top quark mass measurements

Ulrich Heintz

BOSTON UNIVERSITY

outline

- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

outline

- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

the standard model particle zoo

- standard model
  - describes the fundamental particles and their interactions
- fermions
  - six quarks
  - six leptons
  - electroweak doublets
  - constituents of matter

leptons

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

$$e_R \quad \mu_R \quad \tau_R$$

quarks

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \quad c_R \quad t_R$$

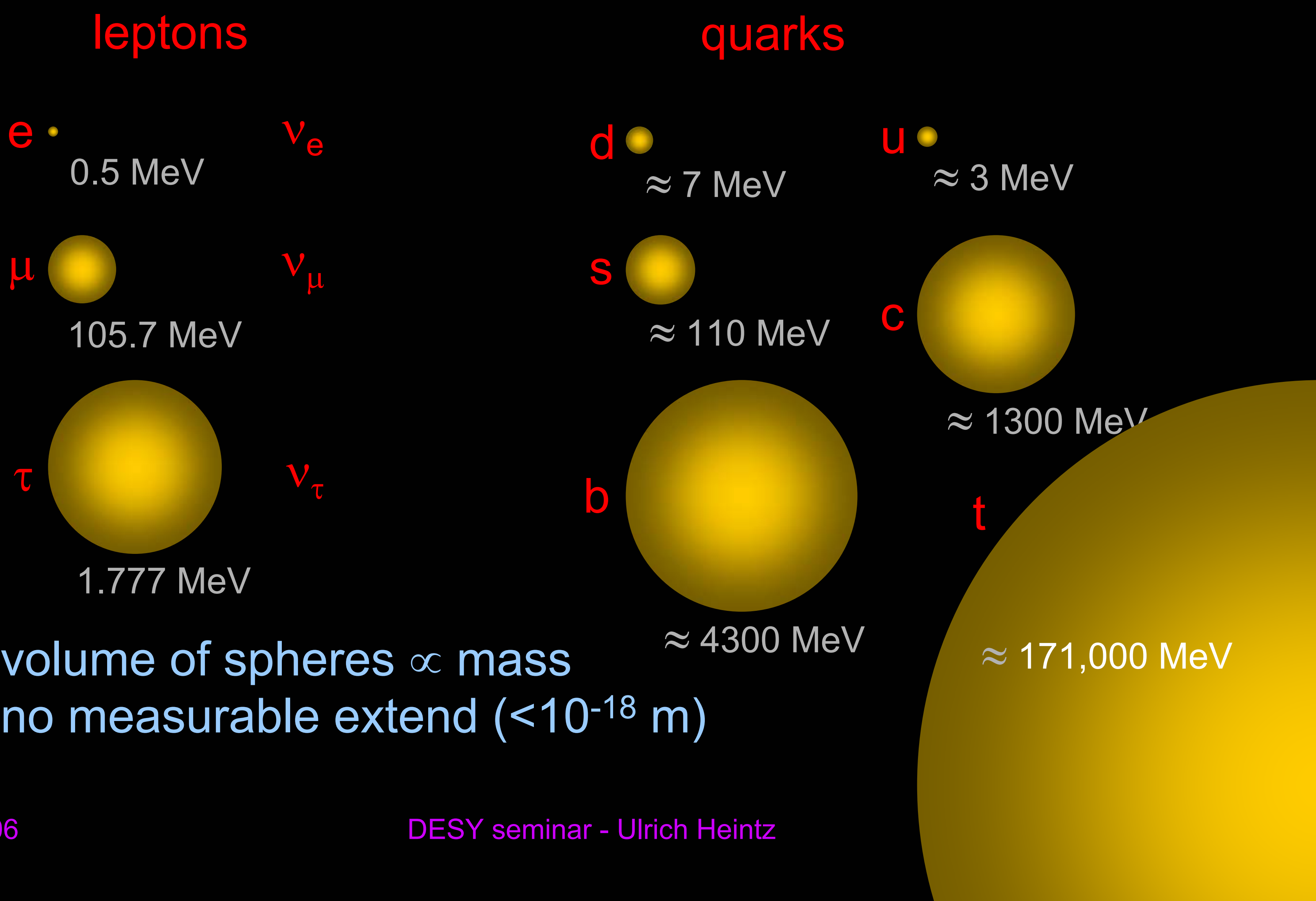
$$d_R \quad s_R \quad b_R$$

- bosons
  - force mediators

electroweak: $U(1)$ $SU(2)_L$ — γ $W^+ Z^0 W^-$

strong: $SU(3)$ — g

the top quark is the most massive quark



volume of spheres ∝ mass

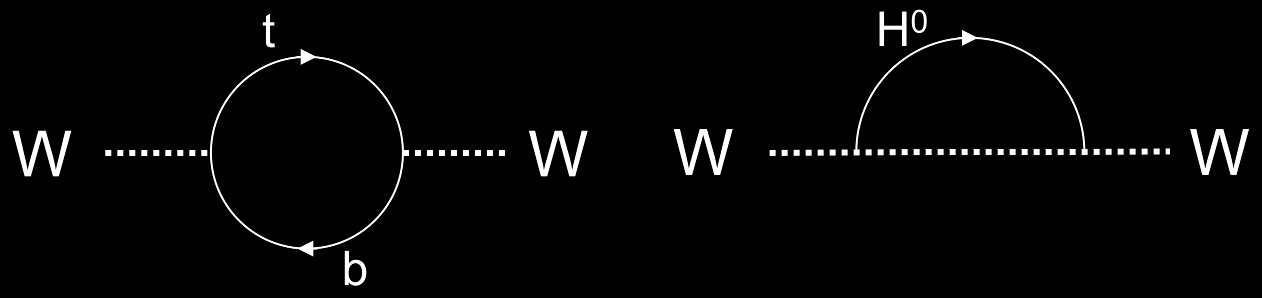
no measurable extend ($<10^{-18}$ m)

why study the top quark?

- it is there
  - properties are fundamental parameters
- it is the dominant contributor to sm corrections
  - $m_t >> m_b$ → largest contributor to radiative corrections, e.g. to W mass
- it couples strongly to the Higgs sector
  - maybe we can learn about EWSB
- it is as close as we can get to a ``bare'' quark
  - short lifetime $\tau \approx 10^{-24}$s < $\Lambda_{QCD}^{-1} \approx 10^{-23}$s → top decays before hadronizing
  - no confinement effects → can perform

top quark mass measurements

- importance of m_t (radiative corrections)



  - $m_W = m_W^{tree}\,(1 + \mathcal{O}(m_t^2) + \mathcal{O}(\log m_H))$
  - measuring α, G_F, θ_w, m_Z, m_W, and m_t checks consistency of model and constrains m_H

how do we measure quark masses?

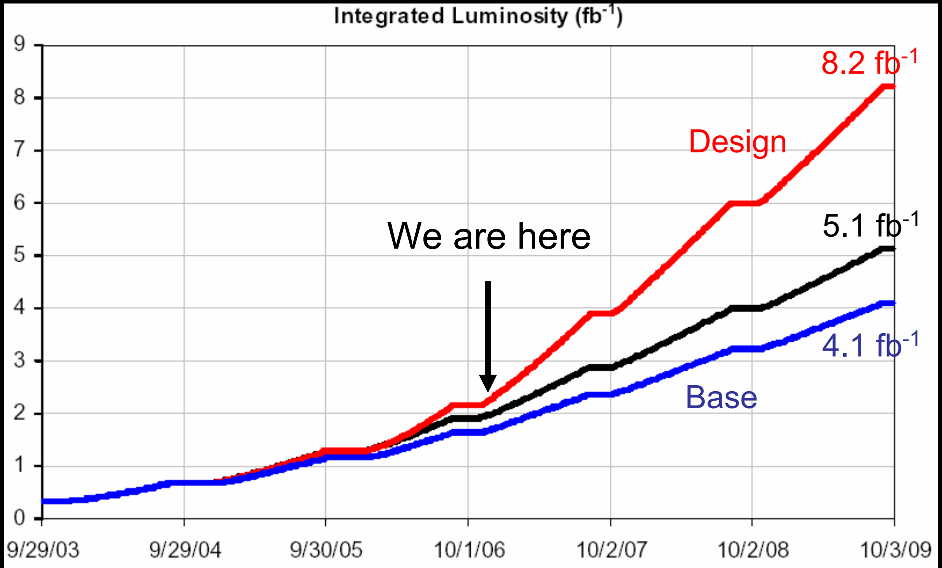
- quarks are confined
  - quarks cannot be observed in isolation
  - measure mass of color-singlet bound states (hadrons)
  - use lattice QCD to relate to quark mass
- top is short-lived
  - $\tau \approx 10^{-24}$ s
  - decays to Wb before it can form hadrons
  - reconstruct mass from its decay products

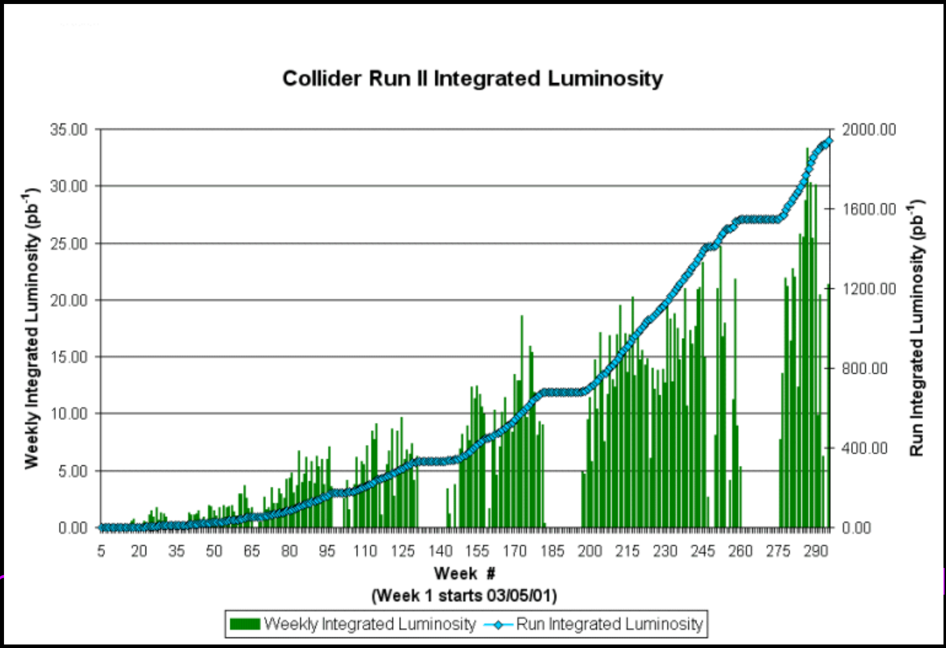
outline

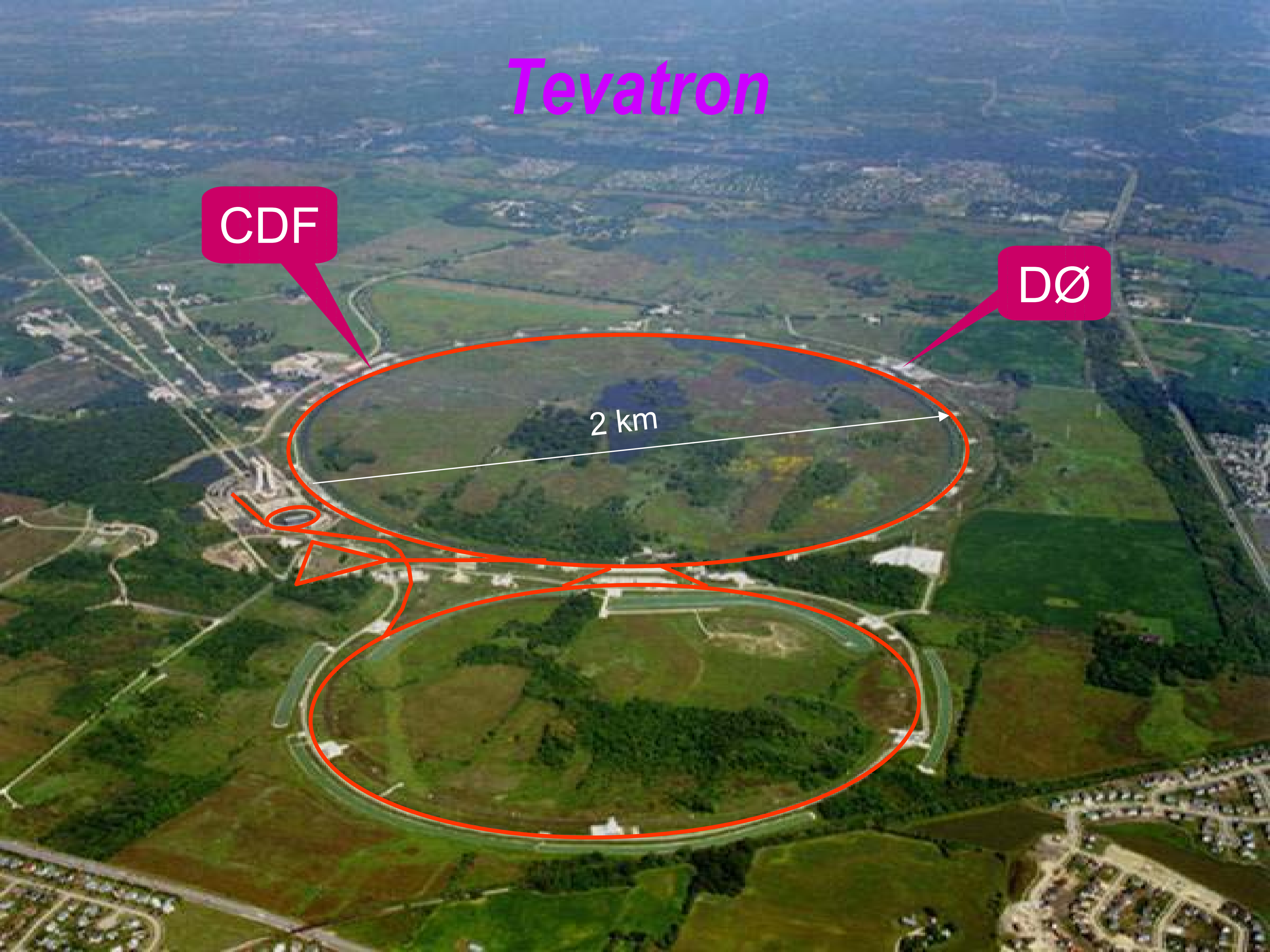
- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

