B Production at the Tevatron

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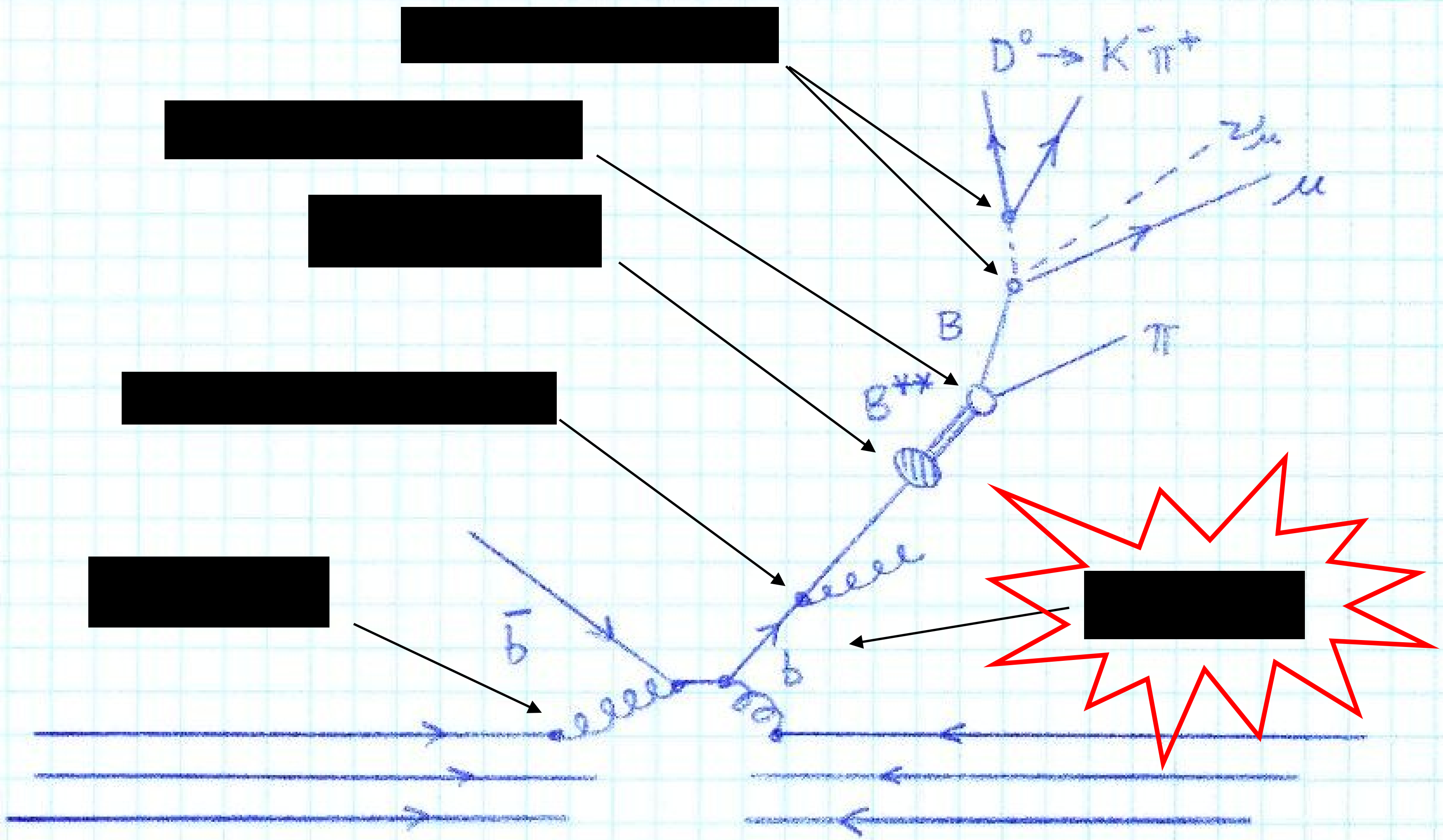
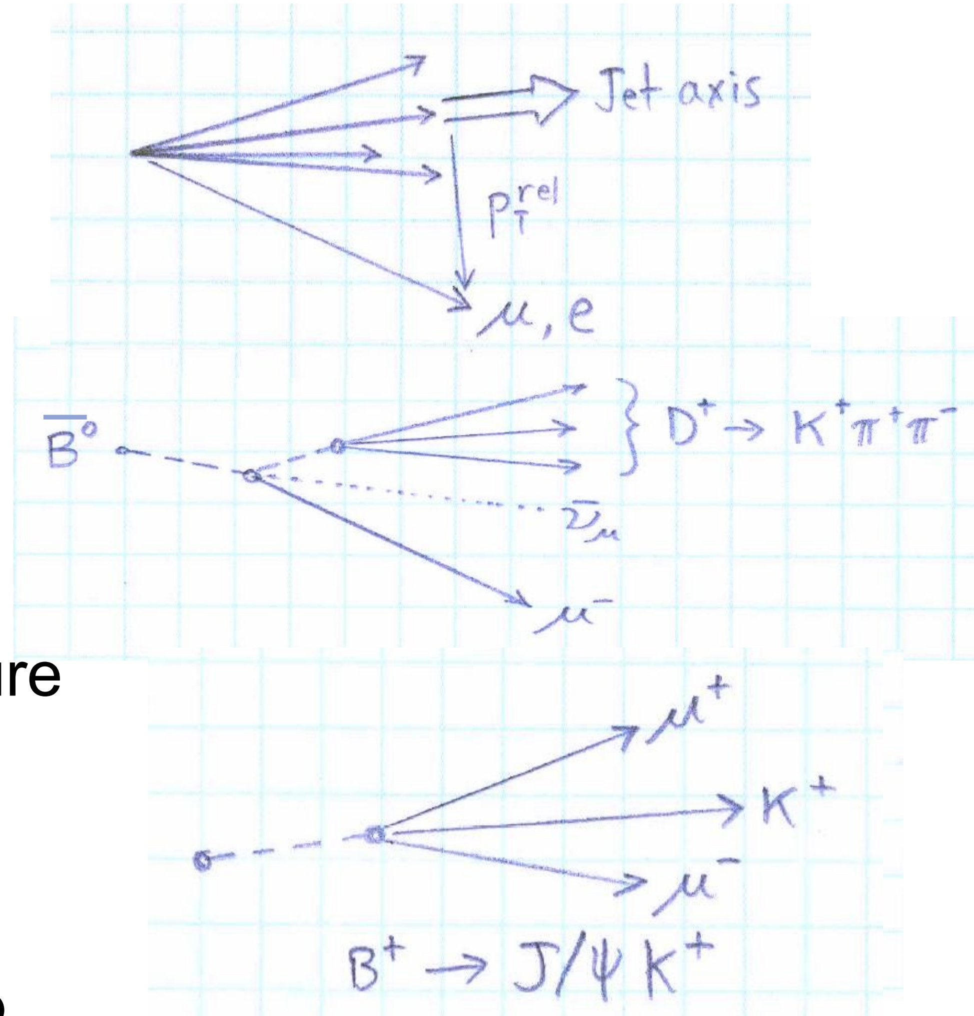
For the CDF and DØ Collaborations.

B Production and Decay



B Cross Section Measurements

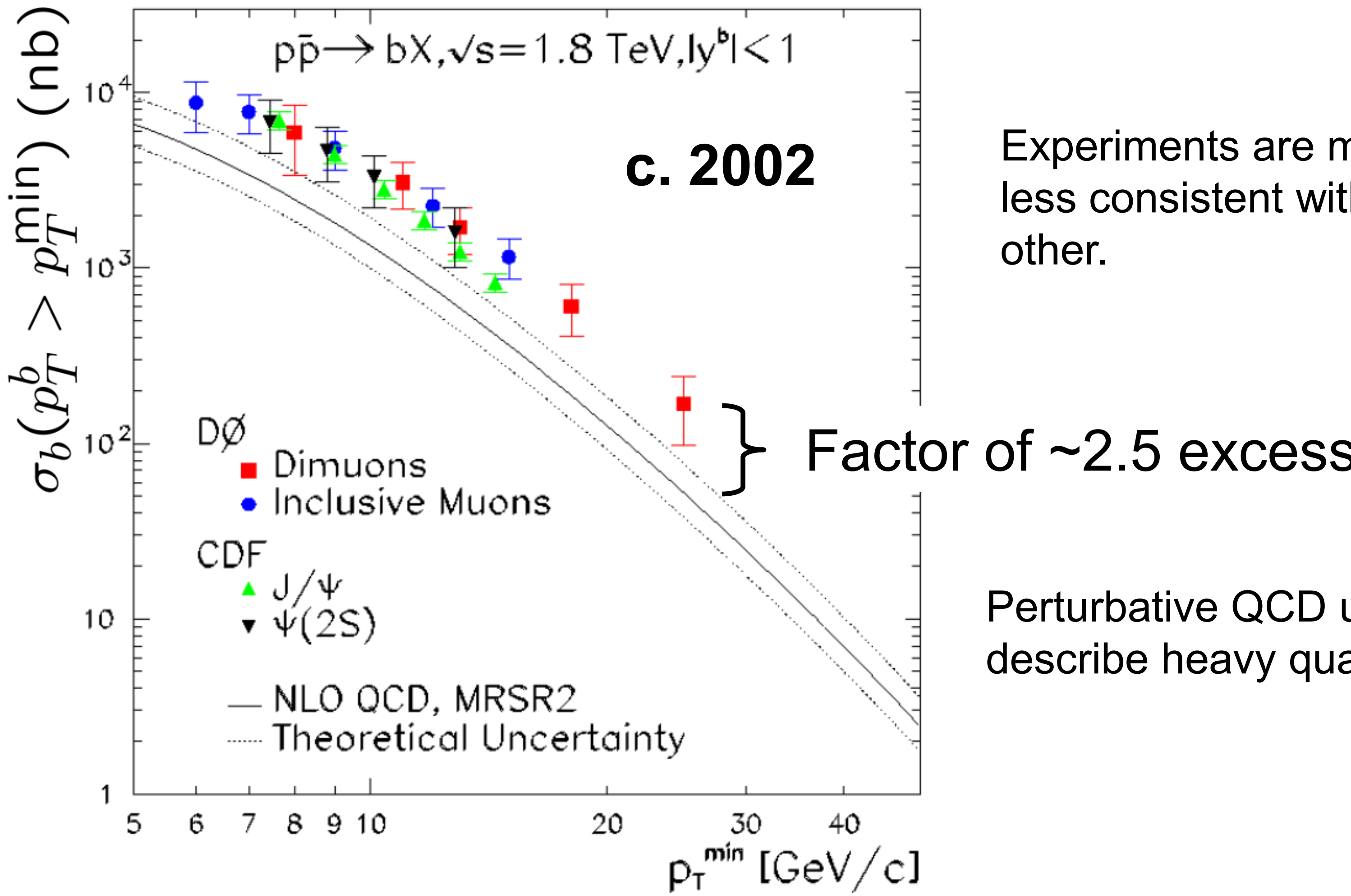
- Inclusive leptons
  - Use p_T^{rel} to select b component
- Lepton + D
  - Naturally enhanced b component
- Inclusive J/ψ
  - Use lifetime to measure b fraction
- Exclusive B reconstruction
  - $B^+ \rightarrow J/\psi K^+$, $B^0_s \rightarrow J/\psi \varphi$



