Heavy Quark Production and Decays at CDF

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YITP, Kyoto

March 17 – 18, 2003

Heavy quarks

Heavy quarks here mean the charm and bottom quarks.
Top will be covered by Yuji Takeuchi.

Physics aspects
Production : Strong, Decays : Weak Interactions

Worth looking ?

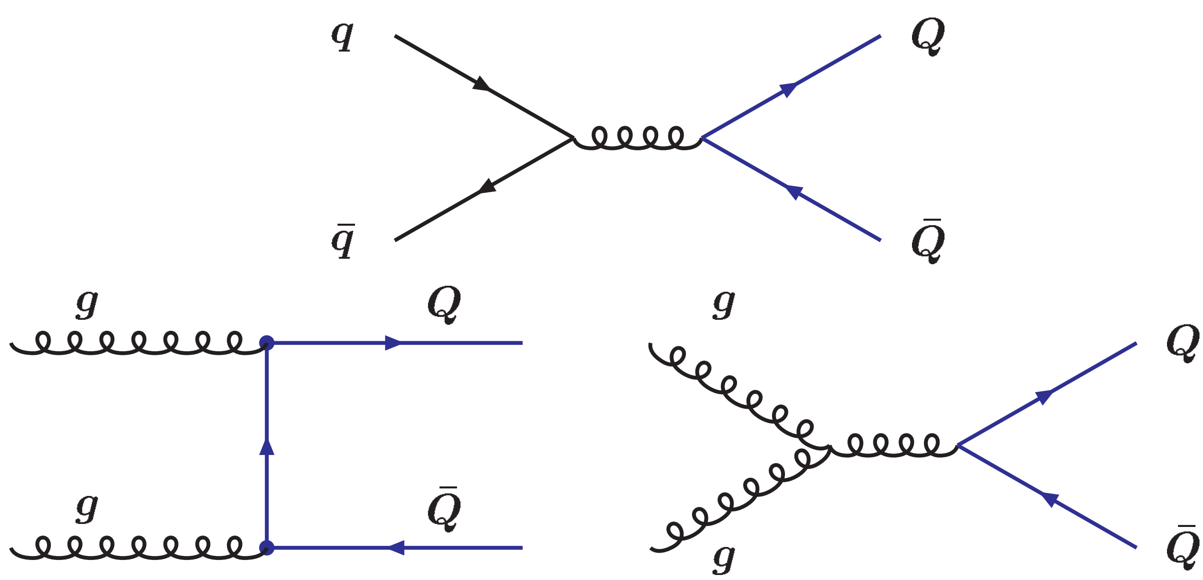
1. Heavy quarks are interesting in their own right.
   - Direct J/ψ production $50\times$ theory. Hum...
   - B decays offer probes of the CKM matrix.
2. Important ingredients for future searches.
   - Needed to underastand $Wb\bar{b}$ as a BG to top.
   - $p\bar{p}\,(pp) \rightarrow$ Higgs $\rightarrow b\bar{b}$.

We had better understand them.

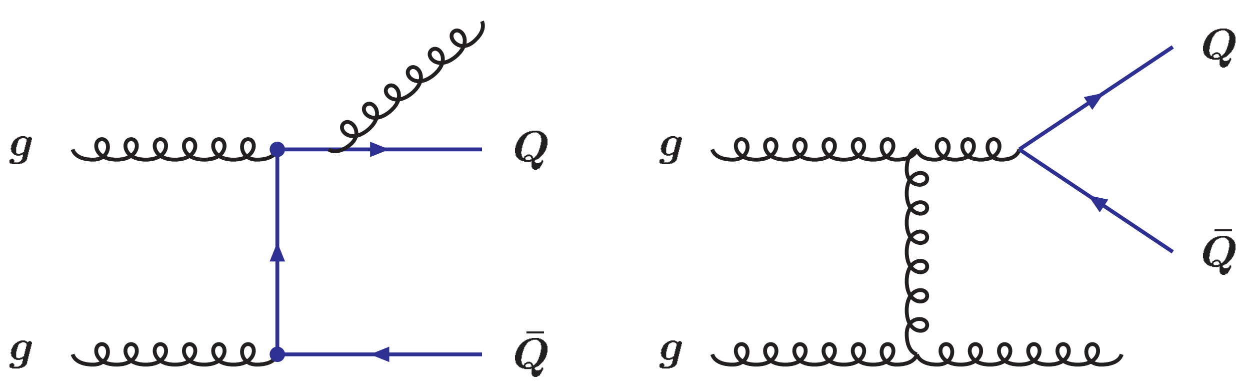
So, here we go.

Open Heavy Quark Production

- Heavy quark mass $M_Q \gg \Lambda_{\mathrm{QCD}}$
  $\Rightarrow$ always a hard process (factorization).
  Perturbative QCD applicable for all momenta.
  LO: α_S^2

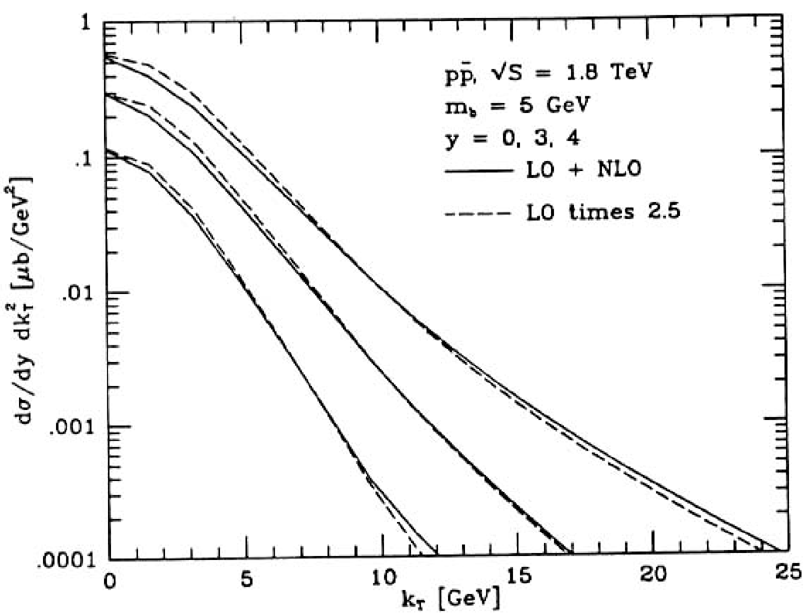


- NLO calculations available for
  - total cross sections
  - one-particle inclusive cross sections : $d\sigma/dp_T^2 dy$
  - two-particle ($b\bar{b}$) correlations, MLM *et al.*

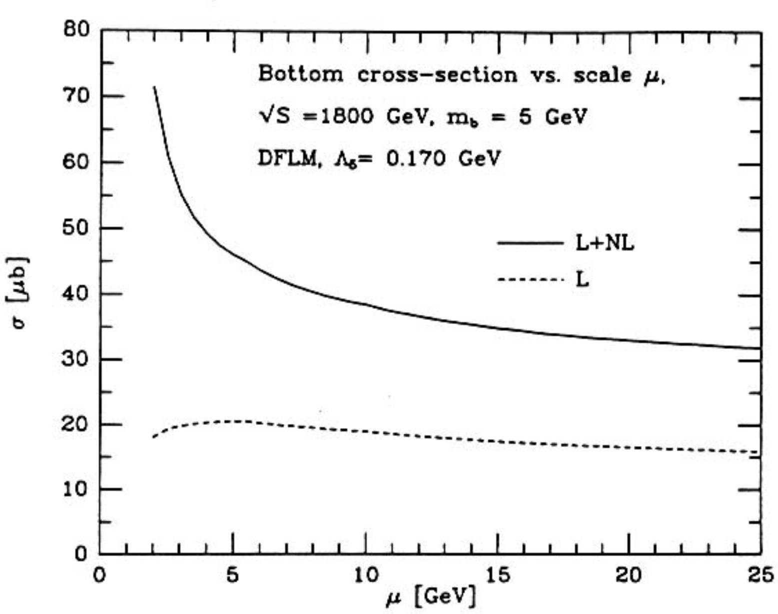


Bottom Quark Production

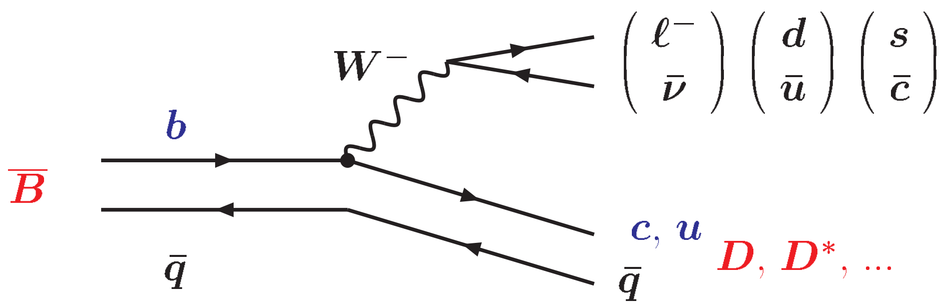
Correction to LO large, $\times 2.5$.
But p_T and rapidity distributions virtually unchanged.



Dependence on renormalization scale μ not reduced in NLO. Worrisome?



How to detect the b quark?
Have to identify its decay.



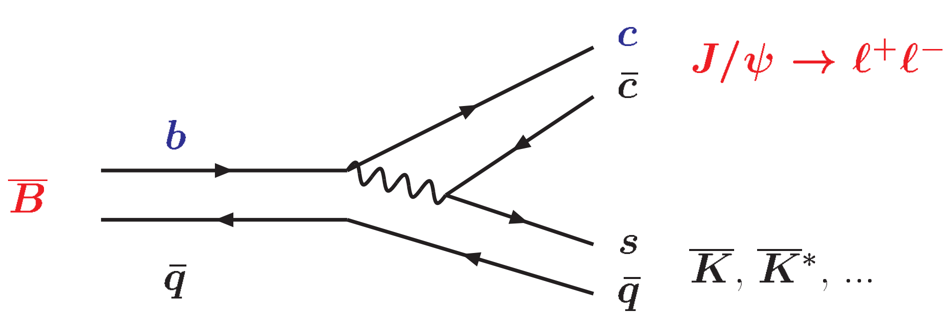
- 0-th order approximation :
  Decay of a heavy hadron $H_Q (\equiv Q\bar q)$ is the decay of the heavy quark Q.
- b quark decays to c or u quark.

  $b \to c$ decay dominant, because $|V_{cb}| \gg |V_{ub}|$.
- Have to isolate among BG of q and g jets.

  $\Rightarrow$ use semileptonic decay and the lepton.

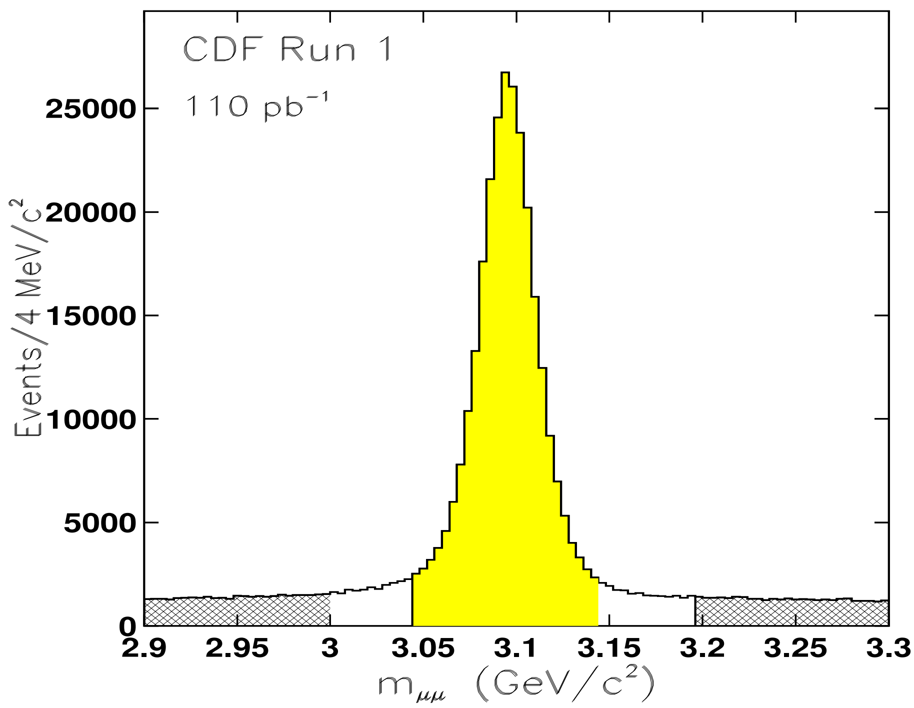
  Rate sizable : $\mathcal{B}(\overline{B} \to \ell^- \bar\nu X) = 10\%$.

  Main source of single leptons at low p_T (below $W^\pm$ and Z^0).
- B decays can also produce two leptons :
  - Sequential decays : $b \to \ell^- \bar\nu c$, $c \to \ell^+ \nu s$.
  - $\overline{B} \to J/\psi\, X$ via $b \to c\,\bar c s$, and $J/\psi \to \ell^+ \ell^-$.

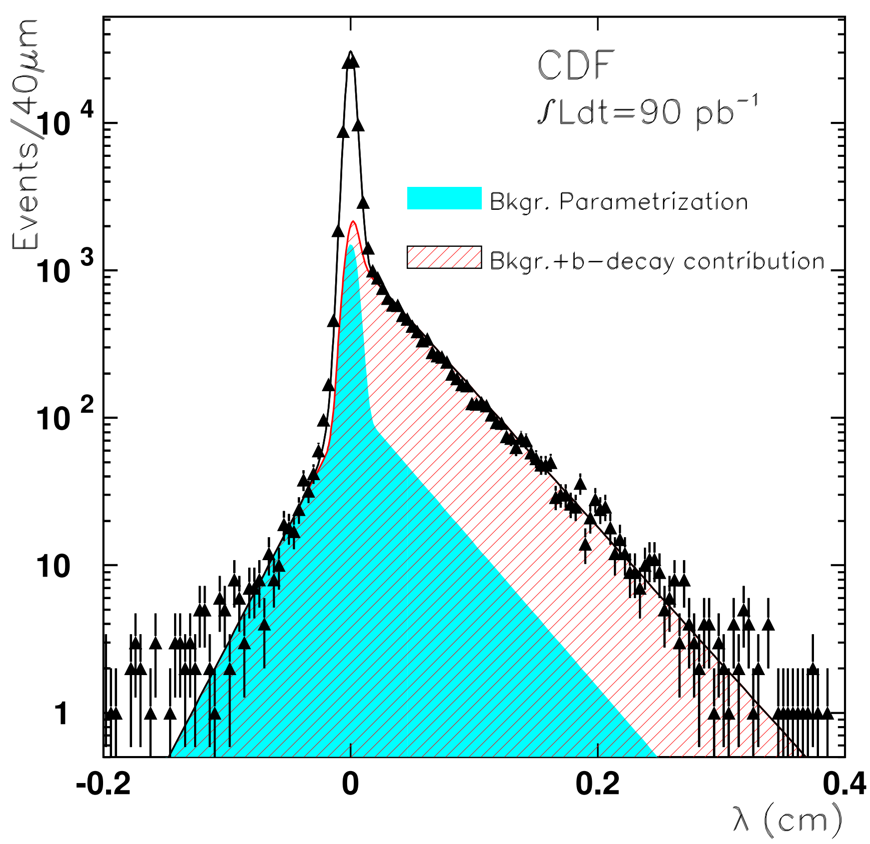


$\mathcal{B}(\overline{B} \to J/\psi\, X) \simeq 1\%$, $\mathcal{B}(J/\psi \to \ell^+\ell^-) = 7\%$.

$J/\psi \to \mu^+\mu^-$ and B decays (Run I)



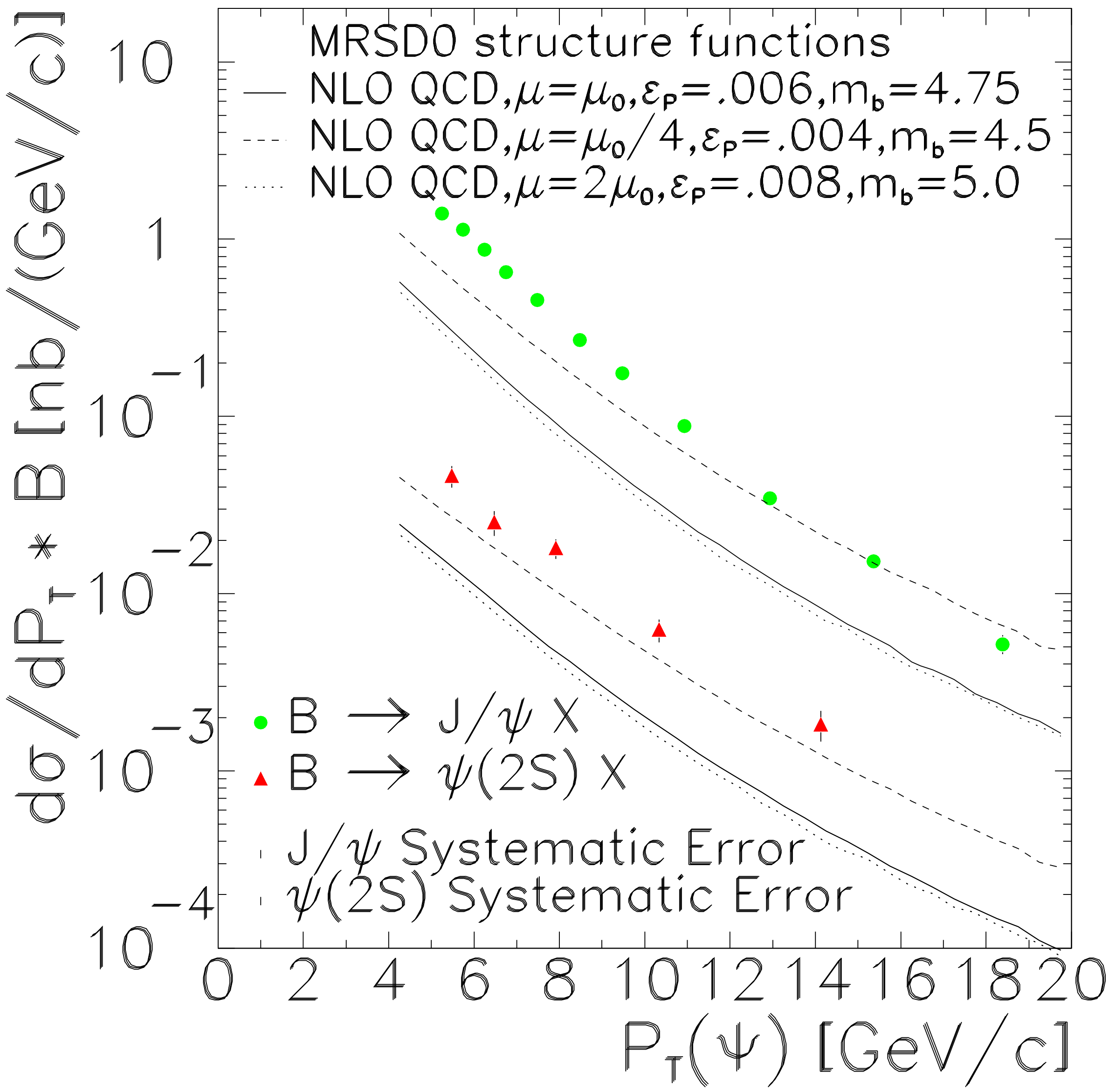
Decay length distribution



$\sim$ 20% of J/ψ's from B decays.

Production of J/ψ and $\psi(2S)$ from B decays

Start from NDE b-quark rates, then fragment into B-hadrons and decay to $J/\psi\, X$.

