Top and *b*-physics at the Tevatron

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for the CDF and DØ collaborations

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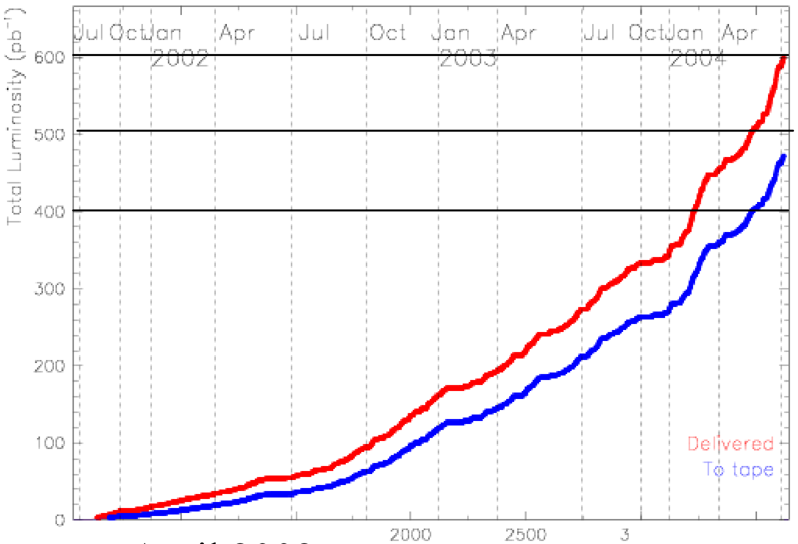
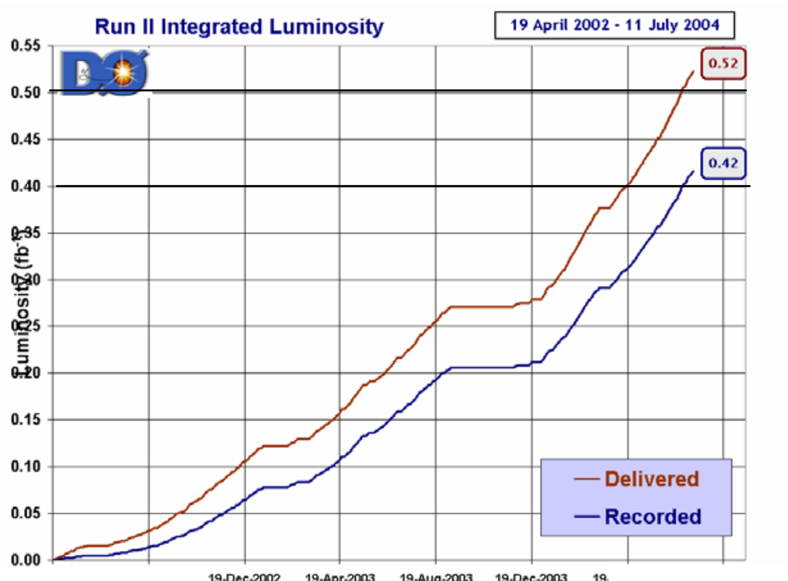
The Tevatron at Fermilab



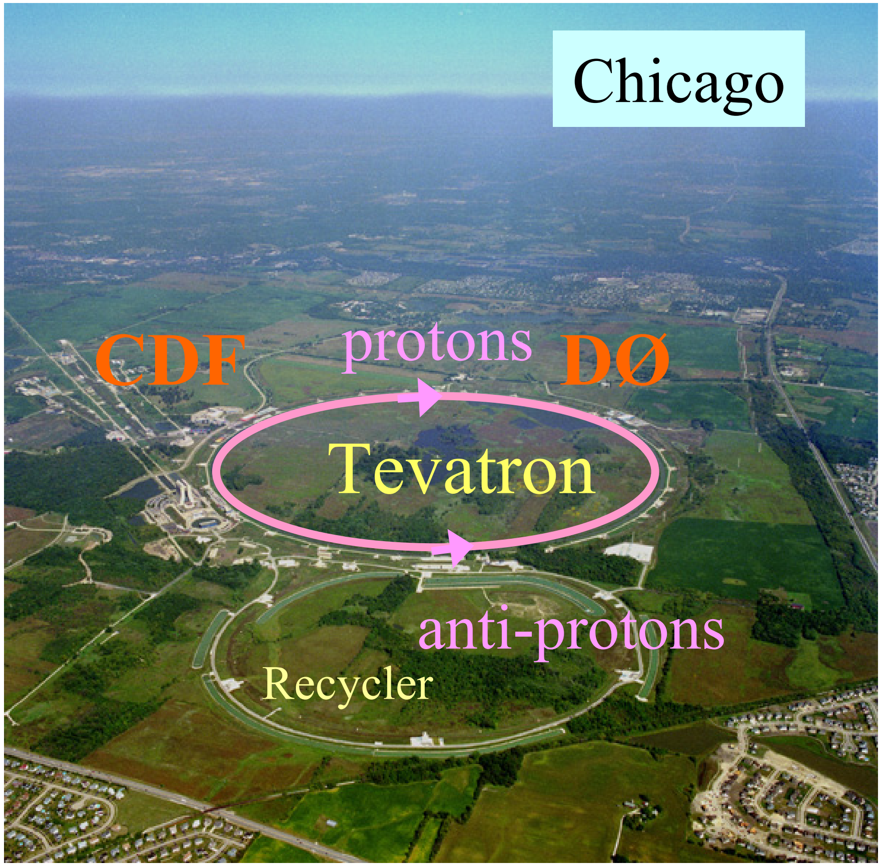
April 2002 July 2002



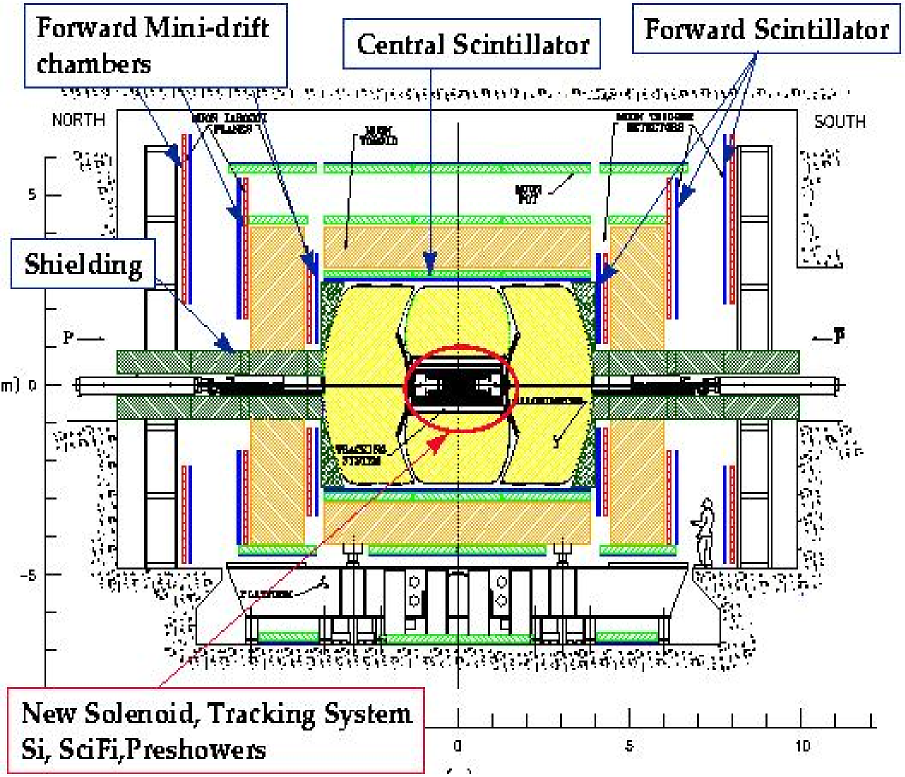
April 2002 July 2002

Run I 1992-1995
E_{CM} = 1.8 TeV
125 pb^{-1}

Run II
E_{CM}= 1.96 TeV
> 500 pb^{-1}

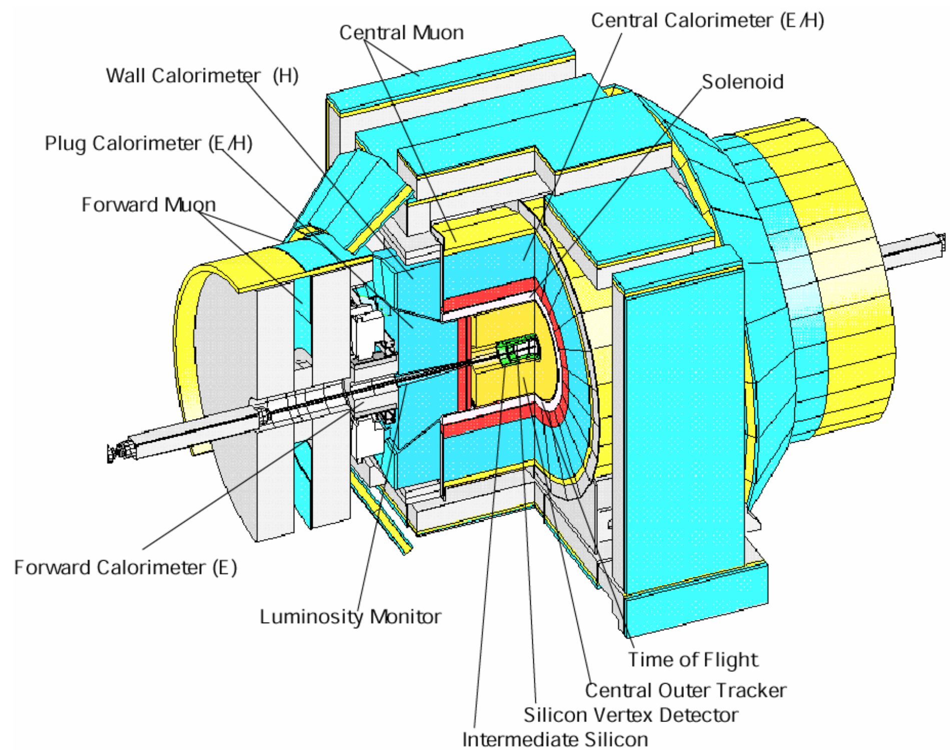


The CDF and DØ detectors



CDF

- excellent tracking resolution
- particle ID (TOF and dE/dx)
- displaced vertex trigger
- new plug calorimeter $1.6 < |\eta| < 3.6$

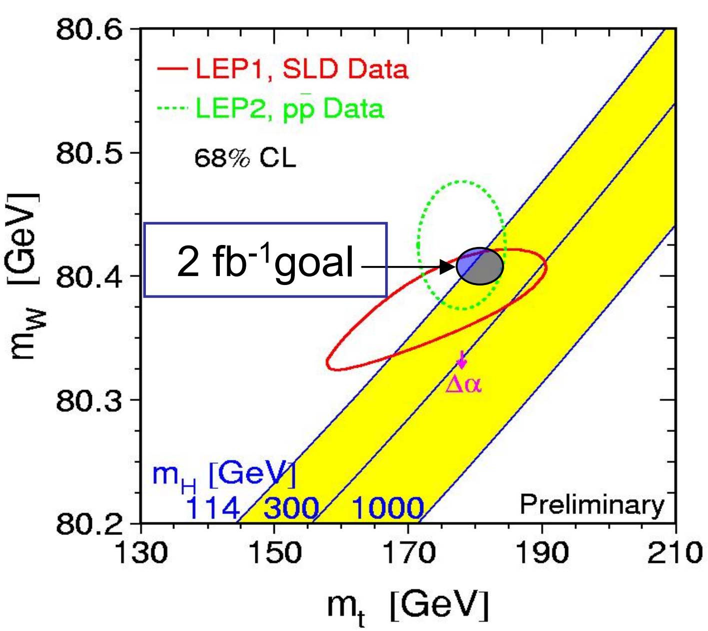


DØ

- excellent muon coverage $|\eta| < 2.0$
- new tracking system (Silicon and Fiber Tracker)
- 2 T magnetic field
- impact parameter trigger

Top physics at the Tevatron

- The top quark is the only known fermion with a mass on the electroweak scale:
  - decays as a 'free quark'
  - may include non-SM contributions in decay
  - m_W and m_{top} together constrain the Higgs mass

