Quarkonium Physics at the Tevatron

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High Energy Vector Meson Production Mechanisms

- **Long history of theoretical models to try to match vector meson data from Tevatron and HERA**
  - **cross section *problem* ⇒ CSM → NRQCD**
  - **polarization problems with NRQCD ⇒ multi-gluon models**
  - **recent theoretical considerations raise questions about k_T factorization approach, Q fragmentation effects at Tevatron energies**
- **See recent review by J.-P. Lansberg for summary of theoretical situation (arXiv:0811.4005)**

Experimental Results

- **This talk's focus: Tevatron experimental results on vector meson production and polarization**
  - **J/ ψ and ψ(2S) cross section and polarization from CDF**
  - **Υ(1S) and Υ(2S) polarization from D0**
  - **new results on Υ(1S) polarization from CDF**
  - **production issues**
- **CDF work on new charmonia X(3872) and Y(4140)**
- **Prospects for further Tevatron work will be given.**

Measuring Polarization - I

- Polarization is an angular asymmetry:

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

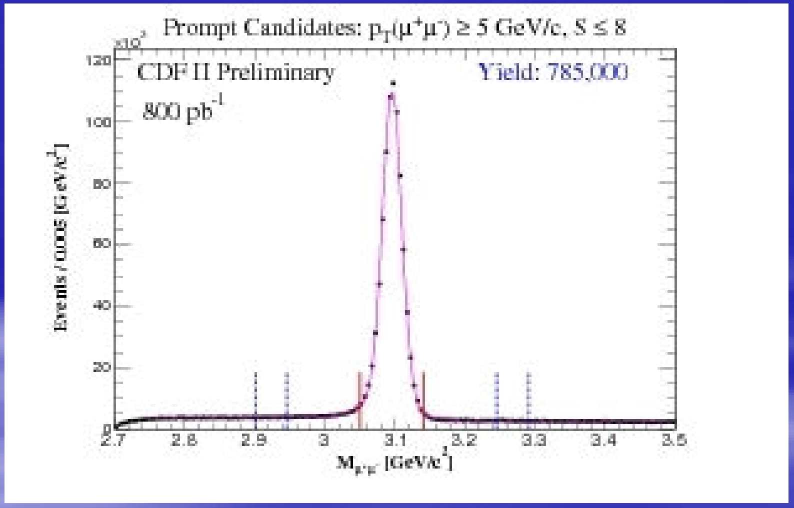
  – what axis? The size of α depends on frame.
    - (aside: think of electron polarized along z-axis. If you measure spin along some other direction with direction cosine γ, the maximum polarization is γ.)

  – **historically, low p_T fixed target experiments have analyzed in Collins-Soper frame.**

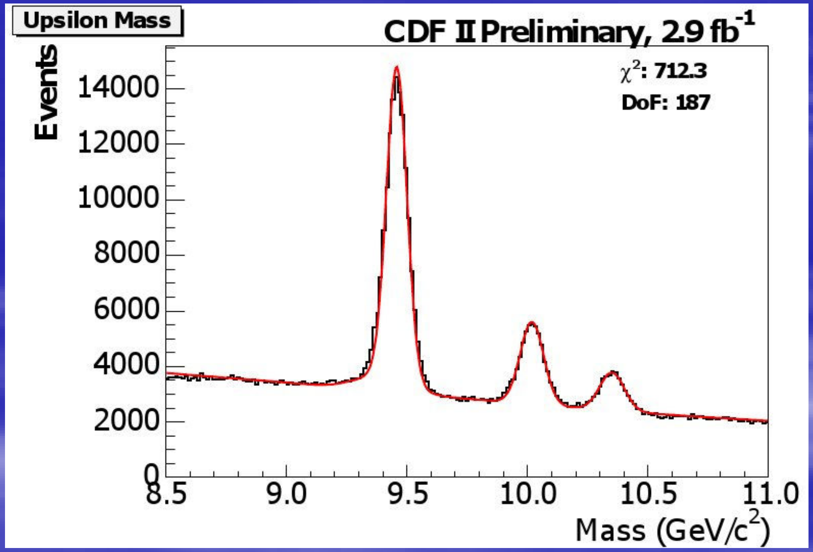
  – **high p_T collider experiments have used s-channel helicity frame**

Measuring Polarization - II

- Background control is essential! Good CDF mass resolution helps enormously.



J/ψ dominates; small backgnd

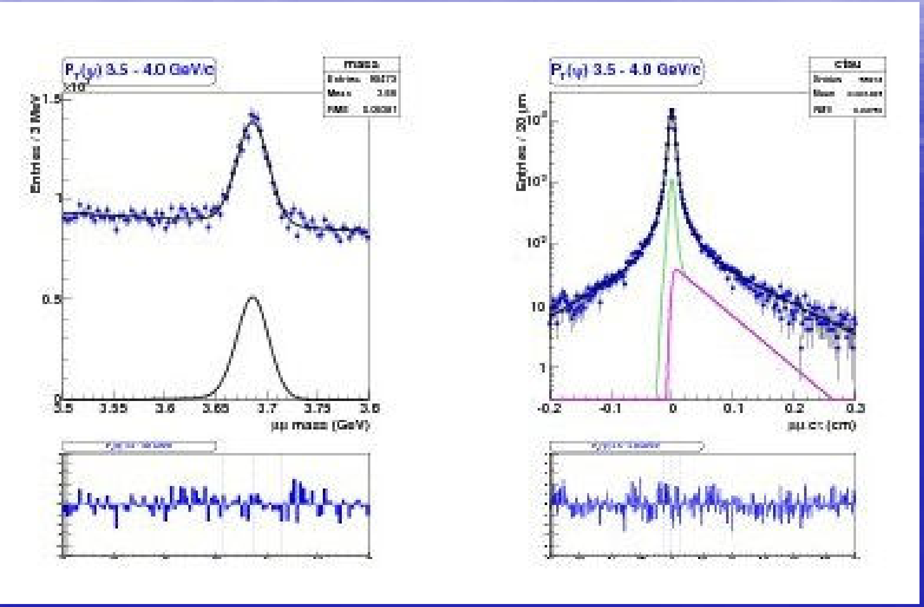


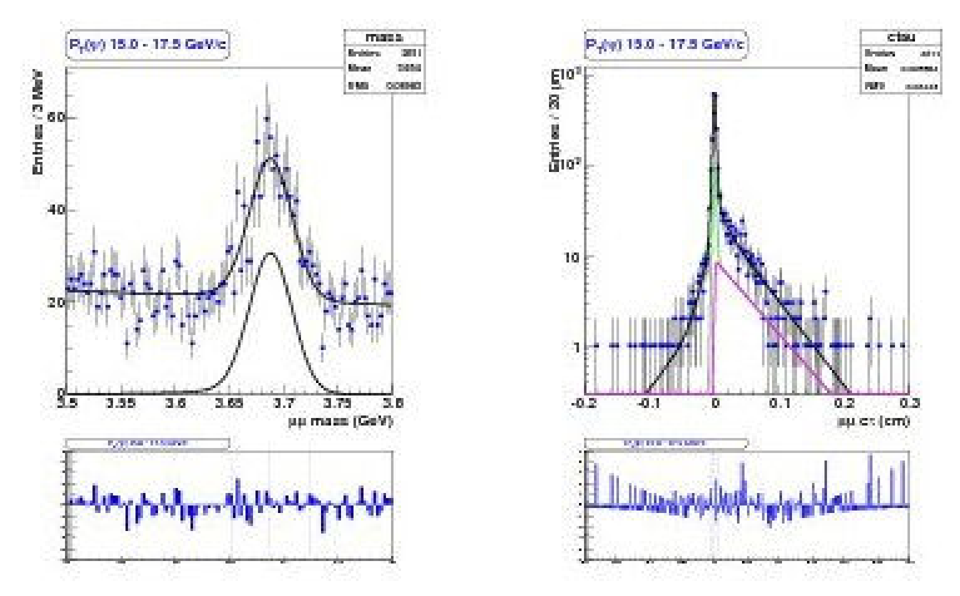
Υ region has higher background, varying with dimuon mass.