Tevatron B Cross Section Measurements

Run	Experiment	Reference	Luminosity	Channel
Run I	CDF	Phys. Rev. Lett. 68, 3403 (1992)	2.6 pb^{-1}	$B^+ \rightarrow J/\psi K^+$
	CDF	Phys. Rev. Lett. 71, 500 (1993)	4.2 pb^{-1}	$e+D^0$
	DØ	Phys. Rev. Lett. 74, 3548 (1995)	4.2 pb^{-1}	$p_T^{rel}(\mu)$
	CDF	Phys. Rev. Lett. 75, 1451 (1995)	19.3 pb^{-1}	$B^+ \rightarrow J/\psi K^+, B^0 \rightarrow J/\psi K^{*0}$
	DØ	Phys. Lett. B370, 239 (1996).	6.6 pb^{-1}	Inclusive J/ψ
	CDF	Phys. Rev. D53, 1051 (1996)	15.8 pb^{-1}	μ + sec vtx
	DØ	Phys. Rev. Lett. 85, 5068 (2000).	5.2 pb^{-1}	$p_T^{rel}(\mu)$
	DØ	Phys. Lett. B487, 264 (2000).	6.5 pb^{-1}	di-muon $p_T^{rel}(\mu)$
	CDF	Phys. Rev. D65, 052005 (2002).	98 pb^{-1}	$B^+ \rightarrow J/\psi K^+$
	CDF	Phys. Rev. D66, 032002 (2002).	0.63 pb^{-1}	μ + track, $\sqrt{s} = 630$ GeV
Run II	CDF	Phys. Rev. D71, 032001 (2005)	39.7 pb^{-1}	Inclusive J/ψ
	CDF	Phys. Rev. D75, 012010 (2007).	739 pb^{-1}	$B^+ \rightarrow J/\psi K^+$
	CDF	Phys. Rev. D79, 092003 (2009).	83 pb^{-1}	$\mu+D^0$

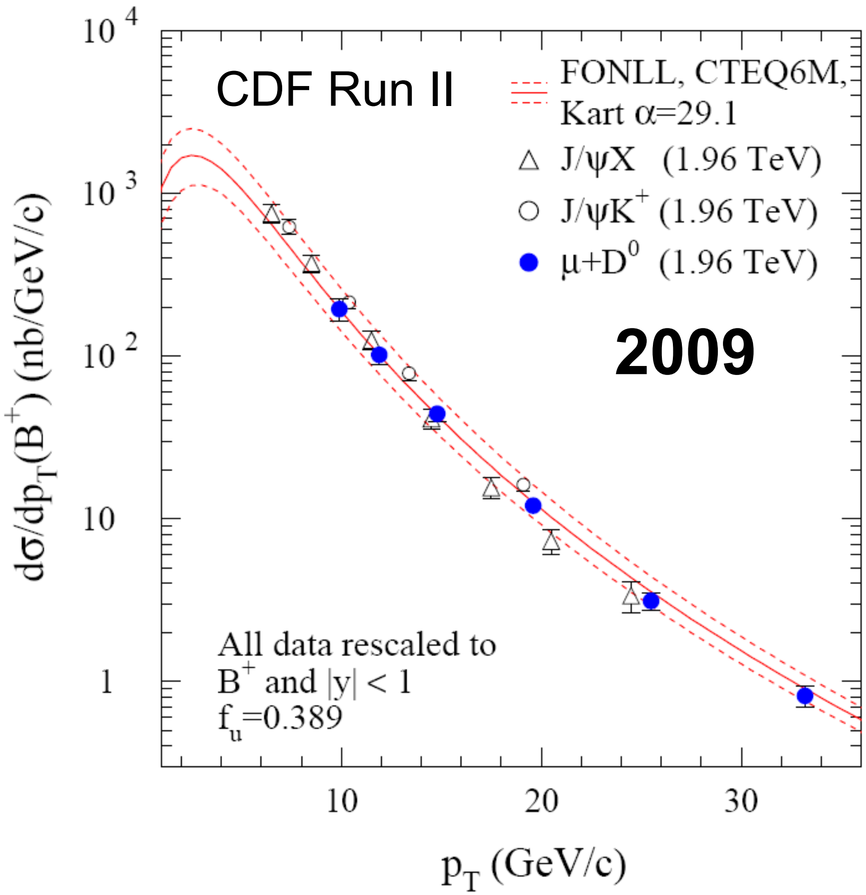
B Cross Section "crisis"?



Experiments are more or less consistent with each other.

Perturbative QCD unable to describe heavy quarks?

B Cross Section Today



- Apparently very good agreement with QCD
- B cross section is now a very good benchmark for the Standard Model at the LHC.

What changed?

Common Issues

B decay products ⟺ $d\widehat{\sigma}_b/dp_T$

- PDF's: MRSD_0 or MRSA'
- Acceptances calculated using exact NLO calculation by Nason, Dawson & Ellis.
- Quark mass, m_b & renormalization scale μ_0
- Peterson fragmentation with $\epsilon_b = 0.006$
- Hadronization fractions: $f_u,\ f_d,\ f_s,\ f_{\text{baryon}}$
- B decay models: QQ → EvtGen
- Decay tables?

⇒ **Can't factor these into uncorrelated parts.**

Non-perturbative inputs

- Fragmentation parameters were tuned to LEP data and LL Monte Carlo → $\epsilon_p = 0.006$
- Correlated with parton shower and decay table
  - More soft gluon emission
  - More B** states

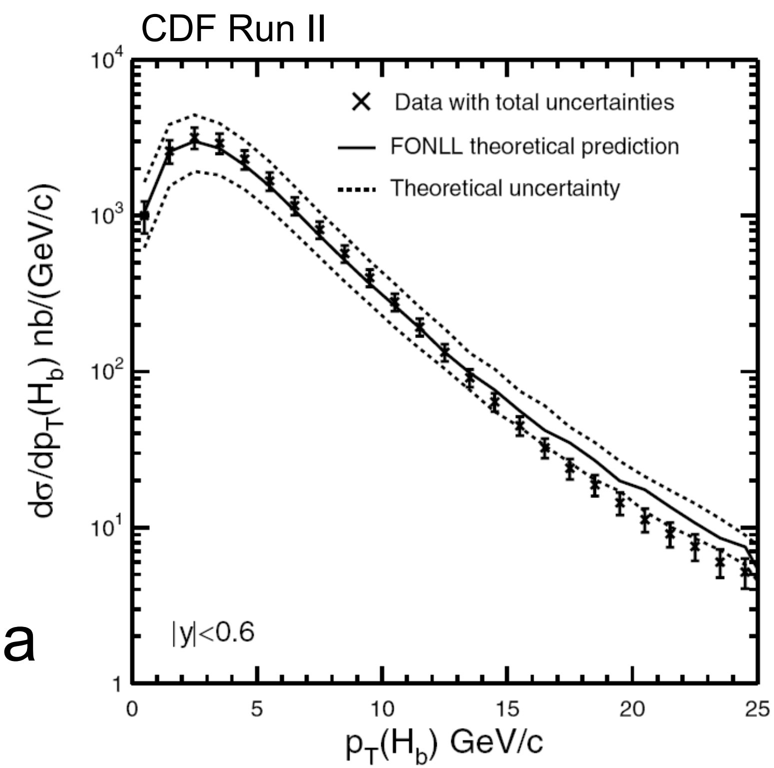
  } Smaller ε_p/harder $p_T(B)$
- NNLO calculations/parton shower
  - co-linear gluon emission shouldn't be counted twice.
- Consistent treatments: CTEQ6M + FONLL + matched fragmentation functions...

JHEP05(1998)007 / JHEP07(2004)033

Newer Measurements: $H_b \rightarrow J/\psi\ X$

Phys. Rev. D71, 032001 (2005).

- $\int L\, dt \sim 40\ \text{pb}^{-1}$
- Di-muon trigger,
  - $p_T(\mu) > 1.5$ GeV/c
  - No lower limit on $p_T(J/\psi)$
- b fraction measured using pseudo-proper decay time
  - Positive for b decays
- Efficiencies measured using a 4 GeV/c single-muon trigger.



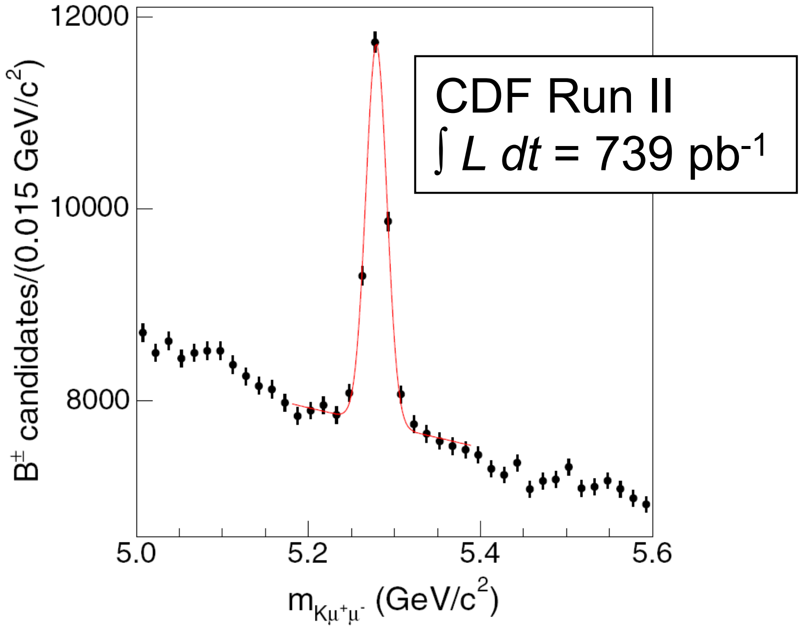
$$\sigma(p\bar{p} \rightarrow b, |y| < 0.6) = 17.6 \pm 0.4^{+2.5}_{-2.3}\ \mu b$$

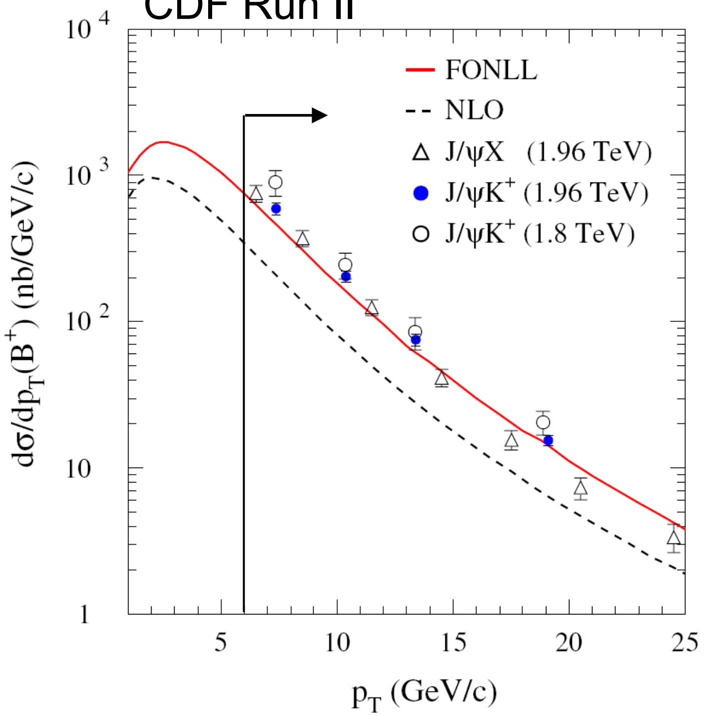
$$\sigma_{\text{FONLL}}(p\bar{p} \rightarrow b, |y| < 0.6) = 16.8^{+7.0}_{-5.0}\ \mu b$$

Consistent…

Exclusive Final States

Phys. Rev. D75, 012010 (2007).





