Heavy-Quark Physics at the Tevatron: Charm, Bottom and Top

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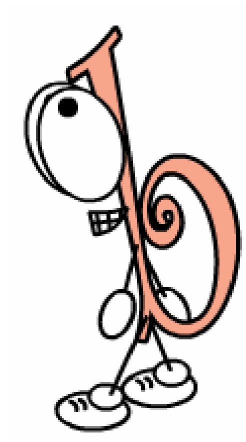
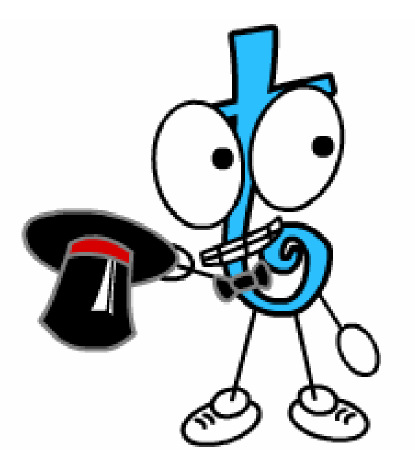
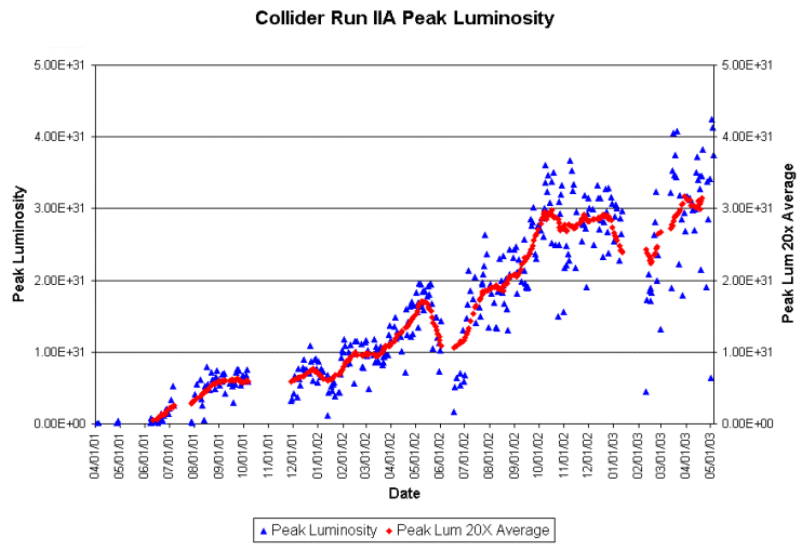
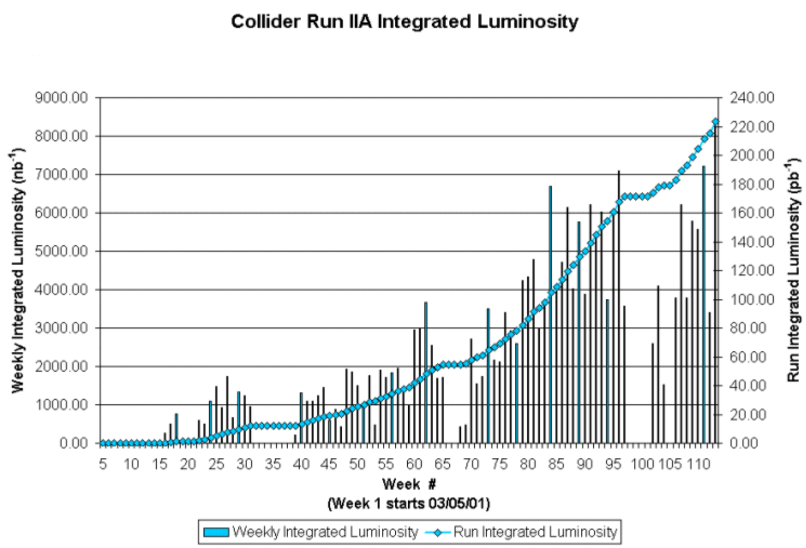
For the CDF and D0 Collaborations

Tevatron upgrades/status

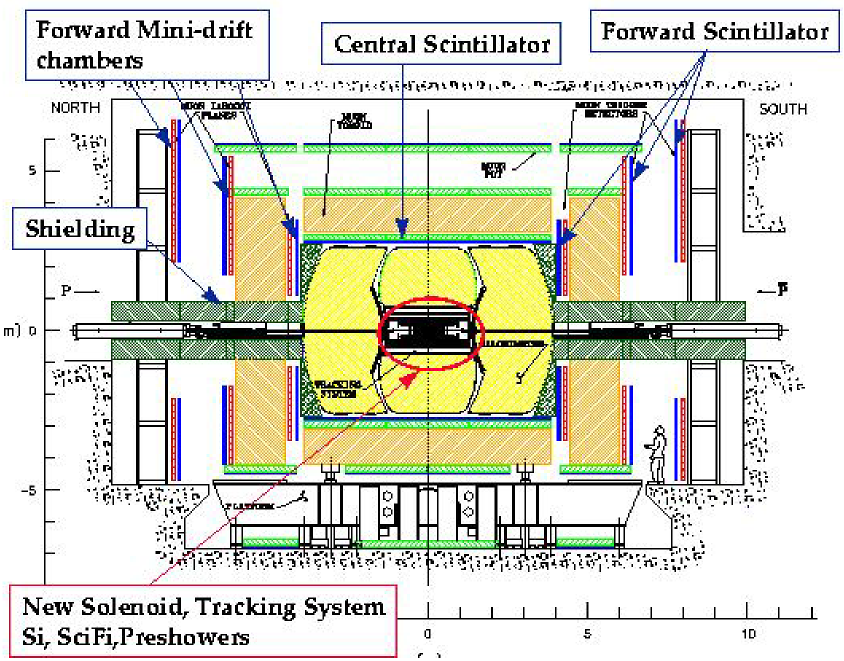
- Run 2 upgrades → new physics opportunities:
  - Peak luminosity (goal): $2 \times 10^{31} \rightarrow 2\text{-}4 \times 10^{32}\ cm^{-2}s^{-1}$ → more events
  - Energy: 1.8 → 1.96 TeV → larger cross sections
- Tevatron has delivered ~220 pb^{-1}, experiments analyzing ~<100 pb^{-1}.
- "Run 2a" goal: 2 fb^{-1}, 20x Run-1 integrated luminosity





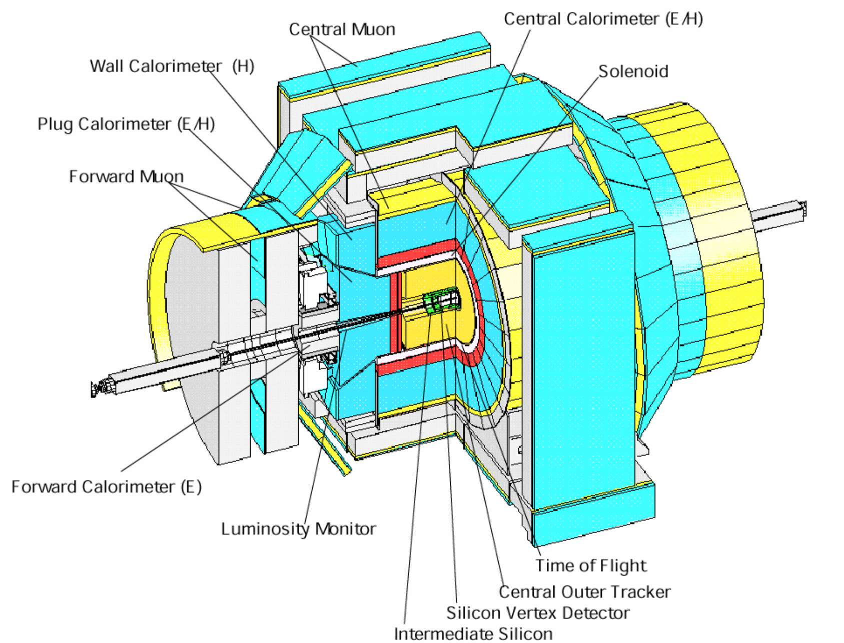
D0 and CDF experiments

D0



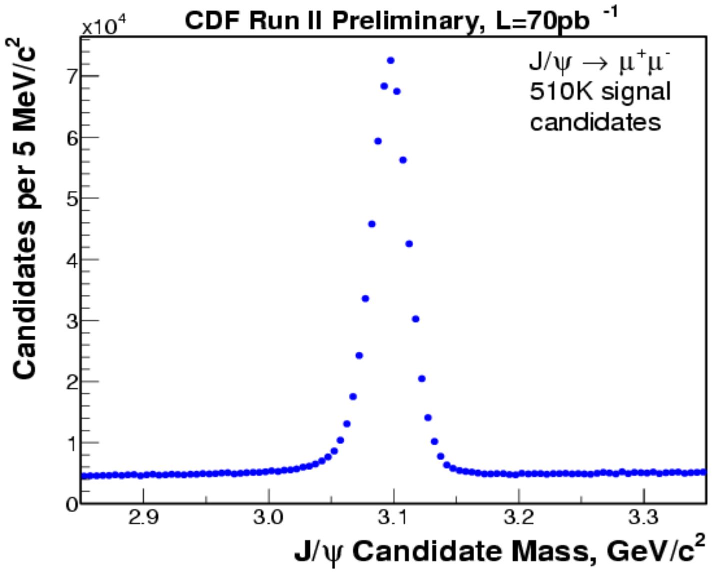
- New tracking: silicon and fibers in magnetic field
- Upgraded muon system
- Upgraded DAQ/trigger (displaced track soon)

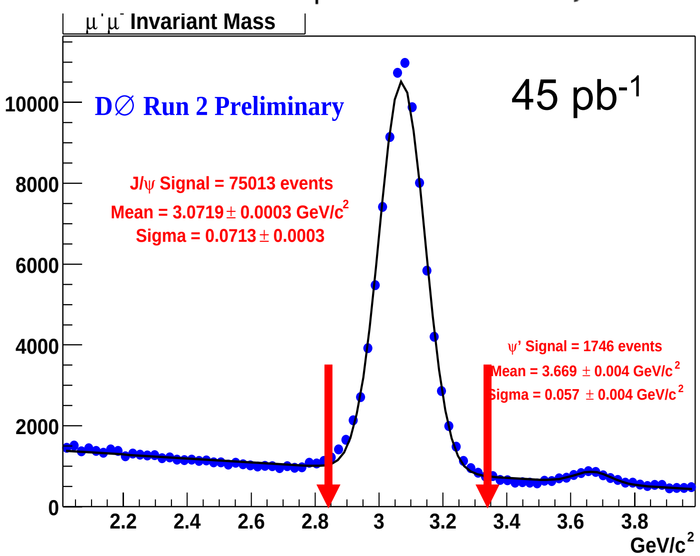
CDF



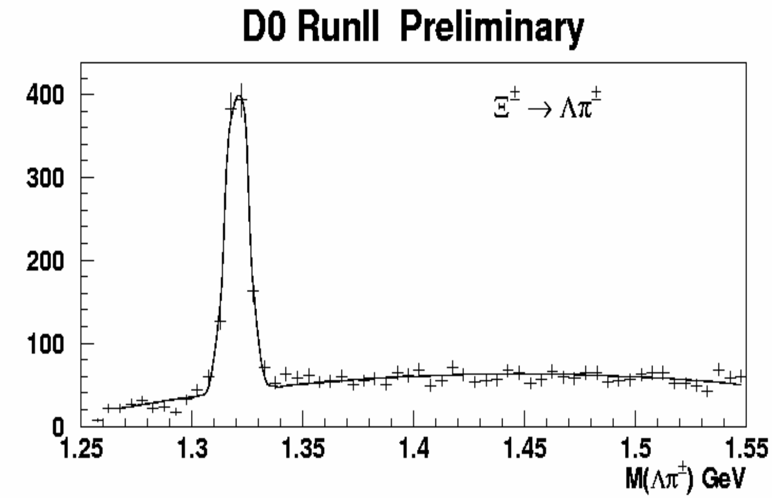
- New bigger silicon, new drift chamber
- Upgraded calorimeter, μ, new TOF
- Upgraded DAQ/trigger, esp. displaced-track trigger

