Flavor physics as a probe of QCD

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Fermilab

Planning Your Experiment at Fermilab

CHAPTER 5

The Fermilab director, with the advice of the Physics Advisory Committee (PAC), determines the experimental program by selecting the experiments to be done at Fermilab. The PAC normally consists of 12 members appointed by the director for overlapping four-year terms. The director customarily seeks advice from the Users' Executive Committee in selecting new PAC members.

The Program Planning Office coordinates the experimental physics program at the laboratory, developing experimental schedules and establishing priorities among experiments, in consultation with the director.

Proposing an Experiment

Scientists who would like to carry out an experiment at Fermilab first submit a formal research proposal to the laboratory director. Although it's not a requirement, it often helps to discuss the proposal with Fermilab staff before making the formal submission.

Consideration of Proposals

In deciding whether or not to approve an experiment, the director usually relies heavily on the recommendations of the PAC, which meets several times a year to consider proposals. During an open PAC session, the proponents, or scientists proposing an experiment, make an oral presentation to the PAC. After the presentation the PAC has a preliminary discussion of the proposal and the presentation. Afterward, the PAC may have questions or comments for the proponents, which are addressed either orally at the time or in written form for the next meeting.

At subsequent meetings the PAC considers all the material available regarding the proposal, including the responses to questions and impact statements prepared by laboratory staff, before making a recommendation to the director.

Deciding on Proposals

The director makes a decision about the proposal on the basis of the PAC recommendation and other factors. The decision may result in approval, deferral or rejection of the experimental proposal.

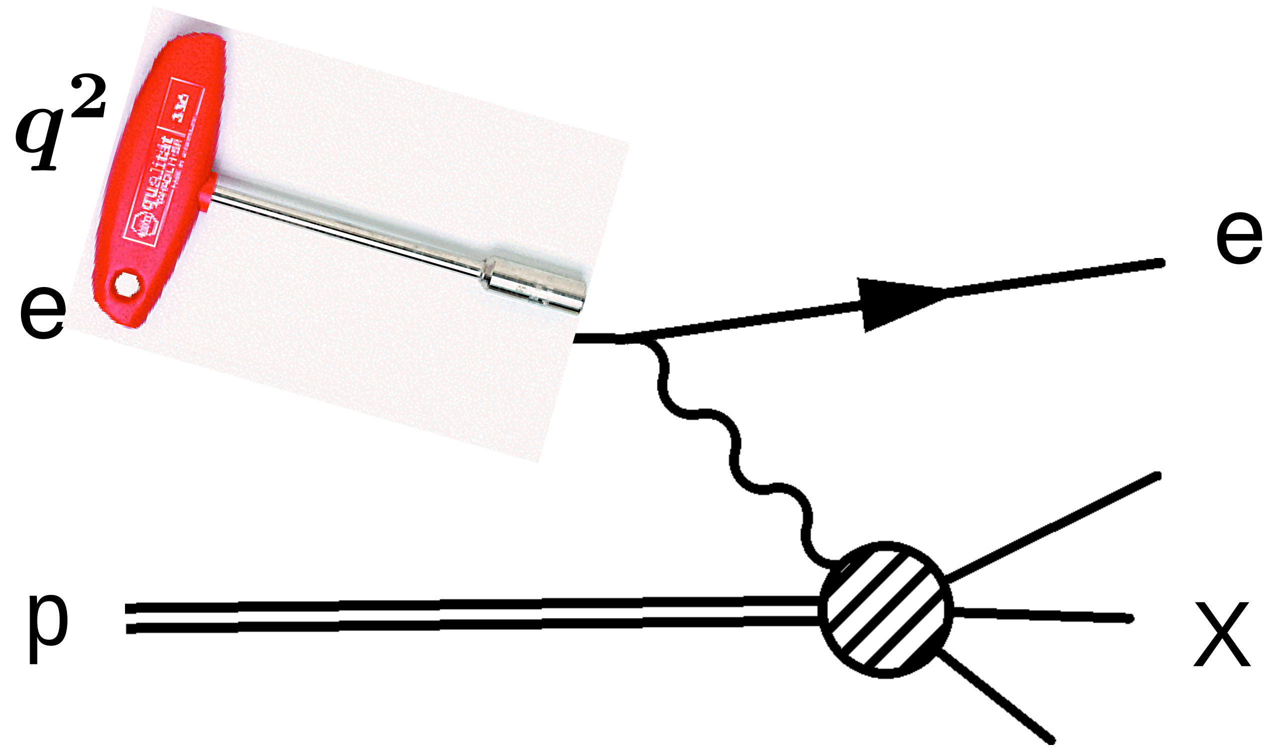
Approval. The director may grant Stage I approval if the proposed physics goals are worthwhile, the experiment seems technically feasible, and the costs in laboratory resources and running time of the experiment appear appropriate for the expected physics results. Experimenters need to recognize that Stage I approval does not represent a commitment of laboratory resources, either in support for setting up the experiment or in running time. Rather, it helps laboratory staff and experimenters in planning long-range projects.

After Stage I approval, the experimenters and the laboratory carry out a careful technical design and cost study for the experiment, and prepare a first draft of the Memorandum Of Understanding (MOU), as described later in this chapter. If the PAC finds the results of this procedure acceptable, and the experiment fits into the overall priorities of the experimental program, the PAC recommends Stage II approval. In some cases, the director grants full approval without the Stage I-II process.

Recall the case of deep inelastic scattering:

Use the electromagnetic interaction as a clean tool to probe strong interactions at short distance

$$e^- p^+ \to e^- X$$

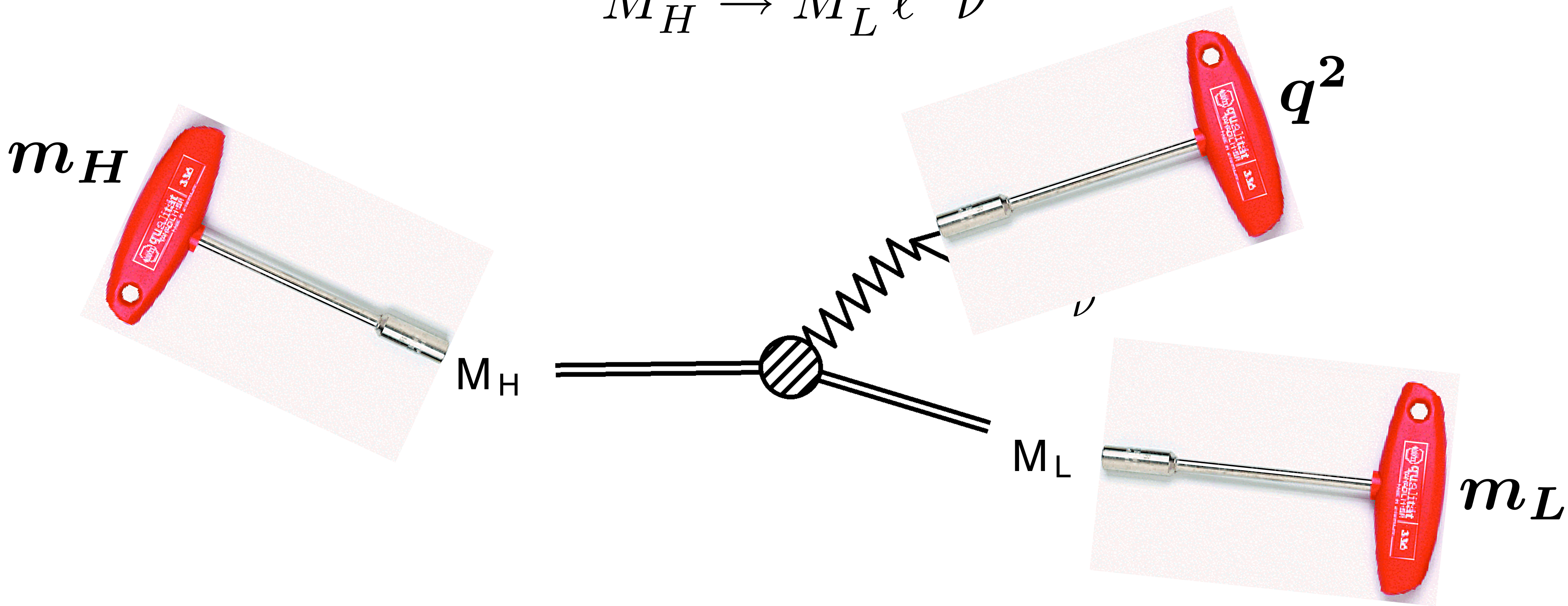


- Explore scaling violations
- Determine α_s
- Measure parton distributions

Similarly with weak transitions of hadrons:

(focus on exclusive semileptonic transitions of flavor-nonsinglet, pseudoscalar mesons)

$$M_H^0 \to M_L^+ \ell^- \bar{\nu}$$

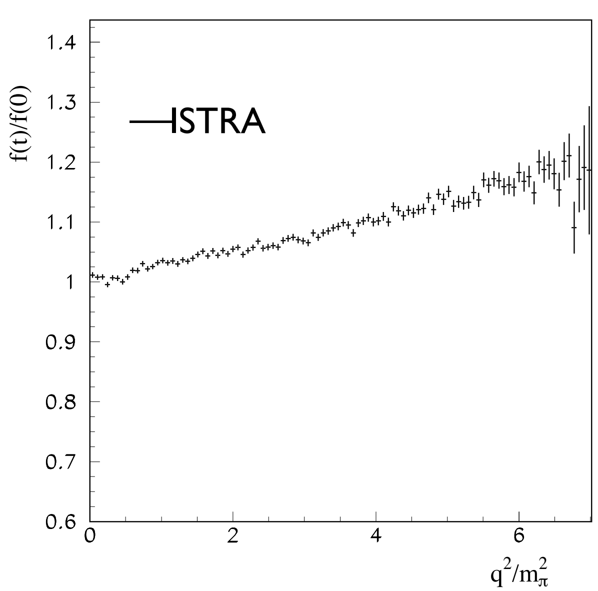


- Explore well-defined limits of QCD
- Determine weak interaction parameters - $|V_{ij}|$
- Measure universal hadronic inputs

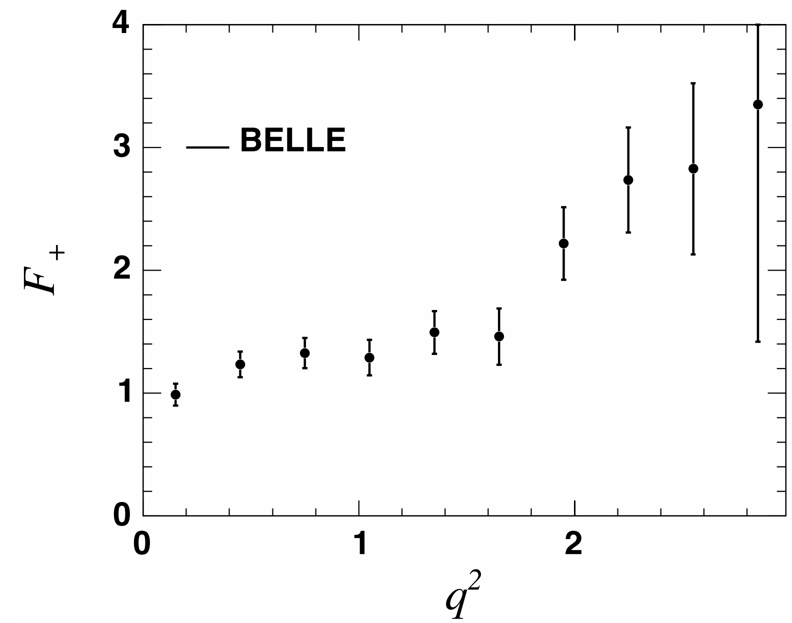
The players: F_+, F_0

$$
\begin{aligned}
\langle M_L(p')|V^\mu|M_H(p)\rangle &= F_+(q^2)(p^\mu + p'^\mu) + F_-(q^2)(p^\mu - p'^\mu) \\
&= F_+(q^2)\left(p^\mu + p'^\mu - \frac{m_H^2 - m_L^2}{q^2}q^\mu\right) + F_0(q^2)\frac{m_H^2 - m_L^2}{q^2}q^\mu
\end{aligned}
$$

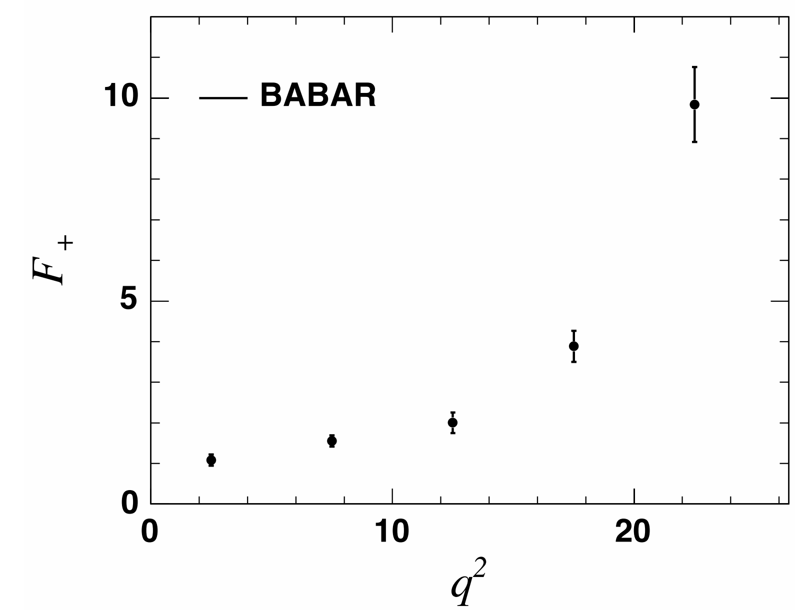
$K \to \pi\ell\nu$



$D \to \pi\ell\nu$



$B \to \pi\ell\nu$



- What are the measurable quantities ?
- What can we learn ?

