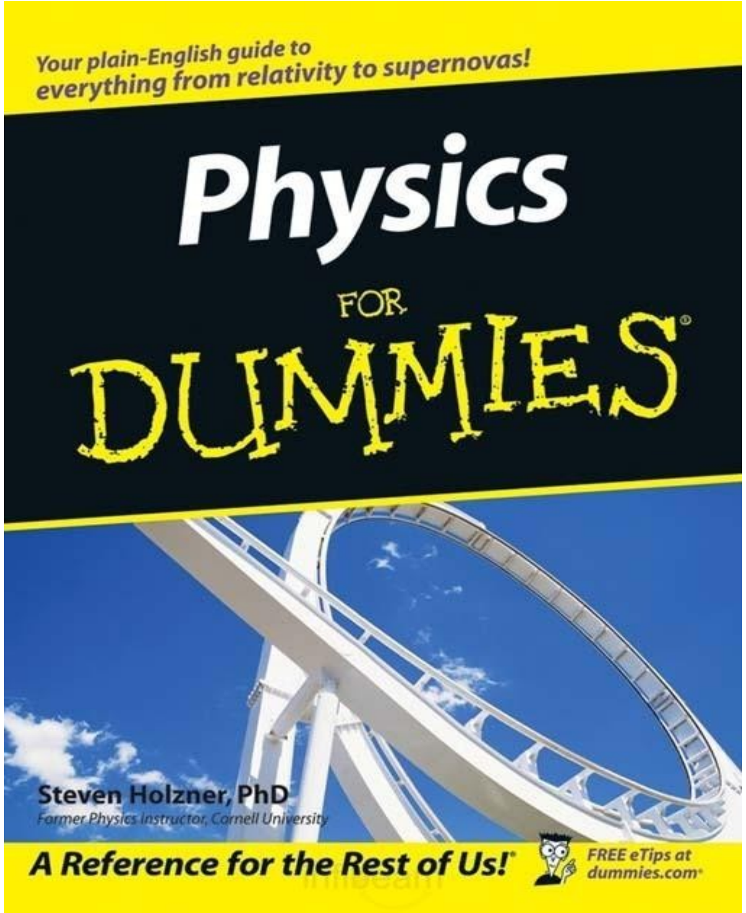
Branching Fraction Measurements for Dummies
($B^0 \rightarrow \pi^+\pi^-$)

Kolja Prothmann



- Motivate basic procedure
- Reconstruct a $B \rightarrow \pi\pi$ event
- Extract the variables

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
MAX-PLANCK-GESELLSCHAFT
TUM LMU Excellence Cluster Universe
BELLE

Young Scientist Workshop Ringberg 26-30.07.2010

- What is the Branching fraction?

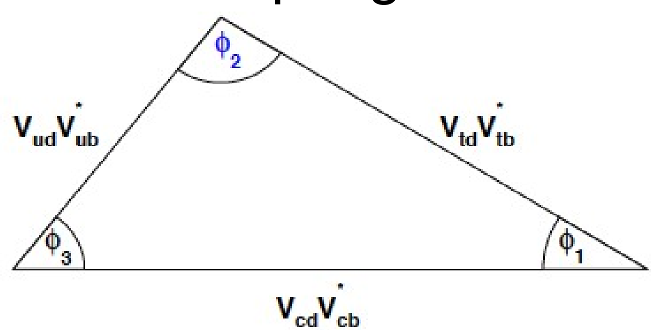
Particle → B, Specific final state → f

$$B(P \to f)$$

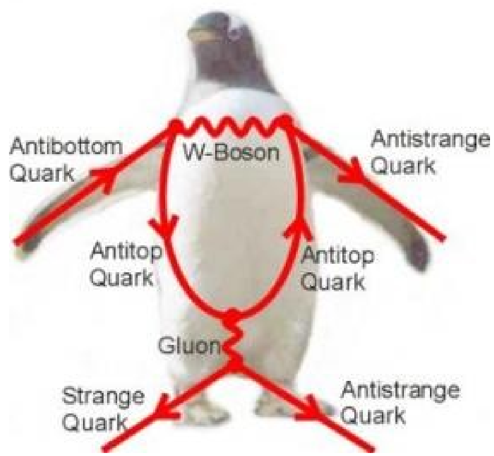
Probability for P to decay to f

- Why is the branching fraction interesting?
  - Probability itself interesting
  - Can measure CKM $|V_{ij}|$
  - Needed on my way to measure CP violation
  - Needed for isospin analysis to remove penguin contributions