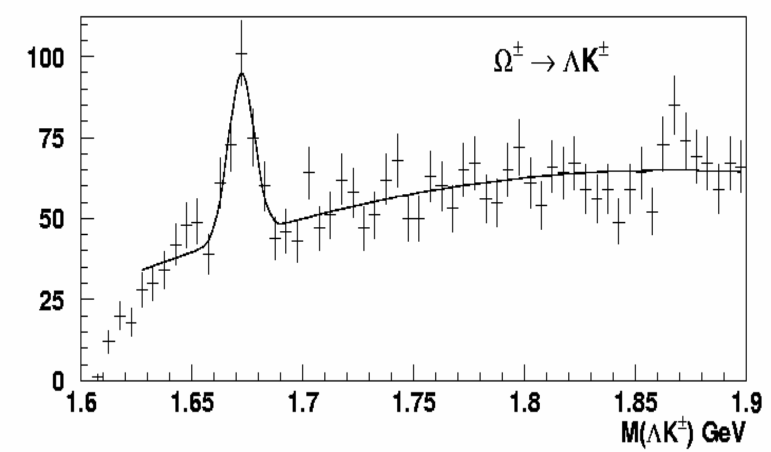
Resonance reconstruction





Both experiments have quality charged-particle tracking!





Why care about charm?

- Study CKM angles, CP asymmetries, production mechanisms
- Huge cross sections: large yields in CKM-suppressed modes, access to rare decays
- Control samples for B physics: testbed for analyses, particle ID

FOCUS has charm!

BaBar has charm!

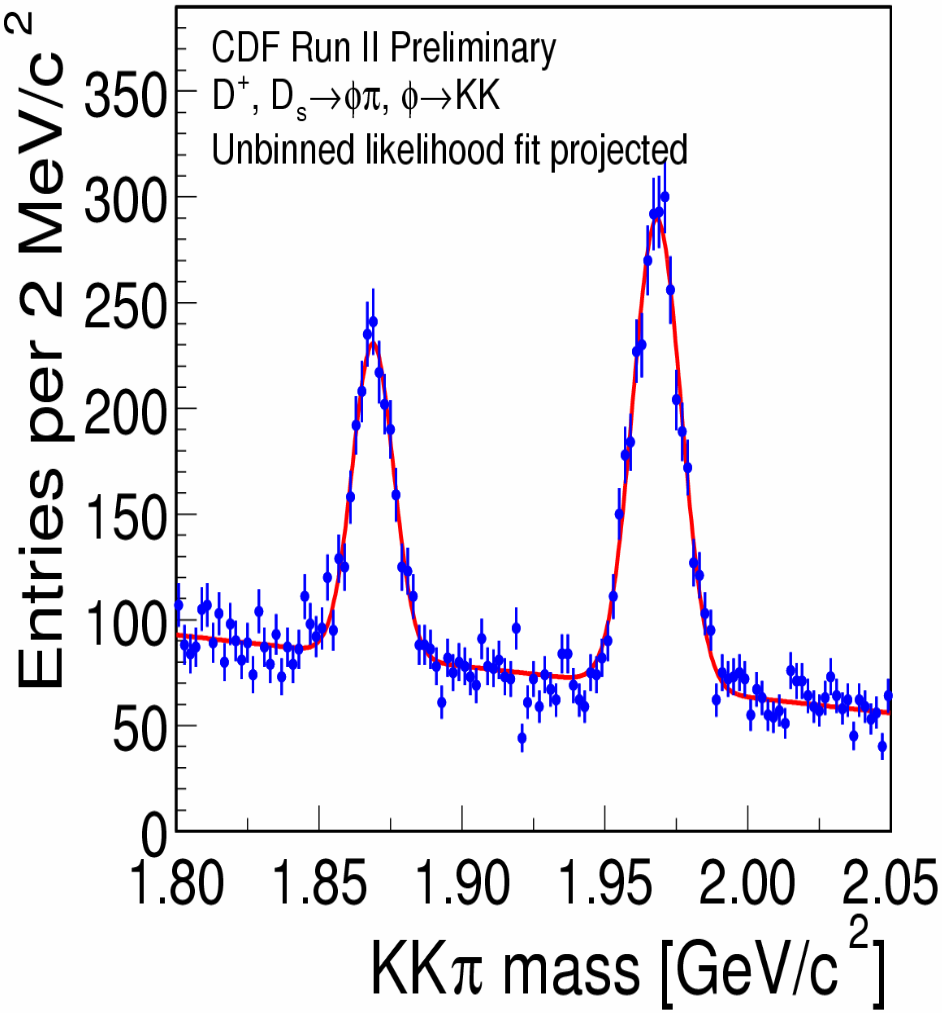
Belle has charm!

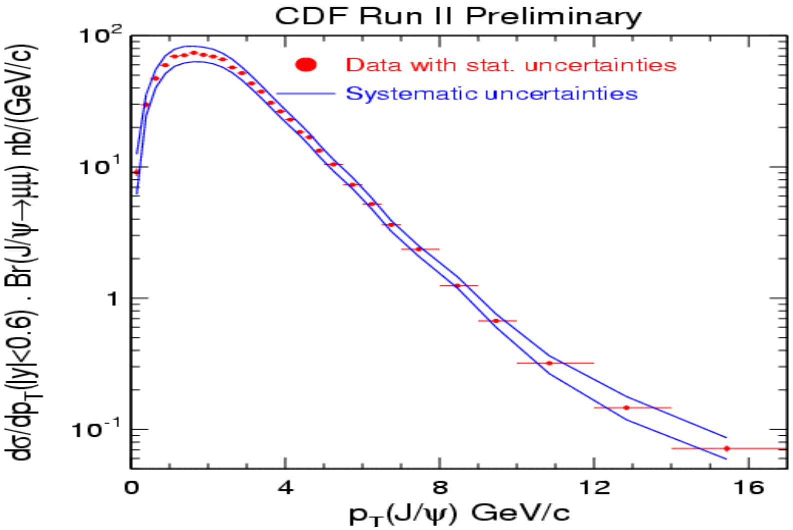
CLEO-c has charm!

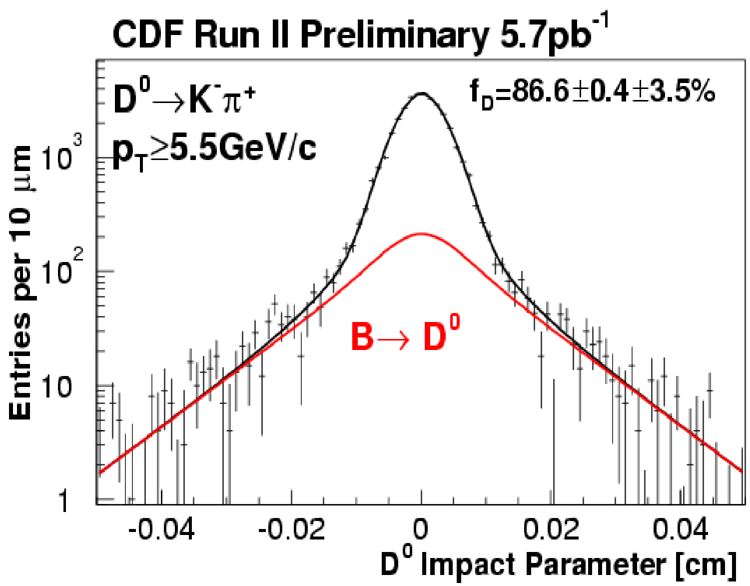
CDF/D0 have charm?!?

CDF: Charm masses, production

First CDF paper submission!







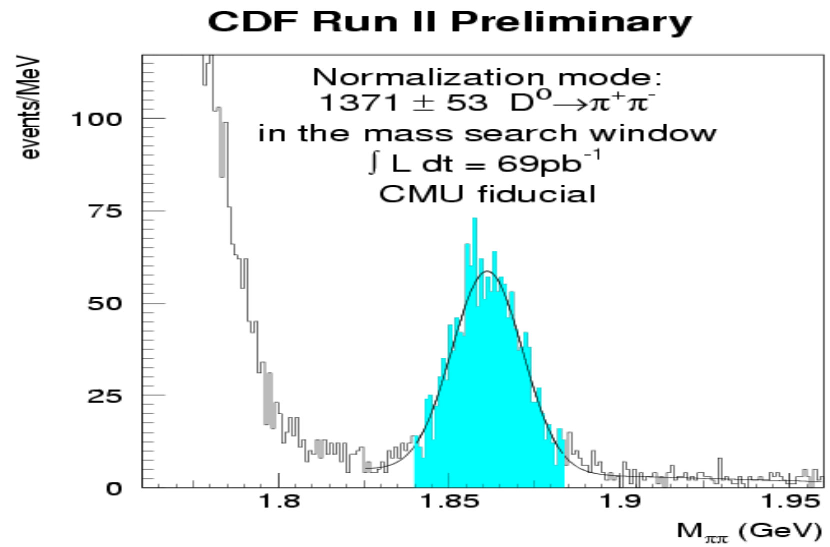
CDF $D^0 \to \mu\mu$ search

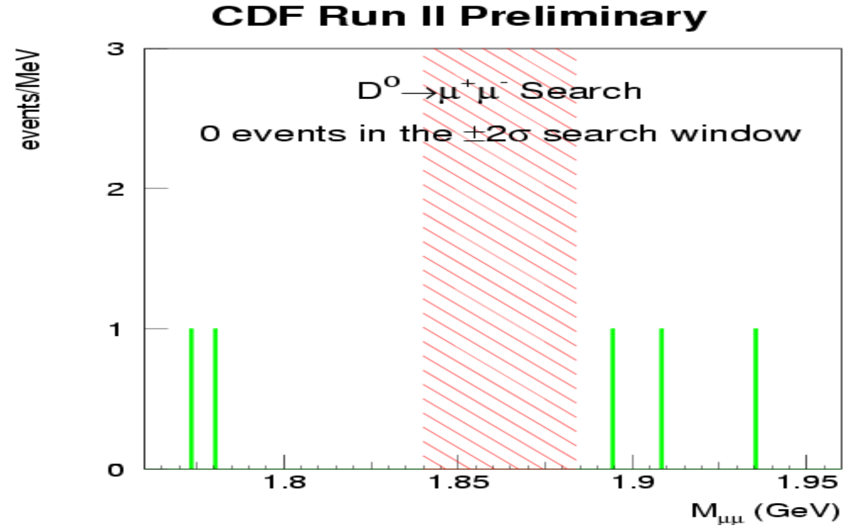
- SM expectation ~ 10^{-13}, RPV SUSY ~ 10^{-6}
- Best limit: <4.1×10^{-6} (90% CL)

