Heavy Flavors

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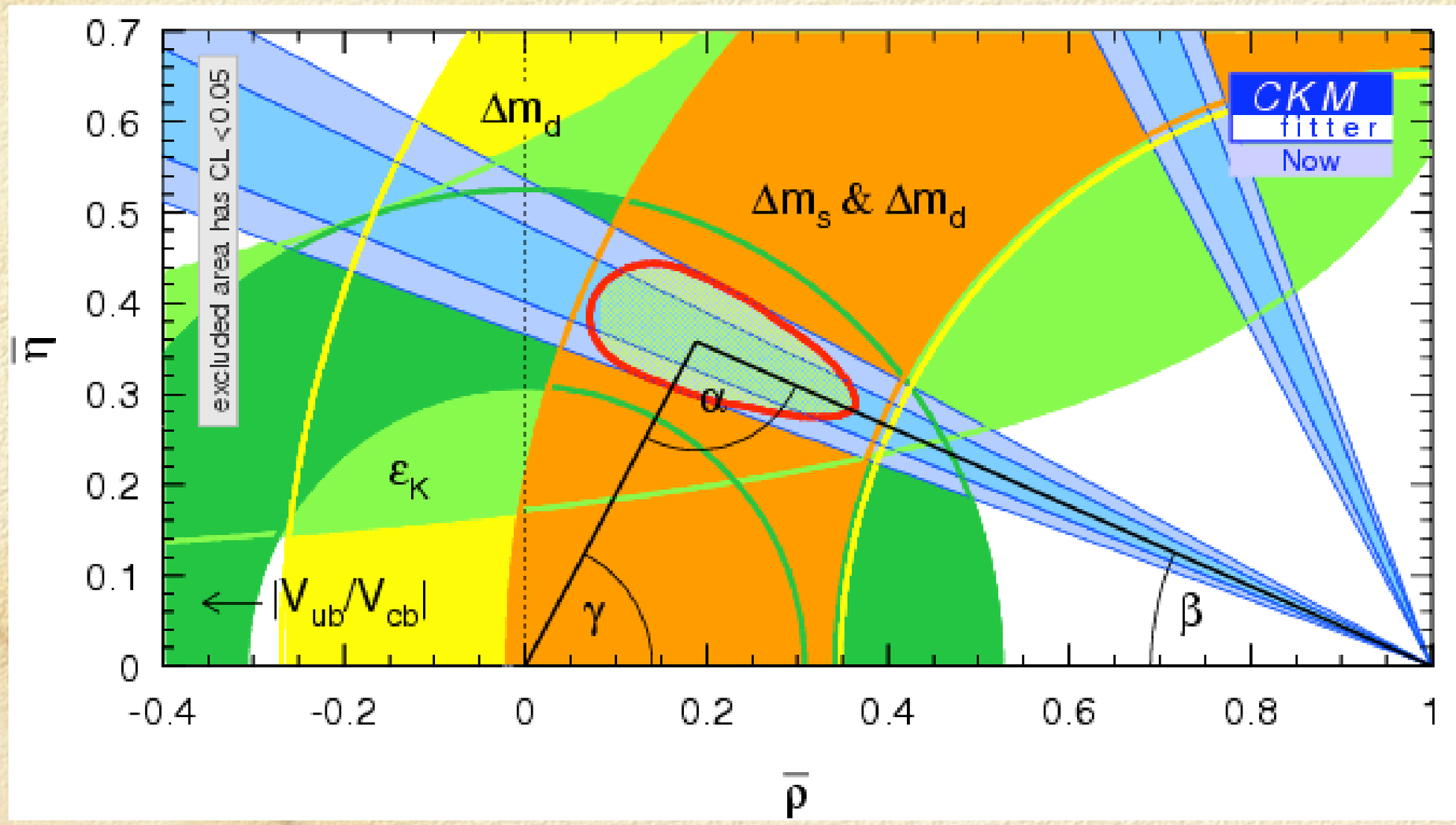
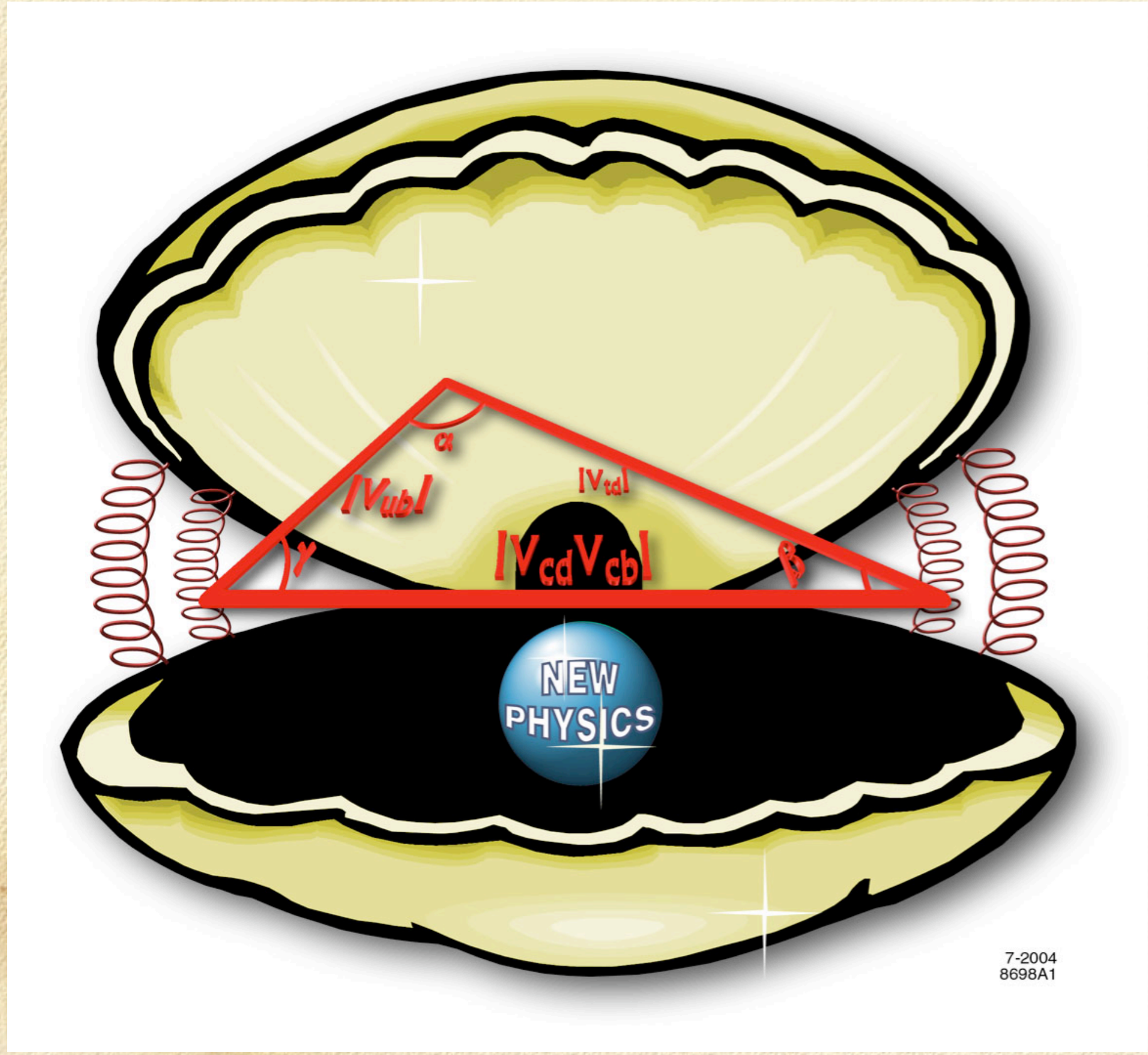
DPF 2004

Weak Quark Interactions

$$V_{\text{up,down}} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & c & b \end{array} \\ \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$



QCD and CKM



Heavy Flavor Physics

- Two Hadronic Currents
  - Charmless Decays
  - Vector Vector Decays
- One Hadronic Current
  - Electro-Weak Penguin Decays
  - Semi-Leptonic B Decays
- No Hadronic Currents
  - Leptonic Decays
- Meson Mixing
  - B^0, D^0, and $\Delta\Gamma(B_s)$
- Topics Not Covered
  - Charmless 3-body decays
  - $B \to DX$ Decays
  - $|V_{cb}|$ or $D \to X\ell\nu$
  - B_c, D_{sJ} states, $X(3872)$
  - Υ spectroscopy

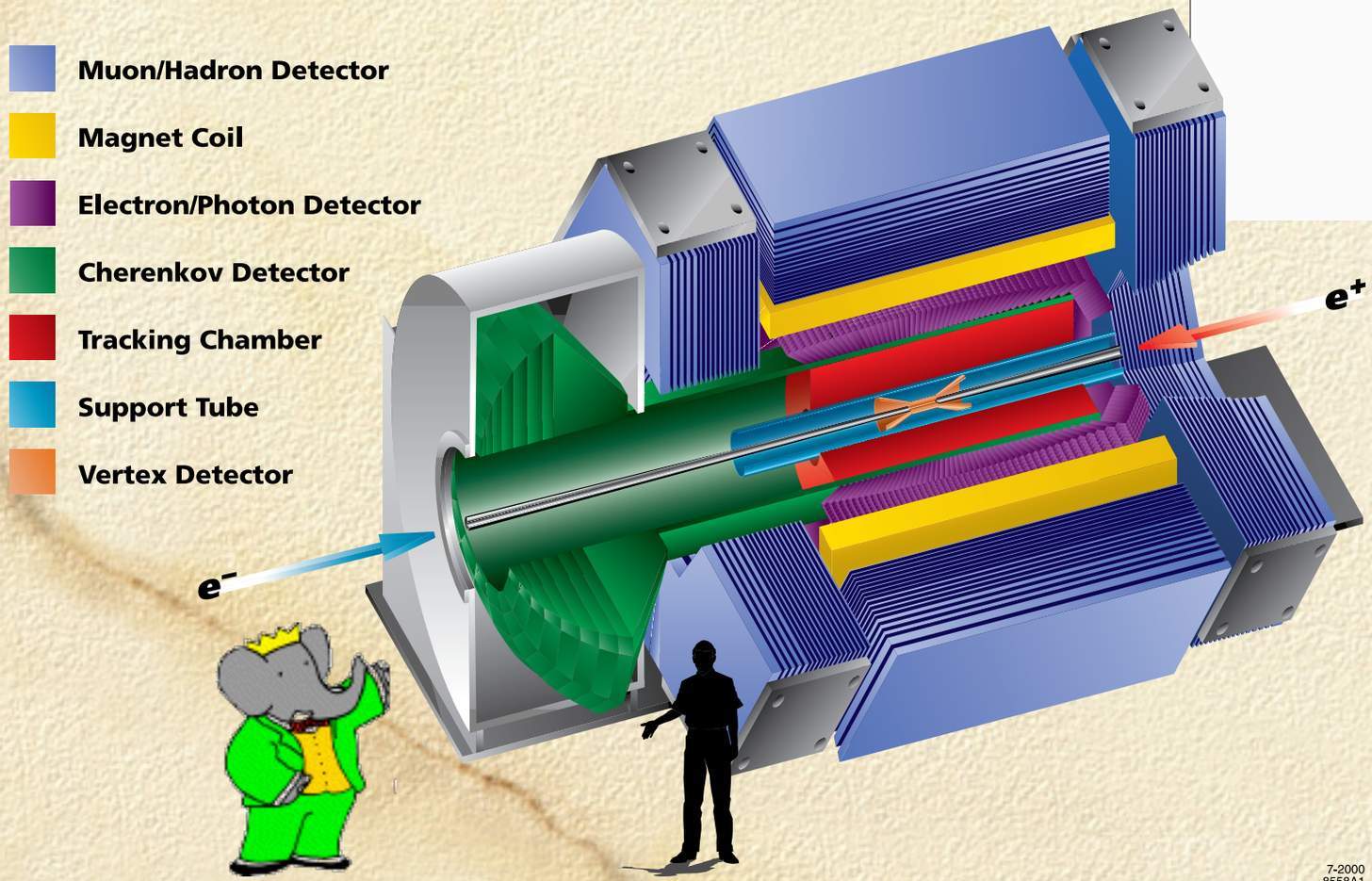
B Factories

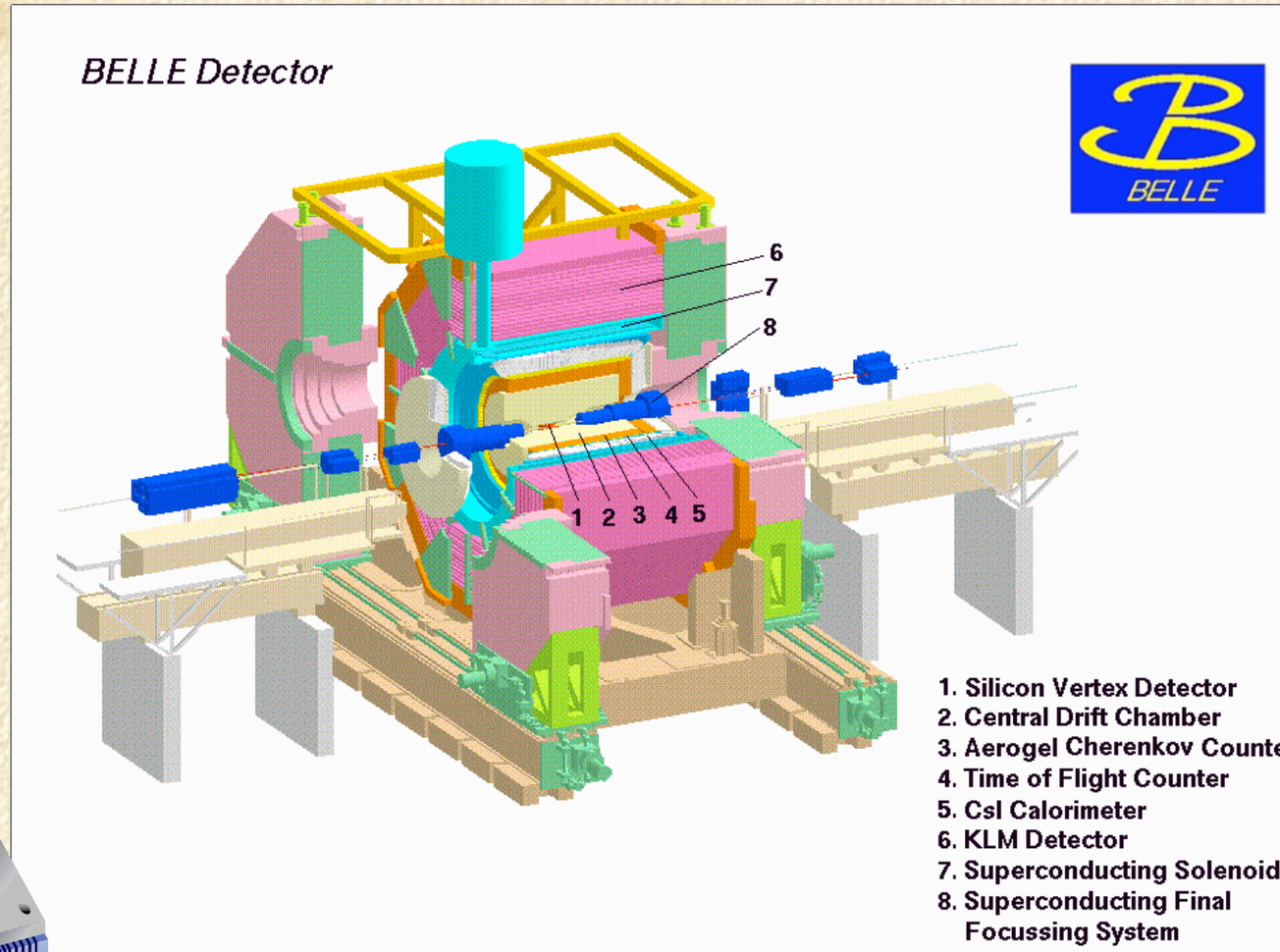
$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

