# CKM Matrix and CP Violation in Standard Model

B physics at B factories

Lecture 14

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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# b Quark is Special!

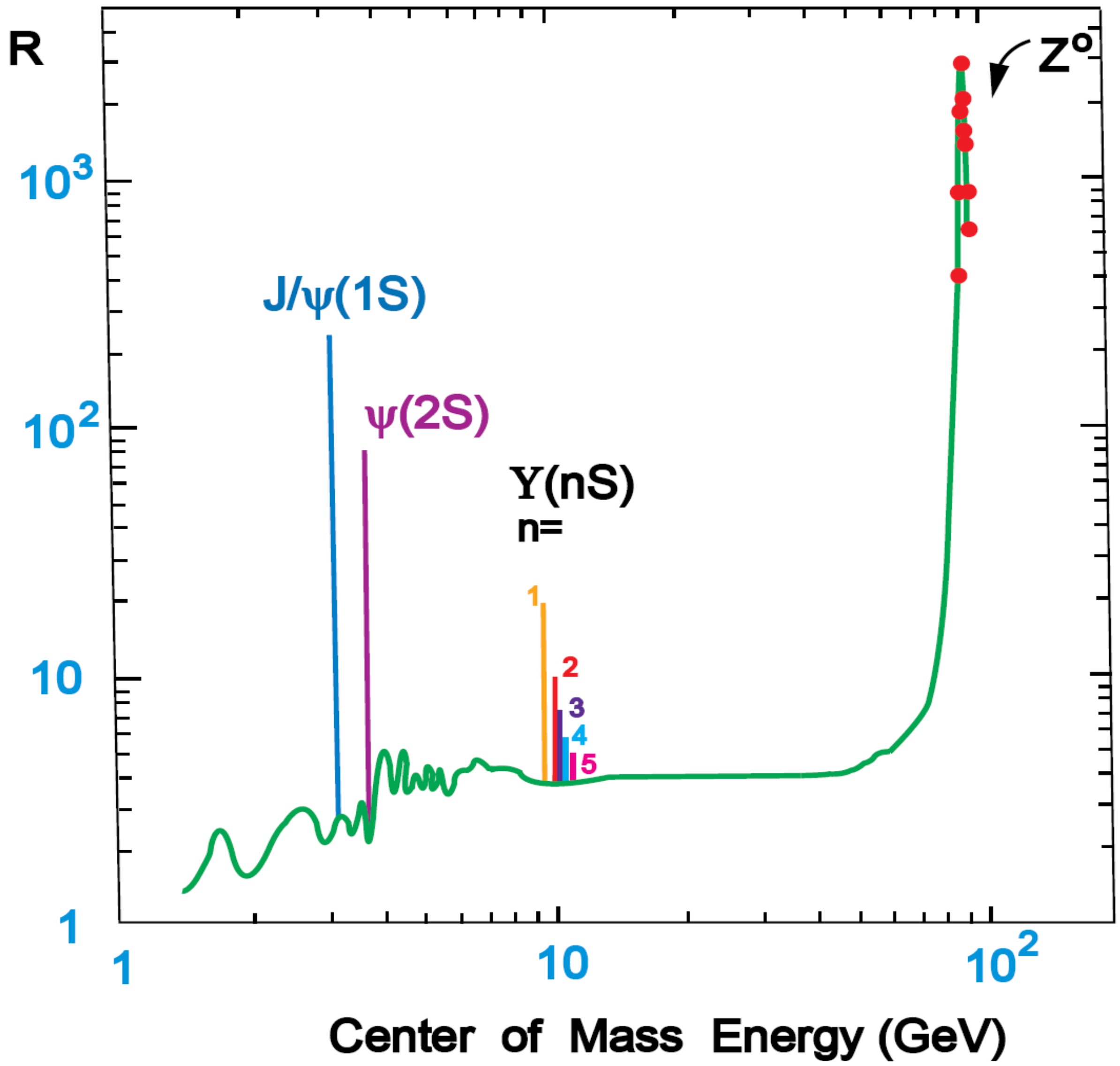
- Processes involving b quark can be used to measure several CKM element magnitudes
- Large mass of b quark allows use of Heavy Quark Effective Theory (HQET) for reliable theoretical calculations
  - Important for interpretation of experimental measurements with B mesons
- B mesons are of particular interest for study of CP violation
  - We will discuss this in detail next week
- 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→u transitions: necessary ingredient for CP violation

# Summary of B properties

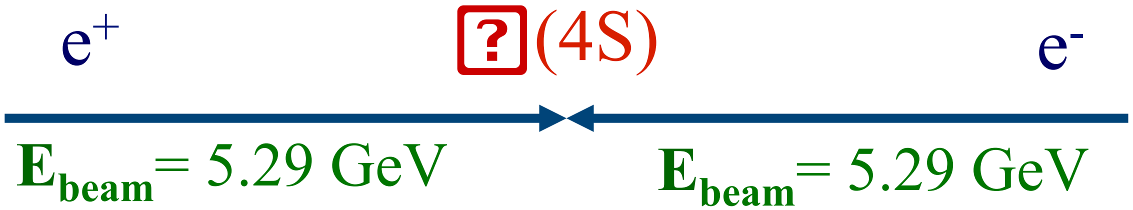
| Particle, $I(J^P)$ | Mass ( in MeV/c$^2$) | Lifetime $\tau = 1/\Gamma$ (in$10^{-12}$ s) |
|---|---|---|
| $B^0_d$ =(bd) , $I(J^P)=½ (0^-)$ | 5279.4 ± 0.5 | 1.536 ±0.014 & ($c\tau$ =460$\mu$m) |
| $B^-$ = (bu), $I(J^P)=½ (0^-)$ | 5279.0 ± 0.5 | 1.671 ±0.018 & ($c\tau$ =501$\mu$m) |
| $B^0_s$ =(bs), $I(J^P)=0(0^-)$ | 5369.6 ± 2.4 | 1.461 ±0.057 & ($c\tau$ =438$\mu$m) |
| $\Lambda_b$ = (bud), $I(J^P)=0(1/2^+)$ | 5624.0 ± 9.0 | 1.229 ±0.080 & ($c\tau$ =368$\mu$m) |