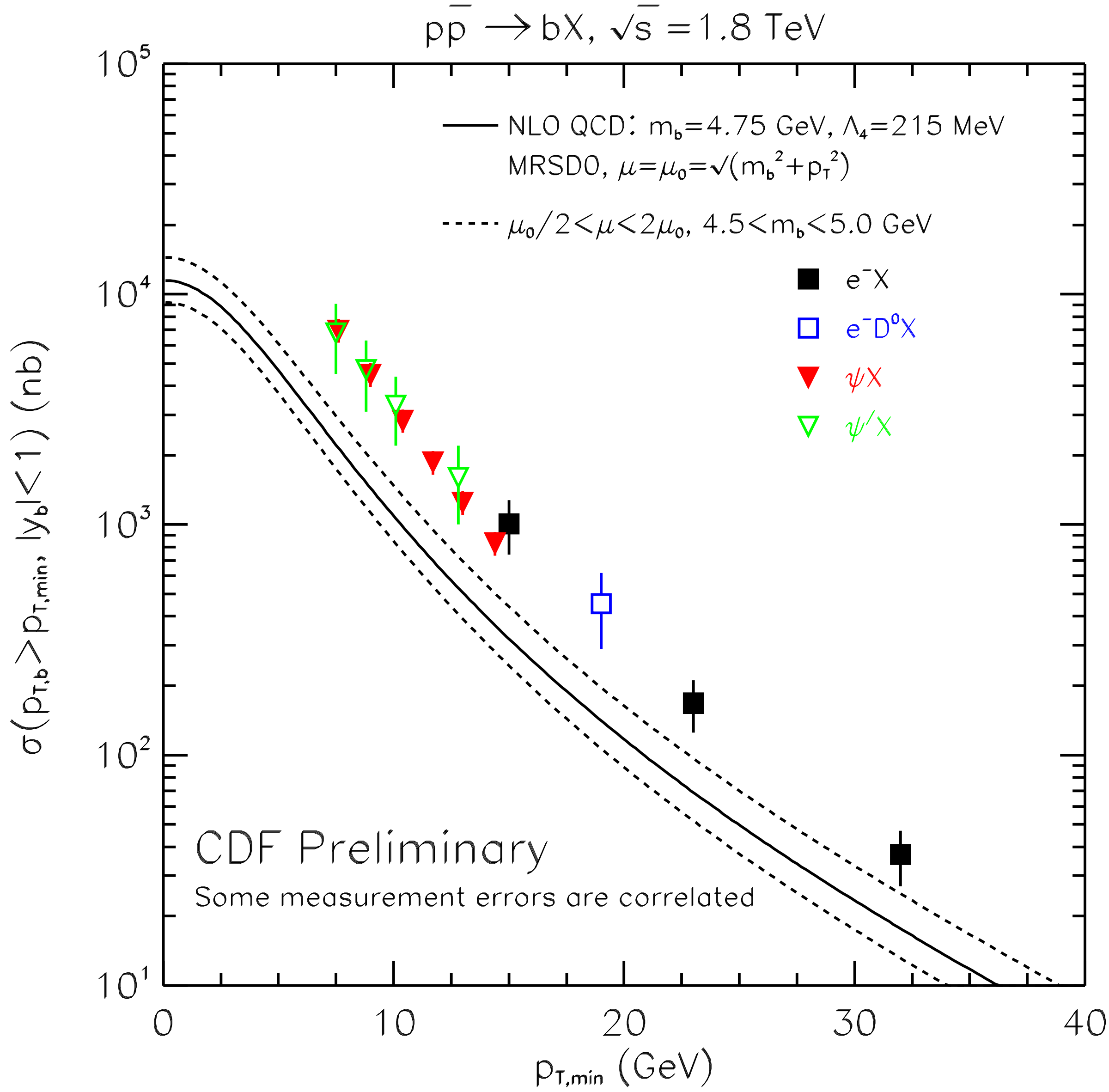


Higher than NLO QCD calculation with "normal" choices of scale μ, Λ_{QCD} and m_b.

PRL 79, 572 (1997).

An obsolete plot, but ...

b-quark Production Cross Section above p_T^{min}, with ψ's and semileptonic decays.

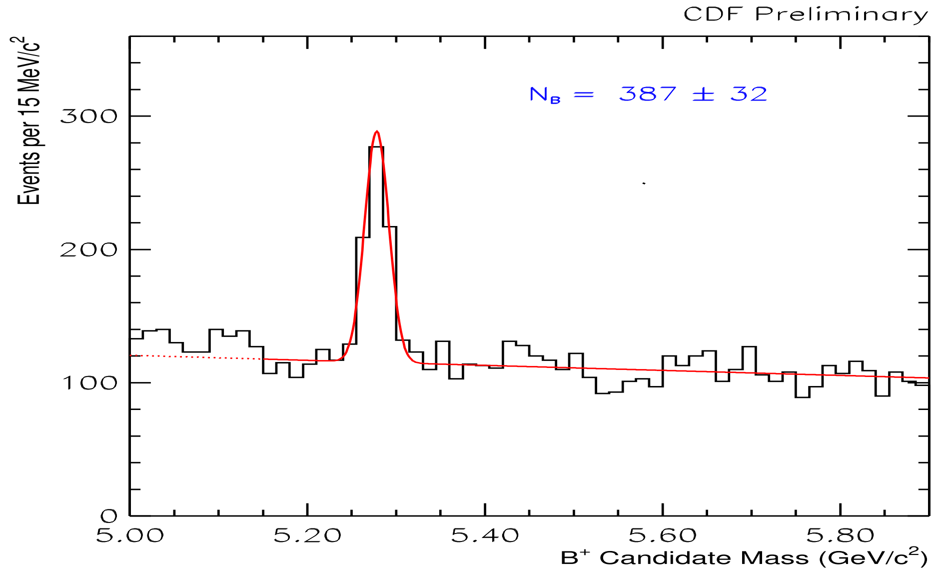


Data $\sim 2 \times$ Theory

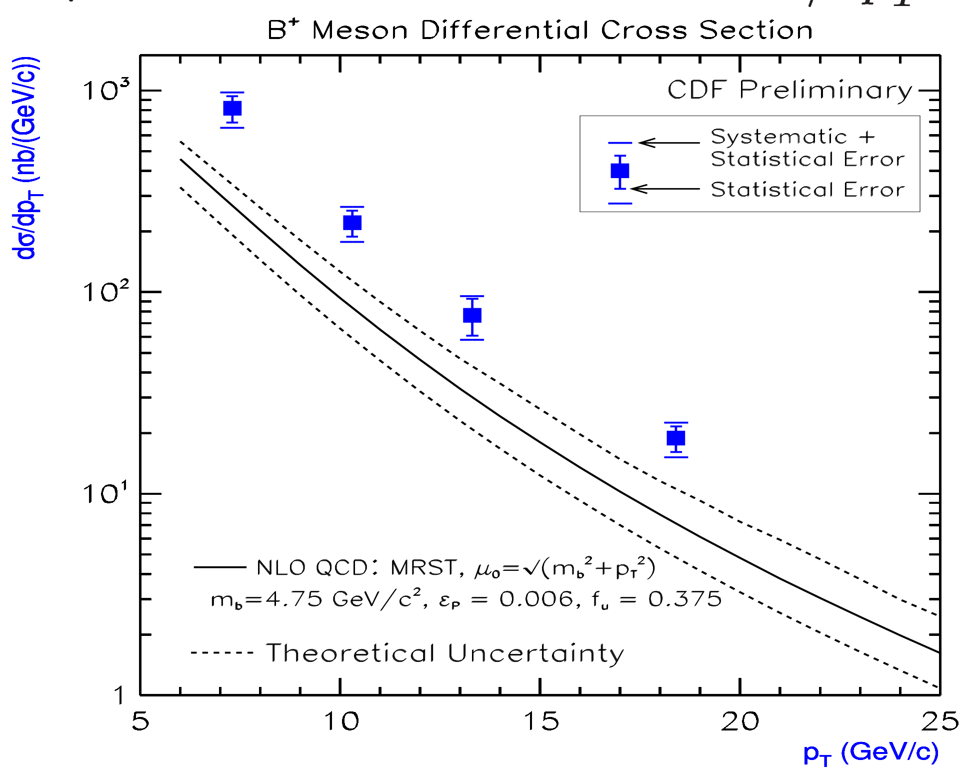
Some data points came from my thesis!
I had to show.

A better measurement

Fully reconstructed $B^+ \to J/\psi\, K^+$ decays



B^+ meson production cross section $d\sigma/dp_T$

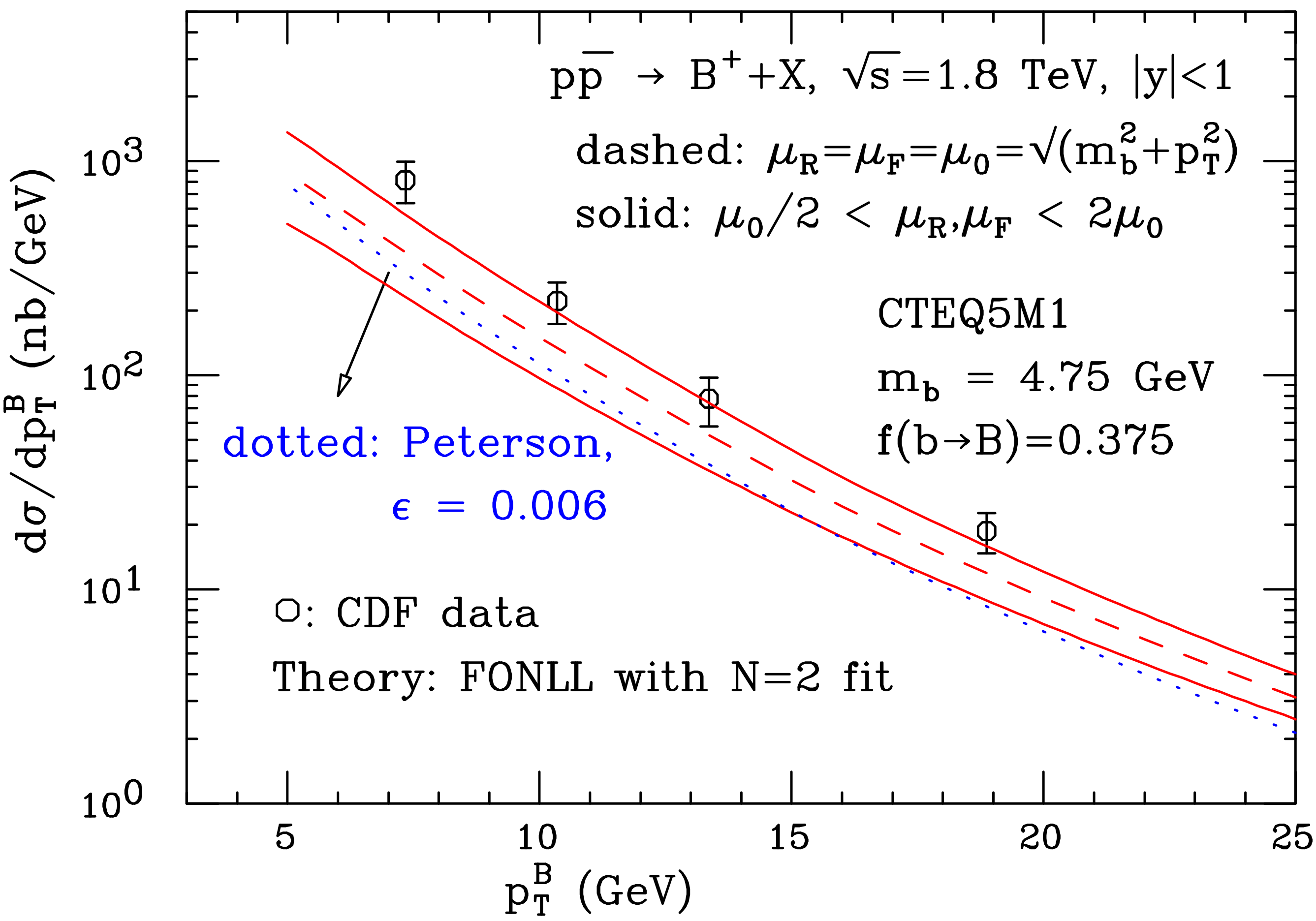


$\sigma(\bar{p}p \to B^+X) = 3.51 \pm 0.42 \pm 0.53$ μb for $p_T > 6$ GeV/c and $|y| < 1.0$. PRD 65, 052005 (2002)

Data / Theory $\sim 2.9 \pm 0.5$

Is it the fragmentation?

Same data points, but with proper treatment of fragmentation function and perturbative calculations.



Data / Theory ~ 1.7.

Cacciari and Nason, PRL 89, 122003 (2002).

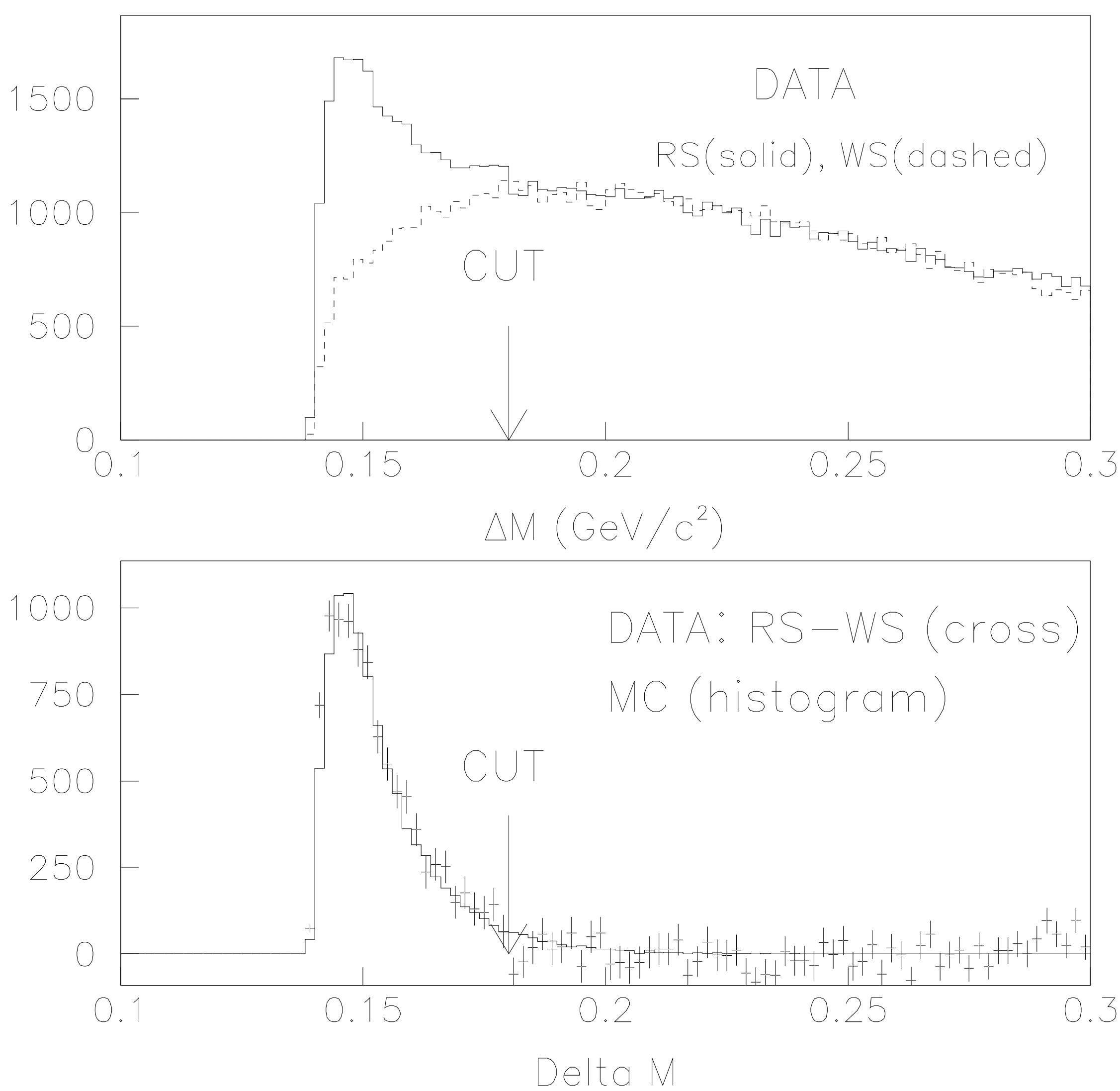
Open Charm Production

Is charm heavy enough?

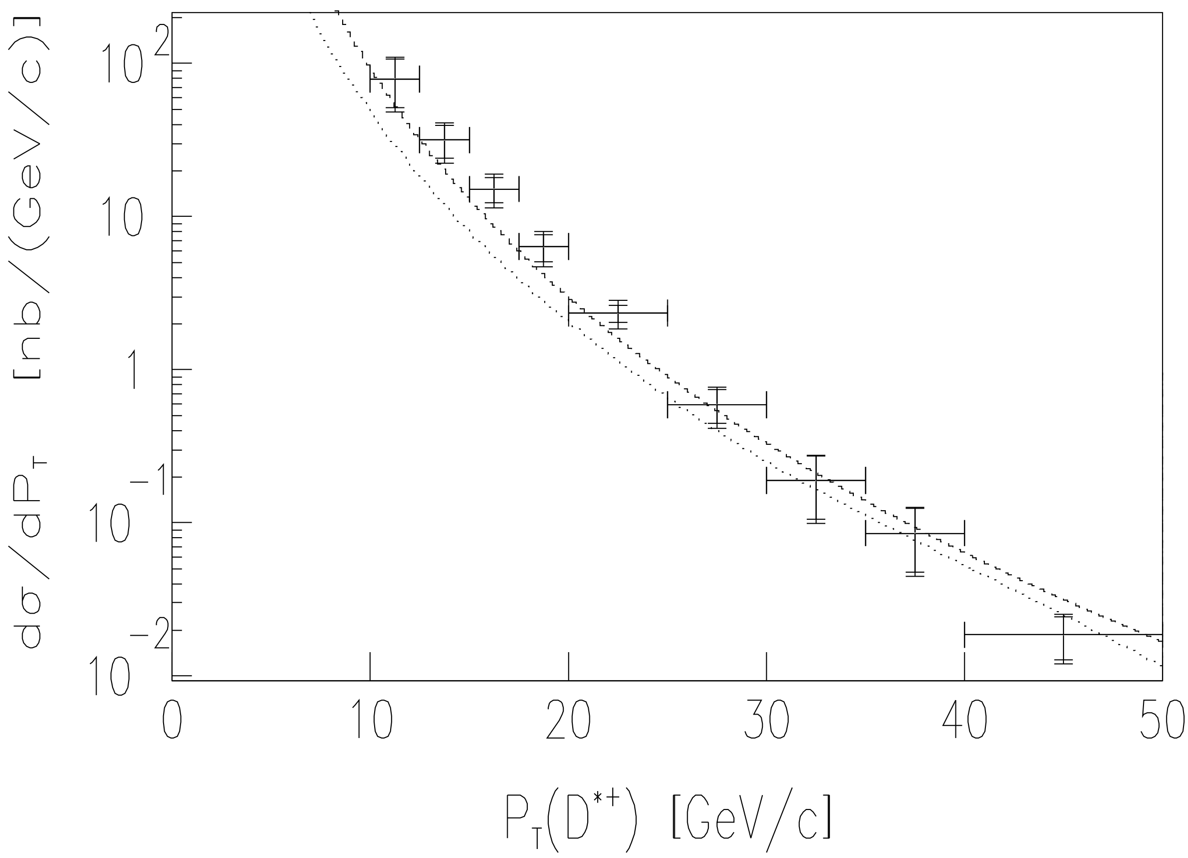
Otherwise similar to bottom.

Measure D^{*+} production.

Start with single μ sample ($p_T > 8$ GeV/c).
Use $D^{*+} \to D^0 \pi^+$, $D^0 \to \mu^+ \nu K^- X$.
Form $\Delta m \equiv m(\mu^+ K^- \pi^+) - m(\mu^+ K^-)$.



D^{*+} production cross section



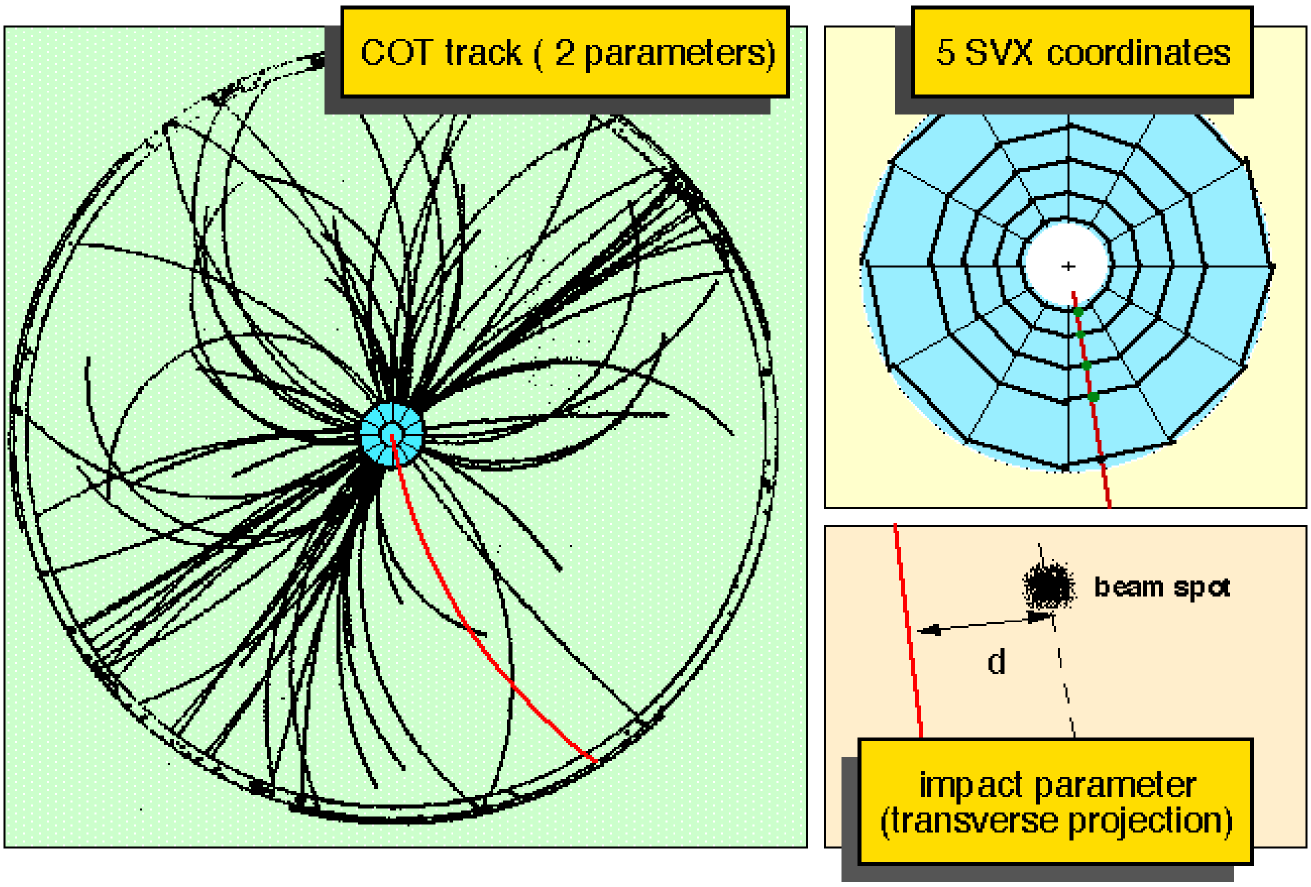
$\sigma(\bar{p}p \to D^{*+}X) = 347 \pm 65 \pm 58$ nb
for $p_T > 10$ GeV/c and $|\eta| < 1.0$.

