The Theory of Nonleptonic B Decays

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NPPC, 2003

Outline

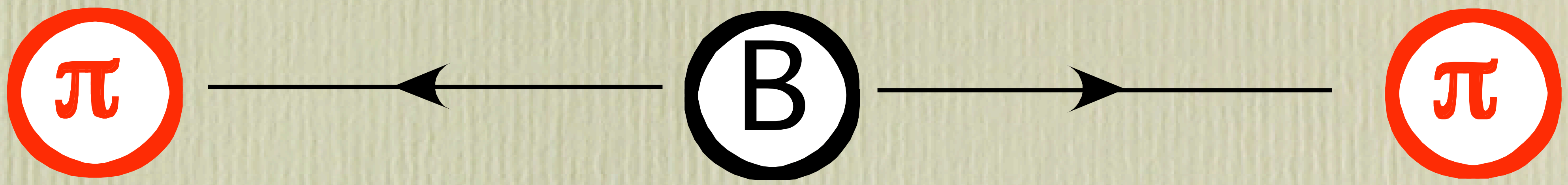
- Nonleptonic Decays - the theoretical challenge
- A bit of history & the Physics we're after
- Factorization and the Soft-Collinear EFT
- Decays $B \to J/\Psi K_s$ $B \to \phi K_s$

  $B \to D\pi$ $B \to D\rho$ $B \to D^* K$

  $\Lambda_b \to \Lambda_c \pi$ $\Theta_b \to \Theta_c \pi$

  $B \to \pi\pi$ $B \to K\pi$ $B \to \rho\pi$
- Conclusion and Outlook

Two body nonleptonic decays. Simple?



$$\Gamma = \frac{|\vec{p}_\pi|}{8\pi m_B^2} |A|^2 \qquad A = \langle \pi\pi | H_{\rm weak} | B \rangle$$

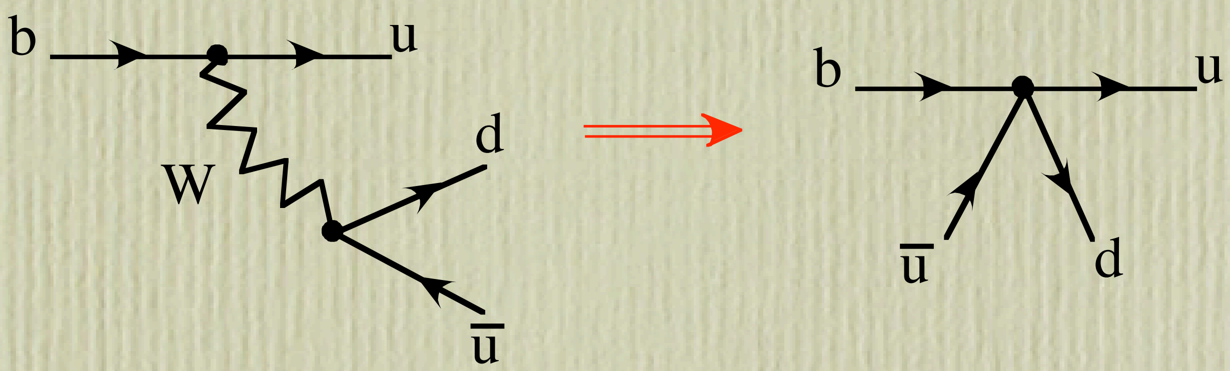
- Weak decay of quarks: $b \to u(\bar{u}d)$
- QCD bound states: $(b\bar{d}) \to (u\bar{d})(\bar{u}d)$

$$\bar{B}^0 \to \pi^- \quad \pi^+$$

Electroweak Hamiltonian

$m_W, m_t \gg m_b$

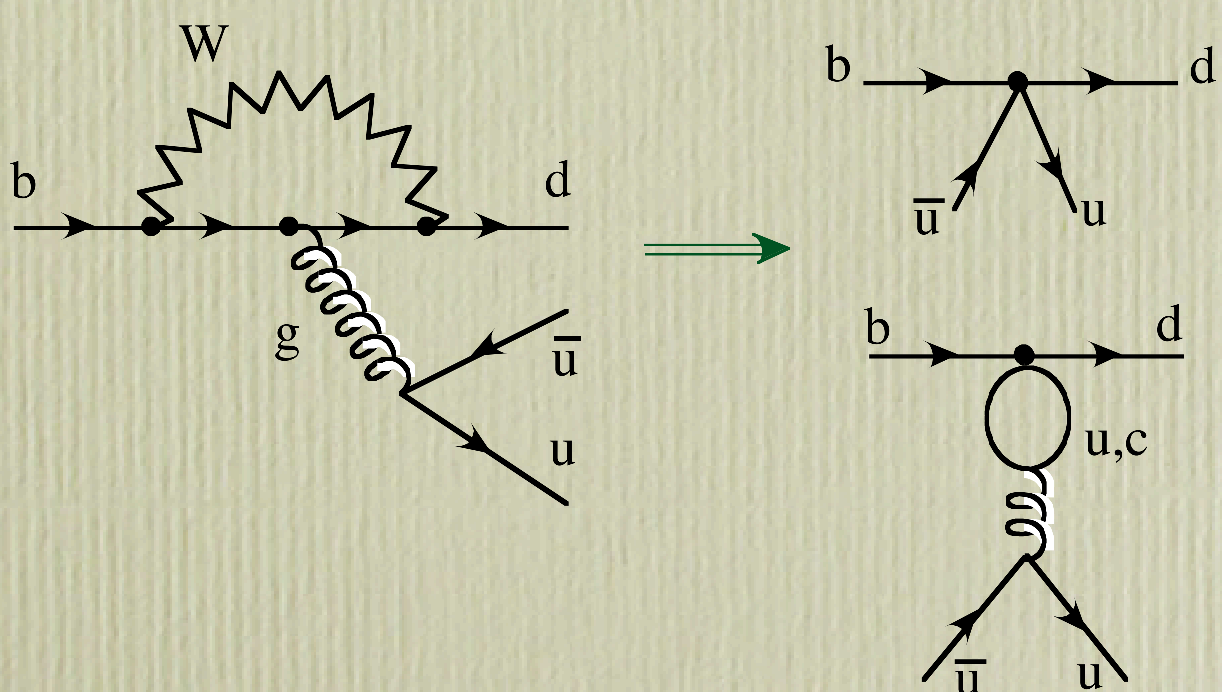
$$H_{\text{weak}} = \frac{G_F}{\sqrt{2}} \sum_i \lambda^i C_i(\mu) O_i(\mu)$$



trees

$$O_1 = (\bar{u}b)_{V-A}(\bar{d}u)_{V-A}$$

$$O_2 = (\bar{u}_i b_j)_{V-A}(\bar{d}_j u_i)_{V-A}$$



penguins

$$O_3 = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V-A}$$

$$O_{4,5,6} = \ldots$$

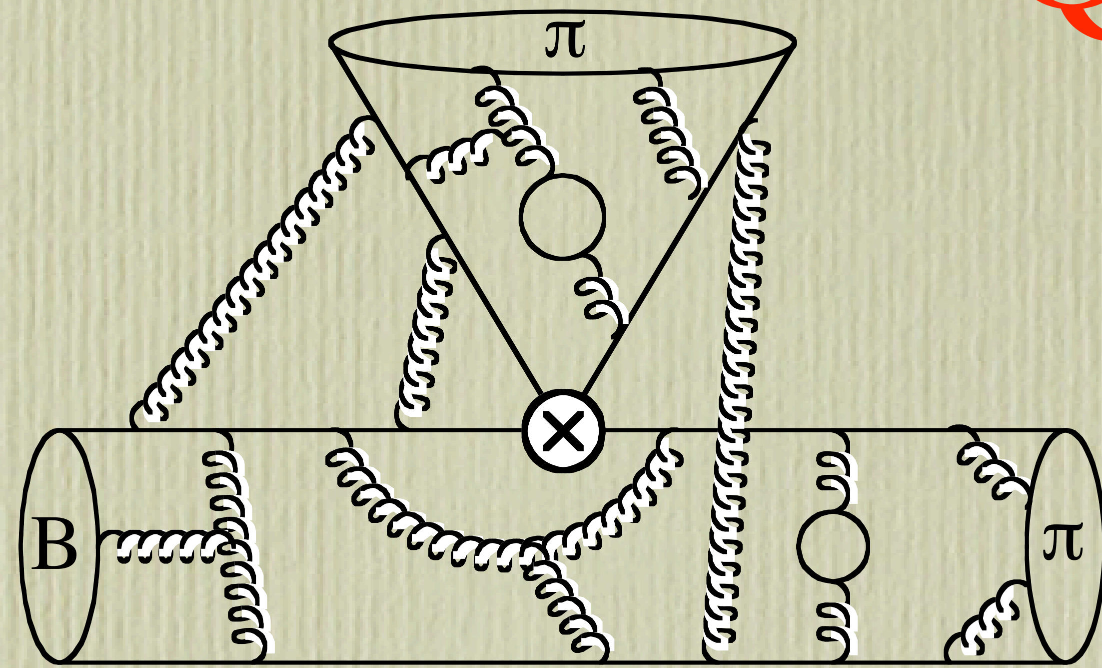
$$O_{7\gamma,8G} = \ldots$$

$$O^{ew}_{7,\ldots,10} = \ldots$$

λ^i = CKM factors

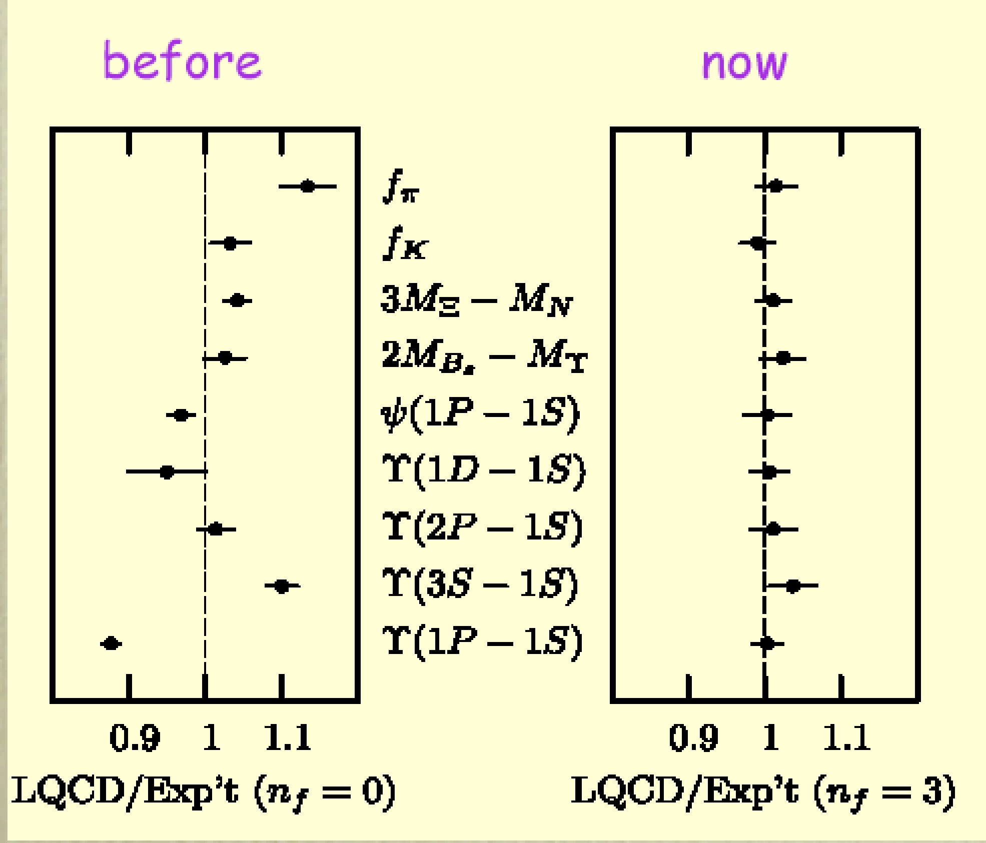
$\lambda^1 = V_{ub}V^*_{ud}$ $\lambda^3 = V_{tb}V^*_{td}$

QCD



- Confinement, Hadronization
- a tough problem

Note: Nonleptonic B-decays are not Gold Plated Observables for Lattice QCD



- two final state hadrons
- energetic pions, slow B
- very hard

HPQCD '03

Theory 1986: Factorization Naive Factorization

$$\langle \pi\pi | (\bar{u}b)_{V-A} (\bar{d}u)_{V-A} | B \rangle \simeq \langle \pi | (\bar{u}b)_{V-A} | B \rangle \langle \pi | (\bar{d}u)_{V-A} | 0 \rangle$$

If that is all there is ....

3) **EXCLUSIVE NONLEPTONIC DECAYS OF D, D(S), AND B MESONS.**
By Manfred Bauer, B. Stech, (Heidelberg U.) M. Wirbel, (Dortmund U.). HD-THEP-86-19, DO-THEP-86-21, Nov 1986. 33pp.
Published in **Z.Phys.C34:103,1987**

TOPCITE = 1000+

- Justified by $N_c \to \infty$ in some cases
- No rescattering, strong phases are zero
- Ok for some decays, fails for others
- Inconsistent with QCD anomalous dimensions

Quarks

quarks	mass
u	$\sim 4\,\mathrm{Mev}$
d	$\sim 7\,\mathrm{MeV}$
s	$\sim 120\,\mathrm{MeV}$
c	$\sim 1.4\,\mathrm{GeV}$
b	$\sim 4.5\,\mathrm{GeV}$
t	$174\,\mathrm{GeV}$

} light (u, d, s)

$\Longleftarrow \Lambda_{\mathrm{QCD}}$

} heavy (c, b, t)

QCD

$\alpha_s(\mu)$, μ resolution

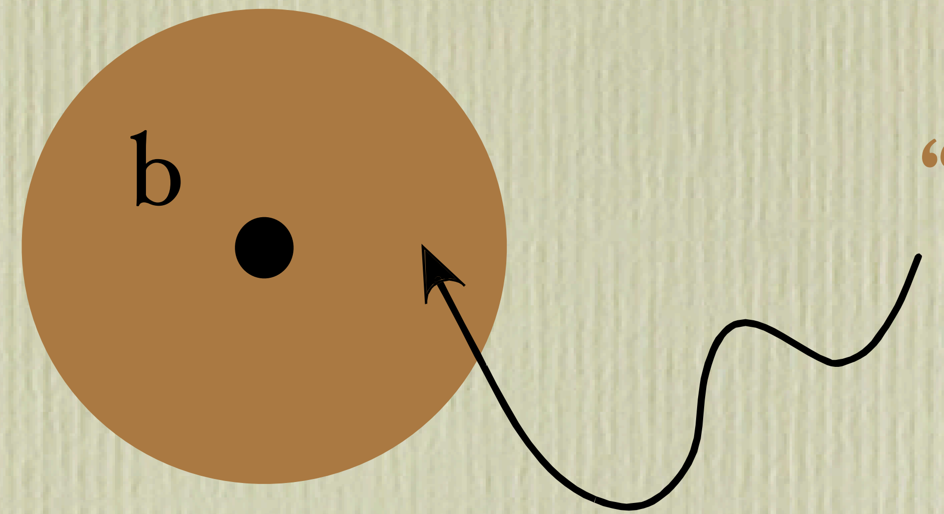
$\alpha_s(\Lambda)$ non-perturbative
$\longrightarrow$ long distance