$$\sigma(B\bar{B}) = 1.10\,\text{nb}$$

Asymmetric e^+e^-

$\beta\gamma = 0.56$ or 0.43





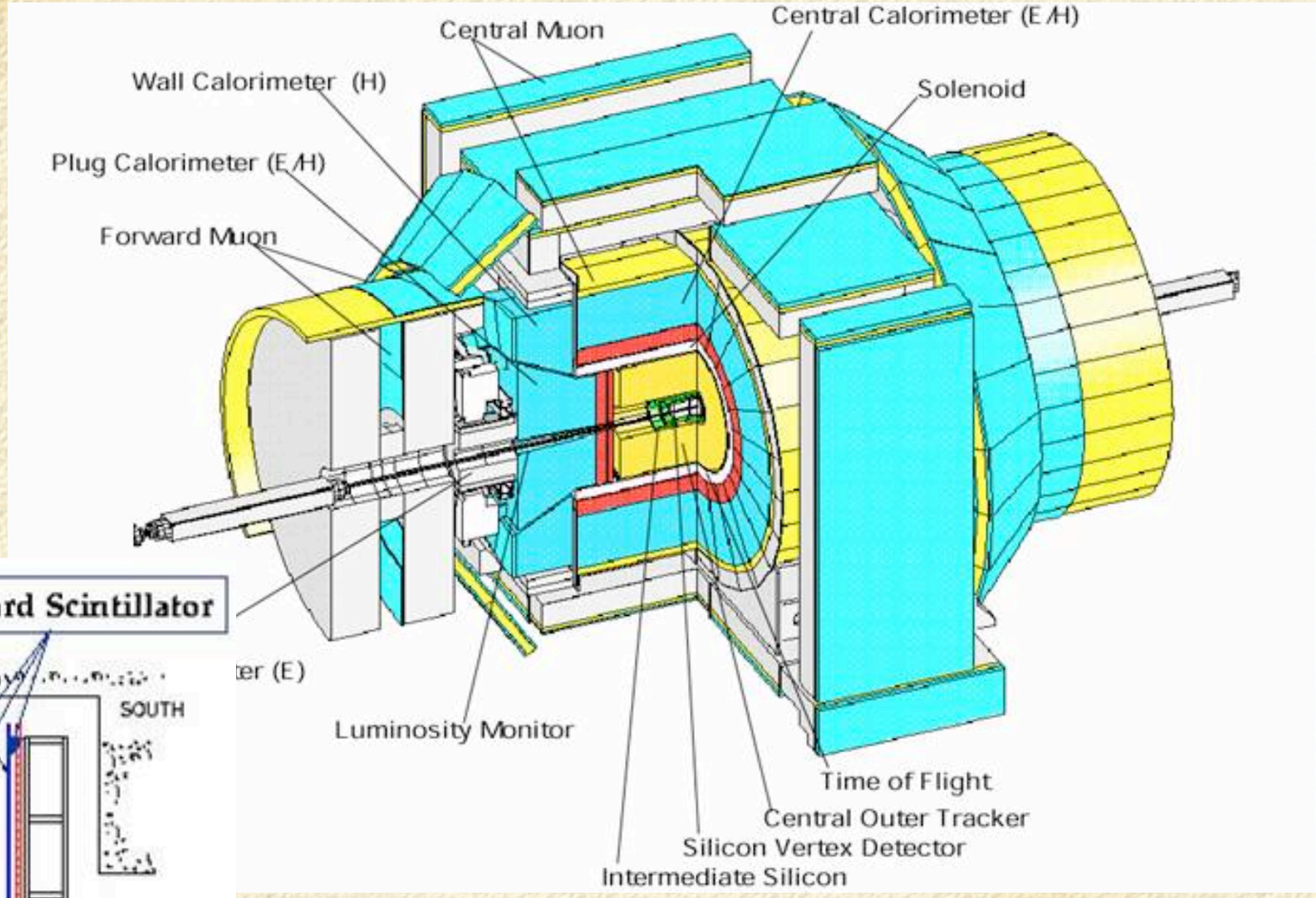
1999-2004

BABAR 205 fb^{-1}

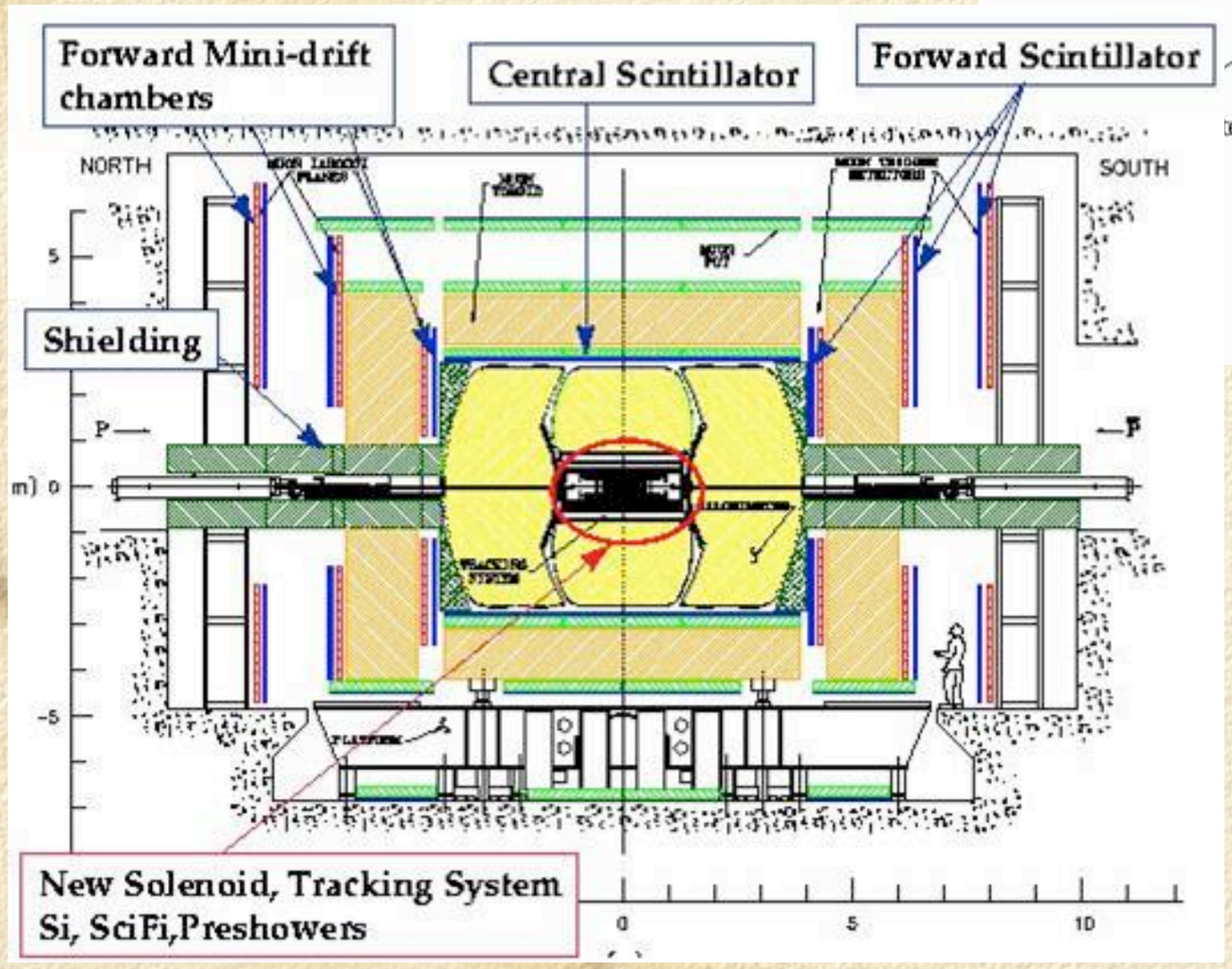
BELLE 253 fb^{-1}

Tevatron Experiments

CDF



D0

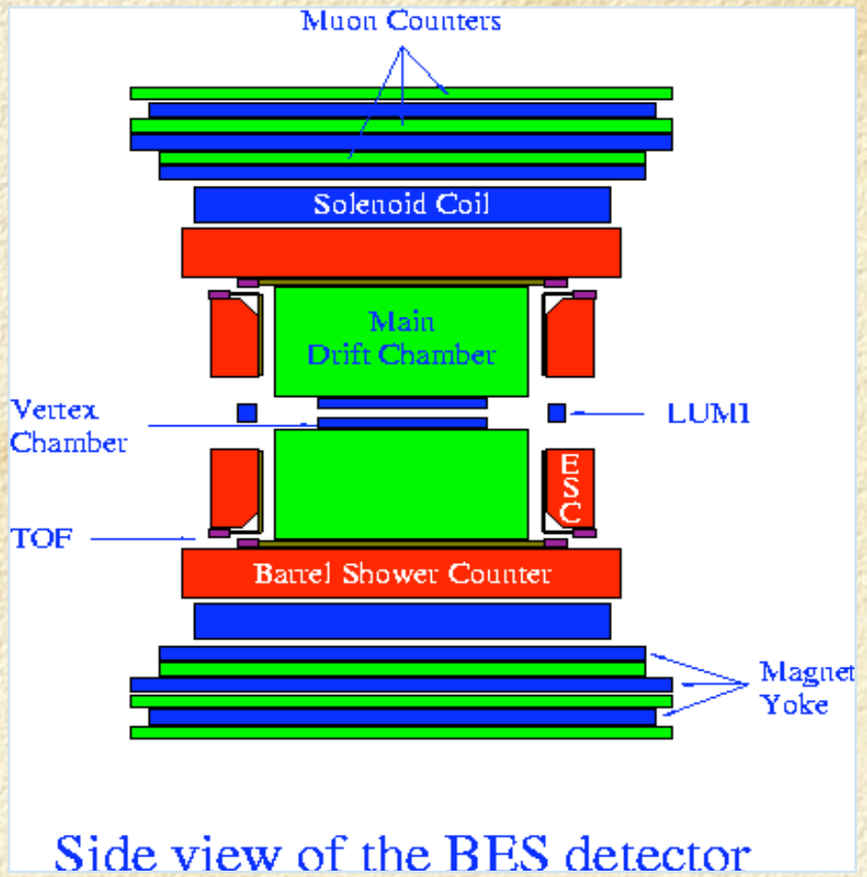


$200 - 250\,\mathrm{pb}^{-1}$ data samples

$\sigma(p\overline{p} \to bX) \sim 100mb$

separated vertex trigger (CDF) and muon triggers

Charm Factories



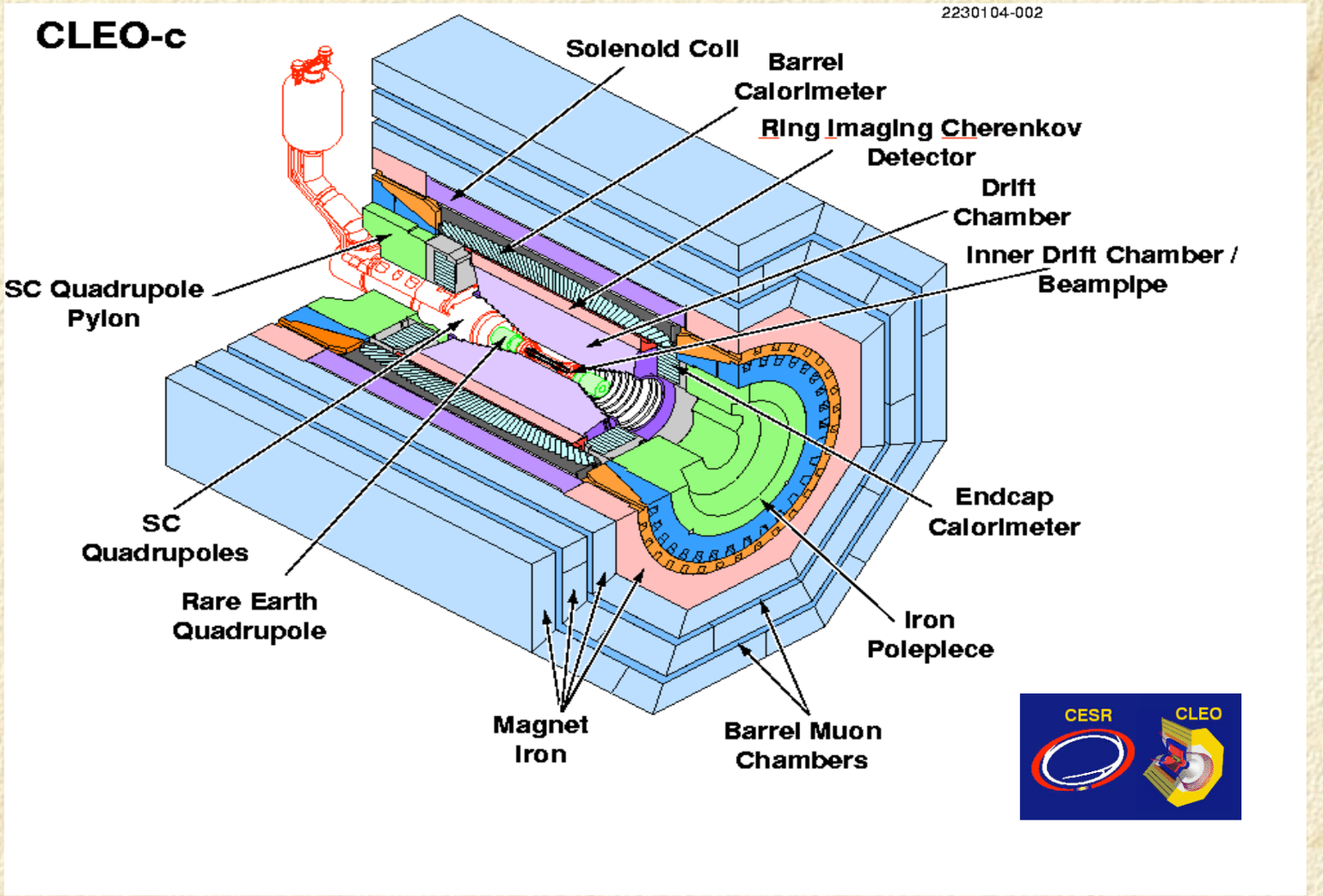
Side view of the BES detector

$\psi(3770) \rightarrow DD$

other topics

J/ψ & $\psi(2S)$ decays

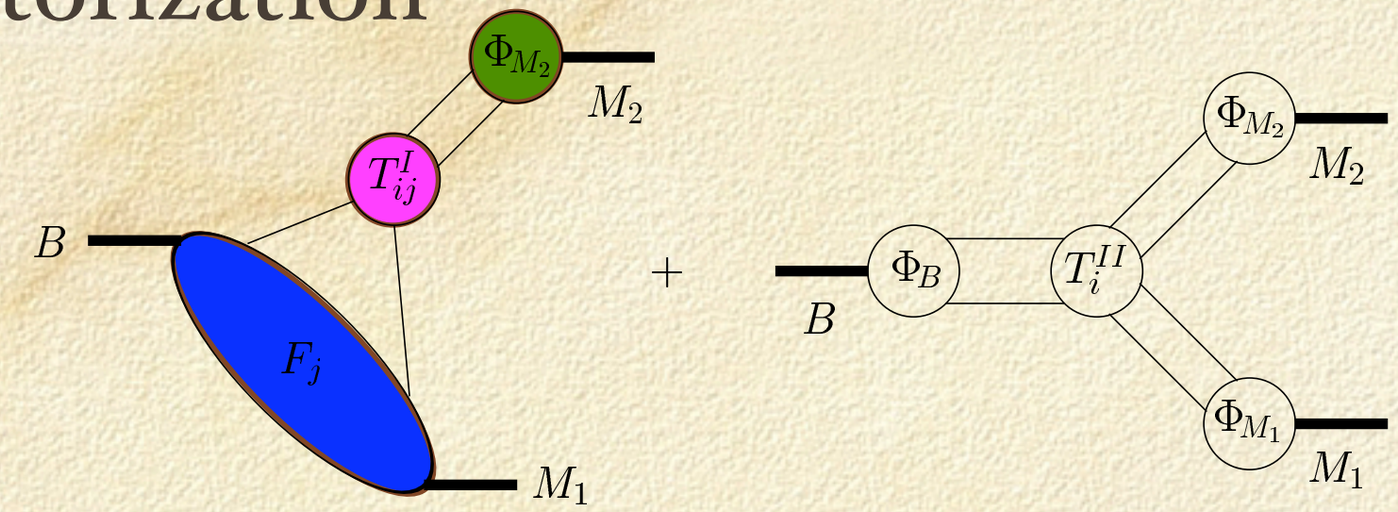
Υ spectroscopy



BES-III upgrade by 2007

Two Hadronic Currents

QCD Factorization



$$\langle M_1' M_2' | Q_i | \bar{B} \rangle = \sum_{\{M_1, M_2\} \in \{M_1', M_2'\}} F_j^{B \to M_1} T_{ij}^I * f_{M_2} \Phi_{M_2} + T_i^{II} * f_B \Phi_B * f_{M_1'} \Phi_{M_1'} * f_{M_2'} \Phi_{M_2'}$$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left(C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3,\ldots,10} C_i Q_i + C_{7\gamma} Q_{7\gamma} + C_{8g} Q_{8g} \right)$$

Factorization: amplitude is a product of terms -

naive factorization - Form Factor, 4-Quark Operator, Decay Constant, Light Cone Φ

QCD improved factorization - include term with hard gluon exchanges

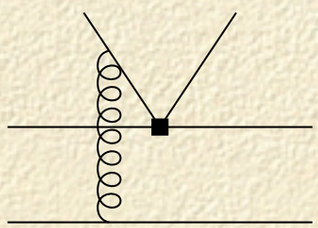
Non-Factorizable contributions

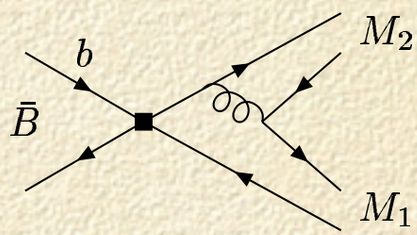
Hard Spectator Scattering

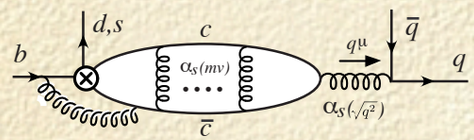
Annihilation

Charming Penguins

SCET



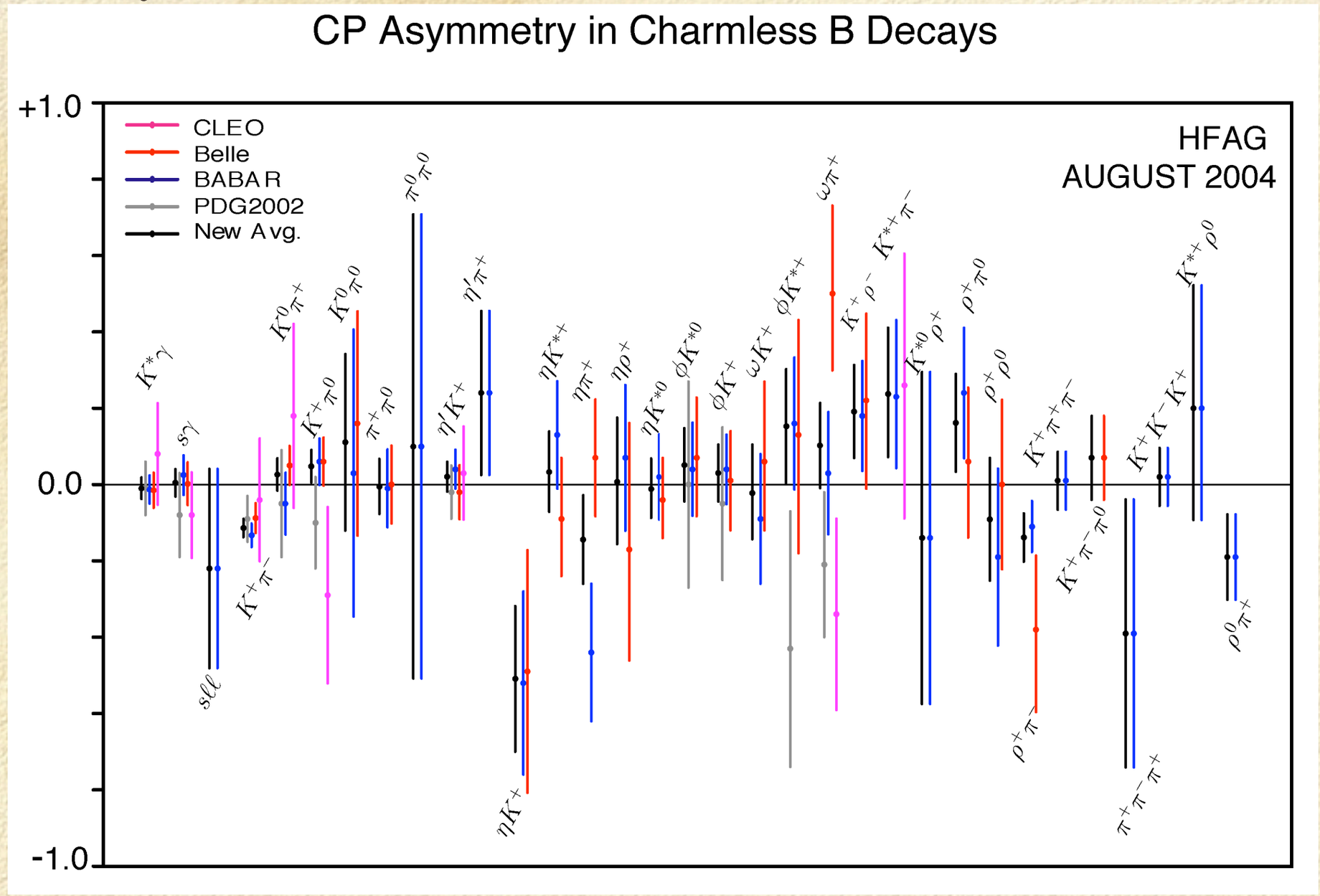




see Beneke, Buchalla, Neubert & Sachrajda Nucl.Phys.B606:245-321,2001 hep-ph/0104110

Charge Asymmetries

A_{CP}



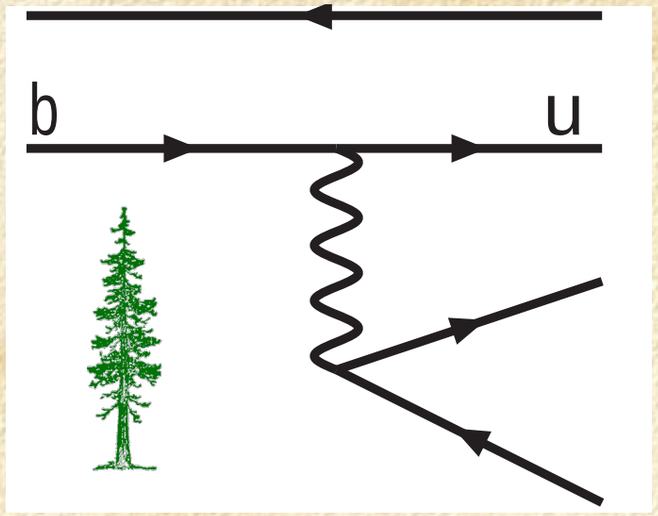
$$A_{CP} \sim |a_2|/|a_1| \sin(\Delta\phi_{\text{weak}}) \sin(\Delta\phi_{\text{strong}})$$

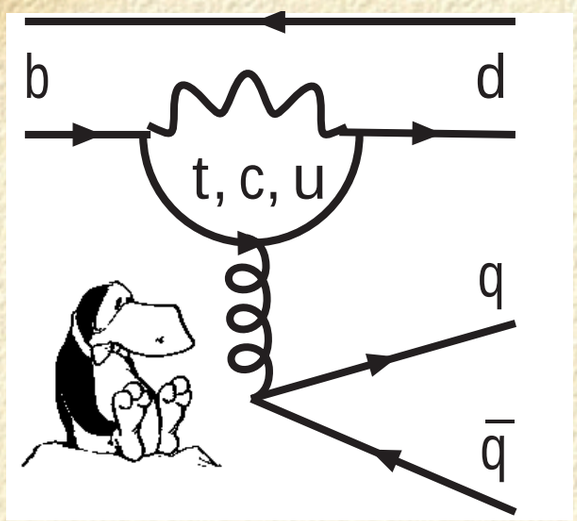
QCD Factorization: strong phases are small

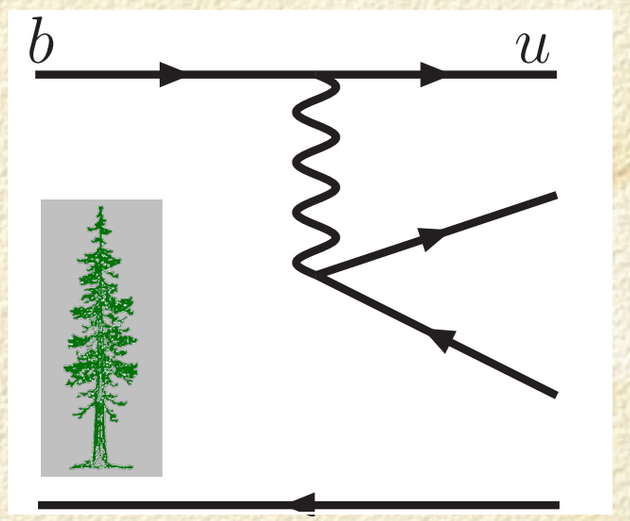
Non-Factorizable amplitudes: may produce strong phases

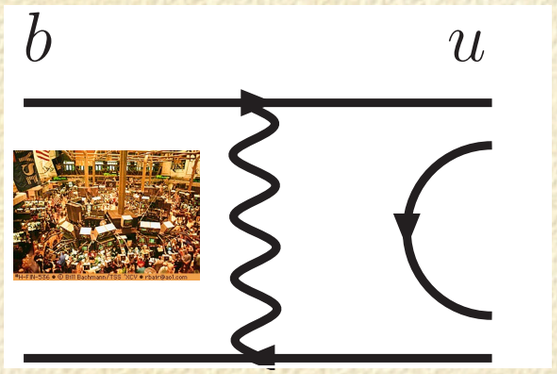
eg. Final State Rescattering

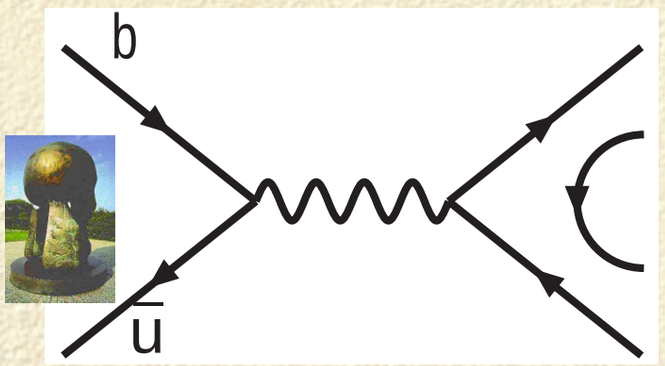
Diagrammatic Analysis

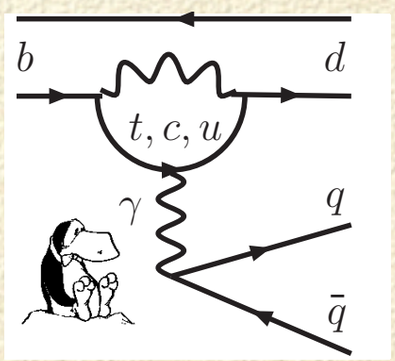






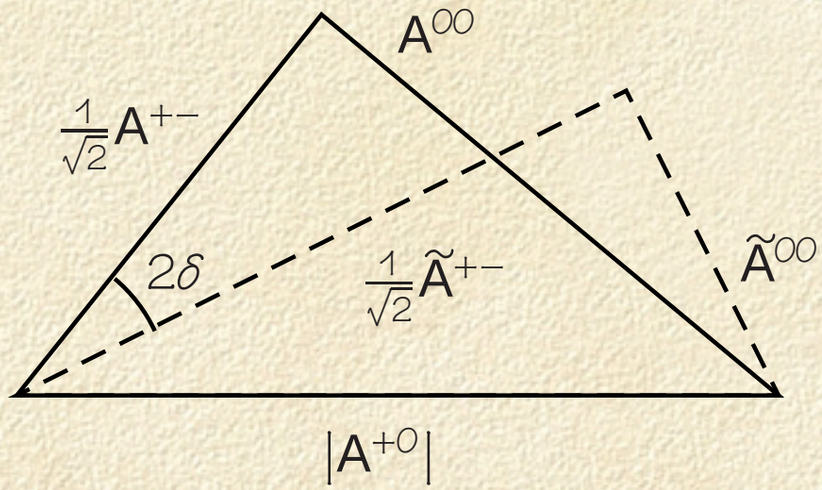






consider $B \to \pi\pi$ or $B \to \rho\rho$

$$A(B^0 \to \pi^+\pi^-) = \sqrt{2}(Te^{i\gamma} + Pe^{-i\beta})$$
$$A(B^0 \to \pi^0\pi^0) = (Ce^{i\gamma} - Pe^{-i\beta})$$
$$A(B^0 \to \pi^+\pi^0) = (C+T)e^{i\gamma}$$



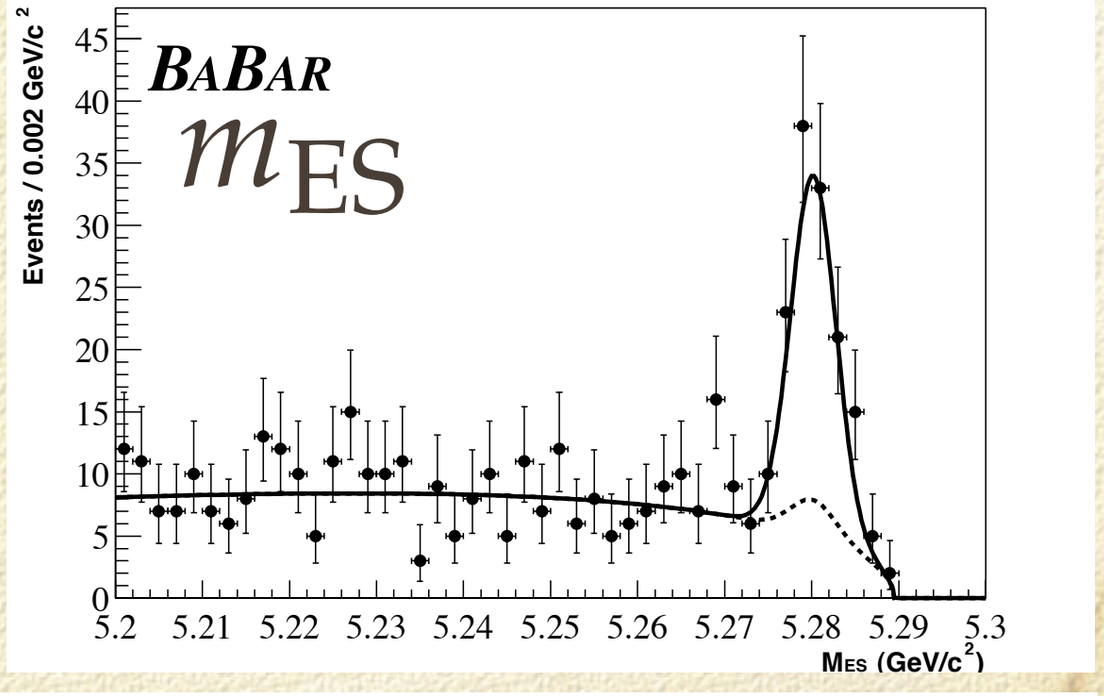
Signal vs. Background in Rare B Decays

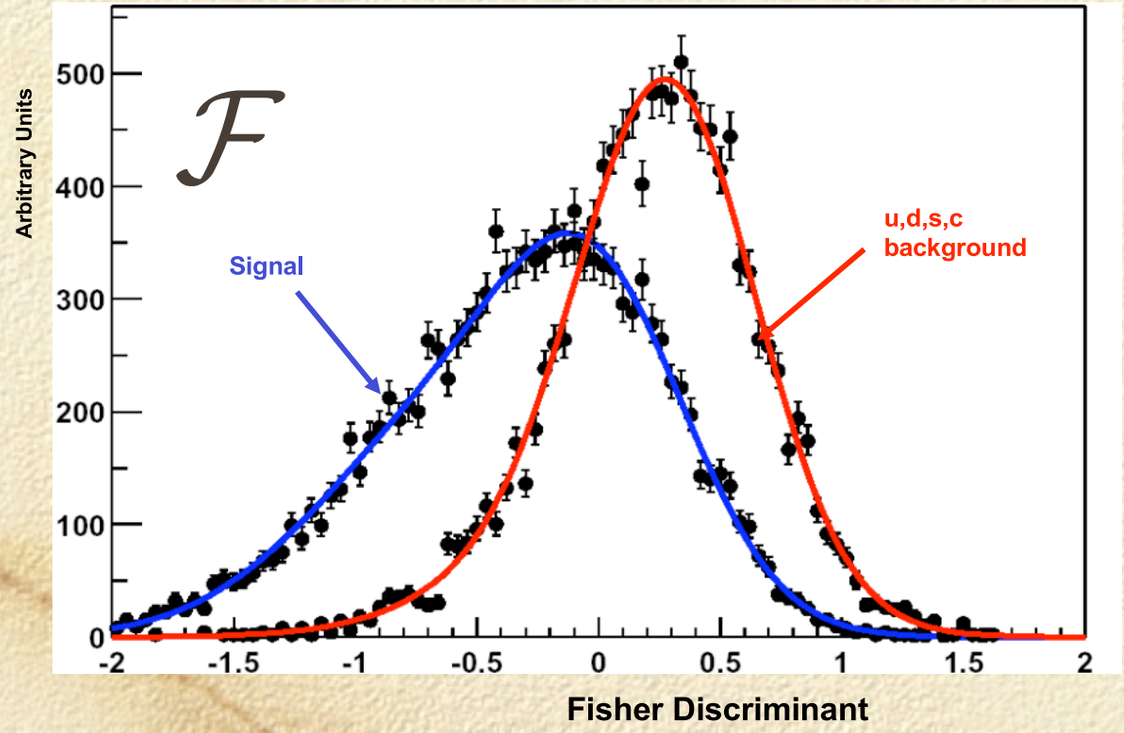
Kinematic Variables

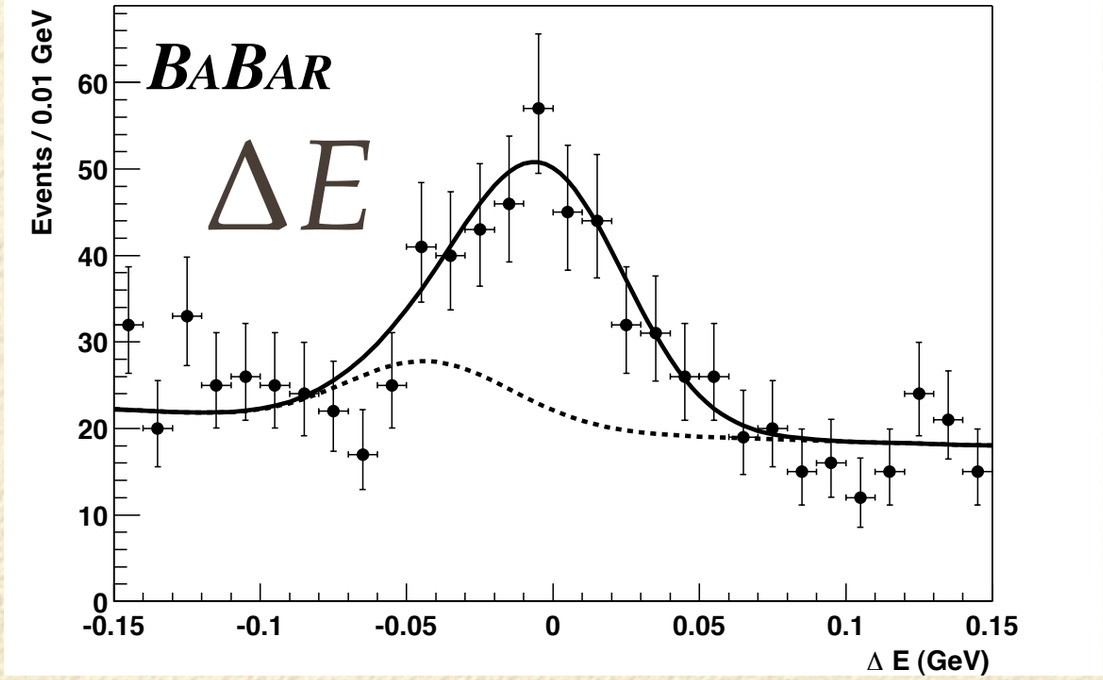
- $m_{\mathrm{ES}} = \sqrt{(E^{CM}_{\mathrm{beam}})^2 - (p^{CM}_{B^0})^2}$
- $\Delta E = E^{CM}_{B^0} - E^{CM}_{\mathrm{beam}}$