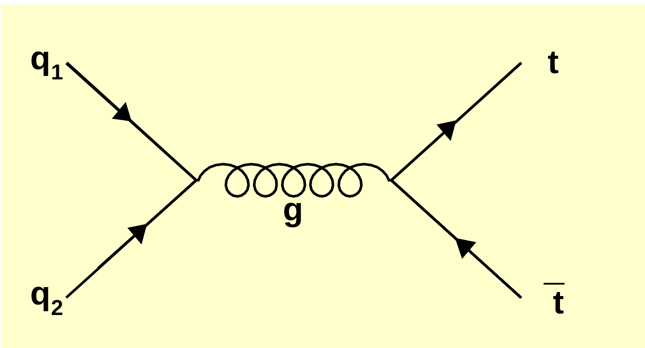


- Discovered in Run I:
  mass and cross-section, *W*-helicity
  → missing: spin, charge, width

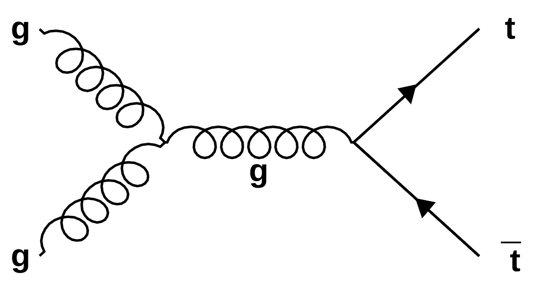
- Run II programme
  - improve previous measurements: mass, cross-section, *W*-helicity and spin-correlations
  - single top
  - branching ratios (non-SM, Higgs)
  - anomalous kinematics (non-SM)
  - resonance production
  - anomalous couplings

Top quark production

In $p\bar{p}$-collisions at $\sqrt{s} = 1.96$ TeV, top quarks are mostly produced in pairs:



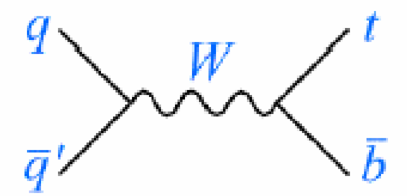
90 %



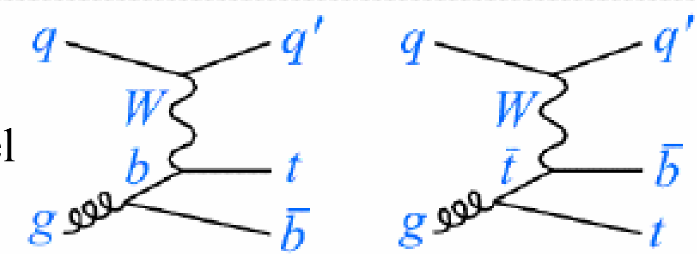
10 %

single top-production

s-channel



t-channel

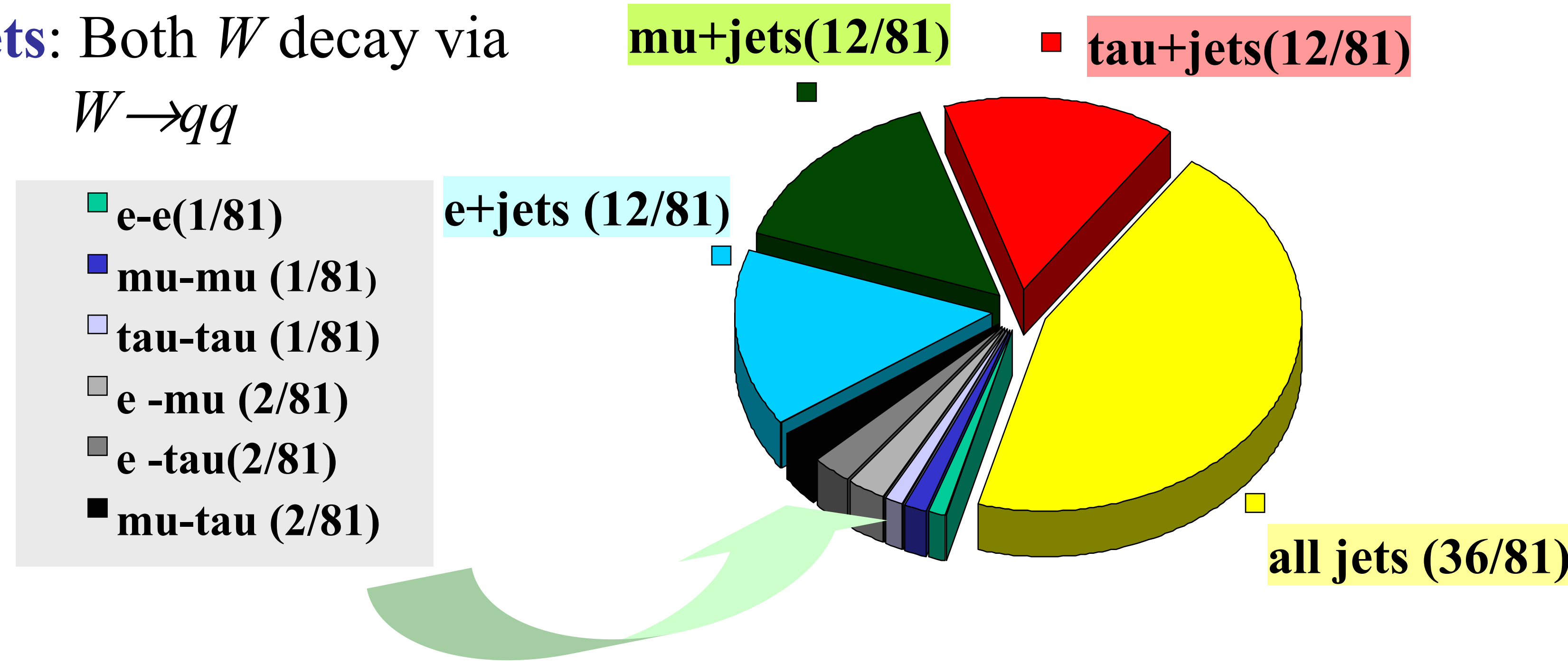


no single top observed (so far)
current Run II **CDF** limits:
$\sigma(s+t) < 13.7$ pb @ 95 % CL
$\sigma(t \text{ only}) < 8.5$ pb @ 95 % CL

Top quark decay

$Br(t \to Wb) \cong 100\%$ in the SM

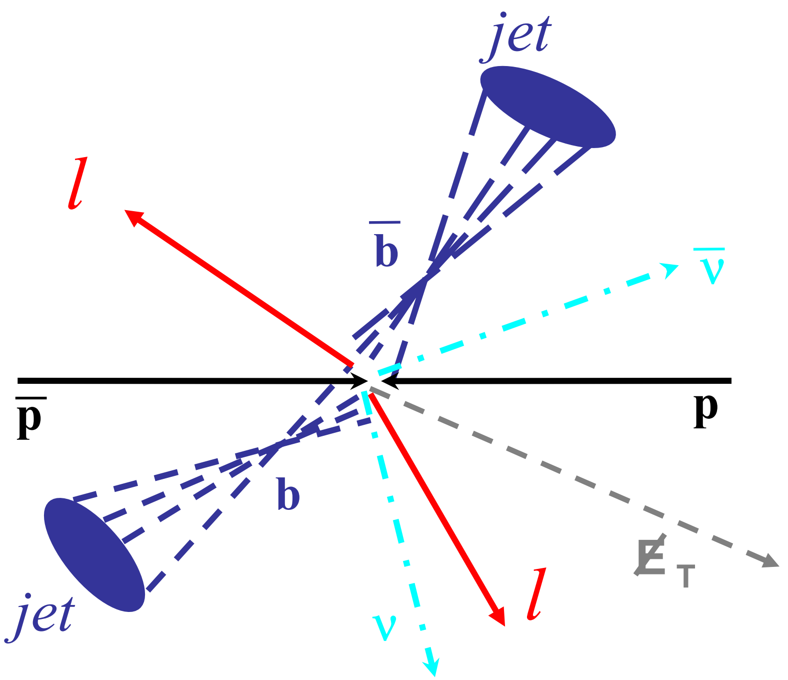
- **dilepton:** Both W decay via $W \to l\nu$ (l=e or μ, ~5%)
- **lepton+jets**: One W decays via $W \to l\nu$ (l=e or μ, ~30%), the other via $W \to qq$
- **all jets**: Both W decay via $W \to qq$



Top cross section: dilepton channels

very clean, low yield

2 high p_T isolated leptons
(e,μ, not τ)
neutrinos: large missing E_T
2 high p_T jets (from b-quarks)



$t(\rightarrow W^+b)\ \bar{t}(\rightarrow W^-b)$

$\rightarrow e^+, \mu^+$ $\rightarrow e^-, \mu^-$

3 channels:

ee, $\mu\mu$, $e\mu$

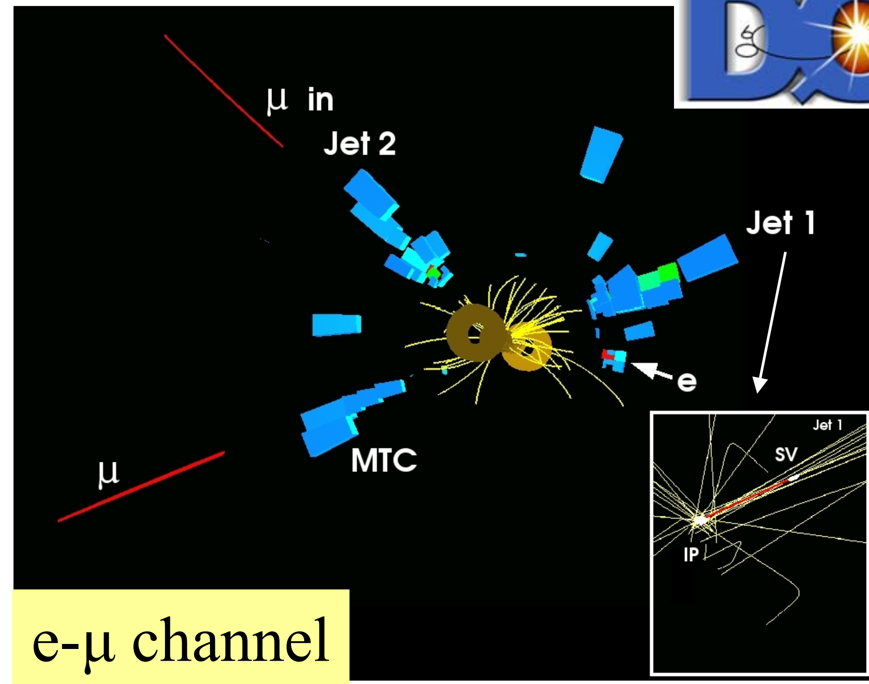
Backgrounds:

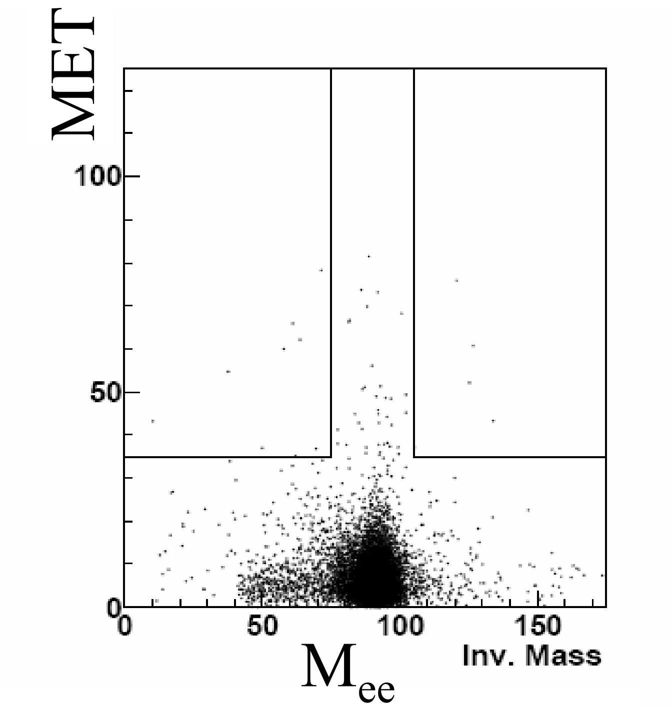
$Z \rightarrow l^+l^-$ (incl. $\tau\tau$)
$WW \rightarrow ee$, $\mu\mu$, $e\mu$ + jets (small, but has very toplike signature)
QCD leptons (esp. μ)

di-lepton

Event selection:

- trigger
- missing $E_T > 25$ GeV ($e\mu$) /35 GeV (ee, $\mu\mu$)
- isolated leptons, p_t lepton > 15 (20 for ee)
- $H_T^{l} > 120$ /140 GeV
- 2 or more jets with $p_t > 20$ GeV
- 105 (110) GeV < M(ee), (M($\mu\mu$)) < 75 (70)GeV





~145 pb $^{-1}$	ee	$e\mu$	$\mu\mu$	$\ell\ell$
Z/γ^*	0.15 ± 0.10	0.47 ± 0.17	2.04± 0.49	2.66 ± 0.53
WW	0.14 ± 0.08	0.29 ± 0.06	0.10 ± 0.04	0.53 ± 0.11
Fakes	0.91 ± 0.30	0.19 ± 0.06	0.46 ± 0.20	1.56 ± 0.36
Total bkg.	1.20 ± 0.33	0.95 ± 0.19	2.61 ± 0.53	4.76 ± 0.65
Observed	5	8	4	17

combined: $\sigma_{ttbar} = 14.3\ ^{+5.1}_{-4.3}\ \text{(stat)}\ ^{+2.6}_{-1.9}\ \text{(syst)} \pm 0.9\ \text{(lumi) pb}$

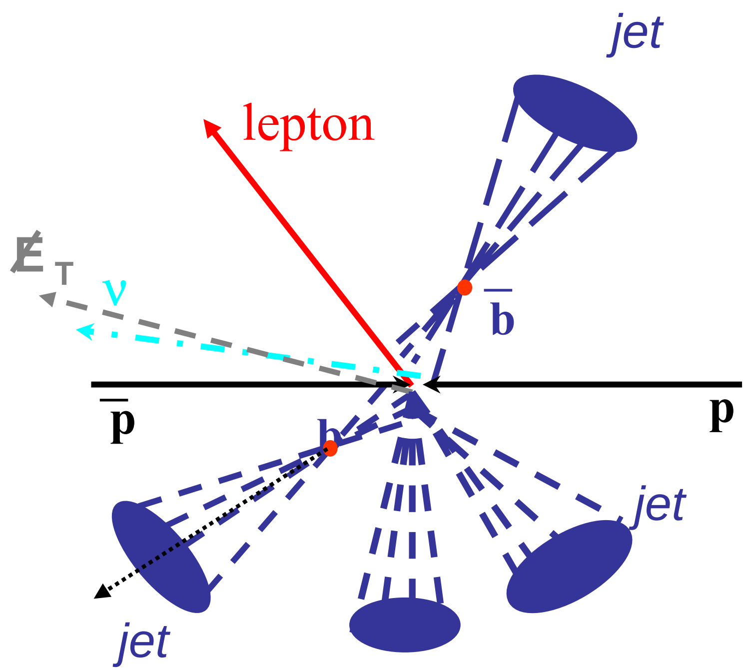
Top cross-section: Lepton + jets

"Golden" mode for top studies: ~30% yield and relatively clean

One (and only one)
high p_T isolated lepton.

Neutrino: large missing E_T

large jet multiplicity ($\geq 3,4$)



Background: QCD+multijet
W+multijet

jet

- topological: event shape, $H_T = \Sigma p_T^{jet} + p_T^W$
- *b*-tagged: secondary vertex tag
  soft lepton tag

$t(\rightarrow W^{\pm}b)\ t(\rightarrow W^{\pm}b)$

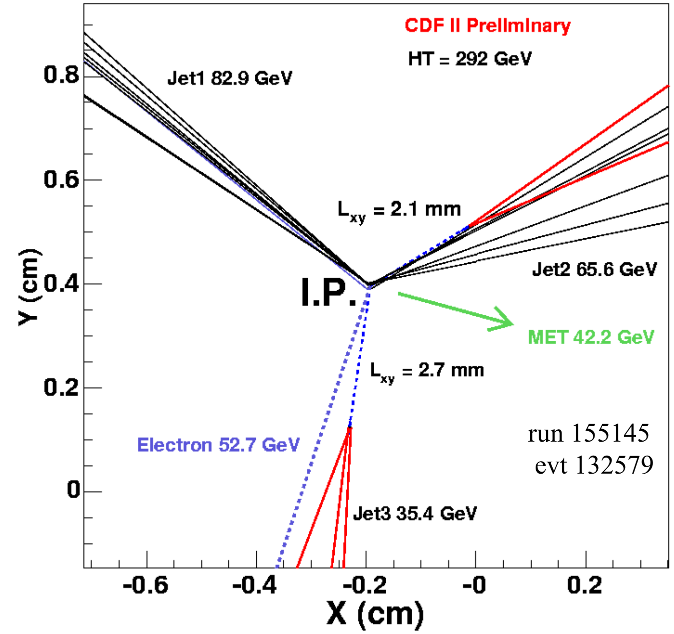
$\searrow e^{\pm},\mu^{\pm}$ $\searrow qq$

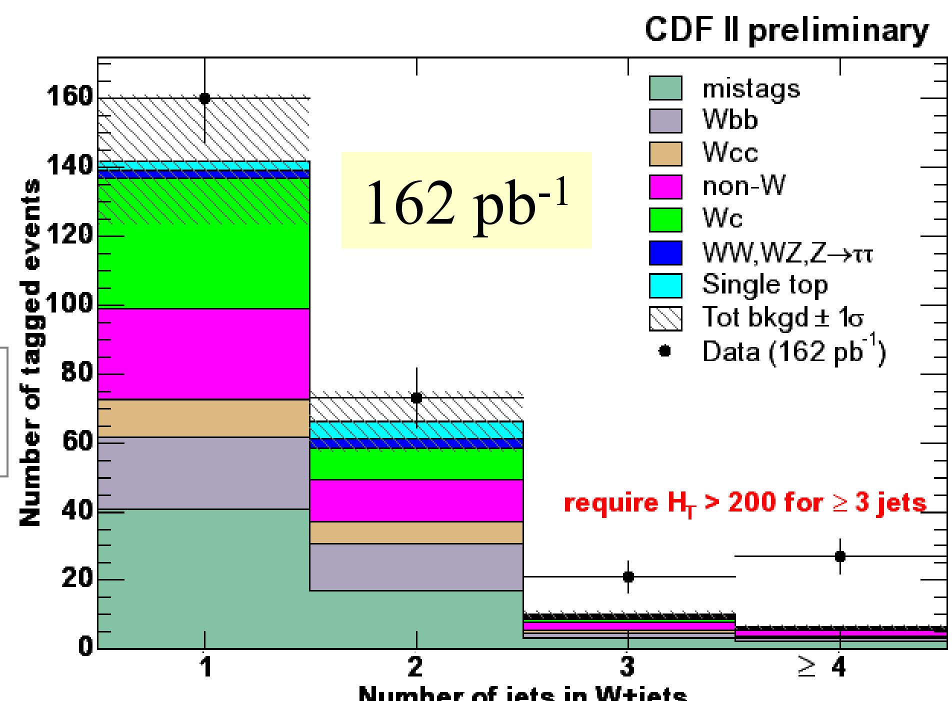
lepton + jets

Event selection:

- lepton trigger
- missing $E_T > 20$ GeV
- E_T, $p_t(\mu) > 20$ GeV
- at least 3 jets with $p_t > 15$ GeV and $|\eta| < 2.0$
- at least one *b*-tagged jet
- $H_T = \Sigma E_T +$ missing $E_T + E_T (p_t(\mu))$
- $H_T > 200$ GeV

$$\sigma(t\bar{t}) = 5.6 ^{+1.2}_{-1.1} (\text{stat}) ^{+1.0}_{-0.7} (\text{syst}) \text{ pb}$$



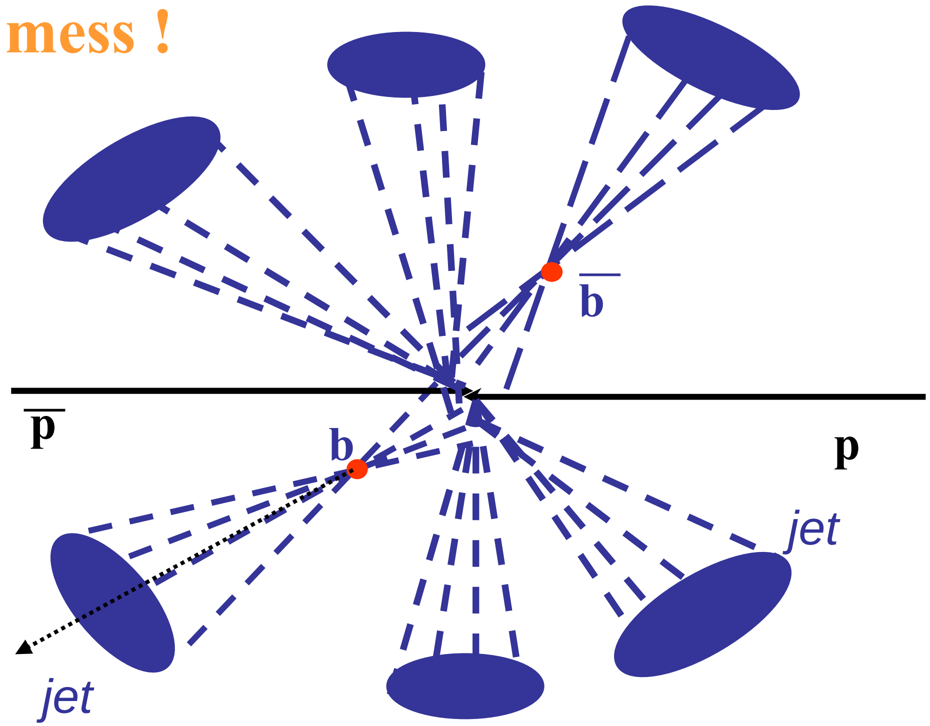


Top to all jets

~45 % of all decays, but what a mess !

50% of all tt→jets have ≤ 5 reconstructed jets

but: swamped by background (QCD hard scatter 2 → 2 parton processes)



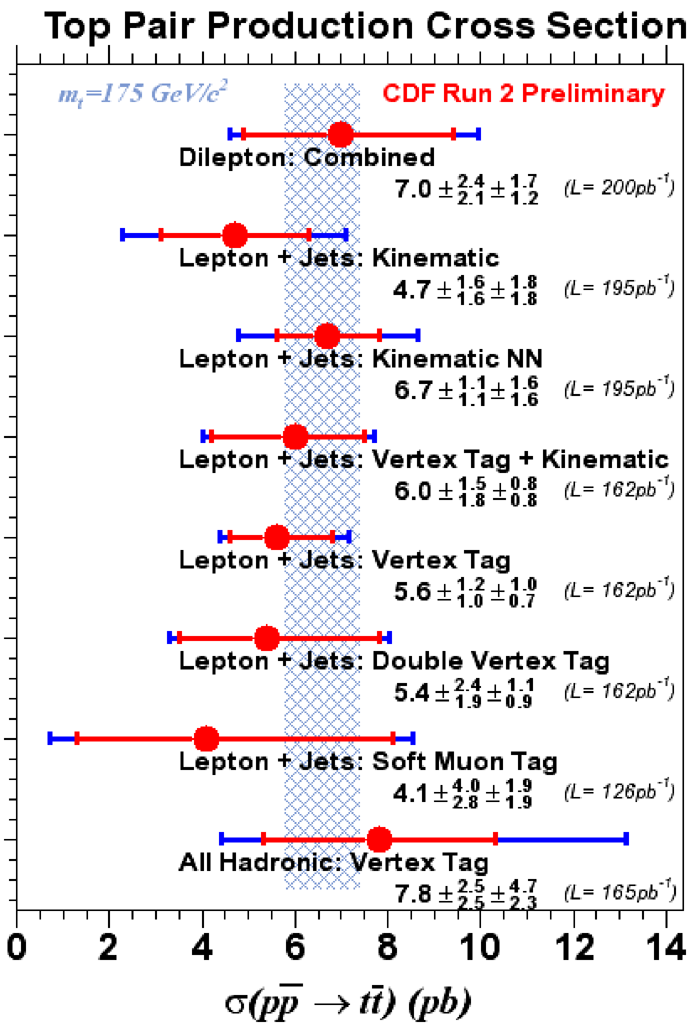
6 or more jets (one jet per parton)
no isolated leptons
b-tagging
event shape

