Study of direct CP violation in $B^+ \rightarrow J/\psi K^+(\pi^+)$ decays with D0 detector

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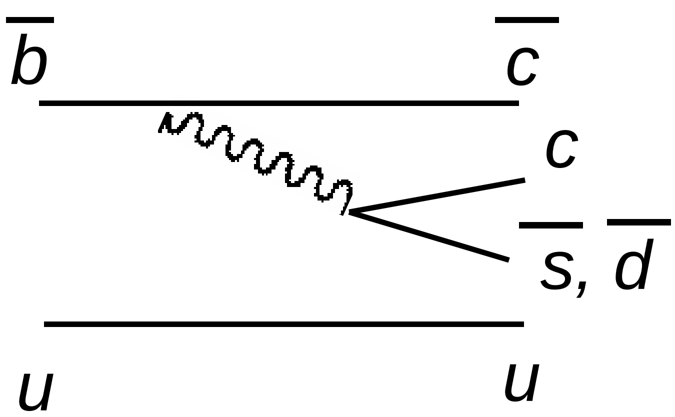
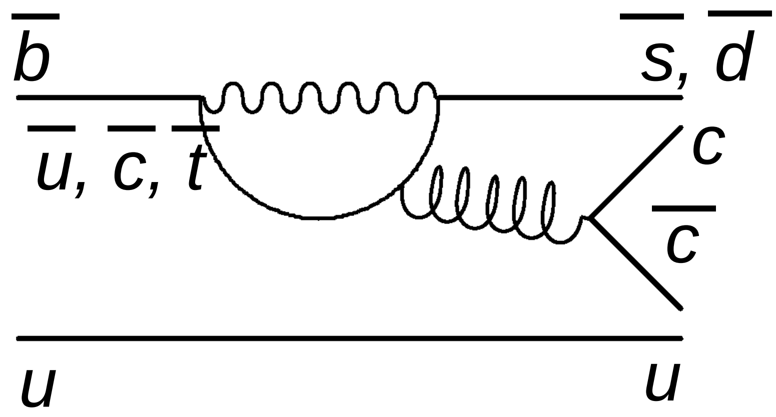
Motivation

Standard Model predicts Direct CP violation due to different phases in:





$$A(B^+ \to J/\psi K^+) \sim 0.003$$

$$A(B^+ \to J/\psi \pi^+) \sim 0.01$$

=> zero-test
recently Belle [PRL 98, 221802] measured A(B0→D+D–)~+0.9±0.2. BaBar disconfirmed [PRL 99, 071801]

BSM phases enter at tree (extra gauge boson, charged Higgs) or loop level

Easy to measure with D0 muon system and tracking: charmonium, kaon charge is a flavor tag:

$$A_{CP}(B^+ \to J/\psi K^+(\pi^+)) = \frac{N(B^- \to J/\psi K^-(\pi^-)) - N(B^+ \to J/\psi K^+(\pi^+))}{N(B^- \to J/\psi K^-(\pi^-)) + N(B^+ \to J/\psi K^+(\pi^+))}$$

Event reconstruction

2 tracks - muons:

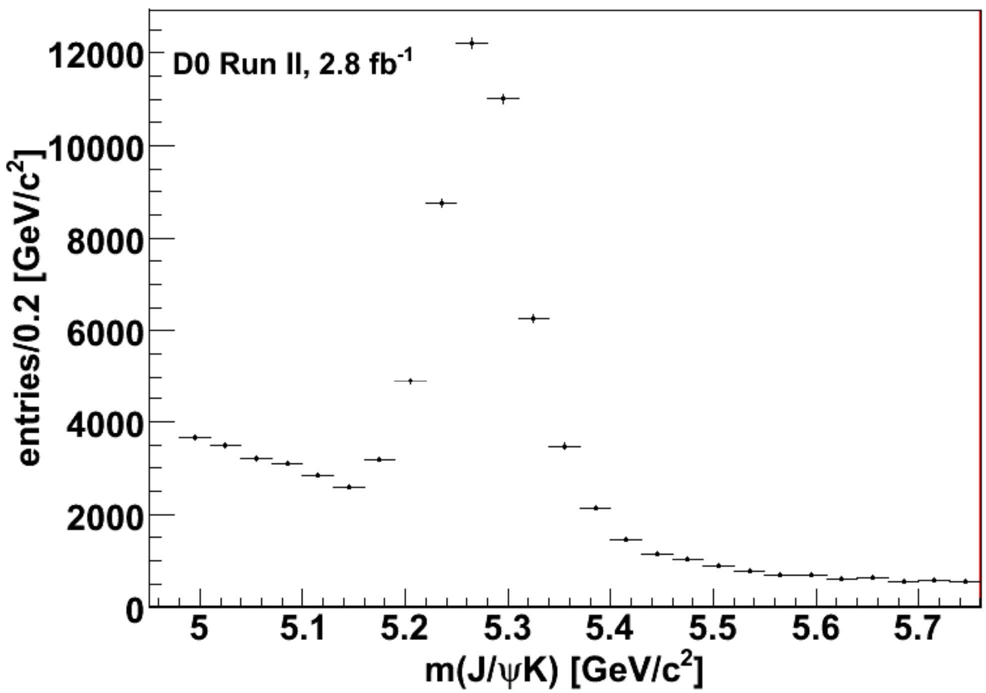
- pT>1.5 GeV/c
- muon cluster + central track,
- hits in D0 central tracking device (SMT)
- invariant mass consistent with J/ψ: $2.80<m(\mu\mu)<3.35$ GeV/c^2

3rd track - hadronic:

- pT>0.5 GeV/c, p>0.7 GeV/c
- hits in D0 central tracking device (SMT)
- common vertex with μμ,
- assigned a kaon mass

Invariant mass of (J/ψ K)

Invariant mass distribution of 3-track system:



- ~40 k events in the peak, so

$$\Delta A(J/\psi K) = \frac{1}{\sqrt{40k}} \sim 0.5\%$$

- J/ψπ has to be dug out from the reflection but roughly

$$\Delta A(J/\psi \pi) = \frac{1}{\sqrt{40k \cdot 0.22^2}} \sim 2\%$$

Problems we face

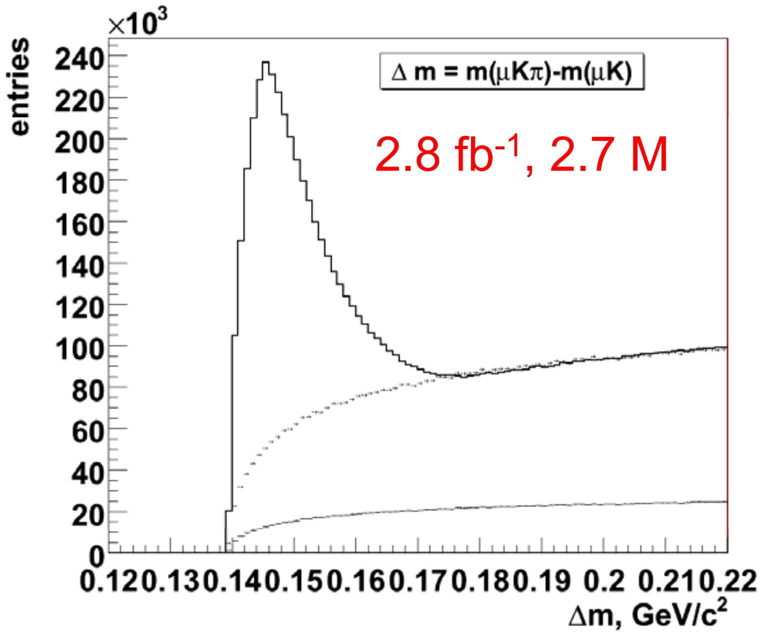
$$B^+ \to J/\psi K^+$$

Could we remain at ΔA(J/ψ) ~ 0.5%?

