高能物理学会第八届全国会员代表大会暨学术年会

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Feasibility Study for Measuring J/ψ Polarization at CMS

Analysis details in CMS AN-2009/091-v3

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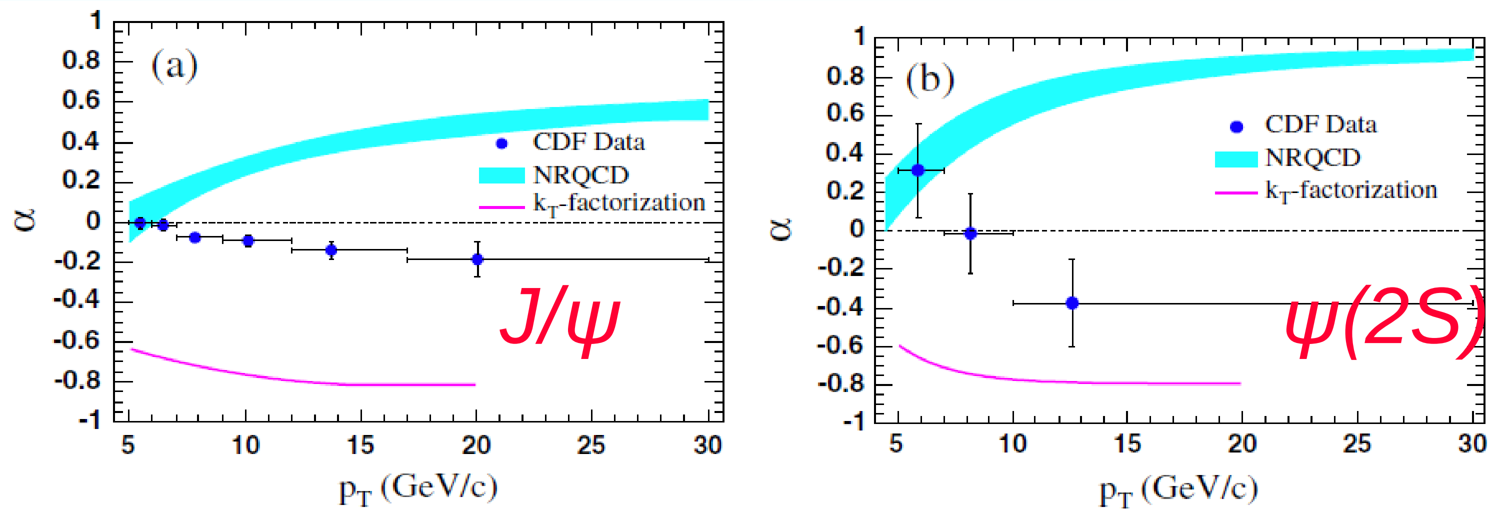
Motivation

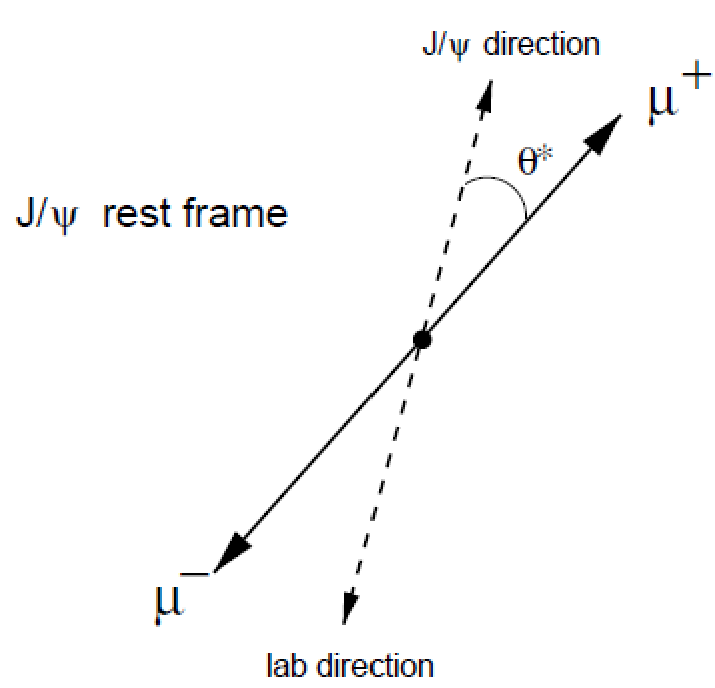
- Non-relativistic QCD theory predicts prompt *J/ψ and ψ(2S)* mesons will be produced with increasingly transverse polarizations as a function of the meson's p_T .
- But the recent measurements at Tevatron by CDF seem to be in dramatic contradiction with this prediction.



- Polarization measurement is also important for measuring *J/ψ* cross section.

Polarization Parameter

- In the J/ψ rest frame, the μ^+ makes an angle θ^* with the J/ψ direction in the lab frame. The angular distribution depends on the polarization parameter α



$$\frac{d\Gamma}{d\cos\theta^*} = I_\alpha(\cos\theta^*) = \frac{3}{2(\alpha+3)}(1+\alpha\cos^2\theta^*)$$

If J/ψ is fully Transverse polarization, α=1

If J/ψ is fully Longitudinal polarization, α=-1

We can use a related alignment parameter η to measure the fraction of longitudinal alignment:

$$\Gamma_L / \Gamma = \eta = (1-\alpha)/(3+\alpha)$$

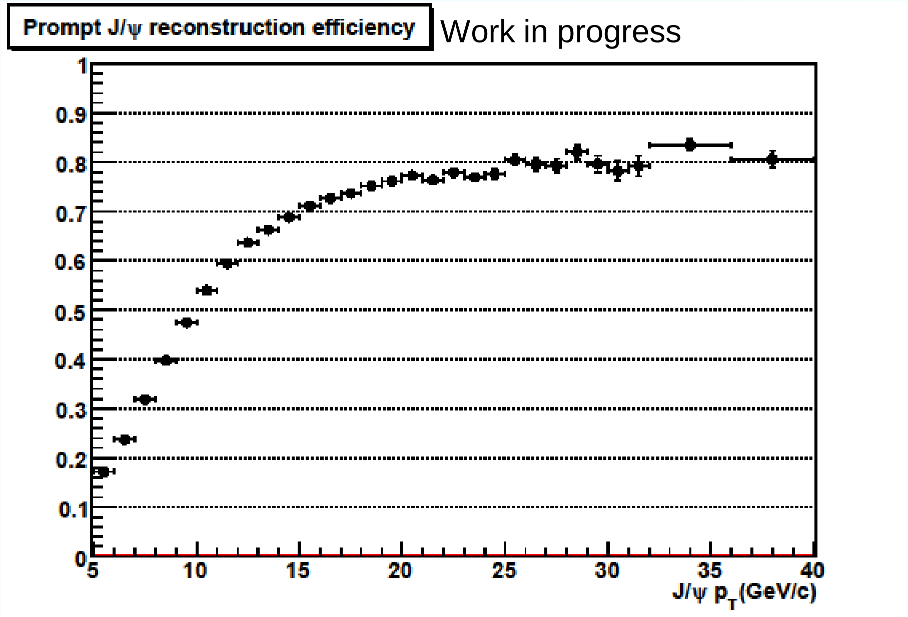
$$I_\alpha(\cos\theta^*) = \eta I_{\alpha=-1}(\cos\theta^*) + (1-\eta) I_{\alpha=1}(\cos\theta^*)$$

