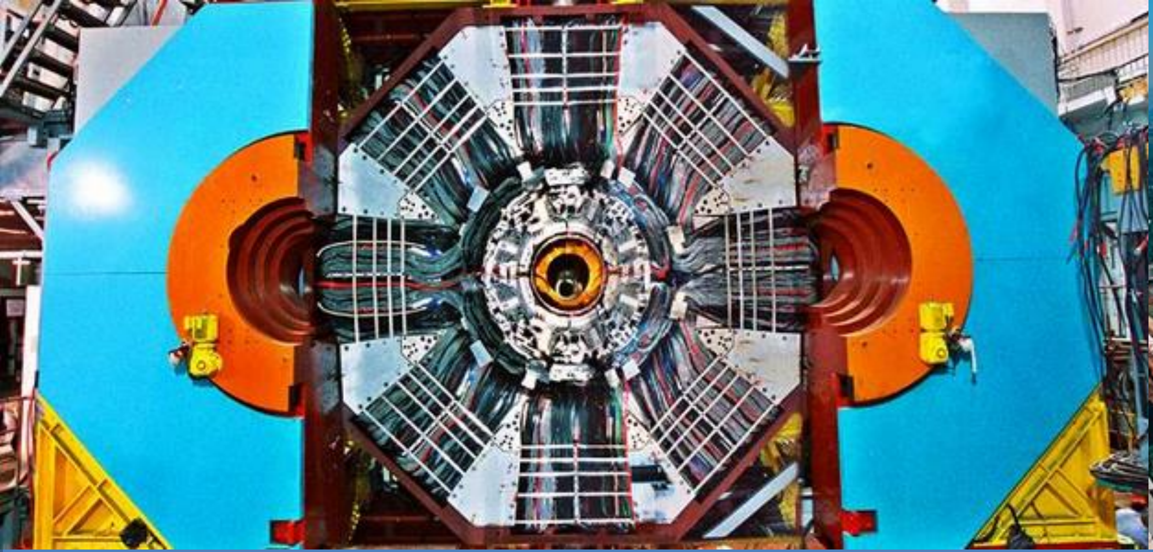


Relative Strong-Phase Difference Between D^0 and $\overline{D}^0$ ($\rightarrow K_s\pi^+\pi^-$) at BESIII

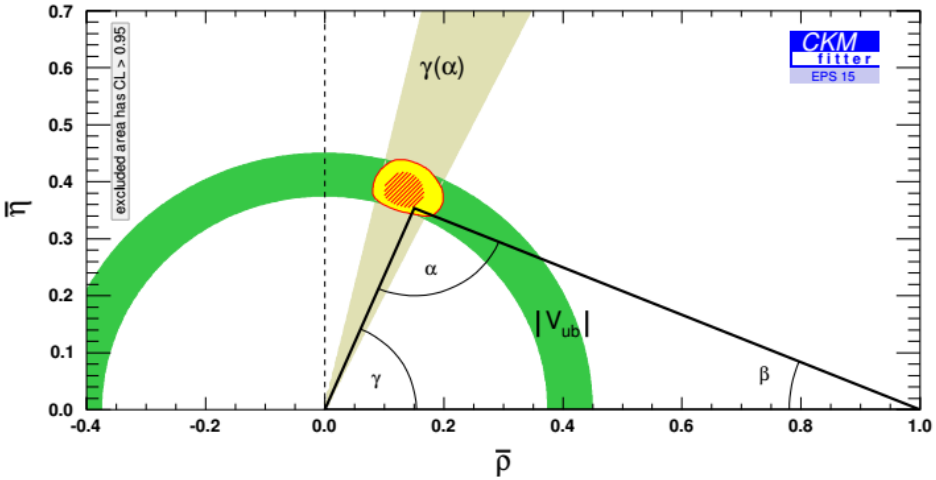
Dan Ambrose
University of Minnesota
B2TiP
Pittsburgh, Pennsylvania
05/23/16

Outline

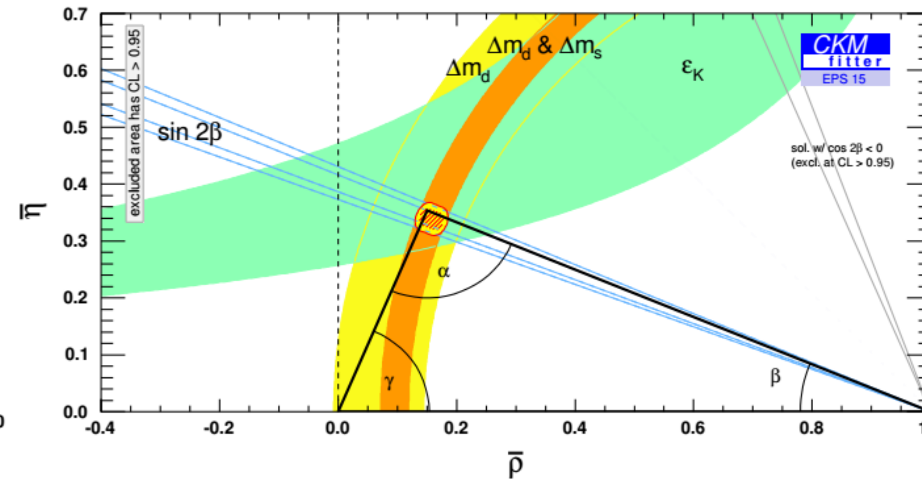
- GGSZ Method
- Strong-Phase difference between D^0 and $\overline{D}^0 \to K_s\pi^+\pi^-$ measurement at BESIII
- Impact on the measurement of CKM UT angle ϕ_3/γ
- Future BESIII measurements

Current Status of the Measurement of the CKM UT

Tree Measurements



Loop Measurements



Differences would imply new physics

$$\phi_1/\beta = \left(21.85^{+0.68}_{-0.67}\right)^\circ$$

$$\phi_2/\alpha = \left(87.6^{+3.5}_{-3.3}\right)^\circ$$

$$\phi_3/\gamma = \left(73.2^{+6.3}_{-7.0}\right)^\circ$$

2015 CKMfitter (Direct Measurements)

$$\phi_1/\beta = \left(22.62^{+0.44}_{-0.42}\right)^\circ$$

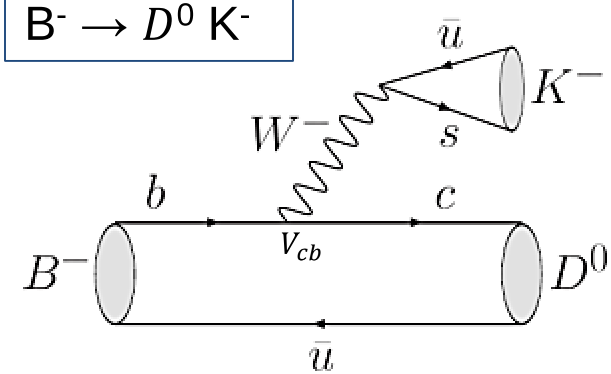
$$\phi_2/\alpha = \left(90.4^{+2.0}_{-1.0}\right)^\circ$$

$$\phi_3/\gamma = \left(67.01^{+0.88}_{-1.99}\right)^\circ$$

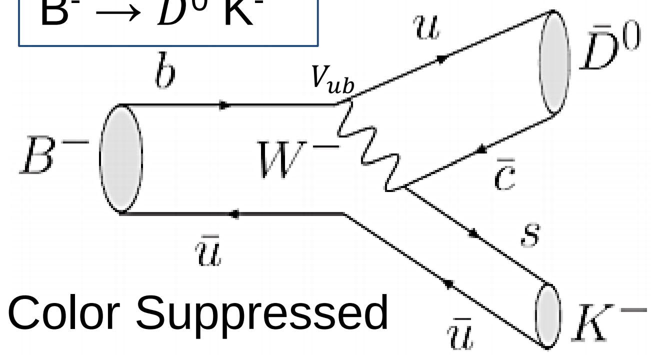
2015 CKMfitter (Global Fits)

Directly Measuring ϕ_3/γ through $B^- \to \widetilde{D}^0 K^-$

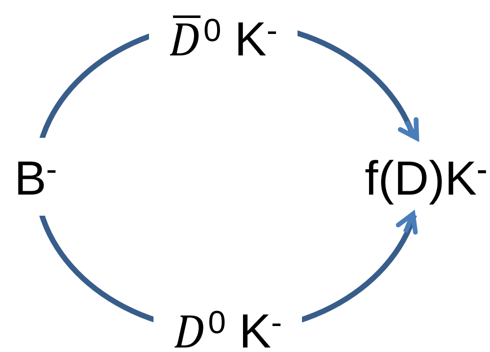
$B^- \to D^0 K^-$



$B^- \to \bar{D}^0 K^-$



$$\frac{\langle B^- \to \overline{D^0} K^- \rangle}{\langle B^- \to D^0 K^- \rangle} = r_B e^{i(\delta_B - \phi_3)}$$



Determine ϕ_3 through the measurement of the interference between b →c and b →u transitions when D^0 and $\bar{D}^0$ both decay to the same final state f(D).