Event Shape Variables

- $\mathcal{F} = c_0 \sum_i p_i + c_2 \sum_i p_i * (\cos\theta_i)^2$





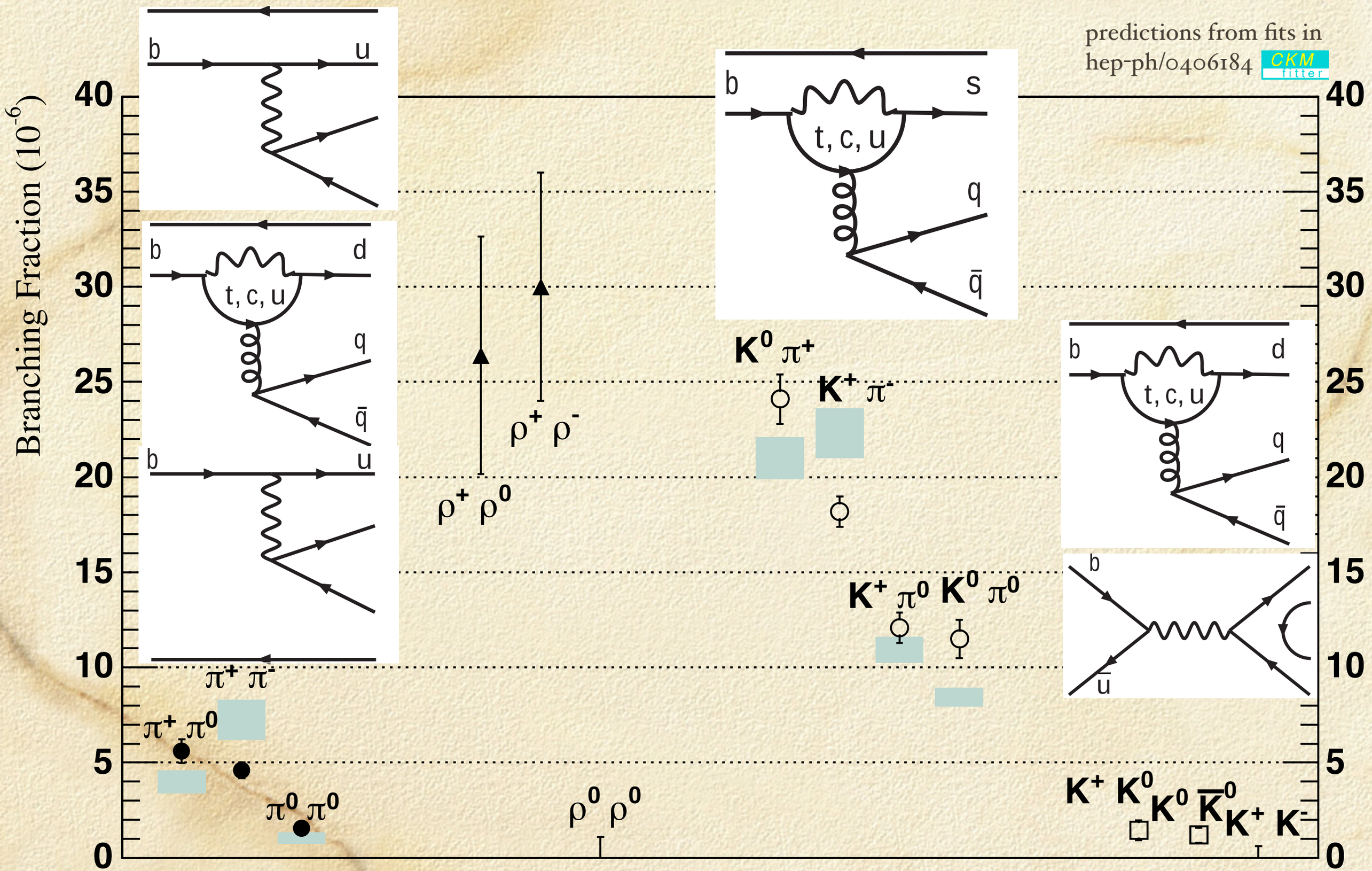


Unbinned Maximum Likelihood Fit $\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_{j=1}^{N} \left[\sum_i n_i \mathcal{P}_i\left(\vec{x}_j; \vec{\alpha}_i\right)\right]$

Charmless Decays

predictions from fits in hep-ph/0406184 CKM fitter

Branching Fraction (10^{-6})



Patterns of Charmless Decays

$B \to K\pi$ Ratios

$$R_L = 2\frac{\Gamma(B^+\to K^+\pi^0)+\Gamma(B^0\to K^0\pi^0)}{\Gamma(B^+\to K^0\pi^+)+\Gamma(B^0\to K^+\pi^-)} = 1.12 \pm 0.07$$

$$R_L = 1 + \mathcal{O}(\tfrac{T+P_{EW}}{P})^2$$

$$R_{FM} = \frac{\Gamma(B^0\to K^+\pi^-)+\Gamma(\bar{B}^0\to K^-\pi^+)}{\Gamma(B^+\to K^0\pi^+)+\Gamma(B^-\to \bar{K}^0\pi^-)} = 0.82 \pm 0.06$$

$\gamma < 75^o$ at 95% C.L.

$B \to \pi\pi$ vs. $B \to \rho\rho$

$$\frac{\mathcal{B}(B^0\to\rho^+\rho^-)}{\mathcal{B}(B^0\to\pi^+\pi^-)} = 6.5 \pm 1.5 \qquad \sim \left(\frac{f_\rho}{f_\pi}\frac{F^{B\to\rho}}{F^{B\to\pi}}\right)^2 = 4.4$$

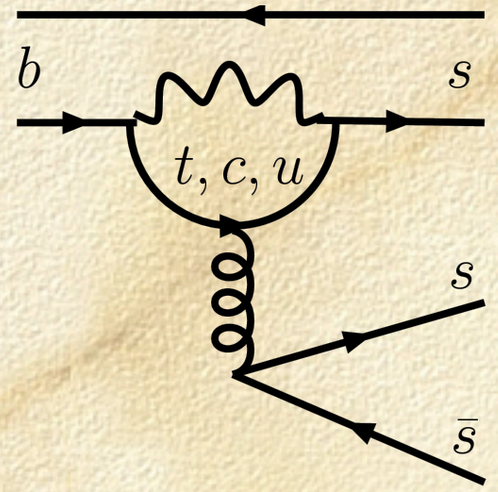
$$\frac{\Gamma(B^0\to\rho^0\rho^0)}{\Gamma(B^+\to\rho^+\rho^0)} << \frac{\Gamma(B^0\to\pi^0\pi^0)}{\Gamma(B^+\to\pi^+\pi^0)}$$

color suppression?

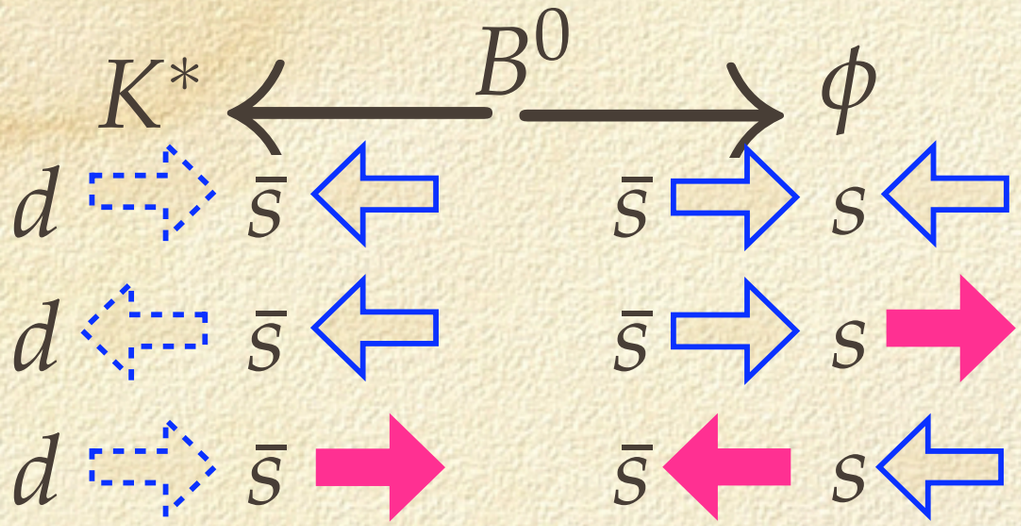
$$\frac{\Gamma(B^+\to\rho^+\rho^0)}{\Gamma(B^0\to\rho^+\rho^-)} = 0.81 \pm 0.26$$

=0.5 w/o EWK Peng

Polarization in B ⇒ VectorVector Decays



Transversity Basis



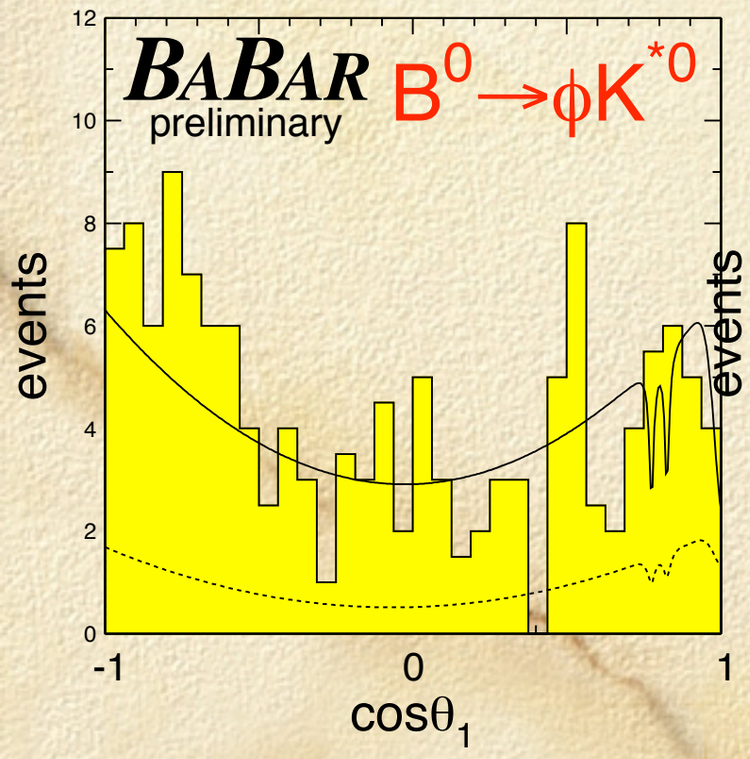
$A_0 \sim 1$

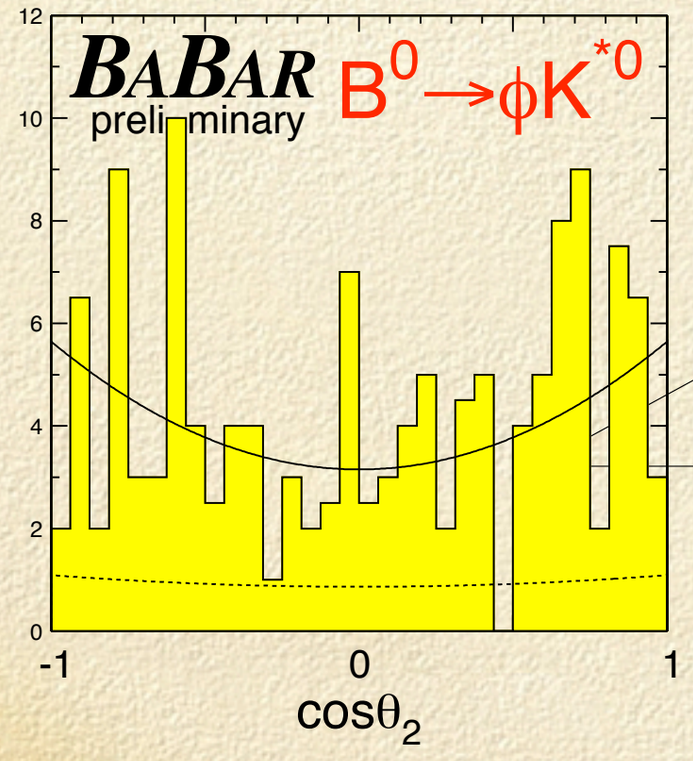
$A_+ \sim m_\phi / m_{B^0}$

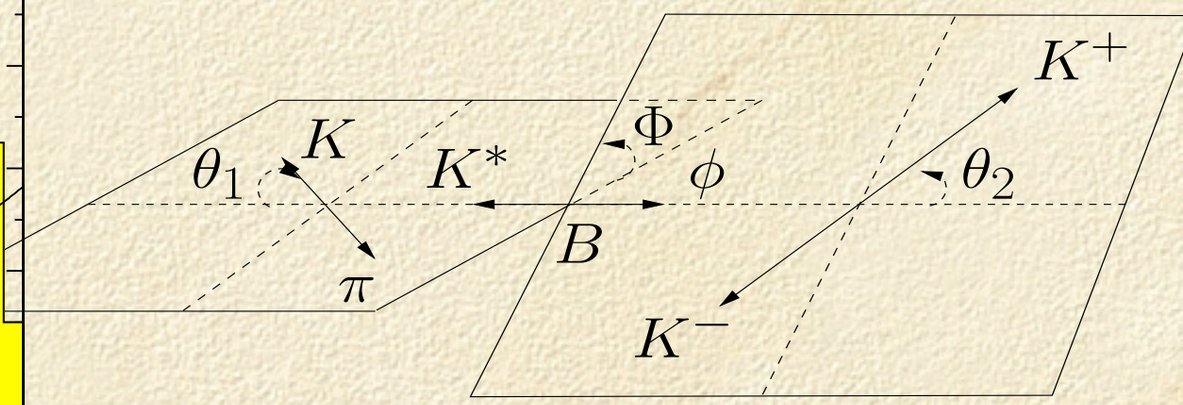
$A_- \sim m_\phi m_{K^*} / m_{B^0}^2$

$A_L = A_0 \quad A_\parallel = 1/\sqrt{2}(A_+ + A_-) \quad A_\perp = 1/\sqrt{2}(A_+ - A_-)$

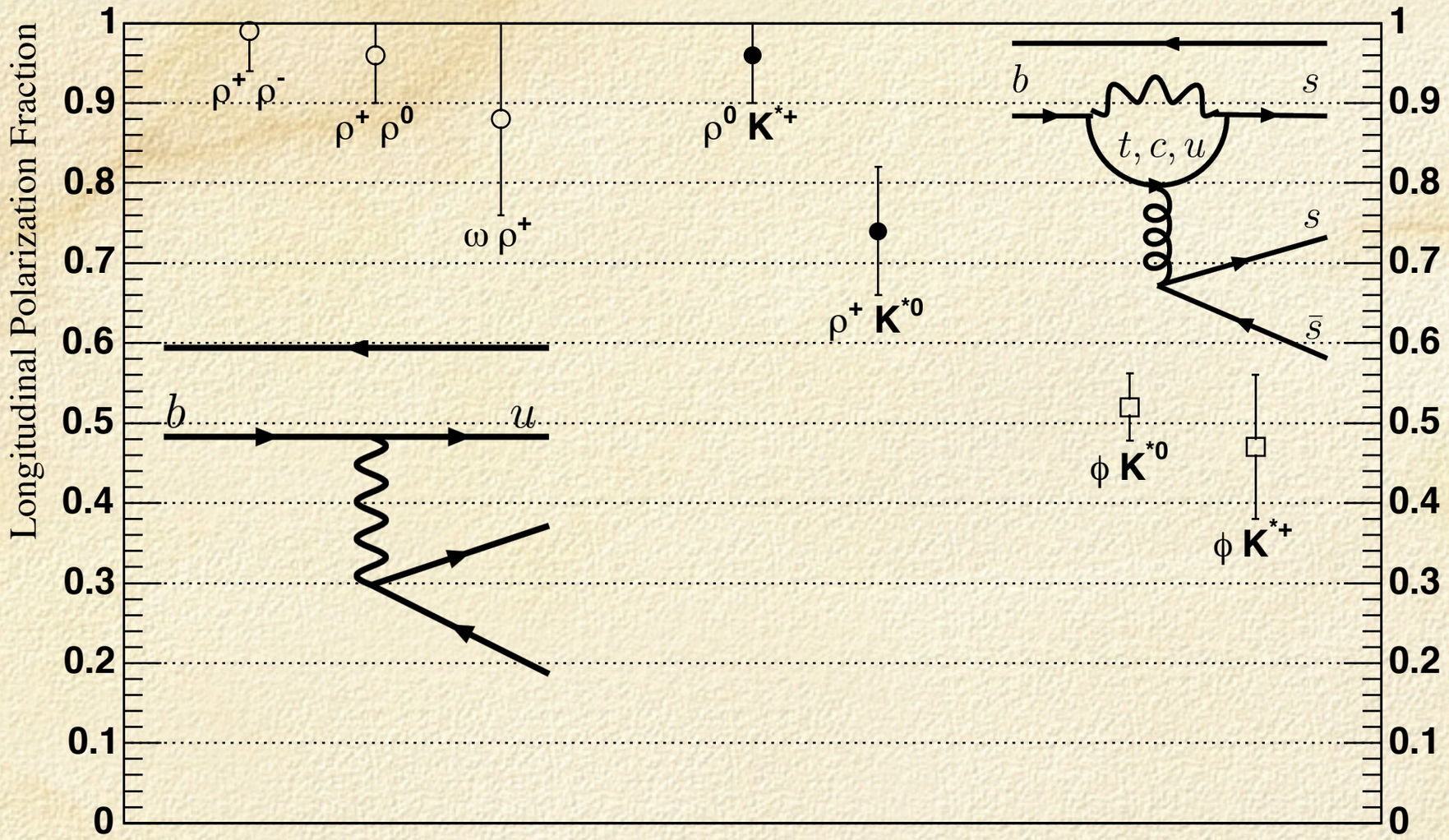
$f_L \sim 1 - \mathcal{O}(1/m_b^2) \quad f_\perp / f_\parallel \sim 1 + \mathcal{O}(1/m_b)$



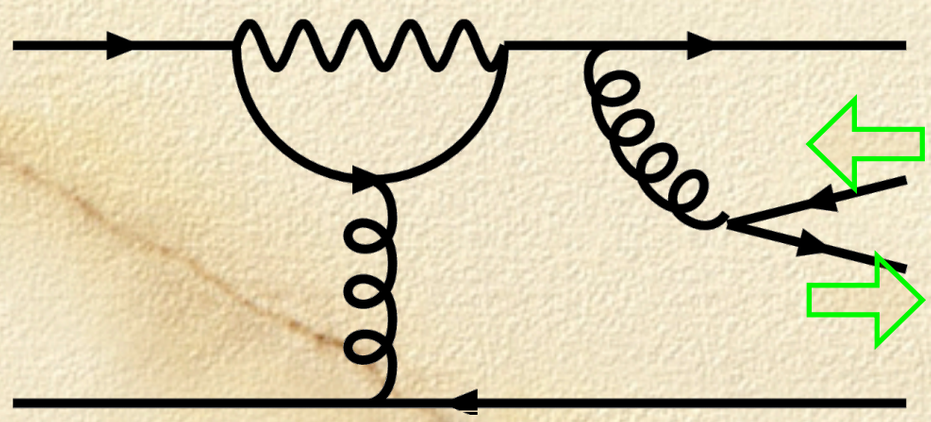


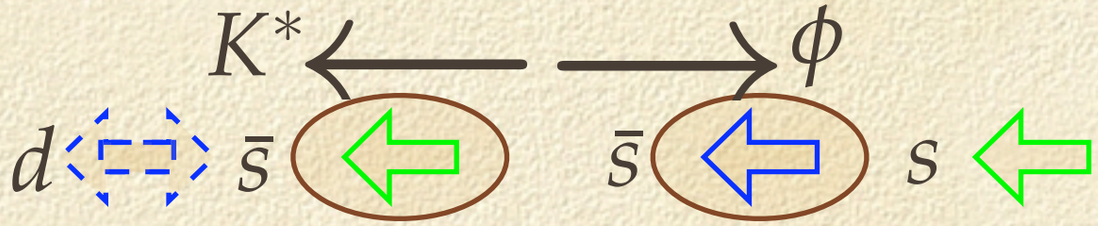


Polarization in B ⇒ VectorVector Decays



non-Factorizable Annihilation amplitude?





flip for Trans.

flip for Long.

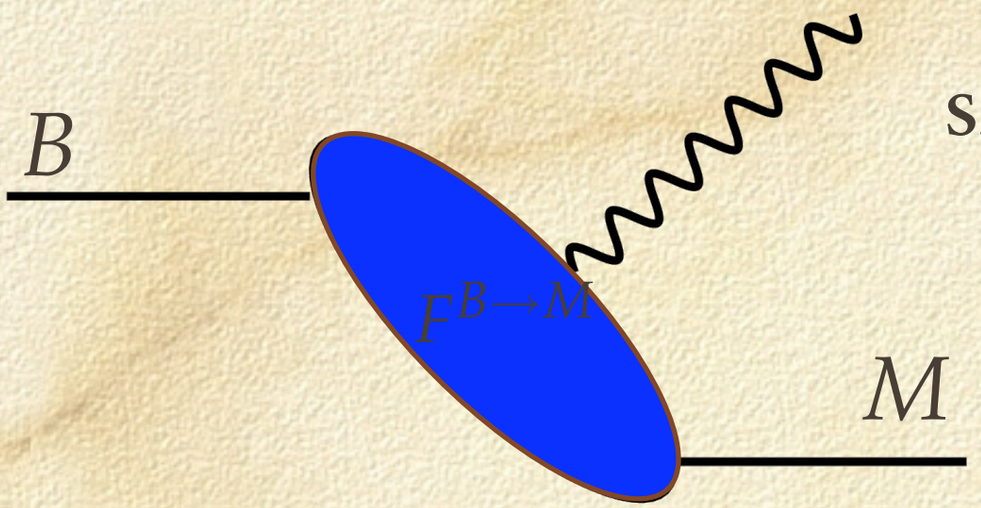
$1 - f_L \gg \mathcal{O}(1/m_b^2)$

$f_\perp / f_\parallel \sim 1 + \mathcal{O}(1/m_b)$

see Kagan hep-ph/0405134

One Hadronic Current

Semi-Leptonic and ElectroWeak Penguin decays

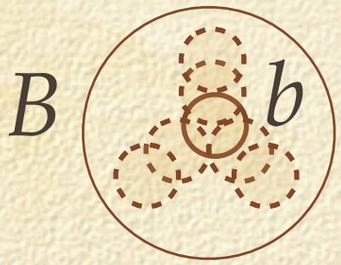


single hadronic current

heavy quark expansion in Λ_{QCD}/m_b

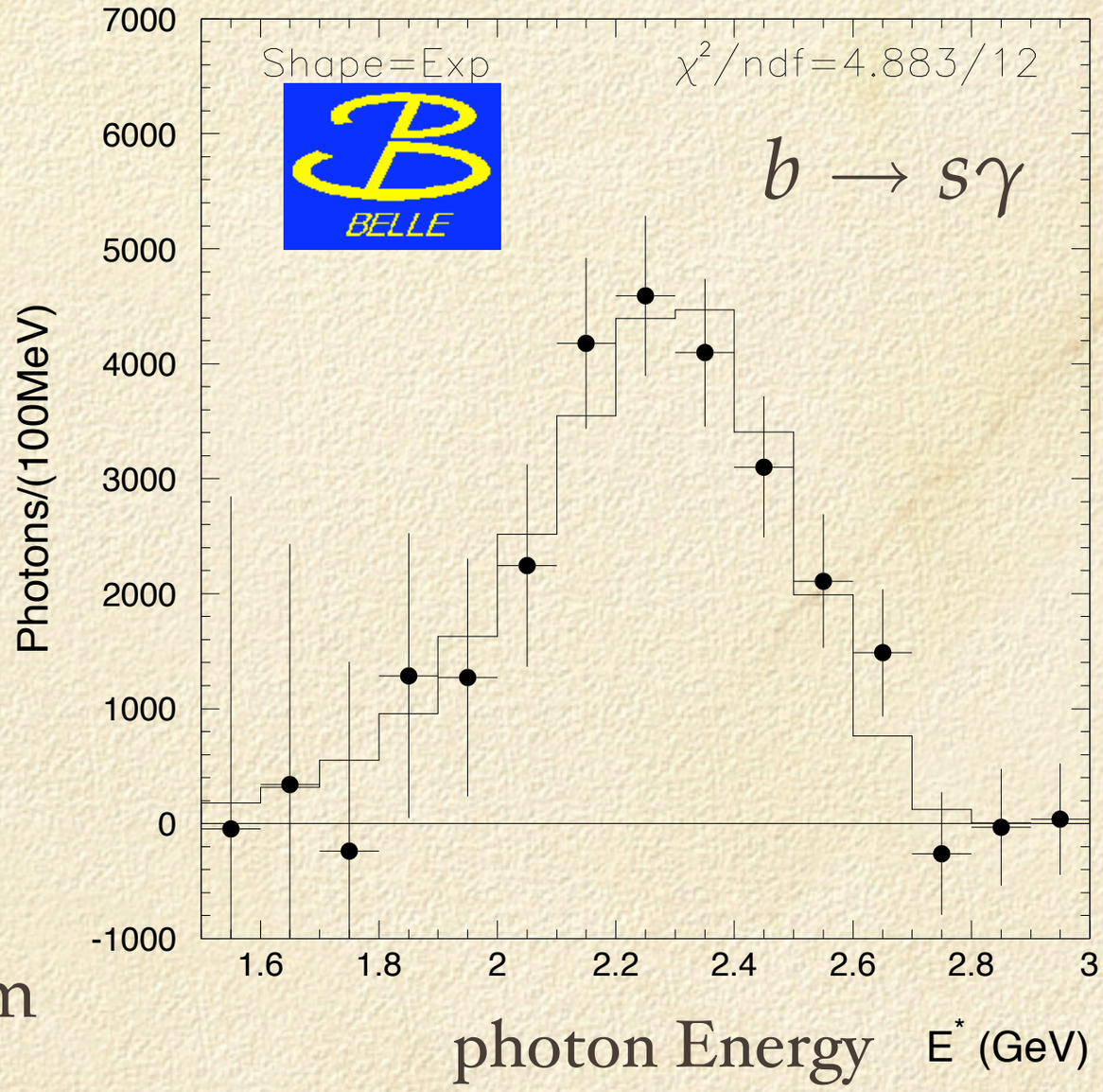
NLO calculations $\mathcal{O}(\alpha_S^2)$