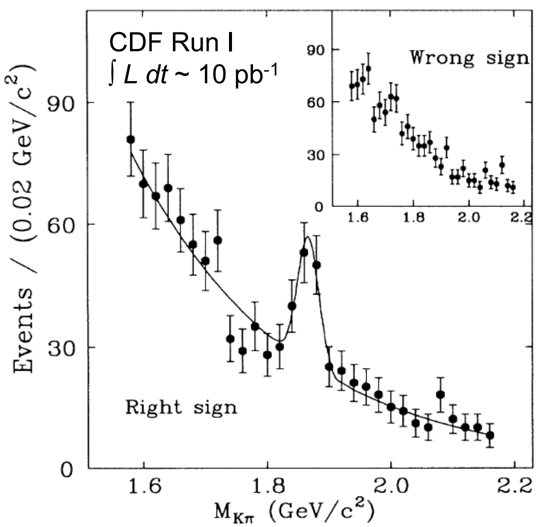
$$\sigma_{B+}(p_T > 6\ \mathrm{GeV}/c, |y| < 1) = 2.4 \pm 0.4\ \mu\mathrm{b}$$

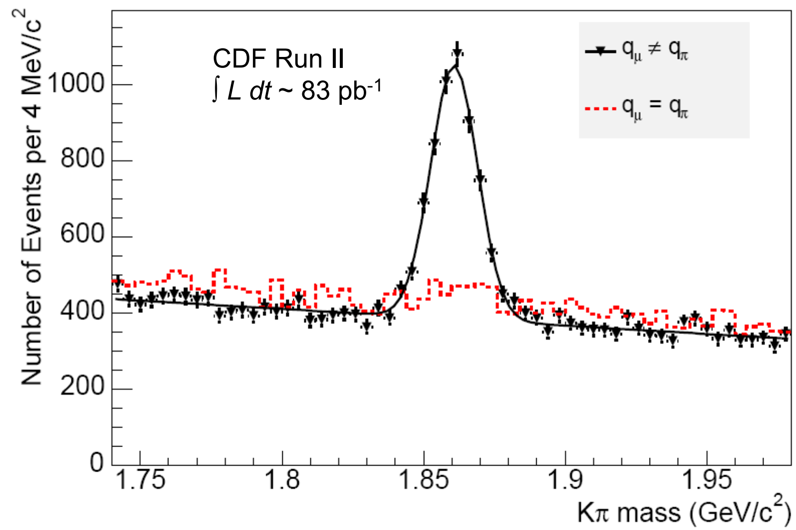
- Consistent with FONLL calculation (2.1±0.6 μb).
- Generally consistent with inclusive J/ψ result.
- Are there systematic differences?

Newer Measurements: B →μ+D

Phys. Rev. Lett. 71, 500 (1993).

Phys. Rev. D79, 092003 (2009).





12 GeV electron trigger

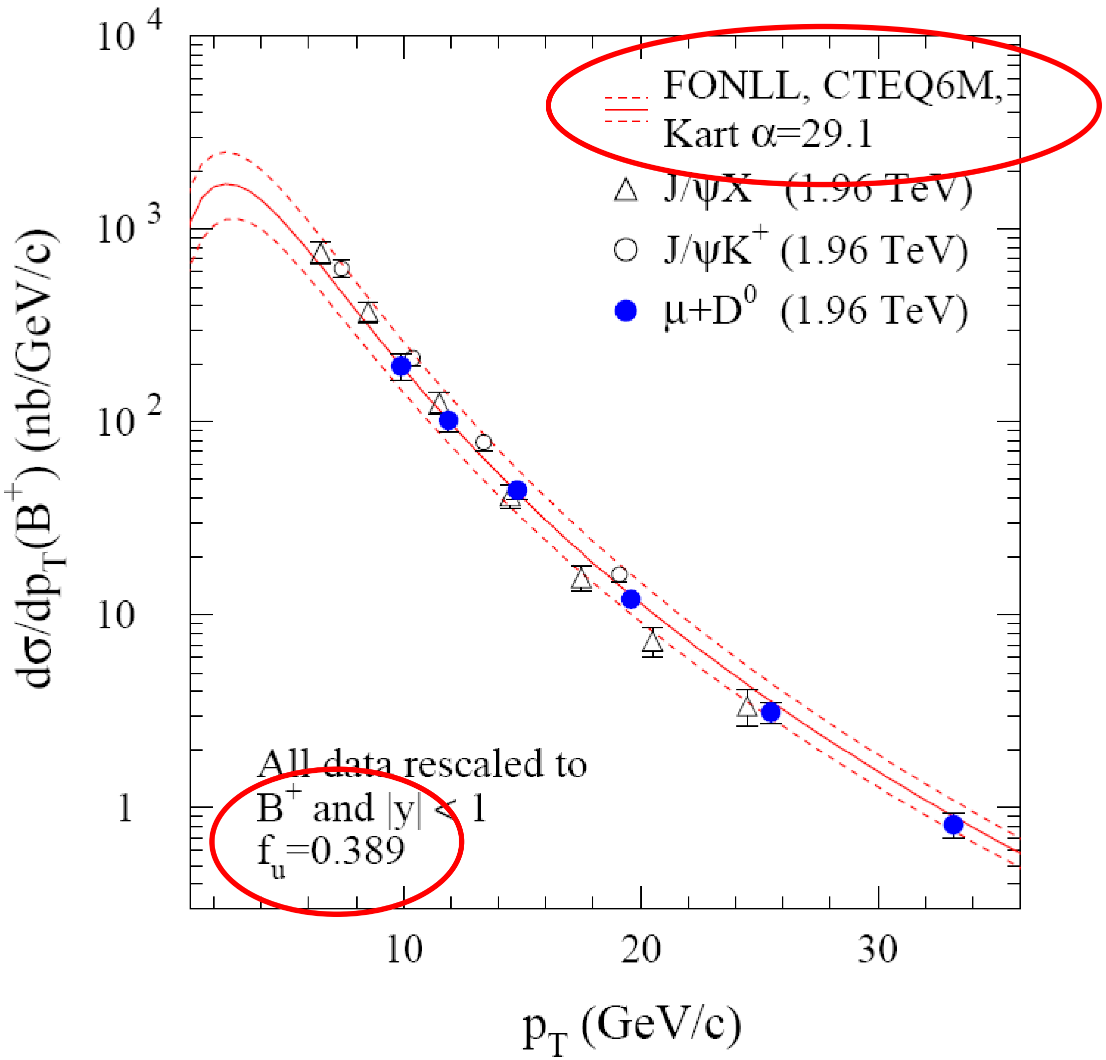
4 GeV muon + displaced track trigger

ε measured using J/ψ sample collected using single 8 GeV muon trigger.

correction	constraint
$c\bar{c}$ background	distribution of d_0(D)
$b\bar{b}$	μ-D candidates
irreducible B background	B decay model: D^{**}'s, $B \to DD$, …

6% uncertainty on $\int \mathcal{L}dt$

Cross Section Summary



Consistent treatment of e^+e^- and $p\overline{p}$ fragmentation function.

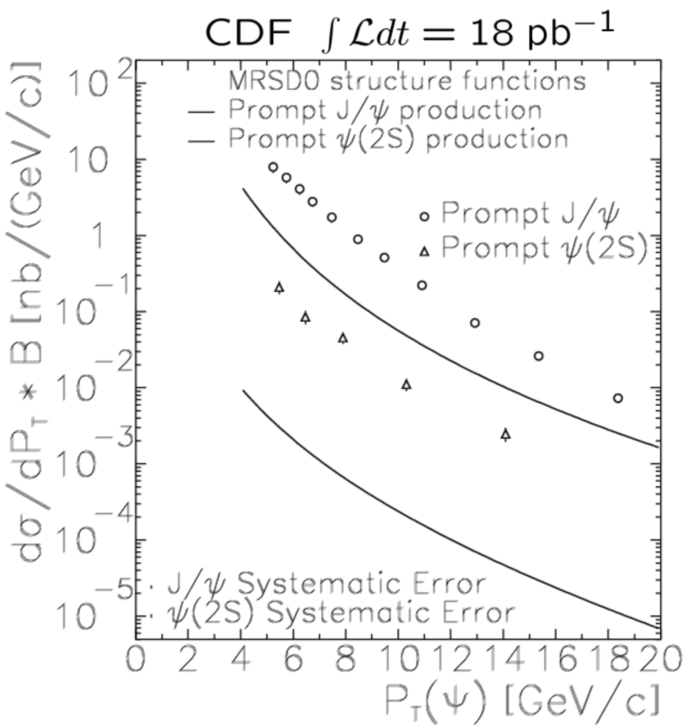
Reduced dependence on renormalization scale.

All are correlated with hadronization fractions...

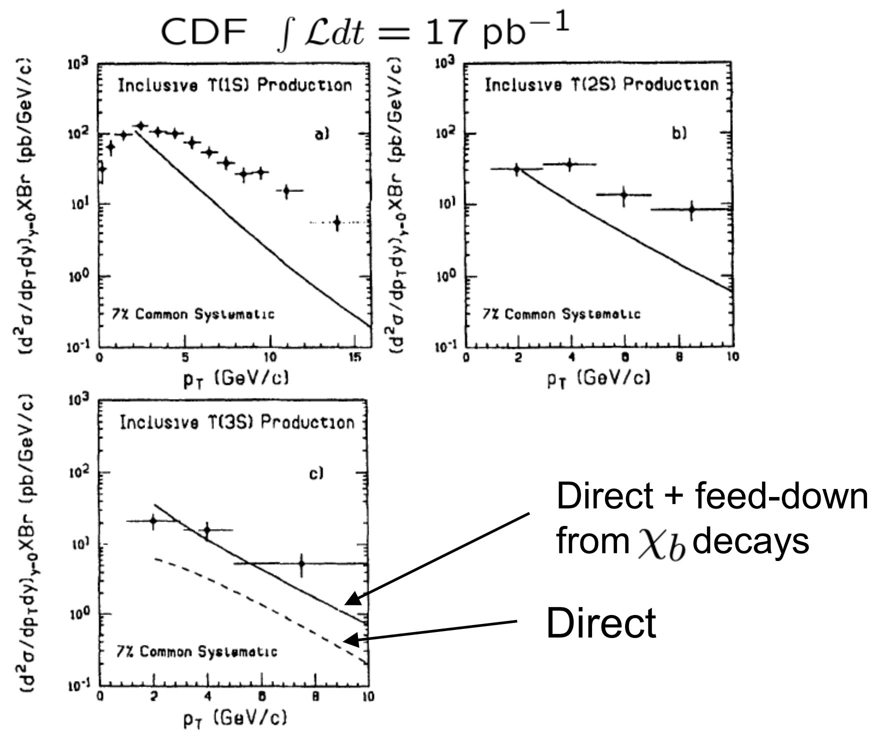
($B^+ \rightarrow J/\psi K^+$ is 100% correlated.)

Run I Quarkonia Cross Sections

Phys. Rev. Lett. 79, 572 (1997)

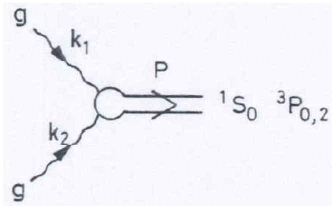


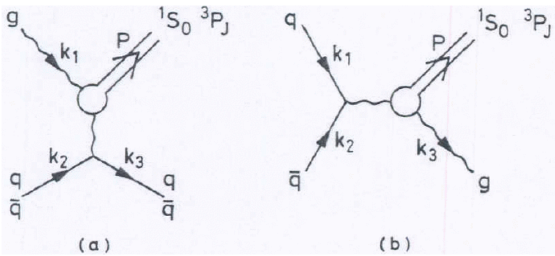
Phys. Rev. Lett. **75**, 4358 (1995)

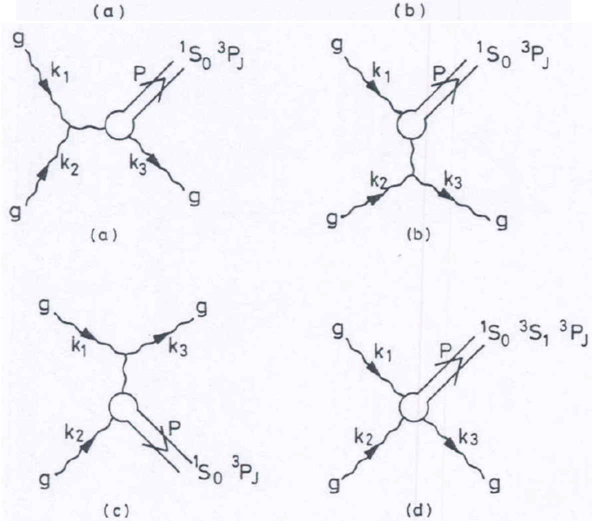


- Excess observed in both prompt J/ψ and ϒ cross sections
  - ⇨ Other production mechanisms, eg, color octet models
    - ⇨ Polarization measurements

Quarkonia Cross Sections







- Color octet production:

Color singlet

$$|\chi_{QJ}\rangle = \mathcal{O}(1)|Q\overline{Q}[^3P_J^{(1)}]\rangle + \mathcal{O}(v)|Q\overline{Q}[^3S_1^{(8)}]g\rangle + \ldots$$

Color octet

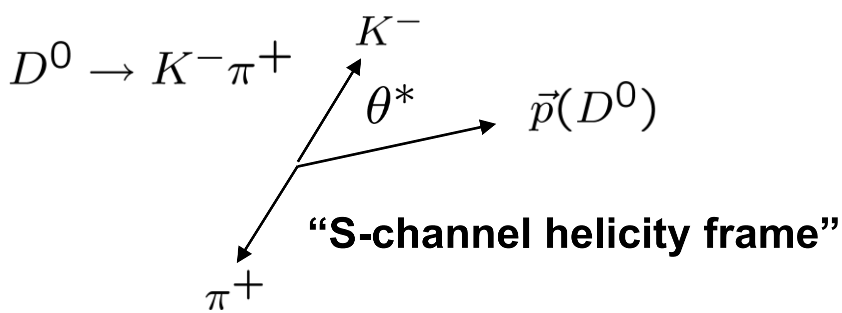
- NRQCD: Expansion in both α_s and v
- k_T factorization: initial gluon virtuality → spin density matrix.
- Others...