Tevatron

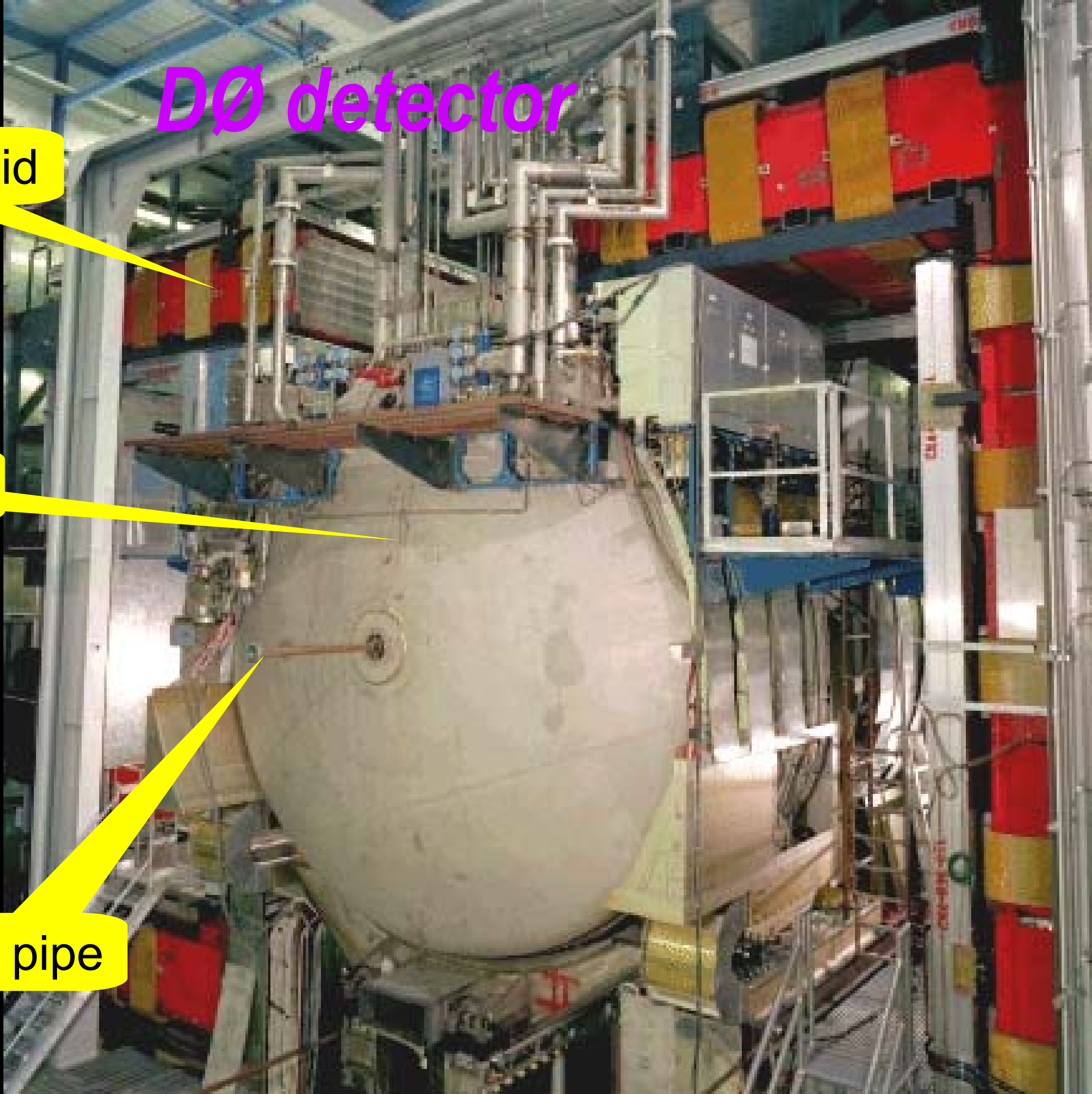
- Run I (1992-1996)
  - $\sqrt{s}$ = 1.8 TeV
  - $\int Ldt$ = 120 pb^{-1}
- Run II (2001-present)
  - $\sqrt{s}$ = 1.96 TeV
  - peak luminosity
    - $2.2\times10^{32}/cm^2/s$
  - $\int Ldt$ today at DØ
    - delivered 2.0 fb^{-1}
    - recorded 1.7 fb^{-1}
    - analyzed ≈ 900 pb^{-1}
  - $\int Ldt$ plan
    - 4-8 fb^{-1} by 2009



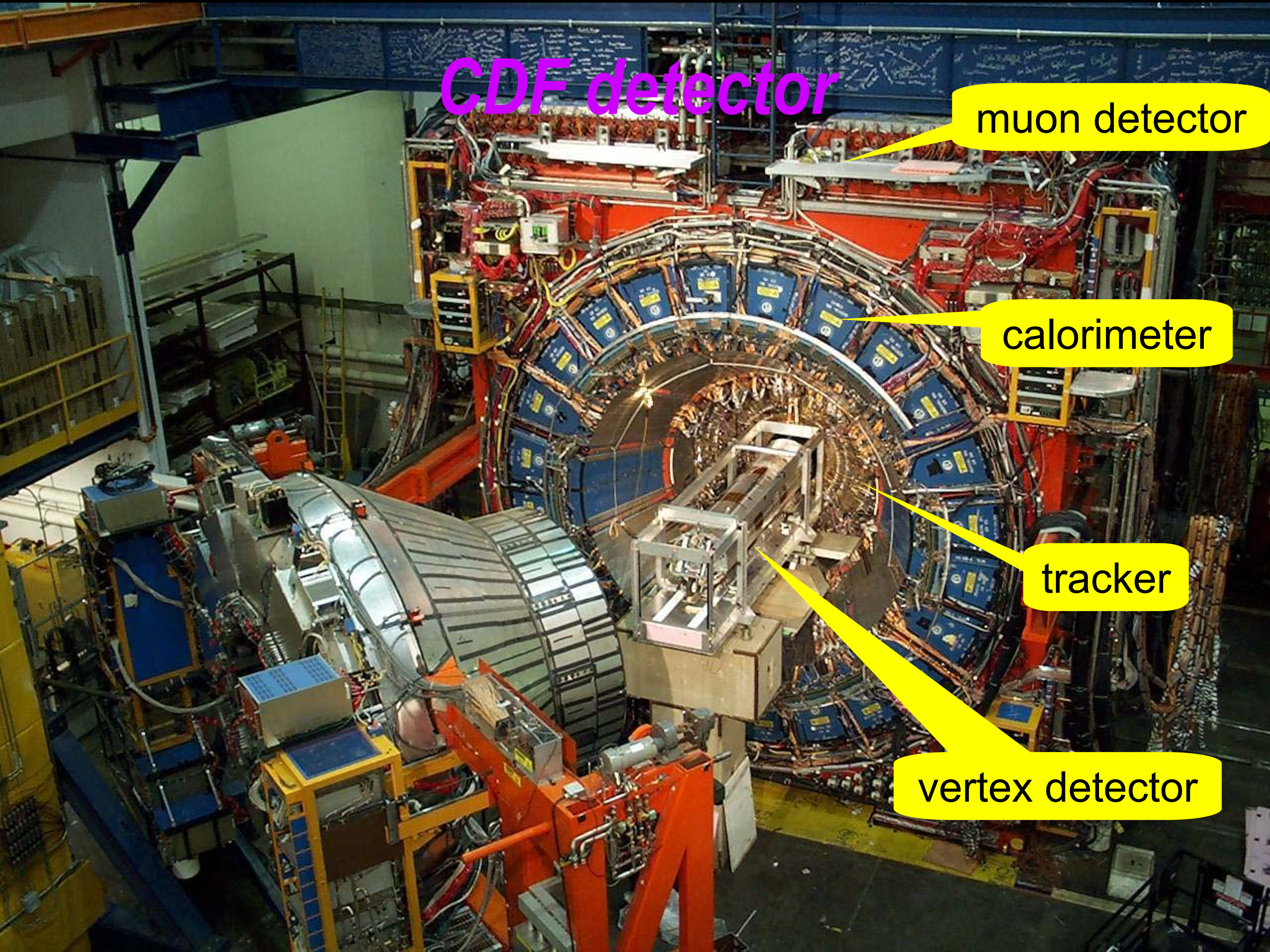



Tevatron
CDF
DØ
2 km

DØ detector



DØ detector

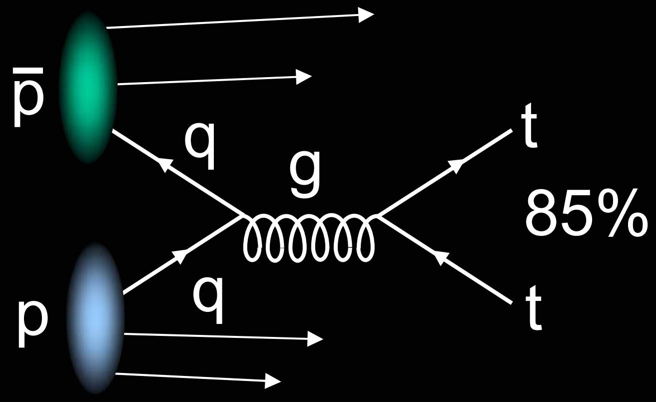

CDF detector
muon detector
calorimeter
tracker
vertex detector

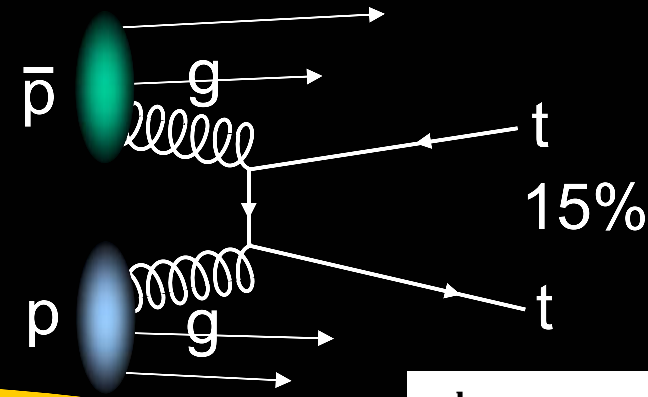
outline

- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

top-antitop pair production

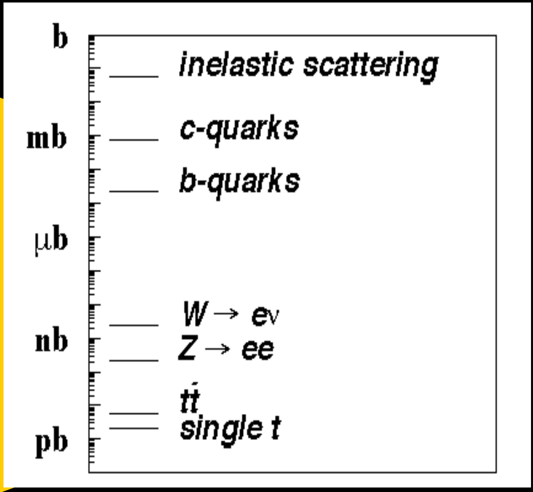
- top-antitop pair production





strong interaction ("flavorblind")
at √s=1.96 TeV
➔ $\sigma(t\bar{t})$ = 6.7±0.4 pb
➔ expect 1 event every 10^{10} crossings!

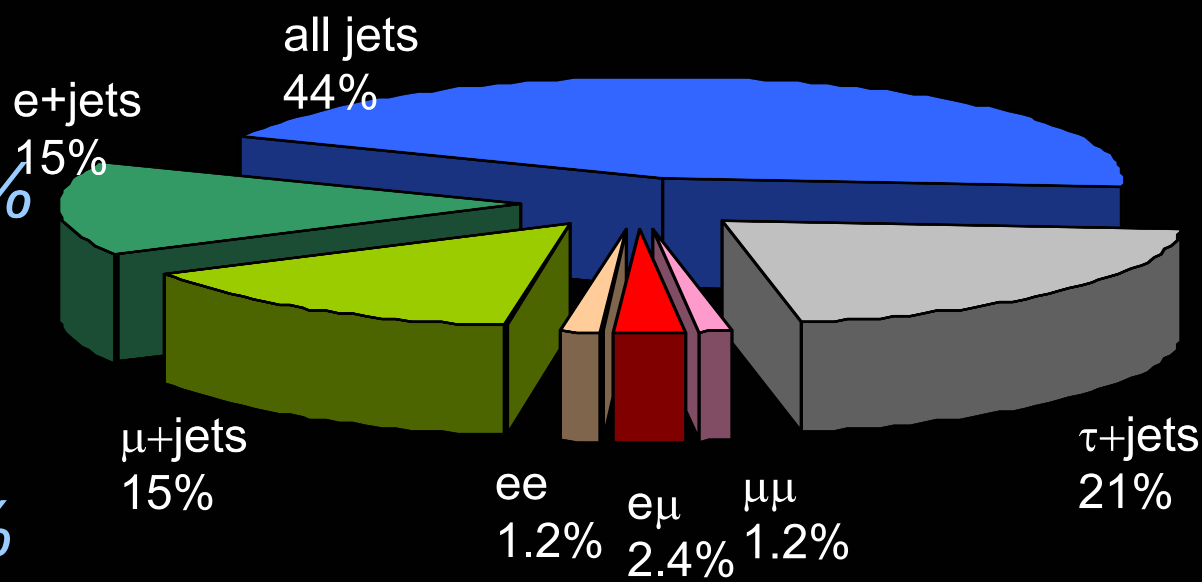
Cacciari et al. JHEP 0404:068 (2004)
Kidonaki & Vogt, Phys. Rev. D 68 114014 (2003)

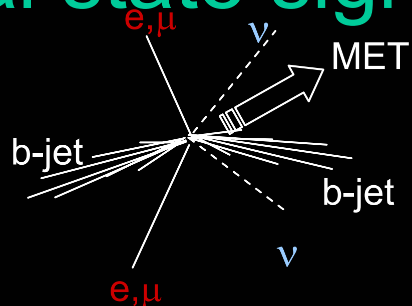


the proverbial needle in a hay stack

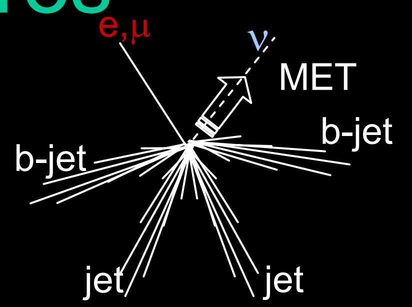
top-antitop pair production

- top decay
  - t→Wb $B \approx 100\%$
- W decay
  - W→ℓν $B \approx 11\%$
  - W→qq $B \approx 67\ \%$
- final state signatures

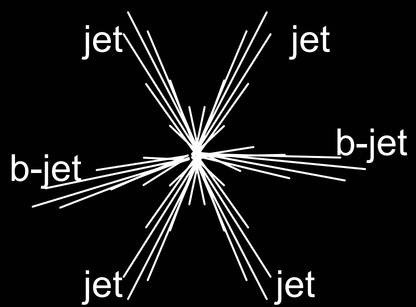




Dilepton
(BR~5%, low background)



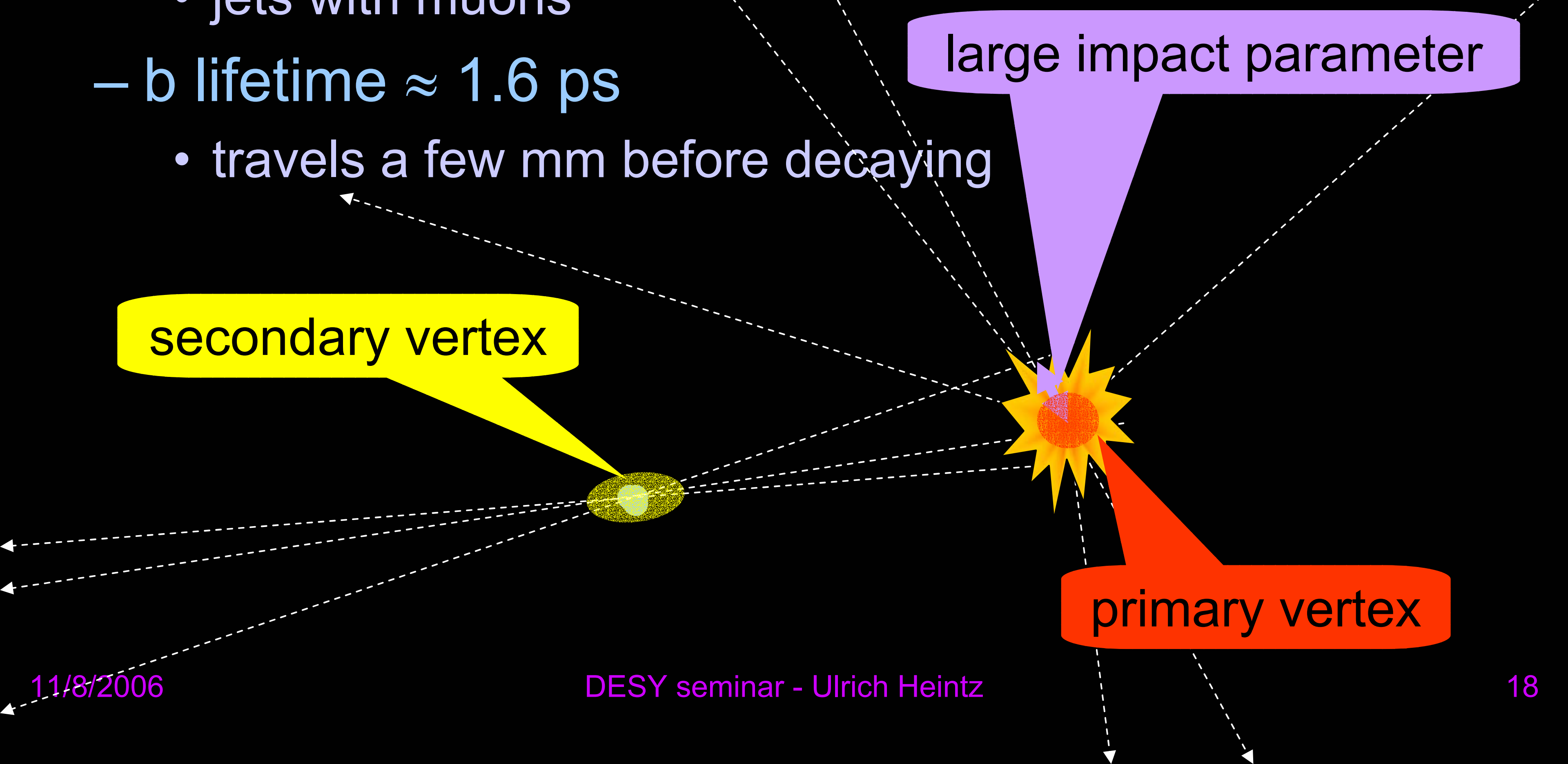
Lepton+jets
(BR~30%, moderate background)



