QCD Effects in Weak Decays

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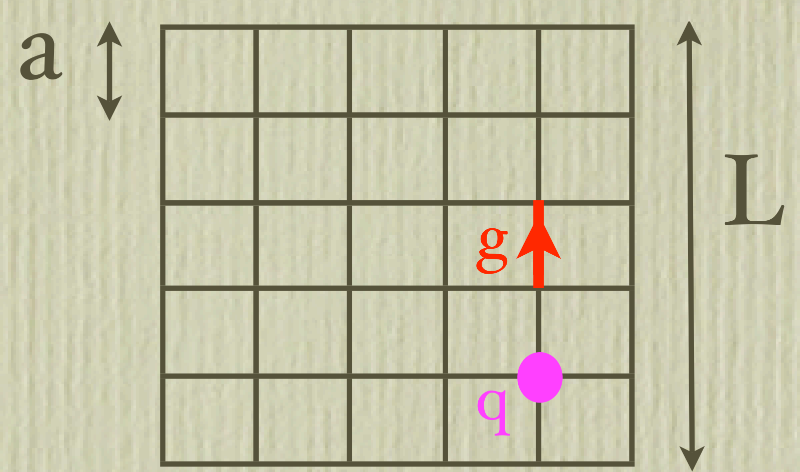
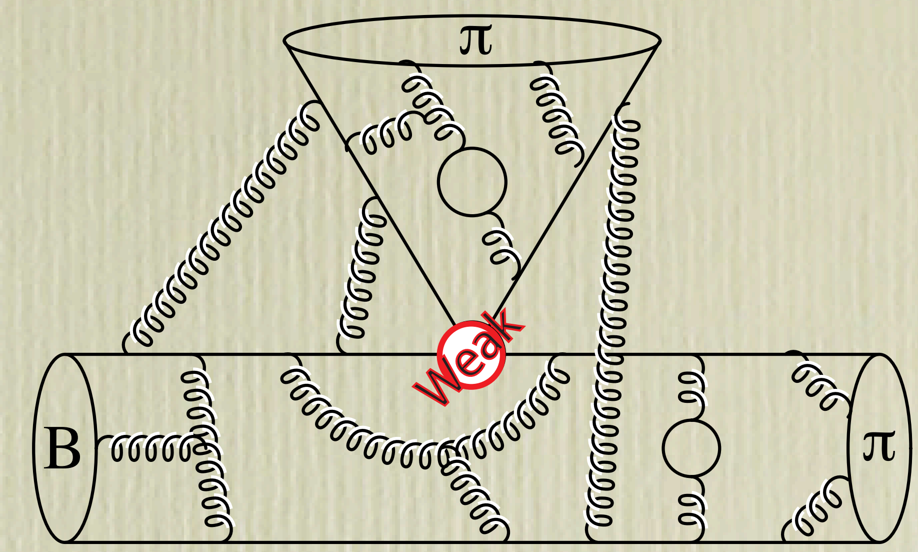
Lepton-Photon 2005

Weak Decays

$b \to u e \bar{\nu}_e \ , \ b \to s \bar{s} s \ \ldots$

- Test our understanding of QCD

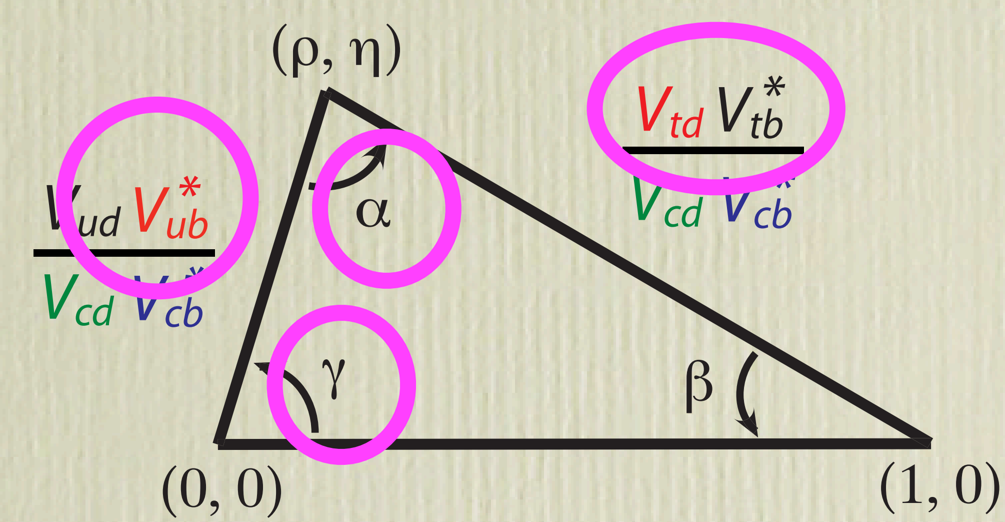




- Measure weak flavor physics of quarks

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

CKM matrix



Unitary Triangle

- Search for new physics

(⟶ talk by L. Silvestrini)

QCD is a rich theory, the appropriate tools depend on the task

Plan for this talk:

- $B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$ — test SM
- spectra, α_s

  $D \to K\ell\bar{\nu}$, $D \to \pi\ell\bar{\nu}$ — test lattice QCD

  f_D, f_{D_s}

  f_B, f_{B_s} — $\Delta m_d, \Delta m_s$
- $B \to \pi\ell\bar{\nu}$ — $|V_{ub}|$
- $B \to D\pi$ — test factorization

  $B \to \rho\rho \quad B \to \pi\pi$

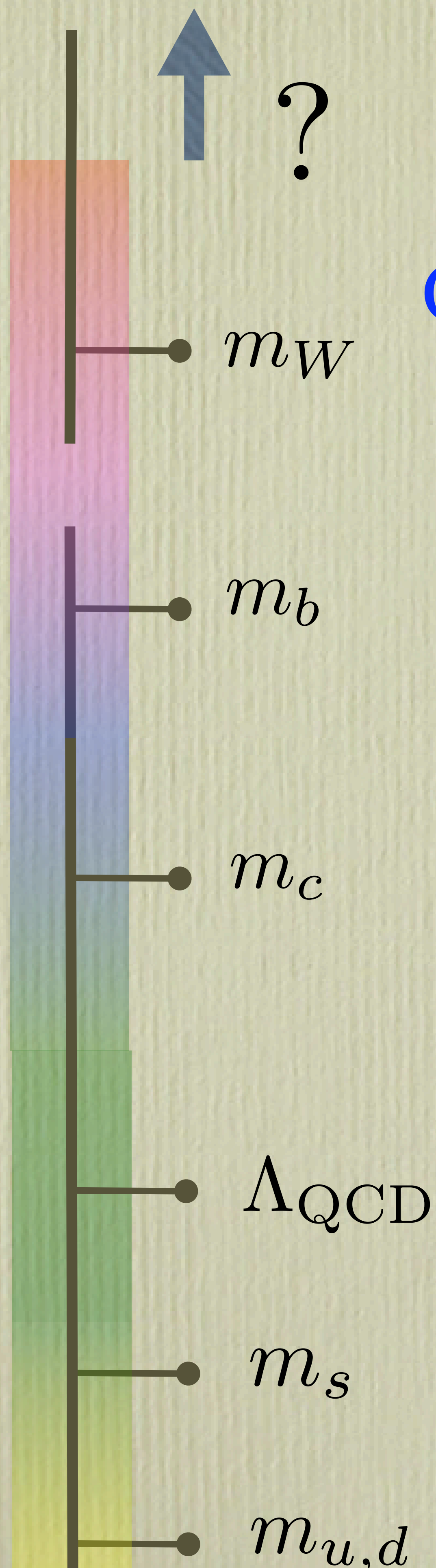
  $B \to K\pi$ — measure $\alpha, \gamma,$ & test SM
- $B \to K^*\gamma \quad B \to \rho\gamma$ — test SM

Operator Product Expansion & Perturbative QCD

Unquenched Lattice QCD

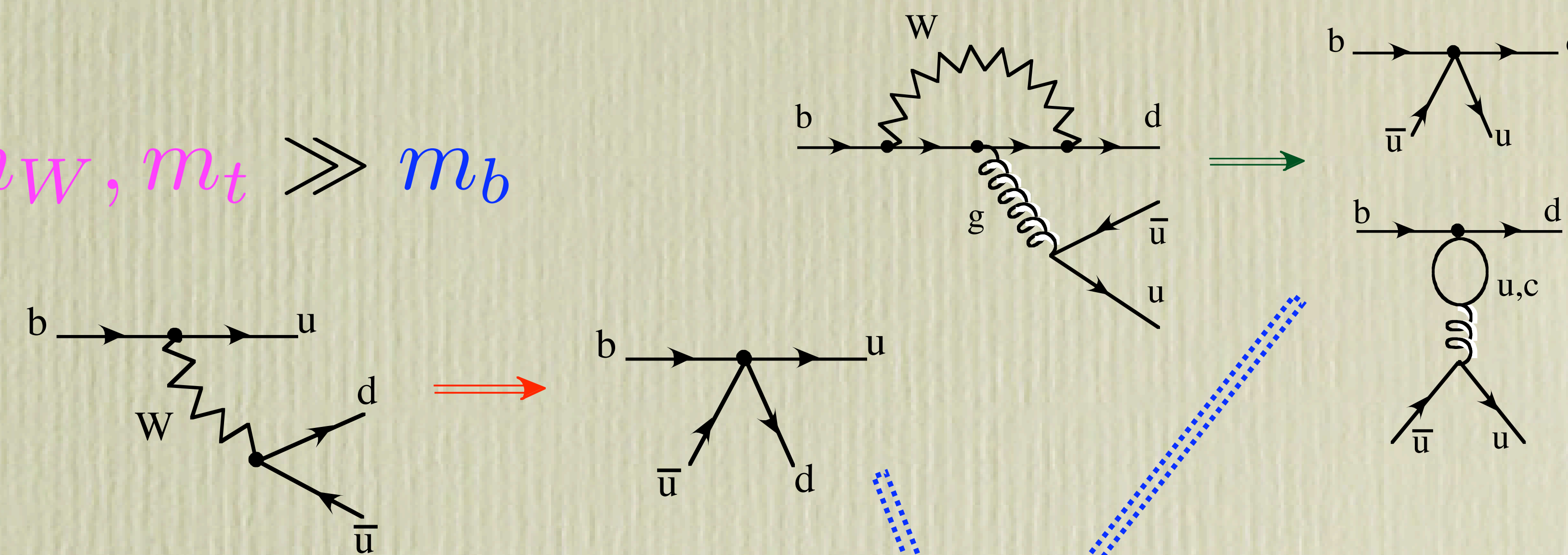
Factorization Theorems for Weak Decays

Kaon decays: $\longrightarrow$ talk by U. Nierste



Operator Product Expansion (I)

- $m_W, m_t \gg m_b$



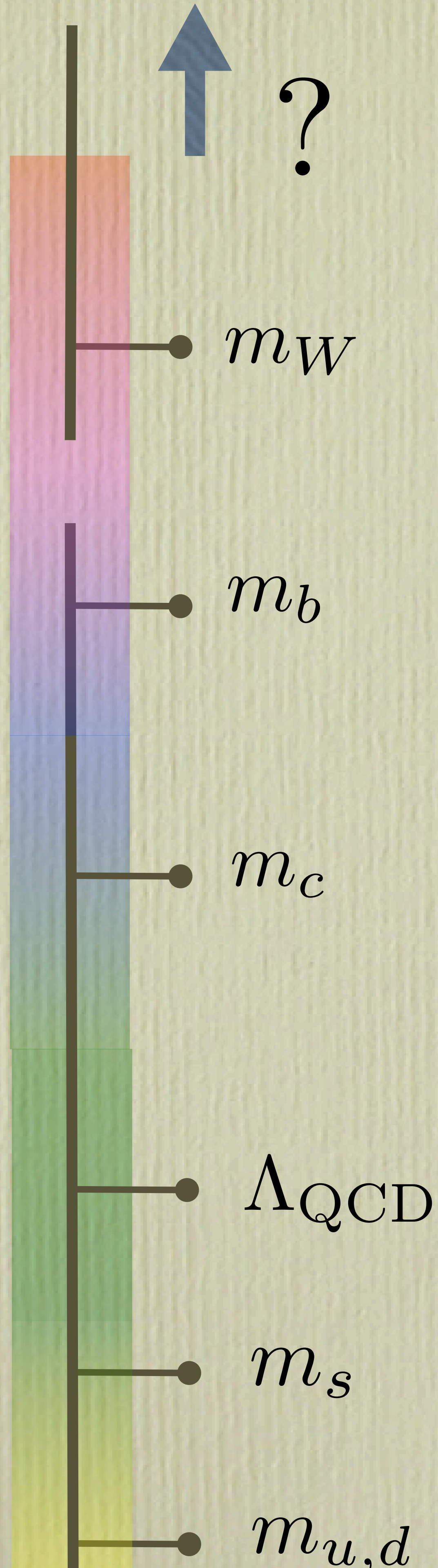
$$\boxed{H_{\text{weak}} = \frac{G_F}{\sqrt{2}} \sum_i \lambda^i C_i(\mu) O_i(\mu)}$$

$\lambda^i = \text{CKM},$
$\lambda^1 = V_{ub} V_{ud}^*$

perturbative QCD

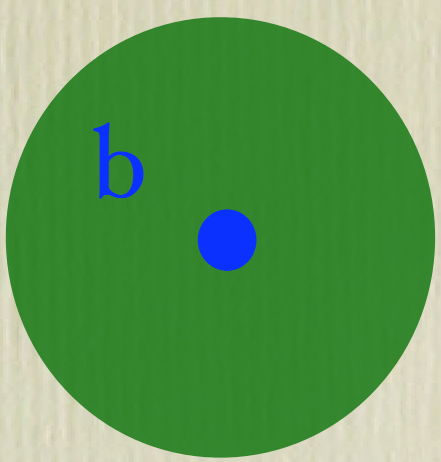
Decays like $B \to X_s \gamma$ & $B \to K\pi$
have contributions from ~ 12 operators

Operator Product Expansion (II)



- $m_b \gg \Lambda_{\rm QCD}$

B-meson



$$\Gamma = c^{(0)} f^{(0)} + \frac{1}{m_b} c^{(1)} f^{(1)} + \ldots$$

Heavy Quark Effective Theory $\quad h_v, q$

Operator Product Expansion for Inclusive Decays

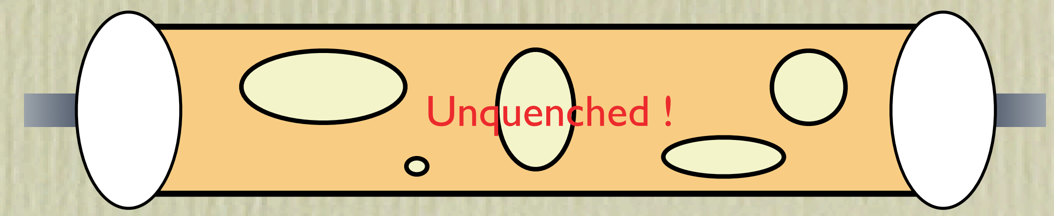
- Justifies free quark decay as leading approximation

$$\frac{\Lambda}{m_b} \simeq 0.1, \quad \alpha_s(m_b) \simeq 0.2$$

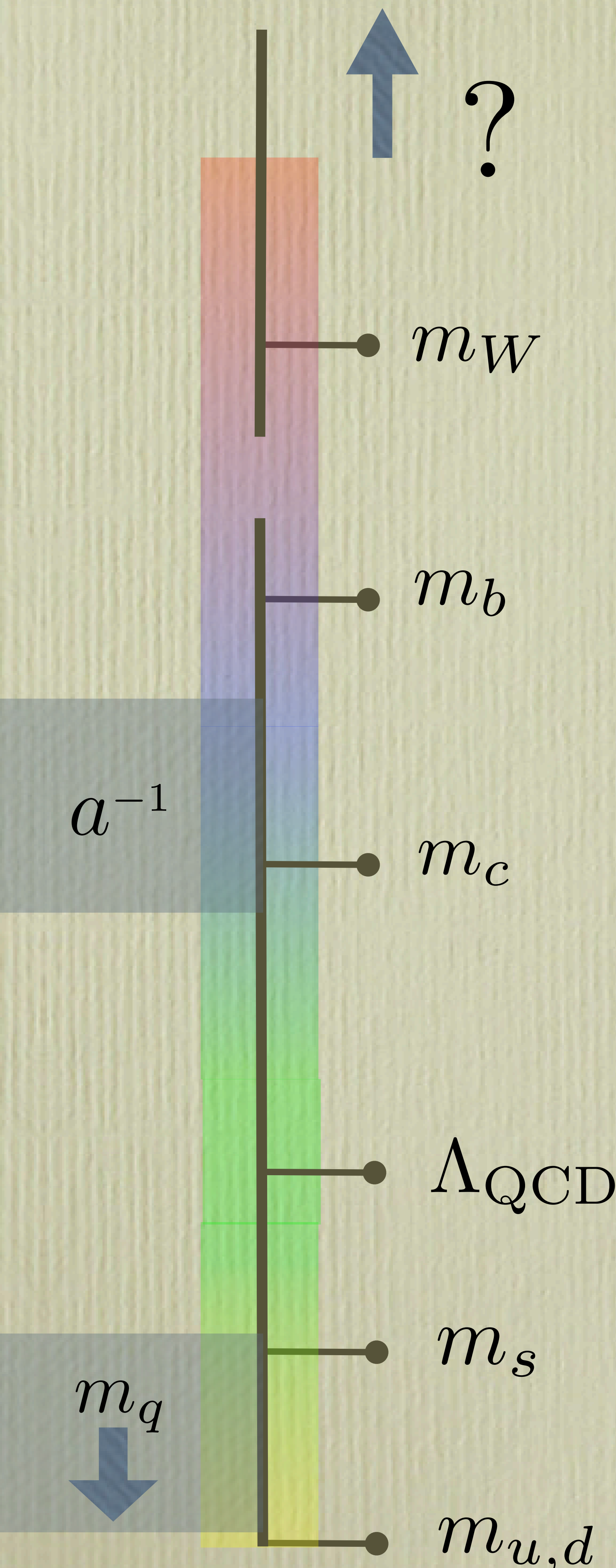
subleading terms are crucial for precision phenomenology

Unquenched Lattice QCD

$\det(\not{D} + m) \neq 1$



nonperturbative QCD



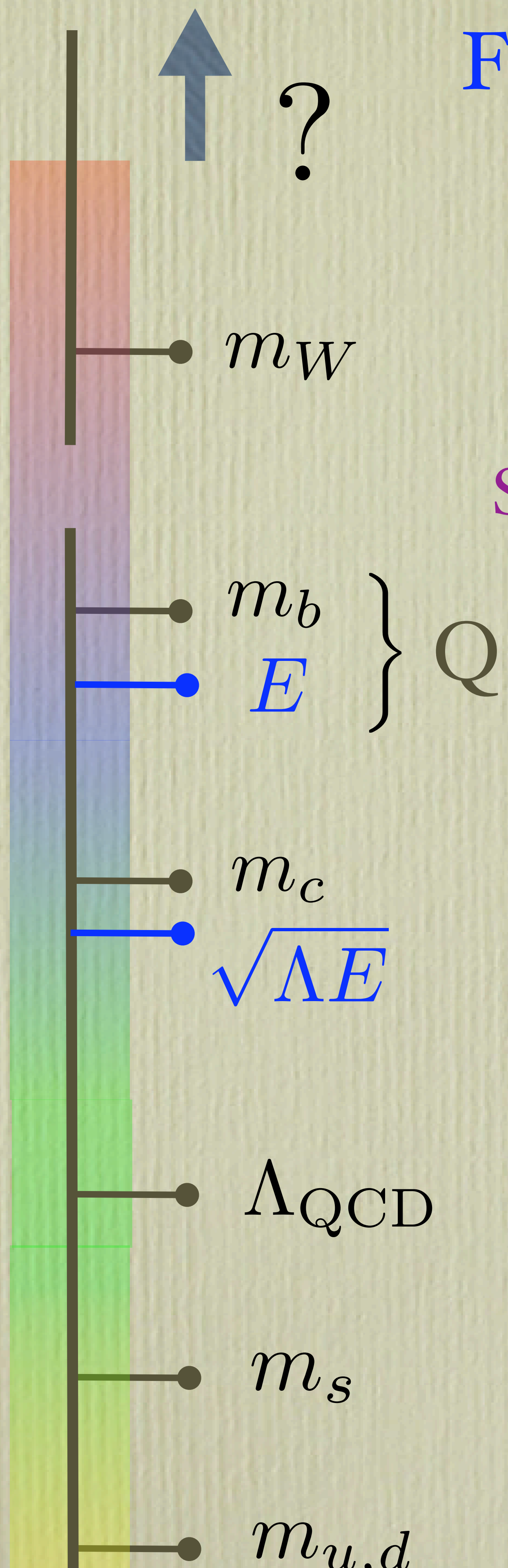
Now:

- Focus on "Gold Plated Observables" for high precision
  - matrix elements with at most one hadron in initial and final state
  - at least 100MeV below threshold, or small widths
- Simulate "real QCD". Use nf=2+1 light flavors, quark masses m_q light enough for extrapolation with chiral perturbation theory (or PQChPT)
- Systematic/parametric estimates of uncertainties using effective field theory methods. eg. heavy quarks:
  - $m_Q \gg \Lambda_{QCD}$ NRQCD, Fermilab action, RHQ action
- Results for a broad spectrum of observables are obtained using common inputs

} ChPT, PQChPT

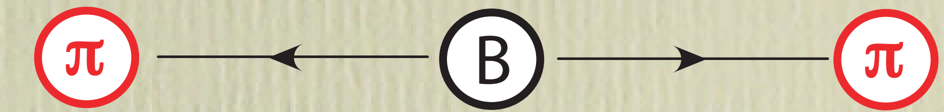
→ tests, predictions, and impact

Factorization Theorems



Energetic Hadrons

eg. $E_\pi \gg \Lambda_{\rm QCD}$



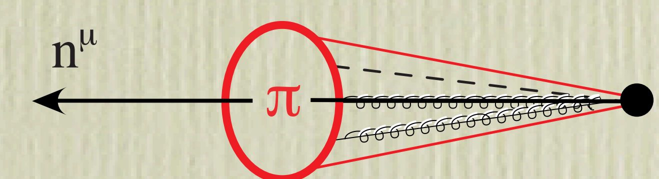
Soft-Collinear Effective Theory (SCET)

Bauer, Pirjol, I.S.
Fleming, Luke

many other authors

Introduce fields for infrared d.o.f.

collinear:



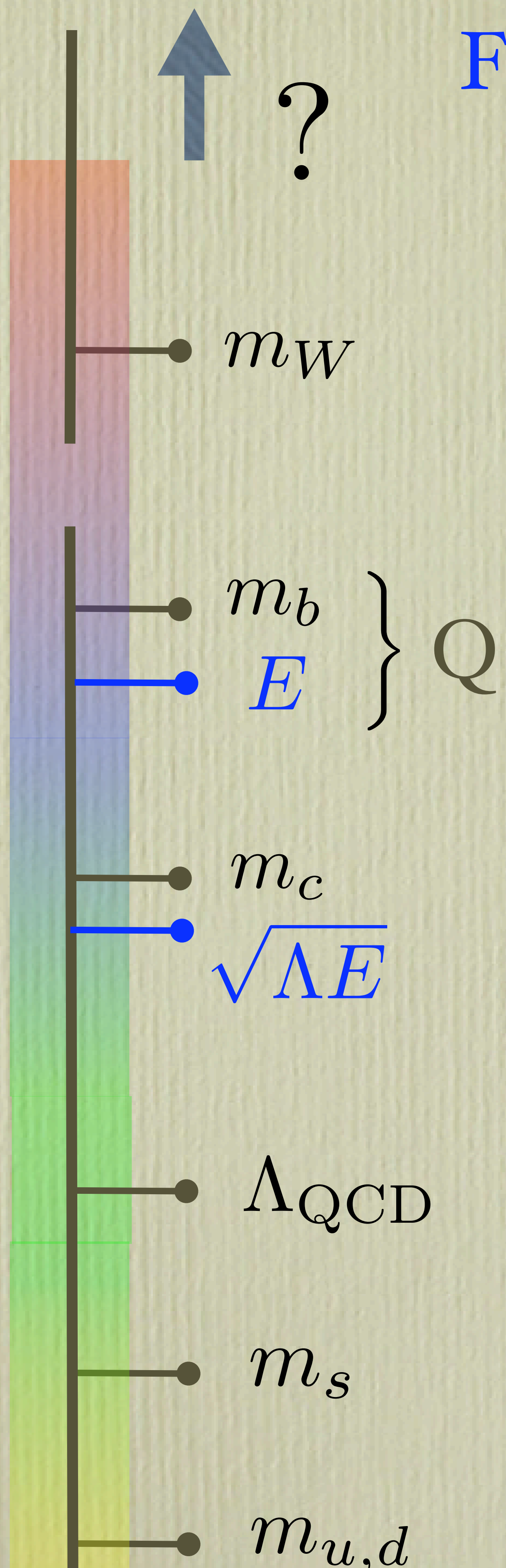
ξ_n, A_n^μ

soft:

h_v, q_s, A_s^μ

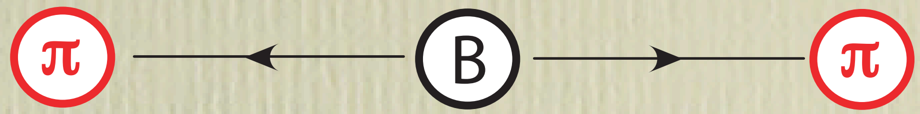
$$\mathcal{L} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \ldots$$