- Events from all-hadronic trigger
- Normalize to $D^0 \to \pi\pi$
- Use D*-tagged D^0
- Backgrounds: 0.22±0.02 fakes, 1.5±0.7 combinatoric
- No events in signal region

- CDF limit: <2.4×10^{-6} (90% CL)

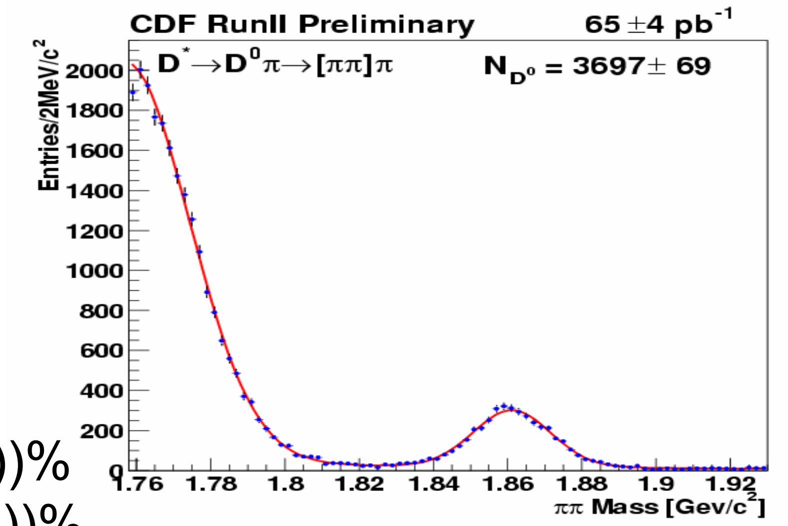
- Can extend to $D^0 \to ee, e\mu$ and $D^+ \to \pi\mu\mu$
- Experience for $B_s \to \mu\mu$





CDF D^0 CP asymmetries – new!

- Large cross section, trigger yield large number of $D^0 \to \pi\pi$, $D^0 \to KK$ $\to$ measure ratio of BR's.
- Requiring $D^{*\pm} \to D^0 \pi^\pm$ identifies flavor $\to$ measure CP asymmetry!

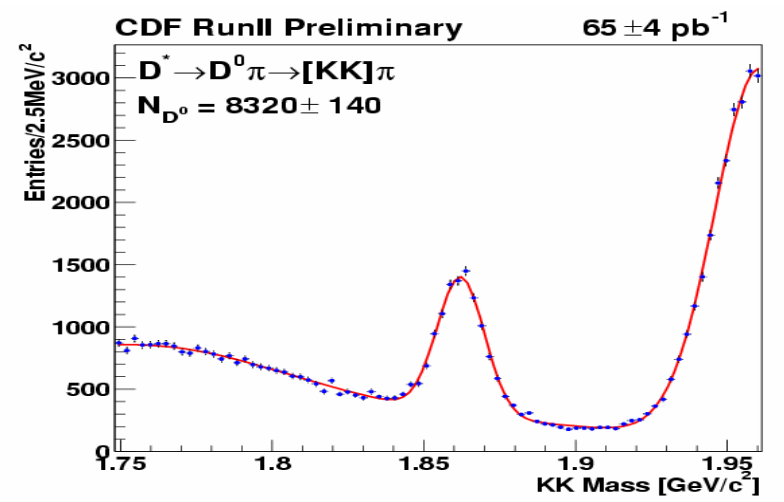


$A_{CP}(D^0 \to \pi\pi) = (2.0 \pm 1.7(stat) \pm 0.6(sys))\%$
$A_{CP}(D^0 \to KK) = (3.0 \pm 1.9(stat) \pm 0.6(sys))\%$

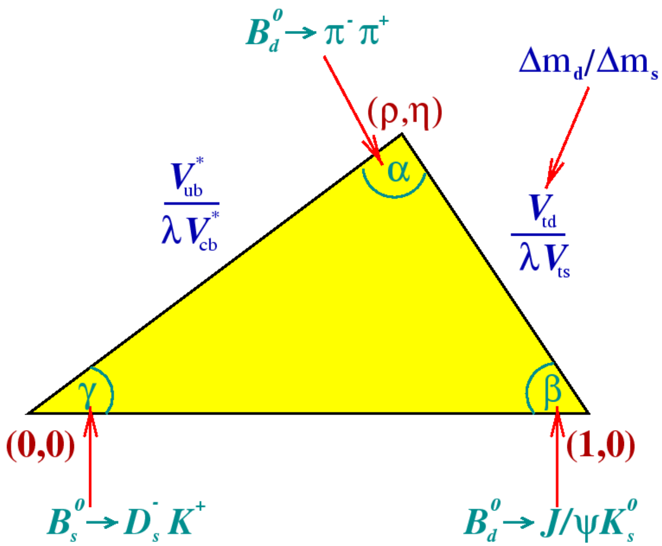
- Current PDG:

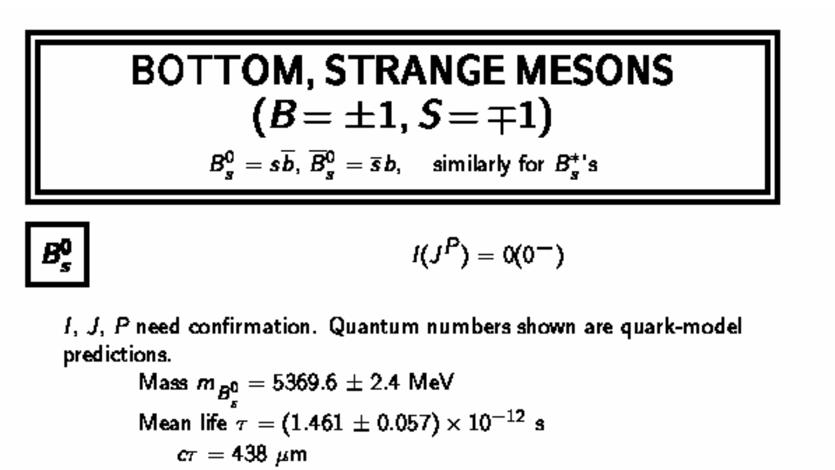
$A_{CP}(D^0 \to \pi\pi) = (0.5 \pm 1.6)\%$
$A_{CP}(D^0 \to KK) = (2.1 \pm 2.6)\%$

- Competitive, statistics-limited!



Why care about bottom?





BOTTOM, STRANGE MESONS
$(B = \pm 1, S = \mp 1)$

$B_s^0 = s\bar{b}$, $\overline{B}_s^0 = \bar{s}b$, similarly for B_s^*'s

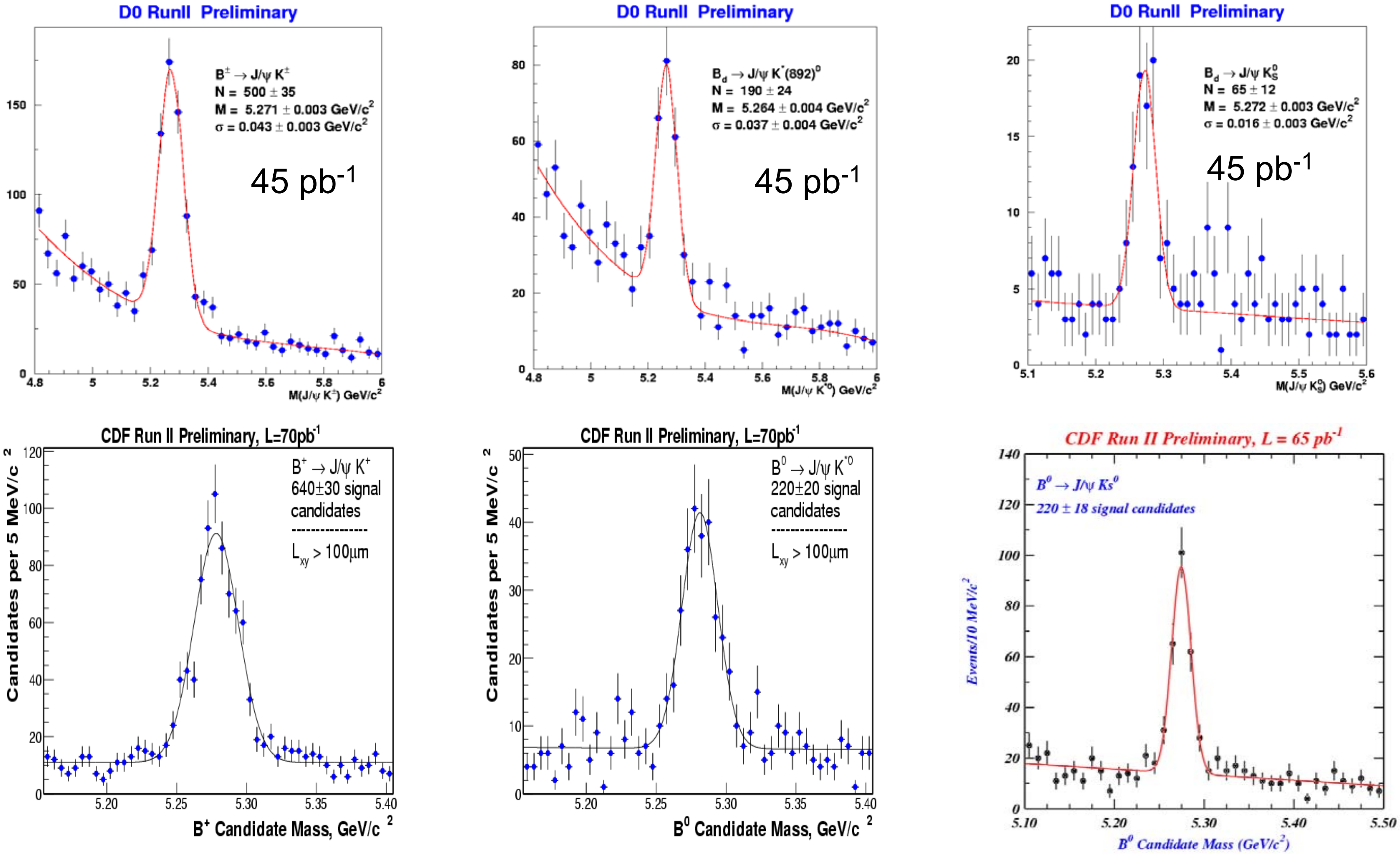
B_s^0 $\qquad I(J^P) = 0(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B_s^0} = 5369.6 \pm 2.4$ MeV
Mean life $\tau = (1.461 \pm 0.057) \times 10^{-12}$ s
$c\tau = 438$ μm

