Beauty and Charm Production Cross Section Measurements at the Tevatron

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Rencontres de Moriond QCD and High Energy Interactions

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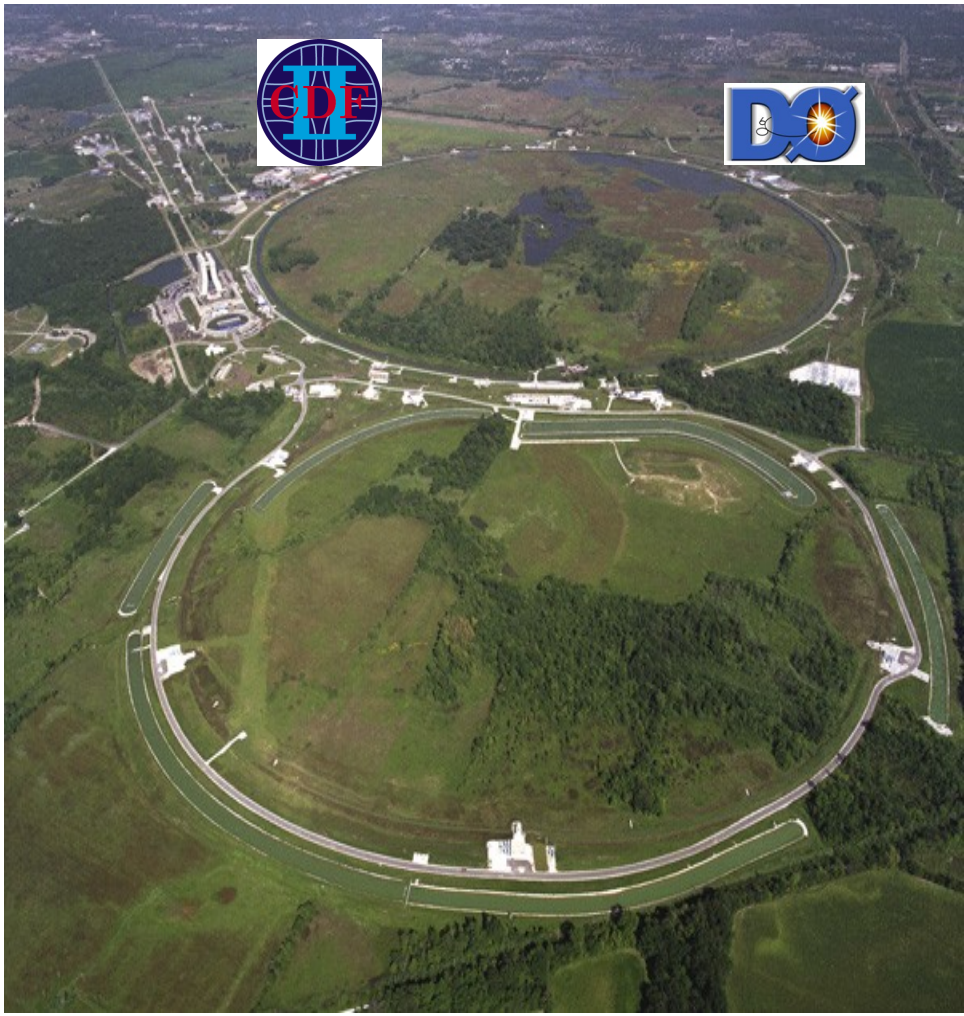
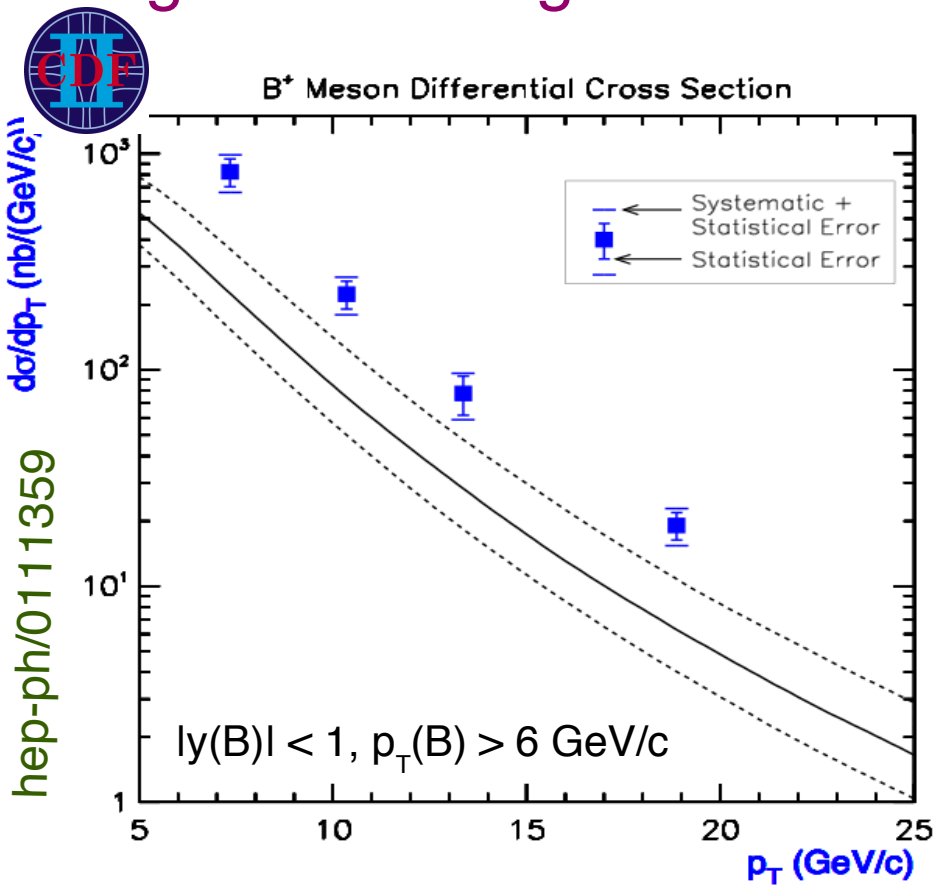
Outline

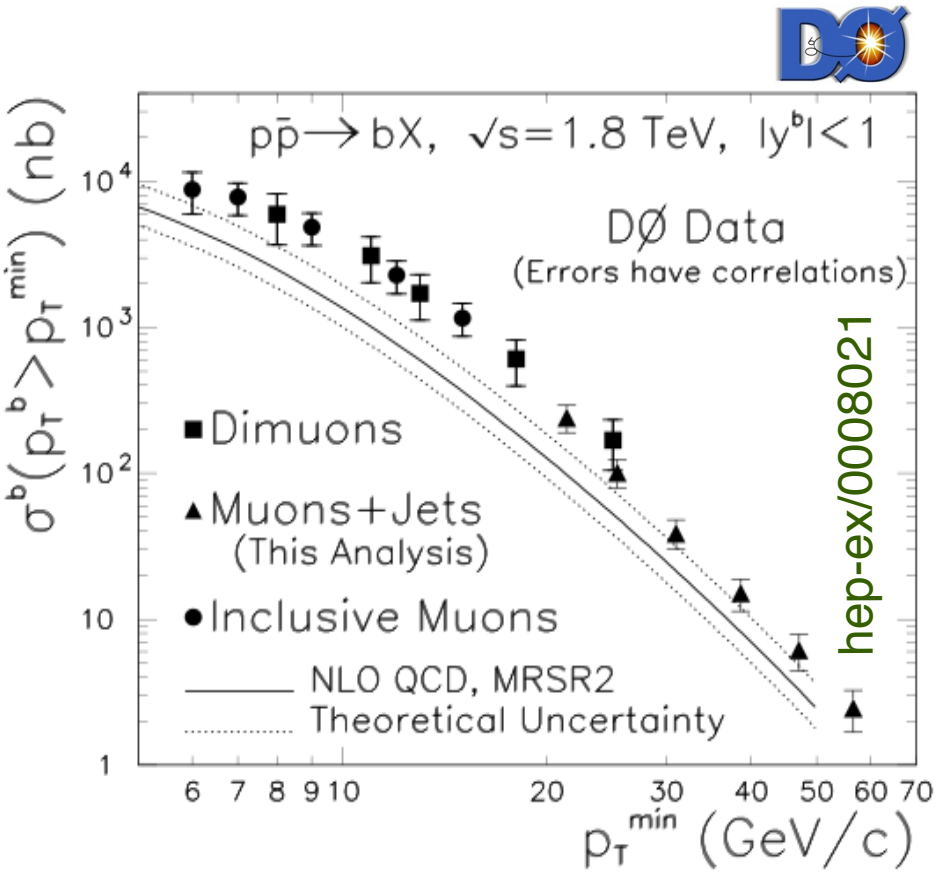
- Motivation
- Quarkonia production
- Recent results:
  - Correlated $b\bar{b}$ production
  - Polarization of Υ(1S) and Υ(2S)
  - ψ(2S) production cross section
    - Polarization of J/ψ and ψ(2S)
- Summary