- Separate physics at different momentum scales
- Model independent, systematically improvable



Factorization Theorems

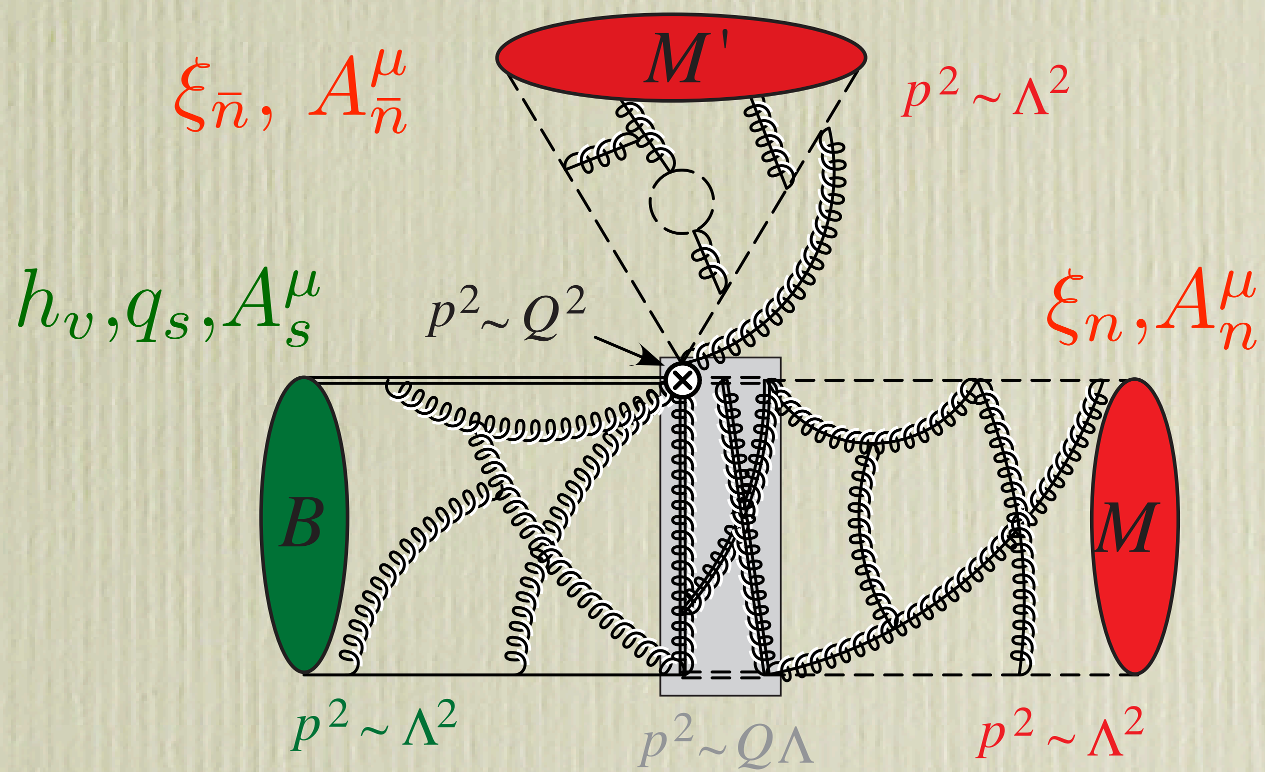
Energetic Hadrons



eg. $E_\pi \gg \Lambda_{\rm QCD}$

$$A = \int dz\,dx_i\,dk^+ \underbrace{T(z)} \; \underbrace{J(z, x_i, k^+)} \; \underbrace{\phi_1(x_1)\phi_2(x_2)\phi_B(k^+)} + \ldots$$

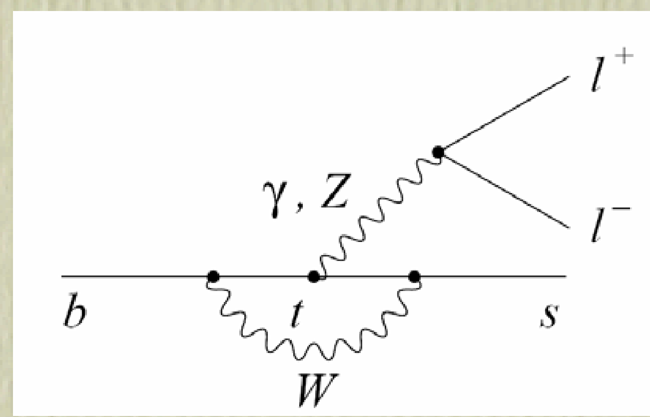
$$Q^2 \gg E\Lambda \gg \Lambda^2$$

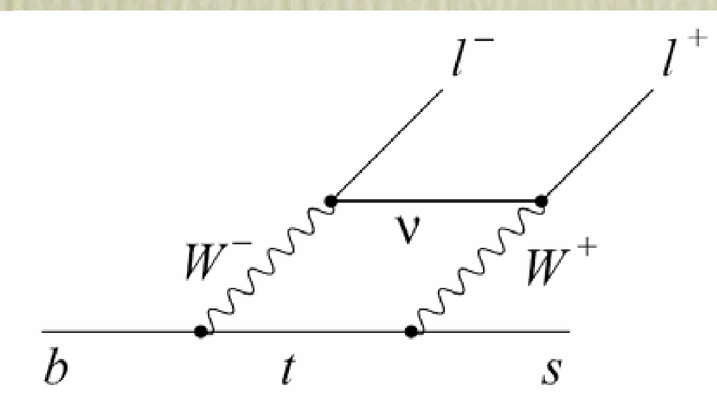


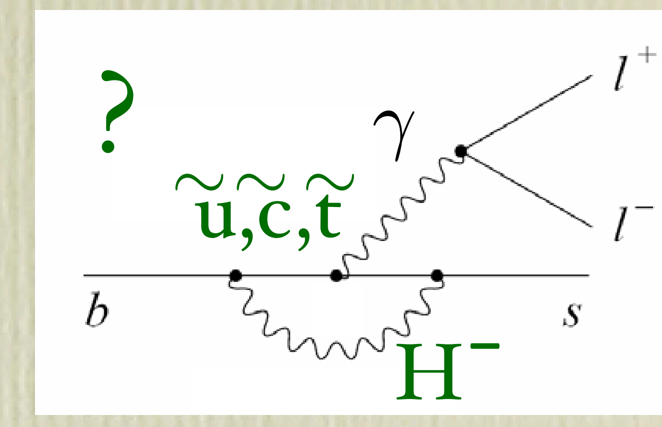
Inclusive Rare Decays

$B \to X_s \gamma$ & $B \to X_s \ell^+ \ell^-$

- SM perturbative and nonperturbative effects are under control
- sensitive to new physics







3 steps

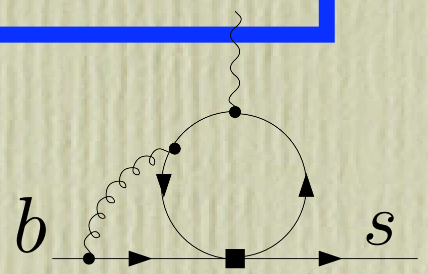
1) Matching $\quad H_W = \frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$ determine $C_i(m_W)$

2) Running (operator mixing) $\quad C_i(m_W) \to C_i(m_b)$

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_{\mathrm{QED}}$$

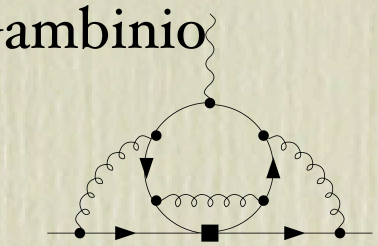
3) Matrix elements of $O_i(\mu)$ with OPE at $\mu \simeq m_b$

$B \to X_s\gamma$



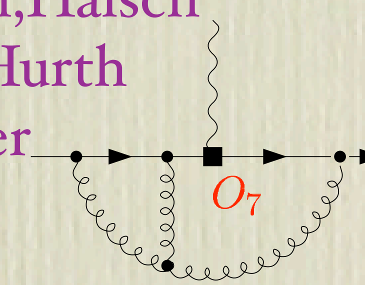
Progress on NNLL calculations, a few entries still missing

		$\sim 25\%$ LL	$\sim 10\%$ NLL	NNLL	
Matching	C_{1-6}	tree	$1L$	$2L$	Bobeth, Misiak, Urban
	$C_{7,8}$	$1L$	$2L$	$3L$	Misiak, Steinhauser
Running	$\hat{\gamma}$	$\begin{pmatrix} \text{1L} & \text{2L} \\ 0 & \text{1L} \end{pmatrix}$	$\begin{pmatrix} \text{2L} & \text{3L} \\ \text{1L} & \text{2L} \end{pmatrix}$	$\begin{pmatrix} \text{3L} & \text{4L} \\ \text{2L} & \text{3L} \end{pmatrix}$	Haisch,Gorbahn,Gambinio Czakon et al.
M.Elts.	$\langle O_{1-6} \rangle$	$1L$	$2L$	$3L$	Bieri, Greub, Steinhauser
	$\langle O_{7,8} \rangle$	tree	$1L$	$2L$	Greub,Hurth,Asatrian Blockland et al., Melnikov, Mitov Gambina,Gorbahn,Haisch Asatrian, Greub, Hurth Misiak, Steinhauser



Grinstein et al.
Buras et al.
Ciuchini, Franco,
Silverstrini et al.
...

Greub, Hurth,
Wyler, Buras, Misak,
Czarnecki, Munz,
Ali, Pott, Adel, Yao, ...



$\frac{1}{(m_b)^k}$ corrections: Falk, Luke, Savage, Bauer

$\frac{1}{(m_c)^k}$: Voloshin, Khodjamirian, Ligeti, Randall, Wise, Grant, Morgan, Nussinov, Peccei, Buchalla, Isidor, Rey

Photon energy cut: $E_\gamma \geq E_0$

$E_0 \geq 1.2\,\text{GeV}$ to avoid corrections where gluon or quark fragments into a photon

Kapustin, Ligeti, Politzer

$E_0 \leq 2.0\,\text{GeV}$ to keep it inclusive and avoid sensitivity to b-quark distribution function (region where standard OPE breaks down)

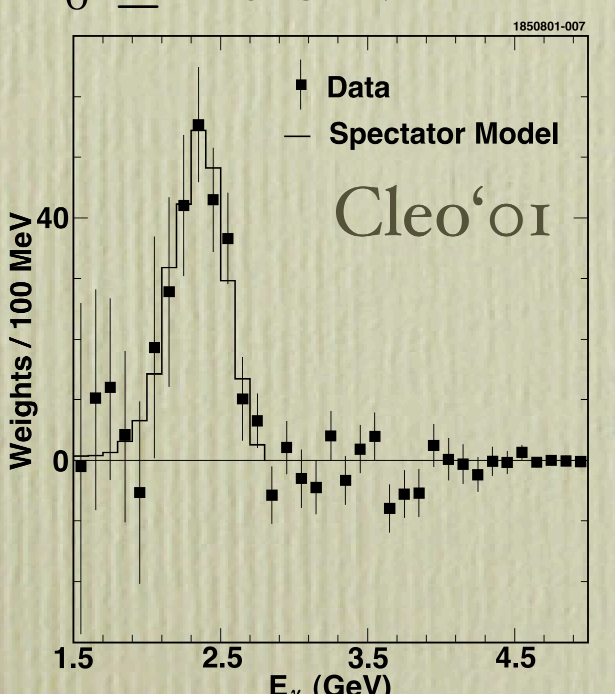
Neubert,
Bigi, Shifman, Uraltsev, Vainshtein,
Falk, Jenkins, Manohar, Wise

(b-quark distn. is useful for Vub, talks by U.Nierste, F.Forti)

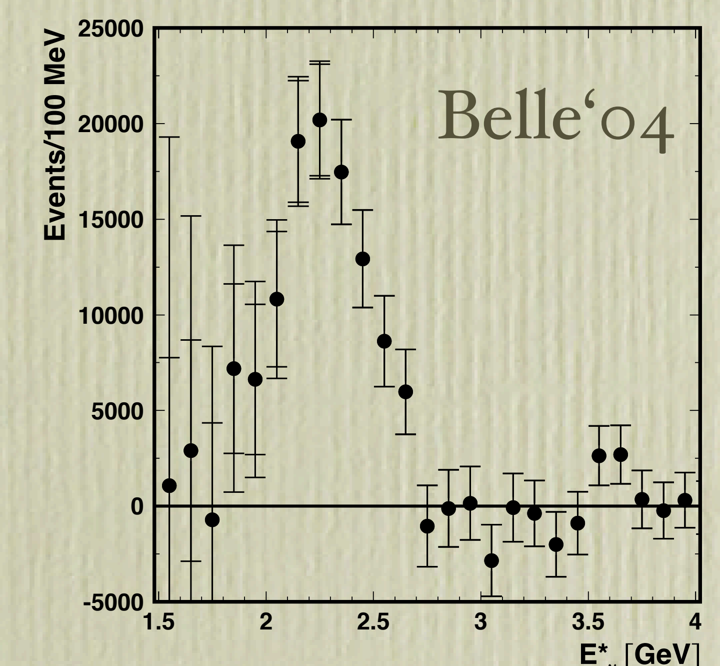
Usually argued that $E_0 = 1.6\,\text{GeV}$ suffices

Experiment:

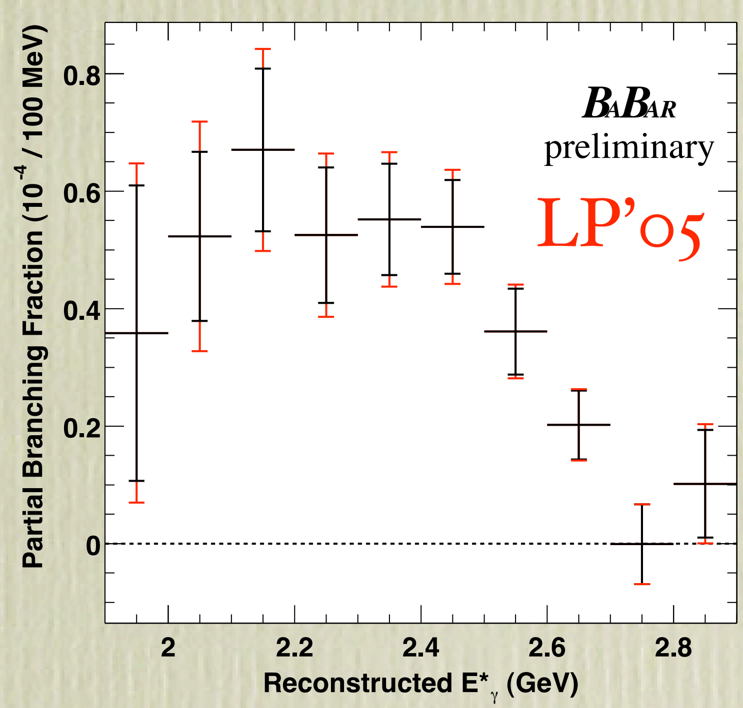
$E_0 \geq 2.0\,\text{GeV}$



$E_0 \geq 1.8\,\text{GeV}$



$E_0 \geq 1.9\,\text{GeV}$



experimental results extrapolated down

- Cut dependence can be systematized (uses SCET and OPE). Recently argued that $\alpha_s^2(m_b - 2E_0)$ terms give an added $\sim 10\%$ uncertainty.

Neubert

Theory Summary $\left(\; E_0 = 1.6\,\mathrm{GeV} \; \right)$ NLL

Gambino, Misiak;
Buras, Czarnecki, Misiak, Urban

$$\mathrm{Br}(B \to X_s\gamma)\Big|_{E_\gamma > 1.6\,\mathrm{GeV}} = 3.57 \times 10^{-4}\big[1 \pm 0.055_{(\mathrm{m_c/m_b})} \pm 0.04_{(\mathrm{otherNNLO})}\big) \pm 0.02_{(C_{\ell\nu})}$$
$$\pm 0.03_{\alpha_s(m_Z)} \pm 0.02_{\mathrm{Br}^{\mathrm{expt}}_{\mathrm{semi}}} \pm 0.01_{m_t} \pm 0.01_{\mathrm{CKM}}\big]$$
$$= (3.57 \pm 0.28) \times 10^{-4}$$

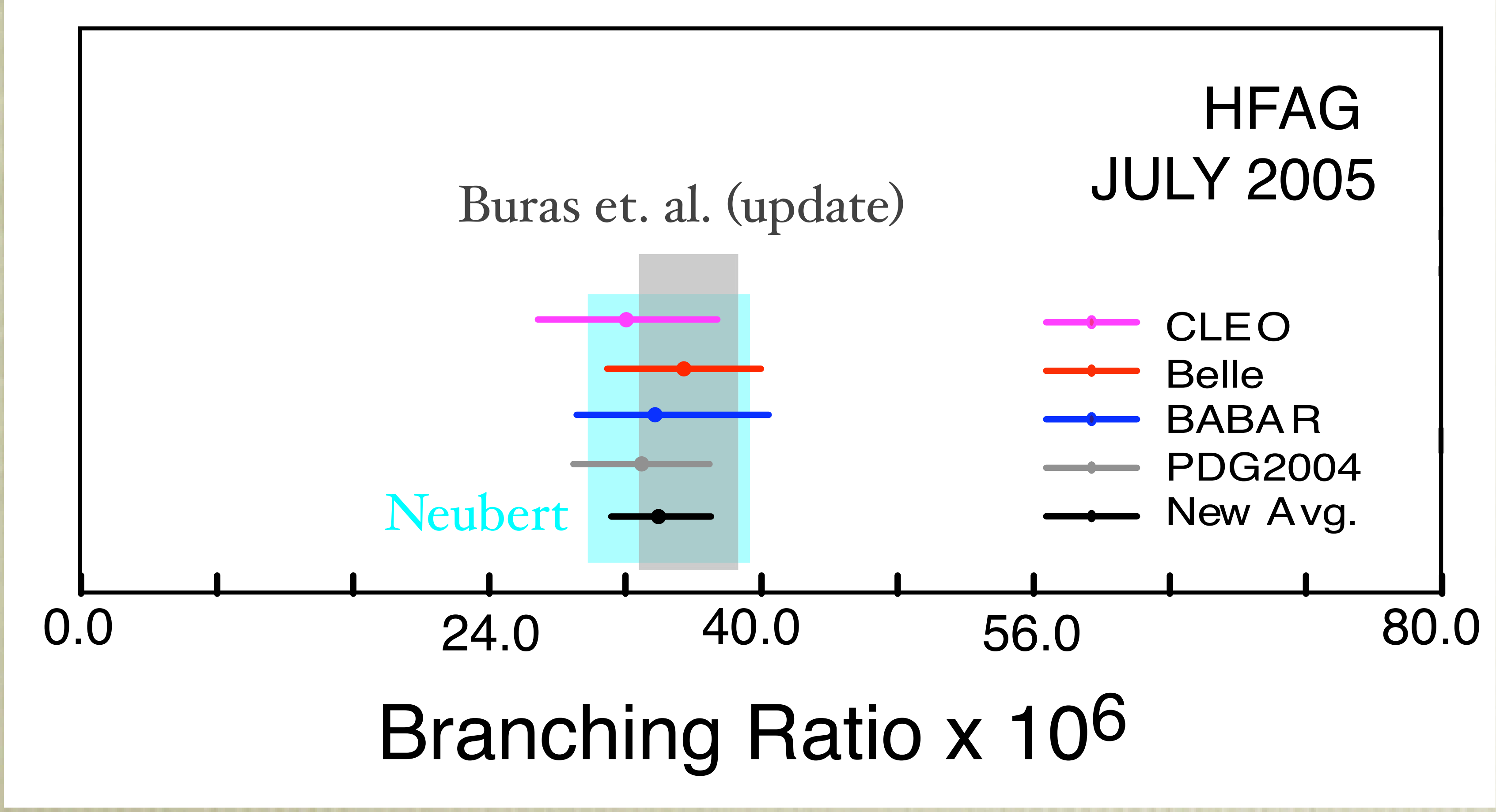
Updated for LP'05 by M.Misiak

$$\left[= (3.47^{+0.46}_{-0.50}) \times 10^{-4} \quad \text{Neubert} \right]$$

Compare to Data

$$Br^{\mathrm{expt}}_{\mathrm{avg}} = (3.39^{+0.30}_{-0.27}) \times 10^{-4}$$

LP'05



a success story for QCD!

