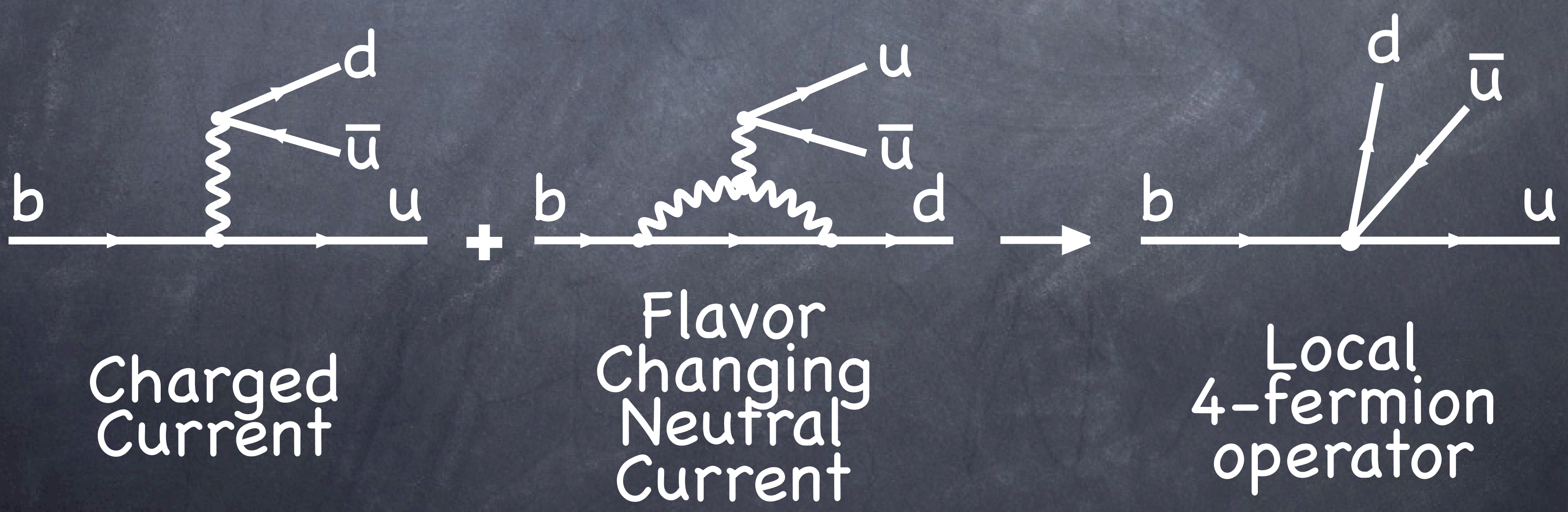
Recent theory advances in B physics

Christian Bauer
LBNL

SuperB Workshop 2006, SLAC

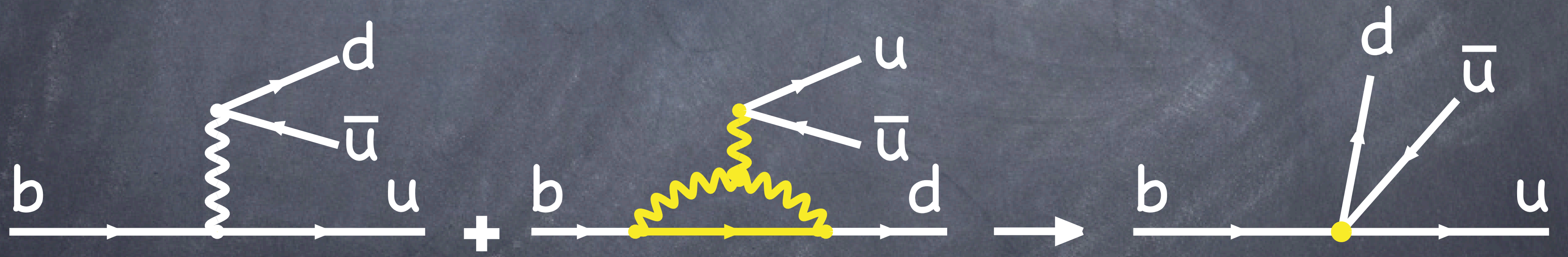
Flavor Physics in the SM

- Decays mediated by electroweak gauge bosons
- Propagate over distance scale ~$1/M_{EW}$ ~0.005 fm
- Much less than distance of colliding particles ~0.1 fm



Flavor Physics beyond the SM

- Loop diagrams can get many additional contributions
- Propagate over distance scale ~$1/M_{EW}$ ~0.005 fm
- Much less than distance of colliding particles ~0.1 fm



Charged Current

Flavor Changing Neutral Current

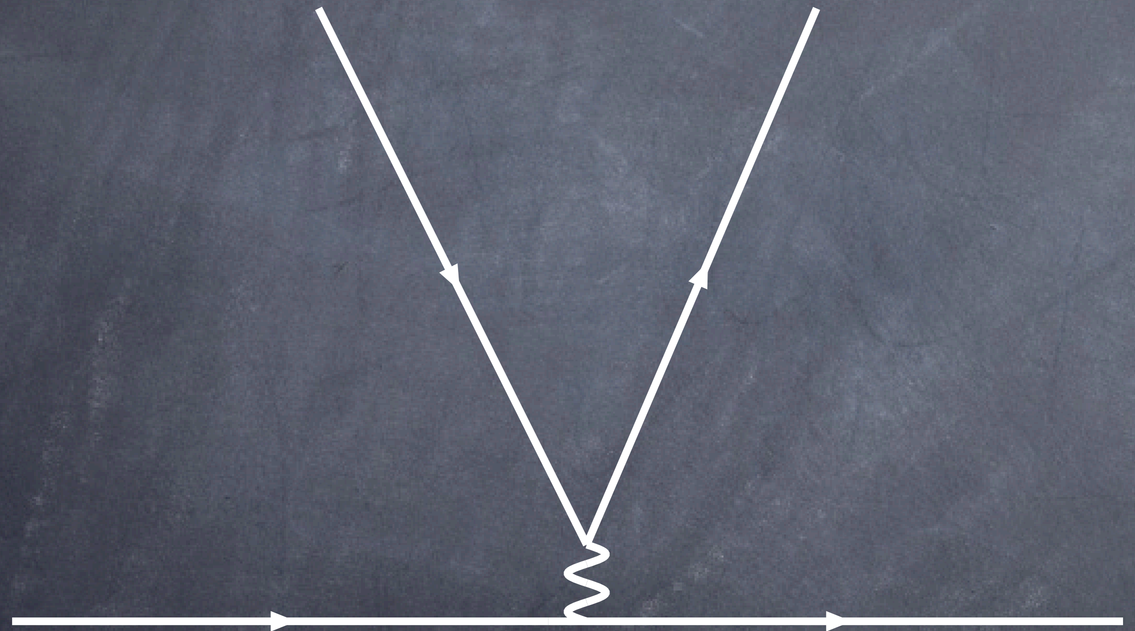
Local 4-fermion operator

The Curse of QCD

- The weak interaction we are after is masked by QCD effects, which are completely non-perturbative

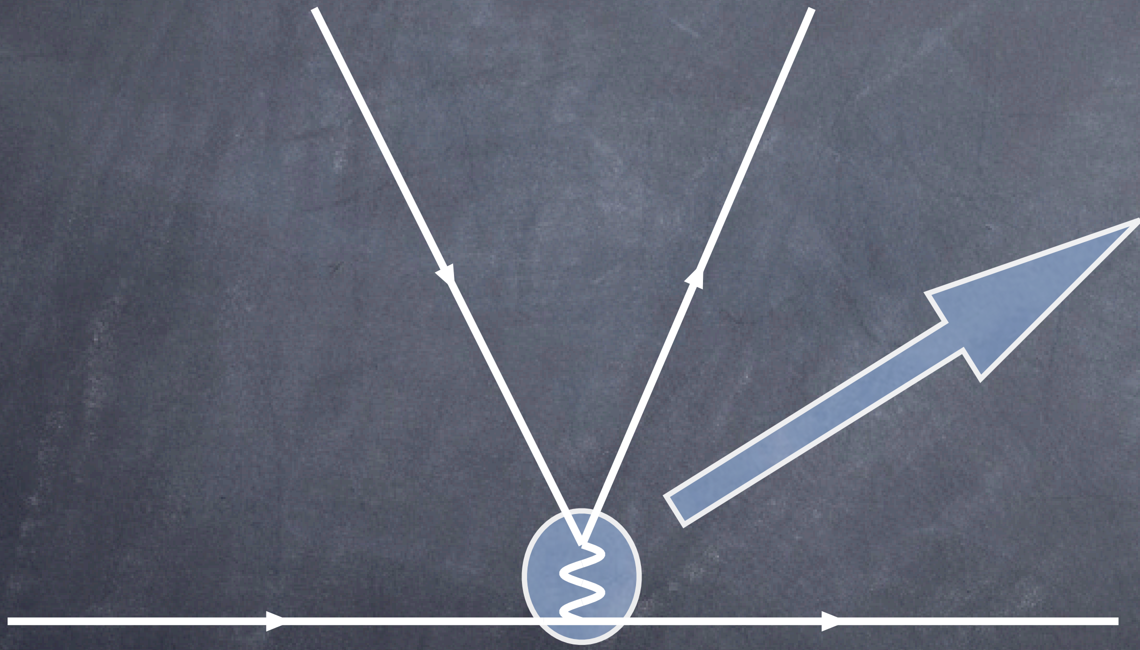
The Curse of QCD

- The weak interaction we are after is masked by QCD effects, which are completely non-perturbative



The Curse of QCD

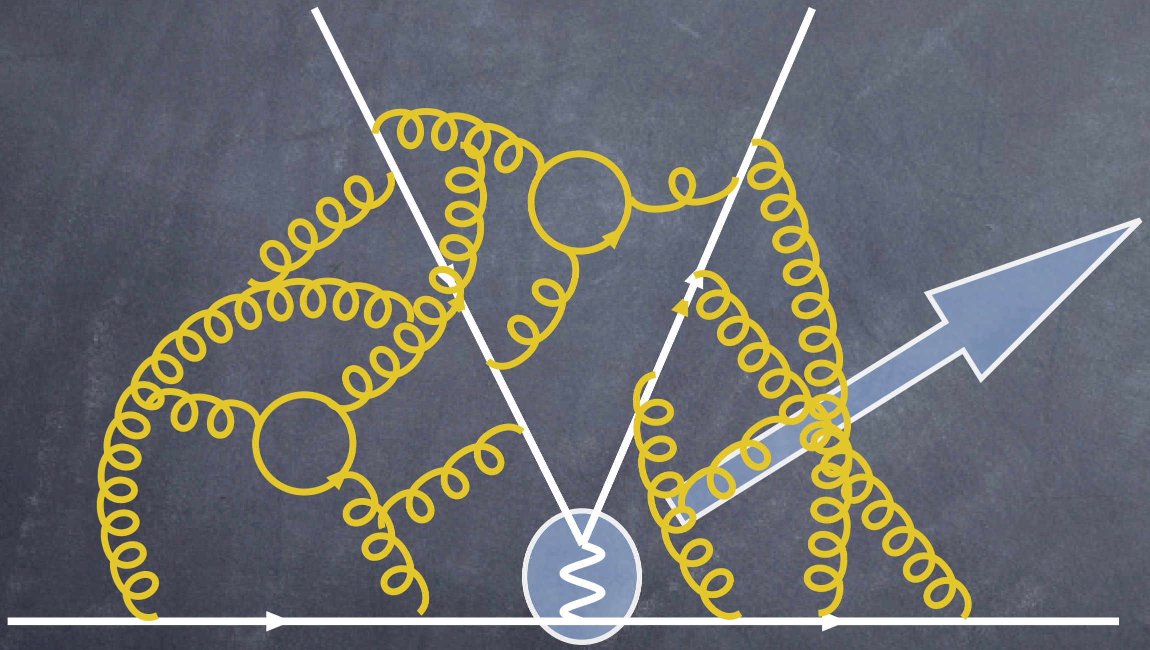
- The weak interaction we are after is masked by QCD effects, which are completely non-perturbative



Weak interaction effect we are after

The Curse of QCD

- The weak interaction we are after is masked by QCD effects, which are completely non-perturbative

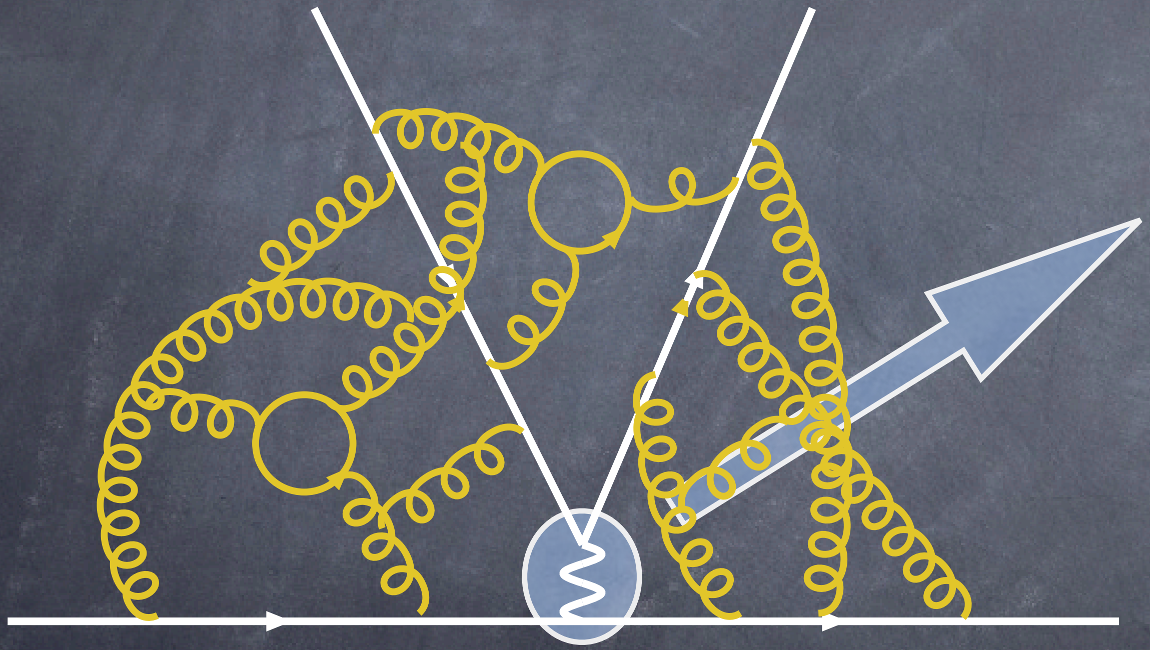


Weak interaction effect we are after

Non-perturbative effects from QCD

The Curse of QCD

- The weak interaction we are after is masked by QCD effects, which are completely non-perturbative



Weak interaction effect we are after

Non-perturbative effects from QCD

Crucial to understand long distance physics to extract weak flavor physics from these decays

Different levels of theory

- "No theory" required
  - leptonic decays, isospin analysis in $B \to \pi\pi$
- Bread and Butter theory
  - Inclusive B decays and V_{cb}
- New developments in inclusive decays
  - Shape functions in rare inclusive decays
- New developments in exclusive decays
  - Factorization in non-leptonic decays

Bread and butter: Determination of V_{cb}

Quote from Babar physics books

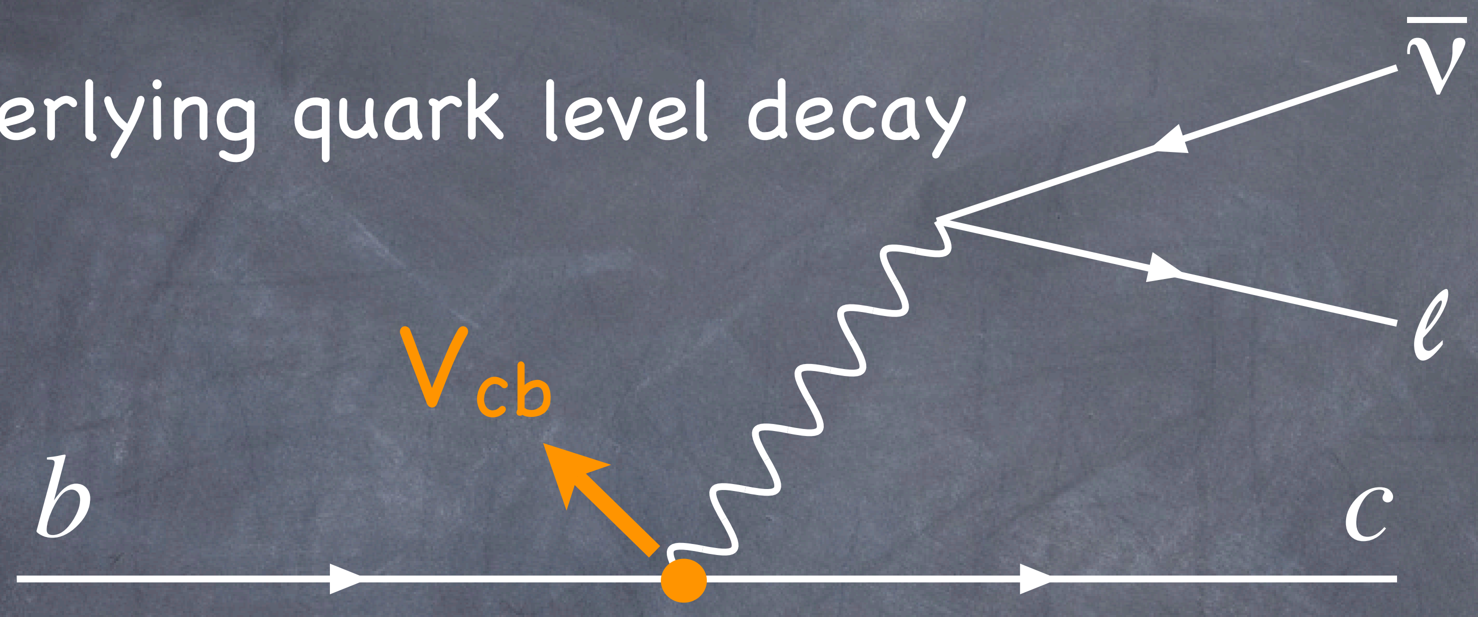
"...a theoretical precision of 3% on the value of $|V_{cb}|$ will be obtained. Looking a few years ahead, anticipating further progress in the theoretical understanding of heavy-flavor transitions, one can hope that ultimately an accuracy of 1% may be reached."

Bread and butter: $B \to X_c \, \ell \, \nu$

Underlying quark level decay

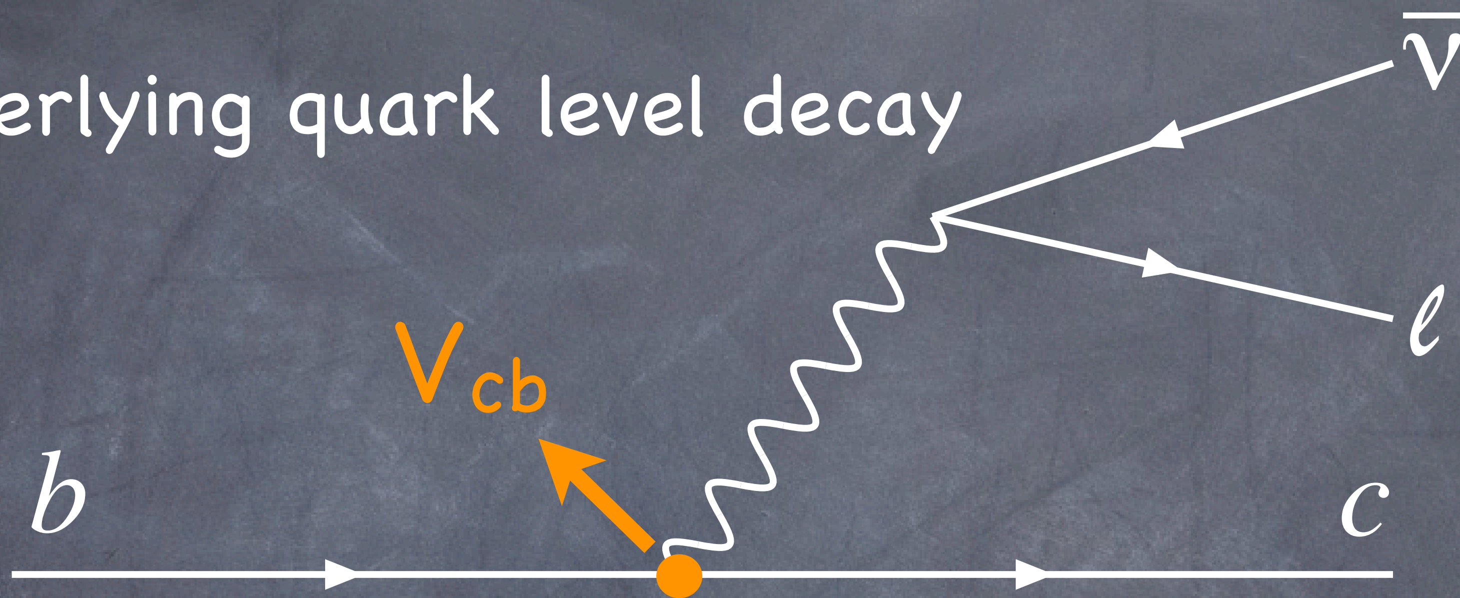
Bread and butter: $B \to X_c \ell \nu$

Underlying quark level decay



Bread and butter: $B \to X_c \ell \nu$

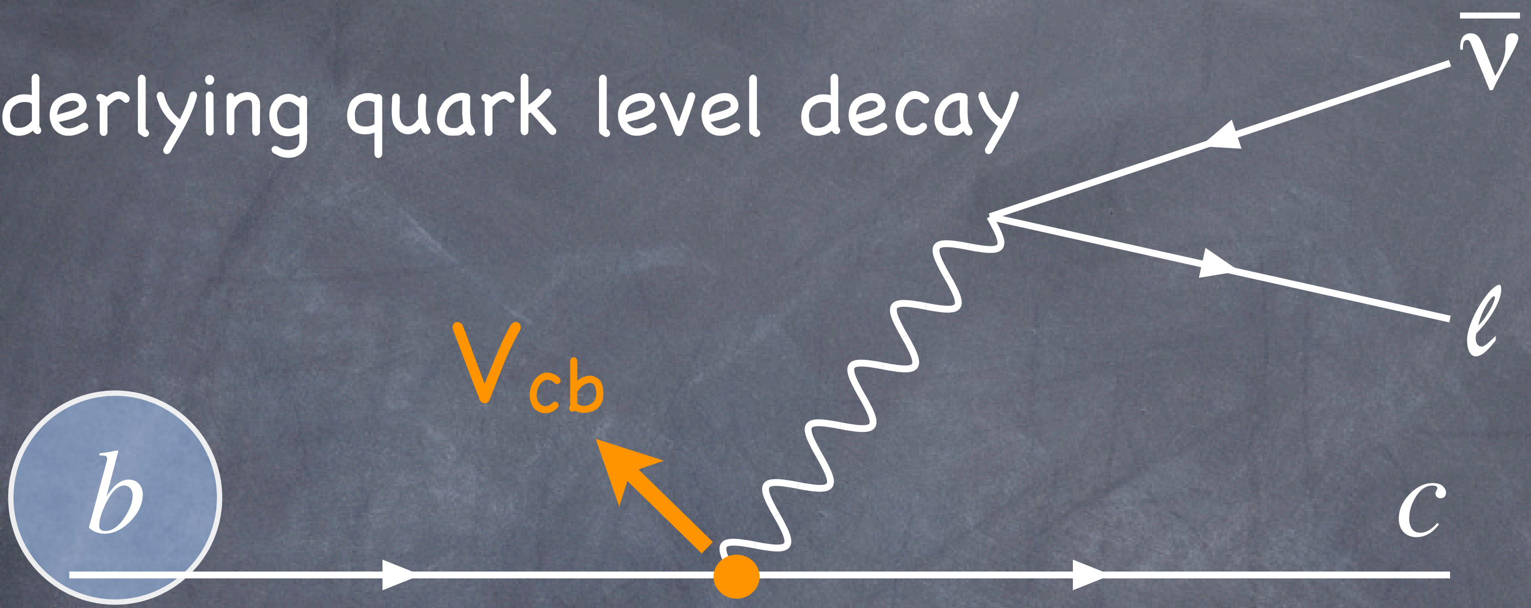
Underlying quark level decay



Two hadronizations to worry about

Bread and butter: $B \to X_c \ell \nu$

Underlying quark level decay

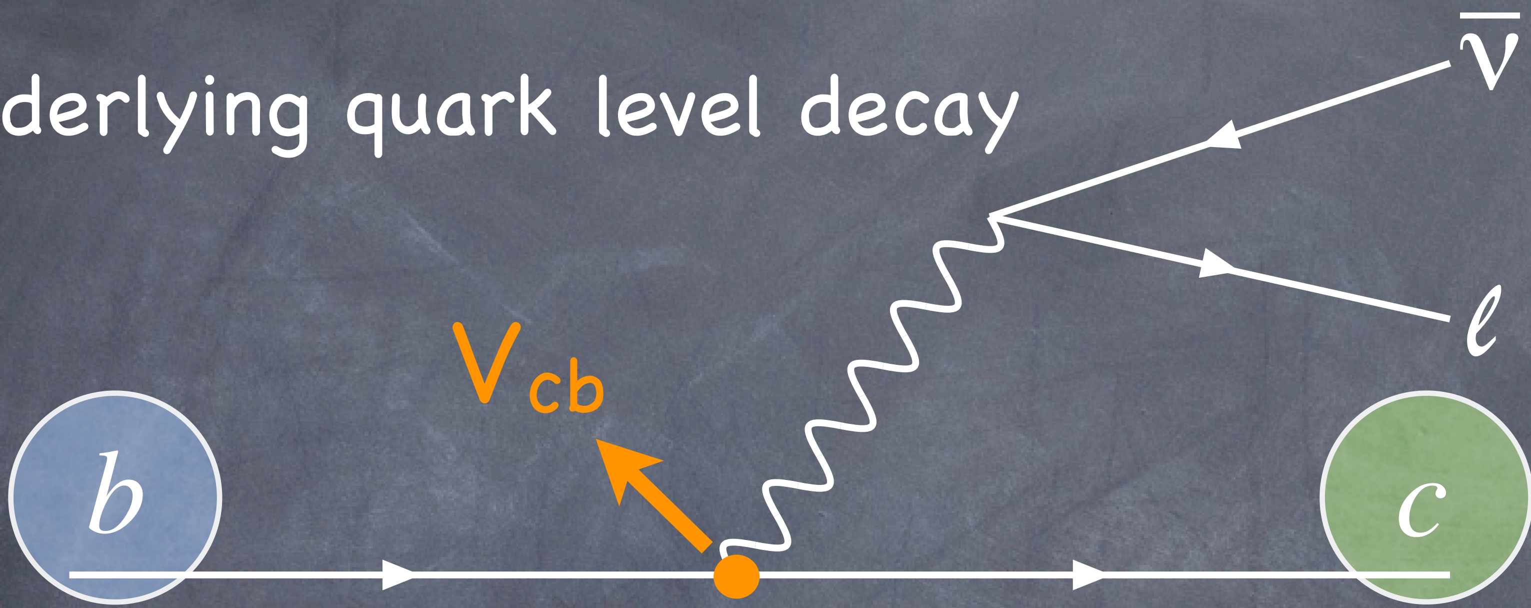


Two hadronizations to worry about

b quark hadronizing into B meson

Bread and butter: $B \to X_c \ell \nu$

Underlying quark level decay



Two hadronizations to worry about

b quark hadronizing into B meson

c quark hadronizing into final state

The decay rate

$\Gamma(B \to X_c \ell \bar{\nu})$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu})$$
$$= \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5$$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu})$$
$$= \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5$$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\left[1 - 0.22 \left(\frac{\Lambda}{500\mathrm{MeV}}\right)\right.$$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu})$$
$$= \frac{G_F^2 |V_{cb}|^2}{192\pi^3}(0.534)\left(\frac{m_\Upsilon}{2}\right)^5 \times$$
$$\left[1 - 0.22\left(\frac{\Lambda}{500\text{MeV}}\right) - 0.011\left(\frac{\Lambda}{500\text{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{500\text{MeV}^2}\right) - 0.071\left(\frac{\lambda_2}{500\text{MeV}^2}\right)\right.$$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3}(0.534)\left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\left[1 - 0.22\left(\frac{\Lambda}{500\mathrm{MeV}}\right) - 0.011\left(\frac{\Lambda}{500\mathrm{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{500\mathrm{MeV}^2}\right) - 0.071\left(\frac{\lambda_2}{500\mathrm{MeV}^2}\right)\right.$$

$$-0.006\left(\frac{\lambda_1\Lambda}{500\mathrm{MeV}^3}\right) + 0.011\left(\frac{\lambda_2\Lambda}{500\mathrm{MeV}^3}\right) - 0.006\left(\frac{\rho_1}{500\mathrm{MeV}^3}\right) + 0.008\left(\frac{\rho_2}{500\mathrm{MeV}^3}\right)$$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu})$$
$$= \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5 \times$$
$$\left[1 - 0.22 \left(\frac{\Lambda}{500\mathrm{MeV}}\right) - 0.011 \left(\frac{\Lambda}{500\mathrm{MeV}}\right)^2 - 0.052 \left(\frac{\lambda_1}{500\mathrm{MeV}^2}\right) - 0.071 \left(\frac{\lambda_2}{500\mathrm{MeV}^2}\right)\right.$$
$$-0.006 \left(\frac{\lambda_1 \Lambda}{500\mathrm{MeV}^3}\right) + 0.011 \left(\frac{\lambda_2 \Lambda}{500\mathrm{MeV}^3}\right) - 0.006 \left(\frac{\rho_1}{500\mathrm{MeV}^3}\right) + 0.008 \left(\frac{\rho_2}{500\mathrm{MeV}^3}\right)$$
$$\left. -0.096\epsilon - 0.030\epsilon^2_{\mathrm{BLM}} + 0.015\epsilon \left(\frac{\Lambda}{500\mathrm{MeV}}\right) + \dots \right]$$

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu})$$
$$= \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5 \times$$
$$\Bigg[1 - 0.22 \left(\frac{\Lambda}{500\text{MeV}}\right) - 0.011 \left(\frac{\Lambda}{500\text{MeV}}\right)^2 - 0.052 \left(\frac{\lambda_1}{500\text{MeV}^2}\right) - 0.071 \left(\frac{\lambda_2}{500\text{MeV}^2}\right)$$
$$-0.006 \left(\frac{\lambda_1 \Lambda}{500\text{MeV}^3}\right) + 0.011 \left(\frac{\lambda_2 \Lambda}{500\text{MeV}^3}\right) - 0.006 \left(\frac{\rho_1}{500\text{MeV}^3}\right) + 0.008 \left(\frac{\rho_2}{500\text{MeV}^3}\right)$$
$$-0.096\epsilon - 0.030\epsilon^2_{\text{BLM}} + 0.015\epsilon \left(\frac{\Lambda}{500\text{MeV}}\right) + \ldots \Bigg]$$

1/m corrections:

~ 20%

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3}(0.534)\left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\left[1 - 0.22\left(\frac{\Lambda}{500\mathrm{MeV}}\right) - 0.011\left(\frac{\Lambda}{500\mathrm{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{500\mathrm{MeV}^2}\right) - 0.071\left(\frac{\lambda_2}{500\mathrm{MeV}^2}\right)\right.$$

$$-0.006\left(\frac{\lambda_1 \Lambda}{500\mathrm{MeV}^3}\right) + 0.011\left(\frac{\lambda_2 \Lambda}{500\mathrm{MeV}^3}\right) - 0.006\left(\frac{\rho_1}{500\mathrm{MeV}^3}\right) + 0.008\left(\frac{\rho_2}{500\mathrm{MeV}^3}\right)$$

$$\left.-0.096\epsilon - 0.030\epsilon^2_{\mathrm{BLM}} + 0.015\epsilon\left(\frac{\Lambda}{500\mathrm{MeV}}\right) + \ldots\right]$$

1/m corrections:

~ 20%

1/m² corrections:

~ 5%-10%

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu})$$
$$= \frac{G_F^2 |V_{cb}|^2}{192\pi^3}(0.534)\left(\frac{m_\Upsilon}{2}\right)^5 \times$$
$$\left[1 - 0.22\left(\frac{\Lambda}{500\mathrm{MeV}}\right) - 0.011\left(\frac{\Lambda}{500\mathrm{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{500\mathrm{MeV}^2}\right) - 0.071\left(\frac{\lambda_2}{500\mathrm{MeV}^2}\right)\right.$$
$$- 0.006\left(\frac{\lambda_1\Lambda}{500\mathrm{MeV}^3}\right) + 0.011\left(\frac{\lambda_2\Lambda}{500\mathrm{MeV}^3}\right) - 0.006\left(\frac{\rho_1}{500\mathrm{MeV}^3}\right) + 0.008\left(\frac{\rho_2}{500\mathrm{MeV}^3}\right)$$
$$\left.-0.096\epsilon - 0.030\epsilon^2_{\mathrm{BLM}} + 0.015\epsilon\left(\frac{\Lambda}{500\mathrm{MeV}}\right) + \dots\right]$$

1/m corrections:
~ 20%

1/m^2 corrections:
~ 5%-10%

1/m^3 corrections:
~ 1%

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\Big[1 - 0.22 \left(\frac{\Lambda}{500\text{MeV}}\right) - 0.011 \left(\frac{\Lambda}{500\text{MeV}}\right)^2 - 0.052 \left(\frac{\lambda_1}{500\text{MeV}^2}\right) - 0.071 \left(\frac{\lambda_2}{500\text{MeV}^2}\right)$$

$$- 0.006 \left(\frac{\lambda_1 \Lambda}{500\text{MeV}^3}\right) + 0.011 \left(\frac{\lambda_2 \Lambda}{500\text{MeV}^3}\right) - 0.006 \left(\frac{\rho_1}{500\text{MeV}^3}\right) + 0.008 \left(\frac{\rho_2}{500\text{MeV}^3}\right)$$

$$- 0.096\epsilon - 0.030\epsilon^2_{\text{BLM}} + 0.015\epsilon \left(\frac{\Lambda}{500\text{MeV}}\right) + \dots \Big]$$

1/m corrections:

~ 20%

1/m^2 corrections:

~ 5%-10%

1/m^3 corrections:

~ 1%

Perturbative corrections:

~ few%

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3}(0.534)\left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\left[1 - 0.22\left(\frac{\Lambda}{500\mathrm{MeV}}\right) - 0.011\left(\frac{\Lambda}{500\mathrm{MeV}}\right)^2 - 0.052\left(\frac{\lambda_1}{500\mathrm{MeV}^2}\right) - 0.071\left(\frac{\lambda_2}{500\mathrm{MeV}^2}\right)\right.$$

$$- 0.006\left(\frac{\lambda_1\Lambda}{500\mathrm{MeV}^3}\right) + 0.011\left(\frac{\lambda_2\Lambda}{500\mathrm{MeV}^3}\right) - 0.006\left(\frac{\rho_1}{500\mathrm{MeV}^3}\right) + 0.008\left(\frac{\rho_2}{500\mathrm{MeV}^3}\right)$$

$$\left. - 0.096\epsilon - 0.030\epsilon^2_{\mathrm{BLM}} + 0.015\epsilon\left(\frac{\Lambda}{500\mathrm{MeV}}\right) + \ldots\right]$$

Precision Physics

1/m corrections:
~ 20%

1/m^2 corrections:
~ 5%-10%

1/m^3 corrections:
~ 1%

Perturbative corrections:
~ few%

The decay rate

$$\Gamma(B \to X_c \ell \bar{\nu}) = \frac{G_F^2 |V_{cb}|^2}{192\pi^3} (0.534) \left(\frac{m_\Upsilon}{2}\right)^5 \times$$

$$\Big[1 - 0.22 \left(\frac{\Lambda}{500\mathrm{MeV}}\right) - 0.011 \left(\frac{\Lambda}{500\mathrm{MeV}}\right)^2 - 0.052 \left(\frac{\lambda_1}{500\mathrm{MeV}^2}\right) - 0.071 \left(\frac{\lambda_2}{500\mathrm{MeV}^2}\right)$$

$$- 0.006 \left(\frac{\lambda_1 \Lambda}{500\mathrm{MeV}^3}\right) + 0.011 \left(\frac{\lambda_2 \Lambda}{500\mathrm{MeV}^3}\right) - 0.006 \left(\frac{\rho_1}{500\mathrm{MeV}^3}\right) + 0.008 \left(\frac{\rho_2}{500\mathrm{MeV}^3}\right)$$

$$- 0.096\epsilon - 0.030\epsilon^2_{\mathrm{BLM}} + 0.015\epsilon \left(\frac{\Lambda}{500\mathrm{MeV}}\right) + \dots \Big]$$

Precision Physics

1/m corrections:
~ 20%

1/m² corrections:
~ 5%-10%

1/m³ corrections:
~ 1%

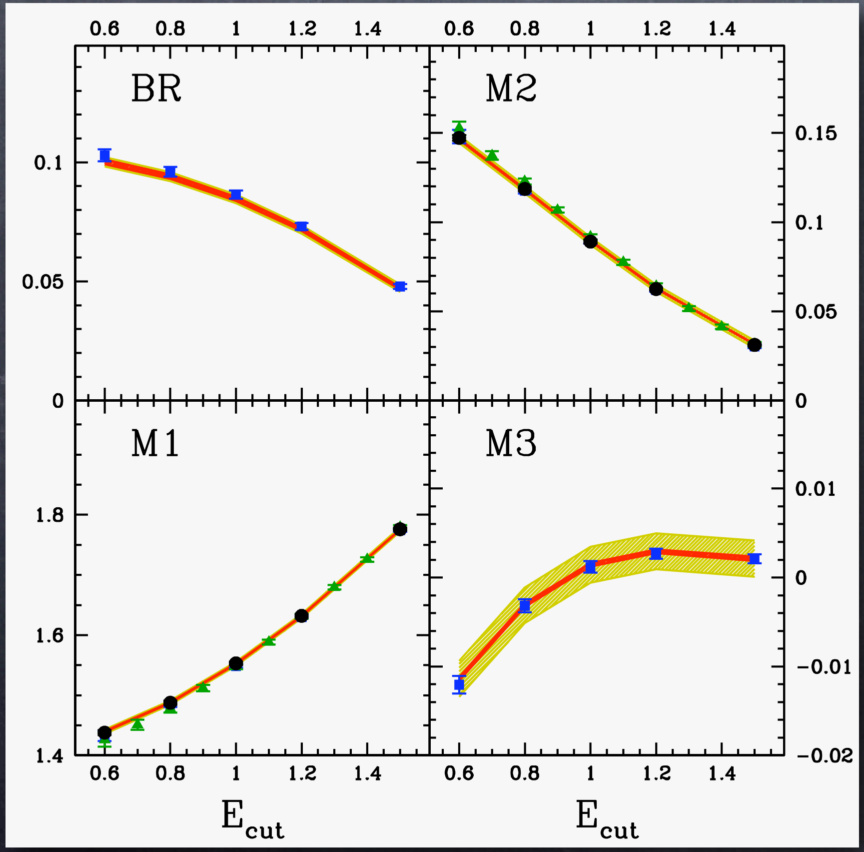
Perturbative corrections:
~ few%

Global fits

Many other observables (spectra) depend on same hadronic parameters⇒perform global fits

CWB, Ligeti, Luke, Manohar, Trott ('02 ,'04)

92 (highly correlated) datapoints, 7 parameters



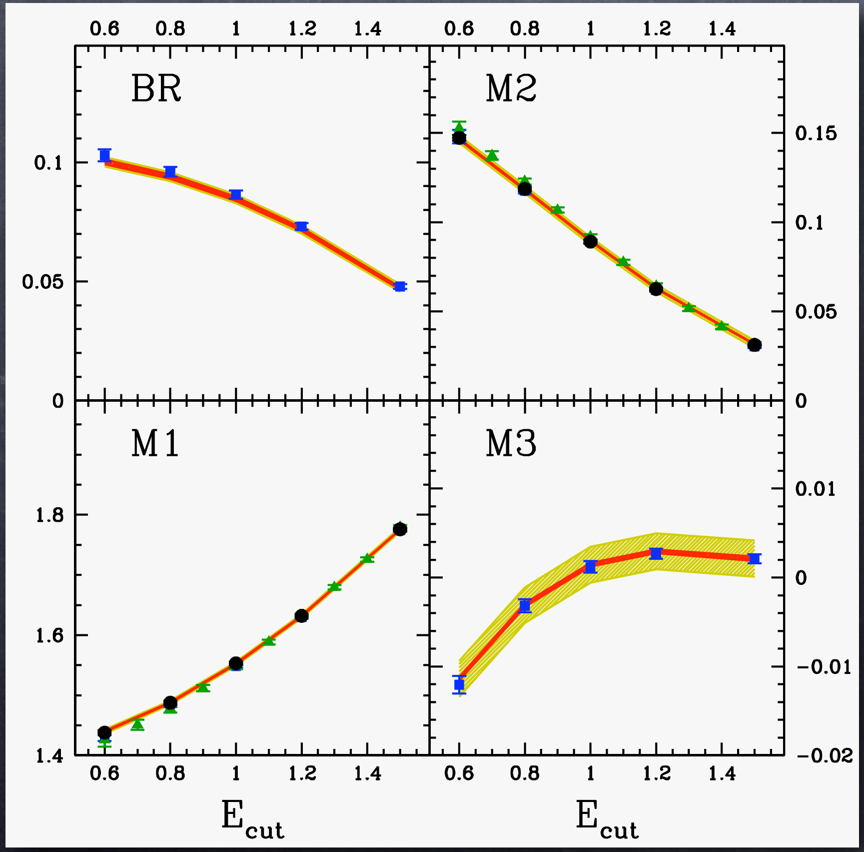
$$
\begin{aligned}
V_{cb} &= (41.4 \pm 0.6) \times 10^{-3} \\
m_b^{1S} &= (4.68 \pm 0.03)\,\mathrm{GeV}
\end{aligned}
$$

Global fits

Many other observables (spectra) depend on same hadronic parameters ⇒ perform global fits

CWB, Ligeti, Luke, Manohar, Trott ('02 ,'04)

92 (highly correlated) datapoints, 7 parameters



1.5% uncertainty in V_{cb}

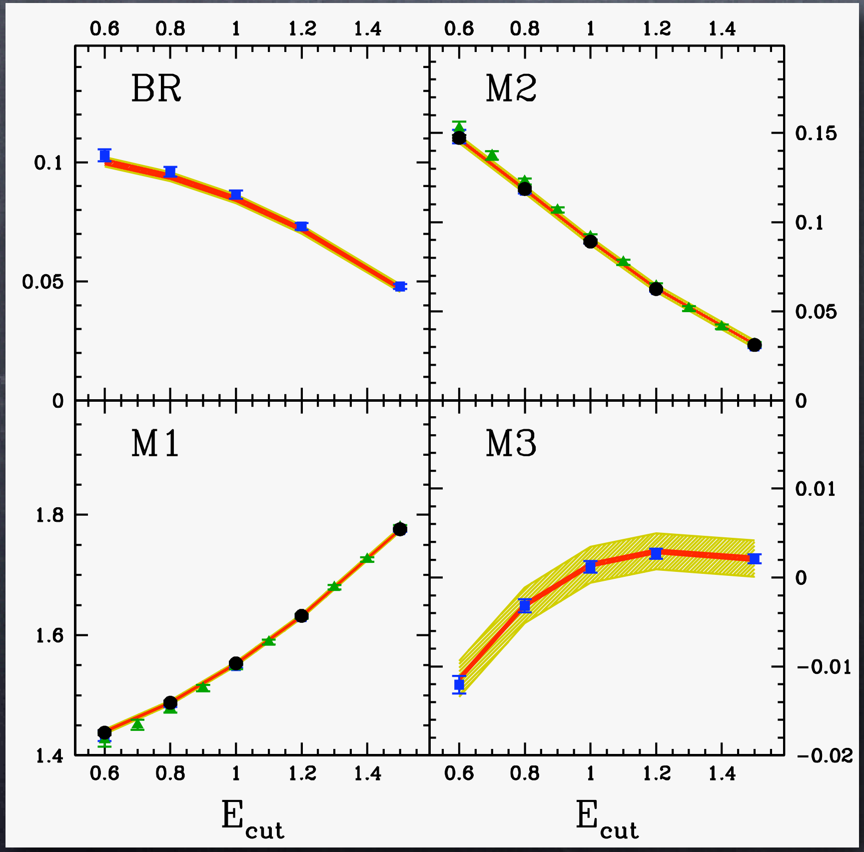
$$V_{cb} = (41.4 \pm 0.6) \times 10^{-3}$$
$$m_b^{1S} = (4.68 \pm 0.03)\,\mathrm{GeV}$$

Global fits

Many other observables (spectra) depend on same hadronic parameters⇒perform global fits

CWB, Ligeti, Luke, Manohar, Trott ('02 ,'04)

92 (highly correlated) datapoints, 7 parameters



1.5% uncertainty in V_{cb}

$$V_{cb} = (41.4 \pm 0.6) \times 10^{-3}$$

$$m_b^{1S} = (4.68 \pm 0.03)\ \mathrm{GeV}$$

30 MeV uncertainty in m_b

Some more tests

Find observables insensitive to hadronic parameters

CWB, Trott ('02)

$$D_3 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{0.7} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{1.5} \frac{d\Gamma}{dE_\ell} dE_\ell} = \Bigg\{$$

$$D_4 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{2.3} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{2.9} \frac{d\Gamma}{dE_\ell} dE_\ell} = \Bigg\{$$

Some more tests

Find observables insensitive to hadronic parameters

CWB, Trott ('02)

$$D_3 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{0.7} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{1.5} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.5166 \pm 0.0048 & \text{(theory)} \\ & \end{cases}$$

$$D_4 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{2.3} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{2.9} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.6016 \pm 0.0058 & \text{(theory)} \\ & \end{cases}$$

Some more tests

Find observables insensitive to hadronic parameters

CWB, Trott ('02)

$$D_3 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{0.7} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{1.5} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.5166 \pm 0.0048 & \text{(theory)} \\ 0.5193 \pm 0.0008 & \text{(experiment)} \end{cases}$$

$$D_4 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{2.3} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{2.9} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.6016 \pm 0.0058 & \text{(theory)} \\ 0.6036 \pm 0.0006 & \text{(experiment)} \end{cases}$$

Some more tests

Find observables insensitive to hadronic parameters

CWB, Trott ('02)

$$D_3 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{0.7} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{1.5} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.5166 \pm 0.0048 & \text{(theory)} \\ 0.5193 \pm 0.0008 & \text{(experiment)} \end{cases}$$

$$D_4 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{2.3} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{2.9} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.6016 \pm 0.0058 & \text{(theory)} \\ 0.6036 \pm 0.0006 & \text{(experiment)} \end{cases}$$

These were real predictions, not postdictions

Some more tests

Find observables insensitive to hadronic parameters

CWB, Trott ('02)

$$D_3 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{0.7} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{1.5} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.5166 \pm 0.0048 & \text{(theory)} \\ 0.5193 \pm 0.0008 & \text{(experiment)} \end{cases}$$

$$D_4 = \frac{\int_{1.6\mathrm{GeV}} E_\ell^{2.3} \frac{d\Gamma}{dE_\ell} dE_\ell}{\int_{1.5\mathrm{GeV}} E_\ell^{2.9} \frac{d\Gamma}{dE_\ell} dE_\ell} = \begin{cases} 0.6016 \pm 0.0058 & \text{(theory)} \\ 0.6036 \pm 0.0006 & \text{(experiment)} \end{cases}$$

These were real predictions, not postdictions

Hadronic uncertainties at the 1% level!

Some more tests

After the combined fit even higher precision

$$D_3 = \begin{cases} 0.5190 \pm 0.0007 & \text{(theory)} \\ 0.5193 \pm 0.0008 & \text{(experiment)} \end{cases}$$

$$D_4 = \begin{cases} 0.6034 \pm 0.0008 & \text{(theory)} \\ 0.6036 \pm 0.0006 & \text{(experiment)} \end{cases}$$

Hadronic uncertainties at the 0.2% level!

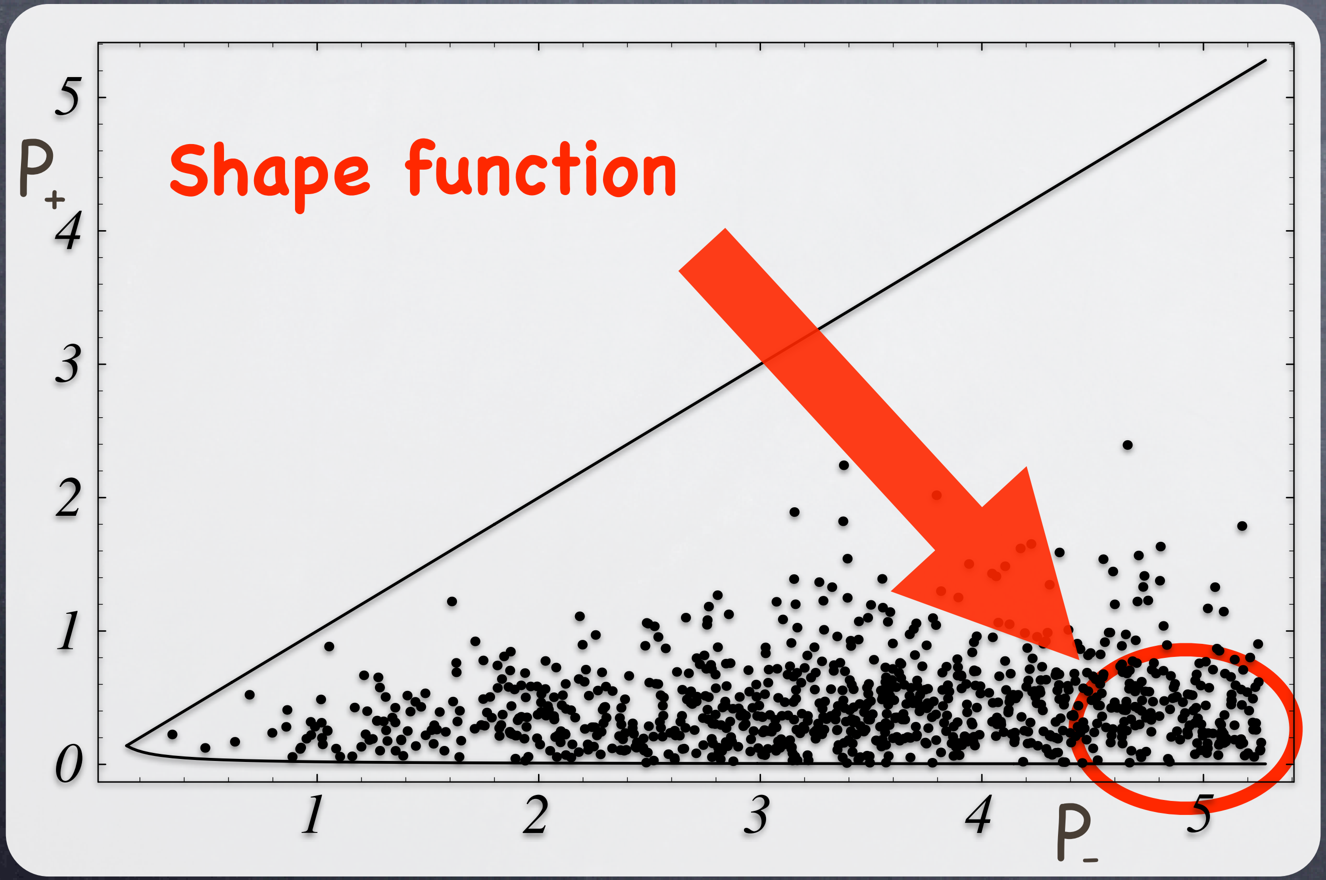
Rare inclusive decays

Quote from Babar physics books

"With the present theorical tools, it seems a realistic goal to reach a precision of 10% on $|V_{ub}|$. An optimistic hope for the long-term future, counting again on significat theoretical progress, is to achieve an accuracy of 5%."

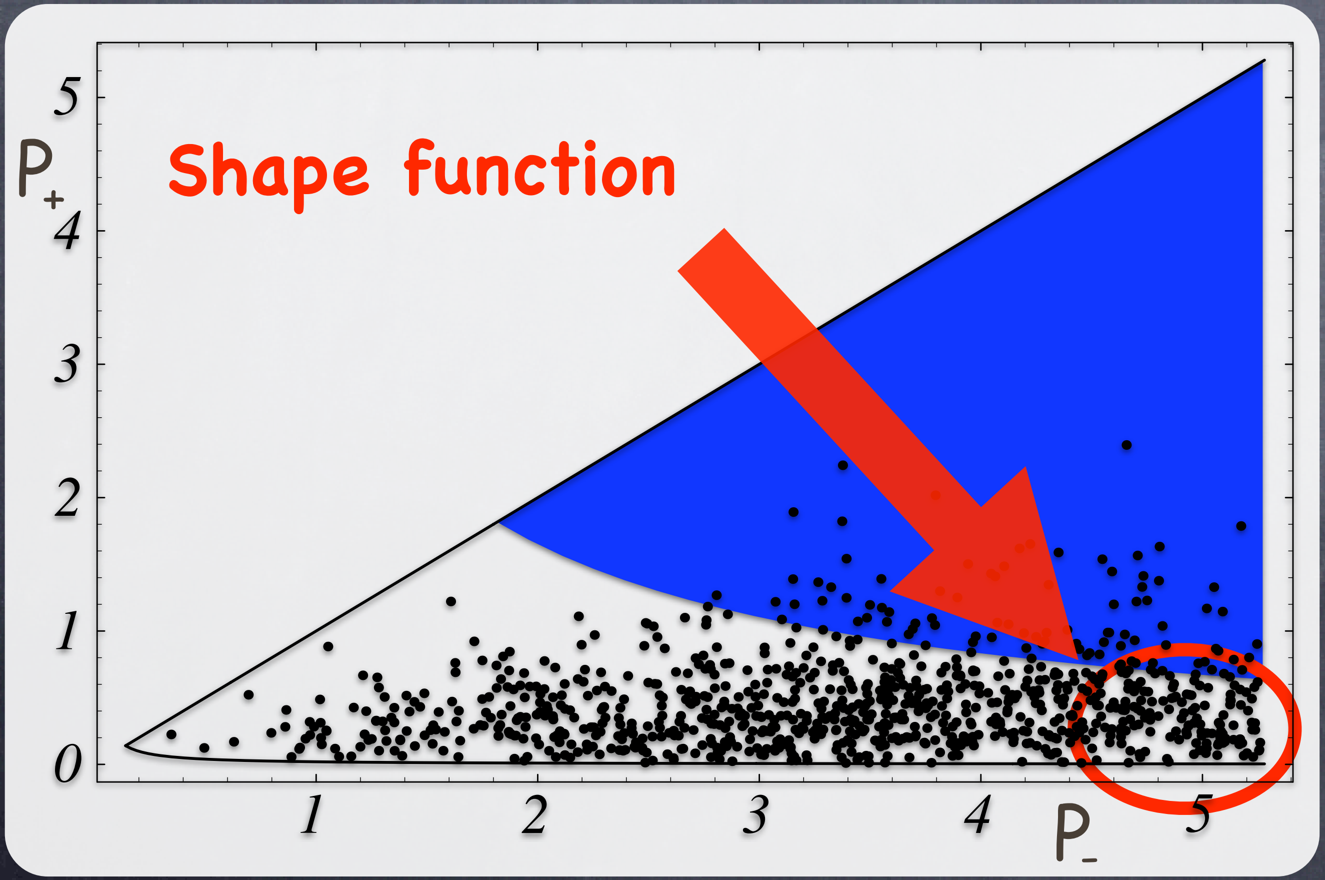
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)



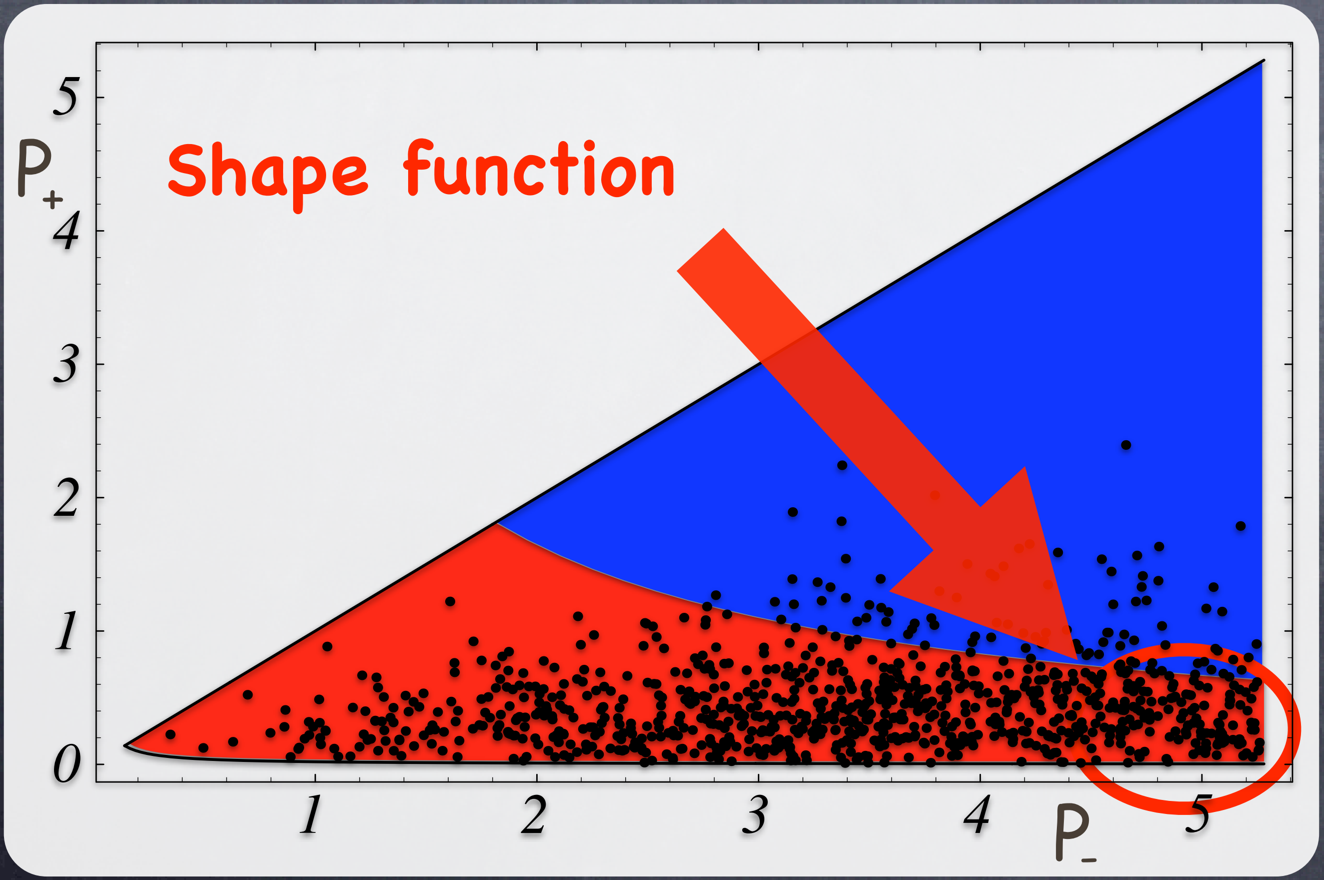
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)



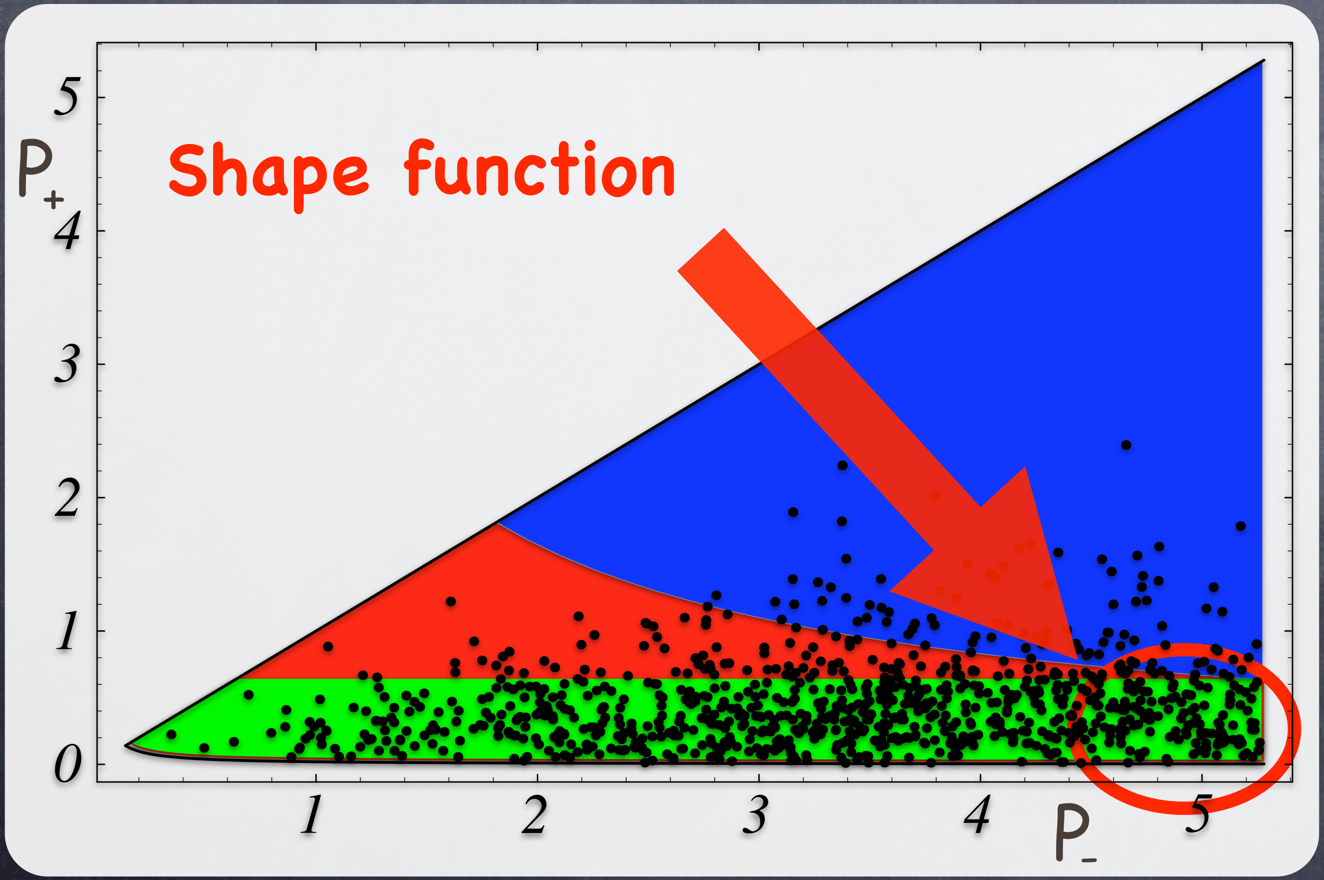
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)



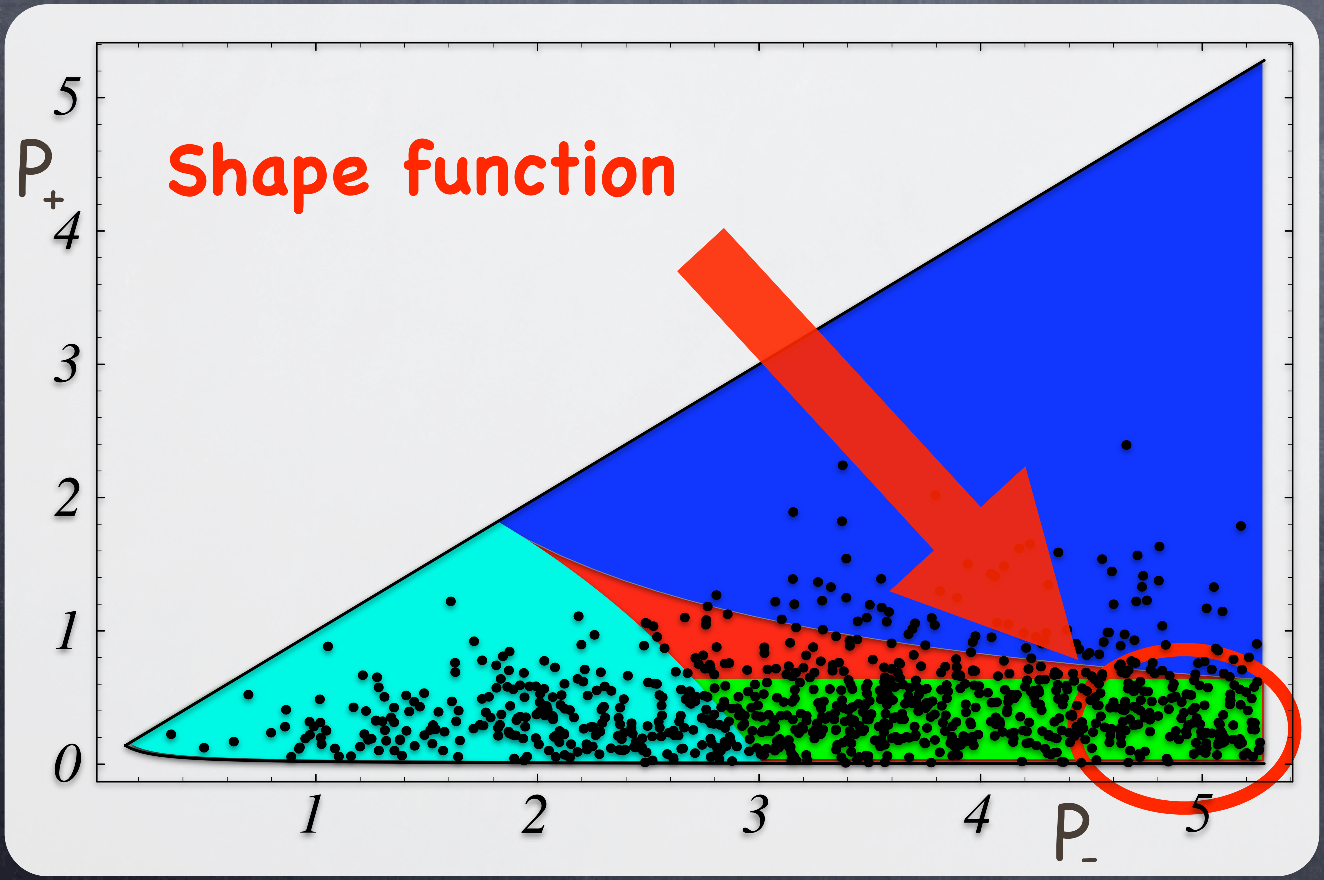
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)



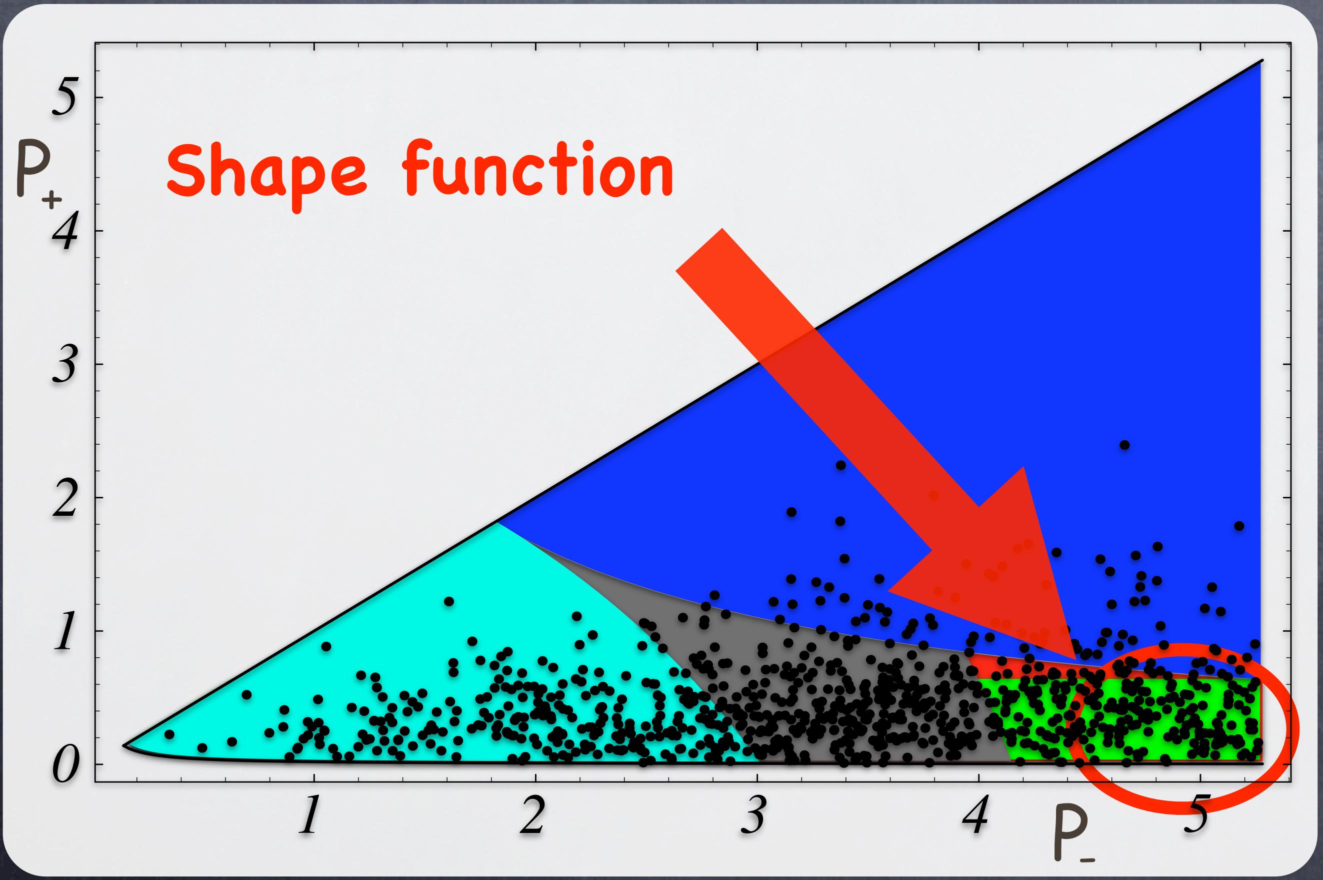
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)



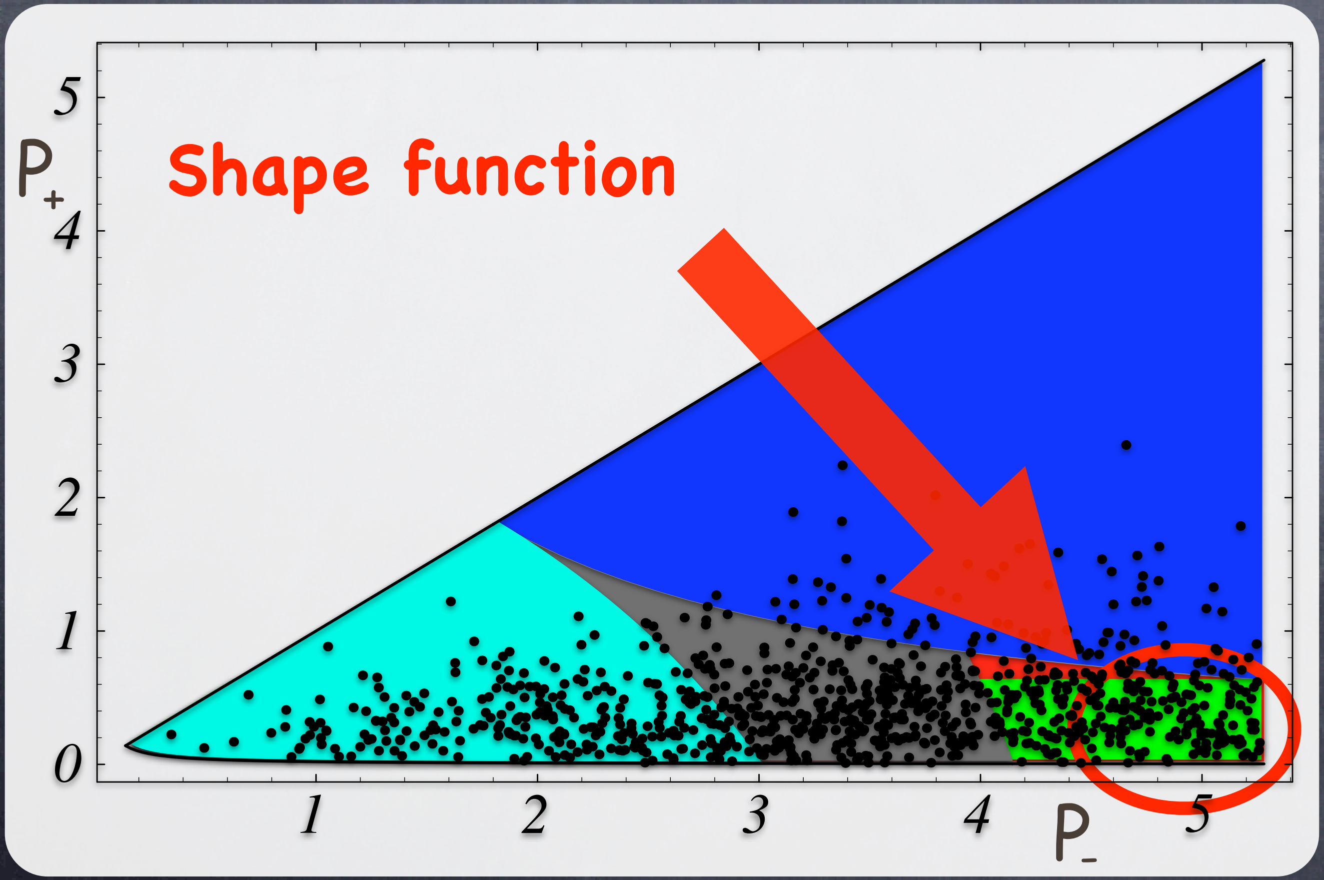
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)



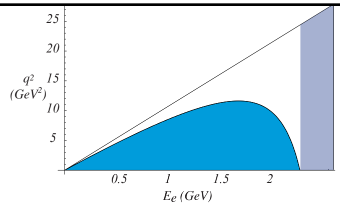
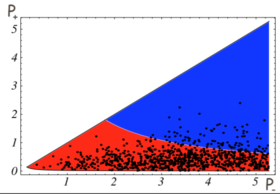
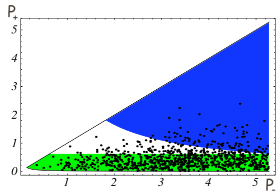
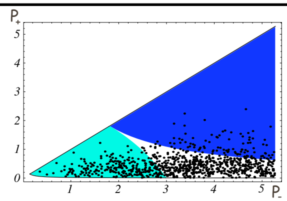
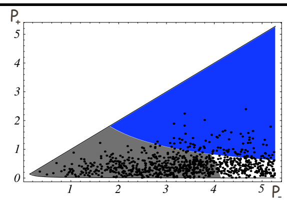
Shape functions

For rare inclusive B decays need kinematic cuts to beat down background ($B \to X_u l \nu$, $B \to X_s l^+ l^-$)

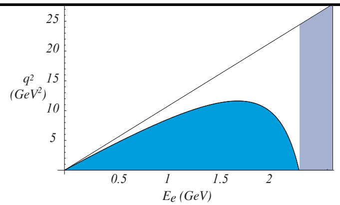
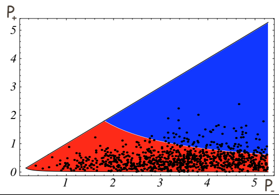
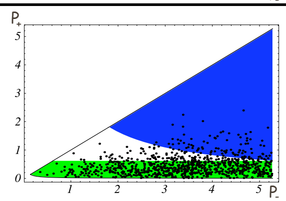
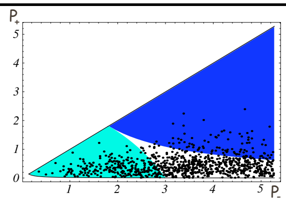
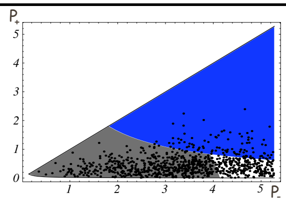


- Many possible cuts to avoid charm
- Some cuts include the "shape function region", others don't
- Cuts including "shape function region need information beyond OPE

Determination of V_{ub}

cut	% of rate	good	bad
	~10%	don't need neutrino	- depends on $f(k^+)$ (and subleading corrections) - reduced phase space - duality issues?
	~80%	lots of rate	depends on $f(k^+)$ (and subleading corrections)
	~70%	-still lots of rate - relation to radiative decays simplest	depends on $f(k^+)$ (and subleading corrections)
	~20%	insensitive to $f(k^+)$	- very sensitive to m_b - effective expansion parameter is $1/m_c$
	~45%	- insensitive to $f(k^+)$ - lots of rate - can move cuts from kinematic limits	

Determination of V_{ub}

cut	% of rate	good	bad
	~10%	don't need neutrino	- depends on $f(k^+)$ (and subleading corrections) - reduced phase space - duality issues?
	~80%	lots of rate	depends on $f(k^+)$ (and subleading corrections)
	~70%	-still lots of rate - relation to radiative decays simplest	depends on $f(k^+)$ (and subleading corrections)
	~20%	insensitive to $f(k^+)$	- very sensitive to m_b - effective expansion parameter is $1/m_c$
	~45%	- insensitive to $f(k^+)$ - lots of rate - can move cuts from kinematic limits	

Current theoretical uncertainty on $|V_{ub}|$: 5%

Measurement of $B \to X_s l^+ l^i$

Again, m_X cut required to suppress $b \to cl\nu \to sll\nu\nu$

Lee, Ligeti, Stewart, Tackmann ('06)

Universality

Define $\eta_{ij}(m_X^{\rm cut})$ with $ij = (99, 00, 77, 79) \sim (C_9^2, C_{10}^2, C_7^2, C_7 C_9)$

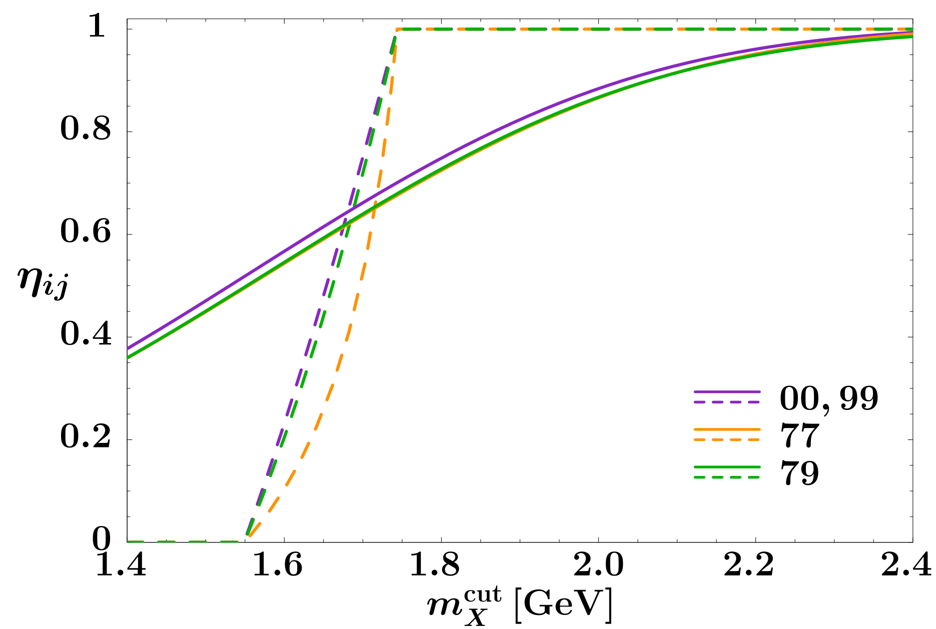
- encode $m_X^{\rm cut}$ effect, $\Gamma_{ij}^{\rm cut} = \eta_{ij}(m_X^{\rm cut})\Gamma_{ij}^{(0)}$ with $\Gamma^{(0)}$ lowest order rate
- at *lowest order* equal to fraction of events with $m_X < m_X^{\rm cut}$

η_{ij} at lowest order

dashed: local OPE (*wrong*)

solid: leading shape function

- *strong* $m_X^{\rm cut}$ dependence, 25% effect at $m_X^{\rm cut} = 1.8\,\mathrm{GeV}$
- try to raise $m_X^{\rm cut} \gtrsim 2.2\,\mathrm{GeV}$



Universality (ij independence)

- $m_X^{\rm cut}$ effect approximately universal for different SD contributions
- deviation $\lesssim 3\%$ for $m_X^{\rm cut} > 1.7\,\mathrm{GeV}$, maintained at $\mathcal{O}(\alpha_s)$

Measurement of $B \to X_s l^+ l^-$

Again, m_X cut required to suppress $b \to c l \nu \to s l l \nu\nu$

Lee, Ligeti, Stewart, Tackmann ('06)

Universality

Define $\eta_{ij}(m_X^{\rm cut})$ with $ij = (99, 00, 77, 79) \sim (C_9^2, C_{10}^2, C_7^2, C_7 C_9)$

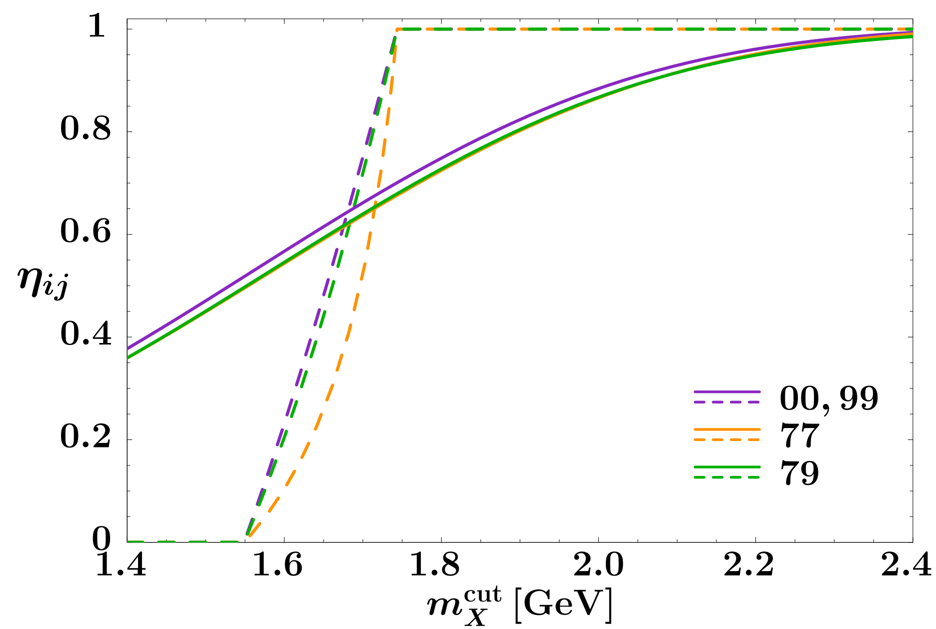
- encode $m_X^{\rm cut}$ effect $\boxed{\Gamma_{ij}^{\rm cut} = \eta_{ij}(m_X^{\rm cut})\Gamma_{ij}^{(0)}}$ with $\Gamma^{(0)}$ lowest order rate
- at *lowest order* equal to fraction of events with $m_X < m_X^{\rm cut}$

η_{ij} at lowest order

dashed: local OPE (*wrong*)

solid: leading shape function

- *strong* $m_X^{\rm cut}$ dependence, 25% effect at $m_X^{\rm cut} = 1.8\,\mathrm{GeV}$
- try to raise $m_X^{\rm cut} \gtrsim 2.2\,\mathrm{GeV}$



Universality (ij independence)

- $m_X^{\rm cut}$ effect approximately universal for different SD contributions
- deviation $\lesssim 3\%$ for $m_X^{\rm cut} > 1.7\,\mathrm{GeV}$, maintained at $\mathcal{O}(\alpha_s)$

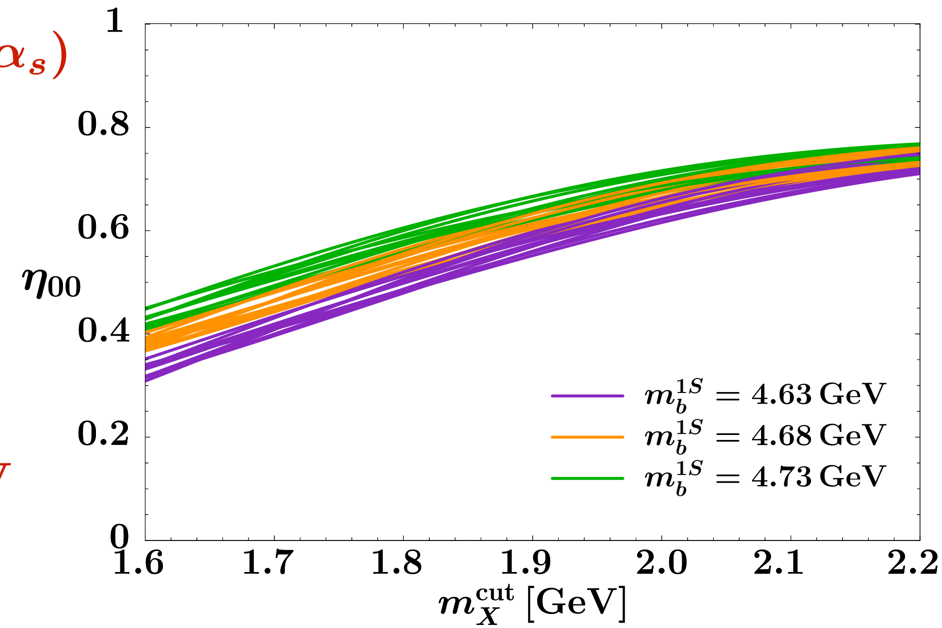
Measurement of $B \to X_s l^+ l^-$

Again, m_X cut required to suppress $b \to c l \nu \to s l l \nu \nu$

Lee, Ligeti, Stewart, Tackmann ('06)

Uncertainties

η_{00} at $\mathcal{O}(\alpha_s)$



Largest uncertainties

- shape function uncertainty, estimated using $B \to X_s \gamma$ (10 models for $f_0(\omega)$)
- b quark mass, use 1S mass $m_b^{1S} = (4.63, 4.68, 4.73)$ GeV

$\mathcal{B}(1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2)/10^{-6}$ including $\mathcal{O}(\alpha_s)$

local OPE, no $m_X^{\rm cut}$	1.63 ± 0.20	
We get	$1.48 \pm 0.14 \pm \cdots$	$(m_X^{\rm cut} = 2.0\,\mathrm{GeV})$
	$1.20 \pm 0.15 \pm \cdots$	$(m_X^{\rm cut} = 1.8\,\mathrm{GeV})$

- Not all uncertainties included yet, most important from $1/m_b$ corrections.

New developments in non-leptonic deacys

Quotes from Babar physics books

"...a complete theoretical treatment of hadronic decays is not close at hand."

"Color transparence is the basis for the factorization hypothesis (...) Its validity, however, is not demonstrated by any quantitative theoretical argument..."

"In order to gain a complete understanding of the hadronic (two-body) decays (...) additional QCD-based methods must be found. (...) Unfortunately, no systematic treatment exists and only scattered results are available."

Kinematics

Typical size of hadrons $\sim 1/\Lambda_{QCD}$

$E \gg \Lambda_{QCD}$

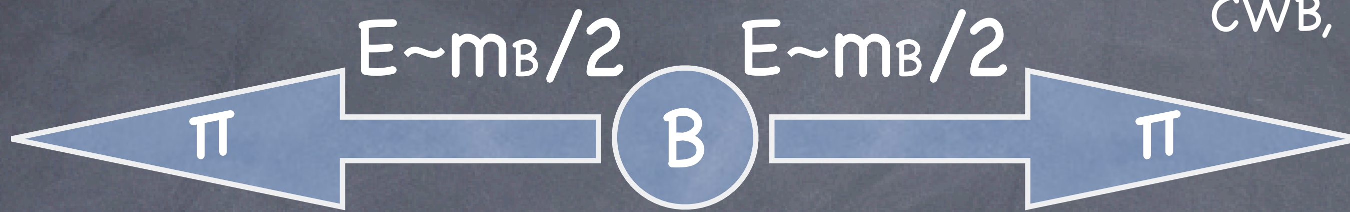
Soft Collinear Effective Theory

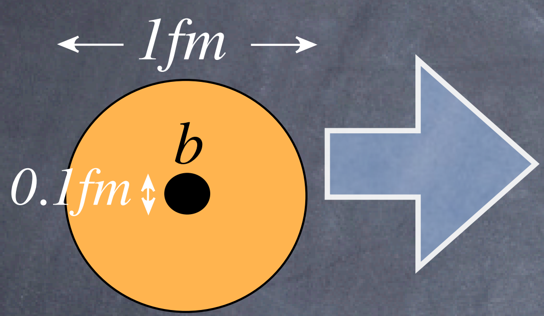
General Idea

- SCET is effective theory describing interactions of collinear with soft particles
- Separate distance scales d~1/E and d~1/Λ_{QCD} and study interactions of long distance modes
- Factorization theorems emerge naturally in SCET
  - Separate d~1/E & d~1/Λ. Study non-perturbative effects in limit $\Lambda_{QCD}/E \to 0$
  - At leading order, coupling between soft and collinear simple and in many cases absent
- Factorization is not assumed in SCET. The theory will tell you when amplitudes factorize and when not

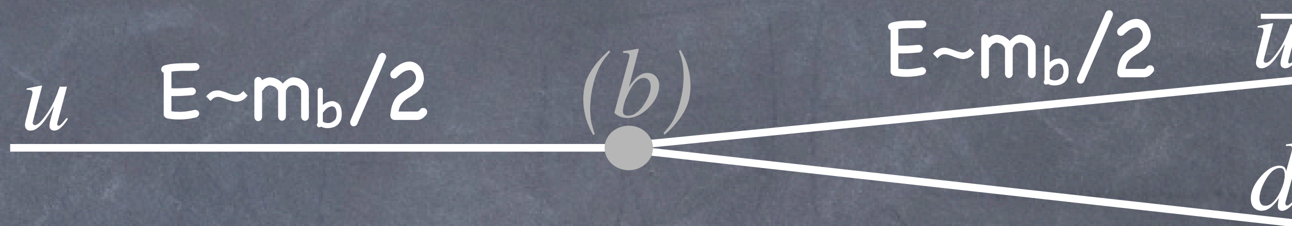
SCET in pictures

CWB, Pirjol, Rothstein, Stewart ('03)

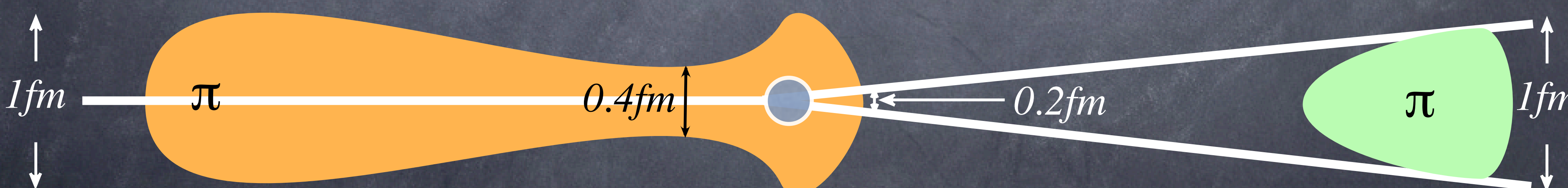




Heavy b quark almost at rest in B meson



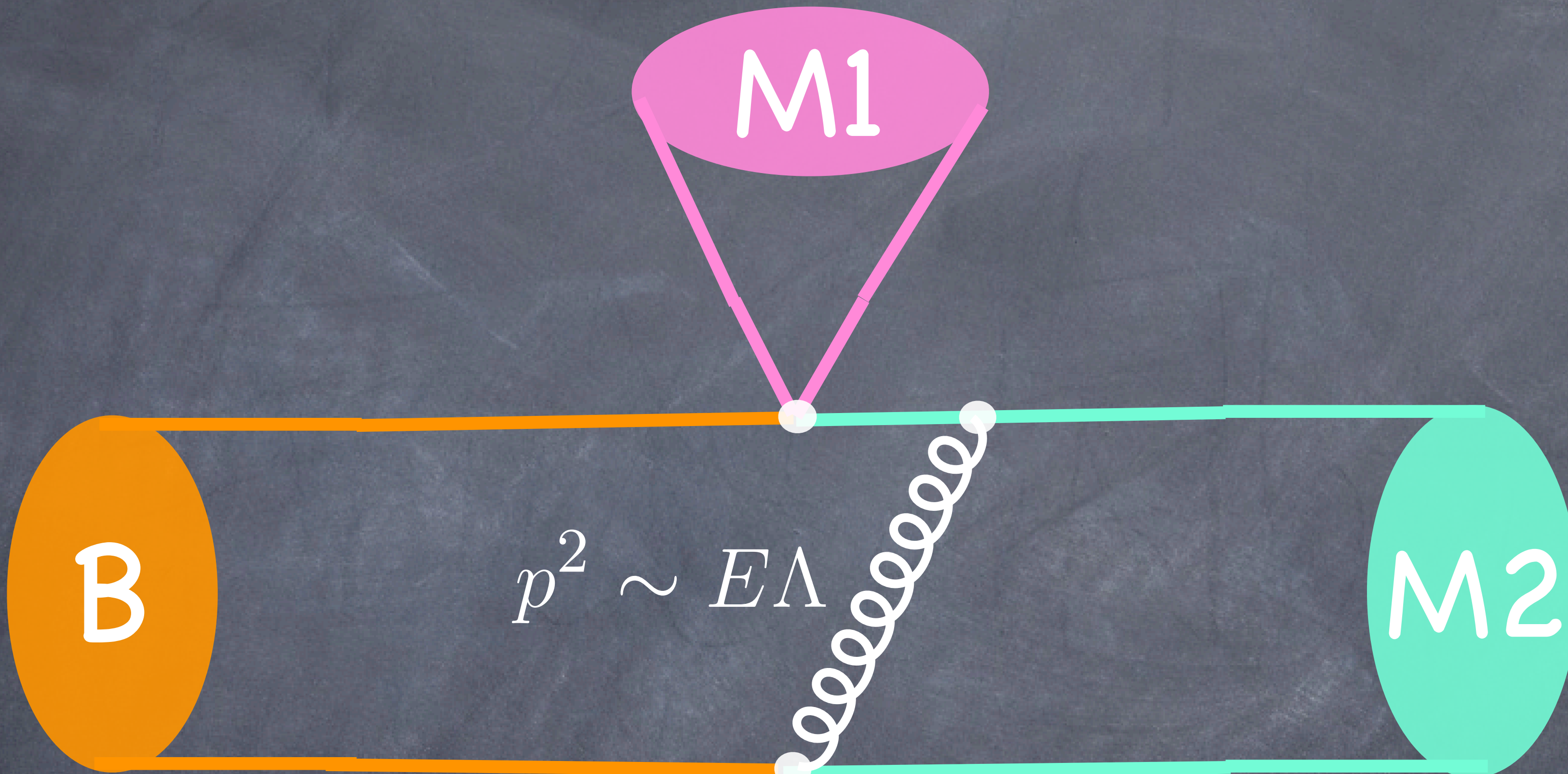
b quark decays into three light quarks, two in the same direction, one in opposing direction



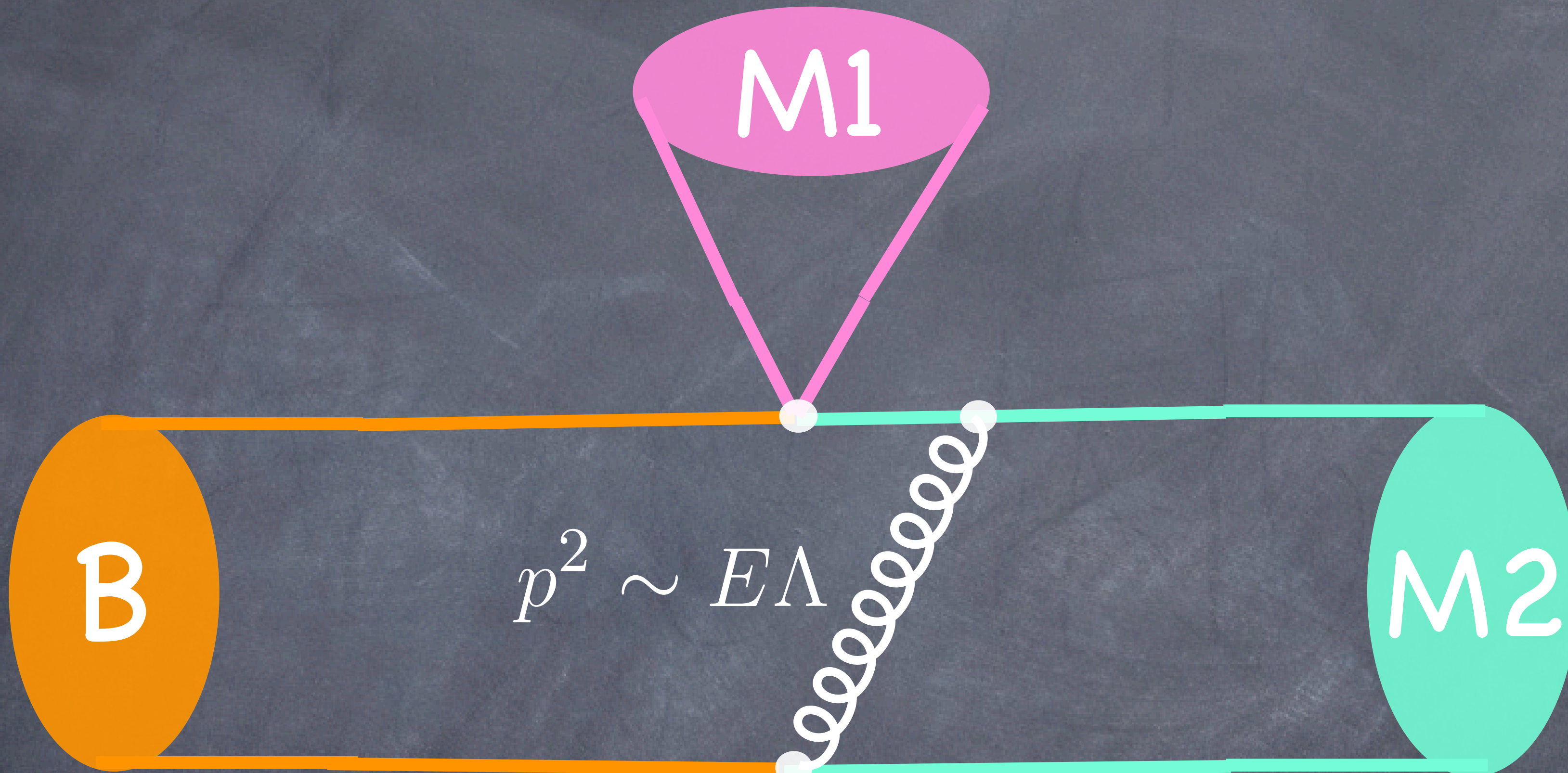
energetic quark requires spectator of the B meson to form pion. Factorization more subtle

two quarks are very close until far from B meson. Thus no coupling between B and pion

The factorization formula

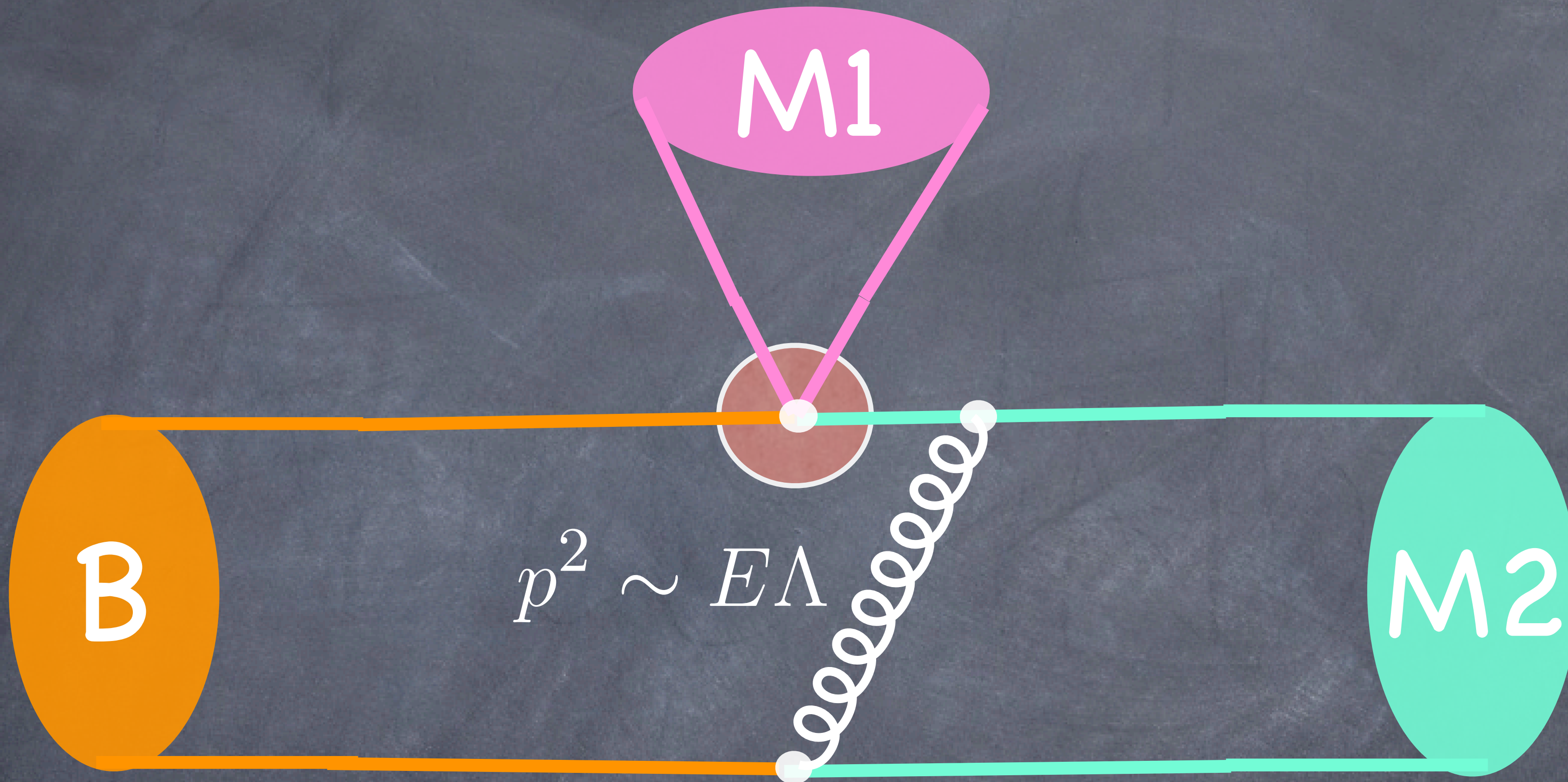


The factorization formula



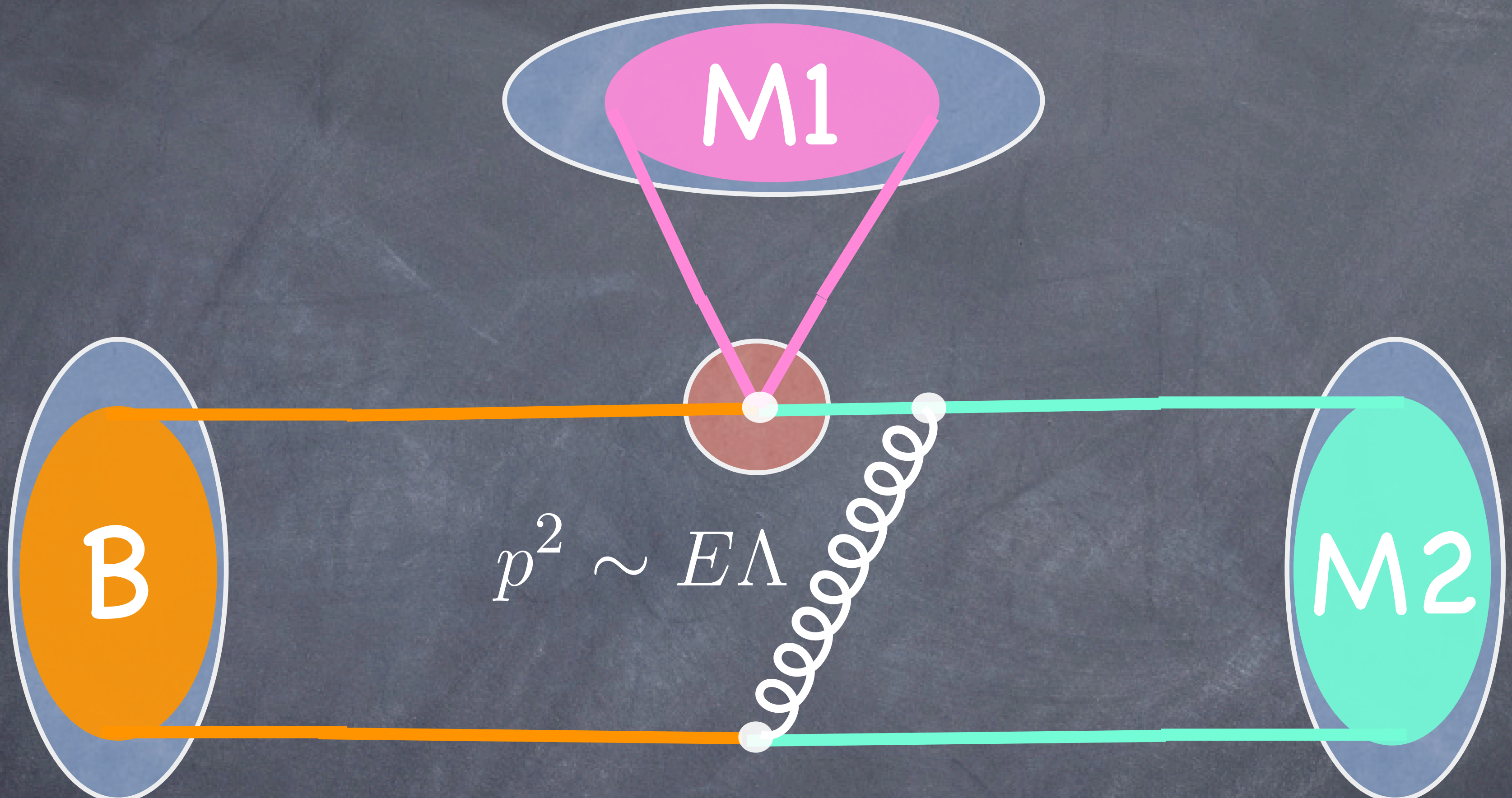
$$A \;=\; N\Big\{ f_\pi \int du\, dz\, T_{1J}(u,z)\zeta_J^{B\pi}(z)\phi^\pi(u) + \zeta^{B\pi} f_\pi \int du\, T_{1\zeta}(u)\phi^\pi(u) \Big\} + \lambda_c^{(f)} A_{c\bar{c}}^{\pi\pi}$$

The factorization formula



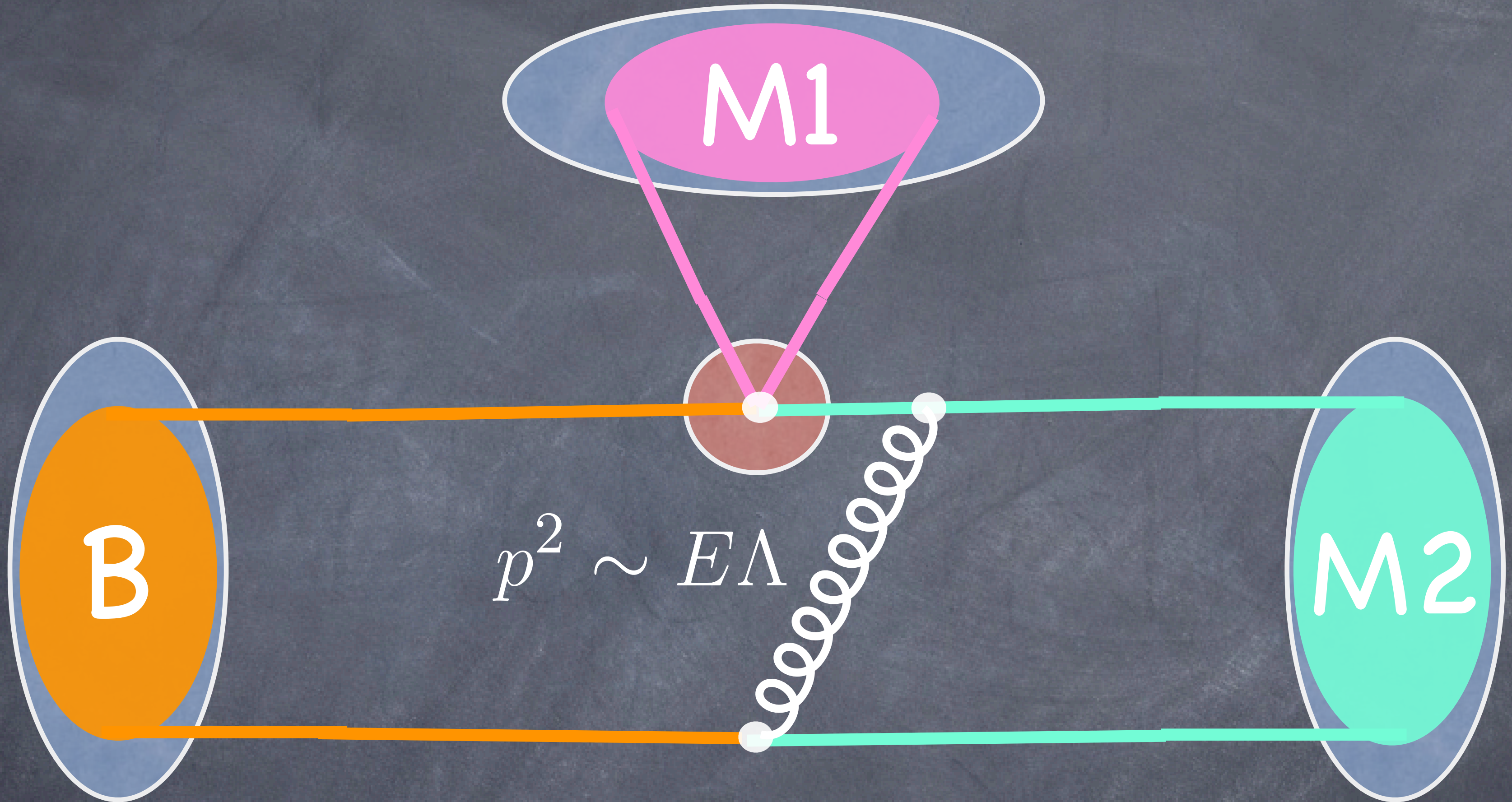
$$A \;=\; N\left\{ f_\pi \int du\, dz \boxed{T_{1J}(u,z)} \zeta_J^{B\pi}(z)\phi^\pi(u) + \zeta^{B\pi} f_\pi \int du \boxed{T_{1\zeta}(u)} \phi^\pi(u) \right\} + \lambda_c^{(f)} A_{c\bar{c}}^{\pi\pi}$$