All-hadronic
(BR~46%, huge background)

b-jet tagging

- b-jet tagging
  - b ➞ μ + anything (11%)
    - jets with muons
  - b lifetime ≈ 1.6 ps
    - travels a few mm before decaying



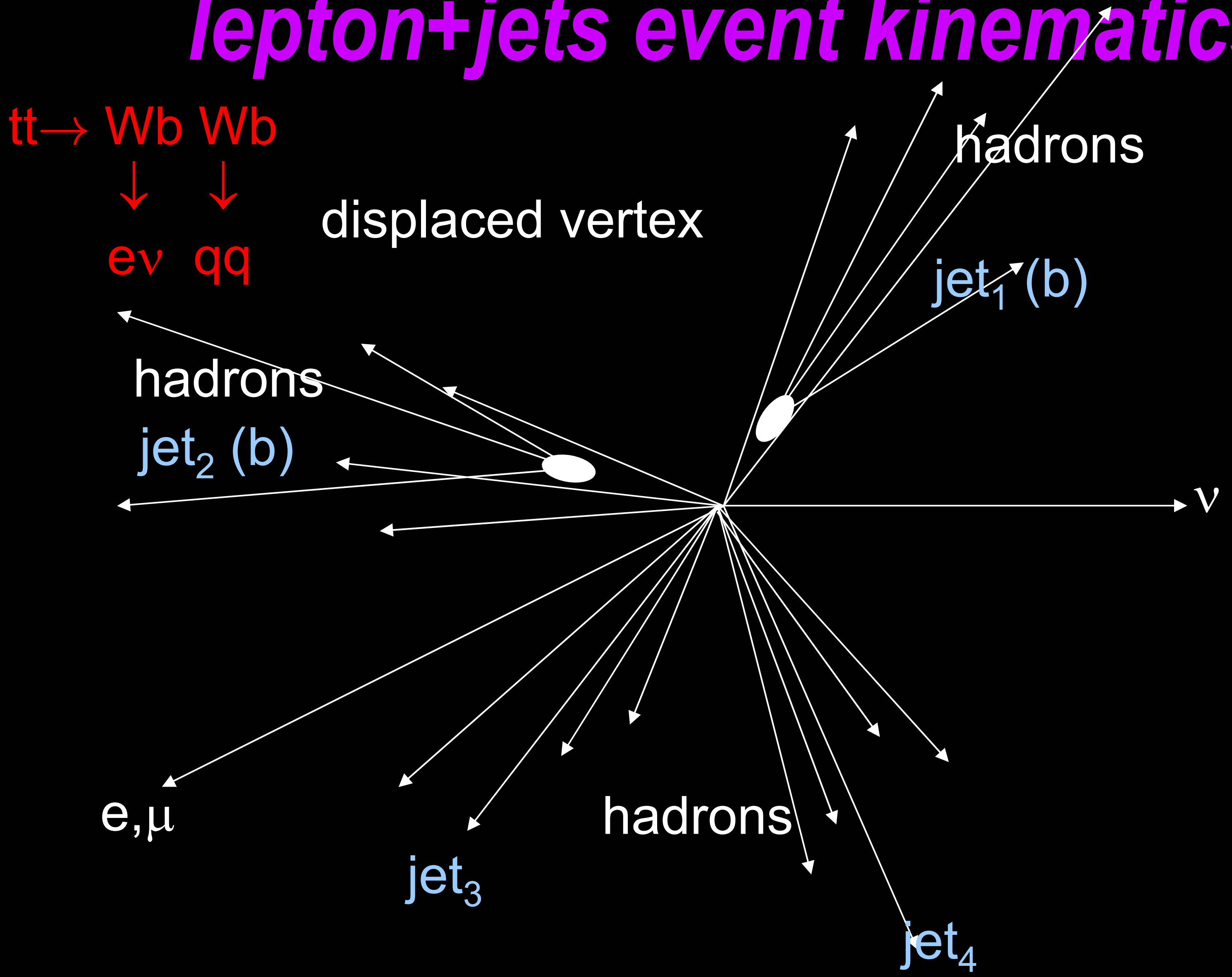
jet energy scale calibration

- transverse momentum balance
  - "γ" + jet events
  - calibrate jets against electromagnetic response
  - calibrate electromagnetic response with $Z \rightarrow e^+e^-$
  - systematically limited
- $W \rightarrow$jets
  - $tt \rightarrow Wb\ Wb \rightarrow l\nu b\ qqb$ events
  - fit for m_t and jet energy scale α_{jes} simultaneously
  - statistically limited

outline

- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

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
  - $m(e,\nu,j_1)=m_t$
  - $m(j_3,j_4)=m_W$
  - $m(j_2,j_3,j_4)=m_t$
- 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

template method

- first technique used to measure top quark mass
  - used by DØ and CDF
  - pick an estimator (e.g. mass from kinematic fit)
  - compute probability density using events simulated with a range of values of m_t (templates)
  - maximum likelihood fit to extract measured m_t

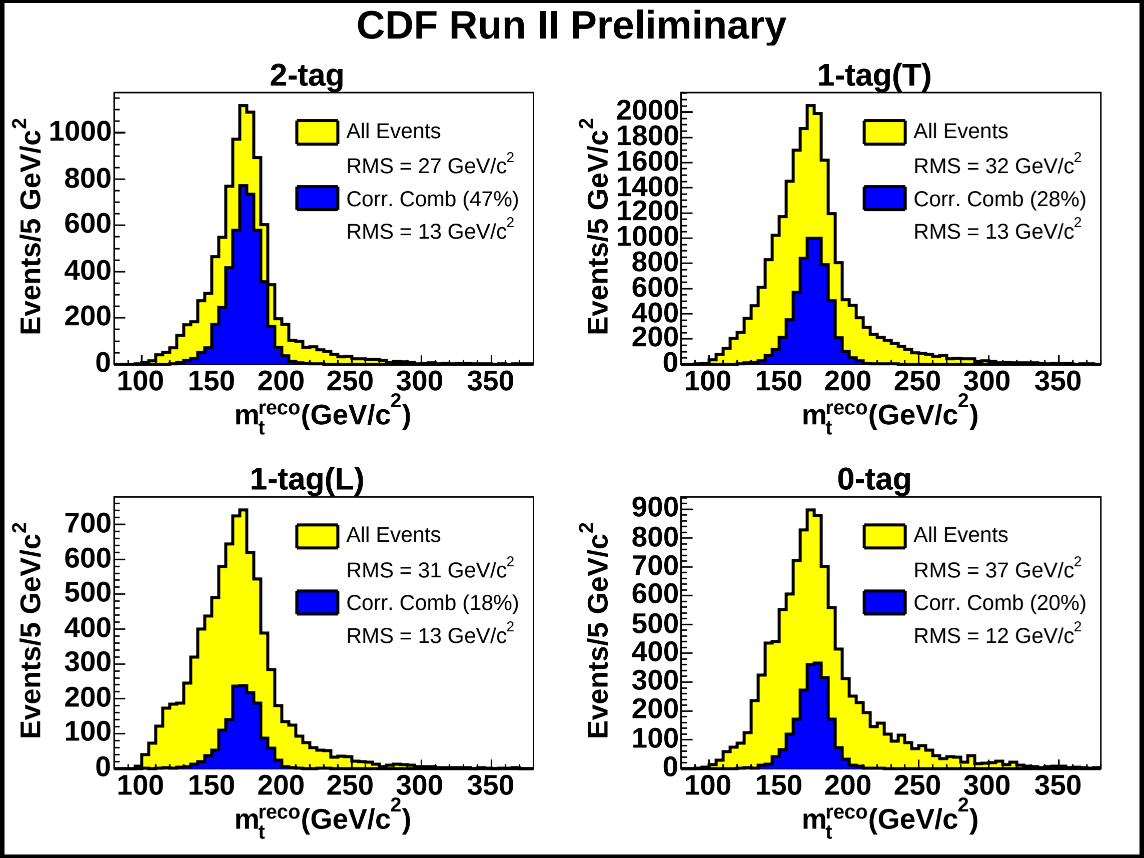
CDF lepton+jets channel (680 pb^{-1})

- require
  - one electron or muon
  - ≥ 4 jets
  - missing p_T

	2 tags	1 tag tight	1 tag loose	0 tags	
b-tags	2	1	1	0	
p_T jets 1-3	>15	>15	>15	>21	GeV
p_T jet 4	>8	>15	>8	>21	GeV
background	4.0±1.3	22.2±4.7	30.6±6.7	≈ 70	
top	46.8	104.4	64.2	≈ 41	
events	38	105	61	97	

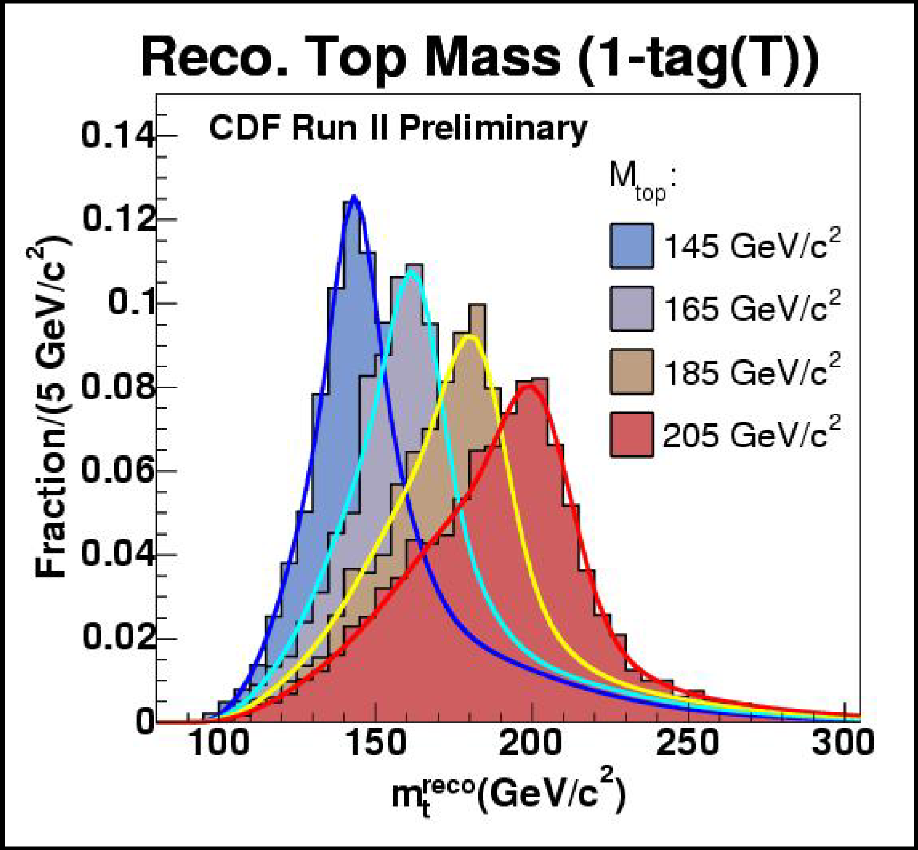
template method

- perform kinematic fit → m_{fit}
- keep jet assignment with lowest χ^2 if $\chi^2<9$



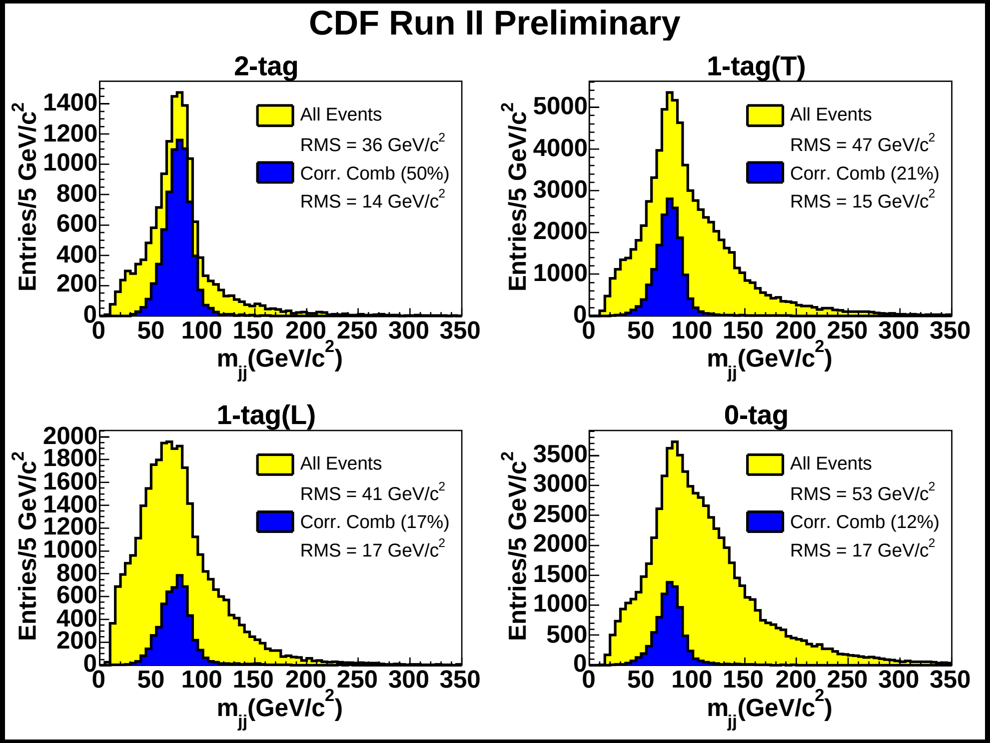
template method

- parametrize histograms of m_{fit} as a function of m_t and α_{jes}



template method

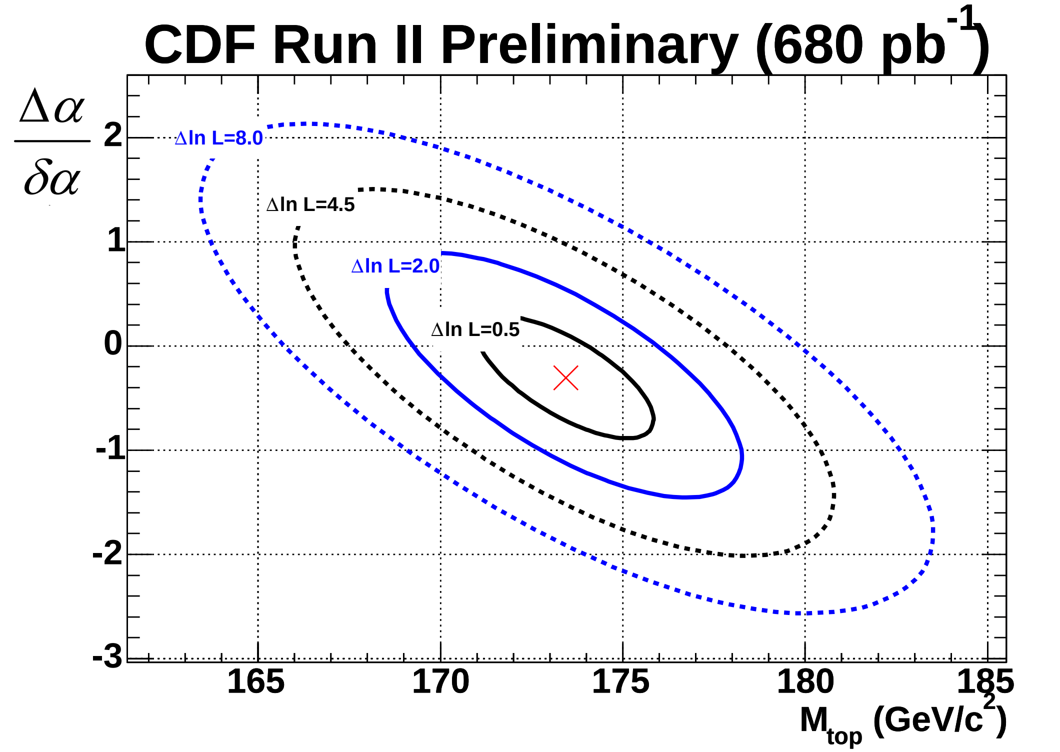
- reconstruct hadronic W decay
  - mass of all pairs of untagged jets
  - parametrize as function of m_t and α_{jes}