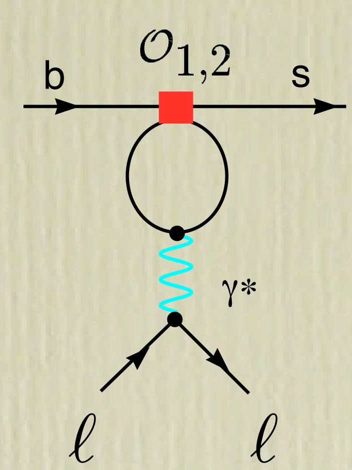
eg. $\dfrac{\mathrm{Br}^{LL}}{\mathrm{Br}^{LO}} \simeq 3$

The errors will be decreased by ongoing computations

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

numerically comparable

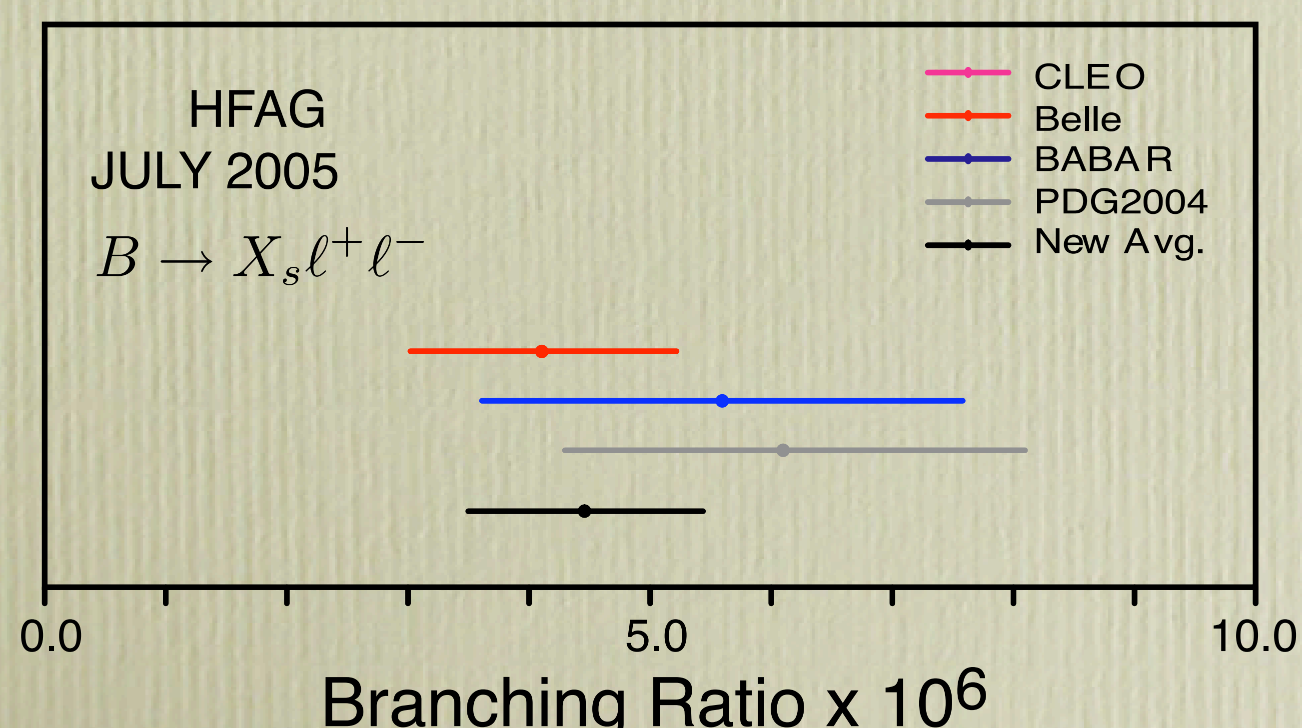
		uncertainty
LL :	$C_9(\mu) = \frac{4}{9} \ln \frac{m_W^2}{m_b^2} + \mathcal{O}(\alpha_s)$	
NLL :	counting is like LL $B \to X_s \gamma$	$\sim 25\%$
NNLL :	counting is like NLL $B \to X_s \gamma$	$\sim 15\%$



Bobeth, Misiak, Urban
Gambinio,Gorbahn, Haisch,
Asatryan et al.,
Asatrian et al.,
Ghinculov, Hurth, Isidori, Yao

Nonperturbative corrections: Falk et al., Ali et al., Buchalla, Isidori, Rey

$$Br^{\text{expt}}_{\text{avg}}(M_{\ell^+\ell^-} > 0.2\,\text{GeV}) = (4.46^{+0.98}_{-0.96}) \times 10^{-6}$$

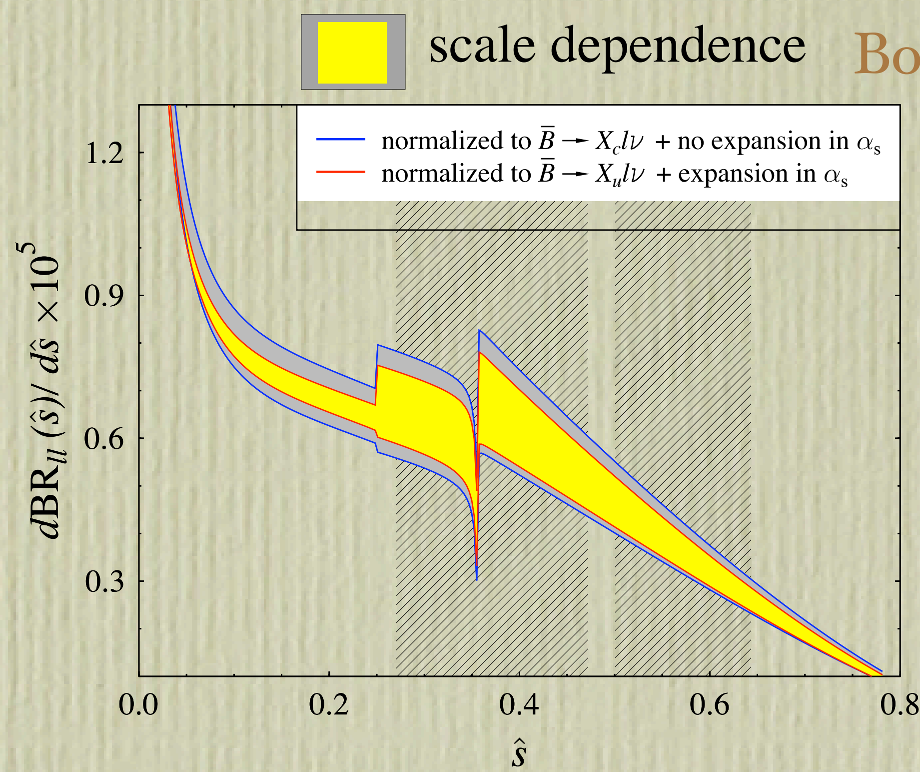


NNLL: Ali, Greub, Hiller, Lunghi

$$\text{Br}(B \to X_s \ell^+ \ell^-) = 4.17 \pm 0.70$$

17% error

$B \to X_s \ell^+ \ell^-$ NNLL Spectrum



Bobeth, Gambino, Gorbahn, Haisch

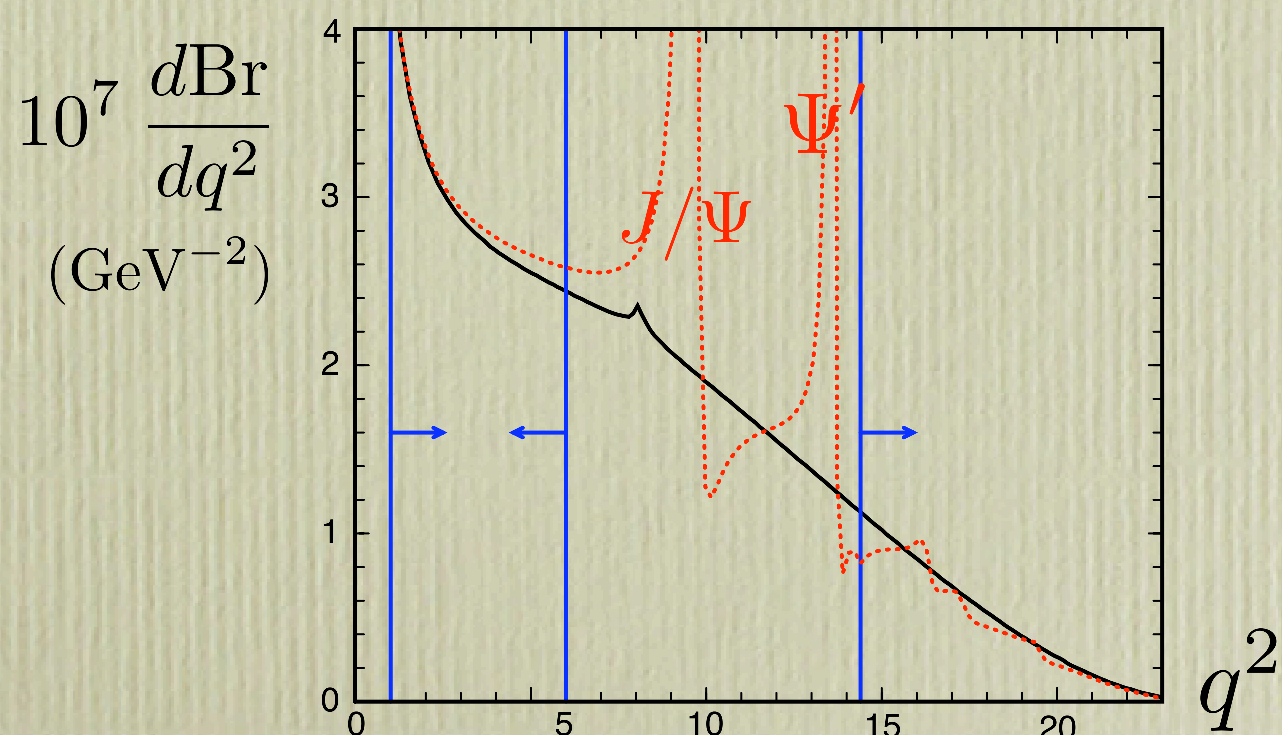
[computed dominant higher order e.w.]

- Experiments remove backgrounds from J/Ψ, Ψ'
- Reduced theory uncertainty for:

  (1) $1\,\mathrm{GeV}^2 \le q^2 \le 6\,\mathrm{GeV}^2$

  (2) $14.4\,\mathrm{GeV}^2 \le q^2$

sensitive to different Wilson coefficients for new physics tests



NNLL spectrum in OPE

Ghinculov, Hurth, Isidori, Yao

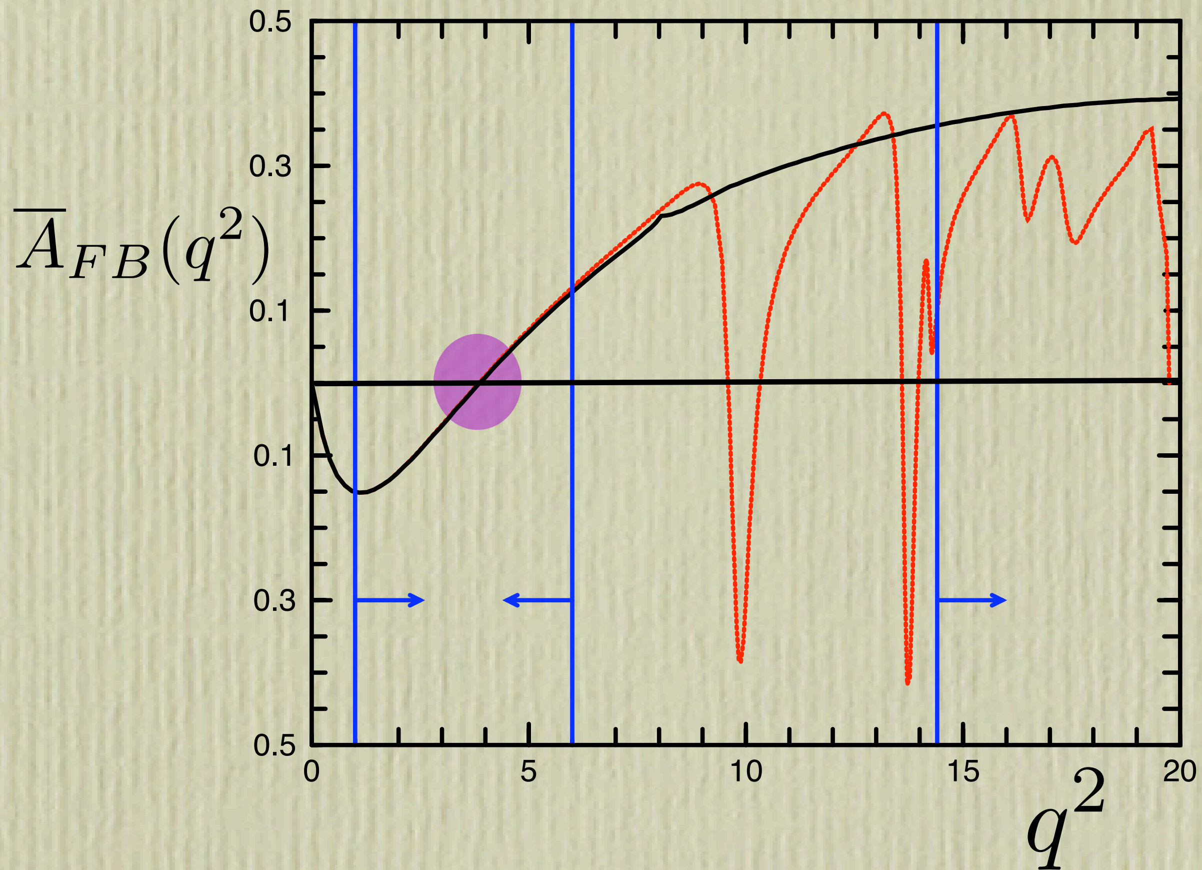
model for long-distance $c\bar{c}$ contributions Kruger, Sehgal

10% total theory error

eg. $\mathrm{BR}_{\ell\ell}\left(1\,\mathrm{GeV}^2 \le q^2 \le 6\,\mathrm{GeV}^2\right) =$

$$\left[1.574 \pm^{0.106}_{0.100}\,|_{M_t} \pm^{0.072}_{0.067}\,|_{m_b} \pm^{0.059}_{0.075}\,|_{\mathrm{scale}} \pm 0.045_C \pm 0.035_{\mathrm{BR}_{sl}} \pm^{0.001}_{0.013}\,|_{m_c}\right] \times 10^{-6}$$

$B \to X_s \ell^+ \ell^-$ NNLL Forward - Backward Asymmetry



Ghinculov, Hurth, Isidori, Yao

$$\overline{A}_{FB}(q^2) = \left[\frac{d\Gamma}{dq^2}\right]^{-1} \int_{-1}^{1} d\cos\theta \, \frac{d^2\Gamma}{dq^2 d\cos\theta} \, \mathrm{sign}(\cos\theta)$$

- Location of zero of the FB-Asymmetry tests the SM

$q_0^2 = (3.90 \pm 0.25)\,\mathrm{GeV}^2$ (Ghinculov et al.)

$q_0^2 = (3.76 \pm 0.22_{\mathrm{theory}} \pm 0.24_{m_b})\,\mathrm{GeV}^2$ (Bobeth et al.)

Not measured yet

Lattice QCD

Sources of Uncertainty

- statistics from Monte Carlo
- m_q, chiral extrapolation
- a, action discretization
- L, finite volume
- $(\alpha_s)^k$, perturbative matching
- $\frac{1}{m_Q}, a$ corrections in matching

(nf=2: unquenched u=d, quenched s)
(nf=2+1: unquenched u=d, & s)

Unquenched Simulations

Wilson [nf=2: CP-PACS, JLQCD, QCDSF, UKQCD, qq+q, SPQcdR]
[nf=2+1: CP-PACS / JLQCD]

- expensive, chiral symmetry only recovered as $a \to 0$

Domain-wall [nf=2: RBC]

- most expensive, exact chiral symmetry

Improved Staggered [nf=2+1: MILC]

- fast, residual chiral symmetry, but 4 "tastes" for each flavor

} valence/sea m_q's down to $0.1\, m_s$ ($m_\pi \simeq$ 260-320 MeV)

“4-th root trick” for Staggered Fermions

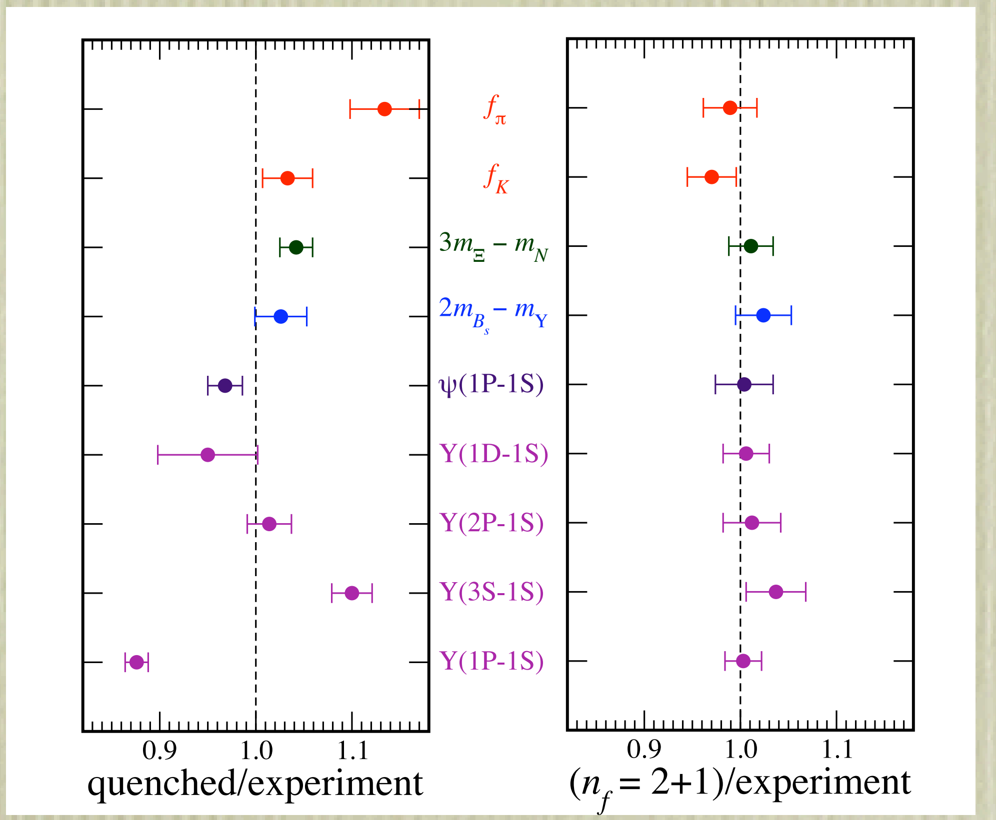
$\det(\not{D}+m) \to \det(\not{D}+m)^{1/4}$ removes bad tastes, but **Not Proven!**

not an issue in pert. QCD; some eigenvalue spectrum checks

Follana et al.
Durr et al.

warrants more serious attention
from friends and foes

(HPQCD, UKQCD, MILC, Fermilab ‘03)



- tested at 3% level by comparison with mass spectra & light meson decay constants
- common input parameters
  $m_\pi \to m_u = m_d, m_K \to m_s, m_{D_s} \to m_c,$
  $m_\Upsilon \to m_b, \quad m_\Upsilon - m_{\Upsilon'} \to \alpha_s(1/a)$
- effect of unquenched calculation is clear

I’ll assume that the fourth rooted staggered fermion is valid
This will be tested by other (nf=2+1) fermion formulations in the future

Focus on results submitted to me for Lepton Photon 2005

$\boxed{\alpha_s}$

recent results

HPQCD-UKQCD

Mason et al., hep-lat/0503005

- $n_f = 2+1$ sea quarks
- $\mathcal{O}(a^2)$ improved actions for both quarks and gluons

QCDSF-UKQCD

Gockeler et al., hep-ph/0502212

- $n_f = 2$ sea quarks
- down to $a \simeq 0.07\,\mathrm{fm}$

$\overline{\mathrm{MS}}$ scheme :

Lattice Quantified Errors

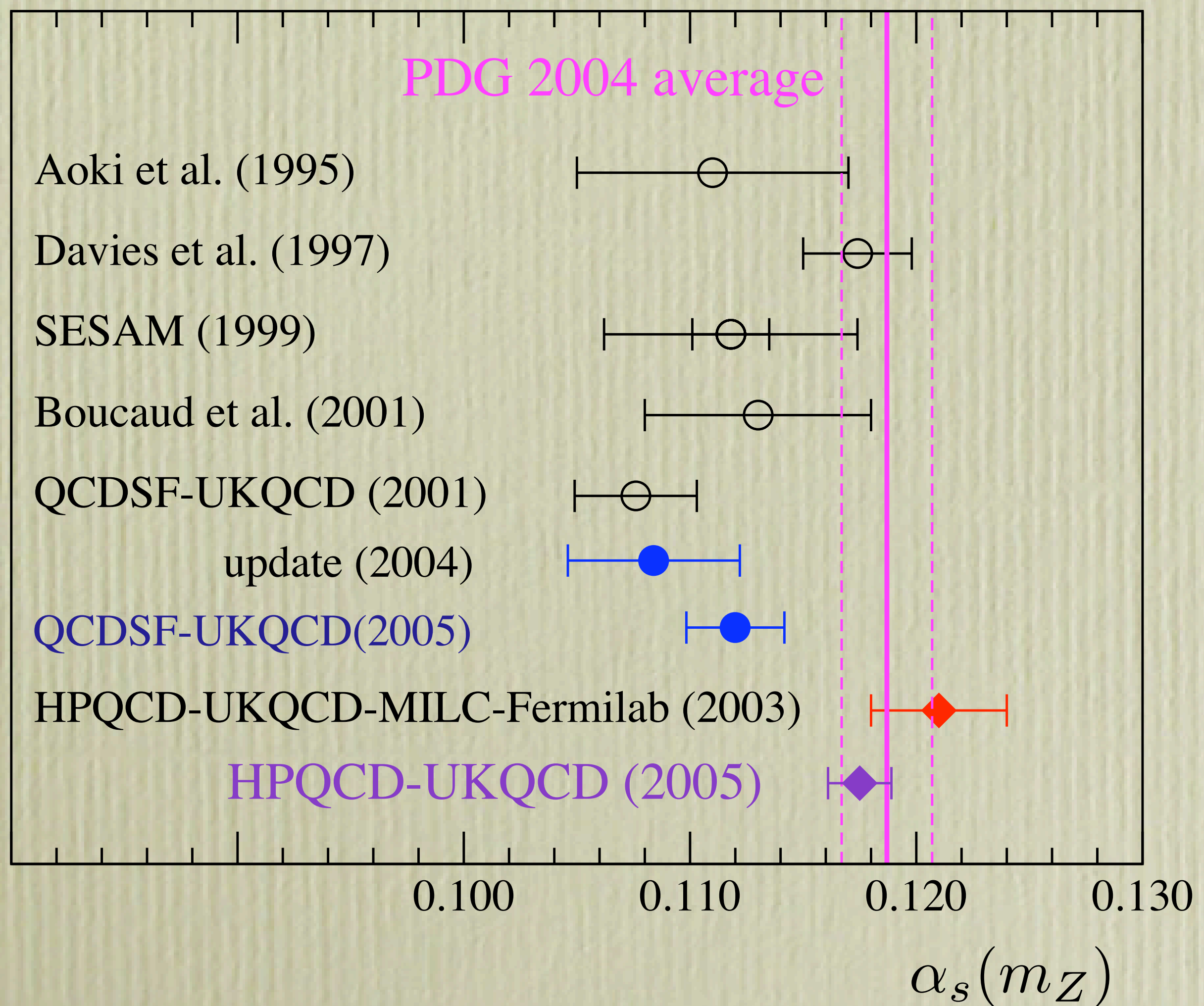
$$\alpha_s^{(5)}(m_Z) = 0.1120(22)$$ Gockeler et al.

$$\alpha_s^{(5)}(m_Z) = 0.1177(13)$$ Mason et al.

compare:

$$\alpha_s^{(5)}(m_Z) = 0.1187(20)$$

PDG 2004 World Avg.



