Semileptonic *B* Decays

— *B* Physics Beyond *CP* Violation —

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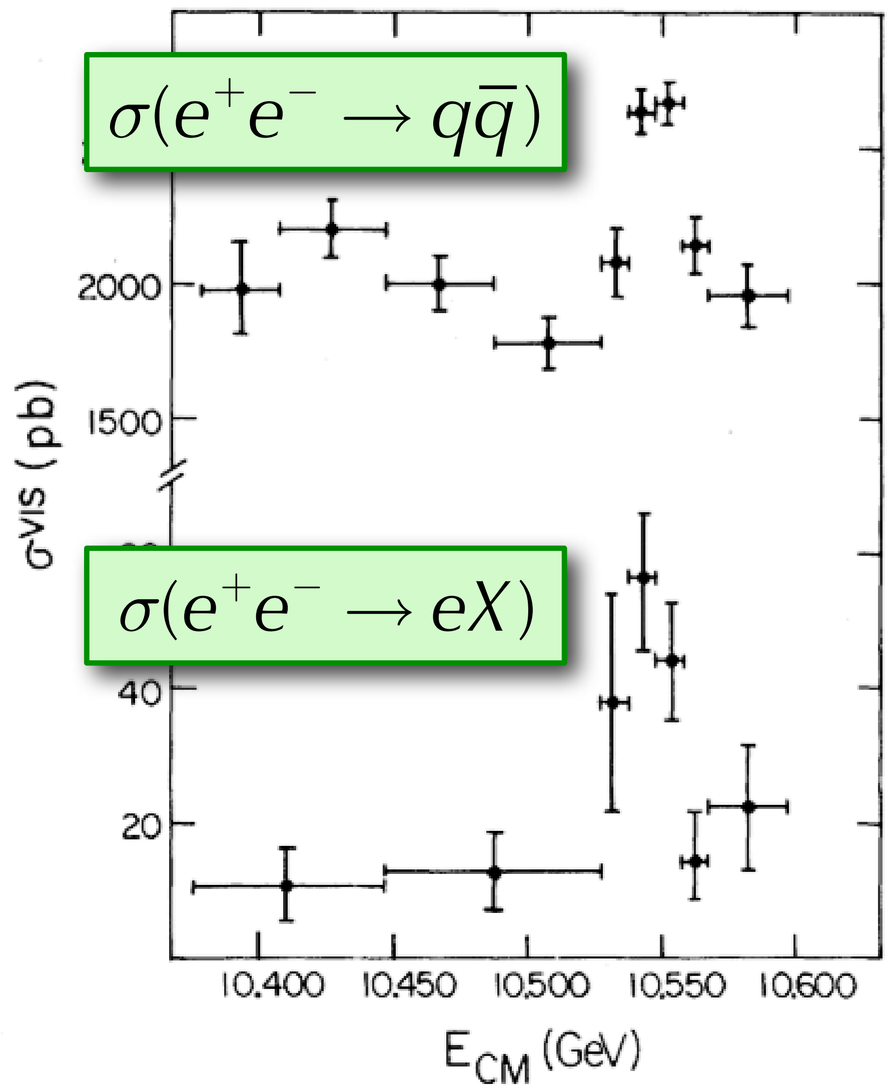
Outline

- Introduction: Why semileptonic B decays?
- $|V_{ub}/V_{cb}|$ from inclusive semileptonic decays
  - Measurements: Branching fractions and kinematic spectra
  - Theoretical challenge: Shape Function
    - Determining the SF from data: $B \to X_c \ell \nu$, $B \to X_s \gamma$
    - Avoiding the Shape Function
- $|V_{ub}/V_{cb}|$ from exclusive semileptonic decays
  - Measurements: $\Gamma(B \to D^* \ell \nu)$, $\Gamma(B \to \pi \ell \nu)$
  - Theoretical challenge: Form Factors
    - Determining the shape of the FF from data
- Summary

Semileptonic B Decays

- $B \to X\ell\nu$ decays were seen as soon as the $\Upsilon(4S)$ resonance was discovered

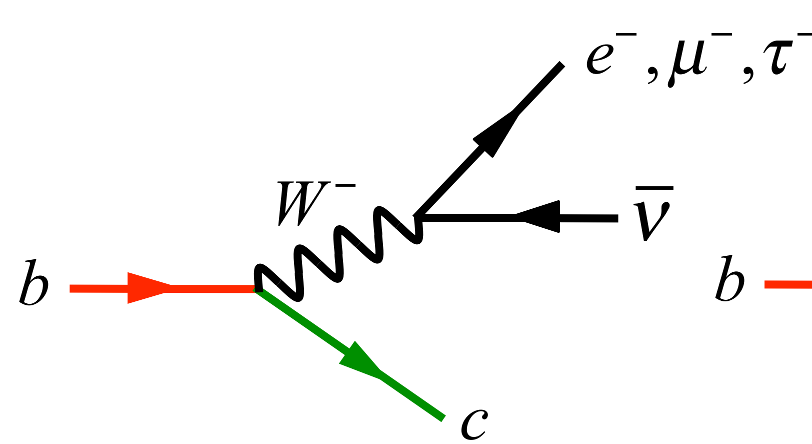


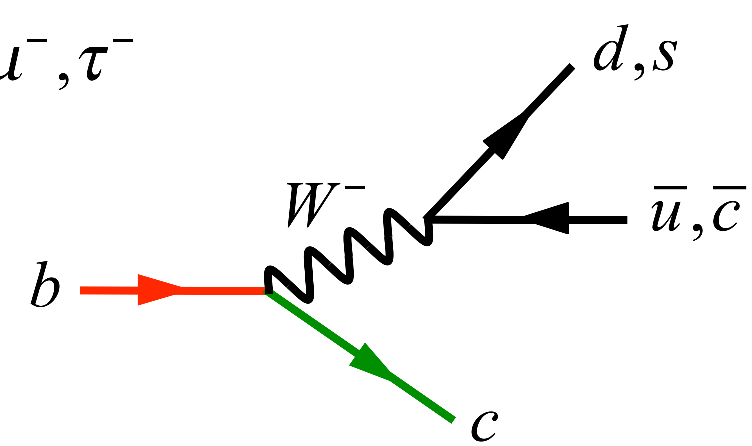
CLEO PRL 46:84 (1981)

- CLEO measured in 1981

$$\mathcal{B}(B \to Xe\nu) = (13 \pm 3 \pm 3)\%$$
$$\mathcal{B}(B \to X\mu\nu) = (9.4 \pm 3.6)\%$$

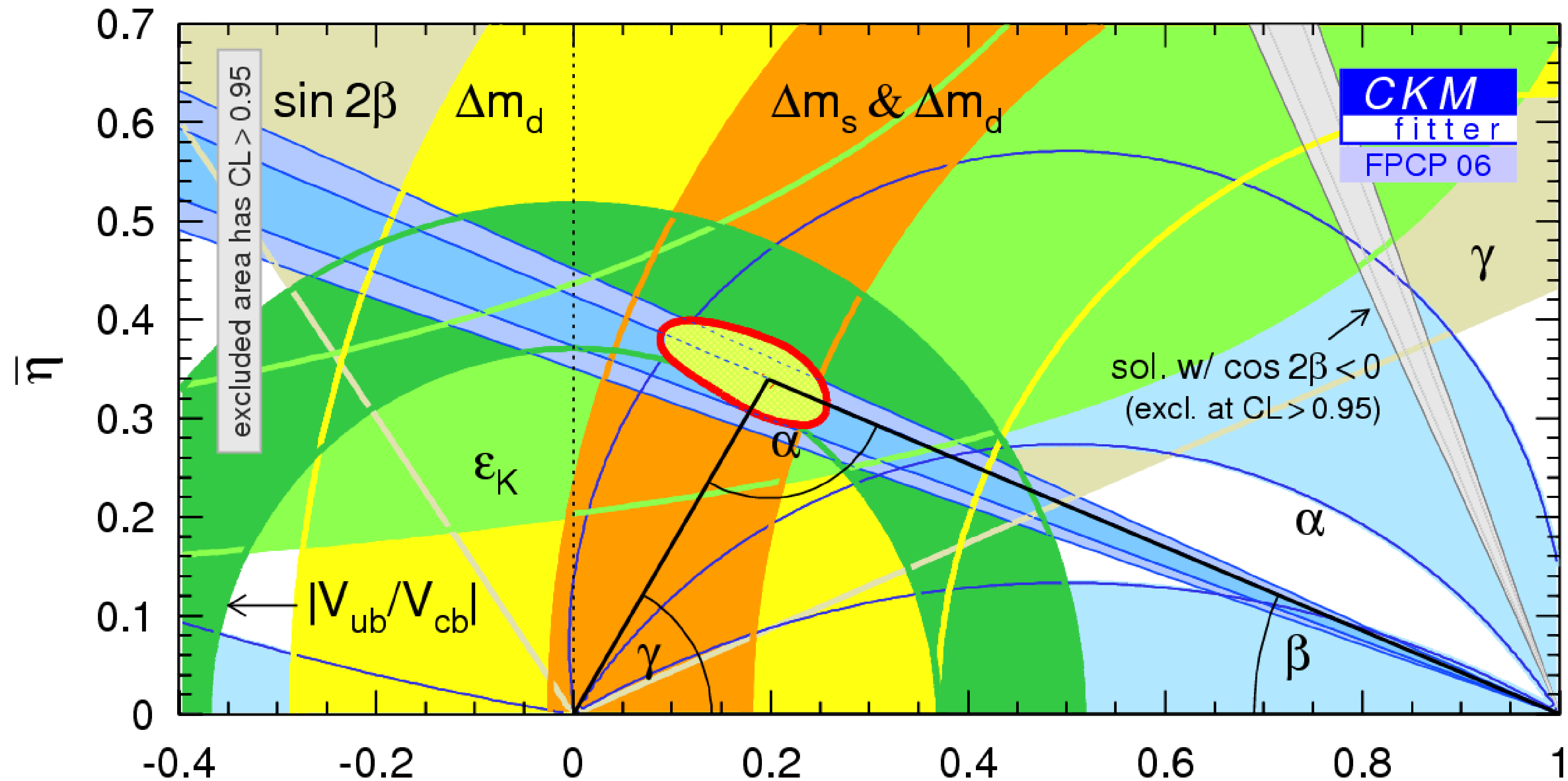
- Weakly decaying "new" quark would give BF = 1/9 for each lepton





Fast Forward 25 Years

- *B* Factories have accumulated over 1 billion $B\bar{B}$ events
  - Original goal: Use *CP* violation in B^0 decays to test if the Cabibbo-Kobayashi-Maskawa model is "correct"



CP violation measures the angles of the Unitarity Triangle

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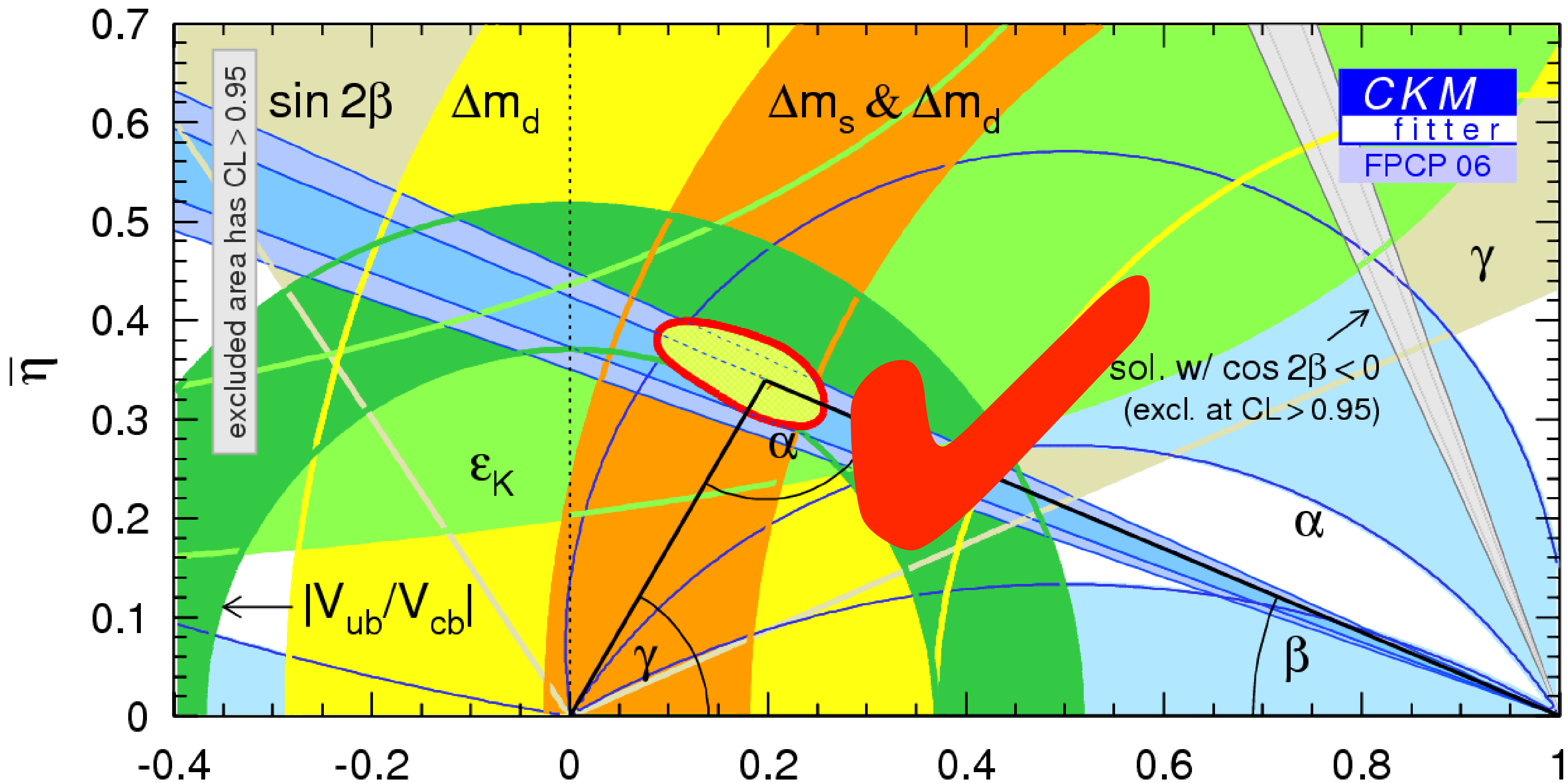
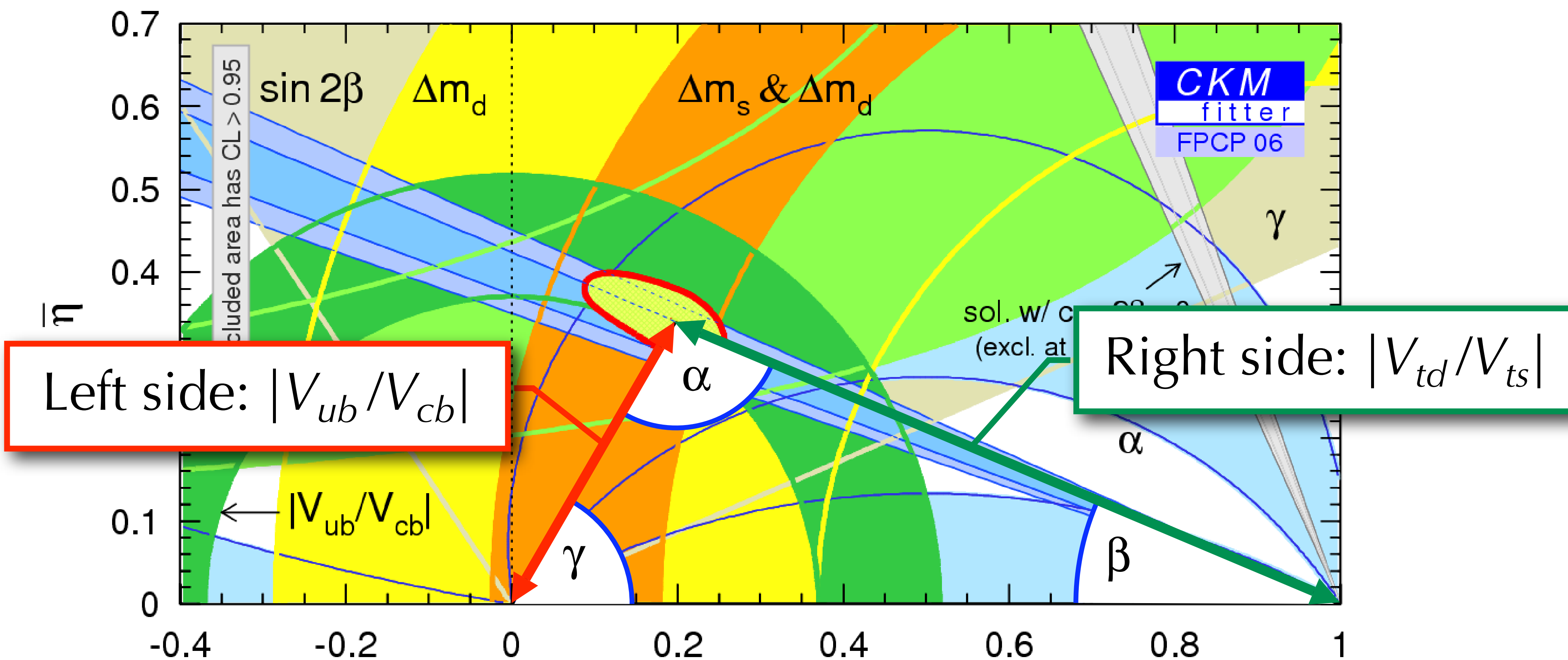


CP violation measures the angles of the Unitarity Triangle

In Search of New Physics

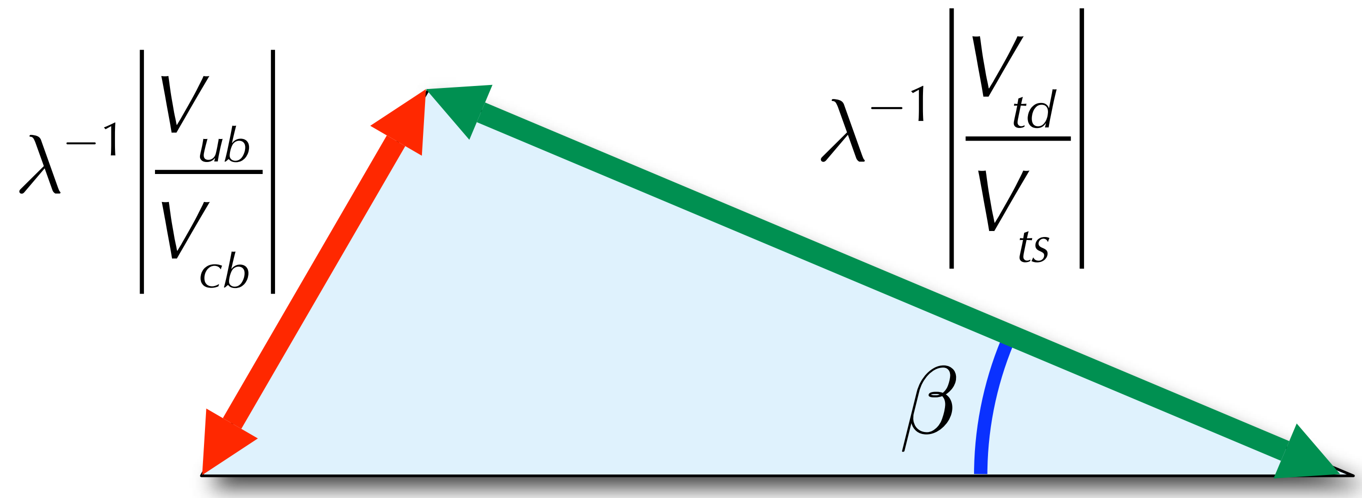
- New goal: Use *every* information to test if the Cabibbo-Kobayashi-Maskawa model is "complete"
  - We need both precision and redundancy



  - How many things can we measure "precisely"?

