Recent Physics Results from CDF and D0

Evelyn J. Thomson
The Ohio State University

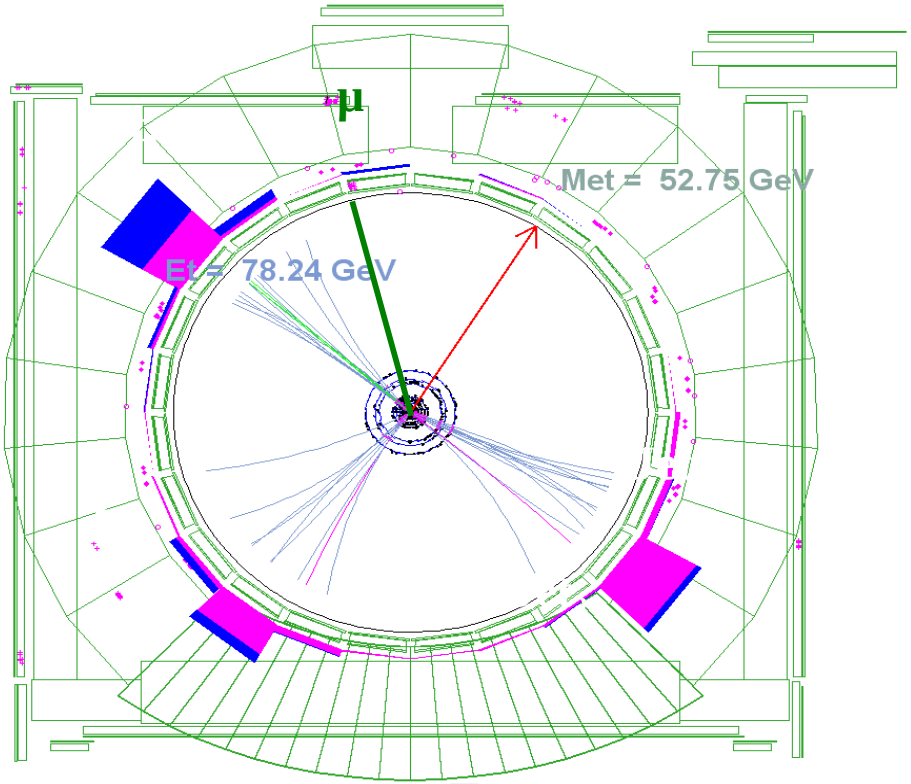
B physics
- B_s and Λ_b properties
- B_s mixing

Electroweak physics
- W width
- Z FB asymmetry

Top physics
- Top production
- Top mass

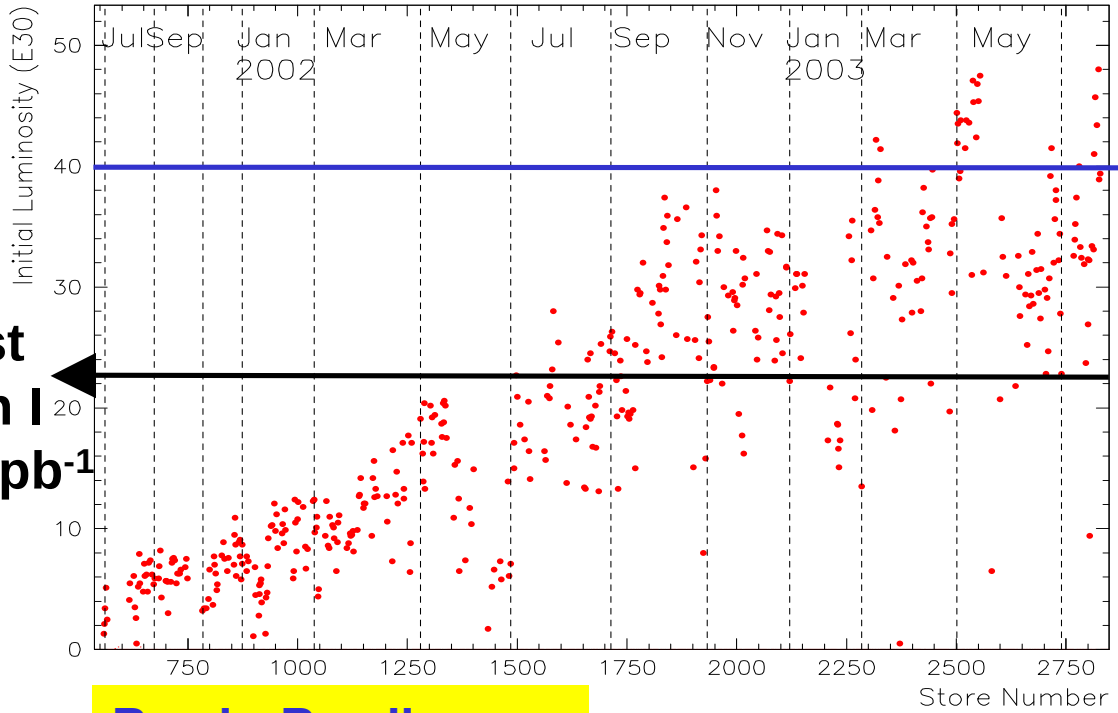
QCD
- Inclusive jet production

Searches for new physics
- Extra dimensions
- SUSY
- Leptoquarks
- Rare decays



$t\bar{t} \rightarrow \mu\nu q\bar{q}'b\bar{b}$ candidate from CDF Run II

Performance of Fermilab Tevatron



Best Run I 110pb^{-1}

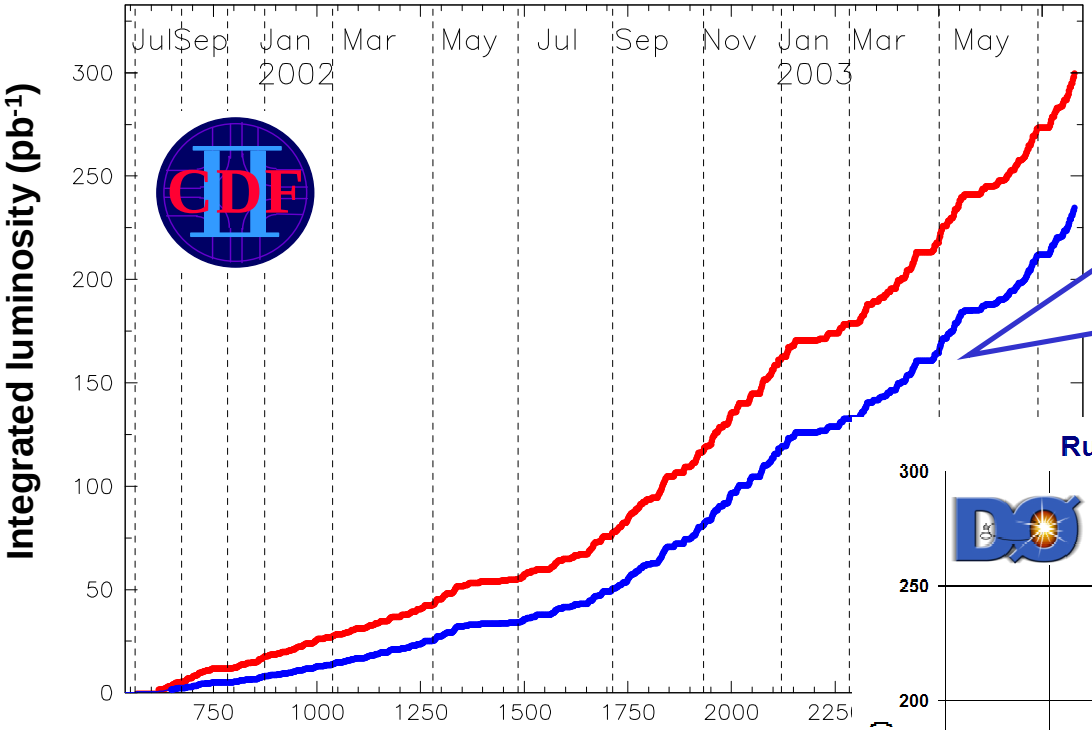
Current Initial Luminosity ~40x10^{30} cm^{-2}s^{-1}

Integrated Luminosity ~200 pb^{-1} this year

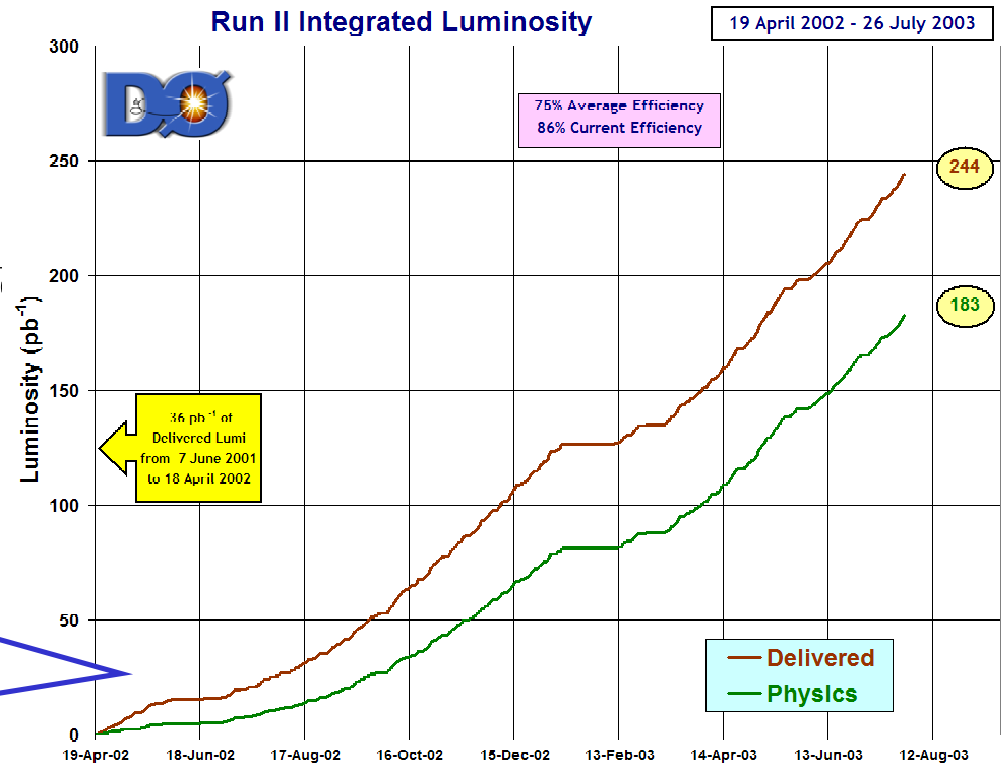
Run II Goals
>2000 pb^{-1} in 2007
>4000 pb^{-1} in 2009

Run I→Run II
E_{CM}=1.8→1.96 TeV
T_{bunch}=3500→396 ns

CDF and D0 status: Run II > Run I!



CDF since June 2001
Delivered ~ 300 pb^{-1}
Recorded ~ 230 pb^{-1}
Summer 2003 prelim. results ~ 140 pb^{-1}



D0 since April 2002
Delivered ~ 240 pb^{-1}
Recorded ~ 180 pb^{-1}
Summer 2003 prelim. results ~ 130 pb^{-1}

“Physics at a hadron collider…

…is like drinking from a fire-hose!”
…is like panning for gold!”
…is all about the trigger!’

High p_T lepton
High E_T jet, photon
High Missing E_T (MET)
Displaced hadrons from bottom and charm decay

Examine each $p\bar{p}$ collision (1.7 MHz)
Select few interesting events (<70 Hz)
Store for further offline analysis

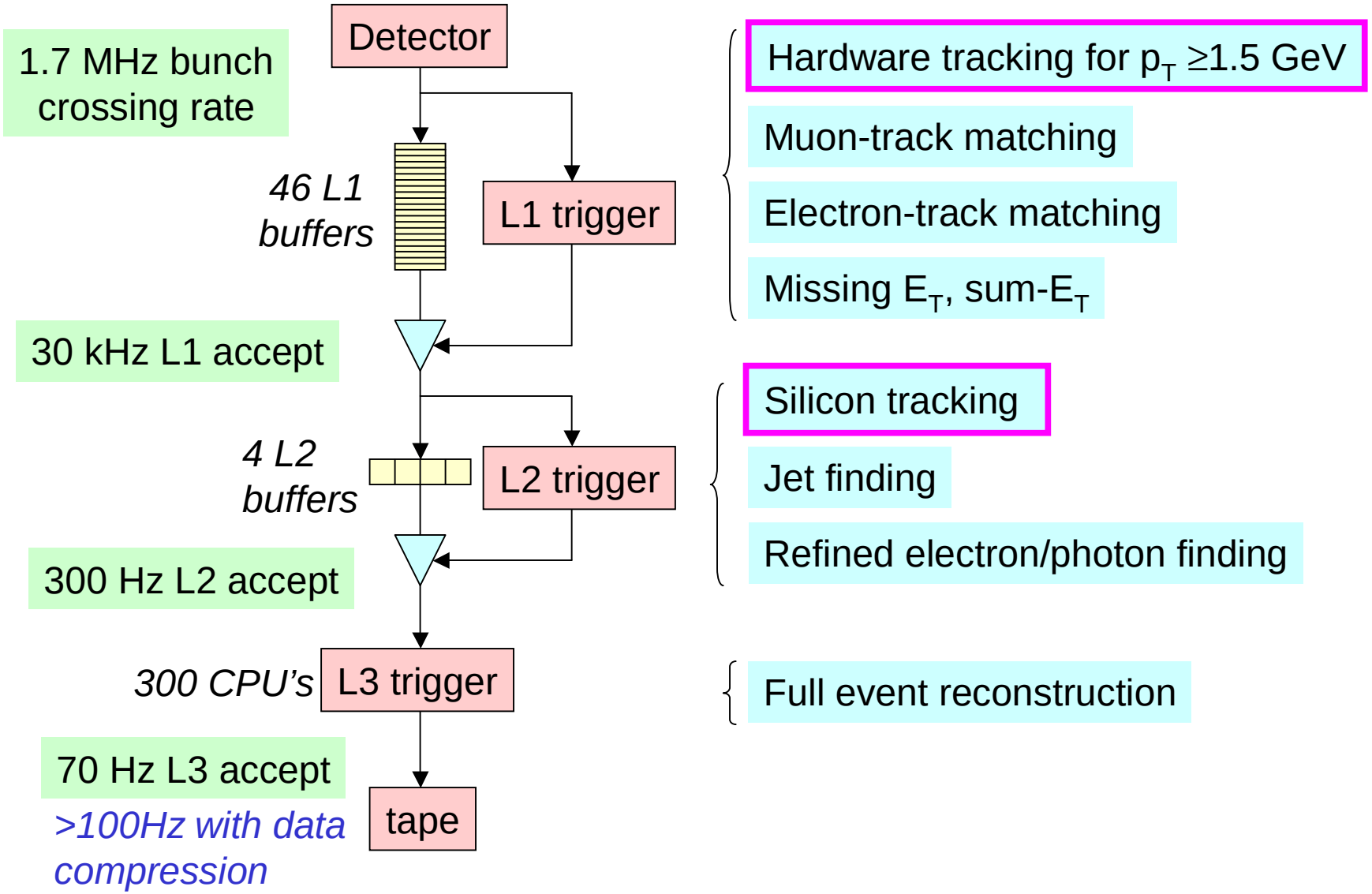
Keep 1 out of 25,000

Process	Cross-section	Event Rate
Inelastic $p\bar{p}$	60 mb	6 MHz
$p\bar{p}\rightarrow b\bar{b}$ (b p_T>6 GeV, $\lvert\eta\rvert$<1)	10 μb	1 kHz
$p\bar{p}\rightarrow WX\rightarrow \ell\nu X$	5 nb	0.4 Hz
$p\bar{p}\rightarrow ZX\rightarrow \ell\ell X$	0.5 nb	0.04 Hz
$p\bar{p}\rightarrow t\bar{t}\rightarrow WWb\bar{b}\rightarrow \ell\nu b\bar{b}X$	2 pb	0.0002 Hz
$p\bar{p}\rightarrow WH\rightarrow \ell\nu b\bar{b}$ (if M_H=120GeV)	15 fb	0.0000015 Hz

Assume L =100x10^{30} $cm^{-2}s^{-1}$, ℓ=electron or muon

$$\eta = 0.5\ln\left(\frac{p+p_z}{p-p_z}\right) = -\ln\tan\frac{\theta}{2}$$

Three level trigger - CDF



CDF Level 1 Track Trigger

Heart of CDF Run II trigger

L1 tracks p_T>1.5GeV every 132ns

Efficiency=96% $\sigma(\Phi)$=5mr

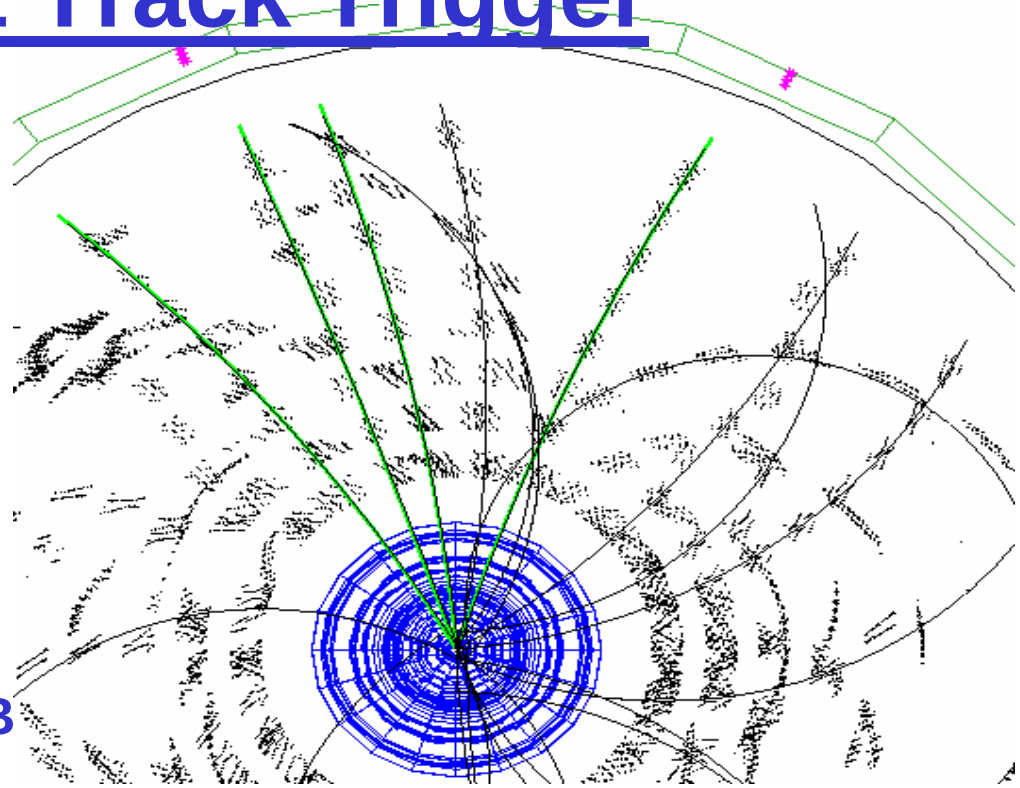
$\sigma(p_T)$=(1.74 p_T)%

L1 electron = L1 track + EM cluster

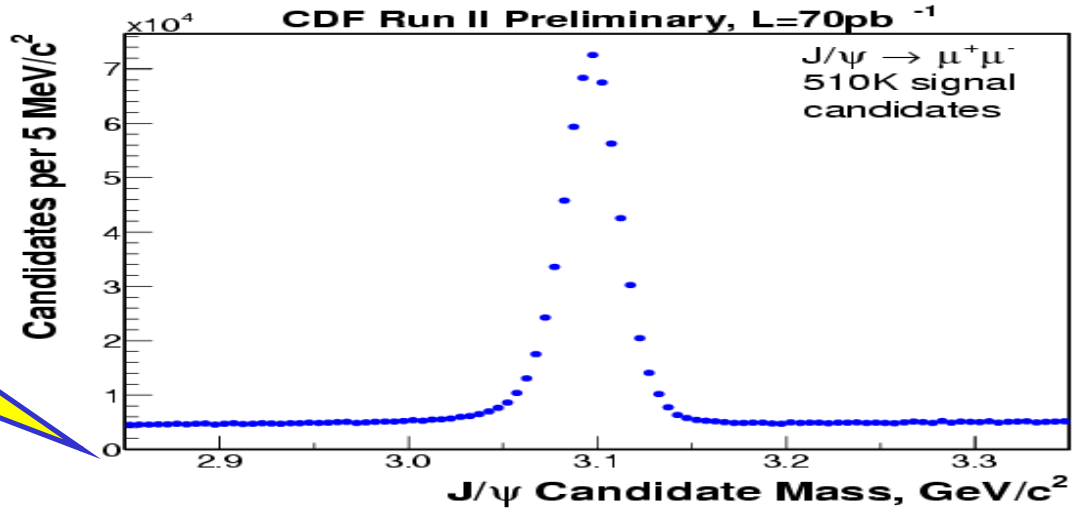
L1 muon = L1 track + muon stub

L1 high p_T lepton triggers for W/Z

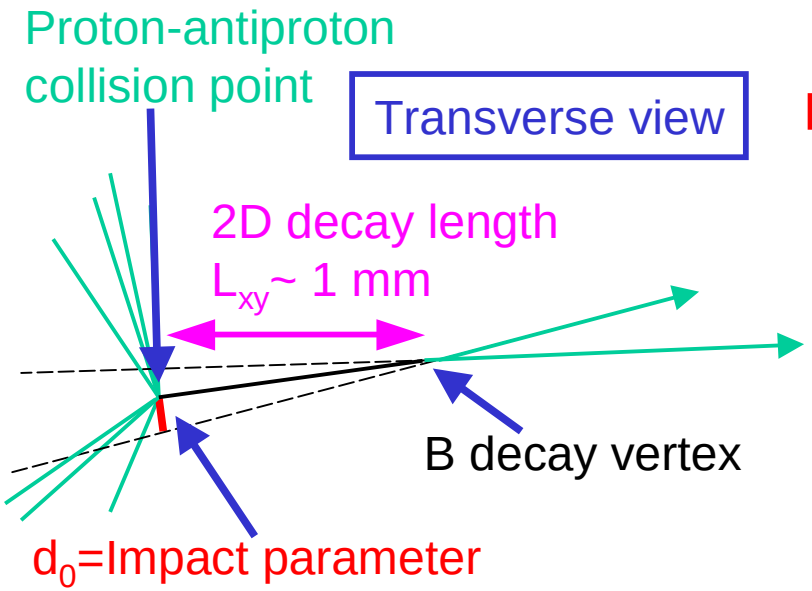
L1 low p_T lepton/track triggers for B



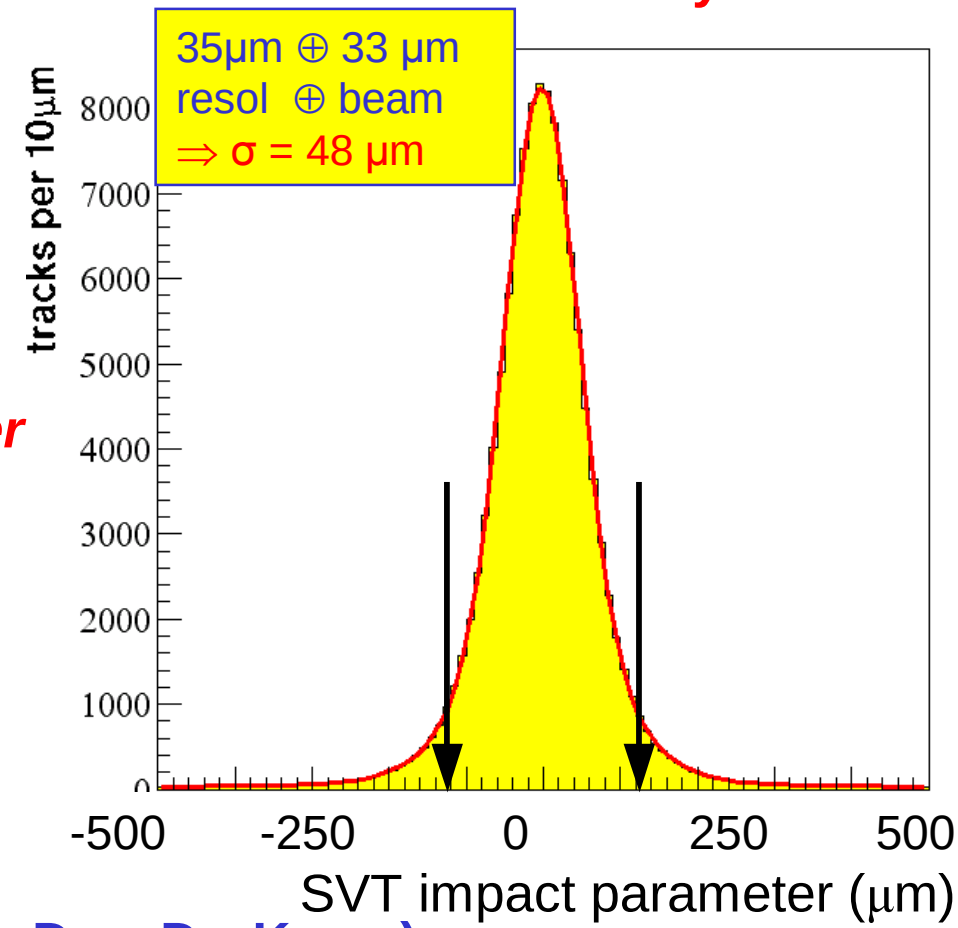
Low p_T di-muon trigger:
2 L1 muons p_T>1.5 GeV
Collect J/Ψ's for calibration and B physics



CDF Level 2 Silicon Vertex Trigger



Exploit long b, c lifetimes in Trigger!
L1 track + Si hits = Impact parameter @L2
A first at a hadron collider!
CDF is a charm/ B Factory!