Total Decay Rate

$$\Gamma(B^- \to f(D^0)K^-) = A_B^2 A_f^2 (r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D - \phi_3))$$

ϕ_3 fit through GGSZ method

Due to both amplitude and having only charged tracks, $K_s\pi^+\pi^-$ is the preferred final state for this method.

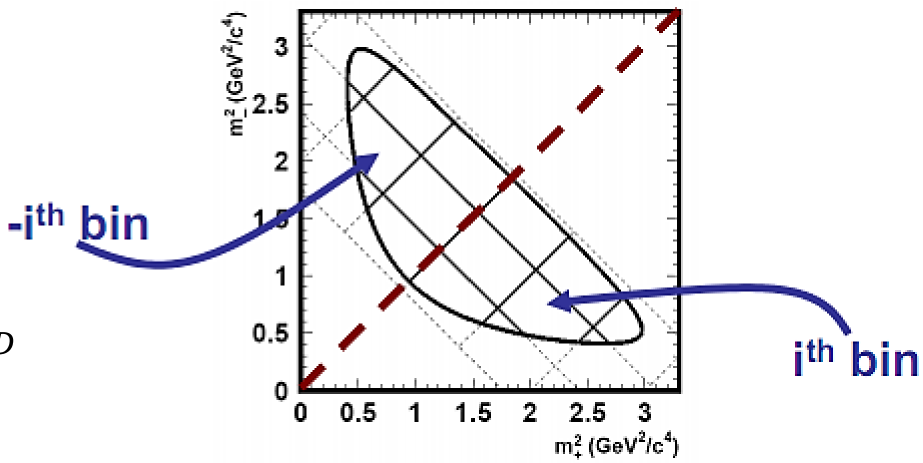
Distribution sensitive to variables:

T_i : Bin yield measured in flavor decays

r_B : color suppression factor ~ 0.1

δ_B : strong phase of B decay

c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively where $\Delta\delta_D$ is the difference between phase of D^0 and $\overline{D}^0$



Mirrored binning over x=y makes it so $c_i = c_{-i}$ and $s_i = -s_{-i}$

T_i , r_B, δ_B are measured at B-Factories

c_i and s_i can be found through $K_s\pi^+\pi^-$ Analysis at BESIII

Binned decay rate:

$$\Gamma(B^\pm \to D(K_s\pi^+\pi^-)K^\pm)_i = T_i + r_B^2 T_{-i} + 2r_B\sqrt{T_i T_{-i}}\cos(\delta_B \pm \phi_3 - \Delta\delta_D)$$
$$= T_i + r_B^2 T_{-i} + 2r_B\sqrt{T_i T_{-i}}\{c_i\cos(\delta_B \pm \phi_3) + s_i\sin(\delta_B \pm \phi_3)\}$$

Status of Direct Measurement of ϕ_3

Example of ϕ_3 measurements from GGSZ method

Belle Model-Dependent Dalitz [Phys. Rev. D 81, 112002 (2010)]

$$78.4^{+10.8}_{-11.6}(stat) \pm 3.6(syst) \pm \boxed{8.9(Model)}$$

Belle Model-Independent Dalitz [Phys. Rev. D 85, 112014 (2012)]

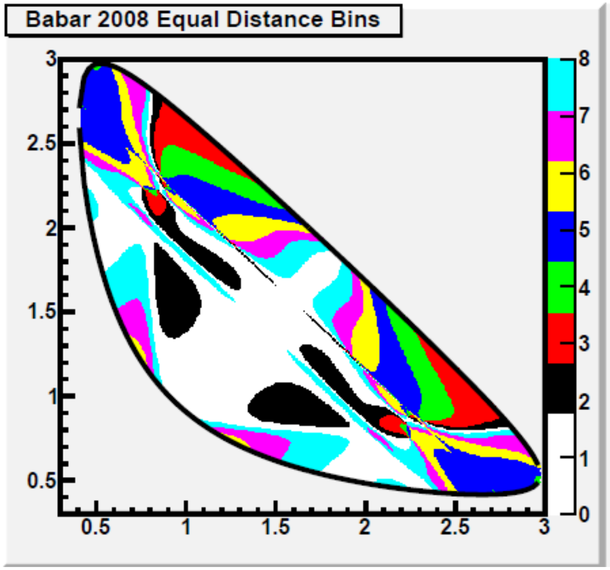
$$77.3^{+15.1}_{-14.9}(stat) \pm 4.2(syst) \pm \boxed{4.3(c_i/s_i)}$$

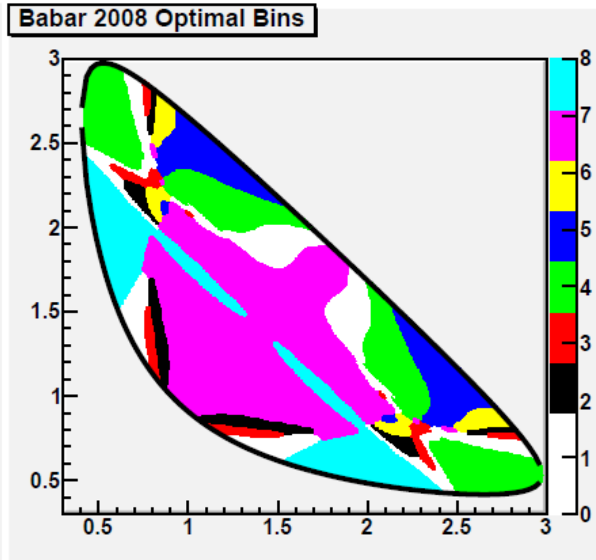
Currently statistically limited,
but soon systematically limited

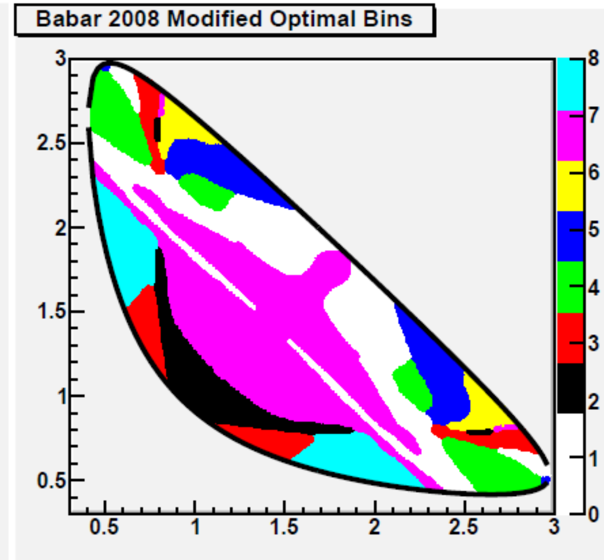
Combine methods measurement

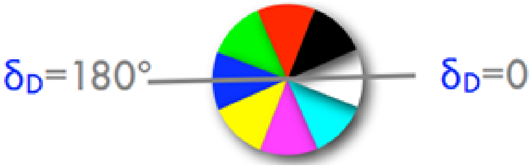
$$\phi_3 = \begin{cases} \left(69^{+17}_{-16}\right)^\circ \; BABAR(2013) \\ \left(68^{+15}_{-14}\right)^\circ \; Belle(2013) \\ \left(62^{+15}_{-14}\right)^\circ \; LHCb(2014) \end{cases}$$

