

Time-Dependent Analysis of $B^0 \rightarrow K_S \rho^0 \gamma$ Decays



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Road map

- **Introduction:**
 - ▶ The BaBar Experiment
 - ▶ Time Dependent Measurements and Flavor Tagging
 - ▶ Phenomenological Context
- **Measurement Strategy:**
 - ▶ Control Channel
 - ▶ Discriminating Signal from Backgrounds
 - ▶ Modeling the Signal
 - ▶ Modeling the Backgrounds
- **Model Validation:**
 - ▶ Validation tests: pseudo-experiments
 - ▶ Validation tests: "sPlots"



Road map

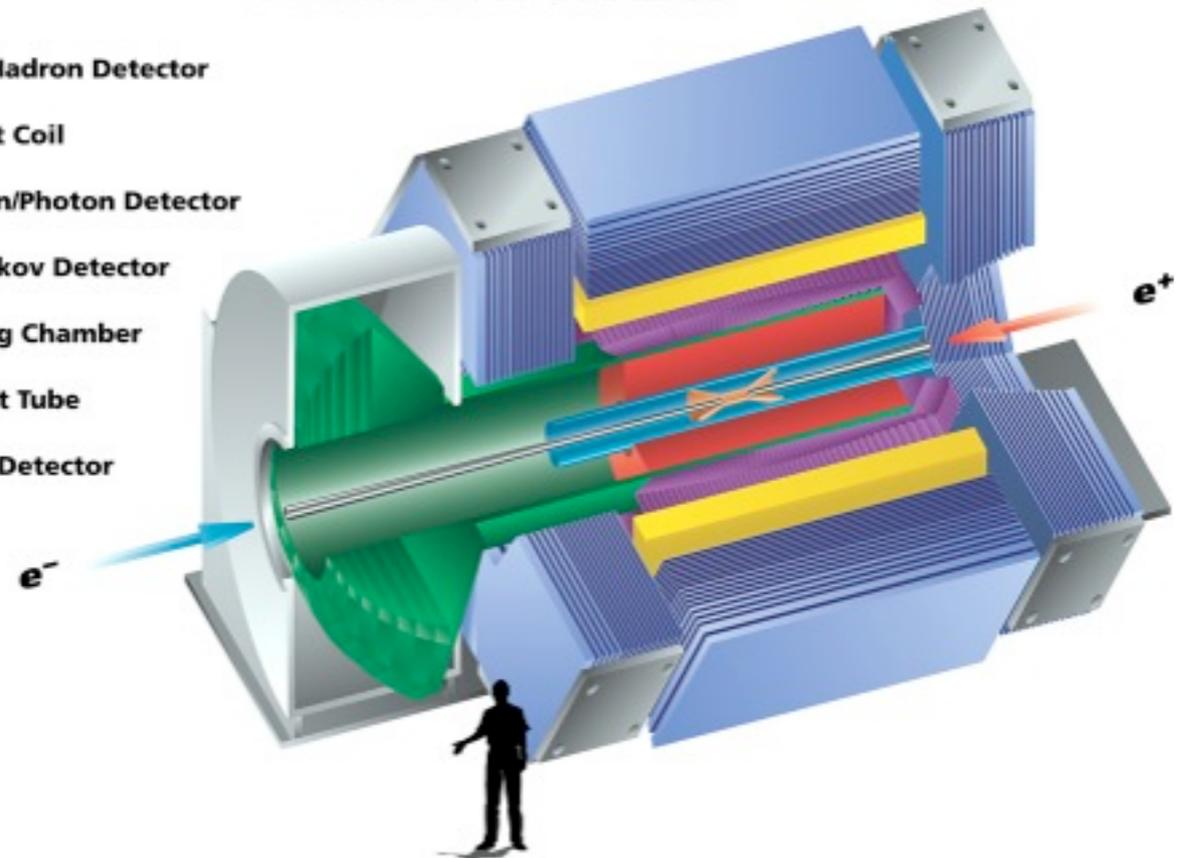
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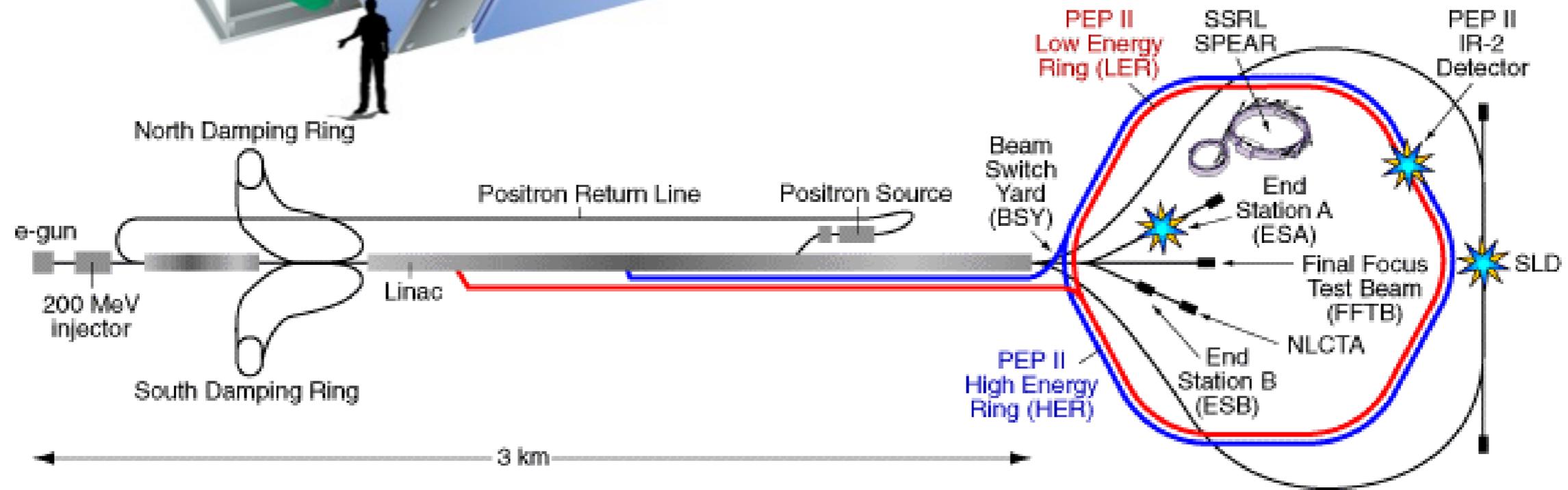
The BaBar Experiment

BABAR Detector

- Muon/Hadron Detector
- Magnet Coil
- Electron/Photon Detector
- Cherenkov Detector
- Tracking Chamber
- Support Tube
- Vertex Detector