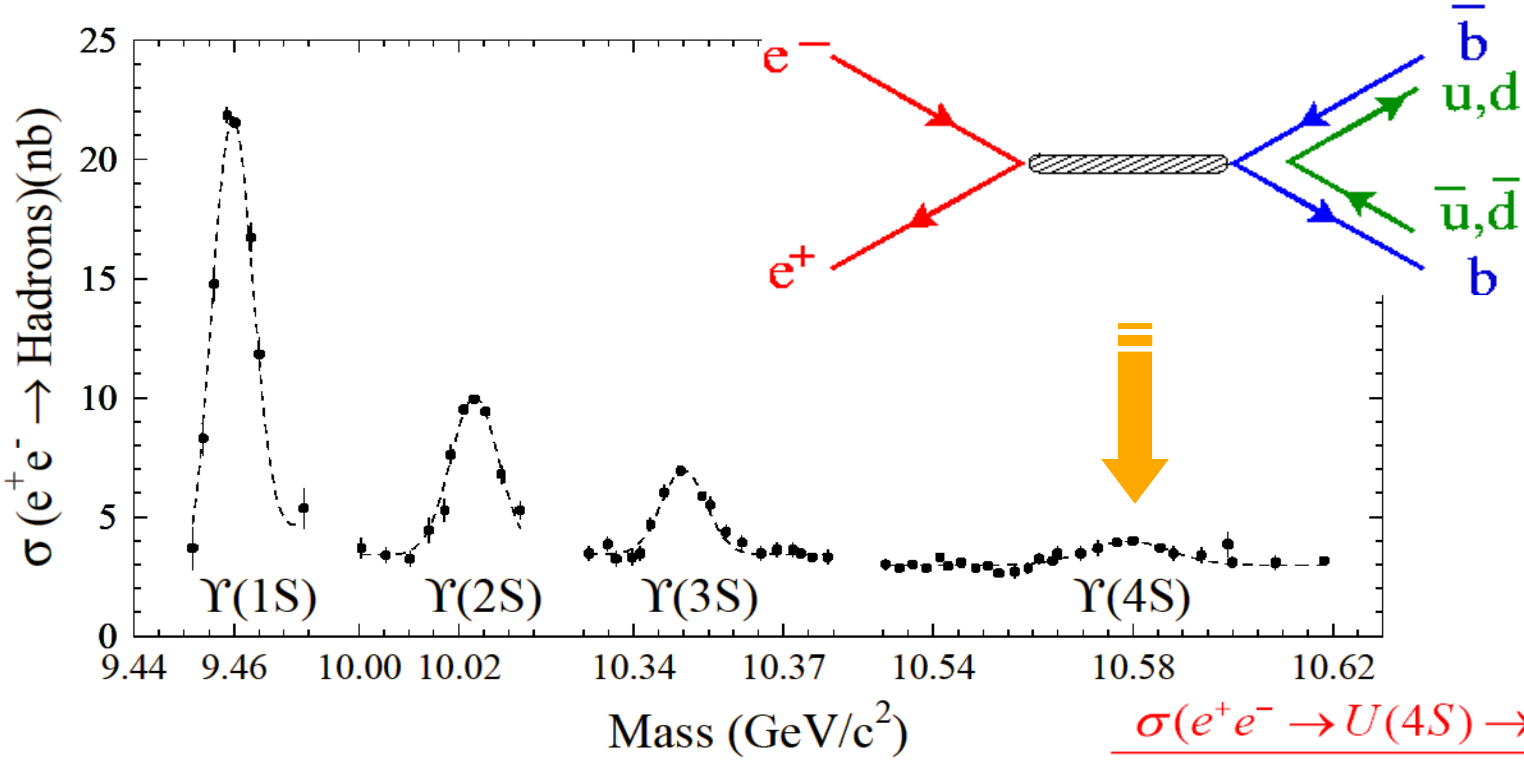
# B Production in $e^+e^-$ Collisions

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



# B Production at Upsilon resonance: B Factory

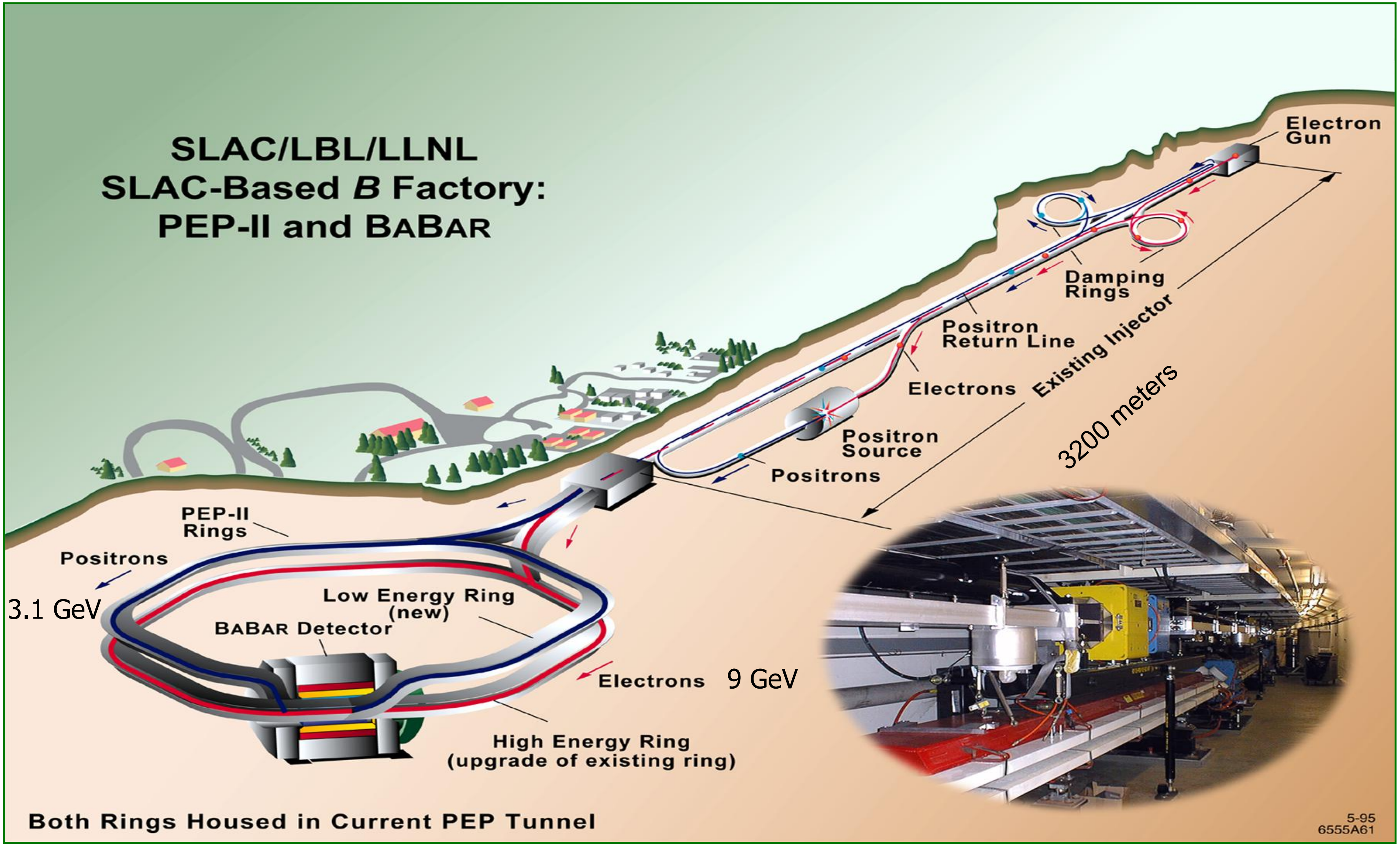



$$\frac{\sigma(e^+e^- \to U(4S) \to bb)}{\sigma(e^+e^- \to U(4S) \to TOT)} = \frac{1.2nb}{3.5nb} = 25\%$$

