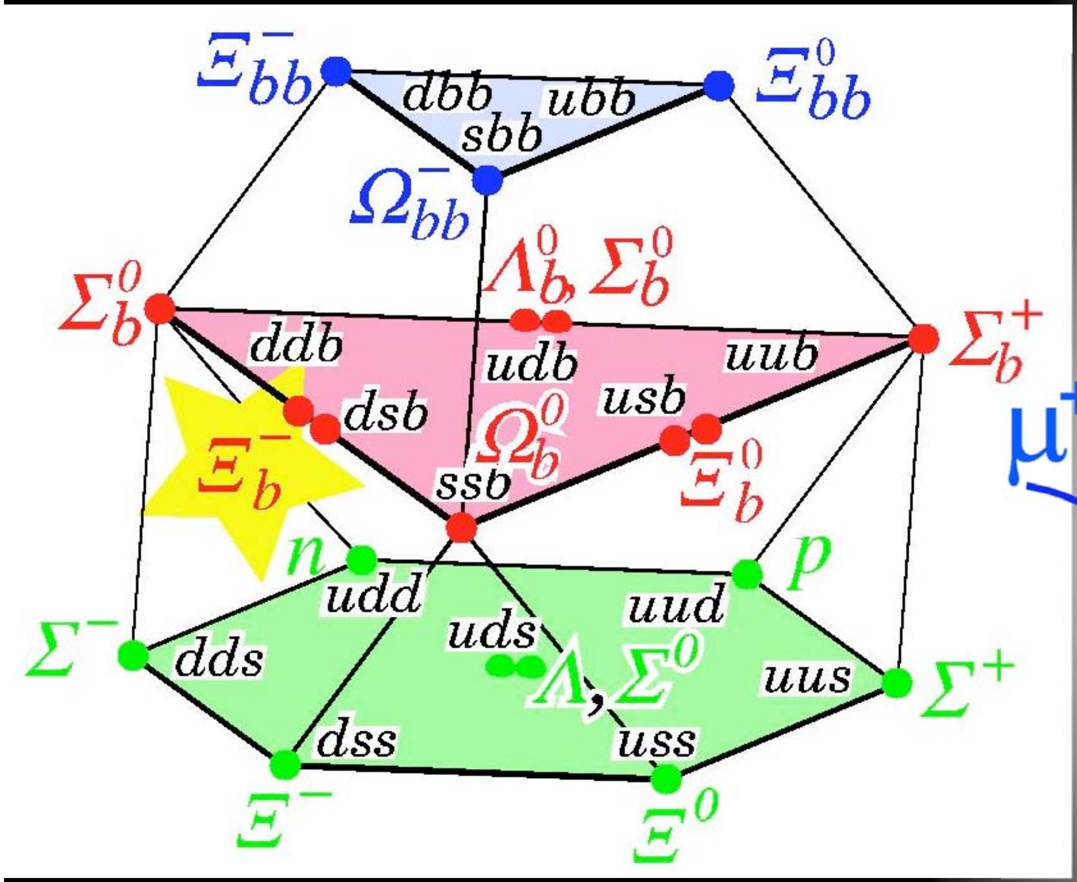
discovery of the Ξ_b baryon

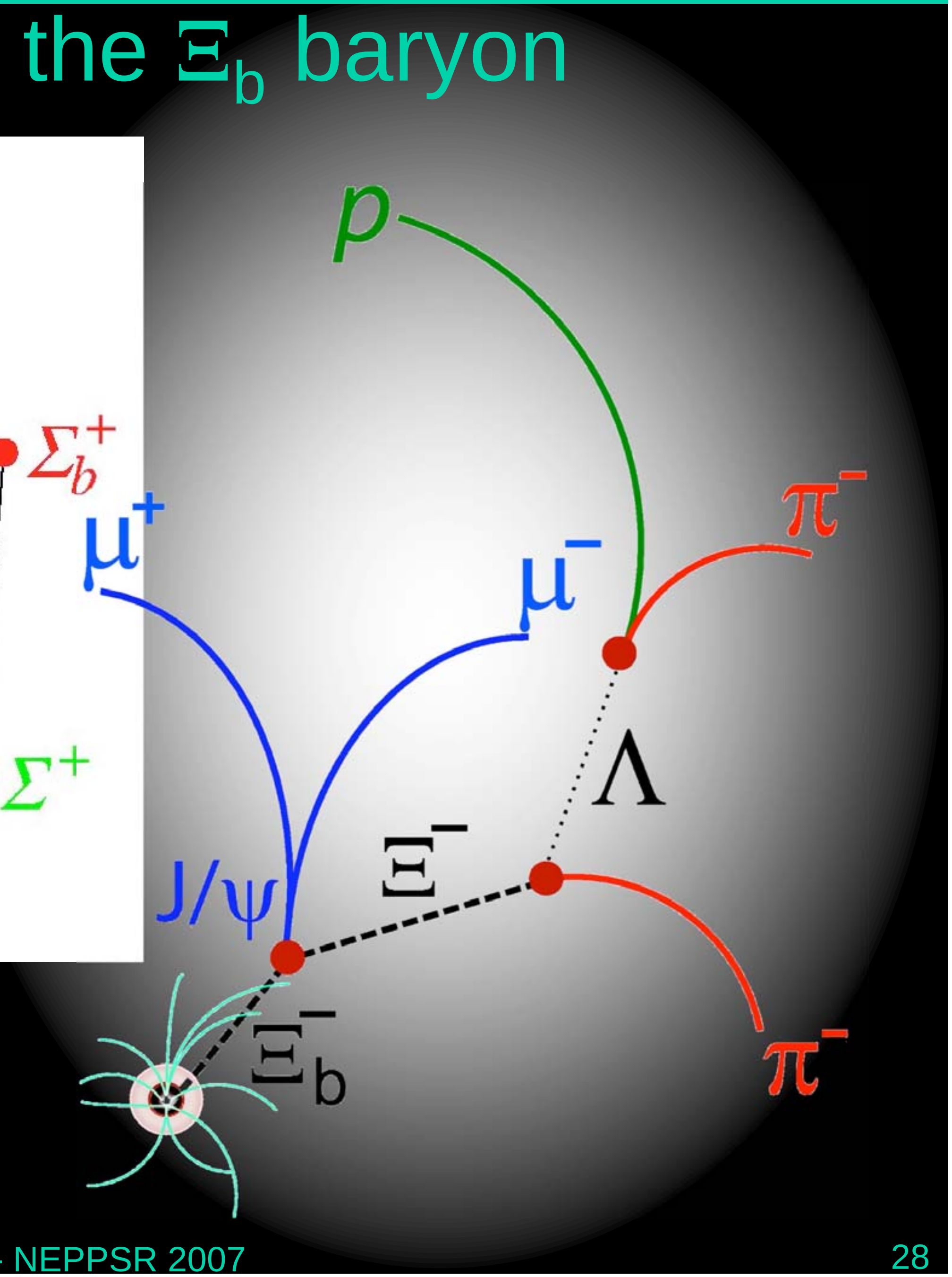
how to discover a new particle?

now take events with a jay-sigh and a zigh

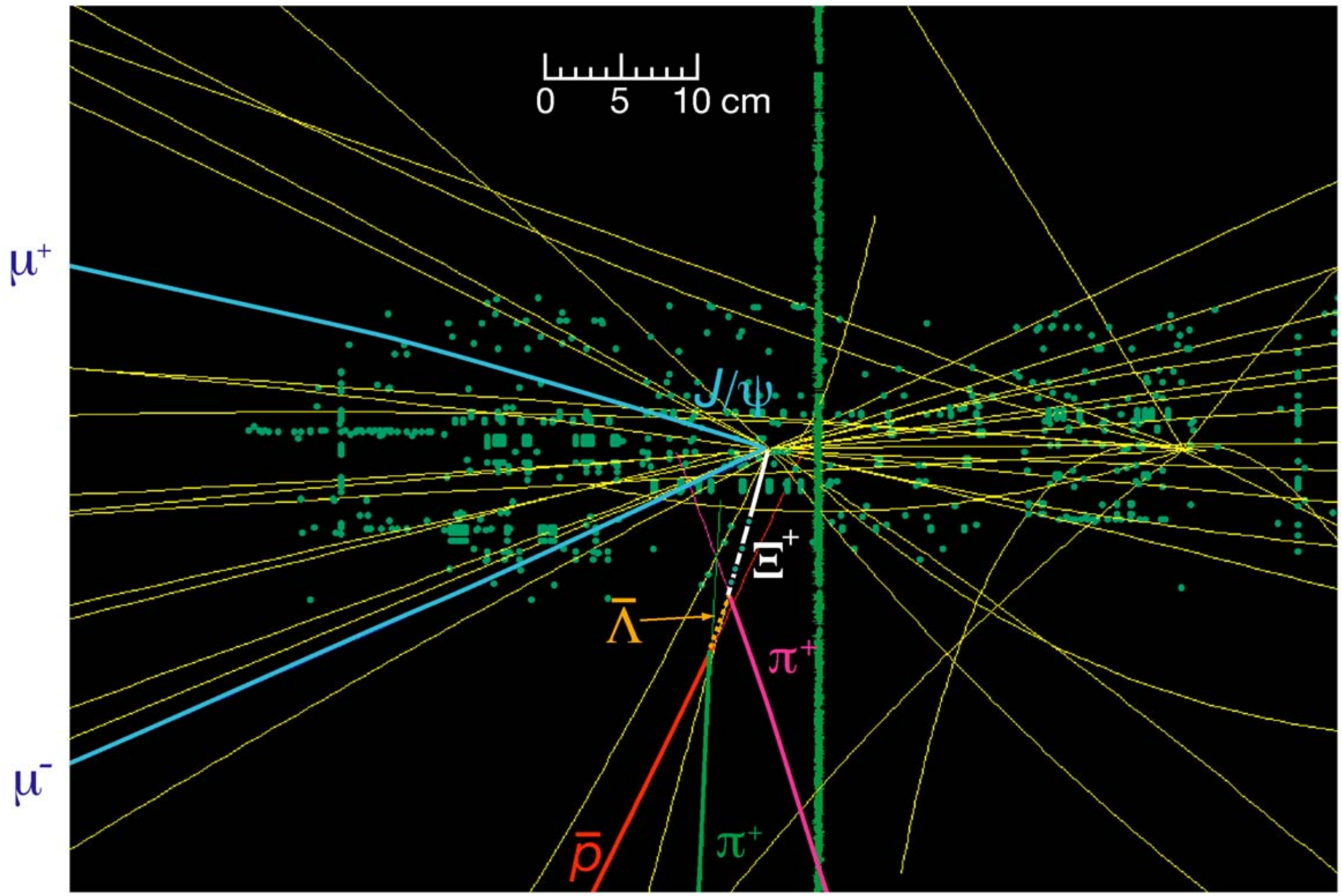


discovery of the Ξ_b baryon



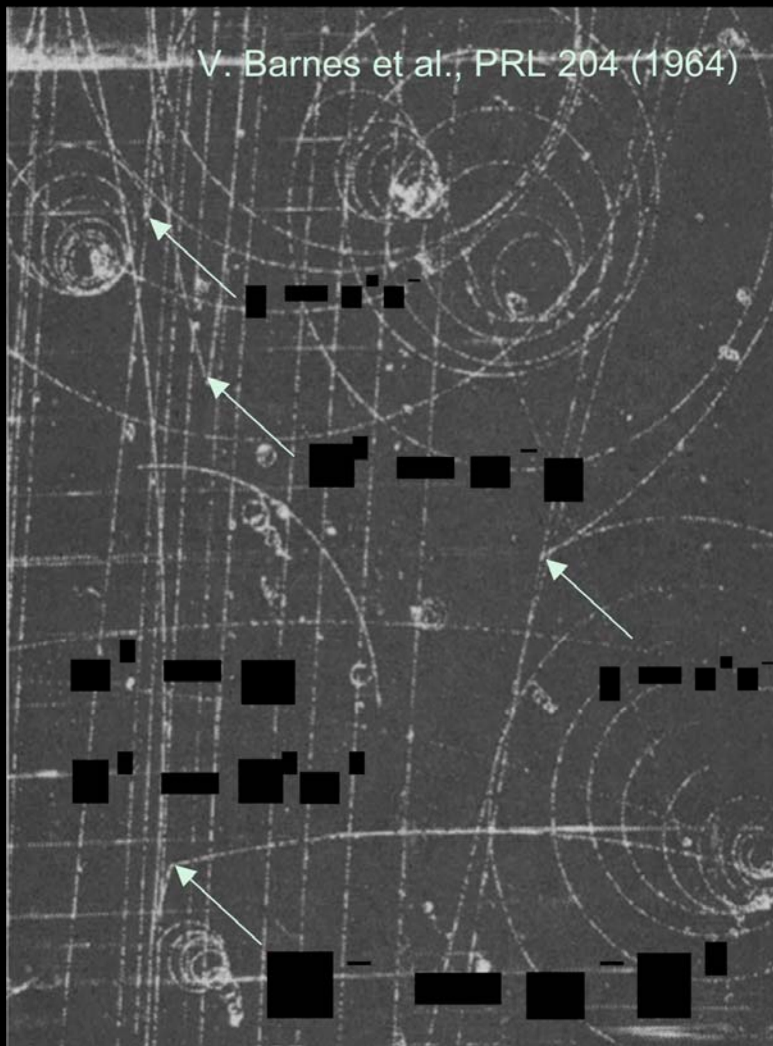


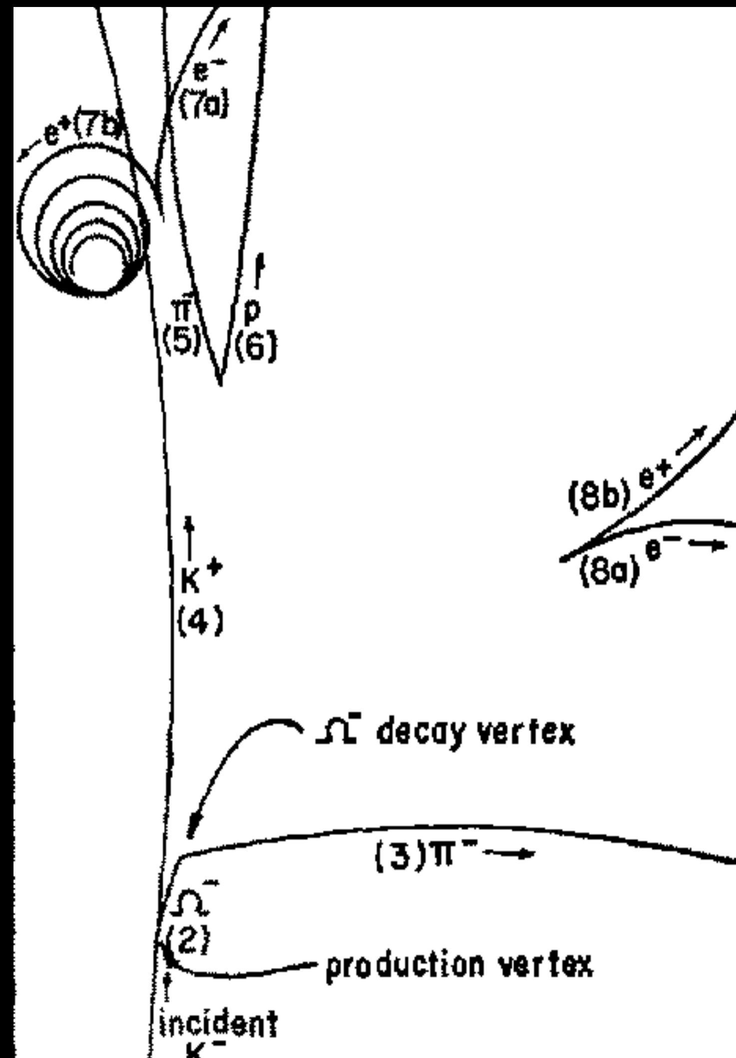
discovery of the Ξ_b baryon



Run 179200, Event 55278820, $M(\Xi_b)$ = 5.788 GeV

is one event enough to discover a particle?





Horwitz, The Physics Teacher, Volume 2, Issue 8, pp. 366-395 (1964)

electroweak physics

- W boson mass
- diboson couplings

W boson mass

at tree level

with [illegible]

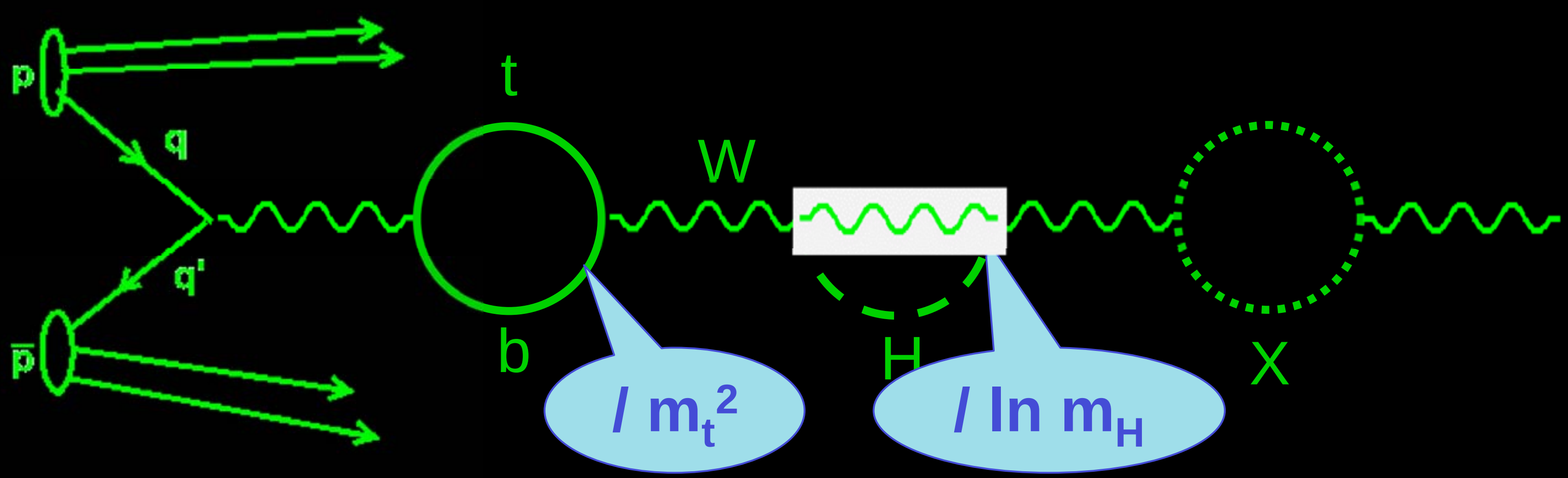
[illegible]

[illegible]