Redundancy and Precision

	WA	Prec.
$\lvert V_{td}/V_{ts}\rvert$	$0.208^{+0.008}_{-0.007}$	3.7%
β	$(21.7 \pm 1.0)^\circ$	4.7%
$\lvert V_{ub}/V_{cb}\rvert$	0.107 ± 0.008	7.6%

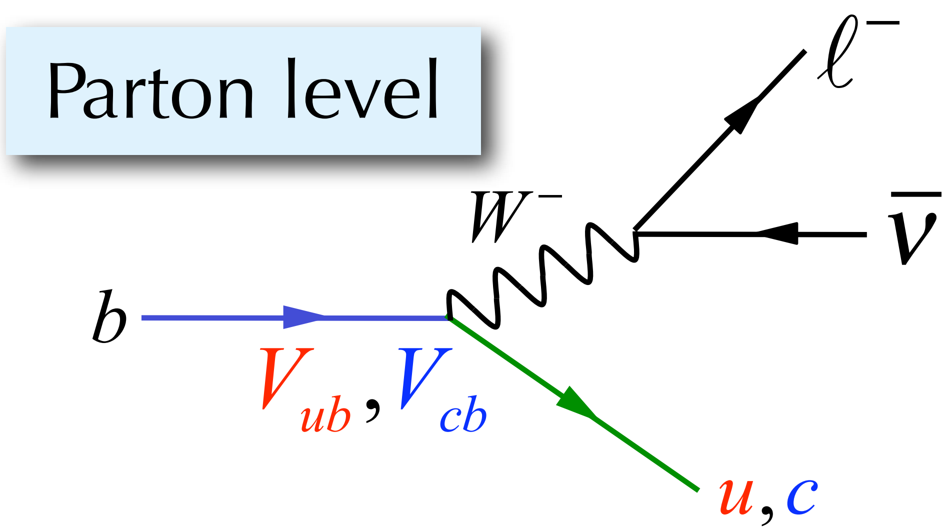


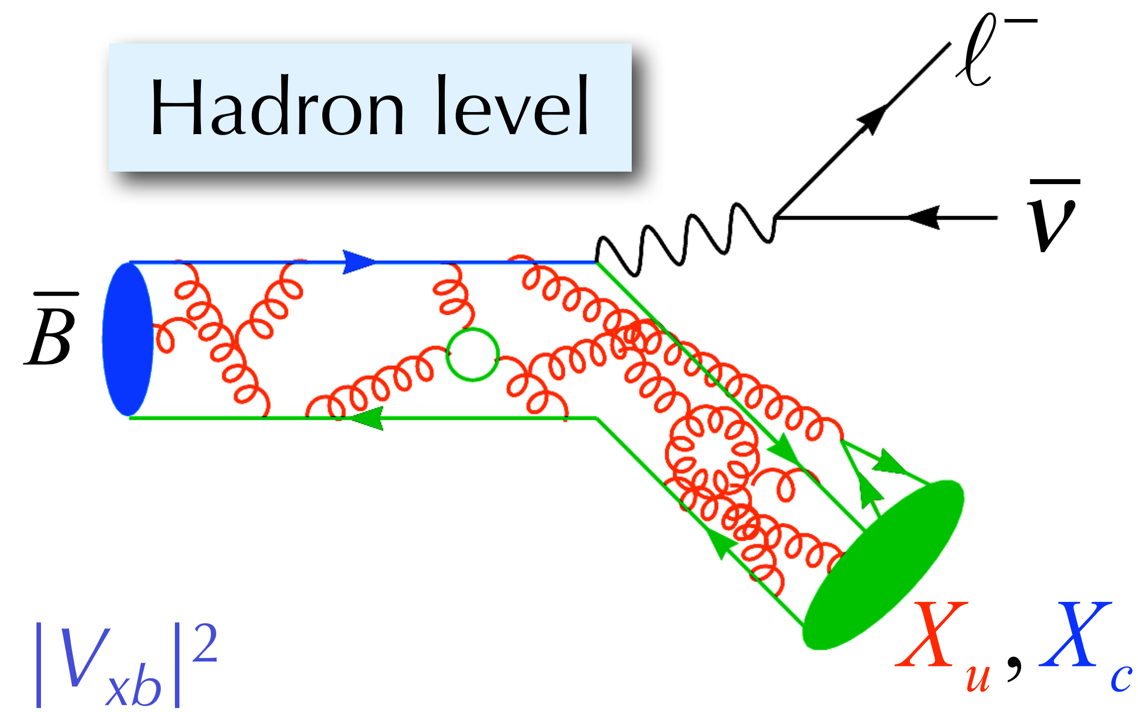
- Angle β and the right-side measured to better than 5%
  - Orthogonal constraints ➔ Anchor the (ρ, η) apex
- Next: the left side over-constrains the Triangle
  - Uncertainty dominated by $\lvert V_{ub}\rvert$
  - Precision is improving — was ±15% in 2003

Goal: Measure $\lvert V_{ub}\rvert$ with <5% precision

Semileptonic B Decays

- Natural probe for $|V_{ub}|$ and $|V_{cb}|$

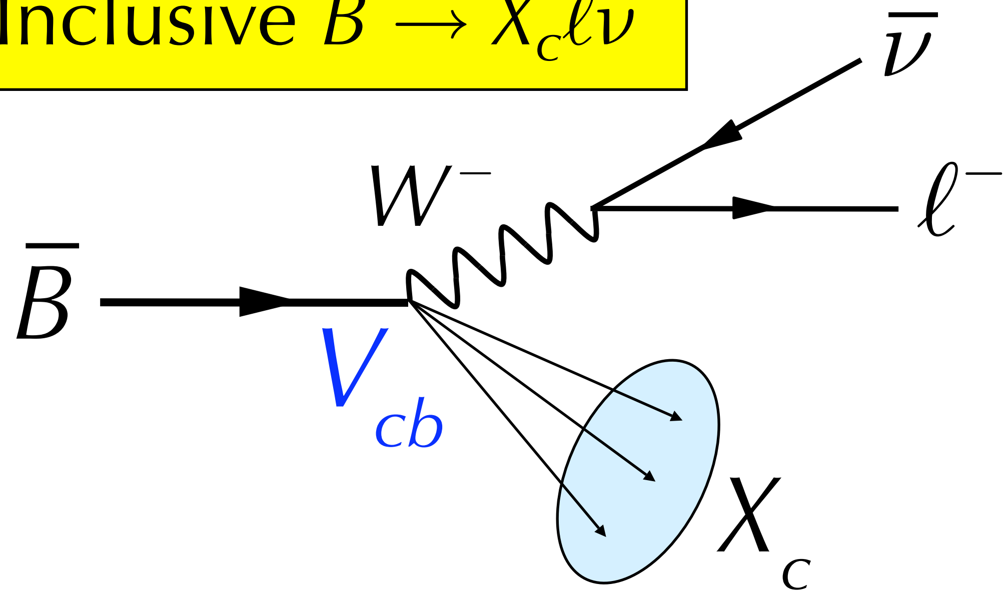




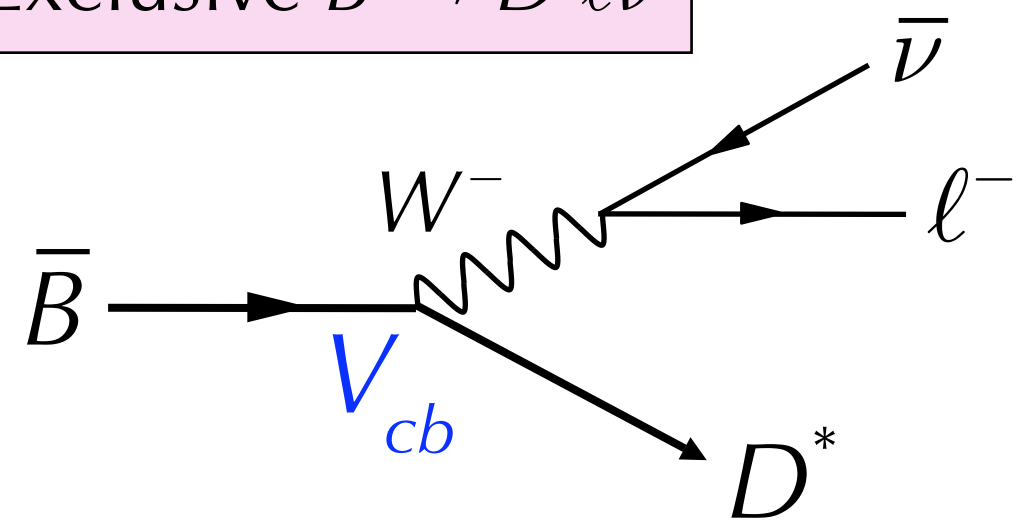
  - Decay rate $\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$
- $|V_{ub}/V_{cb}| \approx 0.1$ ➜ Γ_c larger than Γ_u by a factor ~50
  - Extracting $b \to u\ell\nu$ signal challenging
- Sensitive to hadronic effects
  - Must understand them to extract $|V_{ub}|$, $|V_{cb}|$

Inclusive vs. Exclusive

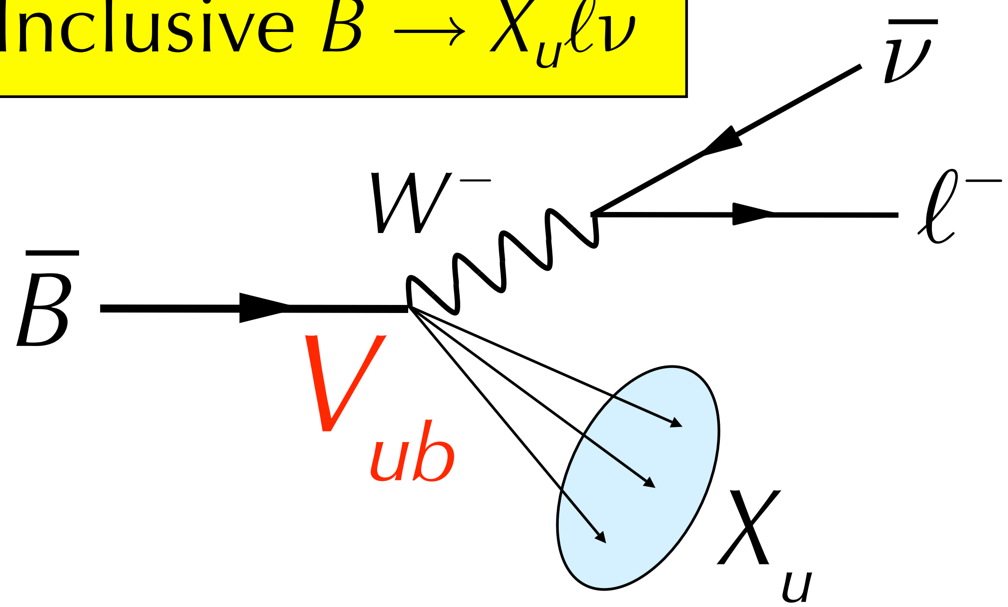
Inclusive $B \to X_c \ell \nu$



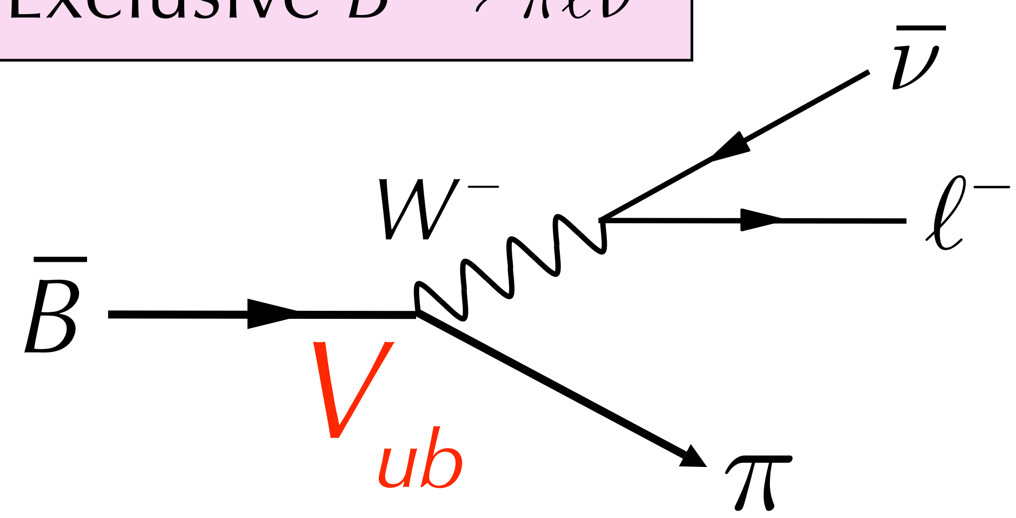
Exclusive $B \to D^* \ell \nu$



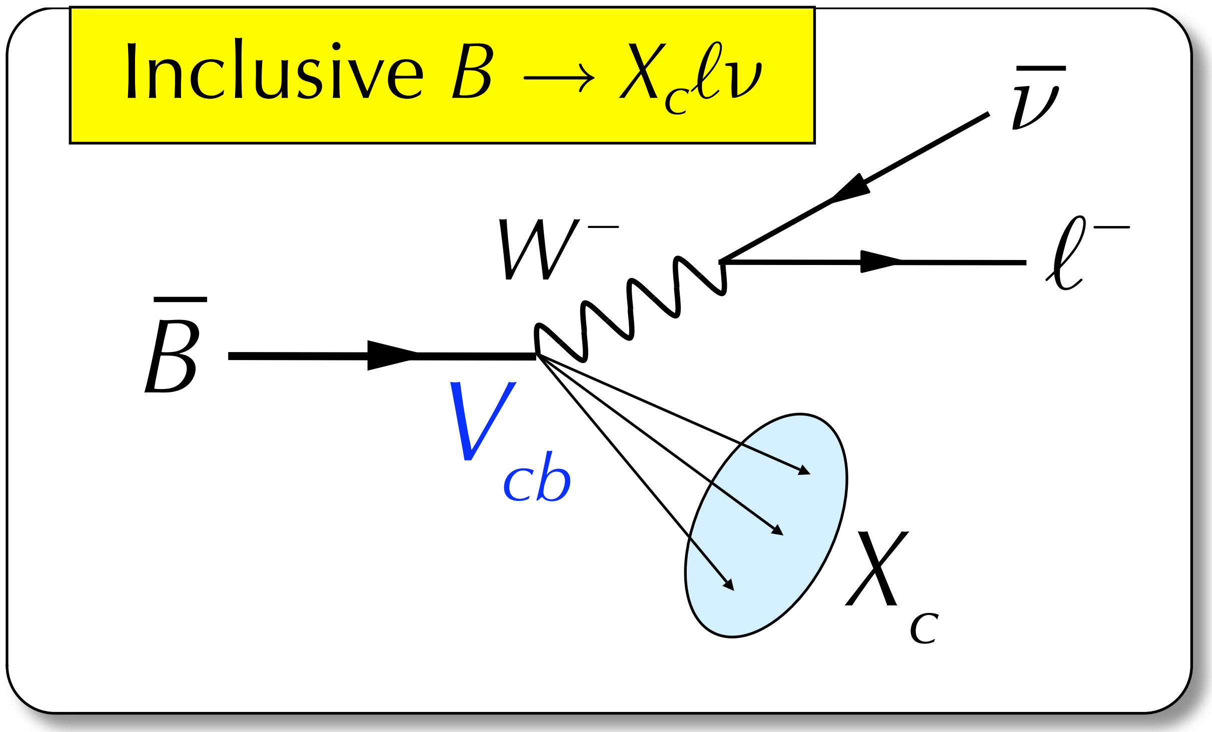
Inclusive $B \to X_u \ell \nu$

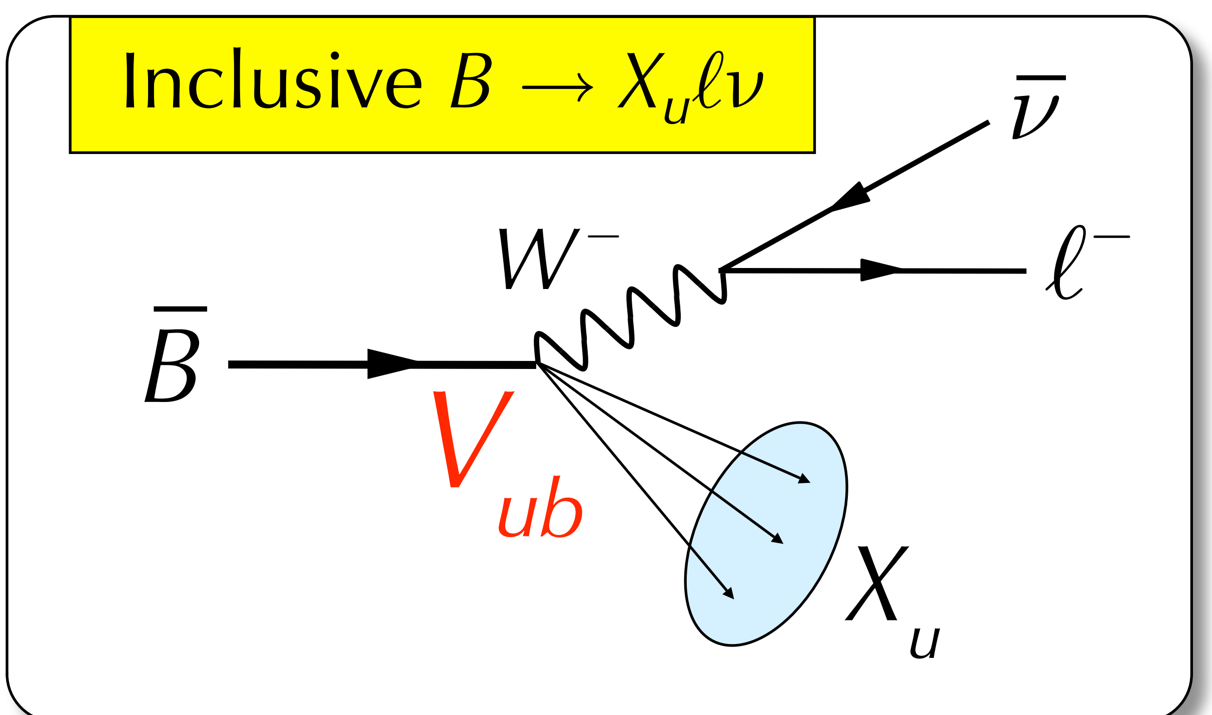


Exclusive $B \to \pi \ell \nu$



Inclusive Measurements





- Operator Product Expansion predicts the total rate Γ_u as

$$\frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 - \mathcal{O}\left(\frac{\alpha_s}{\pi}\right) - \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}^2}{m_b^2}\right) + \cdots\right]$$

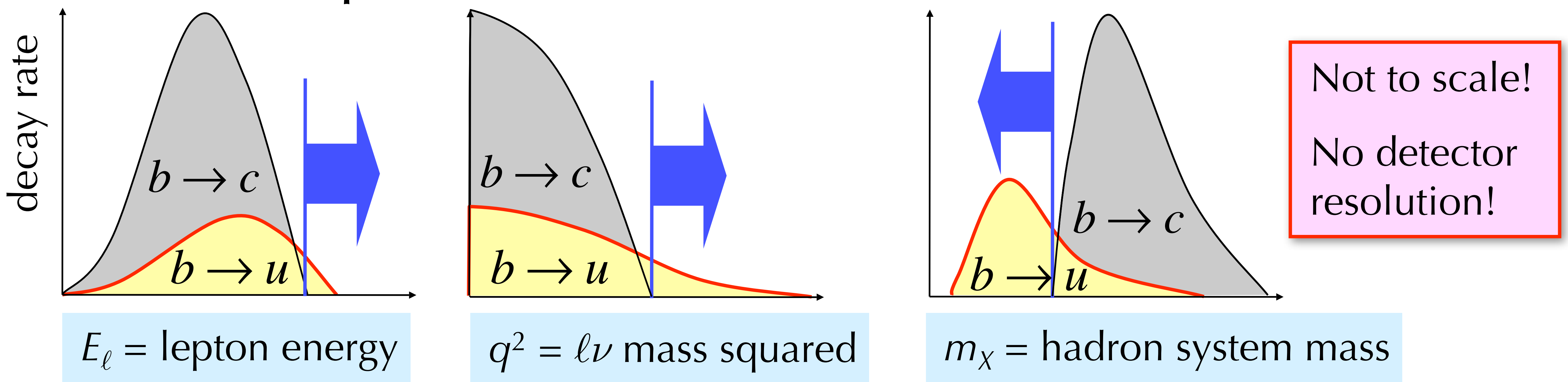
Perturbative terms known to $\mathcal{O}(\alpha_s^2)$

Non-perturb. terms suppressed by $1/m_b^2$

  - Dominant error from m_b^5
    - m_b measured to ±1% ➔ ±2.5% on $|V_{ub}|$
- Total rate can't be measured due to $B \to X_c \ell\nu$ backgd.
  - Must enhance S/B with cuts

Kinematical Cuts

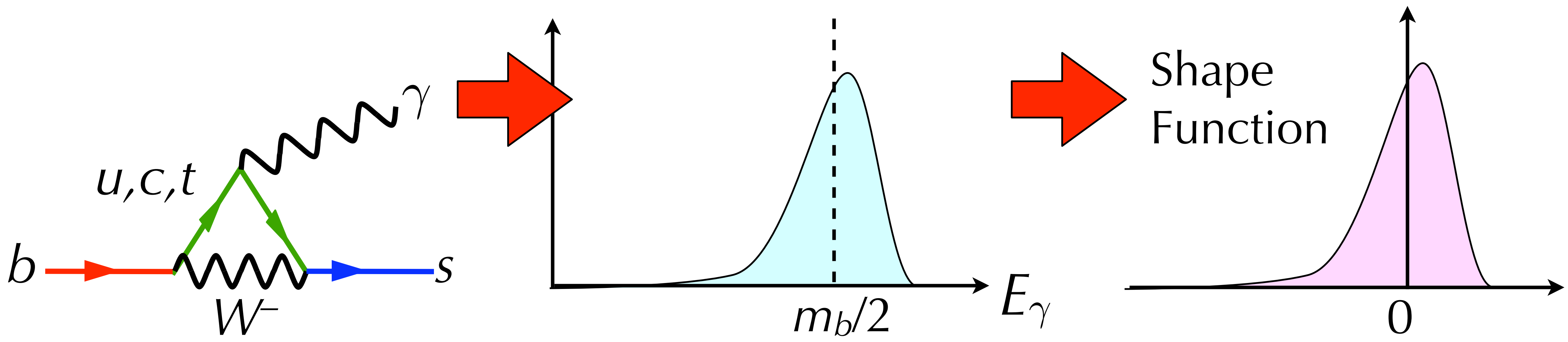
- Three independent kinematic variables in $B \to X\ell\nu$



  - Measure partial rates in favorable regions of the phase space
- Caveat: Spectra more sensitive to non-perturbative effects than the total rate ➔ $\mathcal{O}(1/m_b)$ instead of $\mathcal{O}(1/m_b^2)$
  - Need to know the **Shape Function** (= what the *b* quark is doing inside the *B* meson)
- Solution: Determine the Shape Function from the data

