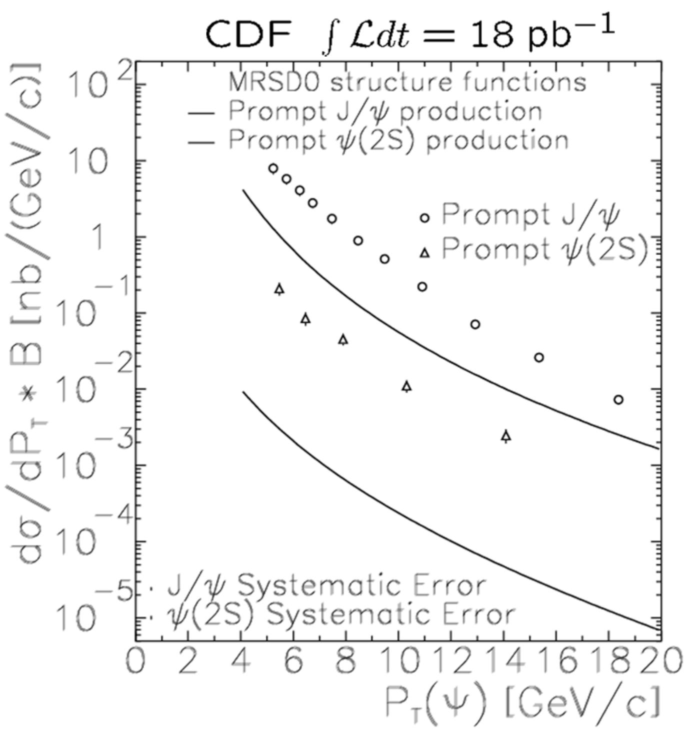
Angular Distributions of Muons from ϒ Decays at CDF

(ϒ Polarization)

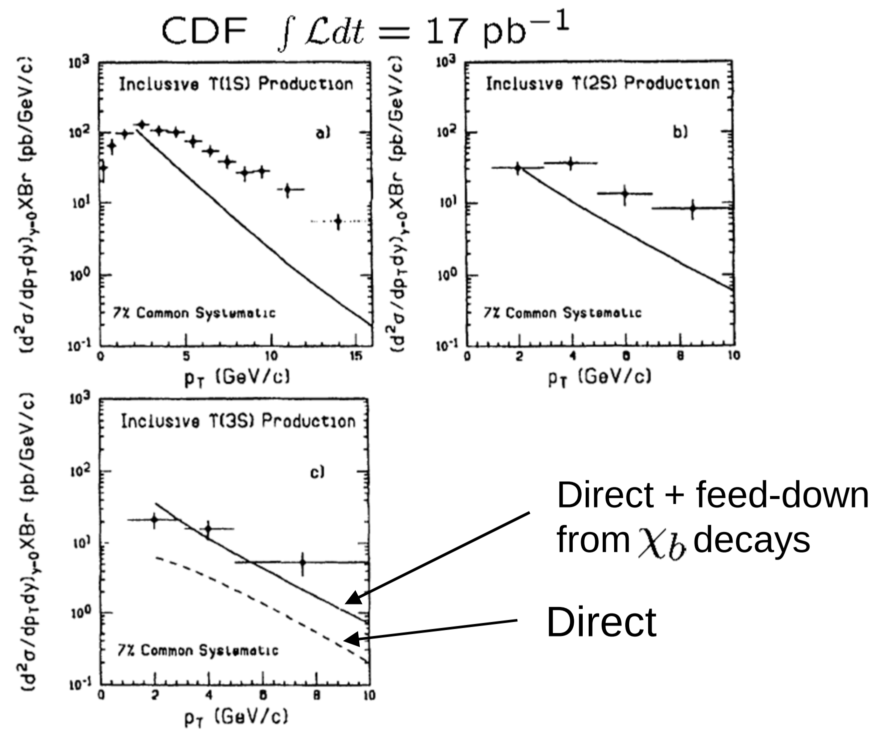
Matthew Jones
Purdue University
for the CDF Collaboration

Puzzling for over 20 years…

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



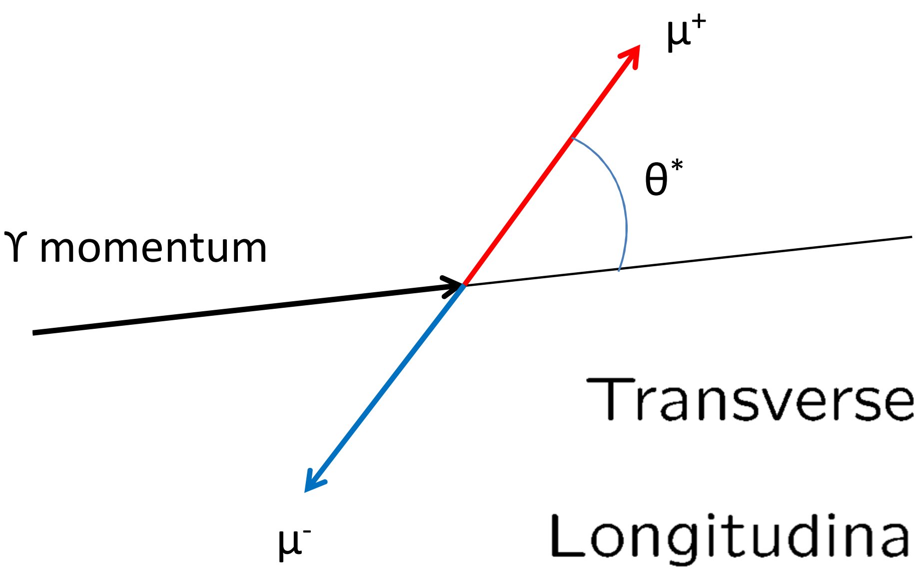
Phys. Rev. Lett. **75**, 4358 (1995)



- Prompt J/ψ and ϒ cross sections much larger than expected…
  - Color octet production mechanisms
    - ***Polarization measurements***

Upsilon “Polarization”

- A better term is *spin alignment*…
  - *Transverse* polarization: $|J, \lambda\rangle = |1, \pm 1\rangle$
  - *Longitudinal* polarization: $|J, \lambda\rangle = |1{,}0\rangle$

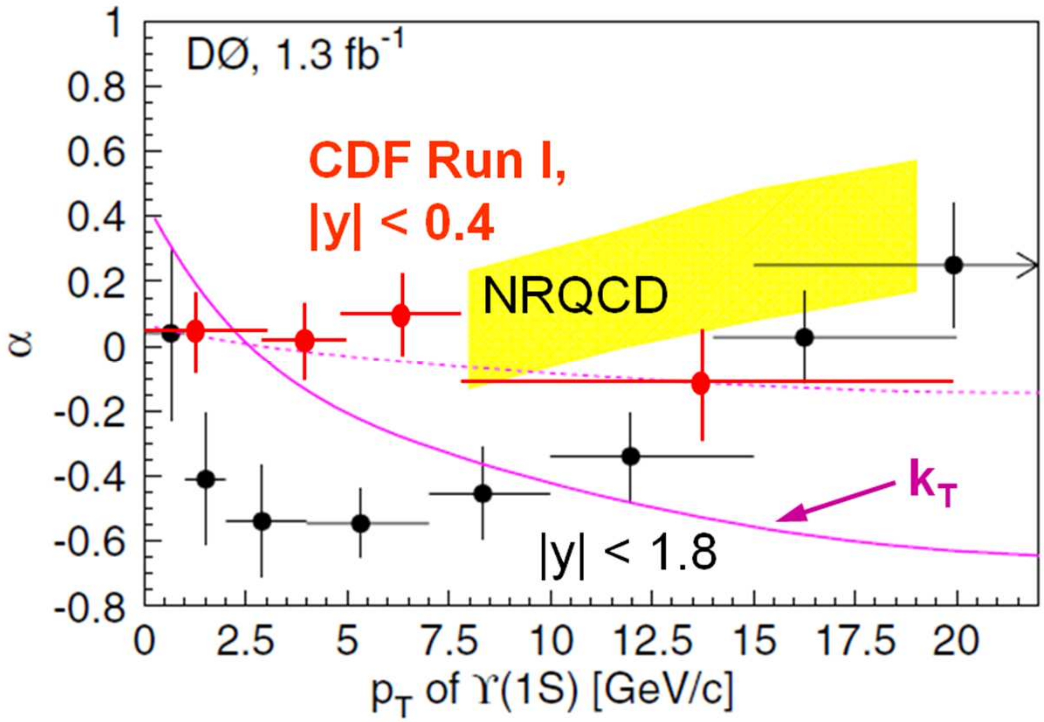


$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \alpha\cos^2\theta^*$$

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

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

Current Status



- CDF found no evidence for polarization in Run I

  Phys. Rev. Lett. 88, 161802 (2002).

- DØ finds it to be longitudinal at low p_T, then transverse at high p_T

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

- Models:

  NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)

  k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)

- But pure states are naturally polarized…

Maybe not even wrong...