Motivation

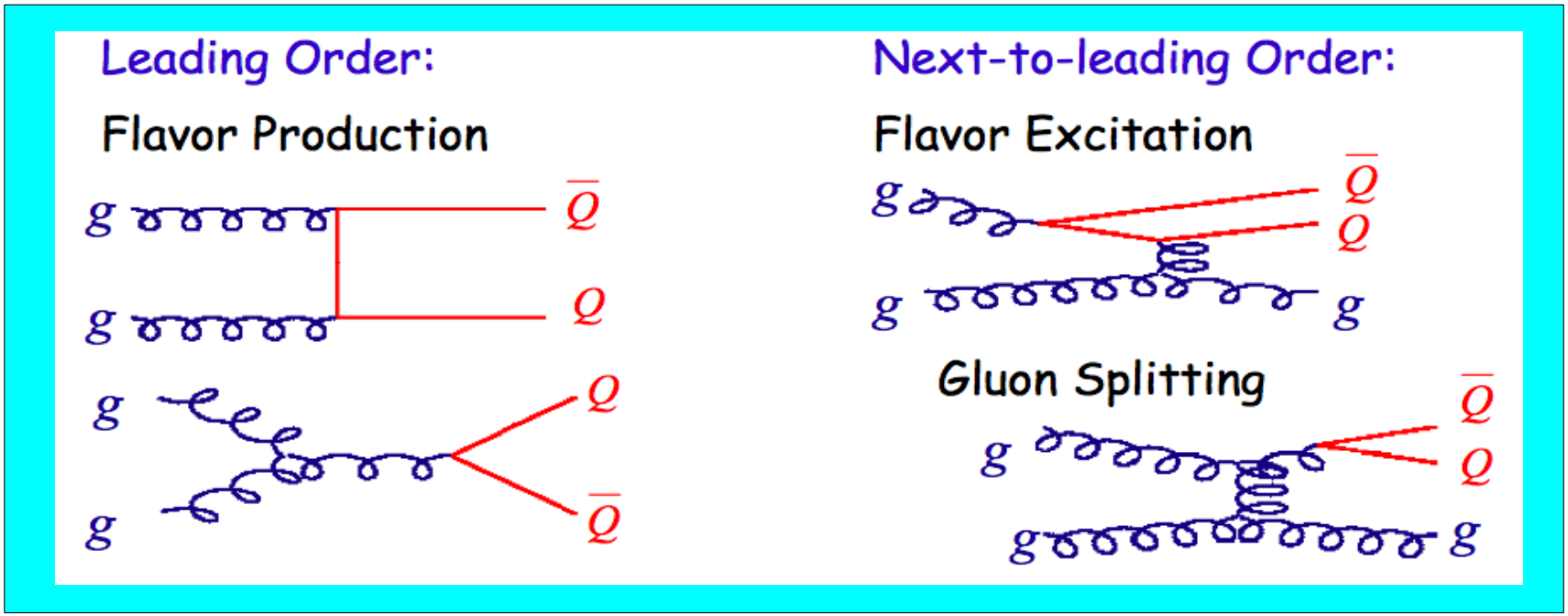
- Heavy quark production probes QCD at perturbative and non-perturbative interface → important test of models
- Tevatron Run I, many cross section measurements higher than original theoretical predictions:



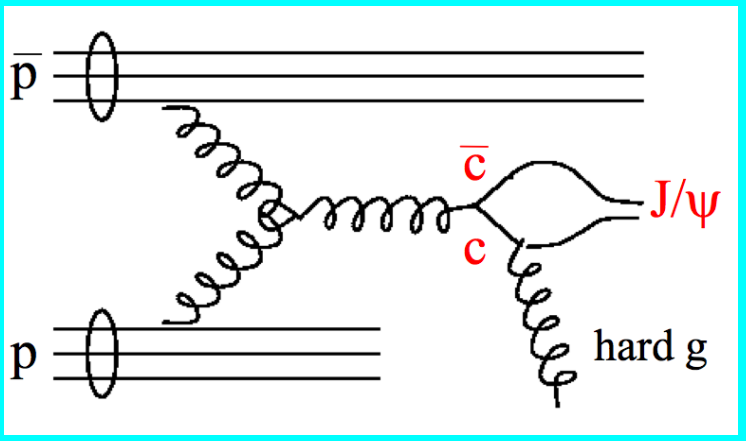


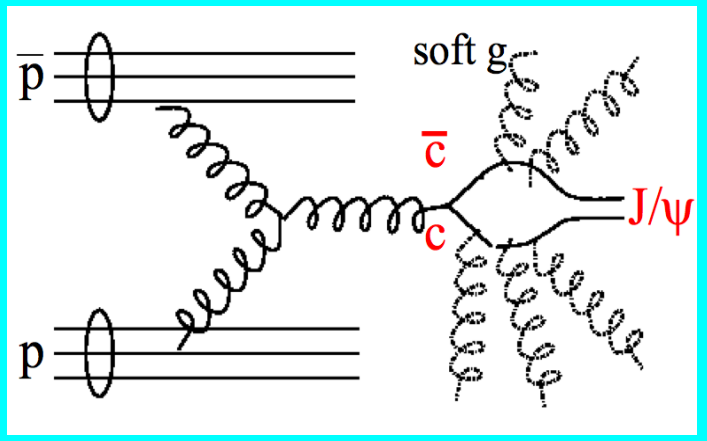
Charm and Beauty Production

- Led to improved measurements and better theoretical understanding – nonrelativistic QCD (NRQCD)
- Now much better agreement between data and theory!
- Fixed Order Next to Leading Log calculations available



Quarkonia Production

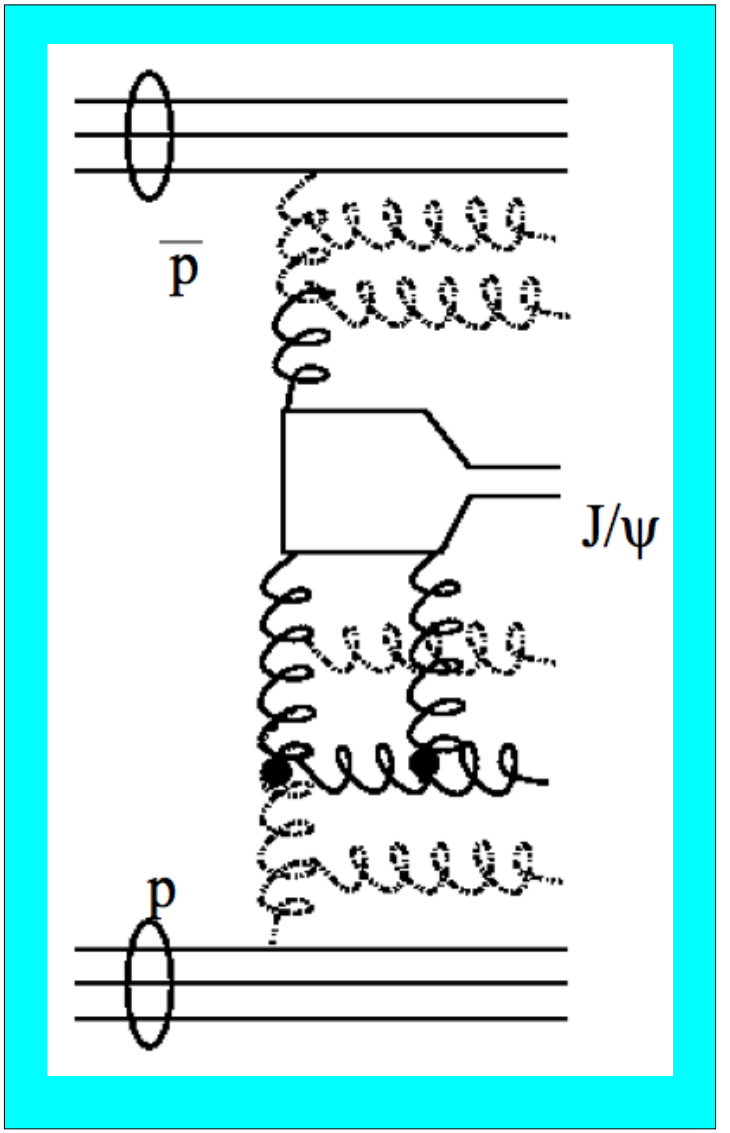




- Color Singlet Model
  - One hard gluon carries away color
  - p_T spectrum does not match data
  - Underestimates cross sections by factors of 10-50
- From NRQCD, Color Octet Mechanism
  - Soft gluons
  - Adjustable hadronization parameter → match data p_T and cross section
  - Predicts transverse polarization at high p_T

Quarkonia Production

- Pomeron inspired idea:
  - Fusion of symmetric color octet and a gluon
  - LO pQCD calculation matches data p_T spectrum and cross section
  - Expect increasing longitudinal polarization at high p_T