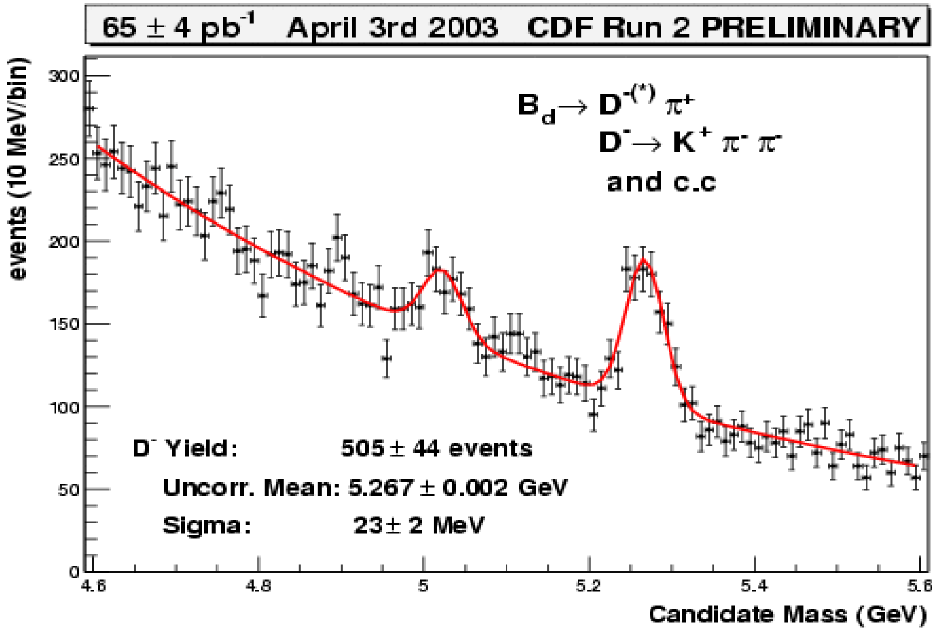
- B_d, B_u provide proof of principle, calibration:
  - Measure CKM angles
  - Rare decay
- B_s, B_c, Λ_b are unique to hadron colliders:
  - Explore properties
  - Test SU(3) flavor symmetry
  - Rare decays
  - Access to $|V_{ts}|$ via B_s mixing – short-term goal!
    - Reconstruct final states
    - Measure decay time
    - Identify flavor

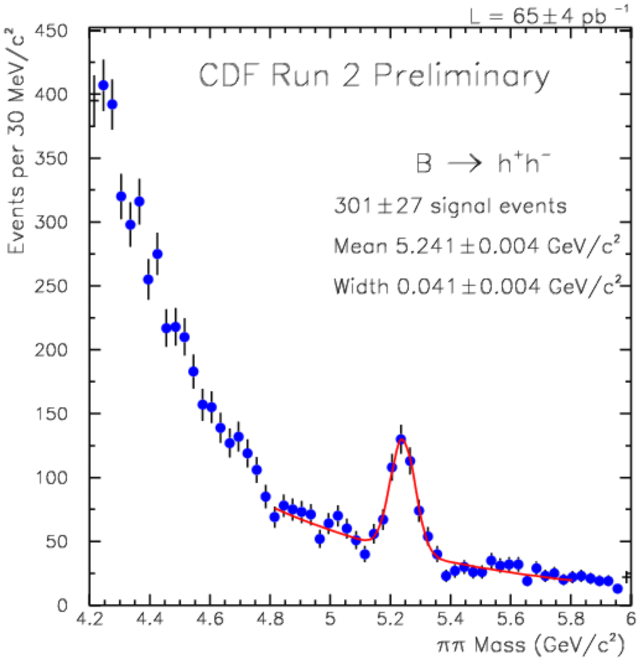
D0/CDF B_u,B_d decays with J/ψ



CDF other B_u,B_d decays

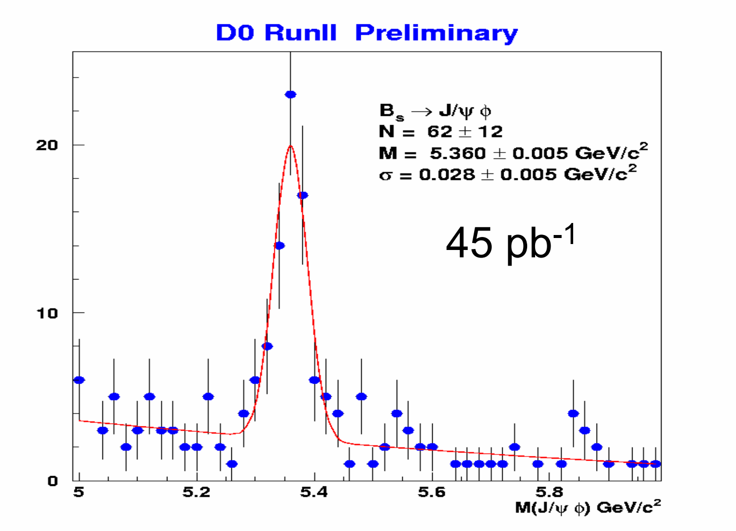
Find B decays in all-hadronic trigger samples – PID for B→hh soon

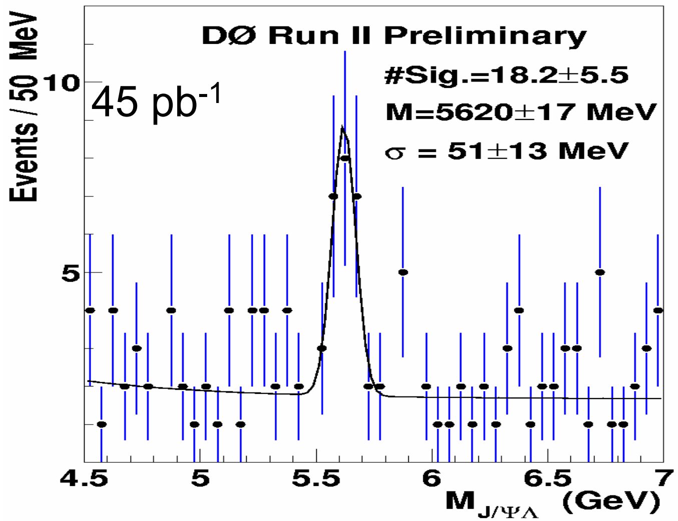


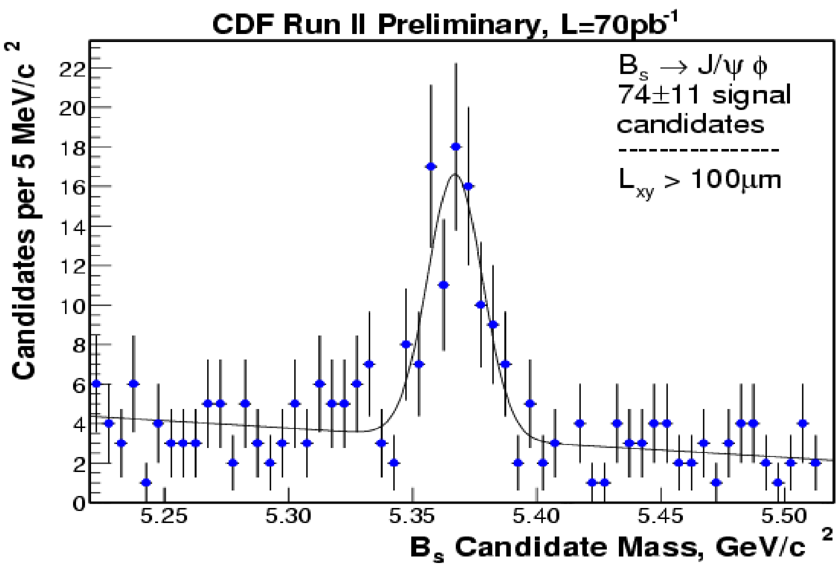


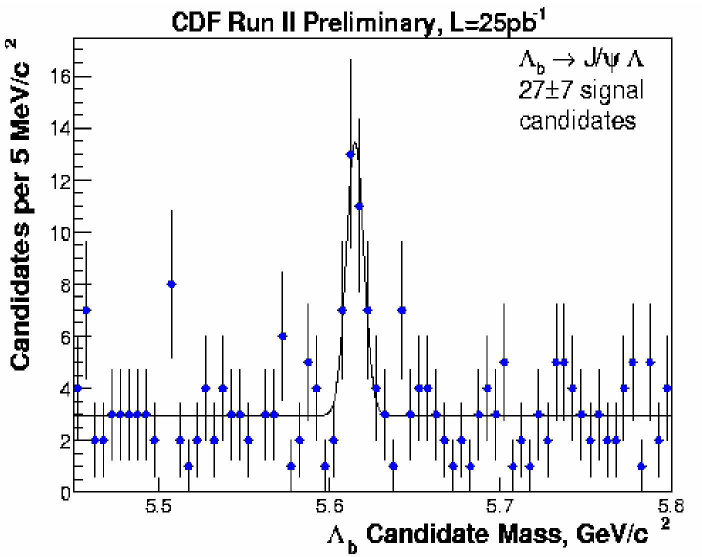
Also have signals for semileptonic decay modes

D0/CDF B_s, Λ_b decays to J/ψ



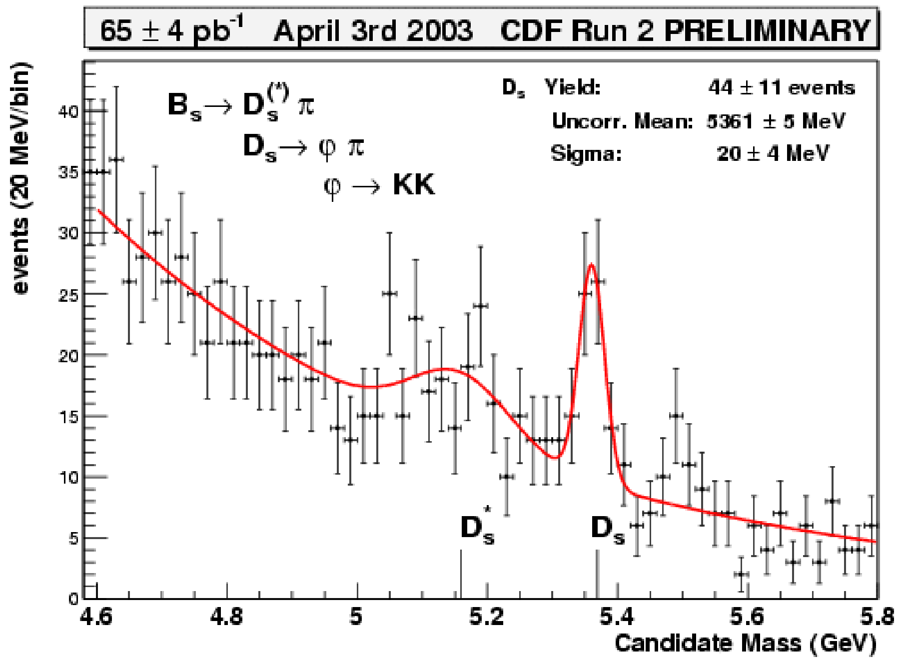


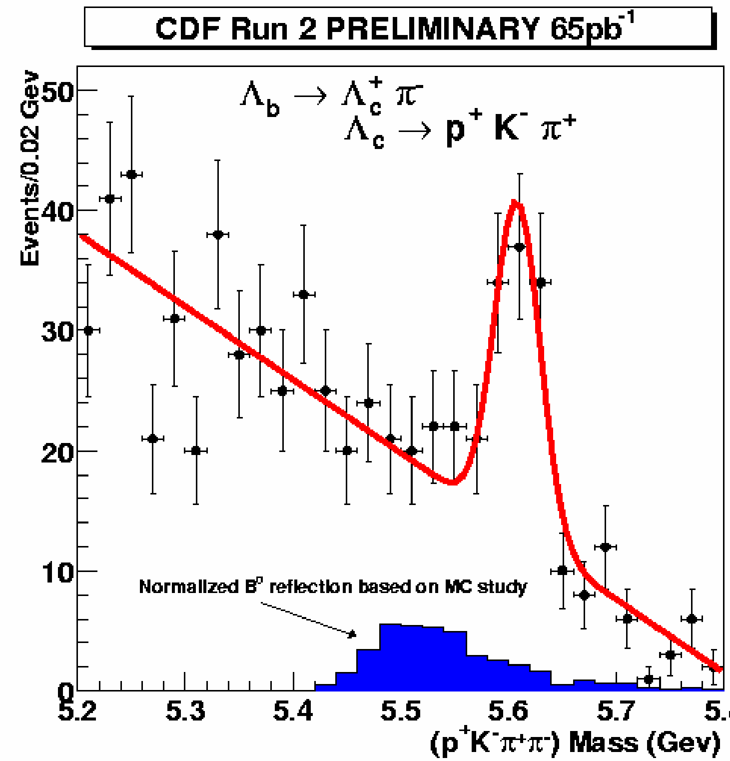




CDF other B_s, Λ_b decays

$D_s\pi$ is a golden mode for B_s mixing!