Monte Carlo Samples

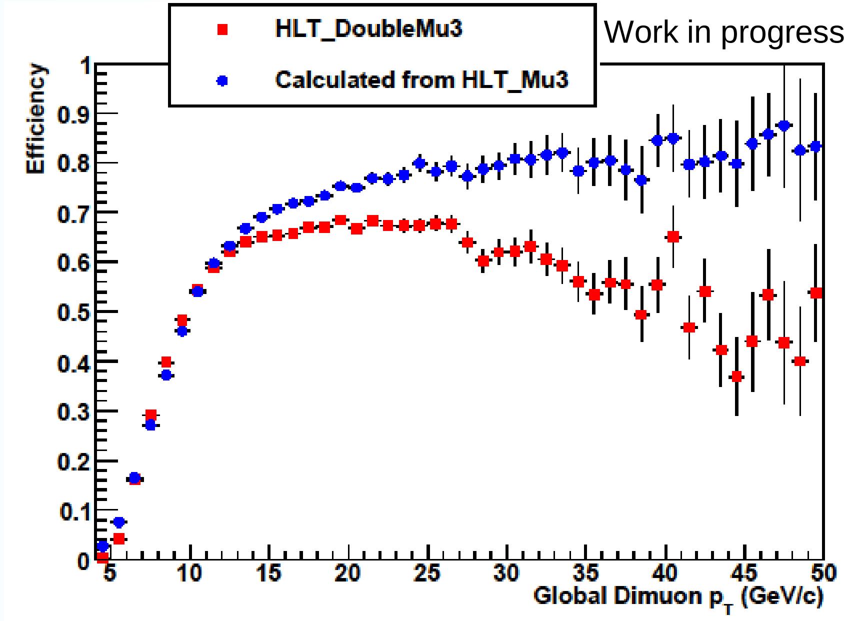
MC Sample	Production	Effective cross section (pb)	Number of Events	∫L (pb-1)	Pre-selection
Jpsi	**Summer08**	**127,206**	**1,847,135**	**14.5**	**2μ |η|<2.5, p_T>2.5GeV/*c***
BtoJpsi	**Summer08**	**24,652**	**2,434,076**	**98.7**	**2μ |η|<2.5, p_T>2.5GeV/*c***
ppMuX	**Summer08**	**118,845,800**	**5,232,662**	**0.044**	**1μ |η|<2.5, p_T>2.5GeV/*c***
Jpsi	**Private**	**621,464**	**4,000,000**	**6.4**	**2μ |η|<2.5**
BtoJpsi	**Private**	**78,027**	**2,200,000**	**28.2**	**2μ |η|<2.5**
ppMuMuX	**Private**	**618,720**	**303743**	**0.5**	**2μ |η|<2.5, p_T>2.5GeV/*c***

- In order to have sufficient statistics, we currently use only a single p_T bin for the analysis (assuming constant α for all p_T).
- The official ppMuX sample is only 0.044 pb^{-1}. The lack of statistics prevent us from incorporating this background into our pseudo-experiments. To get around this limitation, we have generated a private ppMuMuX sample corresponding to 0.5 pb^{-1}

Acceptance Measurement



Prompt J/ψ offline reconstruction efficiency versus J/ψ p_T integrating over generated J/ψ in the pseudorapidity range | η |<2.5



- Red dots: Double muon trigger efficiency
- Blue dots: $\varepsilon^{J/\psi}_{\text{Trigger}} = 1 - (1 - \varepsilon^{\mu 1}_{\text{HLT\_Mu3}}) \cdot (1 - \varepsilon^{\mu 2}_{\text{HLT\_Mu3}})$

Two curves mostly agree in low p_T region, but exhibit disagreement in higher p_T region where the two muons are more likely to overlap.

Analysis Strategy

- Step #1 : Create separate samples of mostly prompt J/ψ and mostly $B \to J/\psi$ events

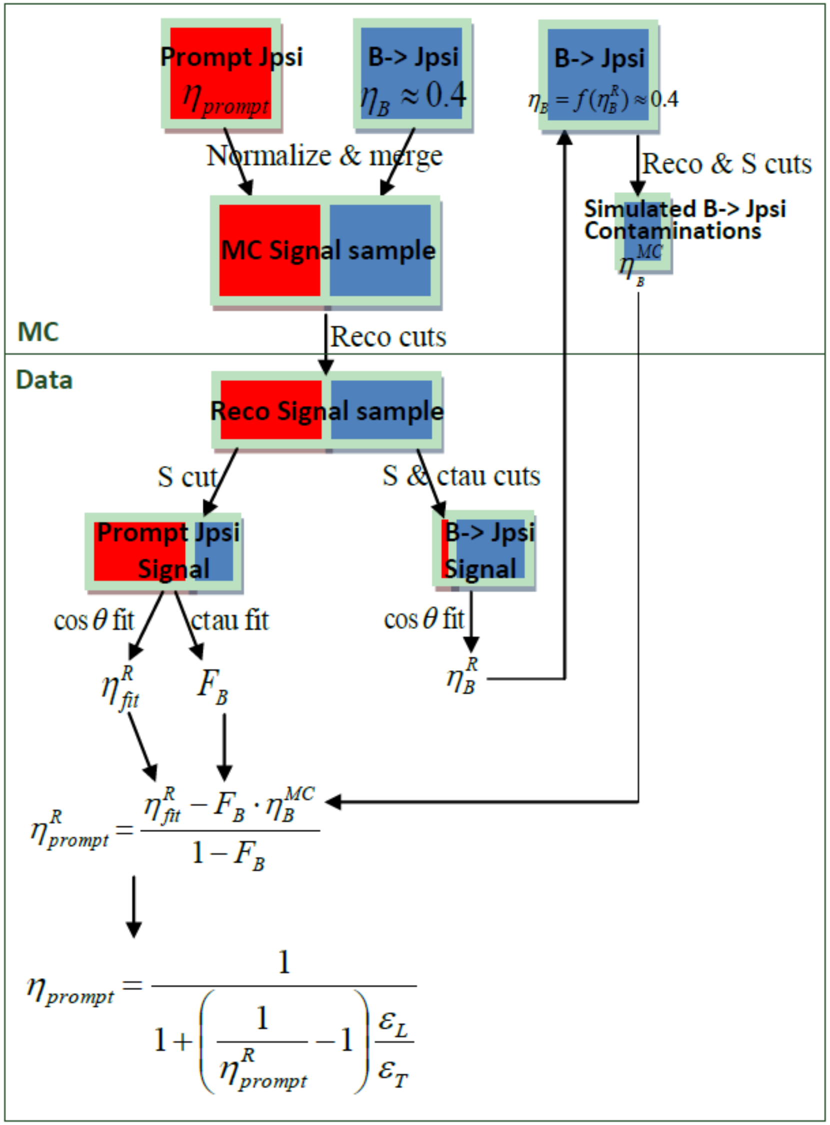
  Use cuts on quantities associated with b-quark lifetime (S and $c\tau$).

- Step #2: Modeling the residual $B \to J/\psi$ contamination in the prompt J/ψ sample

1. Fit for the residual $B \to J/\psi$ event fraction (F_B)
2. Measure the $B \to J/\psi$ polarization (η_B) in the orthogonal (mostly pure $B \to J/\psi$) sample
3. Model the residual $B \to J/\psi$ contribution to the signal sample using F_B and η_B.

- Step #3 : Measure prompt J/ψ polarization

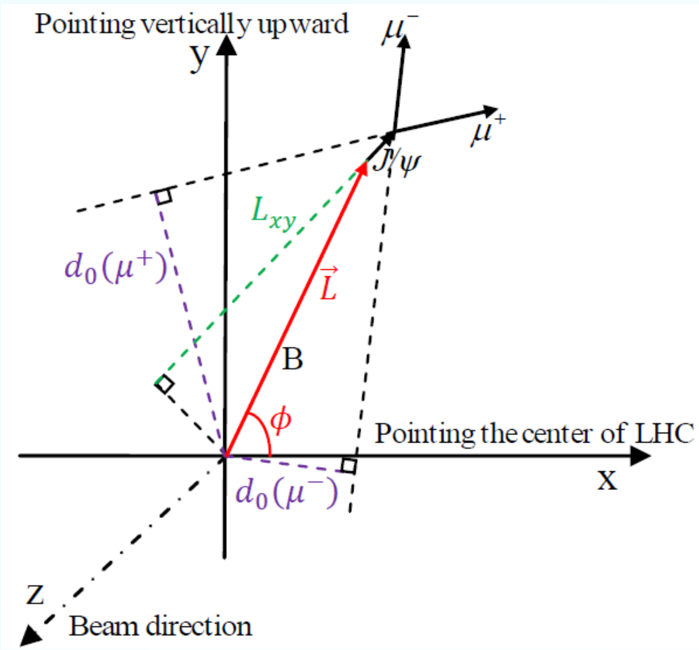
1. Fit cosθ* distribution at reconstruction level for transverse and longitudinal components
2. Extrapolate back to generator level using the measured acceptances (ε_T and ε_L).



$$\eta_{prompt}^{R} = \frac{\eta_{fit}^{R} - F_B \cdot \eta_B^{MC}}{1 - F_B}$$

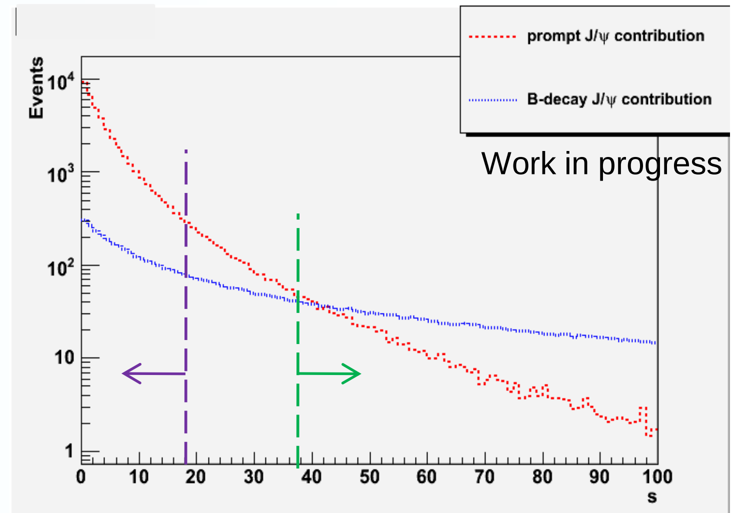
$$\eta_{prompt} = \frac{1}{1 + \left(\frac{1}{\eta_{prompt}^{R}} - 1 \right) \frac{\varepsilon_L}{\varepsilon_T}}$$