Theory : 240 nb, M. Cacciari (1998).

Better agreement than in bottom?

Run-II Silicon Vertex Trigger : SVT

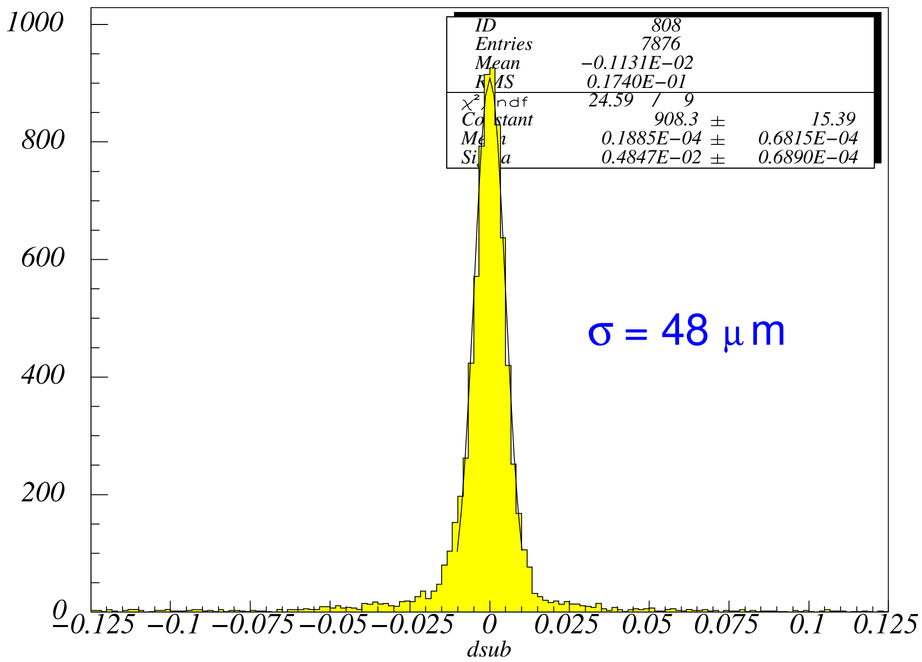
Use silicon information at 2nd level of trigger.



- Find a track in the main tracker COT.
- Extrapolate inwards to Si detector.
- Find Si hits along the road.
- Calculate impact parameter d with respect to the primary vertex (beam spot, $\sim$ 20 μm).

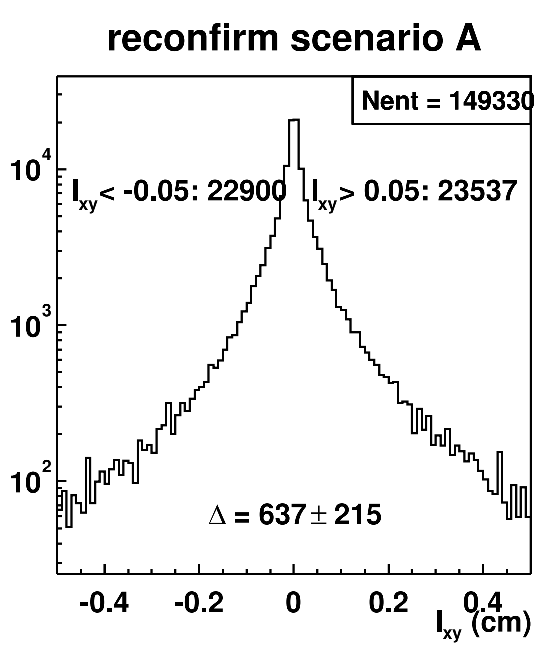
Resolution $\sigma_d \sim$ 50 μm for $p_T > 2$ GeV/c.

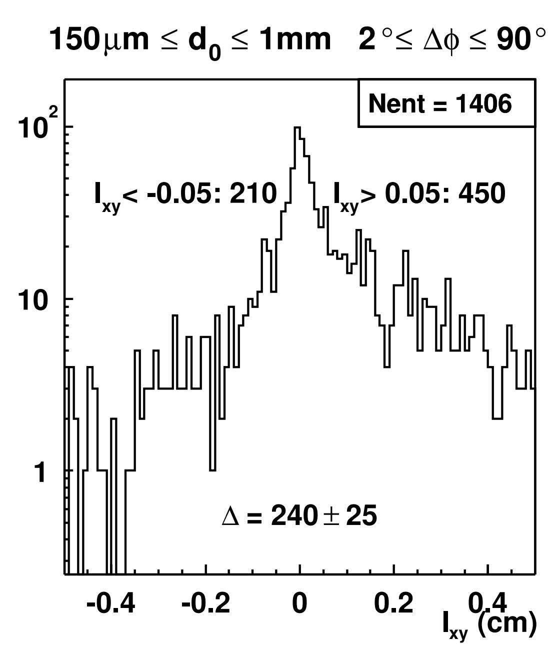
SVT Performance



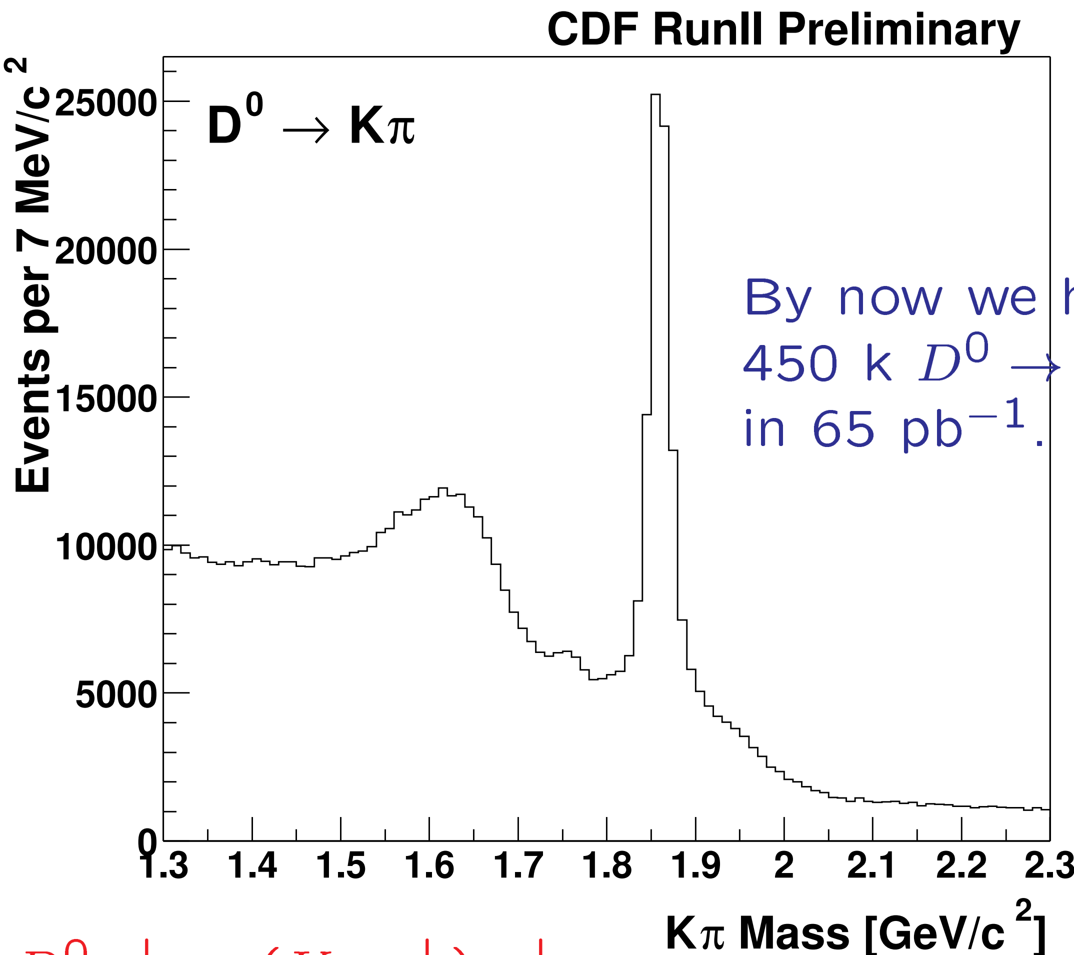
Trigger on tracks ($p_T > 2$ GeV/c) with 100 μm $< |d| <$ 1000 μm.

Calculate decay length L_{xy}, require $L_{xy} > 500$ μm.



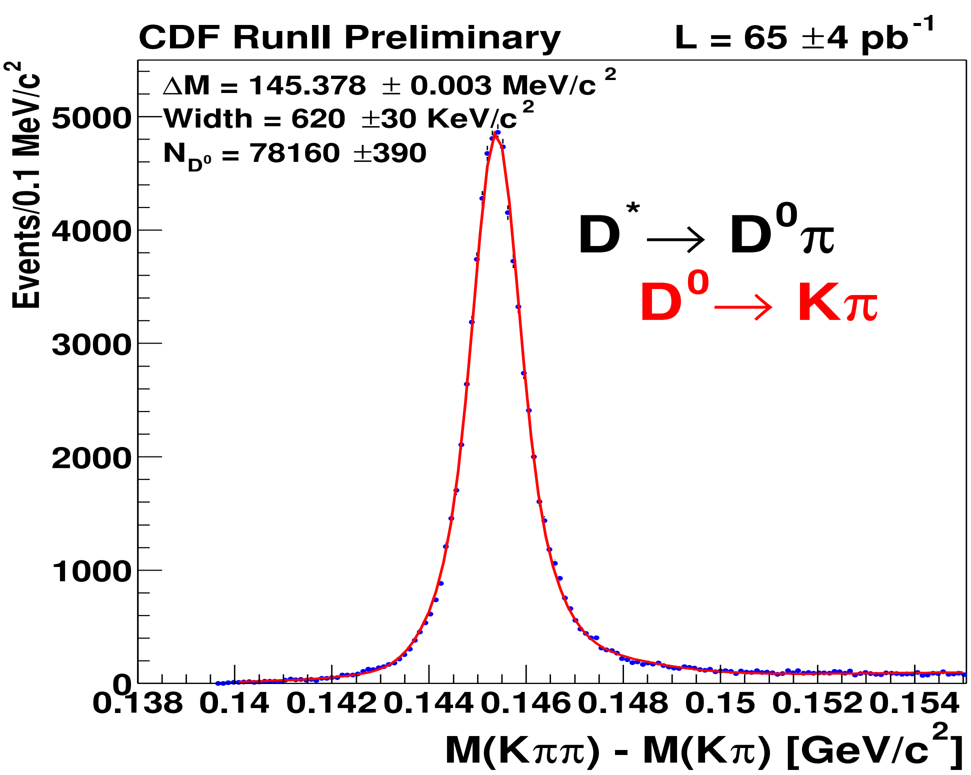


$D^0 \to K^-\pi^+$ from SVT trigger

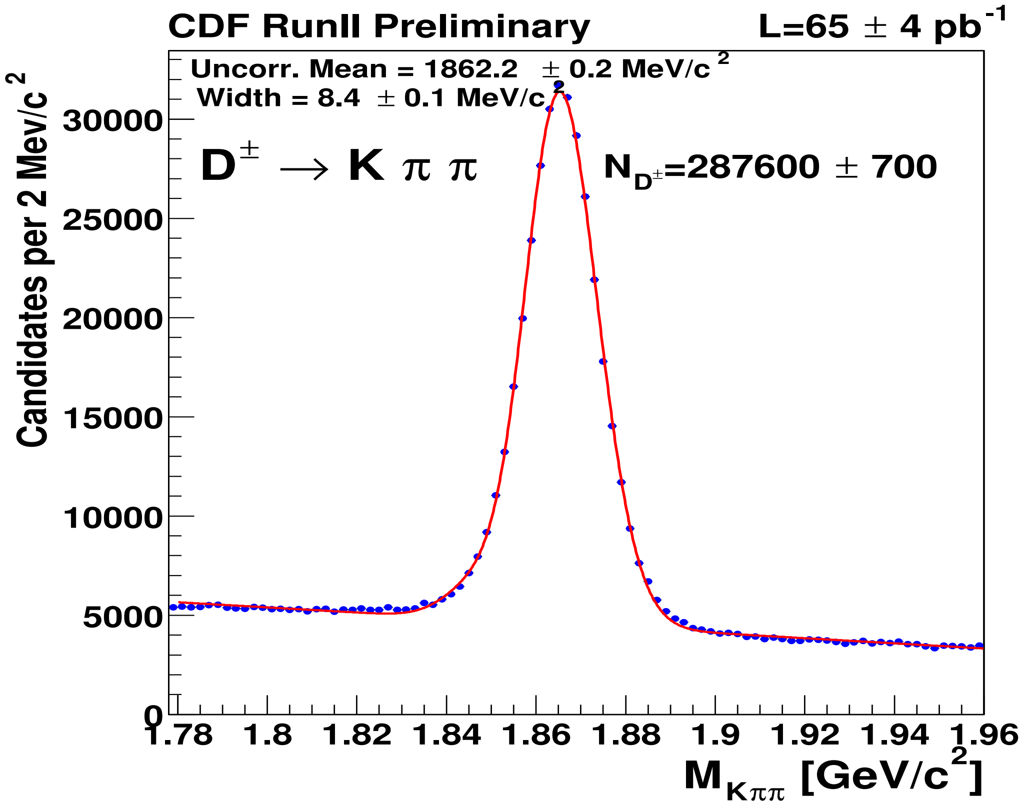


By now we have 450 k $D^0 \to K^-\pi^+$ in 65 pb^{-1}.

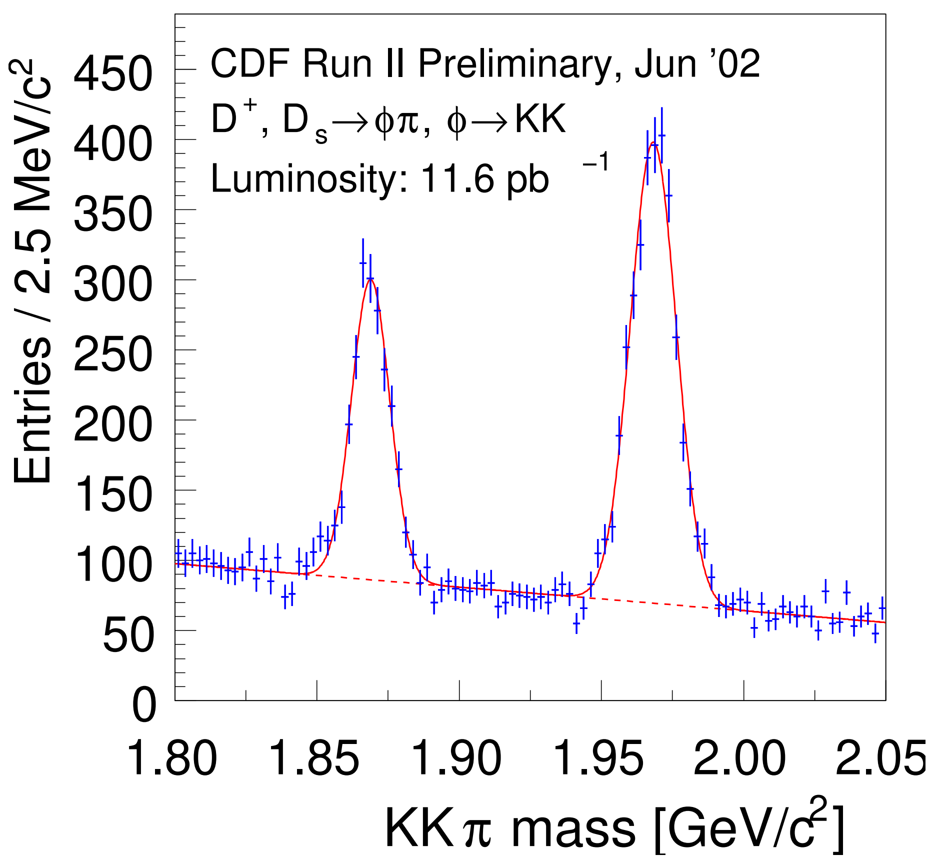
$D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\,\pi^+$



More charm : $D^+ \to K^-\pi^+\pi^+$ (290 k ev)



$D^+,\ D_s^+ \to \phi\pi^+,\ \phi \to K^+K^-$

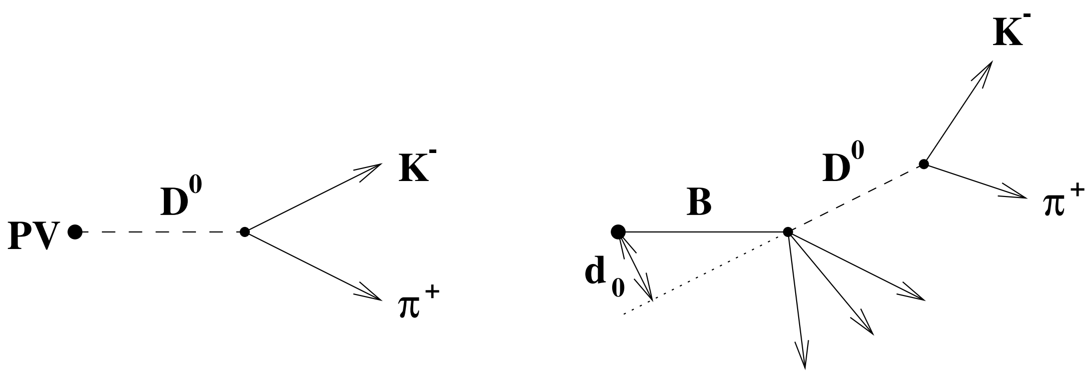


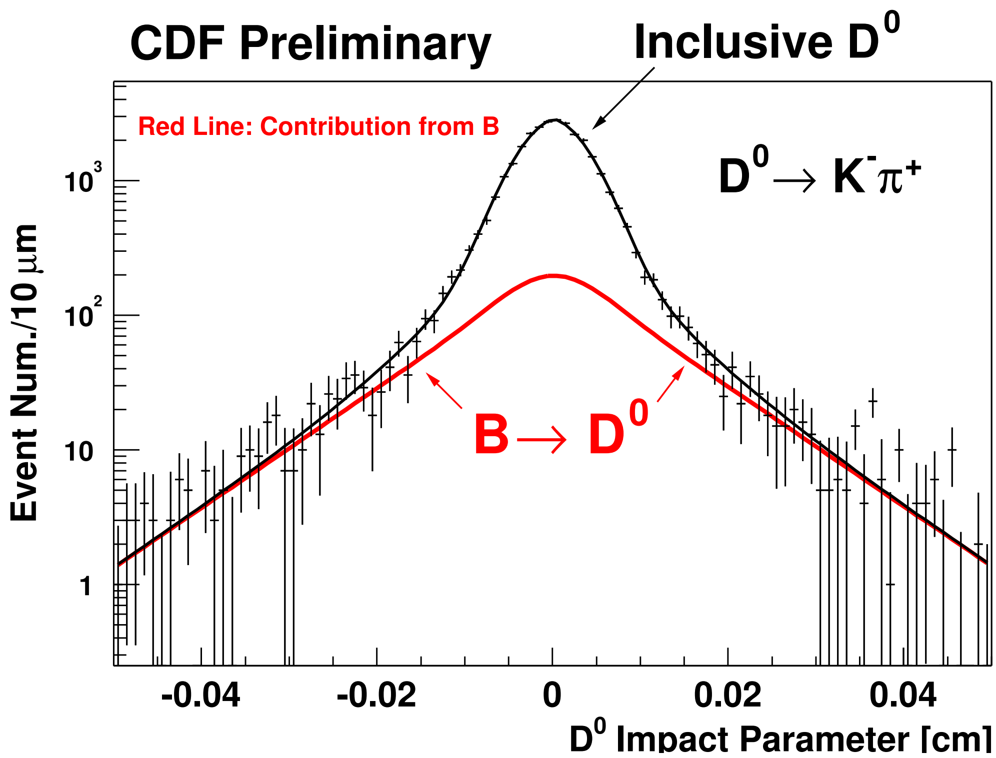
Sources of D mesons :

$\bar{p}p \to c \to D$ (Direct) vs. $\bar{p}p \to b \to \bar{B} \to D$ (Secondary).