Binning of $D^0 \rightarrow K_s\pi^+\pi^-$ Dalitz Plot









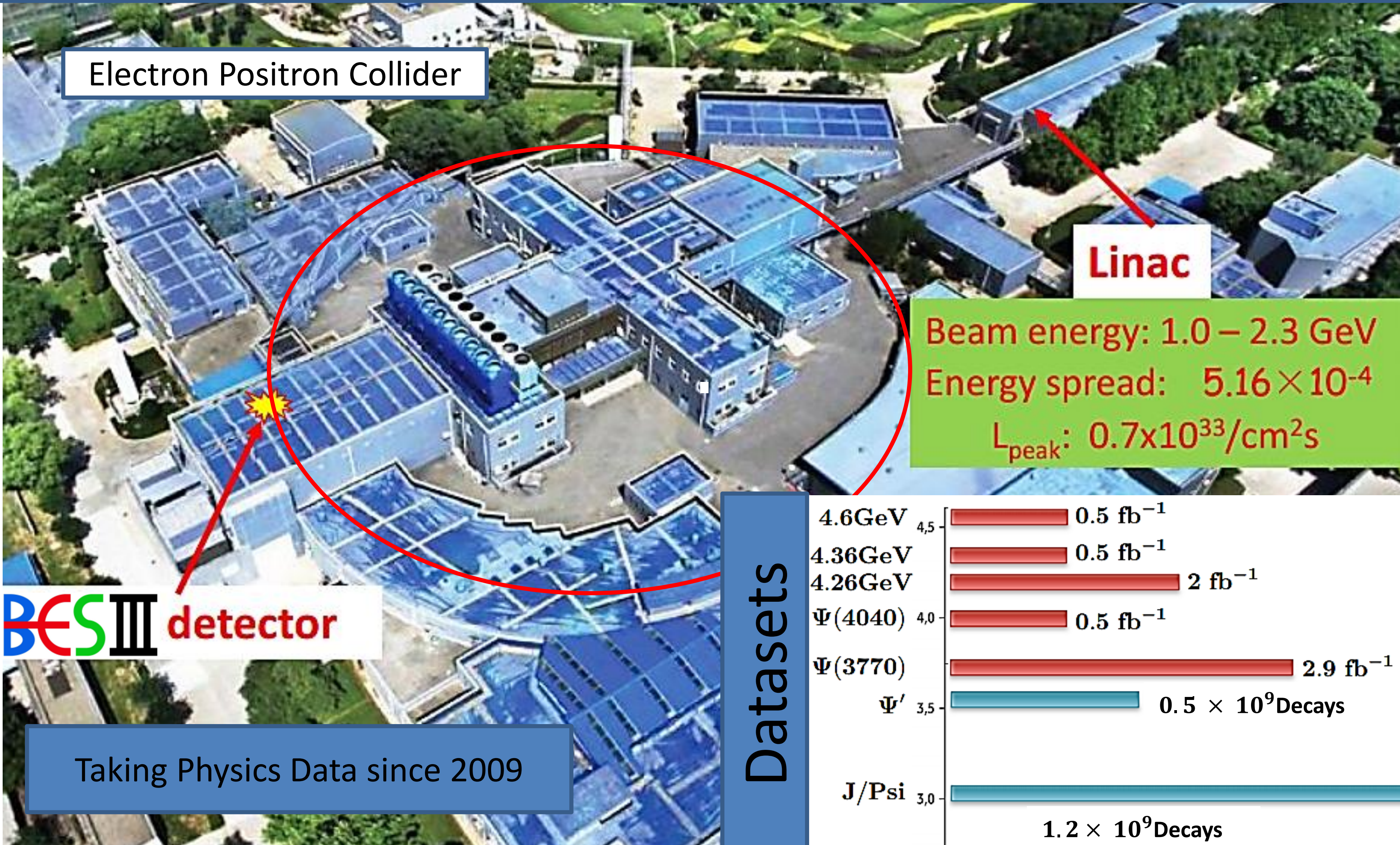
Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

Starting with the equally spaced bins, bins are adjusted to optimize the sensitivity to ϕ_3. A secondary adjustment smooths binned areas smaller than detector resolution.

Similar to the "optimal binning" except the expected background is taken into account before optimizing for ϕ_3 sensitivity.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

BEPCII and BESIII

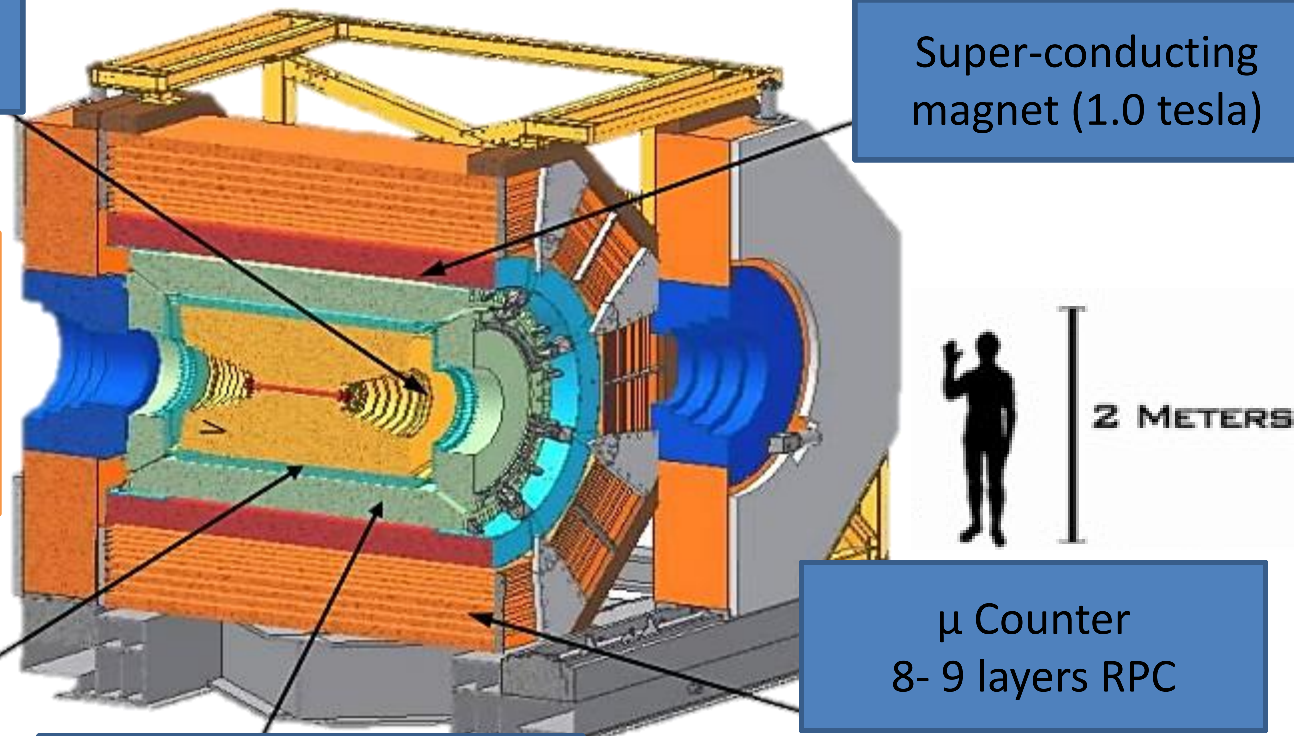


BESIII Detector

Drift Chamber (MDC)
$\sigma_P/P = 0.5\%$ @1 GeV
$\sigma_{dE/dx} = 6\%$

Super-conducting magnet (1.0 tesla)

BESIII collaboration consists of 58 institutions from 13 different countries.



Time Of Flight (TOF)
σ_T : 90 ps Barrel
110 ps endcap

μ Counter
8- 9 layers RPC

EMC :
σ_E/E = 2.5%@1GeV
σ_Z = 0.6cm

M. Ablikim et al., (BESIII Collaboration), Nucl. Instrum. Meth. A 614, 345 (2010).

ψ(3770) Dataset

2.9 fb^{-1} is the largest set of at this type in the world by 3.5 times.

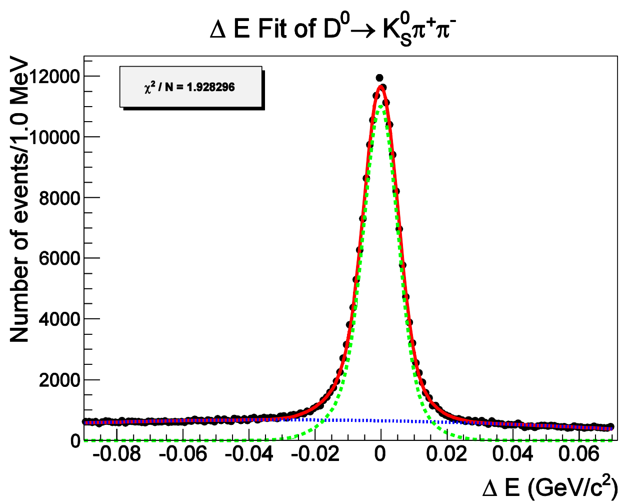
ψ(3770) excited $c\bar{c}$ state which decays primarily into a $D\bar{D}$ pair.