Selecting Prompt and $B \rightarrow J/\psi$ Samples



The squared sum of the impact parameter significance :

$$S \equiv \left(\frac{d_0(\mu^+)}{\sigma_{d_0(\mu^+)}}\right)^2 + \left(\frac{d_0(\mu^-)}{\sigma_{d_0(\mu^-)}}\right)^2$$



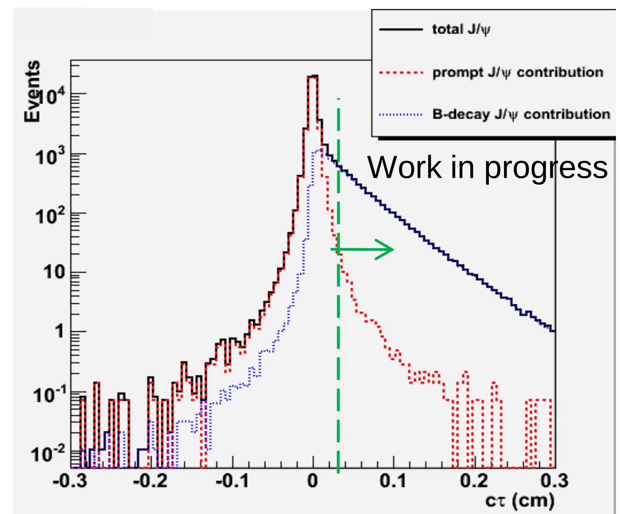
Prompt *J/ψ* sample (S<18) :

$$\text{prompt J/}\psi\text{ selection efficiency} = \frac{N_P(S < S_P)}{N_P} = 93.0\%$$

$$\text{prompt J/}\psi\text{ purity} = \frac{N_P(S < S_P)}{N_P(S < S_P) + N_B(S < S_P)} = 93.6\%$$

Pseudo-proper decay length :

$$c\tau \equiv \frac{L_{xy}^{J/\psi} \cdot M^{J/\psi}}{p_T^{J/\psi}}$$



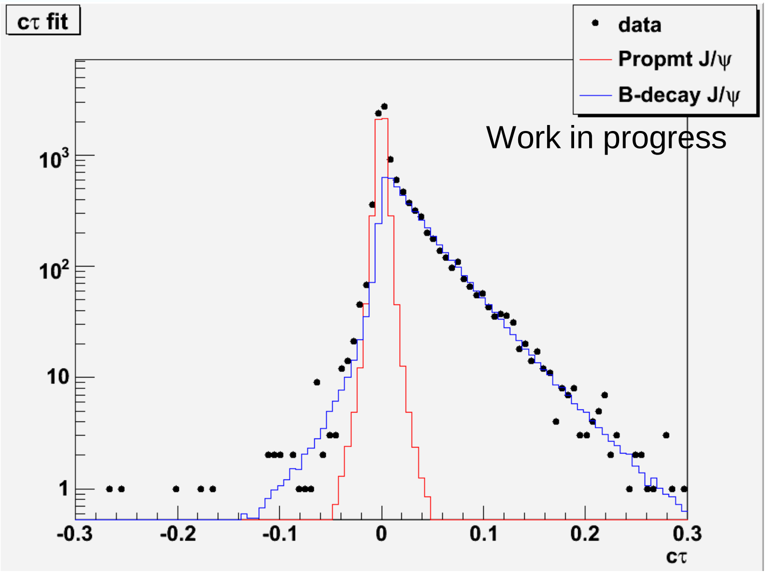
B→J/ψ sample (S>38, cτ>0.03) :

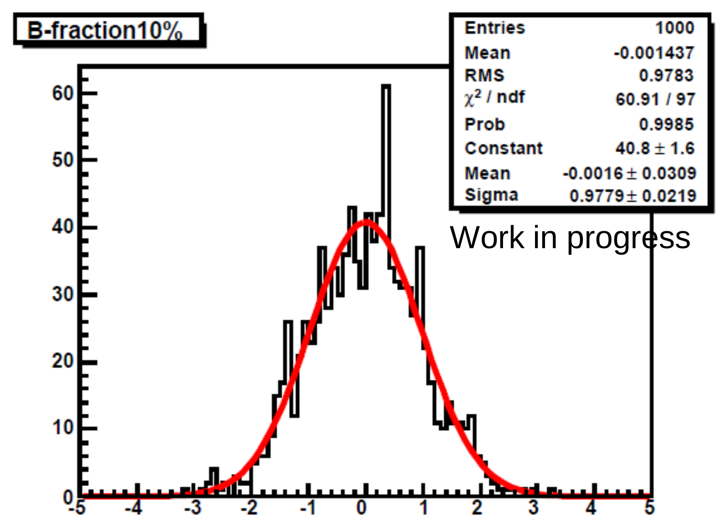
$$\text{B-decay J/}\psi\text{ selection efficiency} = 89.0\%$$

$$\text{B-decay J/}\psi\text{ purity} = 99.0\%$$

Fit for F_B in low S sample

- We fit the $c\tau$ distribution to extract the $B \rightarrow J/\psi$ fraction
- Each pseudo-experiment has a slightly different fraction since the number of prompt and $B \rightarrow J/\psi$ events for each experiment are independently varied within their Gaussian expectations
- Pseudo experiments indicate that we can fit for F_B with high precision (expected bias less than 0.0002)

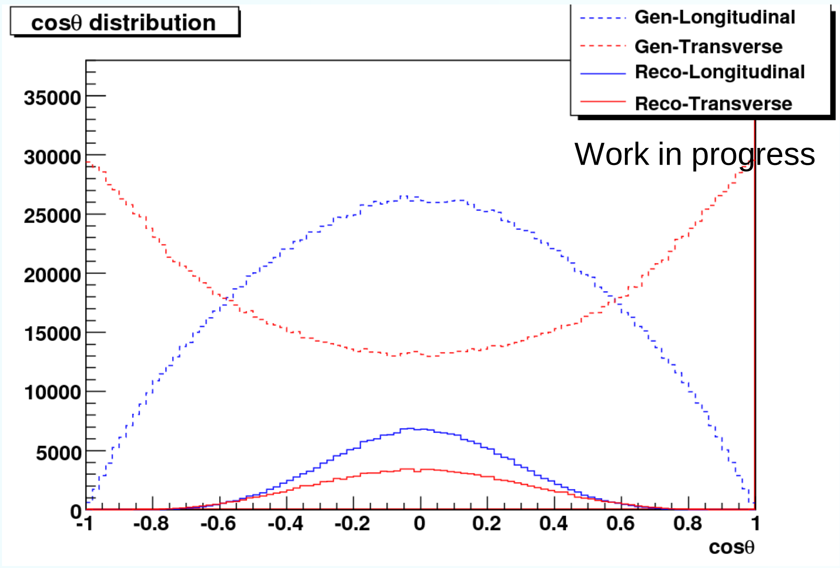




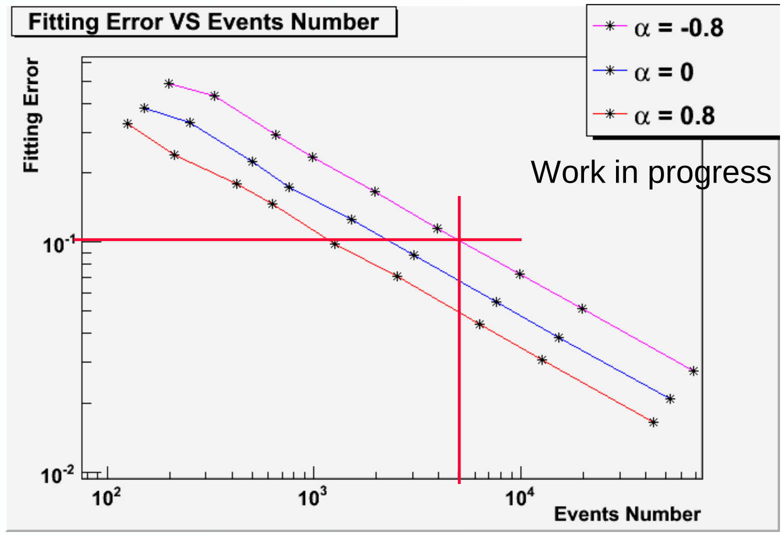
Templates and Fitting Method

Preparing fully polarized templates

- For each event in unpolarized sample, calculate the probability for longitudinal polarization based on generator level cosθ*.
- Assign a random number (0,1). If it is less than the above value, then assign event to fully longitudinal sample; otherwise, assign it to transverse sample.



