Electroweak, Top and Bottom Physics at the Tevatron

In the context of SUSY ?

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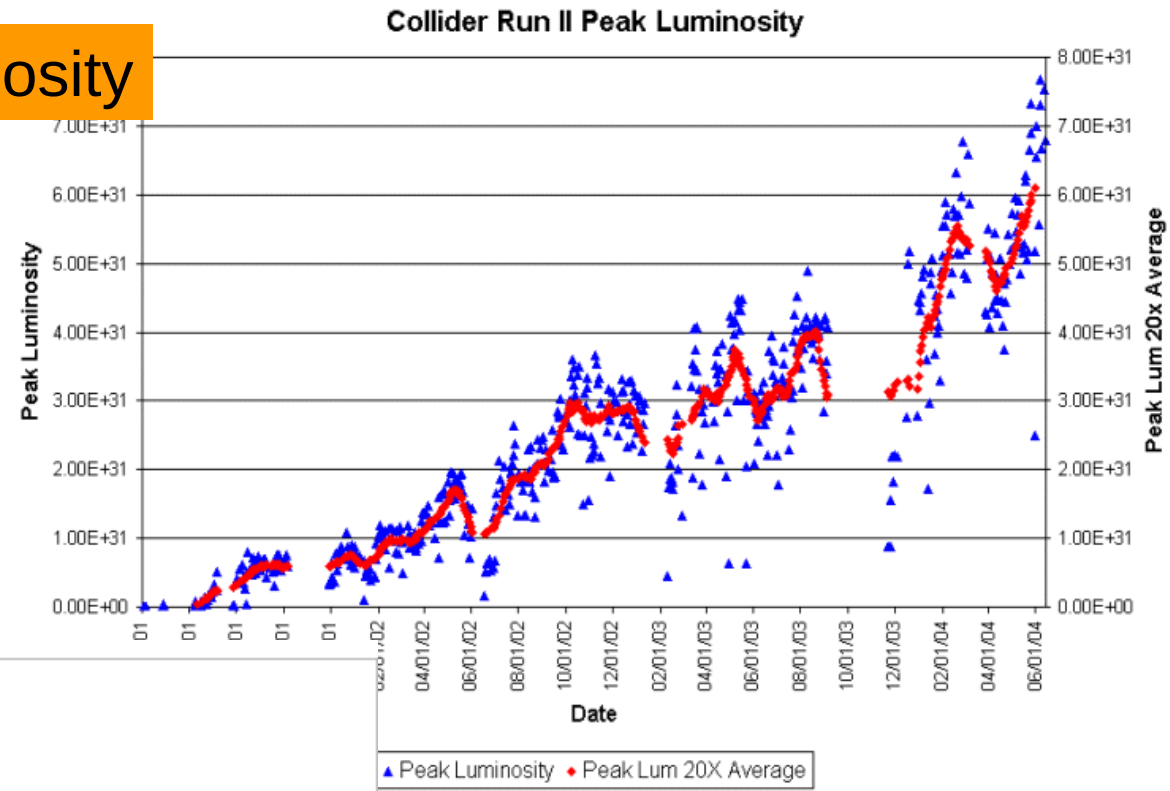
SUSY04
June 17 – 23, 2004
Epochal Tsukuba, Tsukuba, Japan

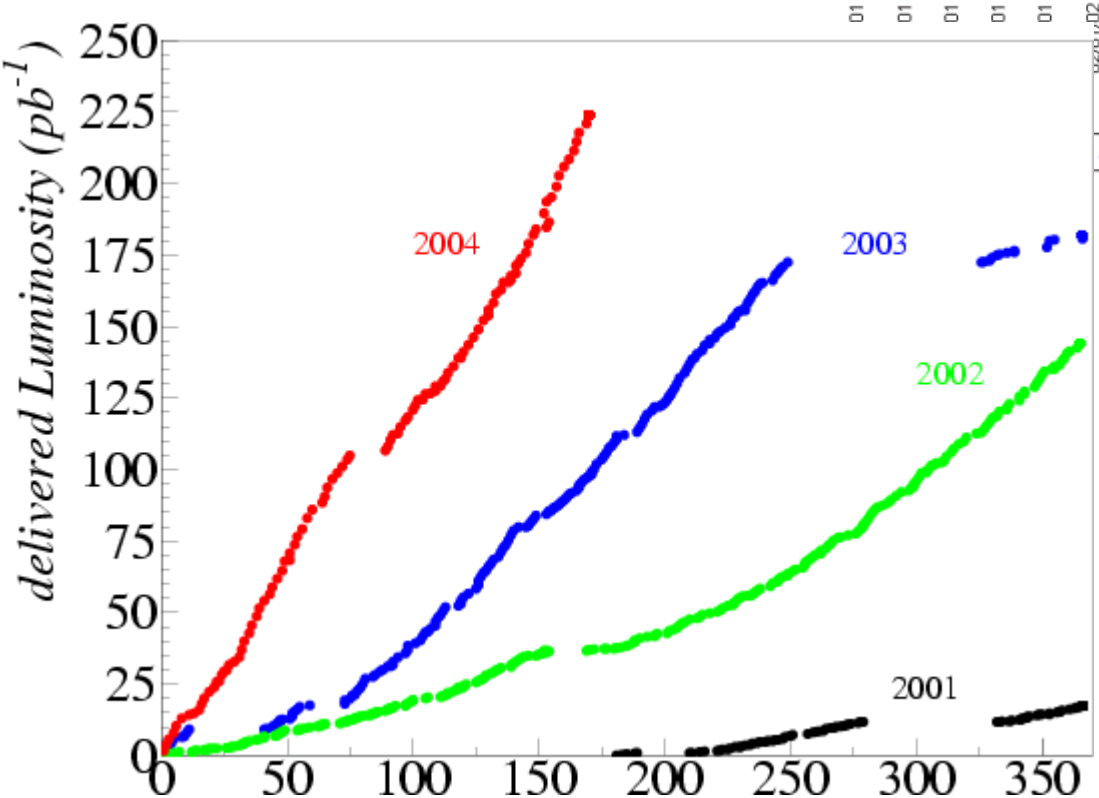
Tevatron Accelerator

- New 120/150 GeV Main Injector replaced Main Ring
  - Increased intensity of protons and antiprotons.
- Tevatron operates with 36 x 36 bunches
- Increased CM energy 1.8 TeV to 1.96 TeV

Run II started in March 2001

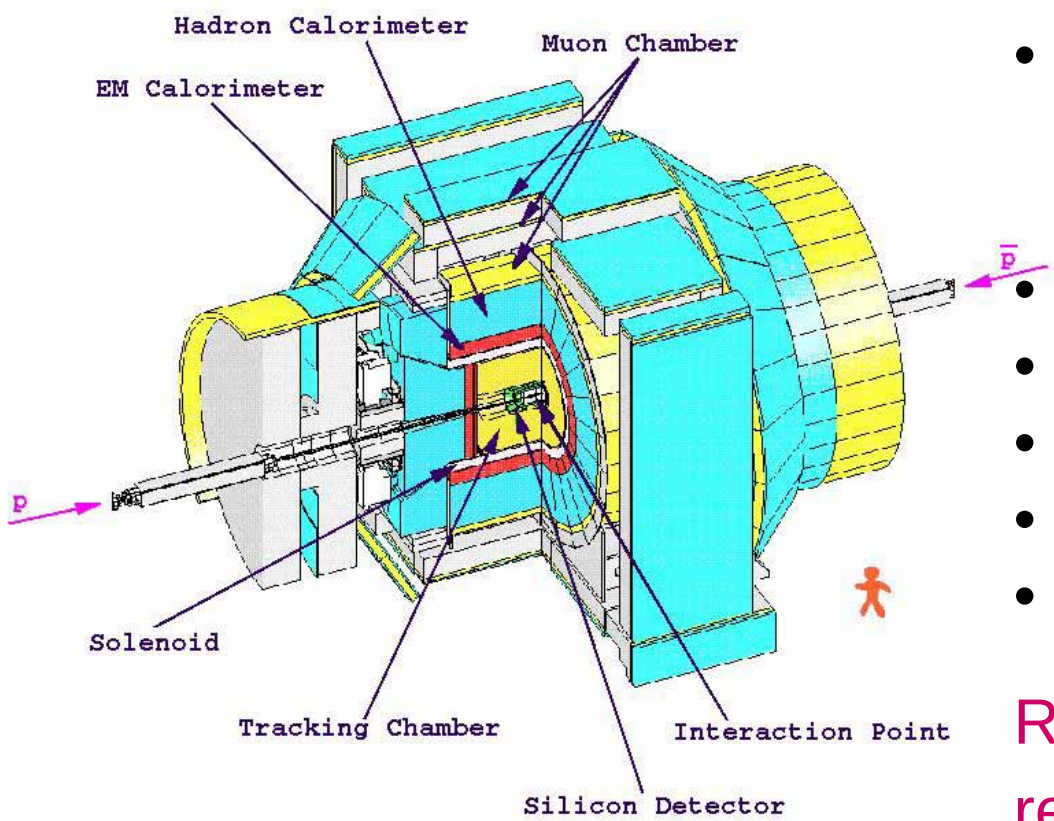
Tevatron Run-II Luminosity





- Peak luminosity
  8.3×10^{31} cm^{-2} s^{-1} (Jun 21)
- Delivered luminosity
  > 500 pb^{-1}
- Recorded luminosity
  > 400 pb^{-1}

Run-II CDF Detector

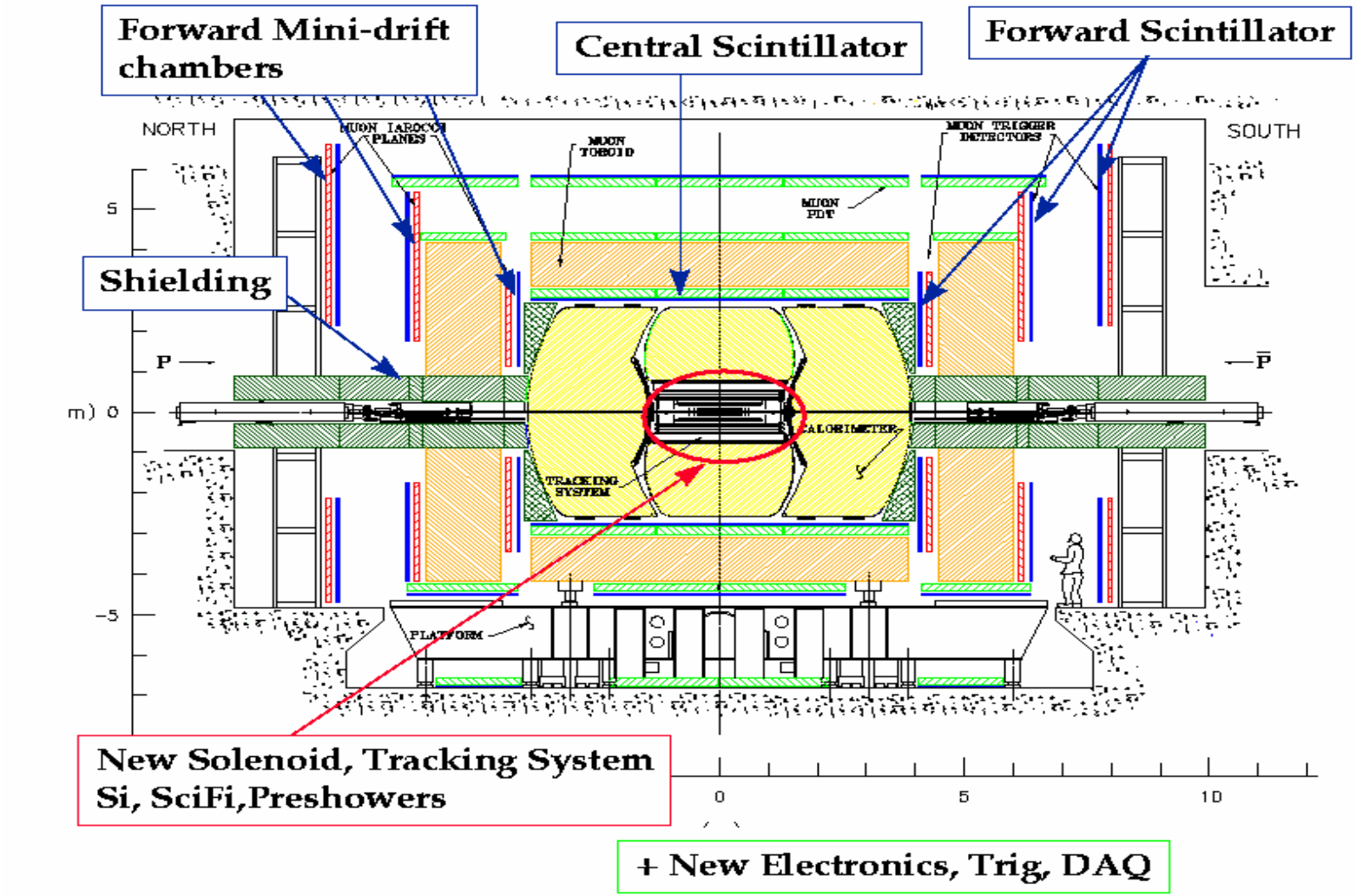


Many detector components are brand-new

- Tracking system
  - Silicon detectors
  - Main drift chamber
- FE electronics
- Trigger/DAQ
- Plug calorimeter
- Extended muon coverage
- TOF system

Retained good momentum resolution & lepton ID.

Run-II DØ Detector

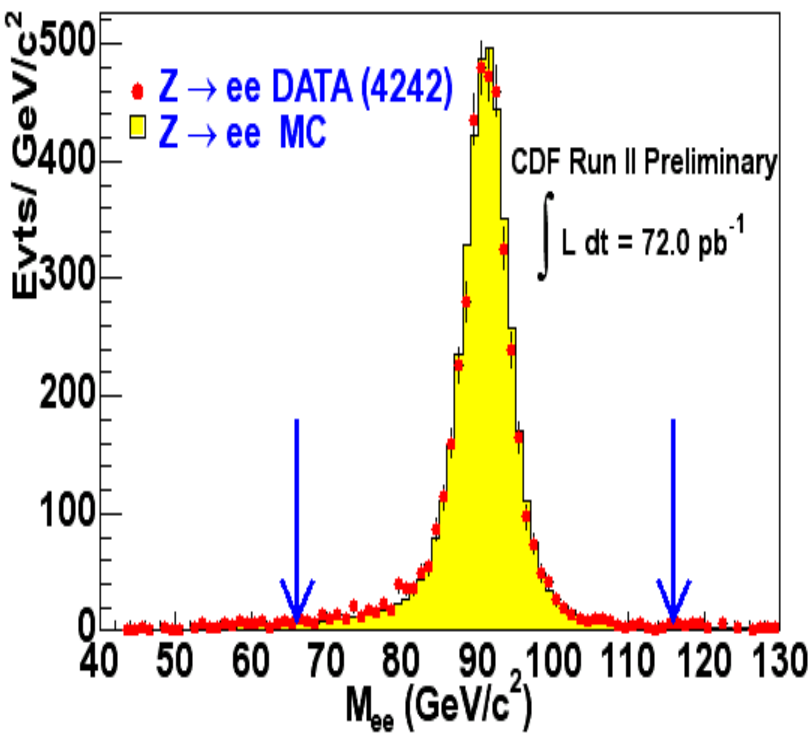


- Now with solenoid. New fiber tracker + silicon detectors.
- Excellent calorimetry, hermetic detector.
- Upgraded μ system for better μ-ID. New electronics, DAQ.

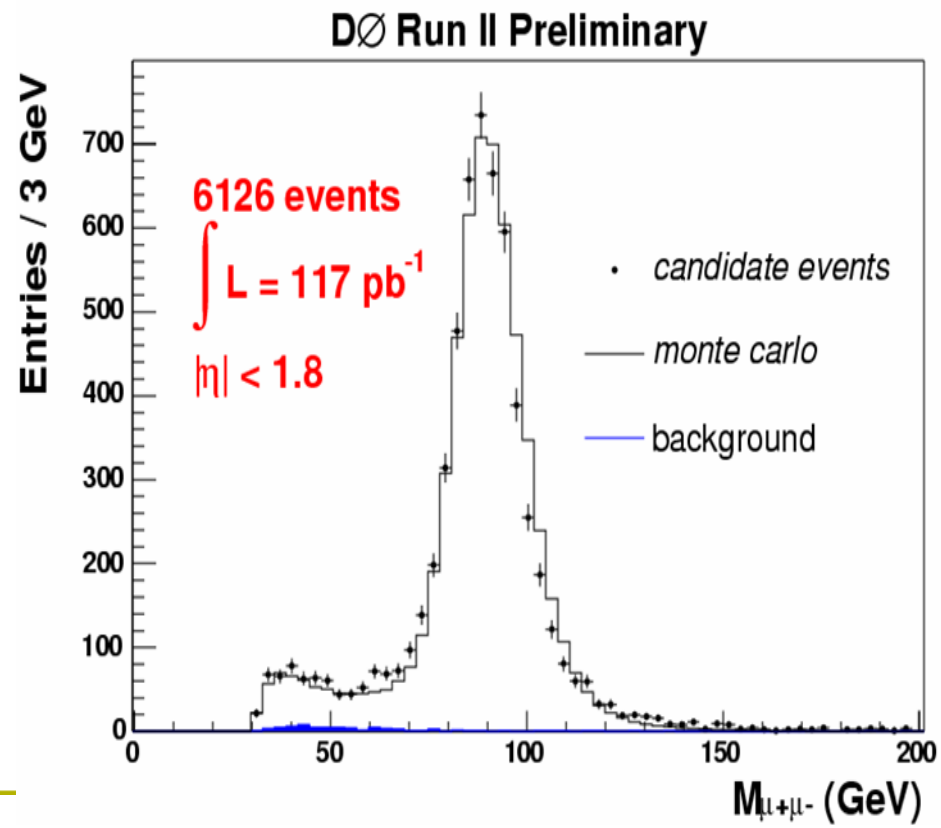
Electroweak Physics

$$Z^0 \to \ell^+\ell^-$$

CDF *ee*



DØ μμ, large acceptance



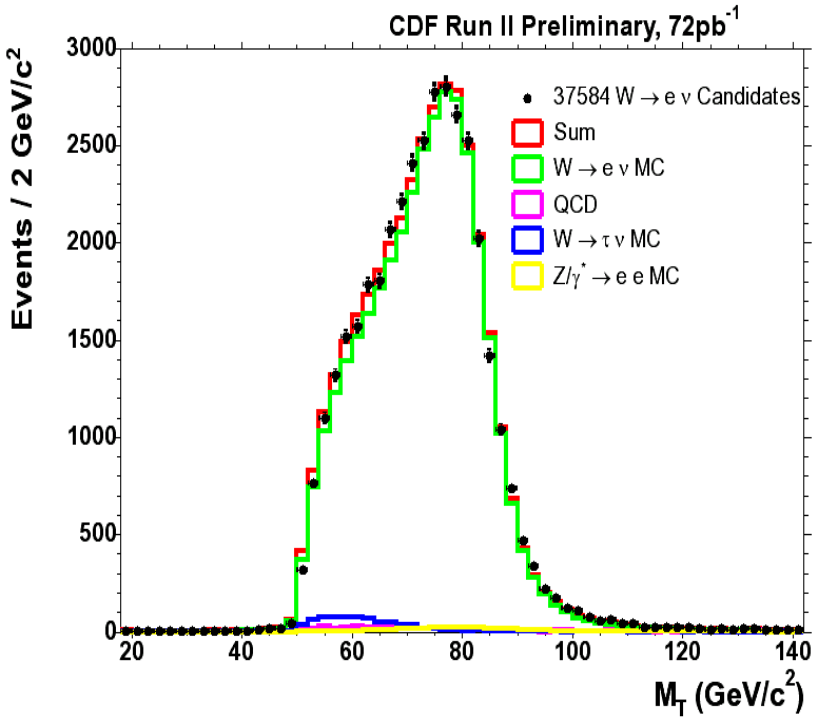
$$\sigma(\bar{p}p \to Z^0 \to \ell^+\ell^-) = 254.3 \pm 3.3 \pm 4.3 \pm 15.3 \text{ pb (CDF)}$$

$$261.8 \pm 5.0 \pm 8.9 \pm 26.2 \text{ pb (D0)}$$

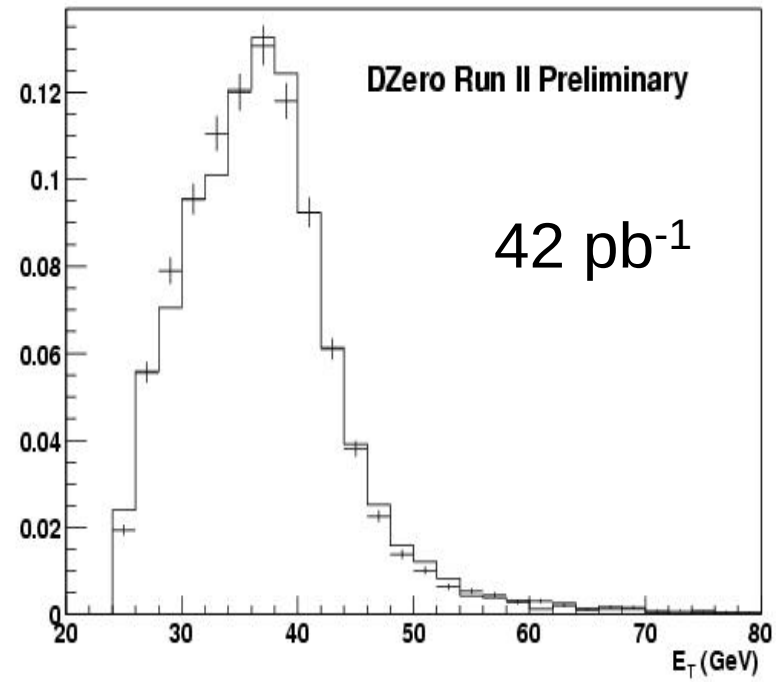
$$250.5 \pm 3.8 \text{ pb (NNLO, MRST)}$$