$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



Feynman diagram:
Shape of a penguin



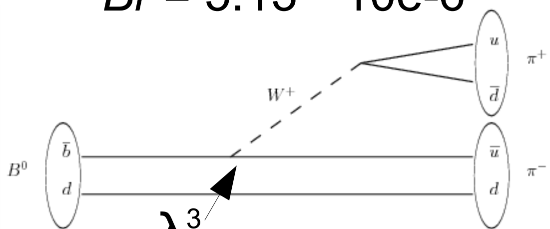
$B^0 \to \pi^+\pi^-$

Br = 5.13 * 10e-6

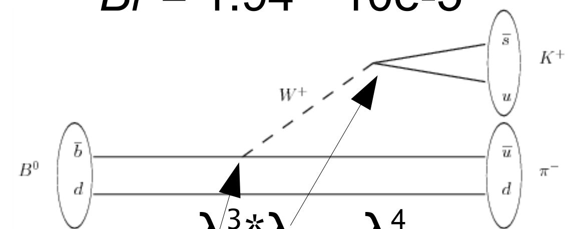
$B^0 \to K^+\pi^-$

Br = 1.94 * 10e-5

Tree diagram



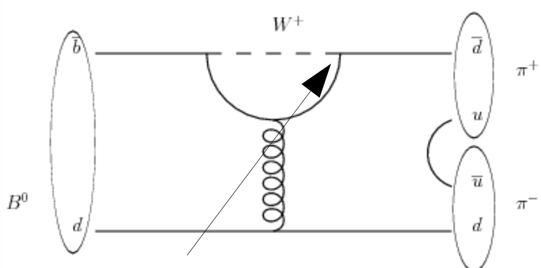
λ^3



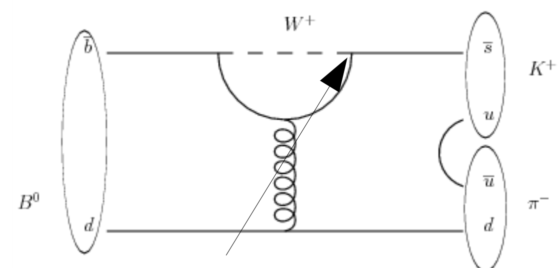
$\lambda^3 * \lambda = \lambda^4$

\+ +

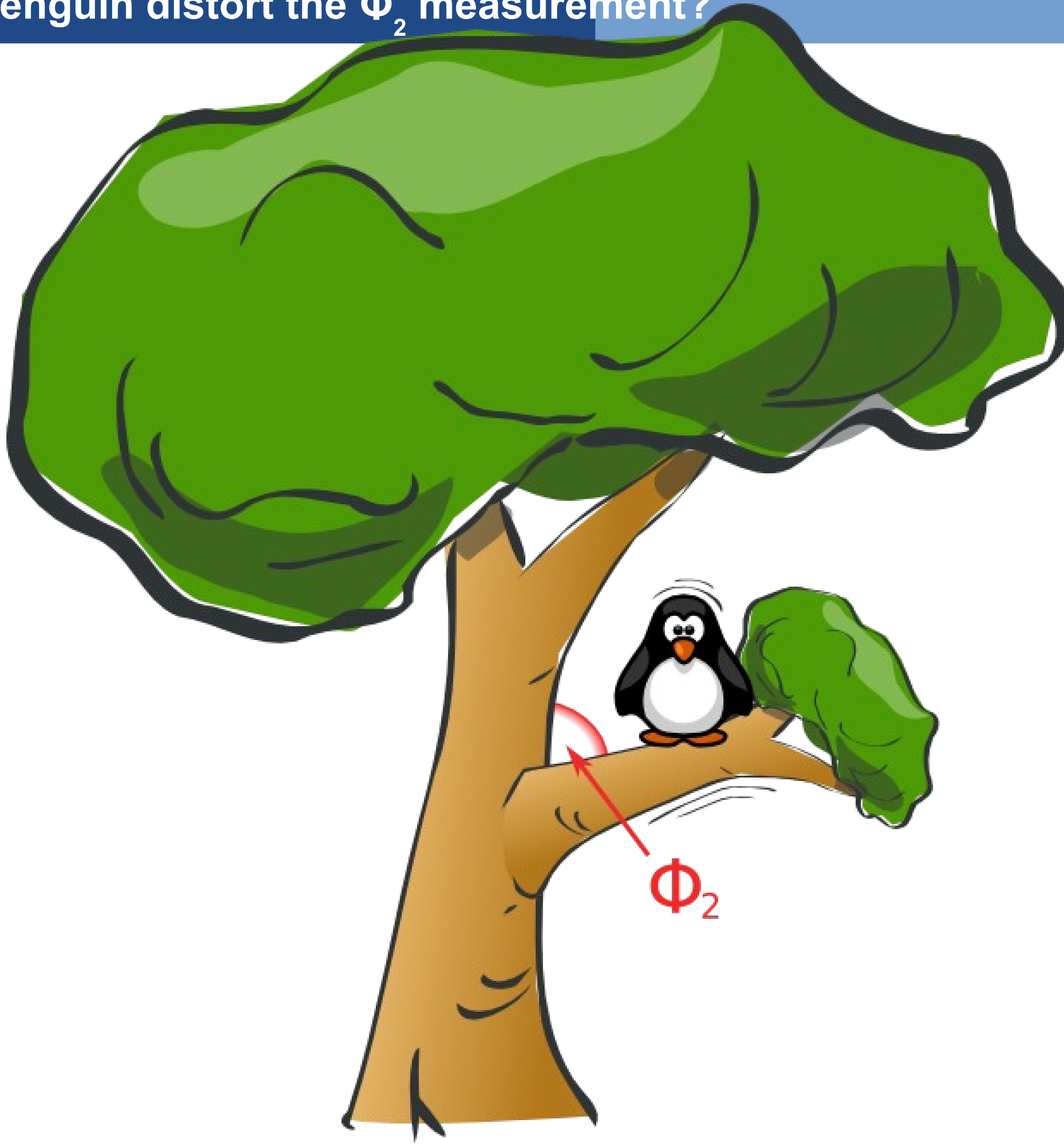
Penguin diagram



λ^3 + color - suppression ~ 1/9



λ^2 + color – suppression ~ 1/9



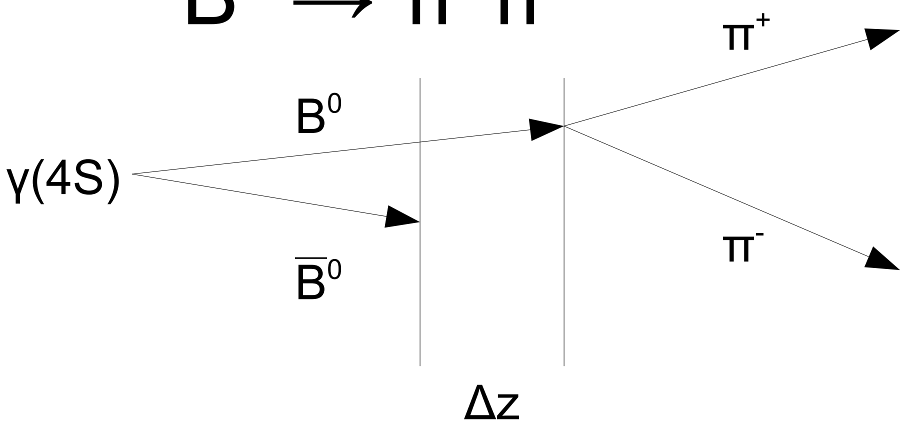
How the penguin distorts the tree level measurement

How to measure branching fractions for $\Upsilon(4S) \to B^0 \overline{B^0}$?

$$\mathcal{B}(B^0 \to f) = \frac{Y(B^0 \to f)}{N(BB)\,\epsilon(B^0 \to f)}$$

- Yield ← Result of my analysis
- N(BB) ← Proportional to Luminosity delivered from KEKB accelerator (removed QED, Bhabha, ...)
- Efficiency ← Result of my analysis convoluted with detector effects

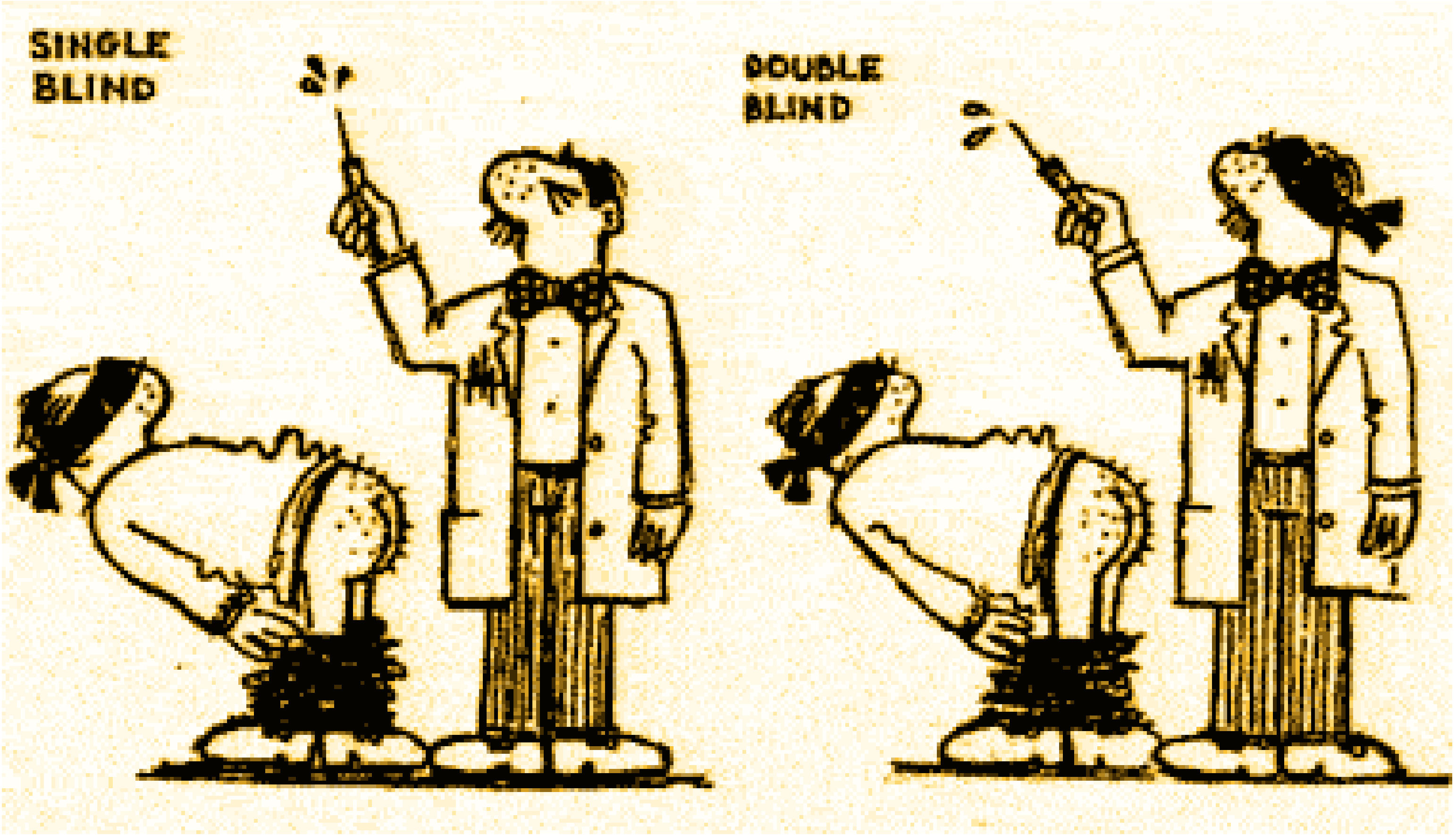
$B^0 \rightarrow \pi^+\pi^-$



Topology similar to $B^0 \rightarrow K^+\pi^-$
- it is a strong background
- therefore we want to include it in the fit

- Belle recorded 1ab^{-1} (nearly two times the BaBar dataset)
- About 770 mio. $B\overline{B}$ pairs
- Final goal: measure CP violation and branching fractions in one fit

Task: Find the ~ 2000 events where $B^0 \rightarrow \pi^+\pi^-$ out of 770 mio. other events


SINGLE
BLIND
DOUBLE
BLIND

1. "Blind": do not look at the data!