Lepton (e, μ) + displaced track trigger

Lepton:p_T>4 GeV
Track: p_T>2 GeV, d_0>120 μm
Semi-leptonic B decays (B→ℓνX)

Displaced two track trigger

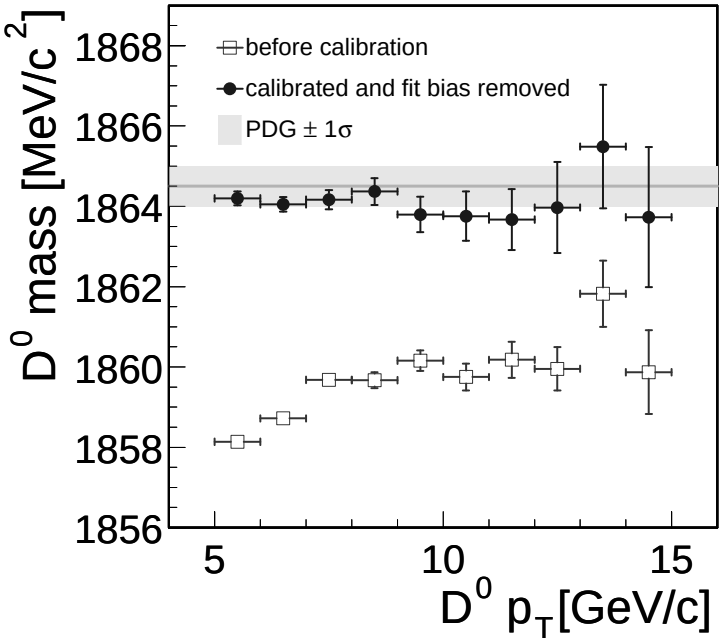
Tracks: p_T>2 GeV, d_0>120 μm
Σp_T>5.5 GeV
Fully hadronic B decays (B→hh', B_s→D_sπ, D→Kπ …)

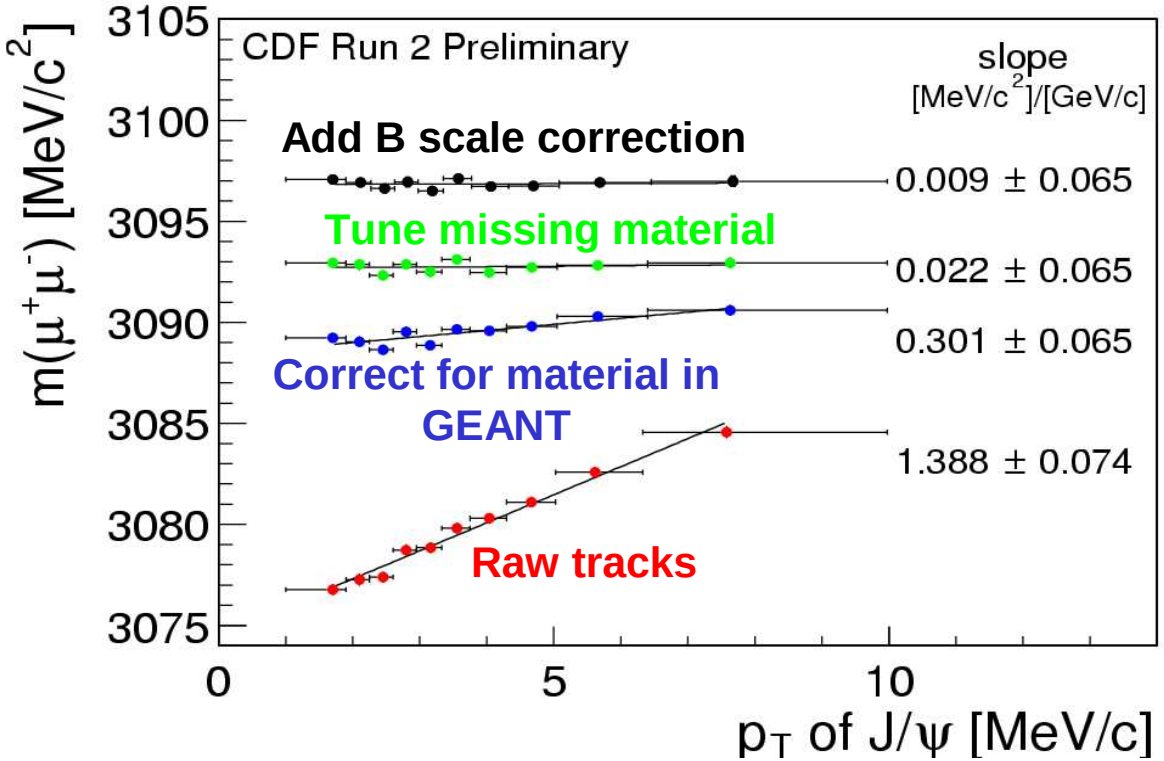
CDF Momentum Scale Calibration

Essential for
Mass differences
Mass measurements

Use 500k $J/\Psi \rightarrow \mu^+\mu^-$
Measure detector material to remove p_T dependence
- **Energy loss corrections**

Compare to PDG J/Ψ mass
- **B field calibration**





Using calibration from J/Ψ, test with
Low momentum (π): $K_s \rightarrow \pi^+ \pi^-$
High statistics (K, π): $D^0 \rightarrow K^+ \pi^-$
High momentum (μ): $\Upsilon \rightarrow \mu^+ \mu^-$

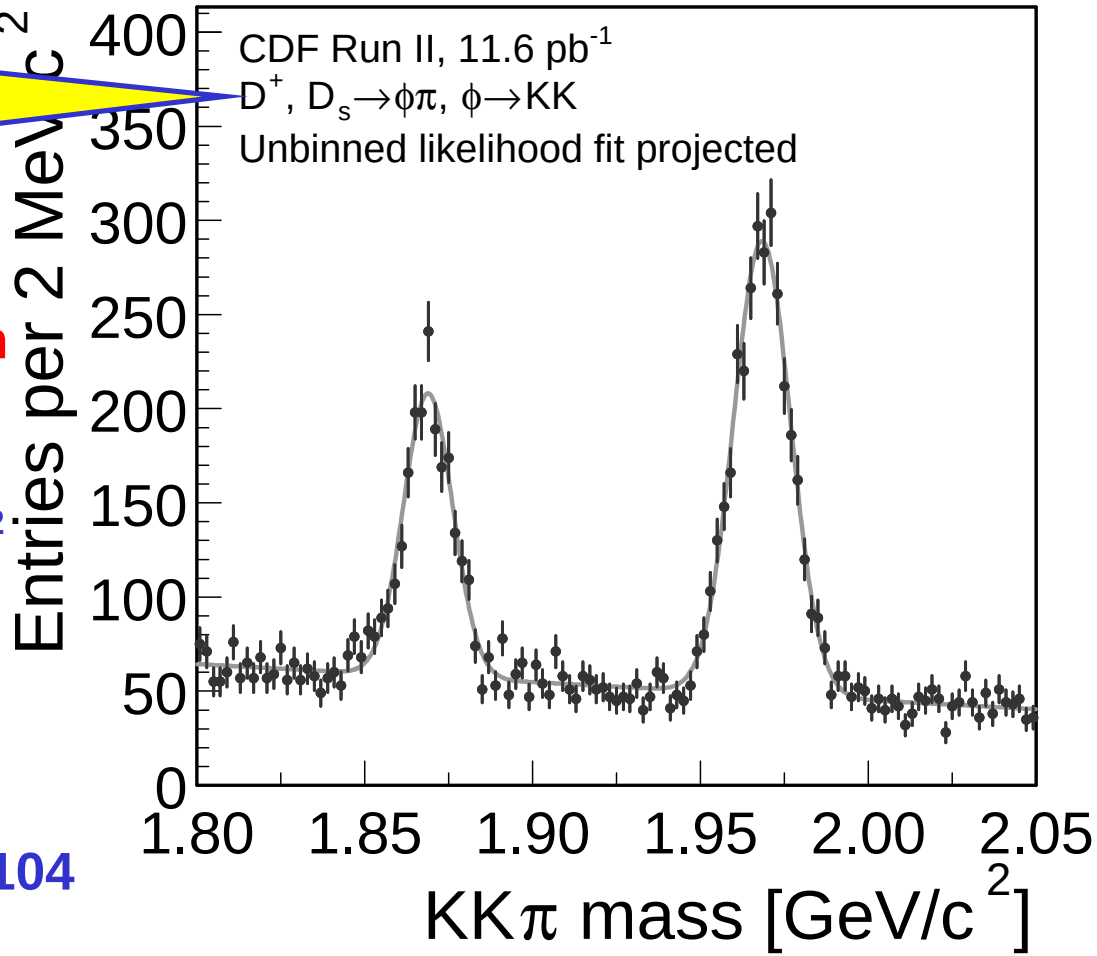
D Meson Mass Difference

Test lattice QCD and Heavy Quark Expansion

$$m(B_s^0) - m(B_d^0) = m(D_s^+) - m(D^+)$$

Displaced two track trigger

Common final decay state
Almost identical kinematics
Many systematics cancel



First Tevatron Run II publication (PRD accepted June 2003)

$$m(D_s^+) - m(D^+) =$$

$99.41 \pm 0.38_{(stat)} \pm 0.21_{(sys)}$ MeV/c^2

Agrees with old world average
99.5 ± 0.50 MeV/c^2

Recent BaBar PRD 65(2002)091104
$98.4 \pm 0.1_{(stat)} \pm 0.3_{(sys)}$ MeV/c^2

Prompt Charm Meson Cross-section

First measurement at a hadron collider
Above theory as for B mesons
Test NLO QCD

(Rapidity<1)

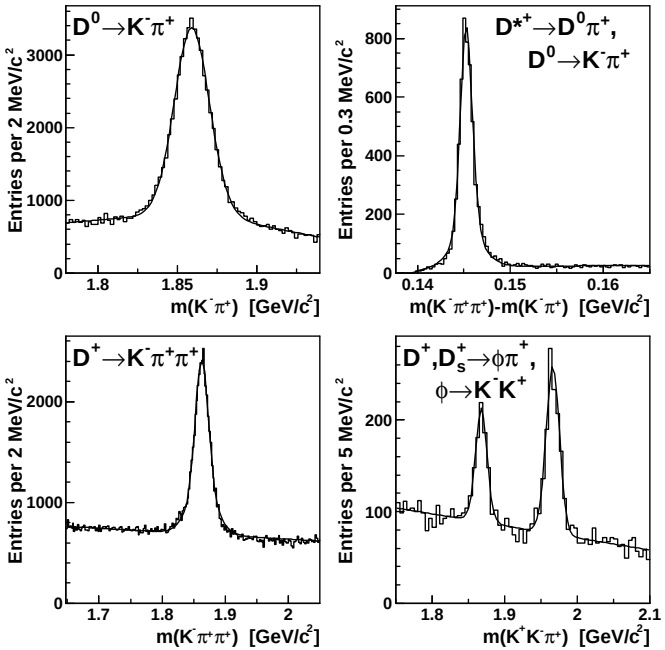
$$\sigma(D^0, p_T > 5.5\,GeV) = 13.3 \pm 0.2 \pm 1.5\ \mu b$$

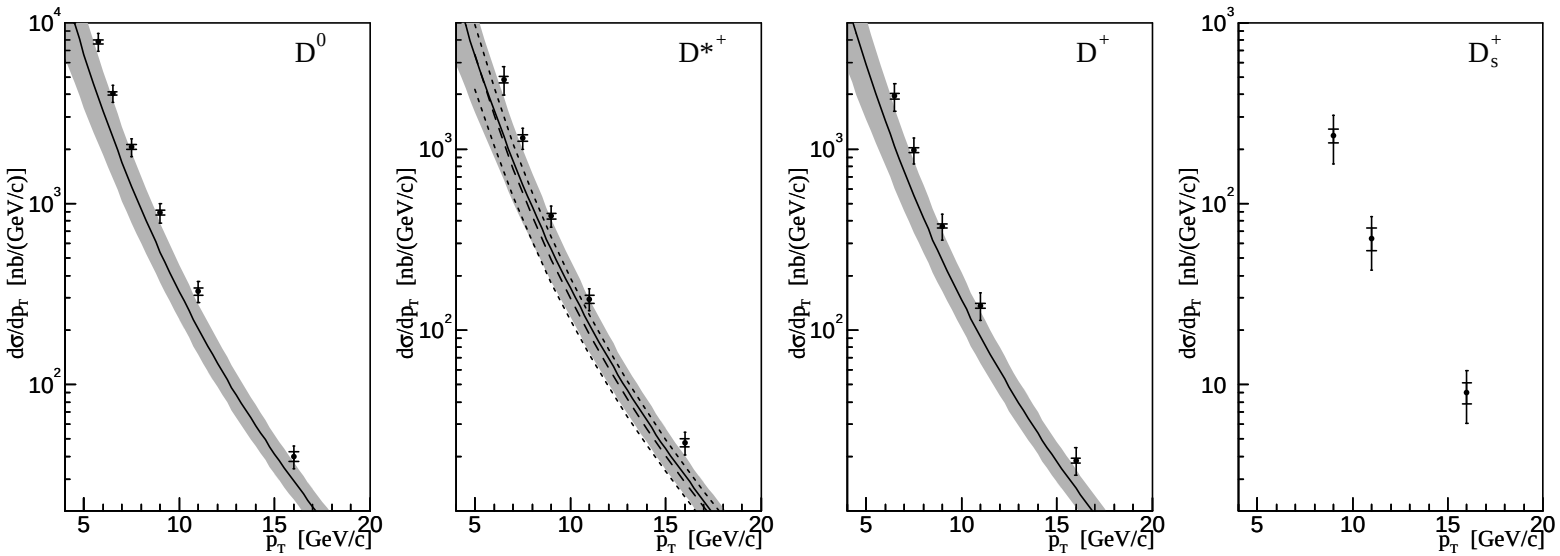
$$\sigma(D^{*+}, p_T > 6.0\,GeV) = 5.2 \pm 0.1 \pm 0.8\ \mu b$$

$$\sigma(D^+, p_T > 6.0\,GeV) = 4.3 \pm 0.1 \pm 0.7\ \mu b$$

$$\sigma(D_s^+, p_T > 8.0\,GeV) = 0.75 \pm 0.05 \pm 0.22\ \mu b$$

Submitted to PRL (hep-ex/0307080)



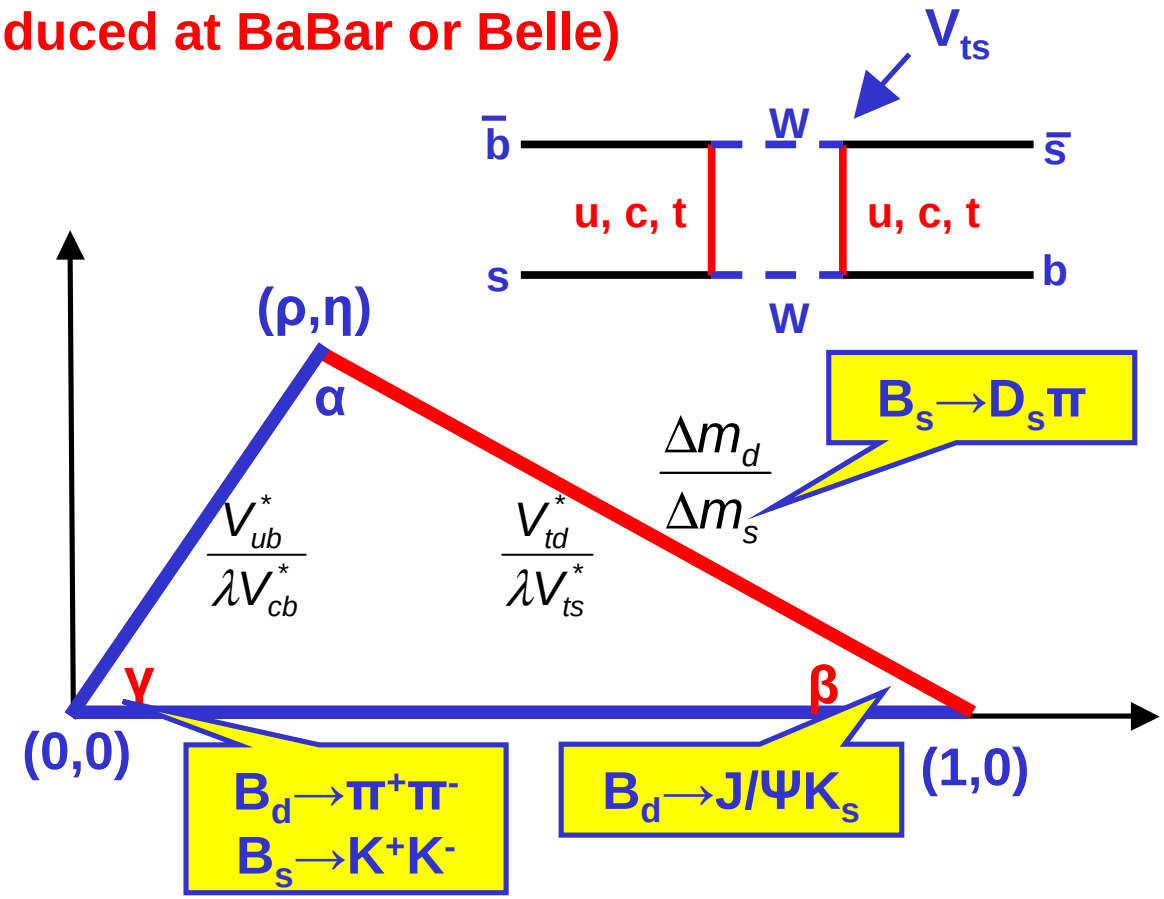


B Physics

Why should you care?
B_s meson and Λ_b baryon unique to Tevatron now
(Not produced at BaBar or Belle)

B_s meson properties:
- Mass
- Lifetime
- Δm_s frequency
- $\Delta\Gamma_s$
- CP violation
- CKM angle γ

Λ_b baryon properties:
- Mass
- Lifetime
- CP violation
- Test of HQE



CKM matrix triangle

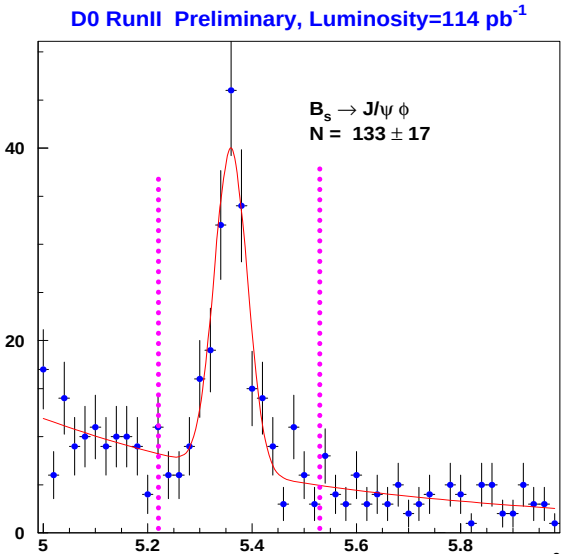
B_s Meson Mass and Lifetime

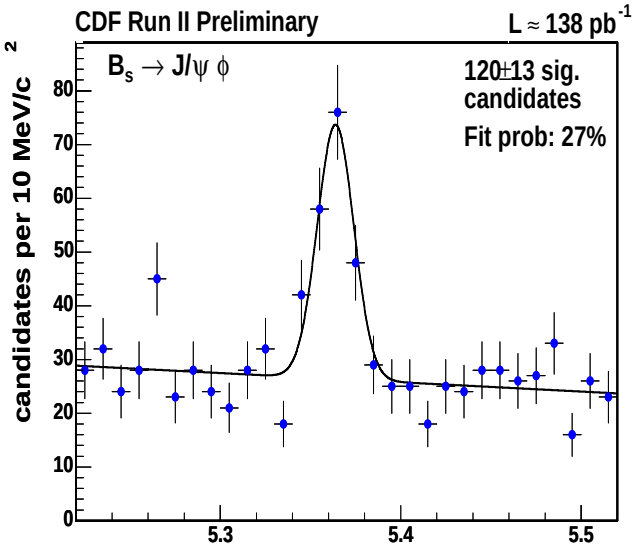
$B_s \to J/\psi\ \Phi$ with $J/\psi \to \mu^+\mu^-$ and $\Phi \to K^+K^-$
$B^+ \to J/\Psi K^+$, $B^0 \to J/\Psi K^{*0}$ check technique, systematics

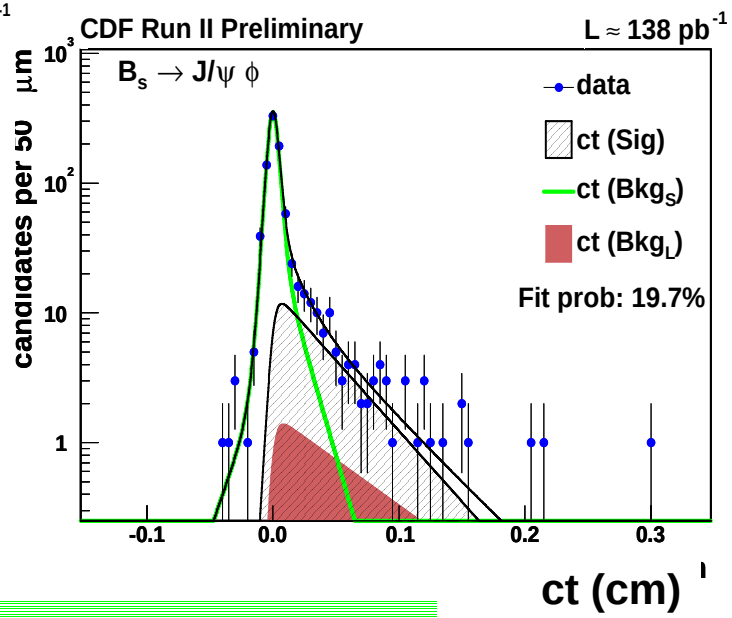
$$ct = L_{xy}\frac{m_B}{p_T^B}$$

B_s mass – PDG 5369.6 ± 2.4 MeV/c^2
CDF 5365.5 ± 1.3$_{(stat)}$ ± 0.9$_{(sys)}$ MeV/c^2
D0 5360 ± 5 MeV/c^2

B_s lifetime - PDG 1.461 ± 0.057 ps
CDF 1.33 ± 0.14$_{(stat)}$ ± 0.02$_{(sys)}$ ps
D0 1.19 $\pm^{0.19}_{0.16}$ $_{(stat)}$ ± 0.14$_{(sys)}$ ps







Future:
Search for CP violation and measure β_s
Compare to lifetime from $B_s \to \ell\nu D_s$ and extract $\Delta\Gamma_s$

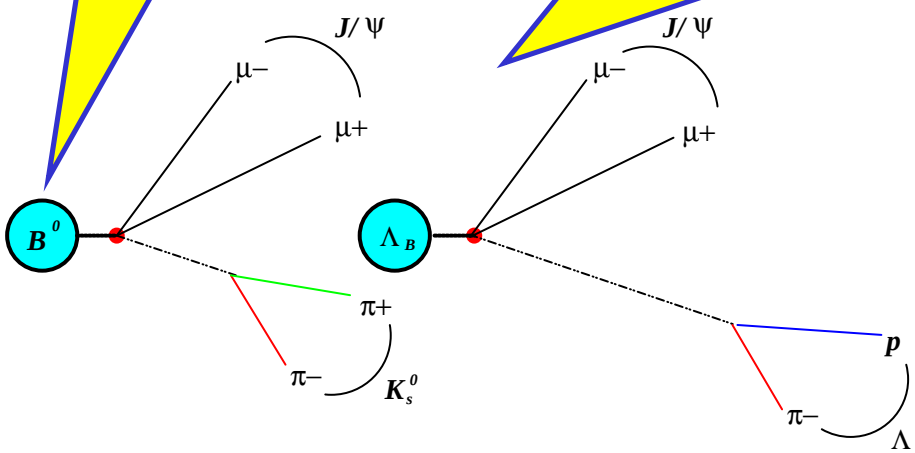
Λ_b mass and lifetime

Check technique systematics

First lifetime from fully reconstructed Λ_b decay!

$\Lambda_b \rightarrow J/\Psi\Lambda$

with $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda \rightarrow p\pi$



Λ_b mass – PDG 5624 ± 9 MeV/c^2

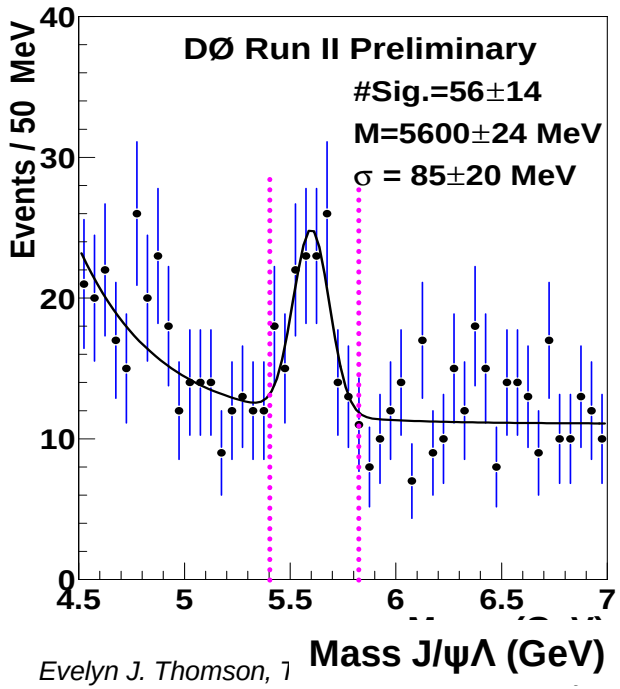
CDF 5620.4 ± $1.6_{(stat)}$ ± $1.2_{(sys)}$ MeV/c^2

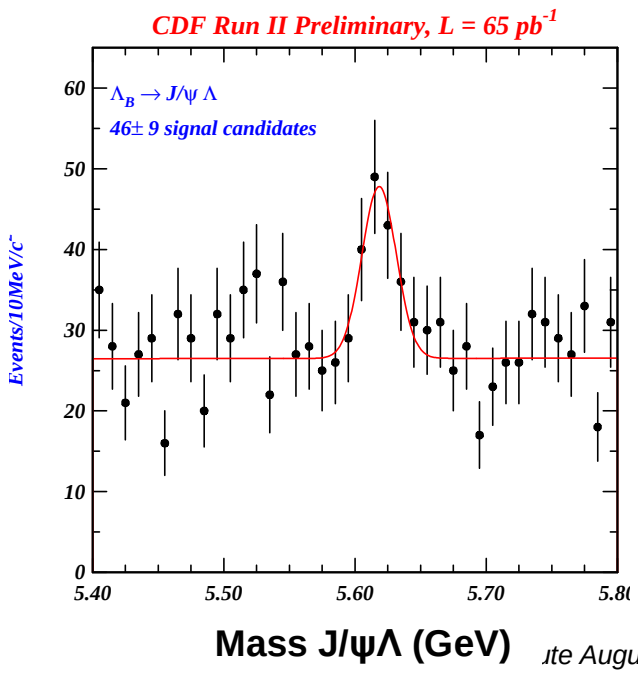
D0 in progress

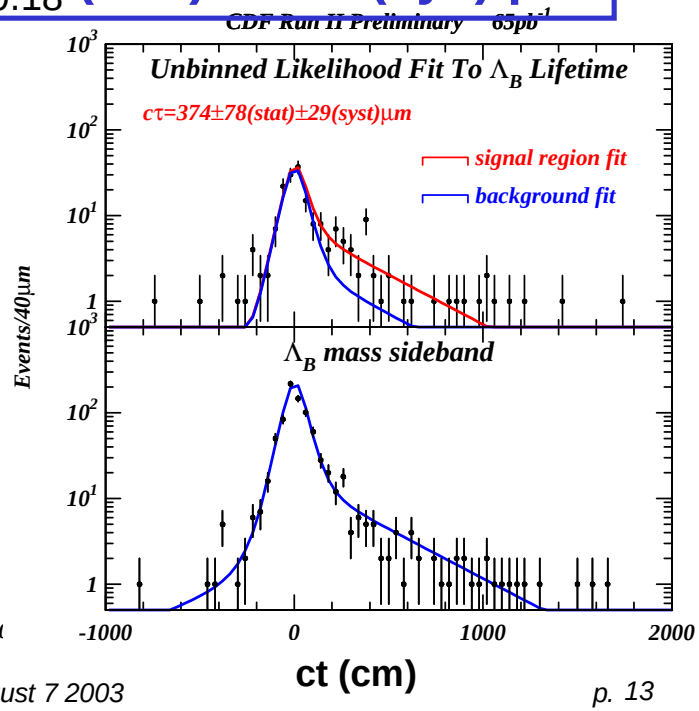
Λ_b lifetime – PDG 1.229 ± 0.080 ps

CDF 1.25 ± $0.26_{(stat)}$ ± $0.10_{(sys)}$ ps

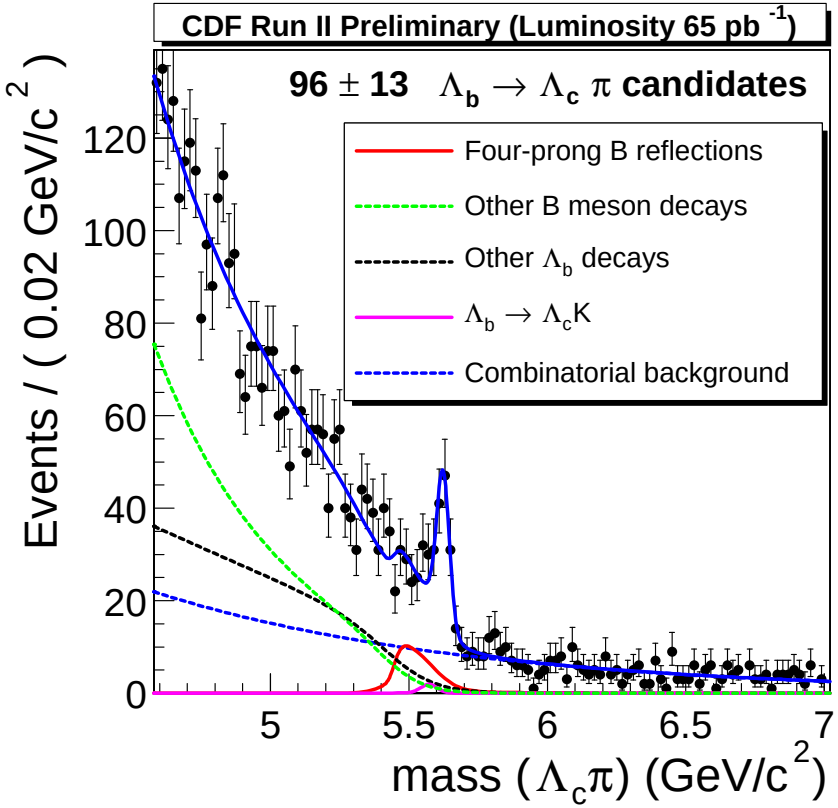
D0 1.05 $\pm^{0.21}_{0.18}$ (stat) ± 0.12(sys) ps



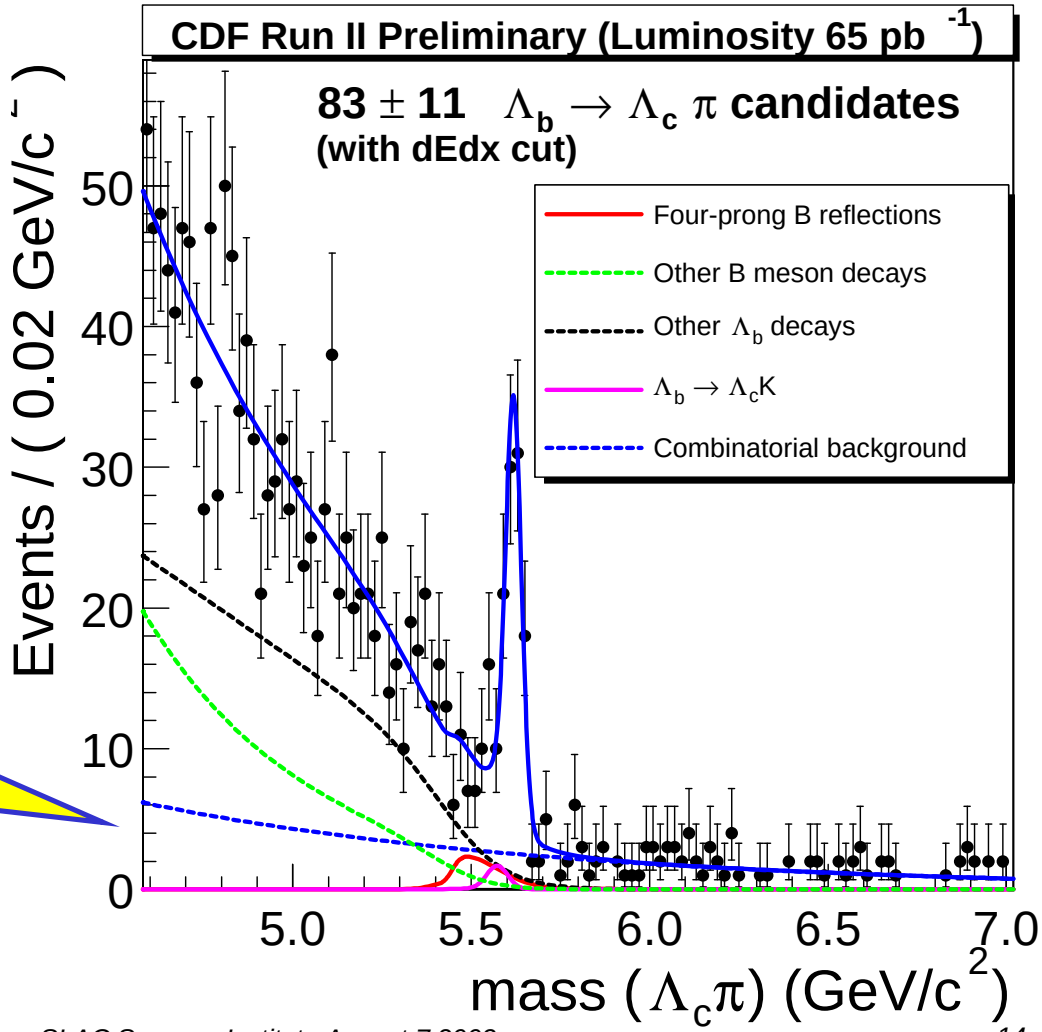




In Future: Particle Identification!