Examine impact parameter wrt primary vertex :

Direct Production	**Secondary Production**
D points back to PV	**D has finite impact parameter**





B fraction : (11 – 13)% for D^0, D^+, D^{*+}

23% for D_s^+

Production cross sections soon.

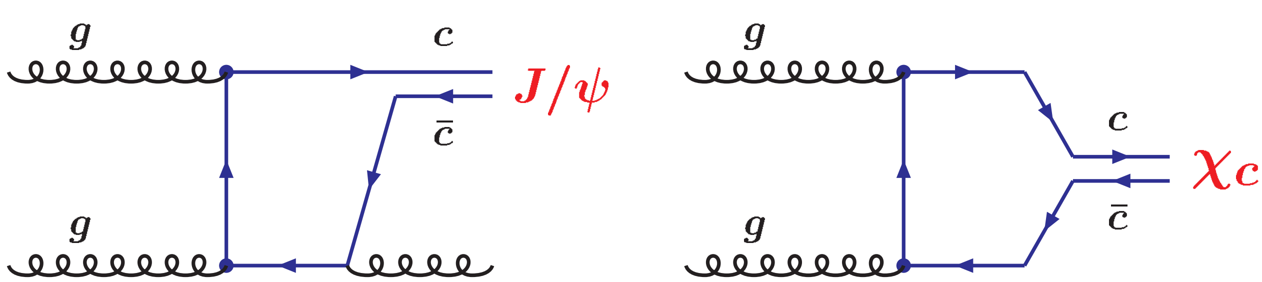
Quarkonium Production

Quarkonia: bound states of heavy quark Q and its anti-quark $\bar{Q}$.

$c\bar{c}$ states :
$L = 0,\ S = 0,\ J^P = 0^-$: η_c
$L = 0,\ S = 1,\ J^P = 1^-$: $J/\psi,\ \psi(2S),\ \ldots$
$L = 1,\ S = 1,\ J^P = 0^+,\ 1^+,\ 2^+$: $\chi_{c0},\ \chi_{c1},\ \chi_{c2}$

Similarly for $b\bar{b}$:
$L = 0,\ S = 0,\ J^P = 0^-$: η_b
$L = 0,\ S = 1,\ J^P = 1^-$: Υ
$L = 1,\ S = 1,\ J^P = 0^+,\ 1^+,\ 2^+$: $\chi_{b0},\ \chi_{b1},\ \chi_{b2}$

$J/\psi \to 3g$, $\chi_{c(0,2)} \to 2g$.



"Old" theory had predicted :
$\sigma(\psi(2S), \text{direct } J/\psi) \ll \sigma(\chi_c)$.

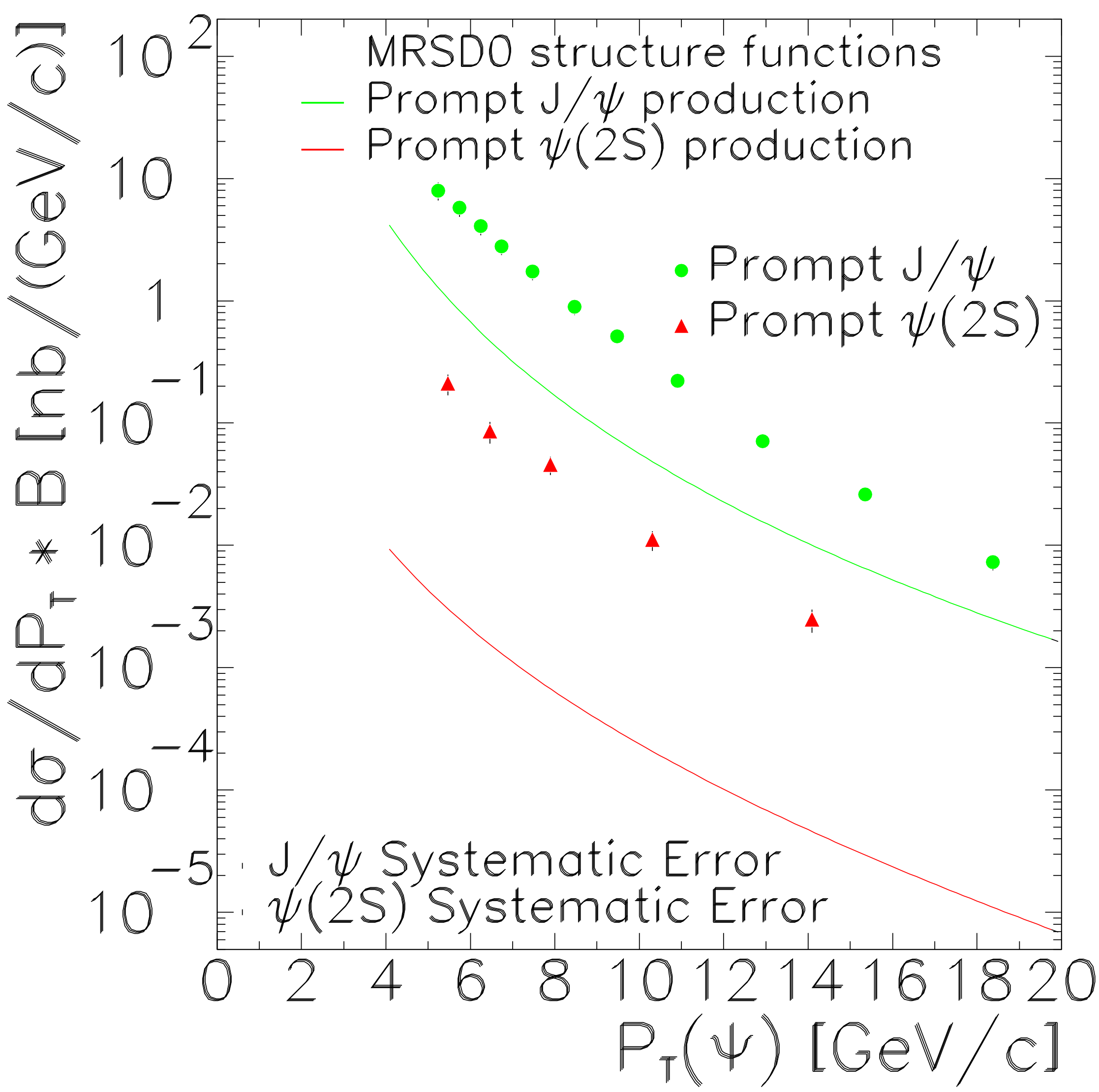
CDF has found $\times 50$ direct J/ψ and $\psi(2S)$ yields above "color singlet model".

J/ψ and $\psi(2S)$ Production

Sources:

- $B \to J/\psi,\ \psi(2S)\, X$ (lifetime, $\sim 20\%$ of all)
- Direct J/ψ, $\psi(2S)$
- Direct $\chi_c \to J/\psi\, \gamma$ (not for $\psi(2S)$)

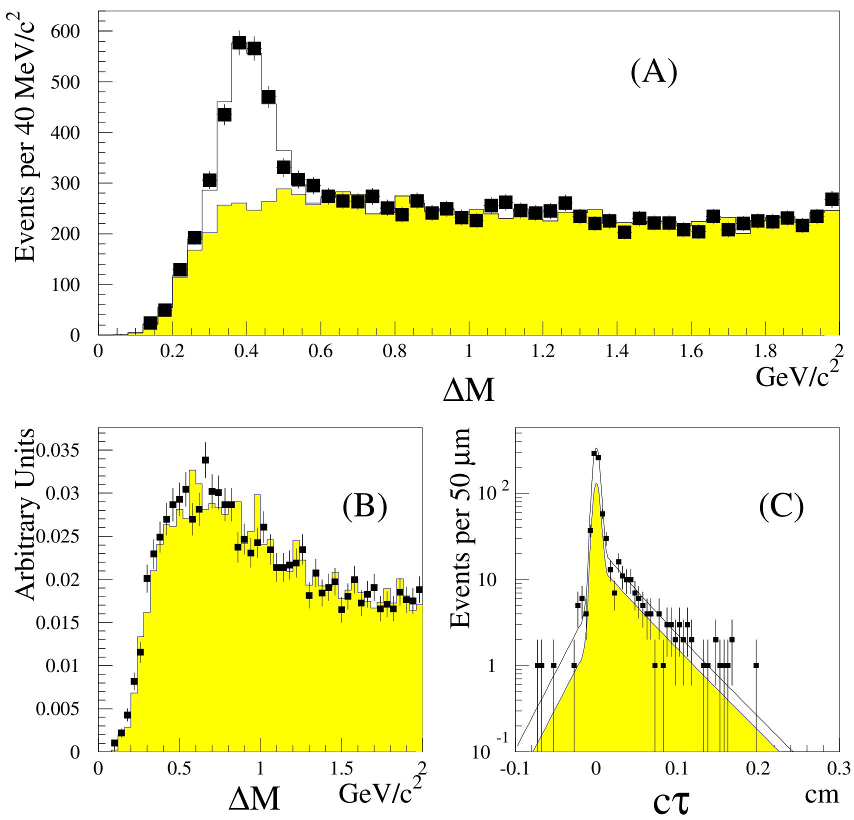
The latter two have zero lifetime : "prompt"



PRL 79, 572 (1997).

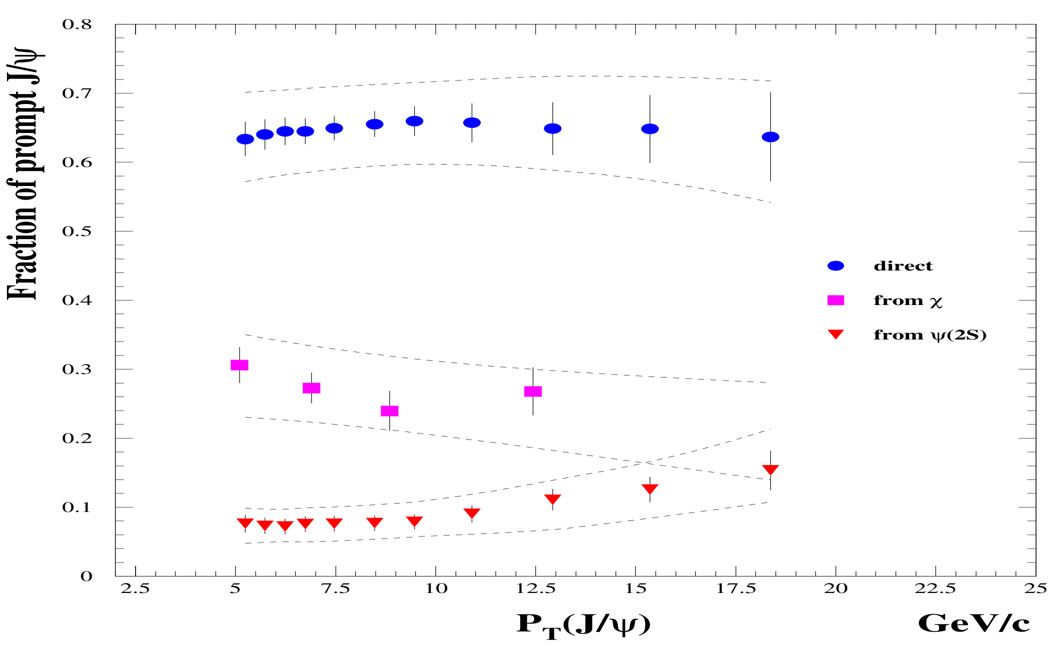
J/ψ from χ_c : $\chi_c \to J/\psi\,\gamma$

Identify γ with CEM/CES, combine it with J/ψ, calculate $\Delta M \equiv M(J/\psi\,\gamma) - M(J/\psi)$.



Use lifetime to subtract $B \to \chi_c X$.

Then extract sources of prompt J/ψ's.



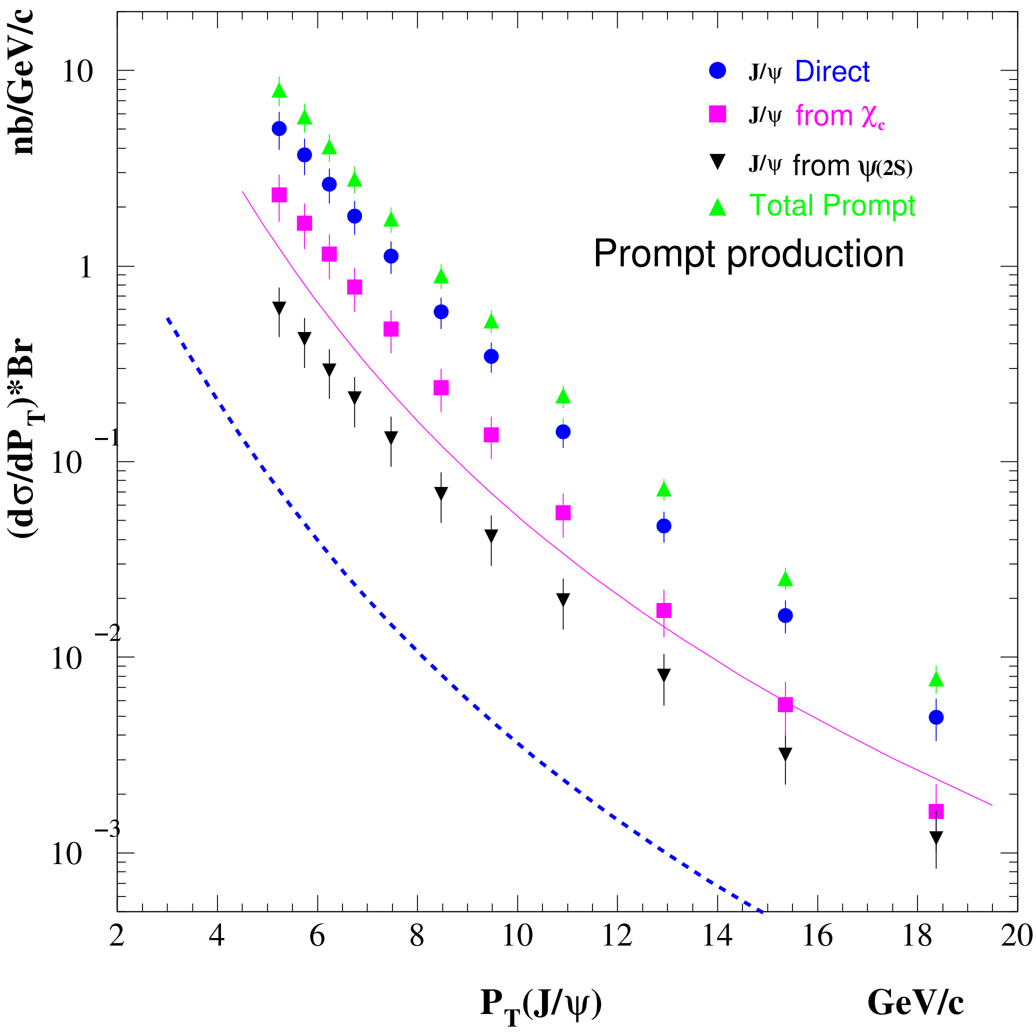
direct

from χ_c

from $\psi(2S)$

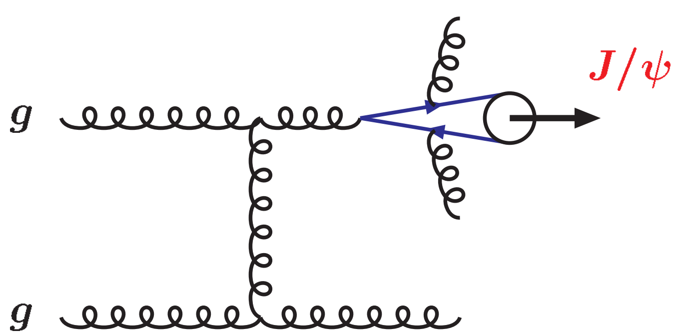
Prompt J/ψ Production Breakdown

PRL 79, 578 (1997)



Direct production: both J/ψ and $\psi(2S)$ higher than prediction by a factor of ~ 50.

Other mechanisms must exist.
Gluon fragmentation? Color octet?

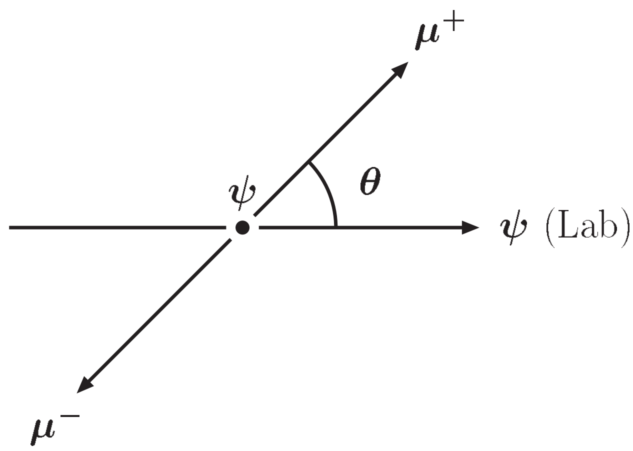


J/ψ and $\psi(2S)$ Polarization

Gluon fragmentation into ψ :

Gluons are massless ($p_T \gg m_\psi$) and thus transversely polarized.
ψ should inherit the gluon polarization.

Helicity angle θ :



$$\frac{dN}{d\cos\theta} = 1 + \alpha \cos^2\theta$$

$\alpha = +1 \Rightarrow$ 100% transverse.
$\alpha = -1 \Rightarrow$ 100% longitudinal.

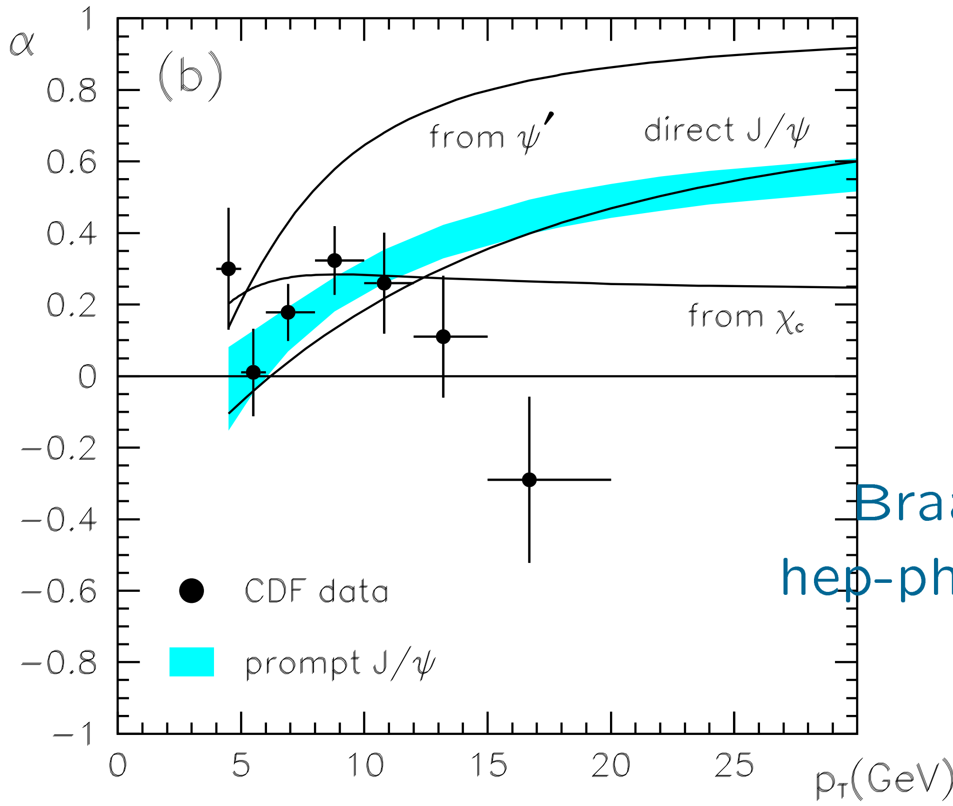
Prediction for direct production :

Beneke and Krämer	$\alpha = +0.77 \pm 0.08$
Leibovich	$\alpha = +0.90 \pm 0.04$

at $p_T = 20$ GeV/c.