Fermi motion



$$F(k_+) \sim (1-x)^a e^{(1+a)x}$$

$x = \frac{k_+}{\Lambda^{SF}}$ k_+ light-cone momentum



Experimental Methods - Inclusive or Exclusive

Quark-Hadron Duality

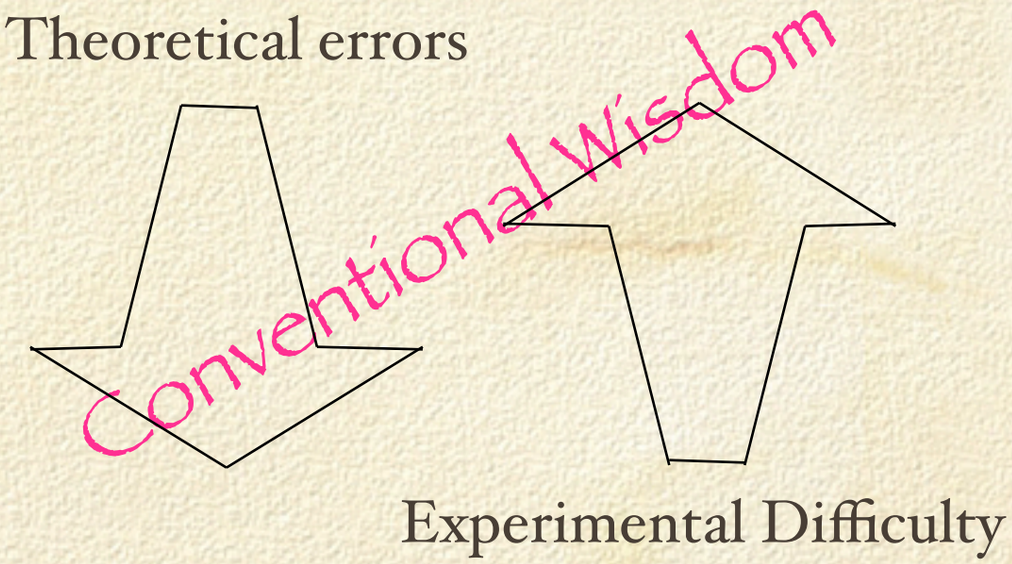
Quarks ⇩ Hadrons

Form-Factors Lattice QCD

Fully Inclusive

Sum of Exclusive Modes

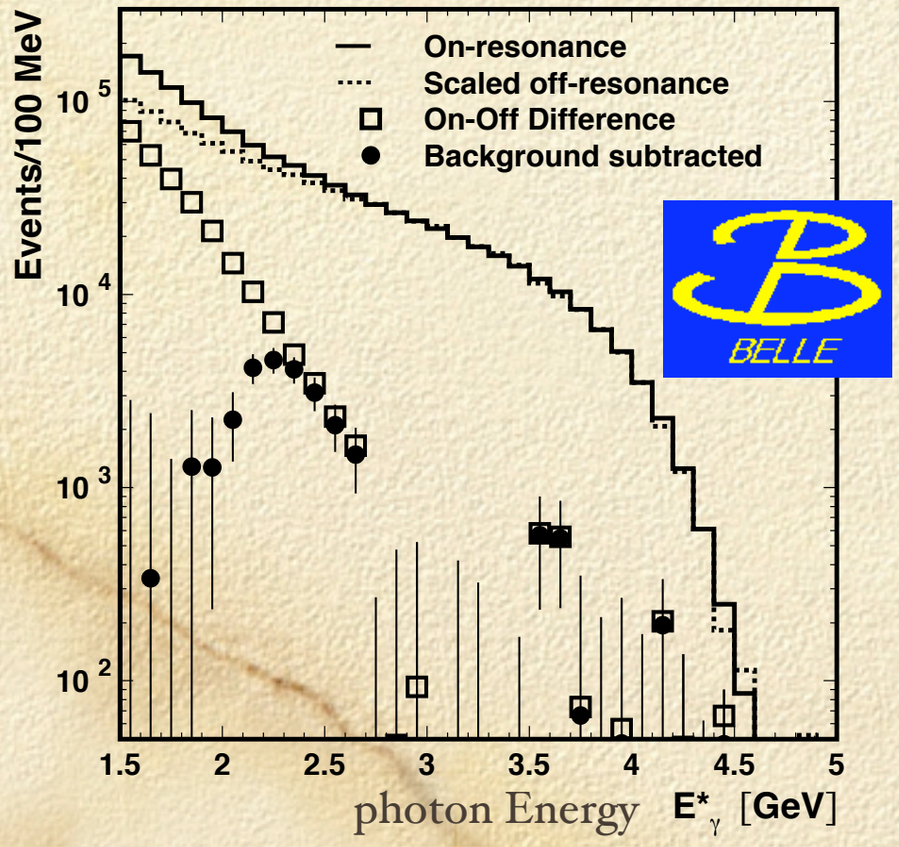
Exclusive

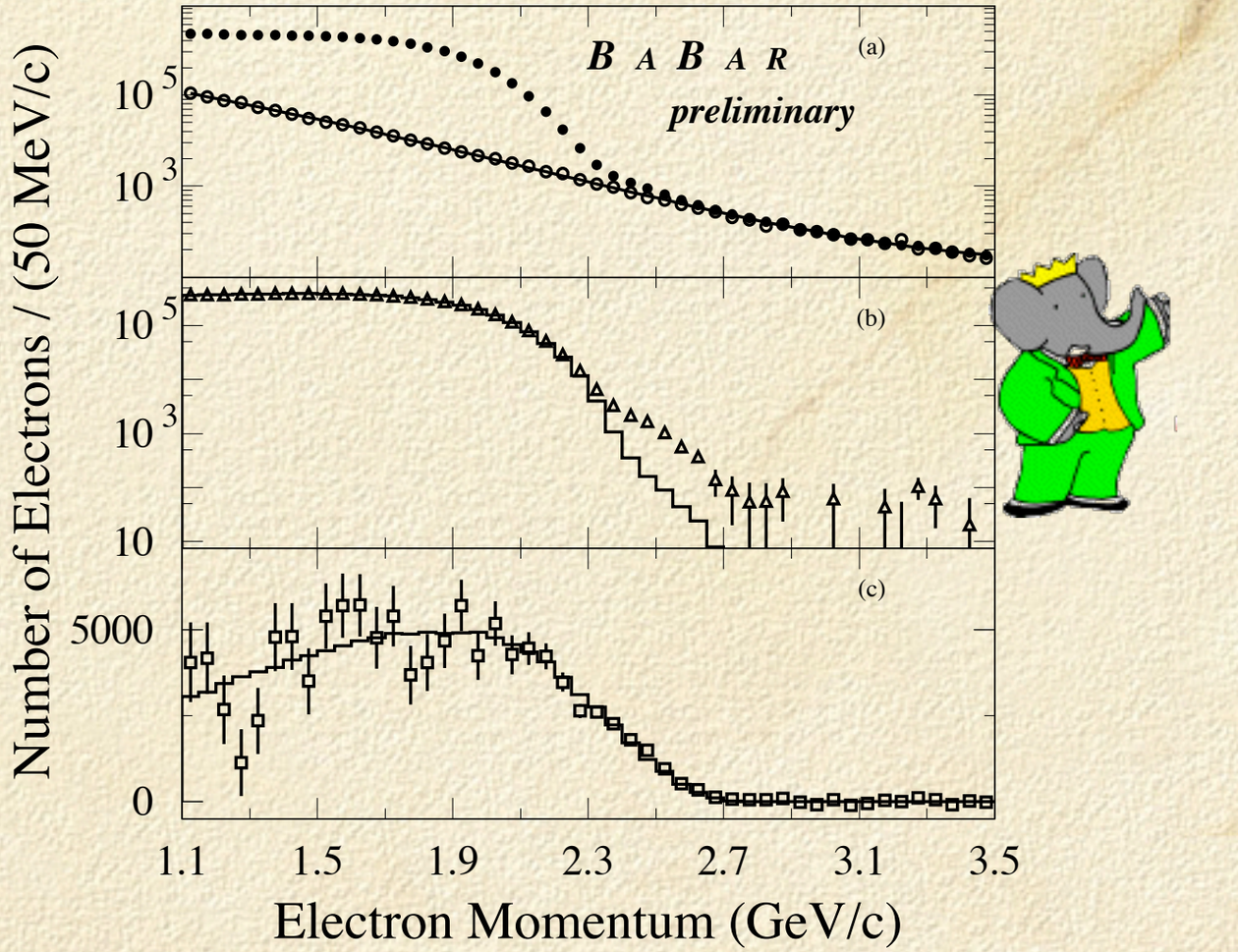


Fully Inclusive

$b \to u\ell\nu$

$b \to s\gamma$

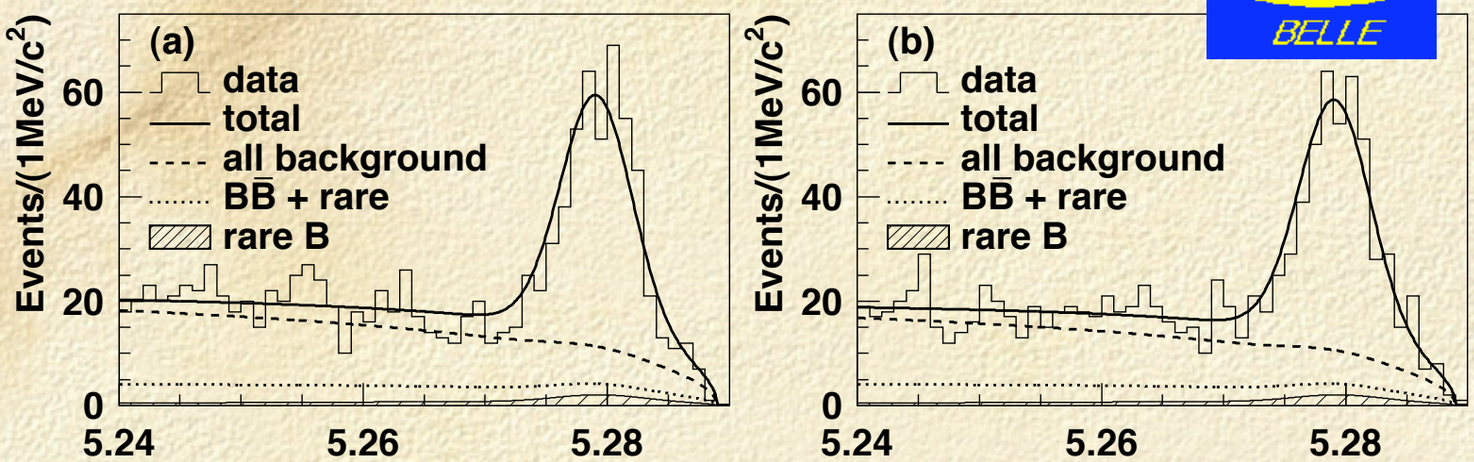




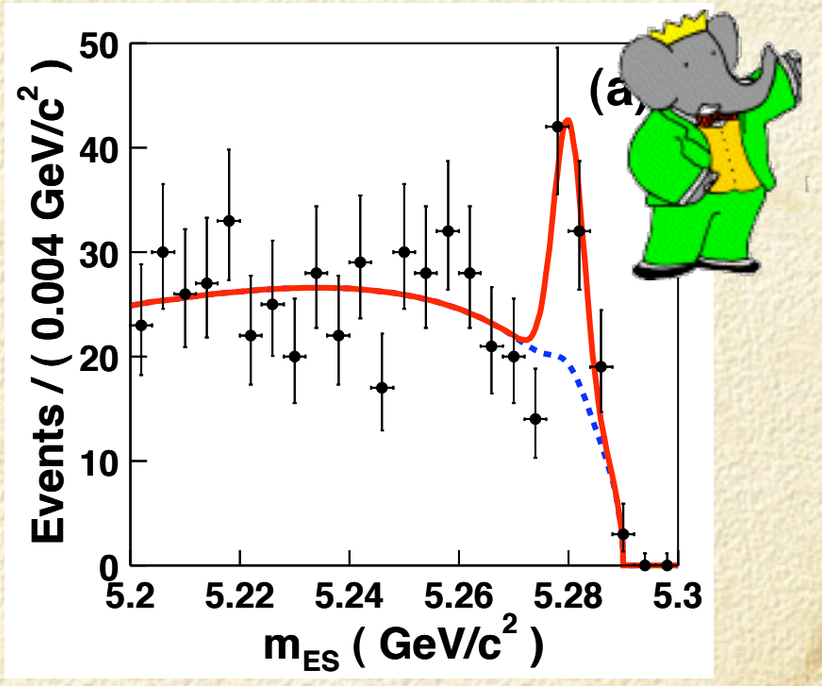
Experimental Methods - Inclusive or Exclusive

Sum of Exclusive Modes

$B \to X_S \gamma$

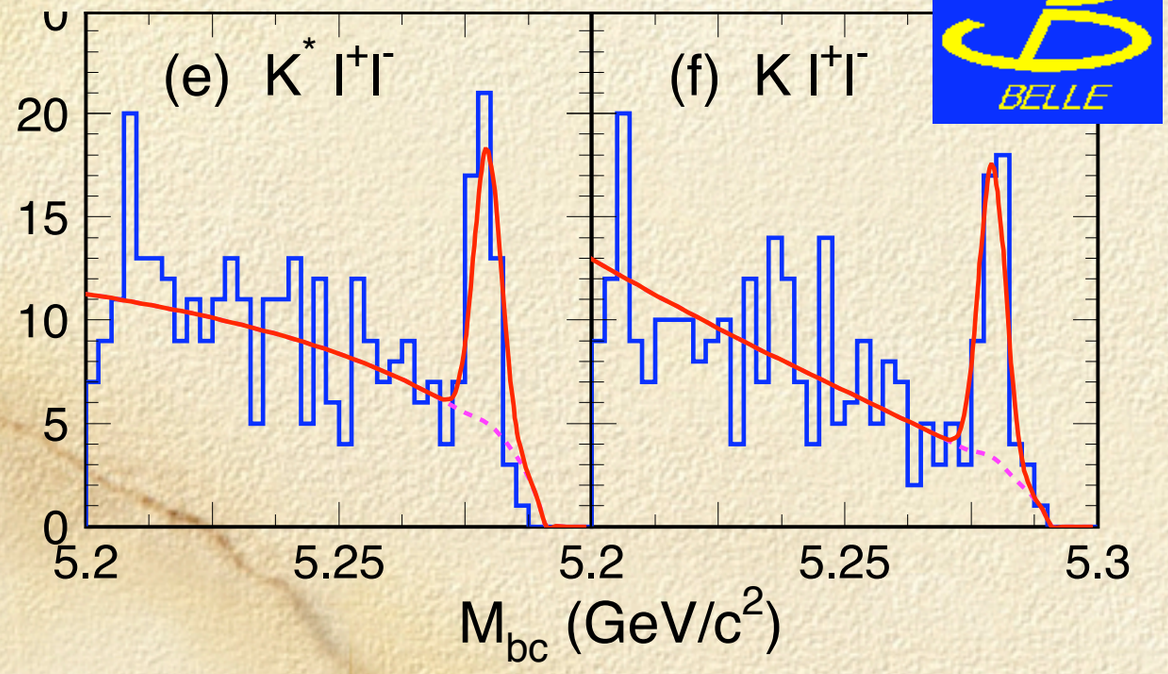


$B \to X_S \ell^+ \ell^-$

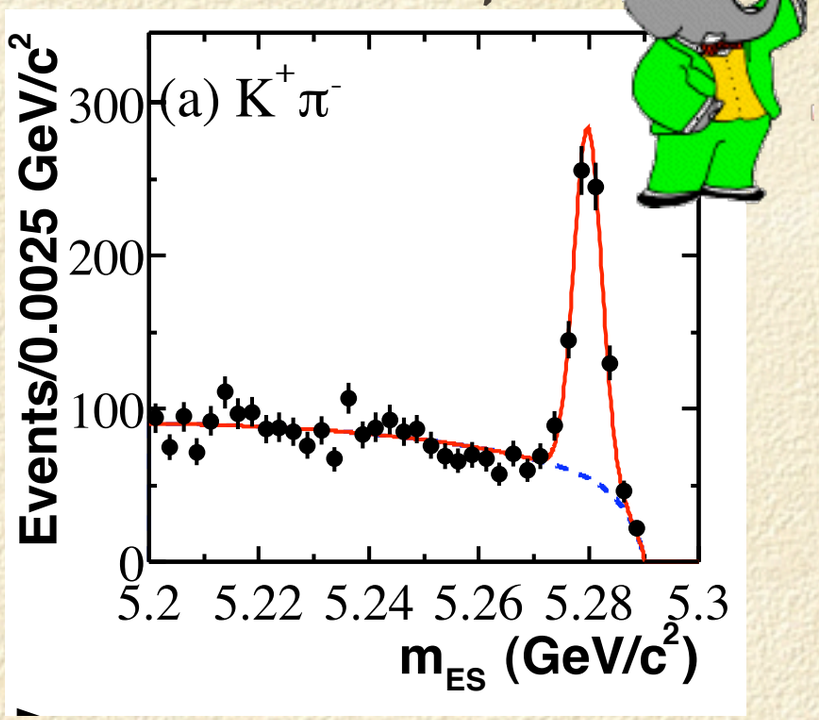


Exclusive

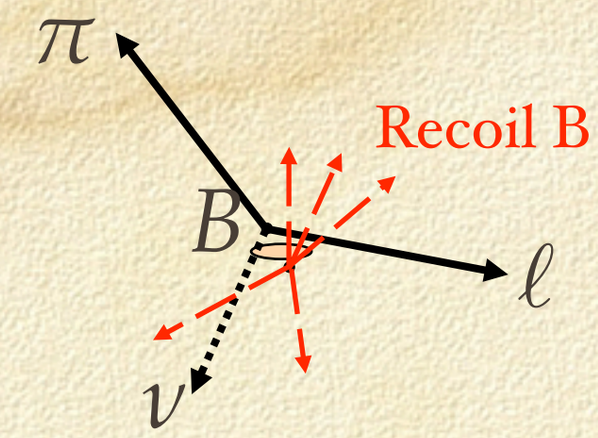
$B \to K^* \ell^+ \ell^-$



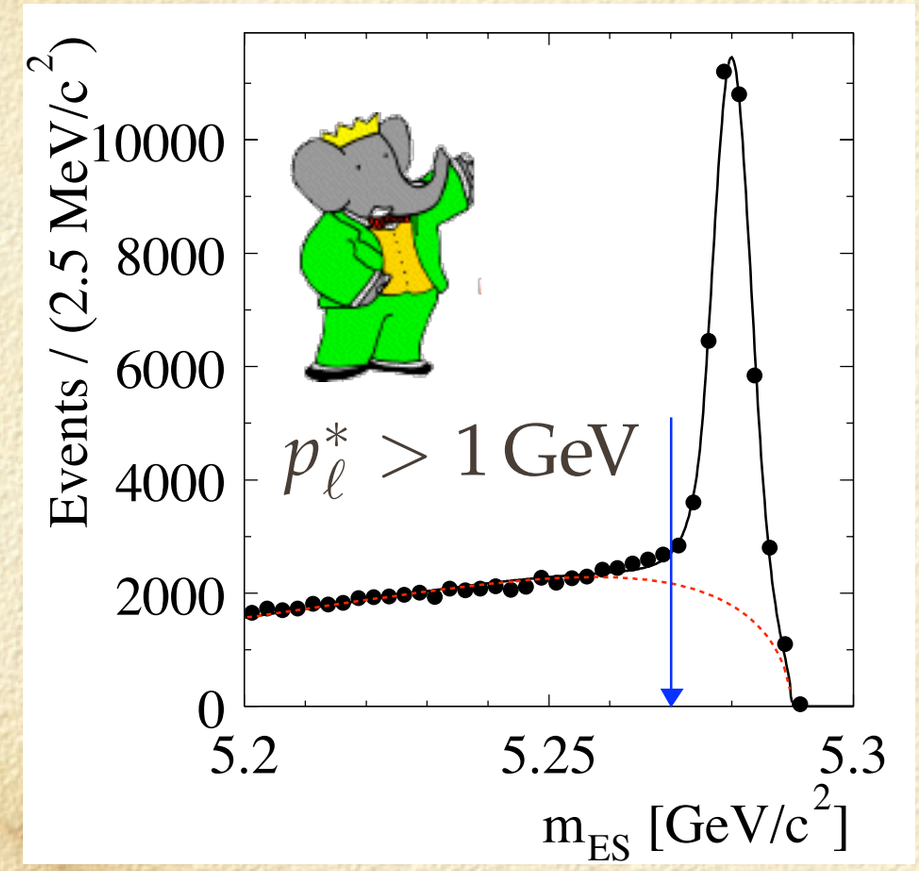
$B^0 \to K^{*0} \gamma$

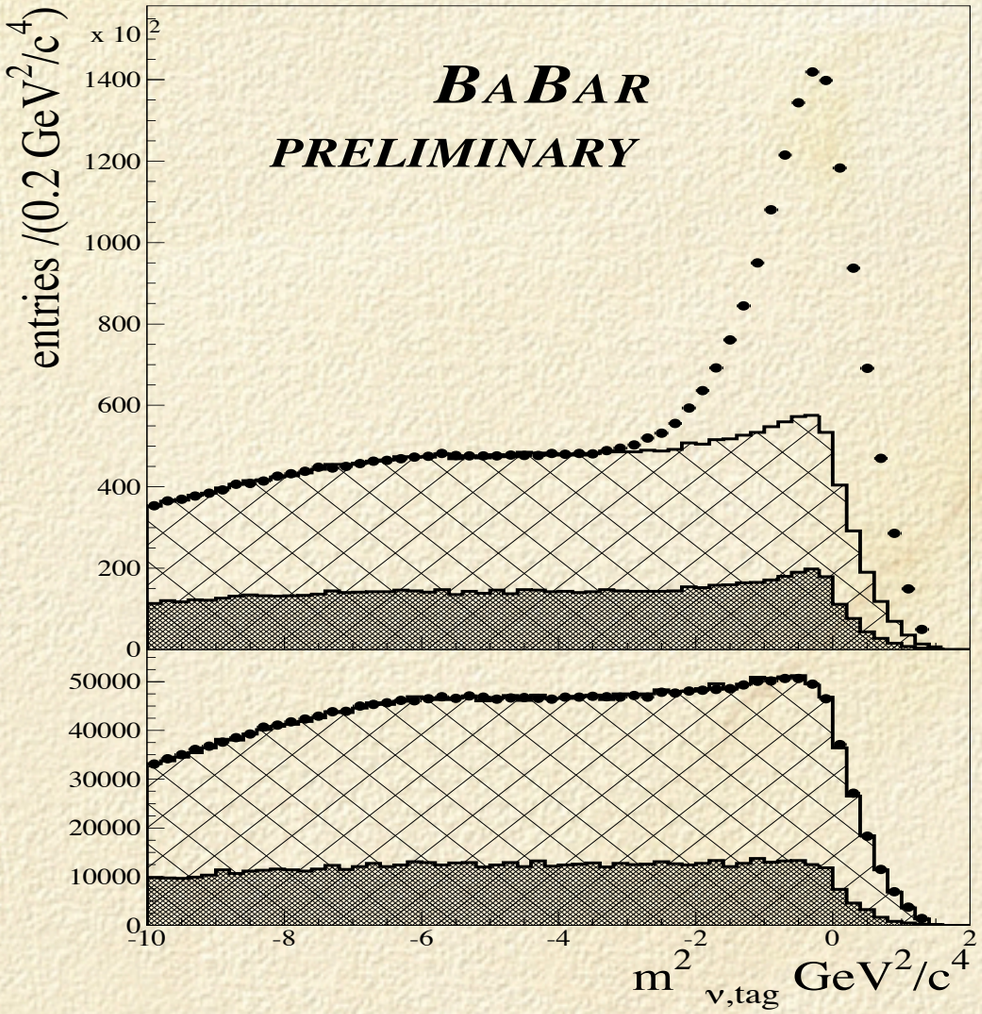


Experimental Methods - Recoil



Fully or partially reconstruct the recoil B

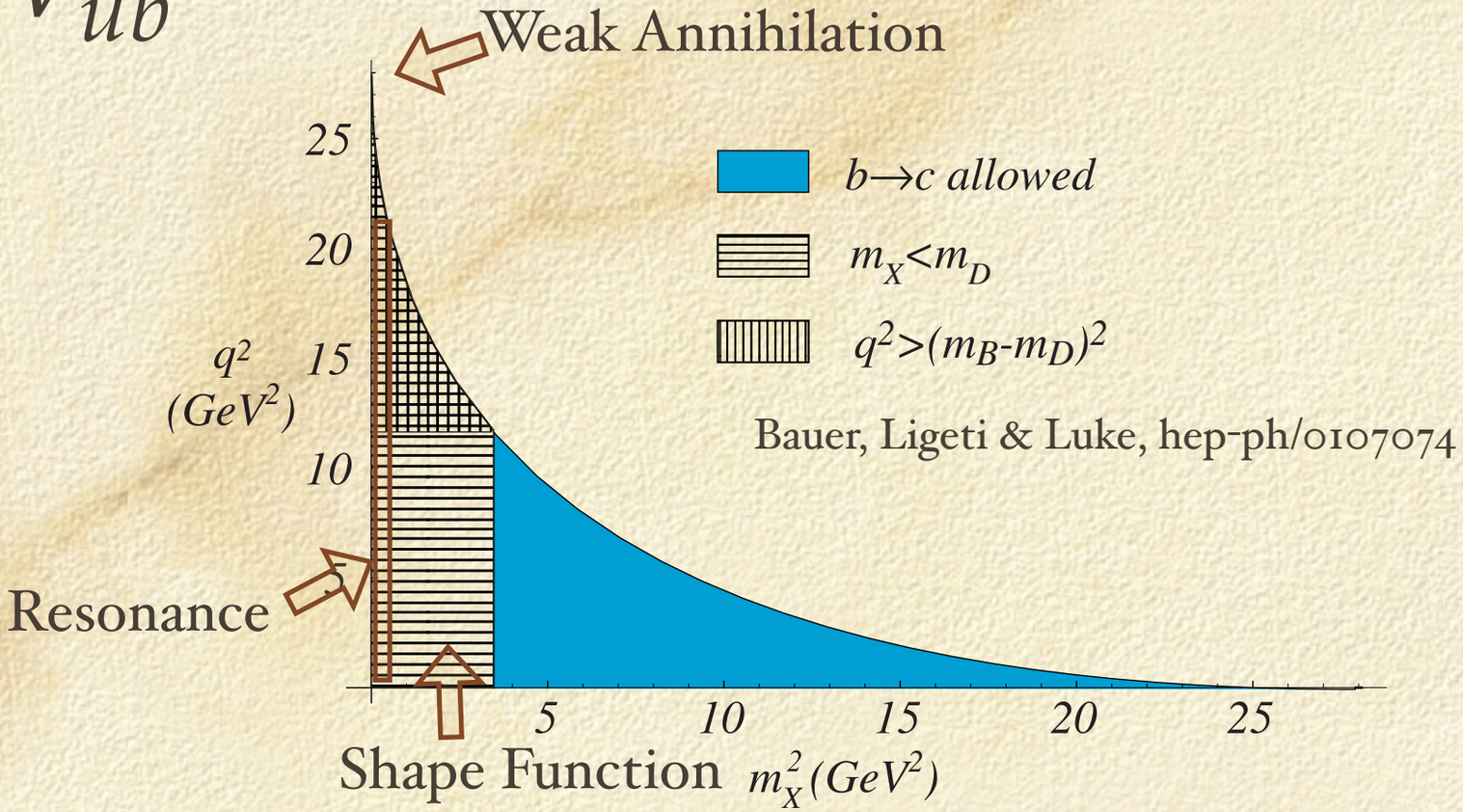




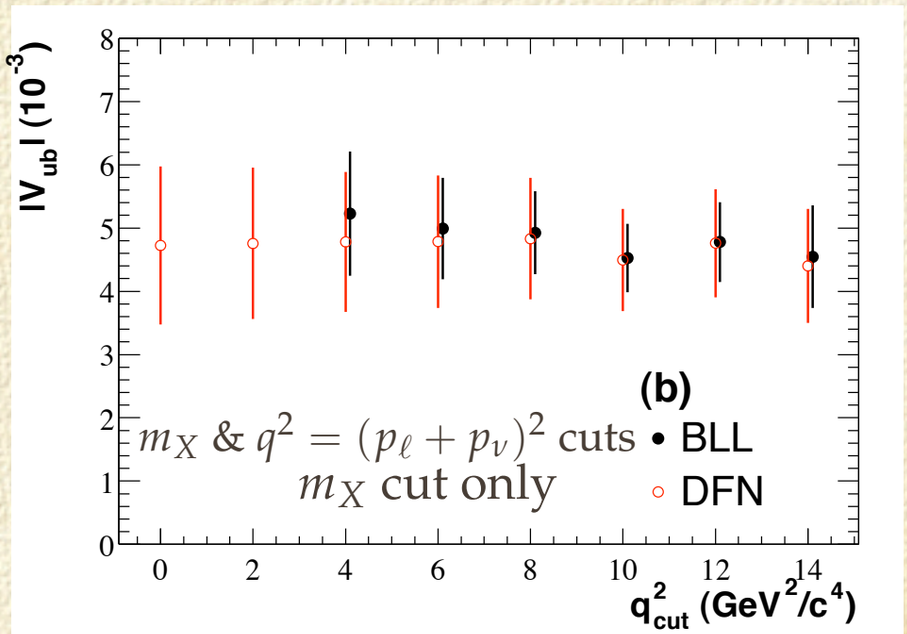
$B(\text{recoil}) \to D^{(*)}\, m\pi^\pm\, nK^\pm\, pK^0_S\, q\pi^0$
$\epsilon \sim 0.3\%(0.5\%)\ B^0(B^\pm)$