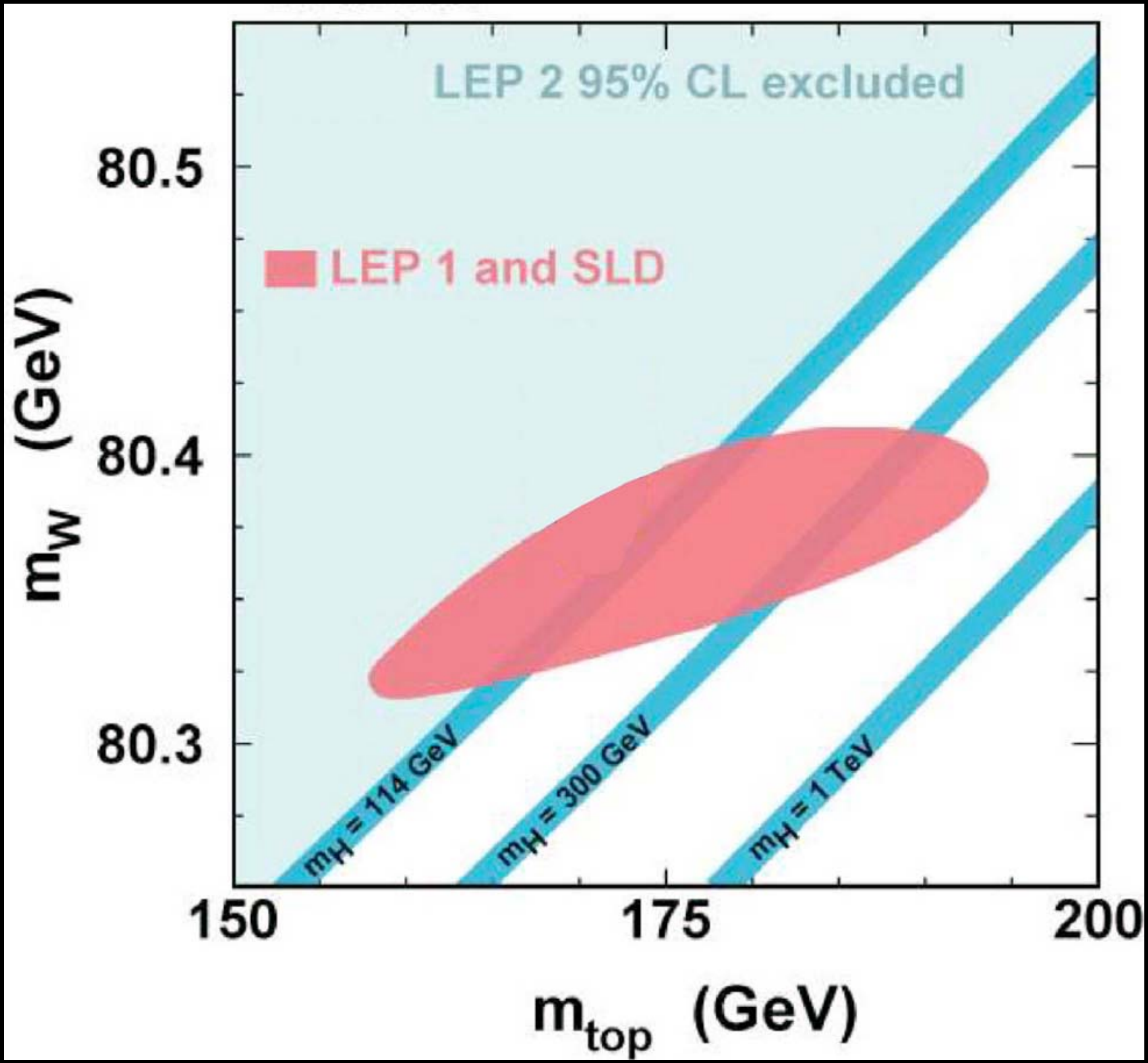
W boson mass

at tree level

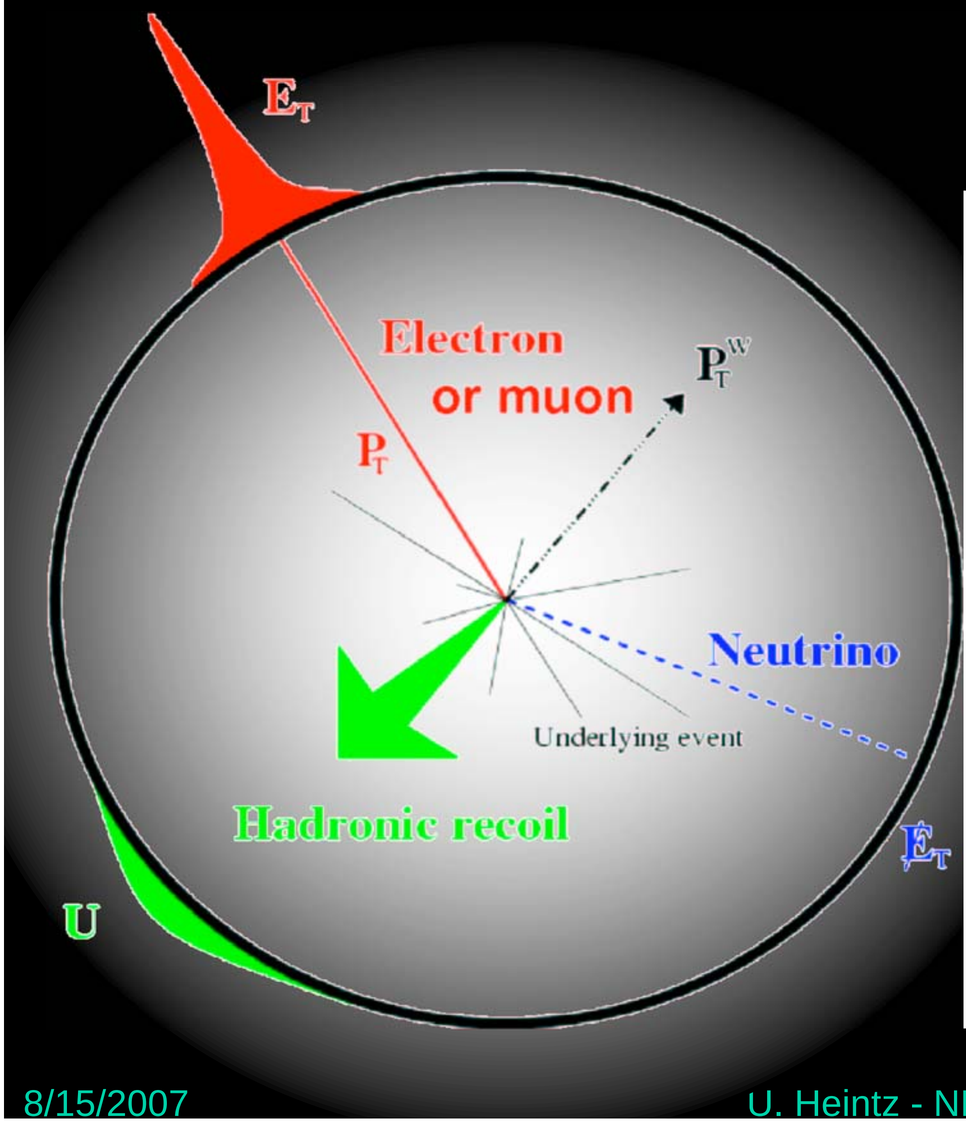
loop corrections

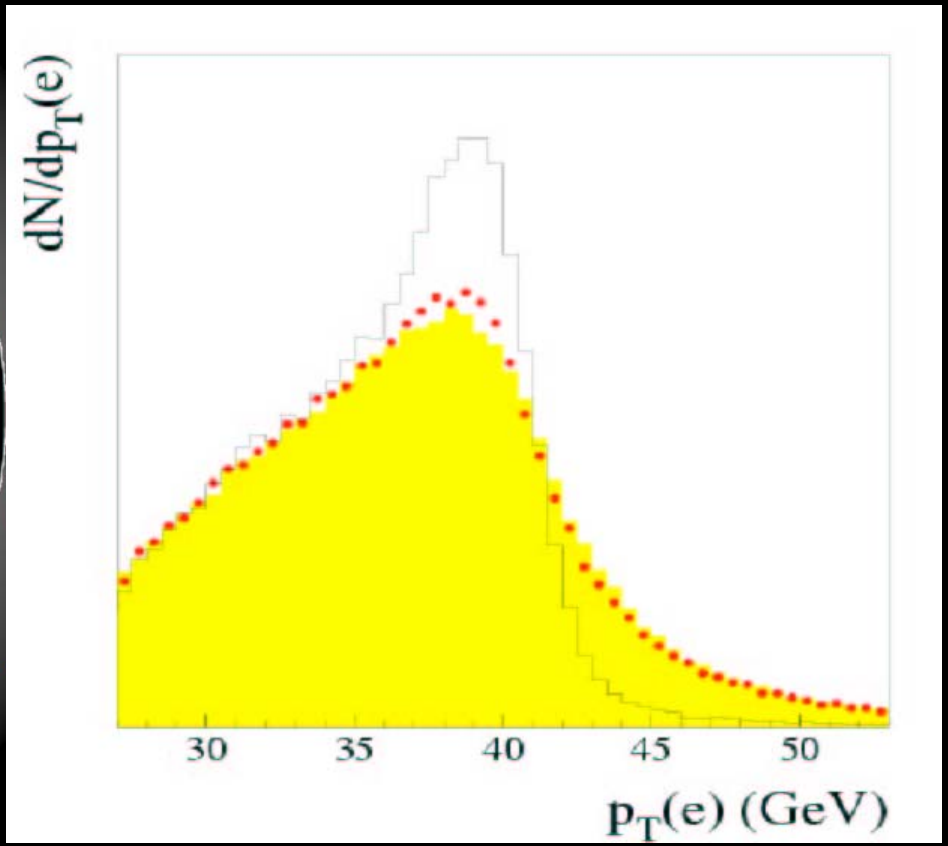


Higgs mass constraint

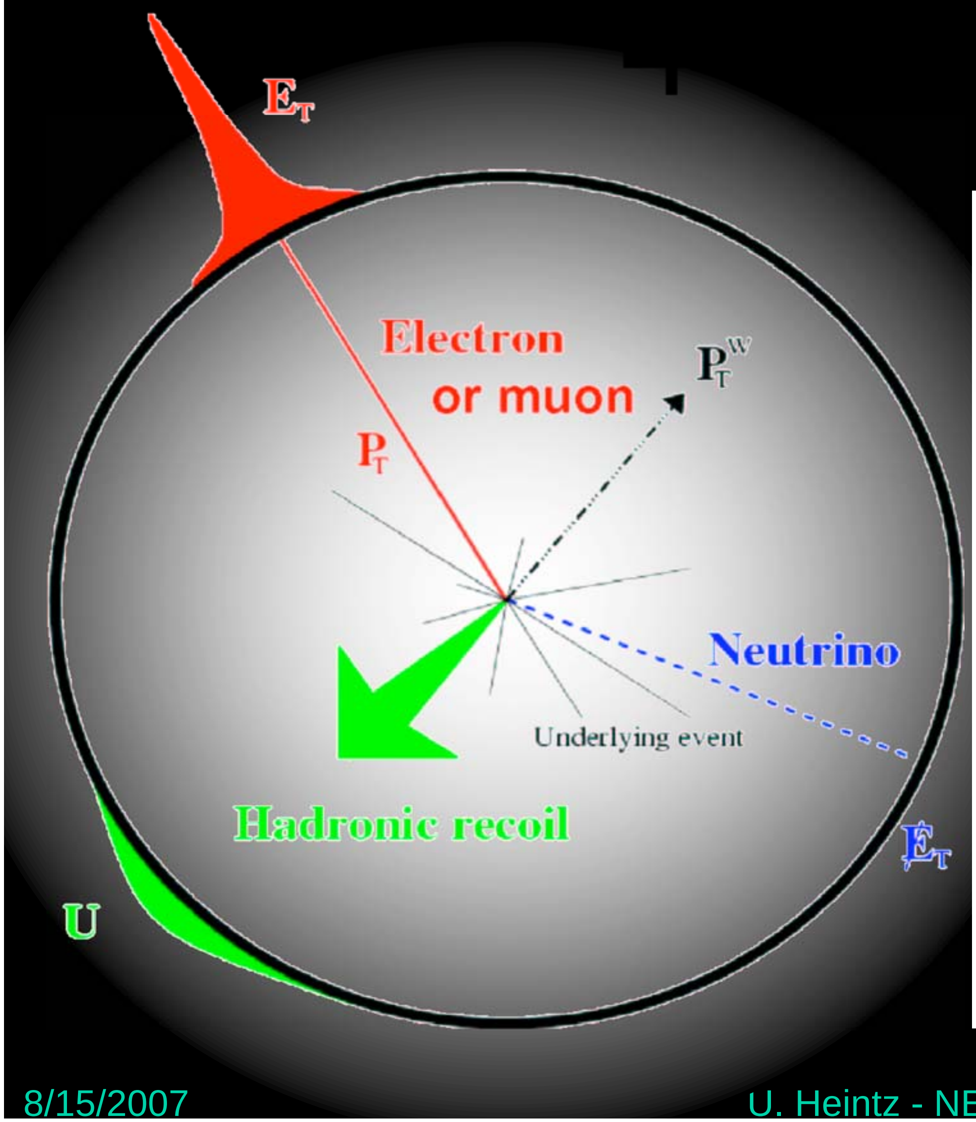


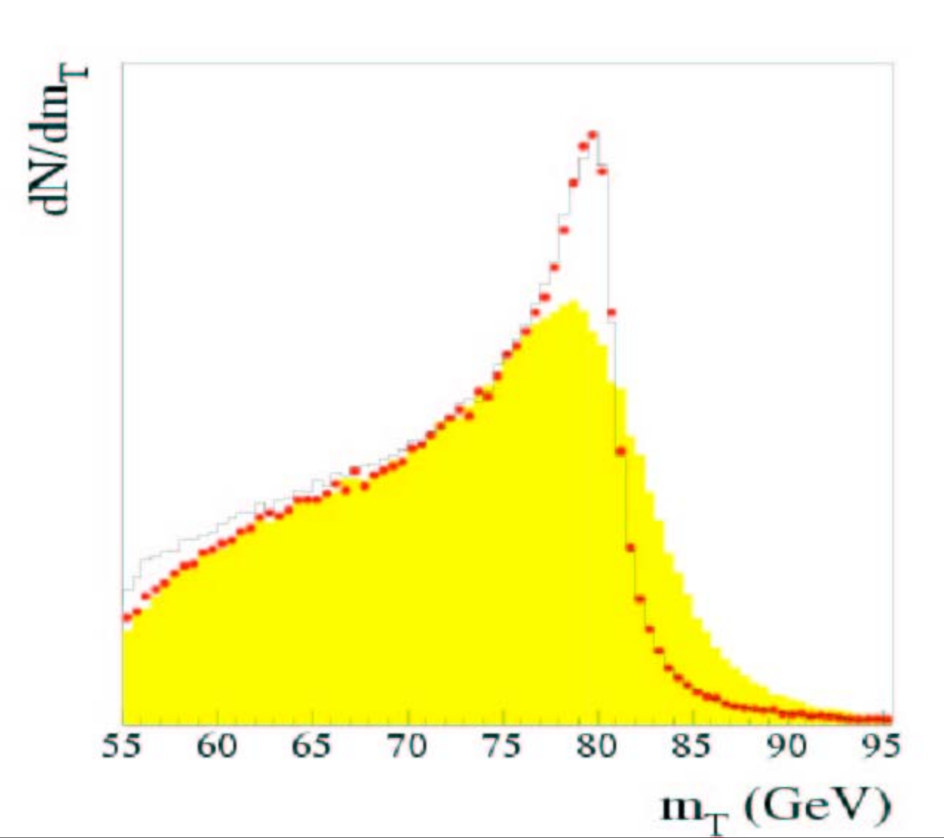
how to measure the W boson mass?





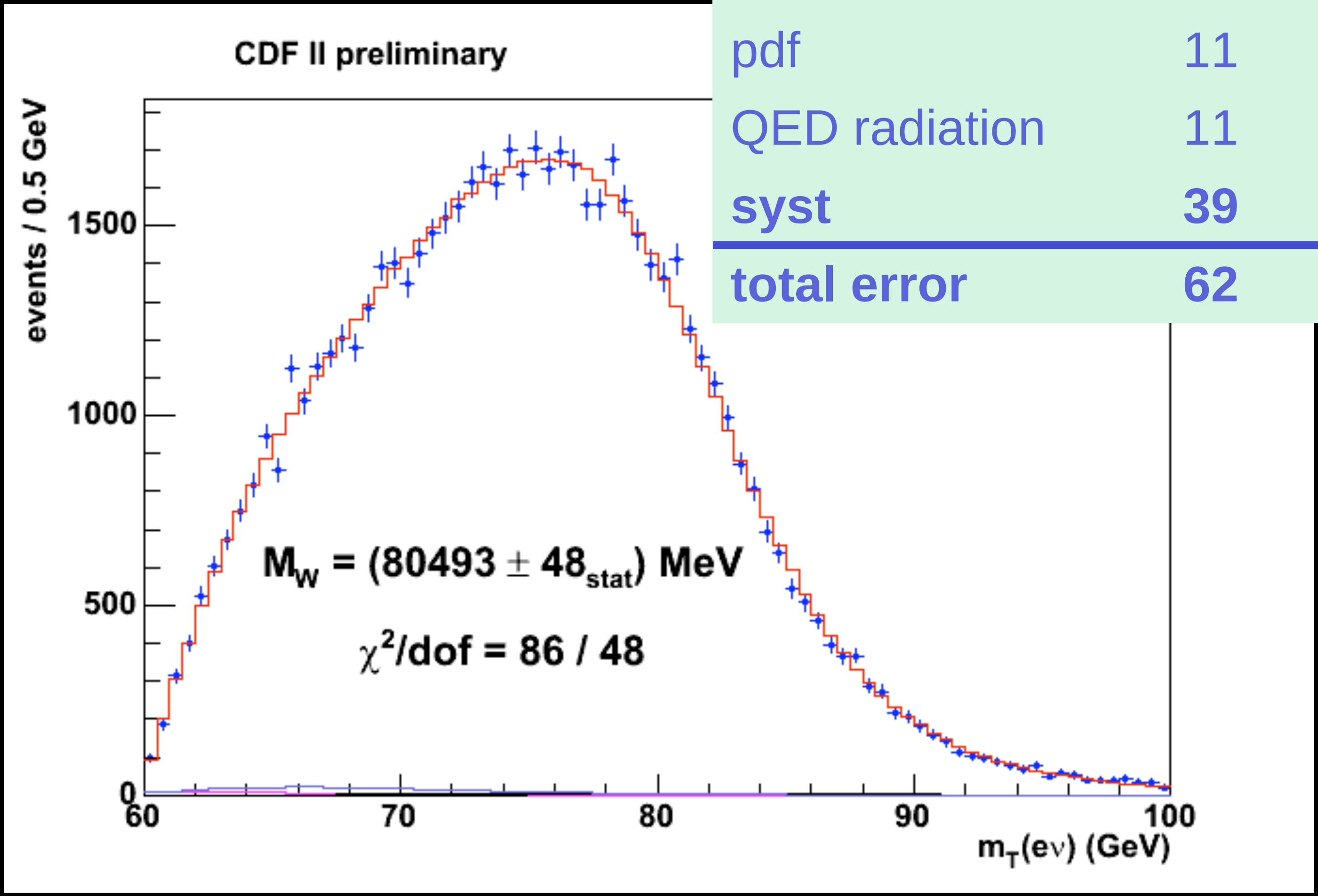
how to measure the W boson mass?





