Upsilon Polarization Measurements

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For the CDF and DØ Collaborations

The Puzzle

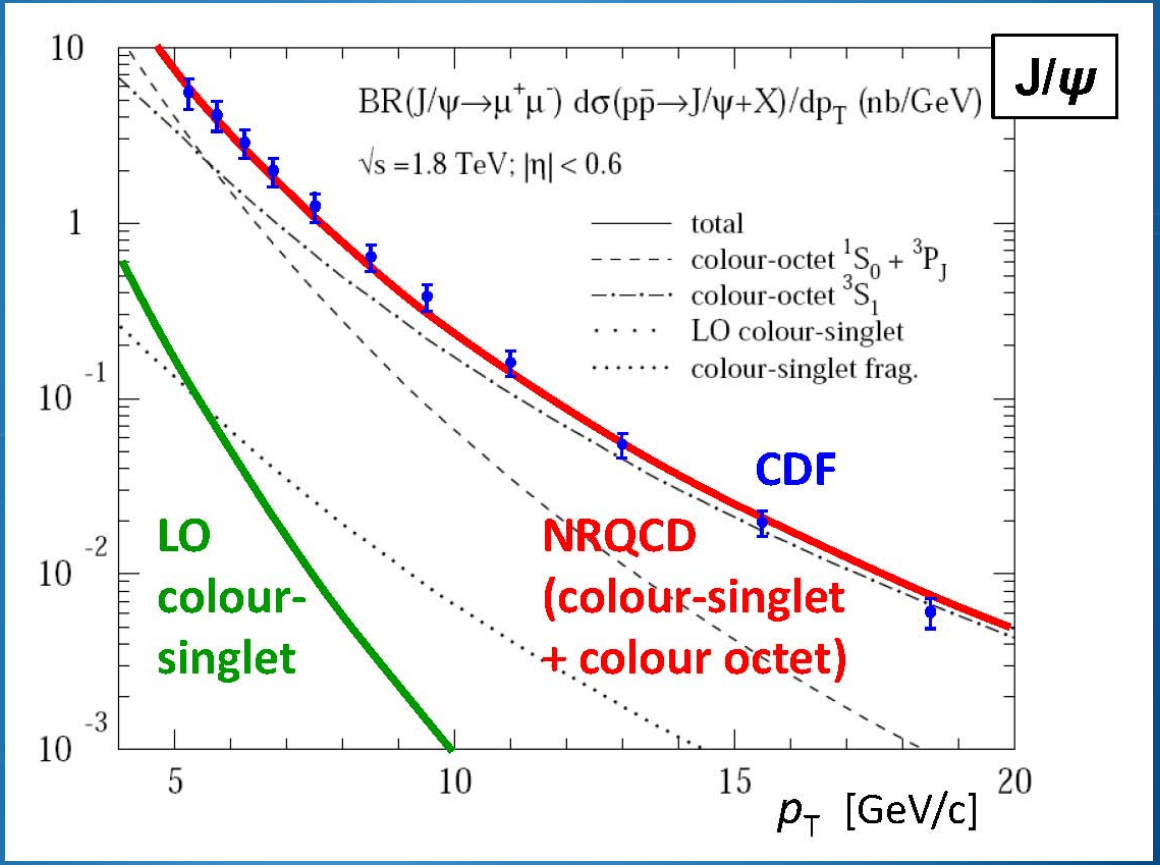
- Quarkonium production has not been explained adequately by QCD
  - Naïvely expect vector-meson production suppressed
    - Like OZI in reverse: require 3 gluons for colorless state
    - Feed-down from χ states should dominate
      - Two-gluon production
  - CDF in early ’90s found enhanced prompt J/ψ and ψ’ production
    - No feed-down to ψ’
    - σ(ψ’) was 50x LO expectation
  - Υ(nS) cross sections similarly large
    - But reduced p_T reach

Enter Theory

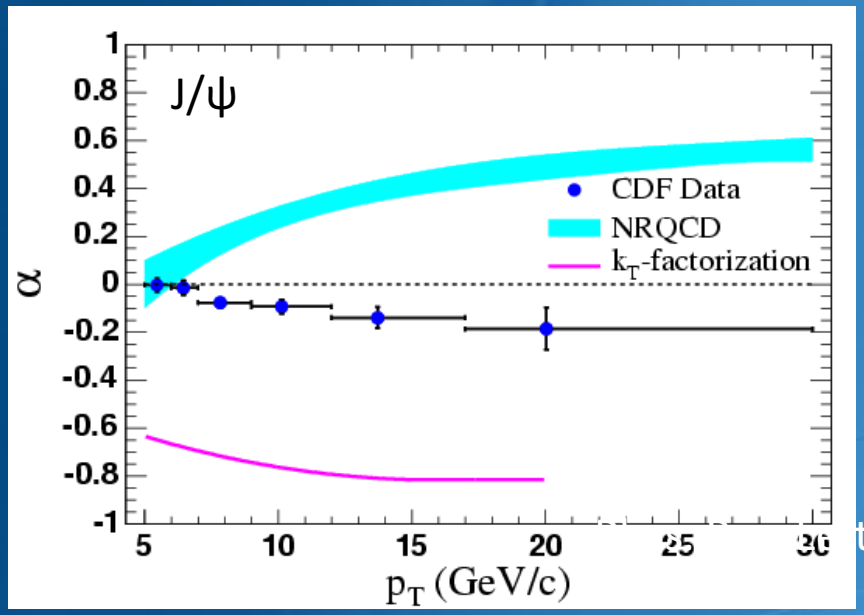
- Non-Relativistic QCD proposed as a remedy
  - Factorize
    - Short-distance hard process creates $Q\bar{Q}$
      - May be color singlet or octet state
    - Long distance process hadronization
      - Radiates extra gluons
      - Expansion in powers of *v*
      - Universal 4-quark operators
  - Can largely fit J/ψ and ϒ(1S) production spectra
  - Predict strong transverse polarization at high momentum ($p_T^2/M^2 >> 1$)
    - Carries properties of the hard gluon parent