- The current situation is unsatisfactory... 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 $\mu^+\mu^-$:

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

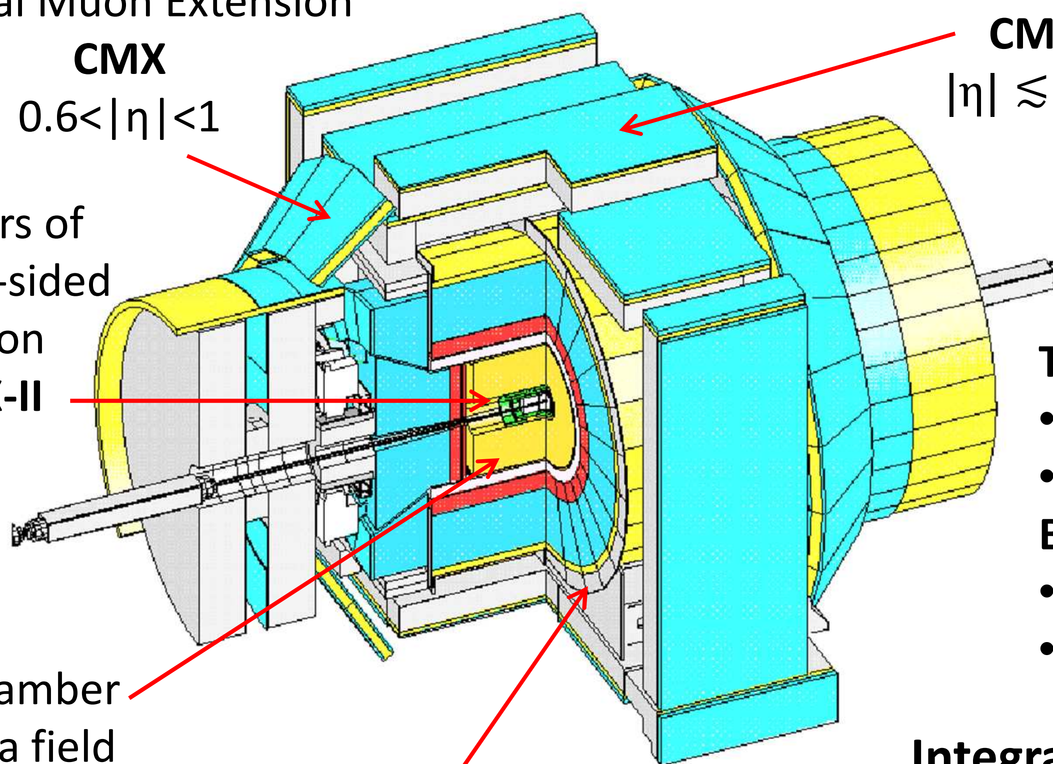
$$\lambda_\theta = \frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \lambda_\phi = \frac{2\mathrm{Re}\, a_{+1}^* a_{-1}}{1+|a_0|^2} \qquad \lambda_{\theta\phi} = \frac{\sqrt{2}\mathrm{Re}(a_0^* a_{+1} - a_0^* a_{-1})}{1+|a_0|^2}$$

Un-polarized only when λ_θ, λ_φ and $\lambda_{\theta\varphi}$ are all zero.

New CDF Analysis

- Goals:
  - Measure all three parameters simultaneously
  - Measure in Collins-Soper and S-channel helicity frame
  - Test self-consistency by calculating rotationally invariant combinations of λ_θ, λ_φ and $\lambda_{\theta\varphi}$
  - Minimize sensitivity to modeling the $\Upsilon(nS)$ resonance line shape
  - Explicit measurement of angular distribution of di-muon background

The CDF II Detector



Two triggers used:

- CMUP (4 GeV) + CMU (3 GeV)
- CMUP (4 GeV) + CMX (3 GeV)

Both require:

- opposite charge
- $8 < m(\mu^+\mu^-) < 12$ GeV/c^2

Integrated luminosity: 6.7 fb^{-1}

Sample size: 550,000 Υ(1S)
150,000 Υ(2S)
76,000 Υ(3S)

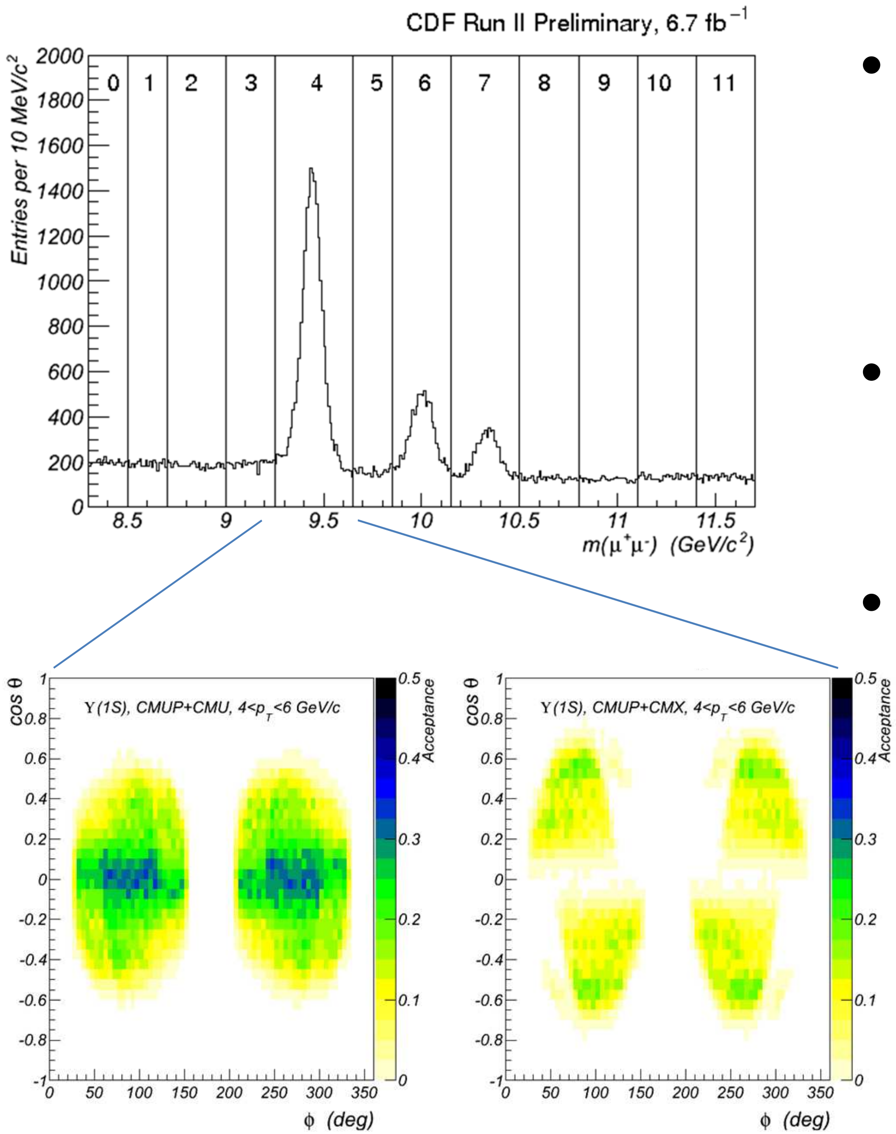
Analysis Method

- Reconstruct $\mu^+\mu^-$ candidates, boost into rest frame, calculate decay angles ($\cos\theta,\varphi$)
  - Analyze in both S-channel helicity and Collins-Soper frames
- Factor acceptance and angular distribution:

$$\frac{d\sigma}{d\Omega} \sim A(\cos\theta, \varphi) \times w(\cos\theta, \varphi; \vec{\lambda})$$

  - $A(\cos\theta,\varphi)$ from high statistics Monte Carlo
  - $w(\cos\theta,\varphi; \lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi})$ from angular distribution
- Performed binned likelihood fit to observed distribution of ($\cos\theta,\varphi$) to determine λ_θ, λ_φ, $\lambda_{\theta\varphi}$.
  - Binning is large compared with angular and p_T resolution

Analysis Method

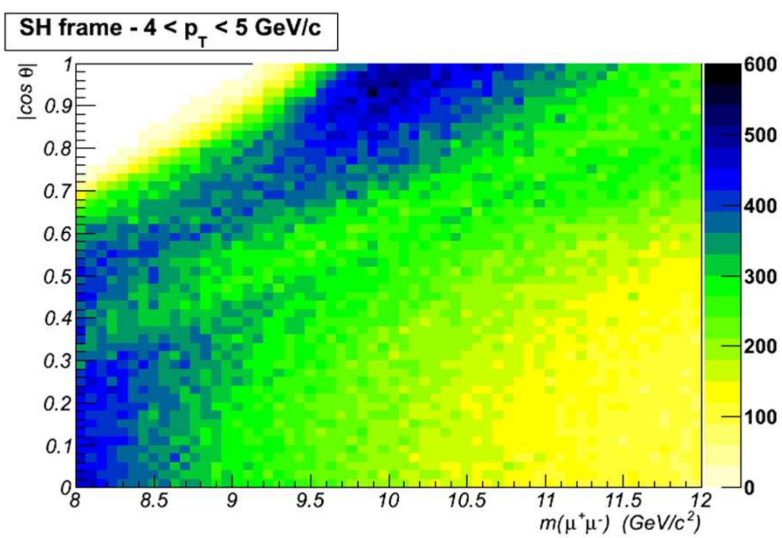


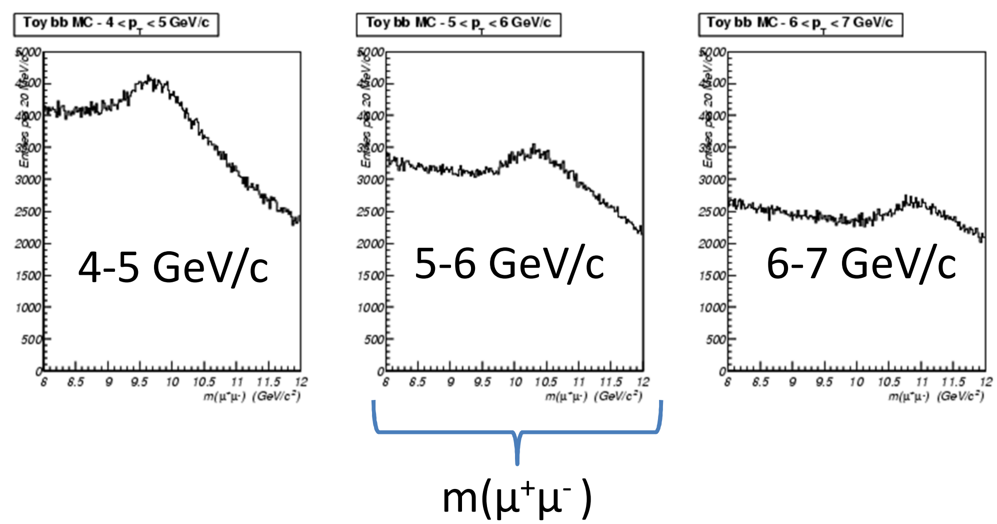
- Trigger and reconstruction efficiencies measured using $J/\psi \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ control samples
- Geometric acceptance calculated using full detector simulation
- Two component fit:
  signal + background

$$\bar{\lambda} = f_s\lambda_s + (1 - f_s)\lambda_b$$

The Background is Complicated

- Dominant background: correlated $b\bar{b}$ production
- Triggered sample is very non-isotropic
  - $p_T(b)$ spectrum falls rapidly with p_T
  - Angular distribution evolves rapidly with p_T and $m(\mu^+\mu^-)$
- Very simple toy Monte Carlo: ***the background might peak right under the Υ(nS) signals in some p_T ranges.***