$W \to \ell\nu$

CDF e



DØ e



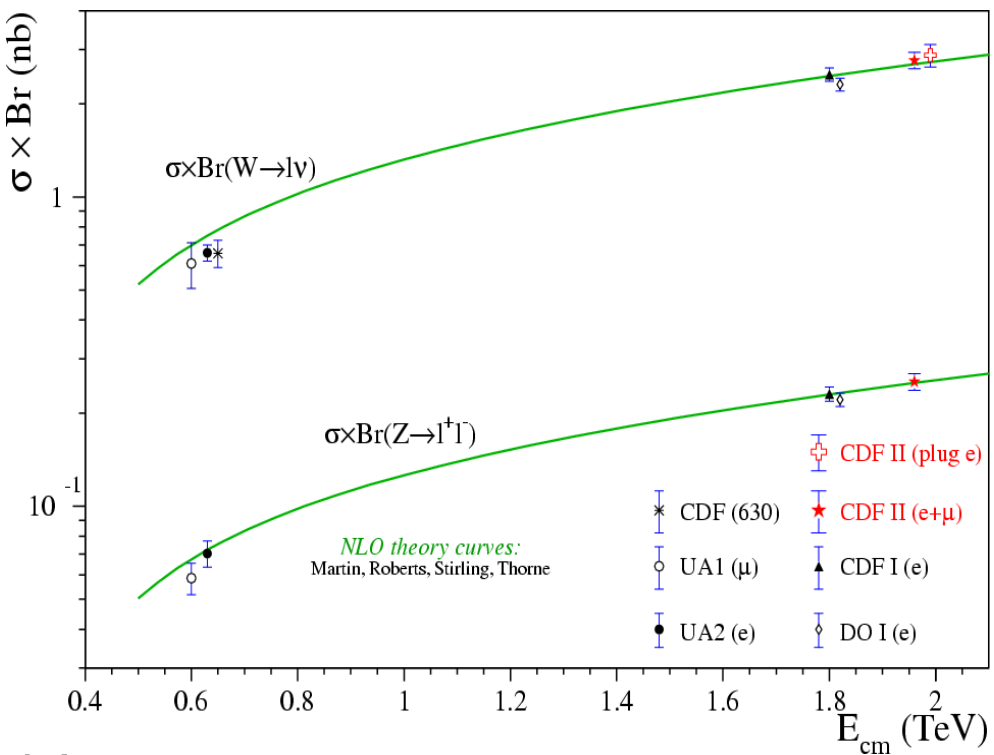
$$\sigma(\bar{p}p \to W \to \ell\nu) = 2777 \pm 10 \pm 52 \pm 167 \text{ pb (CDF)}$$

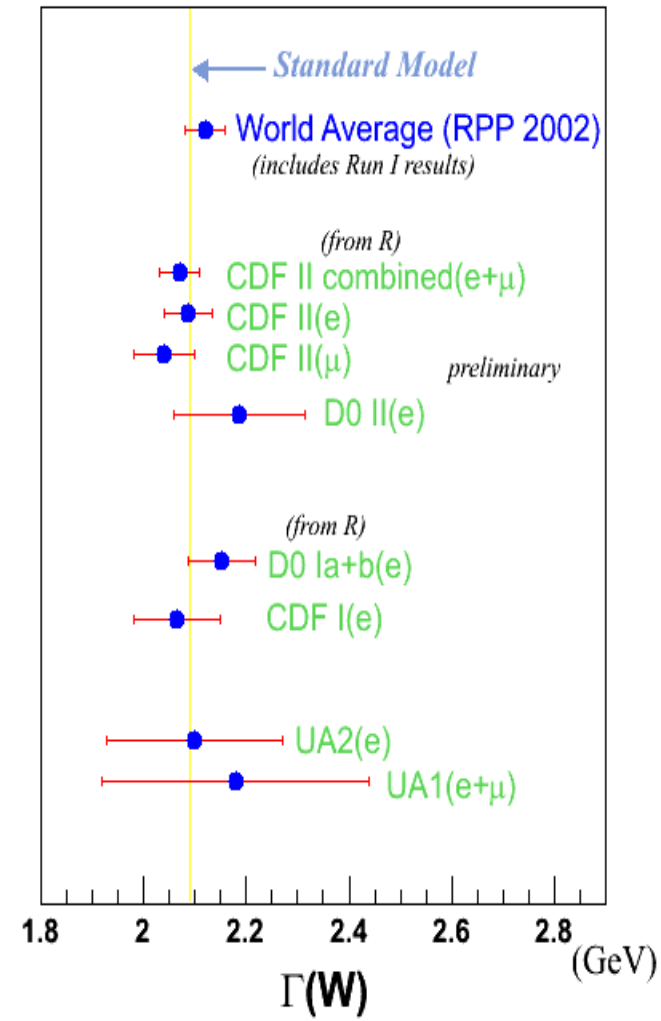
$$2844 \pm 21 \pm 128 \pm 167 \text{ pb (D0 } e\text{)}$$

$$3226 \pm 128 \pm 100 \pm 322 \text{ pb (D0 } \mu\text{)}$$

$$2687 \pm 40 \text{ pb (NNLO, MRST)}$$

$W^{\pm}$, Z^0 production cross sections and W width





Measure R :

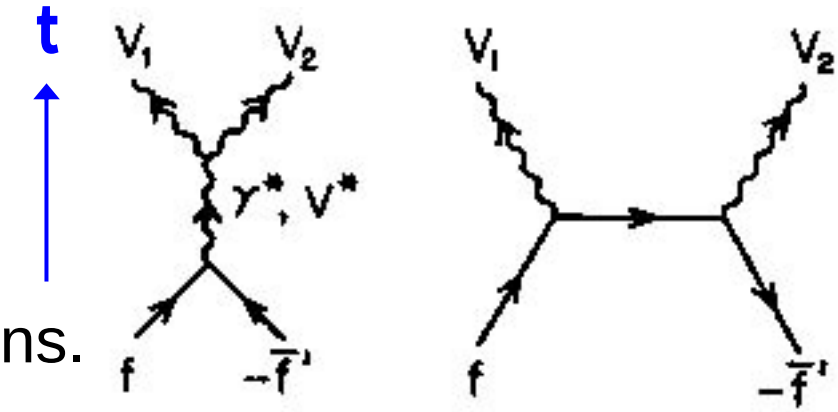
$$R \equiv \frac{\sigma(\bar{p}p \to W^{\pm}) \cdot \mathcal{B}(W^{\pm} \to \ell\nu)}{\sigma(\bar{p}p \to Z^0) \cdot \mathcal{B}(Z \to \ell^+\ell^-)}$$

extract $\mathcal{B}(W \to \ell\nu)$, or Γ_W.

$\Gamma_W = 2.071 \pm 0.040$ GeV (CDF), 2.187 ± 0.128 GeV (D0)

Direct width measurement will also be performed.

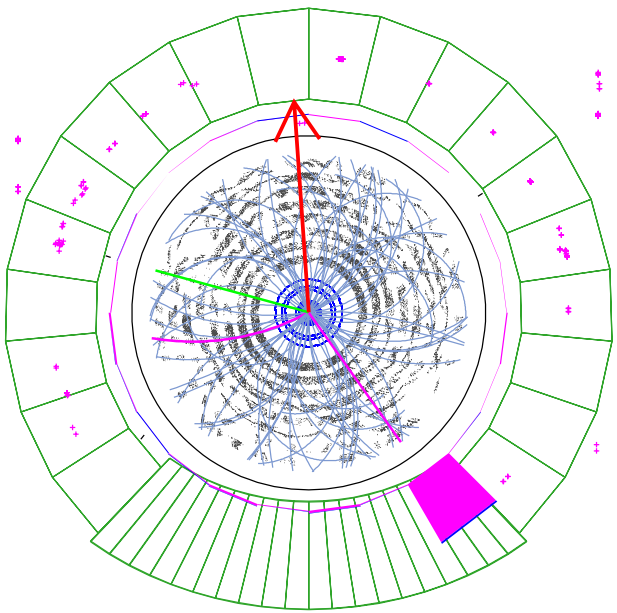
Gauge boson pair production



Unified electroweak theory :
Non-Abelian gauge structure.
$\rightarrow$ self-coupling among gauge bosons.

$$\bar{p}p \rightarrow W^+W^-X \rightarrow (\ell^+\nu)\,(\ell'^-\,\bar{\nu})X$$

2 enegetic leptons, large missing E_T, no jets.

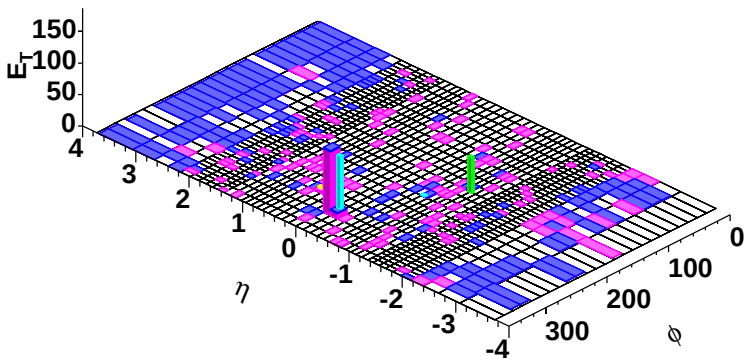


Run 162175 Event 1550545 : $WW \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu$ Candidate

$p_T(e) = 112.7$ GeV/c; $p_T(\mu) = 57.0$ GeV/c; $M_{e\mu} = 165.6$ GeV

$\not{E}_T = 86.8$ GeV; $\Phi(\not{E}_T) = 1.6$

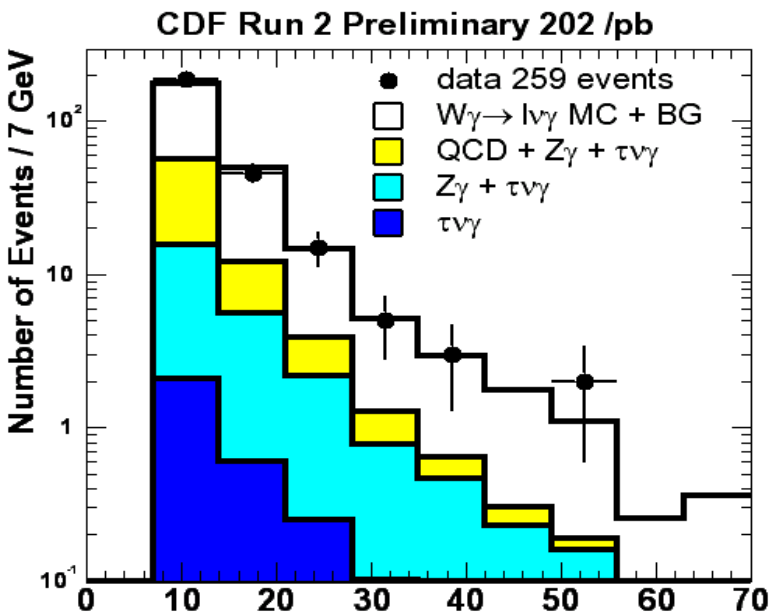
$\Delta\Phi(\not{E}_T, \text{lepton}) = 1.2$; $\Delta\Phi(e,\mu) = 2.4$; Opening-Angle(e^+, e^-)=1.9

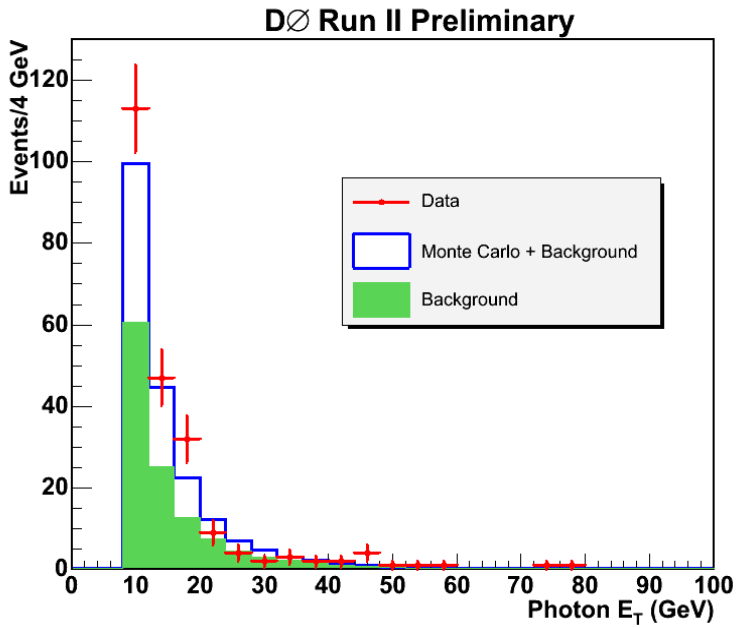


CDF : $\sigma(\bar{p}p \rightarrow W^+W^-) = 14.3\,^{+5.6}_{-4.9} \pm 1.6 \pm 0.9$ pb
(12.5 ± 0.9 pb theory)

W + Photon Production

Photons detected > 7 GeV CDF, > 8 GeV DØ.
Check 3-body mass (l ν γ) for brems.





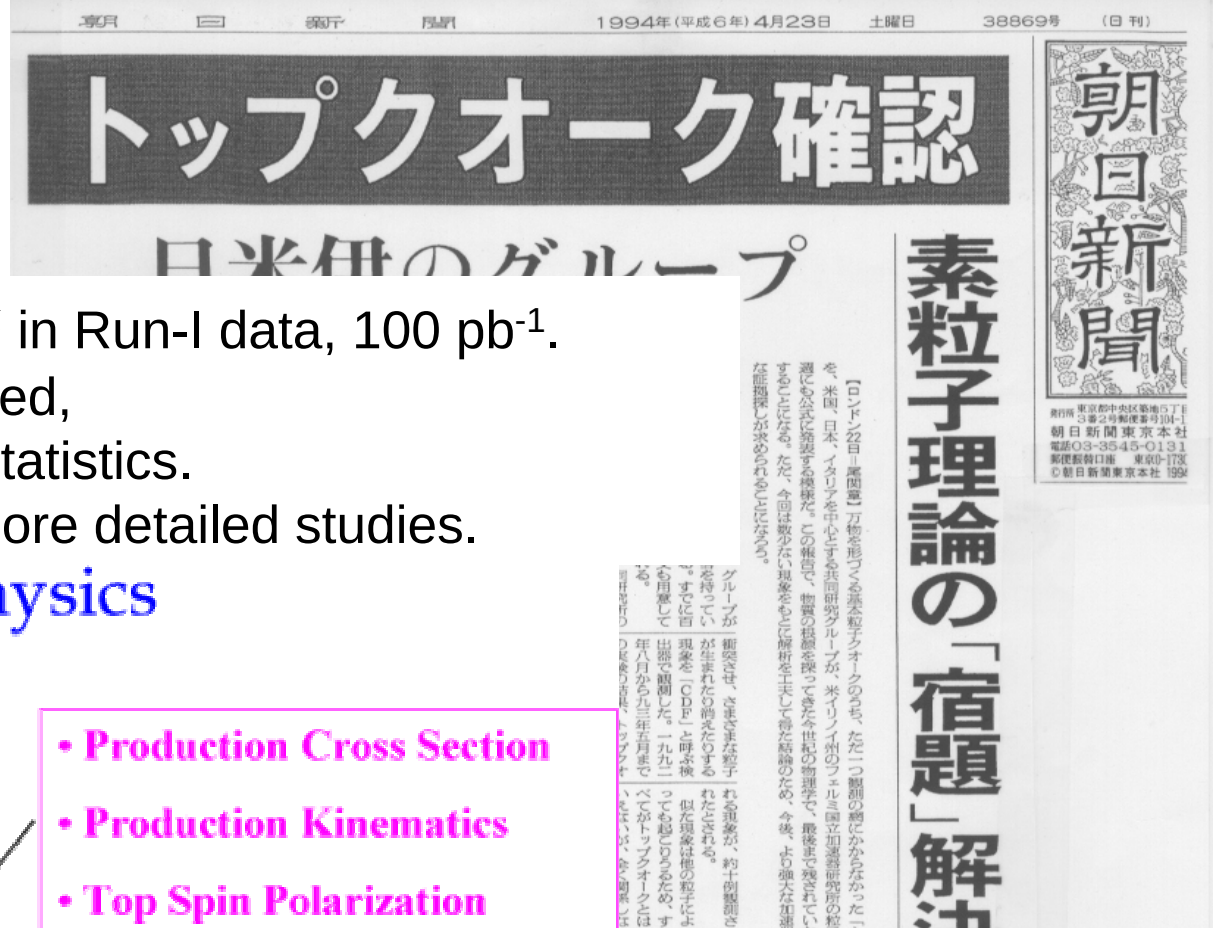
$$\sigma(\bar{p}p \to W\gamma) \cdot \mathcal{B}(W \to \ell\nu)$$

$$= 19.7 \pm 1.7 \pm 2.0 \pm 1.1 \text{ pb} \quad \text{(CDF)} \quad \text{vs. } 19.3 \pm 1.4 \text{ pb}$$

$$= 19.3 \pm 2.7 \pm 6.1 \pm 1.2 \text{ pb} \quad \text{(D0)} \quad \text{vs. } 16.4 \pm 0.4 \text{ pb}$$

More direct test : angular distributions → radiation amplitude zero

Top Quark


朝日新聞 1994年(平成6年)4月23日 土曜日 38869号 (日刊)

トップクオーク確認

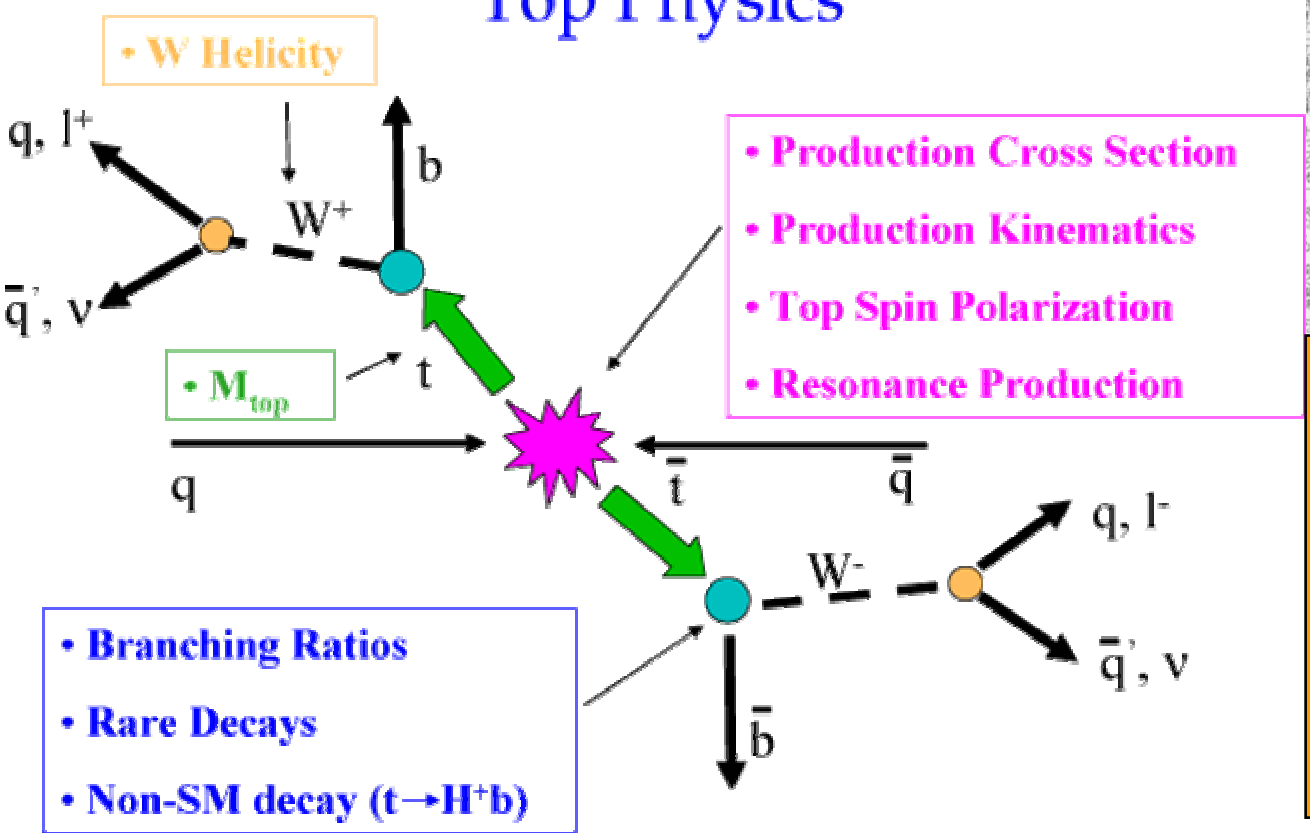
日米仏のグループ

素粒子理論の「宿題」解決

朝日新聞

- Observed by CDF and DØ in Run-I data, 100 pb^{-1}.
- Tens of events reconstructed, measurements limited by statistics.
- Run-II data should allow more detailed studies.

Top Physics



Signature :
- Two W and two b
- W to lepton + ν or, W to quarks.
- b-jets tagged with lifetime or lepton.

Top quark production cross section

Di-lepton channel

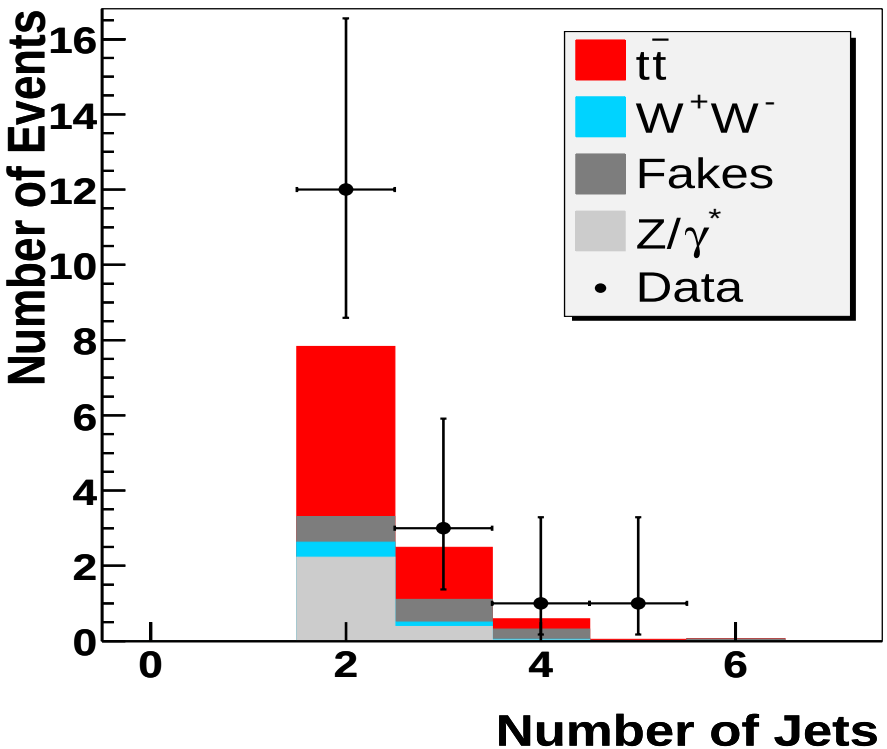
$\bar{p}p \to t\bar{t}X$, $W^+ \to \ell^+\nu$, $W^- \to \ell^-\bar{\nu}$,

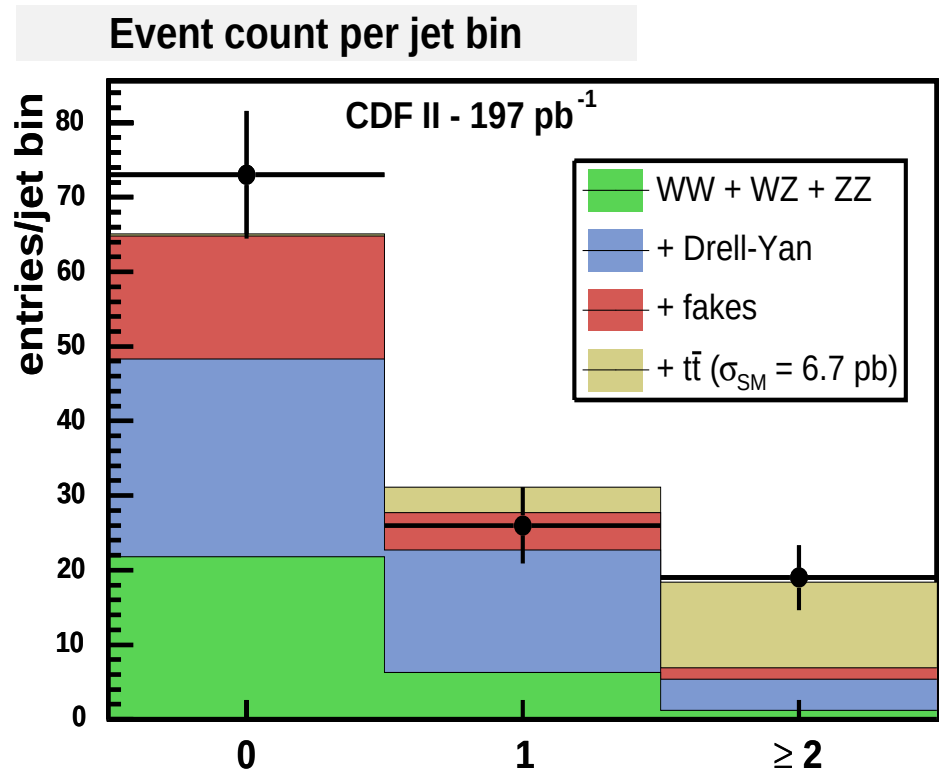
2 additional jets from b quarks.