Kaon asymmetry due to $K^- N \to (\Sigma, \Lambda)\,\pi$, but not K^+: $A(B^+ \to J/\psi K^+) = A(J/\psi K) - A_K$

Rough estimate from material distribution: $A_K \sim 1\%$!

$$D^{*+} \to D^0\pi^+ \to (\mu^+ K^- \nu)\pi^+$$



$$\Delta A_K = \frac{1}{\sqrt{2.7M}} \sim 0.07\%$$

A_K due to kaon asymmetry ONLY:

- no direct CPV: unique SM phase
- CPV in D0 mixing suppressed by 2x2 quark mixing matrix
- Even BSM respect |p/q|=1, [hep-ph/9504306]

Problems to deal with

$$B^+ \to J/\psi K^+$$

Could we remain at ΔA(J/ψ) ~ 0.5%?

So we can keep statistical error at ~0.5%. What about systematics?

Bad news: detector introduces systematic shifts to the charge asymmetries due to different (acceptance x efficiency) for different charges.

Good news: they are canceled at D0 by regularly reversing the magnet polarities! Thus the same piece of the detector is exposed to the particles of both charges.

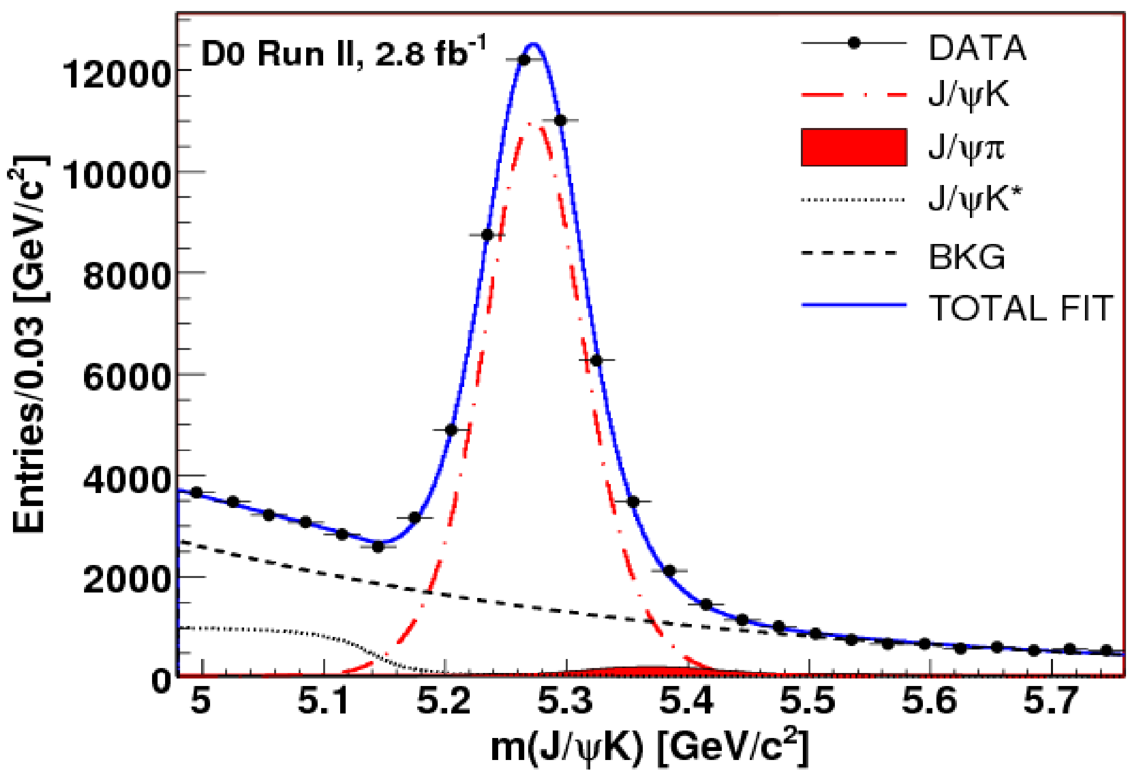
The second-order effects are accounted by the suitable detector model.

D0 is well equipped to go for this measurement!

Counting events in J/ψK peak

We do Log-L fit:

- **B → J/ψ K decay** **(Gauss)**
- **Hadronic track may be a pion => J/ψ π reflection** **(Gauss)**
- **Underreconstructed B → J/ψ K* (K π) decay** **(Threshold function)**
- **Combinatorial background** **(Exponential)**