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

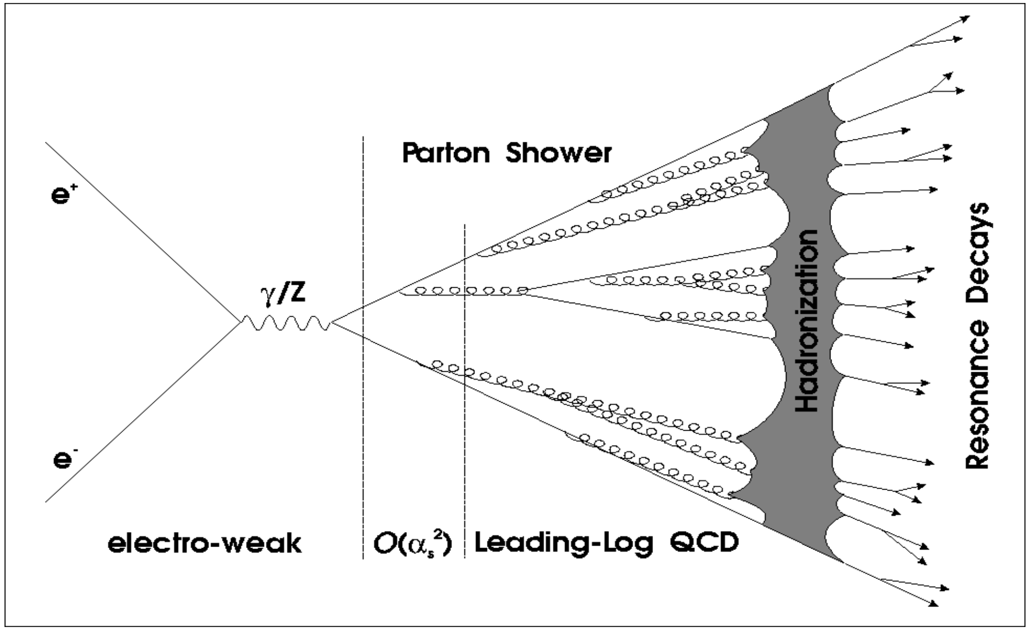
# PEP-II Collider at SLAC (Stanford, CA)




PEP-II accelerator schematic and tunnel view

# B Production at $Z^0$ Resonance

All types of B hadrons produced in Z → bb hadronization




| $b$ hadron | Fraction [%] |
|---|---|
| $B^+$, $B^0$ | $39.7 \pm 1.0$ |
| $B_s^0$ | $10.7 \pm 1.1$ |
| $b$ baryons | $9.9 \pm 1.7$ |

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

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

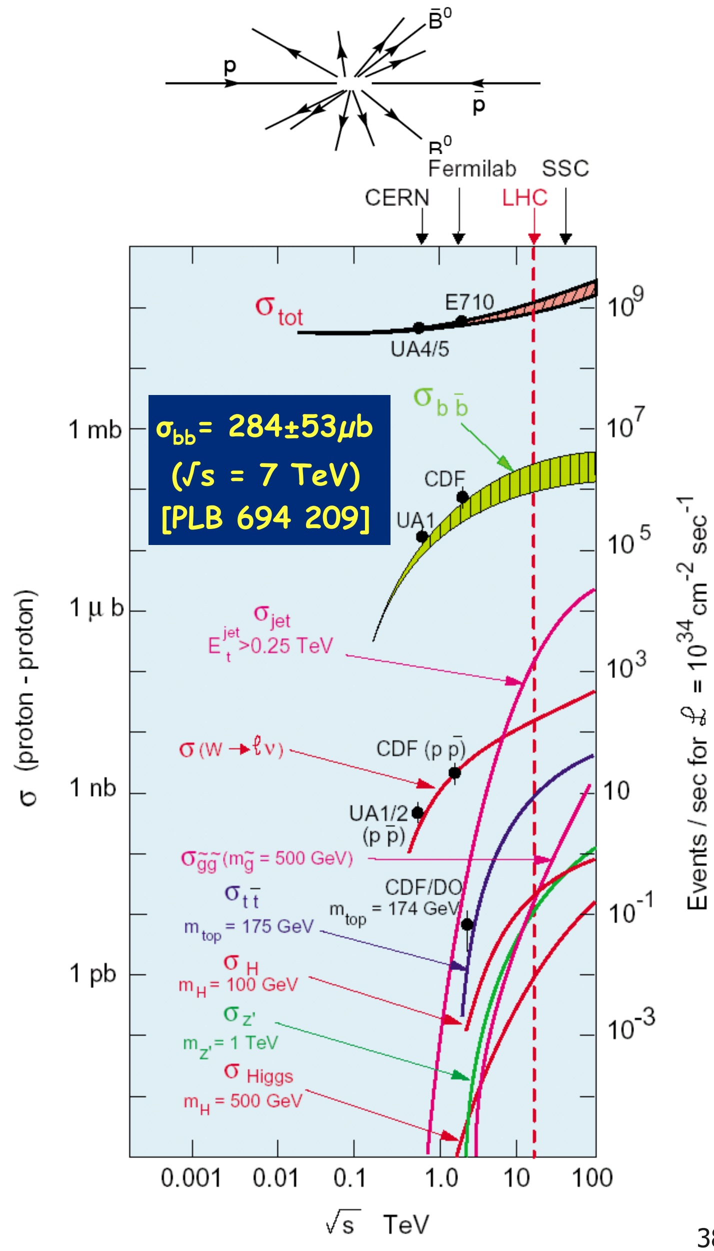
# B Production at Hadron Colliders

- At B factor xsec ~ 1 nb

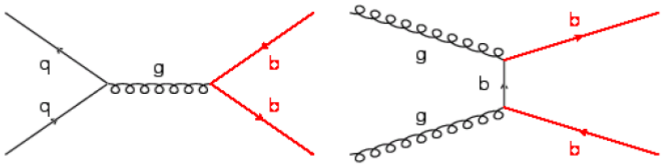
$$\sigma = N_c Q_f^2 \frac{4\pi\alpha^2}{3s} = N_c Q_f^2 \frac{86.8\ \mathrm{nb}}{s\,(\mathrm{GeV}^2)}$$

- At LHC @ 7 TeV xsec ~ 0.3 mb

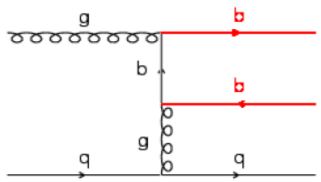
$$\frac{d\sigma}{d\Omega}(q\bar{q}, gg \rightarrow q\bar{q}) \sim \frac{\alpha_s^2}{s}$$



