Heavy Quark Production at CDF

Results, both Recent and New

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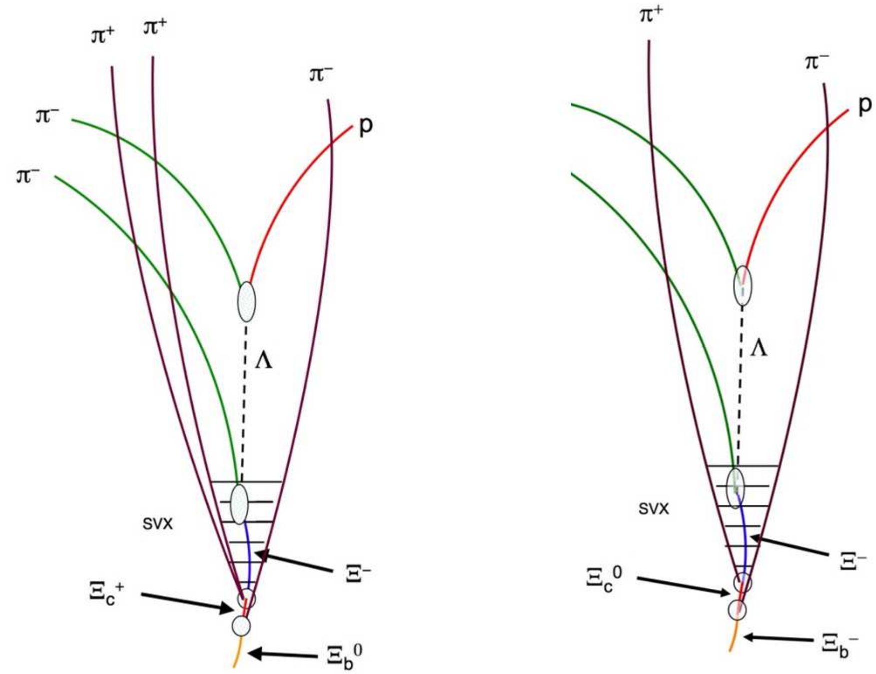
Recent Result: Observation of the Ξ_b^0 baryon

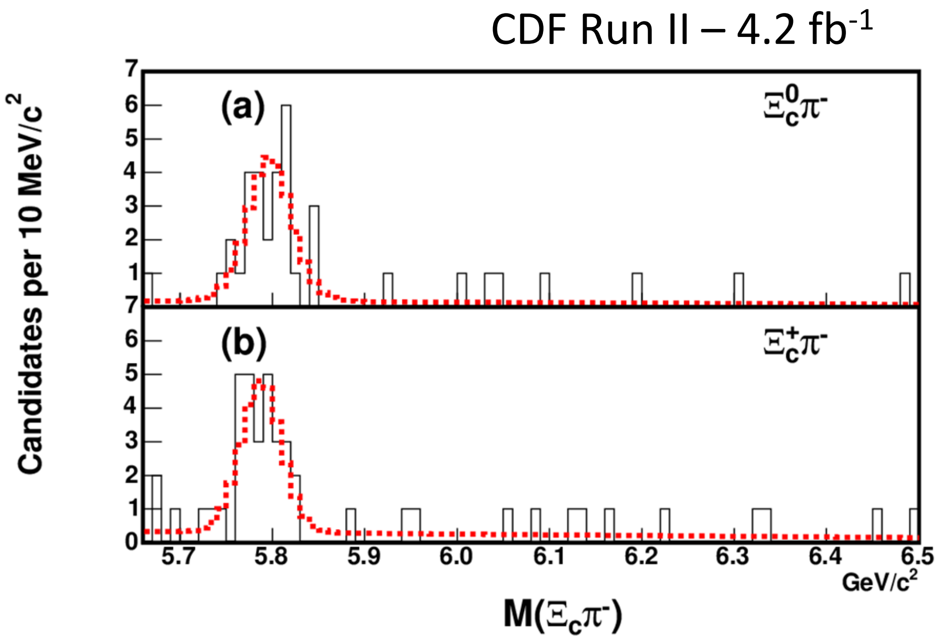
Unlike previous b-baryon observations, the Ξ_b^0 cannot be reconstructed using $\Xi_b^0 \to J/\psi\ \Xi^0$ because $\Xi^0 \to \Lambda\pi^0$.

Instead, search for the all-hadronic decays…



- Charged pions satisfy CDF's displaced track trigger
- Reconstruct the hadronic decays:
  - $\Xi_b{}^- \to \Xi_c{}^0\pi^-, \Xi_c{}^0 \to \Xi^-\pi^+$ (Previously seen in $\Xi_b{}^- \to J/\psi\Xi^-$)
  - $\Xi_b{}^0 \to \Xi_c{}^+\pi^-, \Xi_c{}^+ \to \Xi^-\pi^+\pi^+$ ***(New!)***

Observation of Ξ_b states in 4.2 fb^{-1}



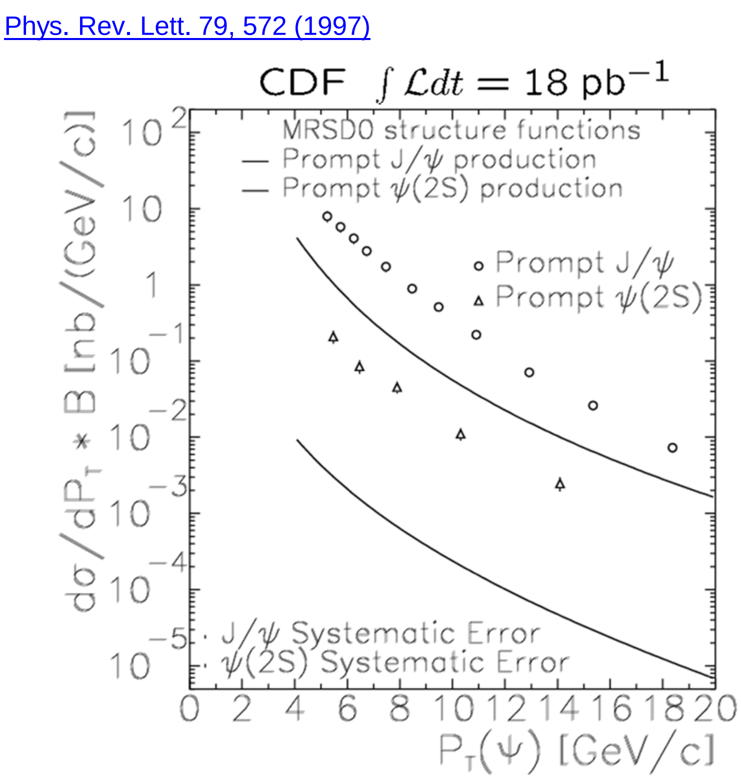
Signal	Candidates	Mass (MeV/c^2)
Ξ_b^-	$25.8^{+5.5}_{-5.2}$	5796.7±5.1±1.4
Ξ_b^0	$25.3^{+5.6}_{-5.4}$	5787.8±5.0±1.3

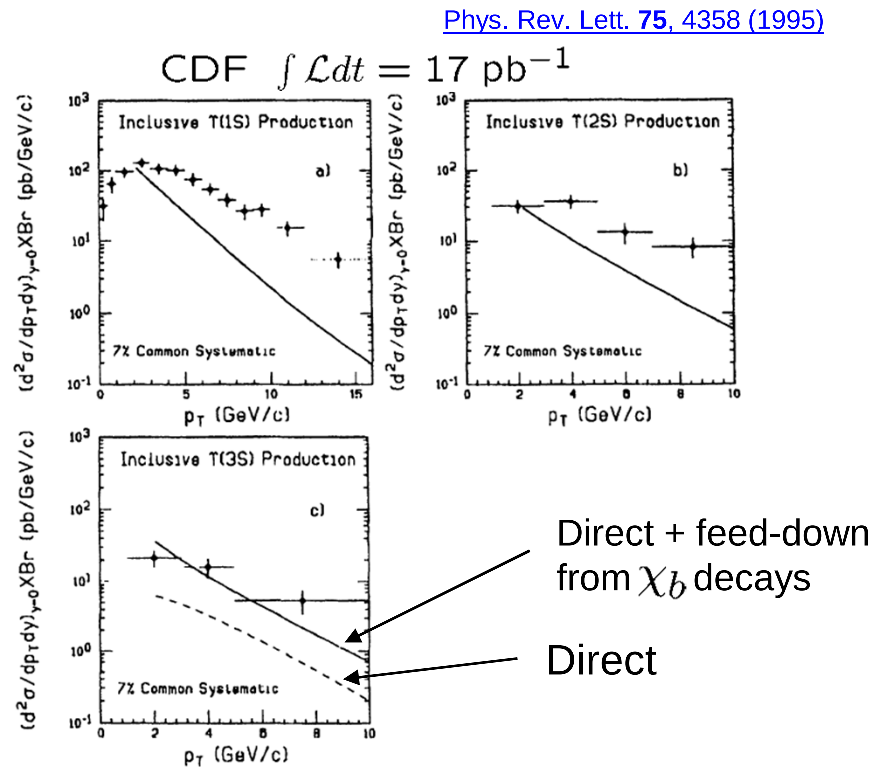
Submitted in July, 2011...
published in August:

Phys. Rev. Lett. **107**, 102001 (2011)

- First observation of either decay channel – 6.8σ significance
- Dedicated hyperon tracking in silicon detector
- In agreement with more precise measurement of $m(\Xi_b^-) = 5790.9 \pm 2.6 \pm 0.8\ MeV/c^2$ from $\Xi_b^- \rightarrow J/\psi\Xi^-$

Some very old results…

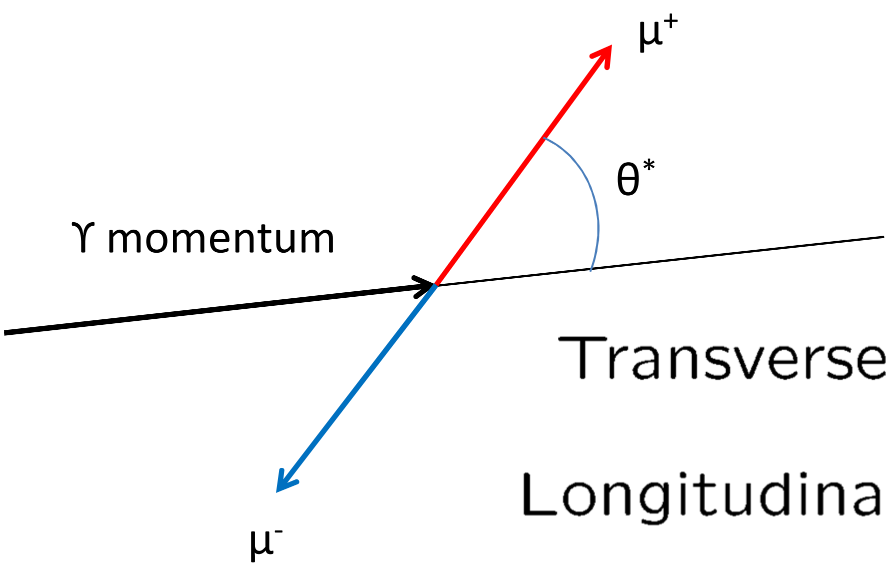




- Prompt J/ψ and ϒ cross sections much larger than expected…
  - color-singlet vs color-octet production mechanisms
    - ***Polarization measurements***

