HEAVY QUARK PRODUCTION AT CDF

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Fermi National Accelerator Laboratory

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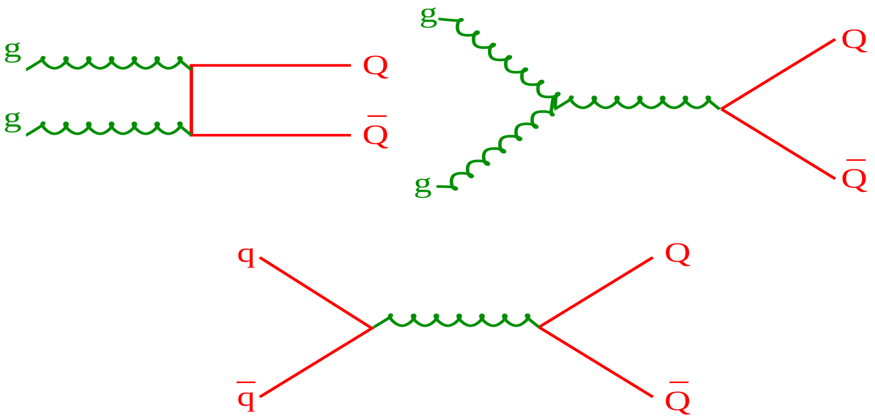
Basics of HVQ Production in $p\bar{p}$



LO HVQ PRODUCTION

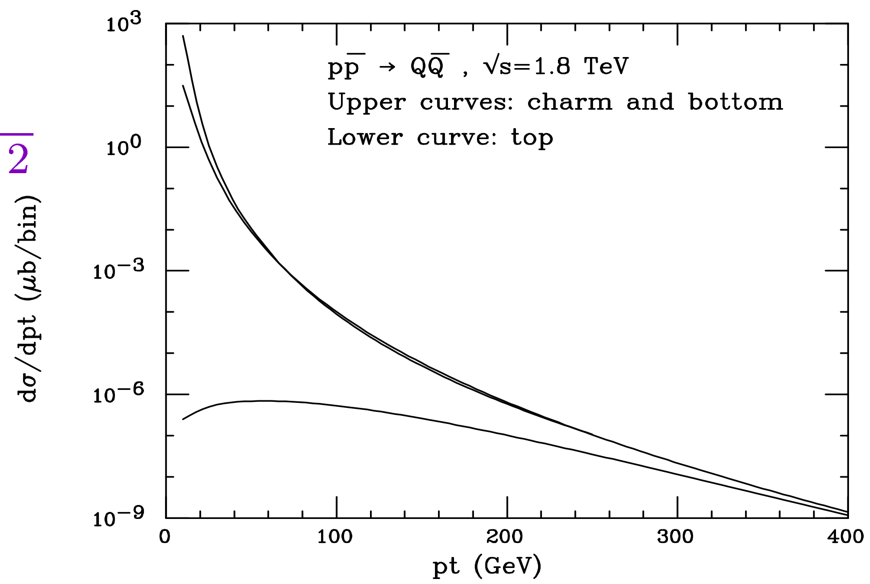
Two leading order perturbative processes:

$$\frac{\hat{\sigma}(gg \to Q_1\bar{Q}_1)}{\hat{\sigma}(gg \to Q_2\bar{Q}_2)} \xrightarrow{s\to\infty} 1-\frac{log(m_1^2/m_2^2)}{log(s/m_2^2)}$$

$$\frac{\hat{\sigma}(q\bar{q} \to Q_1\bar{Q}_1)}{\hat{\sigma}(q\bar{q} \to Q_2\bar{Q}_2)} \xrightarrow{s\to\infty} 1-\mathcal{O}(m_1^4/\hat{s}^2)$$

Hadronic states need PDFs:

$$\frac{d\sigma}{dy\,d\bar{y}\,dp_T^2} \propto \frac{1}{m_T^4}\,\frac{1}{[1+\cosh(y-\bar{y})]^2}$$
$$\times \sum_{i,j} x_1 f_i(x_1) x_2 f_j(x_2)$$
$$\times \bar{\sum} |M(ij \to Q\bar{Q})|^2$$



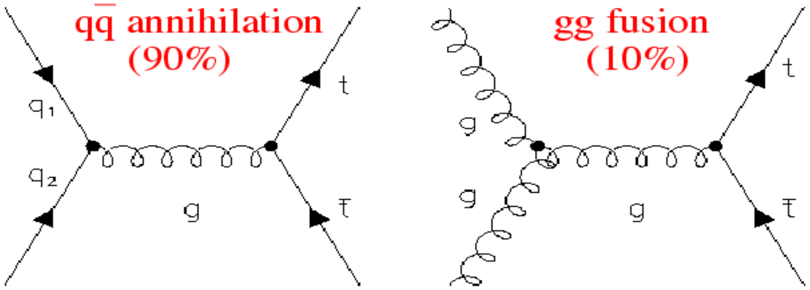
Fragmentation $\Rightarrow$ FS hadrons

Top Production - LO (Run I)

LO contributions to top production cross-section:

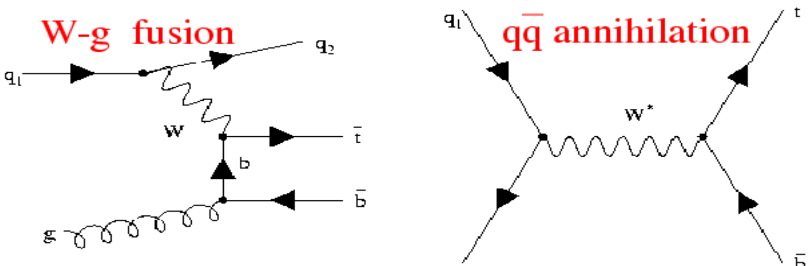
At the Tevatron top quarks are produced:

- In pairs



Theoretical predictions: $\sigma_{t\bar{t}} = 4.7 \div 5.5$ pb

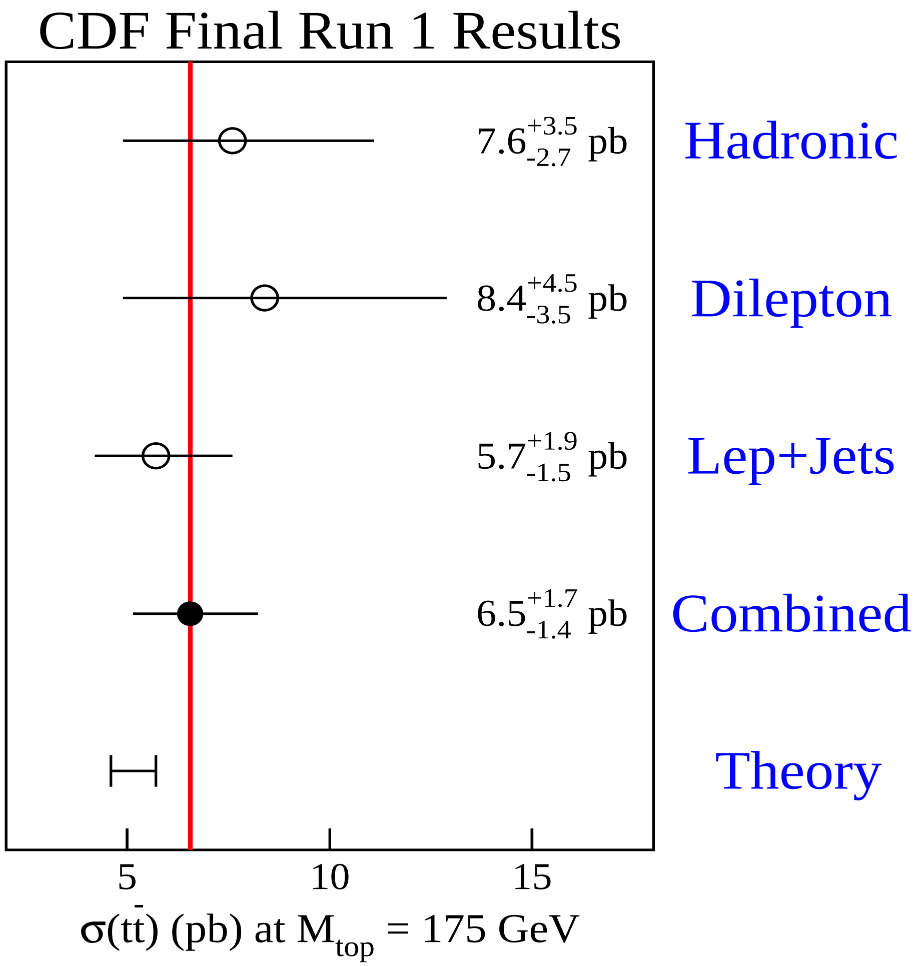
- Via electroweak processes (single top production):



$\sigma_{W\text{-}g} = 1.7 \pm 0.1$ pb

$\sigma_{W*} = 0.74 \pm 0.05$ pb

Run 1: Single top is background

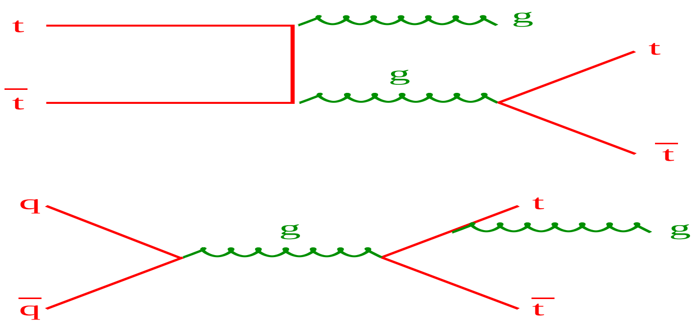


Thursday 9:45 "Top Quark Physics At CDF" - W. Wagner

Top Production - NLO, NNLO

Gluon radiation contributes 1.8-3.1 GeV to $\Delta m_t \sim$ 5GeV

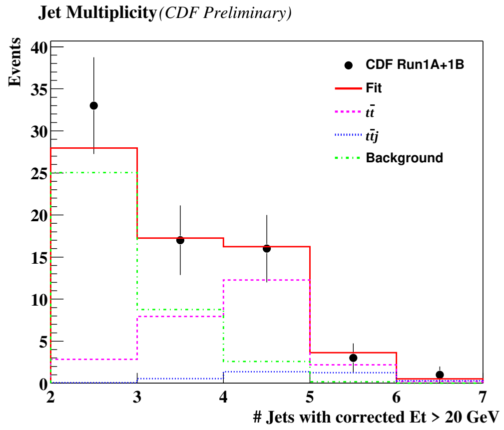
Try to separate fraction of $q\bar{q} \rightarrow t\bar{t}j$, f_{ttj}, *from inclusive* $t\bar{t}$ *cross-section.*