DØ ~150 pb^{-1}

Jet multiplicity distributions

CDF 197 pb^{-1}



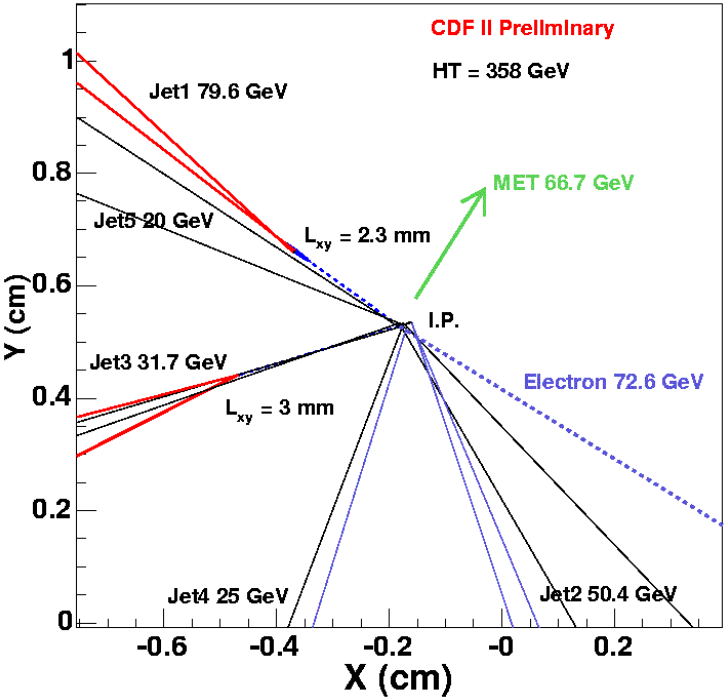


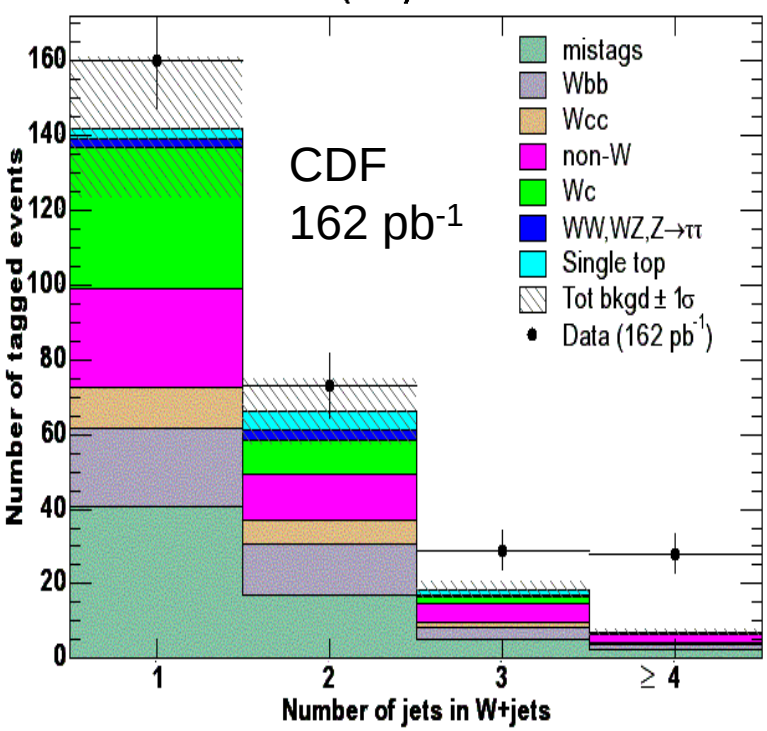
$$\sigma(\bar{p}p \to t\bar{t}X) = 14.3\,^{+5.1}_{-4.3}\,^{+2.6}_{-1.9} \pm 0.9 \text{ pb}, \quad 7.0\,^{+2.7}_{-2.3}\,^{+1.5}_{-1.3} \pm 0.4 \text{ pb}.$$

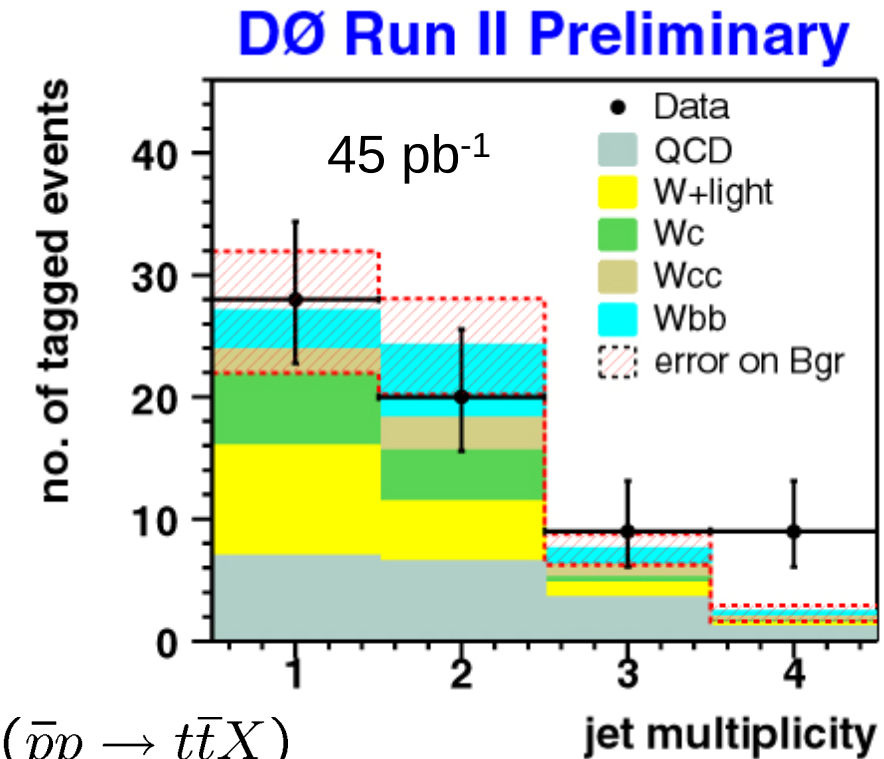
Top cross section

$\bar{p}p \to t\bar{t}X,\ W \to \ell\nu,\ W \to q\bar{q}',$

b-jets tagged with secondary vertices.







$$\sigma(\bar{p}p \to t\bar{t}X)$$

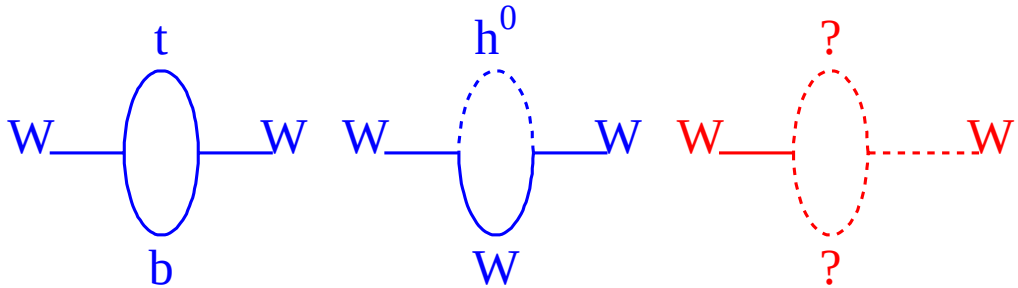
$$= 10.8\,^{+4.9}_{-4.0}\,^{+2.1}_{-2.0} \pm 1.1 \text{ pb} \quad \text{(D0)}$$

$$= 5.6\,^{+1.2}_{-1.0}\,^{+1.0}_{-0.7} \text{ pb} \quad \text{(CDF)}$$

Many other measurements with various techniques.

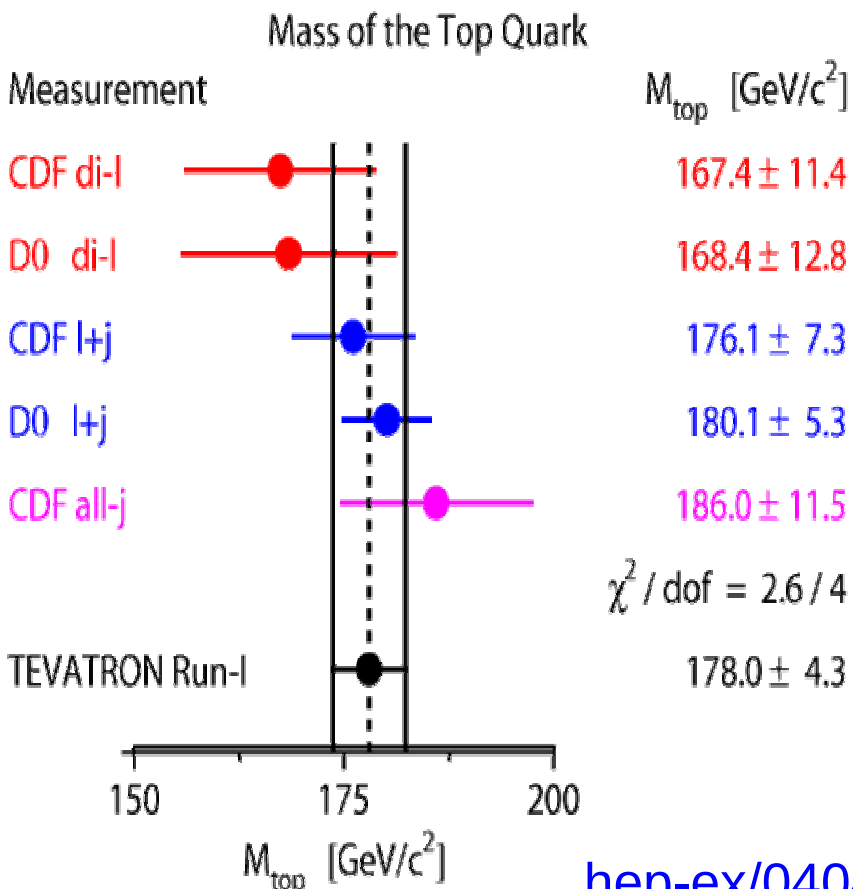
Top Quark Mass

Combine with W mass, probe Higgs indirectly.

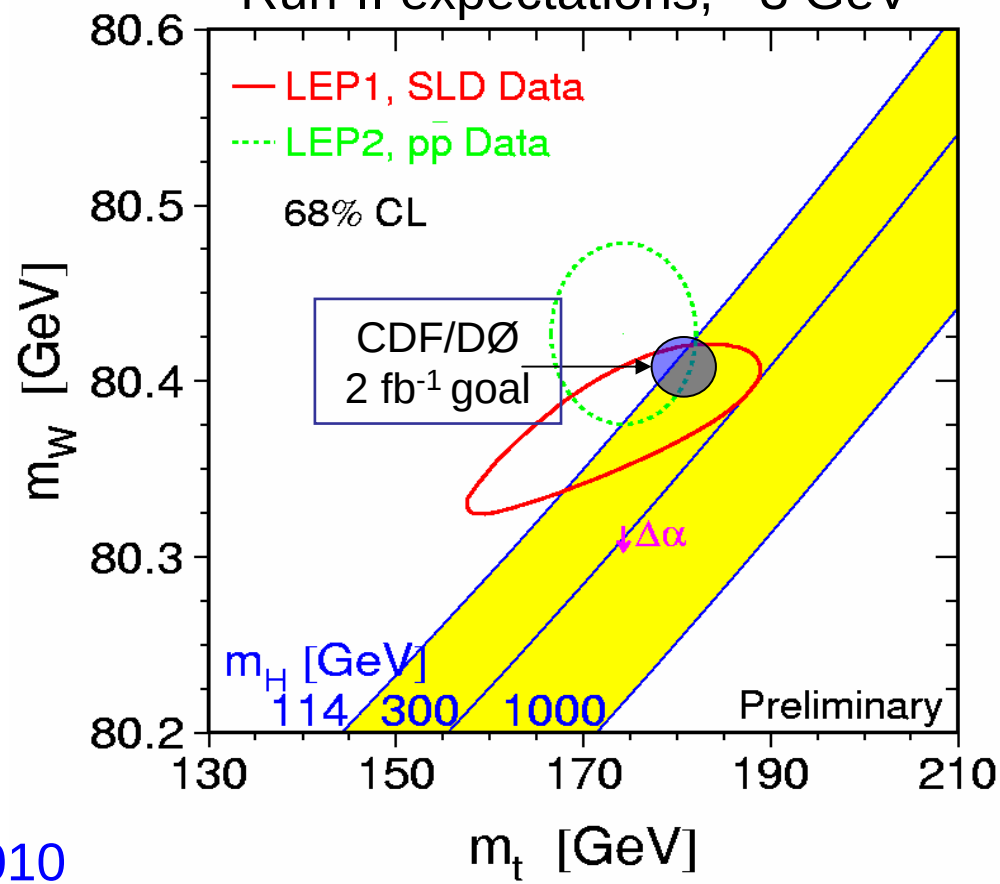


$\Delta M_W \propto M_T^2$ $\Delta M_W \propto \ln M_H$ New Physics

World average : Run I only



Run-II expectations, ~3 GeV

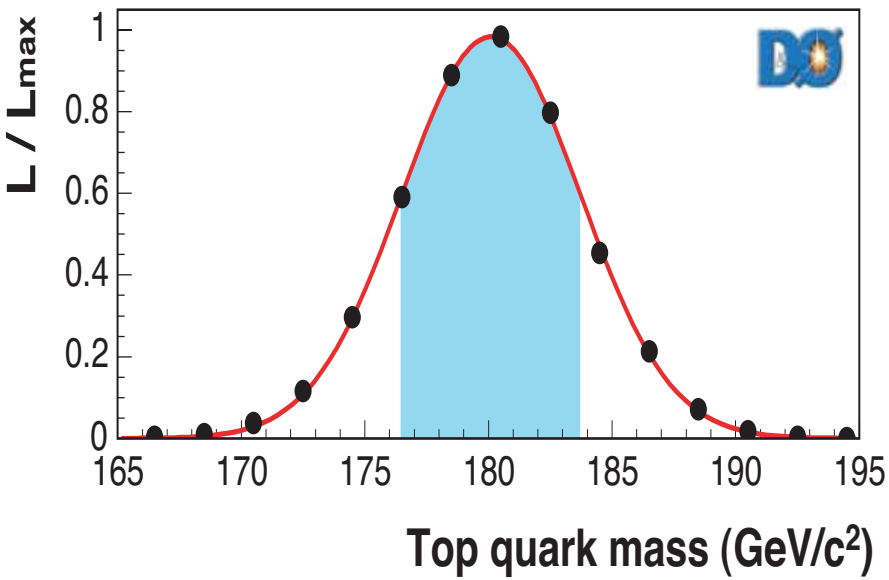


hep-ex/0404010

Top mass measurement examples

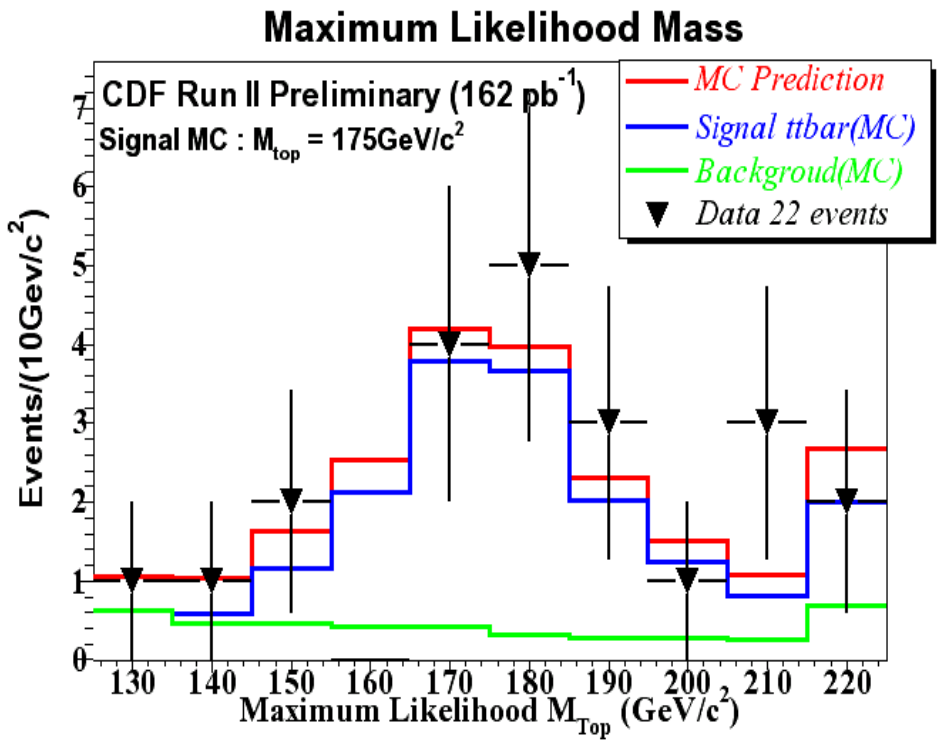
CDF Run II, lep+jet channel,
Dynamical likelihood method
(K. Kondo, J.Phys.Soc.Jap. 57, 4126,1988)

DØ re-analysis of Run I data, a new method using matrix elements, parton distributions.



$$m_t = 180.1 \pm 3.6 \pm 4.0 \ \mathrm{GeV}/c^2$$

Nature 429, 683 (2004)



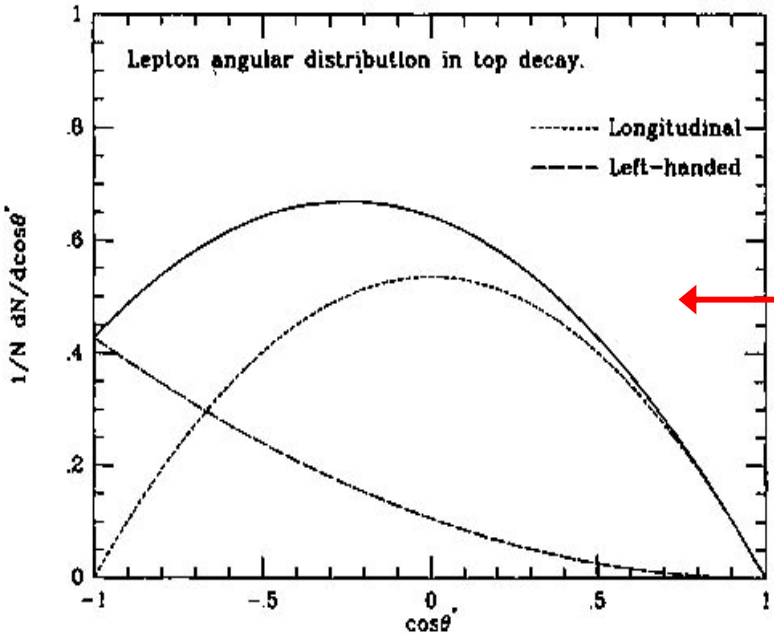
$$m_t = 177.8^{+4.5}_{-5.0} \pm 6.2 \ \mathrm{GeV}/c^2$$

CDF has 3 more Run-II measurements (not in world average yet) ;
D0 Run-II analyses also under way.

Uncertainties expected to decrease as we understand jet energy scale better.