$n_f = 2,$ 2-loop matching, Wilson

$n_f = 2+1,$ 2-loop matching, Staggered

$n_f = 2+1,$ 3-loop matching, Staggered

D-decays

$$D \to K\ell\bar{\nu}\ ,\quad D \to \pi\ell\bar{\nu}$$

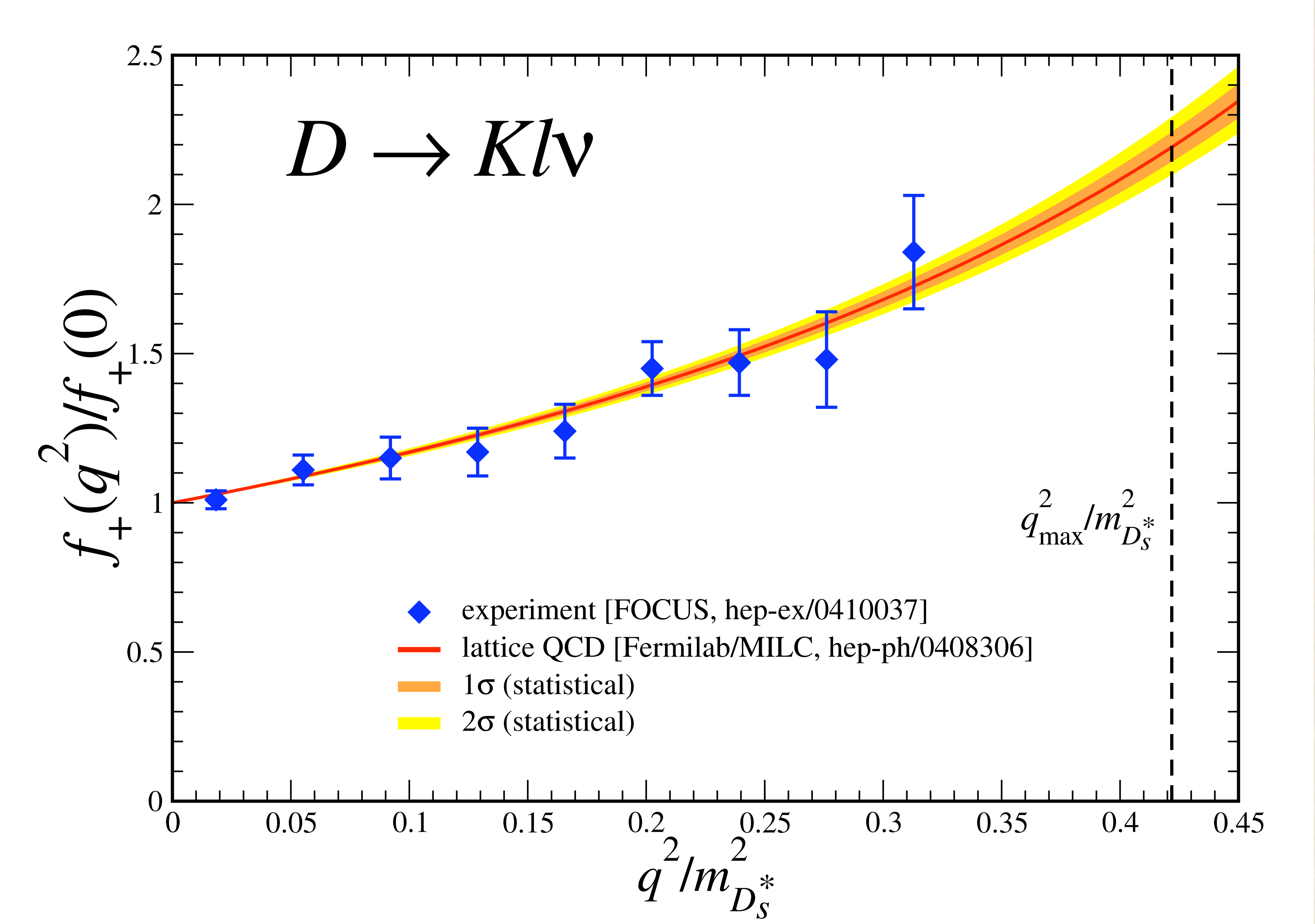
$c \to s(d)$

$$\langle K(p_K)|V^\mu|D(p_D)\rangle = f_+(q^2)\left(p_D^\mu + p_K^\mu - \frac{m_D^2 - m_K^2}{q^2}q^\mu\right) + f_0(q^2)\frac{m_D^2 - m_K^2}{q^2}q^\mu$$

- test of staggered fermion formalism
- FNAL / MILC / HPQCD prediction prior to FOCUS result

Shape agrees

chiral extrapolation uses staggered chiral perturbation theory (and compares Becirevic & Kaidalov model vs. quadratic parametrization for q^2)

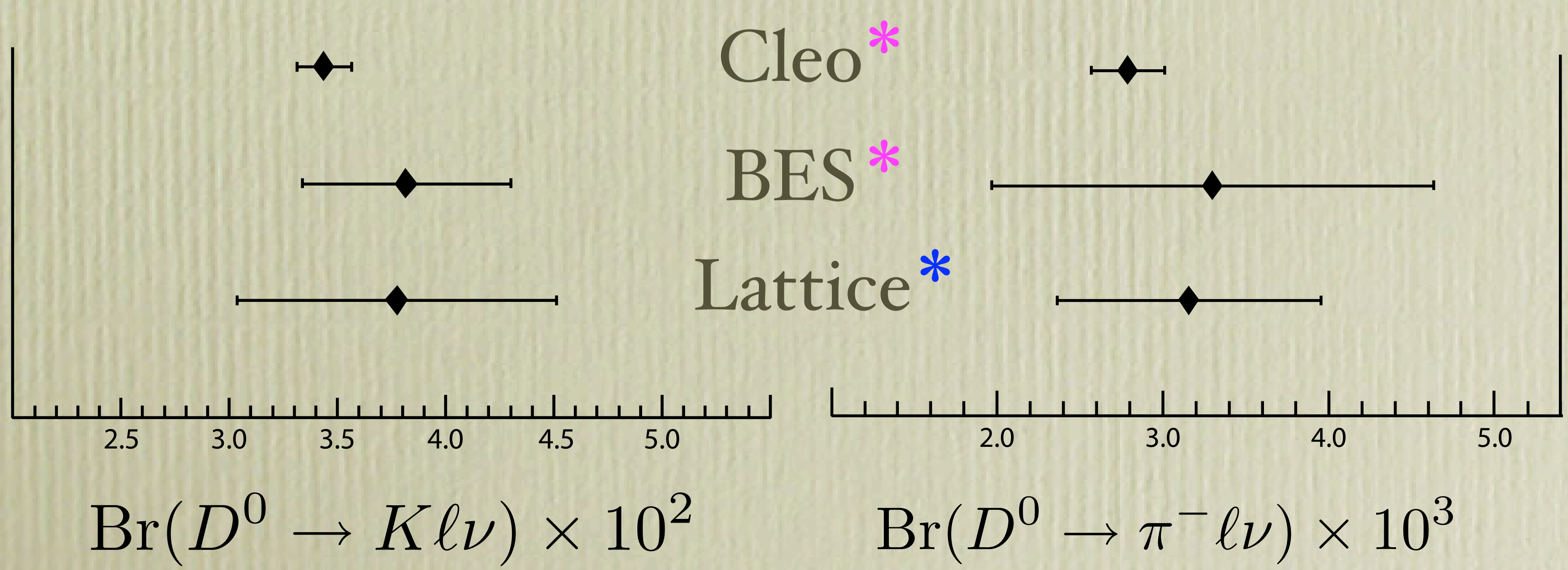


Note: Data not yet precise enough to clearly favor lattice over fits to 1 or 2 poles

Form Factor Normalization

	$f_+^{D\to K}(0)$	$\frac{f_+^{D\to\pi}(0)}{f_+^{D\to K}(0)}$
Lattice	0.73(3)(7)	0.87(3)(9)
CLEO-C		0.86(9)
BES	0.78(5)	0.93(20)
FOCUS		0.85(6)

Systematics	Fermilab/MILC/ HPQCD errors
matching	<1%
chiral extrapolation	2-3%
q^2 interp.	2%
finite a	9%
Total	10%



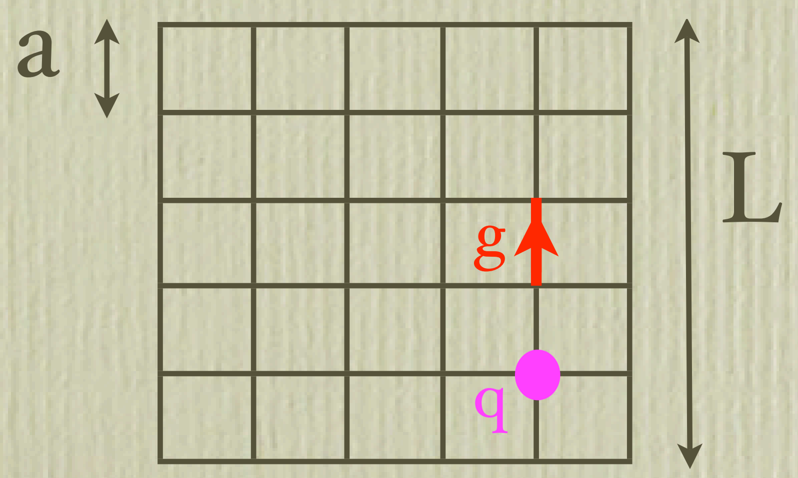
* LP'05 update

* with PDG |Vcs|, |Vcd|

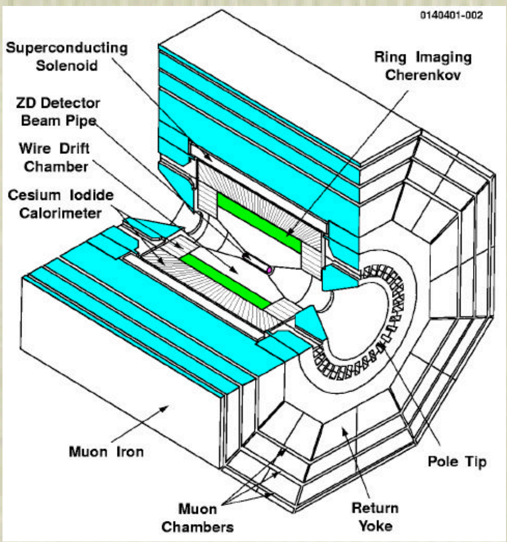
Normalization agrees!

The f_{D^+} Challenge !

Lattice QCD vs. CLEO-C



vs.



The f_{D^+} Challenge !

$$D^+ \to \mu^+ \nu_\mu \qquad \Gamma(D^+ \to \mu^+ \nu) = \frac{G_F^2 m_D}{8\pi} m_\mu^2 \left(1 - \frac{m_\mu^2}{m_D^2}\right)^2 f_{D^+}^2 |V_{cd}|^2$$

$$\langle 0|\bar{d}\gamma^\mu\gamma_5 c|D^+(p)\rangle = f_{D^+} p^\mu$$

	pre-LP'05	new at LP'05
CP-PACS (prelim.)	20%	$\sim$ 13%
Fermilab/MILC/HPQCD (hep-lat/0506030)	24%	$\sim$ 8%
CLEO-C	22%	$\sim$ 8%

Errors decreased
by factor of 3

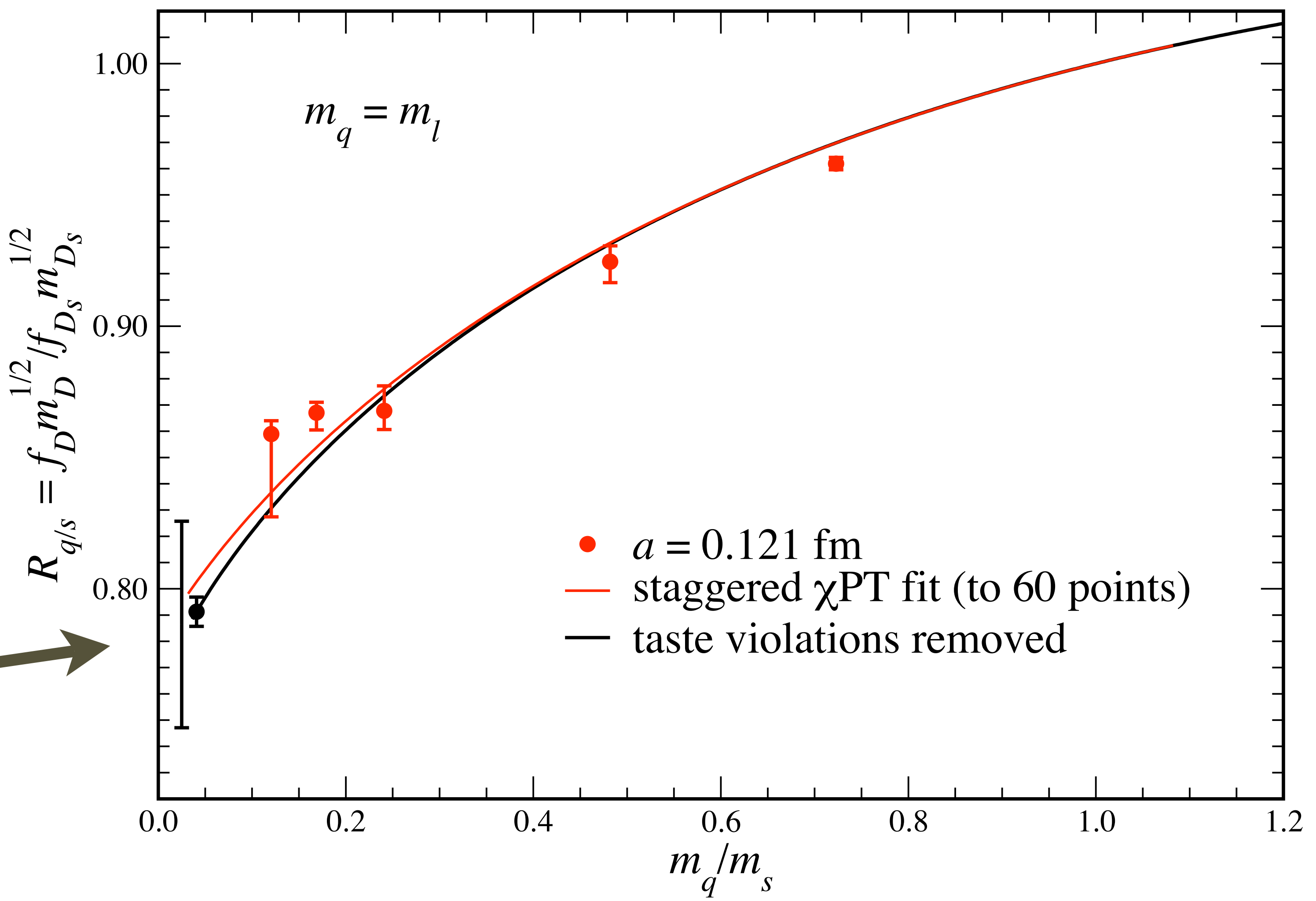
$\boxed{f_{D^+}}$ $n_f = 2+1$

Fermilab/MILC/HPQCD

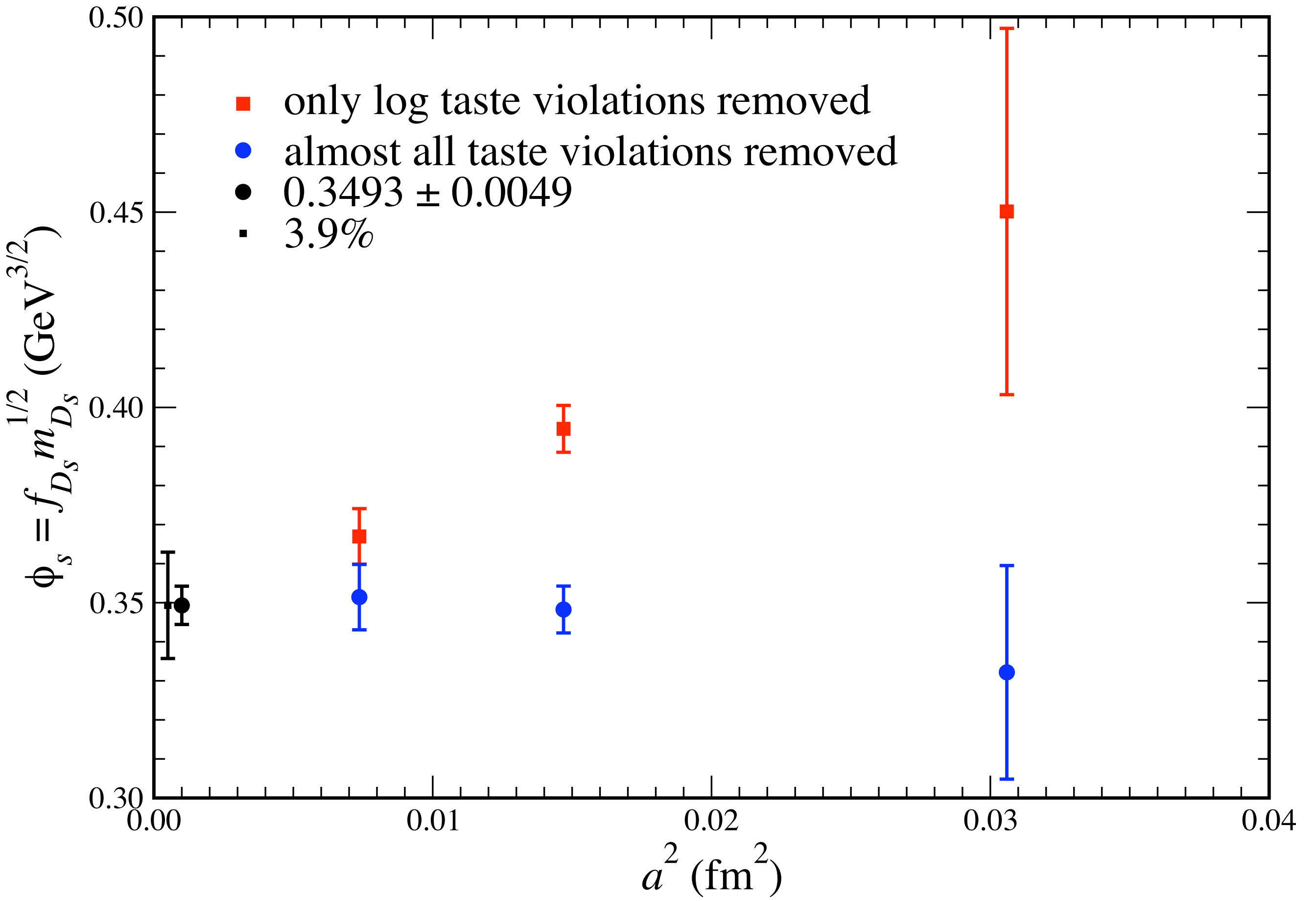
- A test for light quarks & the staggered formalism.

Use staggered ChPT analog of

$$\Delta f_D^{\text{chiral}\atop\log} = -\frac{3}{4}(1+3g^2)\frac{m_\pi^2}{(4\pi f)^2}\ln\frac{m_\pi^2}{\mu^2}$$



- Shift is caused by including the O(a^2) terms in non-log part of the chiral extrapolation (main reason for decrease from prelim. to final)

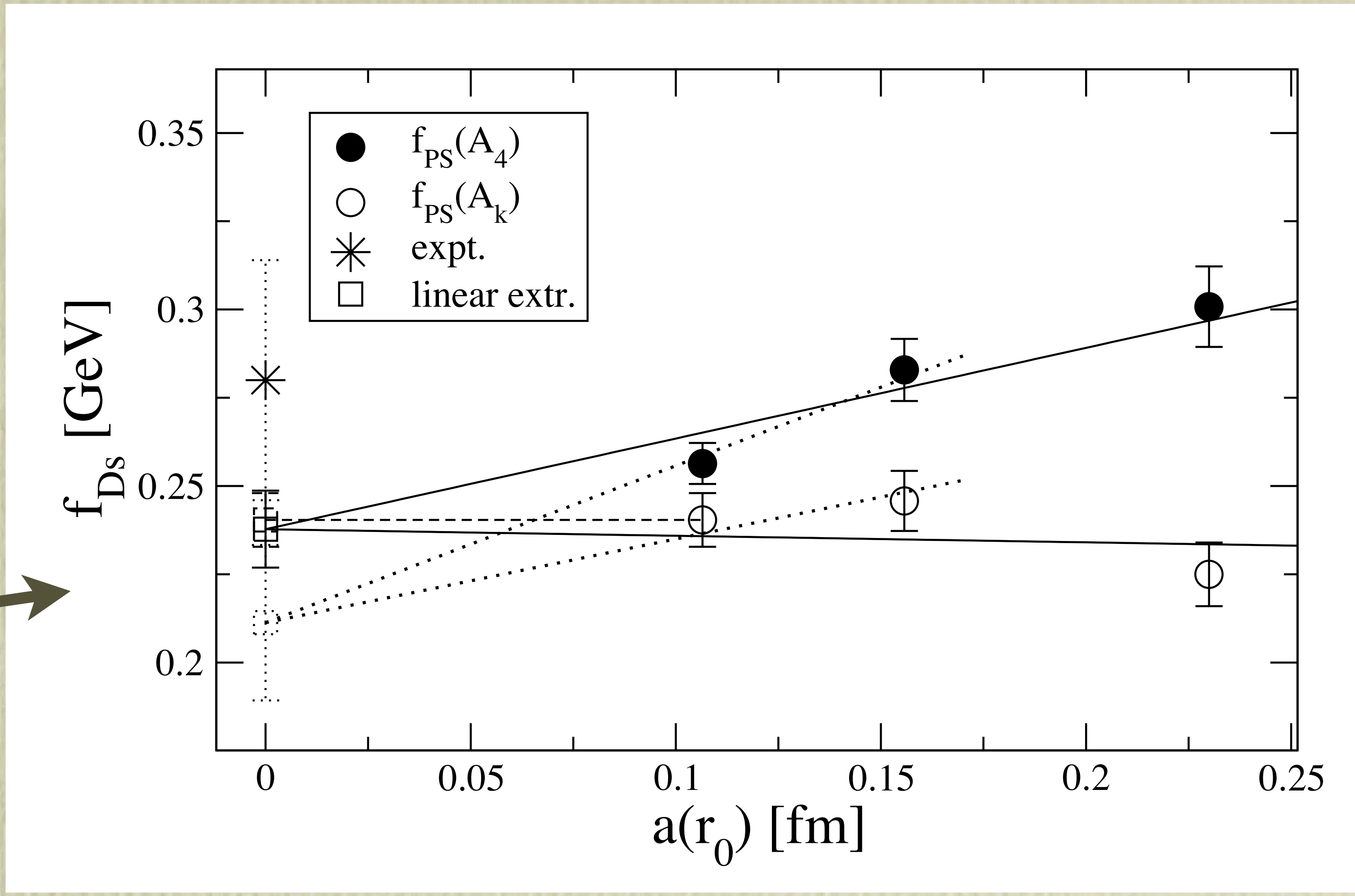


- Largest uncertainty is from light quark discretization & ChPT (but its only 6% !)

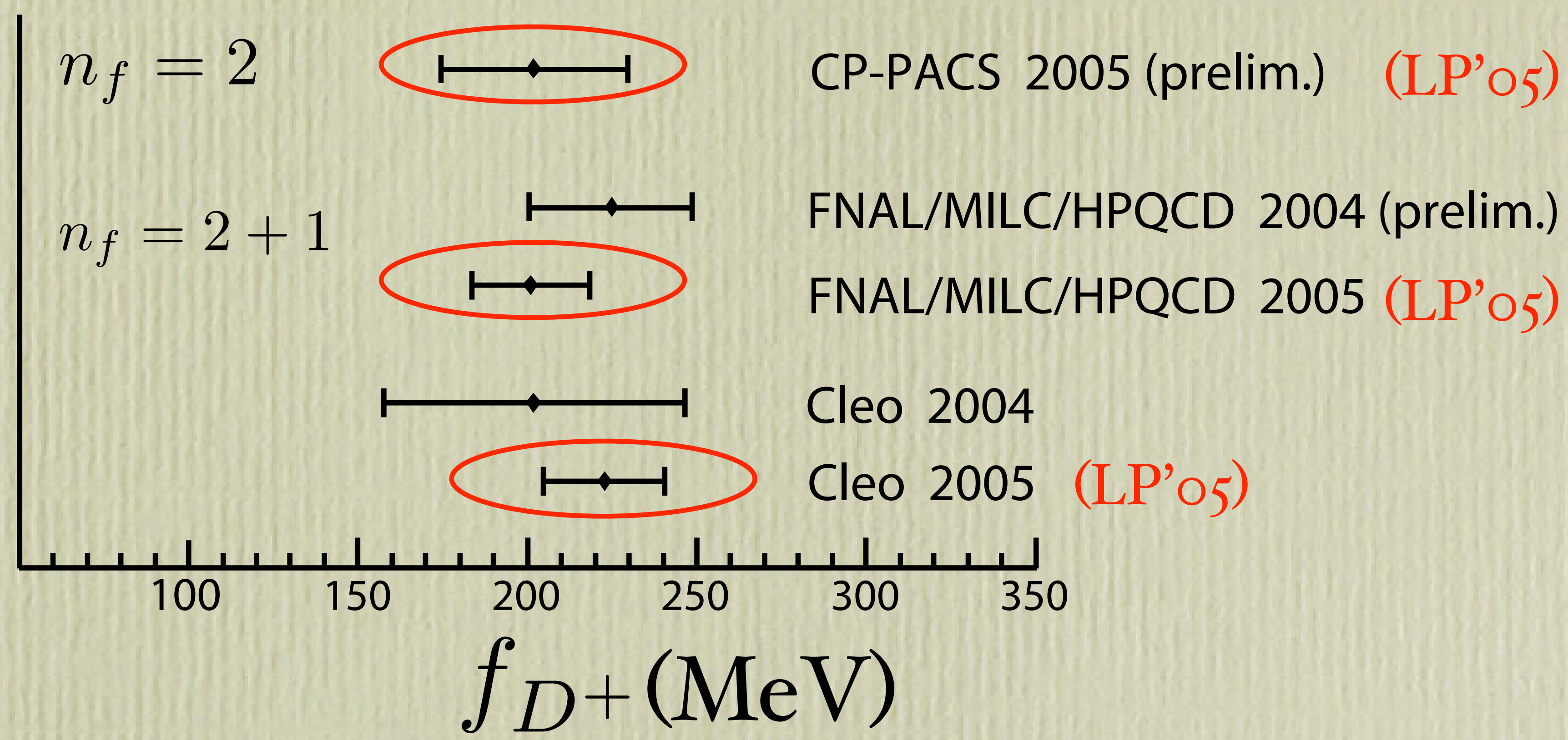
f_{D^+}

CP-PACS $\quad n_f = 2$

- Test of their heavy quark lattice formalism
- Largest uncertainty is from discretization



Results



$f_{D^+} = 202 \pm 12^{+20}_{-25}\,\mathrm{MeV}$

hep-lat/0506030

$f_{D^+} = 201 \pm 3 \pm 17\,\mathrm{MeV}$

$f_{D^+} = 223 \pm 16^{+7}_{-9}\,\mathrm{MeV}$

Good Agreement

Also new: $f_{D_s} = 238 \pm 11^{+46}_{-27}\,\mathrm{MeV}$ CP-PACS (prelim.)

$f_{D_s} = 249 \pm 3 \pm 16\,\mathrm{MeV}$ FNAL / MILC / HPQCD

hep-lat/0506030

$\boxed{f_B \;, f_{B_s}}$

no direct measurement yet (would need Vub)

$Br(B^+ \to \tau^+\nu_\tau) < 2.6 \times 10^{-4}(90\%)$ Babar (LP'05)

$Br(B^+ \to \tau^+\nu_\tau) < 1.8 \times 10^{-4}(90\%)$ Belle (LP'05)

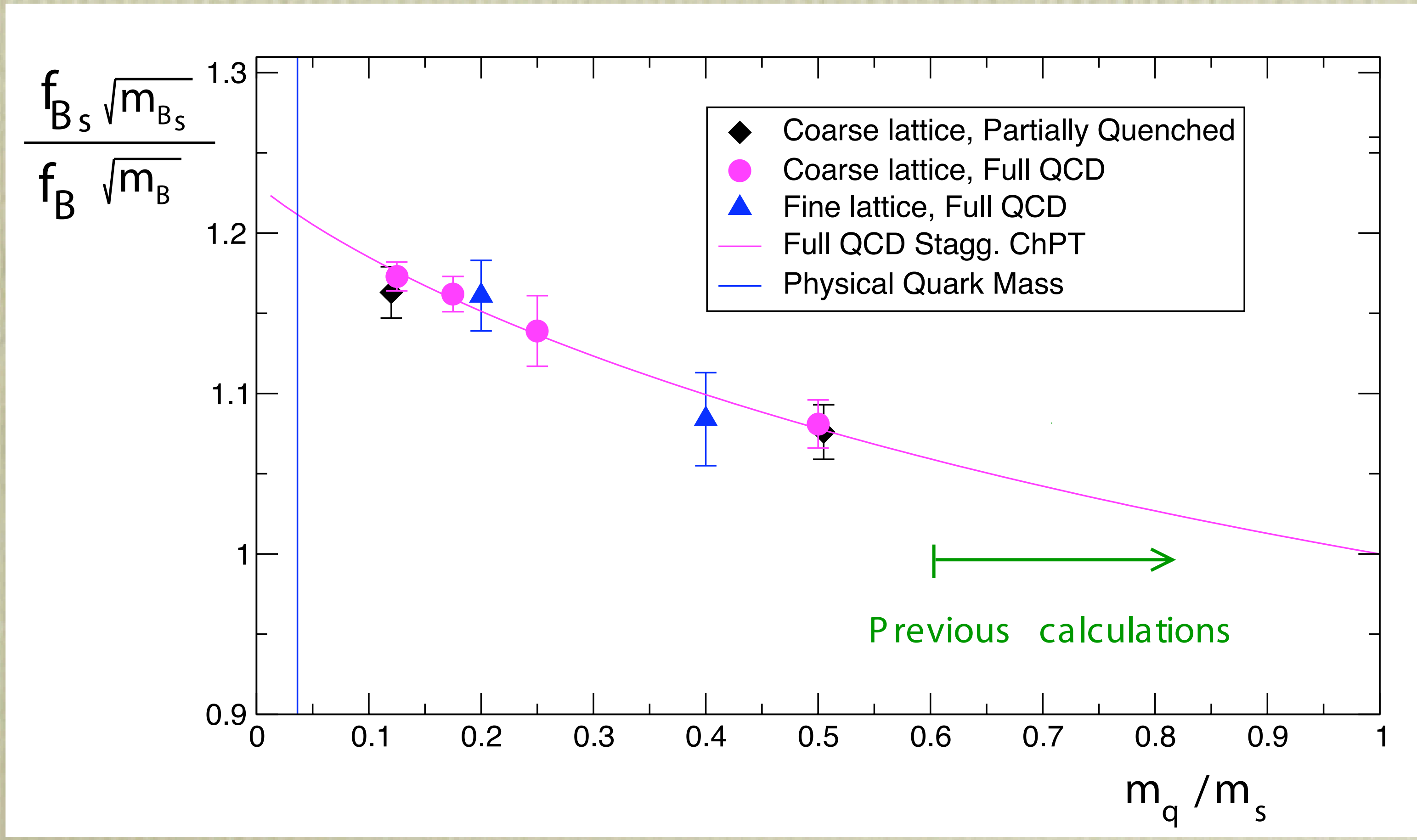
new LP'05 HPQCD results (preliminary, nf=2+1):

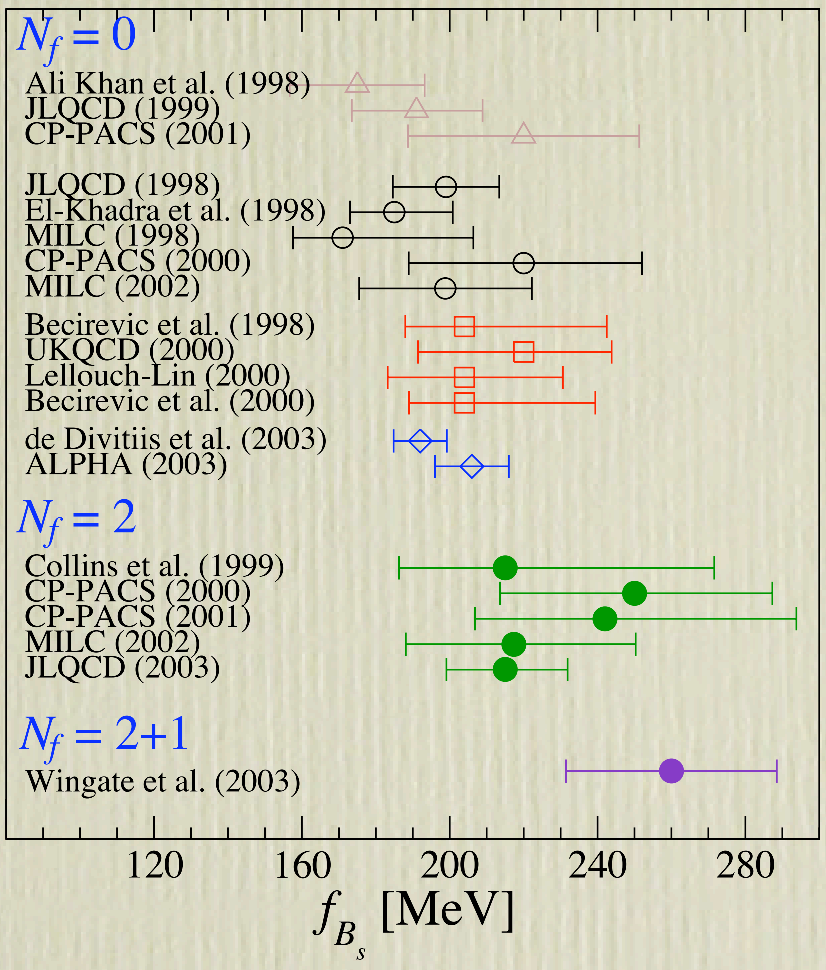
$$\frac{f_{B_s}}{f_B} = 1.20 \pm 0.02 \pm 0.01$$

$$f_B = (218 \pm 9 \pm 21)\ \mathrm{MeV}$$

- chiral extrap. + statistical + a
- α_s^2 is dominant systematic (9%), next is chiral extrap. (4%)

consistent with 2003: $f_{B_s} = (260 \pm 7 \pm 28)\ \mathrm{MeV}$





Δm_s & Δm_d Constraints with Unquenched LQCD

$$\Delta m_d = C_{\rm short}\, m_{B_d} f_B^2 \hat{B}_d\, |V_{td}V_{tb}^*|^2$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \underbrace{\frac{f_B^2}{f_{B_s}^2}}_{\xi^2} \frac{\hat{B}_d}{\hat{B}_s} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$\propto [(1-\bar{\rho})^2 + \bar{\eta}^2]$

use: $\frac{f_{B_s}}{f_B}$ & f_B (HPQCD'05, prelim.,stag.)

with

JLQCD ('03) $\hat{B}_d = 1.271(41)(^{+85}_{-94})$

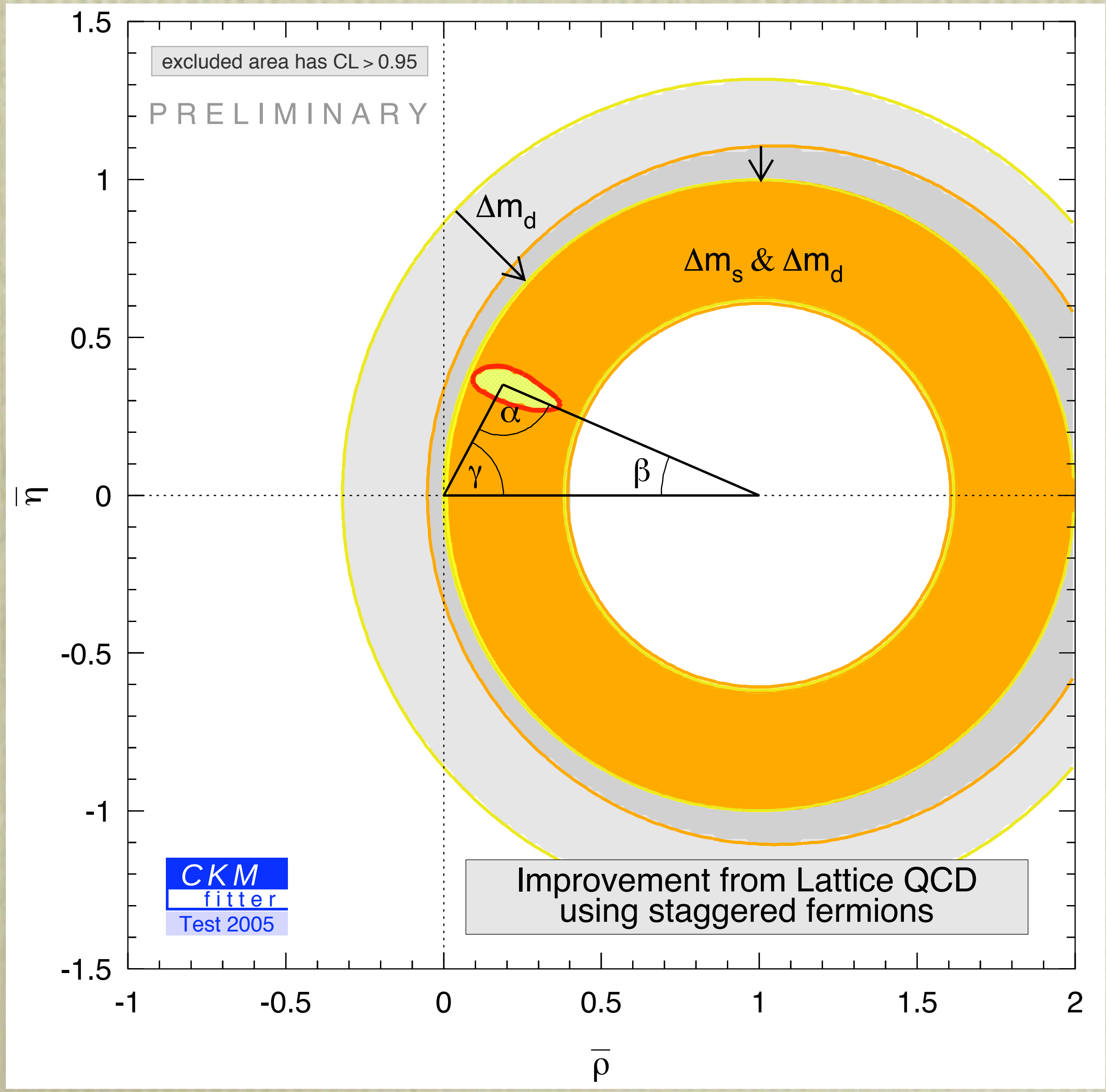
$n_f = 2$ $\frac{\hat{B}_d}{\hat{B}_s} = 1.017(16)(^{+56}_{-17})$

Wilson

$$\xi = 1.21 \pm 0.022^{+0.035}_{-0.014}$$

$$f_B\sqrt{\hat{B}_d} = (246 \pm 11 \pm 25)\ \text{MeV}$$

$$f_{B_s}\sqrt{\hat{B}_s} = (296 \pm 9 \pm 33)\ \text{MeV}$$



- Δm_d : Improvement is from increased central value and decreased statistical error

$$|V_{td}|^2 \propto \frac{1}{f_B^2}$$

good topic for further discussion at Lattice 2005

Δm_s & Δm_d Constraints with Unquenched LQCD

$$\Delta m_d = C_{\rm short}\, m_{B_d} f_B^2 \hat{B}_d\, |V_{td}V_{tb}^*|^2$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \underbrace{\frac{f_B^2}{f_{B_s}^2} \frac{\hat{B}_d}{\hat{B}_s}}_{\xi^2} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\propto [(1-\bar{\rho})^2 + \bar{\eta}^2]$$

use $\frac{f_{B_s}}{f_B}$ & f_B with

JLQCD ('03) $\hat{B}_d = 1.271(41)(^{+85}_{-94})$

$n_f = 2$ $\frac{\hat{B}_d}{\hat{B}_s} = 1.017(16)(^{+56}_{-17})$

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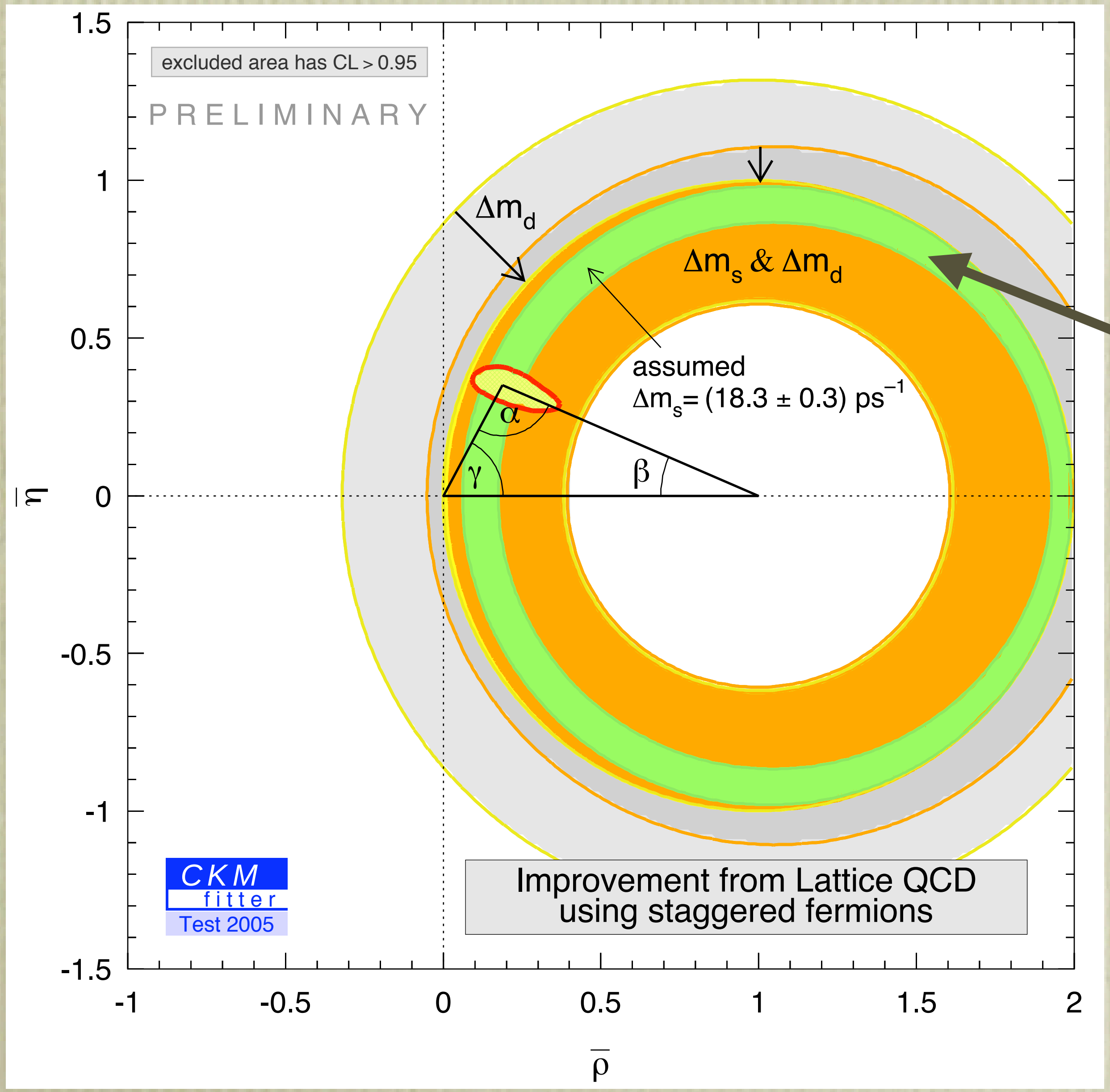
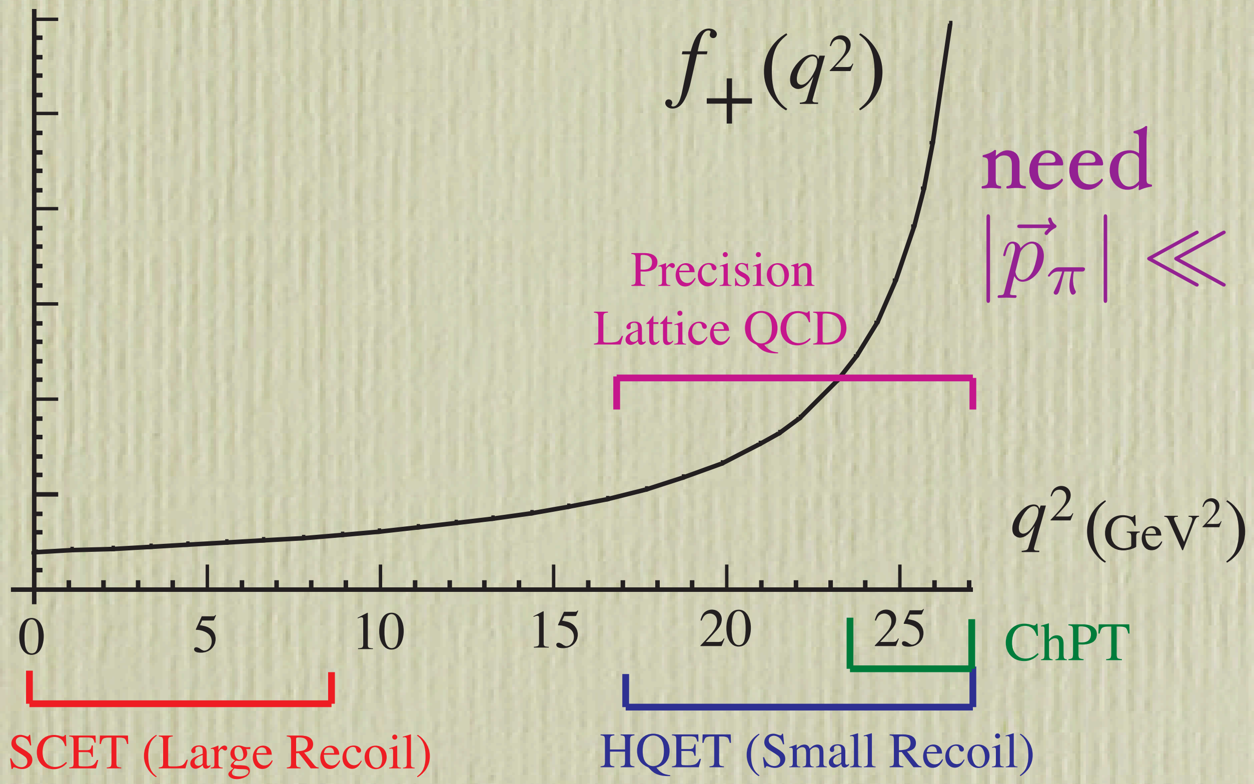


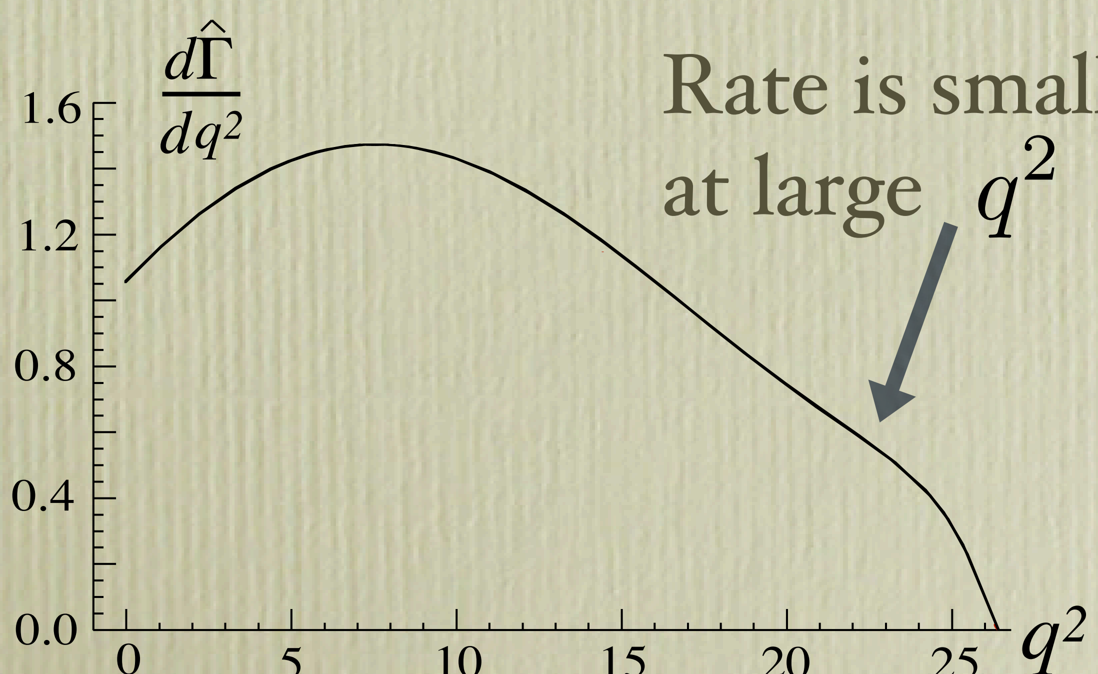
Assume Δm_s was measured.