- Very few independent shape observables are accessible (not obvious)
  - systematic expansion of form factor shape
  - controlled uncertainty on |Vub|, |Vus|, other observables
  - increased effectiveness of lattice simulations
  - model-independent determination of hadronic parameters
- Limits can answer fundamental and interesting questions about QCD
  (interesting = answer is an integer number + answer is not known)

Shape observables: β$_+$, β$_0$

$$\begin{aligned} \langle M_L(p')|V^\mu|M_H(p)\rangle &= F_+(q^2)(p^\mu + p'^\mu) + F_-(q^2)(p^\mu - p'^\mu) \\ &= F_+(q^2)\left(p^\mu + p'^\mu - \frac{m_H^2 - m_L^2}{q^2}q^\mu\right) + F_0(q^2)\frac{m_H^2 - m_L^2}{q^2}q^\mu \end{aligned}$$

Relative slope:

$$1/\beta_i \equiv \frac{m_H^2 - m_L^2}{F_+(0)} \left.\frac{dF_i}{dq^2}\right|_{q^2=0}$$

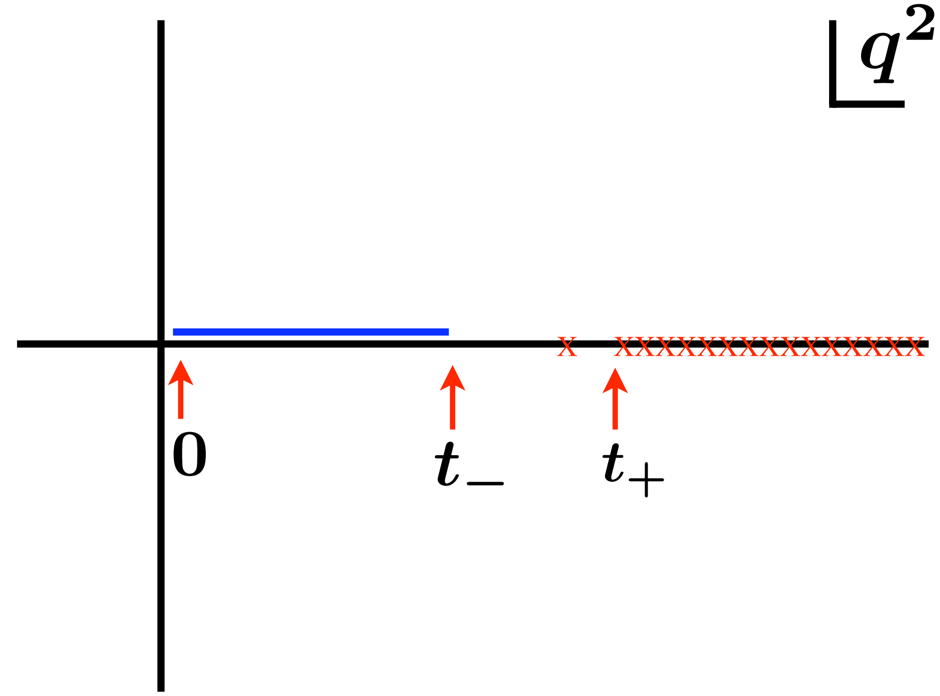
Difference of relative slopes:

$$\delta \equiv 1/\beta_+ - 1/\beta_0 \equiv \frac{F_+(0) + F_-(0)}{F_+(0)}$$

- This one number summarizes all of the current experimental data
- What do we learn from this number ?

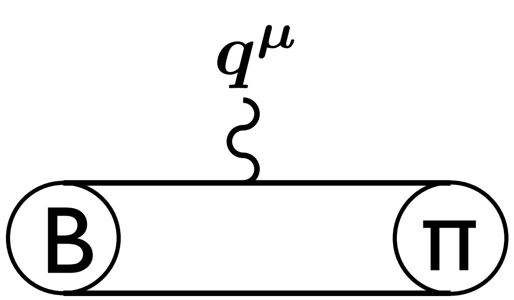
Analyticity

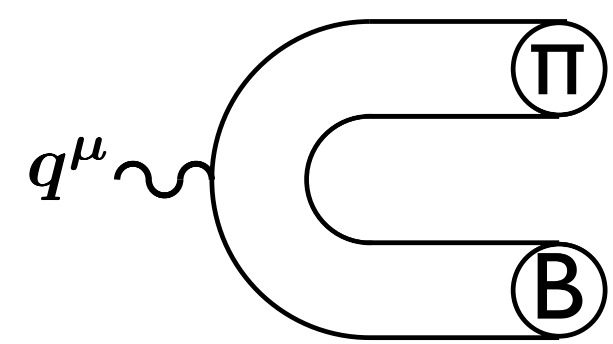
$F(q^2)$ analytic except when $q^2=m^2$ of physical state:



semileptonic region
(B→π decay)

production region
(Bπ production)

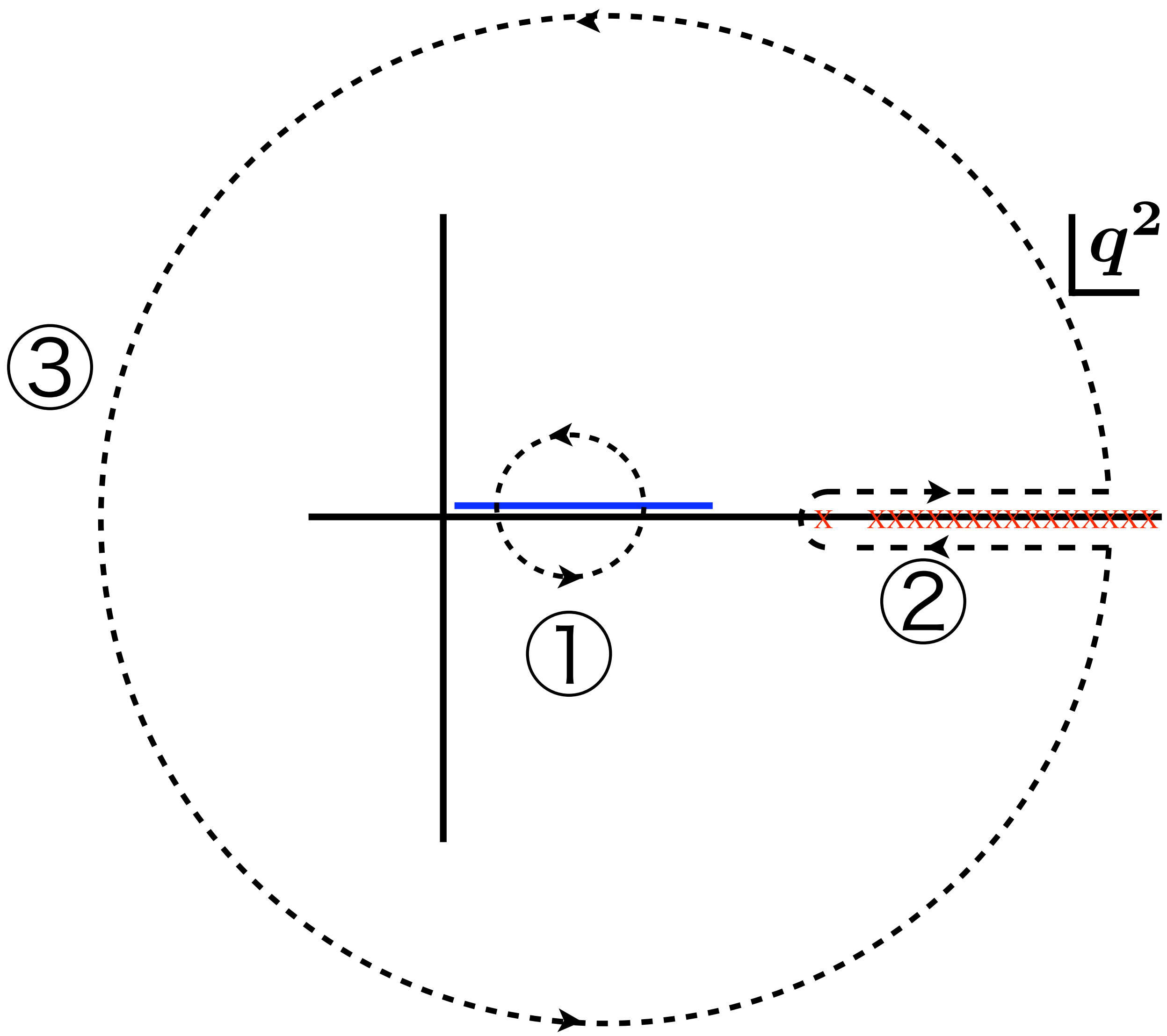




$$0 < q^2 < t_- \equiv (m_B - m_\pi)^2$$

$$q^2 > t_+ \equiv (m_B + m_\pi)^2$$

Again, $F(q^2)$ is analytic except when $q^2=m^2$ of physical state:



Standard complex analysis:

①=②+③=②

$$F(q^2) = \frac{1}{2\pi i} \oint dt \frac{F(t)}{t-q^2} = \frac{1}{\pi} \int_{t_+}^{\infty} dt \, \frac{\mathrm{Im} F(t)}{t-q^2}$$

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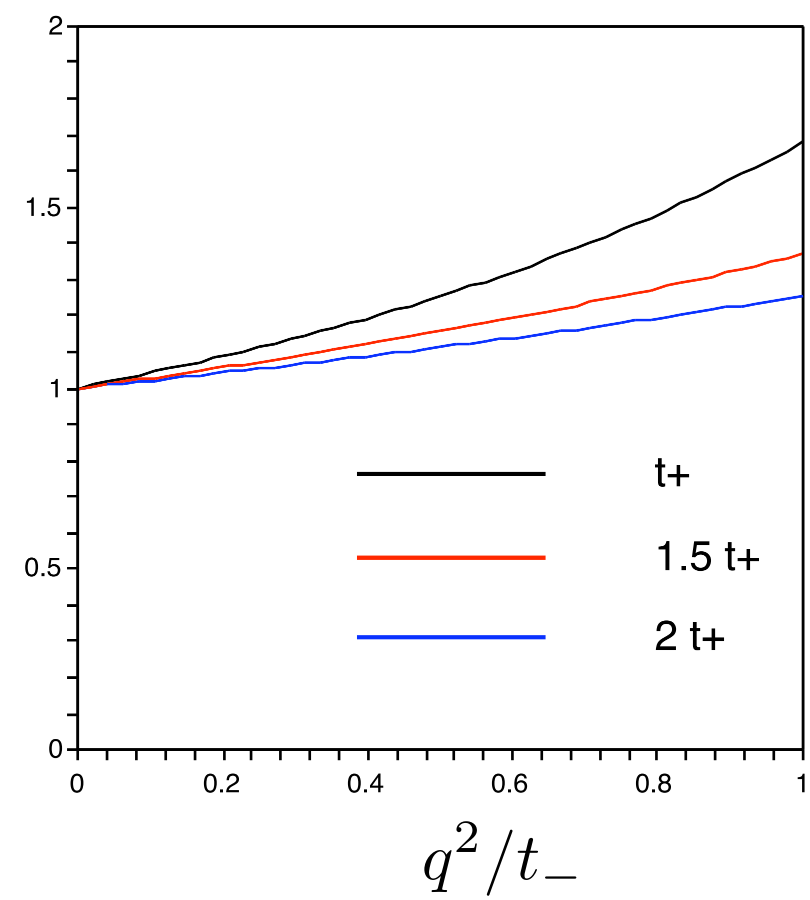
What does this trivial identity buy us?