J/ψ Analysis

- **Classify J/ψ candidates as *prompt* or b-decay**
  - **prompt candidates include feed-down from χ_{c}, ψ(2S) decays.**
  - **separate b-decay candidates by impact parameter cut (equivalent to proper time cut). Measure and correct leak-through.**
  - **divide data into bins of $p_T(\psi)$.**
  - **in each $p_T(\psi)$ bin define signal and sideband region. Assign events to bins of muon CM decay cosine cosθ. Use templates for pure L, T polarization to treat trigger and apparatus effects.**

Prompt/b-decay Separation



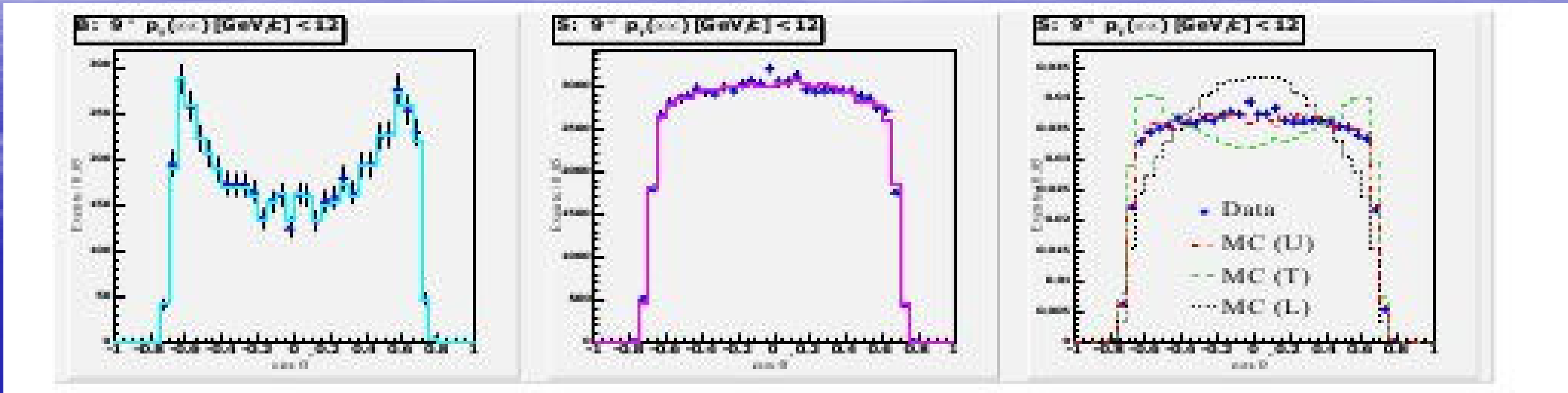


- Mass and ct projections for two p_T bins illustrating joint mass-lifetime fit to identify prompt and b-decay selection.

Prompt J/ψ Polarization

- Select Prompt Events based on decay length
  - in each p_T bin select prompt signal and sideband events from mass plot after cuts
  - make cos θ distribution for each: total, backgnd
  - make simultaneous fit to signal, backgnd distributions. χ^2 can be minimized analytically for backgnd. Determine L fraction, template normalization.
- Analyze b-decay polarization in same way.

Sample Prompt J/ψ Polarization Fits



LEFT: background CENTER: polarization-weighted template fit and data RIGHT: same plot as center plus L and T template to illustrate sensitivity of measurement.

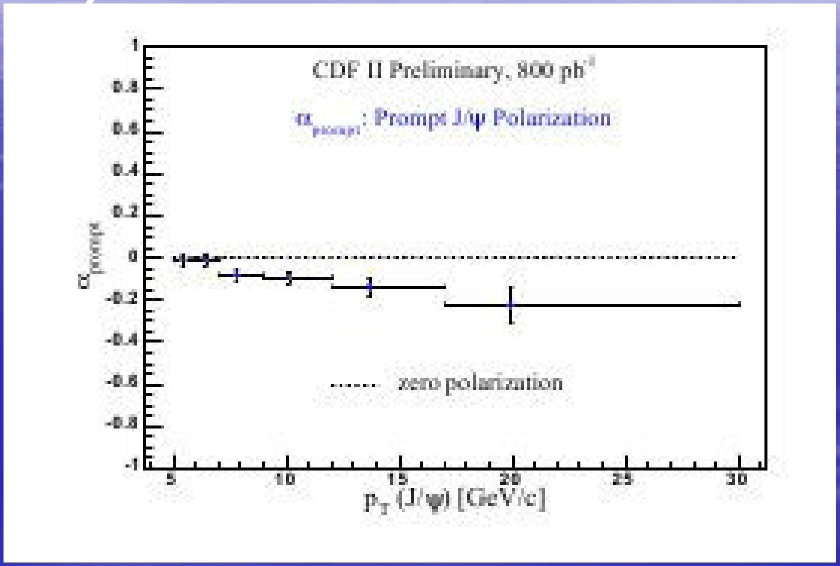
Typical plots; here $9 < p_T(J/\psi) < 12$ GeV/c. Background highly structured but small. Fitted templates give good description of data over whole angular region, esp. ends (tests efficiency function.).

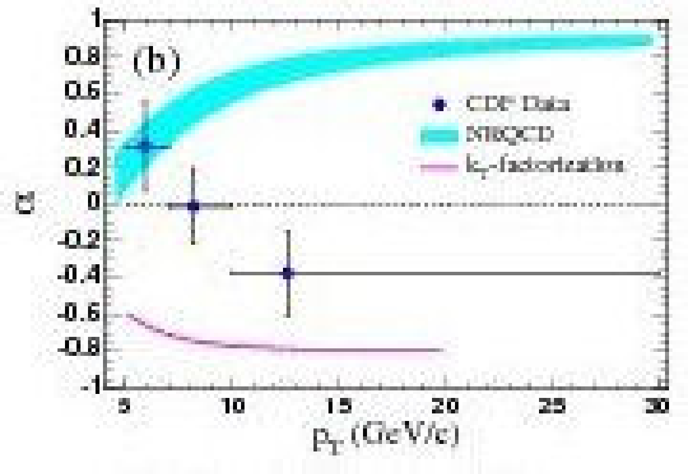
Prompt J/ψ, ψ(2S) Polarization

- Prompt polarization in s-channel helicity frame is always longitudinal

- Trend is to become more longitudinal as $p_T(\psi)$ increases

- Consistent with multi-gluon models but not NRQCD





What About Υ Polarization?

- Various theoretical papers about c quark being too light for factorization.
- Everyone agrees that Υ(ns) polarization at high m_T is the acid test for NRQCD.
- CDF Run I Measurement does not show trend to T polarization, but m_T is limited.
- Recent D0 publication suggests possible trend toward T polarization.
- CDF has new Run II result.

CDF Υ Analysis

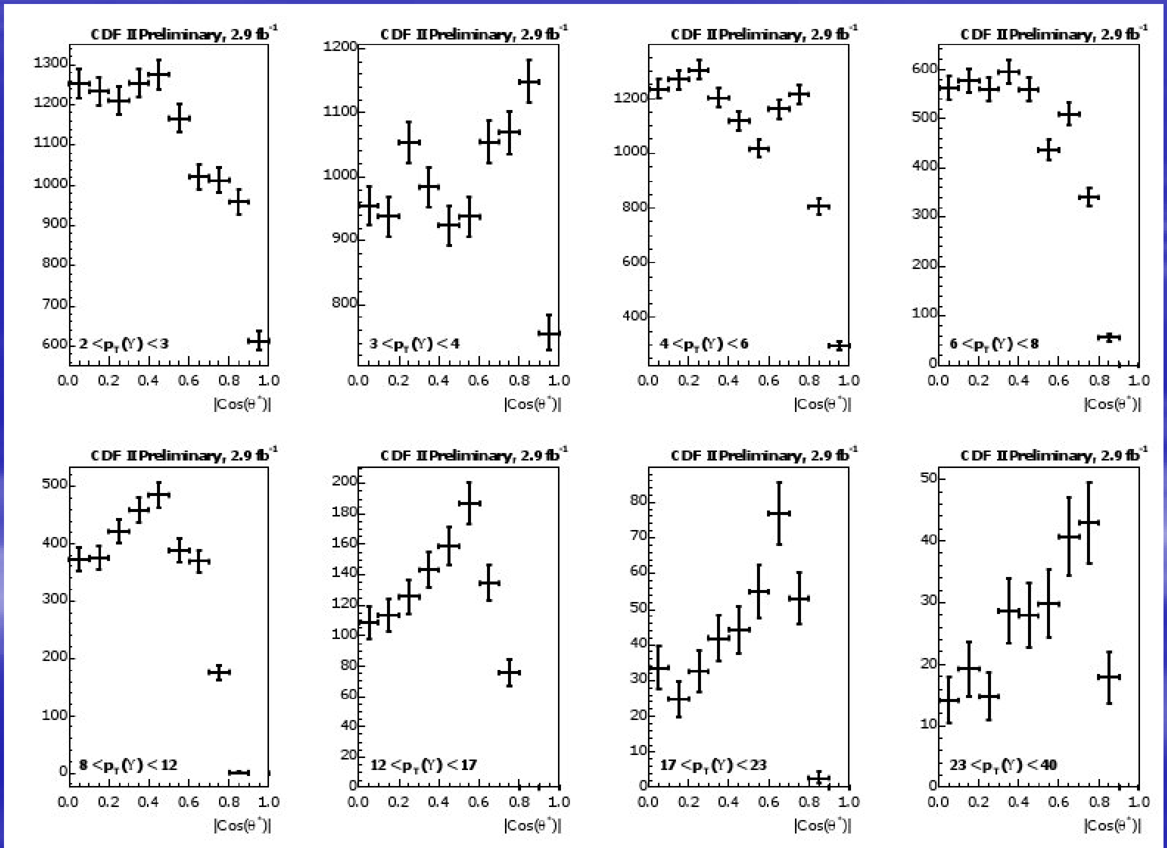
- Follow methodology of J/ψ analysis:
  - make templates for L, T polarization to incorporate trigger, acceptance conditions
  - Make MC-constrained mass fits in each cos θ bin to identify signal yield and background
  - Make simultaneous fit to polarization parameter and background in cos θ bins
- Check that cos θ and p_T resolutions are good enough that there are no bin-smearing corrections.