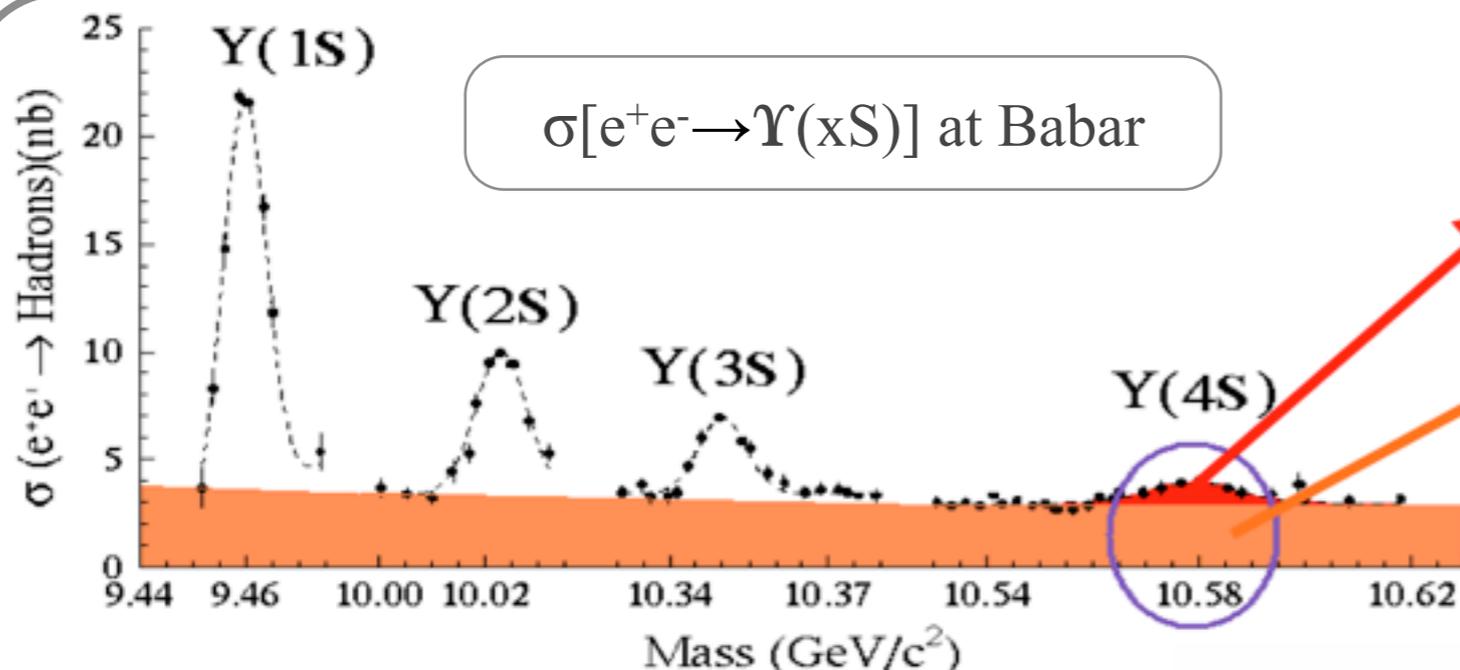


- Babar at SLAC
- Running with PEP-II accelerator

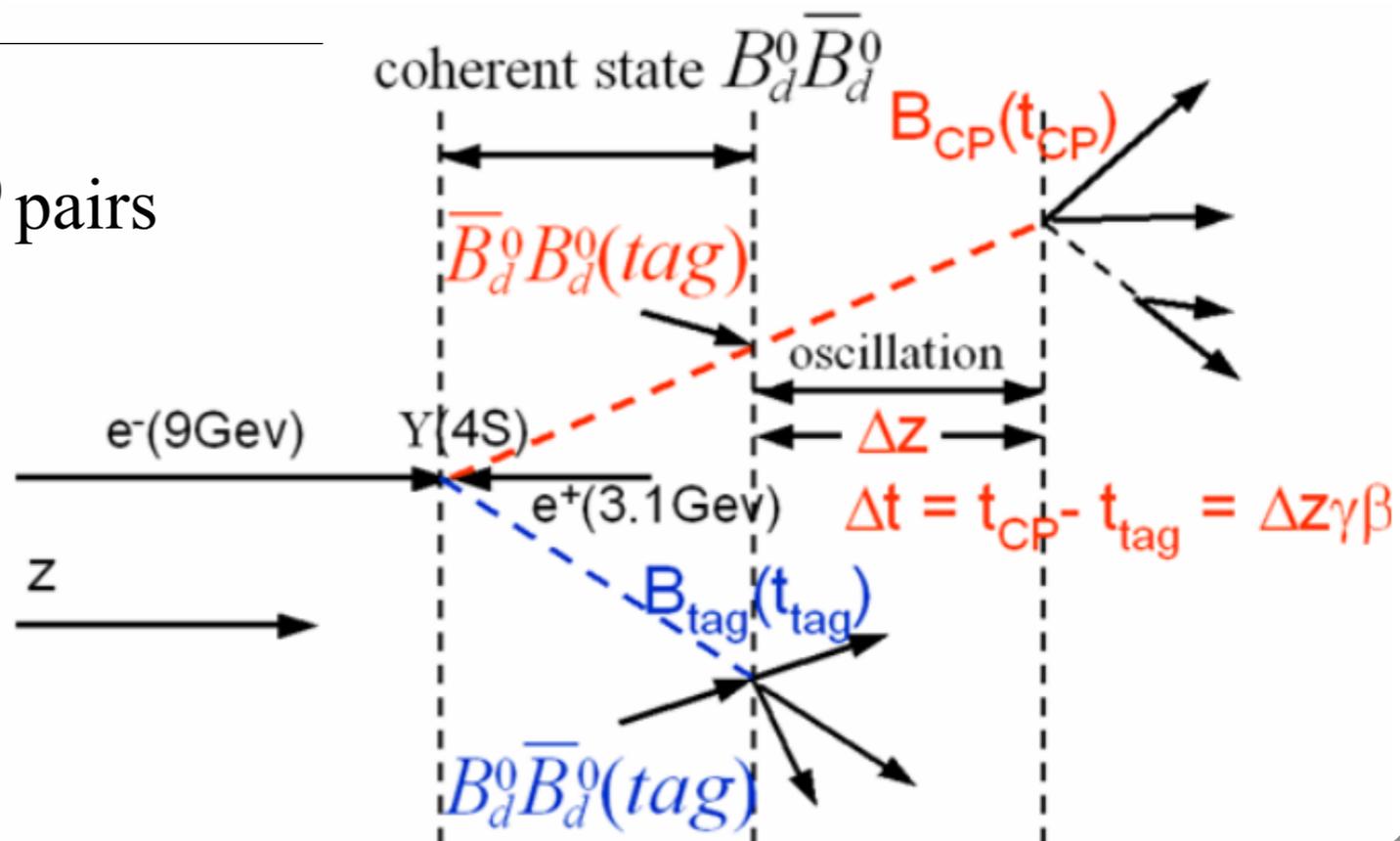




Time dependance and Flavor Tagging



- **Coherent production** of $B^0\bar{B}^0$ pairs
 - ↳ Flavor constraint
- From B_{tag} decay products
 - ↳ Get B_{tag} flavor
 - ↳ Deduce B_{CP} flavor



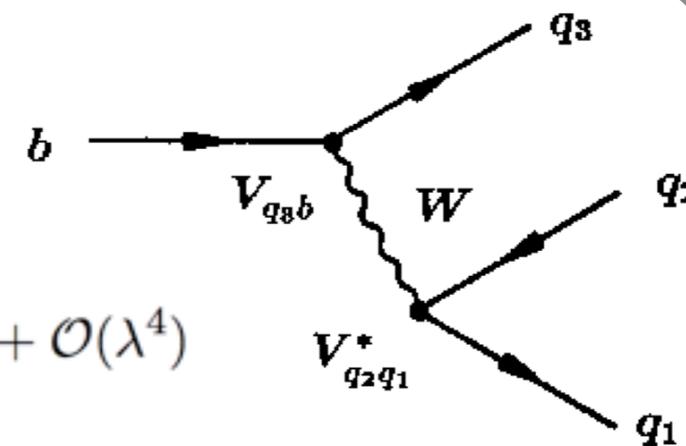


Phenomenological Context (1)