$\Lambda_b \to \Lambda_c \pi$ with $\Lambda_c \to pK\pi$
Plagued with reflections!

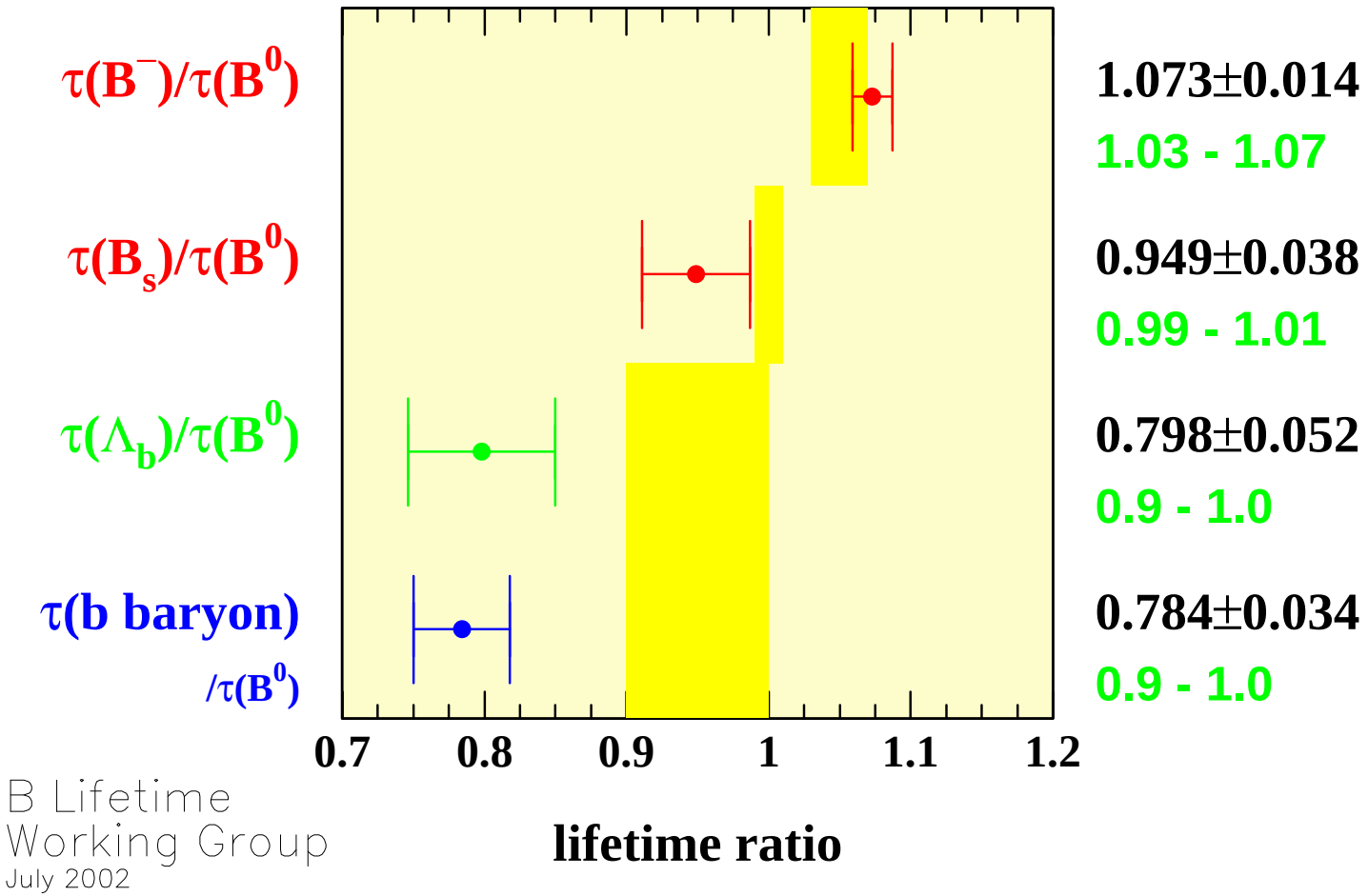


Add dE/dx particle id
Reduce reflection by ~3
Only lose ~15% signal

B lifetime ratios

Why do we care about B lifetimes, especially Λ_b?

Important Test of Heavy Quark Expansion



$B_s \to D_s \pi$ Relative Yield

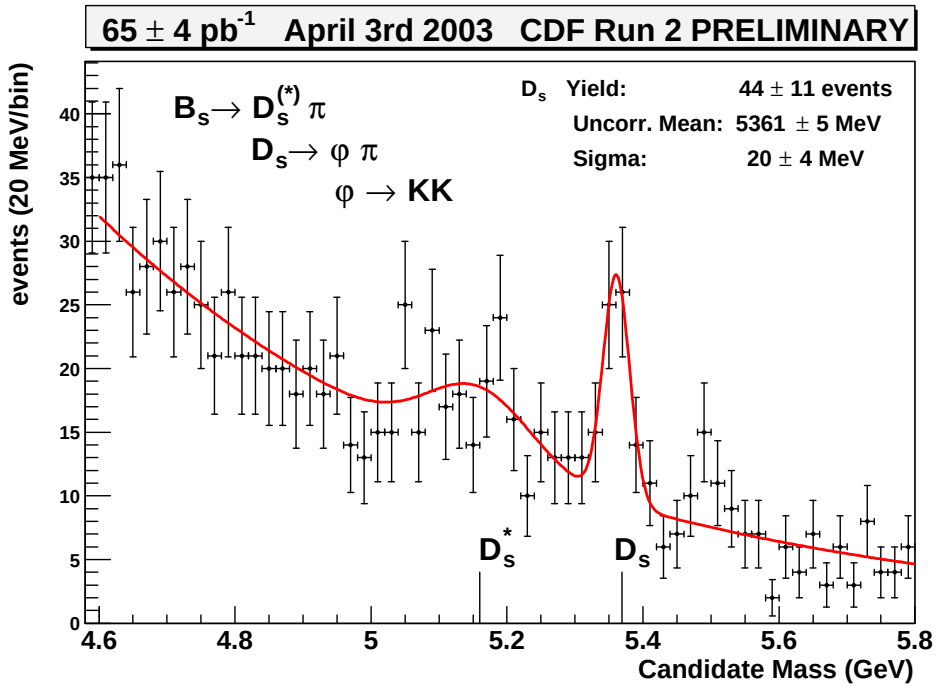
Golden mode for B_s mixing
In progress:
Flavour tagging (εD^2)
Exquisite ct resolution

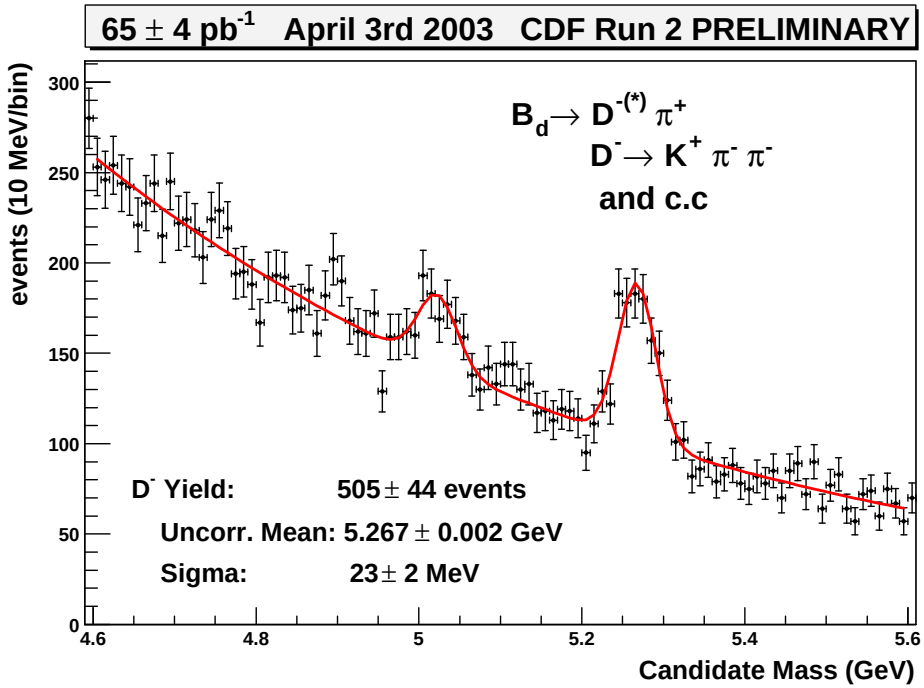
First observation!

- Fully reconstructed hadronic final state
- Two track trigger essential
- Production rate understood

Ratio of branching ratios cancels most systematics

$$\frac{f_s}{f_d}\frac{BR(B_s \to D_s^- \pi^+)}{BR(B^0 \to D^- \pi^+)} = 0.41 \pm 0.11_{(stat)} \pm 0.11_{(BR)} \pm 0.07_{(sys)}$$





Towards B_s mixing

B_s mixing World Average @95% C.L. $\Delta m_s \geq 14.4\ ps^{-1}$

- ***At least 30 times faster than B_d mixing $\Delta m_d = 0.502 \pm 0.006\ ps^{-1}$***
- ***Will need exquisite proper time resolution!***

$$ct = L_{xy} \frac{m_B}{p_T^B}$$

- ***Minimise error on p_T with fully reconstructed decays $B_s \rightarrow D_s \pi$***
- ***CDF ~ 60 fs (45 fs with L00)***
  D0 ~ 75 fs

Flavour tagging

Need everything for εD^2~10%

ε = tag efficiency

D = tag correct (dilution)

Yield – need ~1000 events

CDF yield ~50 events in 65 pb^{-1}

Below expectations…

…but careful with your abacus!

Silicon coverage much improved

Trigger with majority logic

Add more decay modes

$$B_s \rightarrow D_s\pi,\ D_s\,\pi\,\pi\,\pi$$

$$D_s \rightarrow \varphi\pi,\ K^*K,\ \pi\pi\pi$$

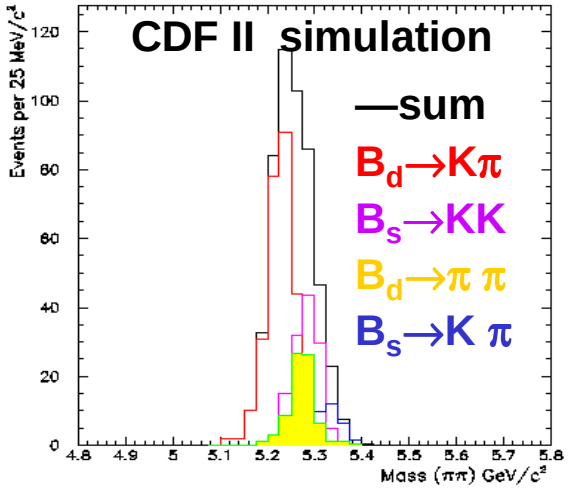
For 2 fb^{-1}, 5σ sensitivity up to

x_s = 63 (S/B = 2/1) **$x_s = \Delta m_s \tau(B_s)$**

x_s = 53 (S/B = 1/2)

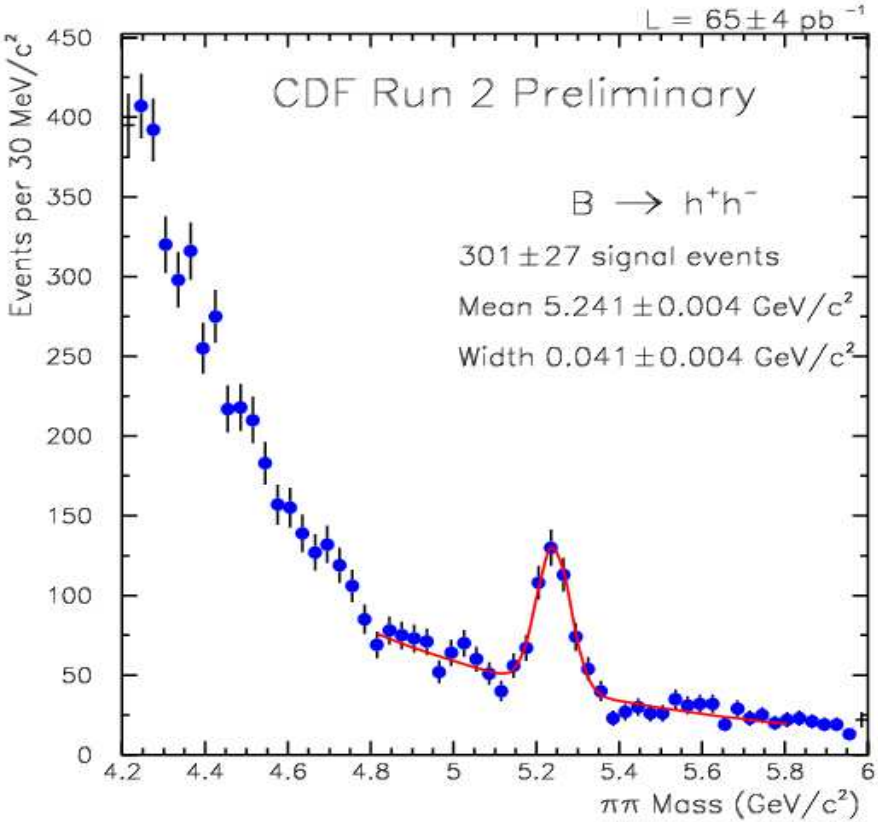
Two-Body Charmless B decays

Future: CKM angle γ



$B \to h^+h^-$ observed at CDF

- **About 280 candidates (S:N=2:1)**
- **Peak is a mix of $B^0, B_s \to \pi\pi, \pi K, KK$**
- **Statistical separation with dE/dx and kinematics**



Raw fit results

$N(B^0 \to K\pi) = 148 \pm 17$

$N(B^0 \to \pi\pi) = 39 \pm 14$

$N(B_s \to KK) = 90 \pm 17$ First observation!

$N(B_s \to K\pi) = 3 \pm 11$

$$\frac{BR(B_d^0 \to \pi\pi)}{BR(B_d^0 \to K\pi)} = 0.26 \pm 0.11 \pm 0.055$$

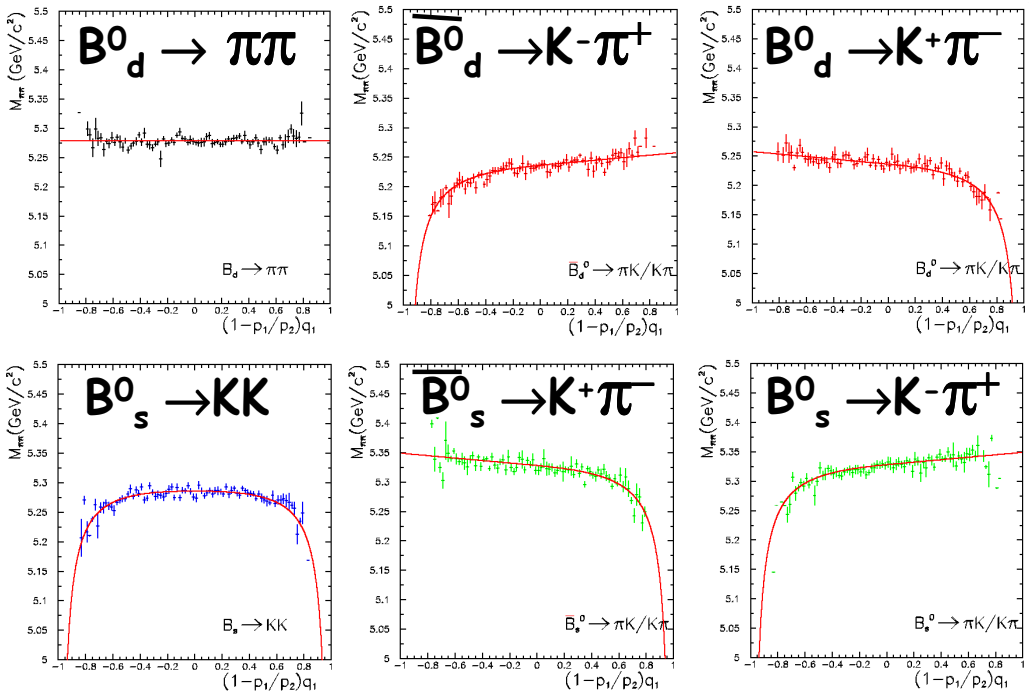
agrees with PDG $0.29 \pm^{0.13}_{0.12} \pm^{0.01}_{0.02}$

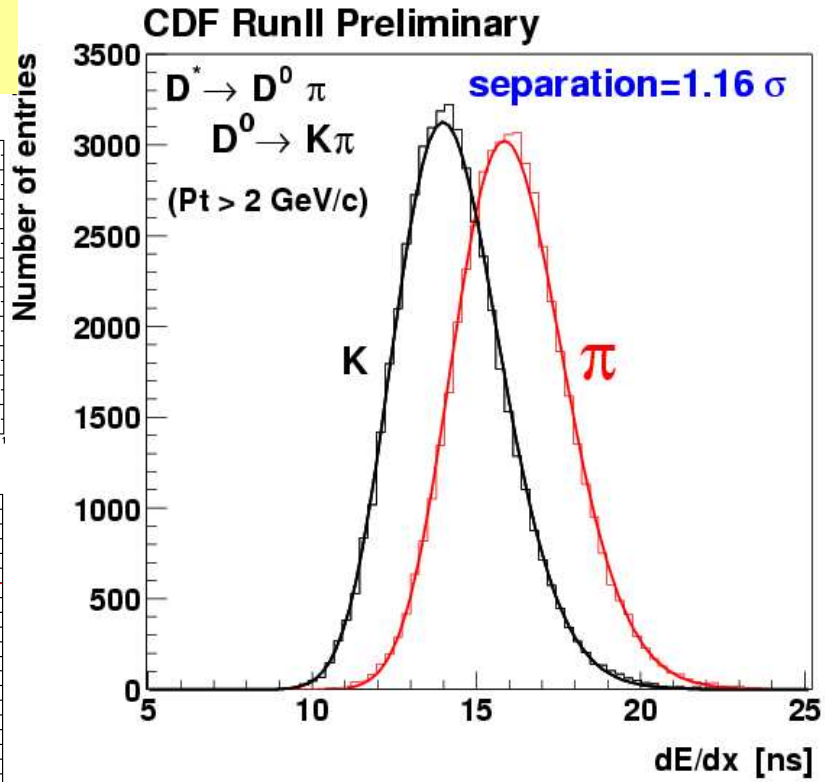
$$A_{CP} = \frac{\overline{B}_d^0 \to K^-\pi^+ - B_d^0 \to K^+\pi^-}{\overline{B}_d^0 \to K^-\pi^+ + B_d^0 \to K^+\pi^-}$$

$$= 0.02 \pm 0.15_{(stat)} \pm 0.017_{(sys)}$$

Disentangling Charmless B decays

Use $M\pi\pi$ vs $(1-p_1/p_2)\cdot q_1$





Use K/π separation dE/dx 1.16σ

Electroweak Physics

Why should you care?

Standard Candles!

W/Z cross-sections

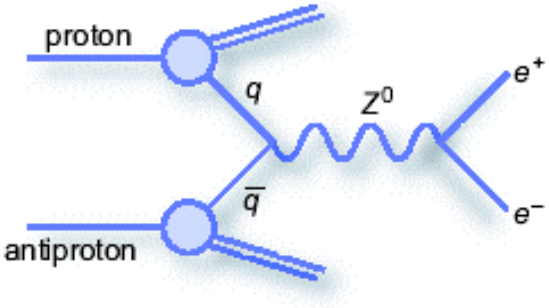
Ratio -> W width

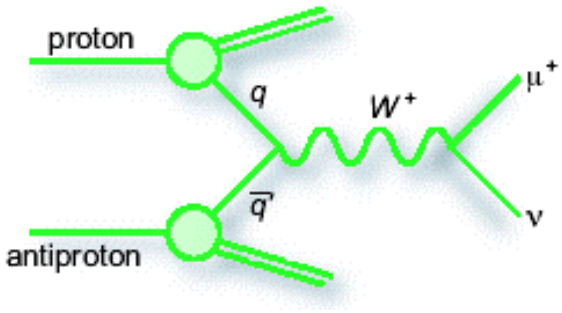
W mass

W charge Asymmetry

Z FB Asymmetry

WW, WZ, ZZ, Wγ, Zγ





Trigger on leptonic decays

Clean low bkg event signatures
W: 1 high p_T lepton + large MET
Z: 2 high p_T leptons

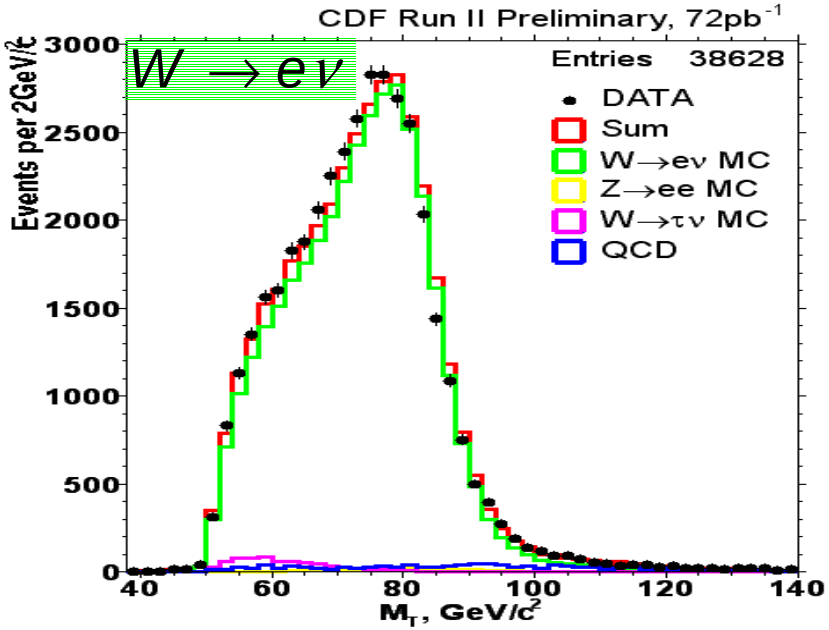
BR~11% per mode for $W \rightarrow \ell \nu$
BR~3% per mode for $Z \rightarrow \ell^+\ell^-$

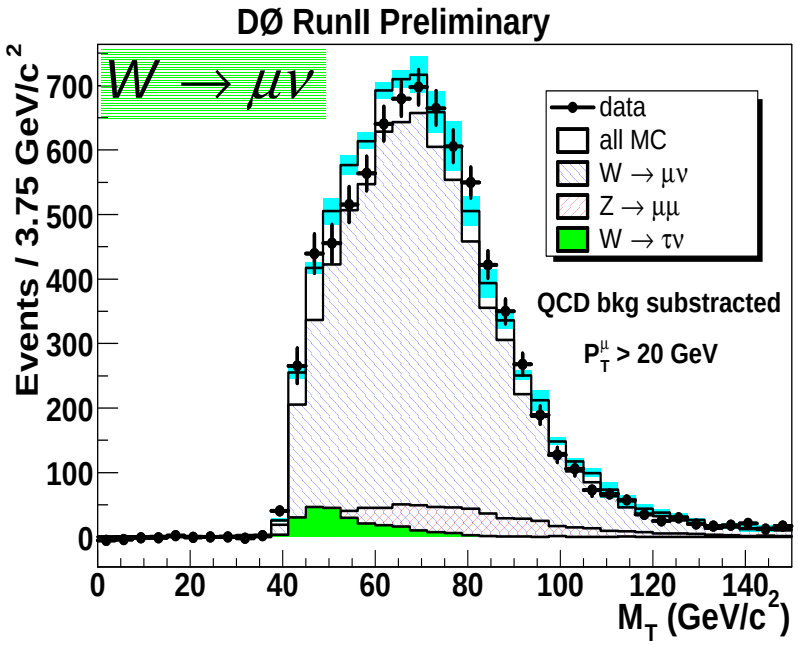
σ(W) x BR(W→ ℓv)

$$M_T = \sqrt{2E_\ell E_\nu (1-\cos\phi_{\ell\nu})}$$

E_T>25GeV, MET>25 GeV
CDF |η|<1.0, D0 |η|<1.1

p_T>20GeV, MET>20 GeV
CDF |η|<0.6, D0 |η|<1.6





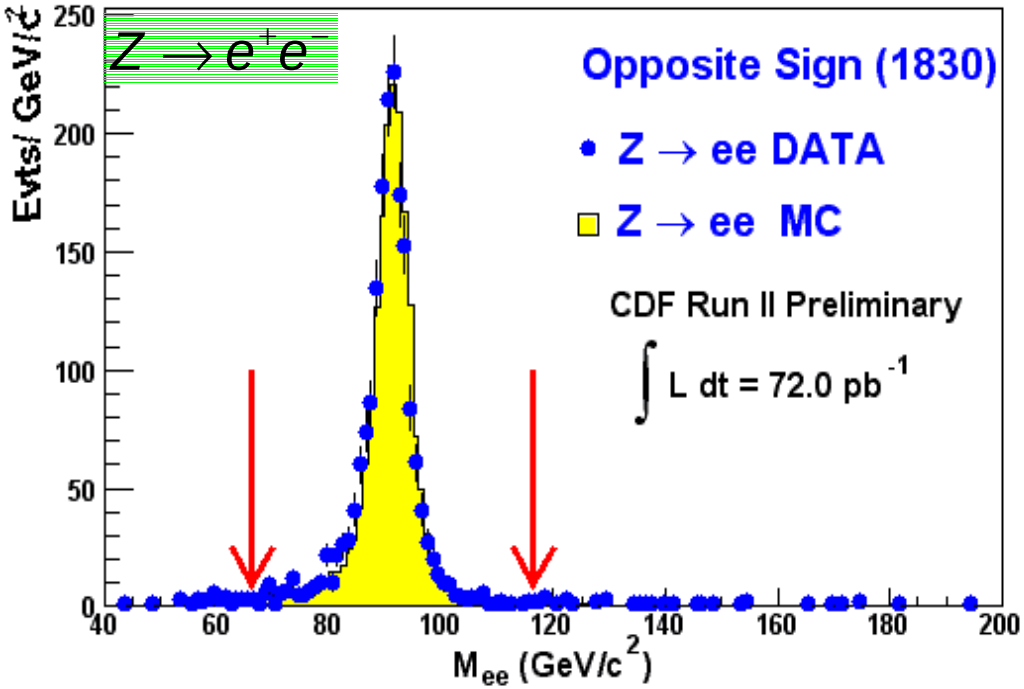
	CDF	CDF (all: 72pb^{-1})	D0	D0 (e: 42pb^{-1}; μ: 17pb^{-1})
ℓ	Events	σ(W) x BR(W→ ℓv) (nb)	Events	σ(W) x BR(W→ ℓv) (nb)
e	38625	2.64 ± 0.01 ± 0.09 ± 0.16	27370	2.84 ± 0.02 ± 0.13 ± 0.28
μ	21599	2.64 ± 0.02 ± 0.12 ± 0.16	7352	3.23 ± 0.13 ± 0.10 ± 0.32
τ	2346	2.62 ± 0.07 ± 0.21 ± 0.16	-	result ± stat ± sys ± lum

