CKM matrix and CP violation in SM (II)

- Origin of the Cabibbo-Kobayashi-Maskawa Matrix (CKM)
- Overview of the measurements of the CKM elements
- CP violation in the Standard Model
- Overview of the measurements

b Quark is Special !

- Processes involving b quark can be used to measure several CKM element magnitudes

- Large mass of b quark allows use of Heavy Quark Effective Theory (HQET) for reliable theoretical calculations
  - Important for interpretation of experimental measurements with B mesons

- B mesons are of particular interest for study of CP violation
  - We will discuss this in detail

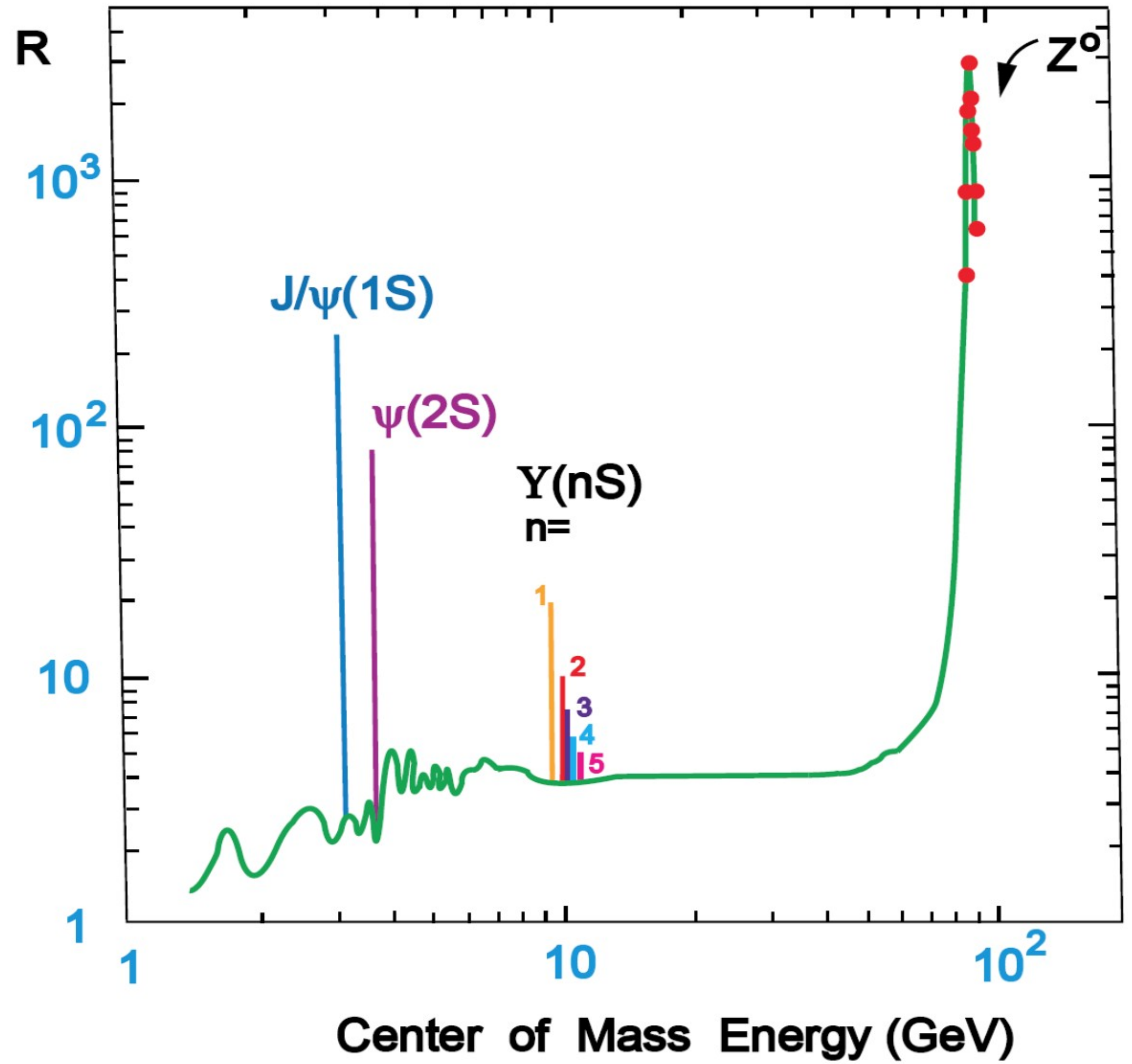
- Highlights of b quark
  - Heavy mass: big phase space an hence variety of final states to decay to
  - Long lifetime: important for experimental techniques to identify B mesons
  - B0-B0bar oscillation: a fine example of quantum entanglement, important ingredient for CP violation
  - $b \rightarrow u$ transitions: necessary ingredient for CP violation

Summary of B properties

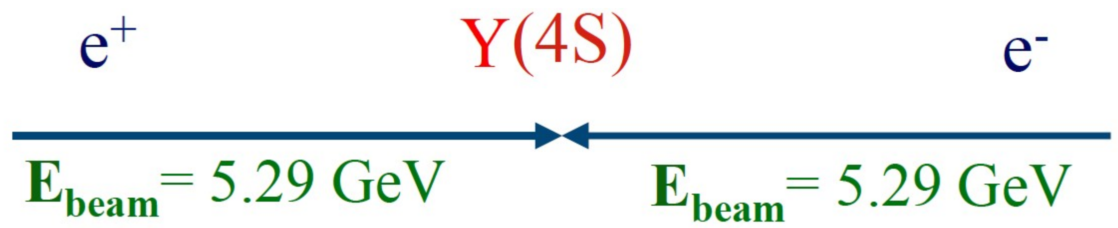
Particle, $I(J^P)$	Mass (in MeV/c^2)	Lifetime $\tau = 1/\Gamma$ (in10^{-12} s)
B^0_d =(bd) , $I(J^P)$=½ (0^-)	5279.4 ± 0.5	1.536 ±0.014 & ($c\tau$ =460μm)
B^- = (bu), $I(J^P)$=½ (0^-)	5279.0 ± 0.5	1.671 ±0.018 & ($c\tau$ =501μm)
B^0_s =(bs), $I(J^P)$=0(0^-)	5369.6 ± 2.4	1.461 ±0.057 & ($c\tau$ =438μm)
Λ_b = (bud), $I(J^P)$=0(1/2^+)	5624.0 ± 9.0	1.229 ±0.080 & ($c\tau$ =368μm)

B production in e+e- Collisions

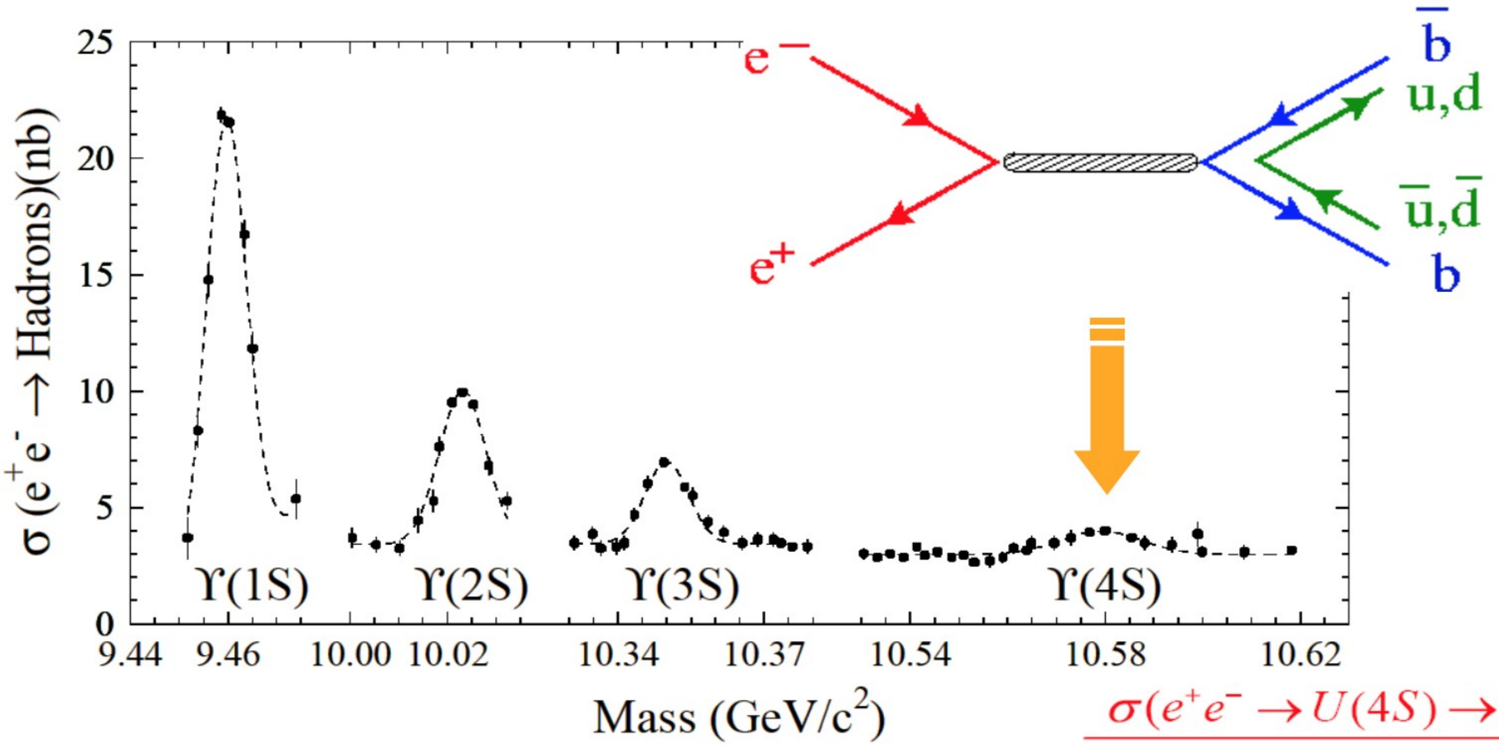
$$R = \frac{e^+e^- \rightarrow \text{all}}{e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-}$$



B production at Upsilon resonance: B Factory



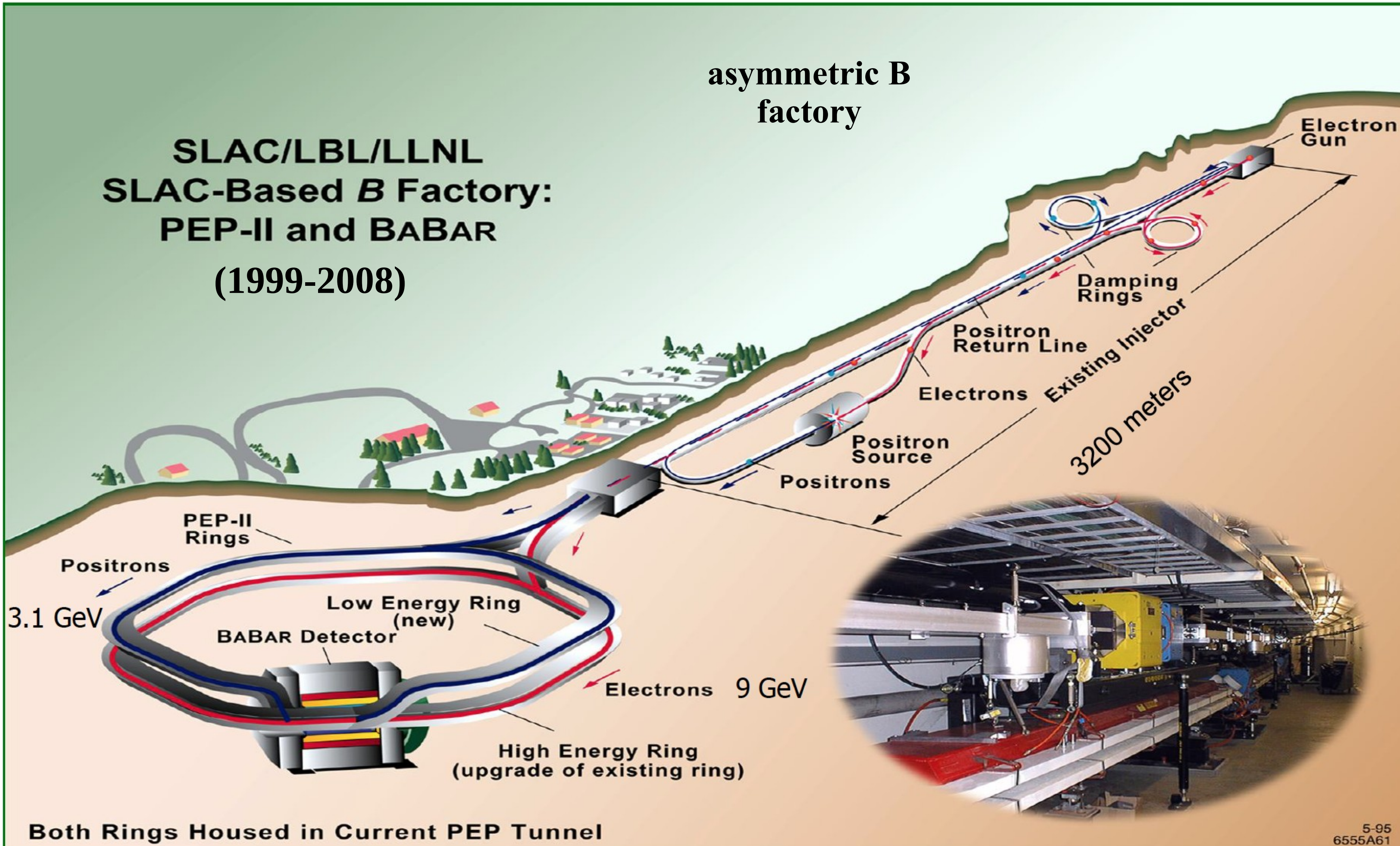
symmetric B factory



$$\frac{\sigma(e^+e^- \rightarrow U(4S) \rightarrow bb)}{\sigma(e^+e^- \rightarrow U(4S) \rightarrow TOT)} = \frac{1.2nb}{3.5nb} = 25\%$$