Y-region Dimuon Background

- Just as in J/ψ case, dimuon background has mass- and p_T-dependent angular variation

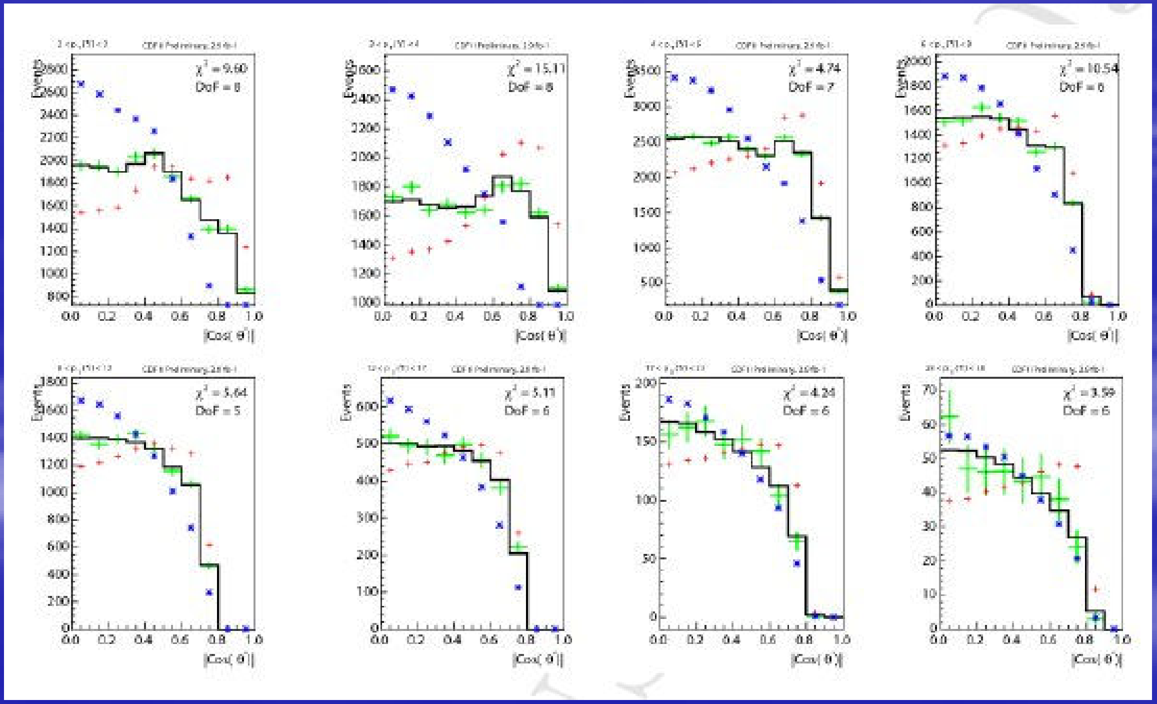
- **Plots show angular dist. of fitted backgnd for Y(1S) in 8 p_T bins**

No prompt selection, so bkg includes heavy flavor + DY + junk



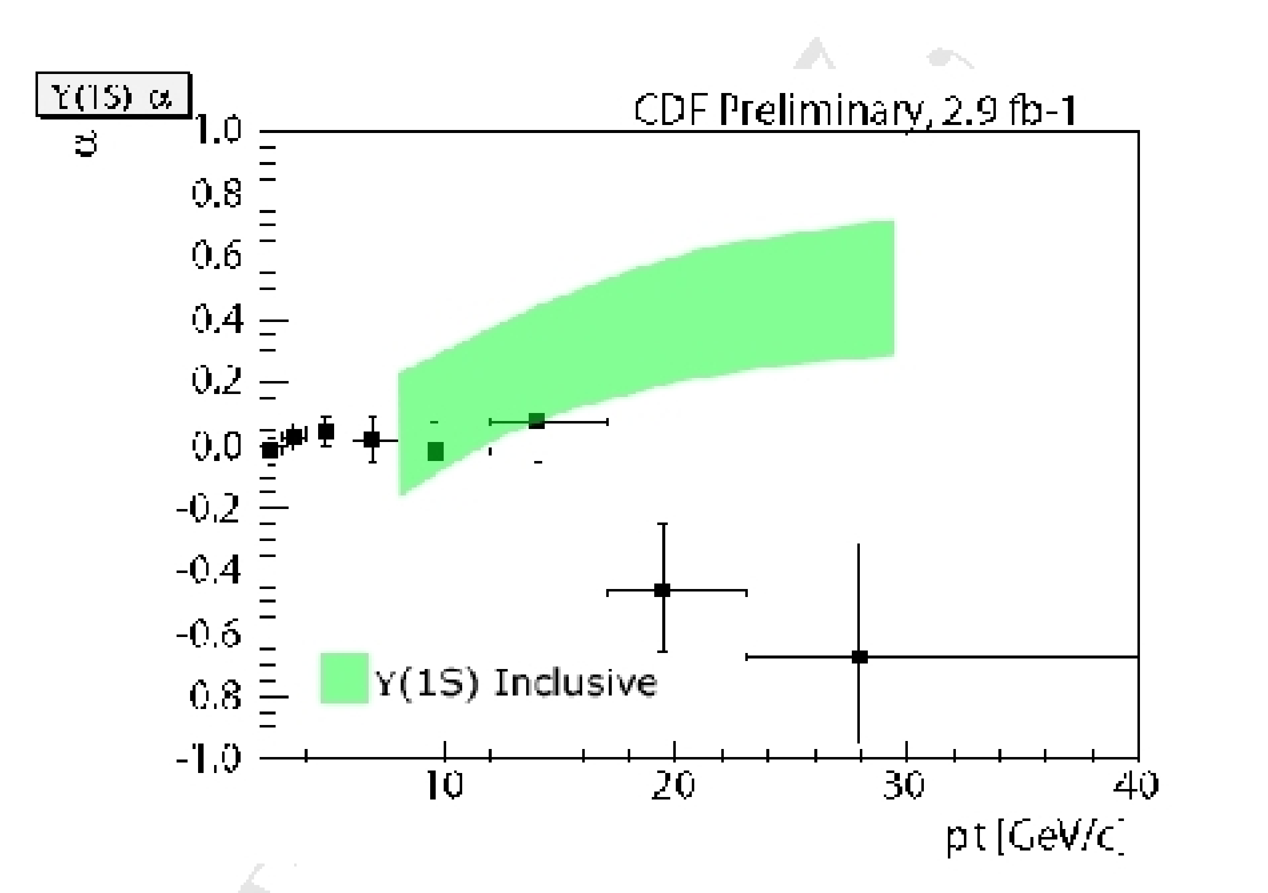
Y(1S) Polarization Fits

- Fitter is same as for J/ ψ . Blue points are L template, green + are T template in 10 |cosθ| bins
- Solid line is best fit.
- All bins have good χ^2 .



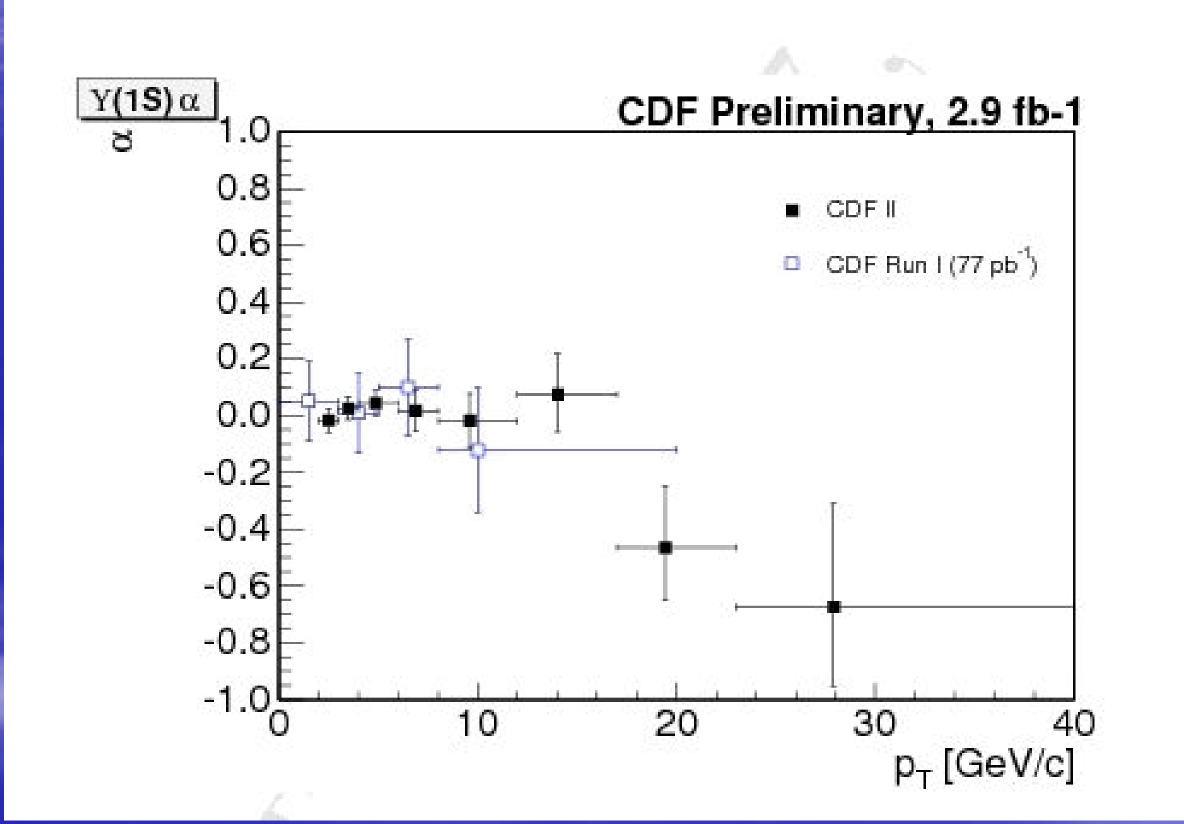
CDF Run II Υ(1S) Polarization

- Υ(1S) prompt polarization, including feed-down from χ_b, Υ(nS).
- Green is NRQCD (Braaten and Lee) including feeddown