$$F(q^2) = \sum_i \frac{\rho_k}{1 - q^2/t_k}$$

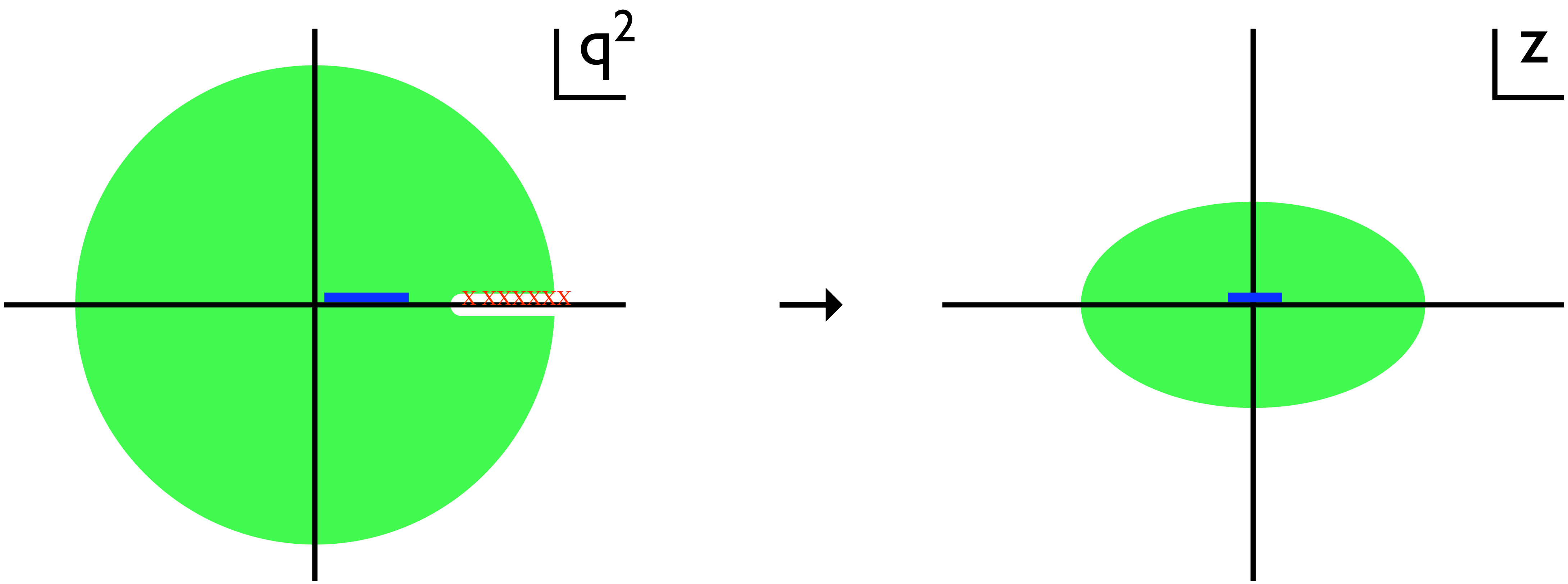
- Simple power counting gives parametric bounds on size of residues, and bounds on sensitivity to positions of effective poles (can make precise with ϵ/δ arguments)

$$\frac{1}{1 - q^2/t_k}$$



Alternatively, consider how many terms are relevant in an optimized power series:

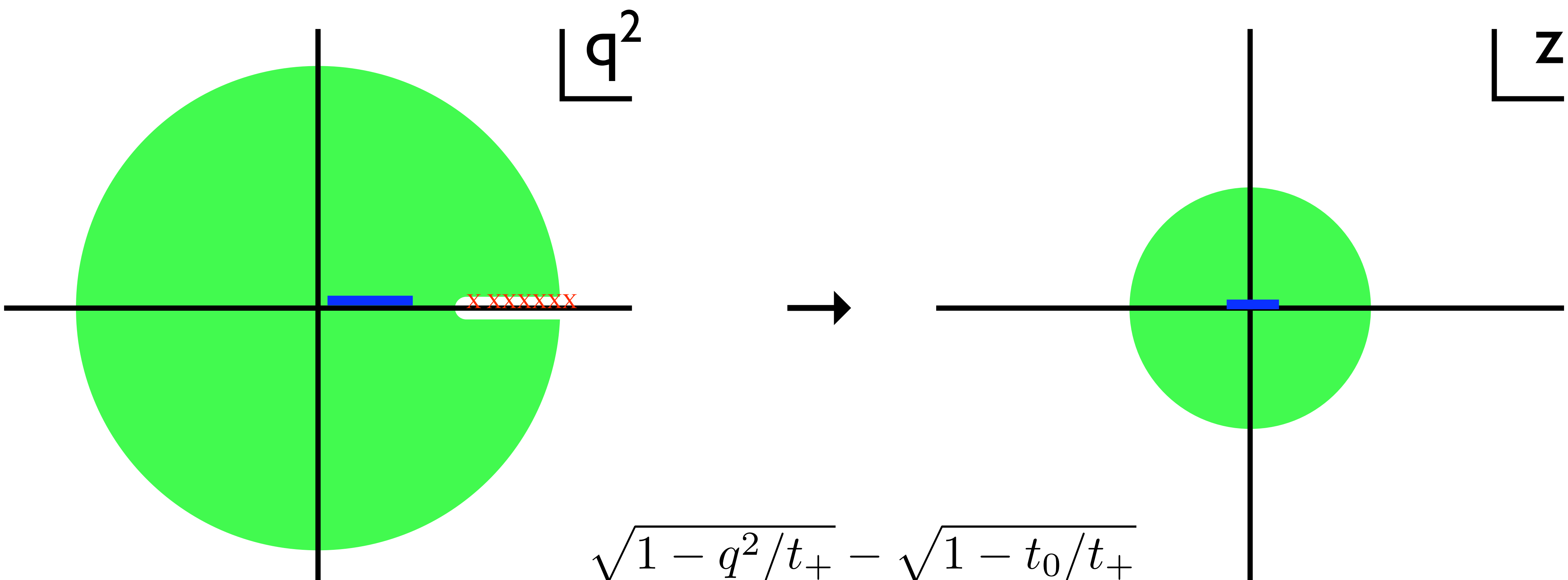
Map domain of analyticity onto ellipse with focal points at semileptonic endpoints



Alternatively, consider how many terms are relevant in an optimized power series:

Map domain of analyticity onto ellipse with focal points at semileptonic endpoints

(almost as good: onto a circle with the interval close to zero)



$$z = \frac{\sqrt{1 - q^2/t_+} - \sqrt{1 - t_0/t_+}}{\sqrt{1 - q^2/t_+} + \sqrt{1 - t_0/t_+}}$$

vanishes at subthreshold poles

$$\begin{aligned} P(q^2)\phi(q^2)F(q^2) &= a_0 + a_1 z + a_2 z^2 + \dots \\ &= a_0 \left(1 + \frac{a_1}{a_0} z + \frac{a_2}{a_0} z^2 + \dots \right) \end{aligned}$$

arbitrary analytic function

$$\Rightarrow \boxed{\sum_k a_k^2 \equiv \frac{1}{2\pi i} \oint \frac{dz}{z} |\phi(z)F(z)|^2 = \int_{t_+}^{\infty} dt\, k(t) |F(t)|^2 \equiv A}$$

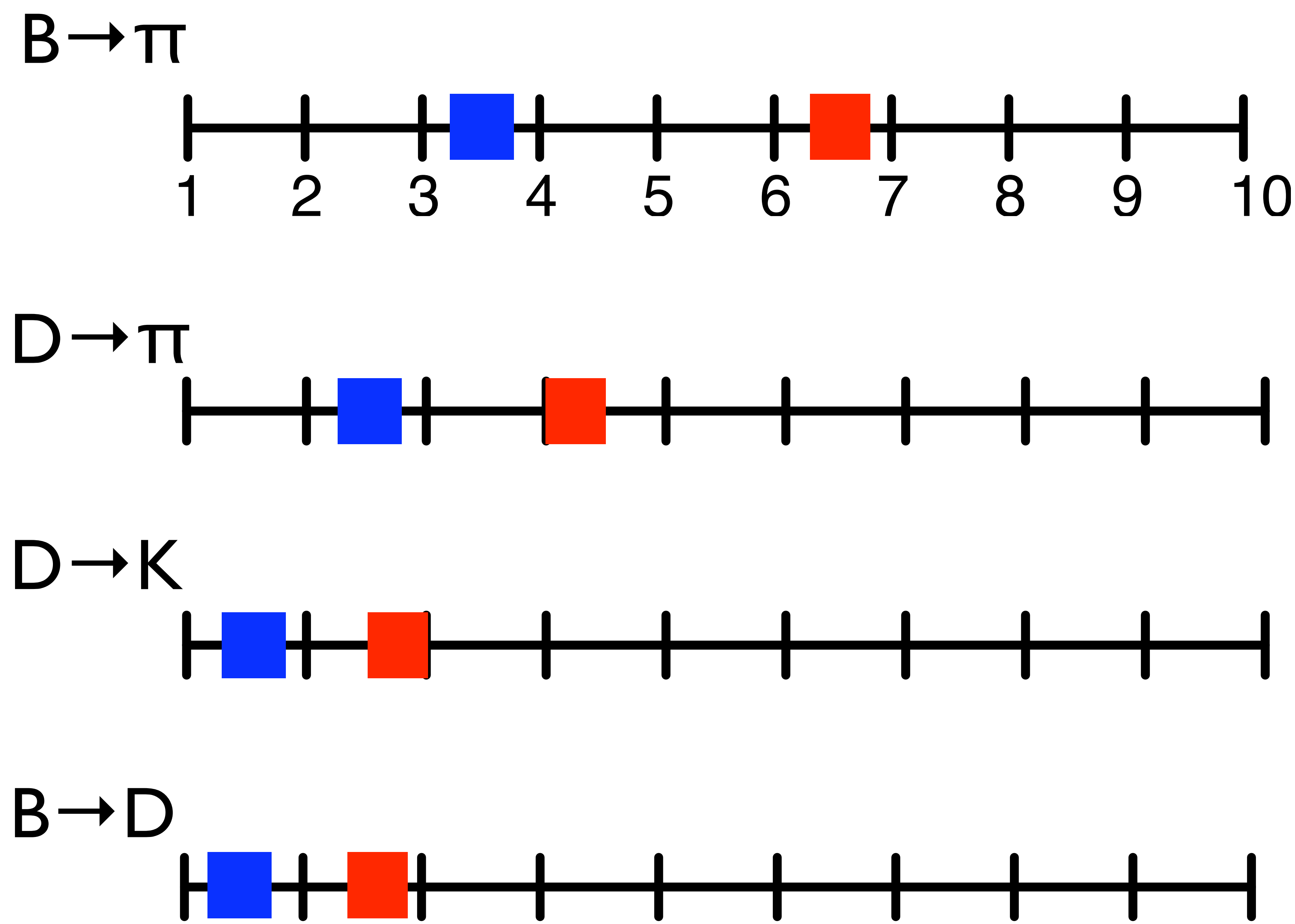
With good choices of Φ, find nice properties:

- when large scale is present: $a_k = \mathcal{O}(1), \quad \sum_k a_k^2 = \mathcal{O}(1)$
- from theorems of perturbative QCD at large spacelike momentum: $\lim_{z \to 1^-} \sum_k k^n a_k z^k = 0, \quad n = 0, 1, 2$

Maximum # parameters at 1% sensitivity:

Blue: $\frac{\Delta F}{F} = \frac{a_k}{a_0} z^k < z^k$

Red: $\frac{\Delta F}{F} = \frac{a_k}{a_0} z^k < \frac{1}{a_0} z^k$ ("unitarity")



- experimental implication: N relevant parameters ⇒ need N independent measurements (bins)

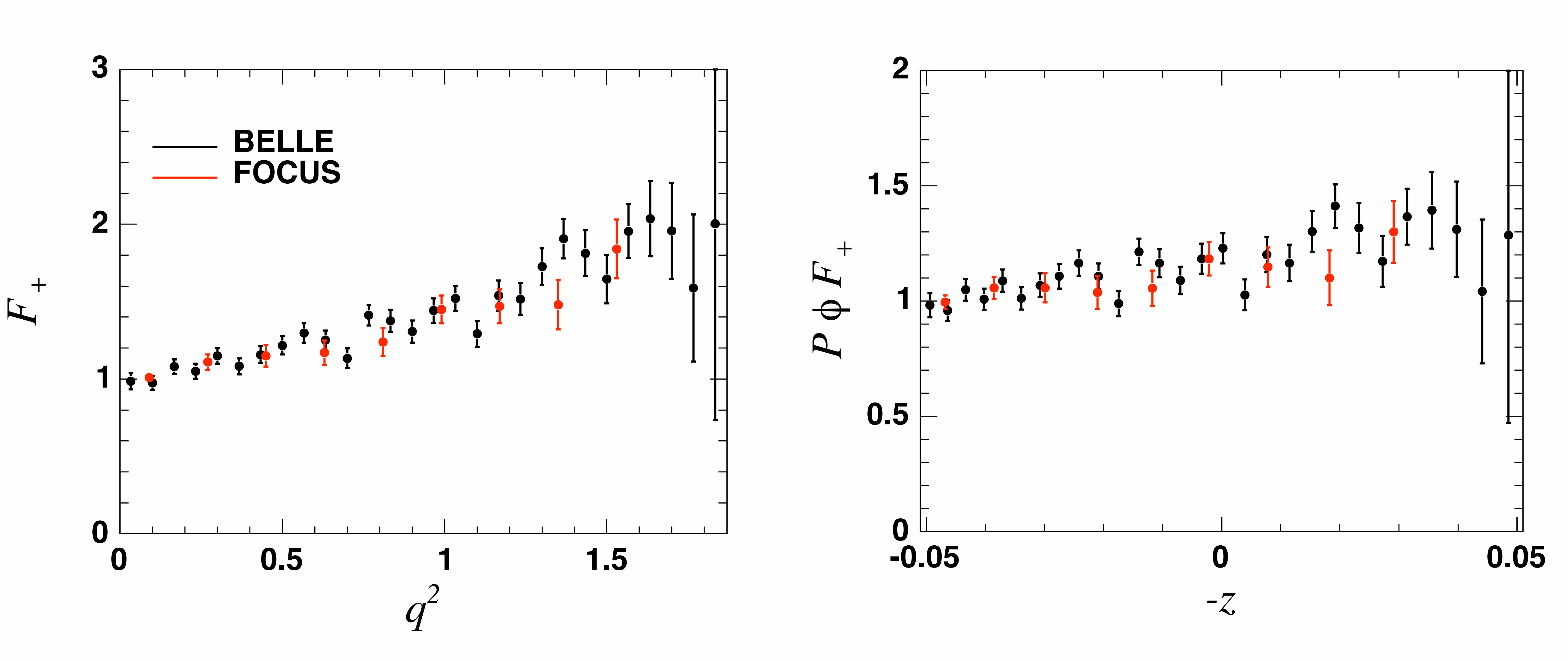
Such a convergence seems surprising:

$$|z|_{\rm max} = \frac{\sqrt{\frac{1+v\cdot v'_{\rm max}}{2}} - 1}{\sqrt{\frac{1+v\cdot v'_{\rm max}}{2}} + 1}$$