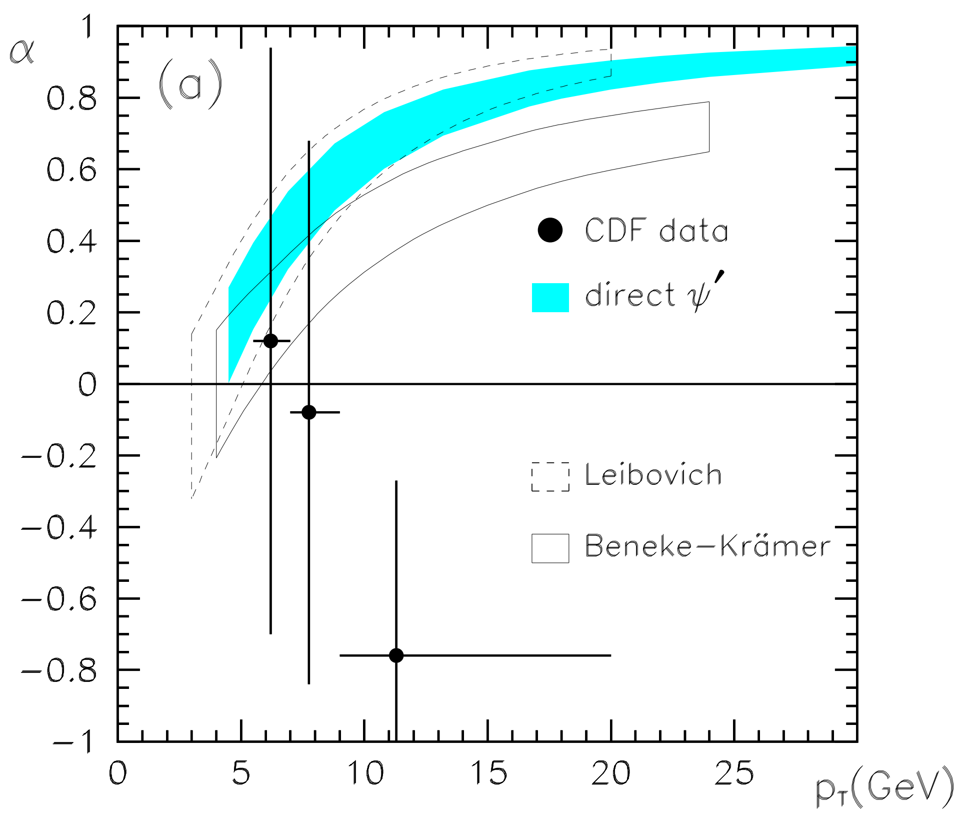
J/ψ and $\psi(2S)$ Polarization

J/ψ



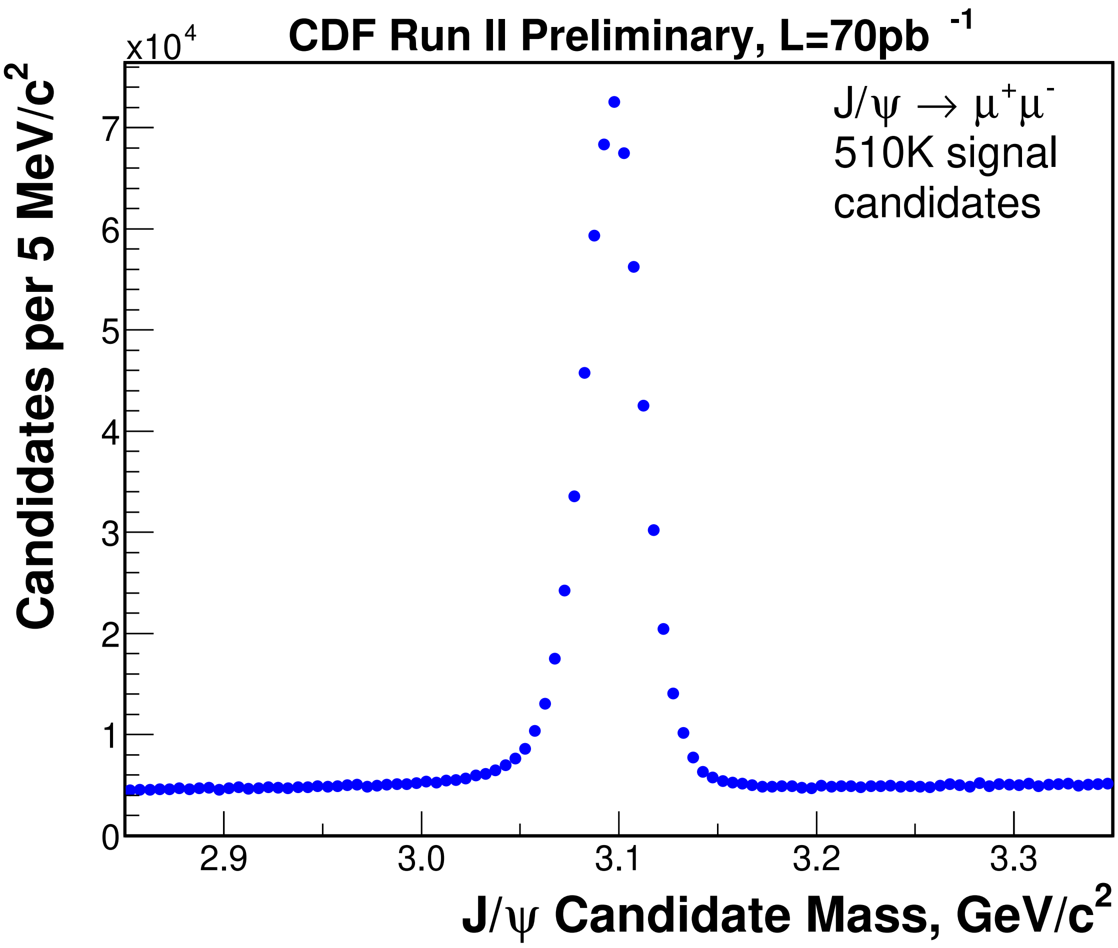
Theory:
Braaten *et al.*
hep-ph/9911436

$\psi(2S)$

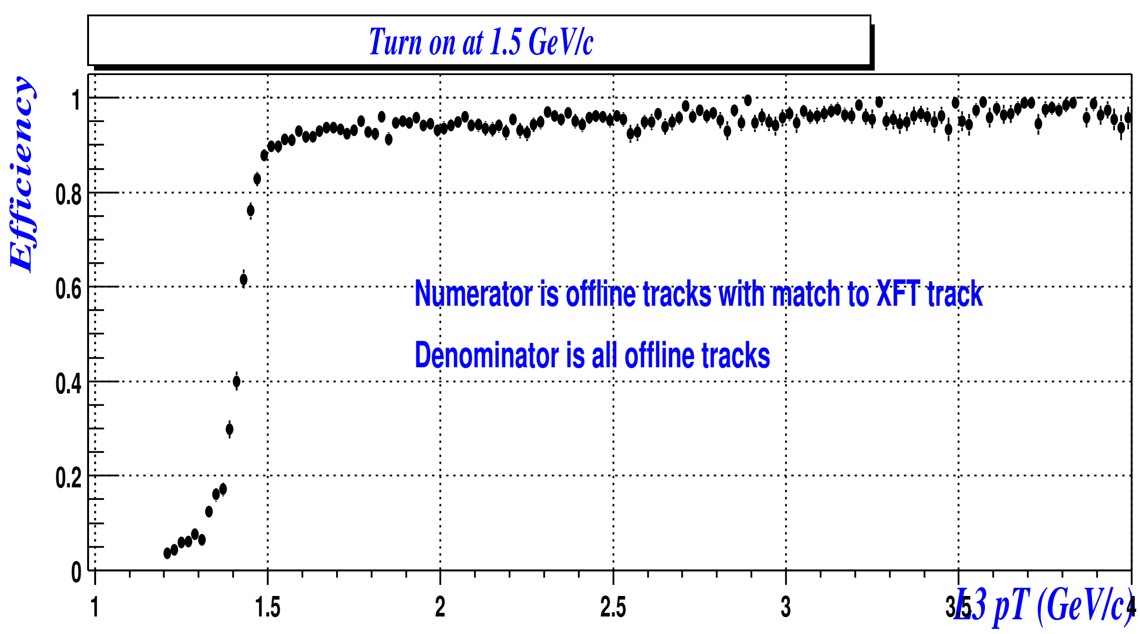


Phys. Rev. Lett. 85, 2886 (2000).

Run-II Di-muon Data

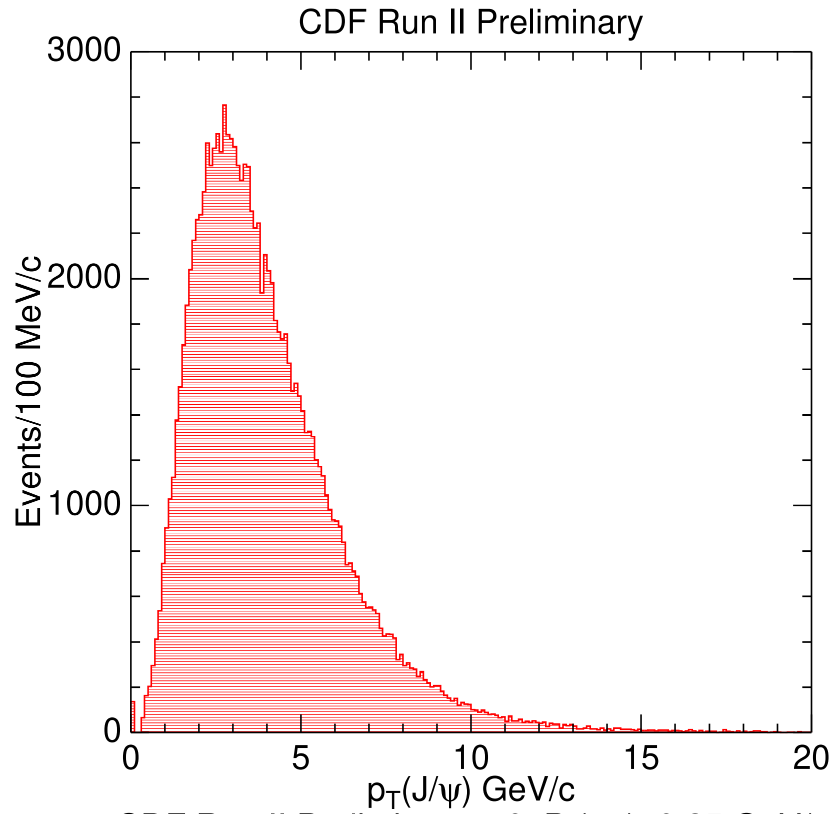


p_T threshold : 2 GeV/c $\Rightarrow$ 1.5 GeV/c.
Yield $\sim 2 \times$ Run-I.

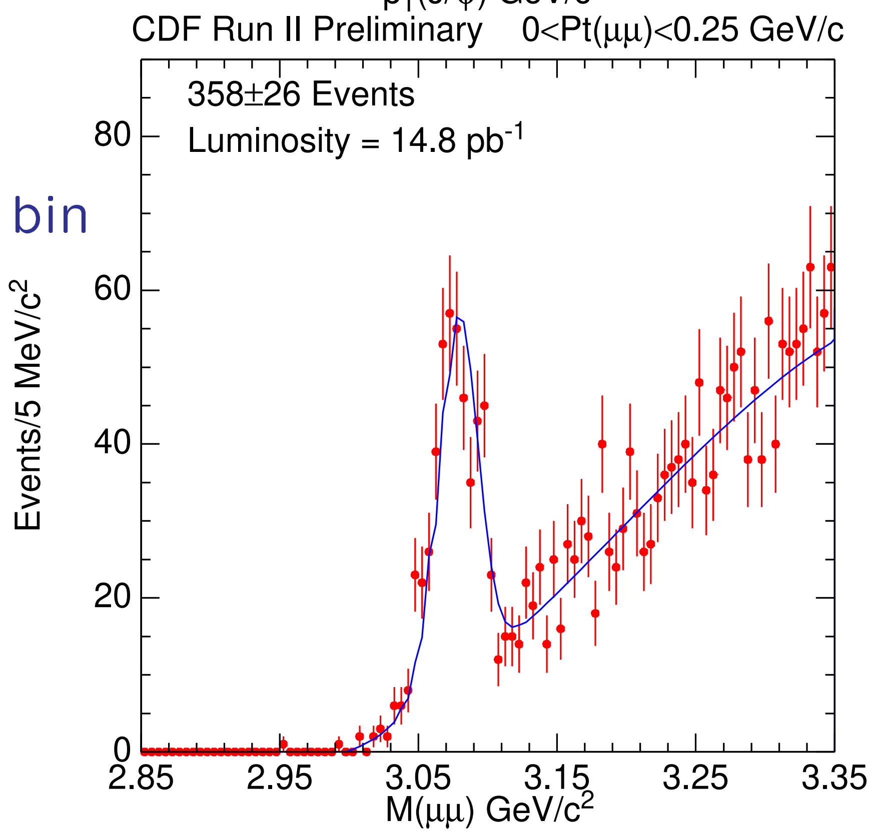


Lower $p_T(\mu)$ threshold gives reasonable acceptance down to $p_T(J/\psi) \simeq 0$:

$p_T(J/\psi)$



Signal for $p_T < 0.25$ GeV$/c$ bin

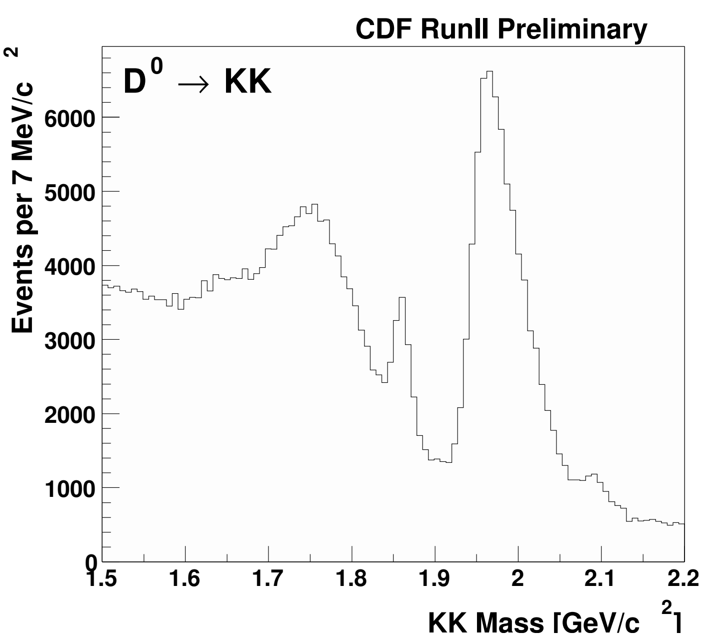


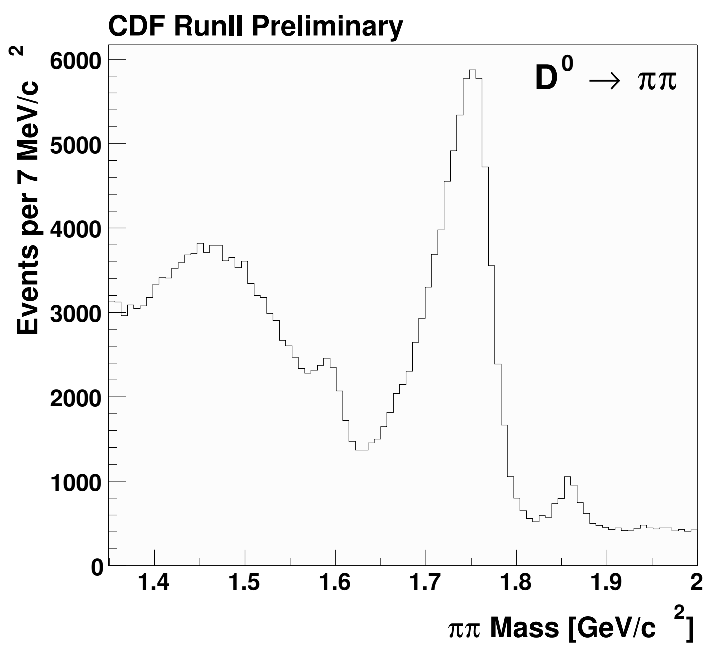
Cross section coming soon. Also allows a better measurement of polarization.

Charm decays

Cabibbo-suppressed D^0 meson decays :

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





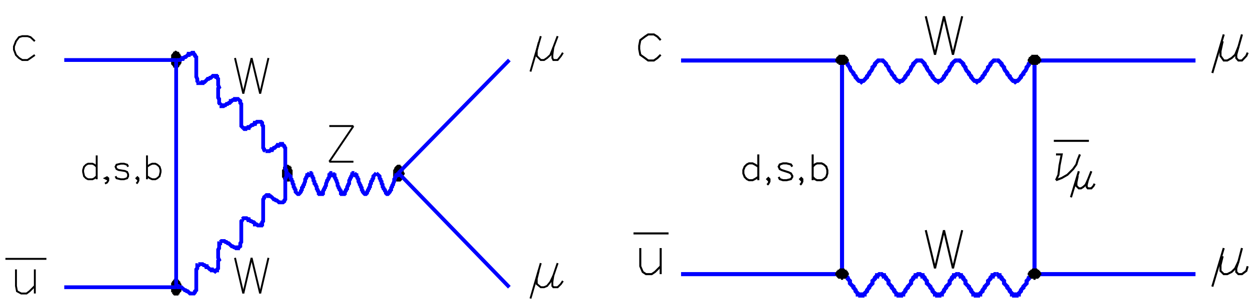
$$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} = (11.17 \pm 0.48 \pm 0.98)\,\%$$

$$\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = (3.37 \pm 0.20 \pm 0.16)\,\%$$

Future : look for $\Delta\Gamma$ and/or Δm in D^0-$\bar{D}^0$ system, CP violation.

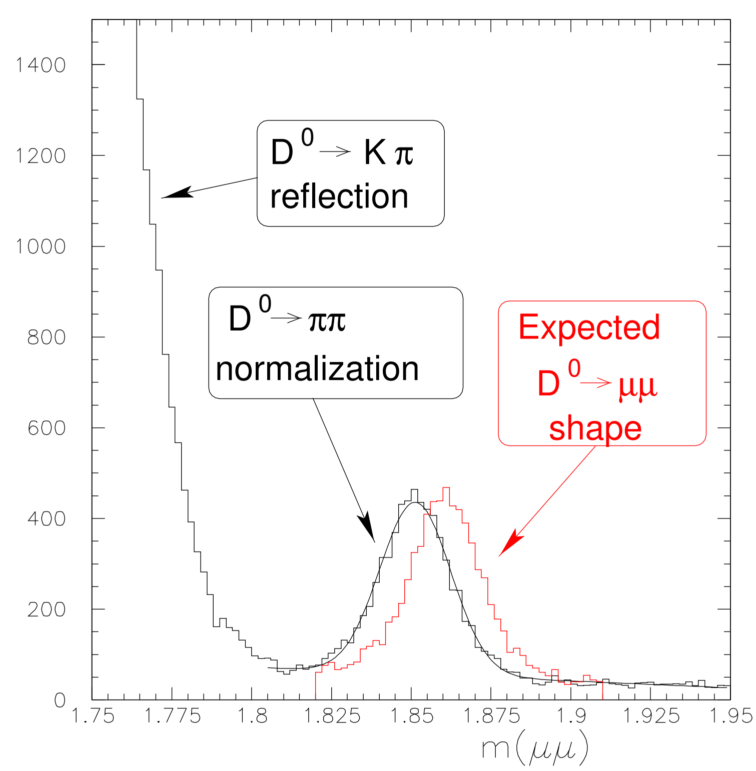
Search for $D^0 \to \mu^+\mu^-$

FCNC decay.
Proceed via loop and box diagrams in SM

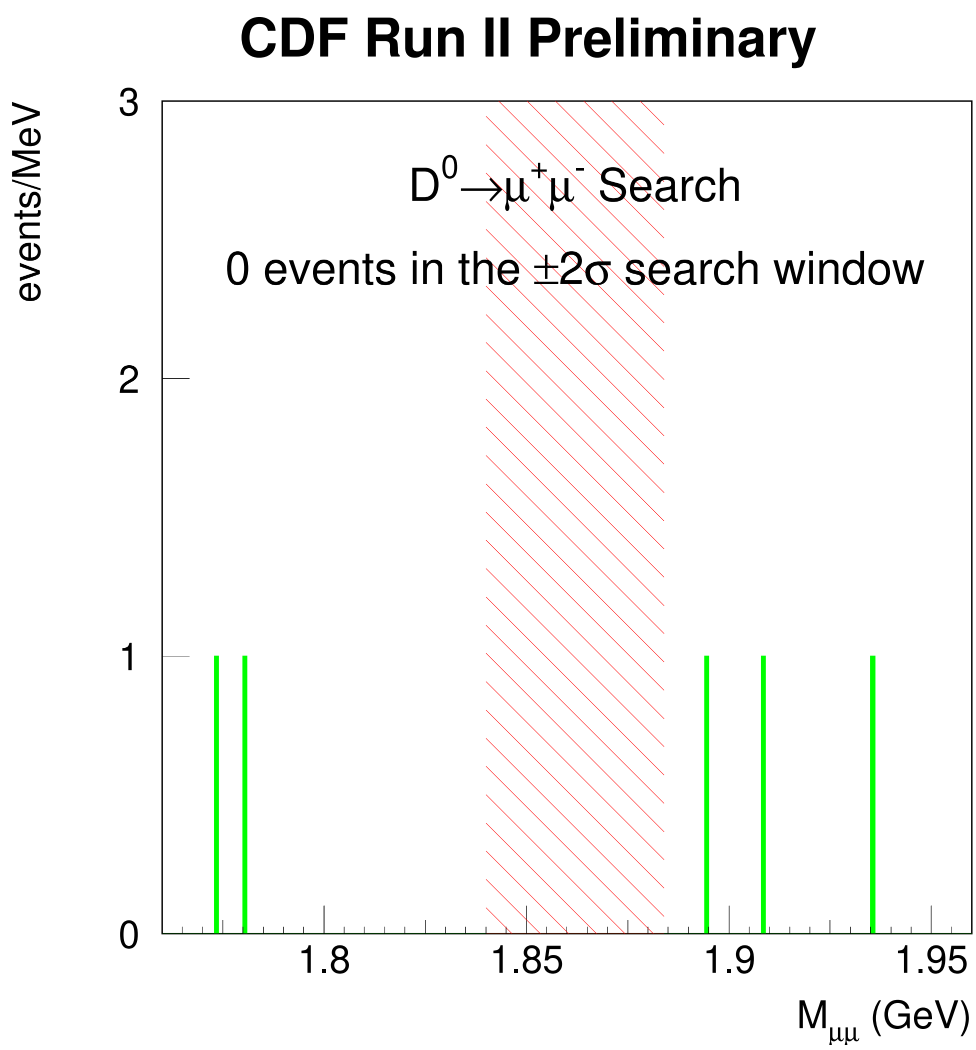


Also helicity suppressed $\Rightarrow$ $\mathcal{B} \sim 10^{-13}$.
So a good place to look for new physics effects.