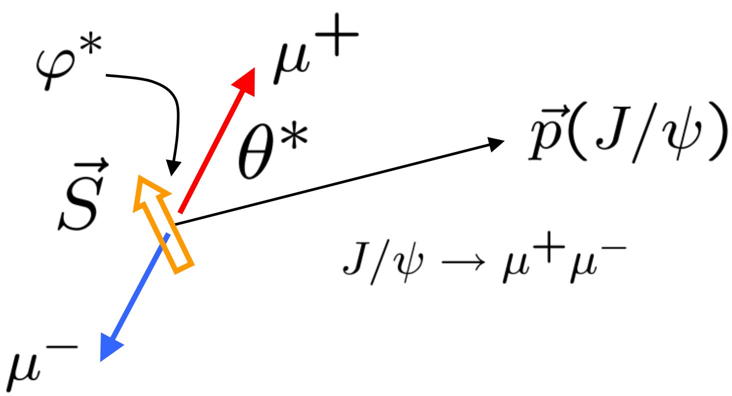
Analysis of Quarkonia

- DØ J/ψ production:
  - Phys. Lett. B370, 239 (1996). (Inclusive J/ψ)
  - Phys. Rev. Lett. 82, 35 (1999). (forward J/ψ)
- CDF J/ψ and ψ(2S) production:
  - Phys. Rev. Lett. 79, 572 (1997). (J/ψ and ψ(2S) cross section)
  - Phys. Rev. D71, 032001 (2005). (Inclusive J/ψ)
  - Phys. Rev. D66, 092001 (2002). (forward J/ψ)
  - Phys. Rev. D80, 031103 (2009). (ψ(2S) cross section)
  - Phys. Rev. Lett. 99, 132001 (2007). (J/ψ and ψ(2S) polarization)
- DØ ϒ(1S) cross section, polarization
  - Phys. Rev. Lett. 94, 232001 (2005). (ϒ(1S) cross section)
    - Phys. Rev. Lett. 100, 049902 (2008). (with updated integrated luminosity)
  - Phys. Rev. Lett. 101, 182004 (2008). (polarization)
- CDF ϒ(1S) production
  - Phys. Rev. Lett. 75, 4358 (1995). (ϒ(ns) cross section)
  - Phys. Rev. Lett. 84, 2094 (2000). $(\chi_{bJ}(nP) \to \Upsilon(1S)\gamma)$
  - Phys. Rev. Lett. 88, 161802 (2002). (ϒ(ns) cross section and polarization)

Cross Sections

$$\frac{d^2\sigma}{dp_T dy} \mathrm{Br}_{\mu^+\mu^-} = \frac{f_{\mathrm{prompt}}\, N}{(\mathcal{L}dt)\Delta p_T \Delta y\, \mathcal{A}\, \epsilon}$$



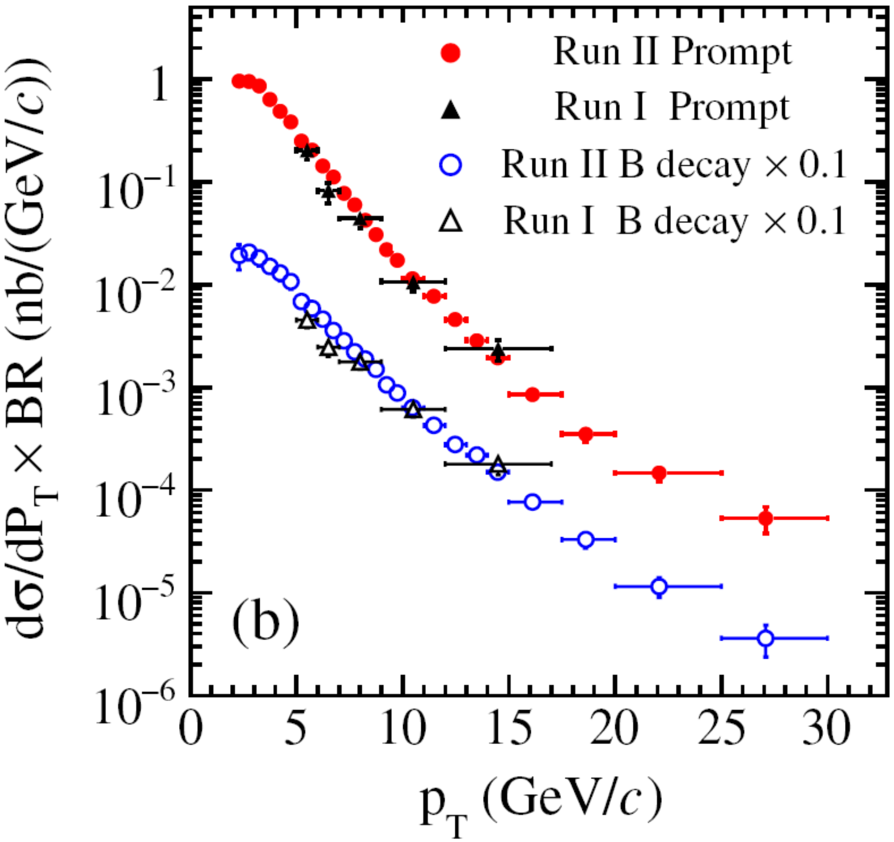


- Prompt fraction of J/ψ estimated from lifetime information.
- Efficiency determined from J/ψ samples obtained with single muon triggers
- Acceptance includes assumed polarization:

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

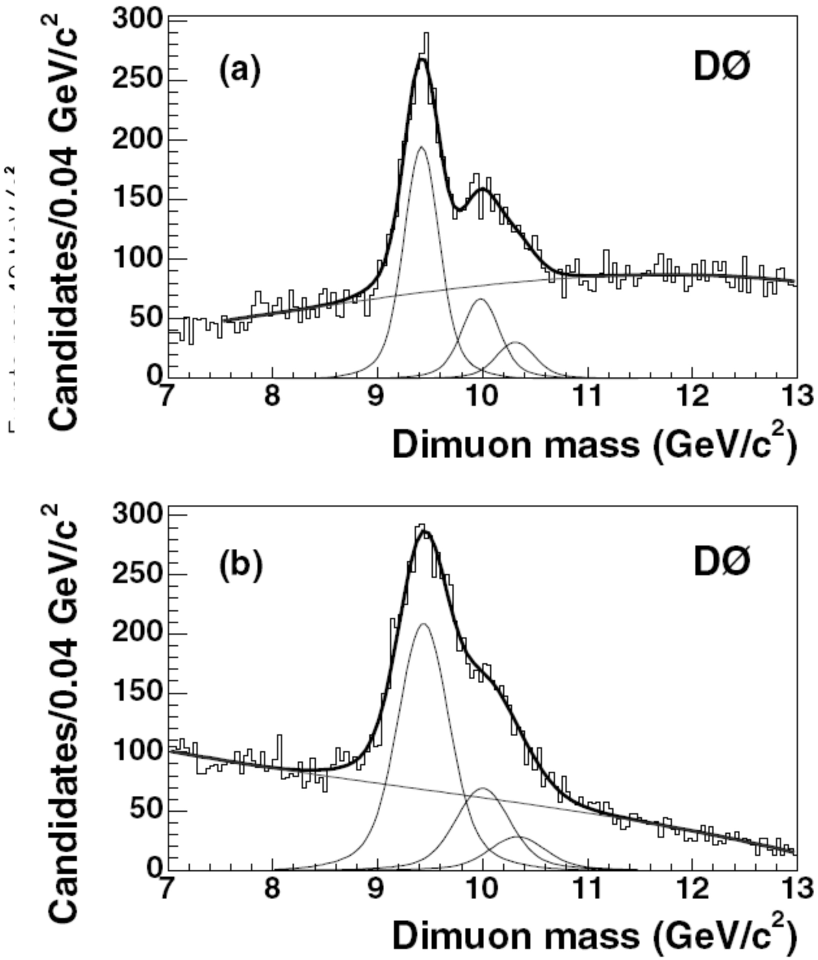
- Consider $-1 < \alpha < 1$ for systematics

Updated ψ(2S) Cross Section



- No known feed-down from χ_c states.
- Acceptance assumes almost no polarization, motivated by ψ(2S) measurement:
  $\alpha = 0.01 \pm 0.13$
- Prompt and B components separated using proper decay time.
- Consistent with Run I results...

Upsilon Cross Section

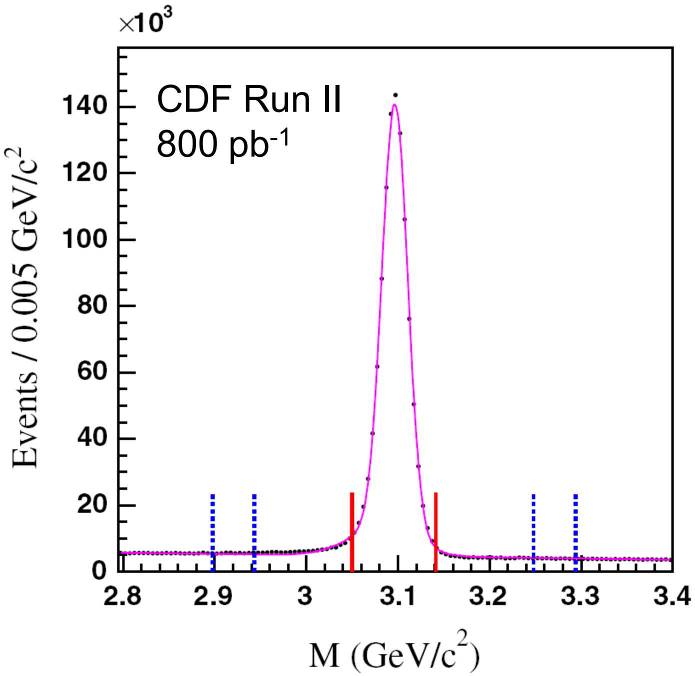


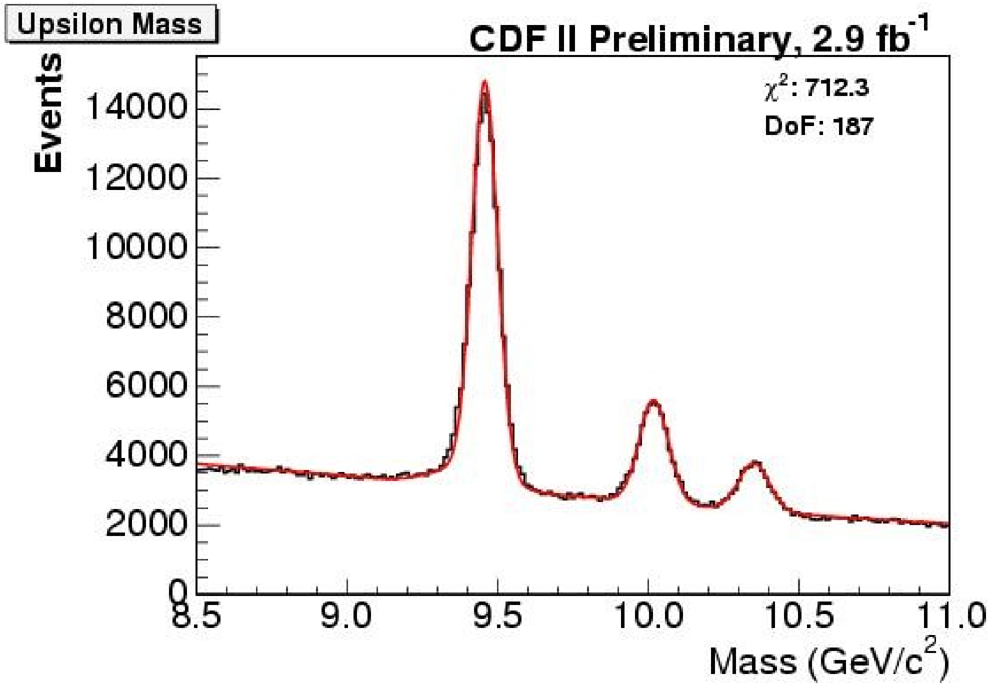
- Systematic uncertainty from polarization evaluated by fitting or varying distribution of cos θ^*

