Flavour studies and searches at the Tevatron

at *"Flavour in the era of the LHC"*

Nov 8, 2005

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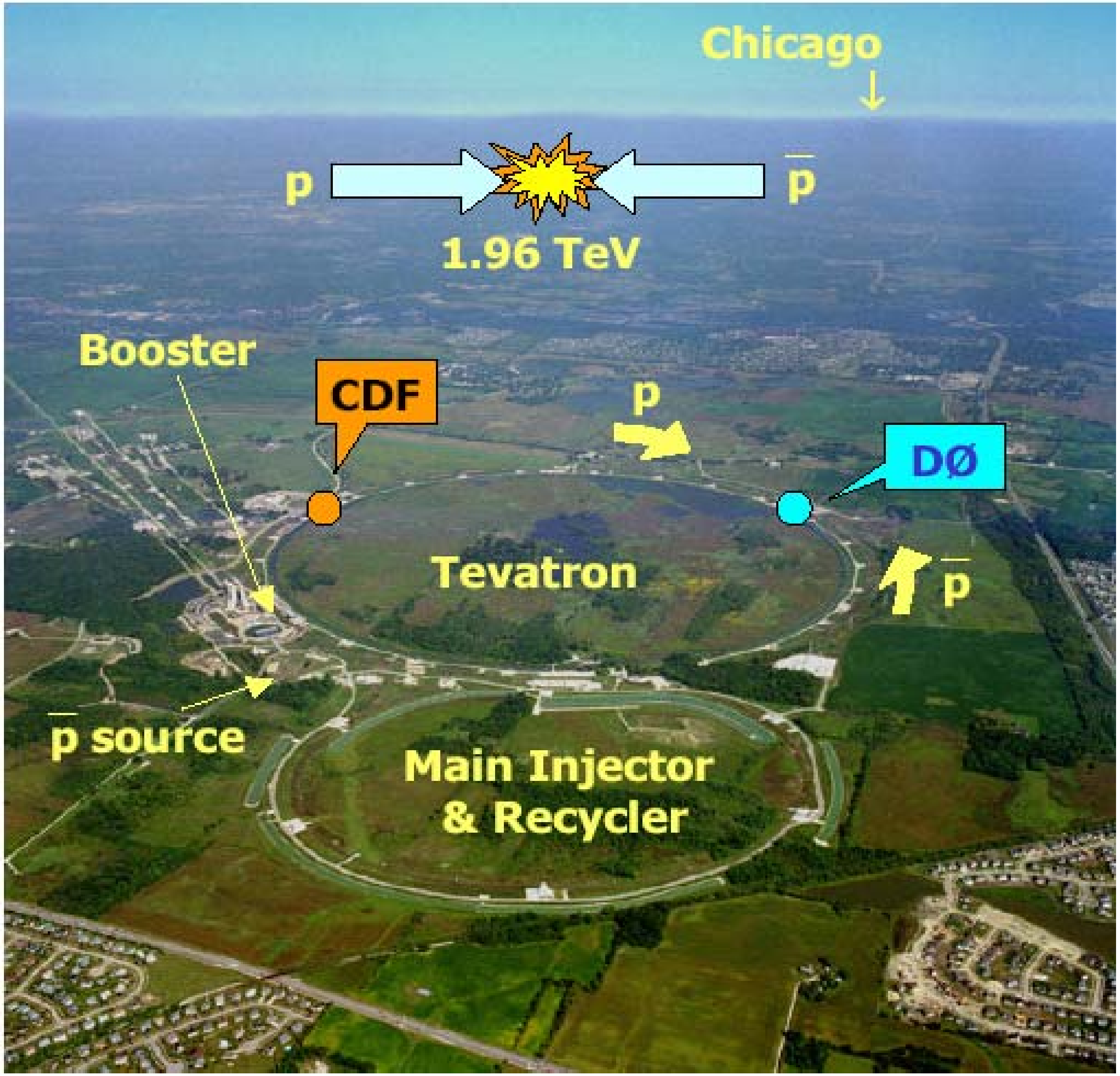
University of Liverpool
for the CDF and D0 collaborations

The Tevatron



- 6.2km ∅
- 396 ns bunch spacing
- Run I: 1989-1995
- Run II: 2001-2009

Tevatron luminosity

Congratulations Fermilab!

Fermilab has set a world record for peak luminosity of a hadron collider! Operations established store 4431 at 9:11 a.m. yesterday, October 4, with an initial luminosity, or brightness, of 141E30 $cm^{-2}sec^{-1}$. This record exceeds the previous Tevatron record by almost 8 percent, and it exceeds the world record for peak luminosity of a hadron collider achieved 23 years ago by the ISR proton-proton collider at CERN. The ISR achieved a peak luminosity of 140E30 $cm^{-2}sec^{-1}$ at a collision energy of 62 GeV. The Tevatron produces collisions between protons and antiprotons at a collision energy of 1960 GeV. The peak luminosity of the Tevatron has greatly increased since Fermilab began Run II in March 2001, and Fermilab expects to improve the Tevatron peak luminosity even further.

Again, Tevatron Sets World Record for Peak Luminosity

On Tuesday, October 25, at 3:28 a.m. the Tevatron improved its world-record peak luminosity to 144.91E30 $cm^{-2}sec^{-1}$. Significant contributions came from the new electron cooling system, which will be featured in an upcoming luminosity series in *Fermilab Today*. Congratulations!

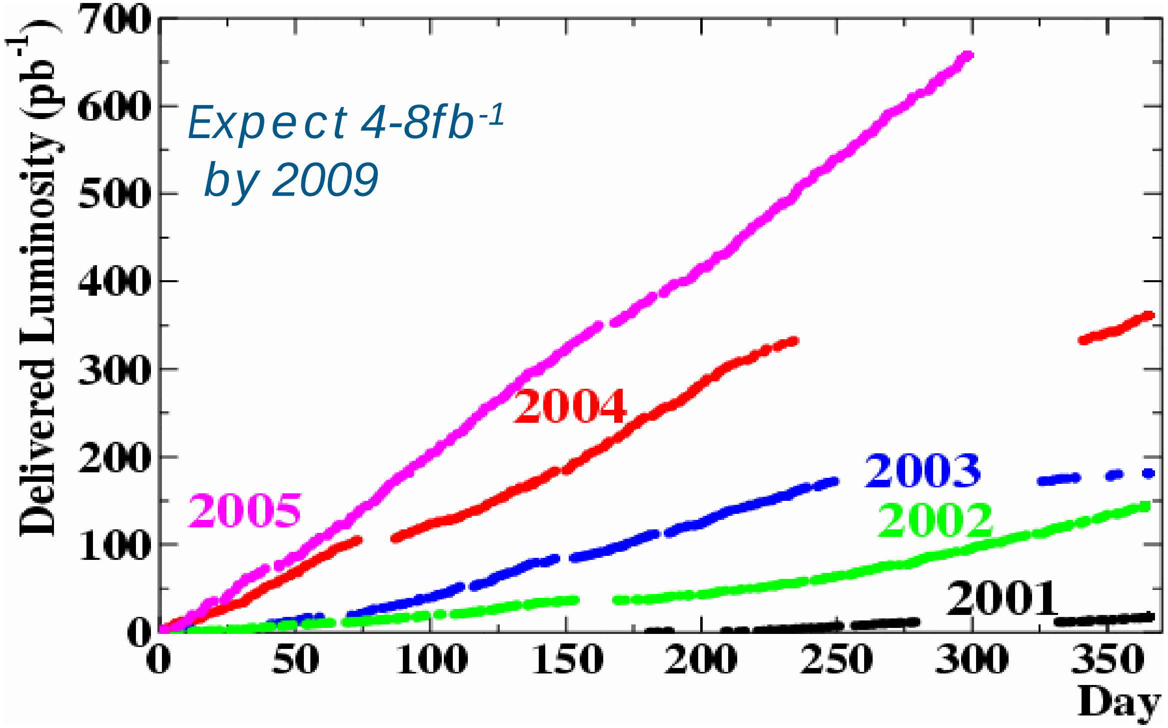
Fermilab Sets Another World Record for Luminosity!

The Tevatron recently made a vast improvement in peak luminosity. Operators set a new record on Thursday, October 27 at 2:54 a.m. The new record of 158E30 $cm^{-2}sec^{-1}$ is almost 10 percent larger than the last record of 145E30 $cm^{-2}sec^{-1}$.

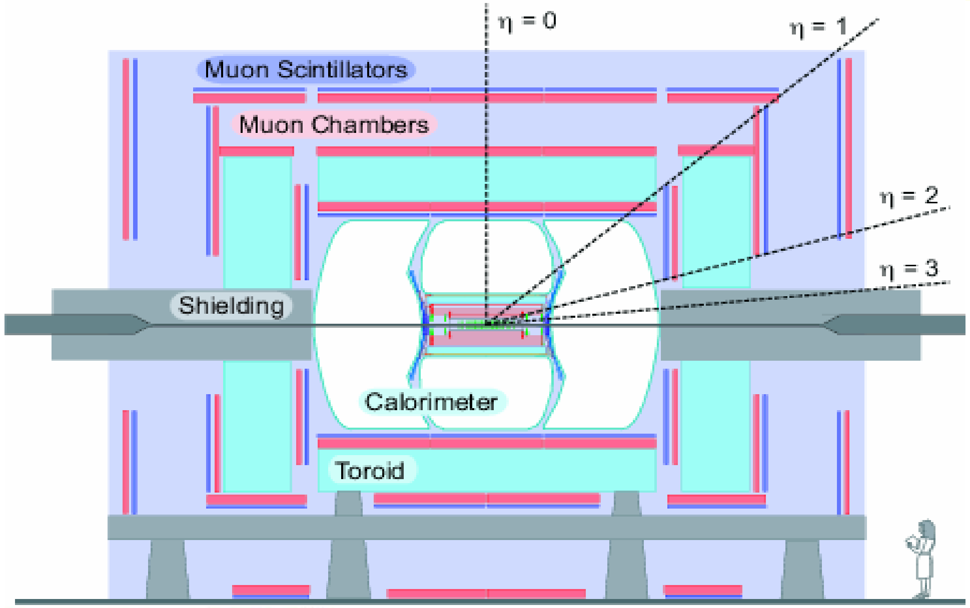
Records Keep Coming

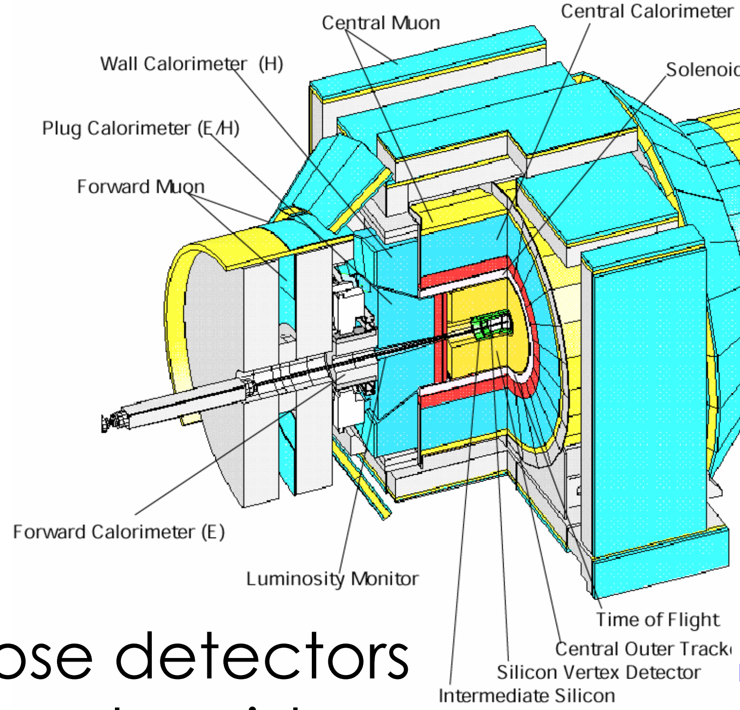
The flurry of Tevatron peak luminosity records of the last couple of months continues. On Monday, October 31, accelerator operators produced a special Halloween treat of 164E30 cm^{-2} sec^{-1}. Since the beginning of the year, the peak luminosity record has increased by about 50 percent. Congratulations.

already 5 overlapping collisions per bunch crossing



The Tevatron detectors





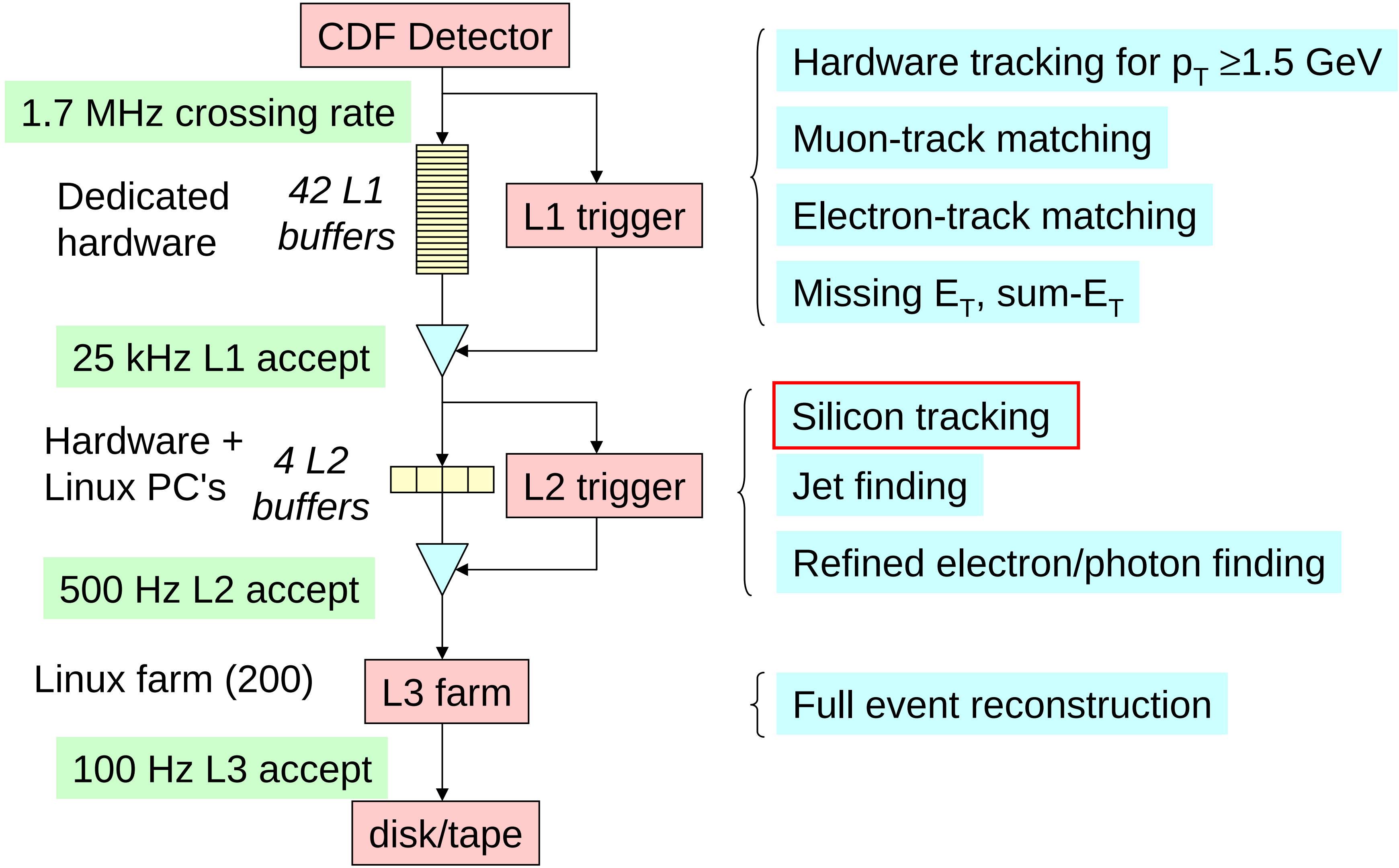
- 4π general purpose detectors
- superconducting solenoids
- silicon vertex detectors

- Excellent calorimetry
- Wide muon coverage

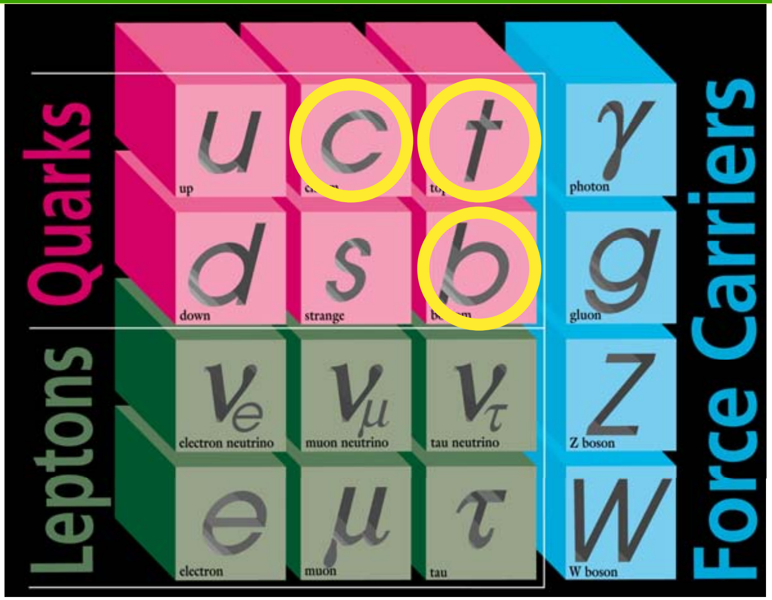
- Excellent momentum resolution
- High-bandwidth trigger

Triggering at hadron colliders

The trigger is the key to flavour physics at hadron colliders



Overview



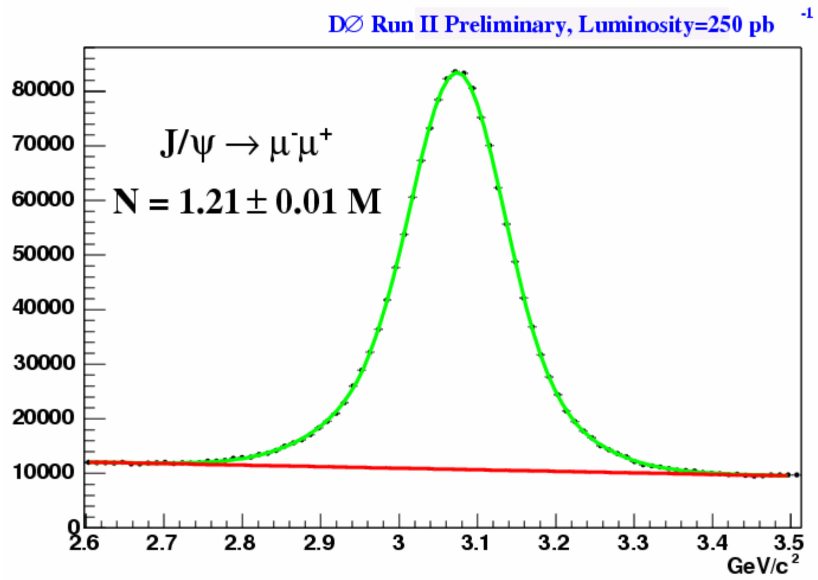
- Charm physics
  - J/ψ, open charm
- Beauty physics
  - B_C, Rare decays, B_s mixing
- Top physics
  - Production, mass, decays
- Direct searches
  - SUSY, leptoquarks