template method

CDF Conf. Note 8125

- simultaneously fit m_{fit} and m_{jj} tem
- gaussian constraint on $\Delta\alpha_{jes} = 0 \pm \delta_\alpha$



m_t = 173.4 ± 2.5(stat⊕jes) ± 1.3(syst) GeV

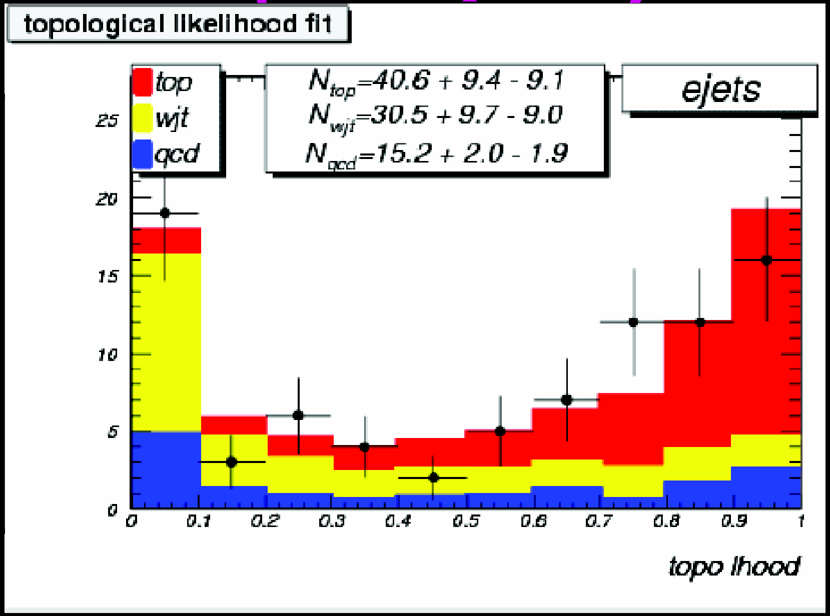
source	error (GeV)
b-jet scale	0.6
res jet scale	0.7
bkg jet scale	0.4
ISR	0.5
FSR	0.2
pdf	0.3
generators	0.2
background	0.5
b-tagging	0.1
MC stats	0.3
total	**1.3**

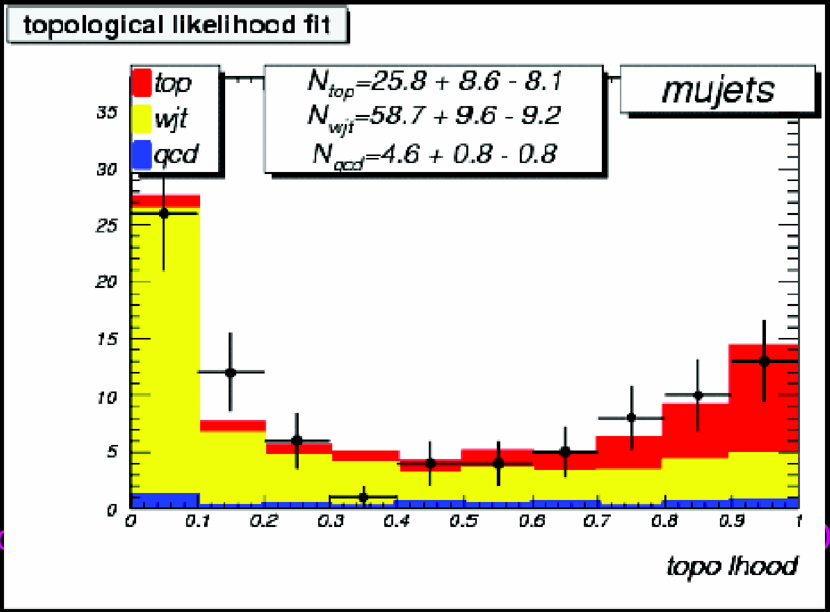
DØ lepton+jets channel (370 pb^{-1})

kinematic event selection

charged lepton	p_T>20 GeV	$|\eta|$<1.1 (e) $|\eta|$<2.0 (μ)
exactly 4 jets	p_T>20 GeV	$|\eta|$<2.5
missing	p_T>20 GeV	

	e+jets	μ+jets	ℓ+jets
events	86	89	175
top	41 ± 9	26 ± 8	66 ± 12
W+jets	30 ± 9	59 ± 8	89 ± 13
QCD	15 ± 2	5 ± 1	20 ± 2





matrix element method

- developed by DØ
  - Nature **429**, 638 (2004)
- compute probability to observe each event
  - build event-by-event likelihood
    - use all kinematic information from the events
    - LO ttbar matrix element
    - relative probability to be signal/background
  - no kinematic fit

matrix element method

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

top fraction

jet scale parameter

$$L_{evt}\left(o \mid m_t, \alpha_{jes}, f_{top}\right) = f_{top}\, p_{sig}\left(o \mid m_t, \alpha_{jes}\right) + \left(1 - f_{top}\right) p_{bkg}\left(o \mid \alpha_{jes}\right)$$

- combine all events in a joint likelihood

$$-\ln L\left(o_1 \ldots o_n \mid m_t, \alpha_{jes}, f_{top}\right) = -\sum_{i=1}^{n} \ln L\left(o_i \mid m_t, \alpha_{jes}, f_{top}\right)$$

- and maximize wrt m_t, α_{jes}, f_{top}

matrix element method

- calculate signal probability

$$p_{sig}\left(o \mid m_t, \alpha_{jes}\right) = \frac{1}{\sigma_{t\bar{t}}\left(m_t\right)} \int dx d\bar{x} f\left(x\right) f\left(\bar{x}\right) d\sigma_{t\bar{t}}\left(q, m_t\right) W\left(o \mid q, \alpha_{jes}\right)$$

pdf

$|M|^2$ dLIPS

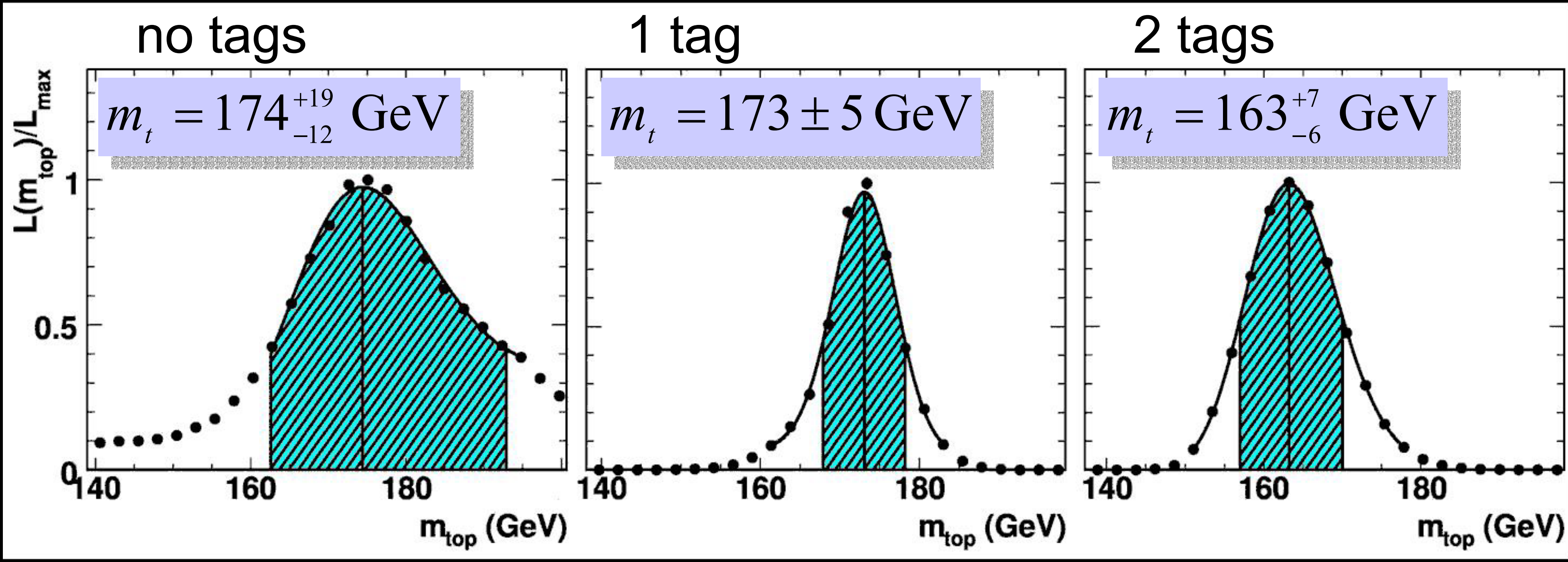
normalization

transfer function parametrize detector response

- use only events with exactly 4 jets to minimize ISR/FSR
- assume
  - $p_T(tt) = 0$
  - all angles and electron momentum are well measured
- use MC integration techniques for remaining 5(6) integrations
- consider
  - all possible jet-parton assignments
  - all possible solutions for the z-component of the neutrino momenta

matrix element method

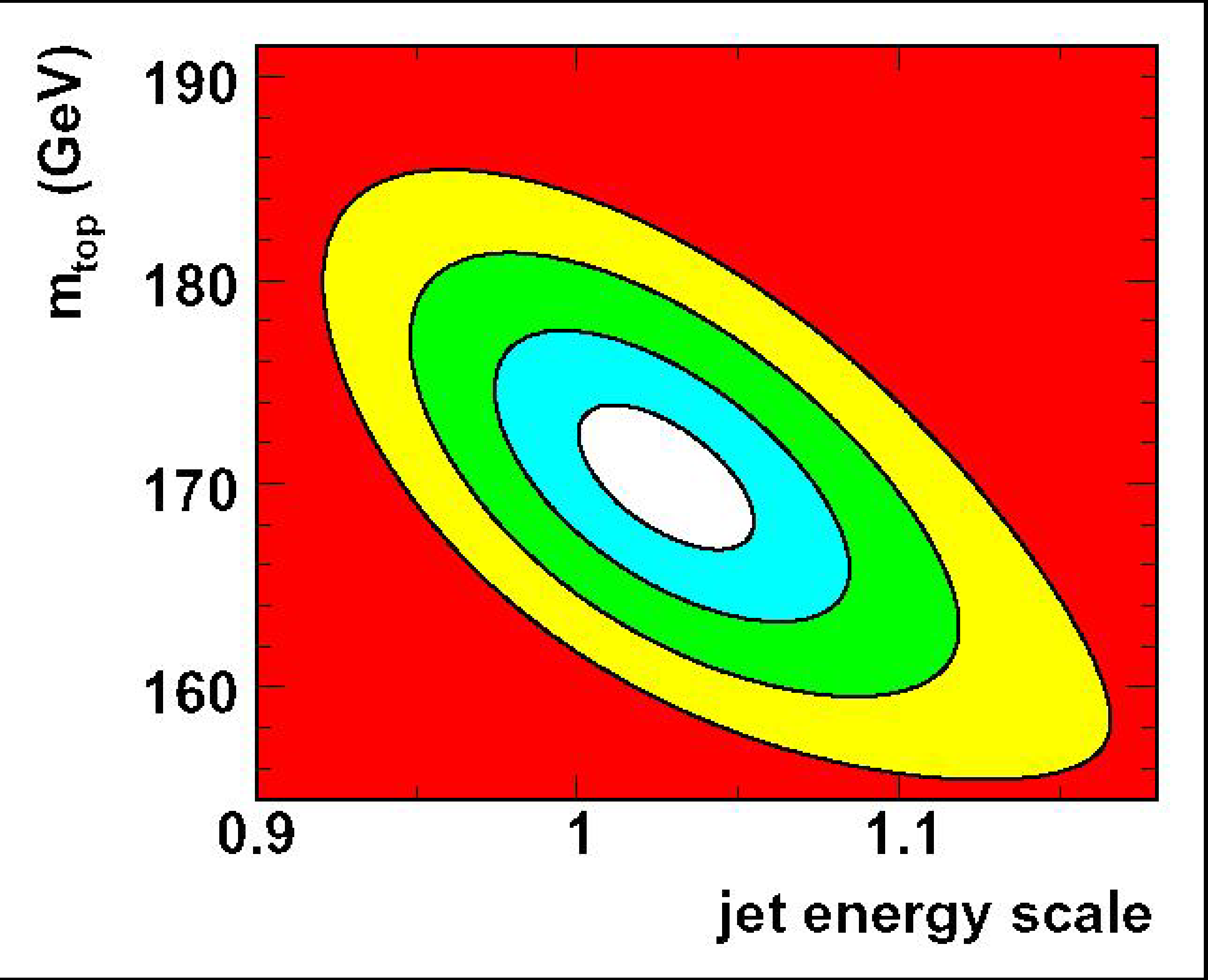
- divide sample into subsamples with 0,1,2 b-tags
  - take advantage of small backgrounds in b-tagged samples
  - use b-tags to assign relative weights to jet permutations



matrix element method

- 2-d fit in m_t, α_{jes}

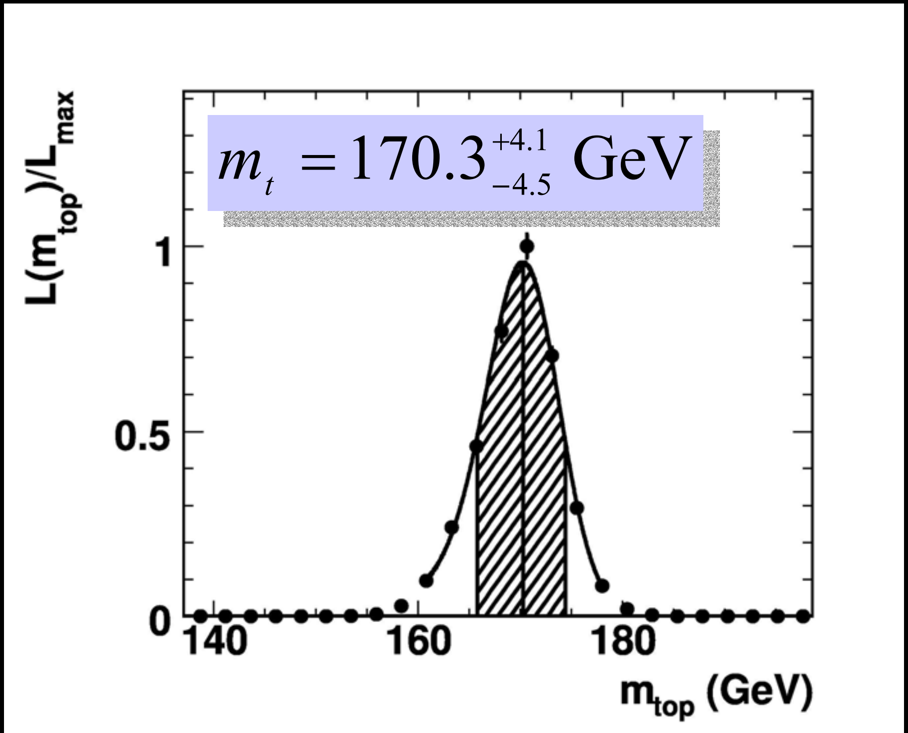
source	error (GeV)
sig/bkg model	0.56
pdf	0.07
b frag/decay	0.71
$\alpha(p_T)$	0.25
b response	+0.87 -0.75
b tagging	0.24
f_{top}	0.15
QCD bkg	0.29
MC calibration	0.48
total	**1.4**