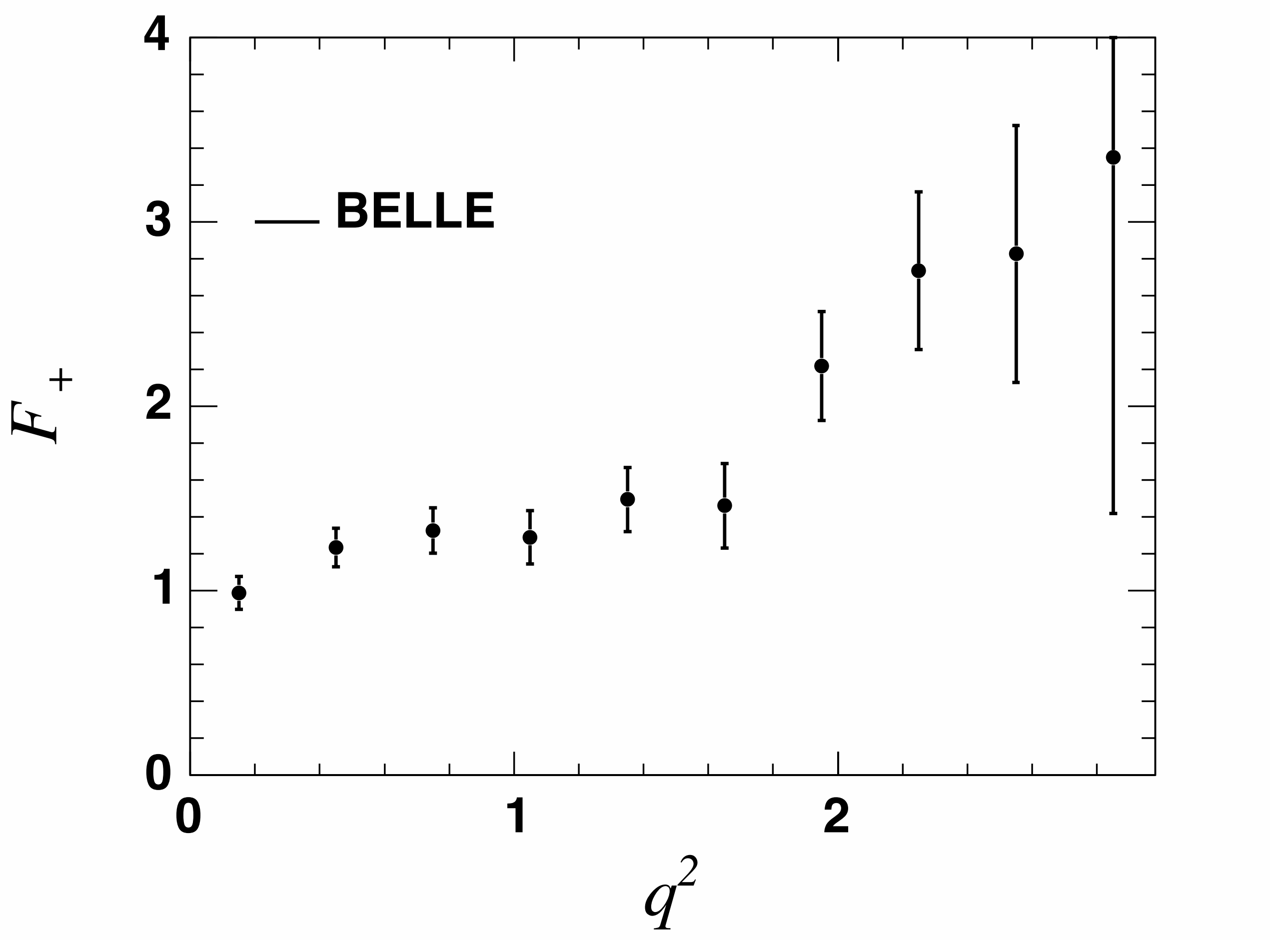
E.g. for B→π, have turned a large recoil parameter ($v\cdot v'_{max}$≈18) into a small expansion parameter (geometrically convergent in $|z|_{max}$≈0.3)

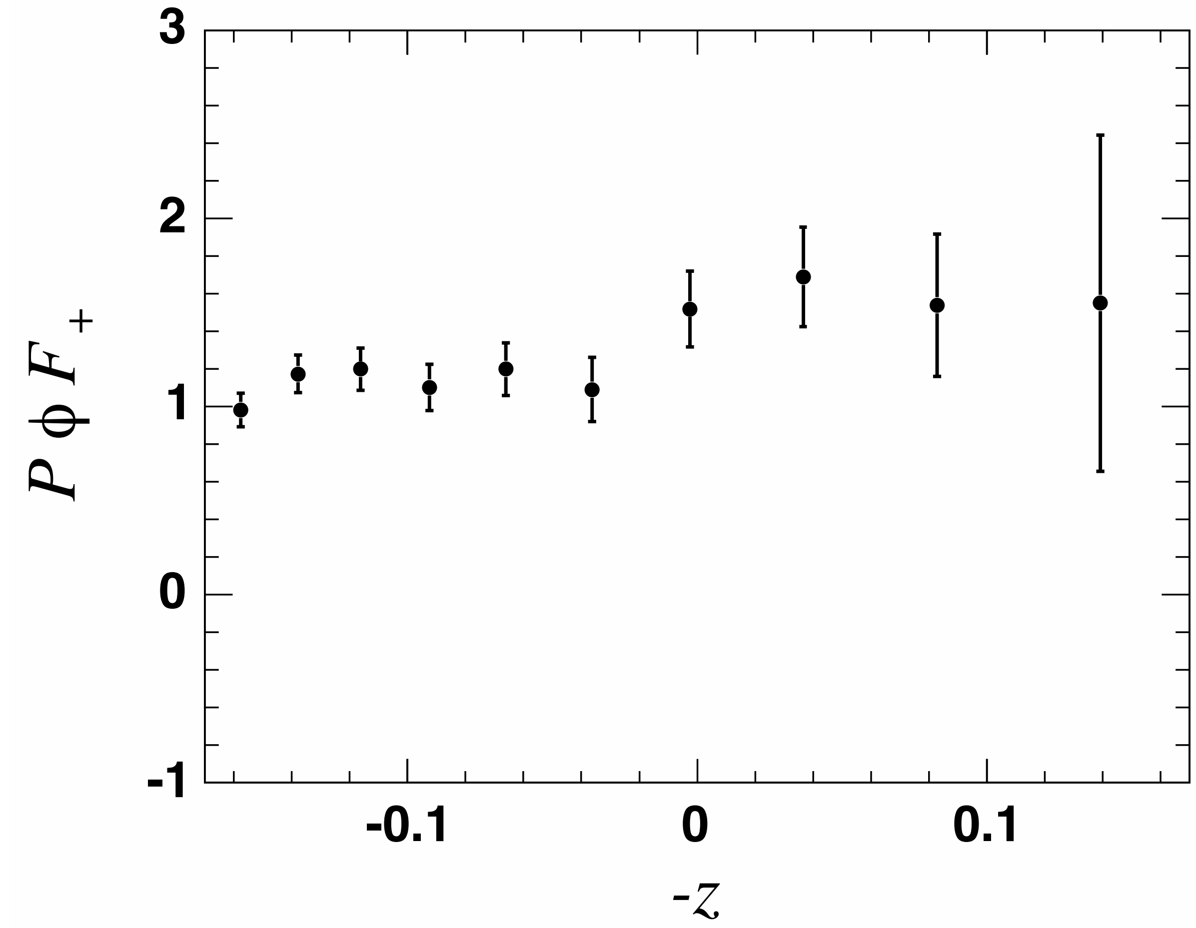
Does it really work?

D→K

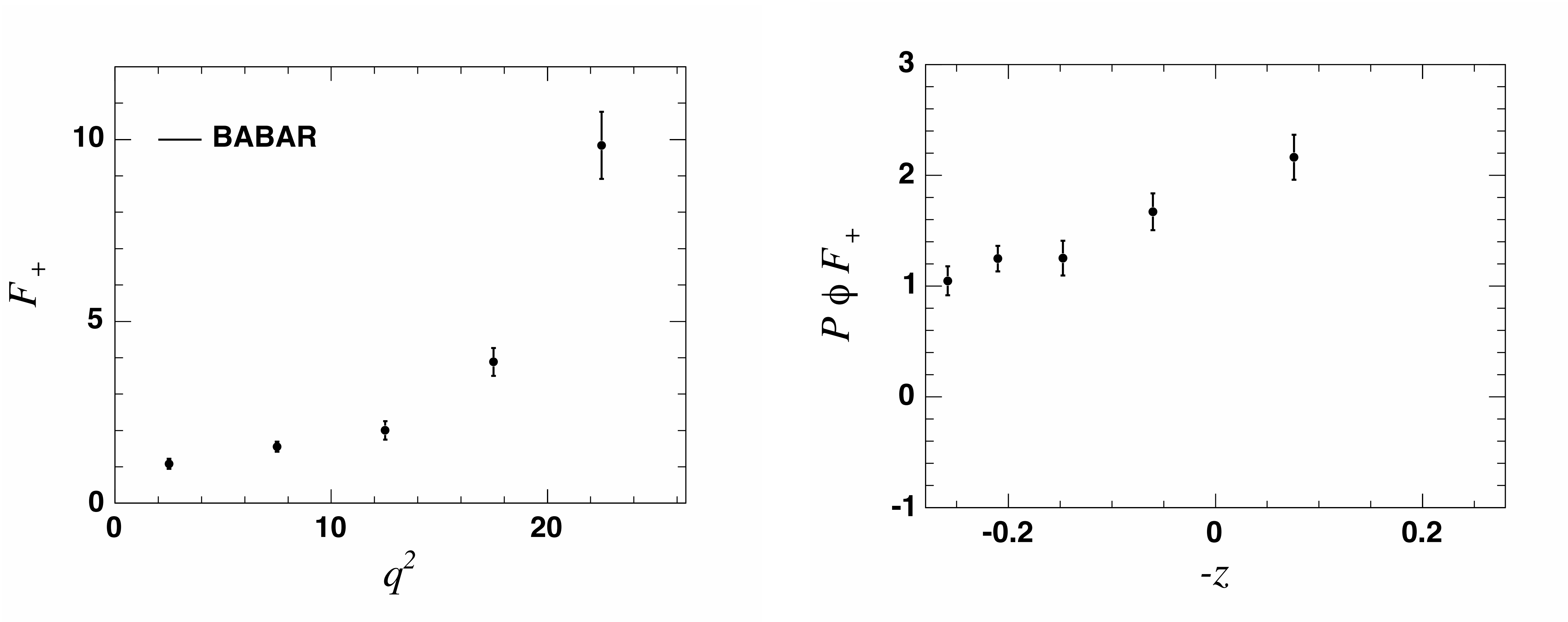


$D \to \pi$





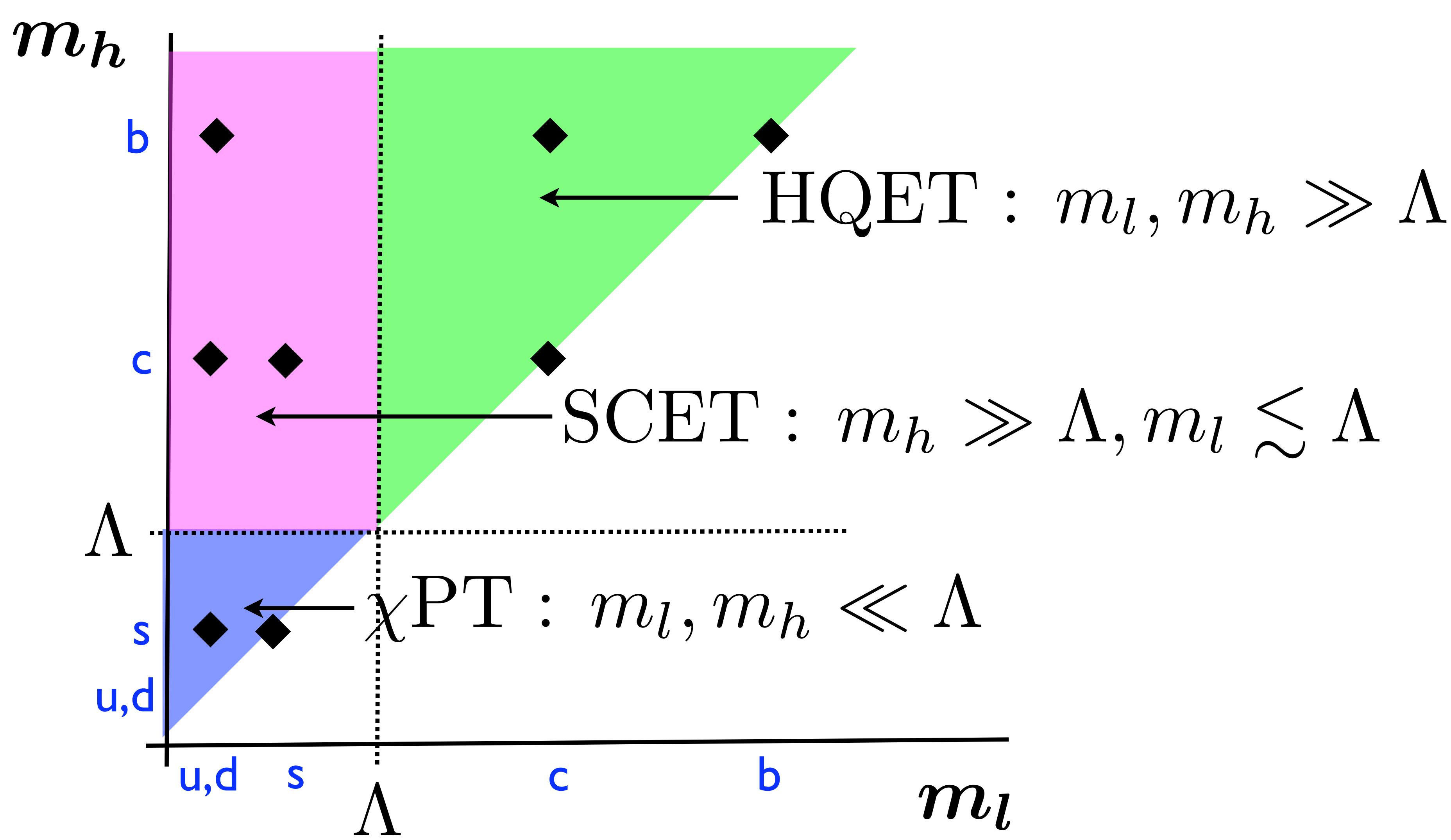
$B \to \pi$



- Experiment has yet to observe more than a normalization and a slope
- What is the significance of this slope?