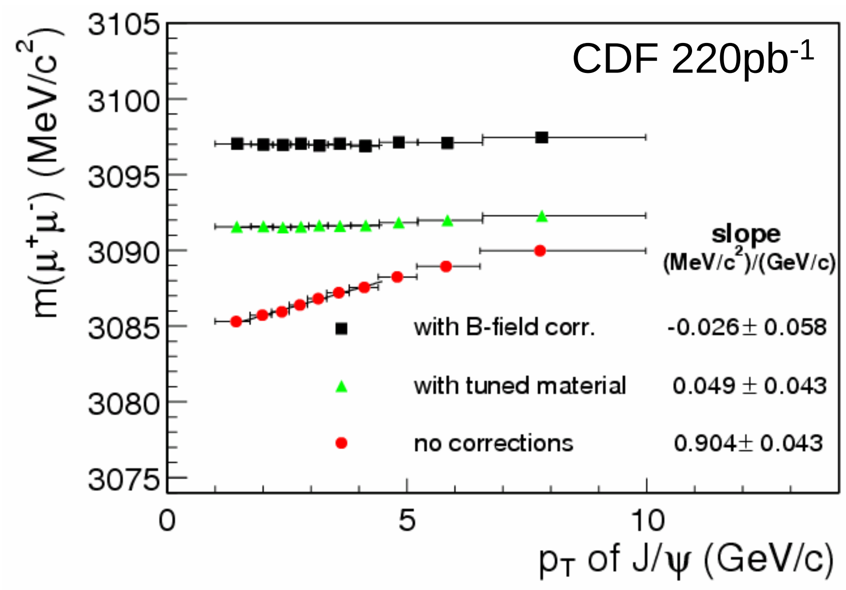
Physics with J/ψ's

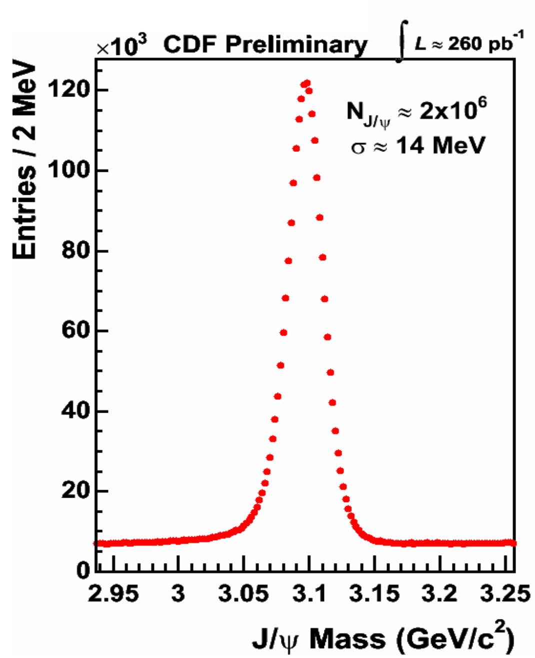
$J/\psi \to \mu^+\mu^-$ easy trigger signature

CDF and D0 collected millions

extensively used for
- momentum calibration
- muon trigger efficiencies
- tracking calibrations





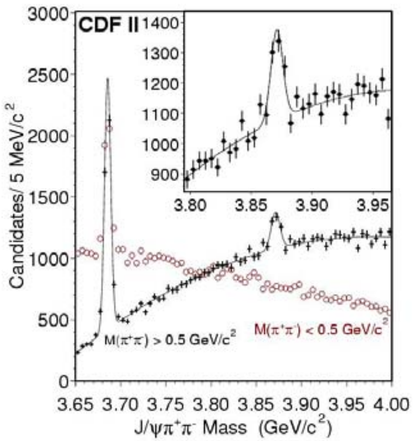


The X(3872)

- 2003: Belle finds new narrow state $X \to J/\psi\pi^+\pi^-$
- Quickly confirmed & studied by CDF and D0

m = 3871.3±0.7±0.4 MeV

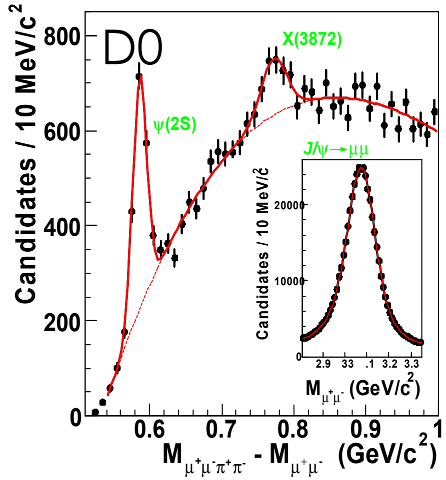
m - m(Jψ) = 774.9±3.1±4.0 MeV

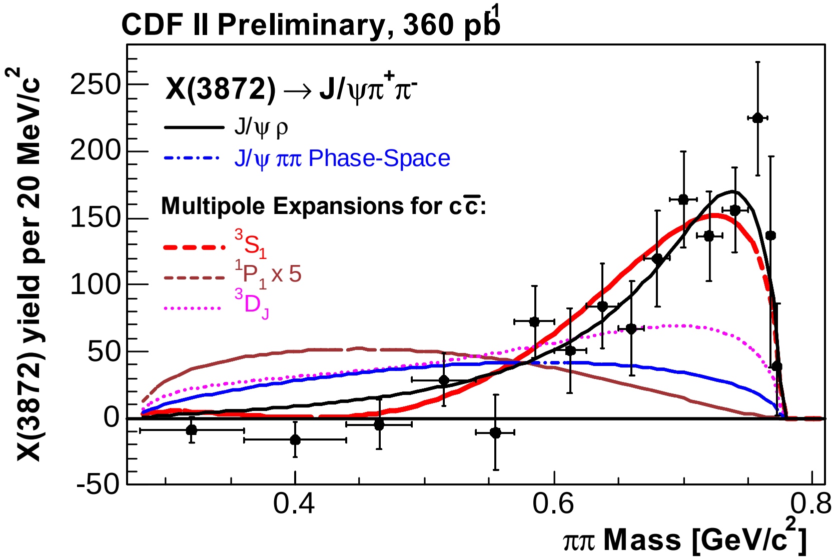


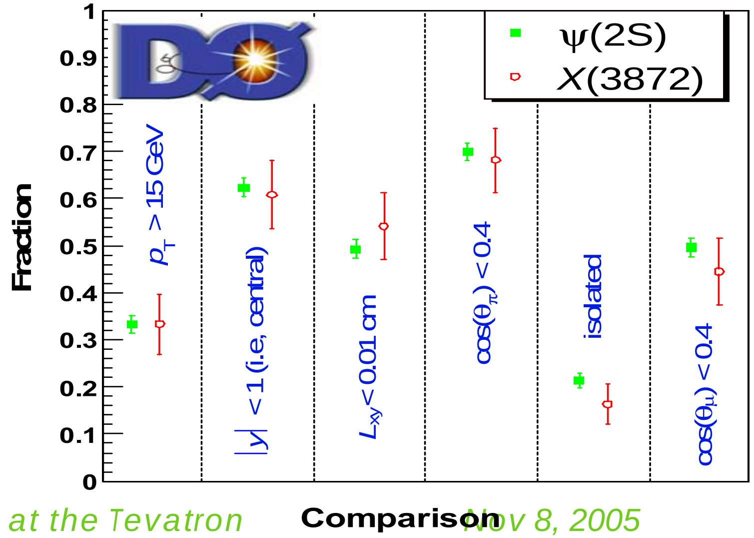
Does not fit any $c\bar{c}$ state.
Is it a $D^0\bar{D}^{*0}$ 'molecule'?
Is it a $c\bar{c}g$ 'hybrid'

$m(\pi^+\pi^-)$ spectrum consistent with $X \to J/\psi\rho$

X behaves like ψ'
- p_T spectrum
- η spectrum
- prompt/b ratio
- helicity angles
- isolation

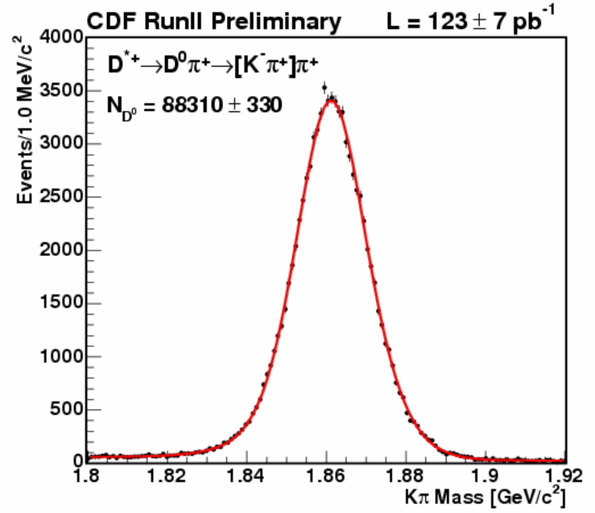




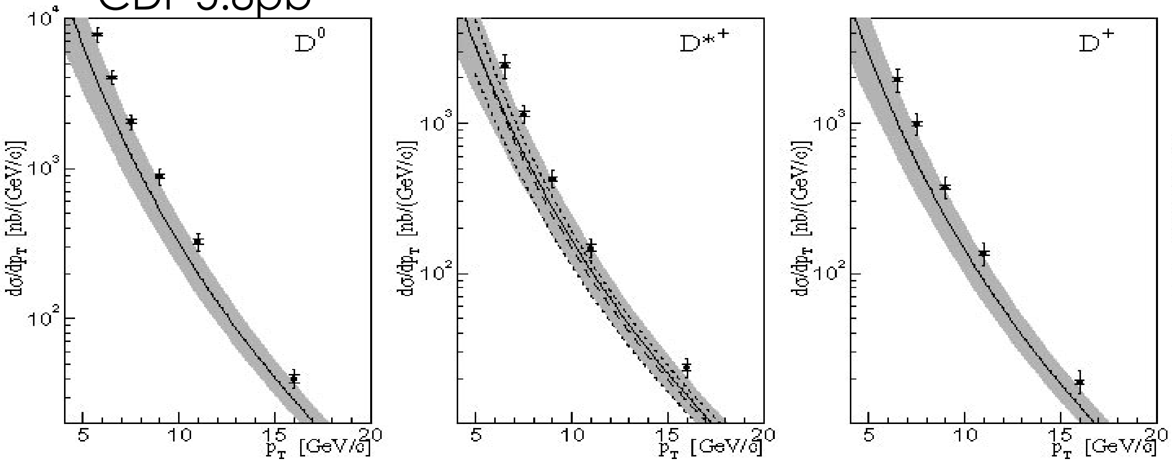


Open charm

Large, clean charm samples can be recorded at a hadron collider with a displaced track trigger:



CDF 5.8pb^{-1}



Cross-sections agree with theory (FONLL)

Cacciari, Nason **JHEP 0309:006,2003**

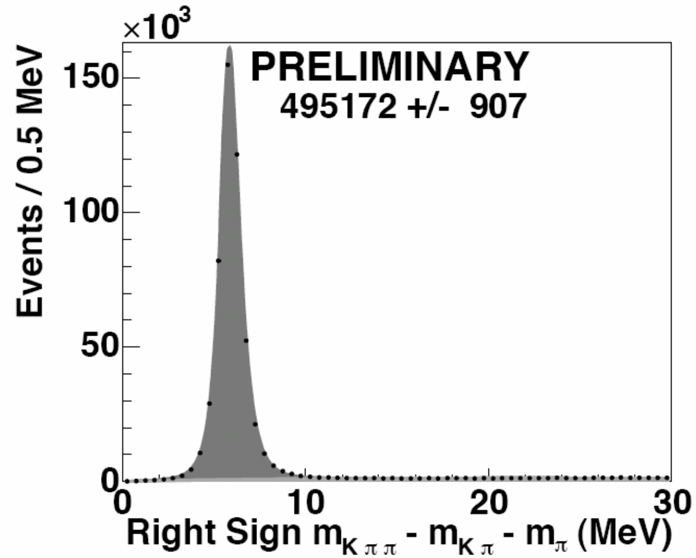
CDF put stringent limits on direct CP violation in D^0 decays

	$D^0 \to K^-K^+$ [%]	$D^0 \to \pi^-\pi^+$ [%]
$\Gamma/\Gamma(K^-\pi^+)$	$9.92 \pm 0.11 \pm 0.12$	$3.594 \pm 0.054 \pm 0.040$
A_{CP}	$2.0 \pm 1.2 \pm 0.6$	$1.0 \pm 1.3 \pm 0.6$

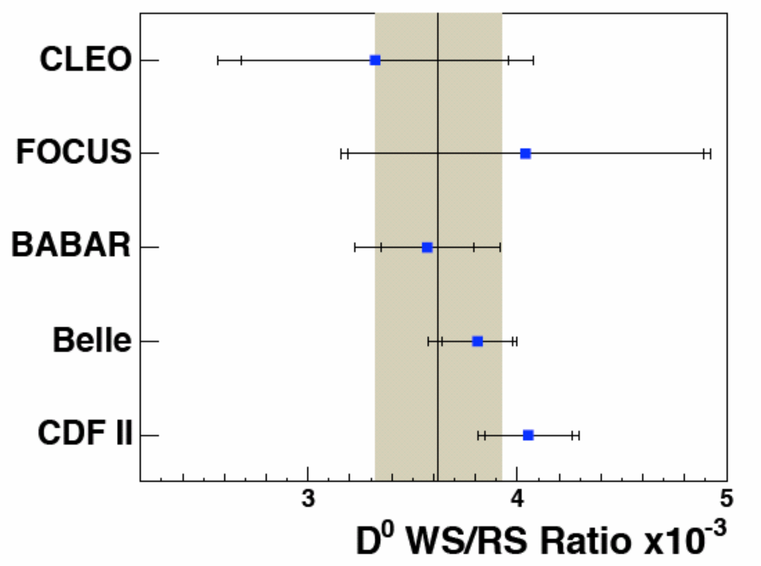
New CDF 350pb^{-1} $D^0 \to K^+\pi^-$ analysis

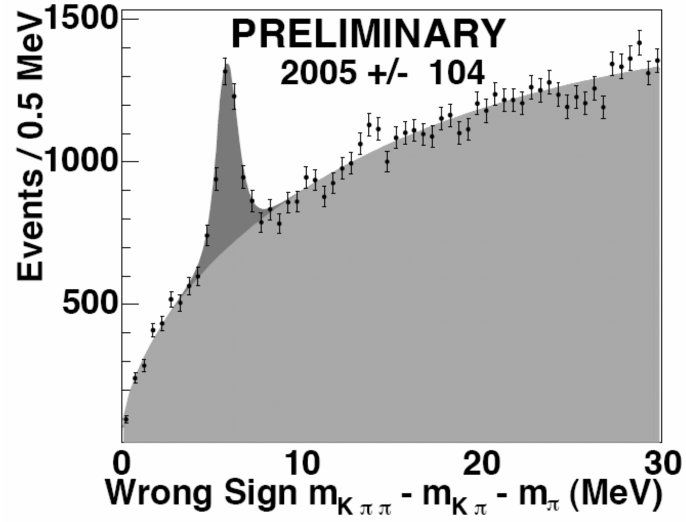
'Wrong sign' $D^0 \to K^+\pi^-$ decay

- Double Cabibbo suppressed decays
- D^0-D^0 mixing.



$$\frac{Br(D^0 \to K^+\pi^-)}{Br(D^0 \to K^-\pi^+)} = (0.405 \pm 0.021 \pm 0.012)\%$$





Next step: time dependent mixing analysis

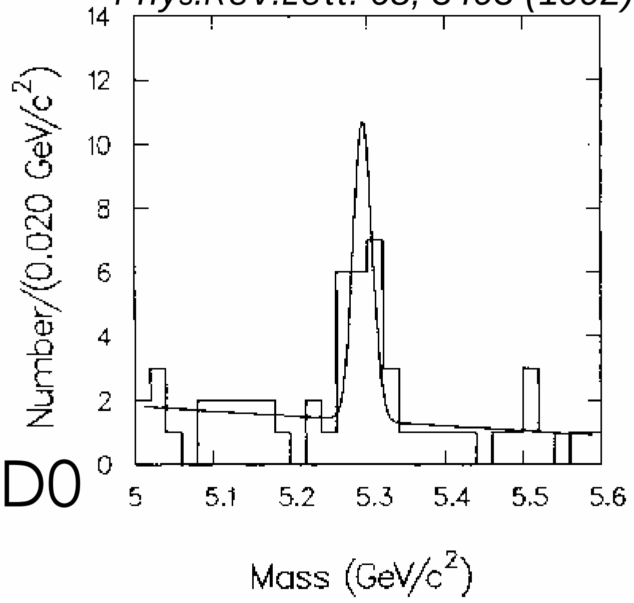
B physics at hadron colliders

has come a long way

From the first $B^+ \rightarrow J/\psi\ K^+$ in CDF Run I

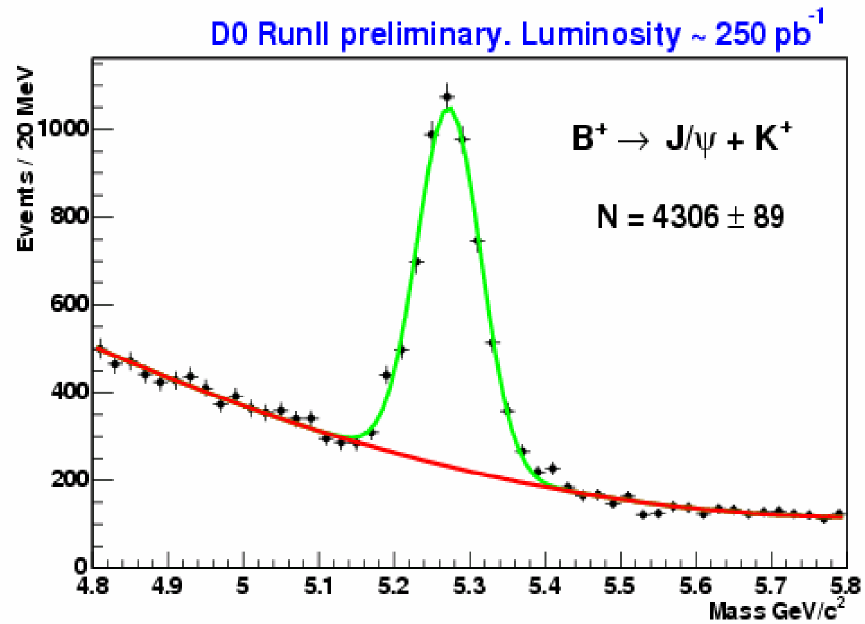
- 2.6 pb^{-1}
- no silicon detector

Phys.Rev.Lett. 68, 3403 (1992)



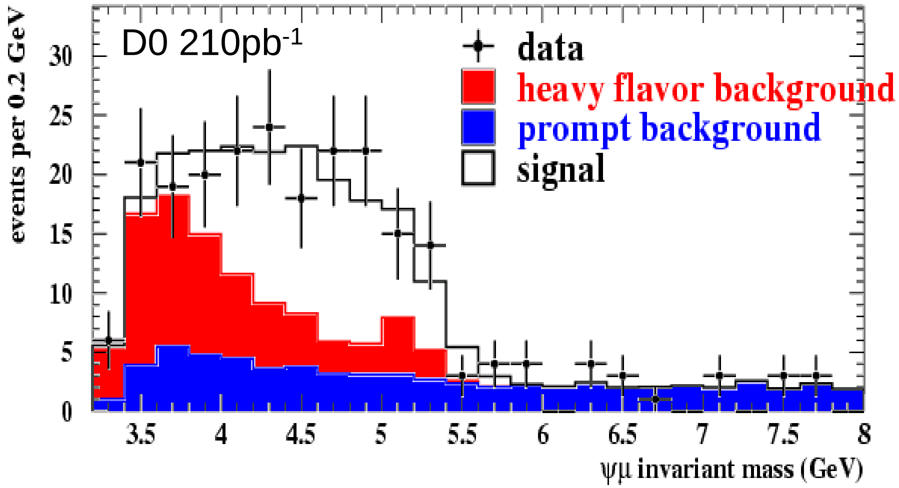
To precision measurements by CDF and D0

- all know B-hadrons: B^+, B^0, B_s B_c, Λ_b
- a myriad of decay modes:
  - ✓J/ψ modes *e.g.* $B_c \rightarrow J/\psi\ \pi$
  - ✓leptonic *e.g.* $B_s \rightarrow \mu^+\mu^-$
  - ✓semi-leptonic *e.g.* $B_s \rightarrow D_s\ \mu\nu_\mu$
  - ✓hadronic *e.g.* $B_s \rightarrow D_s\pi$
  - ✓charmless *e.g.* $B^0 \rightarrow \pi^+\pi^-$