$\alpha_s(m_b)$ perturbative
$\longrightarrow$ short distance

Expansion parameters are useful

$$\alpha_s(m_b) \simeq 0.2 \ , \ \frac{\Lambda}{m_b} \simeq 0.1 \ , \ \frac{m_{u,d}}{\Lambda}$$

B-meson



"Brown muck" $= \bar{q} + glue, q\bar{q}$

Isgur (90's)

$\Lambda_{\rm QCD} \ll m_b$ $\quad v^\mu$ conserved

Heavy Quark Effective Theory $\quad h_v$

eg. Inclusive Decay: $\quad B \to X_c \ell \bar{\nu}_\ell$

$$X_c = D, D^*, D\pi, D\rho\pi, \ldots$$

Operator Product Expansion in $\dfrac{\Lambda_{\rm QCD}}{m_b} \simeq 0.1$

- $m_b \to \infty$ is free quark decay, $\alpha_s(m_b)$ computable
- No $\dfrac{\Lambda_{\rm QCD}}{m_b}$ corrections ⟶ uses HQET
- At $\dfrac{\Lambda^2_{\rm QCD}}{m_b^2}$ two hadronic parameters λ_1, λ_2

Calculate differential rates: $\frac{d\Gamma}{dE_\ell}, \quad \frac{d\Gamma}{dm_X^2}, \cdots$

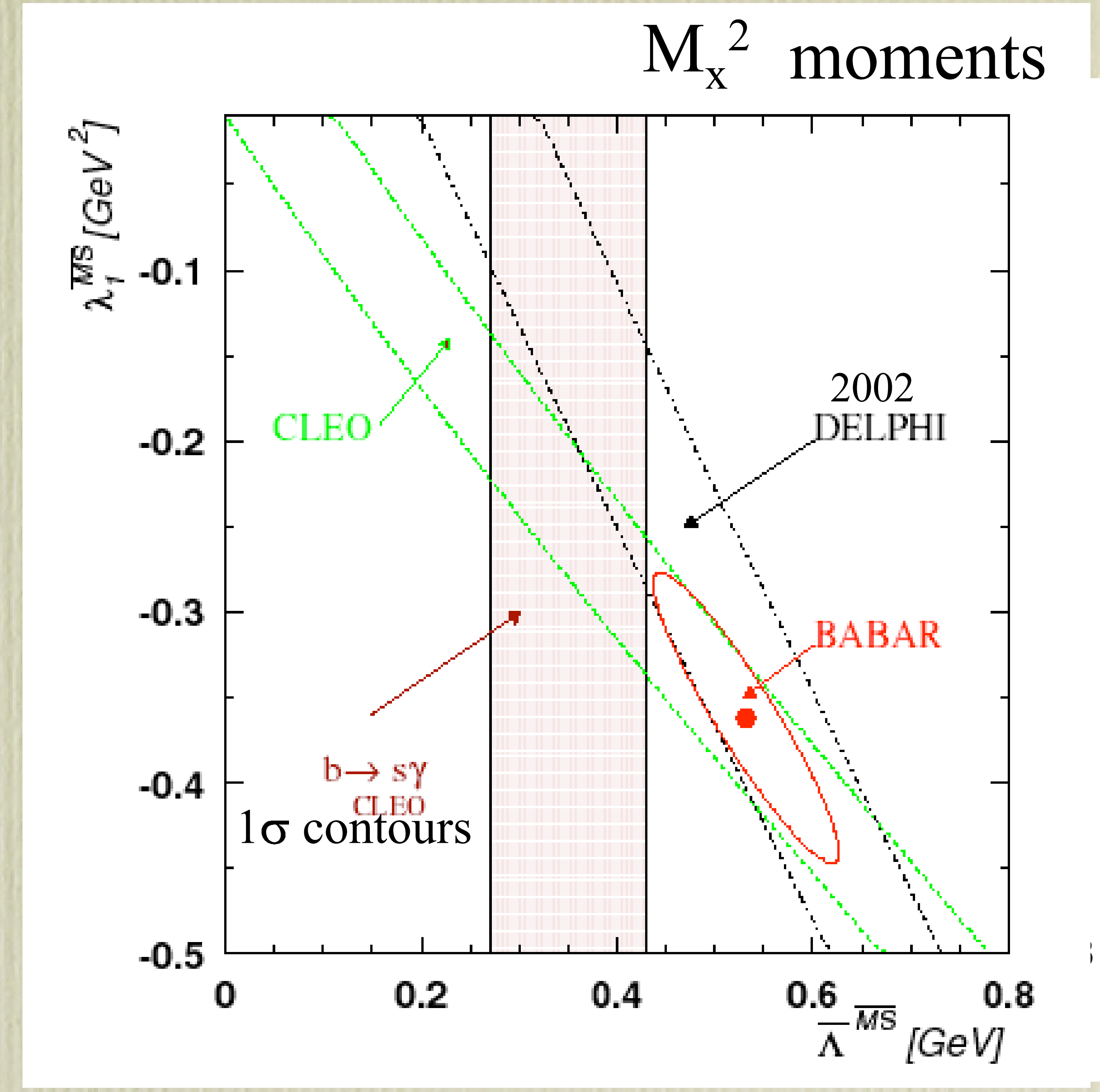
Fit moments to simultaneously extract $V_{cb}, m_b(\bar{\Lambda}), \lambda_{1,2}$

eg. BaBar mX moments

eg. CLEO mX moments

$|V_{cb}| = (42.1 \pm 1.0 \pm 0.7) \times 10^{-3}$

$|V_{cb}| = (40.8 \pm 0.6 \pm 0.9) \times 10^{-3}$



from M. Artuso, Beauty '03

from S. Stone, EPS '03

Nonleptonic Decays are harder than the Semileptonic

"When you have to descend into the brown muck, you abandon all pretense of doing elegant, pristine, first-principles calculations. You have to get your hands dirty with uncontrolled approximations and models. When you are finished with the brown muck, you should wash your hands."

Georgi (1991)

"... drinking the nonlep tonic ..."

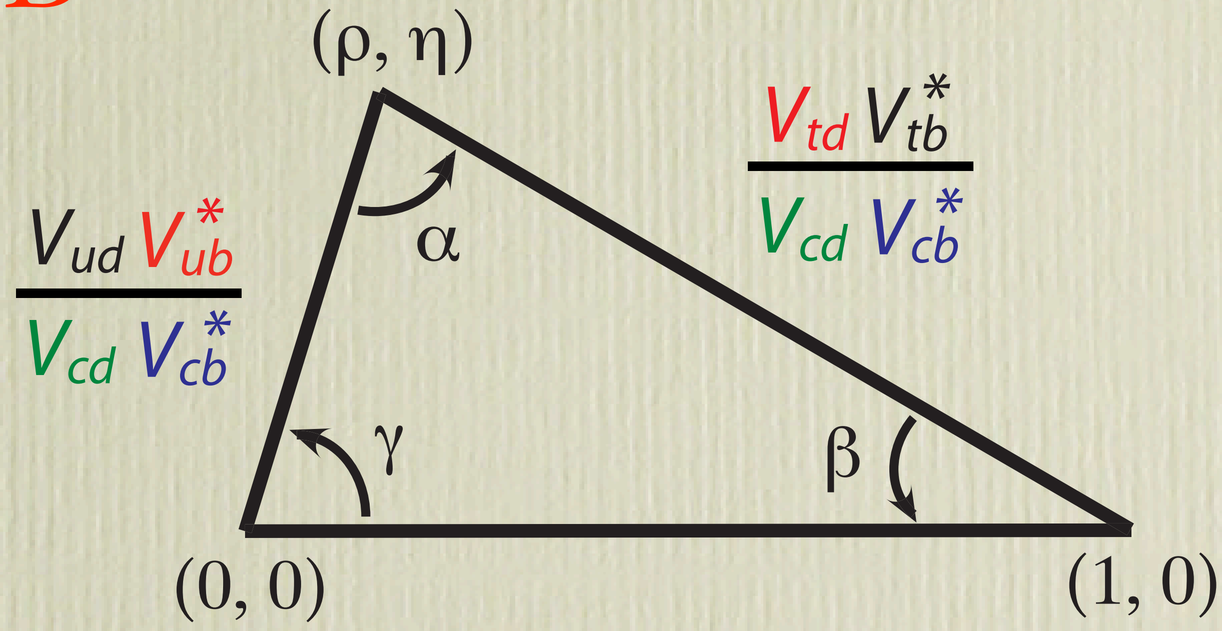
Lipkin

Why Bother ?

- Need nonleptonic decays to measure CP violation
  - Baryon asymmetry of the universe → wants more
  - MSSM has 43 new CP violating parameters

- Study rare nonleptonic decays
  - Loop dominated, look for new physics
  - $Br < 10^{-5}, \;\; B \to \phi K_s, \;\; B \to K\pi$

- Measure fundamental hadronic parameters & improve our understanding of QCD



eg. Measure $\sin(2\alpha)$ with $B^0(t) \to \pi^+\pi^-$, $\bar{B}^0(t) \to \pi^+\pi^-$

$$\mathcal{A}_{CP}(t) = -S_{\pi\pi}\sin(\Delta m_B t) + C_{\pi\pi}\cos(\Delta m_B t)$$

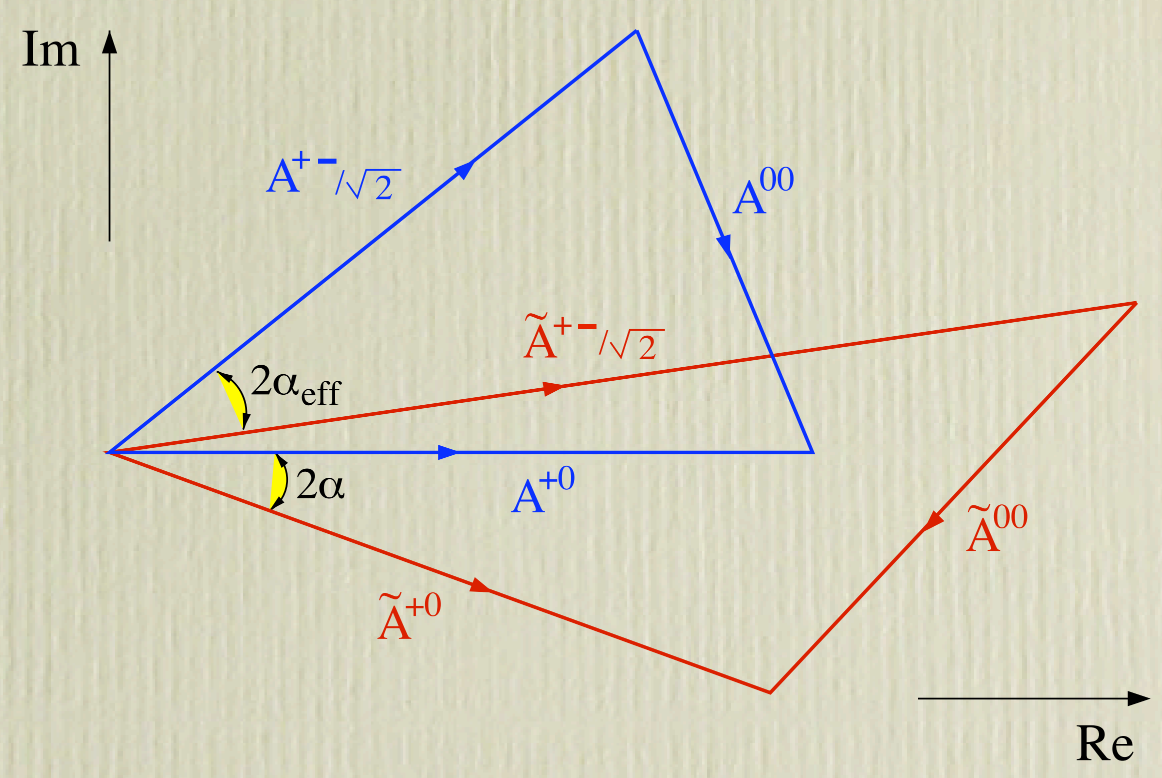
$$S_{\pi\pi} = \frac{2\,\mathrm{Im}\lambda}{1+|\lambda|^2}, \quad C_{\pi\pi} = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \quad \lambda = e^{2i\alpha}\frac{1+e^{i\gamma}P/T}{1+e^{-i\gamma}P/T}$$

