Quarkonium Production at the Tevatron

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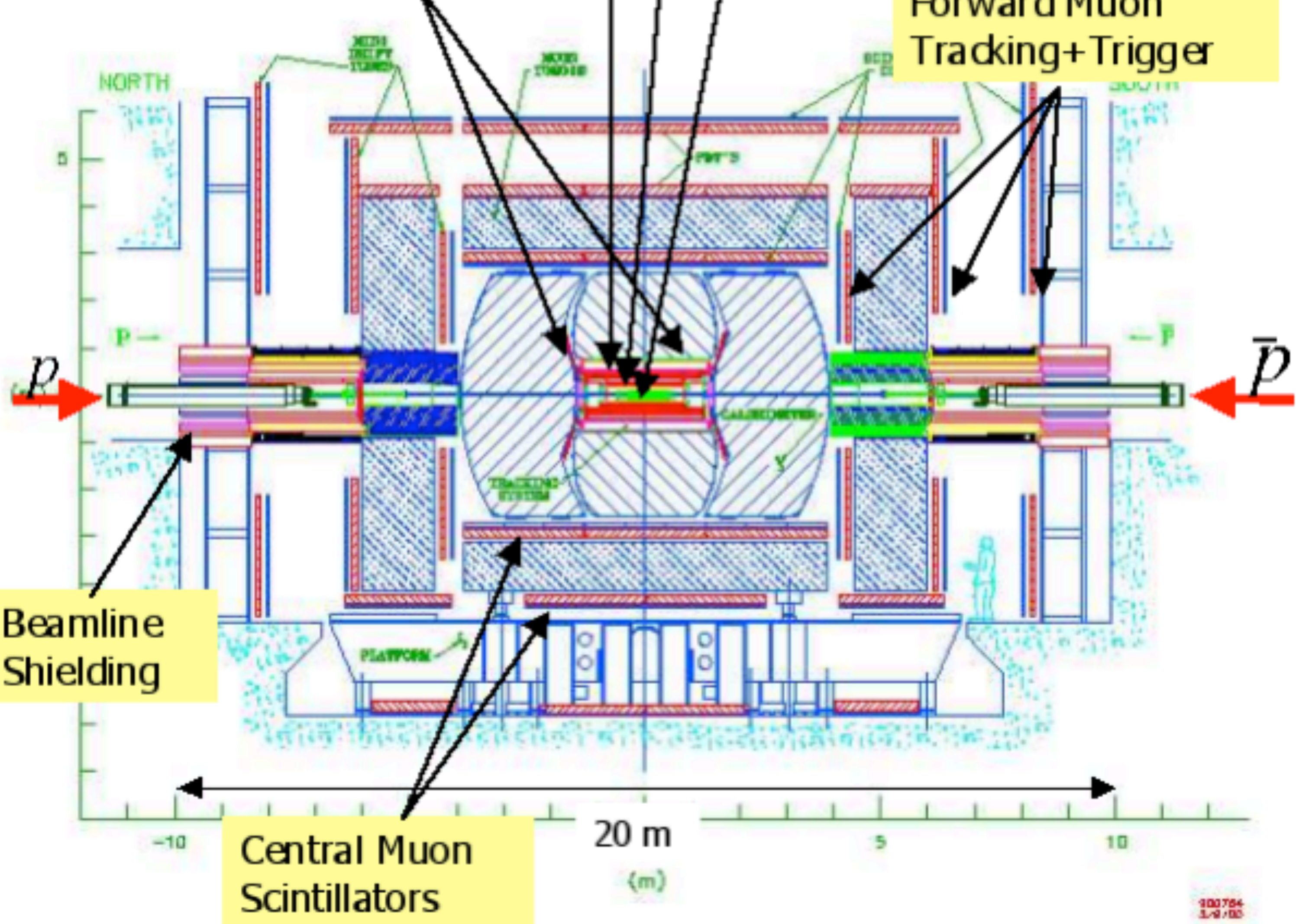
Workshop on Heavy Flavor Production at Hadron Colliders

Outline

- Brief review of issues with quarkonium production
- Upsilon polarization
- χ_b states

- Some topics omitted for lack of time:
  - J/ψ and ψ(2S) cross section and polarization
  - χ_c states
  - X(3872)

D0 Detector



2T Solenoid

Fiber Tracker

Silicon μ-strip Tracker

Preshowers

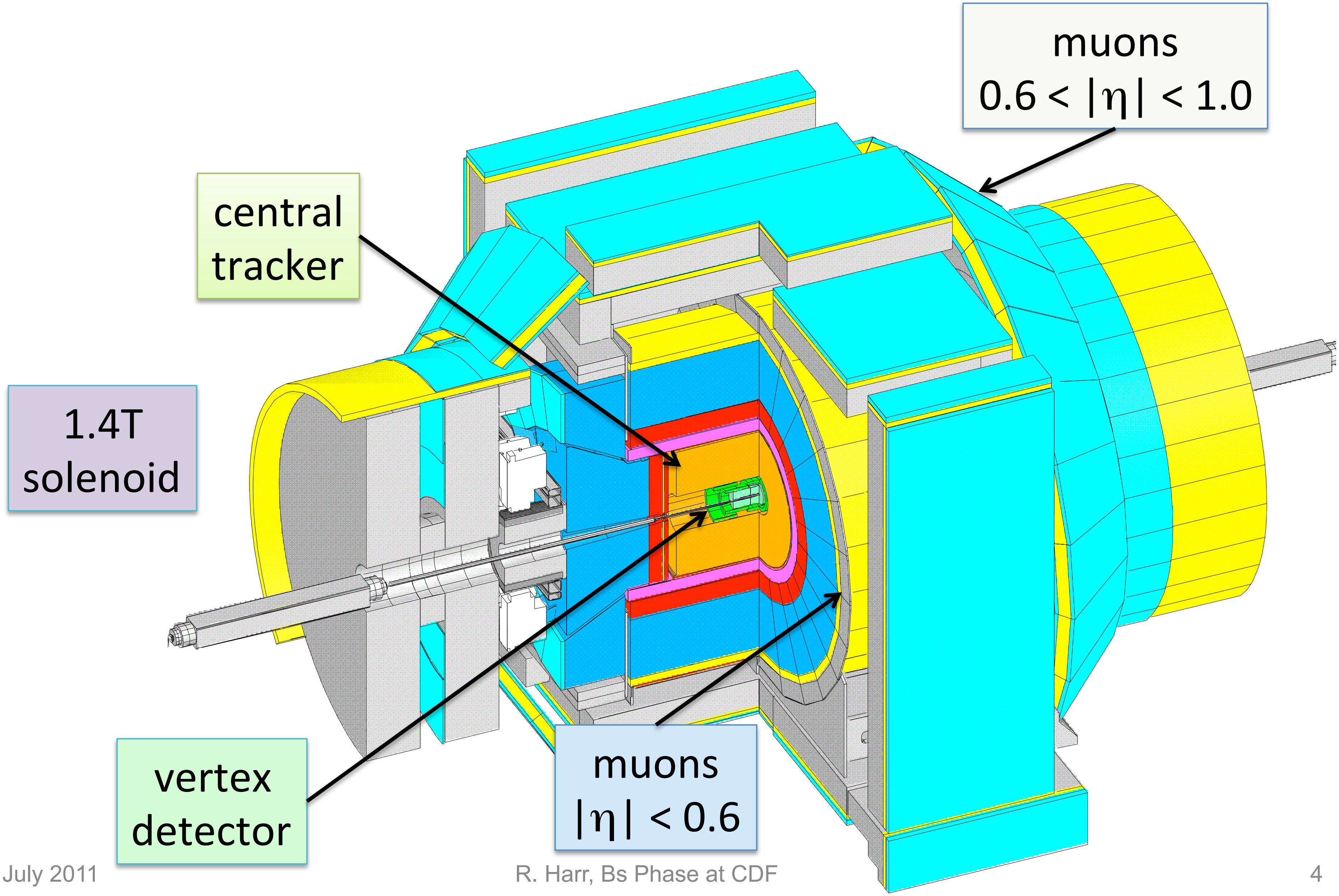
Forward Muon Tracking+Trigger

Beamline Shielding

Central Muon Scintillators

20 m

The CDF Detector



muons
$0.6 < |\eta| < 1.0$

central
tracker

1.4T
solenoid

vertex
detector

muons
$|\eta| < 0.6$

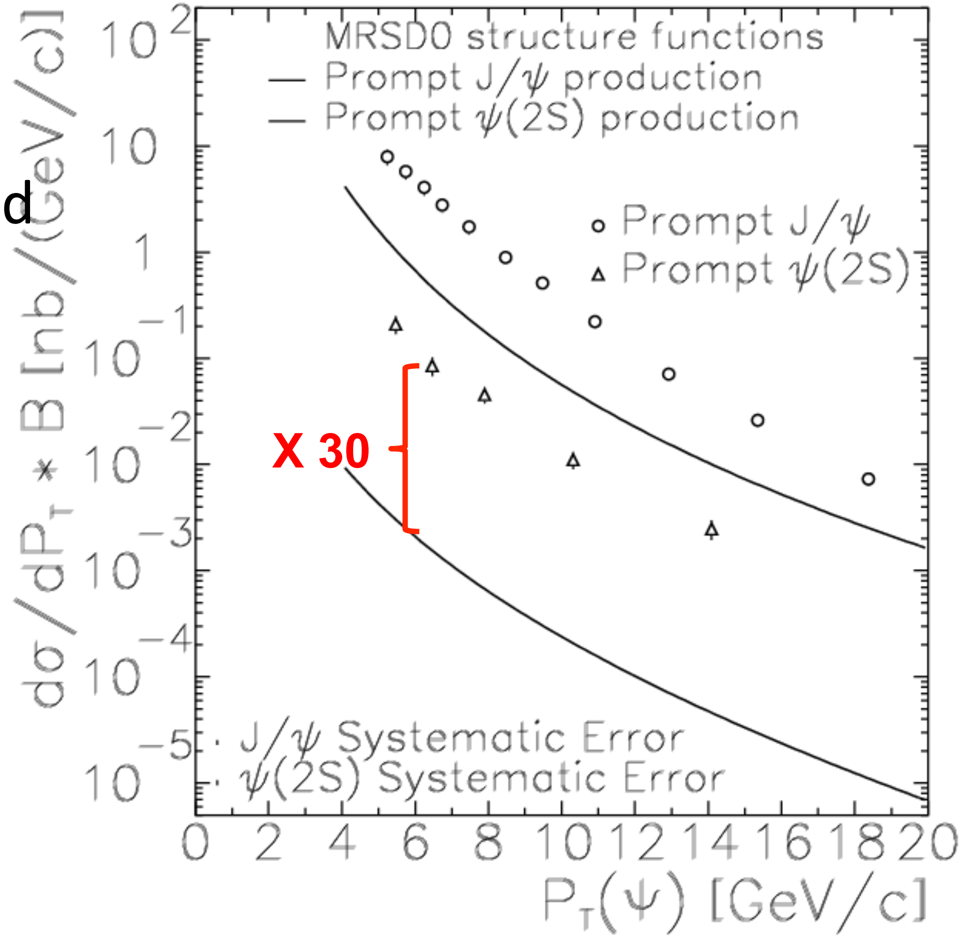
Basic Issues

- Understanding the production cross section has been a long road.
- The quarkonium acceptance depends on the polarization at production.
- The determination of the polarization has been tricky, with unknown feed down, and inconsistent results.
- This has limited the precision of the production cross section measurements.
- Cross section alone has limited power to discriminate among theoretical models.

CDF *J/ψ* Cross Section

- Run I measurement
  - about 18 pb^{-1}
  - non-prompt prod. estimated from displaced vertices
- ×30 not explained by
  - structure functions
  - secondary production
  - feed down from χ_c
- Υ system is “easier”
  - no secondary component
  - calculations more reliable for heavy quarks

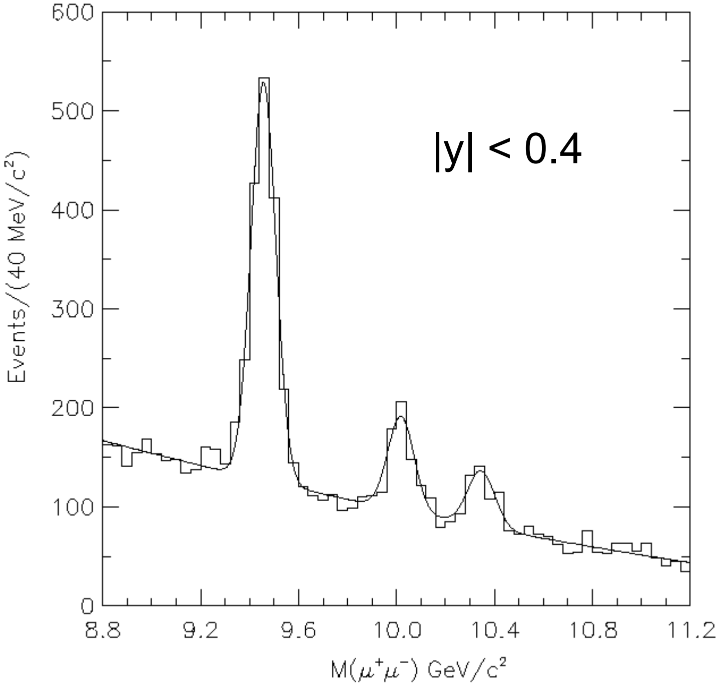
CDF Run I – Phys. Rev. Lett. 79, 572 (1997)



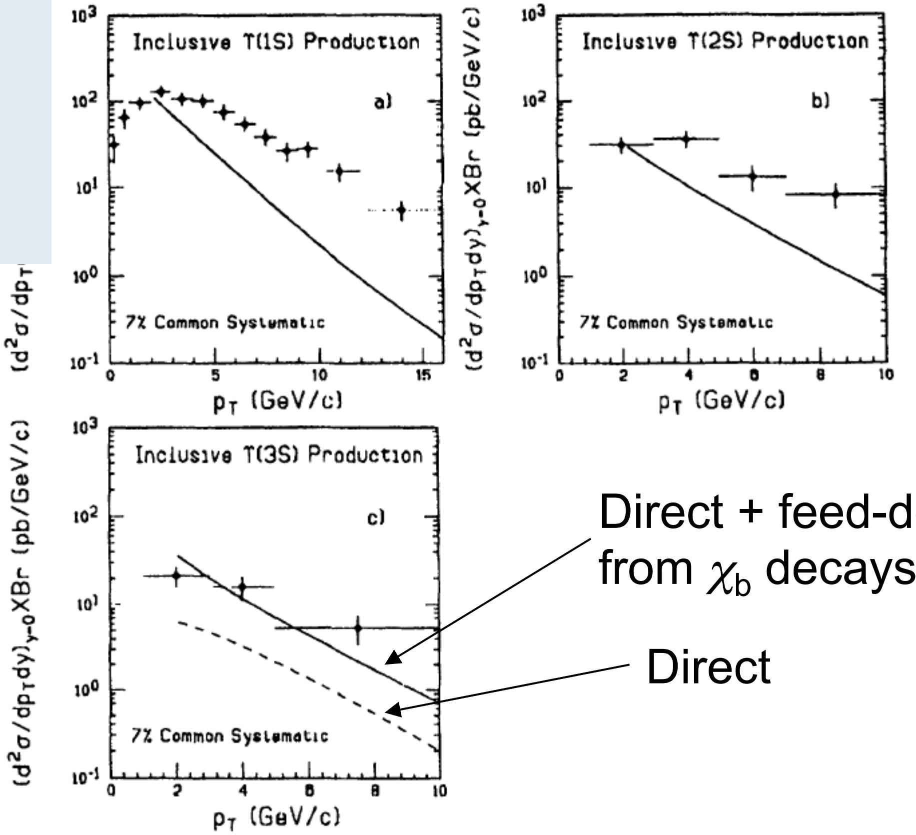
Prompted theory beyond CSM

CDF ϒ(nS) Cross Section

- Run I measurement
  - 17 pb^{-1} of int. lumi.
  - no secondary production



CDF Run I – Phys. Rev. Lett. **75**, 4358 (1995)

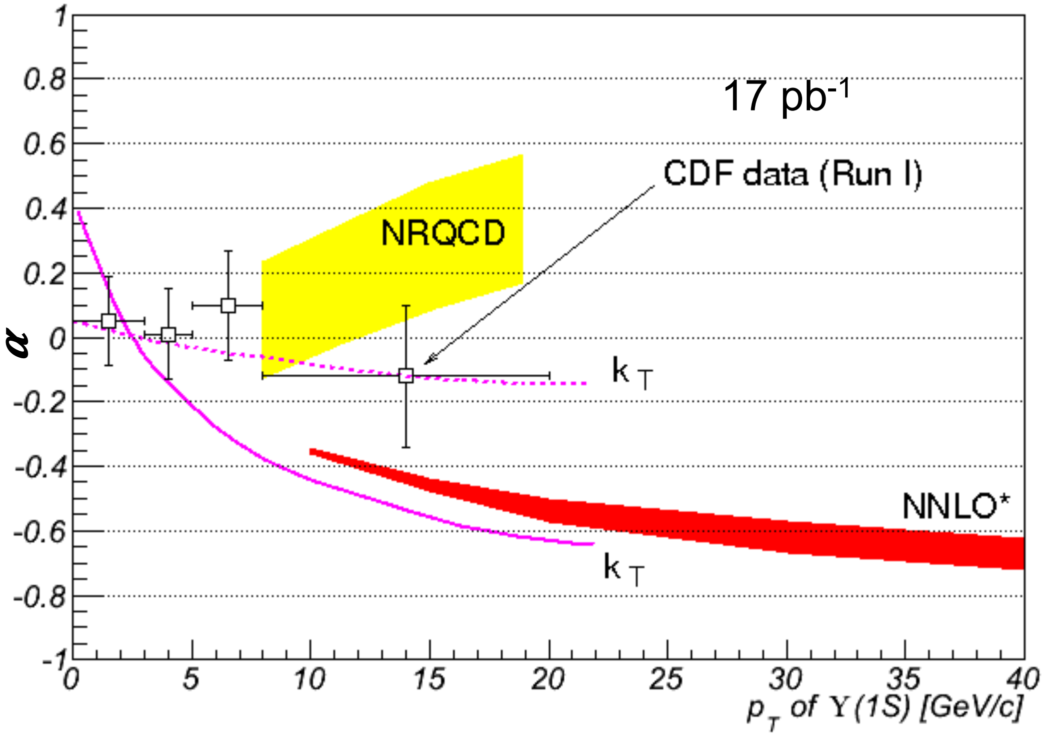


Direct + feed-down from χ_b decays

Direct

- Excess is a factor of a few.
- Still significant.

