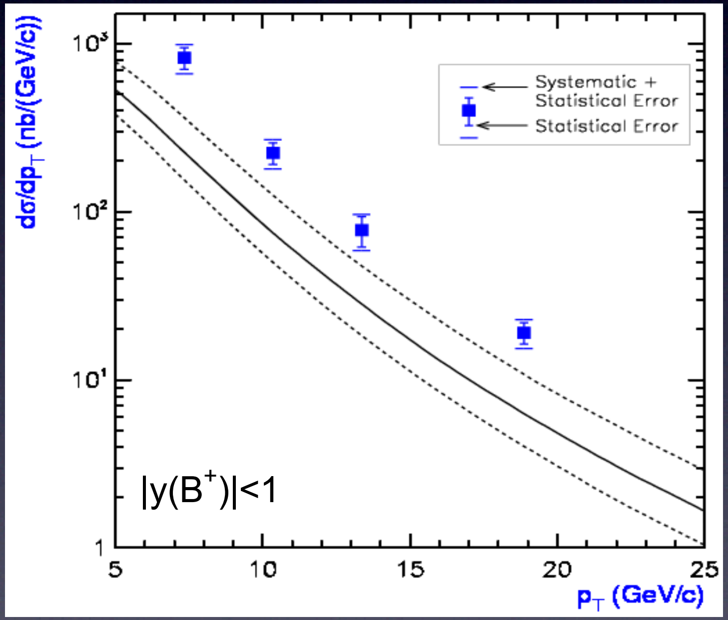
Heavy Flavour Production at the Tevatron

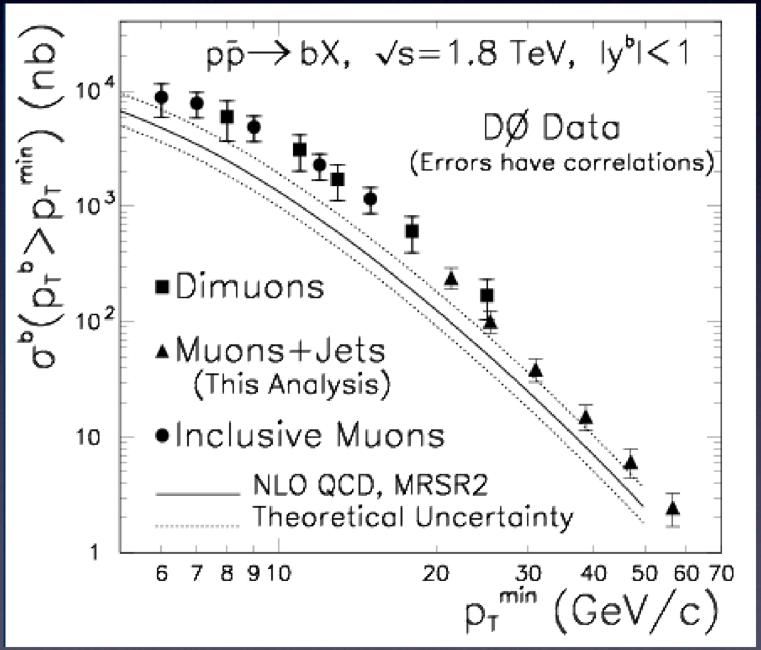
CHARM 07, Ithaca NY, 05 Aug 2007

Jonas Rademacker (University of Bristol) on behalf of CDF and DØ.

Theory hits Reality in Tevatron Run I

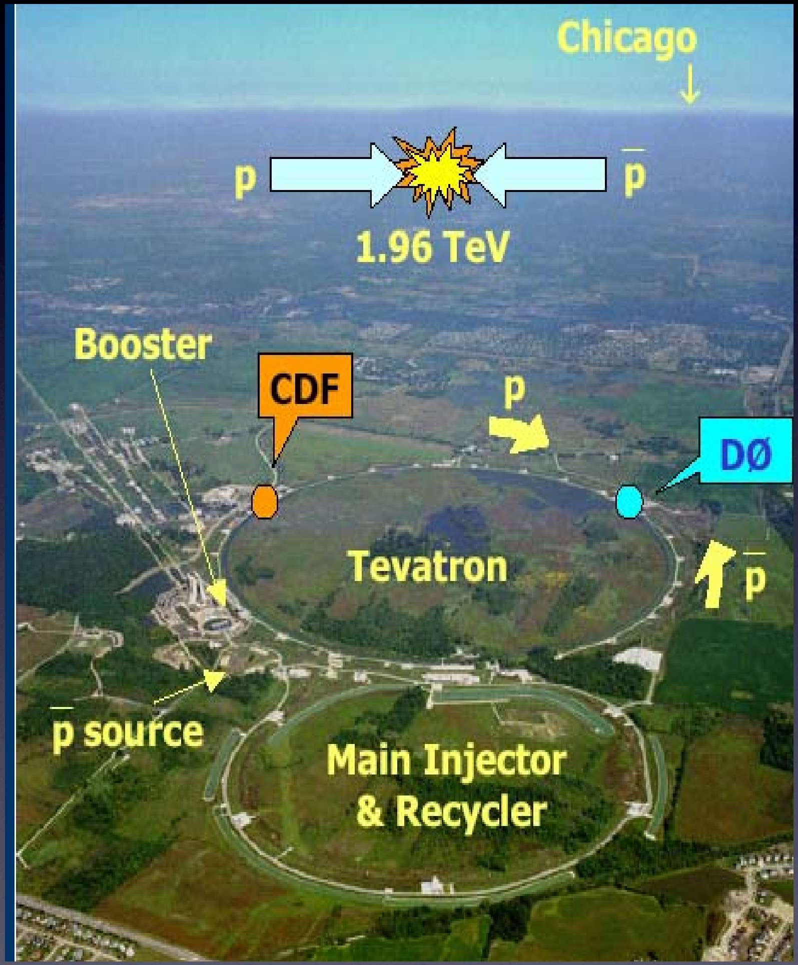
Measured and predicted b production cross section as function of pt at CDF and DØ (B+, and incl b respectively). Measurement > theory.





Since then: better theory (e.g. FONLL). And a better experiment: Tevatron RunII, upgraded collider and detectors

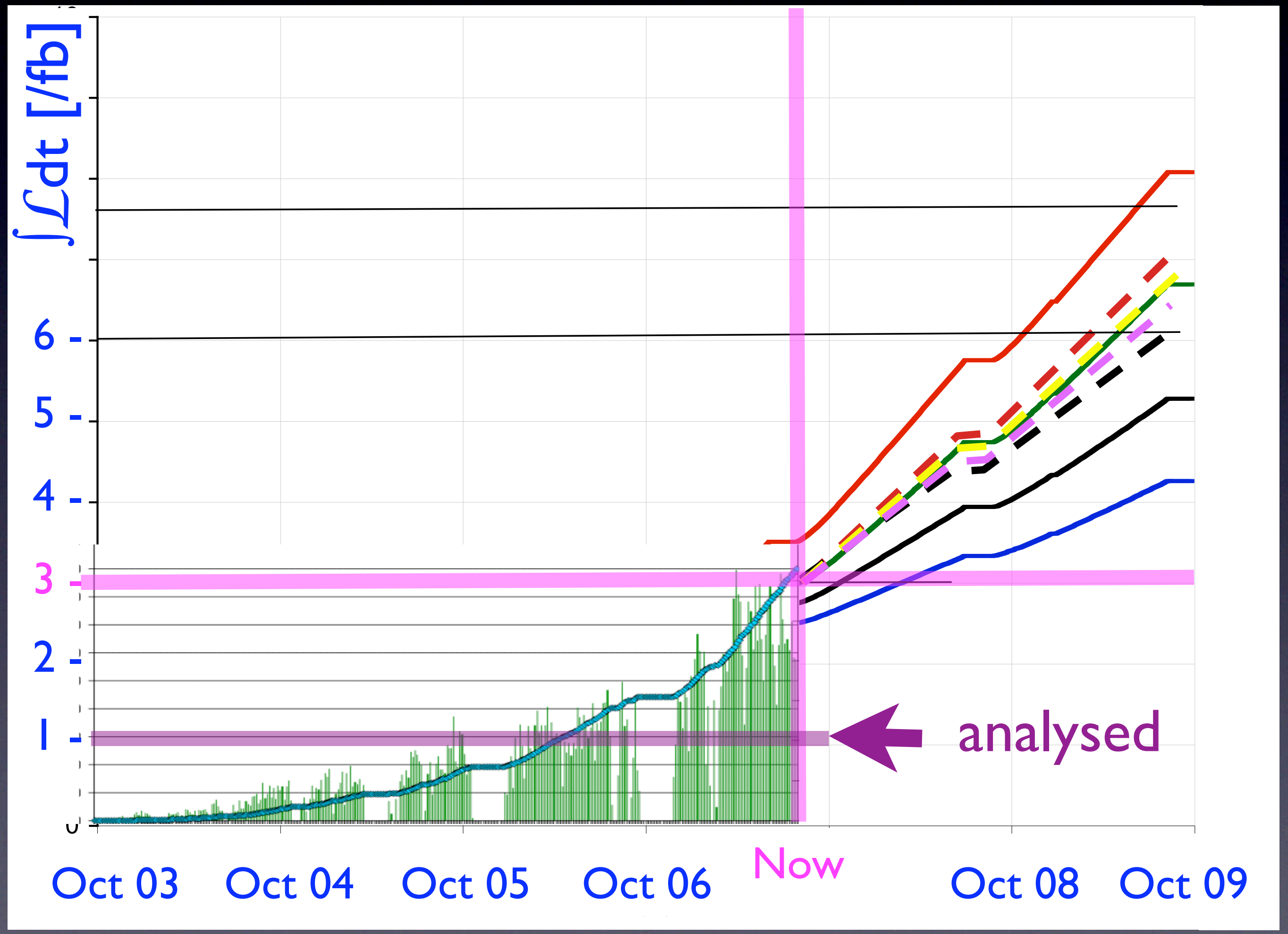
Tevatron Run II



- Run II started in 2001
- Tevatron collides protons and anti-protons at cm energy 1.96TeV
- 2.5 M times per second.
- Huge b and charm x-section.
- Detector upgrades for heavy flavour physics, e.g. high-resolution Si vtx trackers, trigger upgrades.

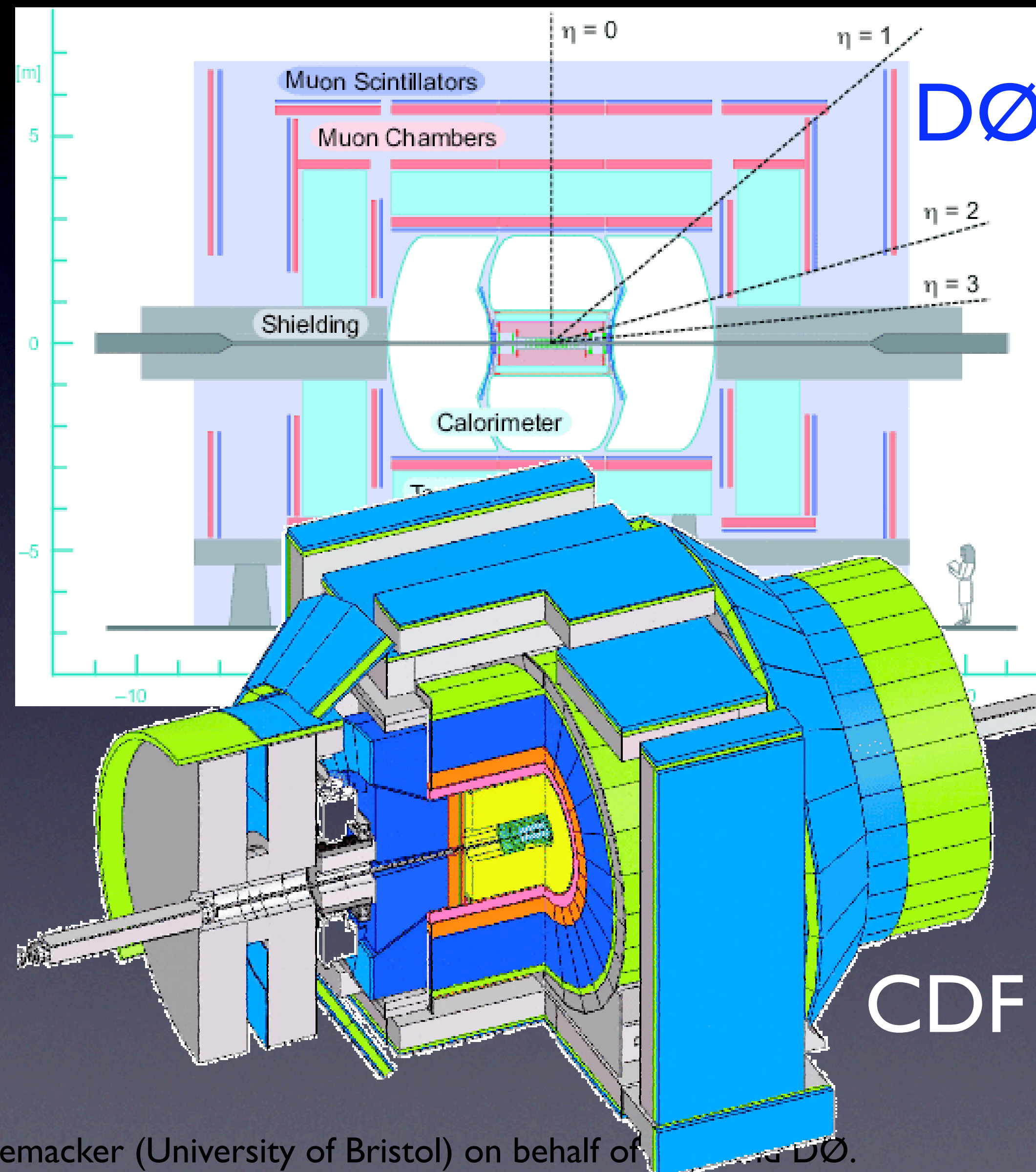
Tevatron Luminosity

- 3/fb delivered
- ca 1/fb of those analysed
- (all numbers per experiment)

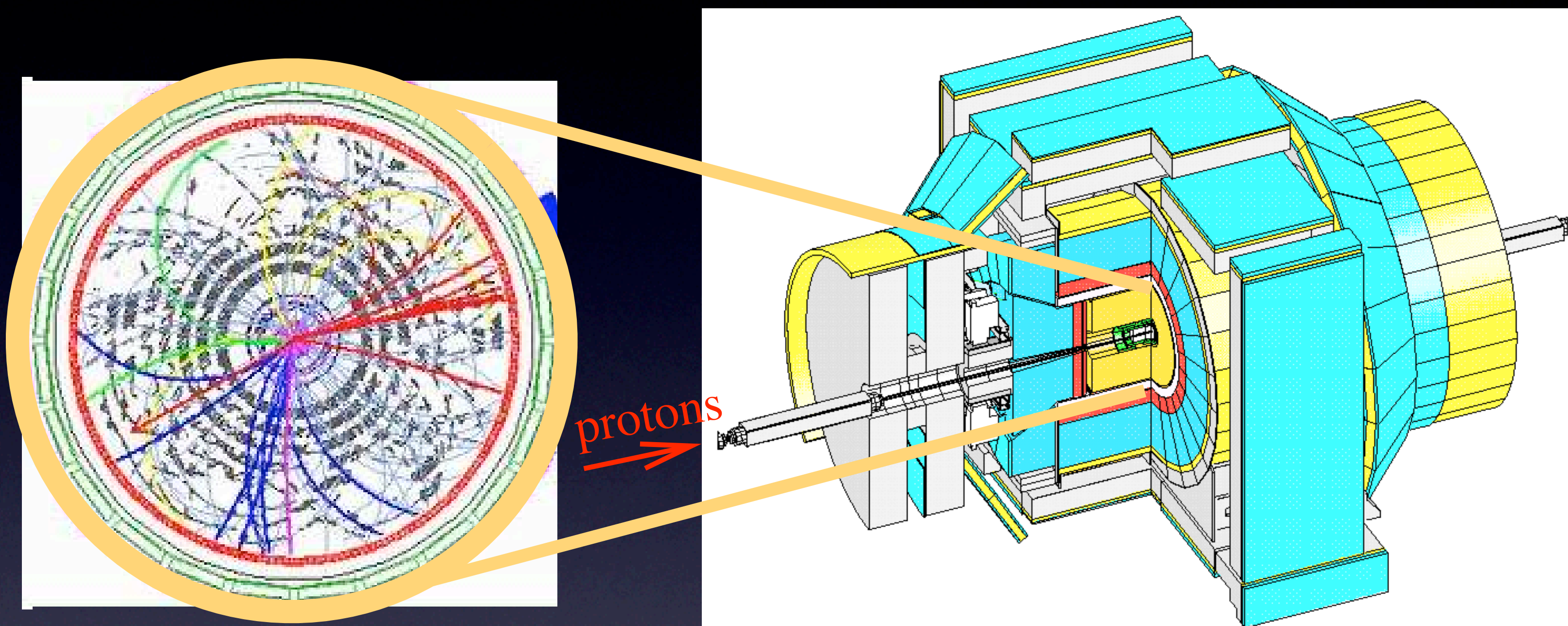


Detectors

- Both detectors good for heavy flavour physics, with excellent vtx resolution, muon coverage, trigger...
- DØ's special skill: Large muon coverage, to $|\eta| \leq 2$. Excellent for leptonic and semileptonic modes.
- CDF's special skill: High bandwidth displaced-track trigger. Unique capabilities in fully hadronic modes.