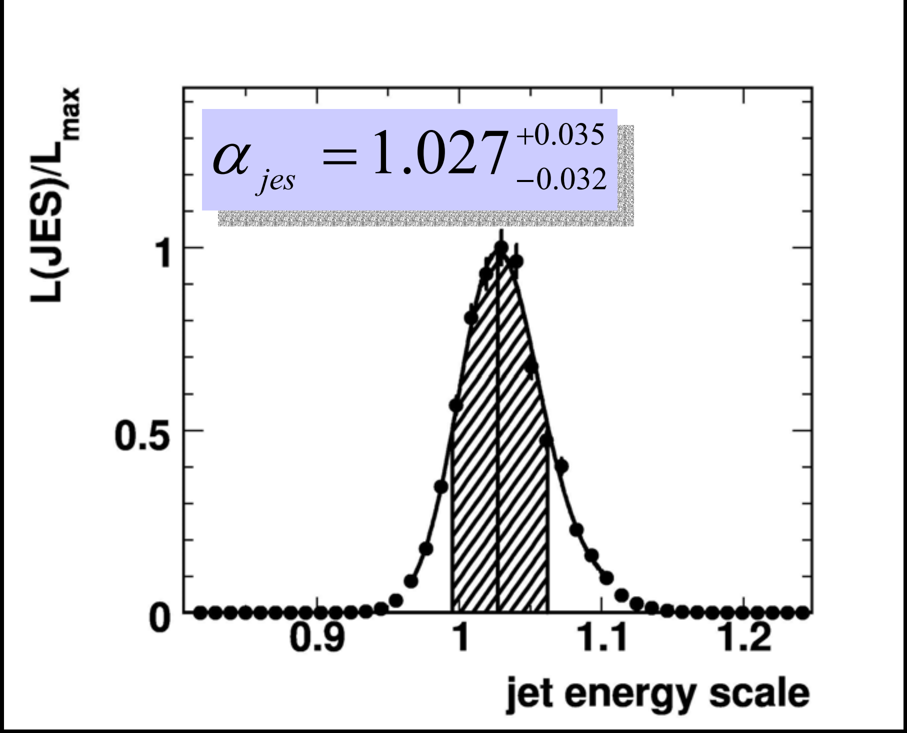


matrix element method

- fit lepton+jets data

accepted by PRD, hep-ex/0609053





$$m_t = 170.6^{+4.0}_{-4.7}(stat \oplus jes) \pm 1.4(syst)\ \text{GeV}$$

ideogram technique

- developed by DØ
  - use ideas by DELPHI for W mass measurement
  - use power of kinematic fit
  - use all kinematic information

ideogram technique

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

top fraction

jet scale parameter

$$L_{evt}(o \mid m_t, \alpha_{jes}, f_{top}) = f_{top}\, p_{sig}(o \mid m_t, \alpha_{jes}) + (1 - f_{top})\, p_{bkg}(o \mid \alpha_{jes})$$

- combine all events in a joint likelihood

$$-\ln L(o_1 \ldots o_n \mid m_t, \alpha_{jes}, f_{top}) = -\sum_{i=1}^{n} \ln L(o_i \mid m_t, \alpha_{jes}, f_{top})$$

- and maximize wrt m_t, α_{jes}, f_{top}

ideogram technique

- compute signal probability
  - convolution of Gaussian and Breit-Wigner at every solution of kinematic fit

probability for D if signal

fit χ^2

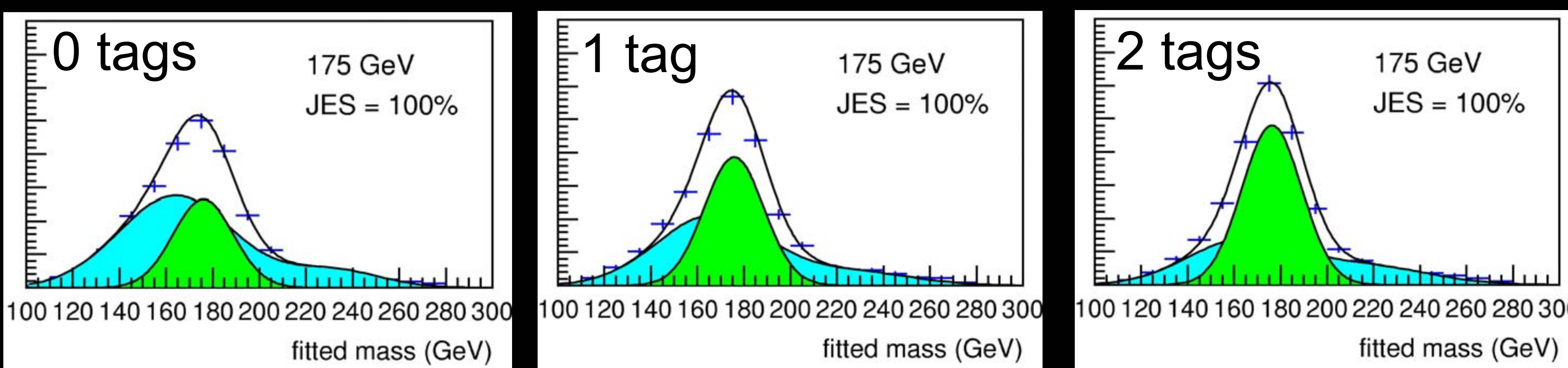
fit mass

fit error

$$p_{sig}\left(o \mid m_t, \alpha_{jes}\right) = p_{sig}(D) \sum_{i=1}^{24} e^{-\frac{\chi_i^2}{2}} \left[f \int G(m_i, m', \sigma_i) BW(m', m_t) dm' + (1-f) S(m_i, m_t) \right]$$

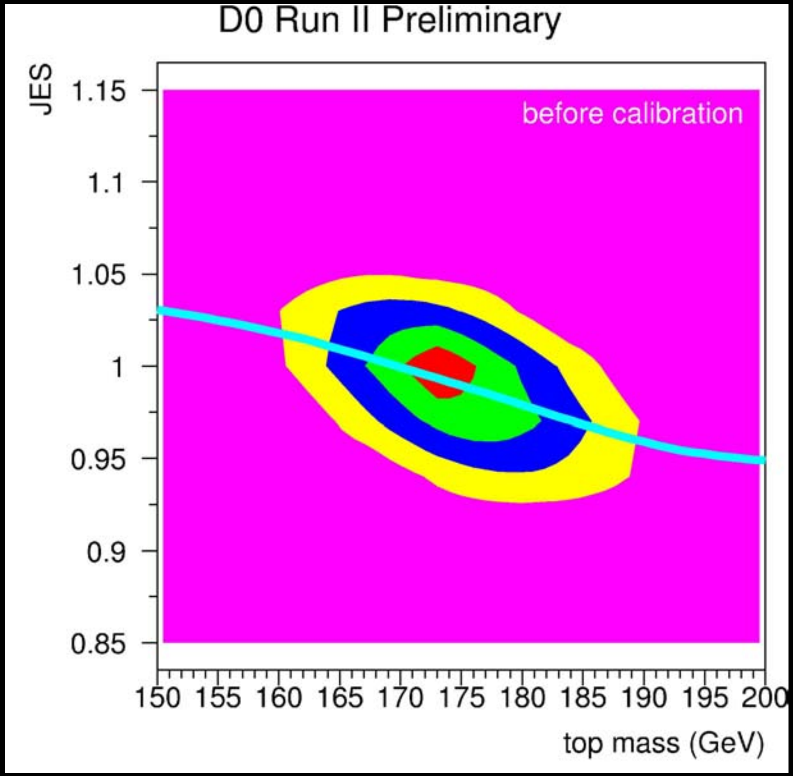
correct permutation

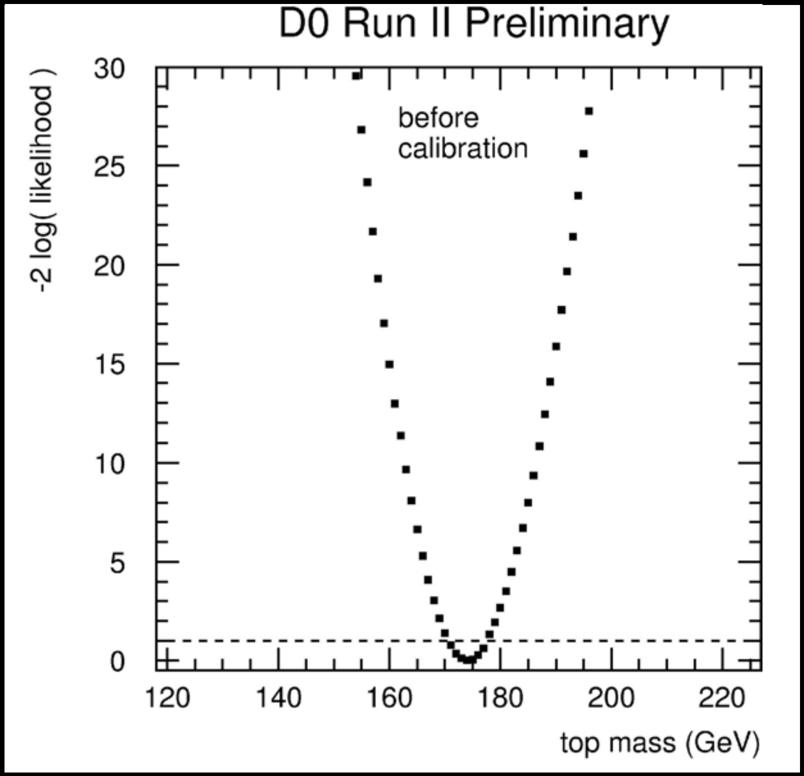
wrong permutation



ideogram technique

- maximize likelihood wrt $m_{t,} f_{top}, \ \alpha_{jes}$





m_t = 173.7±4.4(stat⊕jes) GeV

ideogram technique

source	error
signal model	0.73 GeV
background model	0.20 GeV
pdf	0.02 GeV
b fragmentation	1.30 GeV
p_T dependence of jes	0.45 GeV
b response	1.15 GeV
b tagging	0.29 GeV
trigger	+0.6/-0.3 GeV
jet efficiency/resolution	0.22 GeV
f_{top}	0.12 GeV
QCD background	0.28 GeV
MC calibration	0.25 GeV
total	**2.1 GeV**

$$m_t = 173.7 \pm 4.4(stat \oplus jes) \pm 2.1(syst)\ \mathrm{GeV}$$

D0 note 5099-CONF

outline

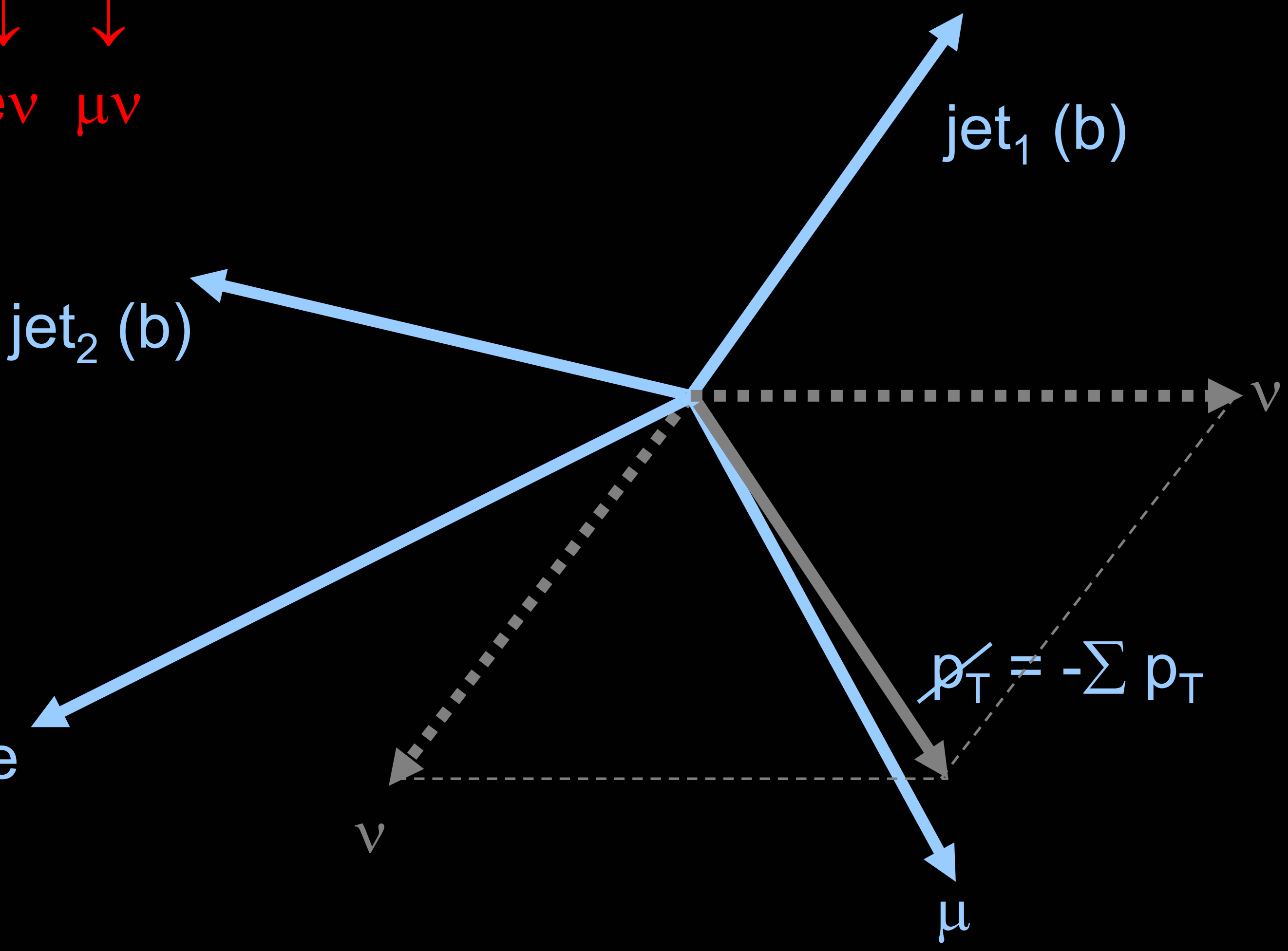
- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

dilepton event kinematics

$t\bar{t} \rightarrow W b\ W b$

$\downarrow \quad \downarrow$

$e\nu \quad \mu\nu$



dilepton event kinematics

- 2 neutrinos → 4 unknowns
- 3 constraints
  - $m(\ell^+\nu) = m(\ell^-\overline{\nu}) = M_W$ and $m(\ell^+\nu b) = m(\ell^-\overline{\nu}\overline{b})$
  - kinematically underconstrained
- 0,2,4 kinematic solutions for each value of m_t
- 2-fold combinatoric ambiguity
- dynamical likelihood methods
  - neutrino weighting (νWT)
    - developed by DØ in Run I
  - matrix element weighting (MWT)
    - following idea by Dalitz&Goldstein, Kondo, first published by DØ

dilepton channel at DØ

- selection
  - $\geq$ 2 jets with p_T>20 GeV
  - 2 charged opposite sign leptons (e,μ) with p_T>15 GeV
- further channel specific selections
- expected/observed event yield in 370 pb^{-1}

	$\ell\ell$ notag	$\ell\ell$ b-tag	$\ell\ell$	ℓ+track
top	7.2	9.9	15.8	6.3
bkg	5.9	0.3	4.0	2.2
all	$13.2^{+2.8}_{-2.1}$	10.1±0.9	19.8±0.6	8.5±0.3
data	12	14	21	9

26 events ($\ell\ell$ notag + $\ell\ell$ b-tag)

30 events ($\ell\ell$ + ℓ+track)

matrix element weighting

- assume m_t
- calculate $p_x^{\nu}, p_x^{\bar{\nu}}, p_y^{\nu}, p_y^{\bar{\nu}}$ using assumptions and kinematic observables
- assign each hypothesis a likelihood