Shape Function

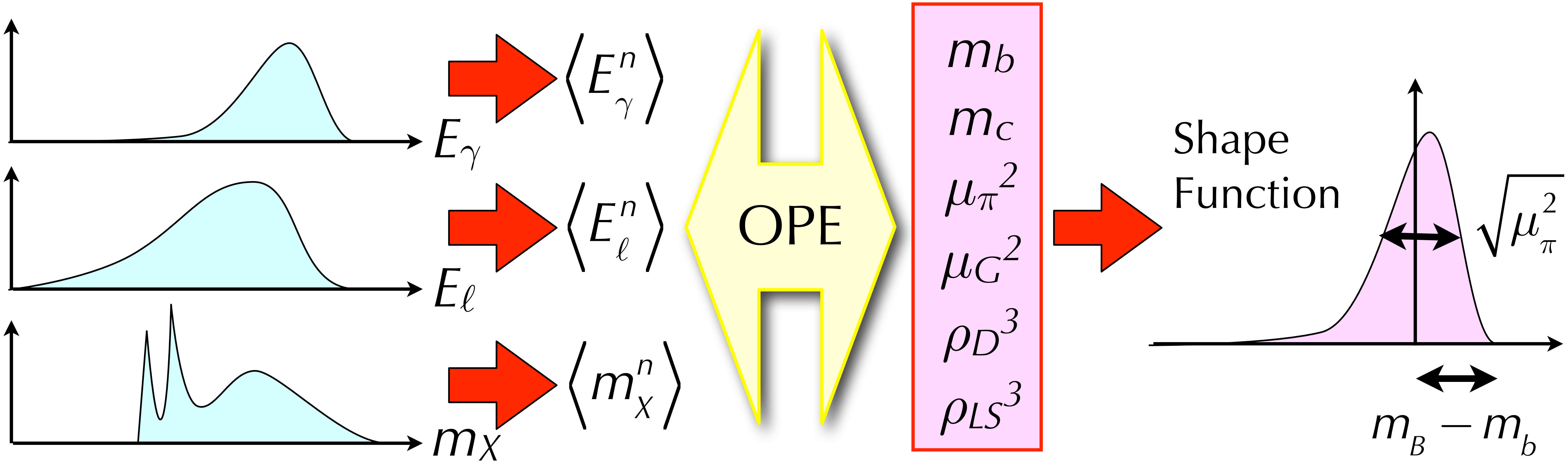
- Two ways to determine the Shape Function from data:
  - Directly from the E_γ spectrum of the $B \to X_s\gamma$ decay



Measurement limited by statistics and background

Shape Function

- Two ways to determine the Shape Function from data:
  - Indirectly from fitting the $B \to X_c \ell \nu$ and $B \to X_s \gamma$ decays
    - OPE predicts observables integrated over large phase space as functions of m_b, m_c, and non-perturbative parameters



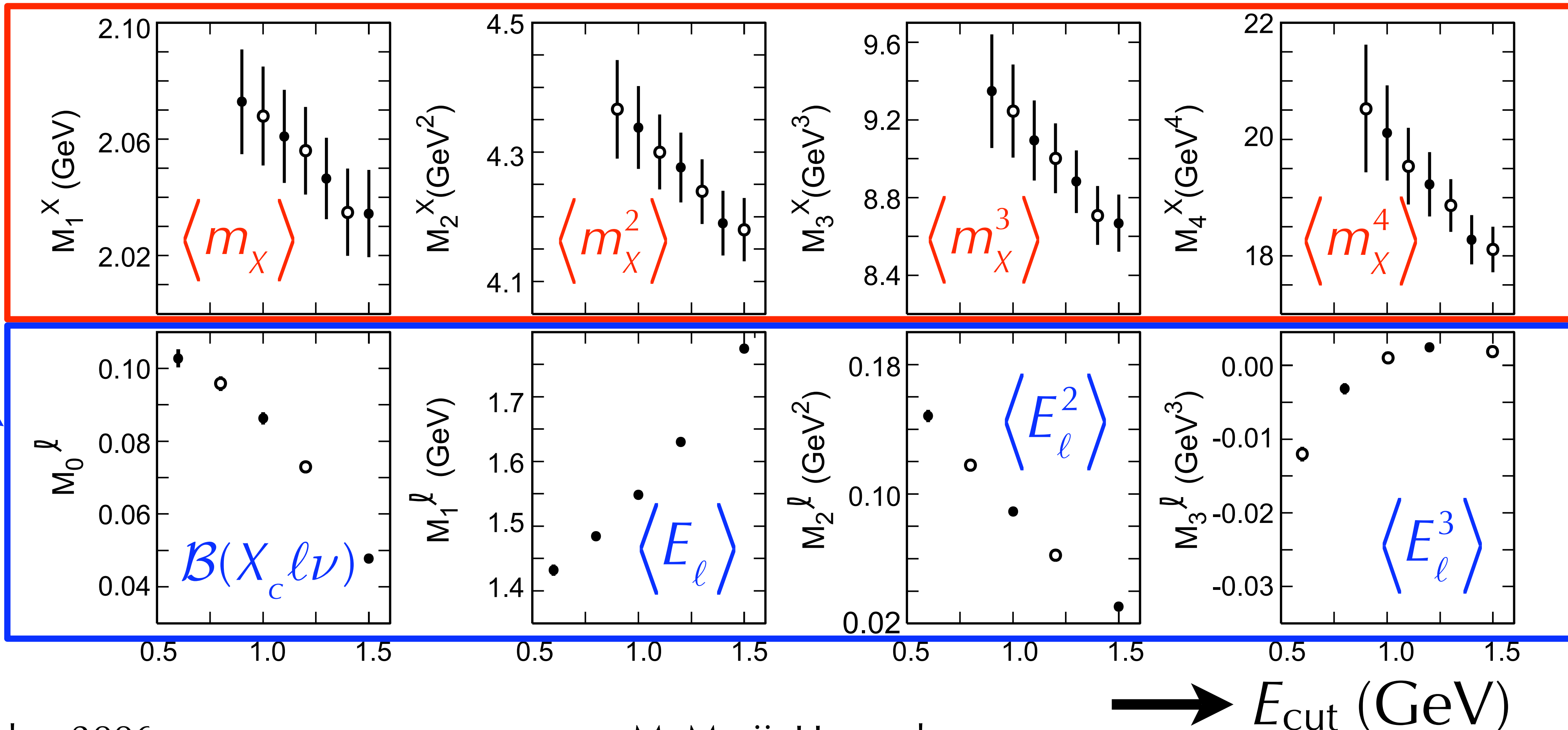
    - Global fit can determine the OPE parameters, which constrain the Shape Function

Inclusive $B \to X_c \ell \nu$

- Observables: E_ℓ (lepton energy) and m_X (hadron mass)

	$\langle E_\ell^n \rangle$	n	$\langle m_X^n \rangle$	n
BABAR	PRD 69:111103, 47 fb^{-1}	0, 1, 2, 3	PRD 69:111104, 81 fb^{-1}	1, 2, 3, 4
Belle Prelim.	Belle-Conf-0667, 140 fb^{-1}	0, 1, 2, 3, 4	Belle-Conf-0668, 140 fb^{-1}	2, 4

Measure moments as functions of minimum-E_ℓ cut



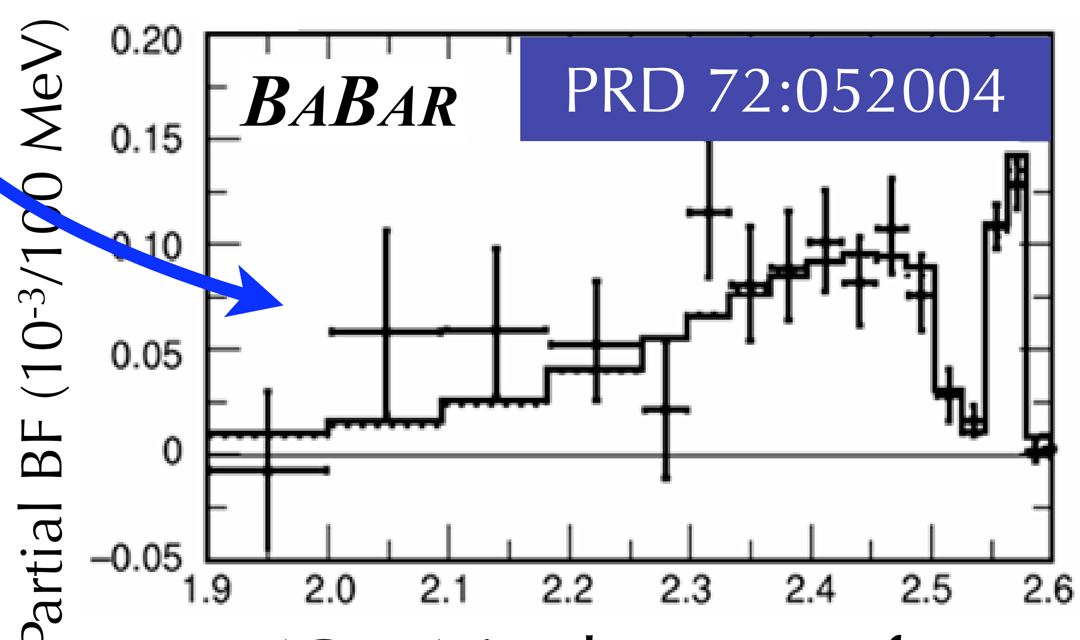
Inclusive $B \to X_s\gamma$

- E_γ spectrum in $B \to X_s\gamma$ decays connected directly to SF
  - Small rate and high background makes it tough to measure

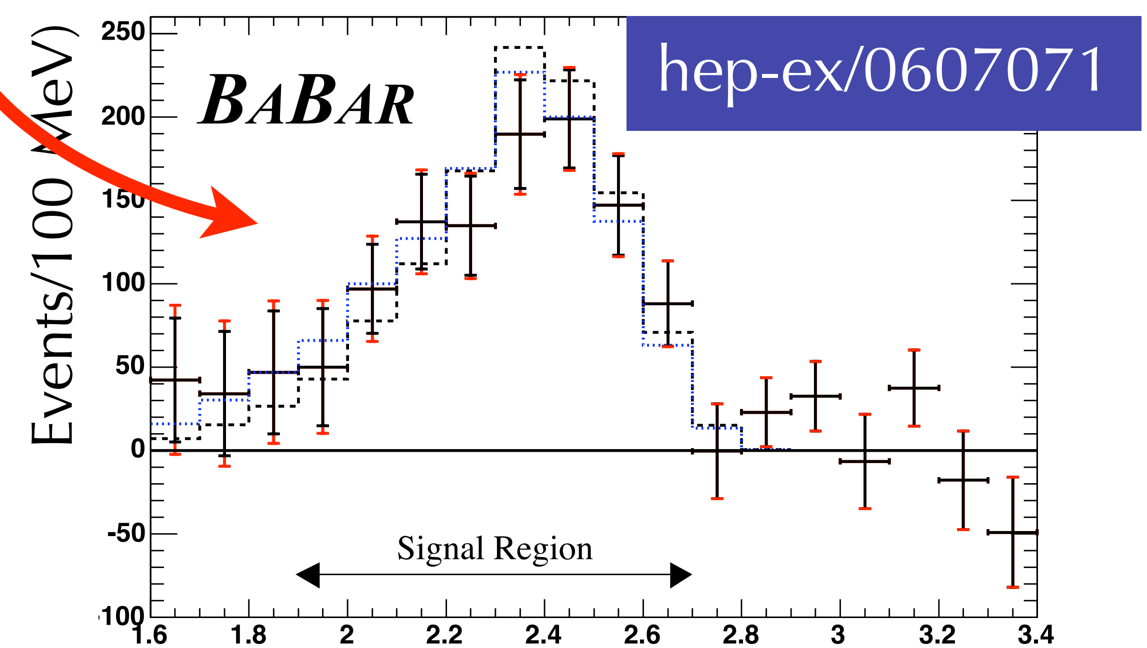
	$\langle E_\gamma{}^n \rangle$	Technique
*B*A*B*AR	PRD 72:052004, 81 fb^{-1}	Sum of exclusive
*B*A*B*AR	hep-ex/0607071, 81 fb^{-1}	Fully inclusive
Belle	PRL 93:061803, 140 fb^{-1}	Fully inclusive

Reconstruct exclusive X_s decays and sum up

Measure inclusive photon spectrum



E_γ (GeV) in the B rest frame



E_γ (GeV) in the CM frame

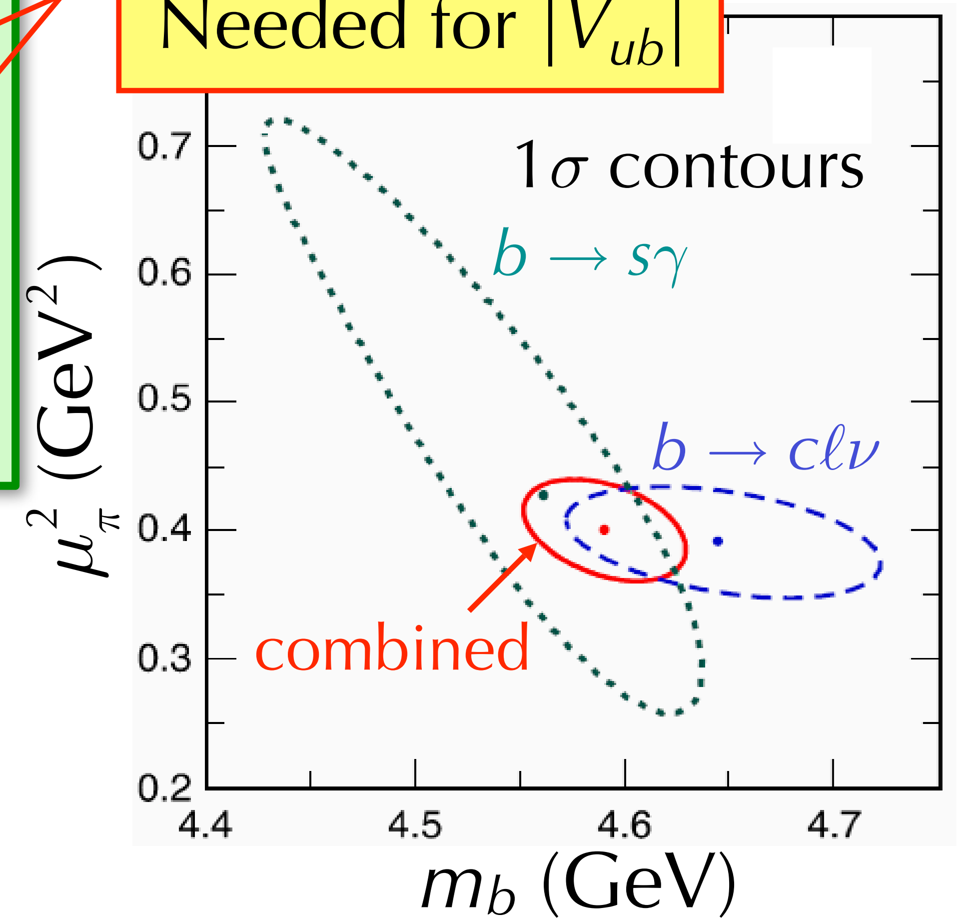
Global OPE Fit

BaBar	PRD69:111103 PRD69:111104 PRD72:052004 hep-ex/0507001
Belle	PRL93:061803 hep-ex/0508005
CLEO	PRD70:031002 PRL87:251807
CDF	PRD71:051103
DELPHI	EPJC45:35

- Buchmüller & Flächer (PRD73:073008) fit data from 10 measurements with an OPE calculation by Gambino & Uraltsev (EPJC34:181)
  - Fit parameters: $|V_{cb}|$, m_b, m_c, μ_π^2, μ_G^2, ρ_D^3, ρ_{LS}^3, $\mathcal{B}(B \to X_c \ell \nu)$

$$|V_{cb}| = (41.96 \pm 0.23_{\text{exp}} \pm 0.35_{\text{OPE}} \pm 0.59_{\Gamma_{sl}}) \times 10^{-3}$$
$$m_b = 4.590 \pm 0.025_{\text{exp}} \pm 0.030_{\text{OPE}}\,\text{GeV}$$
$$m_c = 1.142 \pm 0.037_{\text{exp}} \pm 0.045_{\text{OPE}}\,\text{GeV}$$
$$\mu_\pi^2 = 0.401 \pm 0.019_{\text{exp}} \pm 0.035_{\text{OPE}}\,\text{GeV}^2$$

Needed for $|V_{ub}|$



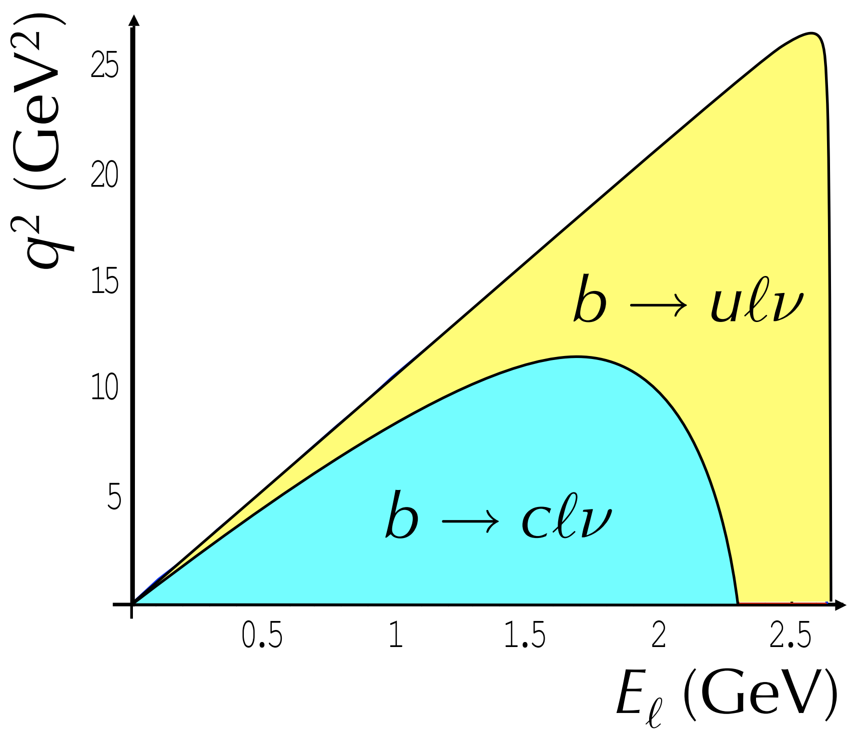
  - $|V_{cb}|$ error ±2%, m_b error ±1%
  - Consistency between $X_c \ell \nu$ and $X_s \gamma$ add confidence to the theory

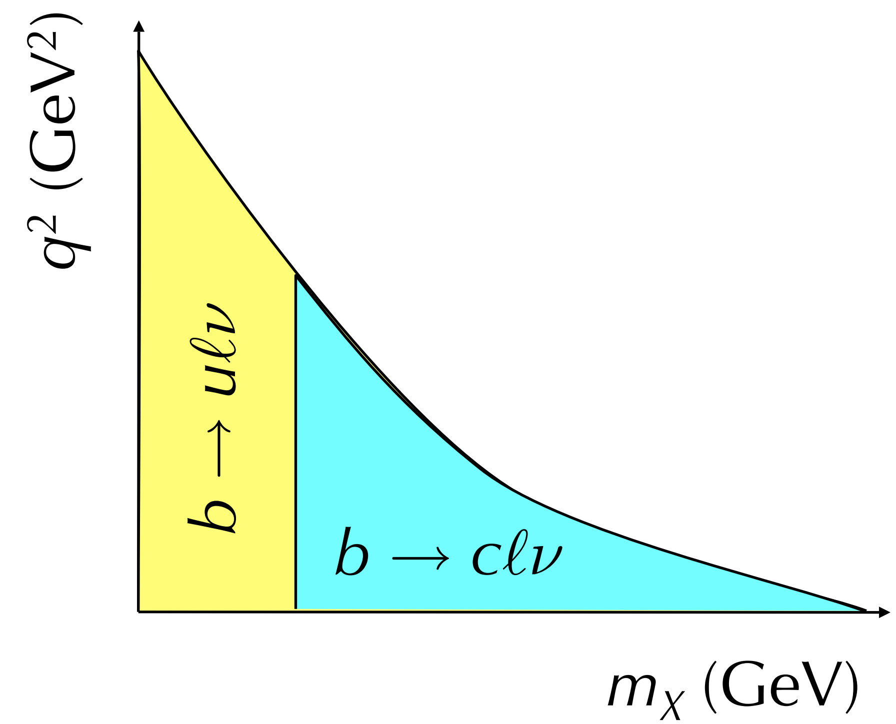
Inclusive $B \to X_u \ell \nu$

- Measure partial BF $\Delta\mathcal{B}(B \to X_u \ell \nu)$ in a region where …
  - the signal/background is good, and
  - the partial rate $\Delta\Gamma_u$ is reliably calculable