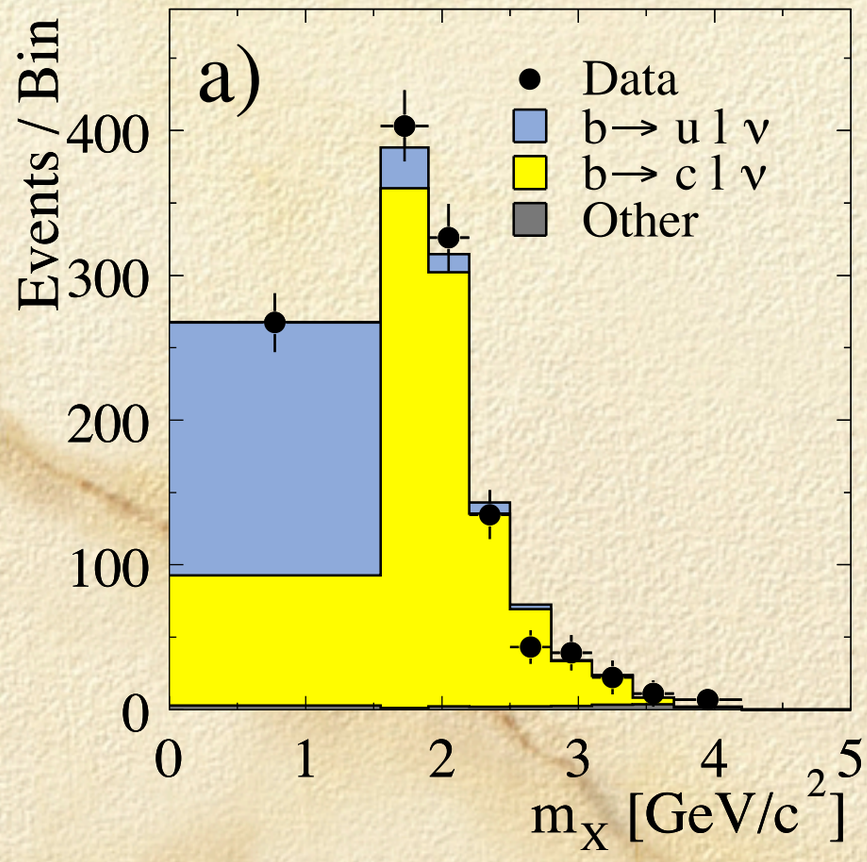
$B^0(\text{recoil}) \to D^{*\pm}\ell^\mp\nu\ \ D^{*\pm} \to D^0\pi^\pm_{\text{slow}}$
$\epsilon \sim 0.7\%\ B^0$

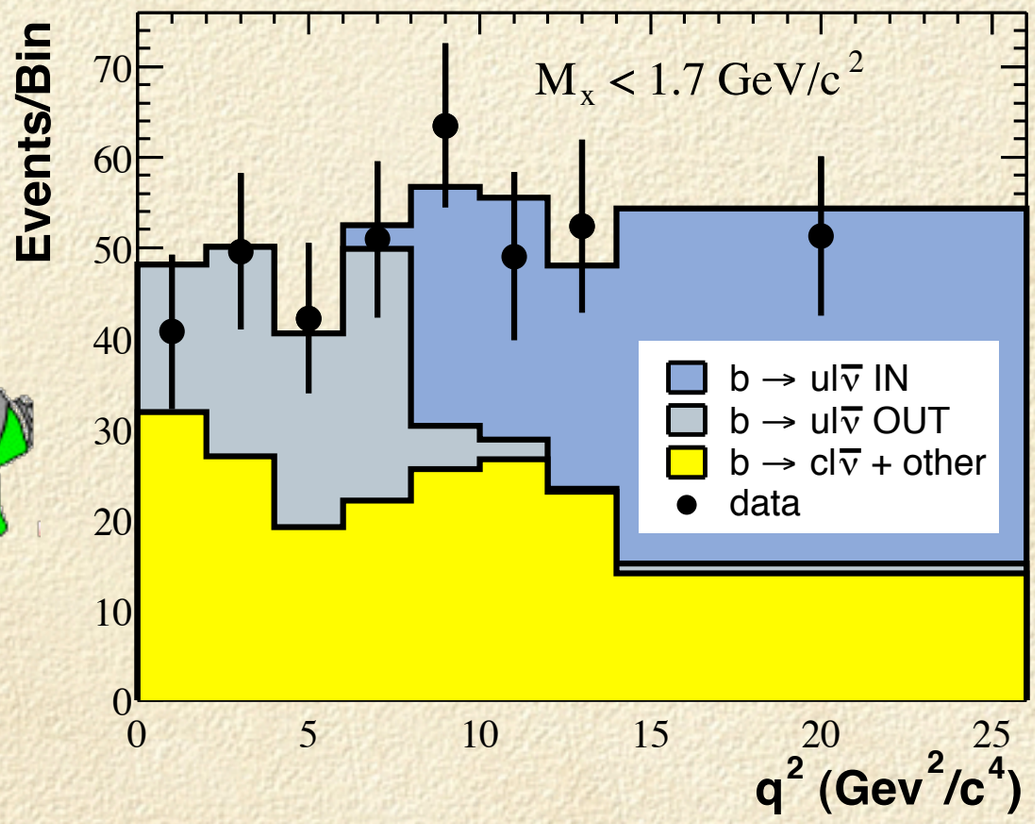
V_{ub}



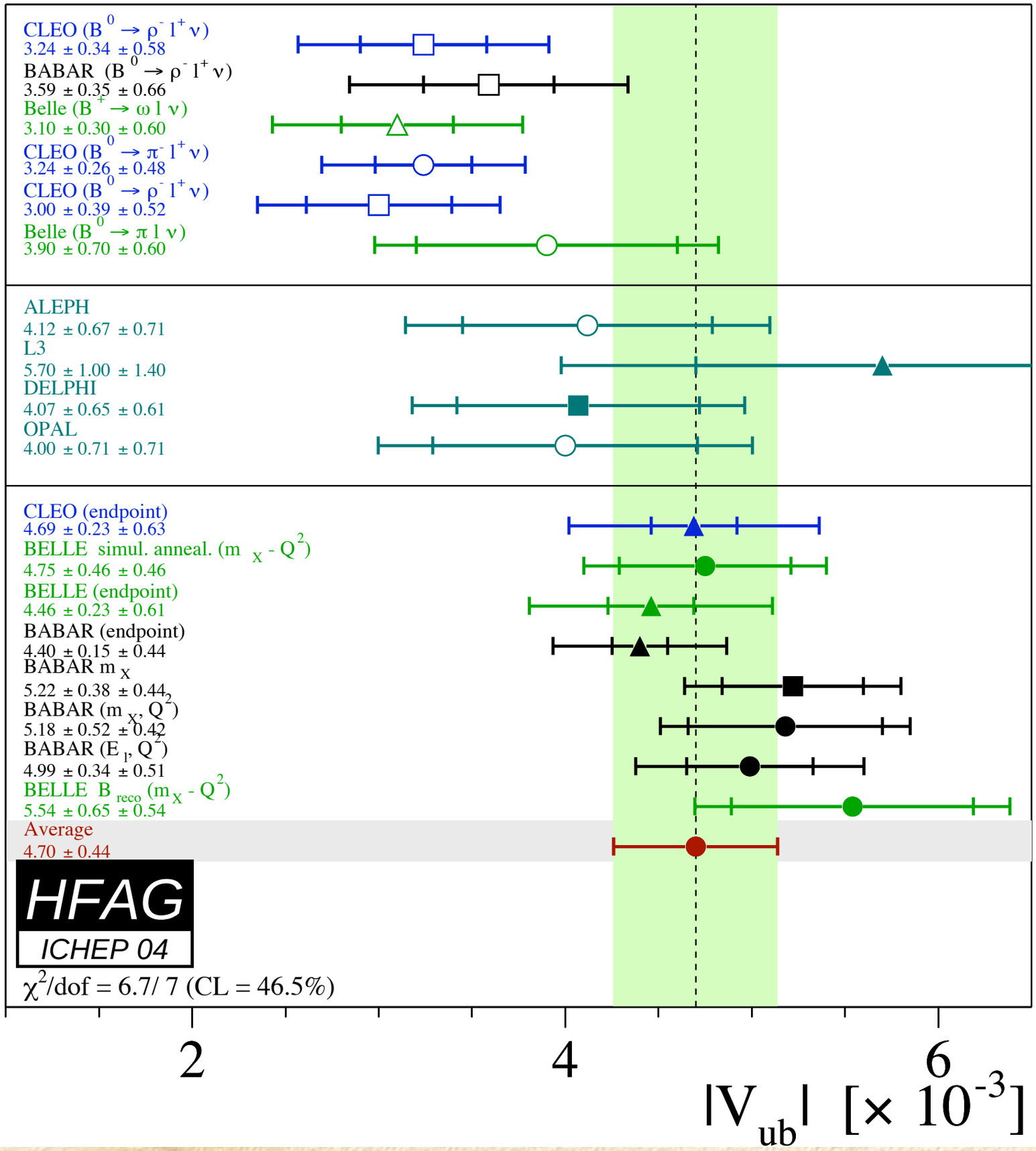
$B \to X_u \ell \nu$





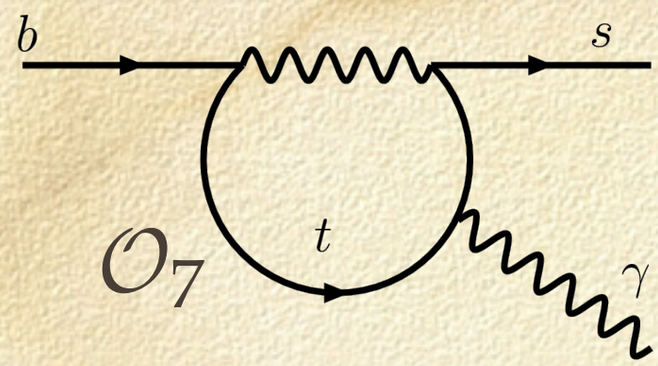


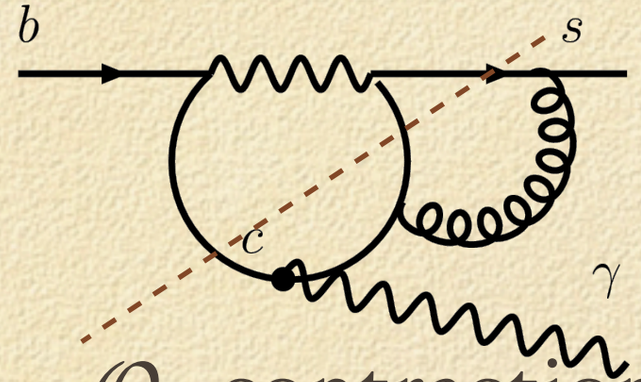
V_{ub}


CLEO (B 0 → ρ- l+ ν)
3.24 ± 0.34 ± 0.58
BABAR (B 0 → ρ- l+ ν)
3.59 ± 0.35 ± 0.66
Belle (B+ → ω l ν)
3.10 ± 0.30 ± 0.60
CLEO (B 0 → π- l+ ν)
3.24 ± 0.26 ± 0.48
CLEO (B 0 → ρ- l+ ν)
3.00 ± 0.39 ± 0.52
Belle (B 0 → π l ν)
3.90 ± 0.70 ± 0.60
ALEPH
4.12 ± 0.67 ± 0.71
L3
5.70 ± 1.00 ± 1.40
DELPHI
4.07 ± 0.65 ± 0.61
OPAL
4.00 ± 0.71 ± 0.71
CLEO (endpoint)
4.69 ± 0.23 ± 0.63
BELLE simul. anneal. (m X - Q2)
4.75 ± 0.46 ± 0.46
BELLE (endpoint)
4.46 ± 0.23 ± 0.61
BABAR (endpoint)
4.40 ± 0.15 ± 0.44
BABAR m X
5.22 ± 0.38 ± 0.44
BABAR (m X, Q2)
5.18 ± 0.52 ± 0.42
BABAR (E l, Q2)
4.99 ± 0.34 ± 0.51
BELLE B reco (m X - Q2)
5.54 ± 0.65 ± 0.54
Average
4.70 ± 0.44
HFAG
ICHEP 04
χ2/dof = 6.7/ 7 (CL = 46.5%)
2
4
6
|Vub| [× 10-3]

ElectroWeak Penguin Decays

$b \to s\gamma$

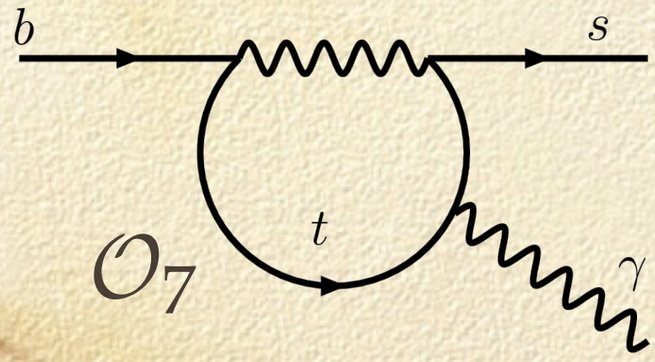


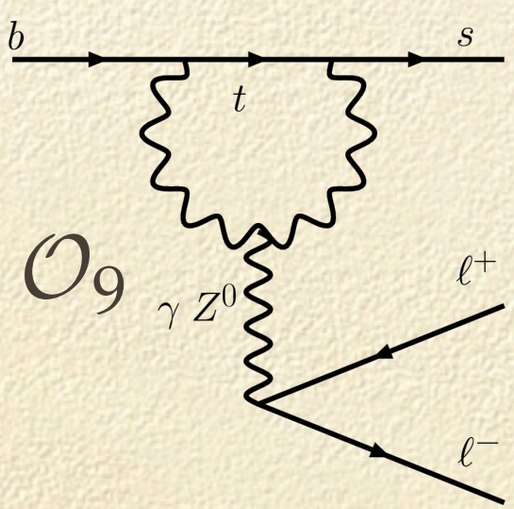


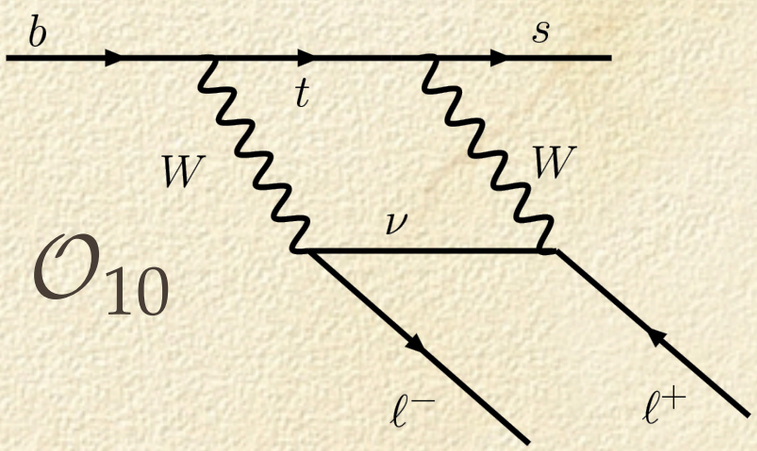
$$\mathcal{O}_{7,9,10} \xrightarrow{\mathcal{O}_2} \mathcal{O}_{7,9,10}^{\text{Eff}}$$