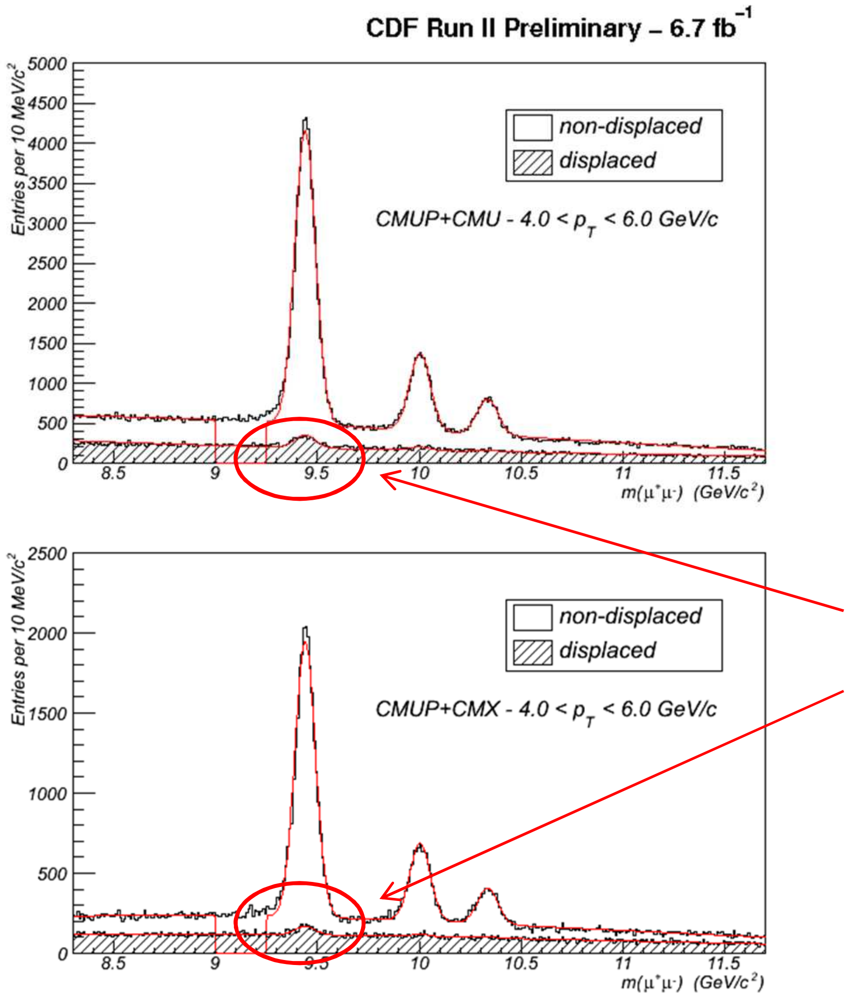


New Approach

- Use muon impact parameter to isolate a background-enhanced (***displaced***) sample
  - Complimentary sample (***prompt***) contains most of the ϒ(nS) signal.
  - Impact parameter requirement must not bias angular distributions
- Fit to invariant mass distribution:
  - Measure fraction of ϒ(nS) signal present in displaced sample
- Fit to displaced sample + prompt sidebands:
  - Measures ratio of prompt/displaced backgrounds
  - Not biased by signal line shape model
  - Allows us to predict the level of prompt background under the ϒ(nS)
- Two component fit to ($\cos\theta,\varphi$) distribution
  - Determines λ_θ, λ_φ,$\lambda_{\theta\varphi}$ for signal and background
  - Purely empirical parameterization of background – helpful to add additional $\cos^4\theta$ term

Background Proxy Sample

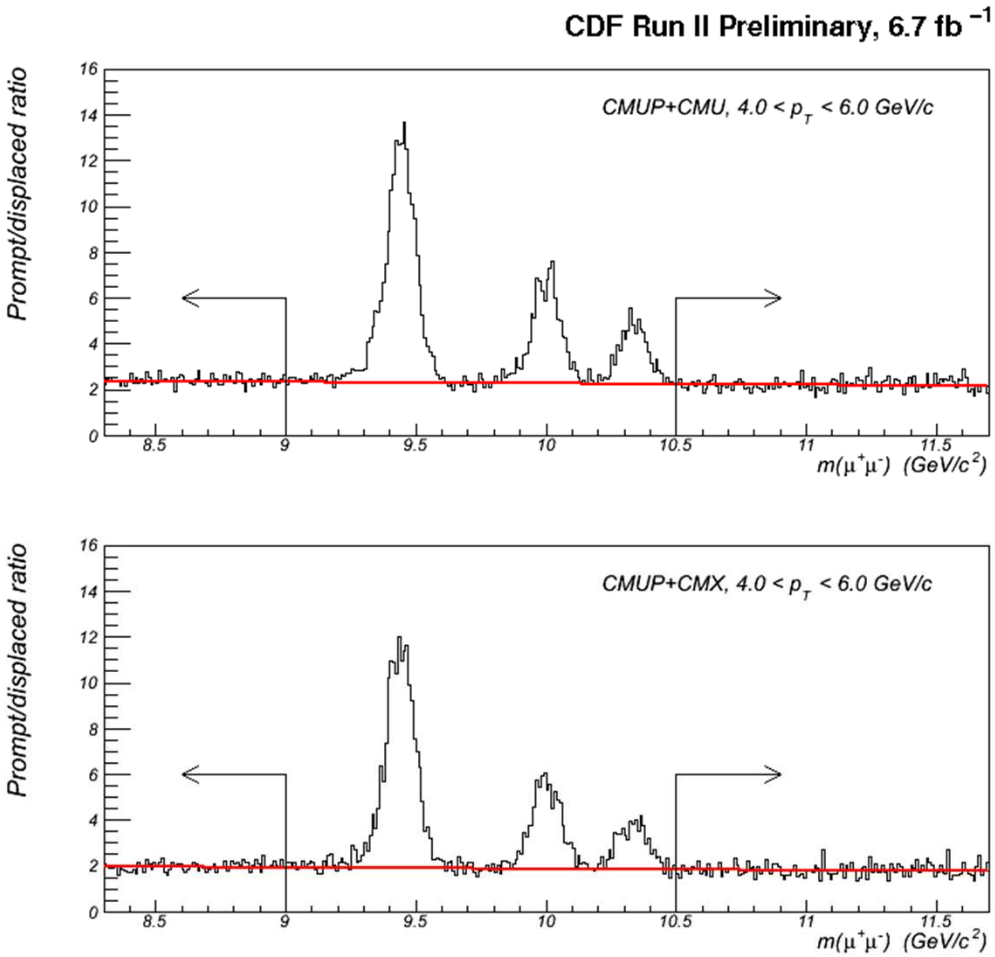
- Measure fraction of signal in displaced sample:



This fit measures the fraction of the ϒ signal that is present in the displaced sample (1-4%)

Background Proxy Sample

- Measure prompt scale factor:



The ratio of prompt/secondary distributions is almost constant.

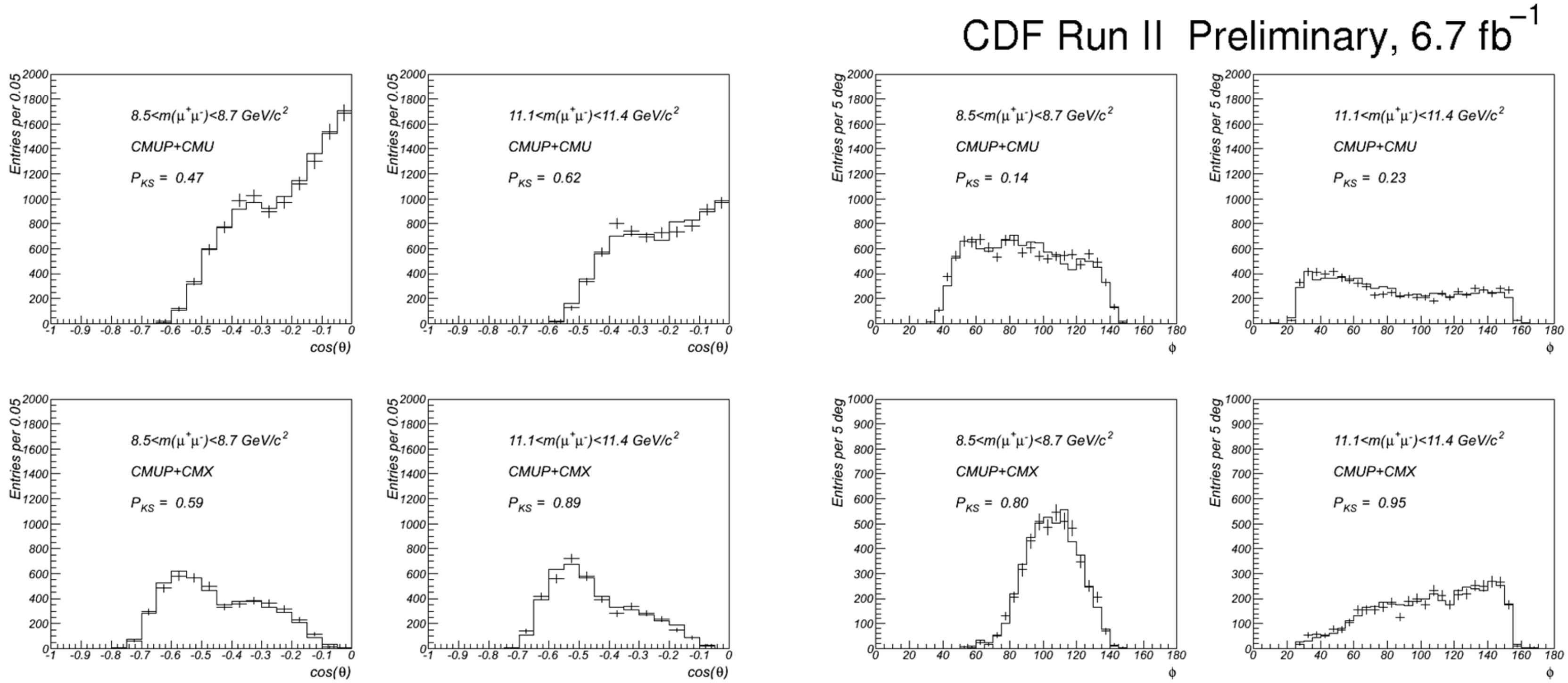
Simultaneous fit to displaced sample and ϒ sidebands.