   Everything is done on Monte Carlo simulation before

   This way you cannot fall in the trap of "producing" a signal

2. "Double"

   - Cross check with other analysis
     - Independent reconstruction by Jeremy Dalseno
     - Independent reconstruction by me (Kolja)

   → Agreement within floating point accuracy!

- Reconstruct event
  - Find 4 vectors of the decay products
  - Combine 4 vectors to obtain mother particles

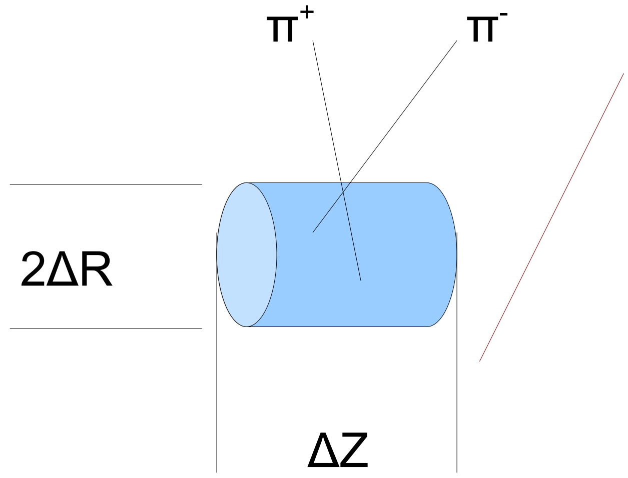
- Variables for event discrimination:
  - ΔE ~ reconstructed energy $\Delta E = E_B^{CMS} - E_{beam}^{CMS}$
  - M_{bc} ~ reconstructed mass $M_{bc} = \sqrt{(E_{beam}^{CMS})^2 - (p_B^{CMS})^2}$

  - $L_{K/\pi}(\pi^+)$
  - $L_{K/\pi}(\pi^-)$

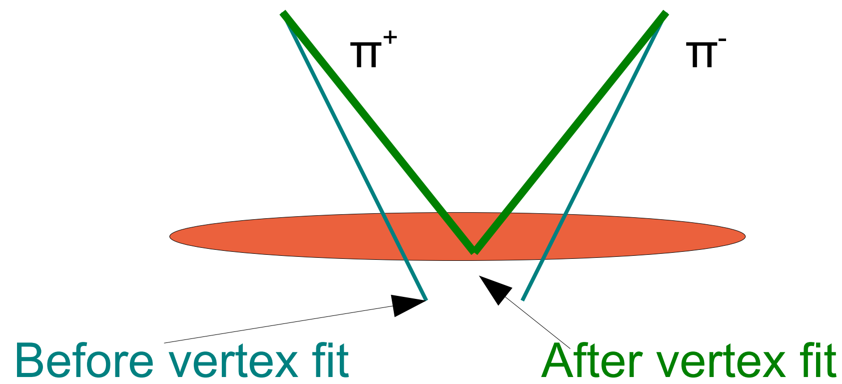
  } Likelihood from the particle identification system (PID)

- tracks:
  - veto electrons
  - veto protons

  (Cuts on PID Likelihood)
  - impact parameter cut (loose)
    - abs(ΔR) < 4 cm
    - abs(ΔZ) < 6 cm

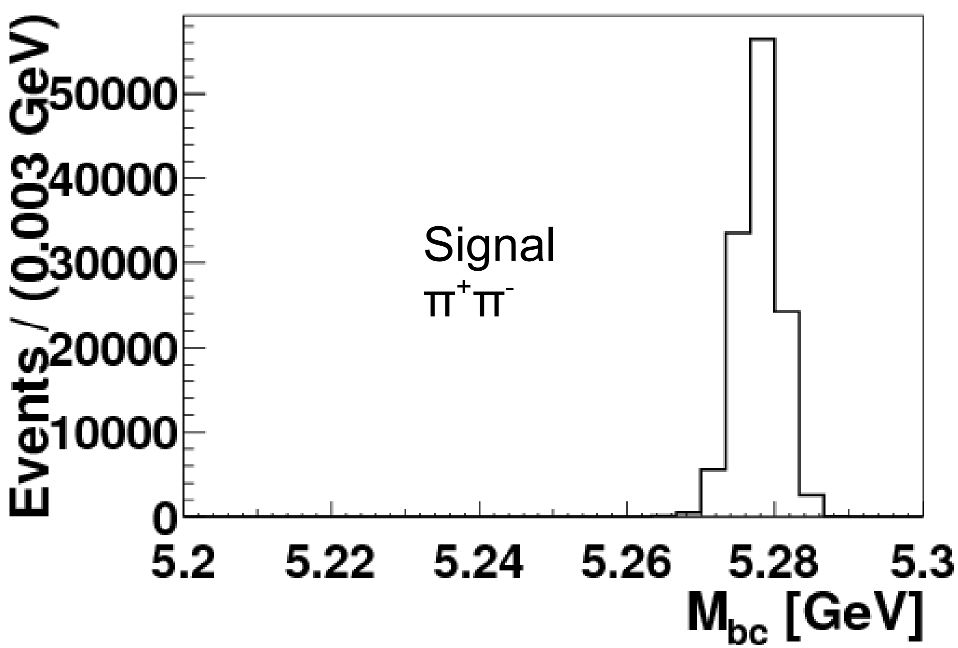


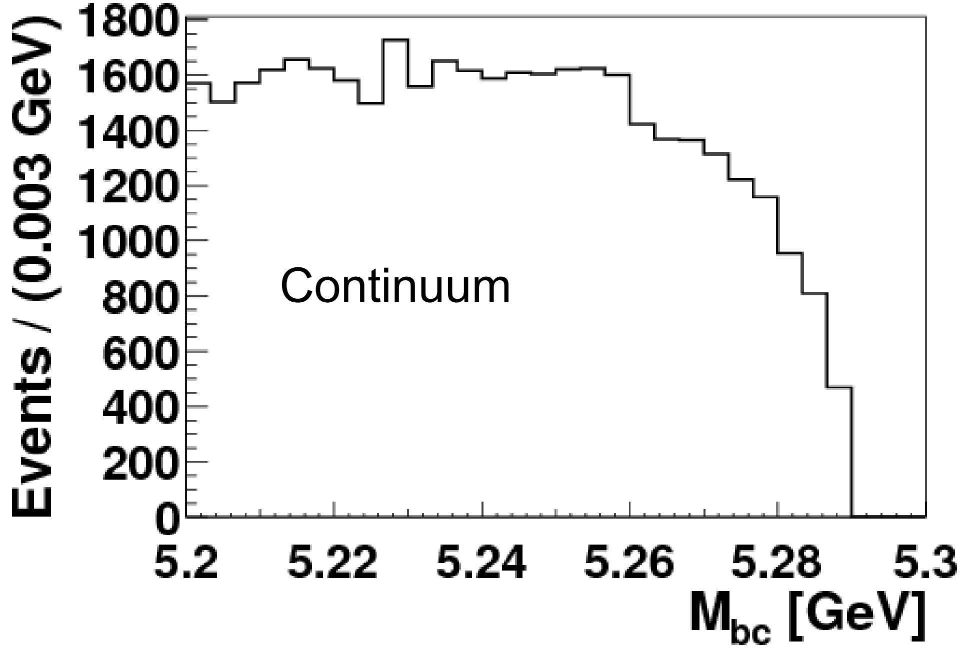
- vertexing:
  - use only good tracks (needed to use resolution function)
    n_rphi_hits >= 1 && n_Z_hits >= 2
  - beam tube constraint
- define analysis window:
  - $M_{bc} > 5.2$
  - $-0.15 < \Delta E < 0.15$