Use $D^0 \to \pi^+\pi^-$ as normalization.
Can also feed into the signal region.



$D^0 \to \mu^+\mu^-$ result



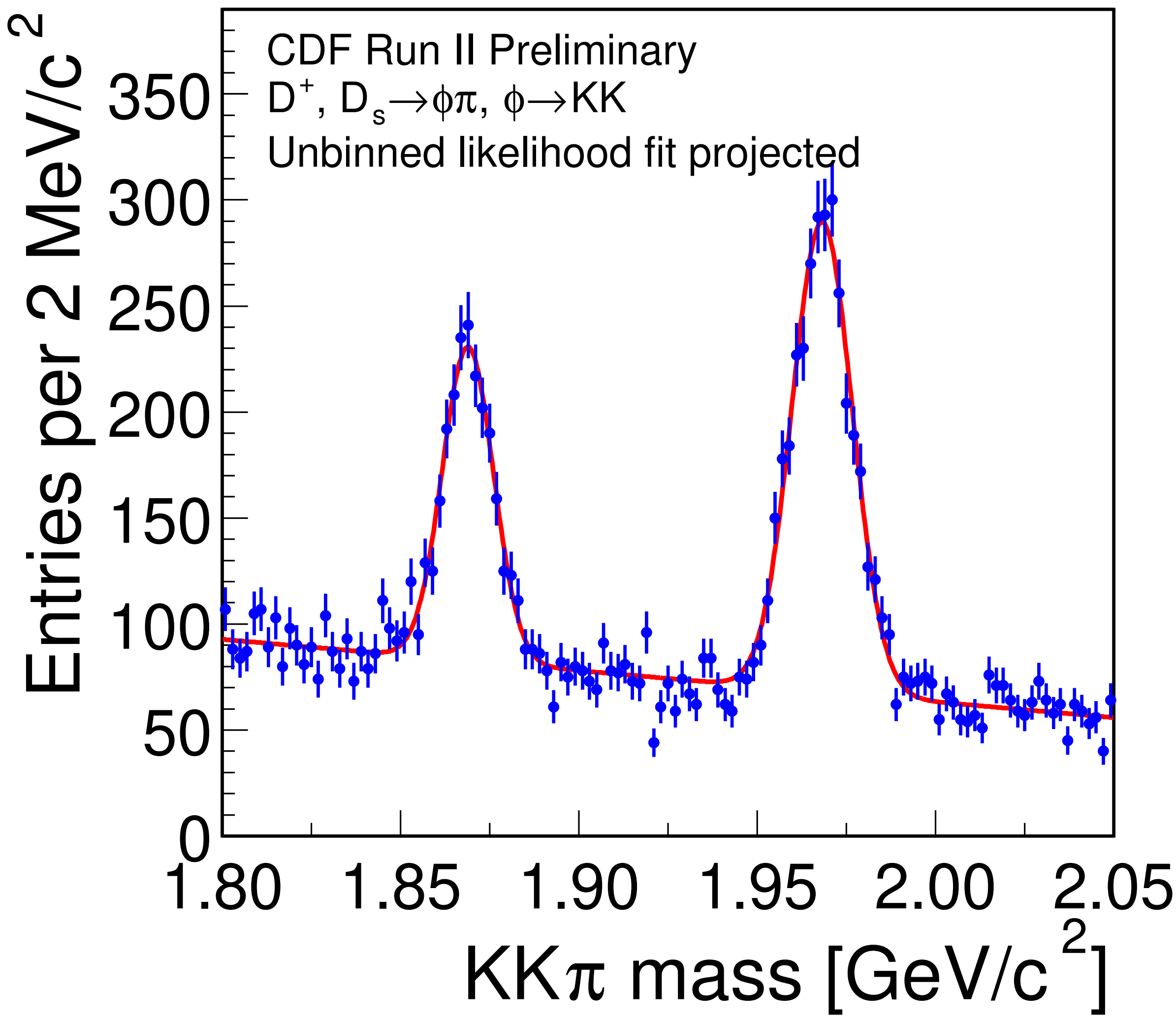
0 candidate observed, 1.7 ± 0.7 BG expected.

$\Rightarrow \mathcal{B}(D^0 \to \mu^+\mu^-) < 2.4 \times 10^{-6}$ (90% CL)

Better than PDG 2002 : $\mathcal{B} < 4.1 \times 10^{-6}$,
but still long way to go.

D_s^+ and D^+ meson masses

Use a common decay mode $\to \phi\pi^+$, $\phi \to K^+K^-$.



$$m(D_s^+) - m(D^+) = 99.41 \pm 0.38 \pm 0.21 \text{ MeV}/c^2$$

PDG 2002 : 99.2 ± 0.5 MeV/c^2

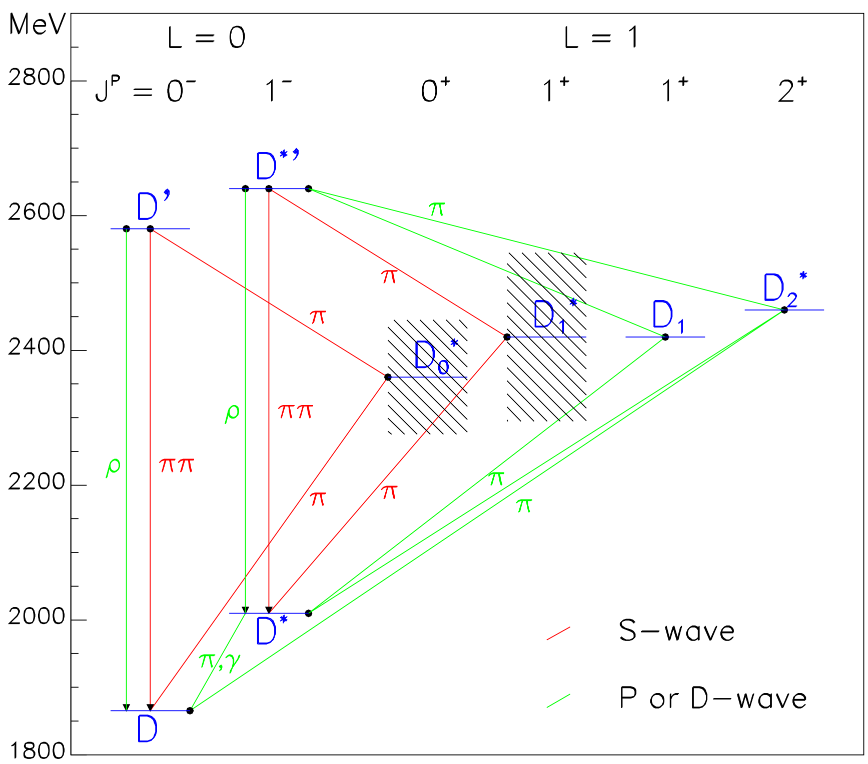
First Run-II paper from CDF, submitted to PRD.

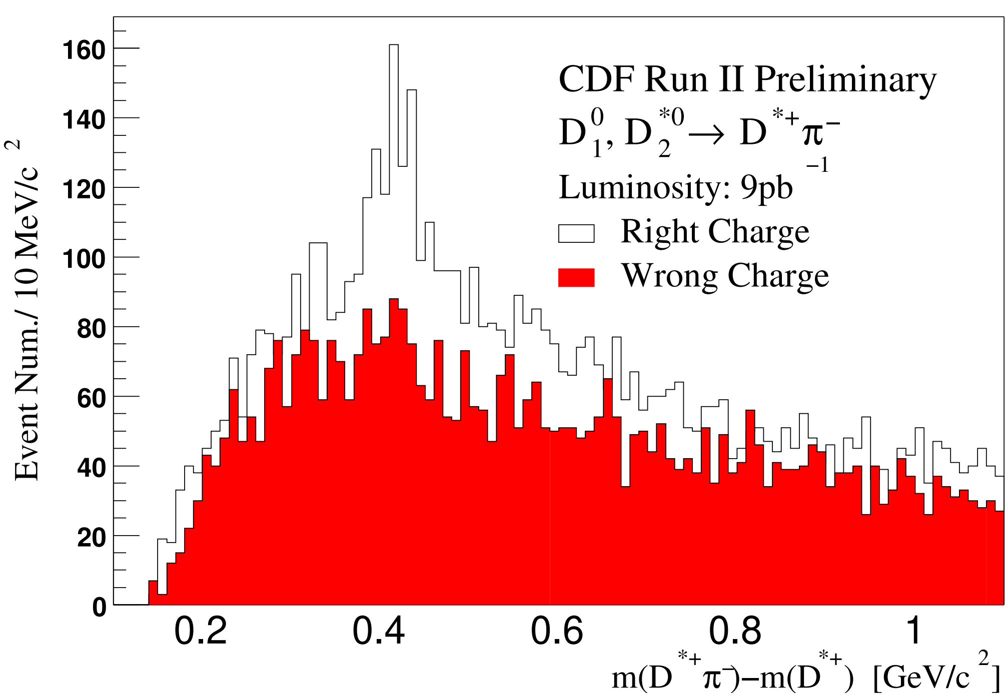
D^{**} mesons

$L = 0$: $J = S = 0,\ 1 \ \Rightarrow\ D,\ D^*$

$L = 1$ and $S = 0,\ 1 \ \Rightarrow J^P = 1^+,\ 0^+,\ 1^+,\ 2^+$

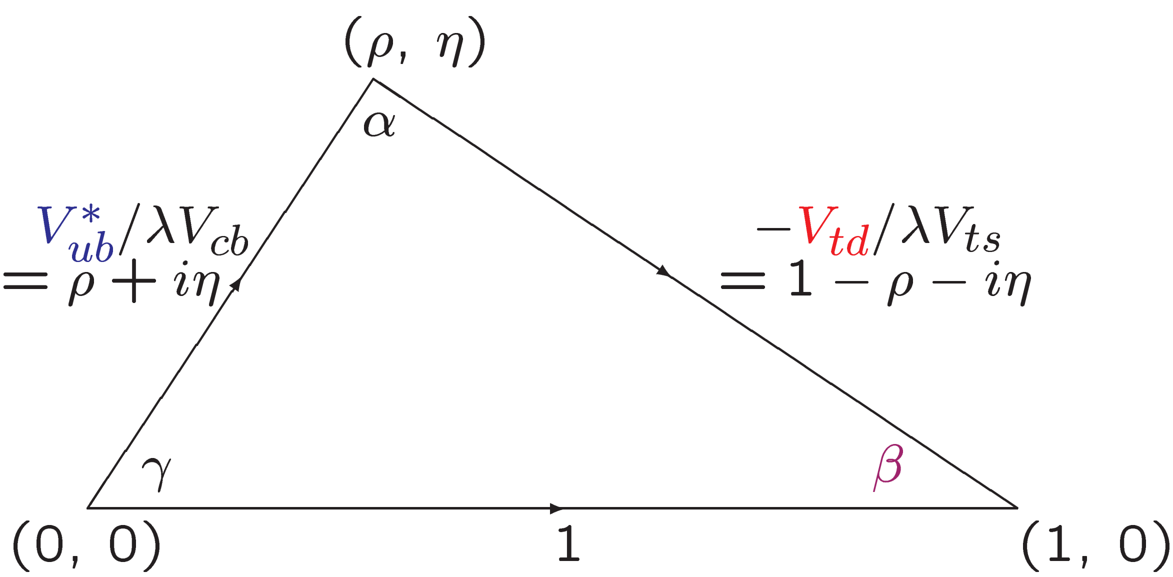
Spectroscopy of D mesons





B phys : does unitarity triangle close?

It may or may not, but Belle/BaBar alone cannot tell you the answer.
You need a CDF measurement, or two.



- $|V_{cb}|$ from $b \to c\ell\nu$, $|V_{ub}|$ from $b \to u\ell\nu$.
- $|V_{td}|$ from Δm_d, but large QCD uncertainties.
- Use ratio to partially cancel the uncertainties:

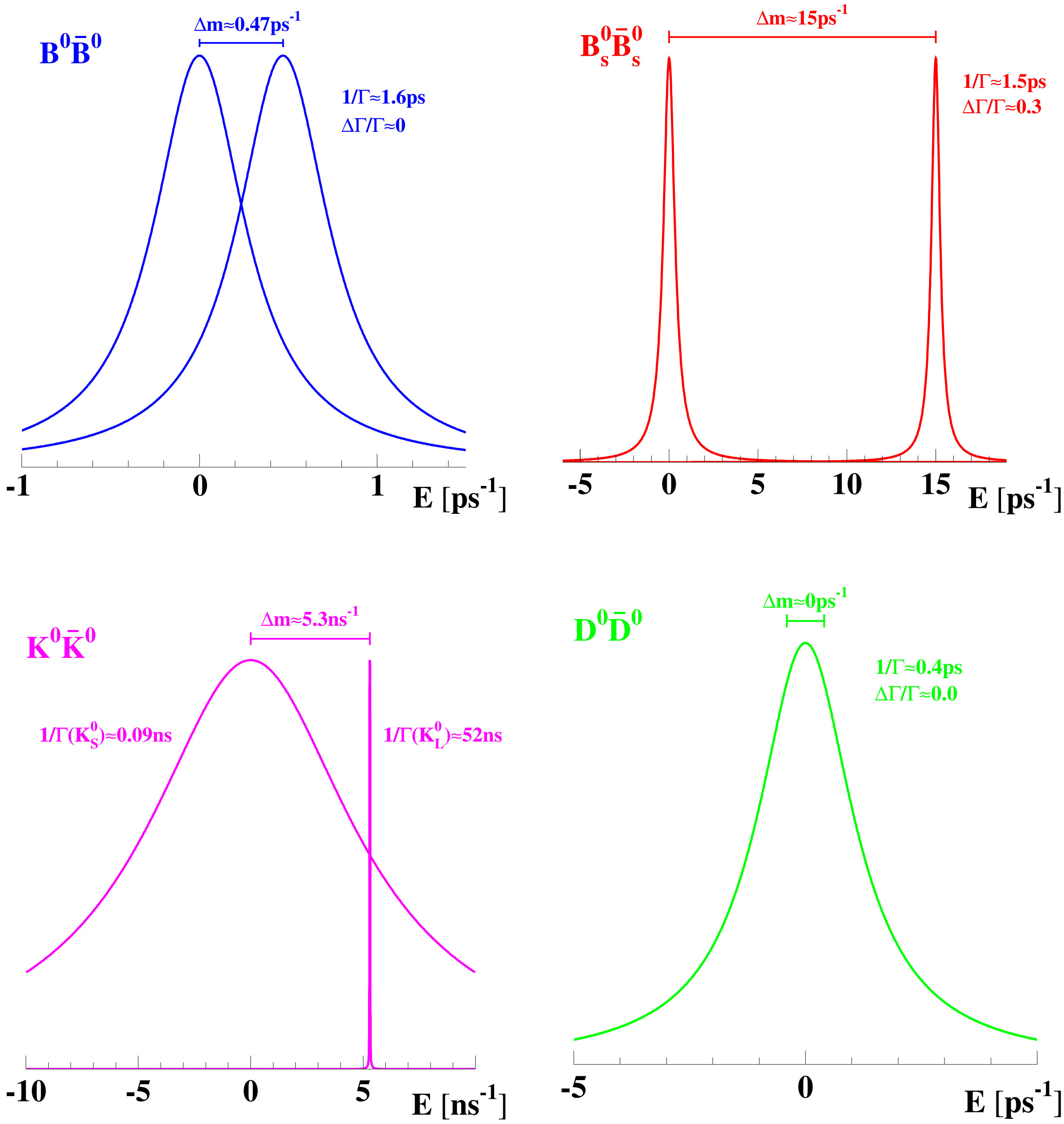
$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{M_{B_s}}{M_{B_d}} \xi^2 \quad (\xi = 1.17 \pm 0.06, \text{Aoki 1999})$$

- Present limit on Δm_s (95% C.L.)

$$\frac{\Delta m_s}{\Delta m_d} > \frac{15.0}{0.487} \implies \frac{V_{td}}{\lambda V_{ts}} < 0.97 \pm 0.06.$$

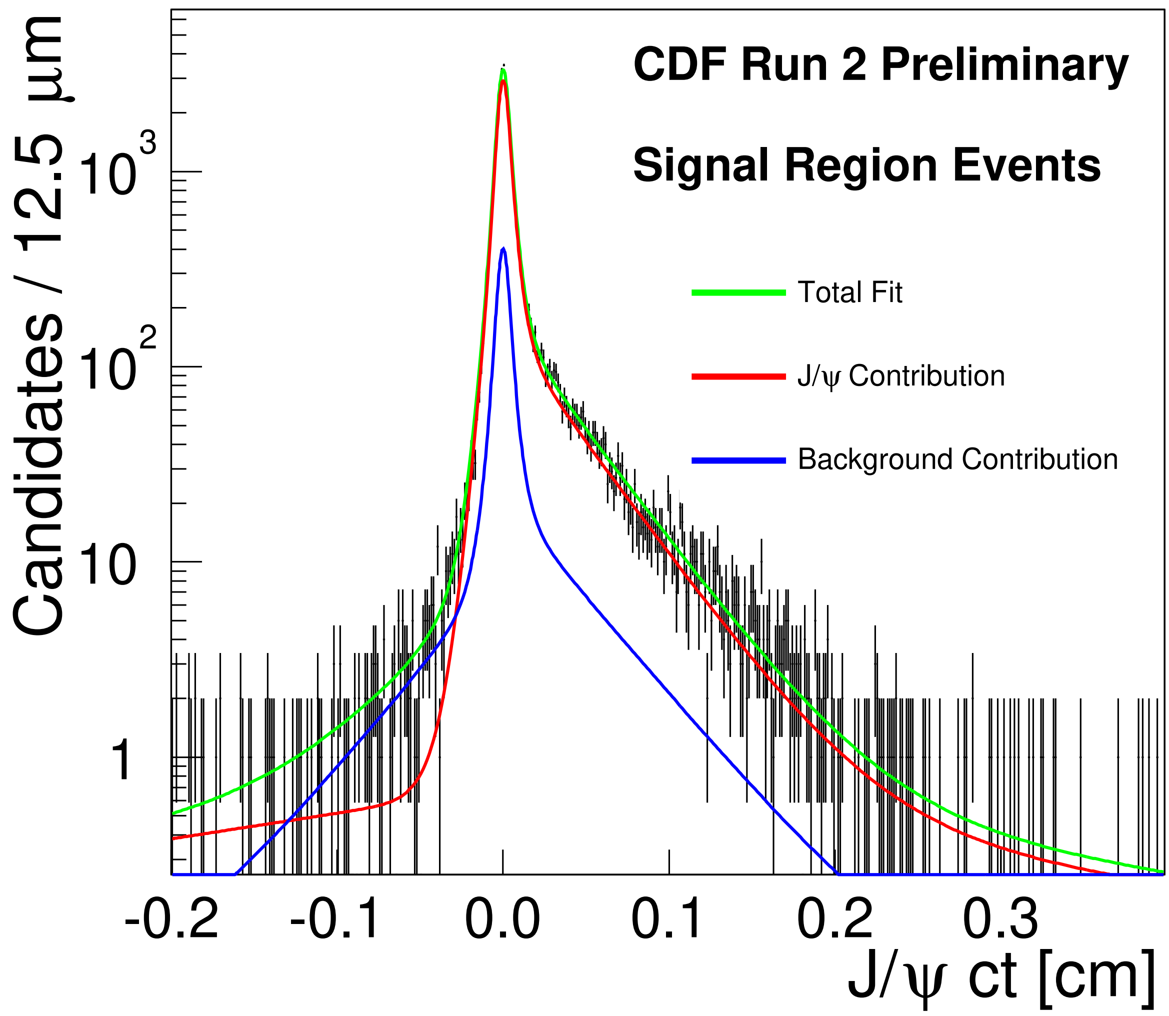
- Angle β from $B^0/\bar{B}^0 \to J/\psi K_S^0$.