Avoids possible bias from modeling the ϒ line shape.

Quadratic scale factor function considered in systematic studies.

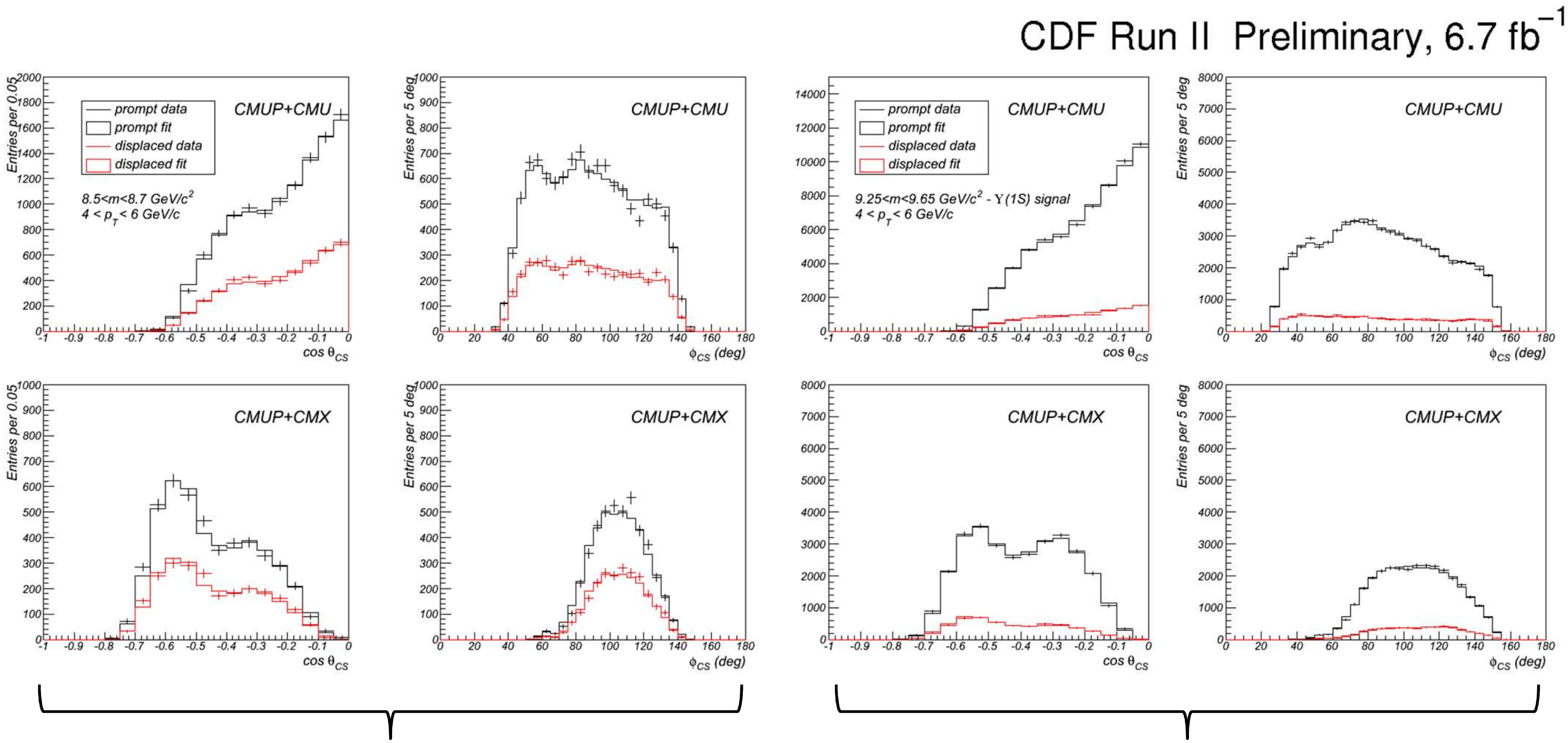
Angular distributions in sidebands

- The sub-sample containing a displaced track ($|d_0| > 150$ µm) is a good description of the background under the ϒ(nS):



- Prompt (histogram) and displaced (error bars) angular distributions match in the sidebands.
- We use the displaced muon sample to constrain the angular distribution of background under the ϒ(nS) peaks.

Fits to signal + background

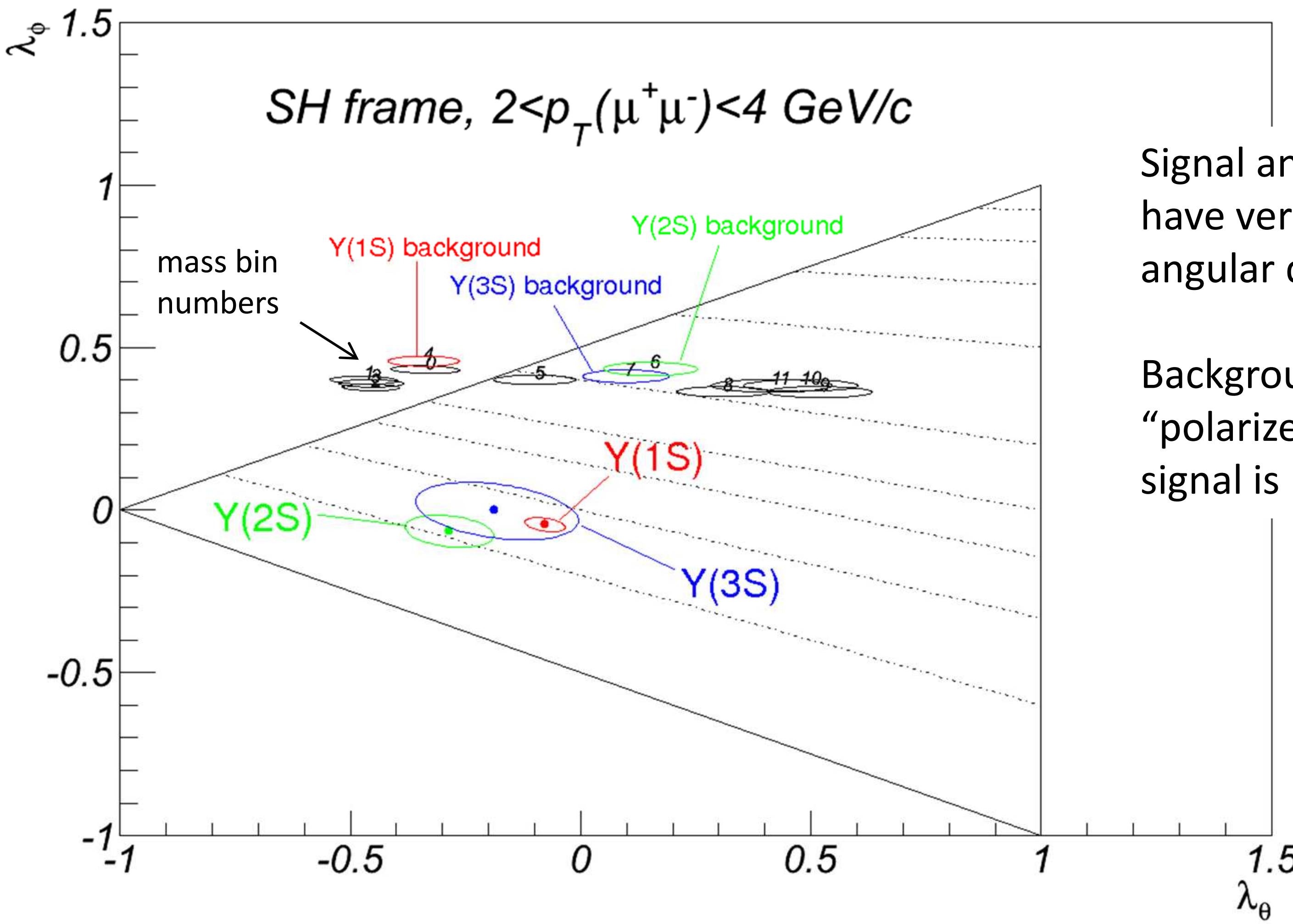


Only background

Signal + background

- The fit provides a good description of the angular distribution in both background and in signal + background mass bins.