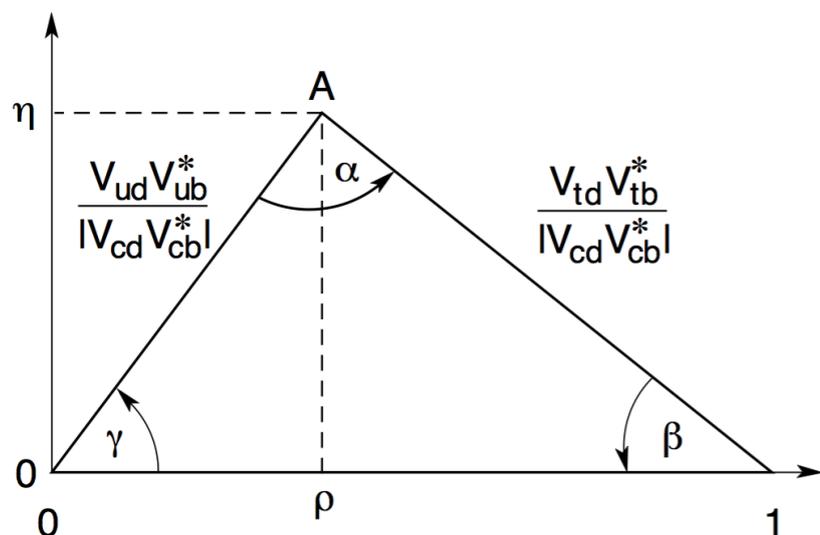
Flavor physics – Introduction

- **CKM matrix** → 3x3, unitary

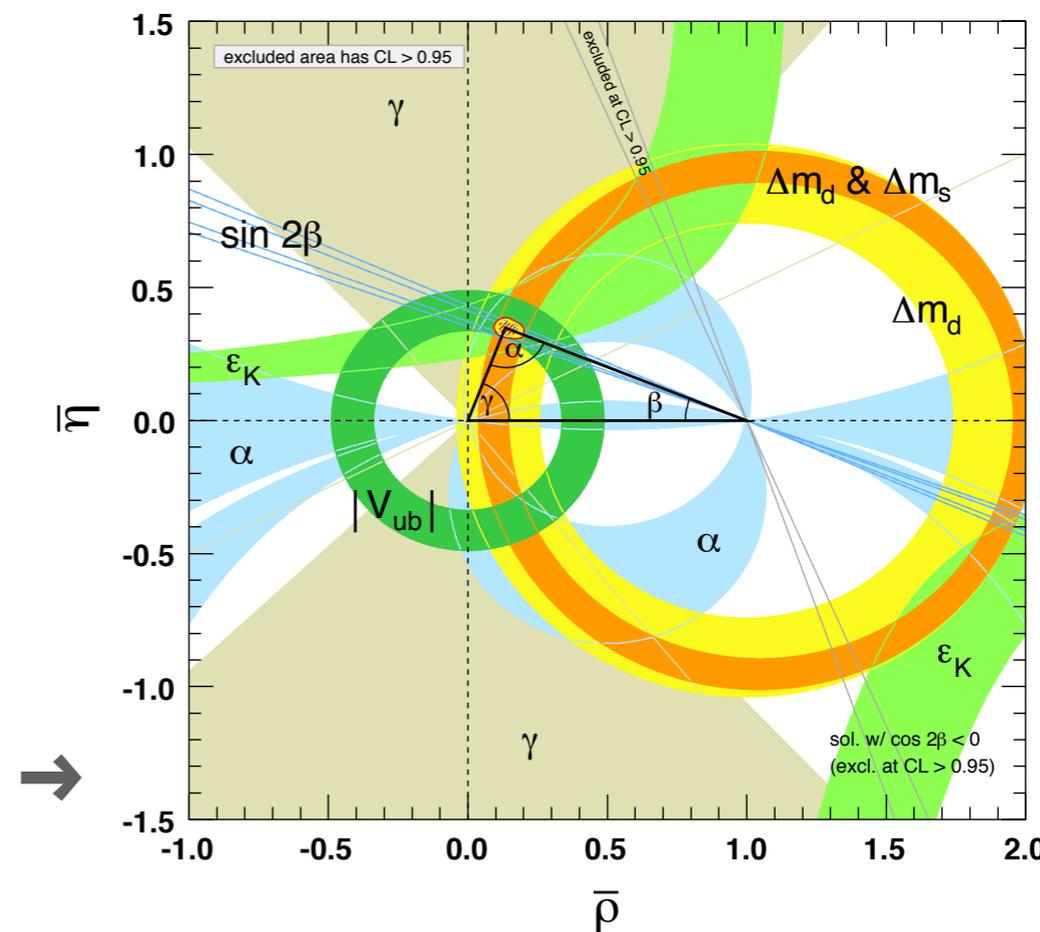
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



- **Unitarity Triangle (UT)** → geometric representation of one CKM unitarity:



- **One of flavor physics goals:**
put constraints on UT sides and angles to test Standard Model (SM) and set constraints on New Physics (NP) models





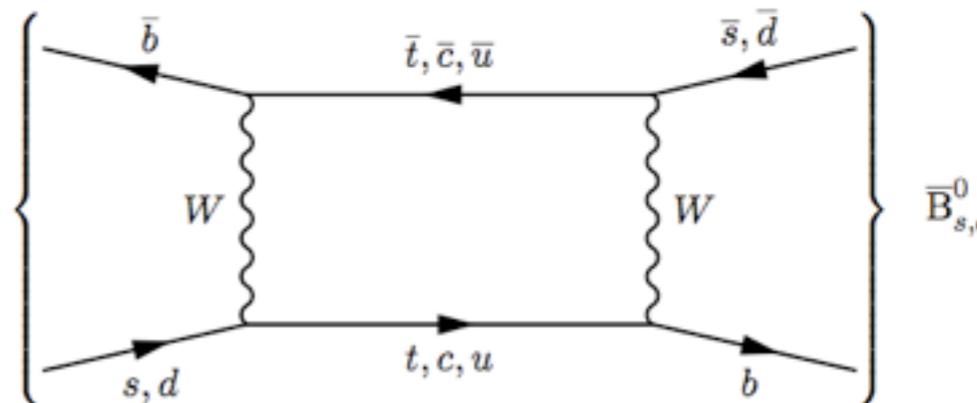
Phenomenological Context (2)

CP Asymmetry – Flavor Mixing

- **B mesons oscillates** (box diagrams)



$B_{s,d}^0$



- CP asymmetry is defined as:

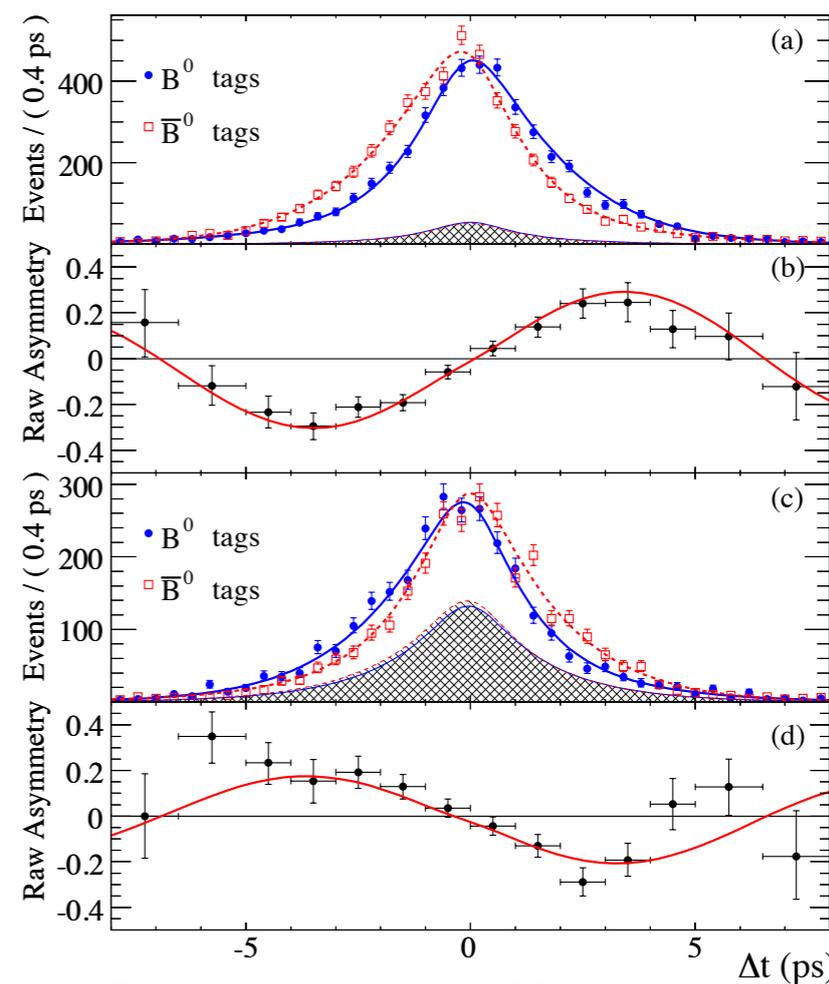
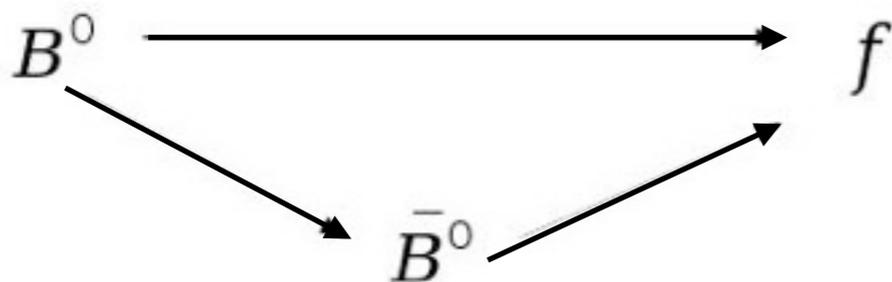
$$A_{CP}(\Delta t) = \frac{\Gamma(B_{tag=B^0}(\Delta t) \rightarrow f_{CP}) - \Gamma(B_{tag=\bar{B}^0}(\Delta t) \rightarrow f_{CP})}{\Gamma(B_{tag=B^0}(\Delta t) \rightarrow f_{CP}) + \Gamma(B_{tag=\bar{B}^0}(\Delta t) \rightarrow f_{CP})}$$

$$= S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t).$$

(Δm_d : B_d states mass difference, oscillation frequency)

(S_f and C_f : direct and induced by mixing CP asymmetry parameters)

- When one final state « f » is accessible to both B^0 and \bar{B}^0 mesons, then **interference** due to $B^0\bar{B}^0$ mixing appears and non-zero value of S_f is predicted:



Babar golden mode: $B^0 \rightarrow c\bar{c}K^{*0}$
time dependent asymmetry



Phenomenological Context (3)

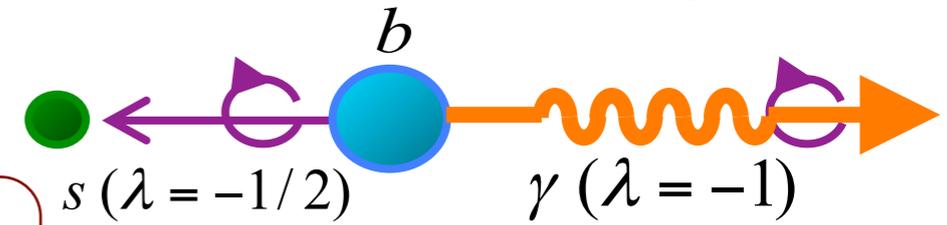
$B^0 \rightarrow K_S \rho^0 \gamma$ – Analysis Goal