B_c the last weakly decaying meson

D0:
Lifetime and mass in
$B_c \to J/\psi\ \mu\nu$



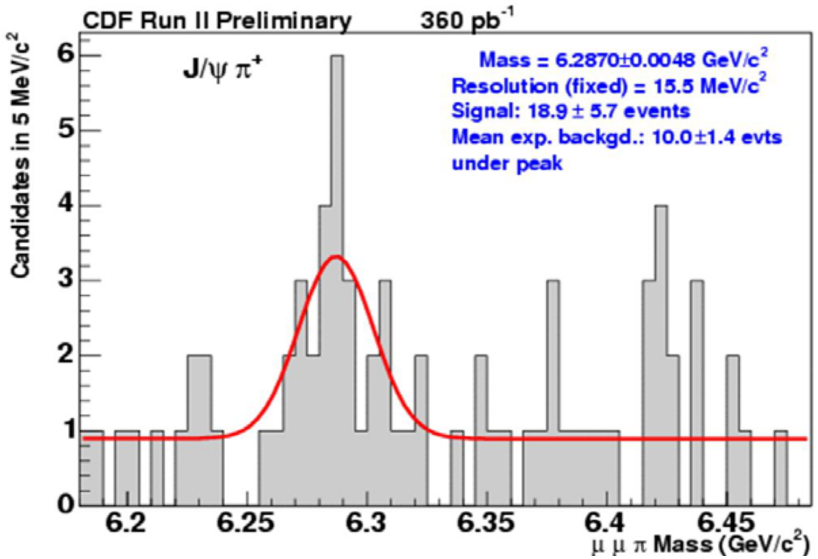
$$m = (5.95^{+0.14}_{-0.12} \pm 0.34)\mathrm{GeV}$$

$$\tau = (0.45^{+0.12}_{-0.10} \pm 0.12)\mathrm{ps}$$

New! CDF 360pb^{-1} $B_c \to J/\psi\ e\nu$:
τ=(0.47±0.07±0.03)ps

B_c has charm-like lifetime

CDF:
Evidence for $B_c \to J/\psi\ \pi^+$



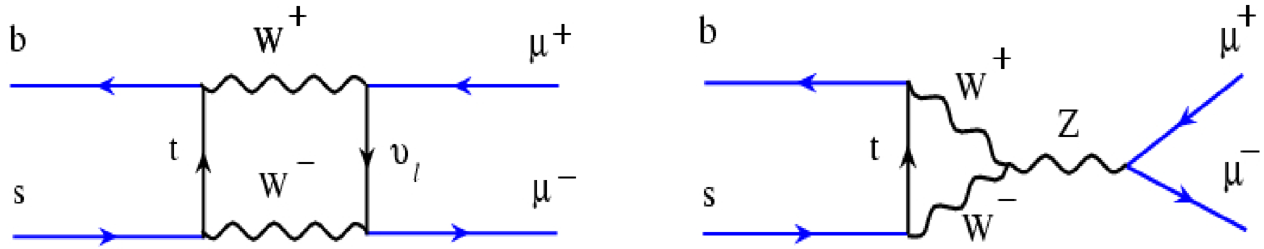
<10^{-3} experiments give false positive result at this level

$$m = (6.2870 \pm 0.0048 \pm 0.0011)\mathrm{GeV}$$

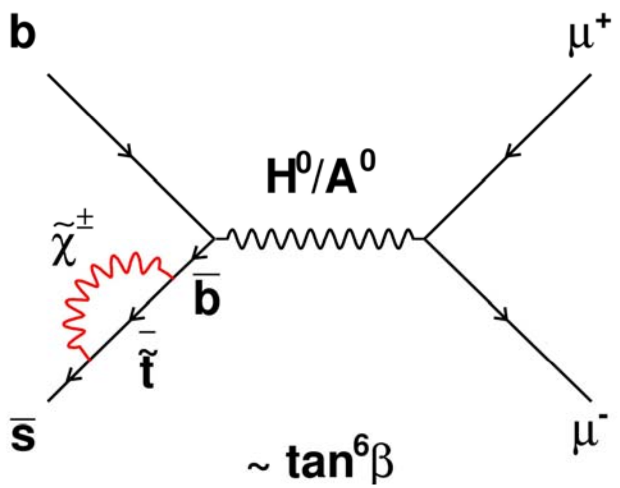
Agrees with lattice QCD predictions

$B_s \to \mu^+\mu^-$

Standard model prediction: $Br(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$

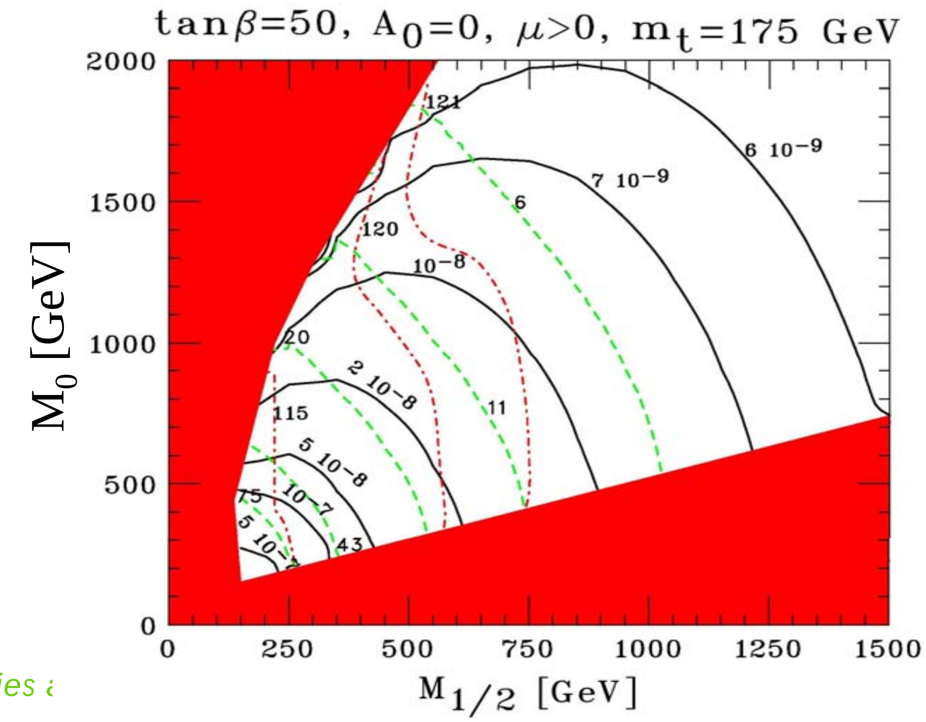


SUSY contribution



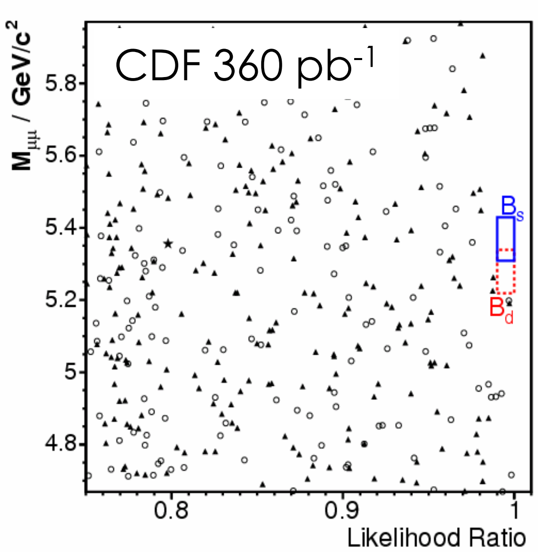
MSUGRA prediction:

Dedes, Dreiner, Nierste PRL87:251804,2001

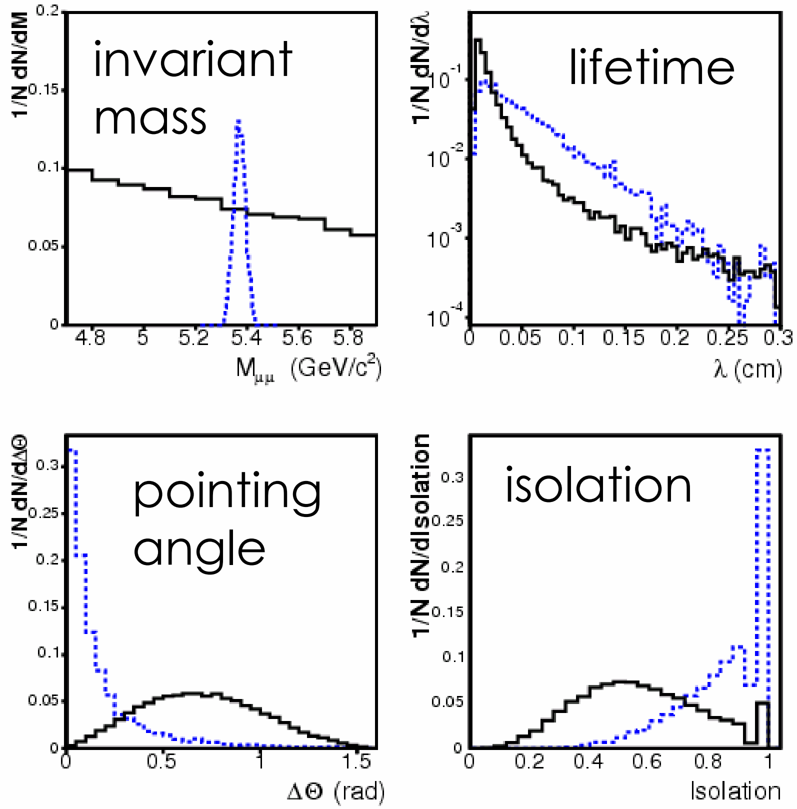


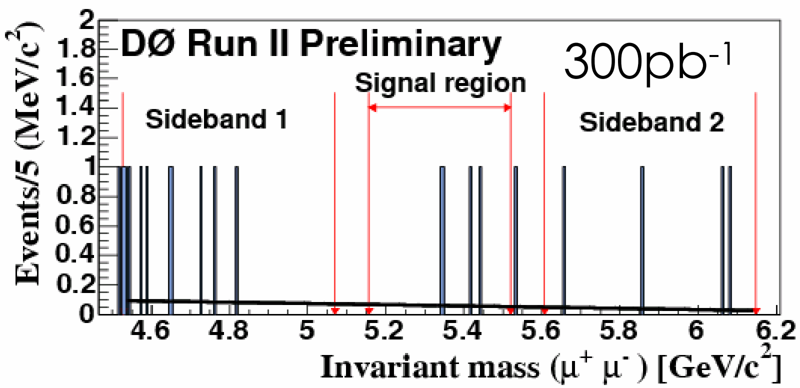
Find a $B_s \to \mu^+\mu^-$ in 10^{12} collisions?

combine discriminating variables into a single likelihood ratio



$B_s \to \mu^+\mu^-$ $<2.0\times10^{-7}$





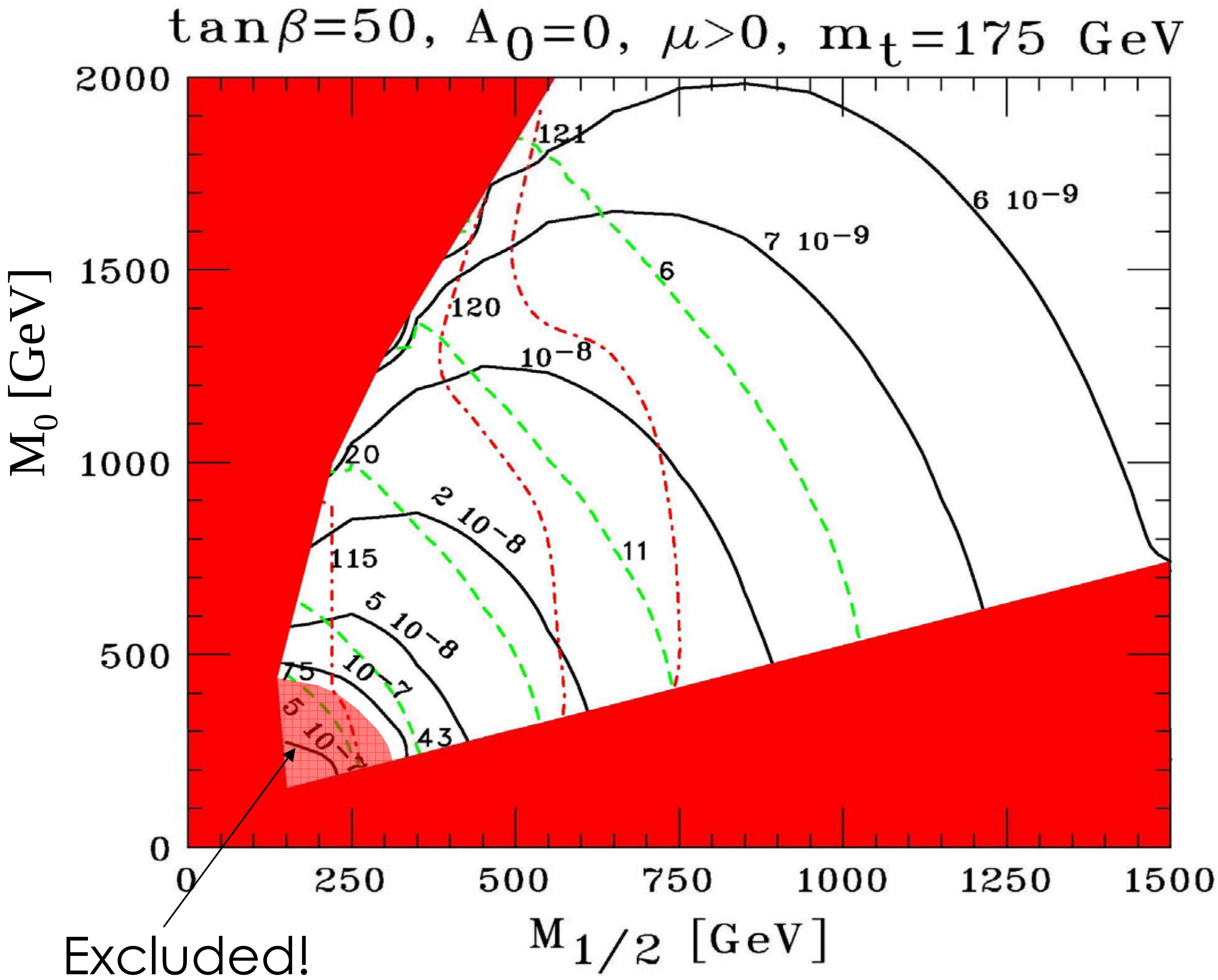
$B_s \to \mu^+\mu^-$ $<3.9\times10^{-7}$

Combined limit:

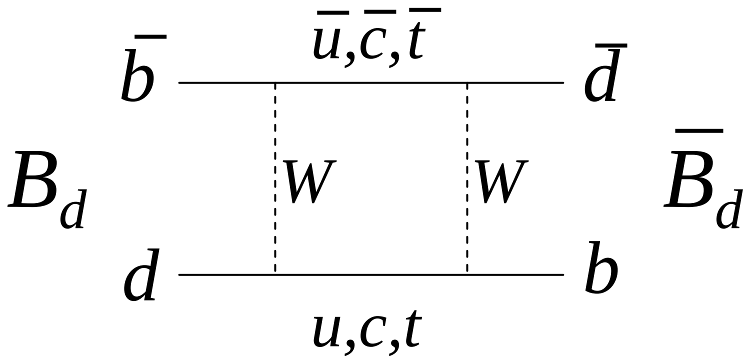
- $B_s \to \mu^+\mu^- < 1.5\times10^{-7}$

hep-ex/0508058

implications of $B_s \to \mu^+\mu^- < 1.5\times10^{-7}$



B_d and B_s oscillations



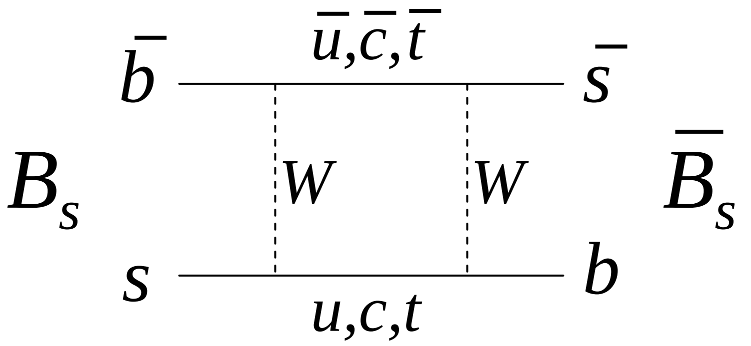
B_d mixing $\propto V_{td}^2$

$\Rightarrow$slow:

Δm_d=0.502±0.007ps^{-1}

$\Rightarrow$large mixing phase:

sin2β=0.736±0.049



B_s mixing $\propto V_{ts}^2$

$\Rightarrow$fast:

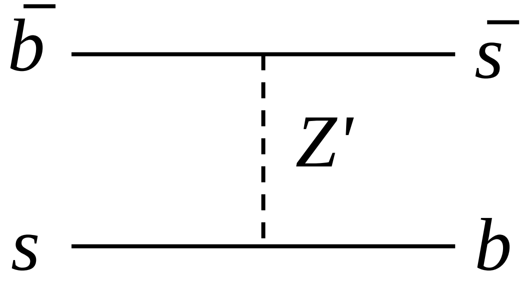
$\Delta m_s \approx$18ps^{-1}?

$\Rightarrow$small mixing phase:

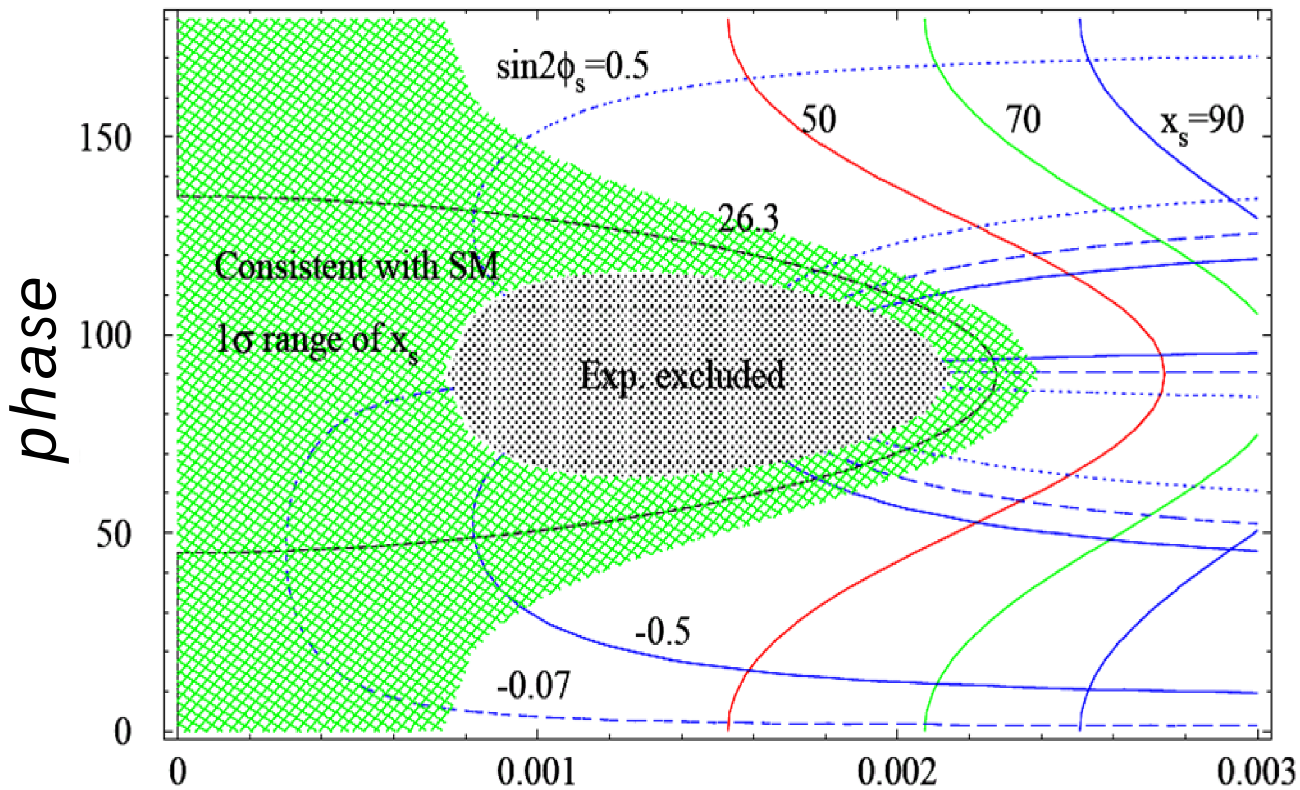
sin2$\beta_s \approx$0.02?