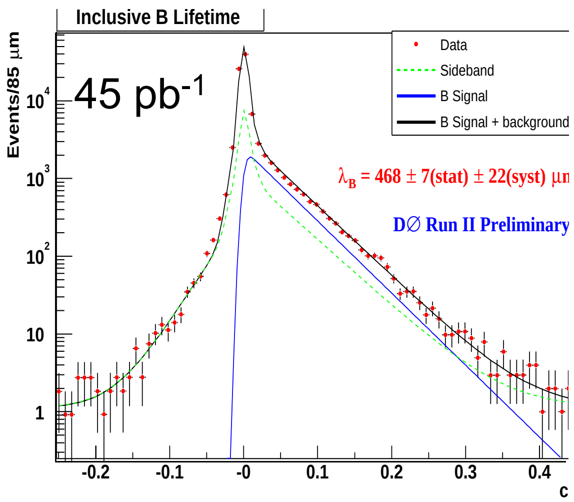


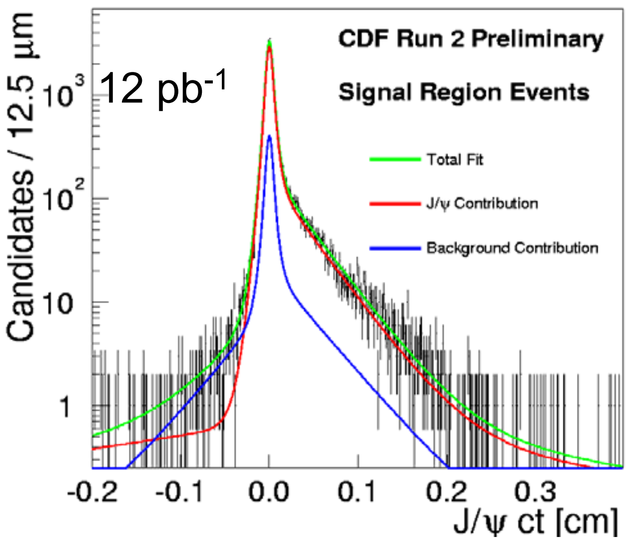
$$\frac{f_s}{f_d}\frac{Br(B_s \to D_s\pi)}{Br(B_d \to D^{\pm}\pi)} =$$

$$0.42 \pm 0.11(stat) \pm 0.11(BR)^{+0.06}_{-0.07}(sys)$$

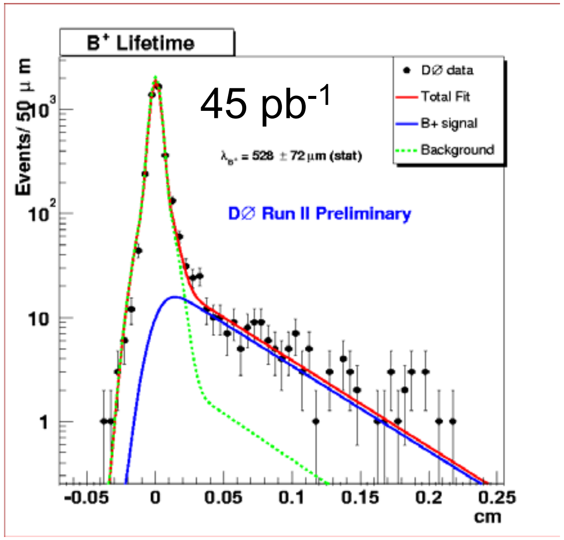
Also have signals for semileptonic decay modes for B_s, Λ_b

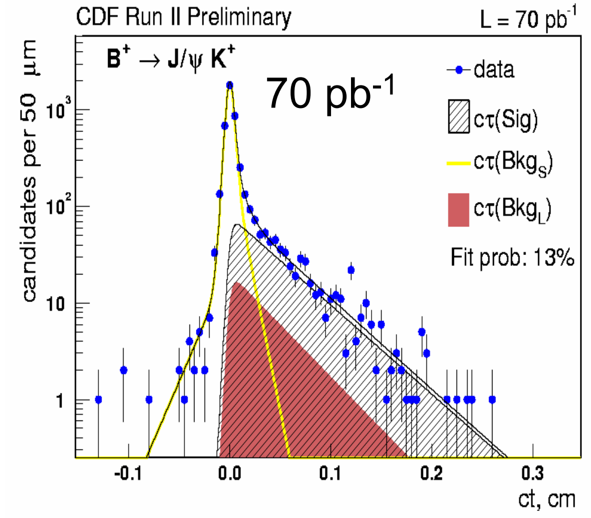
D0/CDF lifetimes with J/ψ





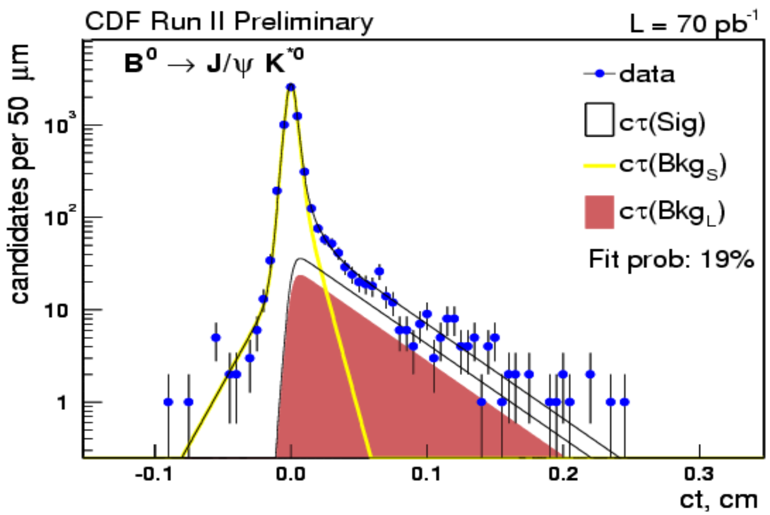
Average lifetime of b hadrons, use J/ψ decay length as approximation, correct with MC.

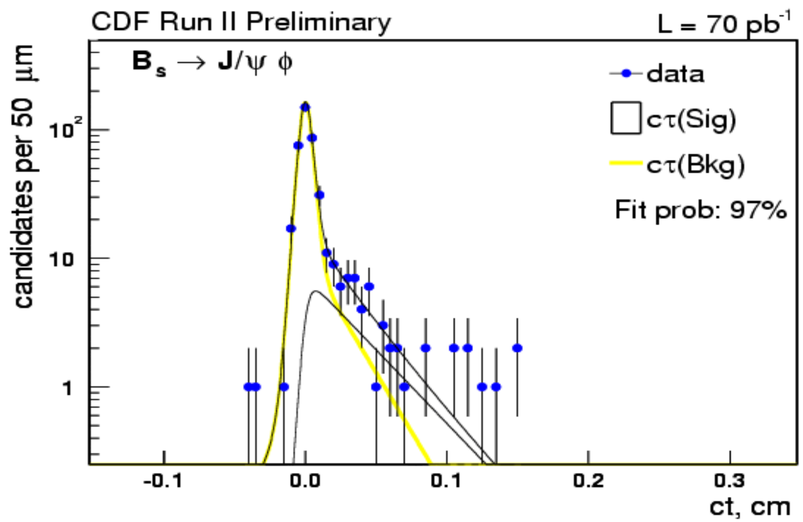




Lifetime of B+, using complete reconstruction of the meson decay length.

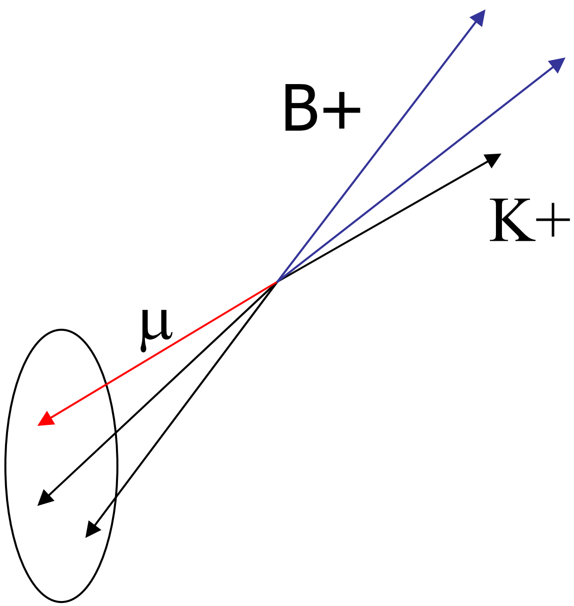
D0/CDF lifetimes with J/ψ





	PDG	CDF	D0
τ_b (ps)	1.564 ± 0.014	1.53 ± 0.03 ± 0.04	1.56 ± 0.02 ± 0.07
τ_{Bu} (ps)	1.674 ± 0.018	1.57 ± 0.07 ± 0.02	1.76 ± 0.24 (stat)
τ_{Bd} (ps)	1.542 ± 0.016	1.42 ± 0.07 ± 0.02	
τ_{Bs} (ps)	1.461 ± 0.057	1.26 ± 0.20 ± 0.02	
τ_{Bu}/τ_{Bd}	1.083 ± 0.017	1.11 ± 0.09	
τ_{Bs}/τ_{Bd}	0.947 ± 0.038	0.89 ± 0.15	

D0 flavor tagging



$$\varepsilon = \frac{N_{right} + N_{wrong}}{N_{right} + N_{wrong} + N_{notag}}$$

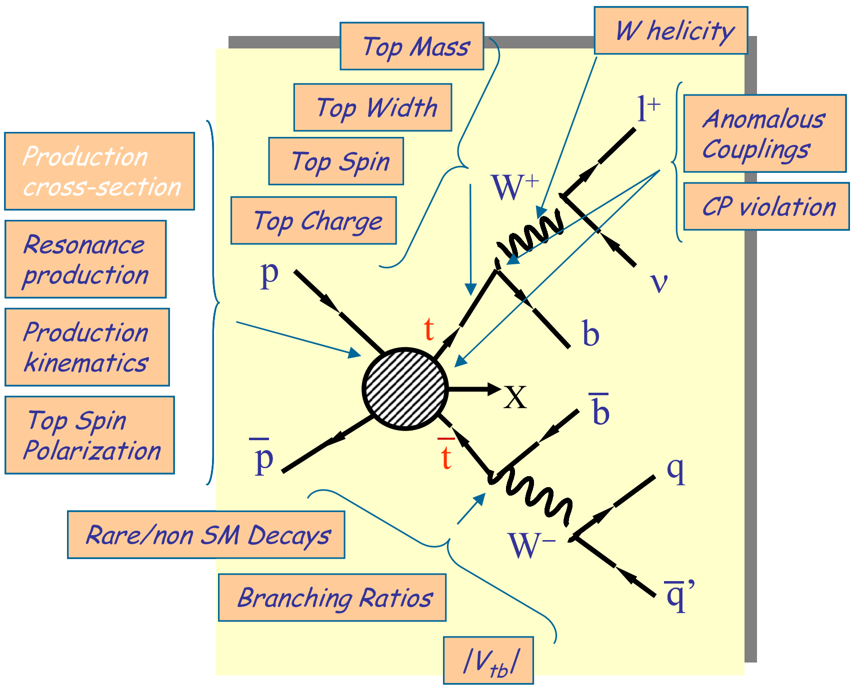
$$D = \frac{N_{right} - N_{wrong}}{N_{right} + N_{wrong}}$$