Υ(1S) Polarization in Run I



CDF Run I: Phys. Rev. Lett. 88, 161802 (2002).
NRQCD: Phys. Rev. D63, 071501(R) (2001).
-factorization: JETP Lett. 86, 435 (2007).
NNLO*: Phys. Rev. Lett. 101, 152001 (2008).

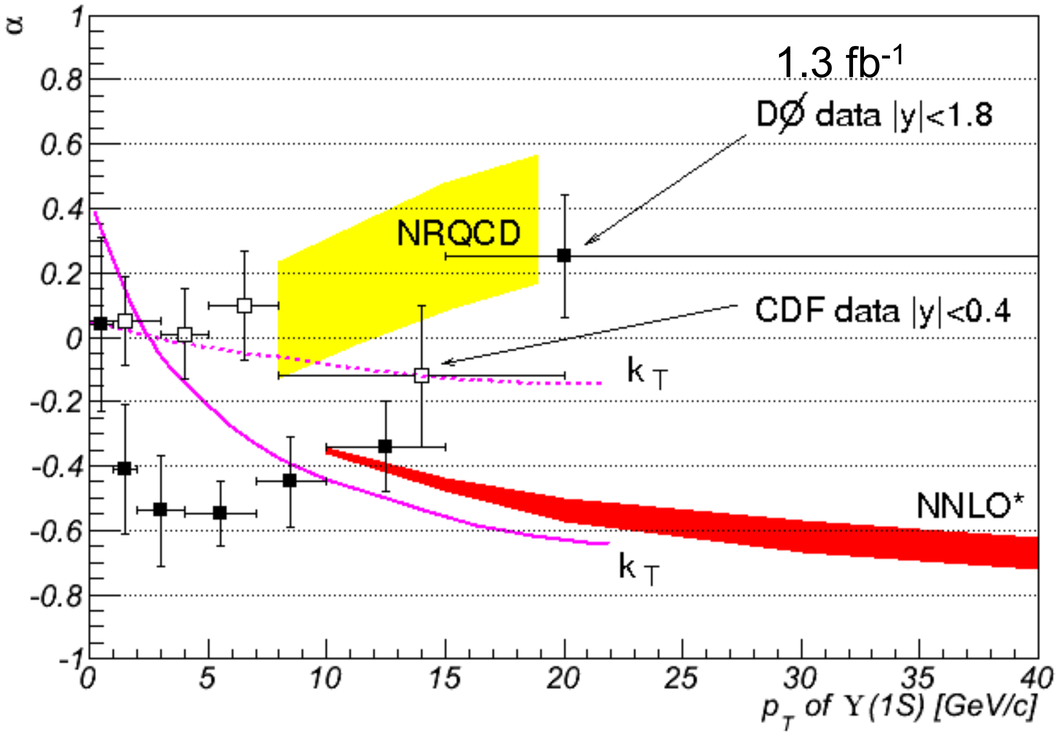
Different feed down assumptions in k_T calculations:

╌╌╌ χ_b decays preserve polarization
─── χ_b decays destroy all polarization

No strong polarization observed in Υ(1S) decays …

- ➢ What happens at high p_T?
- ➢ Feed down from χ_b states?
- ➢ Presumably less feed down for Υ(2S) and Υ(3S) states

Υ Polarization from DØ in Run II



Similar analysis technique:

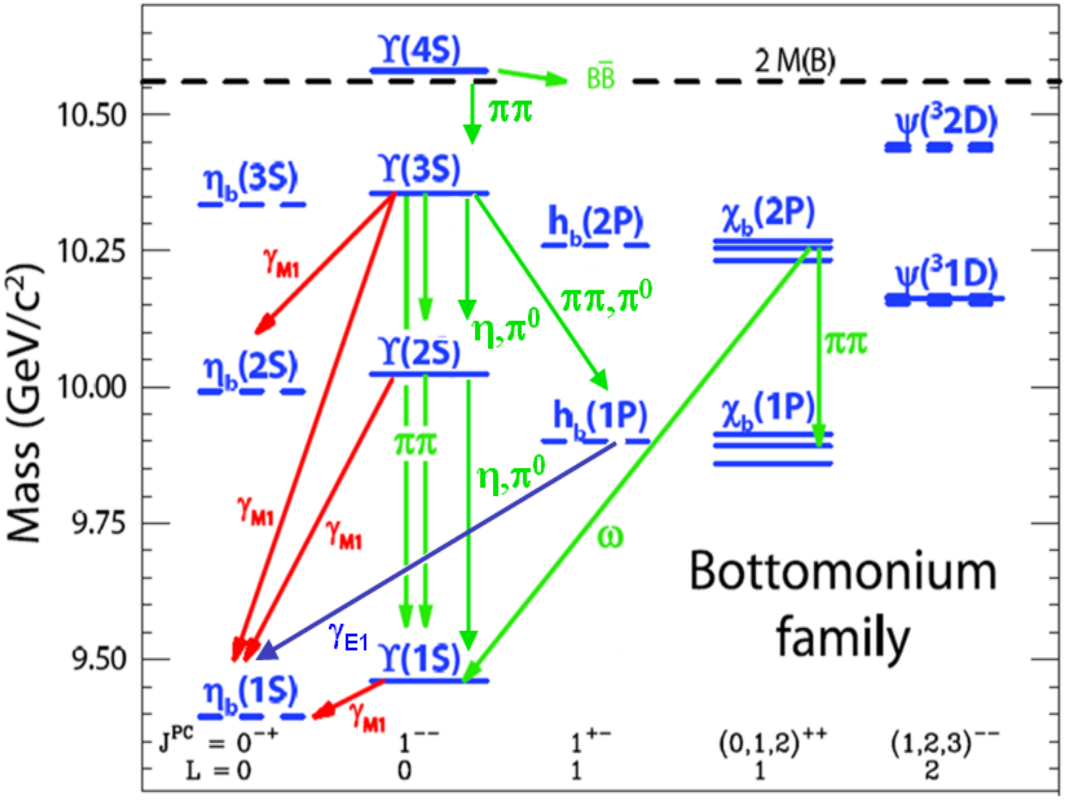
- Fit $\mu^+\mu^-$ mass distribution to get Υ yield in bins of cos θ
- Correct for detector acceptance
- Fit to 1 + α cos^2 θ

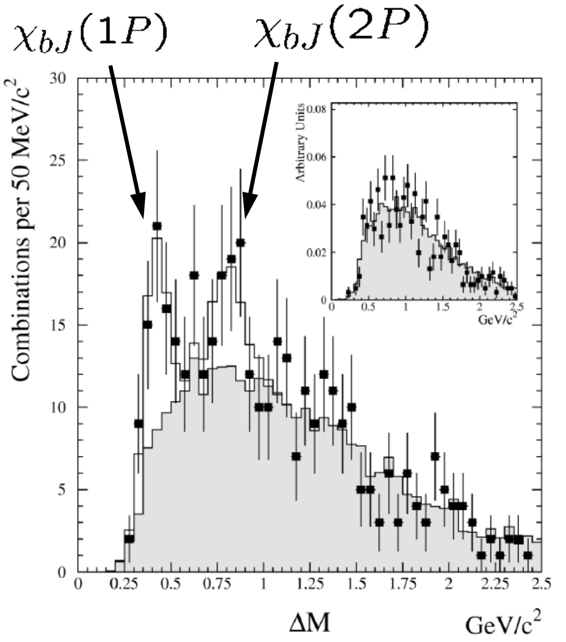
Results are inconsistent …

DØ Run II: Phys. Rev. Lett. 101, 182004 (2008).
CDF Run I: Phys. Rev. Lett. 88, 161802 (2002).
NRQCD: Phys. Rev. D63, 071501(R) (2001).
kT-factorization: JETP Lett. 86, 435 (2007).
NNLO*: Phys. Rev. Lett. 101, 152001 (2008).

…why?!?

Feed Down from Higher States





CDF Run I - Phys. Rev. Lett. 84, 2094 (2000)

- P-wave states feed down to S-wave states and can influence polarization measurement.
- Need feed down fractions to account for effect.

Suggested New Paradigm

- Angular distribution for decays to fermions:

$$\frac{d\Gamma}{d\Omega} \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta cos\phi + \cdots$$

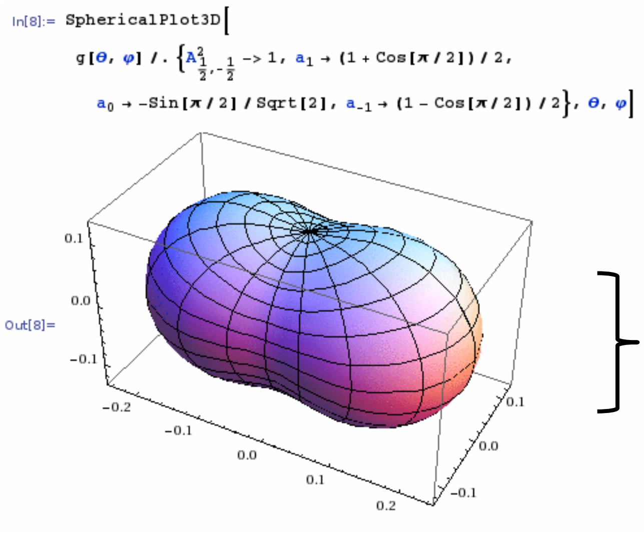
Faccioli *et al.* PRL 102, 151802 (2009)

- A pure state cannot have all λ = 0 simultaneously.
- Measured values can depend on det. acceptance
- Use of different ref. frames could help check acceptance corrections

- **We need to measure more than just λ_θ !**

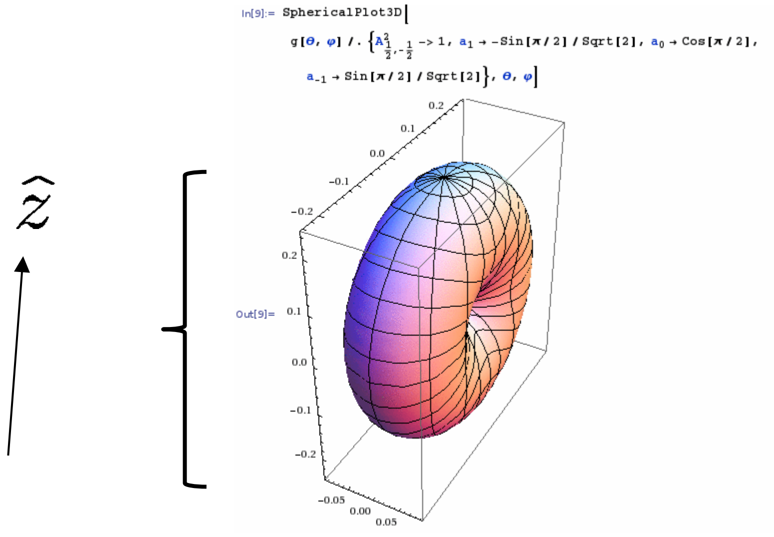
Need for full polarization analysis

Transverse: $a_0 = 0$



```
In[8]:= SphericalPlot3D[
    g[θ, φ] /. {A^2_{1/2,-1/2} -> 1, a_1 → (1 + Cos[π / 2]) / 2,
      a_0 → -Sin[π / 2] / Sqrt[2], a_-1 → (1 - Cos[π / 2]) / 2}, θ, φ]
```

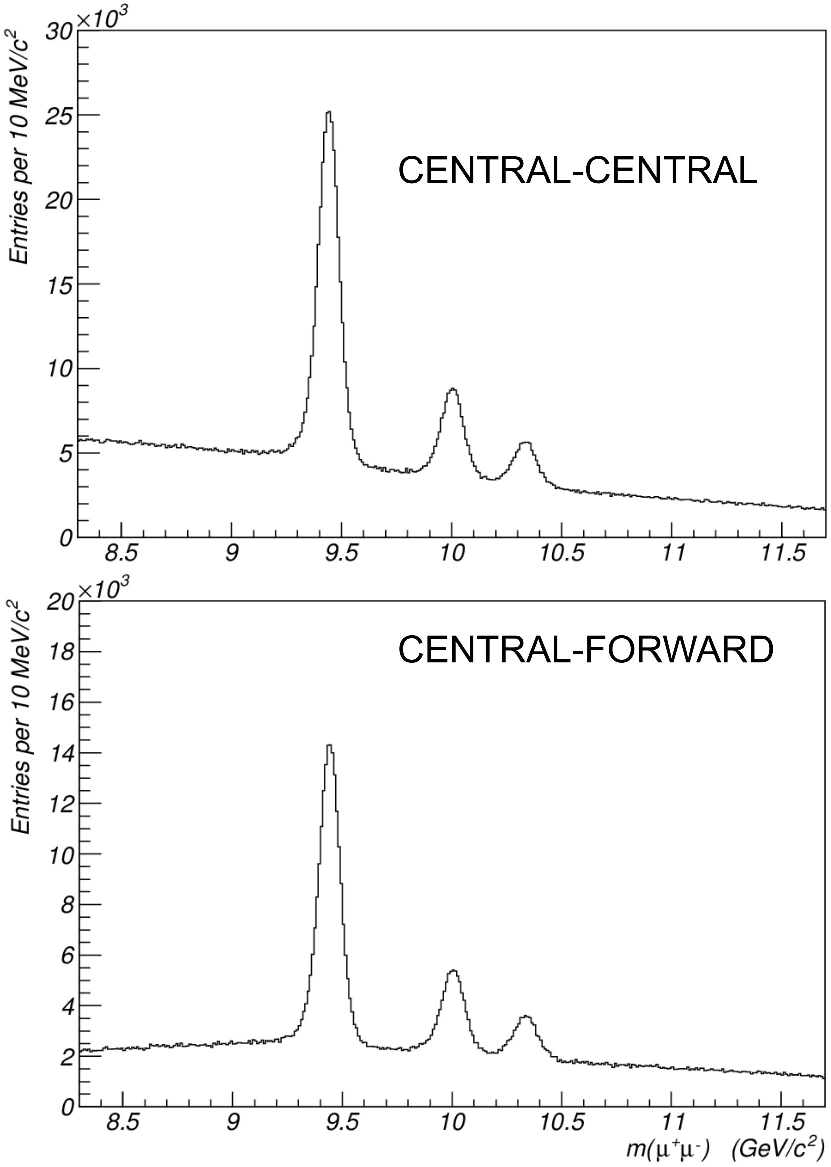
Longitudinal: $a_{\pm1} = 0$



```
In[9]:= SphericalPlot3D[
    g[θ, φ] /. {A^2_{1/2,-1/2} -> 1, a_1 → -Sin[π / 2] / Sqrt[2], a_0 → Cos[π / 2],
      a_-1 → Sin[π / 2] / Sqrt[2]}, θ, φ]
```

- The templates for $dN/d\Omega$ are more complicated than simply $1 \pm \cos^2\theta$
- Need to measure λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$ simultaneously
- Check invariant $\tilde{\lambda} = (\lambda_\theta + 3\lambda_\phi) / (1 - \lambda_\phi)$ w/2 frames

The CDF Upsilon Sample



- Two triggers used:
  - central $\mu^+\mu^-$ pair (CC)
  - central-forward $\mu^+\mu^-$ (CF)
- Rapidity coverage:
  - C: $|\eta(\mu)| \leq 0.6$
  - F: $0.6 \leq |\eta(\mu)| \leq 1$
- Good signal separation
  - $\sigma_m \approx 5$ MeV/c^2
- Yields in 6.7 fb-1:
  - Υ(1S) 550,000
  - Υ(2S) 150,000
  - Υ(3S) 76,000

Analysis Method

- Measure distribution of ($\cos\theta, \phi$) for all $\mu^+\mu^-$ pairs in Upsilon signal regions
- Measure same distributions in background regions.
- Observed distribution depends on physics dist. modified by the detector acceptance:

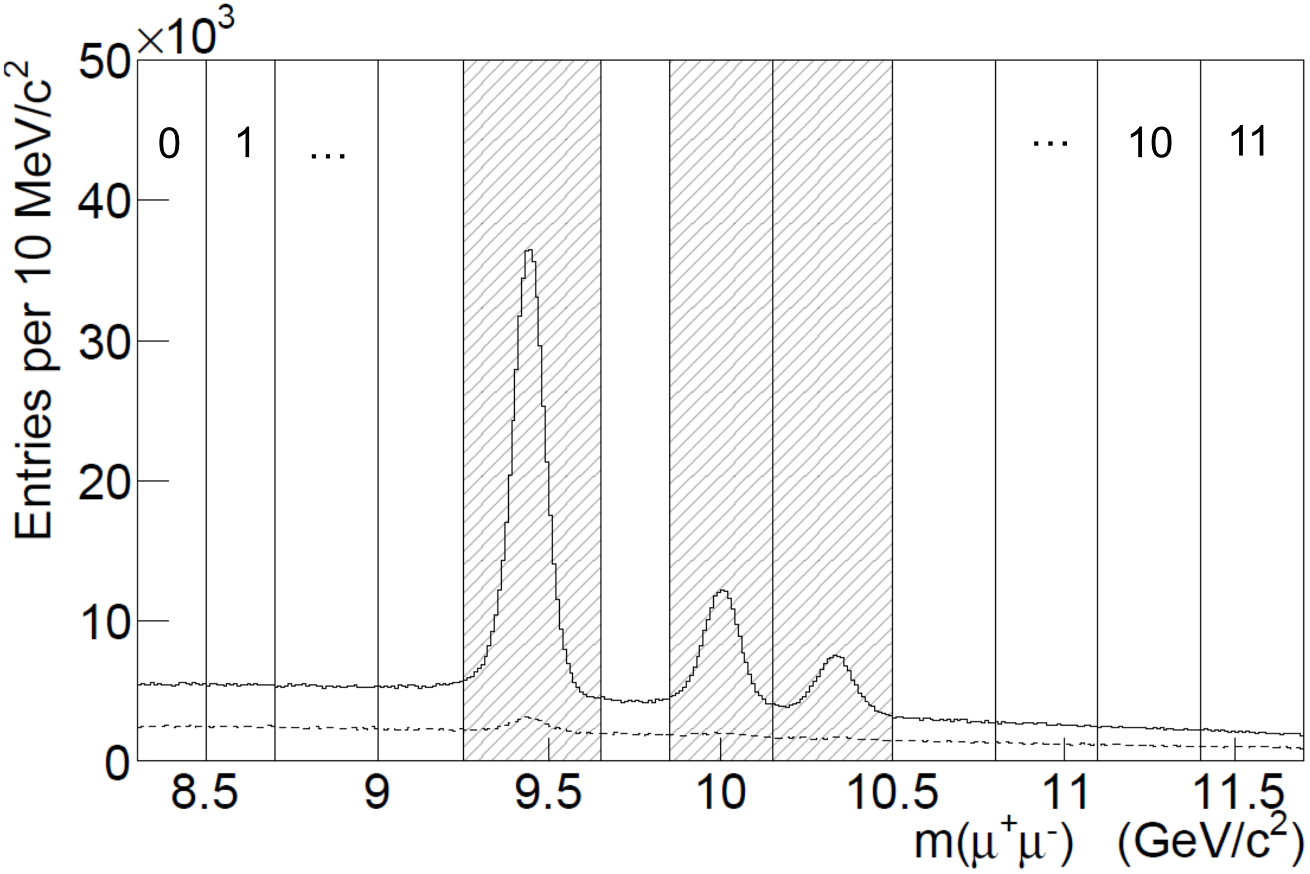
$$\begin{aligned}\frac{dN}{d\Omega} &\sim f_s A_s(\cos\theta,\phi) \times w_s(\cos\theta,\phi;\lambda_s) + \\ &\quad (1-f_s)A_b(\cos\theta,\phi) \times w_b(\cos\theta,\phi;\lambda_b)\end{aligned}$$

- $A(\cos\theta,\phi)$ determined from MC for sig. & bkg.

$$w(\cos\theta,\phi) \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$

- Fit for λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$ in both components.