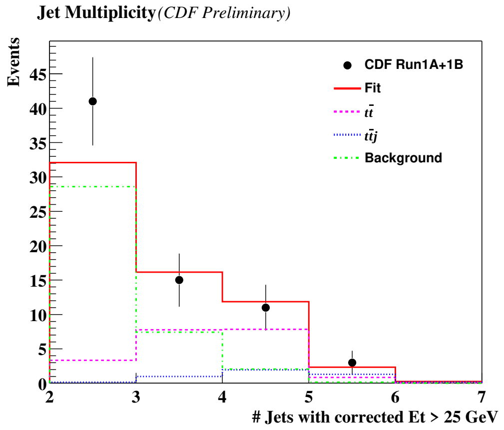


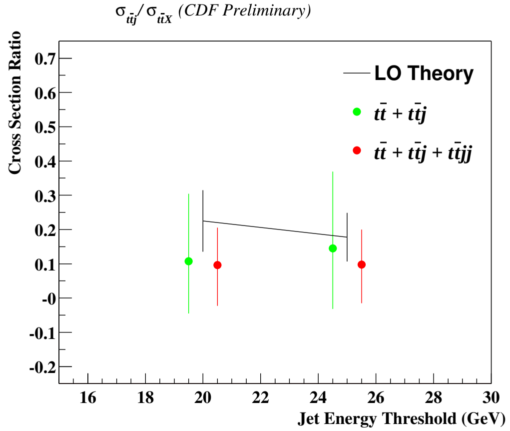
qq -> ttg

$$\sigma_{ttj}^{theory} / \sigma_{ttX}^{theory} \propto f_{ttj}(1 - f_{bg})$$

Binned LL fit to jet multiplicity shapes in l+MET+jj+b-tag $\Rightarrow$ f_{bg}. MADGRAPH+PYTHIA $\rightarrow \sigma_{ttj}^{theory}, \sigma_{ttX}^{theory}$.



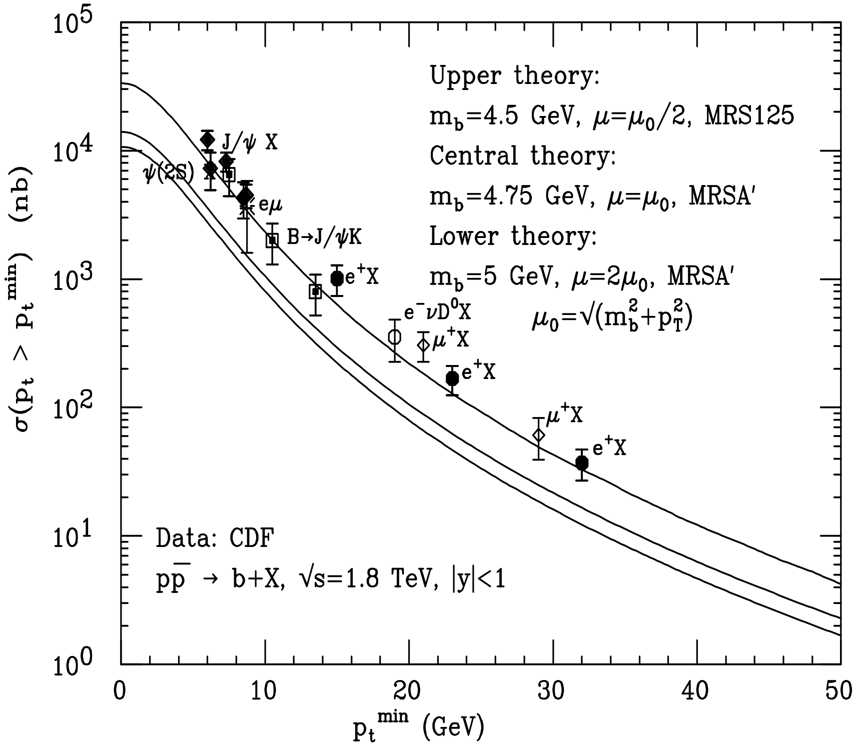




$$\sigma_{ttj}^{theory} / \sigma_{ttX}^{theory} < 0.48(E_T = 20GeV), 0.55(E_T = 25GeV)@90\%\text{C.L.}$$

b production - Run I

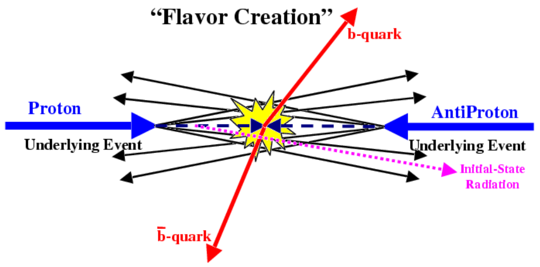
b quark inclusive cross-sections at medium p_t were measured using a lifetime fit to the inclusive ψ data from di-muon trigger to extract the b fraction. At high p_t the cross-sections were measured in the modes $b \to lX$ using data from the high p_t lepton triggers.

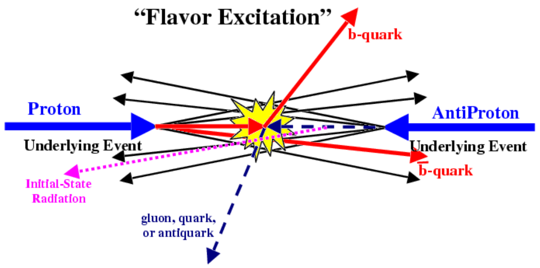


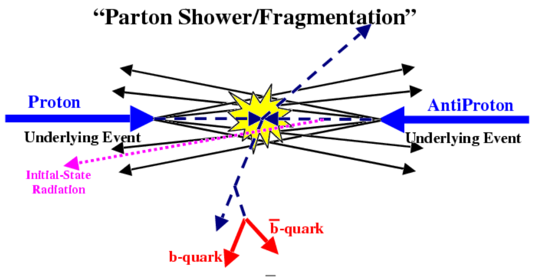
Initially, b production cross-sections at the Tevatron did not agree with NLO QCD calculations with default parameters. Theory and data could be forced to agree by using extreme values of renormalization and factorization scales.

b cross-section components

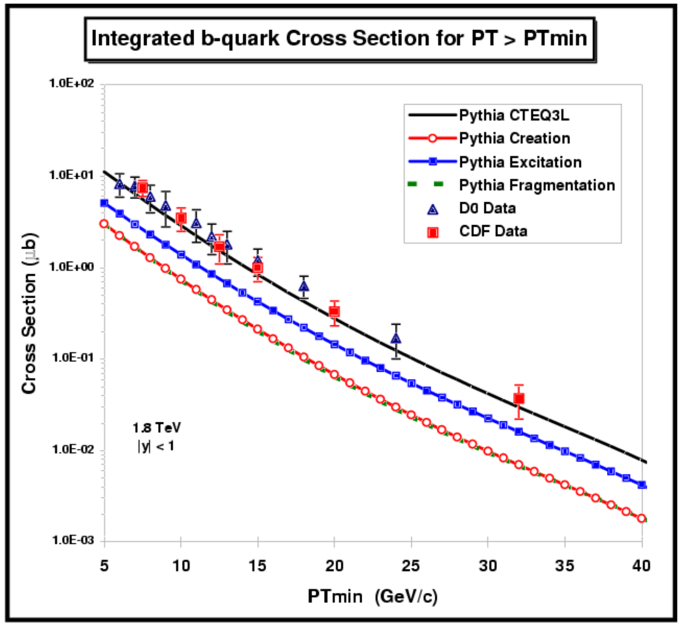
In addition to flavor creation (LO), 2 other processes contribute to b production in $p\bar{p}$:





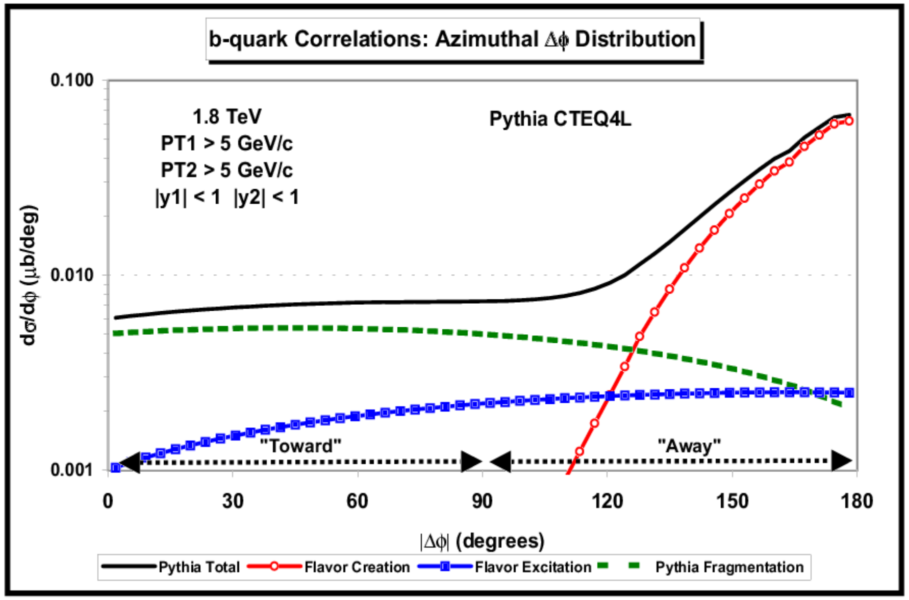


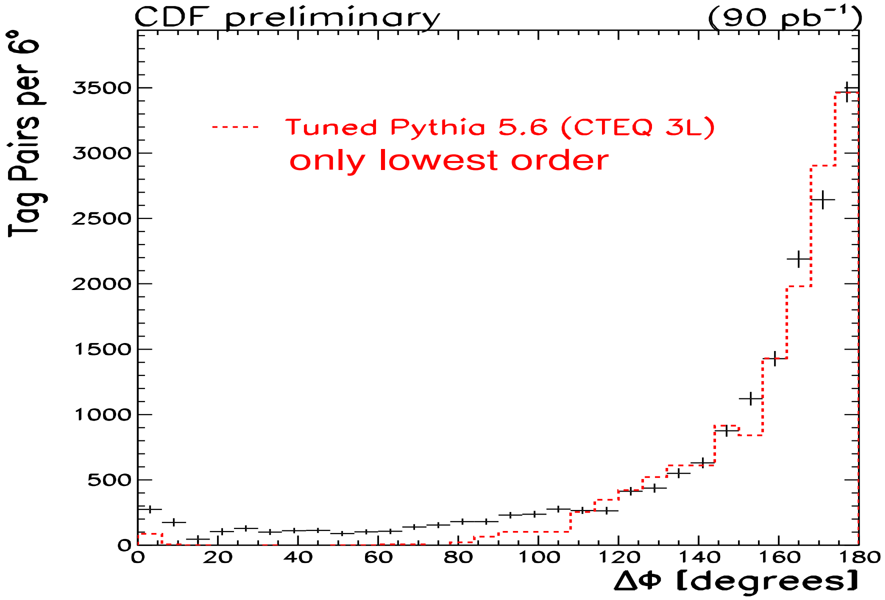
Ansatz: Tuning contributions from these processes can have a large effect on the total cross-section. Flavor excitation is sensitive to PDFs. Different fragmentation models change the contribution from shower fragmentation.



$b\bar{b}$ correlations - Run I

To try and estimate the contributions from the 3 processes, look at $b\bar{b}$ production correlations. Find $b \to J/\psi X$, $\bar{b} \to lX$ pairs.





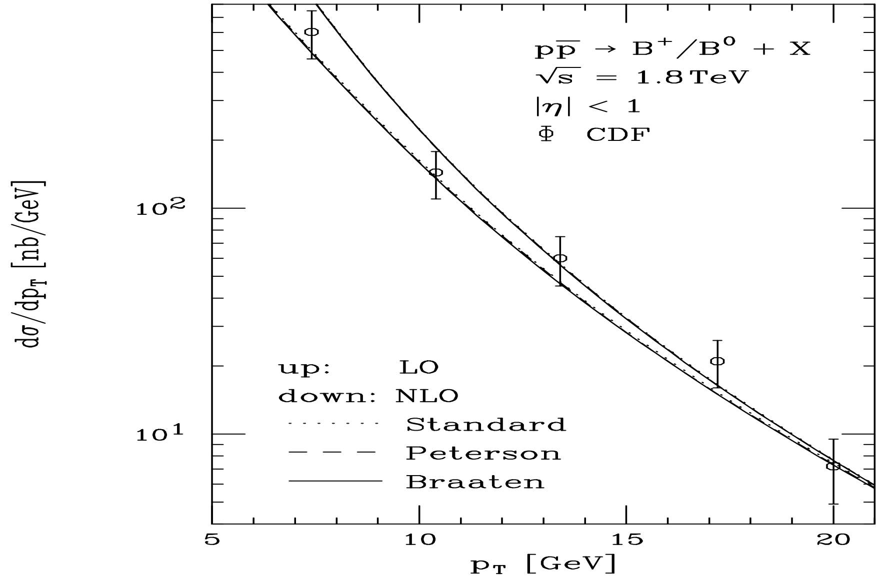
$b\bar{b}$ correlations from LO flavor creation in Pythia do not agree with data at small $\Delta\phi(b\bar{b})$.$\Rightarrow$ Contributions from flavor excitation and gluon splitting diagrams may be important. **Run II: SVXII 3-D with z resolution $\sim 40\mu$m - separate $b\bar{b}$.**

Theory: Fragmentation functions

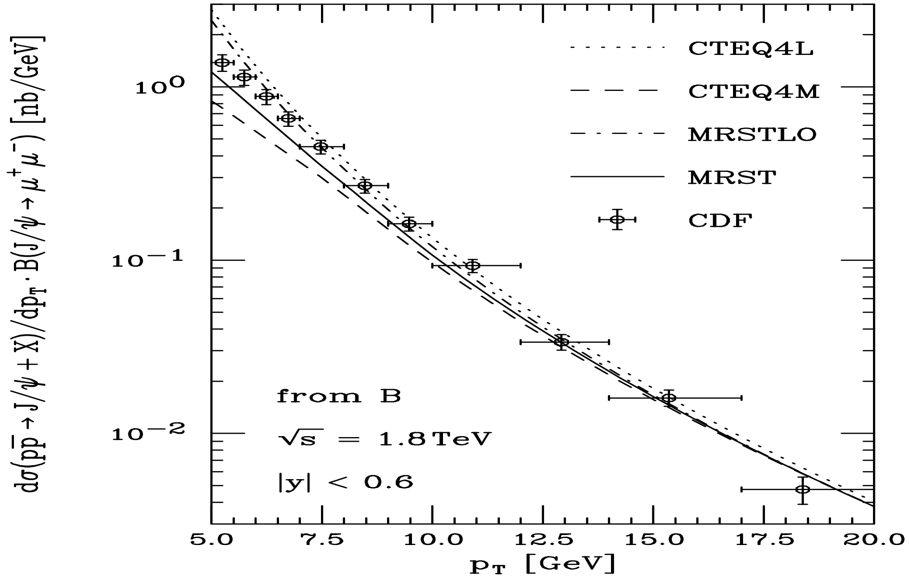
Non-perturbative fragmentation functions for B mesons are extracted from LEP data using 3 different parameterizations.

Applied to LO and NLO QCD with $\bar{M}S$ factorization. $\Rightarrow$ *good agreement with CDF Run I data on B meson cross-section.*

Using the NRQCD factorization scheme: $\Rightarrow$ *good agreement with CDF Run I measurement of J/ψ cross-section from B.*



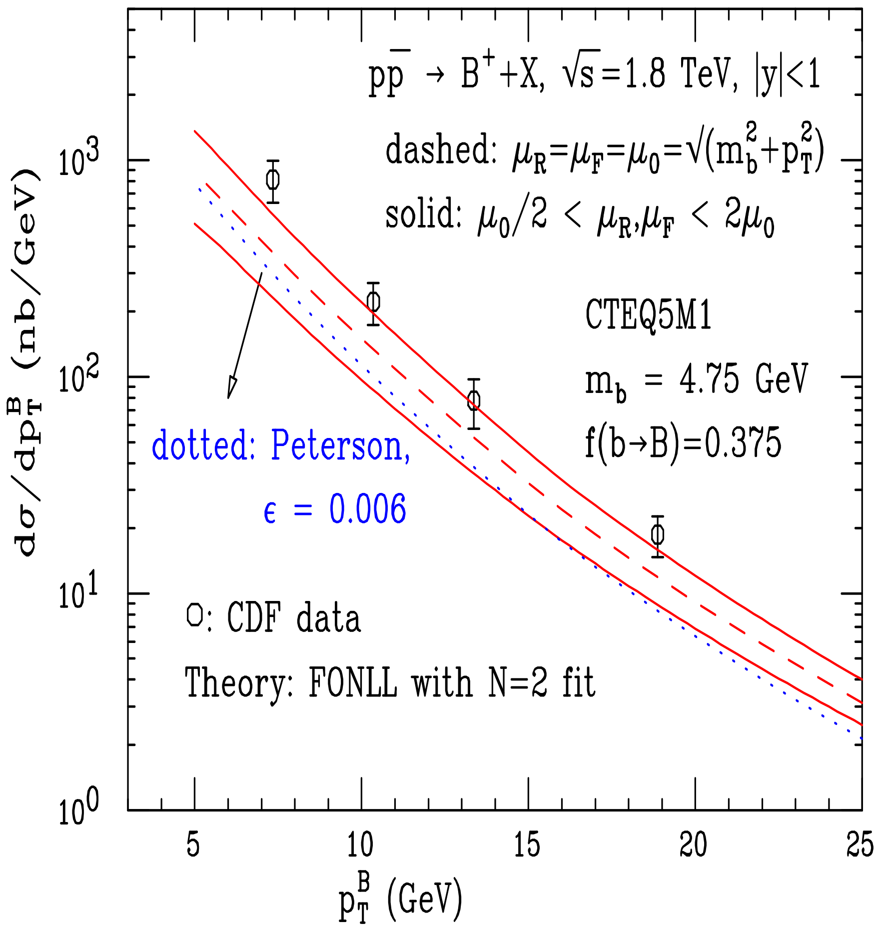
Binnewies, Kniehl, Kramer hep-ph/9802231 (Run I)



hep-ph/9901348 (Run I)

Theory: NLL resummations

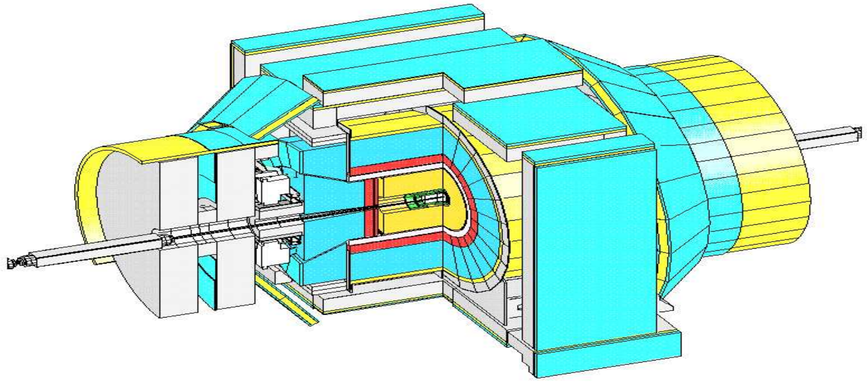
When $p_T >> m_b$, large logarithms of the ratio p_T/m_b arise in the coefficients of the perturbative expansion. Resummation of next-to-leading logs merged with the QCD NLO using a retuned Peterson fragmentation with $\epsilon_b = 0.002 \Rightarrow$ Reasonable agreement with CDF data on B meson cross-sections.