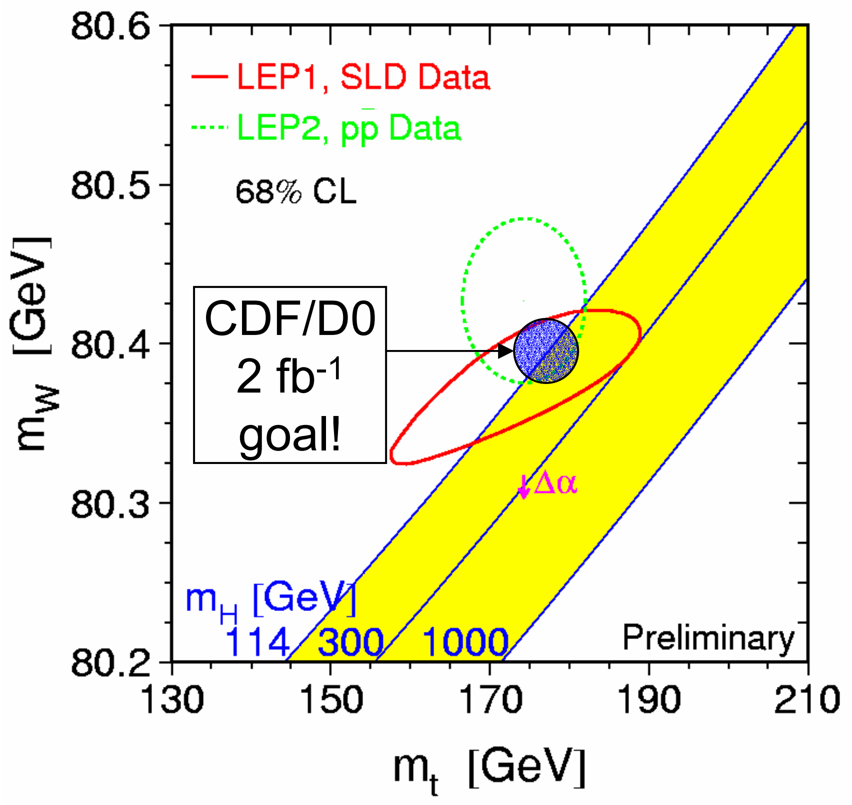
Significance of mixing measurement goes as tagging power εD^2

	Muon	Jet
ε (%)	8.2±1.9	55.1±4.1
D (%)	63.9±30.1	21.0±10.6
εD^2 (%)	3.3±1.8	2.4±1.7

Identify flavor of B with:
- Muon charge
- Jet charge

Why care about top?



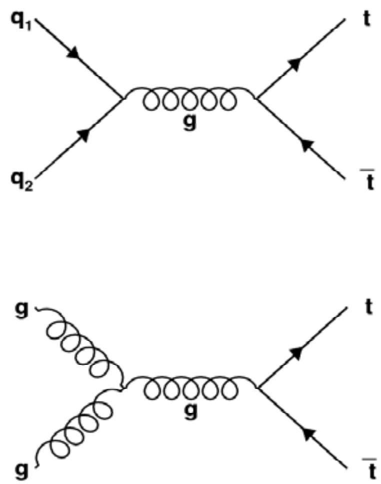


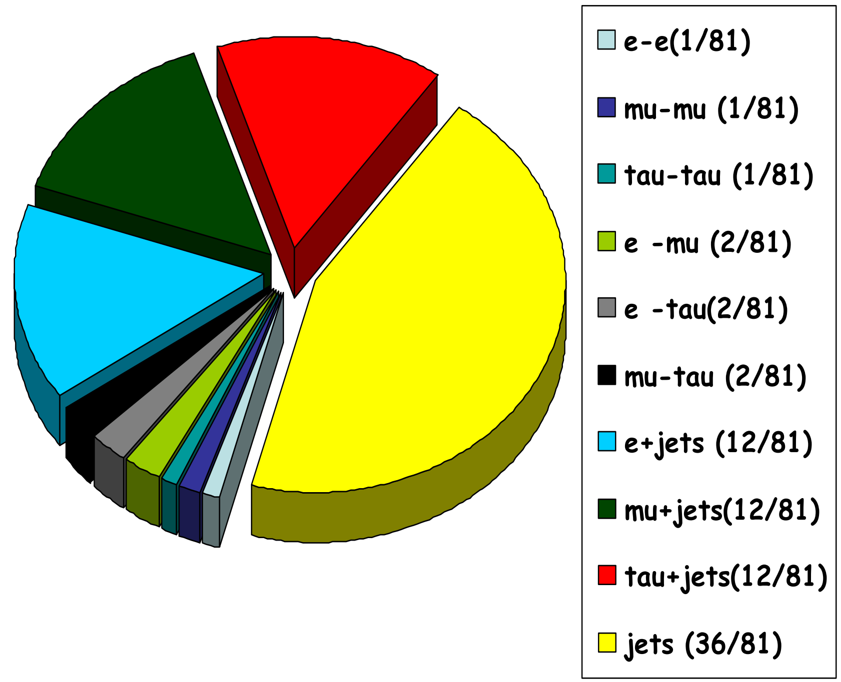
Quantum numbers?
Production properties?
Decay properties?

Relation to other particles?
Is it special?
Clues to new physics?

SM top-physics overview

Top-antitop pair production via strong interaction:





EW single-top production x2 smaller rate, not seen.

$t\bar{t} \rightarrow \ell \nu b \ell \nu b \Rightarrow$ dilepton (5%)

$t\bar{t} \rightarrow \ell \nu b q q b \Rightarrow$ lepton + jets (44%)

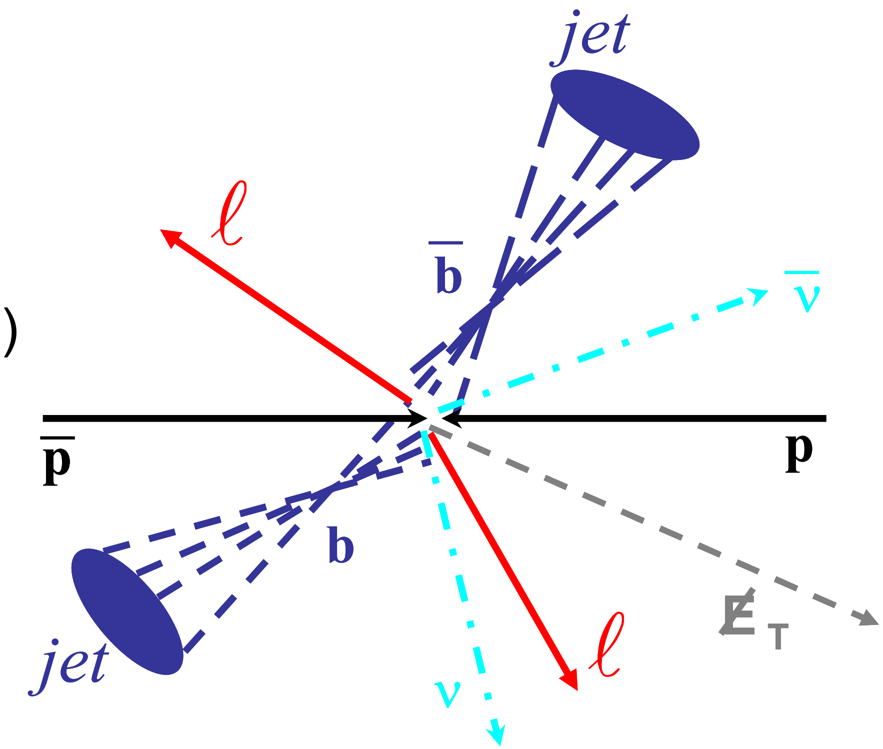
B($t \rightarrow Wb$) = 100%, label decays by W modes

Theory prediction: $\sigma_{tt} = 6.7^{+0.8}_{-0.9}$ pb @ 1.96 TeV (Cacciati *et al.*)

Dilepton mode

- Clean, low background
- Small rate, two neutrinos

- Two isolated high-p_T leptons (e,μ)
- Large missing $\not{E}_T$
- At least two jets
- Large total energy
- Backgrounds from $Z/\gamma \rightarrow ll$, WW/WZ, lepton fakes, QCD

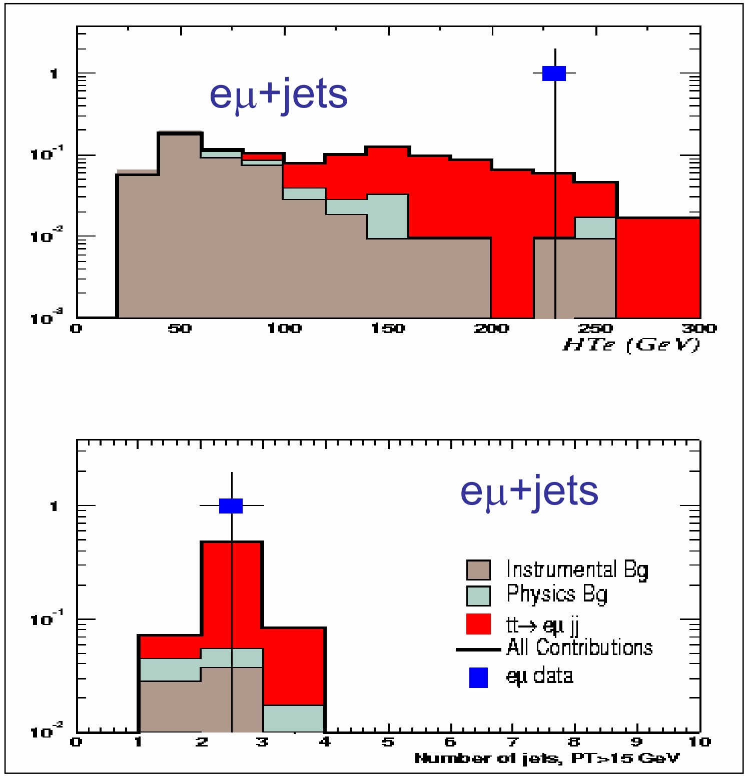


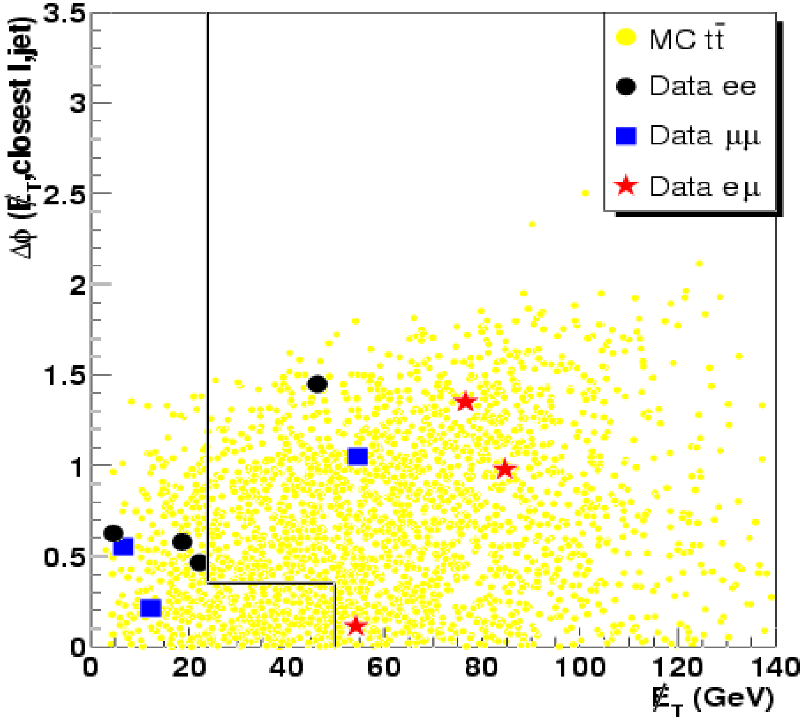
- CDF: Veto Z-mass window for ee,$\mu\mu$; $\not{E}_T$ separated from l, jets
- D0: Raise $\not{E}_T$ cut in Z window