Color-Octet Contributions to J/ψ Production

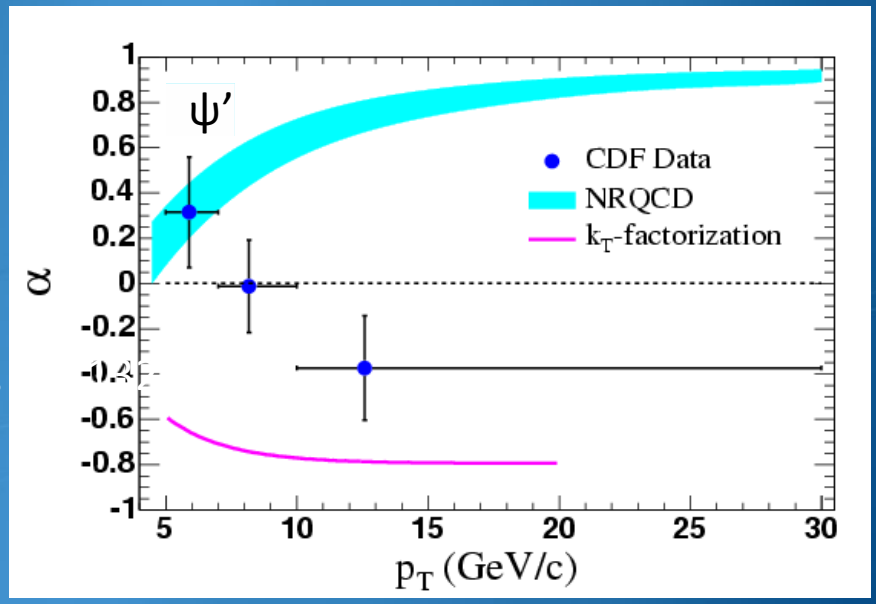
CDF Run I: 18 pb^{-1}
Phys. Rev. Lett. 79, 572



Charmonium Polarization



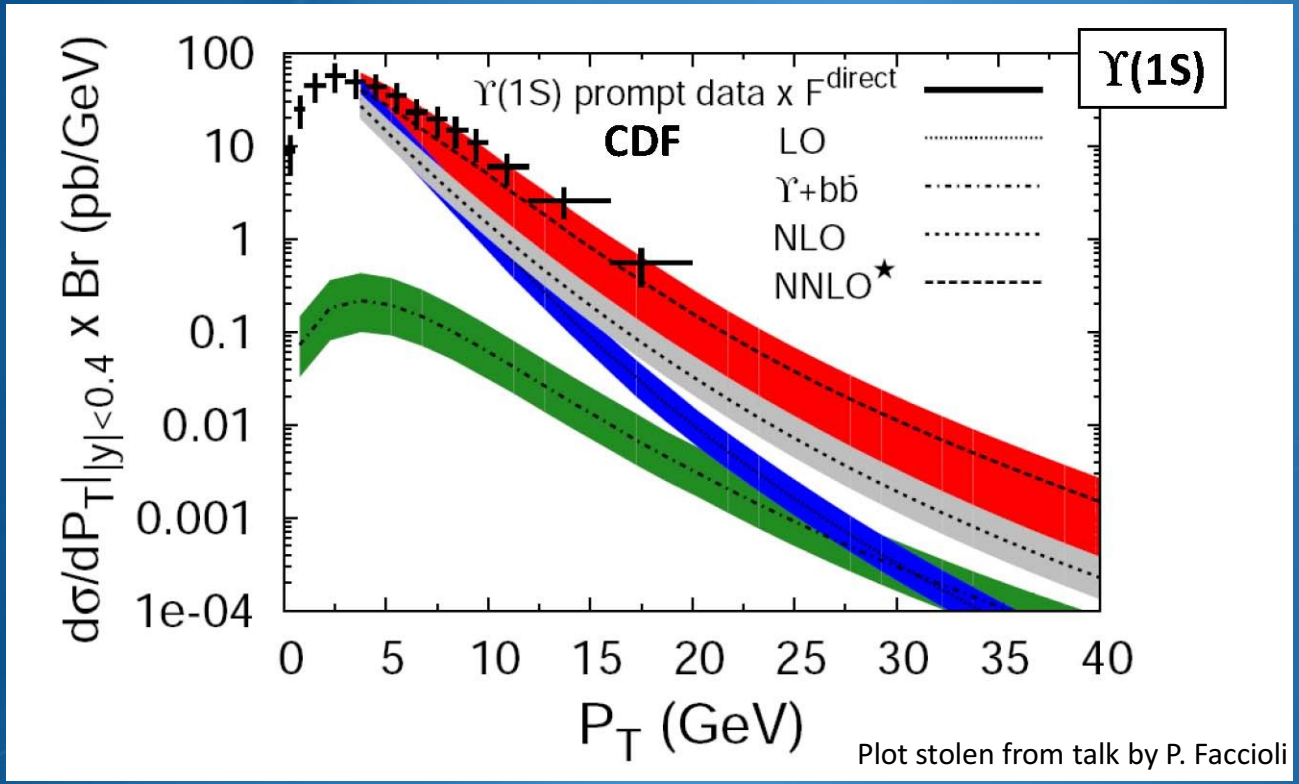
$$dN/d(\cos\theta^*) \propto 1 + \alpha \cos^2\theta^*$$



- Inconsistent with NRQCD
  - But is the charm quark heavy?
  - The bottom quark is!
- Newer NNLO models predict longitudinal ϒ polarization

Phys. Rev. Lett. 99, 132001 (0.8 fb^{-1})

NNLO Can Explain Υ Production

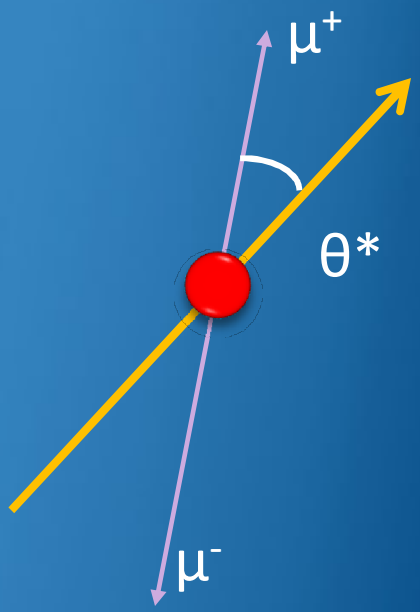


Plot stolen from talk by P. Faccioli

- Predicting production spectra not a sufficient test of models
  - Need polarization, too.