- Radiative decays ($b \rightarrow s\gamma$):
In SM interaction between **left-handed quarks and right-handed antiquarks**

Helicity: spin projection on the momentum of a particle

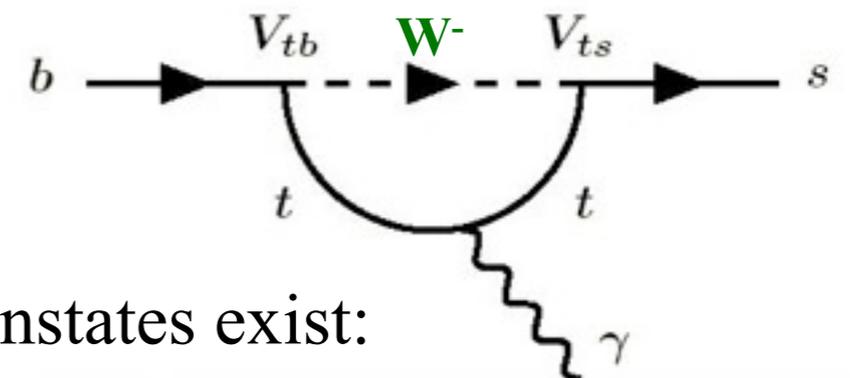
$$\lambda = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}$$

- **SM** $\Rightarrow b \rightarrow s\gamma_l$ or $\bar{b} \rightarrow \bar{s}\gamma_r \Rightarrow B^0 \rightarrow f$
 $\bar{B}^0 \rightarrow f$ **CP asymmetry parameters = 0**



- **NP** $\Rightarrow b \rightarrow s\gamma_{l,r}$ or $\bar{b} \rightarrow \bar{s}\gamma_{r,l} \Rightarrow B^0 \rightarrow f$
 $\bar{B}^0 \rightarrow f$ **CP asymmetry parameters $\neq 0$**

B meson radiative decay, NP particle may be present in the loop, and enhance right-handed photons:



- A few CP asymmetry measurements in radiative CP eigenstates exist:
BaBar and Belle in $B^0 \rightarrow K_S \pi^0 \gamma$, Belle in $B^0 \rightarrow K_S \rho^0 \gamma$

\hookrightarrow **All results are compatible with 0...**

Belle result for $B^0 \rightarrow K_S \rho^0 \gamma$ with
657 millions of BB pairs
arXiv :0806.1980v1 [hep-ex] 12 Jun 2008

$$\begin{aligned} S_{K_S^0 \rho^0 \gamma} &= 0.11 \pm 0.33(\text{stat.})_{-0.09}^{+0.05}(\text{syst.}) \\ A_{eff} &= 0.05 \pm 0.18(\text{stat.}) \pm 0.06(\text{syst.}) \end{aligned}$$

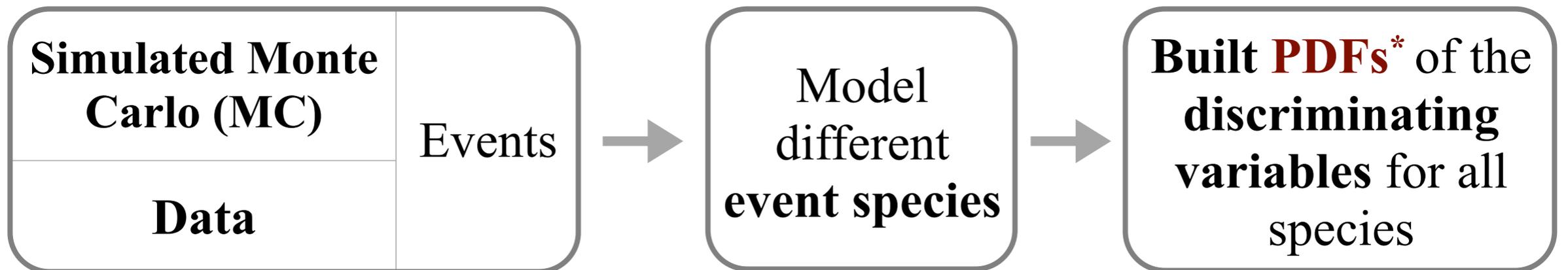


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Strategy Overview



* PDF: Probability Density Function

- **Maximum Likelihood Fit:**

To extract signal and background event yields and parameters of interest

$$\mathcal{L} = \exp\left(-\sum_j N_j\right) \prod_i \mathcal{L}_i \quad ; \quad \mathcal{L}_i = \sum_j N_j \cdot \mathcal{P}_j^i(m_{ES}, \Delta E) \cdot \mathcal{P}_j^i(NN) \cdot \mathcal{P}_j^i(\Delta t)$$

- Use a **charged control channel** first: $\mathbf{B}^+ \rightarrow \mathbf{K}^+ \pi^+ \pi^- \gamma$

Discriminating Variables
(see next slides)



Why use a control channel?

- **$\text{BR}[\mathbf{B}^0 \rightarrow \mathbf{K}_S \rho^0 \gamma] \sim 10^{-6} \otimes \sim 471 \cdot 10^6 \mathbf{B}^0 \bar{\mathbf{B}}^0$ in Babar $\Rightarrow \sim 10^2$ signal events**

↳ We need to test our procedure with a similar mode where:

$$\sigma[\text{similar mode}] \gg \sigma[\mathbf{B}^0 \rightarrow \mathbf{K}_S \rho^0 \gamma]$$

↳ **using $\mathbf{B}^+ \rightarrow \mathbf{K}^+ \pi^+ \pi^- \gamma$ for which:**

$$\text{BR}[\mathbf{B}^+ \rightarrow \mathbf{K}^+ \pi^+ \pi^- \gamma] \approx 2.3 \cdot 10^{-5} \Rightarrow \sim 3.4 \cdot 10^3 \text{ events}$$

- Extract from the $\mathbf{B}^+ \rightarrow \mathbf{K}^+ \pi^+ \pi^- \gamma$ data information about the dynamics (intermediate states) of the **$\mathbf{K}\pi\pi$ system (i.e., $\mathbf{m}_{\mathbf{K}\pi\pi}$ spectrum)**
↳ implement in the $\mathbf{B}^0 \rightarrow \mathbf{K}_S \rho^0 \gamma$ analysis



Backgrounds

- Two types of backgrounds

- ▶ **Continuum background:**

Production of lower mass resonance ($e^+e^- \rightarrow q\bar{q}$; $q = u, d, s, c$)

- ↳ Most **abundant background**

- ↳ **Distinguishable from signal** by shapes of discriminating variables

- ▶ **Backgrounds from B meson decays (B backgrounds):**

Events with final state close to signal (see example below)

- ↳ **Dangerous** \Rightarrow **distributions similar to signal** in discriminating variables

For **example** one of the most abundant B backgrounds:

- ↳ $B^0 \rightarrow K^{*0} (\rightarrow K\pi) \gamma \Rightarrow$ one π of the “**other side**” is wrongly used to reconstruct the candidate



Discriminating signal from background

Using **three discriminating variables** to separate *signal* from *backgrounds*:

- **Energy-substituted mass** (m_{ES}):

$$m_{ES}^{\text{LAB}} = \sqrt{(s/2 + \mathbf{p}_B \cdot \mathbf{p}_0)^2 / E_0^2 - p_B^2} \stackrel{\text{CM}}{=} \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$$



Peak at m_B for signal
(no obvious peaks for backgrounds)

- **Energy difference** (ΔE):

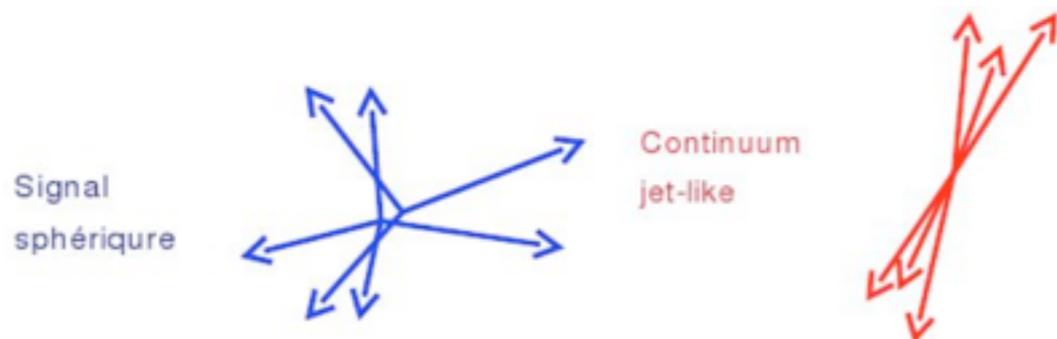
$$\Delta E^{\text{LAB}} = (2q_B q_0 - s) / 2\sqrt{s} \stackrel{\text{CM}}{=} E_B^* - E_{\text{beam}}^*$$



Peak at 0 for signal
(shifted on left or right for backgrounds)