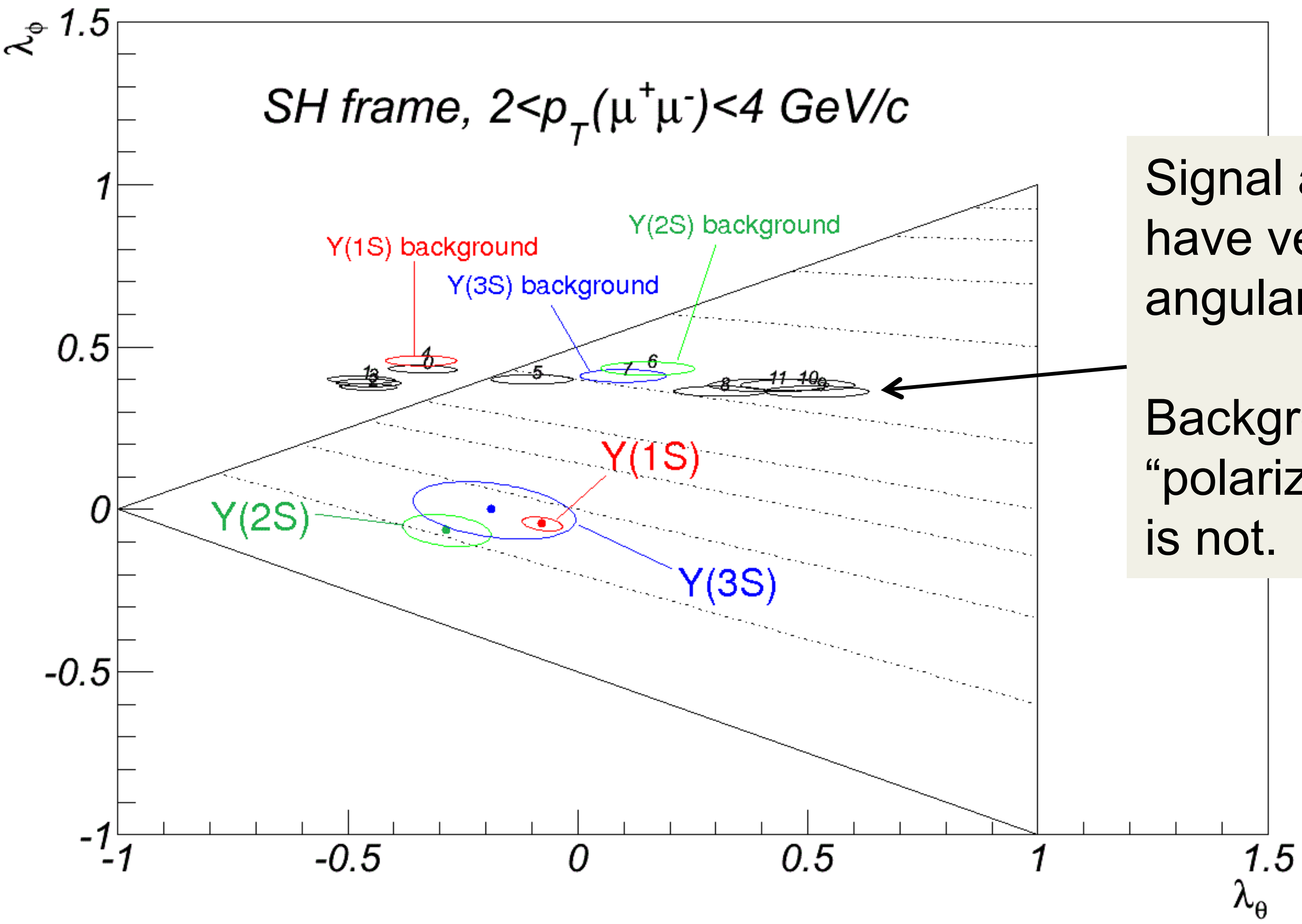
Analysis Method



- Two components in each mass range: signal + background

$$\lambda_{\mathrm{observed}} = f_{\mathrm{sig}}\vec{\lambda}_{\mathrm{sig}} + (1 - f_{\mathrm{sig}})\vec{\lambda}_{\mathrm{bkg}}$$

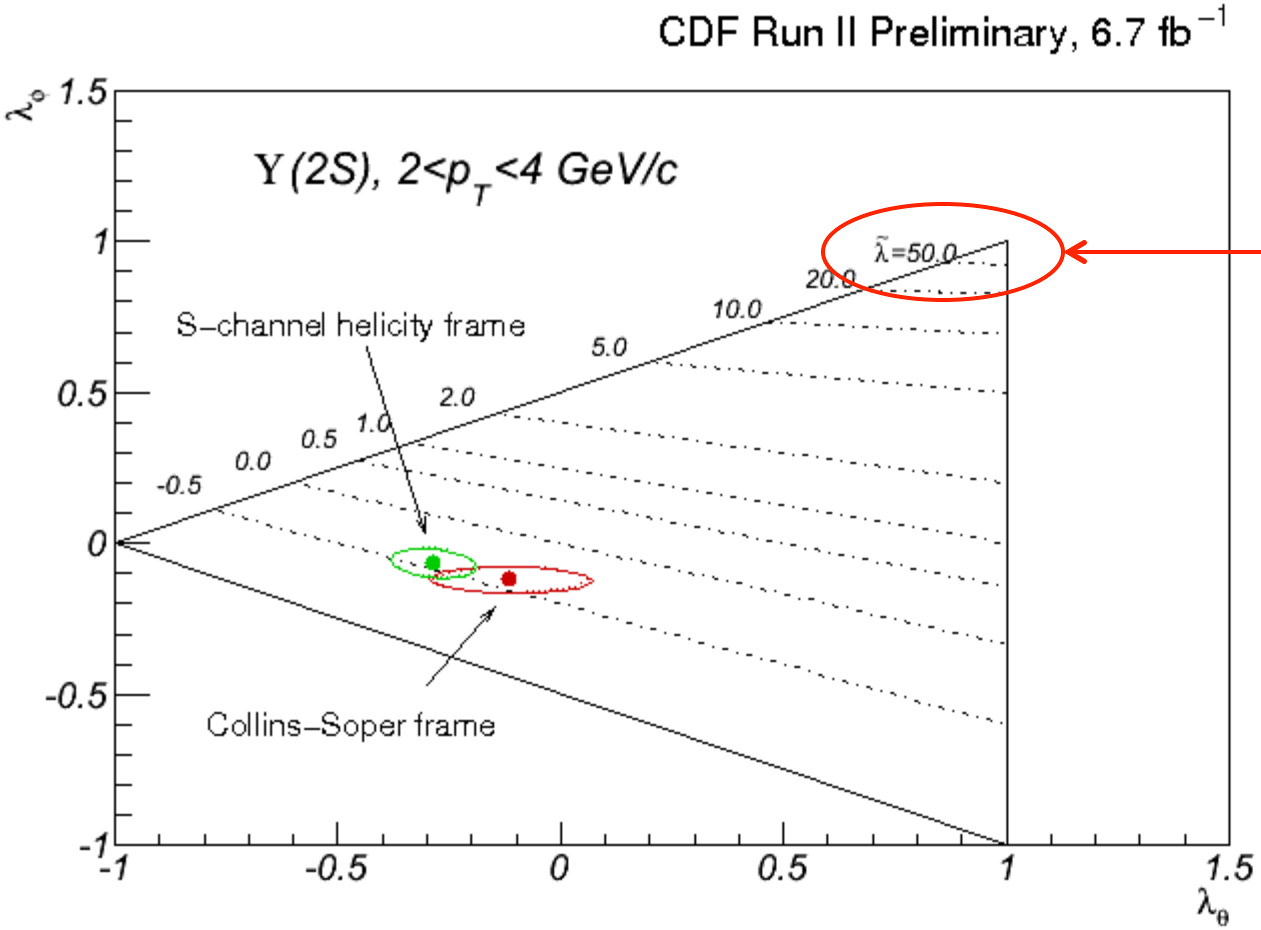
Fitted Parameters



Signal and background have very different angular distributions.

Background is highly “polarized” but the signal is not.

Consistency Tests



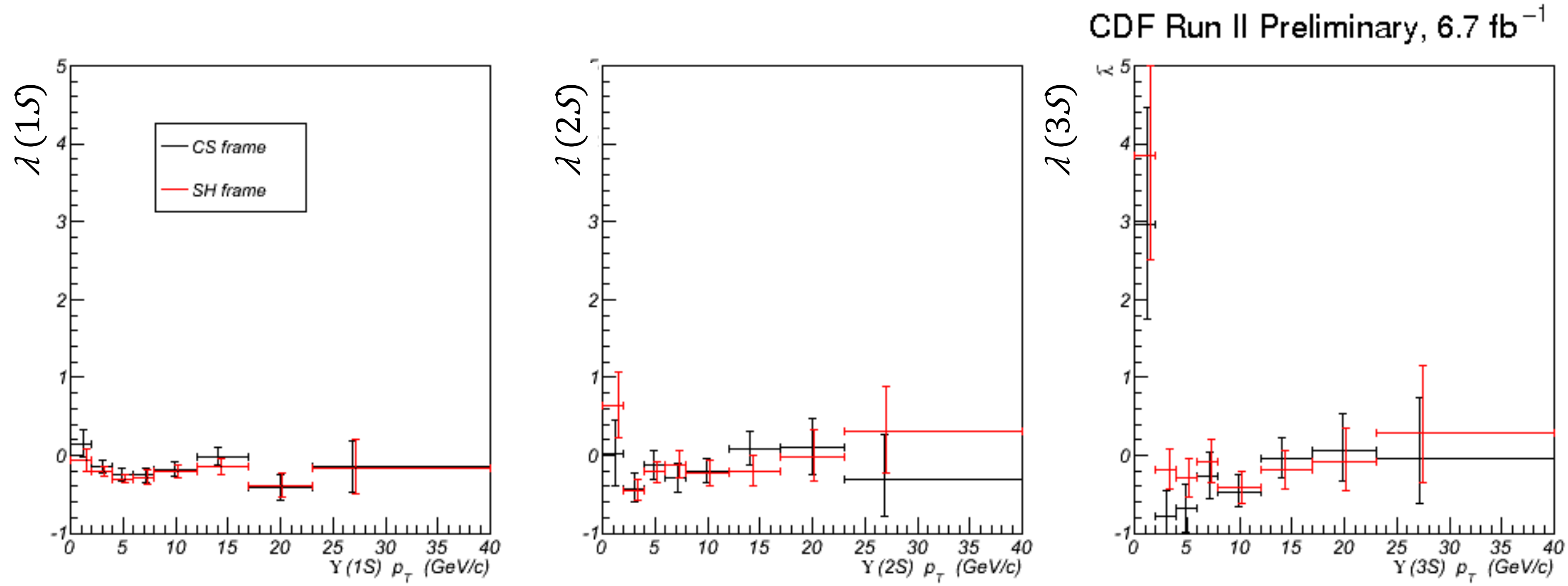
It can be shown that the expression

$$\overline{\lambda} = (\lambda_\theta + 3\lambda_\phi)\,/(1 - \lambda_\phi)$$

is the same in all reference frames.

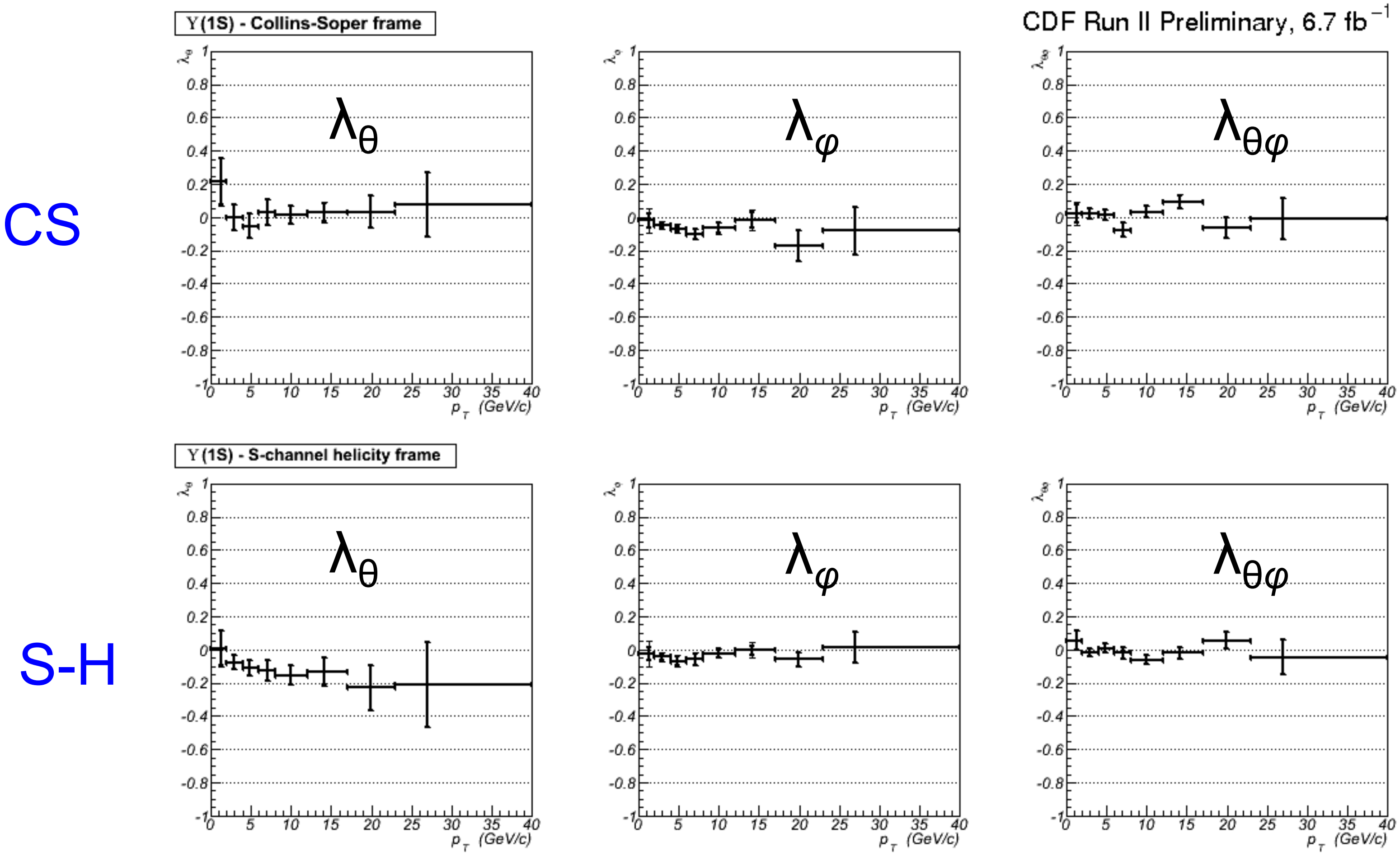
We observe that indeed it is.