$$|C_7^{\text{Eff}}|^2 \sim 5 \times |C_7|^2$$

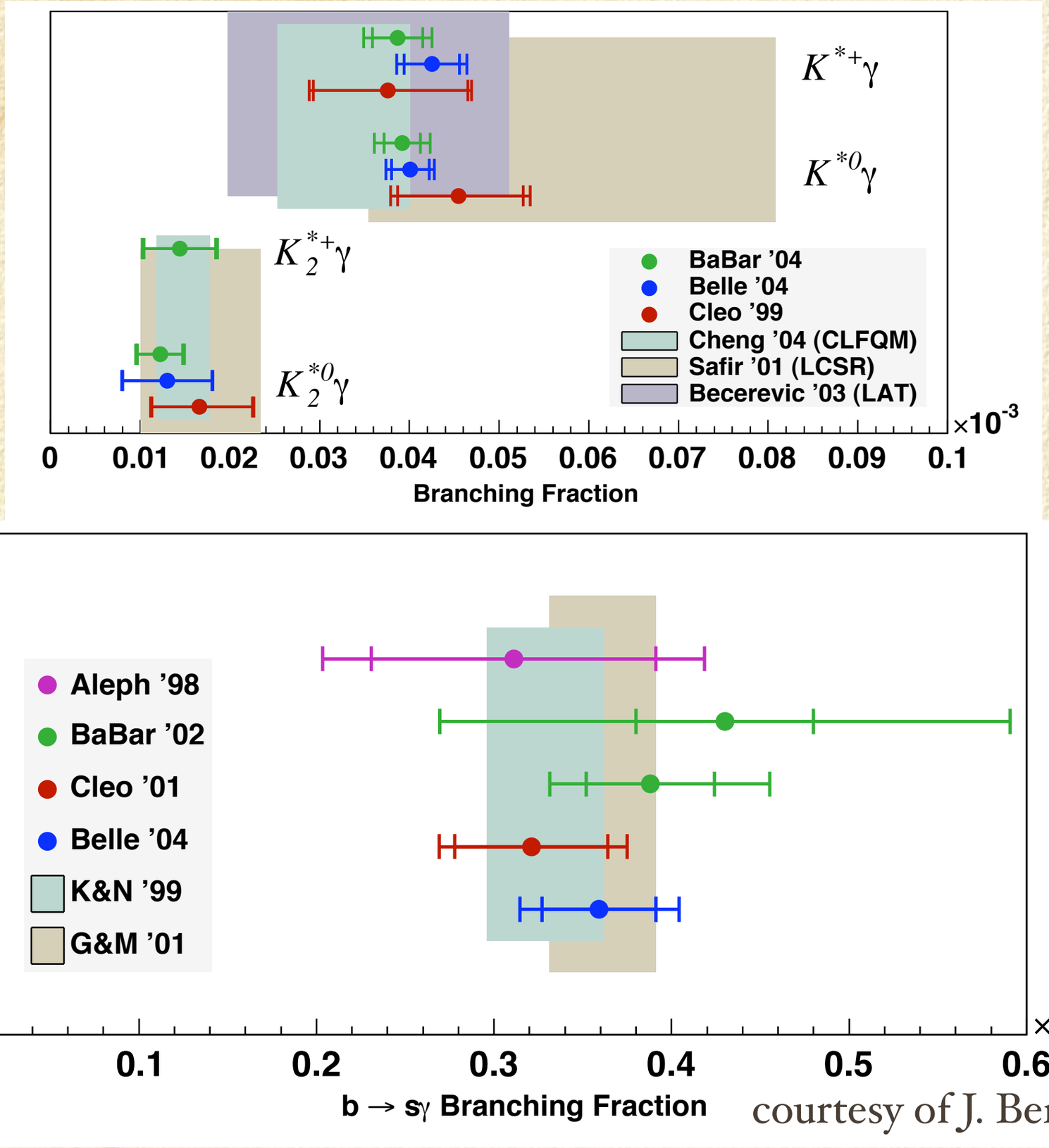
$b \to s\ell^+\ell^-$





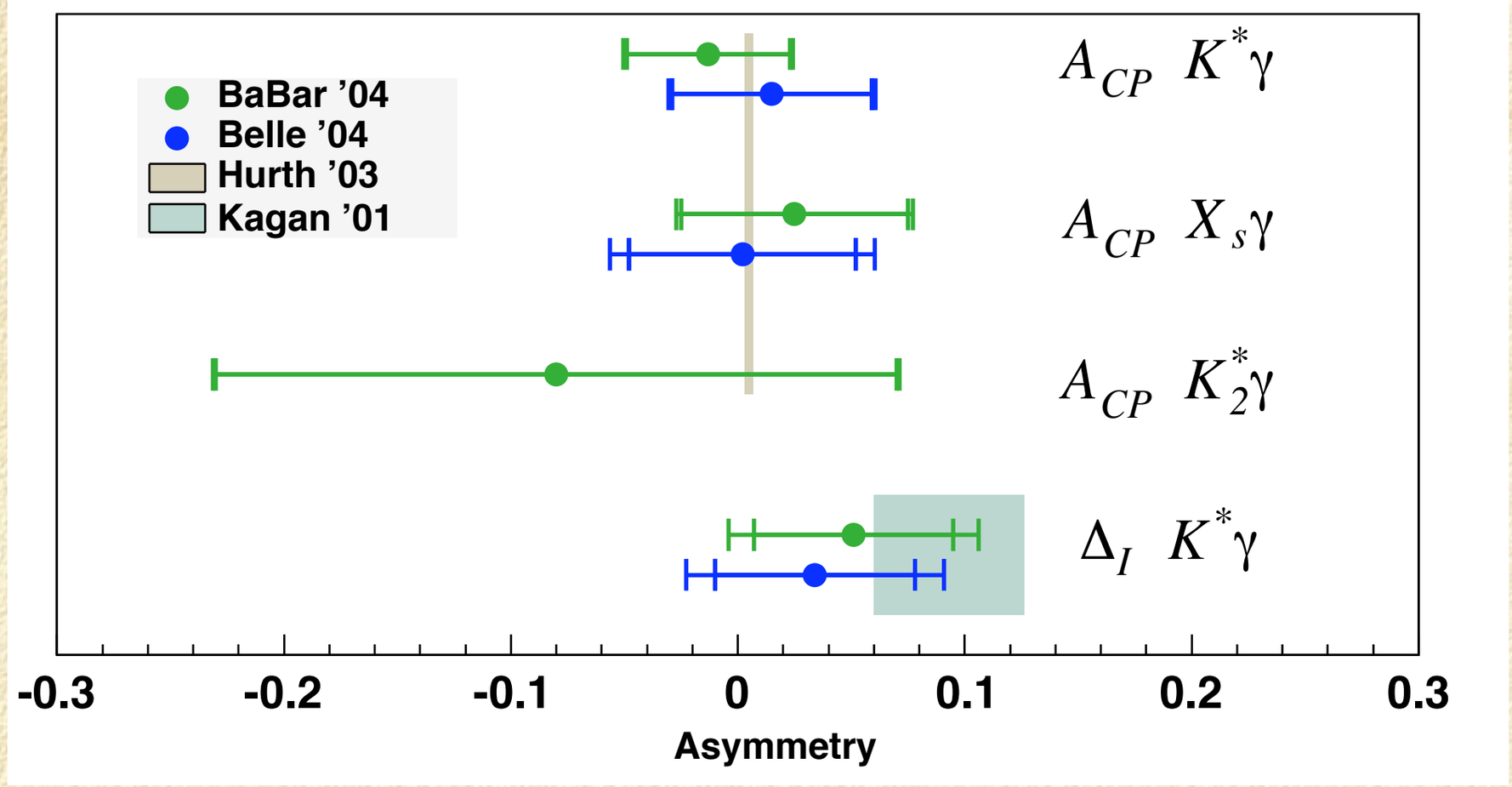


$b \to s\gamma$ Results



courtesy of J. Berryhill

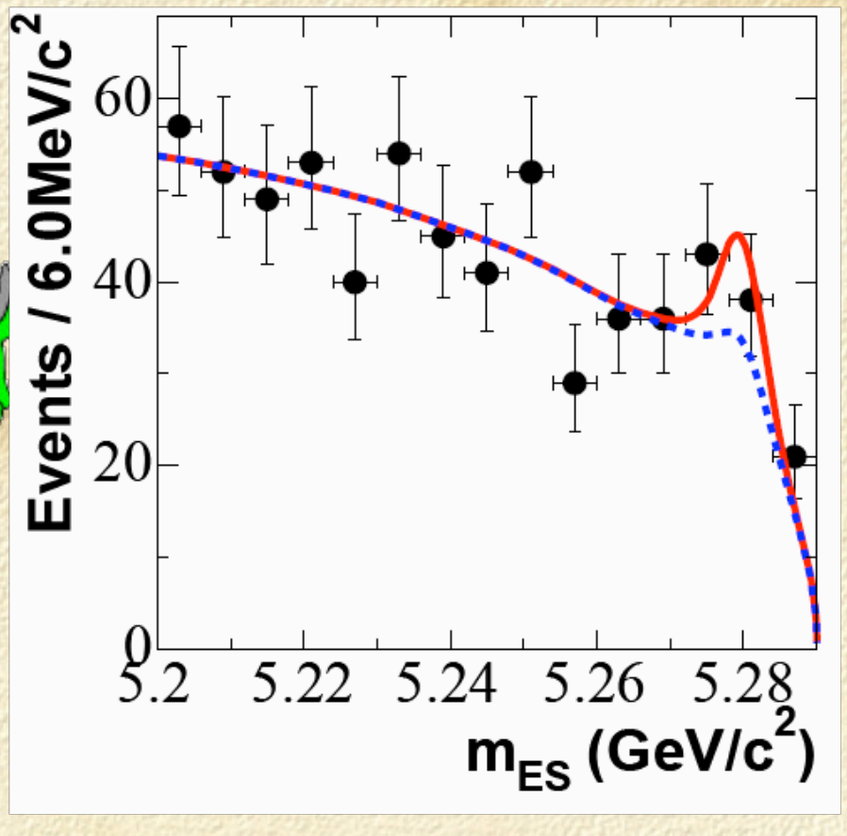
$b \to s\gamma$ Asymmetries

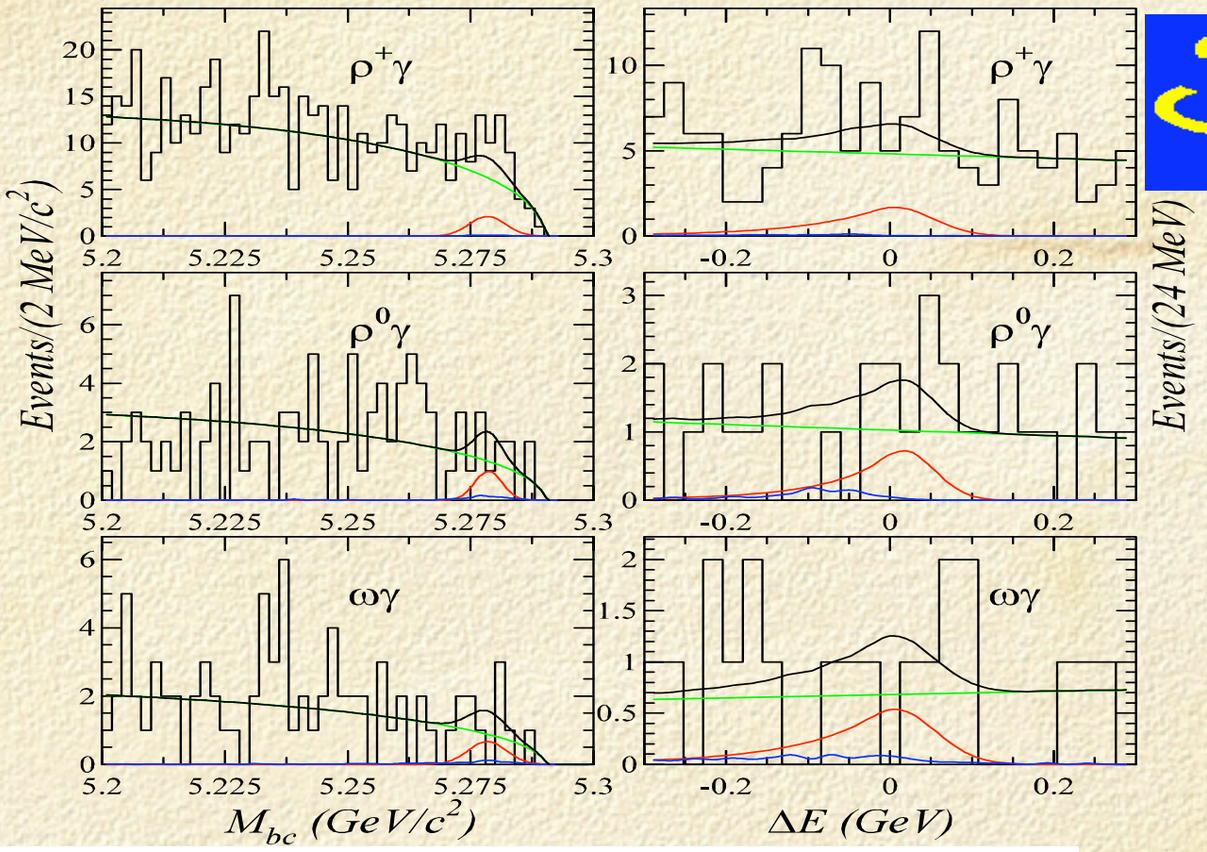


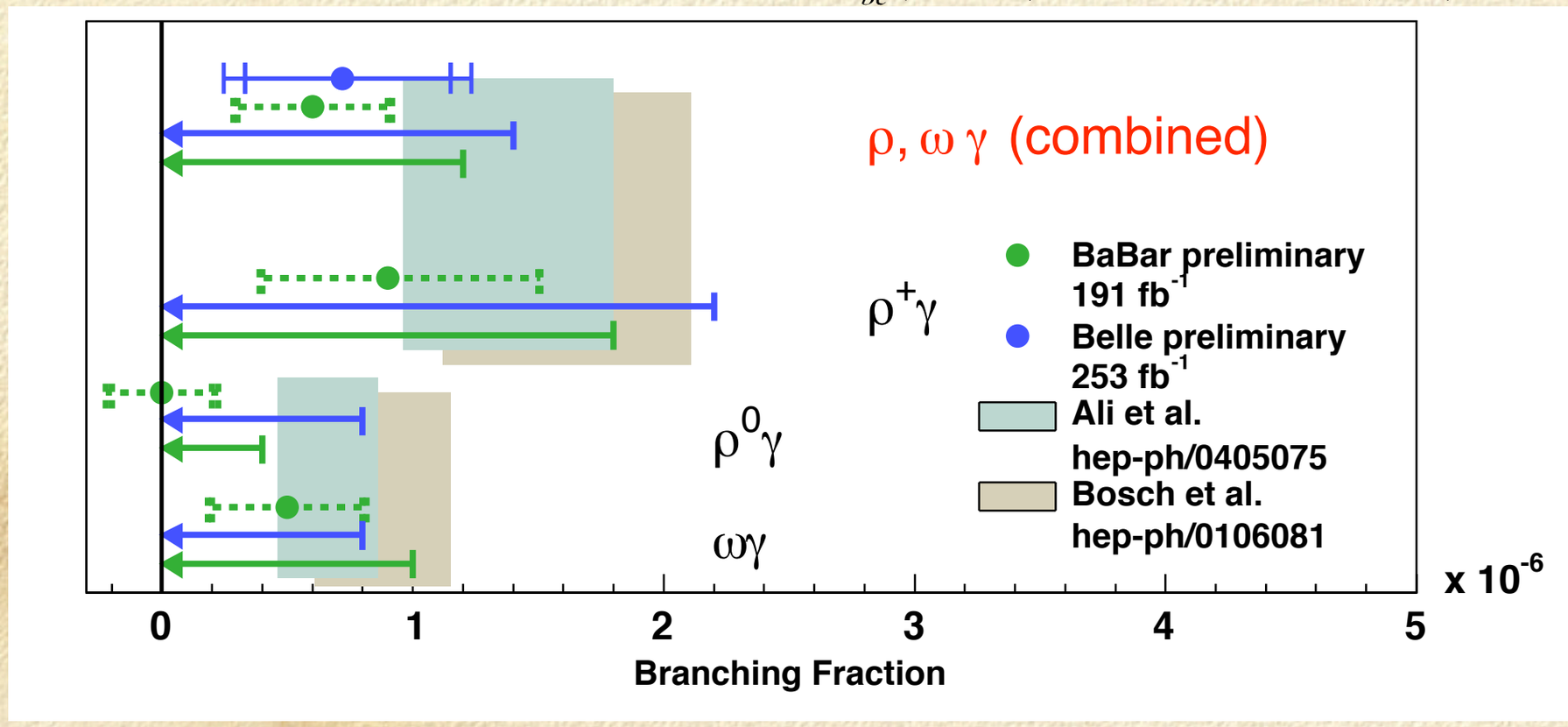
$$\Delta_I = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

$$\Delta_I \sim -C_6/C_7$$

$b \to d\gamma$


Events / 6.0MeV/c^2
60
40
20
0
5.2
5.22
5.24
5.26
5.28
m_{ES} (GeV/c^2)


$\rho^+\gamma$
$\rho^0\gamma$
$\omega\gamma$
Events/(2 MeV/c^2)
Events/(24 MeV)
5.2
5.225
5.25
5.275
5.3
-0.2
0
0.2
M_{bc} (GeV/c^2)
ΔE (GeV)

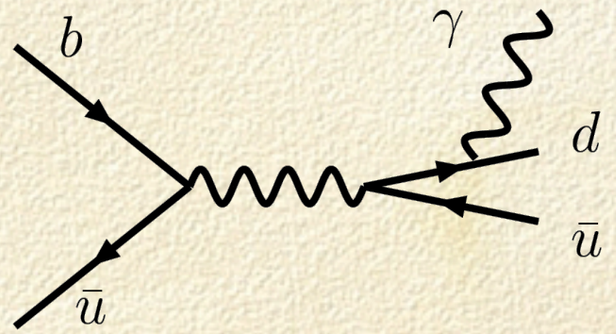

ρ, ω γ (combined)
ρ$^+$γ
ρ^{0}γ
ωγ
BaBar preliminary
191 fb^{-1}
Belle preliminary
253 fb^{-1}
Ali et al.
hep-ph/0405075
Bosch et al.
hep-ph/0106081
x 10^{-6}
0
1
2
3
4
5
Branching Fraction

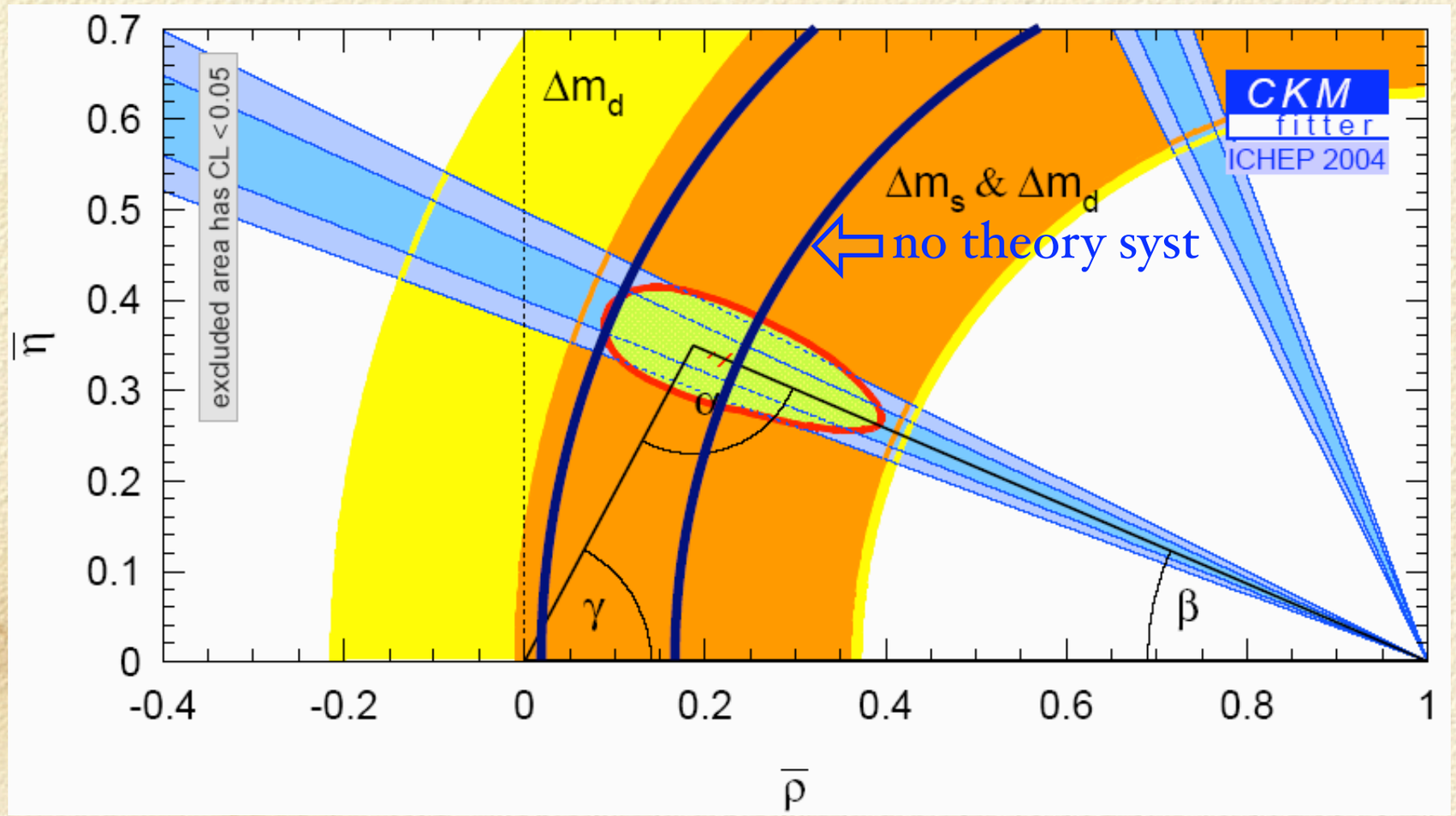
$b \to d\gamma$

$$\frac{\mathcal{B}(B\to\rho\gamma)}{\mathcal{B}(B\to K^*\gamma)} = \frac{|V_{td}|^2}{|V_{ts}|^2}\frac{(M_B^2-m_\rho^2)^3}{(M_B^2-m_{K^*}^2)^3}\xi^2\left[1+\Delta R(\rho/K^*)\right]$$

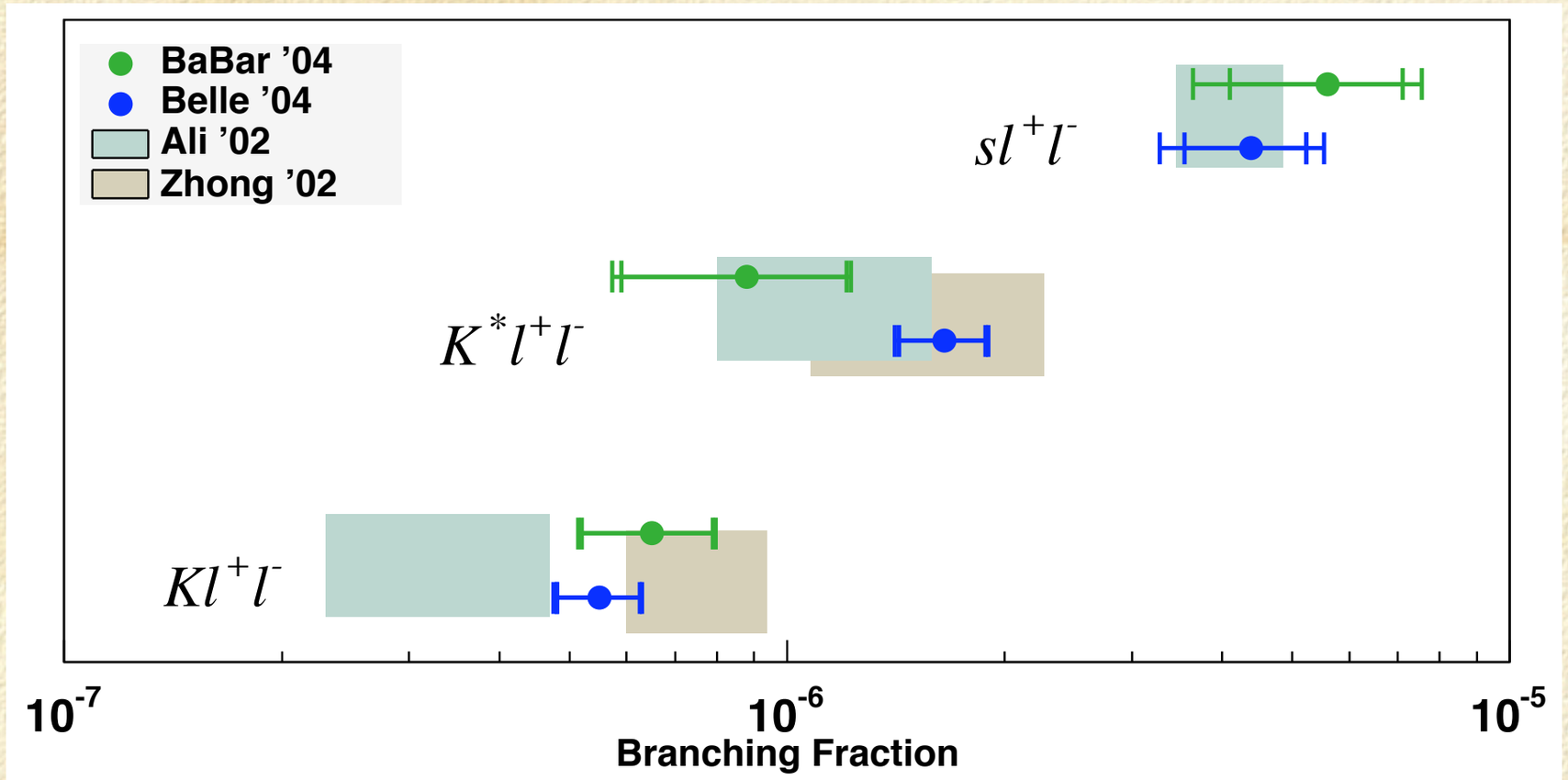
$\xi = F^{B\to\rho}/F^{B\to K^*}$ SU(3) breaking

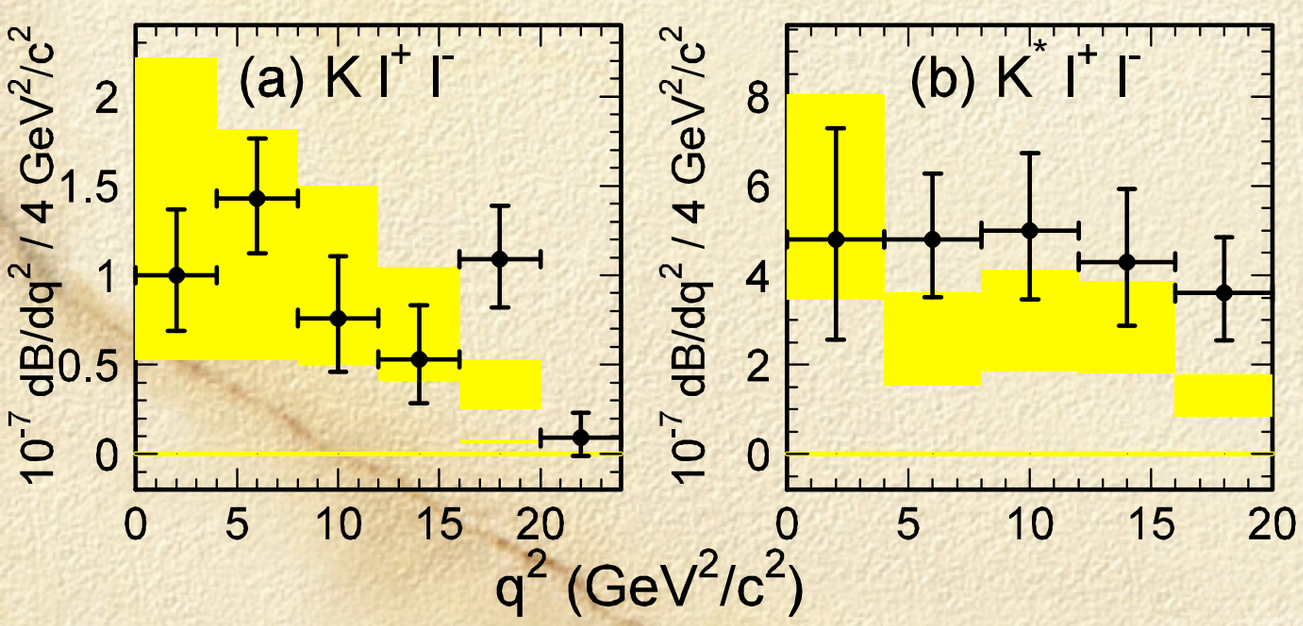
$\Delta R(\rho/K^*)$ annihilation etc.

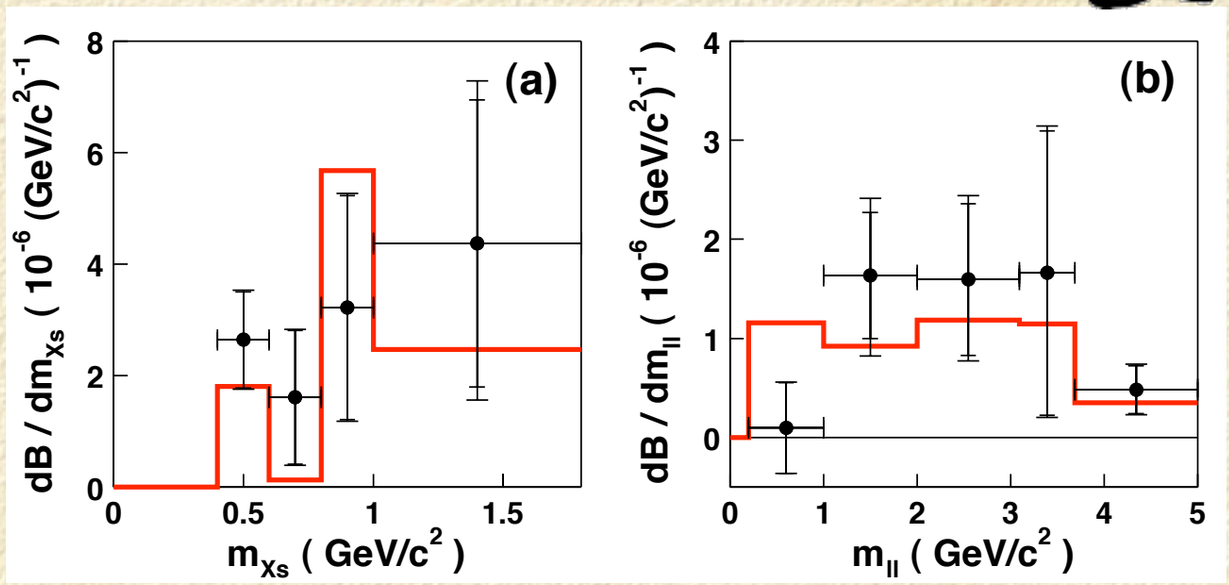




$b \to s\ell^+\ell^-$ Results

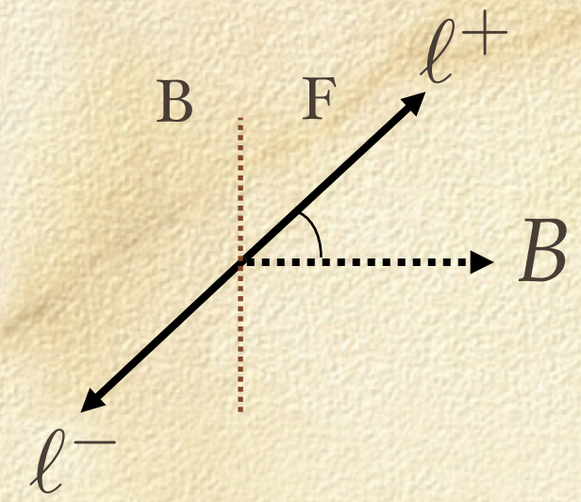


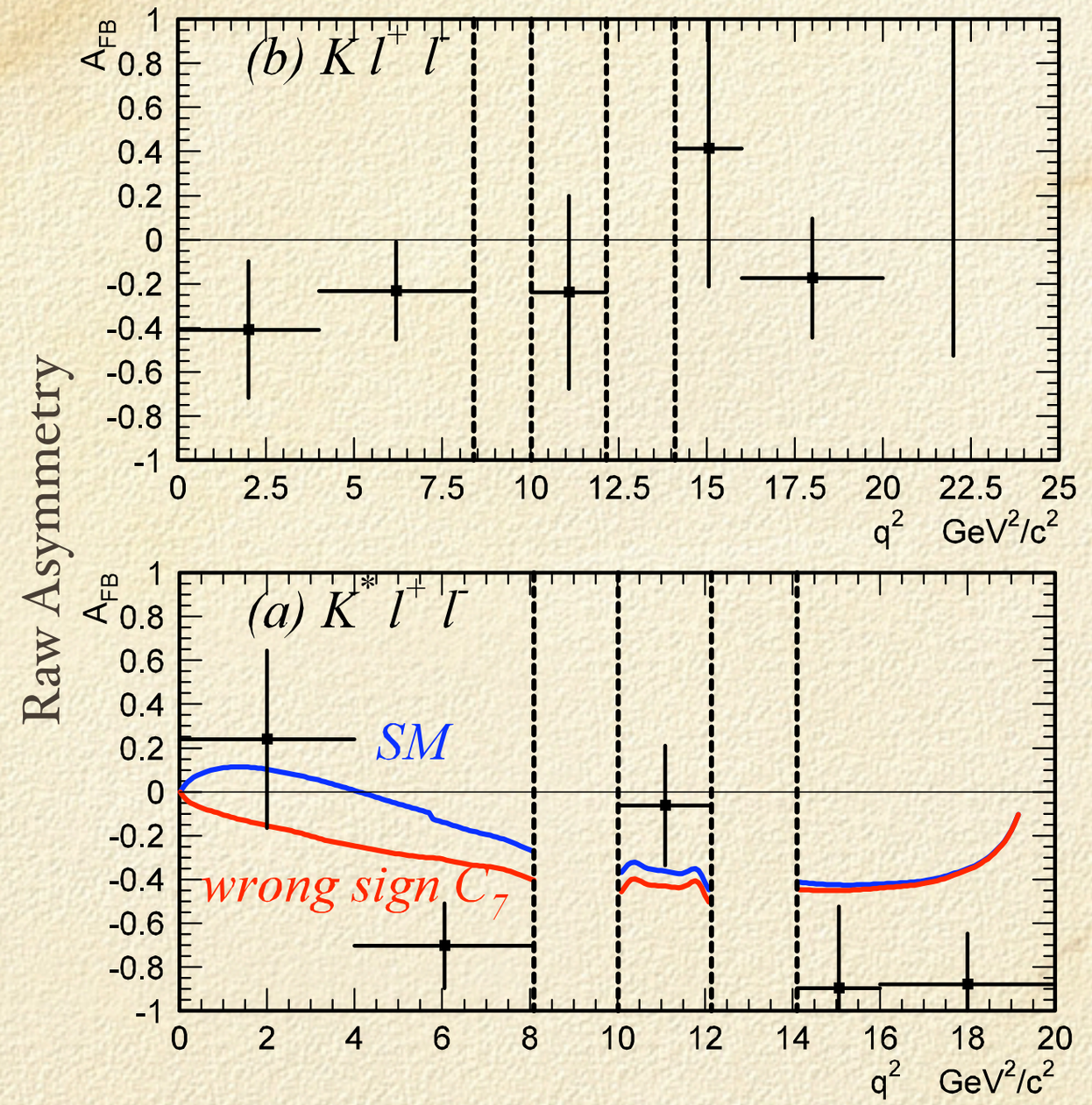




m_{X_s} $m_{\ell^+\ell^-}$

$b \to s\ell^+\ell^-$ Forward-Backward Asymmetry

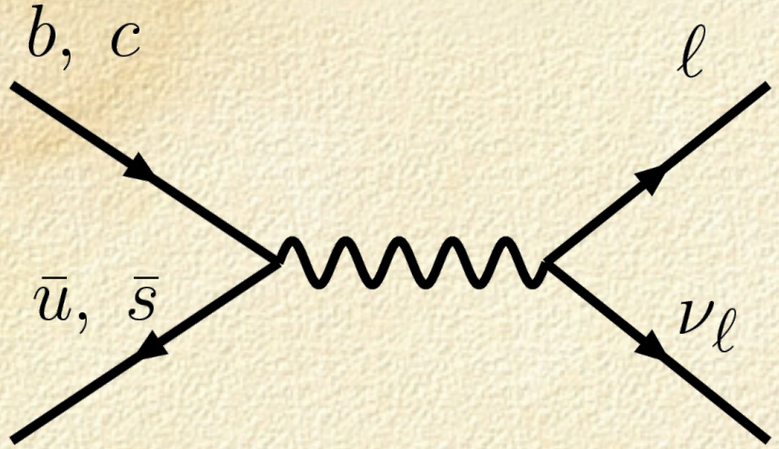




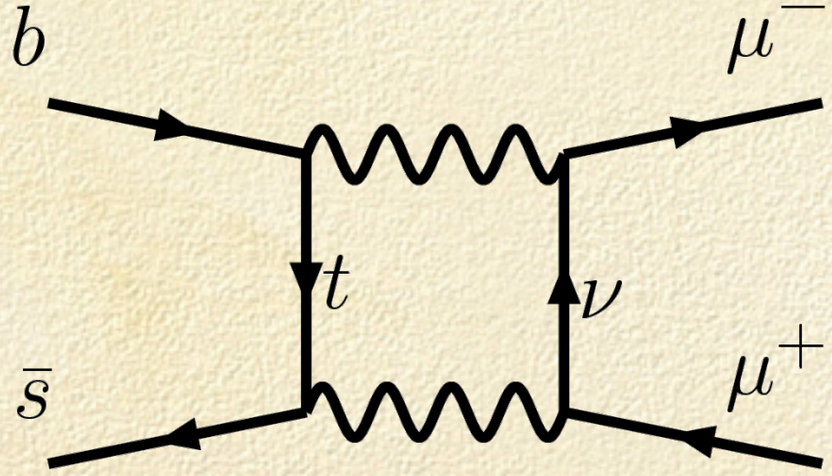
$$A_{FB} \sim C_{10}\left(\mathrm{Re}(C_9^{\mathrm{eff}}) + \frac{r(q^2)m_b}{q^2}C_7^{\mathrm{eff}}\right)$$

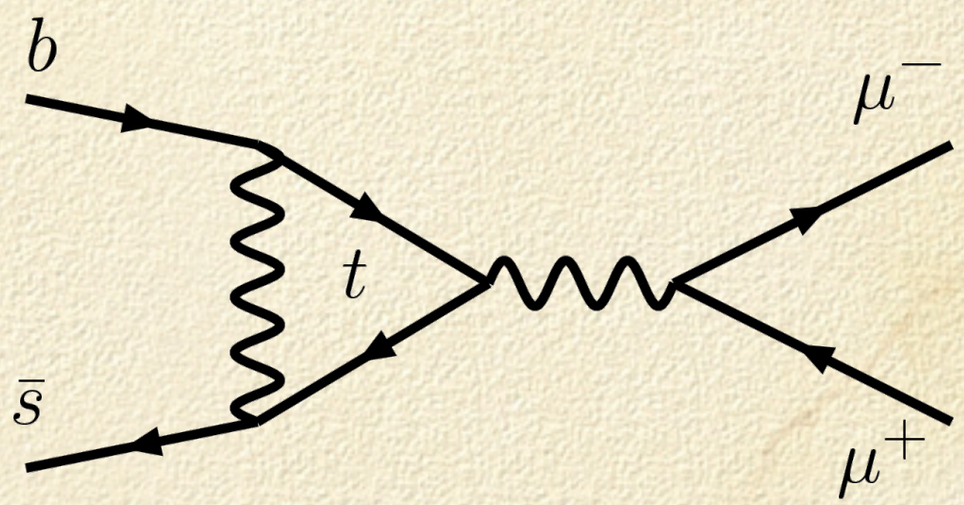
No Hadronic Currents

Leptonic Decays



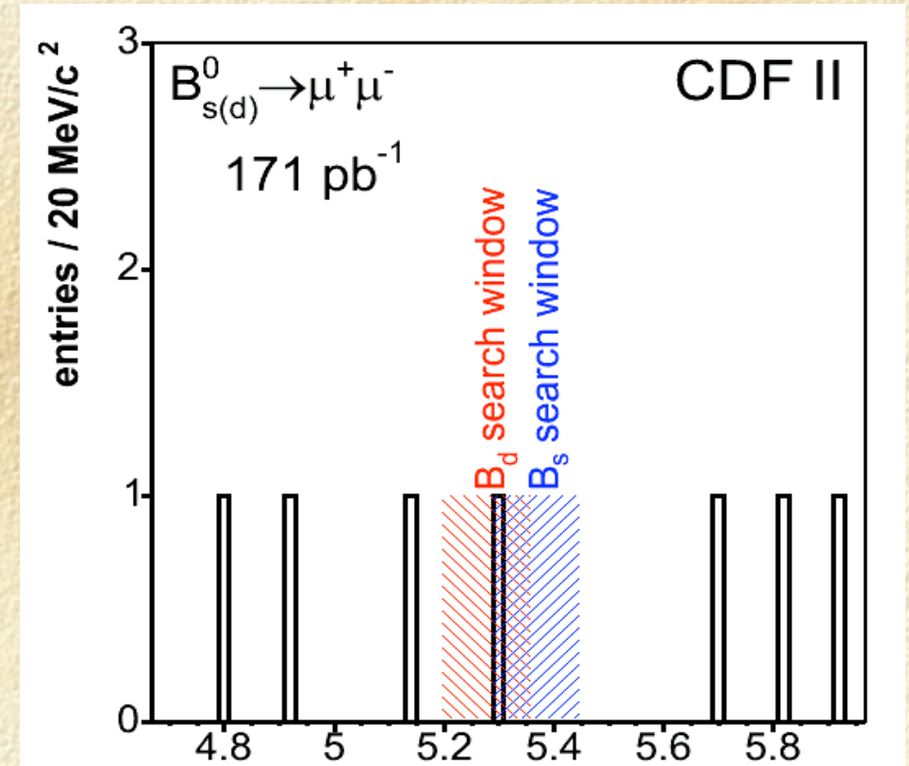
$$\Gamma(M^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 |V_{Qq}|^2}{8\pi} f_M^2 m_M m_\ell^2 \left[1 - \frac{m_\ell^2}{m_M^2}\right]^2$$





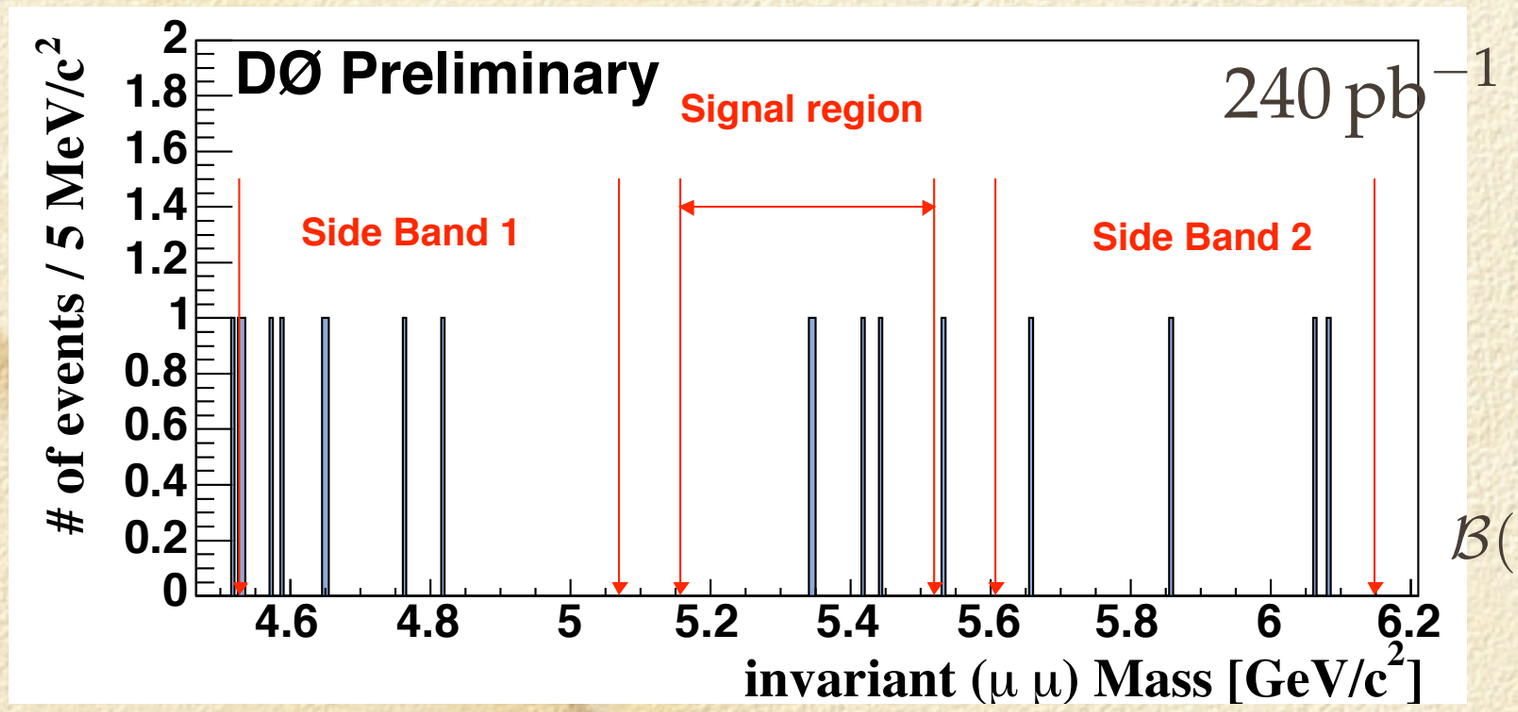
$$\Gamma(B_s \to \mu^+ \mu^-) = \frac{G_F^2 |V_{tb}^* V_{ts}|^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2 \Theta_W}\right)^2 f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - 4\frac{m_\mu^2}{m_{B_s}^2}}\, Y(m_t^2/m_W^2)$$

$B_s \to \mu^+\mu^-$



1 event
1.1 ± 0.3 background

$\mathcal{B}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$ 90% C.L.
$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ 90% C.L.



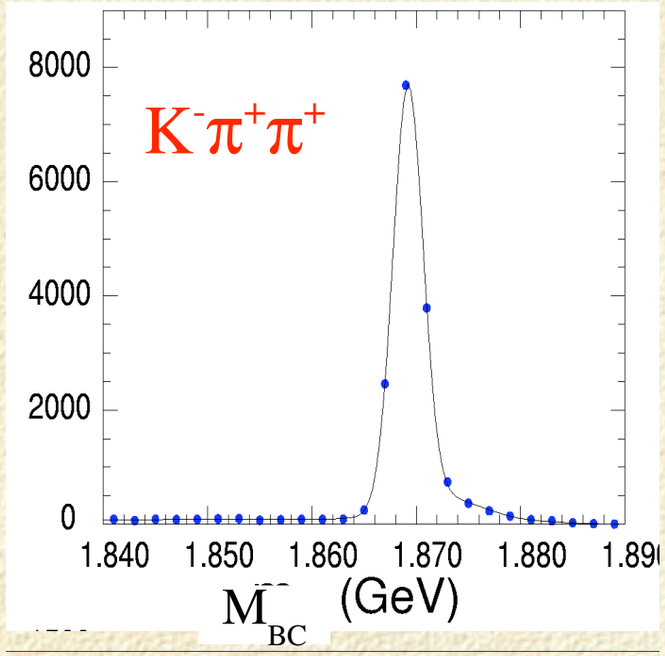
4 events
3.7 ± 1.1 background

$\mathcal{B}(B_s \to \mu^+\mu^-) < 3.8 \times 10^{-7}$ 90% C.L.

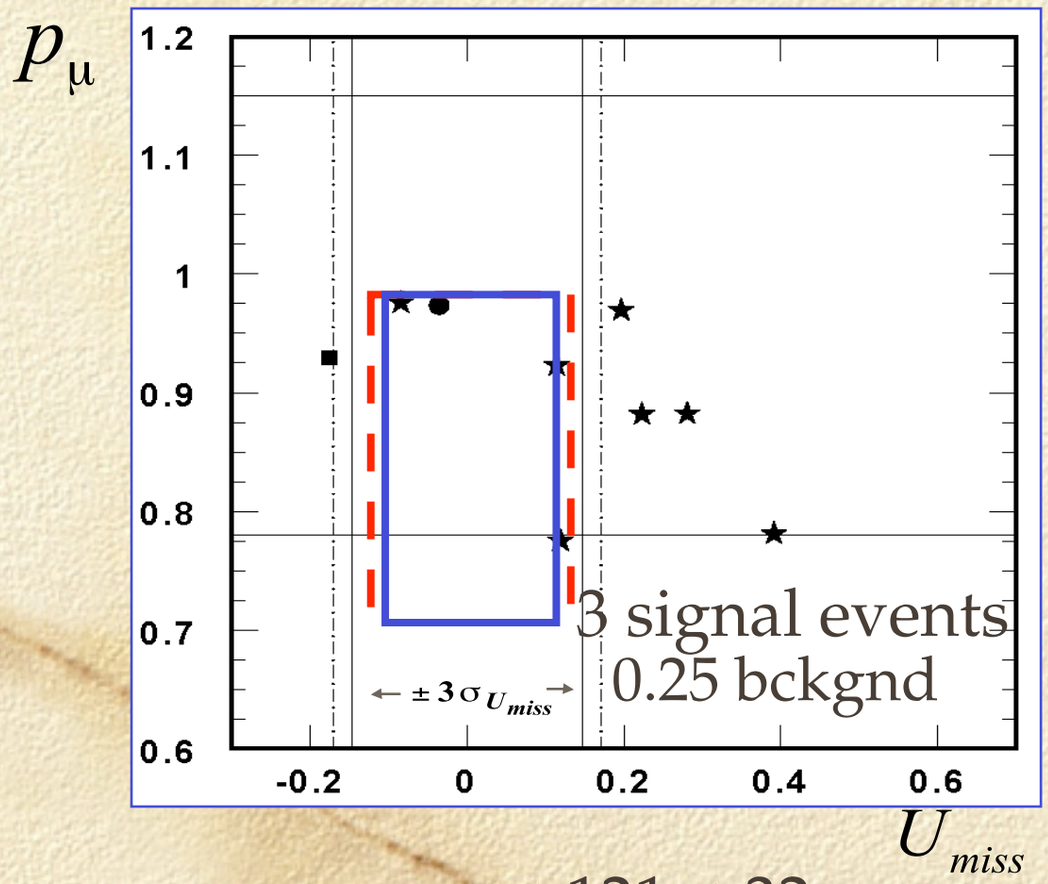
$$D^+ \to \mu^+ \nu$$

$$\psi(3770) \to D^+ D^-$$

Fully reconstruct one D

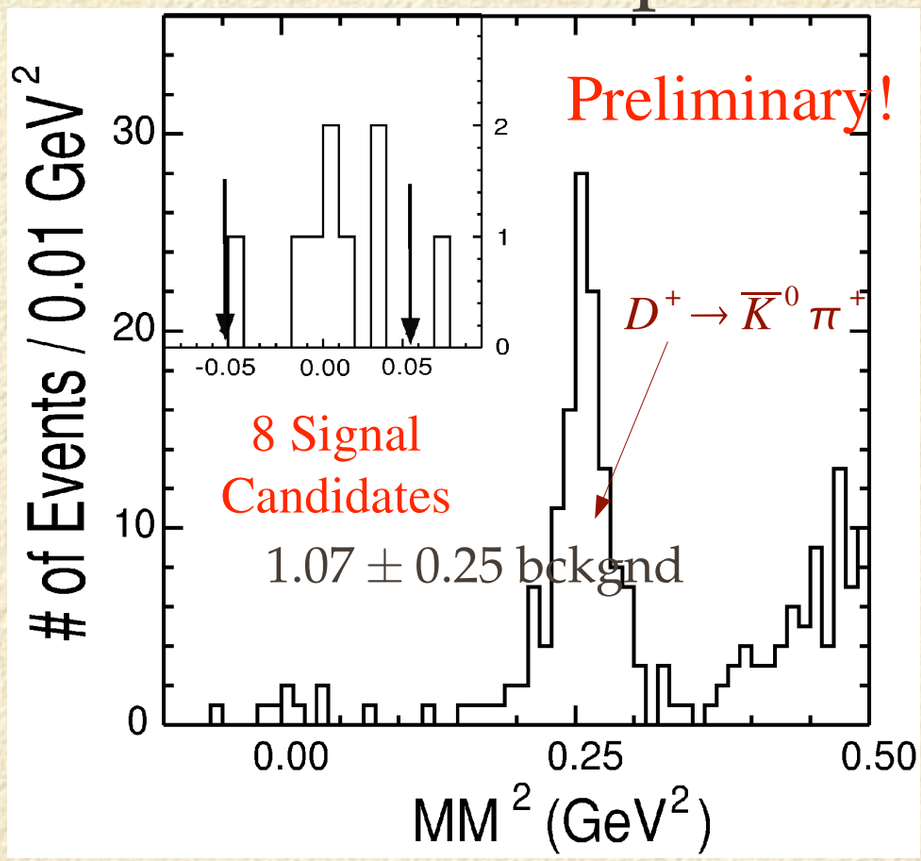


BES-II 18 pb^{-1}



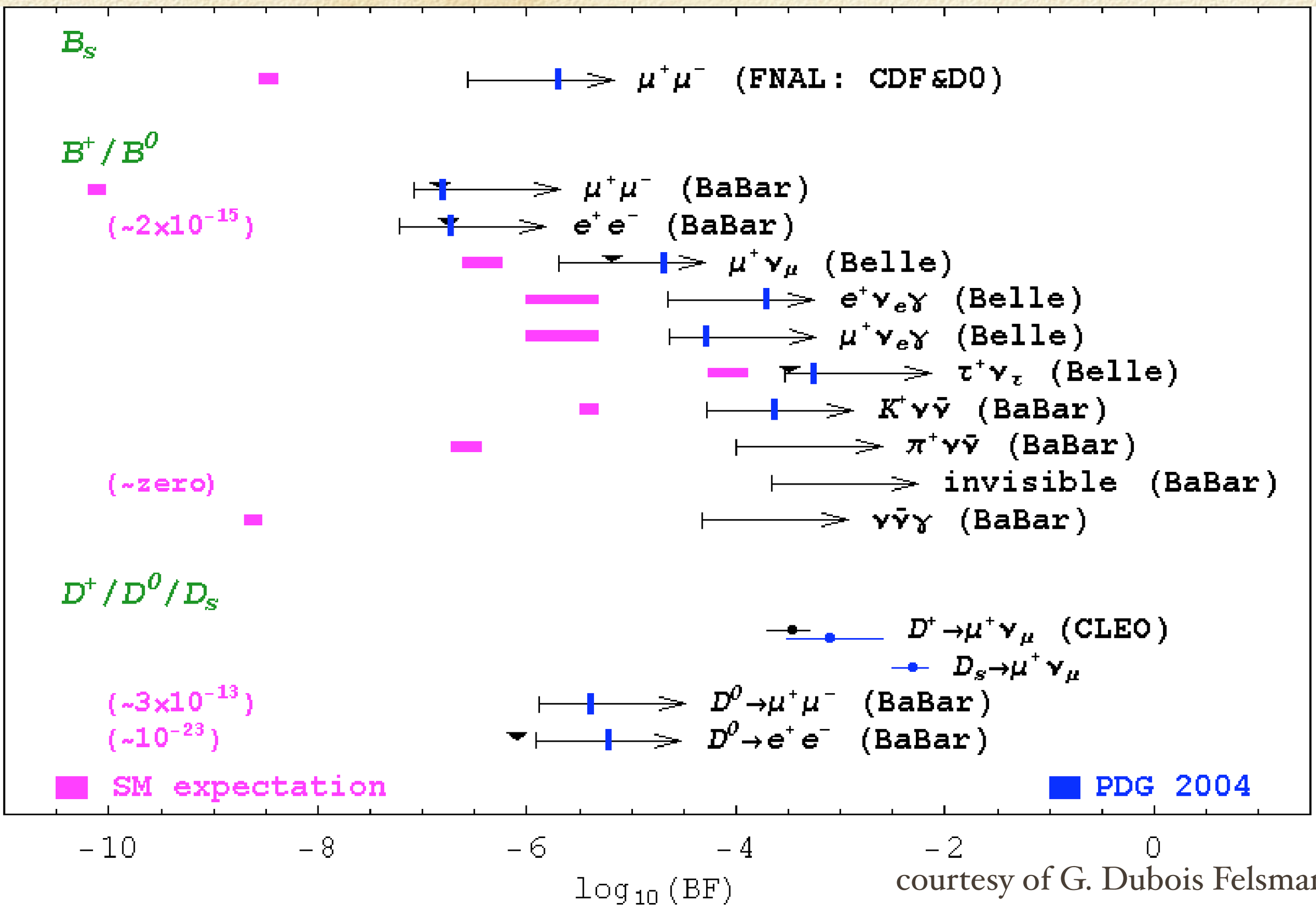
$$f_{D^+} = 365^{+121\ +32}_{-113\ -28}\ \mathrm{MeV}$$

CLEO-c 57 pb^{-1}



$$f_{D^+} = 201 \pm 41 \pm 17\ \mathrm{MeV}$$

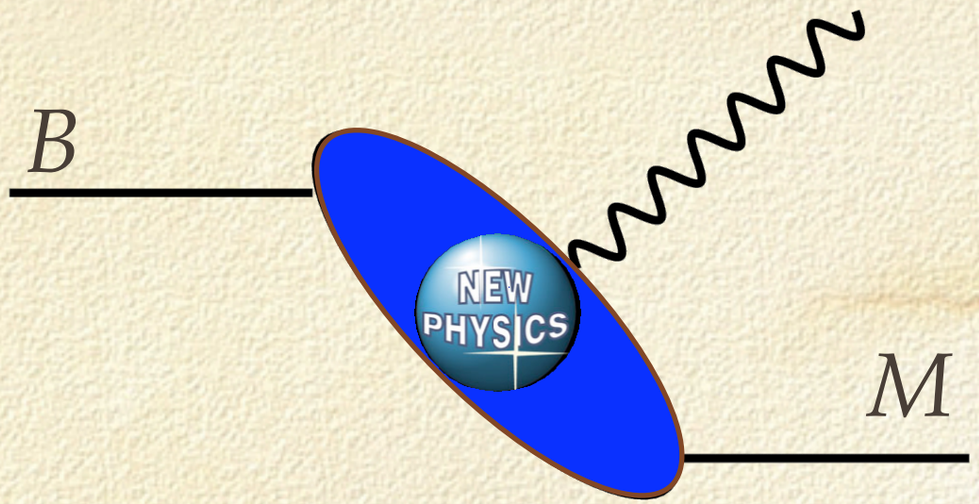
Summary of Leptonic Decays



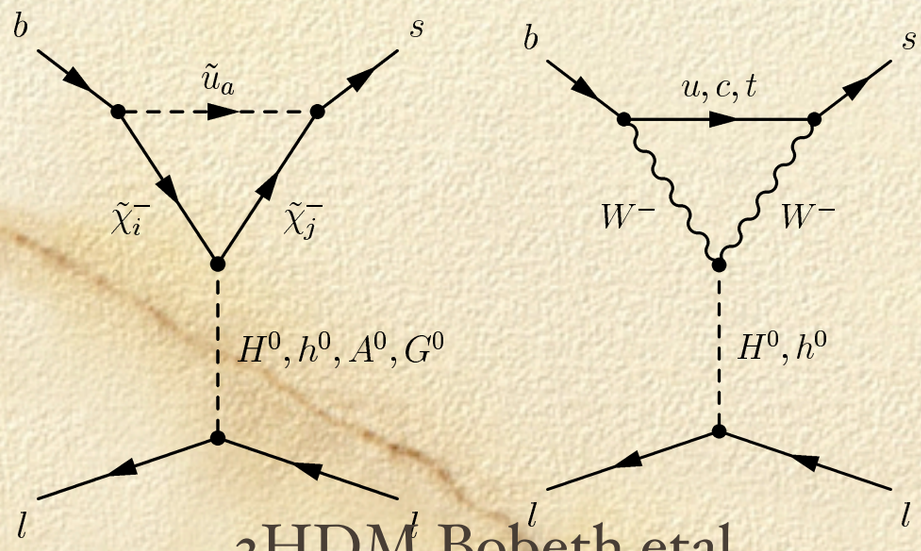
courtesy of G. Dubois Felsmann

SUSY & New Physics Limits

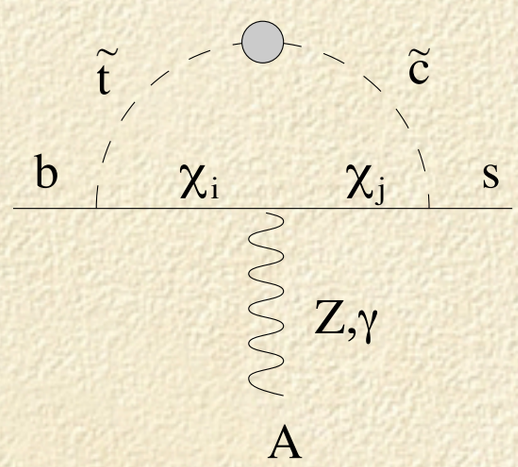
- $\mathcal{B}(b \to s\gamma)$
- $\mathcal{B}(b \to s\ell^+\ell^-)$
- $A_{FB}(q^2)\ b \to s\ell^+\ell^-$
- $\mathcal{B}(B_s \to \mu^+\mu^-)$
- $\dfrac{BR(b\to s\mu^+\mu^-)}{BR(b\to se^+e^-)}$