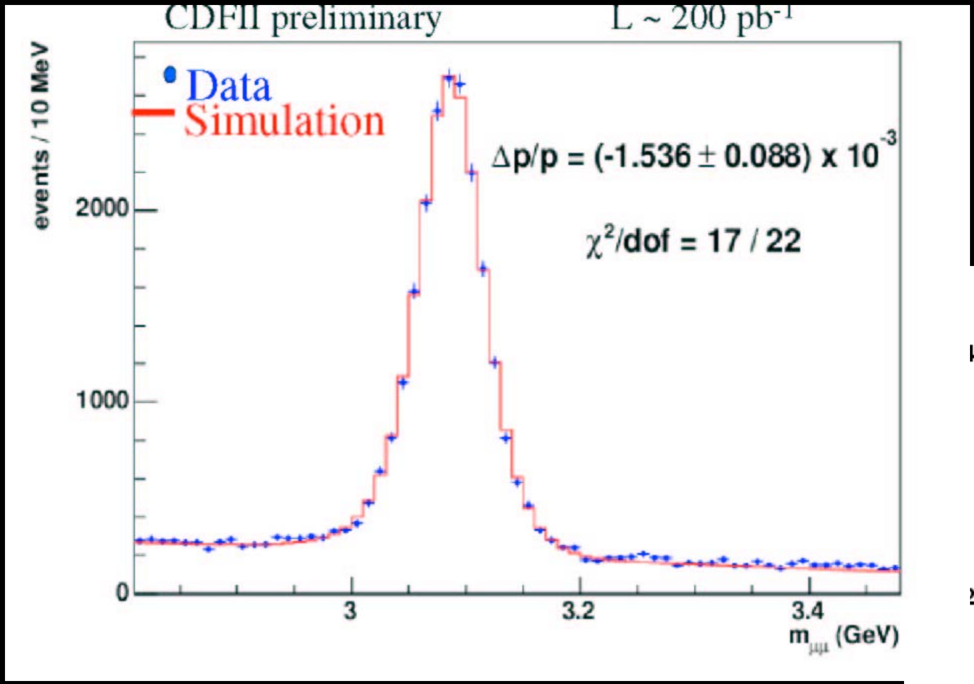
m_T fit

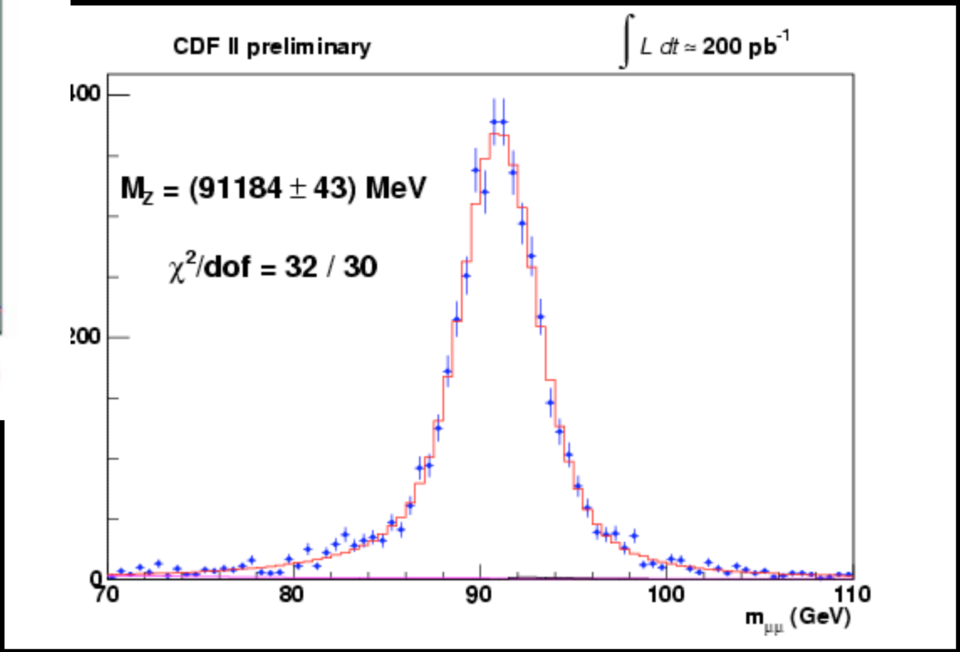
	W→eν	W→μν	common
stat	**48**	**54**	**0**
lepton energy	30	17	17
pdf	11	11	11
QED radiation	11	12	11
syst	**39**	**27**	**26**
total error	**62**	**60**	



lepton energy calibration

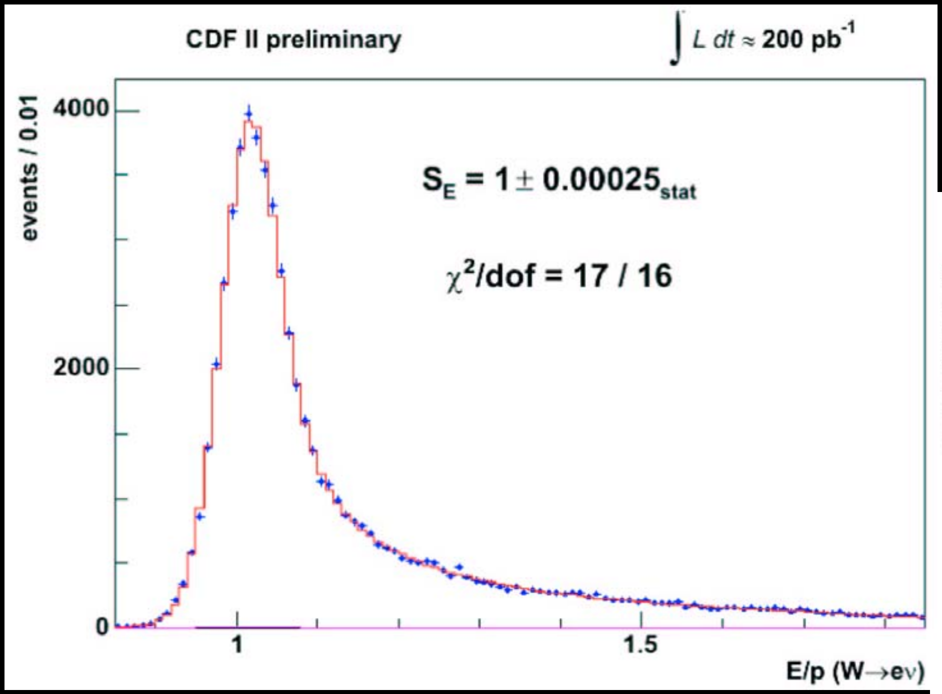
calibrate track momentum with $\mu^+\mu^-$ resonances

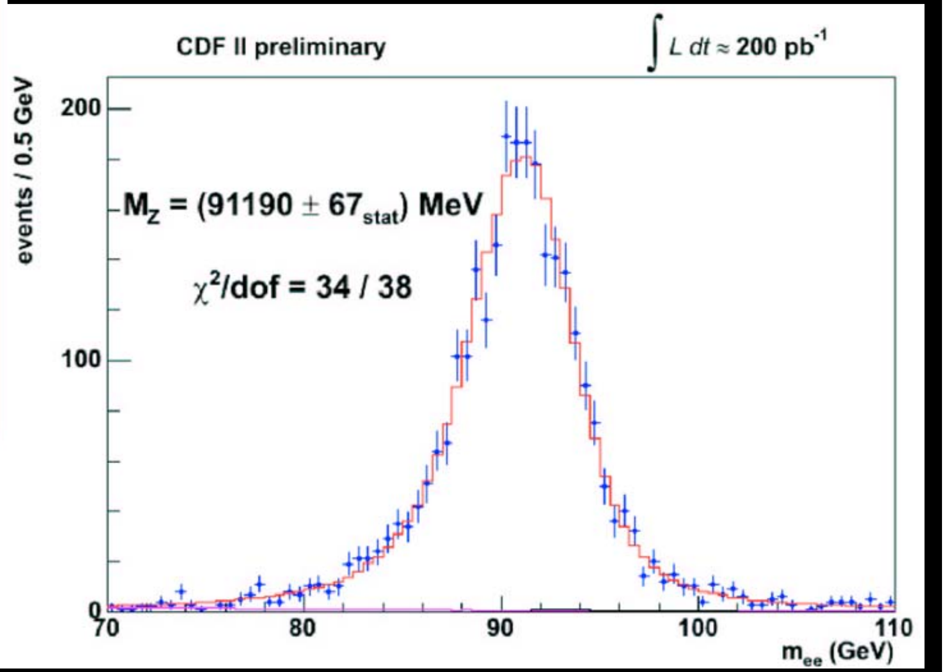




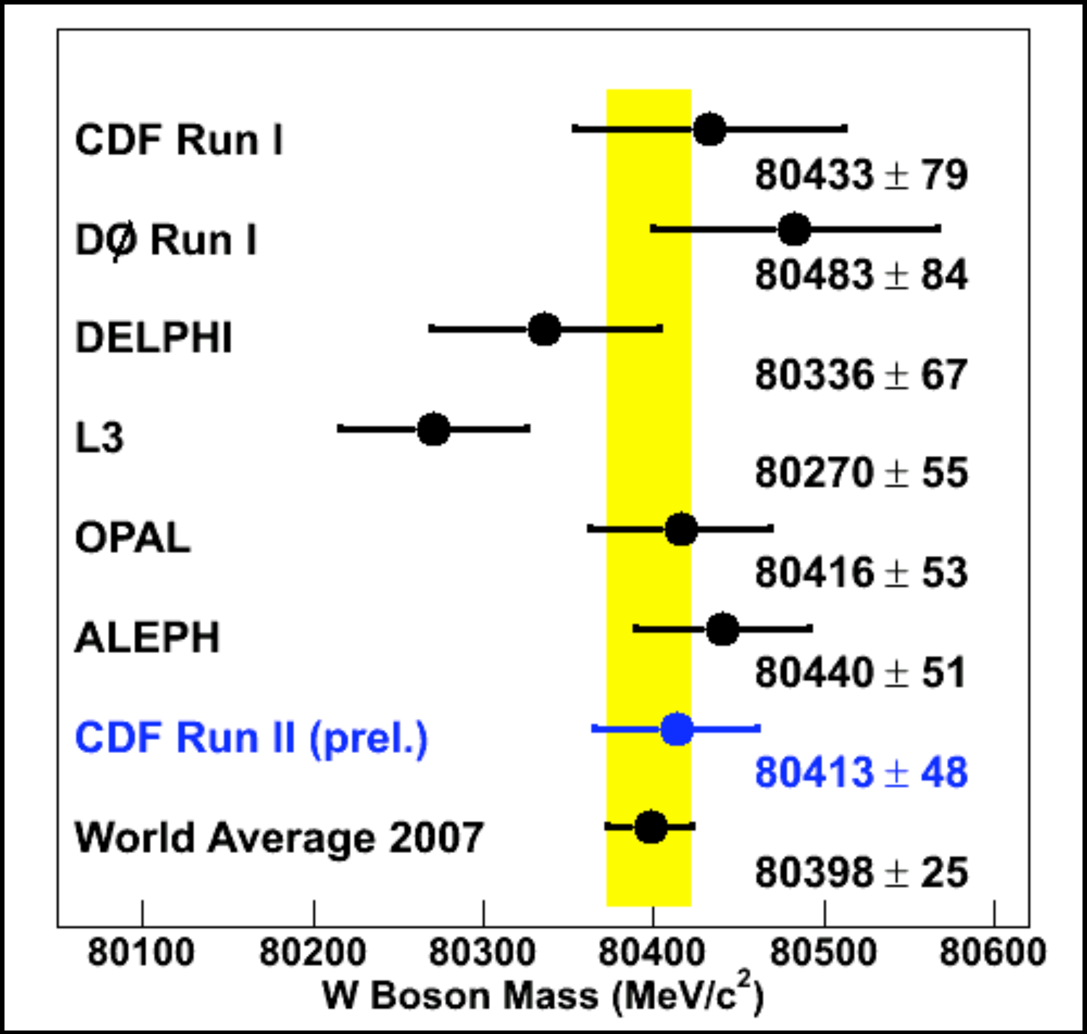
lepton energy calibration

transfer momentum calibration to electron energy with electrons from W decays





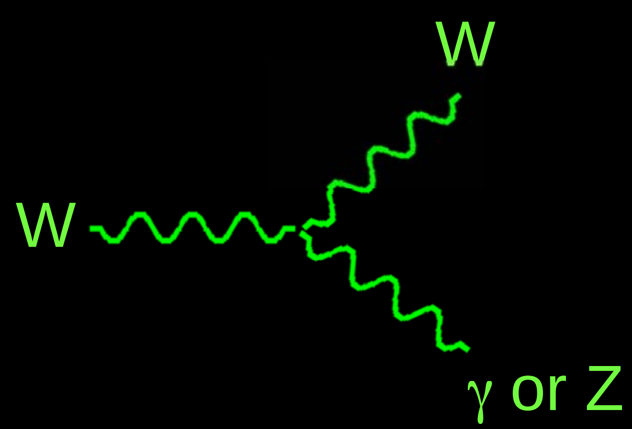
W boson mass



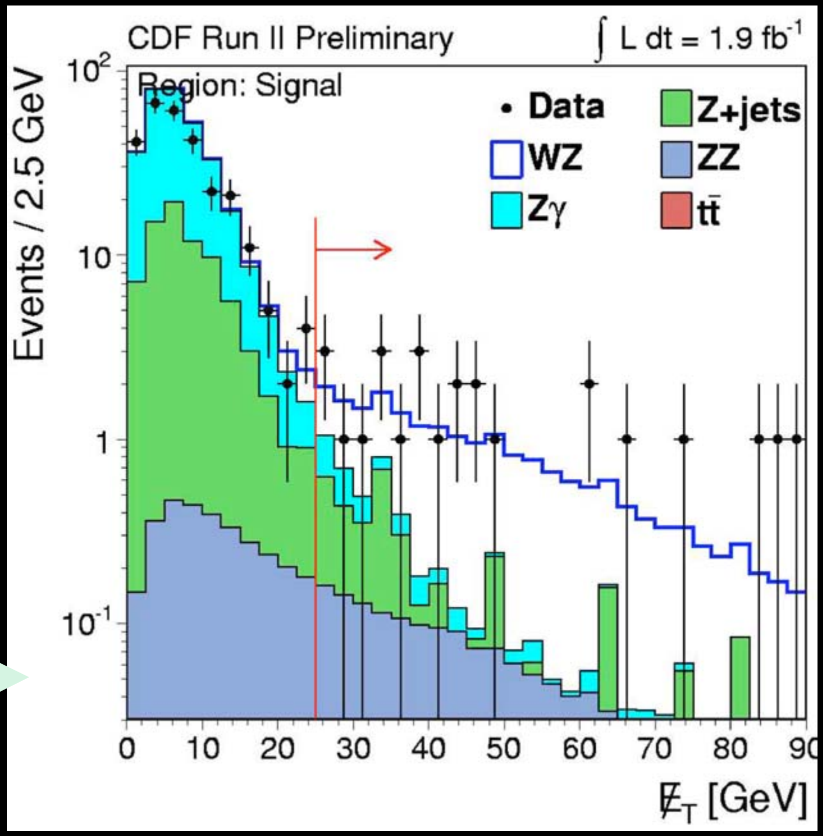
CDF Run I
80433 ± 79
DØ Run I
80483 ± 84
DELPHI
80336 ± 67
L3
80270 ± 55
OPAL
80416 ± 53
ALEPH
80440 ± 51
CDF Run II (prel.)
80413 ± 48
World Average 2007
80398 ± 25
80100
80200
80300
80400
80500
80600
W Boson Mass (MeV/c²)

trilinear gauge couplings

trilinear gauge boson couplings are uniquely specified by the sm



events with 3 leptons

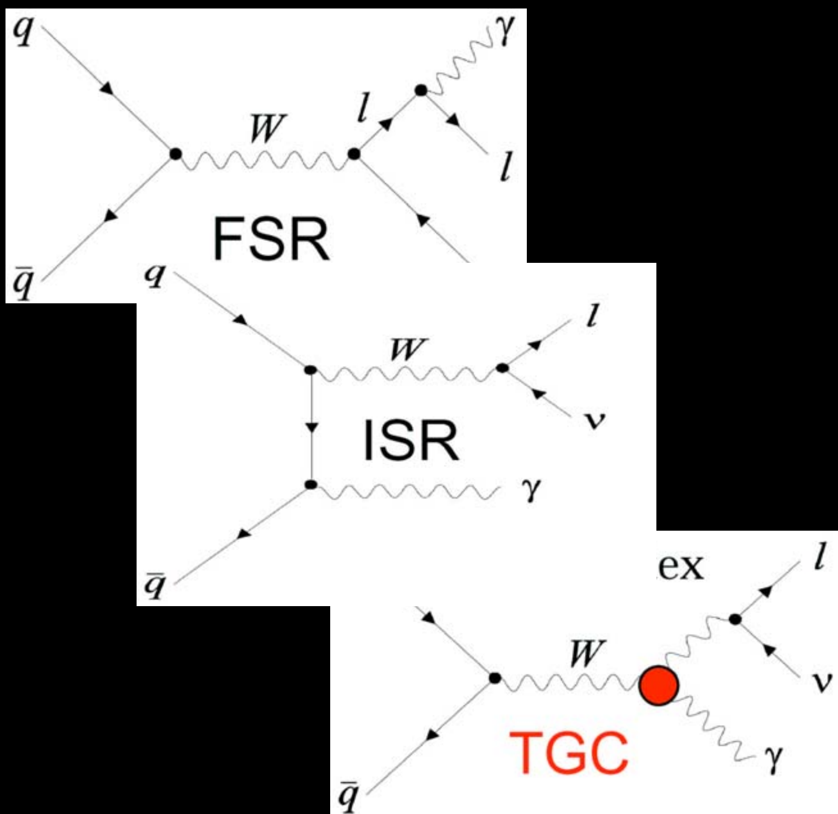


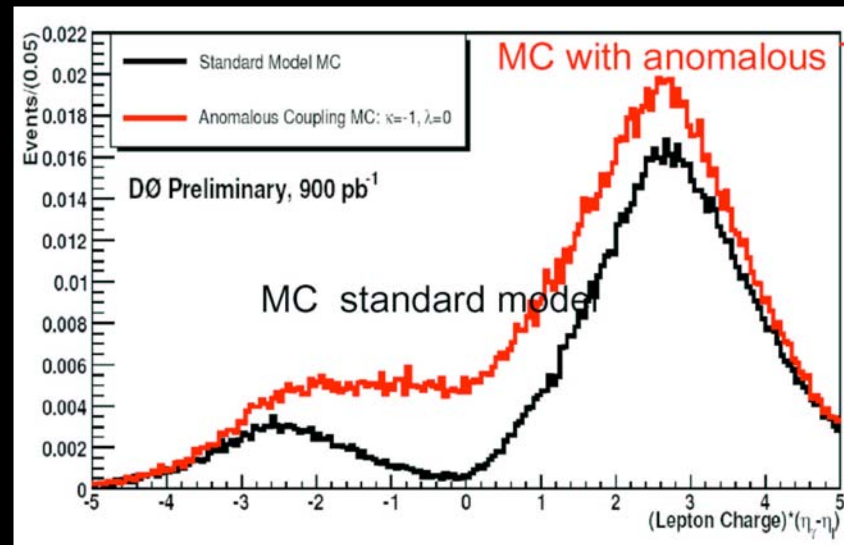
not in sm

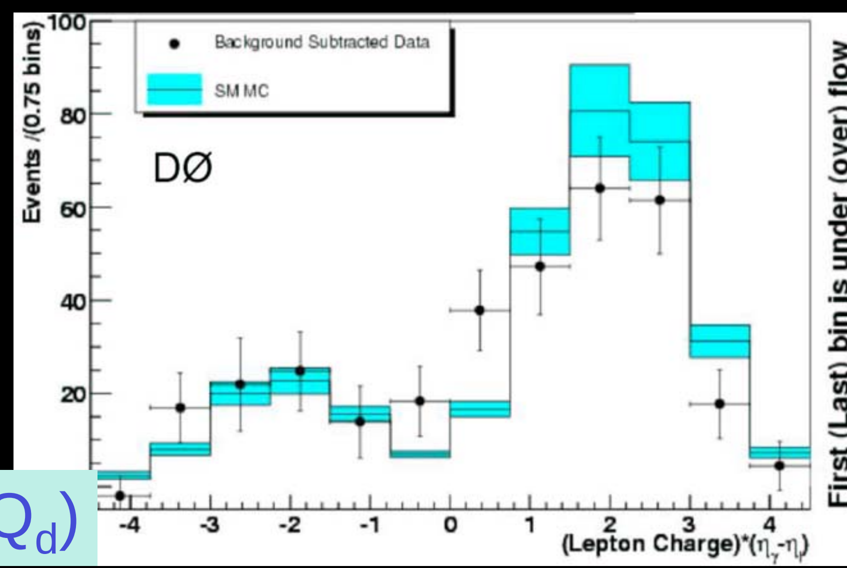
→ 3σ hint

radiation zero in Wγ

interference between tree level diagrams:







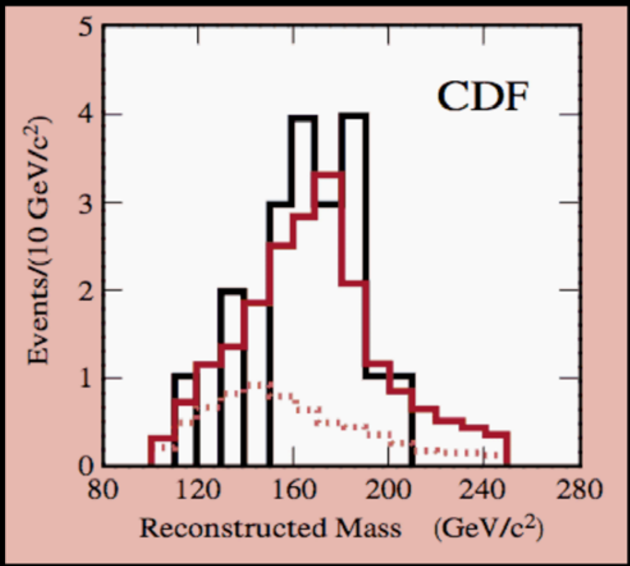
cancellation for $\cos\theta_{q\gamma} = -(1+2Q_d)$

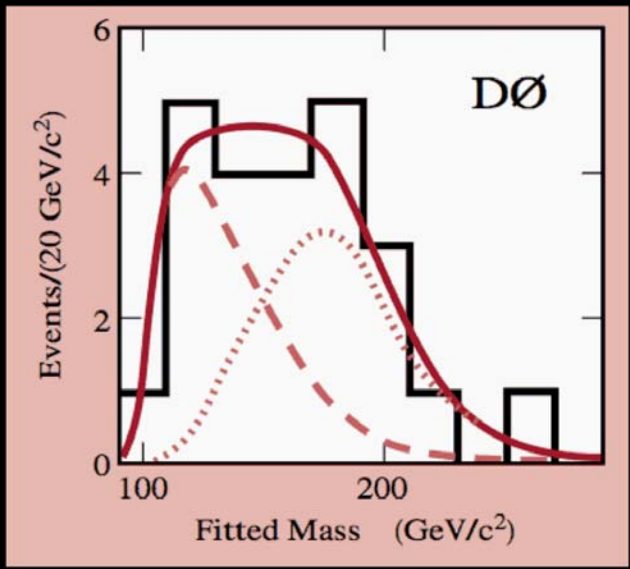
top quark physics

- discovery
- mass
- properties
- single top production

top quark discovery

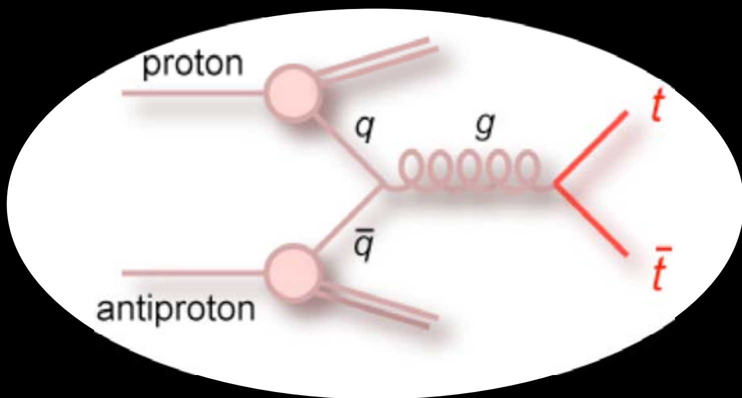
- need weak isospin partner to the b-quark
- in 1995 CDF and DØ observe an excess of events consistent with

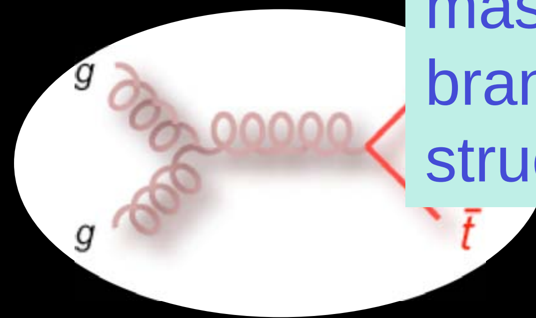




top quark production

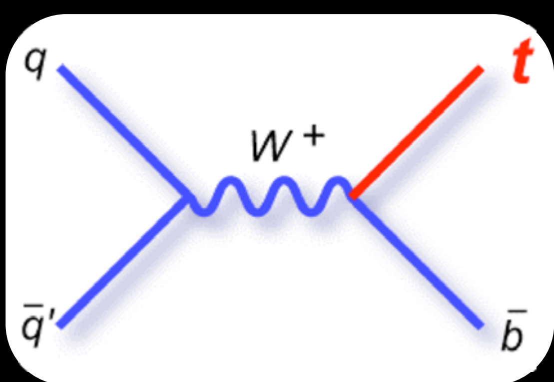
- top-antitop pair production

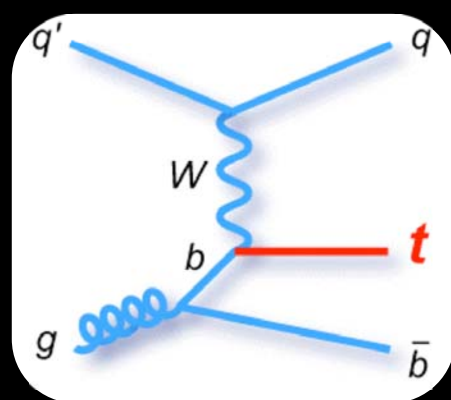




σ(tt) → QCD coupling
mass
branching fractions
structure of Wtb vertex

- electroweak production of top quarks
  - s channel (tb) t channel (tqb)



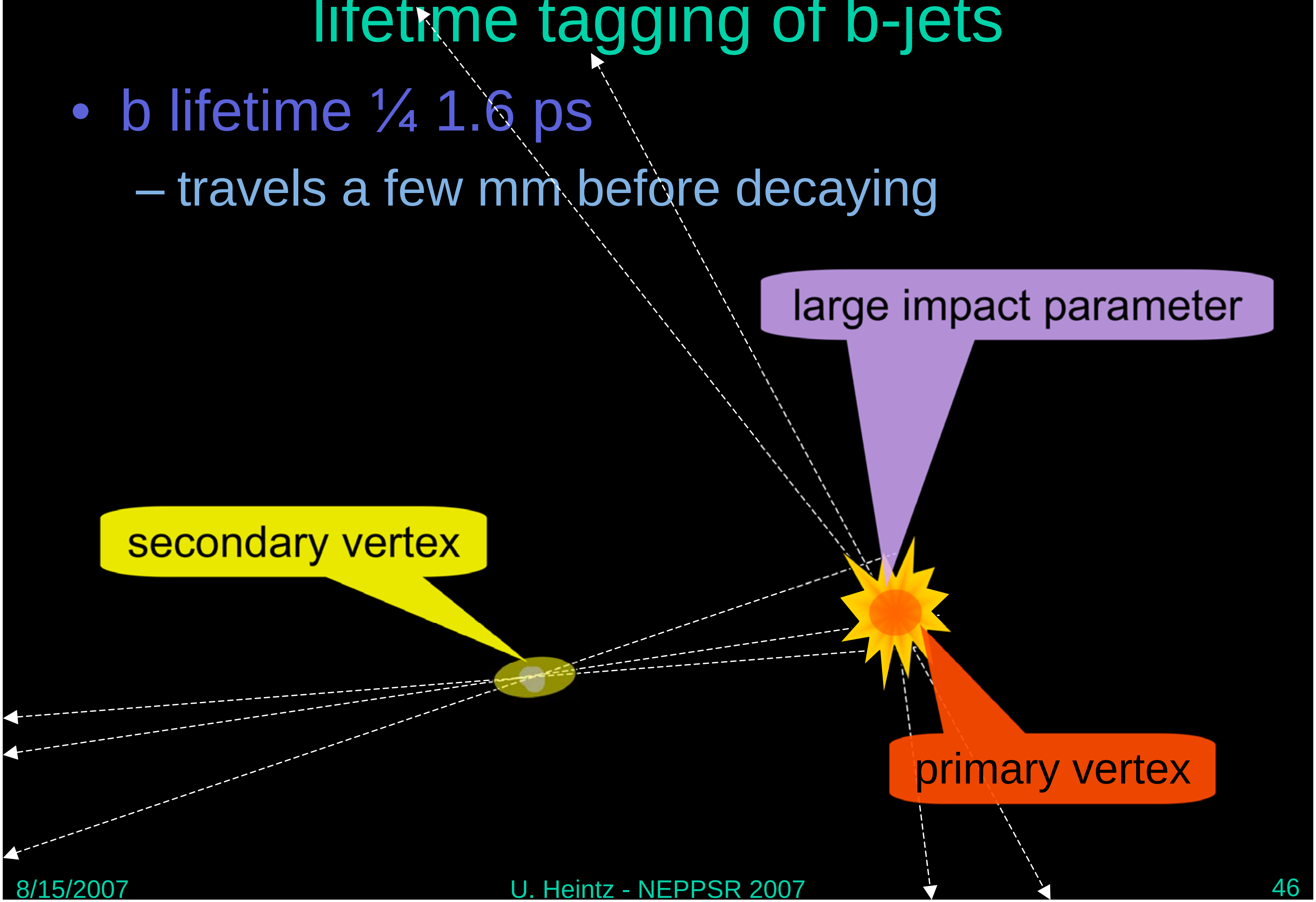


$|V_{tb}|$
width
structure of Wtb vertex

non-standard
production or decay?

lifetime tagging of b-jets

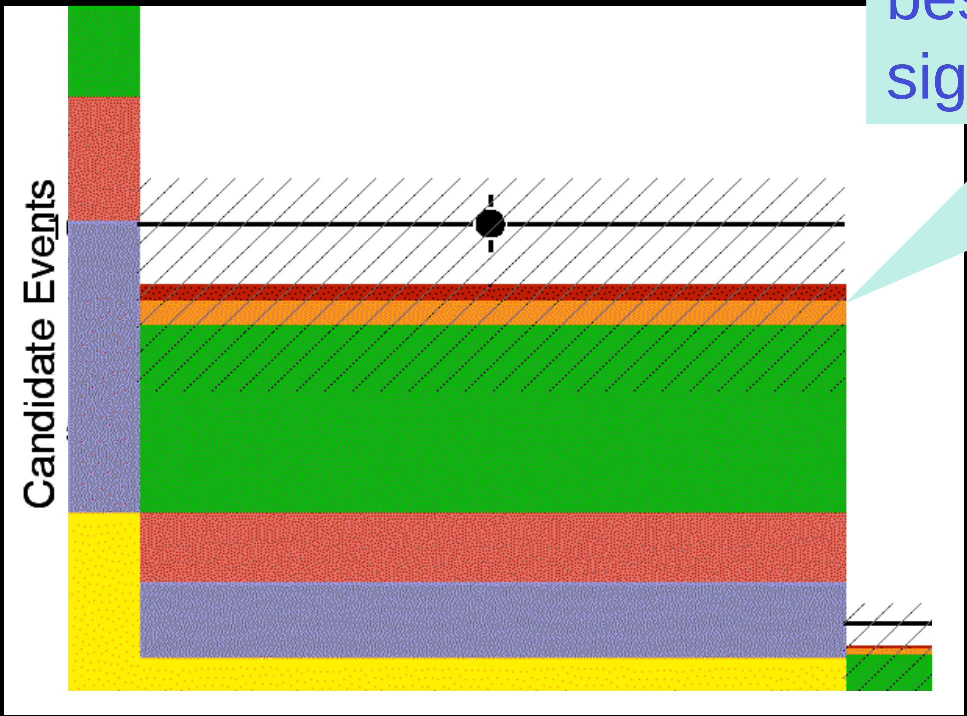
- b lifetime ¼ 1.6 ps
  - – travels a few mm before decaying



single top quark production

select events with high p_T lepton, missing p_T, 2 jets

at least one jet tagged as b-jet



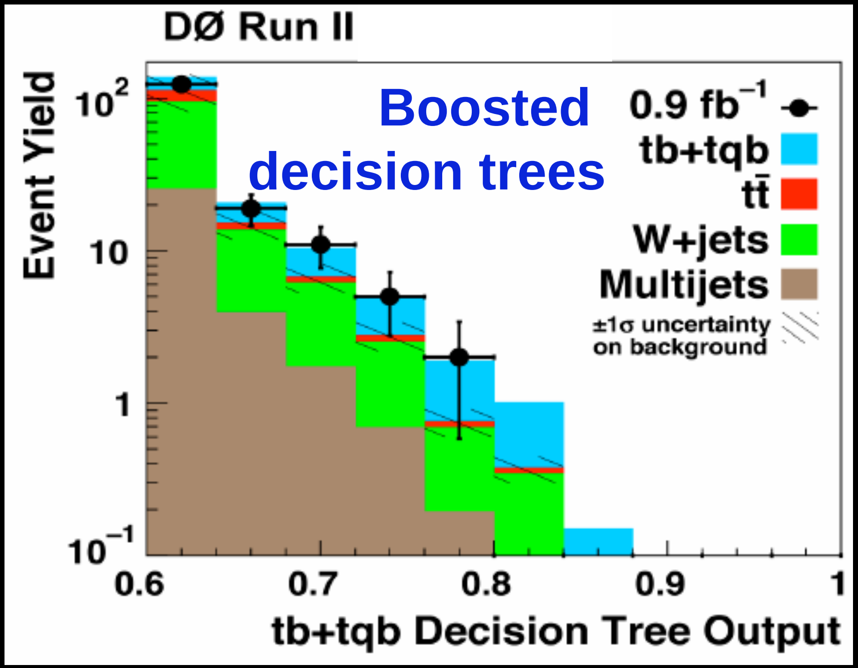
best channels S/B ≈ 1/20

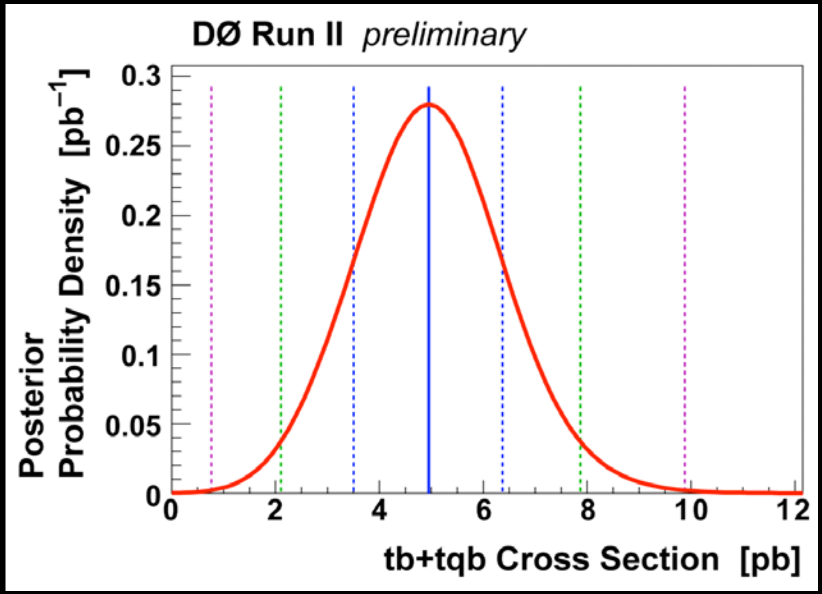
signal < background uncertainty

need advanced techniques

- decision trees
- neural networks
- matrix element discriminants

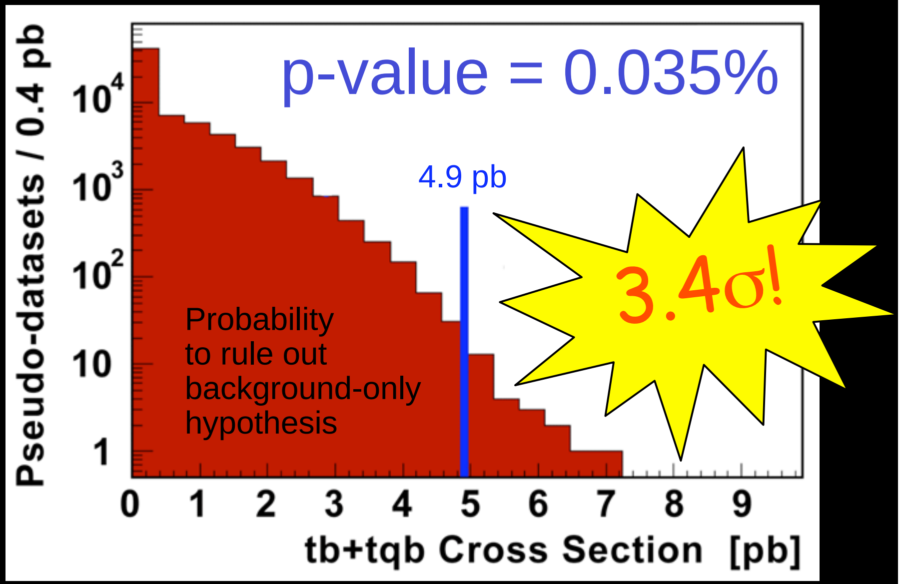
decision tree analysis





$\sigma(tb+tqb) = 4.9 \pm 1.4$ pb

Compatibiliy with SM = 11%



measurement of $|V_{tb}|$

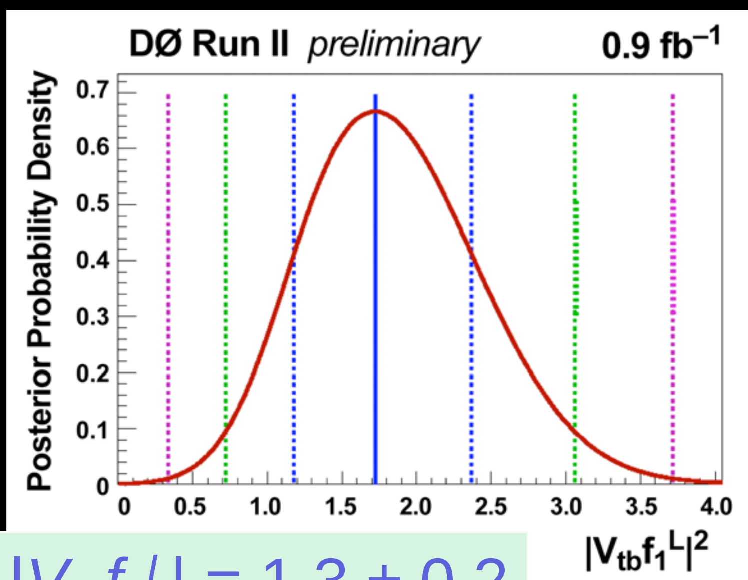
$\sigma(tb,tqb) \propto |V_{tb}|^2 \rightarrow$ calculate a posterior in $|V_{tb}|^2$

assume

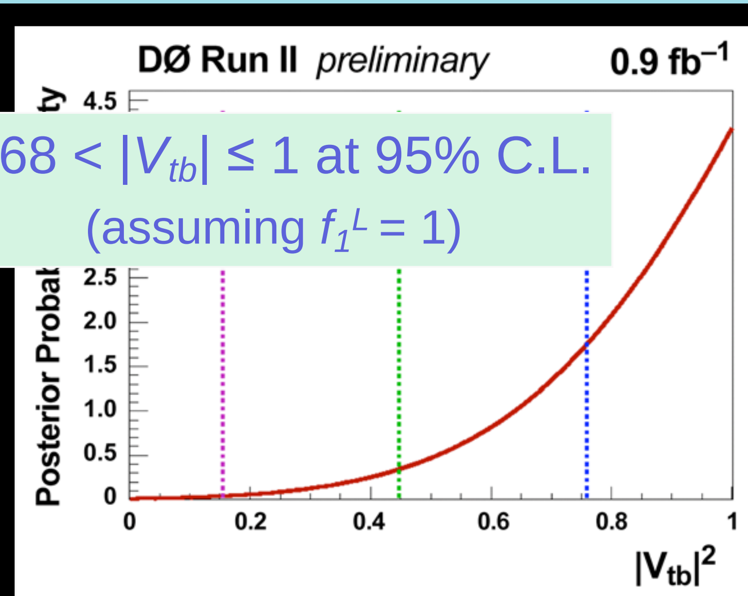
- sm top decay: $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$ and pure V–A coupling