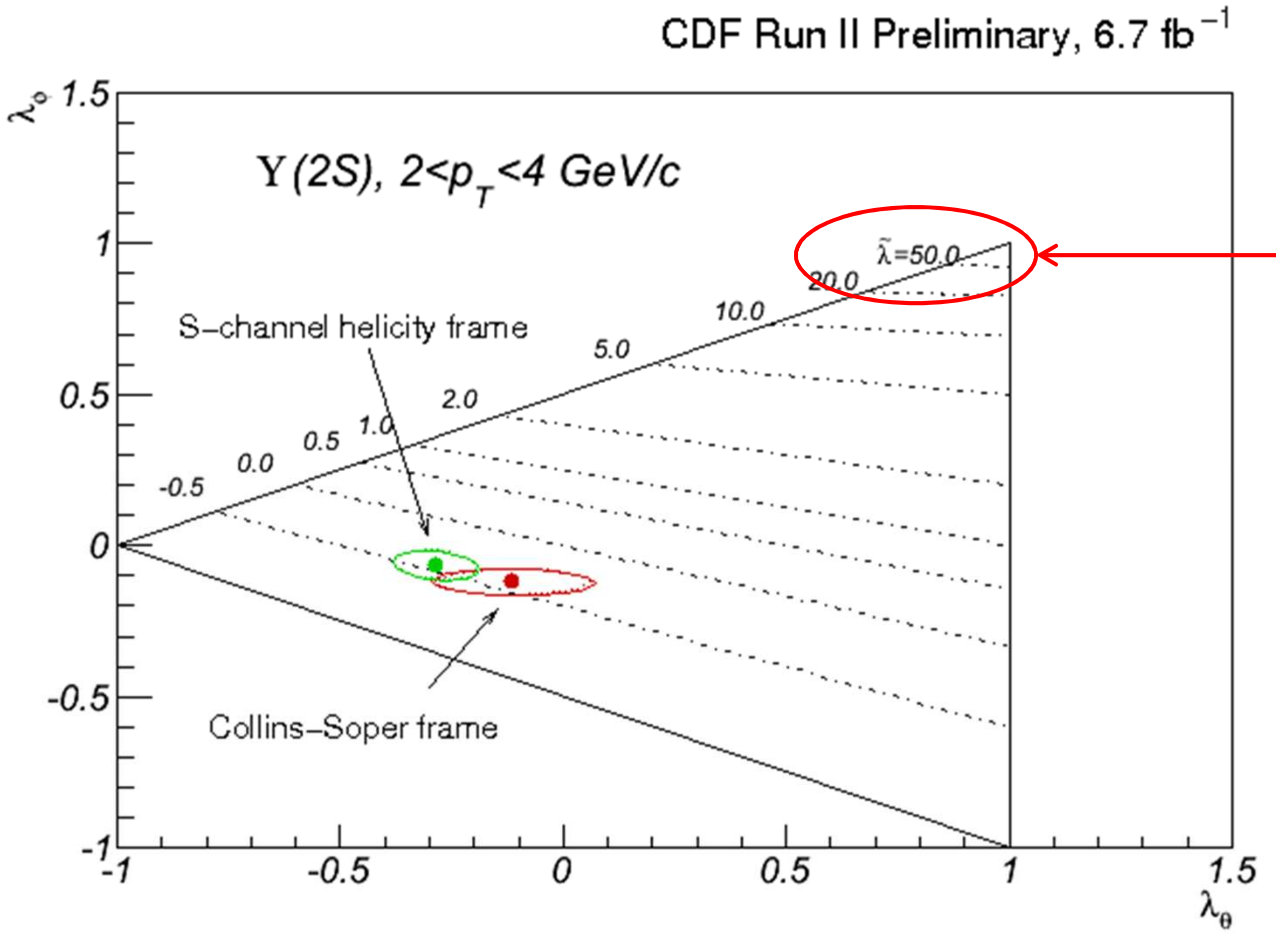
Fitted Parameters



Signal and background have very different angular distributions.

Background is highly "polarized" but the signal is not.

Consistency Tests



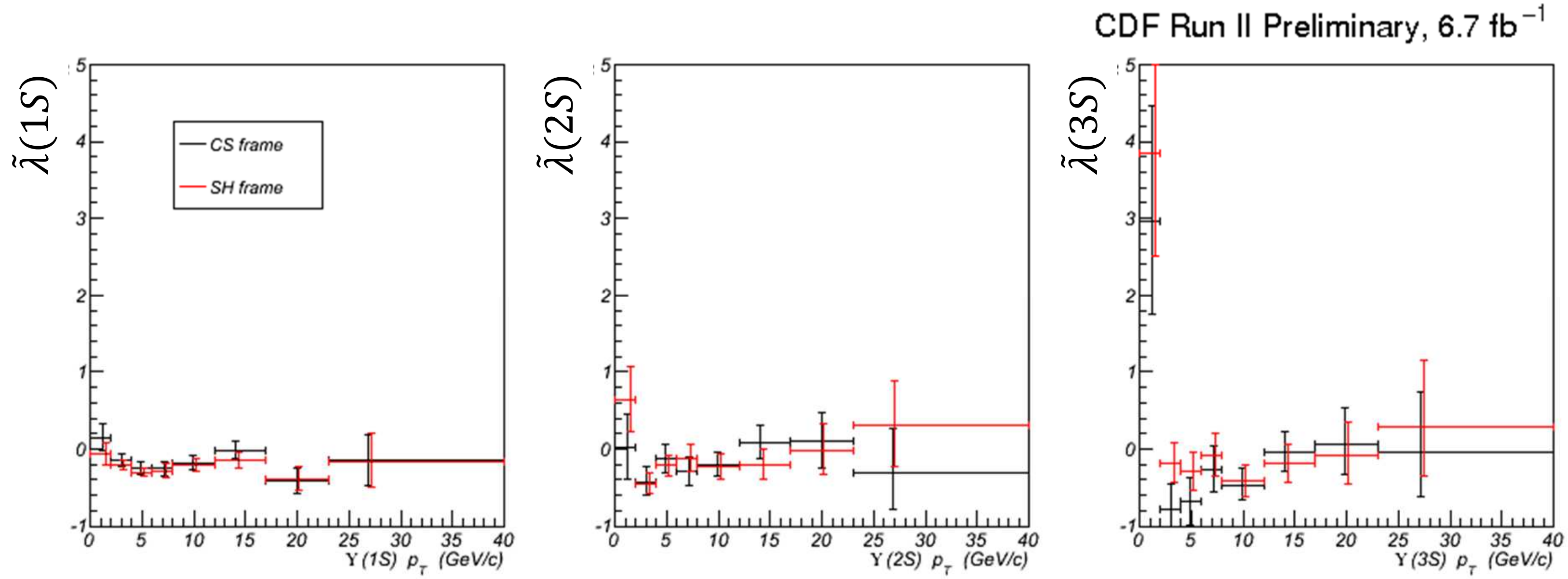
It can be shown that the expression

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

is the same in all reference frames.

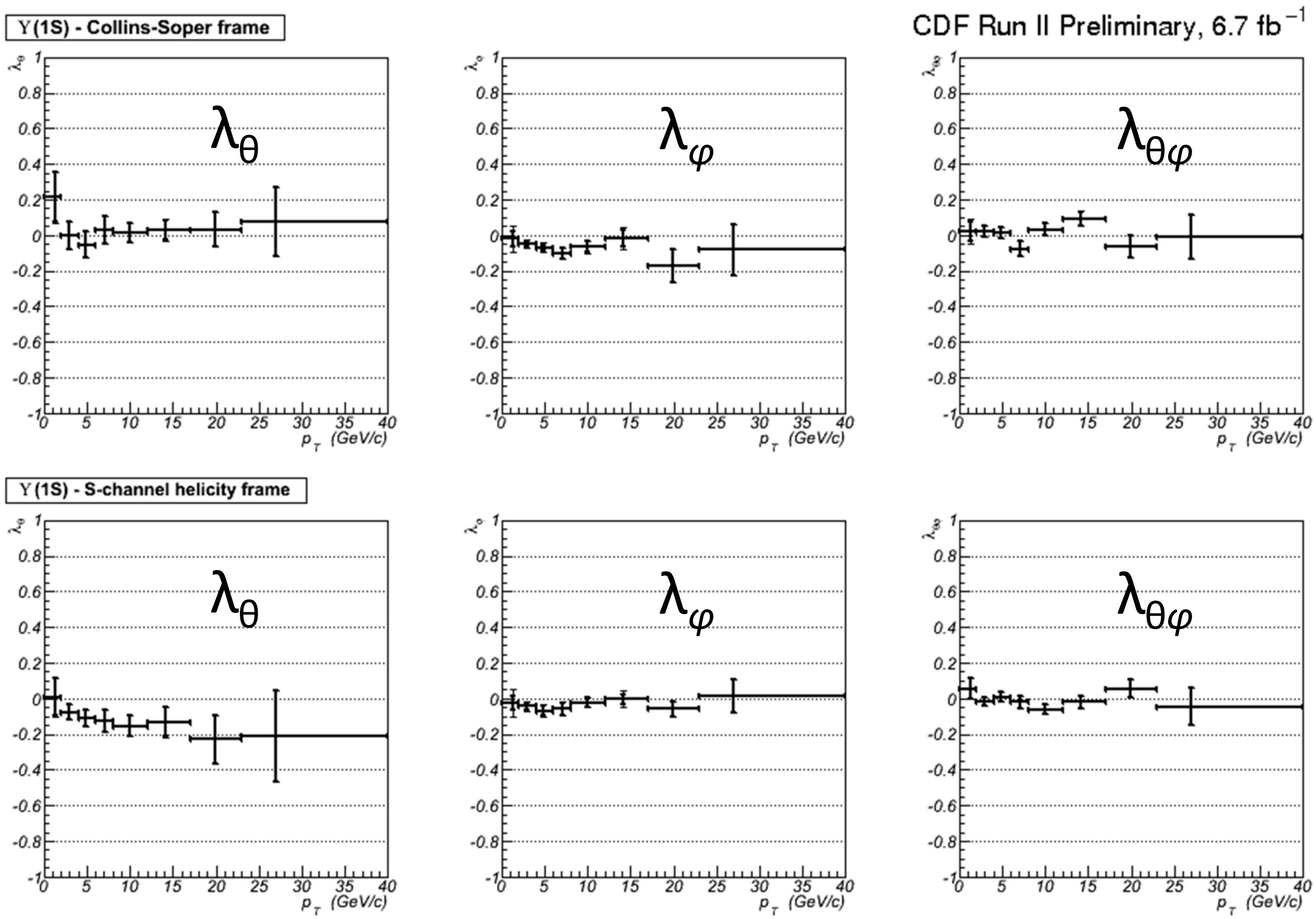
We observe that indeed it is.