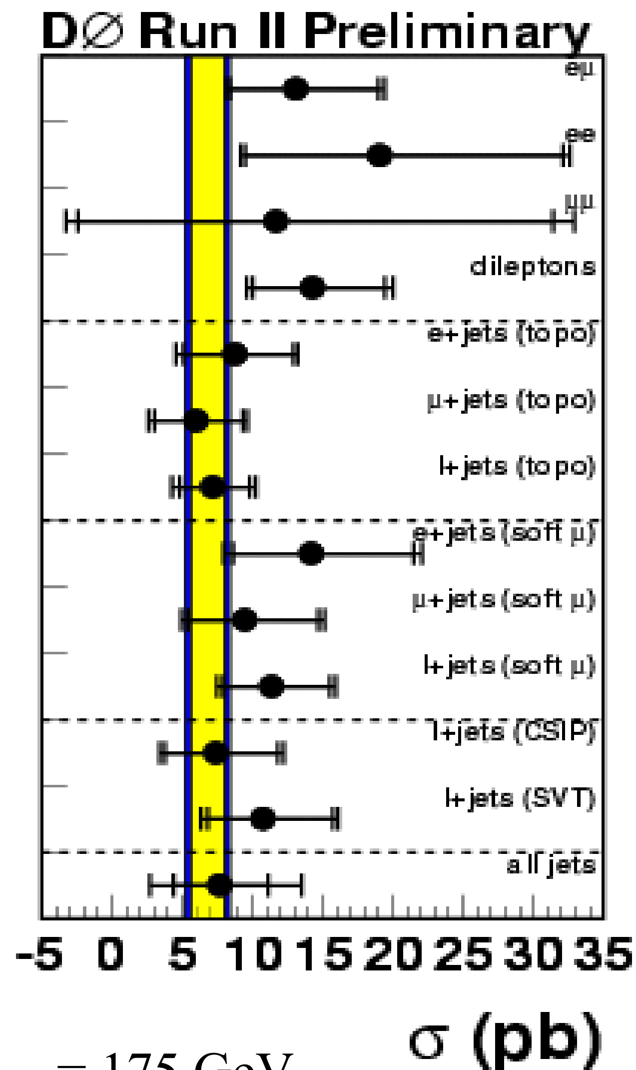
DØ (neural net) $\sigma(t\bar{t}) = 7.7\,^{+3.4}_{-3.3}(\mathrm{stat})\,^{+4.7}_{-3.5}(\mathrm{syst}) \pm 0.5$ (lumi)

CDF (tagging) $\sigma(t\bar{t}) = 7.8 \pm 2.5(stat)^{+4.7}_{-2.3}(syst)$ pb

$t\bar{t}$ Production Cross-Section Summary

All observed cross sections consistent with each other…





Theory predicts $\sigma(t\bar{t}) = 6.7^{+0.7}_{-0.9}$ pb at m_{top} = 175 GeV

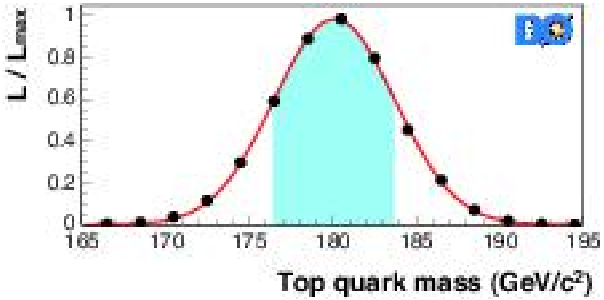
DØ Run I Top Quark Mass Measurement

$m_t = 180.1 \pm 3.6\ (stat) \pm 3.9\ (syst)\ GeV/c^2$

Nature (429, pp. 638-642)

- Statistical uncertainty reduced from 5.6 to 3.6 GeV/c^2

  → equivalent to a 2.4x larger dataset



The probability for a top (or background) event to give rise to observed jets, leptons and MET is computed.

M_{top} is measured by maximizing Poisson likelihood for entire event sample.

This measurement increases the world-average top mass from 174 ± 5.1 GeV to 178 ± 4.3 GeV

Advantages:

- all jet permutations contribute
- event-by-event resolutions considered
- non-Gaussian detector response accounted for

Problems:

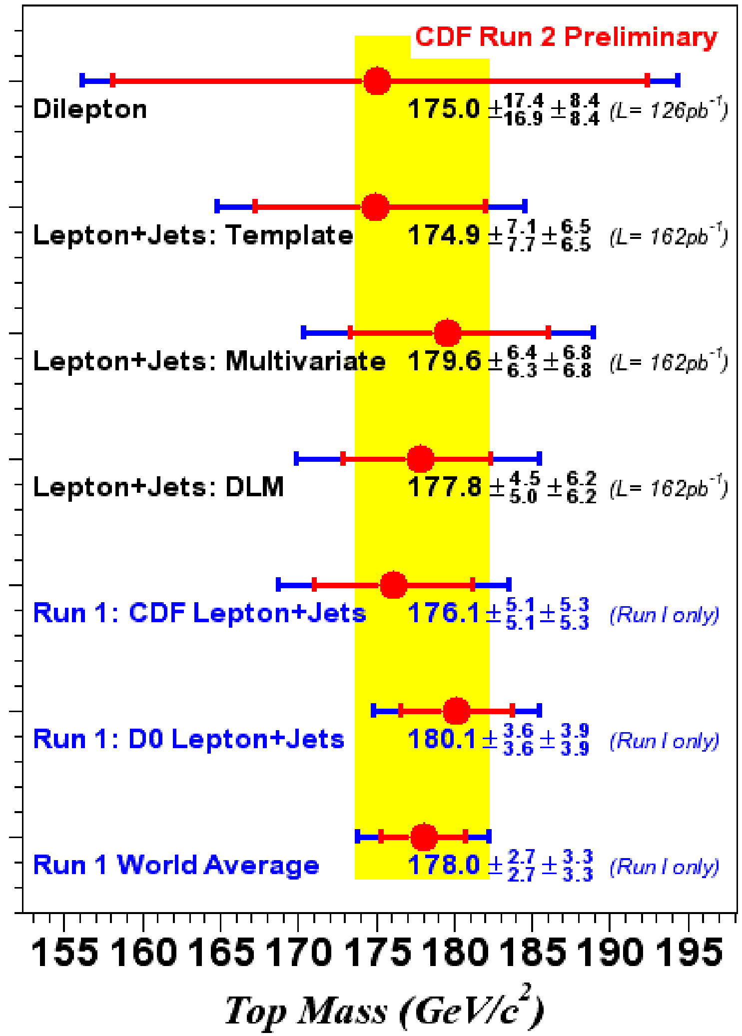
- only leading-order tt cross section is used
  → only events with exactly four jets can be used
- gluon fusion diagrams neglected
- only background process computed is W + jets

Run II top mass CDF

Lepton+ jets:
- template (Run I)
- multivariate
- dynamical likelihood

→ best Run II CDF result so far

$$M_{top} = 177.8 \pm^{4.5}_{5.0} \text{(stat.)} \pm 6.2 \text{ (syst.)GeV}/c^2$$



Systematic error is dominated by modeling of the calorimeter response

improved result for Winter 2005

First Run II DØ mass measurement soon.

W-helicity in top decays

• In the SM only left-handed (W_) and longitudinally polarized (W_0) are produced.

$$F_0 \equiv \frac{\Gamma(t \rightarrow W_0 b)}{\Gamma(t \rightarrow W_0 b) + \Gamma(t \rightarrow W_T b)} = \frac{\frac{1}{2}(m_t/m_W)^2}{1 + \frac{1}{2}(m_t/m_W)^2}$$

With $m_t = 175$ GeV ⇒ $F_0 = 0.703$

Run I results:

CDF (2000): $F_0 = 0.91 \pm 0.37$ (stat) ± 0.13 (syst)

DØ (2004): $F_0 = 0.56 \pm 0.32$ (stat+ m_t) ± 0.07 (syst)

W-helicity Run II

lepton + jets:

$F_0 = 0.88^{+0.12}_{-0.47}$ (stat+syst)

$F_0 > 0.24$ @ 95 % CL

di-lepton:

$F_0 < 0.52$ @ 95 % CL

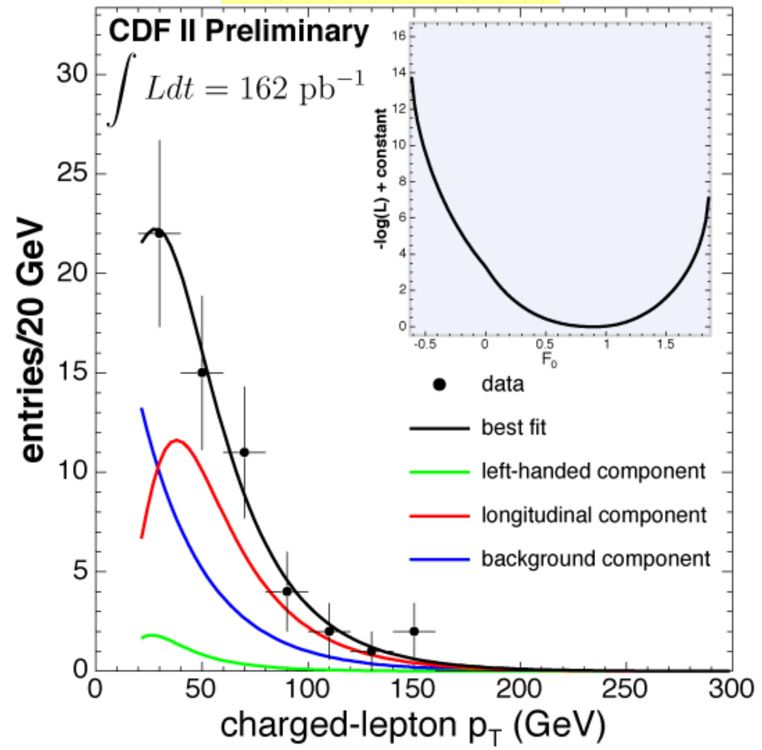
$F_0 < 0.94$ @ 99 % CL

combined:

$F_0 = 0.27^{+0.35}_{-0.21}$ (stat + syst)

$F_0 < 0.88$ @ 95 %CL

lepton+ jets



Updated DØ measurement soon

b-physics at the Tevatron

The Tevatron is a *b*-factory:

$\sigma(pp \rightarrow bb) = 150\ \mu b$ (at 1.96 TeV)

All types of *B*-hadrons are being produced (B_d, B_s, B^{**}, Λ_b etc)

CDF and DØ have a large and varied b-physics programme
→ can only present a limited selection today

- Mixing
- Lifetimes
- Lifetime difference in $B_s \rightarrow J/\Psi\ \Phi$

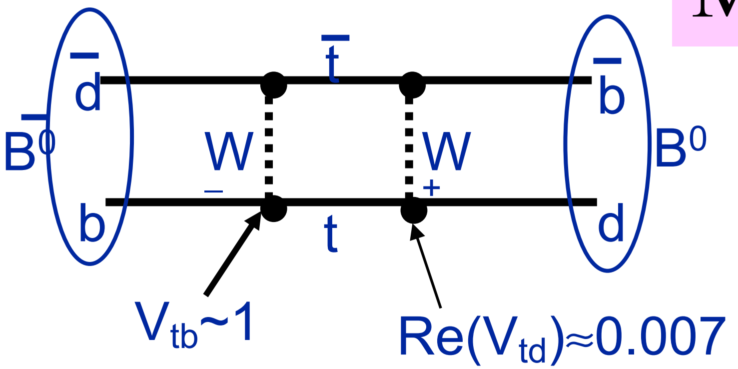
- X
- $B_s \rightarrow \Phi\Phi$
- $B_{s/d} \rightarrow \mu\mu$
- Pentaquarks

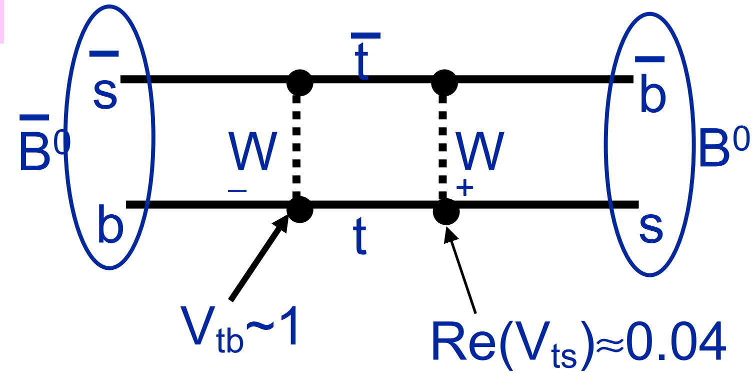
not covered:

- *b* and quarkonia production
- CP violation
- hadronic moments
- B_c
- B^{**}
- $B \rightarrow D^{**}\ X$
- Helicity amplitudes in $B \rightarrow J/\Psi\ K^*/\Phi$

etc.