40,222±242

1,578±119

5,429±217

33,192±425

80,422

A(J/ψK)= – 0.0070±0.0060

A_K still to be subtracted

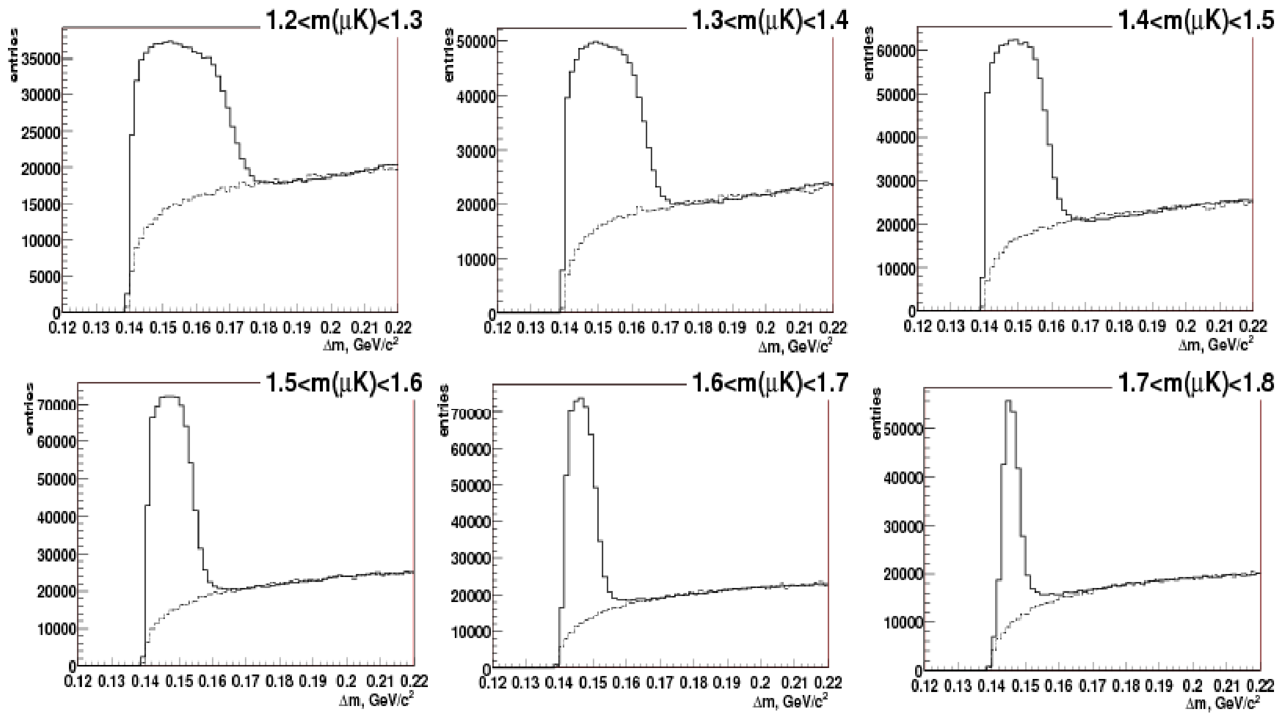
A(J/ψπ)=A(B+→J/ψπ+)= – 0.09±0.08

Result!

Counting events in $\Delta m = m(\mu K \pi) - m(\mu K)$

Signal: μ(+) K(–) π(+), Background: μ(+) K(+) π(+)

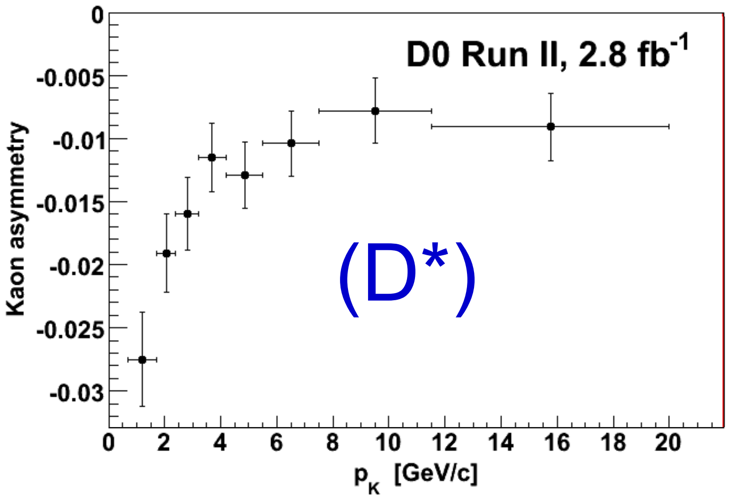
The kinematics depends on m(μK):

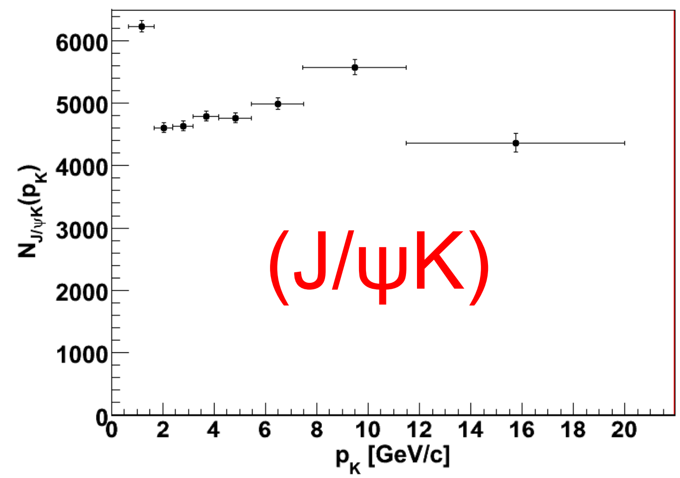


- Sideband subtraction in each m(μK) bin and summing over bins
- Signal band is separately adjusted in each m(μK) bin to maximize S/B

Kaon asymmetry in J/ψK sample

- Need to convert $A_K(D^*)$ into $A_K(J/\psi K)$
- Cross-section $\sigma_{inelastic}(KN)$ depends on kaon momentum. Therefore:





$$A_K(J/\psi K) = \sum_{p_K} A_K(p_K) \cdot \frac{N_{J/\psi K}(p_K)}{N_{J/\psi K}} = -0.0145 \pm 0.0010(stat)$$

Finally

$$A_{CP}(B^+ \to J/\psi K^+) = A(J/\psi K) - A_K(J/\psi K)$$

$$= -0.0070 \pm 0.0060 - (-0.0145 \pm 0.0010) = \boxed{+0.0075 \pm 0.0061}$$

Systematic uncertainties: dominant sources

Source	To see the systematic effect:
from $A(J/\psi K)$, $A(J/\psi\pi)$	
$(J/\psi K^*)$ contribution to likelihood is a threshold function with parameters determined from Monte Carlo	We include $(J/\psi K^*)$ into the background description or drop it altogether. Uncertainty = max deviation from nominal value.
from $A_K(J/\psi K)$	
definition of background for the sideband subtraction as $\mu(+)$, $K(+)$, $\pi(+)$	We try another unphysical combination: $\mu(+)$, $K(+)$, $\pi(-)$

Final result

$A(B^+ \to J/\psi K^+) = A(J/\psi K) - A_K(J/\psi K)$	$+0.0075 \pm 0.0061(stat) \pm 0.0027(syst)$
$A(B^+ \to J/\psi \pi^+)$	$-0.09 \pm 0.08(stat) \pm 0.03(syst)$

$A_{CP}(B^+ \to J/\psi K^+)$: consistent and ~3 more precise then current PDG average:

$A_{CP}(B^+ \to J/\psi(1S)K^+)$

VALUE		*DOCUMENT ID*		*TECN*	*COMMENT*
0.015±0.017 OUR AVERAGE	Error includes scale factor of 1.2.				
0.030±0.014±0.010	636	AUBERT	05J	BABR	$e^+e^- \to \Upsilon(4S)$
−0.026±0.022±0.017		ABE	03B	BELL	$e^+e^- \to \Upsilon(4S)$
0.018±0.043±0.004	637	BONVICINI	00	CLE2	$e^+e^- \to \Upsilon(4S)$

$A_{CP}(B^+ \to J/\psi \pi^+)$: Belle not confirmed

$A_{CP}(B^+ \to J/\psi(1S)\pi^+)$

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.09 ±0.08 OUR AVERAGE				
0.123±0.085±0.004	AUBERT	04P	BABR	$e^+e^- \to \Upsilon(4S)$
−0.023±0.164±0.015	ABE	03B	BELL	$e^+e^- \to \Upsilon(4S)$