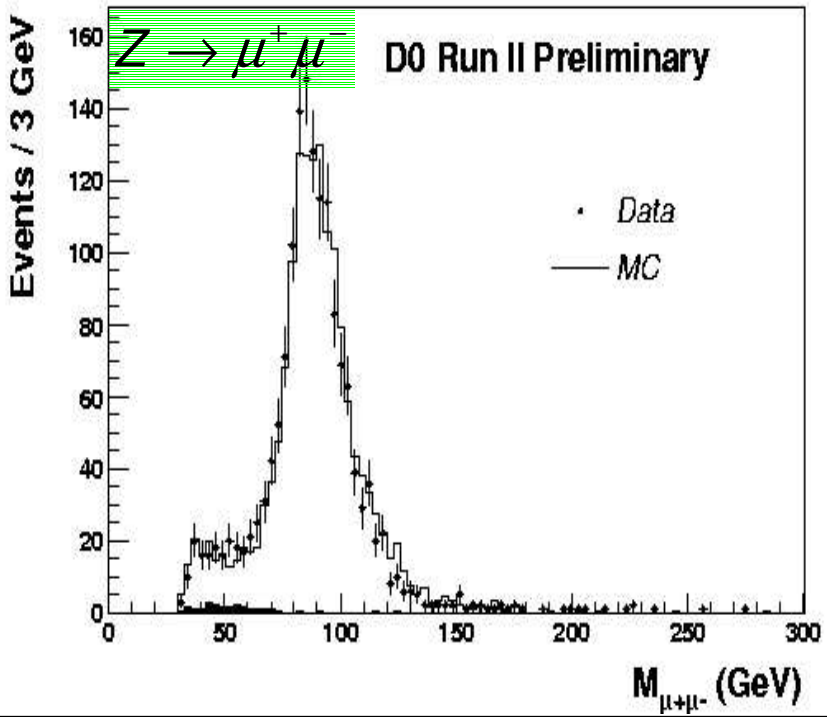
Theory prediction 2.731 ± 0.002 nb NNLO *Stirling et al., Phys Lett B531 (2002)*

σ(Z) x BR(Z→ ℓ⁺ℓ⁻)

E_T>25GeV
CDF |η|<1.0, D0 |η|<1.1

CDF p_T>20GeV, D0 p_T>15GeV
CDF |η|<0.6, D0 |η|<1.8

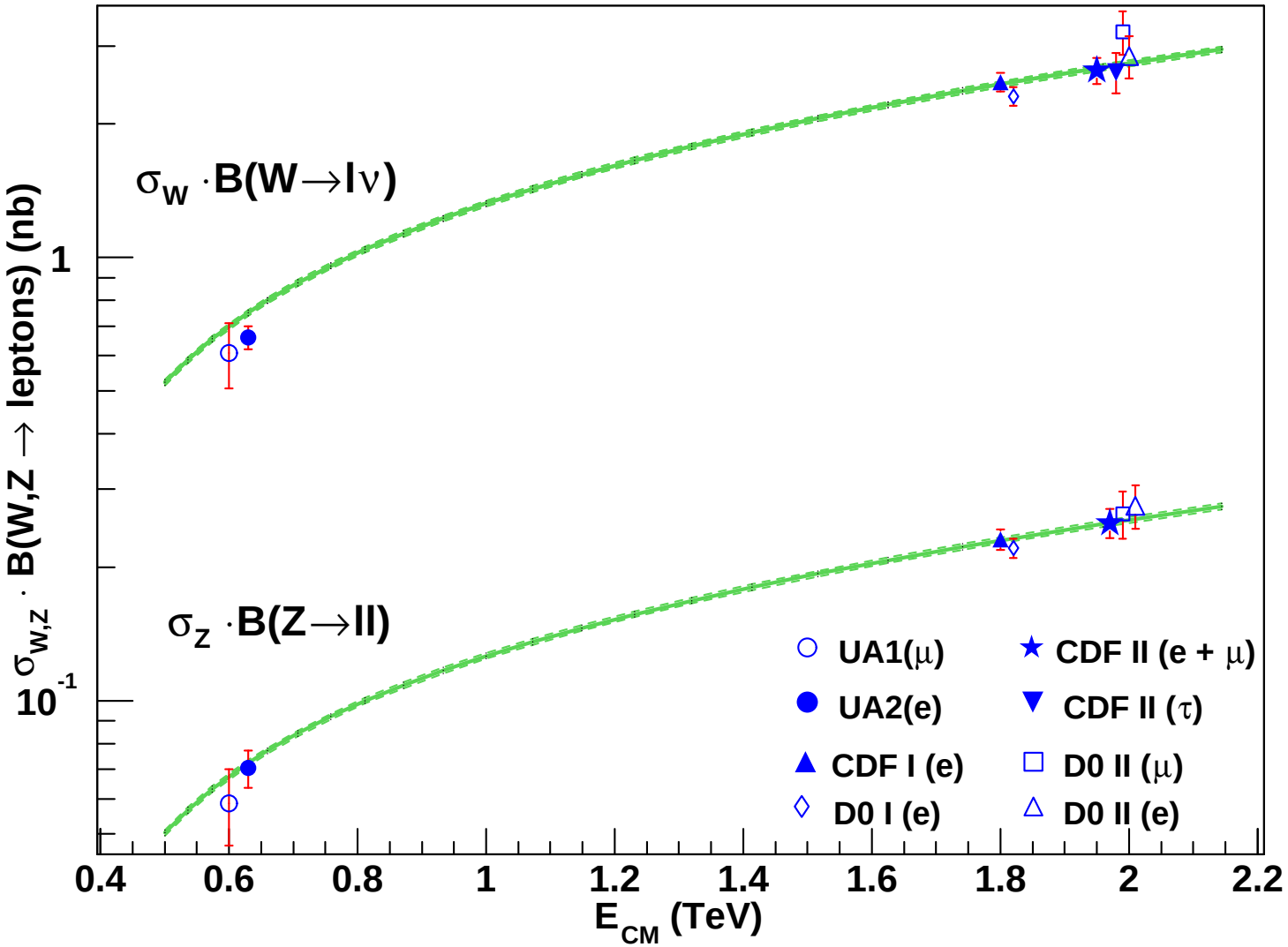




	CDF	CDF (all: 72pb⁻¹)	D0	D0 (e: 42pb⁻¹; μ: 32pb⁻¹)
ℓ	Events	σ(Z) x BR(Z→ ℓℓ) (nb)	Events	σ(Z) x BR(Z→ ℓℓ) (nb)
e	1830	0.267 ± 0.006 ± 0.015 ± 0.016	1139	0.275 ± 0.009 ± 0.009 ± 0.028
μ	1631	0.246 ± 0.006 ± 0.012 ± 0.015	1585	0.264 ± 0.007 ± 0.017 ± 0.026

Theory prediction 0.252 ± 0.009 nb NNLO *Stirling et al., Phys. Lett. B531 (2002)*

W and Z cross-sections vs E_{CM}



Theory: R Hamberg, WL van Neerven and T Matsuura, Nucl. Phys. B359 (1991) 343 CTEQ4M PDF

Indirect Measurement of W Width

W, Z cross-sections systematics limited

Most of systematics cancel in ratio R

- **Indirect measurement of W width**

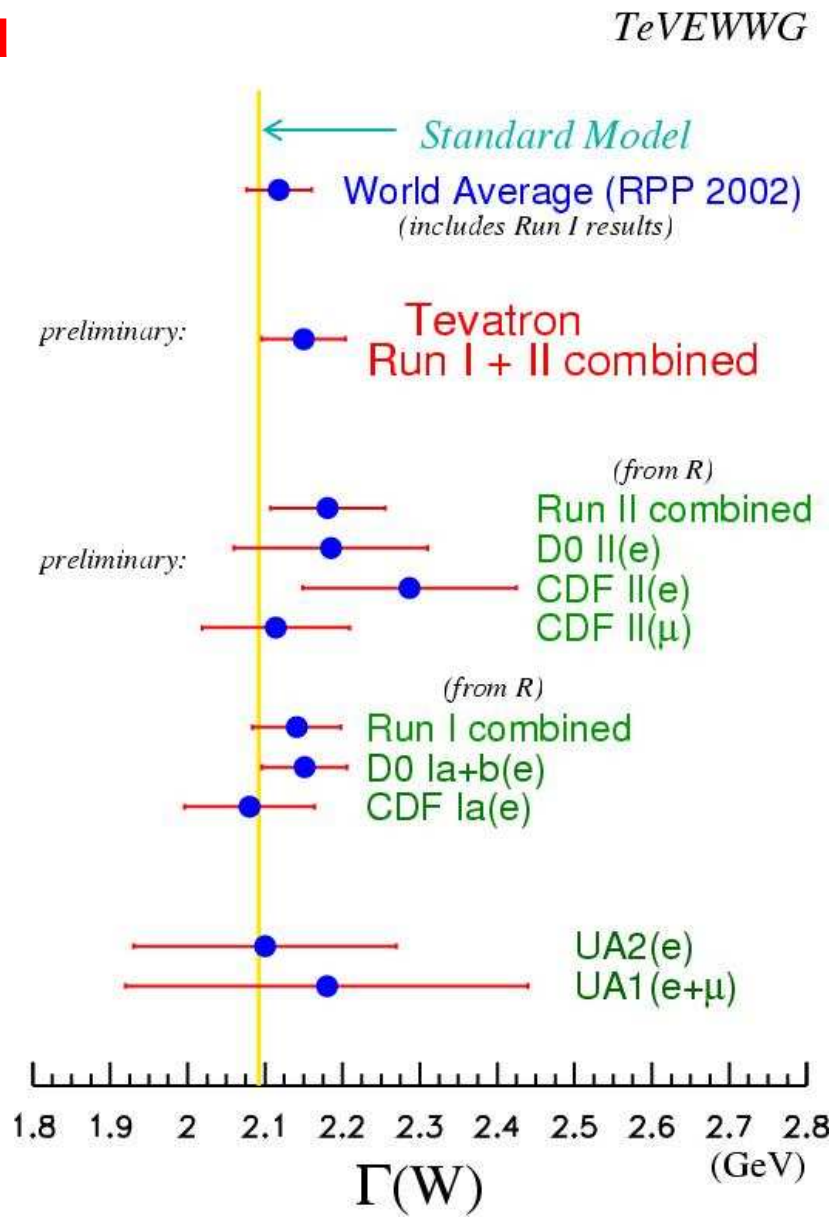
Γ(W) – PDG	**2.118 ± 0.042 GeV**
Run II	**2.181 ± 0.074 GeV**

Theory

$$R = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)}$$

LEP

	R
CDF e	**9.88 ± 0.24 ± 0.44**
CDF μ	**10.69 ± 0.28 ± 0.31**
D0 e	**10.34 ± 0.35 ± 0.49**
Combined	**10.36 ± 0.16 ± 0.27**



Forward-Backward Asymmetry

$$A_{FB} = \frac{d\sigma(\cos\theta > 0) - d\sigma(\cos\theta < 0)}{d\sigma(\cos\theta > 0) + d\sigma(\cos\theta < 0)}$$

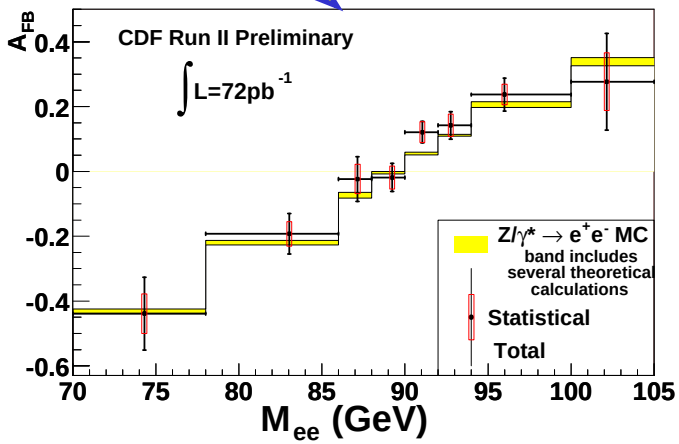
Electron |η|<3 Forward calorimeter crucial!

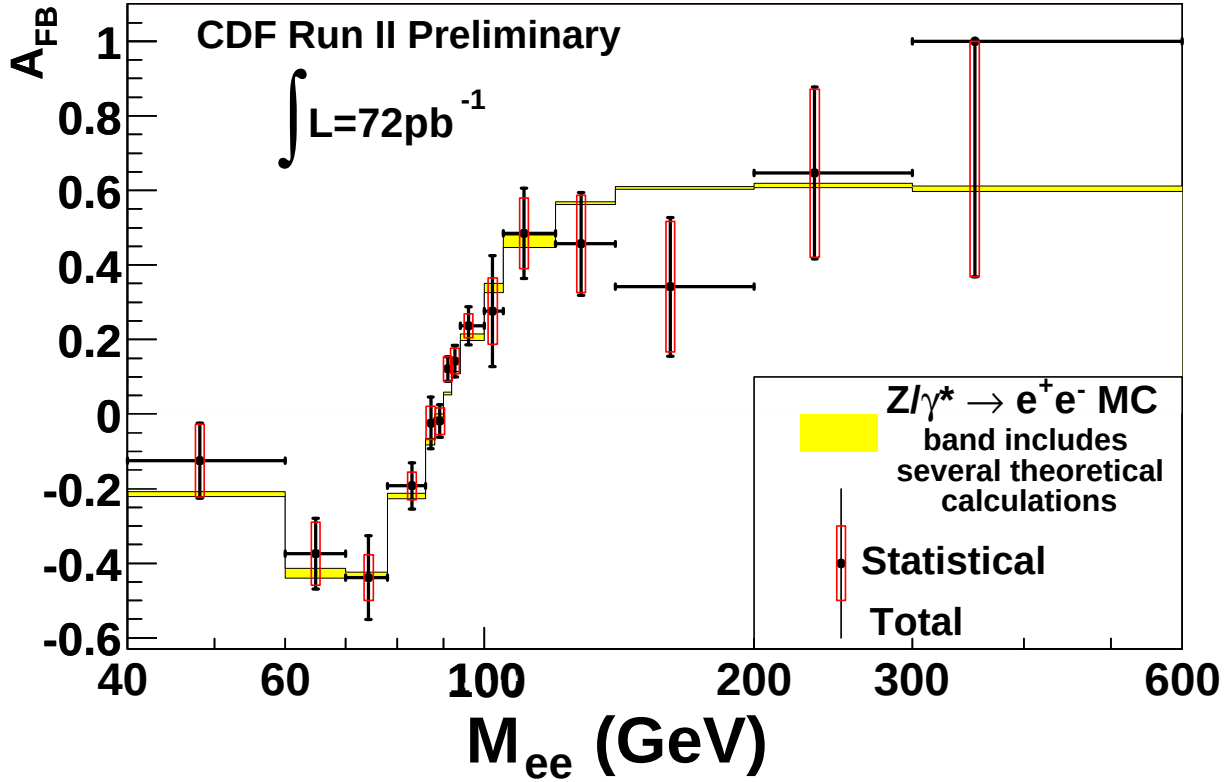
High mass reach unique to Tevatron

- **Probe Z-γ* interference**
- **Complements direct Z' search**

Result agrees with SM

Zoom into high stats Z pole region



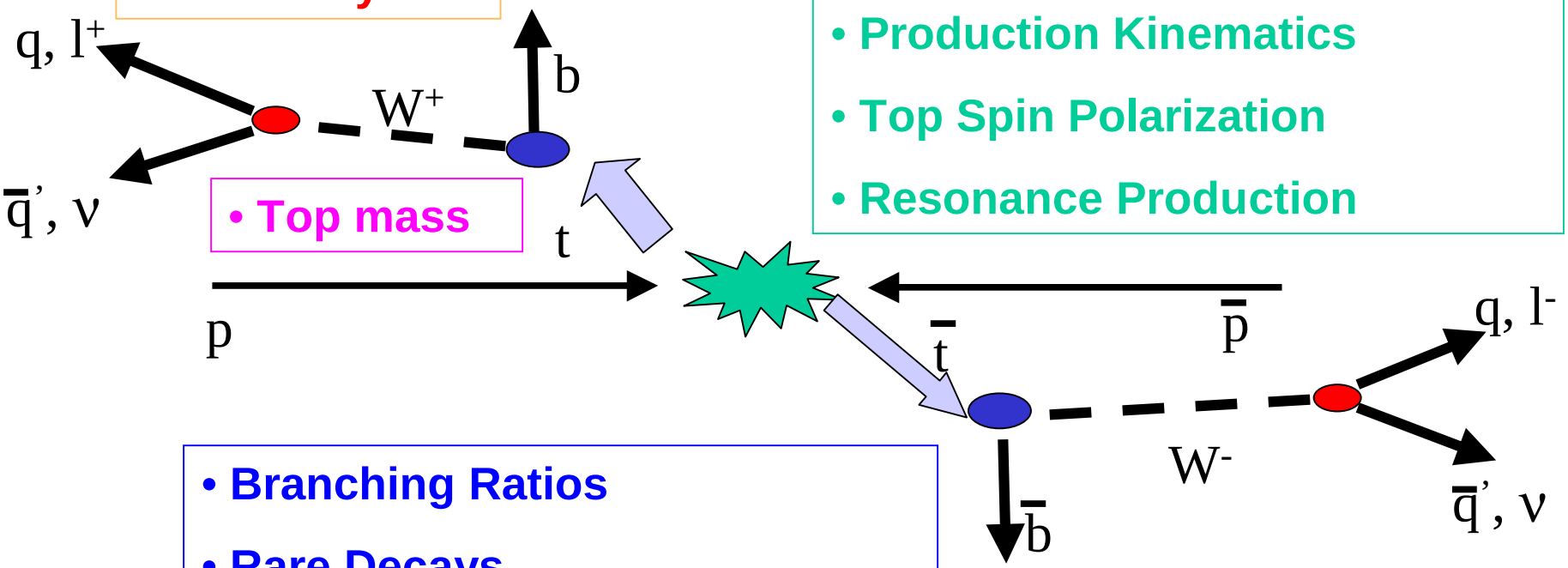


Top Physics

Top discovered by CDF and D0 in 1995
Very heavy! Top mass = 174.3 ± 5.1 GeV
Only ~30 events per experiment
!!!Want more top events to study properties!!!
Run II σ 30% higher at √s=1.96 TeV

Similar mass to Tungsten Atomic # 74 35 times heavier than b quark

- **W Helicity**
- **Top mass**

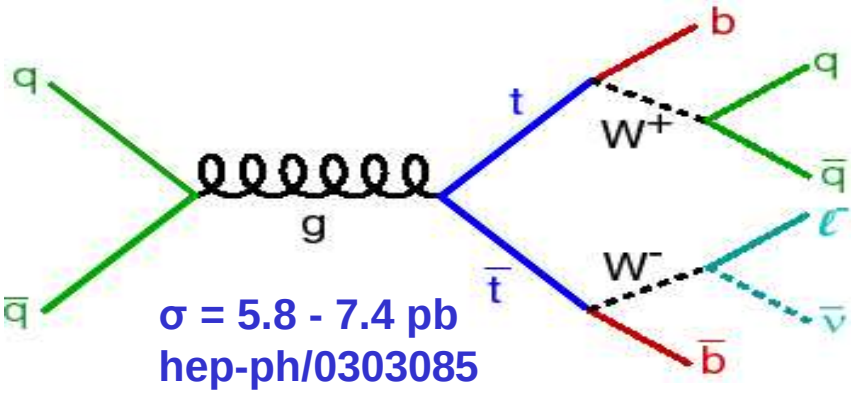


- **Production Cross Section**
- **Production Kinematics**
- **Top Spin Polarization**
- **Resonance Production**

- **Branching Ratios**
- **Rare Decays**
- **Non-SM decay ($t \rightarrow H^+ b$)**

Top Quark Production & Decay

Top quarks produced in pairs via strong interaction: 85% qq, 15% gg



σ = 5.8 - 7.4 pb
hep-ph/0303085

Top quark heavy => decays very fast!

$\Gamma(t \rightarrow bW) \sim 1.5$ GeV, $\tau_{top} \sim 4 \times 10^{-25}$s

c.f. $\Lambda_{QCD} \sim 100$ MeV, $\Lambda^{-1} \sim 10^{-23}$s

Too fast for hadronisation!

- **No top mesons or baryons**
- **Decay products know top spin**

3 characteristic event signatures from WW decay

Dilepton: BR small but pure

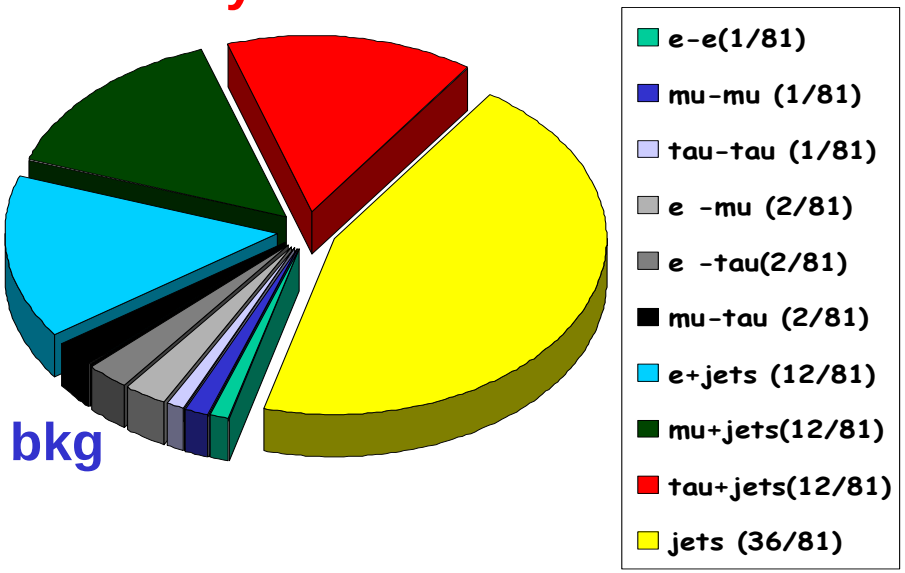
2 high p_T leptons, high MET, ≥2 jets

Lepton+Jets: BR larger but less pure

1 high p_T lepton, high MET, ≥4 jets (1 b-tag)

All-hadronic: BR largest but huge QCD bkg

≥ 6 jets (2 b-tags)



Top Pair Production cross-section

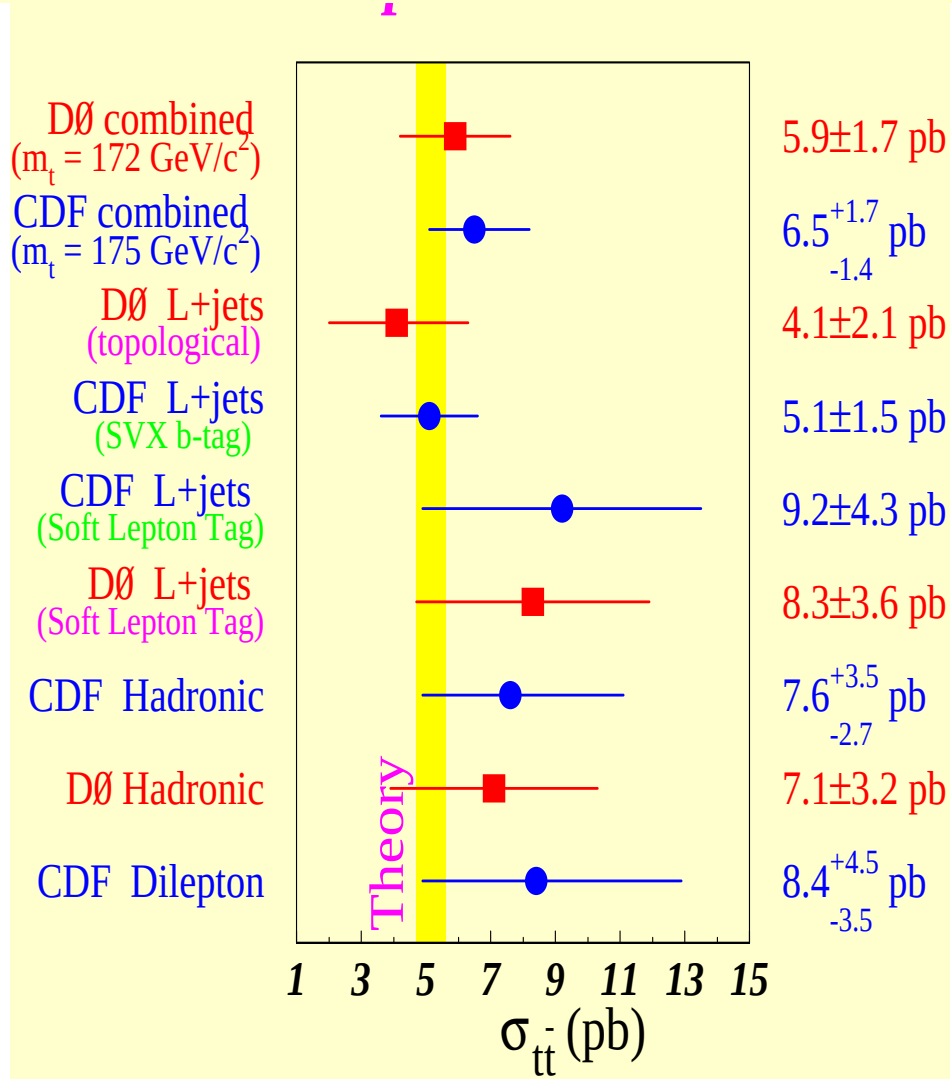
Why is it interesting?