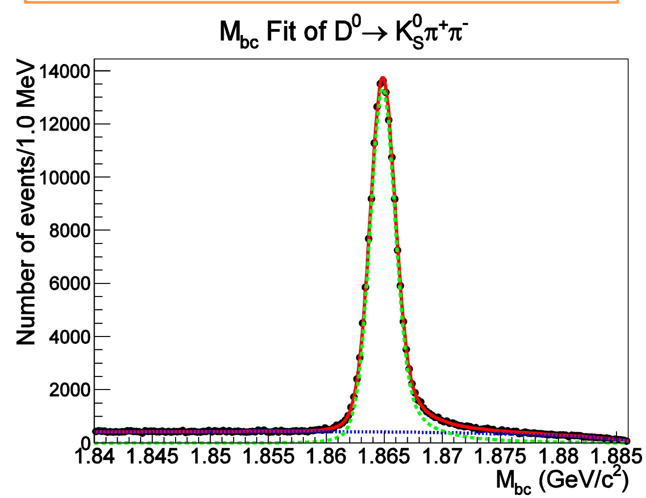
Single Tagging

Reconstruct particles from a single D decay.

$$\Delta E = E_{D\ Rec} - E_{Beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - |\vec{P}_{D\ Rec}|^2}$$



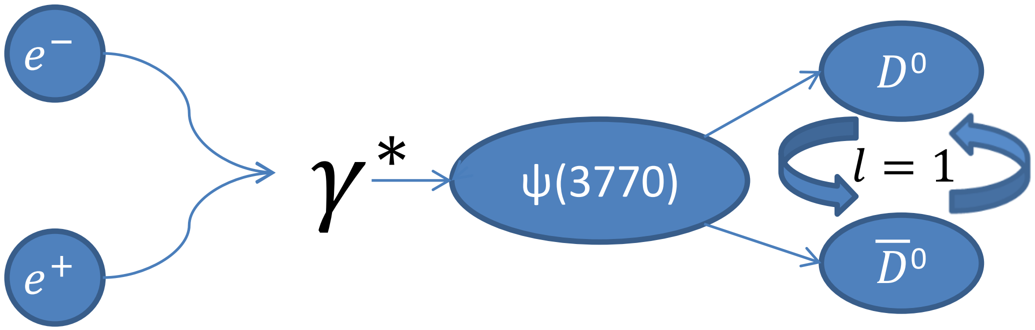


Quantum Correlation in ψ(3770)

Virtual photon ⇒total CP-even state

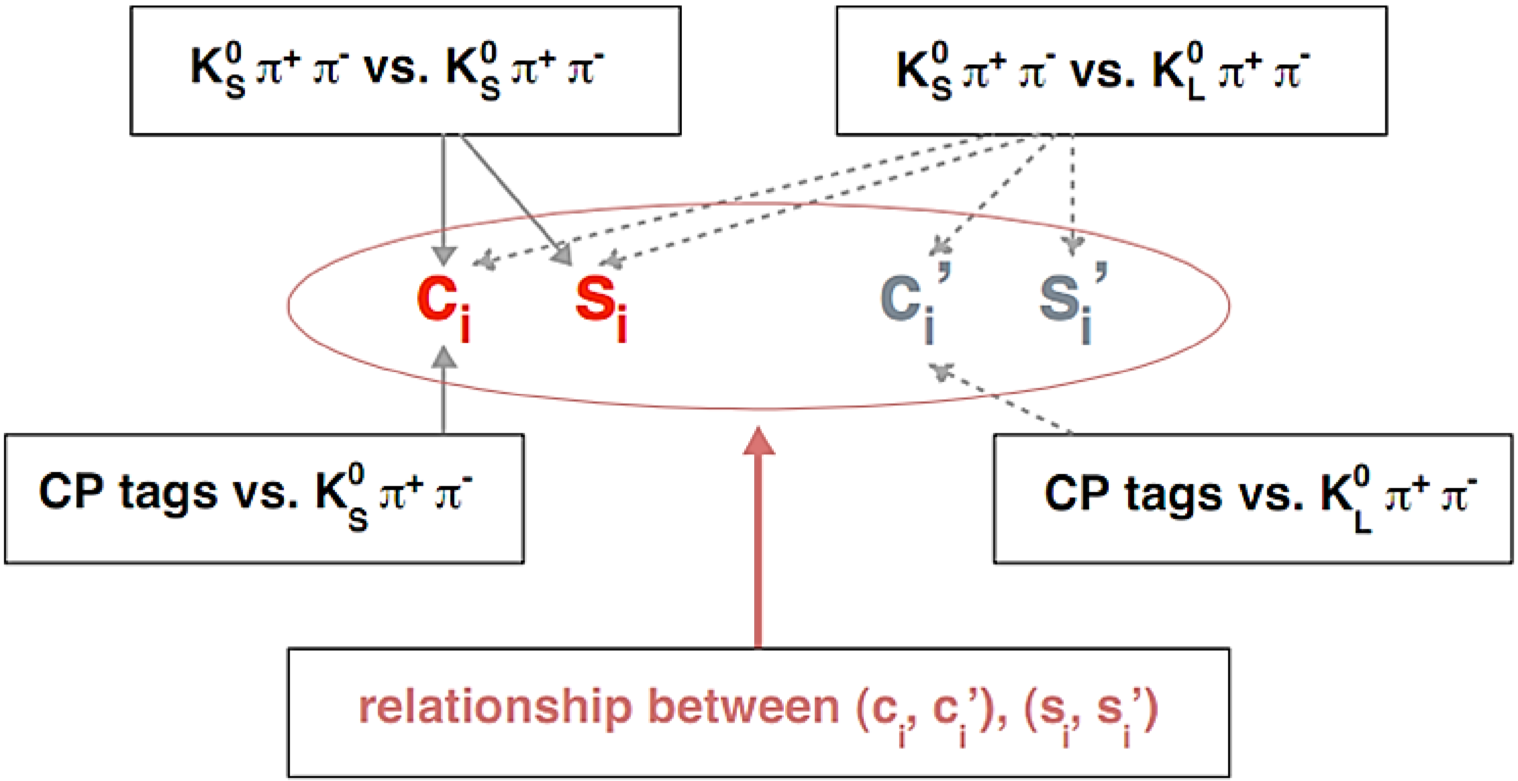
Spin 1 between D^0 and $\overline{D}^0 \Rightarrow CP(D^0) = -CP\left(\overline{D}^0\right)$

Pair correlation leads to different decay amplitudes than an independent D.



Quantum Correlated D^0 / $\overline{D}^0$ pair allows us to know the Flavor or CP of $K_s\pi^+\pi^-$ by tagging the other D.

Constraining c_i and s_i



Only c_i, s_i from $K_s\pi^+\pi^-$ is used to calculate ϕ_3.
However adding in $D^0 \rightarrow K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

Equation on calculating c_i

For the CP tag modes, one can show that the total bin yields are related to c_i by

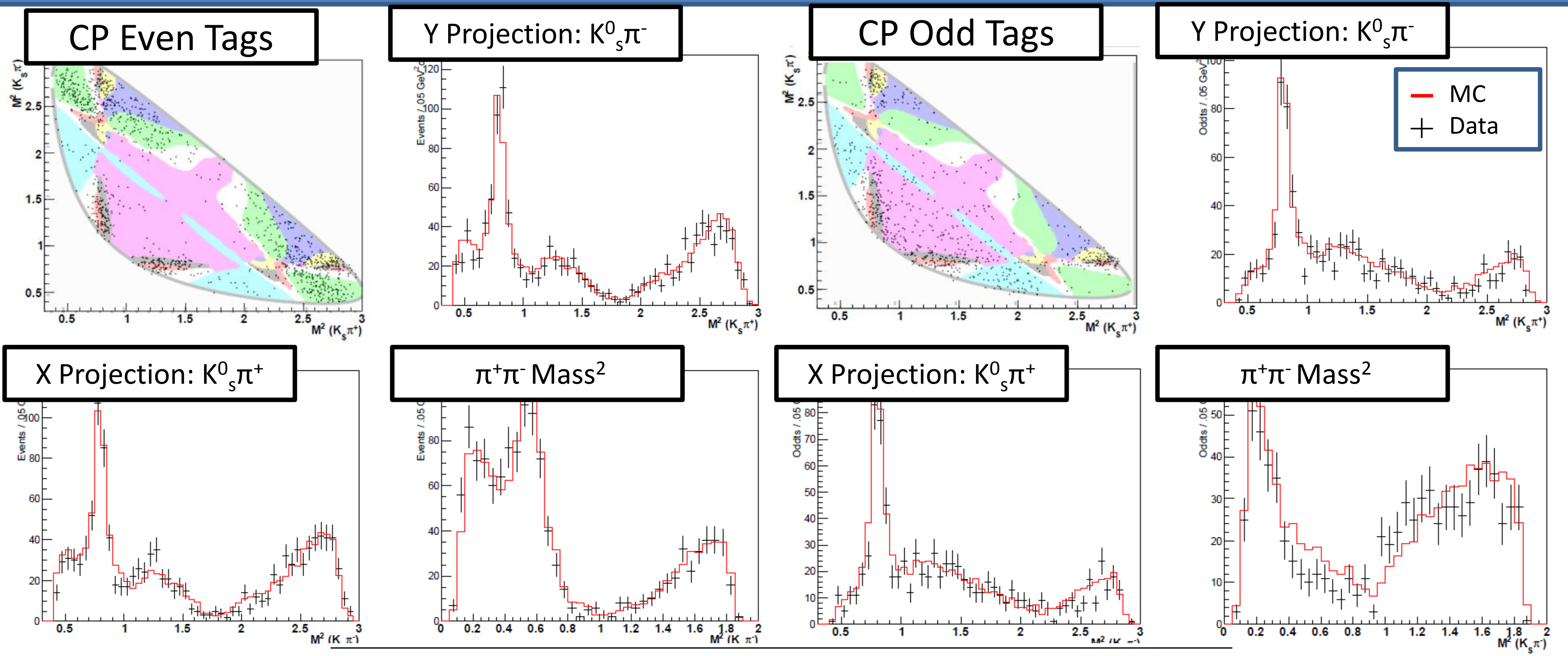
$$\boxed{M_i^{\pm} = \frac{S_{\pm}}{2S_f}\left(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i}\right)}$$