T = tree , P = penguin $\qquad$ P =0 then $S_{\pi\pi} = \sin(2\alpha)$

P/T$\neq$ 0, need information from QCD, or isospin analysis

can remove P with
$B^0 \to \pi^0\pi^0, \bar{B}^0 \to \pi^0\pi^0$,
$B^+ \to \pi^+\pi^0$ plus isospin

$$S_{\pi\pi} = \frac{2|\lambda|}{1+|\lambda|^2}\sin(2\alpha_{\rm eff})$$

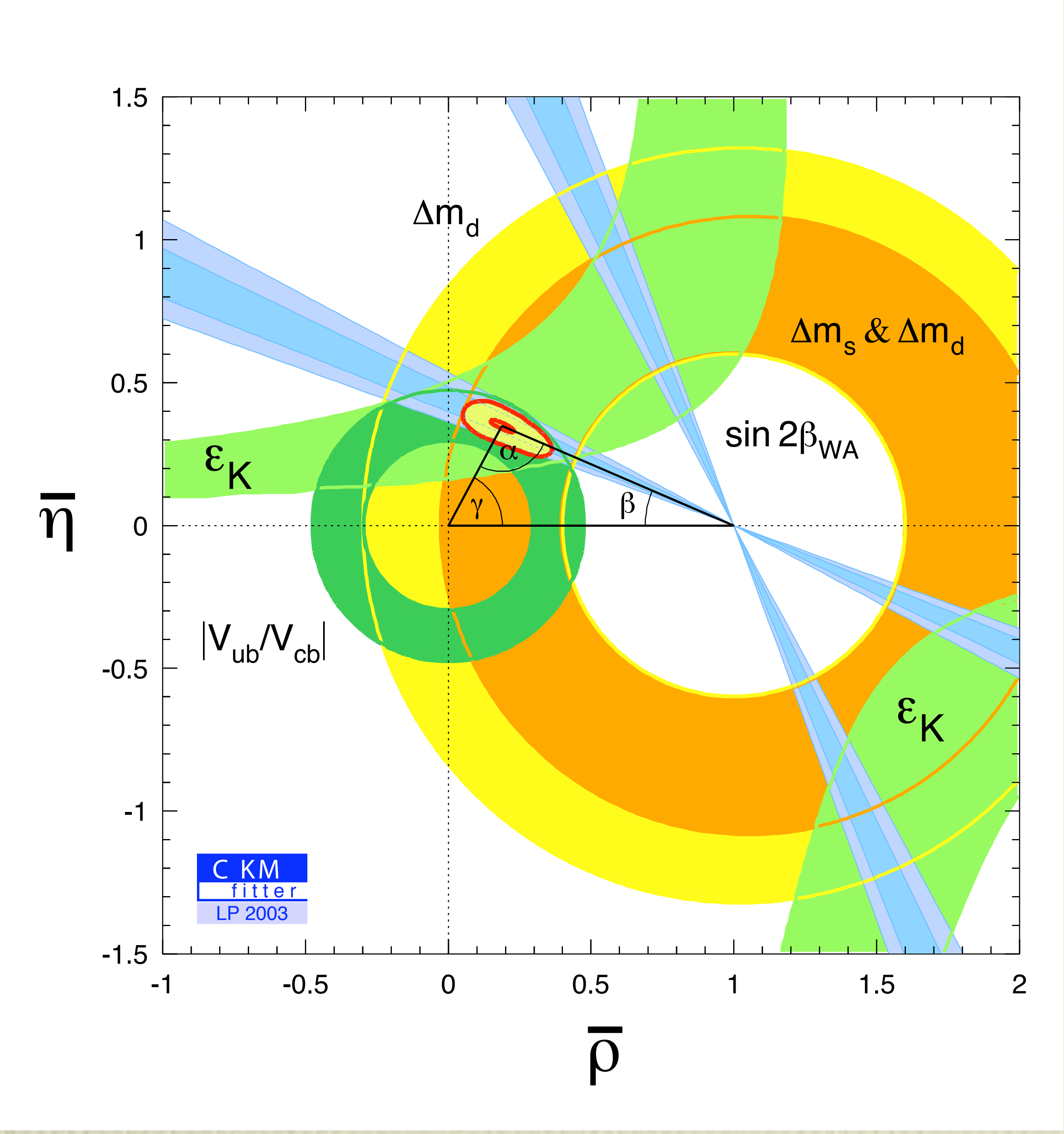


Some Clean Nonleptonic Info

CP asymmetry in $b \longrightarrow c\bar{c}s$ $(B^0, \bar{B}^0 \rightarrow J/\Psi K_s, \Psi' K_s, J/\Psi K_L, \ldots)$

- A dominant weak phase,
  $V_{cb}V_{cs}^* \sim \lambda^2$, $V_{ub}V_{us}^* \sim \lambda^4$
- QCD $\simeq$ CP even
- strong phase cancels in $\bar{A}/A$
- $a_{CP}(t) \propto sin(2\beta)$

$\lambda \sim 0.2$



More Clean Nonleptonic Info

CP asymmetry in $b \to s\bar{s}s \quad (B^0, \bar{B}^0 \to \phi K_s, \eta' K_s, \dots)$

- Dominant weak phase:

$$V_{cb}V_{cs}^* \sim \lambda^2 \;, \quad V_{ub}V_{us}^* \sim \lambda^4$$

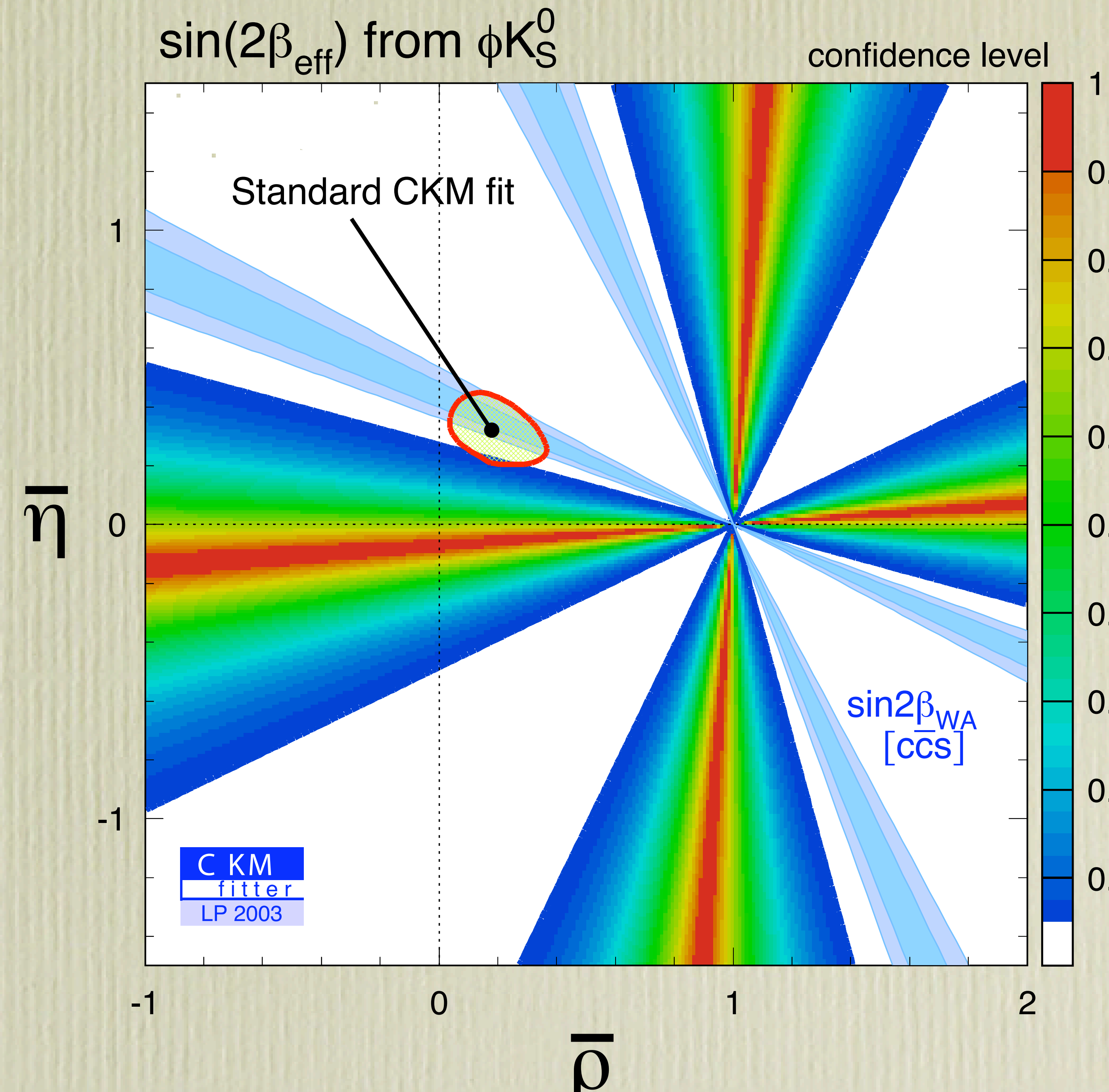
- Penguin Dominated
- At ~ 5% level we expect

$$sin(2\beta)_{\phi K_s} \simeq sin(2\beta)_{J/\Psi K_s}$$

- WA: 2.7σ deviation

Belle: $S_{\phi K} = -0.96 \pm 0.51$
BaBar: $S_{\phi K} = 0.45 \pm 0.43$
WA: $S_{\phi K} = -0.14 \pm 0.33$

WA: $S_{J/\Psi K} = 0.739 \pm 0.048$



Measuring CP violation in other decays requires

1. A fancier analysis strategy. Use SU(2) or SU(3) to relate amplitudes so data can be used to reduce uncertainties.

   - Flavor symmetries of QCD, $m_u, m_d, m_s \ll \Lambda_{\rm QCD}$

2. Factorization from QCD to reduce the amplitudes to simple universal nonperturbative parameters.

   - Expand in $E_\pi \gg \Lambda_{\rm QCD}$

These two possibilities are not exclusive.

The important thing to keep in mind is "what are the uncertainties".

QCD Factorization, QCDF
Factorization in QCD

- In 1999 Beneke, Buchalla, Neubert, Sachrajda proposed a QCD factorization theorem for $B \to \pi\pi$. Builds on earlier proposal by Politzer & Wise for $B \to D\pi$, which in turn built on Brodsky - Lepage type exclusive QCD factorization.

- Amplitude is reduced to simpler matrix elements

$$\langle \pi\pi | \cdots | B \rangle \longrightarrow \langle \pi | \cdots | B \rangle \ , \ \ \langle \pi | \cdots | 0 \rangle \ , \ \ \langle 0 | \cdots | B \rangle$$

- At LO in $\dfrac{\Lambda_{\rm QCD}}{E_\pi}$ strong phases are perturbative, $i\alpha_s(m_b)$, and therefore small.

- Is it right?

Soft - Collinear Effective Theory

Bauer, Pirjol, Stewart
Fleming, Luke

- An effective field theory for energetic hadrons, $E \gg \Lambda_{\rm QCD}$

Effective Field Theory

- Separate physics at different momentum scales
- Power expansion
- Make symmetries explicit
- Model independent, systematically improvable

Effective Theories	Expansion Parameter
(1) Electroweak (Fermi) Hamiltonian	$m_b/m_W \ll 1$
(2) Heavy Quark Effective Theory (HQET)	$\Lambda/m_b \ll 1$
(3) Chiral Perturbation Theory, SU(3)	$m_{u,d,s}/\Lambda \ll 1$

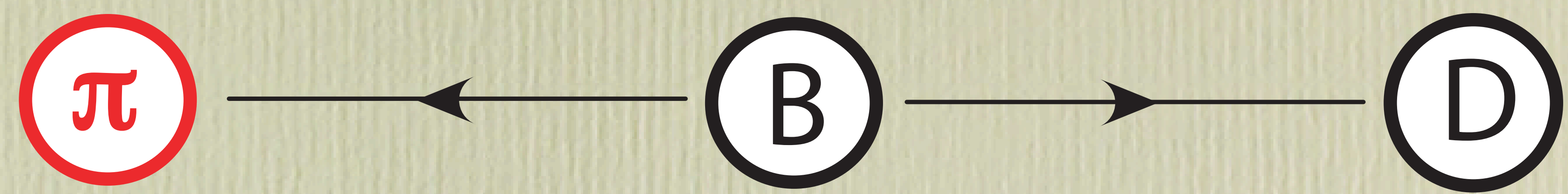
All designed to separate hard $p_h \sim Q$ and soft p_s momenta, $Q^2 \gg p_s^2$

Allow for energetic hadrons $\Longrightarrow$ collinear p_c, new class of processes

$$Q \gg \Lambda_{\rm QCD} \qquad\qquad Q = E_H$$

Soft Collinear Effective Theory

eg.



Pion has: $\quad p_\pi^\mu \quad = \quad (2.3\,\mathrm{GeV})n^\mu = Q\,n^\mu \qquad n^2 = \bar{n}^2 = 0,\ (n\cdot p = p^-)$

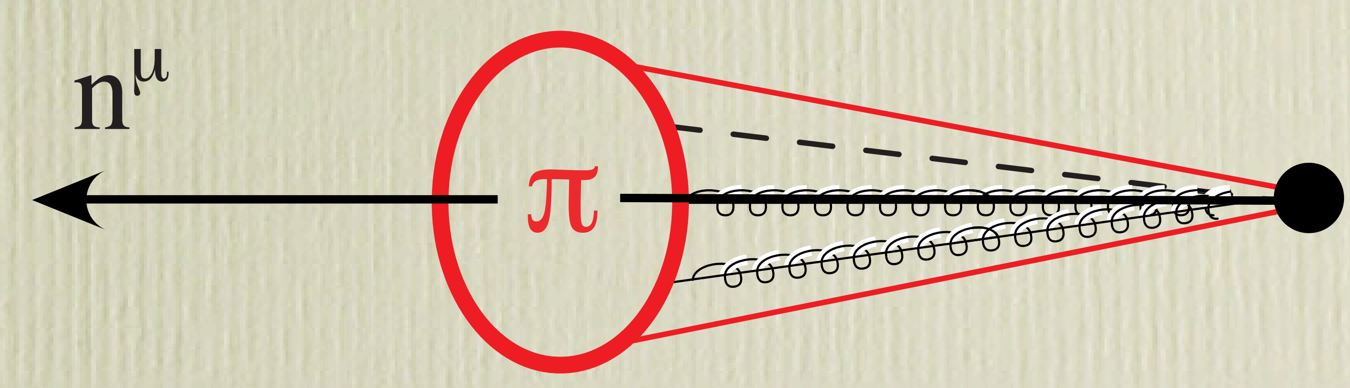
Soft brown muck:

$$p_s^\mu = (p^+, p^-, p^\perp) \sim (\Lambda, \Lambda, \Lambda)$$

Collinear constituents:

$$p_c^\mu = (p^+, p^-, p^\perp) \sim \Big(\frac{\Lambda^2}{Q}, Q, \Lambda\Big) \sim Q(\lambda^2, 1, \lambda)$$

$$\lambda = \frac{\Lambda}{Q}$$



Degrees of freedom in SCET

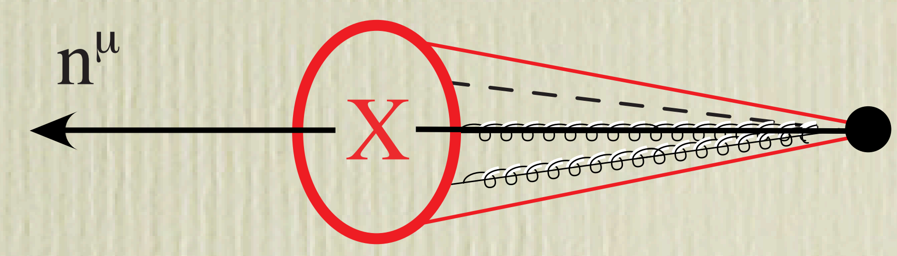
Introduce fields for infrared degrees of freedom (in operators)

modes	$p^\mu = (+,-,\perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$
usoft	$Q(\lambda^2, \lambda^2, \lambda^2)$	$Q^2\lambda^4$	$q_{us},\ A_{us}^\mu$

SCET_I → Energetic jets $\qquad \Lambda \ll \Lambda Q \ll Q^2$

usoft $\quad p^\mu \sim \Lambda$

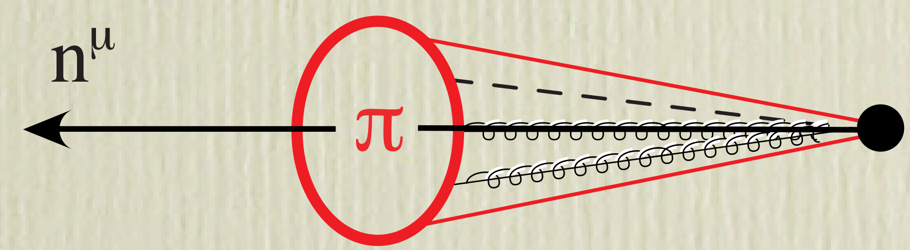
collinear $\quad p_c^2 \sim Q\Lambda, \quad \lambda = \sqrt{\Lambda/Q}$