do not assume

- three quark families and unitarity of 3\times 3 CKM matrix



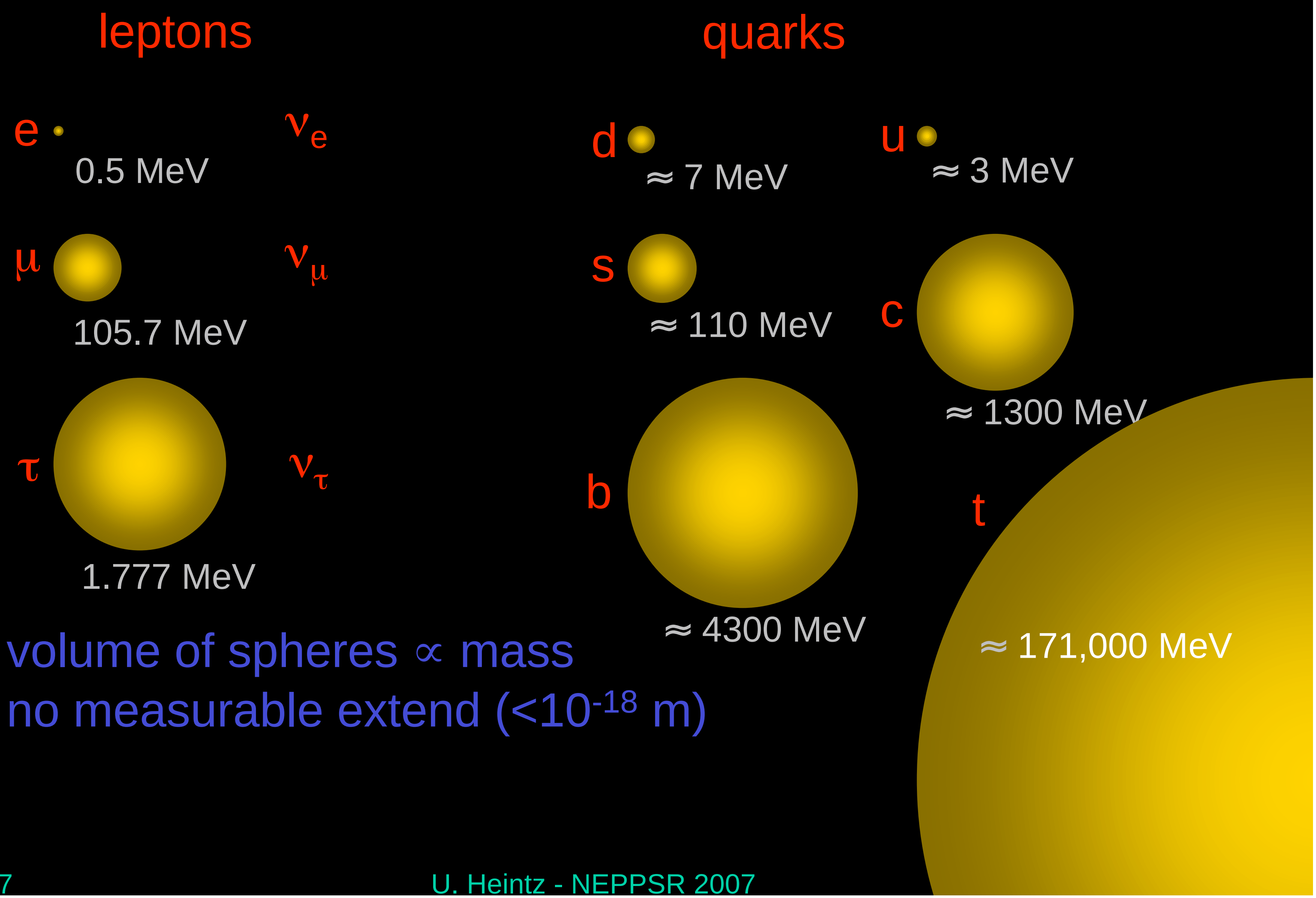
$|V_{tb}f_1^L| = 1.3 \pm 0.2$



$0.68 < |V_{tb}| \leq 1$ at 95% C.L.

(assuming $f_1^L = 1$)

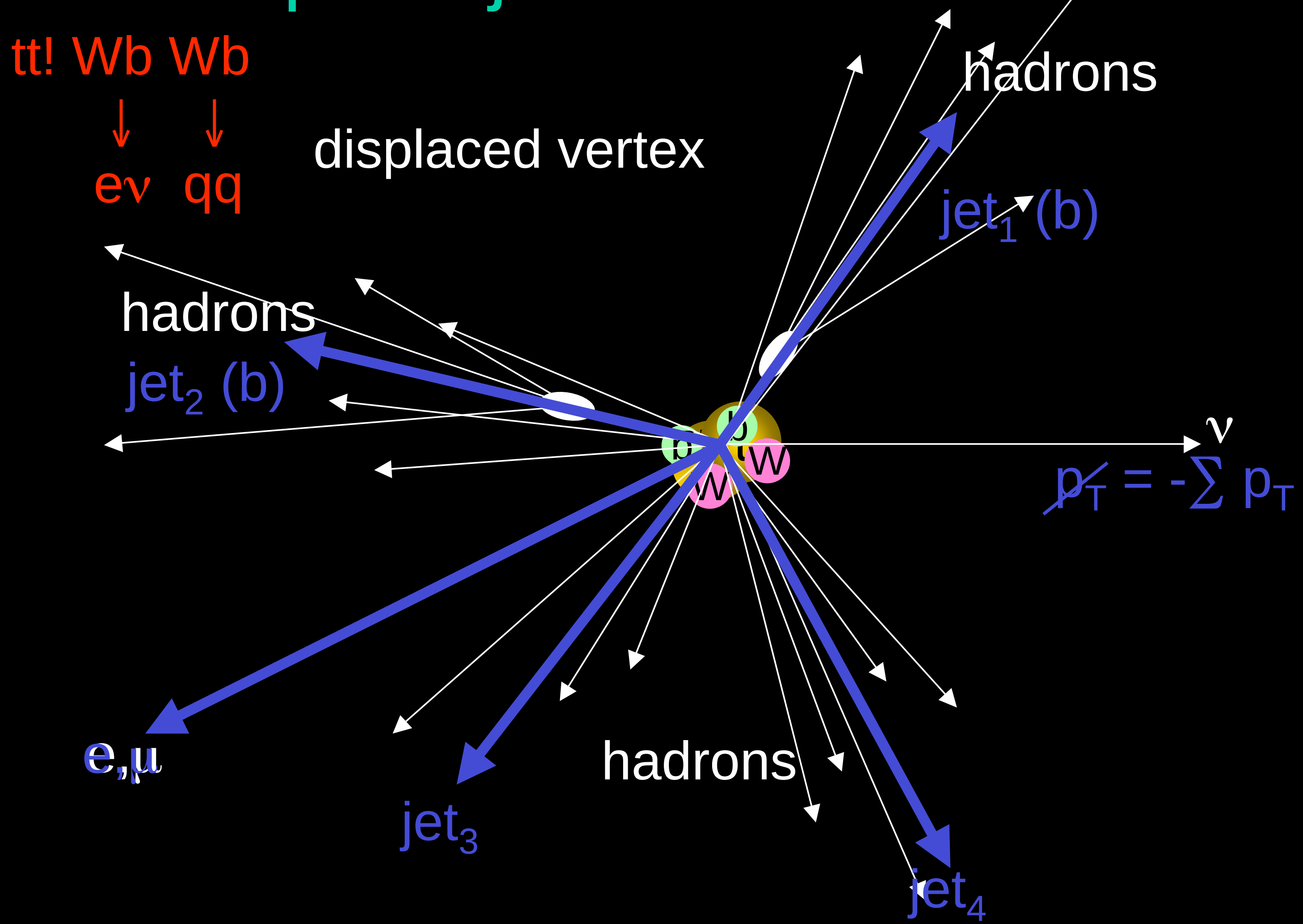
the top quark is the most massive quark



volume of spheres ∝ mass

no measurable extend ($<10^{-18}$ m)

lepton+jets event kinematics

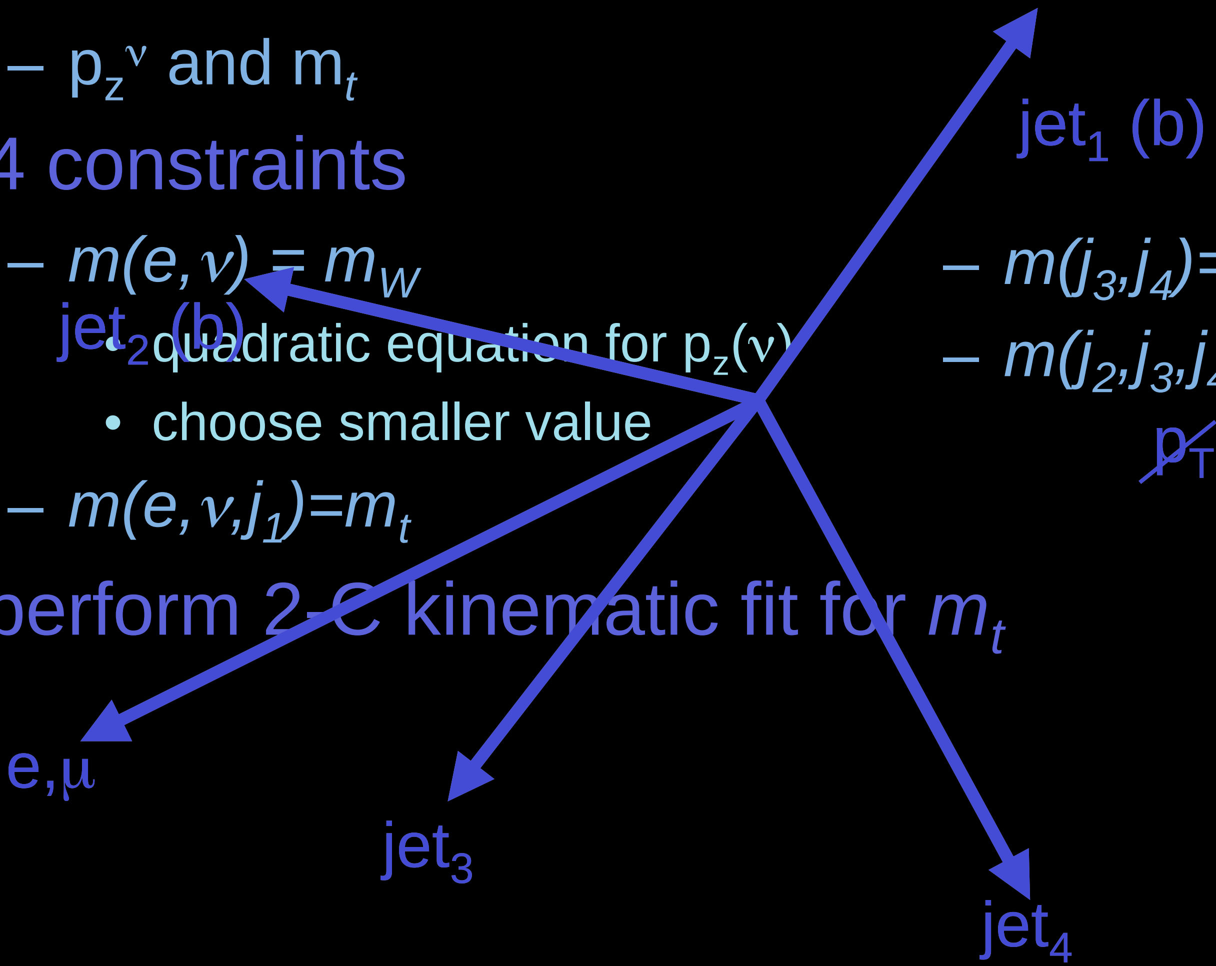


lepton+jets event kinematics

- 2 unknowns
  - p_z^{ν} and m_t
- 4 constraints
  - $m(e,\nu) = m_W$
    - quadratic equation for $p_z(\nu)$
    - choose smaller value
  - $m(e,\nu,j_1)=m_t$
  - $m(j_3,j_4)=m_W$
  - $m(j_2,j_3,j_4)=m_t$

$\not{p}_T = -\sum p_T$

- perform 2-C kinematic fit for m_t



lepton+jets event kinematics

- complications
  - combinatorics
    - j_1,j_2,j_3,j_4 → b,b,W (12 permutations)
    - b,j_2,j_3,j_4 → b,b,W (8 permutations)
    - b,b,j_3,j_4 → b,b,W (2 permutations)
  - gluon radiation
    - initial state radiation
      - momentum from initial quark/antiquark or spectators → overestimate m_t
    - final state radiation
      - momentum from t or b quarks → underestimate m_t
- many techniques

matrix element method

- probability density for an event o if the mass of the top quark is m_t

top fraction

jet scale parameter

- combine all events in a joint likelihood
- and maximize wrt m_t, α_{jes}, f_{top}
- calculate signal probability