$M_i^+(M_i^-)$ yields in each bin of Dalitz plot for CP even(odd) modes.
$S_+(S_-)$ number of single tags for CP even(odd) modes.
S_f number of single tags for flavor modes.
$K_i(K_{-i})$, yields in each bin of Dalitz plot in flavor modes.

Single Tag modes

Type	Tag List
Pseudo-Flavored	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
S^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$, $K_L\pi^0$
S^-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$

$K_S^0\pi^+\pi^-$ Dalitz Plots vs CP Modes



Type	Tag List
S^+	$K^+K^-,\ \pi^+\pi^-,\ K_S\pi^0\pi^0,\ K_L\pi^0$
S^-	$K_S\pi^0,\ K_S\eta(\to\gamma\gamma),\ K_S\eta(\to\pi^+\pi^-\pi^0),\ K_S\omega,\ K_S\eta'$

BESIII Preliminary

- Data is using the full 2.9 fb^{-1} $\psi(3770)$ dataset
- Results presented here will be using Optimal Binning scheme.

Calculating both c_i and s_i

Using $D^0 \to K_s\pi^+\pi^-$ vs $\overline{D}^0 \to K_s\pi^+\pi^-$ we can calculate both c_i and s_i:

$$\boxed{M_{i,j} = \frac{N_{D,\overline{D}}}{2S_f^2}\left(K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}\left(c_ic_j + s_is_j\right)\right)}$$

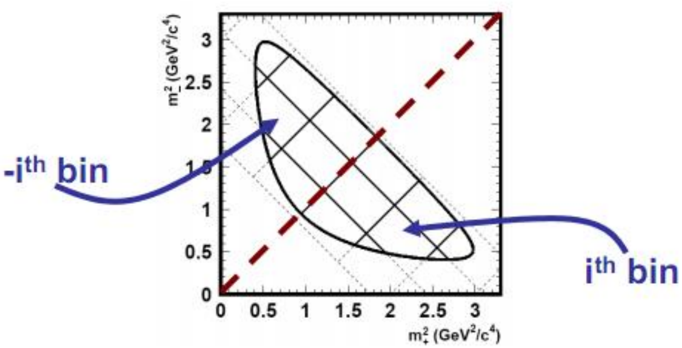
$M_{i,j}$ yields in bin i of first Dalitz plot
and bin j of second Dalitz plot.
S_f number of single tags for flavor modes.
$N_{D,\overline{D}}$ total number of $D^0\overline{D}^0$ events.
$K_i(K_{-i})$, yields in each bin of Dalitz plot
in flavor modes.

Mirroring the bins over the x=y line in the Dalitz plot, we note the following points:

- $M_{i,j} = M_{-i,-j}$
- $M_{i,-j} = M_{-i,j}$
- $M_{i,j} \neq M_{-i,j}$

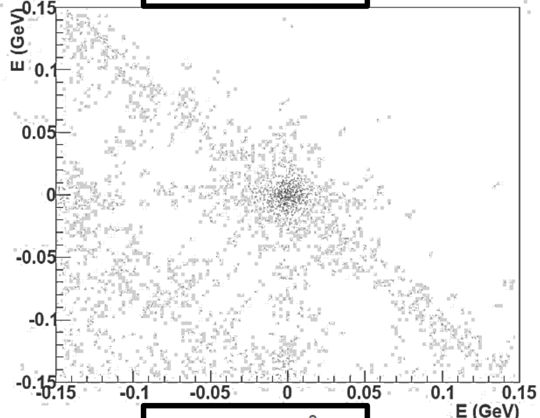
Symmetric Matrix because the order which tag is i or j

- $M_{i,j} = M_{j,i}$

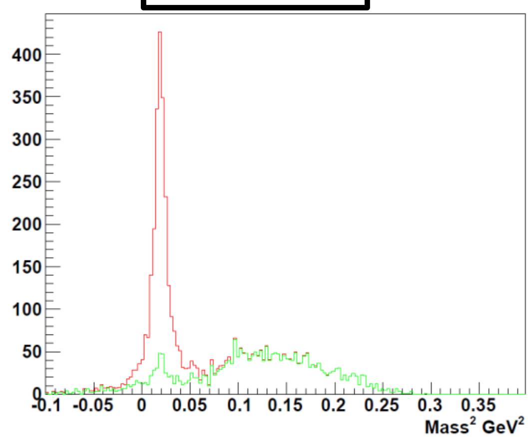


Dalitz Plots: $K_S^0\pi^+\pi^-$ vs $K_S^0\pi^+\pi^-$

ΔE $K_S\pi^+\pi^-$ vs. $K_S\pi^+\pi^-$

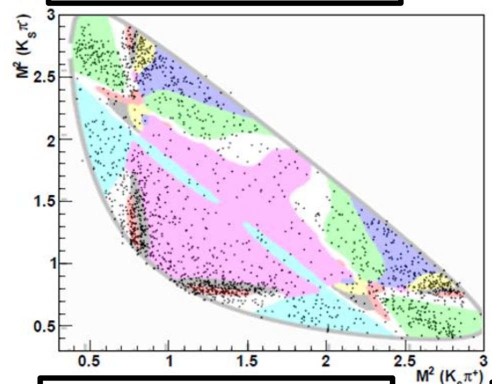


Missing Mass^2 π

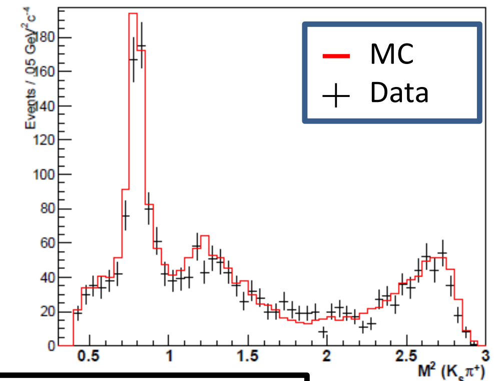


BESIII Preliminary

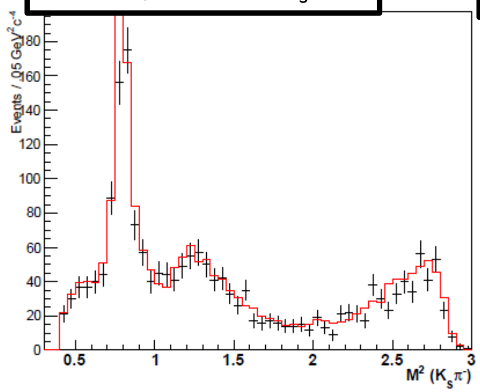
$K^0_s\pi^+\pi^-$ Tags



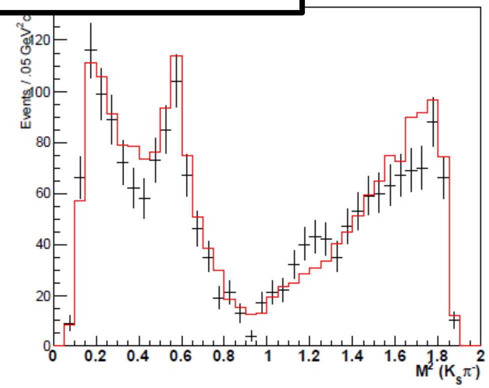
Y Projection: $K^0_s\pi^-$



X Projection: $K^0_s\pi^+$



$\pi^+\pi^-$ Mass^2



- This is the most statistically limited part of the analysis.
- Further increase statistics by reconstructing a missing π.