BACKUP SLIDES

Kaon asymmetry: rough estimate

Loss of kaons:

$$\frac{dN}{N} \sim \exp\left(-\frac{L}{L0}\right)$$

Nuclear interaction length (PDG):

$$L0 = \frac{A}{\sigma_{inelastic} N_A \rho}$$

$$\sigma_{inelastic}(K^+) \sim 35mb$$

$$\sigma_{inelastic}(K^-) \sim 70mb$$

Tracking volume: Material = Beryllium, L~5 cm

$$A_K = \frac{1}{2}\left[\exp\left(-\frac{L}{L0(K^-)}\right) - \exp\left(-\frac{L}{L0(K^+)}\right)\right] \sim 1\%$$

Likelihood function

We maximized on event-by-event basis:

$$L = \prod_{i=1}^{N} \alpha \left[\beta_1 f_{J/\psi K}(m_B, \sigma_B, m) + \beta_1 f_{J/\psi\pi}(m_{B,R}, \sigma_{B,R}, m) \right.$$

← f – Gaussian

$$m_{B,R}^2 - m_B^2 = 2E_{J/\psi}(E_K - E_\pi) + m_K^2 - m_\pi^2 > 0$$

$$\left. + \beta_3 f_{J/\psi K^*}(m) \right]$$

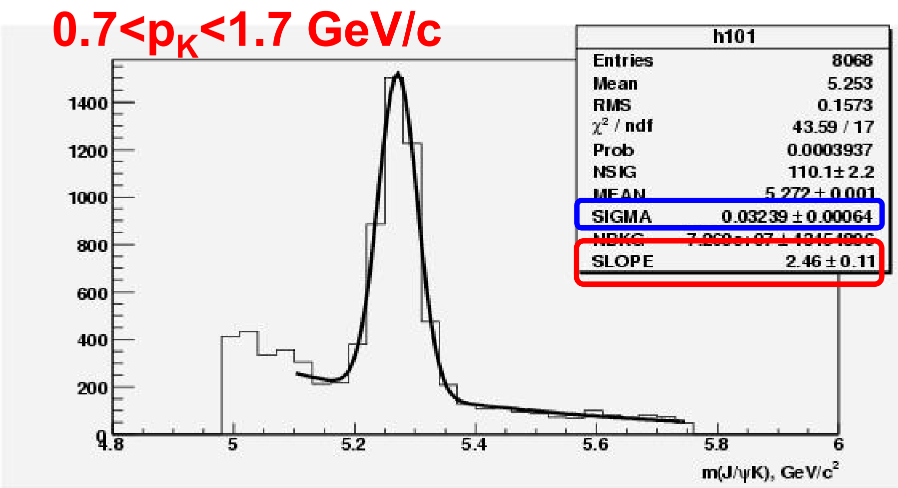
← f – function with threshold at m_B–m_π, parameters from Monte Carlo

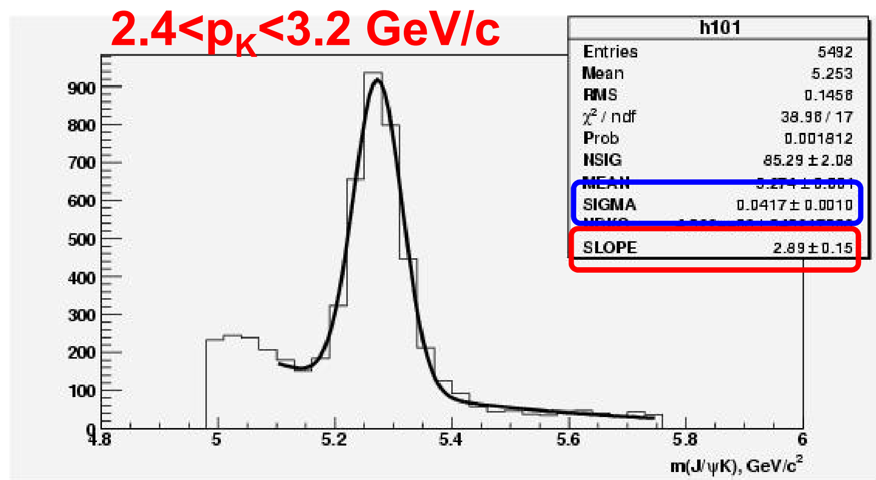
$$+ \left[1 - \alpha(\beta_1 + \beta_2 + \beta_3) \right] f_{BKG}(m)$$

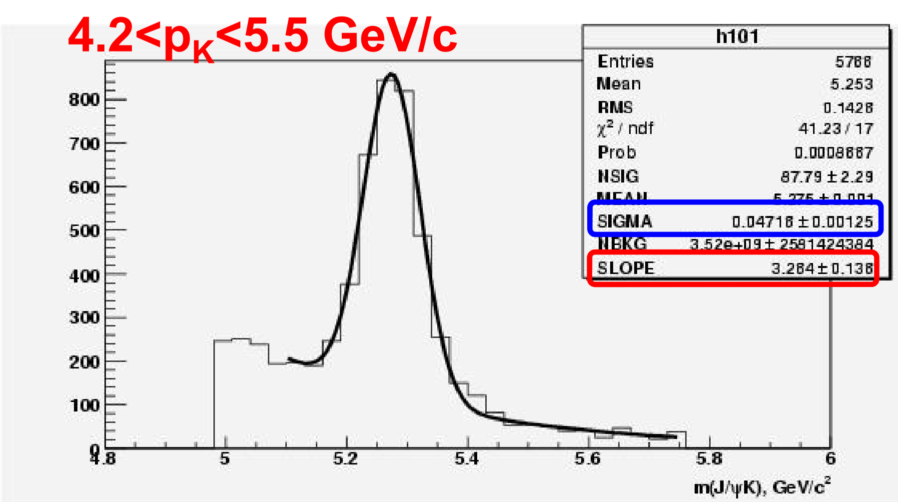
← f – Exponential

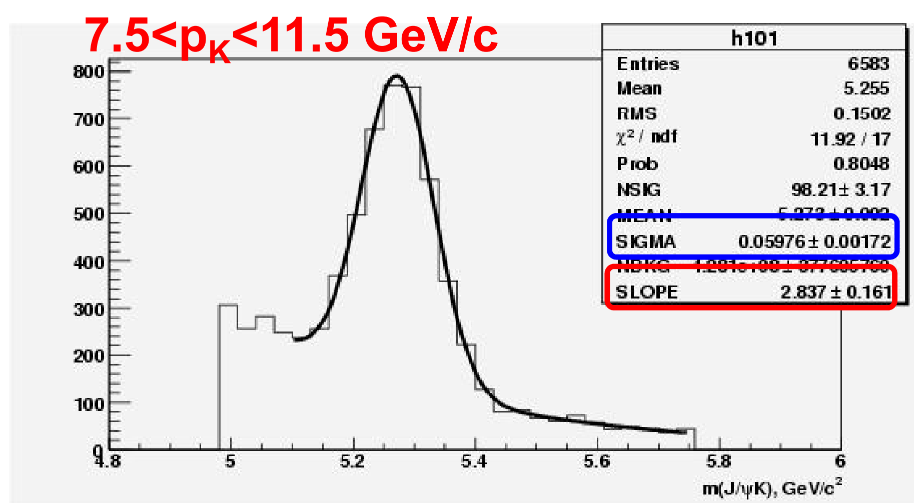
- α contains dependence on E_K (same for J/ψK, J/ψπ, J/ψK*)
- $\beta_{1,2,3}$ – signal fractions