Large $\Delta\Gamma_u$ generally good, but not always

- Many possibilities – Review a few recent results





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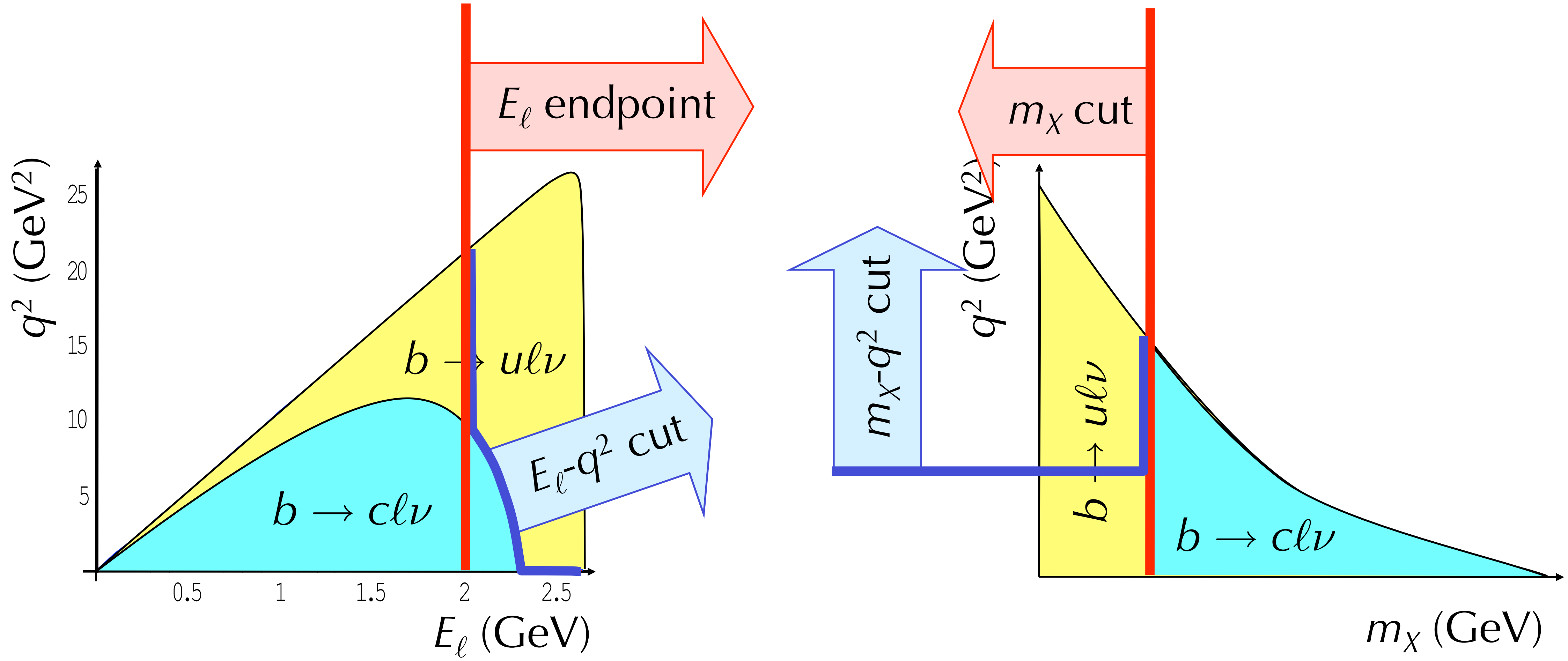


Lepton Endpoint

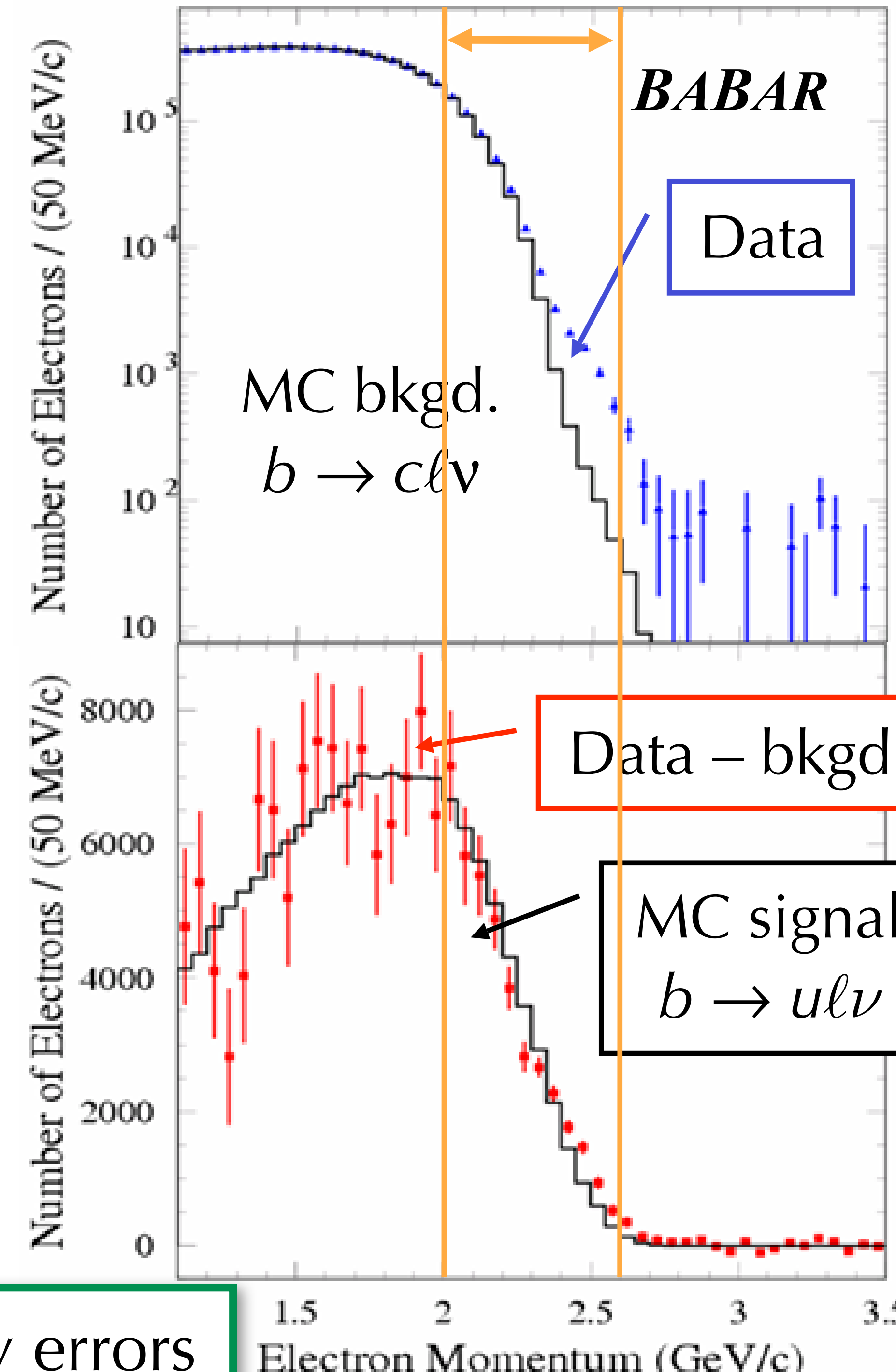
BABAR PRD 73:012006
Belle PLB 621:28
CLEO PRL 88:231803

- Find leptons with large E_ℓ
  - Push below the charm threshold
    - Larger signal acceptance
    - Smaller theoretical error
  - $S/B \sim 1/15$ ($E_\ell > 2$ GeV) ➔ Accurate subtraction of background is crucial!

	E_ℓ (GeV)	$\lvert V_{ub} \rvert$ (10^{-3})
BABAR 80fb^{-1}	2.0–2.6	$4.39 \pm 0.25_{exp} \pm 0.39_{SF+theo}$
Belle 27fb^{-1}	1.9–2.6	$4.82 \pm 0.45_{exp} \pm 0.30_{SF+theo}$
CLEO 9fb^{-1}	2.2–2.6	$4.09 \pm 0.48_{exp} \pm 0.36_{SF+theo}$

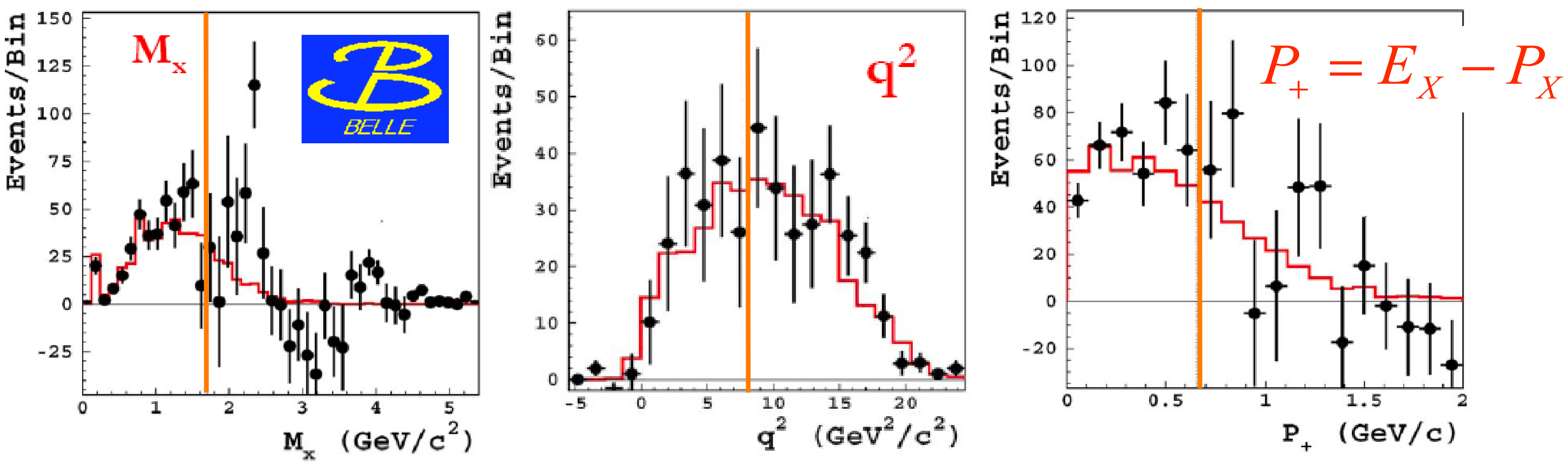
Shape Function

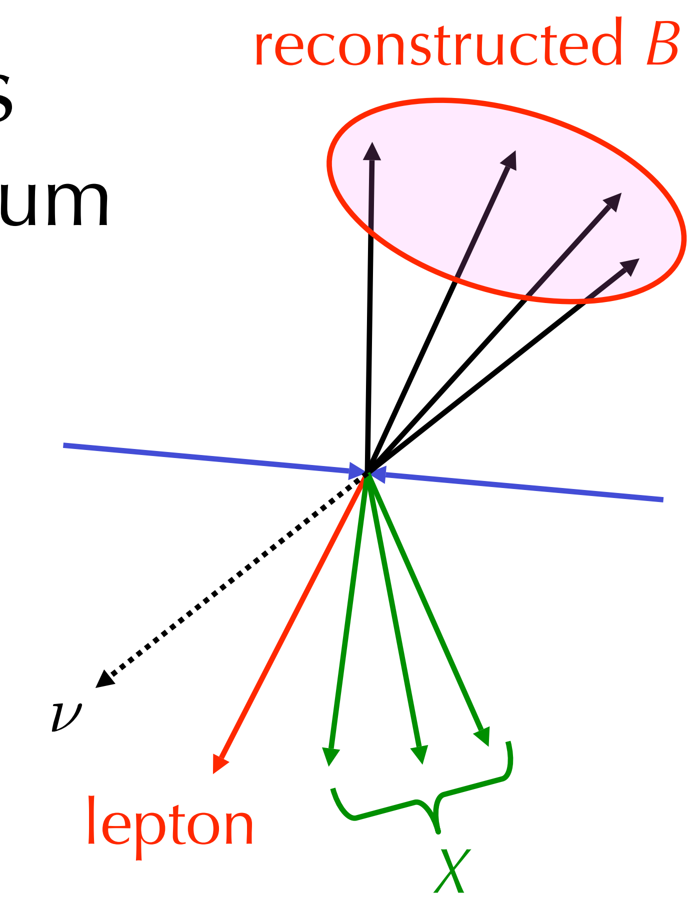
Theory errors



Hadronic *B* Tag

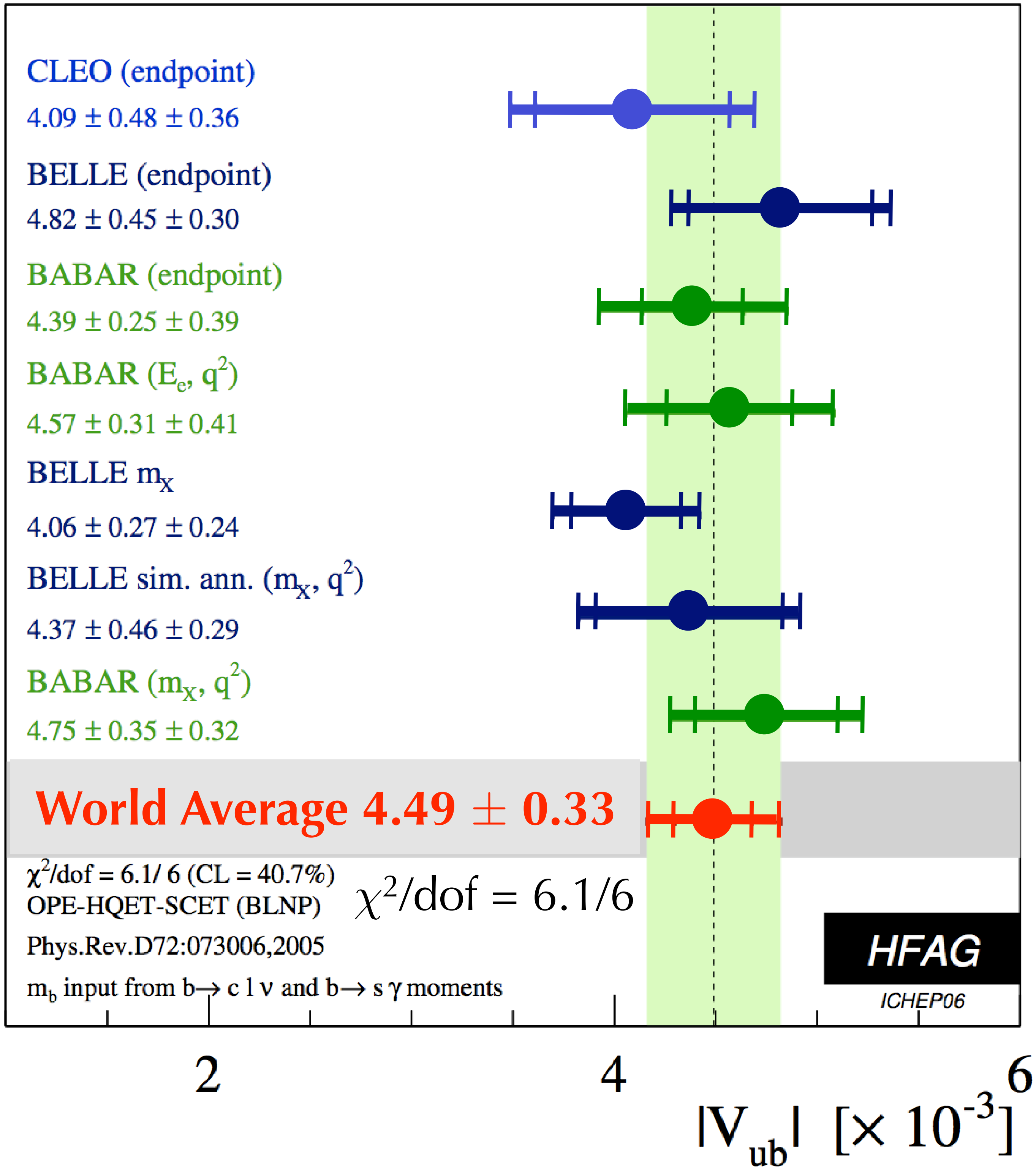
- Fully reconstruct one *B* in hadronic decays
  - Recoiling *B* with known charge and momentum
  - Access to all kinematic variables





	Region	$\lvert V_{ub}\rvert$ (10^{-3})
Belle 253 fb^{-1}	$m_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$4.70 \pm 0.37_{exp} \pm 0.31_{SF+theo}$
	$m_X < 1.7$ GeV	$4.06 \pm 0.27_{exp} \pm 0.24_{SF+theo}$
	$P_+ > 0.66$ GeV	$4.19 \pm 0.36_{exp} \pm 0.28_{SF+theo}$
BABAR 211 fb^{-1}	$m_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$4.75 \pm 0.35_{exp} \pm 0.32_{SF+theo}$ Prelim.

$|V_{ub}|$ from Inclusive $B \to X_u \ell \nu$



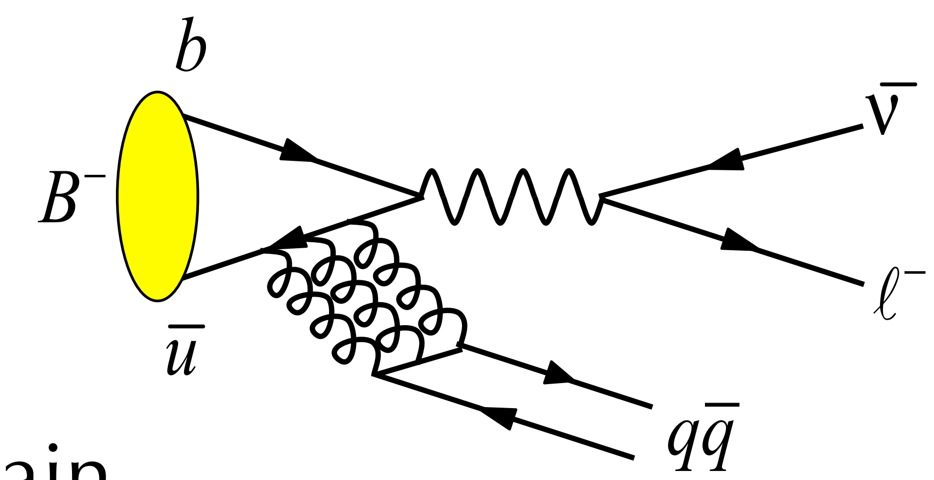
- $|V_{ub}|$ determined to ±7.3%

Statistical	±2.2%
Expt. syst.	±2.8%
$b \to c\ell\nu$ model	±1.9%
$b \to u\ell\nu$ model	±1.6%
SF params.	±4.2%
Theory	±4.2%

- Expt. and SF errors will improve with more data
- What's the theory error?

Theory Errors

- Subleading Shape Function ➔ ±3.8% error
  - Higher order non-perturbative corrections
  - Cannot be constrained with $b \to s\gamma$
- Weak annihilation ➔ ±1.9% error
  - Measure $\Gamma(B^0 \to X_u \ell\nu)/\Gamma(B^+ \to X_u \ell\nu)$ or $\Gamma(D^0 \to X\ell\nu)/\Gamma(D_s \to X\ell\nu)$ to constrain
  - Reduce the effect by rejecting the high-q^2 region



- Quark-hadron duality is believed to be negligible
  - $b \to c\ell\nu$ and $b \to s\gamma$ data fit well with the HQE predictions

- Ultimate error on inclusive $|V_{ub}|$ may be ~5%

Avoiding the Shape Function

- Possible to combine $b \to u\ell\nu$ and $b \to s\gamma$ so that the Shape Function cancels

$$\Delta\Gamma(B \to X_u \ell\nu) = \frac{|V_{ub}|^2}{|V_{ts}|^2} \int W(E_\gamma) \frac{d\Gamma(B \to X_s\gamma)}{dE_\gamma} dE_\gamma$$

Weight function

  - Leibovich, Low, Rothstein, PLB 486:86
  - Lange, Neubert, Paz, JHEP 0510:084, Lange, JHEP 0601:104
- No need to assume functional forms for the SF
- Need $b \to s\gamma$ spectrum in the B rest frame
  - Only one measurement (BABAR PRD 72:052004) available
  - Cannot take advantage of precise $b \to c\ell\nu$ data
- How well does this work? Only one way to find out…

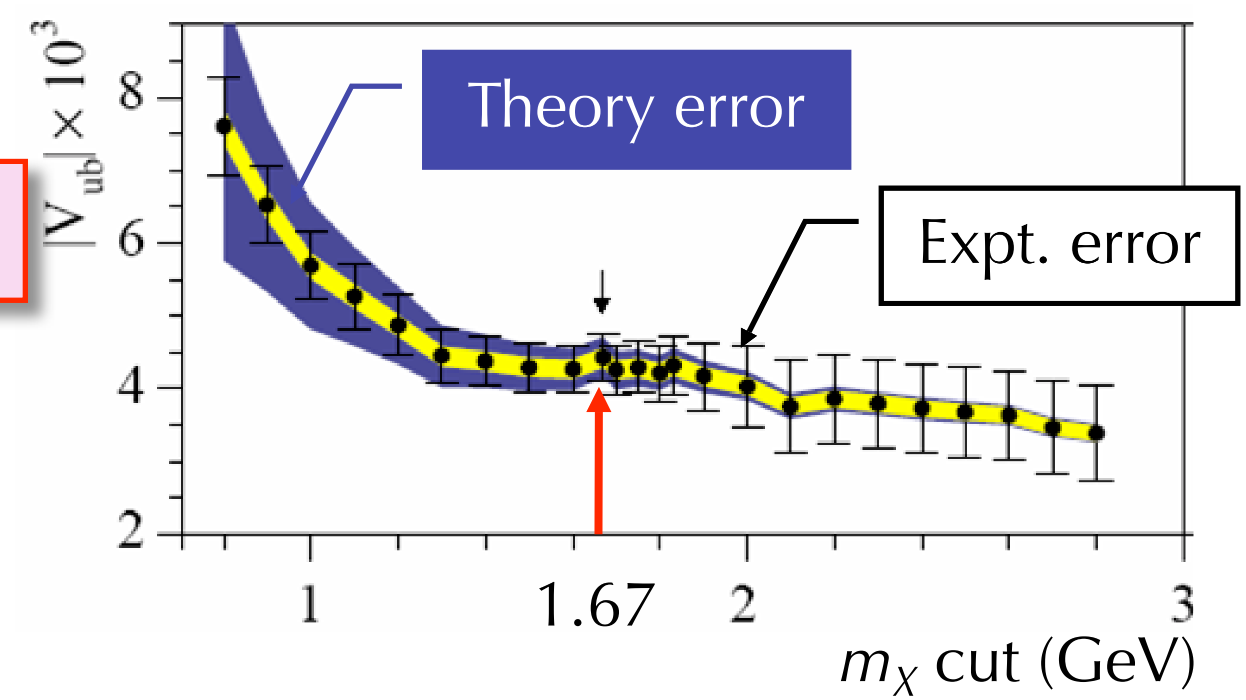
SF-Free $|V_{ub}|$ Measurement

- *BABAR* applied Leibovich-Low-Rothstein to 80 fb^{-1} data
  - $\Delta\Gamma(B \to X_u \ell \nu)$ with varying m_X cut
  - $d\Gamma(B \to X_s \gamma)/dE_\gamma$ from PRD 72:052004
- With $m_X < 1.67$ GeV

$$|V_{ub}| = (4.43 \pm 0.38 \pm 0.25 \pm 0.29) \times 10^{-3}$$

stat. syst. theory

  - SF error ➔ Statistical error



- Also measured $m_X < 2.5$ GeV
  - Almost (96%) fully inclusive ➔ No SF necessary

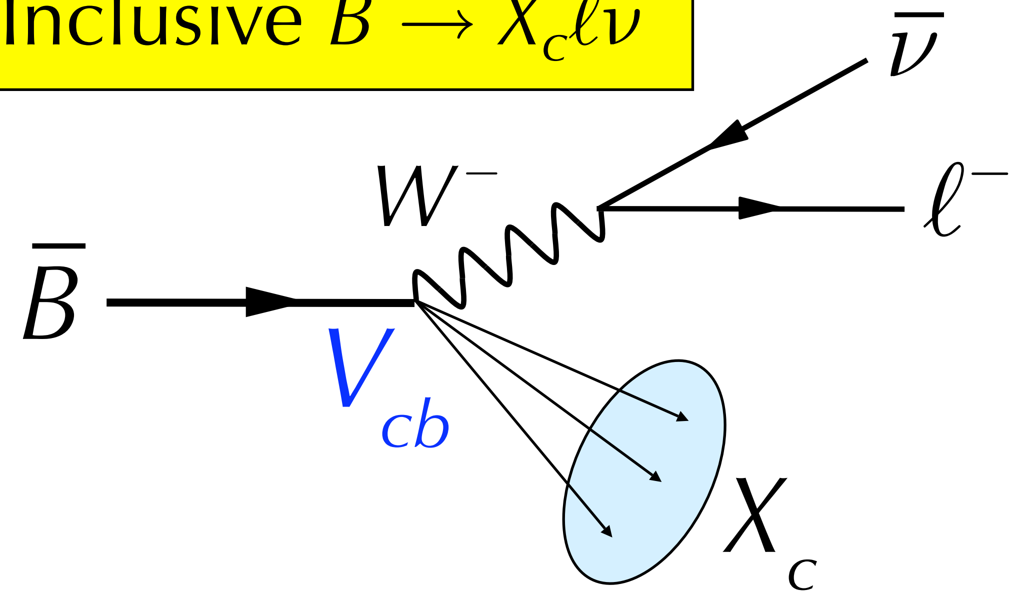
$$|V_{ub}| = (3.84 \pm 0.70 \pm 0.30 \pm 0.10) \times 10^{-3}$$

Theory error ±2.6%!