- **Re-discover top in Run II**
- **Does cross-section increase?**
- **Develop selections and background estimates for other top analyses**

All measurements so far are counting experiments

$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{bkg}}{A \int L\, dt}$$

Run 1 cross section results ~100 pb^{-1}



Top cross-section: Dilepton

2 high p_T leptons, high MET, ≥2 jets

CDF: 72 pb-1	ee	μμ	eμ	Total ℓℓ
Background	0.10 ± 0.06	0.09 ± 0.05	0.10 ± 0.04	0.30 ± 0.12
tt→ℓνℓνbb	0.47 ± 0.05	0.59 ± 0.07	1.44 ± 0.16	2.50 ± 0.30
SM expectation	0.57 ± 0.08	0.68 ± 0.09	1.54 ± 0.17	2.80 ± 0.32
Data	1	1	3	5

CDF ℓℓ
S:B = 8:1
Very pure!

$$\textbf{CDF}\ \sigma(t\bar{t}) = 13.2 \pm 5.9_{(stat)} \pm 1.5_{(sys)} \pm 0.8_{(lum)}\, pb$$

New! Lepton + isolated track (126 pb^{-1}) $\textbf{CDF}\ \sigma(t\bar{t}) = 7.3 \pm 3.4_{(stat)} \pm 1.7_{(sys)}\, pb$

D0	ee: 107 pb^{-1}	μμ: 90 pb^{-1}	eμ: 97 pb^{-1}	Total ℓℓ
Background	0.58 ± 0.51	0.70 ± 0.44	0.60 ± 0.42	1.88 ± 0.79
tt→ℓνℓνbb	0.63 ± 0.10	0.46 ± 0.10	1.73 ± 0.26	2.81 ± 0.30
SM expectation	1.21 ± 0.52	1.16 ± 0.45	2.33 ± 0.49	4.69 ± 0.64
Data	2	0	3	5

D0 ℓℓ
S:B = 3:2

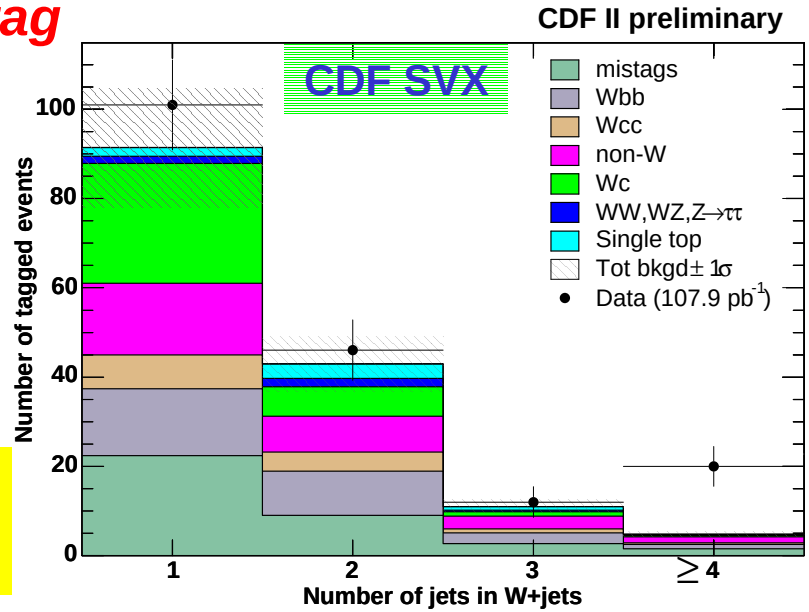
$$\textbf{D0}\ \sigma(t\bar{t}) = 8.7 \pm^{6.4}_{4.7(stat)} \pm^{2.7}_{2.0(sys)} \pm 0.9_{(lum)}\, pb$$

Top cross-section: Lepton + Jets

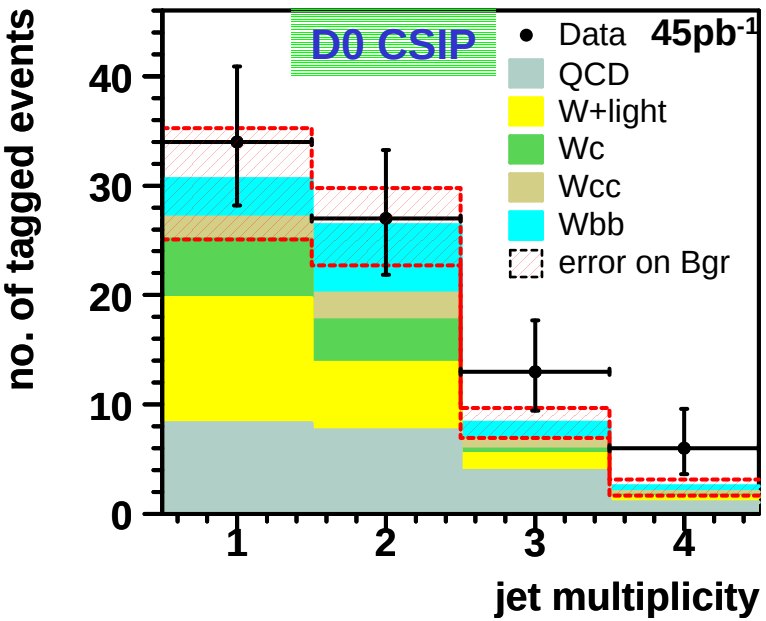
1 high p_T lepton, high MET, ≥3 jets, 1 b-tag

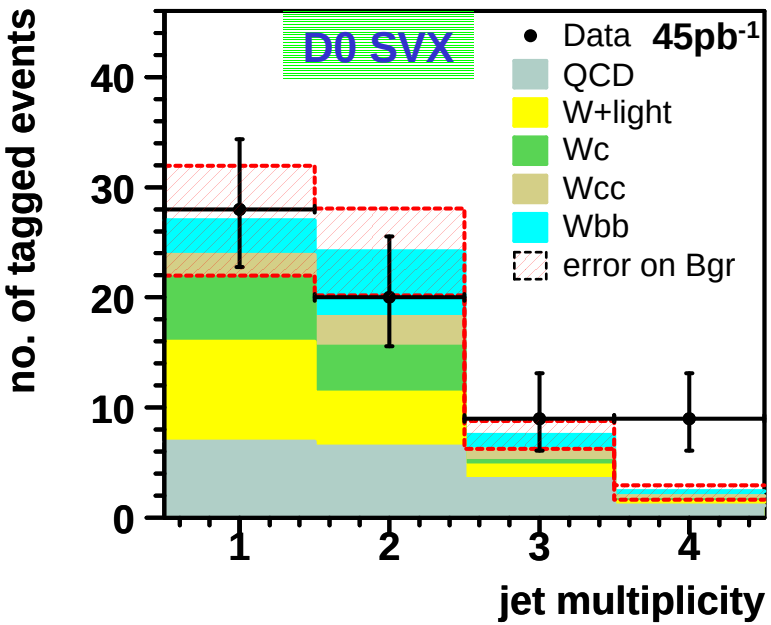
- **SVX: secondary vertex**
  CDF $L_{xy} > 3\sigma(L_{xy})$ D0 $L_{xy} > 5\sigma(L_{xy})$
- **CSIP: count tracks with significant d_0**
  ≥2 tracks with $d_0 > 3\sigma(d_0)$
  ≥3 tracks with $d_0 > 2\sigma(d_0)$

45-55% efficiency for 1 b-tag in tt MC

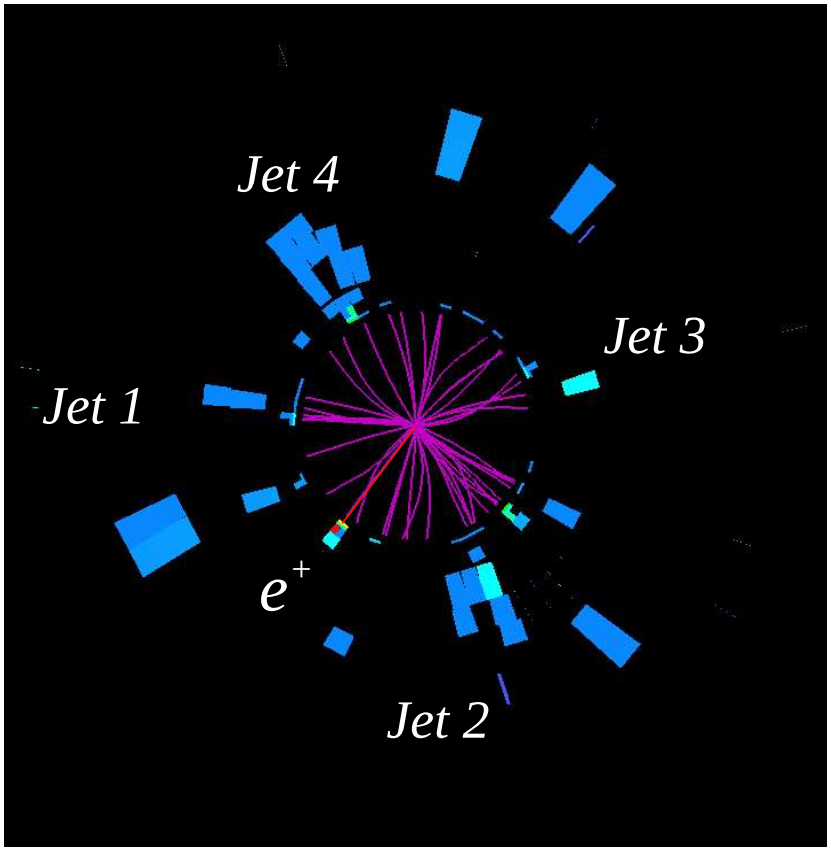


Use 1, 2 jet events to check bkg model
Look for excess in ≥3 jet region



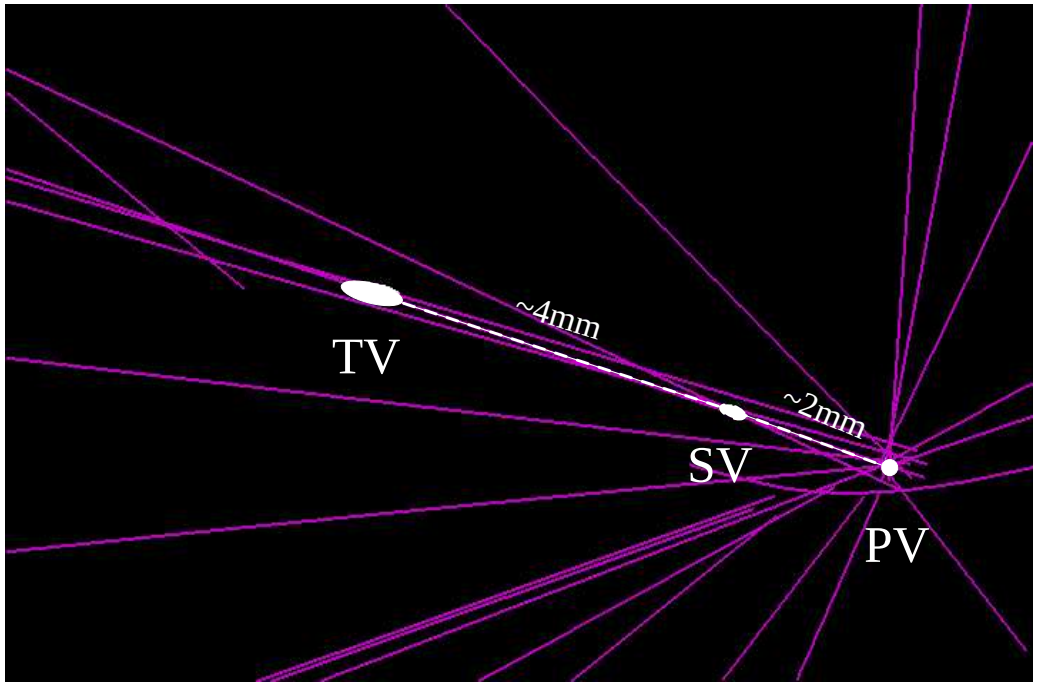


D0 Run II Electron + Jets Candidate



Event is b-tagged by both SVX and CSIP
(run 169923 event 16396718)

4 jets
Electron p_T = 27 GeV
Jet p_T = 51, 36, 30, 53 GeV
Missing E_T = 58 GeV
H_T = 207 GeV
Aplanarity = 0.11

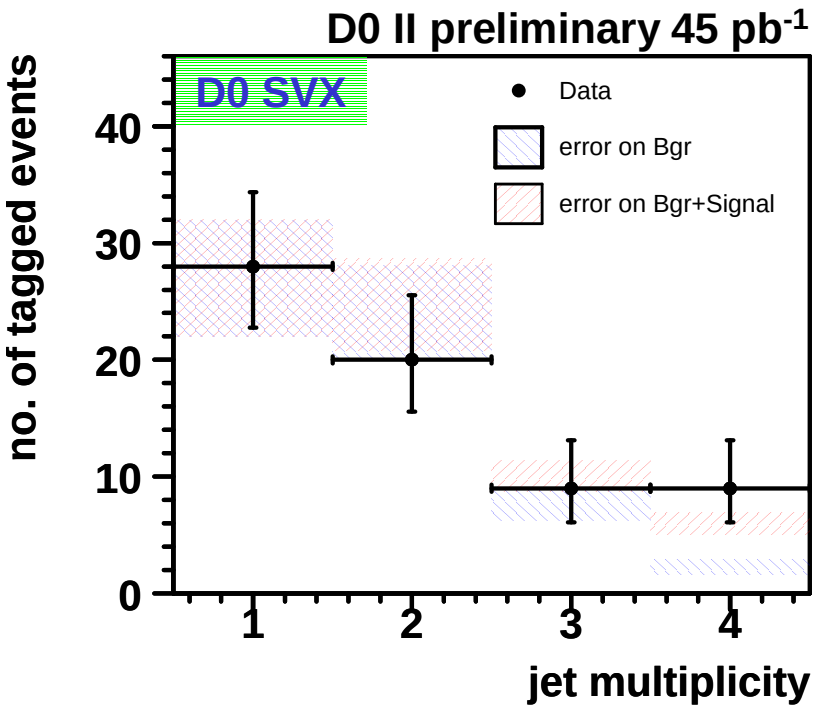


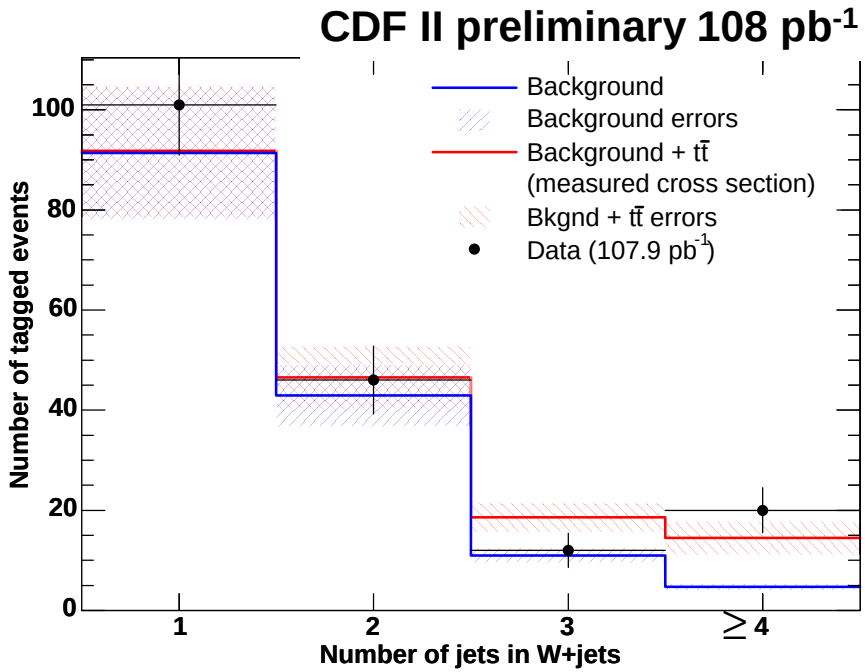
Primary vertex

N_{track} = 17
z = –4.6 cm

Top cross-section: Lepton + Jets

Data	
108 pb^{-1}	**CDF** $\sigma(t\bar{t}) = 3.9 \pm 1.3_{(stat)} \pm 0.7_{(sys)} \pm 0.2_{(lum)} pb$
45 pb^{-1}	**D0 CSIP** $\sigma(t\bar{t}) = 7.4 \pm^{4.4}_{3.6(stat)} \pm^{2.1}_{1.8(sys)} \pm 0.7_{(lum)} pb$
45 pb^{-1}	**D0 SVX** $\sigma(t\bar{t}) = 10.8 \pm^{4.9}_{4.0(stat)} \pm^{2.1}_{2.0(sys)} \pm 1.1_{(lum)} pb$
90 pb^{-1}	**D0 SLT + KIN** $\sigma(t\bar{t}) = 8.0 \pm^{2.4}_{2.1(stat)} \pm^{1.7}_{1.5(sys)} \pm 0.8_{(lum)} pb$





Top Quark Mass and the Standard Model

Why is it interesting?

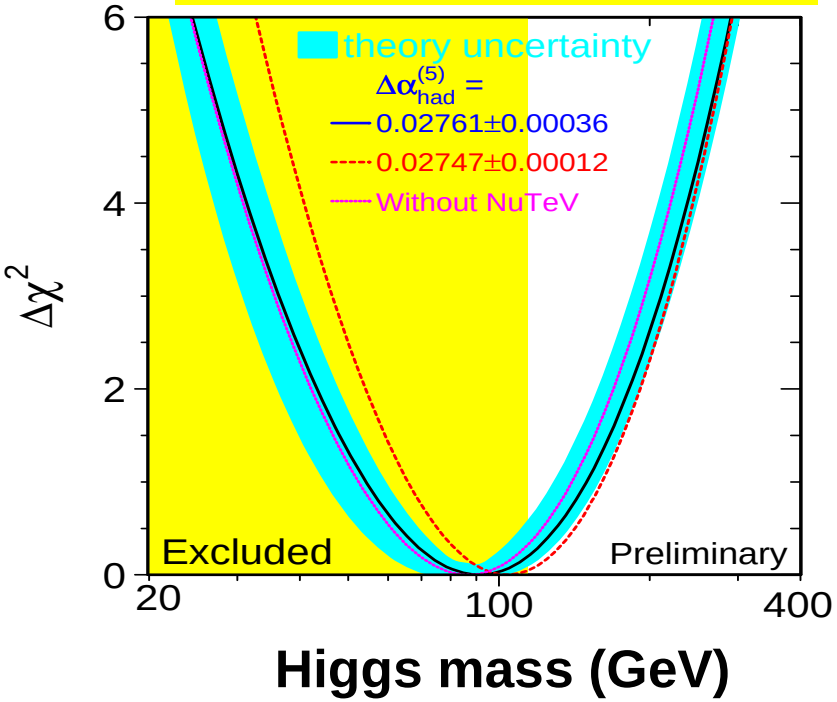
Over-constrains SM

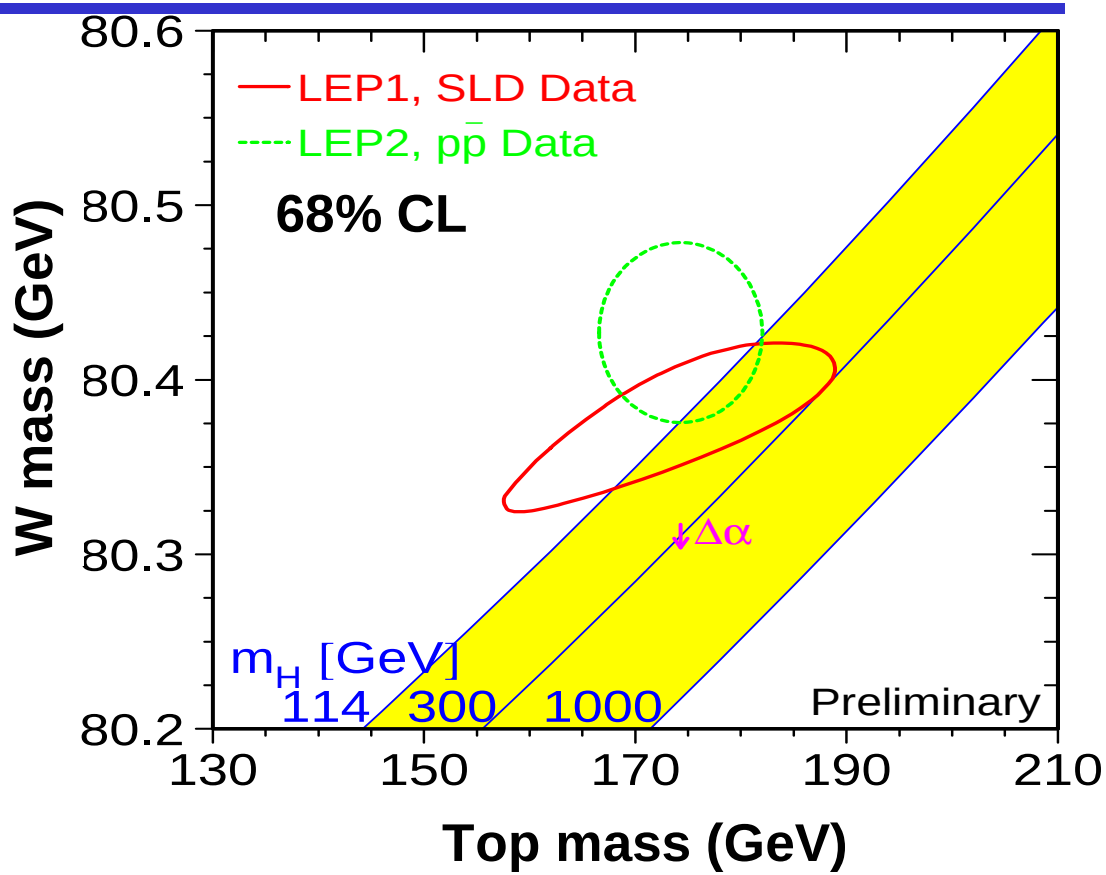
Confronts indirect predictions with direct measurements

- **See good agreement**
- **Both prefer lighter Higgs**

$$m_H = 91^{+58}_{-37}\ GeV$$

$$m_H < 211 GeV @ 95\% C.L.$$





Top strongly correlated with Higgs

5 GeV shift in m_{top} => 37% shift in m_H

(M. Gruenewald DESY-Zeuthen '03)

Top mass measurement crucial to indirect prediction from SM fit!

Run II goal: m_{top} error < 3 GeV

CDF Run II Top Mass: Lepton + Jets

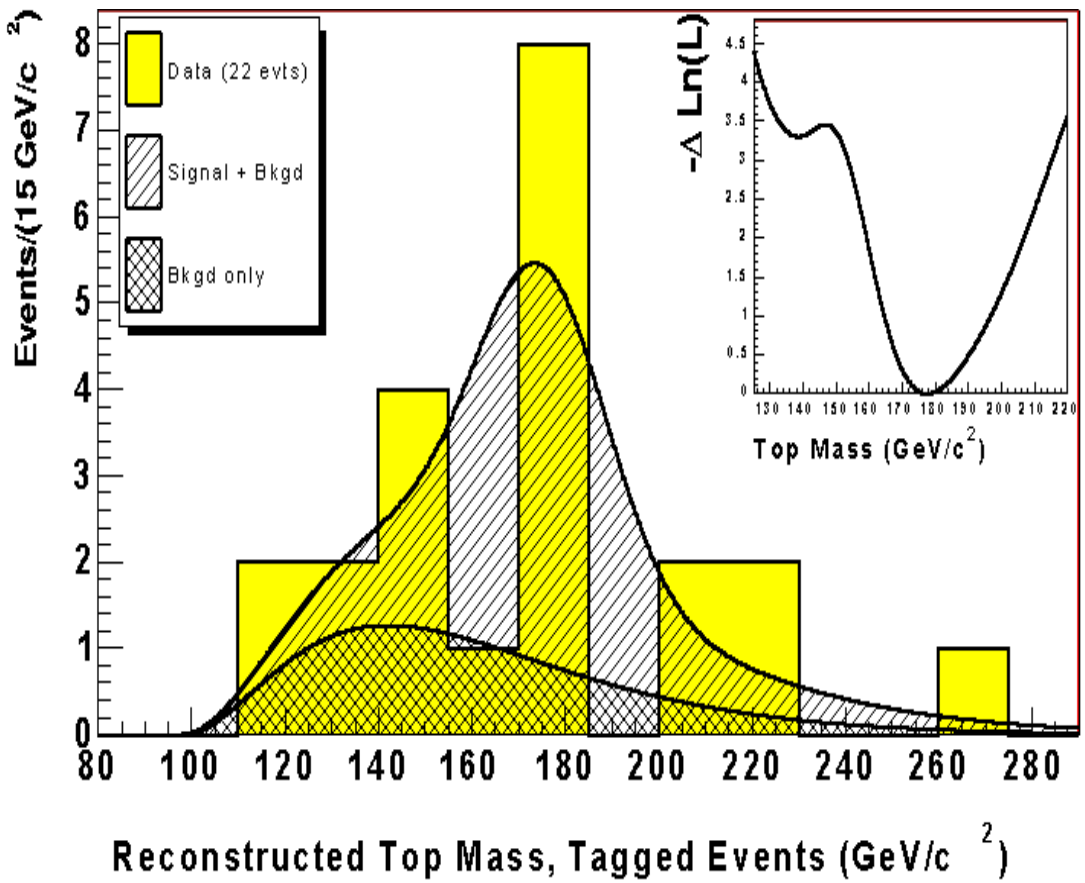
1 high p_T lepton, high MET, ≥3 jets, 1 b-tag
4th jet E_T>8 GeV (usually 15 GeV)
22 events, expect 6.5 ± 2.0 from bkg

CDF Run II preliminary 108 pb^{-1}

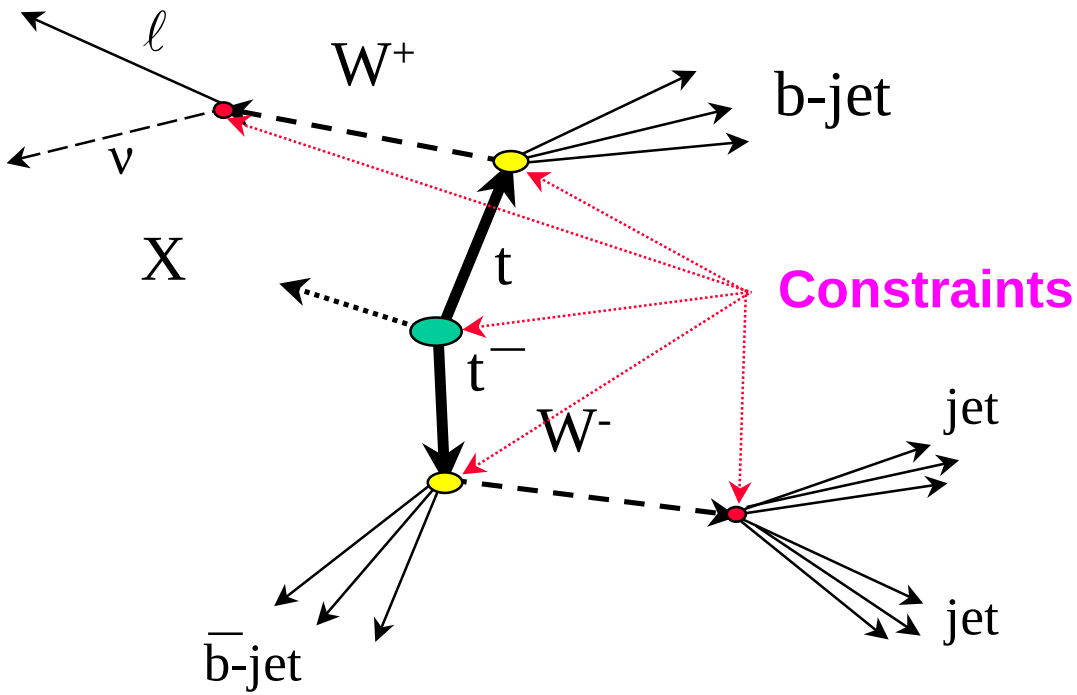
$$m_{top} = 177.5 \pm {}^{12.7}_{9.4}\,_{(stat)} \pm 7.1_{(sys)}\ GeV/c^2$$

Uses one quantity per event
- **All events carry same weight**
- **Fit to shapes from MC**

Source	Systematic (GeV/c^2)
Jets	6.2
ISR/FSR	2.6
PDF	2.0
Other MC modeling	1.0
Generators	0.6
Bkgd shape	0.5
b-tag	0.1
Total	7.1 GeV



Reconstructed event-by-event top mass



Use constrained fit technique with 2 dof

$M_{l\upsilon}=M_W$, $M_{jj}=M_W$, $M_{t1}=M_{t2}$, p_T balance

4 jets = 12 possible jet-parton combinations
x 2 solutions for neutrino p_z
!!!Use b-tagging to reduce permutations!!!

Choose combination with lowest χ^2

Improved D0 Run I Top Mass

Uses event probabilities

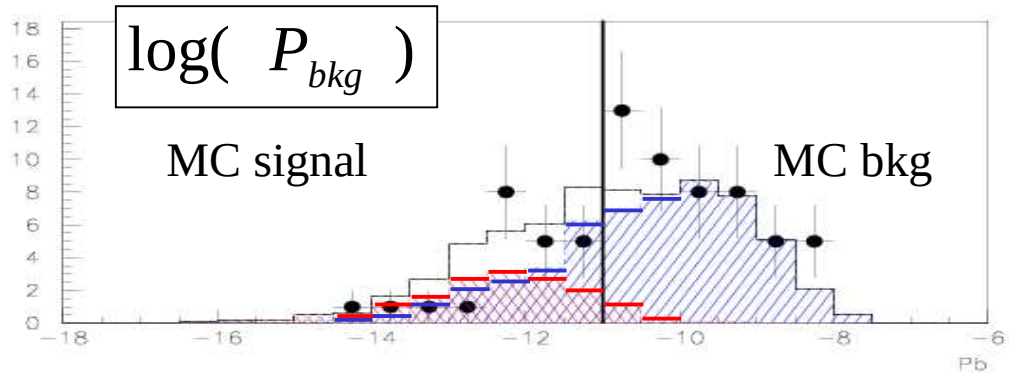
- **Full set of event observables**
- **Better measured events carry more weight**

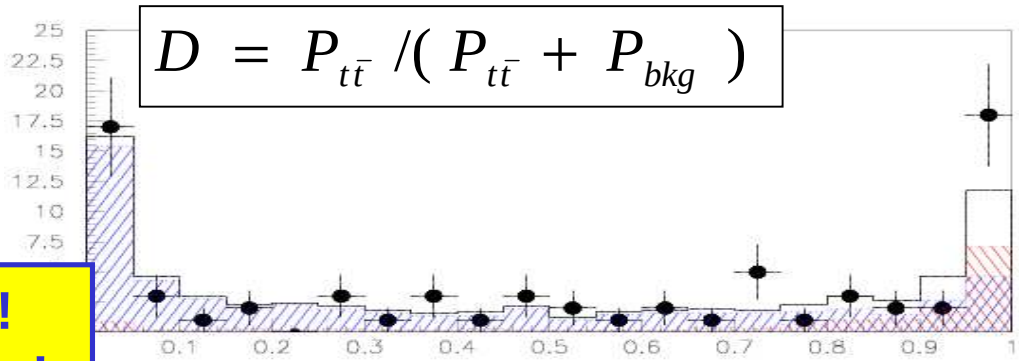
Reduces background

91 original candidates

77 after exactly 4 jets

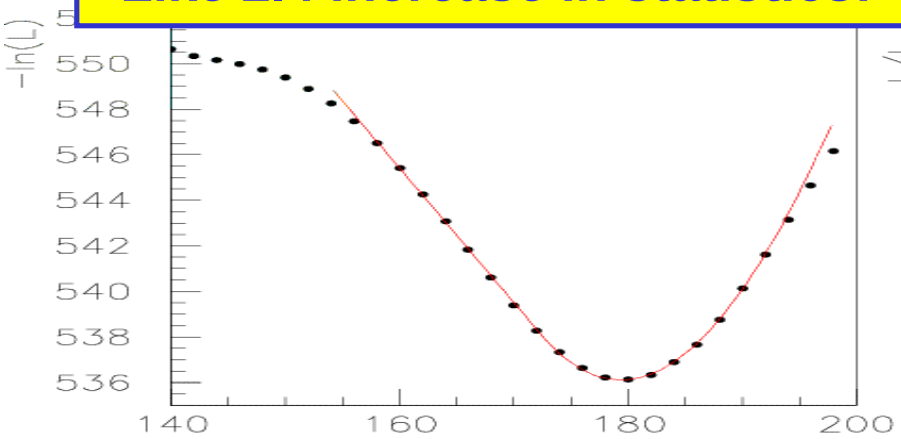
22 after Pbkg<-11

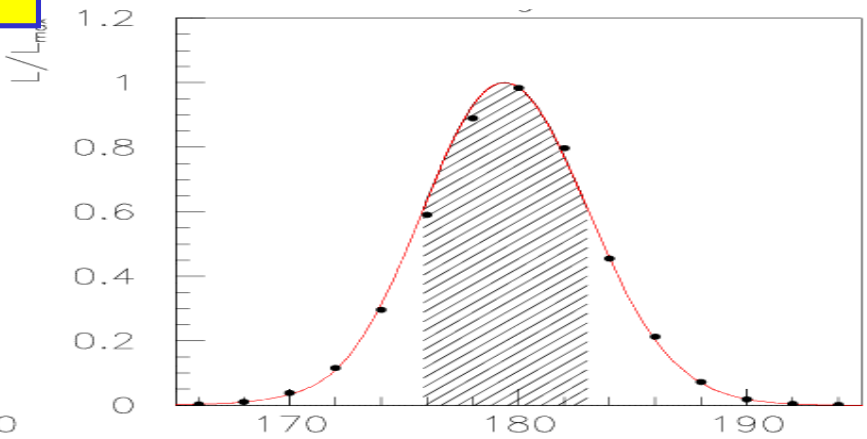




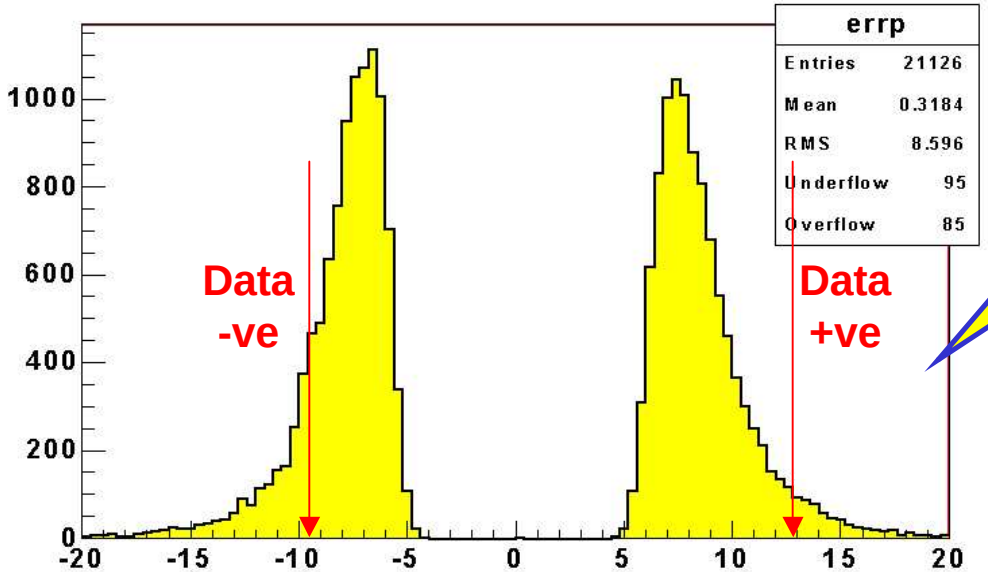
M_{top}=180.1 ± 3.6 ± 4.0 GeV

Old stat error was 5.6 GeV!
Like 2.4 increase in statistics!