- **Fisher discriminant:**

↳ Linear combination of 6 event-shape variables



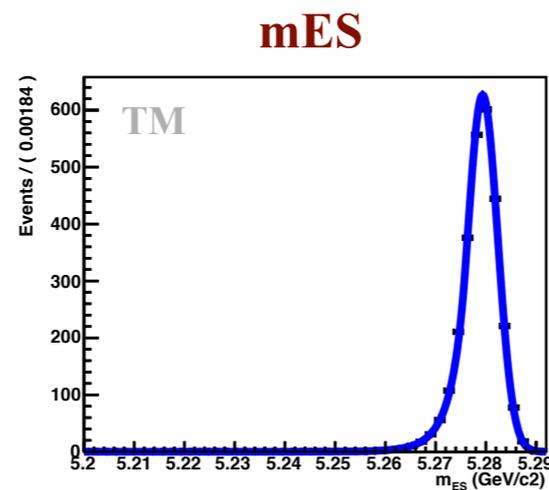
Distributions shifted toward +1 for signal and -1 for continuum



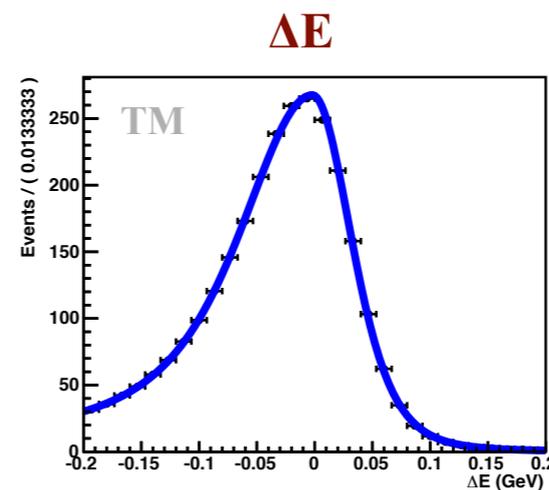
Model for the Signal

- From $B^+ \rightarrow K^+ \pi^+ \pi^- \gamma$ MC samples separate signal events in two categories:
 - ↳ **Truth Matched (TM):** † Signal events well reconstructed (from MC truth information)
 - ↳ **Self Cross Feed (SCF):** † Mis-reconstructed signal events

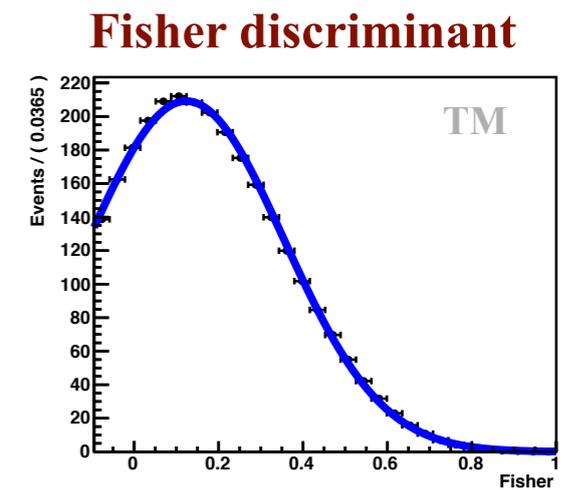
Category	Expected Yield
Signal TM	2649
Signal SCF	794
Total Signal	3443



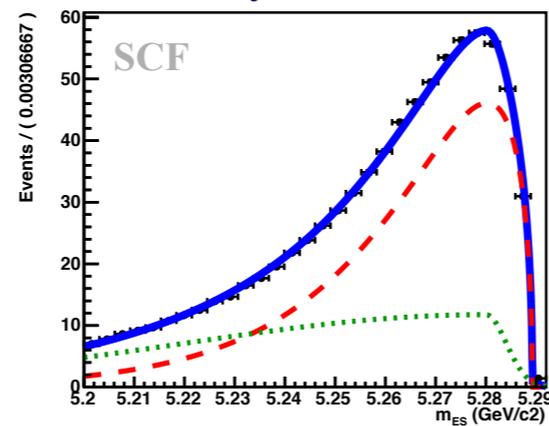
Crystal Ball



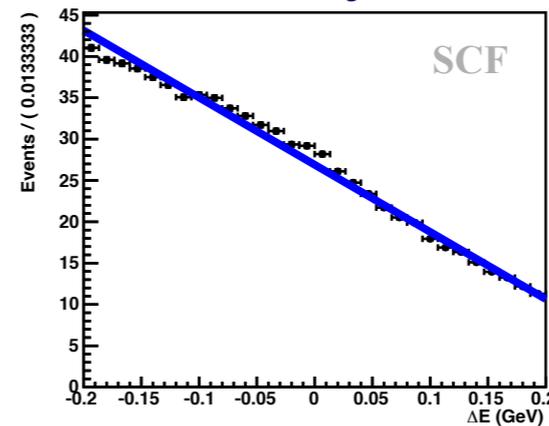
Cruiff



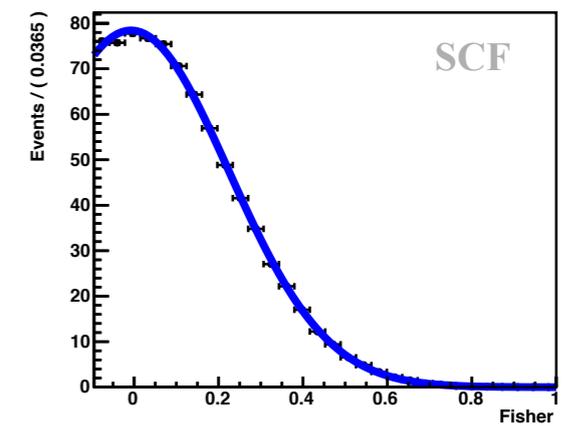
Gaussian



Cruiff + Argus



Linear



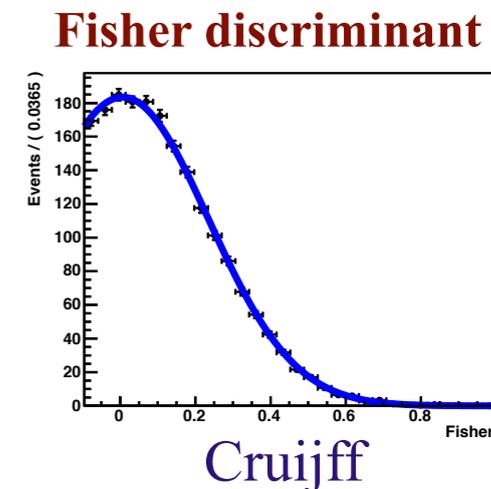
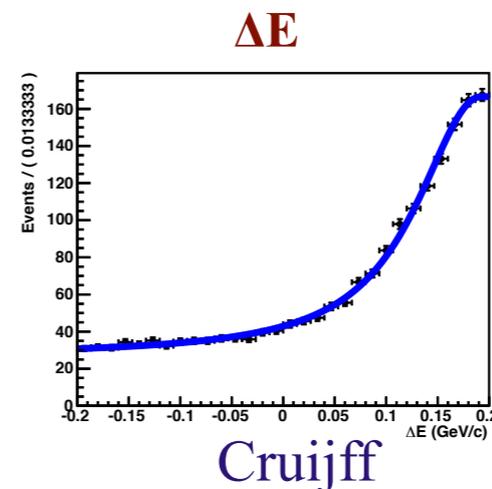
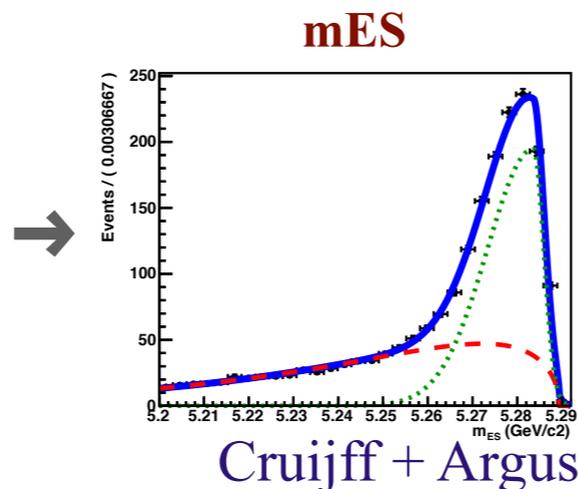
Gaussian