$$\frac{d\sigma_{\Upsilon(1S)}}{dy} = \begin{cases} 684 \pm 24 \text{ pb} & \text{CDF} \\ 628 \pm 75 \text{ pb} & \text{DØ} \end{cases}$$

- Shapes of $d\sigma/dp_T$ also agree.

CDF Polarization Measurements





- Low backgrounds, characterized by sidebands
- Requires prompt/secondary classification
- Divide sample into 6 p_T bins

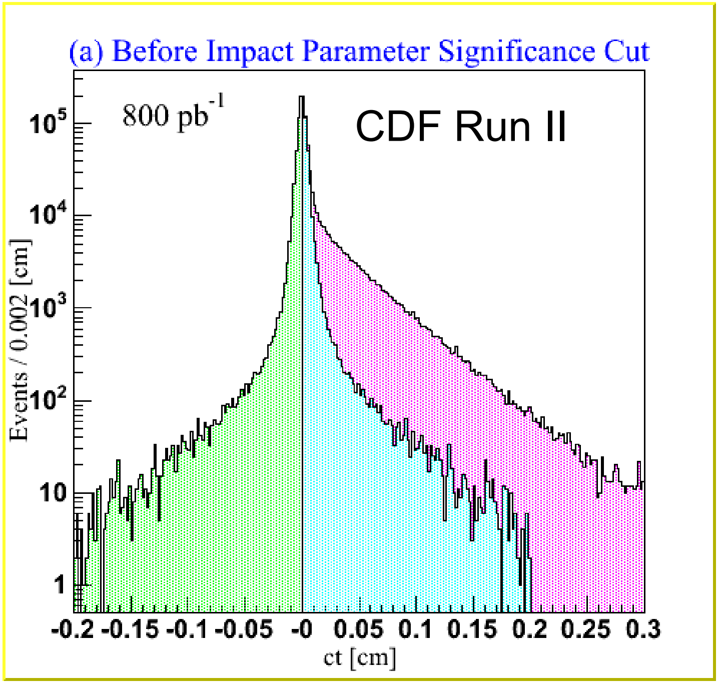
- Higher backgrounds with properties that evolve with $M_{\mu\mu}$
- No secondary component
- Analyze $\Upsilon(1S)$ polarization in 8 p_T bins

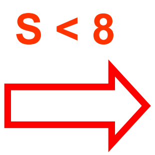
J/ψ and ψ(2S) Polarization

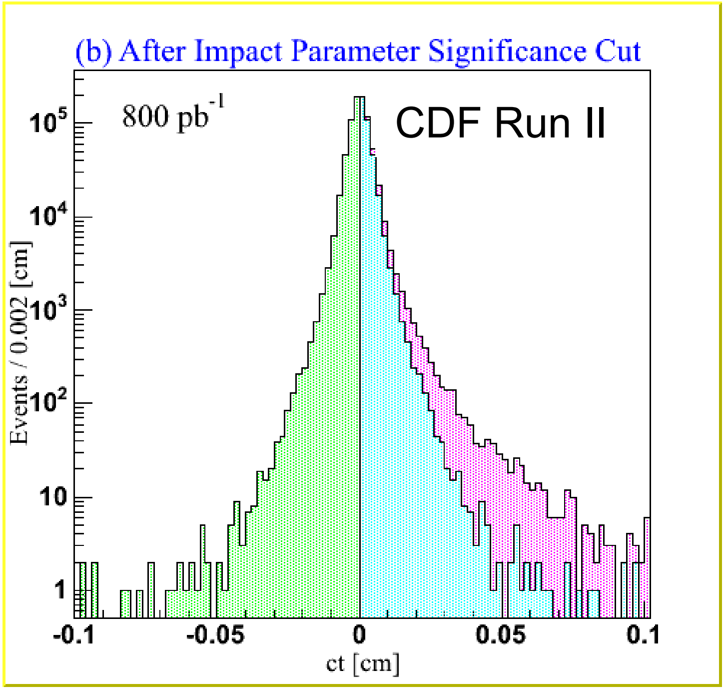
$$S = \left(\frac{d_0(\mu^+)}{\sigma_{d_0}(\mu^+)}\right)^2 + \left(\frac{d_0(\mu^-)}{\sigma_{d_0}(\mu^-)}\right)^2$$

$$ct = \frac{ML_{xy}}{p_T}$$

- S ~ χ^2 distribution
- Positive for B decays

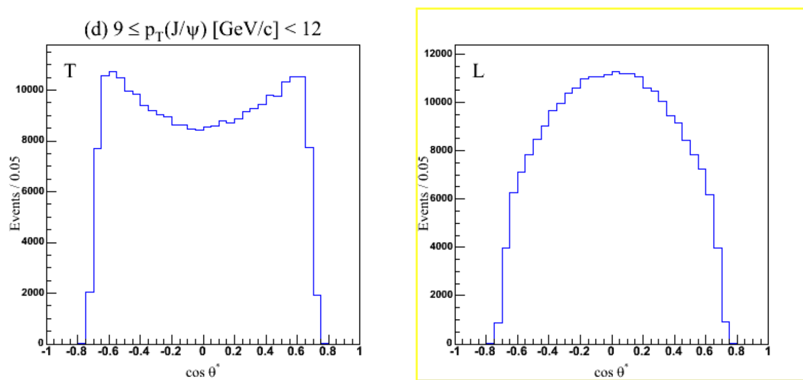






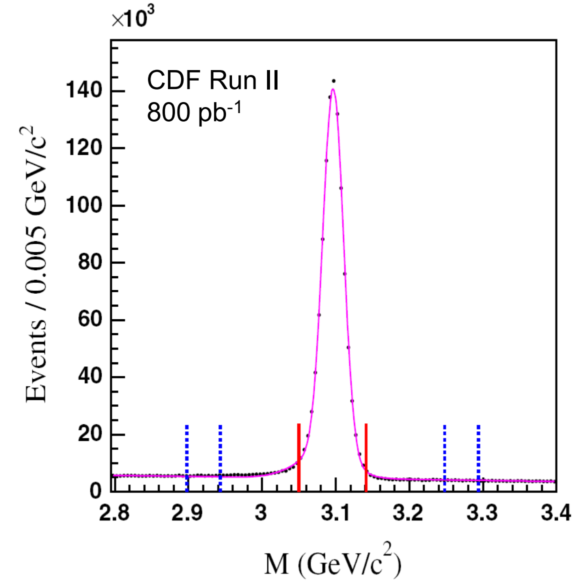
CDF Polarization Fit

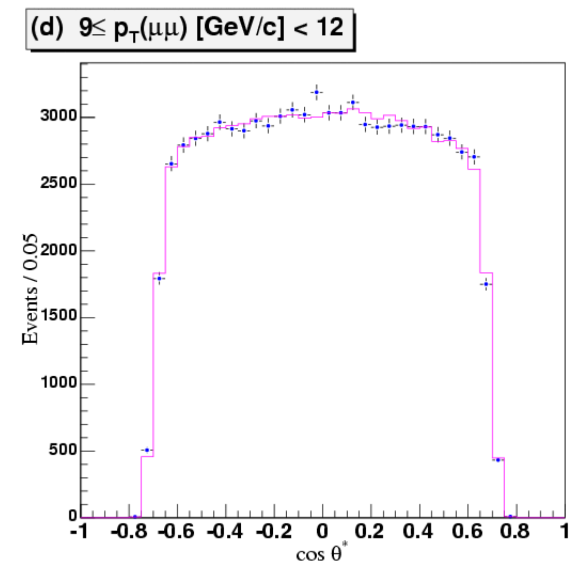
- Background constrained using sidebands.
- Simultaneous fit to extract α_{fit}:
  - Developed for optimal use of low statistics in Run I.



$$N_i(p_T) \propto (1-\eta)T_i + \eta L_i$$

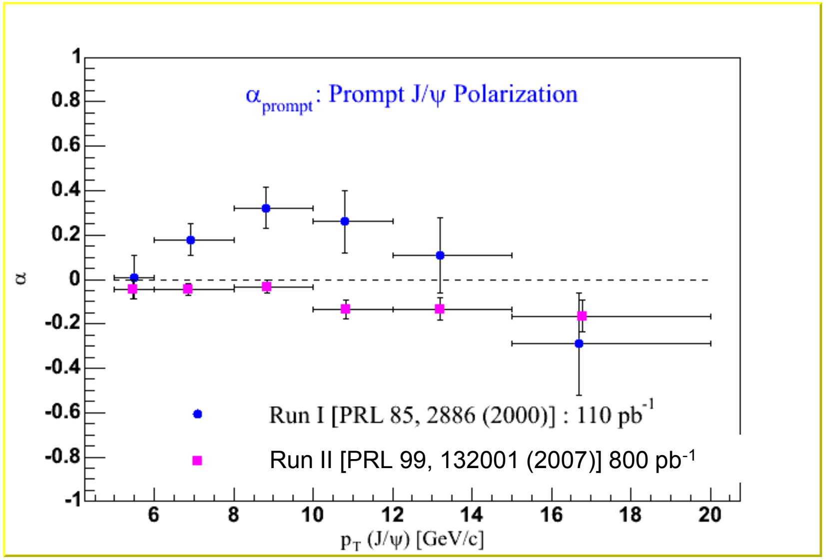
$$\alpha_{\text{fit}} = \frac{1-3\eta}{1+\eta}$$