Upsilon "Polarization"

- A better term is *spin alignment*…
  - *Transverse* polarization: $|J,\lambda\rangle = |1,\pm1\rangle$
  - *Longitudinal* polarization: $|J,\lambda\rangle = |1,0\rangle$



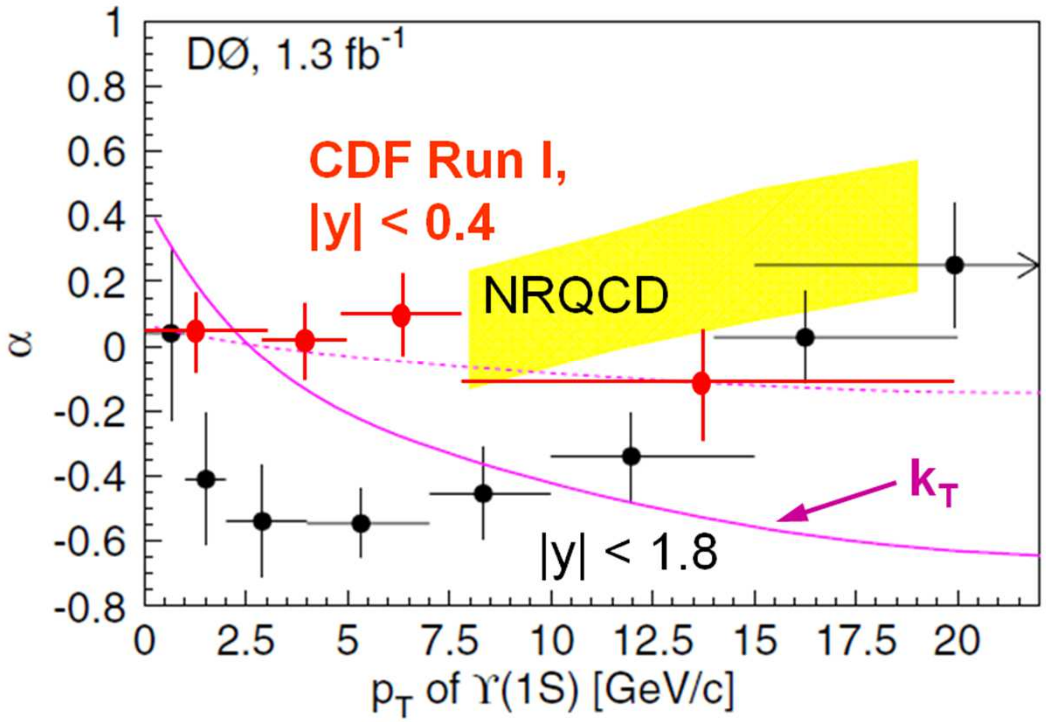
$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \alpha\cos^2\theta^*$$

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

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

(this is called the s-channel helicity frame)

Recent 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)

- Newer NLO calculations show similar trends:

  NLO NRQCD – Gong, Wang & Zhang, Phys. Rev. D83, 114021 (2011)

  Color singlet NNLO* - Artoisenent, *et al.* Phys. Rev. Lett. 101, 152001 (2008)

New (old) analysis paradigm

- The current situation is unsatisfactory... are we missing something obvious? Pietro Faccioli emphasizes basic quantum mechanics...
- Back to the fundamentals:

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

$$\lambda_\theta = \frac{\rho_{11} - \rho_{00}}{\rho_{11} + \rho_{00}} \quad \lambda_\varphi = \frac{\rho_{10}}{\rho_{11} + \rho_{00}} \quad \lambda_{\theta\varphi} = \frac{\rho_{1,-1}}{\rho_{11} + \rho_{00}}$$

- Un-polarized only when λ_θ, λ_φ and $\lambda_{\theta\varphi}$ are *all* zero.
- Compare rotational invariant $\tilde{\lambda} = (\lambda_\theta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$ in different reference frames:

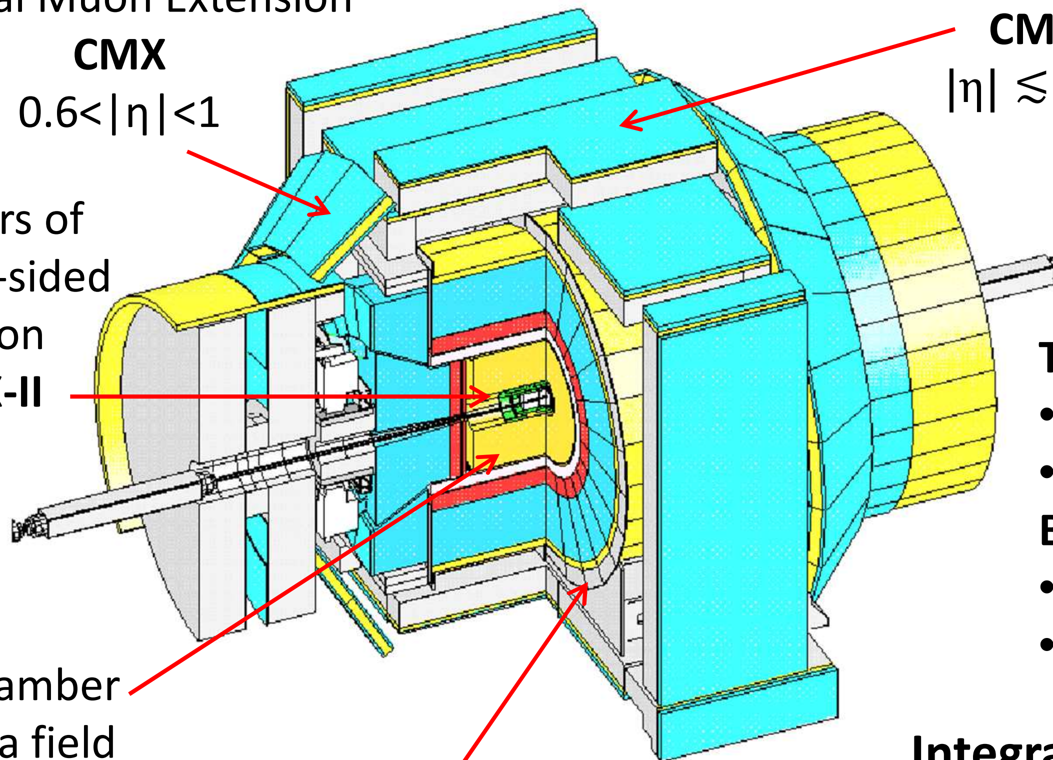
s-channel helicity frame *and* Collins-Soper frame

New CDF Analysis – 6.7 fb^{-1}

- 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 $\lambda_{\theta\varphi}$
  - Provide first measurements on the Υ(3S) state
- Concerns based on past experience at CDF:
  - Minimize sensitivity to modeling the Υ(nS) resonance line shape
  - Explicit measurement of angular distribution of dimuon background

Public note: CDF/PUB/BOTTOM/PUBLIC/10665

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)

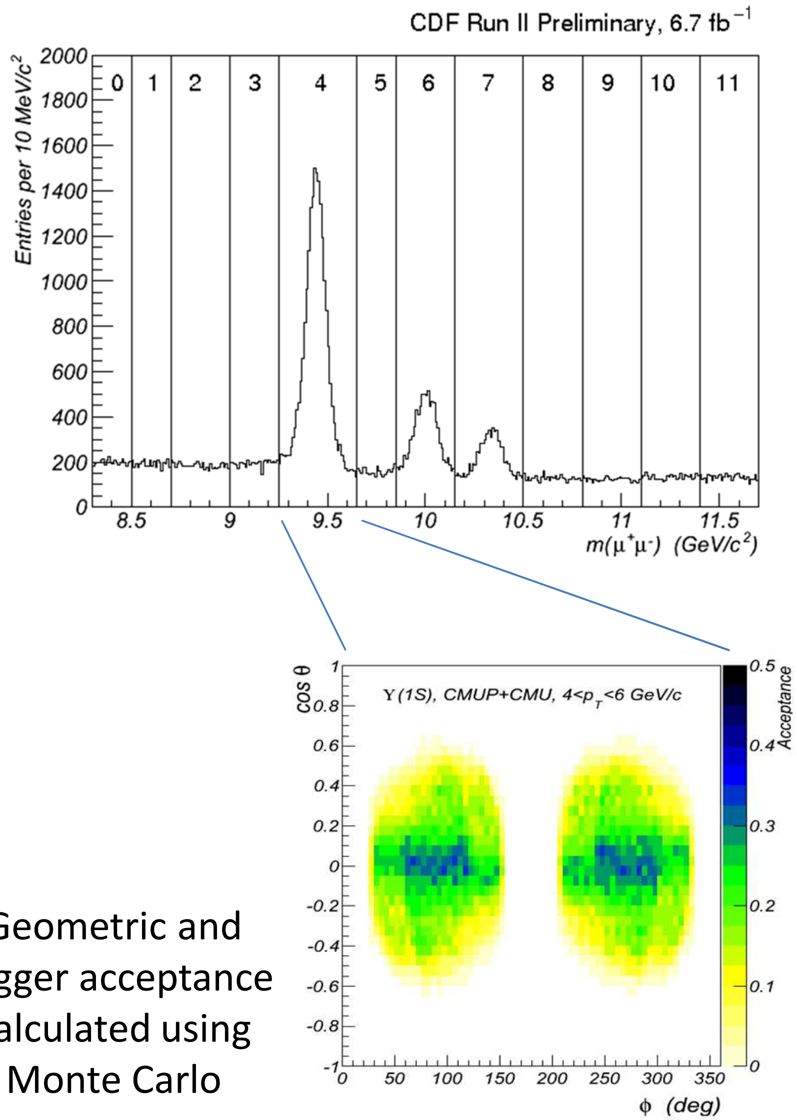
Analysis Method

- Reconstruct $\mu^+\mu^-$ candidates, boost into rest frame, calculate decay angles ($\cos\theta,\varphi$)
- Observed distribution depends on acceptance and the underlying angular distribution:

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

  – $A(\cos\theta,\varphi)$ from high statistics Monte Carlo
  – $w(\cos\theta,\varphi;\lambda_\theta, \lambda_\varphi,\lambda_{\theta\varphi})$ from angular distribution formula
- Performed binned likelihood fit to observed distribution of ($\cos\theta,\varphi$) to determine λ_θ, λ_φ,$\lambda_{\theta\varphi}$.
- But there is background…