Mbc = mass beam constraint

$$M_{bc} = \sqrt{(E_{beam}^{CMS})^2 - (p_B^{CMS})^2}$$



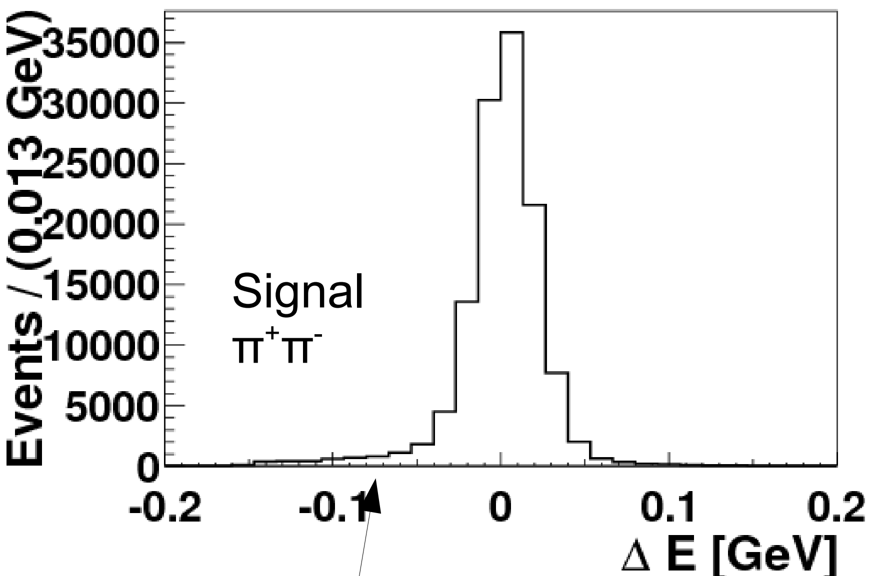


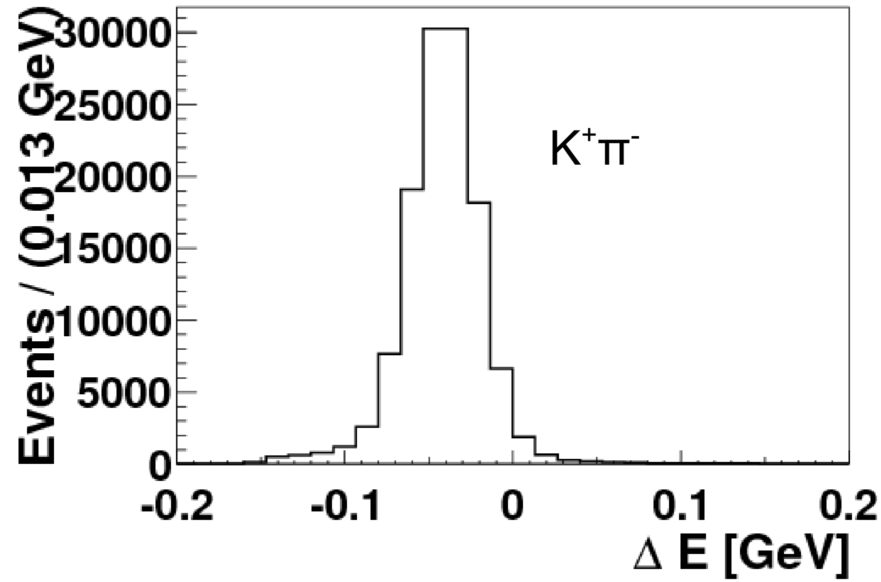
define analysis window: Mbc > 5.2

the upper bound is given by the beam energy (event by event)

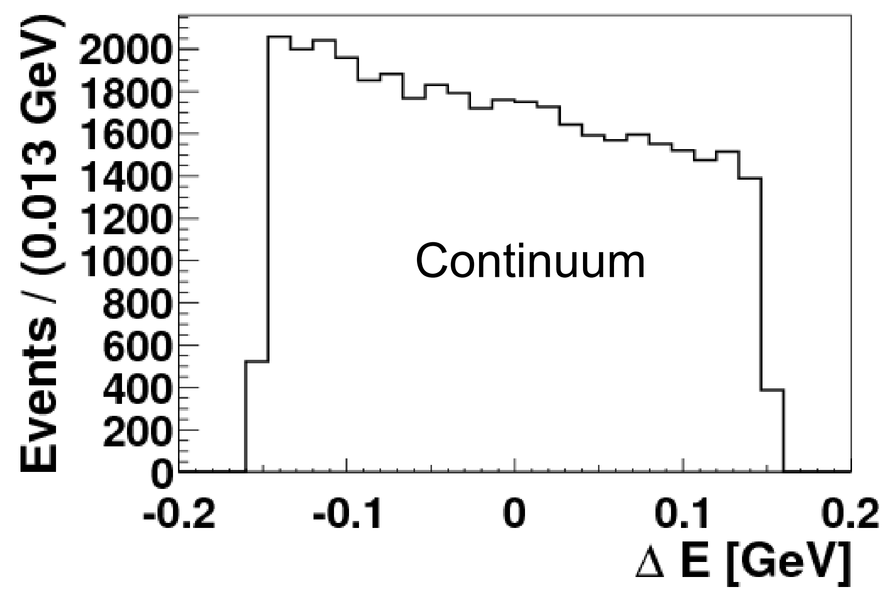
$$\Delta E = E_B^{CMS} - E_{beam}^{CMS}$$