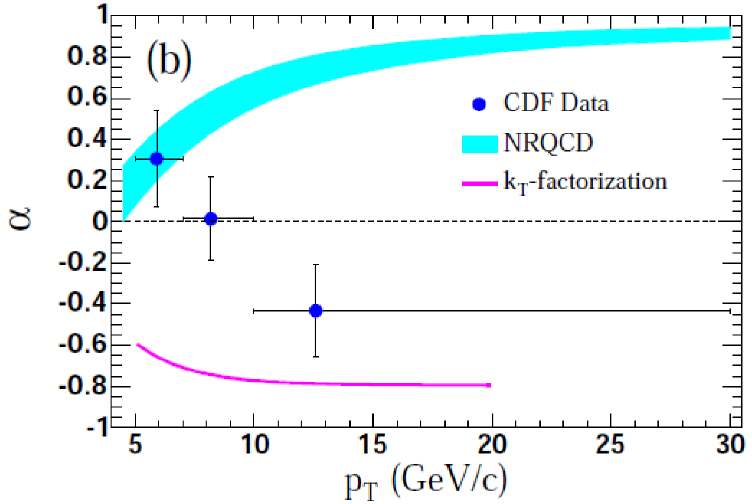




CDF J/ψ Polarization

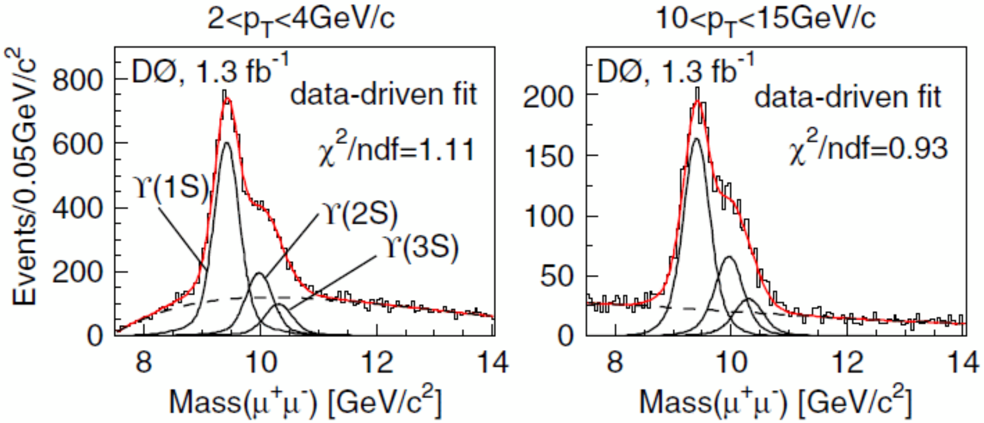
- Not much polarization...
- Maybe becomes slightly longitudinal at high p_T.
- Inconsistent with Run I result...

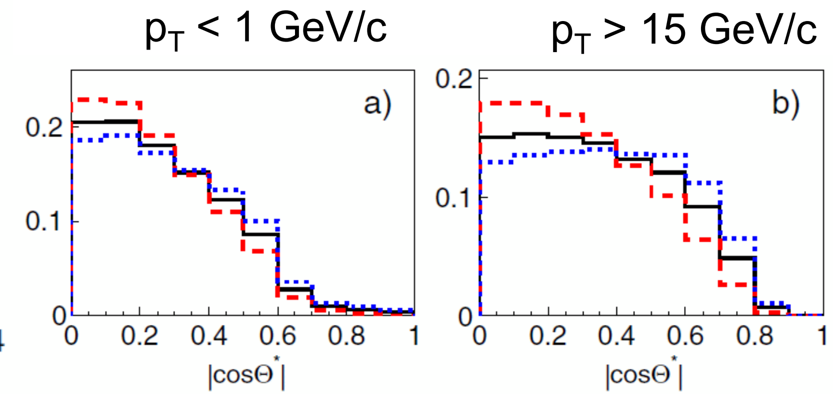


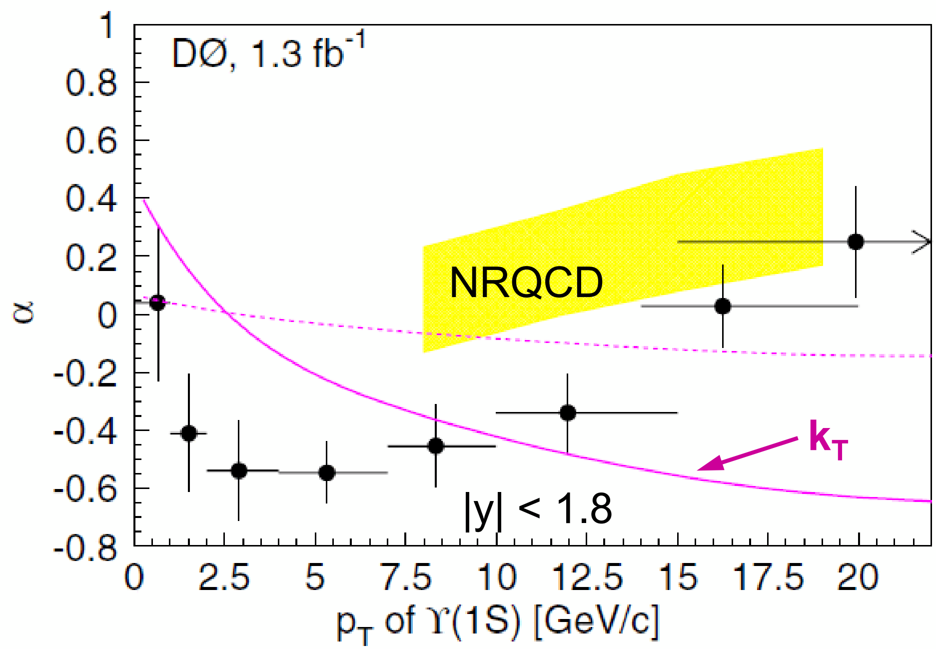


- What about the ϒ(1S)?

DØ ϒ Polarization Measurement

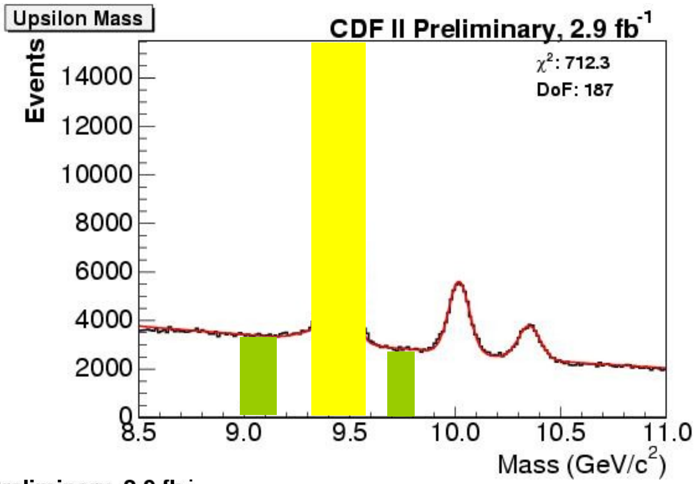


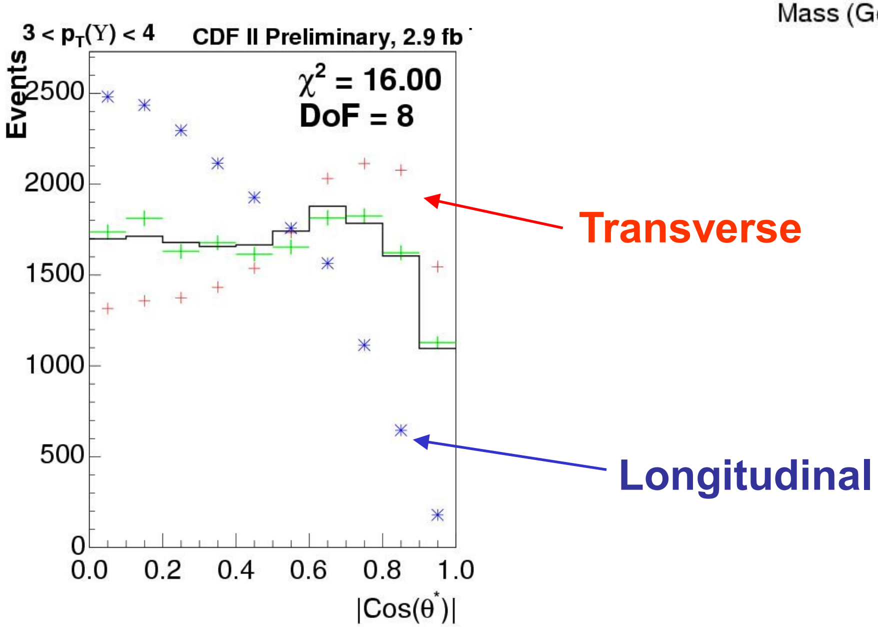




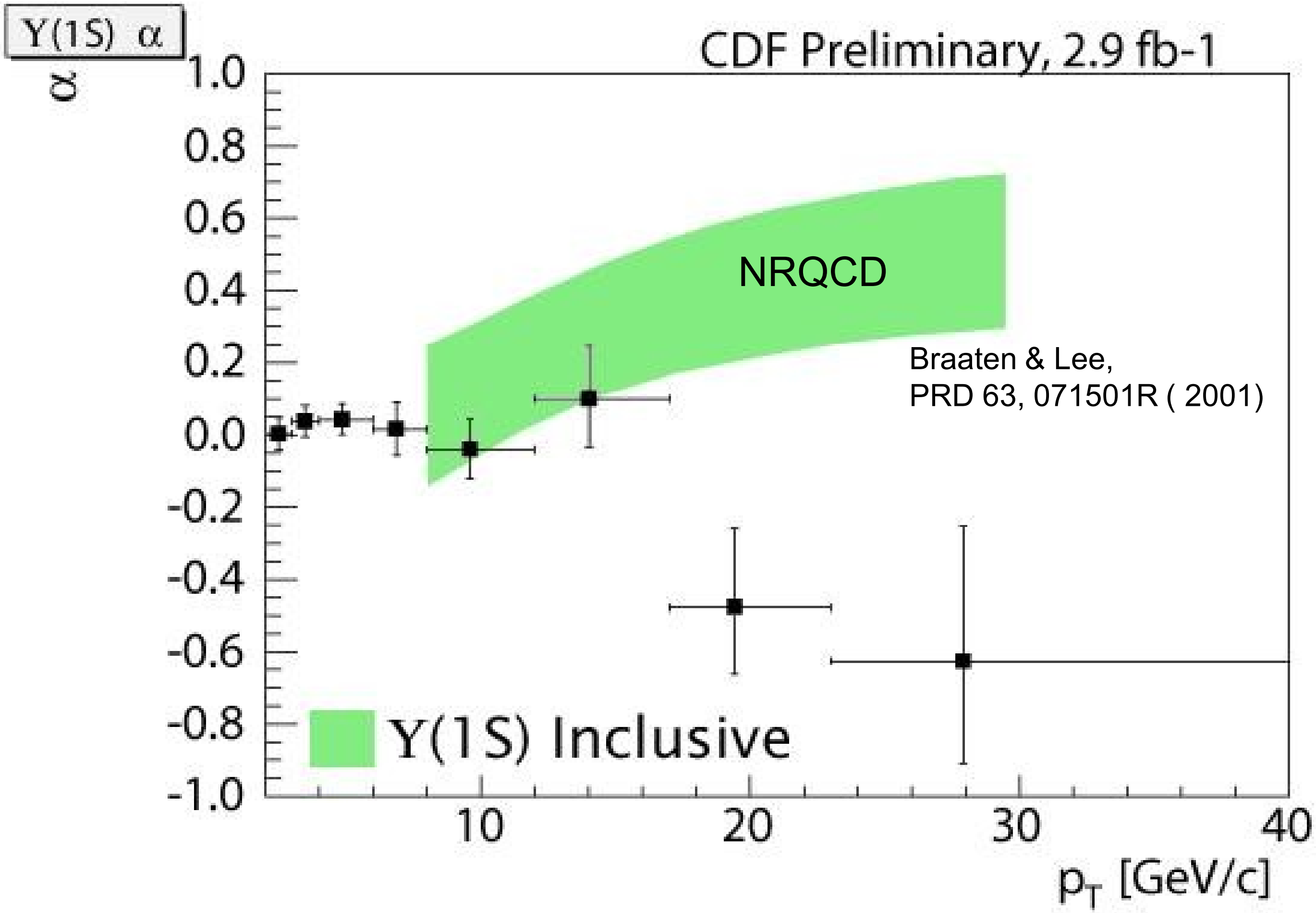
CDF Υ(1S) Polarization

- Same fitting procedure used in Run I and in J/ψ analysis.
- Significant difference between transverse and longitudinal templates in most p_T bins.
- Generally consistent with no polarization at low p_T.