Performing simple polarization fits to signal-only samples of prompt *J/ψ* events, we find a ~5000 events sample ensures a statistical uncertainty no worse than that for the highest p_T bin in the CDF run II measurement

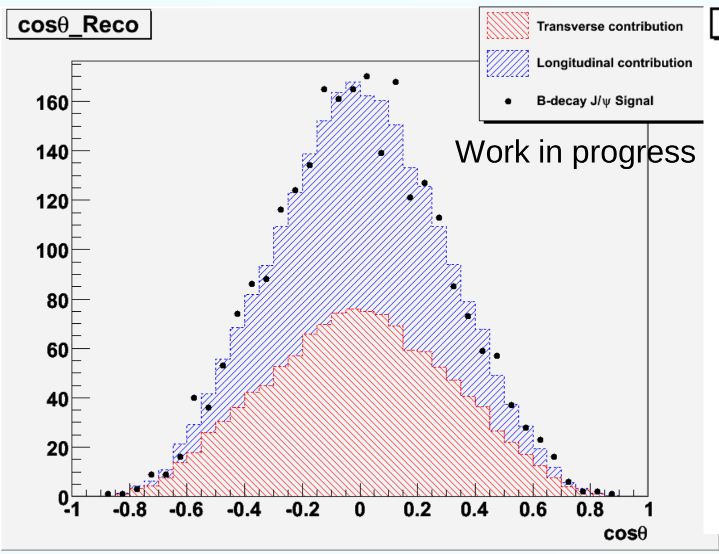


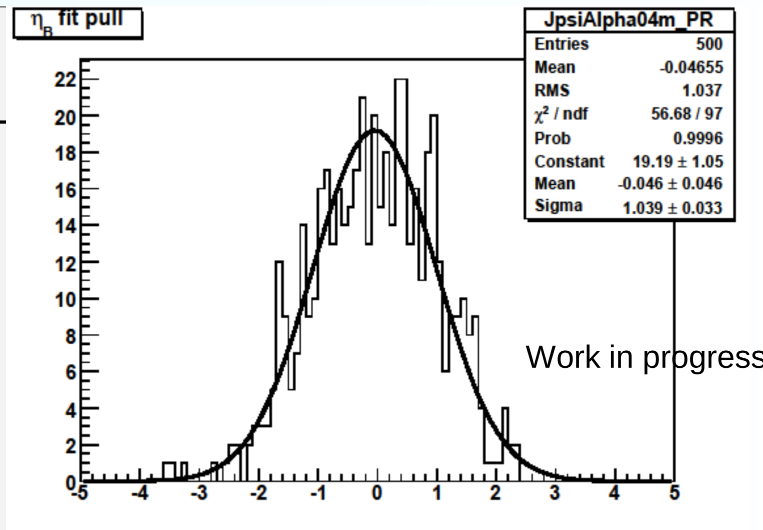
Fit for η_B in high S sample

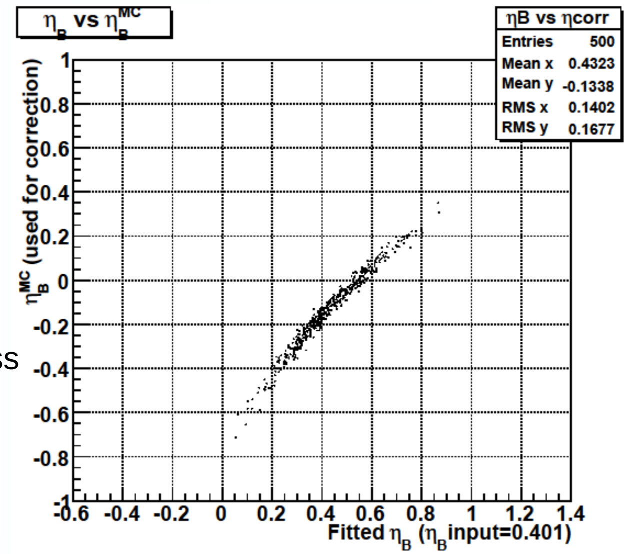
- Fit the cosθ* distribution to get the fraction of longitudinal events (η_B^R)

$$\frac{dN^R}{d\cos\theta^*} = \eta_B^R I_{\alpha=-1}^R(\cos\theta^*) + (1-\eta_B^R) I_{\alpha=1}^R(\cos\theta^*)$$

- Study fit procedure for extracting $B \to J/\psi$ polarization via Monte Carlo pseudo-experiments (default $B \to J/\psi$ α = 0.401)
- S and $c\tau$ cuts affect the cosθ* distribution. The fitted value η_B^R can not be directly used to subtract the B contribution in the signal sample. Instead, use MC to model residual $B \to J/\psi$ in the low S region based on measurement of η_B in high S region







Fit for η_{prompt} in low S sample

- Fit reconstructed cosθ* distribution for fraction of longitudinal events (η_{fit}^{R})

$$\frac{dN^R}{d\cos\theta^*} = \eta^R_{fit} I^R_{\alpha=-1}(\cos\theta^*) + (1-\eta^R_{fit}) I^R_{\alpha=1}(\cos\theta^*)$$

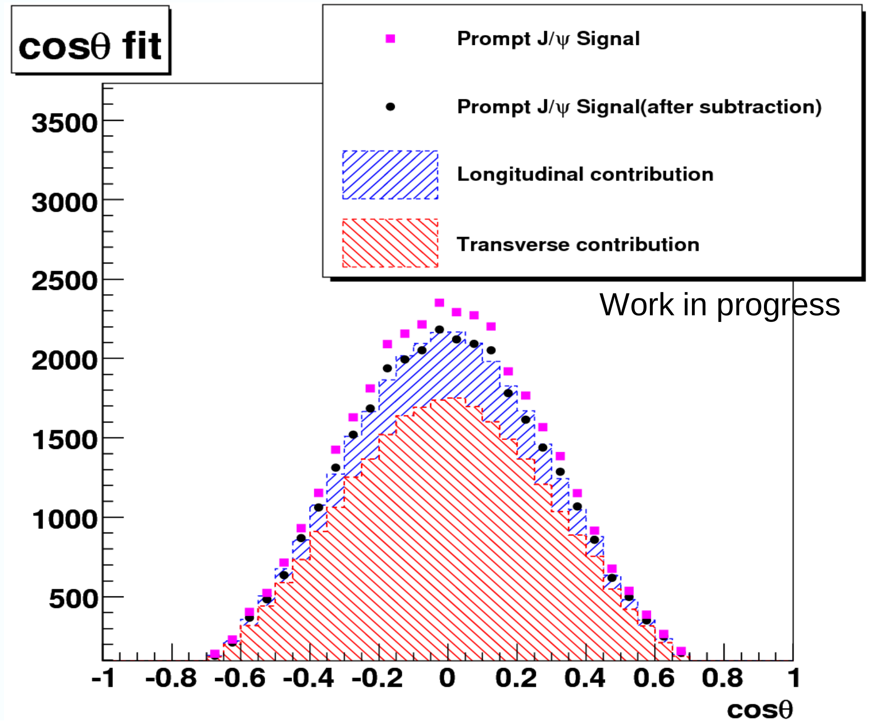
- Correct for $B \to J/\psi$ contamination using fitted F_B and the measured η_B from high S sample

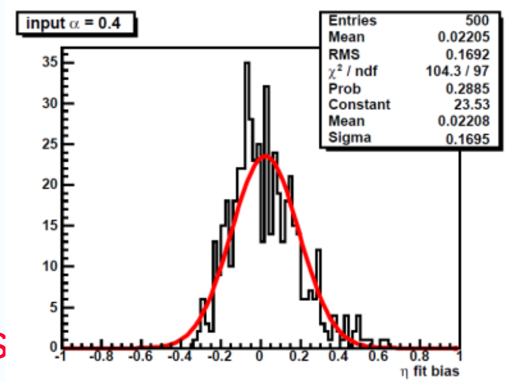
$$\eta^R_{prompt} = \frac{\eta^R_{fit} - F_B \cdot \eta^{MC}_B}{1-F_B}$$