Top Mass – Expected Statistical Errors

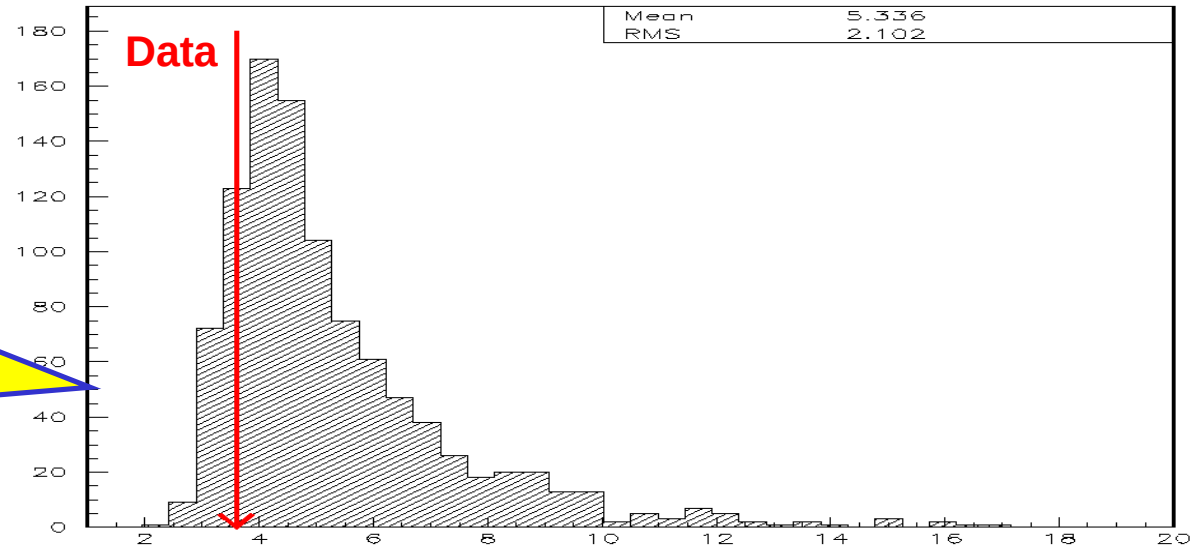


Expected stat. error (GeV)

CDF Run II (108 pb^{-1})
Preliminary
Expected 8.8 GeV
Observed +12.7, -9.4 GeV

Observed errors consistent with expectations

D0 Run I (125 pb^{-1})
Preliminary
Expected 5.4 GeV
Observed 3.6 GeV



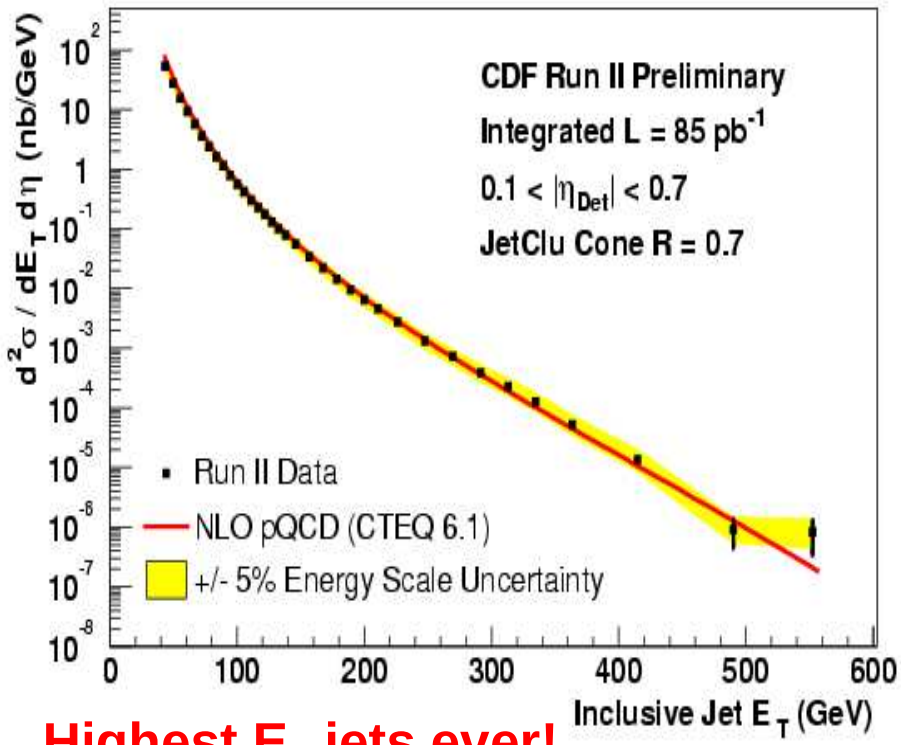
Expected stat. error (GeV)

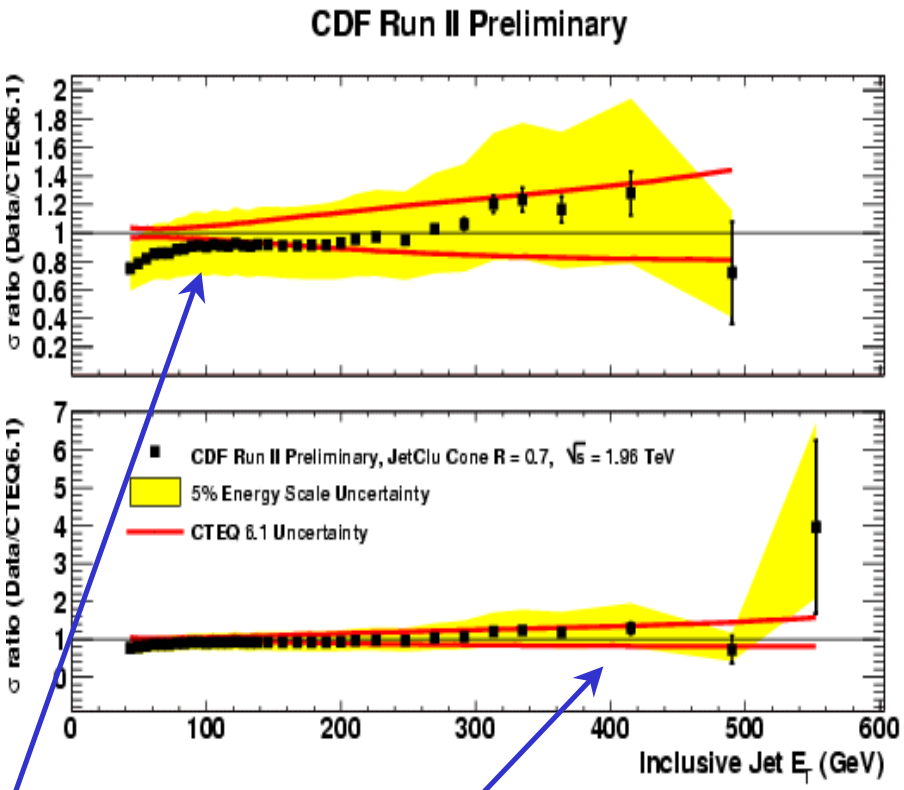
QCD - Inclusive Jet Production

Why should you care? Mother of all backgrounds!

Jet cross-section – sensitive to gluon distribution in proton

Better predictions of many new physics processes at high energies





Highest E_T jets ever!

8 orders of magnitude!

Systematics dominated by Jet Energy Scale…to be reduced

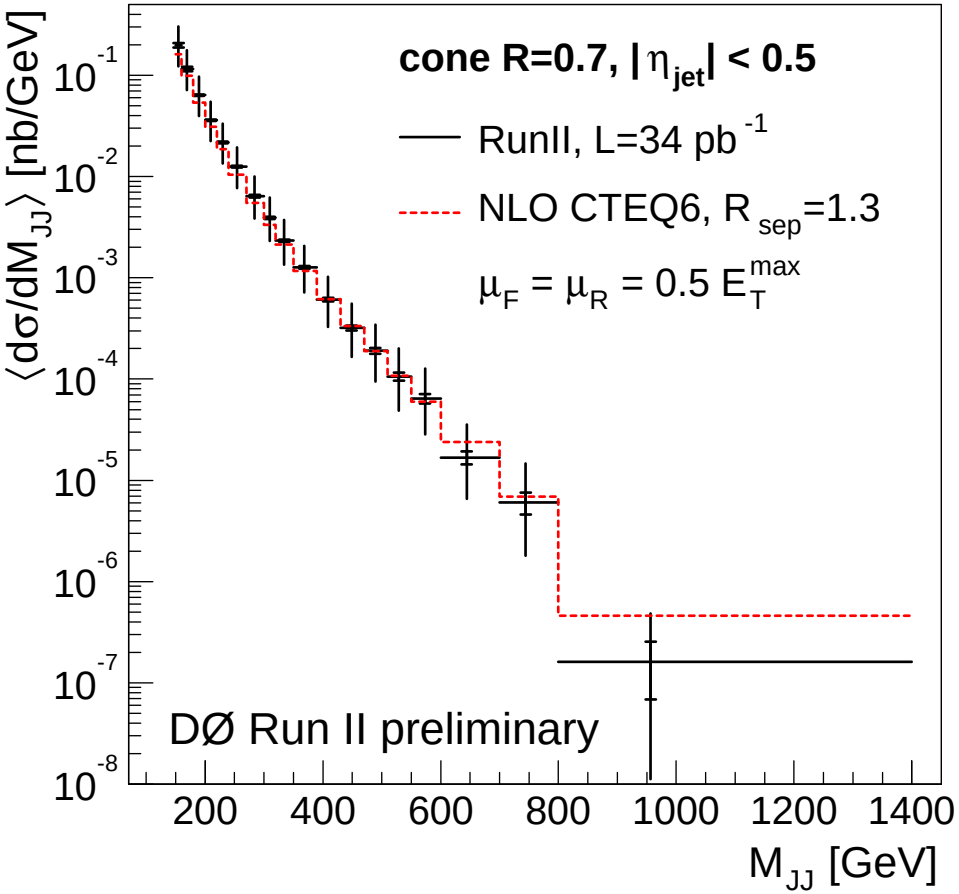
Theoretical error dominated by PDF's (gluon at high-x)

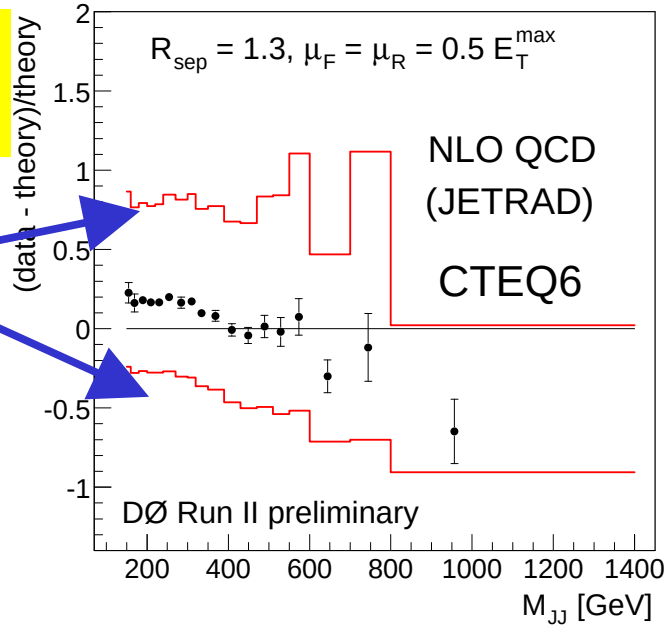
Agreement within uncertainties

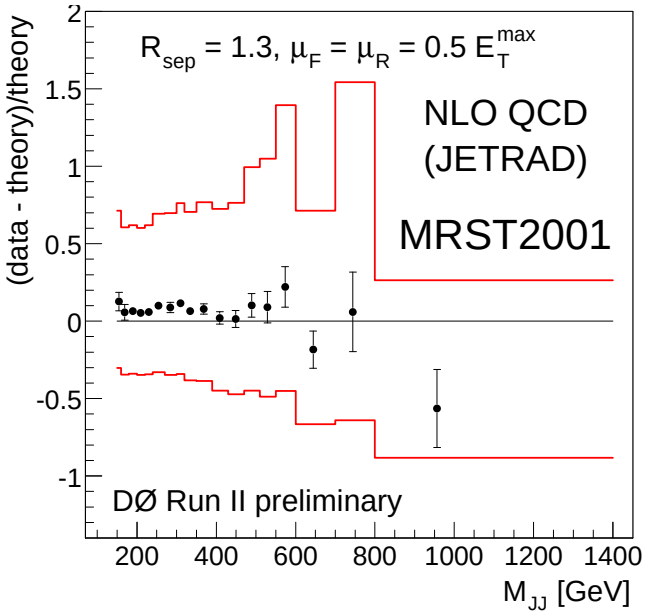
QCD – Dijet cross-section

Cross-section well reproduced by NLO theory over 6 orders of magnitude

Systematics dominated by Jet Energy Scale





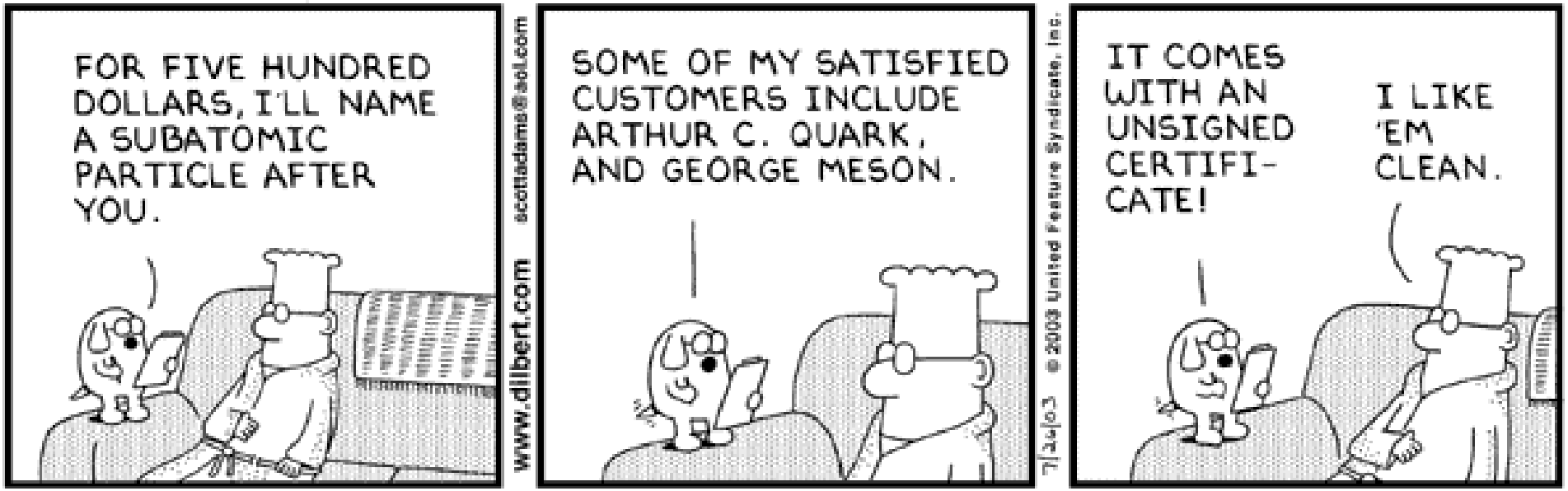


Searches for New Physics

Why? Standard Model is incomplete!

Why $M_{EW} << M_{Pl}$?
How to achieve grand unification?
How to include gravity?
What explains proliferation of quarks and leptons?
What determines their mixings?

More general theories make predictions that can be tested at the Tevatron



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Searches for New Physics

Tevatron is the world's highest energy accelerator and is the most likely place to directly discover a new particle or force

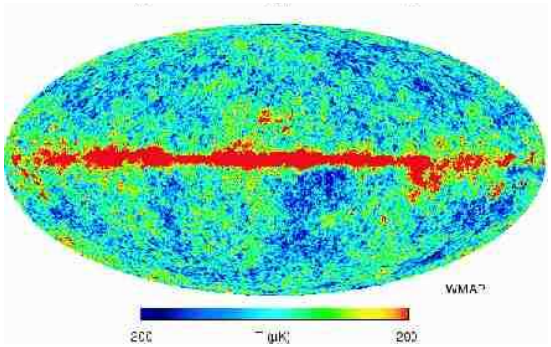
Search for Extra Dimensions, Z'
- Study of high E_T tails

Search for SUSY
- Jets + MET
- Photons + MET
- Trileptons

Search for Leptoquarks
- First generation eejj
- Second generation μμjj
- All generations ννjj

Search for Rare Decays
- $D^0 \rightarrow \mu^+\mu^-$
- $B_s \rightarrow \mu^+\mu^-$

What is dark matter?
SUSY LSP?
Extra dimensions?
Tevatron can put limits on models



$$\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$$

$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

WMAP, astro-ph/0302207

Extra Dimensions Overview

SM particles confined to 4 dimensions
Gravity propagates in extra dimensions
Solves the hierarchy problem!
Can explain dark matter!

ADD Model (Arkani-Hamed, Dimopoulos, Dvali)

n "large" extra dimensions of size

$$R \sim \frac{1}{M_s}(M_{Pl}/M_s)^{2/n}$$

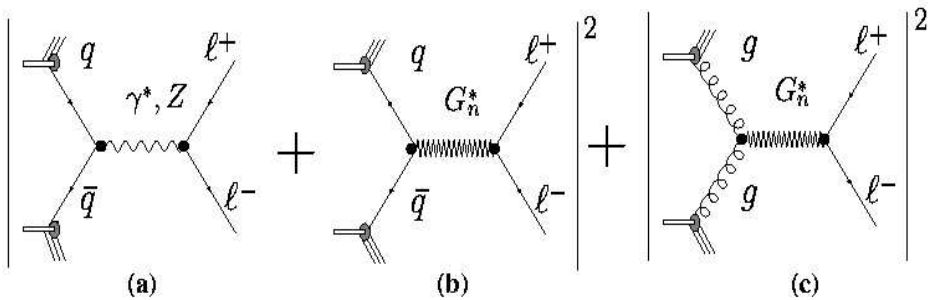
n=1 R~10^8 km – excluded!
n=2 R~1 mm ~ tabletop realm
n≥3 R≤3 nm - collider realm

Randall-Sundrum Model

One "small" extra dimension warped by factor $e^{-2kr_c\pi}$
Spin-2 resonance
- **Graviton mass**
- **Coupling k/M_{Pl}**

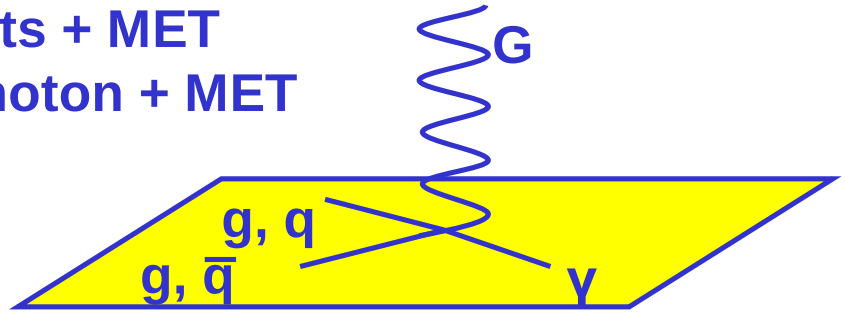
Experimental signatures

Virtual graviton exchange modifies fermion/boson pair production



Direct graviton emission

Jets + MET
Photon + MET



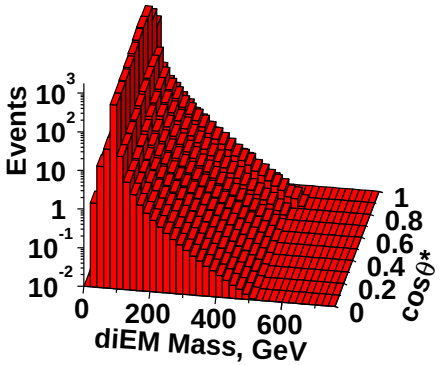
Extra Dimensions – ADD Model

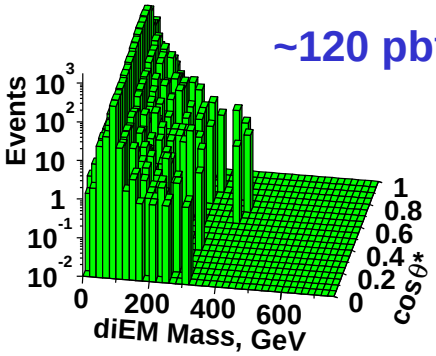
Virtual graviton exchange
Look for excess at
high dilepton or diphoton mass

ee and γγ: 2 EM objects p_T>25 GeV

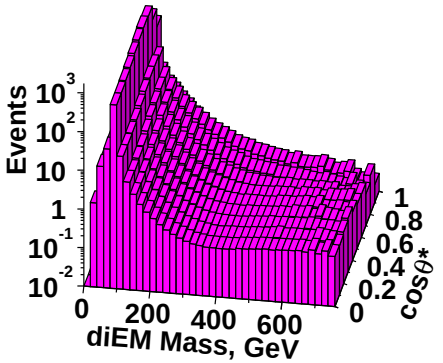
SM Prediction | D0 Run II Preliminary | **Data**

~120 pb^{-1}

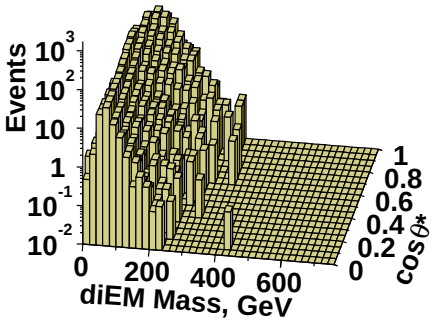




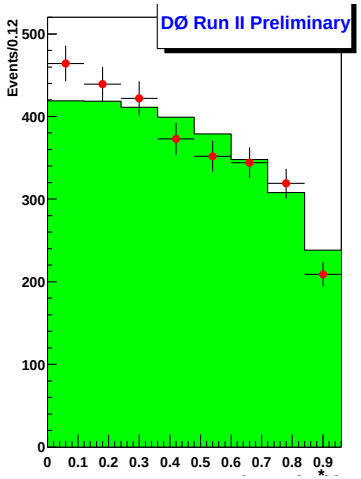
ED Signal

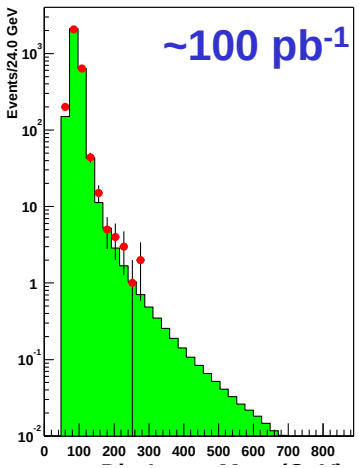


QCD Background



$\mu^+\mu^-$: p_T>15 GeV, $m_{\mu\mu}$> 40 GeV



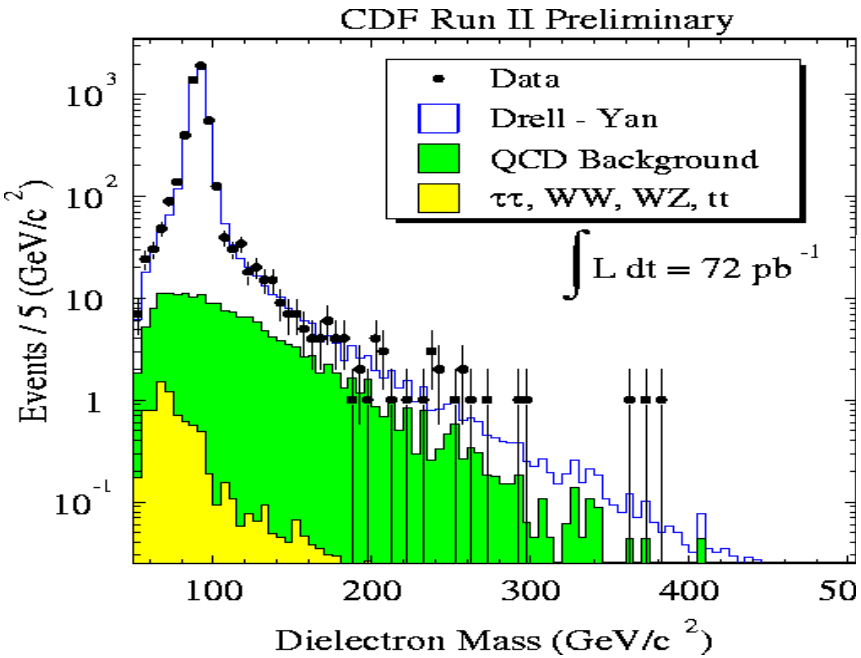


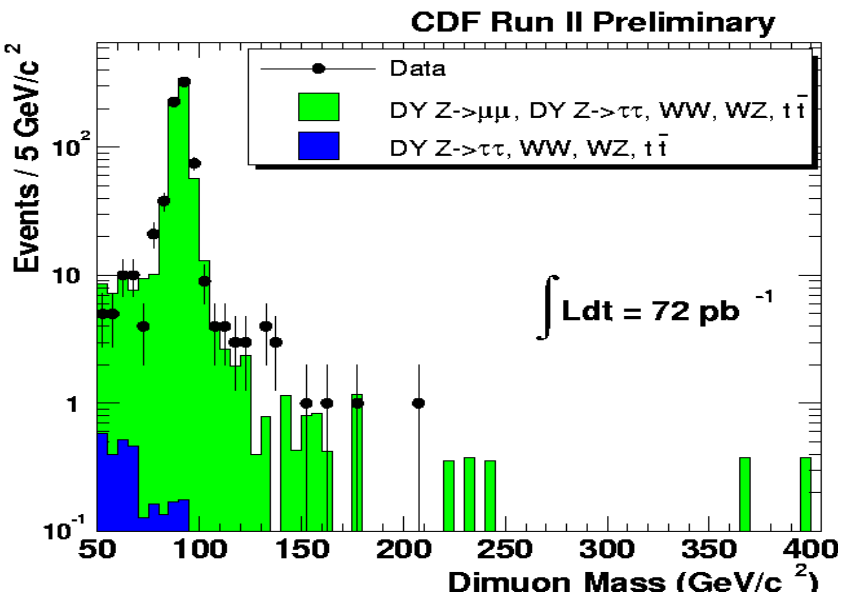
|cosθ*| $M_{\mu\mu}$ (GeV)

Consistent with no signal
D0 now has world's best limit!
Probe up to 2 TeV with 2 fb^{-1}