New physics in B_s oscillations

- Heavy Z' with FCNC.

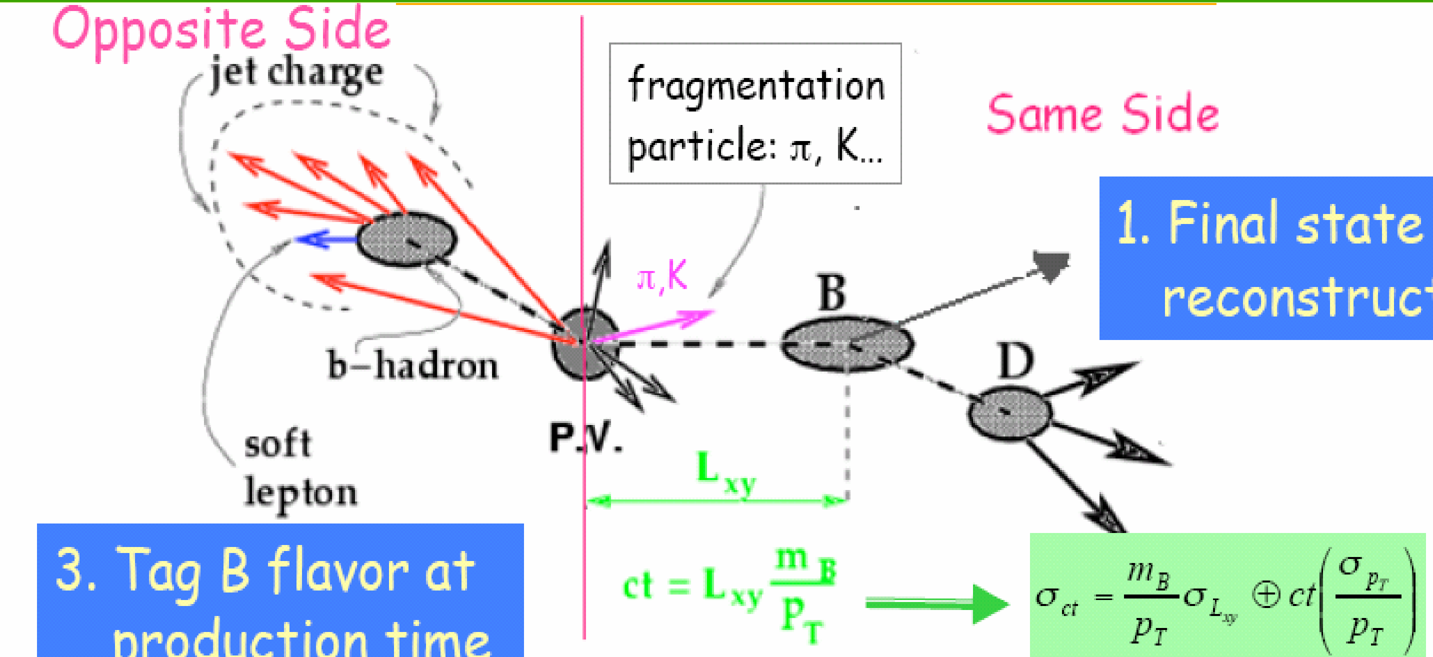


Barger, Chiang, Jiang, Langacker Phys.Lett.B596:229-239,2004



$$magnitude \propto \left| \frac{m_Z}{m_{Z'}} B_{sb}^{LL} \right|$$

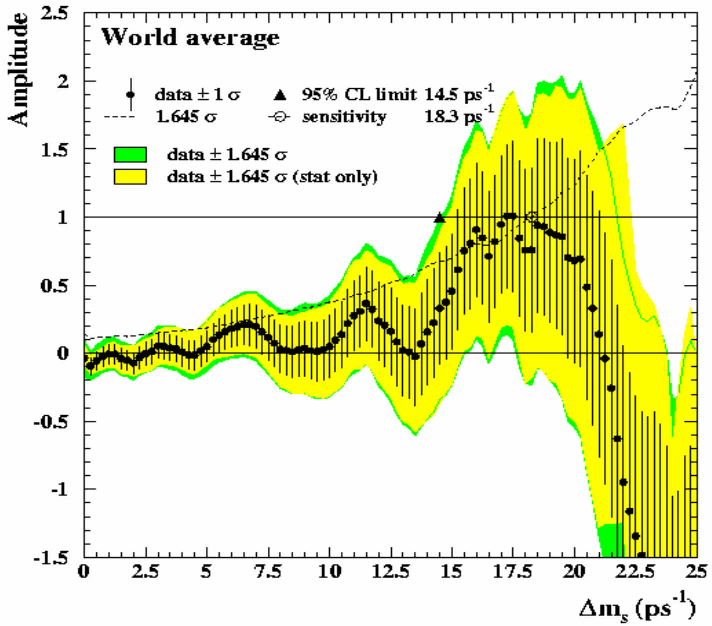
B_s oscillations



1. Final state reconstruction

2. High resolution on proper decay length

3. Tag B flavor at production time



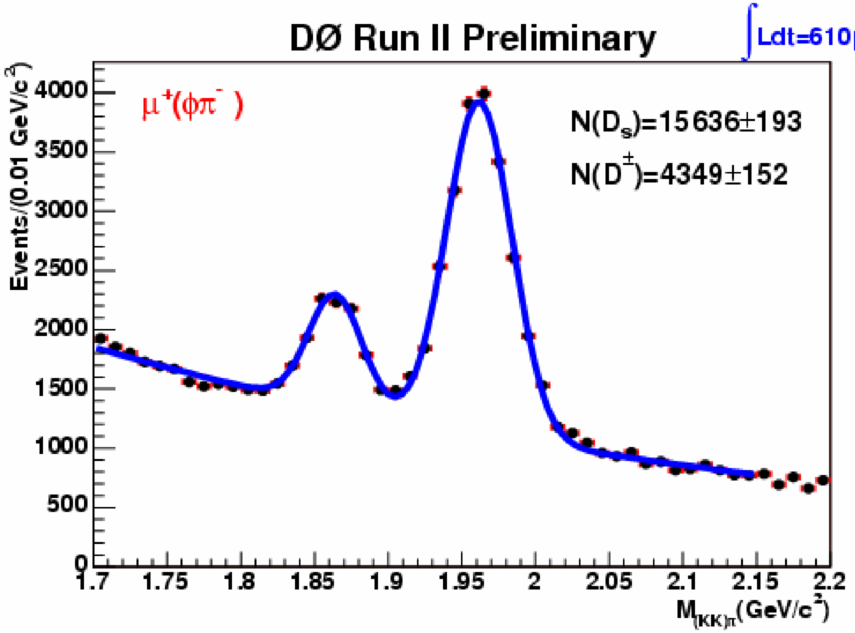
Pre-RunII world average includes LEP, SLC, CDF-RunI

$\Delta m_s > 14.5 ps^{-1}$, sensitivity $18.3 ps^{-1}$

B_s mixing – the D0 analysis

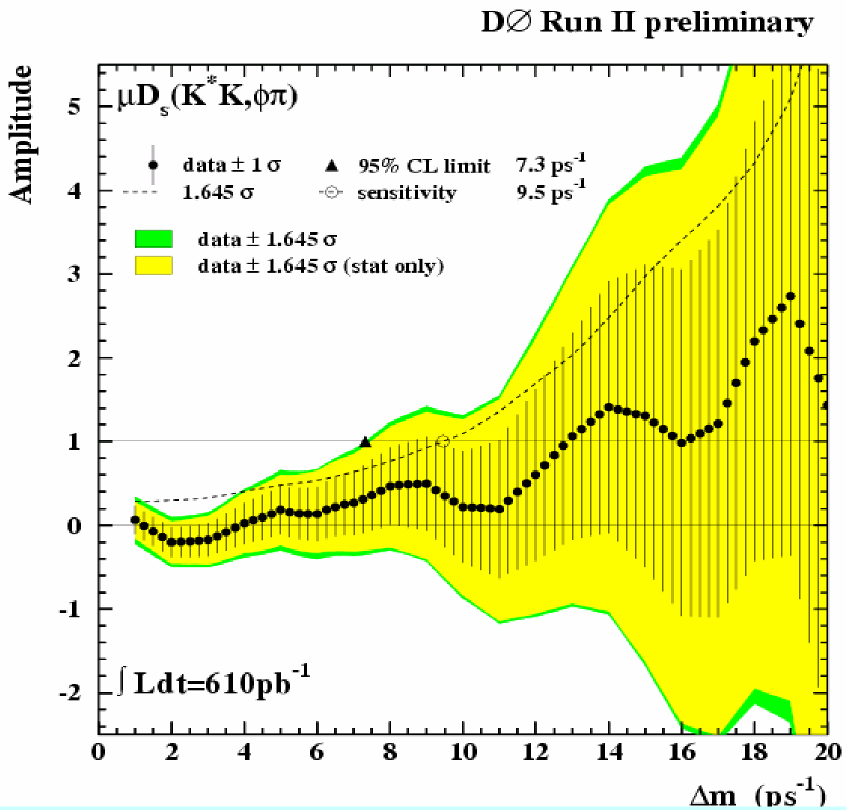
Very efficient low-p_T muon trigger

$B_s \rightarrow D_s \mu\nu$, $D_s \rightarrow K^- K^+ \pi^+$, selecting ϕ and K^{*0} resonances



combine opposite side muon, electron, jet charge:

εD^2=2.17±0.13±0.08%

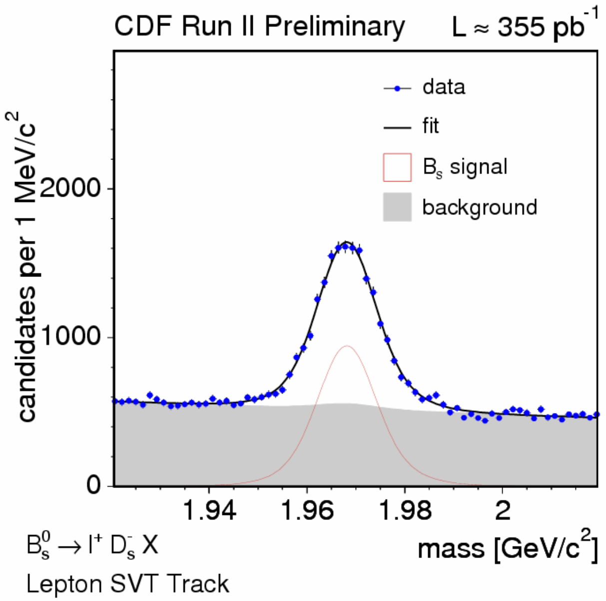


Δm_s >7.3ps^{-1}, sensitivity 9.5ps^{-1}

B_s mixing – the CDF analysis

semileponic $B_s \to D_s\, l$

larger yields

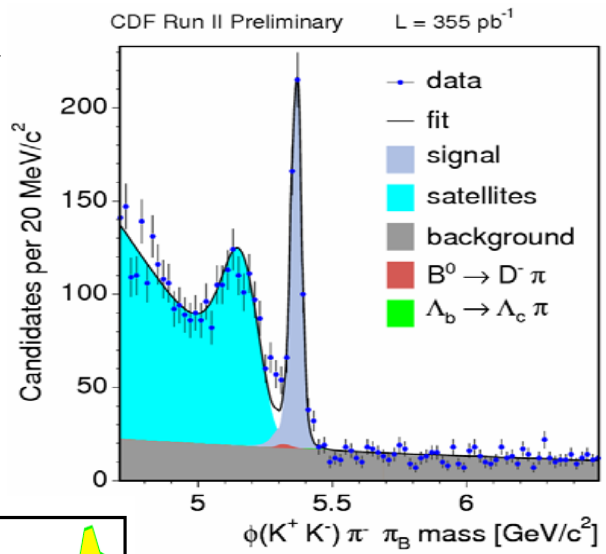


fully hadronic

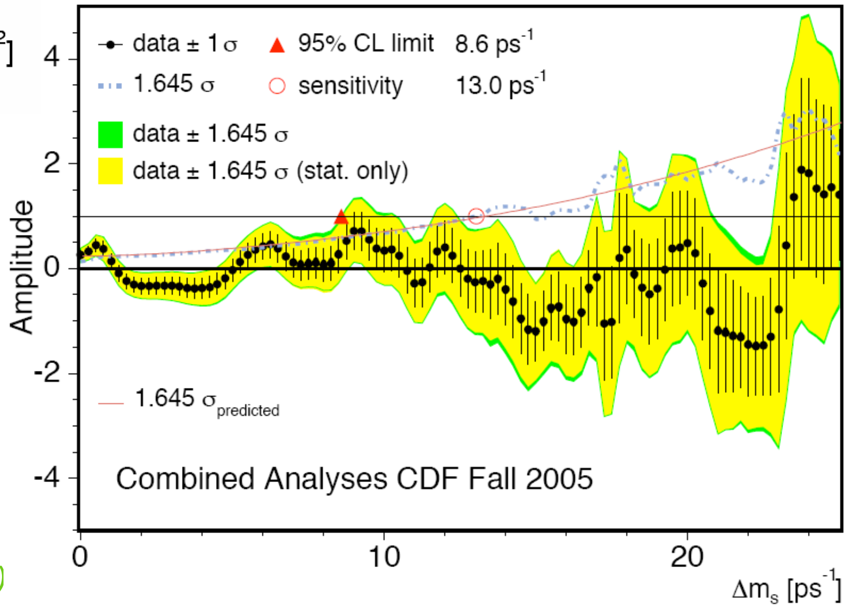
better $\sigma(ct)$

Includes:

- $B_s \to D_s\pi\pi\pi$, $B_s \to D_s\pi$
- $D_s \to KK\pi$, $D_s \to \pi\pi\pi$



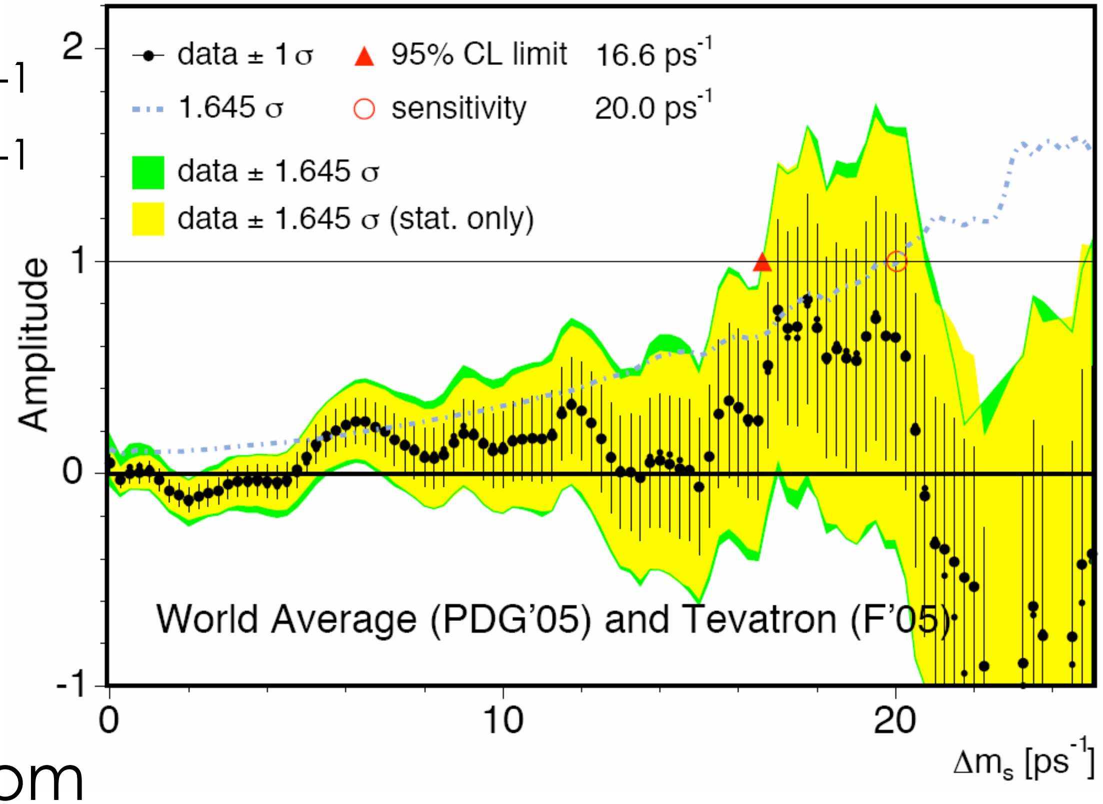
$\varepsilon D^2 = 1.55 \pm 0.09\%$



$\Delta m_s > 8.6 ps^{-1}$,
sensitivity $13.0 ps^{-1}$

New world average

limit 14.5 → 16.6 ps^{-1}
sensitivity 18.3 → 20.0 ps^{-1}

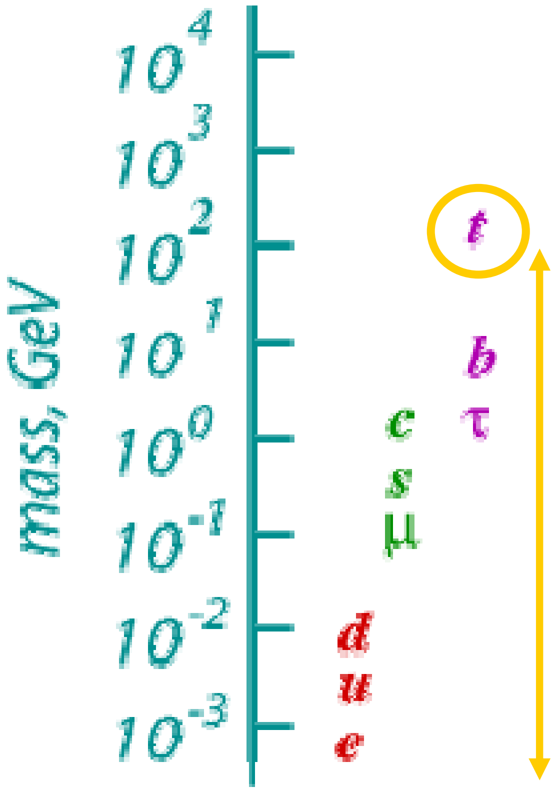


Further improvements from
- more data
- more decay channels (e.g. $B_s \rightarrow D_s^* \pi$)
- Same-side and opposite-side kaon tags

Top physics

Most massive fundamental particle.

Discovered only 10 years ago
at the Tevatron!