Polarization Measurement

- For several p_T ranges, find $dN/d\cos\theta^*$
  - *s*-channel helicity frame
  - Angle between μ in ϒ CM frame and ϒ boost direction
  - Described by $dN/d(\cos\theta^*) \propto 1 + \alpha \cos^2\theta^*$
- Acceptance sculpted by instrumental effects
  - Geometry
  - Muon p_T
  - Trigger turn-on

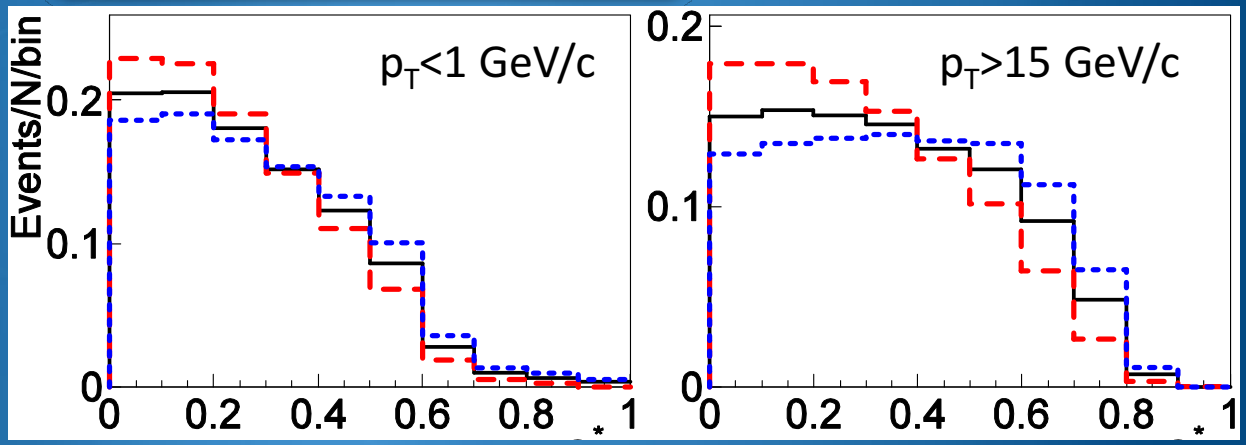


Method, cont.

- Measure yield in bins of p_T and cosθ*
  - DØ: fit mass distributions
  - CDF: side-band subtraction
- Use templates for transverse (α=1) and longitudinal (α=-1) decay distributions to fit data
- Fit parameter:

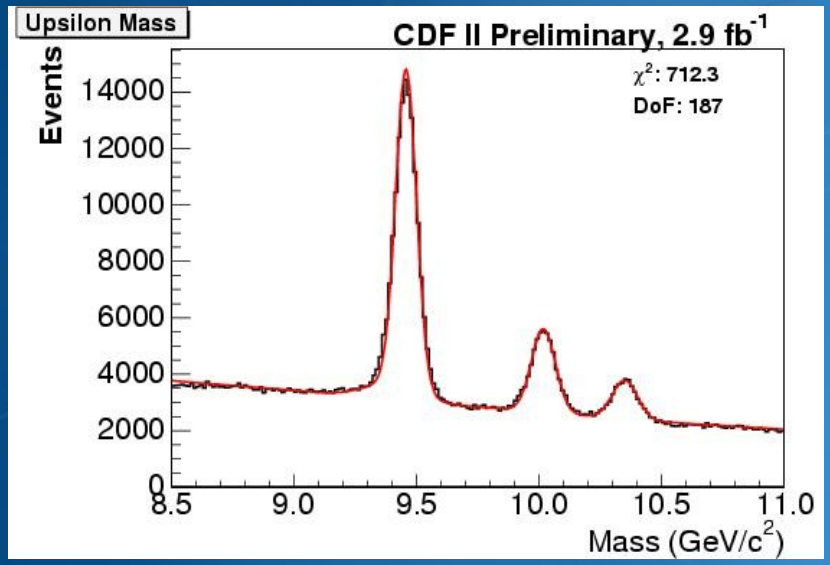
$$\eta \equiv \frac{\sigma_L}{\sigma_T + \sigma_L} = \frac{1-\alpha}{3+\alpha}$$

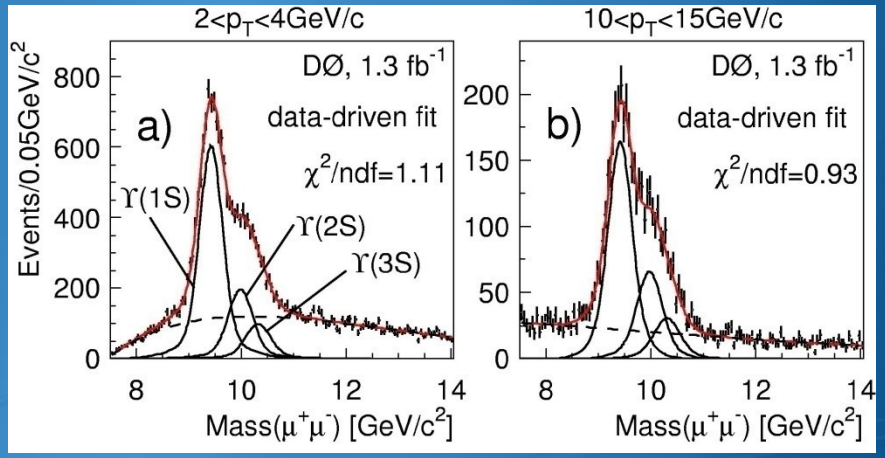
DØ ϒ Monte Carlo
--- Transverse
--- Unpolarized
--- Longitudinal