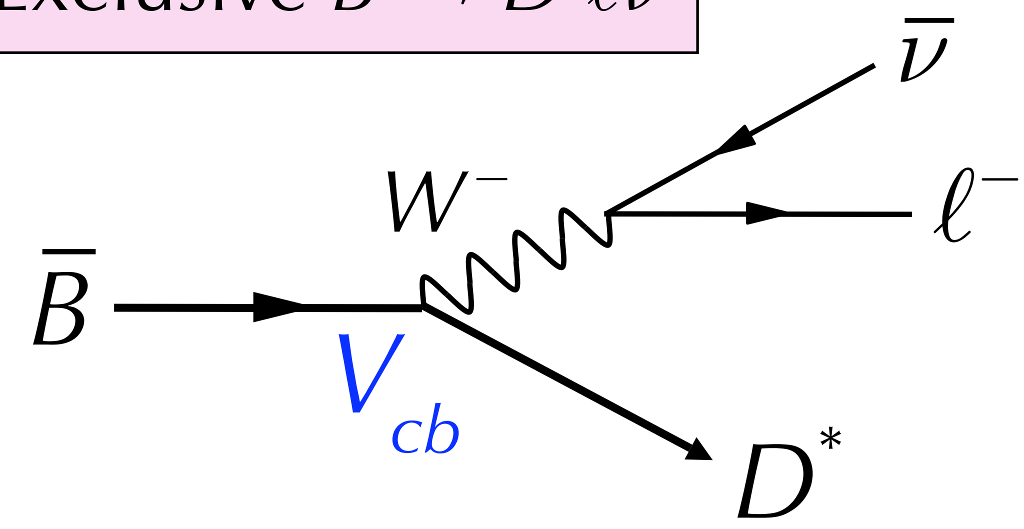
- Attractive new approaches with increasing statistics

Inclusive vs. Exclusive

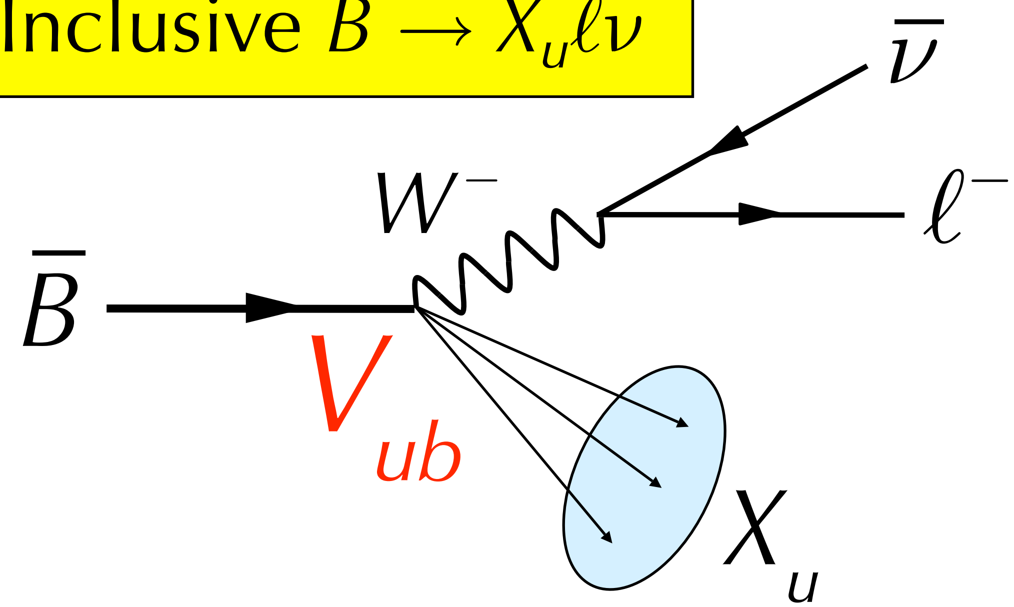
Inclusive $B \to X_c \ell \nu$



Exclusive $B \to D^* \ell \nu$



Inclusive $B \to X_u \ell \nu$



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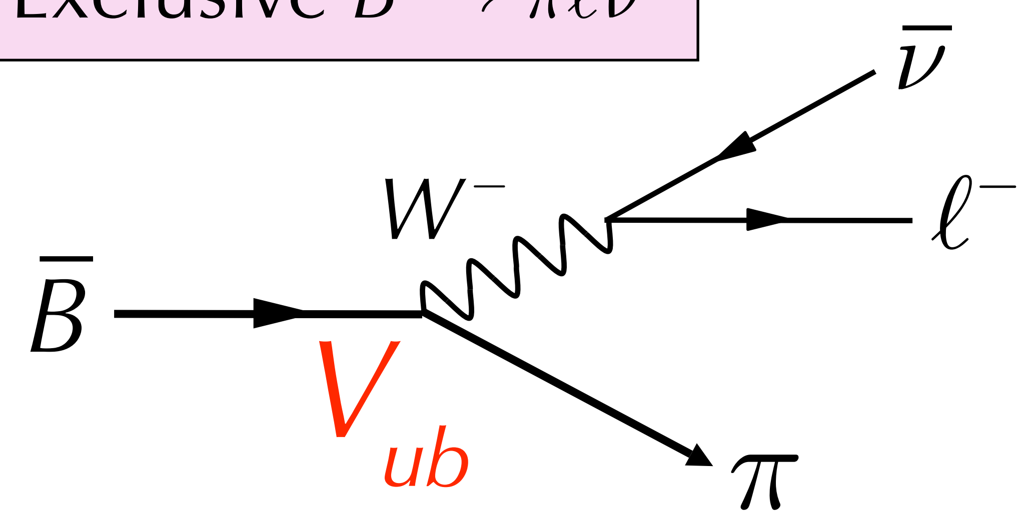
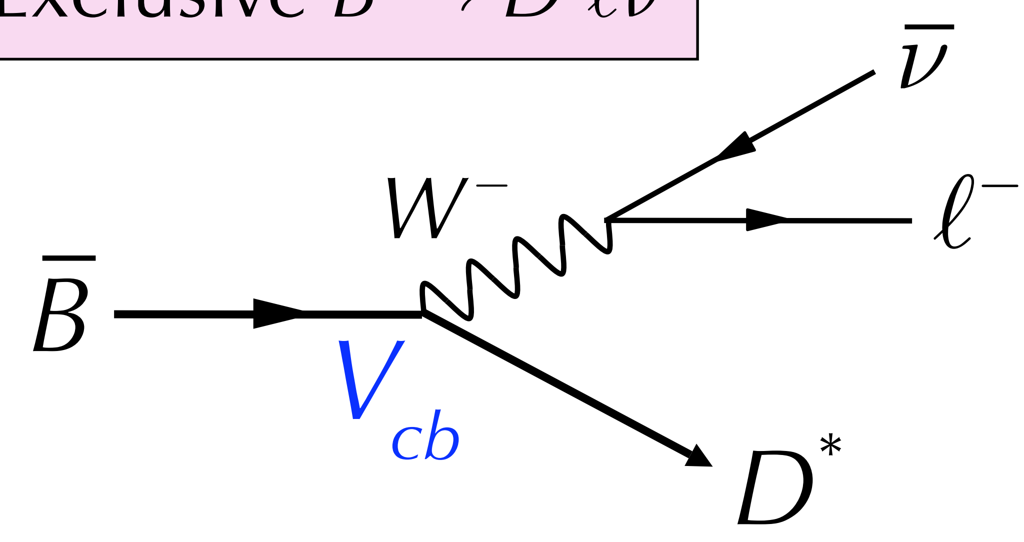


Exclusive Measurements

- Exclusive rates determined by $|V_{xb}|$ and Form Factors
  - Theoretically calculable at kinematical limits
    - Lattice QCD works if D^* or π is ~ at rest relative to B
  - Empirical extrapolation is necessary to extract $|V_{xb}|$ from measurements
- Measure differential rates to constrain the FF shape
  - Then use FF normalization from the theory

Exclusive $B \to D^* \ell \nu$



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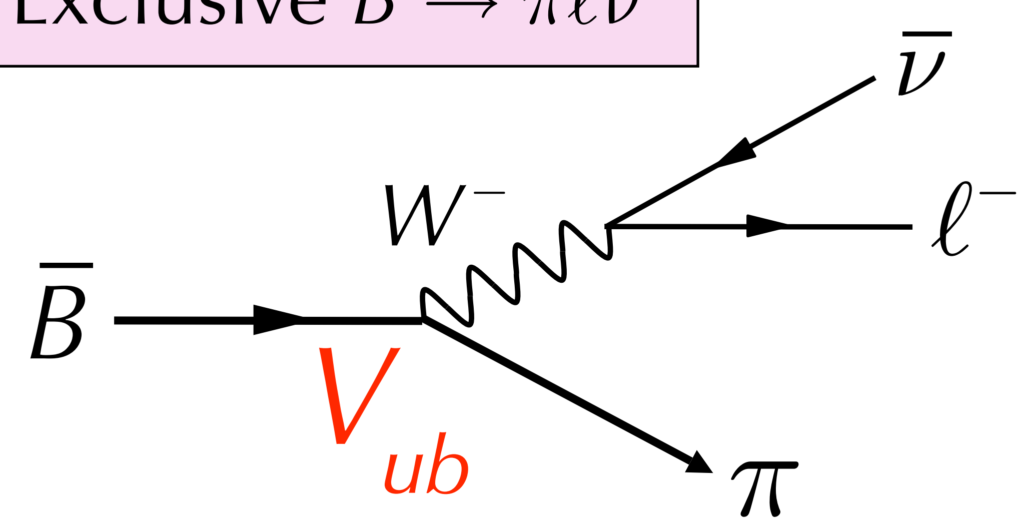


Exclusive $B \to D^* \ell \nu$

- Decay rate is

$$\frac{d\Gamma(B \to D^* \ell \nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} |\mathcal{F}(w)|^2 \mathcal{G}(w)$$

form factor

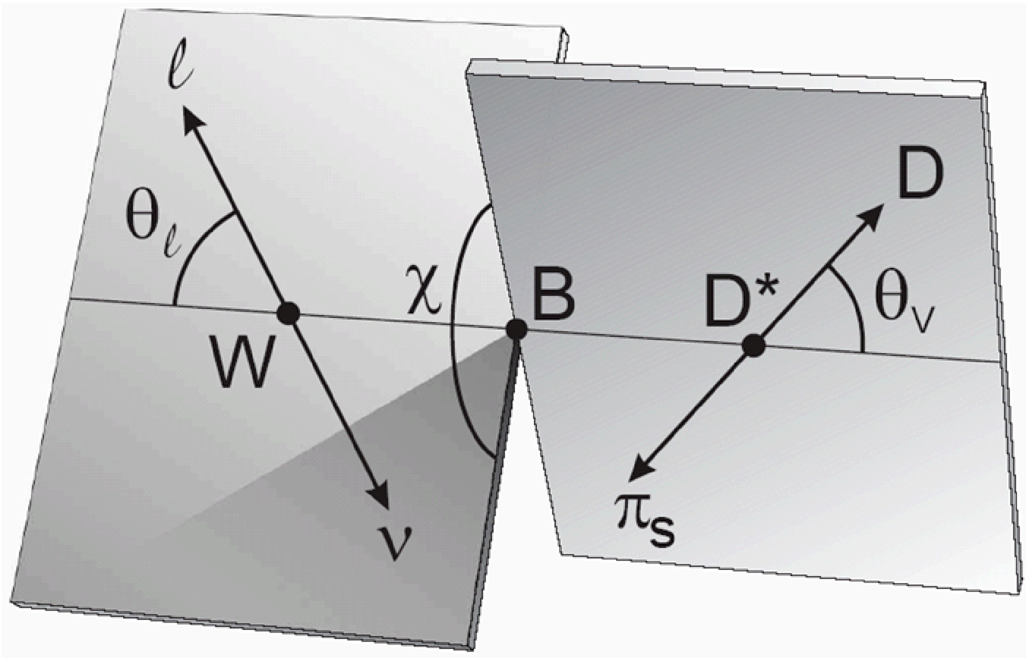
phase space

D^* boost in the B rest frame

  - $\mathcal{F}(1) = 1$ in the heavy-quark limit
    - Quenched lattice QCD gives $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$ Hashimoto et al, PRD 66:014503
  - $\mathcal{F}(w)$ shape expressed by ρ^2 (slope at $w = 1$) and R_1, R_2 (form factor ratios)
    - Analyticity constrains curvature

    Caprini, Lellouch, Neubert, NPB 530:153

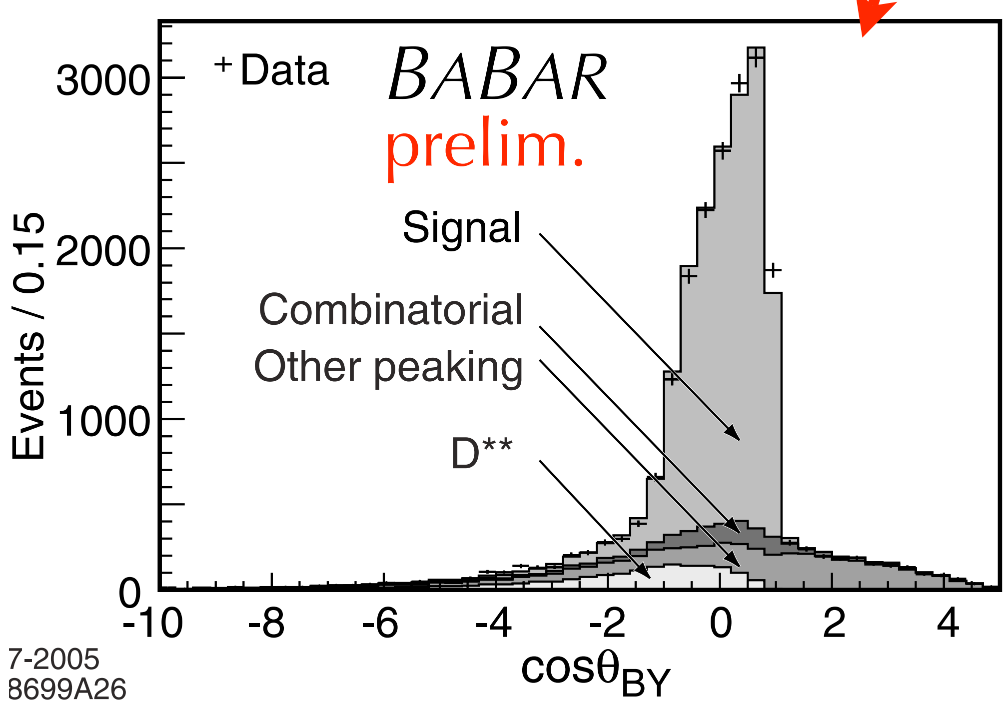
- Measure decay angles θ_ℓ, θ_V, χ
  - Fit 3-D distribution in bins of w to extract ρ^2, R_1, R_2

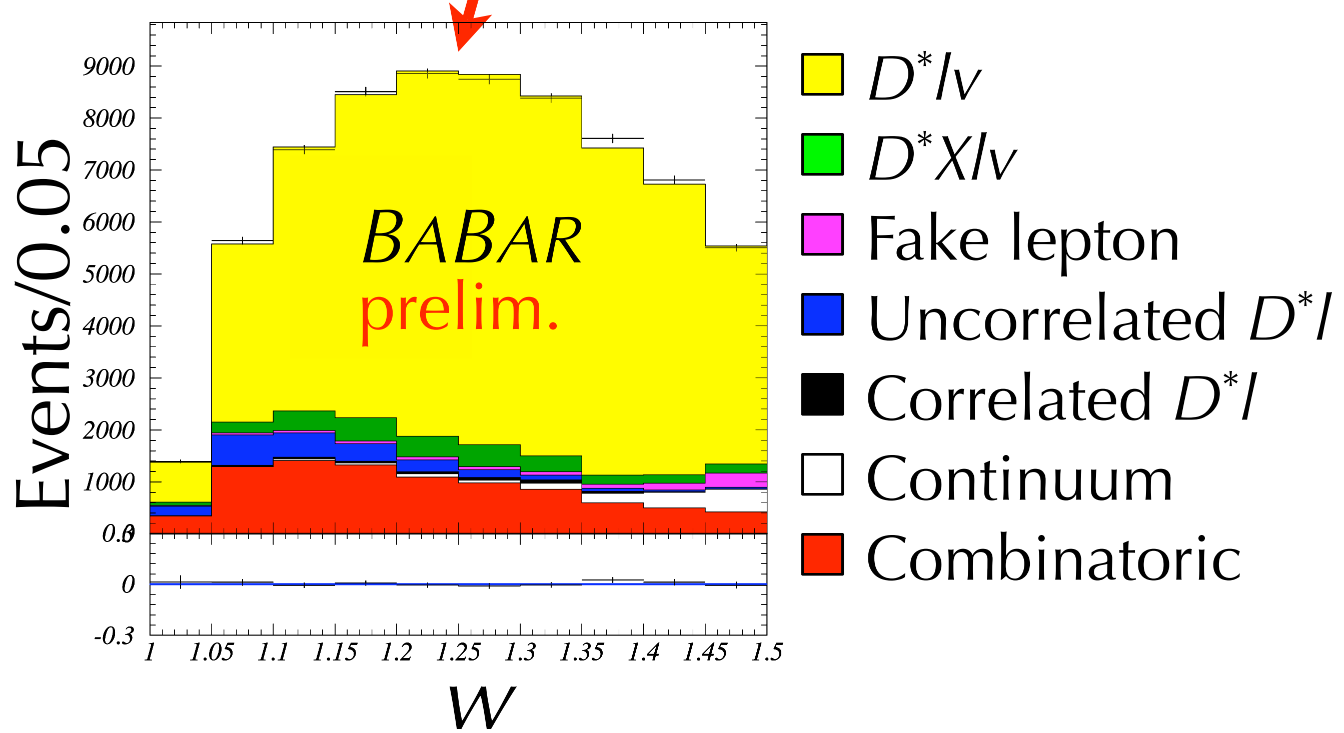


$B \to D^* \ell \nu$ Measurements

- BaBar measured $|V_{cb}|$ and FFs using $D^{*+} \to D^0 \pi^+$
  - Two nearly-independent analyses on the same (79 fb^{-1}) data

	hep-ex/0602023	hep-ex/0607076 Prelim.
D^0 decay modes	$K^-\pi^+$	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$
# of candidates	16,000	69,000
Purity	85%	77%





$B \to D^* \ell \nu$ Results

- Determine the FFs combining two measurements

$$R_1 = 1.417 \pm 0.061_{\text{stat}} \pm 0.044_{\text{syst}}$$
$$R_2 = 0.836 \pm 0.037_{\text{stat}} \pm 0.022_{\text{syst}}$$
$$\rho^2 = 1.179 \pm 0.048_{\text{stat}} \pm 0.028_{\text{syst}}$$