D0/CDF Run II dilepton results

D0 Run II preliminary:
4 ee, 2 μμ, 1 eμ observed
1.7±0.5 background, 33-48 pb^{-1}

CDF Run II preliminary:
1 ee, 1 μμ, 3 eμ observed
0.3±0.1 background, 79 pb^{-1}



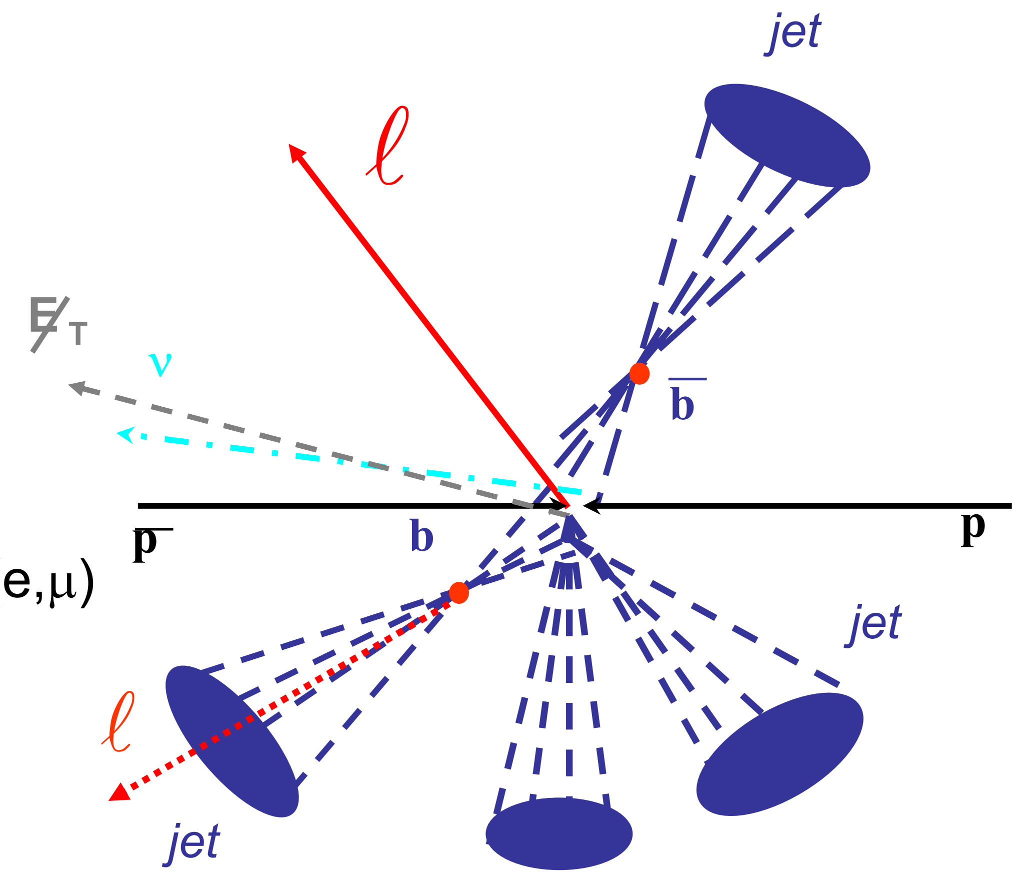


$$\sigma(t\bar{t}) = 13.2 \pm 5.9(\text{stat}) \pm 1.5(\text{sys}) \pm 0.8(\text{lum})\ \text{pb}$$

$$\sigma(t\bar{t}) = 29.9^{+21.0}_{-15.7}(\text{stat})^{+14.1}_{-6.1}(\text{sys}) \pm 3.0(\text{lum})\ \text{pb}$$

Lepton plus jets mode

Larger rate than dileptons, straightforward kinematics, substantial backgrounds:
- W+jets production
- QCD multijets
- Detector fakes, dibosons



- One isolated high-p_T lepton (e,μ)
- Large missing $\not\!\!E_T$
- At least three jets
- Not a dilepton event

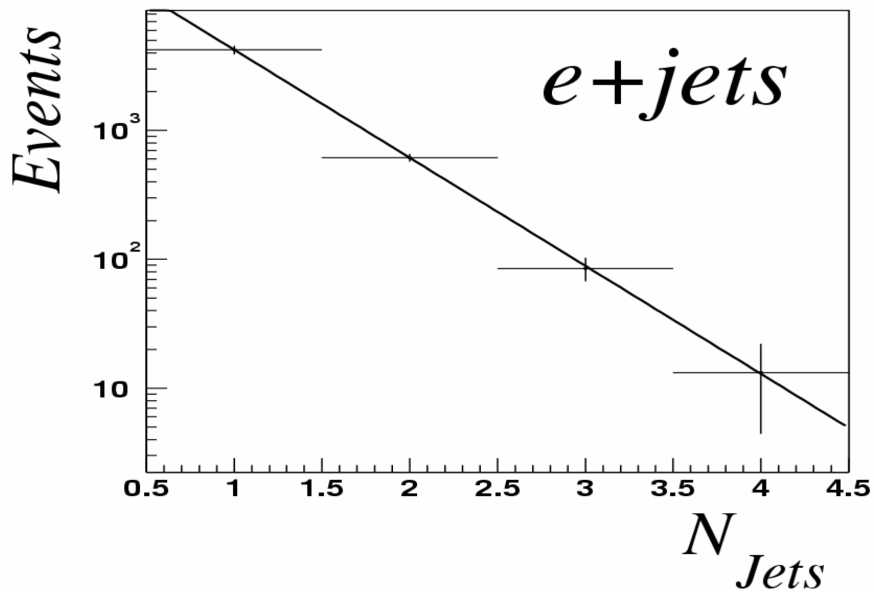
D0: Require four jets and kinematics, or soft-lepton b tag
CDF: Require displaced-vertex b tag

D0 Run II lepton plus jets results

- Select W sample (lepton+$\not{E}_T$), no soft-lepton b tags.

- Evaluate QCD backgrounds from data in each N_{jet} bin
- Evaluate W+jets backgrounds in four-jet events via Berends scaling

- Apply topological cuts: H_T, aplanarity
- Count four-jet events

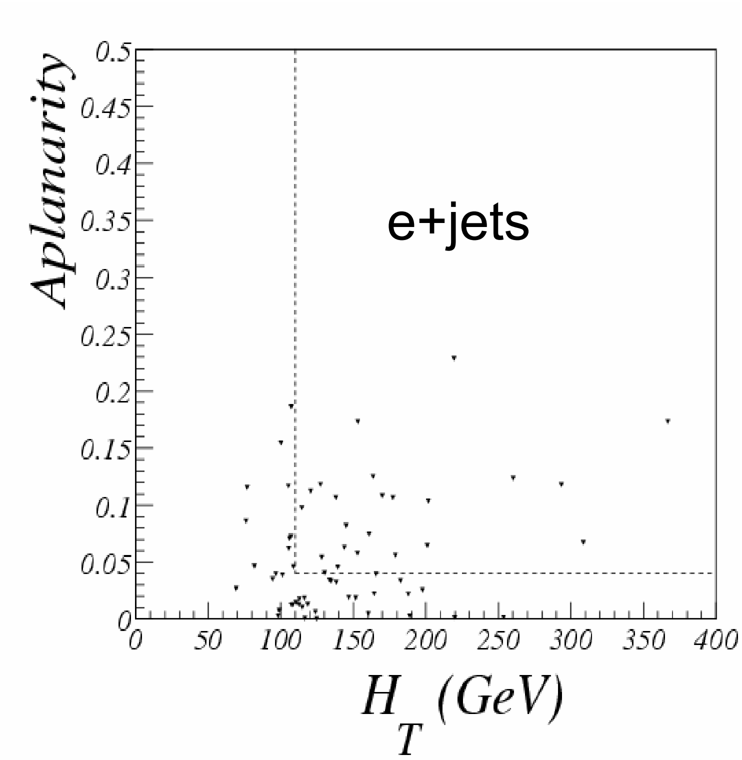


	N_W	N_{QCD}	All BG	N_{obs}
e+jets	1.3±0.5	1.4±0.4	2.7±0.6	4
μ+jets	2.1±0.9	0.6±0.4	2.7±1.1	4

D0 Run II lepton plus jets results

- Enhance S/B with soft-lepton tagging, include three-jet events.
- Similar preselection, looser H_T, aplanarity requirements

	All BG	N_{obs}
e+jets	**0.2±0.1**	**2**
μ+jets	**0.7±0.4**	**0**



Lepton plus jets analyses (40-49.5 pb^{-1}:)

$$\sigma(t\bar{t}) = 5.8^{+4.3}_{-3.4}(\text{stat})^{+4.1}_{-2.6}(\text{sys}) \pm 0.6(\text{lum})\ \text{pb}$$

(preliminary)

Combined D0 top cross section

$$\sigma(t\bar{t}) = 8.5^{+4.5}_{-3.6}(\text{stat})^{+6.3}_{-3.5}(\text{sys}) \pm 0.8(\text{lumi})\ \text{pb}$$

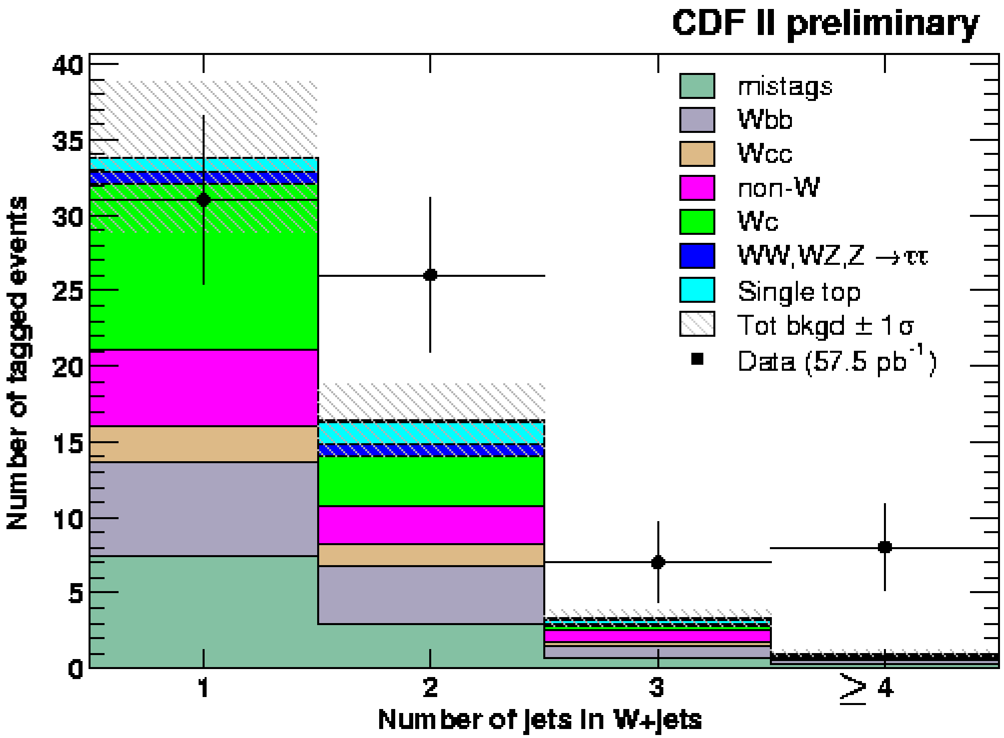
(preliminary)

CDF Run II lepton plus jets results

Require at least one jet w/displaced-vertex tag, ε_{tag} = (45 ± 5)% for $t\bar{t}$.

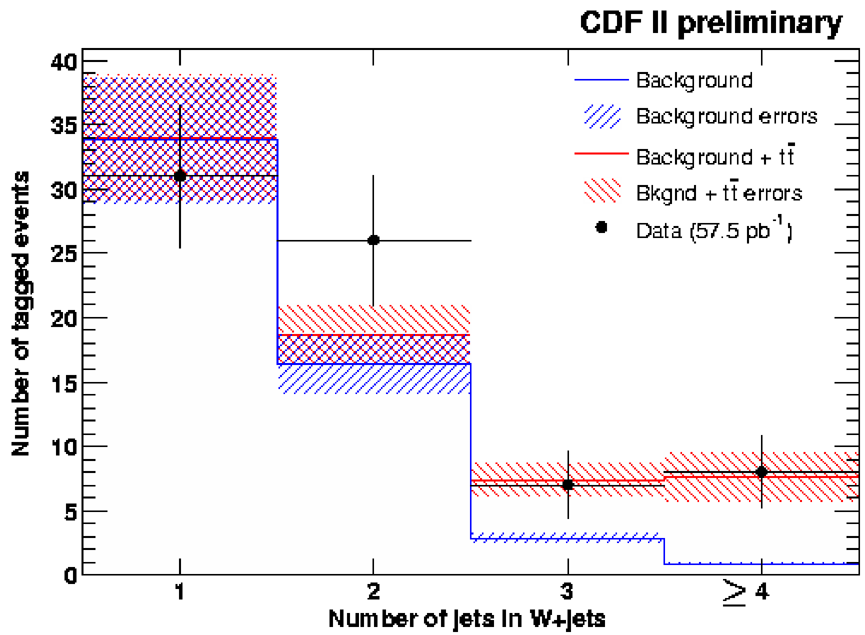
Account for all non-top SM processes:

- Mistags from “negative” tag rate in data
- Non-W from data
- Dibosons, single-top from MC.
- W+heavy flavor from MC fractions, b-tag efficiency, normalized to # of W in data.



Any excess in ≥ 3 jets attributed to top!

CDF Run II lepton plus jets results



	W+1jet	W+2jets	W+3jets	W+≥4jets
Events before tagging	4913	768	99	26
Events after tagging	31	26	7	8
Background	33.8±5.0	16.4±2.4	2.88±0.05	0.87±0.2
SM Bkgnd + $t\bar{t}$	34.0±5.0	18.65±2.4	7.35±1.4	7.62±2.0

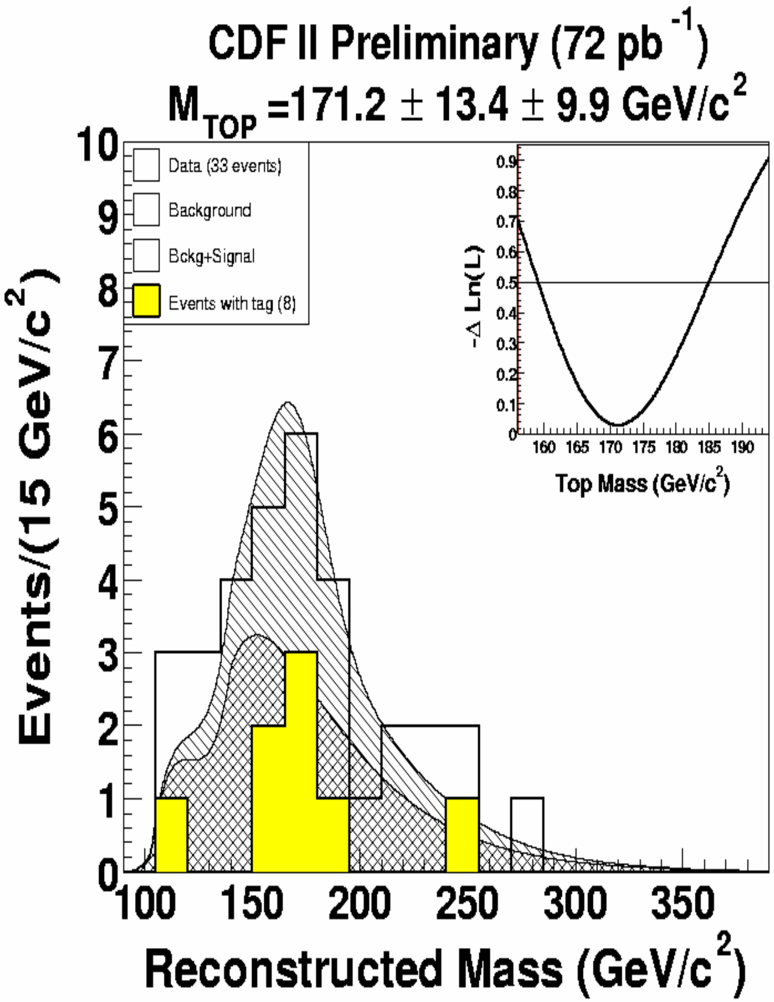
$$\sigma(t\bar{t}) = 5.3 \pm 1.9(\text{stat}) \pm 0.8(\text{sys}) \pm 0.3(\text{lum})\ \text{pb} \quad (57.5\ \text{pb}^{-1})$$

CDF Run II top mass

- 33 lepton plus 4 jets candidates
- No b tags required → 24 jet combinations per event, choose one with minimum χ^2
- Fit to signal, background shapes

- Target jet-energy resolution is 3 GeV for Run 2a.

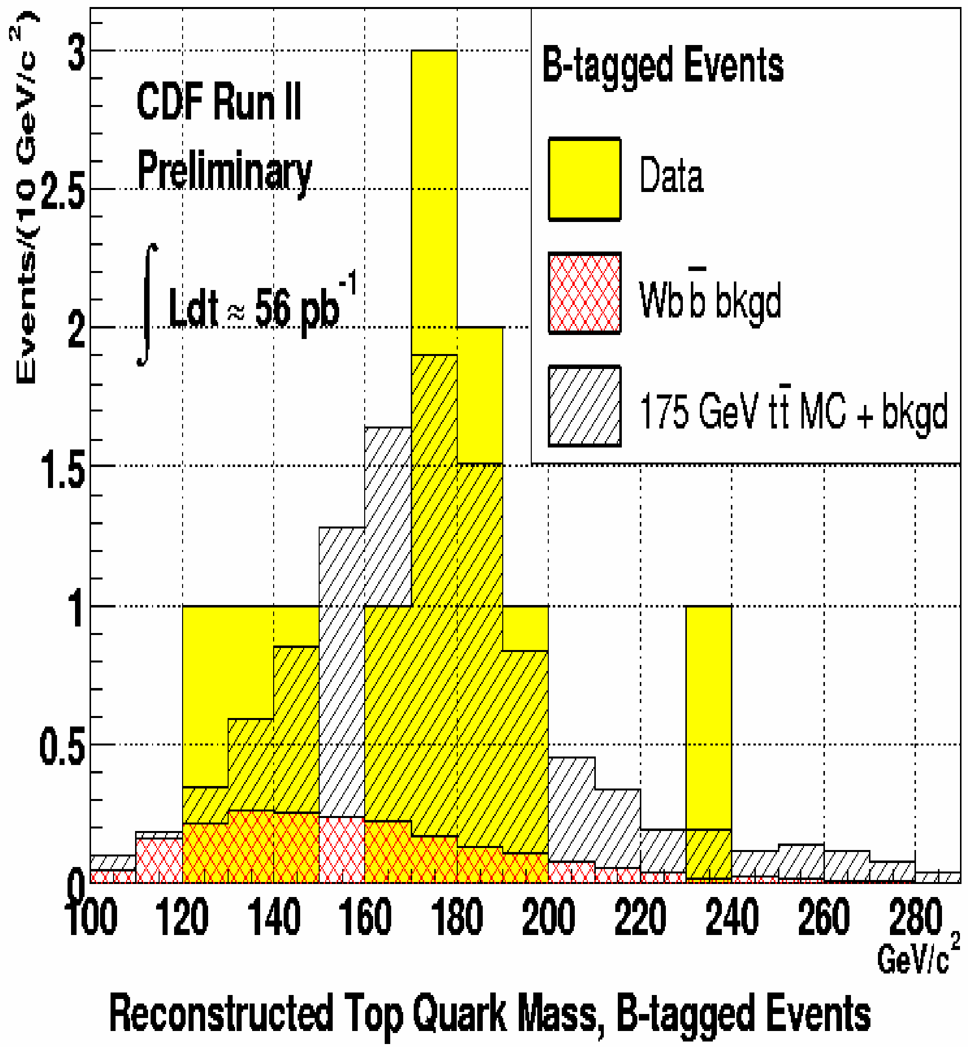
Source	Uncertainty (GeV/c^2)
Jet Energy Measurement	9.3
Initial and Final State Radiation	2.4
Background Shape	0.3
Parton Distribution Functions	1.8
Monte-Carlo Generators	1.8
Total	9.9



CDF Run II top mass – b tags

- Require at least one tagged jet:
    - 12 combinations
    - Better S/B
- Allow lower-energy 4^{th} jet
- 11 candidates

- Work in progress



Summary: charm and bottom

- Charm:
  - Detector upgrades give new physics program!
  - Results already competitive with world's best.
  - Excellent calibration for B physics.
- Bottom:
  - Studies of B_u and B_d give proof of principle.
  - Run 2 already reaching Run 1 precision.
  - Beginning studies of B_s and Λ_b.
  - Work underway for mixing measurements.

Summary: top and beyond

- Top quark is “rediscovered”:
  - Benchmark measurements performed, consistent with expectations.
  - Starting precision studies of top properties, searches for new physics.
- Experiments are performing to expected capabilities, systematics will still be improved, most measurements are statistics-limited.
- Eagerly awaiting additional data!