Good Agreement with CDF-I

- Polarization sm
p_T < 20 GeV/c
($m_T \sim 2.2\ m_\Upsilon$)
- Run II data
L polarized at
larger p_T

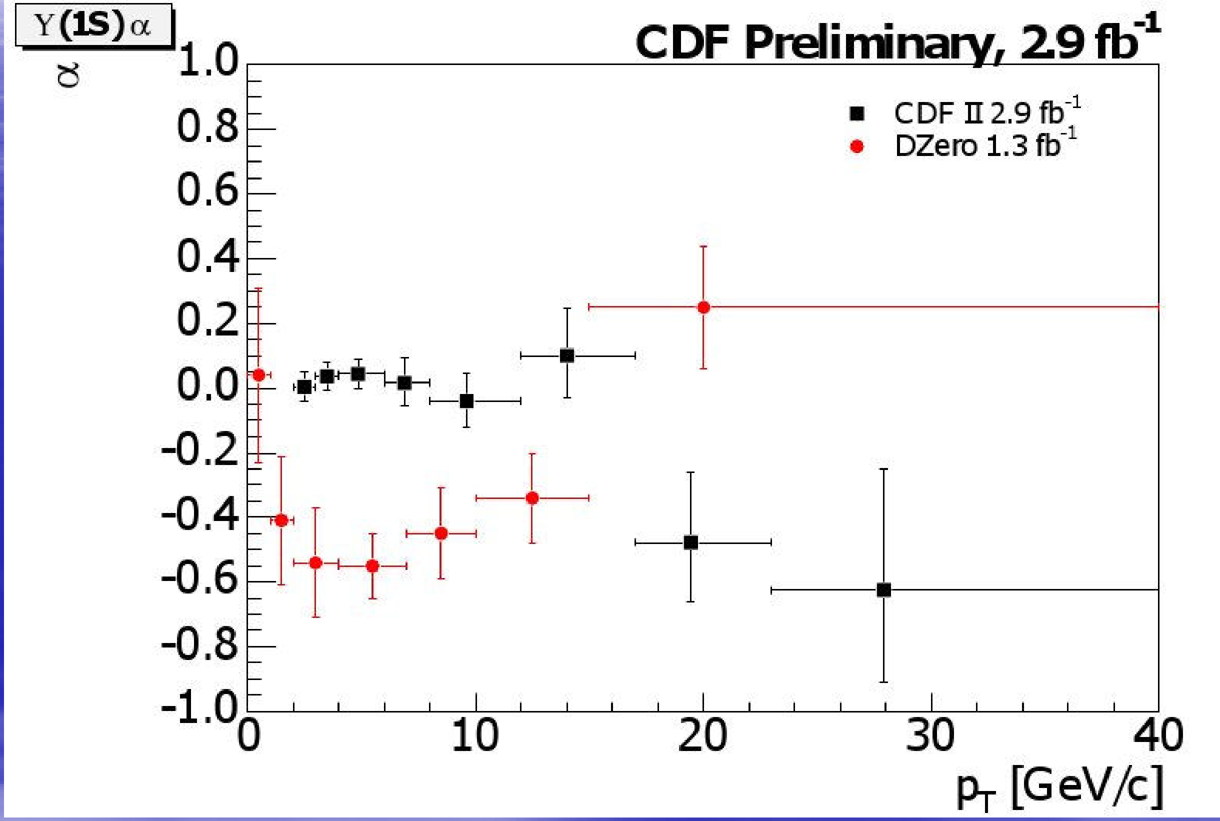


CDF Disagrees with D0

Trends are totally different.

D0: |y|< 1.8
CDF: |y|<0.6

D0: polarization Longitudinal for $p_T < m_T$



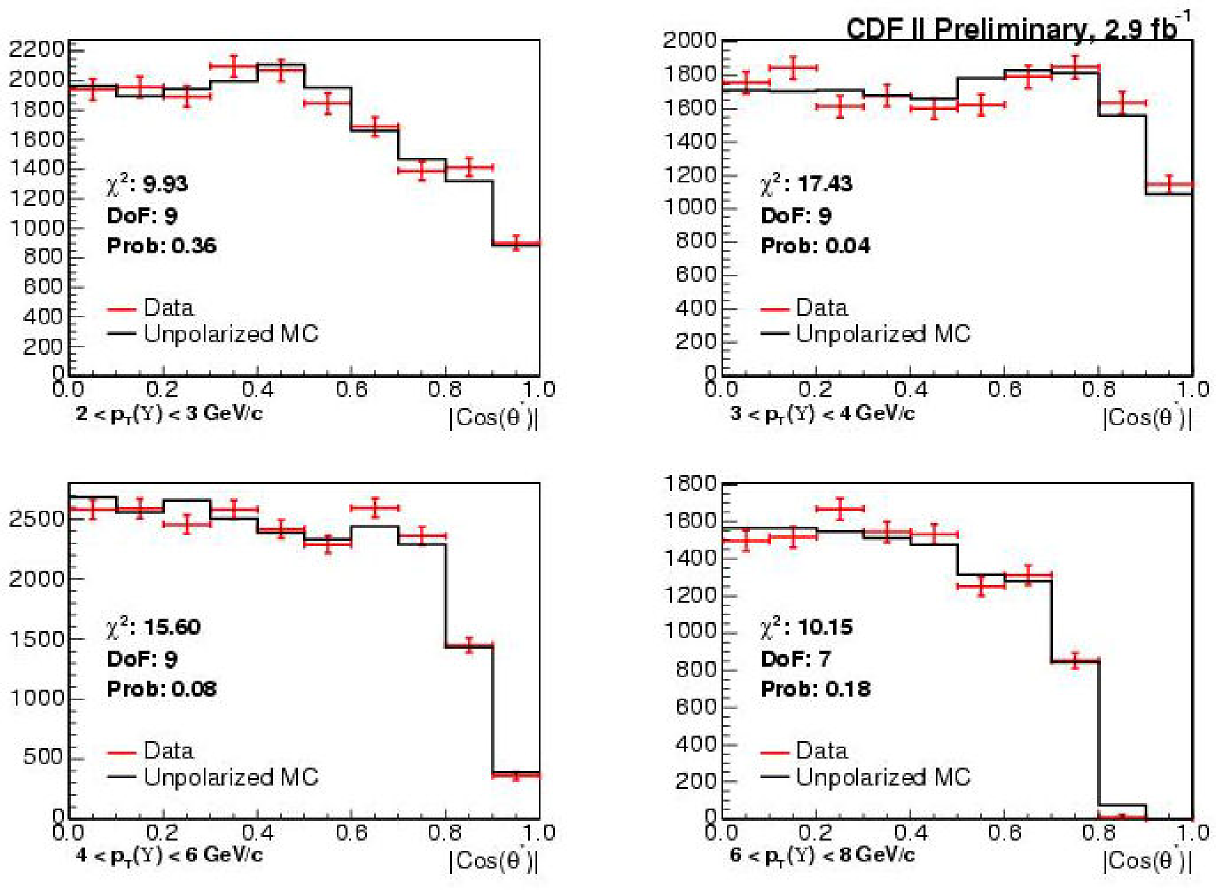
D0 paper: " We expect the CDF and D0 results to be similar and have no explanation for the observed difference." Same remarks apply here – no explanation.

Check: Is low p_T Y(1S) data unpolarized?

- Generate unpolarized decays with Monte Carlo:
  - Processed in same way as fully-polarized template samples
  - Normalize to number of events in data and overlay – no fitting involved.