Frame Invariance Tests



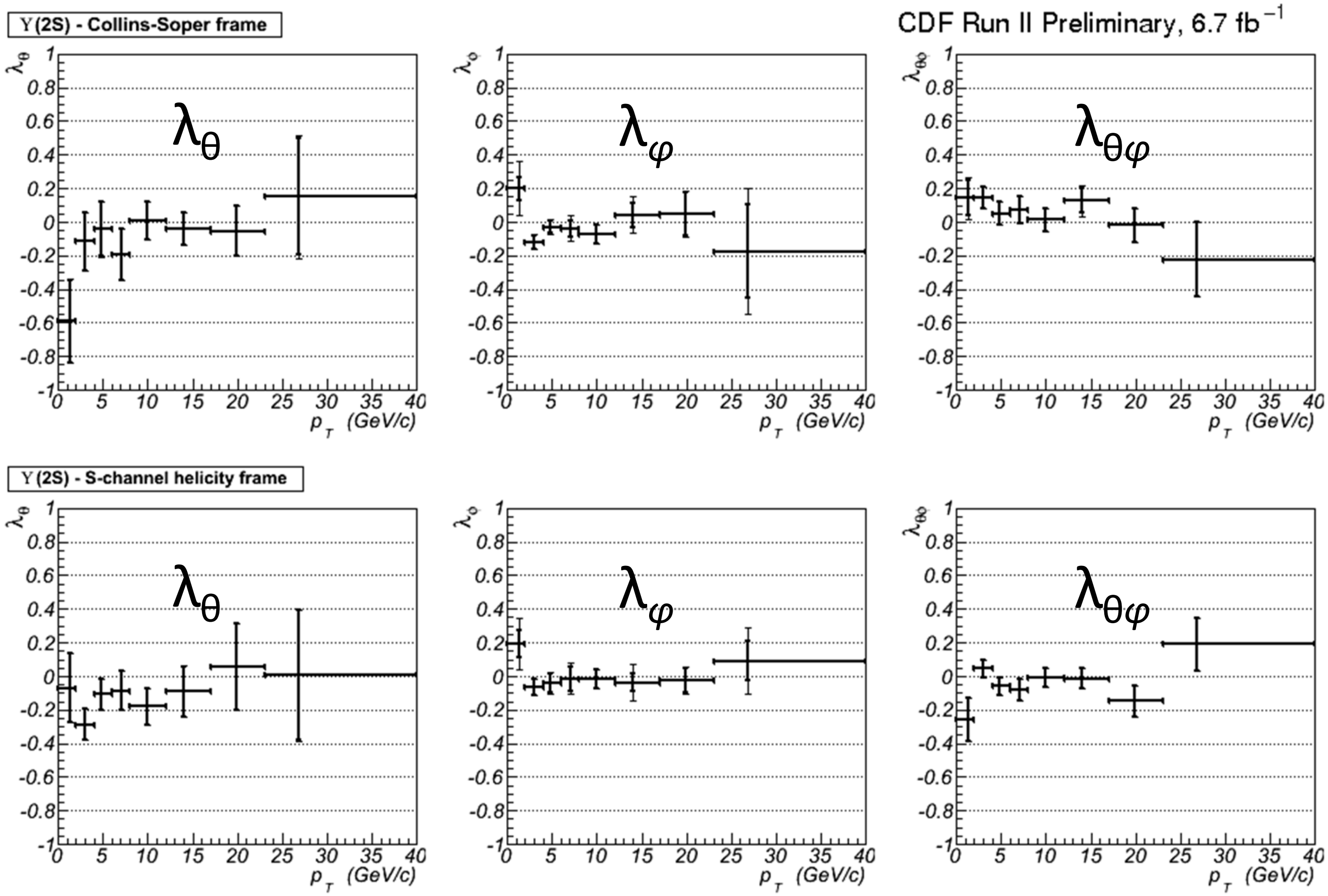
- Differences generally consistent with expected size of statistical fluctuations
- Differences used to quantify systematic uncertainties on λ_θ, λ_φ and $\lambda_{\theta\varphi}$

Results for ϒ(1S) state



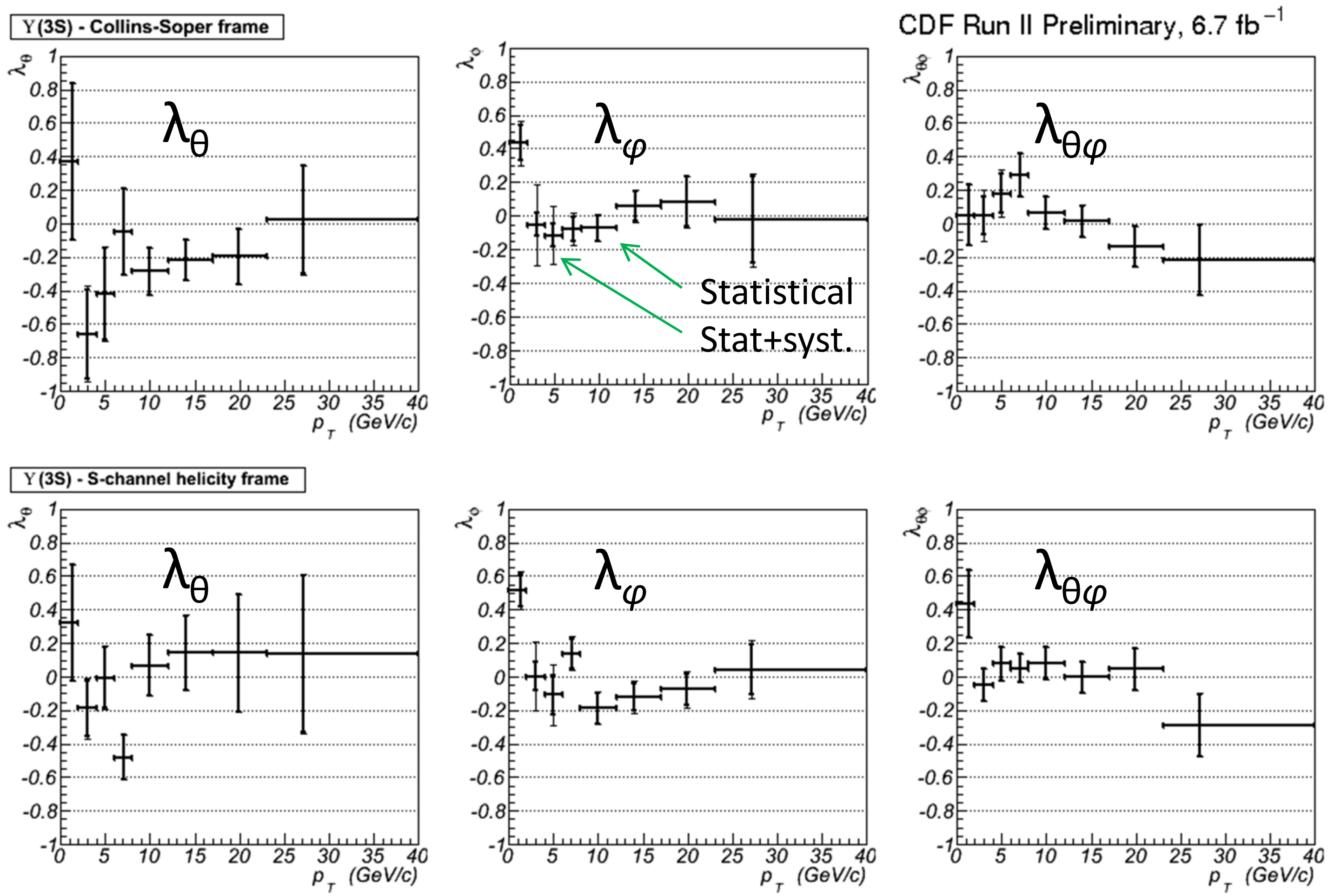
- What about the ϒ(2S) and ϒ(3S) states?

Results for Υ(2S) state



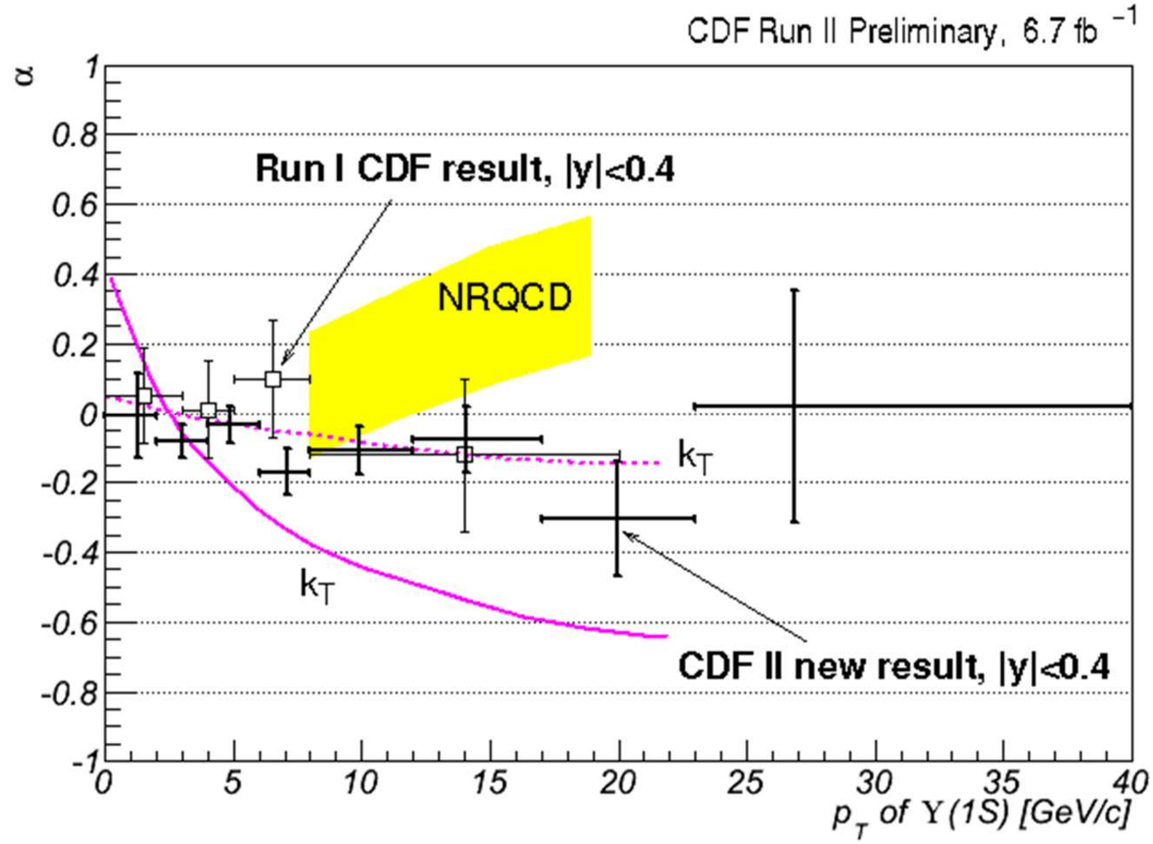
- Looks quite isotropic, even at high p_T…

First measurement of ϒ(3S) spin alignment



- No evidence for significant polarization.