Large $\Upsilon \rightarrow \mu^+\mu^-$ Samples

- CDF
  - 2.9 fb^{-1}
  - 83,000 Υ(1S) candidates
  - $|y|<0.6$
  - Resolve 3 peaks

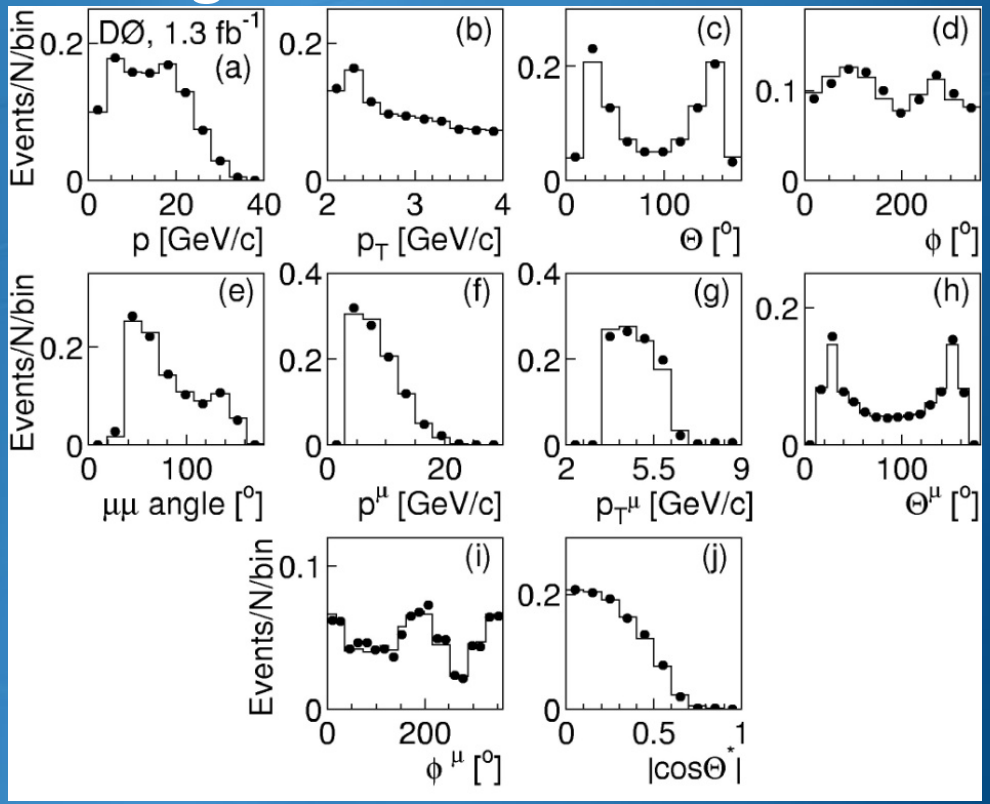




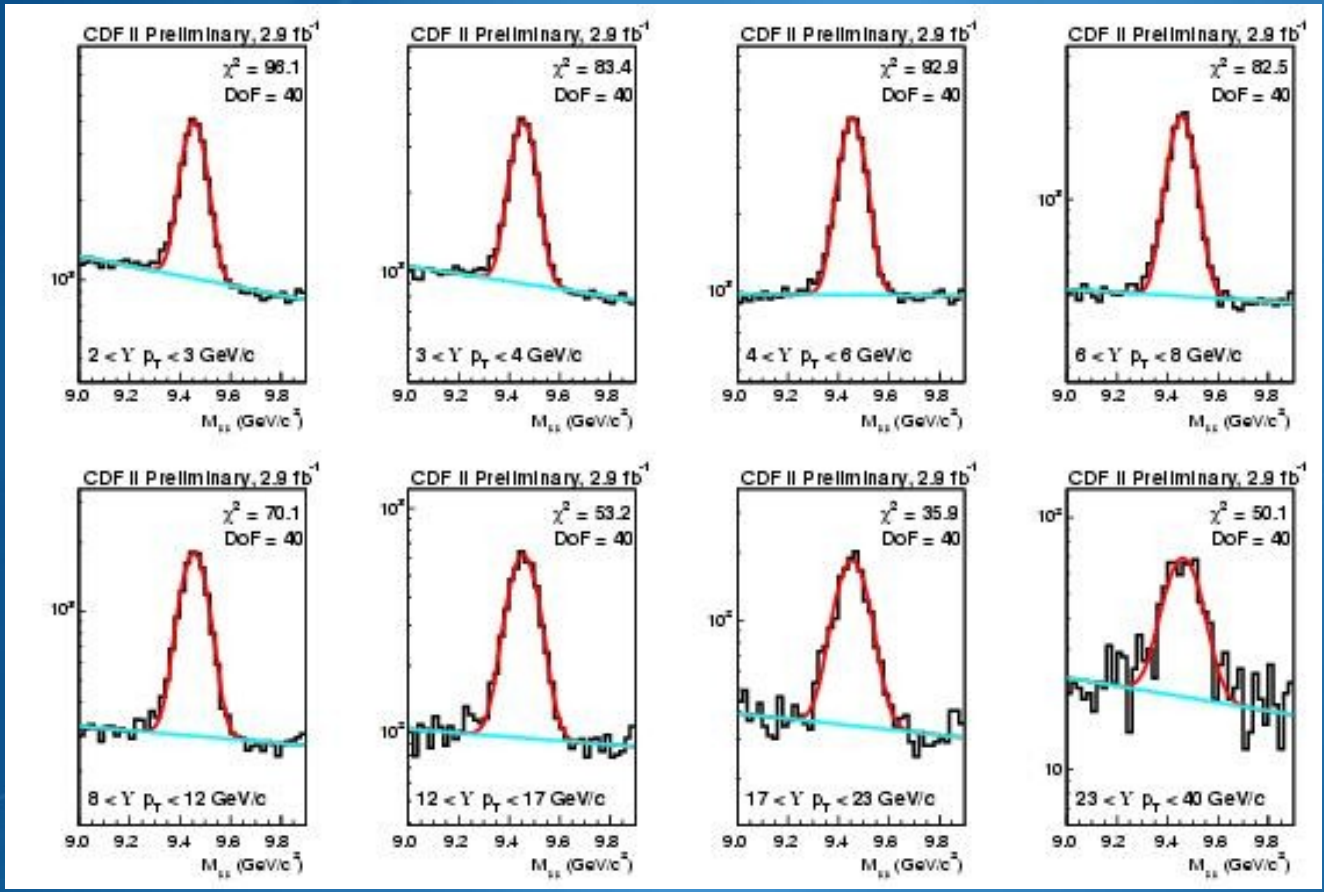
- DØ
  - 1.3 fb^{-1}
  - 260,000 $\Upsilon(nS)$ candidates
  - $|y|<1.8$
  - Yields of peaks extracted from fit