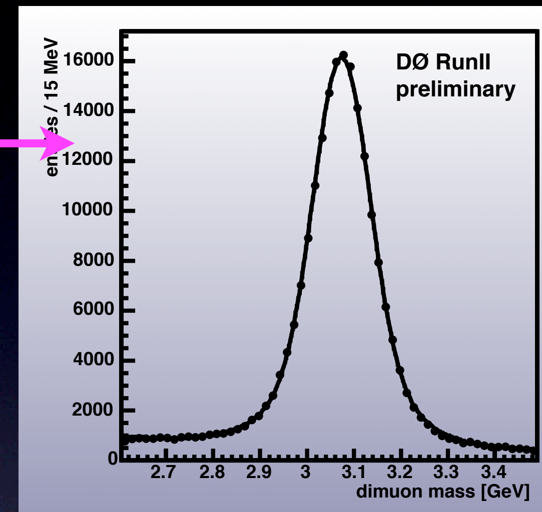
Tevatron Events

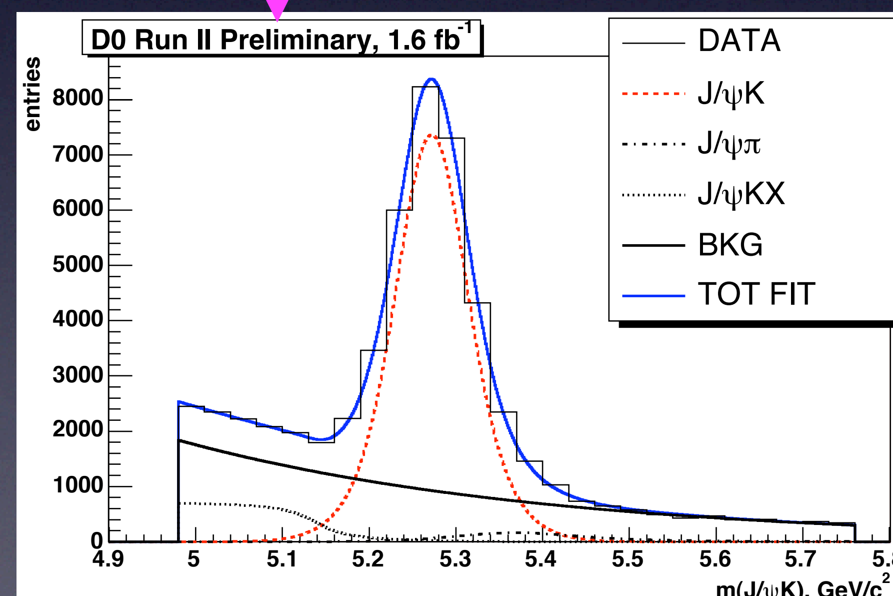


- One (usually very busy) event every 396ns
- Write to tape only ~0.003% (CDF).
- Which ones? Trigger crucial.
- Two strategies for heavy flavour: Leptons, or displaced tracks.

Di-μ trigger

180,000 J/ψ→μμ in 0.11/fb
28,000 B→J/ψK in 1.6/fb
at DØ

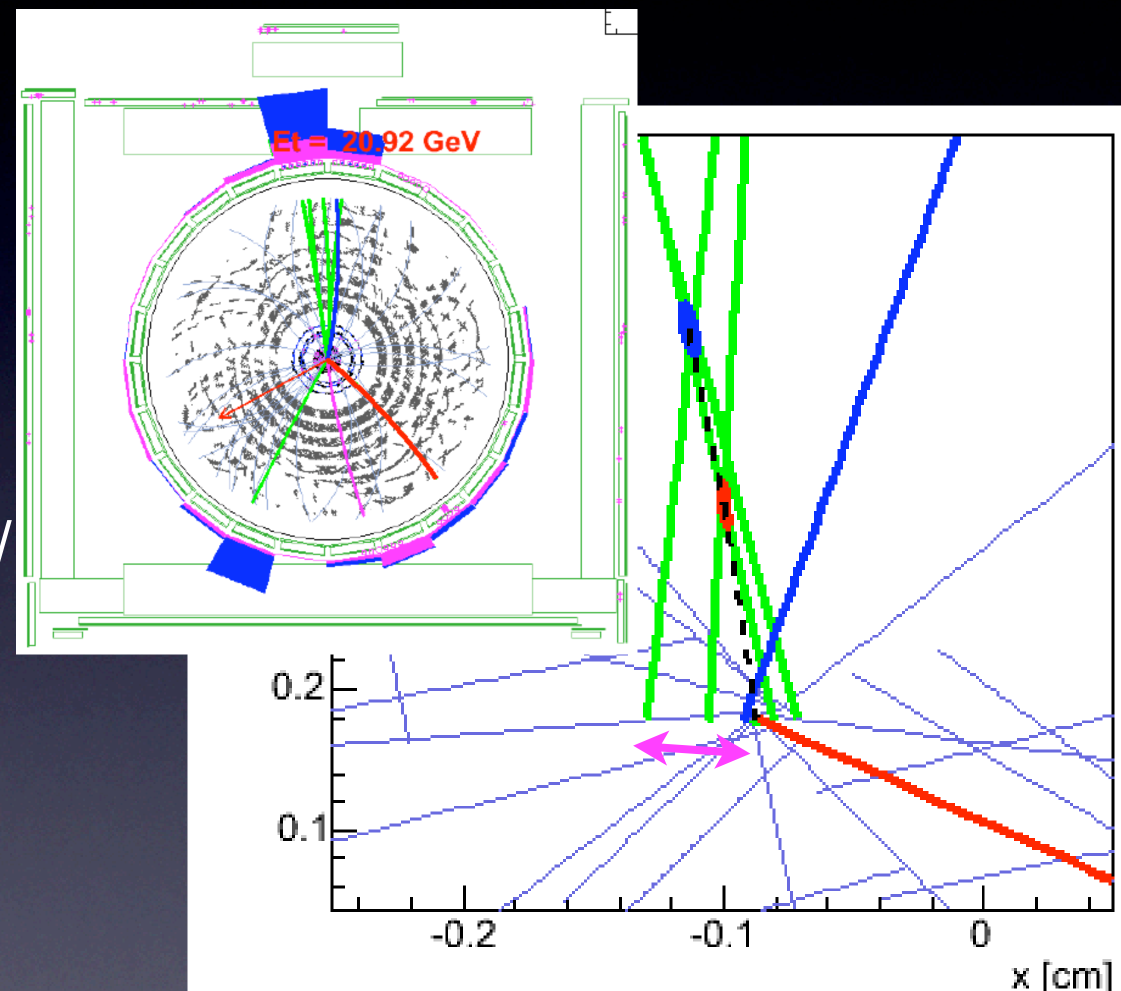




- Finds J/ψ, B→J/ψX, B→μμ(X)
- Very clean trigger in hadron environment.
- Especially powerful at DØ with its excellent μ coverage.

Displaced Track Trigger

- Requires two tracks with pt > 2GeV IP > ~0.1mm
- Finds fully hadronic B and D decays (the majority)
- Designed for B, but also good for Charm. E.g. in 1.1/fb at CDF: 13 M $D^{o} \rightarrow K\pi$, 0.3M $D_s \rightarrow \Phi(KK)\pi$.
- CDF's two-track trigger has enough bandwidth to run w/o additional lepton requirements.

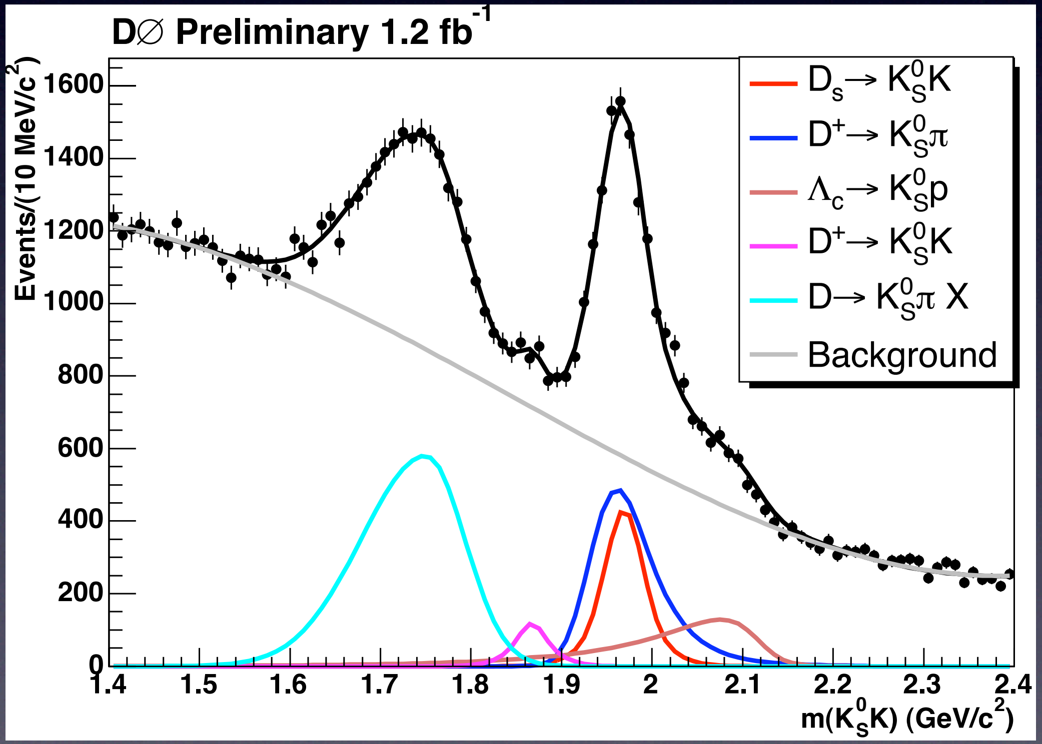


Trigger on this distance

Track + lepton

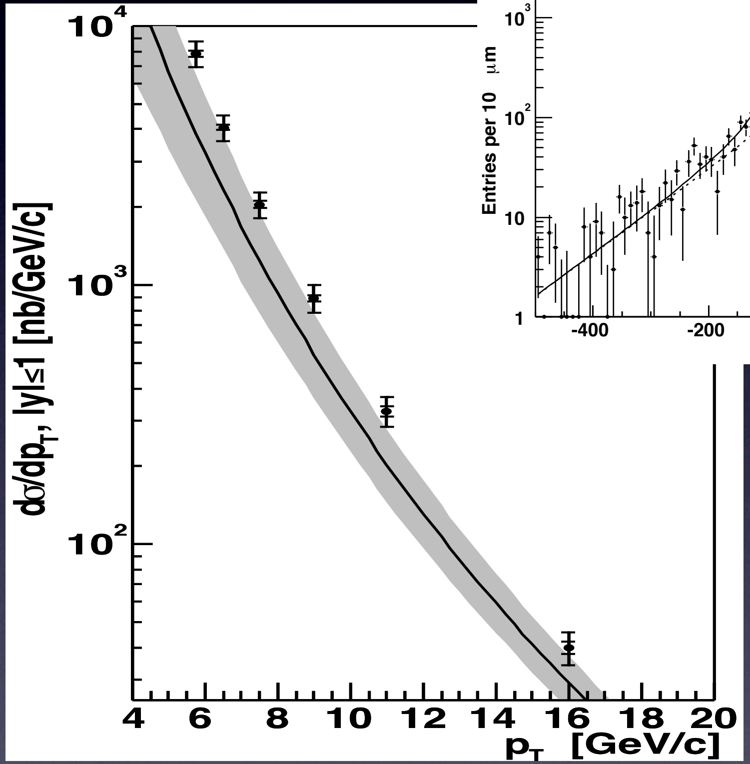
- A mixture between the above
- Requires (at least) one displaced track, and one lepton (e or μ).
- Finds $B \to D \ell \nu$

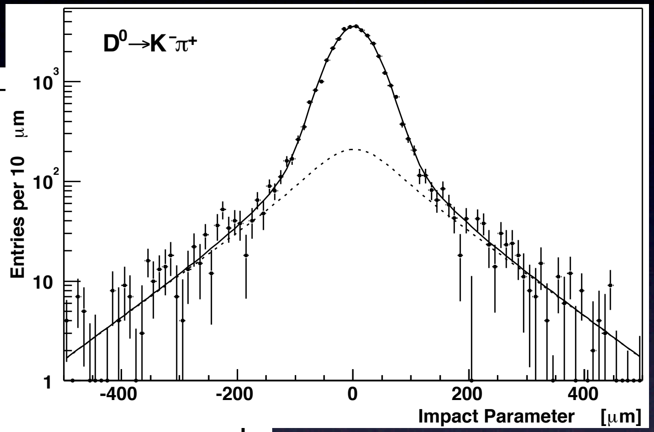
D mass in $B \to D(K_s X) \ell \nu$



Direct Charm Meson production x-section

- Fully reconstructed D meson, hadronic modes from 5.8/pb.
- Plot shows σ(|y|≤1) for D°. Grey band shows FONLL prediction. Plots for D*, D+, Ds look similar.
- Measured/FONLL ~1.5–2, but OK within uncertainties.