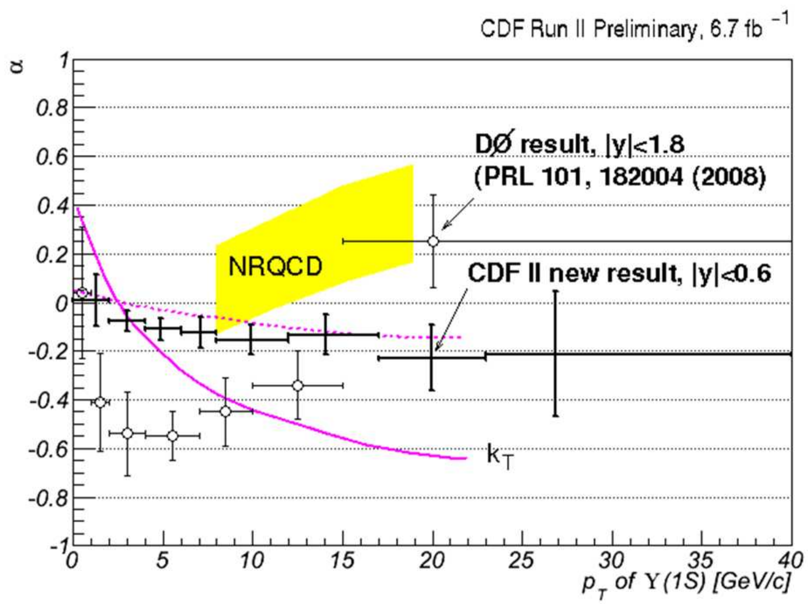
Comparison with previous results

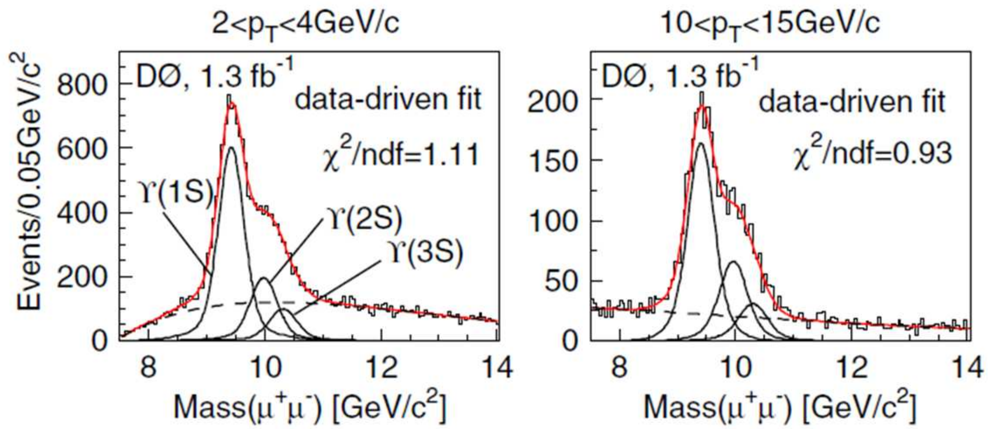


NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)

Agrees with previous CDF publication from Run I

Comparison with previous results





NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)

- Does not agree with result from DØ at the 4.5σ level
  - Different rapidity coverage?
  - Subtraction of highly polarized background?

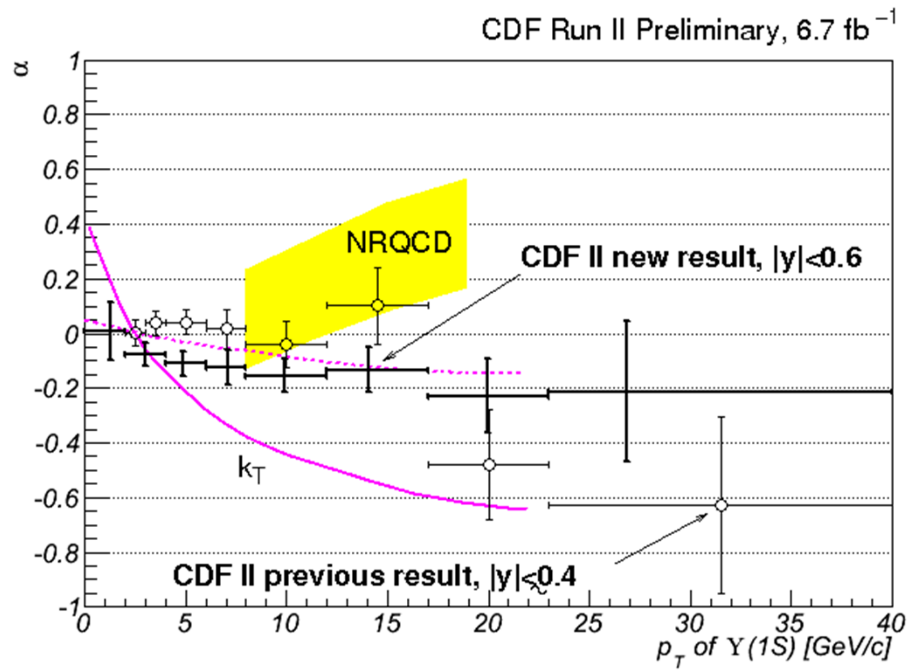
Summary

- First complete measurement of angular distribution of ϒ(nS) decays at a hadron collider.
- First analysis of any aspect angular distributions of ϒ(3S) decays.
- First demonstration of consistency in two reference frames
- ***No evidence for significant polarization***
  - ***Even for the highest p_T bins***
  - ***Even for the ϒ(3S)***

Additional Material

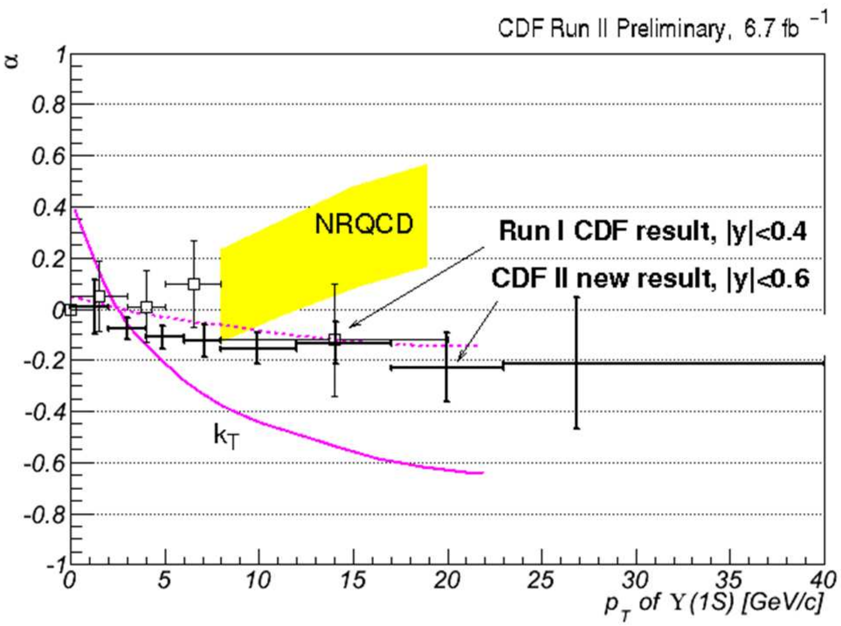
Comparison with Preliminary CDF II Result

- CDF Released a preliminary result based on 2.9 fb^{-1} in 2009

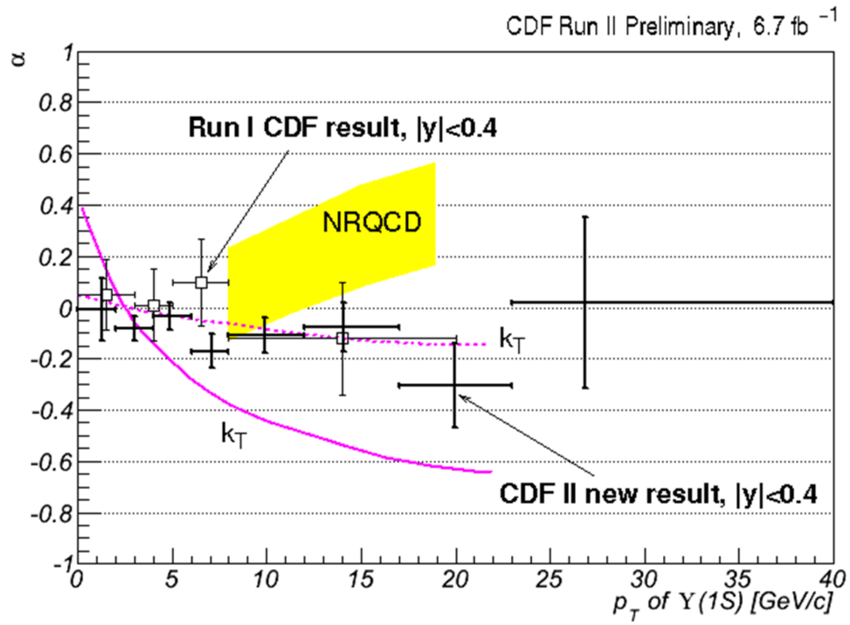


- Measurements are inconsistent.
- We investigated and have understood some potential sources of bias:
  - modeling ϒ resonance line shape, acceptance calculation
  - we now know that the background is highly "polarized" and any misestimate can introduce a significant bias
- *Superseded by new result which by design is less sensitive to these issues and provides assumption-free tests of internal consistency, based only on data.*