Frame Invariance Tests



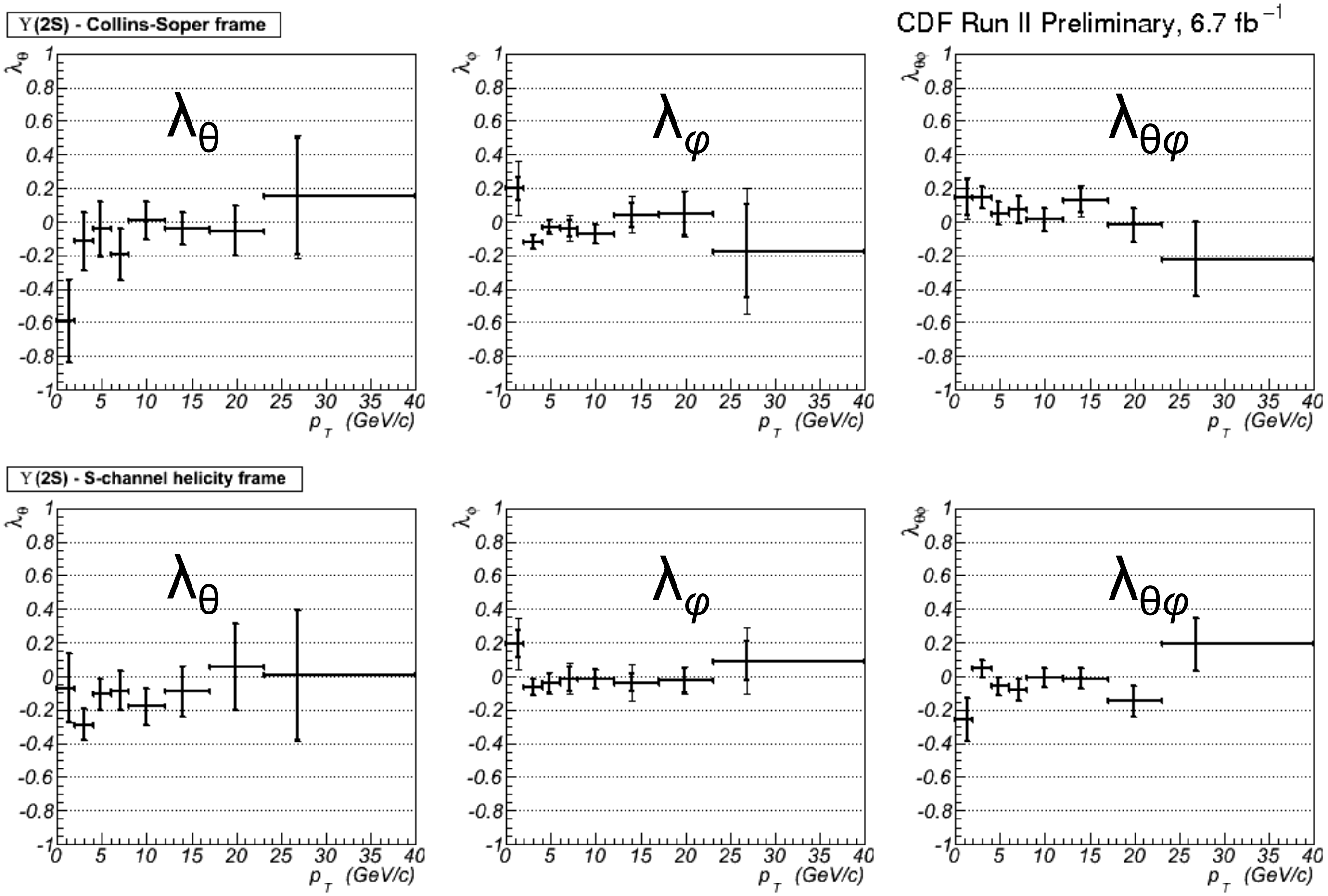
- Differences generally consistent with fluctuation predicted from simulation
- Difference used to quantify systematic uncertainties on λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$

Results for ϒ(1S) state



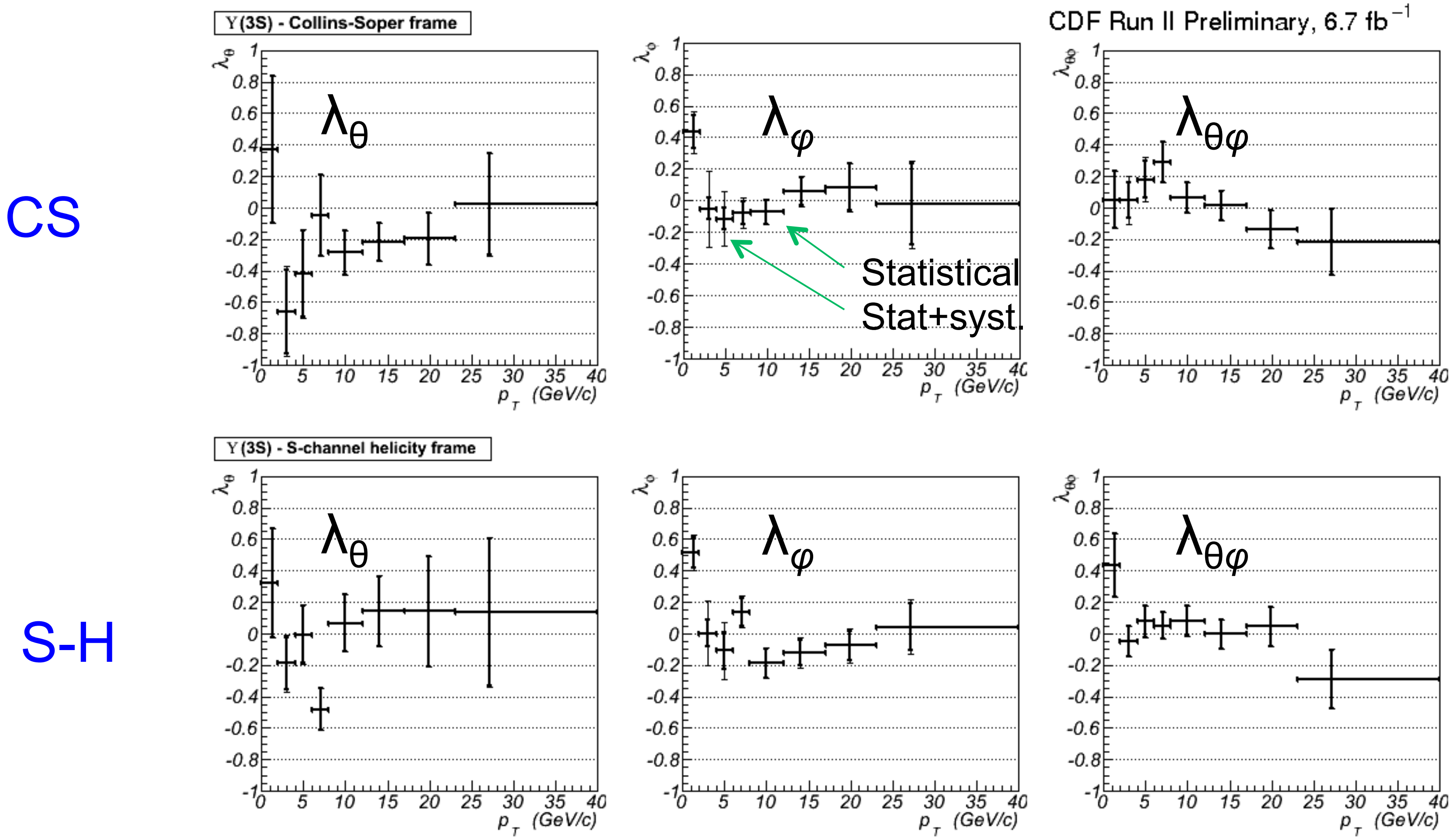
- Nearly isotropic… what about the ϒ(2S) and ϒ(3S) states?

Results for Υ(2S) state



- Looks isotropic, even at large values of p_T …

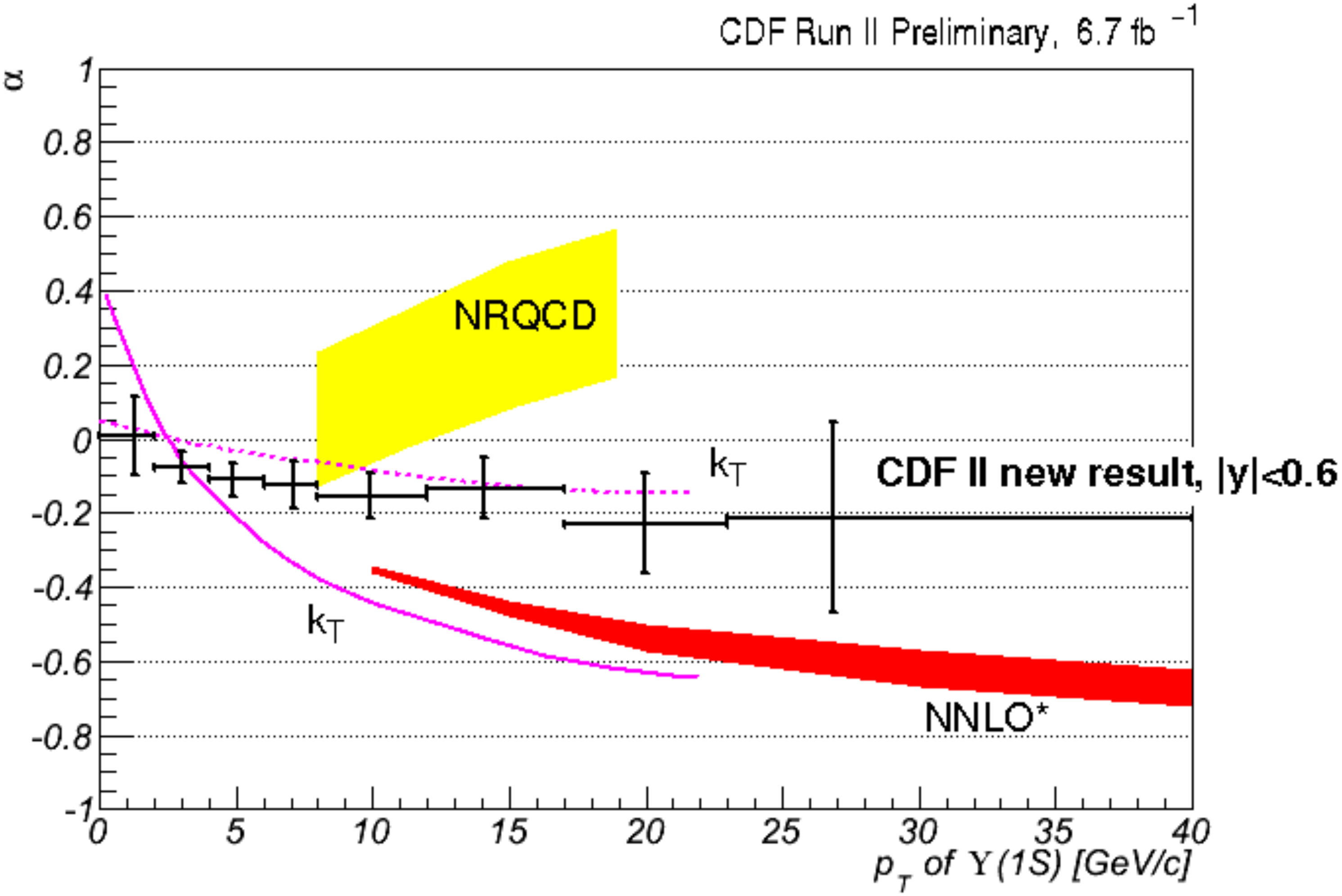
First measurement of ϒ(3S) spin alignment



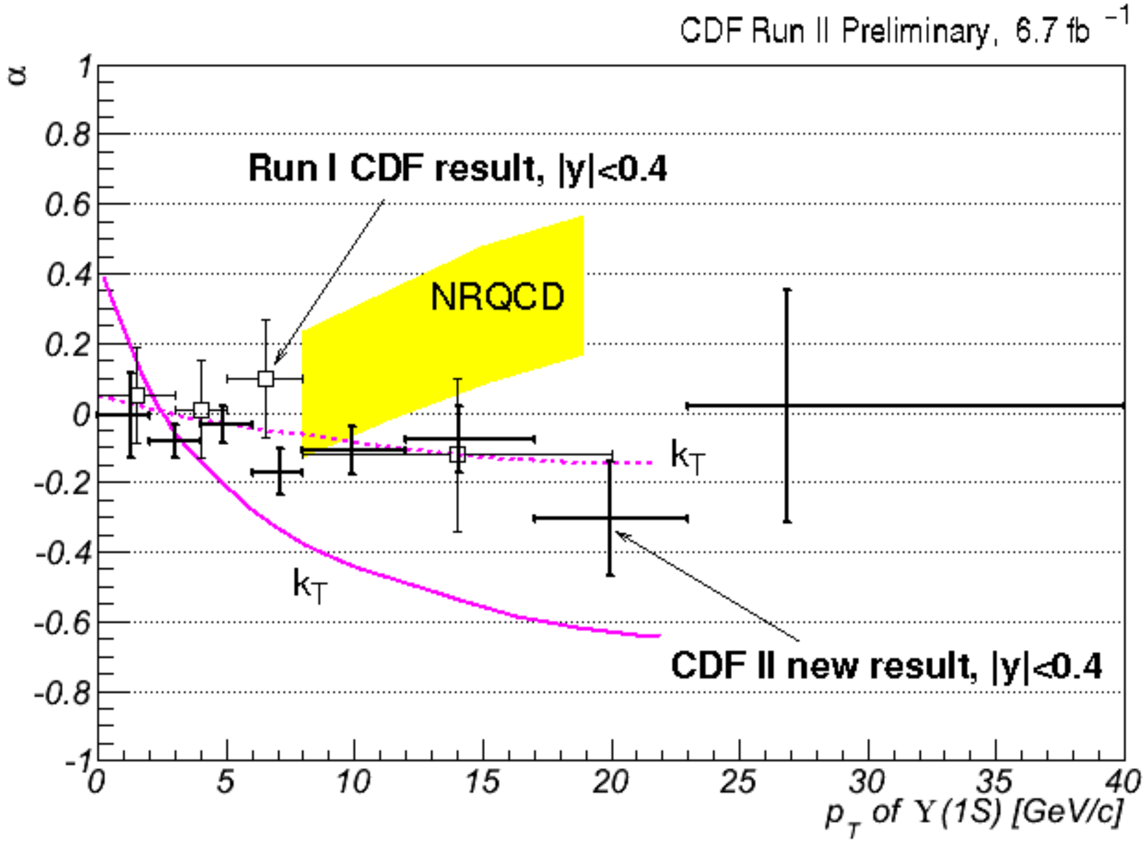
- **No evidence for significant polarization.**

Comparison with Models

- Old predictions for λ_θ in the S-channel helicity frame



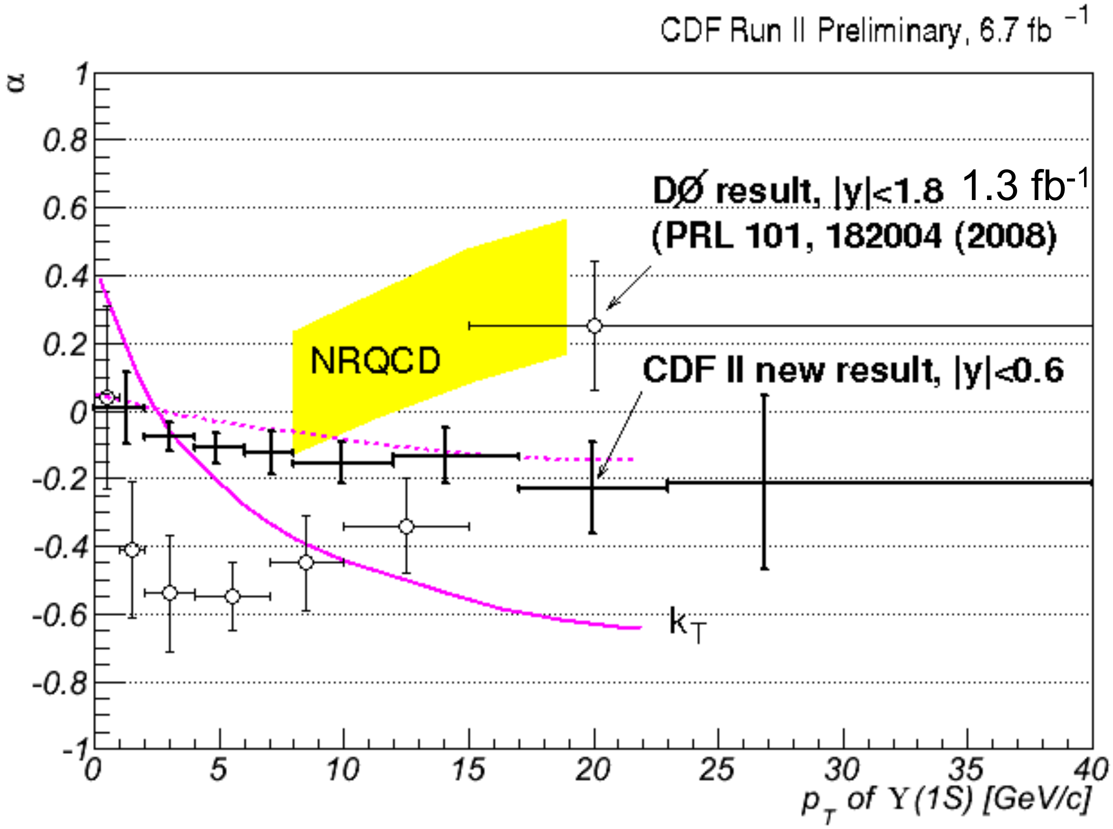
Comparison with previous results



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

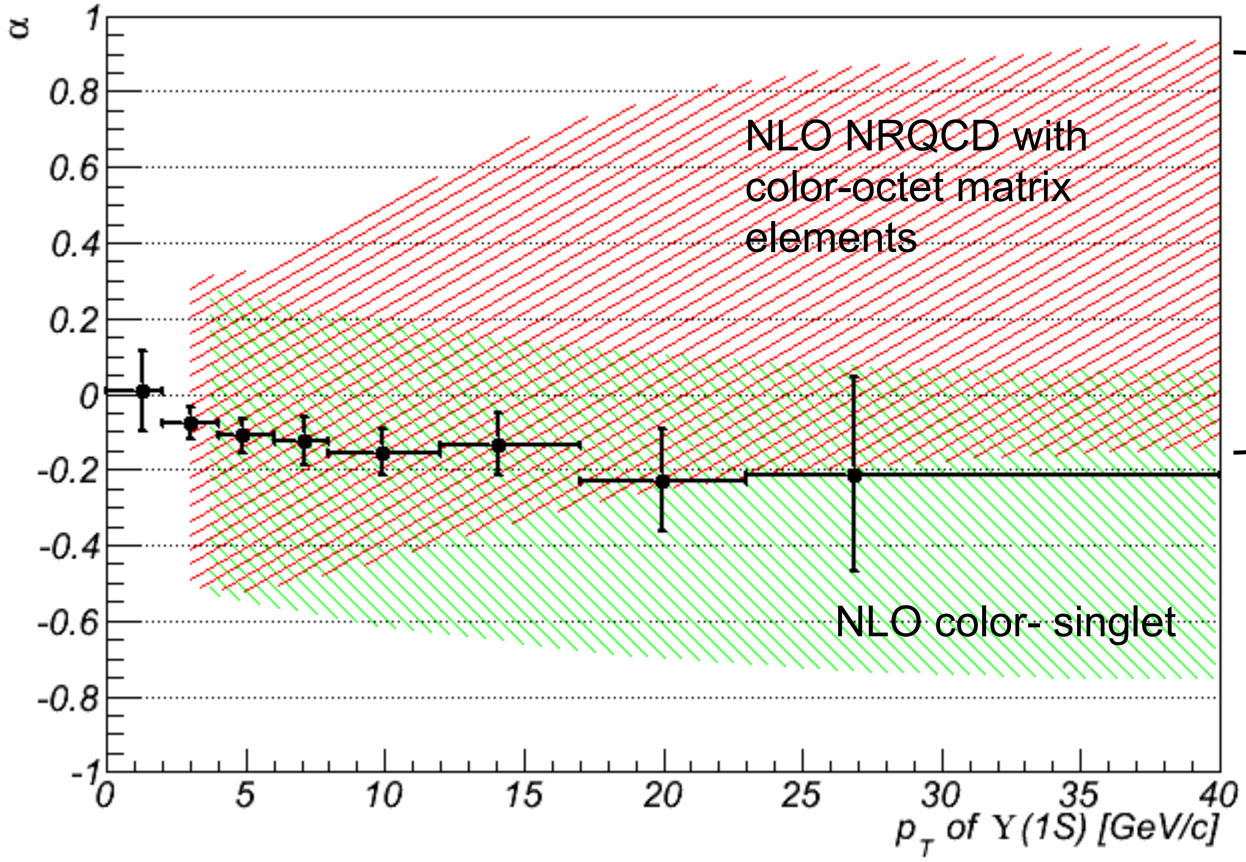


NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)