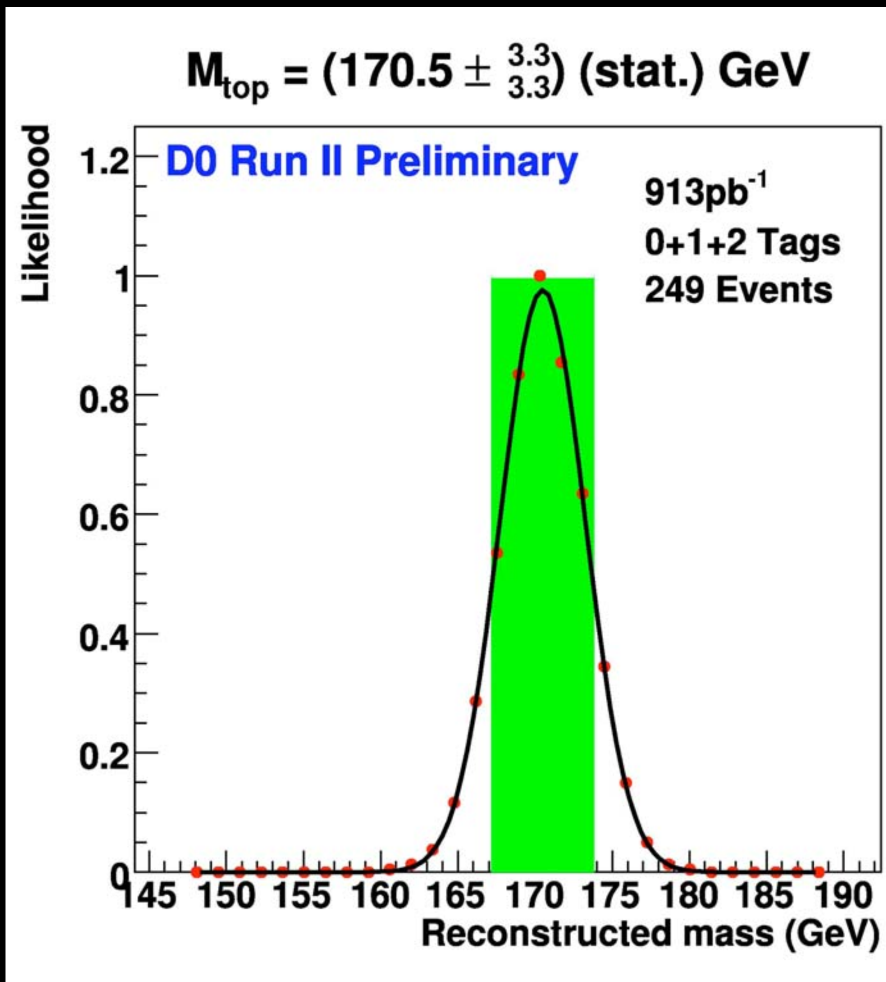
pdf

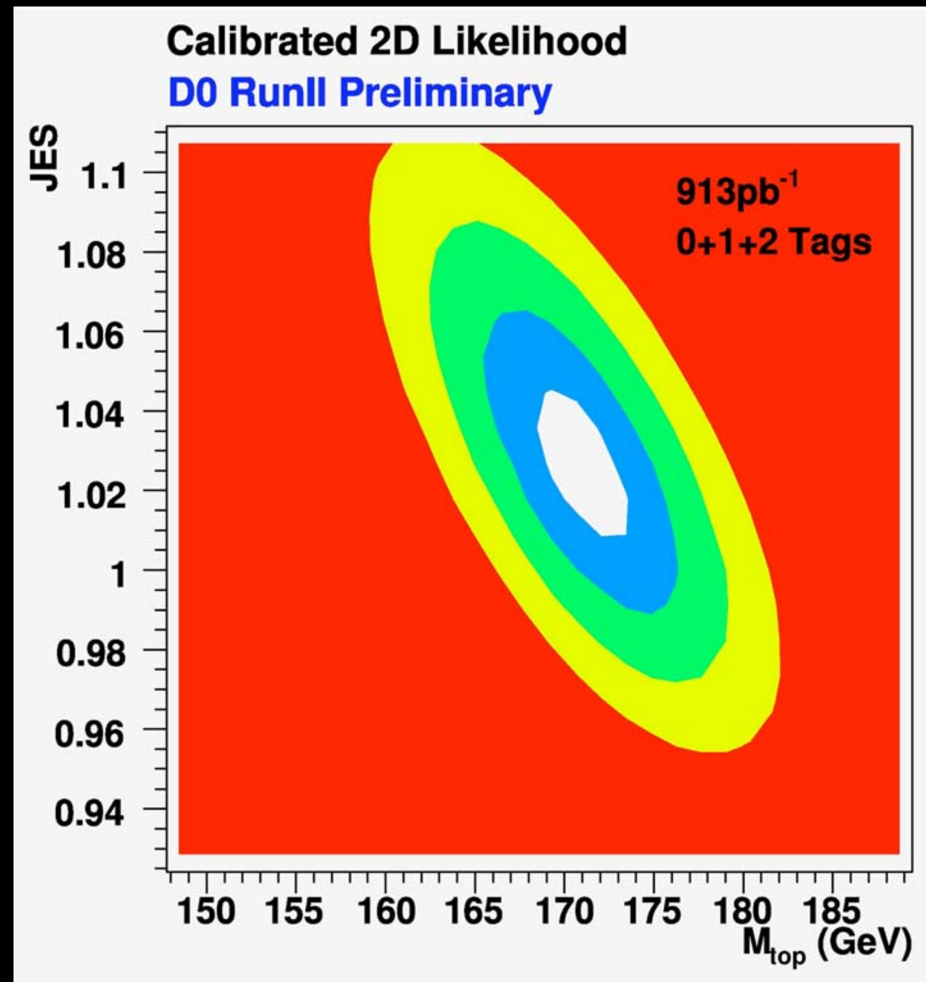
$|M|^2$ dLIPS

normalization

transfer function parametrize detector response

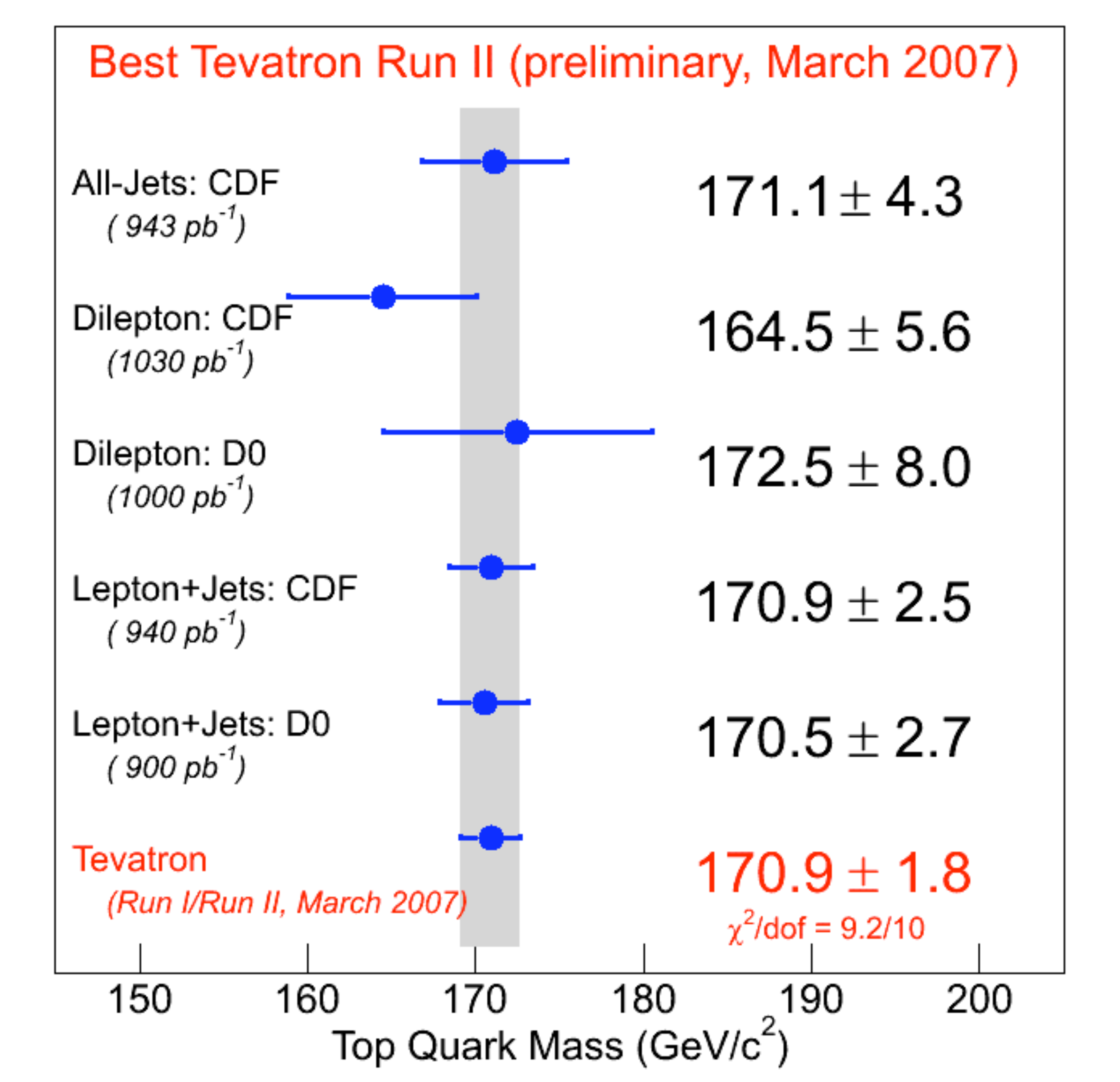
top quark mass



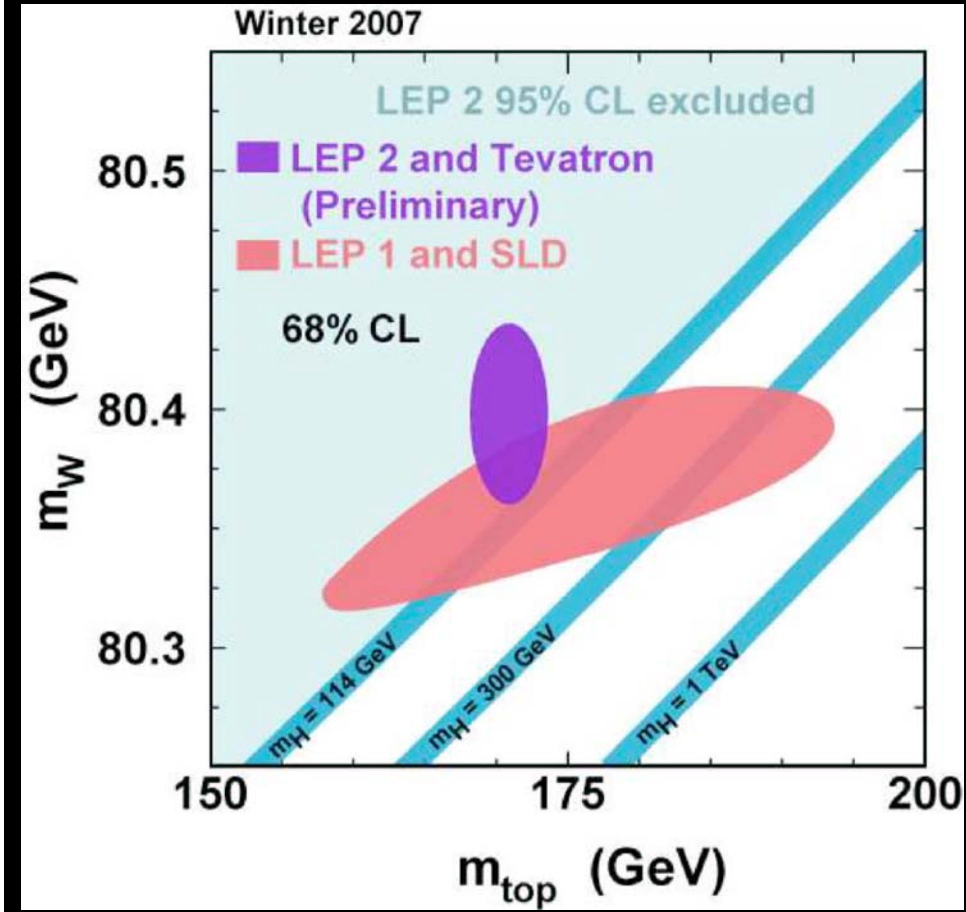


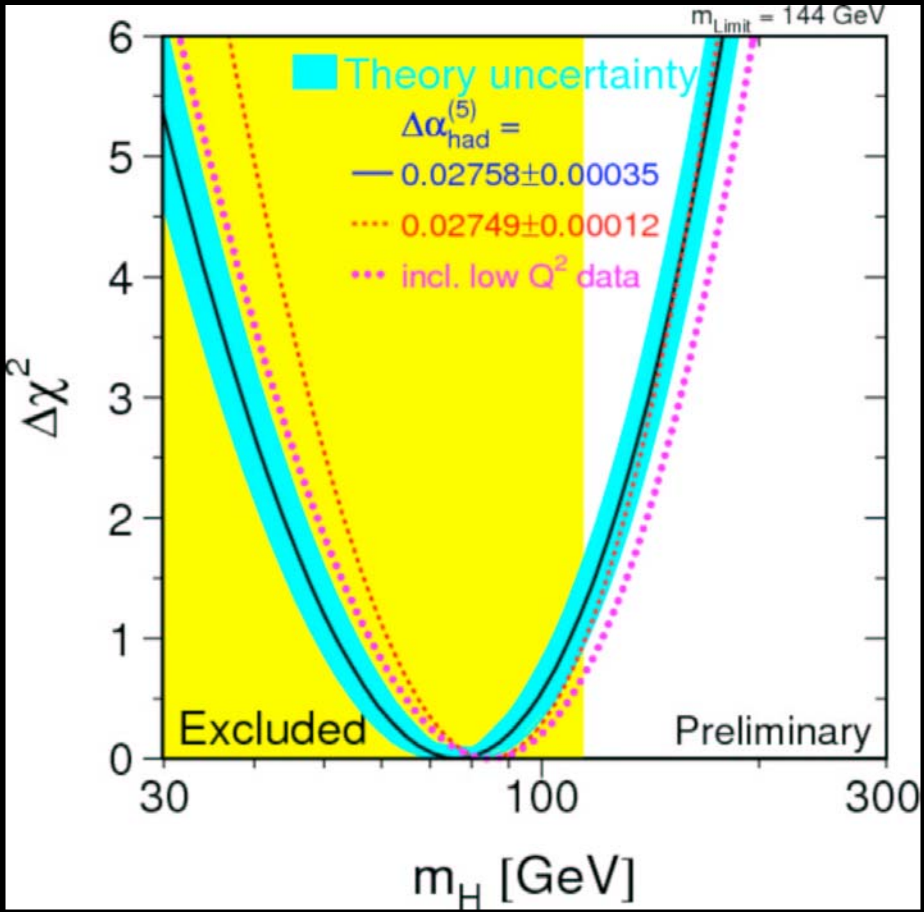
result for e+jets and μ+jets combined: m_{top} = 170.5§2.4§1.2 GeV

top quark mass



Higgs boson mass





Higgs boson

- standard model Higgs boson searches

the Higgs mechanism

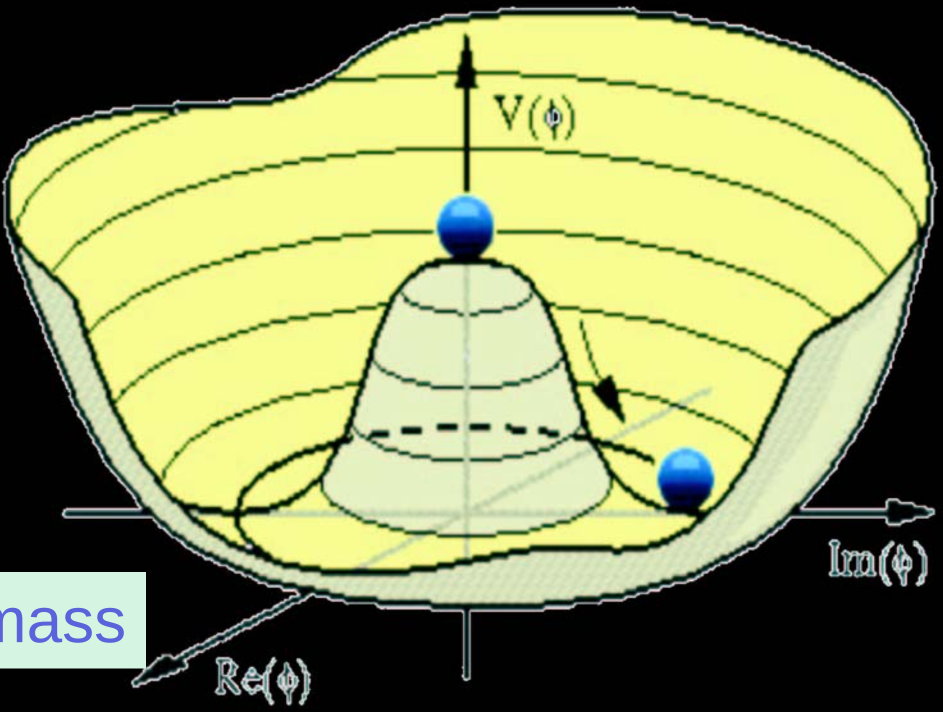
the Higgs field with its "mexican hat" potential breaks the SU(2)×U(1) symmetry

three Higgs degrees of freedom become the longitudinal components of the W and Z bosons

fermions acquire mass through their Yukawa couplings to the Higgs

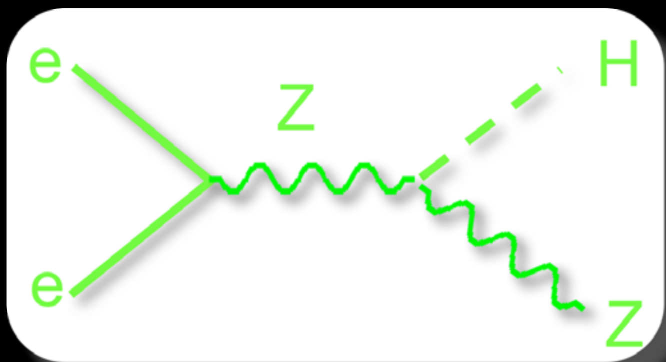
one Higgs degree of freedom represents a massive scalar particle

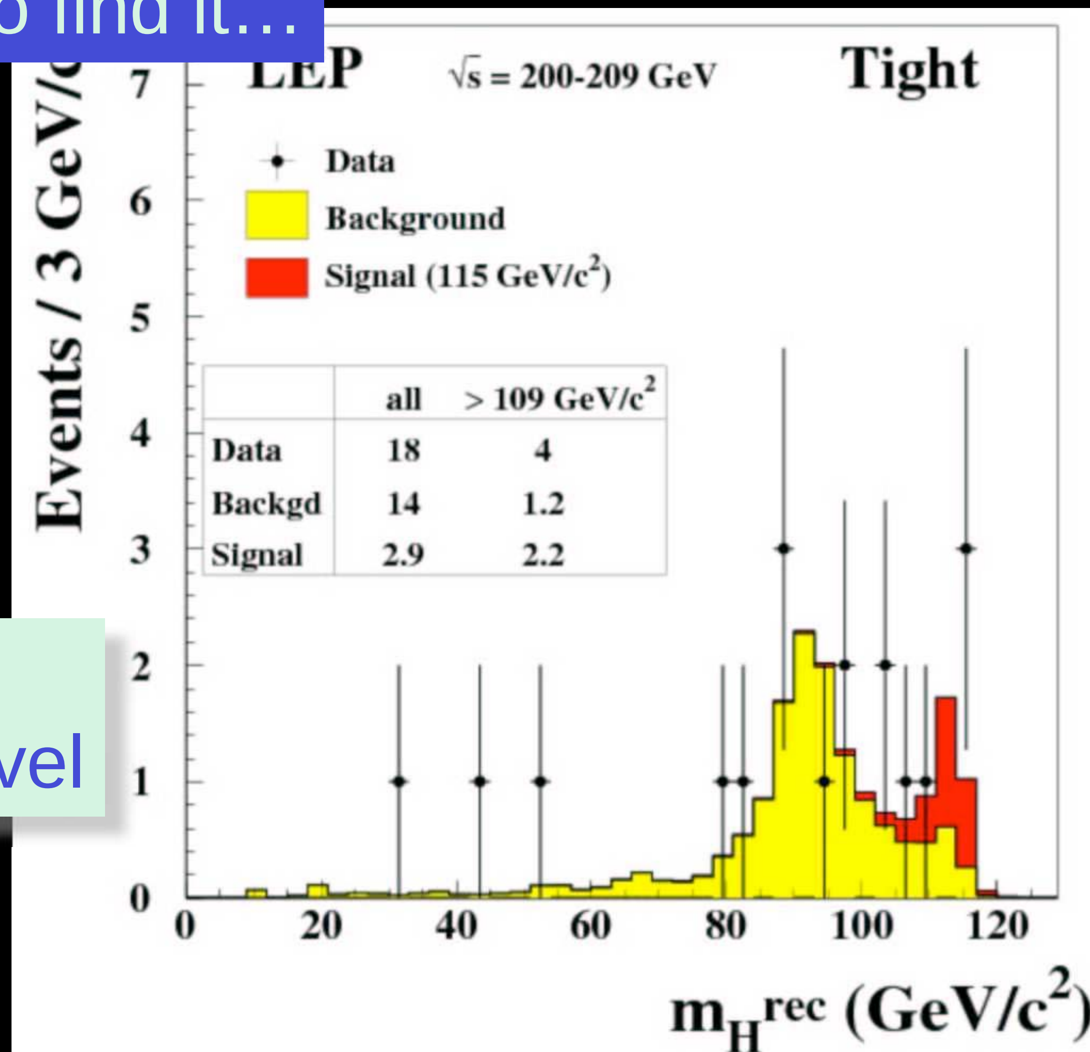
only free parameter is its mass



Higgs at LEP

LEP was supposed to find it…



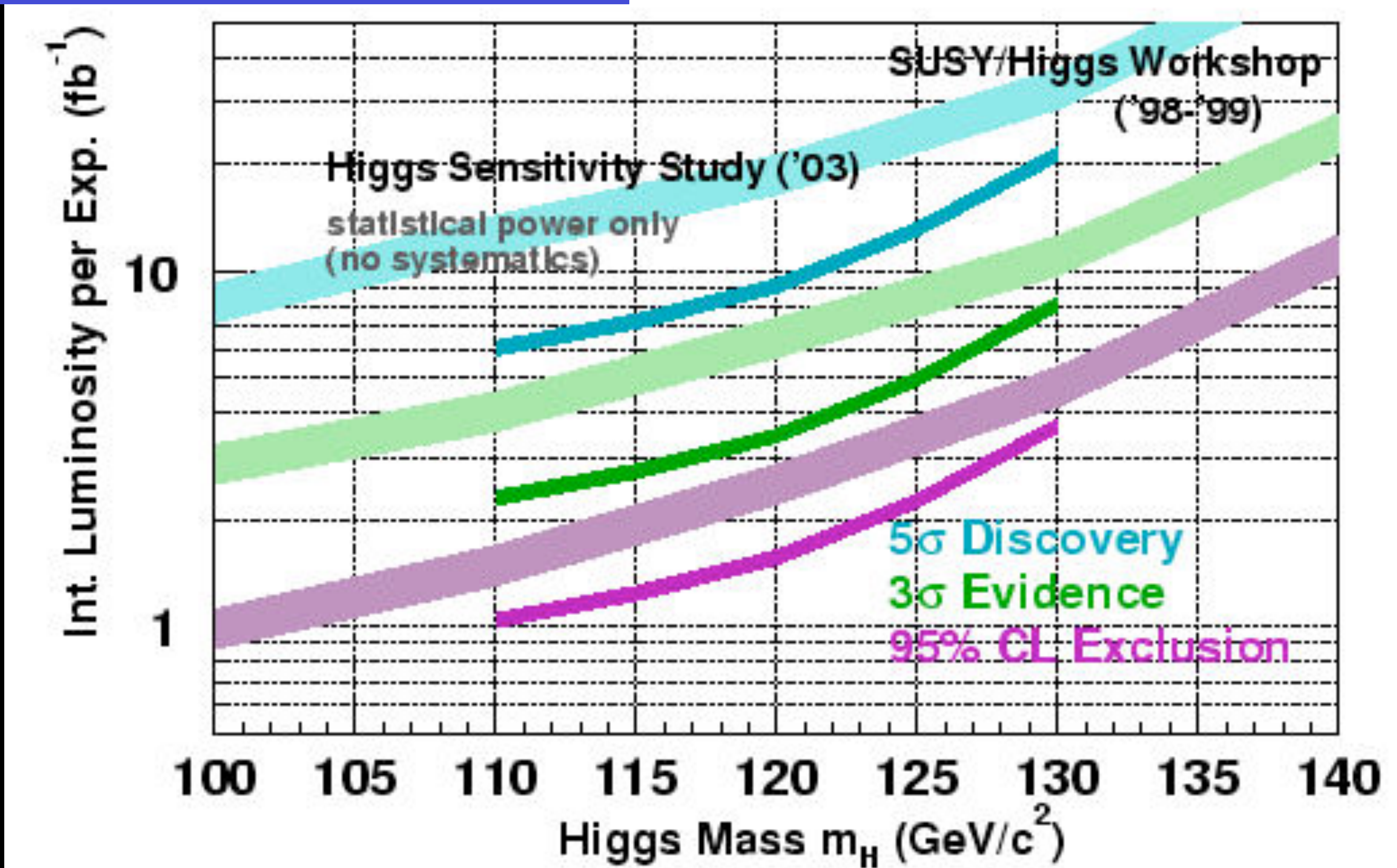


m_H > 114.4 GeV
@ 95% confidence level

Phys. Lett. B565 61 (2003)