- See good agreement

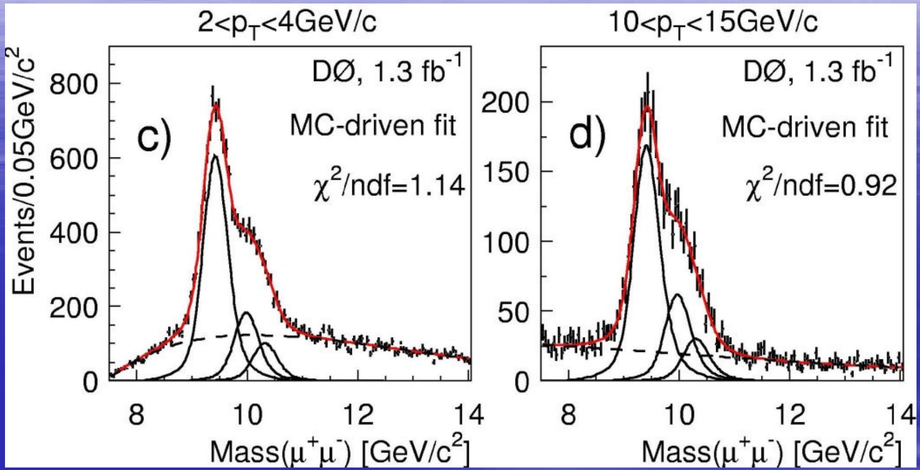
- **CDF data do not support D0 claim of longitudinal polarization at low p_T**

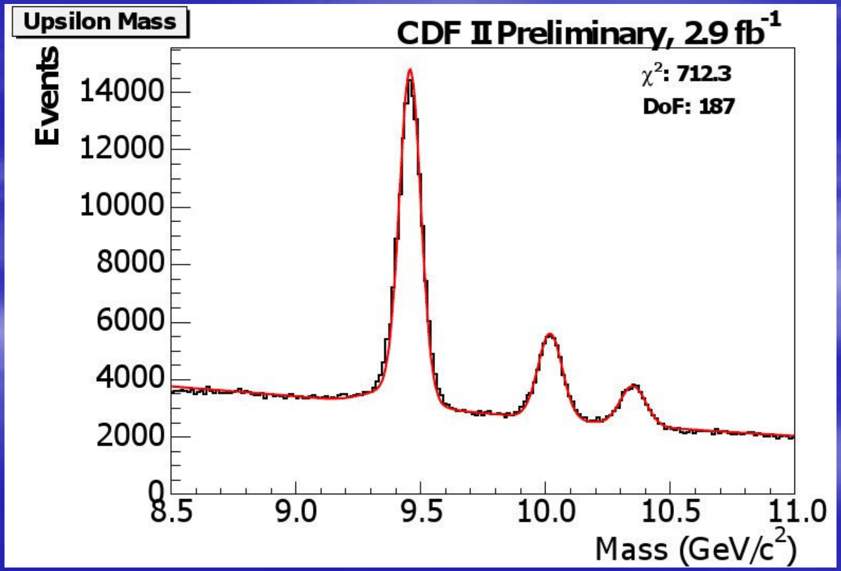


CDF/ D0 Differences

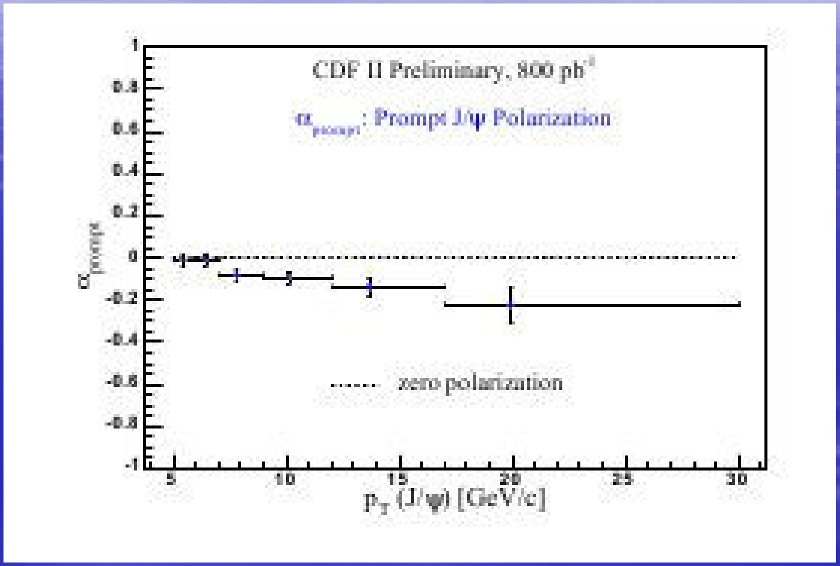
D0:Smooth data-driven backgnd shape under all mass peaks for each angle, p_T bin.

CDF: separate mass fits, backgnd for each Y(nS) peak. Results for Y(2S), Y(3S) ready soon. D0-style mass fit in each angle bin gives same results as this analysis.



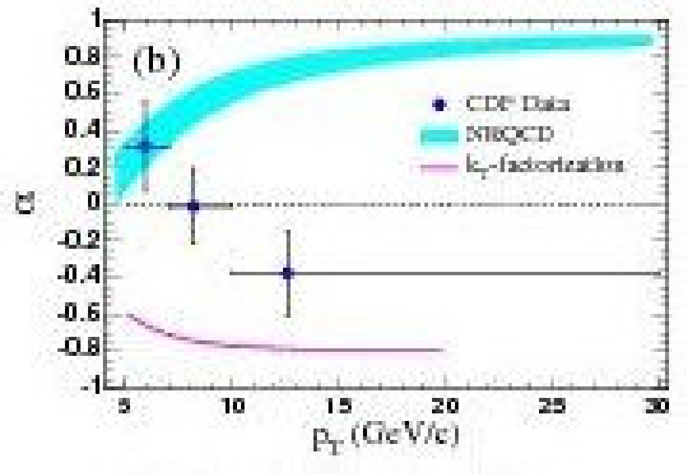


Prompt J/ψ, ψ(2S) Polarization - II



- **Recall that Υ(1S) polarization is longitudinal for m_T(Υ) > 2.2 m(Υ)**

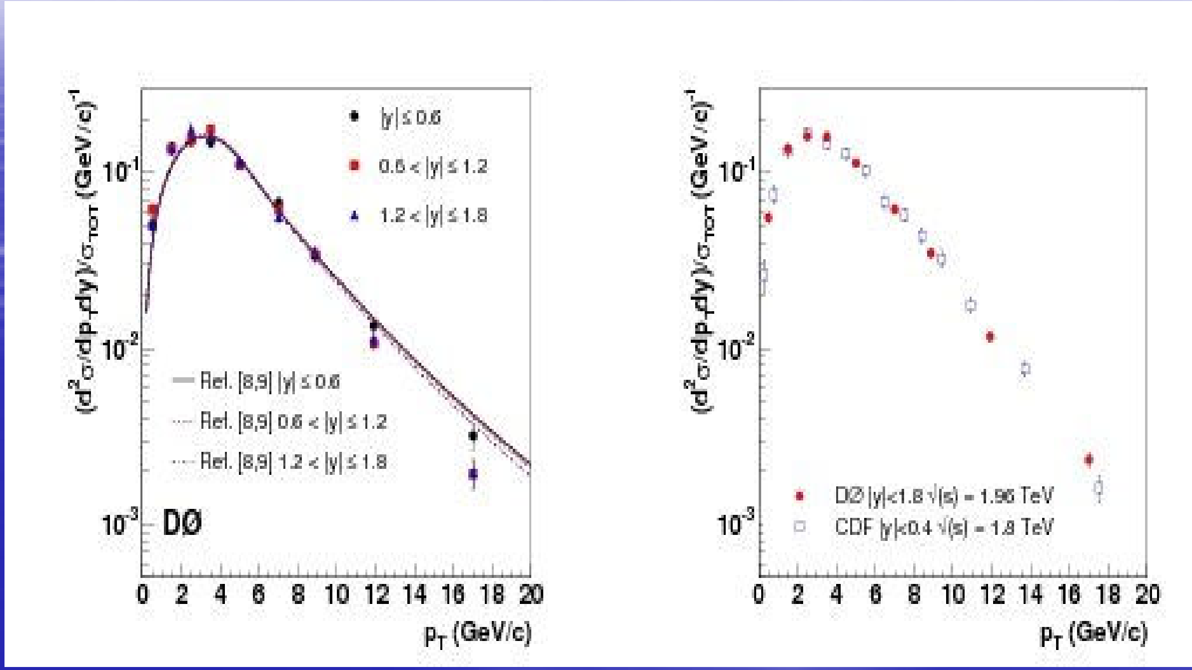
- **Same feature seen in J/ψ at 2.2 m(J/ ψ)**



Polarization Summary

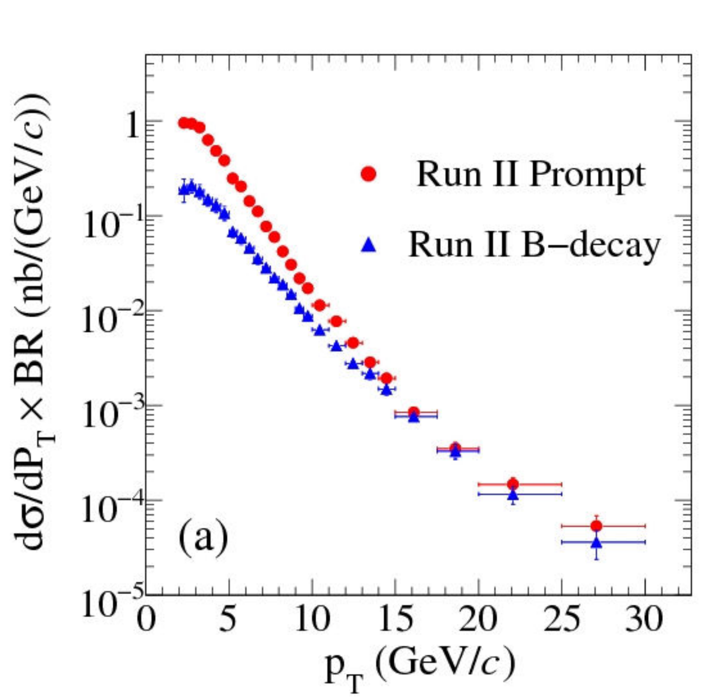
- **CDF prompt vector meson polarizations show trend toward L polarization at high p_T in s-channel helicity frame**
- **Multi-gluon models predict this kind of behavior, but**
  - **models go L at lower p_T than data**
  - **models are for *direct* production – data are prompt**
  - **multigluon models suggest Υ(nS) states are not isolated – have to test in data**
- **Backgrounds have angular structure. How much is due to Drell-Yan? What is DY polarization?**