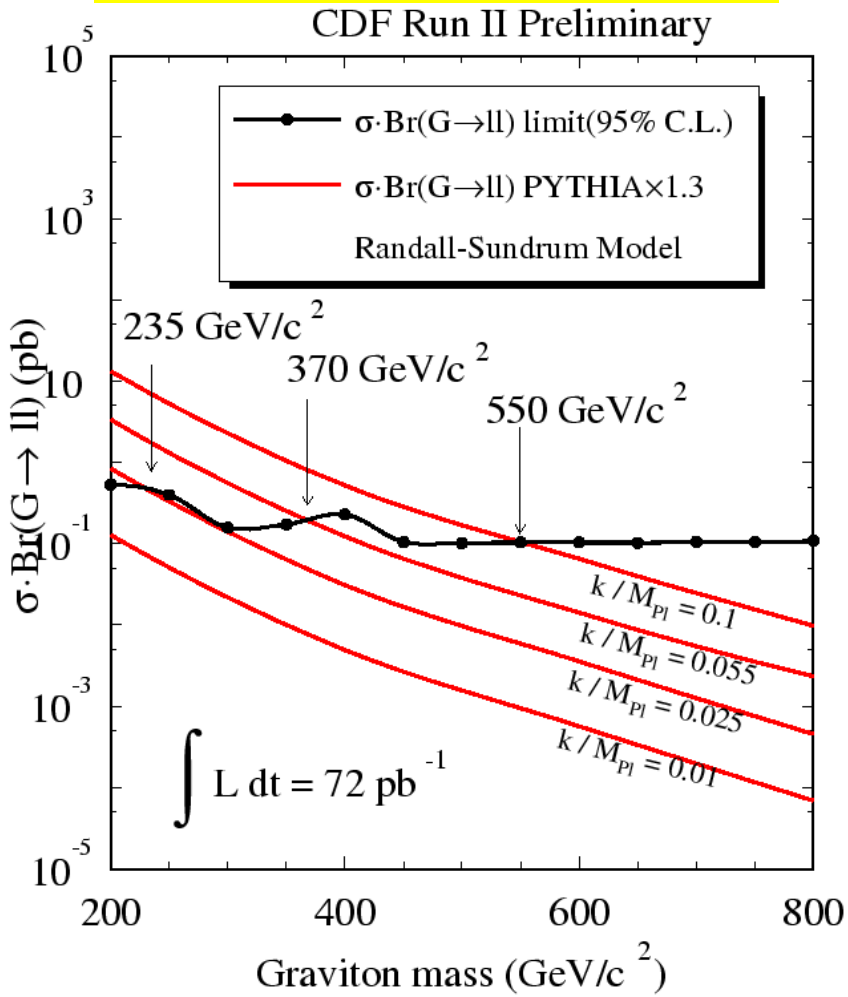
95% C.L. M_S (TeV)	GRW	HLZ n=2, 3, 7	Hewett λ=+1
D0 diEM	1.28	1.42, 1.52, 1.01	1.14
D0 μμ	0.88	1.05, 0.88, 0.70	0.79
CDF diEM	-	-	0.85

Extra Dimensions - Randall-Sundrum Model





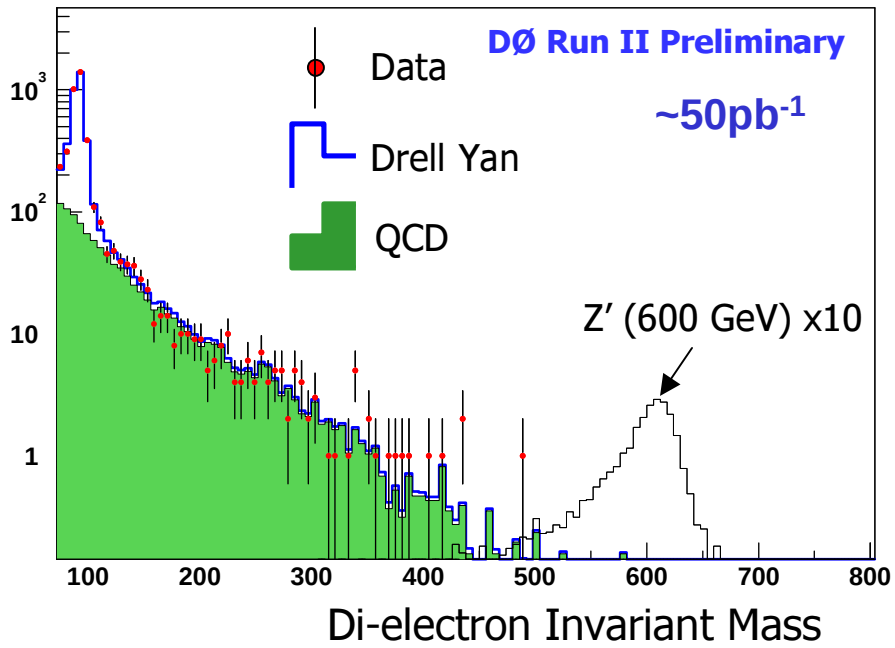
Spin-2 graviton
Look for resonances in dilepton mass
Consistent with no signal



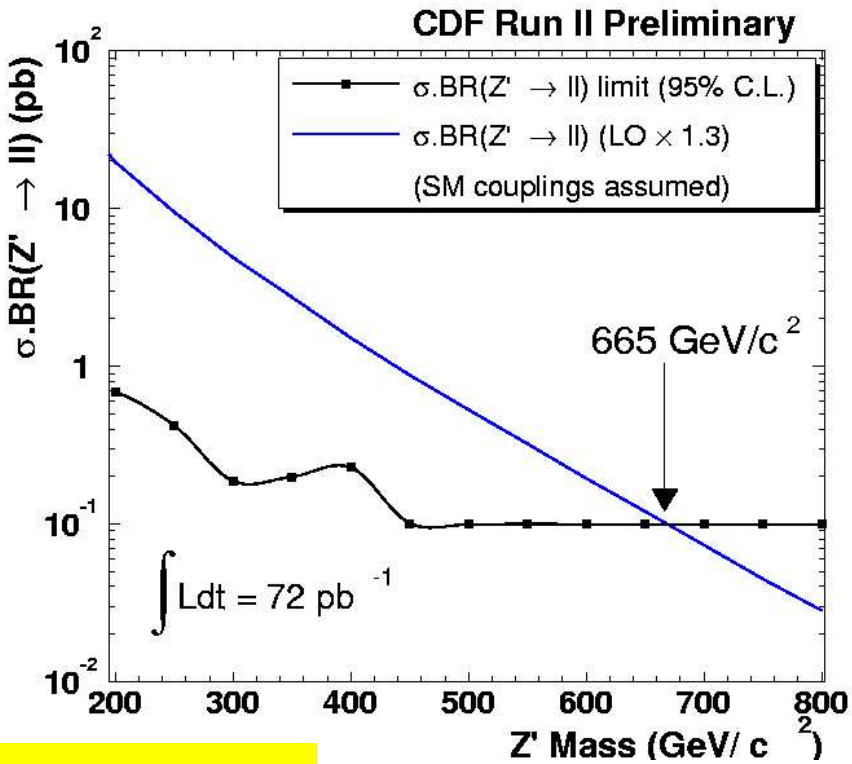
Extra Gauge Bosons

Predicted by many models
Look for resonance in dilepton mass
Consistent with no signal

D0 m(Z')> 719 GeV @ 95% C.L ~100pb^{-1}
World's best limit



CDF m(Z')> 665 GeV @ 95% C.L
Close to Run I 690 GeV

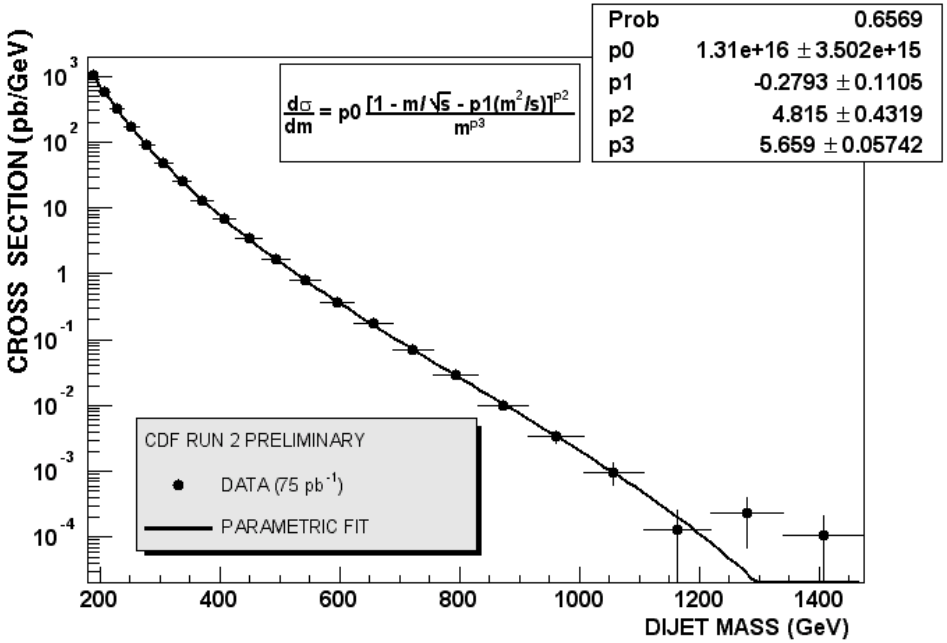


Probe up to 1 TeV with 2 fb^{-1}

Dijet Resonances

New Particles That Decay to Dijets

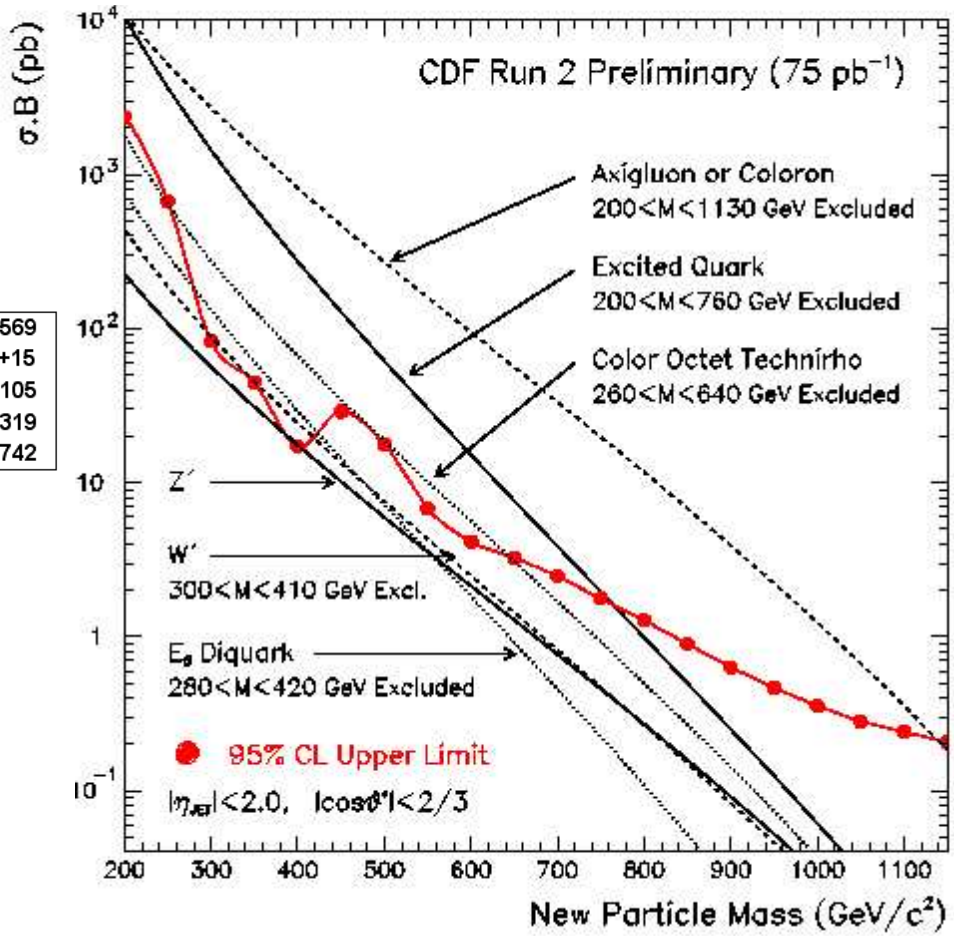
Model	Particle	Production/Decay	J^P(color) & $\Gamma/2$
Chiral Color SU(3)L x SU(3)R	Axigluon A	$\bar{q}\,q \to A \to \bar{q}\,q$	$1^+(8)$ .05 M
Extended Technicolor	Coloron C	$\bar{q}\,q \to C \to \bar{q}\,q$	$1^-(8)$ .05 M
Composite Fermions	Excited Quark q*	$q\,g \to q^* \to q\,g$	$1/2^+(3)$ .02 M
Superstring Inspired E6 Models	Diquarks D, D^c	$u(\bar{u})\,d(\bar{d}) \to D\,(D^c) \to u(\bar{u})\,d(\bar{d})$	$0^+(\bar{3})$ .004 M



Sensitive to a variety of new physics

Probes highest energies

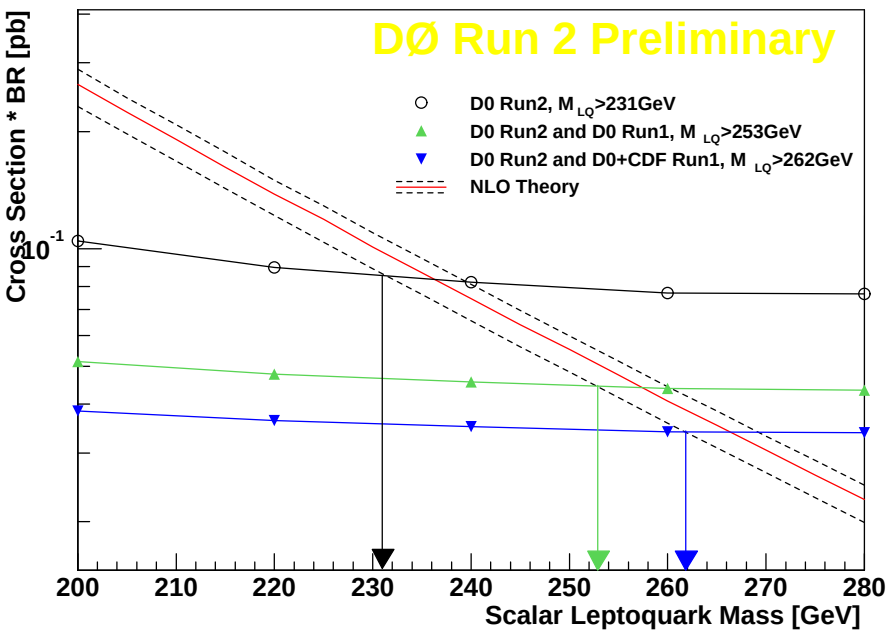
Axigluon mass > 1.1 TeV@95%C.L.



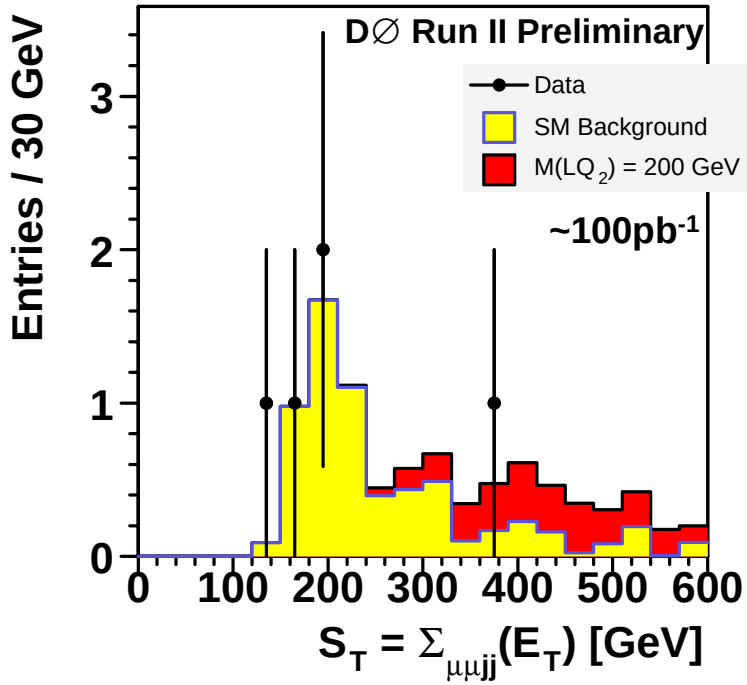
Scalar Leptoquarks

Directly couple quarks to leptons
Predicted by Grand Unified Theories

First generation LQ_1 $LQ_1 \rightarrow eejj$



Second generation LQ_2 $LQ_2 \rightarrow \mu\mu jj$



D0 $M(LQ_1)$>253 GeV @ 95% C.L.
CDF $M(LQ_1)$>230GeV @ 95% C.L.

D0 $M(LQ_2)$>186 GeV @ 95% C.L.
CDF in progress

All three generations LQ $LQ \rightarrow \nu\nu jj$

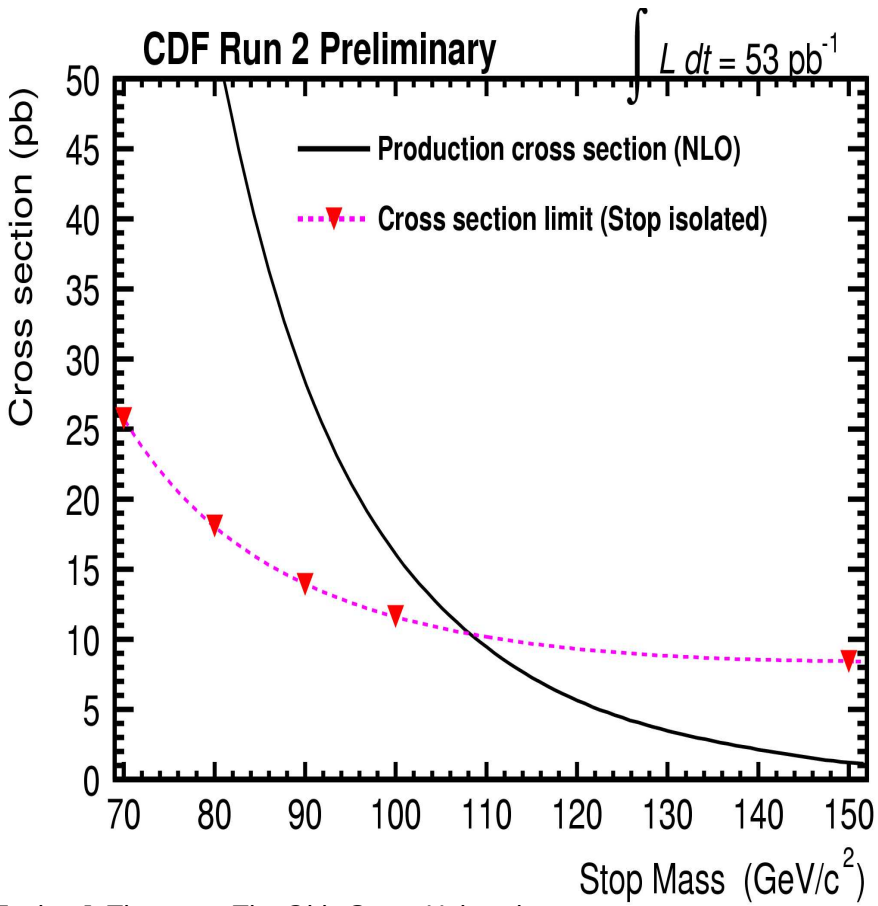
Jets + MET

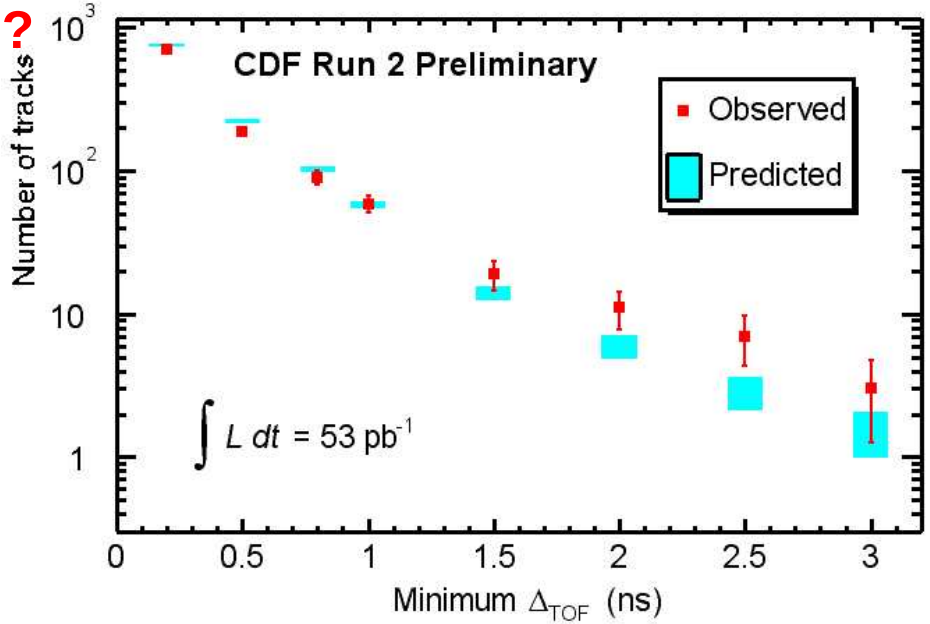
CDF M(LQ)>107 GeV @95%C.L.

SUSY – Search for Long-lived Stop

Long-lived massive charged particles?

- **Move slowly**
- **Measure time-of-flight!**
- **ΔTOF=TOF candidate – TOF at c**





Selection

Tracks with p_T>40 GeV

ΔTOF>2.5 ns

Observe 7 events in 53pb^{-1}

Expect 2.9 ± 0.7$_{(stat)}$ ± 3.1$_{(syst)}$

Consistent with no signal

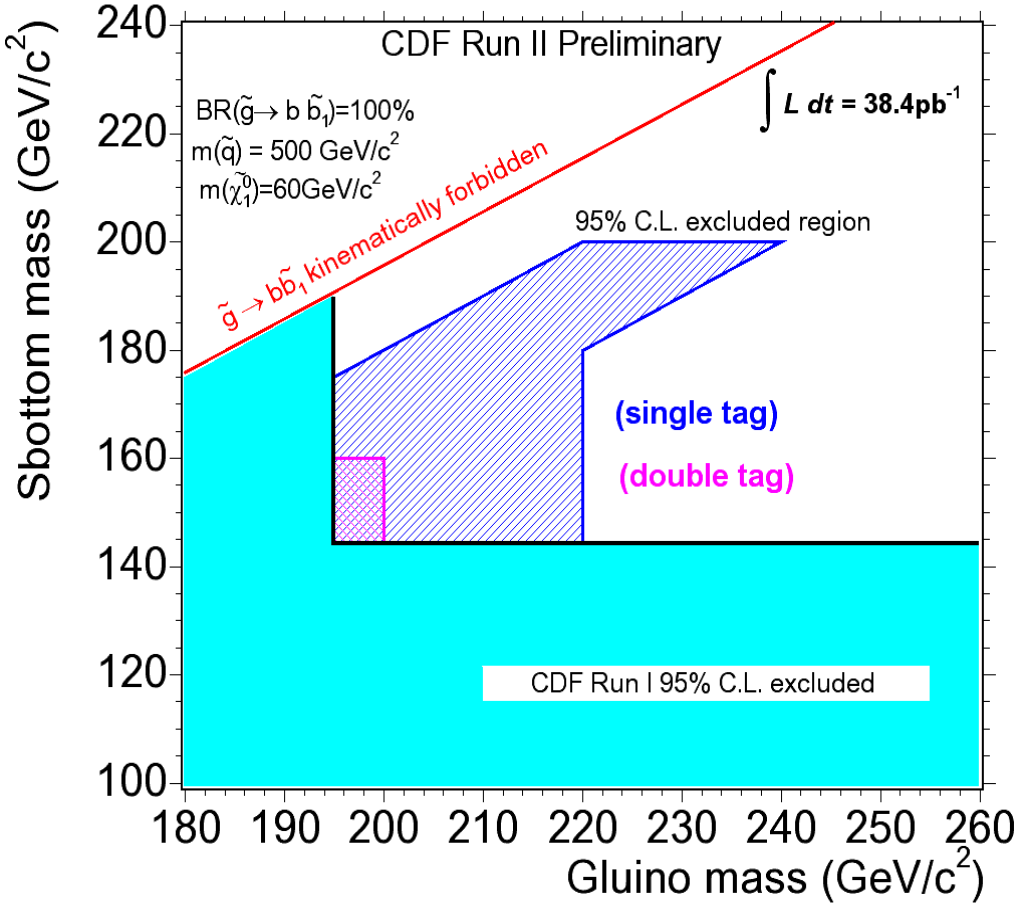
m(stop)> 107 GeV @95% C.L.

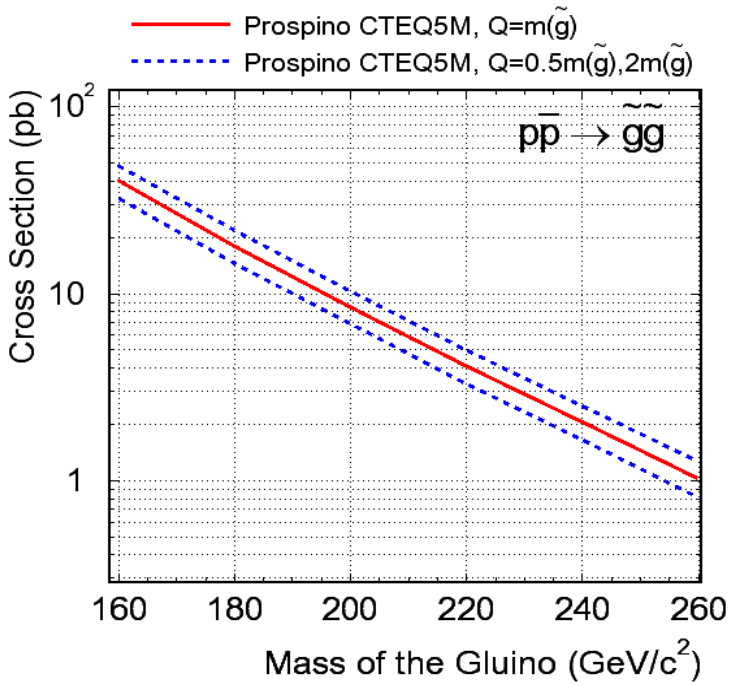
LEP limit is 95 GeV

SUSY – Sbottoms from Gluino Decays

Gluino pair production cross-section large
Very distinctive signature of 4 b jets + MET

$$\tilde{g}\tilde{g} \rightarrow (b\tilde{b}_1)(b\tilde{b}_1) \rightarrow (bb\tilde{\chi}_1^0)(bb\tilde{\chi}_1^0)$$





Selection
3 or more jets
MET> 50 GeV
Lepton veto

Assume
$m_{\tilde{\chi}_1^0} = 60\,GeV$
$m_{\tilde{g}} = 220\,GeV$
$m_{\tilde{b}_1} = 160\,GeV$

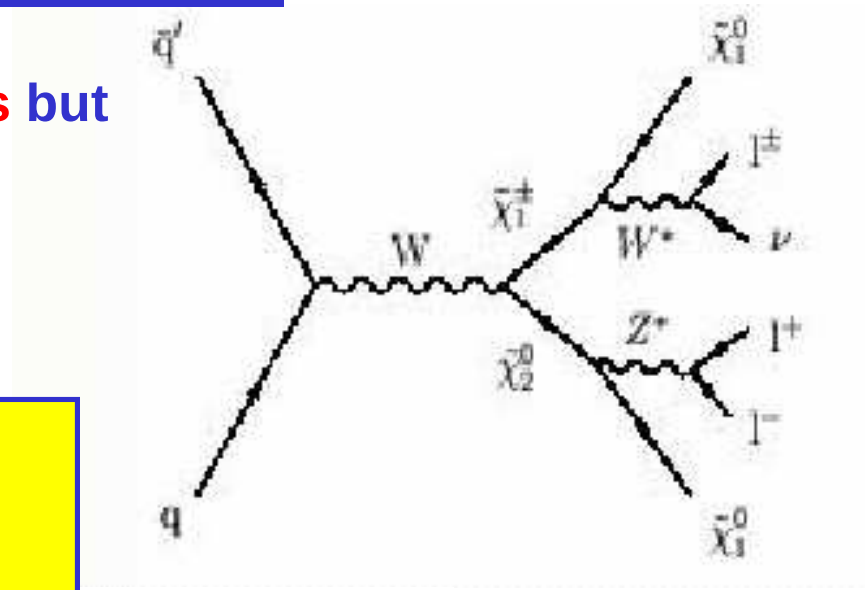
b-tag	Data	Expected Background	Expected Signal
Single	4	5.6 ± 1.4	10.6 ± 1.7
Double	1	0.5 ± 0.1	4.4 ± 0.9