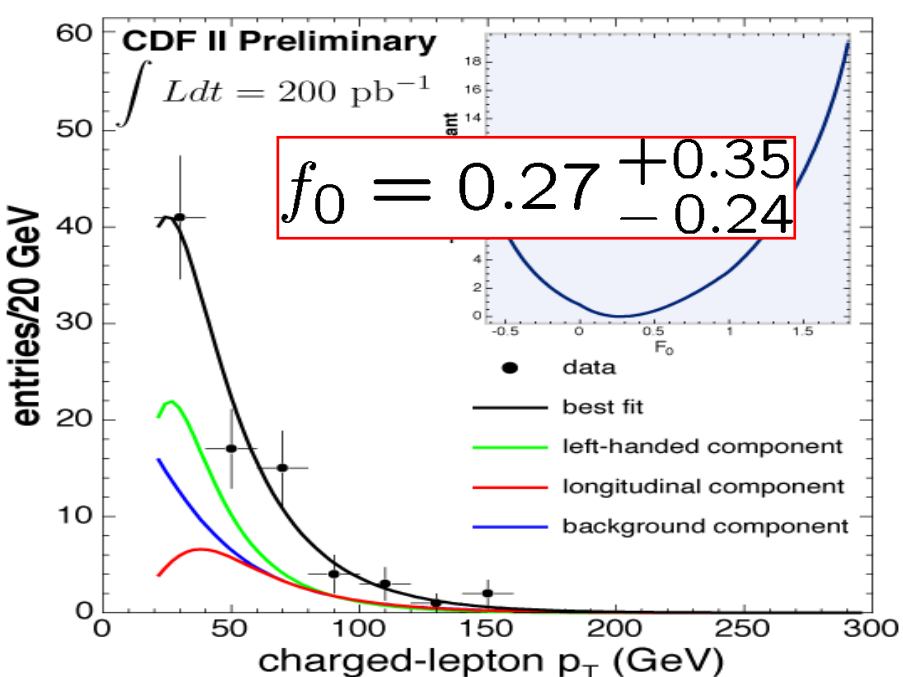
W helicity in top decays

either left-handed (W_L) or longitudinally polarized (W_0)

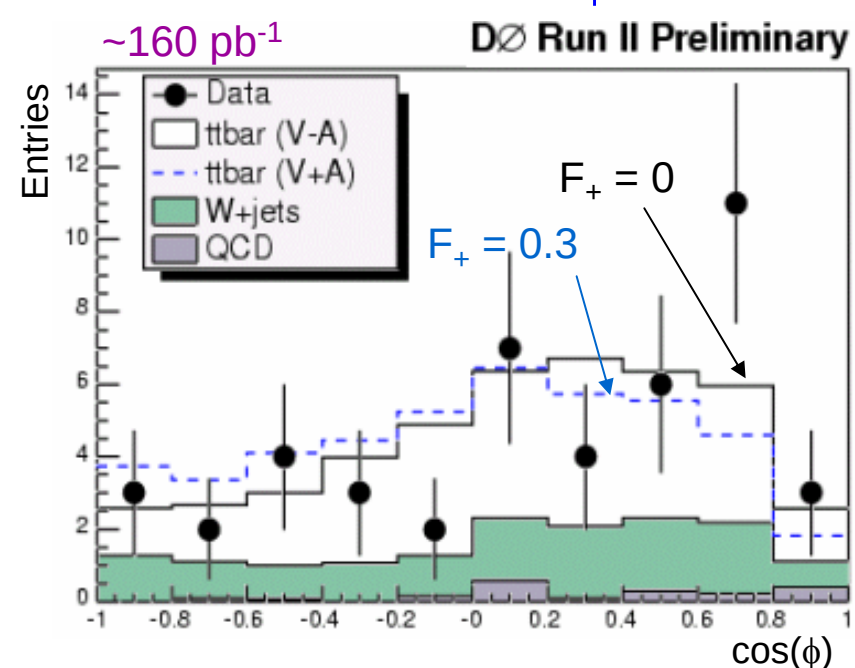


$$f_0 \equiv \frac{\Gamma(t \to b W_0)}{\Gamma(t \to b W_0) + \Gamma(t \to b W_L)} = \frac{m_t^2}{m_t^2 + 2 m_W^2}$$
$$= 0.70 \quad \text{for} \quad m_t = 175 \ \text{GeV}/c^2$$

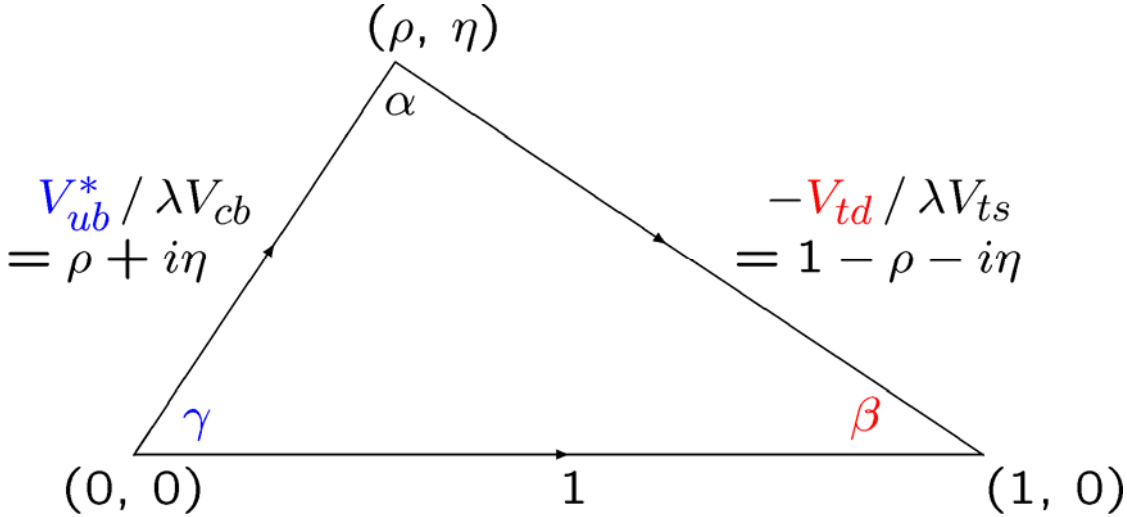
Lepton angular distribution in W rest frame :
Backward peak for left-handed W.
→ smaller momentum in lab.



DØ reconstructs cosϕ = -cosθ*



B physics : does the unitarity triangle close?



- $|V_{cb}|$ from $b \to c\ell\nu$, $|V_{ub}|$ from $b \to u\ell\nu$.
- $|V_{td}|$ from Δm_d, better if we use ratio

$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{m_{B_s}}{m_{B_d}}\,\xi^2 \qquad (\xi = 1.14 \pm 0.03\,^{+0.13}_{-0.02})$$

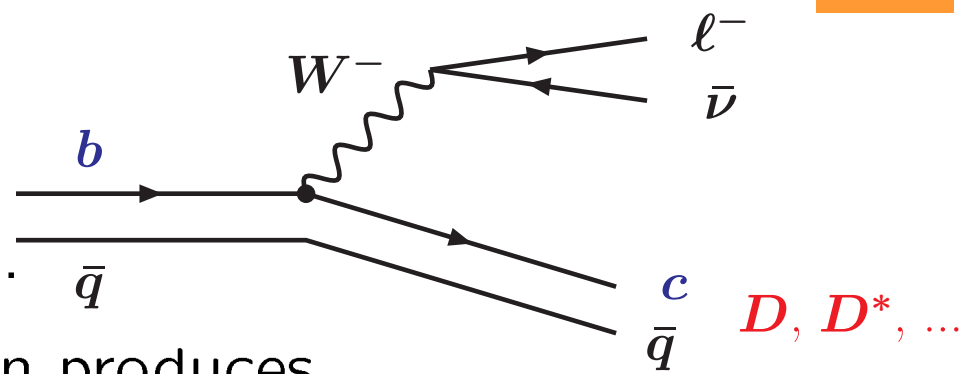
- $\sin 2\beta$ from $B^0/\bar{B}^0 \to J/\psi K_S^0$. Now precisely known.
- α from $B^0/\bar{B}^0 \to \pi^+\pi^-$, etc.
- γ from $B \to DK$, etc.

$B^-/\bar{B}^0$ lifetime ratio

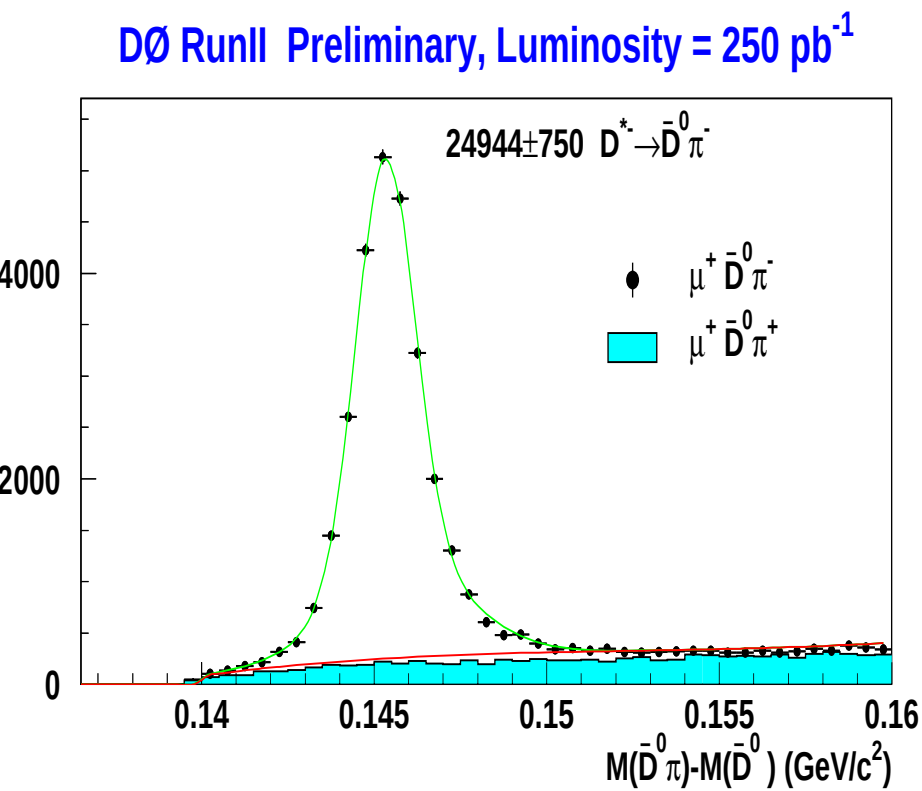
Tests heavy quark expansion

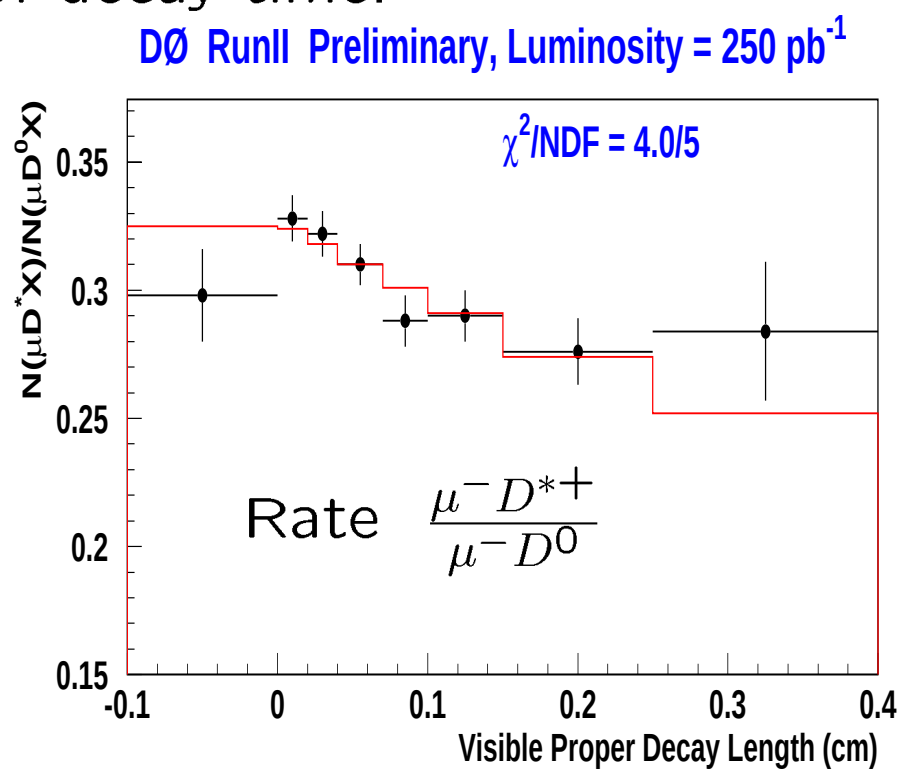
DØ

If only D and D^* are produced,
$\ell^-\bar{\nu}D^{*+}$ from $\bar{B}^0$,
$\ell^-\bar{\nu}D^0$ from B^- (D^{*+} vetoed).



Non-equal lifetime $\tau^- \neq \tau^0$ then produces a rate difference as a function of decay time.



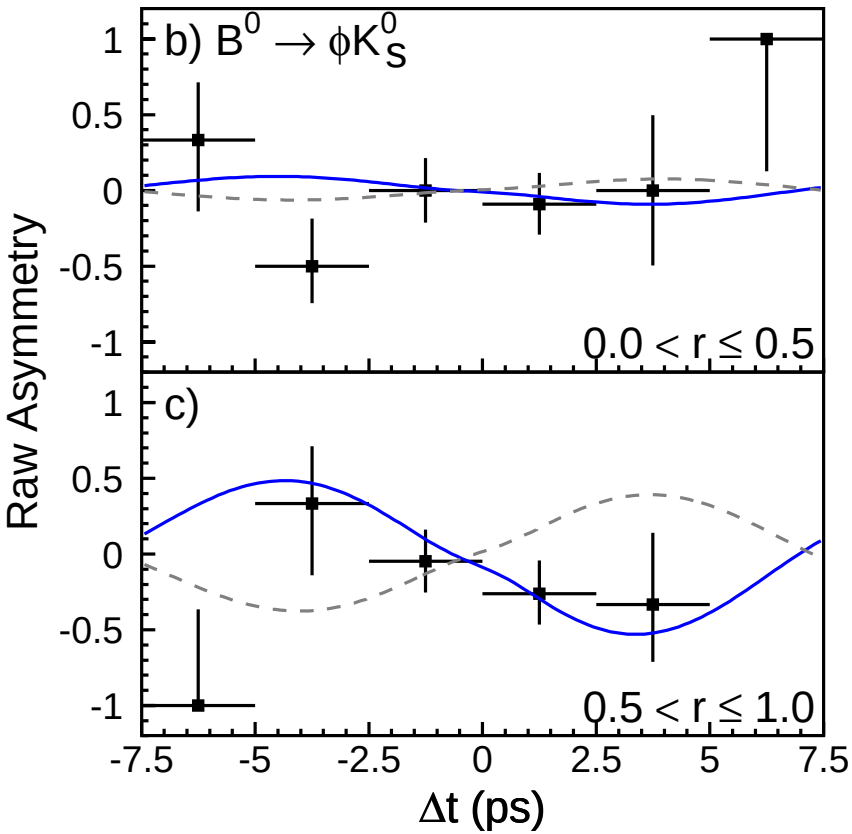


$$\tau^-/\tau^0 = 1.093 \pm 0.021 \pm 0.022$$

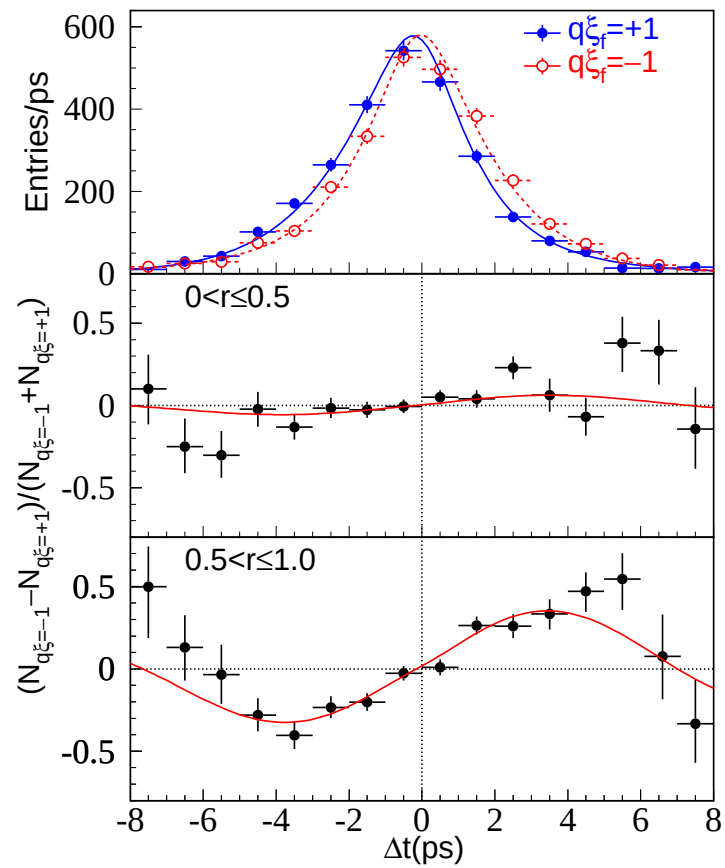
New physics in b → s transition ?

Belle : PRL 91, 261602 (2003)

$B^0/\bar{B}^0 \to \phi K_S^0 \ (b \to s\bar{s}s)$



$B^0/\bar{B}^0 \to J/\psi K_S^0 \ (b \to c\bar{c}s)$



$\sin 2\beta = -0.99 \pm 0.50,$ vs. $+0.731 \pm 0.056.$

3.5 σ away!

CDF/DØ can provide unique tests of b → s (SUSY?)

- Measure Δm_s of $B_s^0 \bar{B}_s^0$ oscillations.
  If $\gg 18$ ps^{-1}, a new particle in the loop.

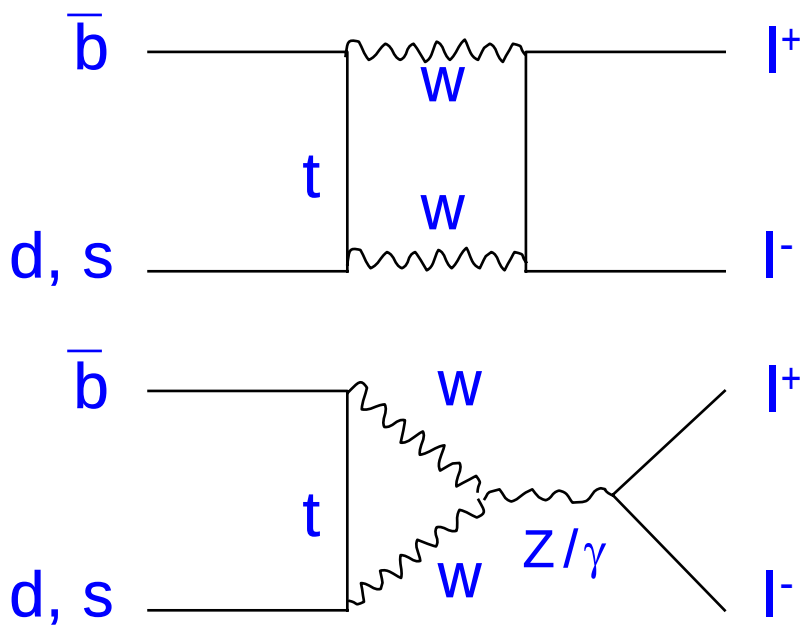
- Look for CP violation in $B_s^0 \to J/\psi\,\phi$.
  This is phase of V_{ts} in SM, so expect ~ 0.

- Measure CP asymmetries in $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$.
  Latter dominated by $b \to s$ penguin.

- Look for rare decays $B_s^0 \to \mu^+\mu^-$.
  Extremely suppressed in SM, $\mathcal{B} \sim 10^{-9}$ predicted.

Rare decays $B_d^0/B_s^0 \to \mu^+\mu^-$

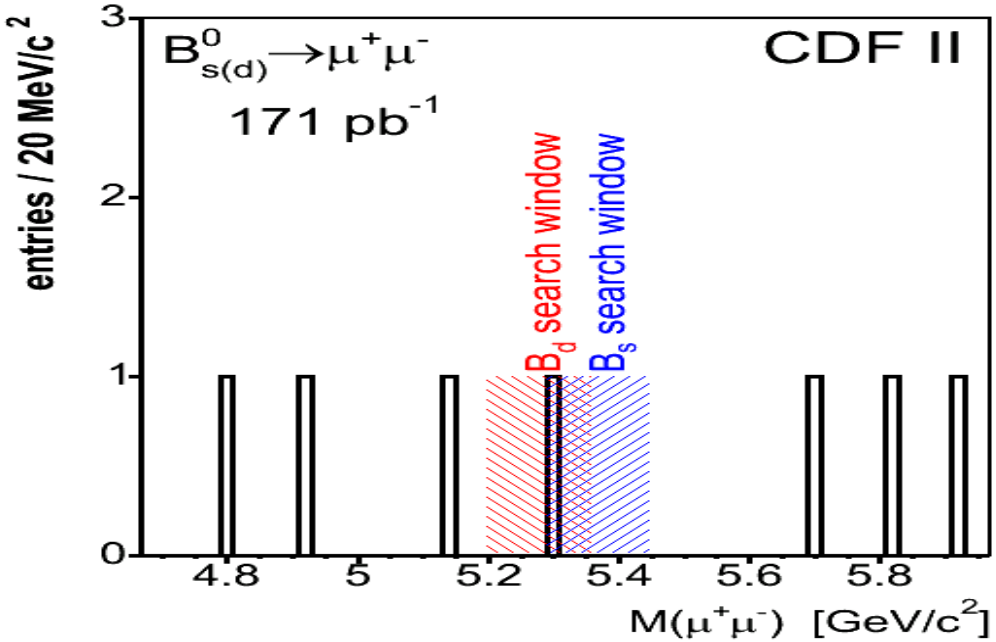
- V_{td} for B^0_d, V_{ts} for B^0_s
- FCNC
- Helicity suppressed.
- B.F. very small.

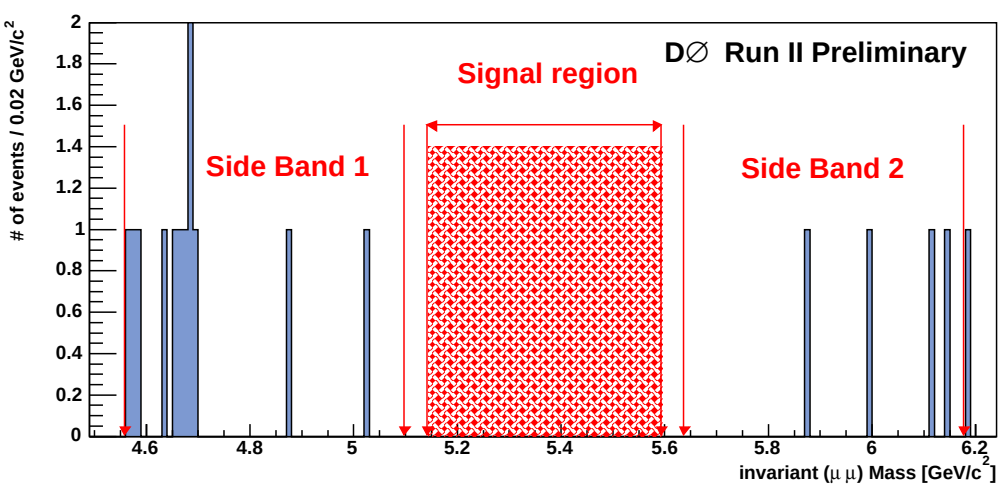


SM predictions for B.F.

- $B^0 \to \mu^+\mu^-$ $(1.00 \pm 0.14) \times 10^{-10}$
- $B_s^0 \to \mu^+\mu^-$ $(3.4 \pm 0.5) \times 10^{-9}$
- Five orders smaller for e^+e^- modes.

Search for $B_d^0/B_s^0 \to \mu^+\mu^-$





One candidate in the overlap region of B^0_d and B^0_s mass windows.

B.R. < 1.9 x 10^{-7} for B^0_d

B.R. < 7.5 x 10^{-7} for B^0_s

@ 95% C.L.

Accepted by PRL.