The factorization formula



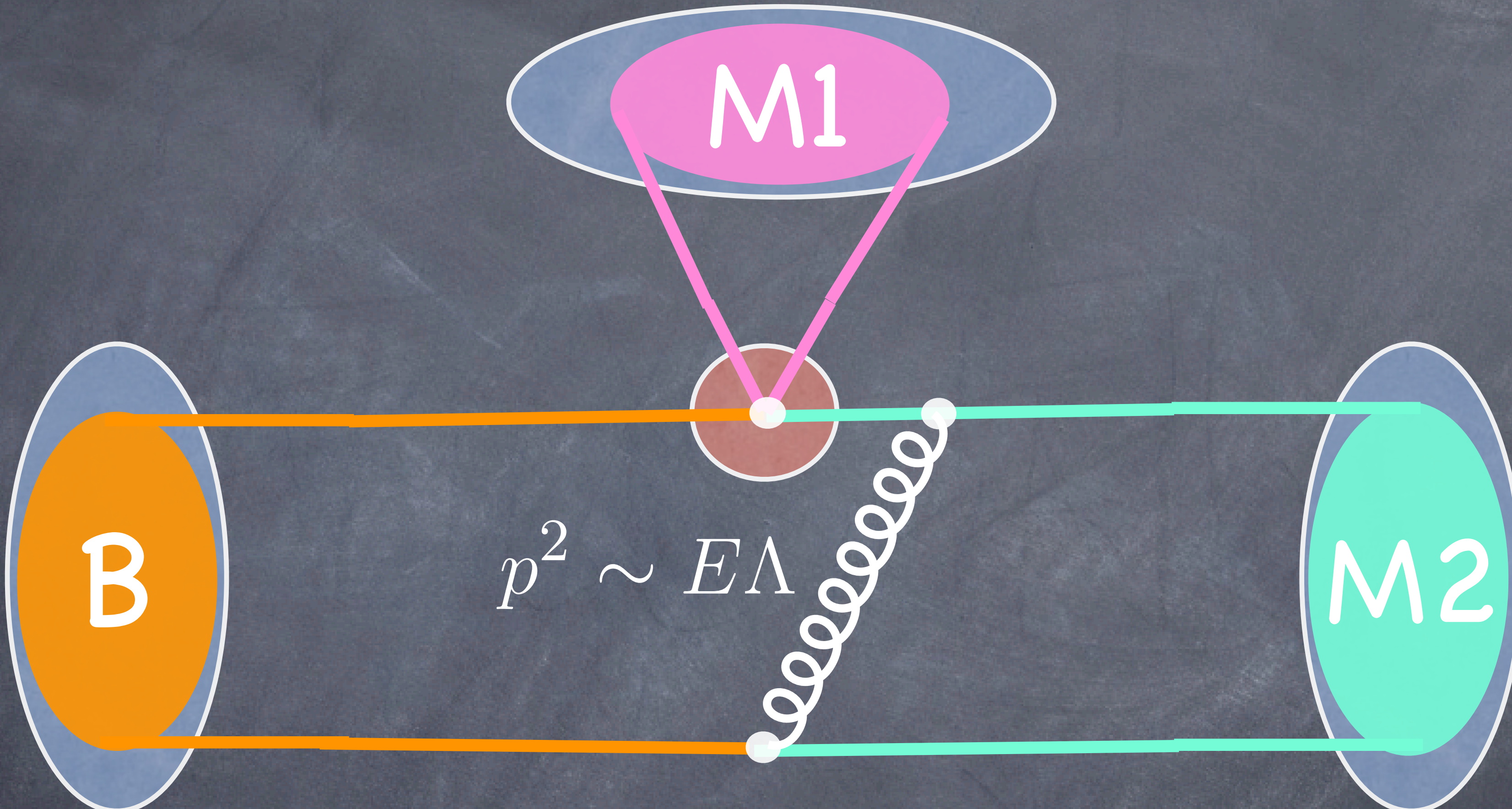
$$A = N\left\{ f_\pi \int du\, dz\, T_{1J}(u,z)\, \zeta_J^{B\pi}(z)\, \phi^\pi(u) + \zeta^{B\pi} f_\pi \int du\, T_{1\zeta}(u)\, \phi^\pi(u) \right\} + \lambda_c^{(f)} A_{c\bar{c}}^{\pi\pi}$$

The factorization formula



$$A = N\left\{ f_\pi \int du\, dz\, T_{1J}(u,z)\, \zeta_J^{B\pi}(z)\, \phi^\pi(u) + \zeta^{B\pi} f_\pi \int du\, T_{1\zeta}(u)\, \phi^\pi(u) \right\} + \lambda_c^{(f)} A_{c\bar{c}}^{\pi\pi}$$

The factorization formula



$$A \;=\; N\Big\{ \boxed{f_\pi} \int du\, dz\, \boxed{T_{1J}(u,z)}\, \boxed{\zeta_J^{B\pi}(z)}\, \boxed{\phi^\pi(u)} + \boxed{\zeta^{B\pi}}\, \boxed{f_\pi} \int du\, \boxed{T_{1\zeta}(u)}\, \boxed{\phi^\pi(u)} \Big\} + \lambda_c^{(f)}\, \boxed{A_{c\bar c}^{\pi\pi}}$$

×2

Parameter counting

Number of hadronic parameters

<table>
<tr><th></th><th>no expns</th><th>SU(2)</th><th>SU(3)</th><th>SCET +SU(2)</th><th>SCET +SU(3)</th></tr>
<tr><td>ππ</td><td>11</td><td>7/5</td><td rowspan="2">15/13</td><td>4</td><td rowspan="3">4</td></tr>
<tr><td>Kπ</td><td>15</td><td>11</td><td>+5(6)</td></tr>
<tr><td>KK</td><td>11</td><td>11</td><td>+4/+0</td><td>+3(4)</td></tr>
</table>

Parameter counting

Number of hadronic parameters

<table>
<tr><th></th><th>no expns</th><th>SU(2)</th><th>SU(3)</th><th>SCET +SU(2)</th><th>SCET +SU(3)</th></tr>
<tr><td>$\pi\pi$</td><td>11</td><td>7/5</td><td rowspan="2">15/13</td><td>4</td><td rowspan="3">4</td></tr>
<tr><td>$K\pi$</td><td>15</td><td>11</td><td>+5(6)</td></tr>
<tr><td>KK</td><td>11</td><td>11</td><td>+4/+0</td><td>+3(4)</td></tr>
</table>

Parameter counting

Number of hadronic parameters

<table>
<tr><th></th><th>no expns</th><th>SU(2)</th><th>SU(3)</th><th>SCET +SU(2)</th><th>SCET +SU(3)</th></tr>
<tr><td>ππ</td><td>11</td><td>7/5</td><td rowspan="2">15/13</td><td>4</td><td rowspan="3">4</td></tr>
<tr><td>Kπ</td><td>15</td><td>11</td><td>+5(6)</td></tr>
<tr><td>KK</td><td>11</td><td>11</td><td>+4/+0</td><td>+3(4)</td></tr>
</table>

Implications of small phases I

Measuring γ from B→ππ

Amplitudes (using isospin and no EW penguins)

$$\begin{aligned}
A(\bar{B}^0 \to \pi^+\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,T - |\lambda_c|\,P \\
A(\bar{B}^0 \to \pi^0\pi^0) &= e^{-i\gamma}\,|\lambda_u|\,C + |\lambda_c|P \\
\sqrt{2}A(B^- \to \pi^0\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,(T + C)
\end{aligned}$$

Implications of small phases I

Measuring γ from B→ππ

Amplitudes (using isospin and no EW penguins)

$$\begin{aligned} A(\bar{B}^0 \to \pi^+\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,T - |\lambda_c|\,P \\ A(\bar{B}^0 \to \pi^0\pi^0) &= e^{-i\gamma}\,|\lambda_u|\,C + |\lambda_c|P \\ \sqrt{2}A(B^- \to \pi^0\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,(T+C) \end{aligned}$$

5 hadronic parameters + γ

$$\begin{aligned} p_c &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\,(P/T) \\ p_s &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\,(P/T) \\ t_c &\equiv |T|/|T+C| \\ TC &\equiv |T+C| \\ \epsilon &\equiv \mathrm{Im}\,(C/T) \end{aligned}$$

Implications of small phases I

Measuring γ from $B \to \pi\pi$

Amplitudes (using isospin and no EW penguins)

$$A(\bar{B}^0 \to \pi^+\pi^-) = e^{-i\gamma}\,|\lambda_u|\,T - |\lambda_c|\,P$$

$$A(\bar{B}^0 \to \pi^0\pi^0) = e^{-i\gamma}\,|\lambda_u|\,C + |\lambda_c|P$$

$$\sqrt{2}A(B^- \to \pi^0\pi^-) = e^{-i\gamma}\,|\lambda_u|\,(T + C)$$

5 hadronic parameters + γ

Gronau, London ('90)

$$\begin{aligned} p_c &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\,(P/T) \\ p_s &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\,(P/T) \\ t_c &\equiv |T|/|T+C| \\ TC &\equiv |T+C| \\ \epsilon &\equiv \mathrm{Im}\,(C/T) \end{aligned}$$

$$\begin{aligned} \mathrm{BR}(\pi^+\pi^-) &= (5.0 \pm 0.4) \\ \mathrm{BR}(\pi^0\pi^-) &= (5.5 \pm 0.6) \\ \mathrm{BR}(\pi^0\pi^0) &= (1.45 \pm 0.29) \\ C_{\pi^+\pi^-} &= -0.37 \pm 0.10 \\ S_{\pi^+\pi^-} &= -0.50 \pm 0.12 \\ C_{\pi^0\pi^0} &= -0.28 \pm 0.40 \end{aligned}$$

Implications of small phases I

Measuring γ from B→ππ

Amplitudes (using isospin and no EW penguins)

$$
\begin{aligned}
A(\bar{B}^0 \to \pi^+\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,T - |\lambda_c|\,P \\
A(\bar{B}^0 \to \pi^0\pi^0) &= e^{-i\gamma}\,|\lambda_u|\,C + |\lambda_c|P \\
\sqrt{2}A(B^- \to \pi^0\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,(T+C)
\end{aligned}
$$

5 hadronic parameters + γ

$$
\begin{aligned}
p_c &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\,(P/T) \\
p_s &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\,(P/T) \\
t_c &\equiv |T|/|T+C| \\
TC &\equiv |T+C| \\
\epsilon &\equiv \mathrm{Im}\,(C/T)
\end{aligned}
$$

Gronau, London (‘90)

$$
\begin{aligned}
\mathrm{BR}(\pi^+\pi^-) &= (5.0 \pm 0.4) \\
\mathrm{BR}(\pi^0\pi^-) &= (5.5 \pm 0.6) \\
\mathrm{BR}(\pi^0\pi^0) &= (1.45 \pm 0.29) \\
C_{\pi^+\pi^-} &= -0.37 \pm 0.10 \\
S_{\pi^+\pi^-} &= -0.50 \pm 0.12 \\
\cancel{C_{\pi^0\pi^0}} &\cancel{= -0.28 \pm 0.40}
\end{aligned}
$$

Implications of small phases I

Measuring γ from B→ππ

Amplitudes (using isospin and no EW penguins)

$$
\begin{aligned}
A(\bar{B}^0 \to \pi^+\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,T - |\lambda_c|\,P \\
A(\bar{B}^0 \to \pi^0\pi^0) &= e^{-i\gamma}\,|\lambda_u|\,C + |\lambda_c| P \\
\sqrt{2}A(B^- \to \pi^0\pi^-) &= e^{-i\gamma}\,|\lambda_u|\,(T + C)
\end{aligned}
$$

5 hadronic parameters + γ

Gronau, London ('90)

$$
\begin{aligned}
p_c &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\,(P/T) \\
p_s &\equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\,(P/T) \\
t_c &\equiv |T|/|T + C| \\
TC &\equiv |T + C| \\
\epsilon &\equiv \mathrm{Im}\,(C/T)
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{BR}(\pi^+\pi^-) &= (5.0 \pm 0.4) \\
\mathrm{BR}(\pi^0\pi^-) &= (5.5 \pm 0.6) \\
\mathrm{BR}(\pi^0\pi^0) &= (1.45 \pm 0.29) \\
C_{\pi^+\pi^-} &= -0.37 \pm 0.10 \\
S_{\pi^+\pi^-} &= -0.50 \pm 0.12 \\
\cancel{C_{\pi^0\pi^0}} &\cancel{= -0.28 \pm 0.40}
\end{aligned}
$$

Getting rid of one parameter

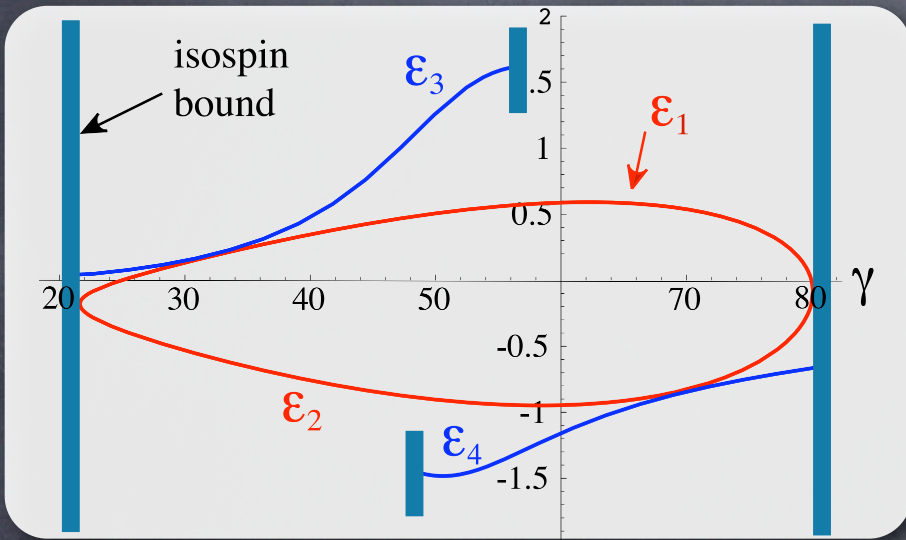
- The SCET analysis contains four hadronic parameters
- Allows us to eliminate one of the 5 in isospin
- In the limit $\Lambda/E \to 0$ one parameter vanishes

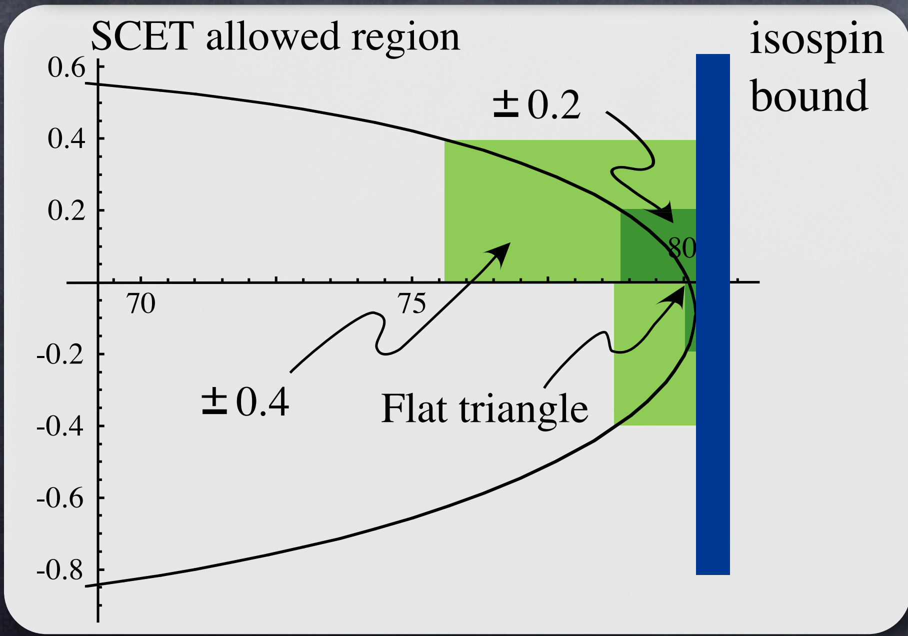
$$\varepsilon \equiv \mathrm{Im}(C/T) = O(\alpha_s, \Lambda/m_b)$$

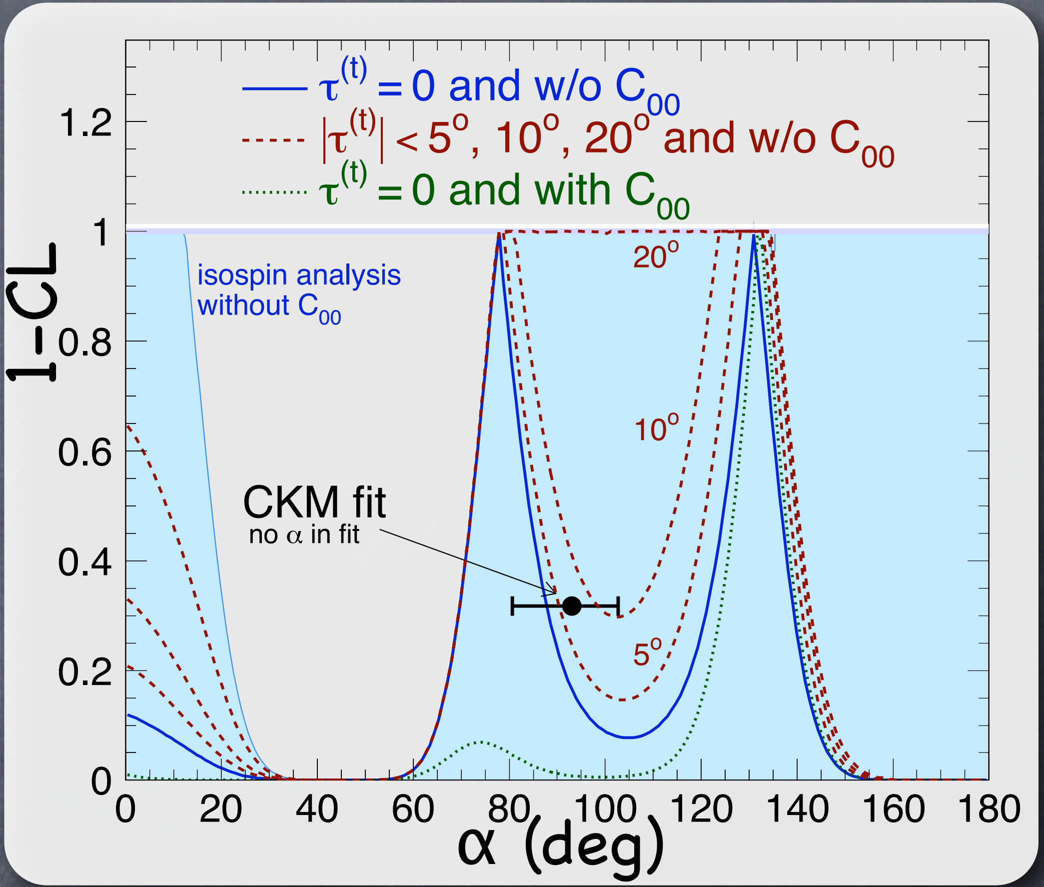
This allows to use the 5 well measured observables to determine the CKM angle γ

Extracting γ

Hadronic parameters
as function of γ







Grossman, Ligeti, Hoecker, Pirjol ('05)