- R_1 and R_2 improved by a factor 5 over previous CLEO measurement PRL 76:3898 (1996)

  - Large impact on other measurements of $B \to D^* \ell \nu$

- Extrapolating the partial rate to $w = 1$, we find

$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32_{\text{stat}} \pm 1.15_{\text{syst}}) \times 10^{-3}$$

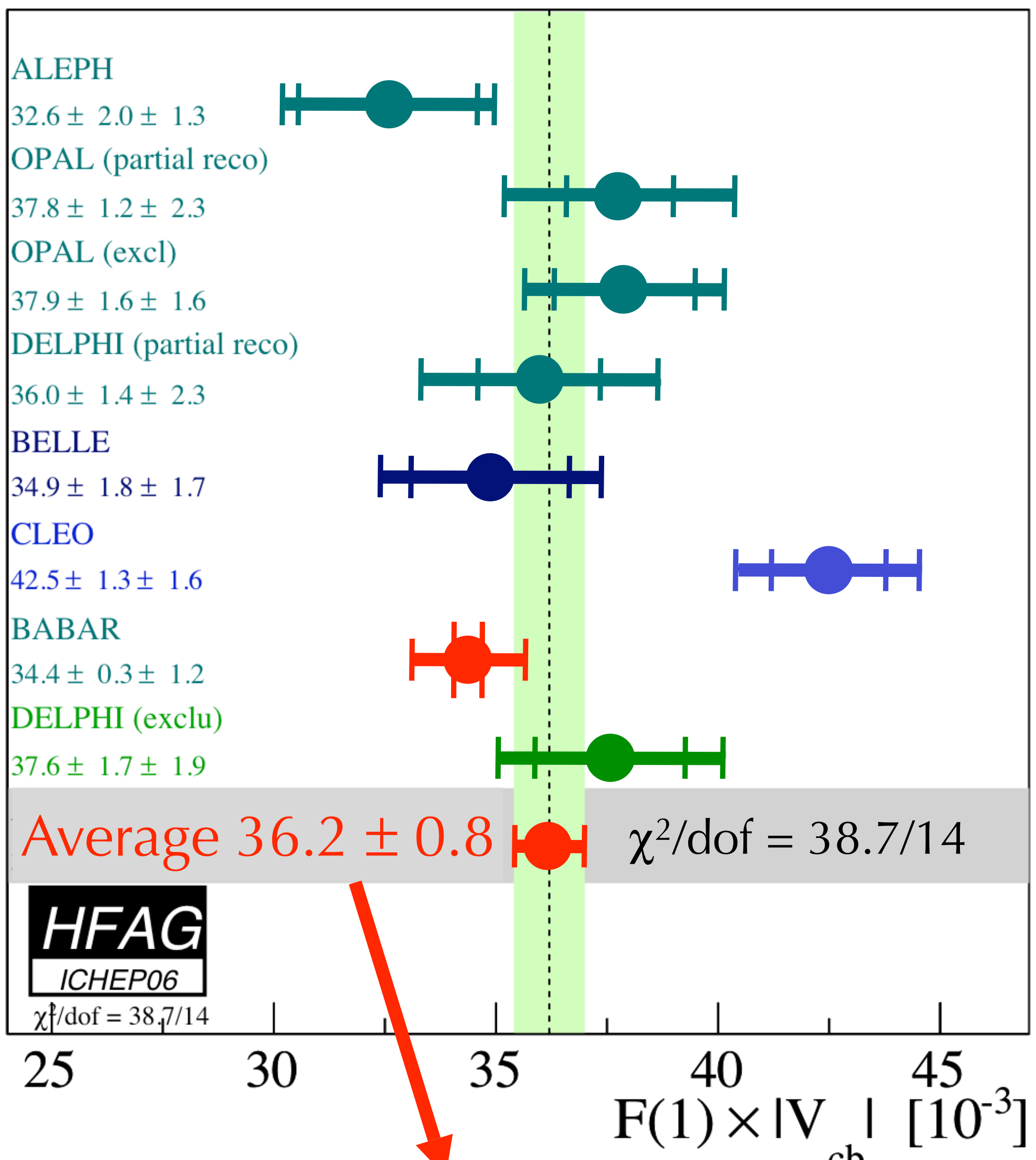
$$|V_{cb}| = (37.7 \pm 0.3_{\text{stat}} \pm 1.3_{\text{syst}} {}^{+1.5}_{-1.2}{}_{\mathcal{F}(1)}) \times 10^{-3}$$

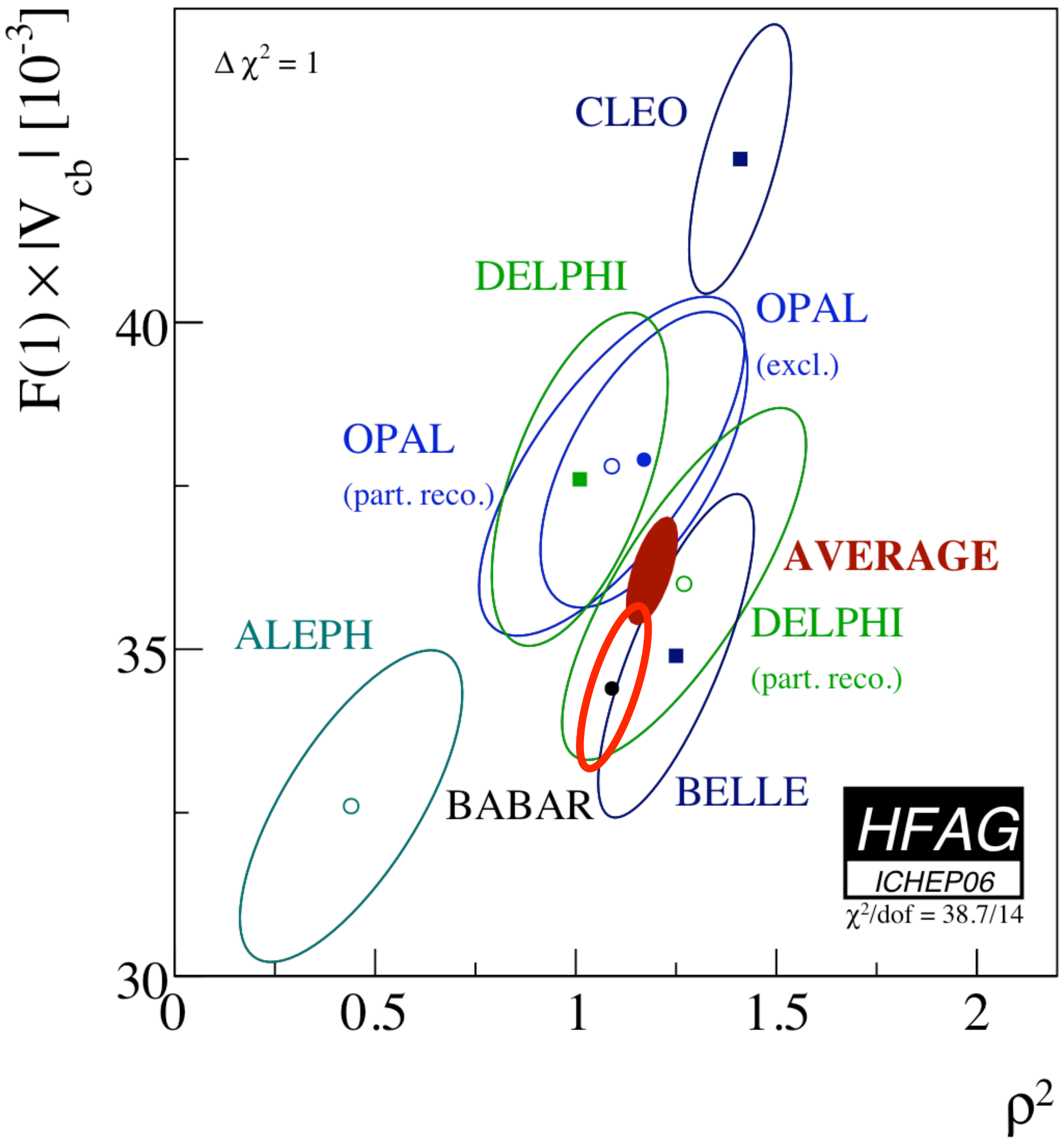
  - We also measure the total rate

$$\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu) = (4.77 \pm 0.04_{\text{stat}} \pm 0.39_{\text{syst}})\%$$

$|V_{cb}|$ from $B \to D^*\ell\nu$

- *BABAR* dominates the world average





$$|V_{cb}| = (39.4 \pm 0.9_{\text{exp}} {}^{+1.6}_{-1.2}{}_{\mathcal{F}(1)}) \times 10^{-3}$$

c.f. $(42.0 \pm 0.7)\times 10^{-3}$ from inclusive OPE fit

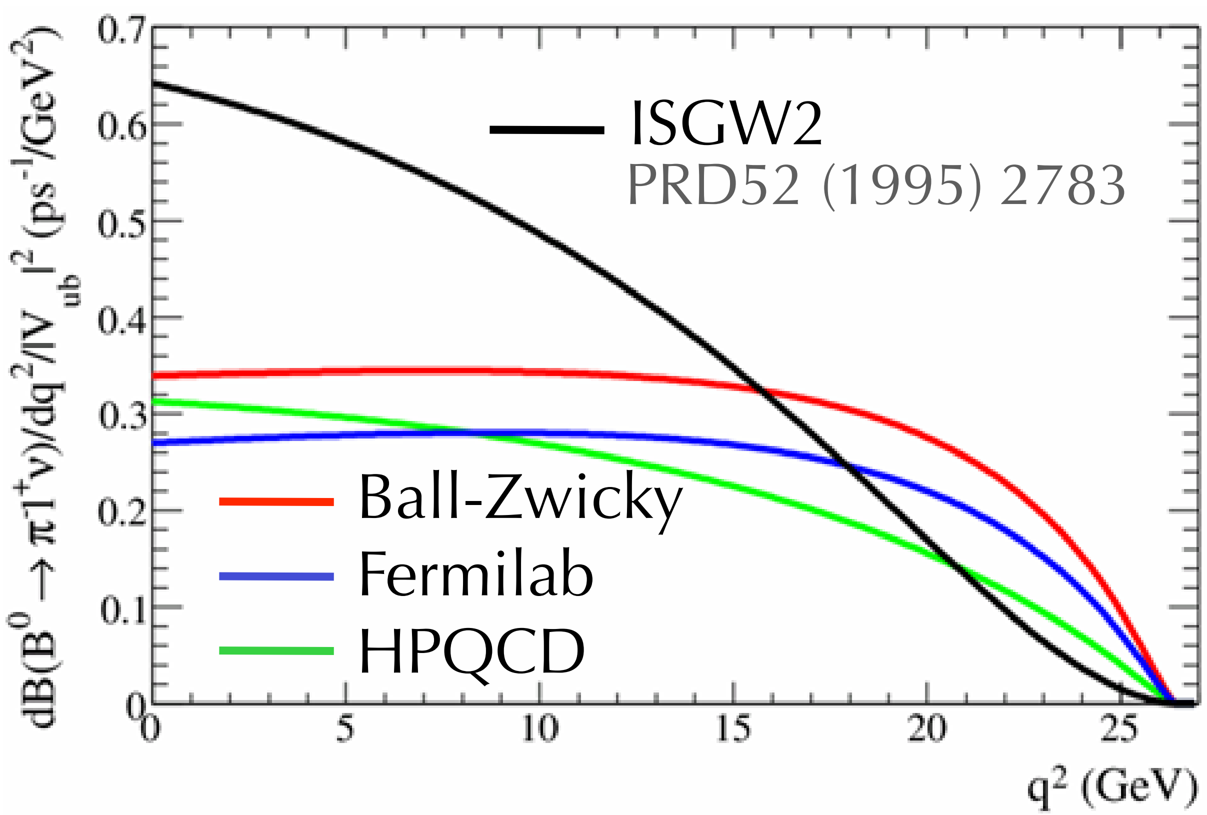
Exclusive $B \to \pi\ell\nu$

- $B \to \pi\ell\nu$ rate is given by

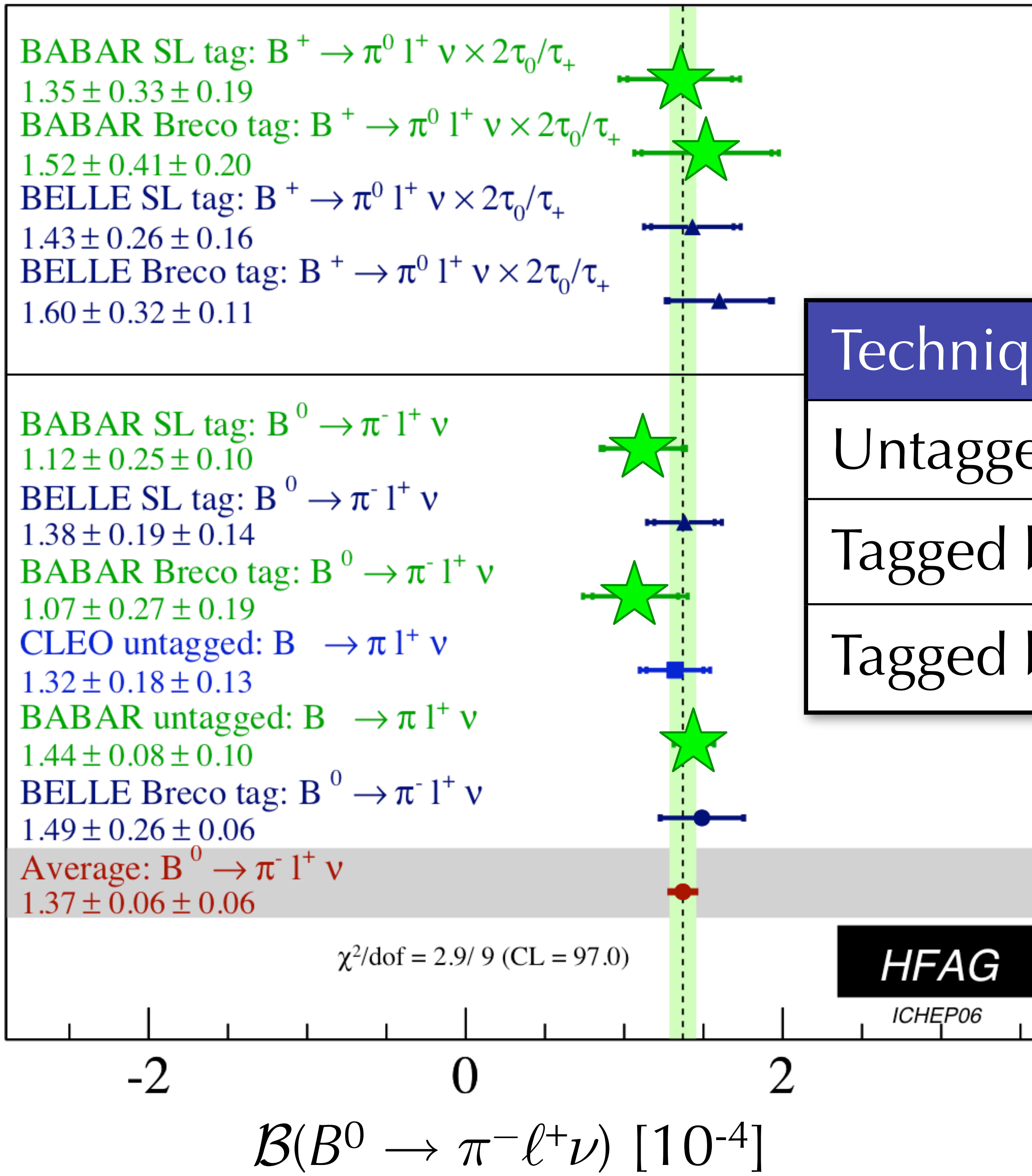
$$\frac{d\Gamma(B \to \pi\ell\nu)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} p_\pi^3 |f_+(q^2)|^2$$

One FF for $B \to \pi\ell\nu$ with massless lepton

- Form factor has been calculated using
  - Lattice QCD
    - Unquenched calculations by Fermilab (hep-lat/0409116) and HPQCD (PRD73:074502)
    - ±12% for $q^2 > 16$ GeV^2
  - Light Cone Sum Rules
    - Ball & Zwicky (PRD71:014015)
    - ±13% for $q^2 < 16$ GeV^2



Measuring $B \to \pi\ell\nu$



- Measurements differ in what you do with the "other" B

Technique	Efficiency	Purity
Untagged	High	Low
Tagged by $B \to D^{(*)}\ell\nu$	↕	↕
Tagged by $B \to$ hadrons	Low	High

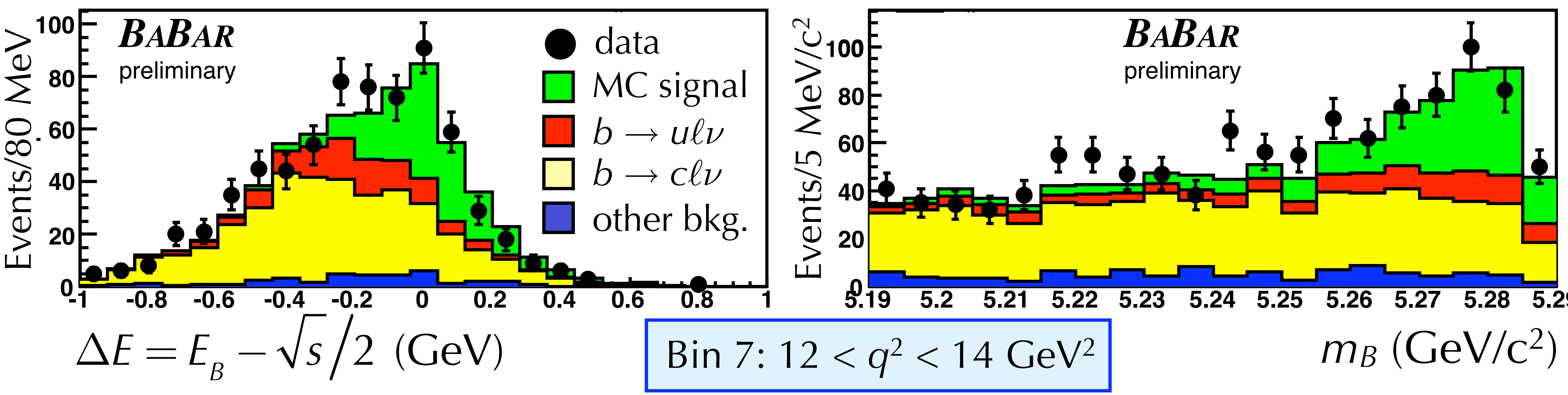
- Total BF is

$$(1.37 \pm 0.06_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$$

  - ±6.2% precision

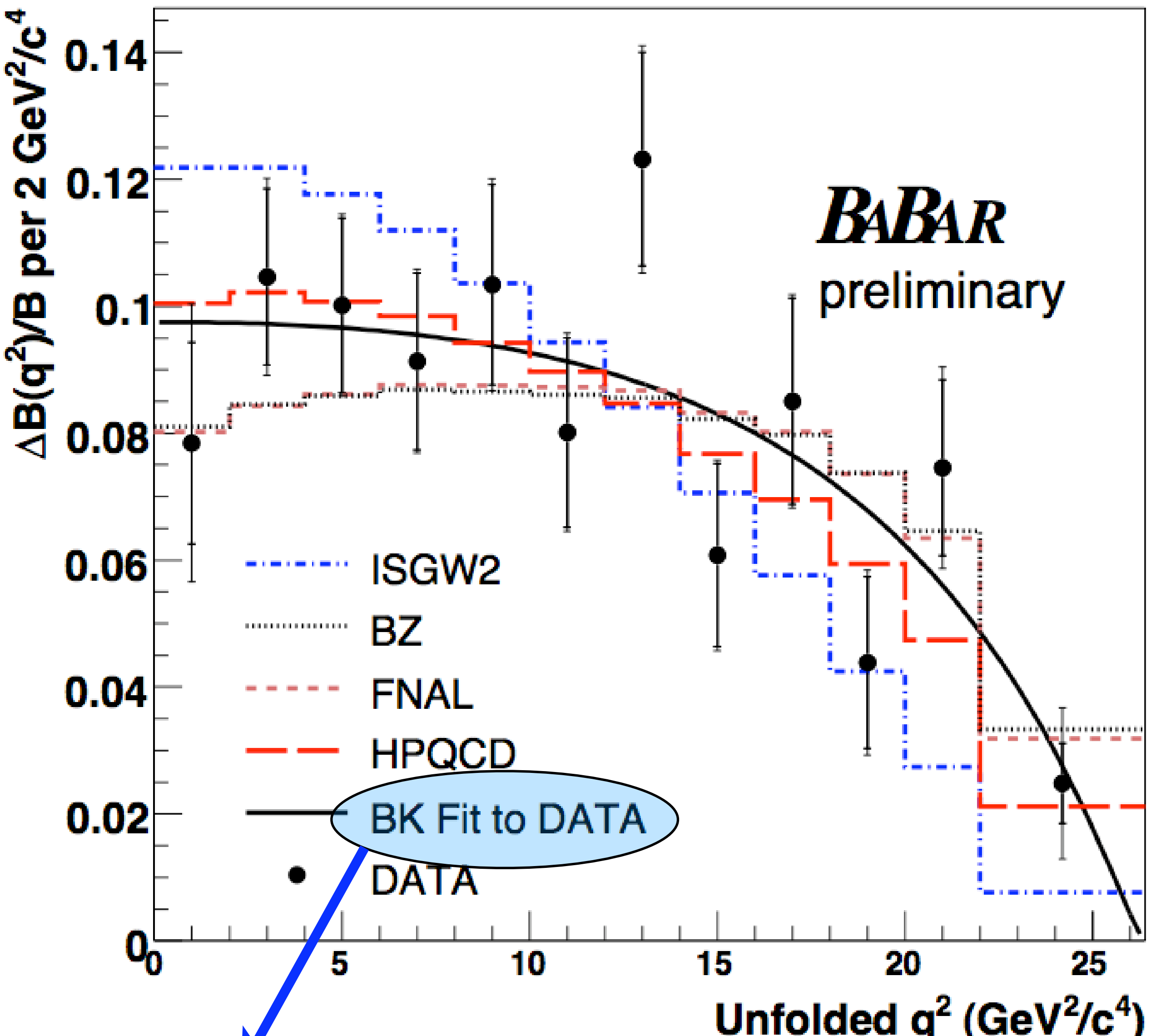
Untagged $B \to \pi \ell \nu$

- Missing 4-momentum = p_ν ➔ Reconstruct $B \to \pi \ell \nu$
  - Calculate m_B and ΔE, and perform 2-D fit for signal yields
- *BABAR*'s new result (206 fb^{-1}, preliminary) uses 12 q^2 bins