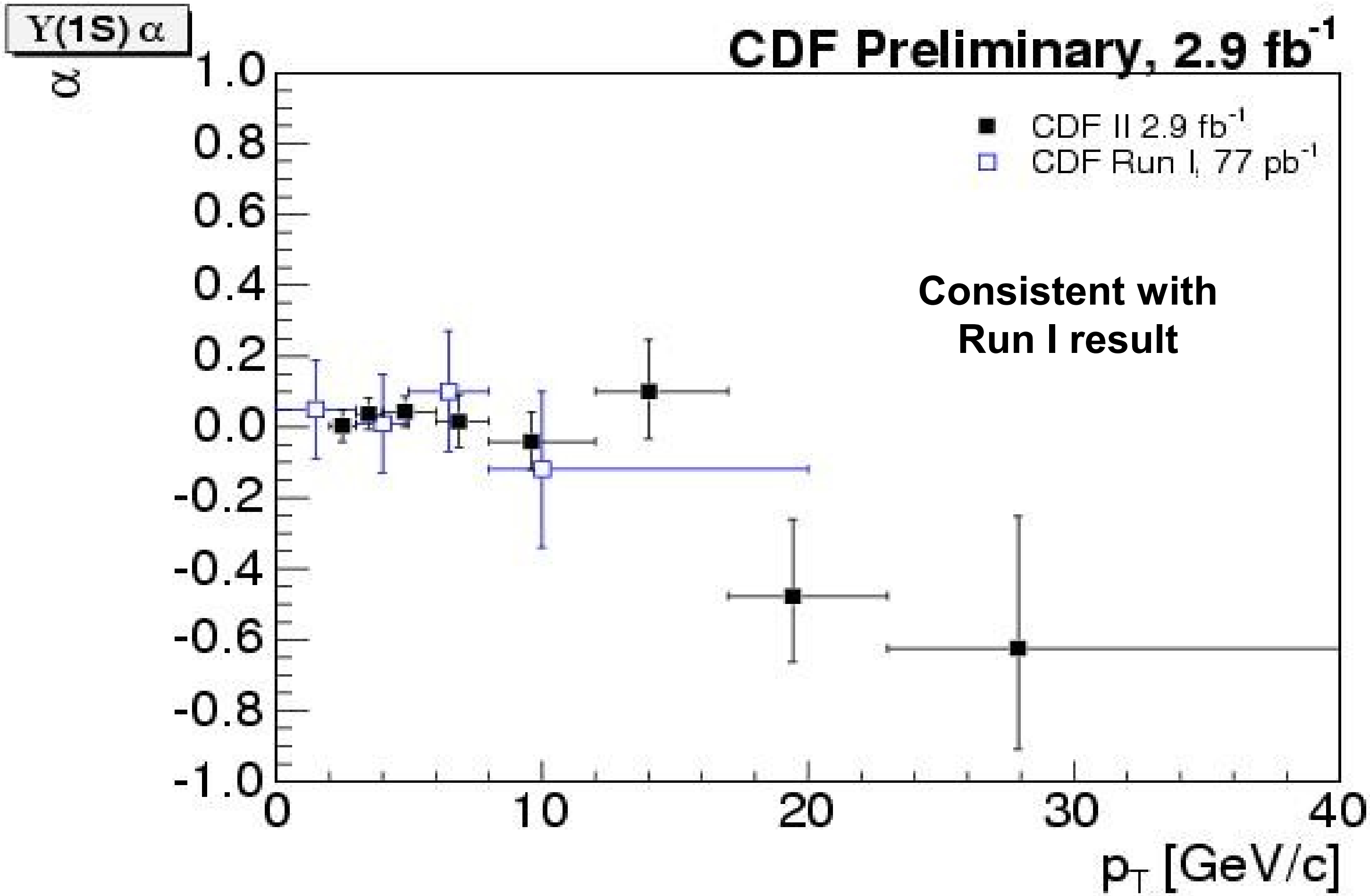




CDF Υ(1S) Polarization

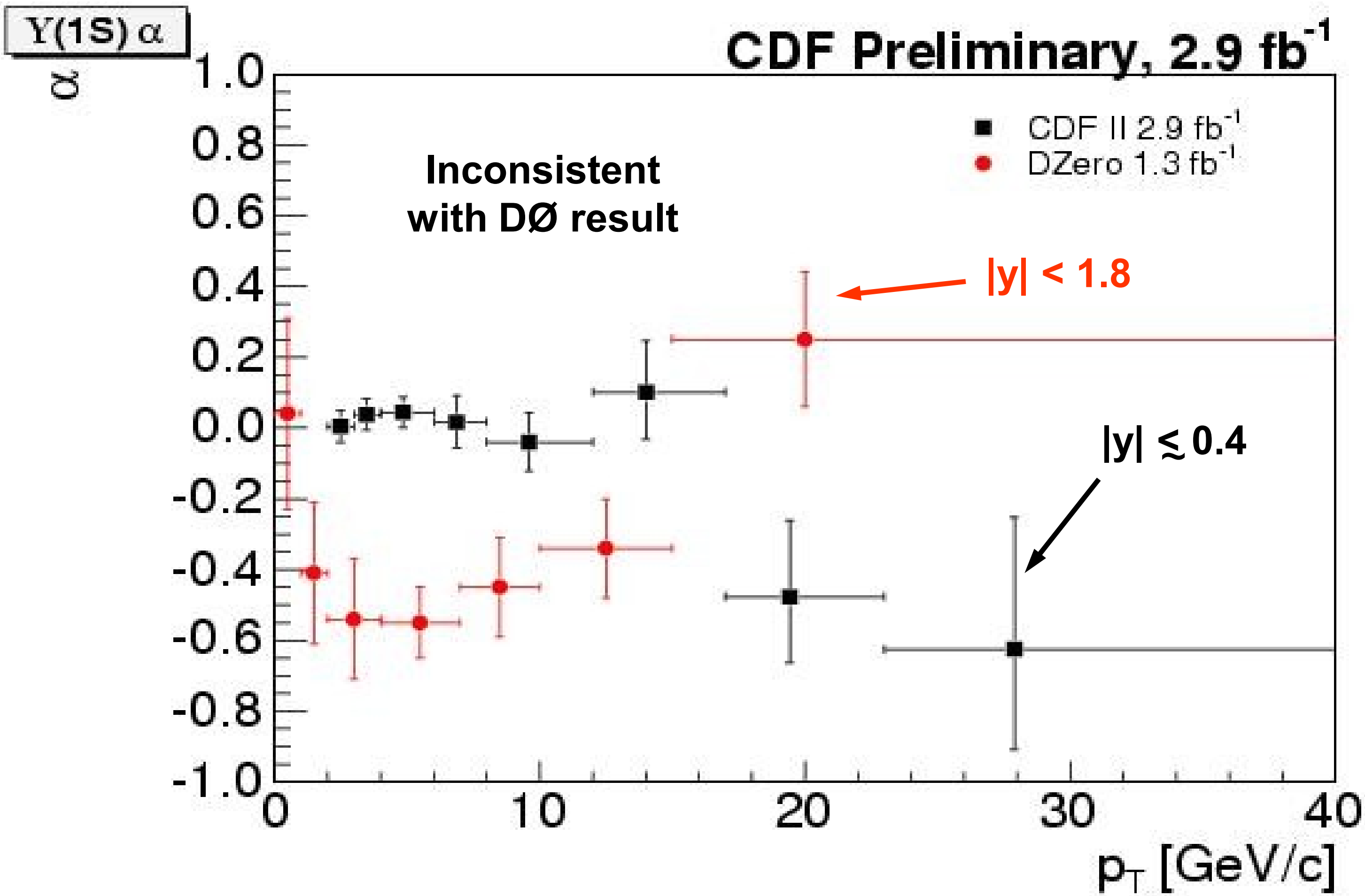


CDF Υ(1S) Polarization



Consistent with Run I result

CDF Υ(1S) Polarization



Maybe not even wrong...

- The current situation is rather murky... are we missing something obvious? Pietro Faccioli emphasizes basic quantum mechanics...
- Back to the fundamentals:
  - General state for a spin-1 particle:

$$|\psi\rangle = a_{+1}|1,+1\rangle + a_0|1,0\rangle + a_{-1}|1,-1\rangle$$

  - Angular distribution when decaying to $\mu^+\mu^-$:

$$\frac{dN}{d\Omega} \propto 1+\lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$

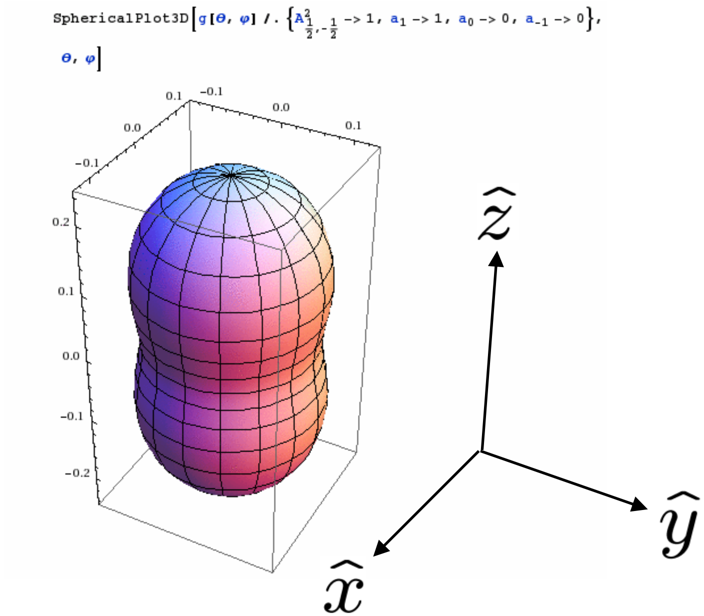
$$\lambda_\theta = \frac{1-3|a_0|^2}{1+|a_0|^2}$$

$$\lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}(a_0^* a_{+1} - a_0^* a_{-1})}{1+|a_0|^2}$$

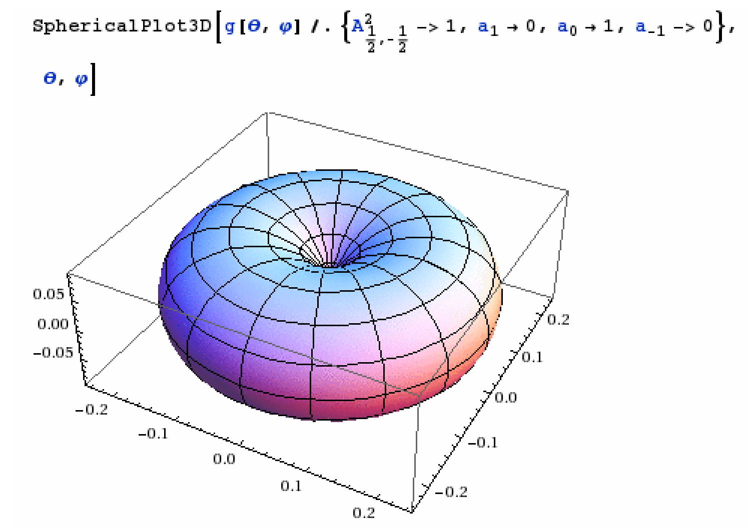
$$\lambda_\phi = \frac{2\mathrm{Re}\, a_{+1}^* a_{-1}}{1+|a_0|^2}$$