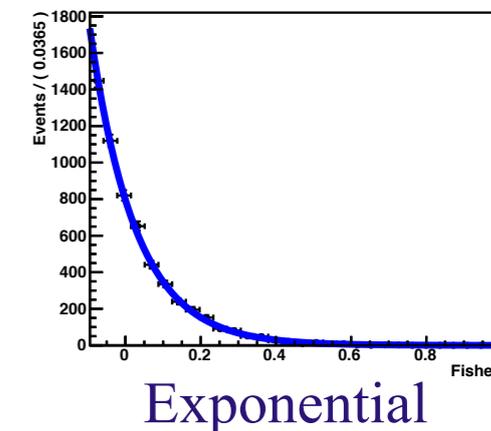
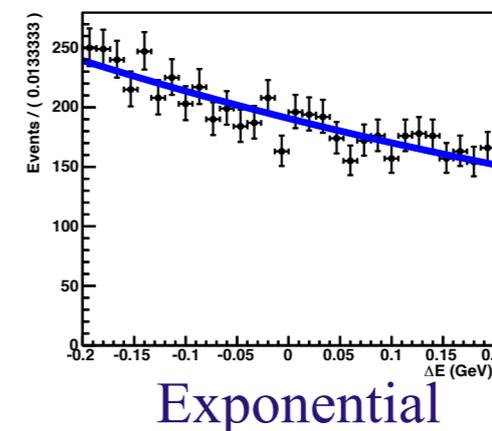
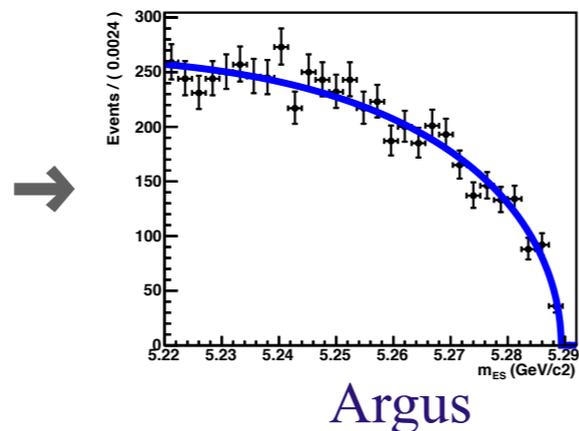
Model for the backgrounds (1)

Distribution of discriminating variables for a few backgrounds

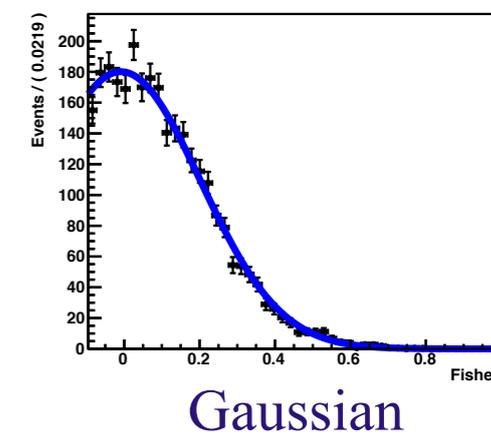
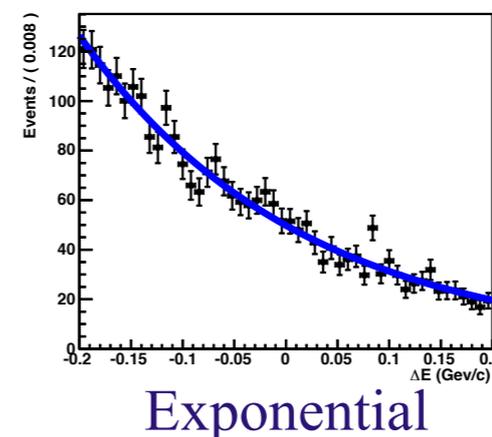
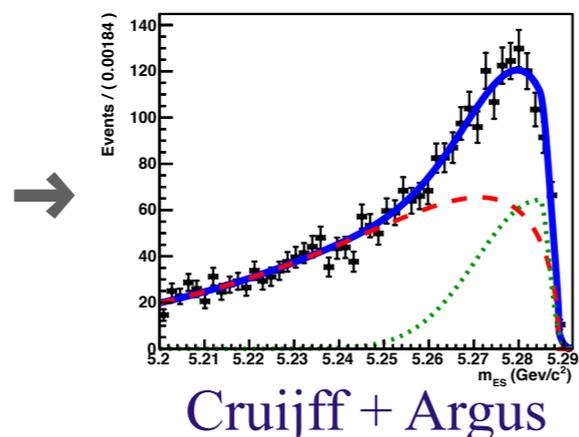
- $B^0 \rightarrow K^{*0} (\rightarrow K\pi) \gamma$
one π originates from the other side



- Continuum**
($e^+e^- \rightarrow q\bar{q}$; $q = u,d,s,c$)



- $B^0 \rightarrow X_s (\rightarrow K\pi) \gamma$
high multiplicity final state:
one particle (or more)
migrate to the other side





Model for the backgrounds (2)

Expected yields of all the backgrounds in the fit model

Category	Estimated yield
Continuum ($udsc$)	70983
$B^0 \rightarrow X_{sd}(\rightarrow K\pi)\gamma$	2872
$B^+ \rightarrow X_{su}(\rightarrow K\pi)\gamma$	1930
$B^0 \rightarrow K^{*0}(\rightarrow K\pi)\gamma$	1065
$B^0 \rightarrow X_{sd}(\rightarrow K\pi)\gamma$	442
Generic B-background	56
$B^+ \rightarrow K^{*+}(\rightarrow K\pi)\gamma$	17
$B^+ \rightarrow X_{su}(\rightarrow K\pi)\gamma$	77365
$B^0 \rightarrow K^{*0}\eta$	
Small Charmless Peaking	
Total Bkg	77365

Compared to signal
TM exp. yield

Category	Expected Yield
Signal TM	2649
Signal SCF	794
Total Signal	3443



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Validation tests (1)

pseudo-experiments

A tool for validation tests:

- From this model, we perform consistency tests:
 - ↳ Create simulated pseudo-experiments based on our model and test the “**pulls**”
- For unbiased fit parameters:
 - ↳ Pull of θ_i is a **gaussian** with:
 - ▶ **mean = 0**
 - ▶ **width = 1**

$$pull = \frac{\theta_i^{true} - \theta_i^{fit}}{\sigma_i^{fit}}$$



Validation tests (2)

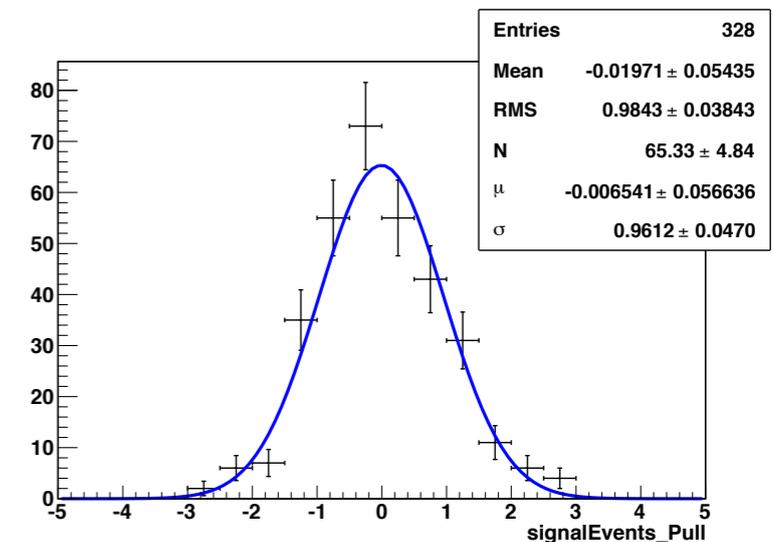
pseudo-experiments

- Test of **internal consistency**

↳ **Pure Toy study** – Events generated directly from the likelihood function (fit variables uncorrelated):

Results for selected parameters of 333 pure toys

Fit parameter	Pull Mean	Pull Width
Signal TM Yield	0.020 ± 0.054	0.970 ± 0.038
qqbar Yield	0.014 ± 0.055	1.004 ± 0.039
Generic Yield	0.025 ± 0.060	1.091 ± 0.043
$K^*0 \gamma + X_{sd}(\rightarrow K\pi) \gamma$ Yield	0.054 ± 0.058	1.057 ± 0.041

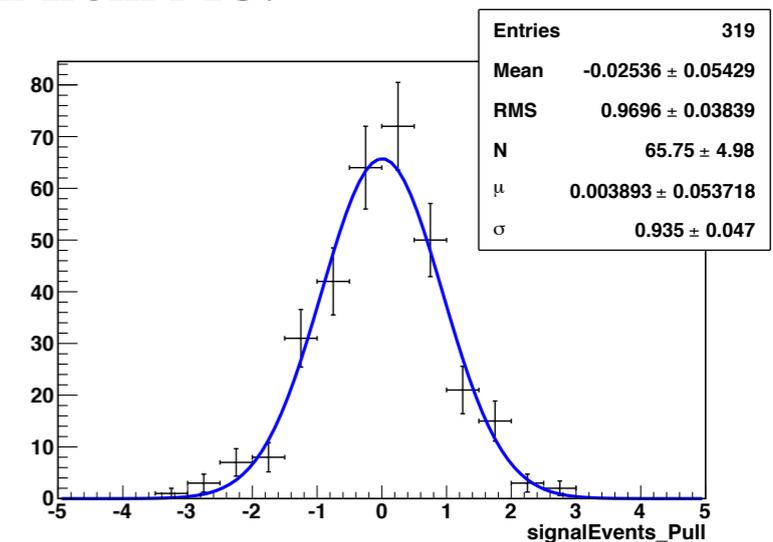


- To take into account **correlations between the fit variables**

↳ **Embedded Toy study** – Signal (TM+SCF) & $K^*0 \gamma$ events taken from MC:

Results for selected parameters of 333 embedded toys

Fit parameter	Pull Mean	Pull Width
Signal TM Yield	0.025 ± 0.054	0.970 ± 0.038
qqbar Yield	0.235 ± 0.056	1.007 ± 0.040
Generic Yield	-0.287 ± 0.055	0.991 ± 0.039
$K^*0 \gamma + X_{sd}(\rightarrow K\pi) \gamma$ Yield	0.017 ± 0.055	0.989 ± 0.039





Validation tests: "sPlots" (1)

$m_{K\pi\pi}$ extraction

- **sPlot technique** allows to **reconstruct a variable distribution without *a priori* knowledge on this variable**
- Use in the **context of a maximum Likelihood method** making use of the discriminating variables
- Apply **event-by-event weights (sWeights*)** based on the likelihood function to extract the distributions for signal events

*sWeight defined as the likelihood ratio for "event species i " over the total Likelihood times element of error matrix given by the fit for "species i ":

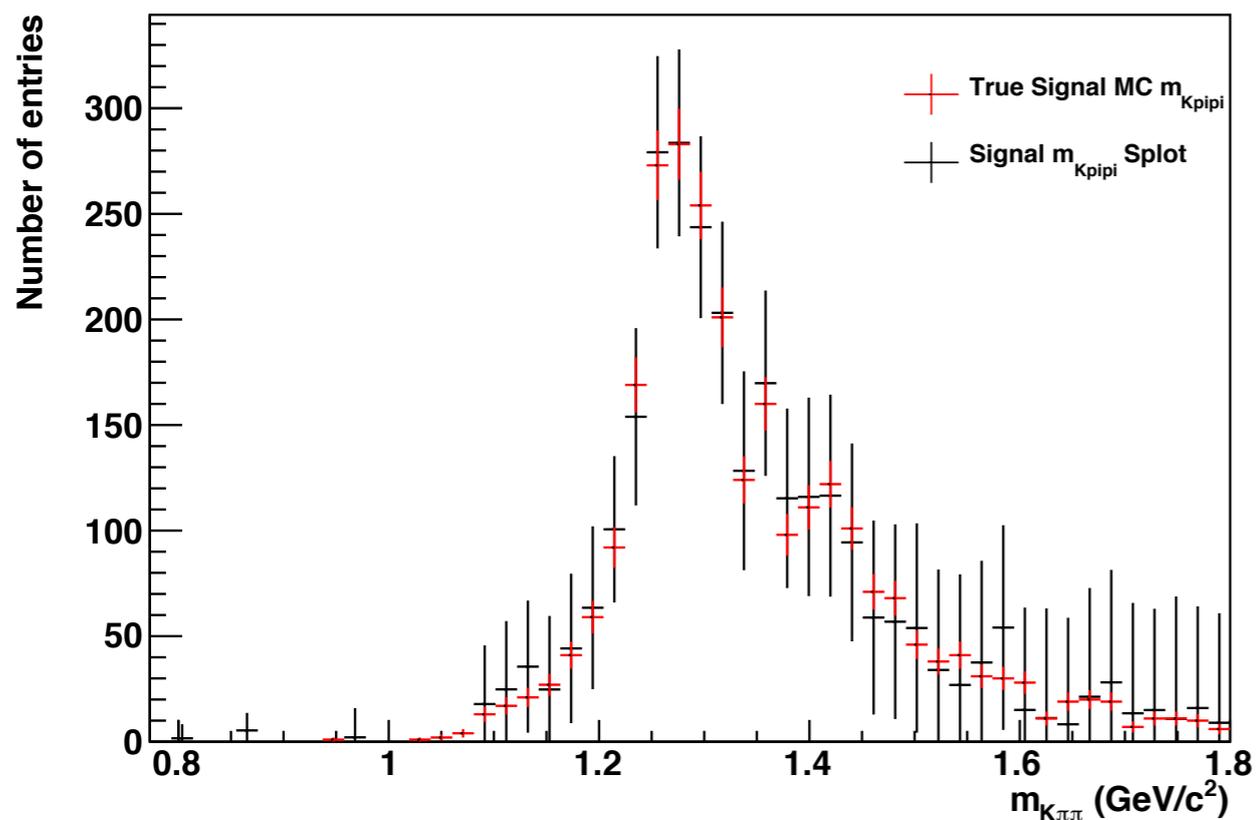
$$(L_i / L_{Tot}) \cdot \text{Cov}(i, i)$$



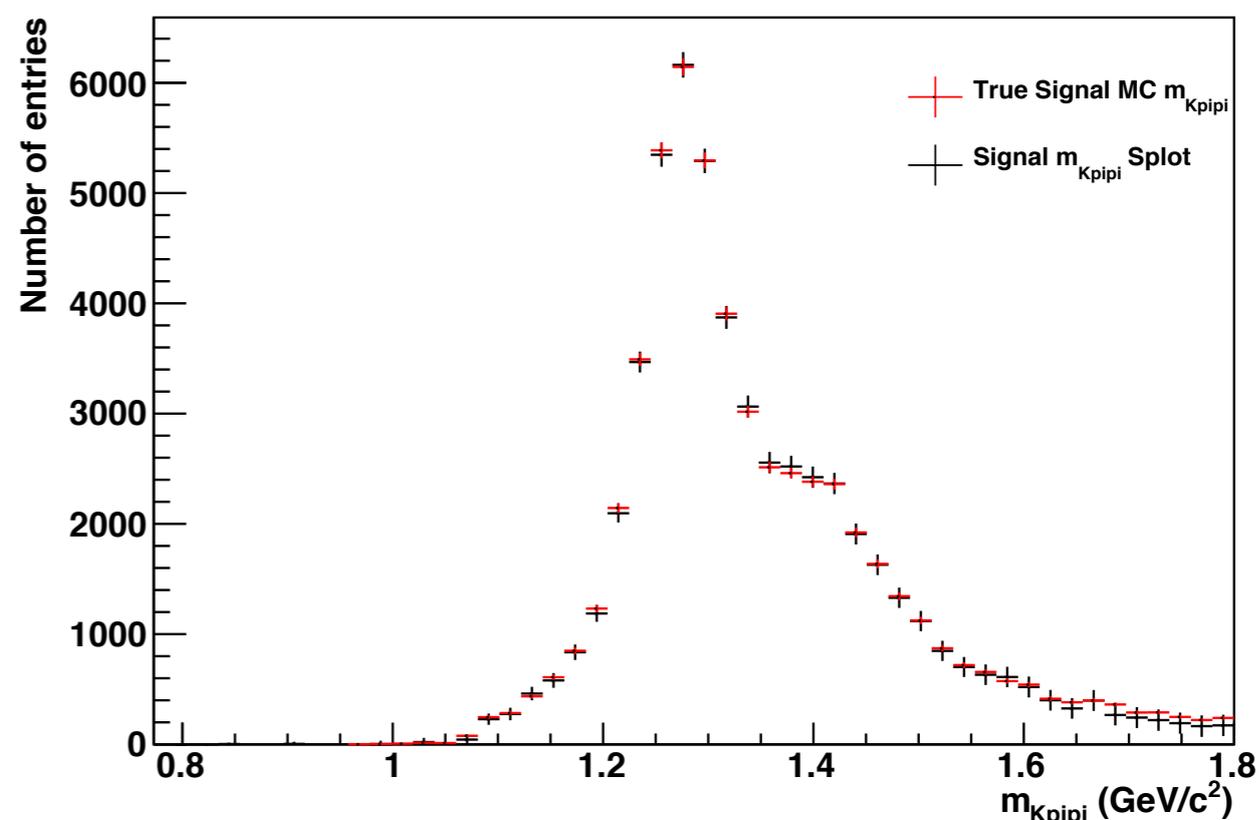
Validation tests: "sPlots" (2)

$m_{K\pi\pi}$ extraction

- Use sWeights to extract **signal $K\pi\pi$ invariant** mass ($m_{K\pi\pi}$) spectrum



$m_{K\pi\pi}$ distribution for 1 pseudo-experiments
(expected statistic)



$m_{K\pi\pi}$ distribution for 20 pseudo-experiments
(expected errors/4.47)



Validation tests: "sPlots" (3)