New lattice errors on ξ reduced the width of the green band by $\sim 50\%$

V_{ub} $\quad B \to \pi \ell \bar{\nu}$

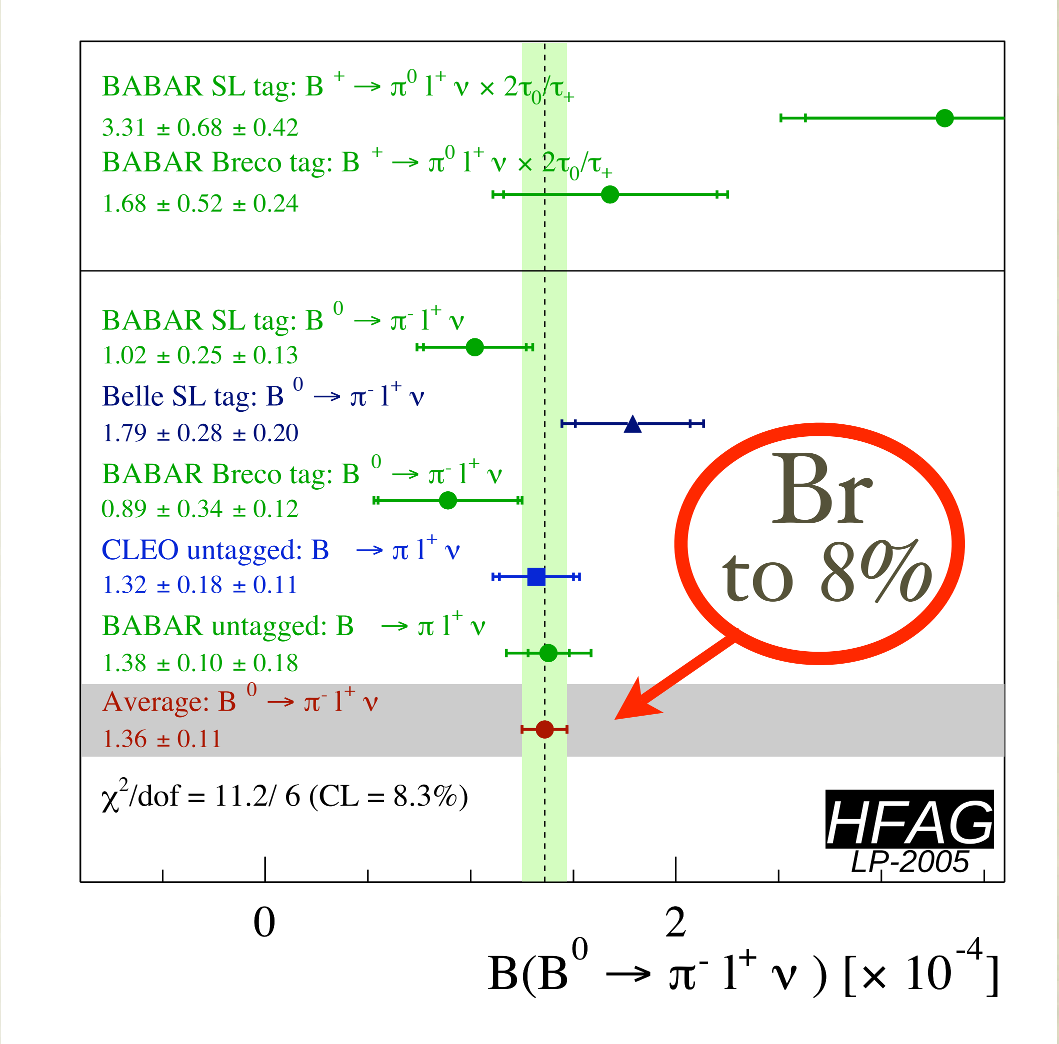


need $|\vec{p}_\pi| \ll 1/a$



Rate is smaller at large q^2

Average from Cleo, Belle, Babar:



$\Rightarrow$ $|V_{ub}|$ to 4% !?!

Uncertainty from theory dominates.

$$\frac{d\Gamma(\bar{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 \, |f_+(q^2)|^2$$

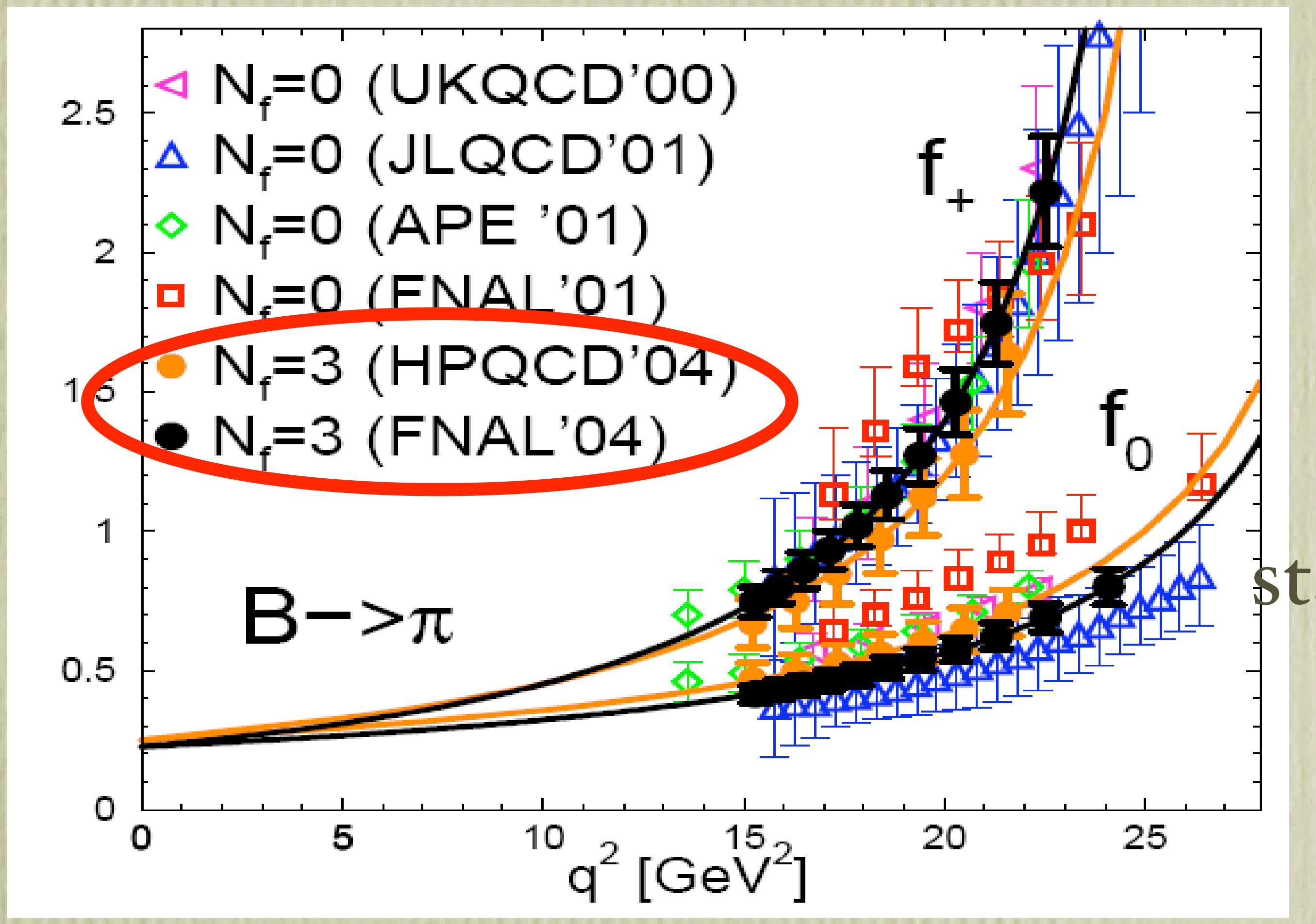
Method 1: Model Independent

Pure Lattice QCD

$q^2 \geq 16\,\text{GeV}^2$

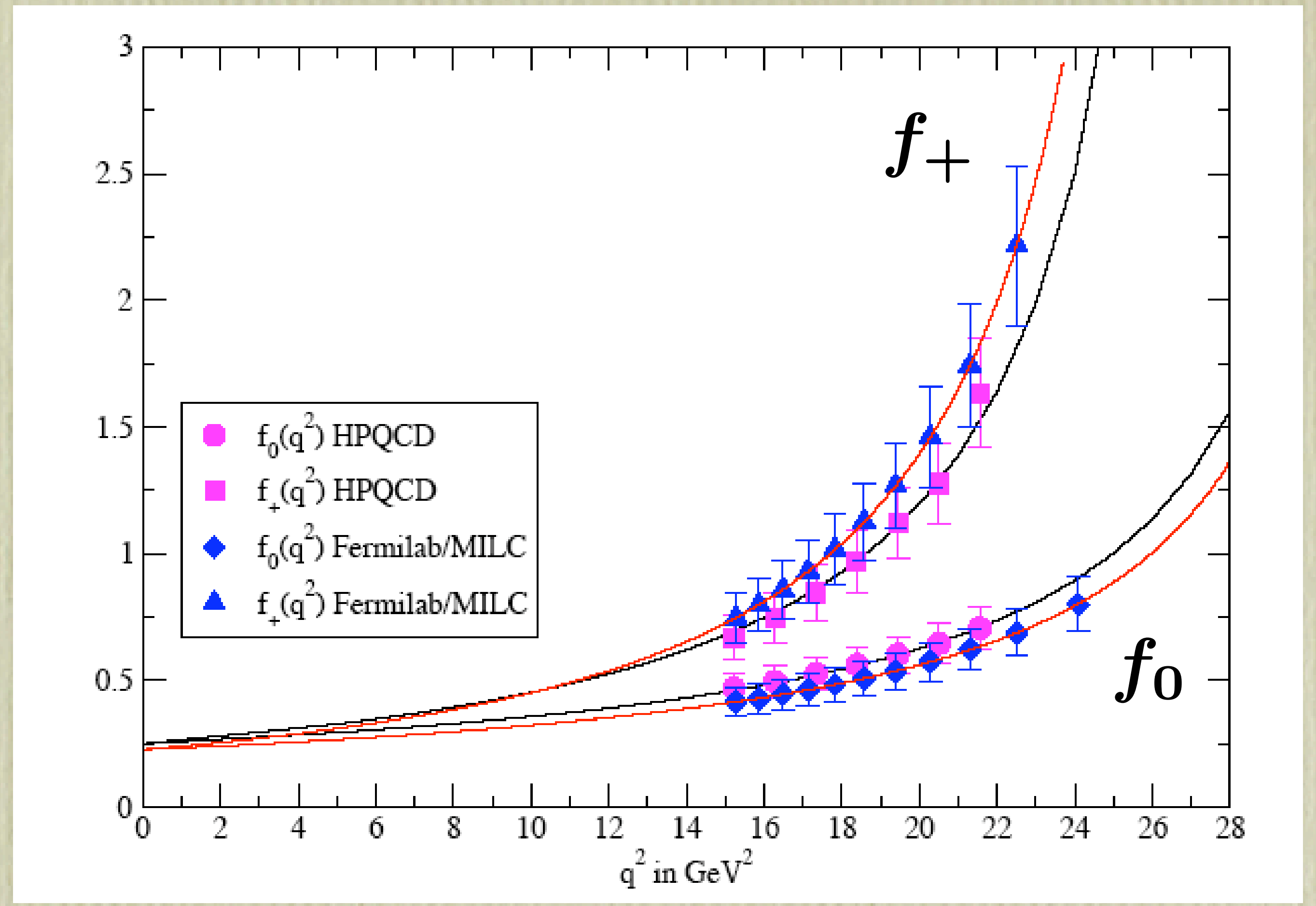
statistics 4-6%

Systematics	HPQCD errors
perturbative matching	9%
chiral extrapolation	4%
action discretization	2%
matching $a, 1/m_Q$	5%
Total	11%



statistics

Systematics	Fermilab/ MILC errors
matching	1%
chiral extrapolation	4%
q^2 interp.	4%
finite a	9%
Total	11%



statistics
4-6%

Systematics	HPQCD errors
perturbative matching	9%
chiral extrapolation	4%
action discretization	2%
matching $a, 1/m_Q$	5%
Total	11%

statistics
$\sim 8\%$

Systematics	Fermilab/ MILC errors
matching	1%
chiral extrapolation	4%
q^2 interp.	4%
finite a	9%
Total	11%

$q^2 \geq 16\,\mathrm{GeV}^2$

HFAG LP'05 expt. theory

$10^3 \times |V_{ub}| = 3.75 \pm 0.27^{+0.64}_{-0.42}$ FNAL

$10^3 \times |V_{ub}| = 4.45 \pm 0.32^{+0.69}_{-0.47}$ HPQCD

My Average for this method:

$10^3 \times |V_{ub}| = 4.1 \pm 0.32^{+0.69}_{-0.42}$

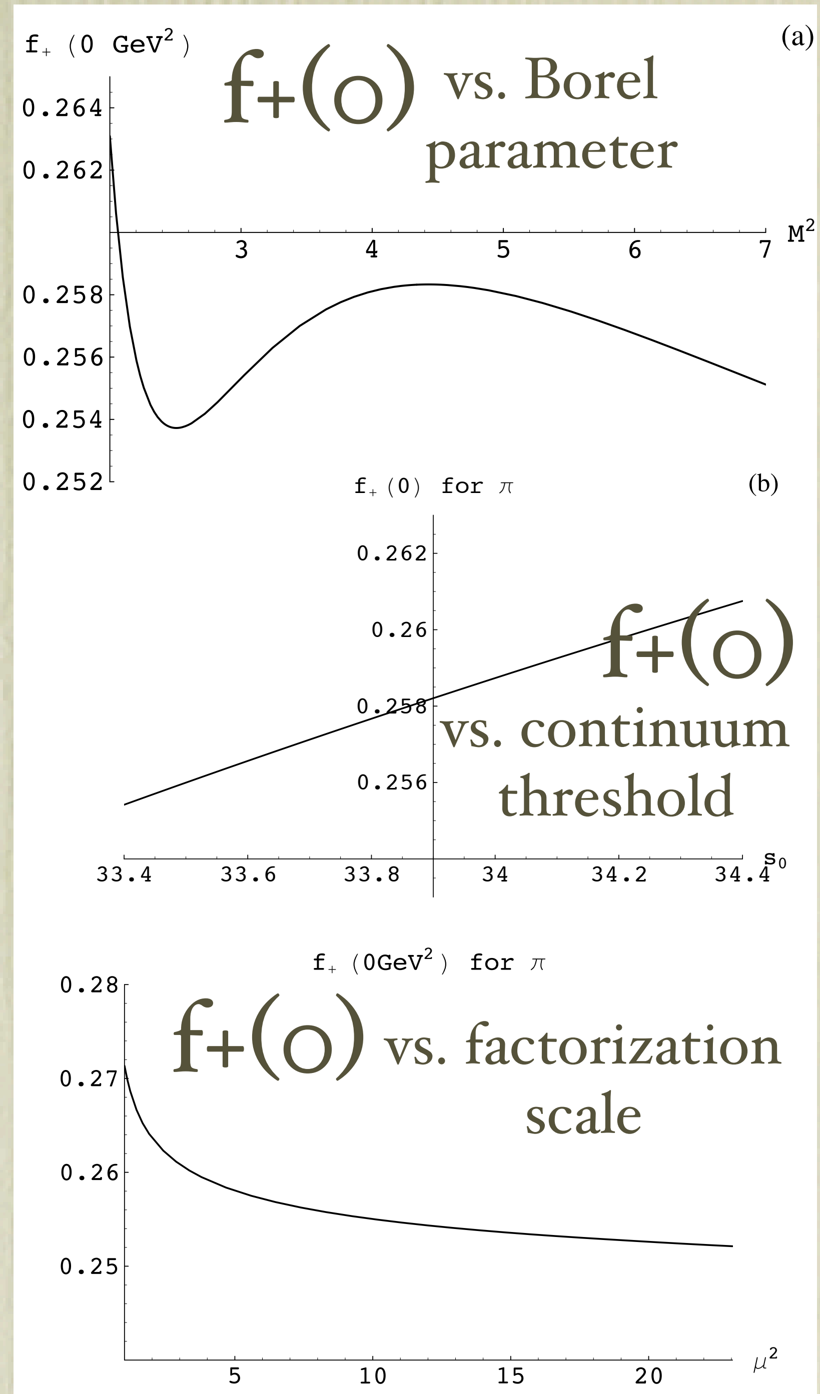
16%
total error

Method II:

Braun et al.
Colangelo, Khodjamirian,
Ball, Zwicky

Light-cone QCD sum-rules

compute form factors for small q^2



Error Analysis for $f_+(0)$ Ball, Zwicky

$$f_+(0) = 0.258 \pm 0.031$$

Babar (LP'05) $q^2 < 16\,\mathrm{GeV}^2$

expt. theory

$$10^3 \times |V_{ub}| = 3.27 \pm \underline{0.25}\, \underline{{}^{+0.54}_{-0.37}}$$

16% total error

Method III:

Model Independent

Lattice & QCD Dispersion Relations

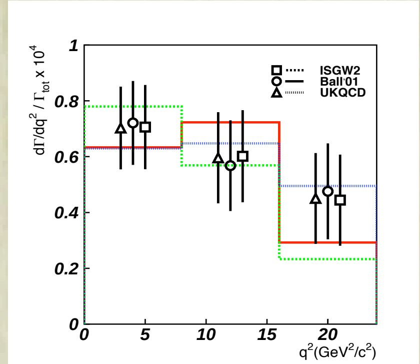
Bourrely et al.,
Boyd, Grinstein, Lebed, Savage;
Lellouch; Fukunaga, Onogi;
Arnesen, Grinstein, Rothstein, I.S.

i) Lattice qcd results at large q^2

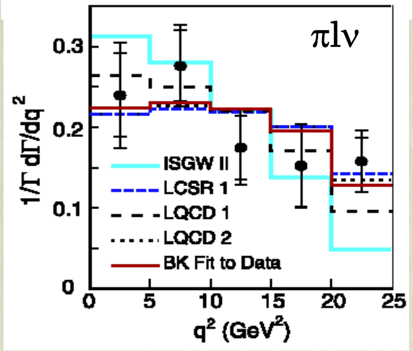
ii) expt. spectra for information at low q^2
(Babar updated at LP'05)

iii) QCD dispersion relations to constrain the form factors shape

Belle



Babar



unknowns

$t = q^2$

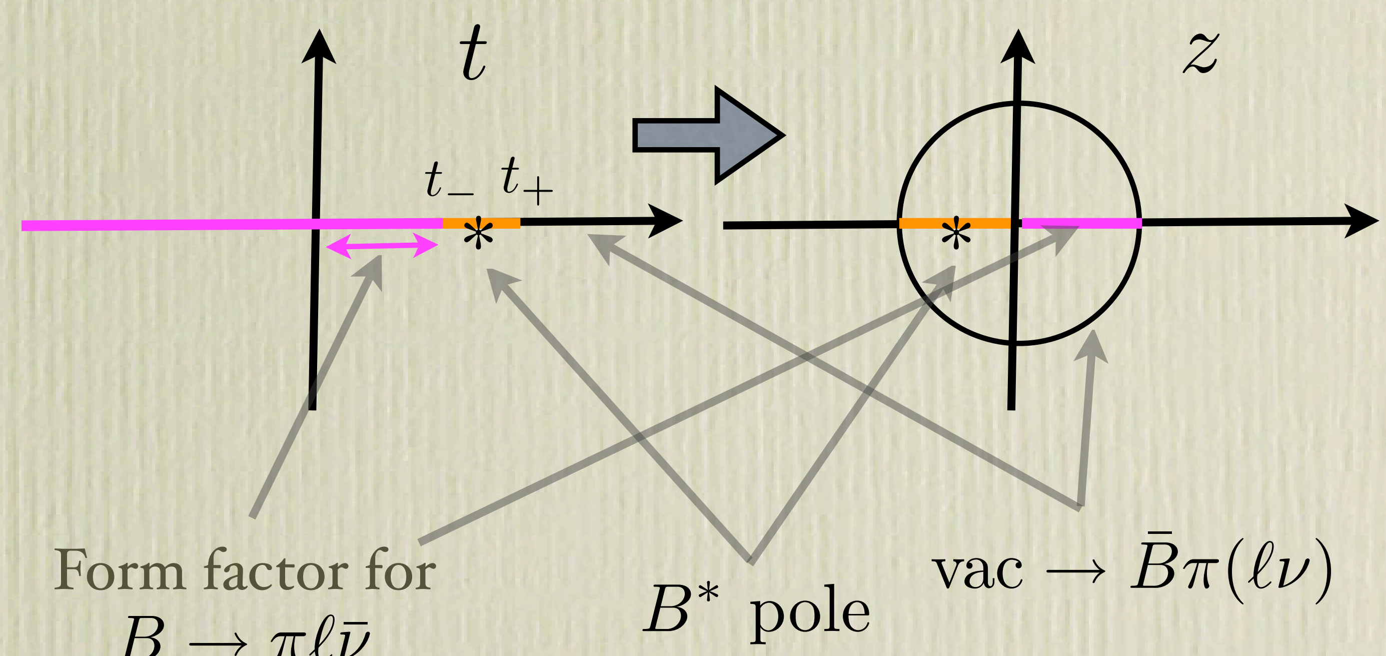
$$\boxed{f_+(t) = \frac{1}{P(t)\phi(t)} \sum_{n=0}^{\infty} a_n\, z^n}$$

$z = z(t)$

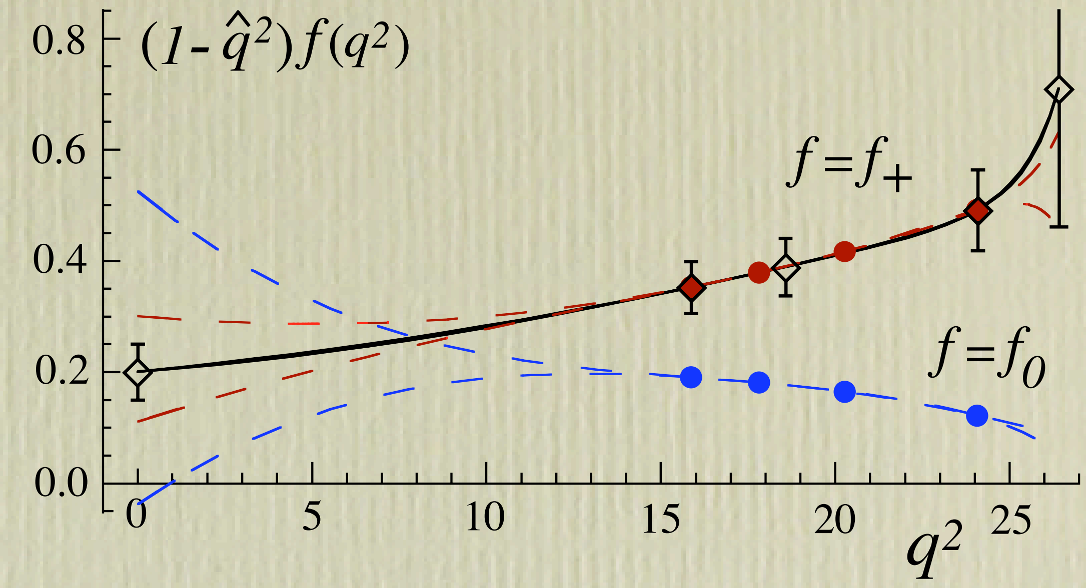
$-0.34 \leq z \leq 0.22$

$\sum_n a_n^2 \leq 1$

convergent



- Dispersion relations show there is a lot of freedom for a pure extrapolation of lattice data



Arnesen et al.

χ^2 fits to data & lattice with dispersion relations

$\chi^2/(dof) \sim 1.0$ expt. & theory

Type of Error	Variation From	$\delta\lvert V_{ub}\rvert^{q^2}$
Input Points	1-σ correlated errors	$\pm 13\%$
Bounds	F_+ versus F_-	$< 1\%$
$m_b^{\rm pole}$	4.88 ± 0.40	$< 1\%$
OPE order	2 loop $\to$ 1 loop	$< 1\%$

$10^3 \times \lvert V_{ub}\rvert = 3.72 \pm 0.52$ FNAL

$10^3 \times \lvert V_{ub}\rvert = 4.11 \pm 0.52$ HPQCD

fit also gives: $f_+(0) = 0.25 \pm 0.06$ like sum-rules

My Average for this method:

$$10^3 \times \lvert V_{ub}\rvert = 3.92 \pm 0.52$$

13% total error (4% expt.)

$$\lvert V_{ub}\rvert^{\rm incl} = (4.39 \pm 0.34) \times 10^{-3}$$

(HFAG LP'05)

$$\lvert V_{ub}\rvert^{\text{treated as output}}_{\text{in global CKM}} = (3.53^{+0.22}_{-0.21}) \times 10^{-3}$$

(CKMfitter LP'05)

Note that this includes the information in the pure lattice method

Nonleptonic Decays

Motivation Going Forward

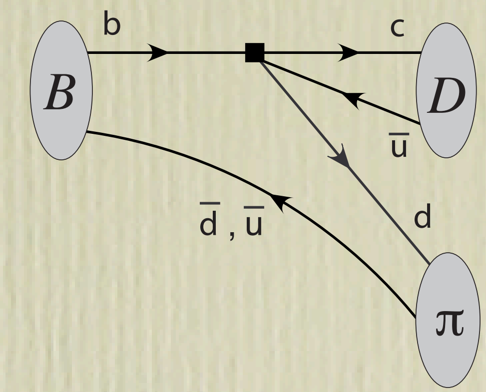
- So far we've been talking about precision theory $\lesssim 10\%$
- Now we will turn to cases where the expansion is worse,
  $\sim 20\%(?)$
- But the odds are higher ! We can look for new physics in many channels, where the sensitivity appears in different ways.
- Need to know what the SM expectation is for Br and CP-Asymmetries

$$\boxed{\bar{B}^0 \to D^0 M^0}$$

Testing Factorization and SCET

Mantry, Pirjol, I.S.
Blechman et al.