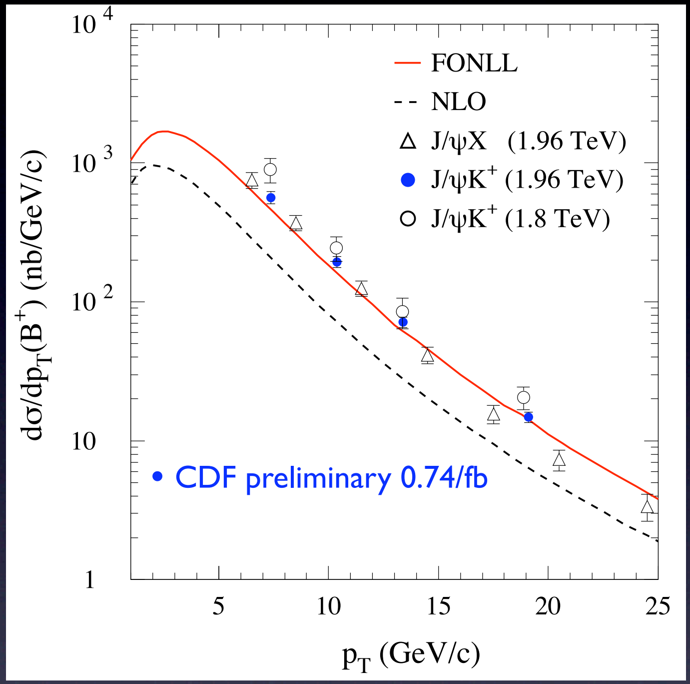


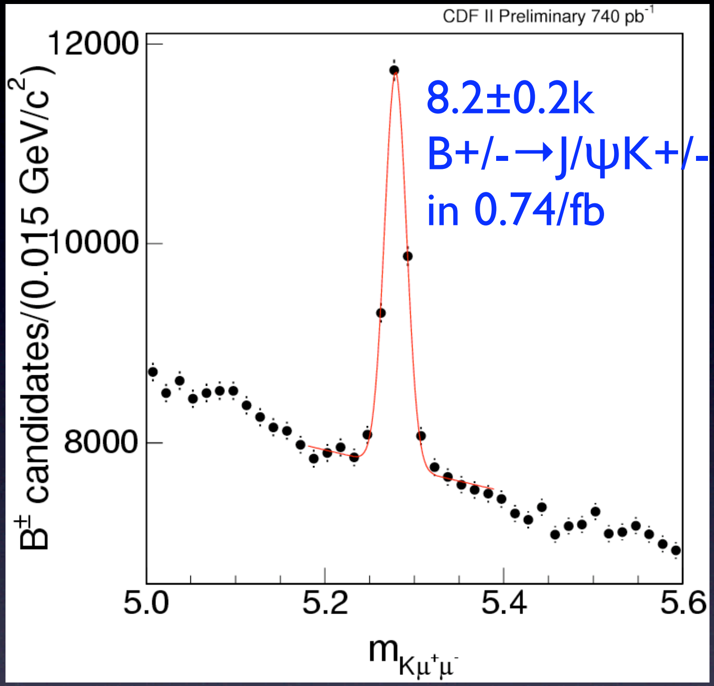
Use impact parameters to distinguish direct charm from B

$$\sigma(D^0, p_T > 5.5\mathrm{GeV}, |y| \leq 1) = (13.3 \pm 0.2(stat) \pm 1.5(sys))\,\mu b$$

For FONLL see: hep-ph/0312132

B x-section





- Inclusive B→J/ψX, B→DℓνX [not in this plot] and excl B+ → J/ψK+ agree well with each other, Run I, and FONLL.
- Latest result: exclusive B+→J/ψK+ — more numbers in backup slides

$$\sigma(p\bar{p} \to B^+, p_t > 6\text{GeV}, |y| < 1) = (2.64 \pm 0.12(\text{stat}) \pm 0.21(\text{sys}))\mu b$$

correlated b-$\bar{b}$ x-section

- For *correlated* b-$\bar{b}$ x-section (*both* b quarks within a certain, central rapidity and pt range), higher order terms expected to be smaller, NLO should work better.
- Past Tevatron results inconclusive/contradictory.
- Table shows ratio of previously measured σ/NLO-prediction. (New result on next slides.)

channel	R_{2b} for $p_T^{\min}$ (GeV/c) =			
	$6-7$	10	15	$\simeq 20$
$b+\bar{b}$ jets			1.2 ± 0.3	
$b+\bar{b}$ jets				1.0 ± 0.3
$\mu + b$ jet		1.5 ± 0.2		
$\mu^+ + \mu^-$	3.0 ± 0.6			
$\mu^+ + \mu^-$	2.3 ± 0.8			

Note: Table 2: Ratio R_{2b} of $\sigma_{b\bar{b}}$, the observed cross section for producing both b and $\bar{b}$ quarks, centrally and above a given $p_T^{\min}$ threshold, to the exact NLO prediction.

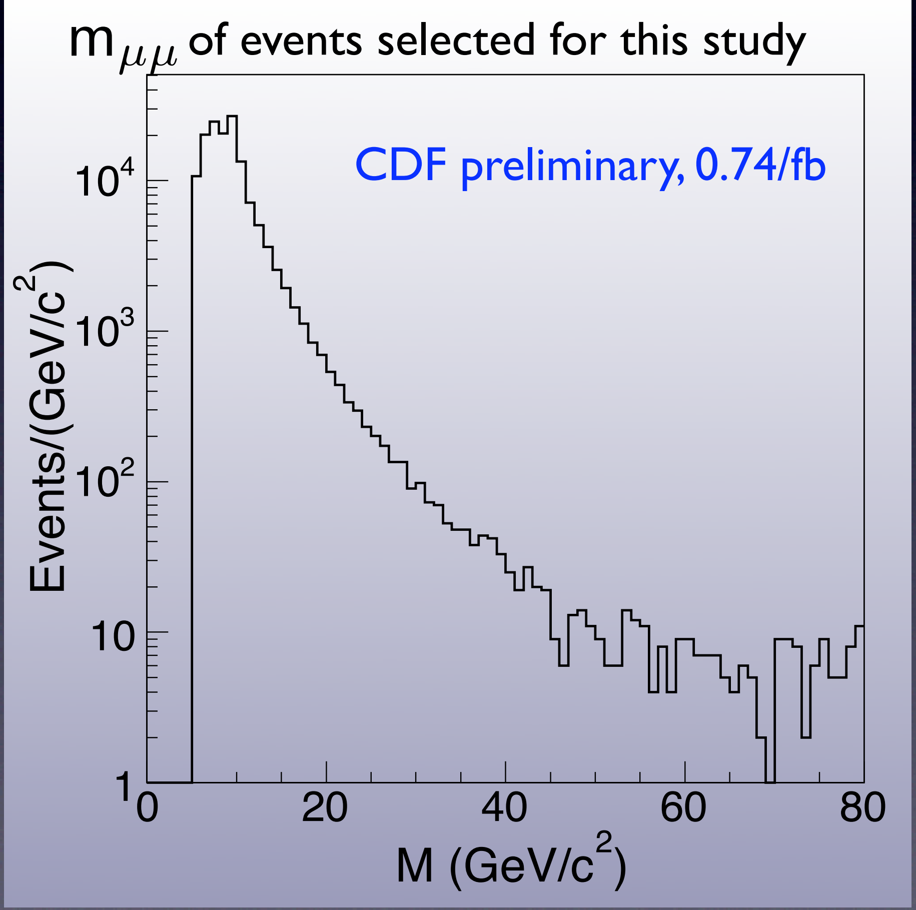
Fabio Happacher showed this table at DIS-06 (http://www-conf.kek.jp/dis06/doc/WG5/hfl20-happacher.ps)

[I modified they ways the uncertainties are presented, possibly adding mistakes and rounding errors in the process]

Correlated $b\bar{b}$ and $c\bar{c}$ x-section using μμ

- Reconstruct μμ pairs with

$$\begin{aligned} p_T &\geq 3GeV \\ |\eta| &\leq 0.7 \\ m_{\mu\mu} &\in [5,80]GeV \end{aligned}$$



- Corresponds to bb pairs with

$$\begin{aligned} p_T &\geq 2GeV \\ |y| &\leq 1.3 \end{aligned}$$

Correlated $b\bar{b}$ and $c\bar{c}$ x-section using μμ

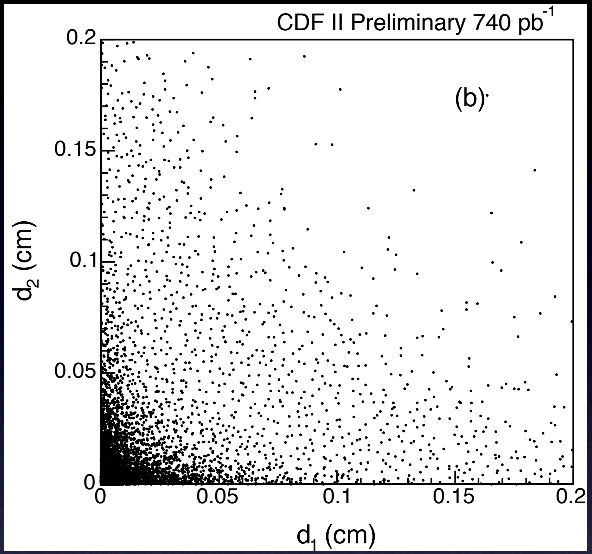
- Use impact parameters to distinguish

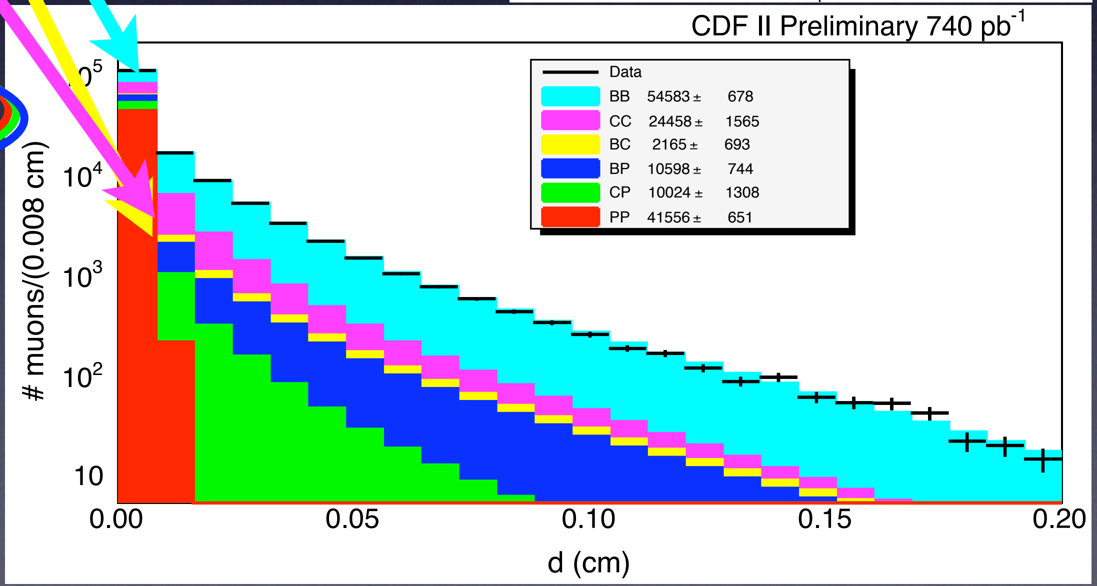
$b \rightarrow \mu \quad , \quad b \rightarrow \mu$

$b \rightarrow \mu \quad , \quad c \rightarrow \mu$

$c \rightarrow \mu \quad , \quad c \rightarrow \mu$

and contributions with one or more prompt μ.





Fit done in 2-D. This is the 1-D projection of 2-D IP distribution and fit

Correlated $b\bar{b}$ and $c\bar{c}$ x-section: results

- x-sections:

$$\sigma_{\mathrm{b}\to\mu,\bar{\mathrm{b}}\to\mu} = (1549 \pm 133)\mathrm{pb} \qquad \sigma_{\mathrm{c}\to\mu,\bar{\mathrm{c}}\to\mu} = (624 \pm 104)\mathrm{pb}$$

$$\sigma_{\mathrm{b}\bar{\mathrm{b}}}\,(\mathrm{p_T} \geq 6\mathrm{GeV},\ |\mathrm{y}| \leq 1) = (1618 \pm 148 \pm [\sim 400\ \mathrm{fragmentation}])\ \mathrm{nb}$$

- Ratios (includes both exp. and theory error):

With Peterson fragmentation parameter....

ϵ=0.006

$$\frac{\sigma^{\mathrm{measured}}_{\mathrm{b}\to\mu\ \bar{\mathrm{b}}\to\mu}}{\sigma^{\mathrm{NLO}}_{\mathrm{b}\to\mu\ \bar{\mathrm{b}}\to\mu}} = 1.2 \pm 0.2$$

$$\frac{\sigma^{\mathrm{measured}}_{\mathrm{c}\to\mu\ \bar{\mathrm{c}}\to\mu}}{\sigma^{\mathrm{NLO}}_{\mathrm{c}\to\mu\ \bar{\mathrm{c}}\to\mu}} = 2.7 \pm 0.6$$

ϵ=0.002*

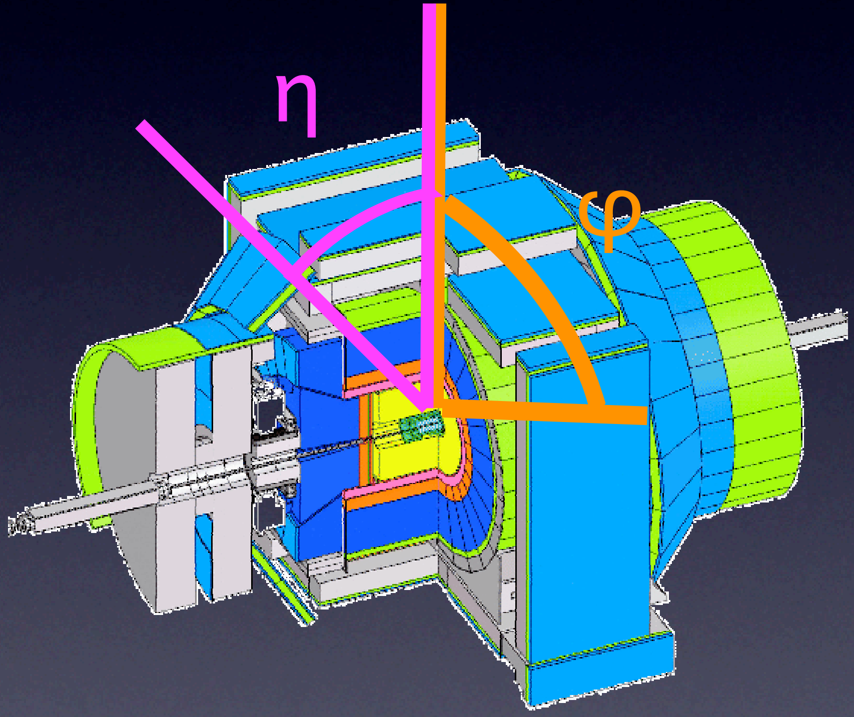
$$\frac{\sigma^{\mathrm{measured}}_{\mathrm{b}\to\mu\ \bar{\mathrm{b}}\to\mu}}{\sigma^{\mathrm{NLO}}_{\mathrm{b}\to\mu\ \bar{\mathrm{b}}\to\mu}} = 1.0 \pm 0.2$$