SCET_II → Energetic hadrons

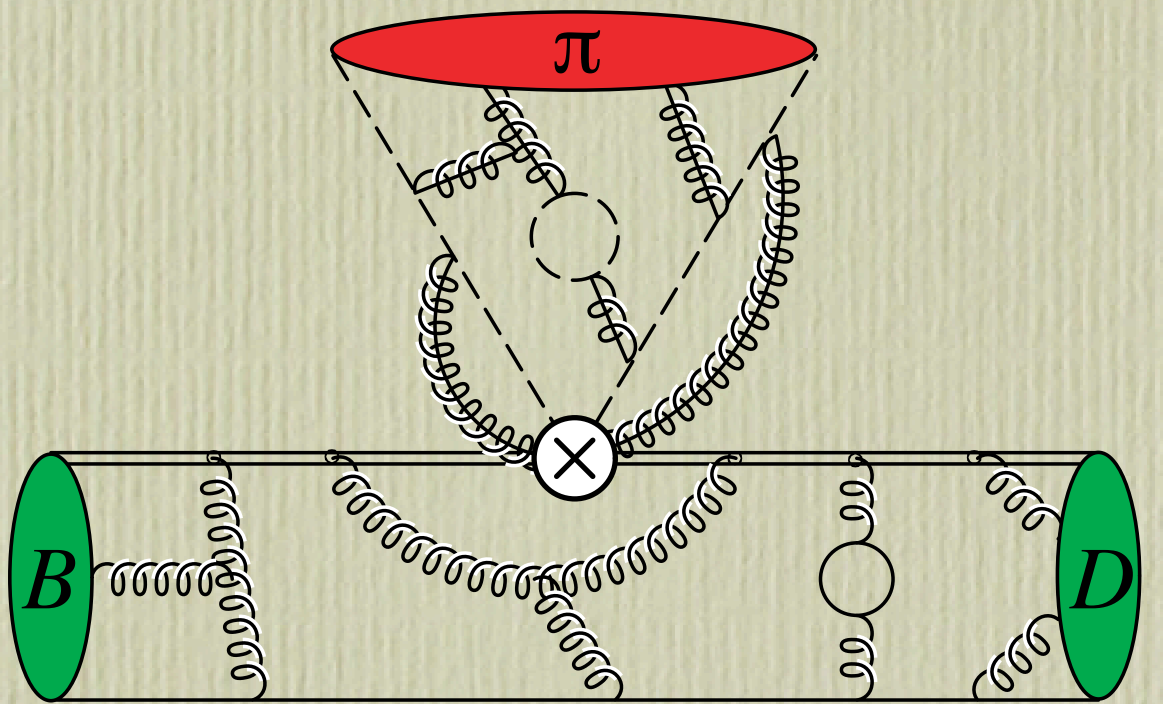
soft $\quad p^\mu \sim \Lambda$

collinear $\quad p_c^2 \sim \Lambda^2, \quad \lambda = \Lambda/Q$



Factorization

LO = λ^5 graphs



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

B, D are soft, π collinear

$$\mathcal{L}_{\rm SCET} = \mathcal{L}_s^{(0)} + \mathcal{L}_c^{(0)}$$

Factorization if $\mathcal{O} = O_c \times O_s$

Bauer, Pirjol, I.S.

$$\langle D\pi|(\bar{c}b)(\bar{u}d)|B\rangle = N\,\xi(v\cdot v')\int_0^1 dx\, T(x,\mu)\,\phi_\pi(x,\mu)$$

Universal functions:

$$\langle D^{(*)}|O_s|B\rangle = \xi(v\cdot v')$$

$$\langle \pi|O_c(x)|0\rangle = f_\pi \phi_\pi(x)$$

Calculate T, $\alpha_s(Q)$

$Q = E_\pi, m_b, m_c$

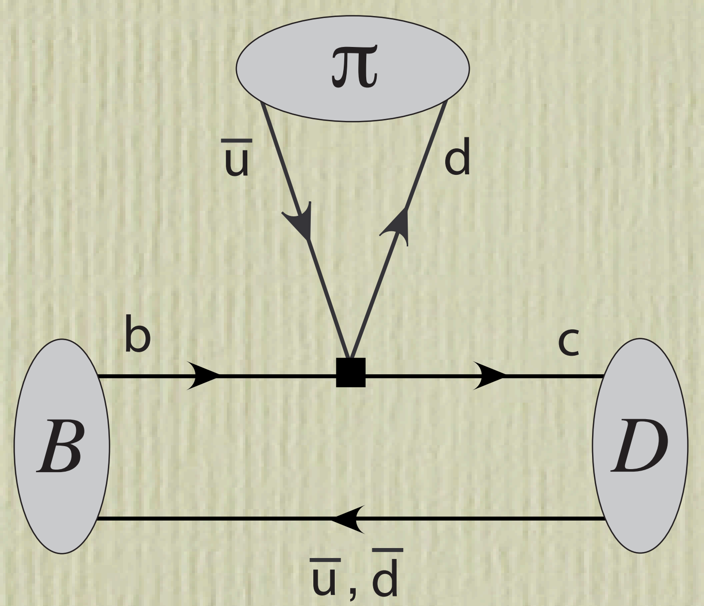
corrections will be $\Lambda/m_c \sim 30\%$

Universal hadronic parameters

Process	Degrees of Freedom (p^2)	Non-Pert. functions
$\bar{B}^0 \to D^+\pi^-, \ldots$	c (Λ^2), s (Λ^2)	$\xi(w)$, ϕ_π
$\bar{B}^0 \to D^0\pi^0, \ldots$	c (Λ^2), s (Λ^2), c ($Q\Lambda$)	$S(k_j^+)$, ϕ_π
$B \to X_s^{endpt}\gamma$, $B \to X_u^{endpt}\ell\nu$	c ($Q\Lambda$), us (Λ^2)	$f(k^+)$
$B \to \pi\ell\nu, \ldots$	c ($Q\Lambda$), s (Λ^2), c (Λ^2)	$\phi_B(k^+)$, $\phi_\pi(x)$, $\zeta_\pi(E)$
$B \to \gamma\ell\nu$, $\gamma\gamma$	c ($Q\Lambda$), us (Λ^2)	ϕ_B
$B \to \pi\pi$	c (Λ^2), s (Λ^2), c ($Q\Lambda$)	ϕ_B, ϕ_π, $\zeta_\pi(E)$
$B \to K^*\gamma$	c ($Q\Lambda$), s (Λ^2), c (Λ^2)	ϕ_B, ϕ_K, $\zeta_{K^*}^\perp(E)$
$e^-p \to e^-X$	c (Λ^2)	$f_{i/p}(\xi)$, $f_{g/p}(\xi)$
$e^-\gamma \to e^-\pi^0$	c (Λ^2), s (Λ^2)	ϕ_π
$\gamma^*M \to M'$	c (Λ^2), s (Λ^2)	ϕ_M, $\phi_{M'}$

$B \to D\pi$

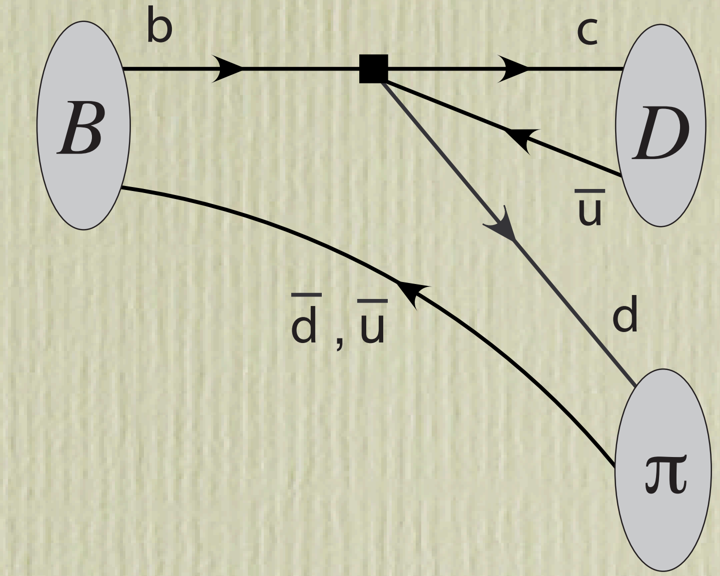
"Tree"



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

$B^- \to D^0\pi^-$

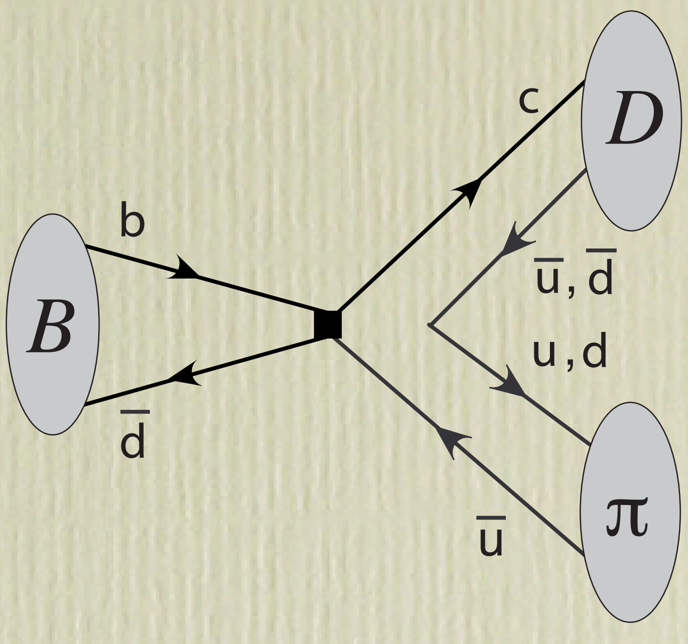
"Color suppressed"



$B^- \to D^0\pi^-$

$\bar{B}^0 \to D^0\pi^0$

"Exchange"



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

$\bar{B}^0 \to D^0\pi^0$

Naive Factorization

Large N_c - not very predictive

$O^0 = (\bar{c}b)_{V-A}(\bar{d}u)_{V-A}$

$O^8 = (\bar{c}T^A b)_{V-A}(\bar{d}T^A u)_{V-A}$

$A(\bar{B}^0 \to D^0\pi^0) \sim a_2 \langle \pi^0|(\bar{d}b)|\bar{B}^0\rangle\langle D^0|(\bar{c}u)|0\rangle$

$(1/N_c)^0$ $1/N_c$

Observed 2001

$1/N_c$

QCDF - $D^0\pi^0$ is nonfactorizable channel

pQCD - predicted with expansion in m_c/m_b

Data

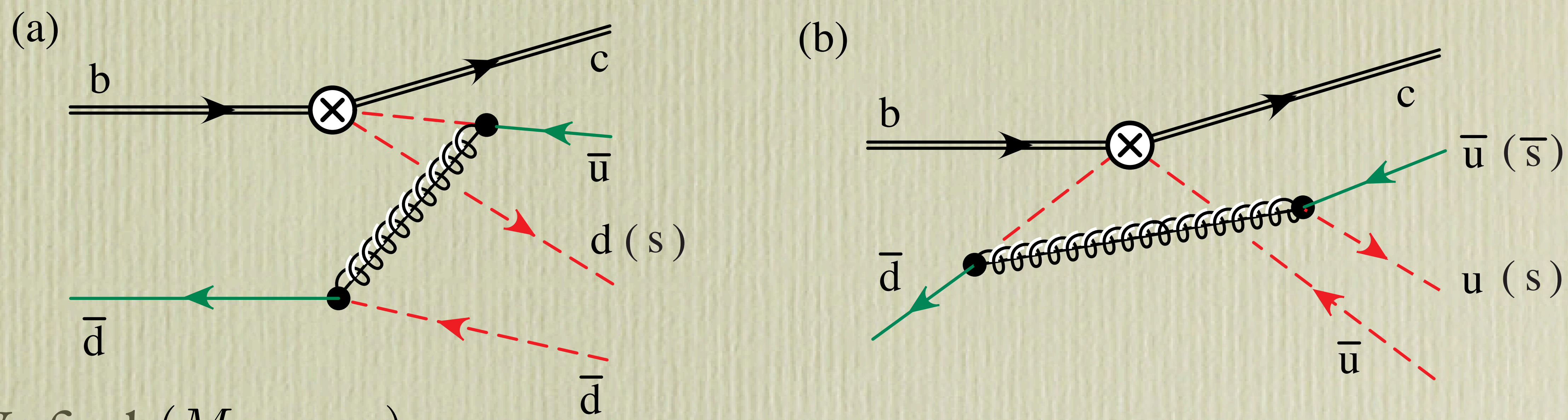
Type	Decay	Br(10^{-3})	Decay	Br(10^{-3})
I	$\bar{B}^0 \to D^+\pi^-$	2.68 ± 0.29 [a]	$\bar{B}^0 \to D^{*+}\pi^-$	2.76 ± 0.21
III	$B^- \to D^0\pi^-$	4.97 ± 0.38 [a]	$B^- \to D^{*0}\pi^-$	4.6 ± 0.4
II	$\bar{B}^0 \to D^0\pi^0$	0.292 ± 0.045 [b]	$\bar{B}^0 \to D^{*0}\pi^0$ [b]	0.25 ± 0.07
I	$\bar{B}^0 \to D^+\rho^-$	7.8 ± 1.4	$\bar{B}^0 \to D^{*+}\rho^-$	6.8 ± 1.0 [c]
III	$B^- \to D^0\rho^-$	13.4 ± 1.8	$B^- \to D^{*0}\rho^-$	9.8 ± 1.8 [c]
II	$\bar{B}^0 \to D^0\rho^0$	0.29 ± 0.11 [d]	$\bar{B}^0 \to D^{*0}\rho^0$	< 0.56

- D = D*
- Br(D^+M^-) agree with factorization
- Br(D^0M^0) small as expected
- but 20-30% power corrections for Br(D^0M^-) / Br(D^+M^-)
- significant strong phase $\delta \sim 30^\circ$

Color Suppressed Decays

Factorization with SCET — Mantry, Pirjol, I.S. '03

Single class of power suppressed $\mathrm{SCET_I}$ operators $T\{\mathcal{O}^{(0)}, \mathcal{L}^{(1)}_{\xi q}, \mathcal{L}^{(1)}_{\xi q}\}$