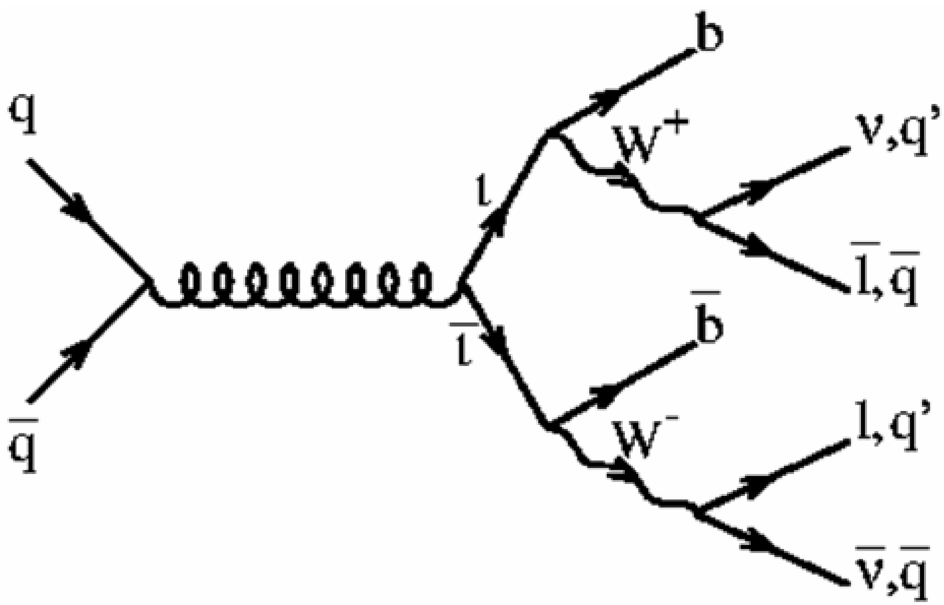


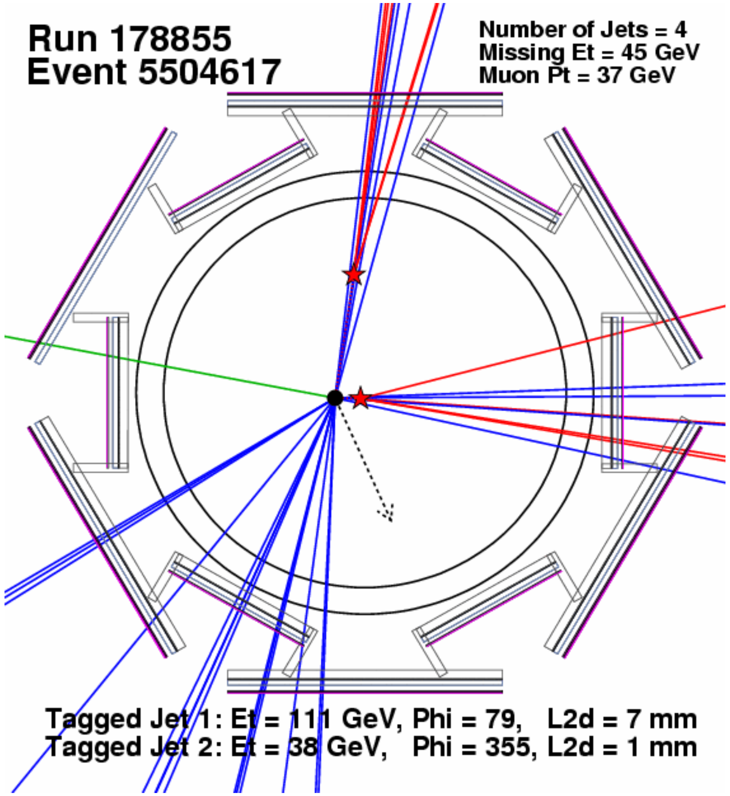
5 orders of magnitude

top physics at the Tevatron

SM: $t\bar{t}$ pair production, Br($t \to bW$)=100%

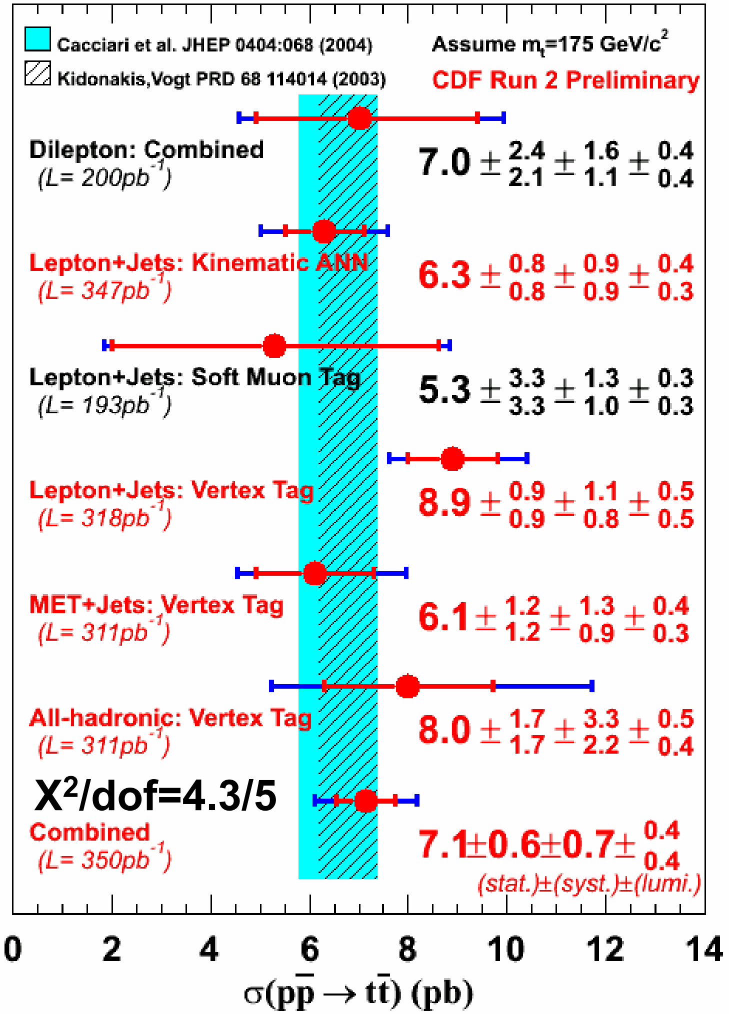
dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
l+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets

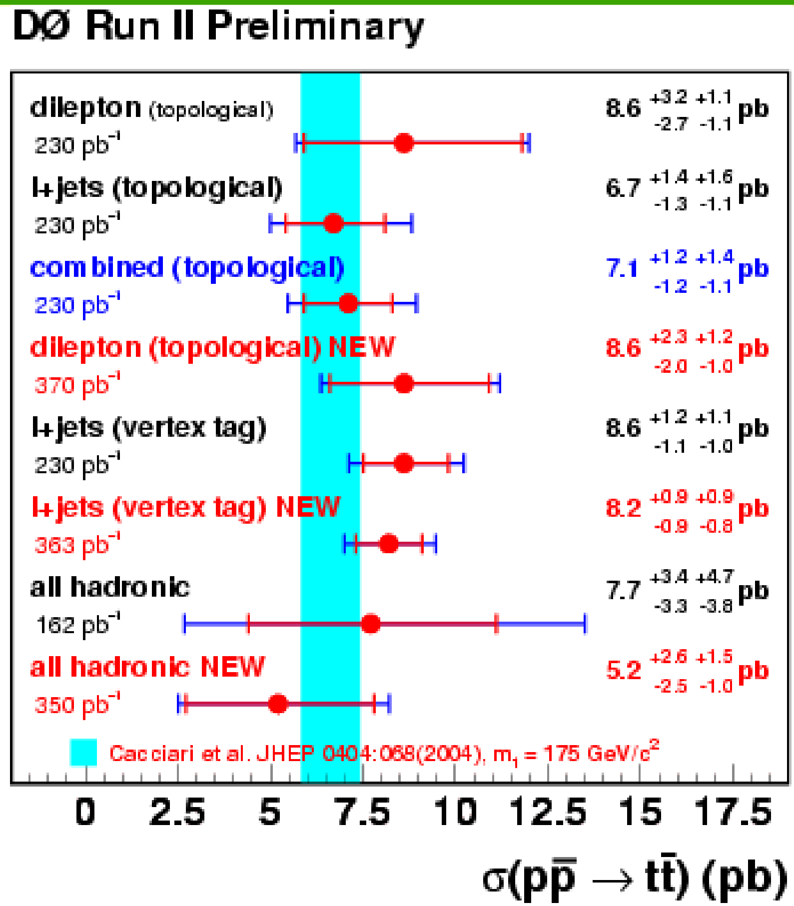




tag one or both b-jets

$t\bar{t}$ cross-section

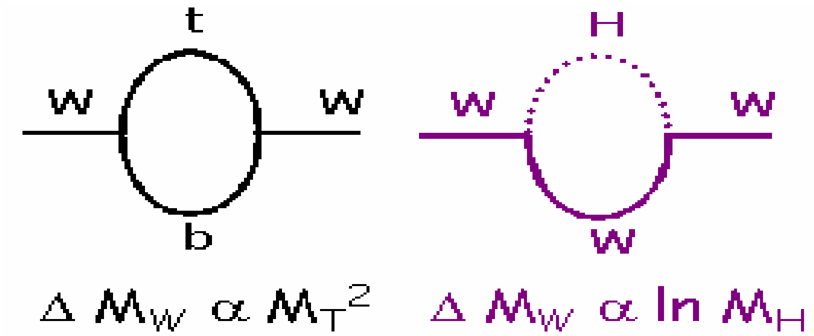




$t\bar{t}$ production cross-section agrees
- between both experiments
- in all channels
- with the theoretical prediction!

The mass of the top quark

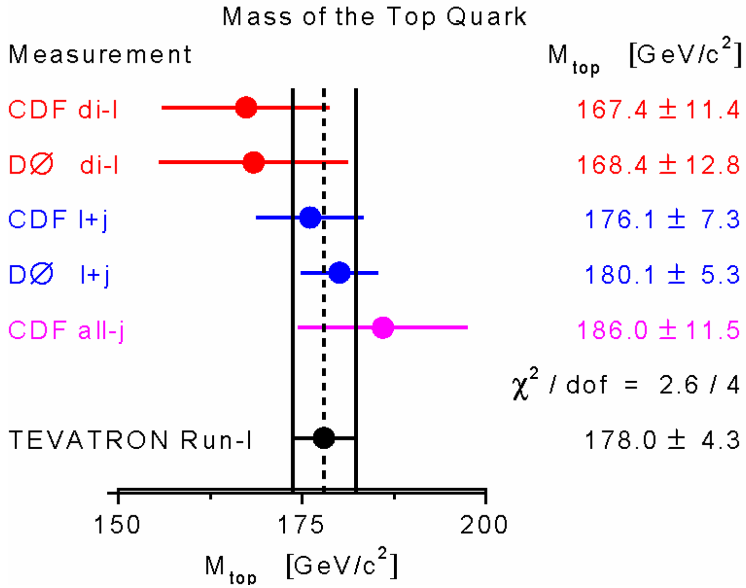
top, Higgs and new physics give radiative corrections to m_W

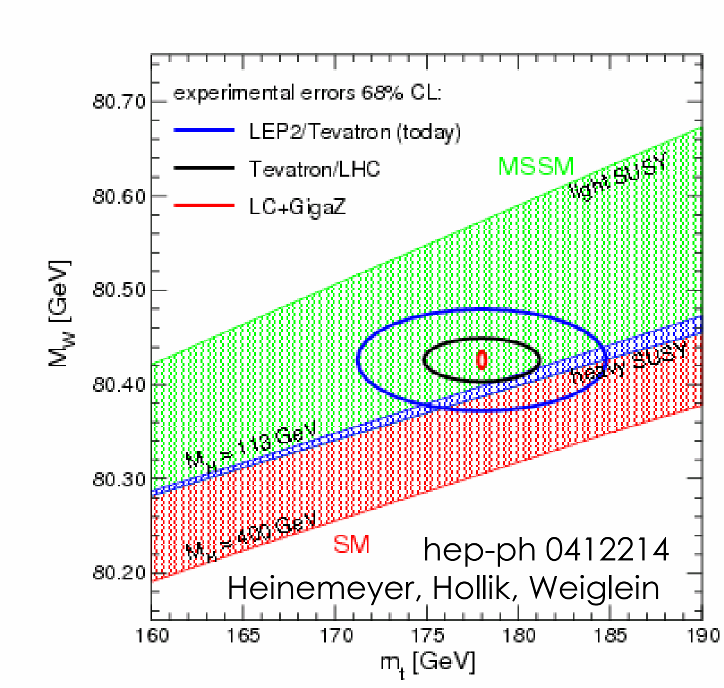


m_t and m_W constrain m_H

Tevatron Run I + LEP2 results favoured light Higgs

Experimental challenges:
- Missing neutrino
- Jet energy scale (JES)
- Understanding backgrounds



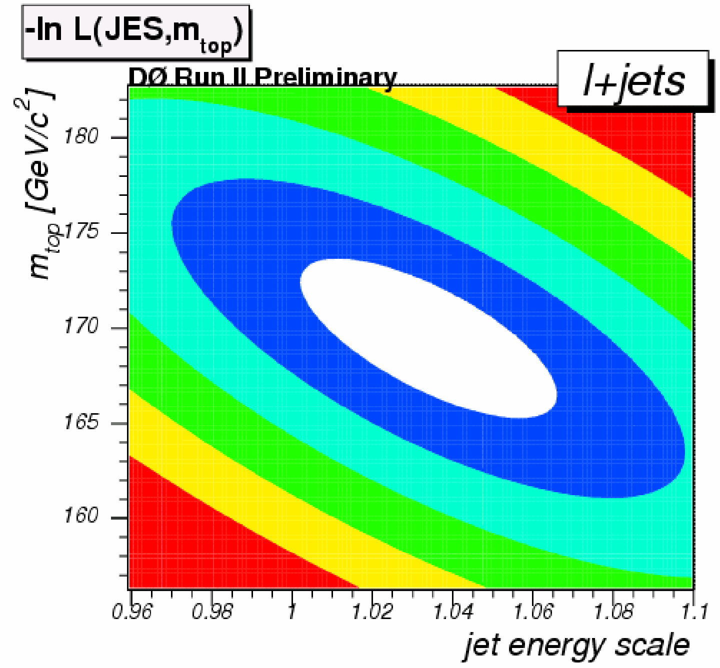


D0 Run II l+jets 320pb^{-1}

'Matrix-element method' :
All kinematic variables used in likelihood fit

Jet Energy scale determined from hadronic W decays in the $t\bar{t}$ sample itself.

cross-check with external calibration



Systematic Source	Uncertainty (GeV/c^2)
ISR/FSR	0.3
Model	0.7
b-jet	1.1
Method	0.9
PDF	0.1
Total	1.7
Jet Energy	3.2

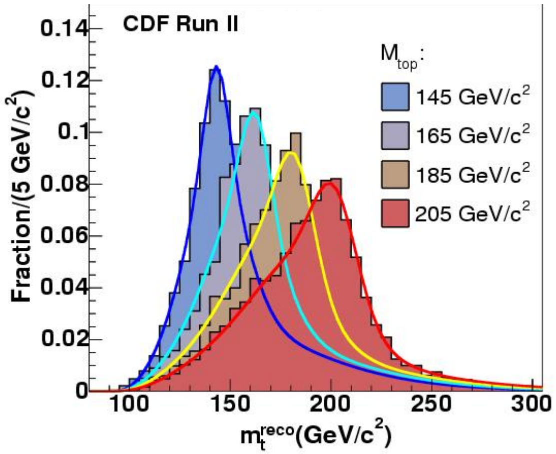
$$m_{top} = 169.5 \pm 3.0_{(stat)} \pm 3.2_{(JES)} \pm 1.7_{(syst)} \, \mathrm{GeV}/c^2$$

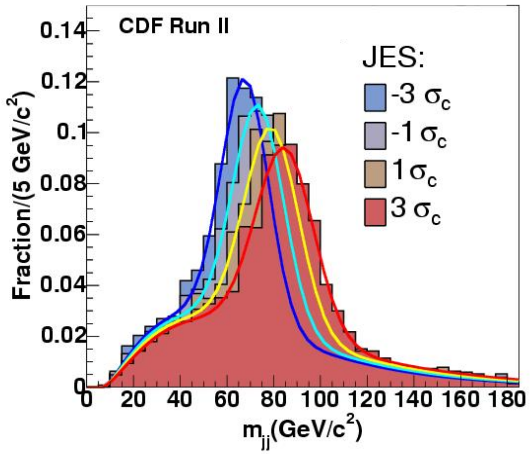
$$\mathrm{JES} = 1.034 \pm 0.034$$

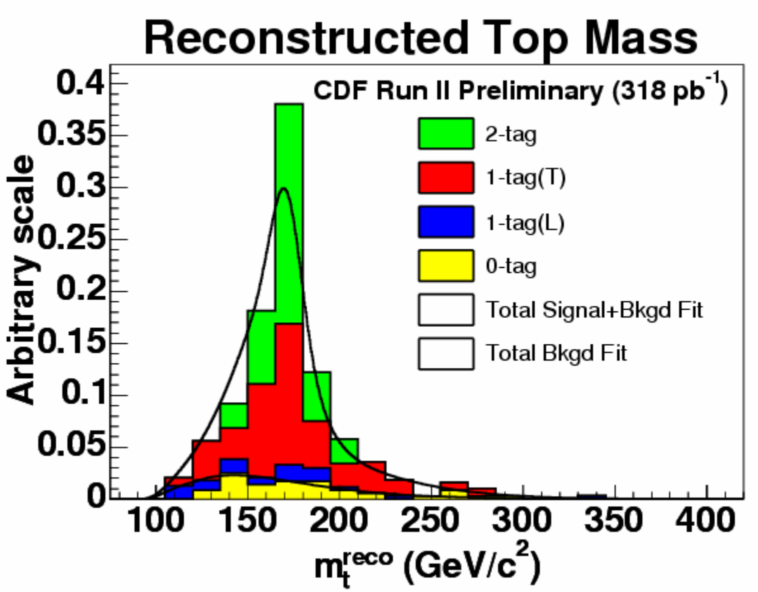
CDF Run II l+jets 320pb^{-1}

Template method:

Compare reconstructed t,W mass to distributions from MC







$$m_{top} = 173.5 \pm^{2.7}_{2.6} \text{(stat)} \pm 2.5 \text{(JES)} \pm 1.3 \text{(syst)} \text{GeV}/c^2$$

$$\text{JES} = -0.10 \pm^{0.78}_{0.80} \ \sigma \text{(apriori)}$$

Systematic Source	Uncertainty (GeV/c^2)
ISR/FSR	0.7
Model	0.7
b-jet	0.6
Method	0.6
PDF	0.3
Total	1.3
Jet Energy	2.5