Mixing





$$i\frac{\partial}{\partial t}\begin{pmatrix}|B_q^0(t)\rangle \\ |\overline{B}_q^0(t)\rangle\end{pmatrix} = \left(\mathbf{M} - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B_q^0(t)\rangle \\ |\overline{B}_q^0(t)\rangle\end{pmatrix}$$

M = mass matrix
Γ = decay matrix

To measure B-mixing:

- proper decay time $c\tau$
- identify *b*-flavour at production
- identify *b*-flavour at decay

Tagging efficiency $\varepsilon = N_{tag}/N_{tot}$
Dilution $D = (N_R - N_W)/(N_R + N_W)$
Tag power $= \varepsilon D^2$

Flavour tagging:

- same side tagging: charge of 'nearby' track correlated with b-quark flavour ($b \leftrightarrow \pi^+$, $bbar \leftrightarrow \pi^-$)
- opposite side jet charge tagging: sign of *b*-quark ~ sign of momentum weighted sum of particles charges in jet
- opposite side lepton (here: μ) tagging: from semileptonic *b*-decays ($b \leftrightarrow l^-$, $bbar \leftrightarrow l^+$)

Mixing Results from CDF

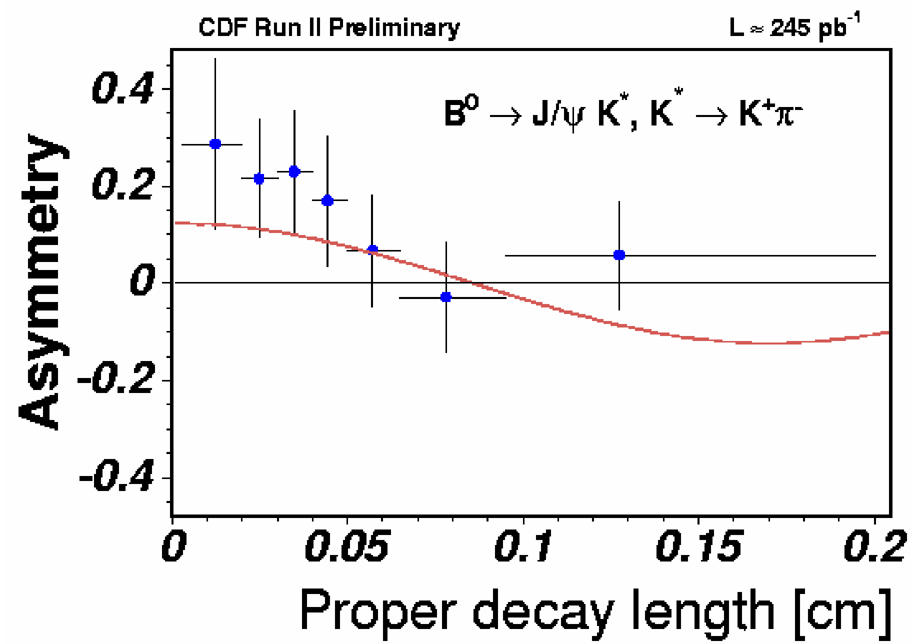
- exclusive decays

$B^0 \rightarrow J/\Psi\ K^{*0}$

$B^0 \rightarrow D^- \pi^+$

$\Delta\ m_d = 0.55 \pm 0.10 \pm 0.01\ \ ps^{-1}$

world average: $\Delta m_d = 0.502 \pm 0.007$



- semileptonic *b*-decays using same side tagging

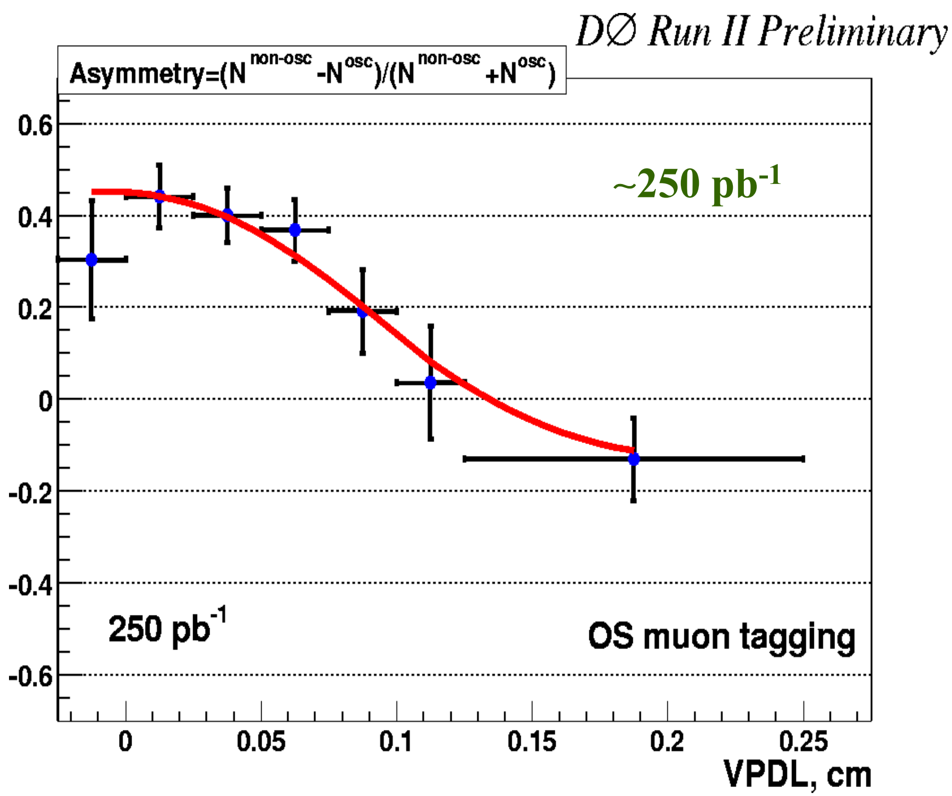
$\Delta m_d = 0.443 \pm 0.052\ (stat.) \pm 0.030\ (s.c.) \pm 0.012\ (syst.)\ ps^{-1}$

$D_0 = 12.8 \pm 1.6\ (stat.) \pm 1.0\ (s.c.) \pm 0.6\ (syst.)\ \%$

$D_+ = 28.3 \pm 1.3\ (stat.) \pm 1.1\ (s.c.) \pm 1.0\ (syst.)\ \%$

$\varepsilon D^2(B^0) = 1.1 \pm 0.3\ (stat.) \pm 0.2\ (s.c.) \pm 0.1\ (syst.)\ \%$

Mixing Results from DØ



Semileptonic *B*-decays:

$B \to D^{*-} \mu^+ \nu X$

$D^{*-} \to D^0 \pi^-$

$D^0 \to K^+ \pi^-$

opposite-side muon tagging

world average: $\Delta m_d = 0.502 \pm 0.007$

$\Delta m_d = 0.506 \pm 0.055$ (stat.) ± 0.049 (syst.) ps^{-1}

- Tagging efficiency: 4.8 ± 0.2 %
- Tagging purity, $N_R/(N_R+N_W) = 73.0 \pm 2.1$ %
- $\to D = 46$ %, $\varepsilon D^2 = 1.0$ %

Run II lifetime measurements

HQET/OPE predict lifetime ratios: $\tau(B^+)/\tau(B^0_d) = 1.053 \pm 0.016 \pm 0.017$

CDF

B meson	N(*B*)	τ(*B*) in ps	PDG 03 in ps
$B^+ \rightarrow J/\Psi\, K^+$	~3390	$1.662 \pm 0.033 \pm 0.008$	1.671 ± 0.018
$B^0 \rightarrow J/\Psi\, K^{*0}$	~1160	$1.539 \pm 0.051 \pm 0.008$	1.537 ± 0.015
$B_s \rightarrow J/\Psi\, \Phi$	~260	$1.369 \pm 0.100 ^{+0.008}_{-0.010}$	1.461 ± 0.057

$\tau(B^+) / \tau(B^0) = 1.080 \pm 0.042$ (*tot.*)
$\tau(B_s) / \tau(B^0) = 0.890 \pm 0.072$ (*tot.*)

correlated errors

DØ

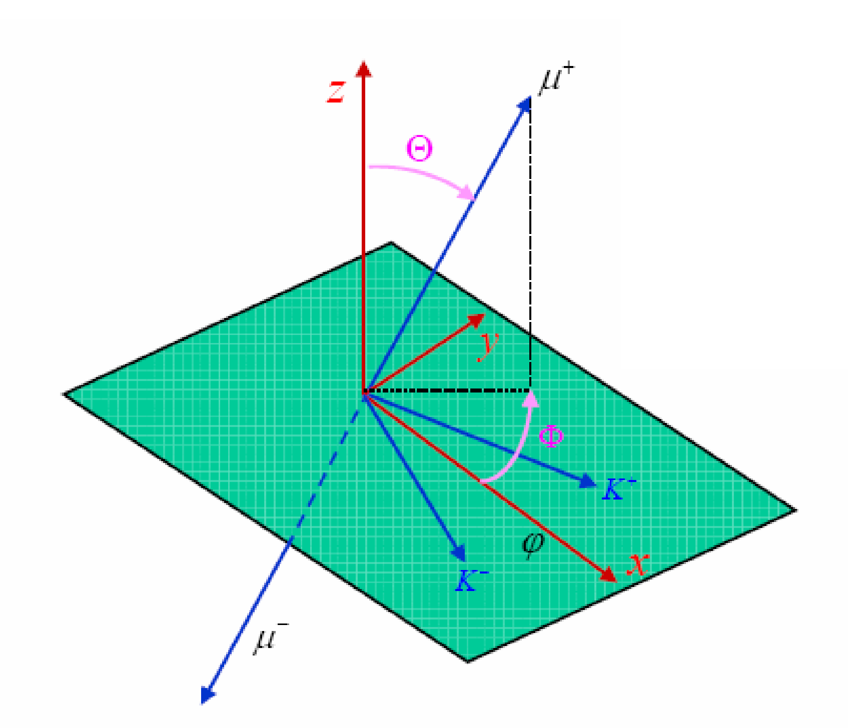
preliminary

semileptonic decays

$\tau(B^+)/\tau(B^0) = 1.093 \pm 0.021\ (stat) \pm 0.022\ (syst)$

updated DØ measurements in exclusive modes (B_d, B_s, Λ_b) at ICHEP

Lifetime difference and in $B_s \rightarrow J/\Psi\ \Phi$ (Method)



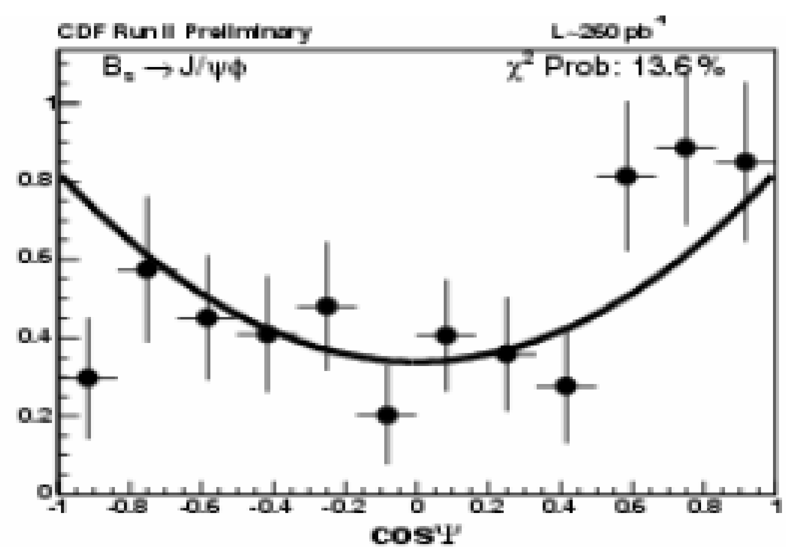
$$B_s^H = \frac{1}{\sqrt{2}}(|B_s\rangle + |\overline{B}_s\rangle) = CP - odd$$
$$B_s^L = \frac{1}{\sqrt{2}}(|B_s\rangle - |\overline{B}_s\rangle) = CP - even$$

scalar → VV decay

➔ 3 amplitudes

L = 0 (even),1 (odd), 2 (even)

described in ***transversity*** basis



In J/Ψ restframe:

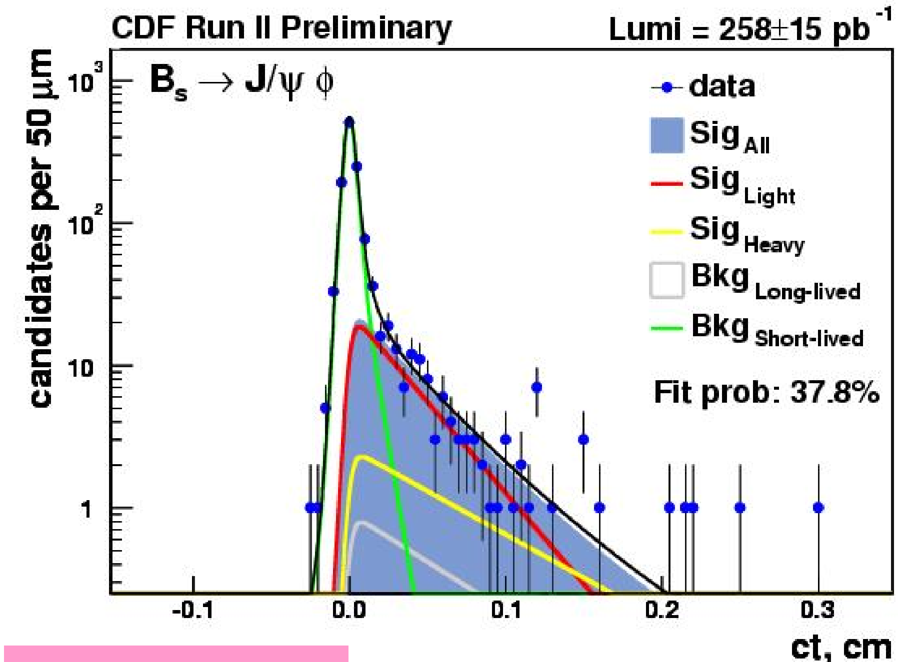
K^+K^- plane defines (x,y) plane

K^+ defines +y direction

Θ, Ψ polar and azimuthal angles of μ^+

φ in Φ restframe: angle(K+, -J/Ψ)

Lifetime difference and in $B_s \rightarrow J/\Psi\ \Phi$ (Results)



$\Gamma = \frac{1}{2}(\Gamma_L + \Gamma_H) \equiv 1/\tau$

$\Delta\Gamma = \Gamma_L - \Gamma_H$

theory:

$\Delta\Gamma/\Gamma_s = 0.12 \pm 0.06$

constrained fit

$\Gamma_s = \Gamma_d$

$\tau_L = 1.13^{+0.13}_{-0.09} \pm 0.02$ ps

$\tau_H = 2.38^{+0.56}_{-0.43} \pm 0.03$ ps

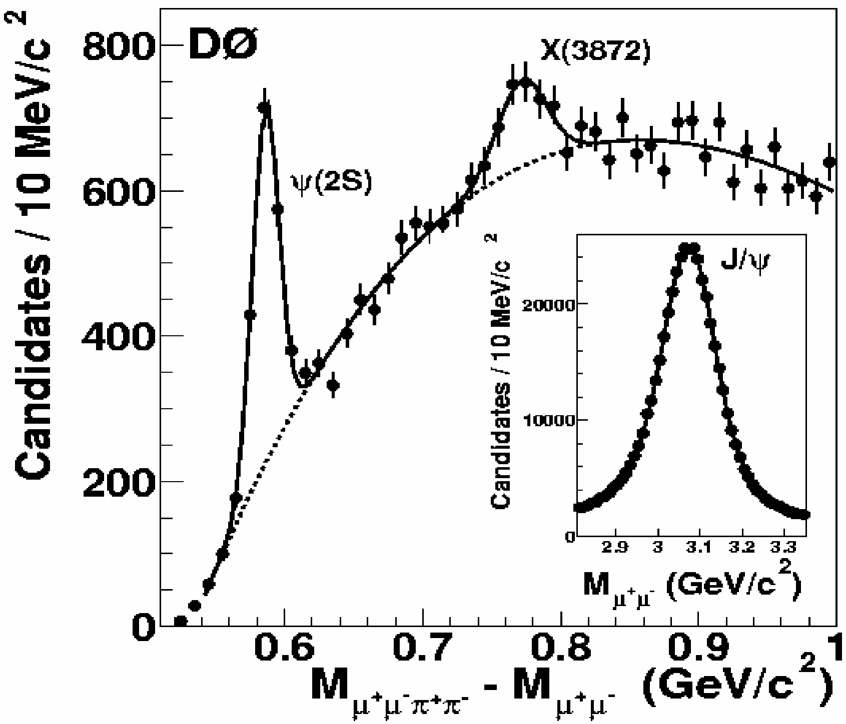
$\Delta\Gamma = 0.46 \pm 0.18 \pm 0.01\ \text{ps}^{-1}$

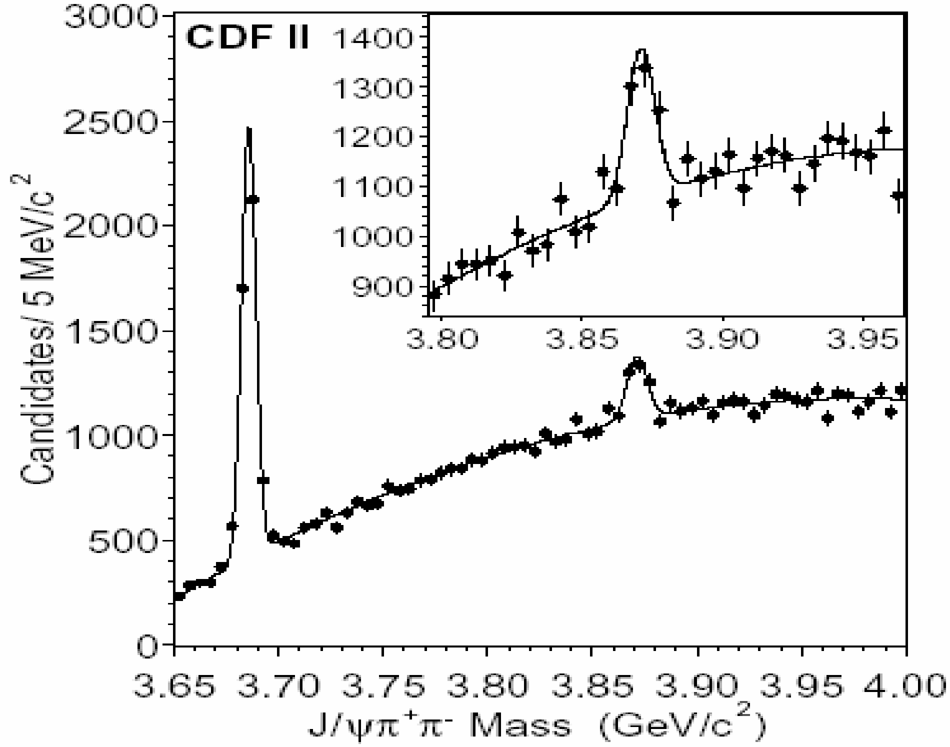
$\Delta\Gamma/\Gamma_s = 0.71^{+0.24}_{-0.28} \pm 0.01$

unconstrained fit: $\Delta\Gamma/\Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$

X(3872) →J/Ψ $\pi^+\pi^-$

Belle: M_X = 3872.0 ± 0.6 (stat) ± 0.5 (sys) MeV/c^2

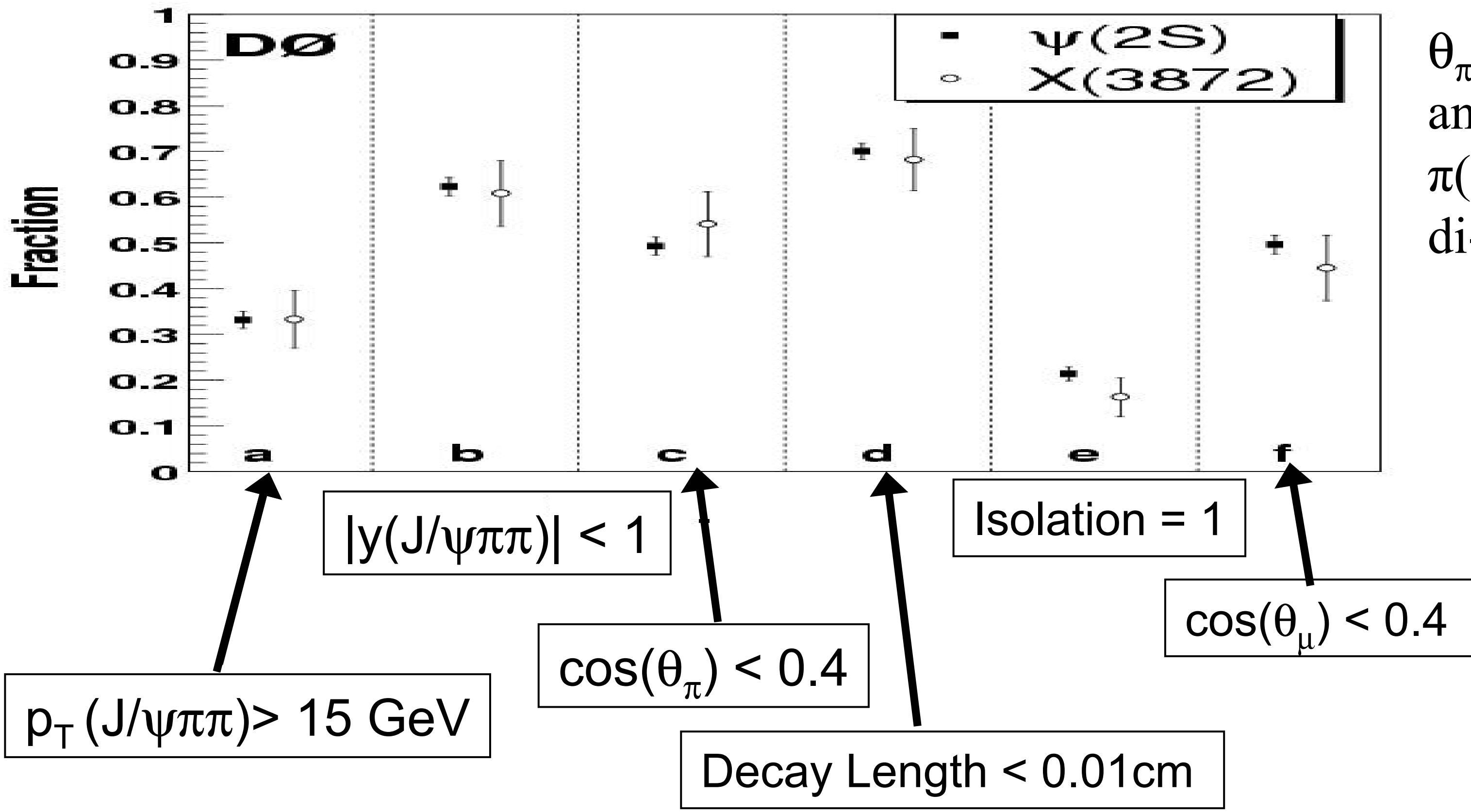




Exp	Lumi [pb^{-1}]	range	Mass [MeV]	Mass res [MeV]	Signal	Significance
CDF	220	|y| < 1	3871.3 ± 0.7 ± 0.3	4.9	730 ± 90	≈ 12σ
DØ	230	|y| < 2	3871.8 ± 3.1 ± 3.0	17	522 ± 100	≈ 5σ

X(3872) – Ψ(2S) comparison

Is the X(3872) charmonium, molecule, … ?