We find $(M = \pi, \rho)$

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

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

new soft function $S^{(i)}(k_1^+, k_2^+)$ - like generalized parton distributions

i) $\langle D^{(*)0}|O_s^{(0,8)}|\bar{B}^0\rangle \to S^{(0,8)}(k_1^+, k_2^+)$ same for D and D^*

ii) $S^{(i)}(k_1^+, k_2^+)$ is complex, new mechanism for rescattering

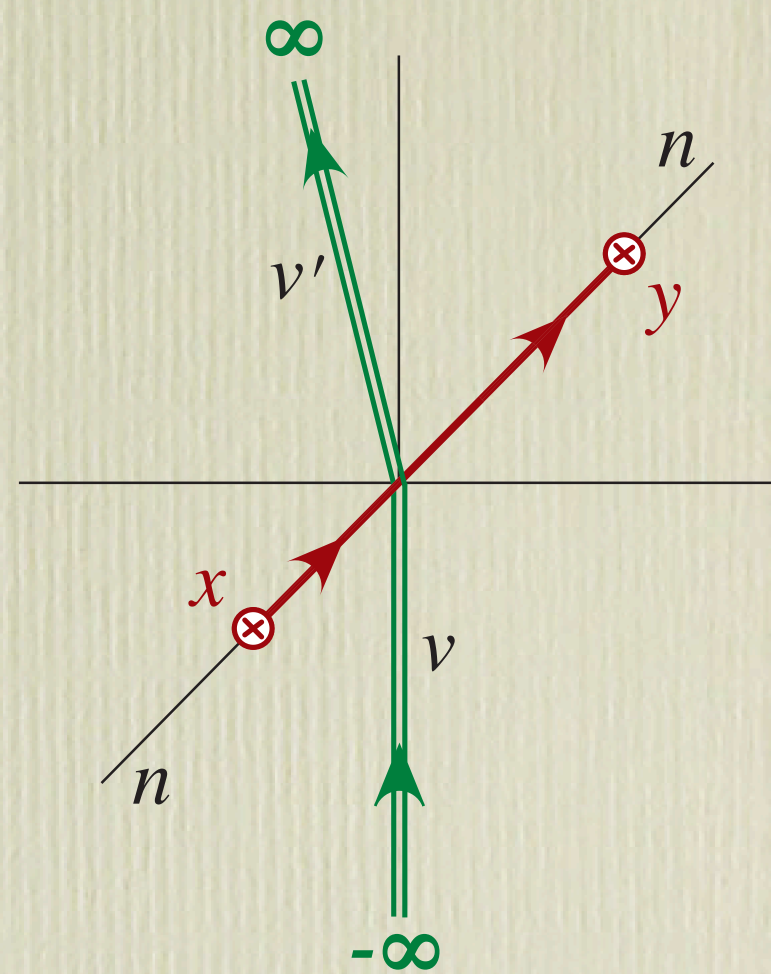
$$O^{(0,8)} = \Big[(h_{v'}^{(c)\dagger} S)\,\Gamma^h\{1, T^a\}\,(S^\dagger h_v^{(b)})\,(\bar{d}\,S)_{k_1^+}\Gamma_s\{1, T^a\}(S^\dagger u)_{k_2^+}\Big]$$

Predict

equal strong phases $\delta^D = \delta^{D^*}$

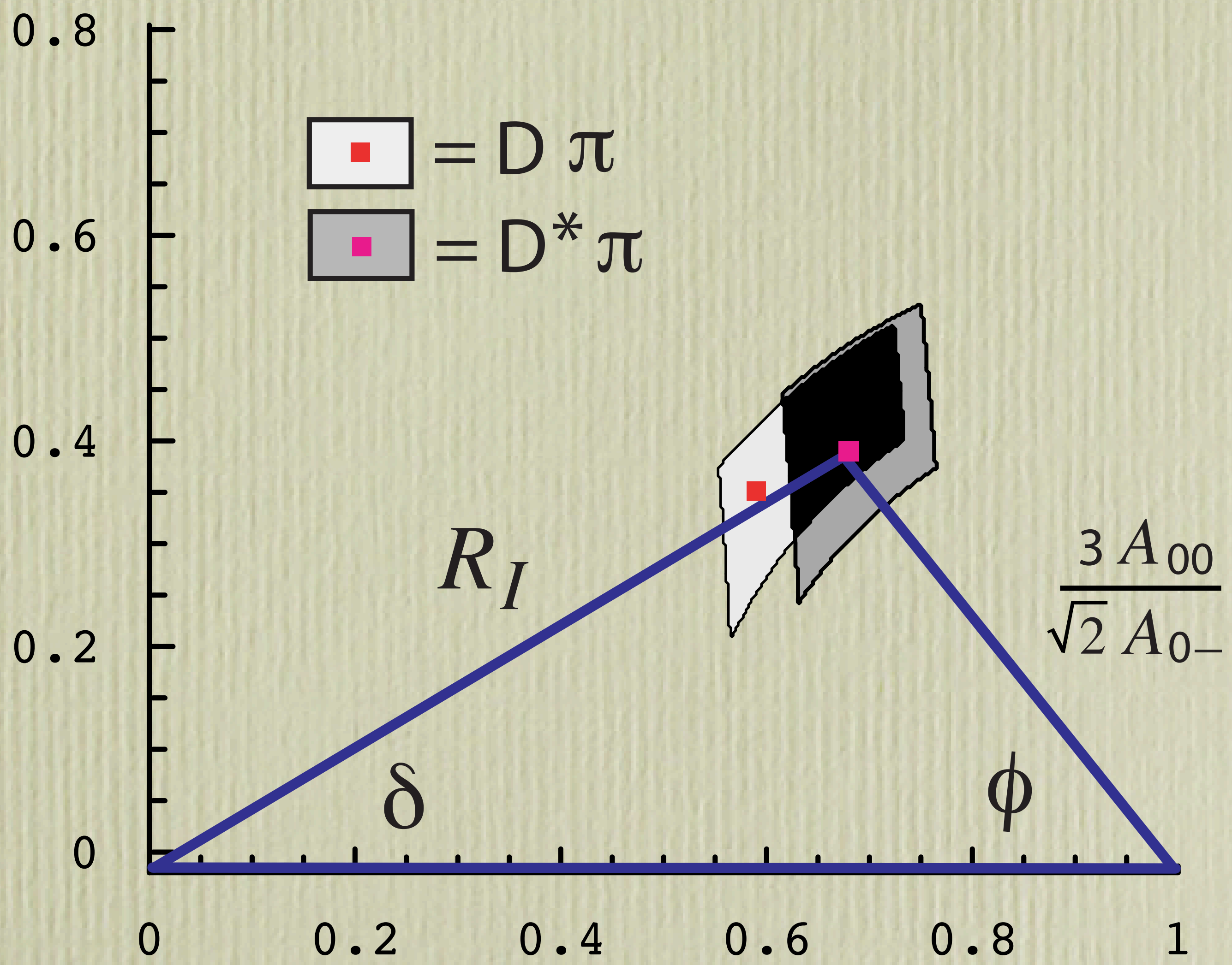
equal amplitudes $A_{00}^D = A_{00}^{D*}$

corrections to this are $\alpha_s(m_b)$, Λ/Q



Tests and Predictions

Expt Average (CLEO, Belle, summer 2003):



isospin gives triangle:

$$A_{0-} = \sqrt{2}A_{00} + A_{+-}$$

rearrange:

$$1 = R_I + \frac{3A_{00}}{\sqrt{2}A_{0-}}$$

$$R_I = \frac{A_{1/2}}{\sqrt{2}A_{3/2}}$$

$$\delta = \arg(A_{1/2}A^*_{3/2})$$

New BaBar results, hep-ph/0310028:

$$Br(\bar{B}^0 \to D^0\pi^0) = (0.29 \pm 0.04) \times 10^{-3}\,, \qquad \delta^{D\pi} = 30^\circ \pm 5^\circ$$

$$Br(\bar{B}^0 \to D^{*0}\pi^0) = (0.29 \pm 0.06) \times 10^{-3}\,, \qquad \delta^{D^*\pi} = 33^\circ \pm 5^\circ$$

Tests and Predictions

Also predict (not post-dict):

$$r_{00}^{\rho} = \frac{A(\bar{B}^0 \to D^{*0}\rho^0)}{A(\bar{B}^0 \to D^0\rho^0)} = 1\,,$$

$$r_{00}^{K^-} = \frac{A(\bar{B}^0 \to D_s^* K^-)}{A(\bar{B}^0 \to D_s K^-)} = 1\,, \qquad r_{00}^{K_\parallel^{*-}} = \frac{A(\bar{B}^0 \to D_s^* K_\parallel^{*-})}{A(\bar{B}^0 \to D_s K_\parallel^{*-})} = 1\,,$$

$$r_{00}^{K^0} = \frac{A(\bar{B}^0 \to D^{0*}\bar{K}^0)}{A(\bar{B}^0 \to D^0\bar{K}^0)} = 1\,, \qquad r_{00}^{K_\parallel^{*0}} = \frac{A(\bar{B}^0 \to D^{*0}\bar{K}_\parallel^{*0})}{A(\bar{B}^0 \to D^0\bar{K}_\parallel^{*0})} = 1$$

ie. same Br and same strong phases

All predictions so far are independent of the form of $J^{(i)}(z, x, k_1^+, k_2^+)$

and $S^{(i)}(k_1^+, k_2^+)\,,\quad \phi_M(x)$

More Predictions

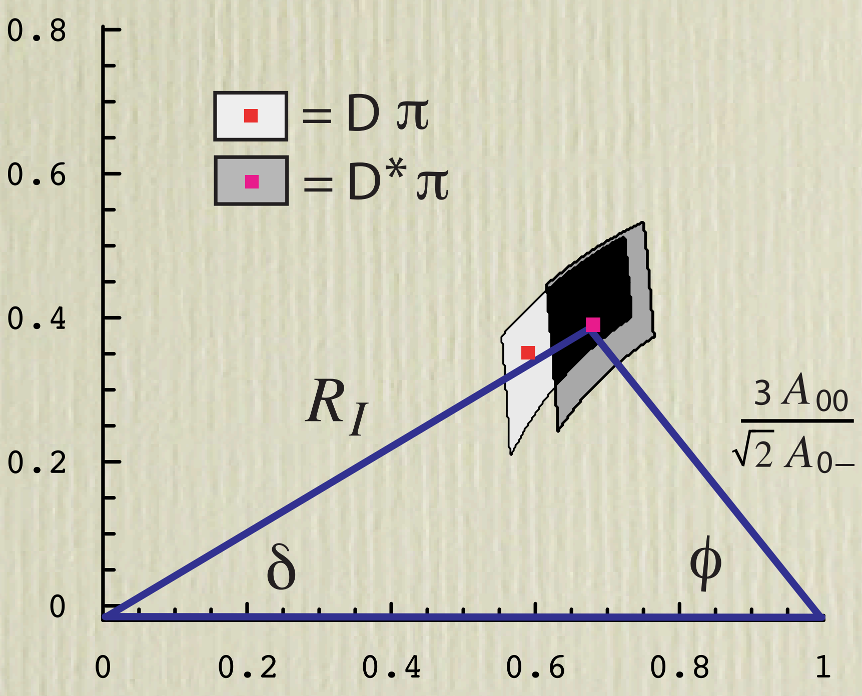
If we expand $J(z, x, k_1^+, k_2^+)$ in $\alpha_s(Q\Lambda)$, we can make more predictions

Relate π and ρ

- $\langle x^{-1}\rangle_\pi \simeq \langle x^{-1}\rangle_\rho$ implies $|r^{D\pi}| = |r^{D\rho}|$. Data gives

$$|r^{D\pi}| \;=\; \frac{|A(\bar{B}^0 \to D^+\pi^-)|}{|A(B^- \to D^0\pi^-)|} = 0.77 \pm 0.05\,, \qquad |r^{D\rho}| = 0.80 \pm 0.09$$

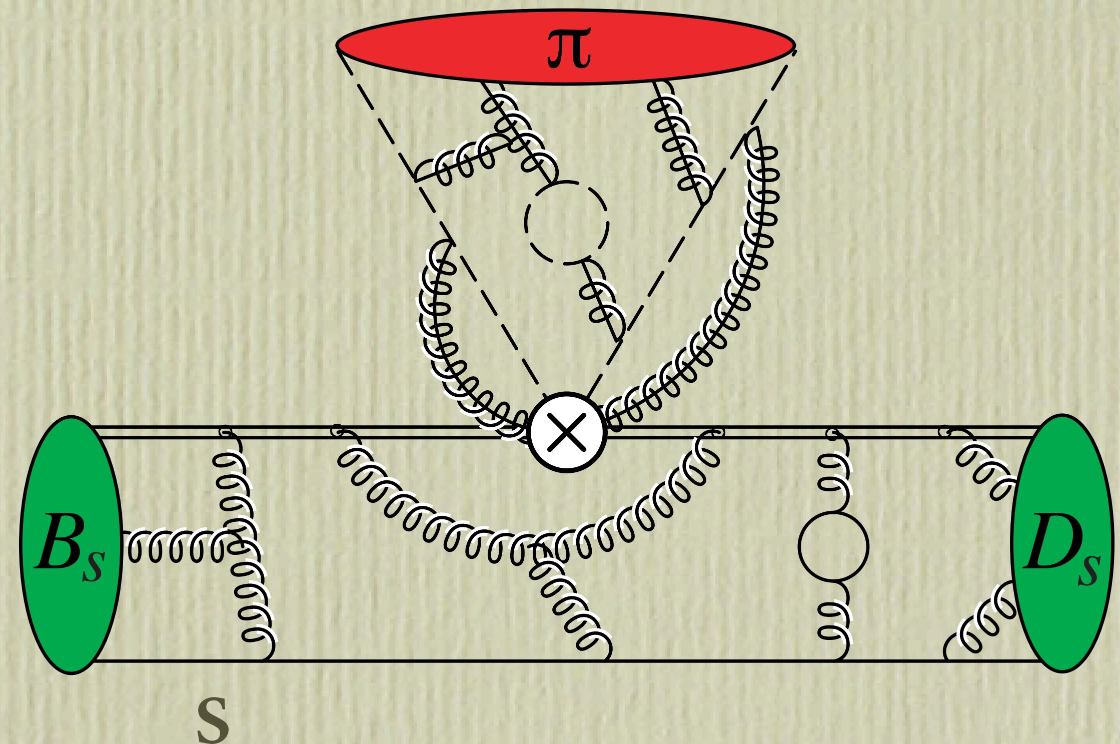
- also predict that $\phi^{D\rho} = \phi^{D\pi}$, not yet tested

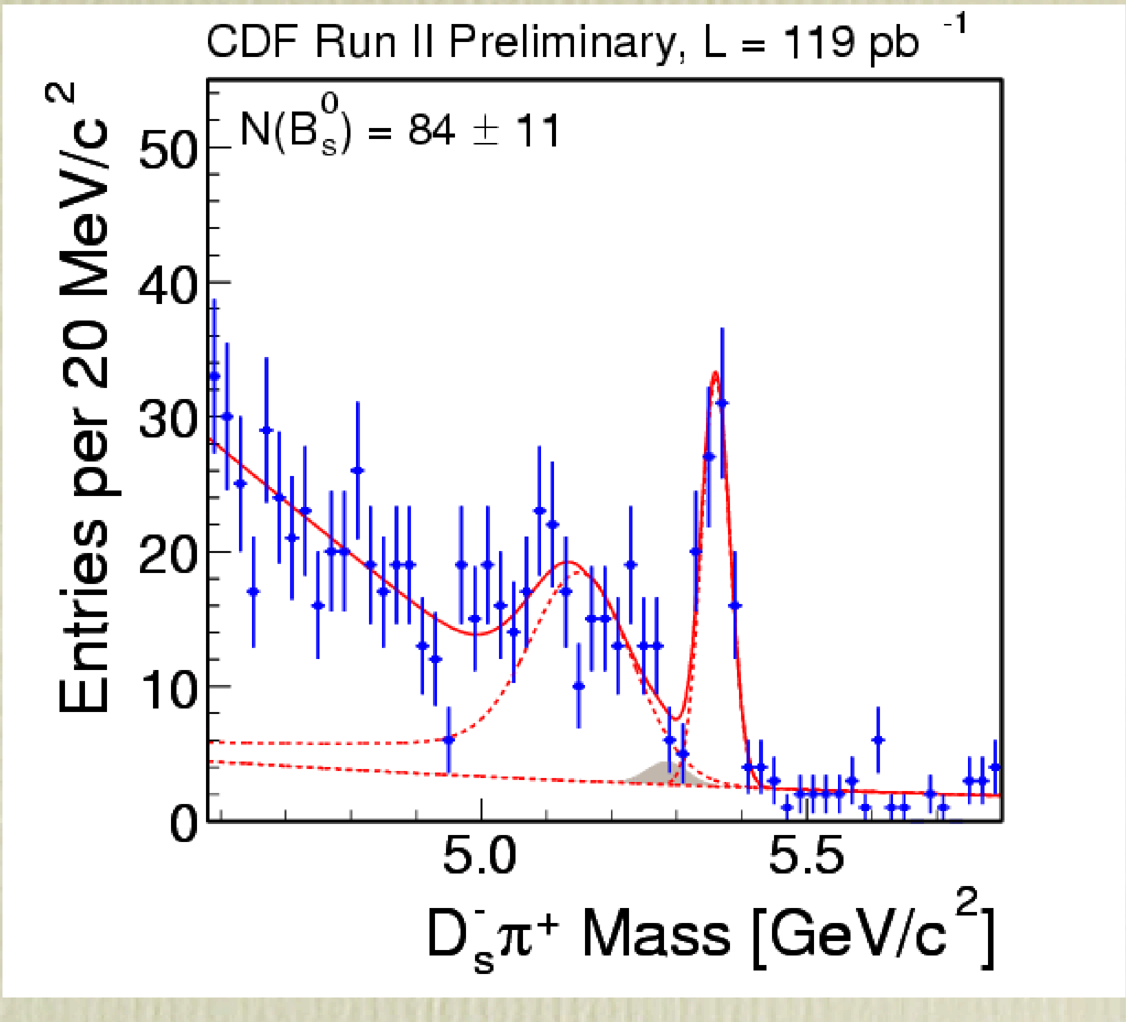


naive factorization for color suppressed decays

Similar Color Allowed Decays

$B_s \to D_s \pi$ from CDF



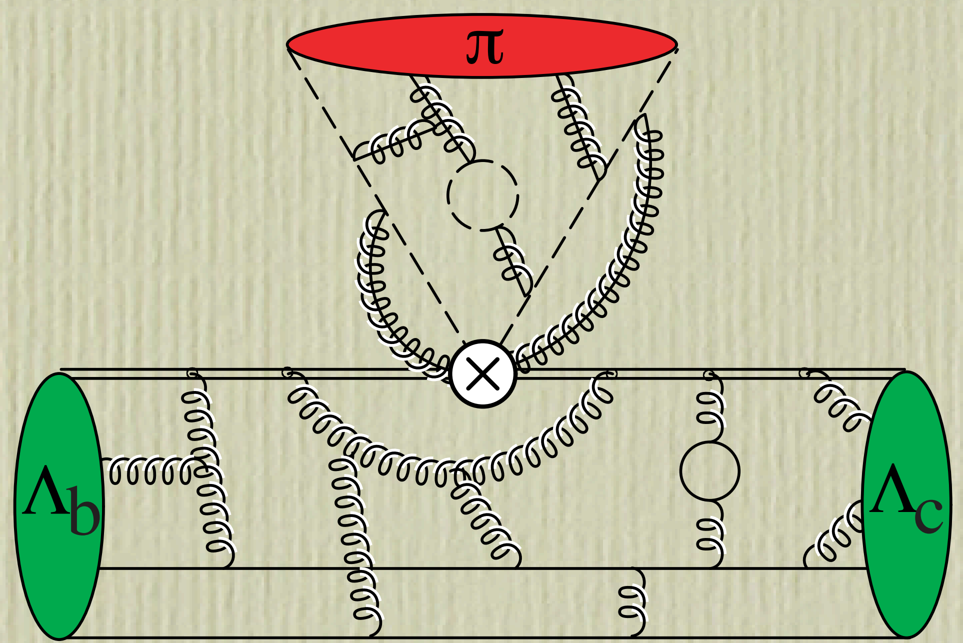


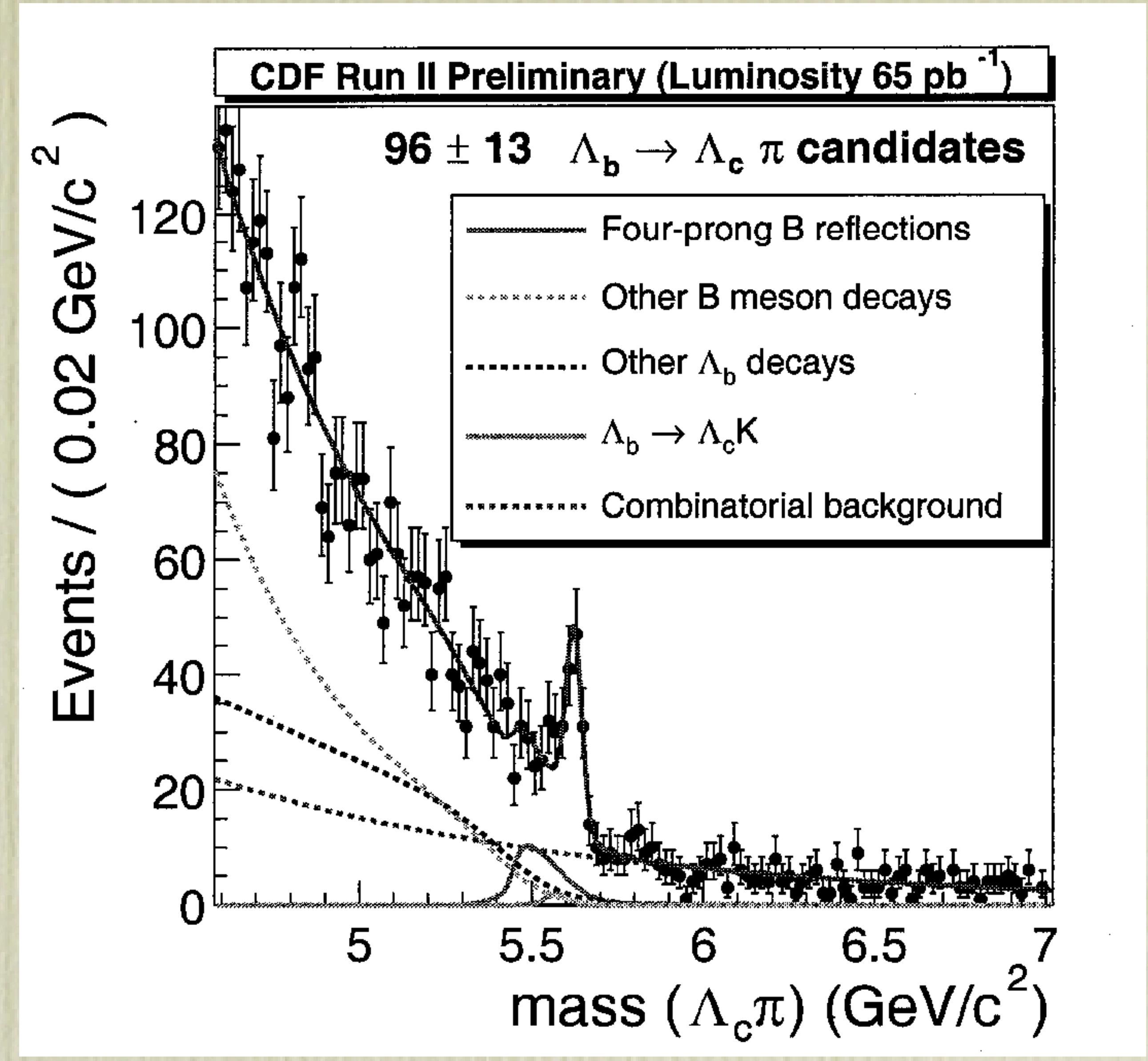
$$Br = (4.2 \pm 1.6) \times 10^{-3}$$

- pure "Tree" topology ➡ gives interesting information
- can handle SU(3) violation with $\left.\frac{d\Gamma}{dq^2}(B_s \to D_s \ell^- \bar{\nu}_\ell)\right|_{q^2=m_\pi^2}$

Add a soft quark

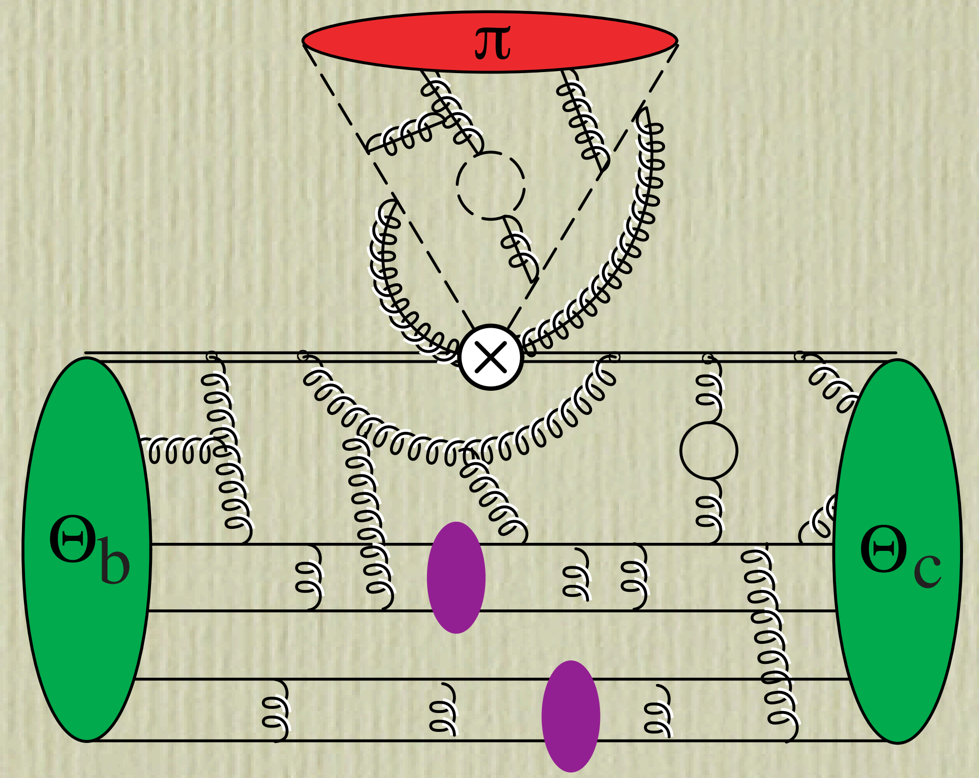
$$\Lambda_b \longrightarrow \Lambda_c \pi$$





Add three soft quarks

$\Theta_b \to \Theta_c \pi$?



Diquark model

Jaffe, Wilczek '03

- Θ_b , Θ_c may decay weakly
- $\Theta_s \to K_S\, p$ penalty for breaking diquark correlation

Look for:

$$\begin{aligned} \Theta_b^+ &\to \Theta_c^0 \pi^+ \\ &\to \Theta_s^+ \pi^- \pi^+ \\ &\to (K_S\, p) \pi^- \pi^+ \\ &\to \pi^+ \pi^- p\, \pi^- \pi^+ \end{aligned}$$

- all Cabbibo allowed
- all charged
- only pay diquark penalty once
- try to calculate it ...

$B \to M_1 M_2$

$B \to \pi\pi$ $B \to \pi K$ $B \to \rho K^*$

$B \to \rho\rho$ $B \to KK$

$B \to \pi K^*$ $B \to \pi\rho$

$B_s \to \pi^0\eta$ $B_s \to K^+ K^{*-}$

PP = 21 + 13 decays
PV = 40 + 23 decays
VV = 21 + 13 decays

→ eg. SU(3) analysis Chiang et al.
many of them observed
QCDF analysis Beneke et al.