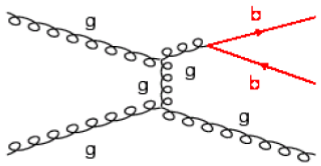

Lowest order




Flavor excitation



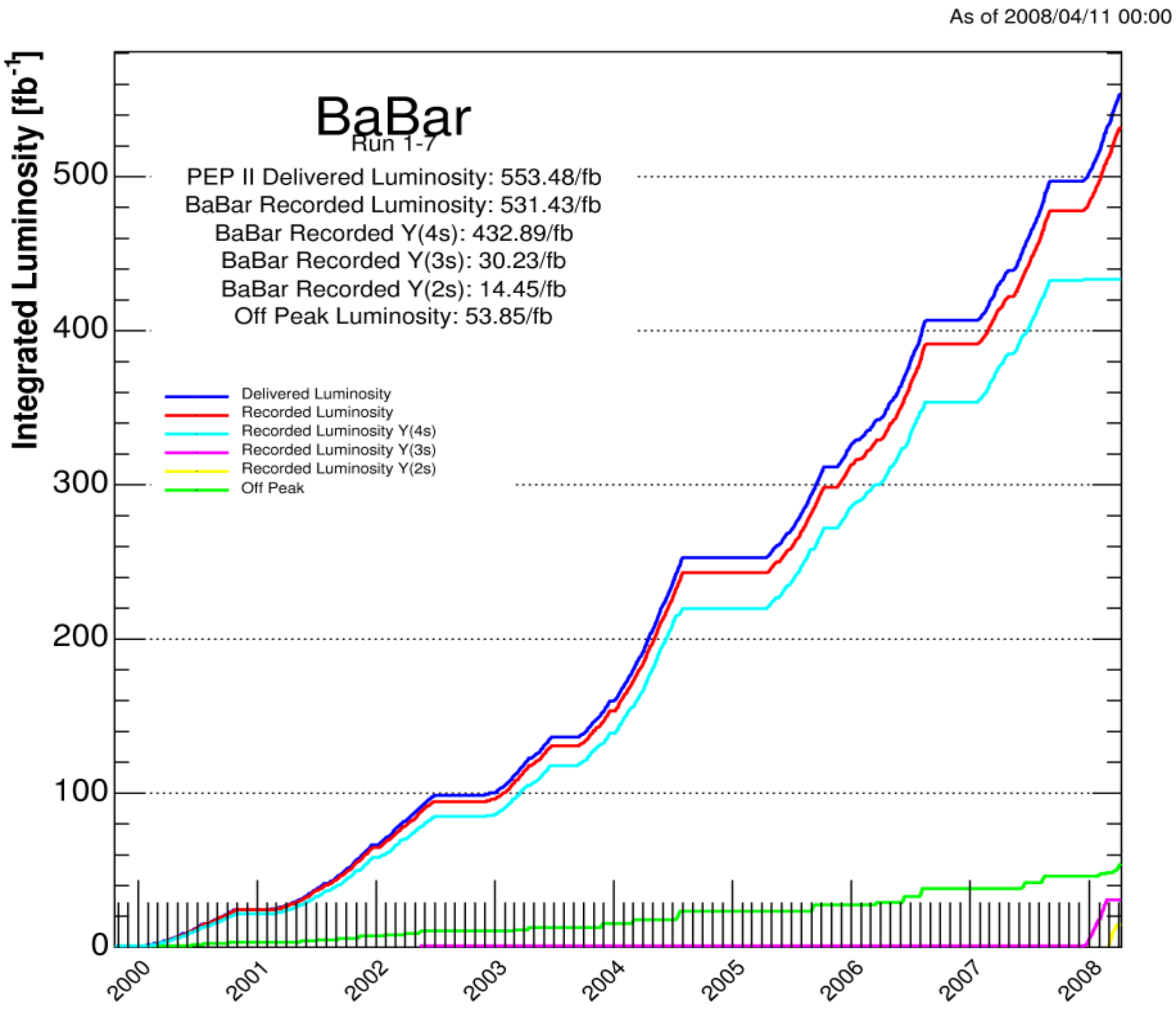

Gluon splitting



# Summary of Past Experiments

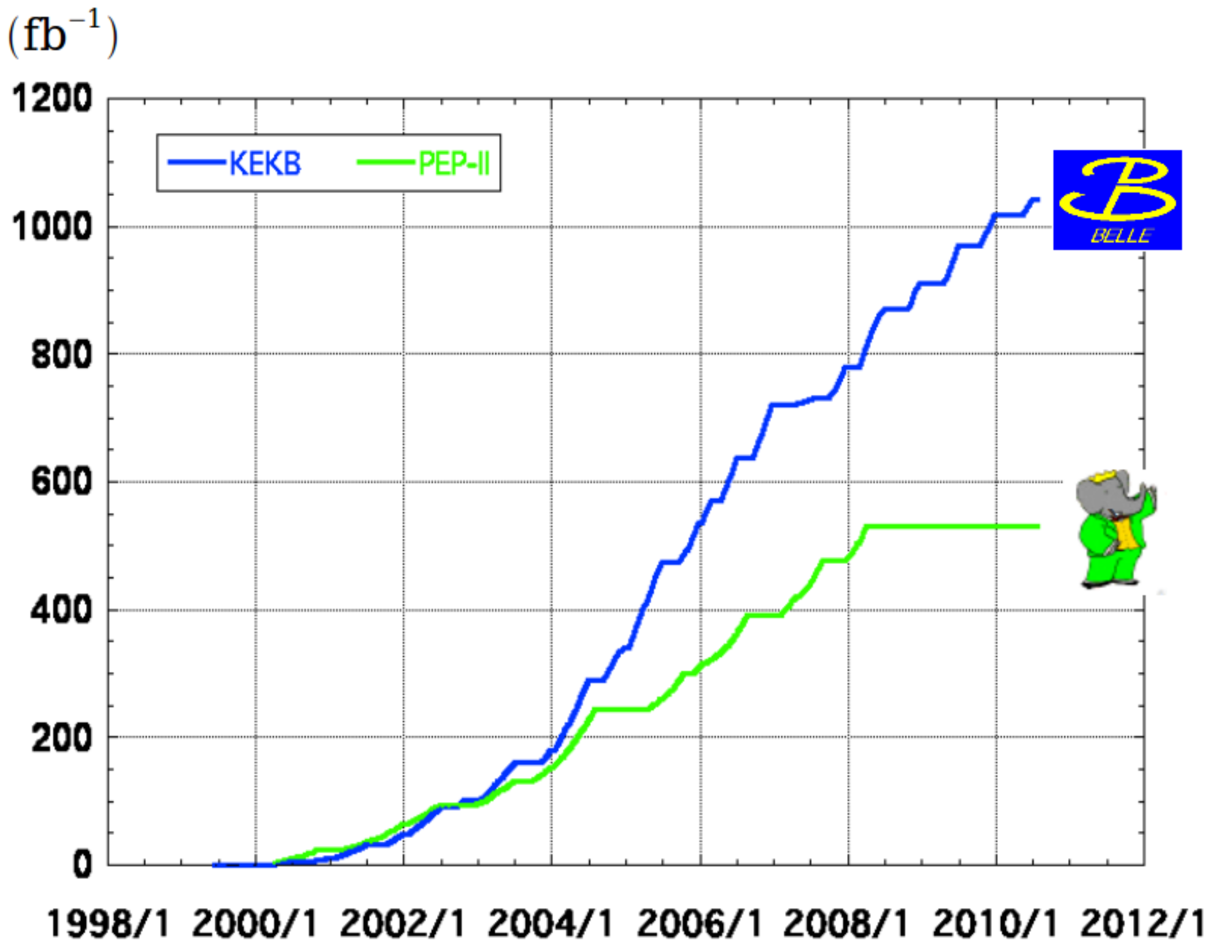
| *Experiments* | *# of b events* | *Environment* | *Characteristics* |
|---|---|---|---|
| LEP Coll.<br>ALEPH/DELPHI/ L3/OPAL | ~1M<br>(each expt.) | $Z^0$ decays ($\sigma$~6nb) | Back-to-back 45GeV b-jets<br>All B hadrons produced<br>**Stopped** |
| SLD | ~0.1M | $Z^0$ decays ($\sigma$~6nb) | Back-to-back 45GeV b-jets<br>All B hadrons produced<br>Beam polarized<br>**Stopped** |
| ARGUS | ~0.2M | $\Upsilon(4S)$ decays ($\sigma$~1.2nb) | B mesons produced at rest<br>$B^0$ and $B^+$ produced<br>**Stopped** |
| CLEO | ~9M | $\Upsilon(4S)$ decays ($\sigma$~1.2nb) | B mesons produced at rest<br>$B^0$ and $B^+$ produced<br>**Running at charm threshold** |
| Belle<br>Babar | | $\Upsilon(4S)$ decays ($\sigma$~1.2nb) | B mesons produced at rest<br>$B^0$ and $B^+$ produced<br>**Running** |
| TeVatron Coll.<br>CDF/D0 | ~several | $p\bar{p}$ collider<br>E(c.d.m)=1.8 TeV | Triggered events<br>All B hadrons produced<br>**Running** |