- Does not agree with result from DØ at about the 4.5σ level

Comparisons with newer calculations

CDF Run II preliminary – 6.7 fb^{-1}



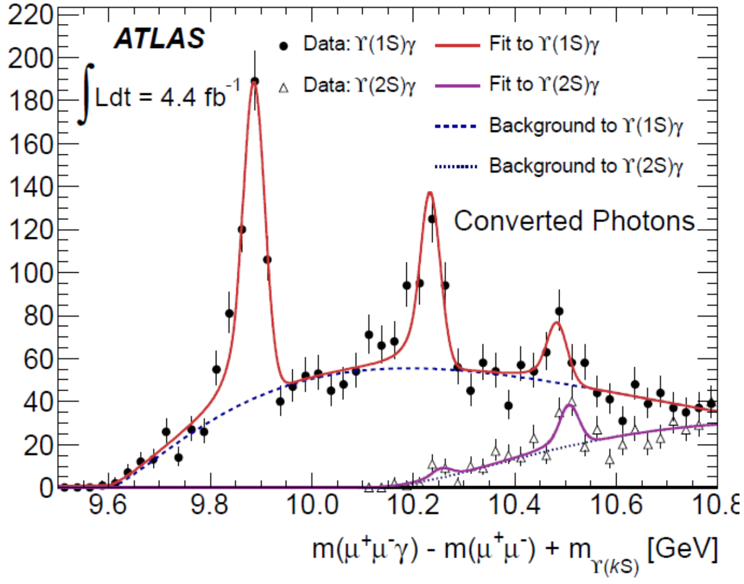
Significant uncertainty due to feed-down from states (conservative assumptions)

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

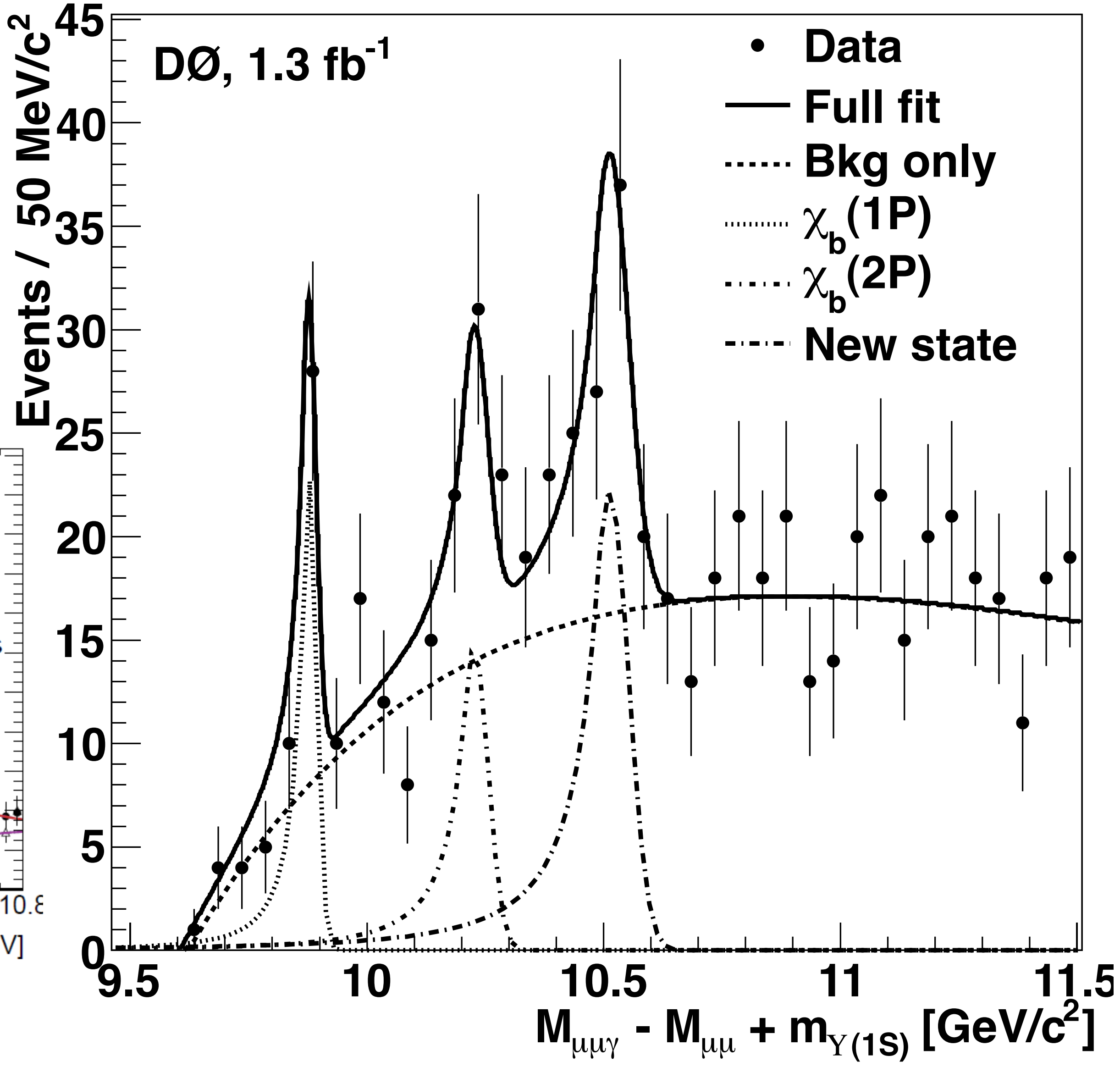
- NLO NRQCD – Gong, Wang & Zhang, Phys. Rev. D83, 114021 (2011)
- Color-singlet NLO and NNLO* - Artoisenet, *et al.* Phys. Rev. Lett. 101, 152001 (2008)

χ_b States in $\Upsilon(1S) + \gamma$

Consistent with ATLAS observation



ATLAS – arXiv:1112.5154



Summary (1)

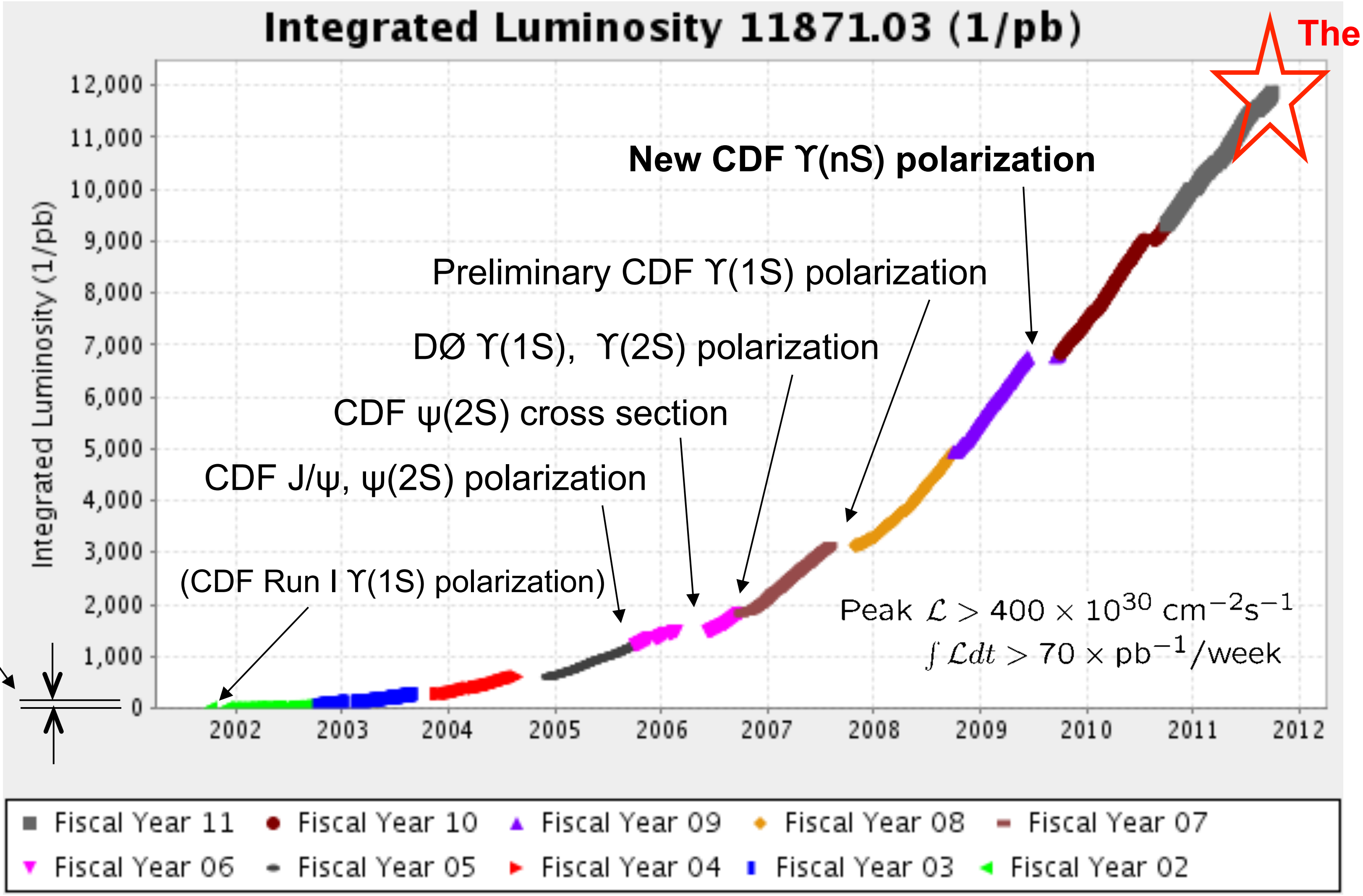
- Polarizations and feed-down provide important tests of production models.
- CDF measurement of Upsilon polarization
  - for 1S, 2S, and 3S states,
  - in Collins-Soper and helicity frames, and
  - using full 3-D measurement,
- Result indicates that production is isotropic, for all pT and even for Y(3S).
- D0 measurements of χ_b(3P) state help establish it as a possible source of feed-down.

Summary (2)

- More effort is needed to
  - complete measurements on bottomonium system
    - better understand feed-down fractions
    - measure the Upsilon cross section
  - and extend the techniques to the charmonium system
    - handle additional non-prompt production

Additional Material

Tevatron Run II



The end!

New CDF Υ(nS) polarization

Preliminary CDF Υ(1S) polarization

DØ Υ(1S), Υ(2S) polarization

CDF ψ(2S) cross section

CDF J/ψ, ψ(2S) polarization

(CDF Run I Υ(1S) polarization)

Run I

Peak $\mathcal{L} > 400 \times 10^{30}$ cm^{-2}s^{-1}

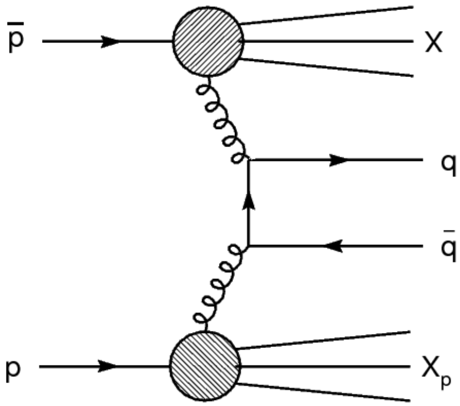
$\int \mathcal{L}dt > 70 \times$ pb^{-1}/week

Another Model: “k$_T$ factorization”

$$\sigma_{pp} = \int G(x_1, \mu^2)\, G(x_2, \mu^2)\, \sigma_{gg}(x_1, x_2)\, dx_1\, dx_2$$

$$G(x, \mu^2) \rightarrow \mathcal{F}_g(x, k_T^2, \mu^2)$$

“un-integrated gluon densities”



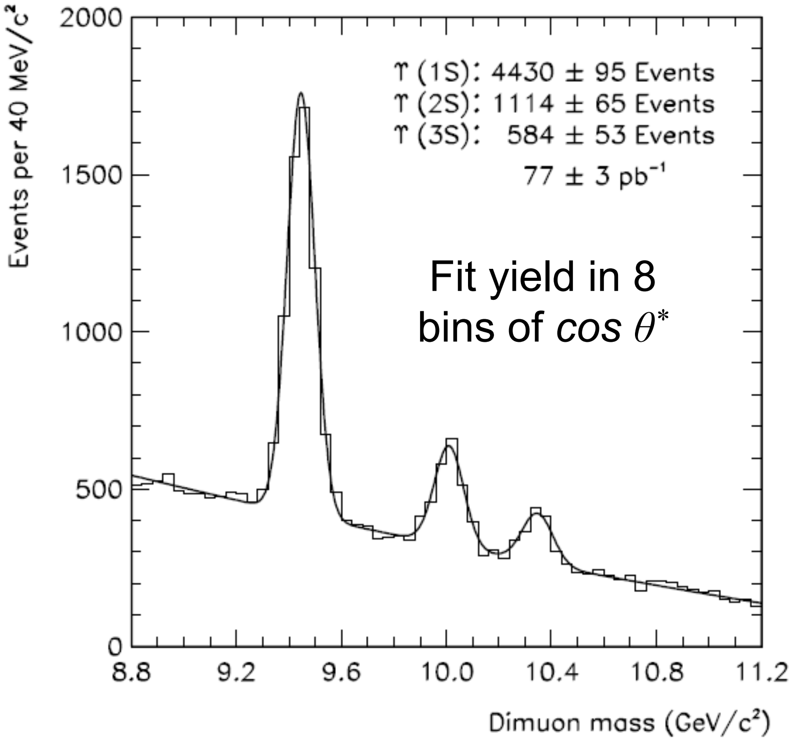
$$\overline{\epsilon_g^{\mu} \epsilon_g^{*\nu}} = k_T^{\mu} k_T^{\nu} / |k_T|^2$$

⇒ Initial state gluon polarization related to kT

- No need for color-octet terms…
- Predicted ***longitudinal*** Υ polarization for $p_T \gg m_Q$

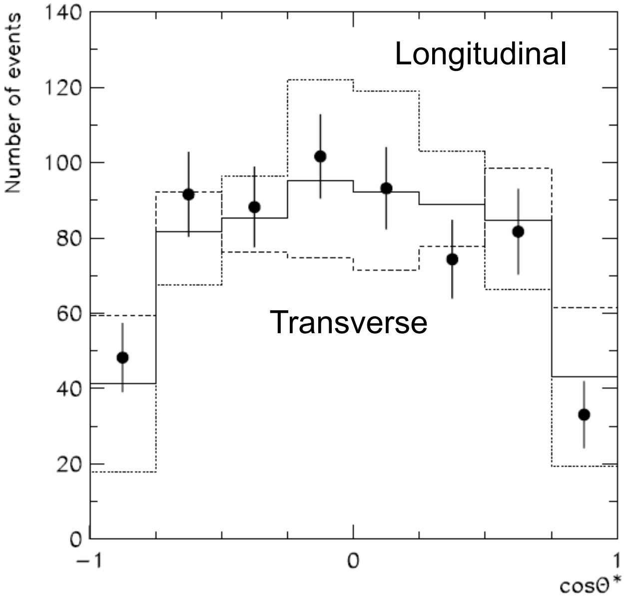
CDF Measurement

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



Fit yield in 8 bins of *cos* θ^*

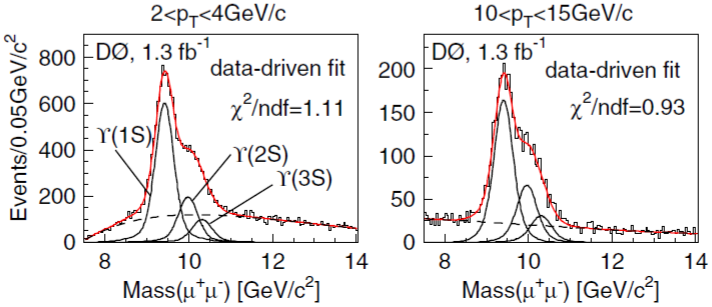
Template distributions for transverse/longitudinal polarization strongly influenced by detector acceptance.



Transverse: $1+\cos^2\theta^*$
Longitudinal: $1-\cos^2\theta^*$

- Observed distribution is ***isotropic*** - neither longitudinal nor transverse.

ϒ Polarization from DØ in Run II



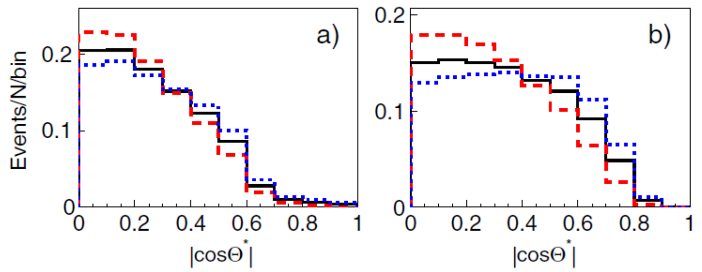
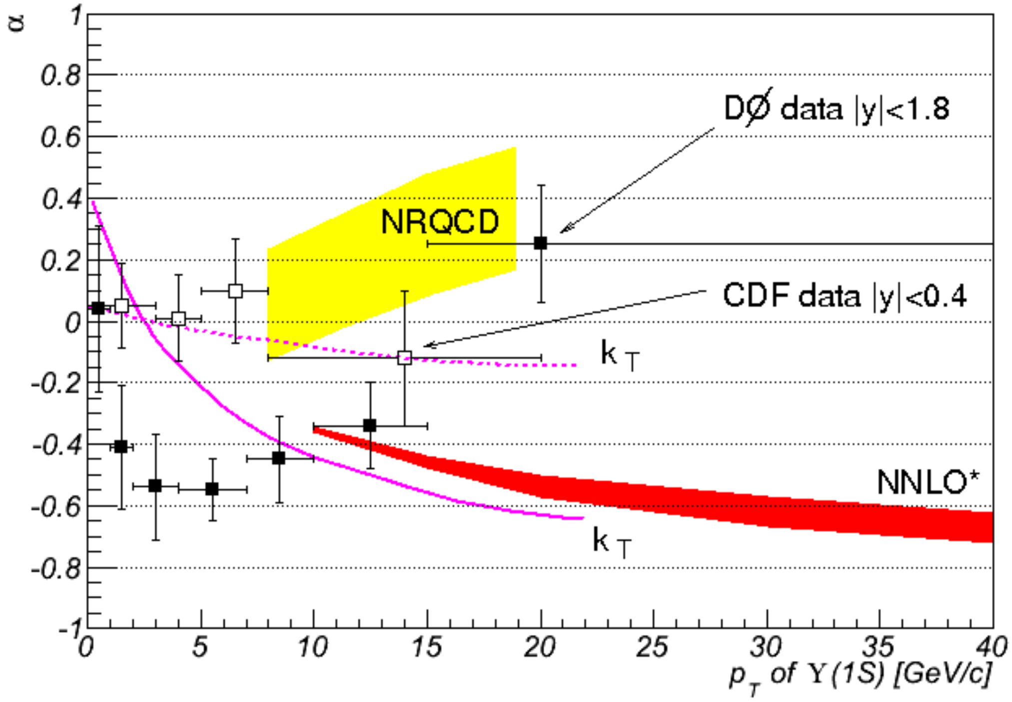


FIG. 2 (color online). Monte Carlo $|\cos\theta^*|$ distributions after all selection requirements for different α values: -1 (dashed histogram), 0 (solid histogram), and $+1$ (dotted histogram). (a) $0 < p_T^\Upsilon < 1$ GeV/c, (b) $p_T^\Upsilon > 15$ GeV/c.