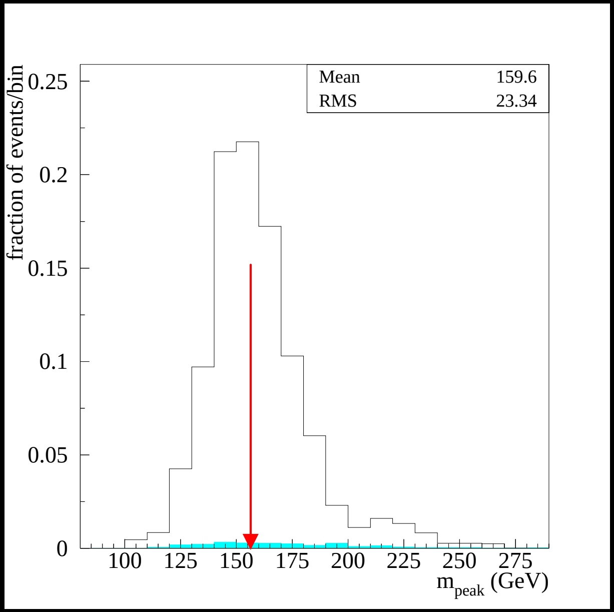
$$w(m_t) = f(x)f(\bar{x})p(E_{\ell}^{*} \mid m)p(E_{\bar{\ell}}^{*} \mid m)$$

*R. H. Dalitz and G.R. Goldstein, Phys. Rev. D **45**, 1531 (1992)*

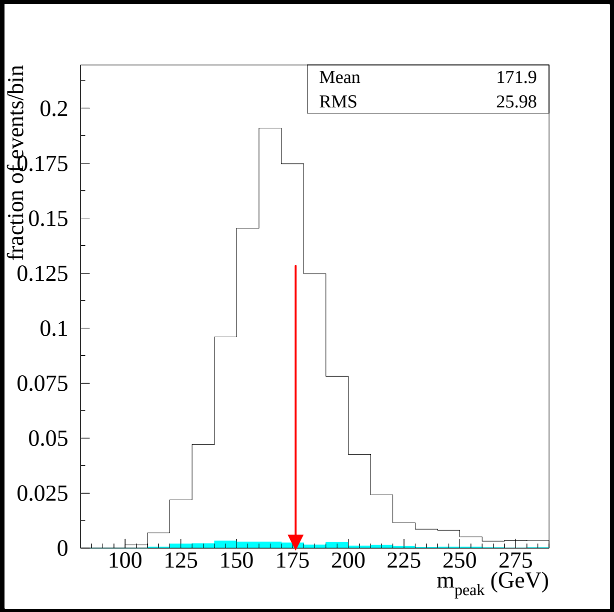
- sum $w(m_t)$ over up to 4 solutions and 2 jet permutations
- average over detector resolution

matrix element weighting

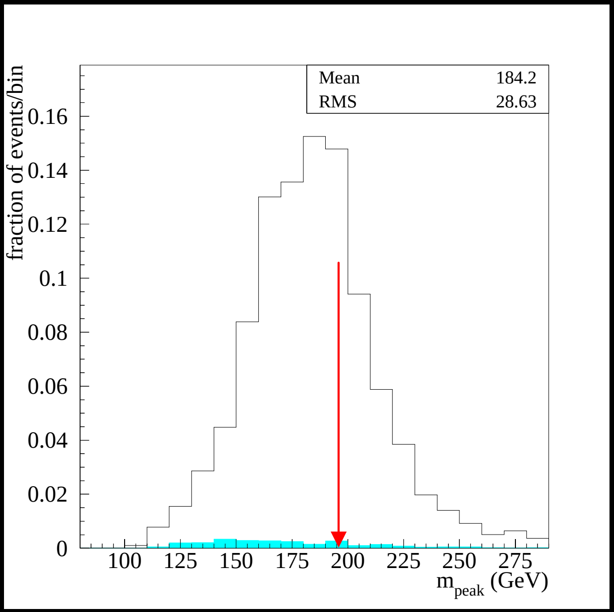
- use value of m_t at which $w(m_t)$ is maximal as mass estimator
- full simulation + background (for b-tagged sample)



m_t=155 GeV



m_t=175 GeV

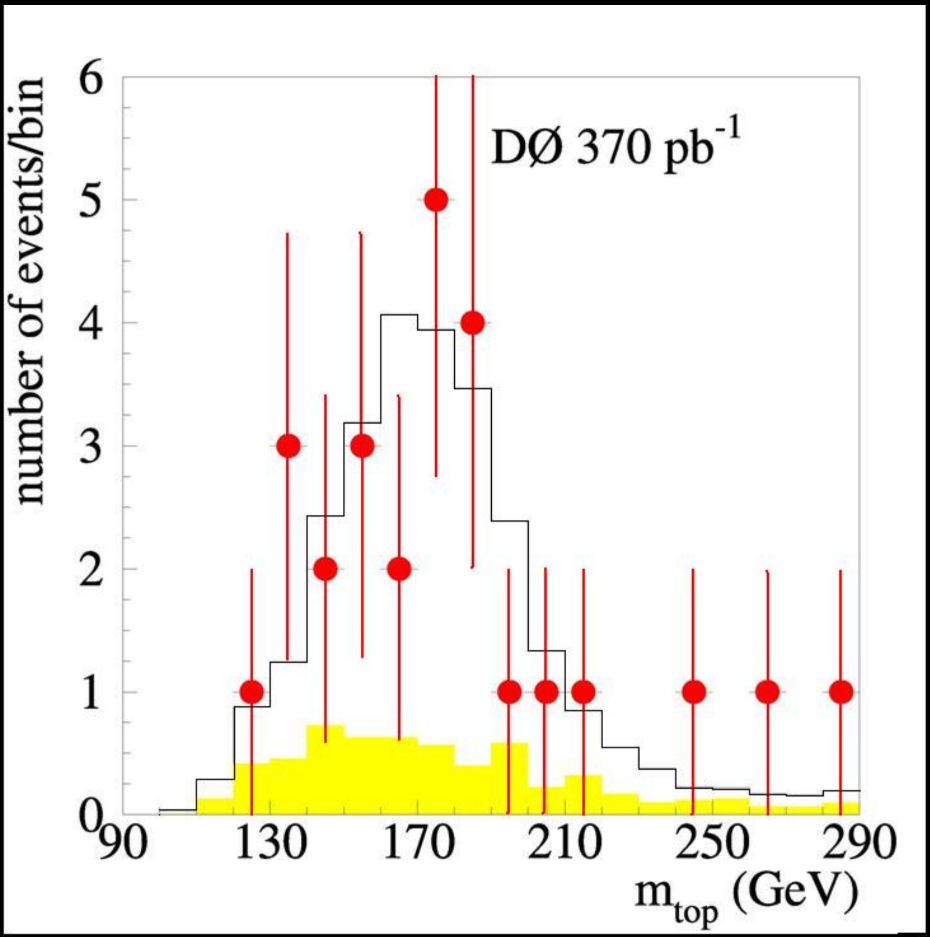


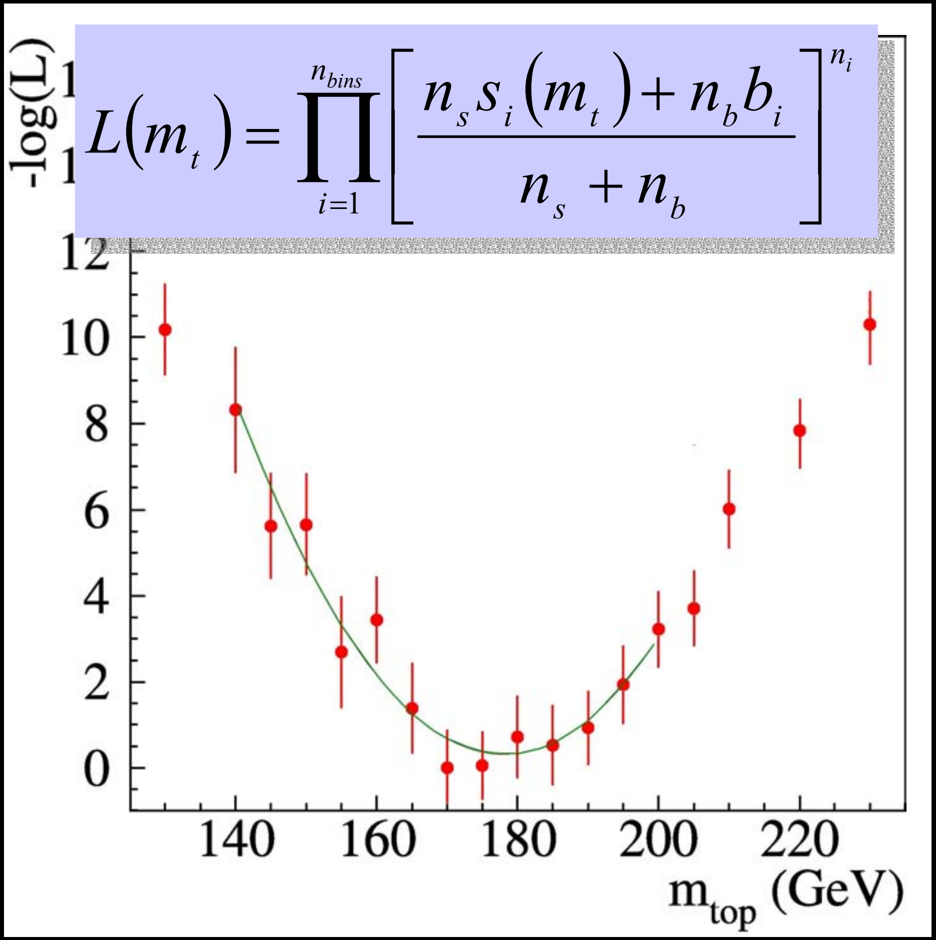
m_t=195 GeV

matrix element weighting

- maximize likelihood wrt m_t

26 events ($\ell\ell$ notag, $\ell\ell$ btag)

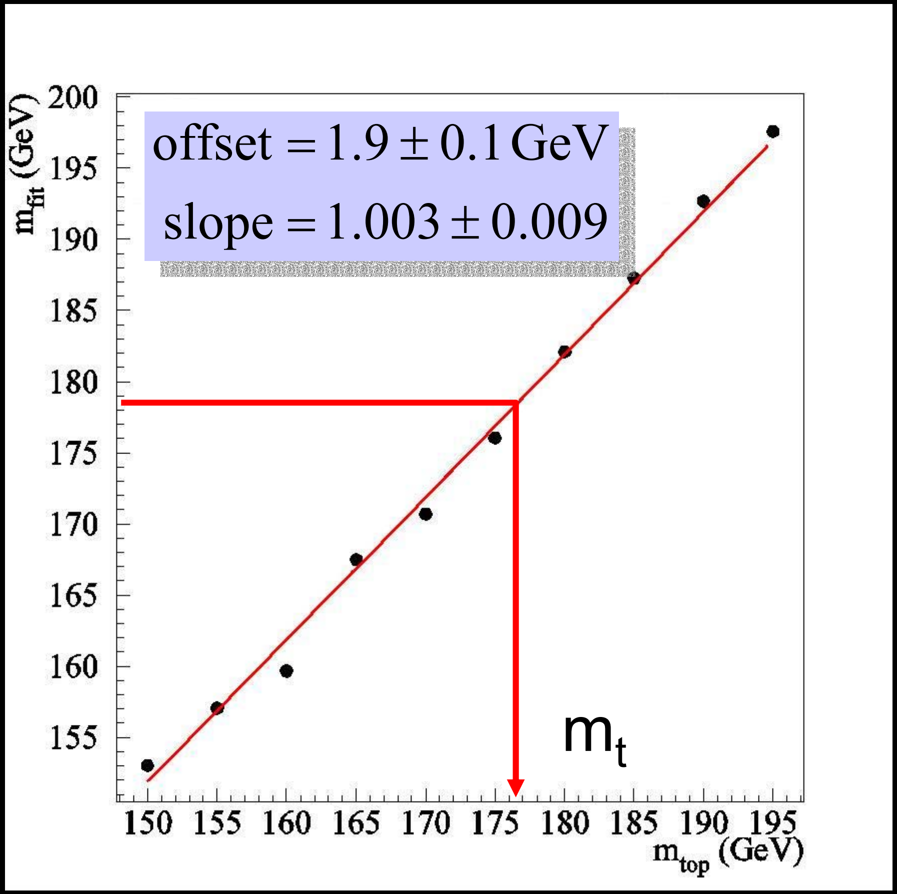


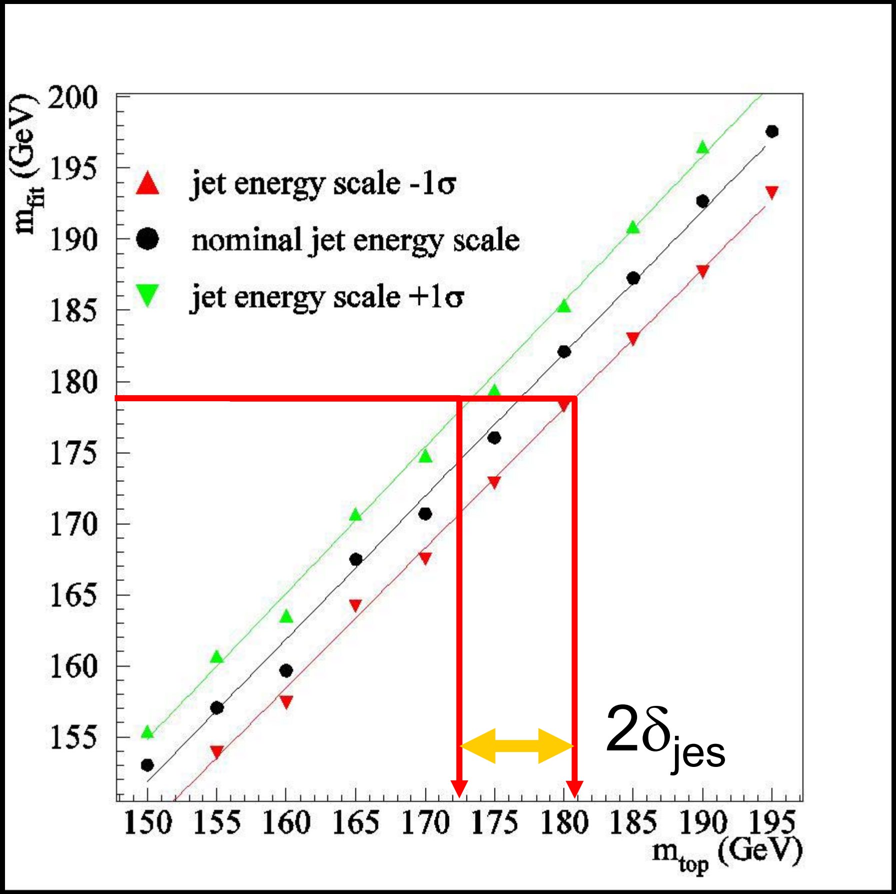


$$L(m_t) = \prod_{i=1}^{n_{bins}} \left[\frac{n_s s_i(m_t) + n_b b_i}{n_s + n_b} \right]^{n_i}$$