Neutral meson masses and widths



Run-II $J/\psi \to \mu^+\mu^-$

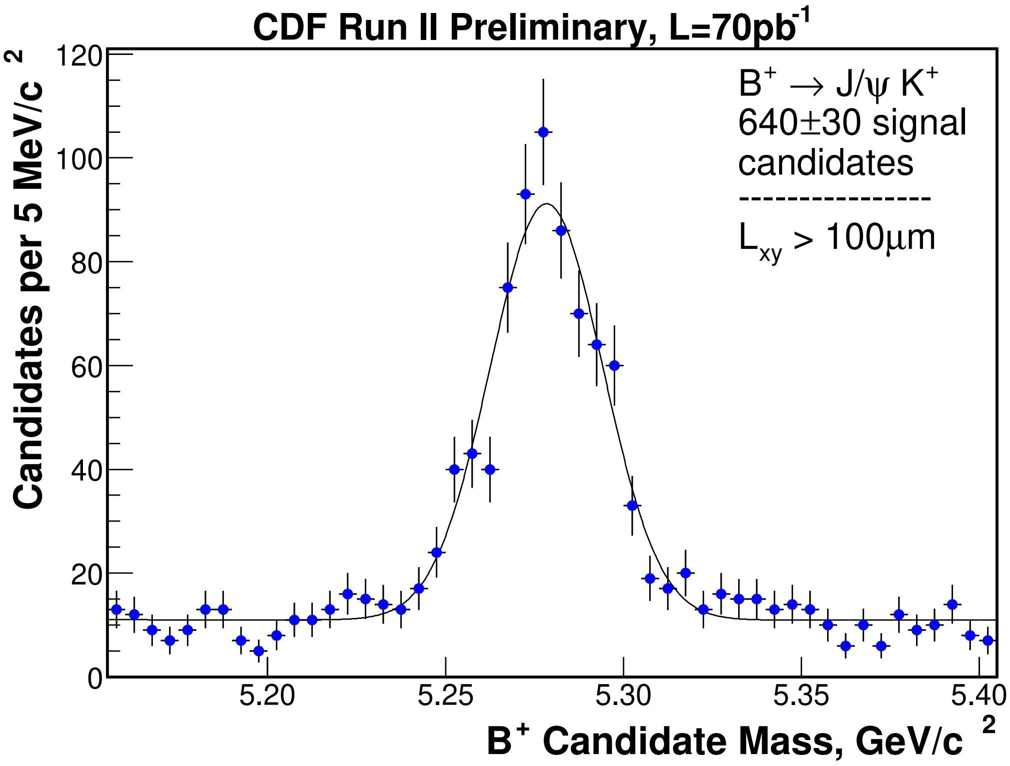
B fraction $\sim$ 15%.



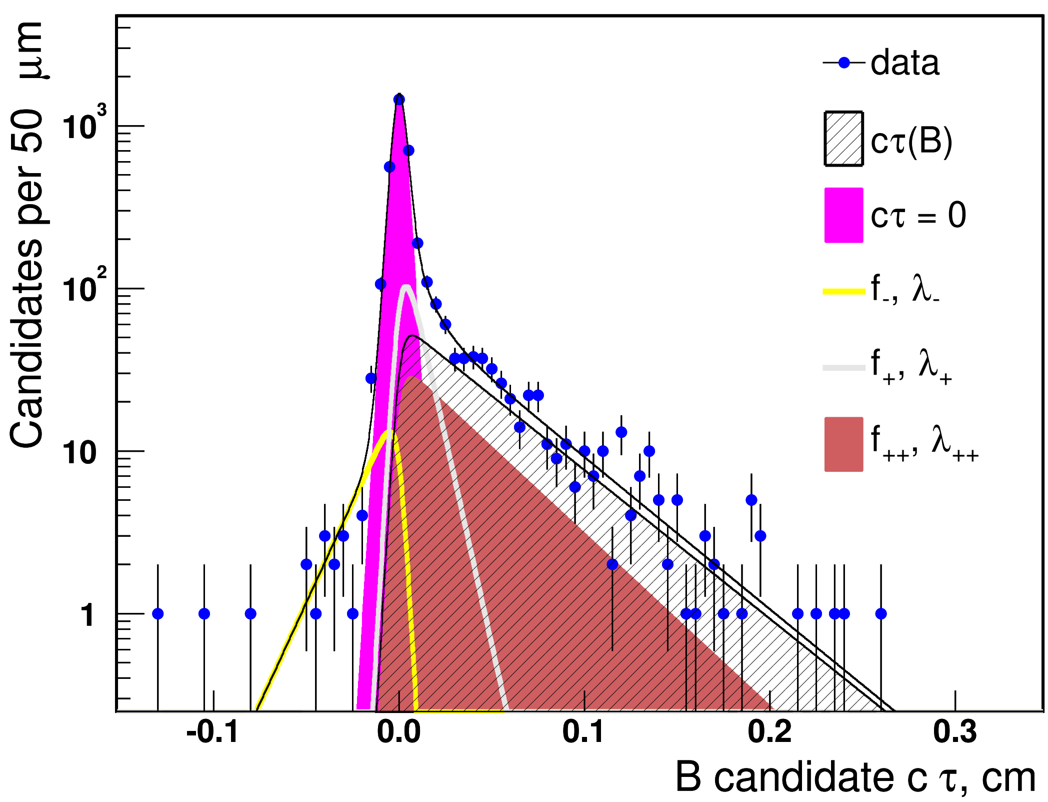
Average B-hadron Lifetime

$\Rightarrow \tau(B) = 1.526 \pm 0.034 \pm 0.035$ ps.

Run-II $B^+ \to J/\psi\, K^+$

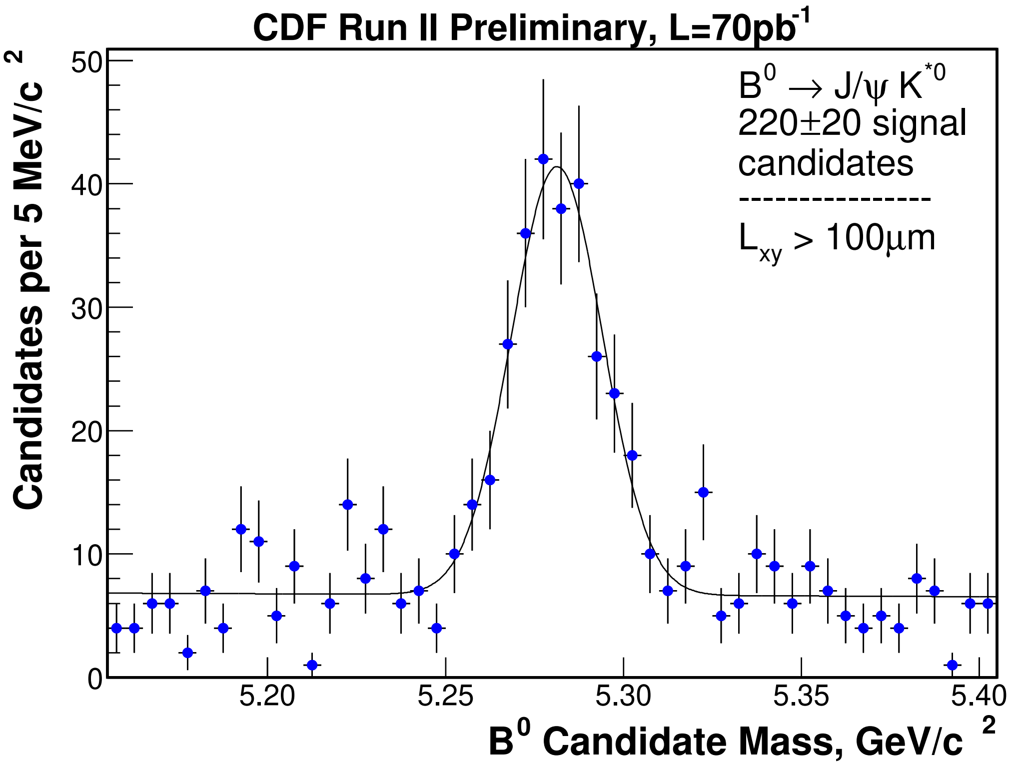


$\Rightarrow m(B_s^0) = 5280.6 \pm 1.7 \pm 1.1\ \text{MeV}/c^2.$



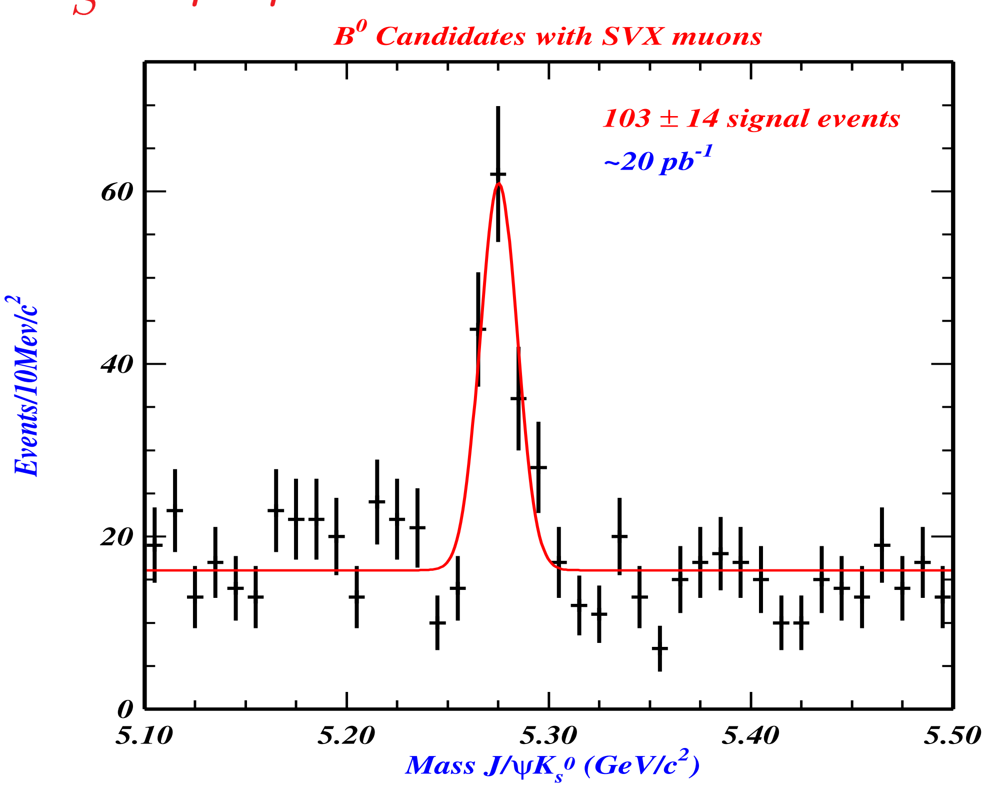
$\Rightarrow \tau(B^+) = 1.57 \pm 0.07 \pm 0.02\ \text{ps}.$

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



$\Rightarrow m(B^0) = 5279.8 \pm 1.9 \pm 1.4$ MeV$/c^2$.

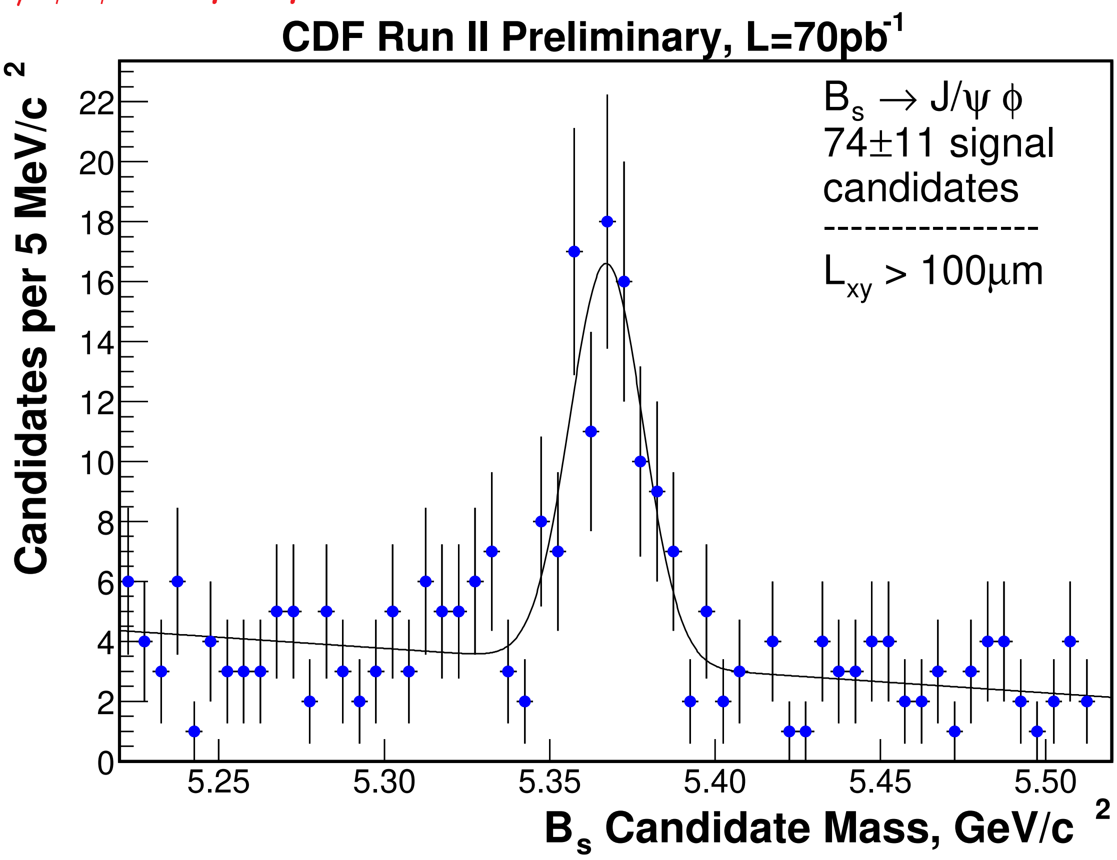
$B^0 \to J/\psi\, K^0_S \to \mu^+\mu^-\, \pi^+\pi^-$



Mode for $\sin 2\beta$. Yield $\sim 2.5 \times$ Run-I.

B_s^0 meson

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



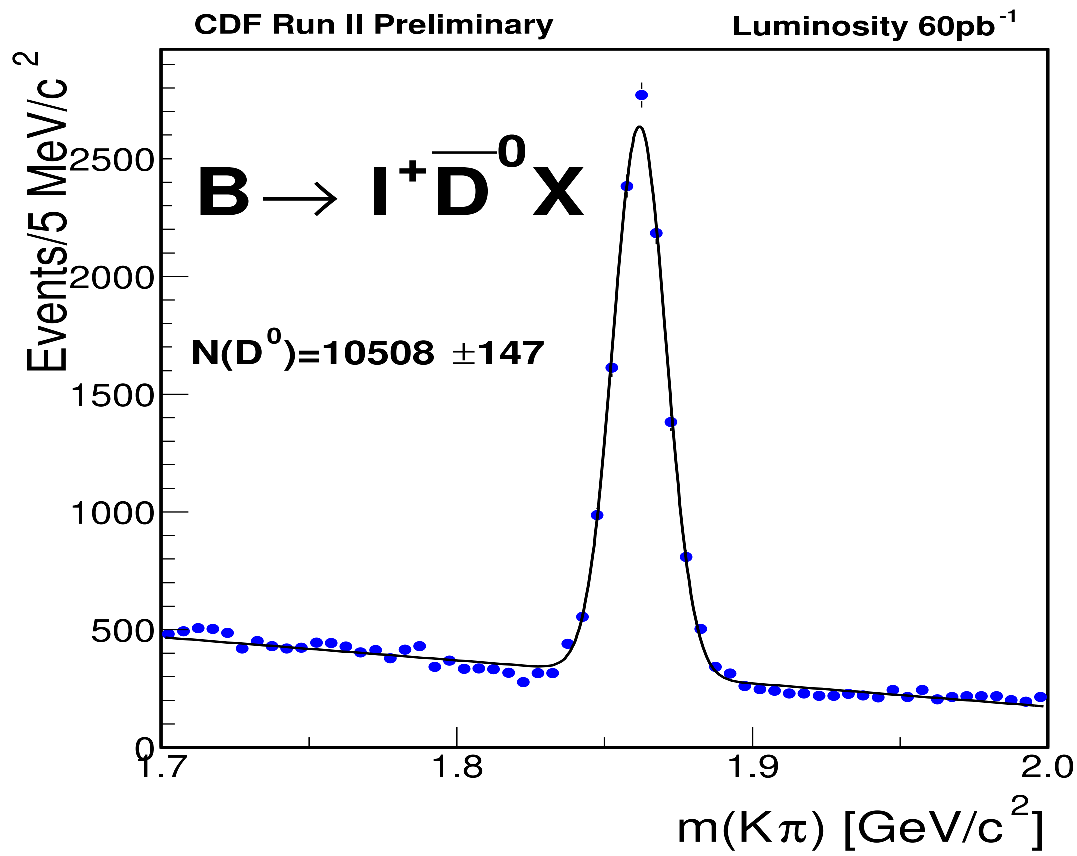
$\Rightarrow m(B_s^0) = 5360.3 \pm 3.8\,^{+2.1}_{-2.9}$ MeV$/c^2$.

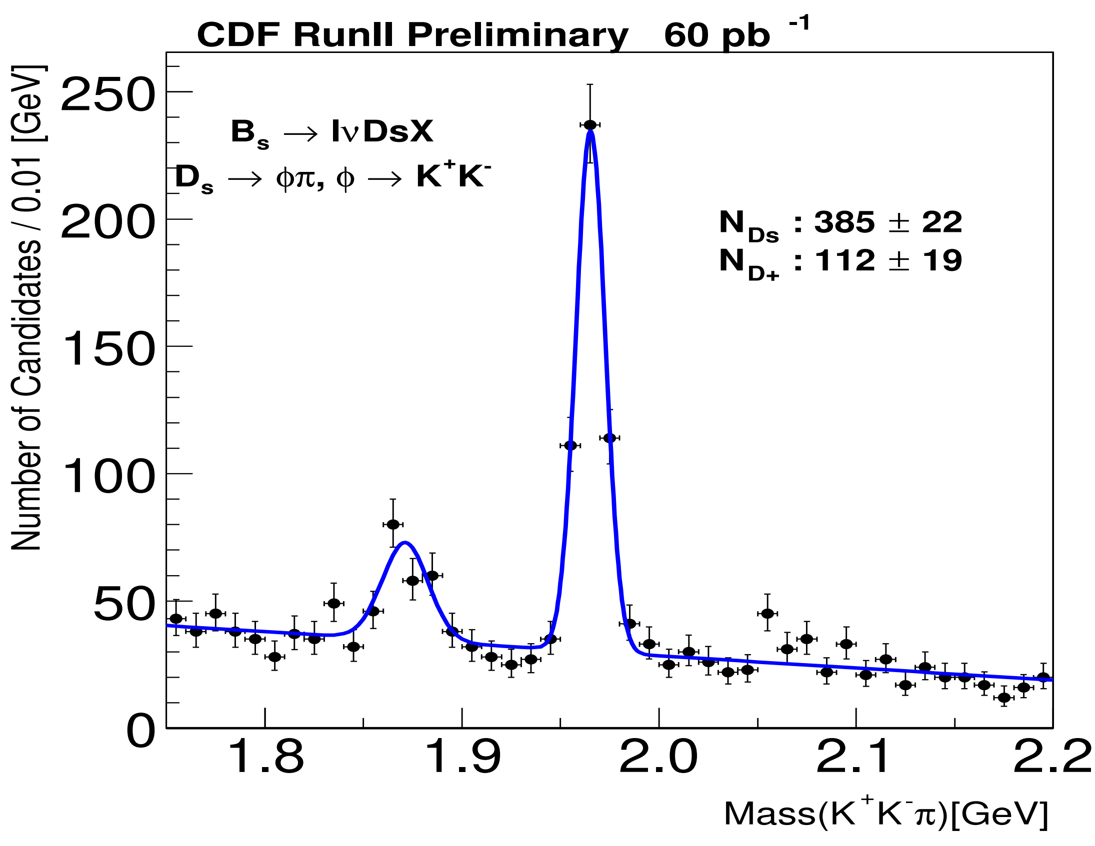
$\Rightarrow \tau(B_s^0) = 1.26 \pm 0.20 \pm 0.02$ ps

Expect $\tau(B_s^0)/\tau(B^0) = 1.0 \pm \mathcal{O}(1\%)$.
The mode is dominated by CP-even eigenstate.
Can exhibit different τ than flavor eigenstates, such as $\ell^-\bar{\nu}D_s^+$ and $D_s^+\pi^-$.

Future : look for CP violation. $\sim$ zero expected in SM.