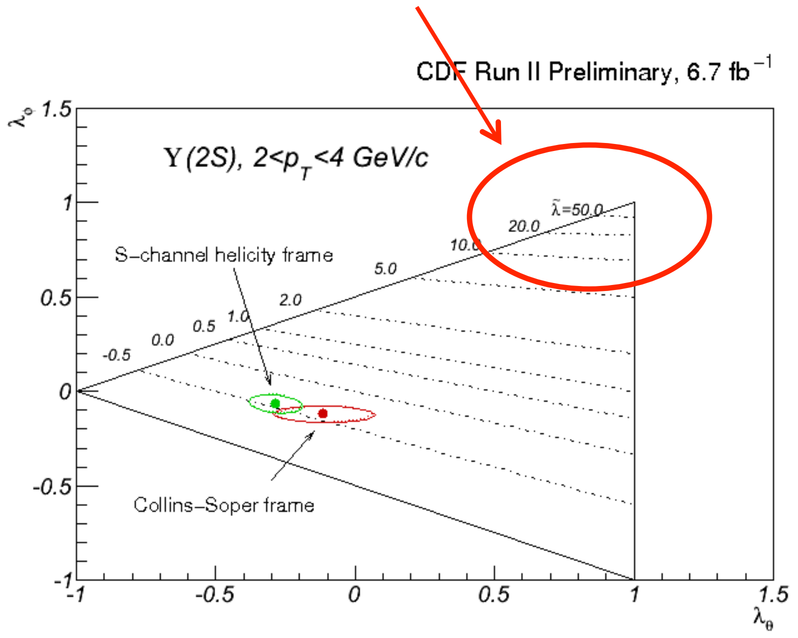


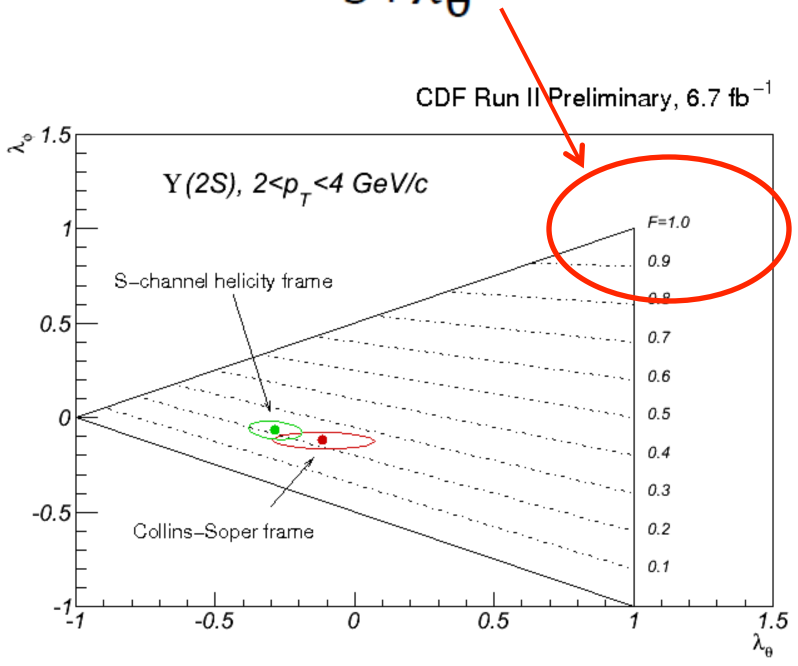
DØ Run II: Phys. Rev. Lett. 101, 182004 (2008).
CDF Run I: Phys. Rev. Lett. 88, 161802 (2002).
NRQCD: Phys. Rev. D63, 071501(R) (2001).
k_T-factorization: JETP Lett. 86, 435 (2007).
NNLO*: Phys. Rev. Lett. 101, 152001 (2008).

Other Rotational Invariants

$\lambda = \lambda_\theta + 3\lambda_\varphi / 1 - \lambda_\varphi$

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





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

This is the part that is invariant under rotations.

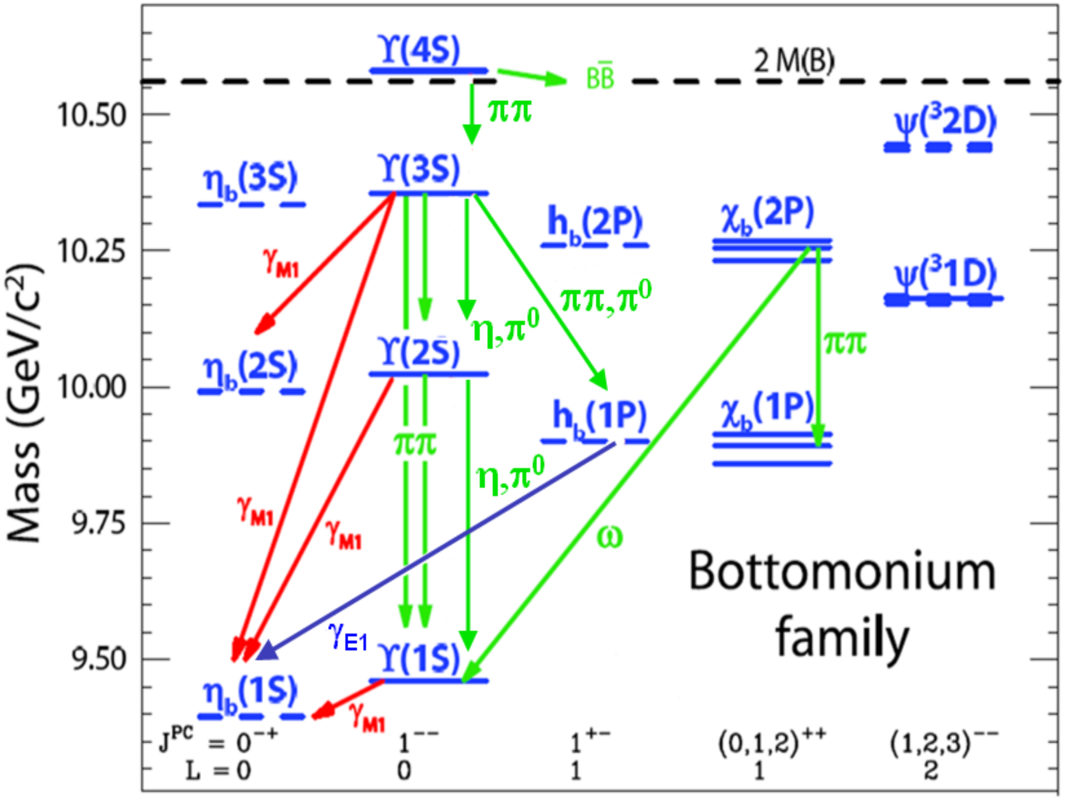
Bottomonium Spectroscopy

$$\eta_b(nS) = n^1S_0$$

$$\Upsilon(nS) = n^3S_1$$

$$h_b(nP) = n^1P_1$$

$$\chi_{bJ}(nP) = n^3P_J$$



Theoretical Description

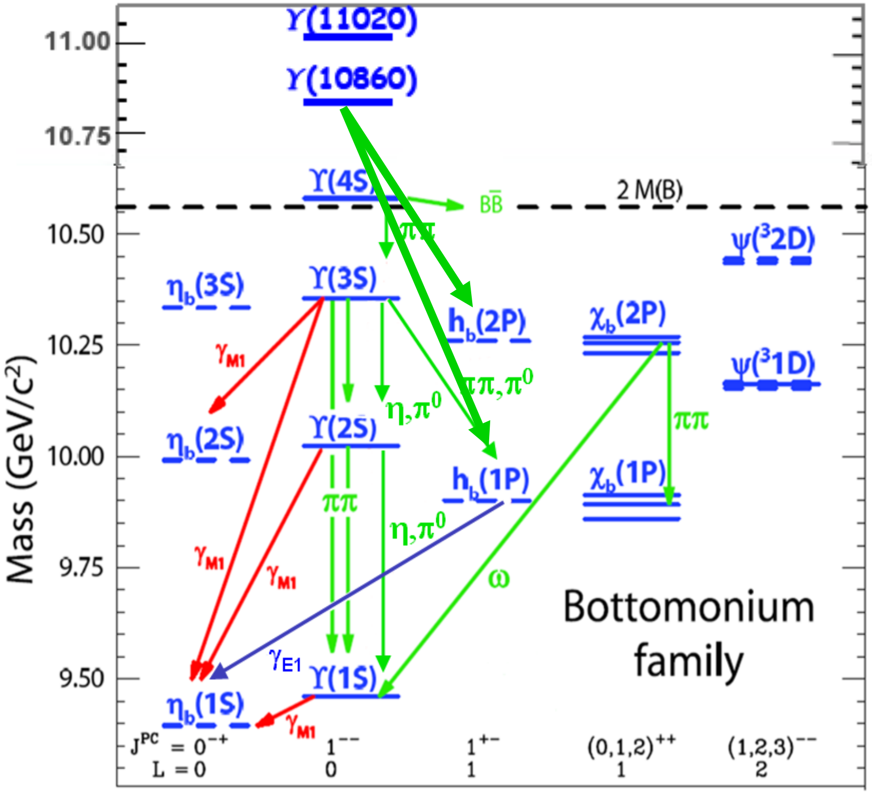
- Heavy quarks → non-relativistic mechanics
- Potential models:

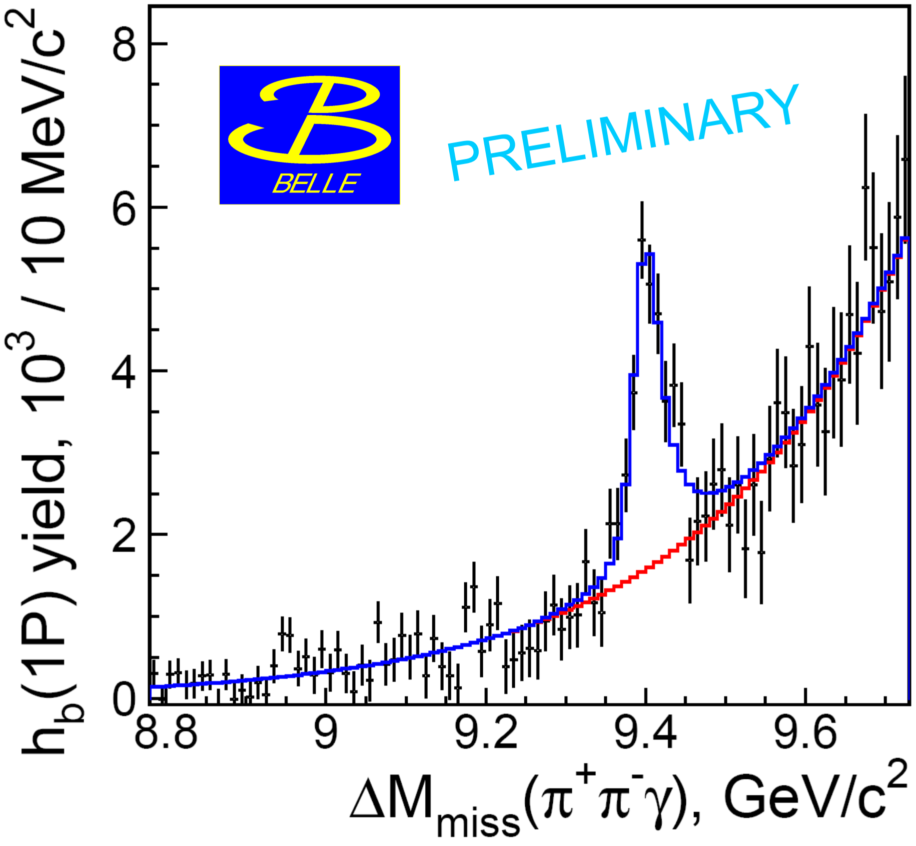
$$V_0(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_Q^2}\delta(r)\vec{S}_Q \cdot \vec{S}_{\overline{Q}}$$

$$V_{spin-dep} = \frac{1}{m_Q^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

- Reasonably good empirical description of spectrum and transitions.
- Small $1/m_Q$ → Effective field theories
  - HQET: $1/m_Q$
  - NRQCD: $\alpha_s, v : (M_Q v^2)^2 \ll (M_Q v)^2 \ll M_Q^2$

Bottomonium Spectroscopy





QWG, October 2011

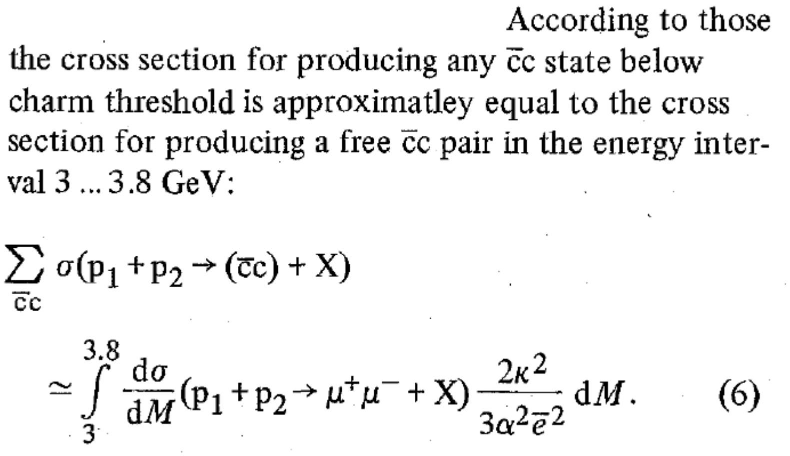
$\Upsilon(5S) \rightarrow Z_b^+ \pi^-$

↳ $h_b\,(nP)\ \pi^+$

↳ $\eta_b(mS)\ \gamma$

Color Evaporation Model

- cc pairs produced with $2m_c < m < 2m_D$ must eventually form a bound state.

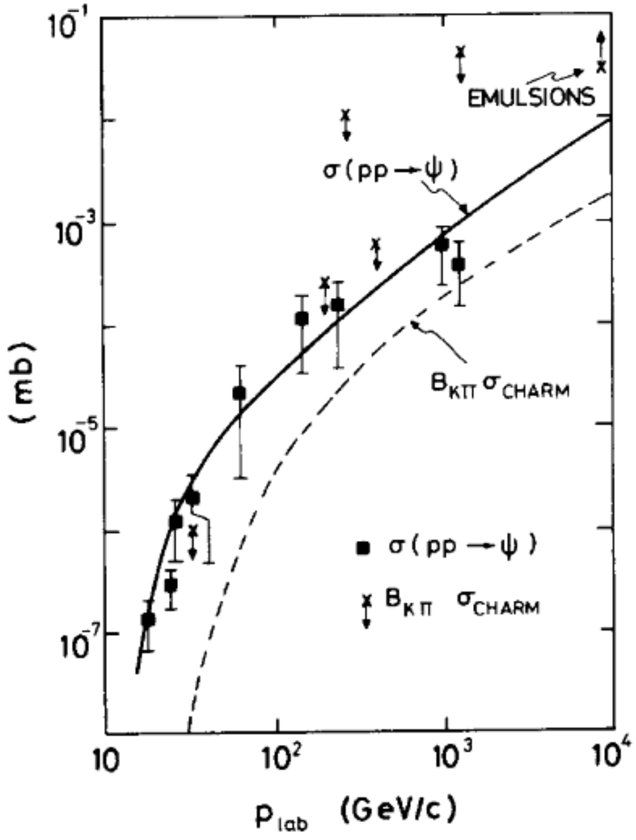


According to those the cross section for producing any $\bar{c}c$ state below charm threshold is approximatley equal to the cross section for producing a free $\bar{c}c$ pair in the energy interval 3 ... 3.8 GeV:

$$\sum_{\bar{c}c} \sigma(p_1 + p_2 \to (\bar{c}c) + X)$$
$$\simeq \int_3^{3.8} \frac{d\sigma}{dM}(p_1 + p_2 \to \mu^+\mu^- + X)\,\frac{2\kappa^2}{3\alpha^2\bar{e}^2}\,dM. \qquad (6)$$

Fritzsch - Phys. Lett. B 67, 217 (1977)

Halzen - Phys. Lett. B 69, 105 (1977)