Dalitz Plot – Introduction

- **What is a Dalitz Plot?**

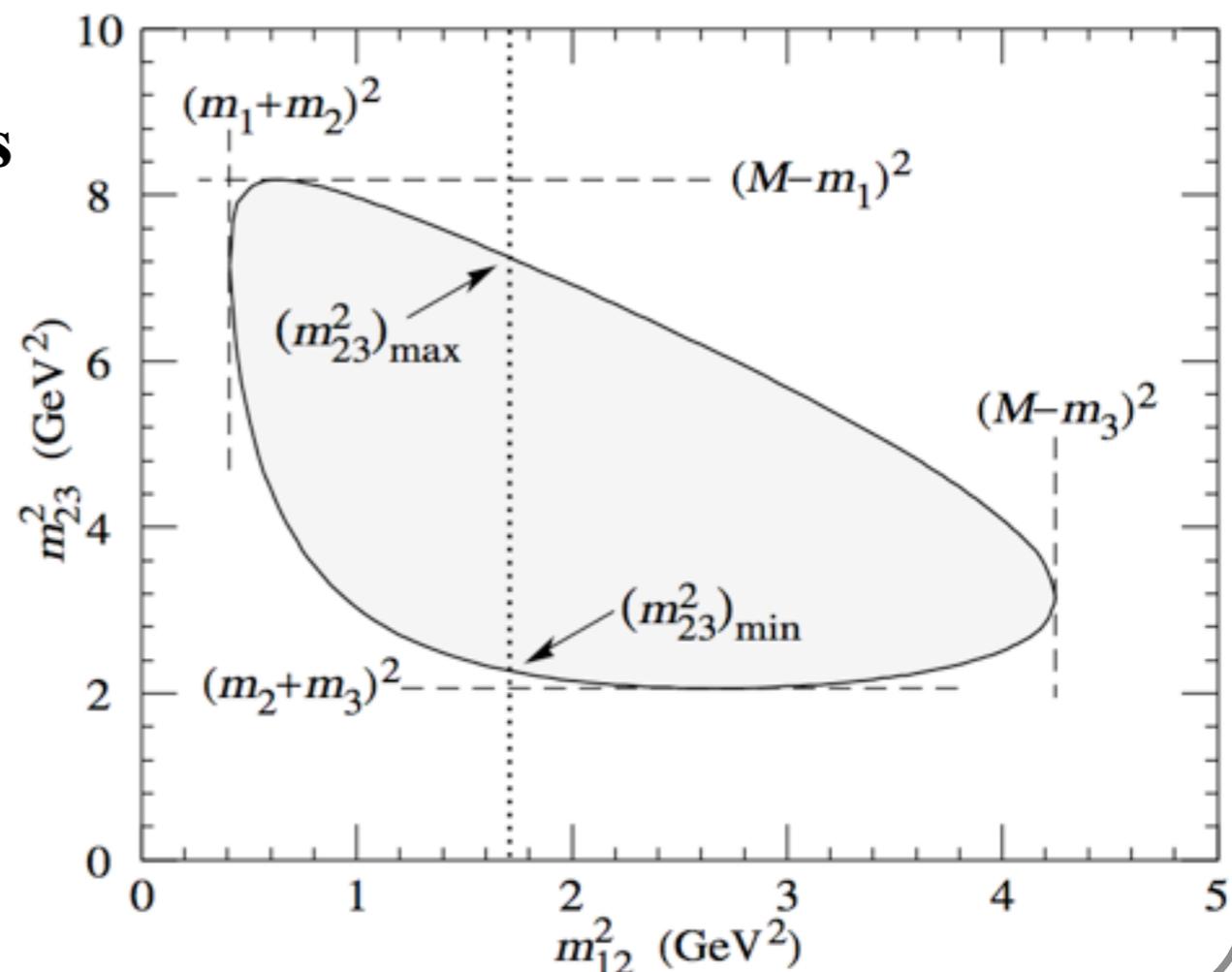
- ▶ Named after its inventor, **Richard Dalitz** (1925–2006)
- ▶ Visual **representation of the phase-space of a three-body decay**
 - often axis are the squares of the invariant mass of the pairs of decayed particles

- **Why Dalitz Plot?**

- ▶ Allow to perform **amplitude analysis** to extract directly information
- ▶ **Interference** provides additional sensitivity to CP violation

Dalitz plot for a three-body final state. In this example, the state is π^+K^0p at 3 GeV.
(*i.e.* $M \rightarrow m_1(\pi^+) m_2(K^0) m_3(p)$; $\text{mass}_M = 3 \text{ GeV}$)
Four-momentum conservation restricts events to the shaded region.

[PDG figure]

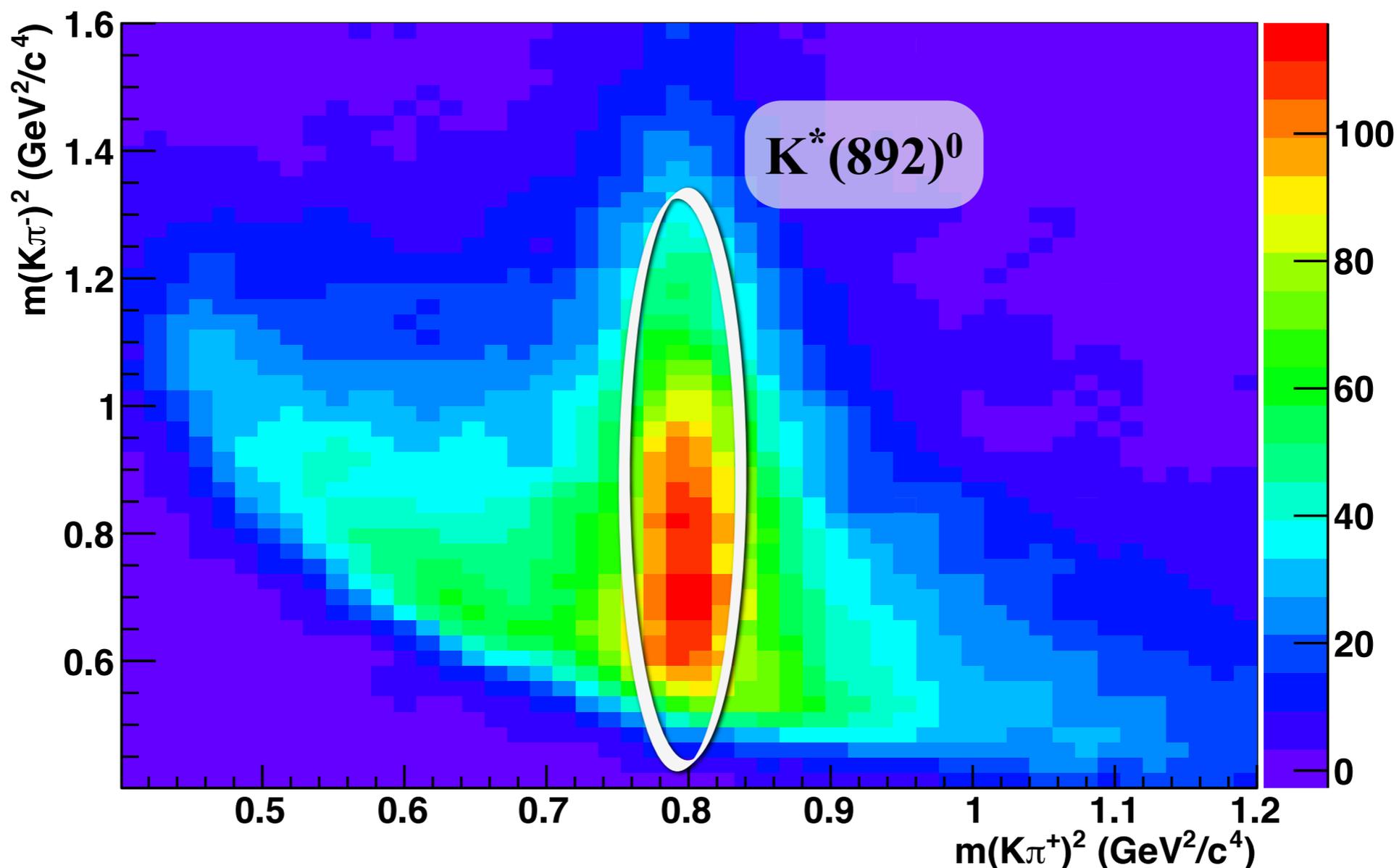




Validation tests: "sPlots" (4)

$K\pi\pi$ Dalitz extraction

- Use sWeights to extract $K^+\pi^+\pi^-$ Dalitz Plot



$K\pi\pi$ Dalitz sPlot distribution for 20 pseudo-experiments



Summary & Outlook

- **BaBar & B physics:**
 - ▶ **Rich and clean environment** (compared to hadronic colliders)
 - ▶ **Sensitive to NP** through “loop processes”
- **Control channel ($K^+\pi^+\pi^-\gamma$) analysis:**
 - ▶ Useful to validate our procedure as well as to extract information as later input of $B^0 \rightarrow K_S \rho^0 \gamma$ analysis
 - ▶ Model for the control channel validated

- **Performed a fit to data for $K^+\pi^+\pi^-\gamma$ (unblinding)**
- **Move to main analysis: $B^0 \rightarrow K_S \rho^0 \gamma$**