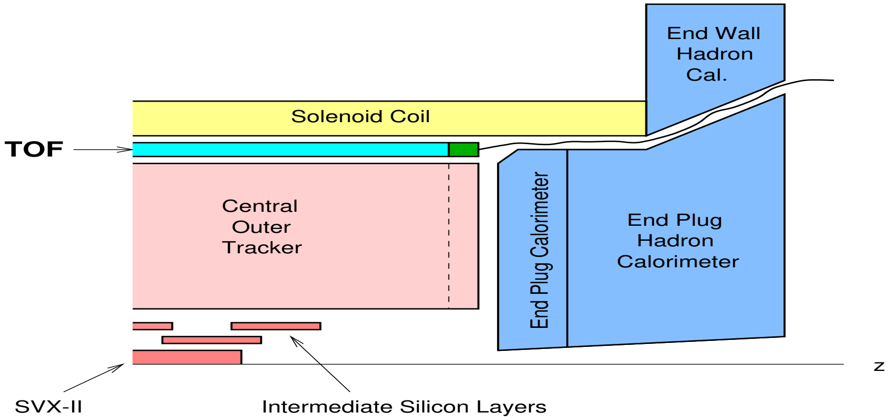
Cacciari, Nason hep-ph/0204025 (Run I)

Run II: test current theory predictions at $p_t^{min} < 5$ GeV

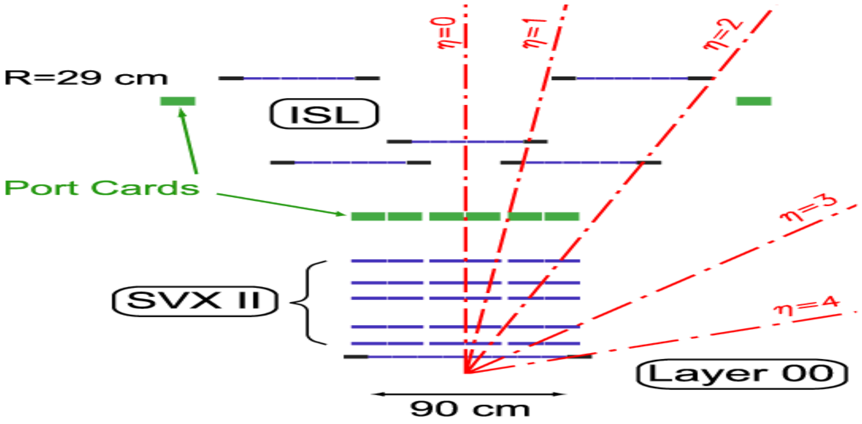
The CDF Run II Detector



Lots more $t/b/c$

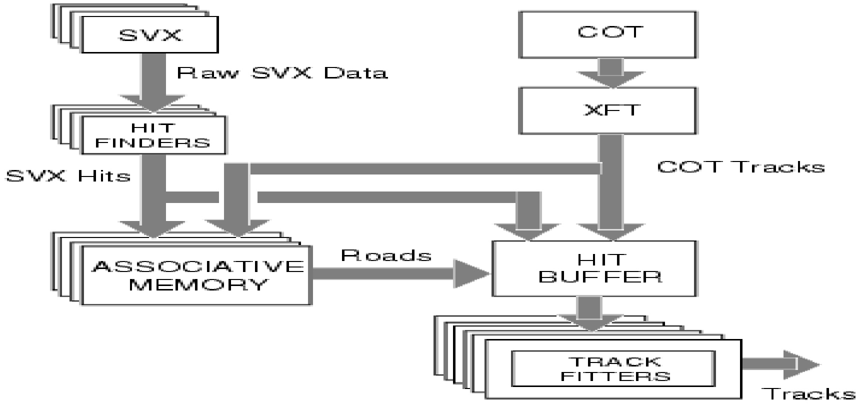


Larger Muon/Calorimeter coverage



8 Layers of Silicon up to

$|\eta| = 2,\ \sigma(d_0) \sim 20\mu m$

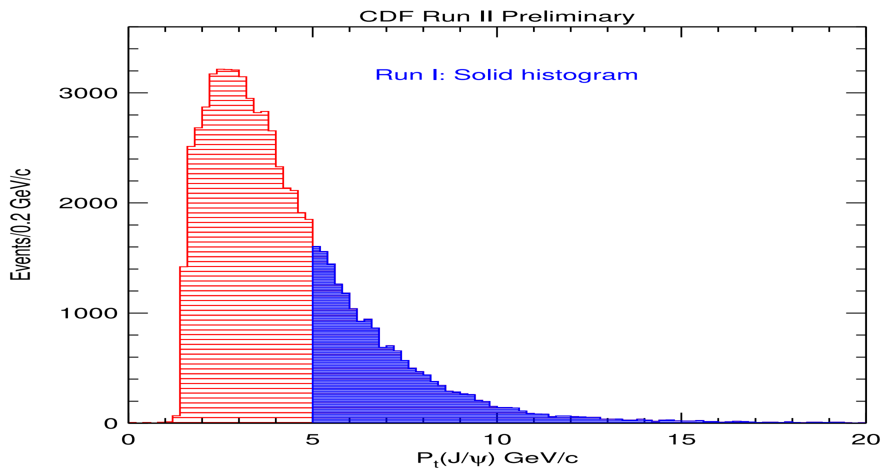


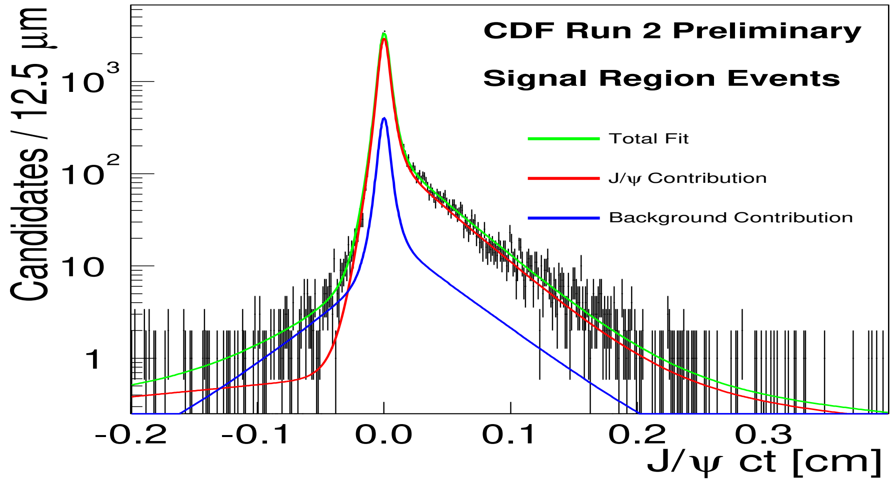
Track Triggers for B and c

with $p_t > 1.5\ GeV/c$

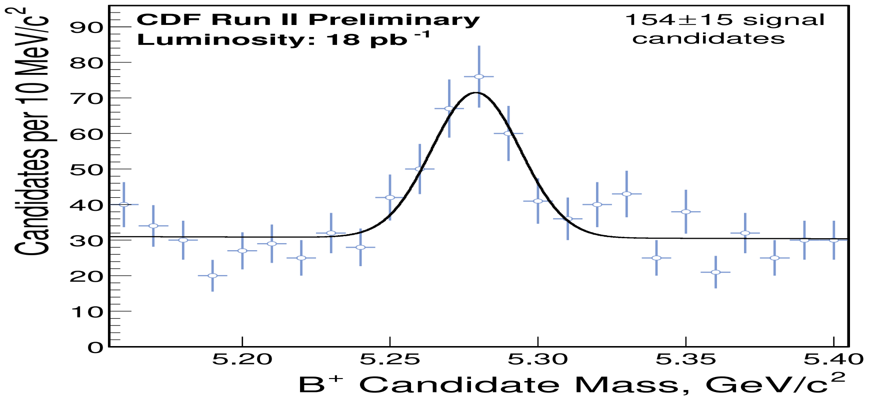
b Production - Run II

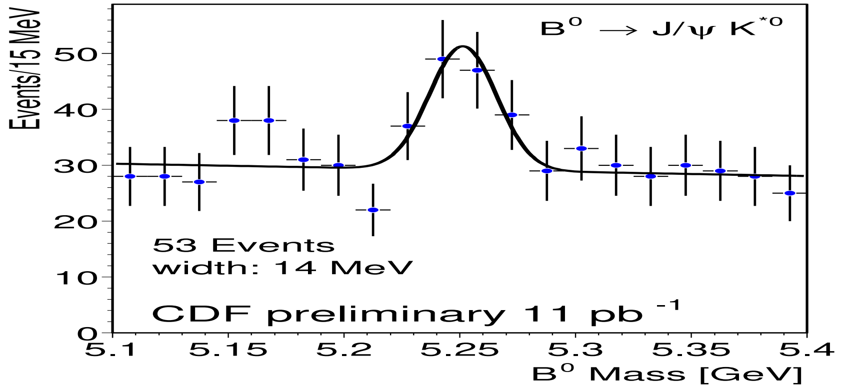
Run II Di-muon triggers, $|\eta| < 1.0$, $p_t(\mu) > 1.5$ $(|\eta| < 0.6)$.





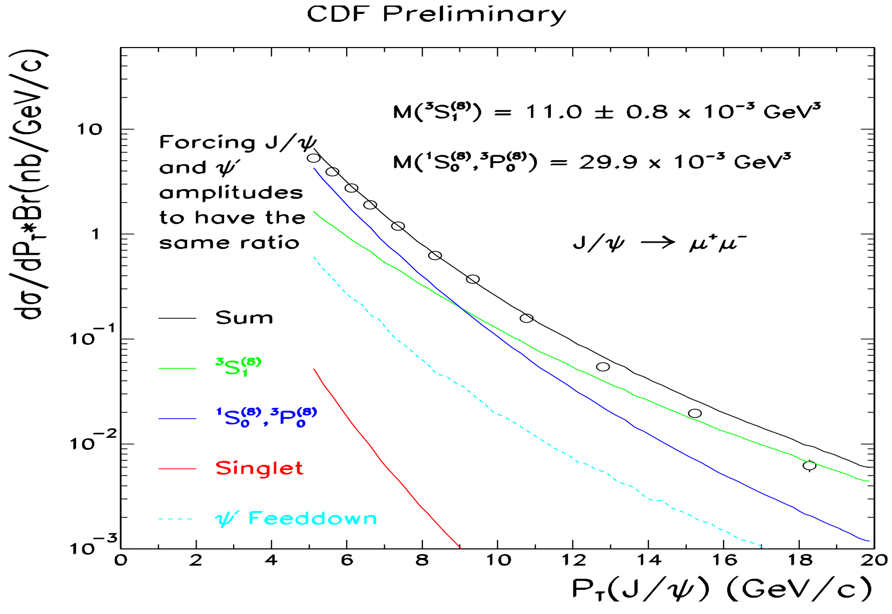
Run II: Inclusive J/ψ *fraction from* $b \to J/\psi X$ *using lifetime fit* $=$ *17%* $(p_t(J/\psi) > 4$ GeV$)$. $p_t(J/\psi) \sim 1.5$GeV $\Rightarrow p_t(B) \sim 0$!