  - High signal efficiency: 6.5 to 10%
  - Total BF: $\mathcal{B}(B \to \pi \ell \nu) = (1.44 \pm 0.08_{stat} \pm 0.10_{syst}) \times 10^{-4}$
    - Best single measurement to date

Untagged $B \to \pi \ell \nu$



- Measured q^2 spectrum constrains the FF shape

Form Factor	χ^2	Prob.
Ball-Zwicky	13.0	37.2%
HPQCD	10.2	60.2%
FNAL	12.5	41.0%
ISGW2	34.1	0.1%

- Recent calculations agree with data

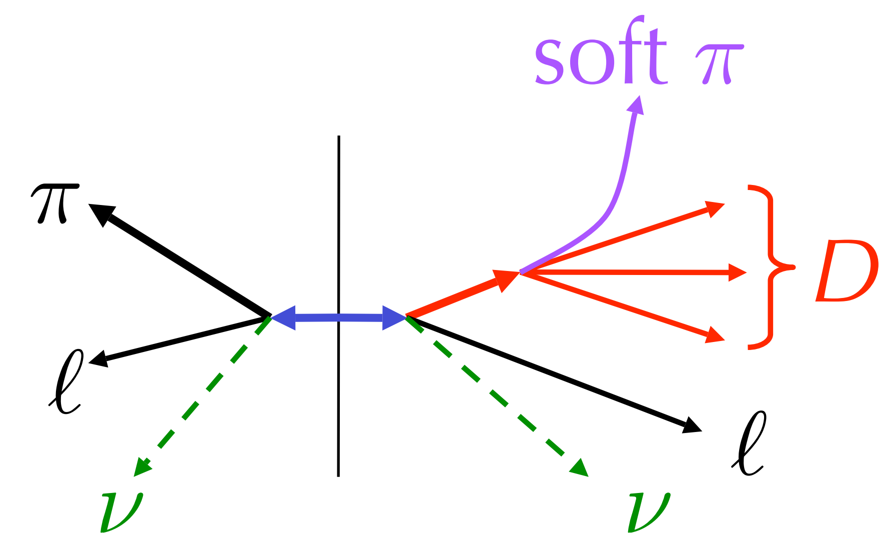
Becirevic-Kaidalov parameterization

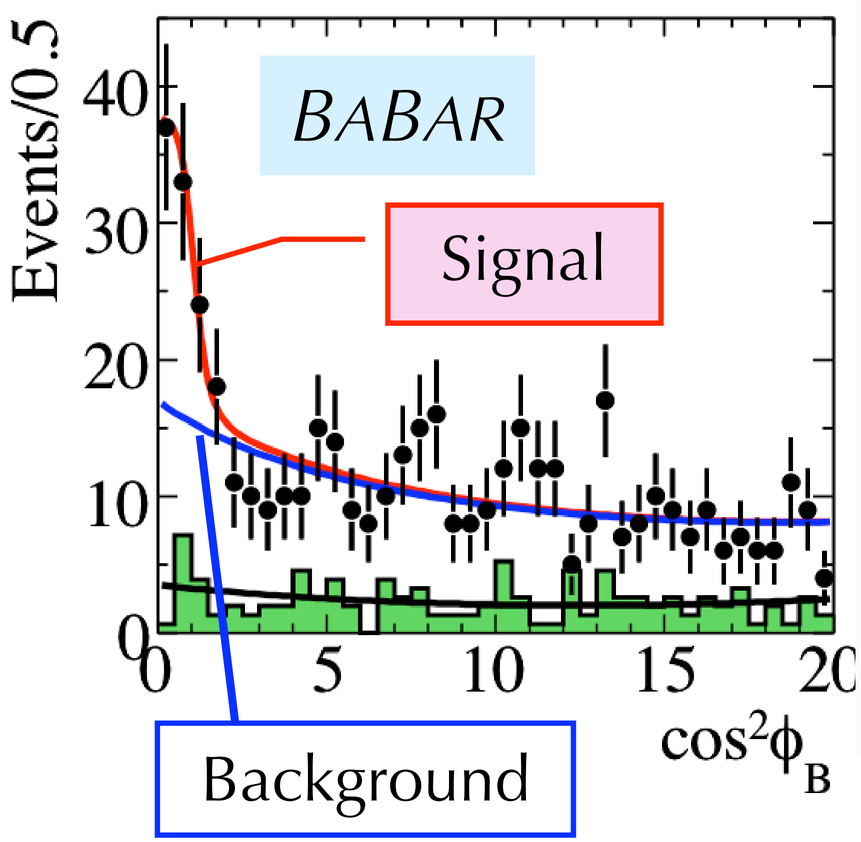
$$f_+(q^2) = \frac{1}{(1 - q^2/m_{B^*}^2)(1 - \alpha q^2/m_{B^*}^2)}$$

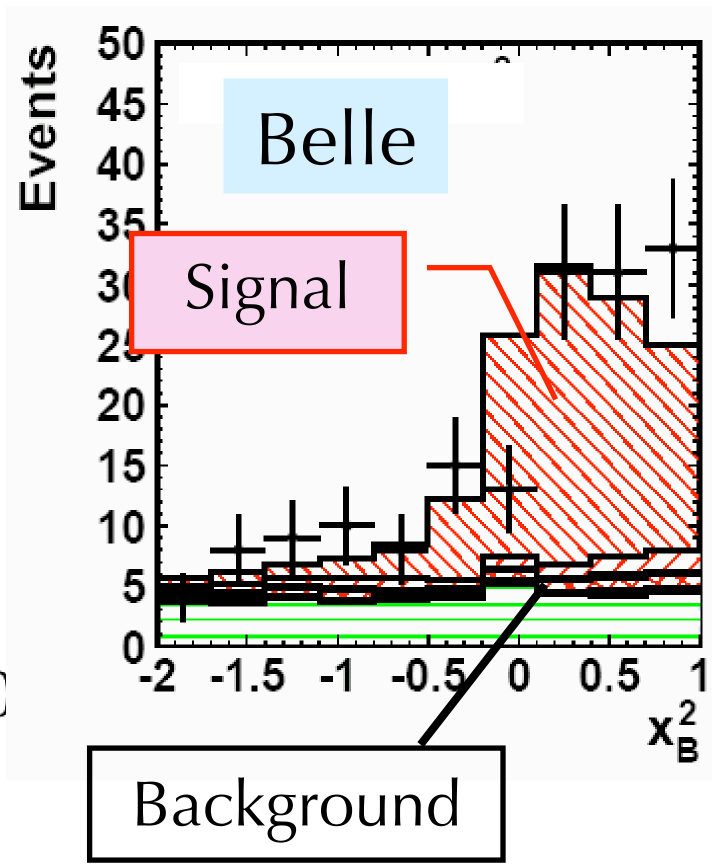
$\alpha = 0.53 \pm 0.05_{stat} \pm 0.04_{syst}$

$D^{(*)}\ell\nu$-tagged $B \to \pi\ell\nu$

- Tag one B in $D^{(*)}\ell\nu$ and look for $B \to \pi\ell\nu$ in the recoil
  - Pro: $B \to D^{*}\ell\nu$ BF large
  - Con: Two neutrinos in the event
- Event kinematics determined assuming known m_B and m_ν



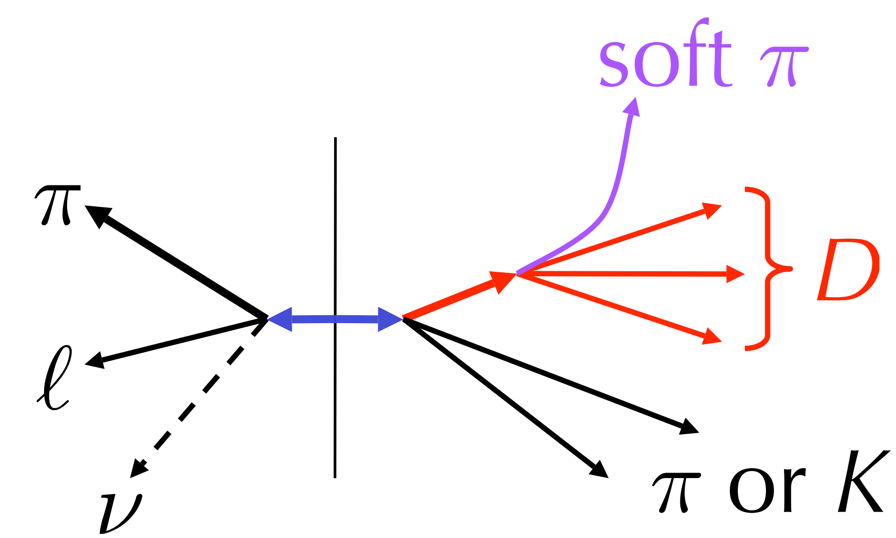


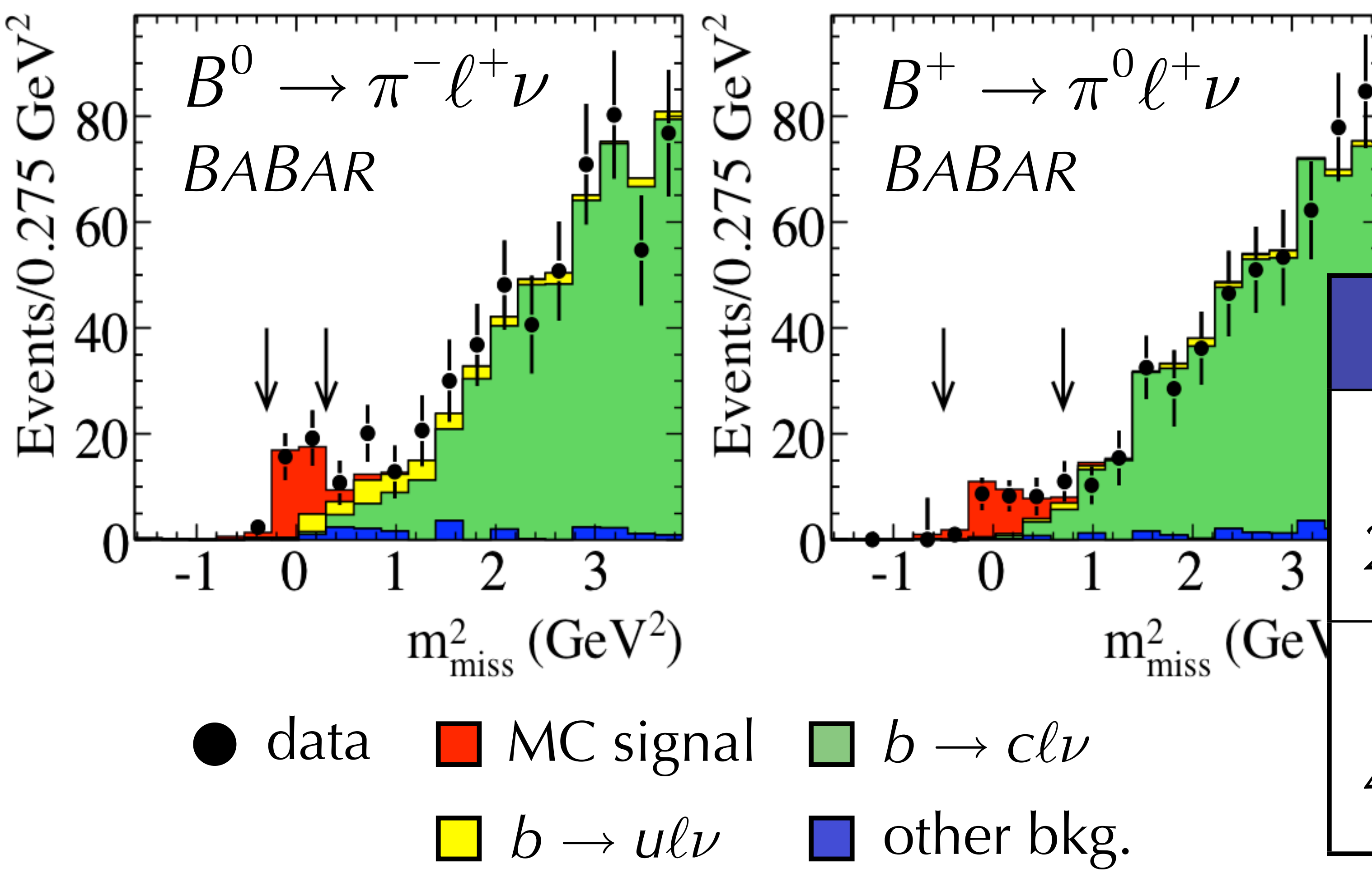


	Mode	BF (10^{-4})
BABAR 211 fb^{-1}	$\pi^-\ell\nu$	1.12 ± 0.27
	$\pi^0\ell\nu$	0.73 ± 0.21
Belle 253 fb^{-1}	$\pi^-\ell\nu$	1.38 ± 0.24
	$\pi^0\ell\nu$	0.77 ± 0.16

Hadronic-tagged $B \to \pi\ell\nu$

- Hadronic tags have high purity, but low efficiency
  - Event kinematics is known by a 2-C fit
  - Use m_B and m_{miss} distributions to extract the signal yield





	Mode	BF (10^{-4})
BABAR 211 fb^{-1}	$\pi^-\ell\nu$	1.07 ± 0.33
	$\pi^0\ell\nu$	0.82 ± 0.25
Belle 497 fb^{-1}	$\pi^-\ell\nu$	1.49 ± 0.27
	$\pi^0\ell\nu$	0.86 ± 0.18

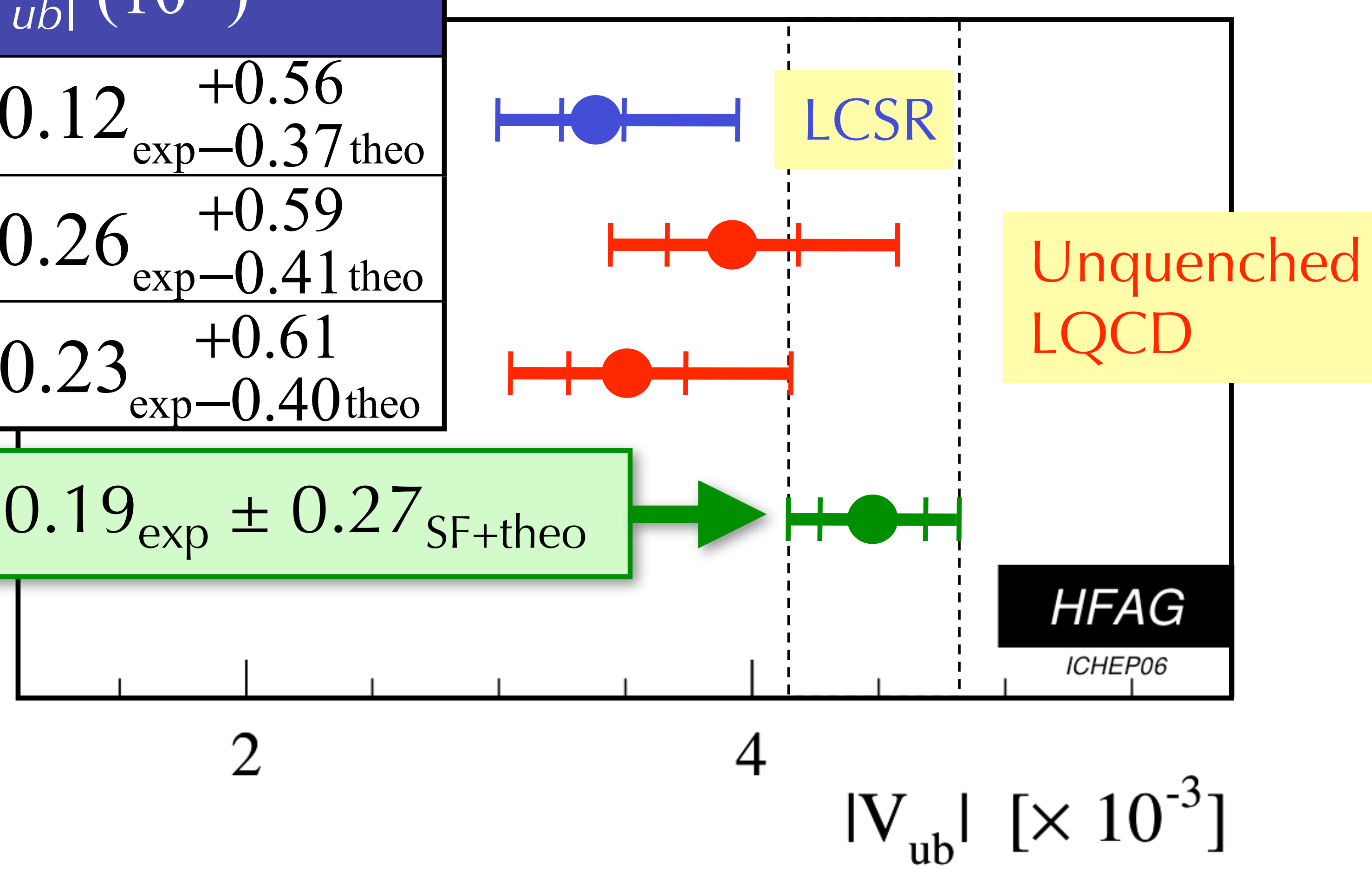
Prelim.

$|V_{ub}|$ from $B \to \pi \ell \nu$

- Average BF measurements and apply FF calculations

$\Delta\mathcal{B}(q^2 < 16)$ (10^{-4})	$\Delta\mathcal{B}(q^2 > 16)$ (10^{-4})	Total $\mathcal{B}$ (10^{-4})
$0.95 \pm 0.05_{stat} \pm 0.05_{syst}$	$0.35 \pm 0.03_{stat} \pm 0.03_{syst}$	$1.37 \pm 0.06_{stat} \pm 0.06_{syst}$

Form Factor	q^2 (GeV^2)	$\lvert V_{ub}\rvert$ (10^{-3})
Ball-Zwicky	< 16	$3.38 \pm 0.12_{exp}{}^{+0.56}_{-0.37}{}_{theo}$
HPQCD	> 16	$3.93 \pm 0.26_{exp}{}^{+0.59}_{-0.41}{}_{theo}$
FNAL	> 16	$3.51 \pm 0.23_{exp}{}^{+0.61}_{-0.40}{}_{theo}$



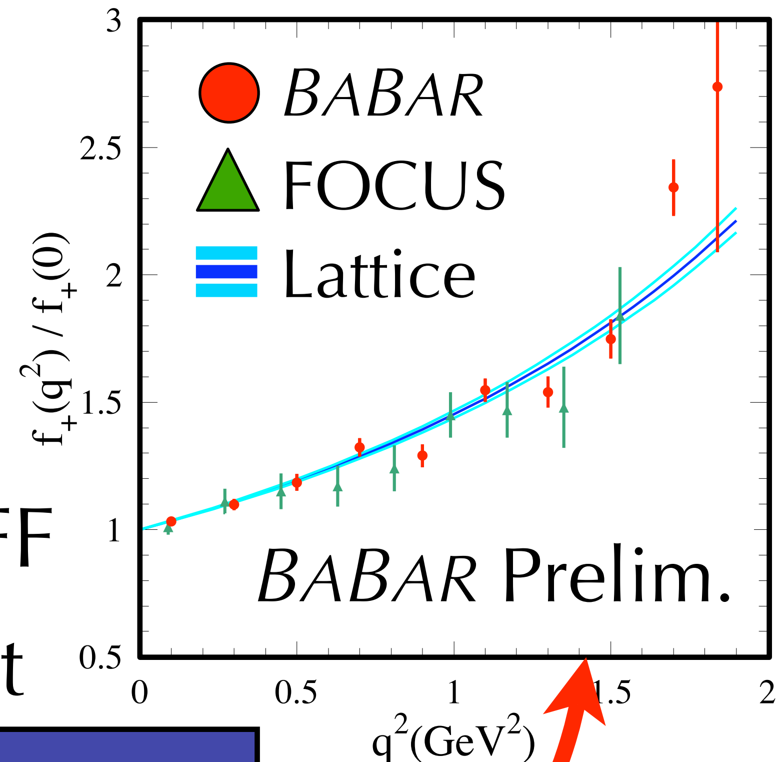
Inclusive: $4.49 \pm 0.19_{exp} \pm 0.27_{SF+theo}$