# Final Luminosity of BaBar in 2008



# Accumulated Luminosity in Belle

## Integrated luminosity of 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:**

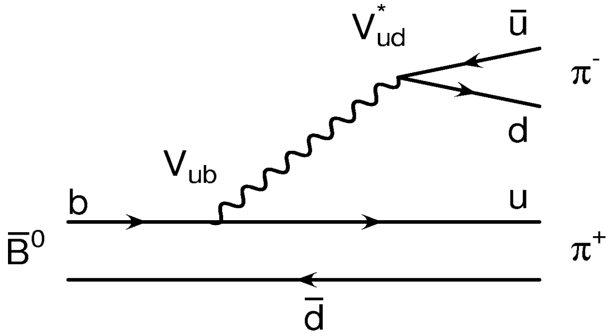
~ 54 fb$^{-1}$

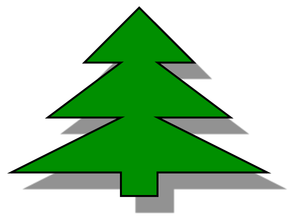
# Catalog of B decays

# Introduction to Diagram Jargon!

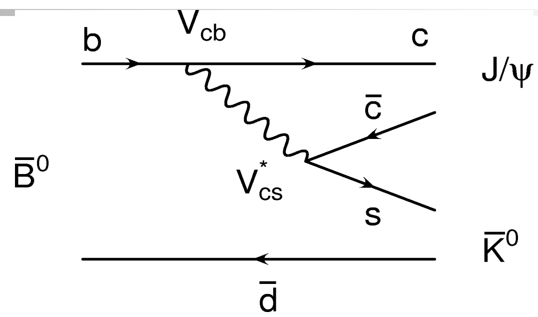
# Tree Diagrams

## Spectator

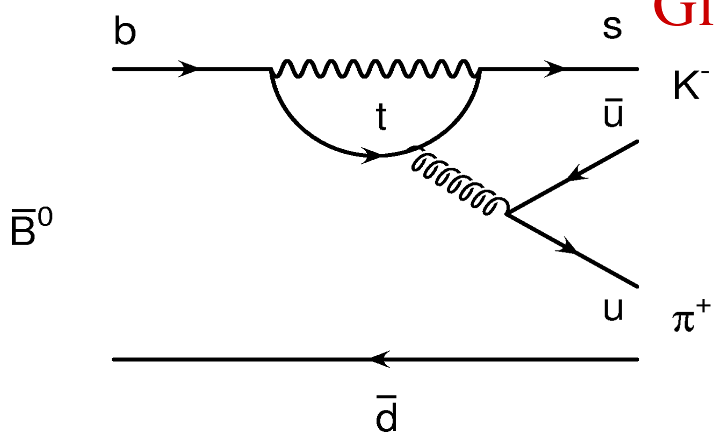


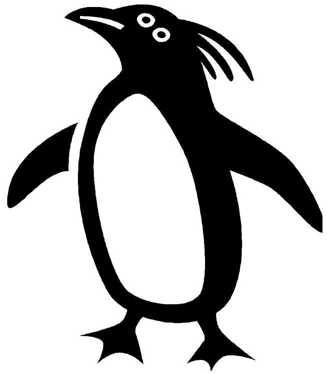



## Color Suppressed

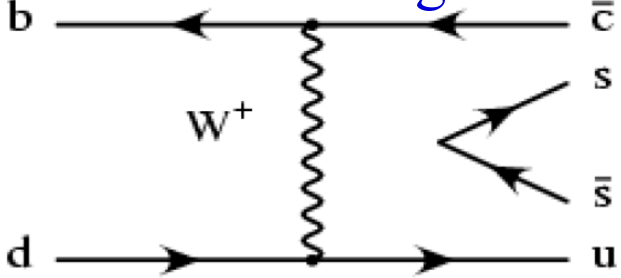



## Gluonic Penguin

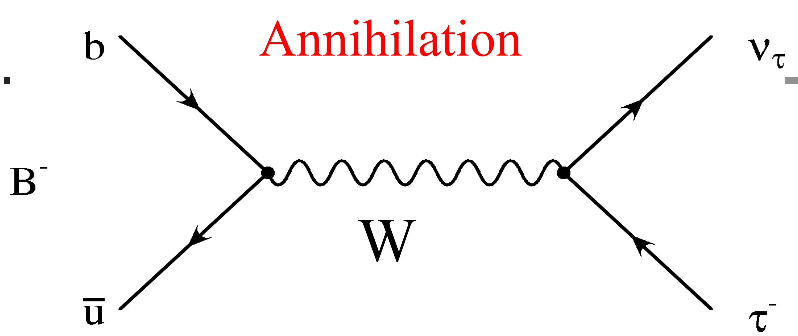