Just transverse is not enough

Transverse: $a_0 = 0$



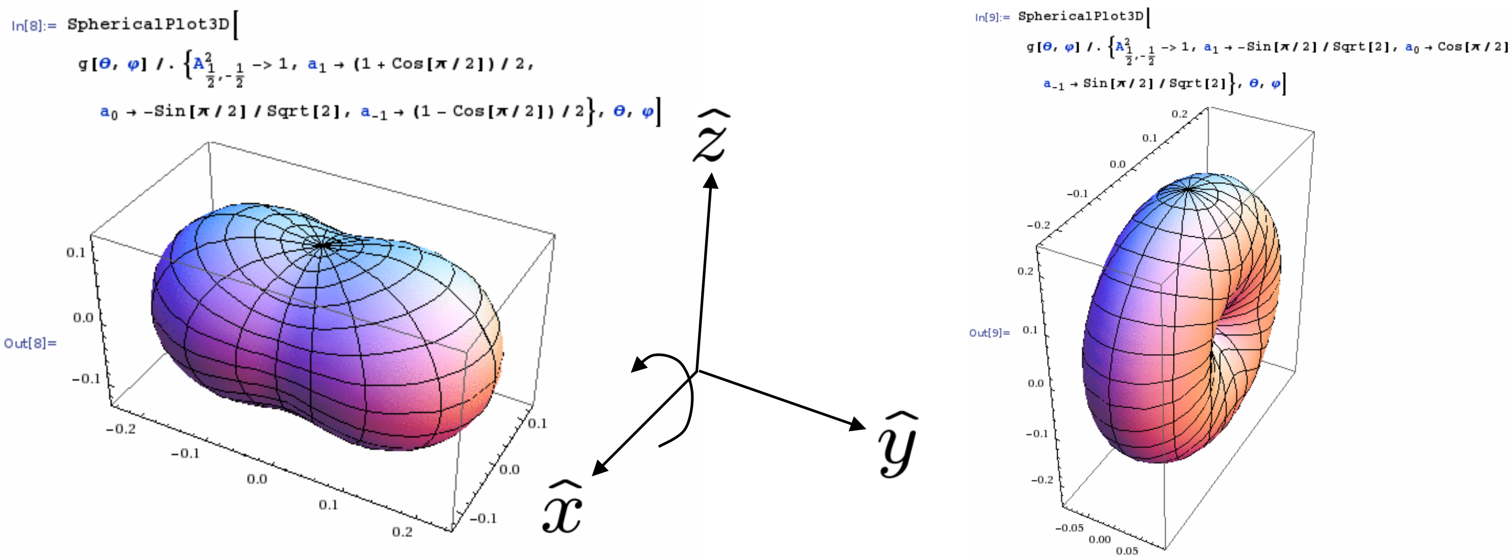
Longitudinal: $a_{\pm 1} = 0$



But an arbitrary rotation will preserve the transverse/longitudinal shape...

Need for full polarization analysis

$$\left|\langle\theta,\phi|\mathcal{R}_x\left(\frac{\pi}{2}\right)|\psi_T\rangle\right|^2 \qquad \left|\langle\theta,\phi|\mathcal{R}_x\left(\frac{\pi}{2}\right)|\psi_L\rangle\right|^2$$



- The templates for $dN/d\Omega$ are more complicated than simply $1 \pm \cos^2\theta$.
- Need to measure λ_θ, λ_φ and λ[redacted] simultaneously.
- Invariant under rotations: [redacted]

Fundamental Benchmarks

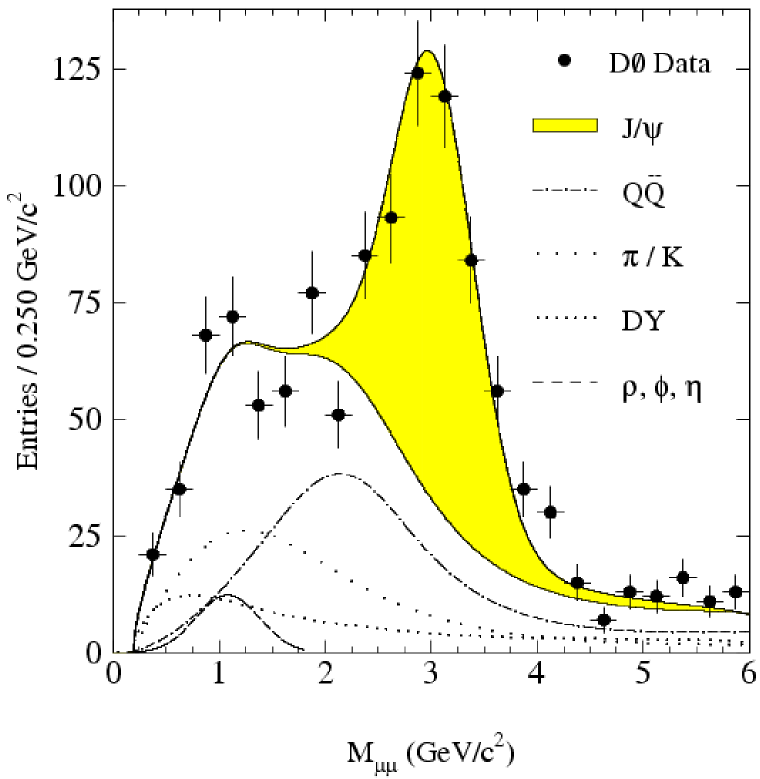
- B Cross sections:
  - Good agreement with current FONLL calculations
  - Demonstrate a non-trivial understanding of the non-perturbative ingredients
  - Remarkable achievement!
- Quarkonia cross sections:
  - Consistent total cross section measurements
  - Inconsistent polarization measurements
  - Several models compatible with measured cross section
  - *Polarization predictions are now an essential test*
  - Working on re-analysis using full angular distributions
    - Won't change cross sections by factors of 20...
    - Could influence the interpretation of polarization measurements
    - Awaiting valuable cross checks from the LHC experiments.

Backup Material

Early Cross Section Measurements

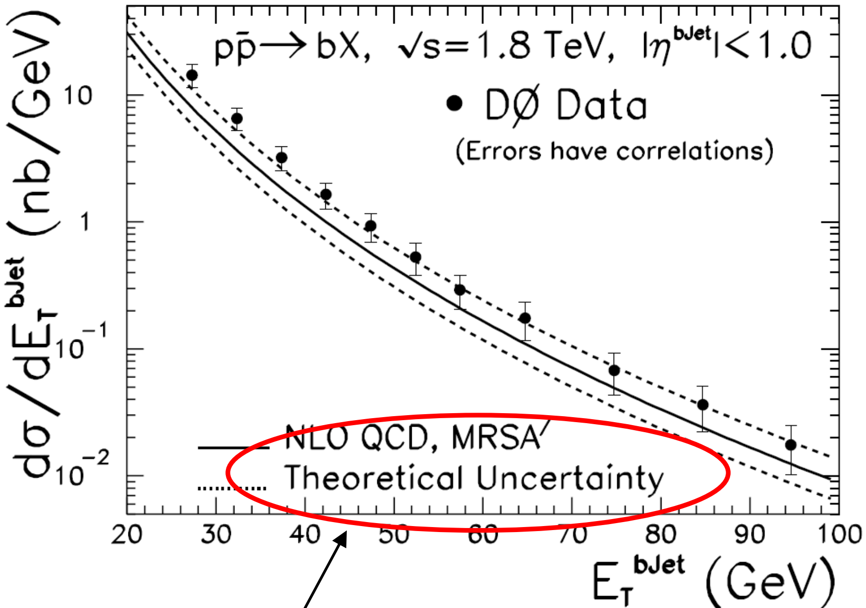
Phys. Lett. B370, 239 (1996)

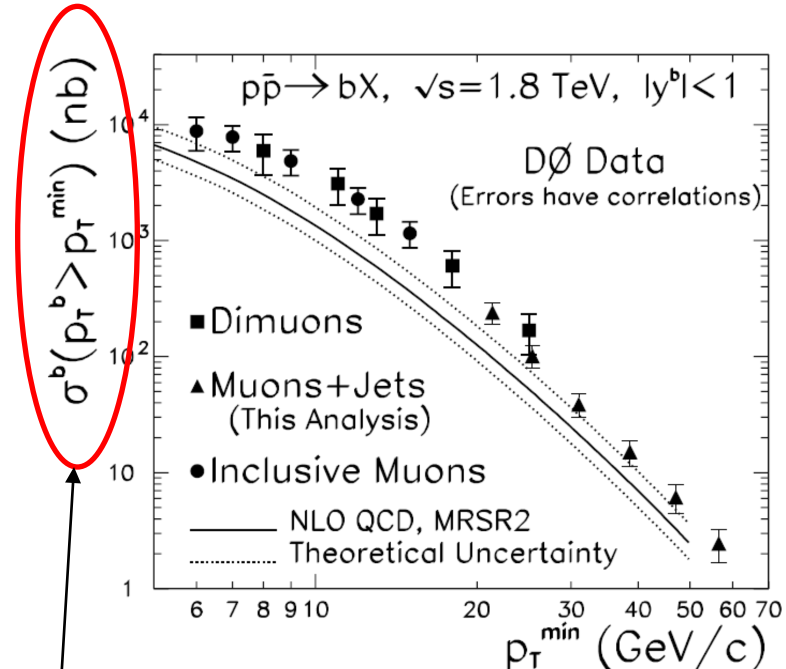
- DØ measurement using 6.6 pb^{-1}.
- No magnetic field in central tracker.
- $f_b \sim 35\%$ from muon impact parameters.
- External inputs:
  - $MRSD_0$ + MNR p_T spectra
  - Peterson fragmentation
  - Assume B → J/ψ K, J/ψ K^*



$$\sigma(p\bar{p} \rightarrow b + X) = 2.25 \pm 0.60 \pm 1.01\ \mu\text{b}$$
$$p_T^{\text{min}} = 9.9\ \text{GeV}/c,\ |y_b| < 1$$

An Early Clue...





from renormalization scale, μ_0.

b-quark cross section, integrated above p_T^{min}, *obtained from a model* relating $p_T(b)$ to $p_T(\mu)$.

More or less consistent with NLO QCD...

Exhibits typical "excess" over NLO QCD.

Efficiencies

- CDF treatment:
  - Track finding efficiency obtained by embedding hits from a simulated track in events from collision data and seeing if the track is reconstructed: $\varepsilon_{track}(p_T > 1.5\ GeV/c) \sim 0.9961$
  - Other efficiencies calculated using ``tag and probe'' method: given that a muon track is reconstructed calculate the probability that it satisfies additional criteria:
    - $\varepsilon_{L1}(p_T)$, $\varepsilon_{L2}(p_T)$, ε_{L3}, ε_{muon}, $\varepsilon_{\chi 2}$
  - p_T independent efficiency:

$$\epsilon_{rec} = \epsilon^2_{L3}\epsilon^2_{track}\epsilon^2_{muon}\epsilon_{z_0}\epsilon_{\Delta z_0}$$

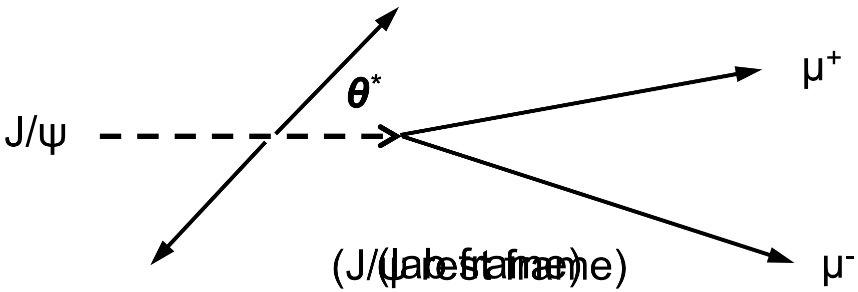
  - p_T dependent efficiencies:

$$1/w_i = \epsilon_{L1}(\mu_1)\epsilon_{L1}(\mu_2)\epsilon_{\chi^2}(\mu_1)\epsilon_{\chi^2}(\mu_2) \cdot \mathcal{A}(p_T, y)$$

Note: there was no L2 muon trigger for this data taking period.

Polarization Templates

- S-channel helicity frame:



Transverse: $\frac{d\sigma}{d\cos\theta^*} \sim 1 + \cos^2\theta^*$

Longitudinal: $\frac{d\sigma}{d\cos\theta^*} \sim 1 - \cos^2\theta^*$

- Include detector acceptance and event selection: