CKM Matrix and CP Violation in Standard Model

B physics at B factories

Lecture 15

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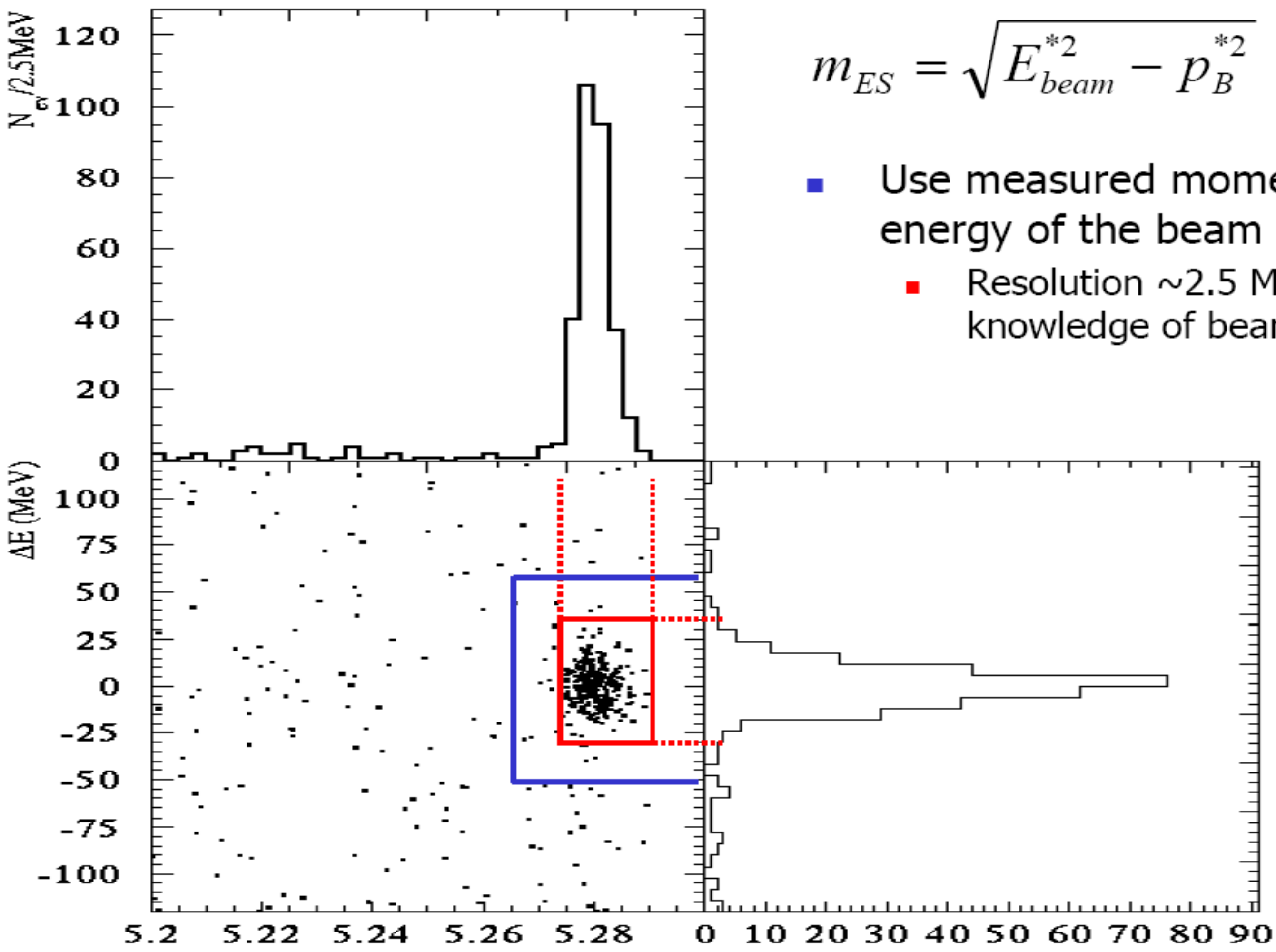
Fisica delle Particelle Elementari, Anno Accademico 2015-16

http://www.roma1.infn.it/people/rahatlou/particelle/

Ingredients of B Reconstruction

- Take advantage of clean environment in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - Energy of each B meson is known in the center of mass



$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

Energy-substituted mass

- Use measured momenta of B daughters and energy of the beam
  - Resolution ~2.5 MeV/c^2 dominated by knowledge of beam energy

Energy difference

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

- Difference between total reconstructed and expected energy
  - Dominated by detector energy resolution
  - Resolution depends on particles in final states

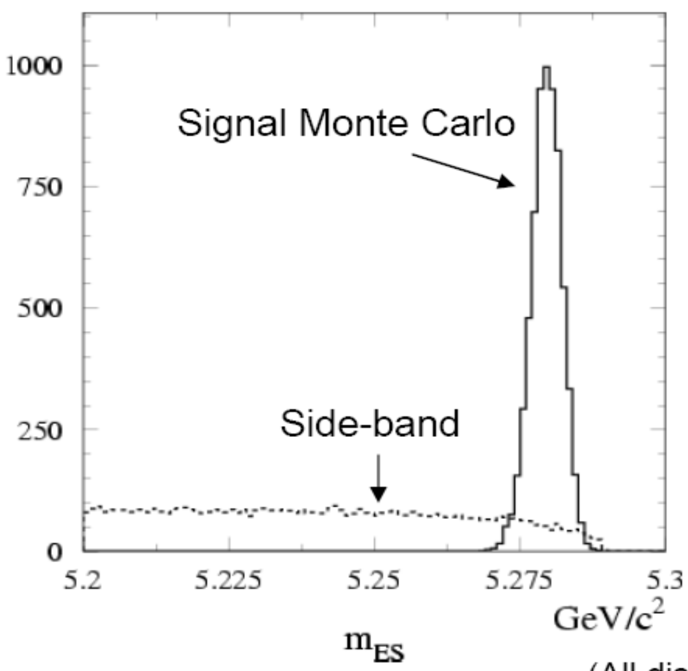
Kinematic Variables

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

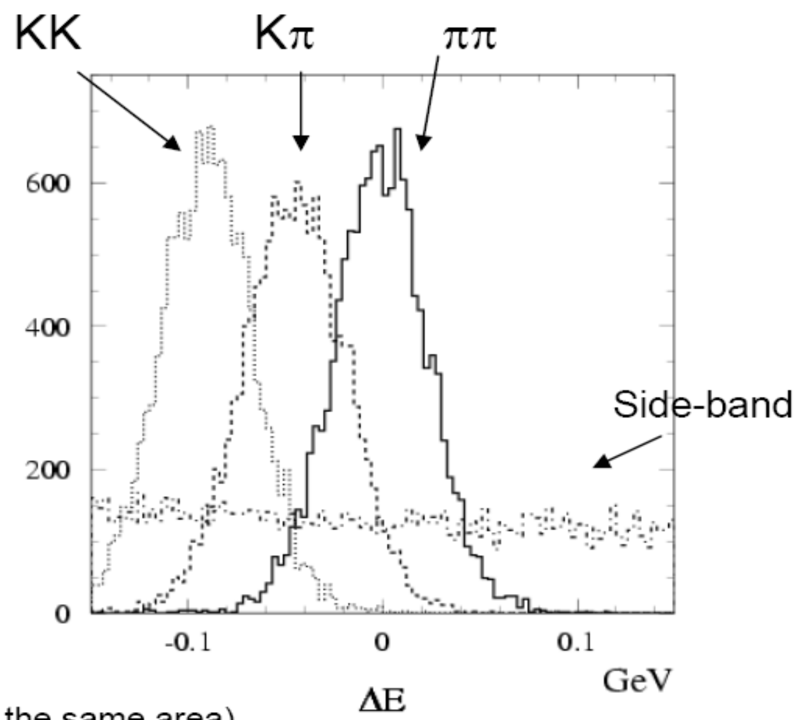
$$m_{\text{ES}} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$$

- Dominated by tracking resolution
- Assume π mass for tracks
- Momentum dependent shift for $K\pi$ and KK

$\sigma(m_{\text{ES}}) \approx 2.6$ MeV/c²



$\sigma(\Delta E) \approx 26$ MeV



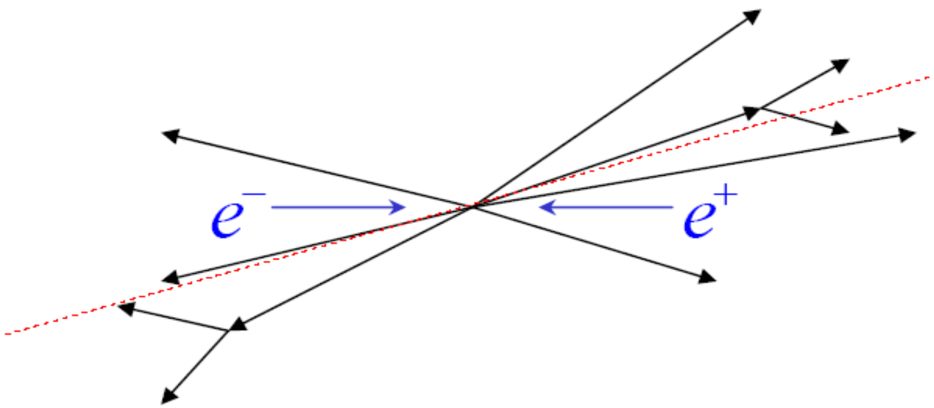
(All distributions are normalized to the same area)

Continuum Background Rejection

- Main source of background: continuum $e^+e^- \to q\bar{q}$ (q = u, d, s, c)
  - Branching fraction of interesting B decays $\leq 10^{-4}$
  - Branching fraction of D decays: $\cong 10^{-2}$

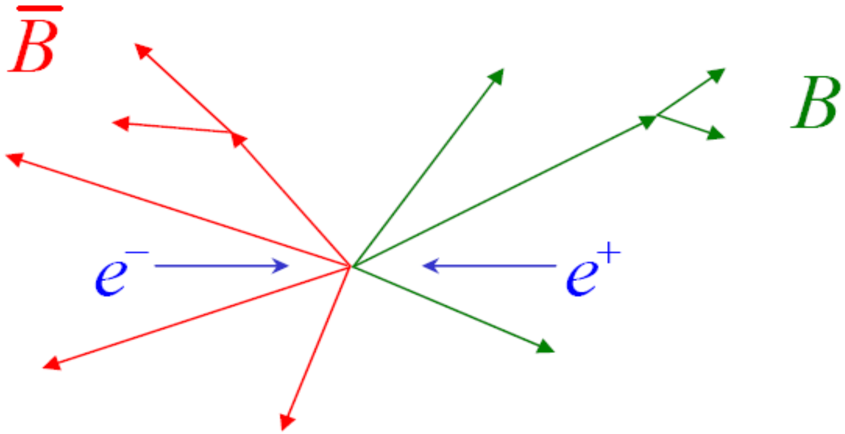
  $\Big\}$ Overall branching fraction $< 10^{-6}$

- Distinguish signal and background based on event topology
  - Neutral networks
  - Fisher discriminant



Thrust Axis

$$e^+e^- \to q\bar{q}$$



$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

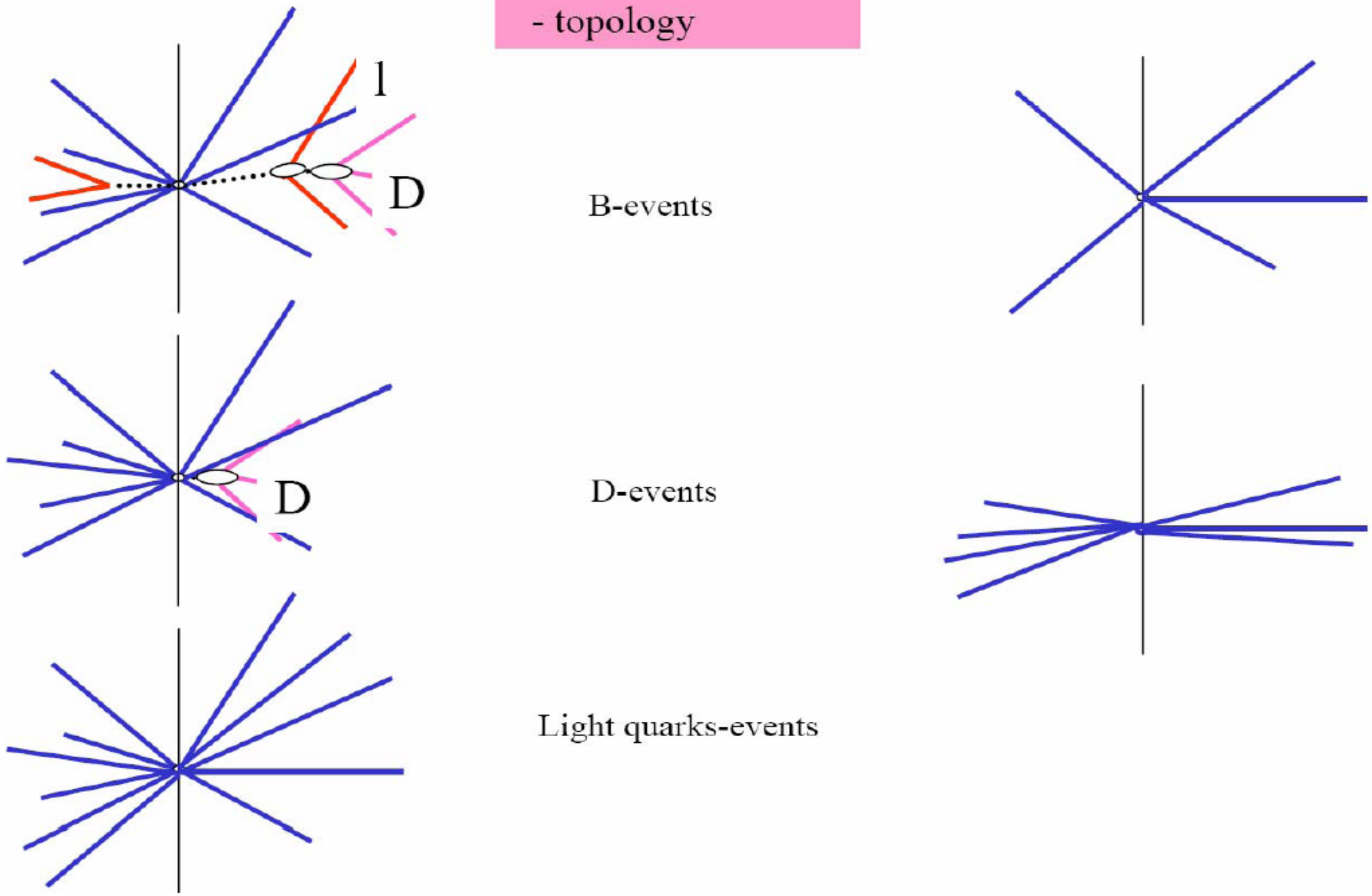
Event Topology at LEP/SLD vs. B Factories

b ⇔ non-b

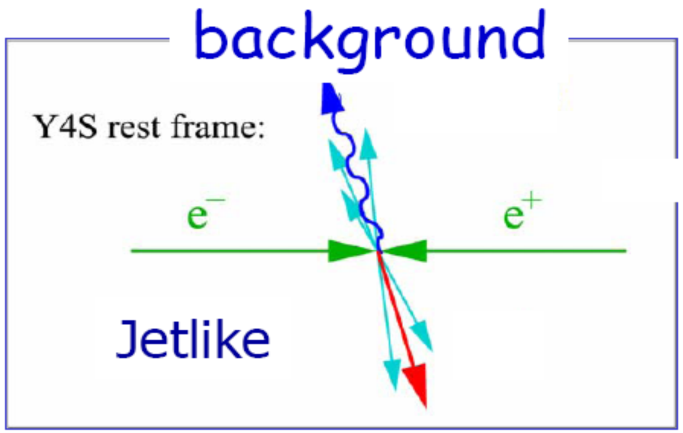
- displaced vertices
- leptons
- topology

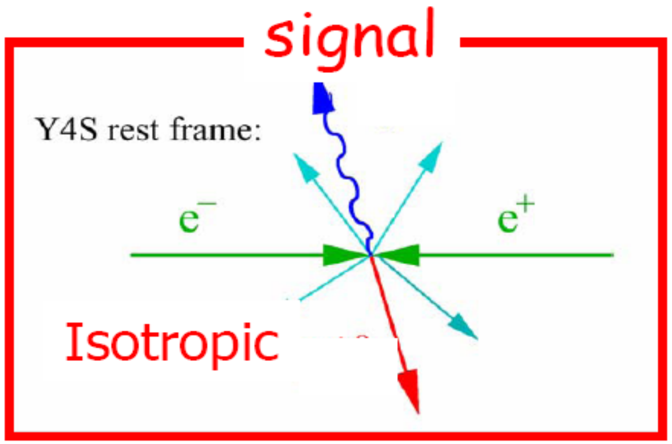
LEP/SLD

B-factories

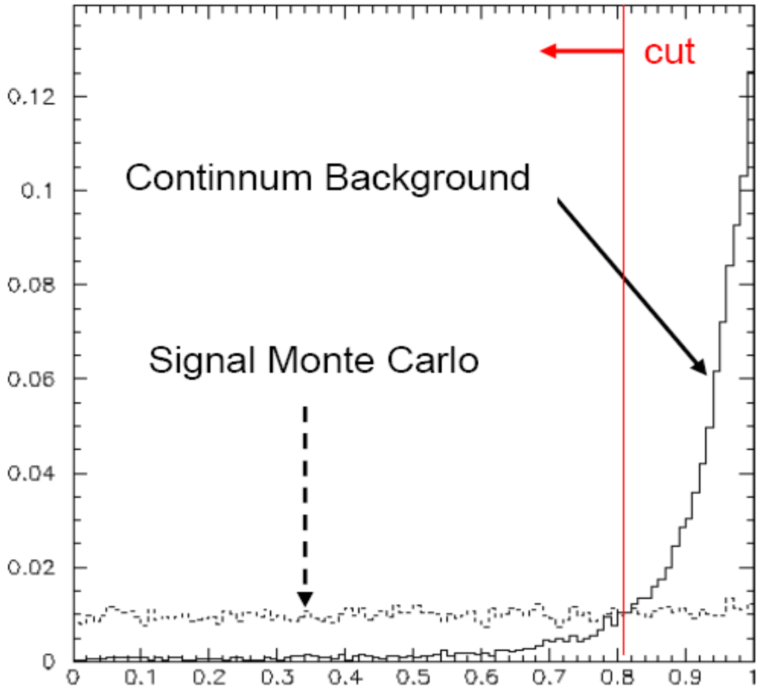


Background Fighting: Sphericity Angle



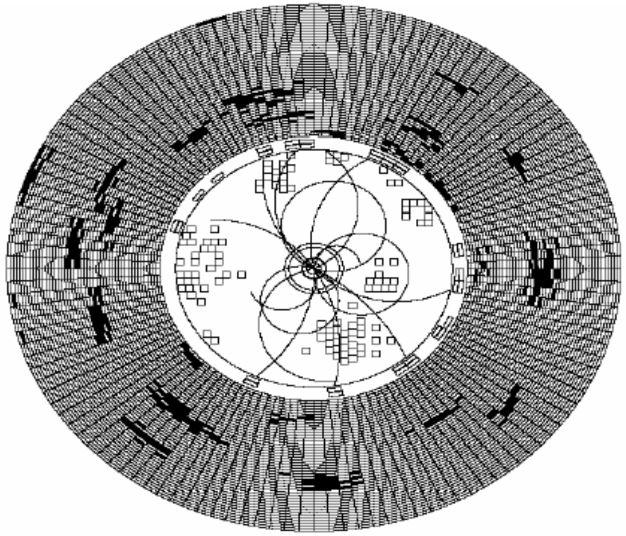


- $\cos\theta_s$: Angle between the B candidate and the rest of event

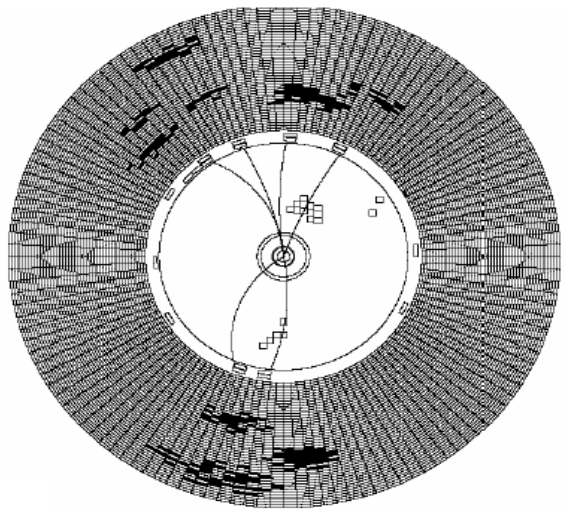


2^{nd} Fox-Wolfram Moment

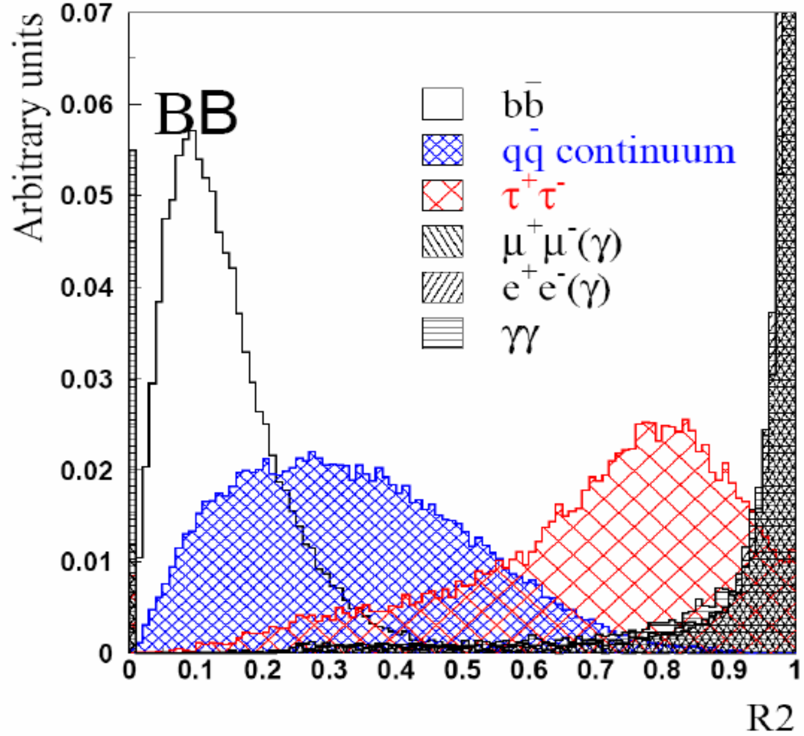
$\Upsilon(4S) \rightarrow B\overline{B}$ Decay



$e^+e^- \rightarrow u\overline{u},\ d\overline{d}\ ,s\overline{s},c\overline{c}$ decays

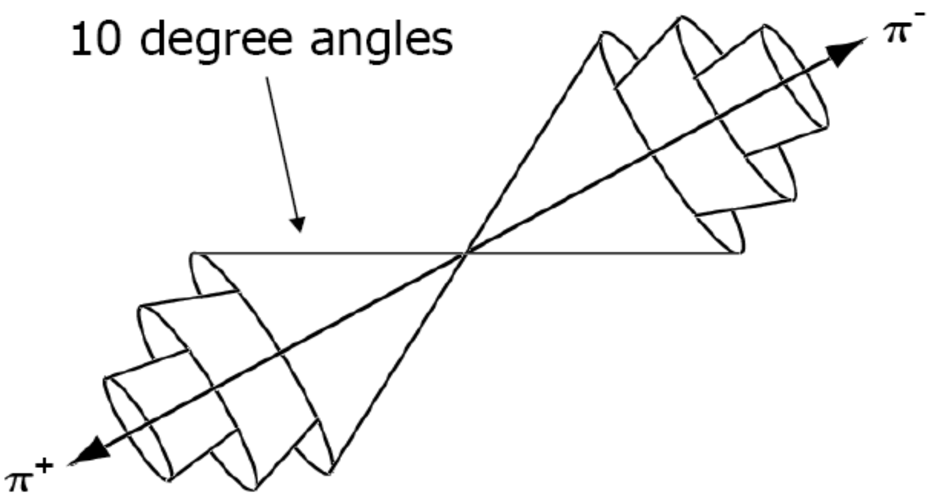


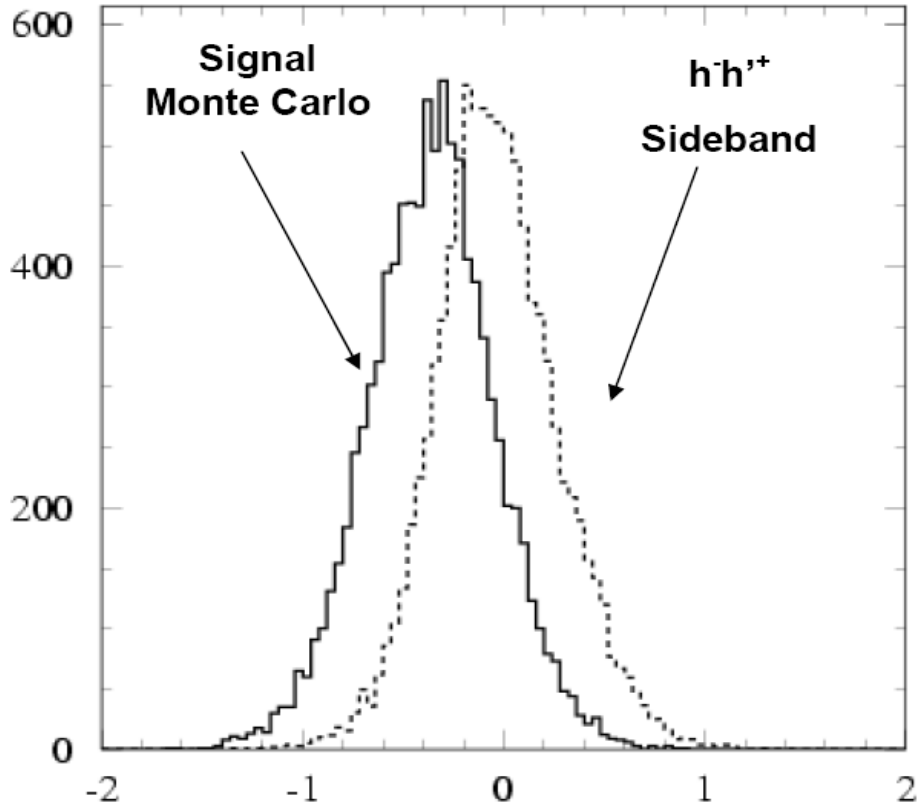
Differences in the event topology (Isotropic B Vs jet-like Continuum) and Energy flow structure in these events used to construct continuum background suppresssion tools.



Background Fighting: Fisher Discriminant

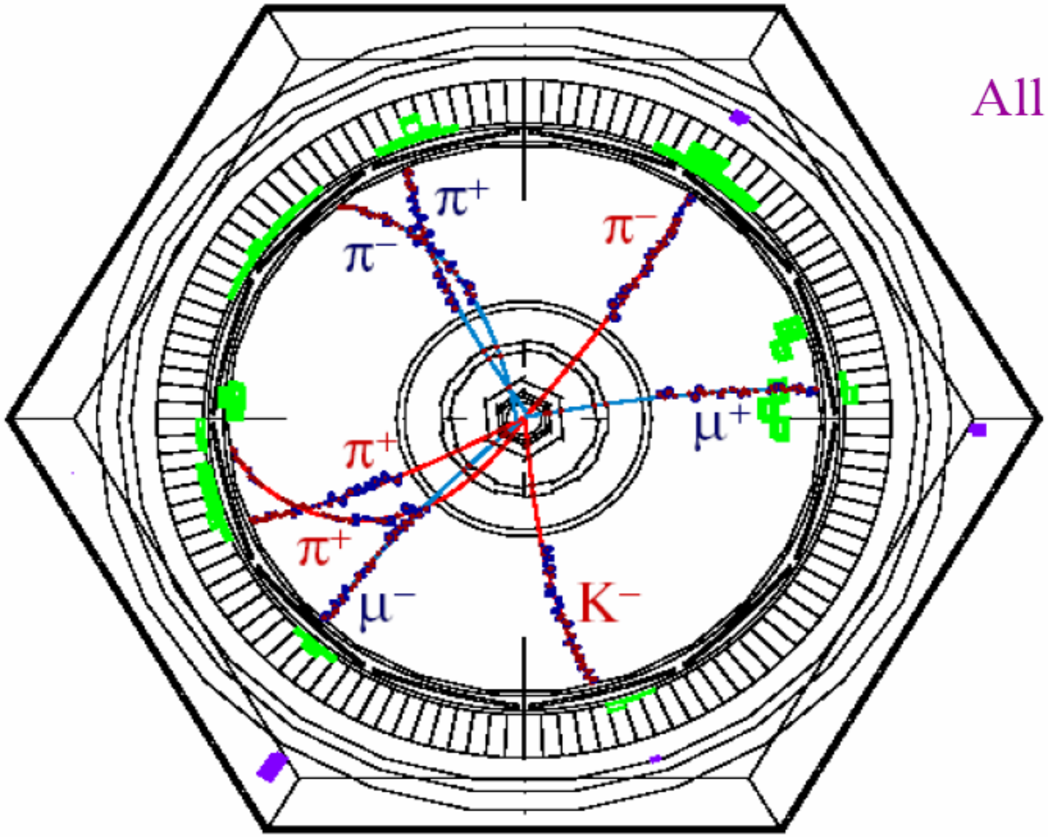
- Optimized linear combination of energy flow into cones about candidates
- Sensitive only to the rest of event
- Studied and calibrated on data: $B \rightarrow D^0\pi^-$, $h^-h'^+$ sideband
- Validated with Monte Carlo





A Completely Reconstructed ϒ(4S) event at BaBar

$\overline{B}^0 \to D^{*+}\pi^-$ $\quad B^0 \to \psi(2S)K^0_s$



All particles accounted for
Nothing Missing !

$D^{*+} \to D^0\pi^+$

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

$\psi(2S) \to \mu^+\mu^-$

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

Measurement of $|V_{ub}|$ and $|V_{cb}|$

$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \mathbf{V}_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \boxed{A\lambda^3(\rho-i\eta)} \\ -\lambda & 1-\lambda^2/2 & \boxed{A\lambda^2} \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$|V_{cb}|$ Exclusive

$|V_{cb}|$ from $B^0 \to D^{(*)} l\nu$ Decays

Differential measurement of $\mathcal{B}(B^0 \to D^* l\nu)$ allows for the extraction of $|V_{cb}|$ through the expression:

$$\frac{d\Gamma}{dw} \propto |V_{cb}|^2 \mathcal{F}^2(w)\mathcal{G}(w)$$

$$w = v_B \cdot v_D = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

Form factor of $B \to D^*$ transition

Known kinematic factor

HQET and LQCD provide calculation at zero recoil

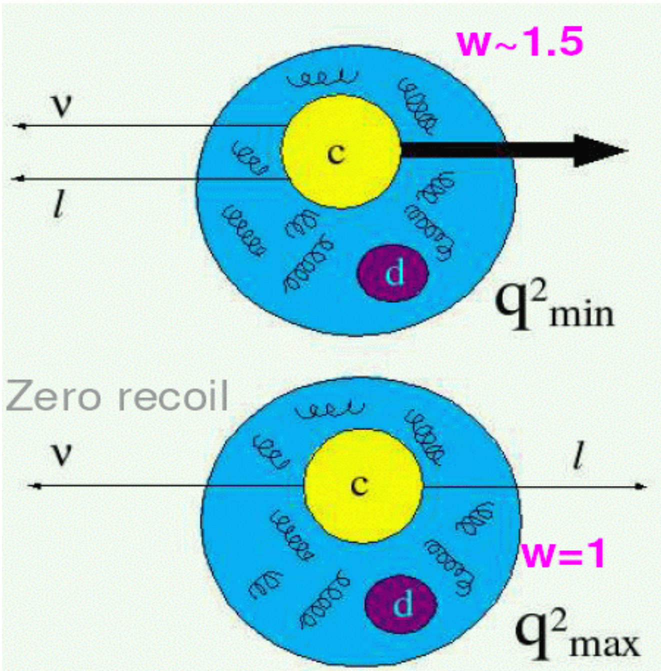
In reality the formula is slightly more complicated:

$$\mathcal{F}^2(w)\mathcal{G}(w) = h_{A_1}^2(w)\sqrt{w-1}\,(w+1)^2 \left\{ 2\left[\frac{1-2wr+r^2}{(1-r)^2}\right] \right.$$

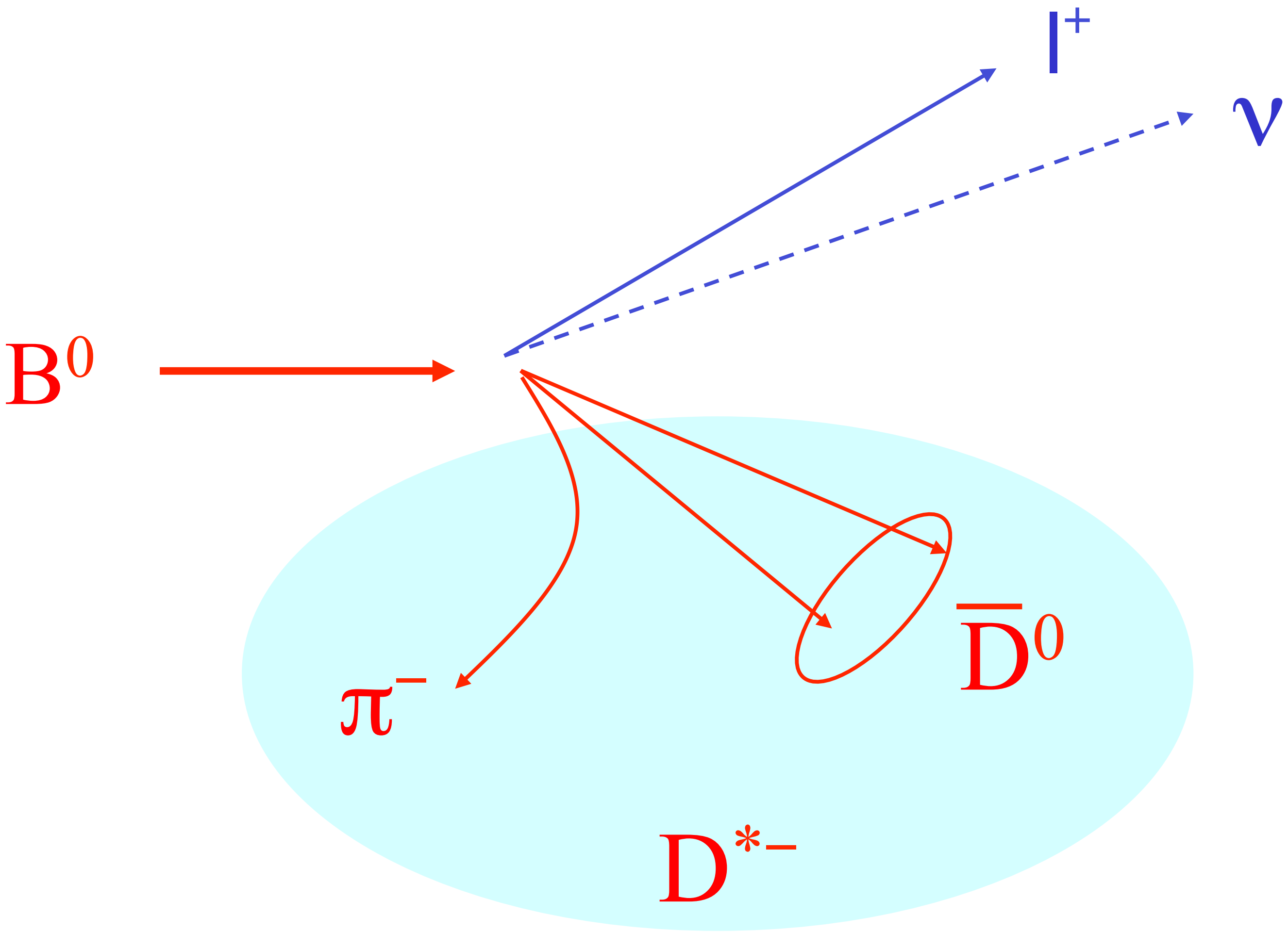
$$\left. \times\left(1+R_1(w)^2\frac{w-1}{w+1}\right) + \left[1+\left(1-R_2(w)\right)\frac{w-1}{1-r}\right]^2 \right\}$$

$$where \quad r = \frac{M_{D^*}}{M_{\bar{B}^0}}$$

F→1 for w→1



$B^0 \rightarrow D^{(*)} l \nu$ Decays

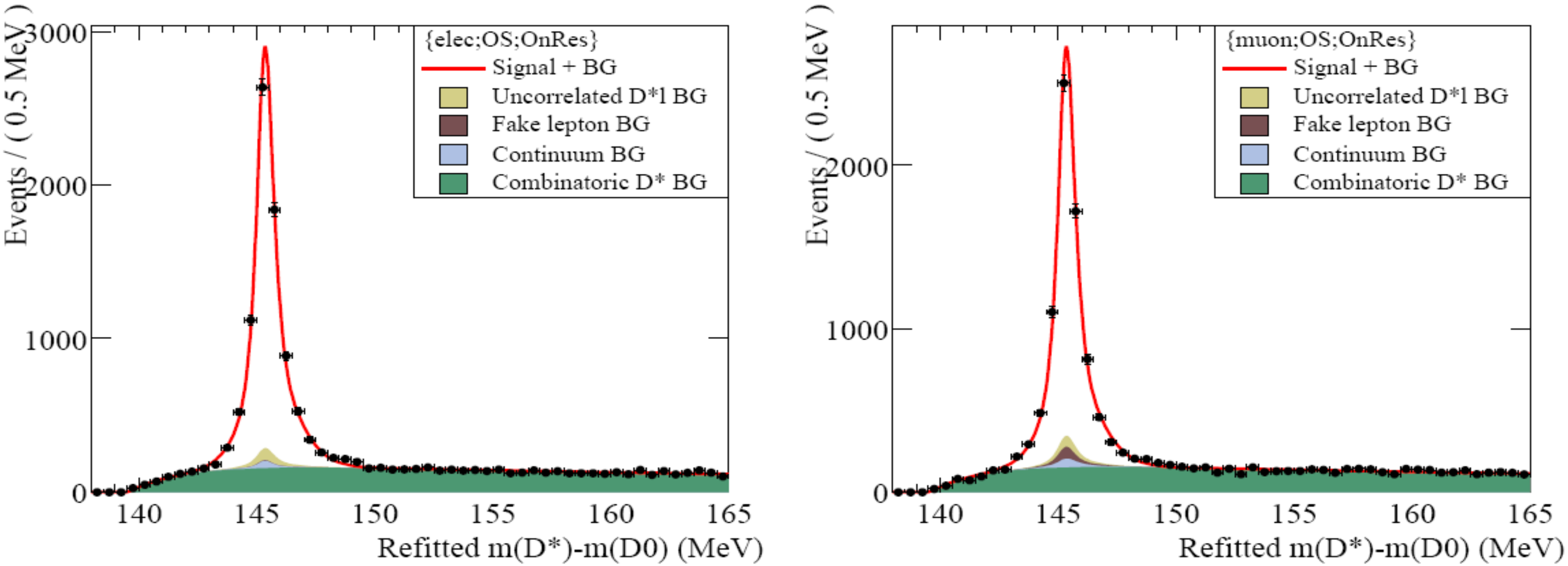


D^{*+}–D^0 mass difference

- D^0 mass: 1864 MeV
- D* mass: 2010 MeV

$$D^{*-} \to \overline{D}^0 \pi^-$$

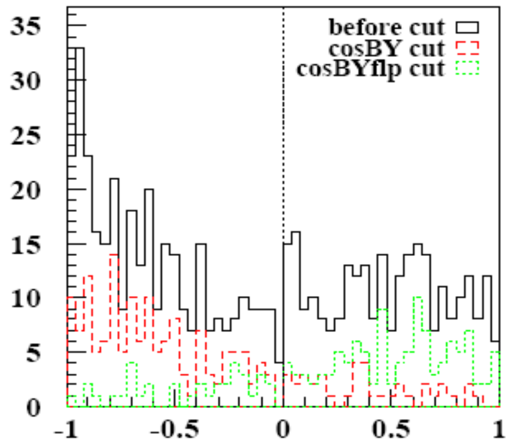
- Fixed momentum for soft pion
  - Only experimental resolution

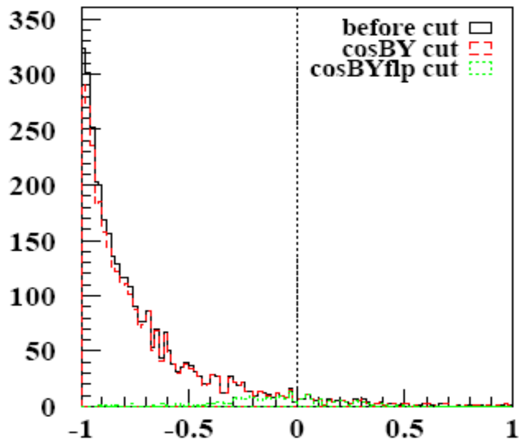


Angular Variables for $B^0 \to D^{(*)} l \nu$ Selection

- Angle between D* and lepton

Background



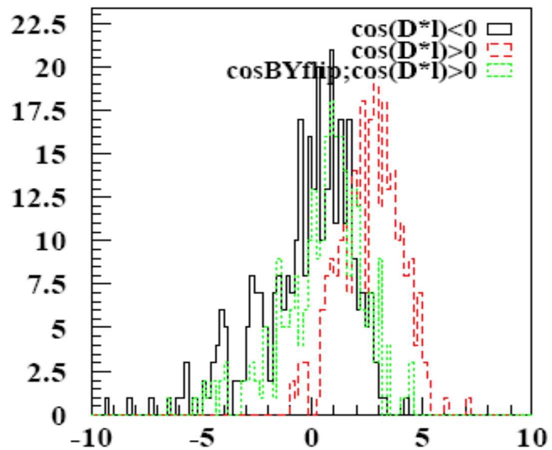


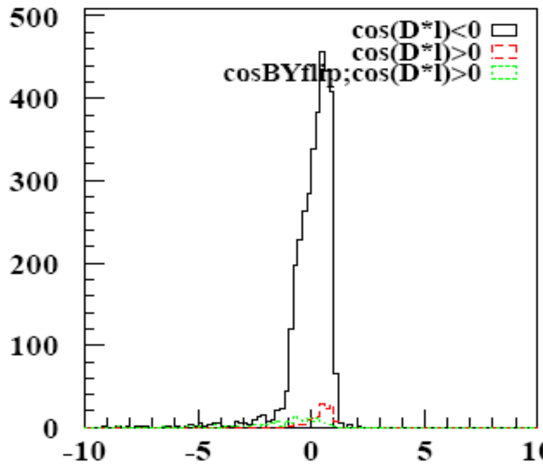
Signal

- Angle between B^0 and the D*l system
  - From kinematic quantities since B direction not measured

$$\cos\theta_{\mathrm{B^0},\mathrm{D^*}\ell} = \frac{-(m^2_{\mathrm{B^0}} + m^2_{\mathrm{D^*}\ell} - 2\,E_{\mathrm{B^0}}E_{\mathrm{D^*}\ell})}{2\,|\vec{p}_{\mathrm{B^0}}|\,|\vec{p}_{\mathrm{D^*}\ell}|}$$

Background





Signal

Extraction of $|V_{cb}|$

Measurement:

- Determine number of $B^0 \to D^{*-} l^+ \nu$ candidates as function of w
- Obtain $h_{A1}(w)|V_{cb}|$ distribution
- Fit differential spectrum and extrapola to w=1

In BaBar:

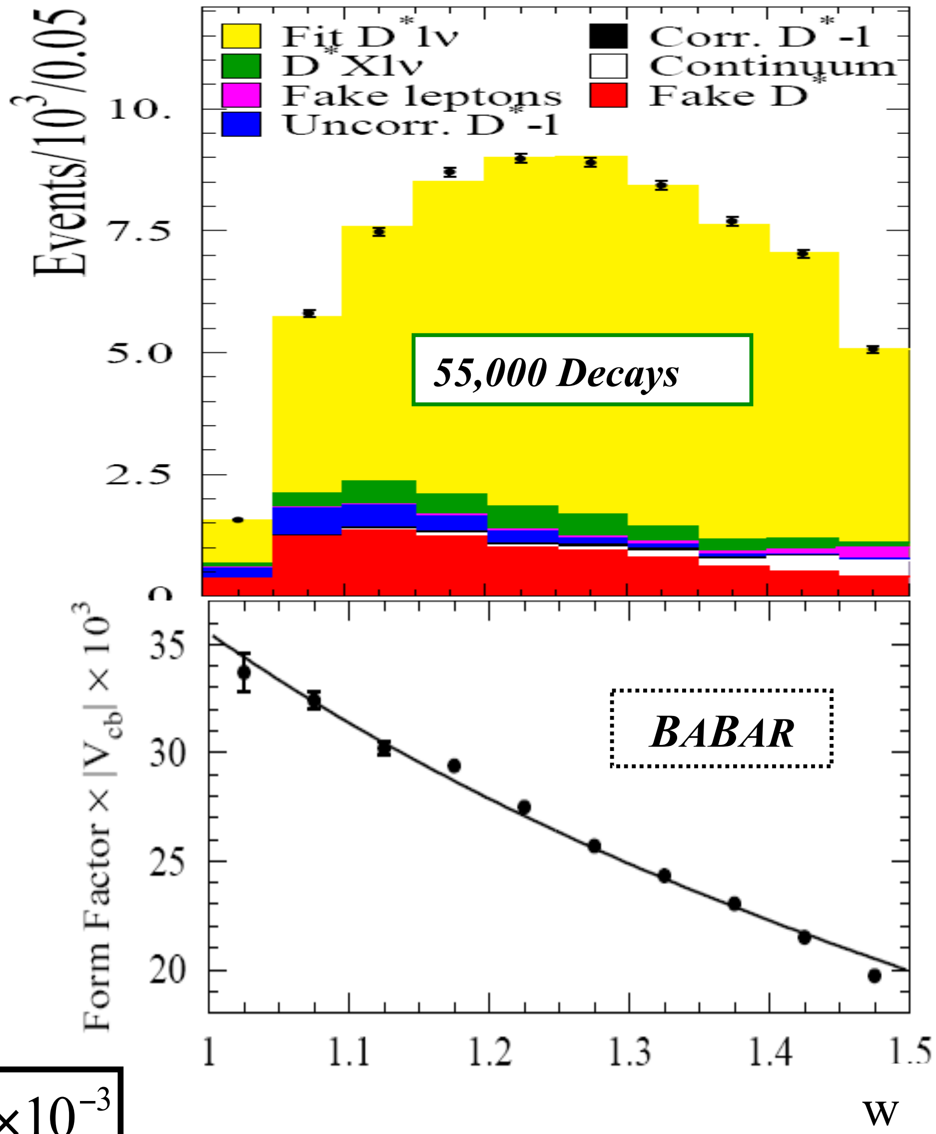
$$\boxed{h_{A_1}(1)|V_{cb}| = (35.5 \pm 0.3_{stat} \pm 1.6_{syst})}$$

and using

$$h_{A1}(w=1) = 0.919^{+0.030}_{-0.035}$$

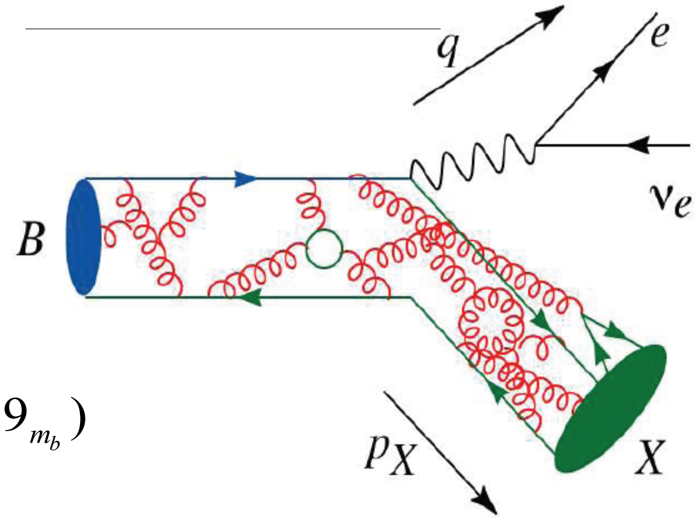
Hashimoto et al.
PRD 66, 014503
(LQCD)

$$\boxed{|V_{cb}| = (38.7 \pm 0.3_{stat} \pm 1.7_{syst} \pm^{1.5}_{1.3\,A_1}) \times 10^{-3}}$$



$|V_{ub}|$ Inclusive

$|V_{ub}|$ from Inclusive Semileptonic B Decays



Inclusive charmless semileptonic B decays,

$B \rightarrow X_u l\nu$, allow for the measurement of $|V_{ub}|$

$$|V_{ub}| = 0.00424\sqrt{\frac{B(B \to X_u l\nu)}{0.002}\frac{1.61ps}{\tau_B}} \times (1 \pm 0.028_{OPE} \pm 0.039_{m_b})$$

Theoretically relatively simple, but

- hadronization effects and Fermi motion of b quark
- non-perturbative parametrizations (Shape Function, SF) affected by large uncertainties

Experimentally challenging, because

- $B \rightarrow X_c l\nu$ background (60 times higher) separated in limited region of phase space
- extrapolation to full phase space introduces uncertainties

Lots of Theory Needed as Input for Interpretation

Traditional method:

* **Measure event yield in restricted phase space**

* **Extrapolate to full BF (usually DeFazio & Neubert)**

* **Full BF => $|V_{ub}|$**

State-of-the-art:

* **Partial BF in restricted phase space ('unfolded')**
Not depending on theoretical calculation on the market

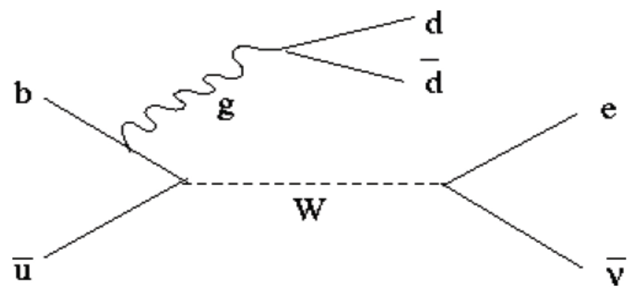
* **Direct translation: Partial BF => $|V_{ub}|$ using existing calculations**

* **Today: Bosch, Lange, Neubert, Paz (Used for recent results)**
Bauer, Ligeti, Luke (Used for M_X-q^2 extraction)
Aglietti, Ricciardi, Ferrera (new; not used yet)
....

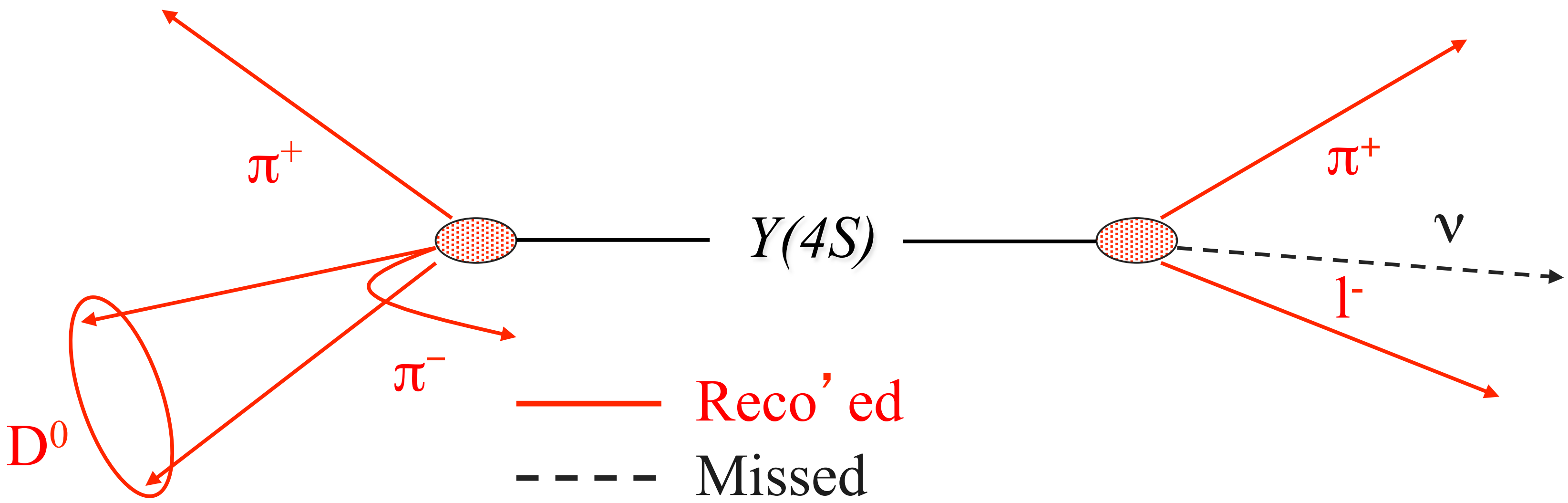
Additional Uncertainties ('estimated'):

* **Subleading Shape Functions**
(contributing differently in B->$X_s\gamma$)

* **Weak Annihilation (important @ high q^2)**



$|V_{ub}|$ inclusive from m_X and recoil

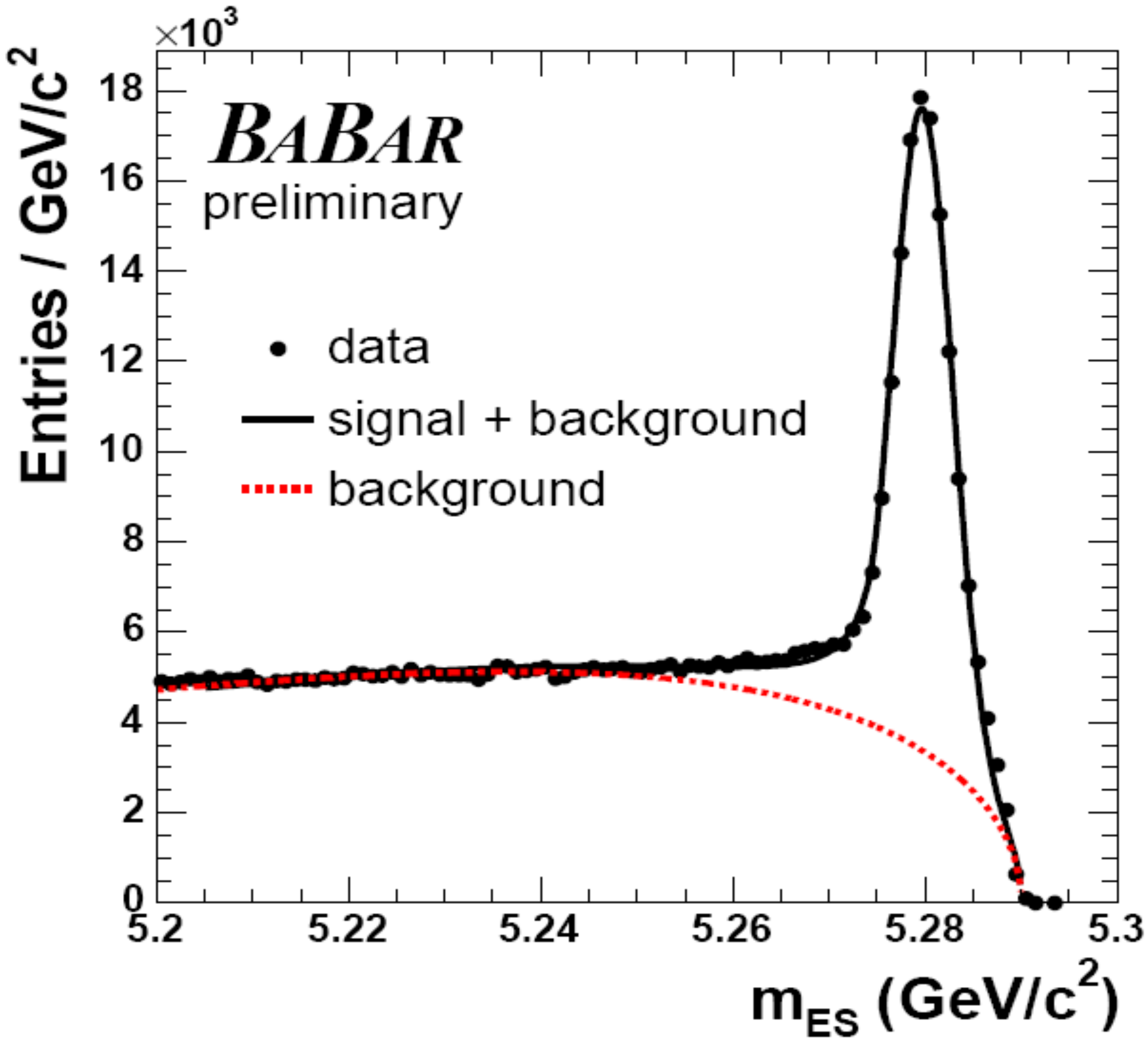


- Background $B \to X_c l\nu$ separated using invariant mass of the X system (M_X)
- Full reconstruction of one B meson to improve signal/background ratio
- Look for semileptonic decay on the recoil side

Fully Reconstructed B Mesons with Leptons in Recoil

Fully reconstruct as many decay modes as possible on one side

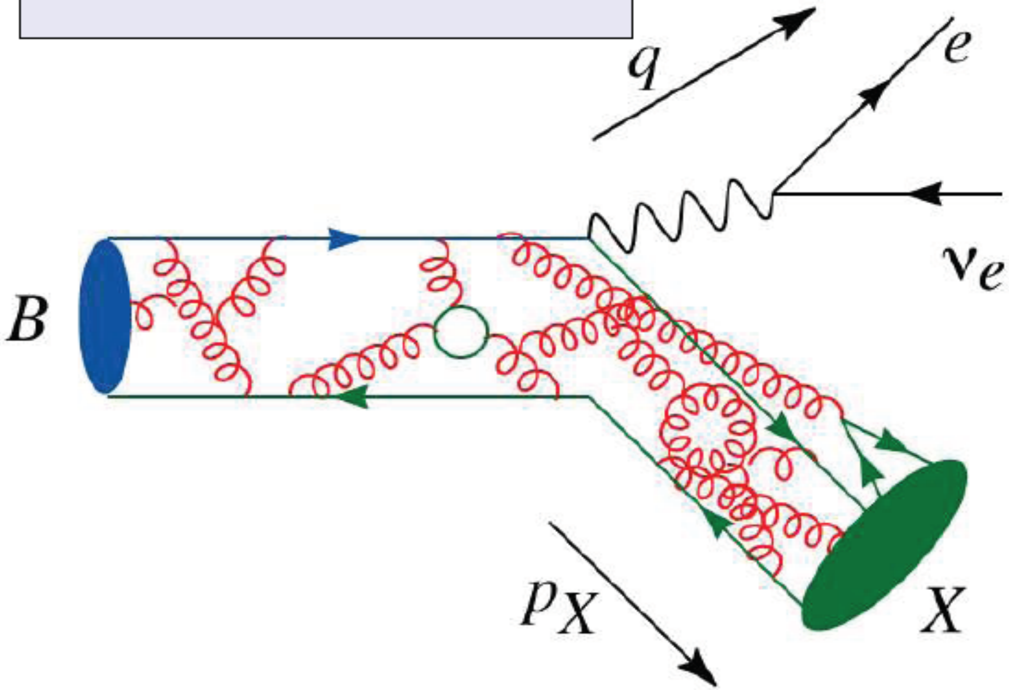
On the other side use lepton identification to clean up the sample:
p*>0.5 GeV for electrons
p*>0.8 GeV for muons



Kinematic Variables Useful for $|V_{ub}|$

$q^2_{max}(B \to X_c\, l\, \nu)$
$= 12\ GeV^2$

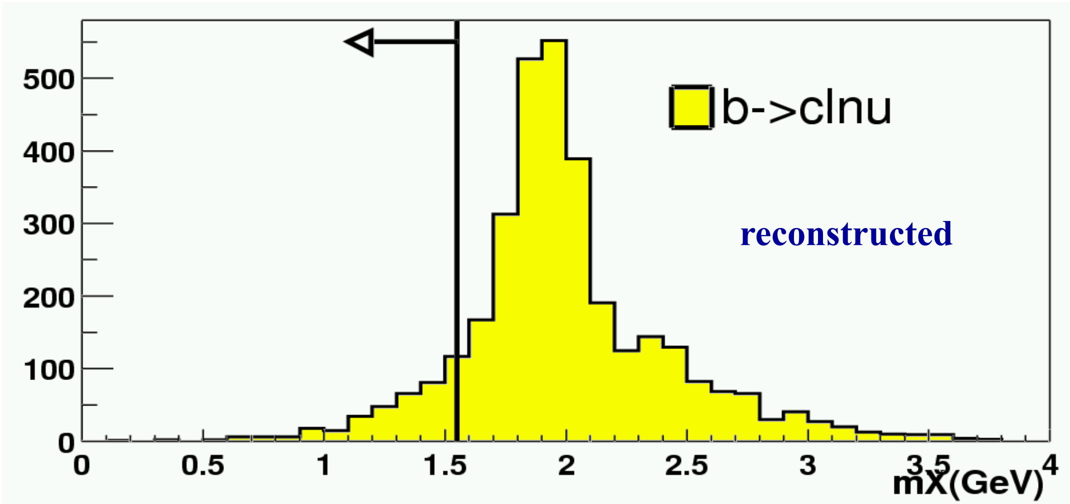
$E_{e,max}(B \to X_c\, l\, \nu)$
$= 2.3\ GeV$



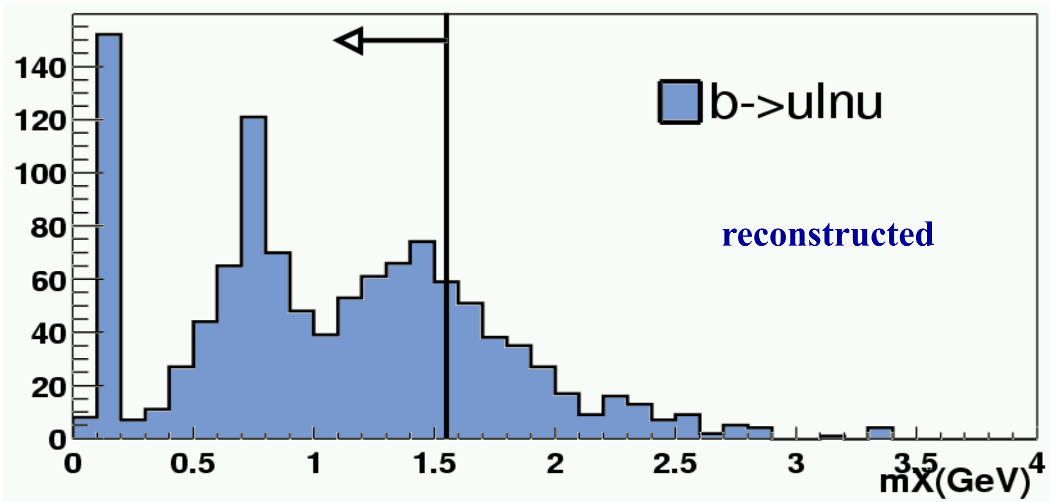
$M_{X,min}(B \to X_c\, l\, \nu)$
$= M_D = 1.87\ GeV$

M_x to separate $b \rightarrow cl\nu$ from $b \rightarrow ul\nu$

$B \rightarrow D^* l\nu$
$B \rightarrow D^* l\nu$
$B \rightarrow D^{**} l\nu$



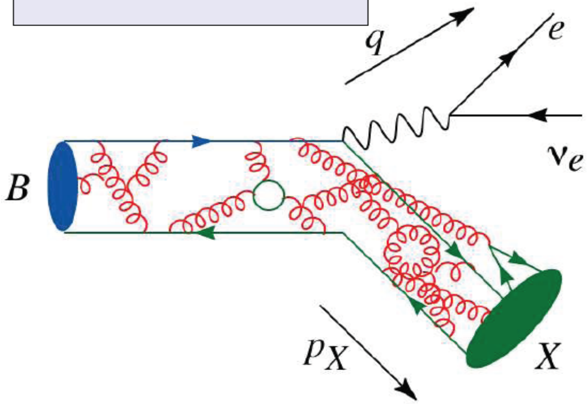
$B \rightarrow \pi l\nu$
$B \rightarrow \rho l\nu$
$B \rightarrow \eta l\nu$

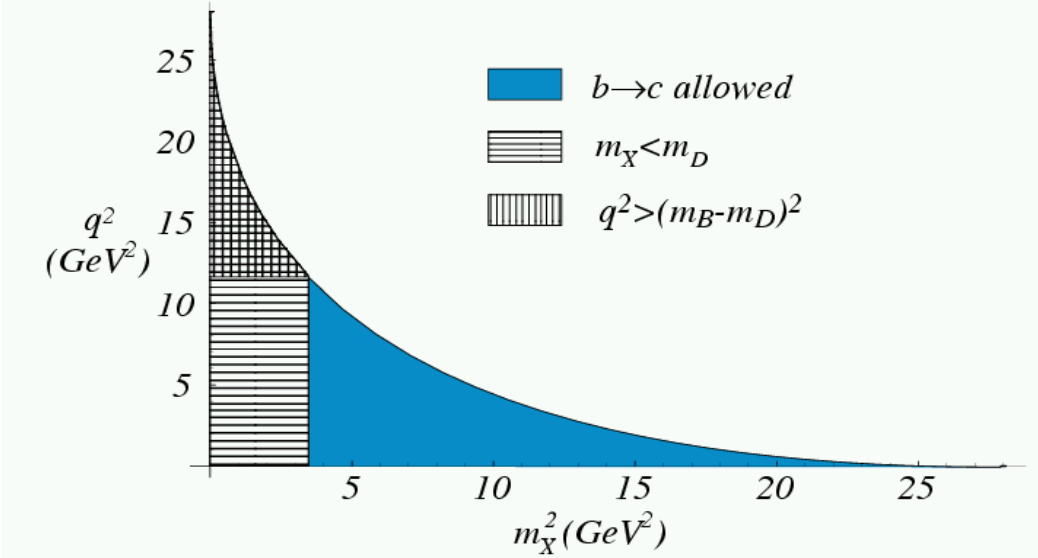


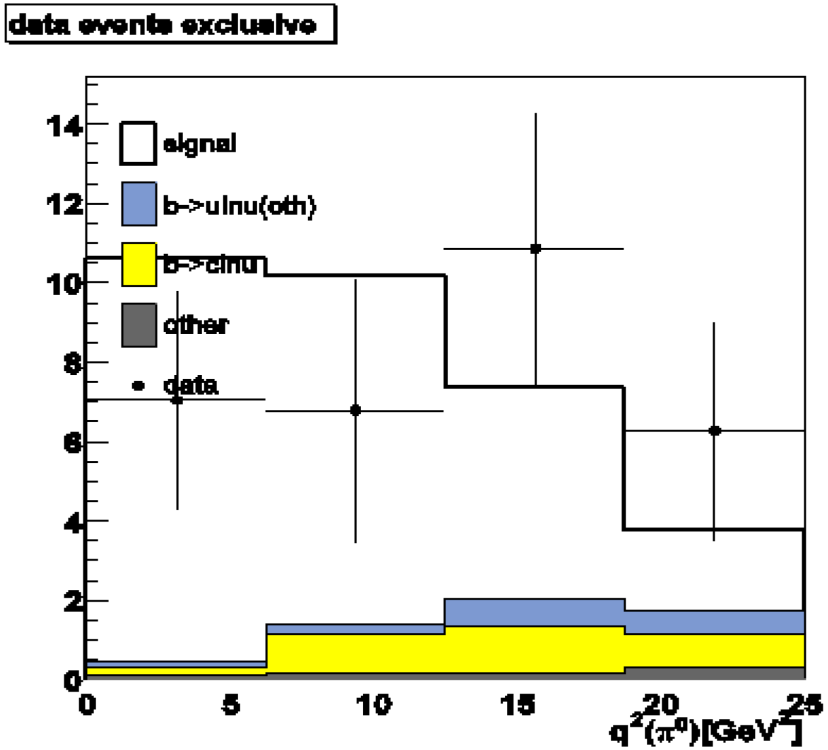
About 60-80% of signal for $M_X < M_D$

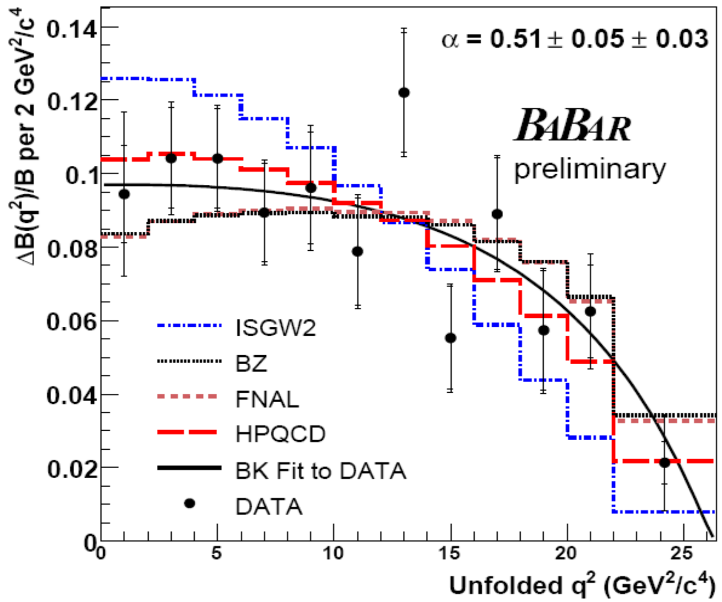
q^2 Spectrum

$q^2_{max}(B \to X_c l \nu)$
$=12\ GeV^2$



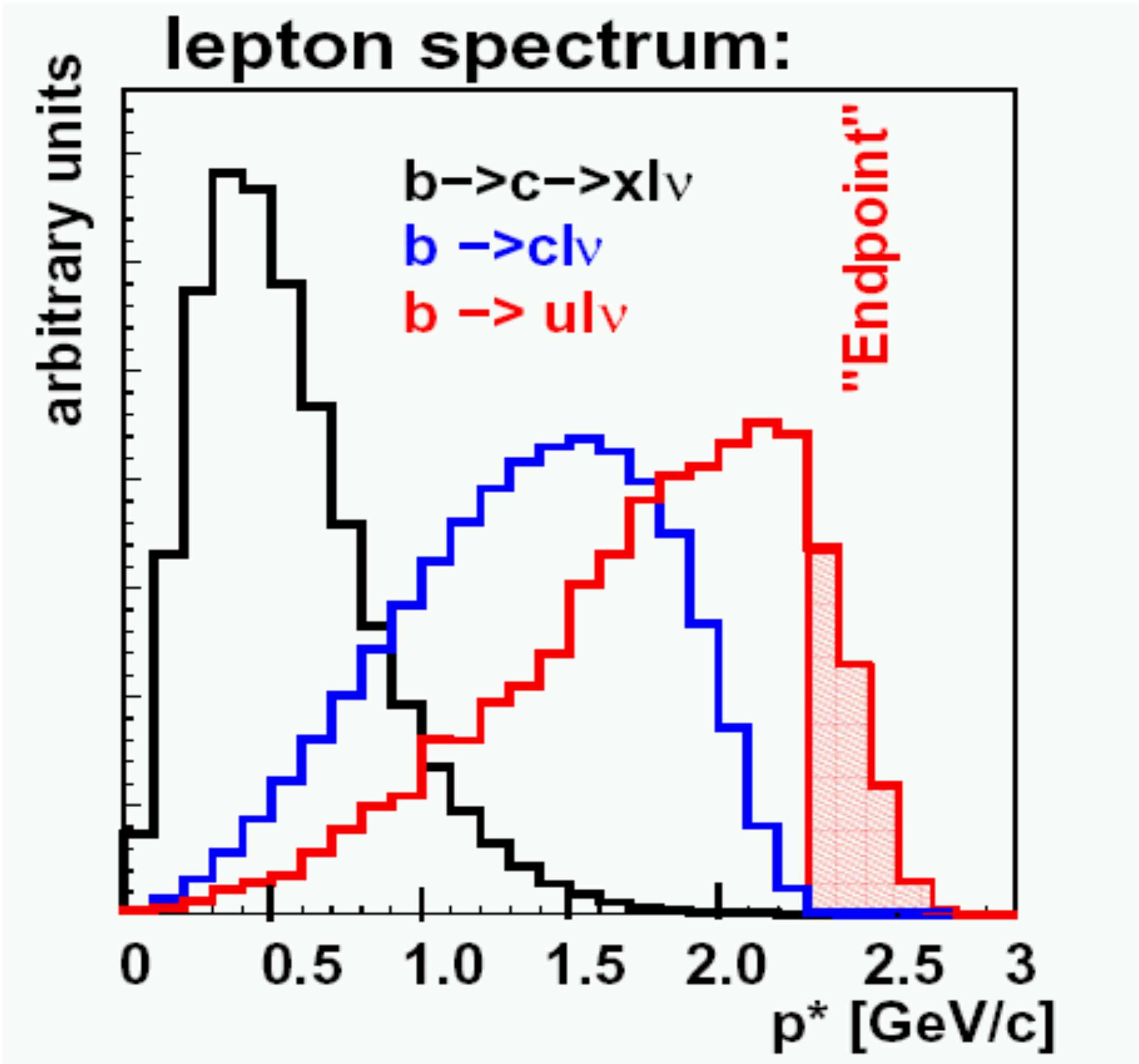






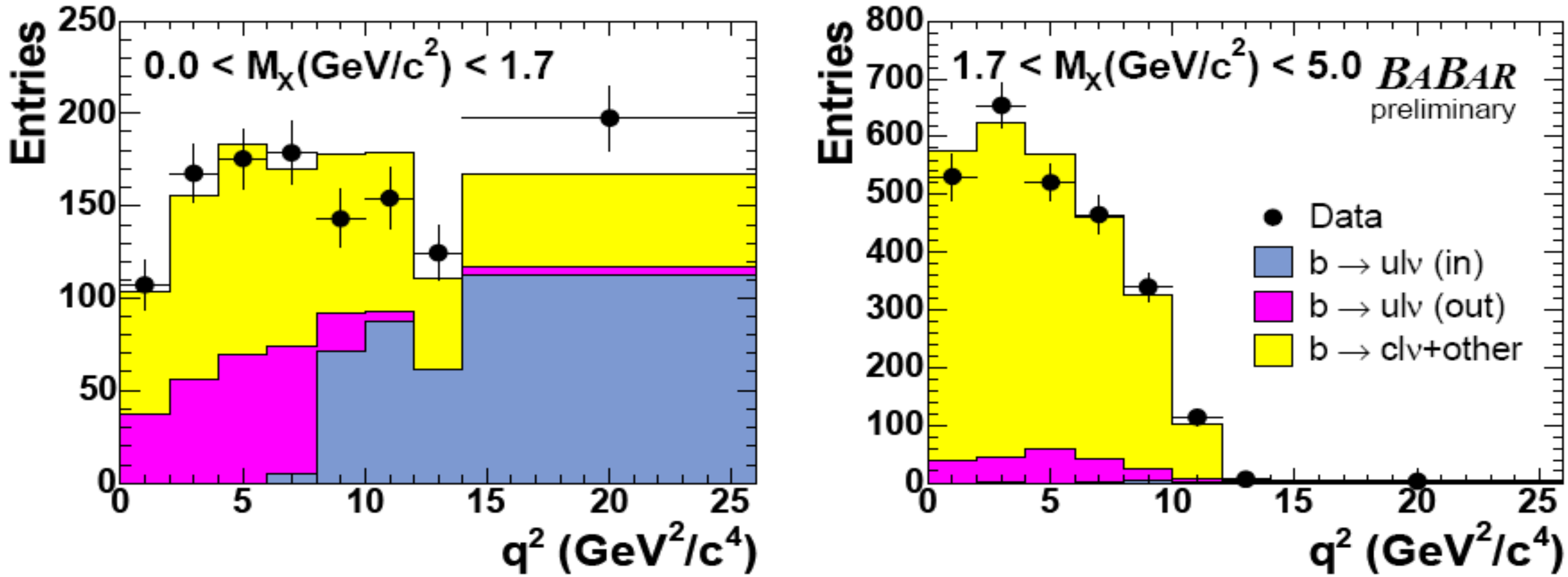
Lepton spectrum in Semileptonic Decays

- Cascade (secondary) leptons have lower momentum
- Requirement on momentum of leptons provides good separation between signal and cascade leptons
- Higher end of the spectrum mostly from decays mediated by Vub
  - Lighter hadrons allows more momentum for leptons



hep-ex/0507017

$|V_{ub}|$ inclusive from m_X vs q^2



$$|V_{ub}|^{\rm BLL} = (4.82 \pm 0.26_{\rm stat} \pm 0.25_{\rm syst} \pm 0.46_{\rm th+SF}) \times 10^{-3}$$

$$|V_{ub}|^{\rm BLNP}_{\rm Belle\ B\to X_s\gamma} = (5.00 \pm 0.27_{\rm stat} \pm 0.26_{\rm syst} \pm 0.46_{\rm SF} \pm 0.28_{\rm th}) \times 10^{-3}$$

$$|V_{ub}|^{\rm BLNP}_{BABAR\ b\to c\ell\bar\nu} = (4.65 \pm 0.24_{\rm stat} \pm 0.24_{\rm syst}{}^{+0.46}_{-0.38\rm SF} \pm 0.23_{\rm th}) \times 10^{-3}$$

- Results vary slightly depending on particular calculation or experimental input to shape functions

- Uncertainty dominated by theory!

CKM Matrix and CP Violation in Standard Model

CP Violation in Standard Model

Lecture 15

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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Fisica delle Particelle Elementari, Anno Accademico 2014-15

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Asymmetric Universe of Matter

- Universe is very empty but in a biased way

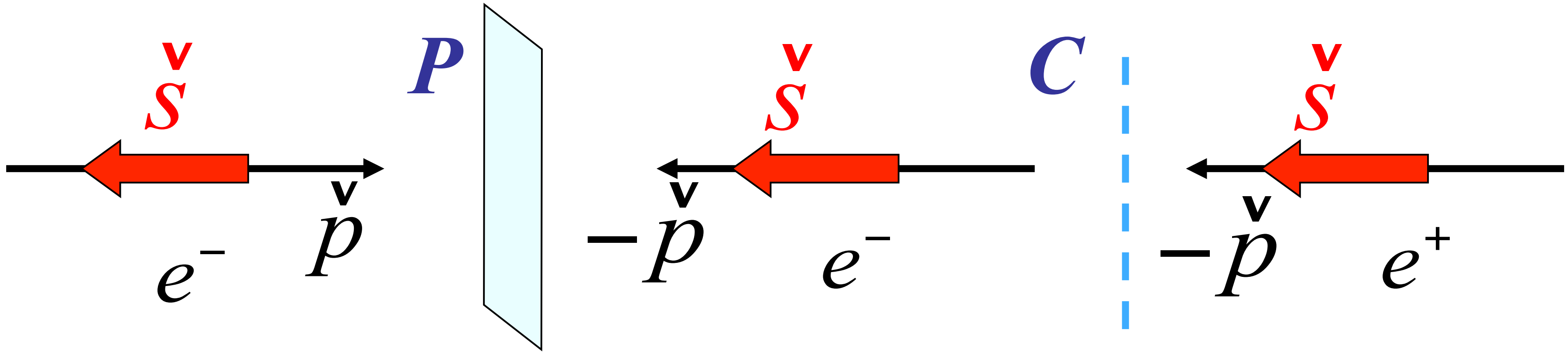
$$\frac{n_{baryon}}{n_{photons}} \approx 10^{-18} \qquad \frac{\mathrm{N(anti\text{-}baryon)}}{\mathrm{N(baryon)}} \leq 10^{-4}\text{-}10^{-6}$$

  - Absence of anti-nuclei amongst cosmic rays in our galaxy
  - Absence of intense γ–ray emission due to annihilation of distant galaxies in collision with antimatter galaxies

- The early universe believed to have equal amount of matter and anti-matter
  - What happened to the anti-matter?

- CP Violation is one of the three ingredients required to generate such an asymmetry after the Big Bang (A. Sakharov, 1967)
  - Baryon-number violating processes
  - Non-equilibrium state during expansion
  - C and CP Violation

C and P Symmetries and Fundamental Interactions



- Parity, *P*
  - Parity reflects a system through the origin. Converts right-handed coordinate systems to left-handed ones.
  - Vectors change sign but axial vectors remain unchanged
    - $\mathbf{x} \to -\mathbf{x}$, $\mathbf{L} \to \mathbf{L}$
- Charge Conjugation, *C*
  - Charge conjugation turns a particle into its anti-particle
    - $e^+ \to e^-$, $K^- \to K^+$, $\gamma \to \gamma$

CP Symmetry, particles and anti-particles

- CP symmetry transforms a particle in its anti-particle

- CP is violated IF particles and anti-particles behave differently!

Weak Interactions and Symmetry Violation

- P and C are good symmetries of the strong and electromagnetic interactions

- Parity violation observed in 1957
  - Asymmetry in β decays of $^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^{-} + \nu$
  - Electrons produced mostly in one hemisphere

- Charge-conjugation violation 1958
  - Only left-handed neutrinos and right-handed anti-neutrinos

- CP believed to be a good symmetry, but …

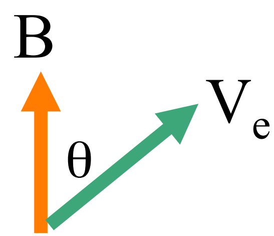
A Shocker : Weak Interaction Violates Parity !

1956

Observation of a spatial asymmetry in the β-decay electrons from $^{60}Co \rightarrow {}^{60}Ni + e^- + \nu$

- Cold ^{60}Co inside a Solenoidal B Field
- ^{60}Co nuclei spin aligned with B field direction
- ^{60}Co undergoes β decay ....electron emitted
- Measure electron intensity w.r.t B field dir.
- Result:Electrons preferentially emitted in opposite spin direction

$$I(\theta) = 1 - \frac{v_e}{c}\cos\theta$$



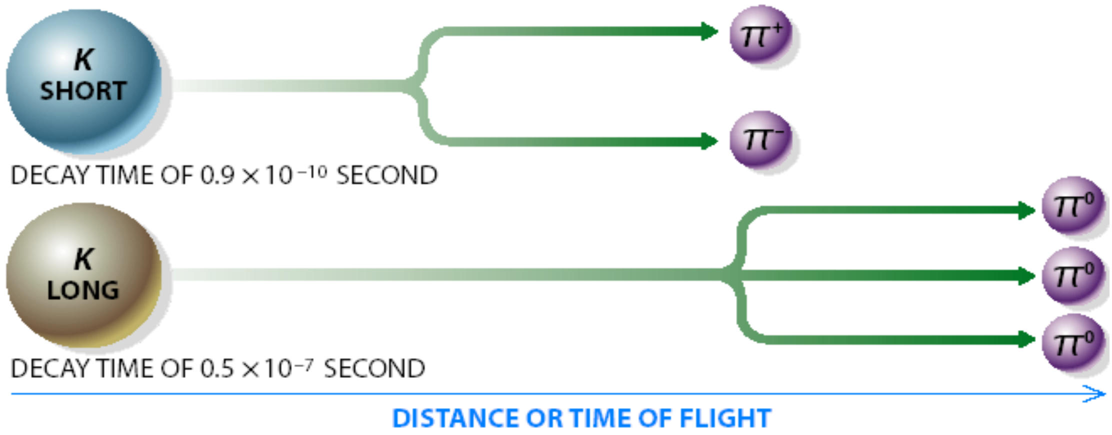
asymmetry of intensity → Weak interaction violated Parity

CP Violation in Kaons

- CP conservation implies

CP = +1

CP = −1



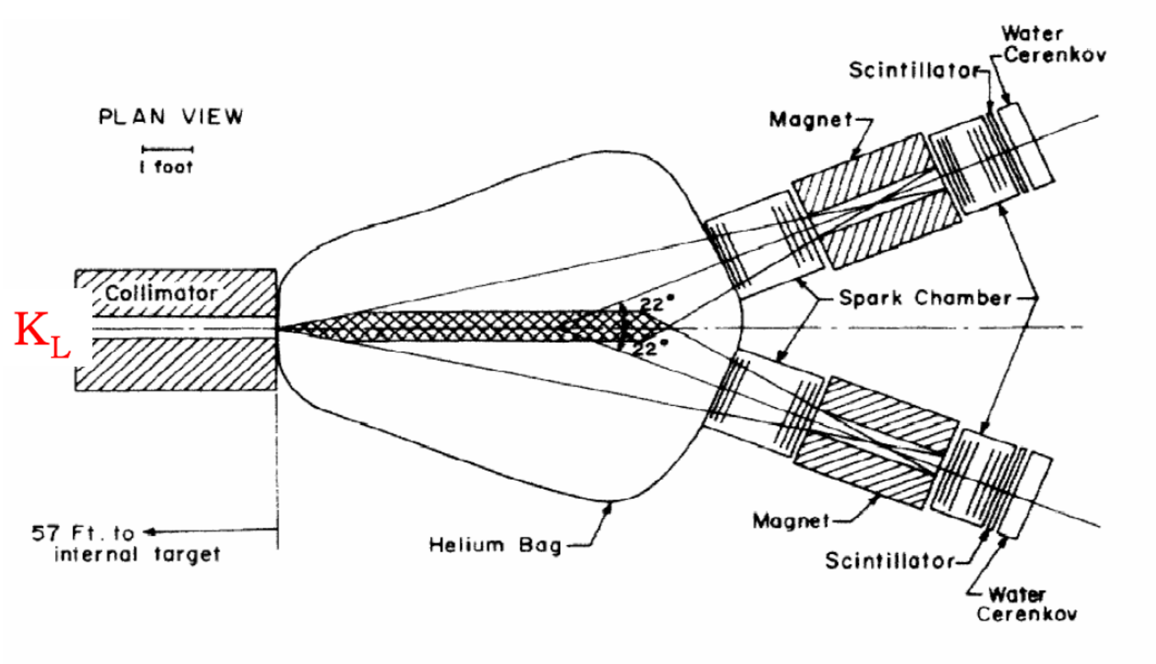
- CP violation in kaons observed in 1964

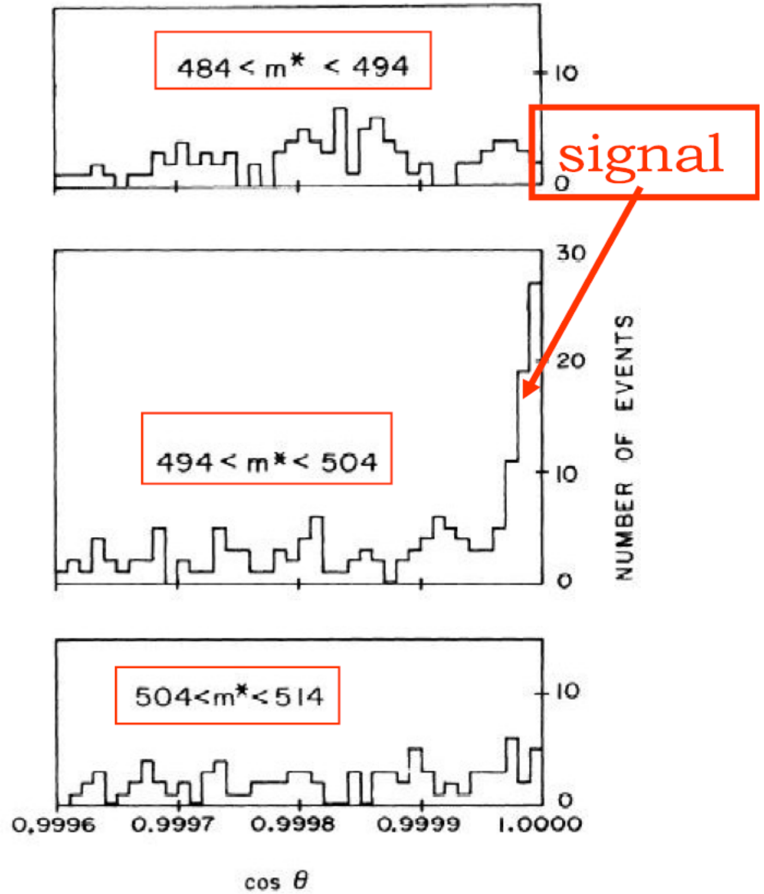
0.2% of the time!

- No theoretical explanation!

Observation of CP Violation in Kaons

$$\frac{A\left(\left|K_L^0\right\rangle \to 2\pi\right)}{A\left(\left|K_s^0\right\rangle \to 2\pi\right)} = (2.27 \pm 0.02)10^{-3}$$





2-body decay : the two π

are back-to-back: |cosθ|=1

Complex Coupling Constants and CP Violation

Fermion bilinear	Boson field F	$\mathbf{P}\,F\,\mathbf{P}^\dagger$	$\mathbf{C}\,F\,\mathbf{C}^\dagger$	$\mathbf{CP}\,F\,\mathbf{CP}^\dagger$
$\overline{\psi}\psi$	Scalar $S^+(t,\vec{x})$	$S^+(t,-\vec{x})$	$S^-(t,\vec{x})$	$S^-(t,-\vec{x})$
$\overline{\psi}\gamma^5\psi$	Pseudoscalar $P^+(t,\vec{x})$	$-P^+(t,-\vec{x})$	$P^-(t,\vec{x})$	$-P^-(t,-\vec{x})$
$\overline{\psi}\gamma_\mu\psi$	Vector $V_\mu^+(t,\vec{x})$	$V_\mu^+(t,-\vec{x})$	$-V_\mu^-(t,\vec{x})$	$-V_\mu^-(t,-\vec{x})$
$\overline{\psi}\gamma_\mu\gamma^5\psi$	Axial $A_\mu^+(t,\vec{x})$	$-A_\mu^+(t,-\vec{x})$	$A_\mu^-(t,\vec{x})$	$-A_\mu^-(t,-\vec{x})$

Table 2.1: Properties of charged boson fields and corresponding fermion bilinear terms under **P**, **C**, and **CP**. γ^5 and γ^μ are the Dirac matrices.

Generic interaction lagrangian with vector and axial fields

$$\begin{aligned}\mathcal{L} \;=\;& a\,V_\mu^+(t,\vec{x})V^{\mu-}(t,\vec{x}) + b\,A_\mu^+(t,\vec{x})A^{\mu-}(t,\vec{x}) + \\ & c\,V_\mu^+(t,\vec{x})A^{\mu-}(t,\vec{x}) + c^*\,A_\mu^+(t,\vec{x})V^{\mu-}(t,\vec{x})\end{aligned}$$

a, b: real constants
c: complex constant

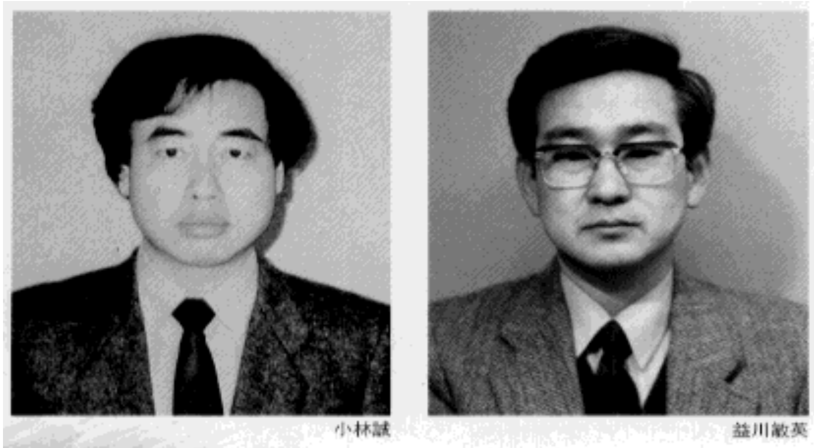
Lagrangian after CP transformation

$$\begin{aligned}\mathbf{CP}\mathcal{L}\mathbf{CP}^\dagger \;=\;& a\,V_\mu^-(t,-\vec{x})V^{\mu+}(t,-\vec{x}) + b\,A_\mu^-(t,-\vec{x})A^{\mu+}(t,-\vec{x}) + \\ & c\,V_\mu^-(t,-\vec{x})A^{\mu+}(t,-\vec{x}) + c^*\,A_\mu^-(t,-\vec{x})V^{\mu+}(t,-\vec{x})\;.\end{aligned}$$

Lagrangian invariant under CP IF AND ONLY IF c=c*! c must be real

Reminder Kobayashi-Maskawa Mechanism of CP Violation

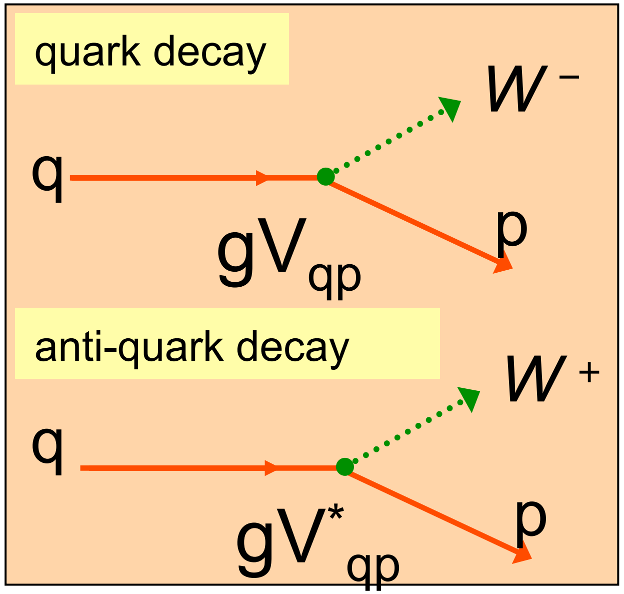
1972



Two Young Postdocs at that time !

- Proposed a daring explanation for CP violation in K decay:
- CP violation appears only in the charged current weak interaction of quarks
- There is a single source of CP Violation $\Rightarrow$ Complex Quantum Mechanical Phase δ_{KM} in inter-quark coupling matrix
- Need at least **3 Generation of Quarks** (then not known) to facilitate this
- **CP is NOT an approximate symmetry**, $\delta_{KM} \cong 1$, it is MAXIMALLY violated !

CKM Matrix Revisited



$$\mathbf{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathrm{V}_{\mathrm{CKM}} \equiv \begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}$$

$$\mathbf{V}_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Quark families	# Angles	# Phases	# Irreducible Phases
n	n(n-1)/2	n(n+1)/2	n(n-1)/2-(2n-1)=(n-1)(n-2)/2
2	1	3	0
3	3	6	1
4	6	10	3

Only Source of CP Violation in SM

CP Violation built in the Standard Model through Kobayashi-Maskawa Mechanism!

Only one complex phase! All CP violating effects in SM related to each other
B and K decays CP Violating phenomena are cause by the same complex phase

Unitarity of CKM Matrix

$$V^\dagger V = V V^\dagger = 1$$

- All rows and columns must be orthonormal
  - 3 conditions for diagonal elements
  - 6 conditions for off-diagonal elements

$$
\begin{aligned}
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 &= 1 \\
|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 &= 1 \\
|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 &= 1
\end{aligned}
$$

	Magnitude of each term
$V^*_{ud} V_{us} + V^*_{cd} V_{cs} + V^*_{td} V_{ts} = 0$	$\lambda \; \lambda \; \lambda^5$
$\boxed{V^*_{ub} V_{ud} + V^*_{cb} V_{cd} + V^*_{tb} V_{td} = 0}$	$\lambda^3 \; \lambda^3 \; \lambda^3$
$V^*_{us} V_{ub} + V^*_{cs} V_{cb} + V^*_{ts} V_{tb} = 0$	$\lambda^4 \; \lambda^2 \; \lambda^2$
$V^*_{ud} V_{td} + V^*_{us} V_{ts} + V^*_{ub} V_{tb} = 0$	$\lambda^3 \; \lambda^3 \; \lambda^3$
$V^*_{td} V_{cd} + V^*_{ts} V_{cs} + V^*_{tb} V_{cb} = 0$	$\lambda^4 \; \lambda^2 \; \lambda^2$
$V^*_{ud} V_{cd} + V^*_{us} V_{cs} + V^*_{ub} V_{cb} = 0$	$\lambda \; \lambda \; \lambda^5$

Only condition with comparable size of all pieces and involving b decays

Unitarity Triangles

Unitarity condition of CKM Matrix → orthonormality of rows & columns

$$\sum_{(i=u,c,t)} V_{ij} V_{ik}^{*} = \delta_{jk} \quad ; \quad \sum_{(i=d,s,b)} V_{ij} V_{kj}^{*} = \delta_{ik}$$

⇒ three conditions are interesting for understanding SM predictions for CP violation

$$V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0,$$

$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0,$$

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0.$$

Each relation requires sum of three complex quantities to vanish

→ can be represented in the complex plane as a triangle

→ known as Unitarity Triangles

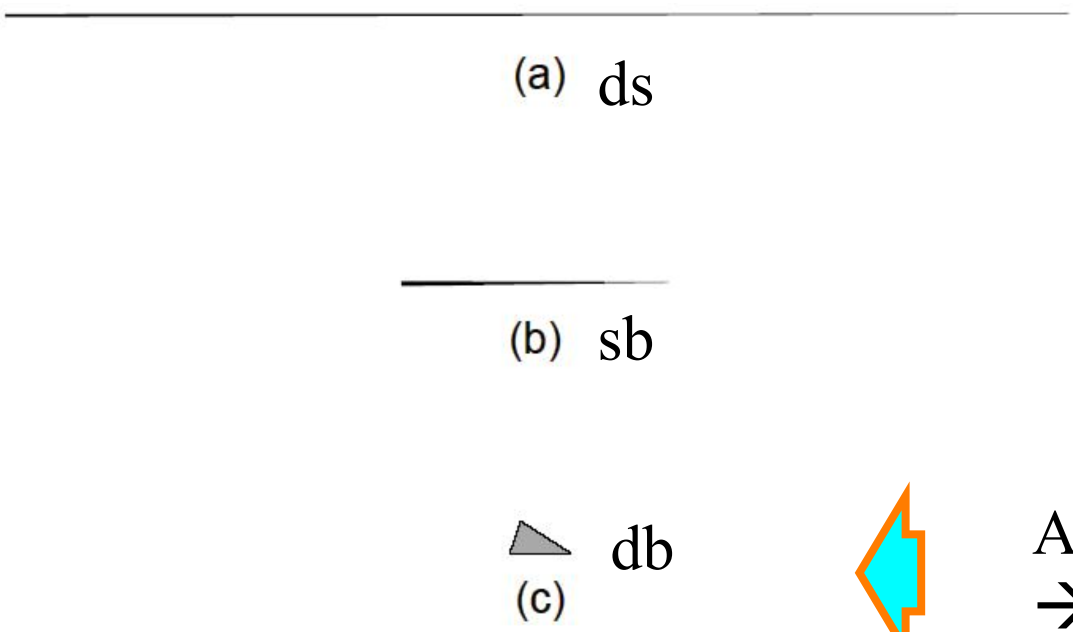
With the knowledge of $|V_{ij}|$ magnitudes, its instructive to draw the triangles

Three Unitarity Triangles Drawn to <u>Common</u> Scale

$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0,$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0,$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0.$$



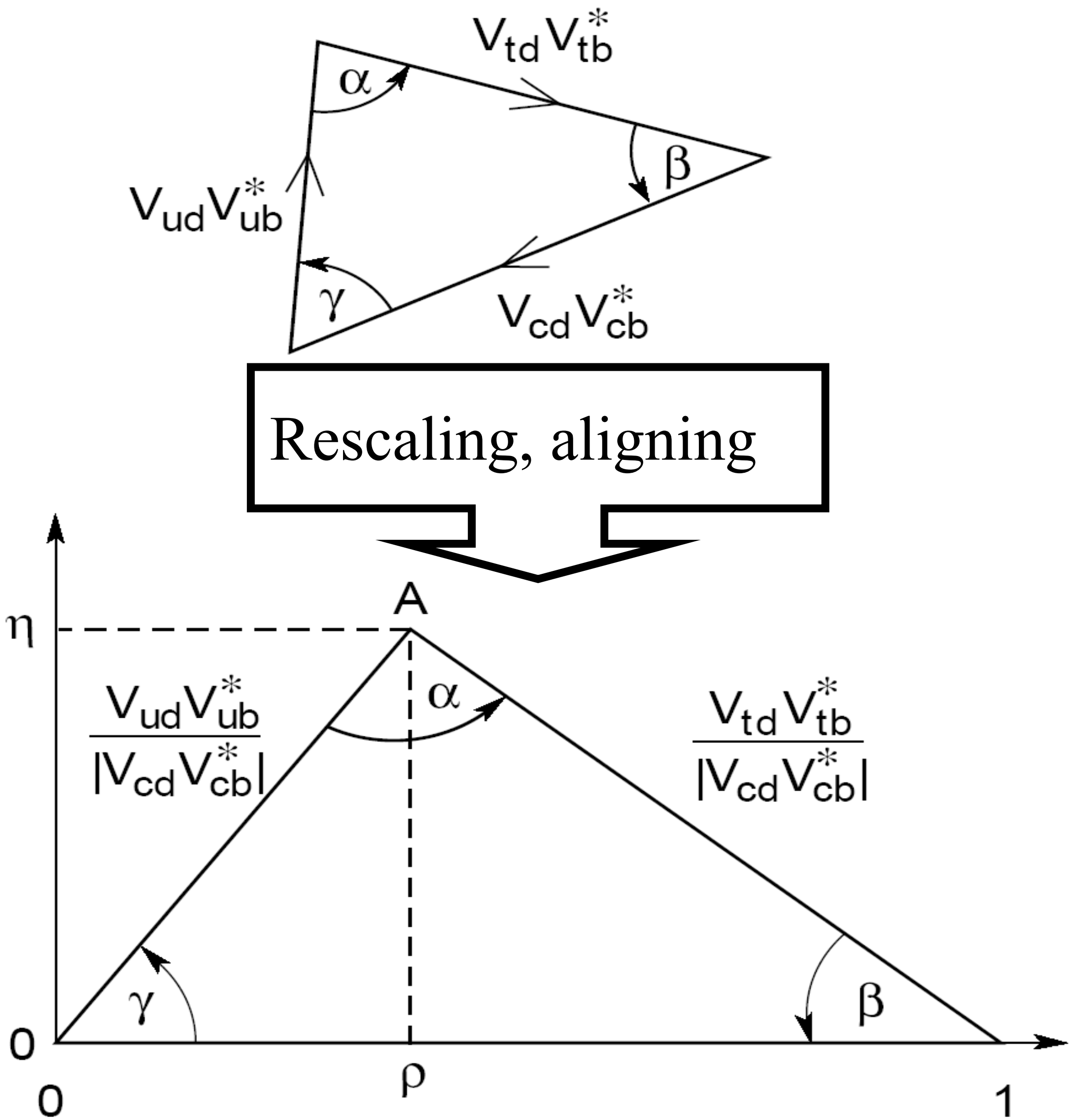
One side is much shorter than the other two→ triangle collapses on a line

All sides of comparable length (λ^3)
→ All angles are large

Experimentally ⇒ hard to measure small numbers easier to measure larger numbers as in (c)

CKM Unitarity Triangle in B Decays

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Angles of Unitarity Triangle

$$\alpha = \phi_2 \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right],$$

$$\beta = \phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right],$$

$$\gamma = \phi_3 \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

All lengths involve b decays
Large CP Asymmetries
predicted , ∝ UT angles