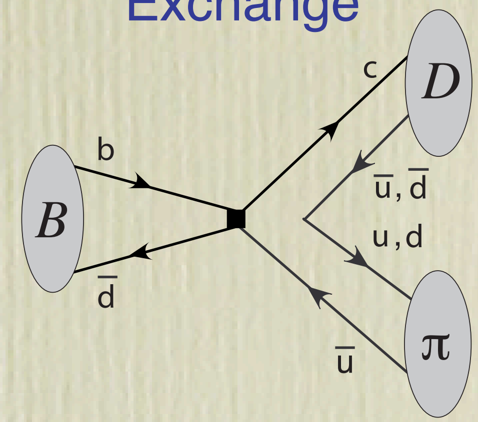
"Color suppressed"



$$A_{00}^{D^{(*)}\pi} = N_0^{(*)} \int dx\, dz\, dk_1^+ dk_2^+\, T^{(i)}(z)\, J^{(i)}(z, x, k_1^+, k_2^+)\, S^{(i)}(k_1^+, k_2^+)\, \phi_\pi(x)$$
$$+ A_{\rm long}^{D^{(*)}\pi}$$

$\frac{\Lambda}{E_M}$ & $\frac{1}{N_c}$ suppressed

"Exchange"



Predict

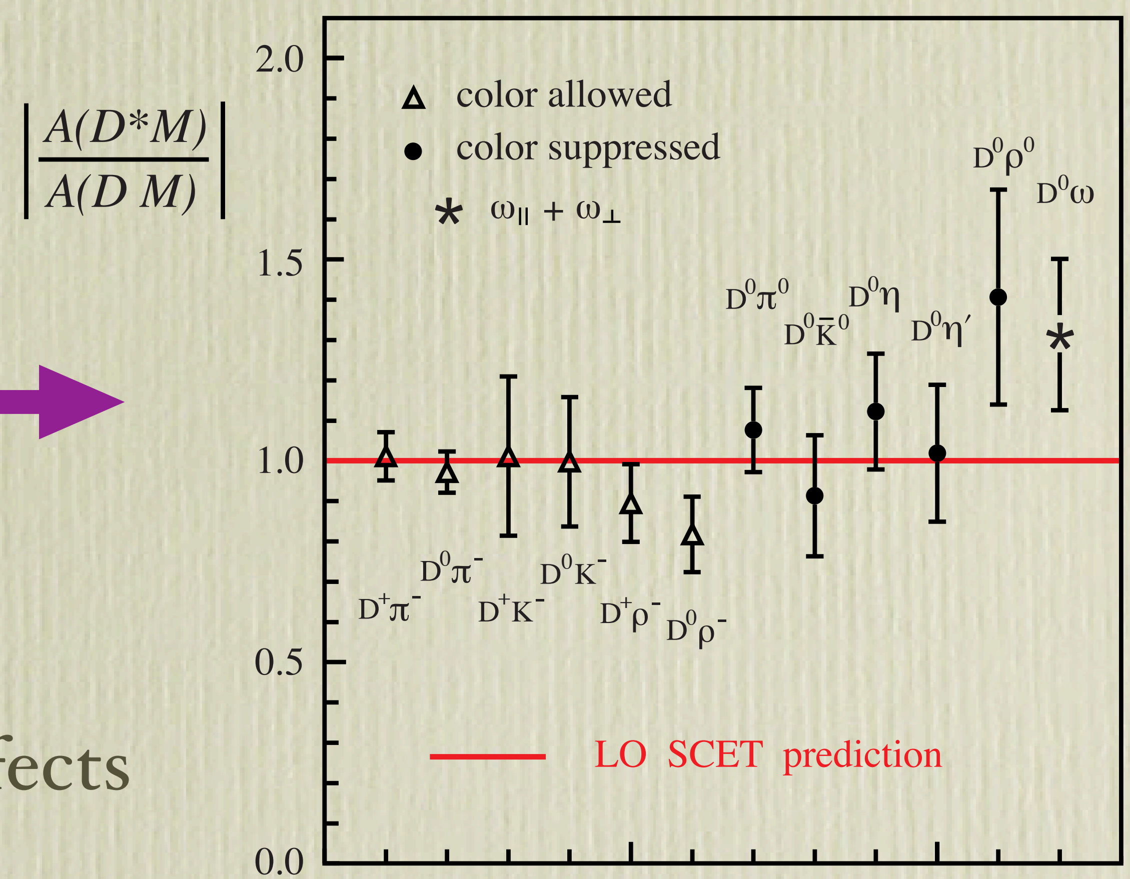
equal strong phases $\delta(DM) = \delta(D^* M)$

equal amplitudes $A(D^* M) = A(DM)$

Find

$$\delta(D\pi) = 30.4 \pm 4.8^\circ$$
$$\delta(D^*\pi) = 31.0 \pm 5.0^\circ$$

and



Without factorization

predictions spoiled by $\mathcal{O}\left(\frac{E_M}{m_c}\right) = \mathcal{O}(1)$ effects

$\boxed{B \to M_1 M_2}$

$C_1 > C_2, C_{7\gamma}, C_{8g} \gg C_{4,6} > C_{3,5,9,10} > C_{7,8}$

Methods

- SU(2), isospin symmetry $\frac{m_{u,d}}{\Lambda} \simeq 0.02$ many authors classic: Gronau, London
- SU(3), isospin symmetry $\frac{m_s}{\Lambda} \simeq 0.3$ many authors Rosner, Lipkin, ...
- Factorization $\Lambda^2 \ll E\Lambda \ll E^2, m_b^2$

Beneke, Buchalla, Neubert, Sachrajda

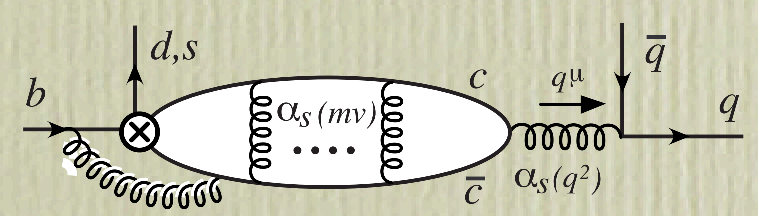
corrections $\sim 20\%$

not great precision, but sufficient for large new physics signals (and improvable)

Chay, Kim

Bauer, Pirjol, Rothstein, I.S.

sizeable charm loops?



Ciuchini et al, Colangelo et al

$k_\perp$ Factorization

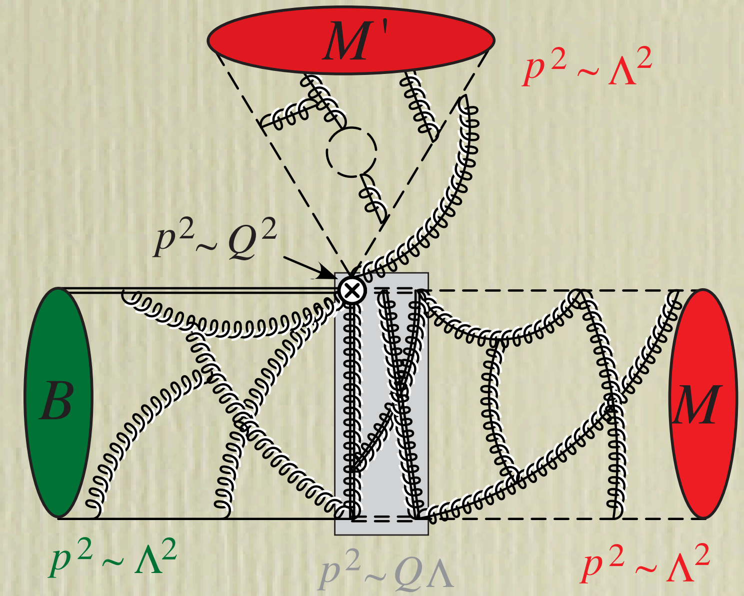
Keum, Li, Sanda, Lu et al.

Large Annihilation

$C_1 \frac{\Lambda}{E}$ competes

(appears to be a good model for soft physics)

Factorization (with SCET)



Factorization at m_b

Bauer, Pirjol, Rothstein, I.S.

Nonleptonic $B \to M_1 M_2$

$$A(B \to M_1M_2) = A^{c\bar{c}} + N\left\{ f_{M_2}\zeta^{BM_1}\int du\, T_{2\zeta}(u)\phi^{M_2}(u) + f_{M_2}\int du dz\, T_{2J}(u,z)\zeta_J^{BM_1}(z)\phi^{M_2}(u) + (1 \leftrightarrow 2)\right\}$$

Form Factors $B \to$ pseudoscalar: $f_+,\ f_0,\ f_T$
$B \to$ vector: $V,\ A_0,\ A_1,\ A_2,\ T_1,\ T_2,\ T_3$

$$f(E) = \int dz\, T(z,E)\,\zeta_J^{BM}(z,E)$$ } "hard spectator", "factorizable"

$$+\ C(E)\,\zeta^{BM}(E)$$ } "soft form factor", "non-factorizable"

universality at $E\Lambda$

Factorization at $\sqrt{E\Lambda}$

expansion in $\alpha_s(\sqrt{E\Lambda})$

$$\zeta_J^{BM}(z) = f_M f_B \int_0^1 dx \int_0^\infty dk^+ J(z,x,k^+,E)\phi_M(x)\phi_B(k^+)$$

$\zeta^{BM} = ?$ (left as a form factor)

Beneke, Feldmann
Bauer, Pirjol, I.S.
Becher, Hill, Lange, Neubert

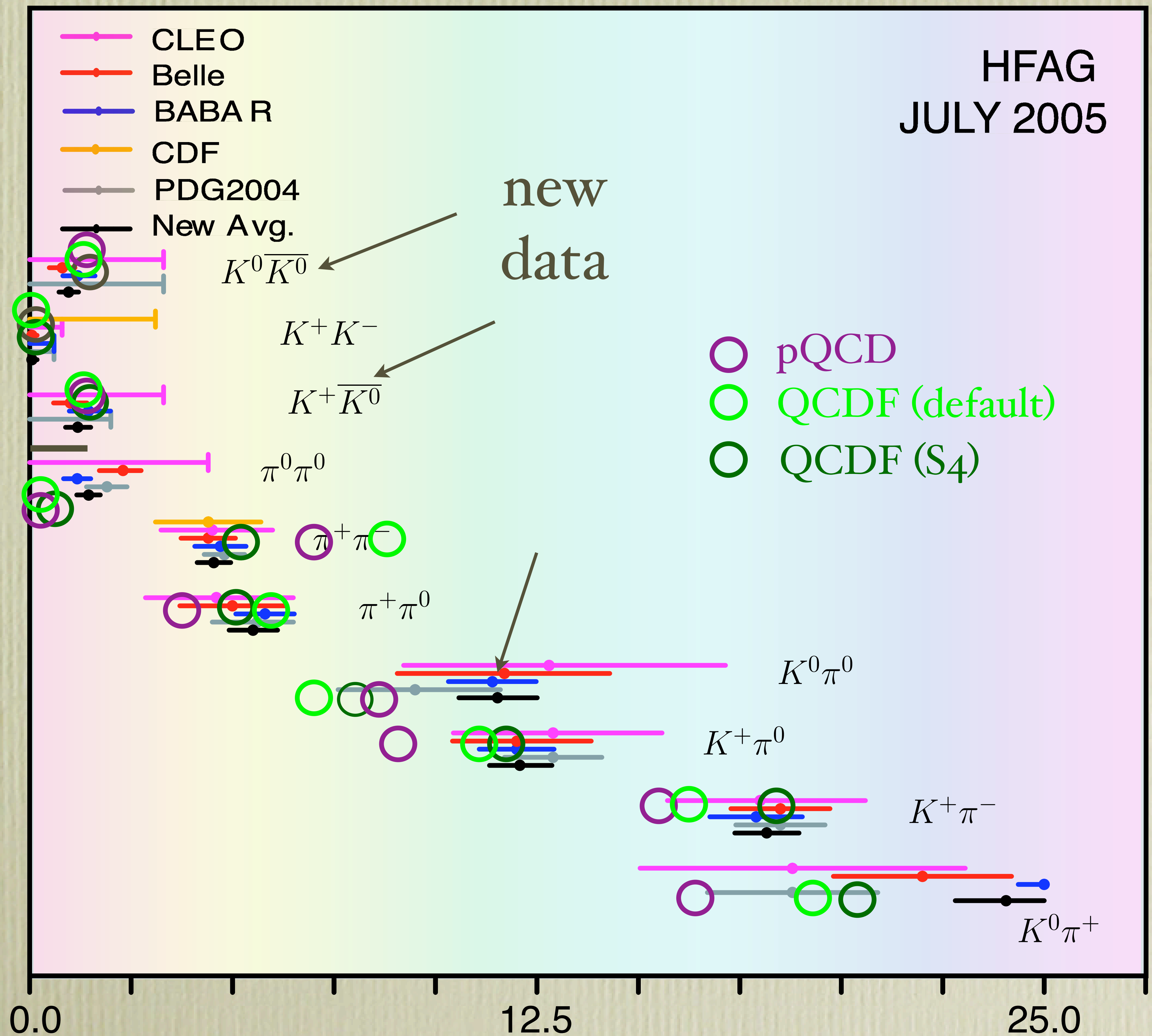
- Choose some reasonable values for hadronic parameters.
  Test Qualitative Agreement with Factorization

QCDF: Buchalla et al.; Neubert, Beneke

pQCD: Keum, Li, Sanda ($k_\perp$)

(NOTE: some power suppressed terms included as well)

$\mathcal{B}(B \to K\pi,\ \pi\pi,\ KK)$

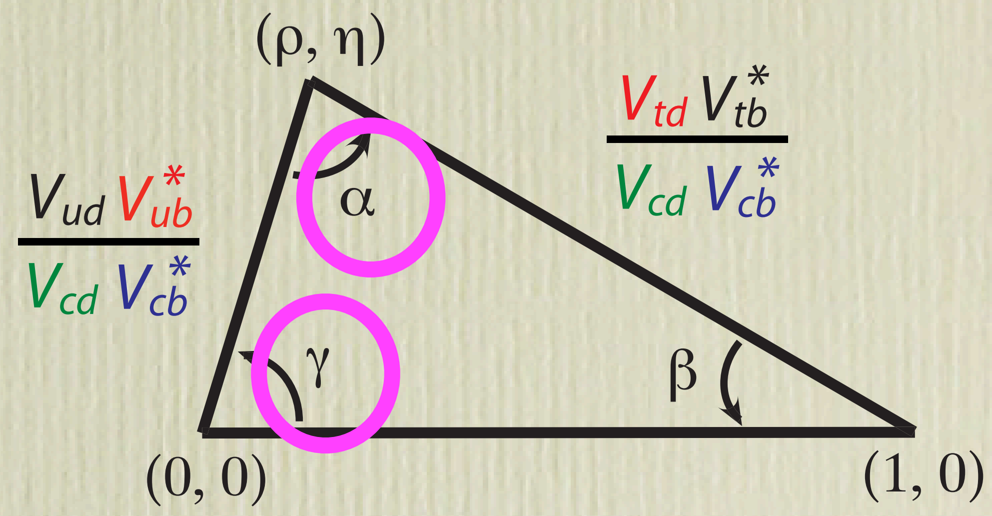


Pattern is reproduced

Note:
I did not add theory error estimates here

A Few Channels

Redundant measurements
in different channels
allow us to probe for new physics



Isospin Analysis

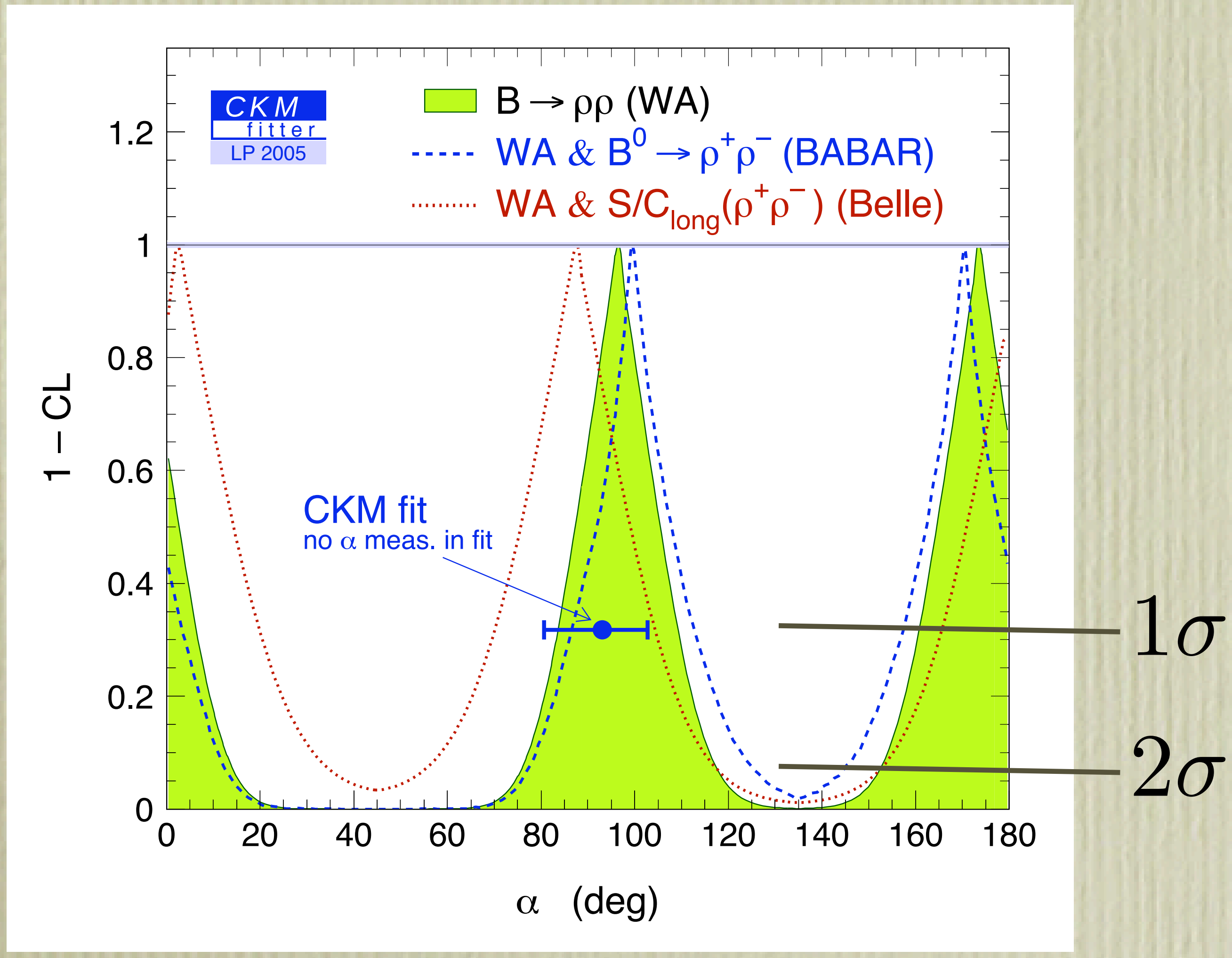
Babar '04 , Belle LP'05

$\boxed{B \to \rho\rho}$ ($\rho_{\|}\rho_{\|}$ dominates as factorization predicts A. Kagan)

Parameters = 6 Observables = 6

γ +5 hadronic

$B \to \rho^0\rho^0$ channel is not measured, but strong experimental bound forbids sizeable penguins

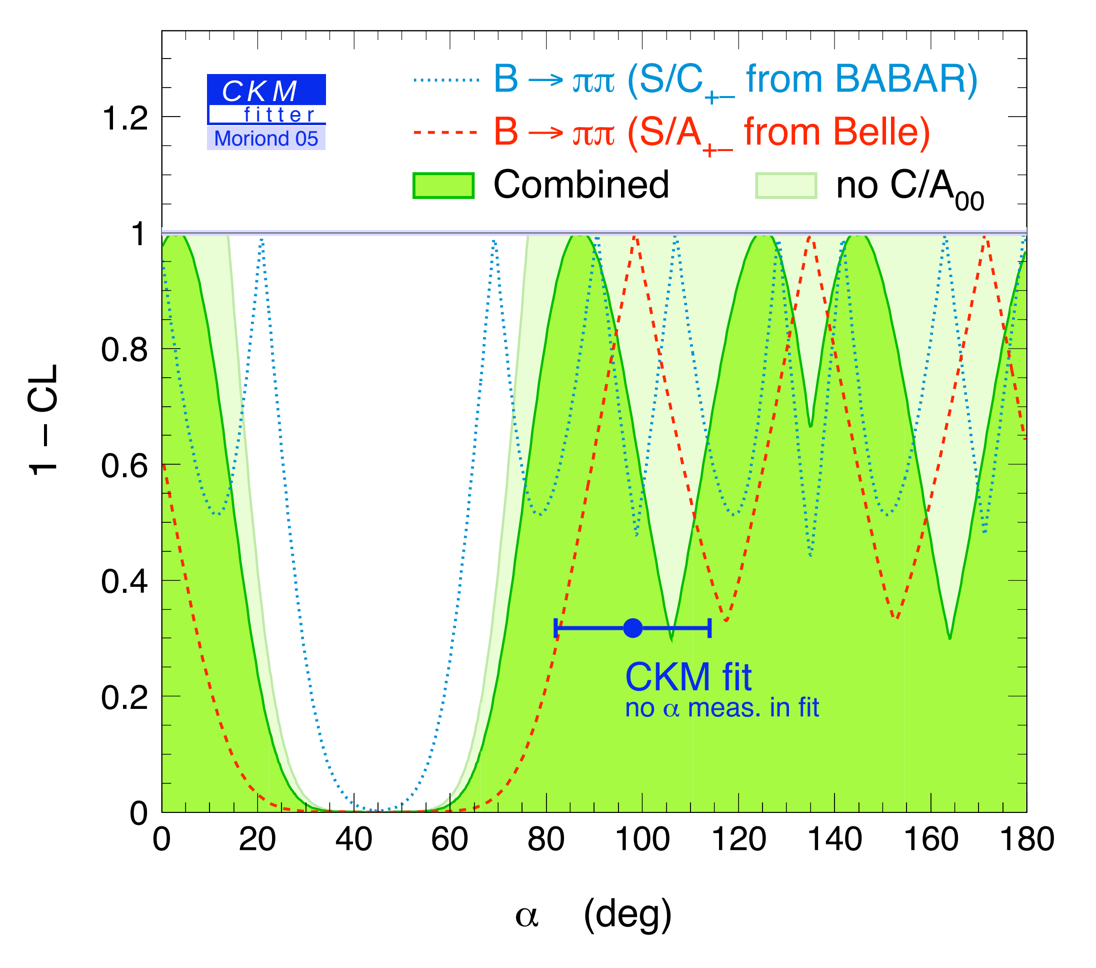


$$\alpha_{\rho\rho} = 96^\circ \pm 13^\circ$$

(see talk by F.Forti)

$B \to \pi\pi$

Isospin Analysis



Known strong isospin breaking effects are small

$\delta\alpha \sim 2^\circ$ Gardner; Gronau, Zupan

Problem is precision of direct
CP - Asymmetry for neutral pions

$$C_{\pi^0\pi^0} = -0.28 \pm 0.39$$

(Belle & Babar)

Add "mild" input from factorization (use data to fix nonperturbative parameters)

Worth remembering:
more input/less fit parameters means more ways to test for new physics

eg. can't see new physics in $I = 0$ amplitudes with the isospin analysis

Baek, Botella, London, Silva

My Language

Strategies for α vs. Methods for α

like PRL: Evidence vs. Observation

Definitions:

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

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

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

$|\lambda_{c,u}| = \text{CKM factors}$, take β known

Data → Significant P, "penguins",

Large C, "color suppressed amplitude"

(see A.Ali, ICHEP'04)

$Br(B \to \pi^0\pi^0) = 1.45 \pm 0.29$ is large (a LP'03 hot topic)

expected ~ 0.3

NOT a contradiction with factorization.