Higgs at Tevatron

… but when it didn’t …

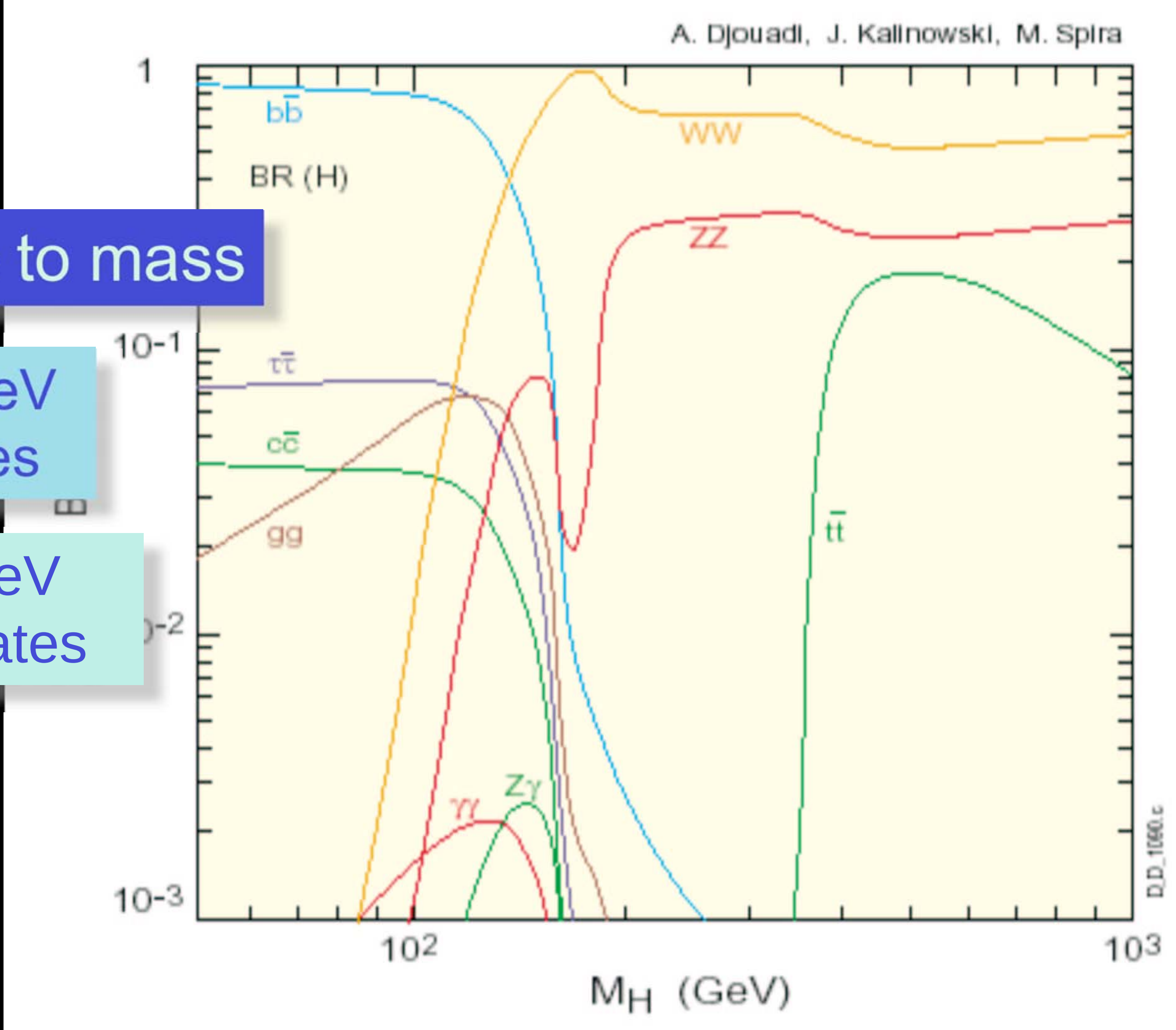


Higgs boson decay

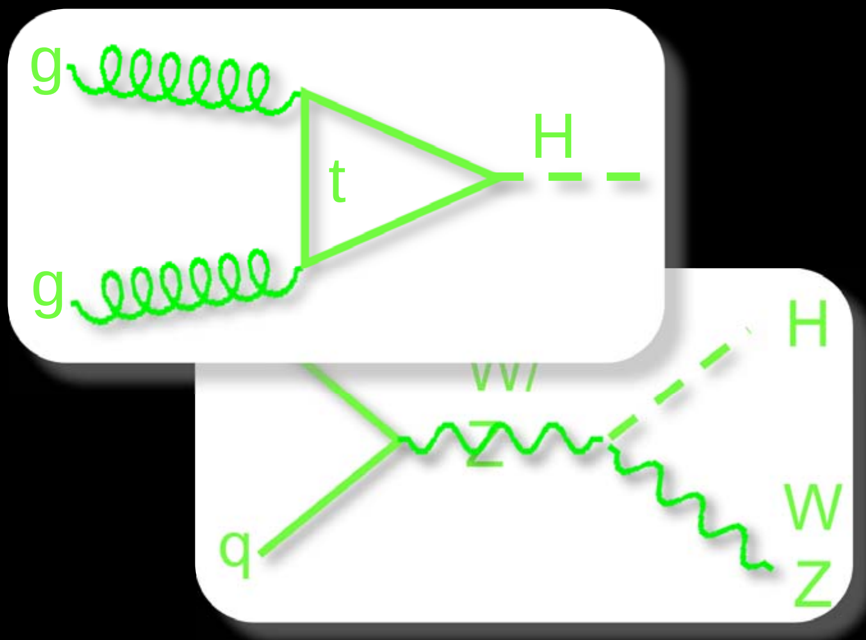
Higgs couples to mass

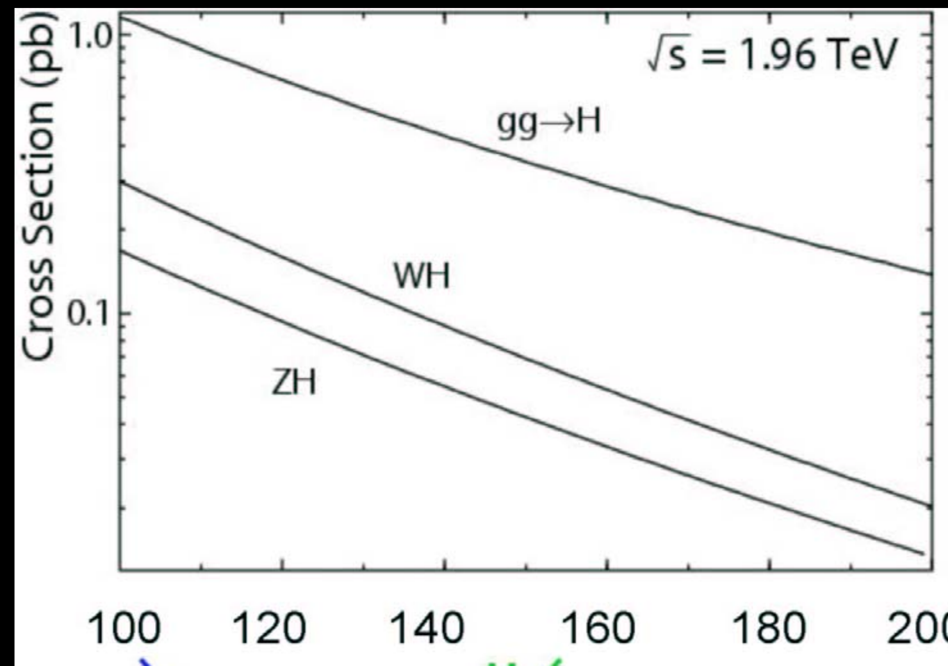
for m_H < 130 GeV
H ! bb dominates

for m_H > 130 GeV
H ! WW dominates



Higgs production at the Tevatron

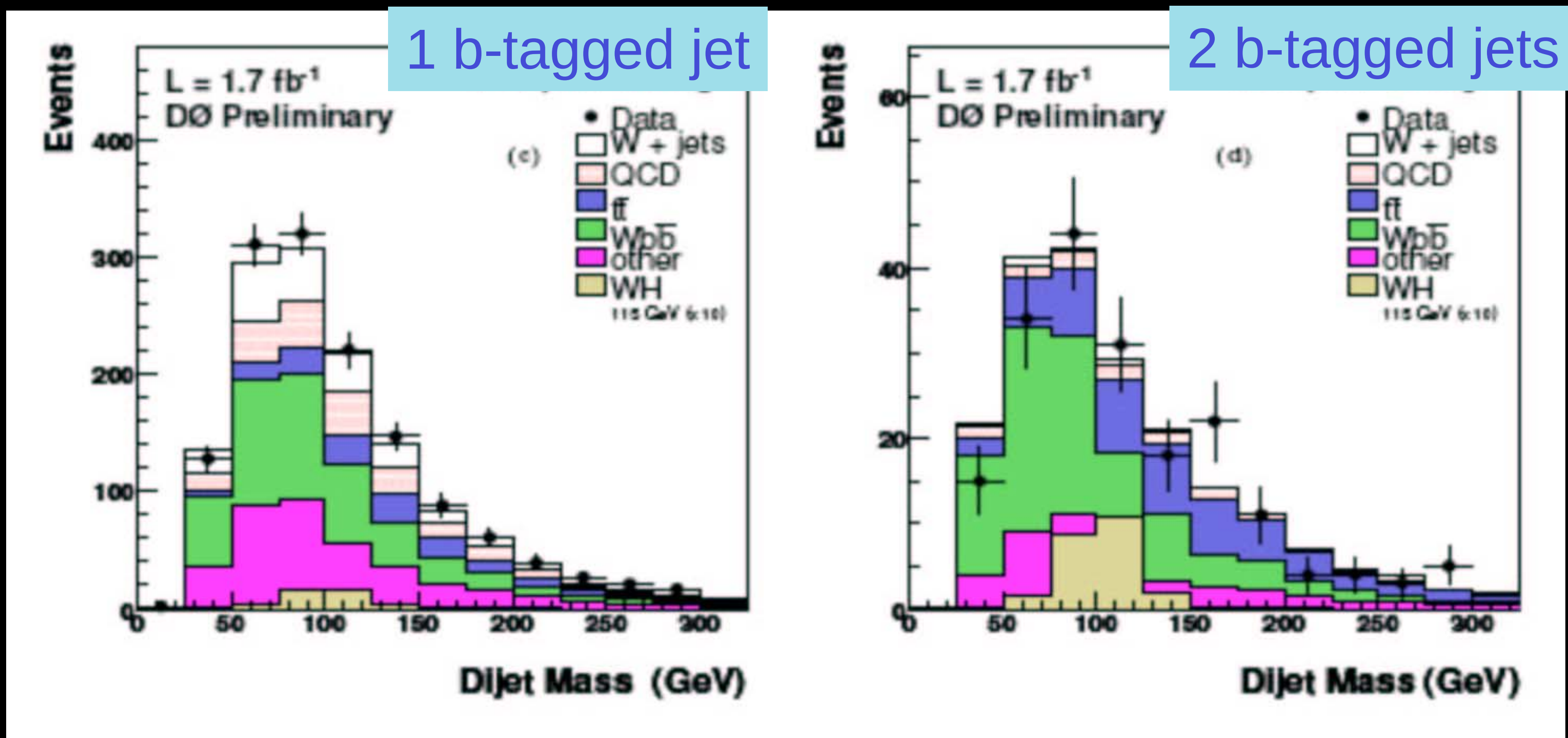




channel	σ	B_H	$B_{W/Z}$	σ£B	m_H
WH! lν bb	0.18 pb	0.8	0.22	0.032 pb	115 GeV
ZH! νν bb	0.11 pb	0.8	0.20	0.018 pb	115 GeV
ZH! llbb	0.11 pb	0.8	0.067	0.006 pb	115 GeV
H! WW! lν lν	0.3 pb	1.0	0.047	0.014 pb	160 GeV
WH!WWW!lνlνX	0.05 pb	1.0	0.083	0.004 pb	160 GeV

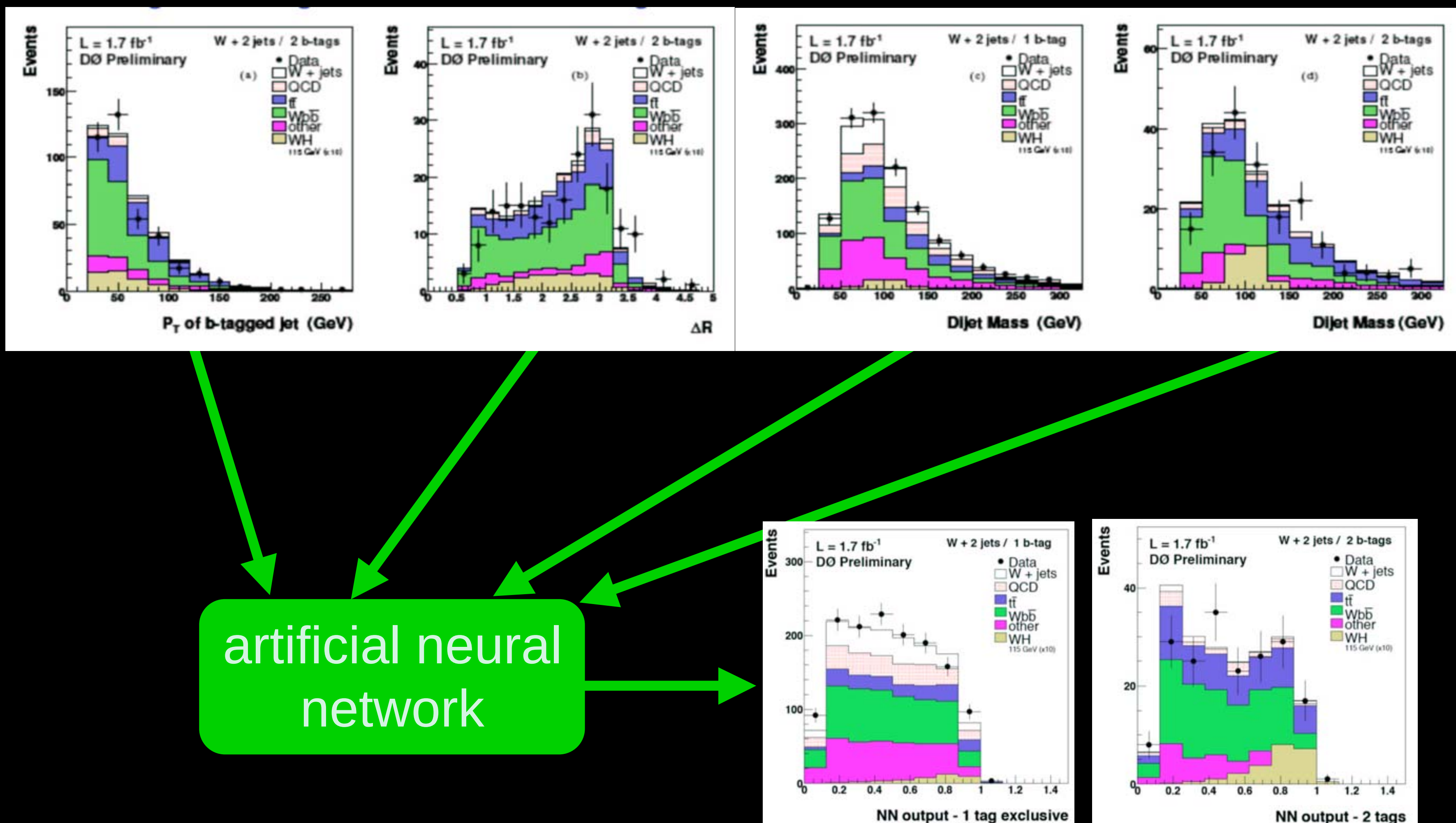
WH! lν bb

select events with high p_T lepton, missing p_T, 2 jets



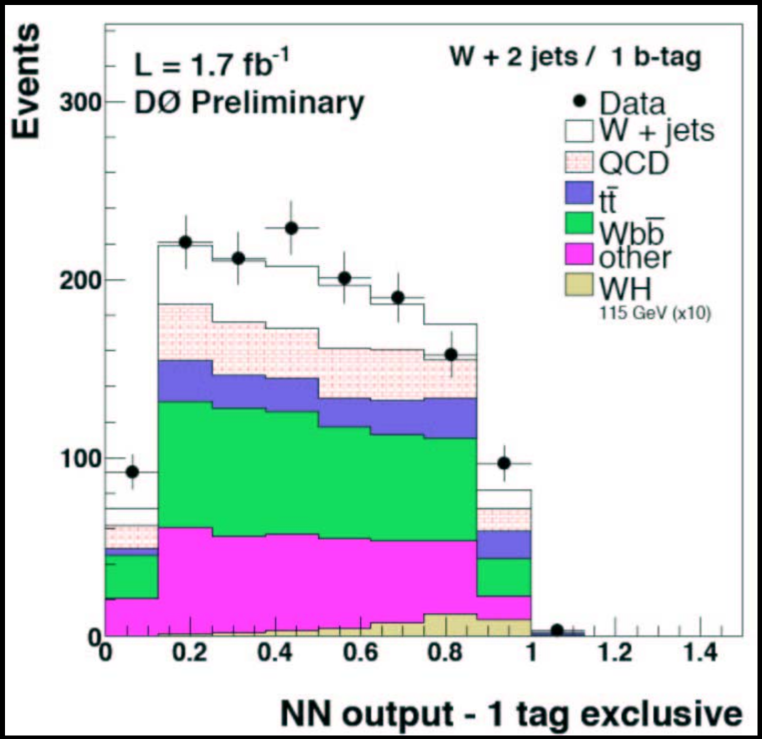
WH! lν bb

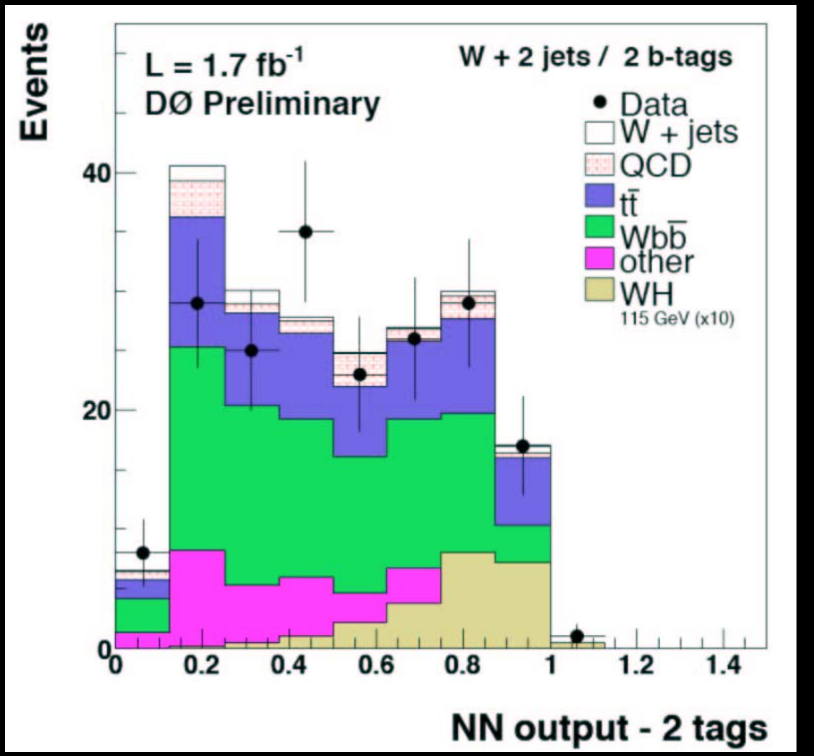
select events with high p_T lepton, missing p_T, 2 jets