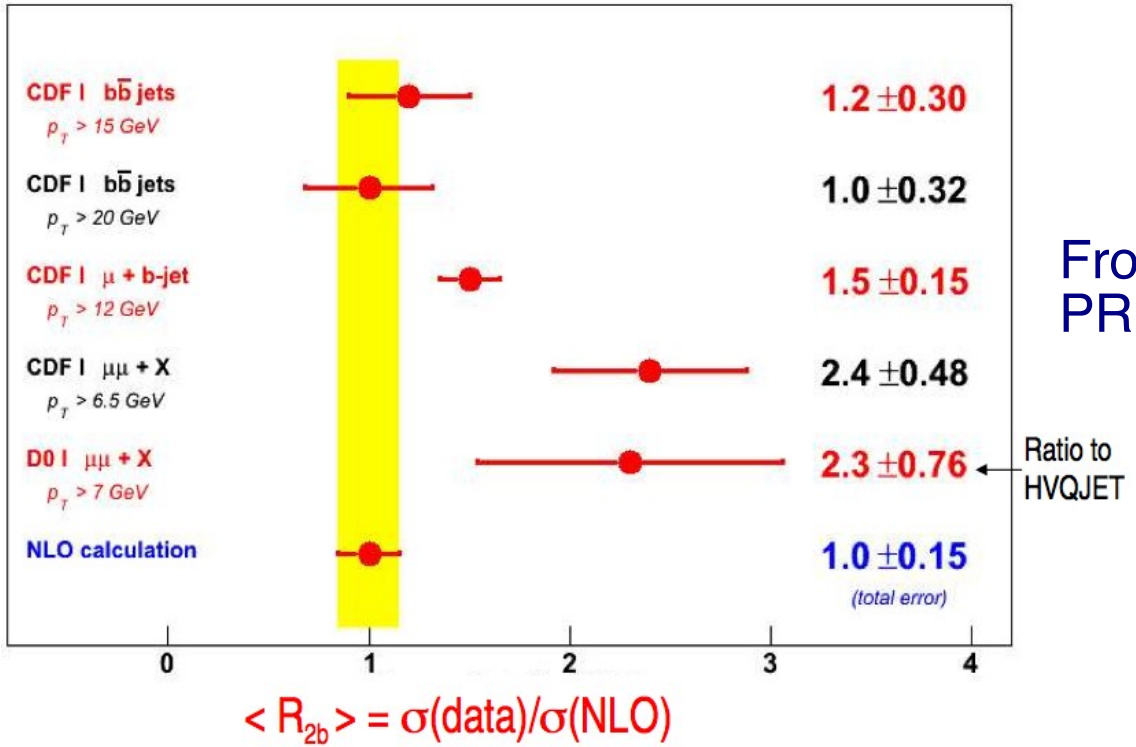


V.A. Khoze, A.D. Martin, M.G. Ryskin, W.J. Stirling; hep-ph/0410020

E.L. Berger, J. Qiu, Y. Wang hep-ph/0411026

Correlated $b\bar{b}$ Production

- For correlated $b\bar{b}$ production (both *b* quarks within central rapidity and above a p_T threshold), expect:
  - Higher order terms to be smaller
  - NLO predictions should be more accurate
- Tevatron Run I results inconclusive/contradictory:

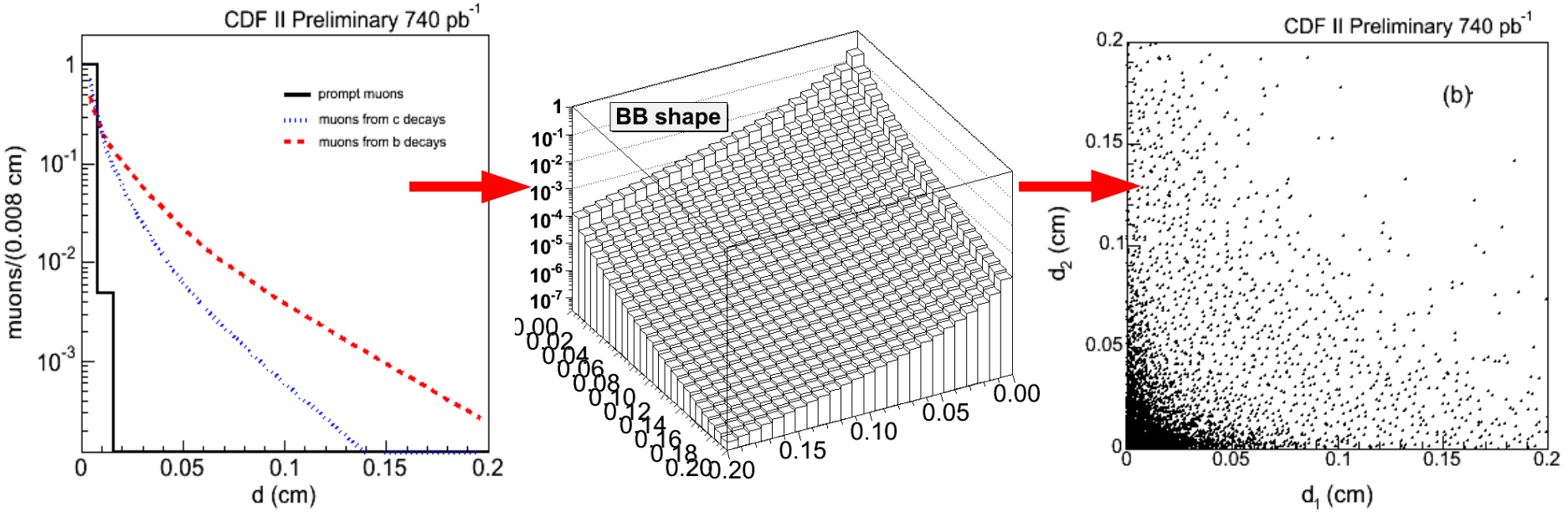


From F. Happacher *et al*, PRD73, 014026 (2006)

Correlated $b\bar{b}$ and $c\bar{c} \to \mu\mu$

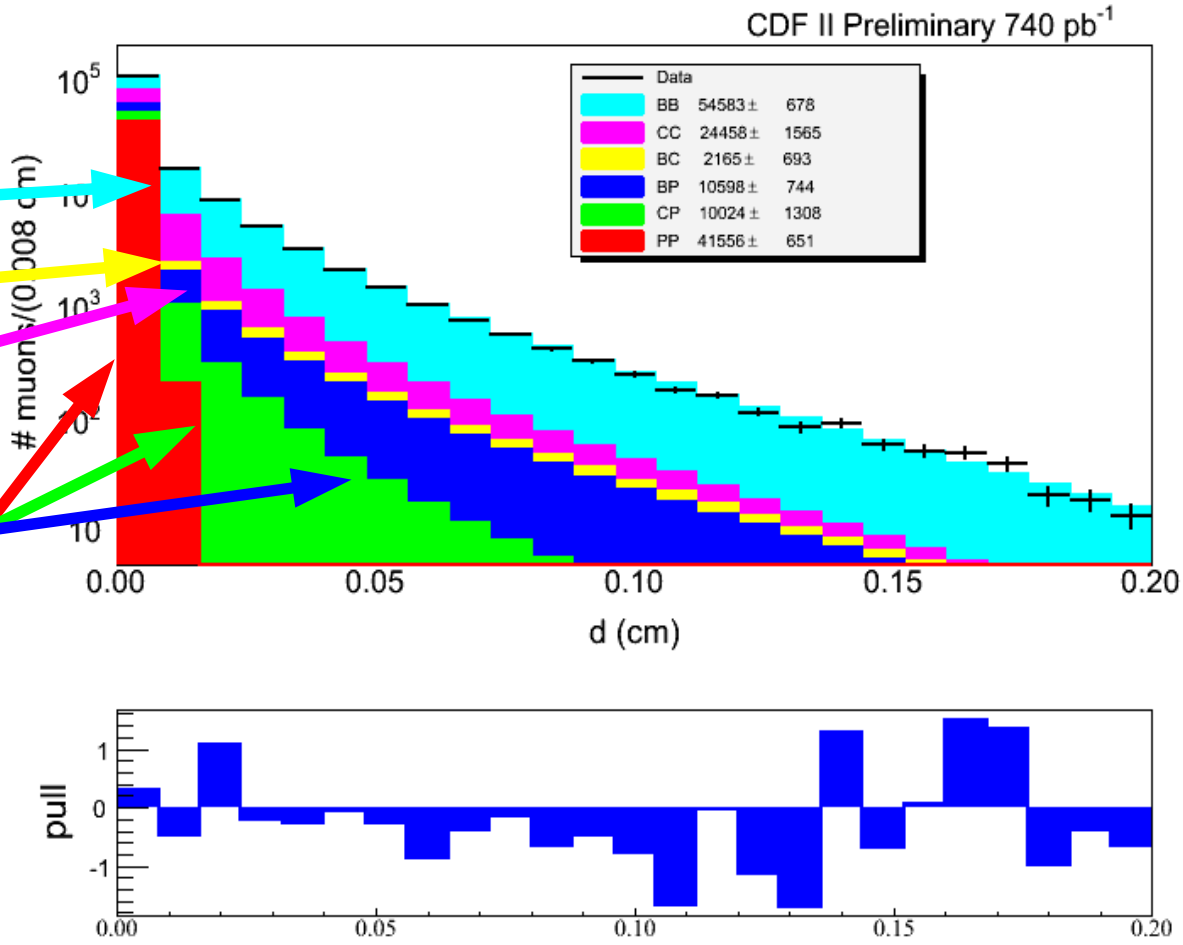
- In 740 pb^{-1} of data, select $\mu\mu$ pairs produced by:
  - Decays of heavy flavor pairs ($b\bar{b}$, $c\bar{c}$)
  - Prompt Drell-Yan processes
  - Charmonium, bottomonium, K and π decays
  - Misidentification of K and π mesons
- Fit 2D impact parameter dist. to extract sample composition

1D template (data, tuned Herwig) 2D template 2D data



Fit Projection

- 2D fit of impact parameter can distinguish:
  - $b \to \mu\,, \bar{b} \to \mu$
  - $b \to \mu\,, c \to \mu$
  - $c \to \mu\,, \bar{c} \to \mu$
  - Contributions with one or more prompt μ
- $c\bar{c}$ measurement is a by-product of background studies



Correlated $b\bar{b}$ and $c\bar{c}$: Results

- Cross sections:

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

- Ratios (includes experimental and theory errors):
  - Peterson fragmentation parameter...

$\varepsilon = 0.006$ $\dfrac{\sigma^{\text{measured}}_{b\to\mu,\bar{b}\to\mu}}{\sigma^{\text{NLO}}_{b\to\mu,\bar{b}\to\mu}} = 1.2 \pm 0.2$ $\varepsilon = 0.06$ $\dfrac{\sigma^{\text{measured}}_{c\to\mu,\bar{c}\to\mu}}{\sigma^{\text{NLO}}_{c\to\mu,\bar{c}\to\mu}} = 2.7 \pm 0.6$

Cacciari, Nason, PRL 89, 122003 (2002); NDE calculation for single *b* x-section uses...