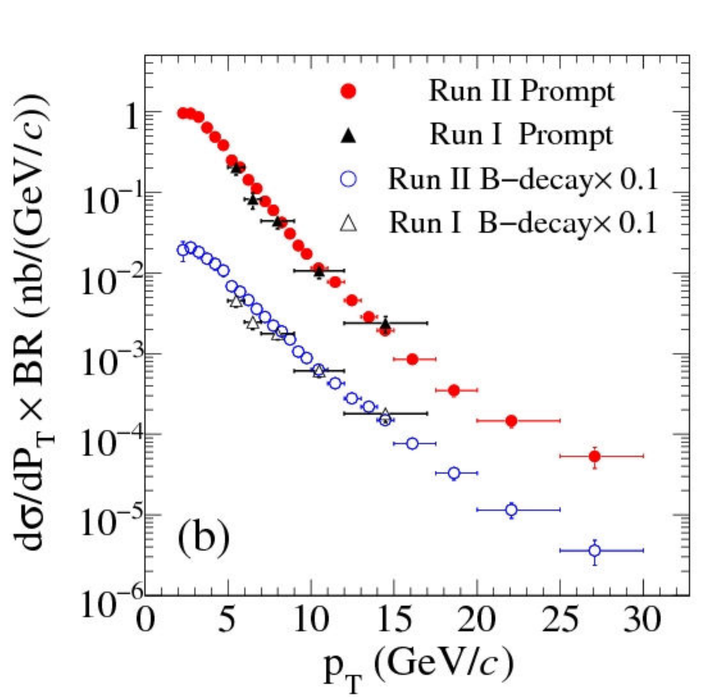
D0: Υ(1S) Cross Section



D0 reported Υ(1S) differential cross section, normalized to unit area, in 3 |y| regions: 0-.6, .6-1.2, 1.2-1.8. Some falloff in highest y-bin. For 0-.6, cross section agrees within uncertainties with CDF Run I result for 0-0.4. Shapes agree with model of Berger, Qui and Wang for $p_T \leq m_T$

CDF: $\psi(2S)$ Production





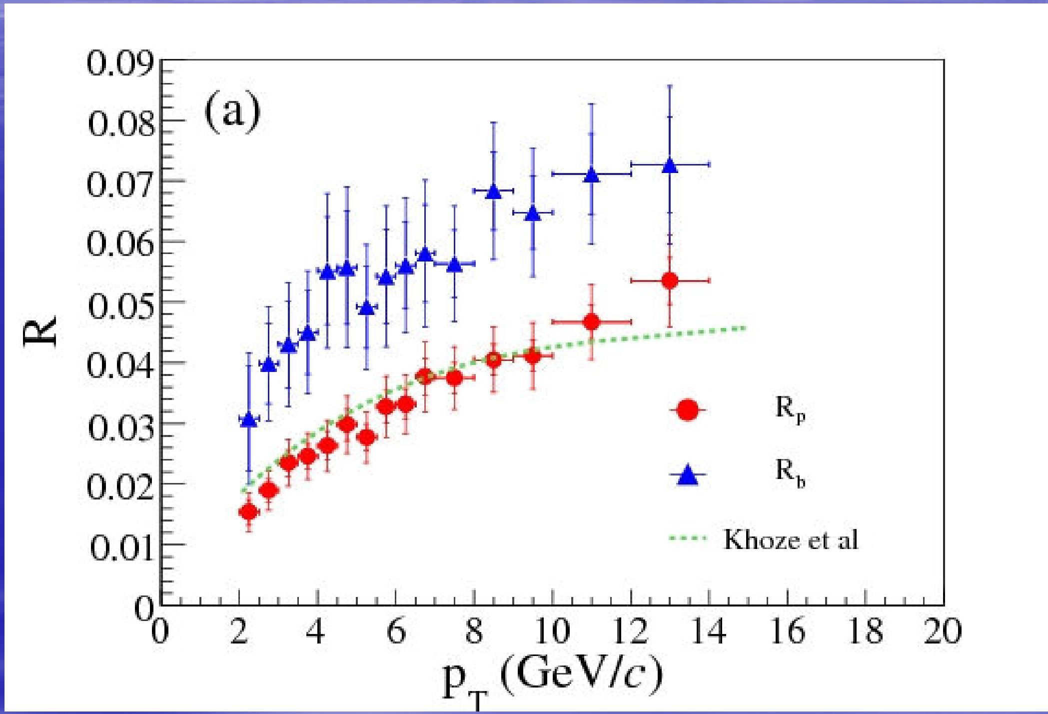
Prompt $\psi(2S)$ production falls off faster with p_T than b-production

Comparing to Run I, see small shift to larger cross section at given p_T for higher energy.

J/ψ Cross Section Curiosities - I

CDF has measured J/ψ and ψ(2S) production cross sections, both direct and B-decay cases.

Question: when the c-cbar pair at a given p_T hadronizes into the 1S or 2S state, does it matter if it is directly produced or occurs in the B-decay environment?

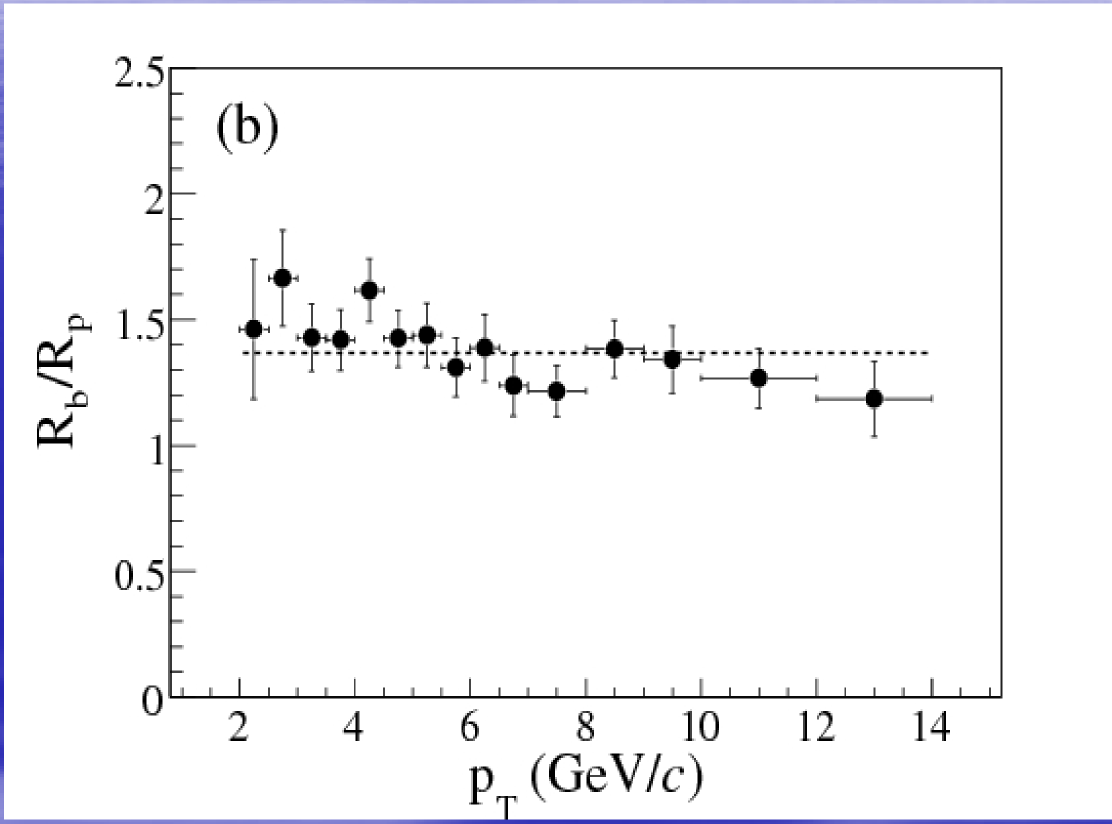


Khoze, et al.: $R = d\sigma/dp_T(2S)/\ d\sigma/dp_T(1S) \propto \alpha(m_T)^5/m_T^6$ on dimensional grounds in direct production. Fix ratio in p_T bin 8-9 GeV/c. Shape looks quite good at all other p_T. Is this fundamental?

J/ψ Cross Section Curiosities - II

In preceding R plot, b-decay result and direct production seemed to track in p_T. Take ratio of ratios:

Why should the ratio of b-decay hadronization to 2S and 1S charmonium have the same p_T-dependence as that of direct production?