Monte Carlo Derived Templates

- Reconstruct like data
  - Includes all detector effects
  - No efficiency corrections to data
  - Requires good MC tuning

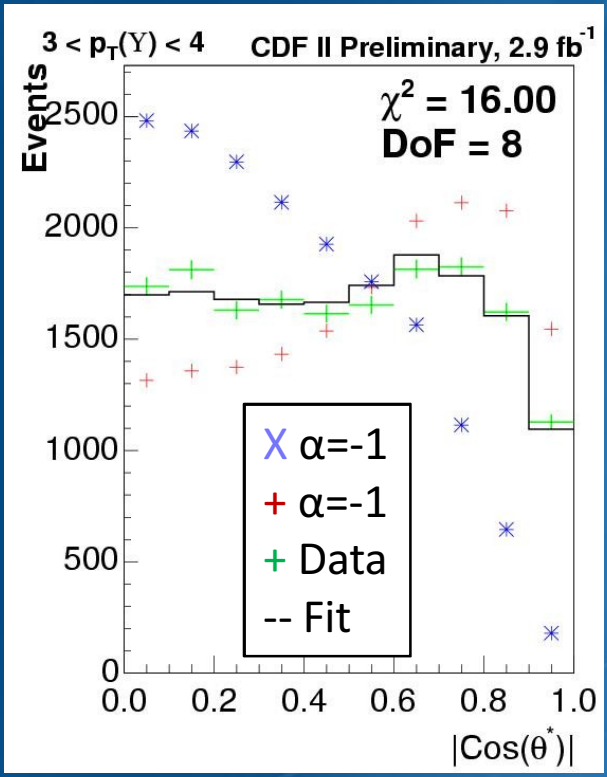


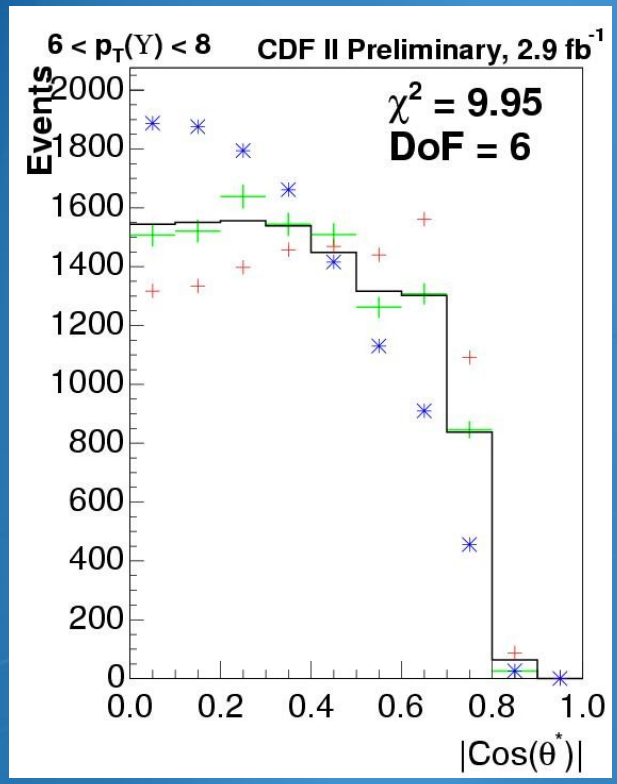
CDF: $\Upsilon(1S) \rightarrow \mu^+\mu^-$ Mass Fits