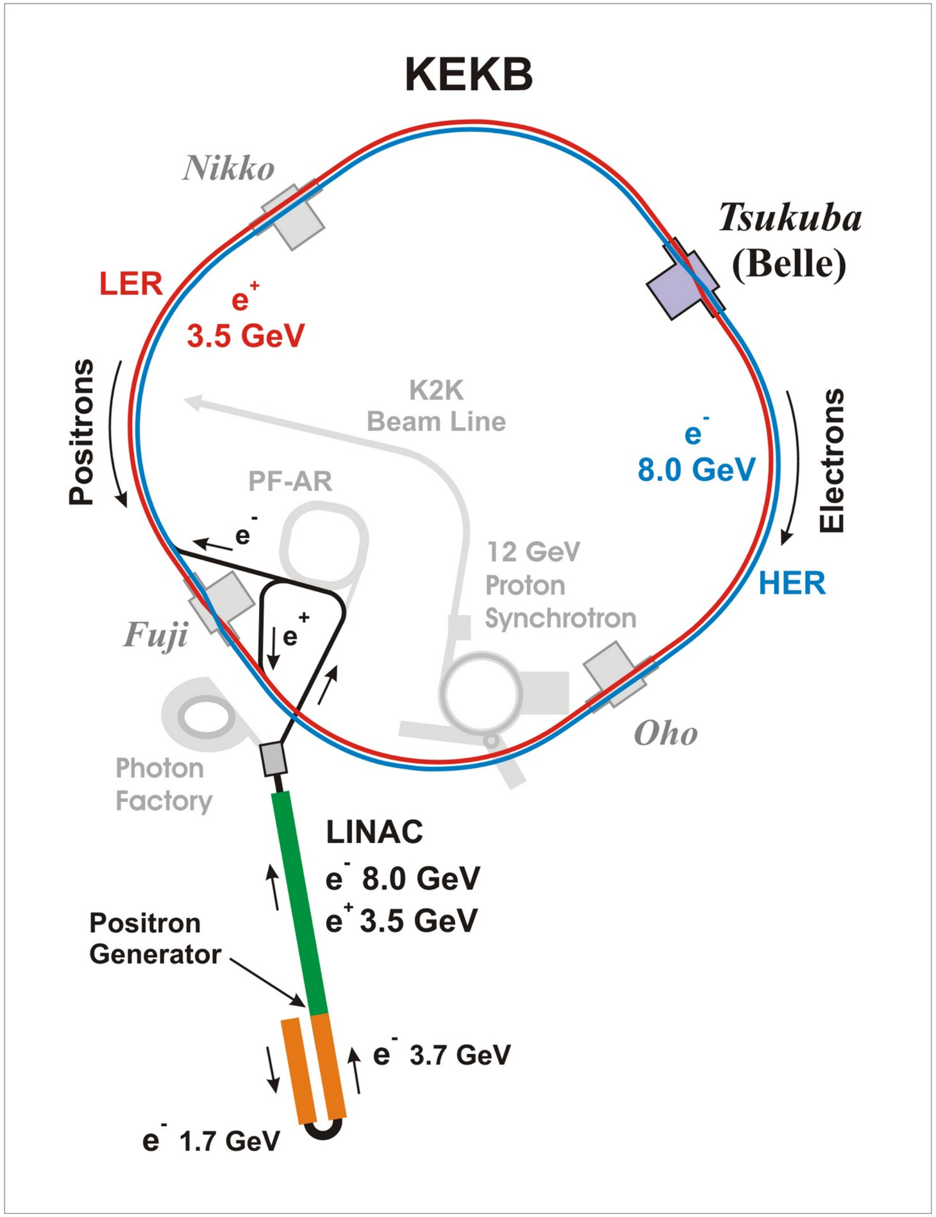
Enough energy to barely produce 2 B mesons, nothing else!
B Mesons produced with ~ 300 MeV momentum
Moving very slowly, don't travel much before decay

PEP-II Collider at SLAC (Stanford, CA)



PEP-II accelerator schematic and tunnel view

KEKB collider at KEK (Tsukuba, Japan)



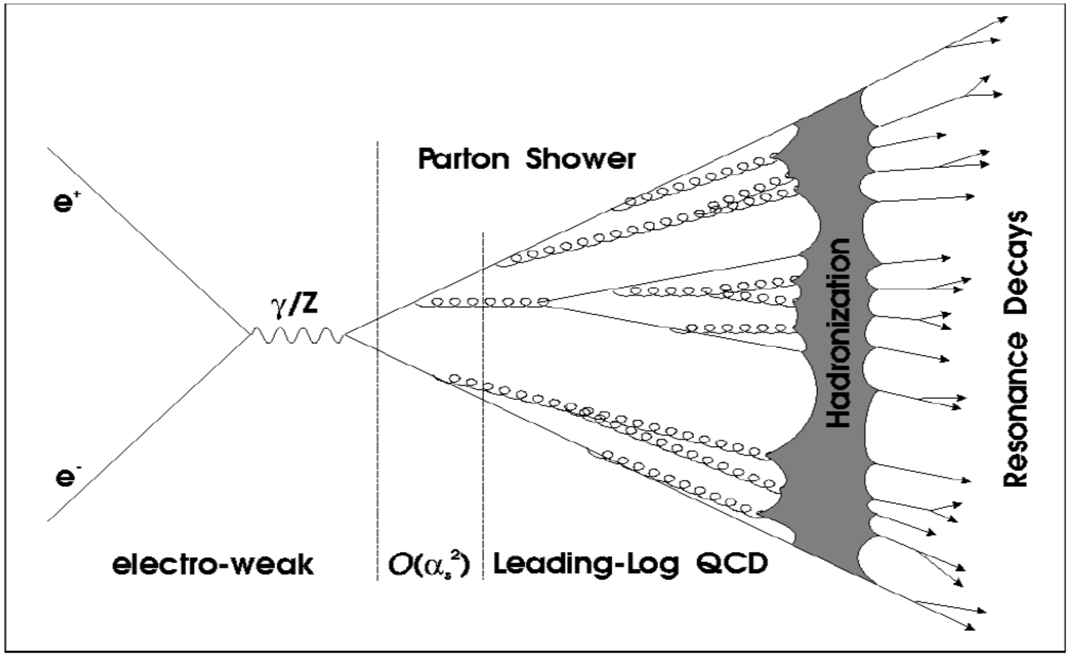
KEKB: 1999-2010

now upgraded to **SuperKEKB** (2019- ...)

asymmetric B factory

B production at Z^0 Resonance

All types of B hadrons produced in $Z \rightarrow b\bar{b}$ hadronization



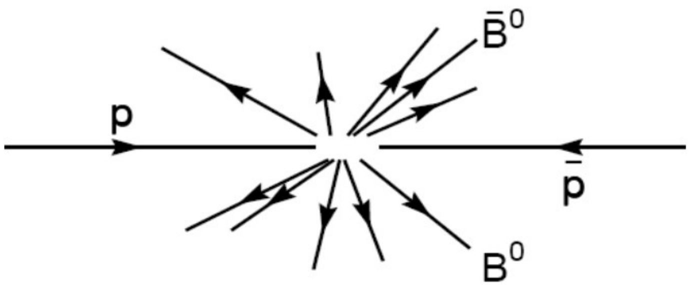
b hadron	Fraction [%]
B^+, B^0	39.7 ± 1.0
B_s^0	10.7 ± 1.1
b baryons	9.9 ± 1.7

$$\frac{\Gamma(b\bar{b})}{\Gamma(TOT)} \sim 17\%$$

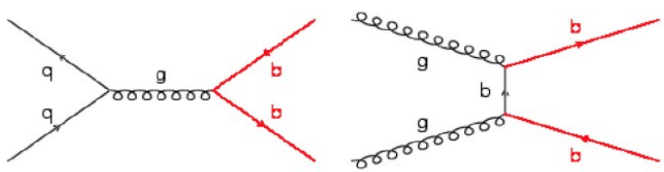
Average B momentum ~ 35 GeV
$\Rightarrow (\beta\gamma)_B \approx 7$ (highly relativistic)

LEP/SLD Program ended in '95, made important contributions to b physics

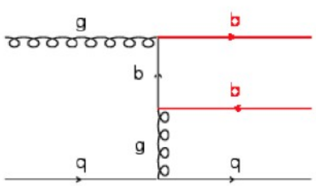
B production at Hadron Colliders



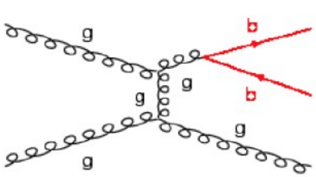
Lowest order

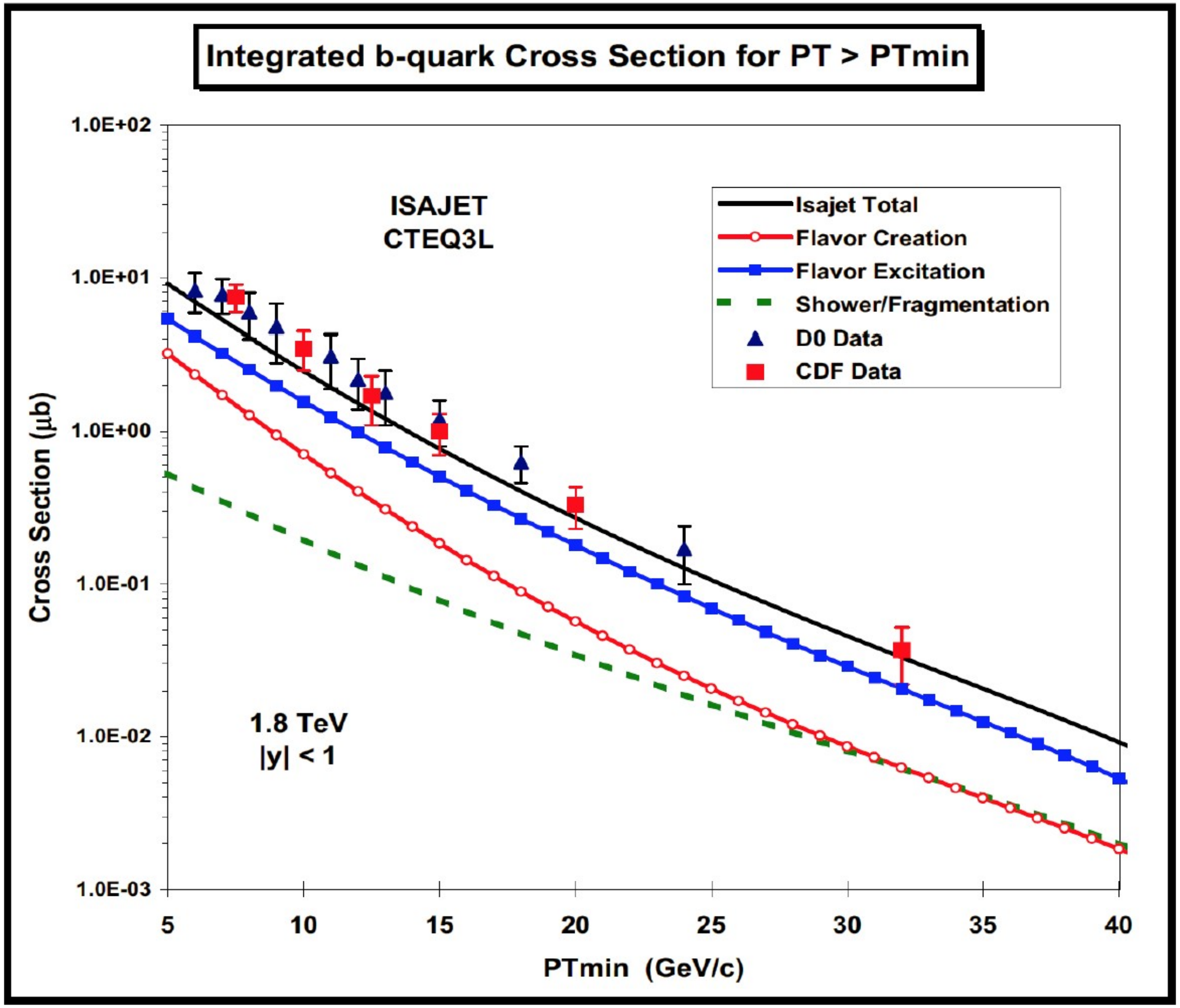


Flavor excitation



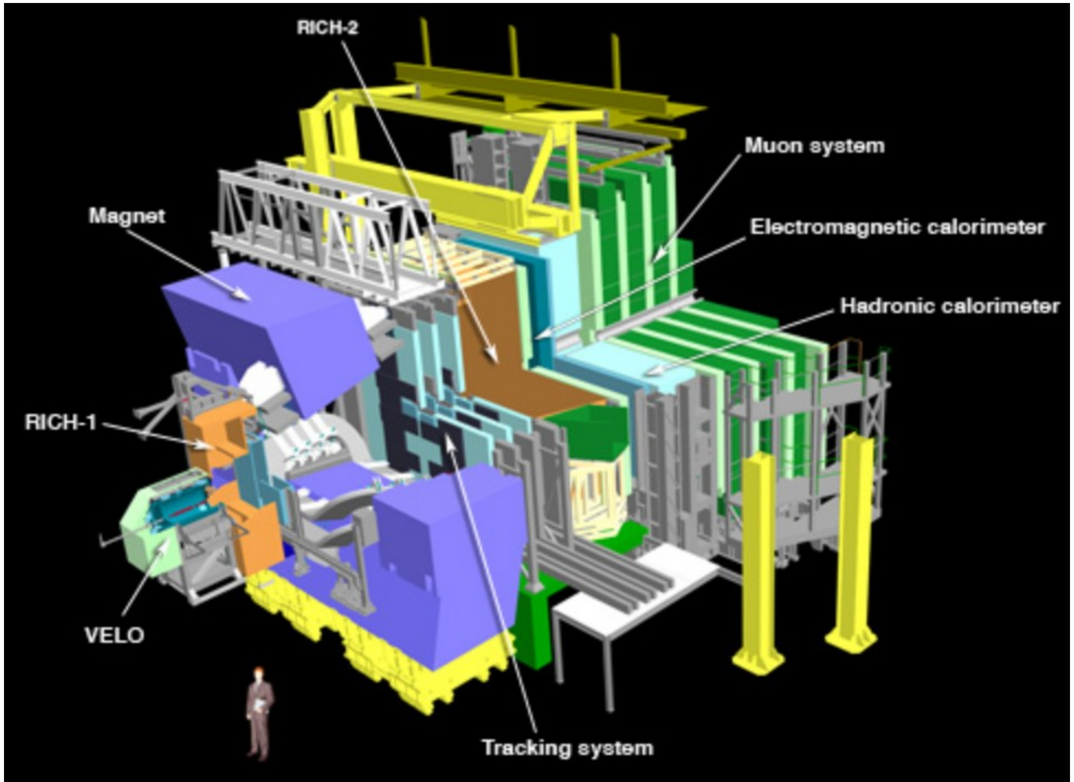
Gluon splitting

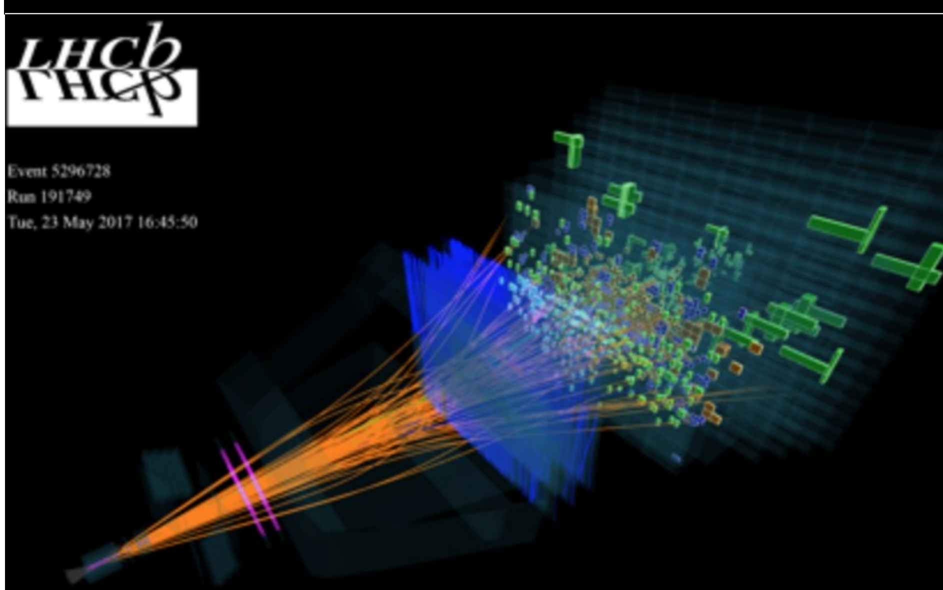


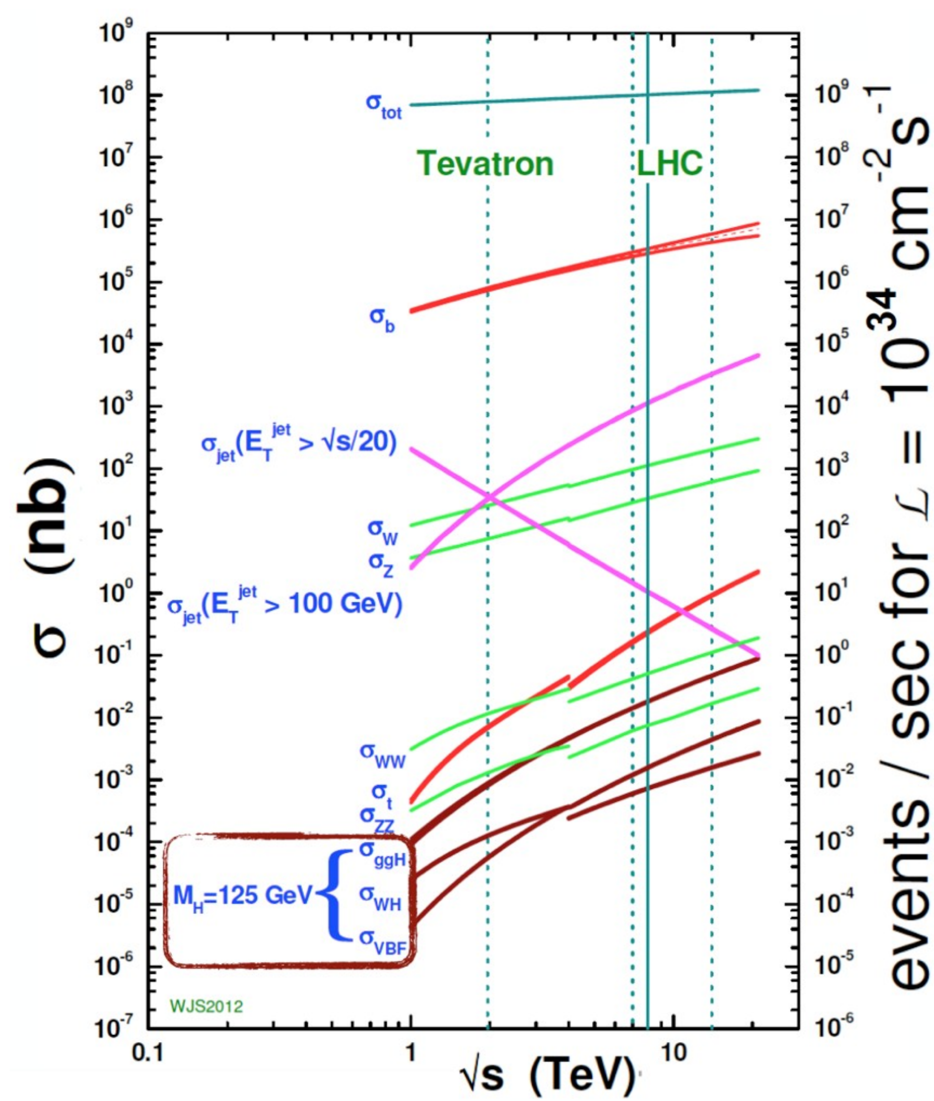


$\sigma(b\bar{b}) \sim > 10\mu b$ $\qquad$ $\frac{\sigma(b\bar{b})}{\sigma(TOT)} = \frac{1}{1000}$

B production at Hadron Colliders







Summary of Past Experiments

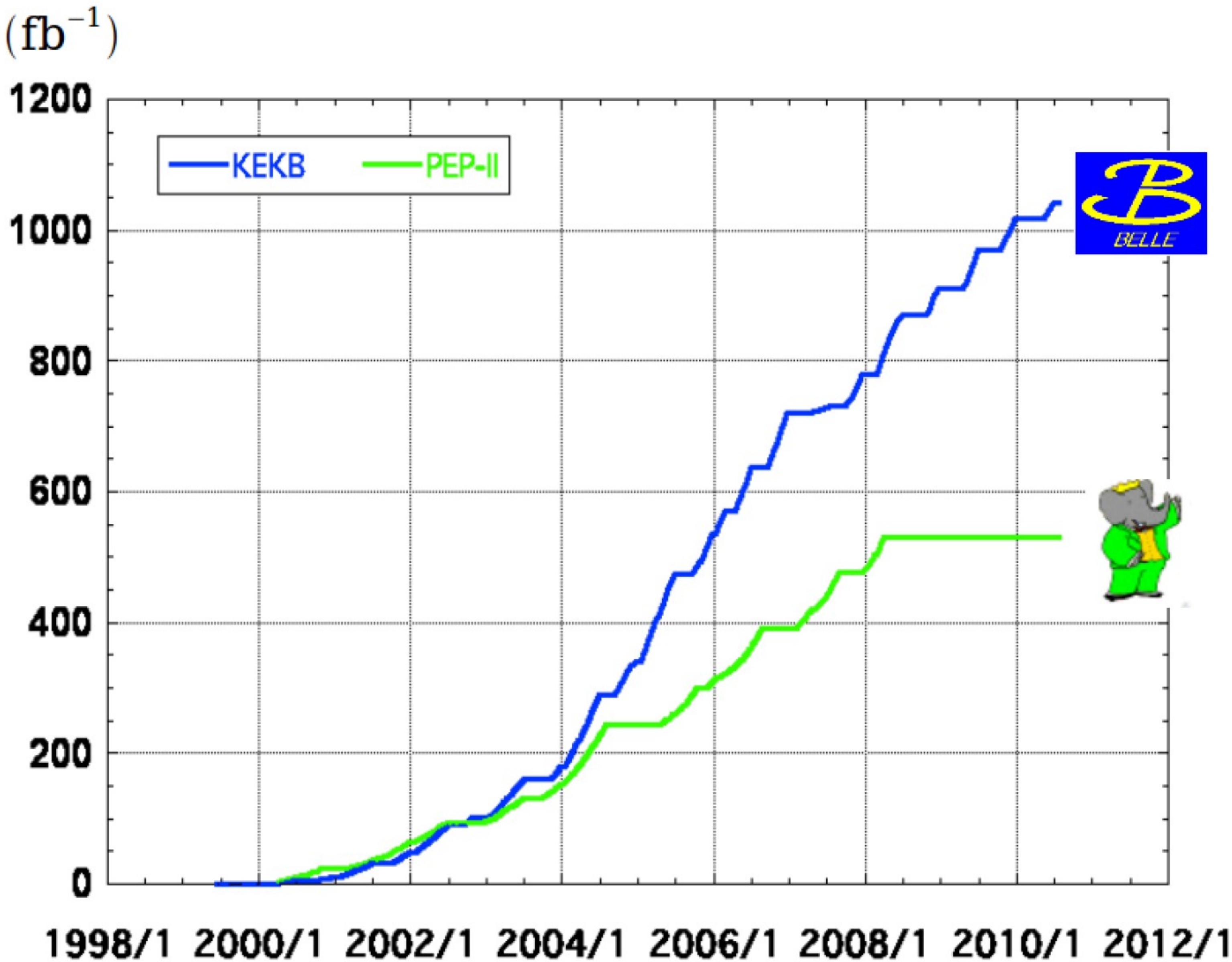
Experiments	*# of b events*	*Environment*	*Characteristics*
LEP Coll. ALEPH/DELPHI/ L3/OPAL	~ 1M (each exp.)	Z^0 decays ($\sigma \sim 6$ nb)	Back-to-back 45GeV b-jets All B hadrons produced **Stopped**
SLD	~0.1 M	Z^0 decays ($\sigma \sim 6$ nb)	Back-to-back 45GeV b-jets All B hadrons produced **Stopped**
ARGUS	~0.2 M	Υ(4s) decays symmetric ($\sigma \sim 1.2$ nb)	B mesons produced at rest B^0 and B^+ produced **Stopped**
CLEO	~9 M	Υ(4s) decays symmetric ($\sigma \sim 1.2$ nb)	B mesons produced at rest B^0 and B^+ produced **Stopped**
Belle Babar	~130 M (each exp.)	Υ(4s) decays asymmetric ($\sigma \sim 1.2$ nb)	B mesons produced at rest B^0 and B^+ produced **Stopped**
Tevatron Coll. CDF/D0	~several	$p\bar{p}$ collider $\sqrt{s} = 1.8$ TeV	triggered events All B hadrons produced **Stopped**

Summary of Present Experiments

Experiments	*# of b events*	*Environment*	*Characteristics*
BelleII	goal: 50 ab^{-1} ~$55 \cdot 10^9$ events	Y(4s) decays asymmetric (σ ~ 1.2 nb)	B mesons produced at rest B^0 and B^+ produced **Running**
LHC Coll. LHCb	~$5 \cdot 10^{10}$ events (*)	pp collider	triggered events All B hadrons produced **Running**
LHC Coll. CMS/ATLAS	~$5 \cdot 10^{10}$ events (*)	pp collider $\sqrt{s}$ = 7,8, 13 TeV	triggered events All B hadrons produced **Running**

(*) very rough estimation

Integrated luminosity of (past) B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

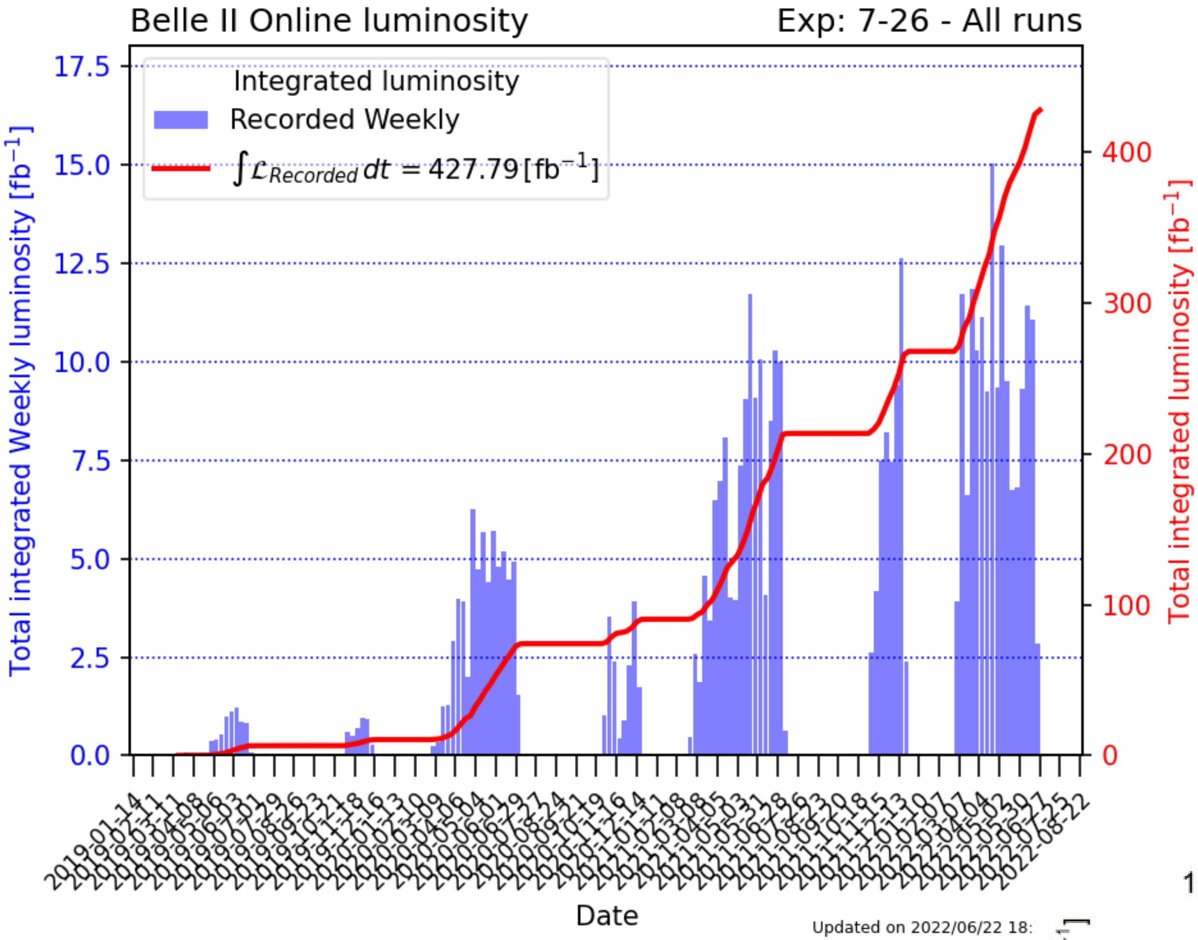
$\Upsilon(3S)$: 30 fb^{-1}

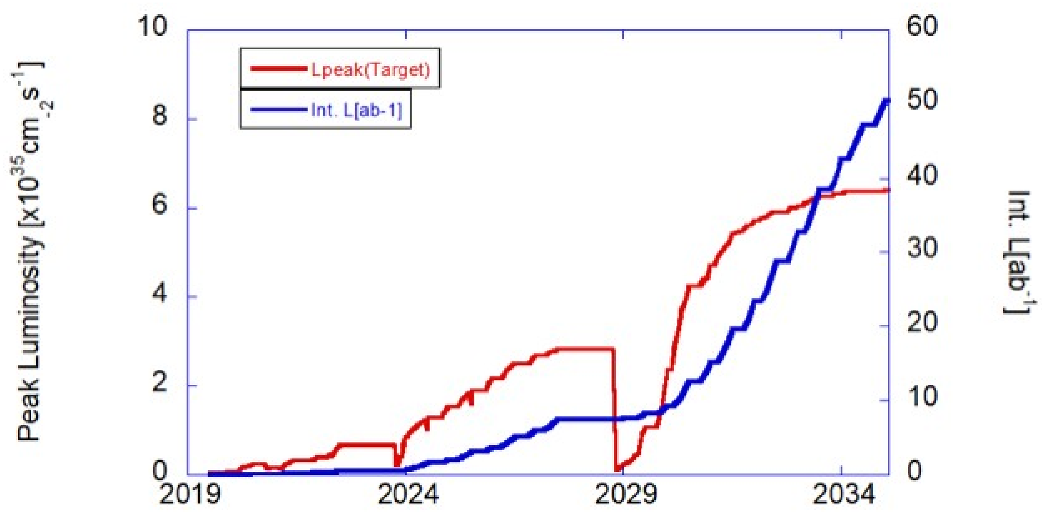
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Integrated luminosity of Belle II B factory



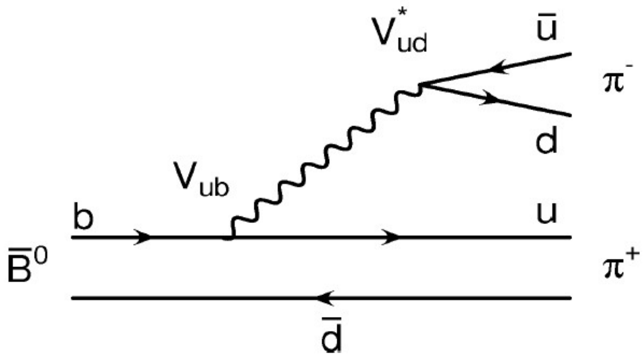


Catalog of B decays

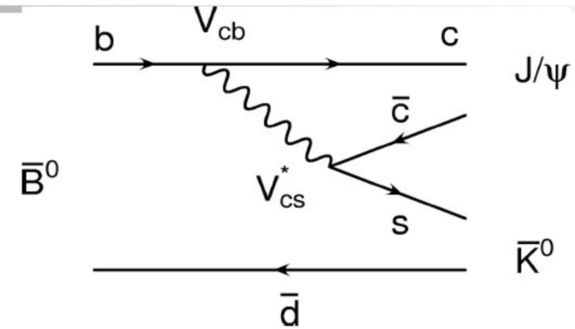
Introduction to Diagram Jargon !

Tree Diagrams

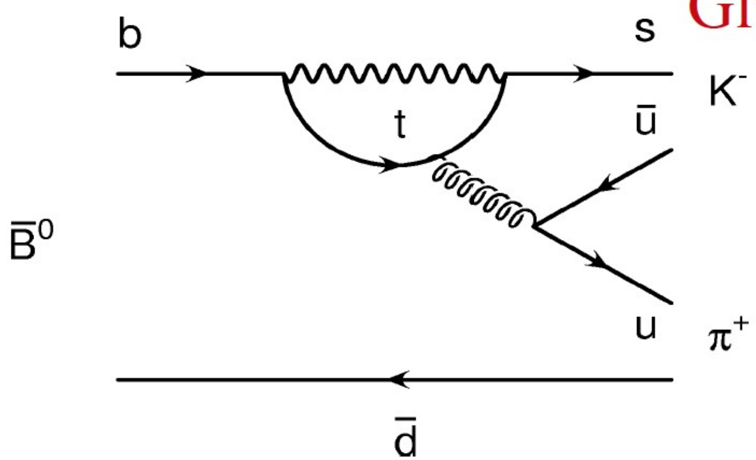
Spectator

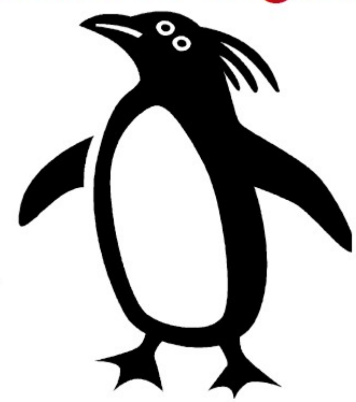


Color Suppressed

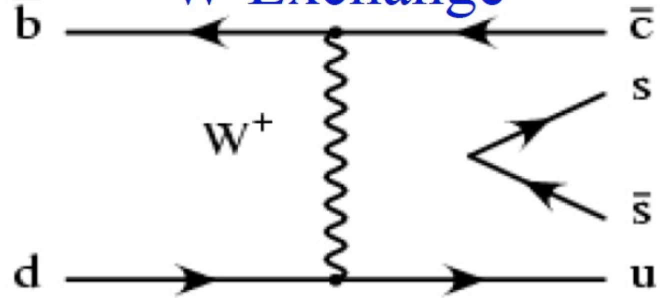


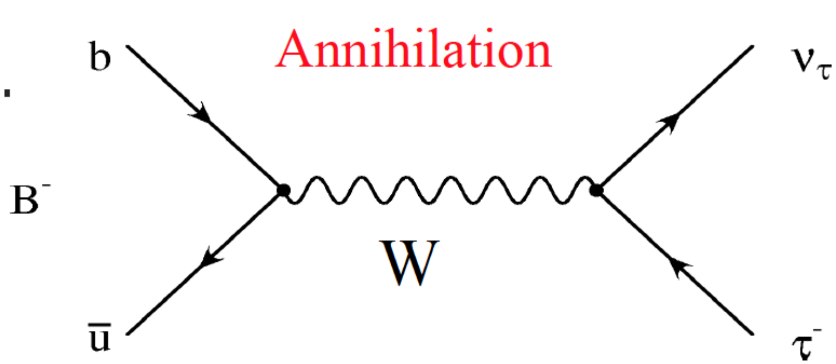
Gluonic Penguin

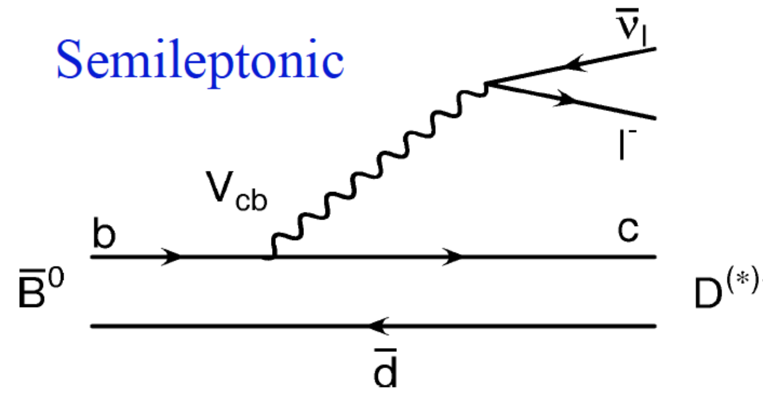


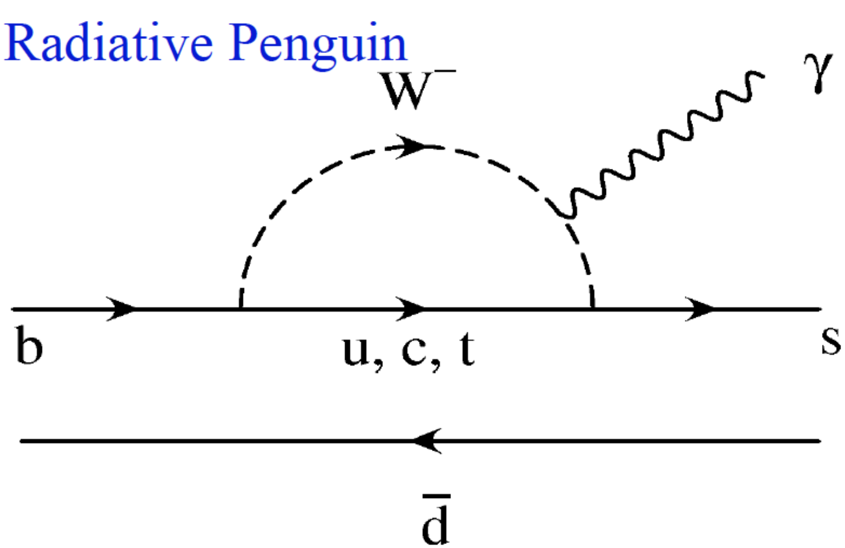


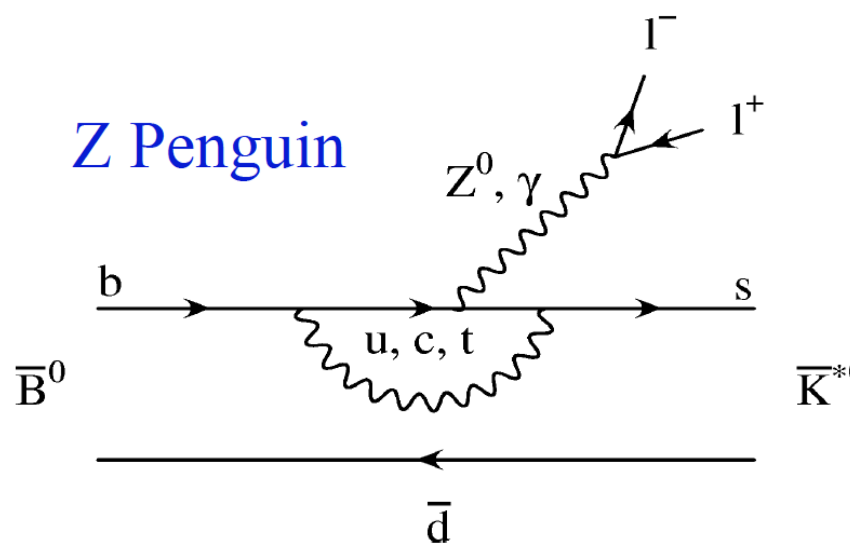
W-Exchange

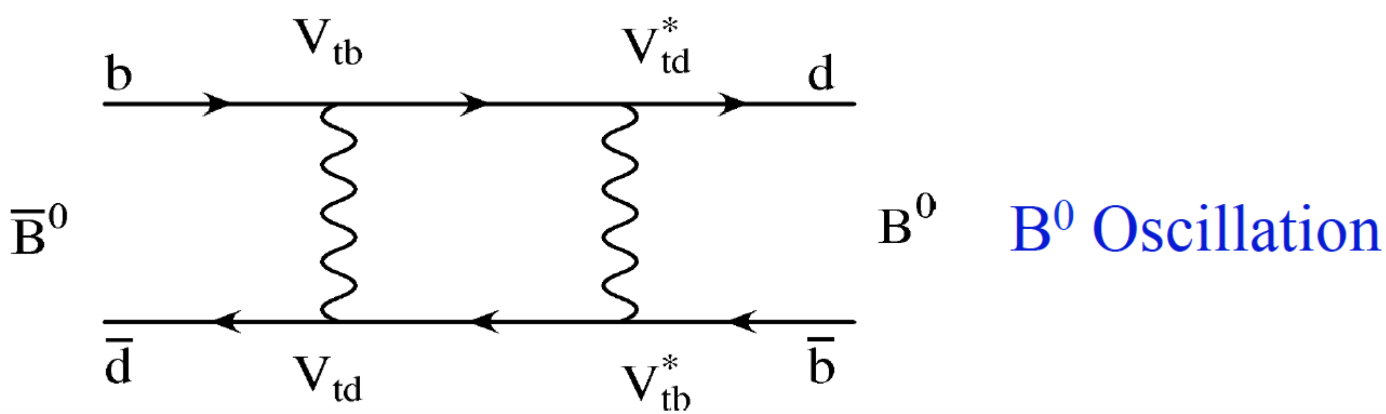



Annihilation
b
B⁻
ū
W
ν_τ
τ⁻


Semileptonic
ν̄_l
l⁻
V_cb
b
c
B̄⁰
D^(*)+
d̄


Radiative Penguin
W⁻
γ
b
u, c, t
s
d̄


Z Penguin
l⁻
l⁺
Z⁰, γ
b
s
u, c, t
B̄⁰
K̄*⁰
d̄

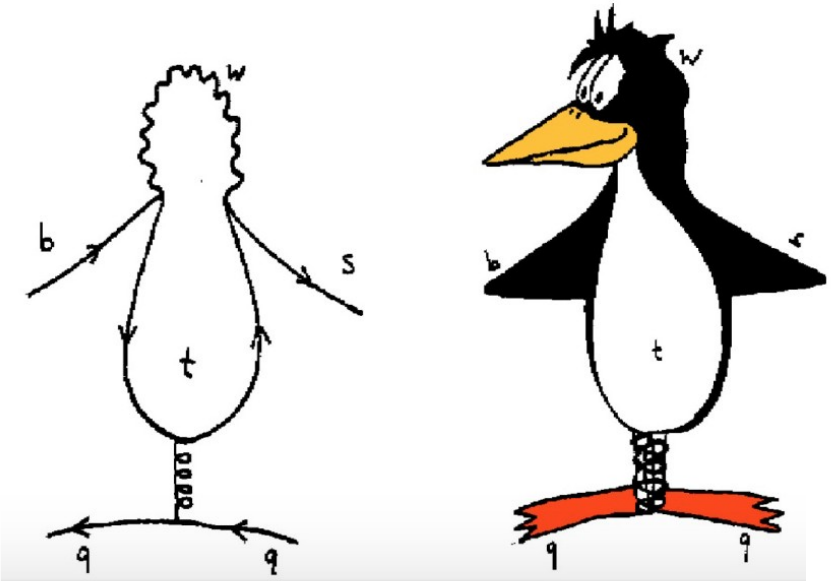

V_tb
V*_td
b
d
B̄⁰
B⁰
B⁰ Oscillation
d̄
V_td
V*_tb
b̄

Penguins in B Decays !?

Ref: Preface to Shifman's 1999 book, ITEP Lectures on Particle Physics and Field Theory, John Ellis recalls how the gluon interference diagram came to be called a penguin diagram.

One night in spring 1977, Ellis lost a bet during a game of darts. His penalty required that he use the word "penguin" in a journal article. “For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time," Ellis wrote.

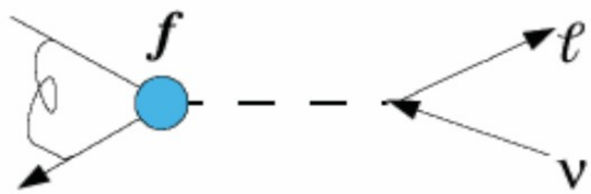
"Then, one evening I stopped on my way back to my apartment to visit some friends living in Meyrin, where I smoked some illegal substance. *Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams looked like penguins.* So we put the name into our paper, and the rest, as they say, is history."



Typology of Tree Decay Amplitudes

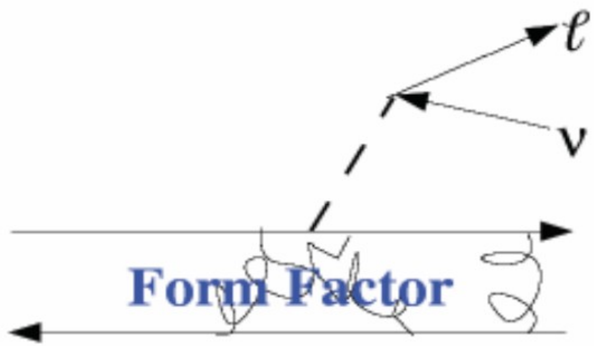
Hadronic & Leptonic current do factorize

Leptonic



* Low energy QCD: decay constant *f*
* Lattice QCD starts to get precise

Semileptonic
(In most cases best way to extract $|V_{ij}|$)

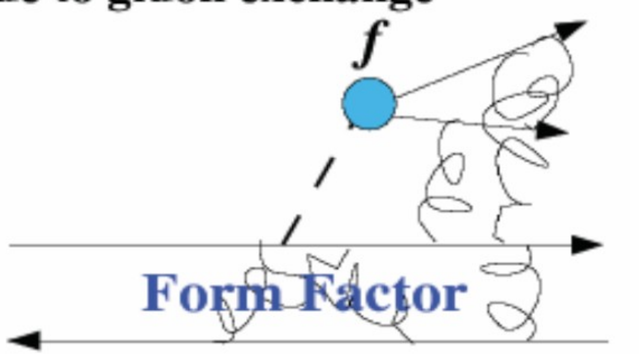


<u>Exclusive Decays:</u>
* FF: Symmetries (χ & HQS)
* FF: Lattice QCD, Sum Rules; ...

<u>Inclusive Decays:</u>
* Operator Product Expansion

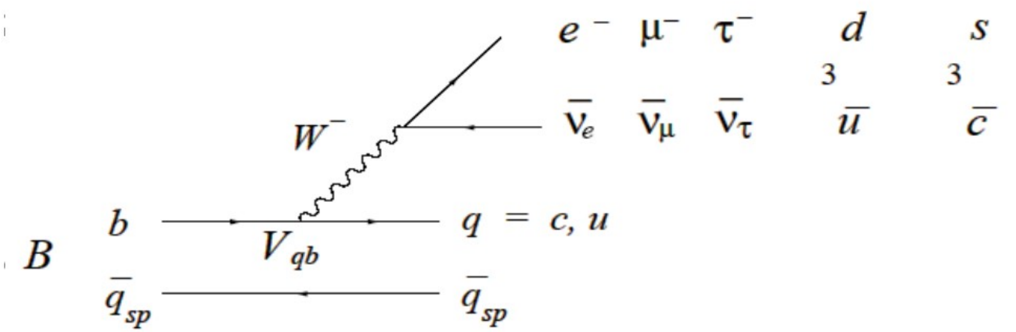
No factorization in naïve sense due to gluon exchange

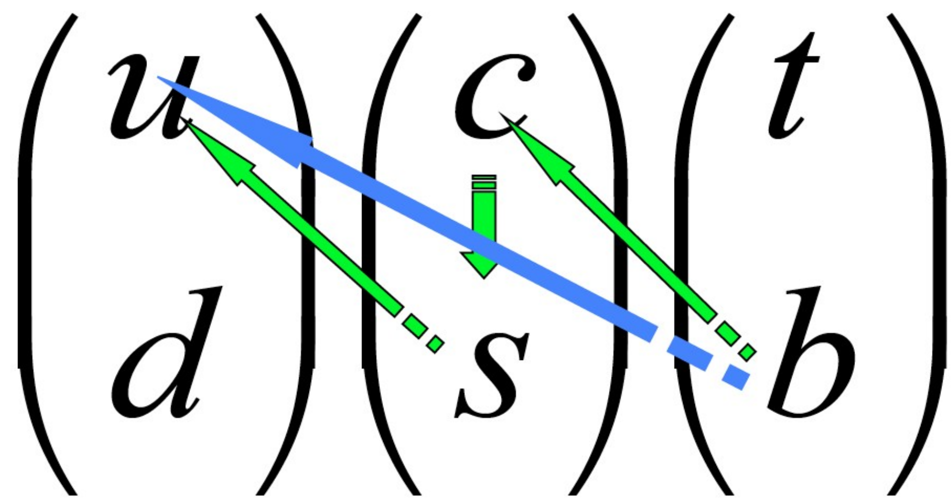
Hadronic



Theoretical developments:
e.g. QCD Factorisation approach
Not used for $|V_{ij}|$ extraction (yet)

Summary of *b*-quark Decay



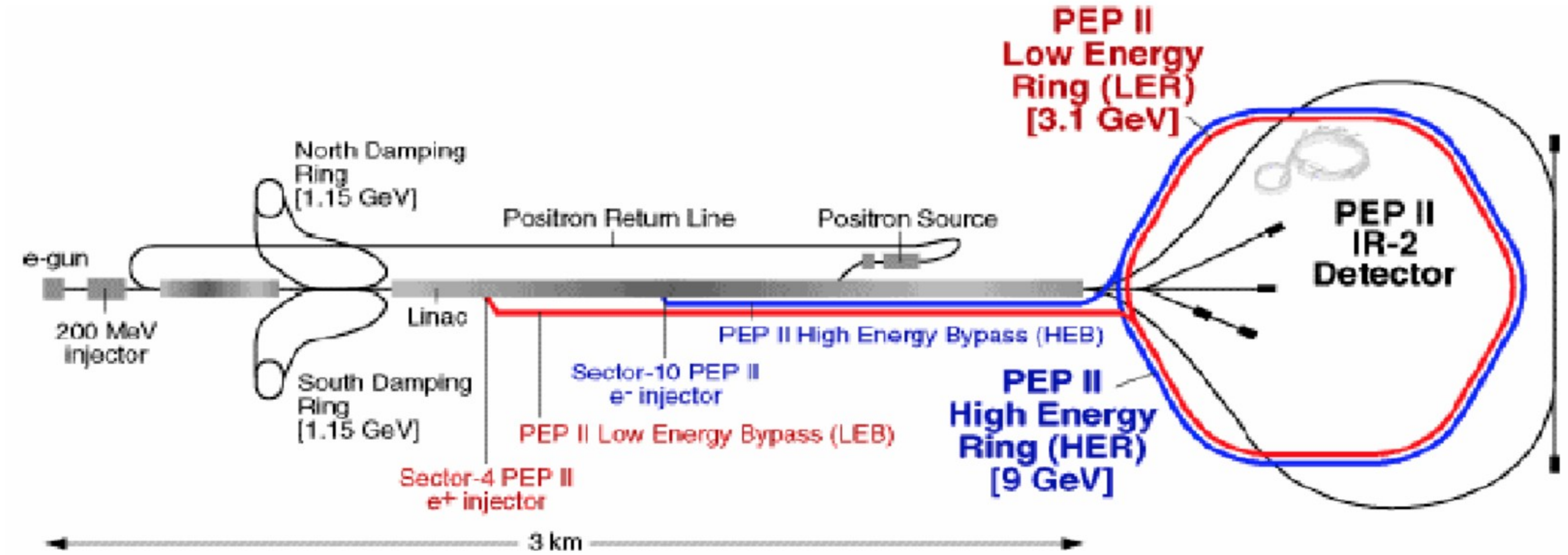


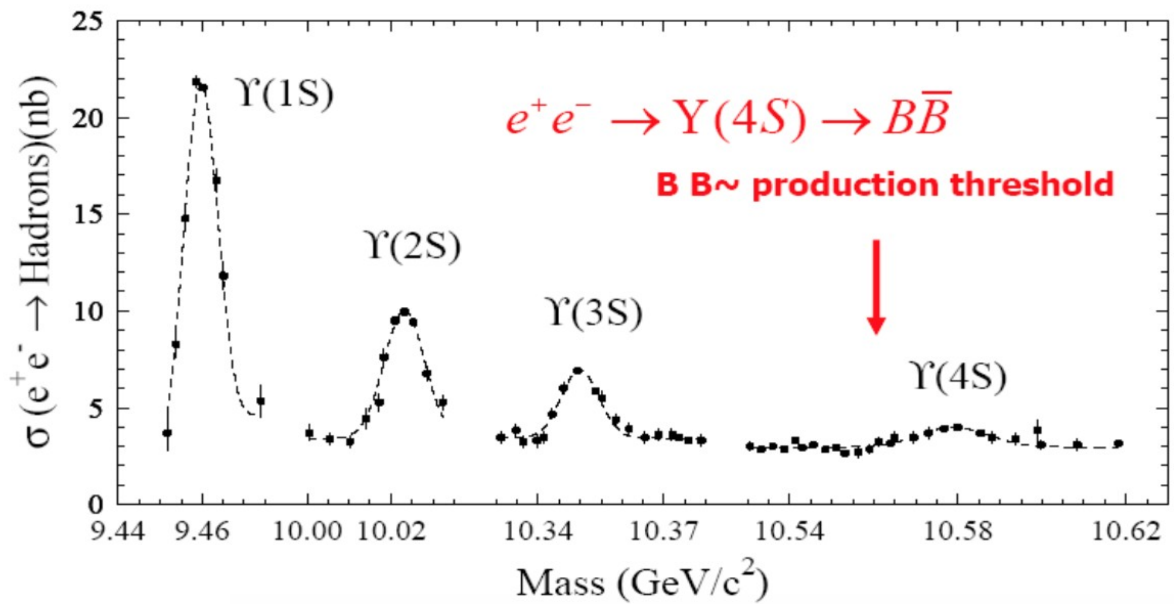
Mode	N_c	f_{QCD}	f_{ps}	V_{xb}	$\mathcal{B}$
$c\bar{u}d'$	3	1.3	0.52	0.038	48%
$c\bar{c}s'$	3	1.3	0.25	0.038	23%
$ce\bar{\nu}_e$	1	1.0	0.52	0.038	12%
$c\mu\bar{\nu}_\mu$	1	1.0	0.52	0.038	12%
$c\tau\bar{\nu}_\tau$	1	1.0	0.13	0.038	3%
$u\bar{u}d'$	3	1.3	1.00	0.003	0.6%
$u\bar{c}s'$	3	1.3	0.52	0.003	0.3%
$ue\bar{\nu}_e$	1	1.0	1.00	0.003	0.1%
$u\mu\bar{\nu}_\mu$	1	1.0	1.00	0.003	0.1%
$u\tau\bar{\nu}_\tau$	1	1.0	0.25	0.003	<0.1%
$s(d)g,\ s(d)\gamma,\ s(d)Z^0 \ldots$					$\mathcal{O}(10^{-3})$

- 99% of B's → D's
- 66(13)% of B's → $K^+(K^-)$: flavor tagging
- 10% semi-leptonic BR: flavor tagging
- 7×10^{-4} of B's → $J/\psi \to \mu^+\mu^-$
- mean track multiplicity for single B ~ 5.5

Brief Primer of B reconstruction at e+e- B factory

PEP-II Asymmetric B-Factory at SLAC

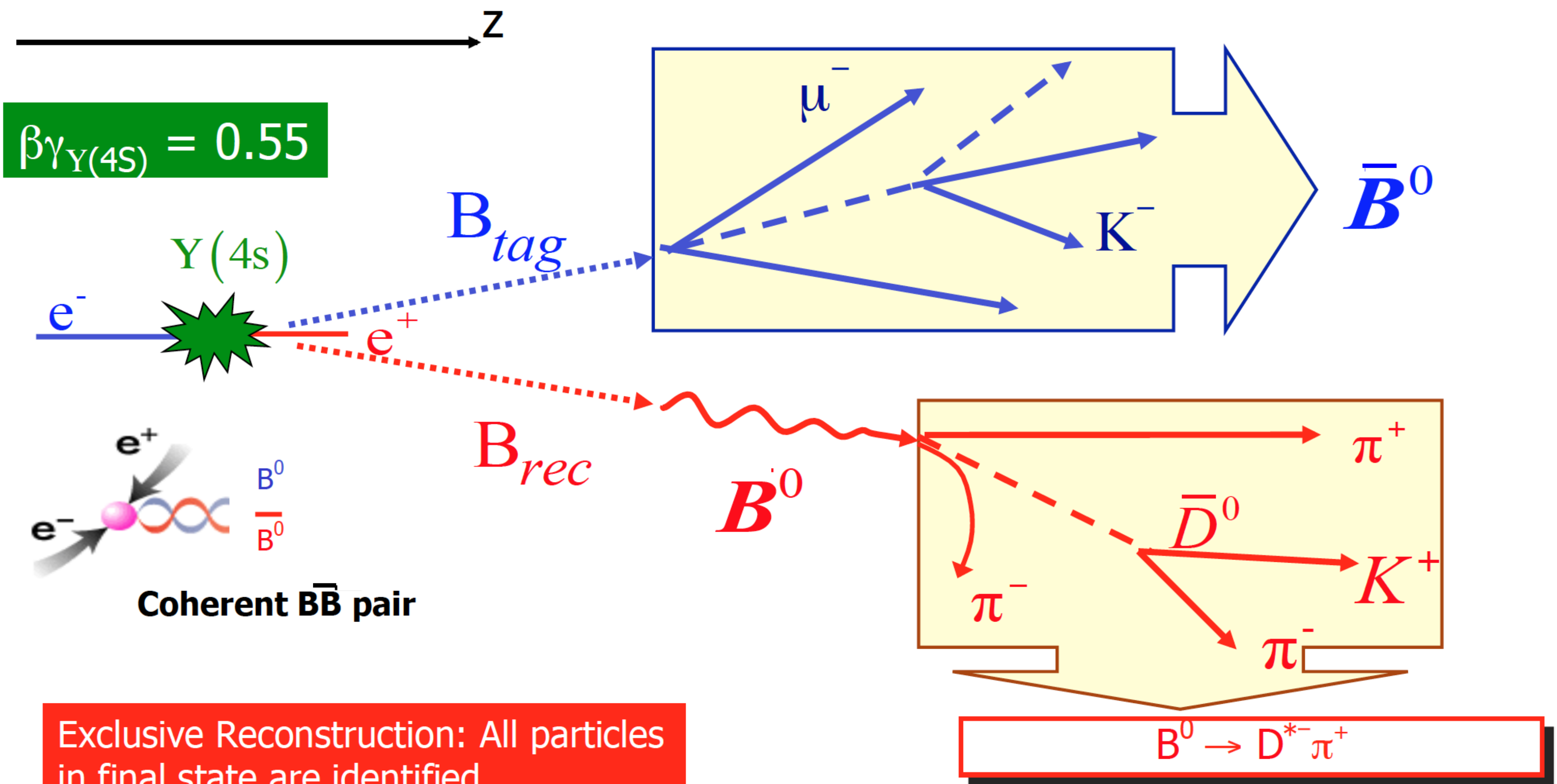




- 9 GeV e^- on 3.1 GeV e^+
- Υ(4S) boost in lab frame
  - $\beta\gamma = 0.55$

Snapshot of $B\bar{B}$ Event at BaBar

Inclusive Reconstruction: Look at some of decay products carrying information about their mother



Exclusive Reconstruction: All particles in final state are identified

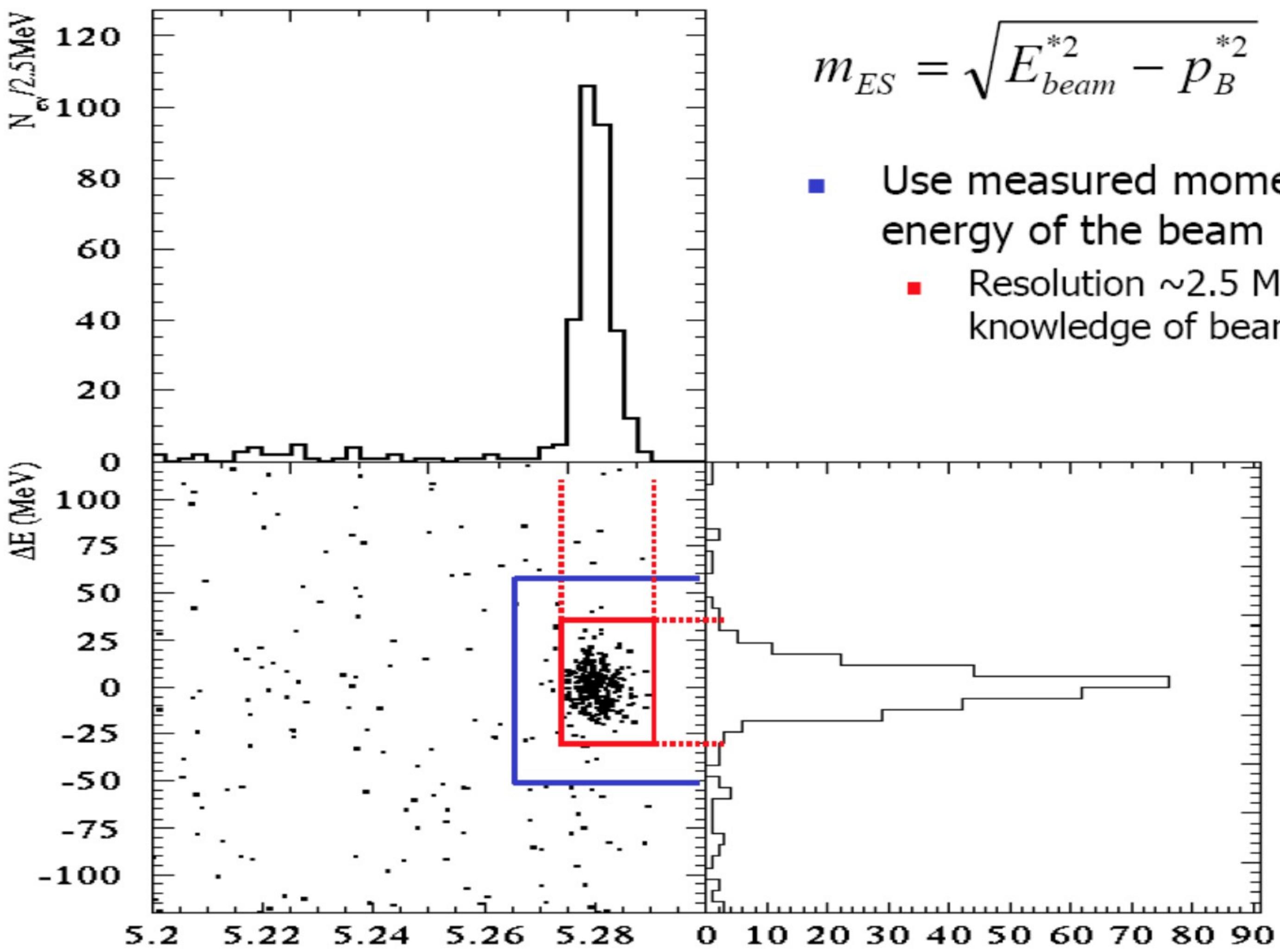
Exclusive or Inclusive ?

- Exclusive Selection
  - All products in selected final states are found in the detector
  - Conservation laws connect measured quantities between initial and final states
  - Advantages:
    - Typically better signal to noise ratio
      - Kinematic constraints remove most of combinatorial background
  - Disadvantages:
    - Usually requires more reliance on theoretical models and theory for interpretation of results

- Inclusive Selection
  - Not all particles in final state selected
  - No kinematic relation between initial and final state
  - Advantage:
    - Closer to transition diagram at quark level, hence typically less dependent on theory models
  - Disadvantage:
    - More background because of reduced constraints

Ingredients of B Reconstruction

- Take advantage of clean environment in $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - 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

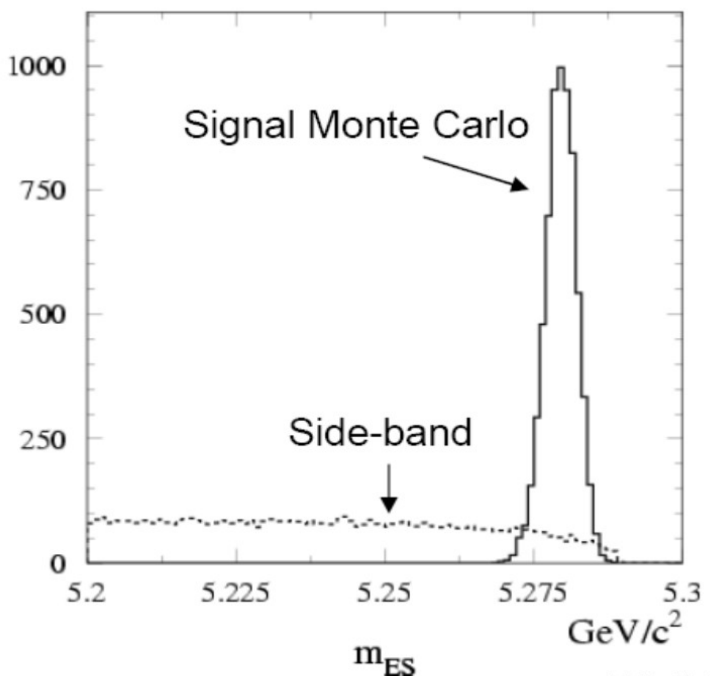
Kinematic Variables

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

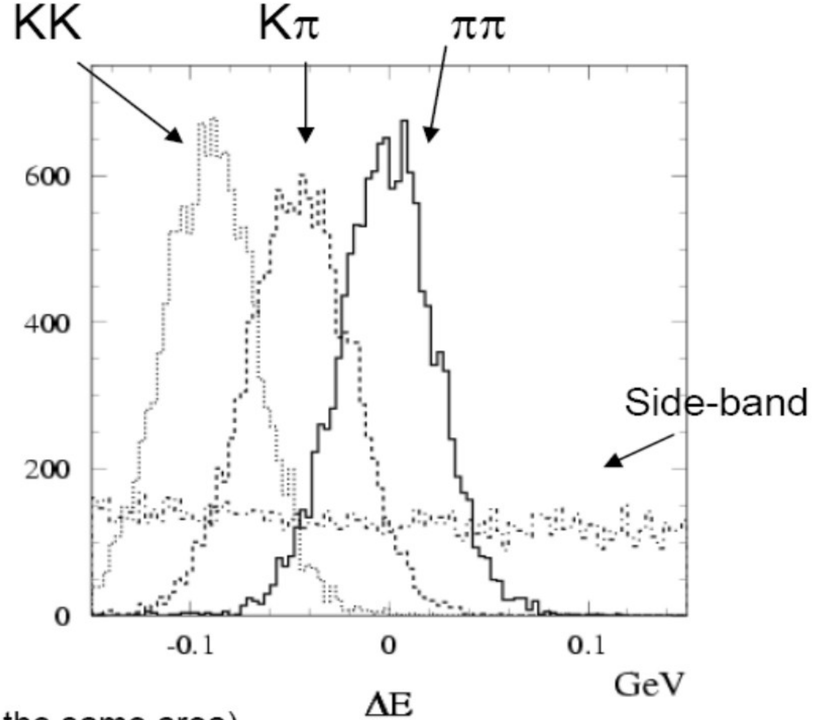
- Dominated by tracking resolution
- Assume π mass for tracks
- Momentum dependent shift for $K\pi$ and KK

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

$\sigma(m_{ES}) \approx 2.6$ MeV/c²



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



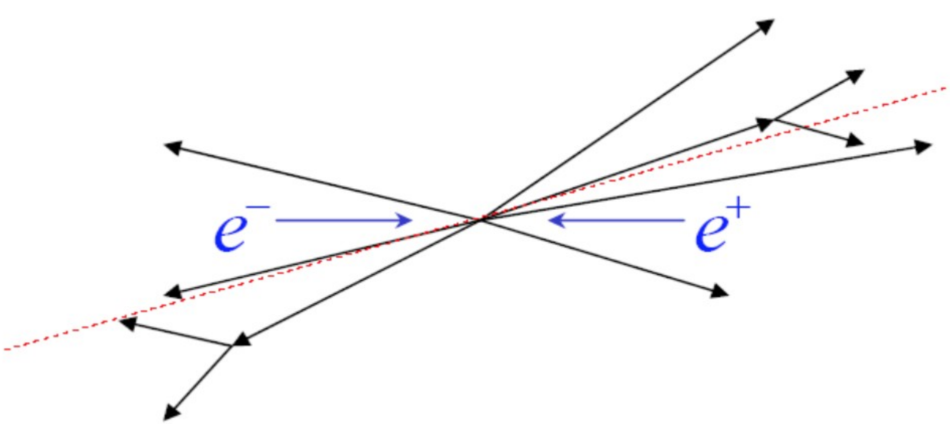
(All distributions are normalized to the same area)

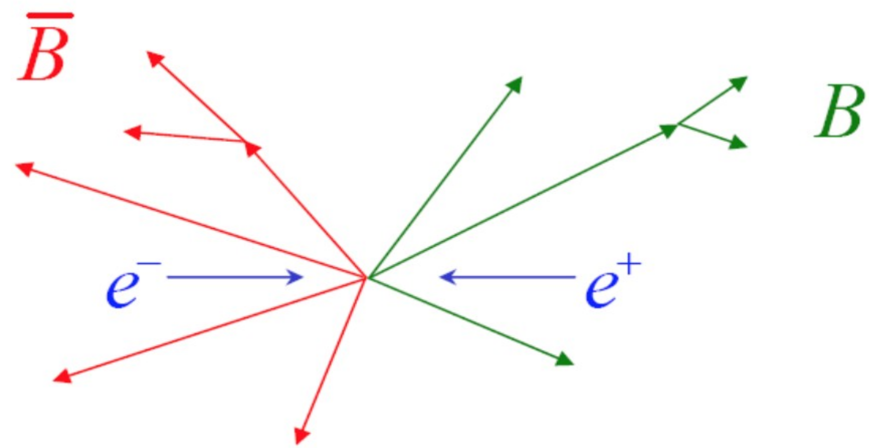
Continuum Background Rejection

- 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: $\cong 10^{-2}$

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

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





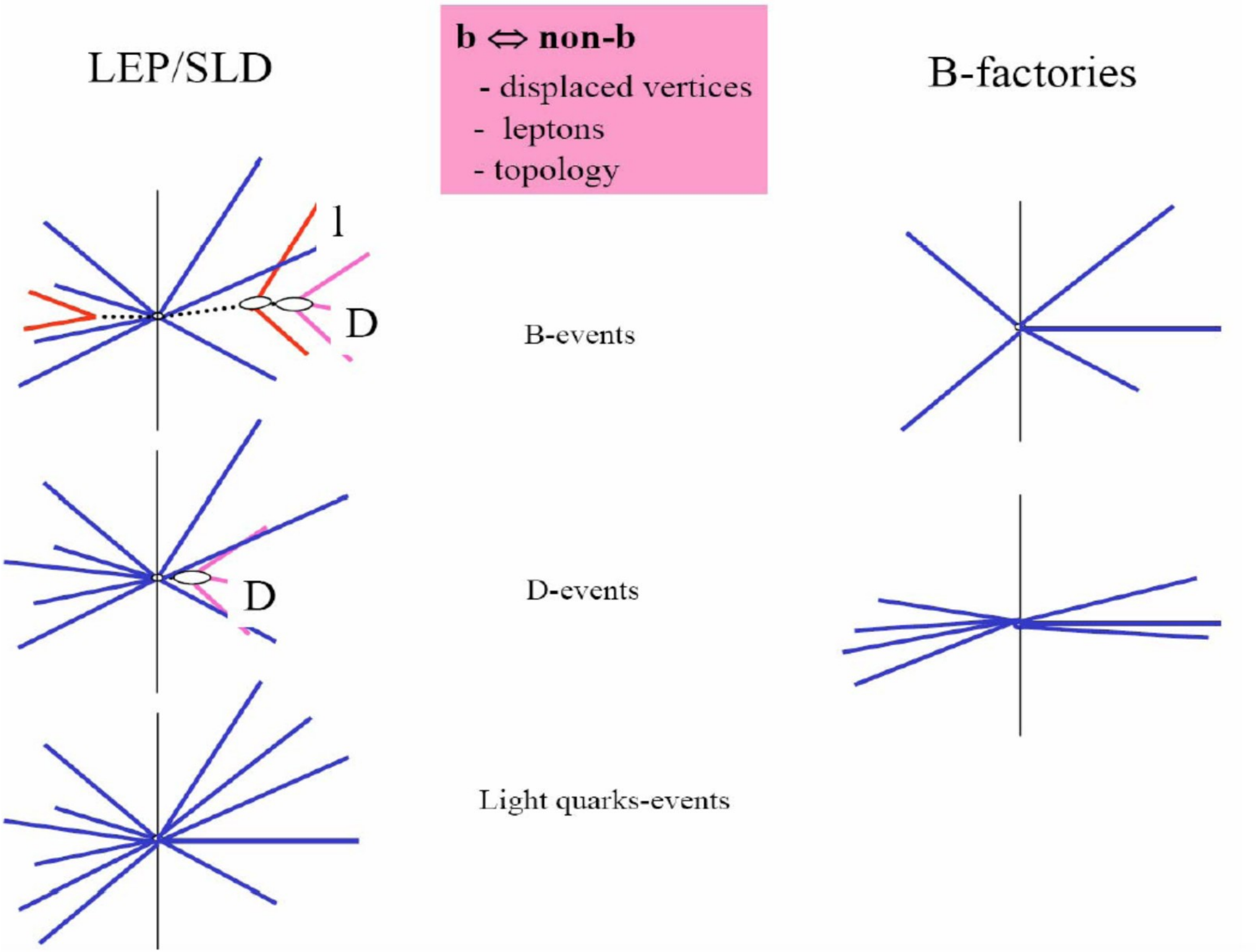
Thrust Axis

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

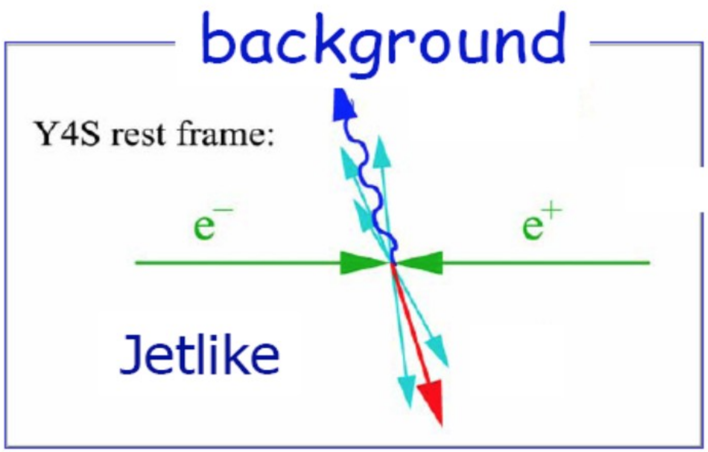
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

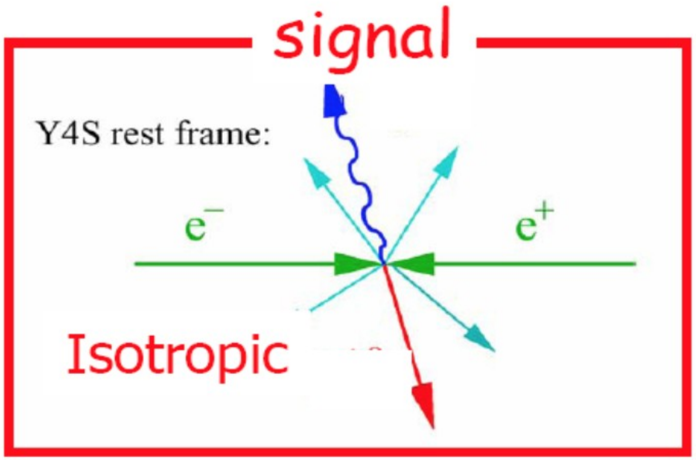
$$T = \frac{\sum |\vec{T}\cdot\vec{p}_i|}{\sum |\vec{p}_i|}$$ quantity to be maximized through $\vec{T}$