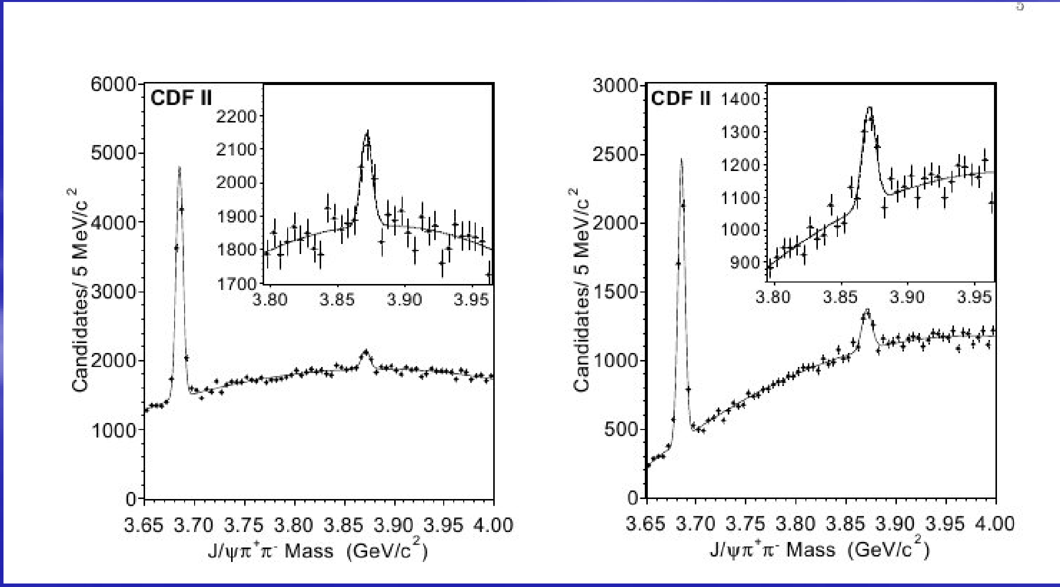
A question to be explored with more data going to higher p_T.

Onium Plans at Tevatron

- Now have ~2X as much data at CDF – double statistics for Υ, quintuple for J/ψ.
- Measure Υ(nS) production cross sections
- Study Υ isolation in production
- Try to identify DY component of dimuon continuum and measure polarization vs m_T
- Measure χ_b, feed-down fractions for Υ(1S)
- D0 J/ψ polarization result in process.

X(3872) Studies at CDF

- **New charmonium states keep coming from Belle, BaBar, and (surprisingly) CDF.**
- **CDF uses natural calibration of $\psi(2S) \rightarrow J/\psi\ \pi\pi$ to set cuts, calibrate mass for X(3872)**
- **Saw that $\pi\pi$ state prefers higher mass - right plot is cut at 500 MeV/c^2**



X(3872) - II

- Improving analysis takes multivariant selection
- Making NN selection requires careful study of discriminating variables, resolution – needs excellent detector understanding.
- Using B-decays and J/ψ decays to calibrate momentum scale is essential for precision. Material budget of detector also enters directly.
- Good vertex precision reduces number of fake candidates and lowers background.

X(3872) - III

- **Measure J^P at a hadron machine? Yes!**
- **$\pi\pi$ mass distribution sensitive to orbital angular momentum in decay and hence to parent's spin-parity**

Top: fit to expected shape for $\psi(2S) \rightarrow \psi(1S)\pi\pi$ (validate)
Bottom: fit to L=0 and L=1 for $X(3872) \rightarrow \psi(1S)\pi\pi$

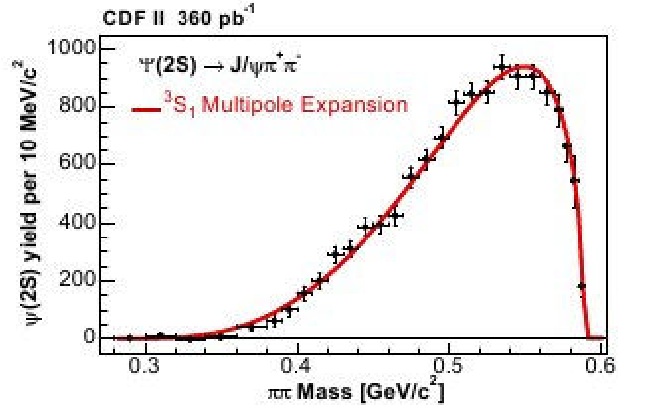


FIG. 2: The CDF dipion mass spectrum for the $\psi(2S)$ with a fit of a QCD multipole expansion calculation for $^3S_1$ [21].

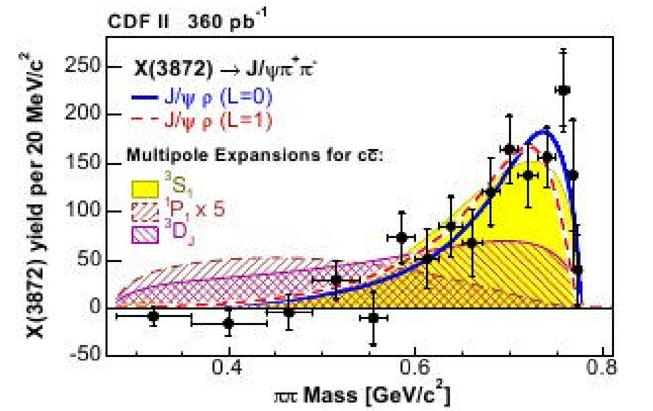


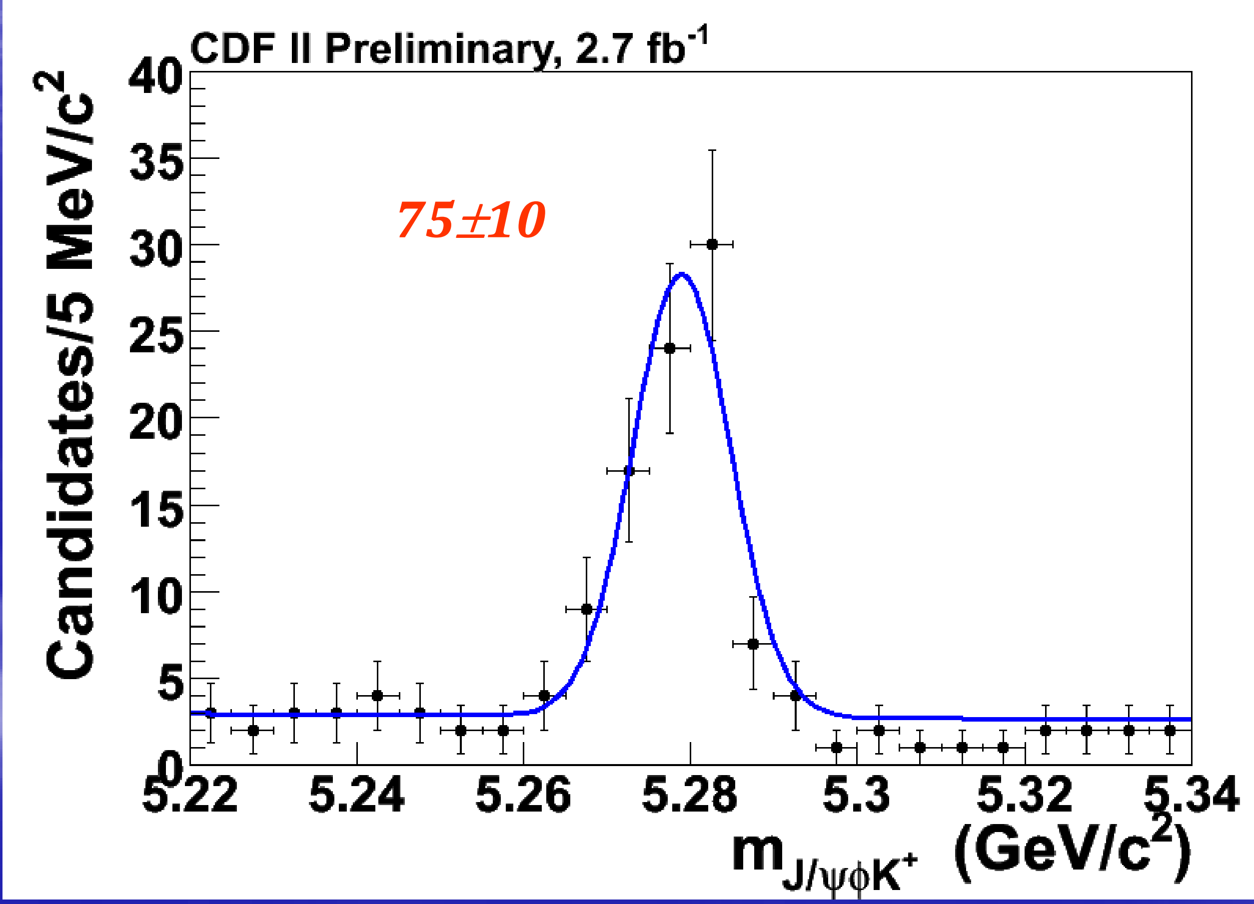
FIG. 3: The dipion mass spectrum for the $X(3872)$, and fits to various hypotheses (see text). The fitted curve for the $^1P_1$ model is scaled up by a factor of 5 for better visibility.