Total Fit

The total fit maximizes the likelihood of

$$-2\log\mathcal{L} = -2\sum_i \log P(M_i^{\pm}, < M_i^{\pm} >)_{(CP, K_S^0\pi^+\pi^-)}$$

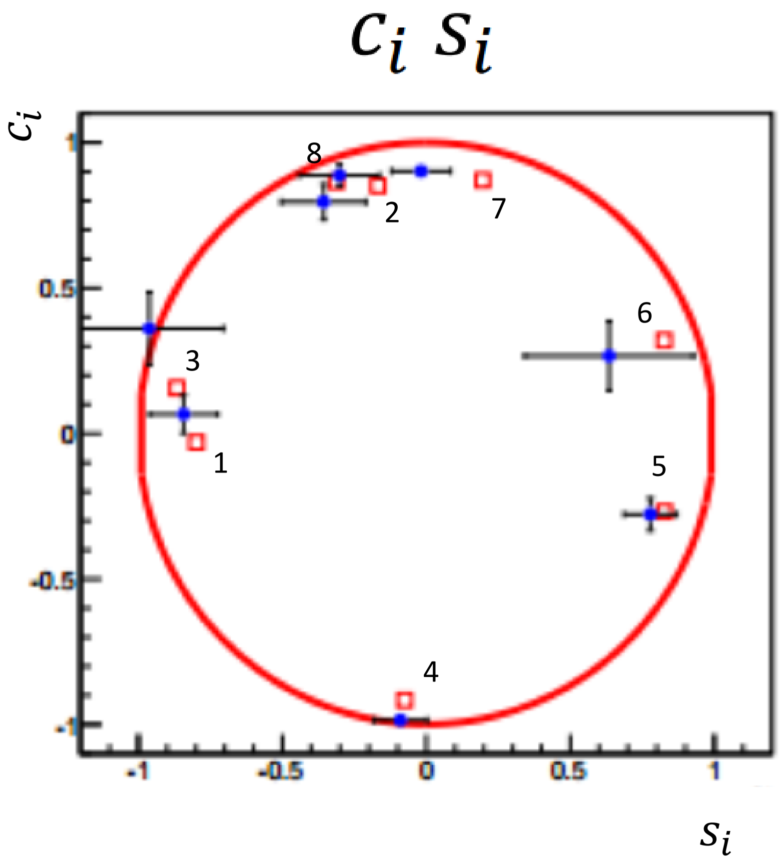
$$-2\sum_i \log P(M_i'^{\pm}, < M_i'^{\pm} >)_{(CP, K_L^0\pi^+\pi^-)}$$

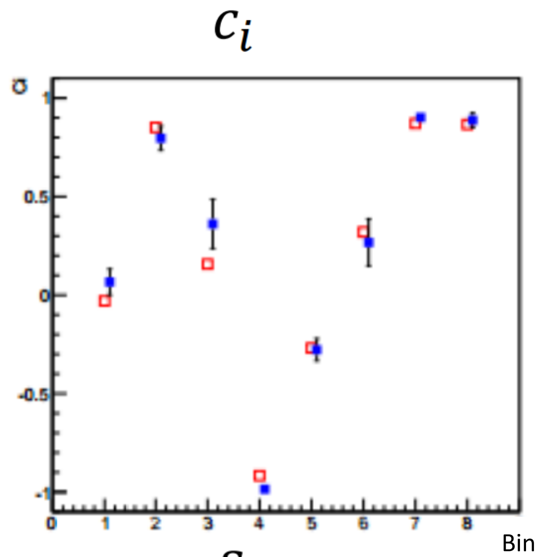
$$-2\sum_{i,j} \log P(M_{i,j}^{\pm}, < M_{i,j}^{\pm} >)_{(K_S^0\pi^+\pi^-, K_S^0\pi^+\pi^-)}$$

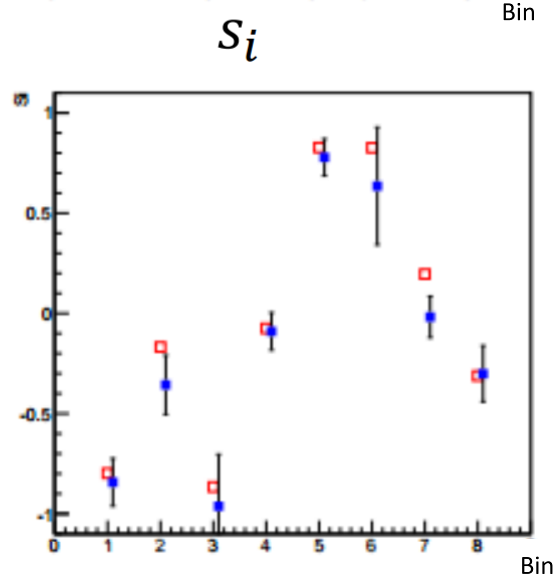
$$-2\sum_{i,j} \log P(M_{i,j}'^{\pm}, < M_{i,}'^{\pm} >)_{(K_S^0\pi^+\pi^-, K_L^0\pi^+\pi^-)}$$

P is Poisson probability of finding M events with the expected number <M>

Preliminary Data Results







- Model prediction
- Data

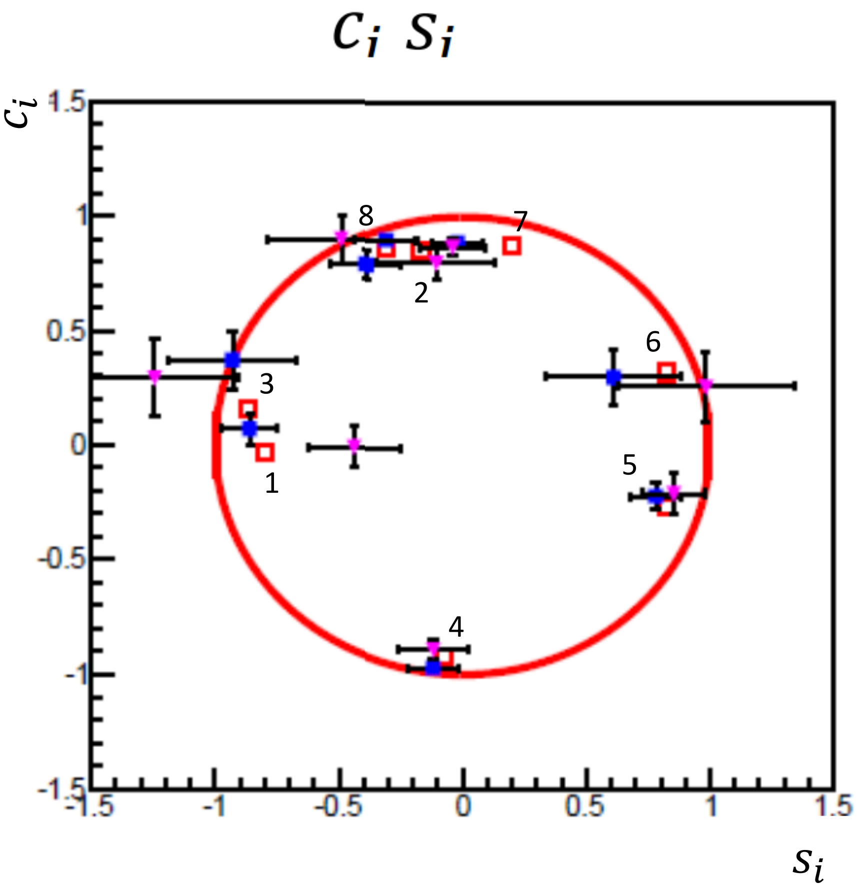
Results of Global fit of c_i, s_i.

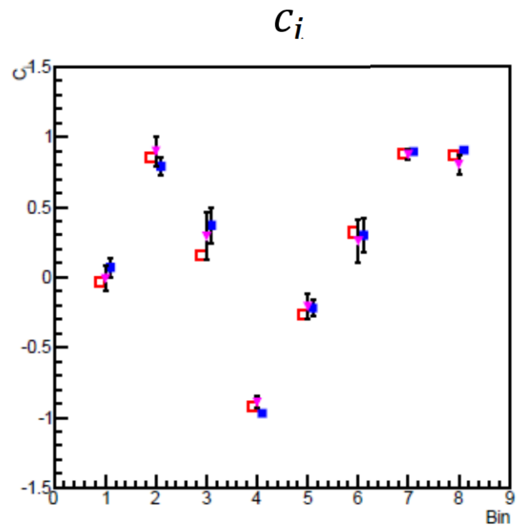
Error bar is the statistical uncertainty.