What has nature given us to work with?

a (not-so?) poor man's lattice simulation



Limit I: HQET

- Take $m_l \to \infty$, $m_h \to \infty$, m_l/m_h fixed

$$\begin{aligned} \langle M_L(p')|V^\mu|M_H(p)\rangle &= F_+(q^2)(p^\mu + p'^\mu) + F_-(q^2)(p^\mu - p'^\mu) \\ &= \sqrt{m_B m_D}\left[h_+(v\cdot v')(v^\mu + v'^\mu) + h_-(v\cdot v')(v^\mu - v'^\mu)\right] \end{aligned}$$

$$1/\beta_+ \equiv \frac{m_H^2 - m_L^2}{F_+(0)} \left.\frac{dF_+}{dq^2}\right|_{q^2=0} = \text{“stuff”} \qquad 1/\beta_0 \equiv \frac{m_H^2 - m_L^2}{F_+(0)} \left.\frac{dF_0}{dq^2}\right|_{q^2=0} = \text{“stuff”}$$

$\xi(v\cdot v'),\ \xi'(v\cdot v')$

$$\boldsymbol{\delta \equiv 1 - 1/\beta_+ + 1/\beta_0 = \frac{2m_L}{m_H + m_L}} + \mathcal{O}(\Lambda/m_l)$$

Limit 2: χPT

- Take $m_l \to 0, m_h \to 0$

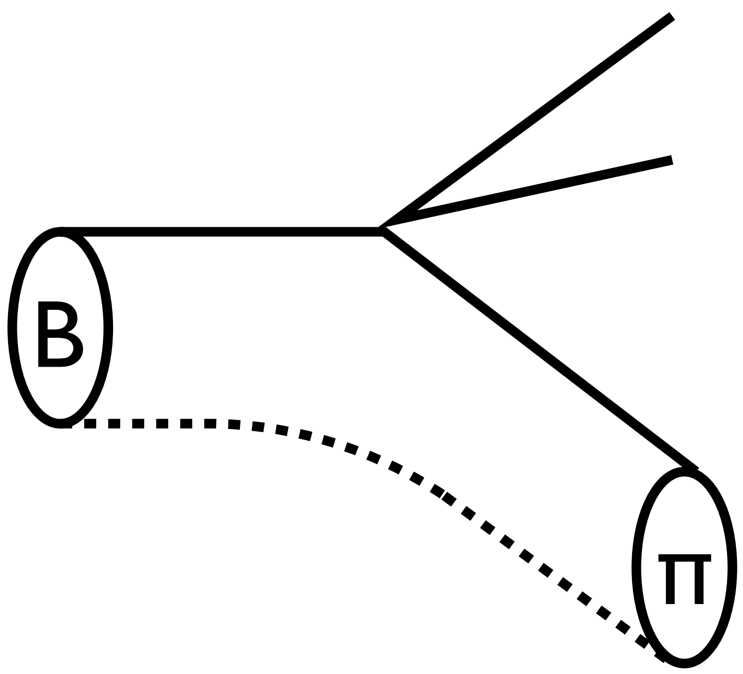
$$\mathcal{L}_0 = \frac{F_0^2}{4}\left\{\mathrm{tr}(\nabla_\mu U^\dagger \nabla^\mu U) + \mathrm{tr}(\chi^\dagger U + \chi U^\dagger)\right\}$$

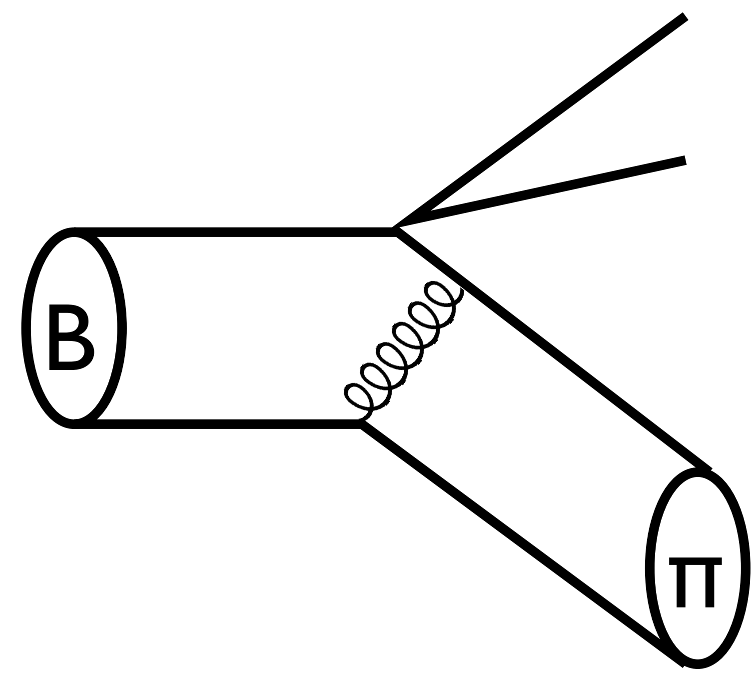
$$\mathcal{L}_2 = L_1 \mathrm{tr}(\nabla_\mu U^\dagger \nabla^\mu U)^2 + (L_2, \ldots, L_{10})$$

$$\mathbf{1 - \delta \equiv 1/\beta_+ - 1/\beta_0 = \frac{2(m_H^2 - m_L^2)}{F_0^2}(L_9 - 2L_5) + \text{“chirallogs”} + \mathcal{O}(m_{l,h}/\Lambda)}$$

Limit 3: SCET

- Take $m_h \to \infty$, $m_l \sim \Lambda$





- After learning to count in SCET, find two distinct contributions at leading order in $1/m_h$

At leading order in $1/m_b \sim 1/E$ and $\alpha_s(m_b)$:

$(q^2 = m_B^2 + m_\pi^2 - 2Em_B)$

$$F_+(E) = \sqrt{m_B}\left[\zeta(E) + \left(\frac{4E}{m_B} - 1\right) H(E)\right]$$

$$\frac{m_B}{2E} F_0(E) = \sqrt{m_B}\left[\zeta(E) + H(E)\right]$$

- ζ: soft overlap, nonfactorizable, $\sim 1/E^2$ (if process contains scales $p^2 \sim \Lambda^2$, $p'^2 \sim \Lambda^2$, then it also $(p^2)(p'^2)/p.p' \sim \Lambda^4/Q^2$)
- H: hard scattering: factorizable, $\sim 1/E^2$ (calculable, given meson wavefunctions)

$$1/\beta_0 = -\left.\frac{d\ln(\zeta+H)}{d\ln E}\right|_{E=m_B/2} - 1$$

$$\delta \equiv 1 - 1/\beta_+ + 1/\beta_0 = \left.\frac{2H}{\zeta+H}\right|_{E=m_B/2}$$

Fake proof that $1/\beta \to 1$

Given:

$$F(q^2) = \frac{1}{\pi}\int_{t_+}^{\infty} dt\, \frac{\mathrm{Im}F(t)}{t-q^2} = \frac{\rho_1}{1-q^2/m_1^2} + \frac{\rho_2}{1-q^2/m_2^2} + \ldots$$

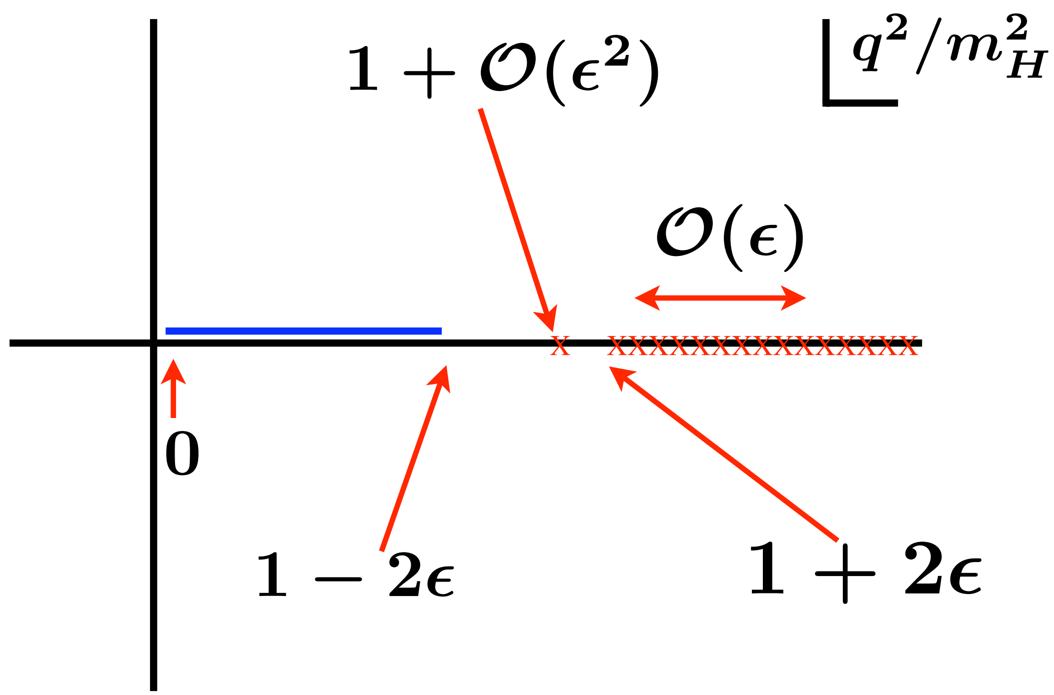
$m_1^2, m_2^2 \leftarrow m_B^2 + \mathcal{O}(m_B\Lambda)$

Then (?) :

$$\begin{aligned} 1/\beta &\equiv \frac{m_B^2 - m_\pi^2}{F(0)} \frac{dF}{dq^2}\Big|_{q^2=0} \\ &= \frac{m_B^2 - m_\pi^2}{\rho_1 + \rho_2 + \ldots} \frac{d}{dq^2}\left(\frac{\rho_1}{1-\frac{q^2}{m_1^2}} + \frac{\rho_2}{1-\frac{q^2}{m_2^2}} + \ldots \right)\Big|_{q^2=0} \\ &= \frac{m_B^2 - m_\pi^2}{m_1^2}\left(\frac{\rho_1 + \frac{m_1^2}{m_2^2}\rho_2 + \frac{m_1^2}{m_3^2}\rho_3 + \ldots}{\rho_1 + \rho_2 + \rho_3 + \ldots} \right) \\ &\to 1 \end{aligned}$$