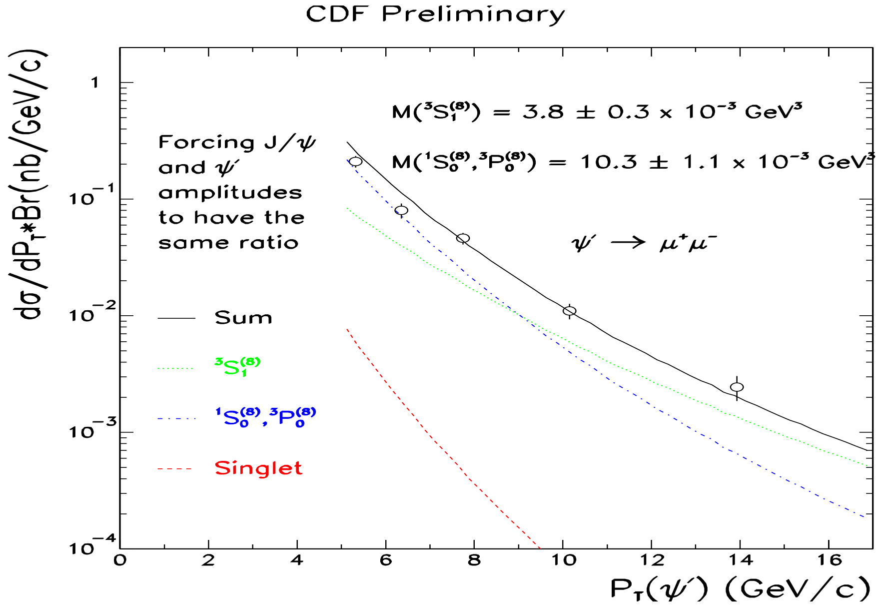


Quarkonia production - Run I

Quarkonia bound states are non-relativistic. NRQCD LO perturbative expansion is $\mathcal{O}(\alpha_s^3 v^0)$ as in the color singlet model (CSM) + higher order $\mathcal{O}(\alpha_s^3 v^4)$. Fragmentation processes $\propto$ color octet matrix element dominate. Predictions agree well with data at the Tevatron at high p_t.



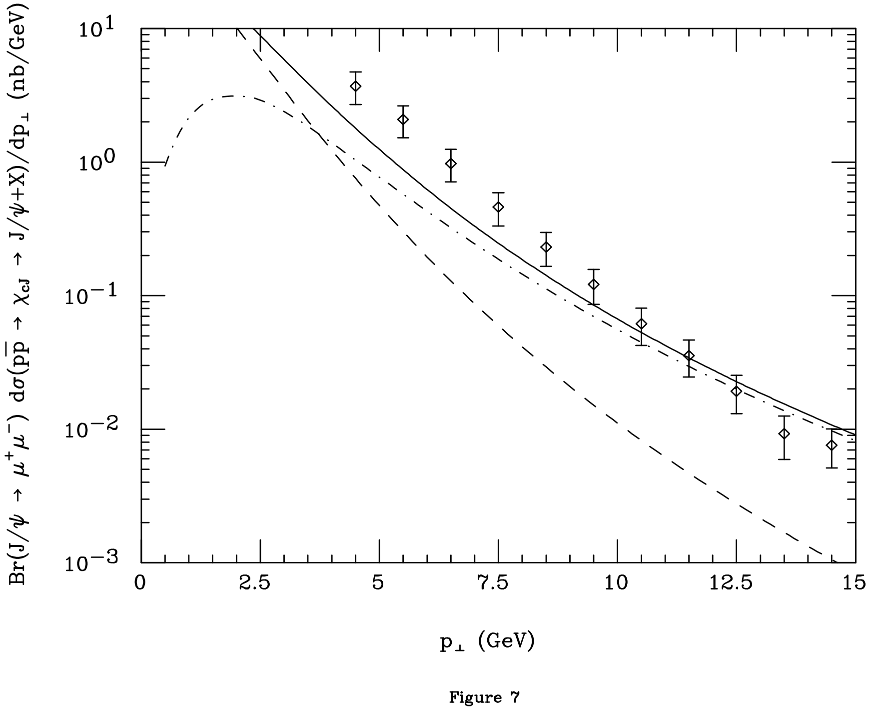
Direct J/ψ production



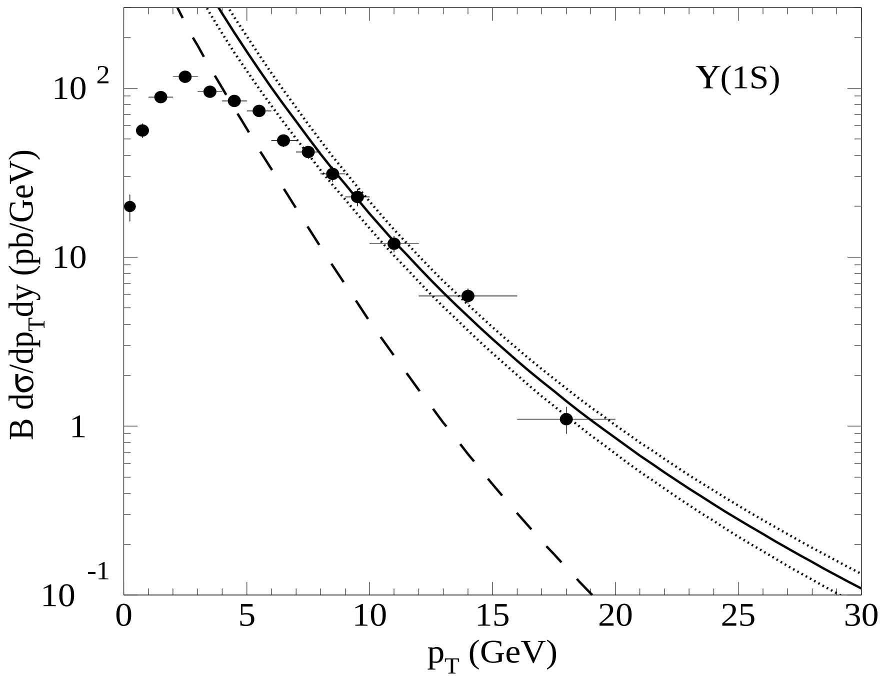
ψ' production

More on Quarkonia - Run I

At lower p_t NRQCD non-fragmentation diagrams from other octet matrix elements are important, soft gluon effects cause rates to diverge.



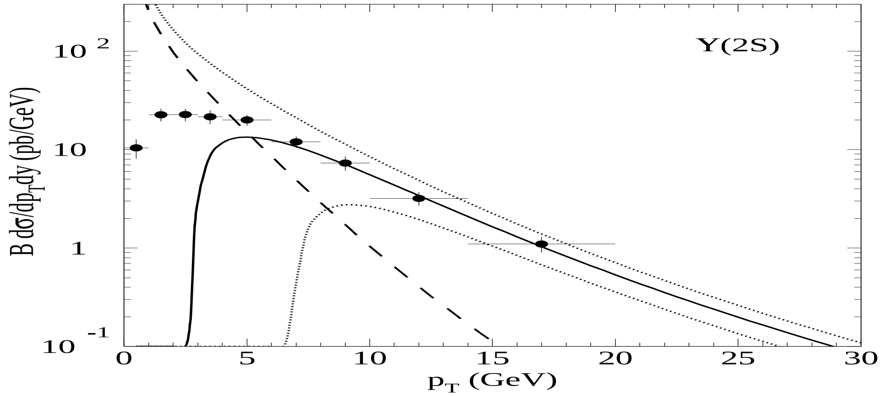
Direct χ_c production

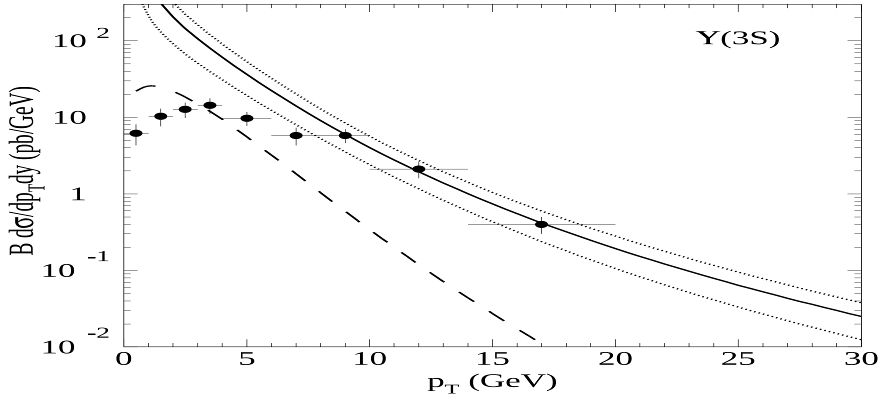


$\Upsilon(1S)$ production

More Bottomonium from Run I!