- Unable to predict polarization…

Color Evaporation Model

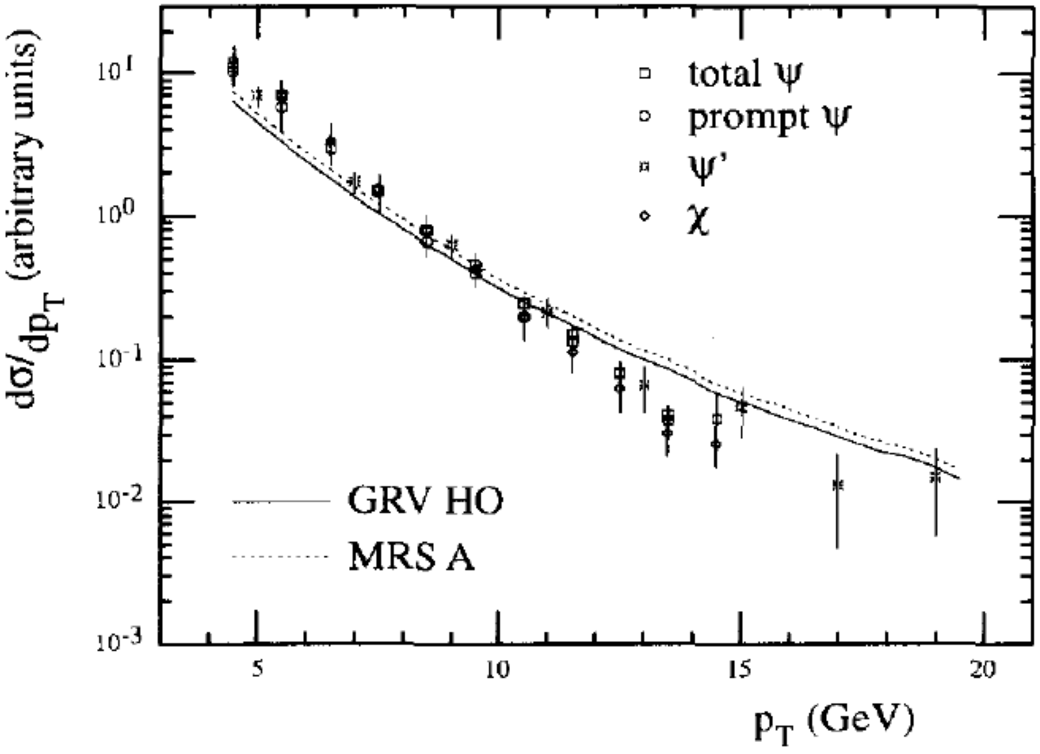


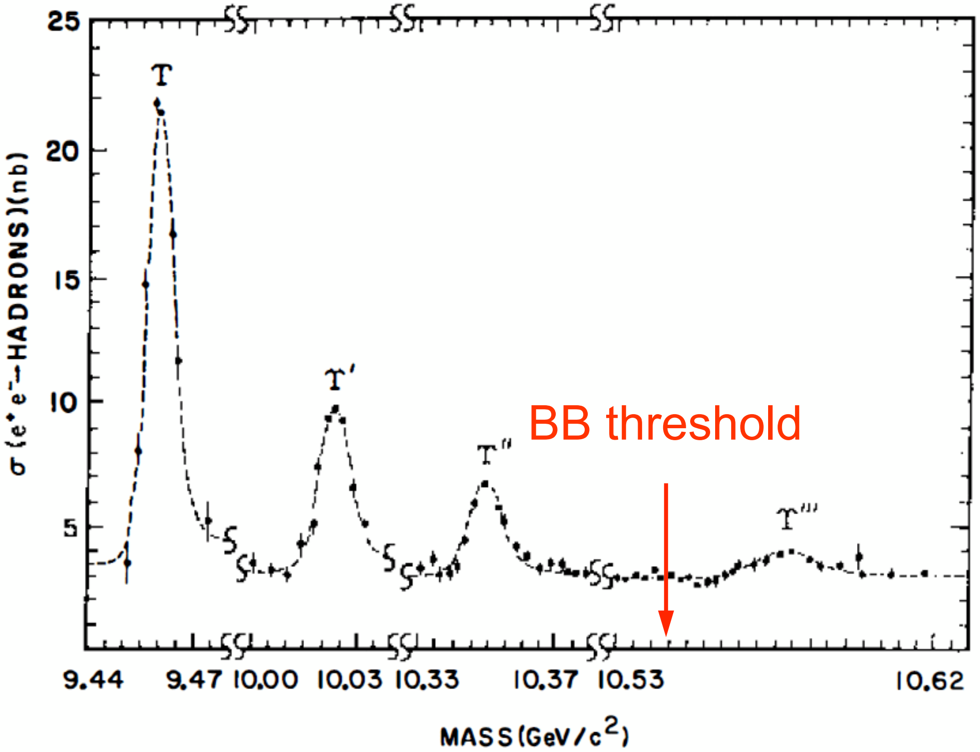
Fig. 6. Data from the CDF Collaboration [23], shown with arbitrary normalization. The curves are the predictions of the color evaporation model at tree level, also shown with arbitrary normalization. The normalization is correctly predicted within a *K* factor of 2.2.

Compare the overall shape of the p_T spectrum…

Maybe okay?

…but everything has been scaled…

Heavy Quarkonium: $\psi(cc)$ and $\Upsilon(bb)$



BB threshold

Figure 3 Cross section for e^+e^- annihilations into hadrons at CESR (CUSB data).

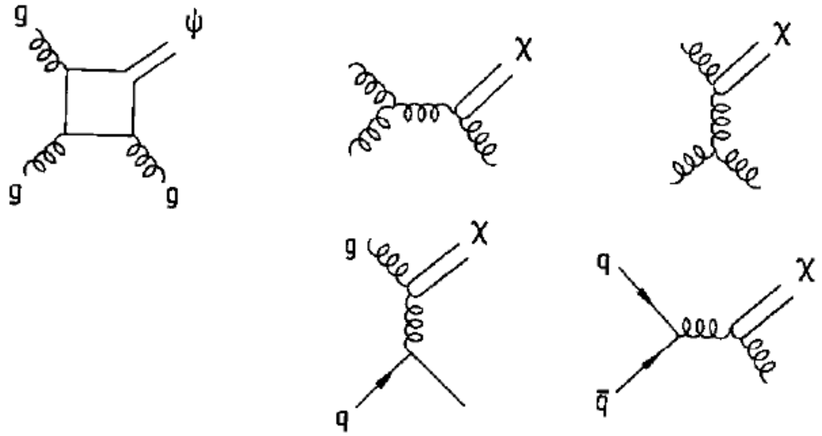
- Very simple system – non-relativistic QM works:

$$E_n \psi_n(x) = \left(-\hbar^2/2m \nabla^2 + V(x)\right)\psi_n(x)$$

Can QCD Describe Heavy Quark Production?

Einhorn & Ellis: Phys. Rev. D12, 2007 (1975).

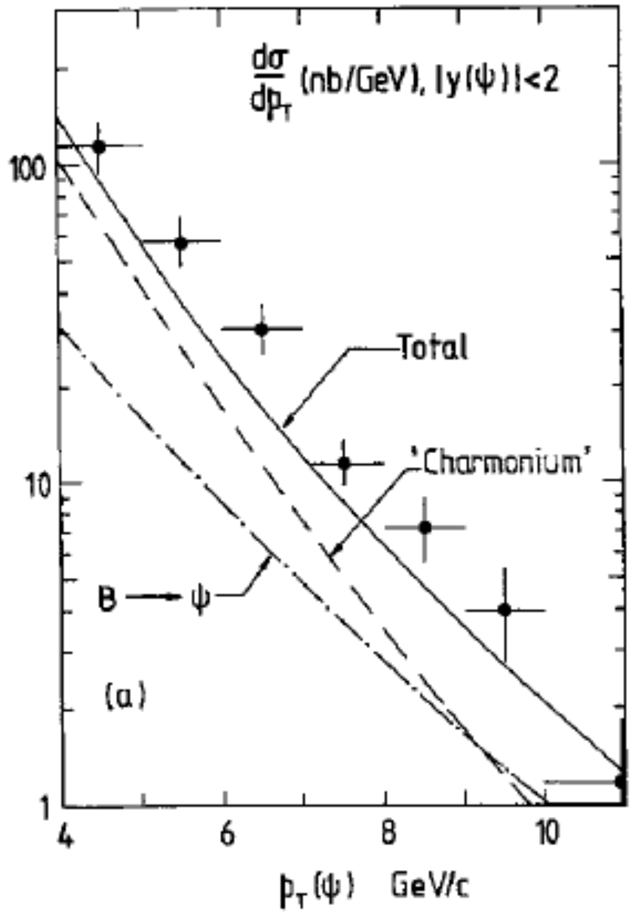
Glover, Martin & Stirling: Z. Phys. C38, 473 (1988).



The observed shape agrees well with the QCD expectations and the normalisation is within the error associated with the QCD calculation.

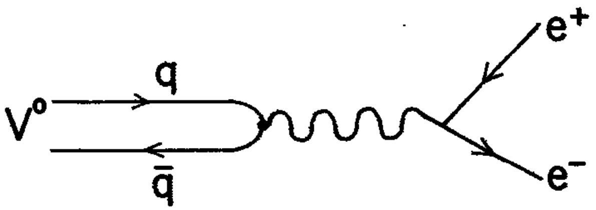
Or not…

Comparison with UA1 data at $\sqrt{s} = 630\ GeV$



Color-Singlet Production Model

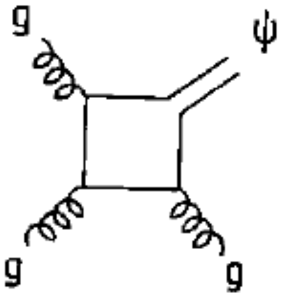
- Production/decay via $e^{+} e^{-}$:



$\langle J/\psi | c\, \gamma^{\mu}\, c | 0 \rangle = \boldsymbol{f_{J/\psi}}\, \varepsilon^{\mu}$

$\boldsymbol{f_{J/\psi}} \propto R(0)$ $\boldsymbol{f_{\chi_c}} \propto R'(0)$

- Production at hadron colliders:



$$\frac{d\hat{\sigma}}{d\hat{t}} = \alpha_s^3(Q^2, \Lambda^2)\,|R(0)|^2\,|\mathcal{M}|^2$$

- Matrix elements also predict ***polarization***.

Non-Relativistic QCD

Caswell & Lepage – Phys. Lett. 167B, 437 (1986)

Bodwin, Braaten & Lepage – Phys. Rev. D 51, 1125 (1995)

- Expansion in powers of and
- Factorization of different energy scales:

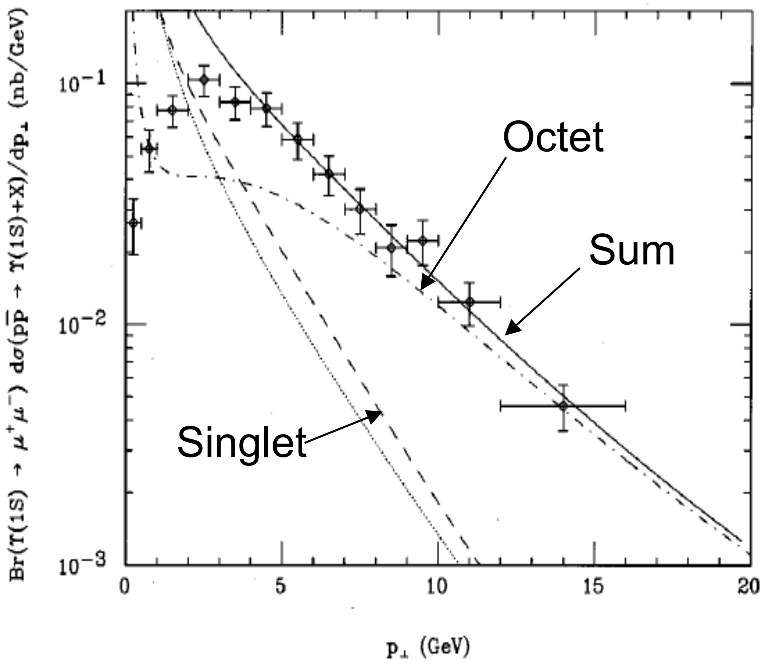
Perturbative QCD

NRQCD matrix elements

- Bound states are "color singlets" – no net color charge.
-
- *Color-octet terms might be really important!*

NRQCD + Color-Octet Models

- Matrix elements tuned to accommodate Tevatron results



Cho & Leibovich, PRD 53, 6203 (1996).

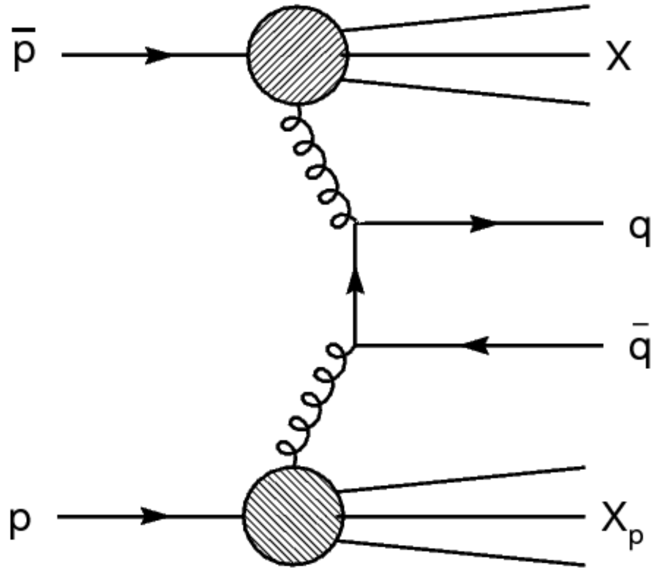
Unknown NRQCD Matrix Elements adjusted to match data.

Agreement with cross section is not too surprising now.

We need an independent observable to really test the model.

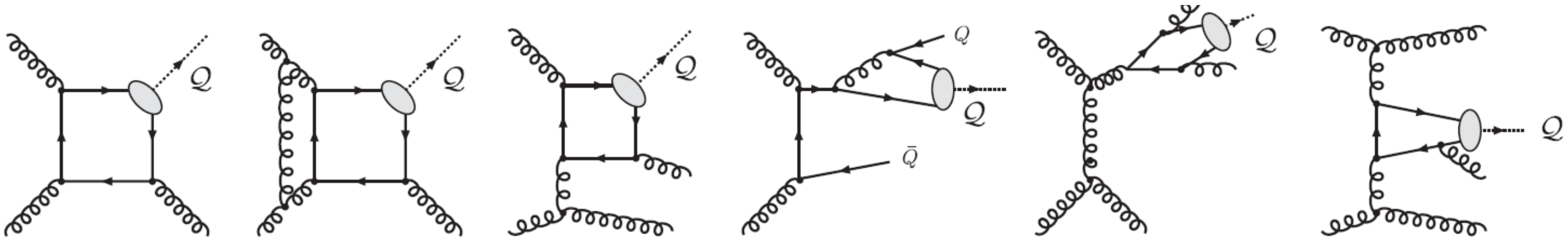
- Nearly on-shell gluons can fragment to form Υ
- Predicted ***transverse*** Υ polarization for $p_T \gg m_Q$

Another Model: "k_T factorization"

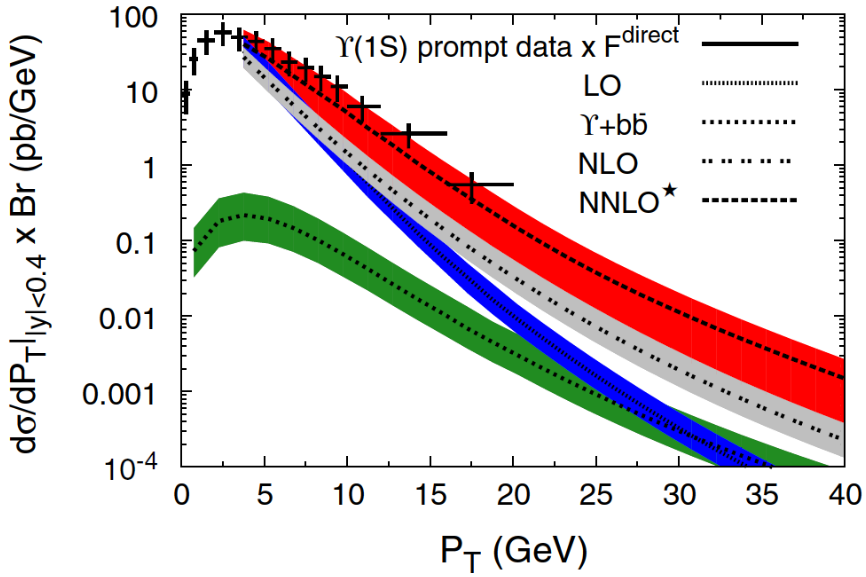


- Initial state gluon polarization related to their transverse momentum, k_T.
- No need for color-octet terms…
- Predicted ***longitudinal*** Υ polarization for $p_T \gg m_Q$

Higher-order QCD calculations



Artoisenet, et al – [Phys. Rev. Lett. 101, 152001 (2008).]