- In order to get $\beta \neq 1$, need strong cancellations

Heavy quark symmetry pulls B* below threshold:
$(m_{B*} - m_B \sim 1/m_b)$



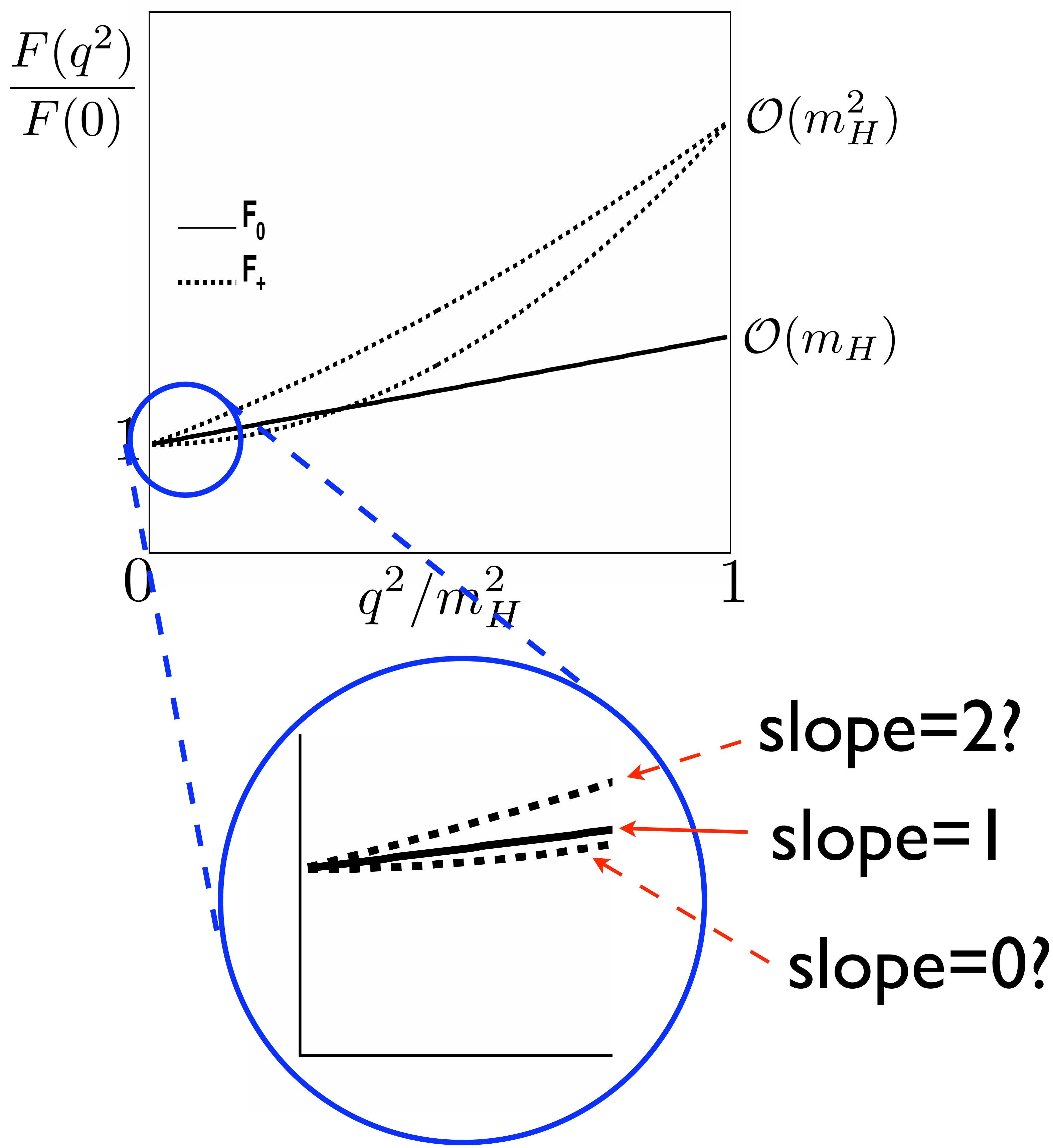
Approximate above-threshold contributions by one effective pole:

$$F_+(q^2) = \frac{F_+(0)\left(1 - \delta \frac{q^2}{m_{B*}^2}\right)}{\left(1 - \frac{q^2}{m_{B*}^2}\right)\left(1 - [\alpha + \delta(1-\alpha)]\frac{q^2}{m_{B*}^2}\right)}$$

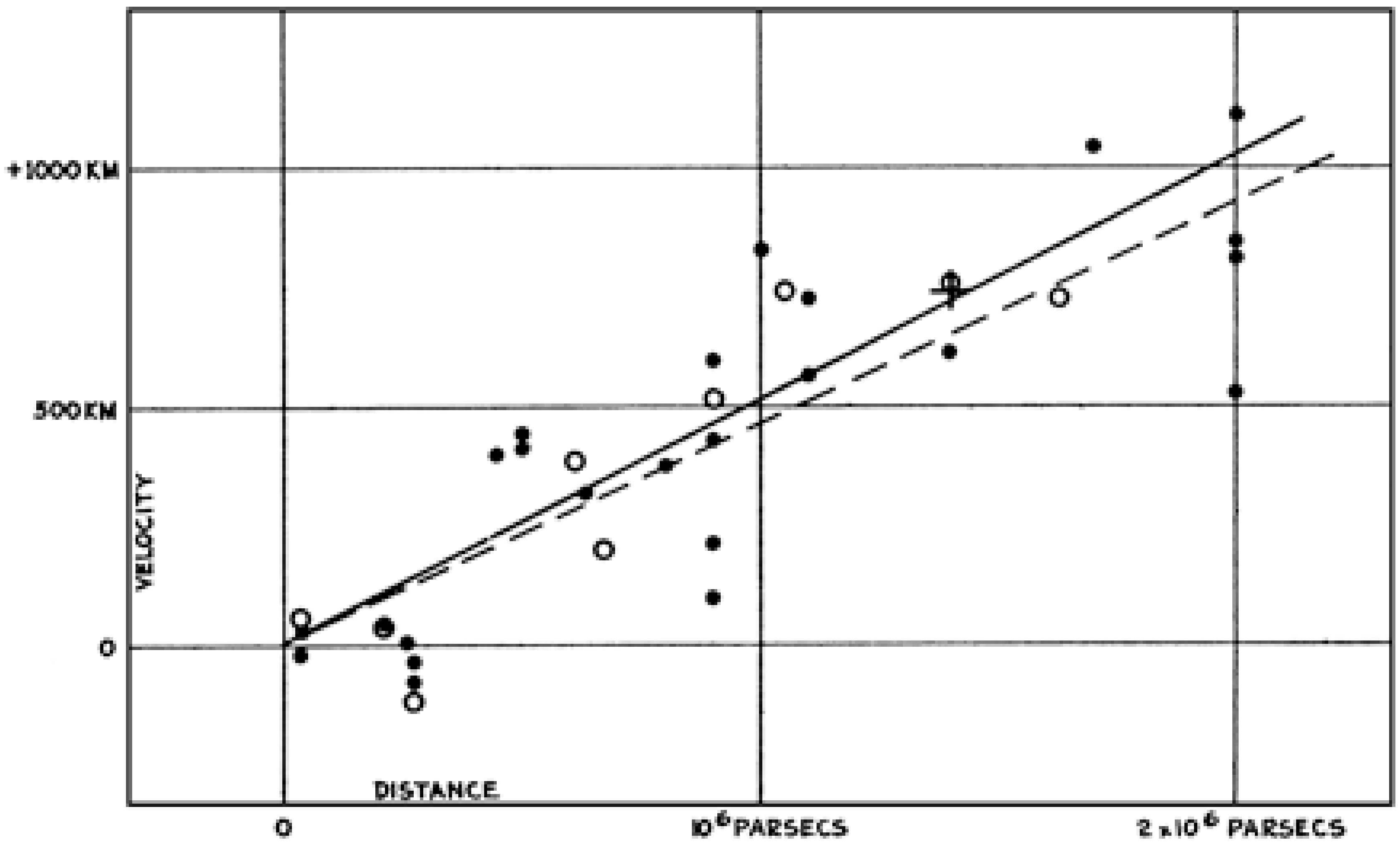
- slope parameters can be calculated (HQET), related to low-energy constants (χPT), or used to ask questions about asymptotic limits (SCET)
- In asymptotic heavy-quark/large-recoil limit
  - $1/\beta_0 \to 1$
  - $1/\beta_+ \to 0$, 1 or 2 ($\delta \to 2$, 1 or 0)

Note: approach of δ to the asymptotic limit is very slow after heavy quark is heavy, and light quark is light (scaling violations)

A simple question in the asymptotic heavy-quark limit:



What’s in a slope?



The New York Times
ON THE WEB

Physicists discover universe is/isn’t expanding!

Pasadena, Feb. 12 — Vice President Dick Cheney accidentally shot and wounded a prominent Austin, Tex., lawyer on Saturday while the two men were quail hunting in South Texas, firing a shotgun at the man while trying to aim for a bird, a member of the hunting party said.

Kelly West/Austin American-Statesman, via Associated Press
Harry Whittington, 78, shown at his office in Austin last year, was accidentally shot by Vice President Dick Cheney on Saturday.

Mr. Cheney, a practiced hunter, shot the lawyer, Harry Whittington, on an outing at the Armstrong Ranch in South Texas. Mr. Whittington, 78, was taken by helicopter to Christus Spohn Memorial Hospital

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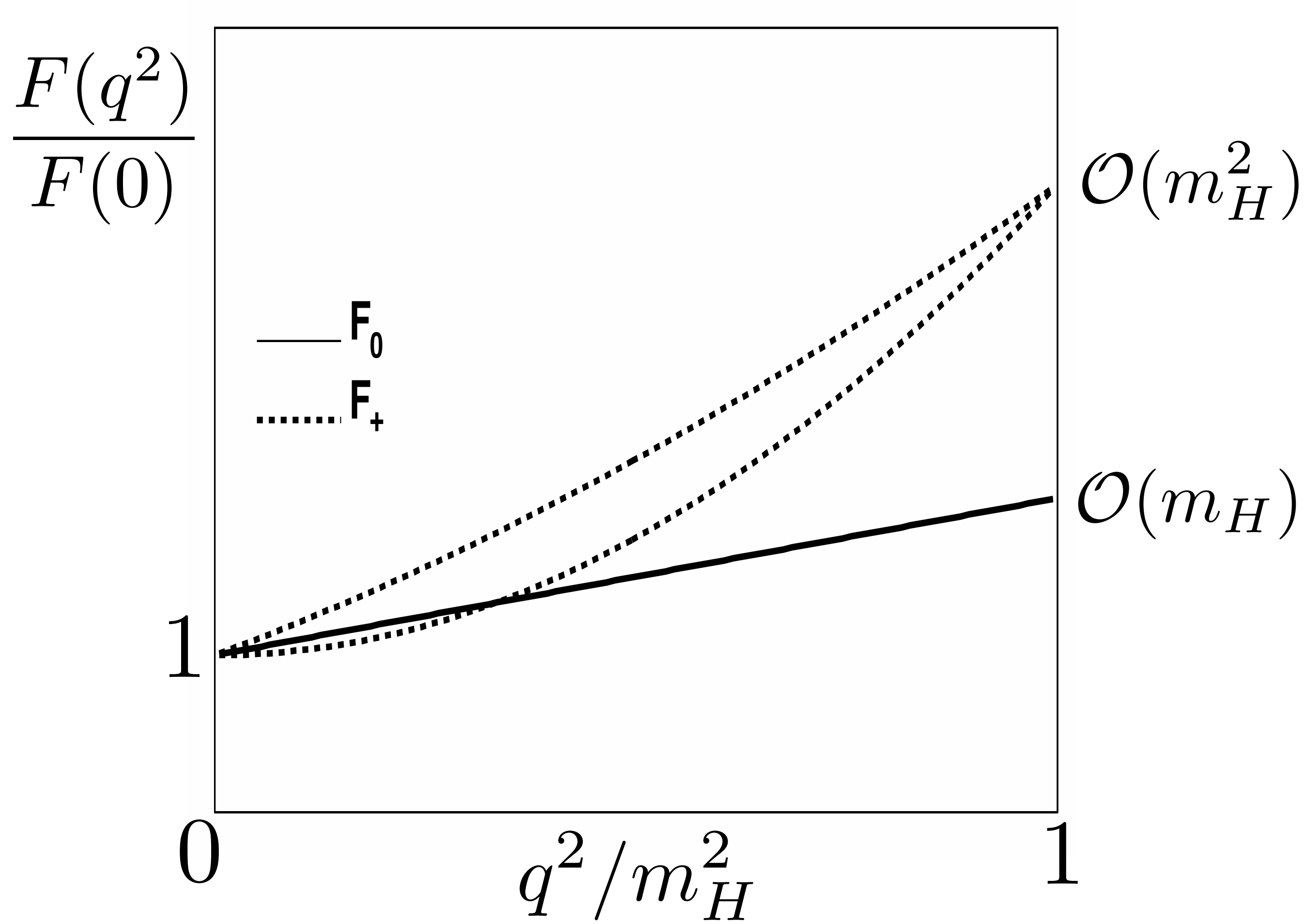
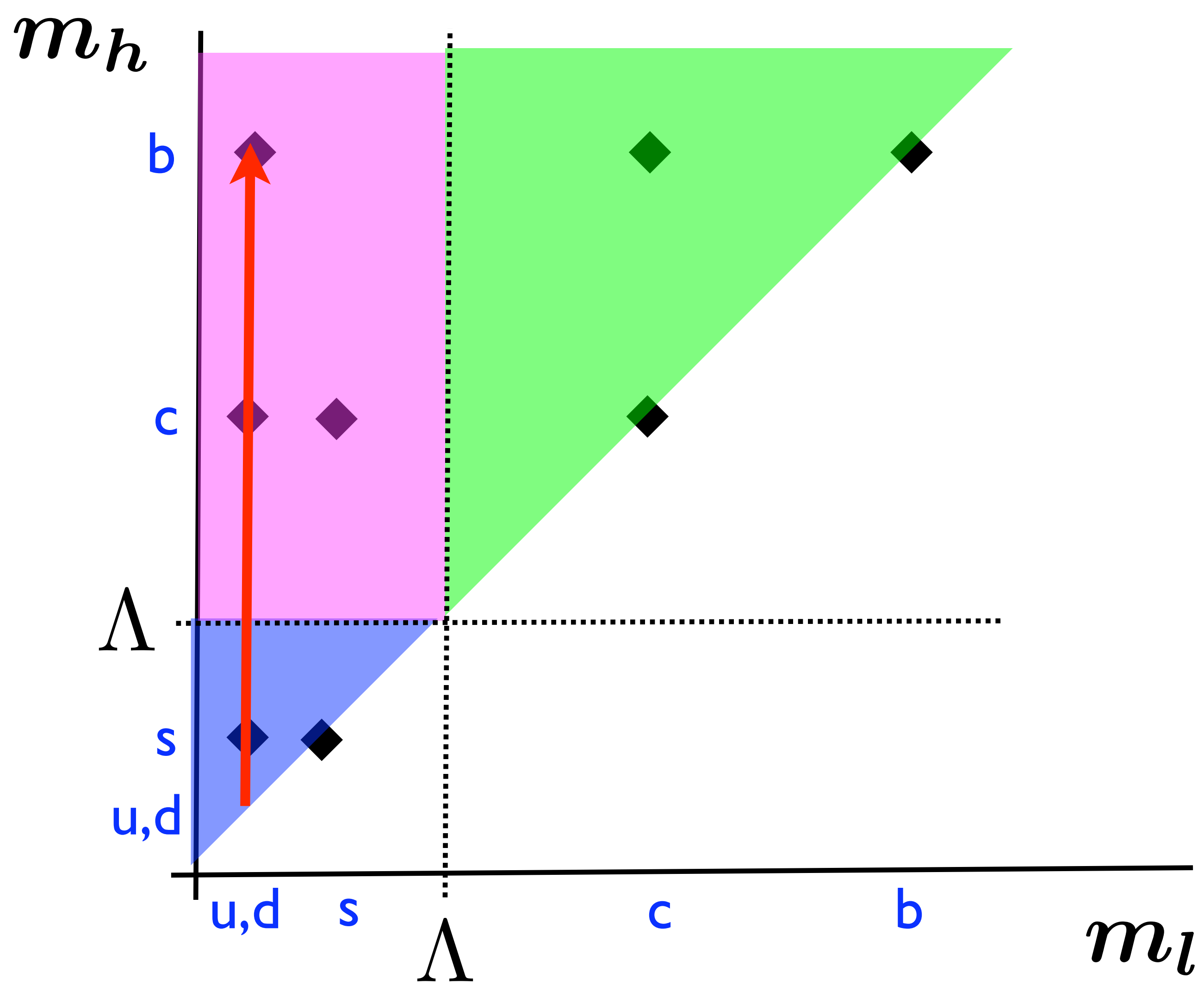