Analysis Method



Geometric and trigger acceptance calculated using Monte Carlo

- Both signal and background are present
- Conceptual problem:

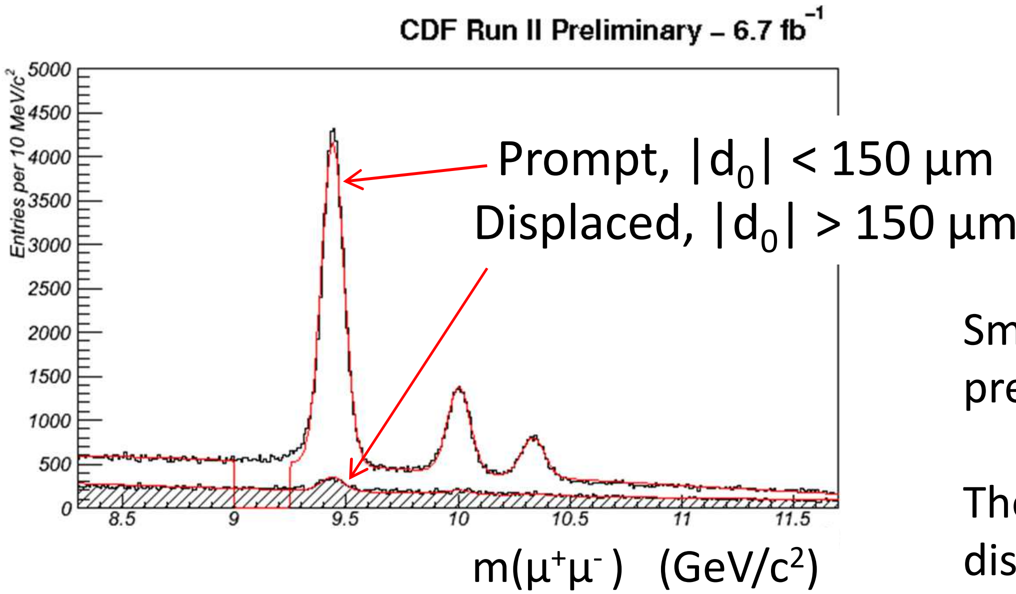
$$\bar{\lambda} = f_s \lambda_s + (1 - f_s)\lambda_b$$

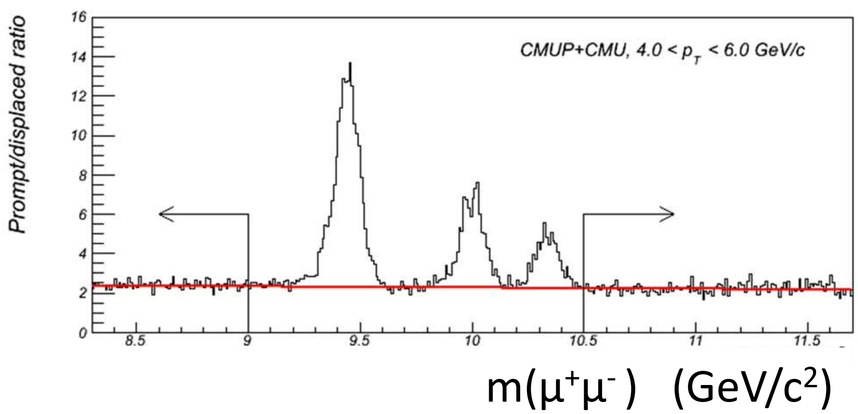
- Signal fraction obtained from fit to mass distribution
- How to constrain angular distribution of the background?
- Side-band extrapolation?
  - Does it vary smoothly enough?
  - Probably not…

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:
  - Require (at least) one muon to have $|d_0| > 150$ μm
- Fit to displaced sample + prompt sidebands:
  - Measures ratio of prompt/displaced backgrounds
  - Scale displaced sample to predict background level under the ϒ(nS)
- Two component fit to $(\cos\theta, \varphi)$ distribution
  - Determines λ_θ, λ_φ, $\lambda_{\theta\varphi}$ for signal and background
  - Background parameterization is purely emperical; an additional $\cos^4\theta$ term is helpful

Background Proxy Sample





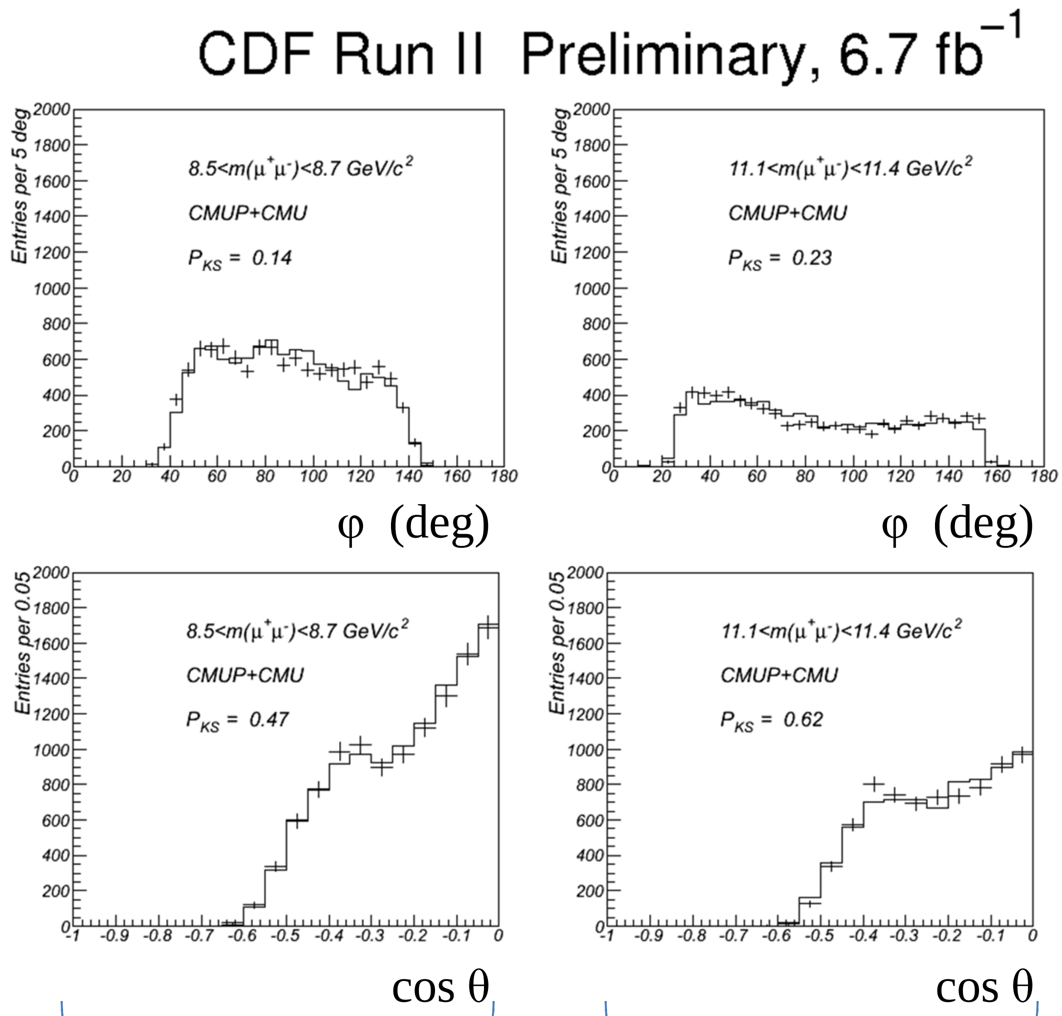
Small fraction of the ϒ signal is still present in the displaced sample (1-4%)