Tevatron combined top mass

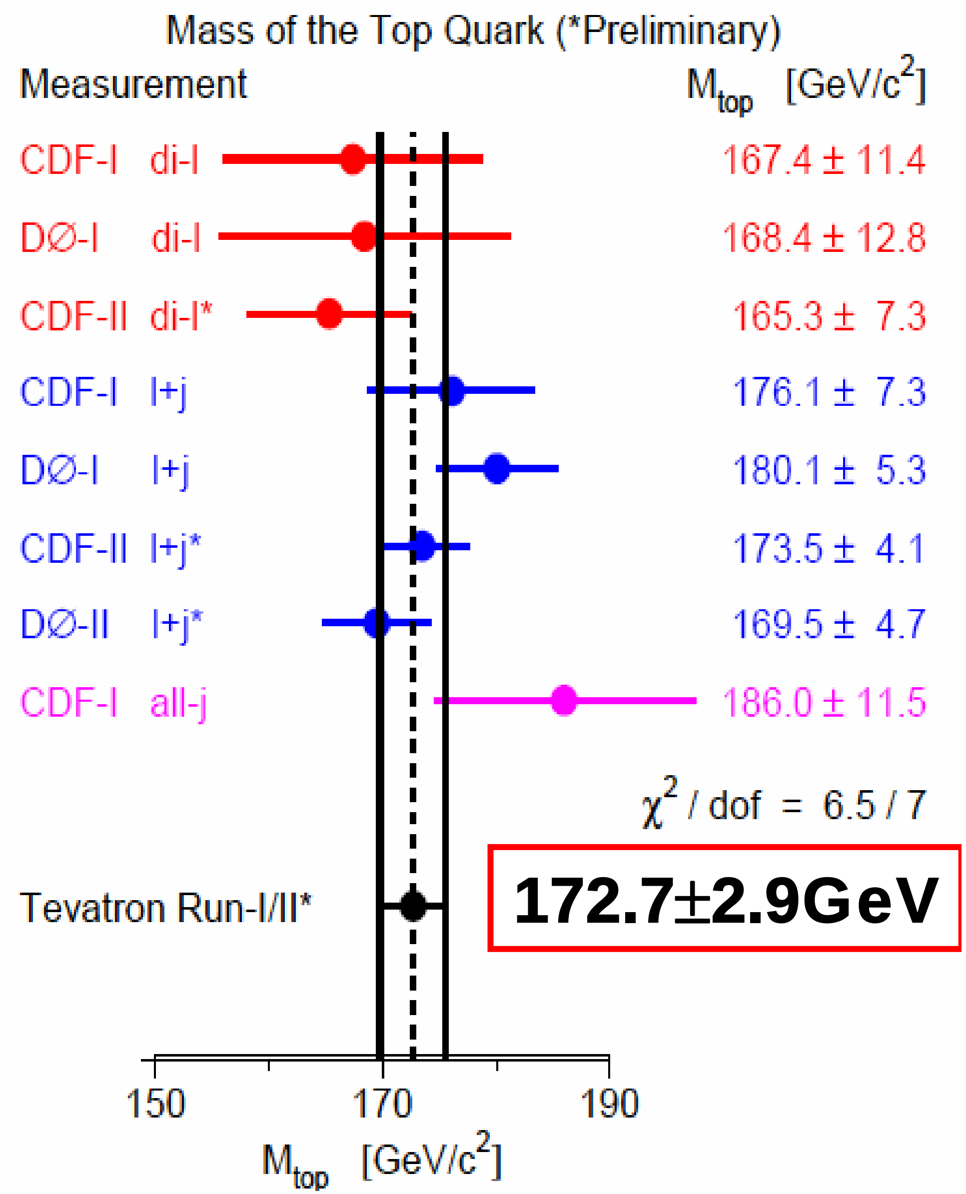
details in hep-ex/050791

Includes 8 measurements
- from Run I and Run II,
- from D0 and CDF
- di-lepton, l+jet, fully-had

Correlations taken into account

Dominated by CDF and D0 Run II l+jet

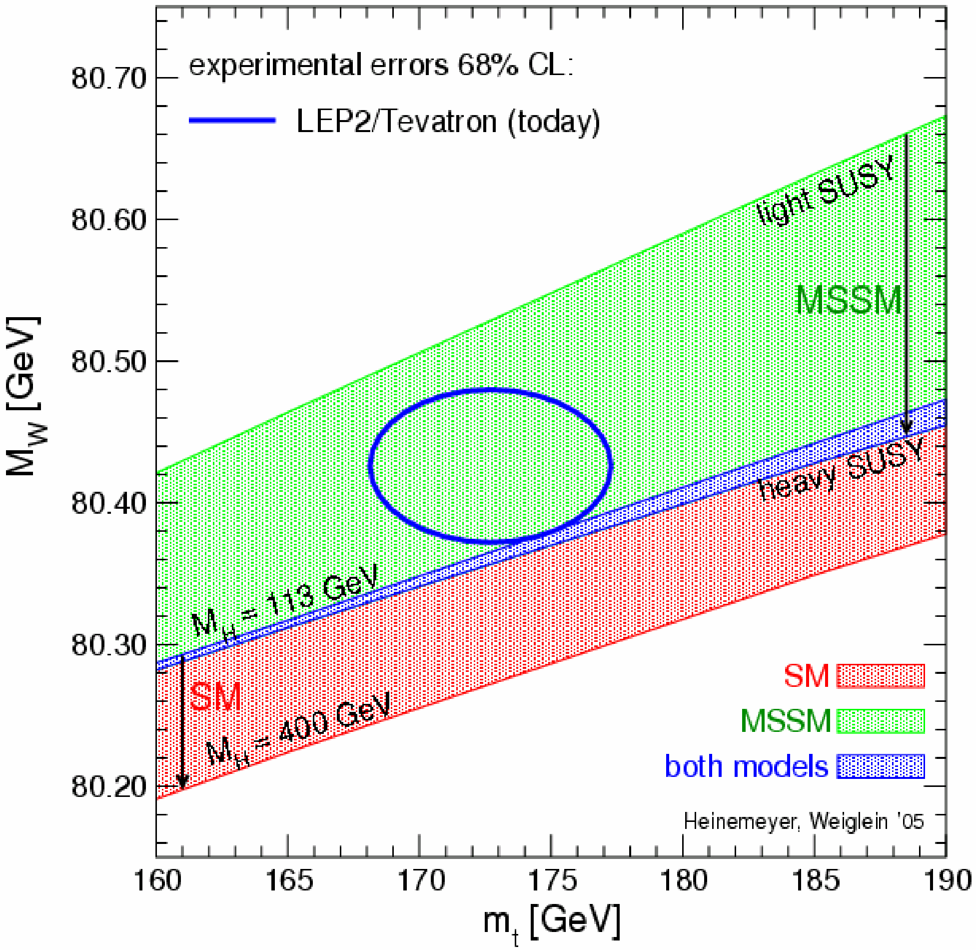
Lower than but consistent with Run I average 178.0±4.3GeV



Implication of new top mass

Standard model interpretation:
Light Higgs favoured

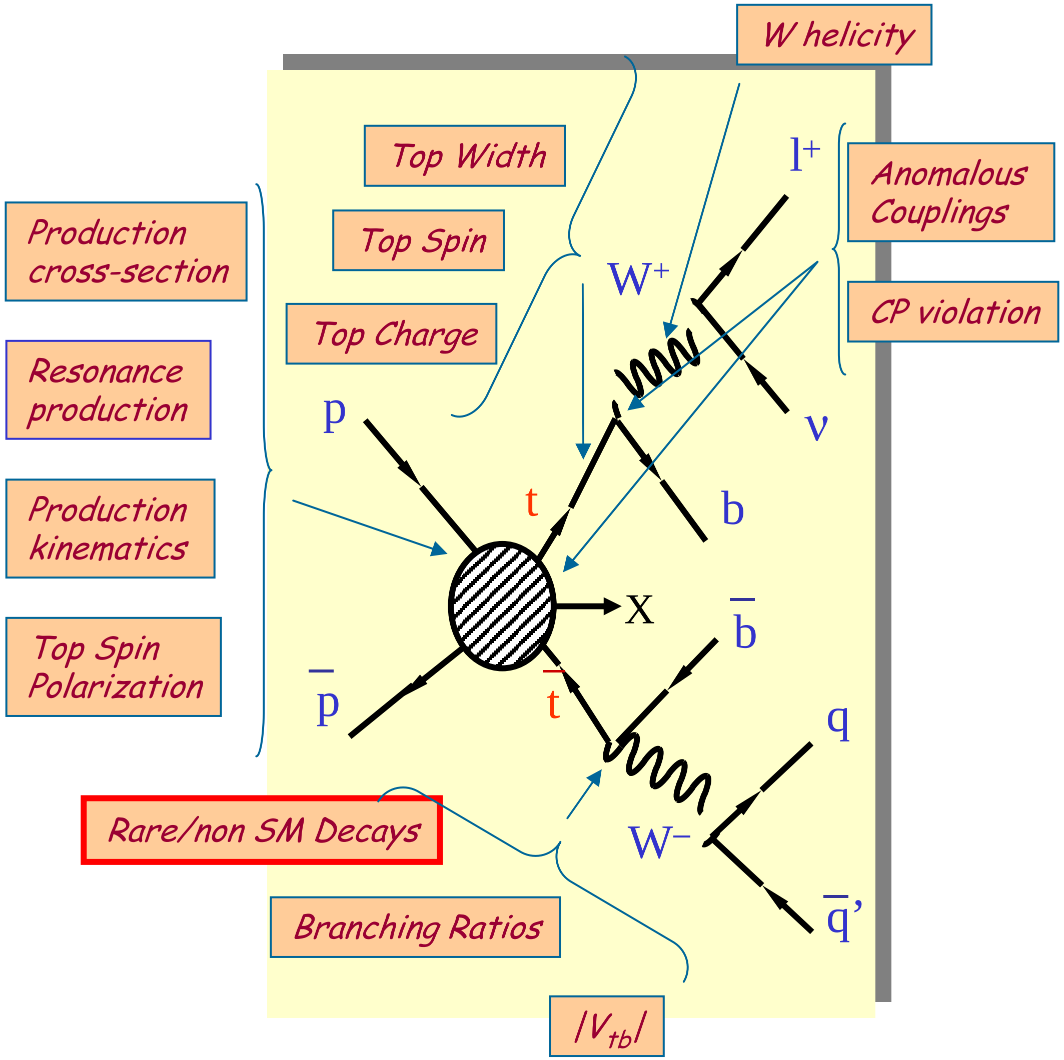
But LEP2 excludes m(H)<114GeV



BSM interpretation:
SUSY favoured over SM

New Tevatron top mass pushes EW fit further towards light Higgs/SUSY!

Beyond masses and cross-sections



top decays to non-b jet

Measuring R=BR(t→Wb)/BR(t→Wq)

$$R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2$$

Unitarity of the CKM matrix predicts R = 0.999999

a 4th generation can change this prediction

method:

- Select $t\bar{t}$ events without requiring b-tags
- Compare 0/1/2 b tags

CDF 161 pb^{-1}:

$$R = 1.12^{+0.21+0.17}_{-0.19-0.13} \text{ (stat + syst)}$$

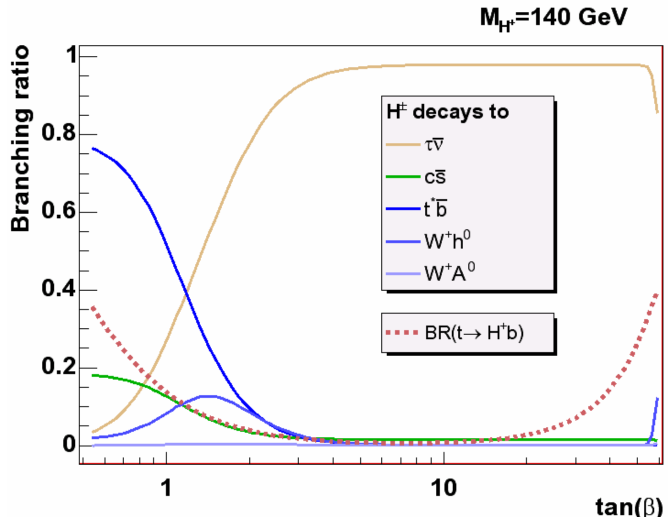
D0 230pb^{-1}:

$$R = 1.03^{+0.19}_{-0.17} \text{ (stat + syst)}$$

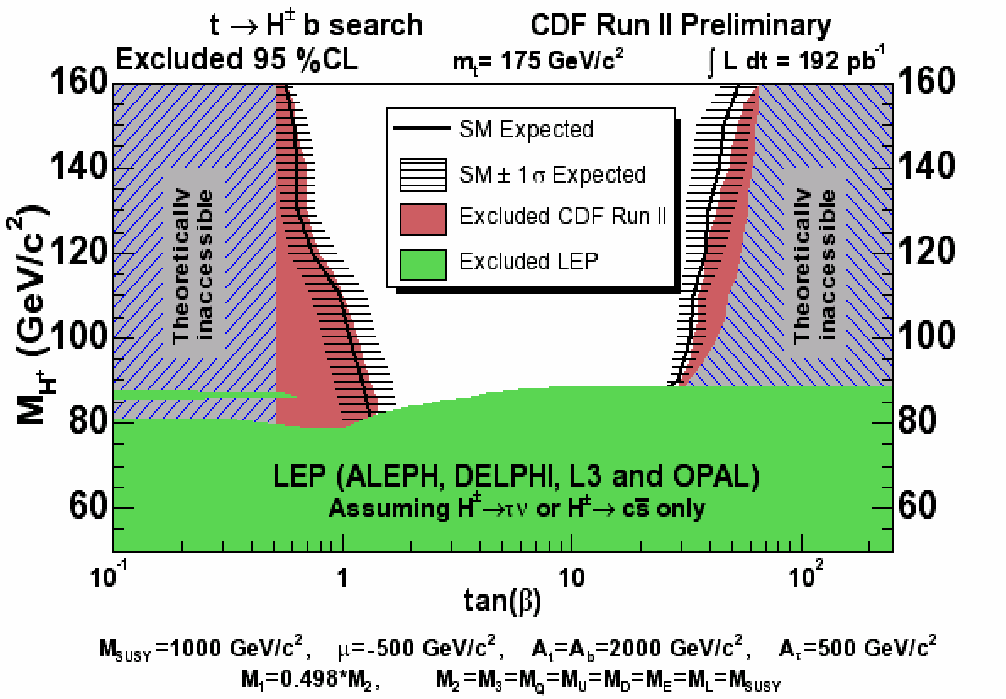
Both experiments confirm within 20%:
All jets from t→Wq decays are b-jets

t →bH⁺ in MSSM

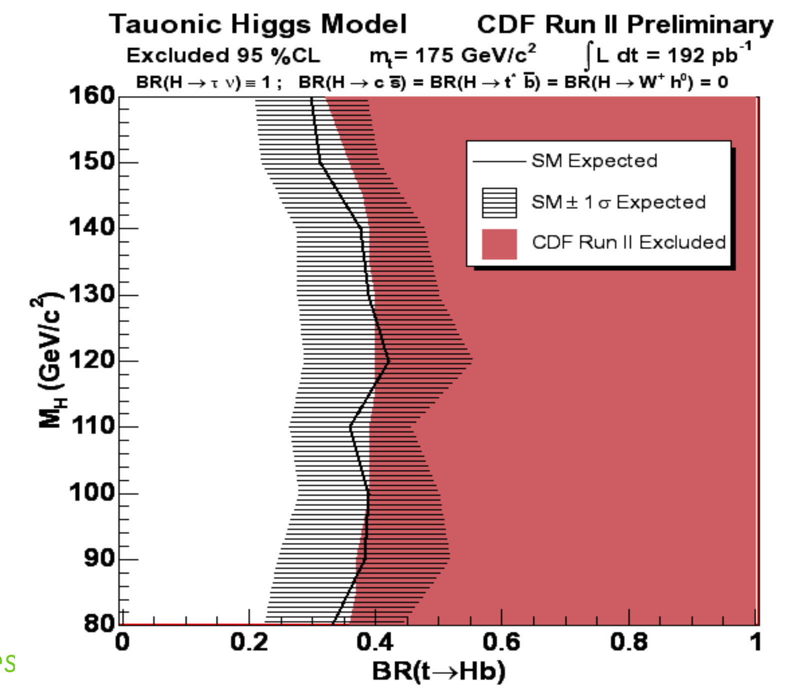
- $t \to H^+ b$ can compete with $t \to W^+ b$ in MSSM
- $H^+ \to t^* b$, $\bar{c}s$, $\tau\nu$, Wh^0
- analyse $\sigma(t\bar{t})$
  - *"dilepton"* ,
  - *"lepton + jets"* 1 b-tag
  - *"lepton + jets"* 2 b-tag
  - *"lepton + hadronic τ"*



exclude MSSM phase space



exclude t→bH⁺ assuming H⁺→τν



Direct searches for BSM flavour

- Leptoquarks
- Exited leptons
- Scalar quarks and leptons

Typical signature: e, μ, τ, b-jet + jet, γ, or missing E_T

Most models require pair-production
$\Rightarrow$ even more distinct signatures!

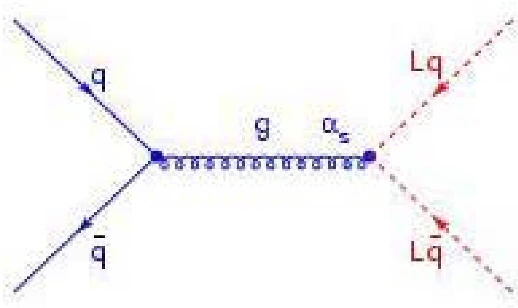
Leptoquarks

Carry both quark and lepton number

Most GUT's predict Lepto-quarks
key parameter:

$$\beta = \frac{B(LQ \to \ell^{\pm} q)}{B(LQ \to \ell^{\pm} q) + B(LQ \to \nu q')}$$

strongly produced in pairs



β=1.0 : LQLQ $\rightarrow$ qql^+l^-

β=0.5 : LQLQ $\rightarrow$ qql^+l^- (25%) qqνl (50%) qq$\nu\nu$ (25%)

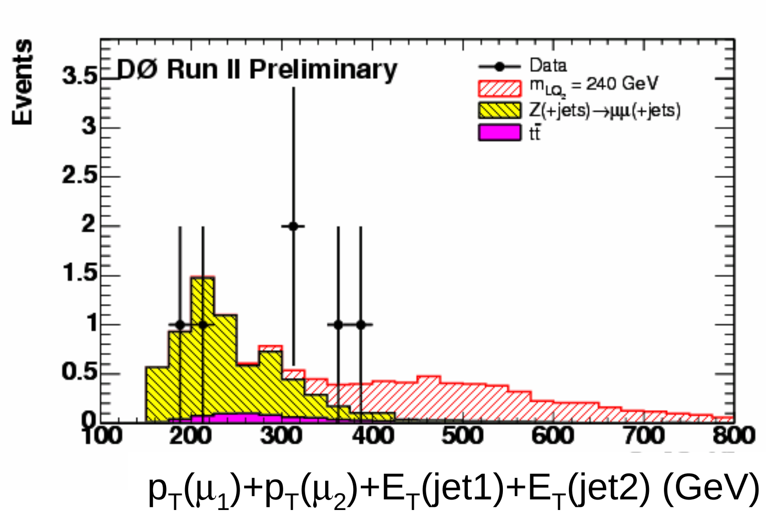
β=0.0 : LQLQ $\rightarrow$ qq$\nu\nu$

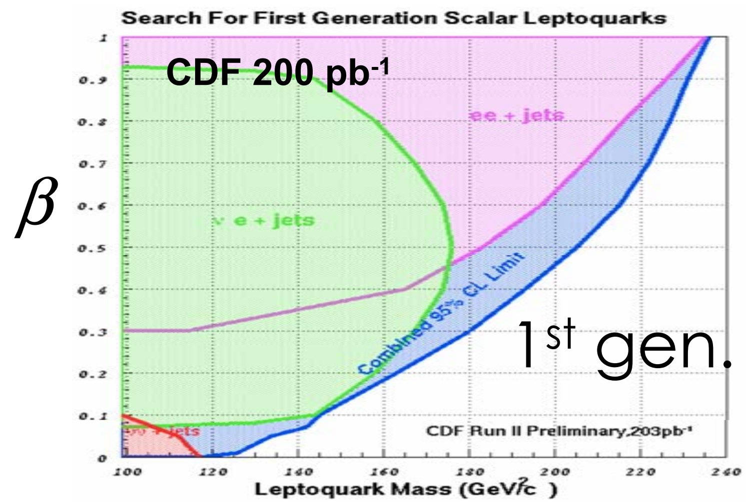
1st generation: $LQ_1 \rightarrow qe$ / $q\nu_e$