ΔE = Energy difference between beam and reconstructed particles



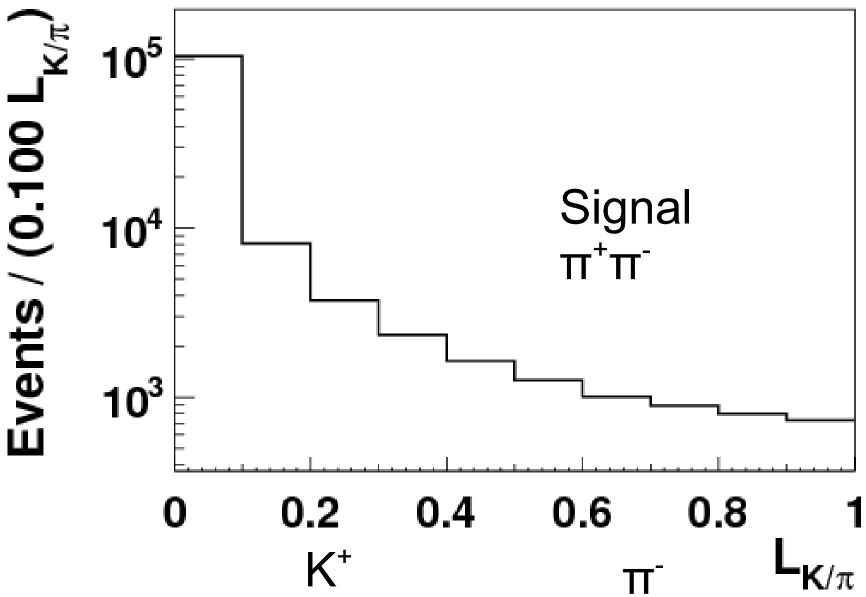


Effect of final state radiation: tails to lower energies

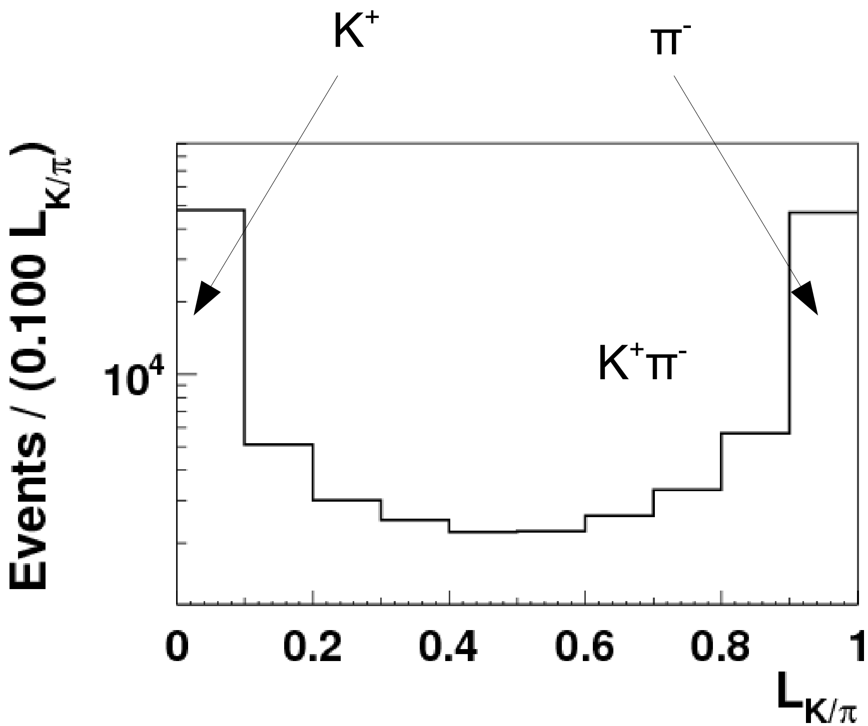


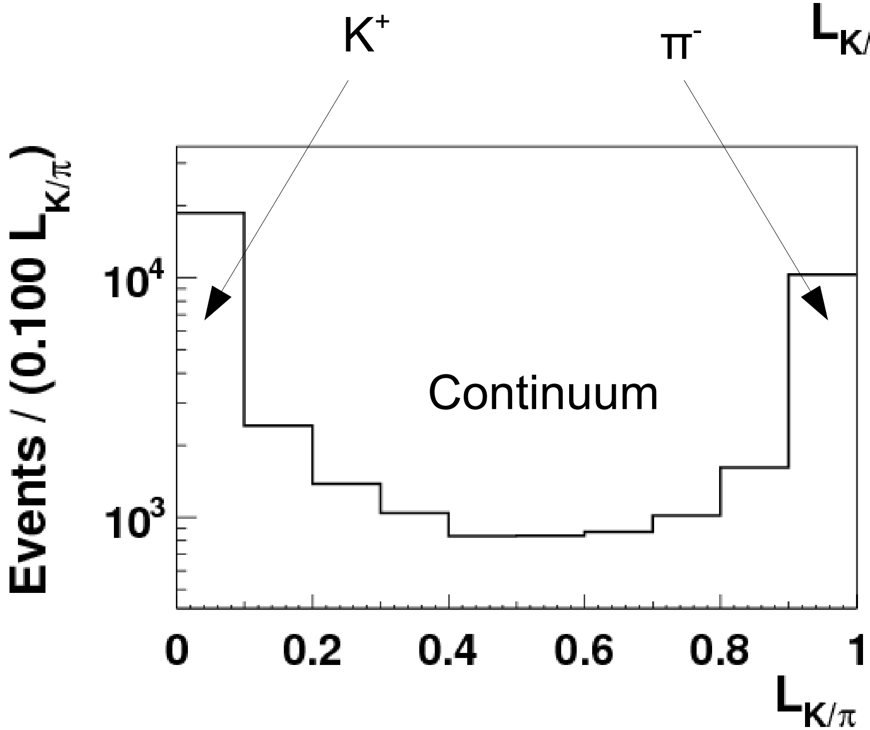
define analysis window: $-0.15 < \Delta E < 0.15$

Likelihood to be a Kaon or Pion:

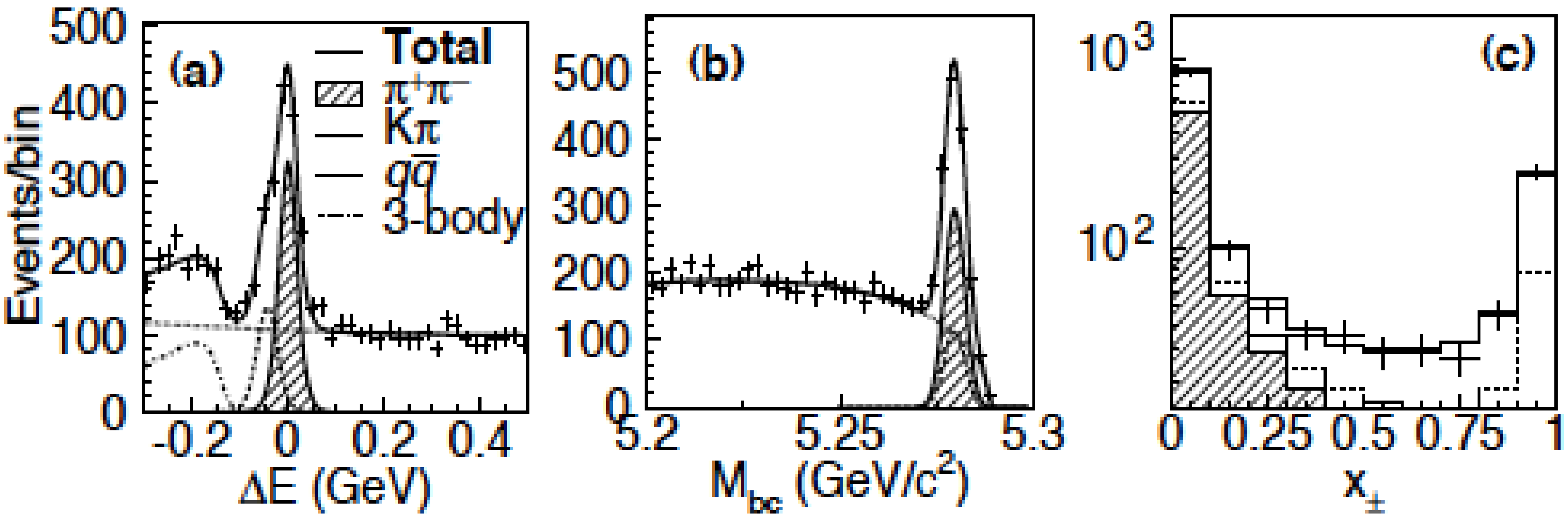


PID: Central drift chamber (CDC)
Time of flight (TOF)
Aerogel Cherenkov Counter (ACL)



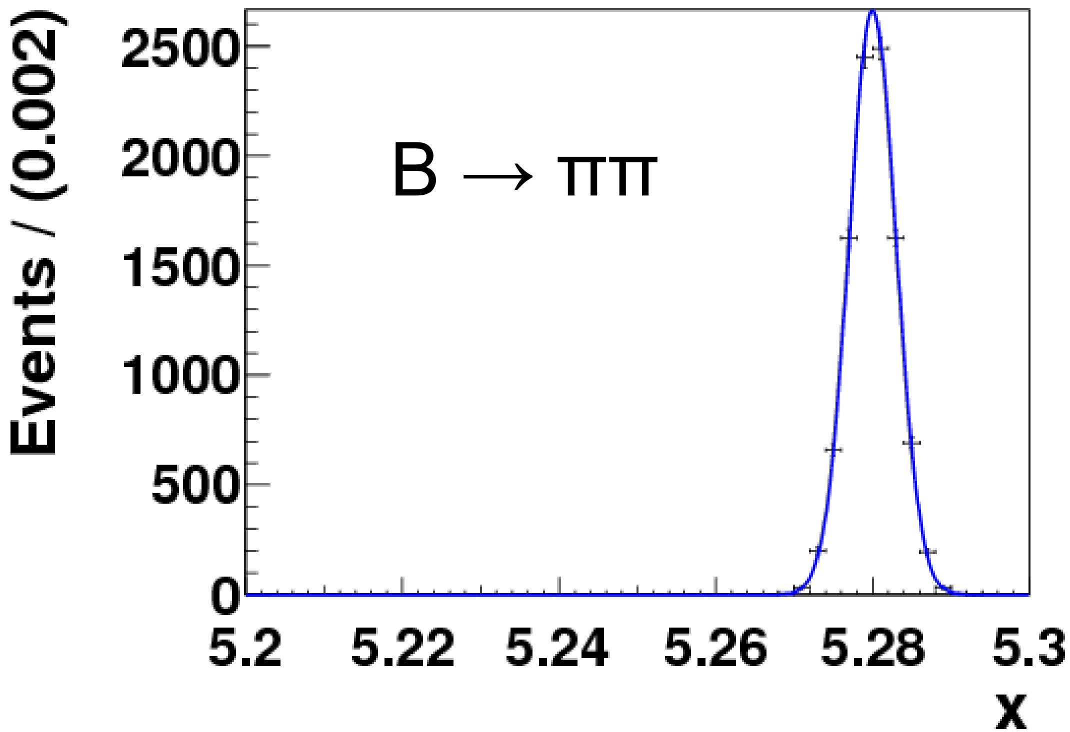


- Model Signal contributions for all possible sources
  - signal
  - generic decays ($b \rightarrow c$)
  - rare decays ($b \rightarrow uds$)
  - off-resonance (continuum $q\bar{q}$)
  - special contributions ($K^+\pi^-$)