Before we tackle the nonlep tonic we should consider the semilep tonic

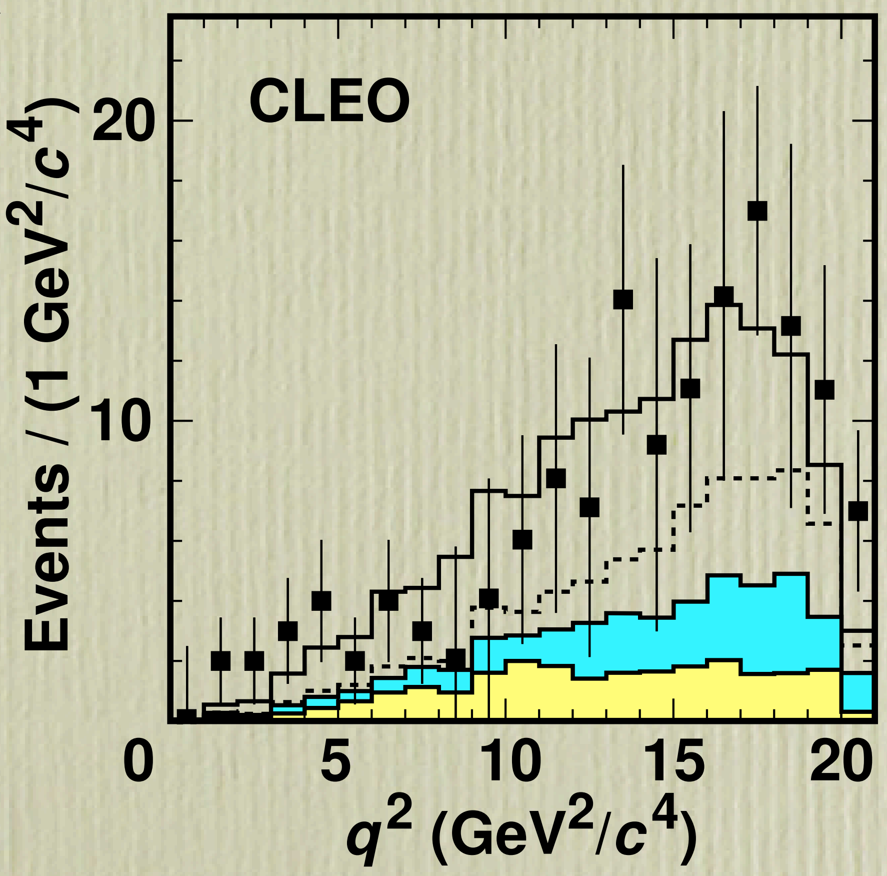
$B \to \pi\ell\bar{\nu}_\ell$ $B \to K^*\gamma$ $B \to \rho\gamma$

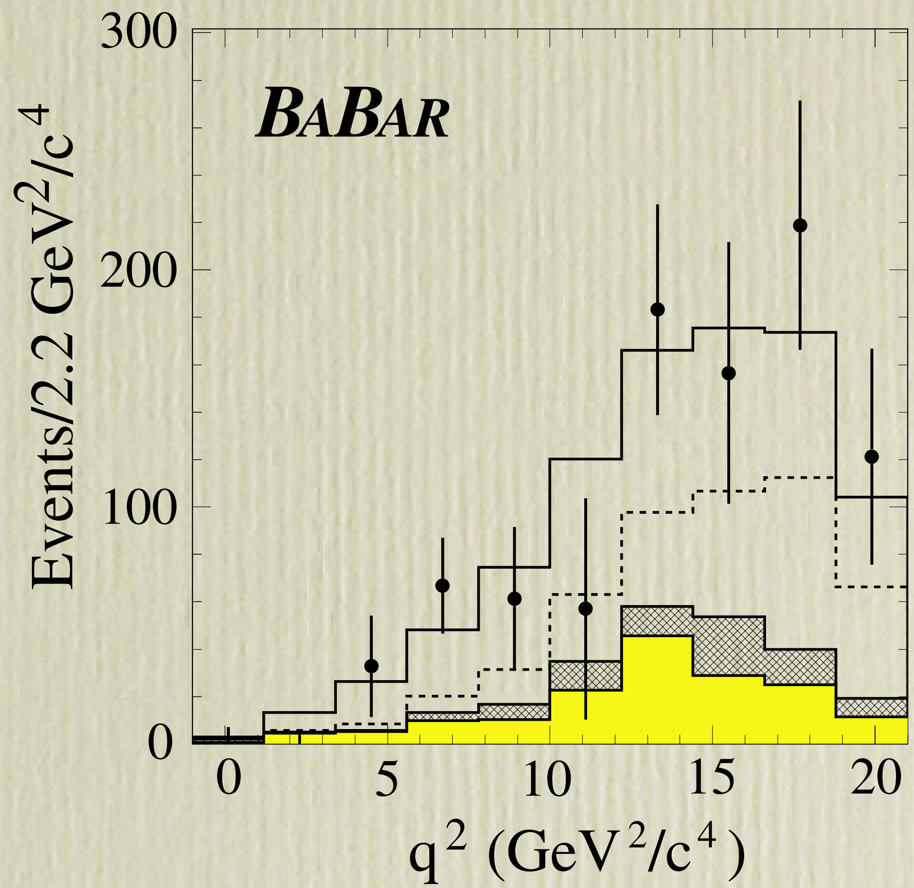
$B \to \rho\ell\bar{\nu}_\ell$ $B \to K e^+ e^-$ $B \to K^*\ell^+\ell^-$

Heavy-to-Light Decays

- Large q^2 accessible on the Lattice ($B \to \pi \ell \nu$, $q^2 > 17\,\mathrm{GeV}^2$)
- For small q^2, $E \gg \Lambda_{\mathrm{QCD}}$ and large energy factorization applies

$B \to \rho \ell \bar{\nu}_\ell$





Form factors

pseudoscalar: f_+, f_0, f_T

vector: V, A_0, A_1, A_2, T_1, T_2, T_3

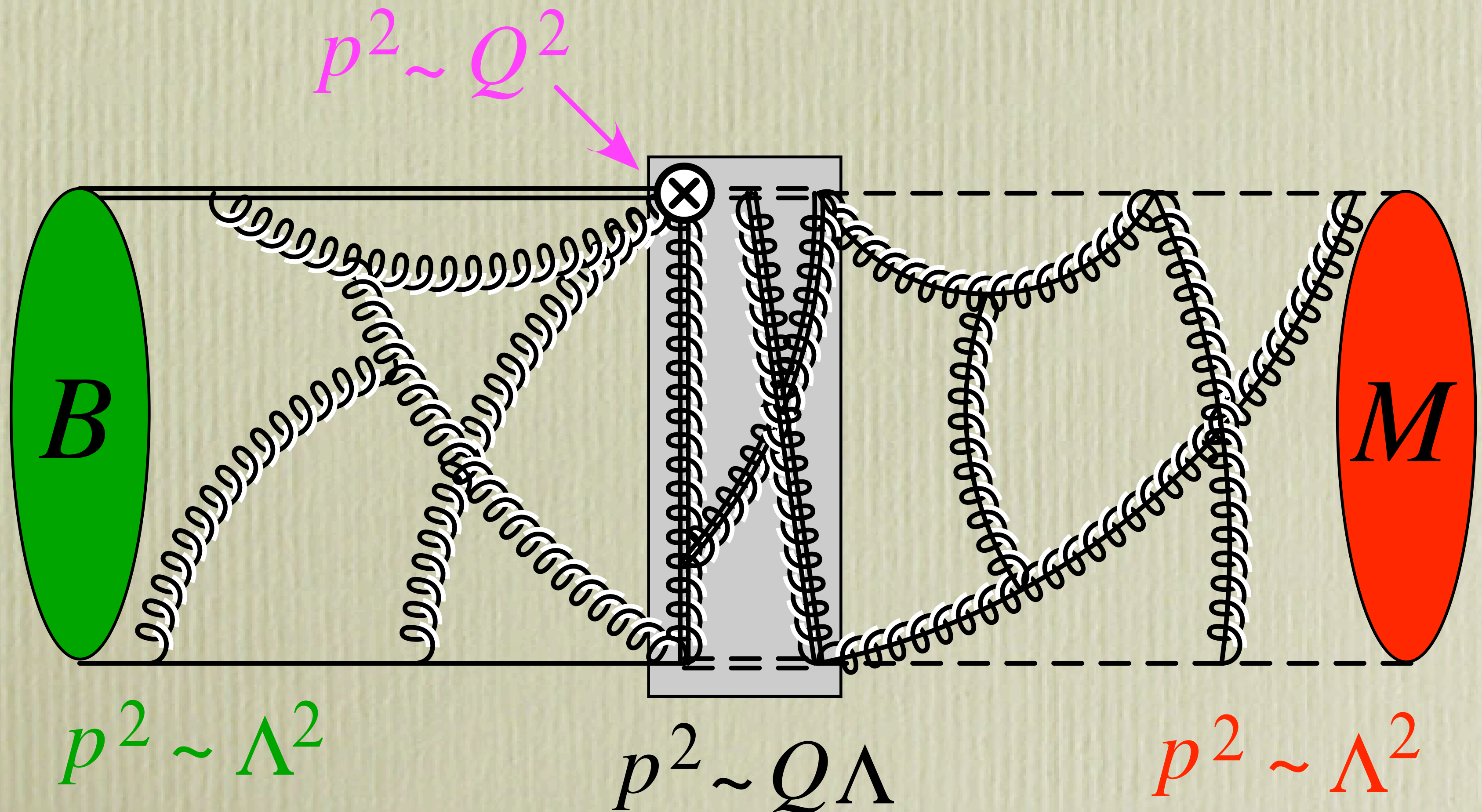
SCET Result

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

$$f^F(Q) = \frac{f_B f_M m_B}{4E^2} \int_0^1 dz \int_0^1 dx \int_0^\infty dr_+ \, T(z, E, m_b) \times J(z, x, r_+, E) \phi_M(x) \phi_B^+(r_+)$$

$$f^{\rm NF}(Q) = C_k(E, m_b)\, \zeta_k(Q\Lambda, \Lambda^2)$$

$\Lambda/Q \ll 1$



result at LO in λ, all orders in α_s, where $Q = \{m_b, E_M\}$

Some Controversy:

- Can $\zeta(Q\Lambda, \Lambda^2)$ be factored further without singularities ?

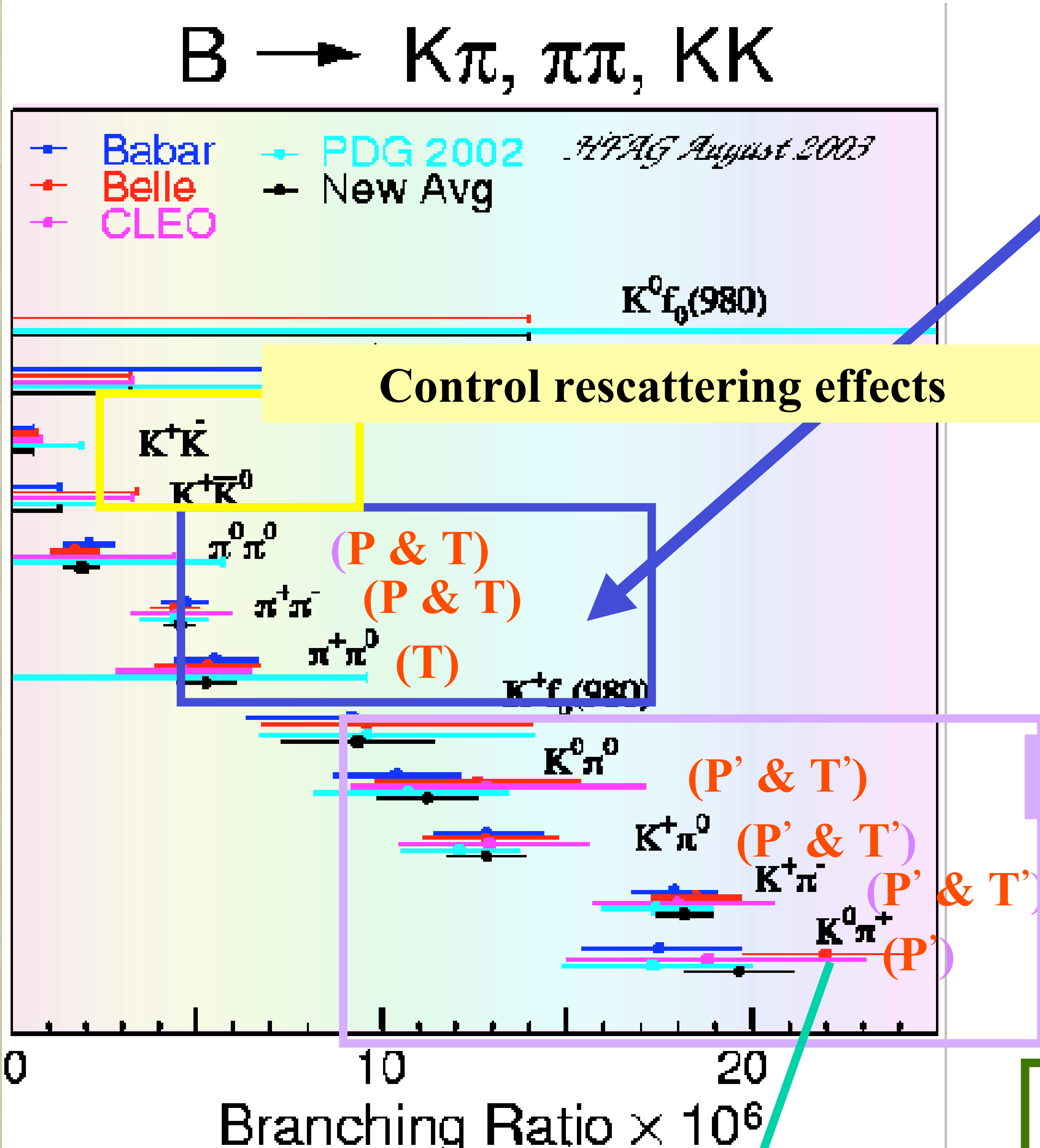
- Does f^{NF} dominate over f^{F} ? (QCDF assumes this)

- How large are the Sudakov double logarithms?

→ can be addressed with SCET

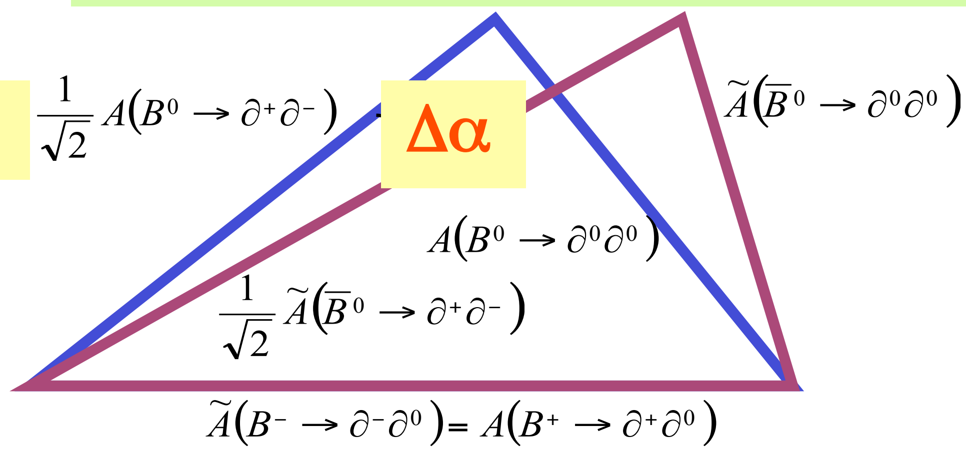
From H. Jawahery, Lepton-Photon '03

A few comments on the already established pattern from charmless 2-body decays



Connected via Isospin symmetry *(Gronau &London)* (Isospin engineering)