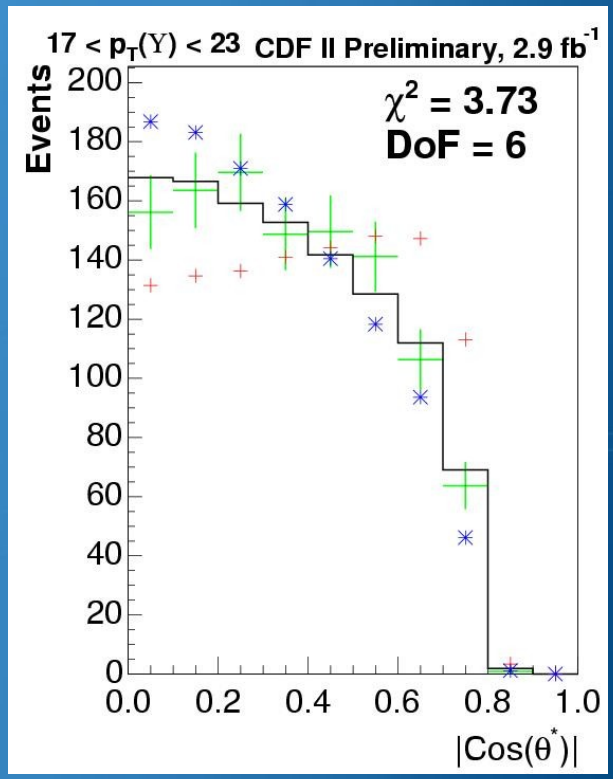


- Fits in p_T bins
  - Shape used when subdividing into cosθ* bins

Template Fits: CDF







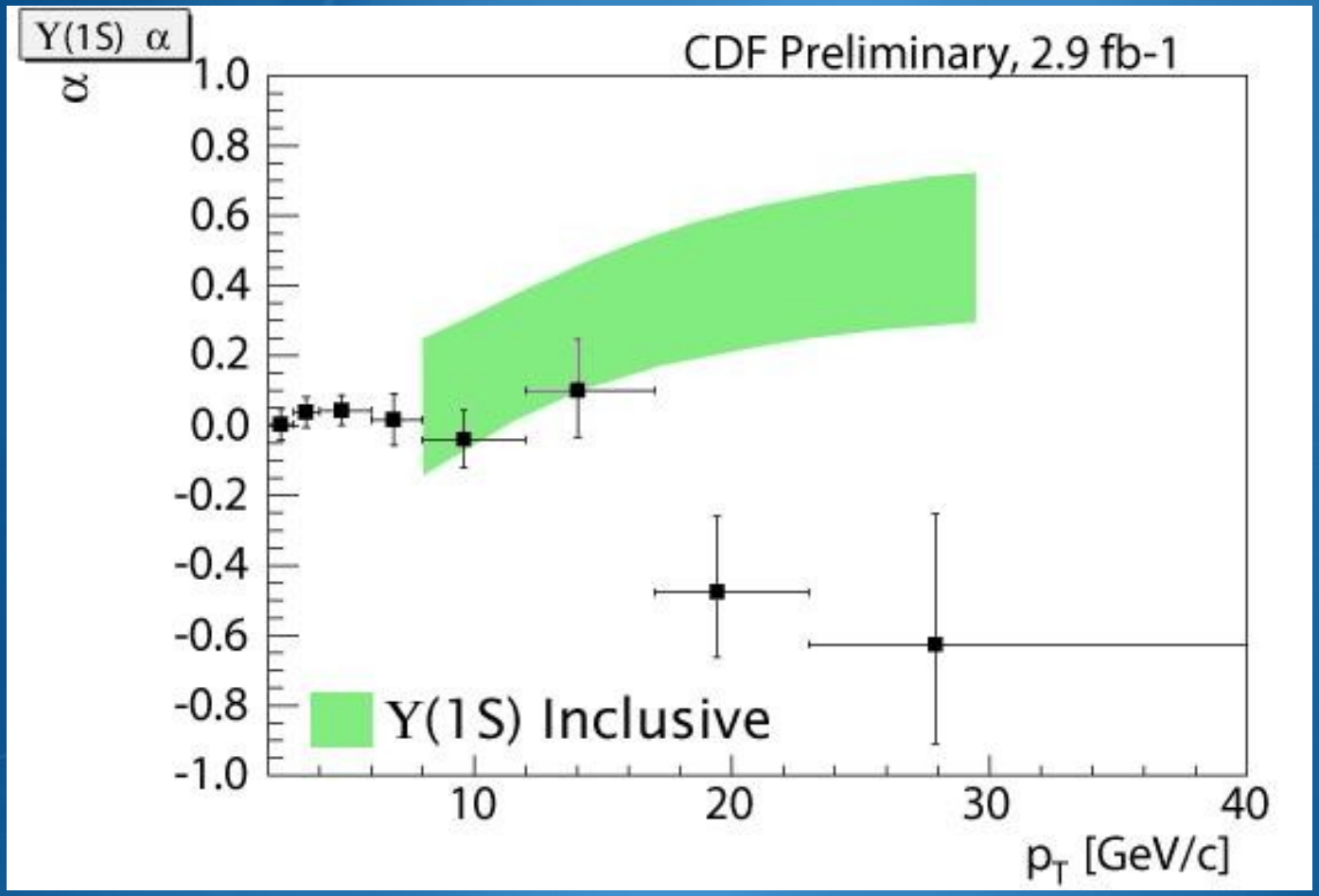
http://www-cdf.fnal.gov/physics/new/bottom/090903.blessed-Upsilon1S-polarization/blessed_plots.html

- Large cosθ* bins with sensitivity to differences between polarizations suffer from acceptance limits

Systematic Uncertainties

- Small
- Dominated by
  - Fitting/counting technique
  - Trigger efficiency turn-on