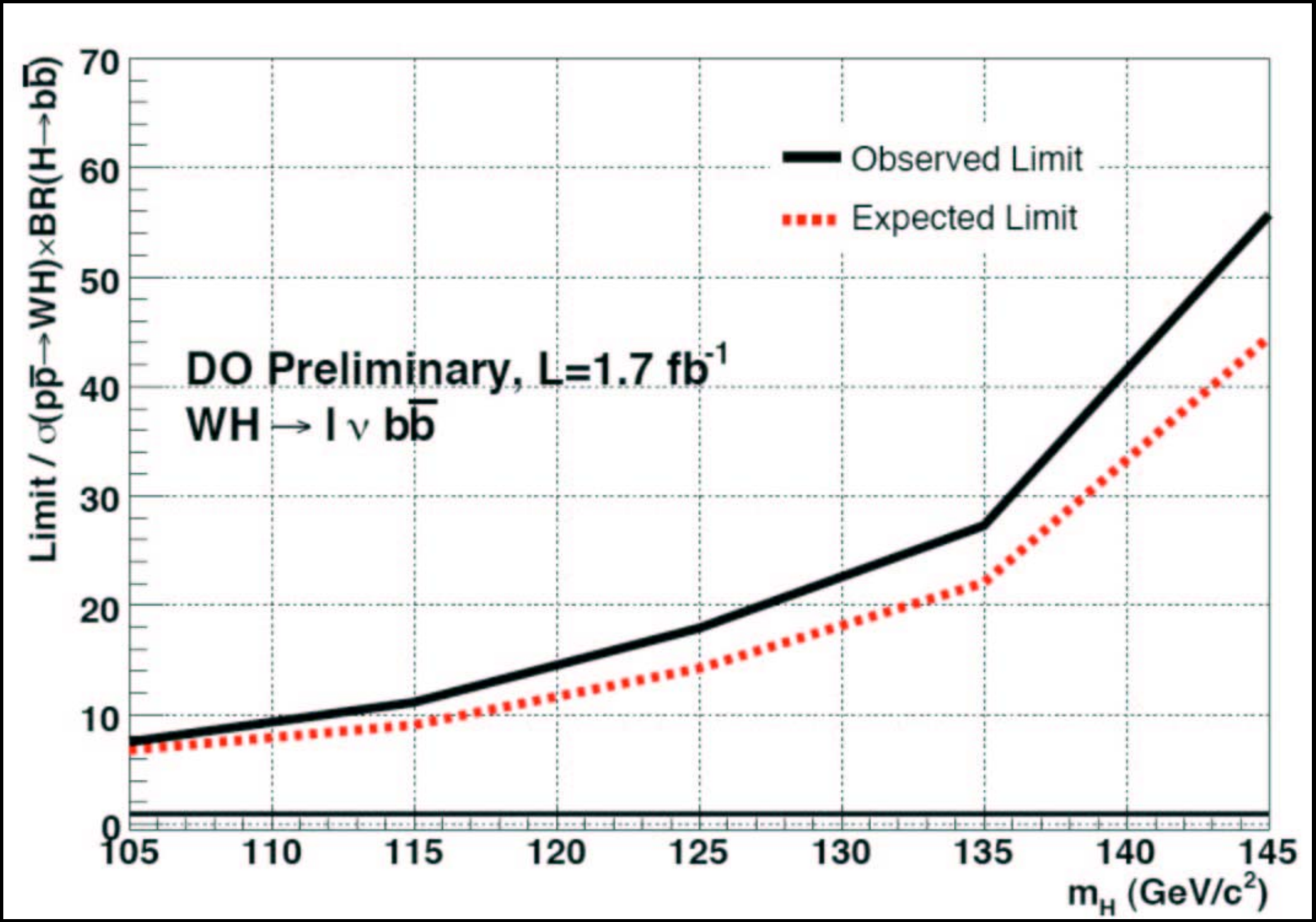
WH! lν bb

select events with high p_T lepton, missing p_T, 2 jets

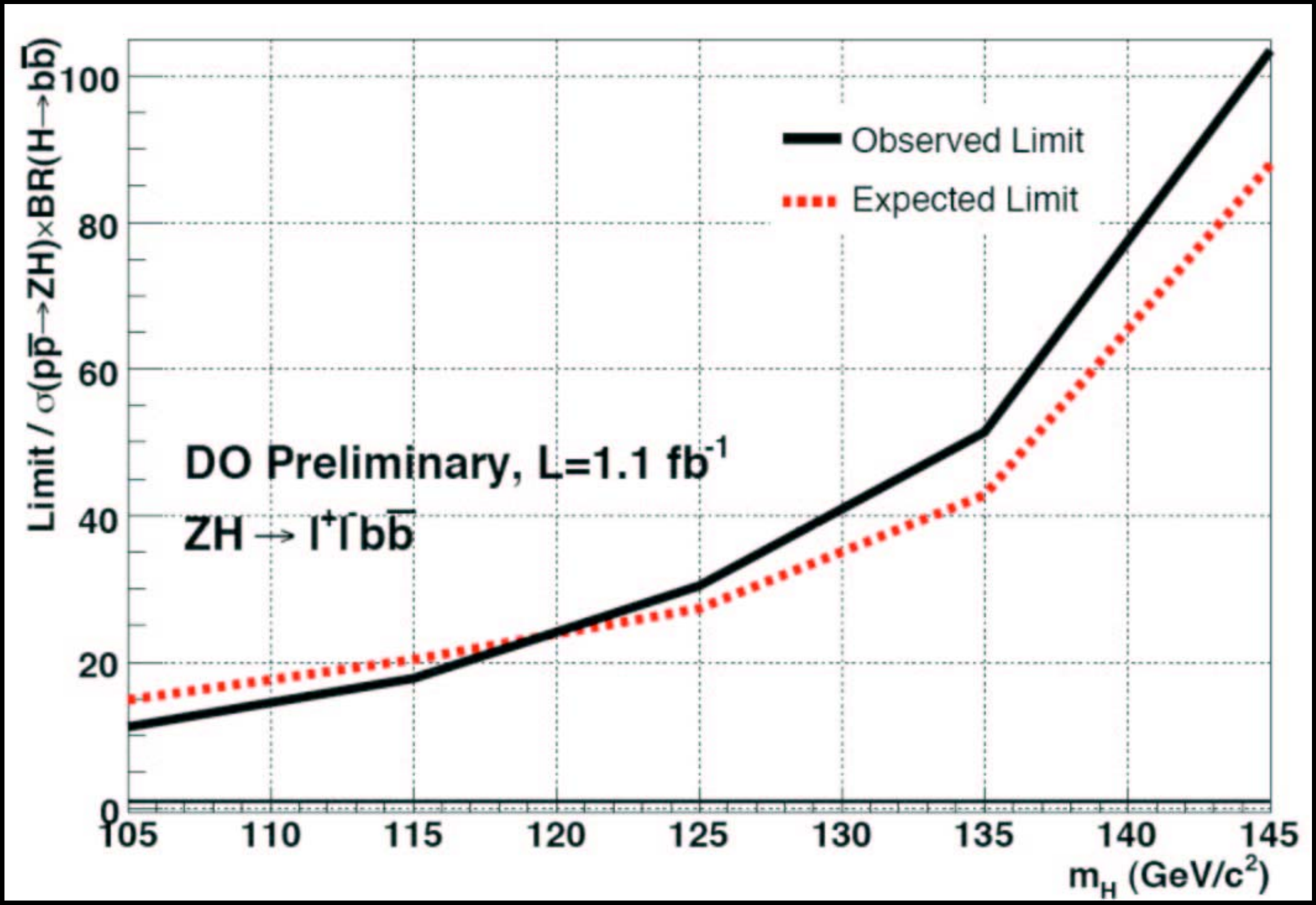




WH ! lν bb

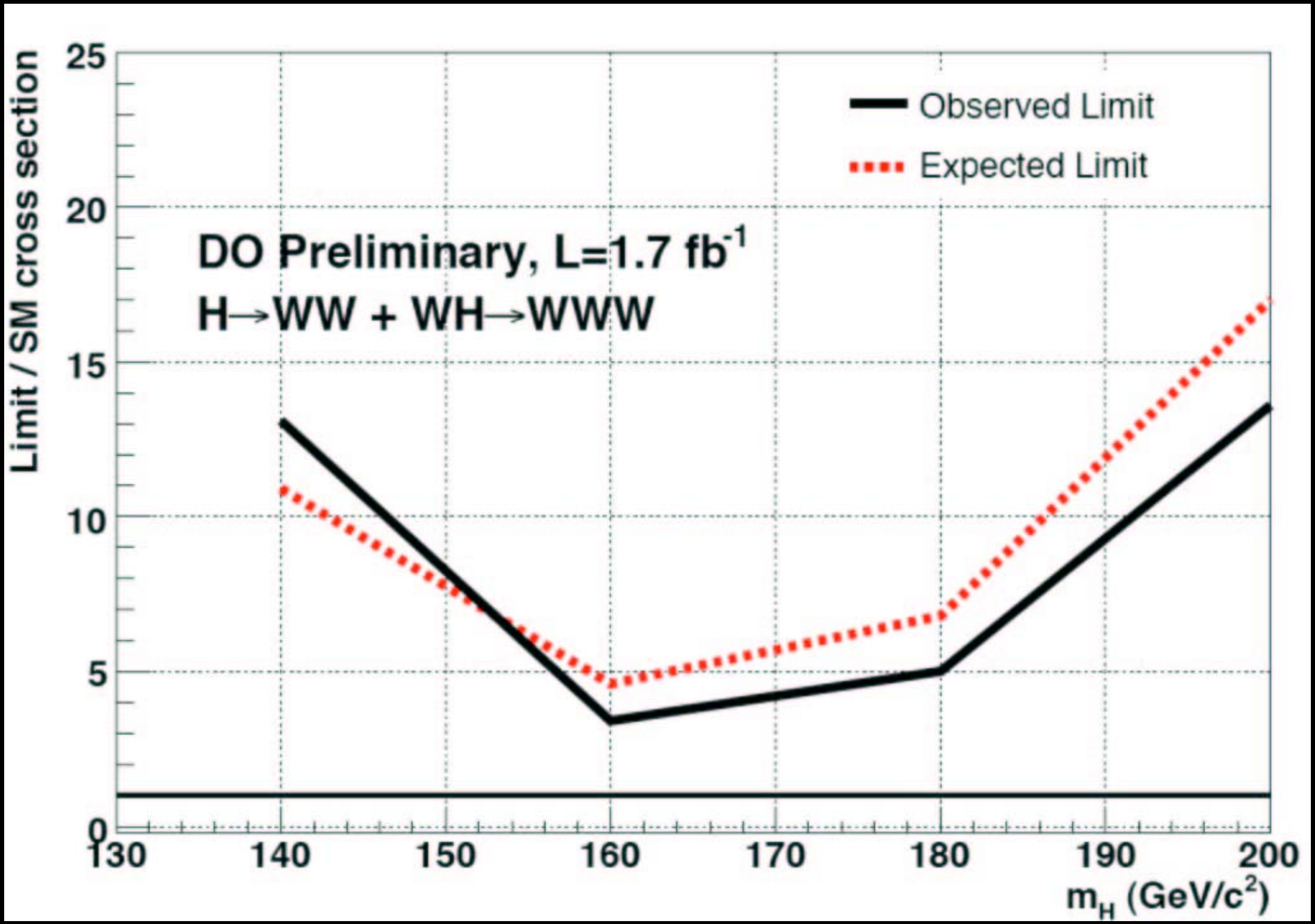

Limit / σ(pp̄→WH)×BR(H→bb̄)
Observed Limit
Expected Limit
DO Preliminary, L=1.7 fb-1
WH → l ν bb̄
0
10
20
30
40
50
60
70
105
110
115
120
125
130
135
140
145
mH (GeV/c2)

ZH ! ll bb

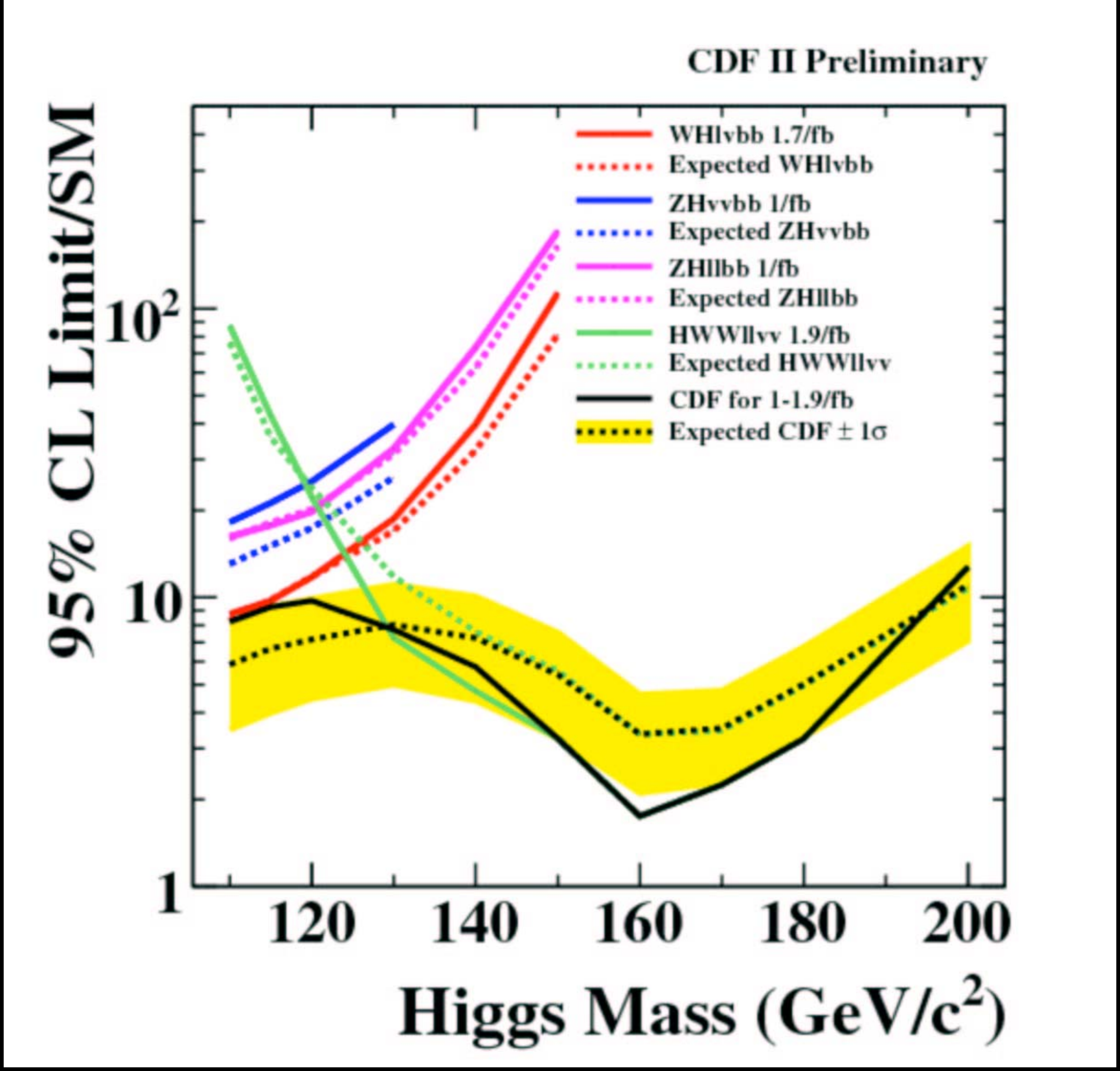


Limit / σ(pp̄→ZH)×BR(H→bb̄)
100
80
60
40
20
0
105
110
115
120
125
130
135
140
145
m_H (GeV/c²)
Observed Limit
Expected Limit
DO Preliminary, L=1.1 fb⁻¹
ZH → l⁺l⁻bb̄

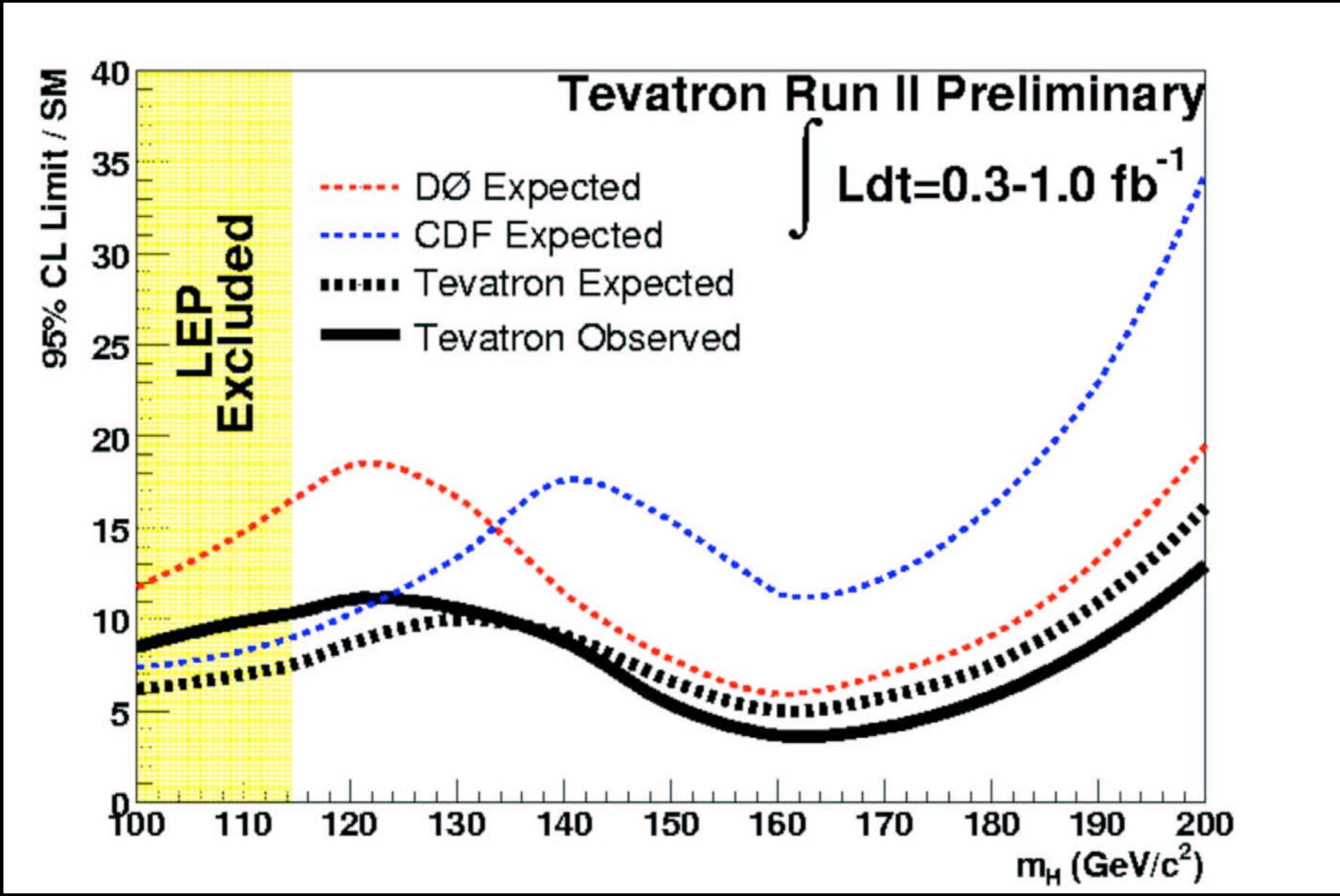
H ! WW


Limit / SM cross section
25
20
15
10
5
0
130
140
150
160
170
180
190
200
m_H (GeV/c^2)
Observed Limit
Expected Limit
DO Preliminary, L=1.7 fb^{-1}
H→WW + WH→WWW

CDF results


CDF II Preliminary
95% CL Limit/SM
10^2
10
1
120
140
160
180
200
Higgs Mass (GeV/c^2)
WHlvbb 1.7/fb
Expected WHlvbb
ZHvvbb 1/fb
Expected ZHvvbb
ZHllbb 1/fb
Expected ZHllbb
HWWllvv 1.9/fb
Expected HWWllvv
CDF for 1-1.9/fb
Expected CDF ± 1σ

combined limits



where is all the new stuff?

- no leptoquarks
- no heavy W/Z bosons
- no compositeness
- no extra dimensions
- no technicolor
- no SUSY

the legacy of the Tevatron

- significant increase in sophistication of collider physics analyses
- the top quark discovery
- precision electroweak measurements
  - top quark mass
  - W boson mass
- QCD, bottom, charm physics
- no new physics – the sm is rock solid
- Higgs boson (limit/hint/discovery?)