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

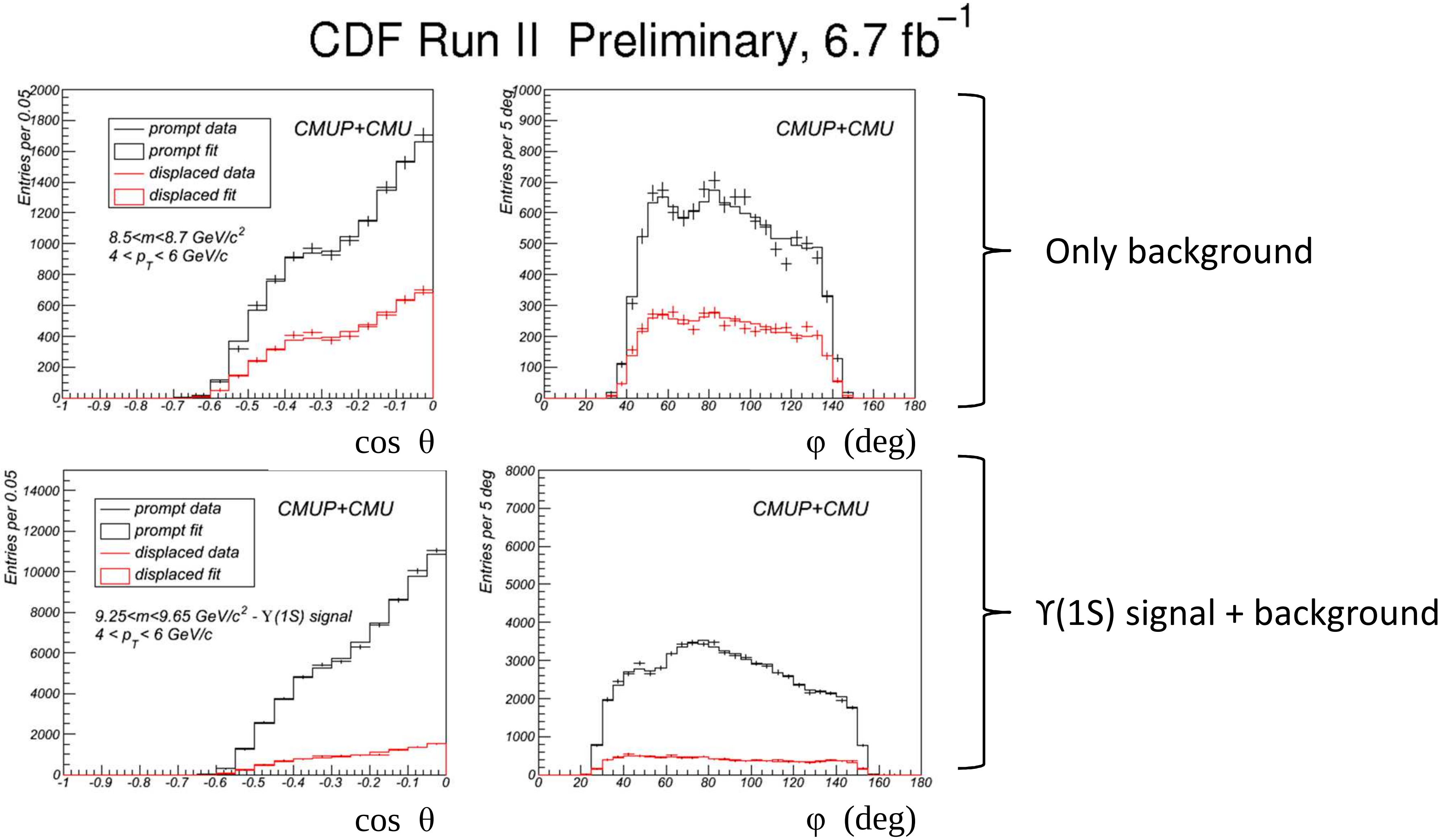


Low-mass sideband

High-mass sideband

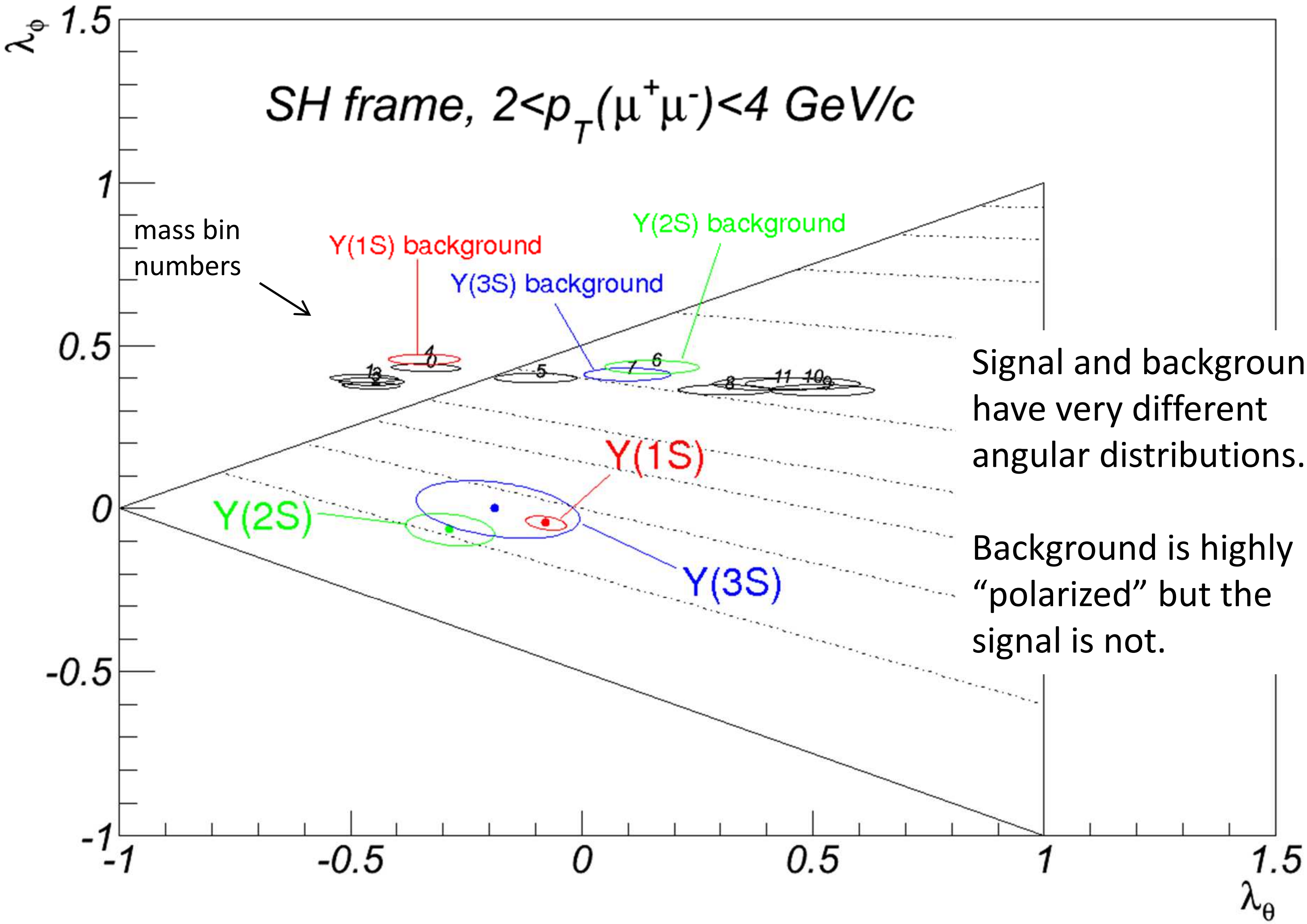
- The sub-sample containing a displaced track ($|d_0| > 150$ μm) is a good description of the background under the ϒ(nS):
- Prompt (histogram) and displaced (error bars) angular distributions match in the sidebands.
- We use the displaced muon sample to constrain the angular distribution of background under the ϒ(nS) peaks.

Fits to signal + background



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

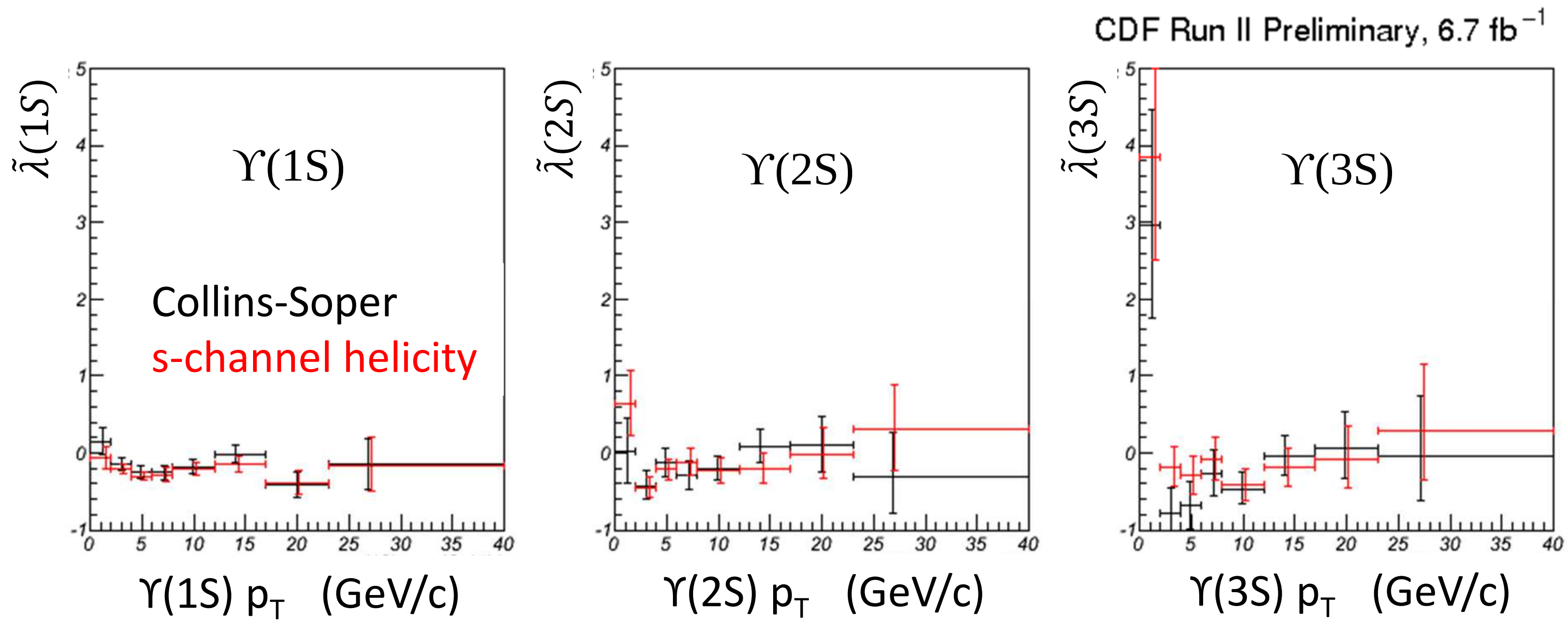
Fitted Parameters



Signal and background have very different angular distributions.

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

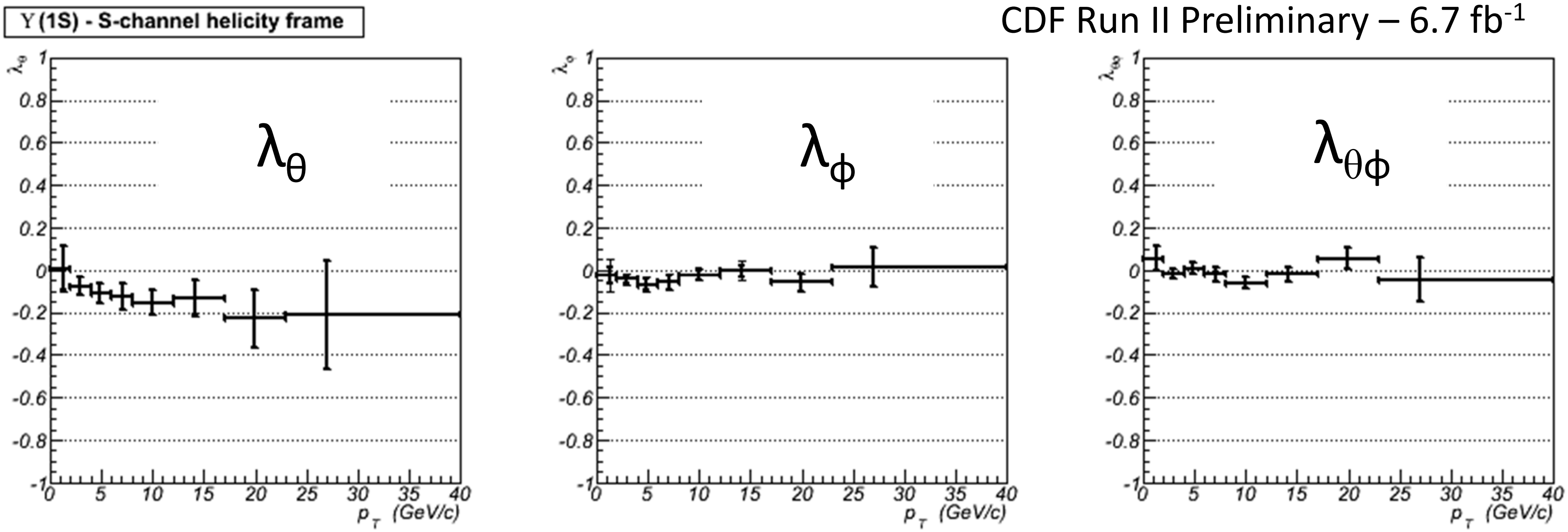
Frame Invariance Tests



- Differences generally consistent with size of statistical fluctuations seen in toy Monte Carlo experiments
- Differences used to quantify systematic uncertainties on λ_θ, λ_φ and $\lambda_{\theta\varphi}$