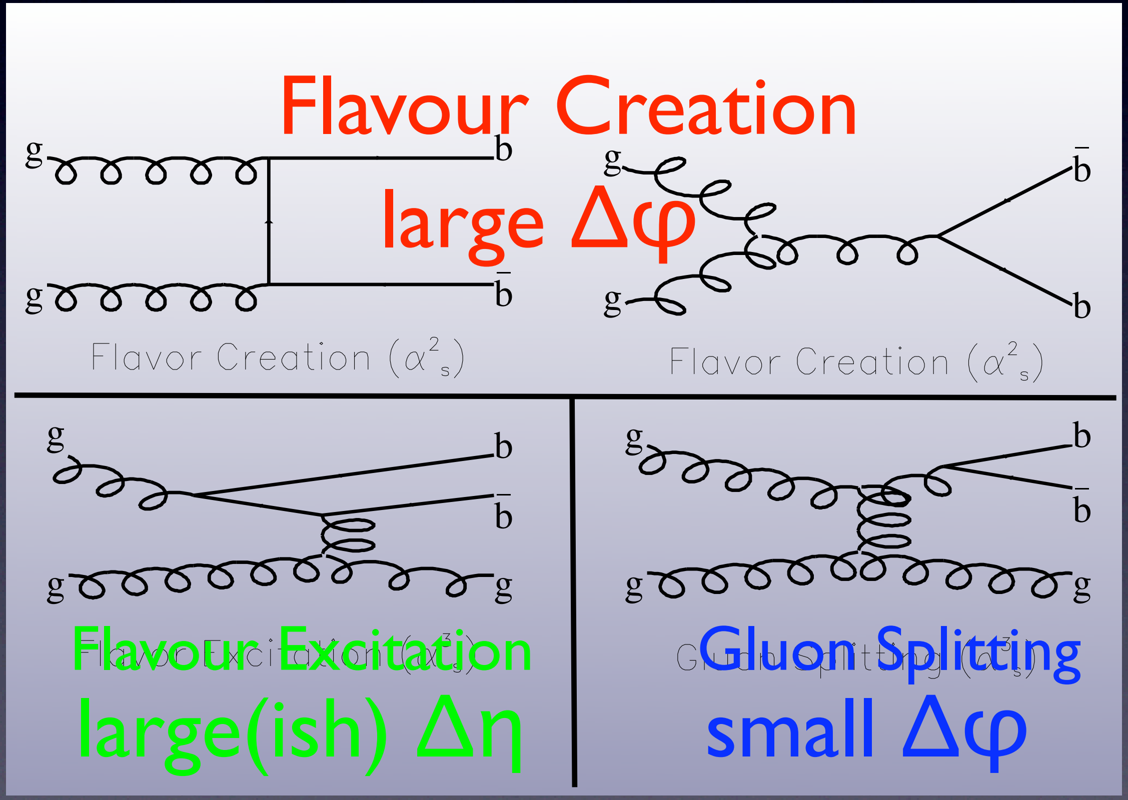
$$\frac{\sigma^{\mathrm{measured}}_{\mathrm{c}\to\mu\ \bar{\mathrm{c}}\to\mu}}{\sigma^{\mathrm{NLO}}_{\mathrm{c}\to\mu\ \bar{\mathrm{c}}\to\mu}} = 1.6 \pm 0.4$$

*Cacciari and Nason, Phys. Rev. Lett. 89, 122003 (2002)

Charm pair x-section

kinematic separation of production mechanisms

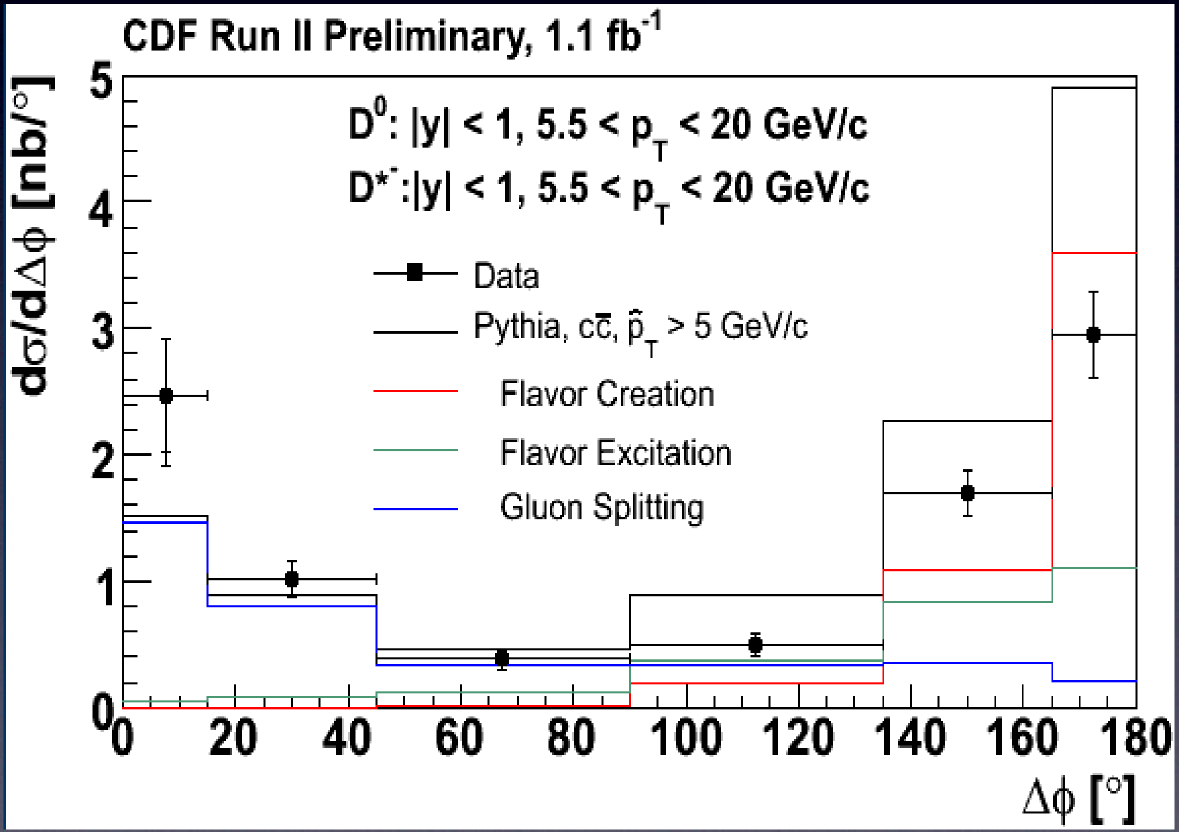




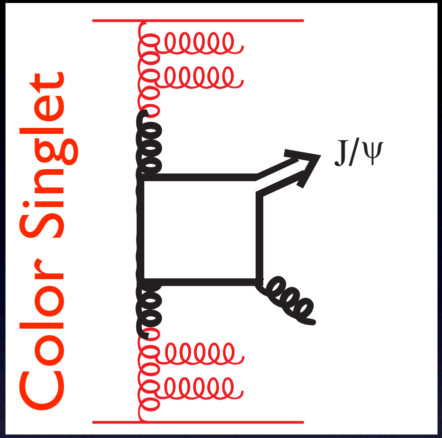
Charm pair x-section

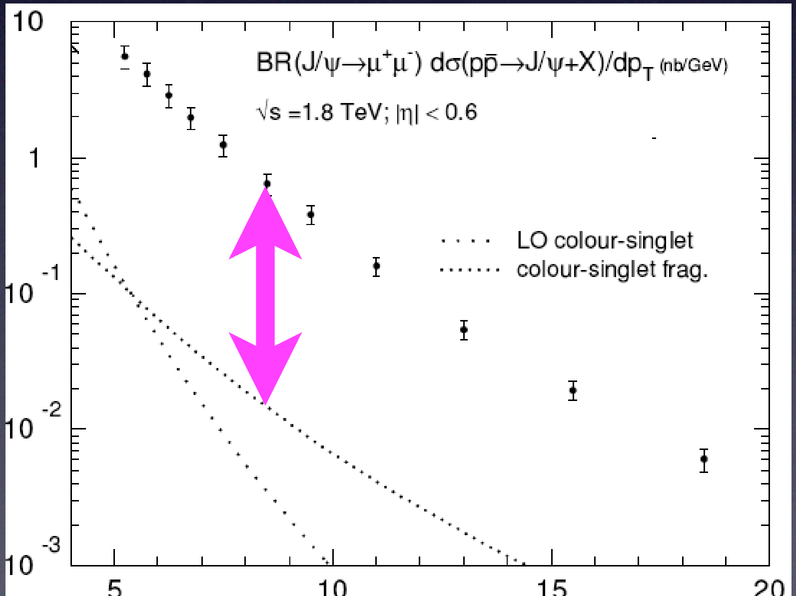
- Collinear production as important as back-to-back.
- Pythia (tune A, LO +parton shower): Overall OK but under-estimates collinear, and over-estimates back-to-back production.
- Similar for D+D*

D° D* x-section vs ΔΦ



Charmonium/Bottomium



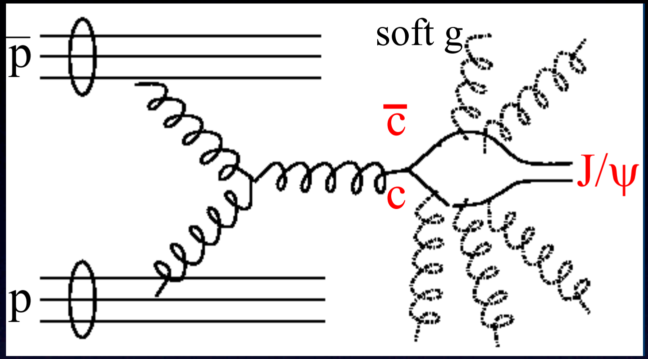


Lansberg, Int. J. Mod. Phys. A21 (2006)

- Can't produce colour-neutral $J^P = 1^-$ pair by simple gluon fusion.
- Simplest solution: produce a coloured state and "bleach" by radiating off one (hard) gluon.
- Dramatically fails to predict x-sections (meas/predict ~30 for J/ψ).

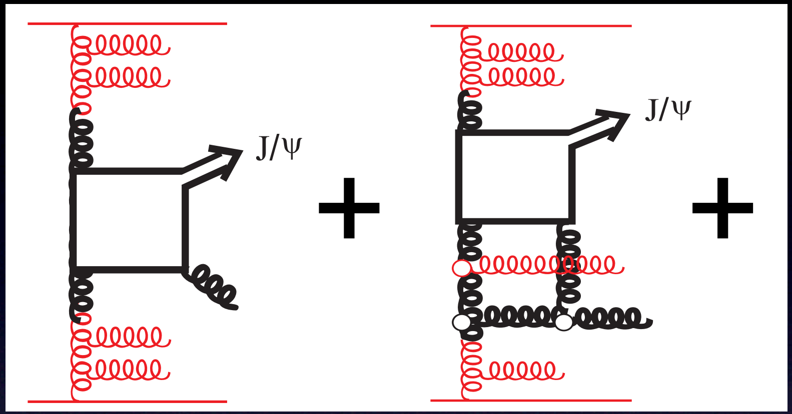
Charmonium/Bottomium

NRQCD - Colour Octet



- colour radiated off by soft gluons.
- Adjustable hadronisation parameters allow match to observed p_t spectra and x-sections.
- Predicts transverse polarisation of J/ψ

pQCD

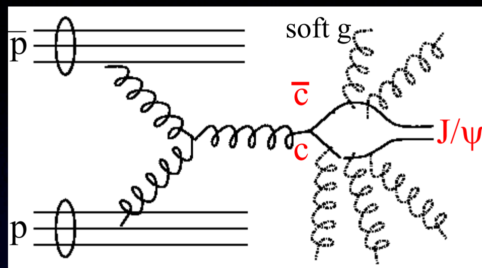


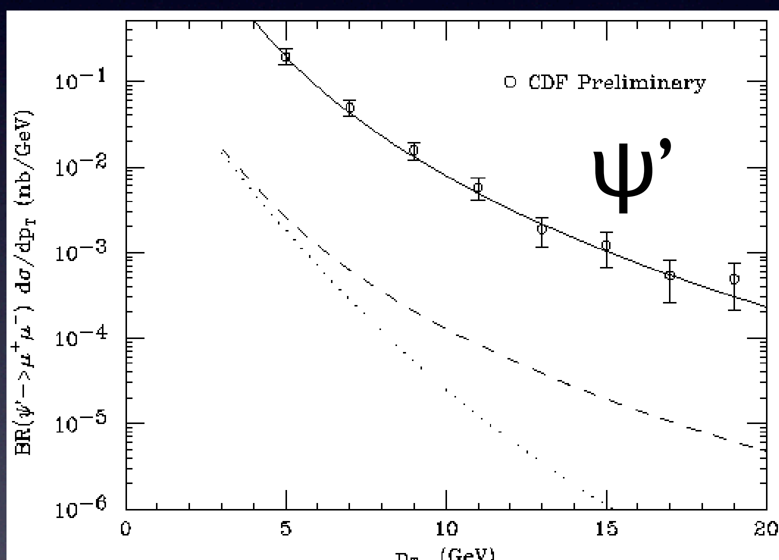
- Include 2nd order diagrams of the type shown above.
- LO pQCD calculation matches observed p_t spectra and x-section.
- Predicts longitudinal polarisation of J/ψ, increasing with pt.