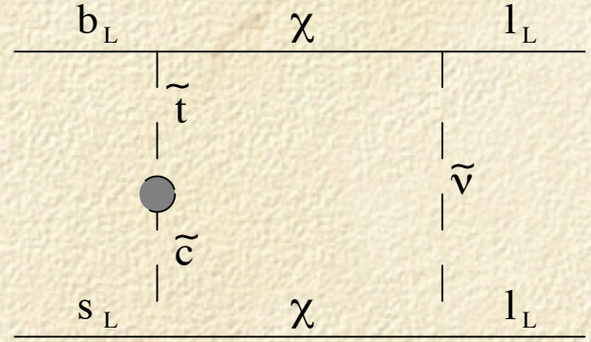


These processes set limits on New Physics models



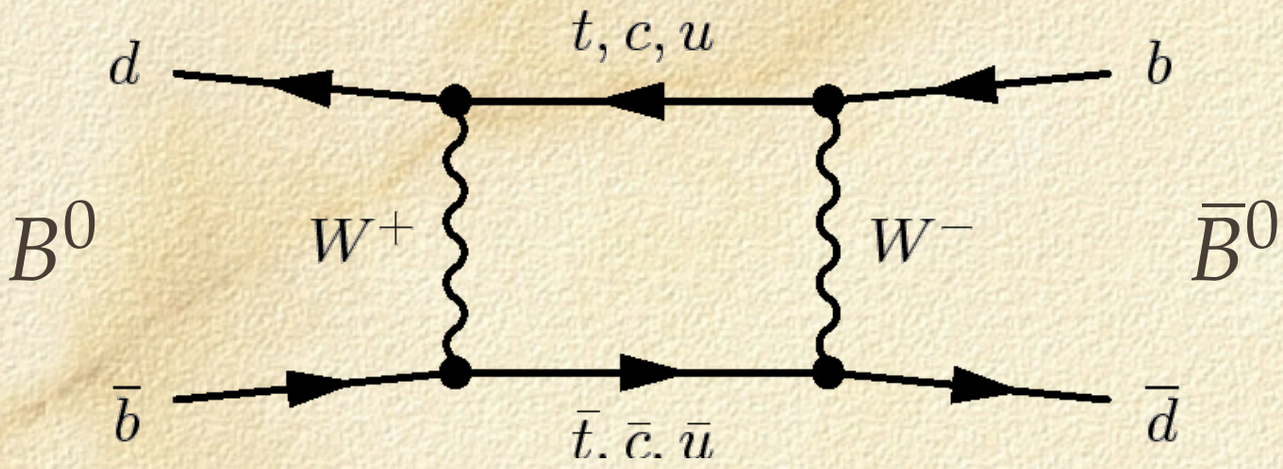
2HDM Bobeth etal





MSSM Lunghi etal

Neutral Meson Mixing



$$B^0_{CP+} = \frac{1}{\sqrt{2}}(B^0 + \bar{B}^0)$$

$$B^0_{CP-} = \frac{1}{\sqrt{2}}(B^0 - \bar{B}^0)$$

$$B^0 \to f_{\text{Flavor}}(\text{e.g. } X\ell^+\nu,\ D^{*+}\pi^-)$$

$$\Delta m_{B^0} = \frac{G_F^2 m_W^2}{6\pi^2}\eta_{QCD} m_{B^0} B_{B^0} f_{B^0}^2 S(m_t/m_W)|V_{td}V_{tb}^*|^2$$

$$\Delta m_{B^0} = 0.502 \pm 0.007$$

$$\frac{\Delta m_{B_s}}{\Delta m_{B_d}} = \frac{m_{B_s}}{m_{B^0}} \frac{f_{B_s}}{f_{B_d}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$$\Delta m_{B_s} > 14.4\ \text{psec}^{-1}$$

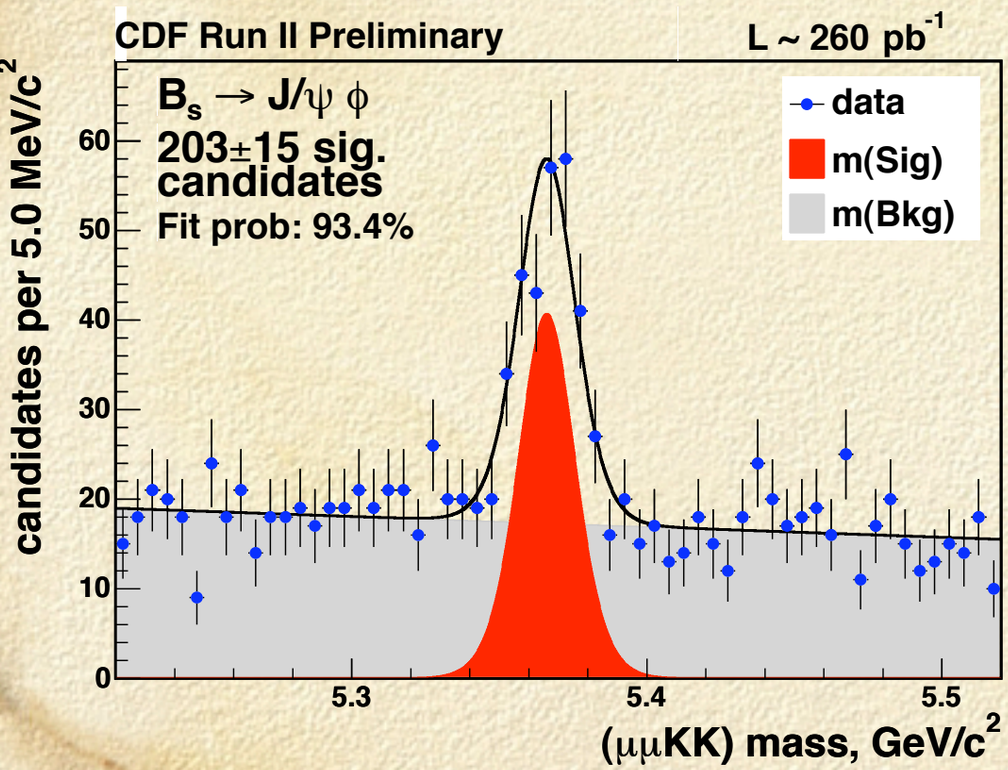
$$\Delta m_{D^0} \sim \frac{m_s^2 - m_d^2}{m_W^2}|V_{cs}V_{us}^*|^2 + \text{LongDist.}$$

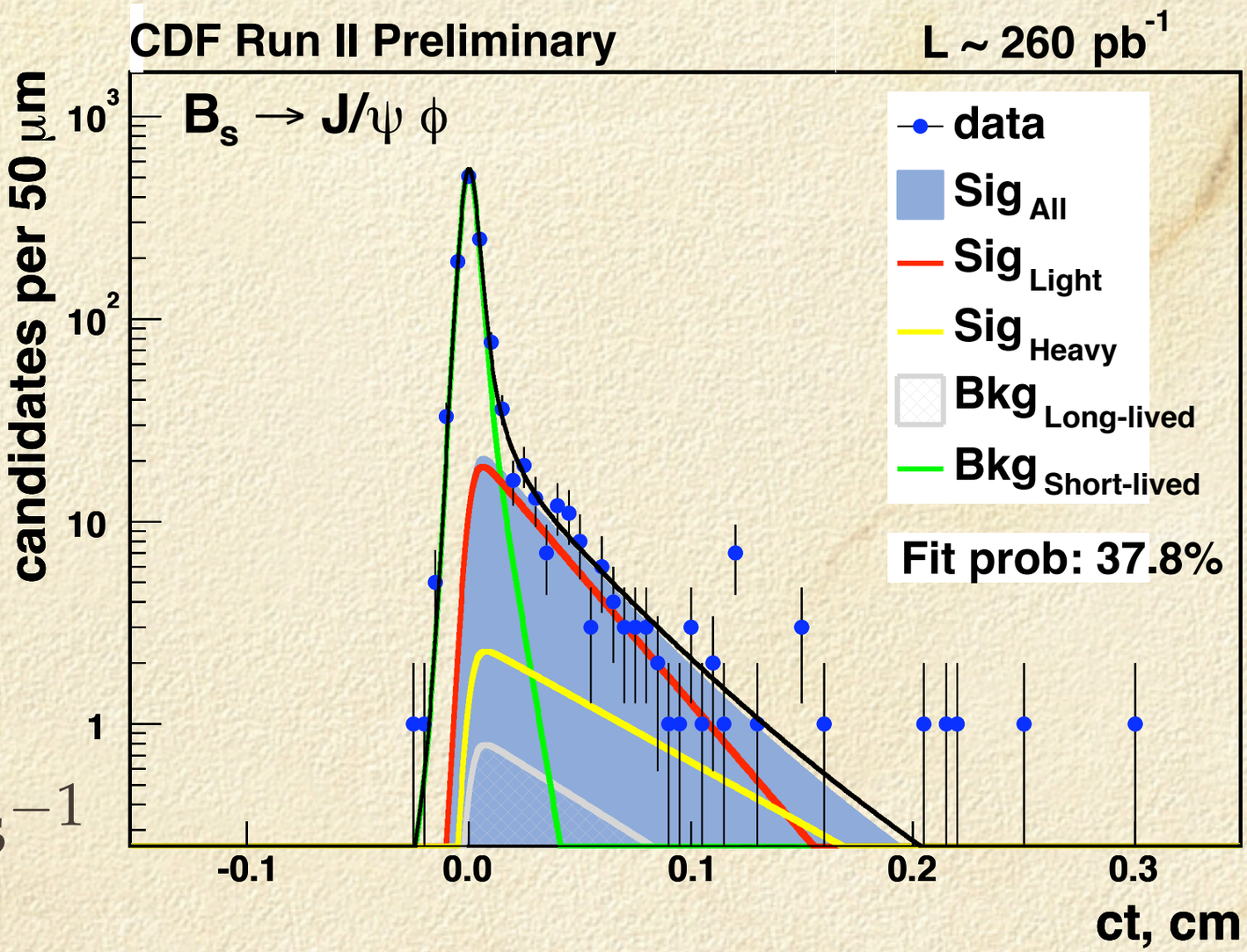
10^{-6}psec^{-1}

B_s Lifetime Difference

isolate CP odd and CP even states
using $J/\psi\phi$ polarization

prediction: $\Delta\Gamma_{B_s}/\Gamma_{B_s} = 0.12 \pm 0.06$

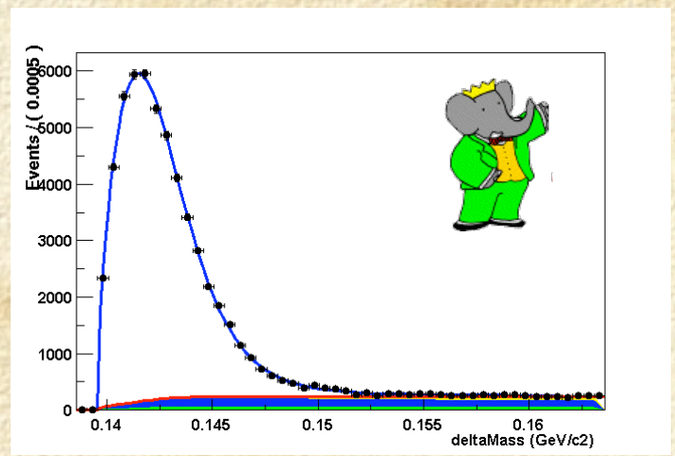




$$\Delta\Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01\,\mathrm{ps}^{-1}$$

D Mixing

$$D^{*+} \to D^0 \pi^+_{\text{slow}}$$



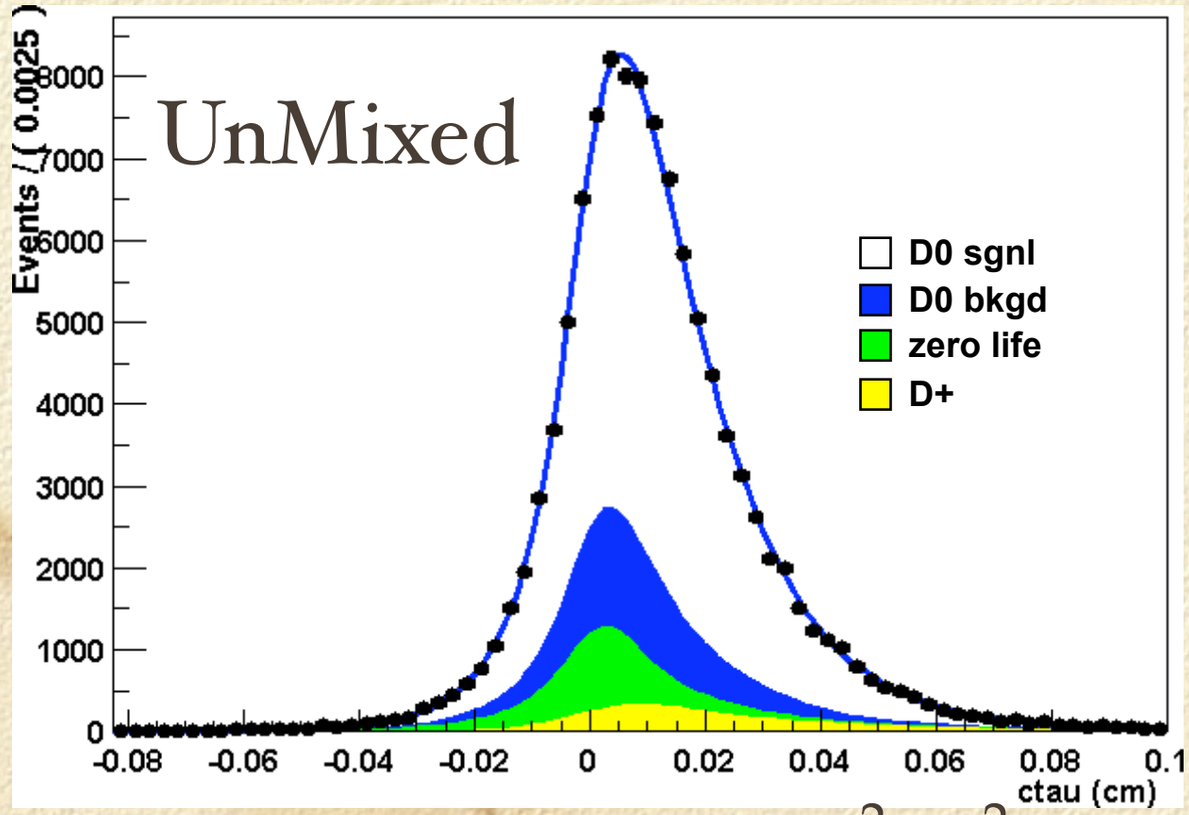
$$\Delta M = m_{D^*} - m_D$$

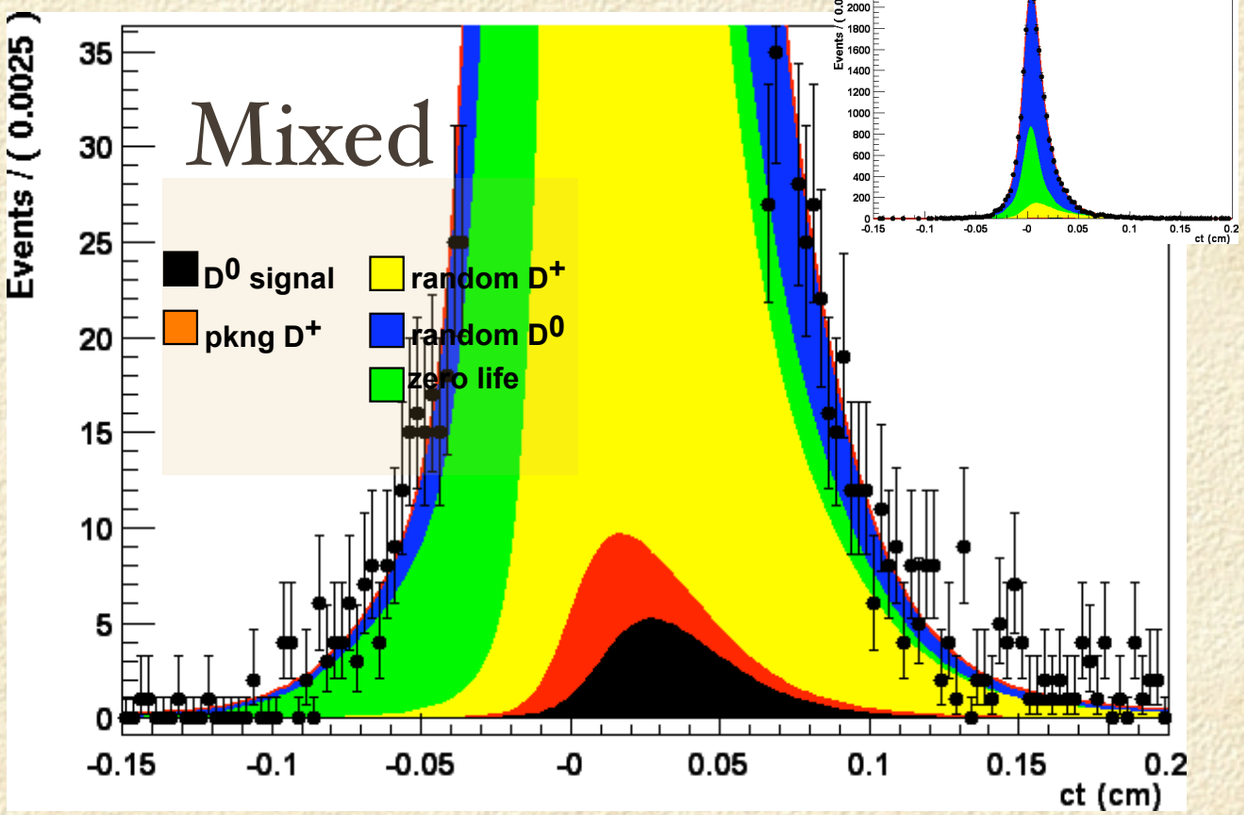
$$f_{\text{Mixed}}(t) = \frac{e^{-t/\tau}}{4\tau}\left\{\cosh\left(\Delta\Gamma t/2\right) - \cos\left(\Delta m t\right)\right\}$$

$$x = \Delta m/\Gamma \qquad y = \Delta\Gamma/2\Gamma$$

$$D^0 \to K^{(*)+} e^- \nu$$

$$f_{\text{Mixed}}(t) \sim e^{-t/\tau}\left\{\frac{(x^2+y^2)}{4}(t/\tau)^2\right\}$$





$$\frac{x^2+y^2}{2} < 4.2 \times 10^{-3}$$

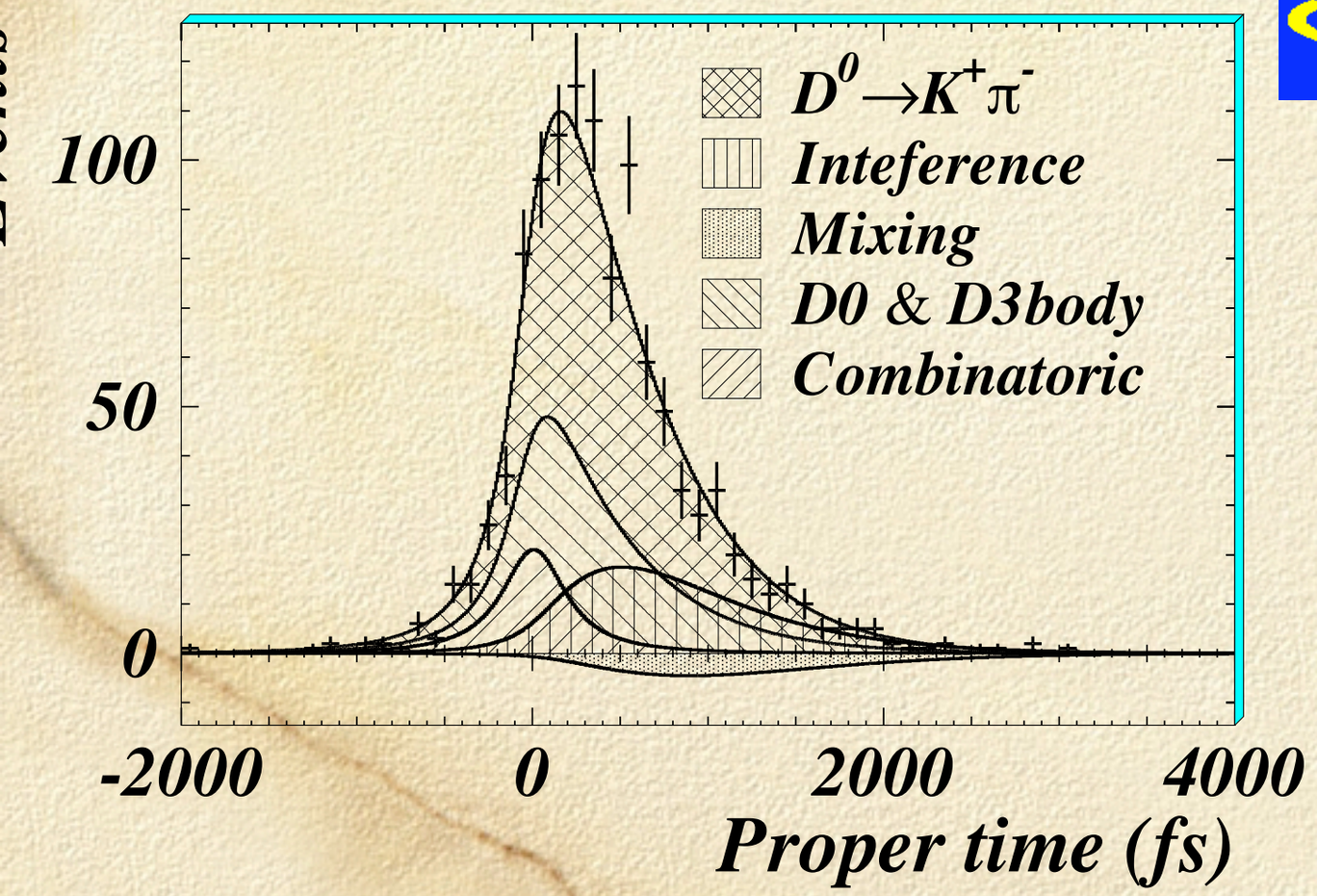
D Mixing

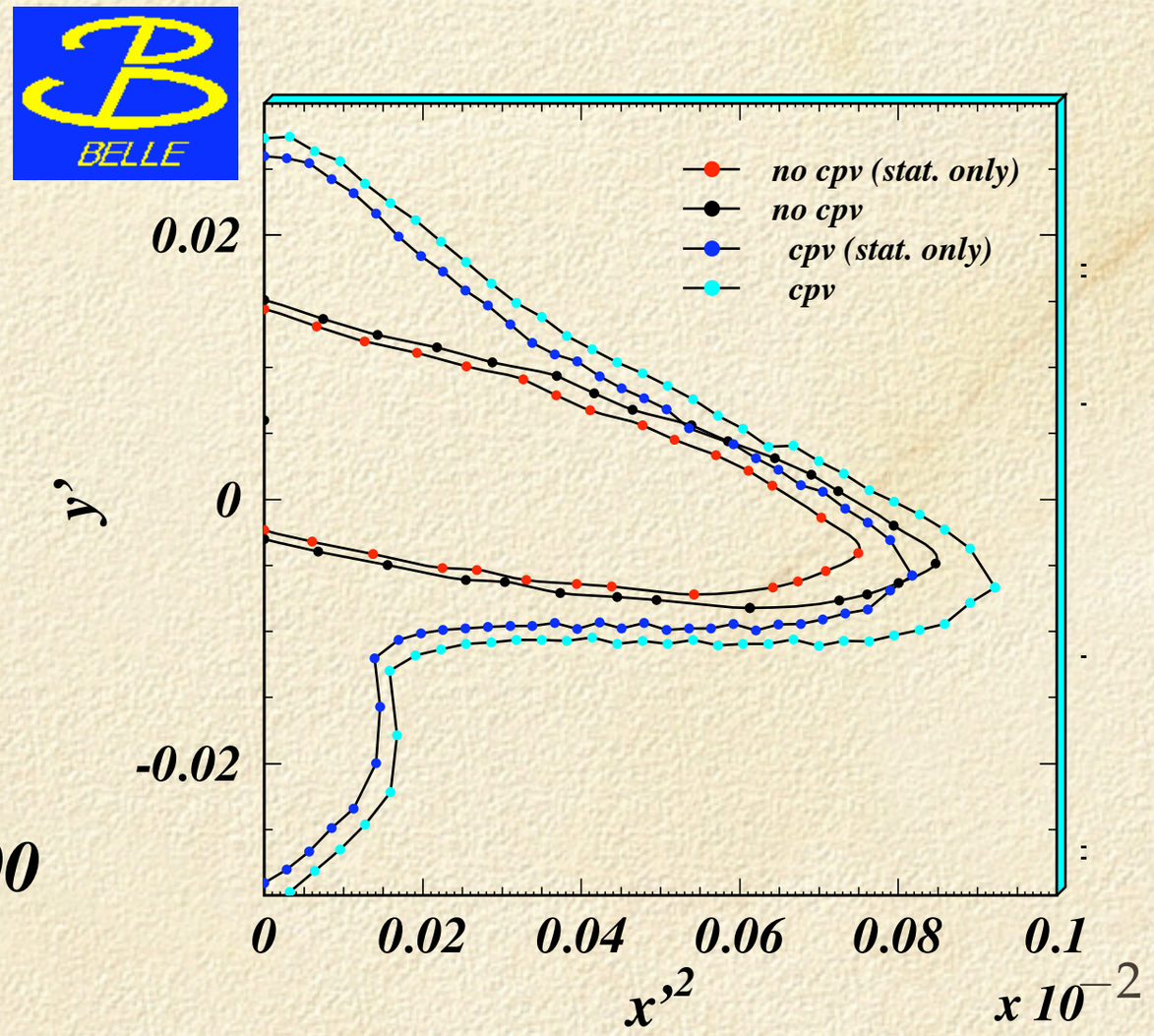
$$D \to K\pi$$

$$A(\overline{D}^0 \overset{\Delta m}{\to} D^0 \to K^+\pi^-) + A(D^0 \overset{\text{DCSD}}{\to} K^+\pi^-)$$

$$f_{\text{Mixed}}(t) \sim e^{-t/\tau}\left\{r_D + \sqrt{r_D}y't + \frac{(x'^2+y'^2)}{4}(t/\tau)^2\right\}$$

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$





Summary

- Two Hadronic Currents
  - importance of Non-Factorizable amplitudes
  - pattern of $B \to \pi\pi$ and $B \to \rho\rho$ decays
- One Hadronic Current
  - new measurements of V_{ub} with less theoretical uncertainty
  - new measurements of $b \to s\gamma$, $b \to s\ell^-\ell^-$, limits on $B_s \to \mu^+\mu^-$ all constrain New Physics
- No Hadronic Currents
  - D meson decay constants
- Meson Mixing

Future

- B Factories
  - data samples of $1 ab^{-1}$ by 2010
  - recoil technique
- Tevatron experiments
  - data samples of more than $4\,\mathrm{fb}^{-1}$ by 2008
  - B_s mixing
- Charm Factories
  - accurate measurements to calibrate calculations
- BTeV, LHC-b, and perhaps Super-B Factories

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