$\varepsilon = 0.002$ $\dfrac{\sigma^{\text{measured}}_{b\to\mu,\bar{b}\to\mu}}{\sigma^{\text{NLO}}_{b\to\mu,\bar{b}\to\mu}} = 1.0 \pm 0.2$ $\varepsilon = 0.02$ $\dfrac{\sigma^{\text{measured}}_{c\to\mu,\bar{c}\to\mu}}{\sigma^{\text{NLO}}_{c\to\mu,\bar{c}\to\mu}} = 1.6 \pm 0.4$

- Using ratio with $\varepsilon = 0.006$:

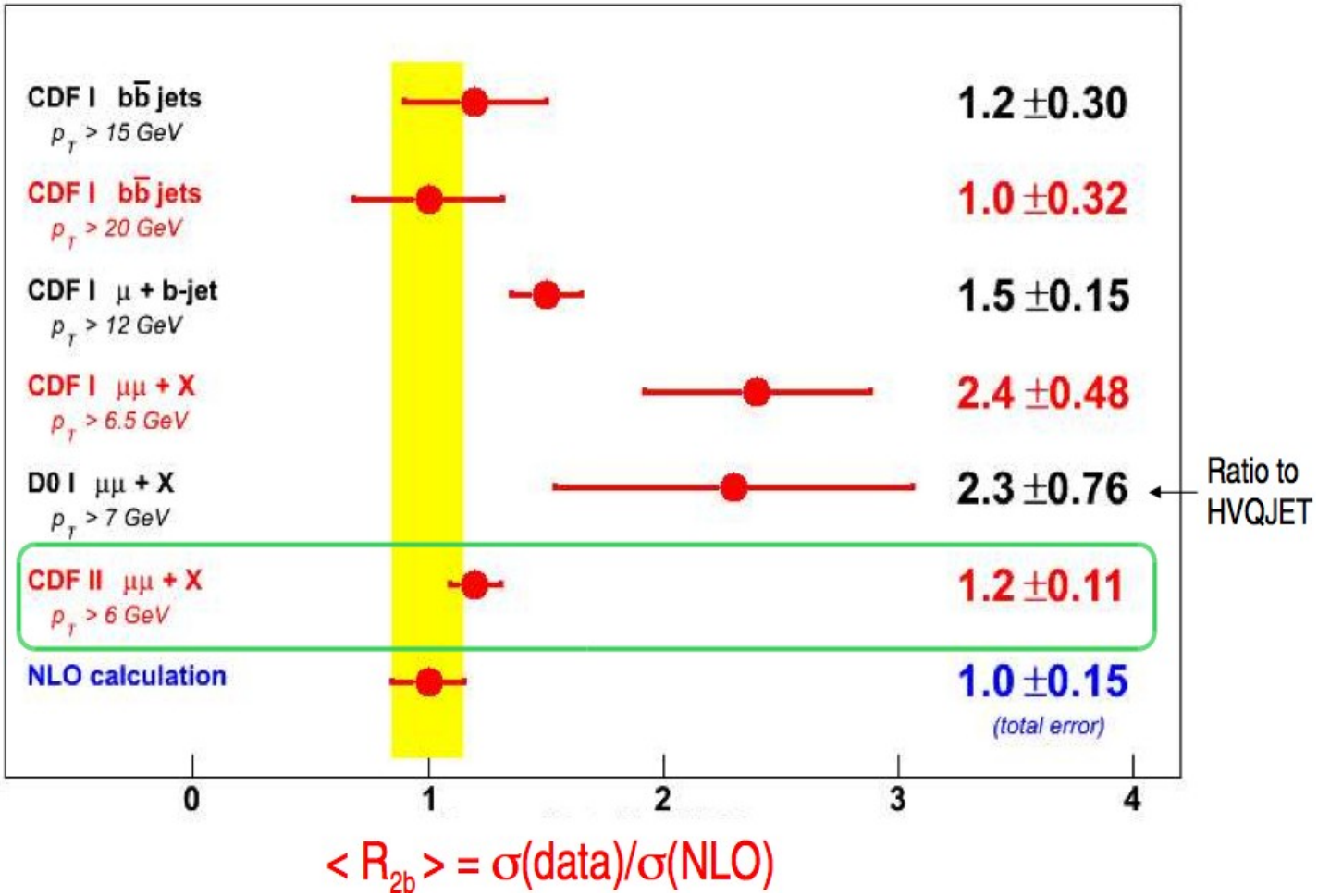
$$\sigma_{b\bar{b}}(p_T \geq 6\,\text{GeV}/c, |y| \leq 1) = 1618 \pm 148\,\text{nb}$$

PRD coming soon

$(\text{NLO prediction} = 1348 \pm 209\,\text{nb})$

Correlated $b\bar{b}$ Production

- High dimuon cross section *not* observed in Run II



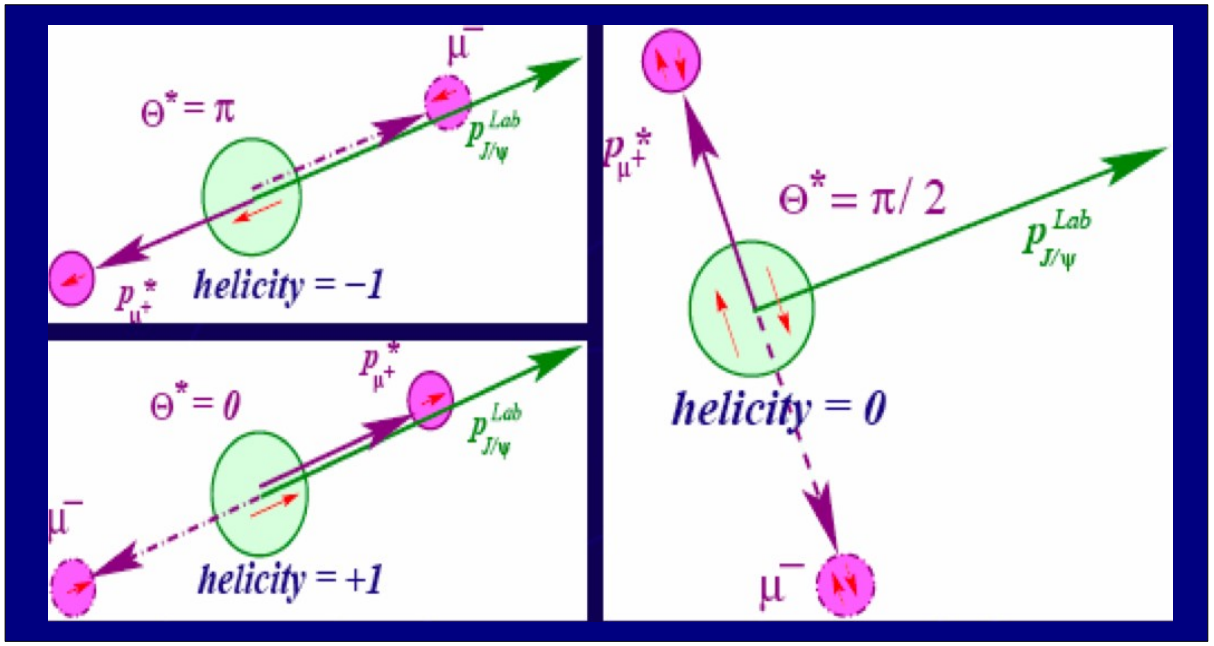
Measuring Quarkonium Polarization

- Measure polarization parameter:

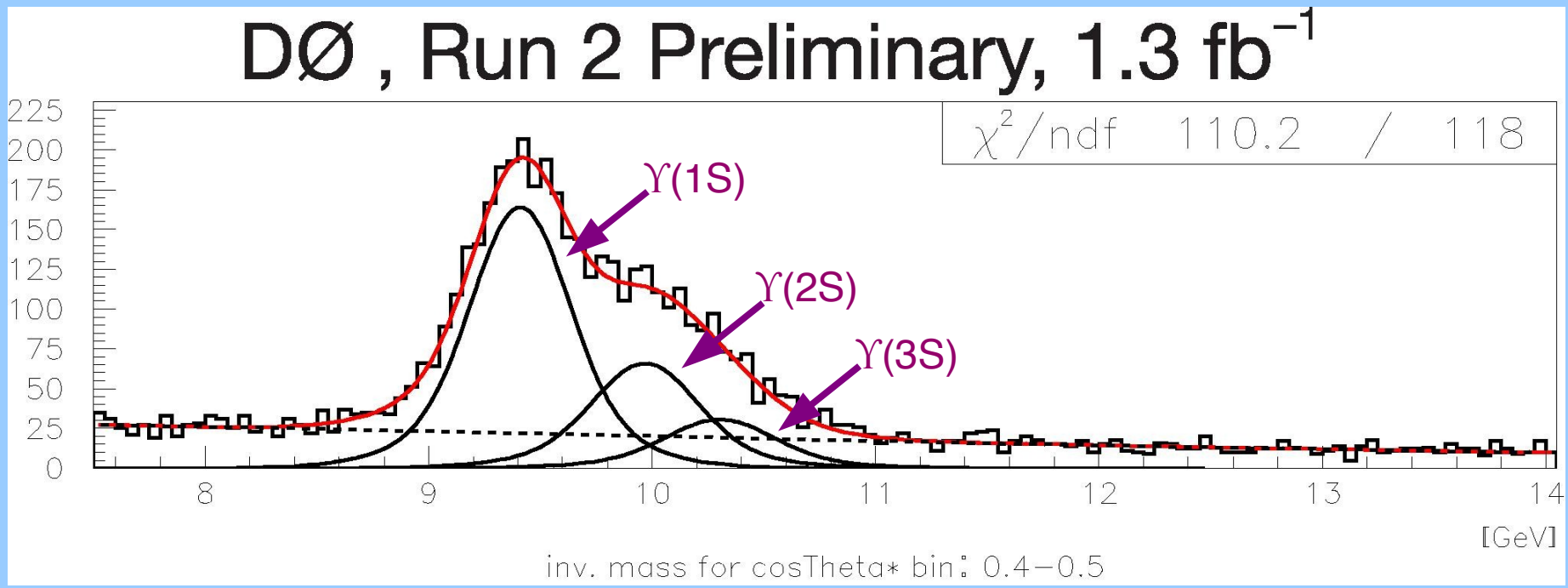
$$\alpha = \frac{(\sigma_T - 2\sigma_L)}{(\sigma_T + 2\sigma_L)}$$