V.A. Khoze, A.D. Martin, M.G. Ryskinand W.J. Sterling Eur. Phys. J. C 39, 163-171 (2005) hep-ph/0410020.
E.L. Berger, J. Qiu, Y. Wang hep-ph/0411026

Charmonium/Bottomium

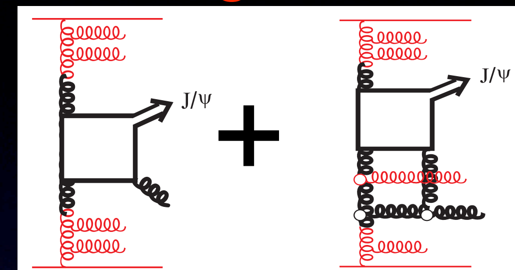
NRQCD - Colour Octed

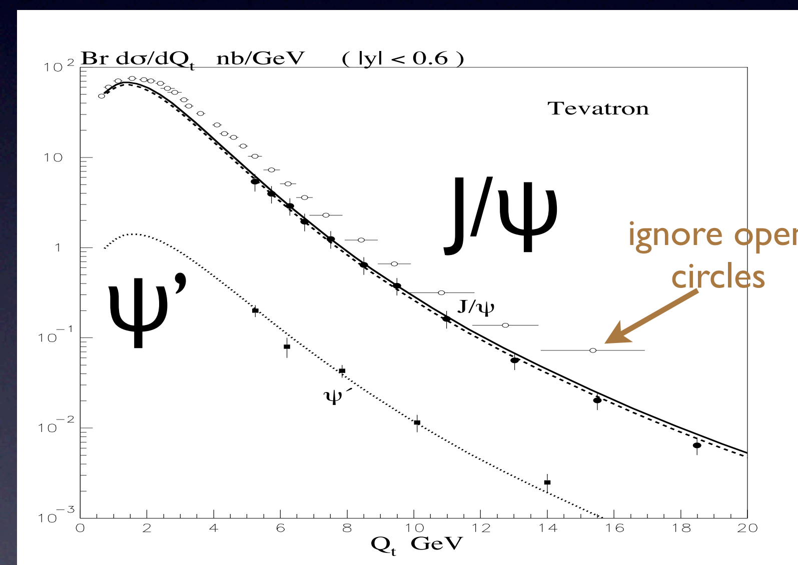




E. Braaten and S. Fleming, Phys. Rev. Lett. 74 (1995) 3327 [arXiv:hep-ph/9411365]

QCD with higher order terms





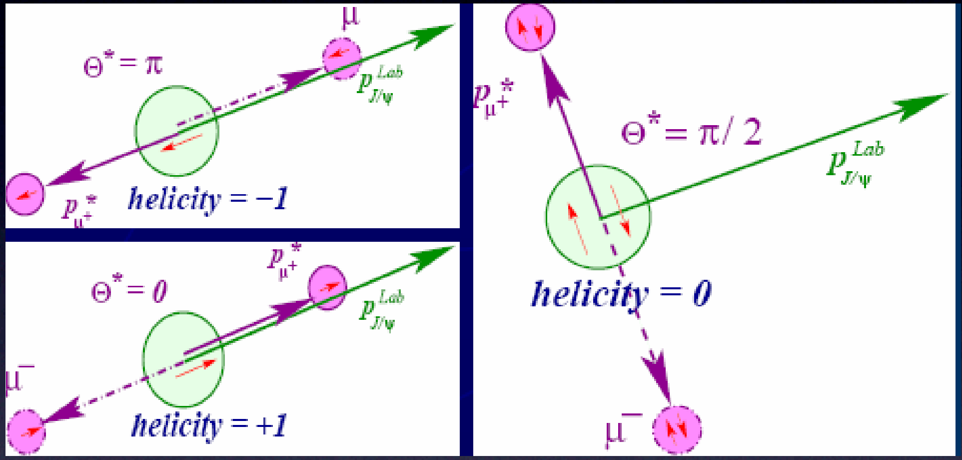
Khoze et al, Eur. Phys. J. C 39, 163-171 (2005) hep-ph/0410020

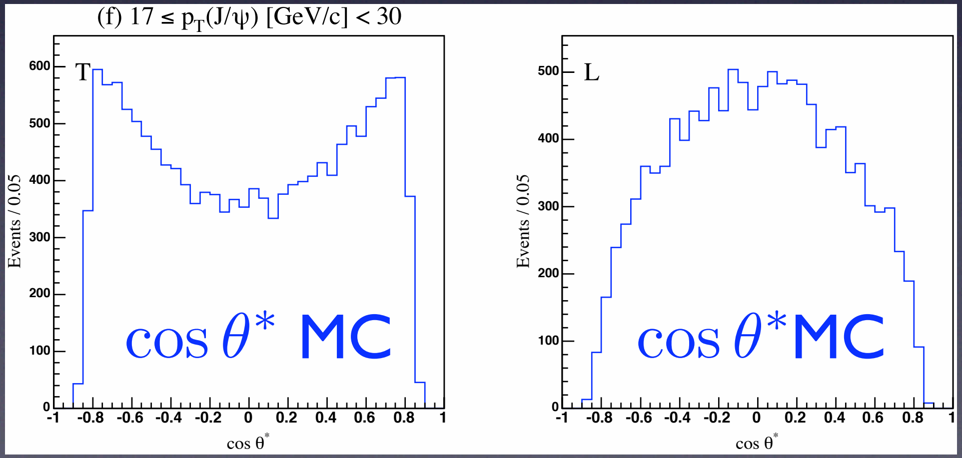
Both models describe differential x-sections well (data from RunI)
But they predict different polarisations - see next slide

Measuring onium polarisation

- Measure
$$\alpha \equiv \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$$
- α=0 if all helicity states equally likely.
- Extract from angular distribution. θ^* is the angle between J/ψ and μ in J/ψ restframe.

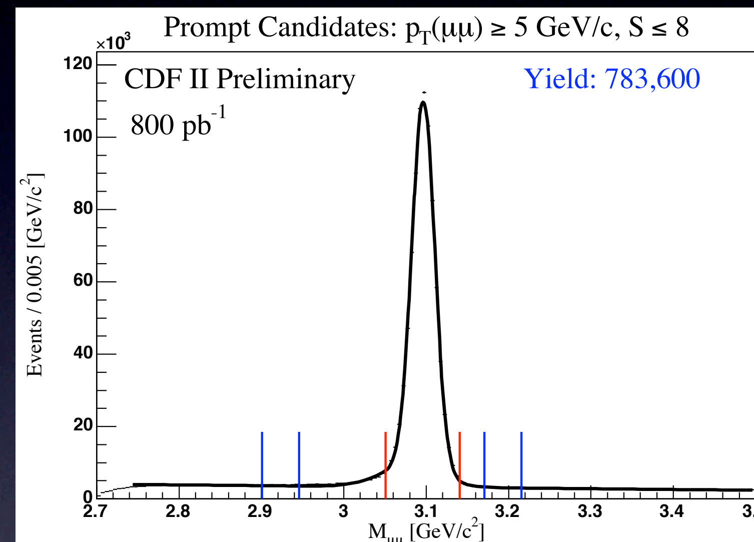
$$\frac{dN}{d(\cos\theta^*)} \propto 1 + \alpha \cos^2\theta^*$$



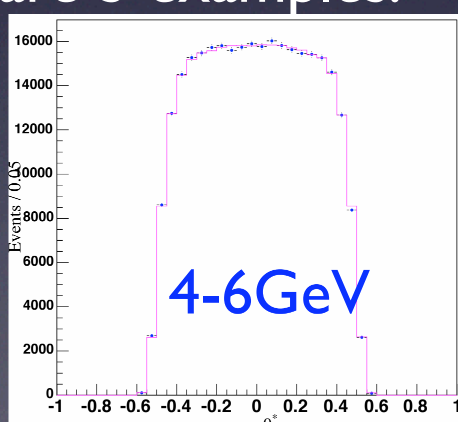


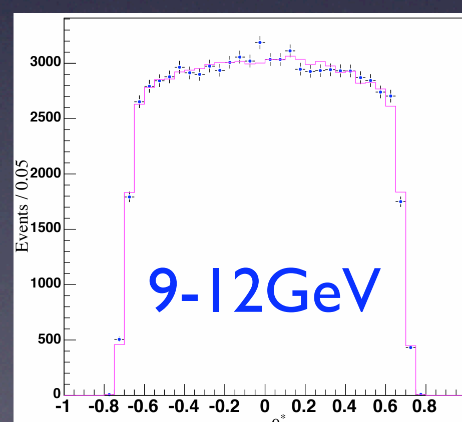
J/ψ polarisation

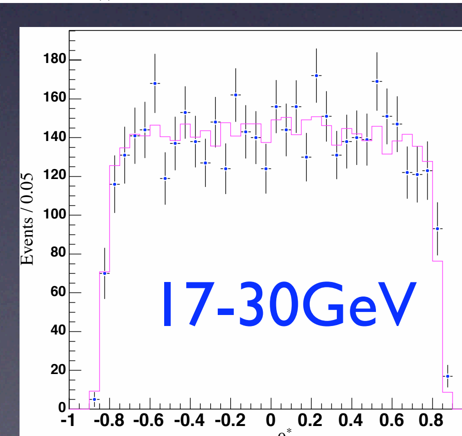
- Select ca 0.8M prompt J/ψ in 0.8/fb (B→J/ψX removed by IP-significance cuts)



- Fit $\cos\theta^*$ distribution in bins of pt - below are 3 examples:

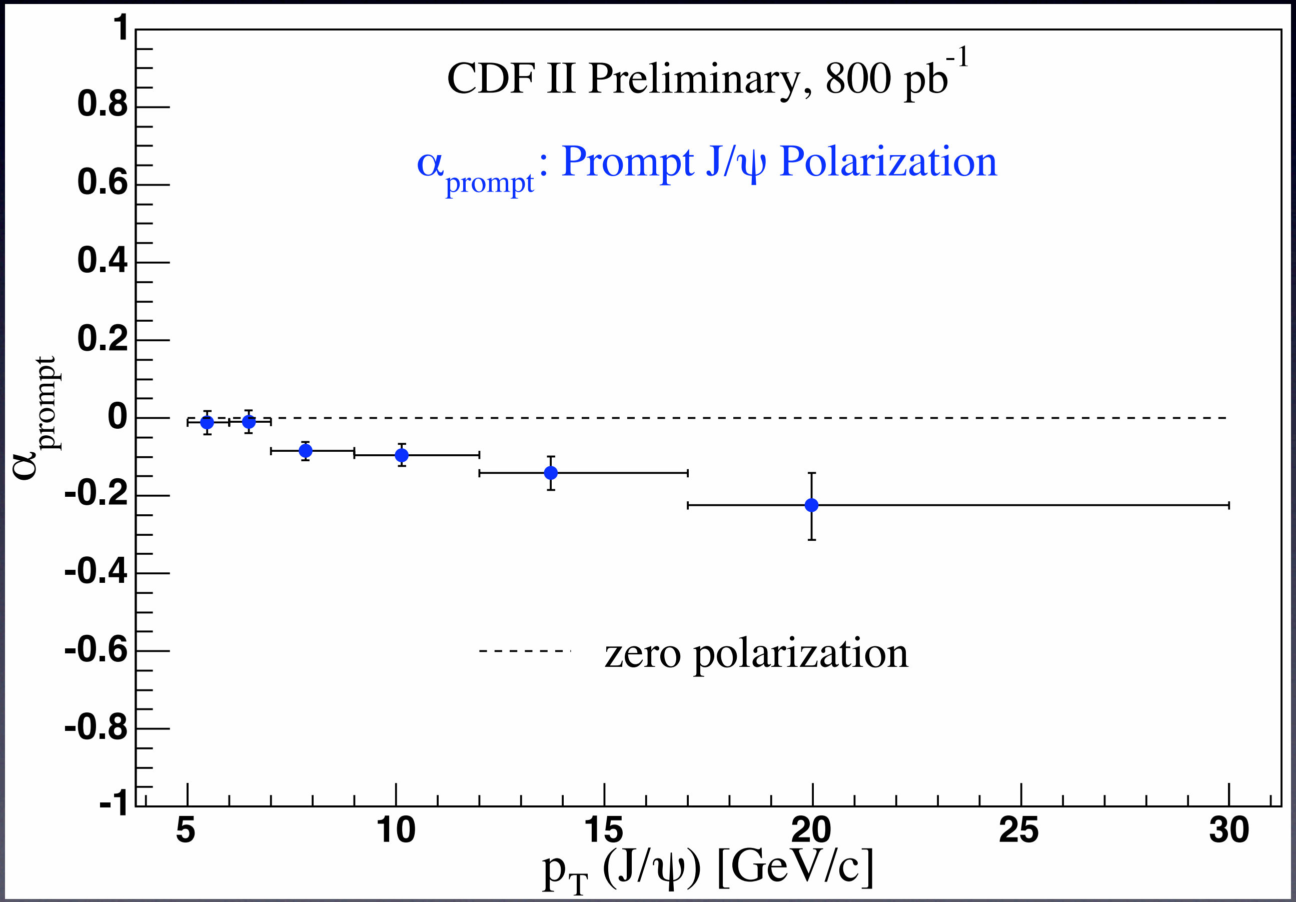






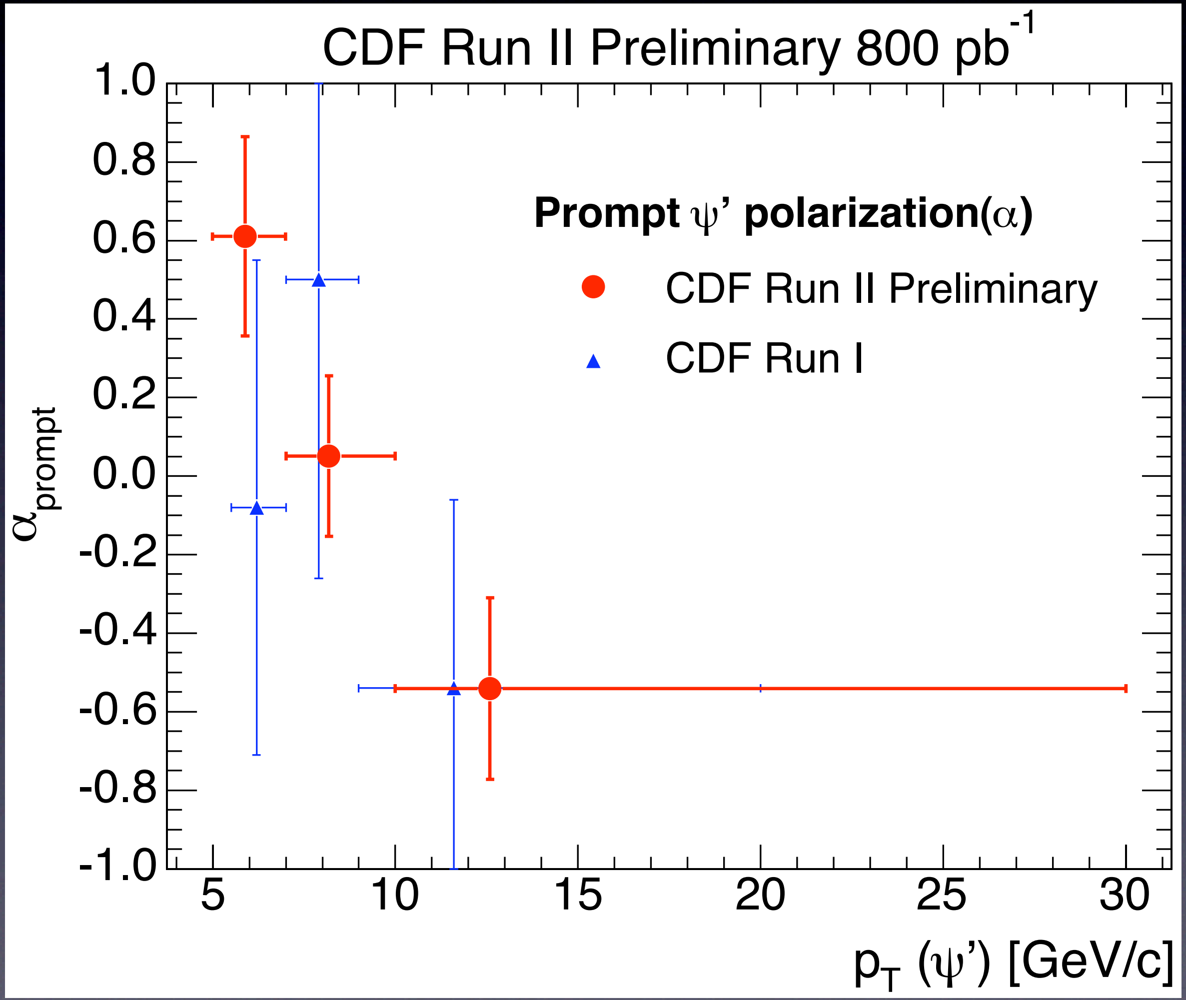
J/ψ polarisation

- Significant longitudinal polarisation, in contradition to to NRQCD/ colour octet prediction.