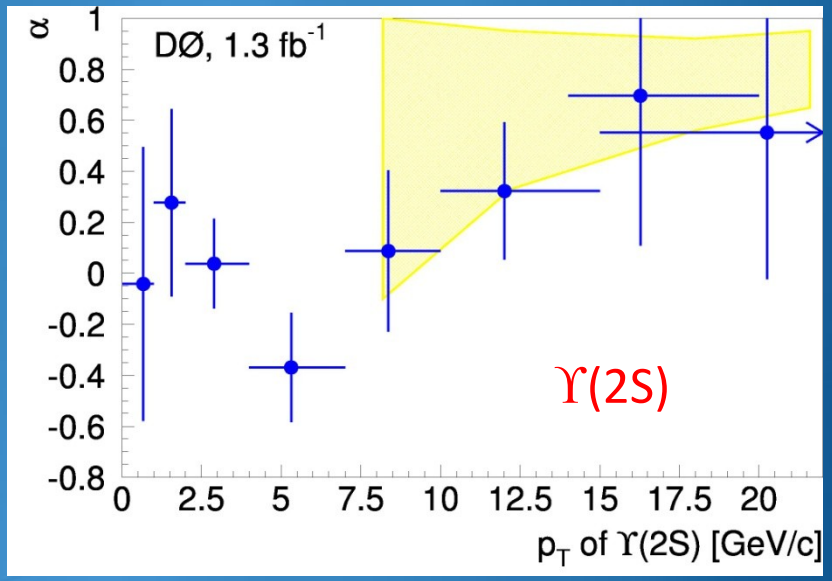
Results: CDF

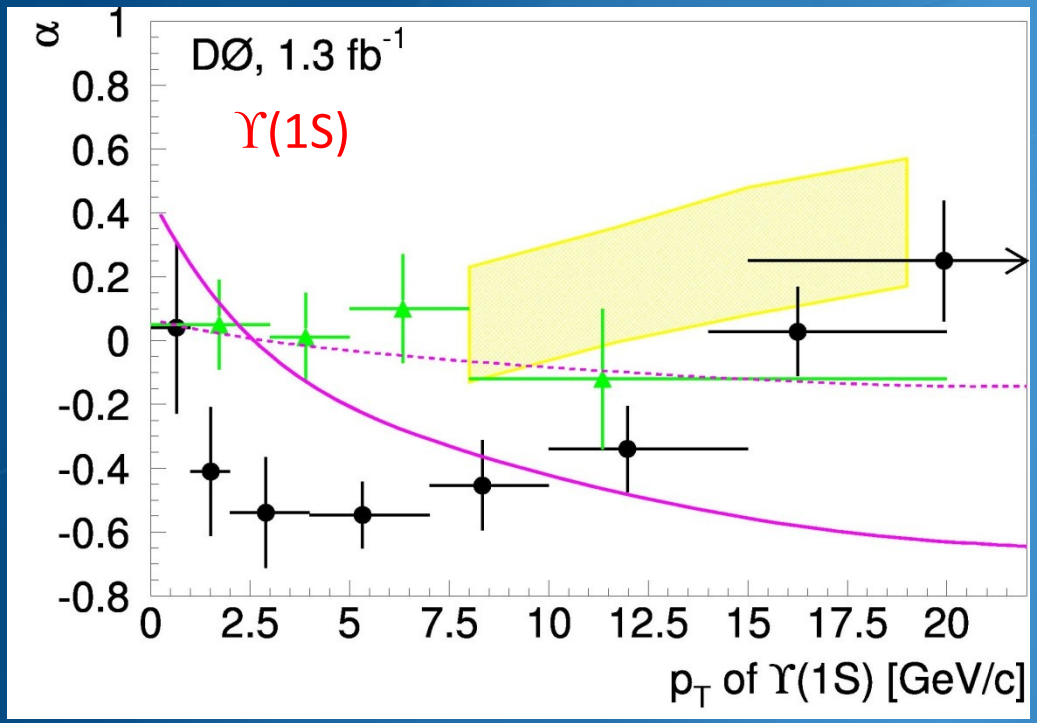


- NRQCD prediction has poor consistency with data
  - Theory band broad as a result in feed-down contributions

Results: DØ

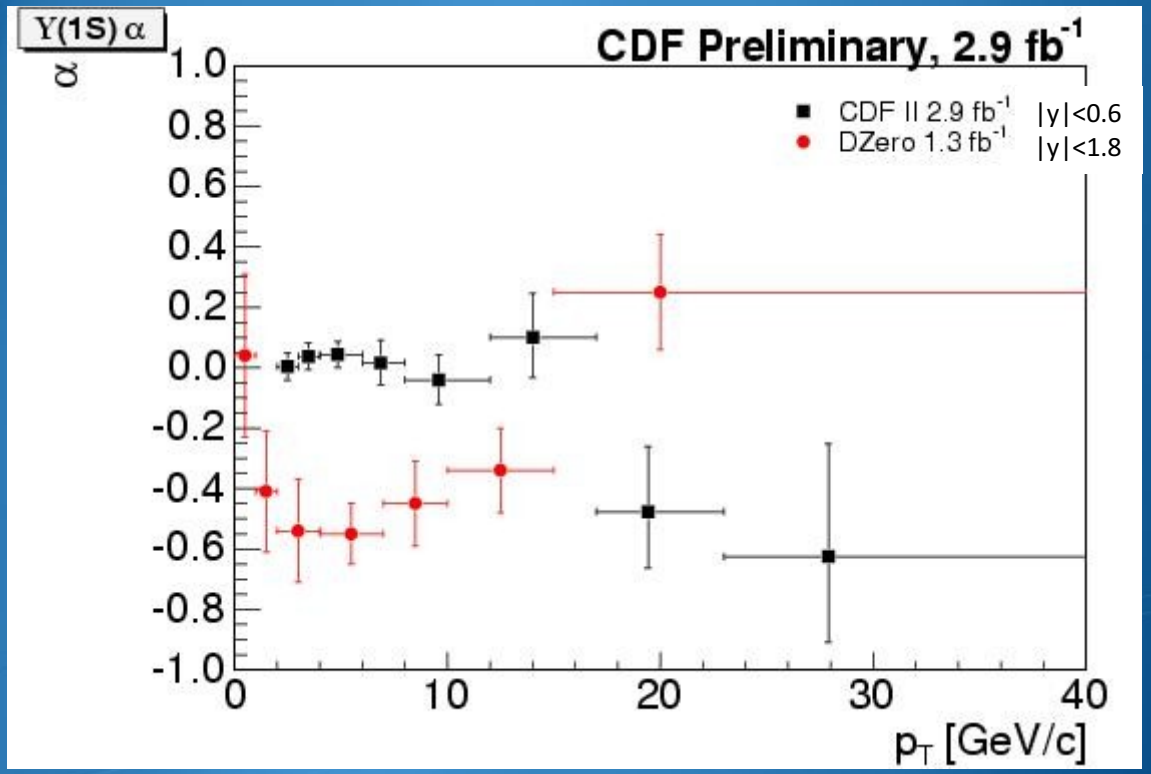
Phys. Rev. Lett. **101**, 182004 (2008)