- Extract α from angular distribution, where θ^* = angle between J/ψ(Υ) in lab frame and μ in J/ψ(Υ) rest frame

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



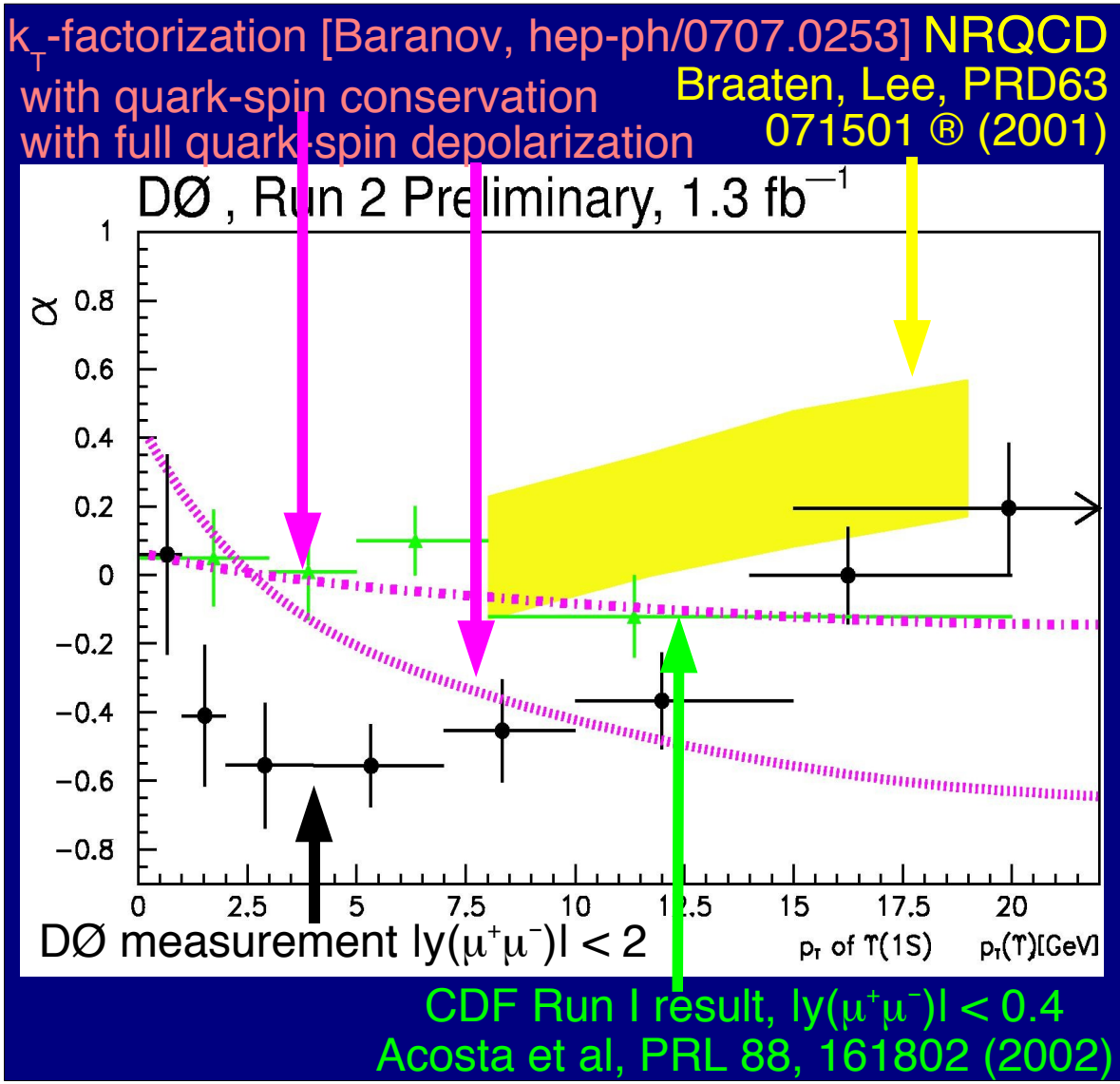
Υ(1S) and Υ(2S) Polarization



- In 1.3 fb^{-1}, find 420,000 Υ(nS) $\rightarrow \mu^+\mu^-$ candidates
- Υ mass differences fixed to measured values
- Number of Υ(3S) insufficient to extract angular distribution

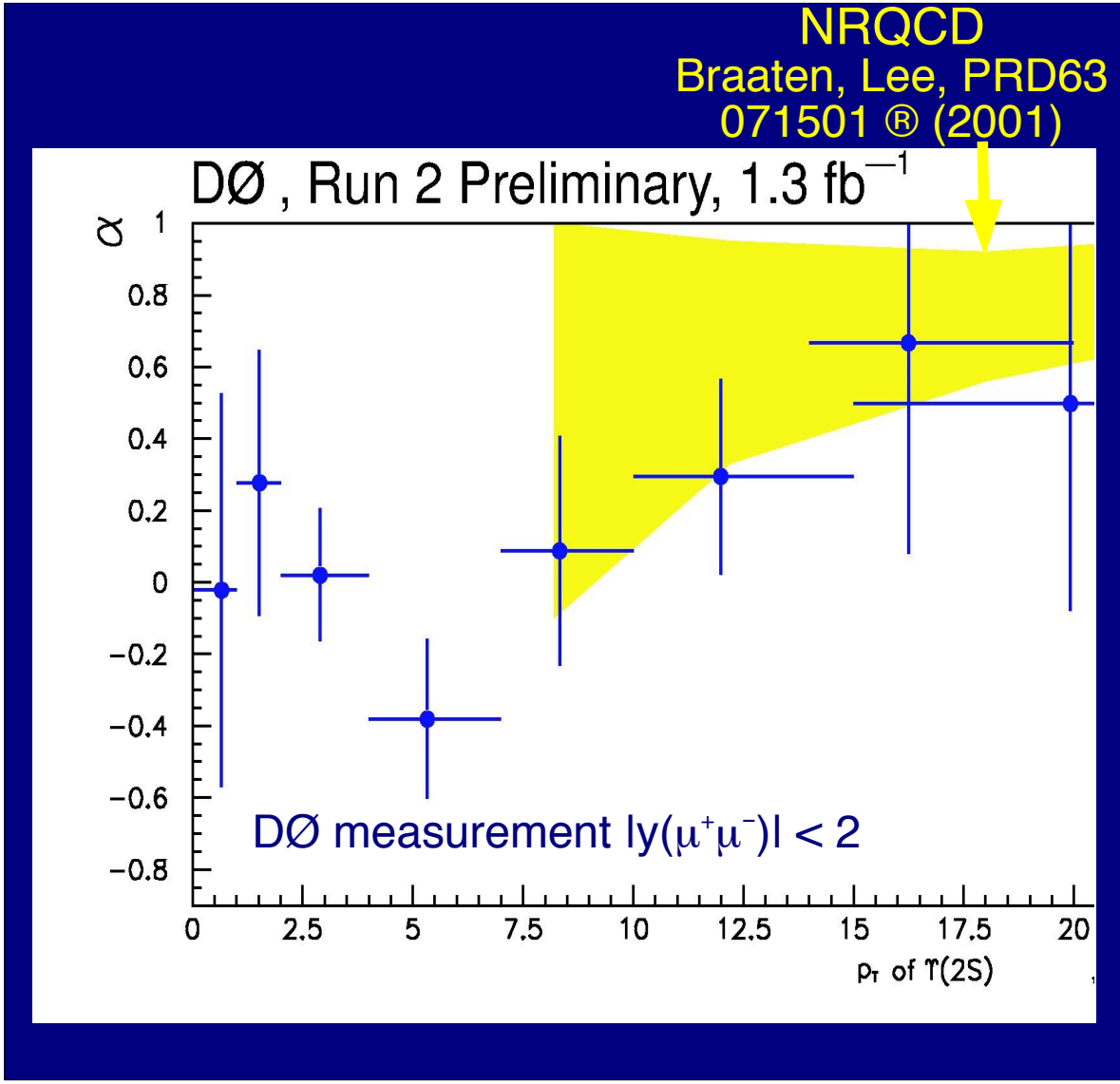
$\Upsilon(1S)$ Polarization

- Data divided into different bins of p_T and $|\cos\theta^*|$
- Extract angular distribution for each p_T interval
- Significant p_T dependent longitudinal polarization