Previous CDF limits :

B.R. < 8.6 x 10^{-7} for B^0_d

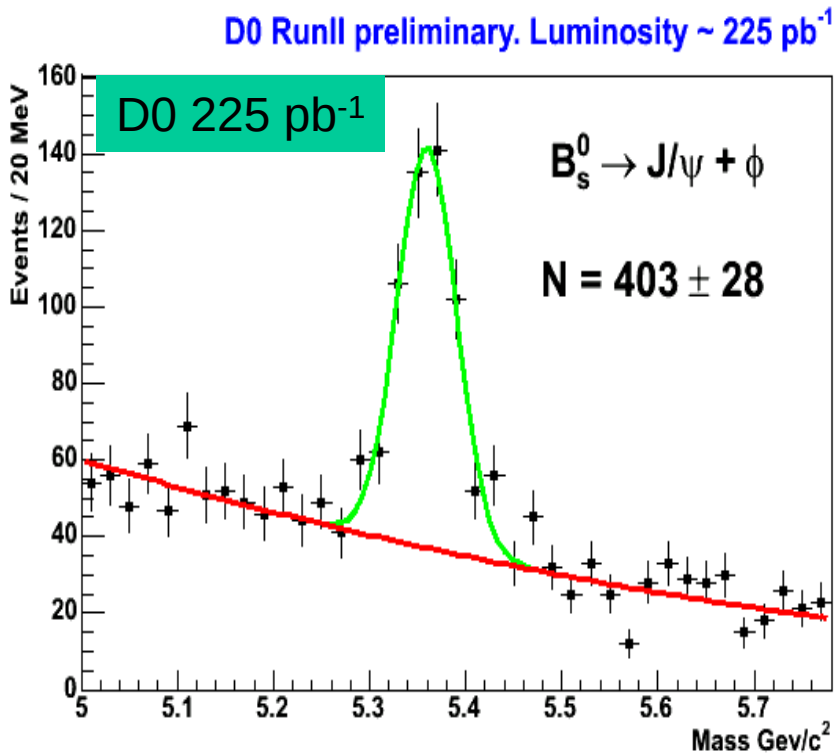
B.R. < 2.6 x 10^{-6} for B^0_s

PRD 57, 3811 (1998)

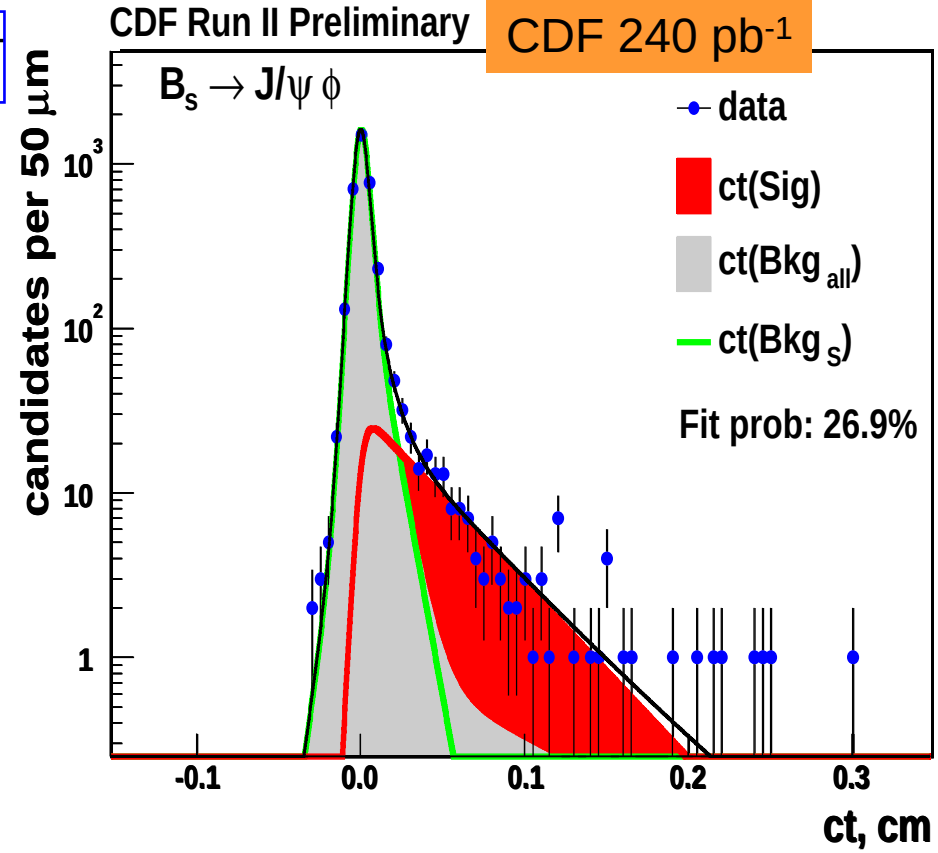
D0 sensitivity is $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \sim 10.1 \times 10^{-7}$ (95% CL), 180 pb^{-1}.

Analysis being re-optimized, better sensitivity expected.

$B_s^0 \to J/\psi\,\phi \to \mu^+\mu^- K^+ K^-$



$\tau(B_s^0) = 1.19^{+0.19}_{-0.16} \pm 0.14$ ps (115 pb^{-1})



$m(B_s^0) = 5366.01 \pm 0.73 \pm 0.33$ MeV/c^2

$\tau(B_s^0) = 1.369 \pm 0.100 \pm 0.010$ ps

Predict $\tau(B_s^0)/\tau(B^0) = 1.0 \pm \mathcal{O}(1\%)$

But expect $\Delta\Gamma_s/\Gamma_s \sim 0.1$.

Mode dominated by CP even

($\Gamma_\perp/\Gamma = 0.232 \pm 0.100 \pm 0.013$, CDF).

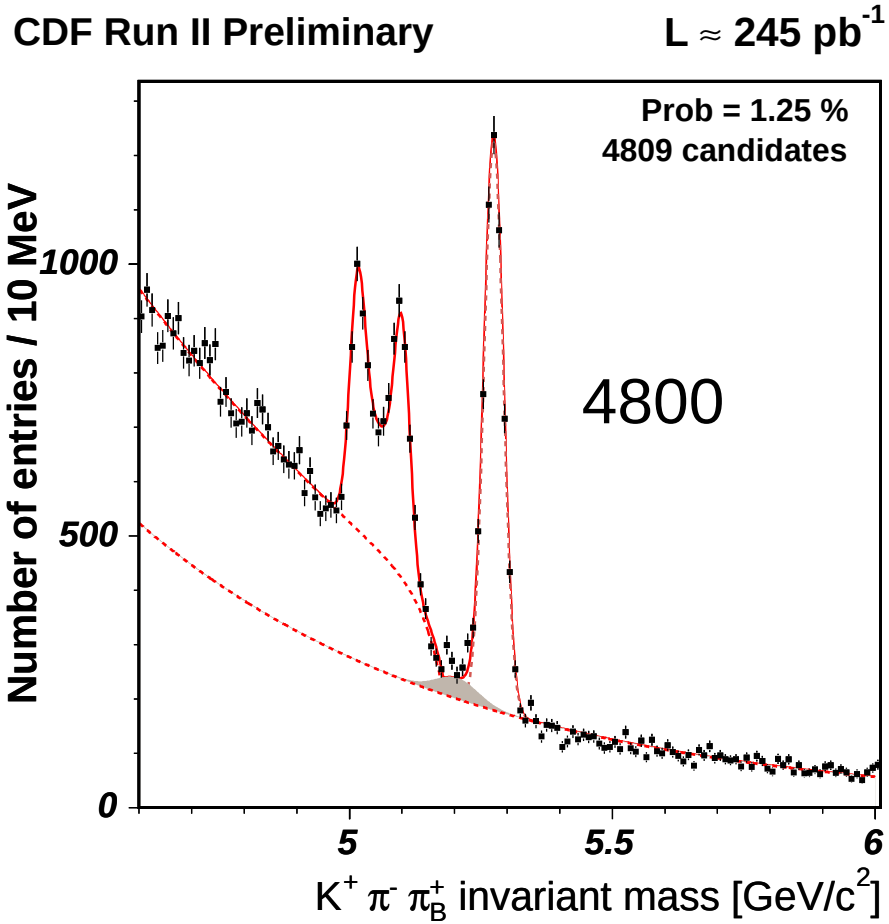
Can exhibit a different τ than in flavor eigenstates.

$\Delta\Gamma_s \neq 0$ may allow CP studies with untagged events.

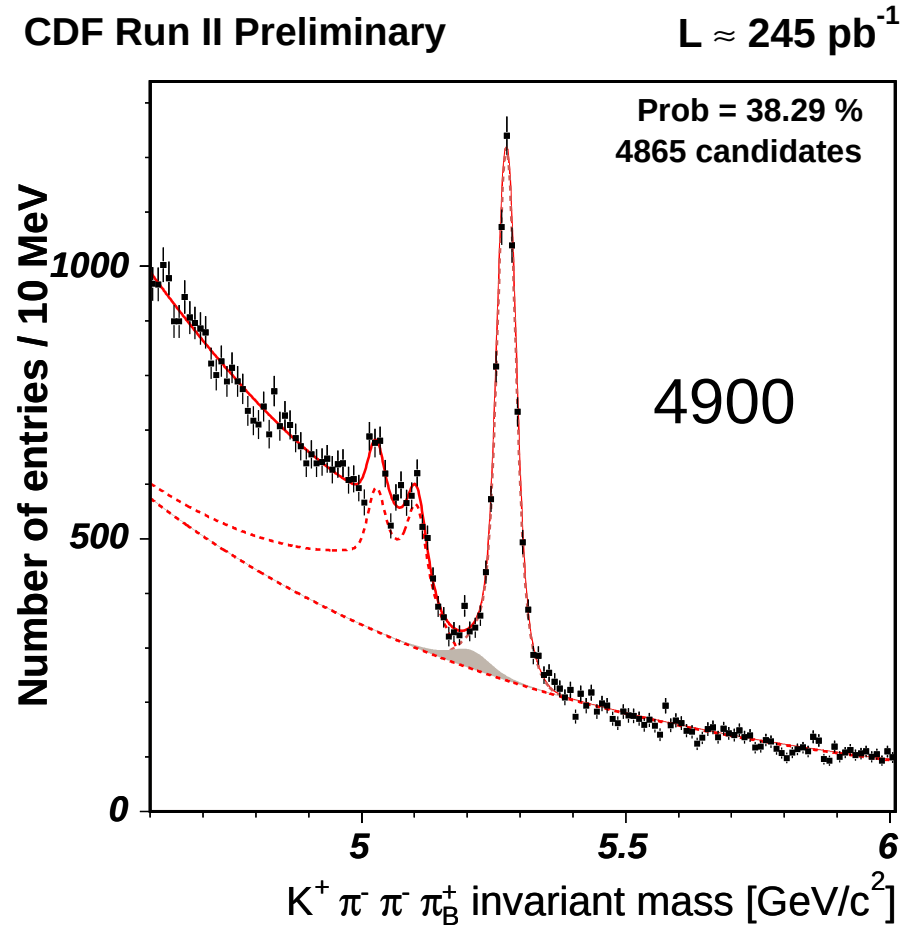
Future : look for CP-violation, ~0 expected in SM, arg(V_{ts}).

B signals from CDF SVT triggers : full reconstruction

$$B^- \to D^0\pi^- \to (K^-\pi^+)\,\pi^-$$



$$\bar{B}^0 \to D^+\pi^- \to (K^-\pi^+\pi^+)\,\pi^-$$

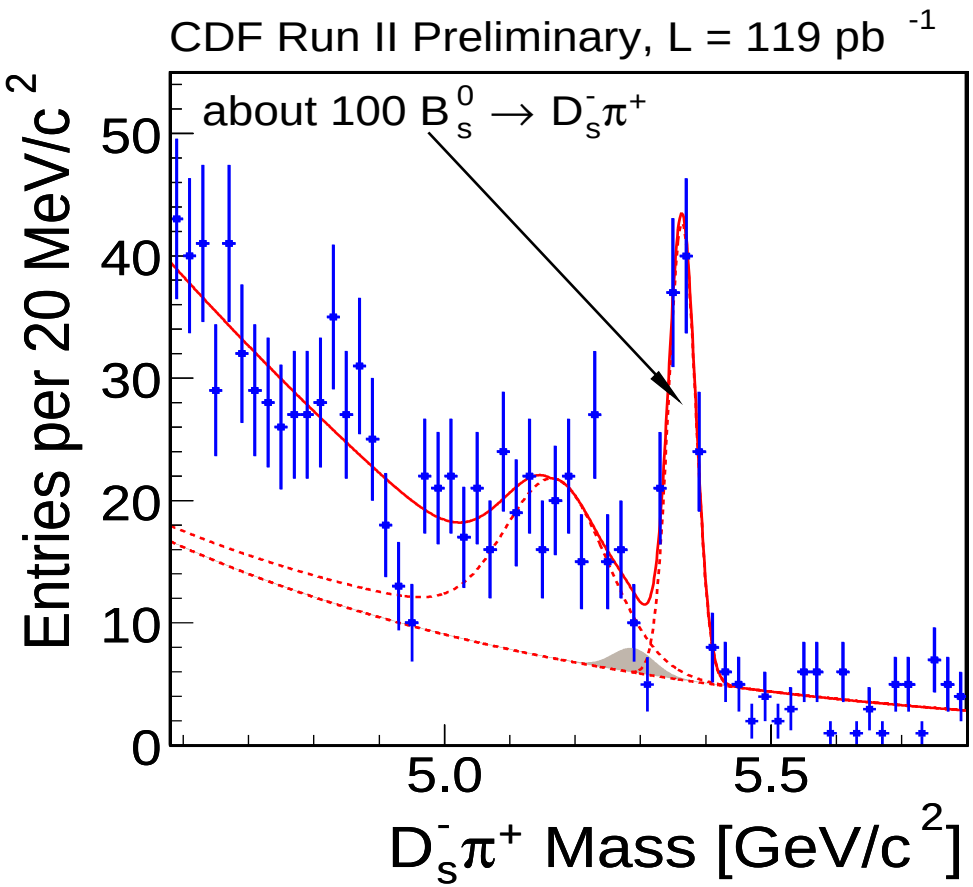


Calibration modes for B_s^0-$\bar{B}_s^0$ oscillations.

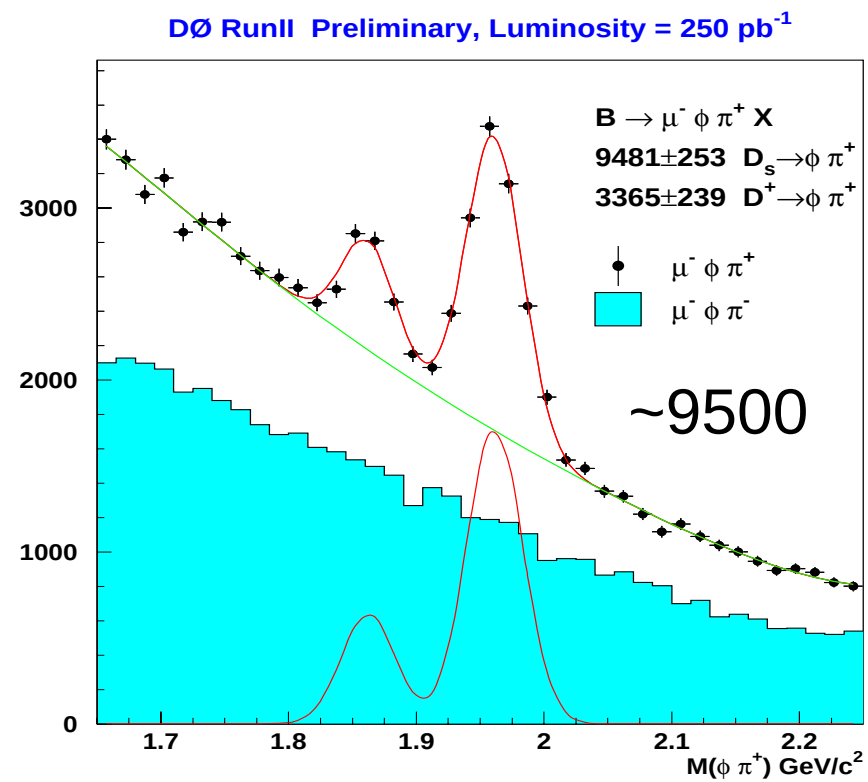
Understand proper time resolution and flavor tagging

Toward $B_s^0 \bar{B}_s^0$ oscillations

$\bar{B}_s^0 \to D_s^+ \pi^-$ (CDF)



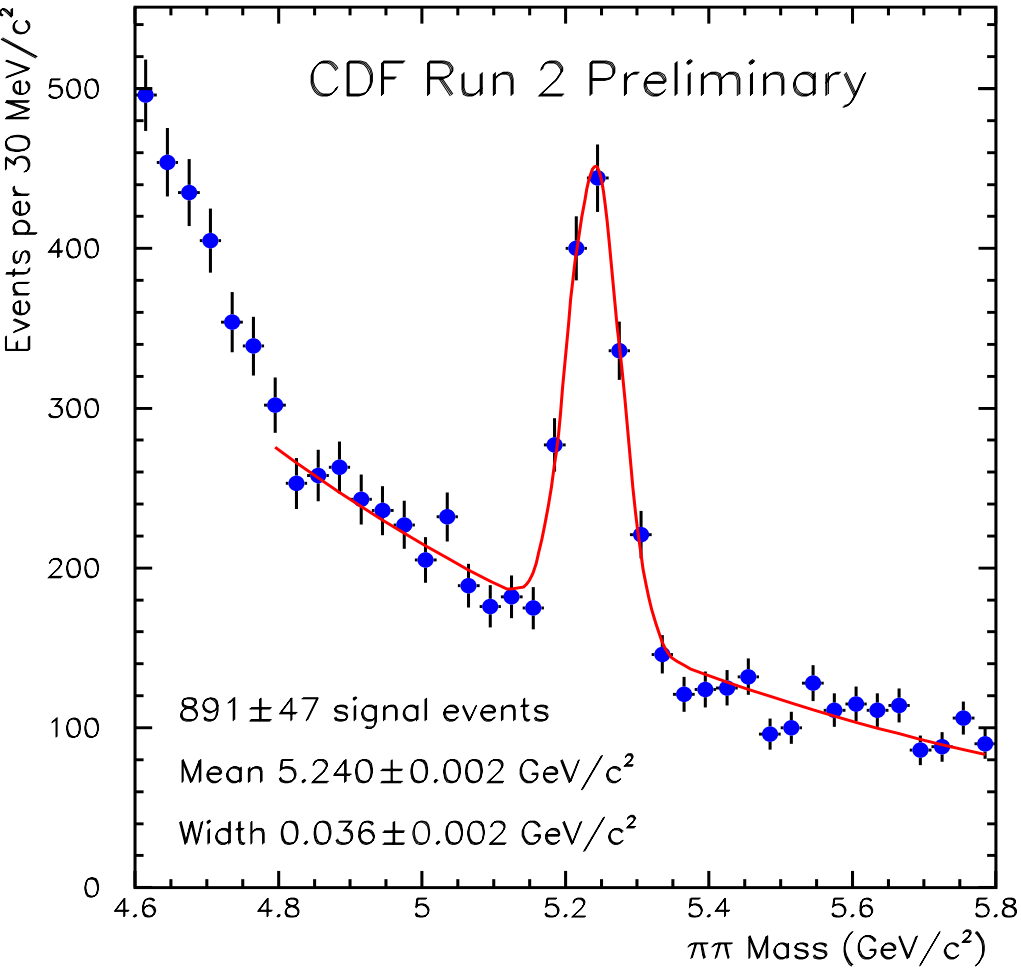
$\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$ (D0)



$\Delta m_s \Rightarrow$ Crucial for $|V_{td}/V_{ts}|$

First attempt expected this summer.

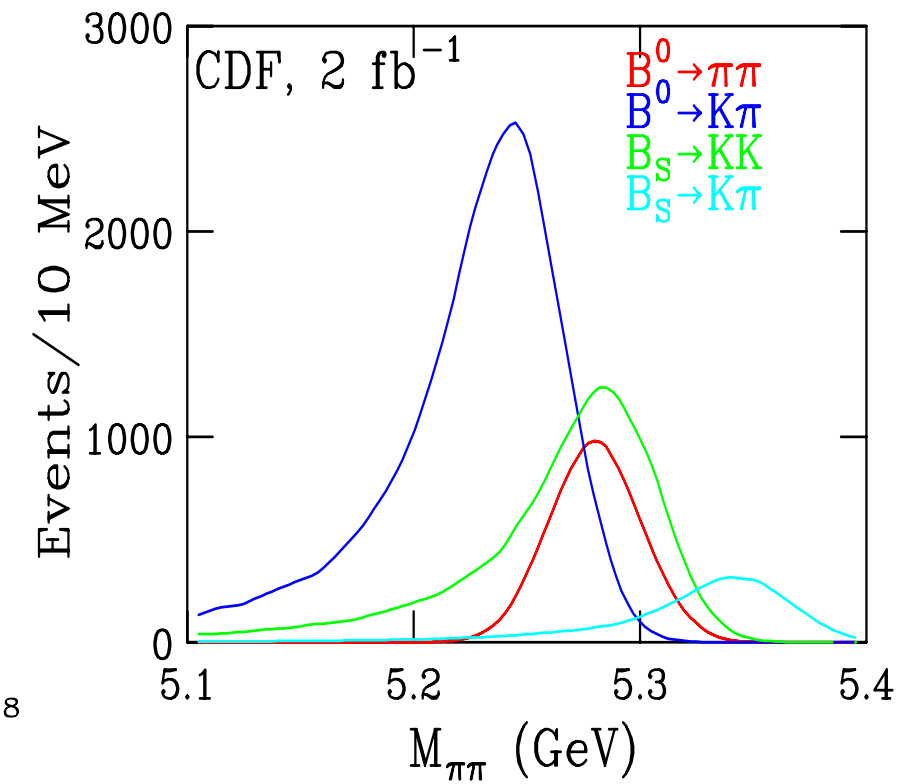
$B_d^0/B_s^0 \to h^+h'^-$



Peak is mixture of

$B^0 \to \pi^+\pi^-,\ K^+\pi^-$

$B_s^0 \to K^+K^-,\ K^-\pi^+$

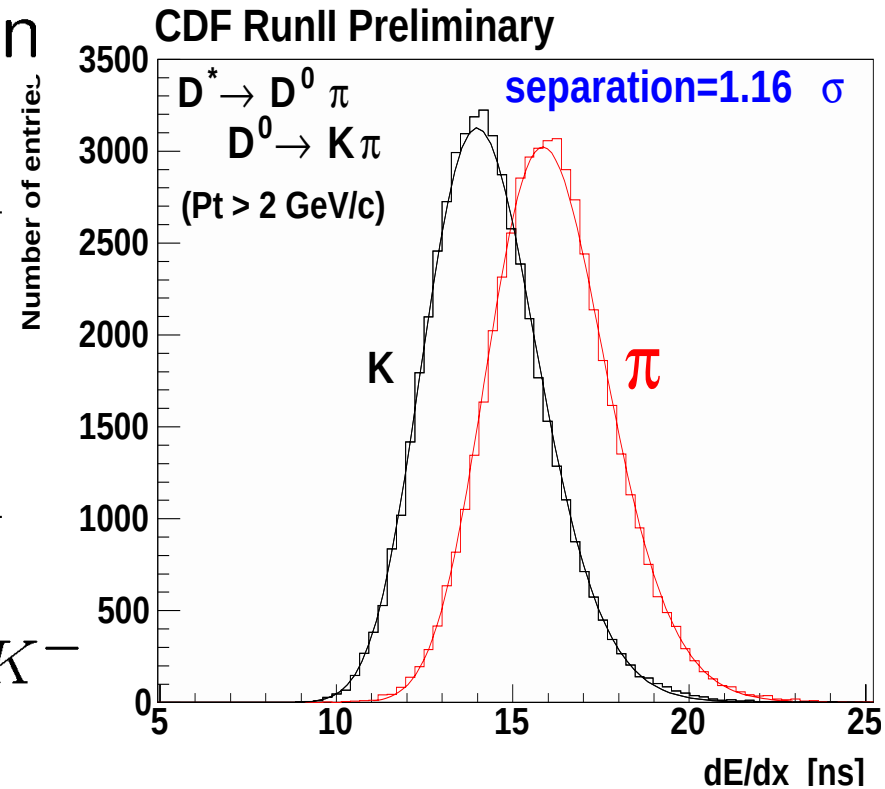


Pion mass assigned to $h^+ h^-$

Use dE/dx and mass distributions to determine composition

$B_d^0/B_s^0 \to h^+h'^-$ composition

Mode	Yield (65 pb^{-1})
$B^0 \to K^+\pi^-$	$148 \pm 17 \pm 17$
$B^0 \to \pi^+\pi^-$	$39 \pm 14 \pm 17$
$B_s^0 \to K^+K^-$	$90 \pm 17 \pm 17$
$B_s^0 \to K^+\pi^-$	$3 \pm 11 \pm 17$