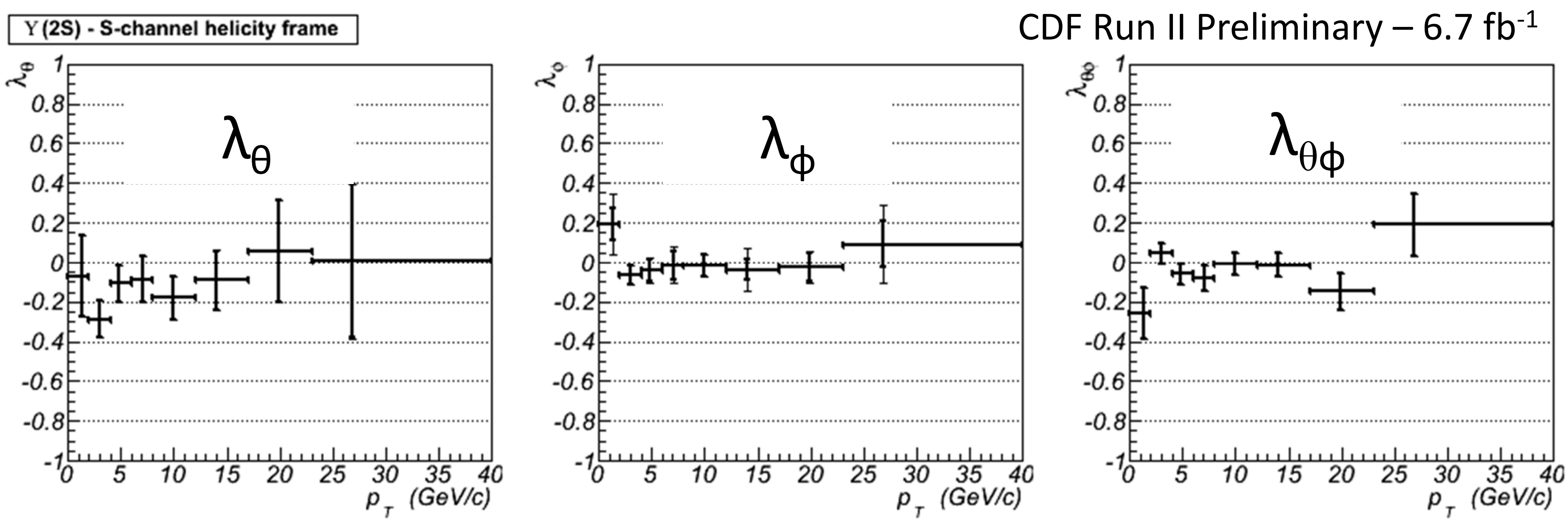
Results for Υ(1S) state

CDF Run II Preliminary – 6.7 fb^{-1}



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

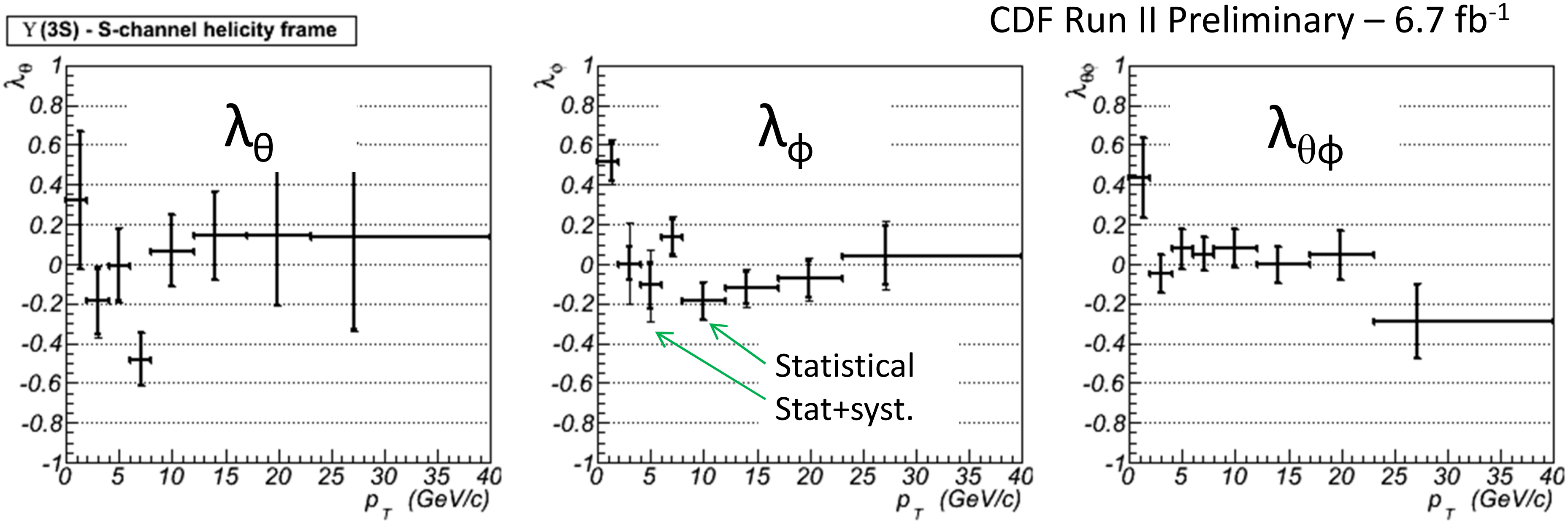
Results for Υ(2S) state



- Looks quite isotropic, even at high p_T…

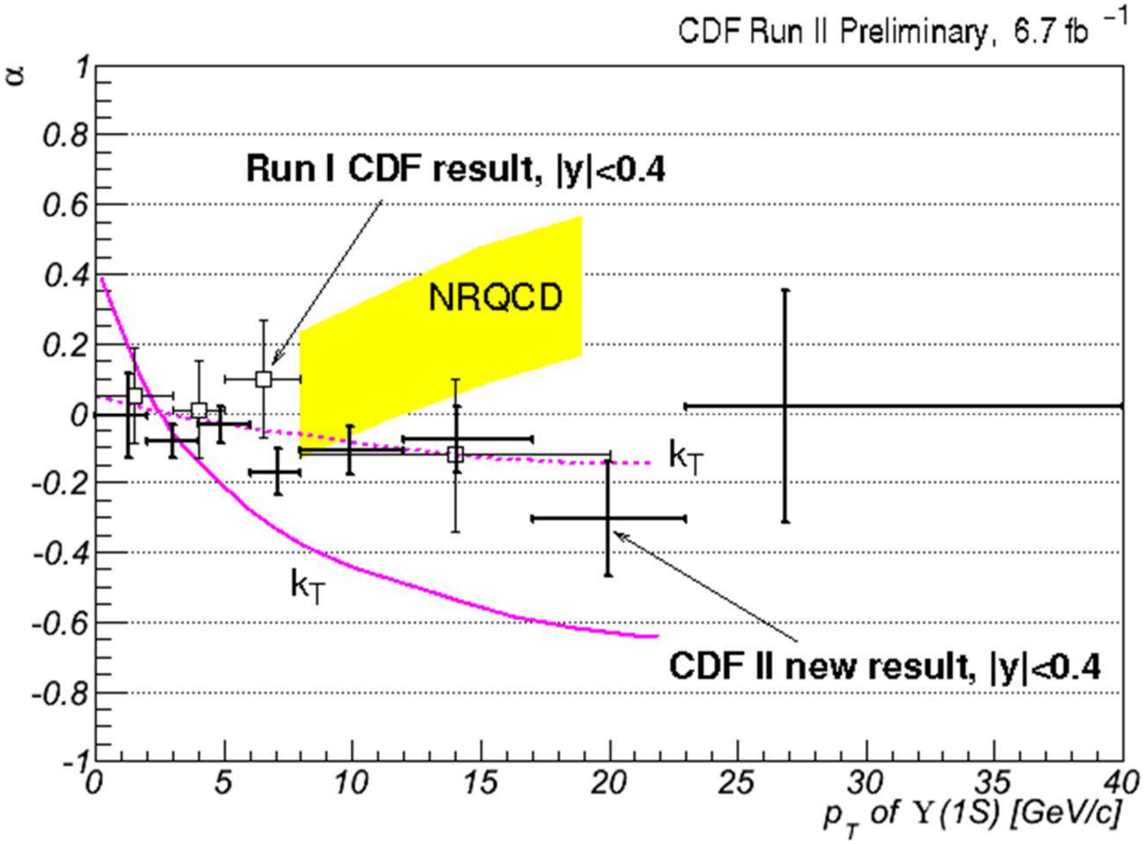
First measurement of Υ(3S) spin alignment

CDF Run II Preliminary – 6.7 fb^{-1}



- No evidence for significant polarization.

Comparison with previous results

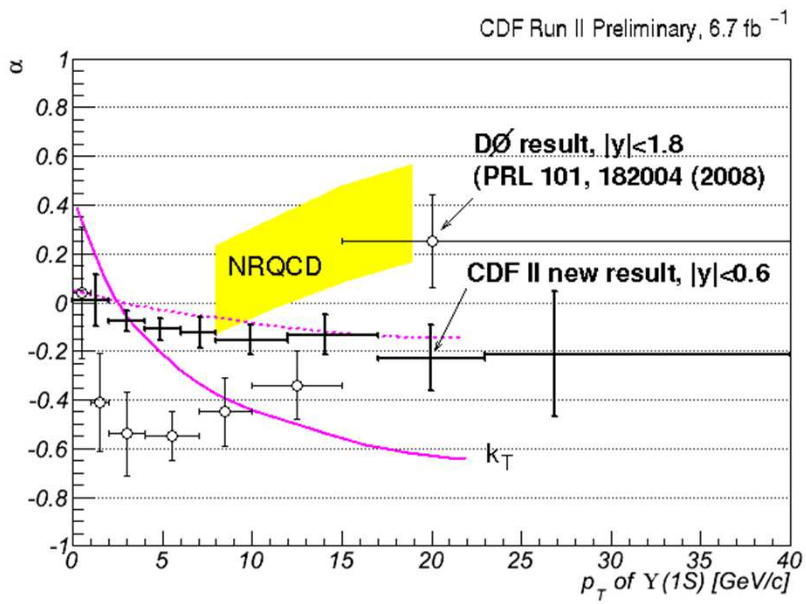


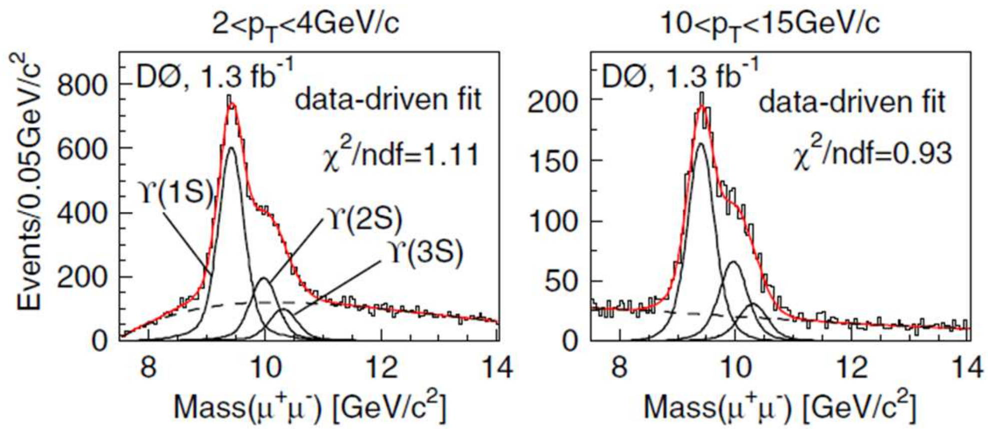
NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)