Comparison with CDF Run I result



$\chi^2/dof \sim 2.1/4$

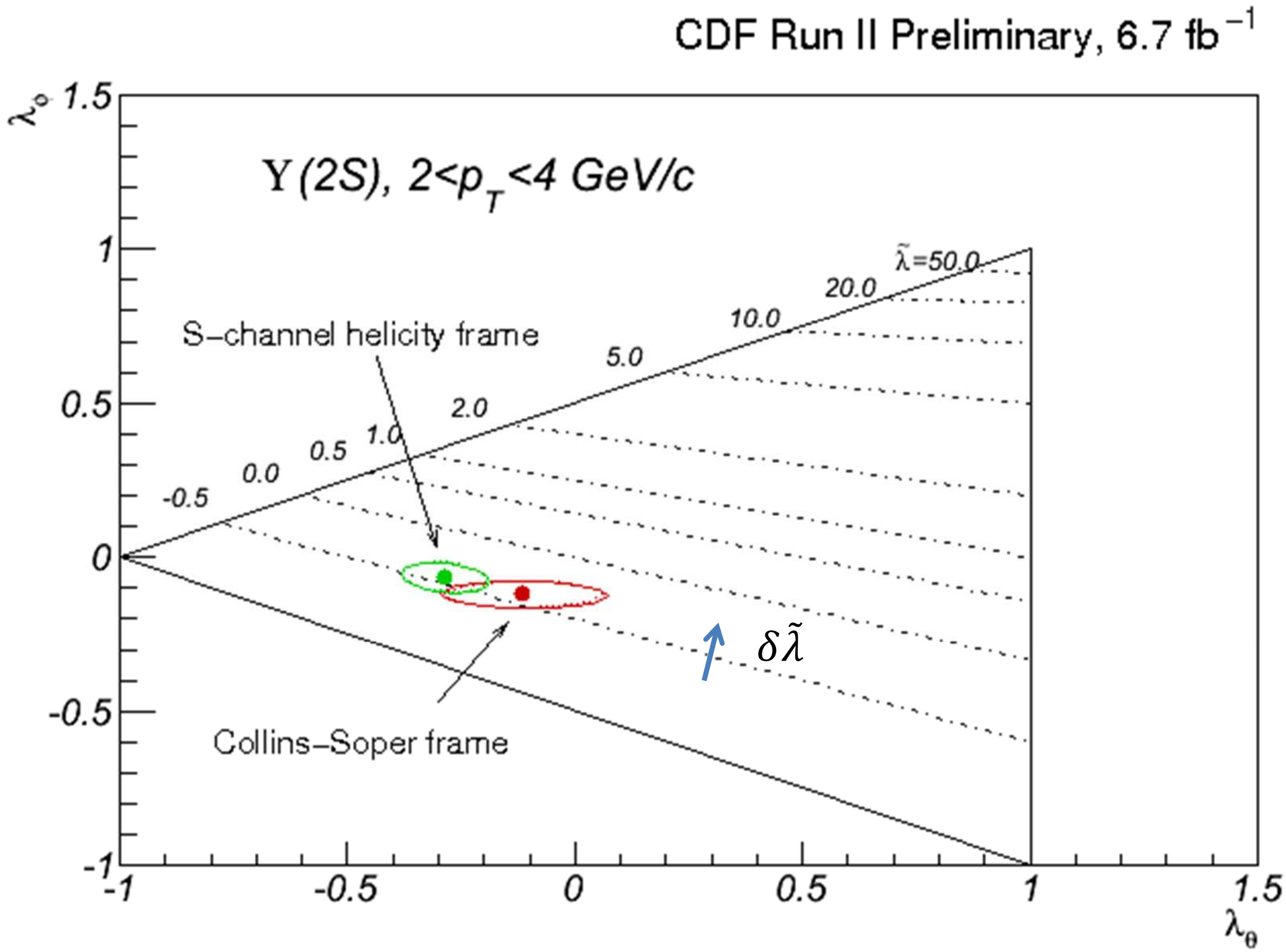


$\chi^2/dof \sim 2.0/4$

NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)

No significant difference between |y|<0.4 and |y|<0.6

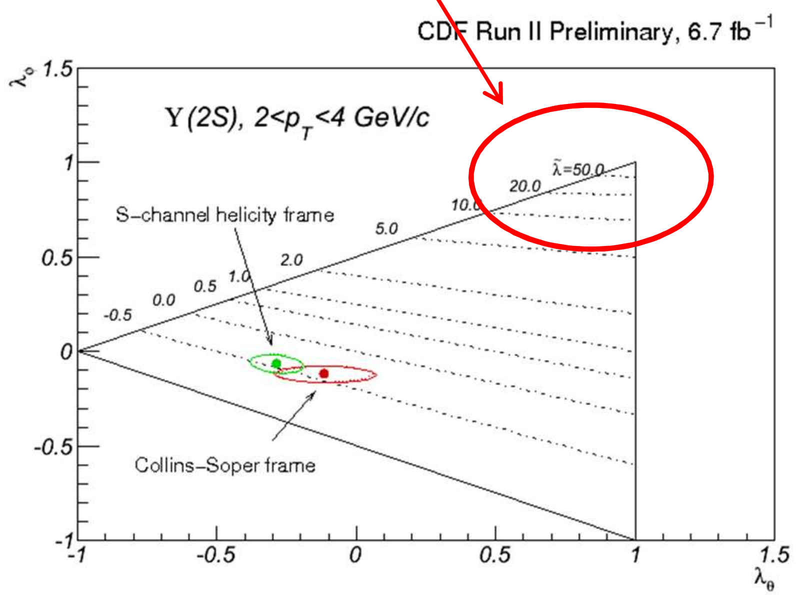
Frame Dependent Systematics

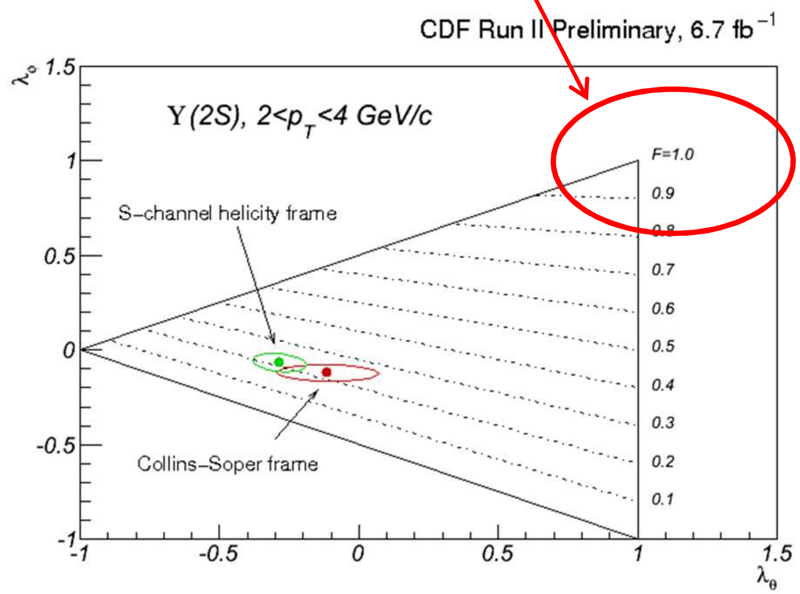


Other Rotational Invariants

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

$$\mathcal{F} = \frac{1+\lambda_\theta+2\lambda_\varphi}{3+\lambda_\theta}$$





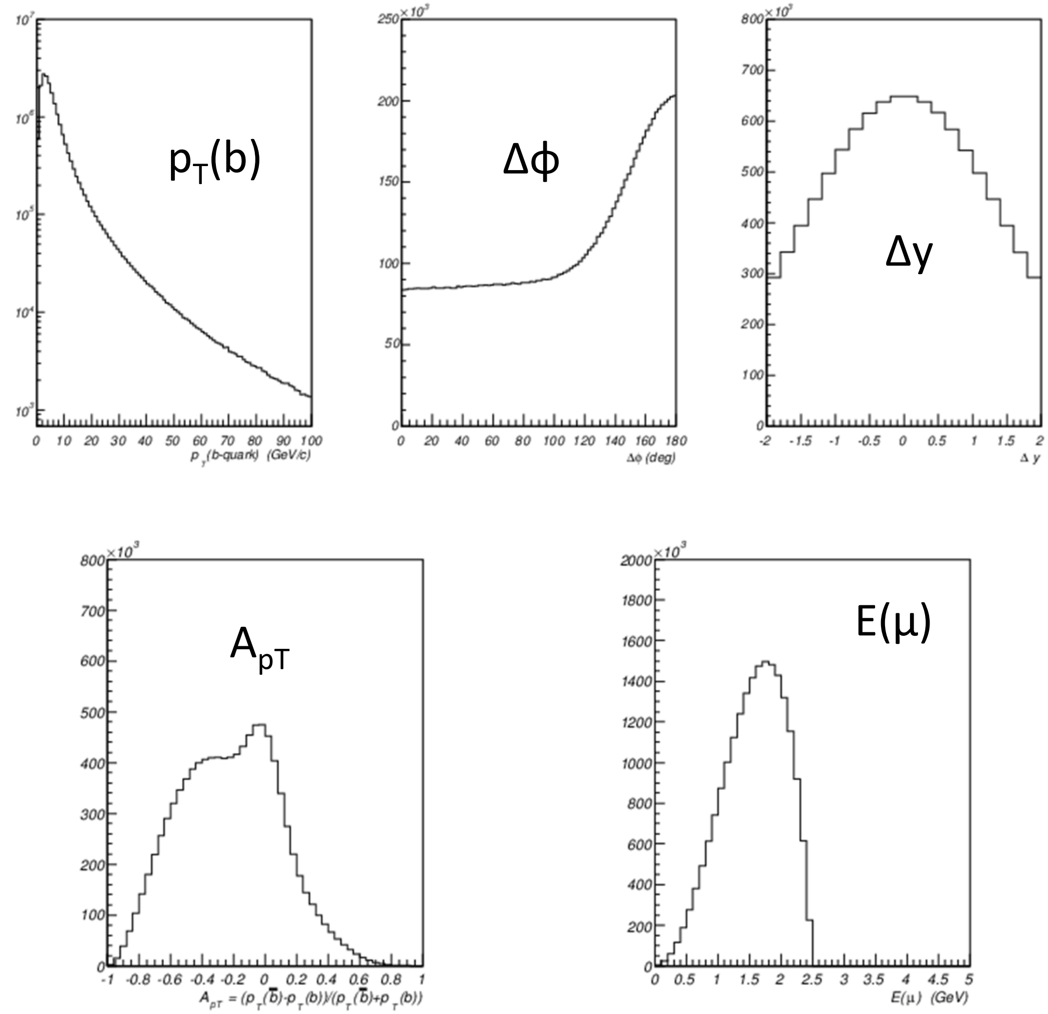
$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi} = \frac{4}{1 + |a_0|^2 - a_1{}^* a_{-1} - a_{-1}{}^* a_1} - 3$$

This is the part that is invariant under rotations.

Toy Monte Carlo for correlated $b\bar{b}$ production

Phys. Rev. D65, 094006 (2002): R.D. Field, *"The sources of b-quarks at the Tevatron and their Correlations".*

- p_T of the b-quark
- $\Delta\phi$ between b-quarks
- Δy between b-quarks
- p_T asymmetry
- E(μ) in B rest frame
- Peterson fragmentation
- Boost muons into lab frame
- Full detector simulation and event reconstruction
- Same analysis cuts applied to data



The Tevatron: a Quarkonium factory

- 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). $(\chi_{bJ}(nP) \rightarrow \Upsilon(1S)\gamma)$
  - Phys. Rev. Lett. 88, 161802 (2002). (ϒ(ns) cross section and polarization)