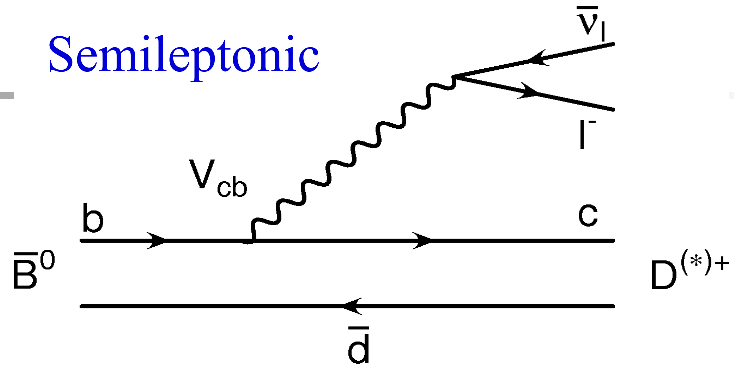
## W-Exchange



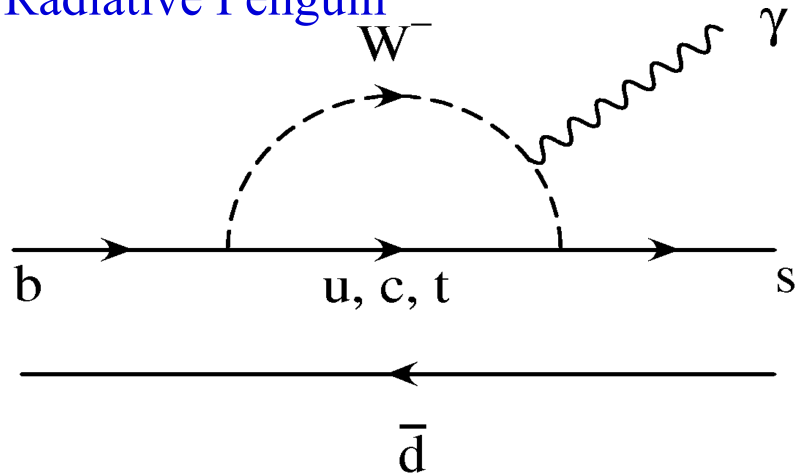
Annihilation



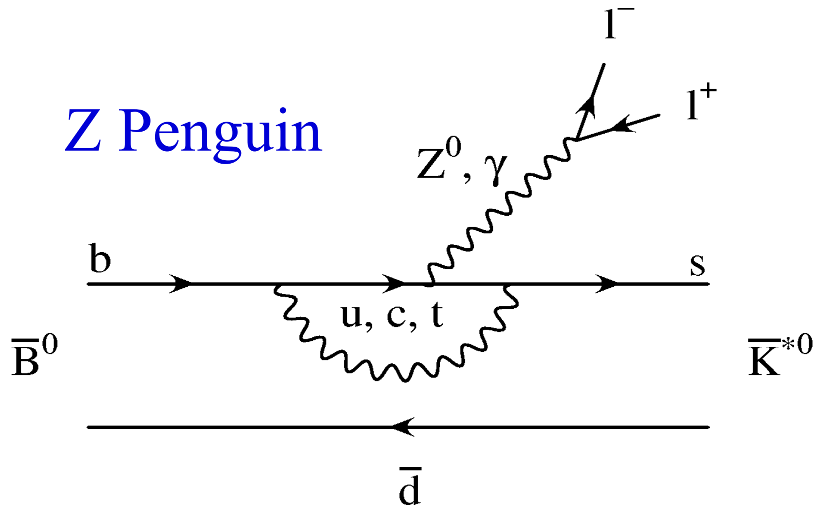

Semileptonic

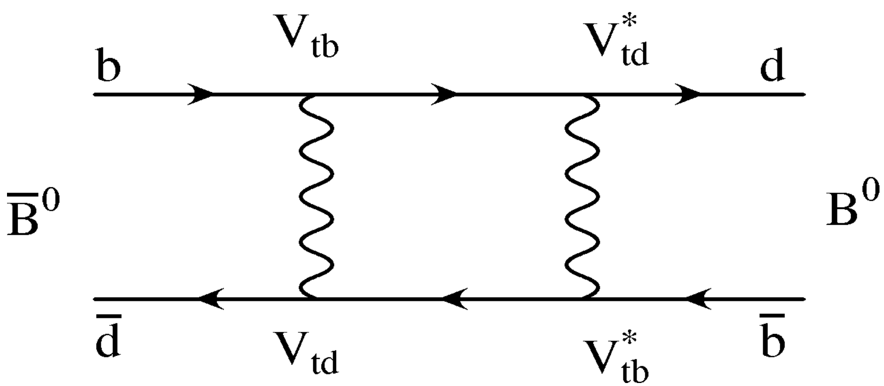



Radiative Penguin




Z Penguin



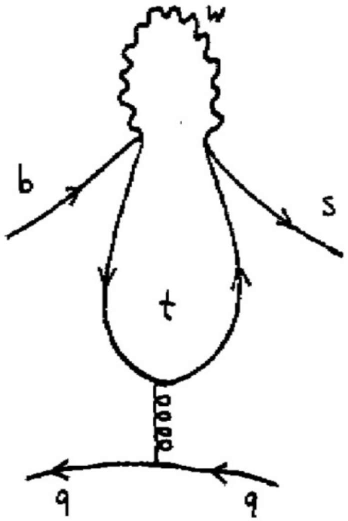

B⁰ Oscillation

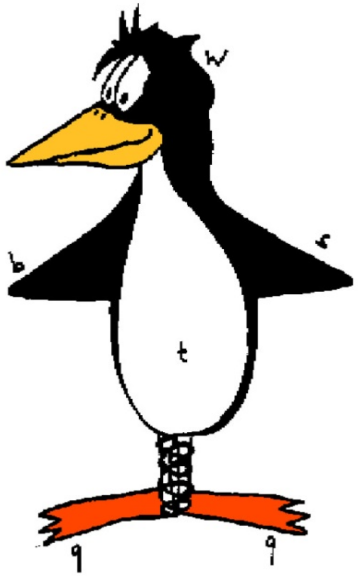
# Penguins in B Decays!?

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."

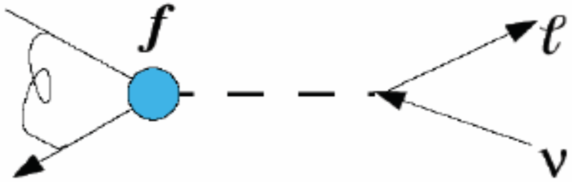


# Topology of Tree Decay Amplitudes

**Leptonic**

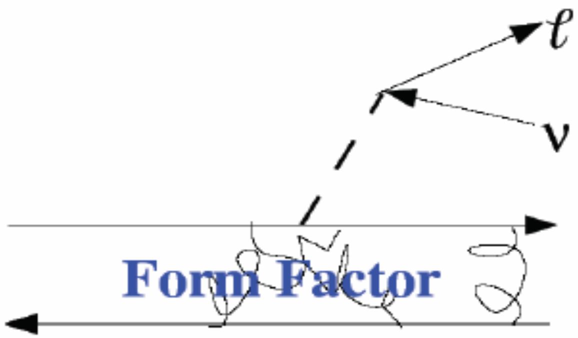
**Hadronic & Leptonic current do factorize**