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

Agrees with previous CDF publication from Run I

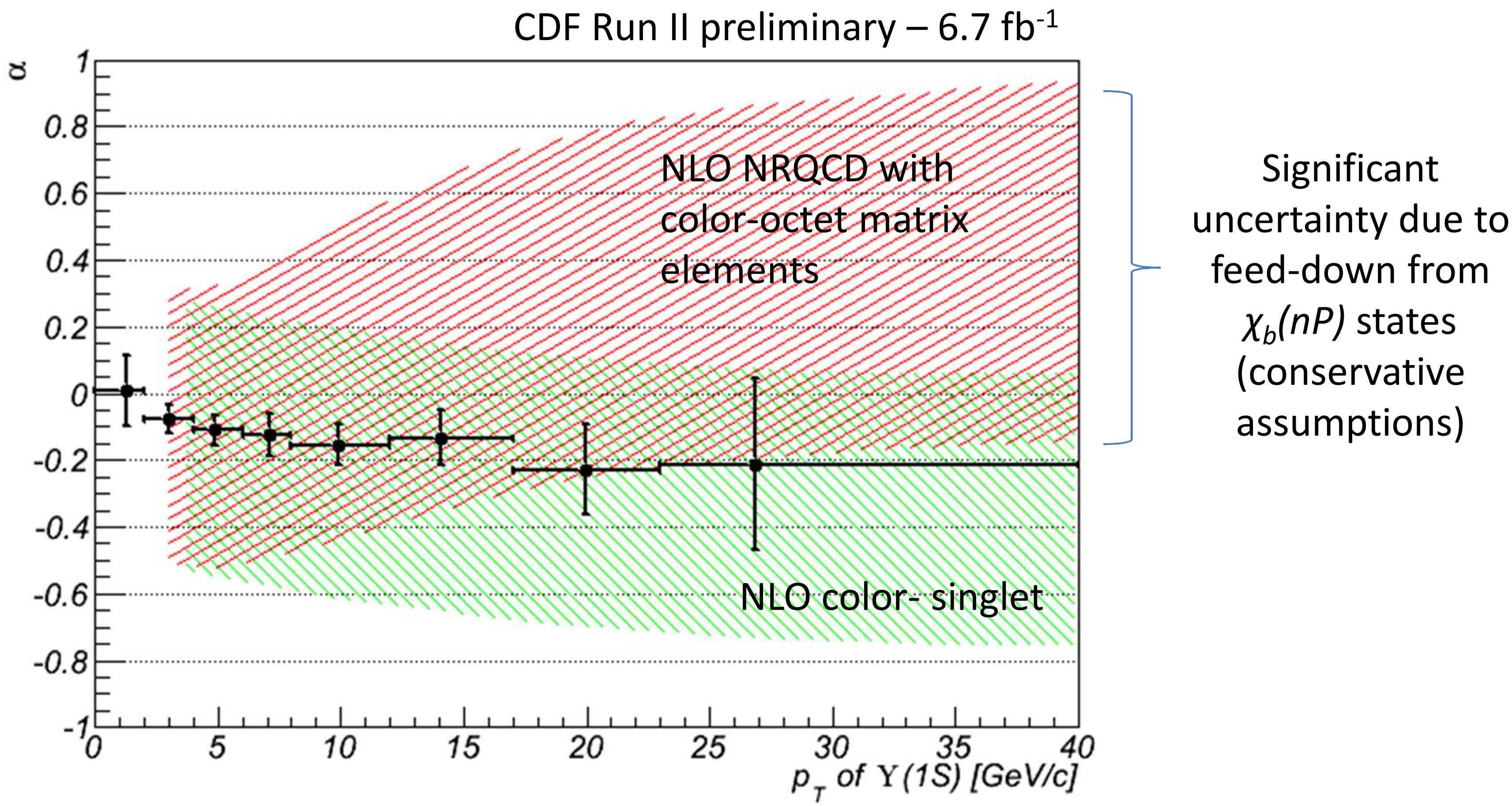
Comparison with previous results





- Does not agree with result from DØ at the 4.5σ level
  - Does the angular distribution evolve rapidly with rapidity?
  - Subtraction of highly polarized background?

Comparisons with newer calculations



Nucl. Phys. B 214, 3 (2011) summary:

- NLO NRQCD – Gong, Wang & Zhang, Phys. Rev. D83, 114021 (2011)
- Color-singlet NLO and NNLO* - Artoisenent, *et al.* Phys. Rev. Lett. 101, 152001 (2008)

Summary

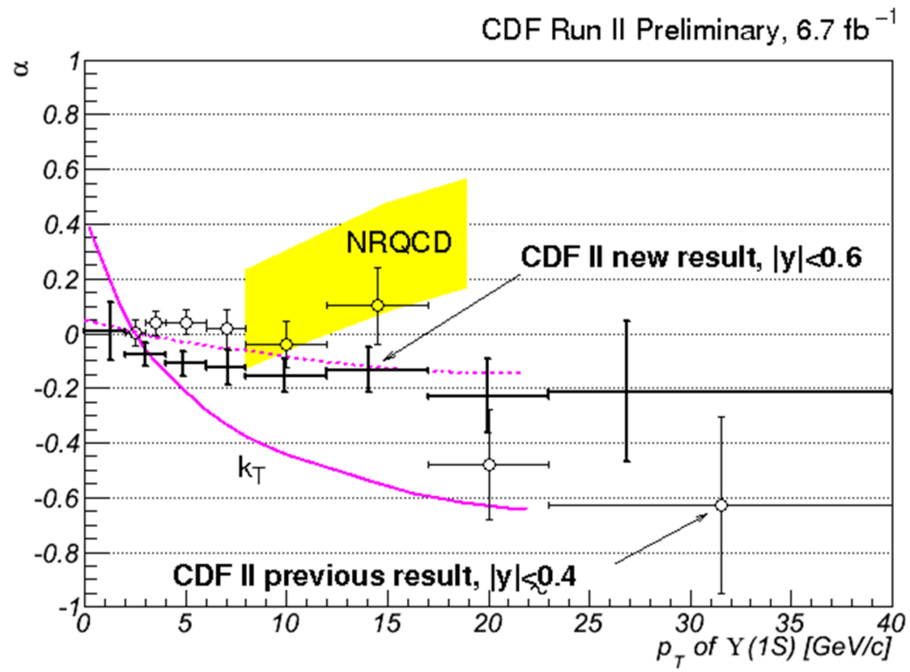
- First complete measurement of angular distribution of ϒ(nS) decays at a hadron collider.
- First measurement of ϒ(3S) spin alignment.
- ***No evidence for significant polarization****
  - ***Even up to p_T of 40 GeV/c***
  - ***Even for the ϒ(3S)***

* In the central region of rapidity, |y|<0.6

Additional Material

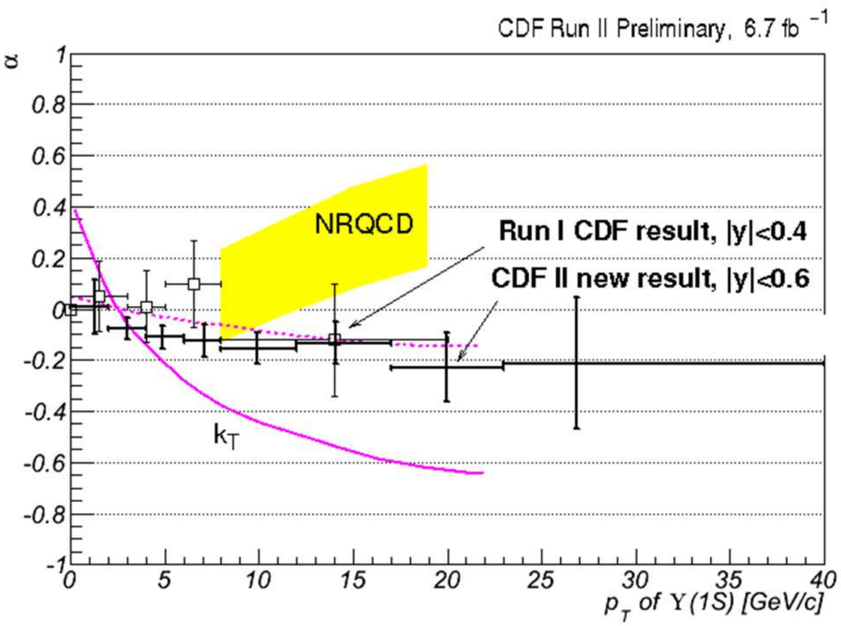
Comparison with Preliminary CDF II Result

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

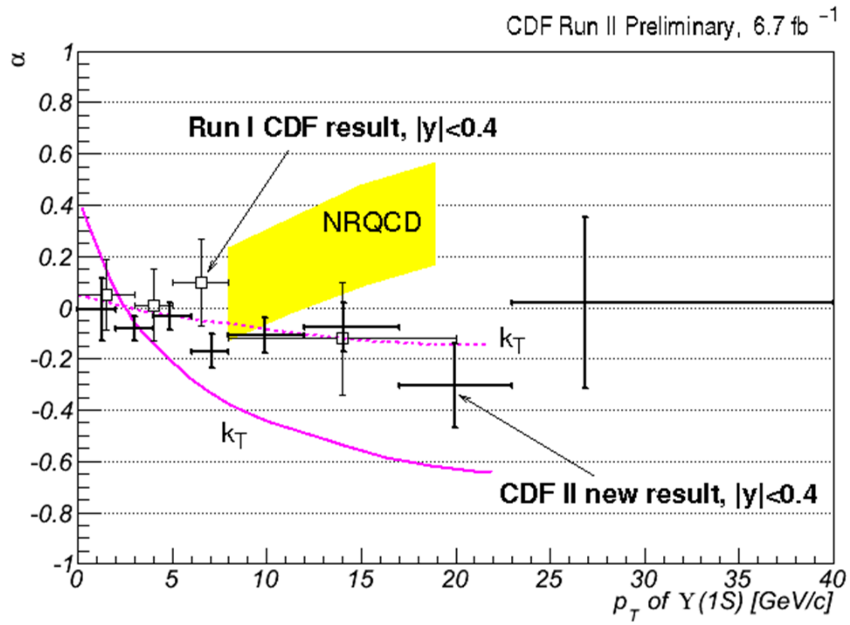


- Measurements are inconsistent.
- We investigated and have understood some potential sources of bias:
  - modeling ϒ resonance line shape, acceptance calculation
  - we now know that the background is highly "polarized" and any misestimate can introduce a significant bias
- *Superseded by new result 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