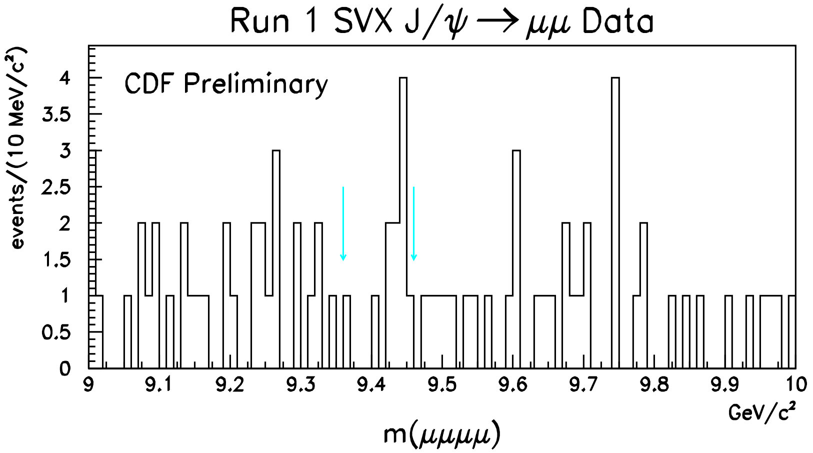
NRQCD Color octet matrix elements determined by fitting to measured cross-section of $\Upsilon(nS)$ at $p_t > 8$ GeV/c.





Predict $\sigma(\eta_b(1S)X)/\sigma(\Upsilon(1S)X) \sim 4.3 \Rightarrow$ Run II $\eta_b \rightarrow J/\psi J/\psi$

From Run I 80 pb^{-1}, 7 candidate events of $\eta_b \rightarrow J/\psi J/\psi$. Mass of potential signal is $9446 \pm 6(stat)$ MeV/c^2



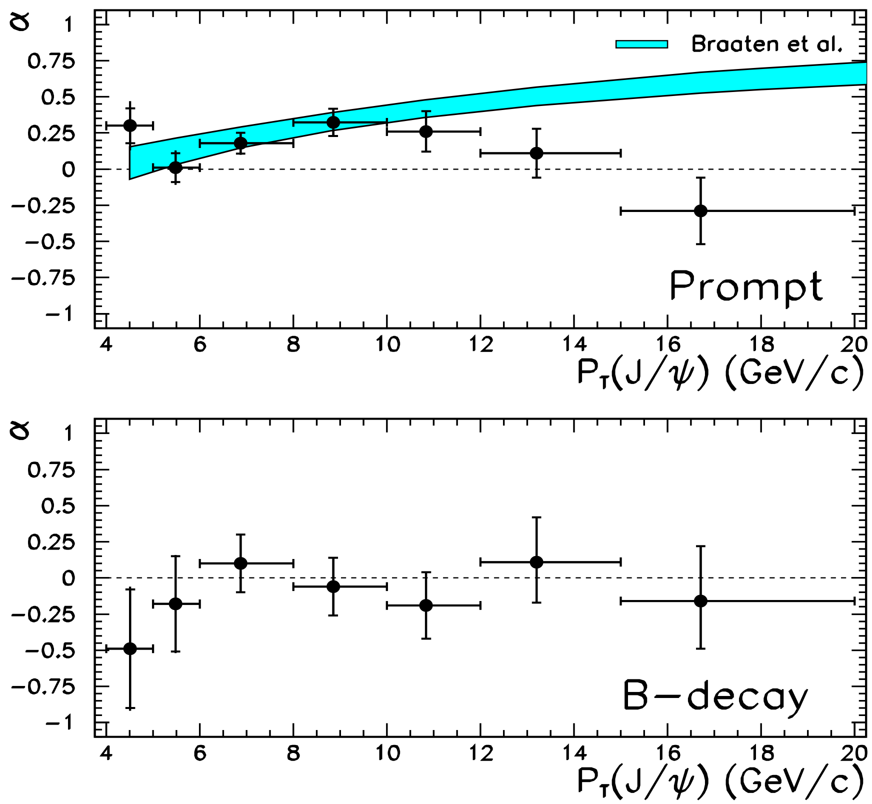
Charmonium Polarization Mystery

BUT Inclusion of color octet in NRQCD leads to a prediction of increasing transverse polarization of charmonium at high p_t.

Method: Fit the production angle, $\cos\theta*$, distribution to MC distribution which is a mixture of transverse and longitudinal polarizations. Use lifetime fit method to separate prompt and $b \to J/\psi X$

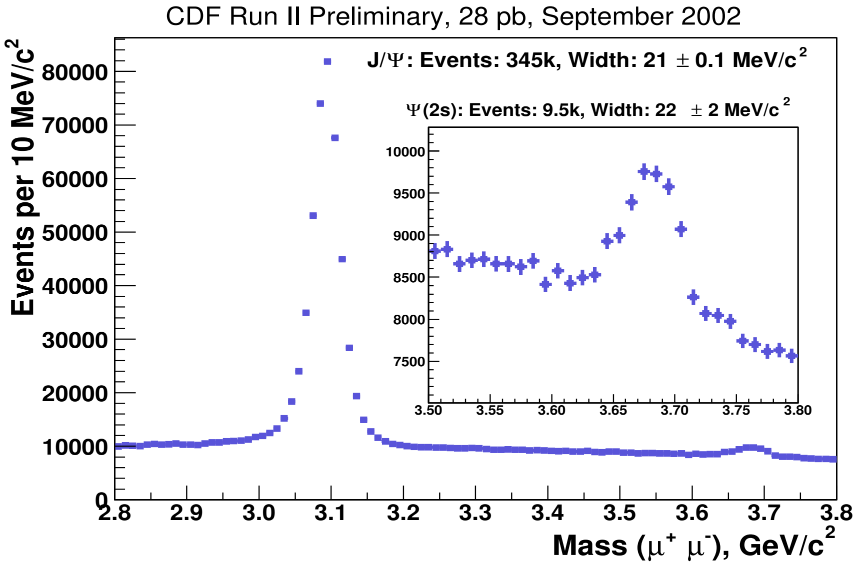
$dN/d\cos\theta^* \propto (1 + \alpha\cos^2\theta^*)$

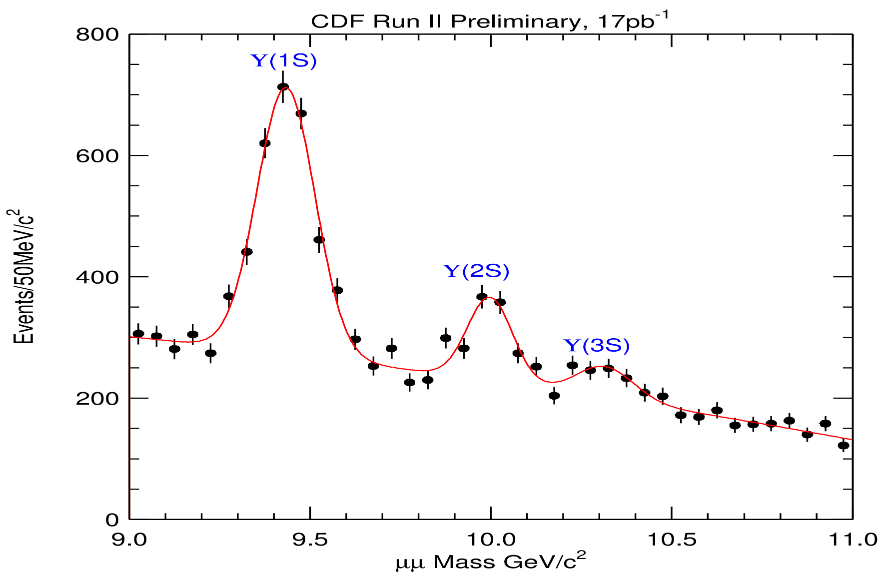
CDF Run I



In the Run I data, polarization is positive at intermediate p_t - does not rise at high p_t.

Run II Quarkonia



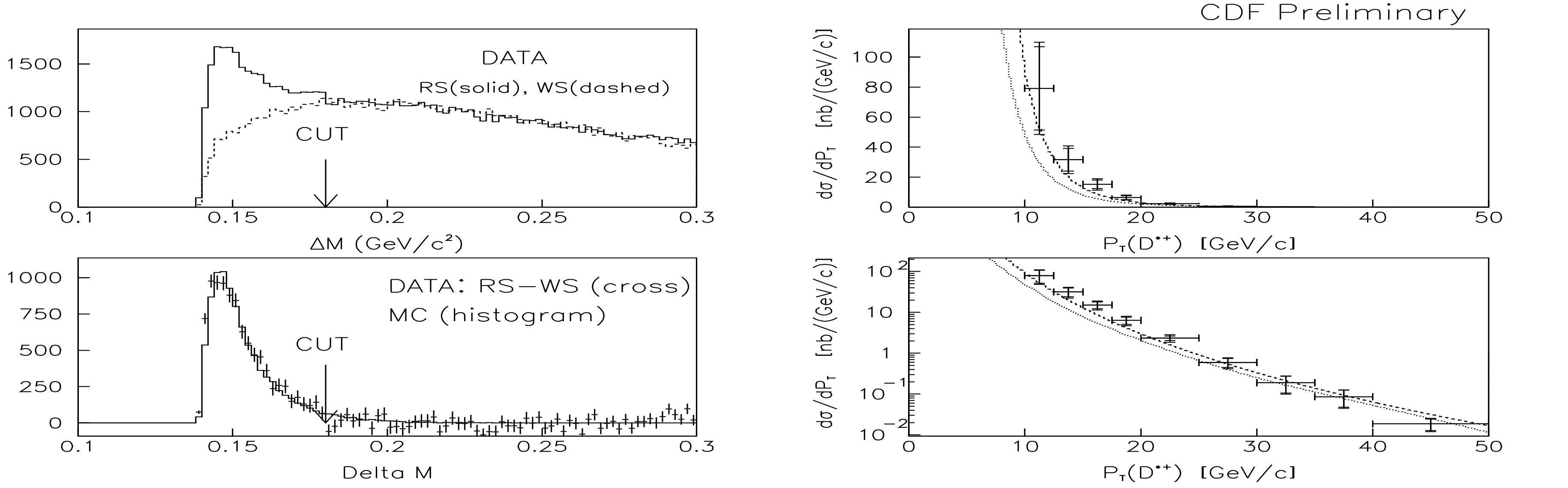


Run II di-muon trigger features:

- *Opening angle* $\Delta\phi > 5^0$ *(was* 15^0*) - polarization.*
- *lower* p_t *reach:* $p_t(\mu) > 1.5(|\eta| < 0.6), 2.0(0.6 < |\eta| < 1.0)$*: cross-sections, greater* $\eta_b \rightarrow J/\psi J/\psi$ *acceptance*
- *More* η *coverage: plug muons + silicon tracking* $1 < |\eta| < 2$.