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

**Semileptonic**

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

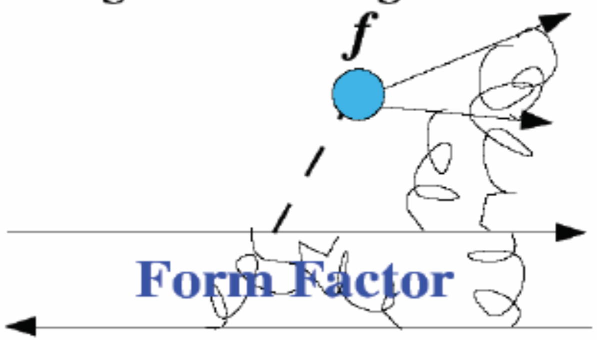



**Exclusive Decays:**
* **FF: Symmetries ($\chi$ & HQS)**
* **FF: Lattice QCD, Sum Rules; ...**

**Inclusive Decays:**
* **Operator Product Expansion**

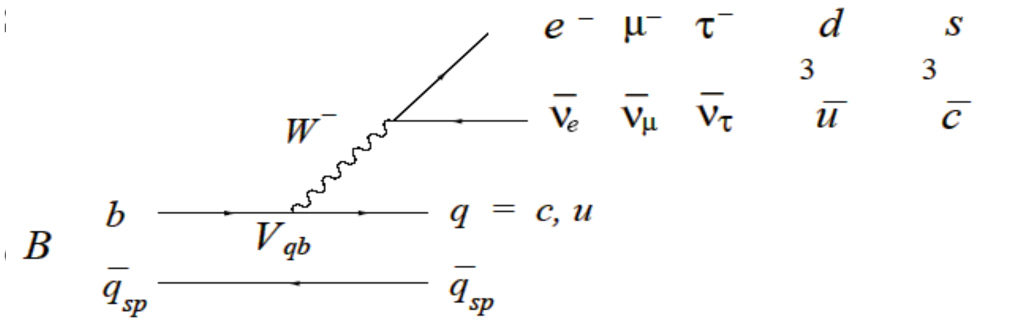
**Hadronic**

**No factorization in naïve sense due to gluon exchange**

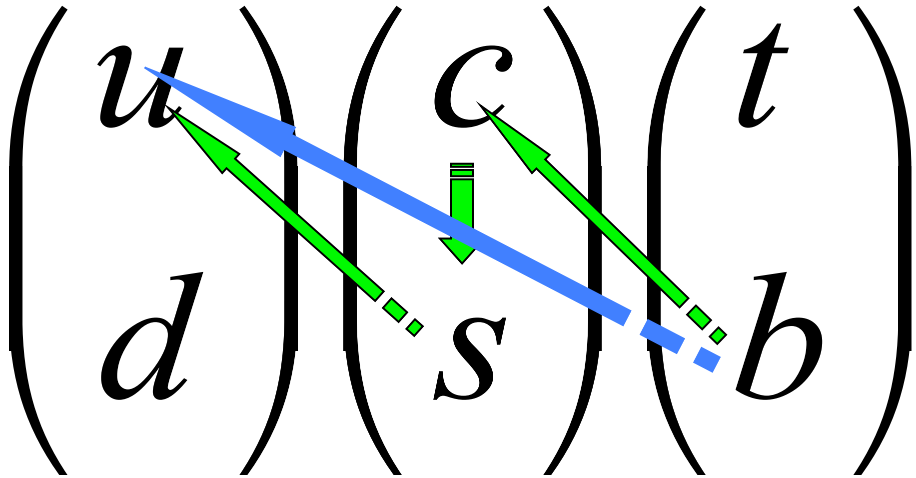



**Theoretical developments:**
**e.g. QCD Factorisation approach**
**Not used for $|V_{ij}|$ extraction (yet)**

# Summary of b-quark Decay



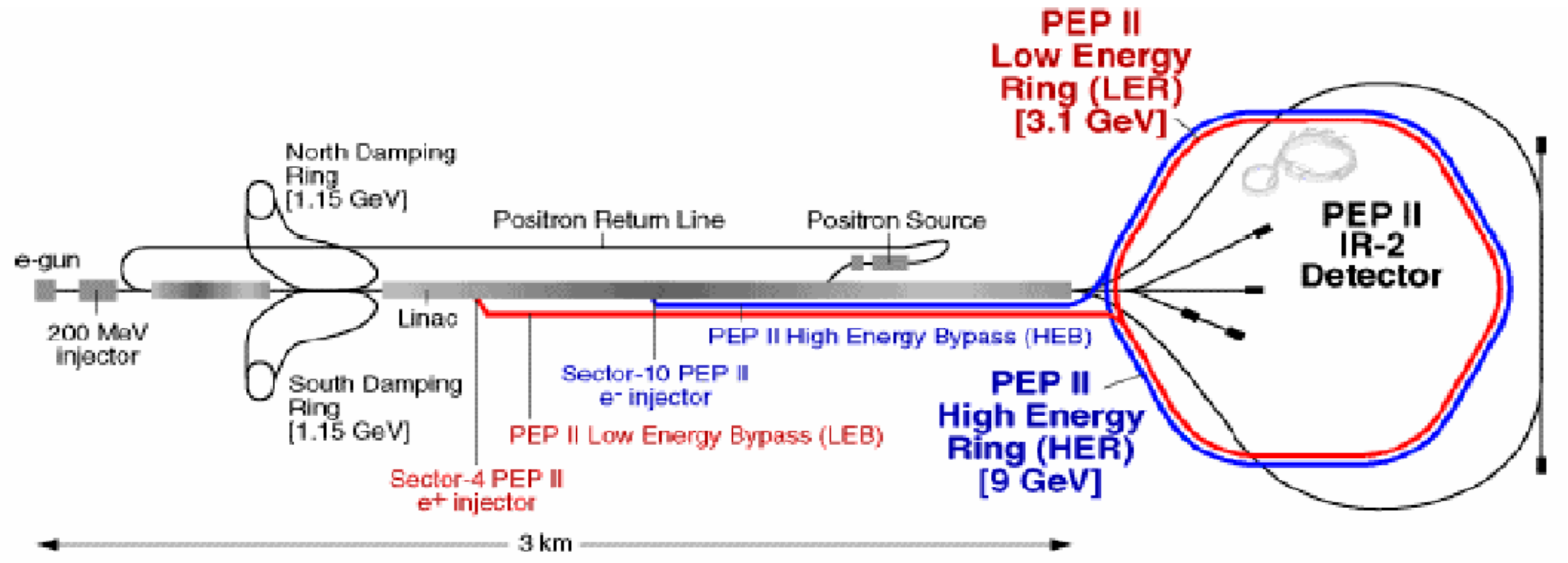

| Mode | $N_c$ | $f_{QCD}$ | $f_{ps}$ | $V_{xb}$ | $\mathcal{B}$ |
|---|---|---|---|---|---|
| $c\bar{u}d'$ | 3 | 1.3 | 0.52 | 0.038 | 48% |
| $c\bar{c}s'$ | 3 | 1.3 | 0.25 | 0.038 | 23% |
| $ce\bar{\nu}_e$ | 1 | 1.0 | 0.52 | 0.038 | 12% |
| $c\mu\bar{\nu}_\mu$ | 1 | 1.0 | 0.52 | 0.038 | 12% |
| $c\tau\bar{\nu}_\tau$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