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

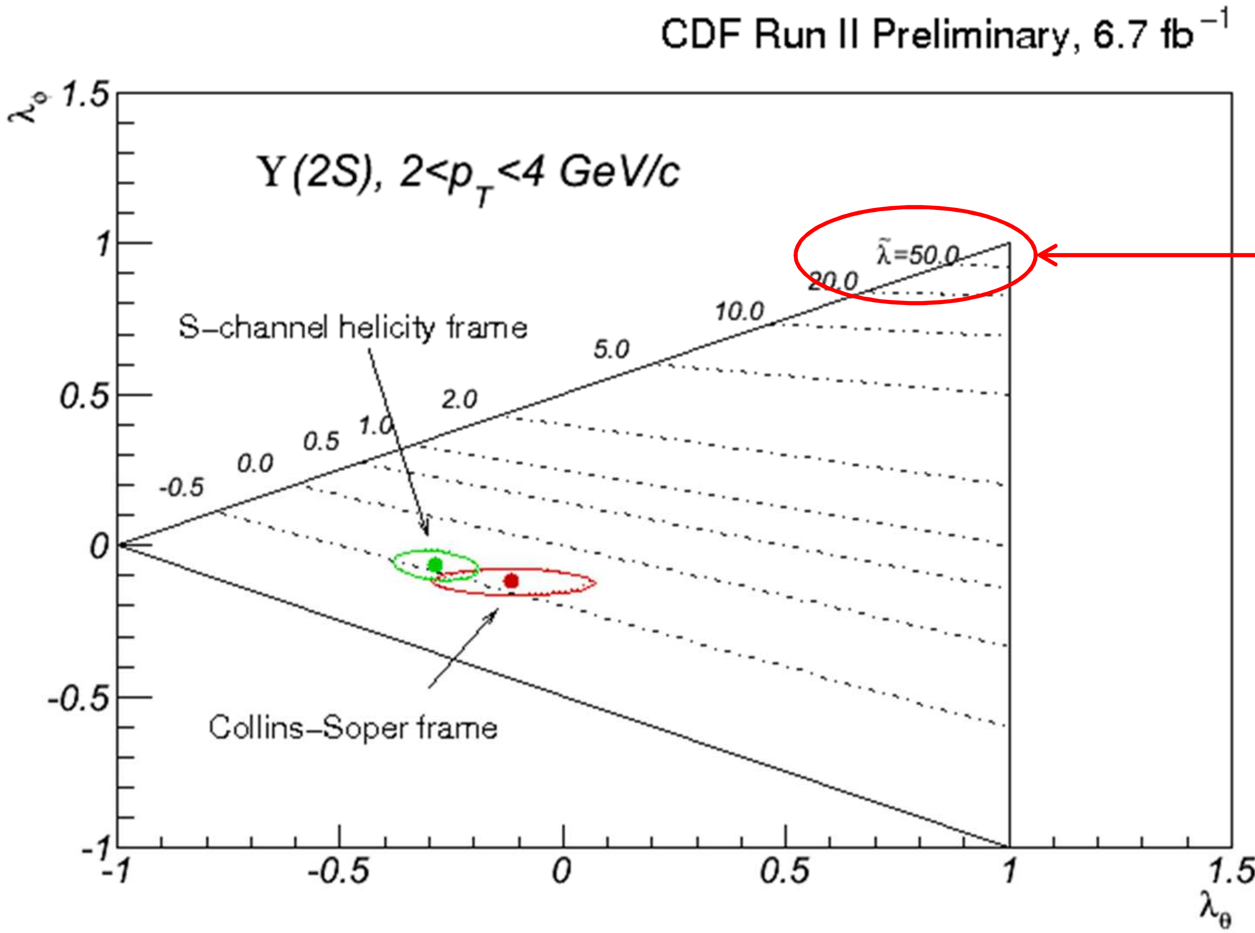


$\chi^2/dof \sim 2.0/4$

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

Consistency Tests



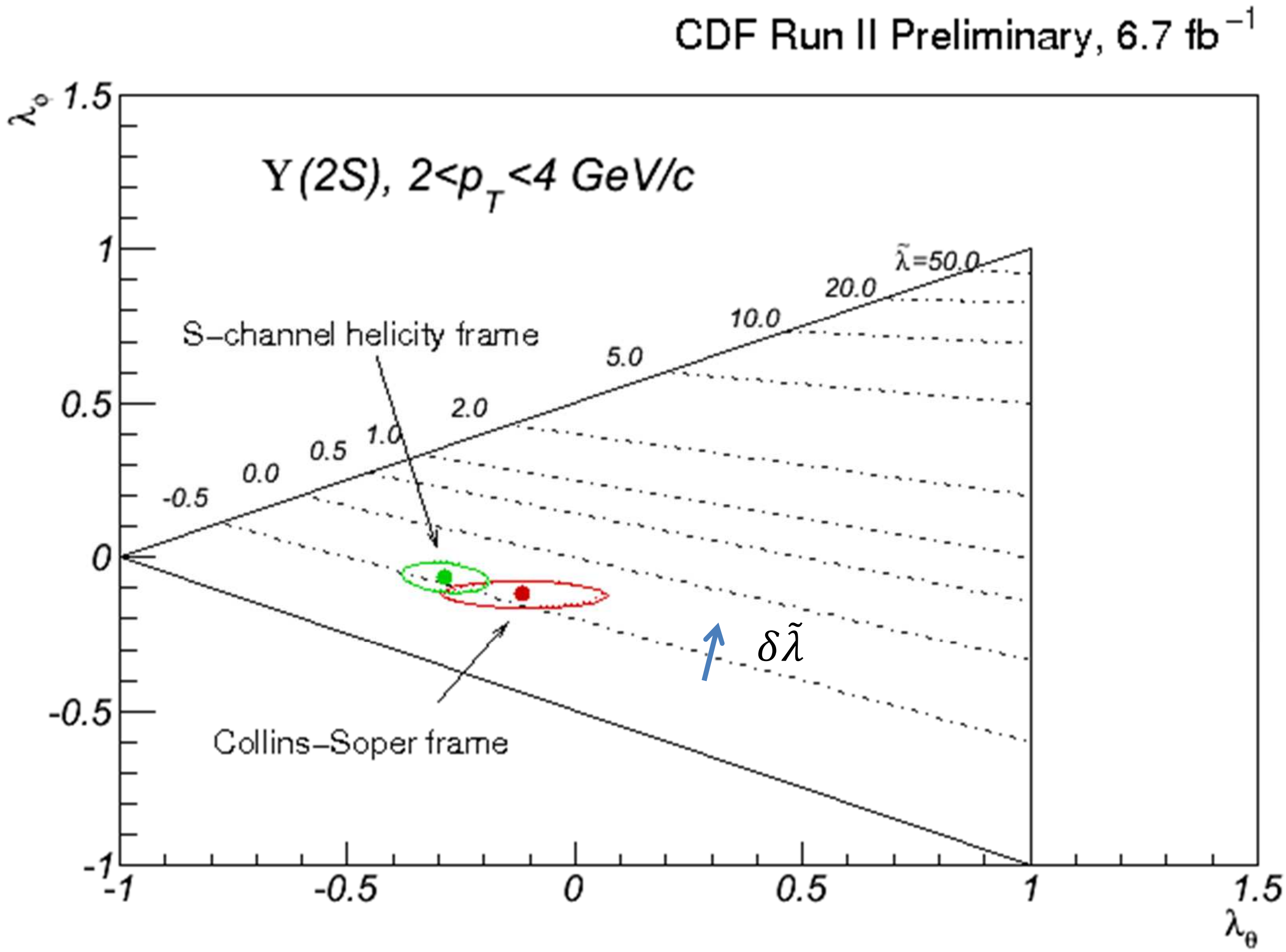
It can be shown that the expression

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

is the same in all reference frames.

We observe that indeed it is.