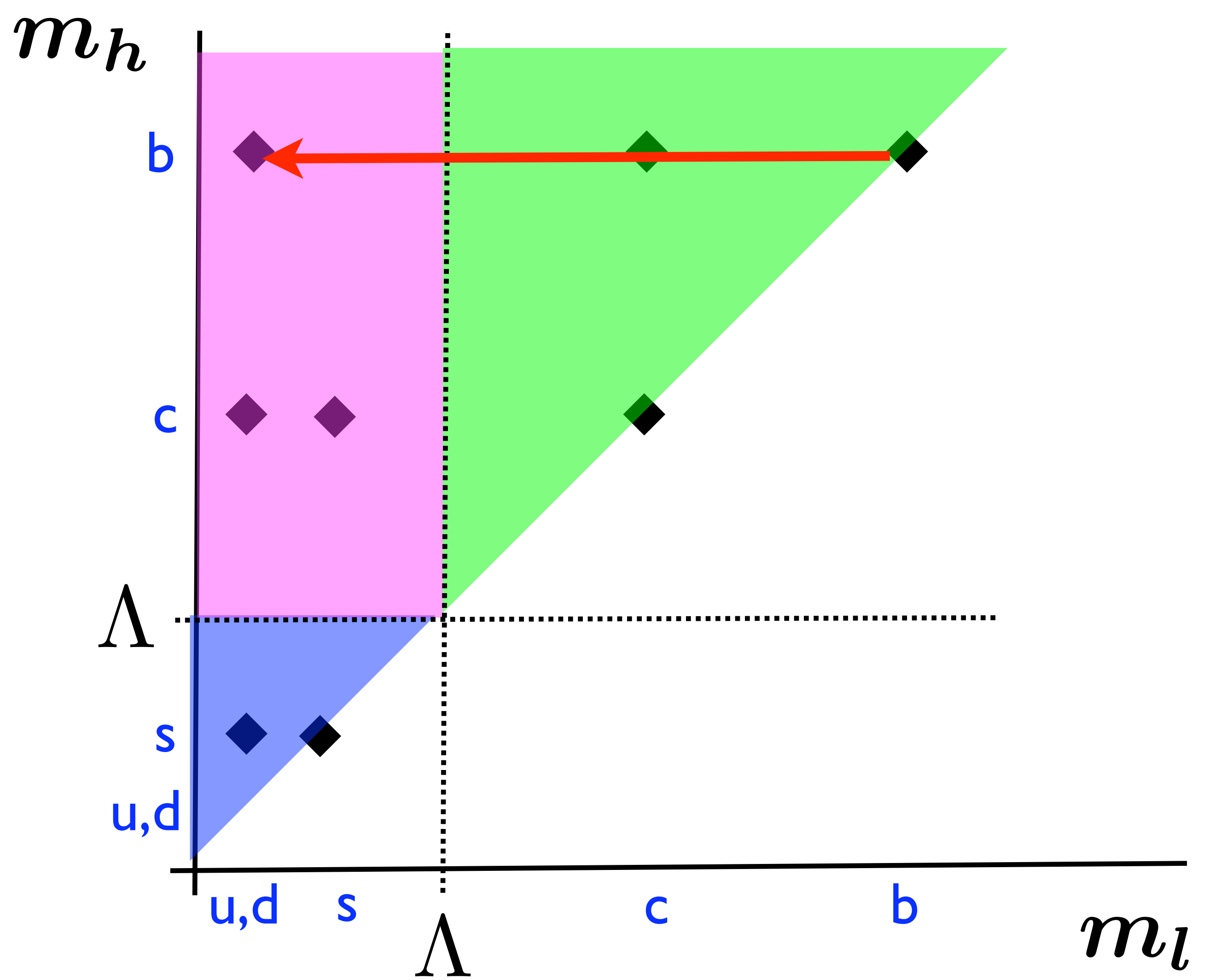
The New York Times ON THE WEB

Soft overlap does/doesn’t dominate over hard-scattering in asymptotic limit!

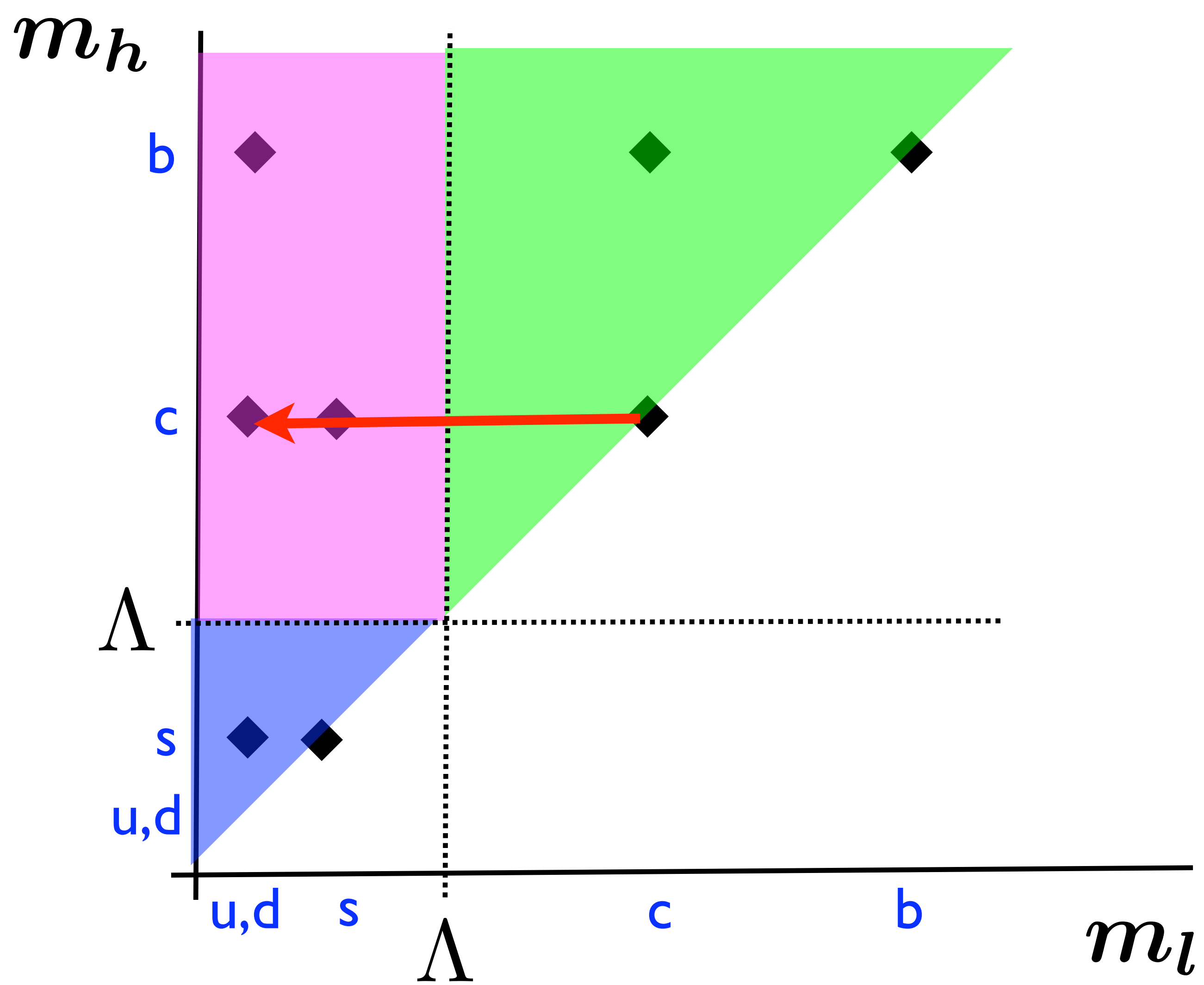
Not going to see this headline, but still a simple and interesting question about QCD



	$[1-f(0)]$	$1/\beta_+$	$1/\beta_0$	$1-\delta$
$\pi-\pi$	0	0	0	0
$K-\pi$	0.038(5)	0.24(2)	0.16(2)	0.08(3)
$D-\pi$	0.27(15)	0.8(4)	?	?
$B-\pi$	0.75(3)	1.5(6)	?	?



	$[1-f(0)]$	$1/\beta_+$	$1/\beta_0$	$1-\delta$
$B-B$	0	0	0	0
$B-D$	0.43(9)	1.1(4)	0.6(4)	0.48(3)
$B-\pi$	0.75(3)	1.5(6)	?	?



	$[1-f(0)]$	$1/\beta_+$	$1/\beta_0$	$(1-\delta)$
$D-D$	0	0	0	0
$D-K$	0.22(5)	0.87(10)	?	?
$D-\pi$	0.27(15)	0.8(4)	?	?

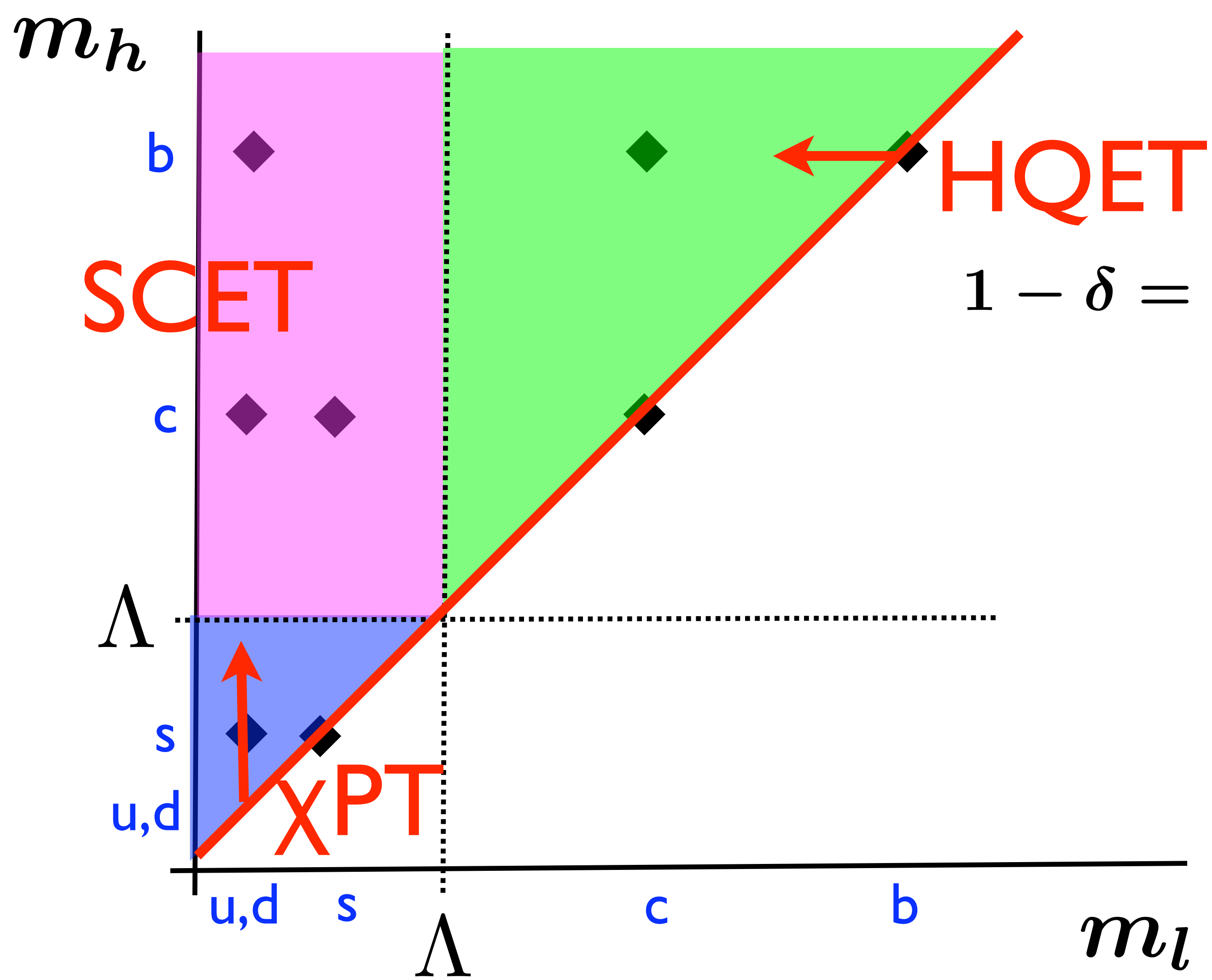
A conjecture

monotonicity conjecture:
δ is a monotonic function of the quark mass

Consequences:

- Soft overlap dominance in asymptotic limit
- Inequality between low-energy constants of χPT
- Testable predictions for experiment

$$1 - \delta = \frac{\zeta - H}{\zeta + H}$$



$$1 - \delta = \frac{m_H - m_L}{m_H + m_L}$$

$$1 - \delta = \frac{2(m_H^2 - m_L^2)}{F_0^2}(L_9 - 2L_5) + \ldots$$

Predicts the sign of this combination (positive)

$$
\begin{aligned}
L_9 &= 7.4 \pm 0.7 \times 10^{-3} \quad (< r^2 >^{\pi}_{\rm e.m.}) \\
2L_5 &= 4.4 \pm 1.0 \times 10^{-3} \quad (\, f_K / f_\pi \,)
\end{aligned}
$$

Pre-(not post-) dictions for experiment

- some $1/\beta_+$ bigger than 1.0 (shows that fake proof of $1/\beta<1$ is fake: cancellations are really happening)
- $[1/\beta_+]^{B\pi} > [1/\beta_+]^{D\pi}$
- $[1/\beta_+]^{B\pi} > [1/\beta_+]^{BD}$
- $[1/\beta_+]^{D\pi} > [1/\beta_+]^{DK}$

	$[1-f(0)]$	$1/\beta_+$	$1/\beta_0$	$1-\delta$
$\pi-\pi$	0	0	0	0
$K-\pi$	0.038(5)	0.24(2)	0.16(2)	0.08(3)
$D-\pi$	0.27(15)	0.8(4)	?	?
$B-\pi$	0.75(3)	1.5(6)	?	?

	$[1-f(0)]$	$1/\beta_+$	$1/\beta_0$	$1-\delta$
$B-B$	0	0	0	0
$B-D$	0.43(9)	1.1(4)	0.6(4)	0.48(3)
$B-\pi$	0.75(3)	1.5(6)	?	?

	$[1-f(0)]$	$1/\beta_+$	$1/\beta_0$	$(1-\delta)$
$D-D$	0	0	0	0
$D-K$	0.22(5)	0.87(10)	?	?
$D-\pi$	0.27(15)	0.8(4)	?	?

$$1/\beta_i \equiv \frac{m_B^2-m_\pi^2}{f(0)} \frac{dF_i}{dq^2}\bigg|_{q^2=0}$$

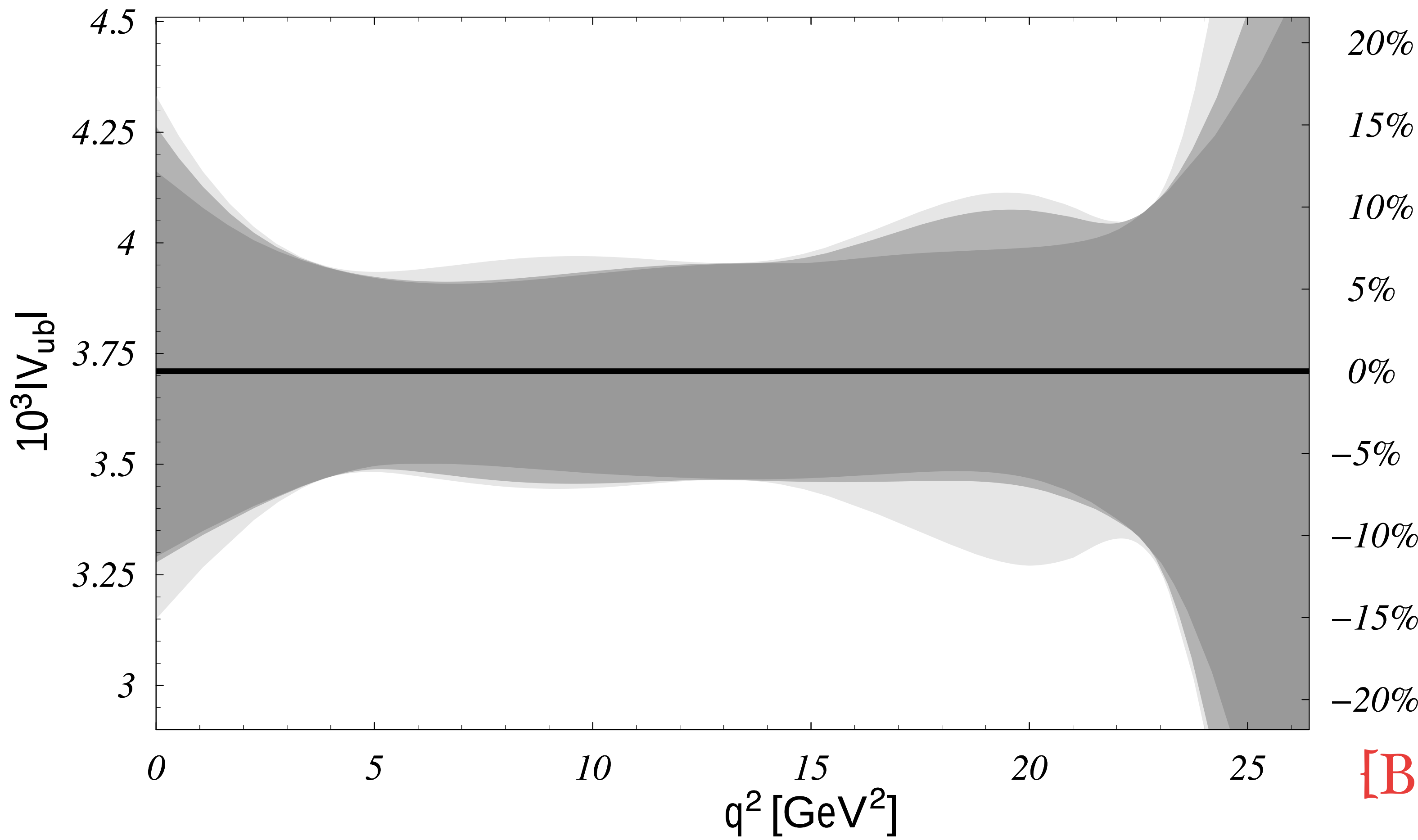
$$1/\beta_+ - 1/\beta_0 \equiv 1-\delta$$

Phenomenological implications

- merging lattice and experiment for $|V_{ub}|$
- inputs to hadronic B decays

Experiment, lattice and |Vub|

partial branching fractions + perversity bounds on the form factor
→ shape is determined by experiment



[CLEO, hep-ex/0304019]
[BELLE, hep-ex/0408145]
[BABAR, hep-ex/0507003]
[BABAR, hep-ex/0506064]

[Becher and Hill, hep-ph/0509090]

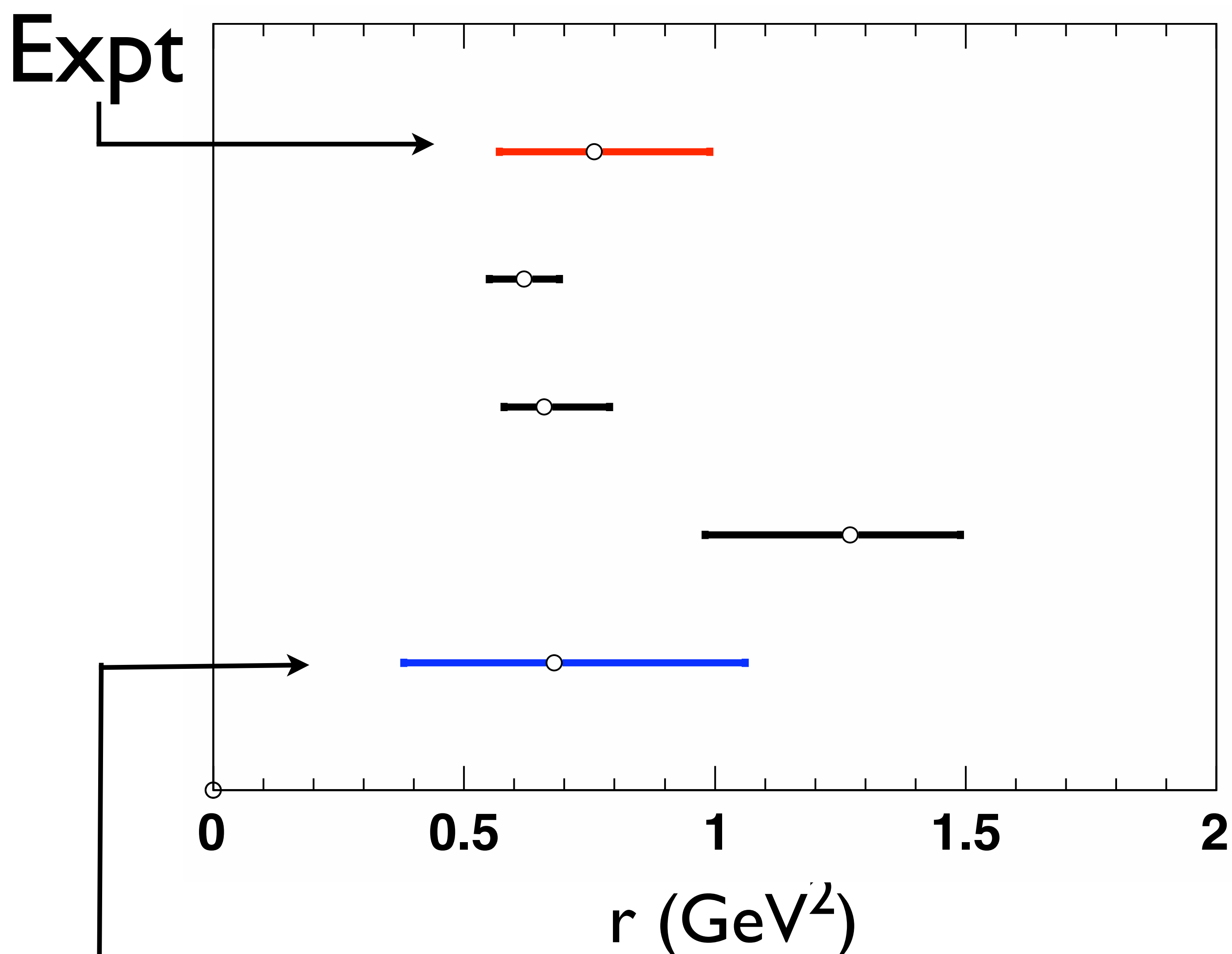
$$10^3|V_{ub}| = (3.7 \pm 0.2 \pm 0.1) \times \frac{0.8}{F_+(16\,\mathrm{GeV}^2)}$$

- use shape information from lattice as a quantitative test
- squeeze every drop of statistics from lattice simulations

Inputs to hadronic B decays

regardless of asymptotic limit, δ not negligible at physical m_b

$$r = \frac{\Gamma(B^-\to\pi^-\pi^0)}{d\Gamma(\bar{B}^0\to\pi^+\ell\bar{\nu})/dq^2|_{q^2=0}} \approx 16\pi^2 f_\pi^2 |V_{ud}|^2/3$$



Treatment of hard-scattering terms:

- neglect them
- from LCSR input [Beneke and Neubert, hep-ph/0308039]
- from other B→ππ [Bauer et al, hep-ph/0401188, Arnesen et.al. hep-ph/0504209]

or Extract from semileptonic data:

$$\left|1 + \alpha_s\left(-0.49 - i/4\right) + 3\delta/8\right|^2 \cdot 16\pi^2 f_\pi^2 |V_{ud}|^2/3$$

Future work

- $|V_{us}|$: current Kl3 experimental data fitted to simple expansion in q^2 (worst case expansion $(m_K-m_\pi)^2/(m_K-m_\pi)^2 \sim 0.3$ vs. $|z| < 0.05$)

- space-like form factors, B→vector f.f.'s: (Vtd from $B\to\rho\gamma$, f.b. asym. in $B\to K^*ll$, inputs to B→PV)

- turning the knobs for $K,D,B\to\pi\pi$ (manifestation of $\Delta I=1/2$ rule for B decays)

- hadronization and jets ($B\to\pi$ = controlled experiment on hadronization)

Summary

- form factors are simple
  - q^2 knob well under control
  - m_h and m_l knobs probe interesting limits of the same underlying theory
- a simple conjecture
  - relates different limits
  - testable predictions for experiment
- systematic tools
  - lattice+expt to obtain |Vub|
  - universal hadronic input to semileptonic/hadronic/radiative B decay modes