$\simeq 3$

Why?

- if $\zeta_J^{B\pi} \sim \zeta^{B\pi}$, then a term $\frac{C_1}{N_c}\langle \bar{u}^{-1}\rangle_\pi \, \zeta_J^{B\pi}$ in the factorization theorem ruins color suppression and explains the rate

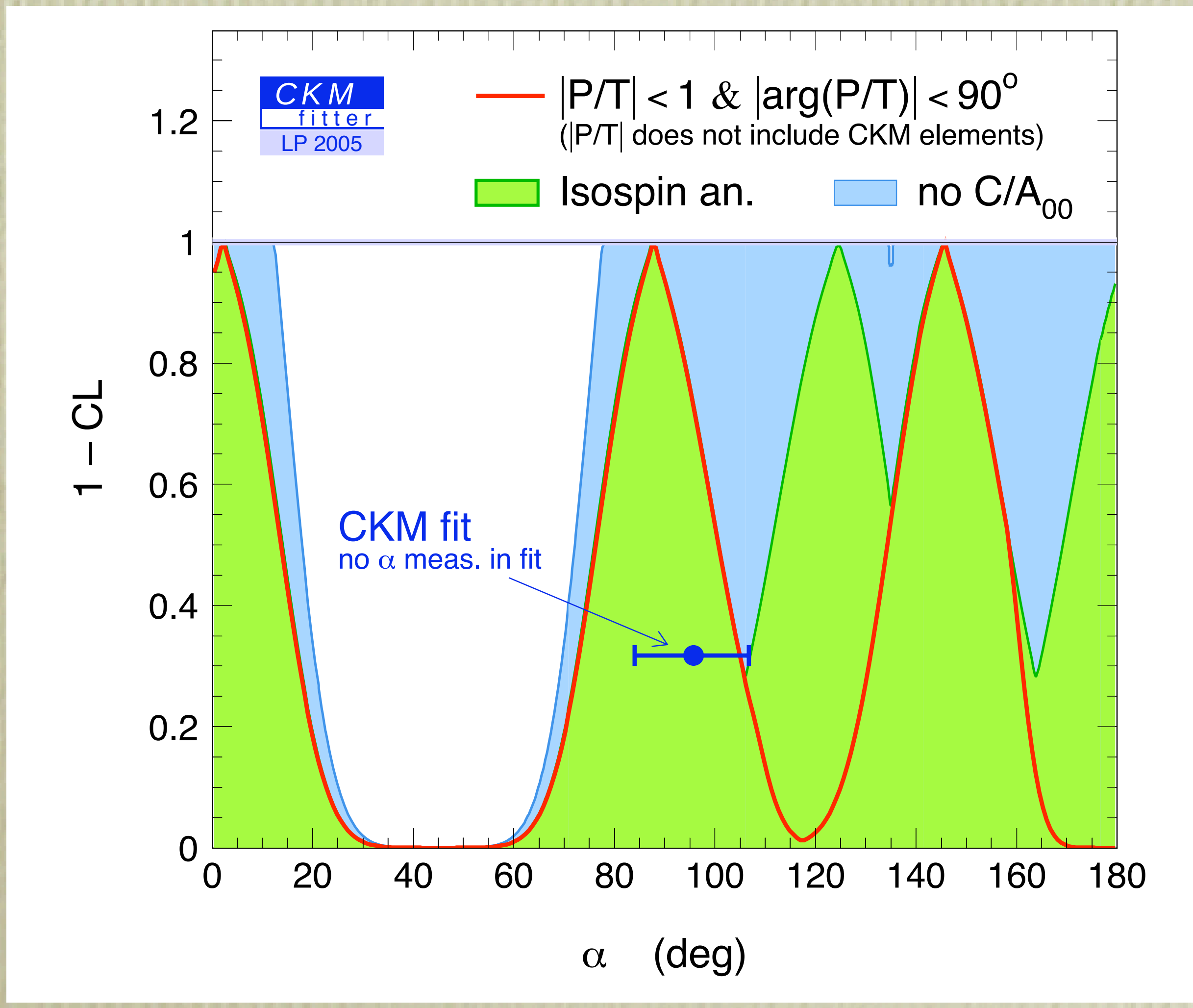
  if $\zeta^{B\pi} \gg \zeta_J^{B\pi}$ this Br is sensitive to power corrections (small wilson coeffs. at LO could compete with larger ones at subleading order) .

- In the future: determine parameters using improved data on the $B \to \pi\ell\bar{\nu}$ form factor at low q^2 to provide a check.

$B \to \pi\pi$

Buchalla, Safir
Lunghi, Gronau, Wyler

- Power counting says Penguins can't be TOO big and their strong phase should not be TOO large (assume factorization gets the sign right)



Impose: $$\frac{|P|}{|T|} \leq 1$$

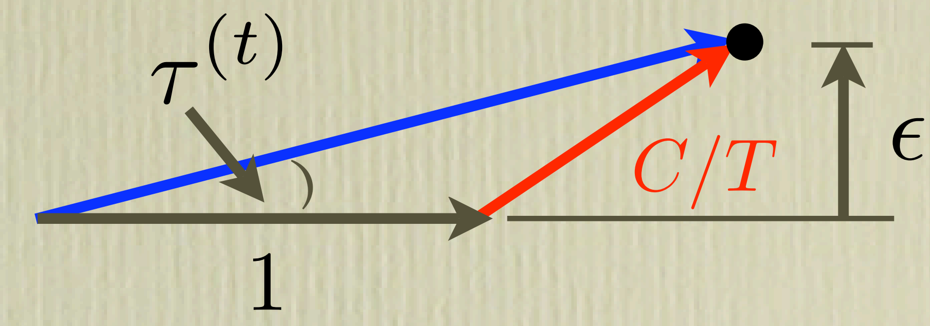
$$-\frac{\pi}{2} \leq \arg\left(\frac{P}{T}\right) \leq \frac{\pi}{2}$$

Removes discrete ambiguities

$B \to \pi\pi$

Factorization predicts a Flat Tree Triangle

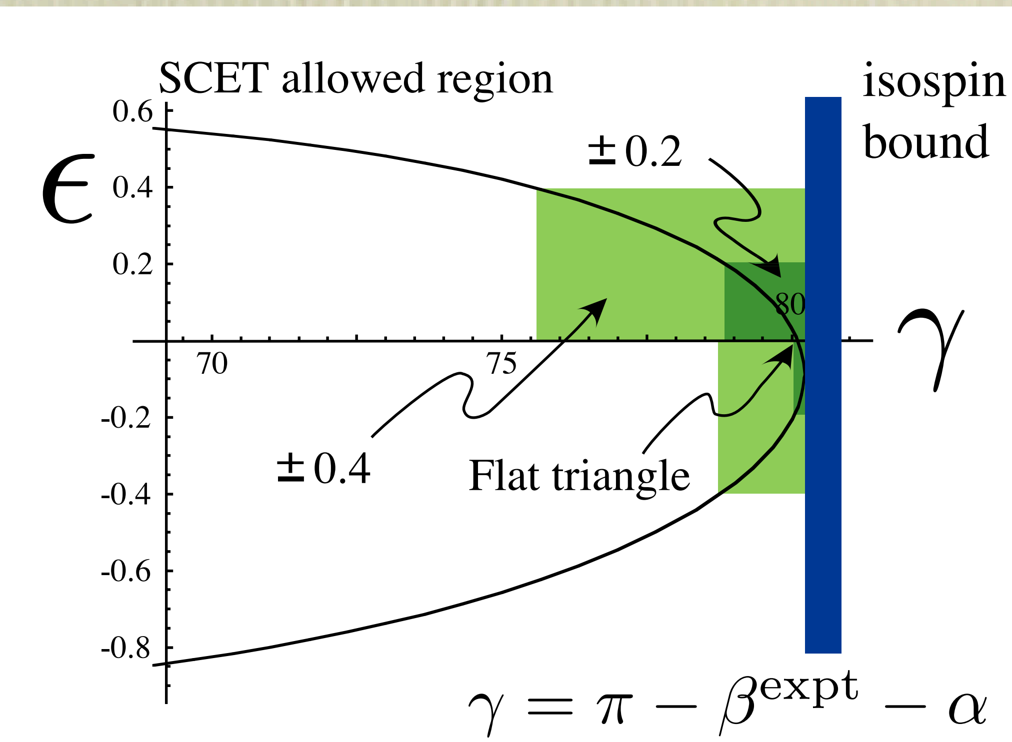
$$\epsilon \sim 0, \ \tau^{(t)} \sim 0$$

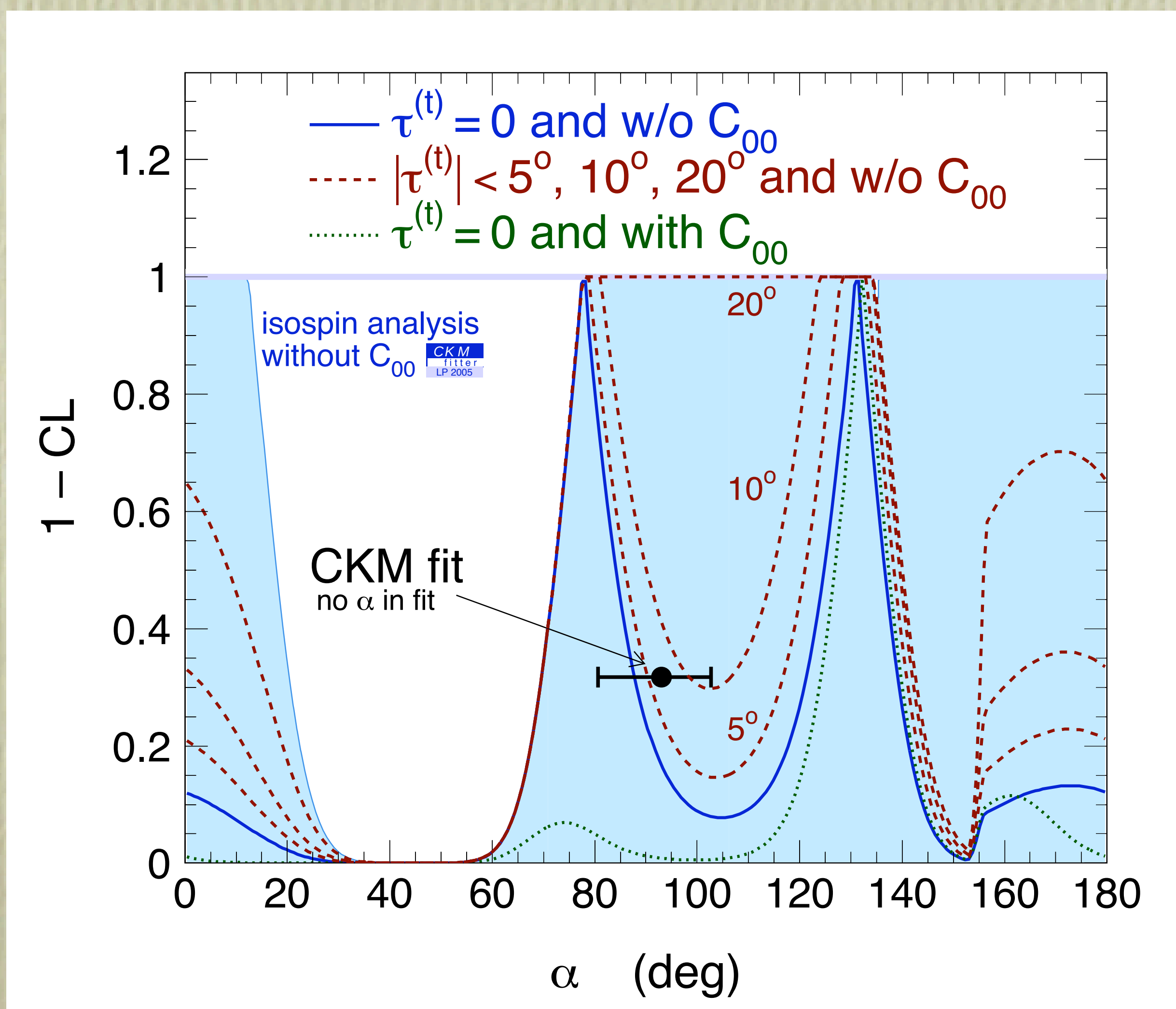


Use this to get α without $C_{\pi^0\pi^0}$.

Bauer, Rothstein, I.S.

$$\epsilon = \mathrm{Im}\left(\frac{C}{T}\right) = \mathcal{O}\left(\alpha_s(m_b), \frac{\Lambda}{E}\right) \lesssim 0.2$$





Grossman, Hoecker, Ligeti, Pirjol

for $\alpha \sim 90^\circ$ $\quad \epsilon = 0.2 \leftrightarrow \tau^{(t)} \sim 5^\circ$

$\epsilon = 0.4 \leftrightarrow \tau^{(t)} \sim 10^\circ$

$B \to K\pi$

Is there a K-pi CP Puzzle ?

Gronau, Rosner

- Direct-CP sum rule: Expand in $\epsilon = \underbrace{\left|\frac{V_{us}^* V_{ub}}{V_{cs}^* V_{cb}}\right|}_{0.02} \frac{T}{P}, \left|\frac{V_{us}^* V_{ub}}{V_{cs}^* V_{cb}}\right| \frac{C}{P}, \frac{P_{ew}^{(c)}}{P}$

$$\Delta(\bar{K}^0\pi^0) - \frac{1}{2}\Delta(K^+\pi^-) + \Delta(K^+\pi^0) = \mathcal{O}(\epsilon^2)$$

$$0.077 \pm 0.070 = \mathcal{O}(\epsilon^2)$$

account for fact that color-suppressed terms can be large

$$\Delta(f) = \frac{A_{CP}(f)\Gamma_{\rm avg}^{\rm CP}(f)}{\Gamma_{\rm avg}^{\rm CP}(\pi^-\bar{K}^0)}$$

no puzzle here yet

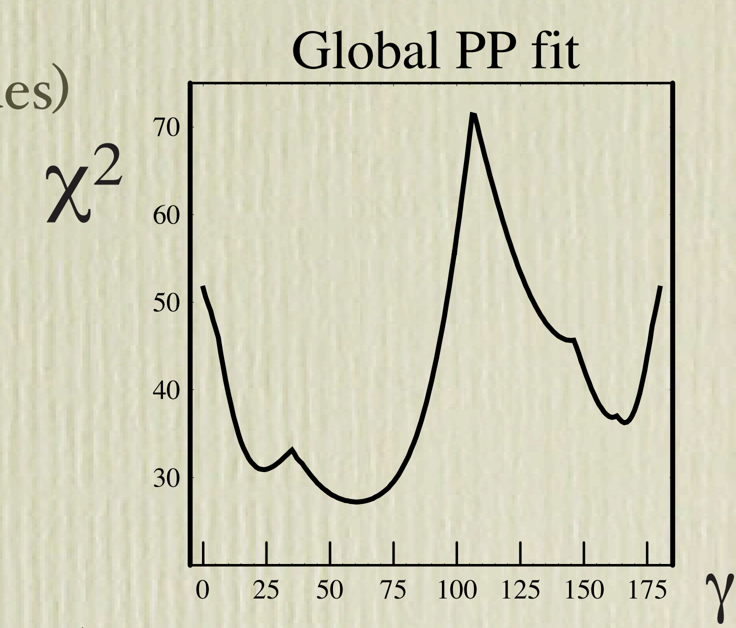
uses LP'05 Belle $A_{\rm CP}$ data

- SU(3), global fits to data (Neglect E, A, PA amplitudes)

12 parameters, 18 predictions

$\pi\pi, KK, \pi\eta, \pi\eta' K\pi, K\eta, K\eta'$

Chiang, Gronau, Luo, Rosner, Suprun



$\Rightarrow$ $\gamma = 61^\circ \pm 11^\circ$ agrees with global fit

$Br(K^+\pi^-), Br(K^0\pi^0), A_{\rm CP}(K^0\pi^0)$ give $\Delta\chi^2 = (2.7, 5.9, 2.9)$

Updated by Suprun (pre-LP'05 data)

hints of a puzzle?

see also Buras, Fleischer, Recksiegel, Schwab; Kim, Oh, Yu

$B \to K^*\gamma$ & $B \to \rho\gamma$

Factorization & Phenomenology

Beneke, Feldmann, Seidel

Ali, Lunghi, Parkhomenko

Bosch, Buchalla

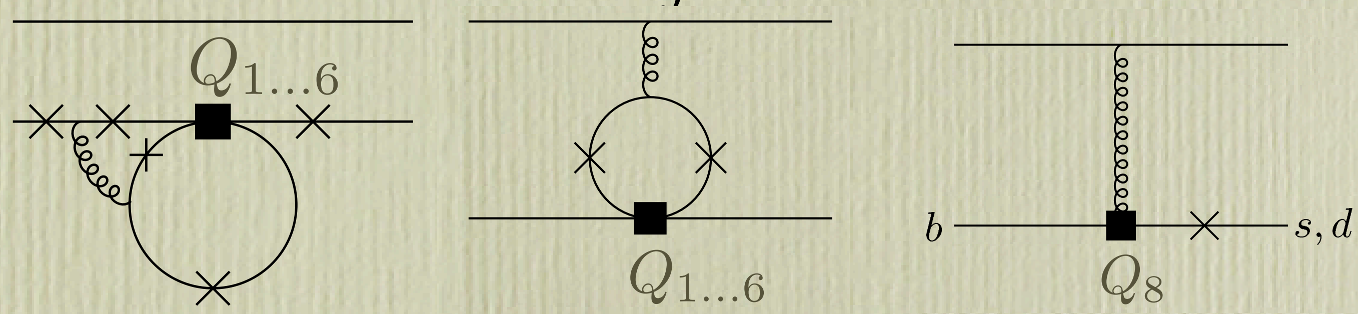
Theory based on Factorization Formula:

$$\langle V\gamma|Q_i|B\rangle = T_i^{\mathrm{I}}\; F_V + \int dx\, dk\; T_i^{\mathrm{II}}(x,k)\; \phi_B(k)\phi_V(x) + \mathcal{O}\Big(C_1 \frac{\Lambda}{m_b}\Big)$$

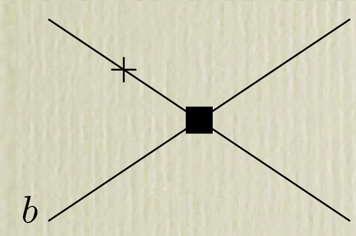
SCET ($K^*\gamma$)

Chay, Kim;

Becher, Hill, Neubert



annihilation



small for ρ^0

$$\frac{\mathrm{Br}(B\to\rho^0\gamma)}{\mathrm{Br}(B\to K^*\gamma)} = \frac{1.023}{2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \xi^{-2}\Big[1+\underbrace{2(\mathrm{ckm})\delta a\Big]\Big|\frac{a_7^c(\rho)}{a_7^c(K^*)}}_{\text{small}}\Big|^2$$

from Bosch,Buchalla

SU(3) violation $\quad \xi = \dfrac{F_{K^*}}{F_\rho}$

$\xi = 1.25 \pm 0.20$ (Ball, Zwicky; sum-rules)

$\xi = 1.1 \pm 0.1$ (Becirevic, Mescia; lattice+extrapolation to small q^2)

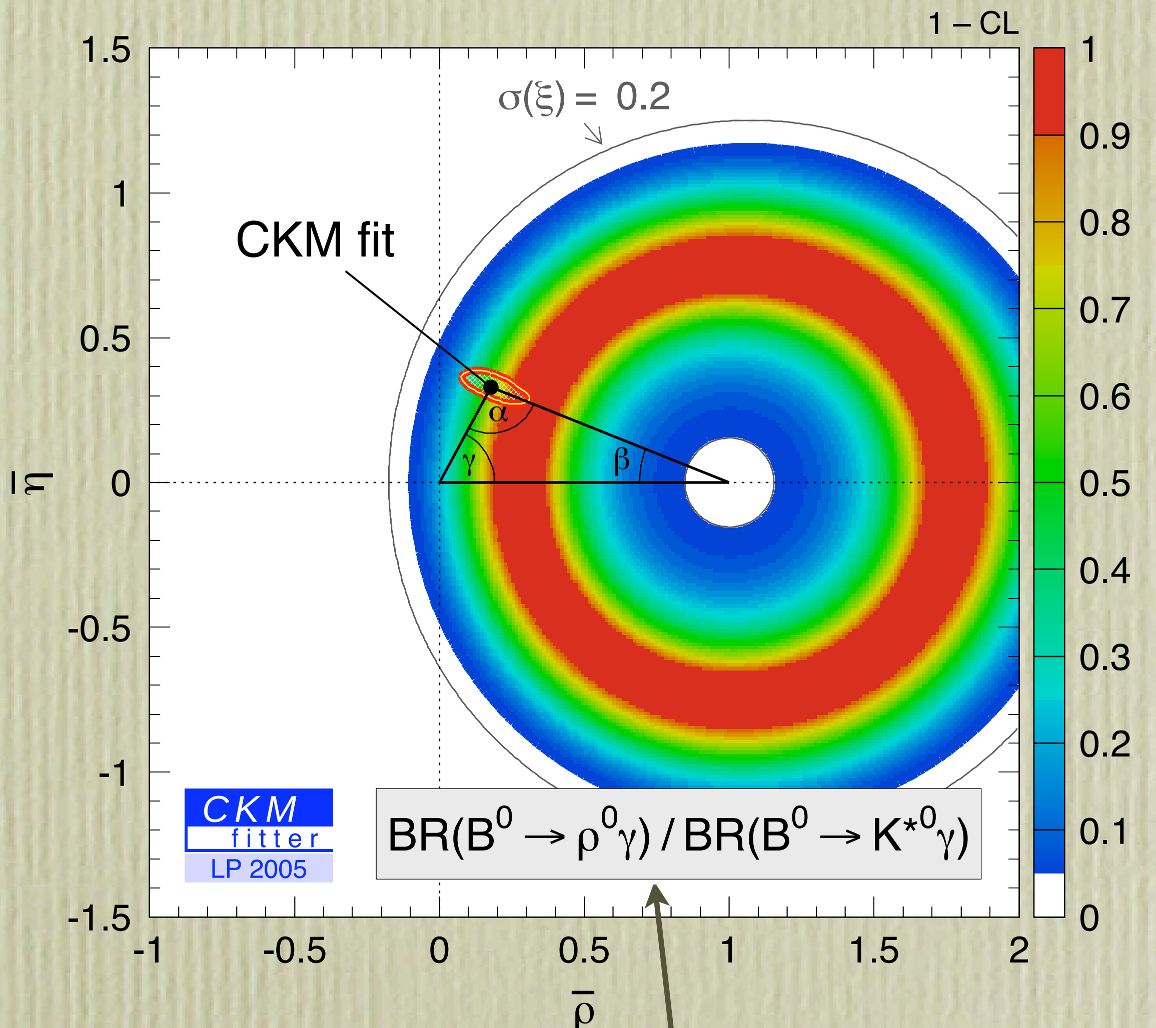
CKM'05

1.2 ± 0.1

is this conservative ?

New observation from Belle (Lp'05, Forti)

$$\mathrm{Br}(B \to \rho^0 \gamma)$$



$$\sigma(\xi) = 0.2$$ curve doubles error estimate

Currently agrees with global fit

WA used

Executive Summary

- Radiative Decays
  - ➡ progress on understanding and reducing the QCD uncertainites
- Lattice QCD
  - ➡ new fD! agrees with new Cleo-C result
  - ➡ new staggered fB, fBs/fB! improves the Δm_d constraint smaller uncertainty for Δm_s constraint
- Lattice QCD & Continuum methods
  - ➡ 2005 yields precise exclusive determinations of Vub
- Factorization Theorems
  - ➡ New tools developed, progress in understanding Nonleptonic B-Decays, new "strategies" for α
  - ➡ Places to watch for "puzzles"!

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