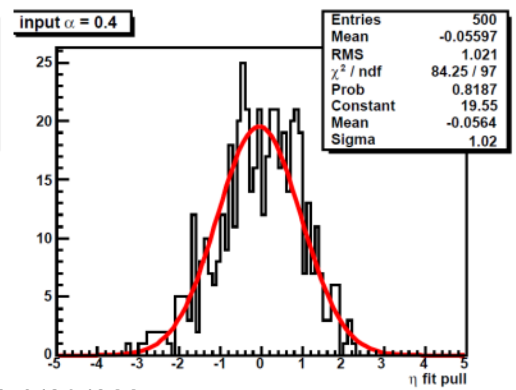
- Use measured acceptances for transversely and longitudinally polarized simulated event samples to extrapolate back to the generator level longitudinal event fraction η_{prompt}

$$\eta_{prompt} = \frac{1}{1+\left(\frac{1}{\eta^R_{prompt}}-1\right)\left(\frac{\varepsilon_L}{\varepsilon_T}\right)}$$

Measured from private samples

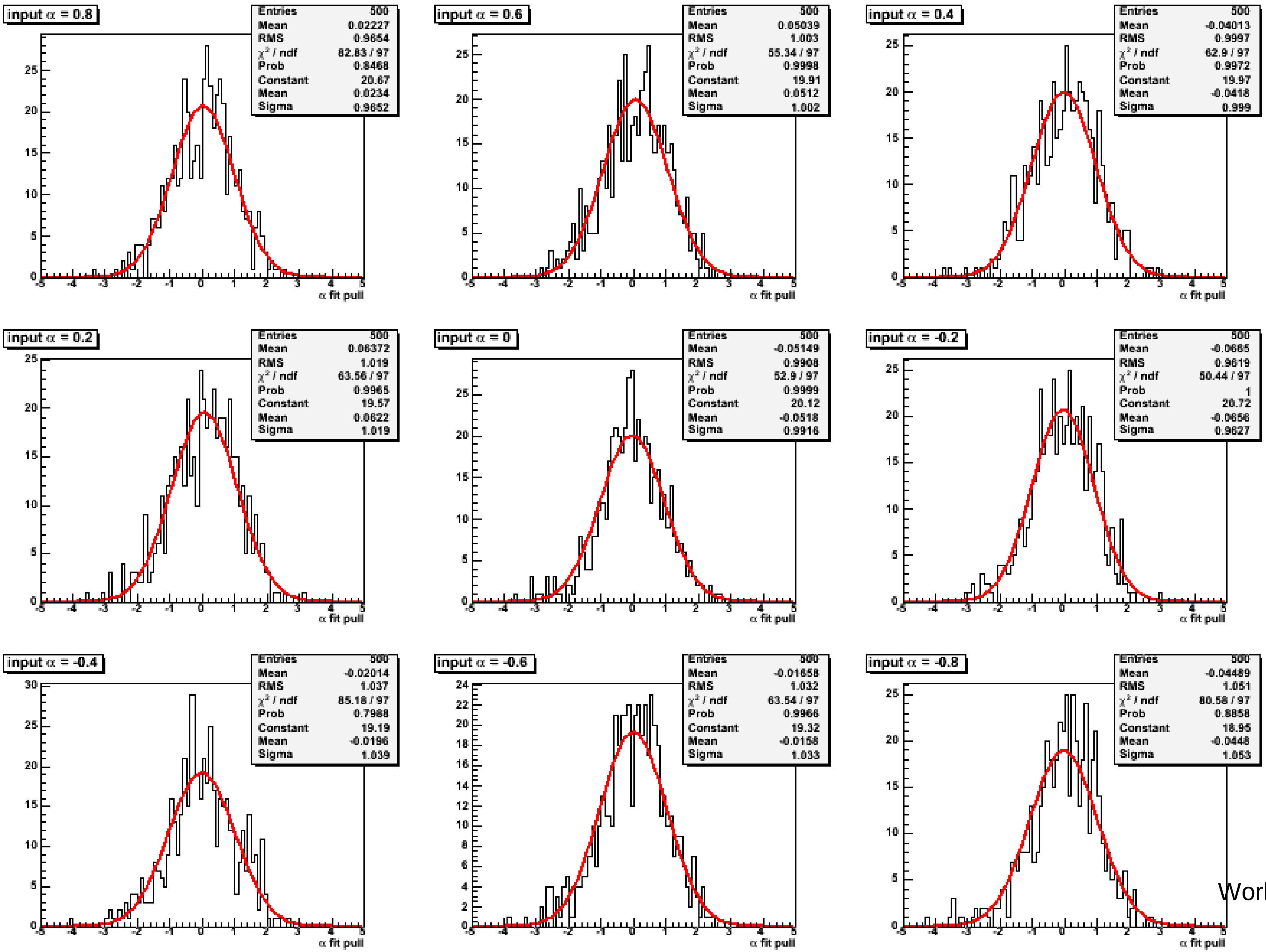






Work in progress

Signal plus Background Pseudo-experiments



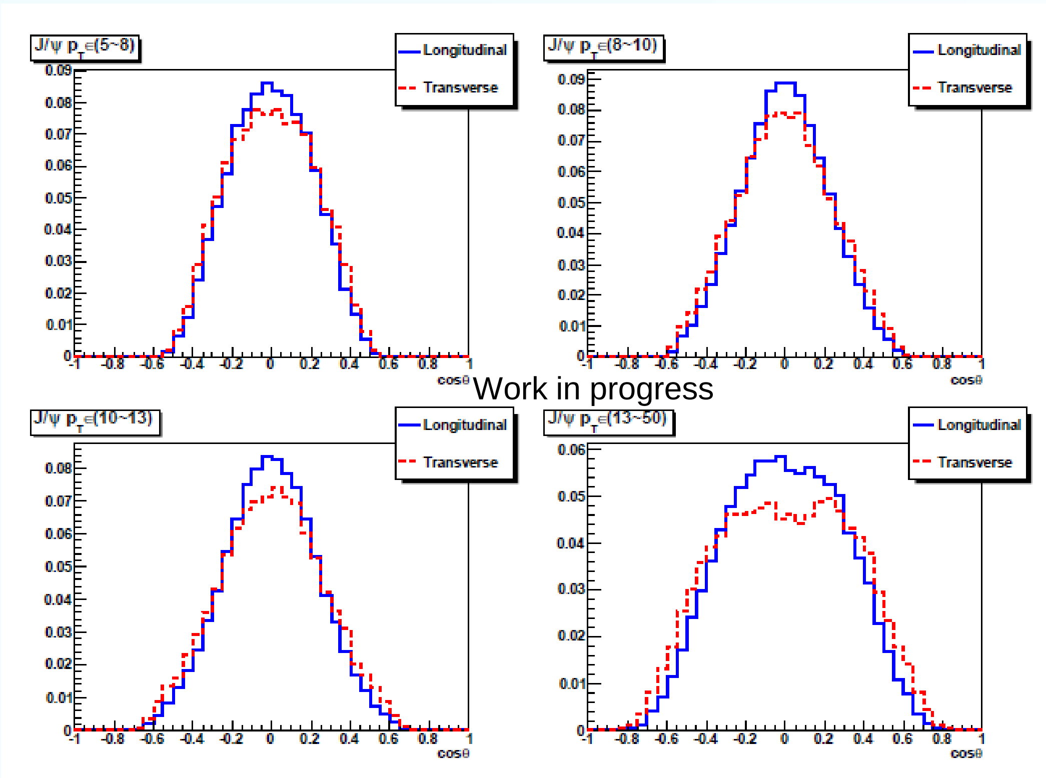
α_{prompt} fit pull distributions with 9 different hypothetical input α_{prompt} values ranging from −1 to 1 in steps of 0.2

Observe small measurement bias and good residuals

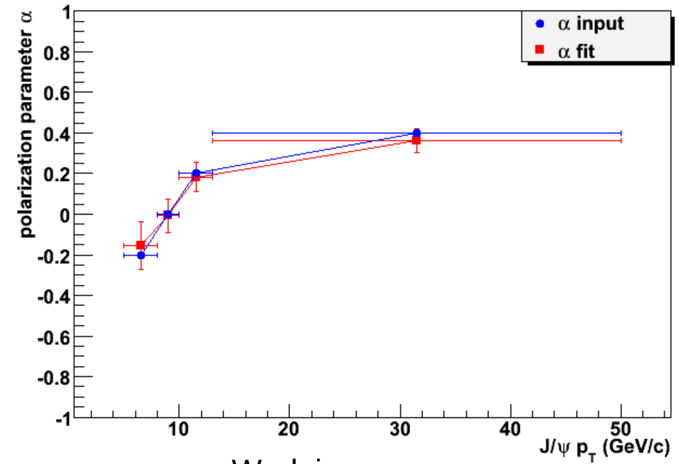
Work in progress

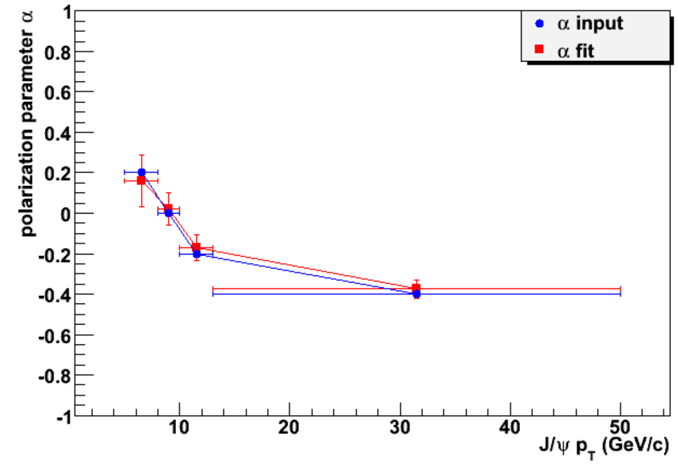
Measure Polarization as a Function of p_T