Fitting recipe

- Describe all variables by a function (or histogram)
  - PDF (Probability Density Function)
- Perform Unbinned Maximum Likelihood Fit
- Extracted the “Signal Shape”



Variable: Mbc

PDF: Gaussian

Free parameters:

Mean
Sigma

$$L = \prod_i P(M_{bc}^i; \vec{\Theta})$$

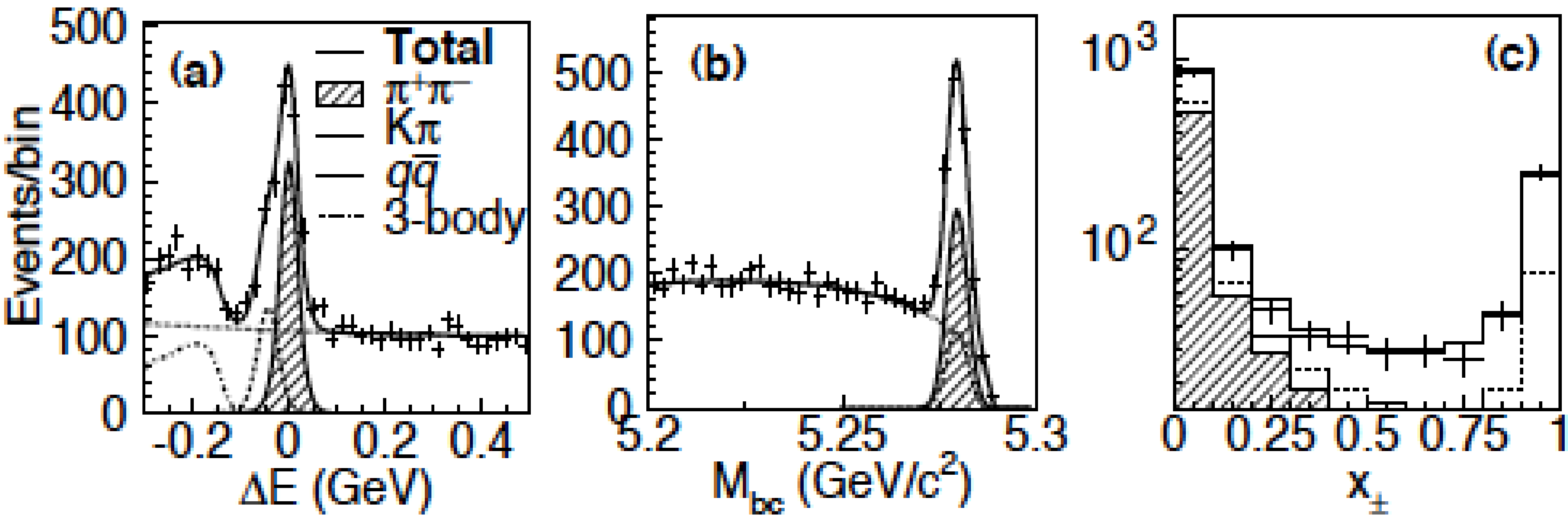
Maximize Likelihood for θ

$$-2\log L = -2\sum \log P(M_{bc}^i; \vec{\Theta})$$

Minimize -2 log L with software Minuit2

- Fix the signal shapes
- let the ratios between the different components float in the fit

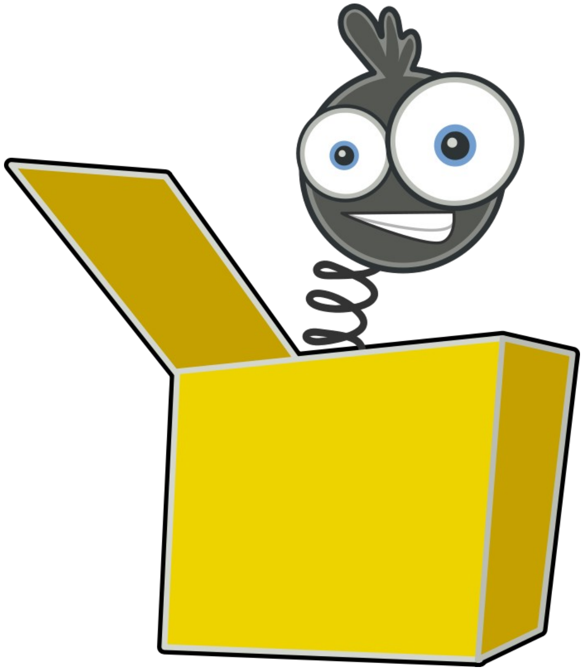
$$Yield = \frac{\text{signal events}}{\text{total number of events}}$$



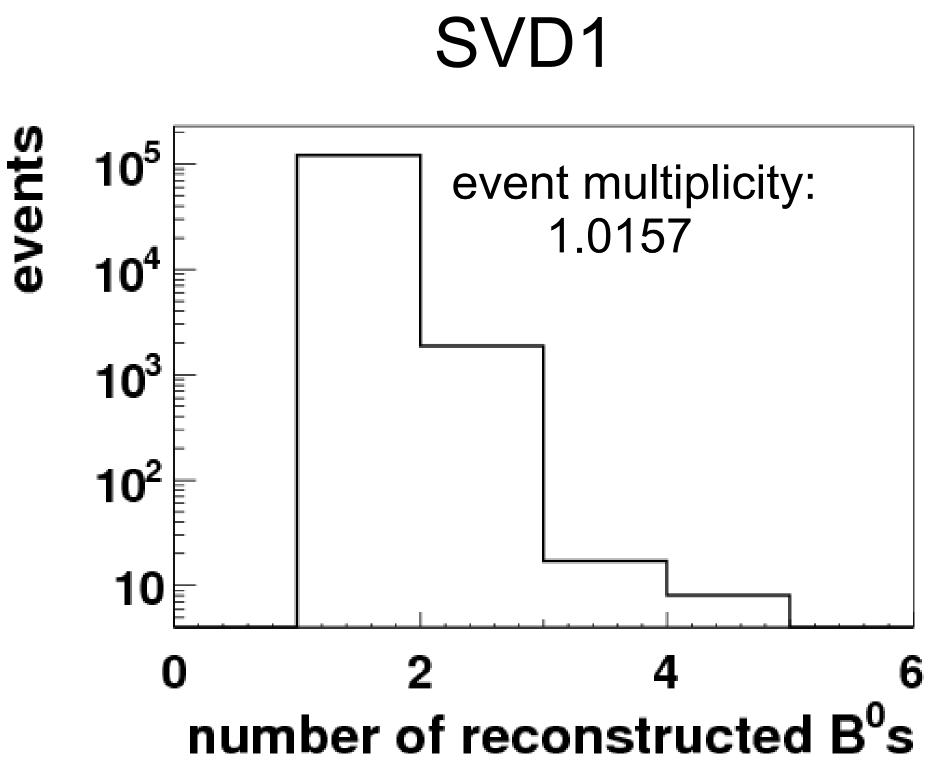
- Toy experiments to find out correlations and biases
  - Vary the expected branching ratio in the simulation
    - Get systematic uncertainty
  - Check if you obtain the simulated branching ratio