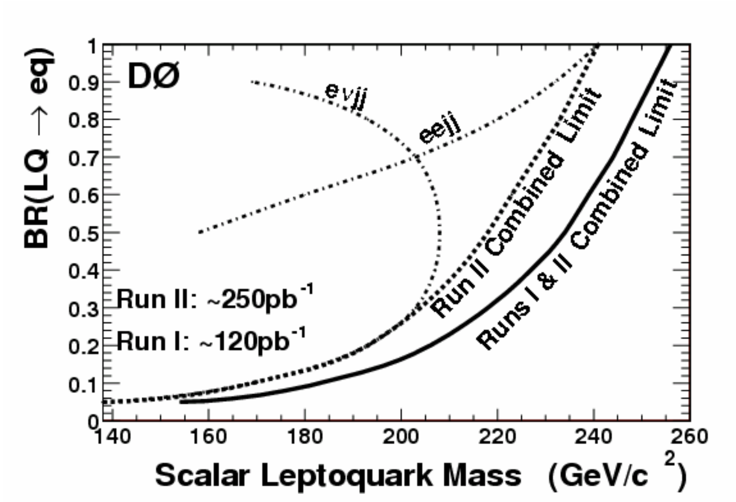
2nd generation: $LQ_2 \rightarrow q\mu$ / $q\nu_\mu$

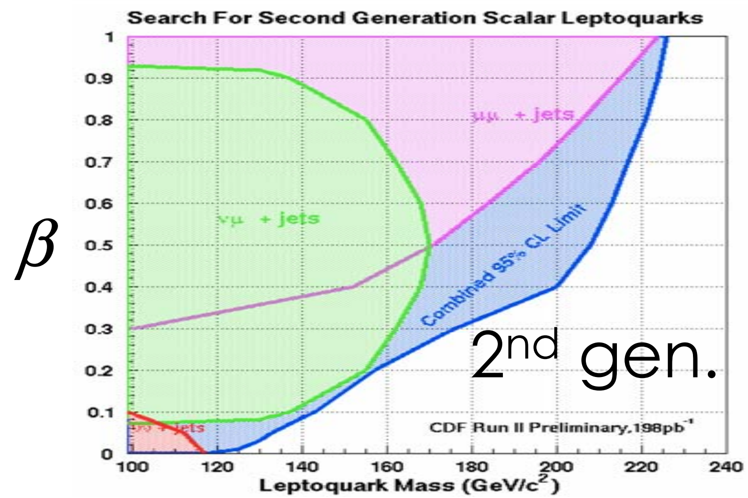
3rd generation: $LQ_3 \rightarrow q\tau$ / $q\nu_\tau$

1^{st} and 2^{nd} gen. leptoquark results









1^{st} and 2^{nd} generation leptoquarks excluded up to m ≈120GeV(β=0) to m≈250GeV(β=1)

3^{rd} generation leptoquarks

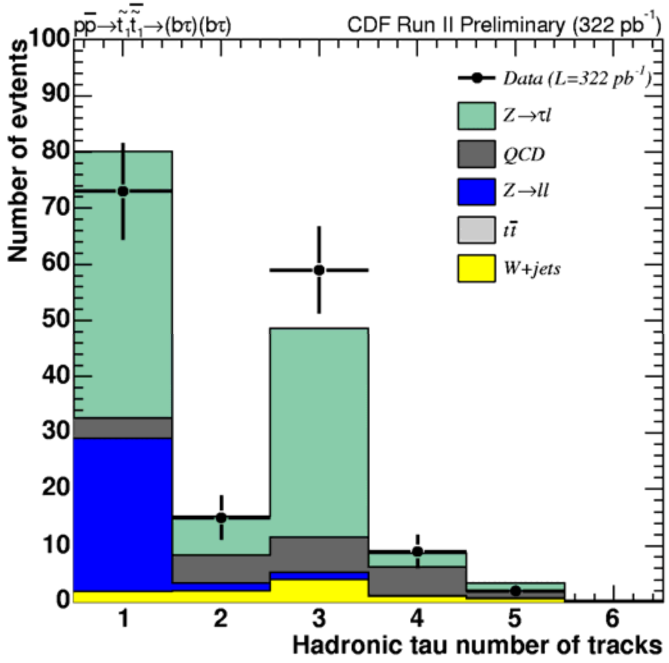
Signature: 2 b-jet + 2τ

same signature as RP-violating stop!

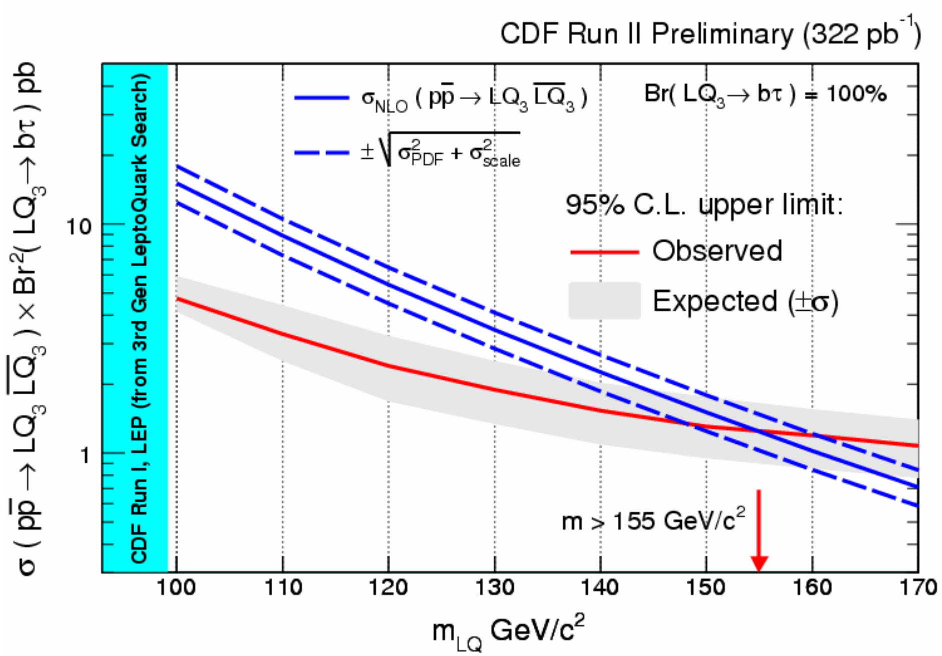
CDF 320 pb^{-1} analysis:

- 1 τ→lepton, 1 τ→hadrons.
- No b-tag applied to jets

$Z \to \tau^+\tau^-$ control sample



τ-identification at hadron colliders works!

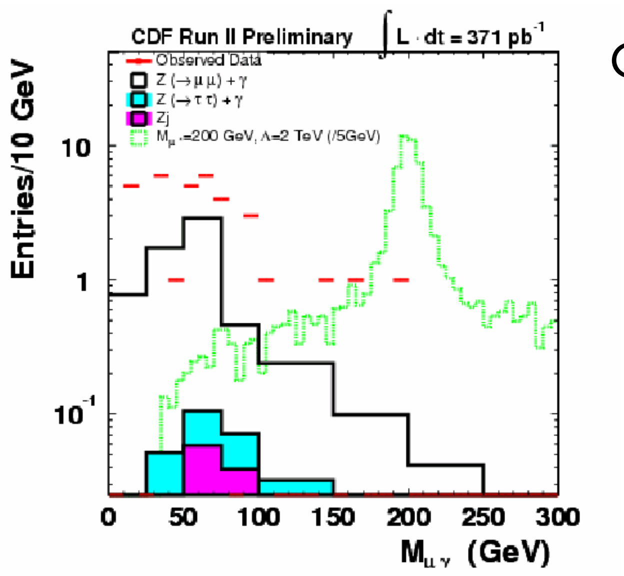


m(LQ_3)>155GeV for β=1

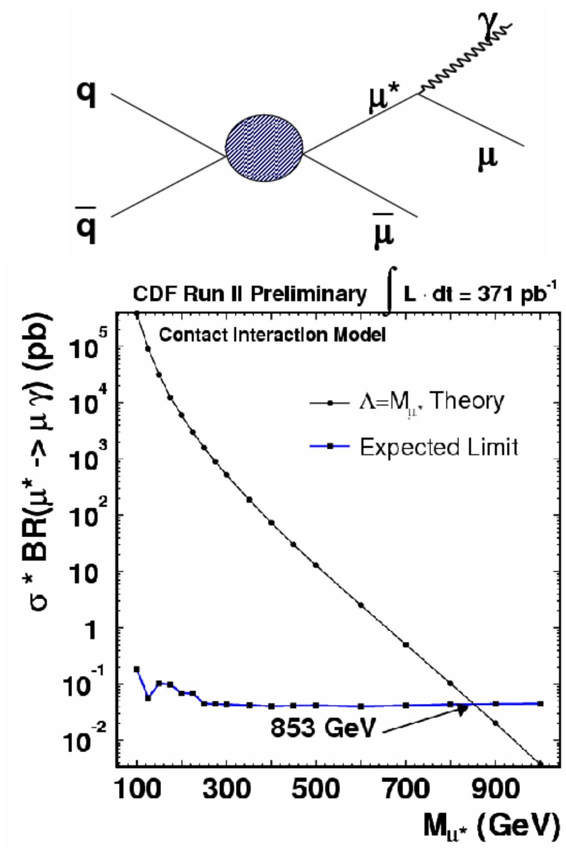
less strict then for 1st and 2nd generation leptoquark

Excited leptons

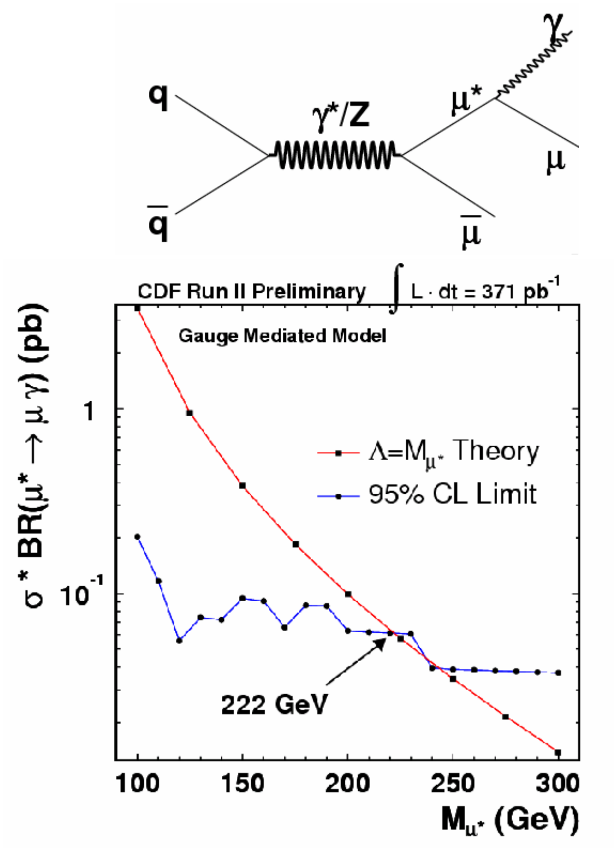
Signature: 2 leptons + photon



contact interaction



gauge mediated

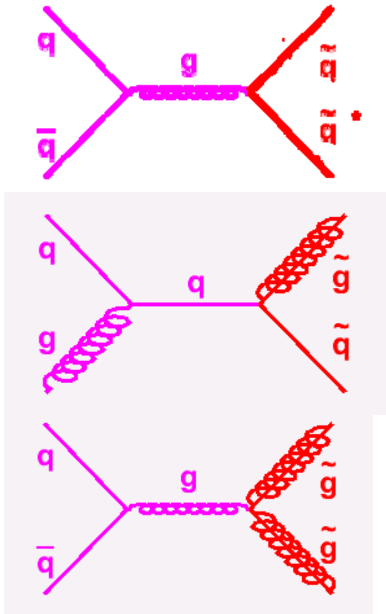


*similar limits on e**

Scalar quarks (SUSY)

'Classic' inclusive signature: jets + missing transverse energy

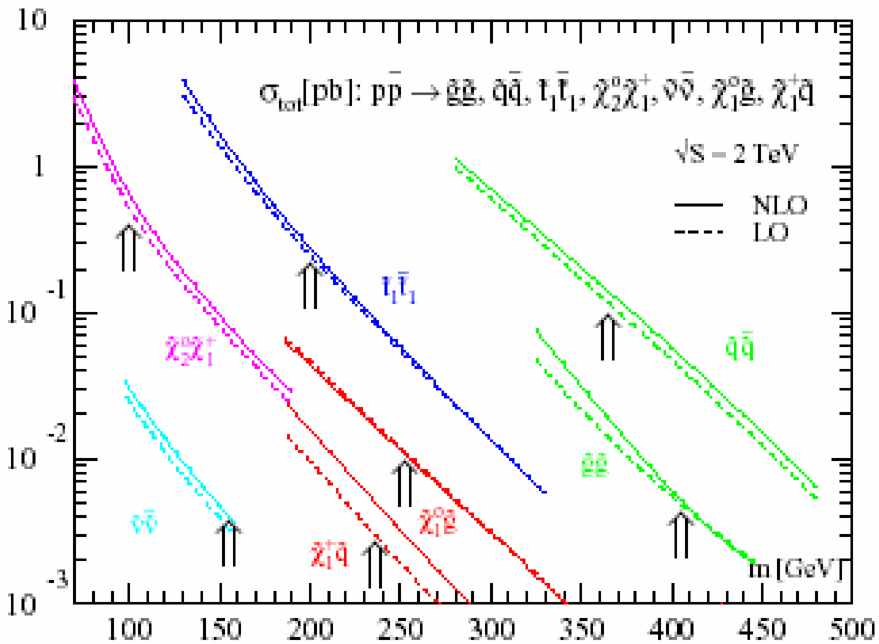
Inspired by MSUGRA models: $\tilde{q} \to q\chi^0$, or $\tilde{g} \to qq\chi^0$
χ^0 is stable, neutral, weakly interacting $\Rightarrow$ missing E_T
$\sigma(\tilde{q}\bar{\tilde{q}}) \propto N_{flav} \times N_{col} \Rightarrow$ large cross-section,
relatively clean signature $\Rightarrow$ very large mass range



2jet+missing E_T

3jet+missing E_T

4jet+missing E_T



Important background: Z+jets, $Z \to \nu\nu$

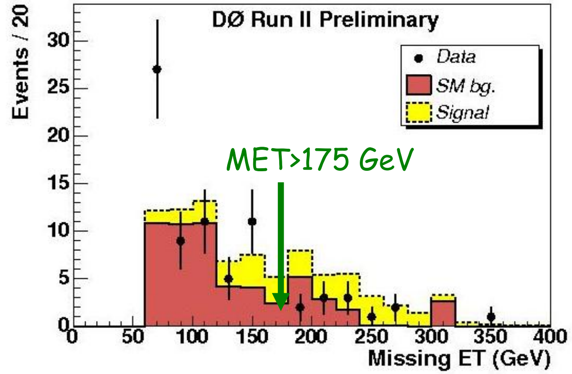
D0 squark/gluino search

2 jets

Main BG: $Z \to \nu\nu$+2 j

expect: 12.8±5.4

observe: 12

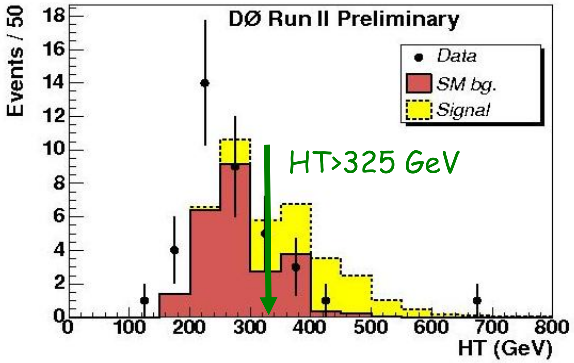


3 jets

Main BG: $W \to \tau\nu$+2j

expect: 6.3±31

observe: 5

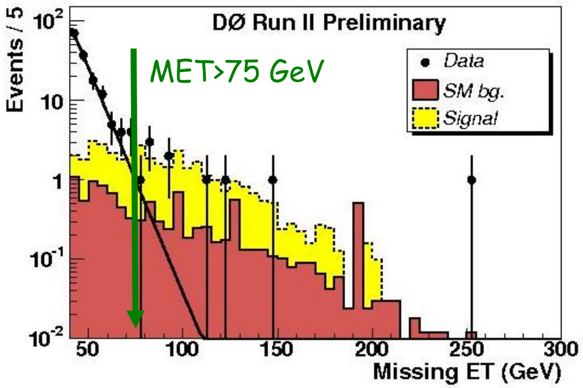


4 jets

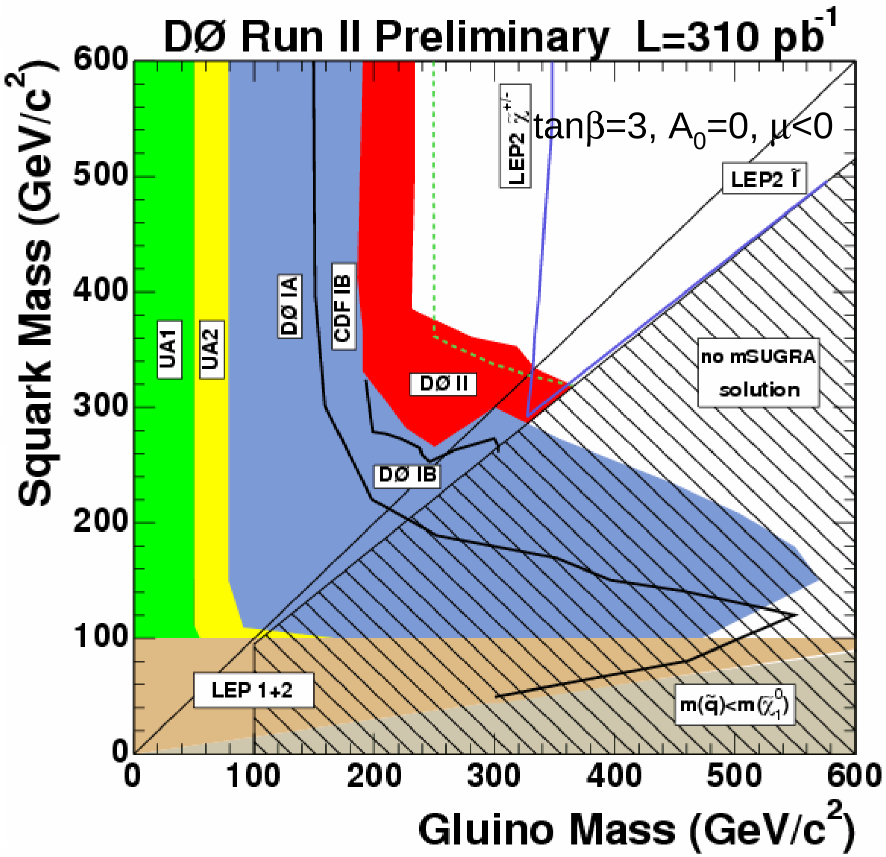
Main BG: $t\bar{t}$

expect: 7.1±0.9

observe: 10



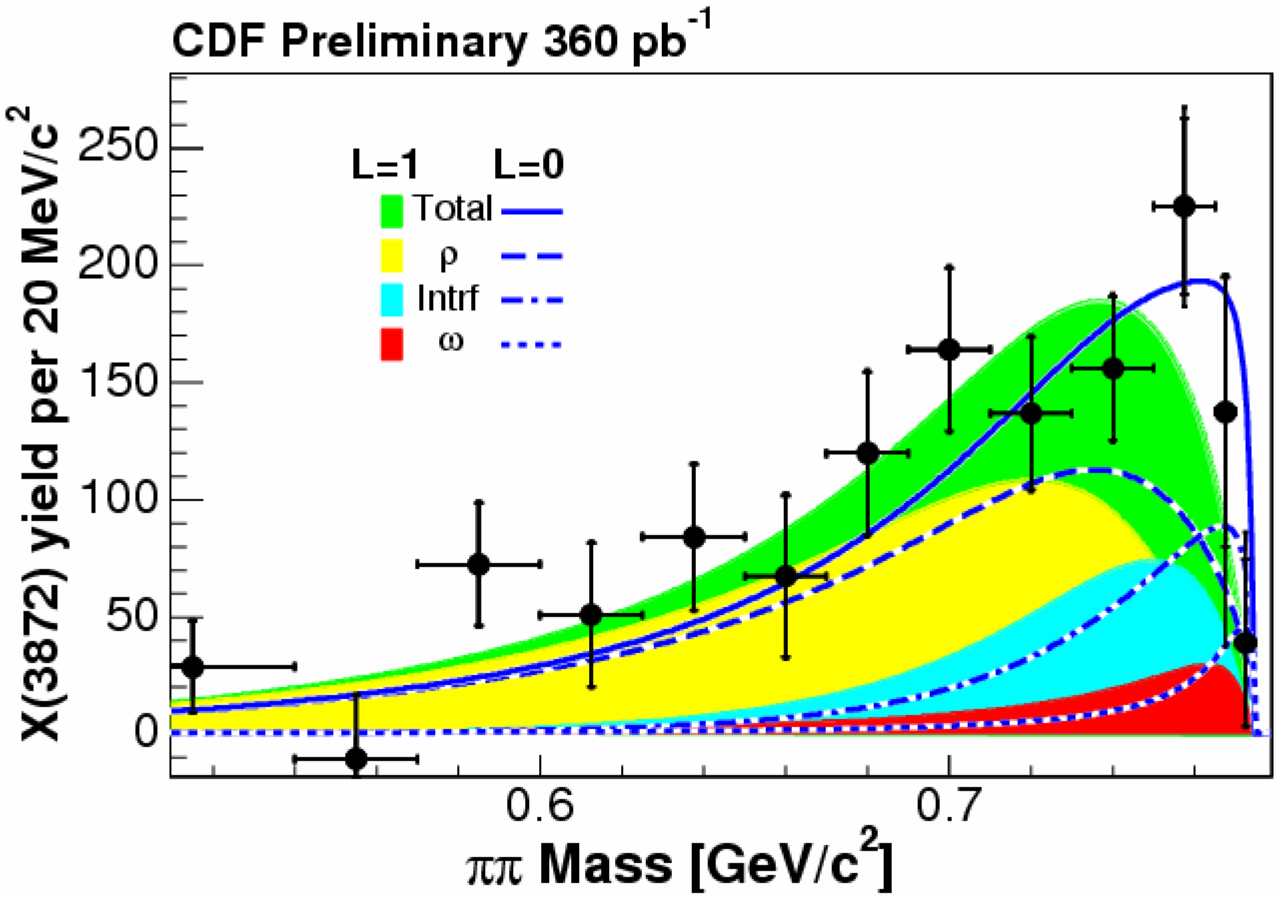
Indirect limit from LEP2
(in SUGRA, $m(\tilde{g}) \approx 3m\chi^{\pm}$