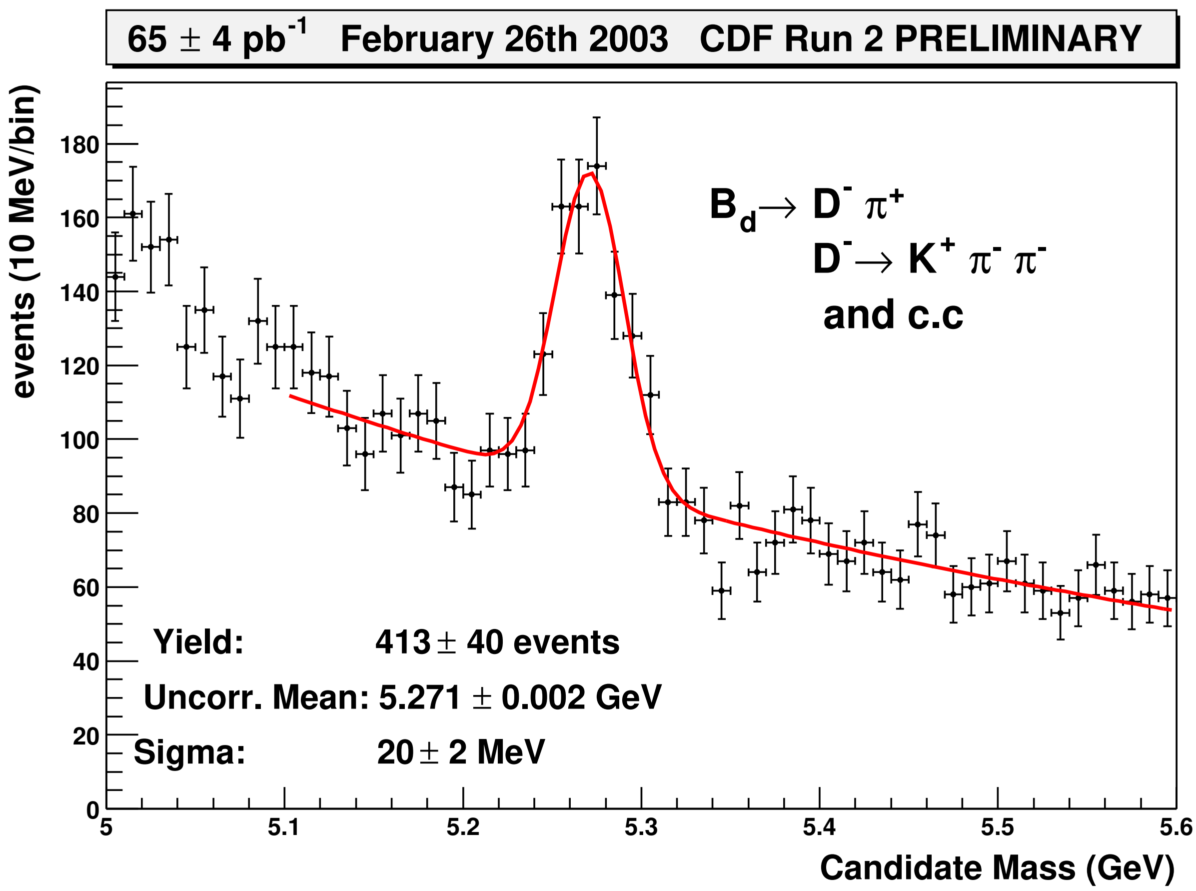
$\bar{B} \to \ell^- \bar{\nu} D X$ signals





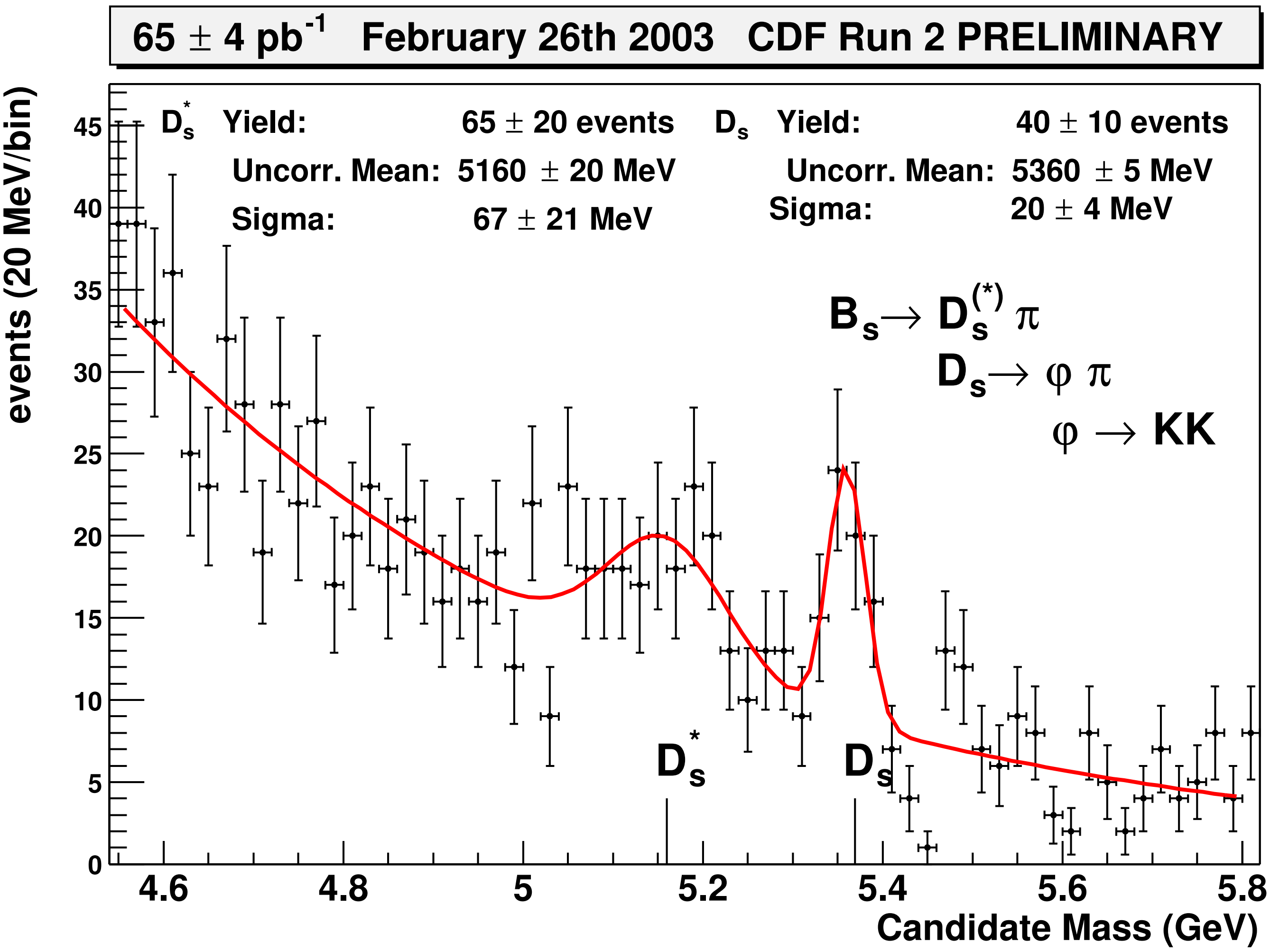
B signals from SVT triggers

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



Measure Δm_d, calibrate/optimize flavor tagging.
Exercise for for B_s^0-$\bar{B}_s^0$ oscillations.

What we wanted : $\bar{B}_s^0 \to D_s^{(*)+} \pi^-$



Next step : accumulate stats, look for oscillations.

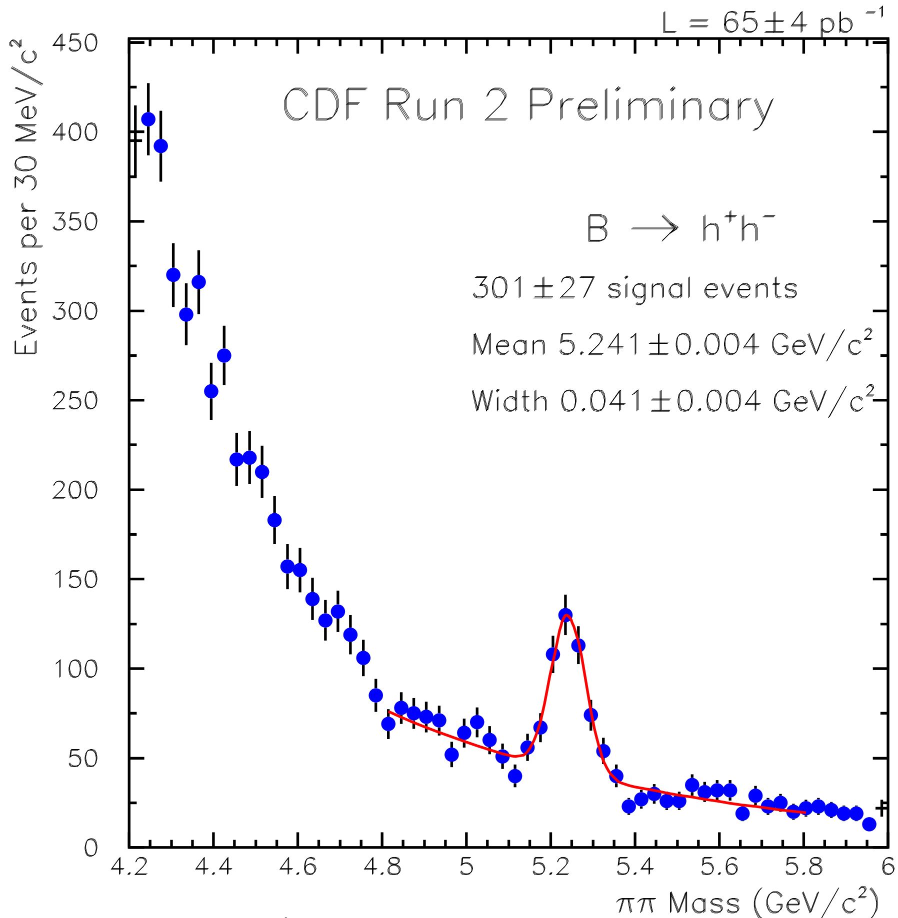
$\Delta m_s \Rightarrow$ Crucial for $|V_{td}/V_{ts}|$.

Theory :

Does the $f_B\sqrt{B_B}$ uncertainty cancel in the ratio?

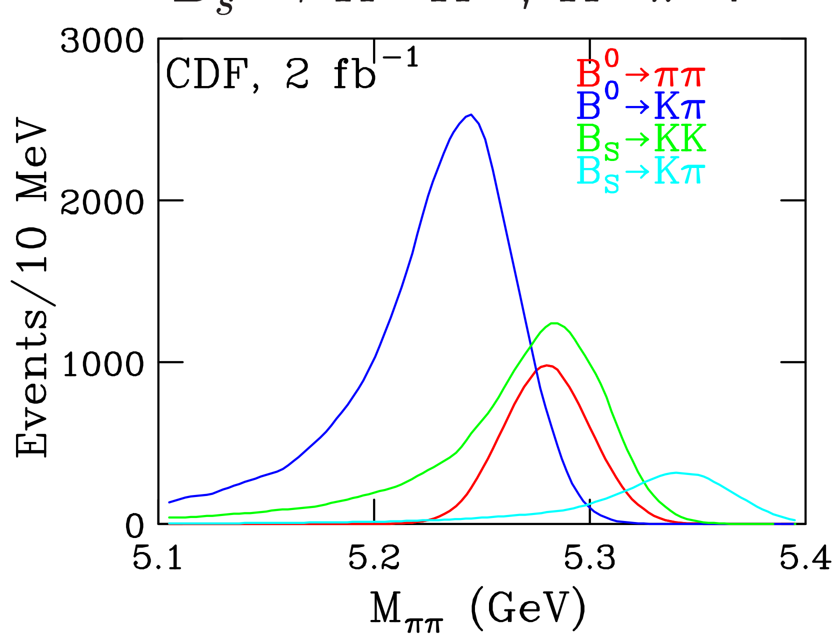
Seems not as simple as we once thought.

What we wanted II : $B^0/B_s^0 \to h^+h^-$



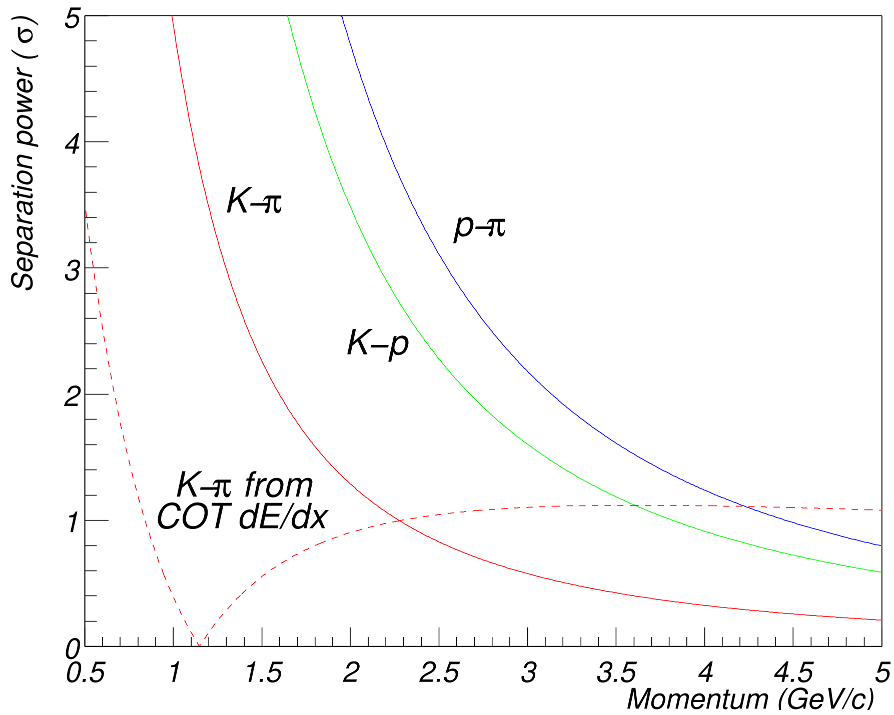
300 events / 65 pb^{-1}

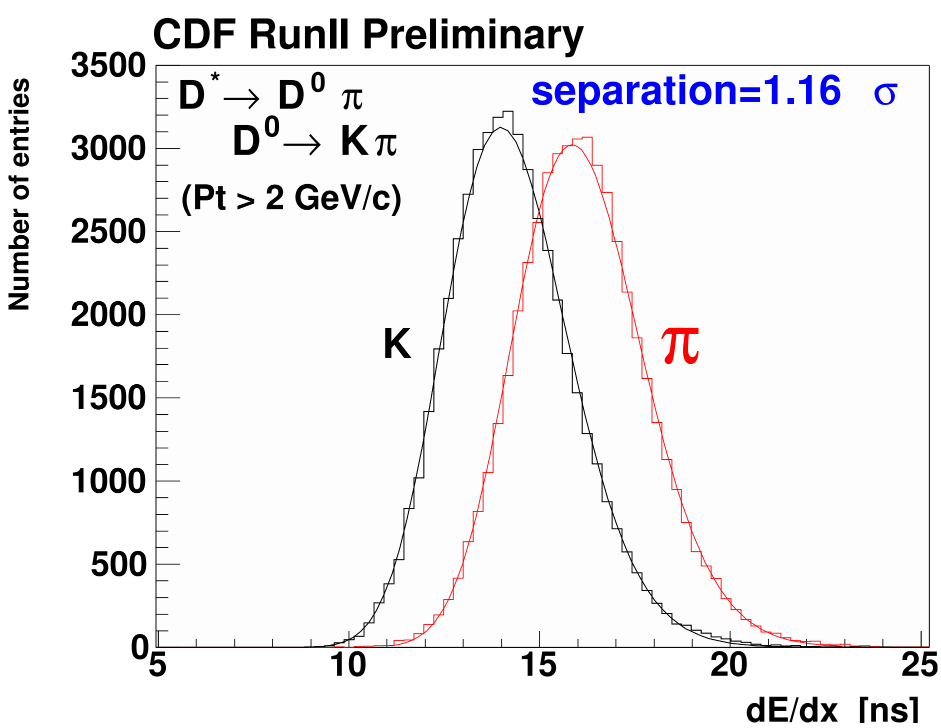
Peak : mixture of $B^0 \to \pi^+\pi^-$, $K^+\pi^-$ and $B_s^0 \to K^+K^-$, $K^-\pi^+$.



$B^0/B_s^0 \to h^+h^-$ cont'd

Next step : measure composition using dE/dx.

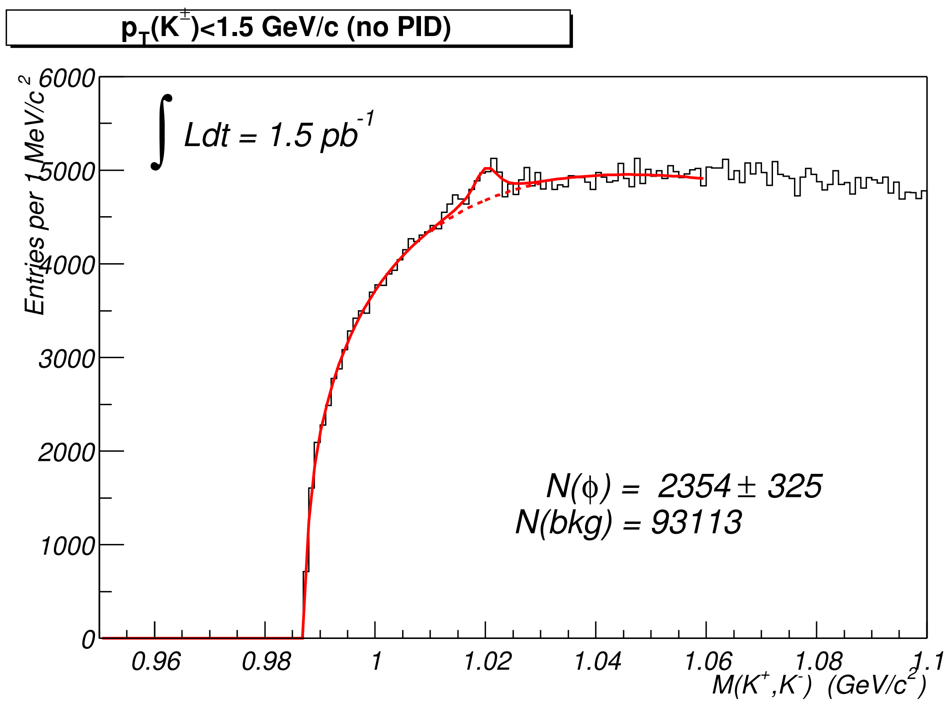


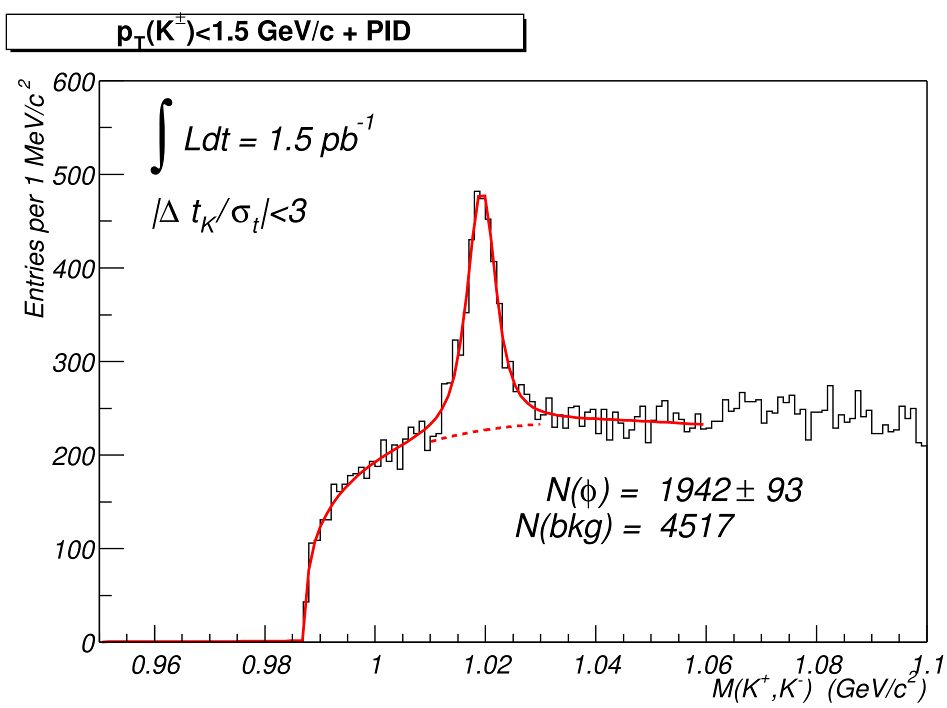


Future : Angle γ from $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, R. Fleischer, Phys. Lett. B459, 306 (1999), utilizing both tree and penguin decays.

Particle ID : TOF

$\phi \to K^+K^-$ before and after TOF cuts.





Next step : measure flavor tagging efficiencty $\epsilon\mathcal{D}^2$

Summary

Run-II status

- CDF has added silicon-based trigger, enabling us to collect all-hadronic final states such as $D^0 \to K^-\pi^+$ and $\bar{B}^0 \to D_s^+\pi^-$.
- $J/\psi \to \mu^+\mu^-$ and single-lepton triggers remain valuable too.

Plans

- Open charm and J/ψ production cross sections.
- B^+, B^0, B_s^0, Λ_b^0, B_c^+ lifetimes. $\Delta\Gamma_s \neq 0$?
- Re-establish B^0-$\bar{B}^0$ oscillations and Δm_d, calibrate flavor tagging.
- Measure $\sin 2\beta$ with $B^0/\bar{B}^0 \to J/\psi K_S^0$.
- Rare decays, $B \to K^{(*)}\ell^+\ell^-$, $B^0/D^0 \to \mu^+\mu^-$.
- Measure Δm_s with $\bar{B}_s^0 \to D_s^+\pi^-$.
- Look for CP violation in $B_s^0/\bar{B}_s^0 \to J/\psi\,\phi$, new phase in V_{ts} ?
- Measure CP violation in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$. Angle γ ??
- γ from $\bar{B}_s^0 \to D_s^\pm K^\mp$???