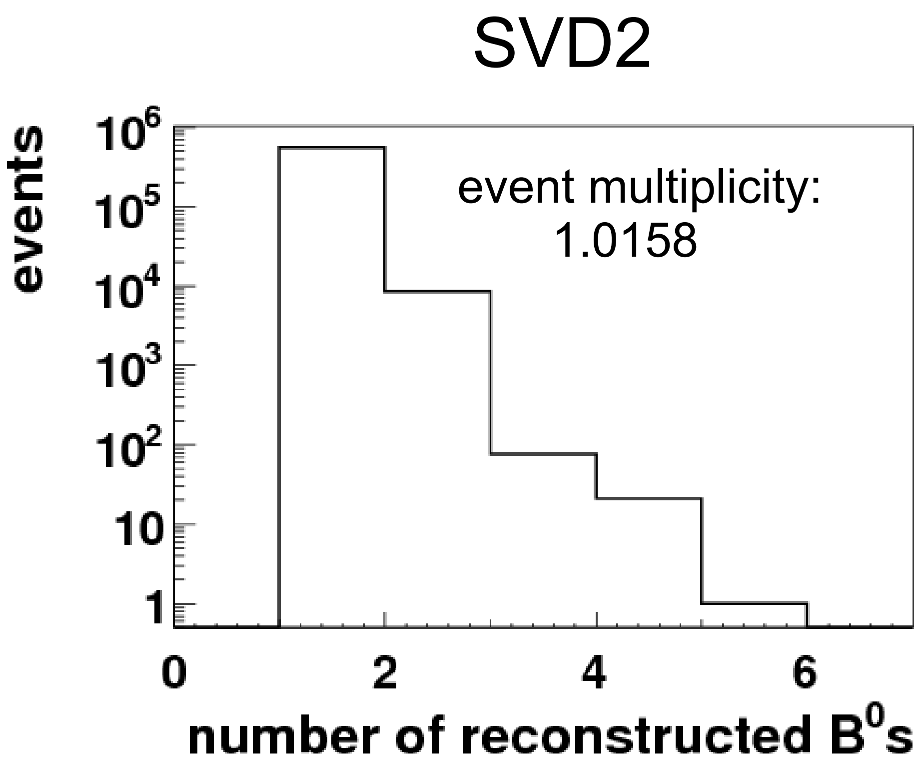
Open the box!

(Run your reconstruction and fitting on the real data)



Backup





Best B selection → take first from list

reconstruction efficiency:
66.7 %

reconstruction efficiency:
73.6 %

How to measure branching fractions for ?

Assuming no direct CP-violation:

$$B(\Upsilon \to f) = \frac{N(B^0 \to f) + N(\overline{B^0} \to \overline{f})}{N(B^0) + N(\overline{B^0})}$$

B^0 and $\overline{B}^0$ are produced in pairs:

$$B(\Upsilon \to f) = \frac{N(B^0 \to f) + N(\overline{B^0} \to \overline{f})}{2\mathrm{N}(B^0 \overline{B^0})}$$

Assuming equal production of $B^0 \overline{B}^0$ and $B^+ B^-$

$$B(\Upsilon \to f) = \frac{N(B^0 \to f) + N(\overline{B^0} \to \overline{f})}{2 \cdot \frac{1}{2} \cdot N(B^0 \overline{B^0})} = \frac{N(B^0 \to f) + N(\overline{B^0} \to \overline{f})}{N(B\overline{B})}$$

Not all $B^0 \to f$ can be observed → introduce Signal Yield (Number of detected events)

$$Y(B^0 \to f) = \epsilon(B^0 \to f)(N(B^0 \to f) + N(\overline{B^0} \to \overline{f}))$$

↑ Efficiency

$$H_l = \sum_{i,j} \frac{|p_i||p_j|}{E_{vis}^2} P_l(\cos(\theta_{ij}))$$

θ_{ij}: angle between hadron i and j
E_{vis}: total visible energy

Normalization:

$H_{0l} = H_l / H_0$

→ balanced Momentum:
$H_1 = 0$
→ 2 jet events:
$H_l = 1$ for l is even

Legendre polynomials:

$$\begin{aligned} P_0(x) &= 1\,, \\ P_1(x) &= x\,, \\ P_2(x) &= \frac{1}{2}(3x^2 - 1)\,, \\ P_3(x) &= \frac{1}{2}(5x^3 - 3x)\,, \\ P_4(x) &= \frac{1}{8}(35x^4 - 30x^2 + 3)\,, \end{aligned}$$

- Other idea: thrust and sphericity (minimization procedure) 80s (PEP/PETRA)
- Belle`s invention: Super-Fox-Wolfram-Moments (R. Enomoto)
- Combine merits of FW moments and thrust axis
  - separate tracks of Signal B and other B

$$R_i^{so} = \sum_{j,k} |p_j||p_k|P_i(\cos\theta_{jk}) / \sum_{j,k} |p_j||p_k|, \left[\begin{array}{l} j \text{ over signal B tracks} \\ k \text{ over other B tracks} \end{array} \right]$$

$$R_i^{oo} = \sum_{j,k} |p_j||p_k|P_i(\cos\theta_{jk}) / \sum_{j,k} |p_j||p_k|, \ (j, k \text{ over other B tracks})$$

- H. Kakuno: Kakuno-Super-Fox-Wolfram Moments (KSFW)

  → include charge

$$H_i = \sum_{j,k} Q_j Q_k |p_k| P_i(\cos(\theta_{ij}))$$

  → separate treatment of charged and neutral tracks

  - g=0: only charged tracks of other B
  - g=1: only photons of other B
  - g=2: only missing momentum of other B

  → include missing momentum vector

- E_T: scalar sum of transverse energy
- MM^2: missing momentum squared

- 17 variables

E_T — scalar sum of transverse energy of all particles
$H_i^{so,c}$ (for i=0 to 4), using only charged tracks of other B
$H_i^{so,n}$ (for i=0,2,4), using only photons of other B
$H_i^{so,\nu}$ (for i=0,2,4), using only missing momentum of other B
H_i^{oo} (for i=0 to 4)

- Strong dependence on MM^2, separate Fisher in 7 MM^2 bins

$$F = \sum_{i=1}^{N} \alpha_i x_i$$

- Find the set of α_i where the distance between the signal and the background events is maximal

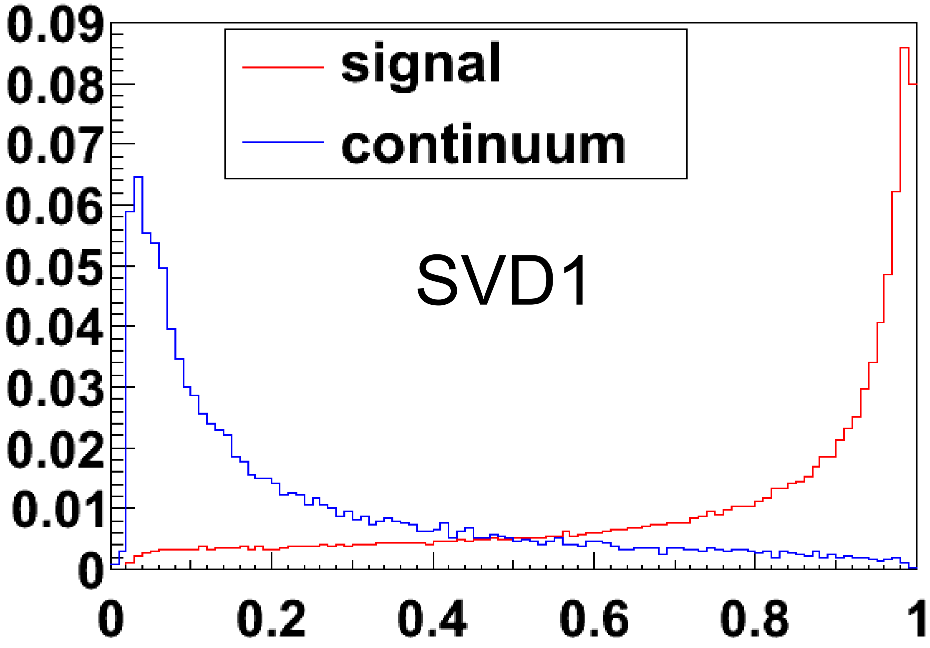
- Procedure (including matrix inversion):