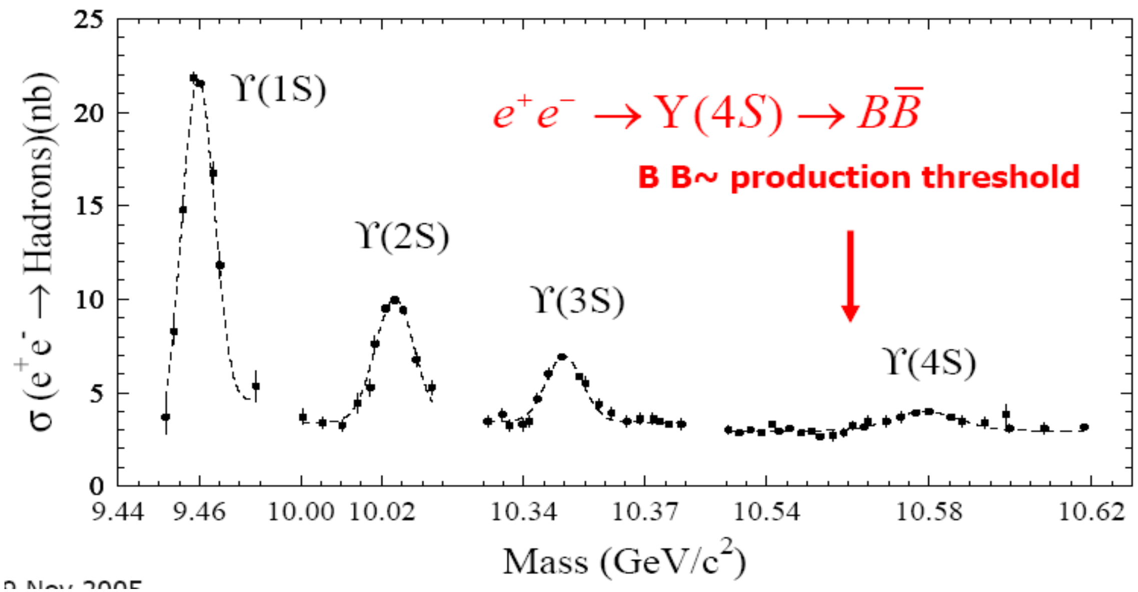



- 99% of B's $\rightarrow$ D's
- 66(13)% of B's $\rightarrow K^+(K^-)$: flavor tagging
- 10% semi-leptonic BR: flavor tagging
- $7 \times 10^{-4}$ of B's $\rightarrow J/\psi \rightarrow \mu^+\mu^-$
- mean track multiplicity for single B $\sim 5.5$

# Brief Primer of B Reconstruction at $e^+e^-$ B Factory

# PEP-II Asymmetric B-Factory at SLAC

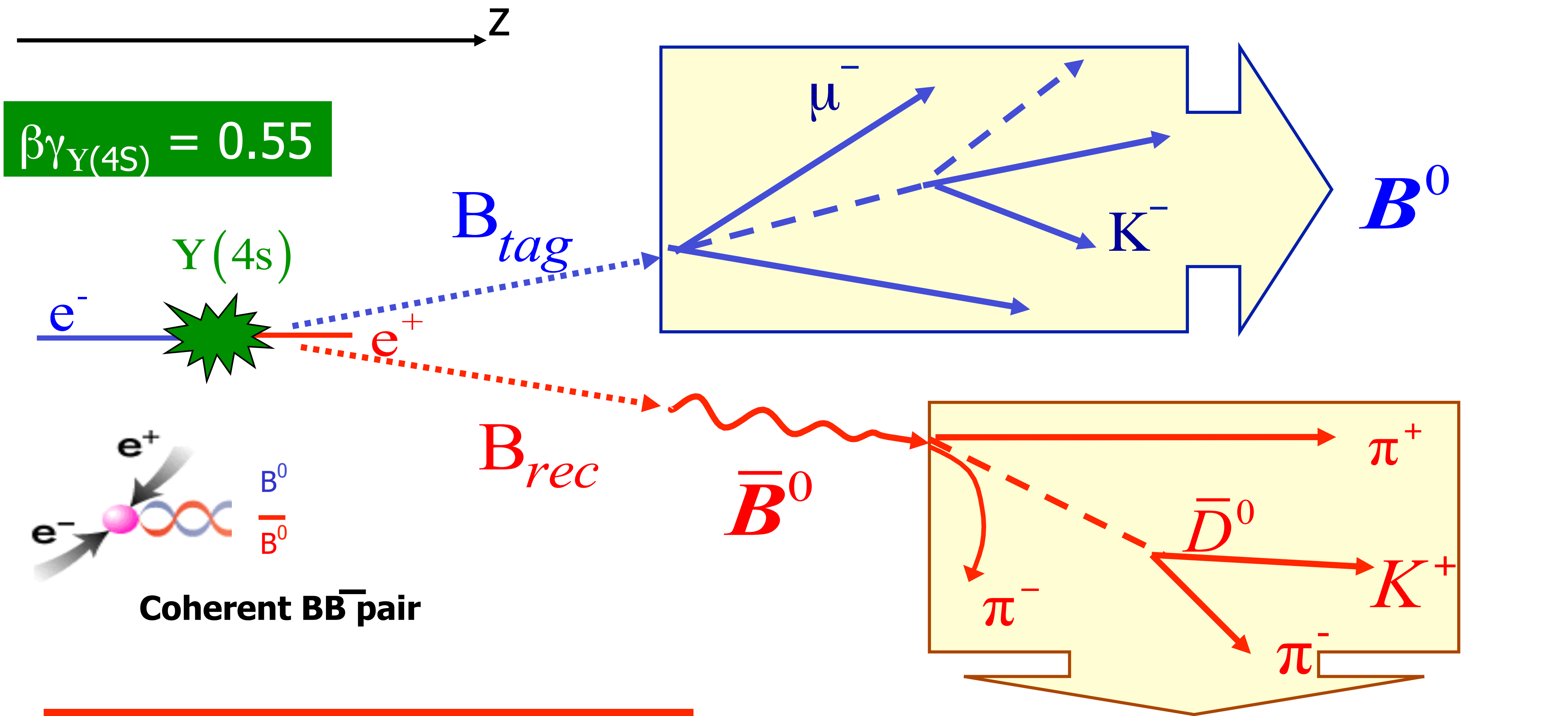



- 9 GeV e⁻ on 3.1 GeV e⁺
- Υ(4S) boost in lab frame
  - $\beta\gamma = 0.55$

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

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




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

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