Likelihood parameterization







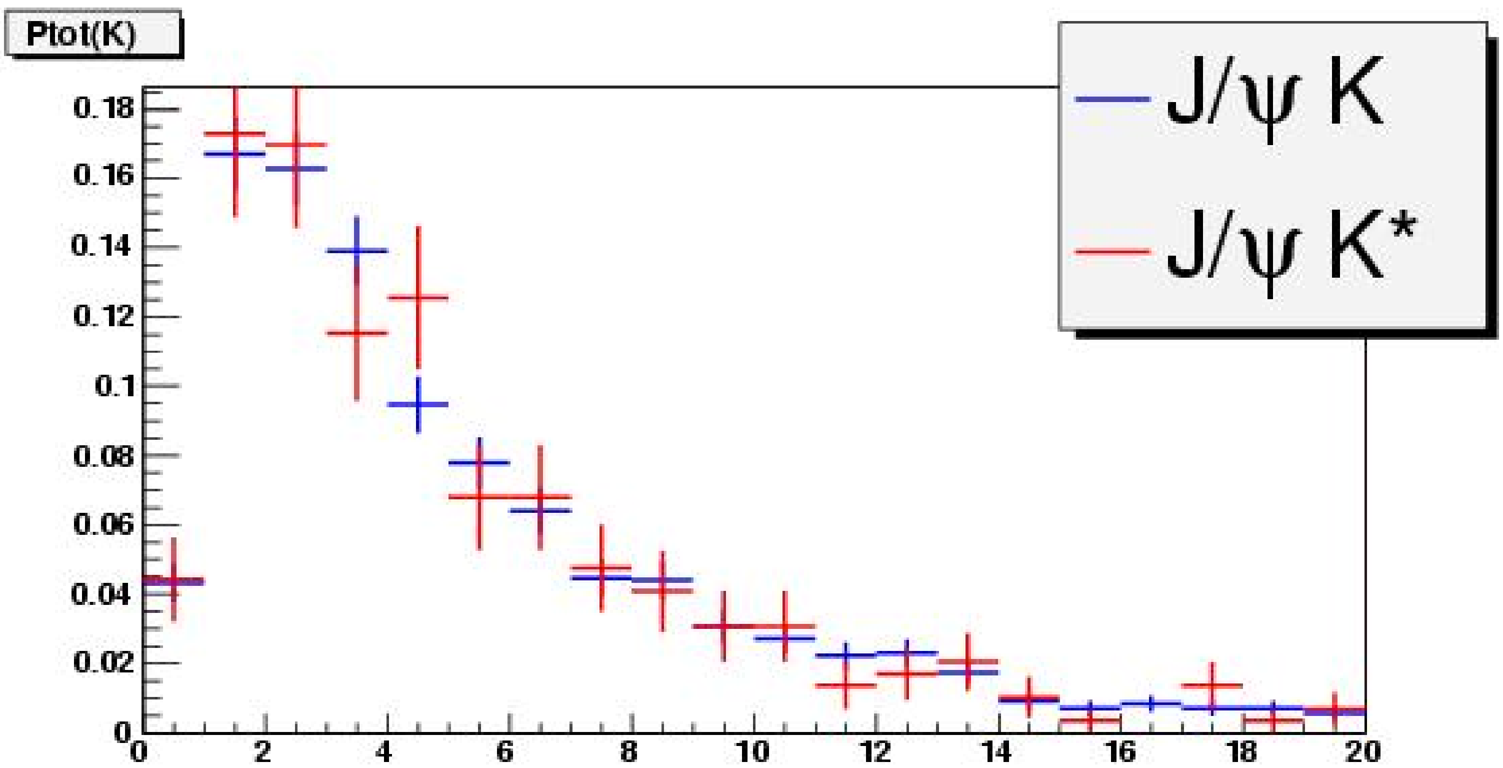


Slope, resolution are parameterized as polynomials in $E_K = \sqrt{p_K^2 + m_K^2}$ (coefficients determined during the fit)

Likelihood parameterization

Monte Carlo:

Signal fractions of J/ψK and J/ψK* have similar dependence on p_K

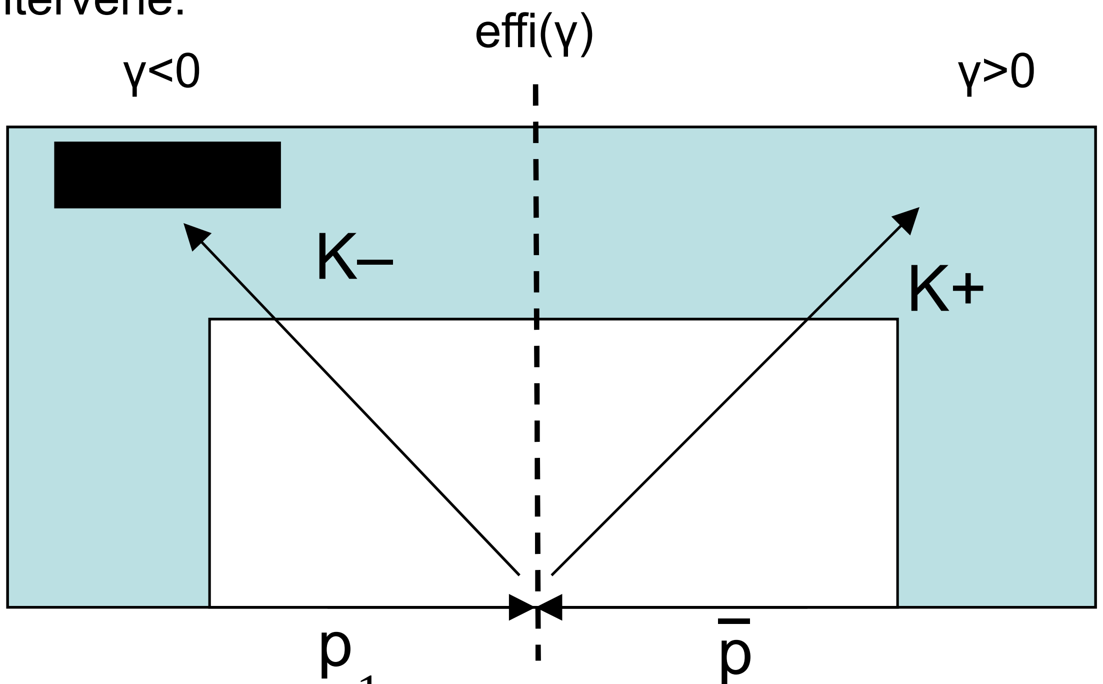


Detector modeling

We want charge asymmetry between J/ψK+ and J/ψK–:

$$A = \frac{N(J/\psi(K^-,\pi^-) - N(J/\psi(K^+,\pi^+))}{N(J/\psi(K^-,\pi^-)) + N(J/\psi(K^+,\pi^+))} = \frac{n_- - n_+}{n_- + n_+} \Rightarrow n_\pm = \frac{1}{2}N(1+qA)$$