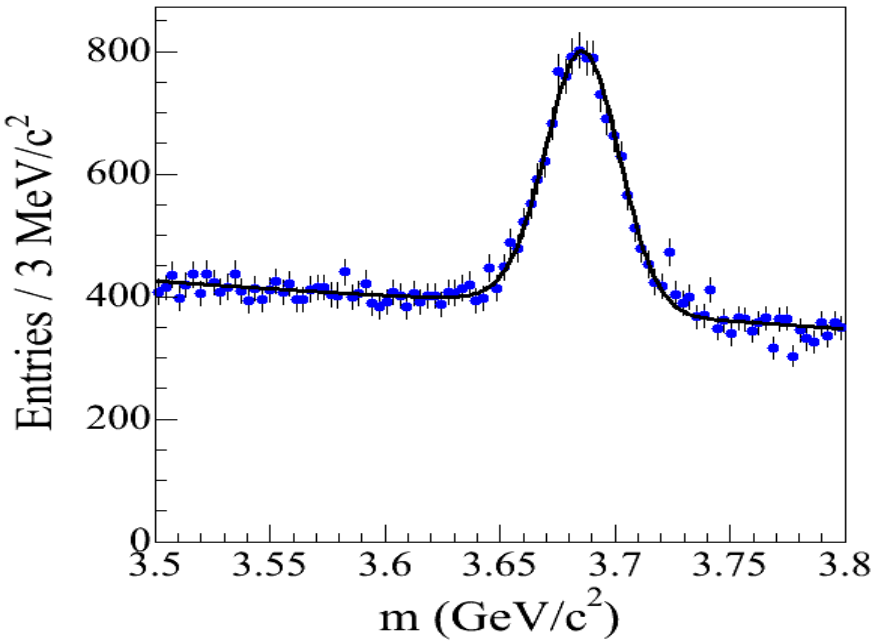
Υ(2S) Polarization

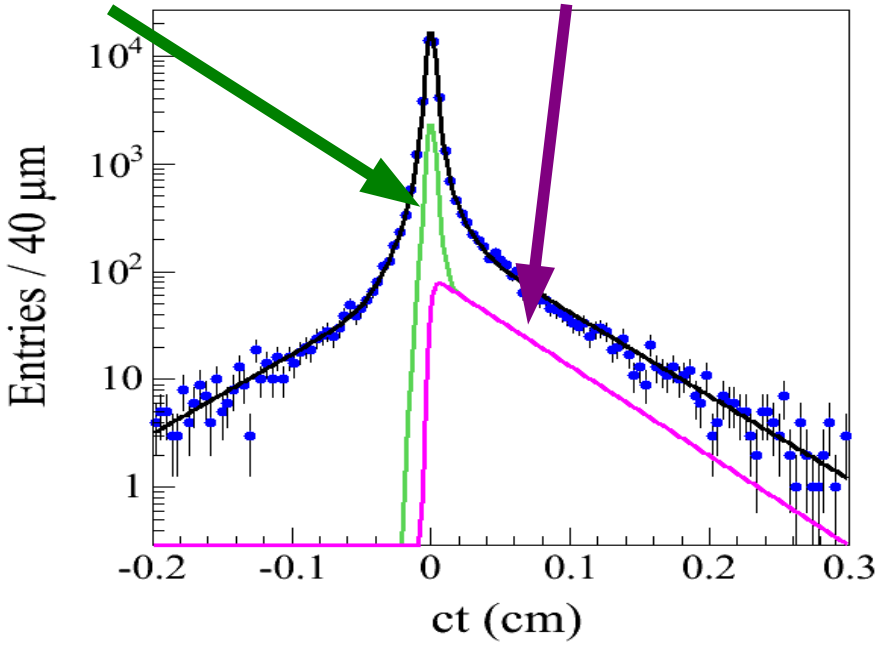
- Same study for Υ(2S)
- Within (lower) statistics, compatible with NRQCD predictions



ψ(2S) Production Cross Section

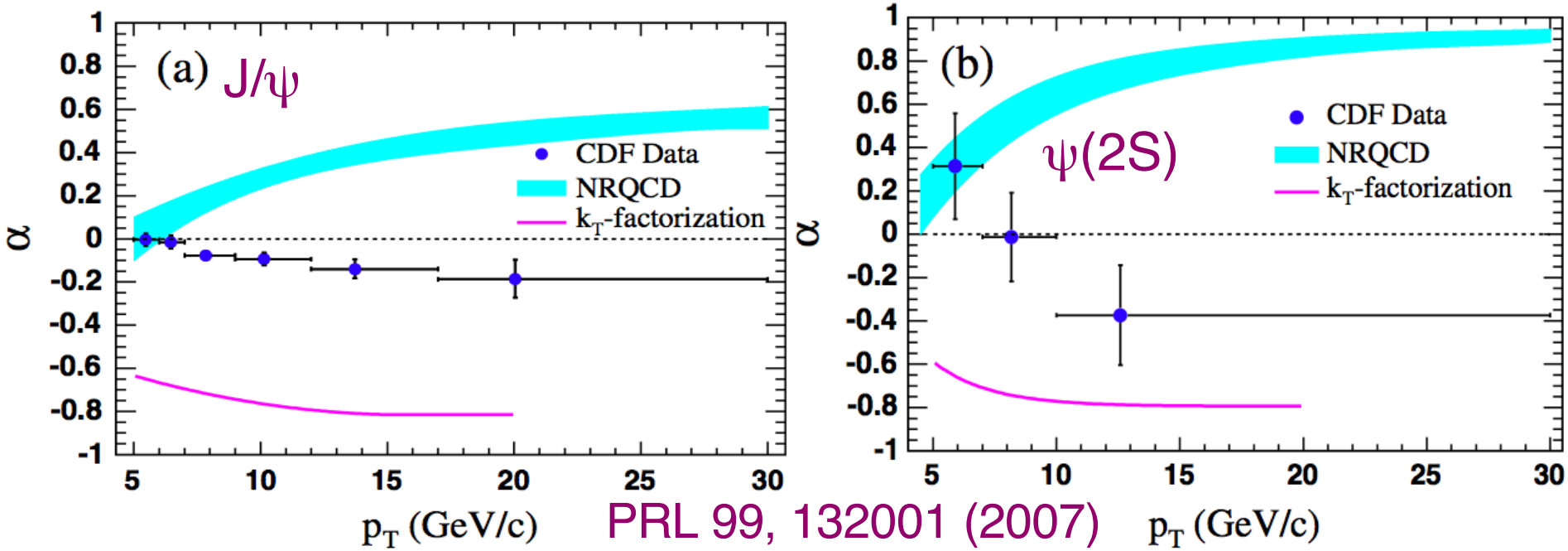
- Reconstruct ψ(2S) → $\mu^+\mu^-$ in 1.1 fb^{-1}
  - Rapidity $|y(\mu^+\mu^-)| < 0.6$, p_T range of 2 – 30 GeV/c
- Maximum likelihood fit in ψ(2S) mass and proper decay length ct
  - Mass fit separates signal from background
  - Proper time fit separates prompt ψ(2S) from B decays





J/ψ and ψ(2S) Polarization

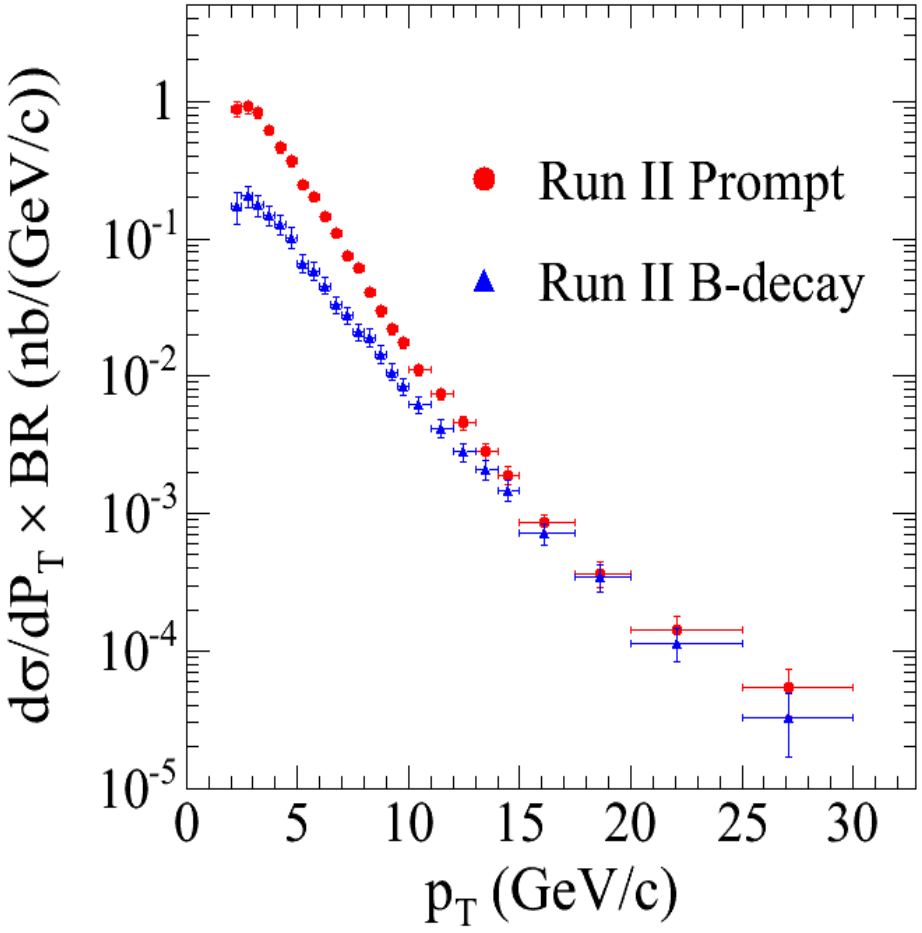
- ψ(2S) acceptance depends on ψ(2S) polarization
- CDF Run II measurement of J/ψ and ψ(2S) polarization shows significant longitudinal polarization
- ψ(2S) measurement statistically limited
  - Theory: prompt ψ(2S) polarization very similar to J/ψ
  - Use J/ψ polarization value at center of p_T(ψ(2S)) bins