Event Topology at LEP/SLD vs. B Factories

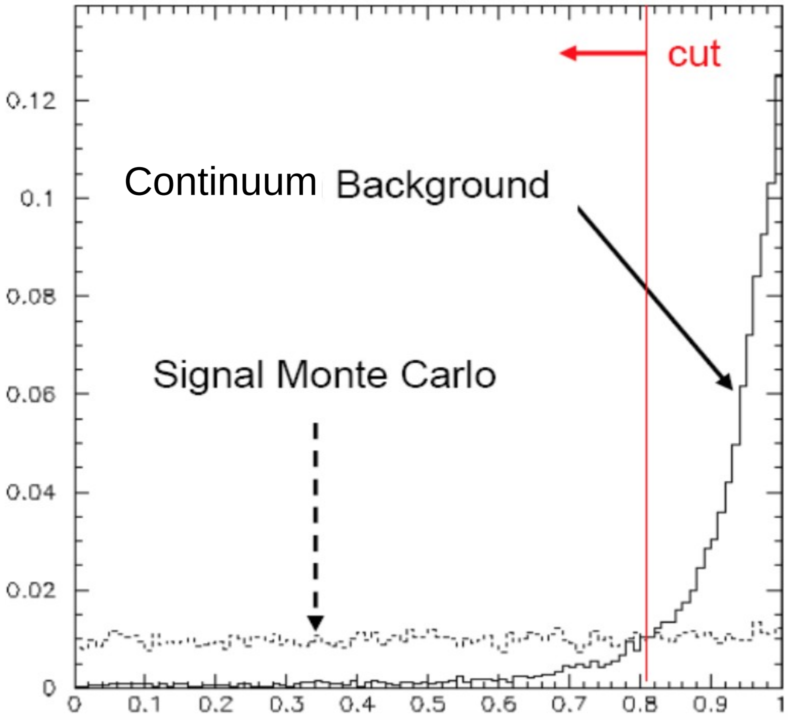


Background Fighting: Sphericity Angle



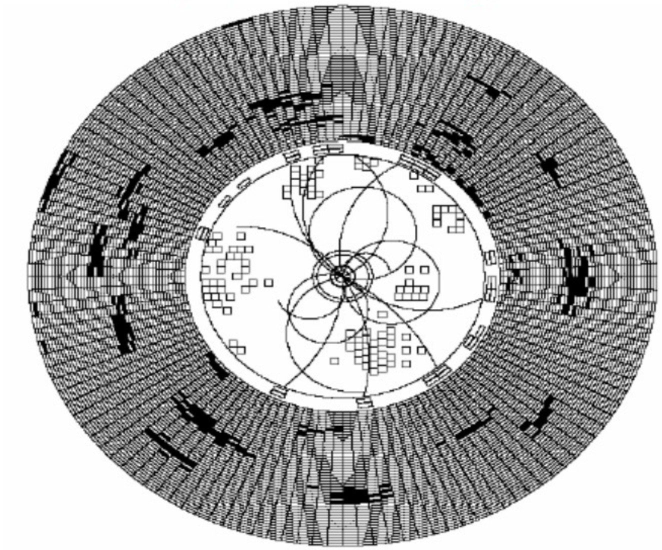


- $\cos\theta_s$: Angle between the B candidate and the rest of event

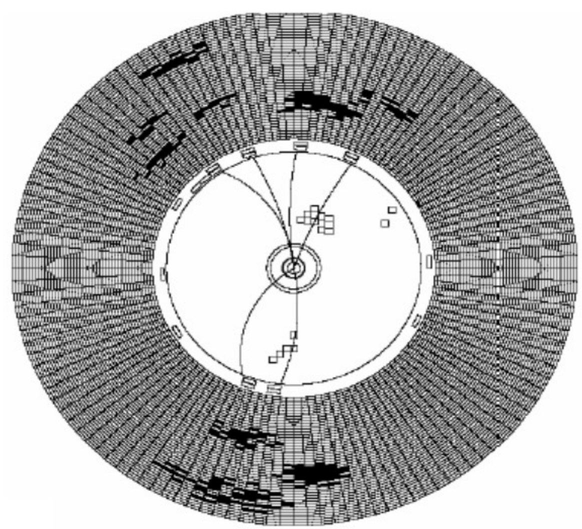


2^{nd} Fox-Wolfram Moment

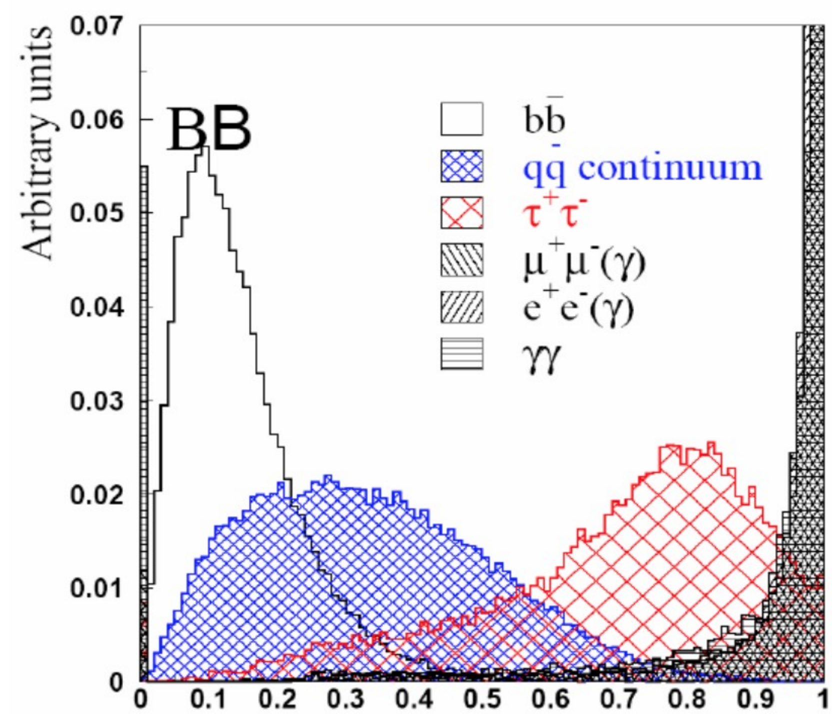
$\Upsilon(4S) \rightarrow B\bar{B}$ Decay



$e^+e^- \rightarrow u\bar{u},\ d\bar{d}\ ,s\bar{s},c\bar{c}$ 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.



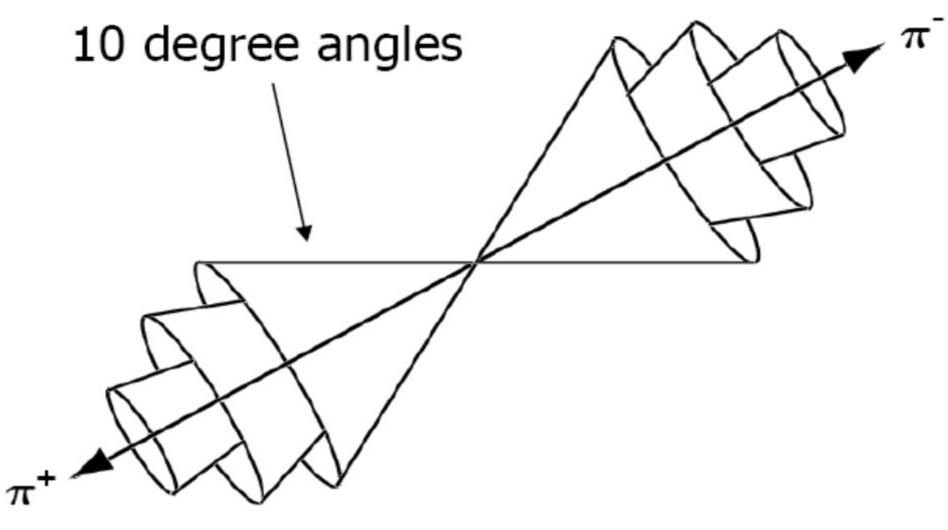
$R2=H_2/|H_2|$

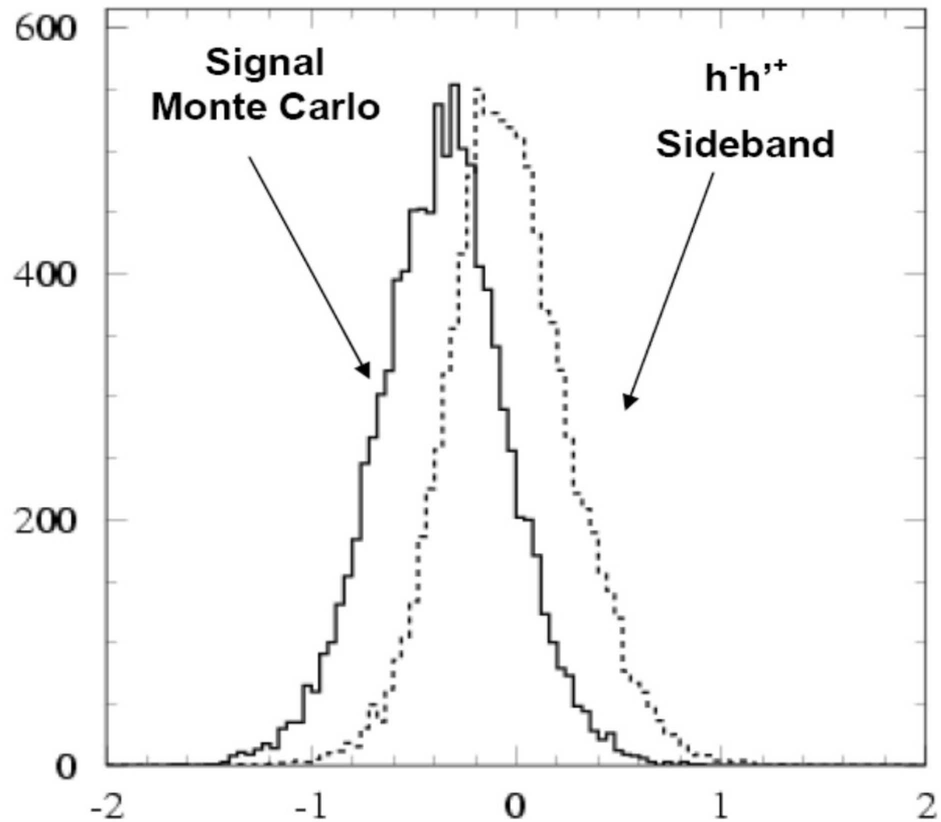
$$H_k = \sum_{i,j}^{N} |\vec{p}_i||\vec{p}_j| P_k(\cos\theta_{i,j})$$

k-th order Fox-Wolfram momen t

Background Fighting: Fisher Discriminant

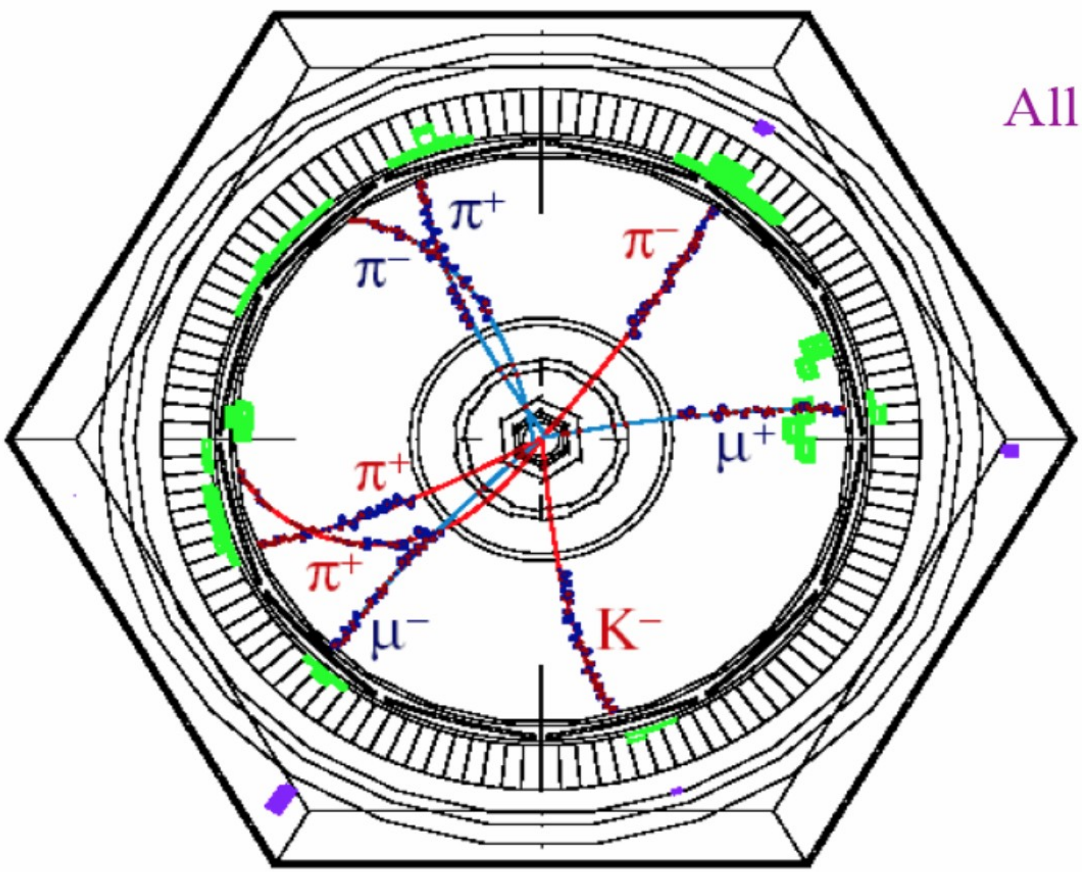
- Optimized linear combination of energy flow into cones about candidates
- Sensitive only to the rest of event
- Studied and calibrated on data: $B \to D^0\pi^-$, $h^-h'^+$sideband
- Validated with Monte Carlo





A completely reconstructed Υ(4s) event at BaBar

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



All particles accounted for
Nothing Missing !