First observation of $B_s^0 \to K^+K^-$

$$\frac{f(b \to B_s^0) \cdot \mathcal{B}(B_s^0 \to K^+K^-)}{f(b \to B_d^0) \cdot \mathcal{B}(B_d^0 \to K^+\pi^-)} = 0.74 \pm 0.20 \pm 0.22$$

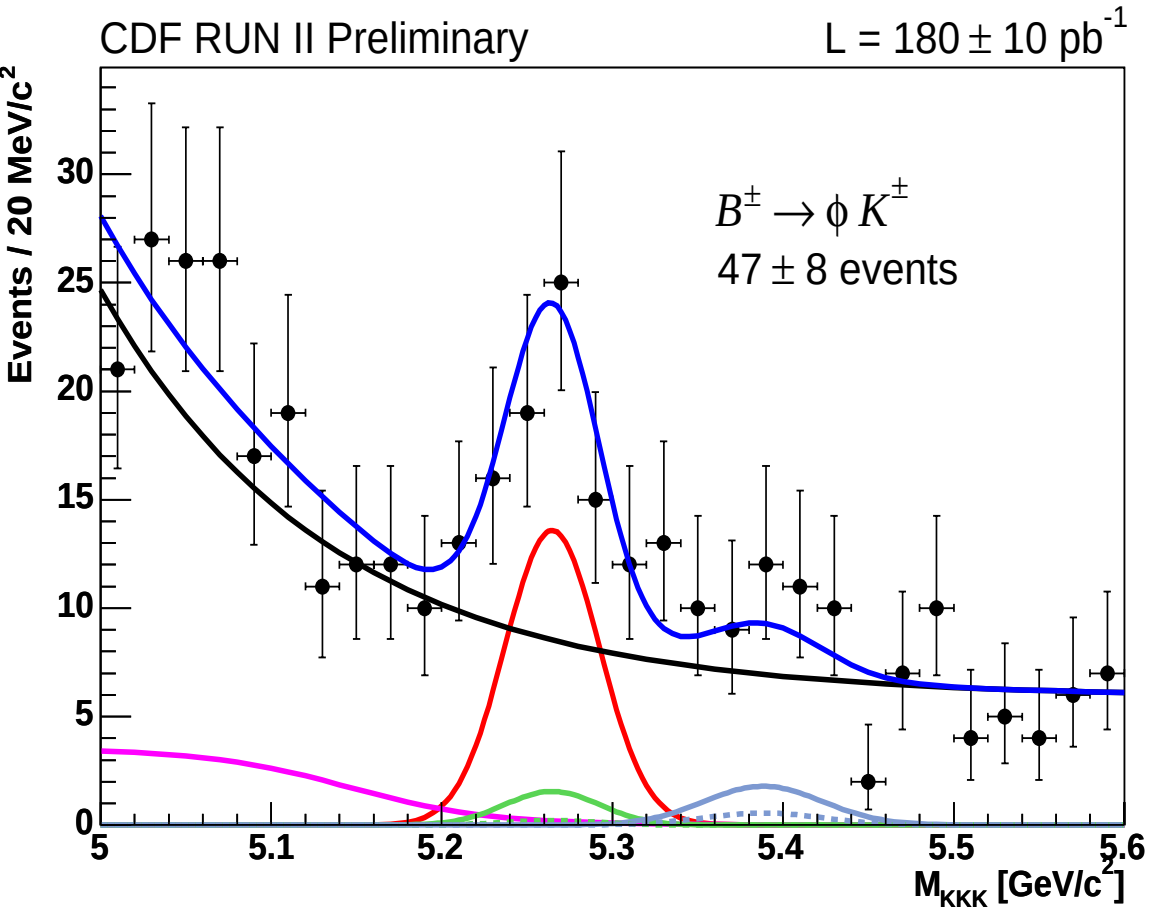
Also :

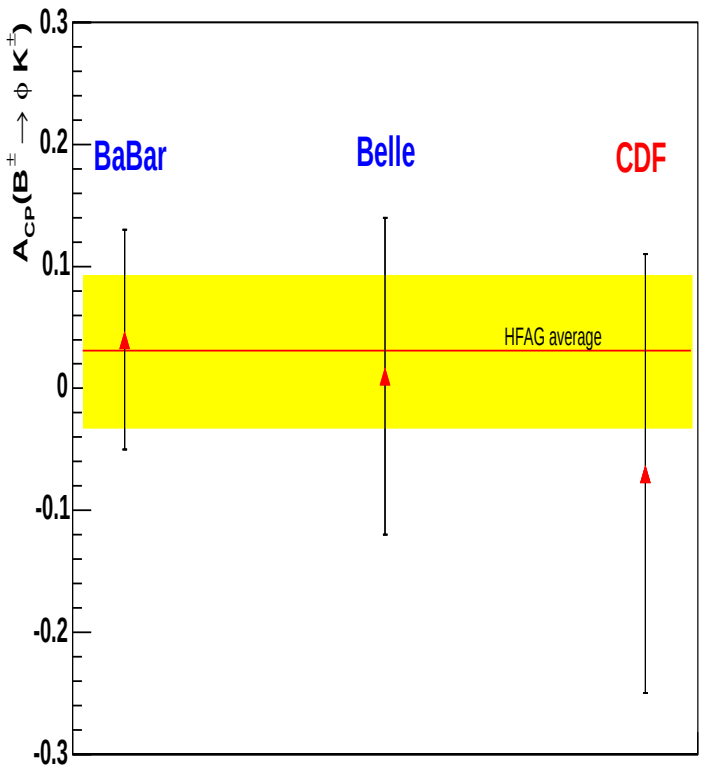
$$\mathcal{B}(B_d^0 \to \pi^+\pi^-)/\mathcal{B}(B_d^0 \to K^+\pi^-) = 0.26 \pm 0.11 \pm 0.06$$

$$\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = 0.02 \pm 0.15 \pm 0.02$$

Hope to extract angle γ in a longer term (after Δm_s)

Direct CP test with $B^+ \to \phi K^+$: CDF





$$\mathcal{A}_{CP} = -0.07 \pm 0.17\,^{+0.06}_{-0.05}$$

$$\frac{\mathcal{B}(B^+ \to \phi K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = (0.72 \pm 0.13 \pm 0.07) \times 10^{-2}$$

Summary

Tevatron Run-II in progress since 2001 :

- Machine luminosity improving, delivered > 500 pb^{-1} to each experiment.
- CDF/DØ each recorded ~400 pb^{-1}.
  - 4 x Run-I total. More to come.
- Top production reconfirmed, new precision / measurements to follow.
- Electroweak physics :
  - Precision $M_W \rightarrow$ indirect Higgs mass. Triple-Gauge couplings.
- Enhanced B physics capabilities :
  - CDF has added silicon-based trigger, enabling to collect all-hadronic final states such as $B \rightarrow D\,\pi$, $B_s \rightarrow K^+K^-$.

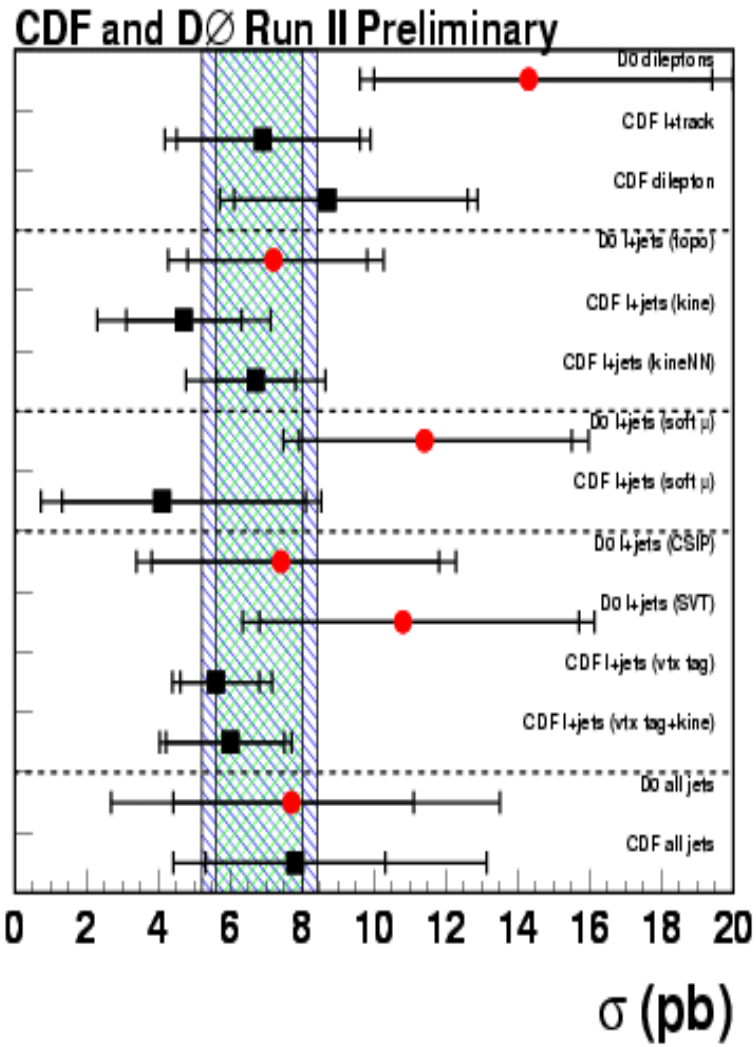
    DØ is also commissioning a displaced-track trigger.
  - Lepton triggers remain valuable, J/ψ K and l ν D.
- Expect to collect ~2 fb^{-1} in the near future,

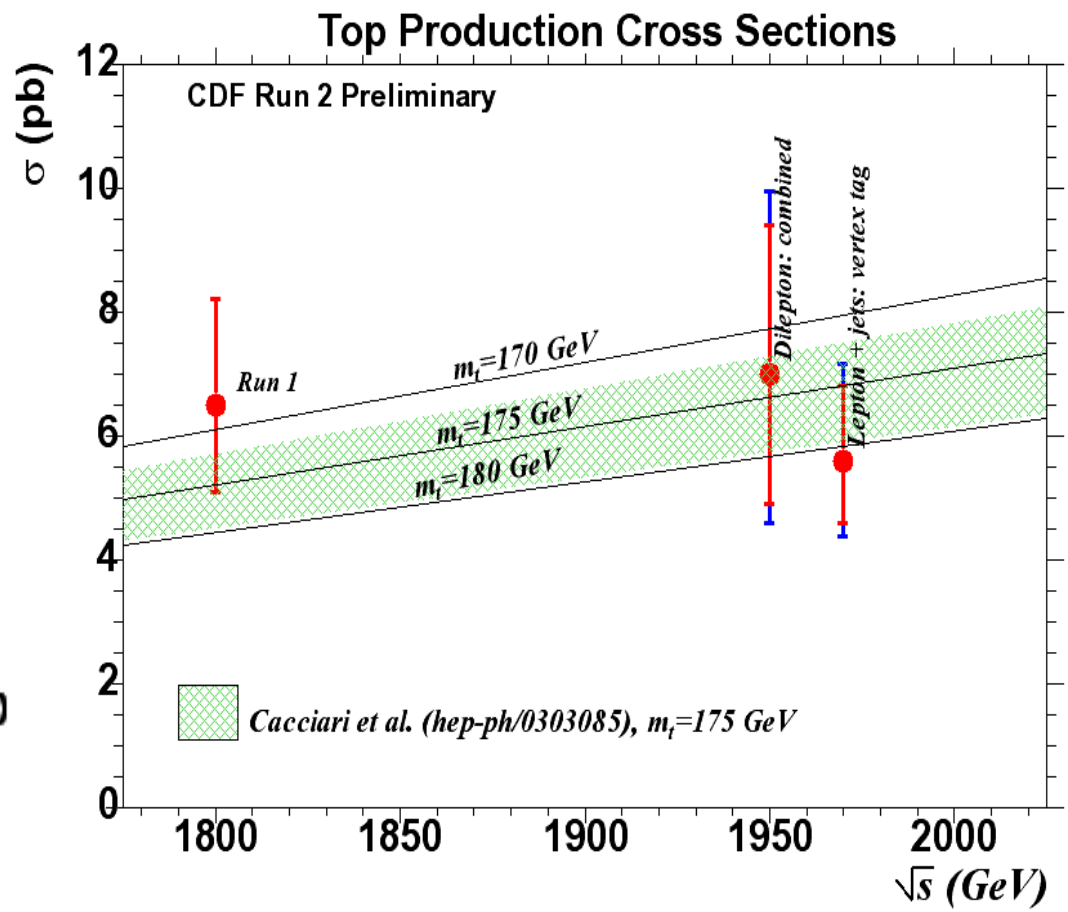
  and to make some significant measurements.

Backup Slides follow

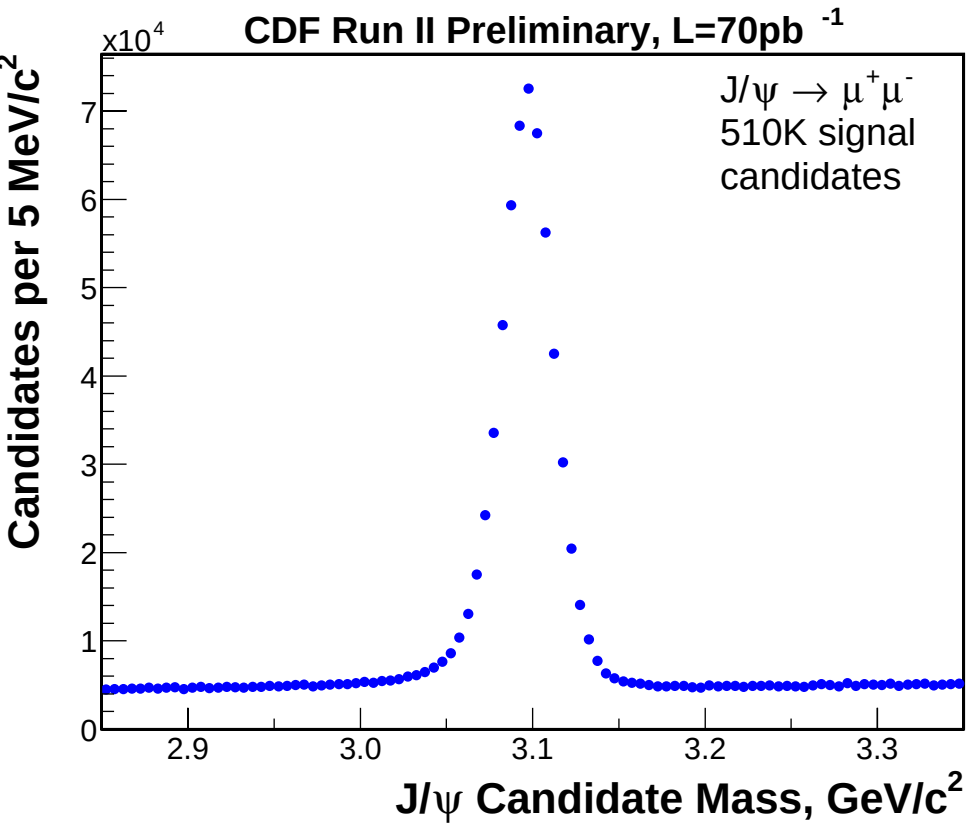
$t\bar{t}$ Production Cross Section

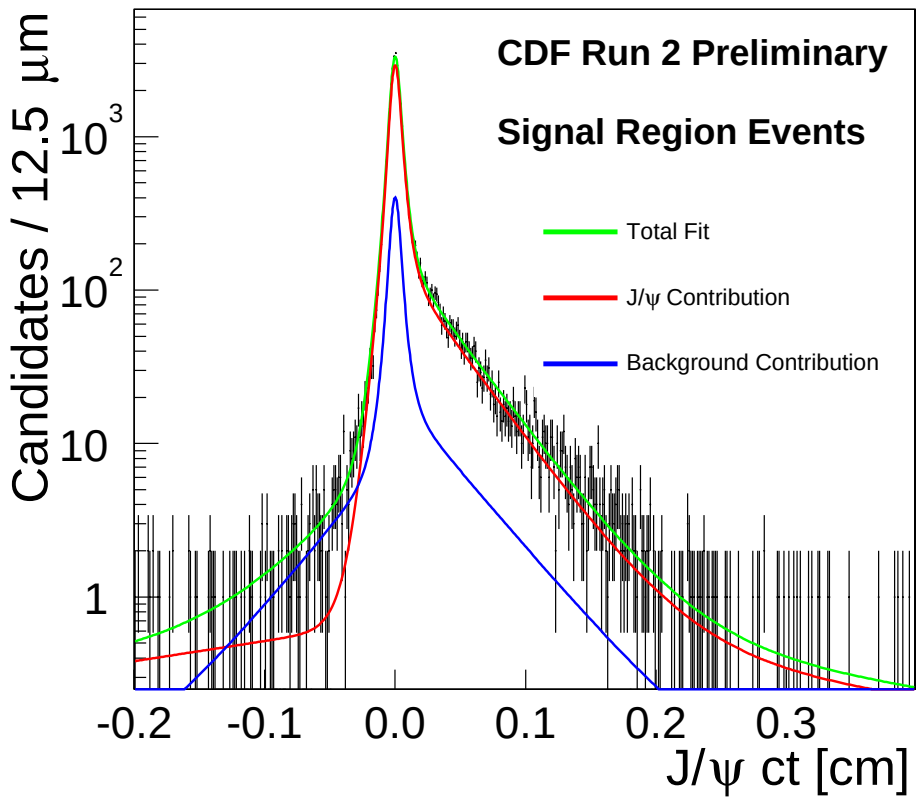
Many channels and techniques.