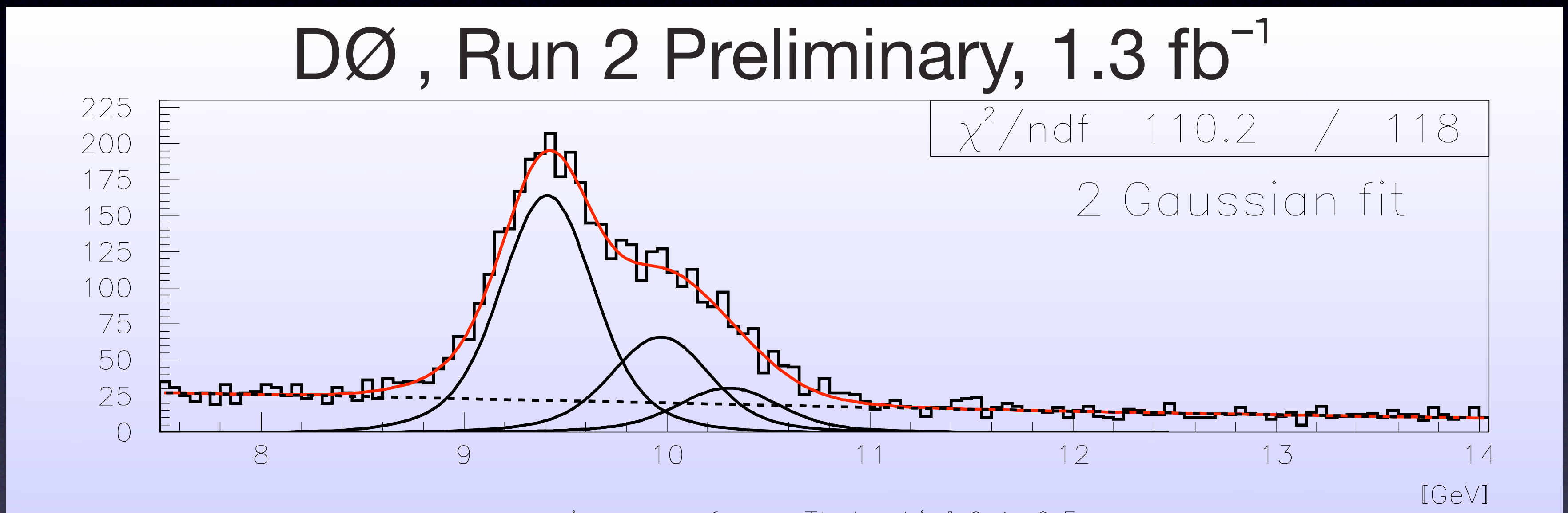


ψ(2S) polarisation

- Theoretically cleaner because no feed-down from higher states
- Also observe significant longitudinal polarisation



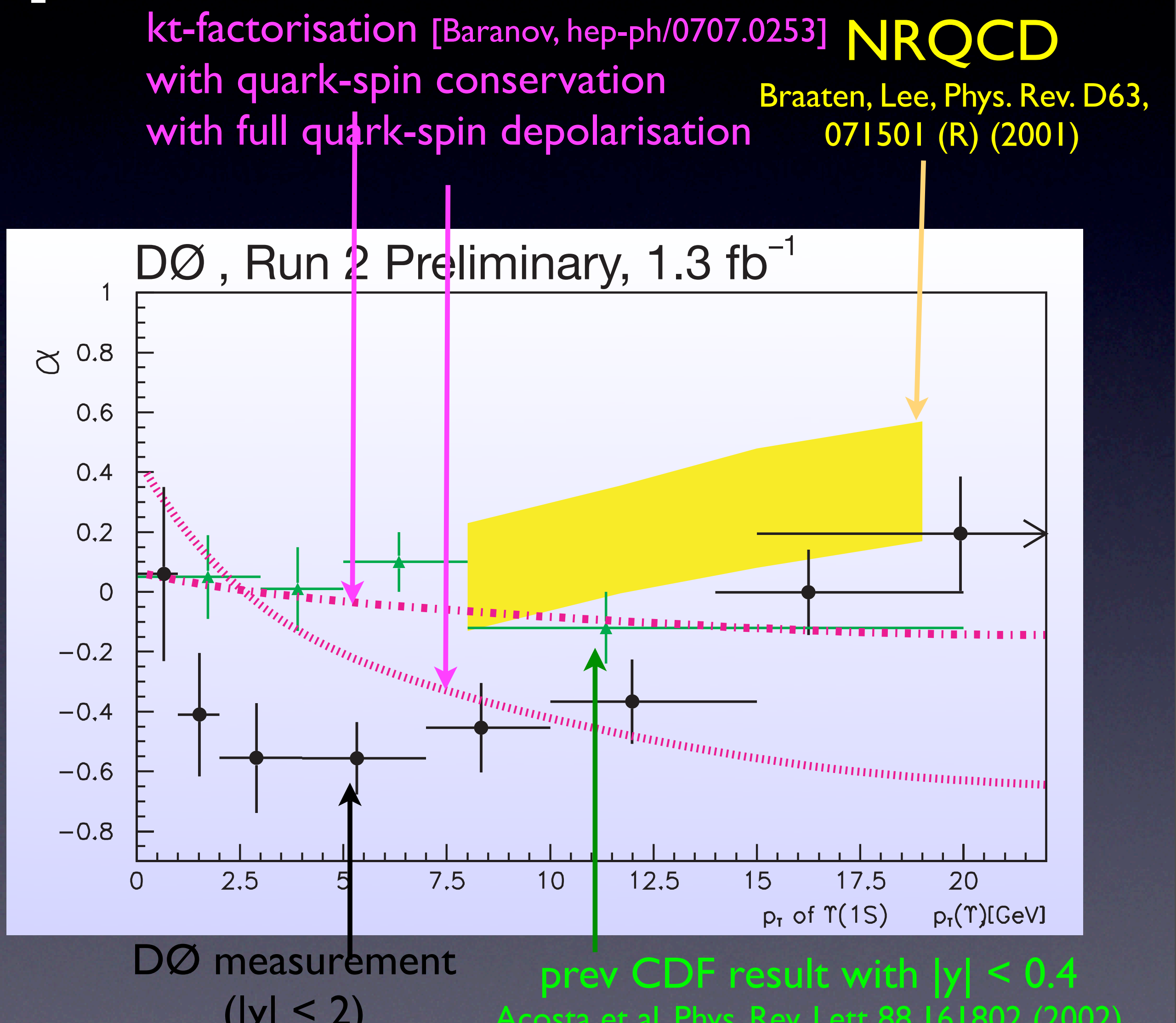
$\Upsilon(1S)$, $\Upsilon(2S)$ polarisation



- DØ find 420,000 $\Upsilon(nS)$.
- Single-trigger selection reduces this to 170,000 $\Upsilon(nS)$ from di-μ trigger.

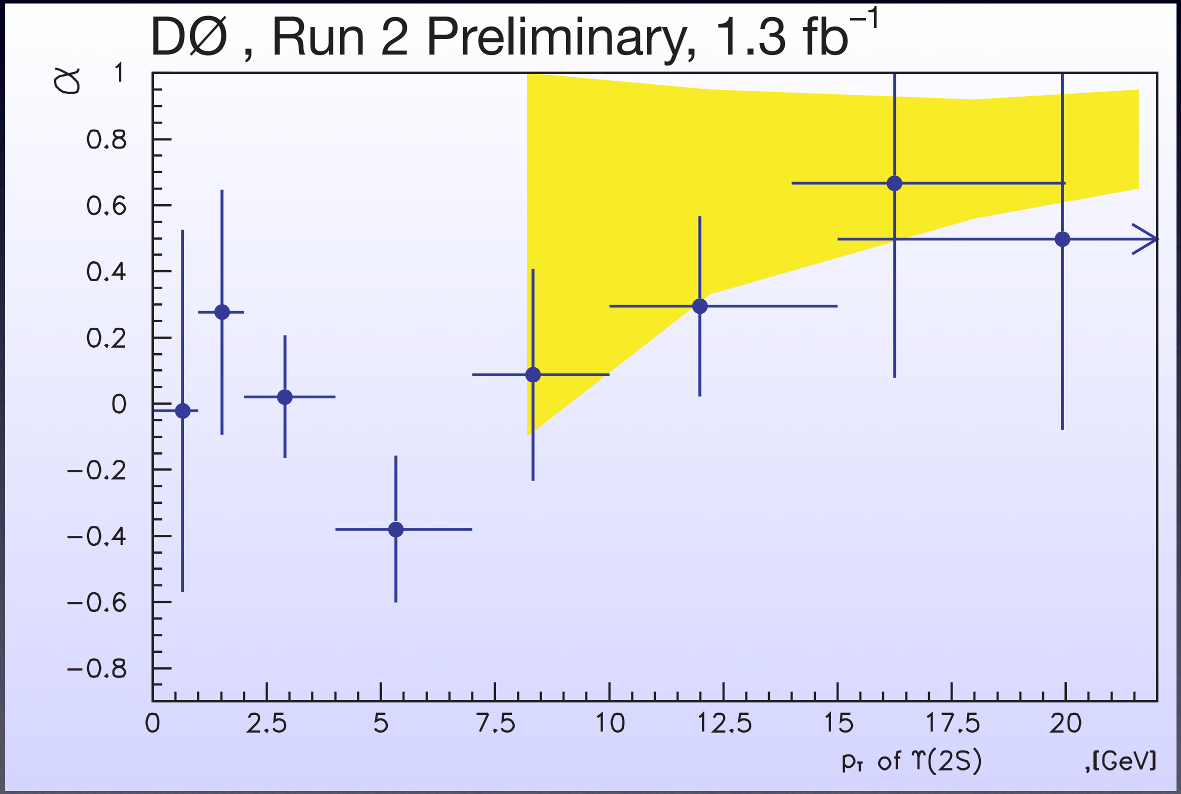
Υ(1S) polarisation

- Find significant, pt dependent longitudinal polarisation.
- Incompatible with NRQCD/ colour-octet



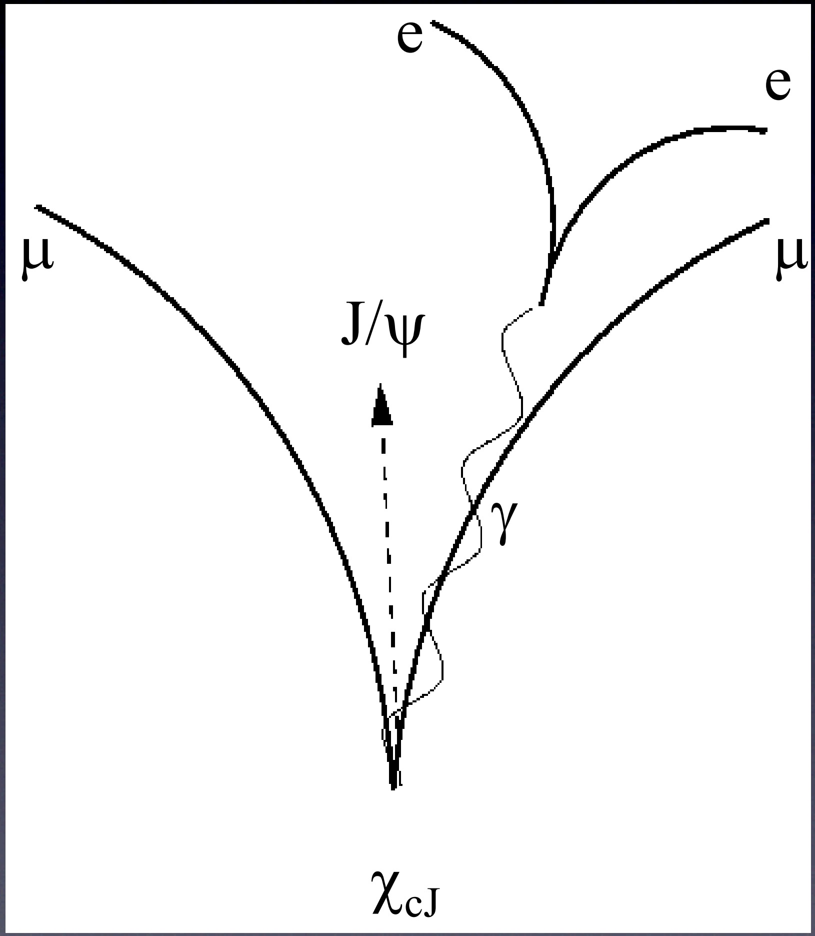
ϒ(2S) polarisation

- Same study for ϒ(2S)
- Not incompatible with NRQCD/colour-octet within (lower) stats.



Measuring $\sigma(\chi_{c2})/\sigma(\chi_{c1})$.

- Experimentally tricky because of soft γ in $\chi_{cJ} \to J/\psi\gamma$. Soft photons give bad energy resolution.
- Good lumi at Tevatron allows use of conversion $\gamma \to e^+e^-$. It's inefficient, but has good energy resolution.



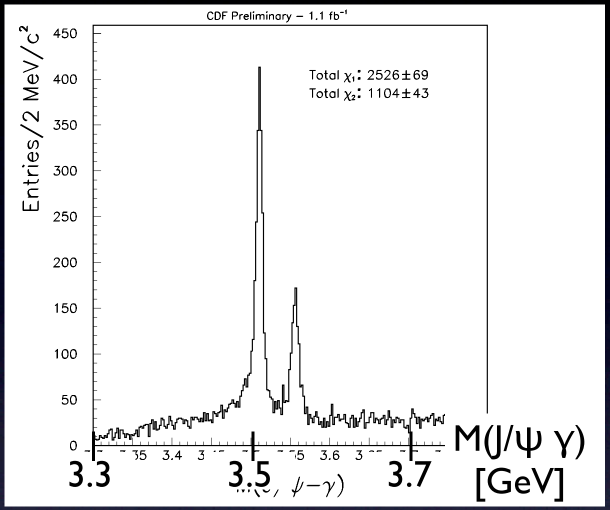
Measuring $\sigma(\chi_{c2})/\sigma(\chi_{c1})$.

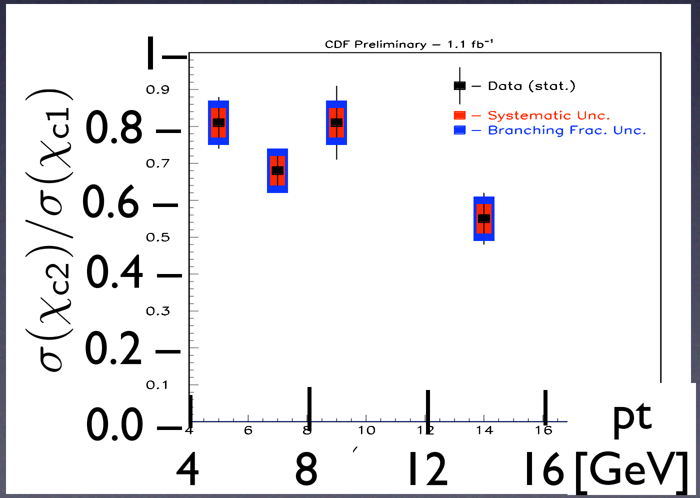
- Excellent mass resolution.
- Separate prompt from B using decay distance
- Find:

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.70 \pm 0.04(\text{stat}) \pm 0.03(\text{sys}) \pm 0.06(\text{BF})$$

for $p_t(\chi_{cJ}) \in [4, 20]\text{GeV}$

- Colour octet predicts 5/3 (counting of spin states).