Charm production - Run I

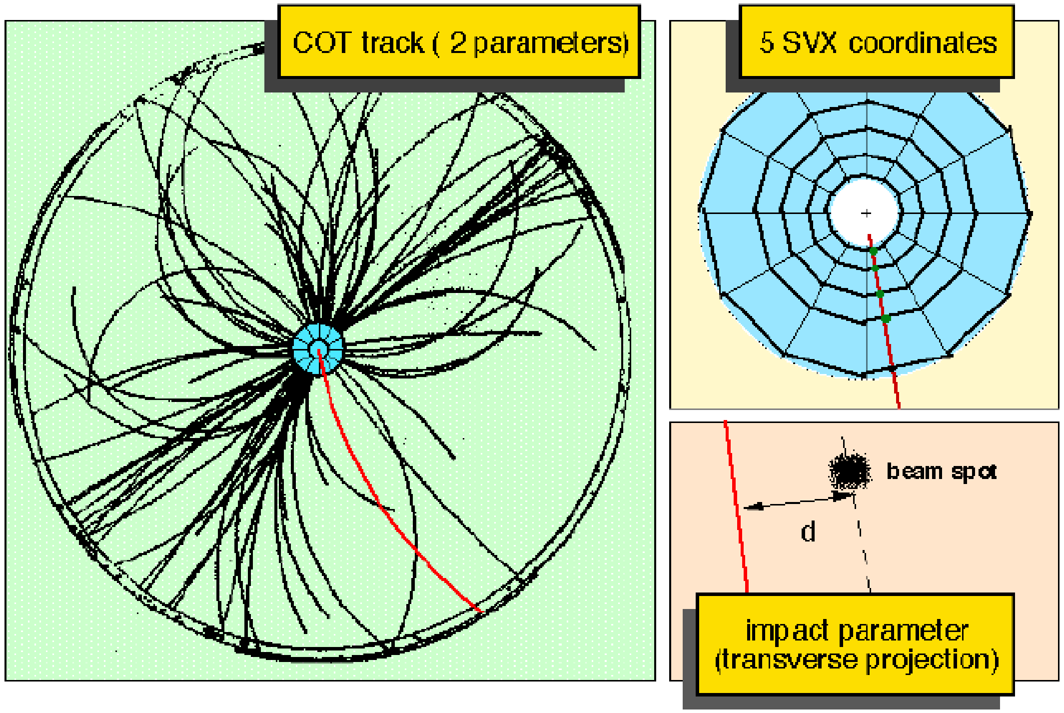
Using data from $> 7.5\ GeV/c$ *inclusive muon trigger reconstruct* $D^* \rightarrow D^0\pi_s, D^0 \rightarrow K\mu + X$. *From lifetime fit to* D^0 *decay vertex found B fraction* $< 6.5\%$.

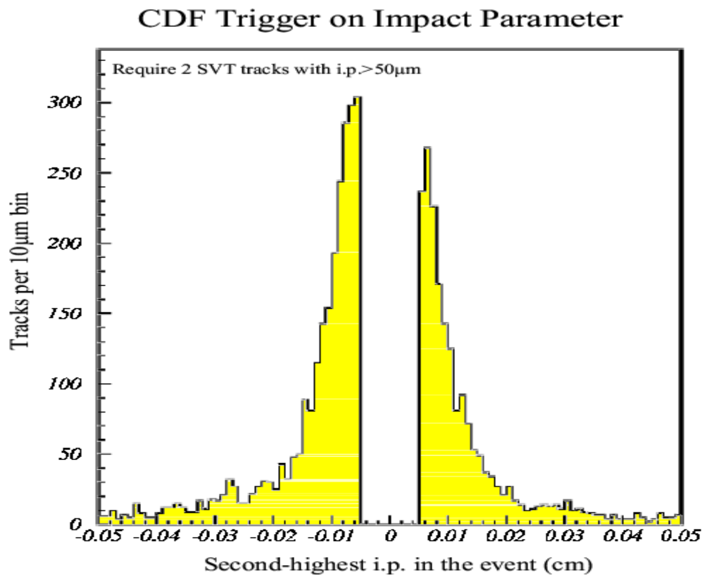


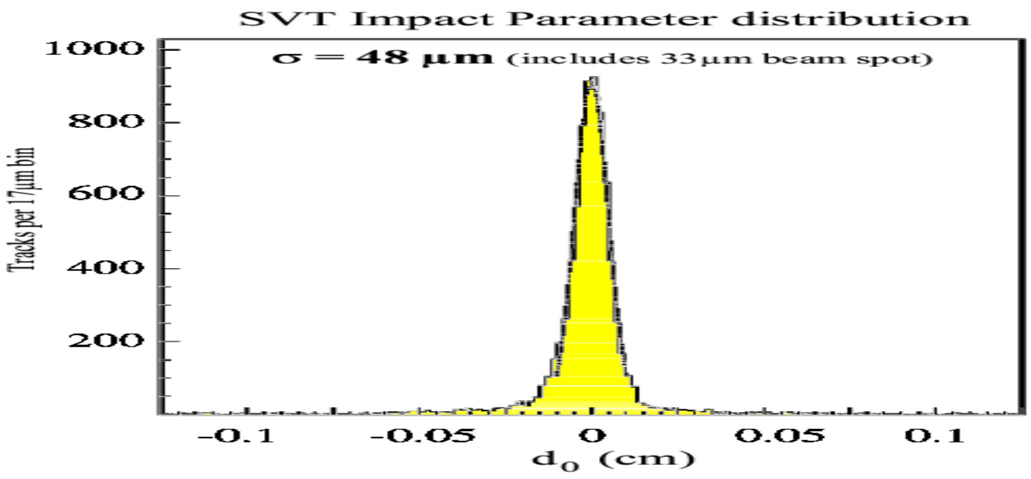
Theory: M. Cacciari $c \rightarrow D^{*+} = 0.222$, $mass_c = 1.5$ GeV/c^2, $\epsilon_q = 0.02$, PDF=CTEQ4M. $\sigma(p\bar{p} \rightarrow D^* X)_{theory} = 240nb$

$\sigma(p\bar{p} \rightarrow D^* X)(|\eta| < 1.0, p_T > 10\ \text{GeV}) = 347 \pm 65(stat) \pm 58(syst)$