matrix element weighting

- check performance using MC ensembles





neutrino weighting

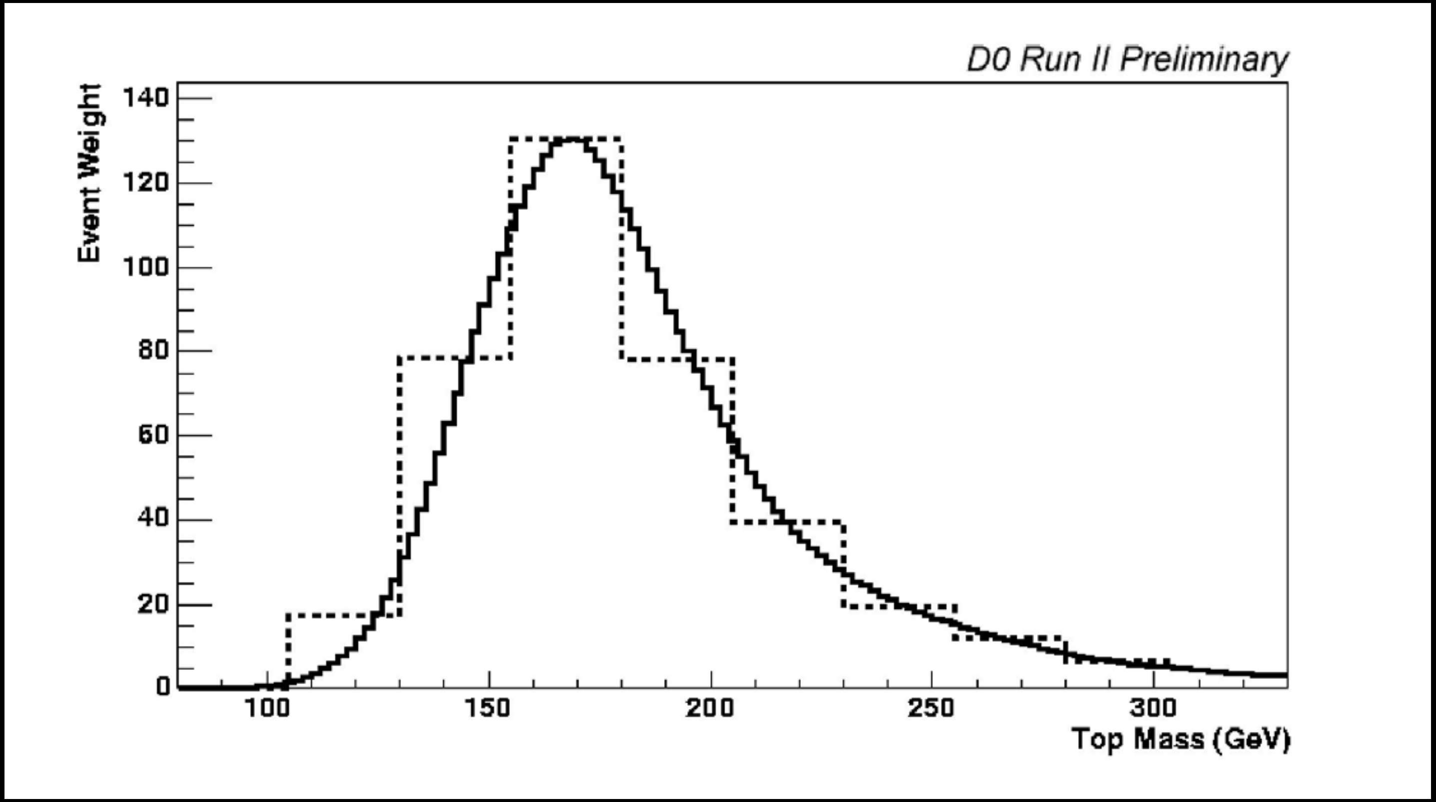
- assume $m_t, \eta^{\nu}, \eta^{\bar{\nu}}$
- calculate $p_x^{\nu}, p_x^{\bar{\nu}}, p_y^{\nu}, p_y^{\bar{\nu}}$ using assumptions and kinematic observables (except missing p_T)
- assign each hypothesis a likelihood

$$w(m_t) = e^{-\frac{\left(\not{p}_x - p_x^{\nu} - p_x^{\bar{\nu}}\right)^2}{2\sigma^2}} e^{-\frac{\left(\not{p}_y - p_y^{\nu} - p_y^{\bar{\nu}}\right)^2}{2\sigma^2}}$$

- sum $w(m_t)$ over all values of $\eta^{\nu}, \eta^{\bar{\nu}}$, up to 4 solutions and 2 jet permutations
- average over detector resolution

neutrino weighting

- divide $w(m_t)$ into 10 bins and normalize
  – each event is characterized by 9 component vector



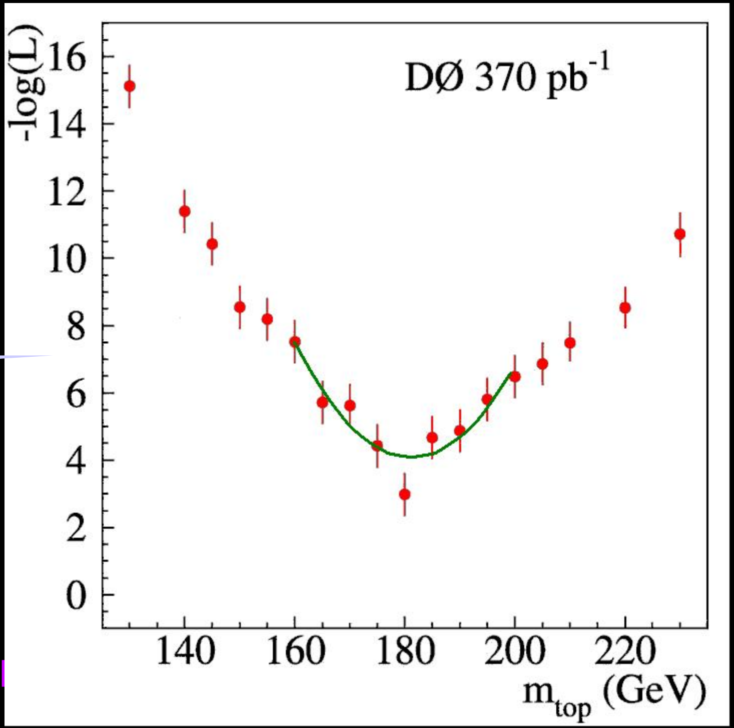
neutrino weighting

- compute likelihood by comparing to MC results for different values of m_t

$$L(\vec{w},\bar{n}_b,n\,|\,m_t,n_b,n_s)=g(n_b,\bar{n}_b,\sigma_b)\,p(n_s+n_b,n)\prod_{i=1}^{n}\frac{n_s f_s(\vec{w}_i\,|\,m_t)+n_b f_b(\vec{w}_i)}{n_s+n_b}$$

$$f_s(\vec{w}\,|\,m_t)=\frac{1}{N}\sum_{j=1}^{N}\prod_{i=1}^{9}\frac{\exp\left[-\left(w_j-\tilde{w}_{ij}\right)^2/2h^2\right]}{\int_0^1\exp\left[-\left(w-\tilde{w}_{ij}\right)^2/2h^2\right]dw}$$

30 events ($\ell\ell$,ℓ+track)



DØ dilepton results

MWT: $m_t = 176.2 \pm 9.2(\text{stat}) \pm 3.9(\text{syst})$ GeV

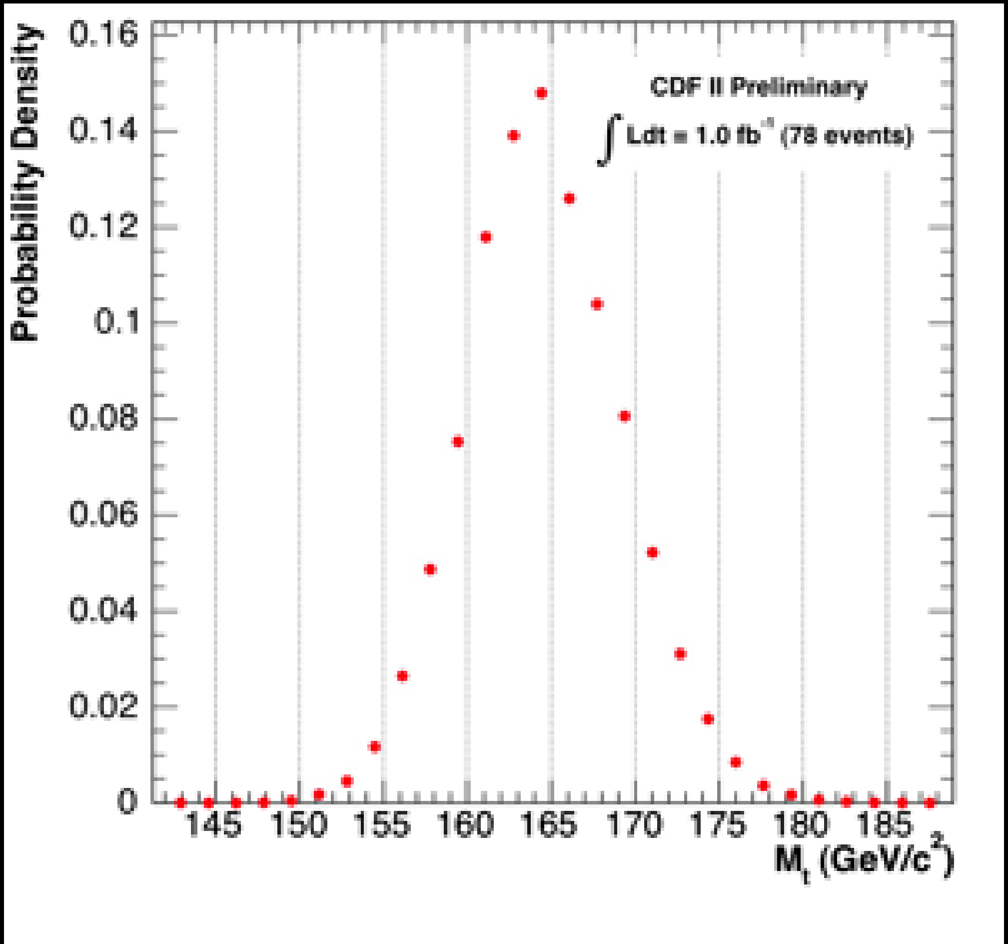
νWT: $m_t = 179.5 \pm 7.4(\text{stat}) \pm 5.6(\text{syst})$ GeV

$m_t = 178.1 \pm 6.7(\text{stat}) \pm 4.8(\text{syst})$ GeV

submitted to PRL
hep-ex/0609056

source	uncertainty
jet scale	4.3
resolutions	0.4
gluon radiation	1.5
pdf	0.8
background	0.9
MC statistics	0.9
total	**4.8**

CDF matrix element analysis



CDF Conf. Note 8369

source	error
jet scale	3.5 GeV
generator	0.9 GeV
method	0.6 GeV
sample composition	0.7 GeV
background	0.7 GeV
ISR/FSR	0.4 GeV
pdf	0.8 GeV
total	**3.9 GeV**

m_t=164.5 ± 3.9(stat) ± 3.9(syst) GeV

outline

- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

all hadronic top decays

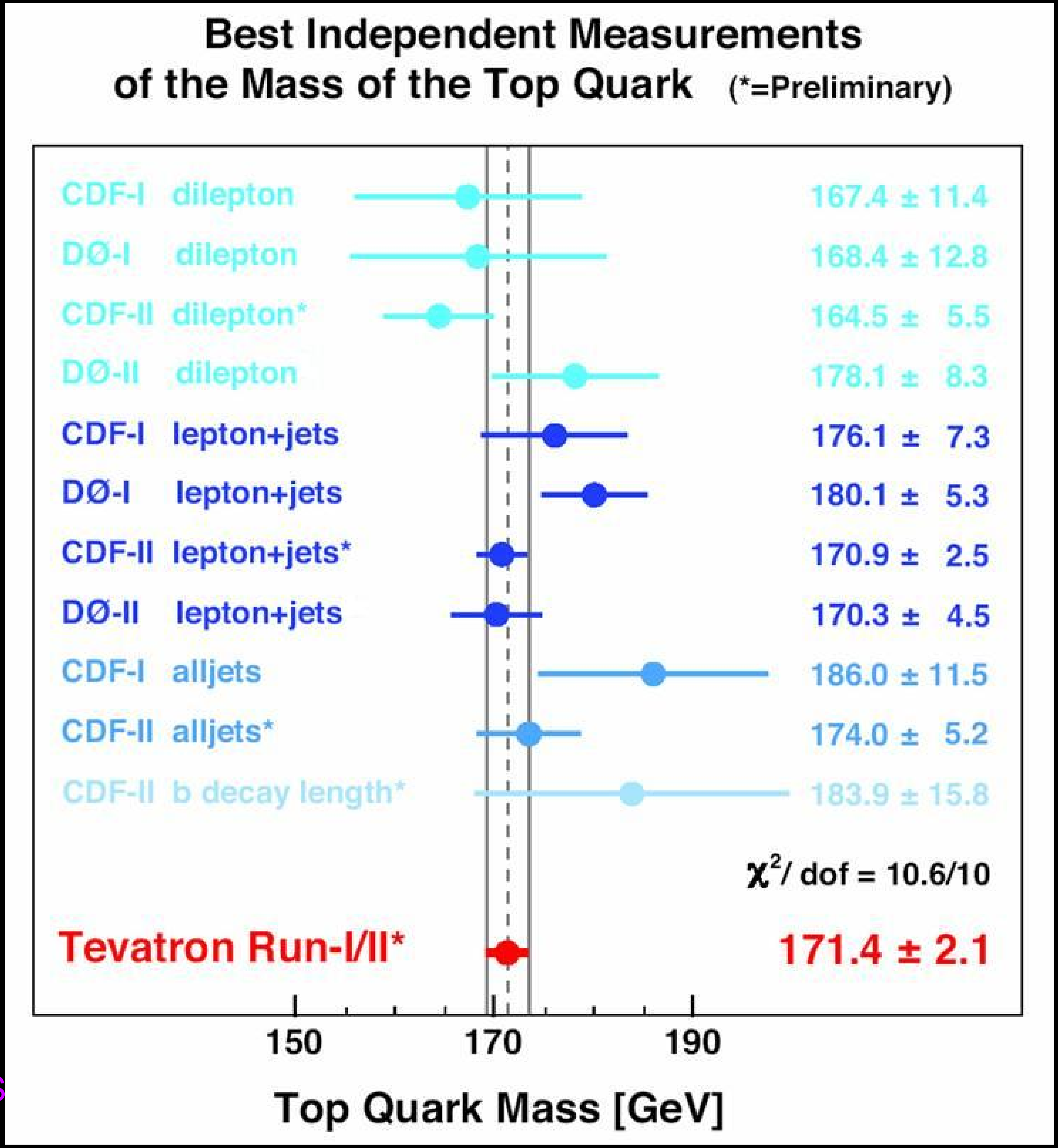
- DØ (Run I – 110 pb^{-1})
  - b-tagging
  - neural network discriminant
  - kinematic fit
  - m_t = 178.5±13.7(stat)±7.7(syst) GeV
- CDF (Run II – 1 fb^{-1})
  - template technique
  - m_t = 174.0±2.2(stat)±4.8(syst) GeV

CDF Conf. Note 8420

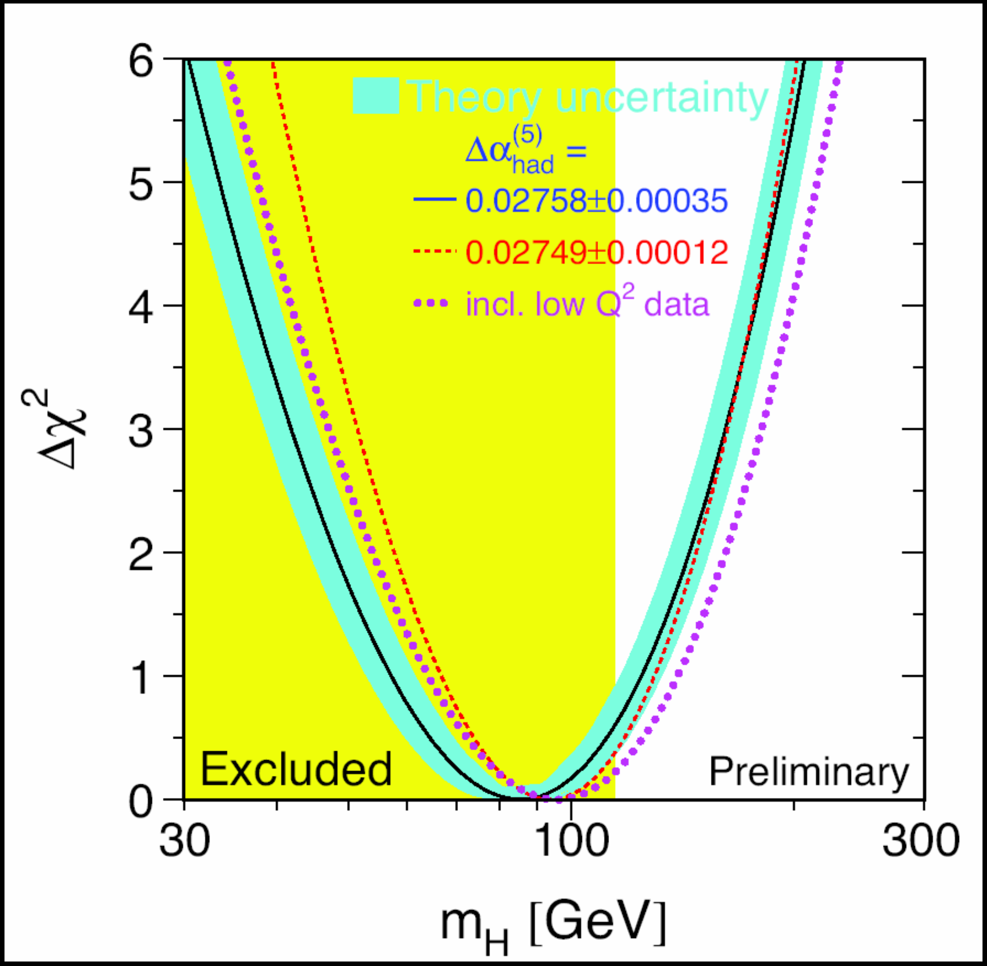
top mass combination

- m_{top}=171.4±2.1 GeV
- δ_{stat} = 1.2 GeV
- δ_{syst} = 1.8 GeV
- χ^2 = 10.6 (10 d.o.f.)

see also hep-ex/0603039



what does top say about the Higgs?