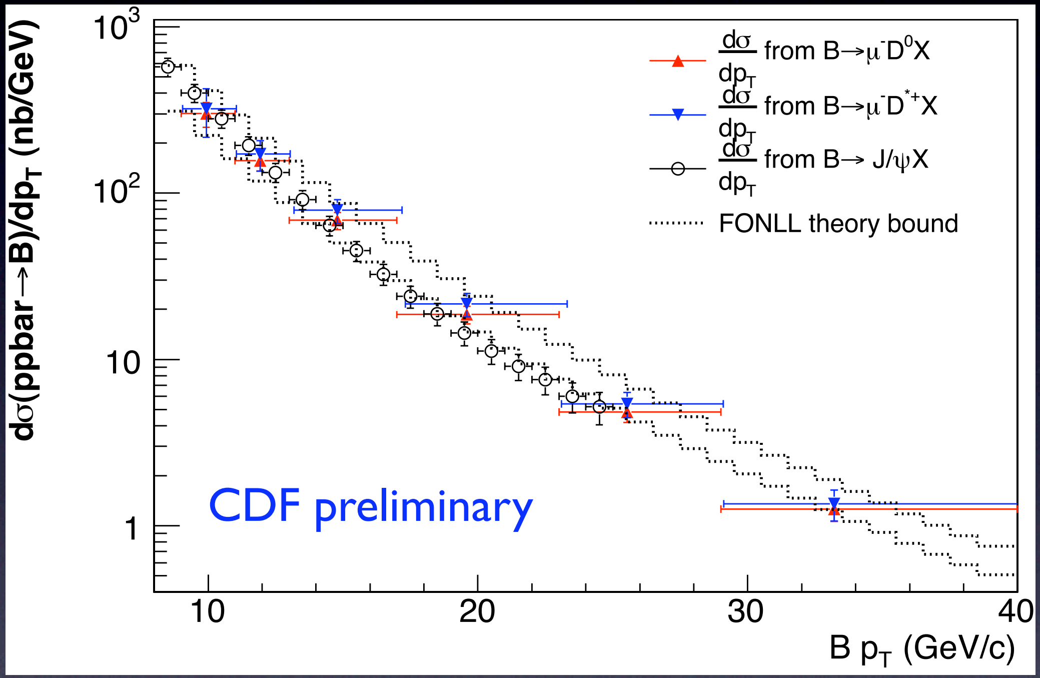
Conclusions

- Plenty of heavy flavour produced at Tevatron. Triggers originally designed for beauty find loads of that - and charm.
- Active field at Tevatron, most results shown < 1y old.
- Keep challenging theory with measurements beyond 'just dσ/dp': angular correlations, polarisation, ... first precision measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$.
- There are 3× as much data on tape, and the machine is doing better than ever, so there's more to come.

Backup

Inclusive B x-section

- $\sigma\left(p\bar{p} \to H_b\right)$ from B→DμνX decays.
- Using only 83/pb but systematics-limited.
- Consistent with prev. result using J/ψ, and FONLL.



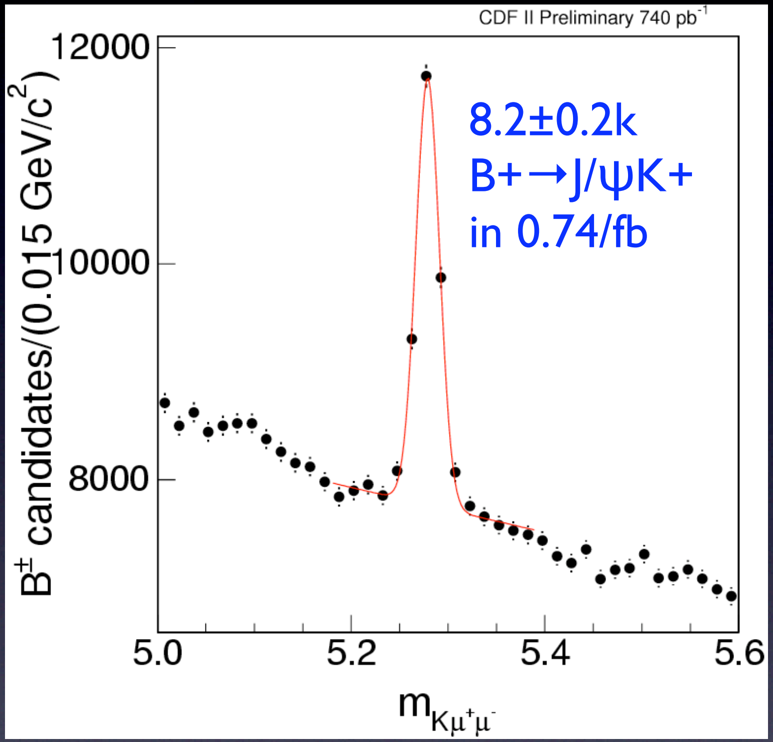
For pt > 9 GeV, |y| < 0.6:

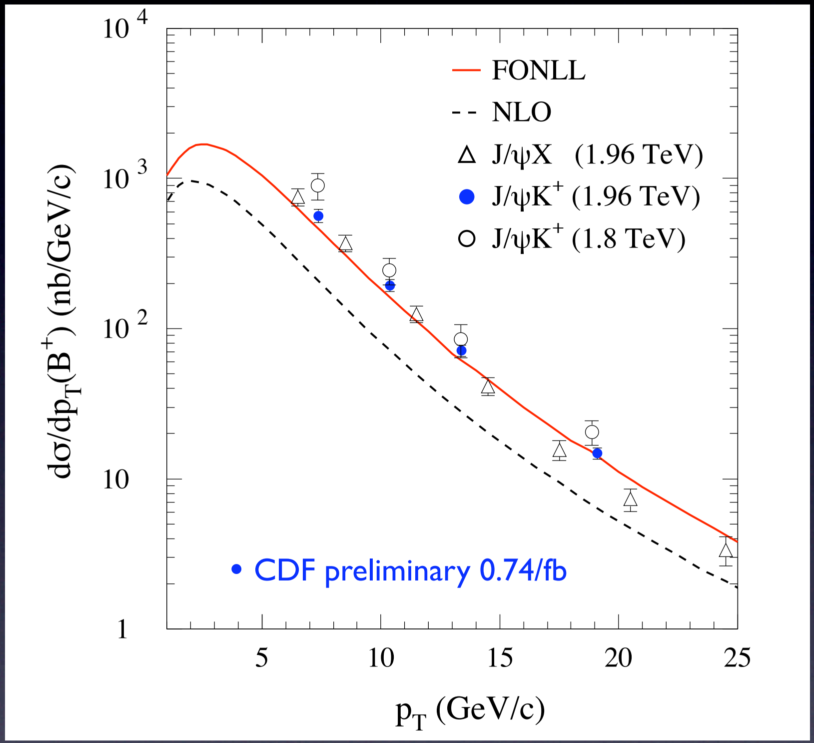
$$\sigma\left(p\bar{p} \to H_b\right) = \left(1.34 \pm 0.08(\text{stat})^{+0.13}_{-0.14}(\text{sys}) \pm 0.07(\text{BR})\right)\,\mu\text{b (from } D^0)$$

$$\sigma\left(p\bar{p} \to H_b\right) = \left(1.47 \pm 0.18(\text{stat})^{+0.17}_{-0.19}(\text{sys}) \pm 0.11(\text{BR})\right)\,\mu\text{b } \left(\text{from } D^{*+}\right).$$

$$\sigma\left(p\bar{p} \to H_b\right) = \left(1.39^{+0.49}_{-0.34}\right)\,\mu\text{b (FONLL)}$$

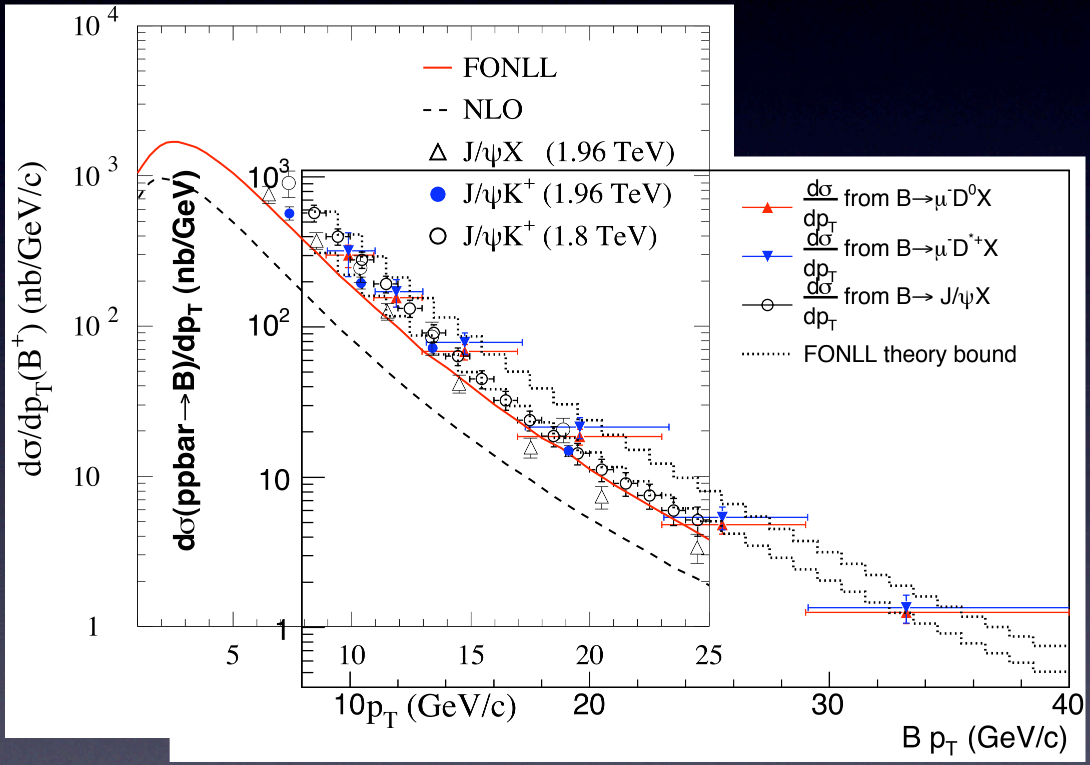
excl B+ x-section

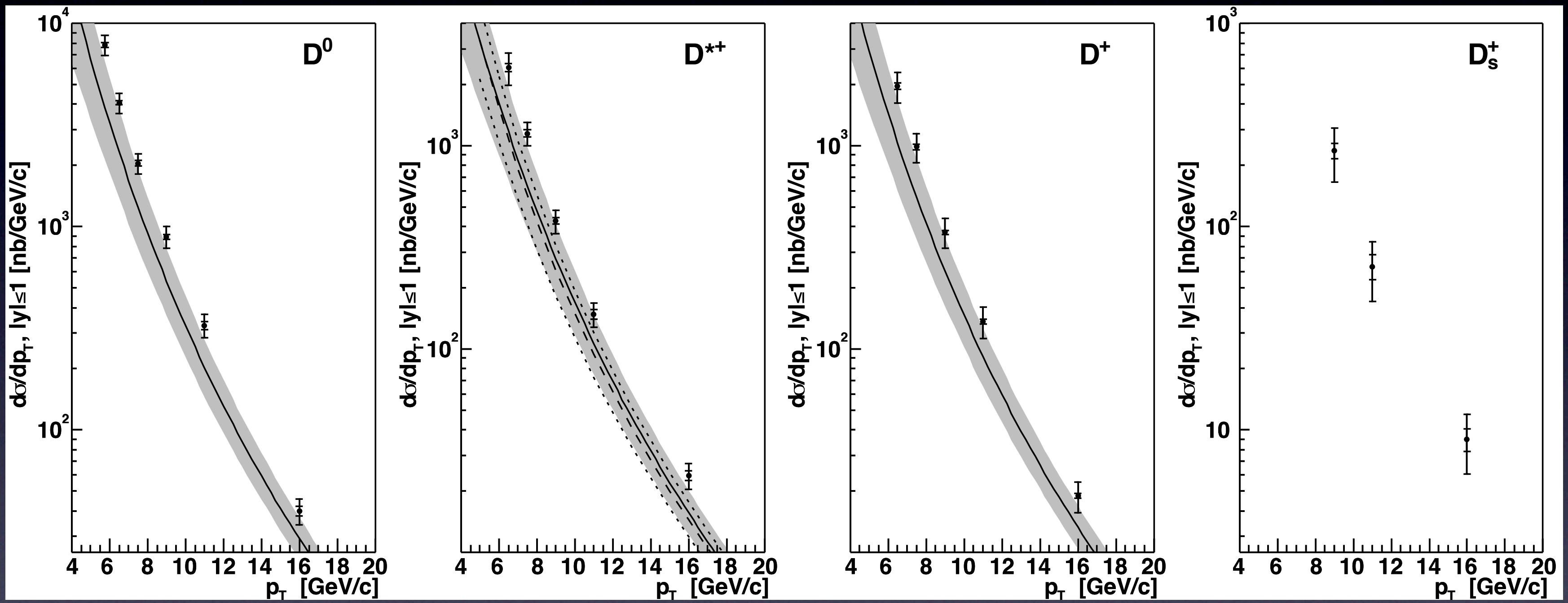




$\sigma\,(p_t > 6\text{GeV}, |y| < 1) = (2.65 \pm 0.12(\text{stat}) \pm 0.21(\text{sys}))\,\mu\text{b}$

- Measurement/NLO = 2.67±0.23
- Agrees with other J/ψ-based analyses and FONNL.


FONLL
NLO
J/ψX (1.96 TeV)
J/ψK+ (1.96 TeV)
J/ψK+ (1.8 TeV)
dσ/dpT(B+) (nb/GeV/c)
pT (GeV/c)
dσ(ppbar→B)/dpT (nb/GeV)
dσ/dpT from B→μ-D0X
dσ/dpT from B→μ-D*+X
dσ/dpT from B→ J/ψX
FONLL theory bound
B pT (GeV/c)