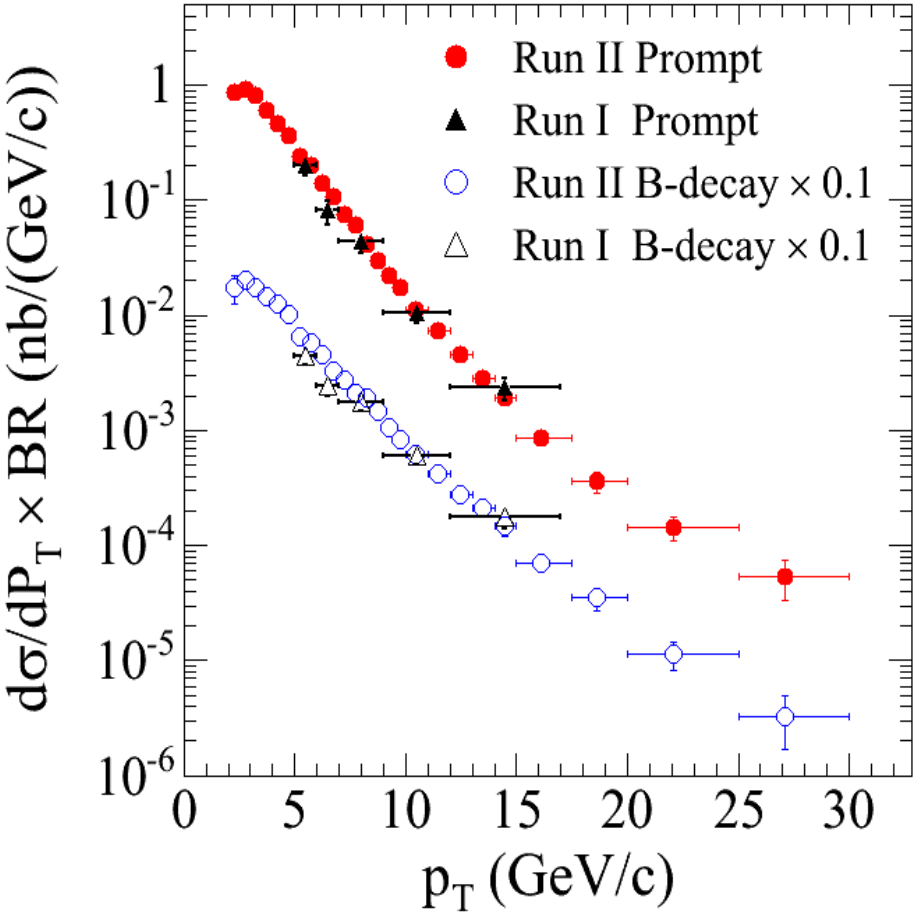
PRL 99, 132001 (2007)

ψ(2S) Production Results

Separate prompt and secondary:



Compare to CDF Run I:



ψ(2S) Production Results

- First Run II measurement
- Integrated differential cross section:

$$\sigma(p\bar{p} \to \psi(2S)X, |y(\psi(2S))| < 0.6,\ p_T > 2\ \mathrm{GeV}/c)_{\sqrt{s}=1.96\ \mathrm{TeV}} \cdot Br(\psi(2S) \to \mu^+\mu^-)$$
$$= 3.141 \pm 0.038(\mathrm{stat})^{+0.225}_{-0.218}(\mathrm{syst})\ \mathrm{nb}.$$

- Compare to inclusive CDF Run I:
  - Predict 1.14 ± 0.08 increase for √s = 1.96 TeV

Run I

$$\sigma(p\bar{p} \to \psi(2S)X, |\eta| < 0.6, p_T > 5\ \mathrm{GeV}/c)_{\sqrt{s}=1.80\ \mathrm{TeV}} \cdot Br(\psi(2S) \to \mu^+\mu^-)$$
$$= 0.571 \pm 0.036(\mathrm{stat})^{+0.082}_{-0.089}(\mathrm{syst})\ \mathrm{nb}$$

Run II

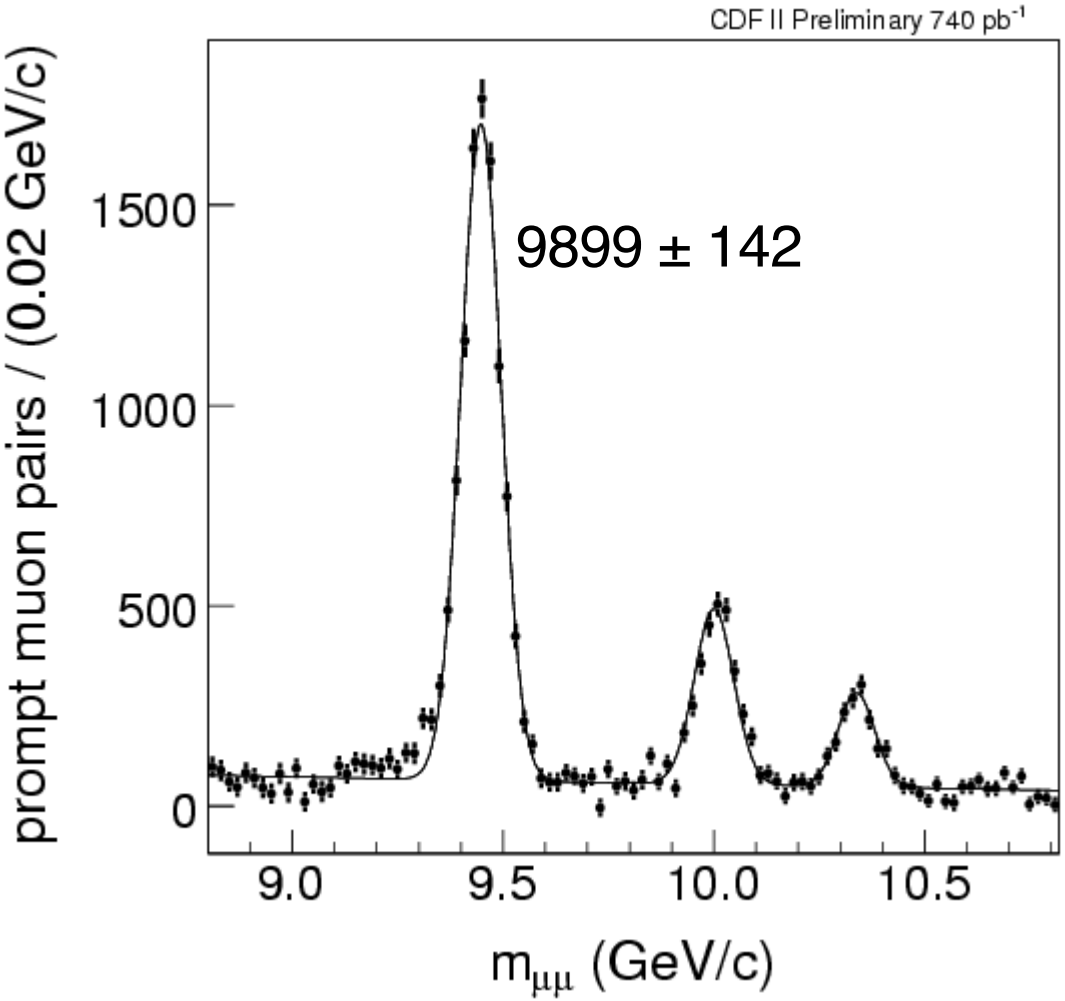
$$\sigma(p\bar{p} \to \psi(2S)X, |y(\psi(2S))| < 0.6, p_T > 5\ \mathrm{GeV}/c)_{\sqrt{s}=1.96\ \mathrm{TeV}} \cdot Br(\psi(2S) \to \mu^+\mu^-)$$
$$= 0.645 \pm 0.006(\mathrm{stat}) \pm 0.044(\mathrm{syst})\ \mathrm{nb}$$

Summary

- Lots of activity in heavy flavor physics at the Tevatron
  - Showed several recent production measurements
  - Both experiments have > 3 fb^{-1} recorded, many more results on the way!
- Detailed studies of heavy flavor production test theoretical understanding
  - Cross section measurements reproduced well by theoretical models
  - Polarization measurements indicate need for better understanding
- Continue challenging theory with measurements
  - Important also for understanding heavy quark production at the LHC