SUSY Trileptons

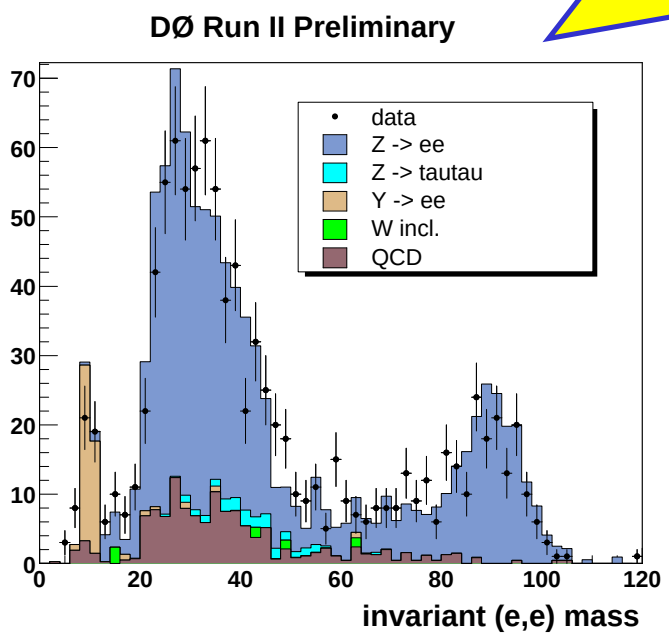
"Golden" channel with low backgrounds but

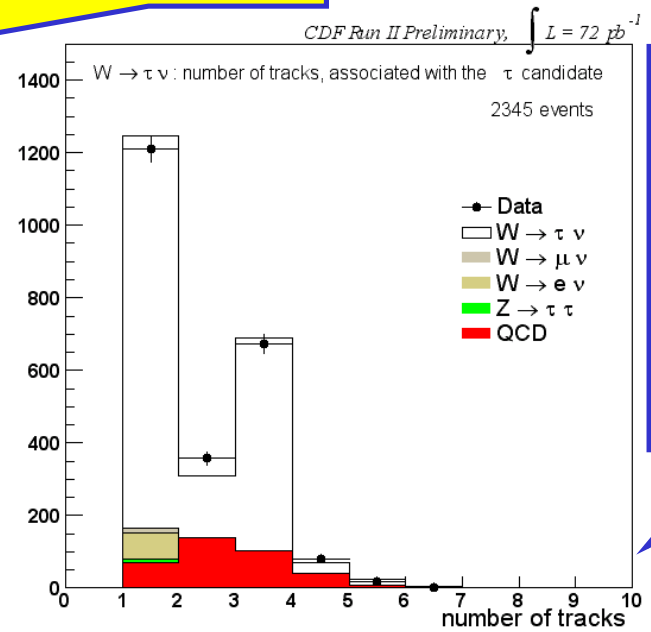
- **Leptons are soft (p_T<20 GeV)**
- **tanβ>8 most leptons are taus!**

Need >300pb^{-1} to improve on LEP



Understanding soft electrons!
Two electrons p_T>10 GeV
At least one electron p_T<20 GeV





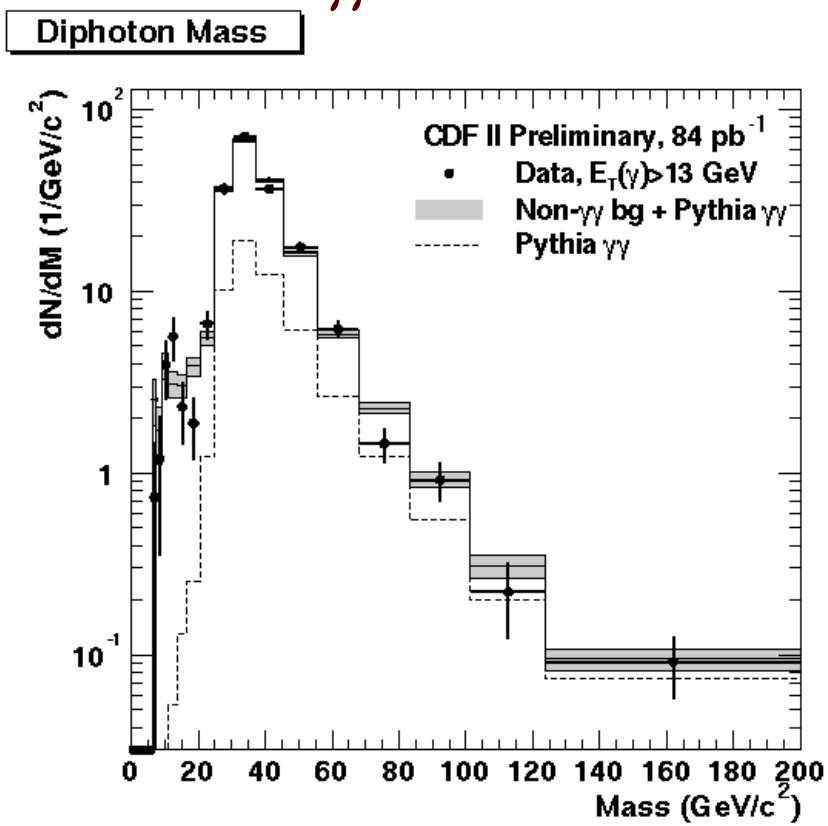
Understanding taus!
CDF has tau (p_T>5 GeV) and di-tau triggers

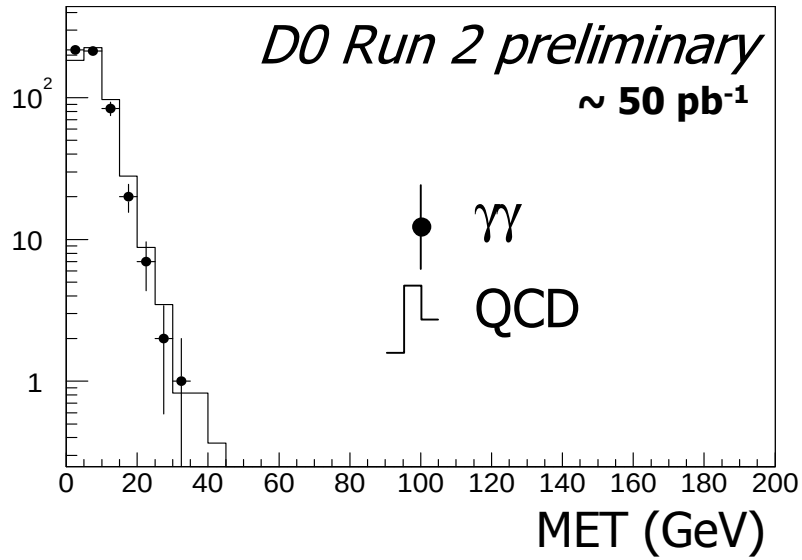
Search for Gauge Mediated SUSY

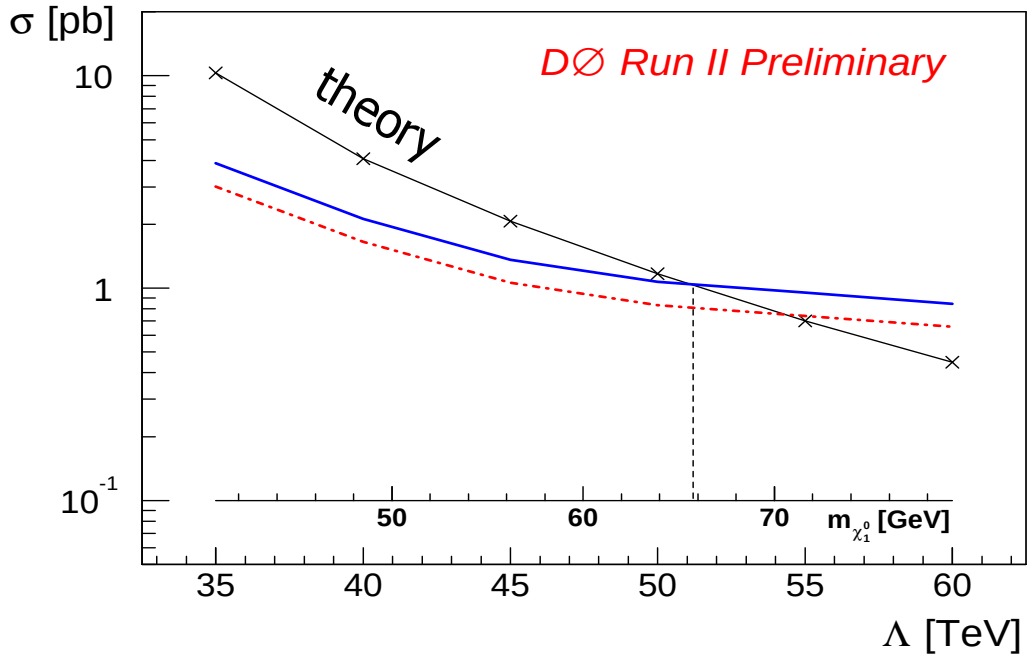
Gaugino pair production and
LSP = gravitino NLSP= neutralino
Experimental signature γγ+MET
Close to Run I limits

$$p\bar{p} \rightarrow gauginos \rightarrow W, Z, \gamma + \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow$$

$$\rightarrow \gamma\gamma + \tilde{G}\tilde{G} + X$$





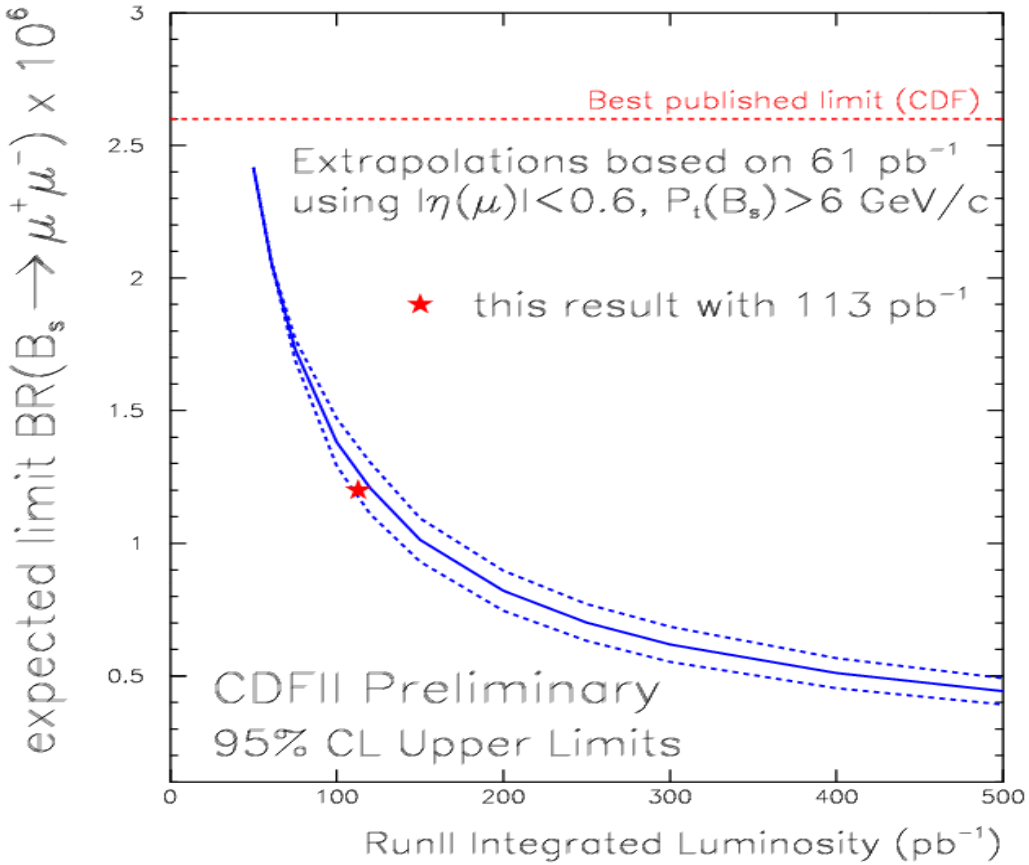


Rare Decays

Search for FCNC $B_s \rightarrow \mu^+\mu^-$
CDF 1 candidate in B_s and B_d window
$BR(B_s \rightarrow \mu\mu) < 9.5E\text{-}7$ @ 90% CL
$< 1.2E\text{-}6$ @ 95% CL
$BR(B_d \rightarrow \mu\mu) < 2.5E\text{-}7$ @ 90% CL
$< 3.1E\text{-}7$ @ 95% CL

D0 3 candidates in B_s window
$BR(B_s \rightarrow \mu\mu) < 1.6E\text{-}6$ @ 90% CL

World's best limits for B_s
May catch up to BaBar/Belle for B_d



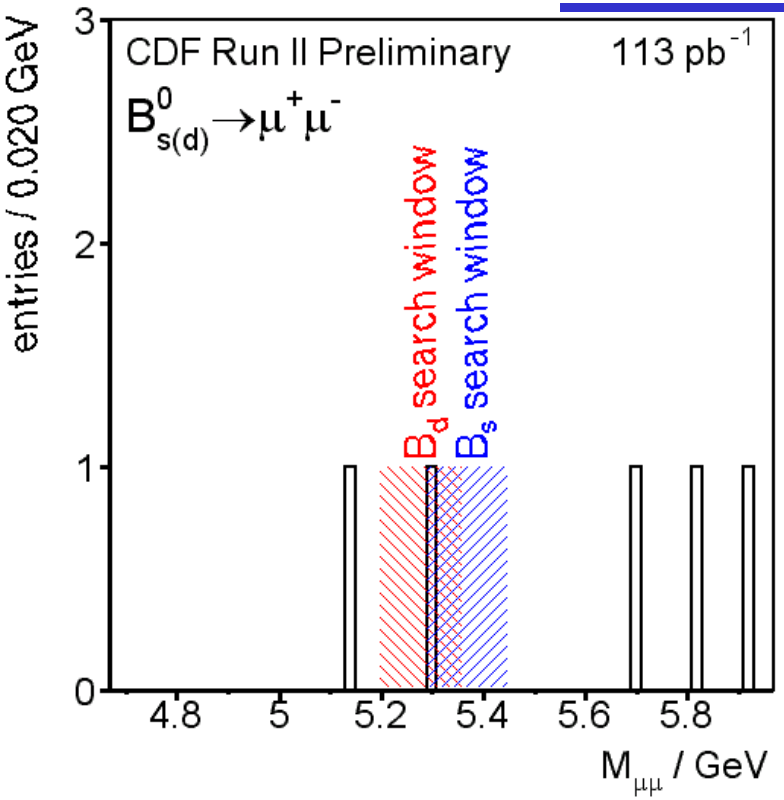
SM $BR(B_s \rightarrow \mu^+\mu^-) \sim 3.8 \times 10^{-9}$

Various SUSY models predict enhancement by 10 to 1000

Recently interesting since same SUSY models predict deviations of $(g\text{-}2)_\mu$

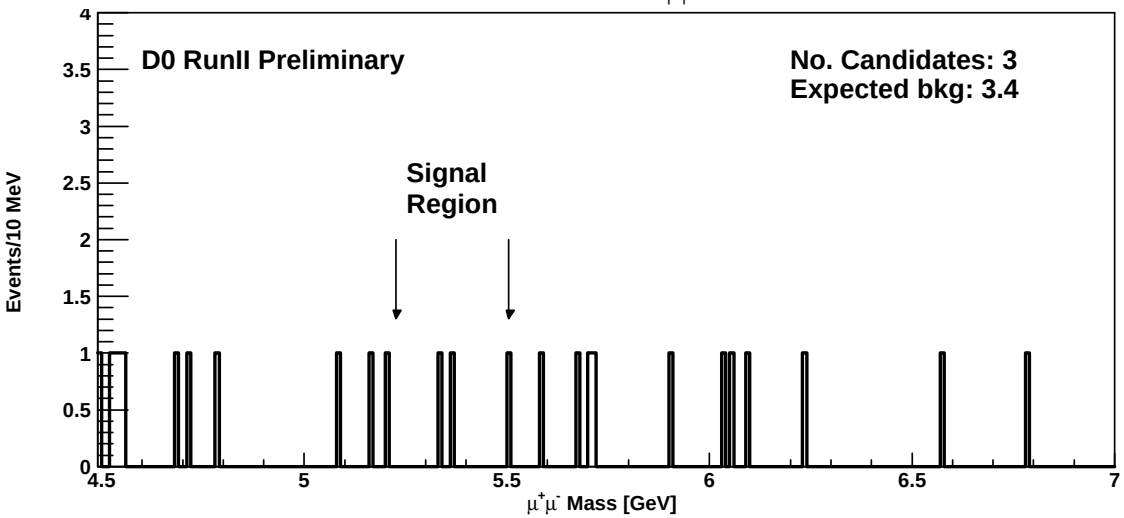
Exp: PRL 89 (2002) 101804,129903
Theory: PRL 87 (2001) 251804

Rare Decays



CDF
1 event in B_s and B_d search window

Expected bkg
0.54 ±0.20 (for B_s)
0.59 ±0.22 (for B_d)



D0
3 events in B_s search window

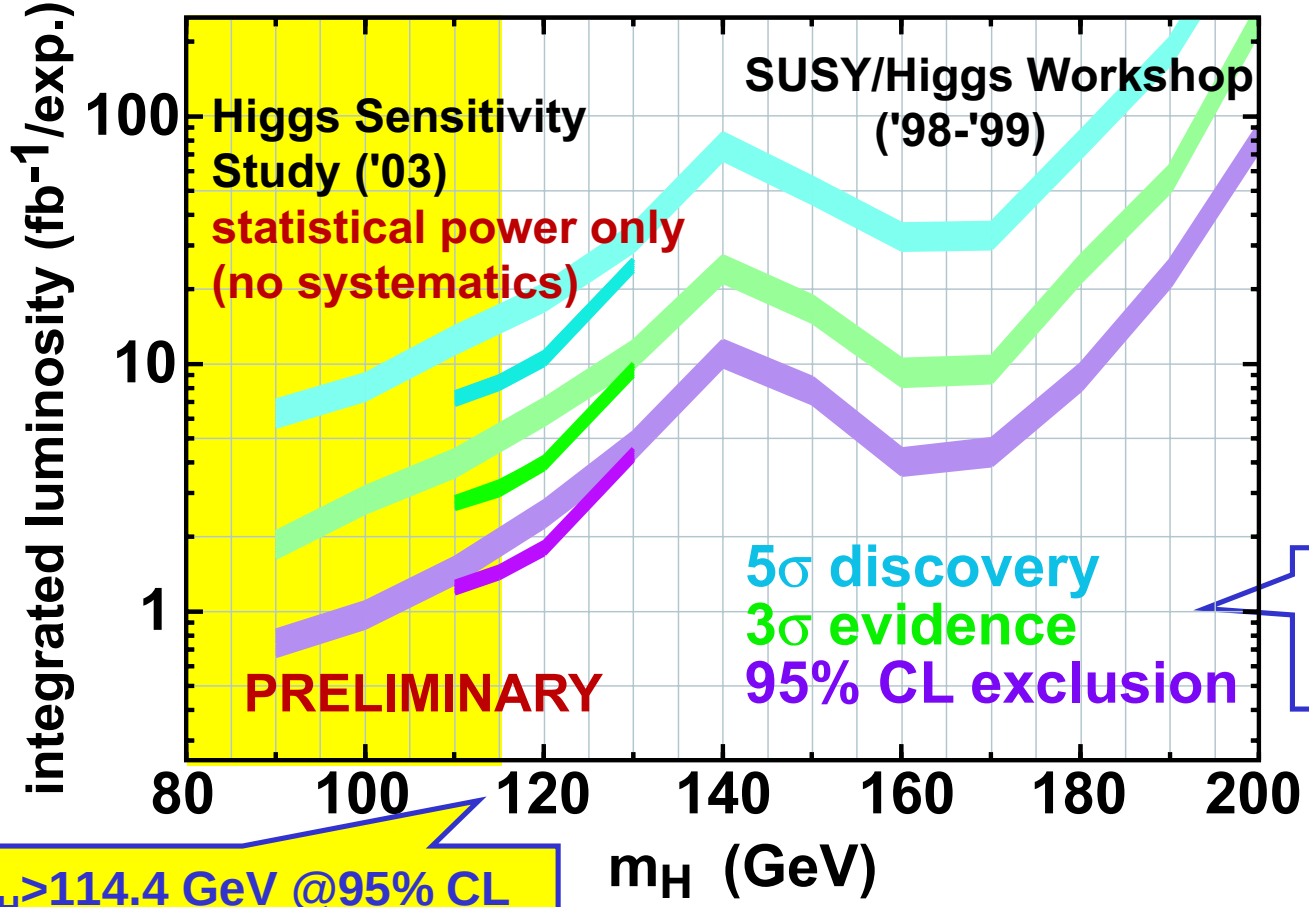
Expected bkg
3.42 ±0.79 (for B_s)

Search for the SM Higgs Boson

20th century CDF/D0 sensitivity study still valid

21st century CDF/D0 search will need:

- Sophisticated techniques to improve sensitivity
- Excellent understanding of backgrounds and systematics
- Enough data!



In 50% of experiments

LEP m_H>114.4 GeV @95% CL

Conclusions

CDF and D0 are back!

First physics measurements well underway

Displaced track trigger for B physics

B_s meson and Λ_b baryon

W and Z bosons

Top quark

Searches for new physics

In next few years

B_s mixing

Top quark mass error < 3 GeV

World's best limits for searches…

…or discovery of new physics!

CDF Detector Upgrades

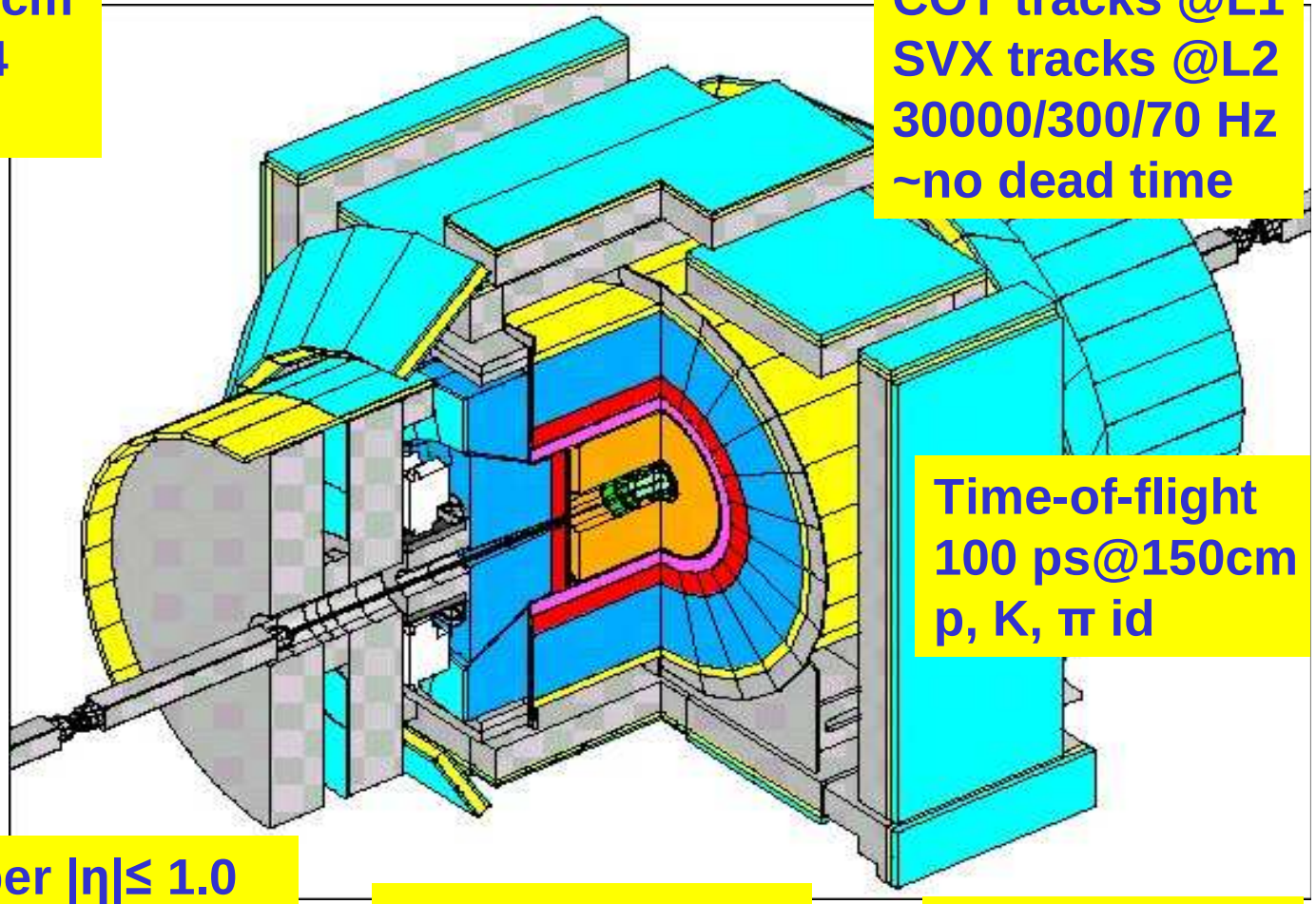
7-8 silicon layers
1.6<r<28 cm, |z|<45 cm
$|\eta| \leq 2.0$, $\cos\theta=0.964$
σ(hit) ~ 14 μm

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
COT tracks @L1
SVX tracks @L2
30000/300/70 Hz
~no dead time

Some resolutions:

$p_T \sim (0.7 \oplus 0.1\, p_T)\%$
J/Ψ mass ~15 MeV
EM E ~ 16%/√E
Had E ~ 100%/√E
$d_0 \sim 6+22/p_T$ μm
Primary vtx ~10 μm
Secondary vtx
r-Φ ~ 14 μm
r-z ~ 50 μm



Time-of-flight
100 ps@150cm
p, K, π id

96 layer drift chamber $|\eta| \leq 1.0$
44<r<132 cm, 30k channels
σ(hit) ~ 150 mm
dE/dx for p, K, π id

Tile/fiber endcap
calorimeter
1.1<|η|<3.5

μ coverage to
$|\eta| \leq 1.5$
80% in phi

D0 Detector Upgrades

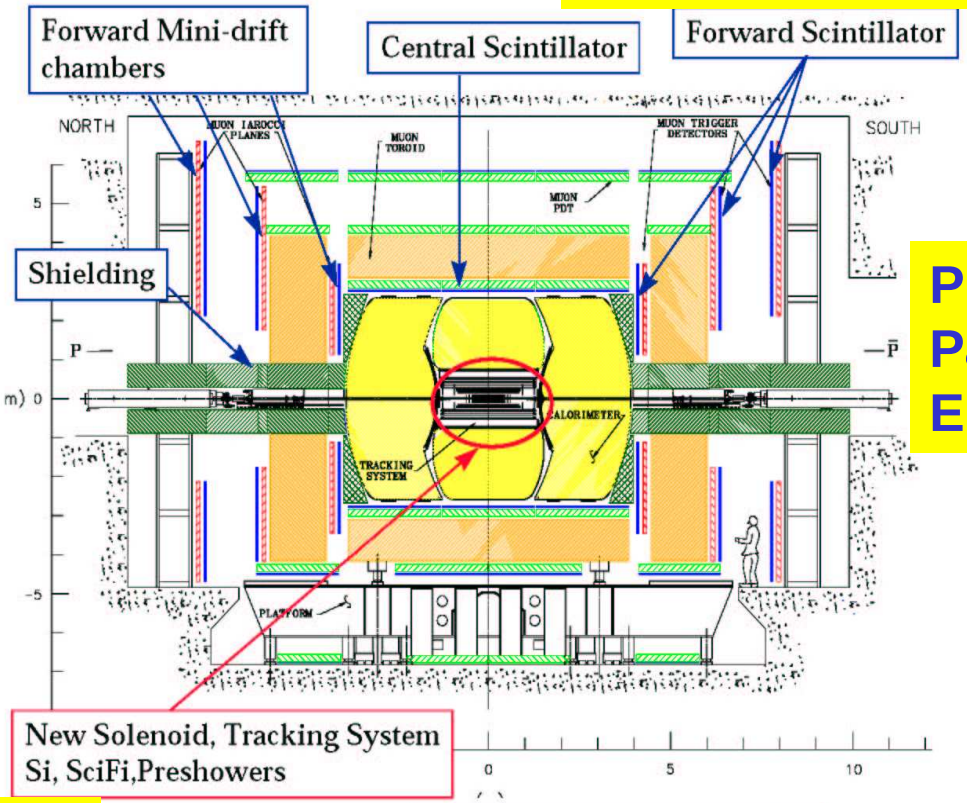
4 silicon layers+disks
Suited to limited space
2.8<r<10 cm
$|\eta| \leq 3.0$, $\cos\theta=0.993$

2.0 T magnetic field
Lever arm 52 cm

Now! Sci-Fi tracks@L1
Next! Silicon tracks@L2
5000/1000/50 Hz

Some resolutions:

$p_T \sim (2.0 \oplus 0.2\, p_T)\%$
J/Ψ mass ~27 MeV
EM E ~ 15%/√E
Had E ~ 80%/√E
$d_0 \sim 13+50/p_T$ μm
Primary vtx ~15 μm
Secondary vtx
r-Φ ~ 40 μm
r-z ~ 80 μm



Pre-shower
Particle id
Energy

8 layer Sci-Fi tracker $|\eta| \leq 1.7$
10<r<52 cm, 80k channels
VLPC's at 9K, 85% QE
σ(hit) ~ 100 μm

μ coverage to
$|\eta| \leq 2.0$
90% in phi