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

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

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

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

Measurement of $|V_{cb}|$

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

$|V_{cb}|$ exclusive →

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

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

w = product of the B and D 4-velocities

$q^2 = (p_B - p_D)^2$

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

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

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

Known kinematic factor

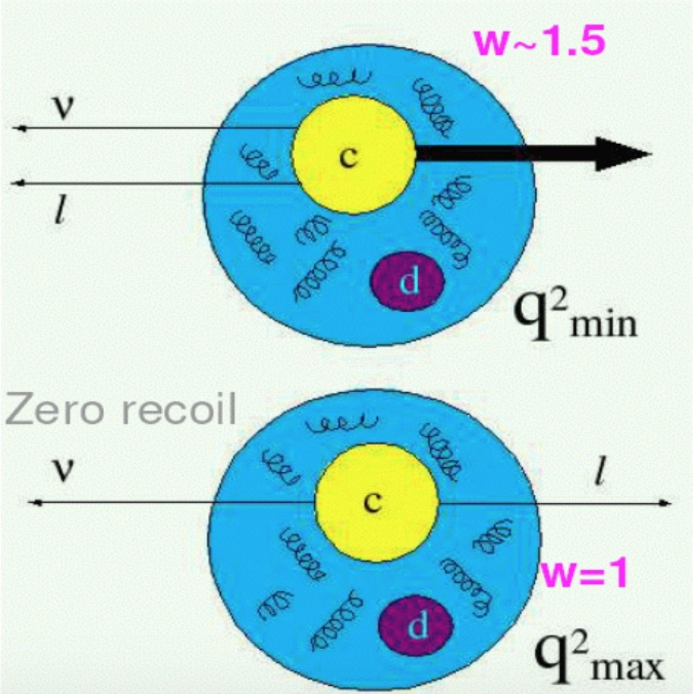
HQET and LQCD provide calculation at zero recoil

In reality the formula is slightly more complicated:

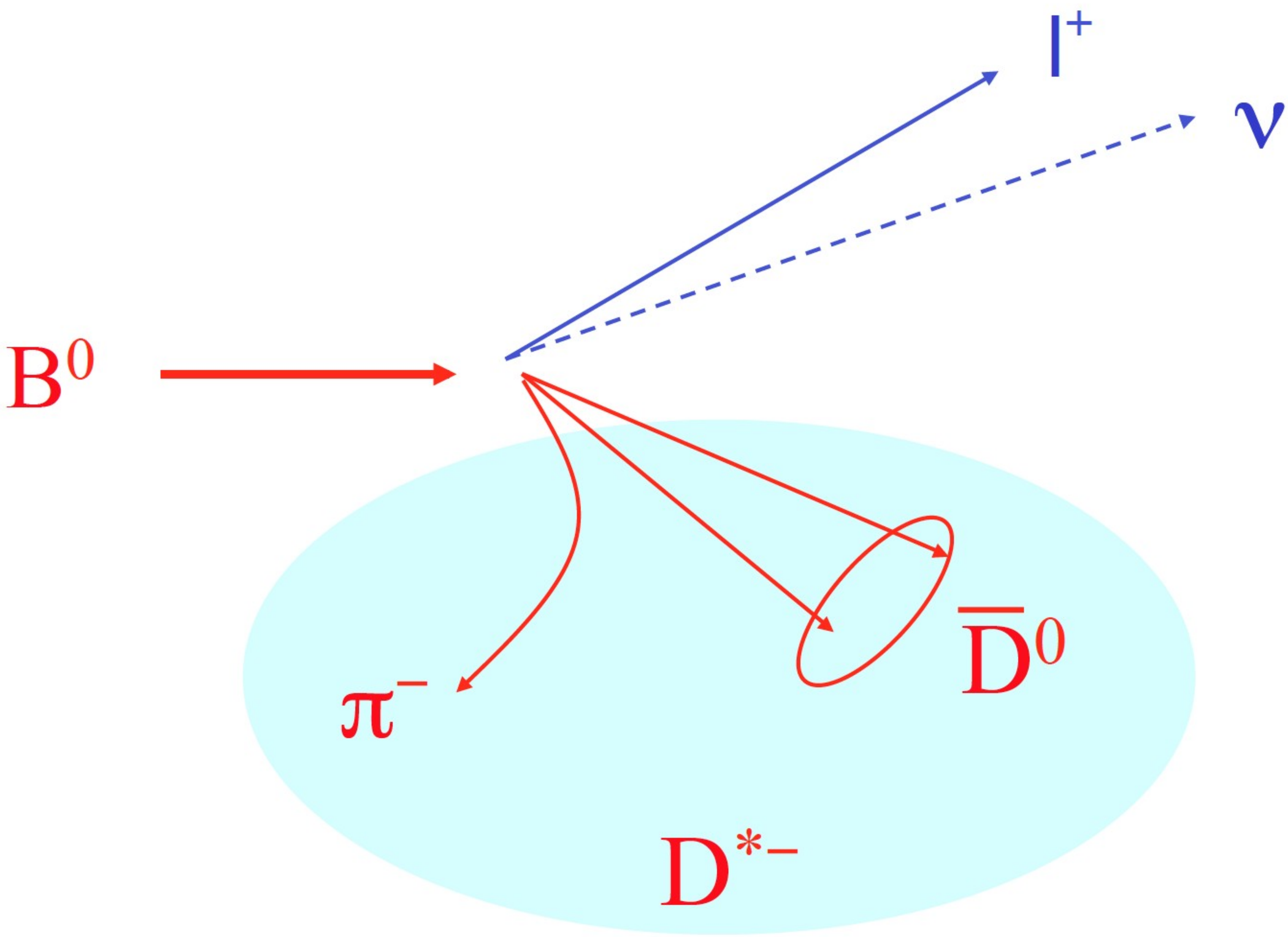
$$\mathcal{F}^2(w)\mathcal{G}(w) = h_{A_1}^2(w)\sqrt{w-1}\,(w+1)^2 \left\{ 2\left[\frac{1-2wr+r^2}{(1-r)^2}\right] \times \left(1 + R_1(w)^2 \frac{w-1}{w+1}\right) + \left[1 + (1-R_2(w))\frac{w-1}{1-r}\right]^2 \right\}$$

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

F→1 for w→1



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

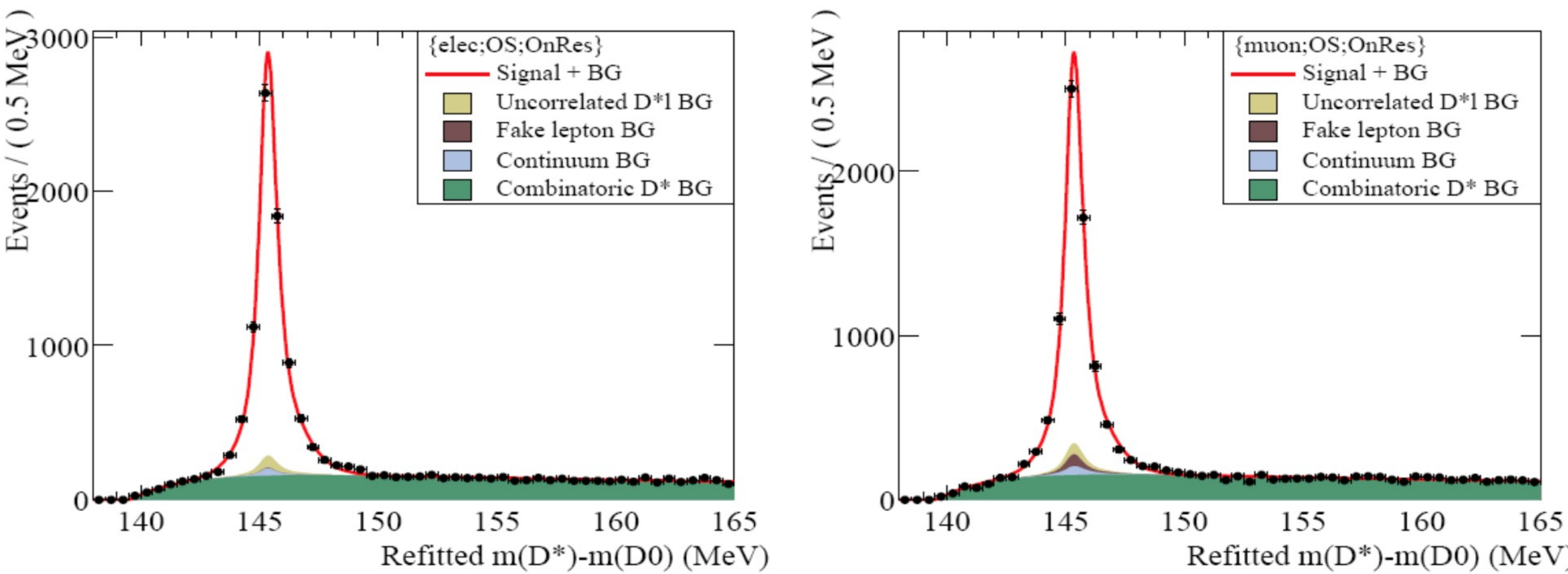


$D^{(*+-)}D^0$ mass difference

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

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

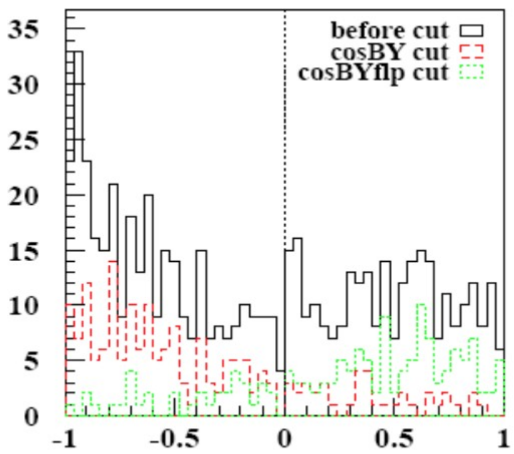
- Fixed momentum for soft pion
  - Only experimental resolution

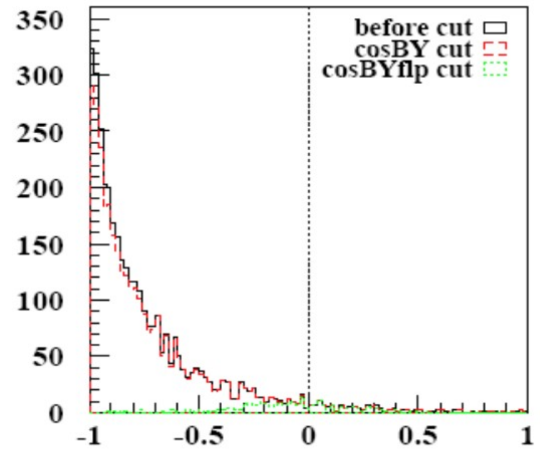


Angular Variables for $B^0 \rightarrow D^{(*)}l\nu$ selection

- Angle between D* and lepton

Background



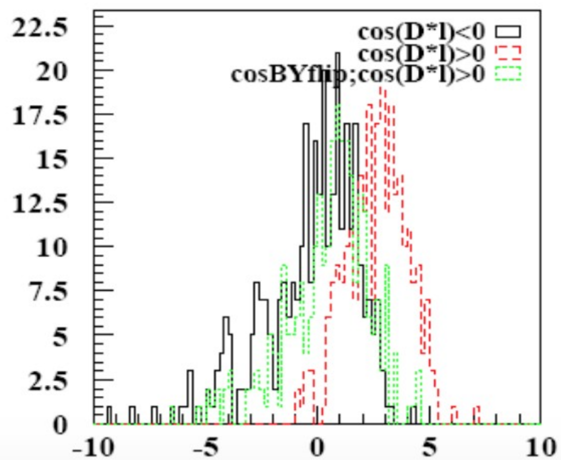


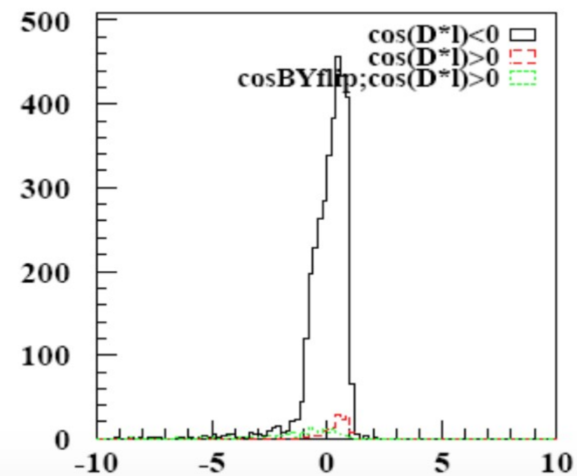
Signal

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

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

Background



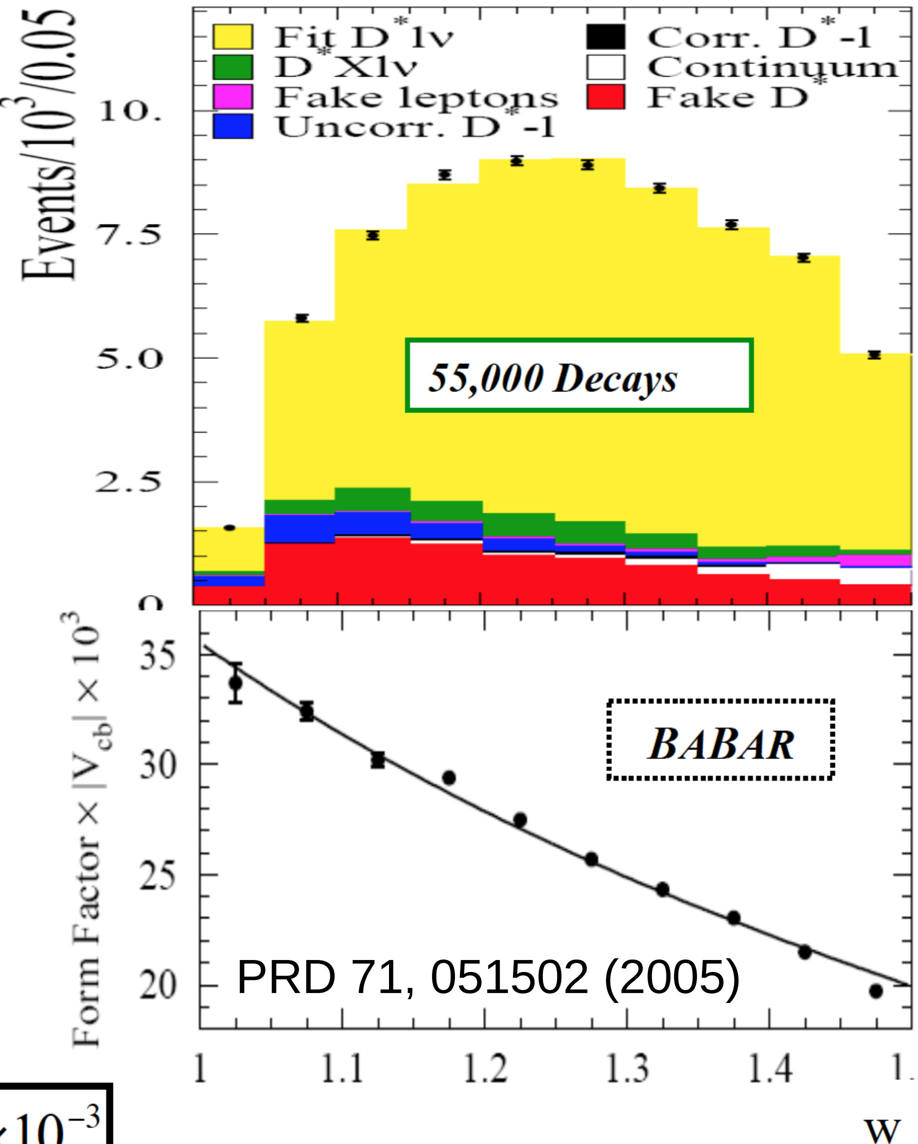


Signal

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 extrapolate to w=1



In BaBar:

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

and using

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

Hashimoto et al.
PRD 66, 014503
(LQCD)

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