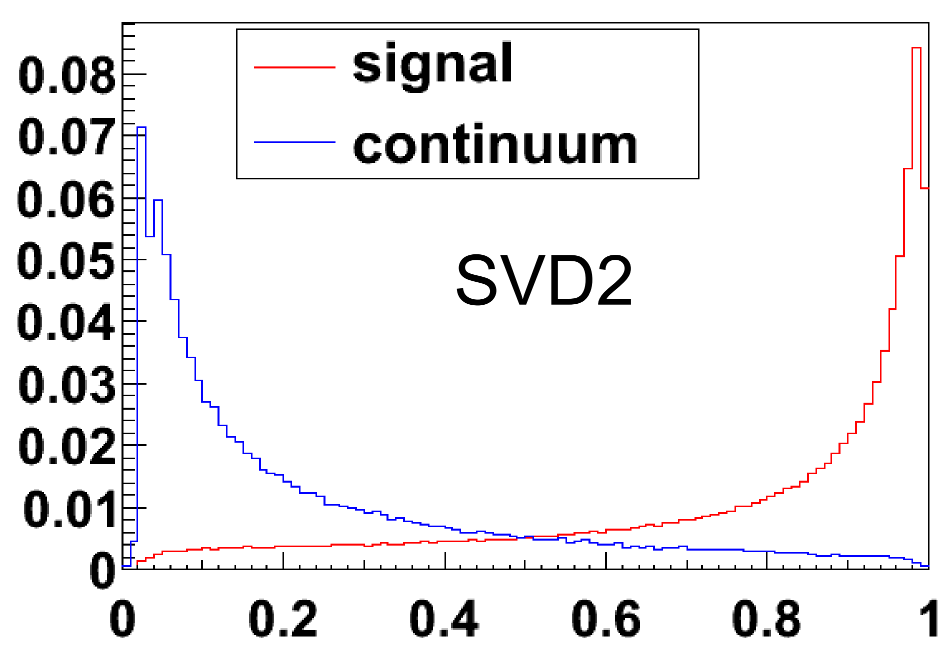
$$\alpha_i = \sum_{i=1}^{N} (U_{ij}^{b} + U_{ij}^{s})^{-1} (\mu_j^{b} - \mu_j^{s})$$

$\mu_{ij}^{b,s}$: mean for background, signal

$U_{ij}^{b,s}$: covariant matrix background, signal

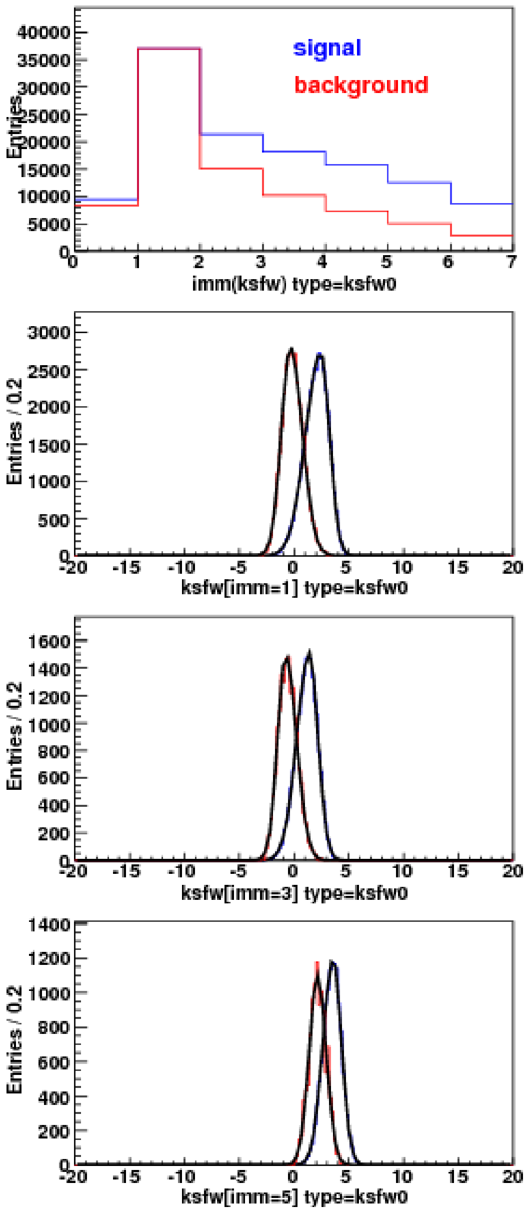
introduced by CLEO (PRD53, 1039(1996)) implemented in brutus_f at Belle



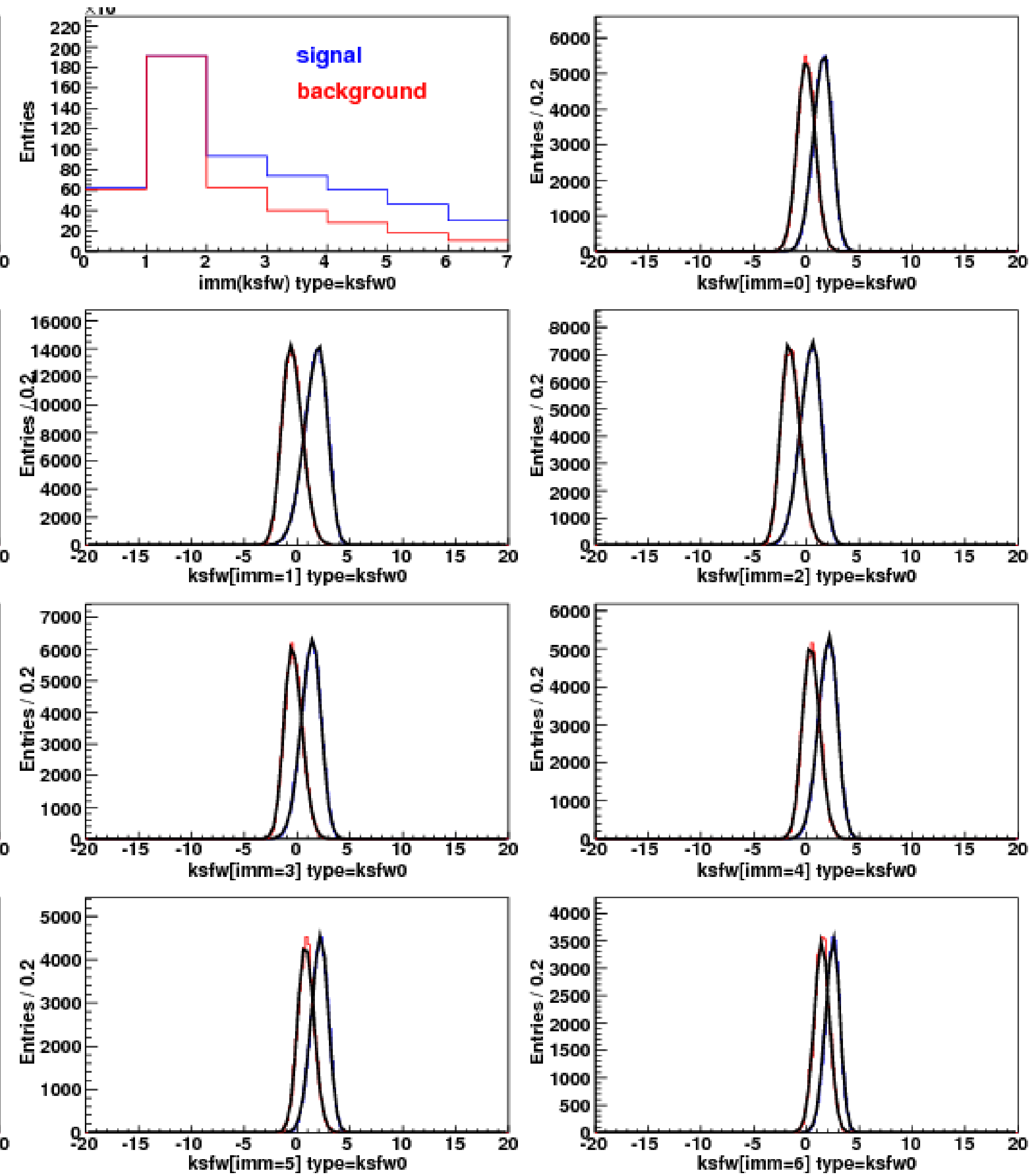


- Signal and Continuum are normalized
- Full off-resonance dataset used
- very smooth curves

SVD1


signal
background
Entries
imm(ksfw) type=ksfw0
Entries / 0.2
ksfw[imm=0] type=ksfw0
ksfw[imm=1] type=ksfw0
ksfw[imm=2] type=ksfw0
ksfw[imm=3] type=ksfw0
ksfw[imm=4] type=ksfw0
ksfw[imm=5] type=ksfw0
ksfw[imm=6] type=ksfw0

SVD2


signal
background
Entries
imm(ksfw) type=ksfw0
Entries / 0.2
ksfw[imm=0] type=ksfw0
ksfw[imm=1] type=ksfw0
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ksfw[imm=3] type=ksfw0
ksfw[imm=4] type=ksfw0
ksfw[imm=5] type=ksfw0
ksfw[imm=6] type=ksfw0