Slightly old data.
Including EW penguins, get
$\alpha=75^\circ$

Implications of small phases

Sum rules for B→Kπ

Lipkin, Gronau, Rosner, Buras et al, Beneke et al

Define Observables

$$R_1 = \frac{2\mathrm{Br}(B^- \to \pi^0 K^-)}{\mathrm{Br}(B^- \to \pi^- \bar{K}^0)} - 1$$
$$= 0.004 \pm 0.086$$

$$R_2 = \frac{\mathrm{Br}(\bar{B}^0 \to \pi^- K^+)\tau_{B^-}}{\mathrm{Br}(B^- \to \pi^- \bar{K}^0)\tau_{B^0}} - 1$$
$$= -0.157 \pm 0.055$$

$$R_3 = \frac{2\mathrm{Br}(\bar{B}^0 \to \pi^0 \bar{K}^0)\tau_{B^-}}{\mathrm{Br}(\bar{B}^0 \to \pi^- \bar{K}^0)\tau_{B^0}} - 1$$
$$= 0.026 \pm 0.105$$

$$\Delta_1 = (1 + R_1) A_{\mathrm{CP}}(\pi^0 K^-)$$
$$= 0.040 \pm 0.040$$

$$\Delta_2 = (1 + R_2) A_{\mathrm{CP}}(\pi^- K^+)$$
$$= -0.097 \pm 0.016$$

$$\Delta_3 = (1 + R_3) A_{\mathrm{CP}}(\pi^0 \bar{K}^0)$$
$$= -0.021 \pm 0.133$$

$$\Delta_4 = A_{\mathrm{CP}}(\pi^- \bar{K}^0)$$
$$= -0.02 \pm 0.04$$

Combinations vanish to LO in $\epsilon \sim |\lambda_u/\lambda_c|$, P_{EW}/P

$$\boxed{R_1 - R_2 + R_3 = O(\epsilon^2)}$$

$$\boxed{\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 = O(\epsilon^2)}$$

Predictions for the R_i and Δ_i

CWB, Rothstein, Stewart ('05)

Experimental Results:

$R_1 - R_2 + R_3 = 0.19 \pm 0.15$

$\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 = 0.14 \pm 0.15$

Predictions for the R_i and Δ_i

CWB, Rothstein, Stewart ('05)

Experimental Results:

$R_1 - R_2 + R_3 = 0.19 \pm 0.15$ $\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 = 0.14 \pm 0.15$

SCET Prediction:

(modest assumptions about hadronic parameters)

$\boxed{R_1 + R_2 - R_3 = O(\epsilon^2) = 0.028 \pm 0.021}$

$\boxed{\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 \sim \epsilon^2 \sin(\varphi_i - \varphi_j) = 0 \pm 0.013}$

Predictions for the R_i and Δ_i

CWB, Rothstein, Stewart ('05)

Experimental Results:

$R_1 - R_2 + R_3 = 0.19 \pm 0.15$ $\quad$ $\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 = 0.14 \pm 0.15$

SCET Prediction:

(modest assumptions about hadronic parameters)

$$\boxed{R_1 + R_2 - R_3 = O(\epsilon^2) = 0.028 \pm 0.021}$$

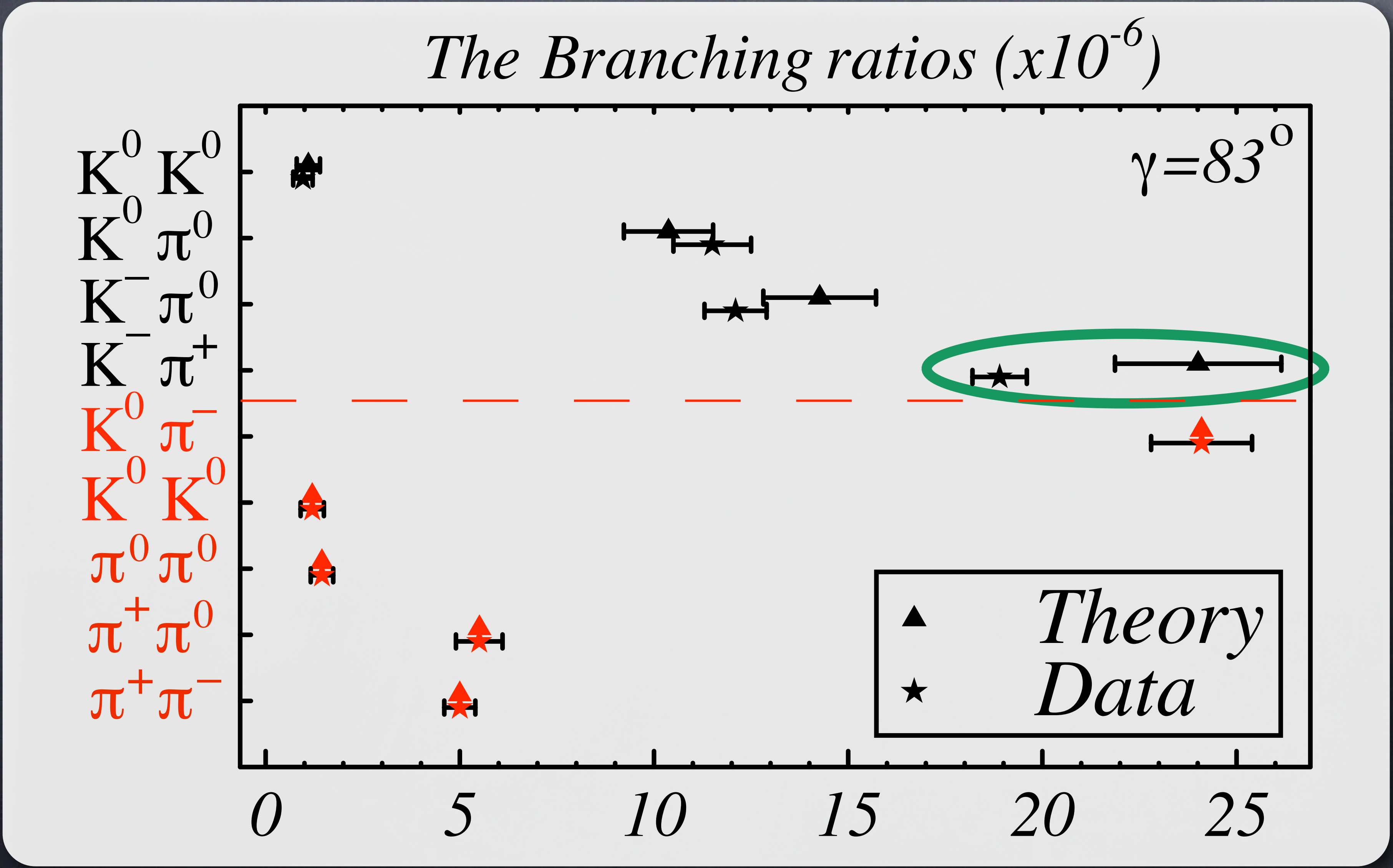
$$\boxed{\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 \sim \epsilon^2 \sin(\varphi_i - \varphi_j) = 0 \pm 0.013}$$

Pretty firm predictions

Need better data to check these predictions

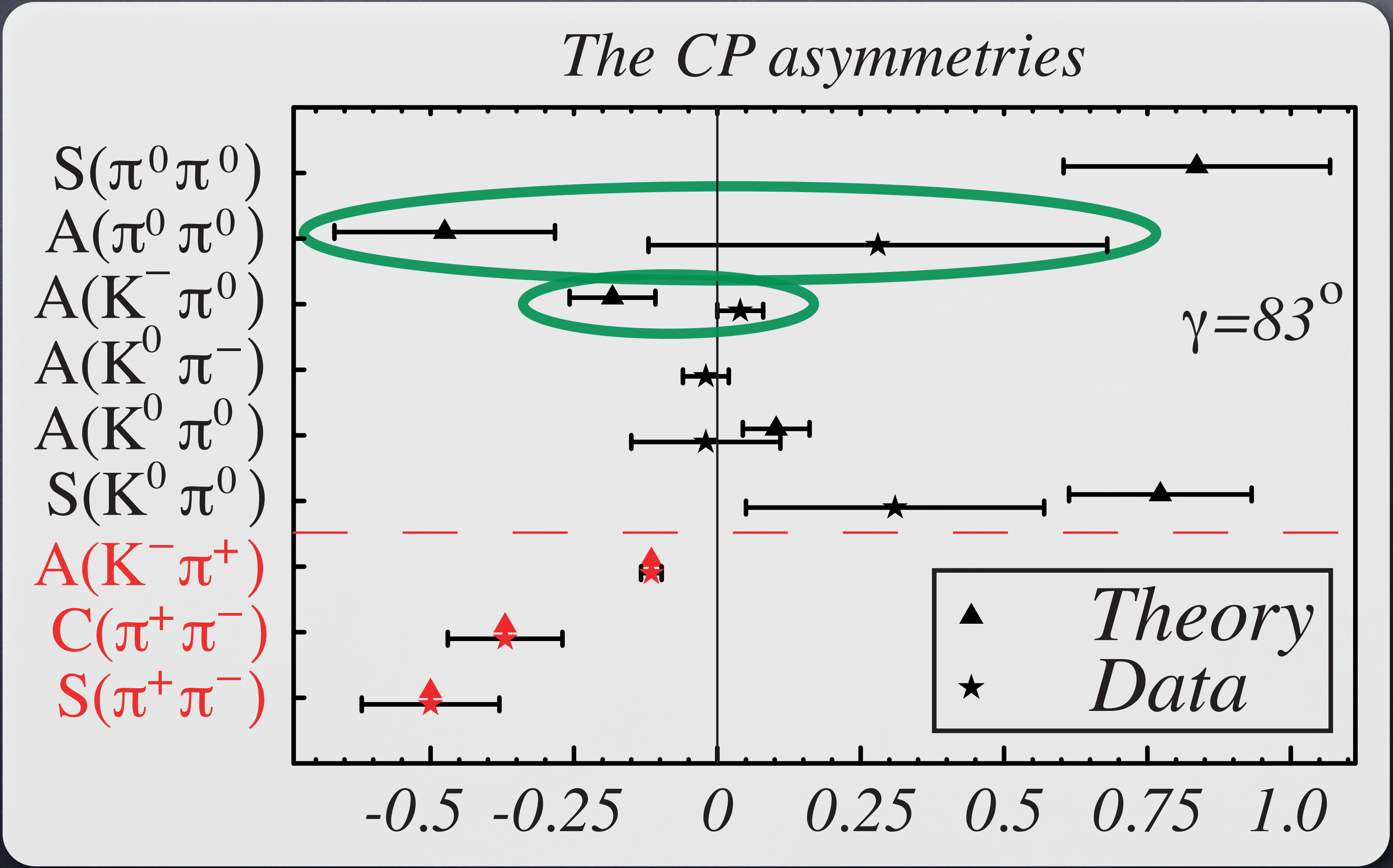
The B→PP predictions

Branching ratios



The B→PP predictions

CP asymmetries



Adding Isosinglets

Williamson, Zupan ('06)

Mode	Exp.	Theory I	Theory II
$B^- \to \pi^- \eta$	4.3 ± 0.5 ($S = 1.3$)	$4.9 \pm 1.7 \pm 1.0 \pm 0.5$	$5.0 \pm 1.7 \pm 1.2 \pm 0.4$
	-0.11 ± 0.08	$0.05 \pm 0.19 \pm 0.21 \pm 0.05$	$0.37 \pm 0.19 \pm 0.21 \pm 0.05$
$B^- \to \pi^- \eta'$	2.53 ± 0.79 ($S = 1.5$)	$2.4 \pm 1.2 \pm 0.2 \pm 0.4$	$2.8 \pm 1.2 \pm 0.3 \pm 0.3$
	0.14 ± 0.15	$0.21 \pm 0.12 \pm 0.10 \pm 0.14$	$0.02 \pm 0.10 \pm 0.04 \pm 0.15$
$\bar{B}^0 \to \pi^0 \eta$	< 2.5	$0.88 \pm 0.54 \pm 0.06 \pm 0.42$	$0.68 \pm 0.46 \pm 0.03 \pm 0.41$
	$-$	$0.03 \pm 0.10 \pm 0.12 \pm 0.05$	$-0.07 \pm 0.16 \pm 0.04 \pm 0.90$
$\bar{B}^0 \to \pi^0 \eta'$	< 3.7	$2.3 \pm 0.8 \pm 0.3 \pm 2.7$	$1.3 \pm 0.5 \pm 0.1 \pm 0.3$
	$-$	$-0.24 \pm 0.10 \pm 0.19 \pm 0.24$	$-$
$\bar{B}^0 \to \eta \eta$	< 2.0	$0.69 \pm 0.38 \pm 0.13 \pm 0.58$	$1.0 \pm 0.4 \pm 0.3 \pm 1.4$
	$-$	$-0.09 \pm 0.24 \pm 0.21 \pm 0.04$	$0.48 \pm 0.22 \pm 0.20 \pm 0.13$
$\bar{B}^0 \to \eta \eta'$	< 4.6	$1.0 \pm 0.5 \pm 0.1 \pm 1.5$	$2.2 \pm 0.7 \pm 0.6 \pm 5.4$
	$-$	$-$	$0.70 \pm 0.13 \pm 0.20 \pm 0.04$
$\bar{B}^0 \to \eta' \eta'$	< 10	$0.57 \pm 0.23 \pm 0.03 \pm 0.69$	$1.2 \pm 0.4 \pm 0.3 \pm 3.7$
	$-$	$-$	$0.60 \pm 0.11 \pm 0.22 \pm 0.29$
$\bar{B}^0 \to \bar{K}^0 \eta'$	63.2 ± 4.9 ($S = 1.5$)	$63.2 \pm 24.7 \pm 4.2 \pm 8.1$	$62.2 \pm 23.7 \pm 5.5 \pm 7.2$
	0.07 ± 0.10 ($S = 1.5$)	$0.011 \pm 0.006 \pm 0.012 \pm 0.002$	$-0.027 \pm 0.007 \pm 0.008 \pm 0.005$
$\bar{B}^0 \to \bar{K}^0 \eta$	< 1.9	$2.4 \pm 4.4 \pm 0.2 \pm 0.3$	$2.3 \pm 4.4 \pm 0.2 \pm 0.5$
	$-$	$0.21 \pm 0.20 \pm 0.04 \pm 0.03$	$-0.18 \pm 0.22 \pm 0.06 \pm 0.04$
$B^- \to K^- \eta'$	69.4 ± 2.7	$69.5 \pm 27.0 \pm 4.3 \pm 7.7$	$69.3 \pm 26.0 \pm 7.1 \pm 6.3$
	0.031 ± 0.021	$-0.010 \pm 0.006 \pm 0.007 \pm 0.005$	$0.007 \pm 0.005 \pm 0.002 \pm 0.009$
$B^- \to K^- \eta$	2.5 ± 0.3	$2.7 \pm 4.8 \pm 0.4 \pm 0.3$	$2.3 \pm 4.5 \pm 0.4 \pm 0.3$
	-0.33 ± 0.17 ($S = 1.4$)	$0.33 \pm 0.30 \pm 0.07 \pm 0.03$	$-0.33 \pm 0.39 \pm 0.10 \pm 0.04$

Adding Isosinglets

Williamson, Zupan ('06)

Mode	Exp.	Theory I	Theory II
$B^- \to \pi^- \eta$	4.3 ± 0.5 ($S = 1.3$)	$4.9 \pm 1.7 \pm 1.0 \pm 0.5$	$5.0 \pm 1.7 \pm 1.2 \pm 0.4$
	-0.11 ± 0.08	$0.05 \pm 0.19 \pm 0.21 \pm 0.05$	$0.37 \pm 0.19 \pm 0.21 \pm 0.05$
$B^- \to \pi^- \eta'$	2.53 ± 0.79 ($S = 1.5$)	$2.4 \pm 1.2 \pm 0.2 \pm 0.4$	$2.8 \pm 1.2 \pm 0.3 \pm 0.3$
	0.14 ± 0.15	$0.21 \pm 0.12 \pm 0.10 \pm 0.14$	$0.02 \pm 0.10 \pm 0.04 \pm 0.15$
$\bar{B}^0 \to \pi^0 \eta$	< 2.5	$0.88 \pm 0.54 \pm 0.06 \pm 0.42$	$0.68 \pm 0.46 \pm 0.03 \pm 0.41$
	–	$0.03 \pm 0.10 \pm 0.12 \pm 0.05$	$-0.07 \pm 0.16 \pm 0.04 \pm 0.90$
$\bar{B}^0 \to \pi^0 \eta'$	< 3.7	$2.3 \pm 0.8 \pm 0.3 \pm 2.7$	$1.3 \pm 0.5 \pm 0.1 \pm 0.3$
	–	$-0.24 \pm 0.10 \pm 0.19 \pm 0.24$	–
$\bar{B}^0 \to \eta\eta$	< 2.0	$0.69 \pm 0.38 \pm 0.13 \pm 0.58$	$1.0 \pm 0.4 \pm 0.3 \pm 1.4$
	–	$-0.09 \pm 0.24 \pm 0.21 \pm 0.04$	$0.48 \pm 0.22 \pm 0.20 \pm 0.13$
$\bar{B}^0 \to \eta\eta'$	< 4.6	$1.0 \pm 0.5 \pm 0.1 \pm 1.5$	$2.2 \pm 0.7 \pm 0.6 \pm 5.4$
	–	–	$0.70 \pm 0.13 \pm 0.20 \pm 0.04$
$\bar{B}^0 \to \eta'\eta'$	< 10	$0.57 \pm 0.23 \pm 0.03 \pm 0.69$	$1.2 \pm 0.4 \pm 0.3 \pm 3.7$
	–	–	$0.60 \pm 0.11 \pm 0.22 \pm 0.29$
$\bar{B}^0 \to \bar{K}^0 \eta'$	63.2 ± 4.9 ($S = 1.5$)	$63.2 \pm 24.7 \pm 4.2 \pm 8.1$	$62.2 \pm 23.7 \pm 5.5 \pm 7.2$
	0.07 ± 0.10 ($S = 1.5$)	$0.011 \pm 0.006 \pm 0.012 \pm 0.002$	$-0.027 \pm 0.007 \pm 0.008 \pm 0.005$
$\bar{B}^0 \to \bar{K}^0 \eta$	< 1.9	$2.4 \pm 4.4 \pm 0.2 \pm 0.3$	$2.3 \pm 4.4 \pm 0.2 \pm 0.5$
	–	$0.21 \pm 0.20 \pm 0.04 \pm 0.03$	$-0.18 \pm 0.22 \pm 0.06 \pm 0.04$
$B^- \to K^- \eta'$	69.4 ± 2.7	$69.5 \pm 27.0 \pm 4.3 \pm 7.7$	$69.3 \pm 26.0 \pm 7.1 \pm 6.3$
	0.031 ± 0.021	$-0.010 \pm 0.006 \pm 0.007 \pm 0.005$	$0.007 \pm 0.005 \pm 0.002 \pm 0.009$
$B^- \to K^- \eta$	2.5 ± 0.3	$2.7 \pm 4.8 \pm 0.4 \pm 0.3$	$2.3 \pm 4.5 \pm 0.4 \pm 0.3$
	-0.33 ± 0.17 ($S = 1.4$)	$0.33 \pm 0.30 \pm 0.07 \pm 0.03$	$-0.33 \pm 0.39 \pm 0.10 \pm 0.04$

Summary

- A super B factory would give rise to many new and improved measurements
- To get useful physics need to ensure that theory can keep up with experimental progress
- Strong experimental program motivates theoretical progress
- We have seen that during the very successful run of Babar and Belle, theory has produced results that were previously thought impossible