Another New State – Y(4140)

- The X(3872) tries to decay to $J/\psi\rho$ … but it's too light.
- Belle observes another threshold $J/\psi V$ state in B decays: $Y(3930) \to J/\psi\ \omega$
- CDF used its huge $B \to J/\psi\ X$ sample to look for a narrow $J/\psi\ \phi$ state near threshold
- No good theory for these objects, but interesting experimental pattern.

$B^+ \to J/\psi\ \phi$ Signal

- Very clean signal, using PID to tag three kaons
- Precise vertex definition keeps bckgnd low

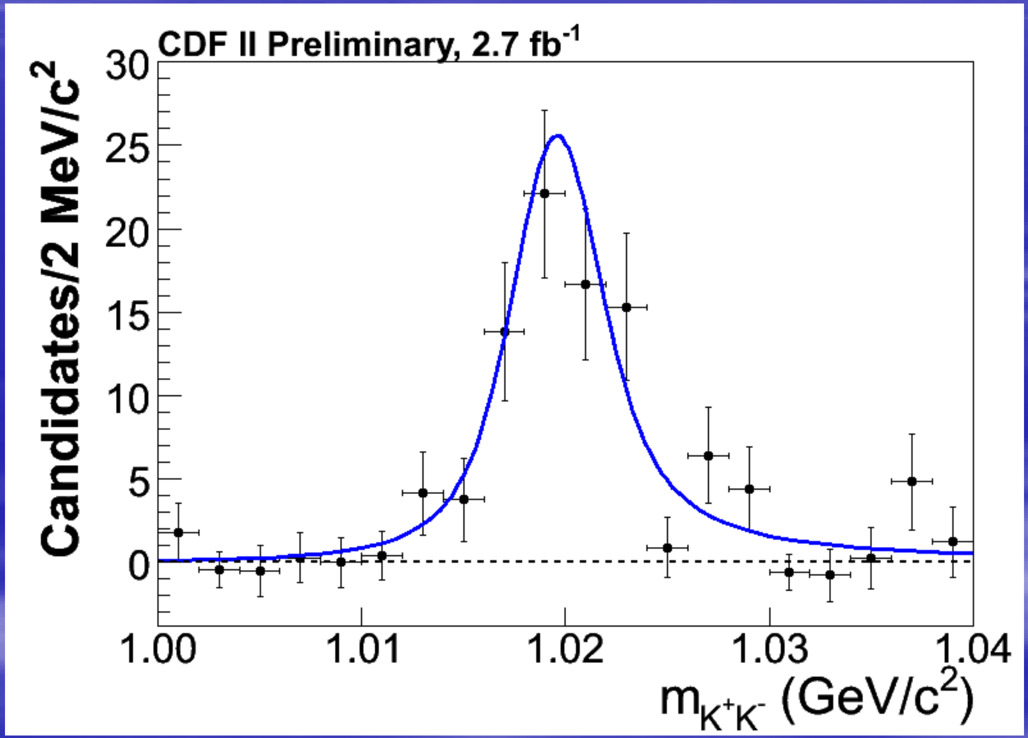


Is There f^0 Contamination?

- **Make sideband-subtracted KK mass plot.**
- **Fit J=1 rel. BW**
- **Low-mass side of**

peak matches data

- **No evidence for f^0**
- **signal is pure $\psi\phi$**



Evidence for a New State

Yield =14±5

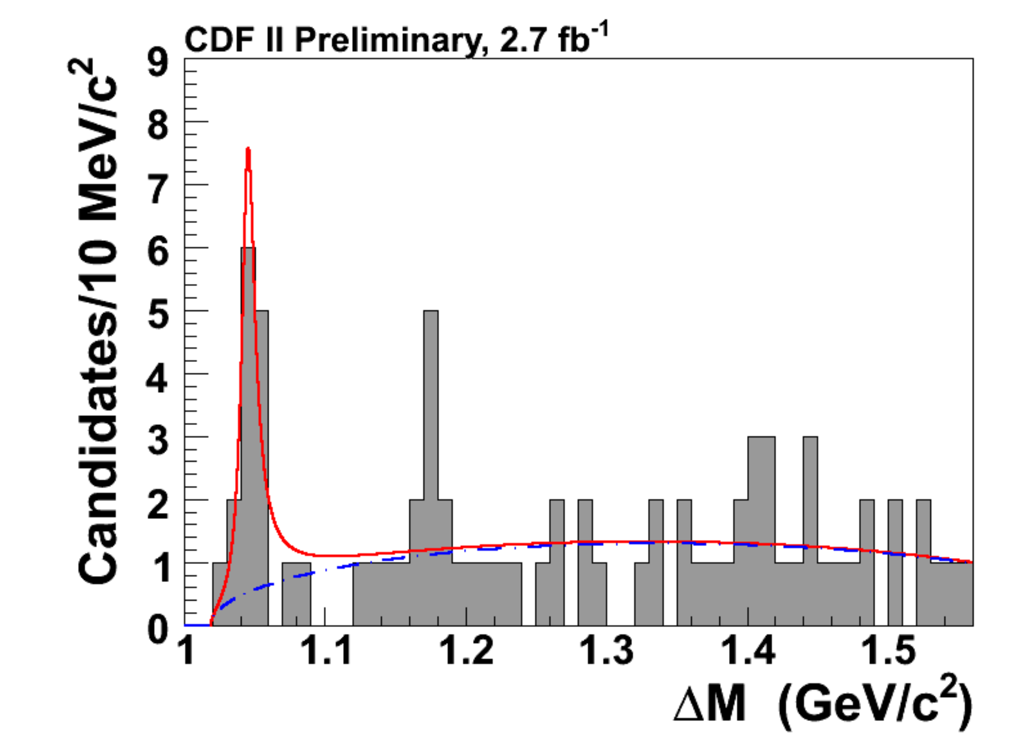
Δm = 1046.3± 2.9

(stat) MeV/c²

Width = 11.7 $^{+8.3}_{-5.0}$ (stat)

MeV

Significance: > 3.8 σ



Studies with ~2x more data now underway

Summary - I

- **Quarkonium studies at hadron colliders benefit from excellent mass resolution to handle complicated background angular behavior.**
- **Prompt production is readily measured. Determining the direct production fraction is much harder but was done at CDF-I. It's important for comparing to theory.**
- **These methods can extend the p_T reach of the measurements toward 100 GeV/c at LHC.**

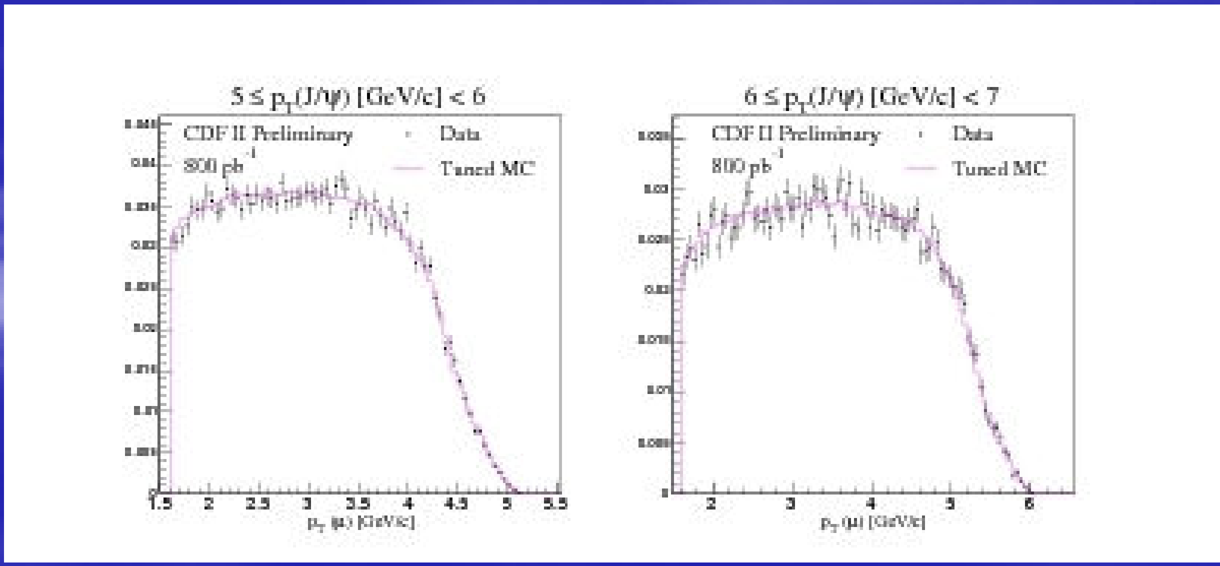
Summary - II

- **Doing B-physics with $\mu\mu$ trigger has been very profitable for J/ ψX and $\mu\mu$X at CDF.**
- **J/ψ trigger can also be entrée to new charmonium states**
- **Using well-understood vector meson systems to probe trigger and detector is the first step toward wisdom at LHC.**

Backup Slides

Data Check – μ^+ Spectra

- Compare sideband-subtracted μ^+ spectra to polarization-weighted template
- Catches bad detector performance, trigger issues, etc.
- This plot identified period of COT trouble as bad for polarization



μ pT distributions for Y(1S)

- MC is weighted combination of T and L templates using α from polarization fit
- Edges and sharp structures are well- reproduced
- Reasonable χ^2 for all bins.
- Data are sideband-subtracted (much more important here than for J/ψ.)