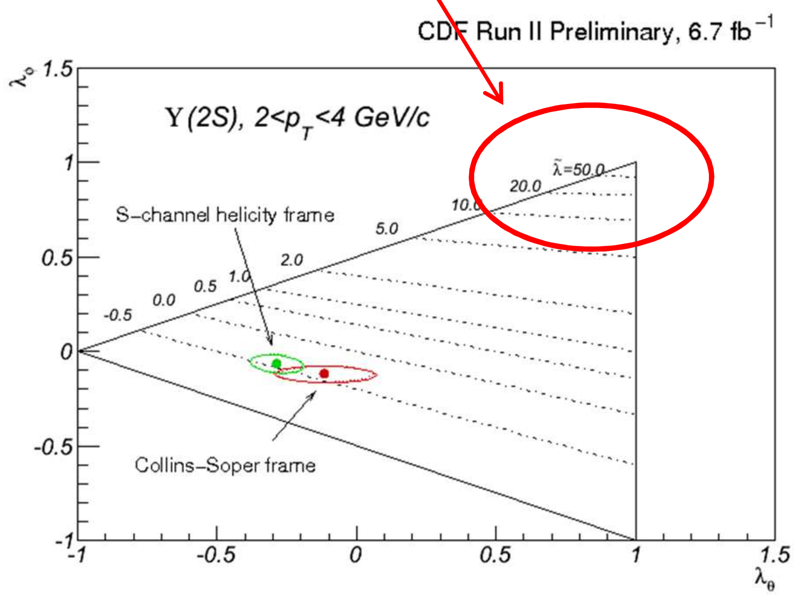
Frame Dependent Systematics

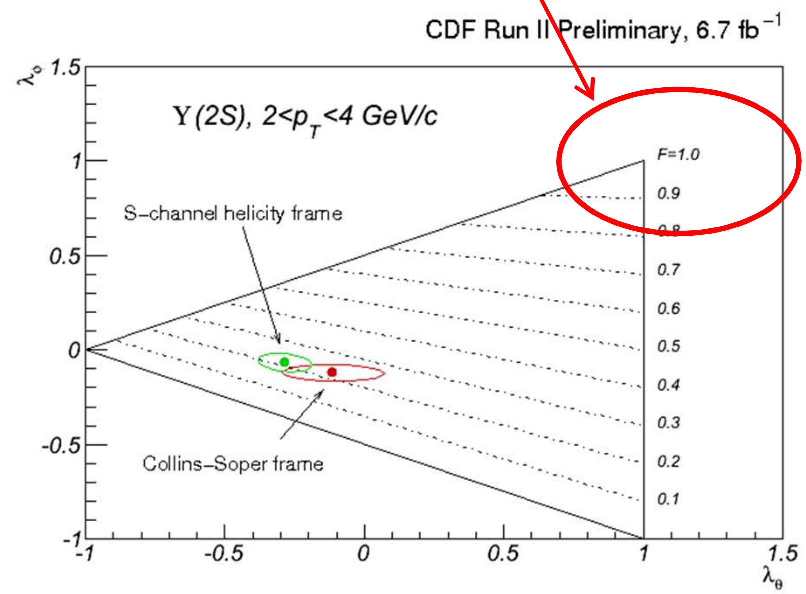


Other Rotational Invariants

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

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



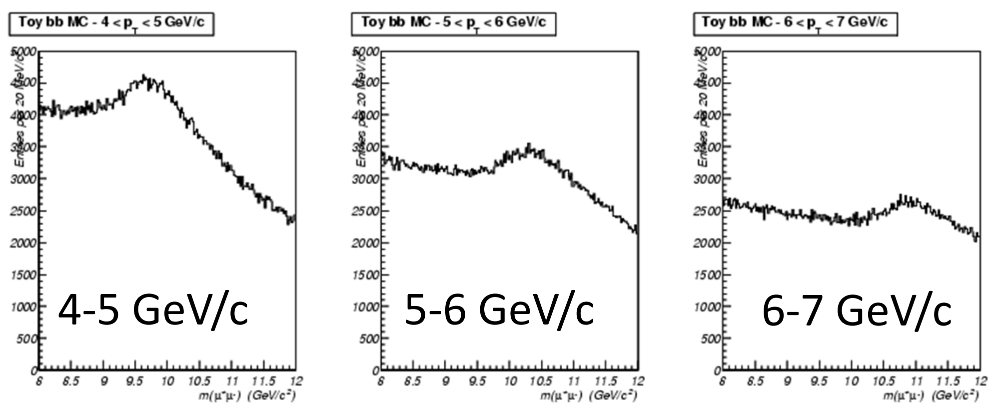


$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi} = \frac{4}{1 + |a_0|^2 - {a_1}^* a_{-1} - {a_{-1}}^* a_1} - 3$$

This is the part that is invariant under rotations.

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 demonstrates complexity of angular distributions in the background
  - ***Background might peak right under the ϒ(nS) signals in some p_T ranges.***
  - ***We chose not to use sidebands to constrain angular distribution in the background under the ϒ(nS) signals.***

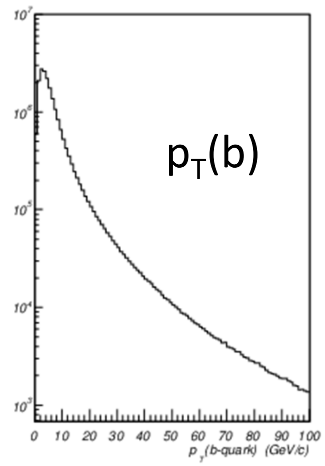


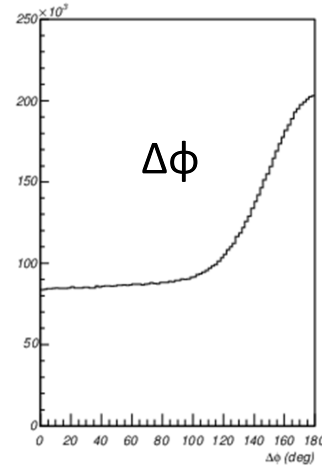
$m(\mu^+\mu^-)$

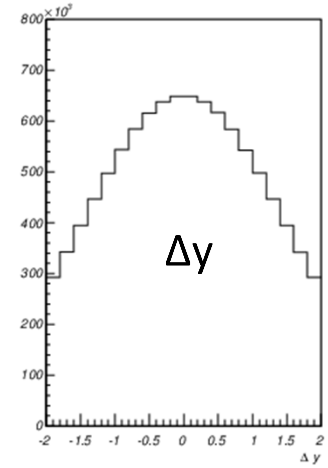
Toy Monte Carlo for correlated $b\bar{b}$ production

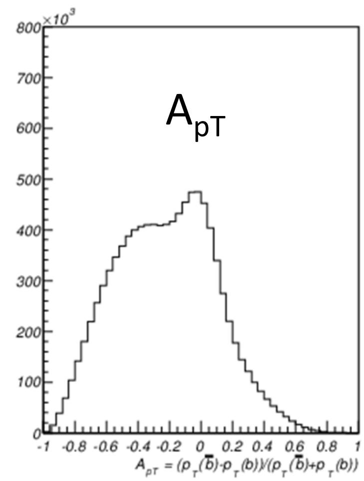
Phys. Rev. D65, 094006 (2002): R.D. Field, *"The sources of b-quarks at the Tevatron and their Correlations".*

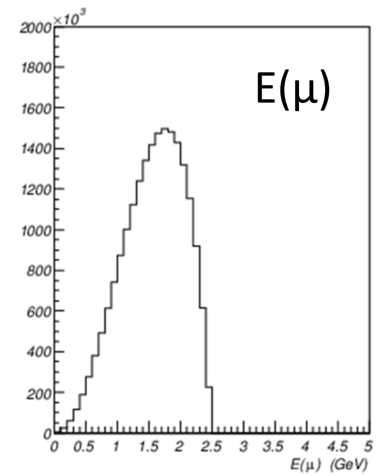
- p_T of the b-quark
- $\Delta\phi$ between b-quarks
- Δy between b-quarks
- p_T asymmetry
- $E(\mu)$ in B rest frame
- Peterson fragmentation
- Boost muons into lab frame
- Full detector simulation and event reconstruction
- Same analysis cuts applied to data





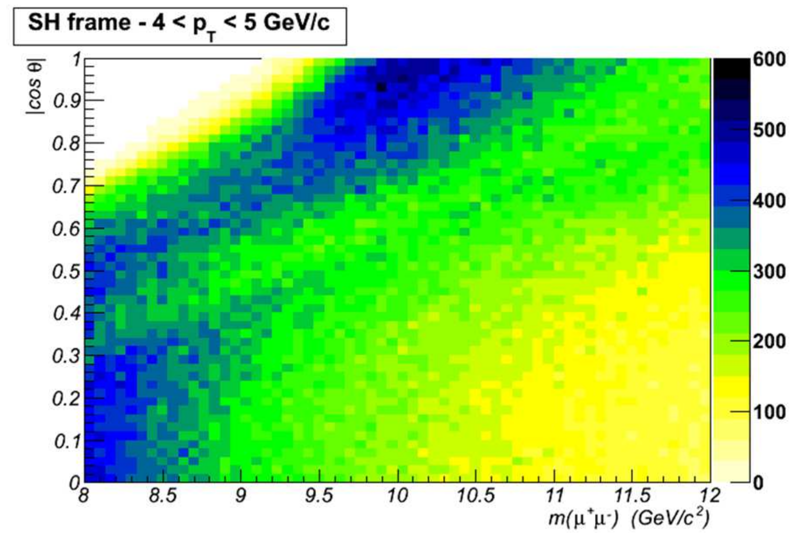




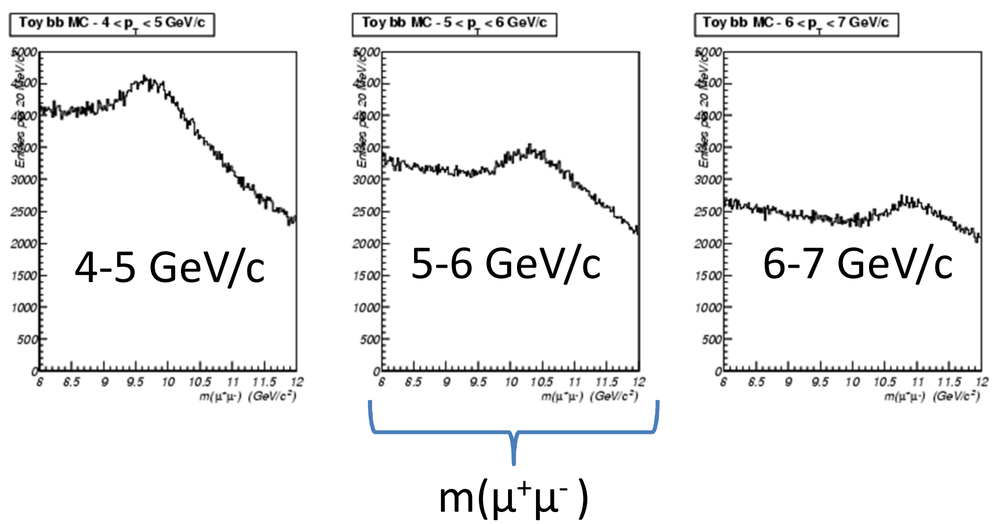


The Background is Complicated

- Complex angular distribution:



- Projection onto mass axis is not smooth:



Systematic Uncertainties

p_T [GeV/c]	λ_θ $\Upsilon(1S)$ — Collins-Soper frame					
0-2	0.2136	$^{+0.1442}_{-0.1395}$(stat)	± 0.0468(MC)	± 0.0008(s_p)	± 0.0199(frame)	± 0.0089(eff)
2-4	-0.0017	$^{+0.0743}_{-0.0733}$	± 0.0280	± 0.0236	± 0.0067	± 0.0102
4-6	-0.0534	$^{+0.0690}_{-0.0684}$	± 0.0257	± 0.0191	± 0.0070	± 0.0155
6-8	0.0298	$^{+0.0739}_{-0.0721}$	± 0.0202	± 0.0087	± 0.0038	± 0.0009
8-12	0.0116	$^{+0.0526}_{-0.0508}$	± 0.0173	± 0.0059	± 0.0046	± 0.0080
12-17	0.0295	$^{+0.0569}_{-0.0546}$	± 0.0105	± 0.0037	± 0.0132	± 0.0074
17-23	0.0326	$^{+0.0990}_{-0.0874}$	± 0.0357	± 0.0290	± 0.0042	± 0.0086
23-40	0.0786	$^{+0.2124}_{-0.1798}$	± 0.0118	± 0.0064	± 0.0024	± 0.0150

- Monte Carlo statistics
  - estimated from toy MC
- Prompt scale factor
  - change when using quadratic vs linear parameterization
- Frame
  - propagated from variation in $\tilde{\lambda}$
- Efficiencies
  - statistical uncertainty from analysis of control samples