BUT: Forward-backward (K+ prefers proton direction) and detector geometric asymmetries intervene:

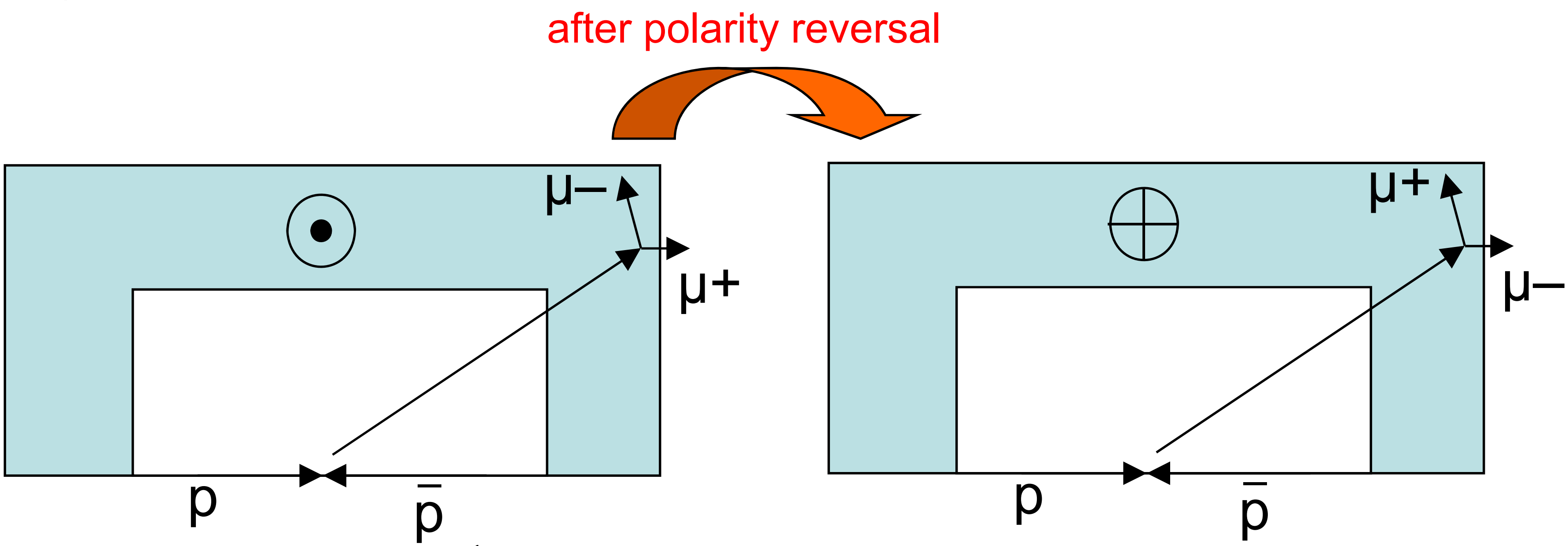


Modeled by: $$n_q^\gamma = \frac{1}{2}N(1+qA)(1+q\gamma A_{fb})(1+\gamma A_{\det})$$

Detector modeling

Range out asymmetry of muons in the toroid.

(Kaon are reconstructed inside solenoid, where there is no range out. Range out asymmetry is necessary for consistency of the model and will become important later)



Modeled by: $$n_q^{\beta\gamma} = \frac{1}{2} N \varepsilon^{\beta} (1+qA)(1+q\gamma A_{fb})(1+\gamma A_{\det})(1+q\beta\gamma A_{q\beta\gamma})$$

- ε^{β} – fraction of signal events recorded at magnet polarity β (±1)

Detector modeling

Finally to fully characterize the detector:

$$n_q^{\beta\gamma} = \frac{1}{4} N\varepsilon^{\beta}(1+qA)(1+q\gamma A_{fb})(1+\gamma A_{\det})(1+q\beta\gamma A_{q\beta\gamma})(1+\beta\gamma A_{\beta\gamma})(1+q\beta A_{q\beta})$$

[Phys.Rev.D74, 092001 (2006)]

This model proposes a method to disentangle intervening asymmetries by measuring them all:

- Divide sample into 8 subsamples according to signs of β (solenoid polarity), γ (sign of pseudorapidity), q (kaon charge)
- Fit invariant mass of J/ψK in every subsample and extract number of events in J/ψK and reflected J/ψπ peaks
- Solve the model for all asymmetries. Now charge asymmetry A is "clean"

Physically reasonable:

- Let only signal fractions in the mass model float, keeping all other parameters fixed to their "best values" (determined from the fit in the un-splitted sample)
- Constrain ε^{β} to be the same for both J/ψK and J/ψπ signals

Charge asymmetries: results

Result of likelihood fit in 8 subsamples of different signs of β, γ, q

$\beta\gamma q$	$J/\psi K$	$J/\psi\pi$
$+++$	$5,104 \pm 87$	337 ± 44
$+-+$	$5,131 \pm 87$	222 ± 42
$++-$	$4,999 \pm 85$	212 ± 40
$+--$	$5,098 \pm 86$	144 ± 38
$-++$	$4,973 \pm 86$	158 ± 41
$--+$	$5,039 \pm 86$	127 ± 39
$-+-$	$4,965 \pm 85$	242 ± 41
$---$	$4,906 \pm 84$	138 ± 39
#tot	$40,222 \pm 242$	$1,578 \pm 119$

Asymmetries:

	$J/\psi K$	$J/\psi\pi$
N	$40,217 \pm 243$	$1,577 \pm 118$
ϵ^+	0.5060 ± 0.0030	
A	-0.0070 ± 0.0060	-0.0887 ± 0.0807
A_{fb}	0.0013 ± 0.0060	0.0453 ± 0.0890
A_{det}	-0.0033 ± 0.0060	0.2061 ± 0.0826
$A_{q\beta\gamma}$	-0.0050 ± 0.0060	-0.0207 ± 0.0873
$A_{q\beta}$	0.0001 ± 0.0060	-0.1896 ± 0.0823
$A_{\beta\gamma}$	-0.0030 ± 0.0060	0.0499 ± 0.0801

$$A(J/\psi K) = -0.0070 \pm 0.0060(stat)$$

Not yet!

$$A_{CP}(B^+ \to J/\psi\pi^+) = -0.09 \pm 0.08(stat)$$

- Result!

Kaon asymmetry: Sample selection

D* candidates constructed from 3 tracks (BANA tracking algorithm):

muon track: muon cluster + track measured in SMT and CFT, with $p_T > 2$ GeV/c

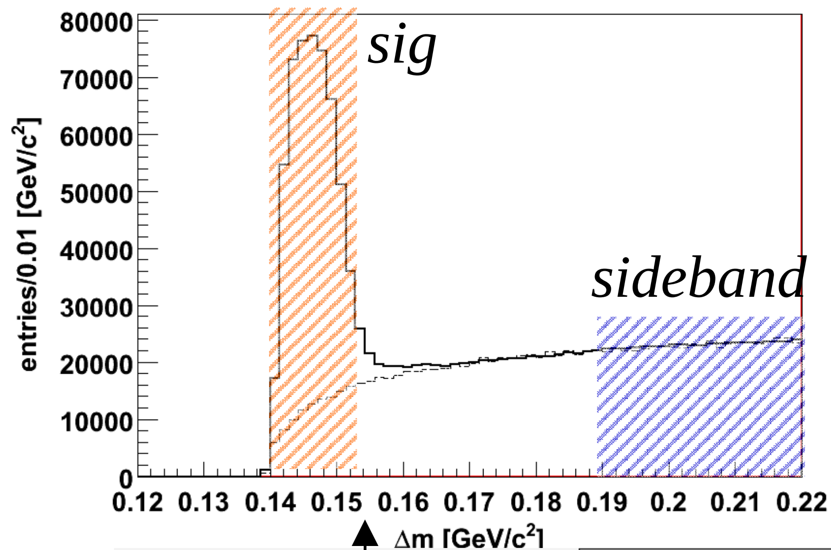
2nd track: assigned a kaon mass, mass of 2 tracks $1.0 < m(\mu K) < 2.2$ GeV/c^2, distance from μK system to Primary Vertex $< 4\sigma$, cosine of pointing angle > 0.9

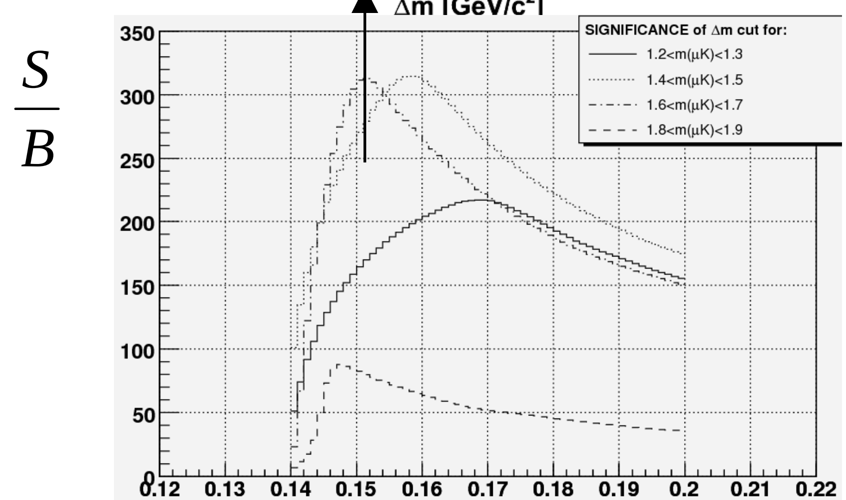
3rd track: assigned a pion mass, distance to Primary Vertex $< 3\sigma$, $\Delta m = m(\mu K\pi) - m(\mu K) < 0.22$ GeV/c^2

In every m(μK) bin:

Right Sign: μ+, K–, π+ and Charge Conj.

Wrong Sign: μ+, K+, π+ and Charge Conj.





$$S = N_{RS}^{sig} - N_{WS}^{sig} \cdot \frac{N_{RS}^{side}}{N_{WS}^{side}}$$

Kaon asymmetry: detector model

After sideband subtracting the background in every m(μK) bin and summing the events up we obtained ~ 2.7M of D* events. To measure the muon charge asymmetry we applied the same detector model:

$$n_q^{\beta\gamma} = \frac{1}{4} N \varepsilon^{\beta} (1 + qA)(1 + q\gamma A_{fb})(1 + \gamma A_{\det})(1 + q\beta\gamma A_{q\beta\gamma})(1 + \beta\gamma A_{\beta\gamma})(1 + q\beta A_{q\beta})$$

The only difference: muons can range out in the toroid.

ε^{β} – toroid polarity, $A_{q\beta\gamma}$ – largest intervening asymmetry.

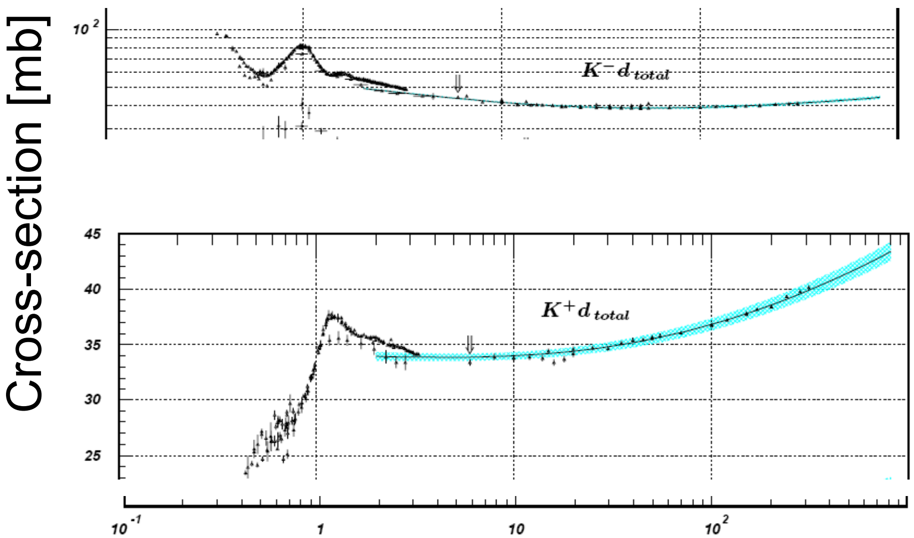
After splitting into subsamples and solving for asymmetries:

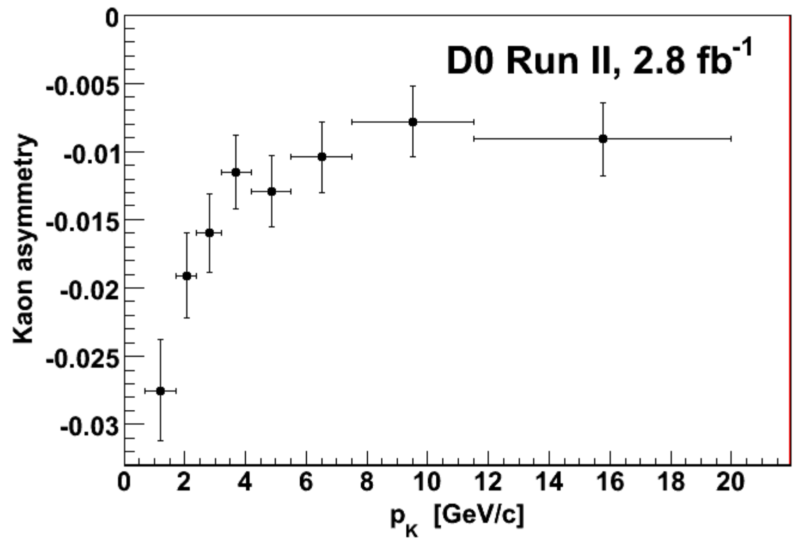
$A_K = -0.0131 \pm 0.0009$ (Range out $A_{q\beta\gamma} = -0.0304 \pm 0.0009$)

After correcting for the sample composition: $A_K = -0.0144 \pm 0.0012$

Kaon asymmetry in J/ψK sample

BUT: still need to convert this number to A_K in J/ψK sample.
Cross-section σ(Kd) depends on kaon momentum. Therefore:





Kaon asymmetry in the J/ψK sample

$$A_K(J/\psi K) = \sum_{p_K} A_K(p_K)\cdot\frac{N_{J/\psi K}(p_K)}{N_{J/\psi K}} = -0.0145 \pm 0.0010(stat)$$

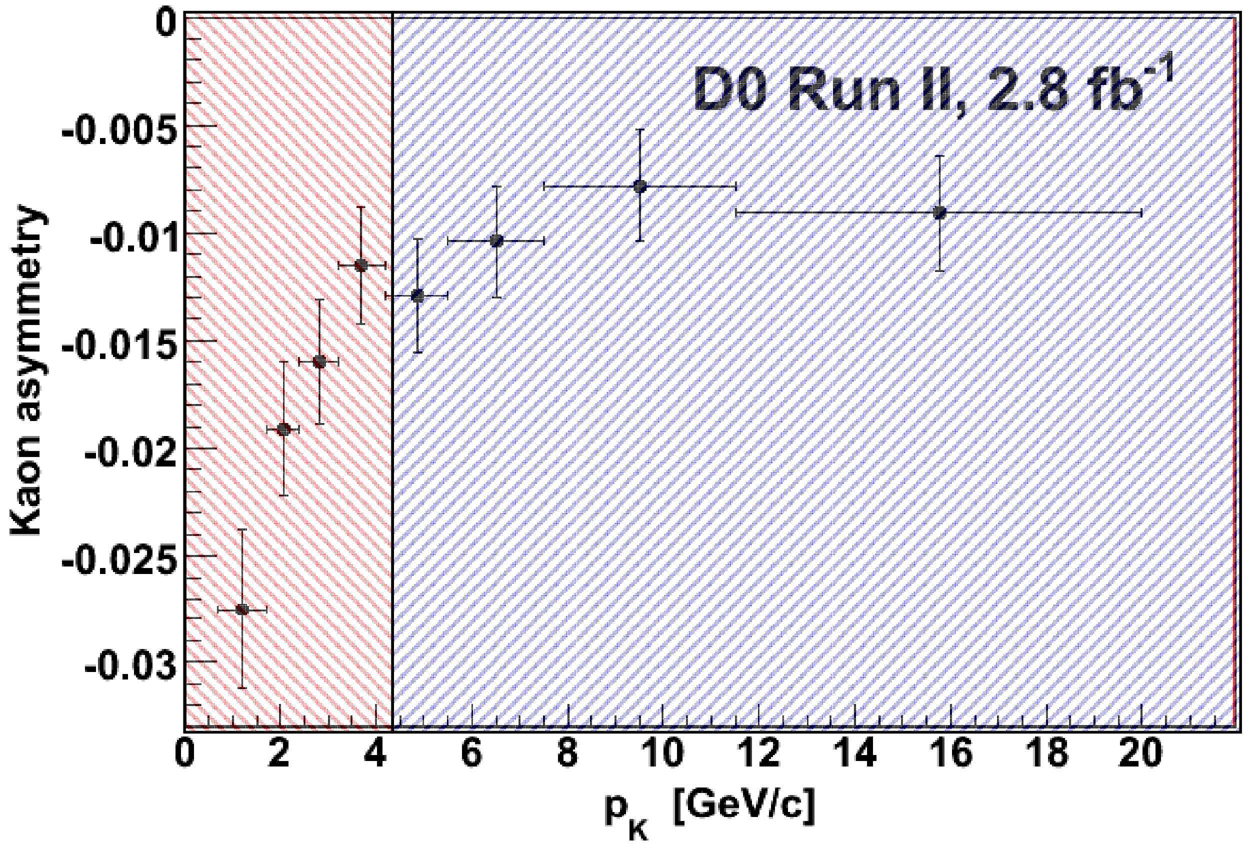
Systematic uncertainties

Source	$A_{CP}(B^+ \to J/\psi K^+)$	$A_{CP}(B^+ \to J/\psi \pi^+)$
from $A(J/\psi K)$, $A(J/\psi \pi)$		
±1σ variation of mass fit parameters	0.0002	0.0004
Fitting range variation	0.0004	0.0129
Likelihood parameterization of $J/\psi K$ and $J/\psi \pi$	0.0025	0.0252
from $A_K(J/\psi K)$		
Choice of side band	(negligible)	–
Background definition	0.0008	–
Unknown reco efficiency of some decay modes of D* sample	0.0005	–
Pion reco asymmetry	–	0.0002
Total	0.0027	0.0283

$A_{CP}(B^+ \to J/\psi K^+)$: cross-check

$$A_{CP}(B^+ \to J/\psi K^+) = A(J/\psi K) - A_K(J/\psi K) =$$

0.0143±0.0081 –0.0009±0.0102



$\Delta A_{CP} = 0.0152 \pm 0.0130$ - consistent with stat fluctuation

Some math

If n_1 and n_2 independent:

$$A = \frac{n_1 - n_2}{n_1 + n_2} = \frac{\Delta n}{N}, \Delta n_1^2 + \Delta n_2^2 = \Delta N^2$$

$$\left(\frac{\Delta A}{A}\right)^2 = \frac{\Delta N^2}{(\Delta n)^2} + \frac{\Delta N^2}{N^2} = \frac{\Delta N^2 (N^2 + \Delta n^2)}{\Delta n^2 N^2} \approx \frac{\Delta N^2}{\Delta n^2}$$

we neglect $\Delta n^2 << N^2$

Therefore for any asymmetry: $\Delta A = \frac{\Delta N}{N}$

If A_K: $n_q \propto (1 + qA_{CP})(1 + qA_K)$

$$\propto (1 + qA_{CP} + qA_K) \propto (1 + q(A_{CP} + A_K))$$

therefore $A = A_{CP} + A_K$