Constructing these triangles is a major goal of the experiments



With Tree alone,expect:

$$\frac{B \to K\pi}{B \to \pi\pi} \approx 5\%$$

Measurements:

$$\frac{B \to K\pi}{B \to \pi\pi} \approx 4$$

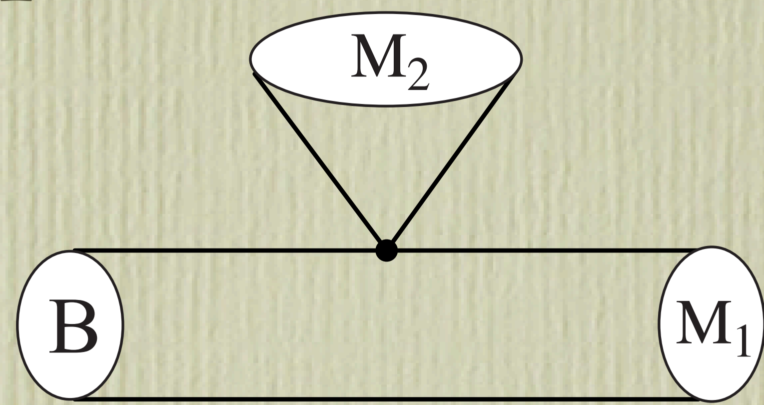
➔ **Penguins are significant players**

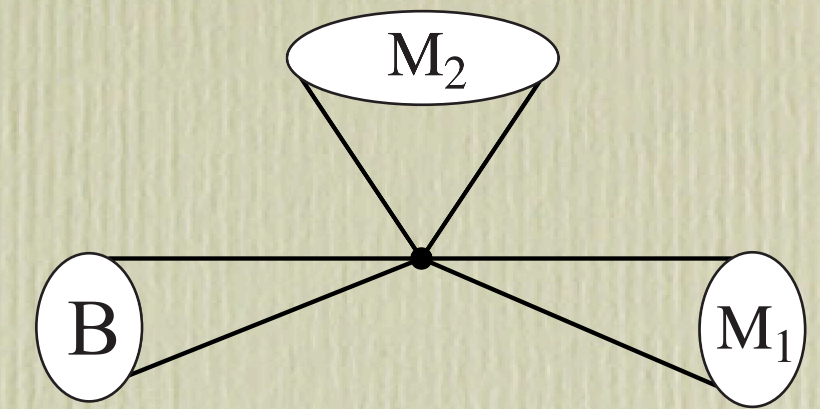
P' & use SU(3)connections to estimate P

$B \to M_1 M_2$ Factorization

QCDF

BBNS



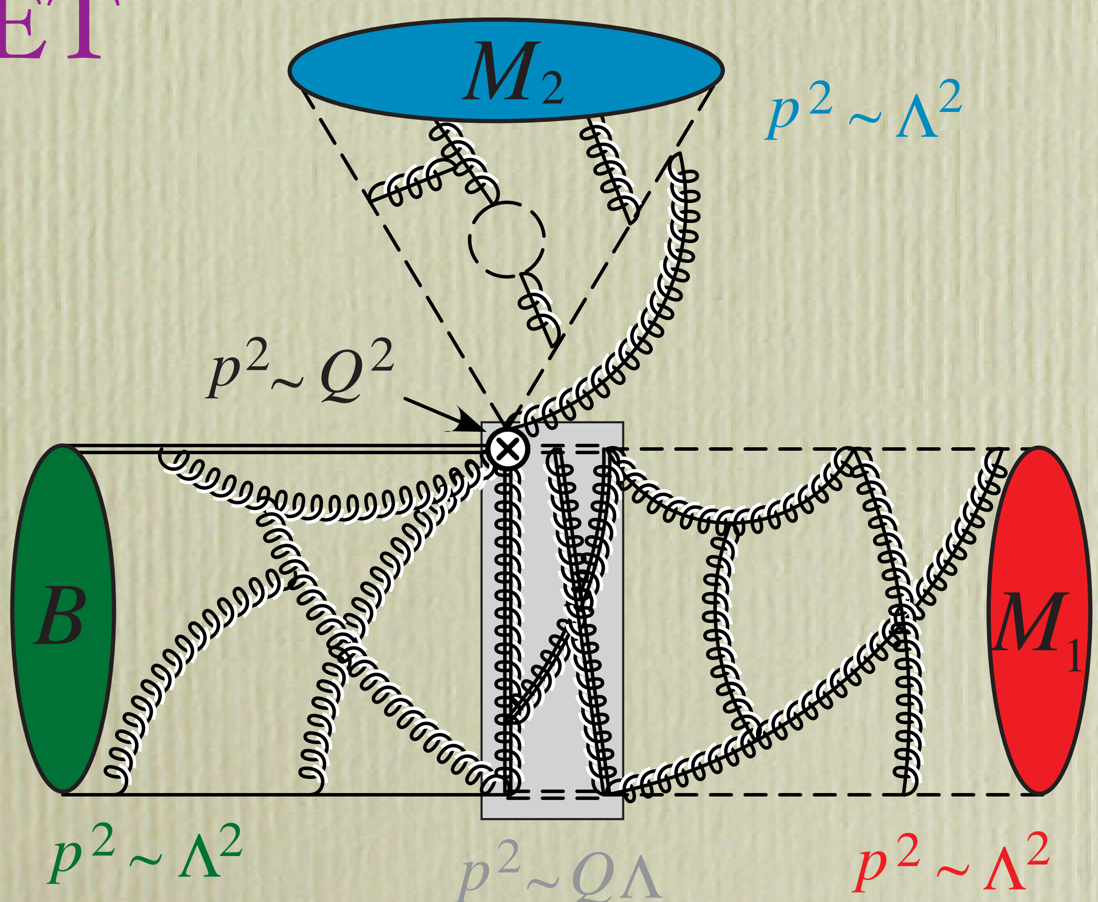


$F^{B\to M_1}$, $\phi_{M_2}(x)$ $\qquad$ $\phi_B(r^+)$, $\phi_{M_1}(x)$, $\phi_{M_2}(y)$

SCET

Chay, Kim

Bauer, Pirjol, Rothstein, I.S.



- involves ζ_{M_1}, $\phi_B(r^+)$, $\phi_{M_i}(x)$
  same as form factors
- same function $J(z, x, r_+, E)$
- one formula for PP, PV, VV

SU(3) Violation in $\phi_M(x)$

J.Chen, I.S. '03

$M = \pi, K, \eta$

Factorization theorems usually do not try to untangle

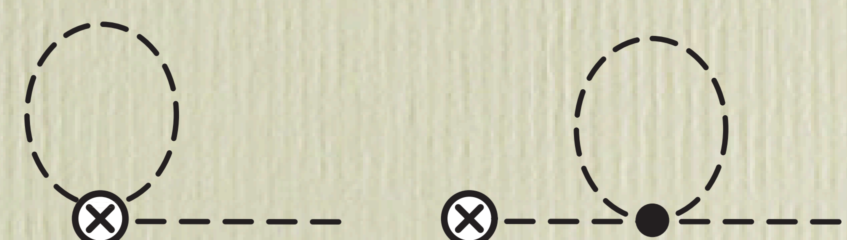
$m_{u,d,s}$ from $\Lambda_{\rm QCD}$ → left in nonperturbative functions

$$\phi_M(x) = \phi_0(x) + \sum_{P=\pi,K,\eta} \frac{m_P^2}{(4\pi f)^2}\Big[a_M^P(x)\ln\Big(\frac{m_P^2}{\mu^2}\Big) + b_M^P(x,\mu)\Big]$$

$$\int_0^1 dx\, \phi_M(x) = 1$$

Using chiral perturbation theory we find:

- Non-analytic terms vanish



all in f_M

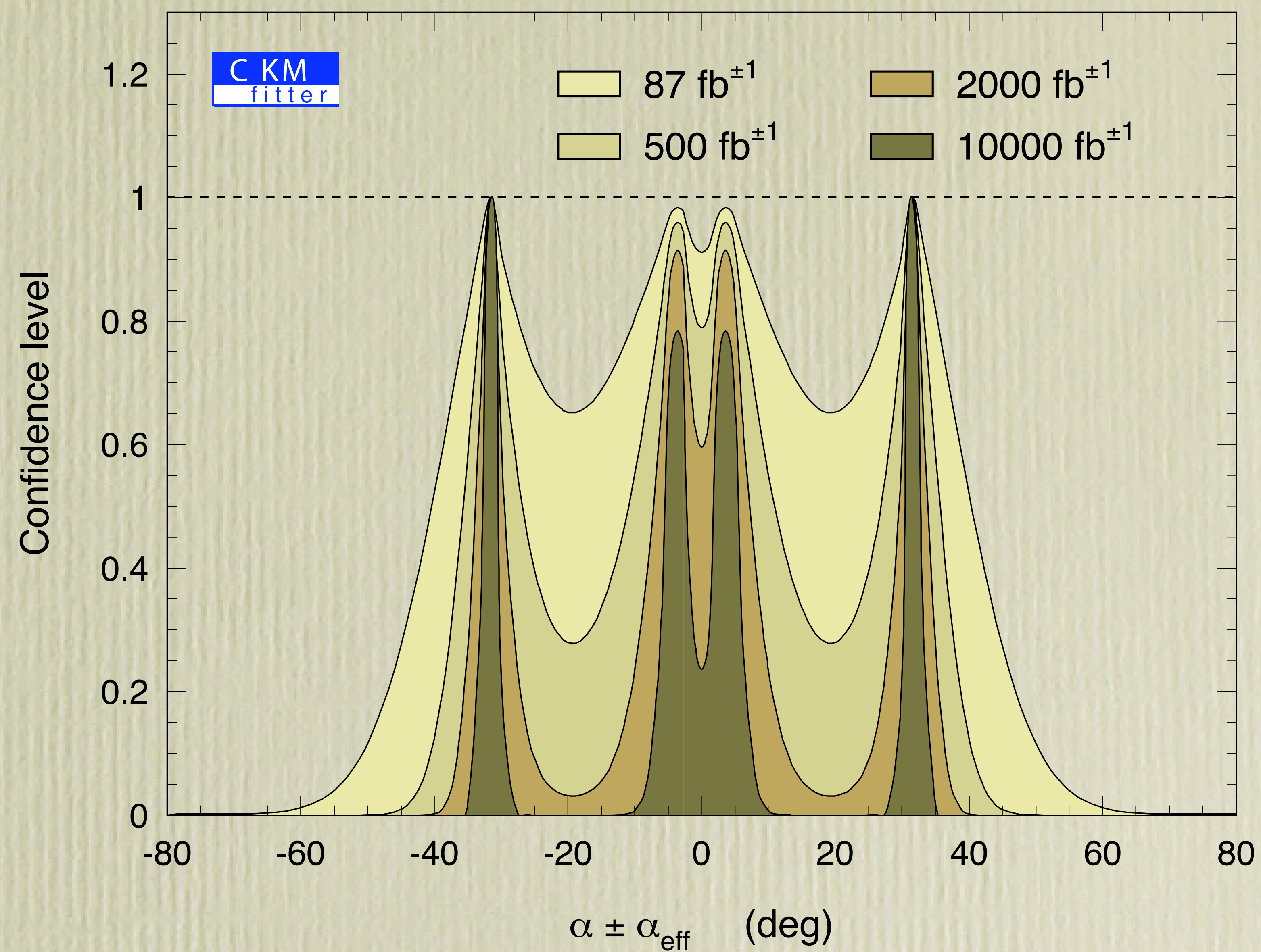
- With all NLO operators, ie all the leading SU(3) violation:

$$\phi_\pi(x) + 3\phi_\eta(x) = 2\big[\phi_{K^+}(x) + \phi_{K^-}(x)\big]$$

"Gell-Mann Okubo"

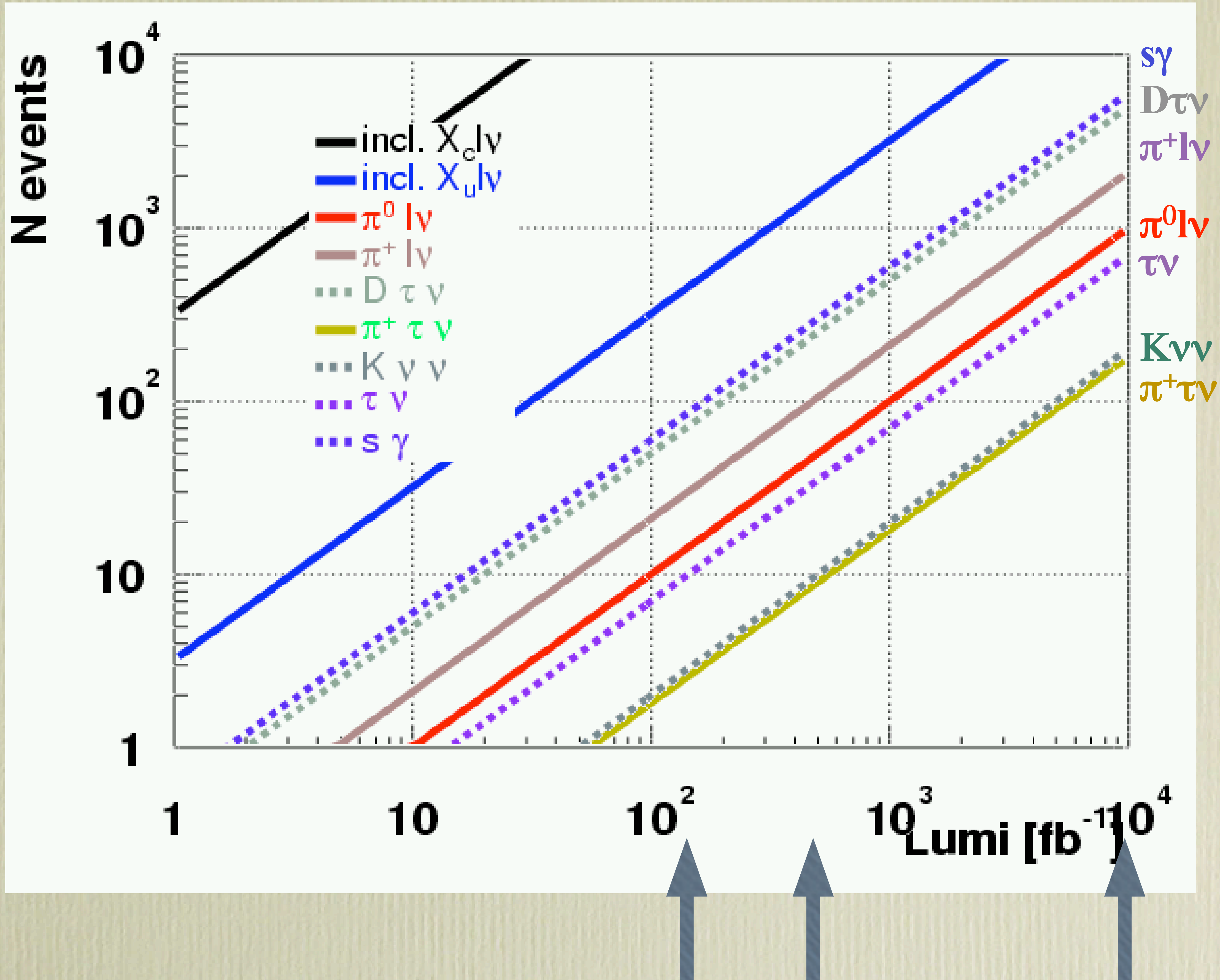
Uncertainty in pure isospin analysis

Extrapolation to future



Future B-factories: LHCb, BTeV, $e^+e^-@10^{36}$ luminosity

D. del Re (SuperB '03 workshop)



Today 2006 1yr @10^{36}

Outlook

- The theory of nonleptonic B decays is challenging, but progress is being made
- The SCET can be applied to:
  Nonleptonic decays, Other B decays
  Jet physics, Exclusive form factors
  Charmonium, Upsilon physics
  ... others ?
  - Allows power corrections to be addressed in a model independent way
  - For B's, need to carefully examine expansion for each process and improve our understanding of power corrections to trust results beyond the 20% level
- Lots of data now, lots of data still to come
- A lot of theory and phenomenology left to study ...