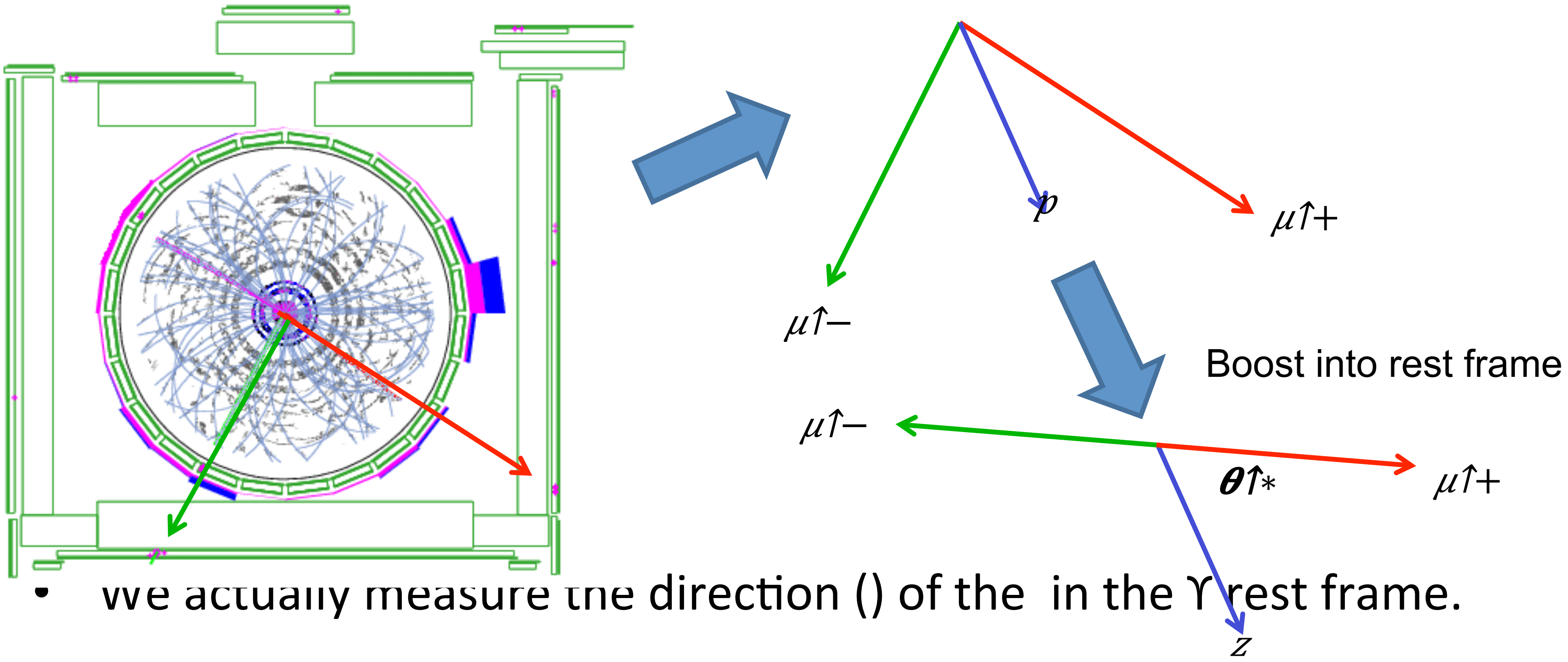


- *Partial* calculation including terms up to α_s^5 …
- Large increase in cross section compared with LO calculation
- No need for color-octet contributions

- Predicts ***longitudinal*** Υ polarization for $p_T \gg m_Q$

Measuring “Polarization”

- We don’t really measure polarization…

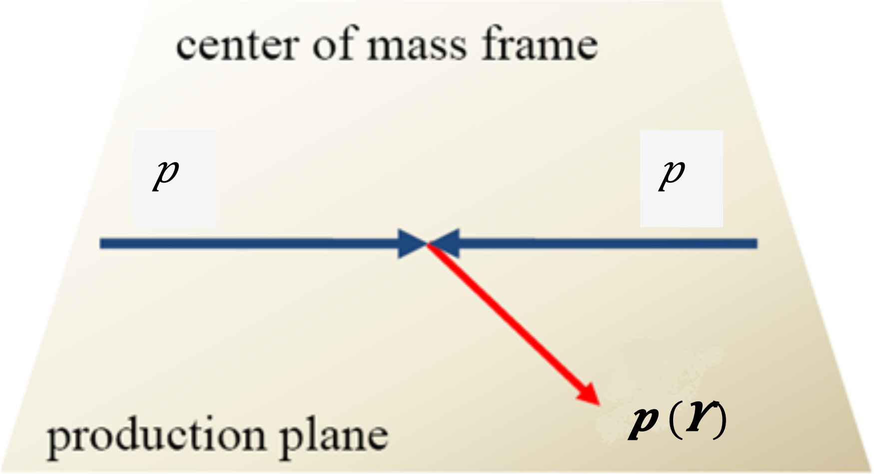


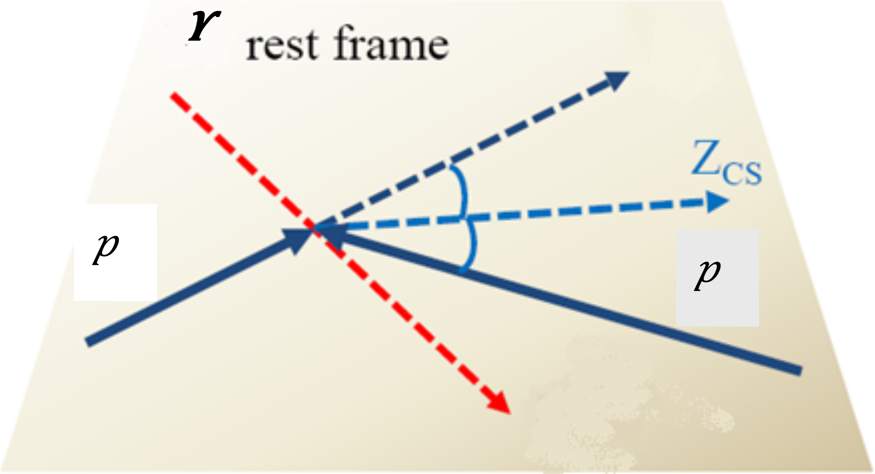
Boost into rest frame

- We actually measure the direction () of the in the ϒ rest frame.

Which coordinate system?

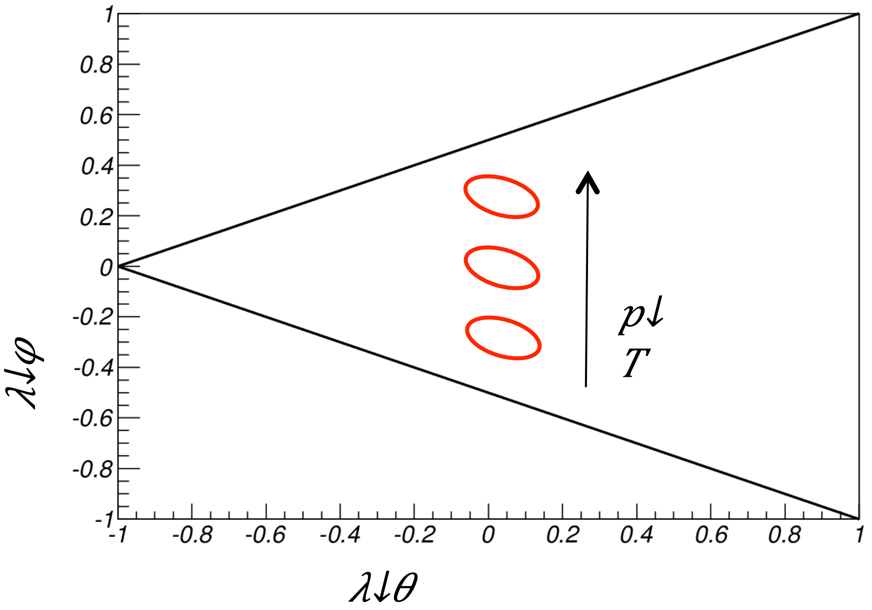
- S-channel Helicity (SH) – Υ momentum vector defines the z-axis, the x-axis is in the production plane
- Collins-Soper (CS) – z-axis bisects beam momentum vectors in Υ rest frame, x-axis in the production plane:



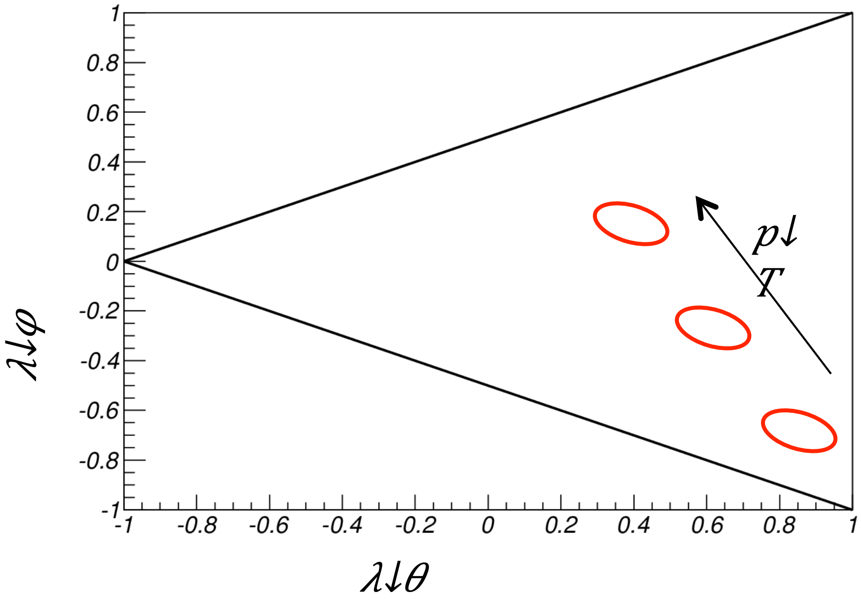


Could it be possible?

S-channel helicity frame



Collins-Soper frame

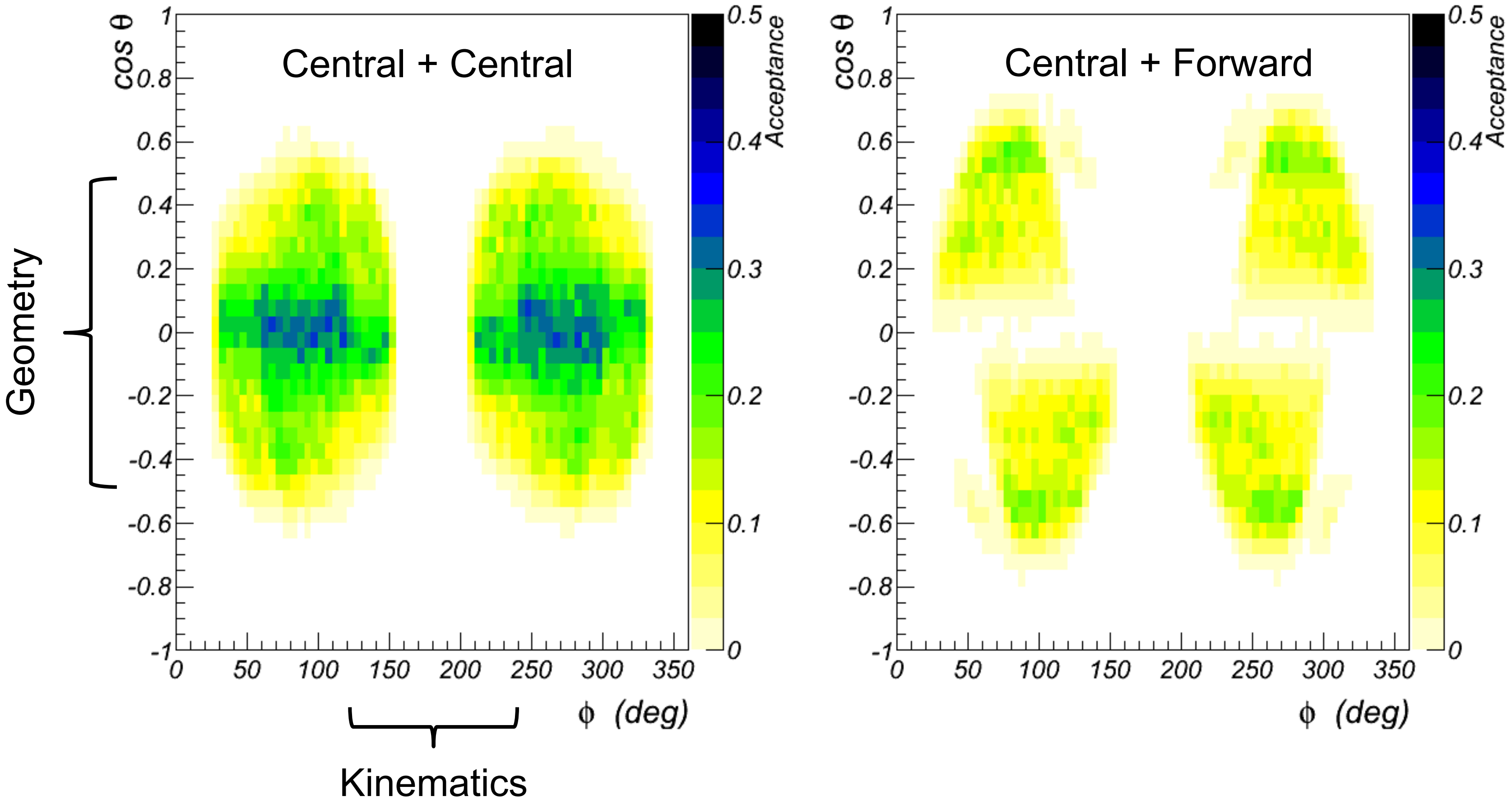


If $\lambda{\downarrow}\theta$ is zero in one coordinate frame, then it ***must*** be non-zero in another frame!

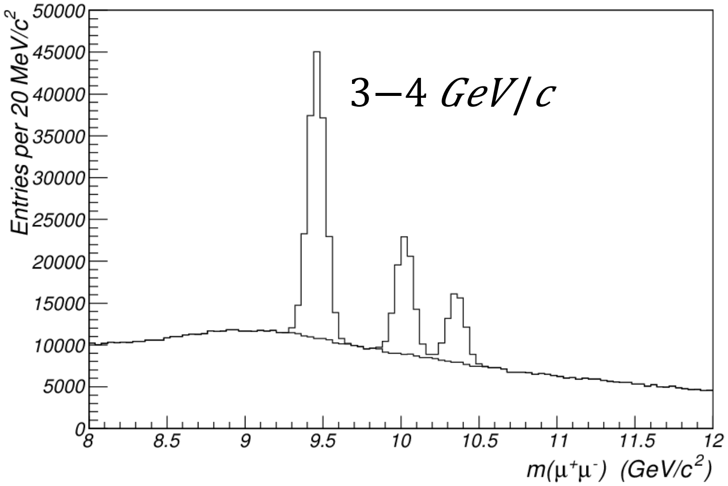
(provided $\lambda{\downarrow}\varphi$ is not also zero)

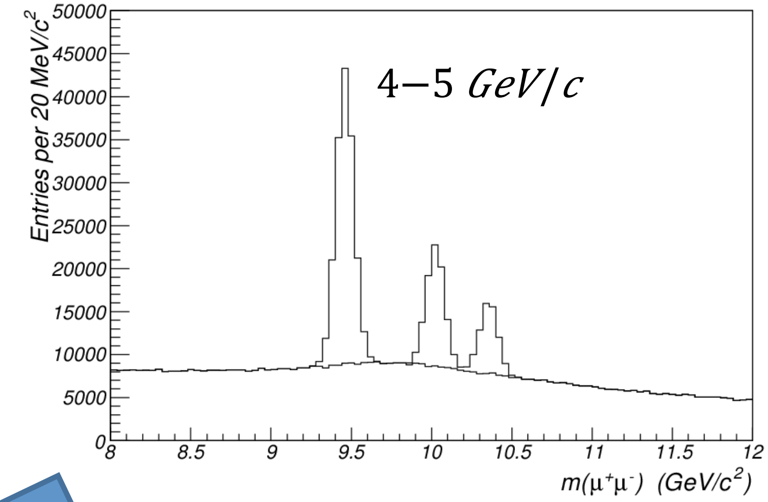
Geometric Acceptance

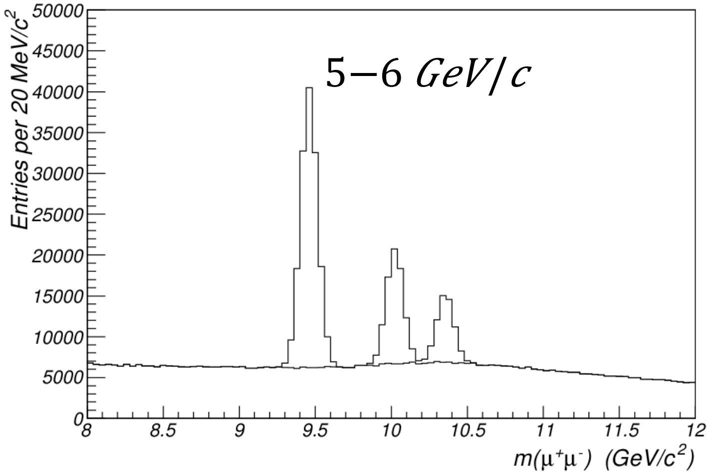
- Geometric acceptance calculated with full detector simulation for each p_T range analyzed
- Muon detectors simulated with 100% efficiency



Background Structure







This is just all toy Monte Carlo but it makes us worried…

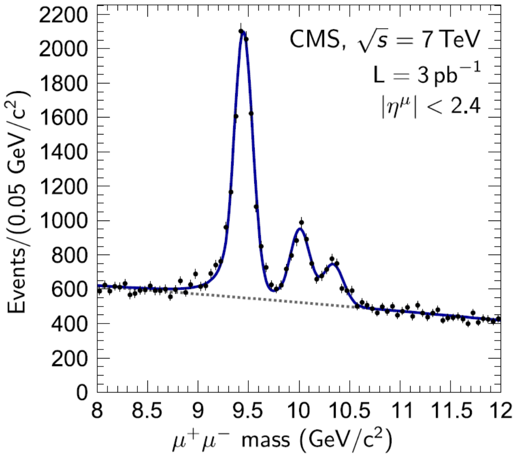
A polynomial may not describe the mass distribution under the signal when fitted using just the sidebands.

Systematic Uncertainties

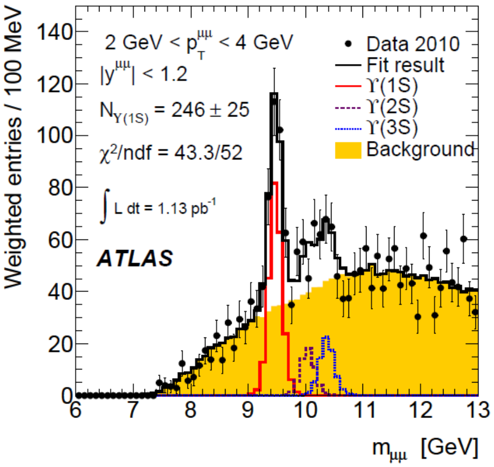
- Efficiency measurement:
  - Vary measured trigger efficiencies by
- Monte Carlo statistics:
  - Impact of finite sample sizes in acceptance calculated using toy Monte Carlo experiments
- Background scale factor:
  - Compare linear and quadratic interpolation from sidebands into signal region
- Frame invariance tests:
  - Treat as a systematic uncertainty
  - Consistent with statistical fluctuations in almost all cases
- All are generally much smaller than statistical uncertainty

New Cross Section Measurements

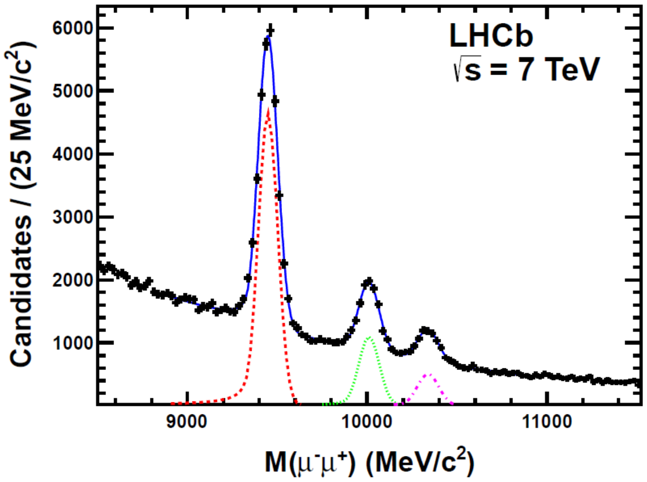
Phys. Rev. D83, 112004 (2011)



Phys. Lett. B 705 (2011), 9



arXiv:1202.6579



- 10-20% systematic uncertainty due to unknown polarization.