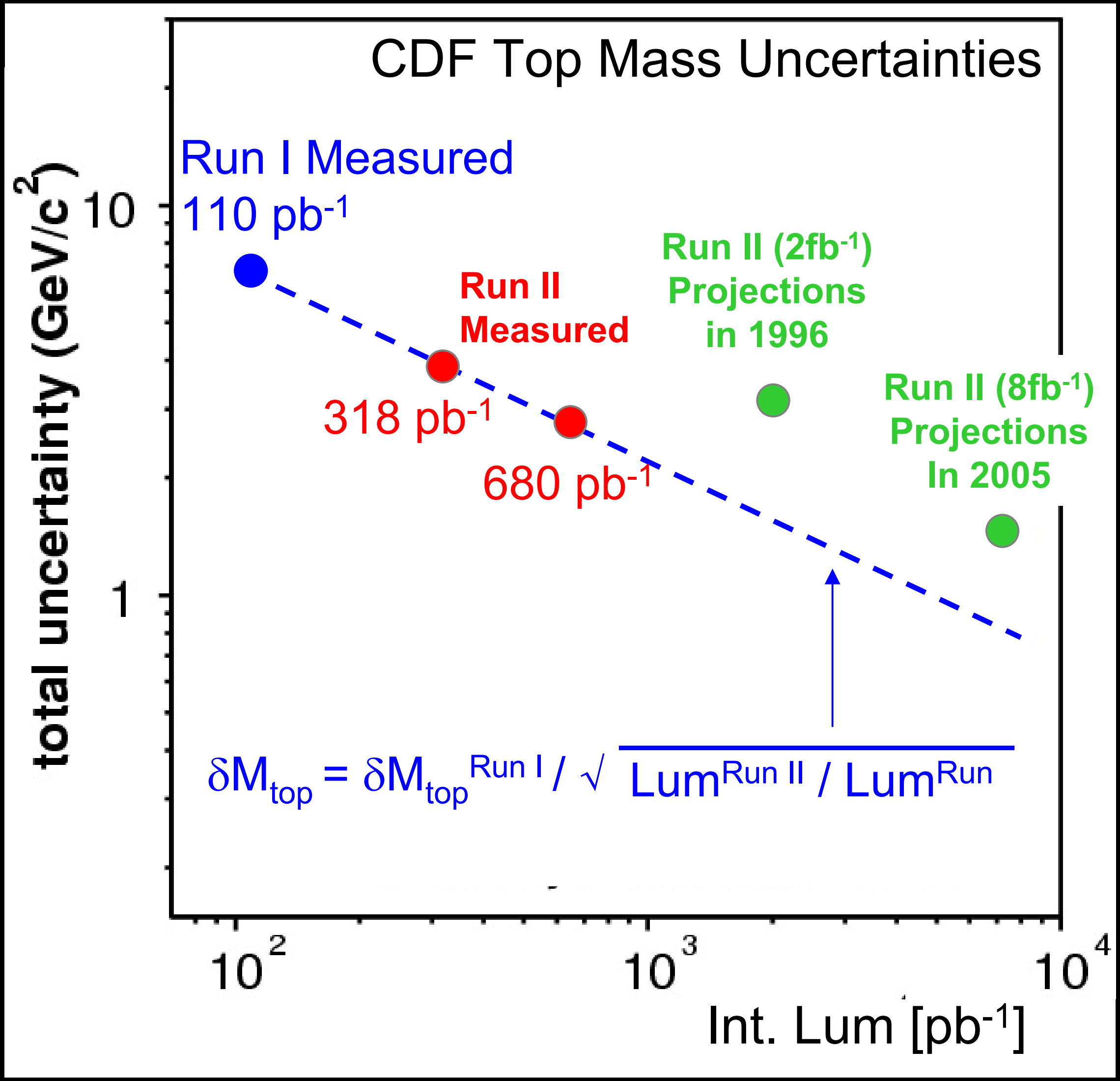


$$m_H = 89 \pm 36\,\mathrm{GeV} \qquad m_H < 175\,\mathrm{GeV}\ @\ 95\%\ \mathrm{CL}$$

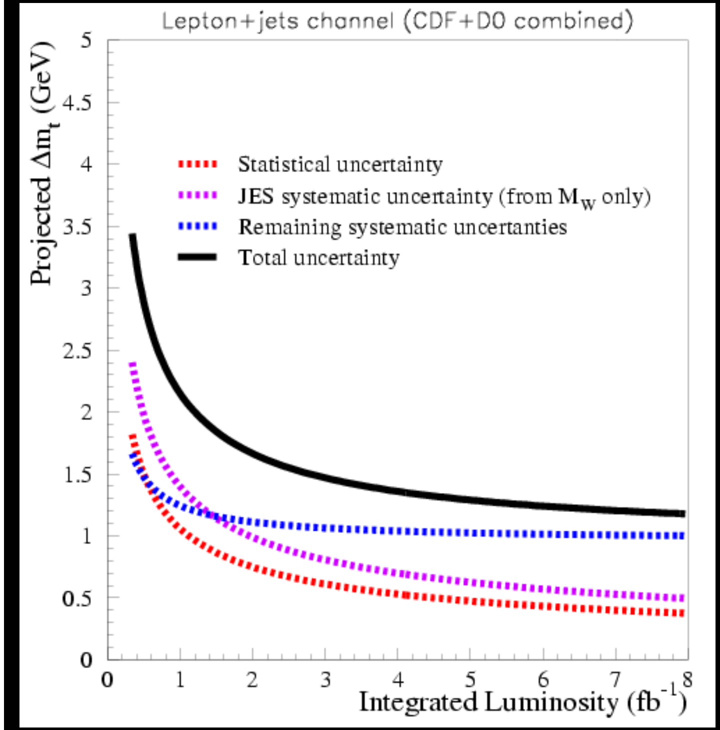
outline

- the top quark
- the top quark factory
- top quark production and decay
- top quark mass in the lepton+jets channel
- top quark mass in the dilepton channel
- putting it all together
- beyond the Tevatron
- conclusion

the future



CDF Top Mass Uncertainties
Run I Measured
110 pb-1
Run II
Measured
318 pb-1
680 pb-1
Run II (2fb-1)
Projections
in 1996
Run II (8fb-1)
Projections
In 2005
δMtop = δMtopRun I / √ LumRun II / LumRun
total uncertainty (GeV/c2)
Int. Lum [pb-1]



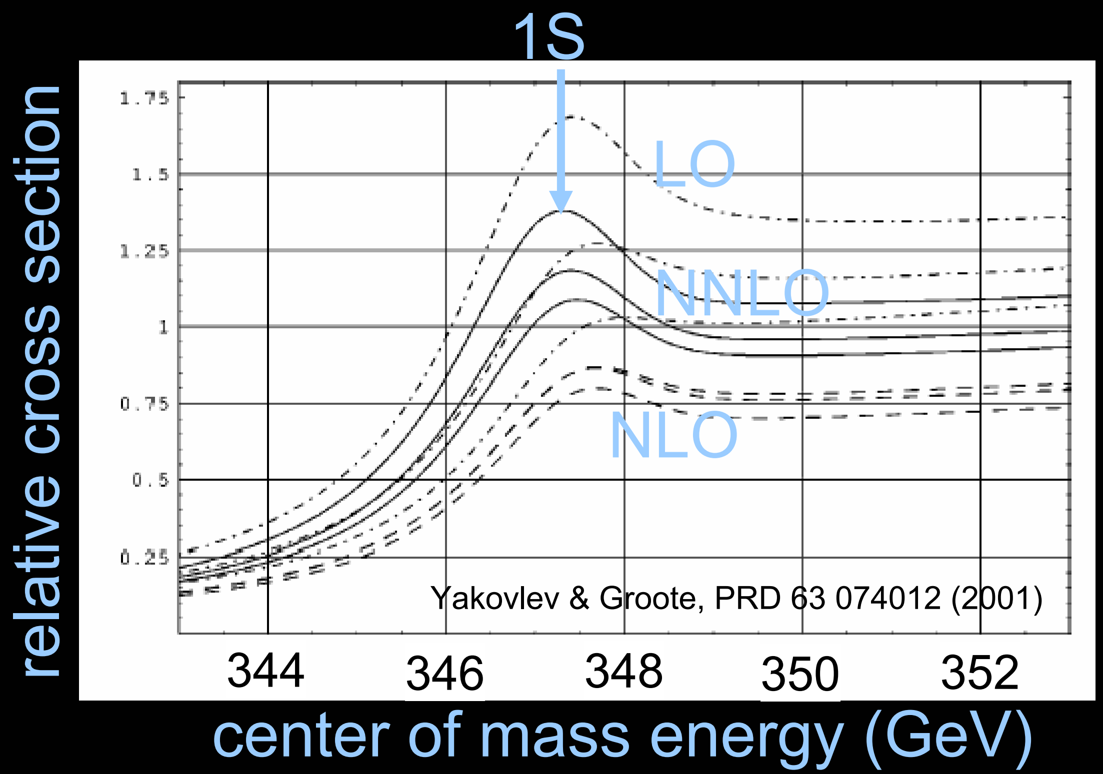
Lepton+jets channel (CDF+D0 combined)
Statistical uncertainty
JES systematic uncertainty (from MW only)
Remaining systematic uncertanties
Total uncertainty
Projected Δmt (GeV)
Integrated Luminosity (fb-1)

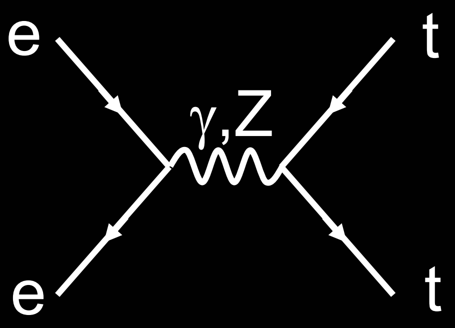
the future

- Large Hadron Collider
  - CERN, Geneva, Switzerland
  - start of operation 2007
  - proton-proton collisions
  - $\sqrt{s} = 14$ TeV
  - $\sigma_{tt} \approx 800$ pb
  - $\delta m_t \approx 1$ GeV

the future

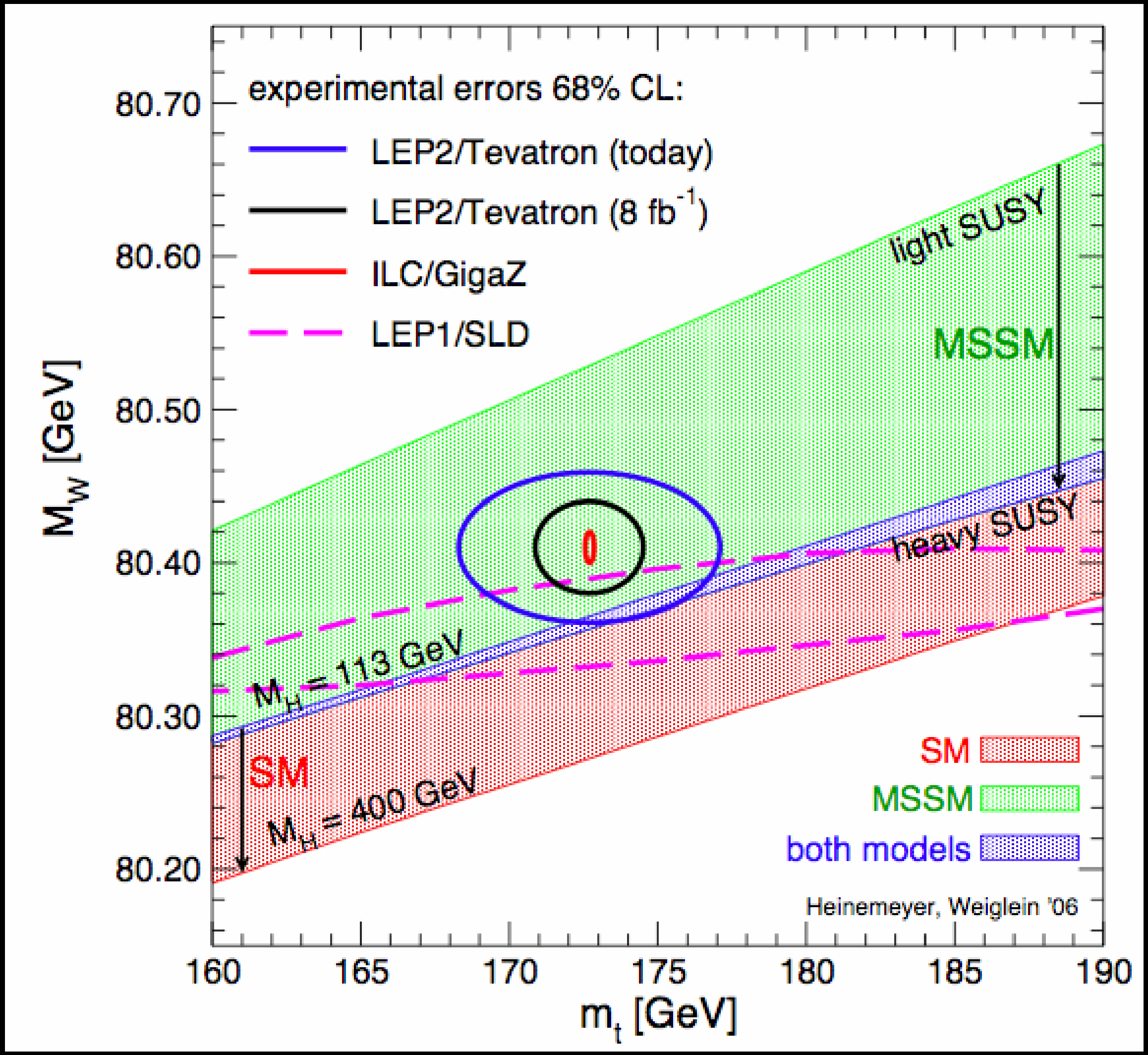
- linear e^+e^- collider





determine m_t to 100-200 MeV from 1S peak

the future


experimental errors 68% CL:
LEP2/Tevatron (today)
LEP2/Tevatron (8 fb^-1)
ILC/GigaZ
LEP1/SLD
light SUSY
MSSM
heavy SUSY
M_H = 113 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Weiglein '06
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
190
m_t [GeV]

outline

- what do we know about the top quark?
- why study the top quark?
- top quark production
- top quark decay
- top quark properties
- beyond the Tevatron
- conclusion

we have come a long way

- 1995:
  - template fit in lepton+jets channel
  - m_t = 176±13 GeV
- 2006:
  - many techniques: template, ideogram, dynamical likelihoods, lifetime
  - many channels: lepton+jets, dileptons, all jets
- the trend is to use maximal information
  - keep all events
  - use all kinematic information in the events
  - use discriminants to determine their signal/background
- world average

$$m_t = 171.4 \pm 2.1 \text{ GeV}$$

thank you