To test the framework for measuring the *J/ψ* polarization in different *J/ψ* p_T bins, we divide the signal sample into four different p_T ranges with similar statistics. Fully polarized templates in these p_T bins are shown below:



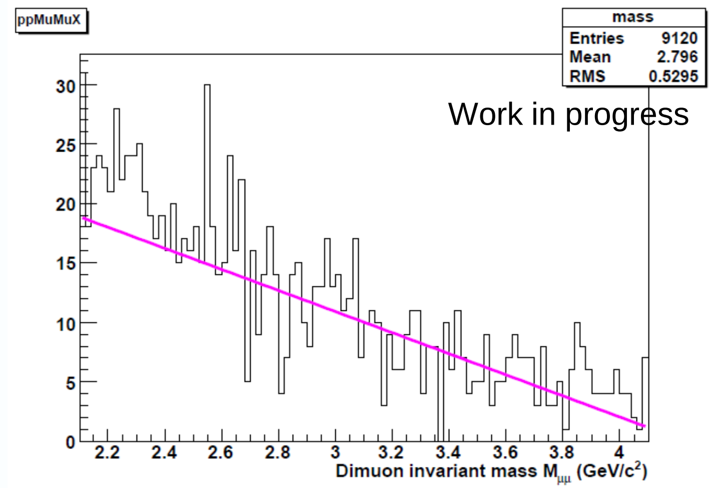
Results from sample pseudo-experiments:

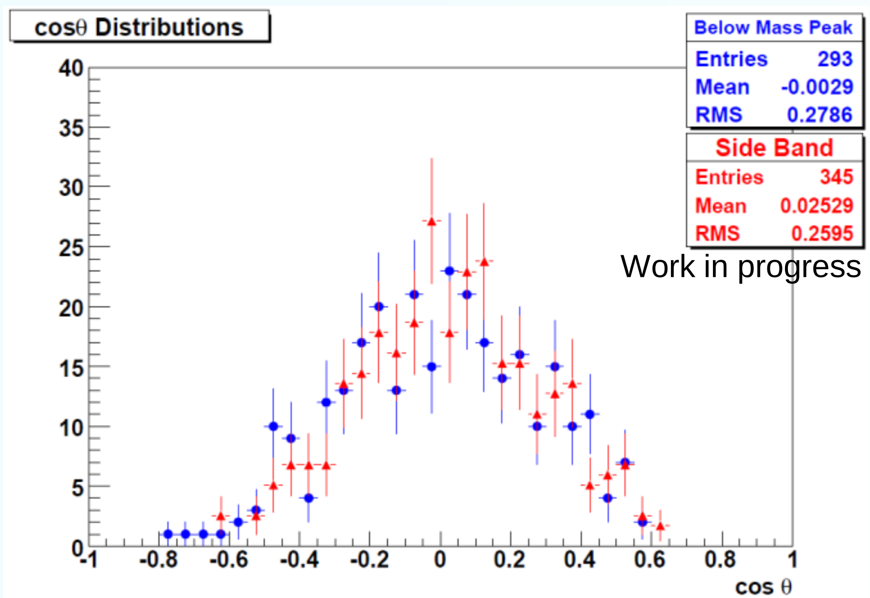


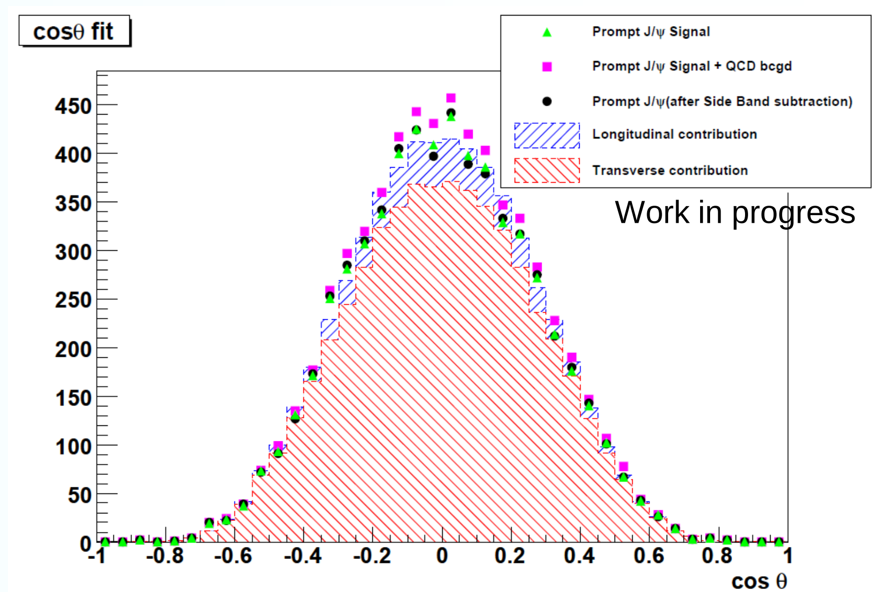


QCD background

- We generated a private ppMuMuX sample corresponding to 0.5 pb^{-1}. There are 303743 events in this sample. After trigger and all necessary cuts, 308 events are found within the *J/ψ* invariant mass window.
- Observe good agreement in cos*θ** shapes obtained from signal and sideband regions. The QCD background is modeled using shape extracted from sideband region normalized to estimated contribution in signal region from linear fit between low and high sideband regions.