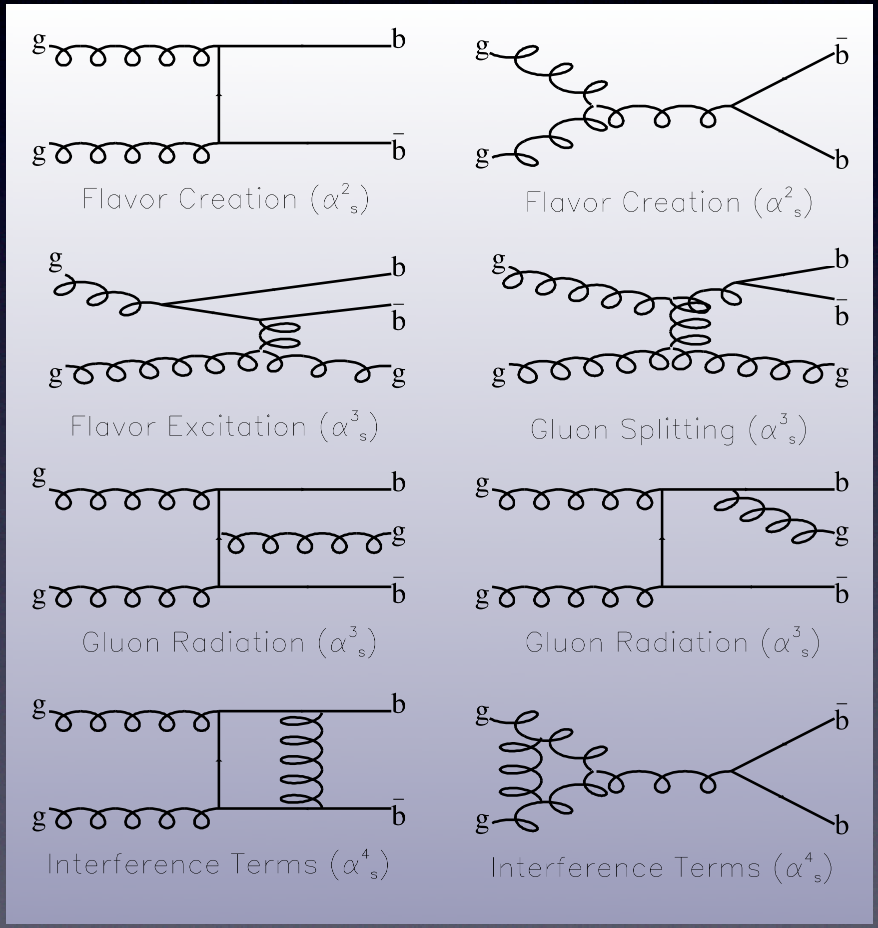


D⁰
D*+
D+
D_s^+
$d\sigma/dp_T$, |y|≤1 [nb/GeV/c]
p_T [GeV/c]

p_T range [GeV/c]	Central p_T [GeV/c]	D^0	D^{*+}	D^+	D_s^+
$5.5-6$	5.75	$7837 \pm 220 \pm 884$	—	—	—
$6-7$	6.5	$4056 \pm 93 \pm 441$	$2421 \pm 108 \pm 424$	$1961 \pm 69 \pm 332$	—
$7-8$	7.5	$2052 \pm 58 \pm 227$	$1147 \pm 48 \pm 145$	$986 \pm 28 \pm 156$	—
$8-10$	9.0	$890 \pm 25 \pm 107$	$427 \pm 16 \pm 54$	$375 \pm 9 \pm 62$	$236 \pm 20 \pm 67$
$10-12$	11.0	$327 \pm 15 \pm 41$	$148 \pm 8 \pm 18$	$136 \pm 4 \pm 24$	$64 \pm 9 \pm 19$
$12-20$	16.0	$39.9 \pm 2.3 \pm 5.3$	$23.8 \pm 1.3 \pm 3.2$	$19.0 \pm 0.6 \pm 3.2$	$9.0 \pm 1.2 \pm 2.7$

TABLE I: Summary of the measured prompt charm meson differential cross sections and their uncertainties at the center of each p_T bin. The first error is statistical and the second systematic. The products of the branching fractions [11] used are $(3.81 \pm 0.09)\%$, $(2.57 \pm 0.06)\%$, $(9.1 \pm 0.6)\%$ and $(1.8 \pm 0.5)\%$ for D^0, D^{*+}, D^+ and D_s^+, respectively.

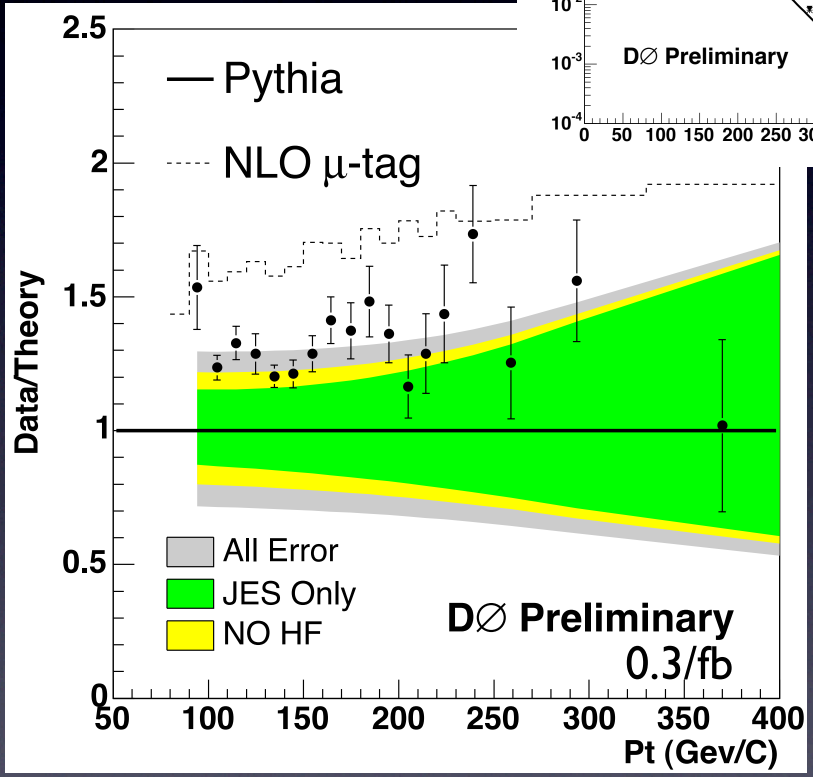
The total cross sections are obtained by summing over all p_T bins. However, the last p_T bin is replaced by an inclusive bin with $p_T > 12\,\mathrm{GeV}/c$. We find $\sigma(D^0, p_T \geq 5.5\,\mathrm{GeV}/c, |y| \leq 1) = 13.3 \pm 0.2 \pm 1.5\,\mu\mathrm{b}$, $\sigma(D^{*+}, p_T \geq 6.0\,\mathrm{GeV}/c, |y| \leq 1) = 5.2 \pm 0.1 \pm 0.8\,\mu\mathrm{b}$, $\sigma(D^+, p_T \geq 6.0\,\mathrm{GeV}/c, |y| \leq 1) = 4.3 \pm 0.1 \pm 0.7\,\mu\mathrm{b}$ and $\sigma(D_s^+, p_T \geq 8.0\,\mathrm{GeV}/c, |y| \leq 1) = 0.75 \pm 0.05 \pm 0.22\,\mu\mathrm{b}$, where the first uncertainty is statistical and the second systematic. To calculate the

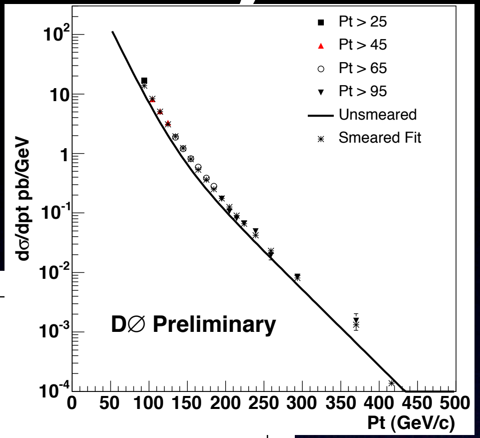


Flavor Creation (α_s^2)
Flavor Creation (α_s^2)
Flavor Excitation (α_s^3)
Gluon Splitting (α_s^3)
Gluon Radiation (α_s^3)
Gluon Radiation (α_s^3)
Interference Terms (α_s^4)
Interference Terms (α_s^4)

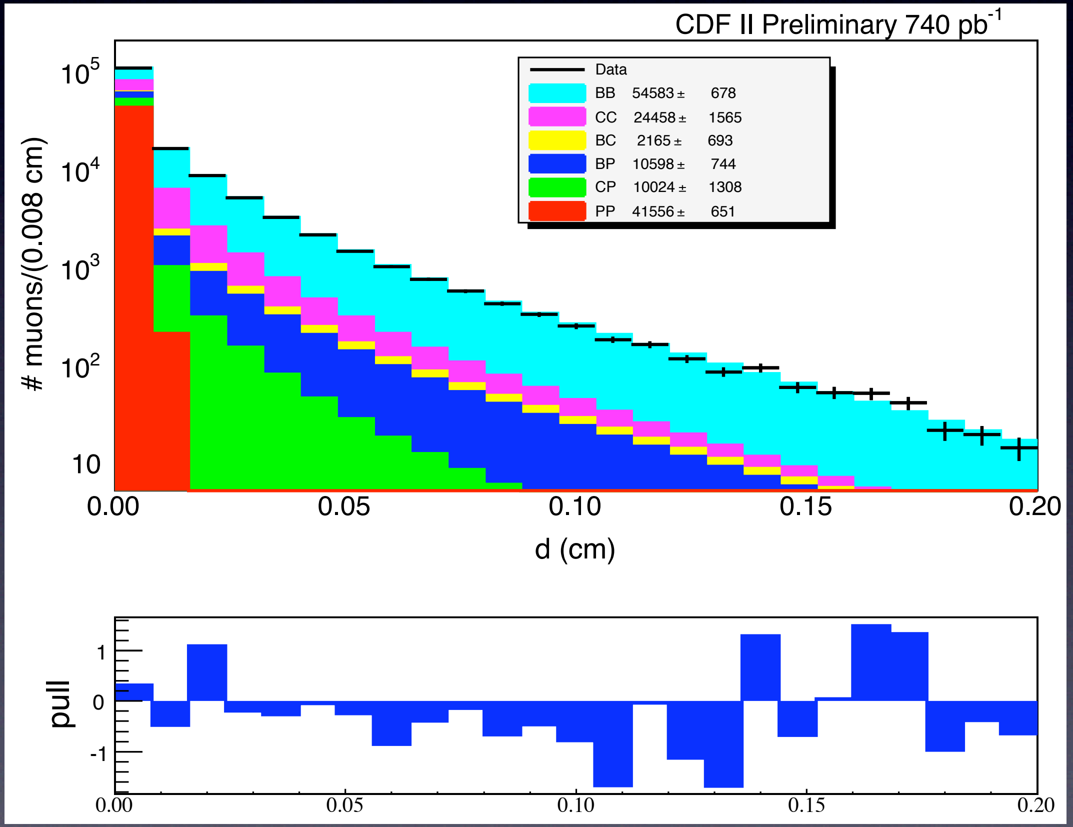
μ-tagged (heavy flavour) Jet x-section

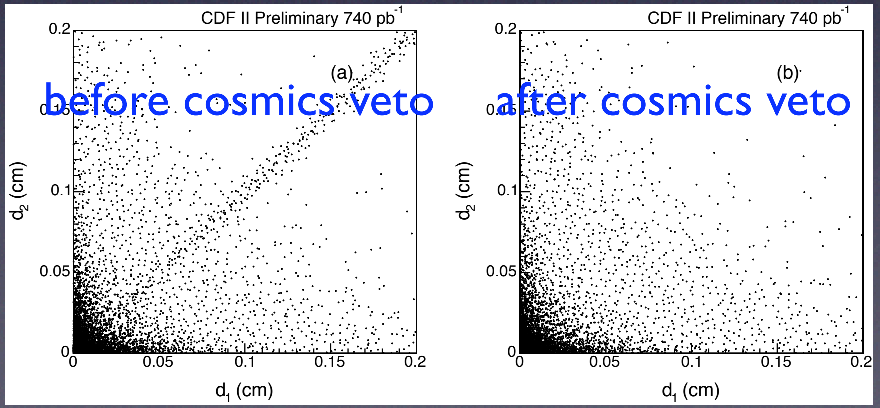
- Find jets with muons; estimate heavy flavour content from MC simulation.
- No attempt yet to separate heavy flavour in data (no IP cut or so).
- $\frac{d\sigma}{dp_t}$ generally higher than NLO prediction, but compatible within errors.

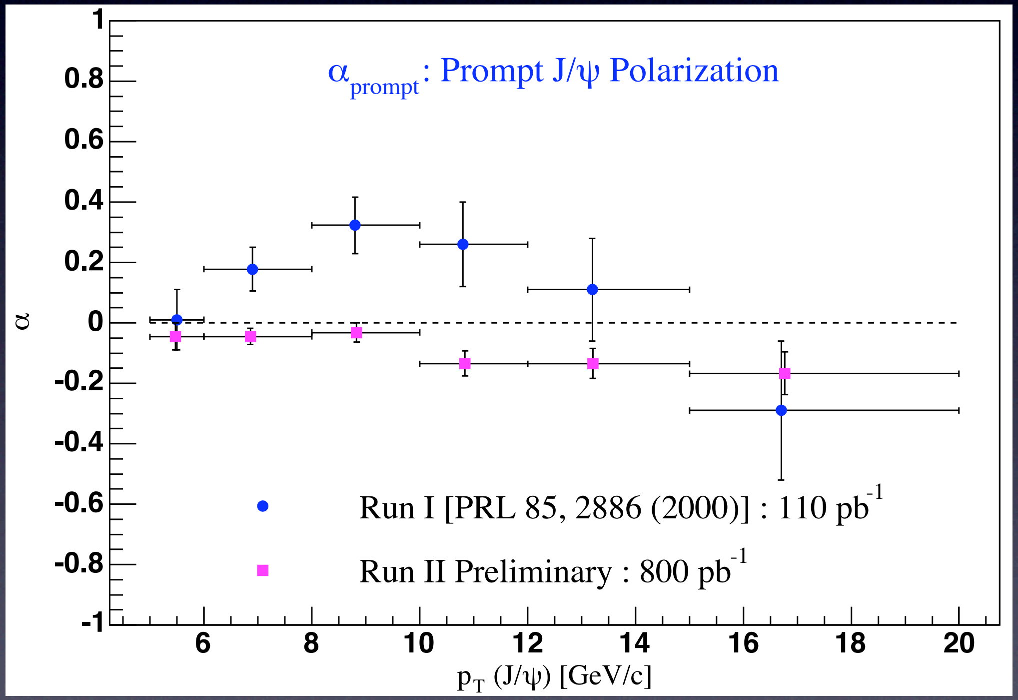




green: σ(Jet-energy-scale) only
yellow: all σ except σ(heavy-flavour fraction)
grey: all systematics


CDF II Preliminary 740 pb-1
10^5
10^4
10^3
10^2
10
muons/(0.008 cm)
Data
BB 54583 ± 678
CC 24458 ± 1565
BC 2165 ± 693
BP 10598 ± 744
CP 10024 ± 1308
PP 41556 ± 651
0.00
0.05
0.10
0.15
0.20
d (cm)
pull
1
0
-1


CDF II Preliminary 740 pb-1
(a)
before cosmics veto
d2 (cm)
d1 (cm)
CDF II Preliminary 740 pb-1
(b)
after cosmics veto
d2 (cm)
d1 (cm)


α_{prompt}: Prompt J/ψ Polarization
α
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
6
8
10
12
14
16
18
20
p_T (J/ψ) [GeV/c]
Run I [PRL 85, 2886 (2000)] : 110 pb^{-1}
Run II Preliminary : 800 pb^{-1}

Correlated $b\bar{b}$ and $c\bar{c}$ x-section: results

- x-sections:

$$\sigma_{b\to\mu,\bar{b}\to\mu} = (1549 \pm 133)\text{pb}$$

$$\sigma_{b\bar{b}}\,(p_T \geq 6\text{GeV},\ |y| \leq 1) = (1618 \pm 148 \pm [\sim 400 \text{ fragmentation}])\text{ nb}$$

$$\sigma_{c\to\mu,\bar{c}\to\mu} = (624 \pm 104)\text{pb}$$

- Ratios (includes both exp. and theory error):

$$\frac{\sigma^{\text{measured}}_{b\to\mu\ \bar{b}\to\mu}}{\sigma^{\text{NLO}}_{b\to\mu\ \bar{b}\to\mu}} = 1.20 \pm 0.21$$

$$\frac{\sigma^{\text{measured}}_{c\to\mu\ \bar{c}\to\mu}}{\sigma^{\text{NLO}}_{c\to\mu\ \bar{c}\to\mu}} = 2.71 \pm 0.64$$

Error contributions in % of measured x-section		
	$b\to\mu, b\to\mu$	$c\to\mu, c\to\mu$
$\int \mathcal{L}\, dt$	6%	6%
acceptance	3%	3%
fake muons	4%	11%
fit model	3%	8%
stat	1.2%	6.4%
Total	8.6%	17%