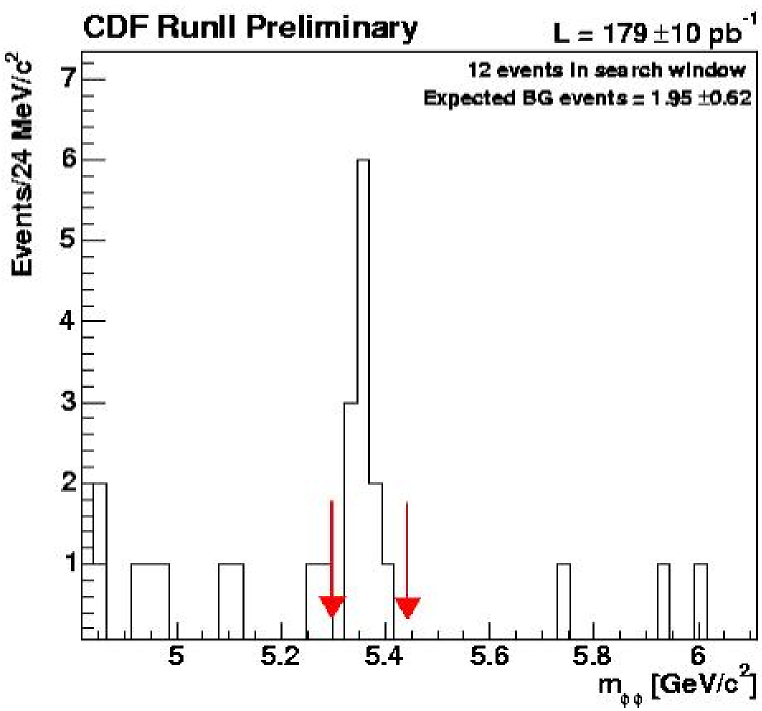
θ_π,θ_μ helicity: angle between π(μ) and X in di-π(μ) restframe

Similar in decay length and isolation → similar prompt production fraction as Ψ(2S)

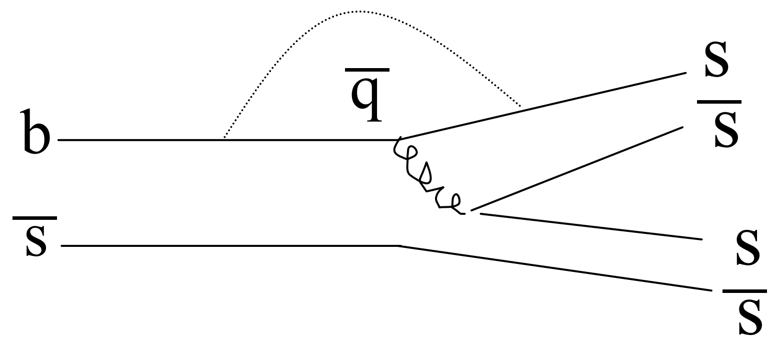
No significant differences between **ψ(2S)** and ***X*** have been observed yet.

Charmless *B*-decays: $B_s \rightarrow \Phi\Phi$

First 'observation' ($\sigma = 4.7$) at CDF



gluonic penguin decay



12 events seen
expected bkg 1.95 events

$BR(B_s \rightarrow \Phi\Phi) = (1.4 \pm 0.6\ (\text{stat}) \pm 0.2\ (\text{syst}) \pm 0.5\ (\text{BRs})) * 10^{-5}$

You won't see this at the *b*-factories…..

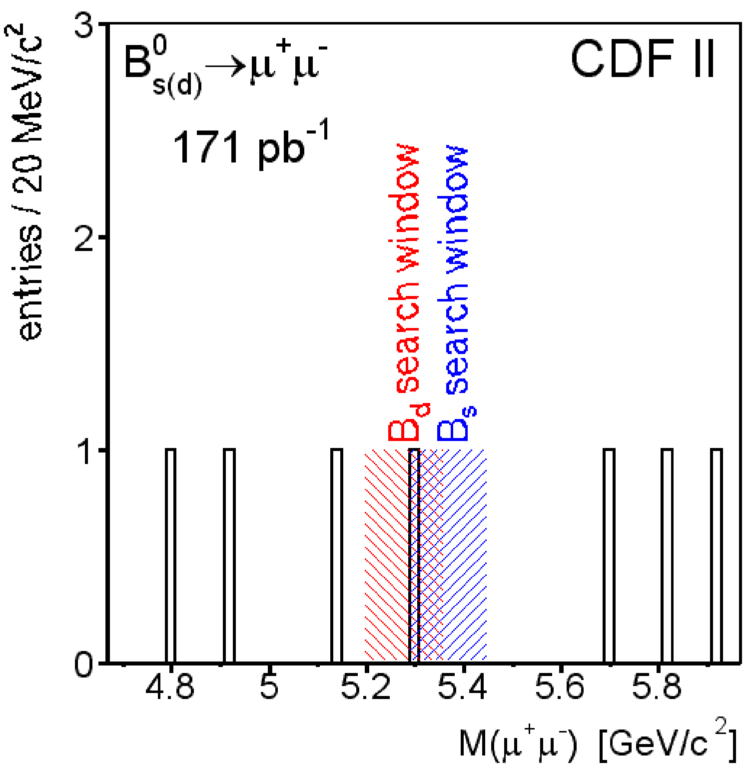
Rare decays: $B_{s/d} \rightarrow \mu^+\mu^-$

SM prediction: $BR(B_s \rightarrow \mu\,\mu) = (3.4 \pm 0.5) \cdot 10^{-9}$
$B_d \rightarrow \mu\mu$ suppressed by $|V_{td}/V_{ts}| \cong 4 \cdot 10^{-2}$

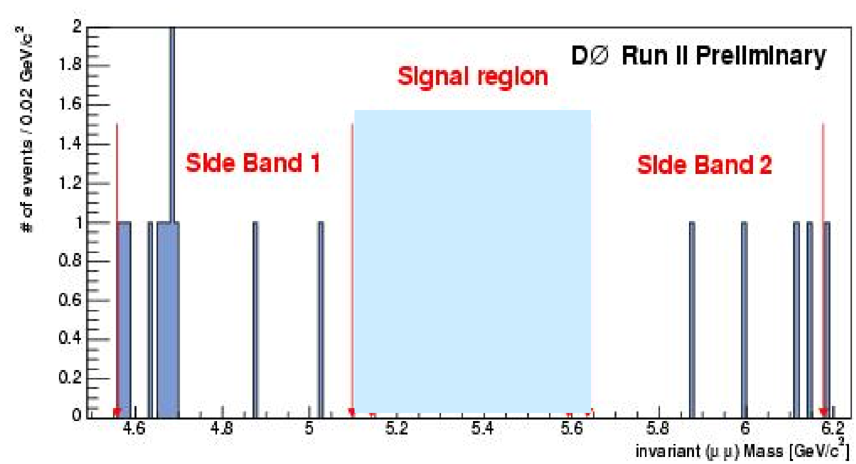
CDF Run II limits:

$BR(B_s \rightarrow \mu\,\mu) < 5.8 \cdot 10^{-7}$ @ 90 % CL
$BR(B_d \rightarrow \mu\,\mu) < 1.5 \cdot 10^{-7}$ @ 90 % CL

DØ
Sensitivity @ 95 % CL **:**
$BR(B_s \rightarrow \mu^+\,\mu^-) < 9.1 \cdot 10^{-7}$ (stat only)
$BR(B_s \rightarrow \mu^+\,\mu^-) < 1.0 \cdot 10^{-6}$ (stat+syst)
Box will be opened for ICHEP



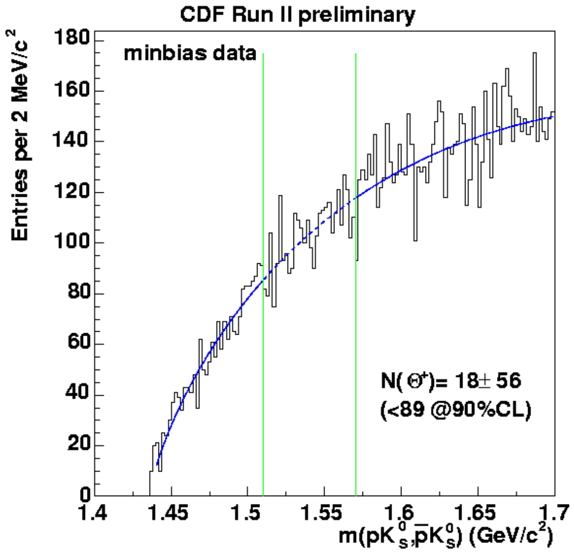
~180 pb-1



Pentaquarks

CDF has performed a search in the following channels:

- Θ^+ ($uudd\bar{s}$)) → p K_s → p $\pi^+ \pi^-$
- Θ_c ($uudd\bar{c}$) → D^{*-} p → $D^0 \pi^-$ p
- $\Xi^0_{3/2}$ ($ssdu\bar{d}$) → $\Xi^- \pi^+$ → $\Lambda \pi^+ \pi^-$
- $\Xi^{--}_{3/2}$ ($ssdd\bar{u}$) → $\Xi^- \pi^-$ → $\Lambda \pi^- \pi^-$



So far CDF has not observed any pentaquark states.

Summary

- The Tevatron integrated luminosity > 500 pb^{-1}/experiment

- Top
  - Run II luminosity in measurements now exceeds Run I
  - Sophisticated analysis techniques in place
  - Measurement of top properties in progress

- *b*-physics
  - Rich programme, not all covered in this talk
  - Competitive and complementary to *b*-factories

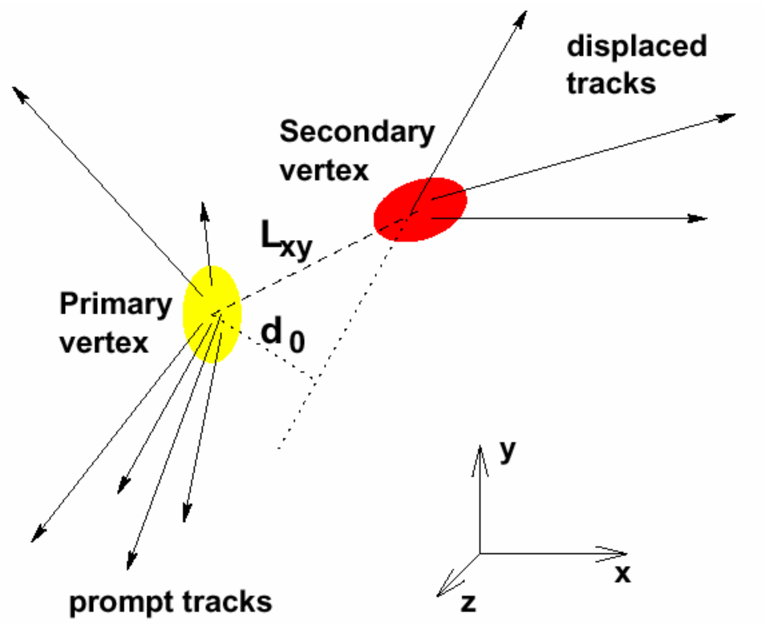
***** Many more results coming soon *****

Backup Slides

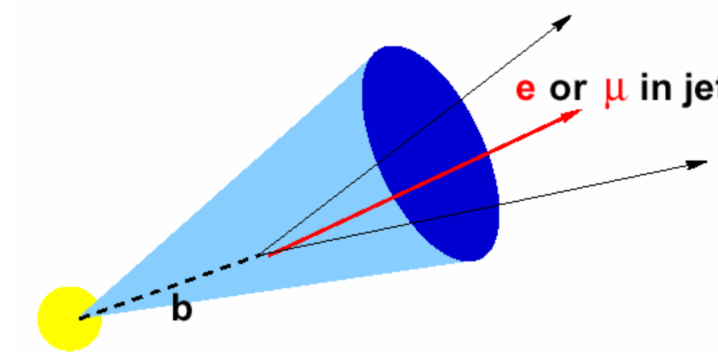
Tagging Tools: Vertexing and Soft Muons

B hadrons in top signal events

Vertex of displaced tracks



Identify low-pt muon from decay



- $b \to \ell \nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell \nu s$ (BR $\sim$ 20%)

Lepton+jets: topological

$H_T = \Sigma p_T^{jet} + p_T^W$ Highly correlated with the top mass!

Aplanarity A = 3/2 × smallest eigenvalue of the normalized momentum tensor M_{ij}

$$M_{ij} = \frac{\sum_o p_i^o p_j^o}{\sum_o |\vec{p}^o|^2}$$

Large values of A indicate spherical (top) events.