Run-II Di-muon data : CDF





p_T threshold lowered :
from 2 GeV/c to 1.5 GeV/c

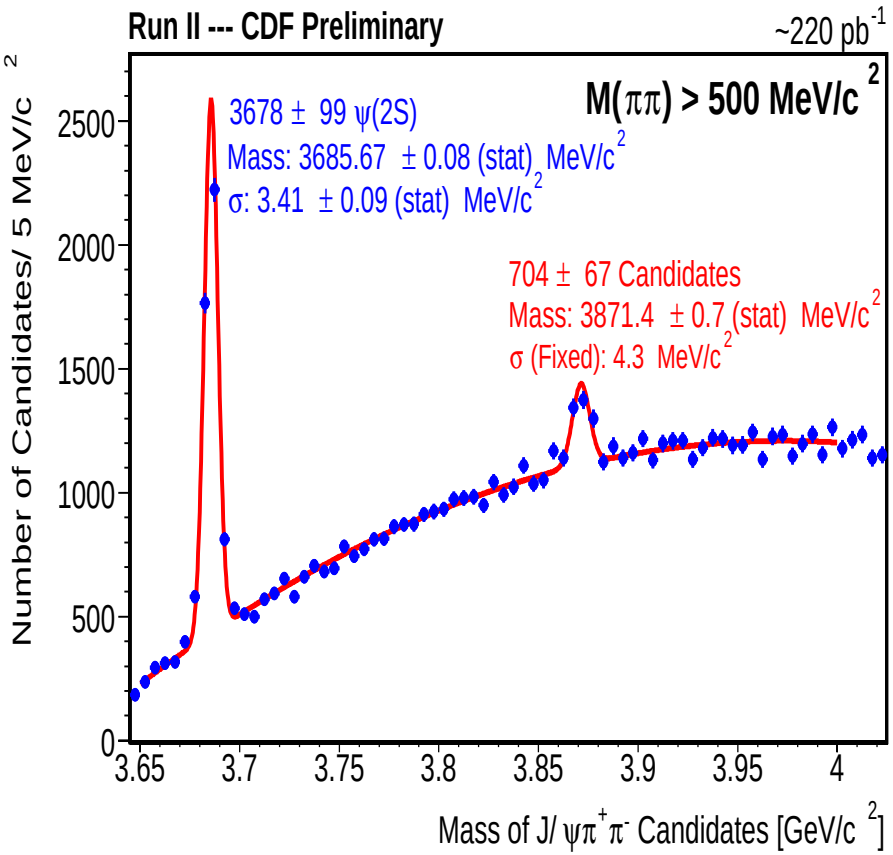
Yield ~2 x Run I

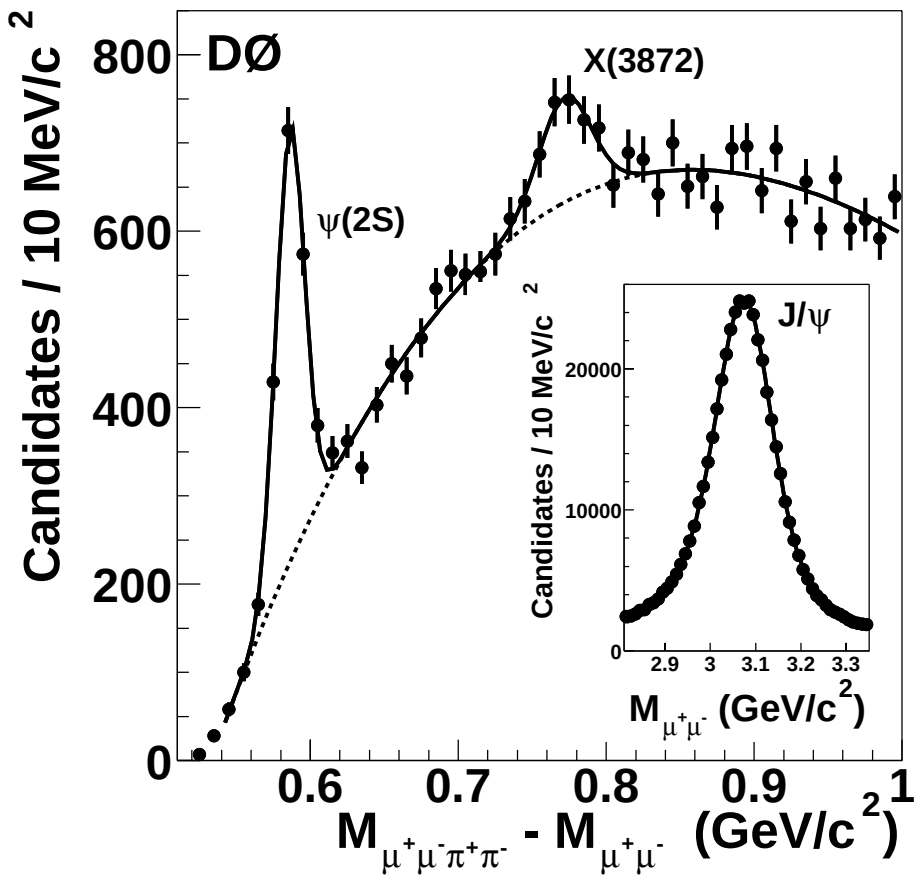
B fraction ~15%

$$\tau(B) = 1.526 \pm 0.034 \pm 0.035 \text{ ps}$$

State $X(3872) \to J/\psi\,\pi^+\pi^-$

CDF and DØ confirm Belle discovery

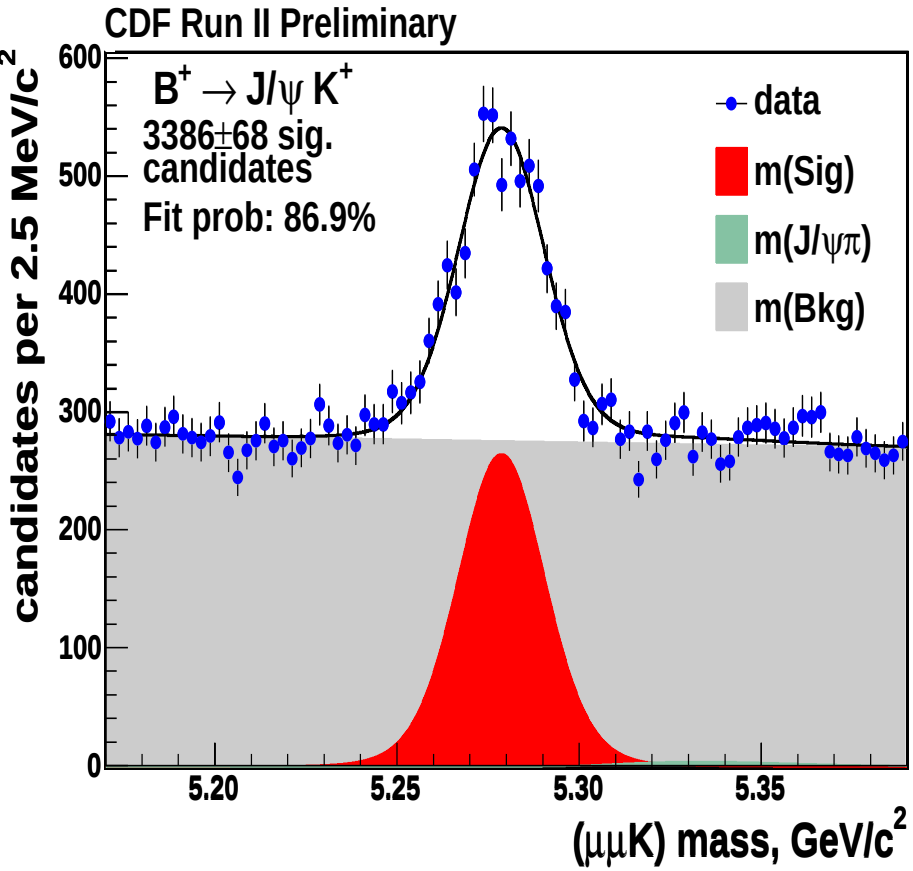


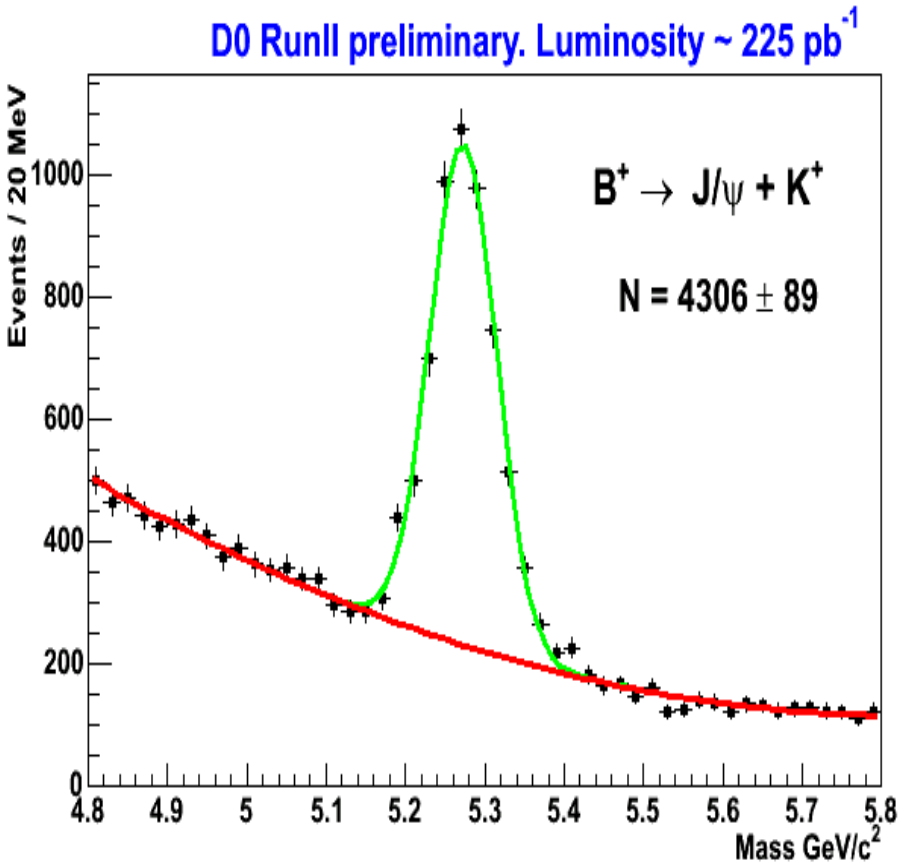


Mass : $3871.4 \pm 0.7 \pm 0.4$, $3871.8 \pm 3.0 \pm 3.0$ MeV/c^2.

Width : narrow, consistent with resolution (CDF).

$B^+ \to J/\psi\, K^+$

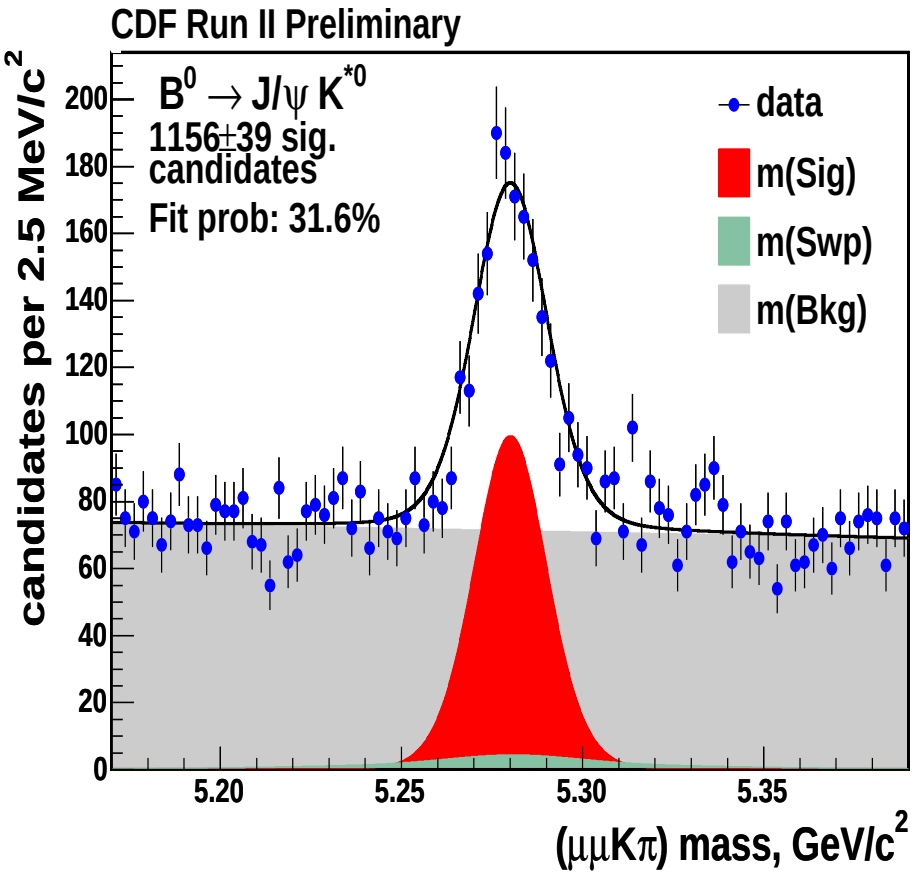


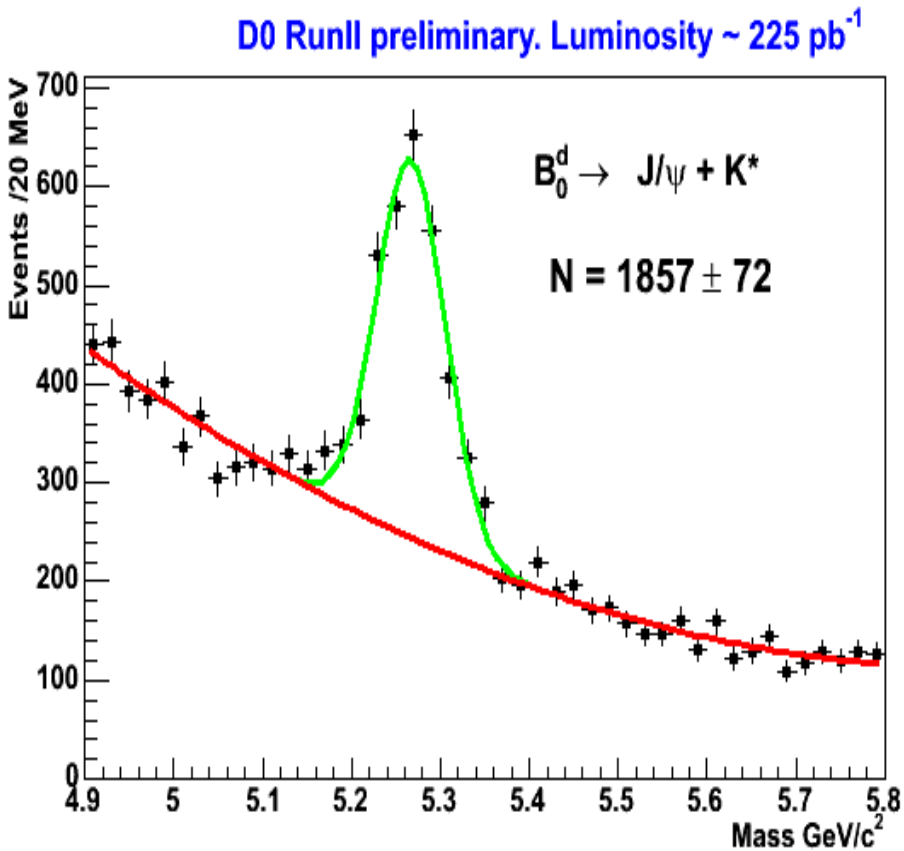


$$m(B^+) = 5279.32 \pm 0.68 \pm 0.94 \ \text{MeV}/c^2$$

$$\tau(B^+) = 1.662 \pm 0.033 \pm 0.008 \ \text{ps}, \quad 1.650 \pm 0.083 \, {}^{+0.096}_{-0.123} \ \text{ps}$$

$B^0 \to J/\psi\, K^{*0} \to \mu^+\mu^-\, K^+\pi^-$





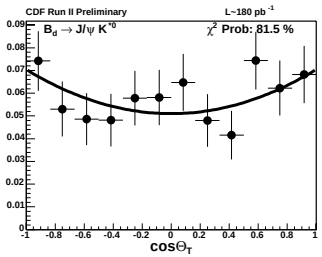
CDF :

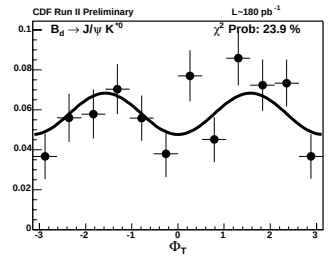
$m(B^0) = 5280.30 \pm 0.92 \pm 0.96$ MeV$/c^2$

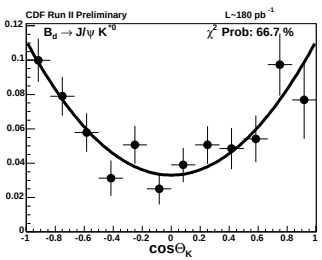
$\tau(B^0) = 1.539 \pm 0.051 \pm 0.008$ ps

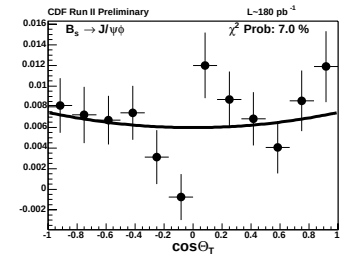
$B^0 \to J/\psi\, K^{*0}$ and $B_s^0 \to J/\psi\, \phi$ polarizations

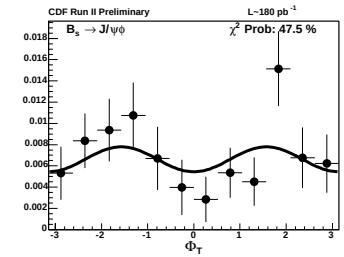
CDF

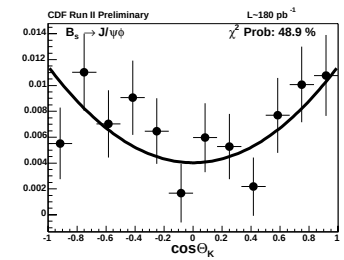


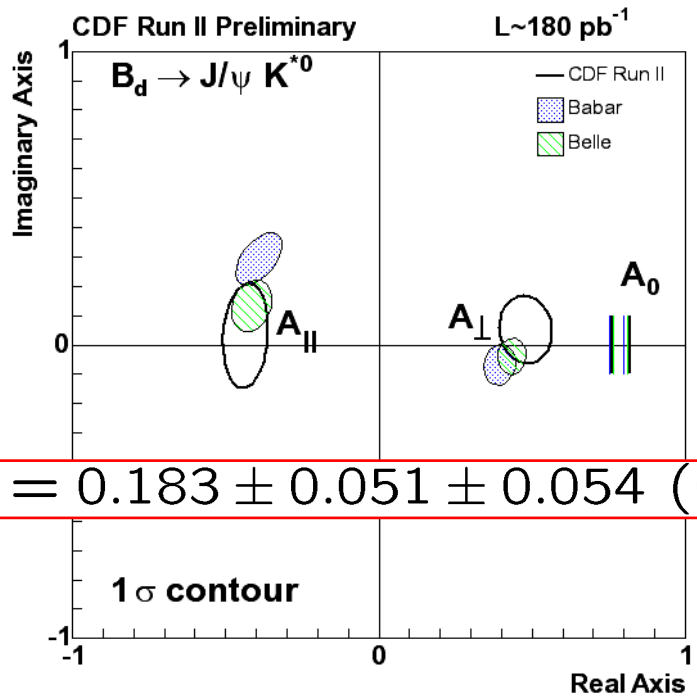




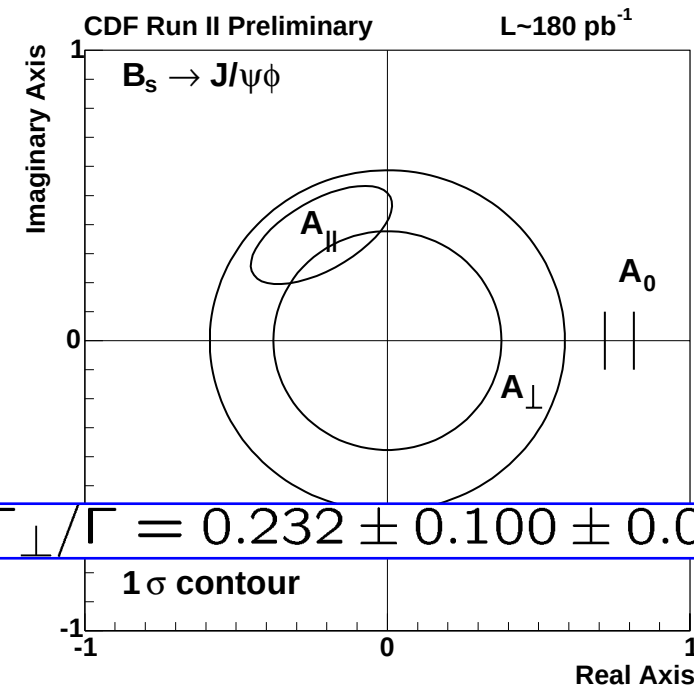








$\Gamma_\perp/\Gamma = 0.183 \pm 0.051 \pm 0.054$ (CDF)

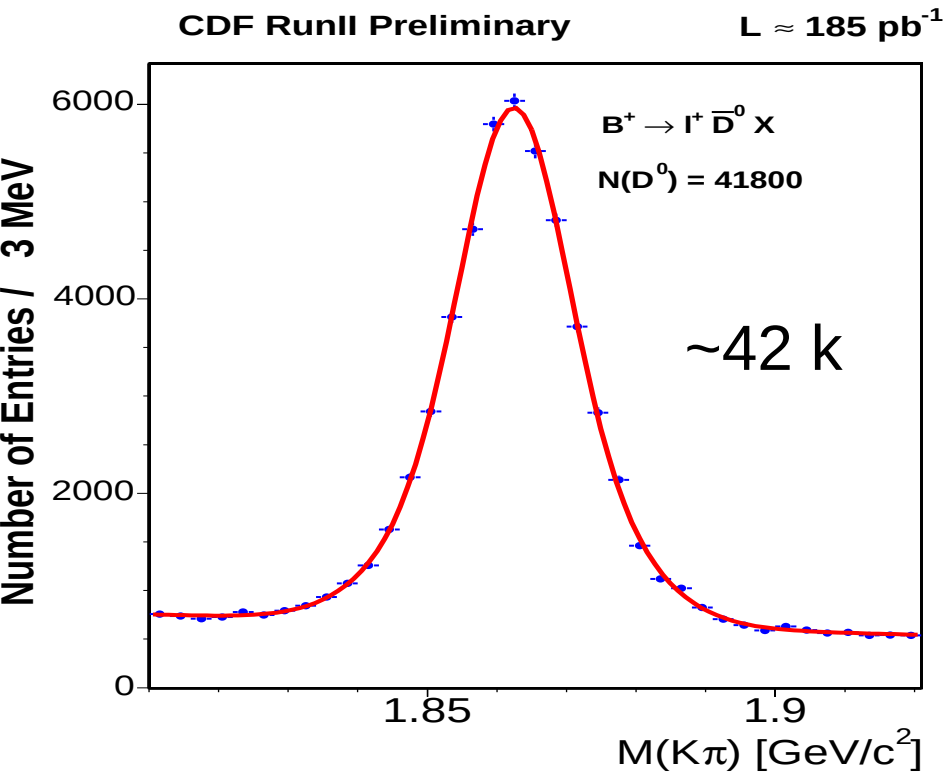


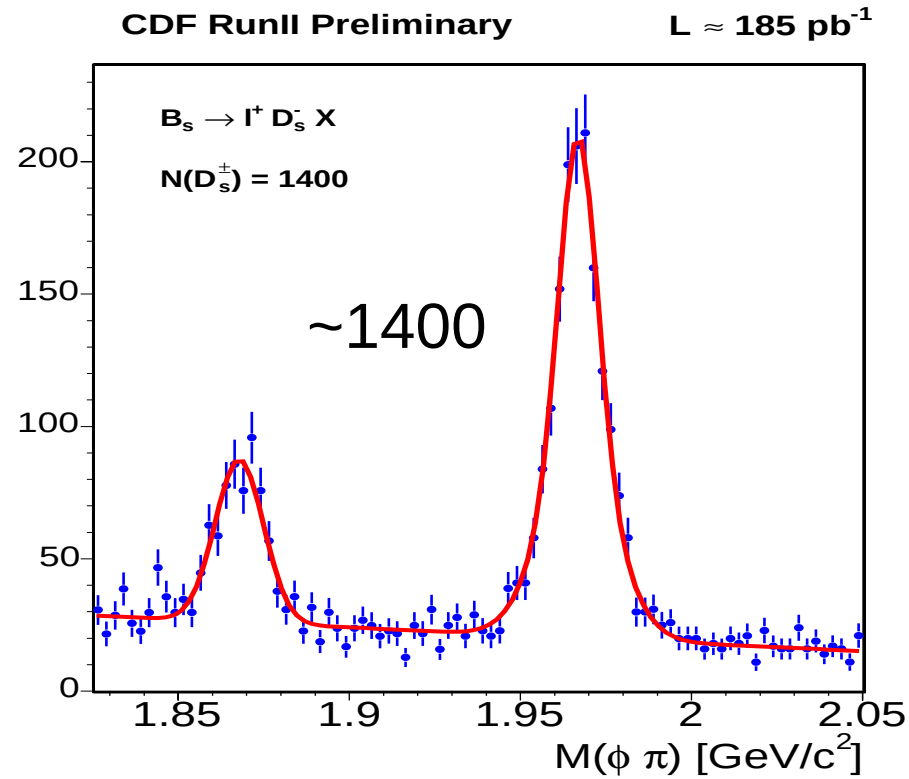
$\Gamma_\perp/\Gamma = 0.232 \pm 0.100 \pm 0.013$