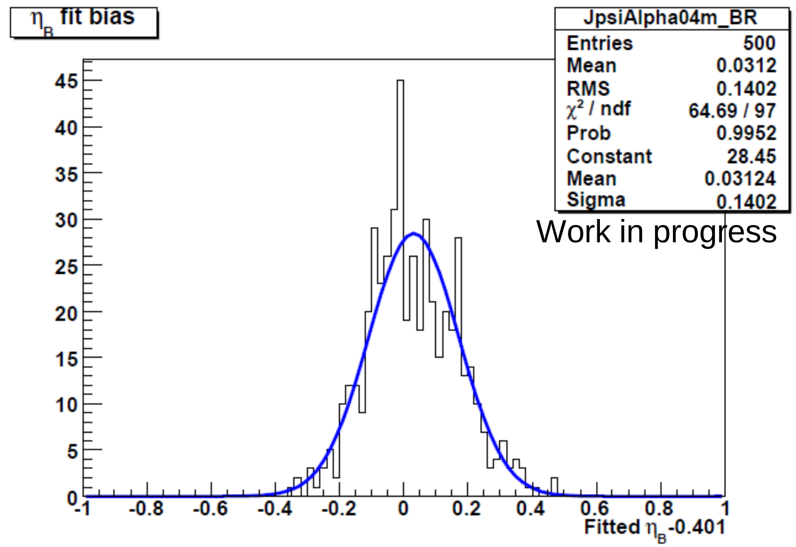


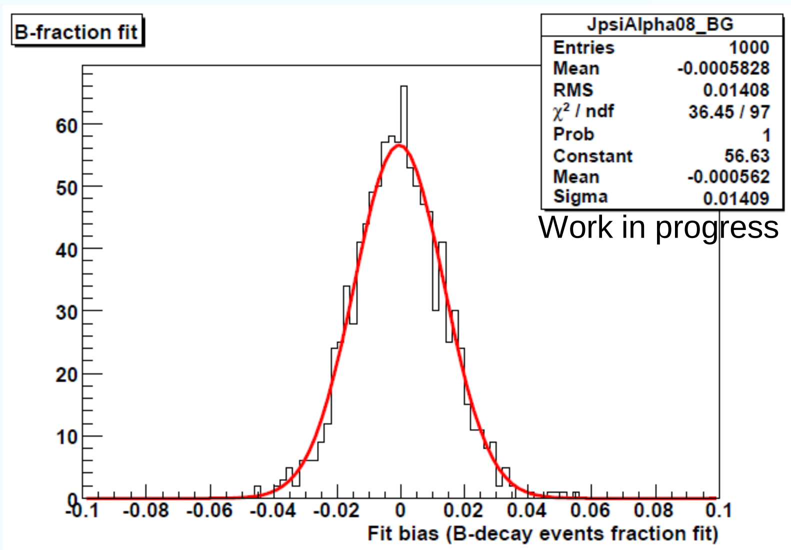


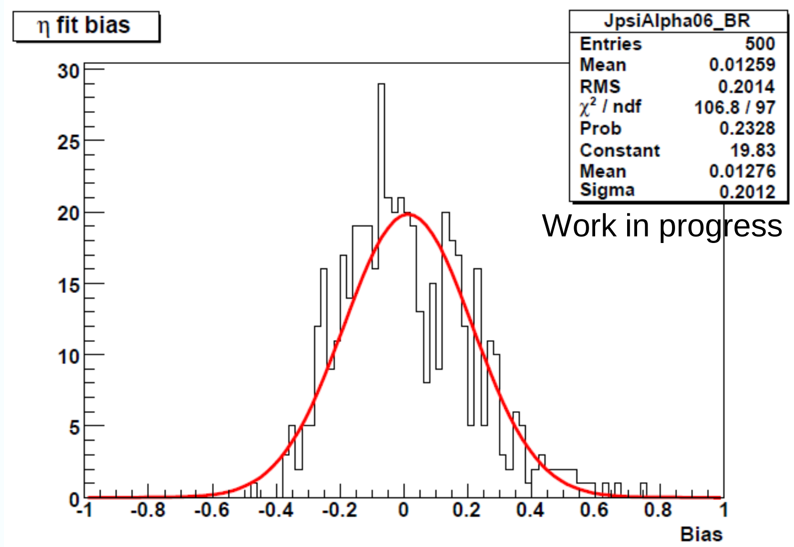


QCD background

- 500 pseudo-experiment for the 3 main fits ($c\tau$ fit, η_B fit and η fit) incorporating QCD background event contributions.







Systematic Uncertainty

Three main aspects of systematic uncertainties are evaluated in this analysis, which are acceptance measurement, fitting algorithm, and *b*-decay background contamination.

- The absolute acceptance and luminosity does not affect the polarization measurement because the factor used in this analysis is the ratio of longitudinal and transverse acceptance $\varepsilon_L/\varepsilon_T$
- The p_T spectrums of the templates are varied by $\pm 1\sigma$ which produces the changes on α in the order of 0.001
- The $\cos\theta^*$ binning are varied from 0.05 to 0.10, and no change in the polarization is observed
- Raising the muon p_T cut reduces the discrimination between transverse and longitudinal polarizations and thus enlarges the fitting uncertainty. By varying the muon p_T cut from 1.5 to 3 GeV/*c*, the systematic due to this effect is limited to less than 0.005
- The polarization of J/Ψ from *b*-decay has been measured precisely by the BaBar experiment. The value measured by CDF is larger than it by 1.2σ. Due to the modest disagreement, no further systematic uncertainty is assigned to the *b*-decay polarization

Systematic Uncertainty

- After applying all the uncertainties discussed in the previous page onto the pseudo-experiments in different p_T bin, the final results are summarized in the table below.
- The precision of the measurement is estimated about $\Delta\alpha_{stat} < 0.13$, $\Delta\alpha_{syst} < 0.01$ for the worst situation. The systematic uncertainty is about one order of magnitude lower than the size of the statistical uncertainties for the collected data up to 50 pb^{-1}.

	$5 < p_T < 8$ GeV/c	$8 < p_T < 10$ GeV/c	$10 < p_T < 13$ GeV/c	$13 < p_T < 50$ GeV/c
$\alpha = 0.4$				0.3623±0.0579±0.0093
$\alpha = 0.2$	0.1606±0.1279(stat) ±0.0085(syst)		0.1823±0.0719±0.0075	
$\alpha = 0.0$	−0.0131±0.1216±0.0081	−0.0185±0.0824±0.0075	0.0110±0.0681±0.0070	0.0223±0.0519±0.0070
$\alpha = -0.2$	−0.1554 ±0.1166±0.0080		−0.1719±0.0637±0.0069	
$\alpha = -0.4$				−0.3748±0.0451±0.0067

Summary

- We measure *J/ψ* polarization by fitting reconstructed cosθ* distribution to longitudinal and transverse templates built from an unpolarized MC sample.
- We generate Monte Carlo pseudo-experiments to study potential biases in the fit procedure used to extract the polarization parameter. We observe reliable pull distributions and no significant measurement biases
- These measurements are expected to provide some insight into the current observed disagreement between the NRQCD theory and recent CDF *J/ψ* polarization measurements.

Thank you!!

谢谢！

Back up

Relations of some Polarization Parameters

Polarization sample	Helicity	η	α	θ	$\cos\theta$	I_α
fully transverse	"+1", "-1"	0	1	tend to 0, or π	tend to1, or -1	$I_{T(\alpha=1)} = \frac{3}{8}(1+\cos^2\theta)$
transverse	"+1", "-1", "0" (more "+1", "-1")	(0, 1/3)	(0, 1)			$\eta I_L + (1-\eta) I_T$
unpolarized	"+1", "-1", "0" (equal fraction)	1/3	0	uniform distribution in (0, π)	uniform distribution in (-1, 1)	constant 1/2
longitudinal	"+1", "-1", "0" (more "0")	(1/3, 1)	(-1, 0)			$\eta I_L + (1-\eta) I_T$
fully longitudinal	"0"	1	-1	tend to $\pi/2$	tend to 0	$I_{L(\alpha=-1)} = \frac{3}{4}(1-\cos^2\theta)$

Acceptance Measurement

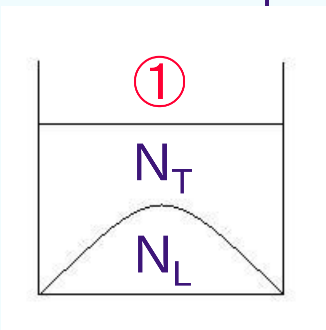
- *J/ψ* acceptances and the number of expected events per pb^{-1} of data for different *J/ψ* p_T bins

J/ψ pT GeV/c	Generator level events	Reco eff	Reconstrion level events	HLT di-muon trigger efficiency	Events passing trigger
all	127389	33.7	42975	37.4	16073
5-6	25601	17.2	4402	4.04	178
6-7	25903	23.7	6144	15.9	977
7-8	19885	31.8	6327	28.7	1816
8-9	14002	39.8	5573	39.3	2190
…	…	…	…	…	…
17-20	1449	74.8	1083	66.2	717
20-24	783	77.1	604	66.1	399
24-30	403	79.5	320	64.1	205
30-50	203	81.0	165	54.2	89

Templates Construction with Generator Level Cuts

Essence of the analysis :
calculate N_T / N_L

What we can measure from data : N_T^R / N_L^R

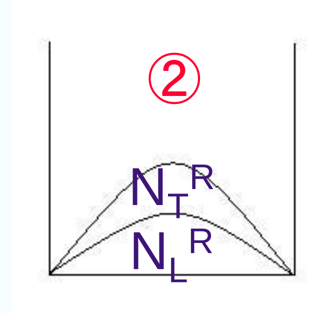


Private sample : no muon p_T cut at generator level

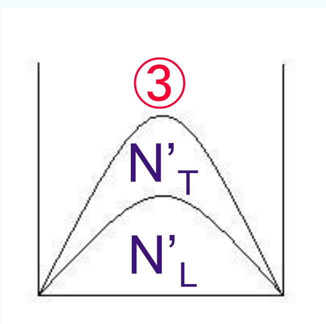
Reconstruct:

$N_T^R = \boldsymbol{\varepsilon_T} \cdot N_T$

$N_L^R = \boldsymbol{\varepsilon_L} \cdot N_L$



Reconstruction level

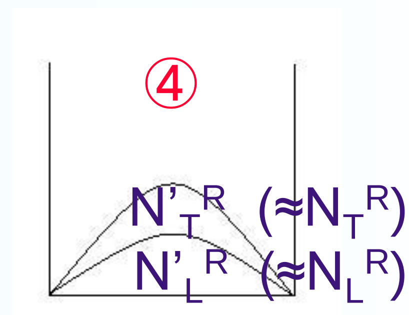


Official sample : muon p_T > 2.5 GeV/*c* at generator level

Reconstruct:

$N'^R_T = \varepsilon'_T \cdot N'_T$

$N'^R_L = \varepsilon'_L \cdot N'_L$



Reconstruction level

Conclusion:

The generator level p_T cut doesn't affect template shapes at reconstruction level.