- Comparisons to CDF Run I and to NRQCD and k_T-factorization models

Comparison



- CDF and DØ results largely inconsistent
  - Use similar techniques
  - Different rapidity regions
    - CDF: $|y|<0.6$
    - DØ: $|y|<1.8$
  - CDF also agrees with Run I (77 pb^{-1}) result

Conclusions

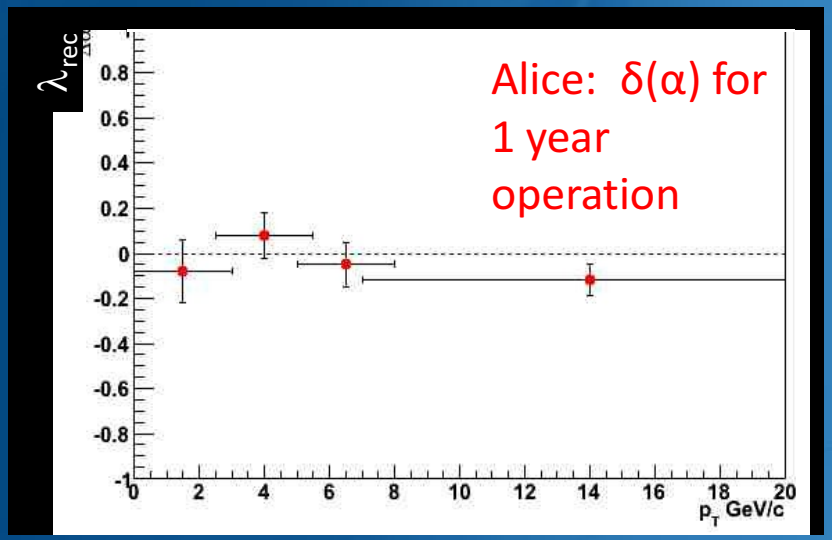
- Much progress
- The theoretical puzzle remains, and is joined by an experimental one
- Some Hints:
  - See P. Faccioli et al. hep-ph/1005.2855
  - More detailed angular analysis needed
    - Collins-Soper frame
      - Relative to production plane
    - Include azimuthal as well as polar asymmetries

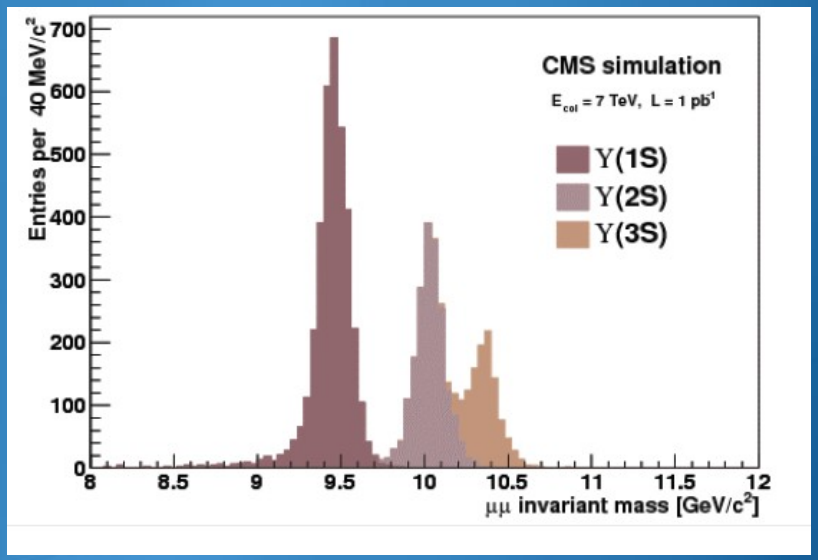
    $dN/d\Omega \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$
  - Need comparisons in common rapidity range
- More data may bring resolution

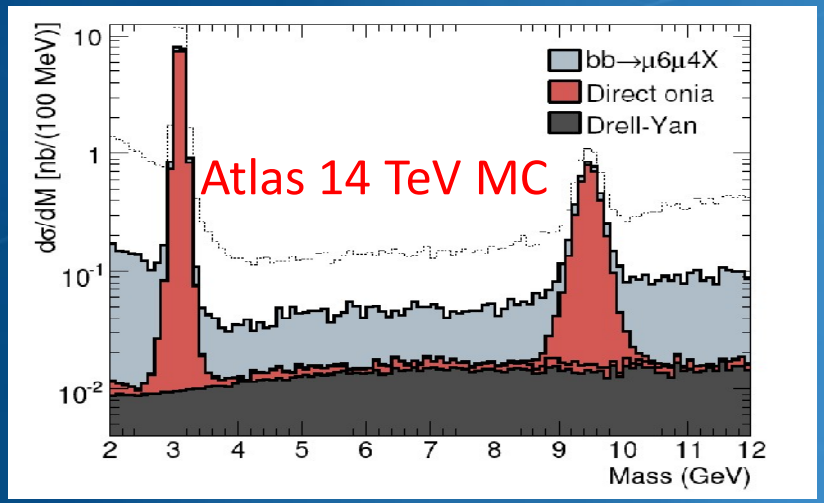
Outlook

- Tevatron experiments now have ~7 fb^{-1} on tape
- CDF expanding analysis as well
  - 2S and 3S
  - Adding Collins-Soper frame
    - More appropriate for production polarization
  - Investigating azimuthal asymmetry
  - Information from Υ isolation may also help discriminate between models

Outlook II: LHC







- Good analysis for early data
  - Atlas and CMS expect σ~10nb to tape for $\Upsilon \rightarrow \mu^+\mu^-$
  - May be challenging to resolve peaks
  - Same caveats about full angular analysis and common rapidity ranges apply