Conclusions

- Tevatron has achieved an extremely rich flavour program:
  - charm
  - beauty
  - top
  - exotic
- Possible thanks to versatile general-purpose detectors:
  - tracking with high p_T resolution
  - electon, muon and photon identification
  - large trigger bandwidth
- Expect first $1 fb^{-1}$ analyses this winter

BACKUP



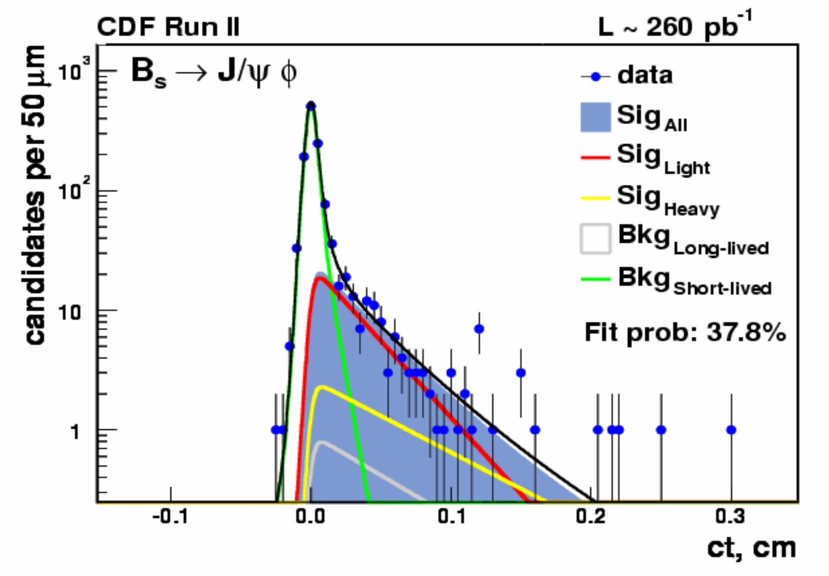
CDF Preliminary 360 pb^{-1}
L=1 L=0
Total
ρ
Intrf
ω
X(3872) yield per 20 MeV/c^2
0
50
100
150
200
250
0.6
0.7
ππ Mass [GeV/c^2]

Lifetime difference in $B_s \to J/\psi\ \phi$

- Both the J/ψ and the ϕ are vector-mesons
  - spin 1 $\Rightarrow$ polarization degree of freedom
- Three components in VV final state:
  - A_0 : longitudinal component *CP even*
  - $A_{\parallel}$: transverse parallel component *CP even*
  - $A_{\perp}$: transverse perpendicular comp. *CP odd*
- Standard model prediction:
  - CP-even = short lived
  - CP-odd = long lived
  - $\Delta\Gamma/\Gamma=0.12\pm0.06$
- New physics can only(?) ***decrease*** $\Delta\Gamma$

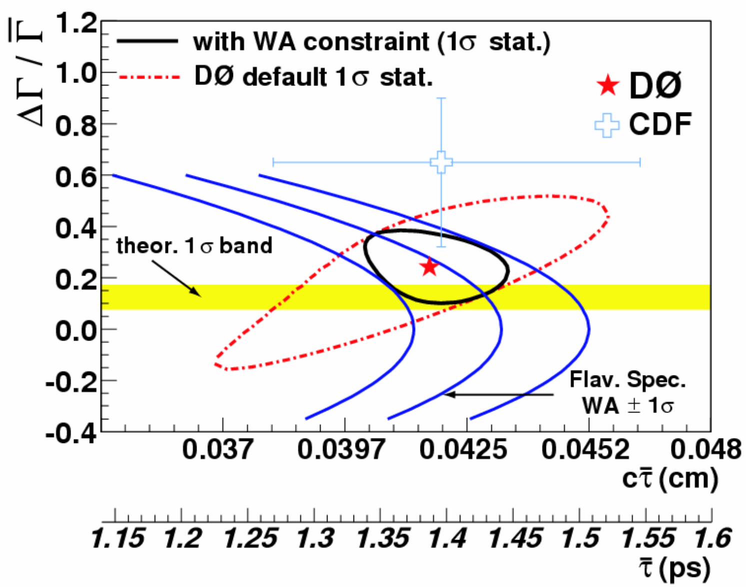
Bs mixing I – Lifetime difference

- $B_S \rightarrow J/\psi\,\phi \rightarrow \mu^+\mu^- K^+K^-$
- B→VV decays: Heavy and Light state decay with distinct angular distributions and different lifetimes.



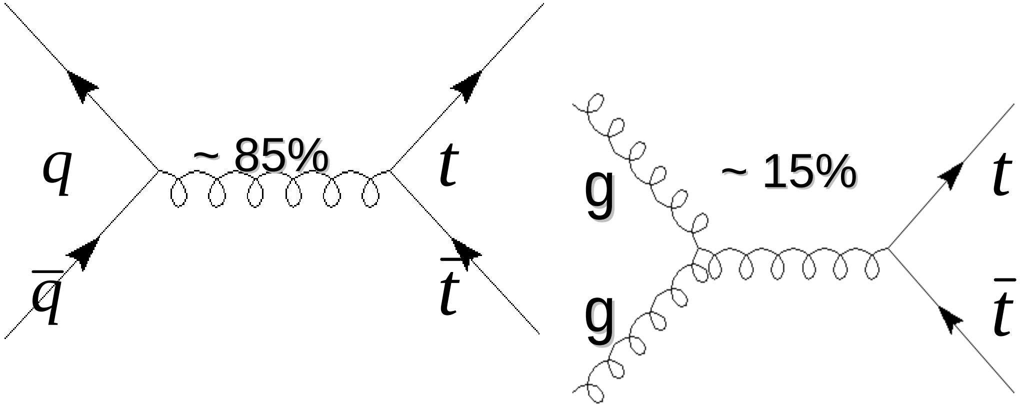
- CDF (260 pb^{-1}) $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01$
  - 1/4 heavy - 3/4 light state
  - Lifetime - $\tau_{heavy} \sim 2 \times \tau_{light}$

D0 (450pb^{-1}) $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.21^{+0.33}_{-0.45}$



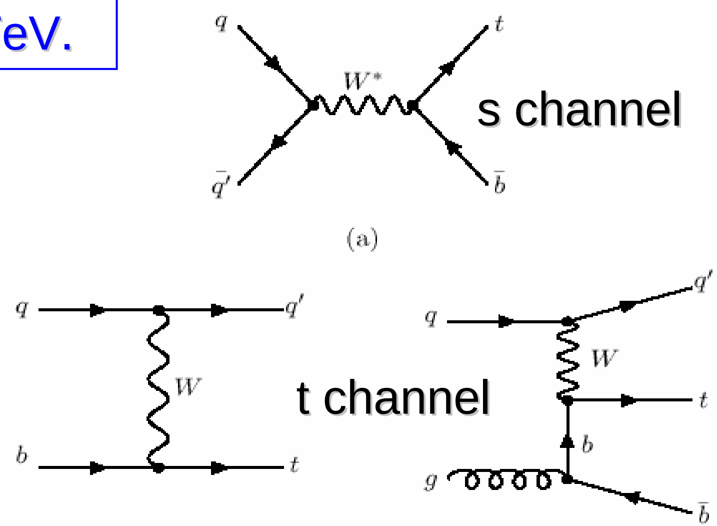
Top Production at the Tevatron

- Pair production
  - $\sigma_{\text{pair- theory}}$ = 6.7 pb.



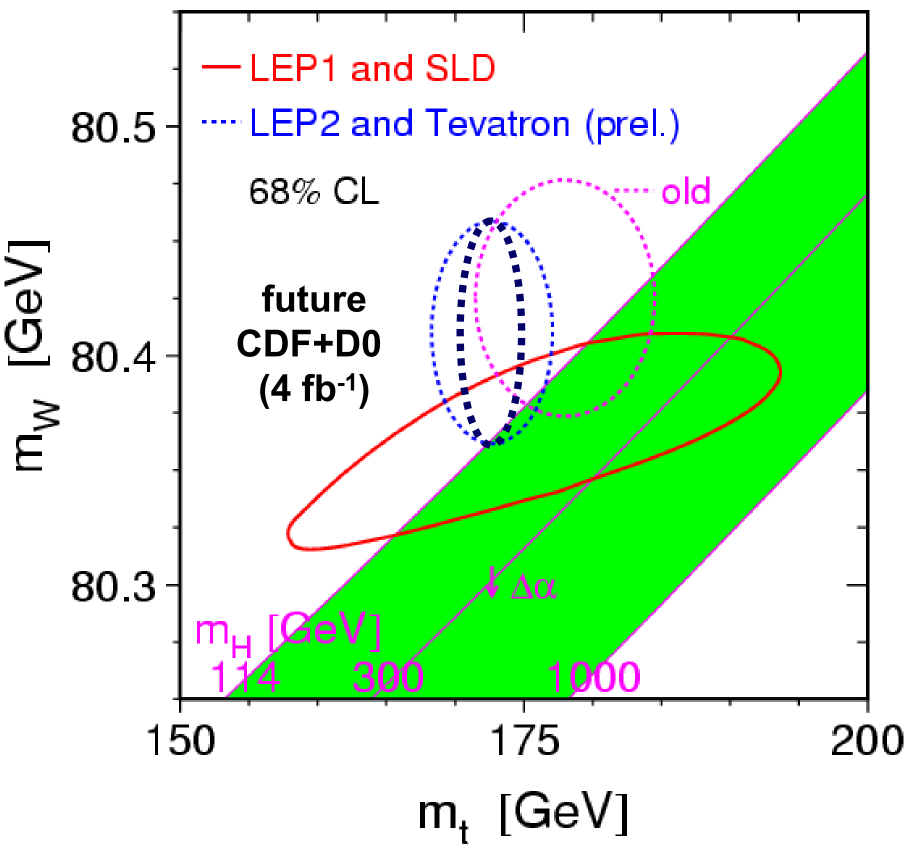
All of these theoretical values assume
a top quark mass of 175 GeV/c^2
at a center of mass energy of 1.96 TeV.

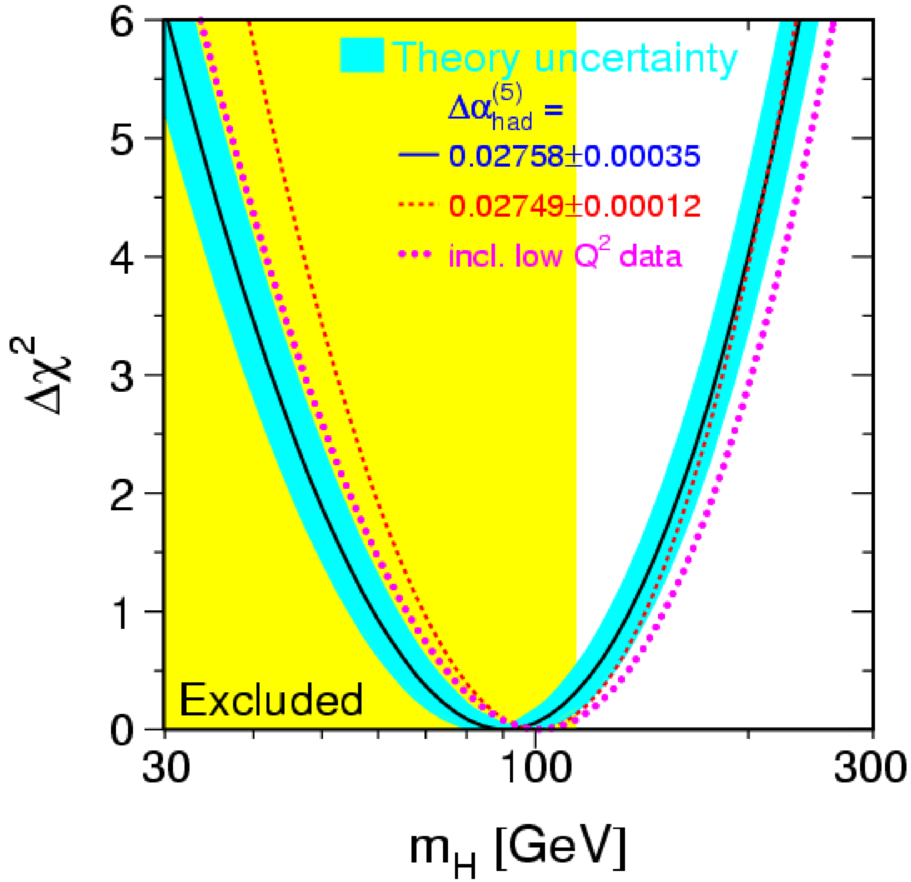
- Single top
  - Not yet observed
  - $\sigma_{\text{s-channel - theory}}$ = 0.88 pb.
  - $\sigma_{\text{t-channel - theory}}$ = 1.98 pb.



Test of Standard Model

Impact of CDF+D0 Top Quark Mass = 172.7 ± 2.9 GeV





Good agreement between
direct measurements
and
indirect SM prediction

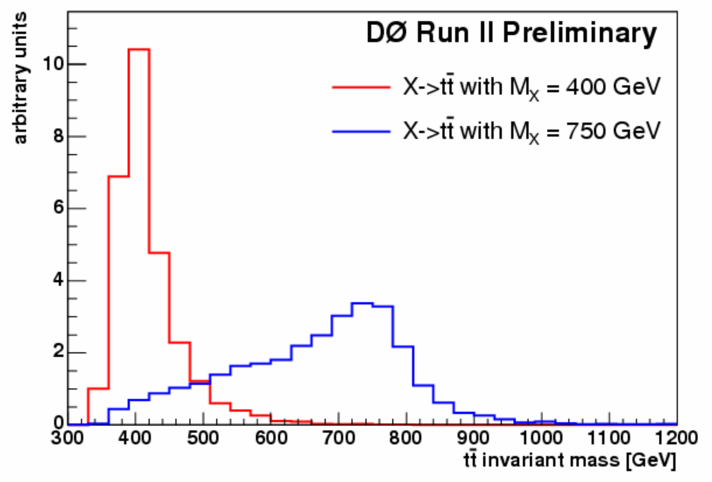
$= 91 \pm^{45}_{32}$ **GeV**

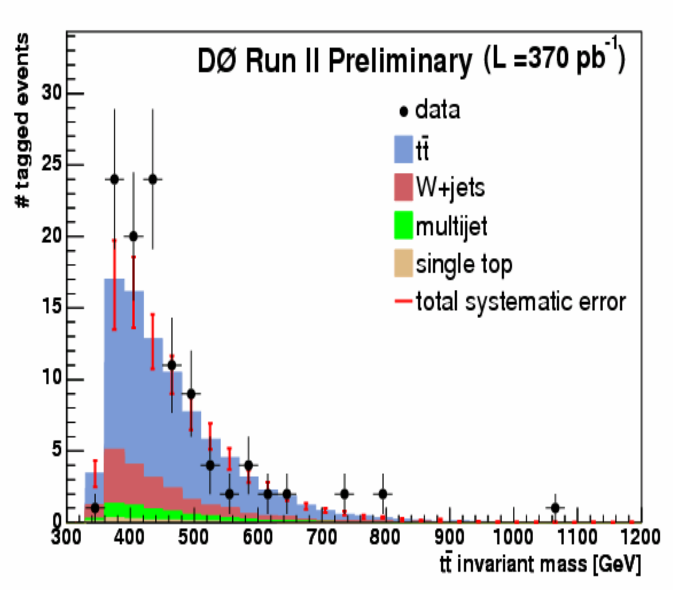
< 186 **GeV @ 95% C.L.**

<219 GeV with LEP Excluded

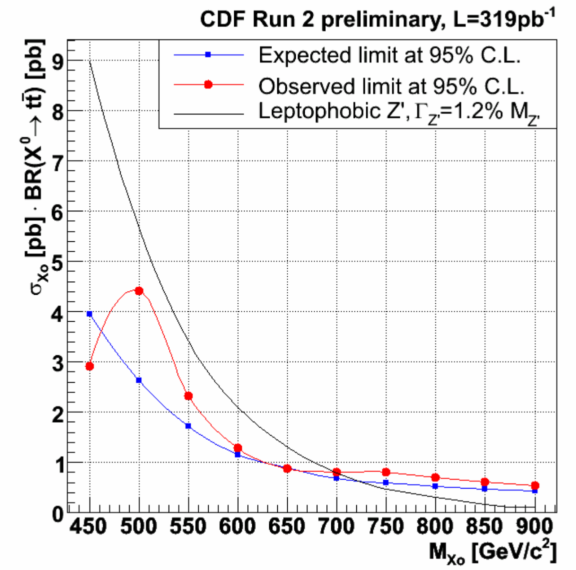
Heavy states decaying to ttbar

D0 370pb^{-1} l+jets





CDF 320 pb^{-1} l+jets



Both experiments exclude X→ttbar Br×σ larger than few pb^{-1}.

Leptophobic Z' in topcolor models with Γ(Z')=0.012m(Z') are excluded for up to Z' masses of about 700 GeV

sbottom and stop searches

- to be completed