Semileptonic B decay signals : CDF

$$\bar{B} \to \ell^- \bar{\nu} D^0 X$$

$$\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$$

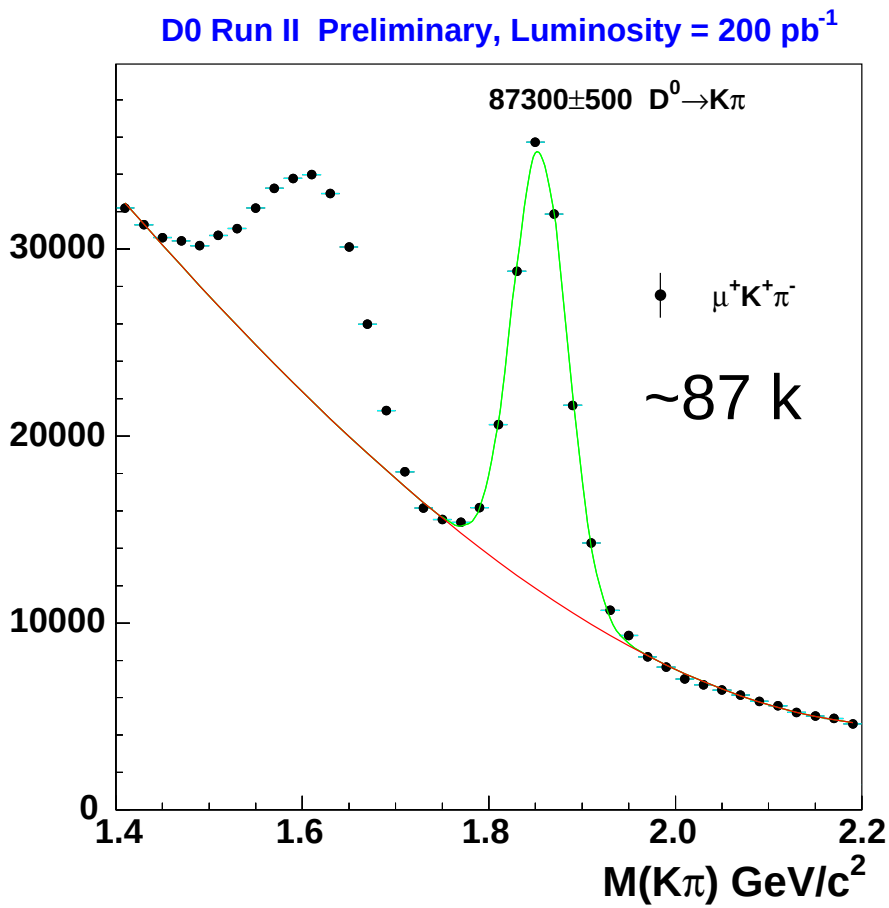


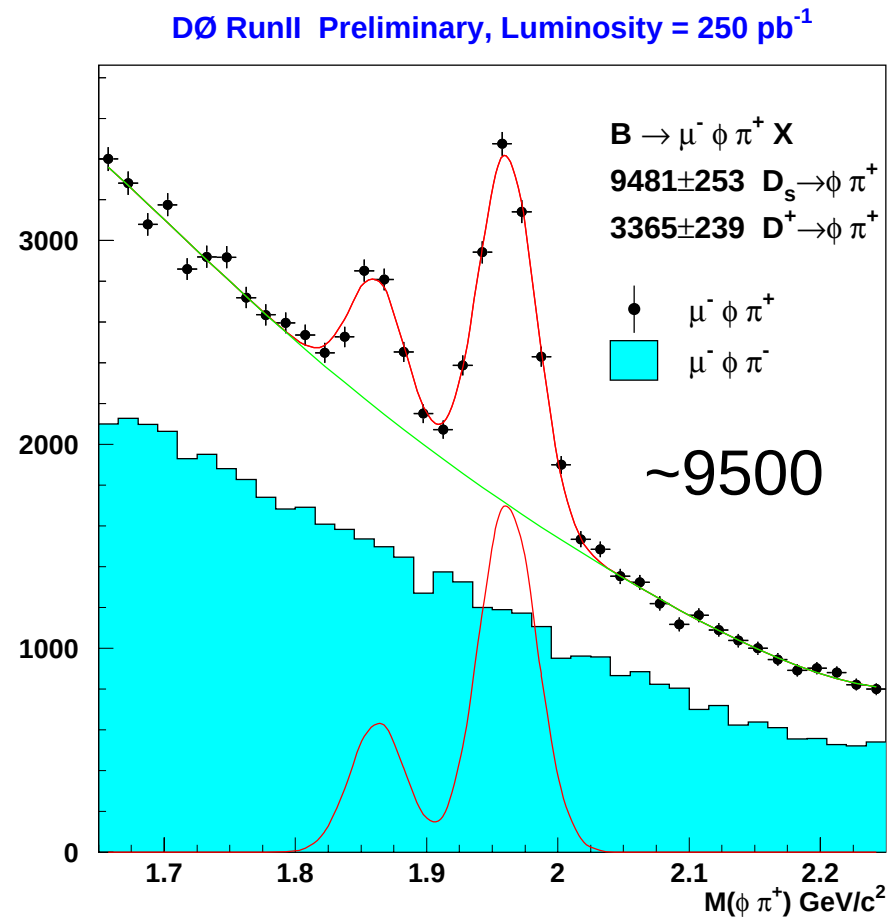


Large semileptonic B decay signals : DØ

$$\bar{B} \to \ell^- \bar{\nu} D^0 X$$

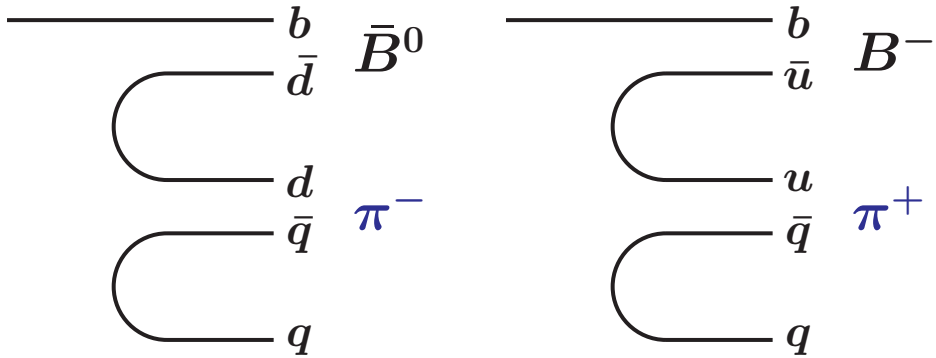
$$\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$$

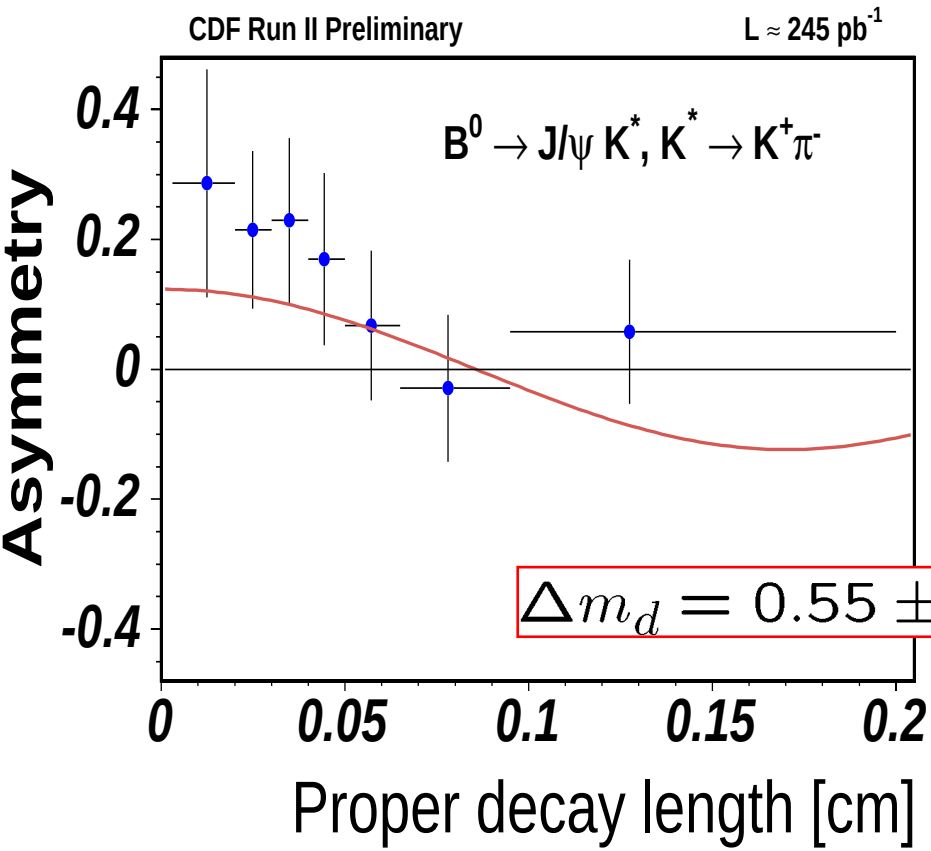


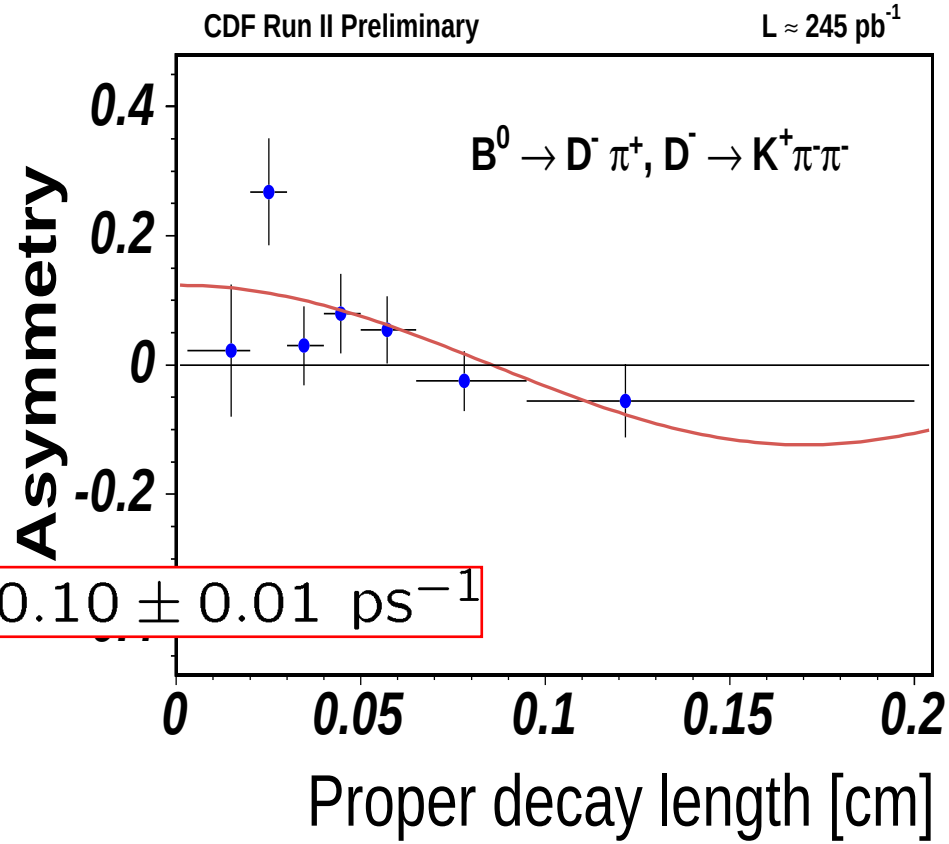


Flavor tagging example : same-side pion tag (CDF)

Look at near $\bar{B} \to D\pi$ and $\bar{B} \to J/\psi \bar{K}^{(*)}$







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

εD^2 = (2.8 +/- 0.5)% for B^+

εD^2 = (1.0 +/- 0.5)% for B^0

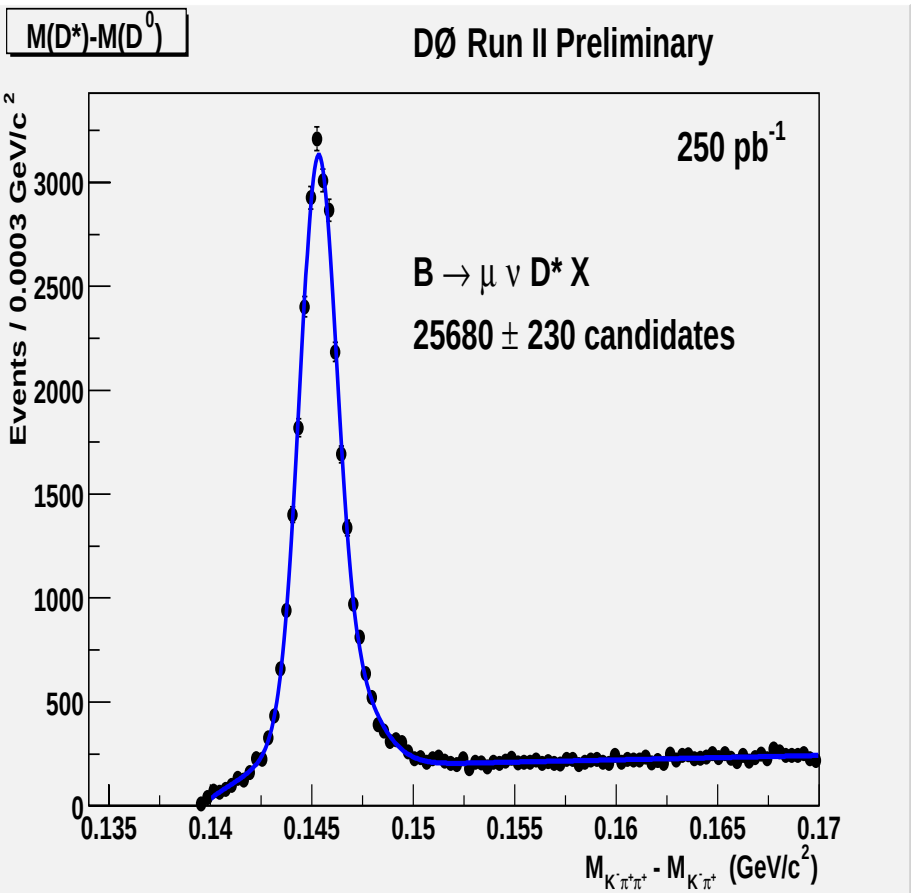
Also, muon tagging

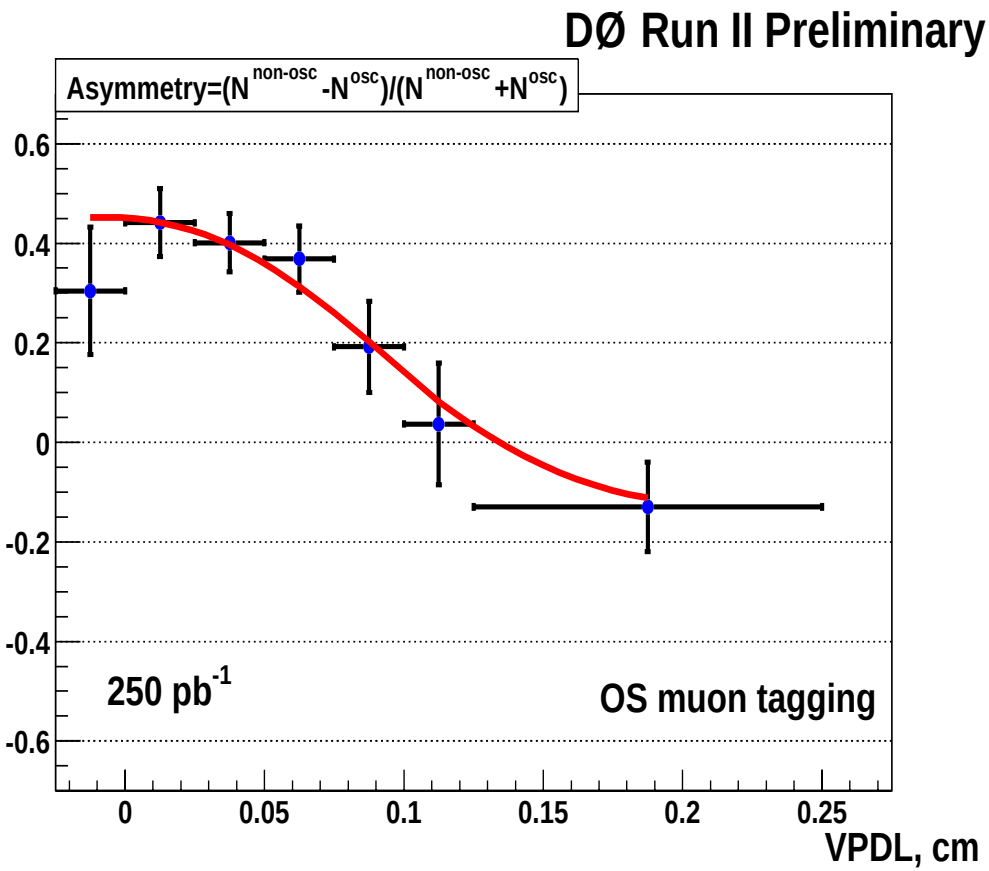
εD^2 = (0.7 +/- 0.1)%

Flavor tagging example : opposite-side muon tag (DØ)

Look at the opposite side of the event for muons from semileptonic decays : tag.

$\bar{B} \to \mu^- \bar{\nu} D^{*+} X$, mostly $\bar{B}^0$

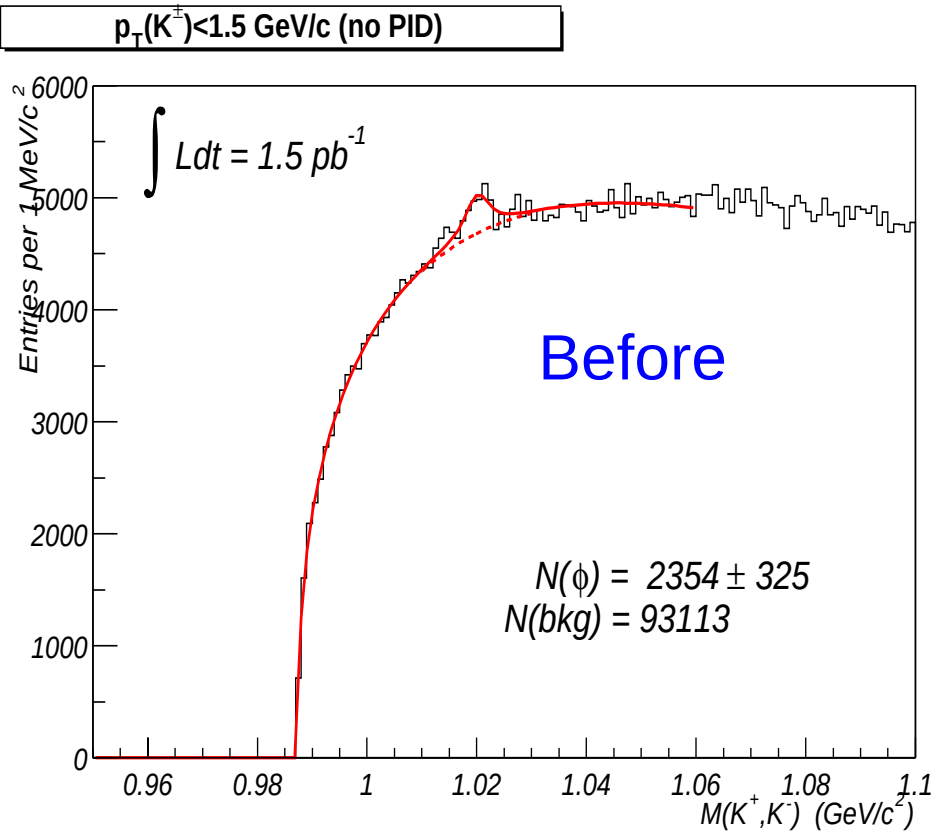


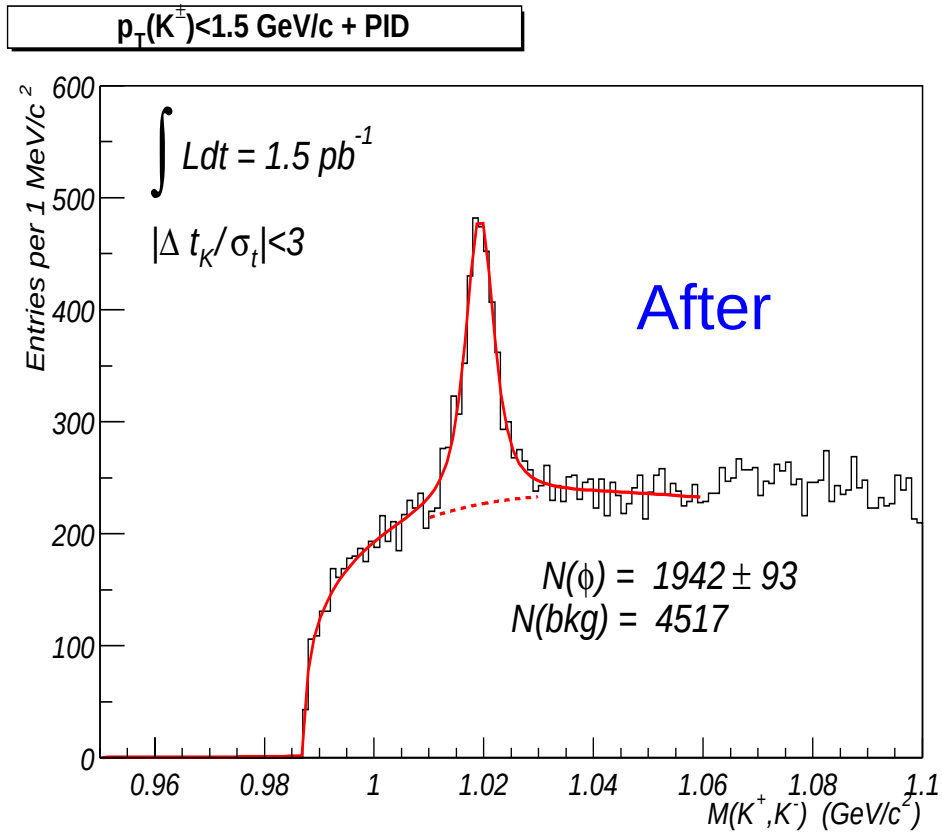


$$\Delta m_d = 0.506 \pm 0.055 \pm 0.049 \ \mathrm{ps}^{-1}.$$

TOF kaon identification

$$\phi \to K^+K^-$$
$$(p_T < 1.5\ \mathrm{GeV}/c)$$

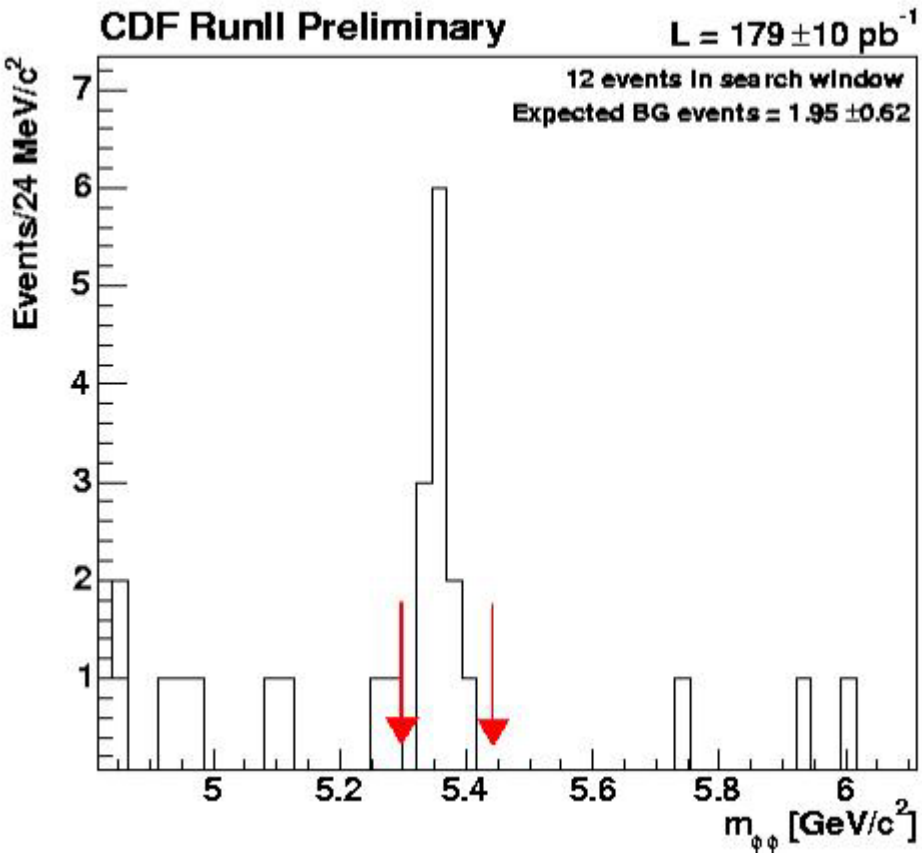




S/N improves by a factor of 20, while keeping 82% of signal.

$B_s^0 \to \phi\,\phi$: another $b \to s\bar{s}s$ mode.

CDF



12 candidates seen.
1.95 +/- 0.62 BG expected.

$$\mathcal{B}(B_s^0 \to \phi\,\phi) = (1.4 \pm 0.6 \pm 0.2 \pm 0.5) \times 10^{-5}$$

Theory : $(1.8 - 3.7) \times 10^{-5}$, hep-ph/0309136