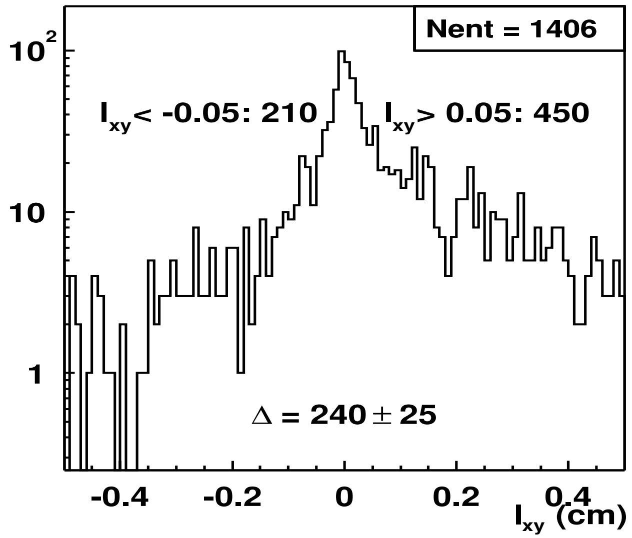
Run II Secondary Vertex Trigger



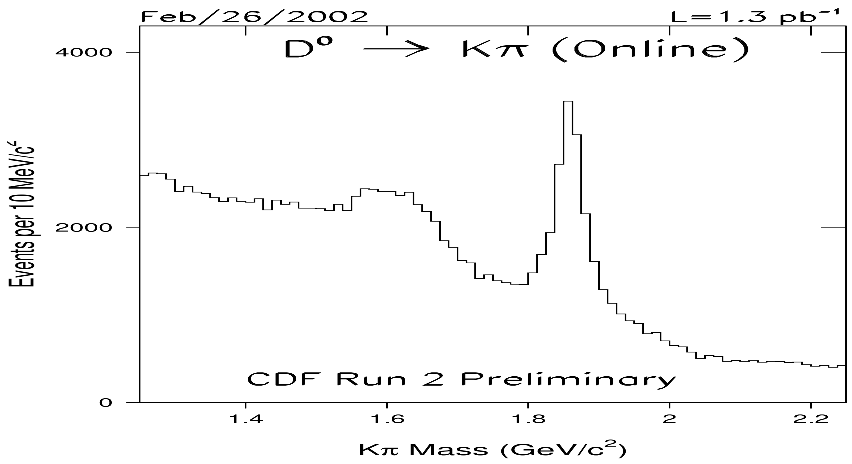


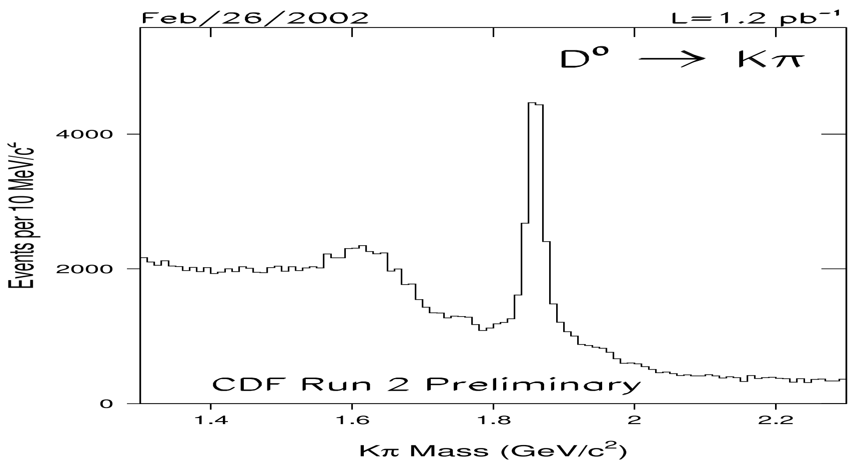


$150\mu m \le d_0 \le 1mm \quad 2^\circ \le \Delta\phi \le 90^\circ$



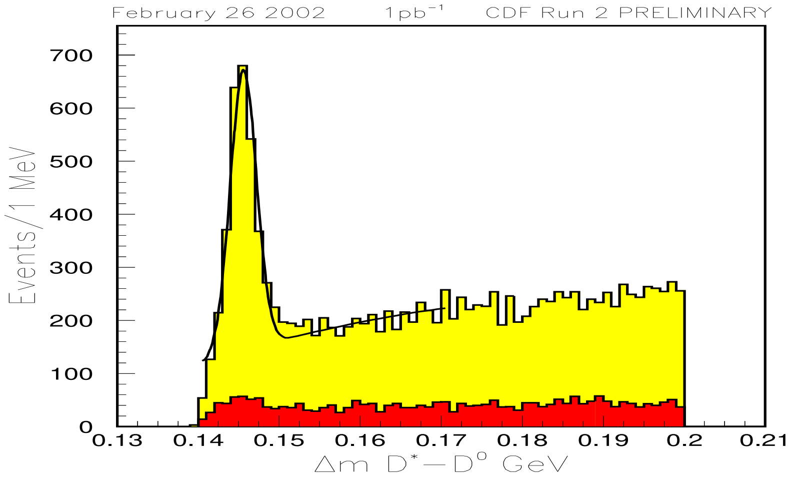
Charm in Run II

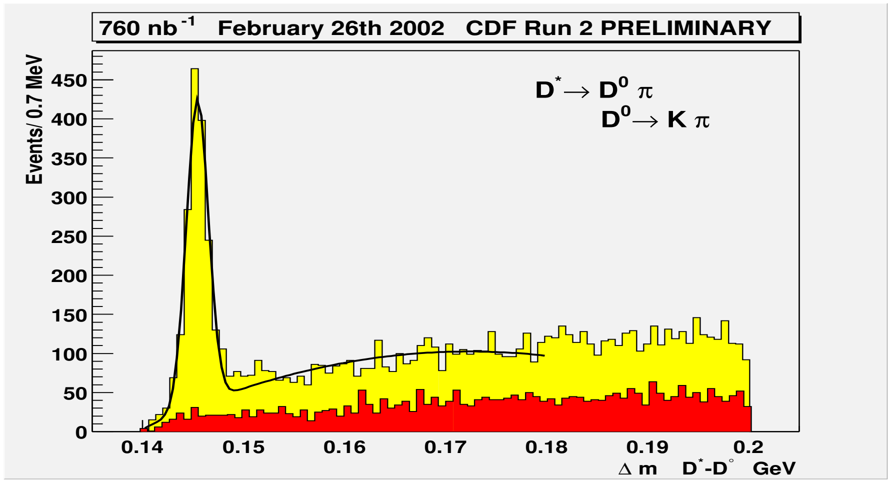




SVT + trigger info

Offline reconstruction





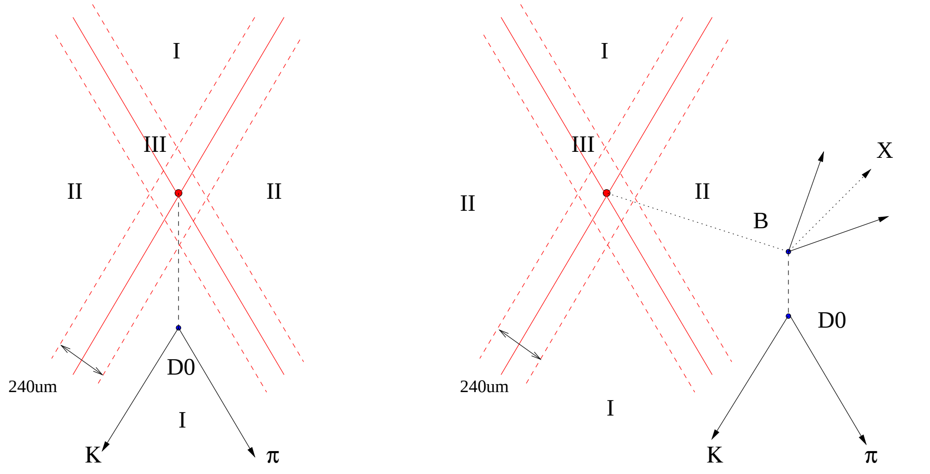
SVT + trigger info

Offline reconstruction

Charm Production Run II

SVT D mesons with $p_T > 5.0\ GeV$. $\sigma(c\bar{c}) >> \sigma(b\bar{b})$ at low p_T.

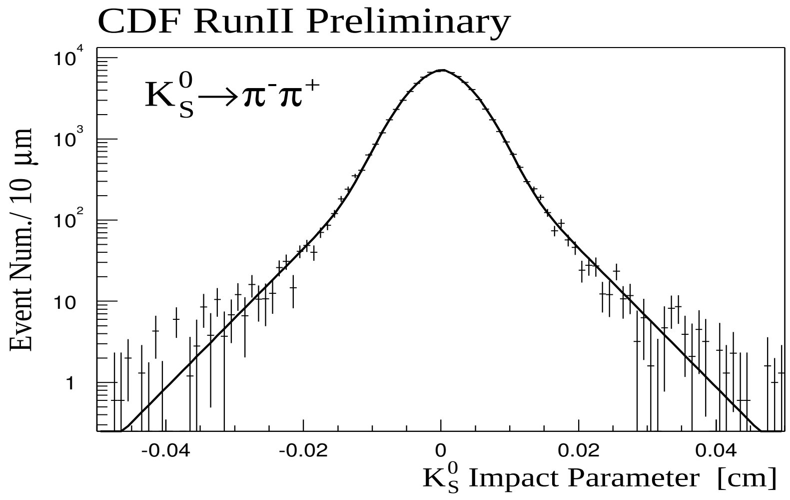
Need to measure f_b, *fraction of D from* $B \rightarrow D$ *- proper time fit is difficult because of trigger bias* $\Rightarrow$ *use impact parameter of D to PV:*



- Model the SVT D from B impact parameter in MC, $F_B(d_0)$.
- Measure the detector d_0 resolution using $K_s \rightarrow \pi\pi$ with the same selection critiria as $D \rightarrow K^-\pi^+$, $F_D(d_0)$.

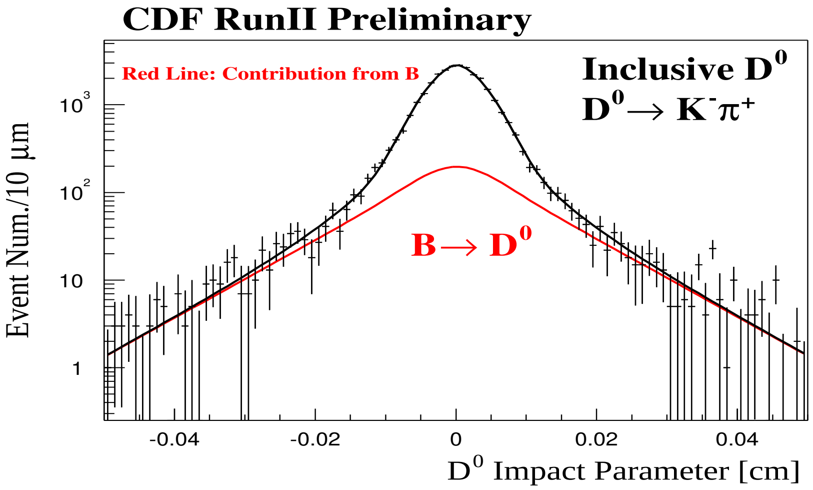
$$F(d_0) = f_B \int F_B(x) F_D(d_0 - x)dx + (1 - f_B) F_D(d0)$$

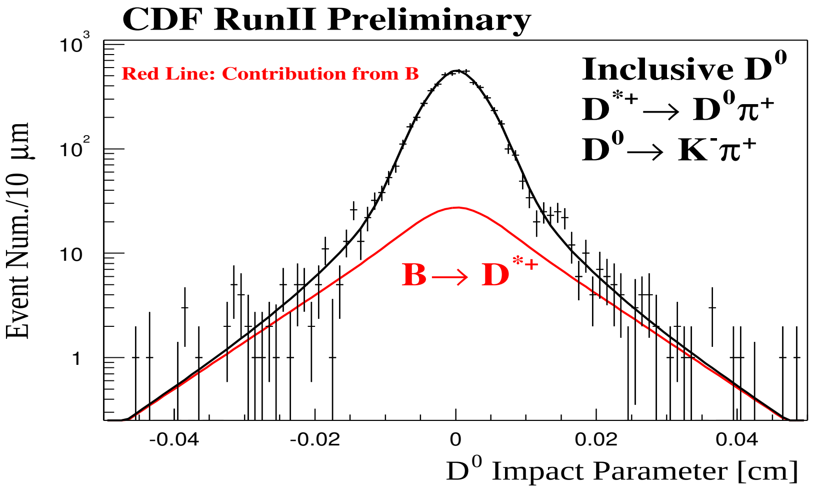
Direct Charm Production Run II



From $K_s \rightarrow \pi\pi$ we find $F_D(d_0)$ = Gaussian + exp tails. *Tails need to be modeled carefully*

Fraction of $B \rightarrow D$ *is* $\propto$ 16% for D^0, 11% for $D^{+,*+}$ and 35% for D_s. *Much larger when tails excluded from* $F_D(d_0)$





CONCLUSION

Lots of questions unanswered in Run I Top cross-section contributions, low momenta b and onia differential production cross-sections, charmonium polarization, double differential production correlations, is there an η_b?....

Run II new and improved triggers ! Larger kinematic coverage of the dimuon triggers, $|\eta| < 2$, $p_t(\mu) < 1.5$ GeV/c ($|\eta| < 0.6$) compared to Run I. Track triggers $\Rightarrow$ large SVT b/c yields at $p_t(l) < 6GeV/c$ and $p_t(track) > 2GeV/c$. *Test theory predictions in a different kinematic region.*

Milestones on the road to HVQ production: Sufficient statistics of reconstructed onia, c/b signals collected with stable triggers, separation of prompt J/ψ and D from bs. New W cross-section measurement on the road to top.

CONCLUSION

Run II HVQ production measurements at $\sqrt{s} = 2$ TeV - winter '02/'03