Top Quark Mass Measurements

DØ: New analysis of Run I Data

Nature 429, 638 (2004)

• Rather than a kinematic fit, the probability for a top (or background) event to give rise to observed jets, leptons and MET is computed

• Also define background probability for each event

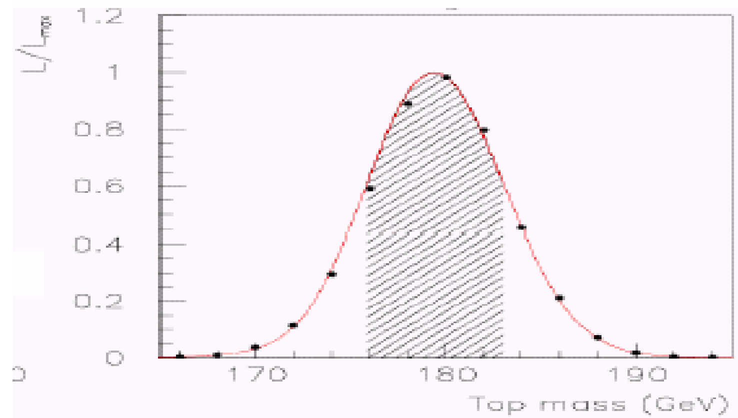
• M_t measured by maximizing Poisson likelihood for entire event sample

• Advantages

- - all jet permutations contribute
- - additional kinematic information used
- - event-by-event resolutions considered
- - non-Gaussian detector response accounted for

• Compromises

- - only leading-order tt cross section is used
- → only events with exactly four jets can be used
- - gluon fusion diagrams neglected
- - only background process computed is W + jets



22 events including 10 background

M_t = 180.1 ± 3.6 (*stat*) ± 4.0 (*syst*) GeV

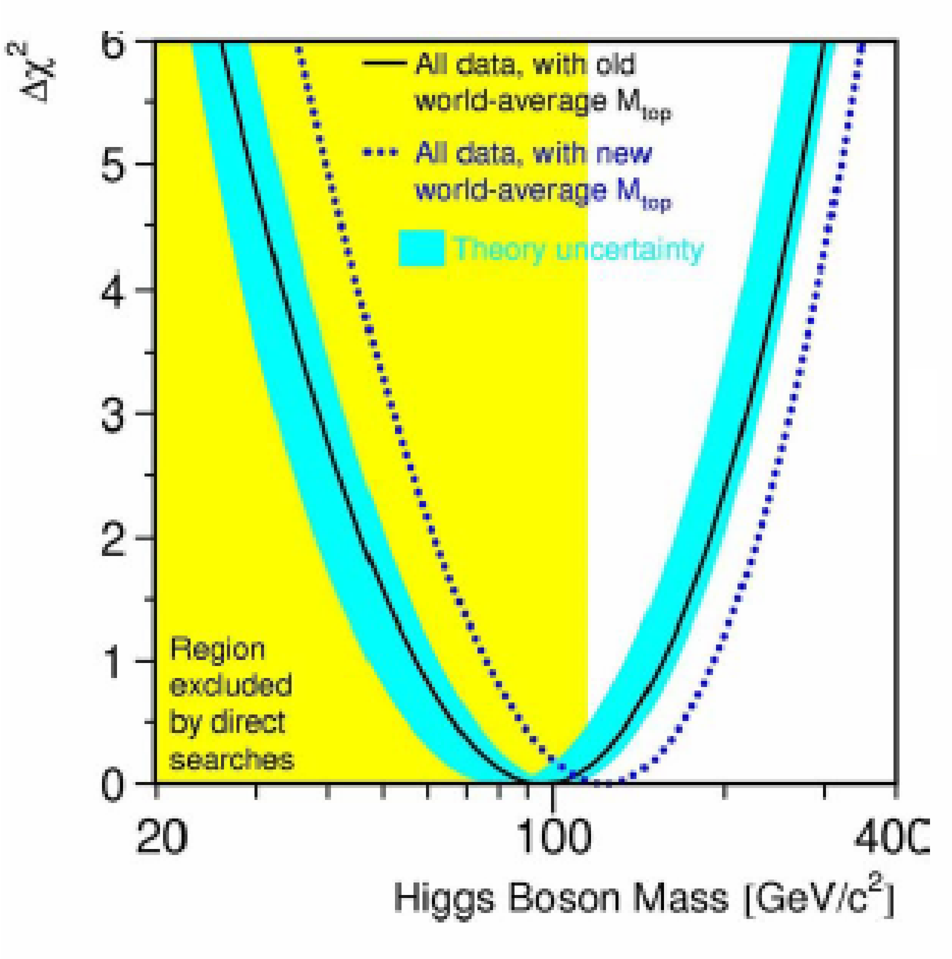
Lepton + jets CDF Run II mass measurements -- methods

Template Method (Run I method):
• Kinematic fitter to reconstruct top mass
• Kinematic constraints ($m_t = m_{tbar}$ etc)
• Use best (smallest χ^2) of 12 (4 if double btag) solutions
• One dinemsional templates parametrized for top and background as function of top mass

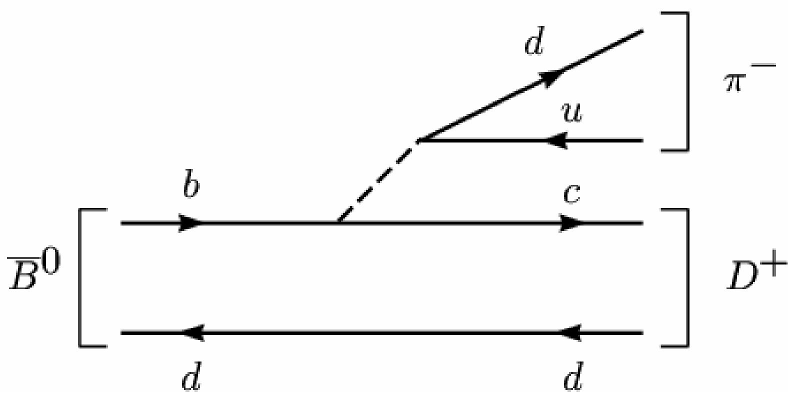
Multivariate Template Method:
• Refined kinematic fitter with jet energy scale optimization
• Kinematic constraints
• best combination, weight according to correct permutation probability
• mulitidimensional non-parametric templates

Dynamical Likelihood Method:
• Matrix Element Method
• use all 12 (4) combinations
• calorimeter transfer functions

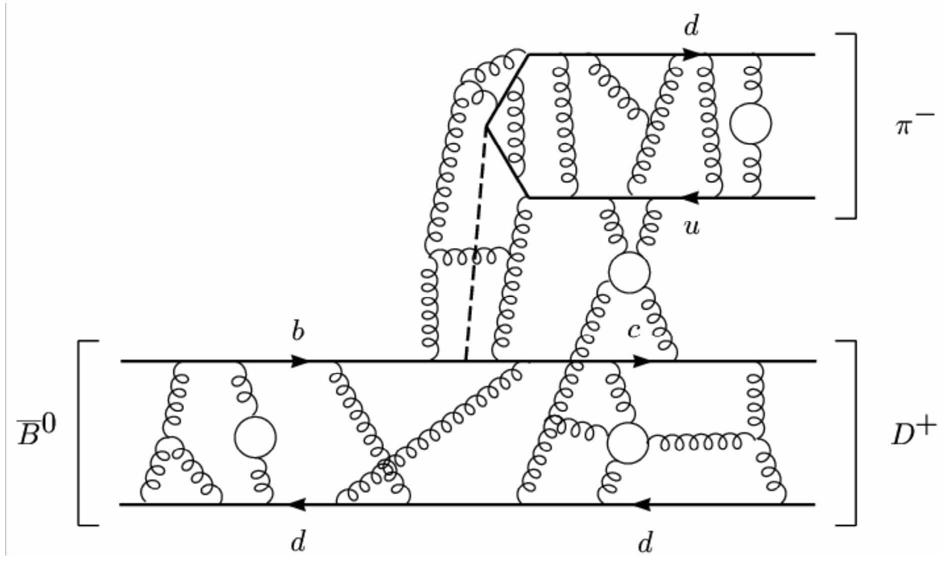
Top mass constraint on the Higgs mass



b - Lifetimes



spectator model



Heavy Quark Effective Theory ($m_Q \gg \Lambda_{QCD}$) but not top !

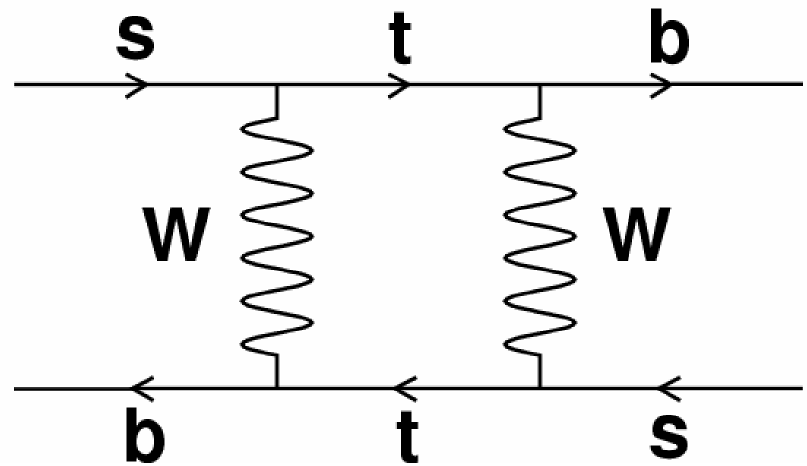
Mixing

B_s ($\sim\bar{b}s$), $\bar{B}_s$($\sim b\bar{s}$) are produced in one of the two possible flavour states. This initial state evolves into a time-dependent superposition of the two states according to:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\left|B_q^0(t)\right\rangle \\ \left|\overline{B}_q^0(t)\right\rangle\end{pmatrix} = \left(\mathbf{M} - i\frac{\Gamma}{2}\right)\begin{pmatrix}\left|B_q^0(t)\right\rangle \\ \left|\overline{B}_q^0(t)\right\rangle\end{pmatrix}$$

M = mass matrix
Γ = decay matrix

$\Delta\Gamma_s/\Gamma < 0.52$ at 95% c.l.
$\Delta\Gamma_s/\Gamma_{light} = 0.26\ (^{+0.30})$ ALEPH
theory: 0.12 ± 0.06

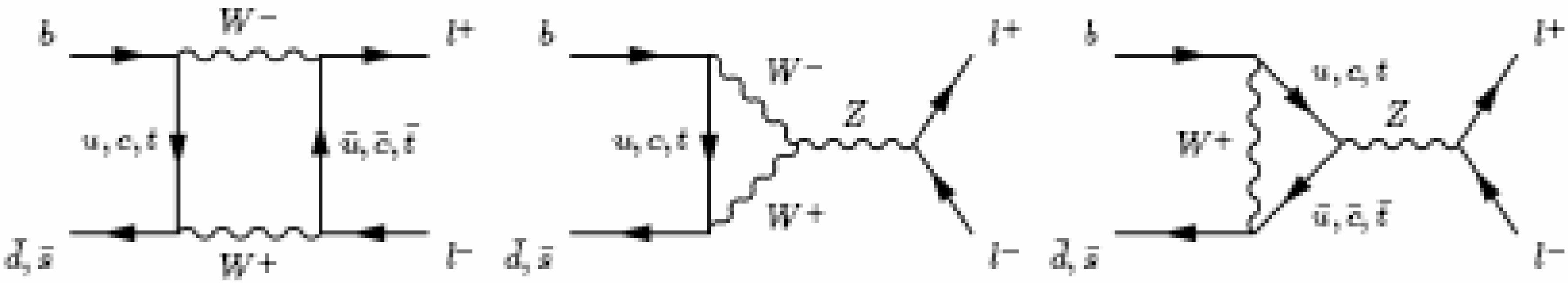


B_s mixing via top quarks

$x_s = \Delta m_{B_s}/\Gamma > 19.0$ at 95 % confidence level
$x_d = \Delta m_{B_d}/\Gamma = 0.755 \pm 0.015$

Rare decays: $B_{s/d} \rightarrow \mu\,\mu$ – theoretical predictions

Main contributing Standard Model diagrams



Theoretical predictions

	$BR(B_d \rightarrow l^+l^-)$	$BR(B_s \rightarrow l^+l^-)$
$l = e$	$(3.4 \pm 2.3) \cdot 10^{-15}$	$(8.0 \pm 3.5) \cdot 10^{-14}$
$l = \mu$	$(1.5 \pm 0.9) \cdot 10^{-10}$	$(3.4 \pm 0.5) \cdot 10^{-9}$
$l = \tau$	$(3.1 \pm 1.9) \cdot 10^{-8}$	$(7.4 \pm 1.9) \cdot 10^{-7}$

Experimental upper limits (at 90% (95%) confidence level)

	$BR(B_d \rightarrow l^+l^-)$	$BR(B_s \rightarrow l^+l^-)$
$l = e$	$< 5.9 \cdot 10^{-6}$	$< 5.4 \cdot 10^{-5}$
$l = \mu$	$< 1.5(1.9) \cdot 10^{-7}$	$< 5.8(7.5) \cdot 10^{-7}$
$l = \tau$	$< 2.5\%$	$< 5.0\%$