- Errors dominated by the FF normalizations

BABAR hep-ex/0607077
Belle hep-ex/0604049
CLEO-c Talk at ICHEP'06

Form Factor Tests

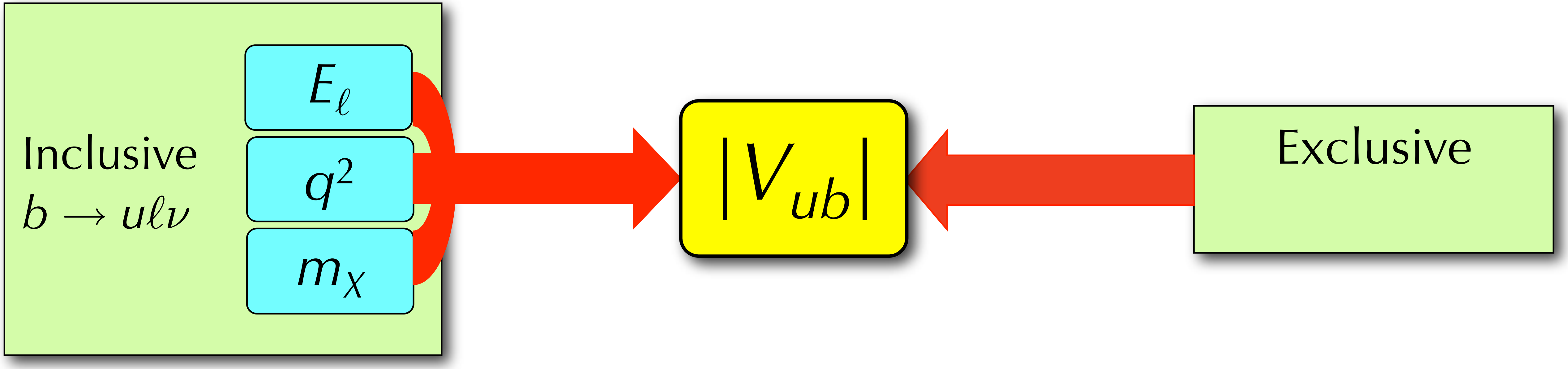
- Measured q^2 dependence of $B \to \pi \ell \nu$ can constrain input parameters to LCSR
  - Ball, Zwicky PLB 625:225
- Ultimate test: $D \to \pi \ell \nu,\ K \ell \nu$
  - We know $|V_{cd}|$ and $|V_{cs}|$ ➜ Measure the FF
  - Preliminary measurements are coming out



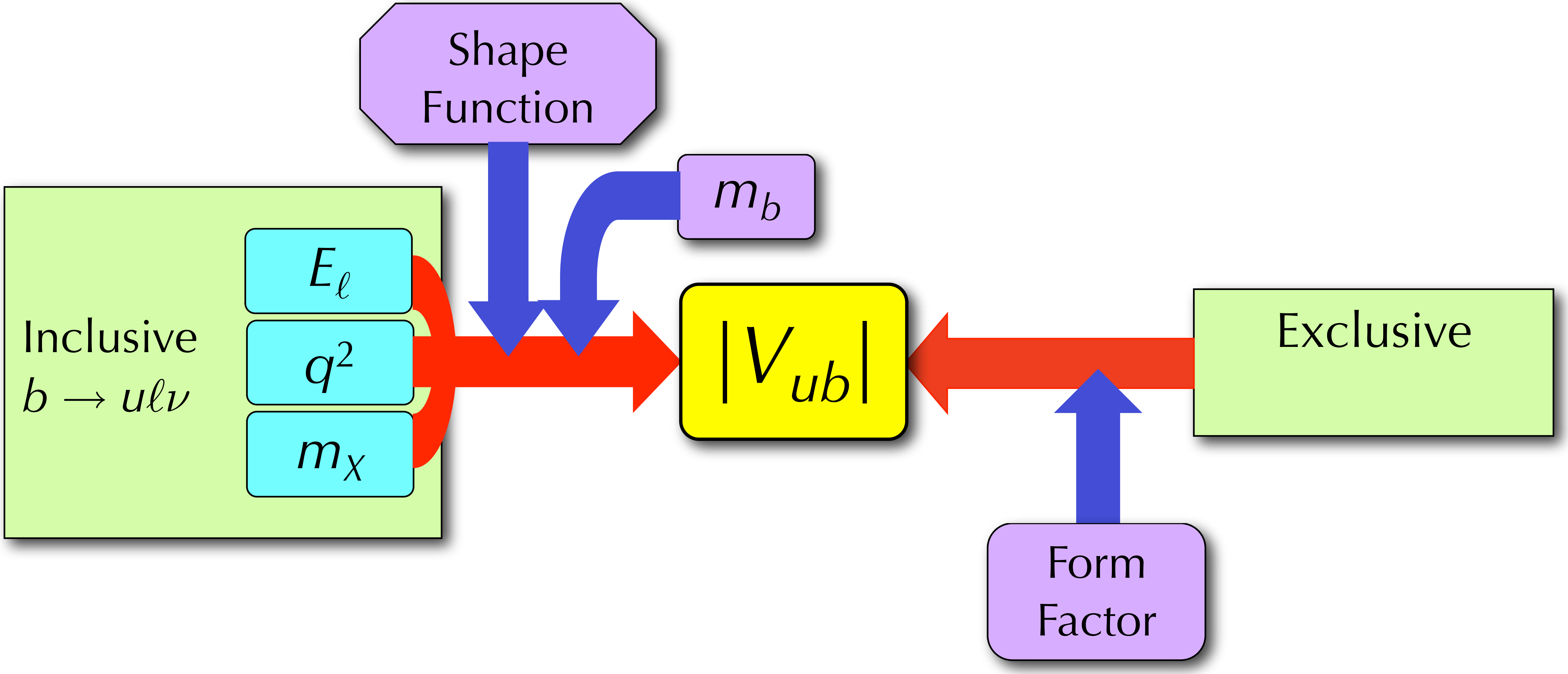
	$m_{pole}(D \to \pi)$ [GeV]	$m_{pole}(D \to K)$ [GeV]
BABAR 75 fb^{-1}	In progress	$1.85 \pm 0.02_{stat} \pm 0.02_{syst}$
Belle 282 fb^{-1}	$1.97 \pm 0.08_{stat} \pm 0.04_{syst}$	$1.82 \pm 0.04_{stat} \pm 0.03_{syst}$
CLEO-c 281 pb^{-1} at $\psi(3770)$	$1.95 \pm 0.04_{stat} \pm 0.02_{syst}$	$1.96 \pm 0.03_{stat} \pm 0.01_{syst}$
	$1.88 \pm 0.03_{stat} \pm 0.02_{syst}$	$1.98 \pm 0.03_{stat} \pm 0.02_{syst}$
Lattice QCD	*1.99 ± 0.04*	*1.72 ± 0.05*

Aubin et al., PRL 94:011601

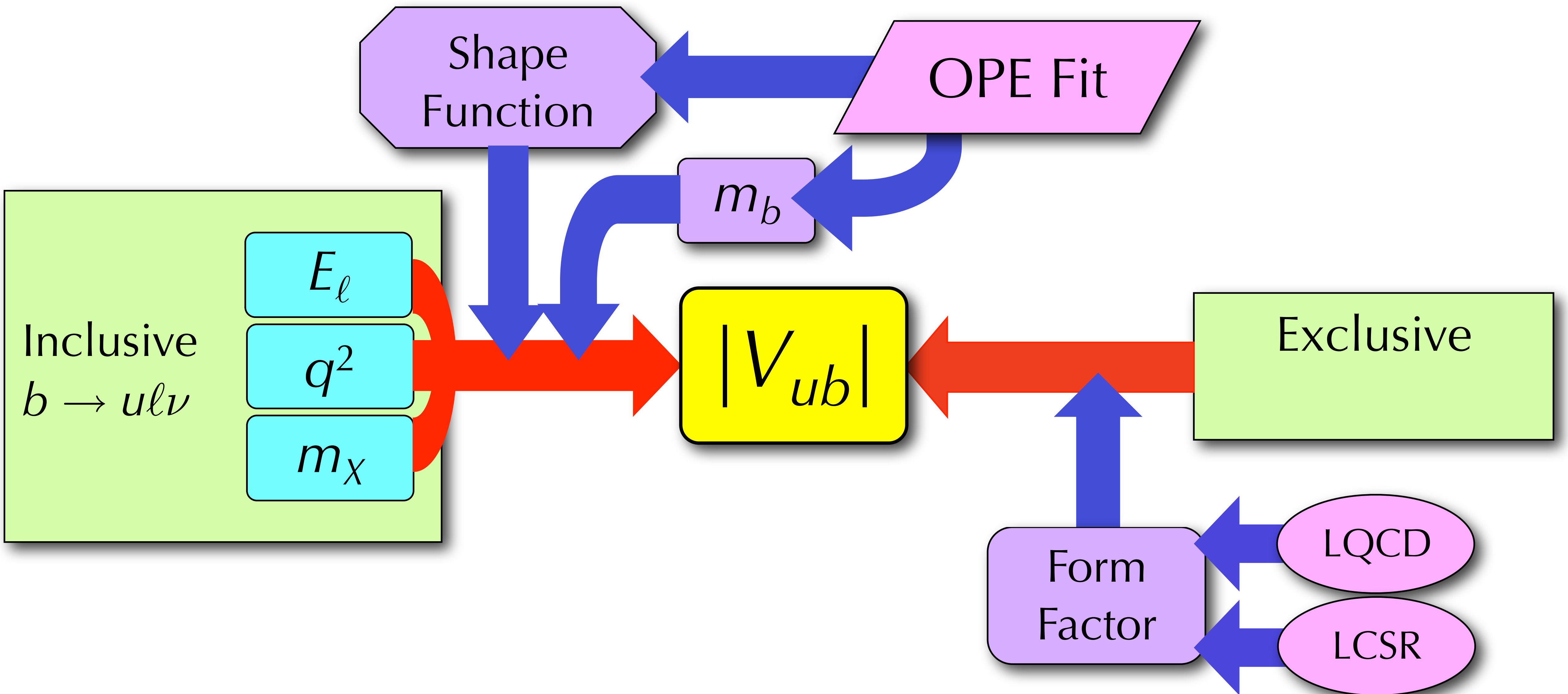
How Things Mesh Together



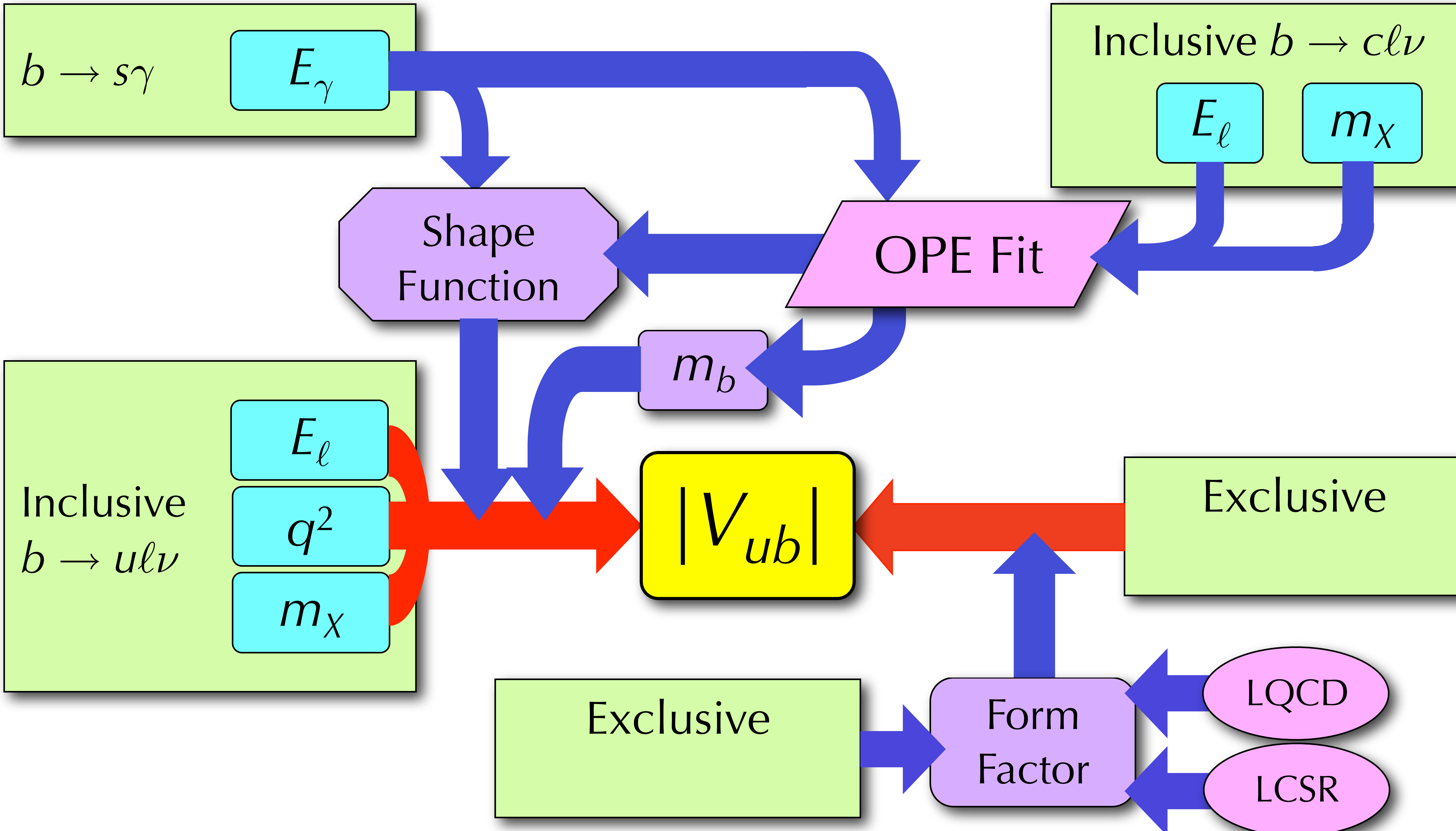
How Things Mesh Together



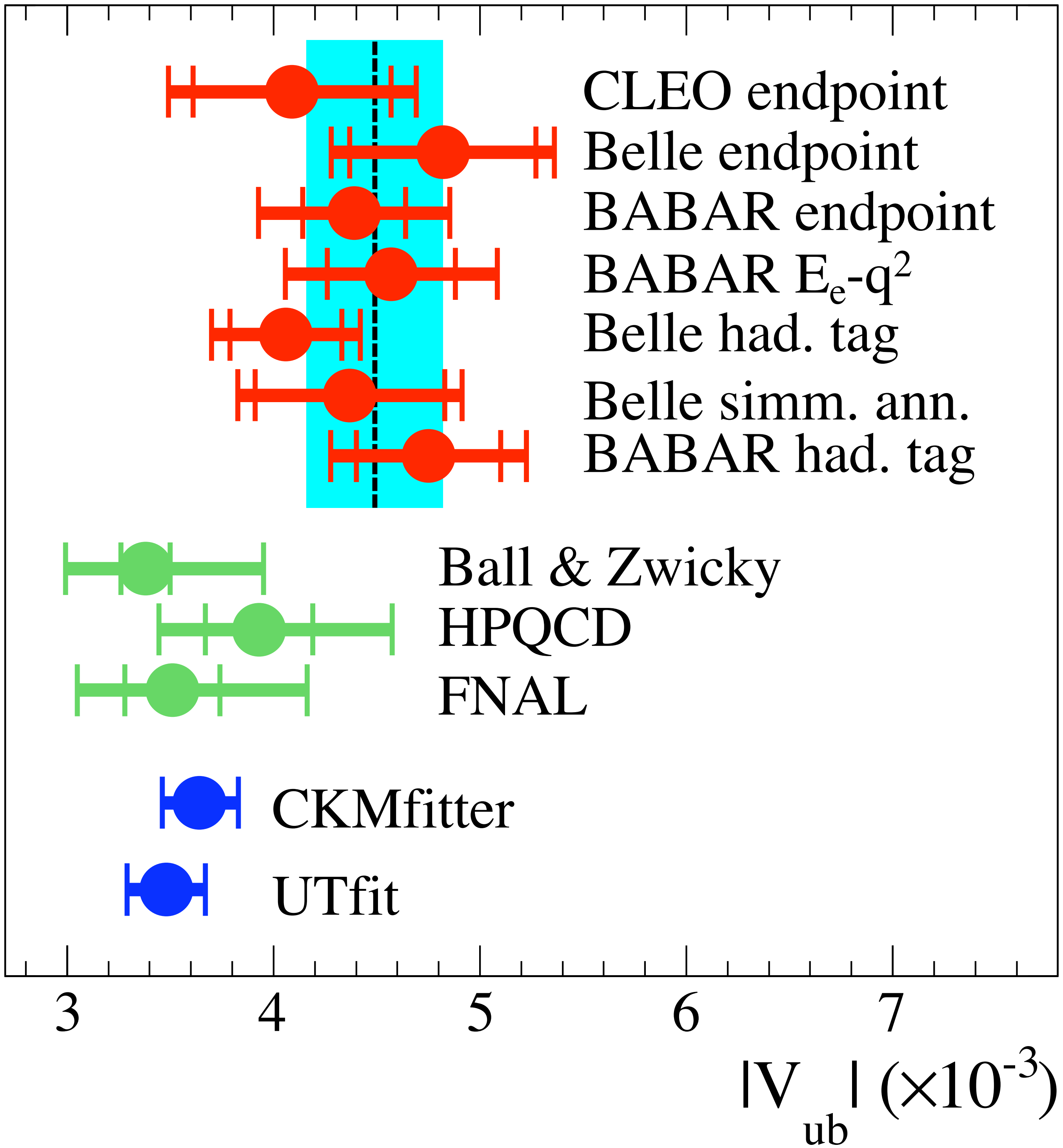
How Things Mesh Together



How Things Mesh Together



Where We Stand Now



- Marginal consistency across different determination methods
  - Inclusive measurements prefer higher values than exclusive measurements and fits to the Triangle
- What gives?
  - Unknown theory error in inclusive $B \to X_u \ell \nu$?
  - Form factor in $B \to \pi \ell \nu$?
  - Something more exciting?

Things to Come

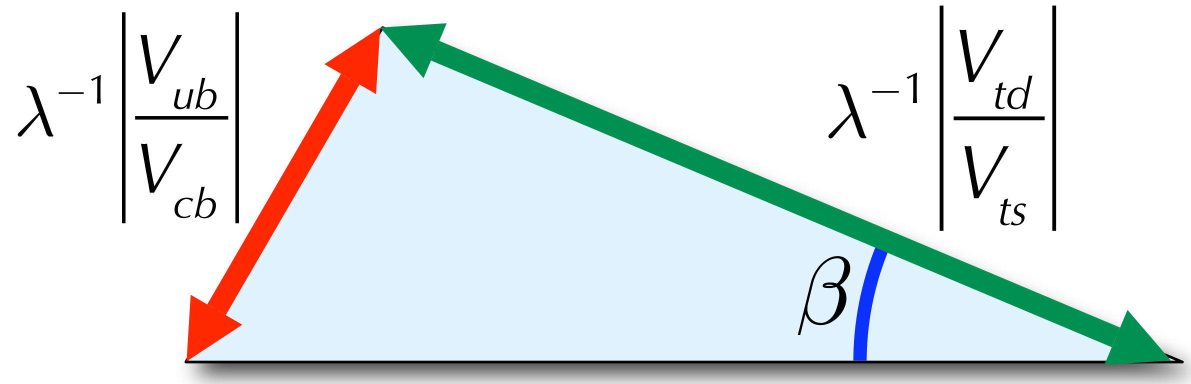
- *BABAR* has analysed only a fraction of its data
  - 390 fb^{-1} recorded. Expect ~1000 fb^{-1} by the end of 2008

	Measurement	Published?	Data
Inclusive $X_c \ell \nu$	E_ℓ spectrum	PRD (2004)	47 fb^{-1}
	m_X spectrum	PRD (2004)	81 fb^{-1}
Inclusive $X_u \ell \nu$	E_ℓ endpoint	PRD (2006)	81 fb^{-1}
	E_ℓ vs q^2	PRL (2005+2006)	81 fb^{-1}
	Hadronic tag	Preliminary	211 fb^{-1}
Exclusive $D^* \ell \nu$		Submitted to PRD	79 fb^{-1}
		Preliminary	79 fb^{-1}
Exclusive $\pi \ell \nu$	Untagged	Preliminary	206 fb^{-1}
	Tagged	Submitted to PRL	211 fb^{-1}

Expect large gains with additional statistics

Summary

- Semileptonic B decays continue to offer exciting physics opportunities
  - Determination of $|V_{ub}/V_{cb}|$ complements $\sin 2\beta \cap |V_{td}/V_{ts}|$ to test the (in)completeness of the Standard Model



- Challenge of hadronic physics is met by close collaboration between theory and experiment
  - Inclusive $B \to X_c \ell \nu$ & $X_s \gamma$ precisely determines $|V_{cb}|$, m_b, etc.
  - Inclusive $B \to X_u \ell \nu$ achieved ±7.3% accuracy on $|V_{ub}|$
    - Room for improvements with additional data statistics
  - Exclusive $B \to \pi \ell \nu$ measurements becoming precise
    - Improved form factor calculation needed

Future Experiments

- Future *B*-physics programs will pursue New Physics through CP violation and rare decays
  - e.g. $b \to s\bar{s}s, b \to s\gamma, b \to s\ell^+\ell^-, B \to \tau\nu, B \to D\tau\nu, B_s \to \mu^+\mu^-$
  - $|V_{ub}/V_{cb}|$ provides a crucial New-Physics-free constraint
- Will they improve $|V_{ub}|$ to << 5%?
  - A Super *B* Factory can produce high-statistics, high-purity, hadronic-tag sample to measure $b \to u\ell\nu$
  - LHCb's primary strength lies in B_s physics
- NB: the real challenge lies in theory
  - Precision data can inspire and validate theoretical advances
  - Lattice QCD holds the key
    - We need to see inclusive and exclusive $|V_{ub}|$ converge!