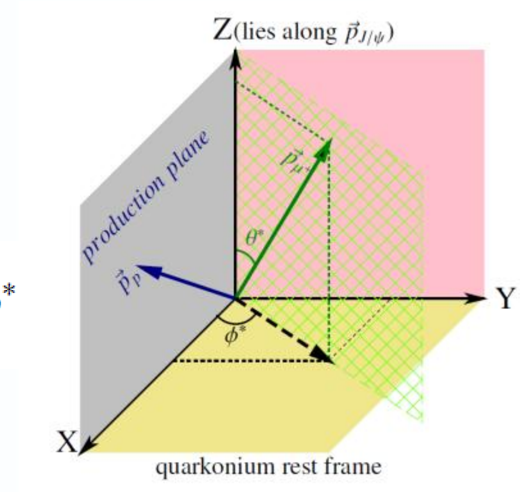
So, we can also use the official samples to produce reconstruction level fitting templates.

However, we still need a "no muon p_T cut" sample to calculate $\boldsymbol{\varepsilon_L}$ and $\boldsymbol{\varepsilon_T}$

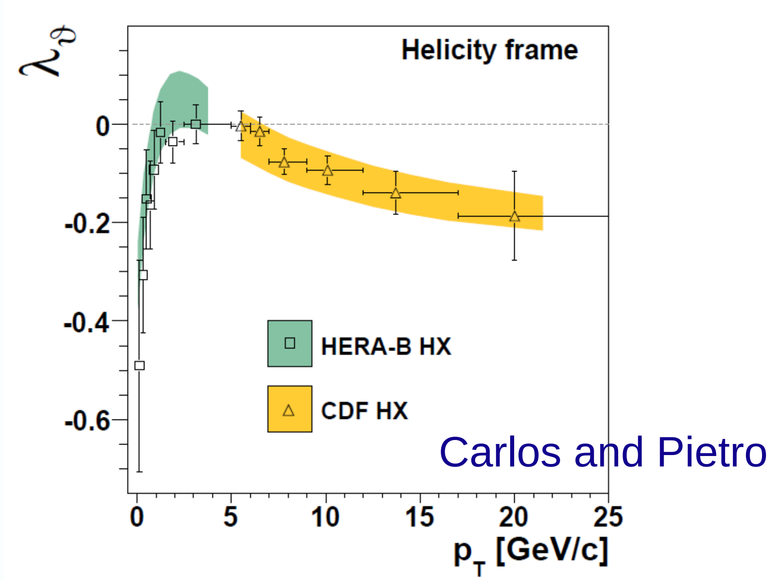
Polarization Frames

- The polarization analysis is performed by measuring the two-body angular decay distribution which depends on the polarization frame.

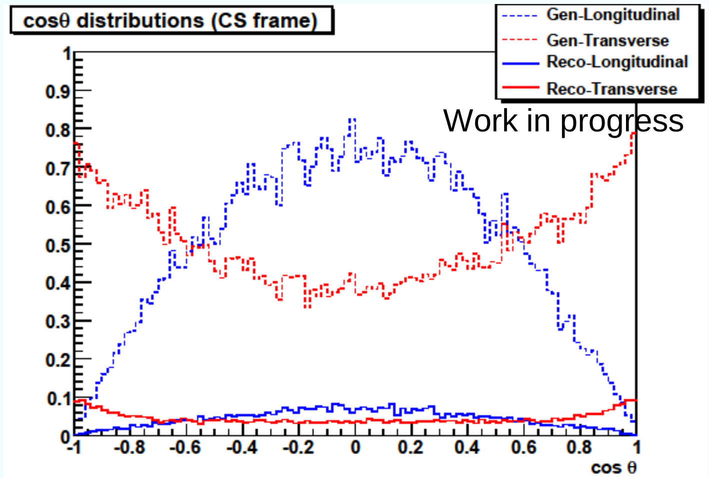
$$\frac{dN}{d(\cos\theta^*)d\phi^*} \propto 1 + \lambda_{\theta^*}\cos^2\theta^* + \lambda_{\phi^*}\sin^2\theta^*\cos(2\phi^*) + \lambda_{\theta^*\phi^*}\sin(2\theta^*)\cos\phi^*$$



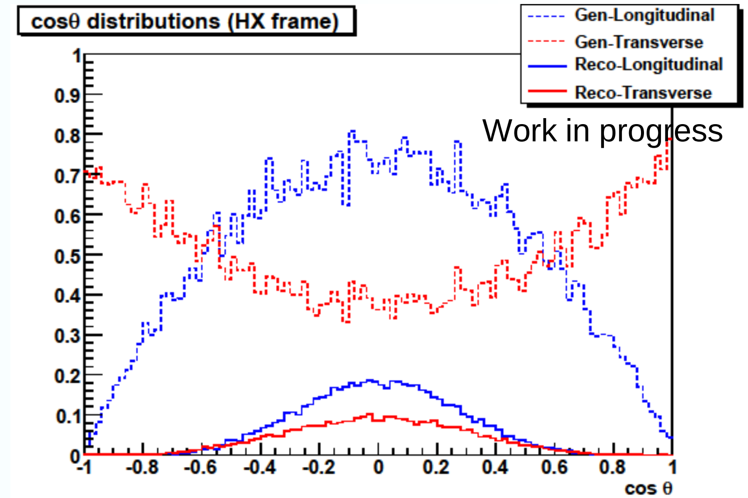
- Several definitions of the polarization axis exist. For different frames the polarization parameter that one measures is different.
- If one assumes that the real polarization axis is close to the Collins-Soper (CS) axis and the CS axis is more or less orthogonal to the standard helicity (HX) axis, then the CDF data is found to agree much better with the NRQCD theory prediction.



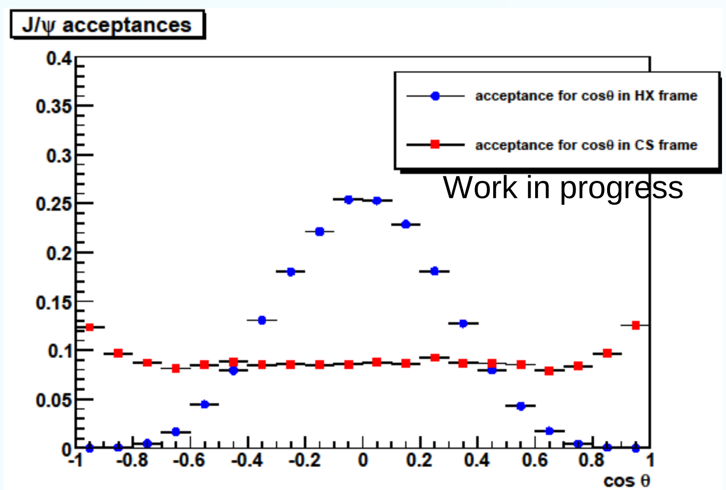
Polarization Frames



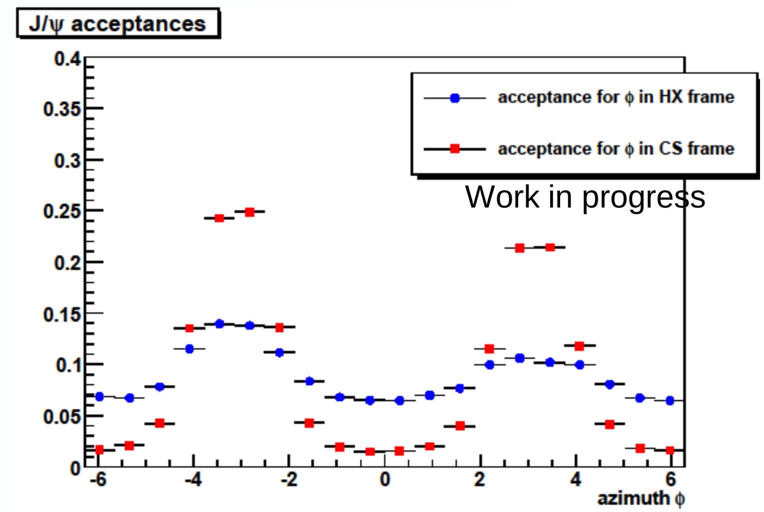
Fully polarized templates in CS frame



Fully polarized templates in HX frame



Acceptance as a function of cosθ*



Acceptance as a function of ϕ*

Reference Frames

Carlos and Pietro

The varying direction of decay lepton (ℓ^+) in the J/ψ rest frame is measured wrt a system of axes. Existing definitions of the ***polarization axis*** (*z*):

1) **helicity (HX)**: **quarkonium momentum** in ($h_1 + h_2$) CM frame

2) **Gottfried-Jackson (GJ)**: direction of h_1 *or* h_2 in quarkonium rest frame

3) **Collins-Soper (CS)**: bisector between h_1 and $(-)h_2$ directions in quarkonium rest frame → ~ direction of **relative velocity of colliding partons**