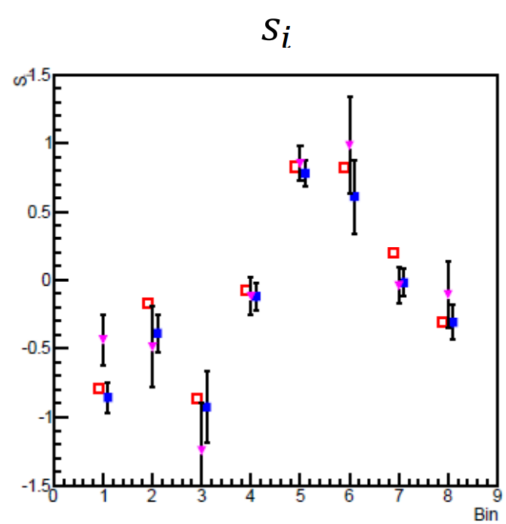
Fit of the data is in good agreement with the model prediction.

BESIII Preliminary

Comparison to Model/Previous Measurement







- Model prediction
- BESIII
- CLEO-c

Comparison	χ^2/DOF	Probability
CLEO-c	9.57/16	88%
Model	26.9/16	4.3%

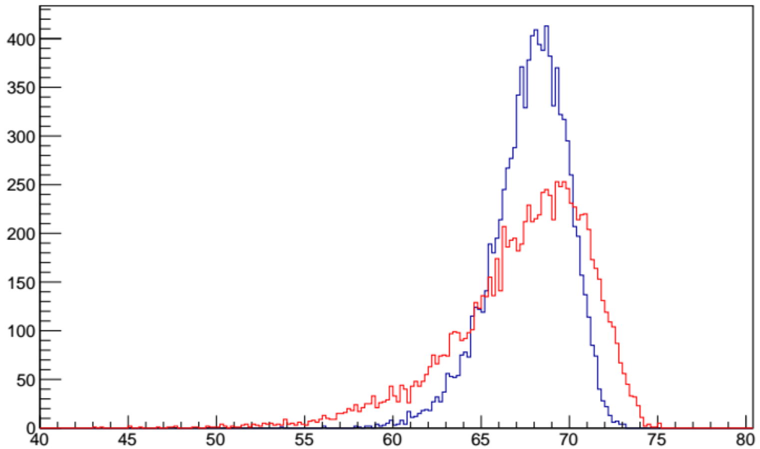
Consistent agreement with CLEO-c measurements.

BESIII Preliminary

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Impact on ϕ_3

Toy MC ϕ_3 estimate



ϕ_3

BESIII : RMS 2.165
CLEO-c : RMS 3.927

Toy MC estimates the effects on ϕ_3 by letting c_i, s_i vary by a Gaussian of their given uncertainty.

Width of variation due to BESIII uncertainty is 55% the previous measurement.

We are still statistically limited with 3 fb^{-1}.
Future measurements with 10 fb^{-1} and 20 fb^{-1} reduce the uncertainty to 33% and 27% the CLEO-c measurement, respectively.

Future Analysis from BESIII

Results to be available mid-summer.

Future strong-phase measurements of $K_S\pi^+\pi^-$ will benefit from more statistics.

- reduces dominant statistical uncertainty
- allows us to use cleaner modes, reducing systematic uncertainty
- allows for more bins, increasing sensitivity to ϕ_3.

BESIII is working on many other analysis,
including strong-phase measurements of $K_SK^+K^-$ and $\pi^+\pi^-\pi^0$.

Please come talk to me after if you have thoughts on topics or measurements which you would like to see from our unique datasets.

Summary

- We have measured and presented our preliminary results on strong phase difference between D^0 and $\overline{D}^0$ ($\rightarrow K_s\pi^+\pi^-$) decays based on the world largest sample of $\psi(3770)$, taken at E_{CM} = 3.773 GeV.
- Our preliminary results are consistent with the latest results from CLEO-c collaboration, but superior in terms of total uncertainties.
- Reduction in the c_i s_i contribution to the uncertainty in ϕ_3 of 45%. Improved statistics from B factories could place uncertainty from the c_i s_i contribution at <1%.
- The GGSZ method using other modes is being pursued at BESIII

Future ϕ_3 measurements will be exciting!

Dan Ambrose, University of Minnesota
B2TiP Pittsburgh, Pennsylvania

Backup Slides

Methods of Direct Measurement for γ

Total Decay Rate

$$\boxed{\Gamma(B^{\pm} \to f(D^0)K^{\pm}) = A_B^2 A_f^2\left(r_D^2 + r_B^2 + 2r_D\, r_B\ \cos(\delta_B + \delta_D \pm \gamma)\right)}$$

Methods of Direct measurement

- GLW method - f(D^0) →CP eigenstates

Pro's
1. $r_D = 1$
2. $\delta_D = 0, \pi$

Con's
1. Small interference term when $r_D / r_B \approx 10$
2. γ found only in $\cos(\gamma)\cos(\delta_B)$ or $\sin(\gamma)\sin(\delta_B)$

- ADS method - f(D^0) →Doubly Cabbibo-suppressed flavor states

Pro's
1. $r_D \approx r_B$

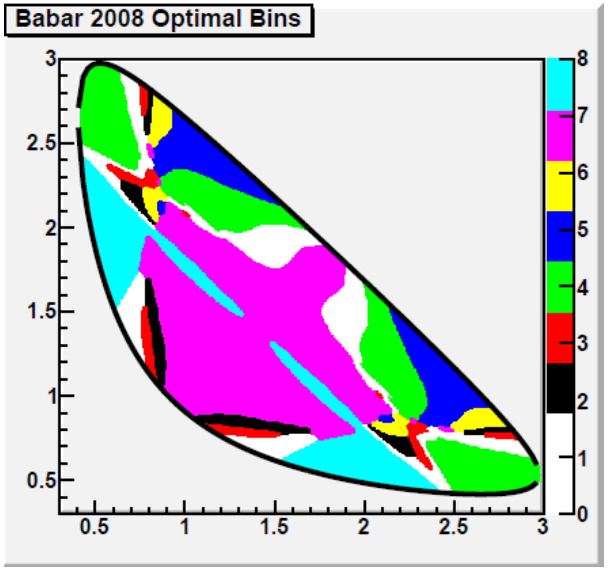
Con's
1. *Small statistics*
2. *Must measure r_D , δ_D for each mode*
3. γ found only in $\cos(\gamma)\cos(\delta_B)$ or $\sin(\gamma)\sin(\delta_B)$

- GGSZ method - f(D^0) →Dalitz analysis of 3 body final states

Pro's
1. Substructure allows regions of $r_D \approx r_B$
2. Sizeable statistics
3. Only two-fold ambiguity in γ

Con's
1. *Must measure r_D , δ_D for across all phases space*

$K_L^0\pi^+\pi^-$ Model Dependence



	Optimal	
i	Δc_i	Δs_i
1	0.39 ± 0.17	0.07 ± 0.06
2	0.18 ± 0.05	0.01 ± 0.10
3	0.61 ± 0.15	0.30 ± 0.12
4	0.09 ± 0.08	0.00 ± 0.08
5	0.16 ± 0.17	0.06 ± 0.06
6	0.57 ± 0.21	-0.15 ± 0.24
7	0.03 ± 0.01	-0.04 ± 0.06
8	-0.10 ± 0.15	-0.15 ± 0.21

’ indicates numbers from $K_L\pi^+\pi^-$ decays

Same bins but different amplitudes

Leads to c'_i and s'_i with difference defined as

$$\Delta c_i \equiv c'_i - c_i$$

$$\Delta s_i \equiv s'_i - s_i.$$

The amplitude difference is due to a change of sign on DCSD.

$$\frac{A(K_L^0\pi^+\pi^-(DCSD))}{A(K_S^0\pi^+\pi^-(DCSD))} \approx 0.89$$

$K^{*+}\pi^-$ is easy to model with its DCSD as it has been measured.

$K^0\rho^0$ is much harder to model its DCSD.

Source: CLEO Collaboration, Physical Review D, vol 82., pp. 112006 - 112035

Calculation of c_i, c'_i, s_i, s'_i

For CP tag vs $K_L^0\pi^+\pi^-$, we are able to find c'_i

' indicates numbers from $K_L\pi^+\pi^-$ decays

$$M'^{\pm}_i = \frac{S_\pm}{2S_f}\left(K'_i \mp 2c'_i\sqrt{K'_i K'_{-i}} + K'_{-i}\right)$$

$M'^{+}_i(M'^{-}_i)$ yields in each bin of Dalitz plot for CP even(odd) modes.
$S_+(S_-)$ number of single tags for CP even(odd) modes.
S_f number of single tags for flavor modes.
$K'_i(K'_{\bar{i}})$, yields in each bin of Dalitz plot in flavor modes.