Backup Slides

Υ in prompt dimuons

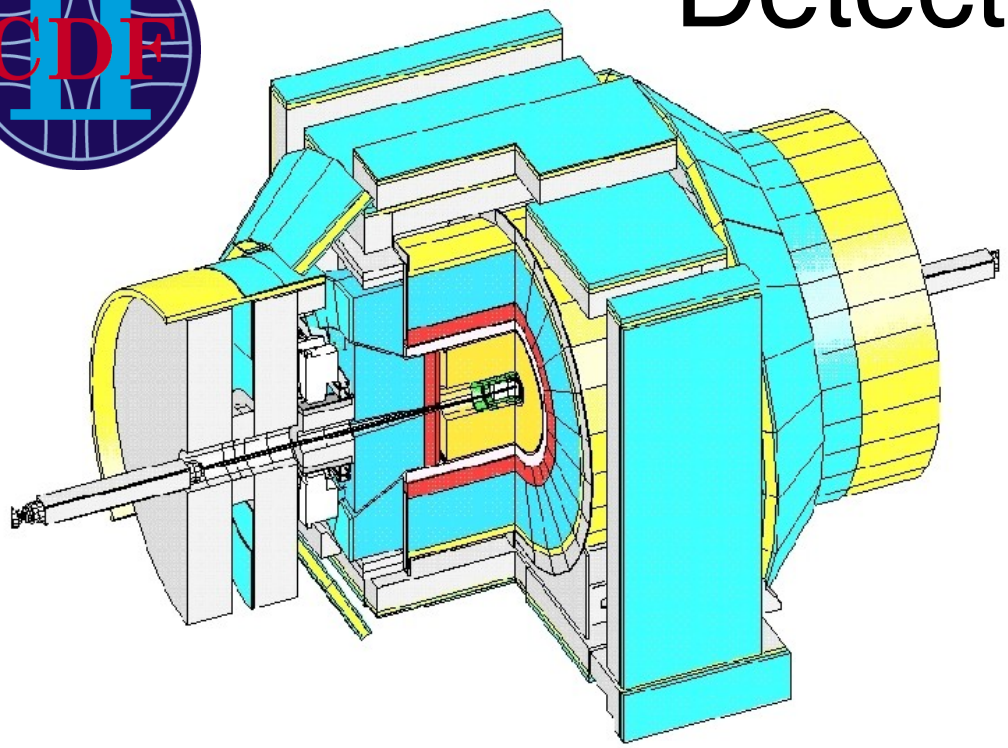


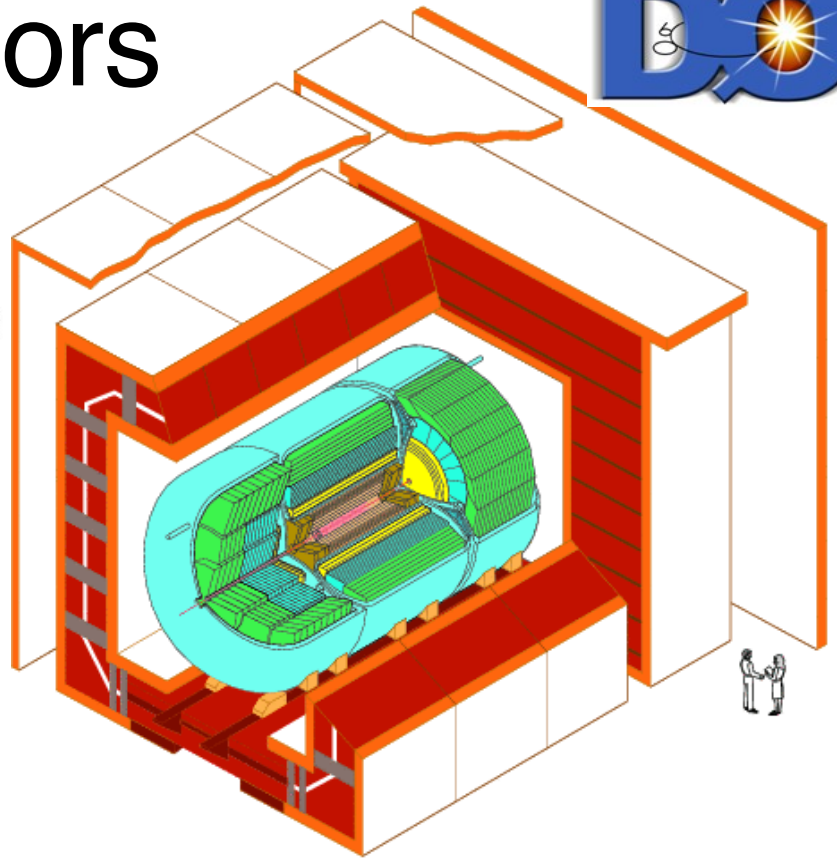
- Υ(1S) decays used to extract impact parameter template for prompt muons

Summary of $b\bar{b}$ Systematics

Source	BB	CC
Stat.	1.2%	6.4%
Fit likelihood	2.9%	8%
Fake removal	4.2%	11.6%
Acceptance	3.2%	3.9%
Luminosity	6%	6%
Total	8.9%	16.7%

Detectors

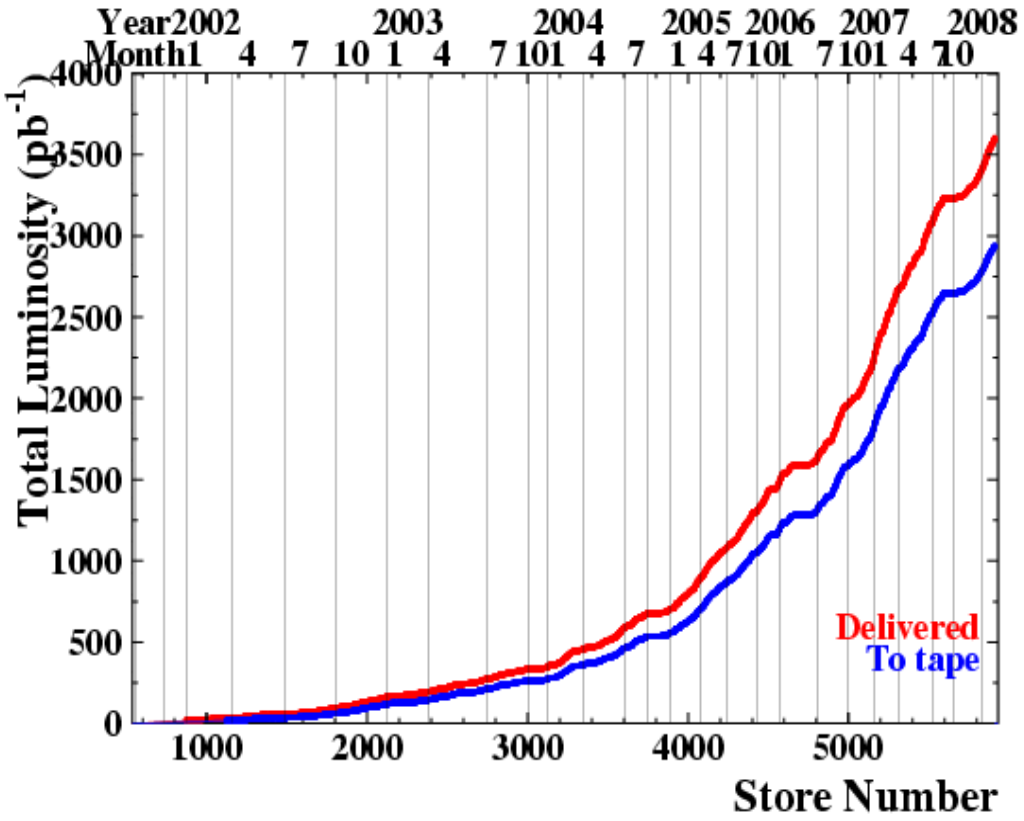


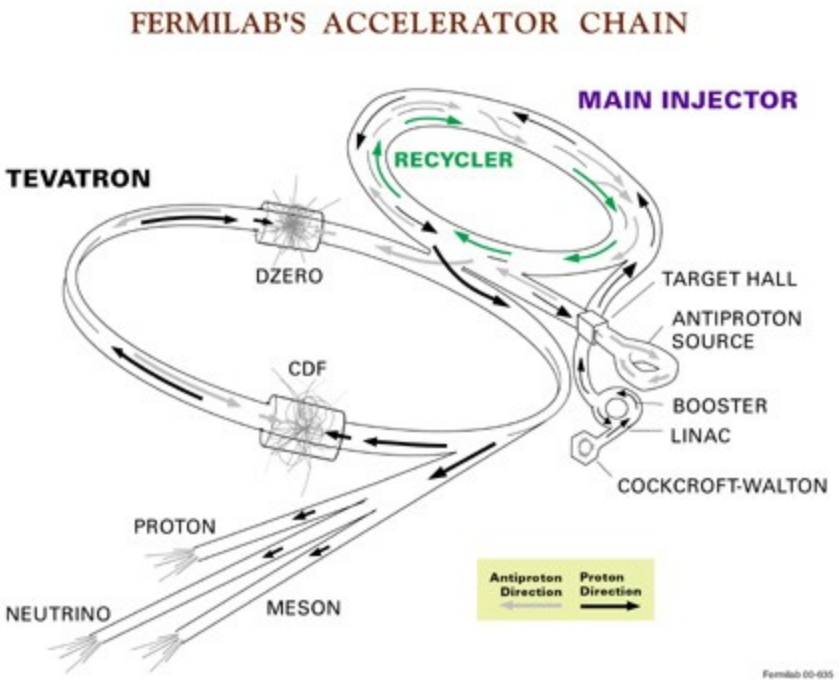


- CDF:
  - Excellent mass resolution and particle ID
  - Displaced vertex trigger → hadronic decays
- DØ:
  - Excellent muon coverage ($|\eta| < 2$) and forward tracking
  - Di muon + semileptonic decays

Tevatron Performances

- Collide $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
- Record peak luminosity 2.85×10^{32} sec^{-1} cm^{-2}
- Each experiment has collected ~ 3 fb^{-1} out of > 3.5 fb^{-1} delivered





- Current analyses use between ~1 - 2 fb^{-1} of data
- Analyses with more data in the works
- Expect 6 - 7 fb^{-1} by 2009