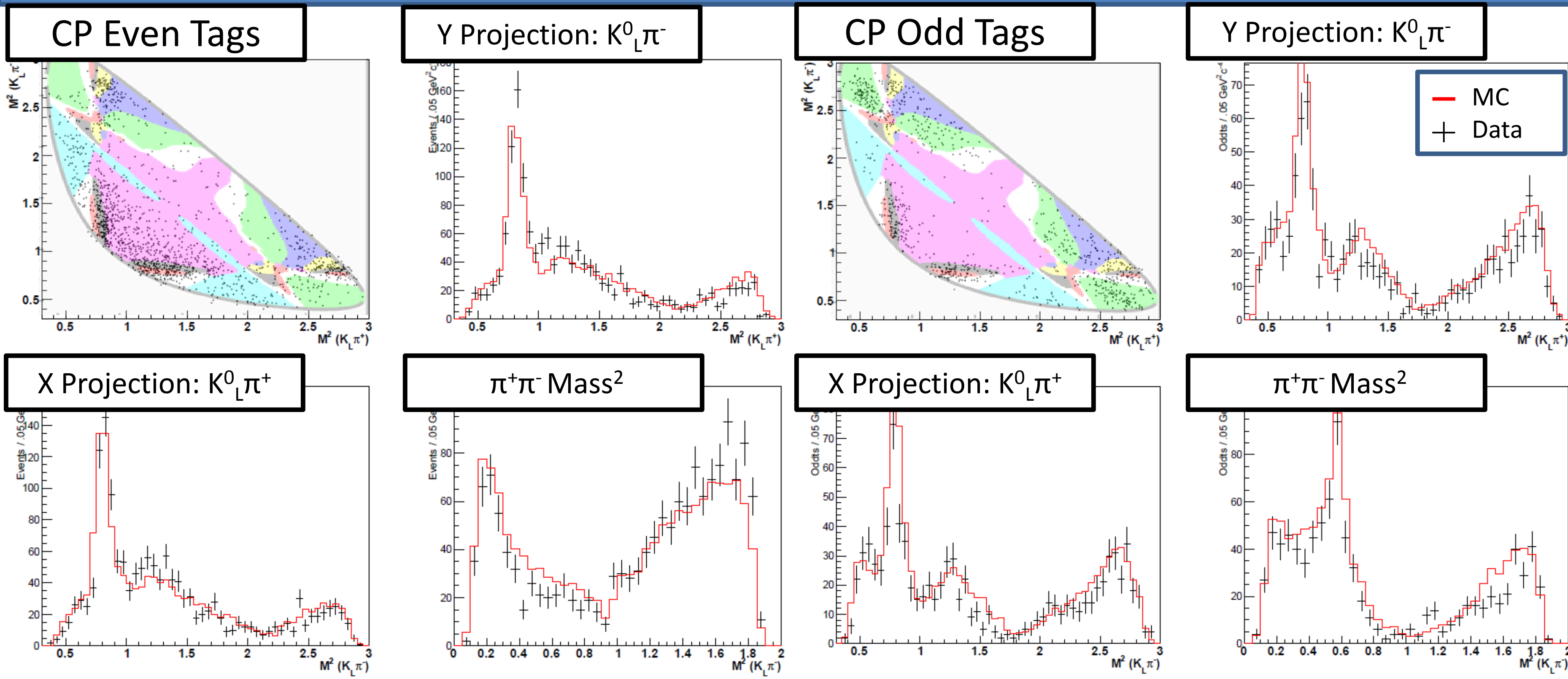
From the Double Dalitz modes, we are able to find c_i, c'_i, s_i, s'_i

$$M'_{i,j} = \frac{N_{D,\bar{D}}}{2S_f^2}\left(K_i K'_{-j} + K_{-i}K'_j - 2\sqrt{K_i K'_{-j} K_{-i} K'_j}\left(c_i c'_j + s_i s'_j\right)\right)$$

i^{th} bin for $K_S^0\pi^+\pi^-$
j^{th} bin for $K_L^0\pi^+\pi^-$

$M_{i,j}$ yields in bin i of $K_S^0\pi^+\pi^-$ Dalitz plot and bin j of $K_L^0\pi^+\pi^-$ Dalitz plot.
S_f number of single tags for flavor modes.
$N_{D,\bar{D}}$ total number of $D^0\overline{D}^0$ events.
$K_i(K_{-i})$, yields in each bin of $K_S^0\pi^+\pi^-$ Dalitz plot in flavor modes.
$K'_j(K'_{-j})$, yields in each bin of $K_L^0\pi^+\pi^-$ Dalitz plot in flavor modes.

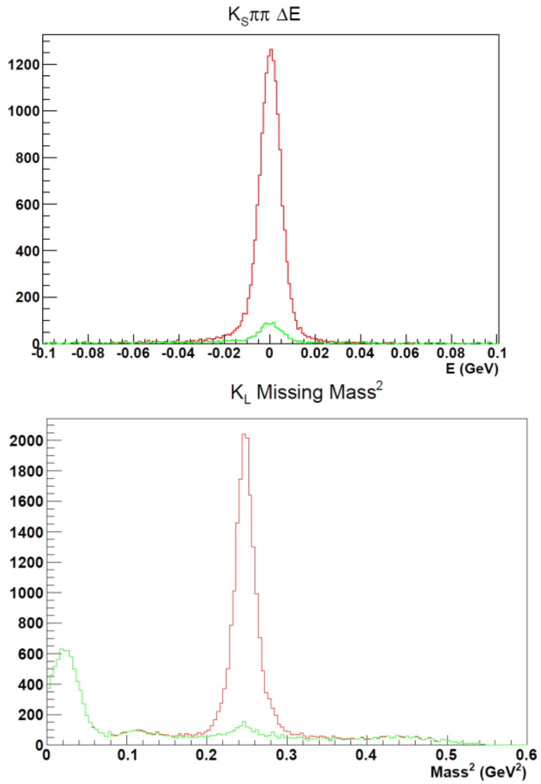
$K_L^0\pi^+\pi^-$ Dalitz Plots vs CP Modes

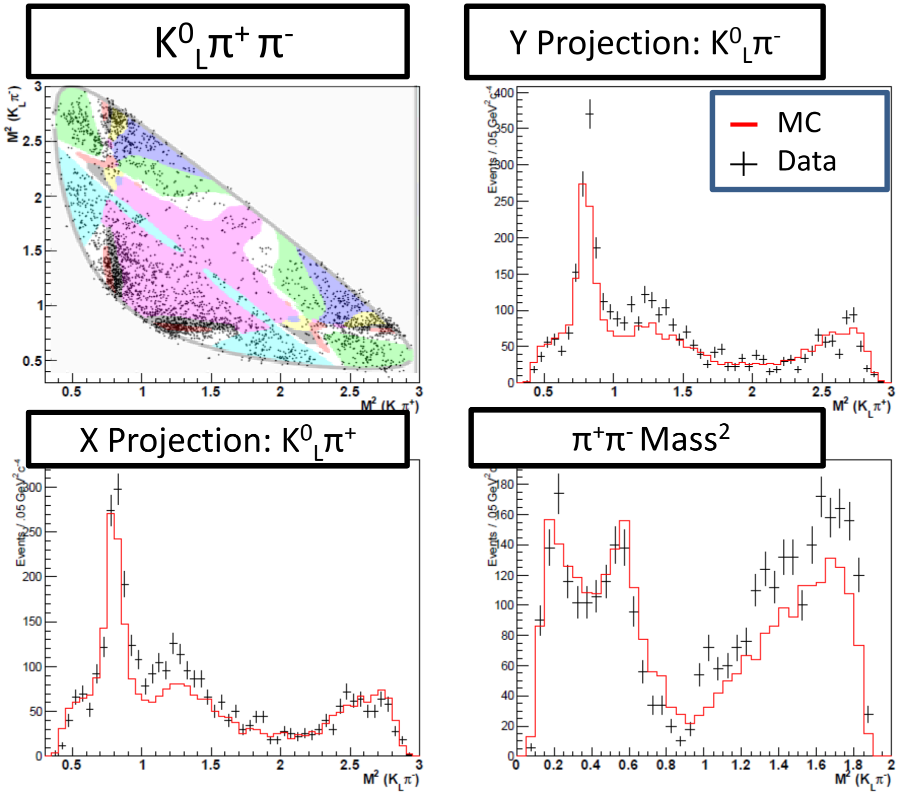


BESIII Preliminary

Type	Tag List
S^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$
S^-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$

Dalitz Plots: $K_S^0\pi^+\pi^-$ vs $K_L^0\pi^+\pi^-$





BESIII
Preliminary