Charmless Semileptonic Decays and Determination of $|V_{ub}|$

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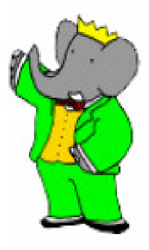


Seminar , June 25th 2007

Outline

- *Introduction and motivation*
  - *B decays and CKM sector*
  - *PEP II and BaBar*
  - *Why charmless semileptonic B decays?*
- *Inclusive vs Exclusive approach*
- *Experimental techniques*
- *Inclusive approach*
  - *Theoretical framework*
  - $b \to u \ell \nu$ *measurement and* $|V_{ub}|$
- *Exclusive approach*
  - *Theoretical framework*
  - $B \to \pi \ell \nu \, (B \to (\rho, \omega, \eta, \eta') \ell \nu)$ *measurement and* $|V_{ub}|$
- *Prospect and Conclusion*

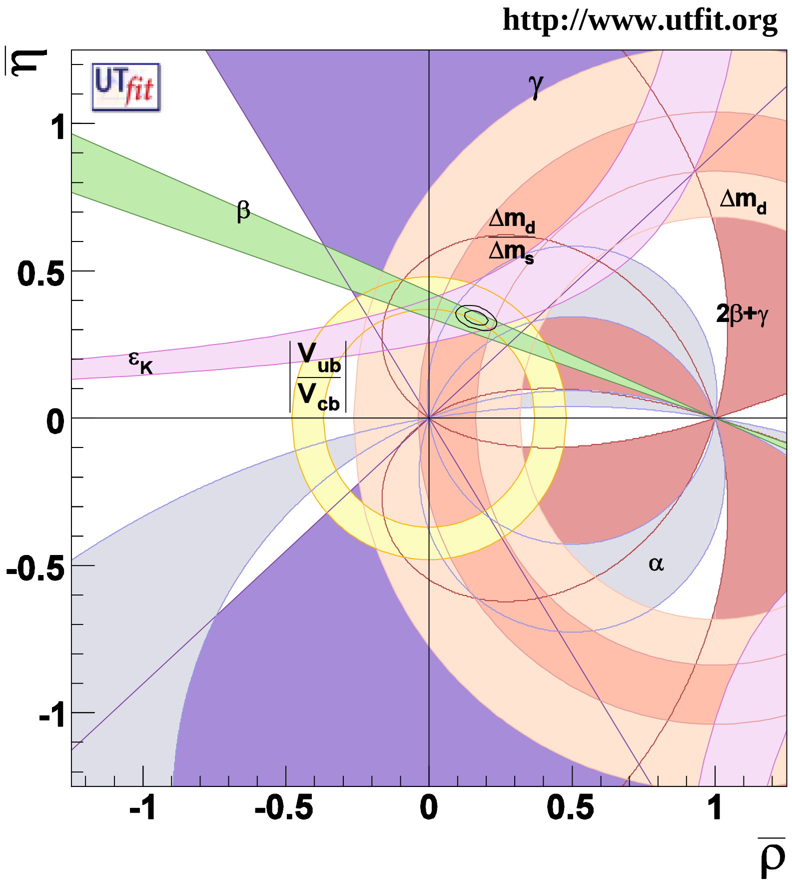
Unitarity Triangle

- Angles and sides have been measured in a B factory and they can offer two independent tests of the SM
- Measurements are consistent with SM → independent constraints on the apex of the UT overlap in a small area in the (ρ,η) plane…but…

there is still enough room for New Physics to hide

Precision of sin2β (~4%) outstripped the other measurement :

Must improve the others to make more stringent test



Next step: | V_{ub}|

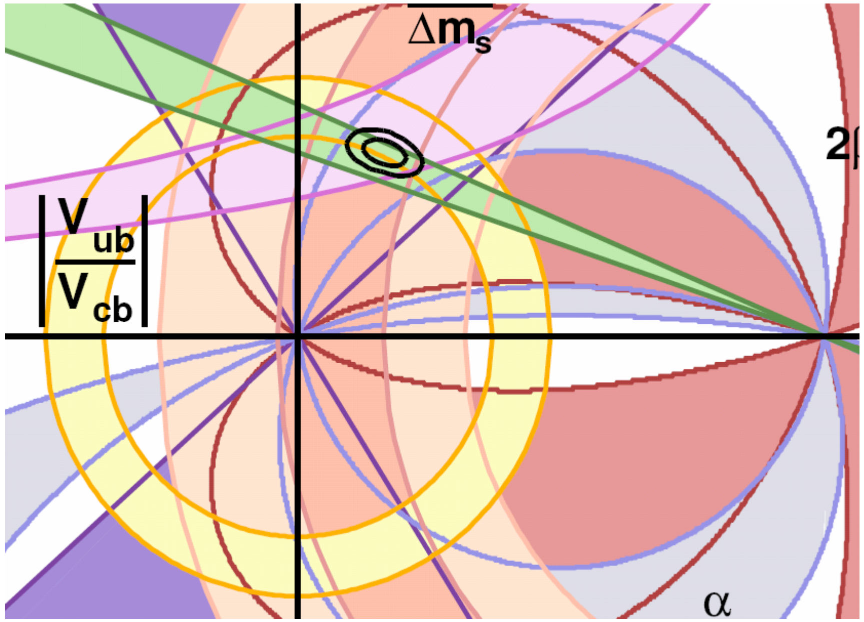
- Zoom in to see the overlap of the "other" contours
  - we must make the **yellow ring** thinner

- Left side of the Triangle is

$$\left| V_{ud} V_{ub}^{*} / V_{cd} V_{cb}^{*} \right|$$

|V_{cb}| known with a precision of ~ 2%

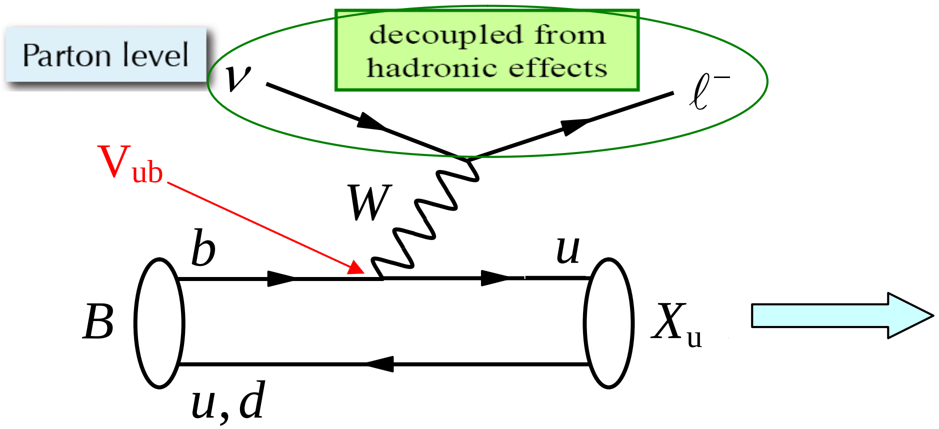
|V_{ub}| current uncertainty ~ 8%

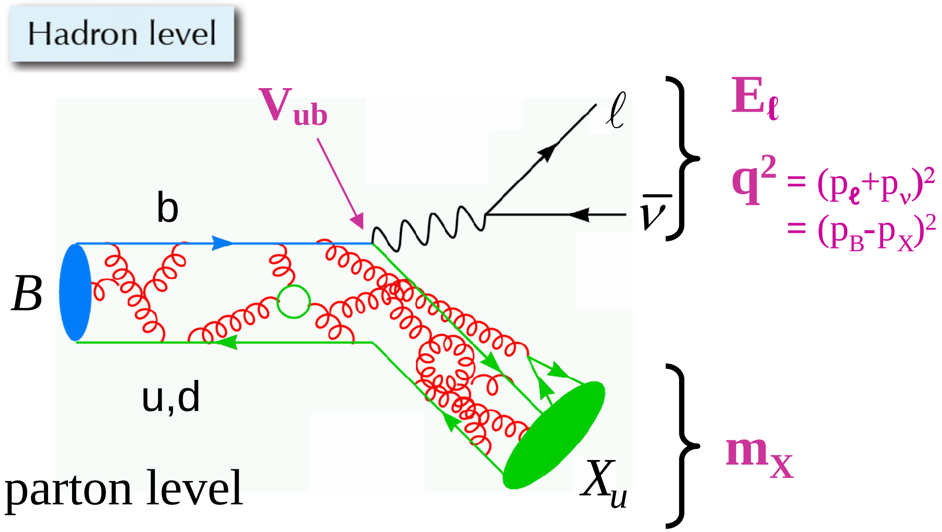


error on the length of the side opposite to β dominated by errors on |V_{ub}| →
Improved precision needed on |V_{ub}|

Charmless Semileptonic B decays

Semileptonic B decays provide the best method to measure $|V_{ub}|$



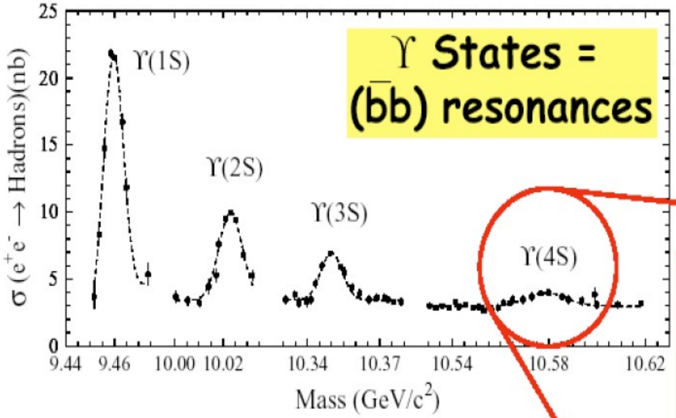


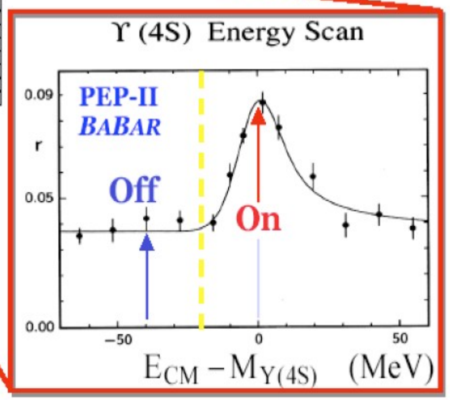
- Simple theoretical description at parton level
  - Leptonic and hadronic currents factorize
  - Sensitive to strong interactions in B mesons
    - Study structure of B meson
    - Allow test of e.g. Lattice QCD
- Rates depend on CKM matrix element and quark masses

$$\Gamma_u \equiv \Gamma(b \to u \ell \nu) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5$$

tree level

The B Factory concept





Cross Sections at Υ(4S):

$b\bar{b} \sim 1.1$ nb

$c\bar{c} \sim 1.3$ nb

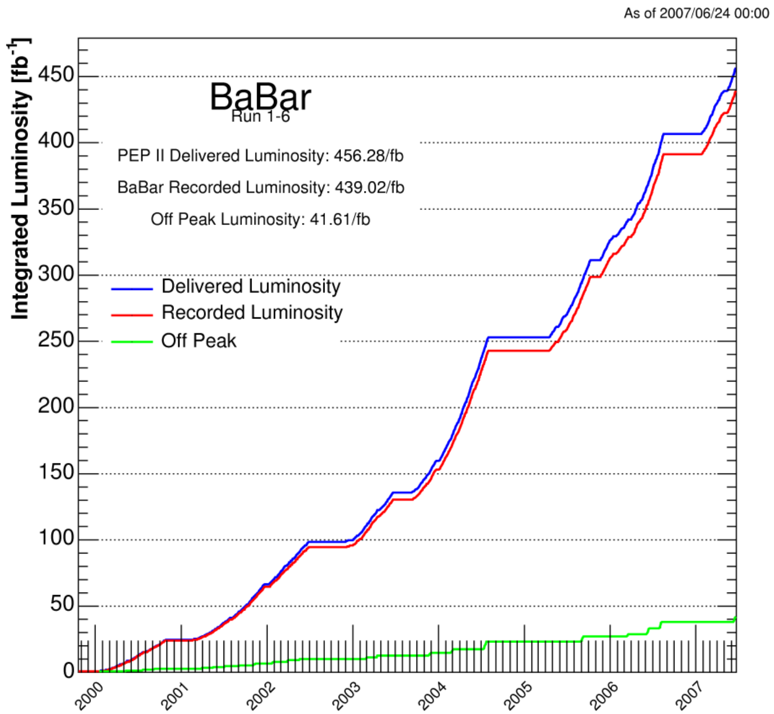
$d\bar{d}, s\bar{s} \sim 0.3$ nb

$u\bar{u} \sim 1.4$ nb

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$
$$L = 1 \text{ state}$$

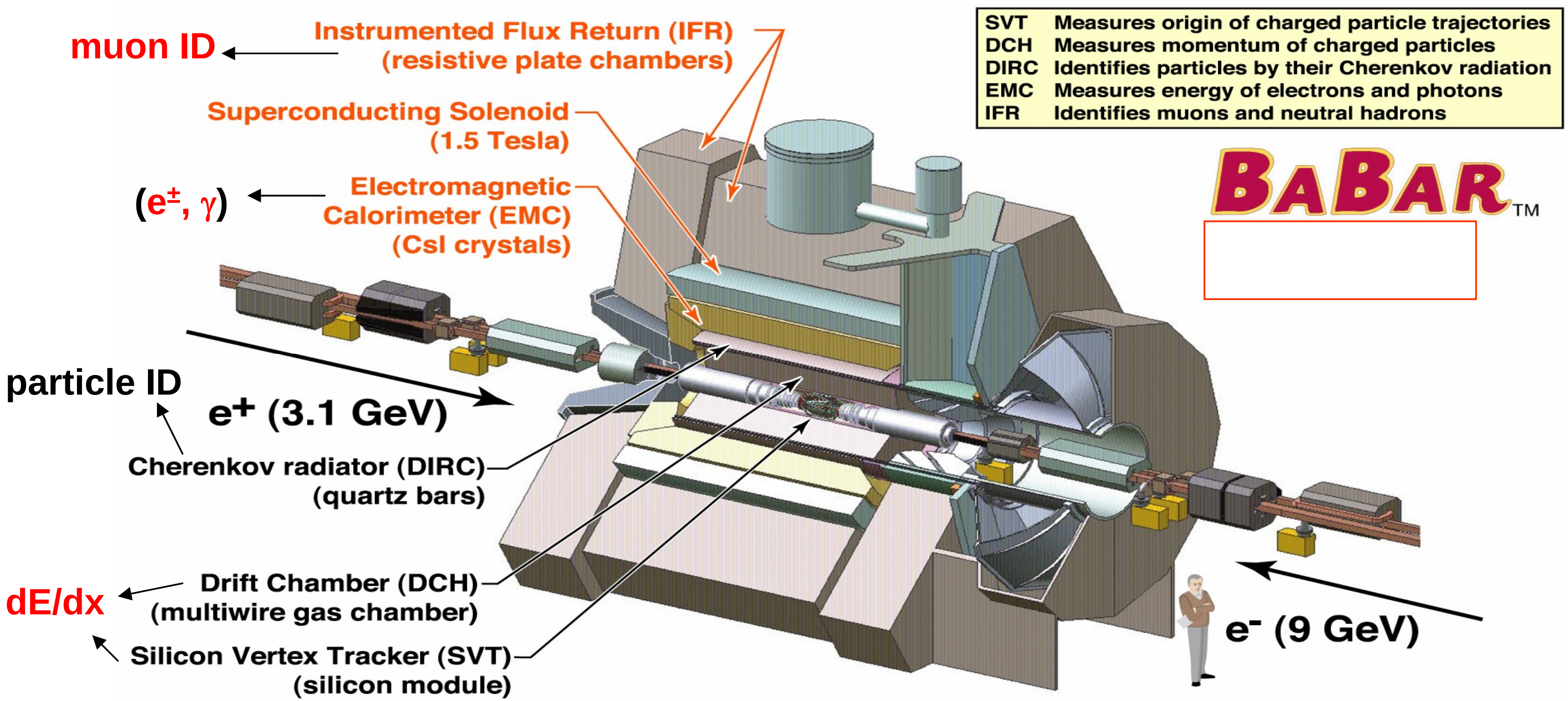
- BaBar: 9 GeV e^- →← 3.1 GeV e^+
- E_{cm} = 10.58 GeV = Mass of Y(4S)
- BB production rate ≈ 10 Hz

1 fb^{-1} of luminosity corresponds roughly to one million BB pairs

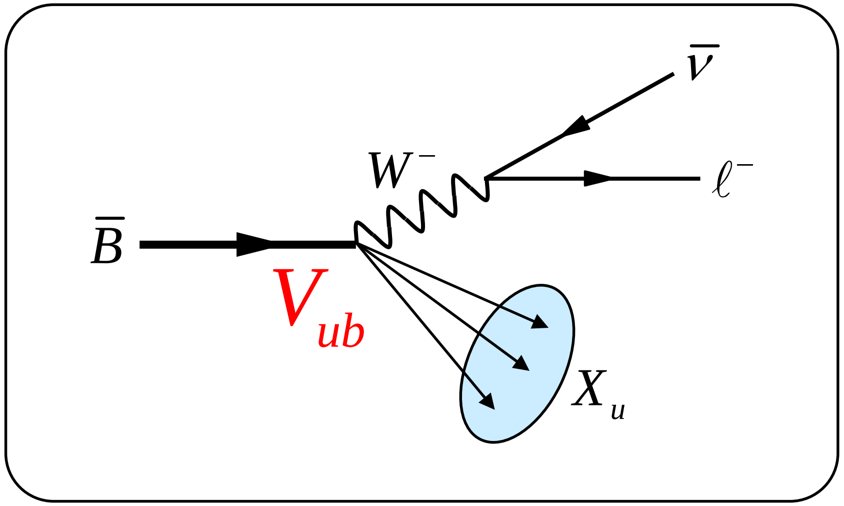


Our research tools

- Good e, μ ID ($p^*_\ell > 1$GeV)
- Good hadron ID (e.g. π/K separation)
- Angular coverage ≈ 91% of 4π in CMS
  (challenge for ν reconstruction)



Inclusive vs Exclusive decays



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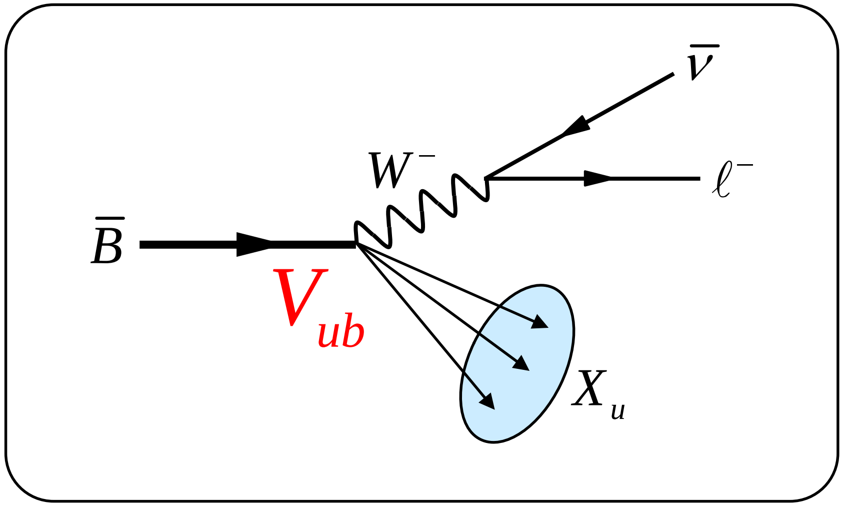

Inclusive Decays

select lepton and look at the rest of the event inclusively

- Large signal rate, high $b \to c\ell\nu$ bkg
- "Easy" to calculate (OPE/HQE)
- Need Shape Function (b-quark motion inside B meson) . Constrain SF param. m_b, μ_π^2 with $b \to s\gamma$ or $b \to c\ell\nu$.

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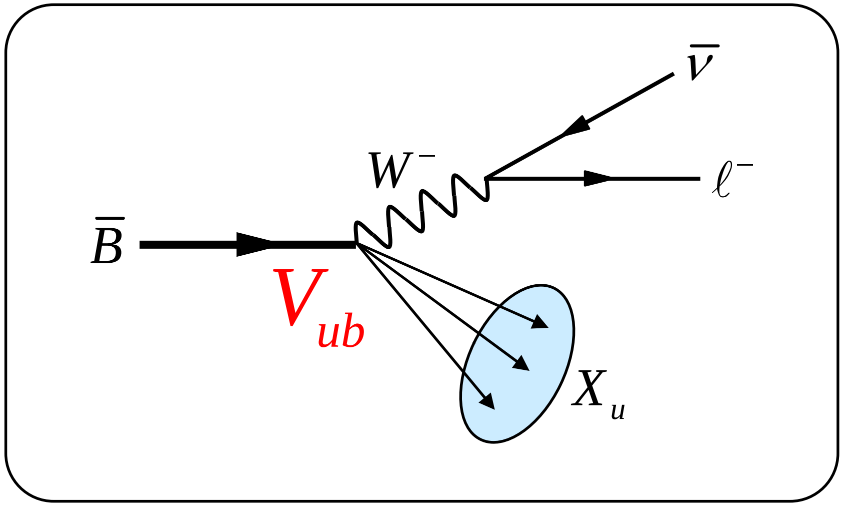

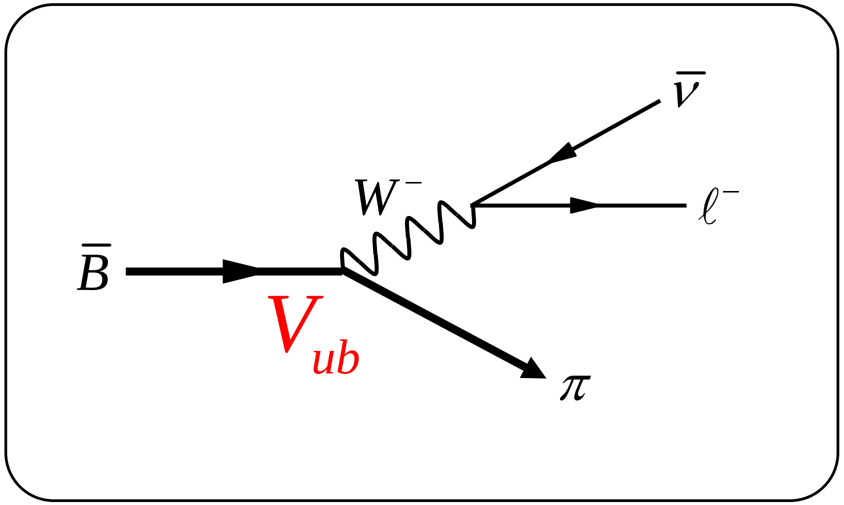

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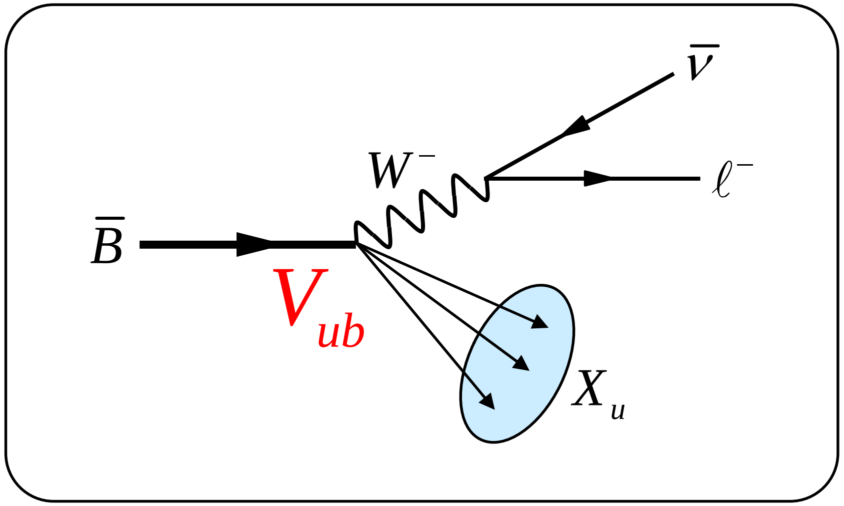

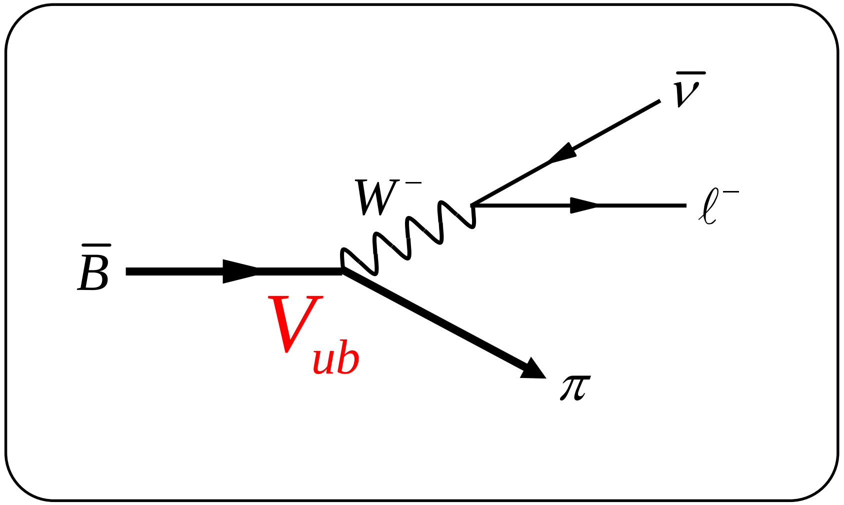

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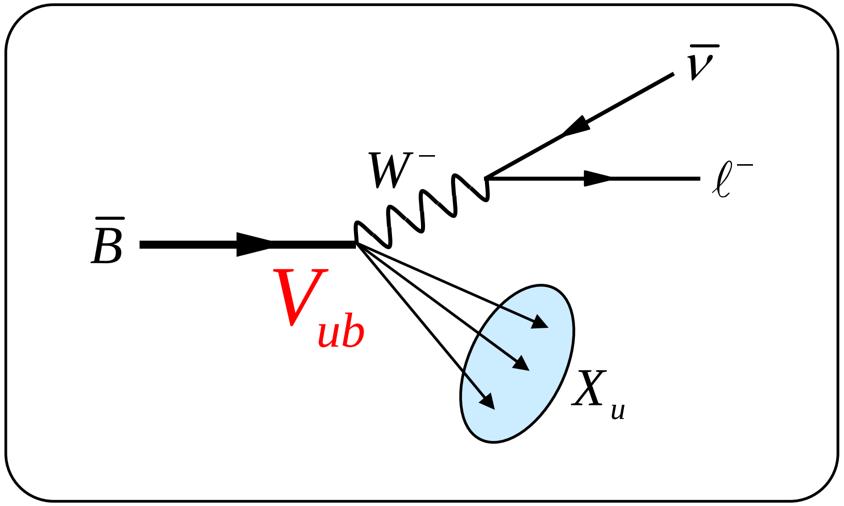
Exclusive Decays

hadronic final states X_u reconstructed

- Low signal rate, better bkg reduction and kinematic constraints
- Need Form Factor $F(q^2)$ to describe the hadronization process $u \to \pi, \rho, \ldots$
- Measurement as function of q^2

Inclusive vs Exclusive decays



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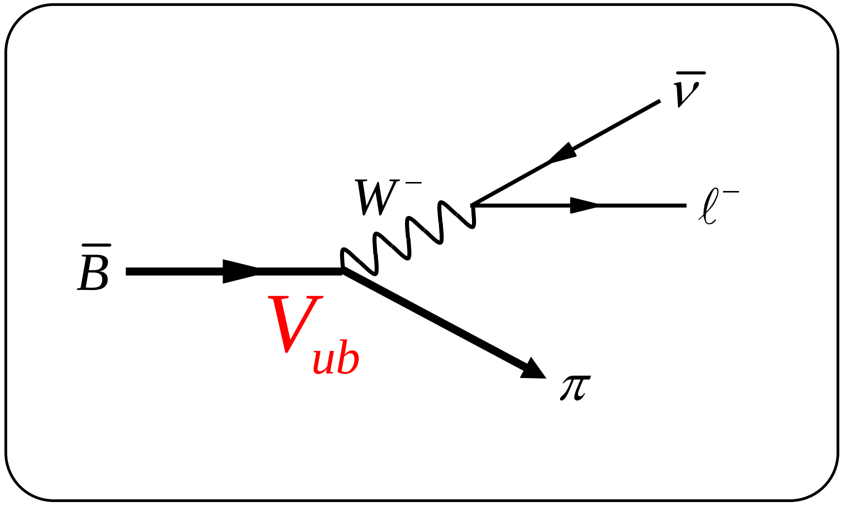

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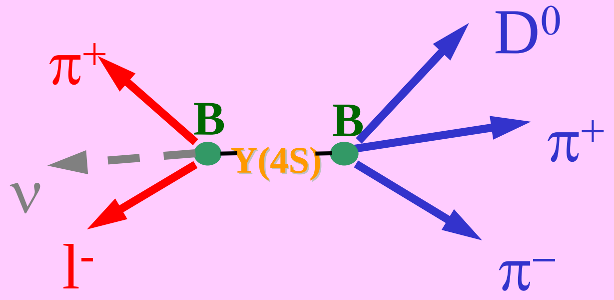
Theoretical uncertainties complementary

Experimental methods: tagged vs untagged

Complementary approaches:
- different systematic errors
- statistically independent samples

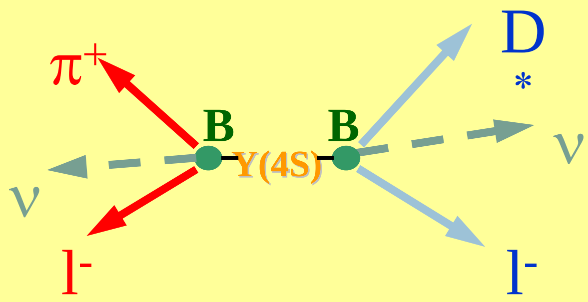


Hadronic Tag:

Fully reconstruct hadronic decay of one B:

$B \to D^{(*)} + (\pi^+, \pi^0, K^+, K^0)$ **≈ 1000 modes**

→ know kinematics of other B



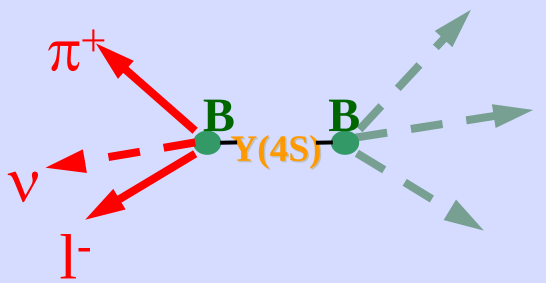
Semileptonic Tag:

Reconstruct $B \to D^{(*)} \ell \nu$ **and study recoil**

- Full reconstruction of $D^{(*)}$

- Partial reconstruction of D^* **(only** l, π_{soft}**)**

Two ν → tag-B kinematics incomplete



No Tag:

High statistics

High backgrounds and cross-feed

→ Fully reconstruct signal side (ν reco.)

Experimental methods: tagged vs untagged

Complementary approaches:
- different systematic errors
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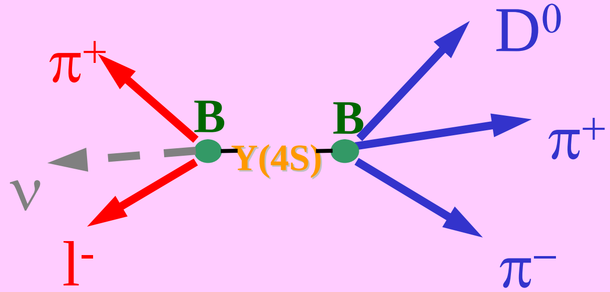

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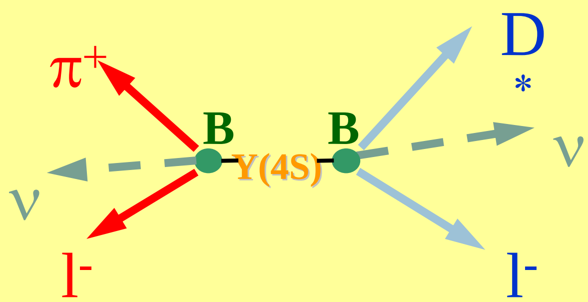

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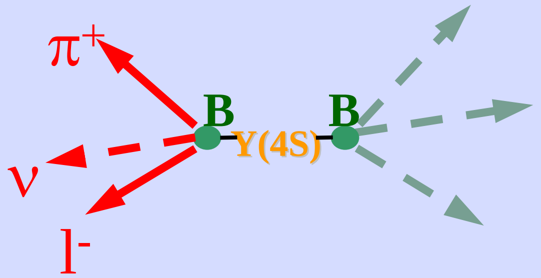


No Tag:

High statistics

High backgrounds and cross-feed

→ Fully reconstruct signal side (ν **reco.)**

tagged

☺ high signal purity for almost all phase space

☹ low signal efficiency

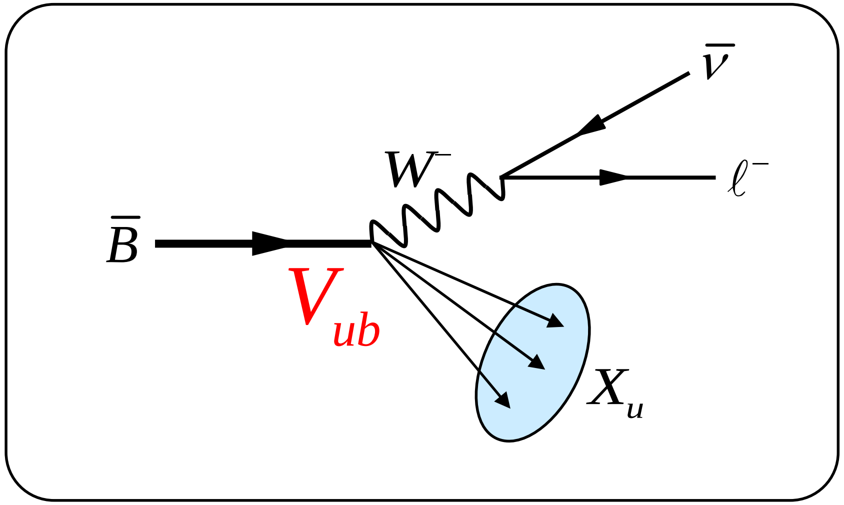
untagged

☹ lower signal purity and restricted phase space

☺ high signal efficiency

Only B-Factories could explore tagged technique

Inclusive Approach



Theory for b → $u \ell \nu$

- Heavy Quark Expansion gives us total $B \to X_u \ell \nu$ decay rate
  - Expansion in $\alpha_s(m_b)$ (perturbative) and $1/m_b$ (non-perturbative)

$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 - O\left(\frac{\alpha_s}{\pi}\right) - \frac{9\lambda_2 - \lambda_1}{2m_b^2} + \cdots\right]$$

known to $O(\alpha_s^2)$

Suppressed by $1/m_b^2$

- but…inclusive decay width cannot be directly measured
  - experiments measure partial widths in limited region of phase space that are free from the $B \to X_c \ell \nu$ background
- Poor convergence of HQE in region where $B \to X_c \ell \nu$ decays are kinematically forbidden
- non-perturbative Shape Function (SF) must be used to calculate partial rates

Shape Function : What is it ?

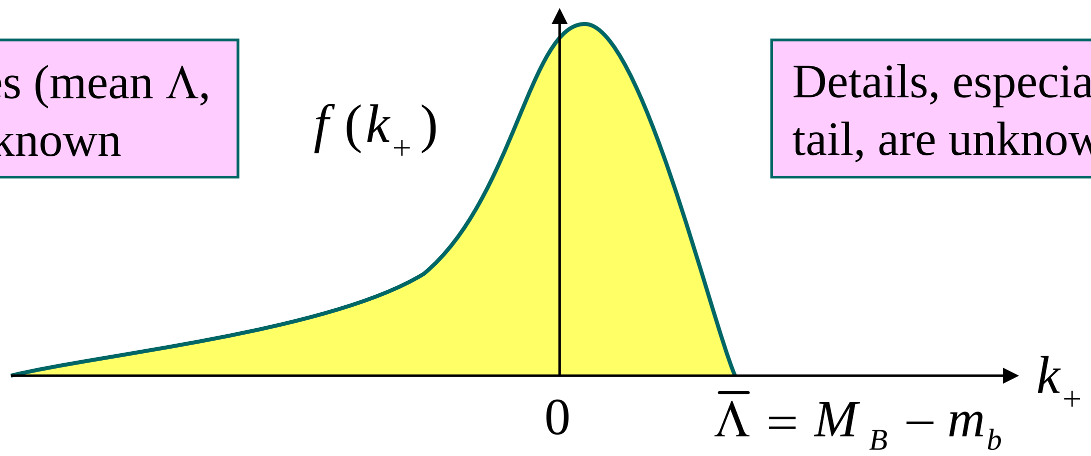
- Light-cone momentum distribution of b quark : $f(k_+)$
  - Fermi motion of b quark inside B meson
  - Universal property of a B meson (to Leading Order) but…

  ….subleading SFs arise at each order in $1/m_b$

- Consequences : changes effective $m_b \rightarrow$ smear kinematic spectra

- SF depends on 2 parameters related to the mass and kinetic energy of the b-quark: Λ or m_b and λ_1 or μ_π^2

Rough features (mean Λ, r.m.s. λ_1) are known



Details, especially the tail, are unknown

Extraction of the Shape Function

SF cannot be computed → must be determined experimentally:

- we can fit the $b \to s\gamma$ spectrum with theory prediction
  - must assume a functional form of $f(k_+)$

for example: $$f(k_+) = N(1-x)^a e^{(1+a)x}; \quad x = \frac{k_+}{\bar{\Lambda}}$$

- calculation connects SF moments with b-quark mass m_b and kinetic energy μ_π^2 (Neubert, PLB 612:13)
  - determined precisely from $b \to s\gamma$ and $b \to c\ell\nu$ decays
    - $\langle E_\gamma^n \rangle$ from $b \to s\gamma$, $\langle E_\ell^n \rangle$ and $\langle m_X^n \rangle$ from $b \to c\ell\nu$
  - fit data from BaBar, Belle, CLEO, Delphi, CDF :

Buchmüller & Flächer
hep-ph/0507253

$$m_b = (4.60 \pm 0.04)\,\mathrm{GeV}, \quad \mu_\pi^2 = (0.20 \pm 0.04)\,\mathrm{GeV}^2$$

(precision on m_b better than 1%)

- Use SF together with calculation of triple-diff. decay rate

Inclusive b $\to u\ell\nu$: how to measure it

- Need to suppress the high $b\to c\ell\nu$ background:

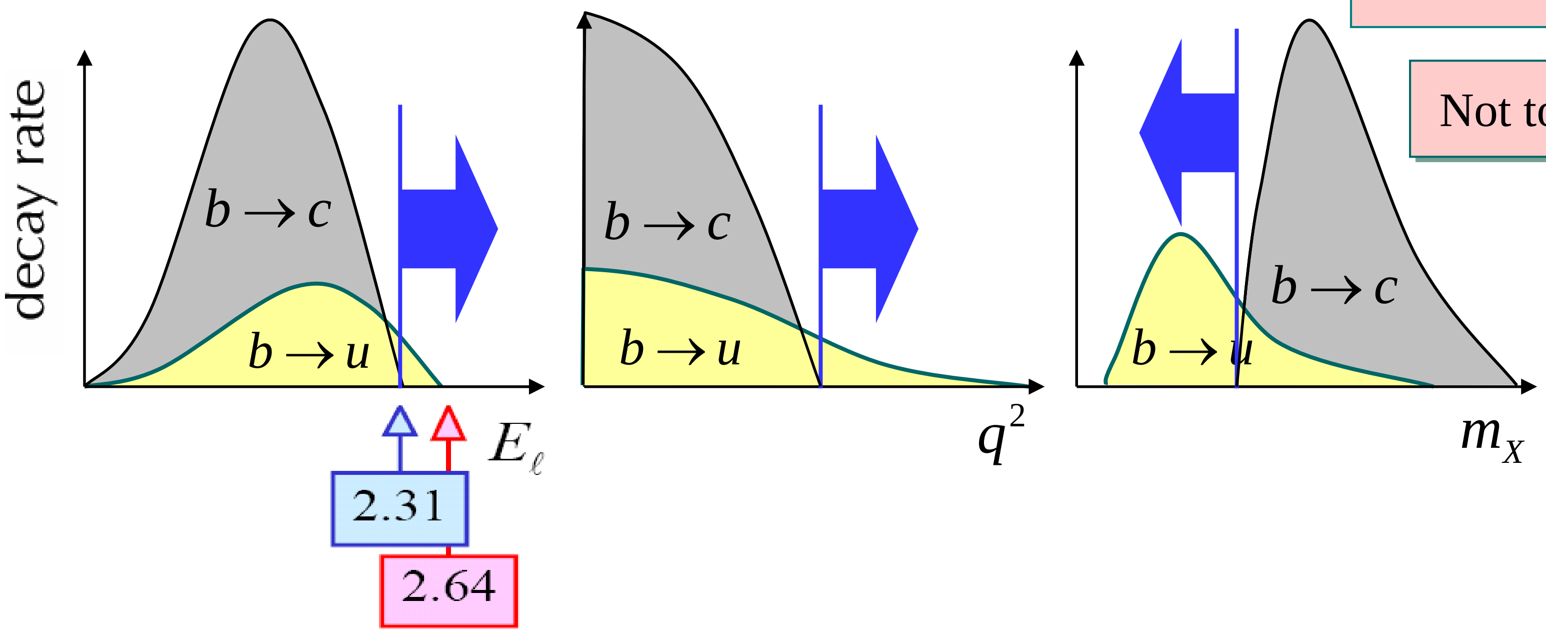
$$\frac{\Gamma(b\to u\ell\bar{\nu})}{\Gamma(b\to c\ell\bar{\nu})}\approx\frac{|V_{ub}|^2}{|V_{cb}|^2}\approx\frac{1}{50}$$

  - ✓ m_u << m_c → differences in kinematics

- There are 3 independent variables in $b\to u\ell\nu$:
  - ✓ Signal events have smaller m_X → larger E_l and q^2

no detector resolution!

Not to scale!



we measure **partial rates** in favorable regions of the phase space

Getting | V_{ub}| from the partial rate

- Take your favorite theory calculation and convert the partial rates into $|V_{ub}|$:

OPE gives good results for full phase space but break down in the "SF region" (low M_X and low q^2)

$$BR(B \to X_u l\nu) = \frac{\Delta BR}{f_u(m_b, \underline{\Lambda}^{SF}, \lambda_1^{SF})}$$

↓

<u>various approaches to solve the problem</u>

$$|V_{ub}| = \sqrt{\frac{\Delta BR}{\Delta\zeta(\Lambda^{SF}, \mu_\pi^{2\,SF}) \cdot \tau_B}}$$

- **DFN** (De Fazio, Neubert) → **HQE with ad-hoc inclusion of SF**

JHEP9906:017(1999)

- **BLNP** (Bosch, Lange, Neubert, Paz) → **HQE with systematic incorporation of SF**

PRD72:073006(2005)

- **BLL** (Bauer, Ligeti, Luke) → **HQE for $m_X < m_D$ and $q^2 > 8$ ('non SF region') to minimize SF effect**

PRD64:113004(2001)

Predicted rate (BLNP, BLL)

- **DGE** (Anderson,Gardi) → **use "Dressed Gluon Exponentiation" to convert on-shell b quark calculation into meson decay spectra**

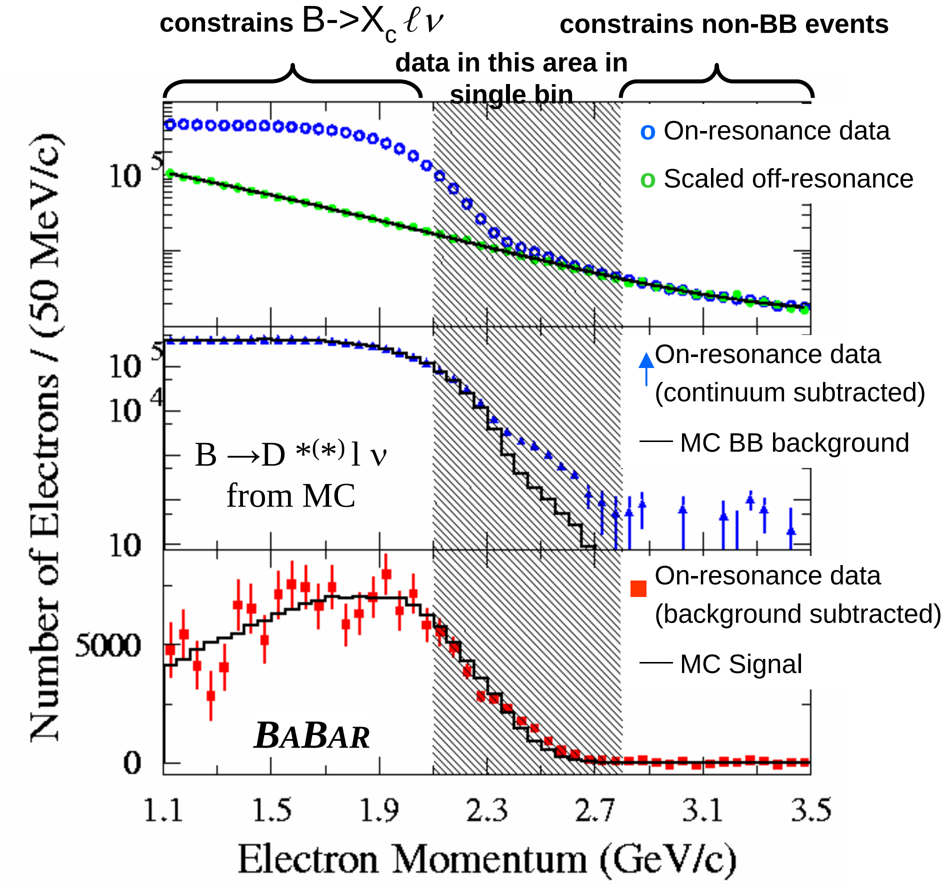
NEW

JHEP0601:097(2006)

PRD73, 012006 (2006)

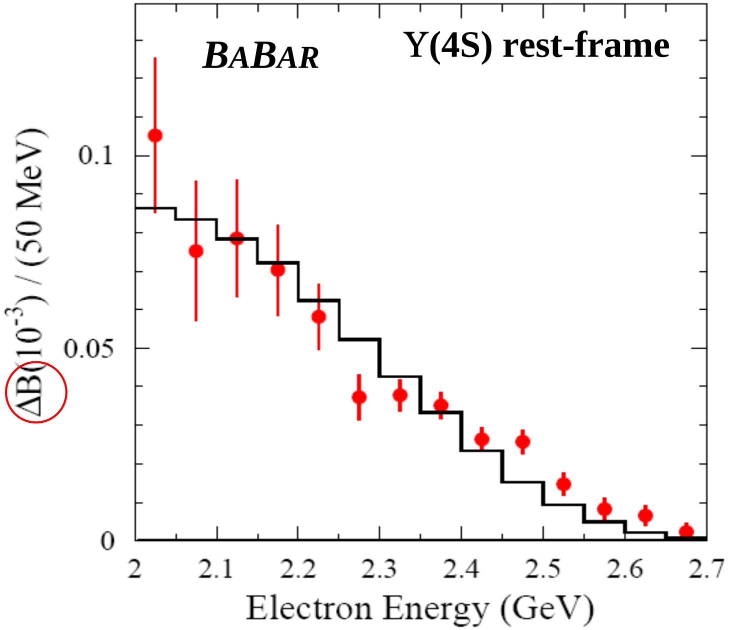
$|V_{ub}|$ from inclusive $B \rightarrow X_u \ell \nu$ endpoint spectrum

80 fb^{-1}



- Select electrons with : 2.0 < E_e < 2.6 GeV
- accurate subtraction of background is crucial !
  - non BB bkg subtracted using off-peak and on-peak (with p_e > 2.8GeV)
  - BB bkg from MC : fit $b \rightarrow c \ell \nu$ individual compositions
- S/B ~ 1/15 for endpoint E_e > 2.0 GeV
- push below the charm threshold (2.3 GeV)
  - larger signal acceptance
  - less dependence of SF

$|V_{ub}|$ from inclusive $B \to X_u \ell \nu$ endpoint spectrum



Inclusive electron spectrum

fully corrected for efficiencies and radiative effects

|Vub| extracted from the measurement of partial Branching Ratios

$\Delta B\ (B \to X_u \ell \nu) = (0.572 \pm 0.041_{stat} \pm 0.065_{syst})$ x 10-3

$2.0 < E_e < 2.6$ GeV

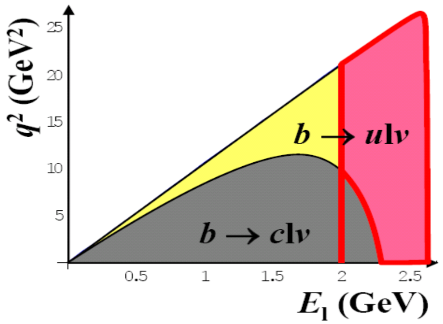
Using BLNP to translate partial rate directly into |Vub|

$$|V_{ub}| = (4.44 \pm 0.25_{exp}\ {}^{+0.42}_{-0.38}{}_{SF} \pm 0.22_{th\text{-}BLNP}) \times 10^{-3}$$

$b \to s\gamma$, $b \to c\ell\nu$ moments (from BaBar) combined fit

PRL95, 111801 (2005)

E_l-q^2 analysis with ν reconstruction



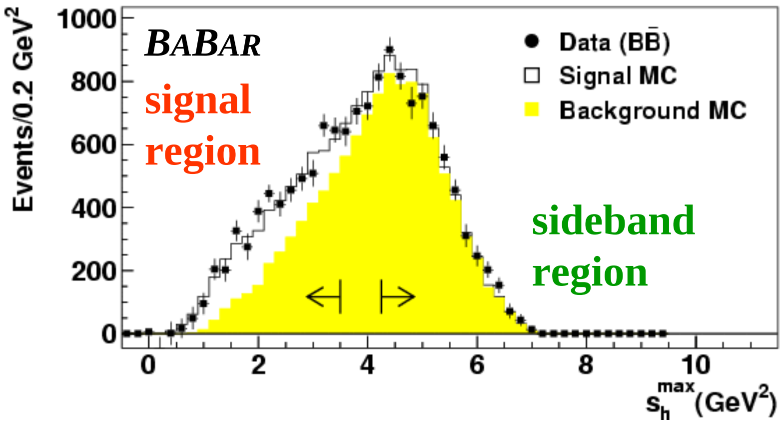
80 fb^{-1}

- Try to improve signal to background
- Use $p_\nu = p_{miss}$ in addition to $p_e \rightarrow$ calculate q^2

- define s_h^{max} = maximum hadronic mass squared

$$s_h^{max} = m_B^2 + q^2 - 2m_B(E_e + \frac{q^2}{4E_e}),$$

Cutting at $s_h^{max} < m_D^2$ removes b → clν while keeping most of the signal



- BB bkg normalization for $s_h^{max} > 4.25$ GeV²
- S/B ~1/2 achieved for $E_e > 2.0$ GeV and $s_h^{max} < 3.5$ GeV²

Unfolded partial BR : $\Delta B\ (B \rightarrow X_u \ell \nu)_{(2.0,3.5)} = (4.41 \pm 0.42_{stat} \pm 0.42_{syst}) \times 10^{-4}$

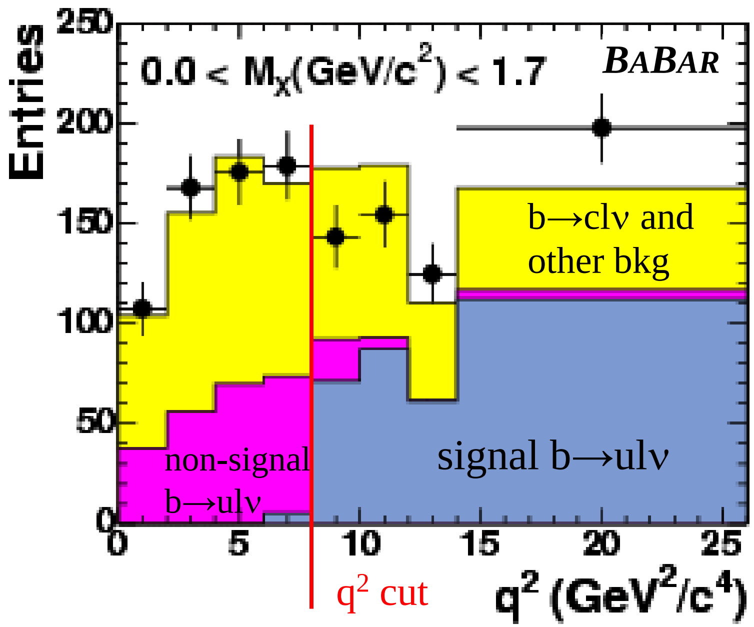
Used BLNP to traslate into $|V_{ub}|$: $|V_{ub}| = (4.41 \pm 0.30_{exp}\ {}^{+0.65}_{-0.47}{}_{HQ} \pm 0.28_{theo}) \times 10^{-3}$

HQE parameters taken from BaBar $B \rightarrow X_c l\nu$ moments

m_X-q^2 analysis with hadronic B tag

211 fb^{-1}

- must reconstruct all decay products to measure m_X and q^2
  - Use (fully recontructed) hadronic B tag
  - Study the recoiling B→known kinematics/B flavour
- signal side:
  - look for one lepton (p_l >1 GeV) and $\nu(m^2_{miss})$
  - m_X and q^2 from the X system
- Suppress $b \to c\ell\nu$ bkg by vetoing against D(*) decays → kaon veto and soft pions
- Normalized to total semileptonic rate



- Measure the partial BR in region of $m_X < 1.7$ GeV and $q^2 > 8$ GeV^2

$$\Delta Br(M_X < 1.7\text{GeV}, q^2 > 8\text{GeV}^2) = (0.87 \pm 0.09_{stat} \pm 0.09_{syst} \pm 0.01_{th}) \times 10^{-3}$$

Using BLNP to traslate into $|V_{ub}|$:

$$|V_{ub}| = (4.65 \pm 0.24_{stat} \pm 0.24_{syst} {}^{+0.46}_{-0.36}{}_{SF} \pm 0.23_{th}) \times 10^{-3}$$

HQE parameters taken from BaBar $B \to X_c l\nu$ moments

Avoiding the Shape Function

- Combine $B \to X_u \ell \nu$ and $B \to X_s \gamma$ without going through the SF:

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

Weight function

Reduced dependence on SF

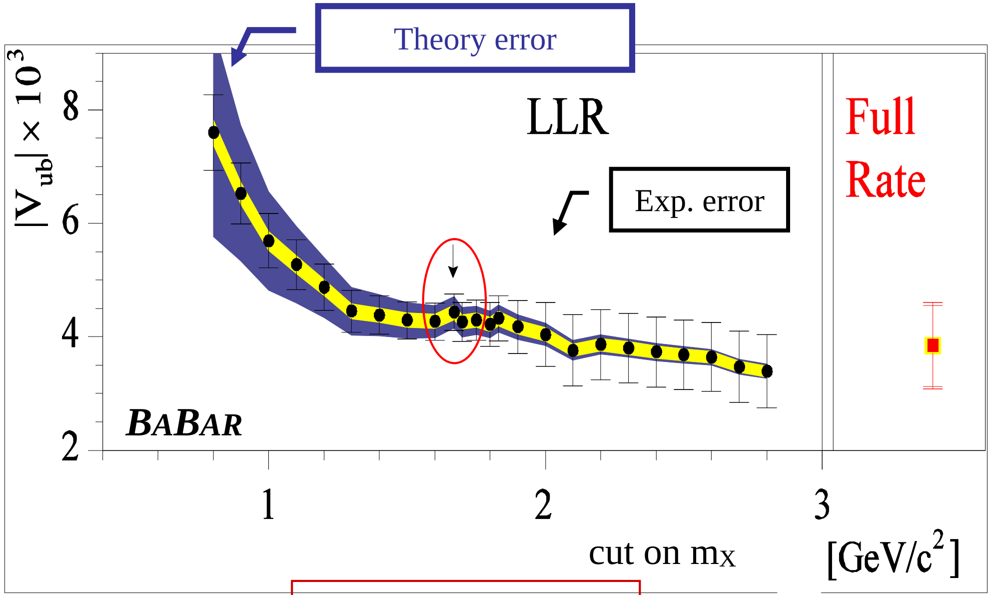
- **LLR** (Leibovich, Low, Rothstein) **PRD61:053006(2000), PL B513:83(2001)**
  - Relates $|V_{ub}|^2/|V_{tb}V_{ts}^*|$ to m_X or E_l spectrum in b->ulv and E_γ spectrum in b->sγ
  - Includes higher order corrections
- **Neubert** **PL B513:88(2001)**
  - Similar to LLR
- **BLNP/ Lange** **JHEP0510:084(2005), JHEP0601:104(2006)**
  - Relates $|V_{ub}|$ to the measured partial BF(b->ulv) and normalised E_γ spectrum in b->sγ decays

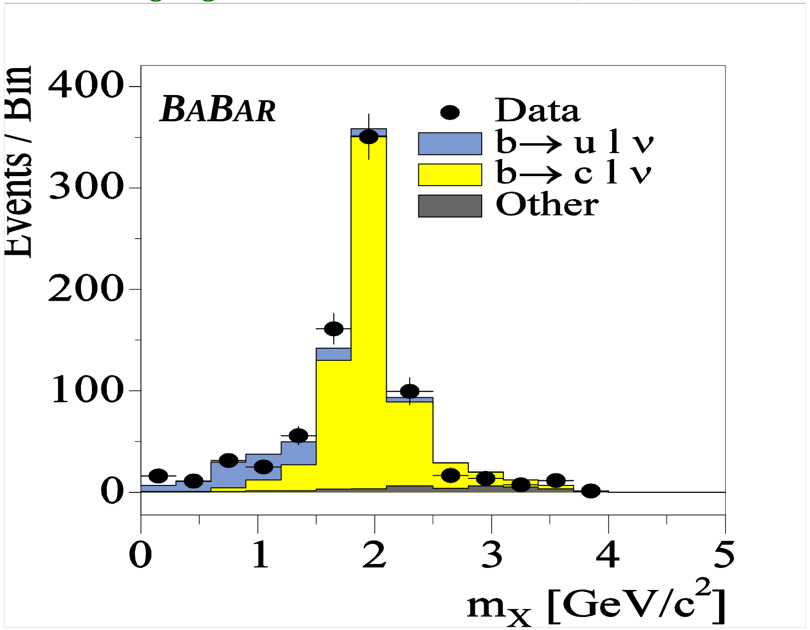
Inclusive $|V_{ub}|$ with reduced model dependence

80 fb^{-1}

- based on measurements of the m_X spectrum using hadronic tag
- two approaches to reduce SF dependence
  - relating $b \to u\ell\nu$ to $b \to s\gamma$ using weight functions (LLR)
  - measurement from the full m_X spectrum (HQE)

Uraltsev hep-ph/9905520,
Hoang,Ligeti,Manohar **PRD 59, 074017 (1999)**





LLR : $M_X < 1.67$ GeV:

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

HQE : $M_X < 2.50$ GeV:

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

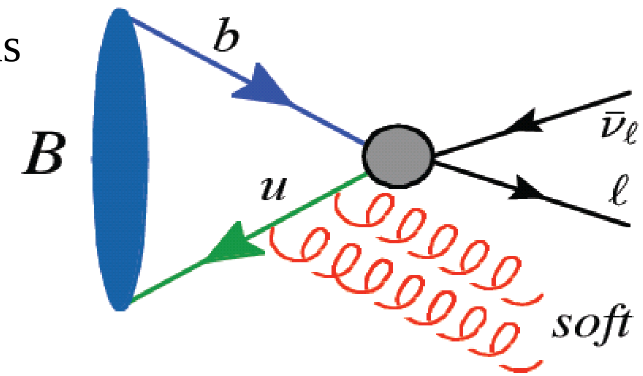
reduced theory error as no extrapolation to full rate necessary

Closer look at uncertainties

Statistical	±2.2%
Exp. systematic	±3.8%
SF params. (m_b, μ_π^2)	±4.2%
Theory	±4.2%

- The SF parameters can be improved with $b \to s\gamma$, $b \to c\ell\nu$ measurements

- Quark-hadron duality is not considered
  - $b \to c\ell\nu$ and $b \to s\gamma$ data fit well with the HQE predictions
- Weak annihilation → ±1.9% error
  - Expect <2% of total rate,
  - Potential problem for all inclusive determinations including large E_l, q^2 region
  - Measure $\Gamma(B^0 \to X_u\ell\nu) / \Gamma(B^+ \to X_u\ell\nu)$ to improve the constraints

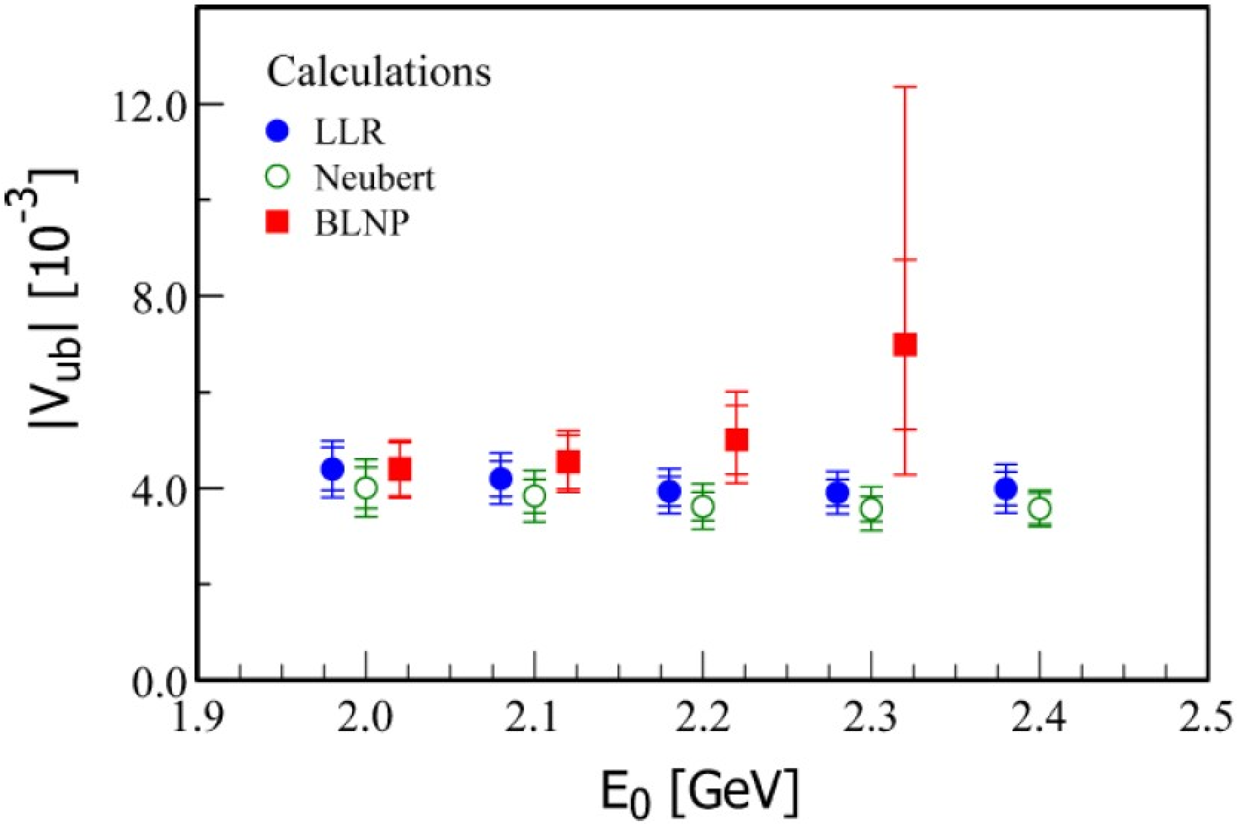


- Subleading Shape Function → ±3.8% error
  - Higher order non-perturbative corrections
  - Cannot be constrained with $B \to X_s\gamma$
- The goal is to reach total error on inclusive $|V_{ub}|$ of ~ 5%

Reinterpretation of Lepton Endpoint

Take the partial Branching Ratio from the BaBar lepton endpoint measurement and use the BaBar semi-inclusive photon spectrum from $b \to s\gamma$ to calculate $|V_{ub}|$:

- ✓ different theoretical methods
- ✓ different energy cuts



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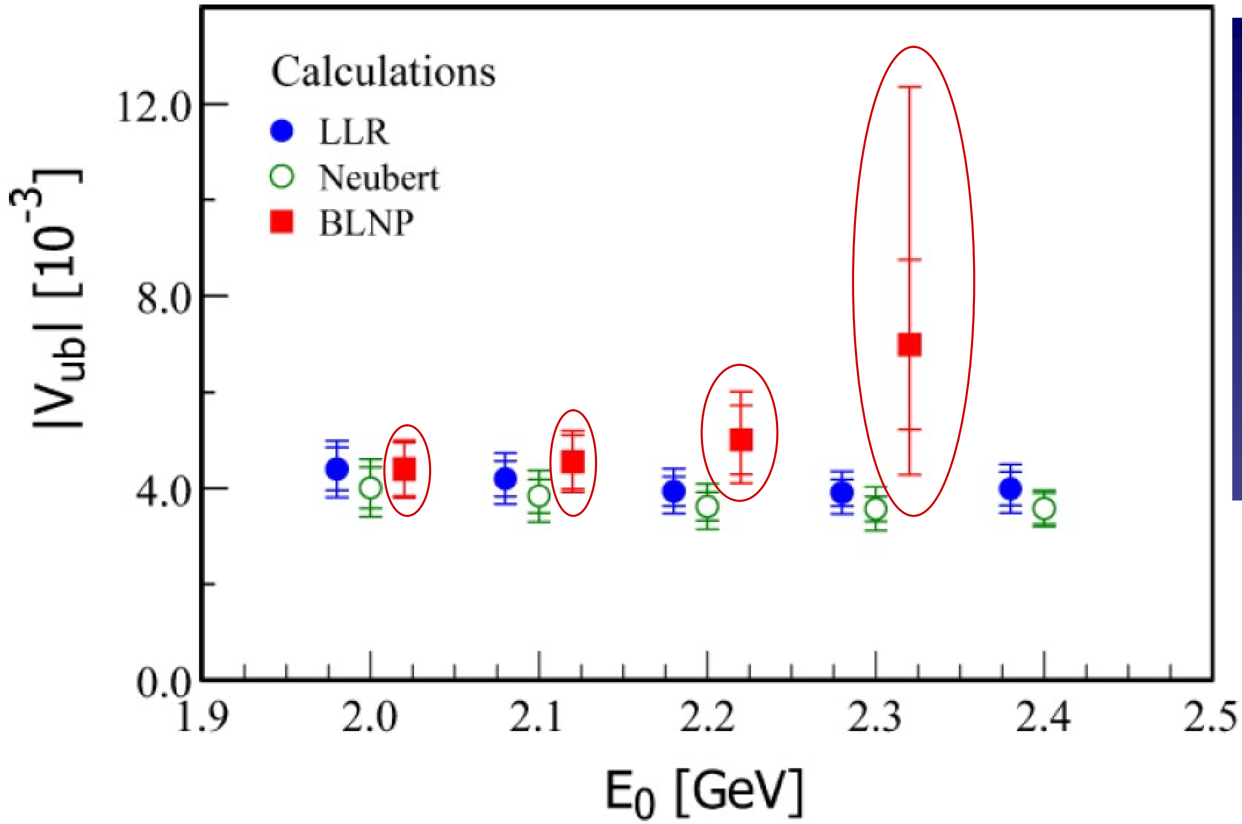

- caution on treatment of theory errors in exp. analyses
- only BLNP includes power corrections and complete error analysis

Reinterpretation of Lepton Endpoint

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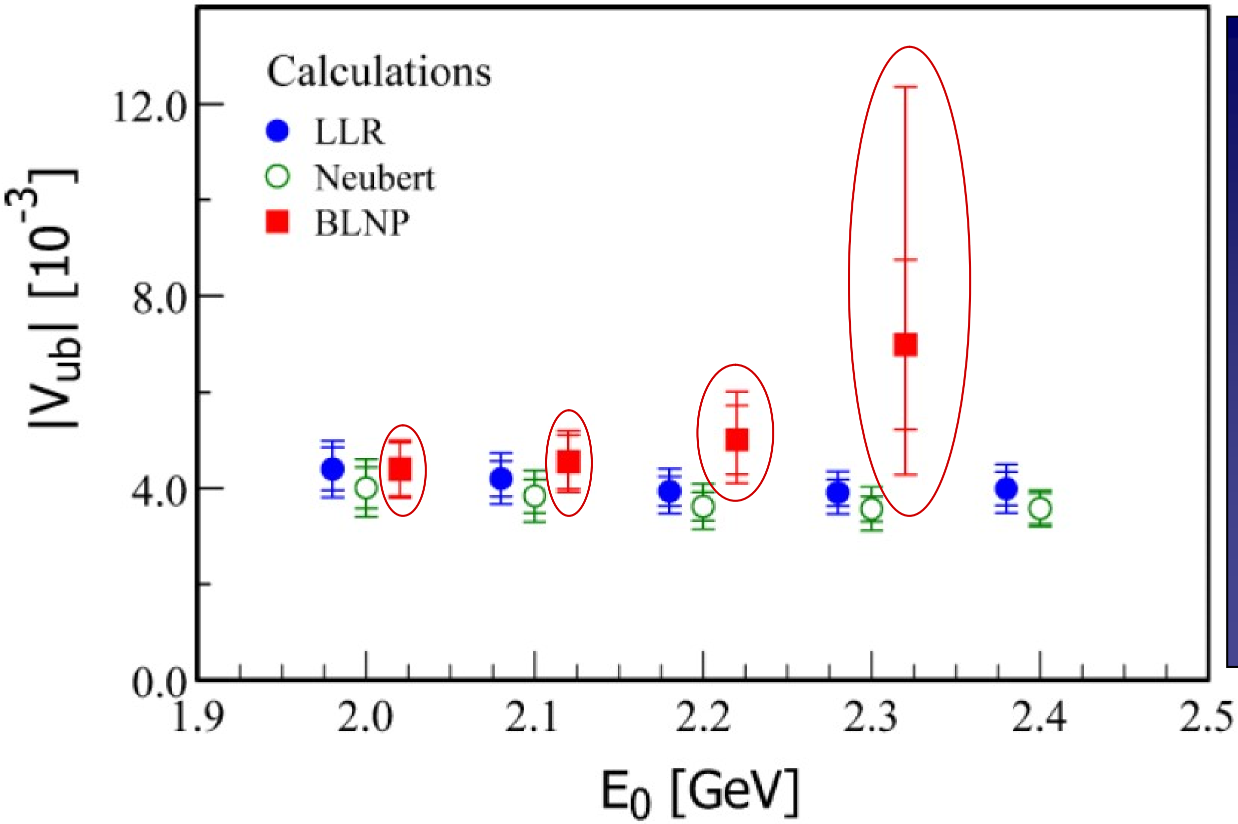
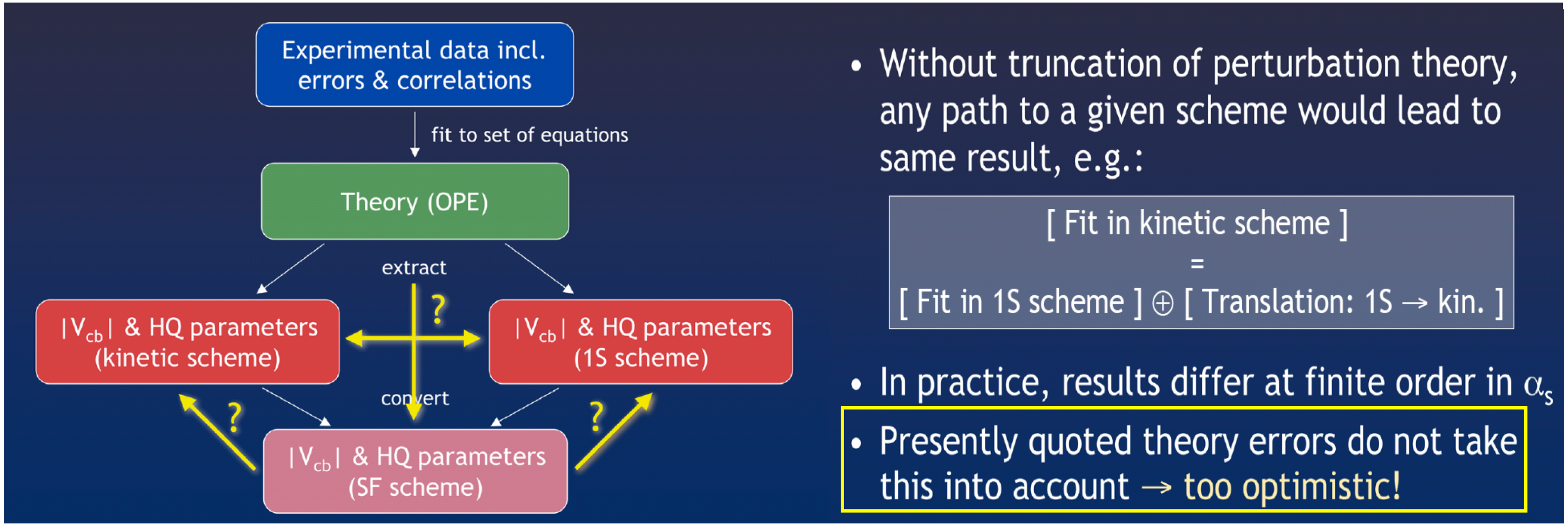


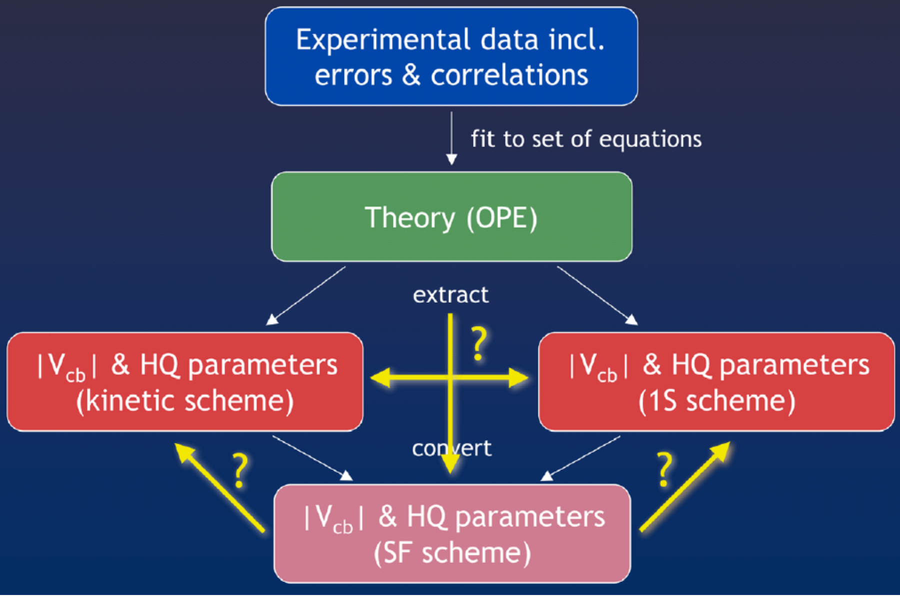
- caution on treatment of theory errors in exp. analyses
- only BLNP includes power corrections and complete error analysis
- Errors must blow up at large E_0 !

Discussion is open…



M.Neubert talk @ FPCP07 (Bled, Slovenia May'06)

Discussion is open…



- Without truncation of perturbation theory, any path to a given scheme would lead to same result, e.g.:

  [Fit in kinetic scheme]
  =
  [Fit in 1S scheme] ⊕ [Translation: 1S → kin.]

- In practice, results differ at finite order in α_s
- Presently quoted theory errors do not take this into account → too optimistic!

Perturbative error om m_b

$$\delta m_{b,pert} = \pm 60 \text{ MeV} \quad (1.3\%)$$

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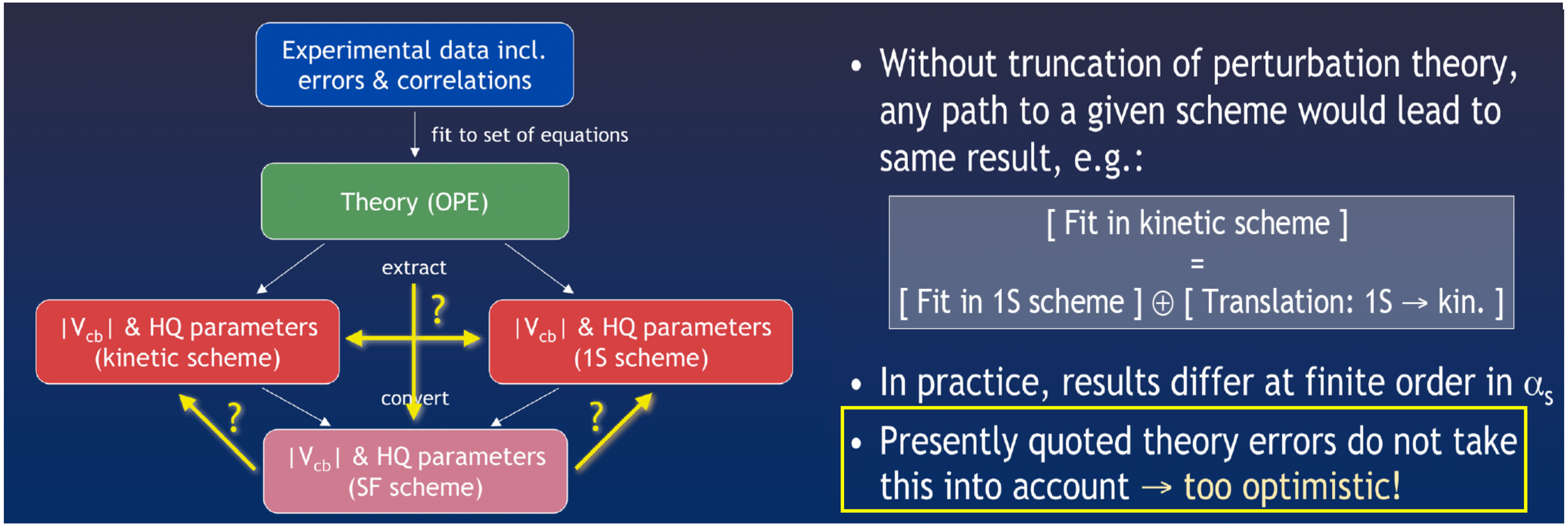


Perturbative error estimation on m_b from Neubert

$\delta m_{b,pert} = \pm 60$ MeV (1.3%)

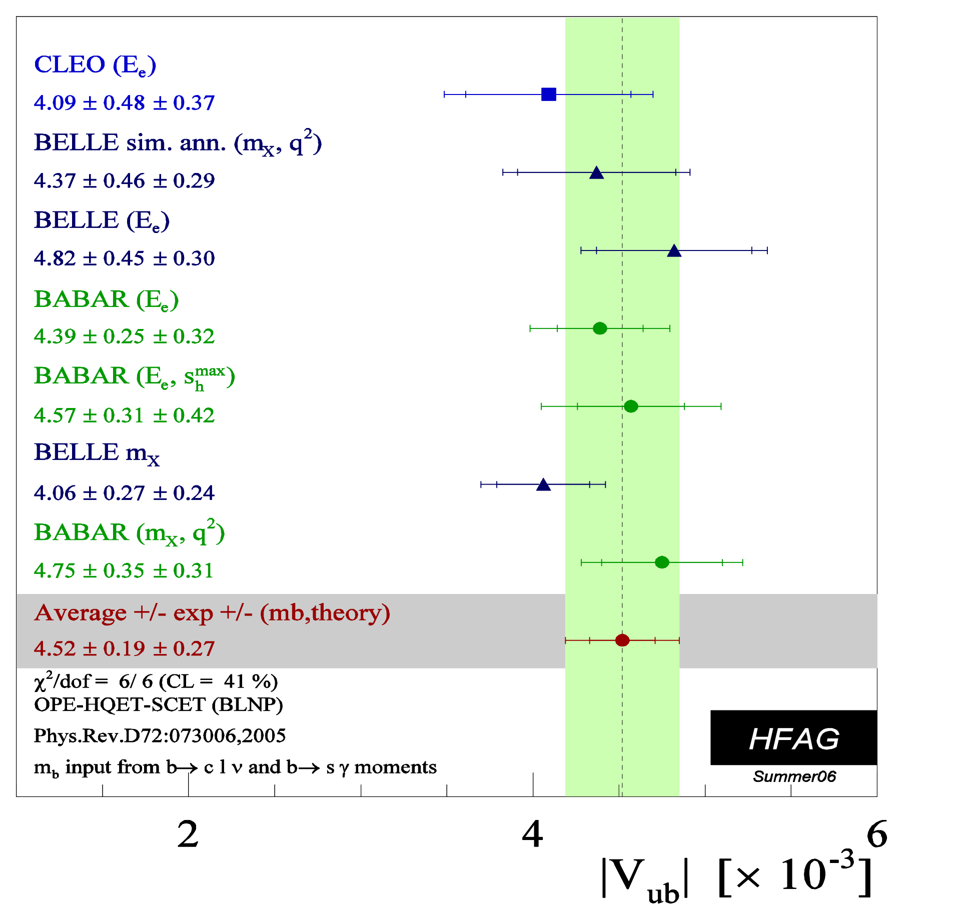
from global fit :

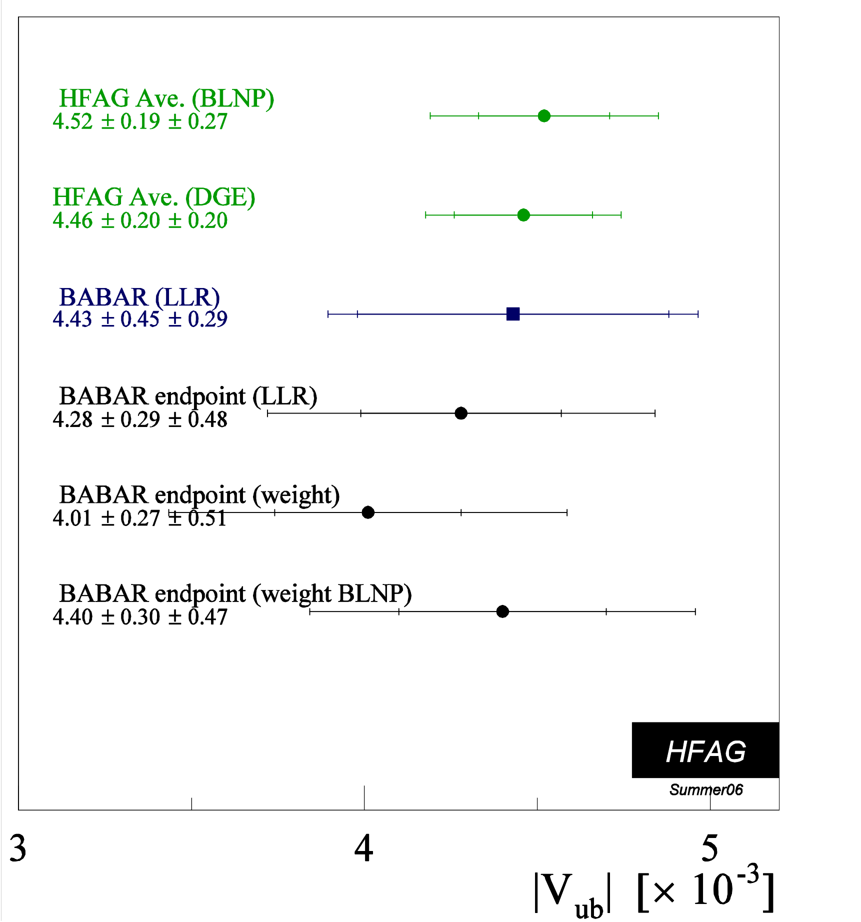
$\delta m_{b,pert} = \pm 30$ MeV (< 1%)

Very important for |Vub| determination : actual error under-estimated (?)

Interesting to hear opinions of others theorist on this point

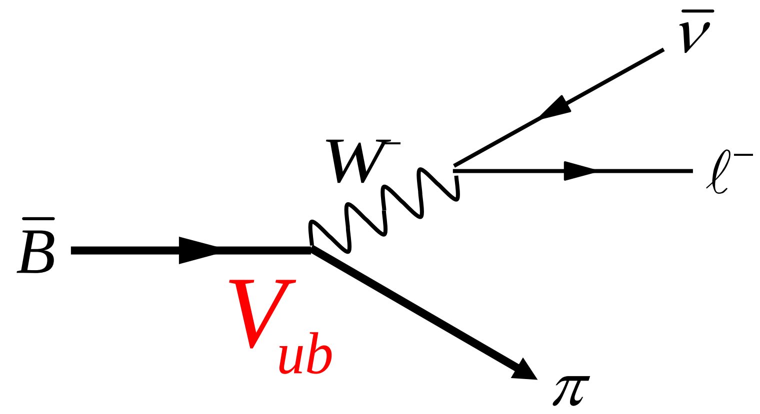
Status of Inclusive $|V_{ub}|$





Numbers rescaled by HFAG.
SF parameters from hep-ex/0507243,
predicted partial rates from BLNP

Exclusive Approach



Exclusive decays B → $X_u \ell \nu$

- $B \to \pi\ell\nu$, $B \to \eta\ell\nu$, $B \to \eta'\ell\nu$, $B \to \rho\ell\nu$, $B \to \omega\ell\nu$
  - Branching Ratios are $\mathcal{O}(10^{-4})$ → statistics limited
  - measurements can achieve good signal to background ratio
- Theoretical point of view
  - effect of strong interactions on the hadronization of the Xu final states described by Form Factors : f (q^2)
- In principle $|V_{ub}|$ could be determined from all exclusive channels but….

$B \to \pi \ell \nu$ most promising, both experimentally and theoretically

- decay rate related to |Vub| through hadronic form factor :

massless leptons and isospin symmetry assumption

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

just one form factor needed

Form Factor calculations

form factor has been calculated using :

✓Light Cone Sum Rules PRD71:014015(2005)

✓valid for $q^2 < 14$ GeV^2 → **11% uncertainty**

✓Lattice QCD → **11% uncertainty**

✓unquenced calculation by HPQCD PRD73:074502(2006)

FNAL hep-lat/0409116

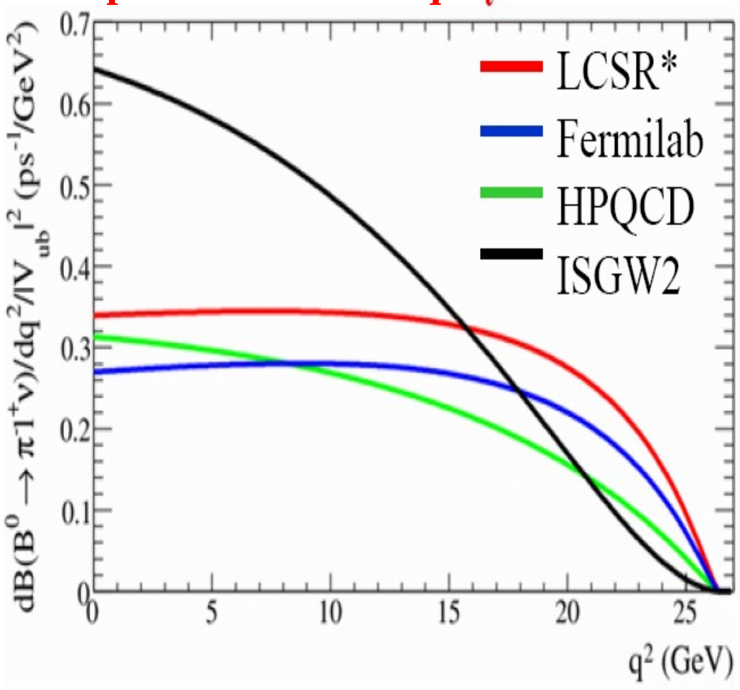
✓valid for $q^2 > 16$ GeV^2

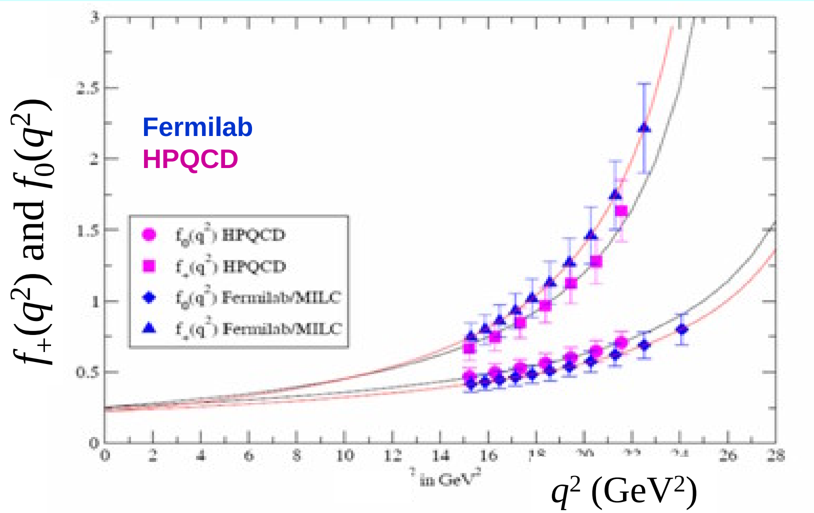
✓Quark models : ISGW II PRD52:2783(1995)

(no error quoted)

LQCD and LCSR valid in different q^2 ranges→No crosscheck
important to measure differential decay rate as function of q^2 to discriminate among models

different theoretical calculations predict different q^2 distributions





Need for a parametrization for extrapolation to low q^2 → additional uncertainty

Theory and Uncertainties

Need for theoretical input on Form Factor introduce uncertainties in the experimental measurements :

- FF shape → acceptance

Measure shape on data to reduce dependence on theoretical predictions

- FF normalization → extraction of $|V_{ub}|$ from partial BRs

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{BR}(B^0 \to \pi^- \ell^+ \nu)}{\Delta\zeta \cdot \tau_B}}$$

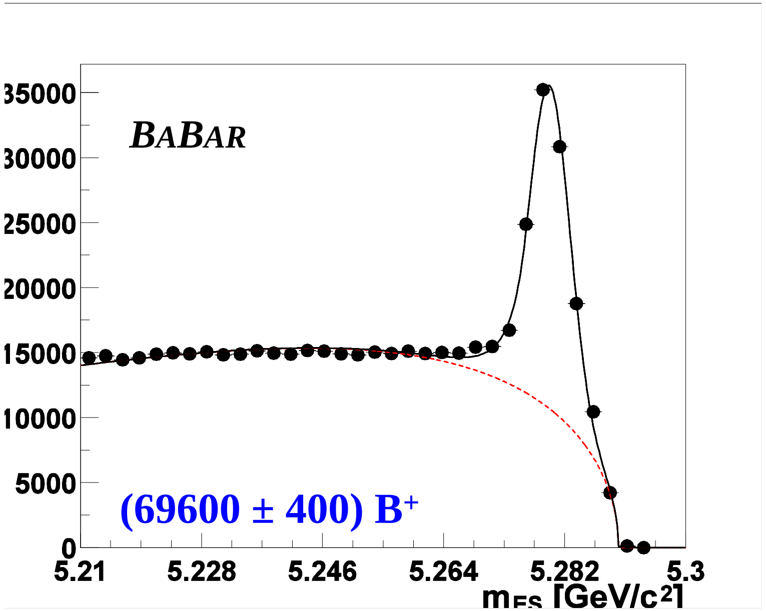
$$\Delta\zeta = \frac{G_F^2}{24\pi^3} \int_{q^2_{min}}^{q^2_{max}} |f_+(q^2)|^2 p_\pi^3 dq^2$$

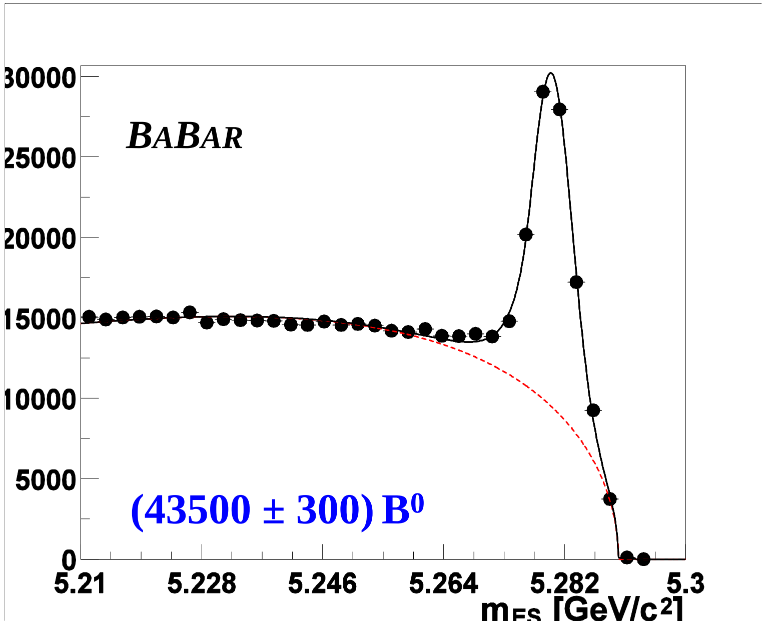
$|V_{ub}|$ extraction from partial BR doesn't have extrapolation uncertainties

$B \to X\ell\nu$ semileptonic selection

events are selected requiring an energetic prompt lepton
in the recoil of a fully reconstructed B

- Minimum lepton momentum in B rest frame → reduce bkg
  p*> 0.5 GeV/c for electrons and p*> 0.8 GeV/c for muons
- Lepton charge and B_{reco} flavour correlation (mixing correction included to take into account the B^0-$\overline{B}^0$ mixing)





$$m_{ES} = \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$$

PRD73:012006(2006)

211 fb^{-1}

$B \rightarrow \pi \ell \nu$ with hadronic tags

plots in full q^2 range

- starting from sample with a signal lepton (right charge) and searching for a pion among the remaining particles
- no additional tracks and small residual energy
- specific cuts applied to reject peaking background events: $b \rightarrow u \ell \nu$ (other than signal), $b \rightarrow c \ell \nu$ and **other** background components

Cut on missing mass $mm^2 = P^2_{miss} = (P_{Y(4S)} - P_{Breco} - P_{Xu} - P_{lept})^2$

is a powerful tool to reject events $b \rightarrow cl\nu$

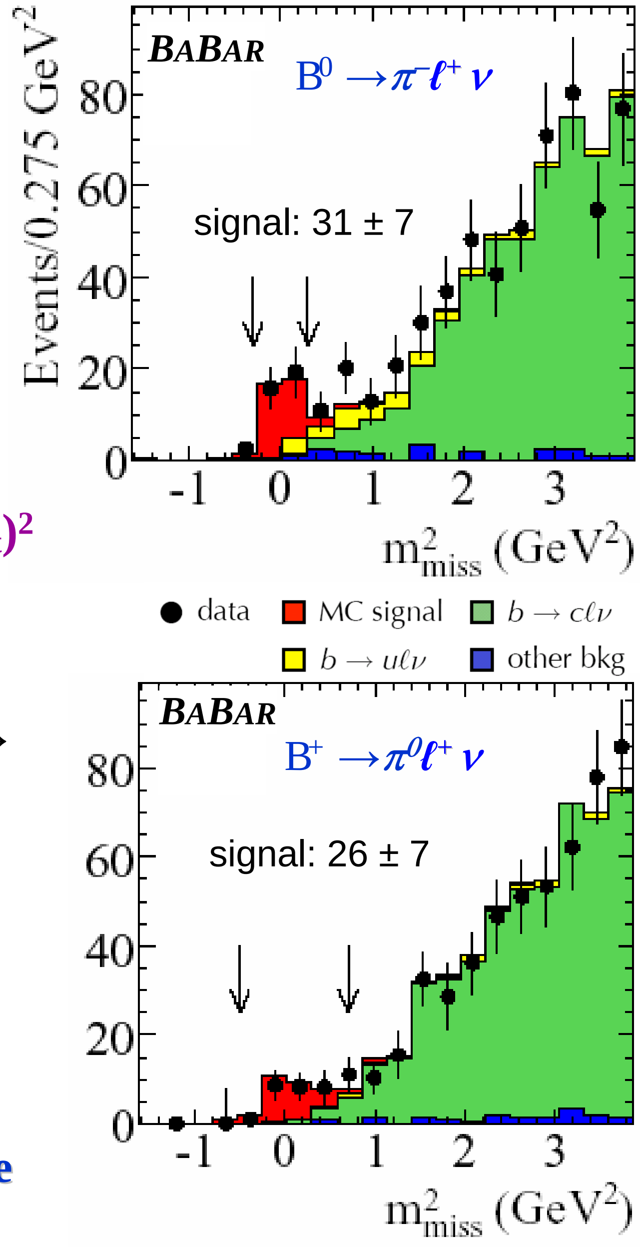
- signal events : mm = $m_\nu \rightarrow mm^2$ peaks at 0
- bkg events : undetected or poorly measured particles $\rightarrow mm^2$ tends to larger values

- use m_{ES} and mm^2 distribution to extract the signal

Extract the signal in 3q^2 ($(p_l+p_\nu)^2$) bins

q^2<8 GeV^2, 8< q^2<16 GeV^2, q^2>16GeV^2

to measure Form Factor shape and reduce model dependence

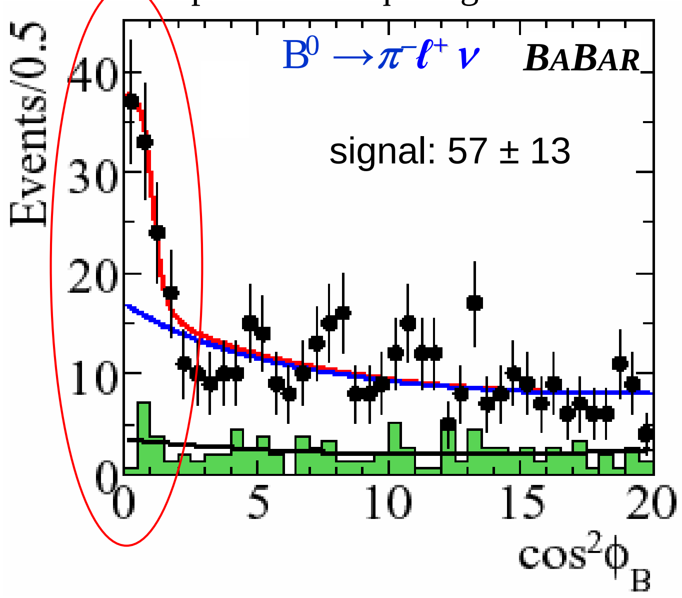


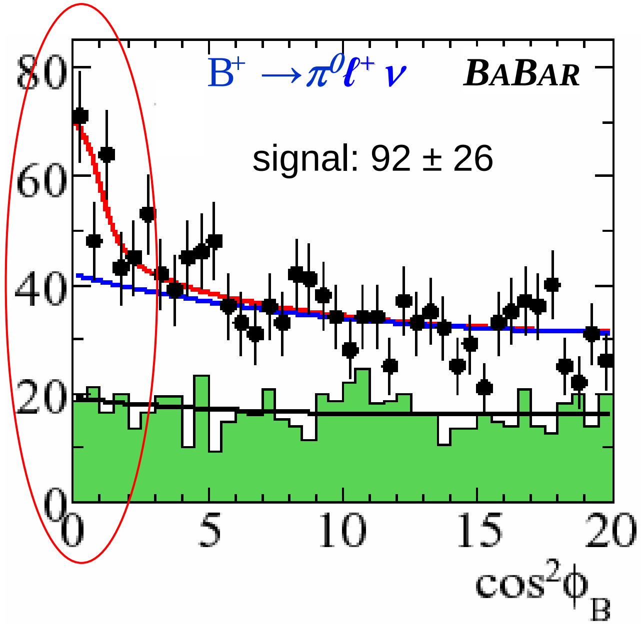
PRD73:012006(2006)

$B \to \pi \ell \nu$ with semileptonic tag

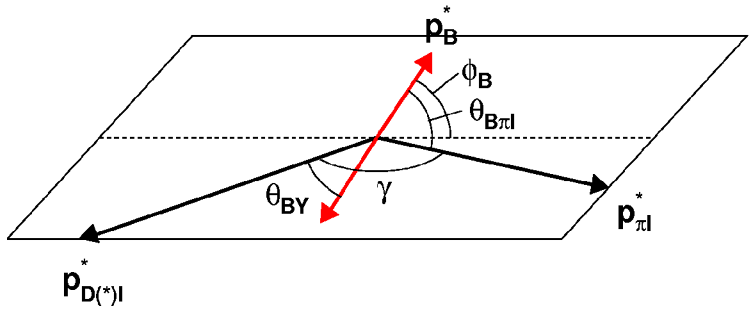
211 fb^{-1}

plots in full q^2 range





- use semileptonic tagged B
- identify a signal lepton (right charge) and search for a pion among the remaining particles
- no additional tracks and (low) neutral energy
- unbinned maximum likelihood fit to $\cos^2\phi_B$ distribution to extract signal yield



- signal events : $\cos^2\phi_B < 1 \to$ event where only ν undetected
- bkg events : flat distribution

Extract the signal in 3 q^2 ($(m_B-E_\pi)^2 - |p_\pi|$)bins

$q^2<8$ GeV^2, $8< q^2<16$ GeV^2, $q^2>16$GeV^2

$B \to \pi \ell \nu$ and $|V_{ub}|$: tagged analysis results

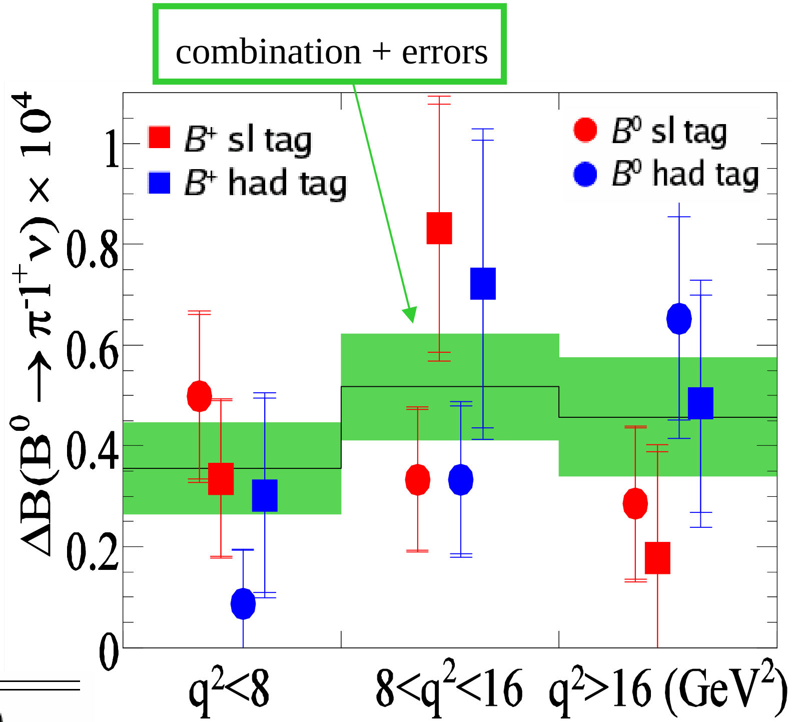
measurements combination of $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \pi^0 \ell^+ \nu$ BRs using hadronic and semileptonic tags assuming isospin symmetry $\Gamma(B^0 \to \pi^- \ell^+ \nu) = 2 \times \Gamma(B^+ \to \pi^0 \ell^+ \nu)$:

Weighted averages assuming :

- statistical errors are uncorrelated
- most systematic errors fully correlated

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.33 \pm 0.17_{\text{stat}} \pm 0.11_{\text{syst}}) \times 10^{-4}$$

- Experimental error dominated by statistics, with smaller systematics than previous measurements
- Very promising with increasing BaBar dataset !!



	q^2 (GeV^2)	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
Ball-Zwicky [5]	< 16	5.44 ± 1.43	$3.2 \pm 0.2 \pm 0.1^{+0.5}_{-0.4}$
HPQCD [6]	> 16	1.46 ± 0.35	$4.5 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}$
FNAL [7]	> 16	1.83 ± 0.50	$4.0 \pm 0.5 \pm 0.3^{+0.7}_{-0.5}$
APE [8]	> 16	1.80 ± 0.86	$4.1 \pm 0.5 \pm 0.3^{+1.6}_{-0.7}$

PRL98:091801(2007)

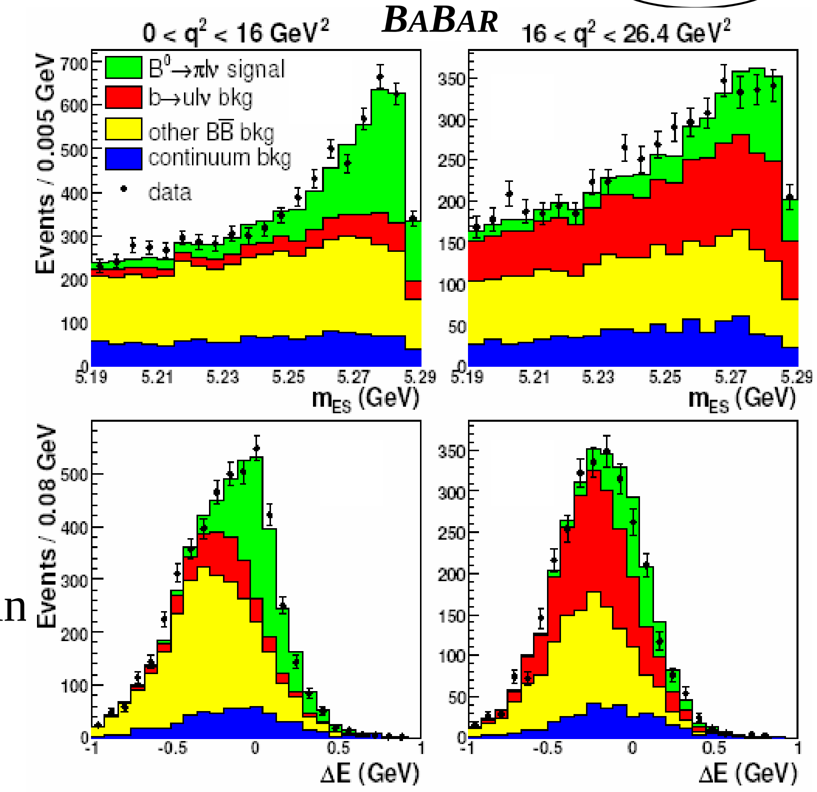
$B \to \pi \ell \nu$ (untagged): loose ν reconstruction technique

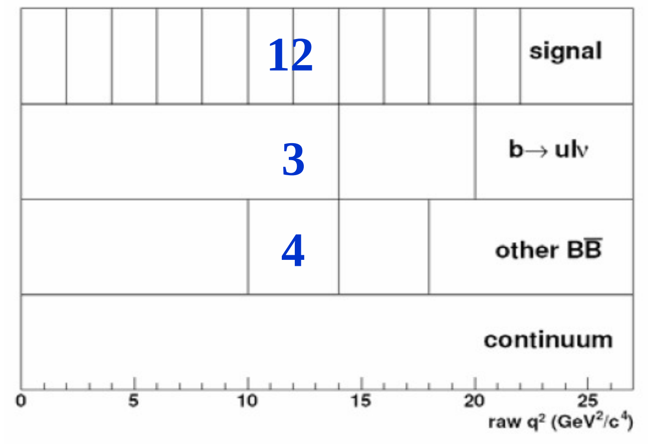
- need for ν reconstruction from full event

compared with previous untagged analysis(PRD72, 051102) new in this approach:

- *no 'neutrino quality' cuts* :
  - significantly increased signal efficiency : 5 → 25 signal ev./fb^{-1} , somewhat higher background(S/B from ~1.5 →0.5)
  - use $q^2 = (p_B - p_\pi)^2$ instead of $q^2 = (p_l + p_\nu)^2$
- signal and background given by a multi-parameter fit in $\Delta E - m_{ES}$ on **12** signal bins of q^2

206 fb^{-1}





Fit background normalization in bins of q^2

reduces syst. uncertainties due to background modeling

Untagged $B \to \pi \ell \nu$ and $|V_{ub}|$: results

Also measure full covariance matrix of q^2 spectrum, form-factor parameters and test QCD calculations:

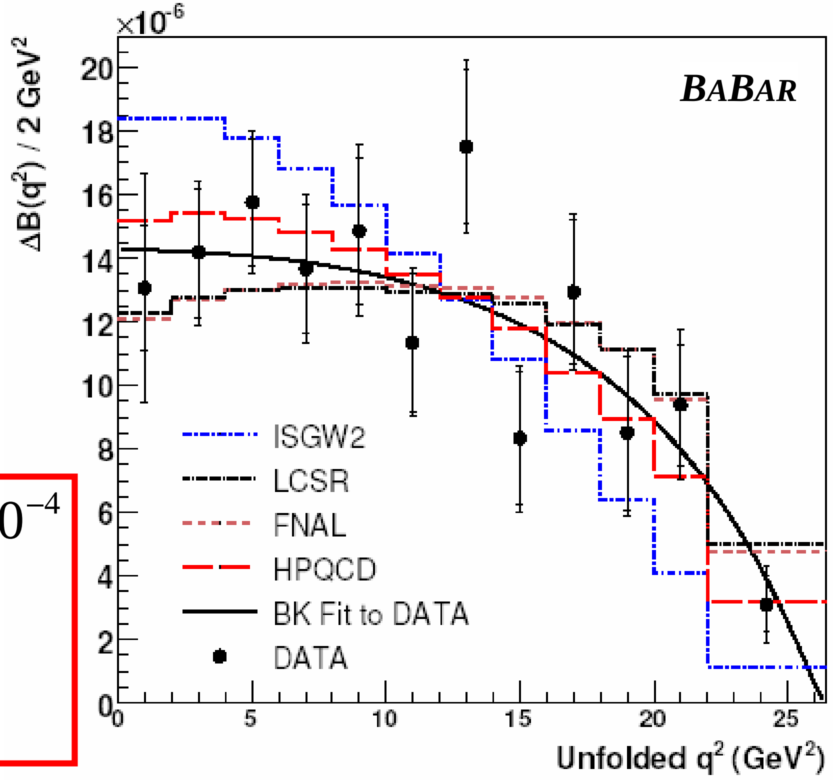
→LQCD and LCSR compatible with our data

→ISGW2 quark-model incompatible (Prob<0.06%).

$$BF(B^0 \to \pi \ell \nu) = (1.46 \pm 0.07_{stat} \pm 0.08_{syst}) \times 10^{-4}$$

$$|V_{ub} f_+(0)| = (9.6 \pm 0.3_{stat} \pm 0.2_{syst}) \times 10^{-4}$$

$$\alpha = 0.52 \pm 0.05_{stat} \pm 0.03_{syst}$$



Smallest statistical and systematic uncertainties of all individual $B \to \pi l \nu$ measurements to date!

	q^2 (GeV^2)	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
HPQCD [3]	> 16	1.46 ± 0.35	$4.1 \pm 0.2 \pm 0.2\ ^{+0.6}_{-0.4}$
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ISGW2 [6]	0–26.4	9.6 ± 4.8	$3.2 \pm 0.1 \pm 0.1\ ^{+1.3}_{-0.6}$

Other channels $B \to (\eta, \eta', \rho, \omega)\ell\nu$

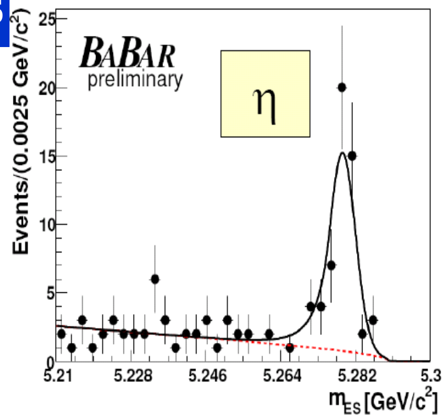
315 fb^{-1}

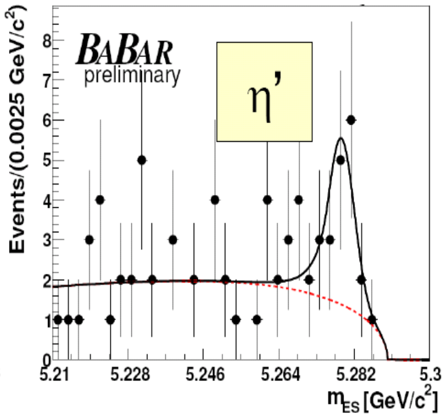
- $B \to (\eta, \eta')\ell\nu$ with hadronic tag **hep-ex/0607066**
- same technique of $B \to \pi\ell\nu$
- meson reconstructed in

  $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0, \pi^0\pi^0\pi^0$

  $\eta' \to \rho\gamma, \eta\pi^+\pi^-$

  VERY LOW statistics!





$\mathcal{BR}(B^+ \to \eta\, l^+\nu) < 1.4 * 10^{-4}$ (90% *CL*)

$\mathcal{BR}(B^+ \to \eta'\, l^+\nu) < 1.3 * 10^{-4}$ (90% *CL*)

•Measurements of $B \to (\rho, \omega, \eta)\ell\nu$ on full dataset with different techniques in progress

$B \to \rho l \nu$:

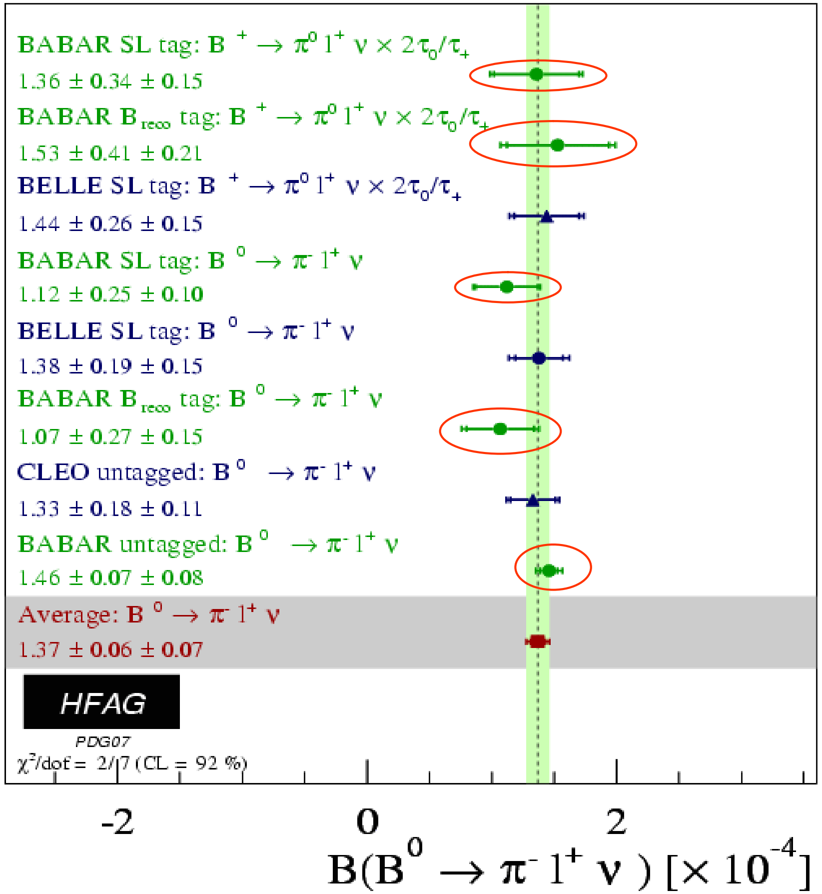
- In **3 q^2 bins**
- Even with 1/ab, will be difficult to extract the full 4-D $\frac{d\Gamma}{dq^2 d\cos\theta_\ell \cos\theta_V d\chi}$ rate (5^4 bins !)

  Would need help from th. : integrate over the angles ? FF ratios ?

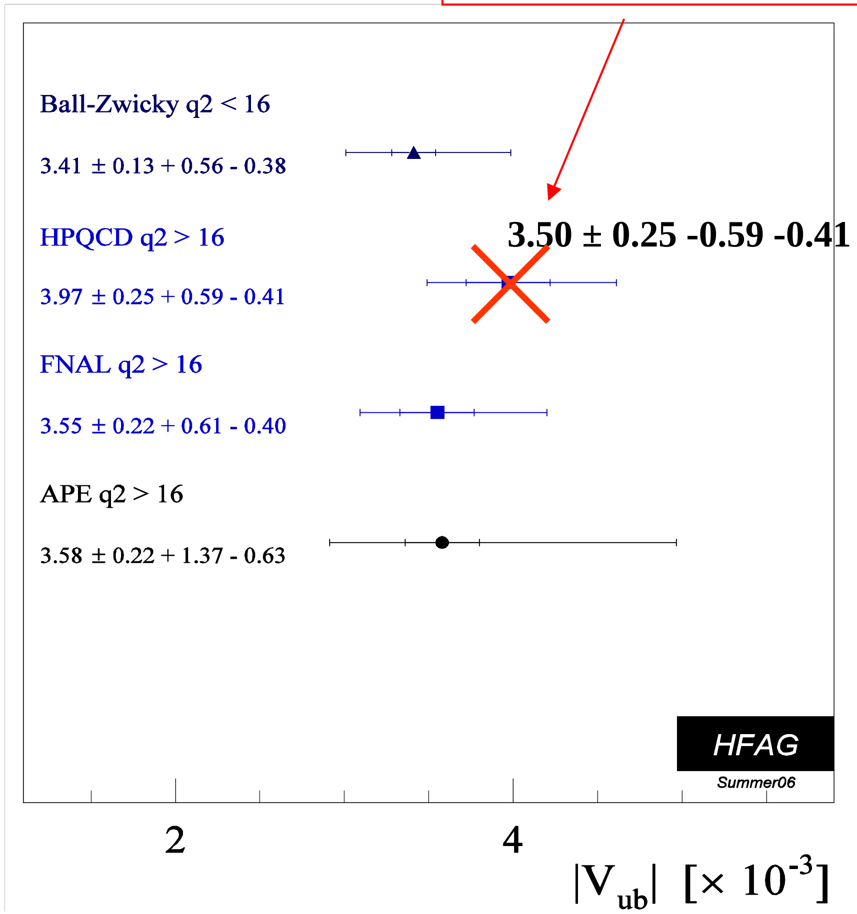
These measurements will yield a nice improvement of the experimental knowledge of these channels. Theoretical progress needed to fully take advantage of this ($|V_{ub}|$ extraction, constraints on FF,...)

- Existing model: Ball-Zwicky [3] (not for η') ; Nothing (?) from LQCD...

Status of exclusive $|V_{ub}|$



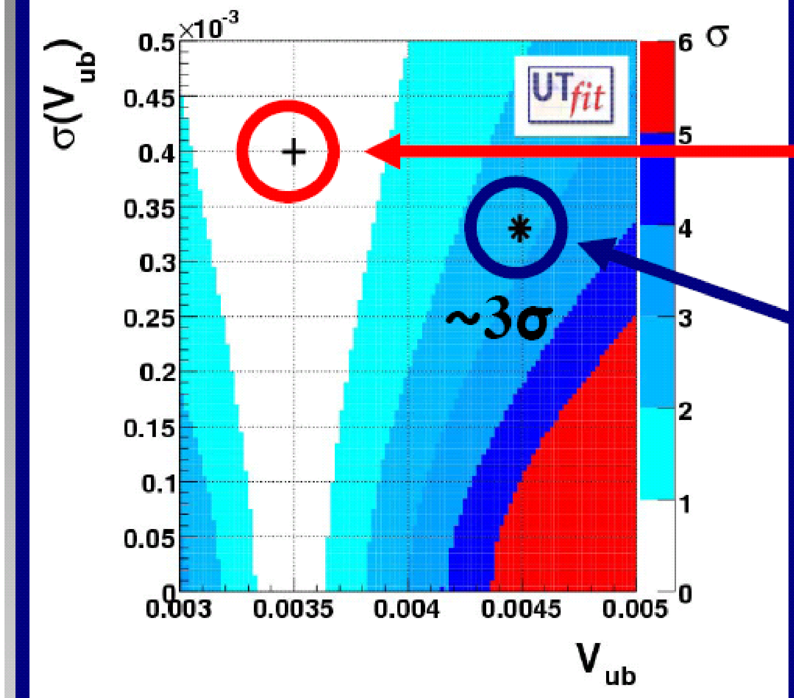
PRD Erratum 75:119906(2007)



Considering only statistical error, actual $BR(B \to \pi \ell \nu)$ measurement can determine $|V_{ub}|$ with a precision of ~ 2.2%

Currently error for exclusive $|V_{ub}|$ dominated by FF normalization uncertainty ~10-12%

$B \to X_u \ell \nu$ and $|V_{ub}|$ puzzle



EXCLUSIVE

$V_{ub}^{excl.} = (35.0 \pm 4.0)\ 10^{-4}$

Form factors from LQCD and QCDSR

INCLUSIVE

$V_{ub}^{incl.} = (44.9 \pm 3.3)\ 10^{-4}$

Model dependent (BLNP, DGE,..)
Non perturbative parameters most not from LQCD (fitted from experiments)

A New Physics effect is unlikely in this tree-level process

➡ i) Statistical fluctuation

ii) Problem with the theoretical calculations and/or the estimate of the uncertainties

Improve $|V_{ub}|$ exclusive to solve the tension

Future experiments

- future B physics program 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!

Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
V_{ub}| (exclusive)	8% (*)	3.0%
V_{ub}| (inclusive)	8% (*)	2.0%

Conclusions

✓Lot of work done on the experimental and theoretical side

✓Many different methods on how to suppress the background

✓Many different theoretical calculation

✓Big progress in both measurement and interpretation of $B \to X_u \ell \nu$ in the last 2 years

✓ Inclusive $|V_{ub}|$ achieved ±7.4% accuracy

✓Exclusive $B \to \pi \ell \nu$ measurement has reached an experimental precision of 5% for the full q^2 range but… theoretical uncertainties are dominant

✓Improved FF calculation needed: **Uncertainty on exclusive $|V_{ub}|$ ~10-12% dominated by theory!**

✓Statistics alone will not be enough but it will help

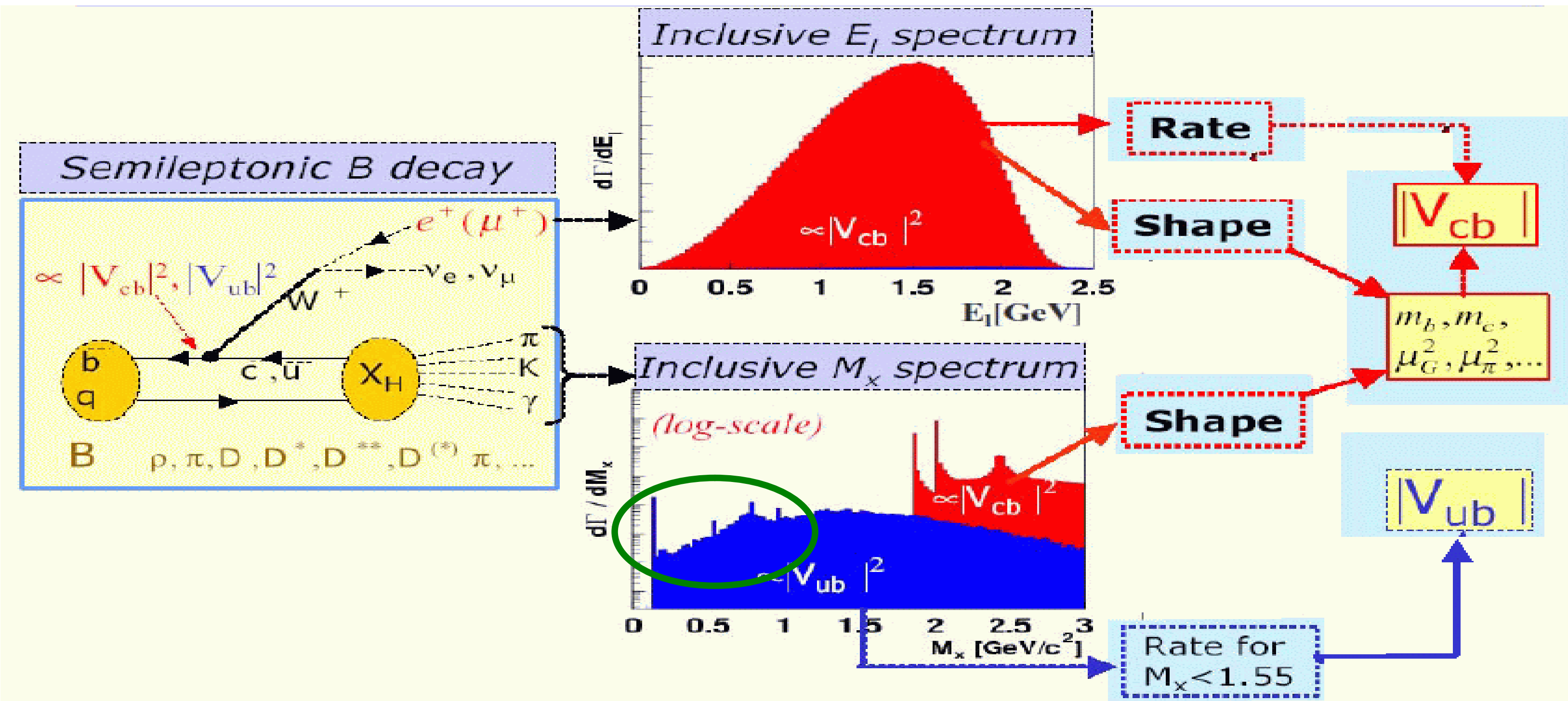
✓Inclusive: SF parameters, weak annihilation constraint, $b \to c \ell \nu$ and $b \to u \ell \nu$ modelling

✓Exclusive: FF shape

we could reach total error of ≈ 2% / 3% in incl / excl Vub in the "next" future…

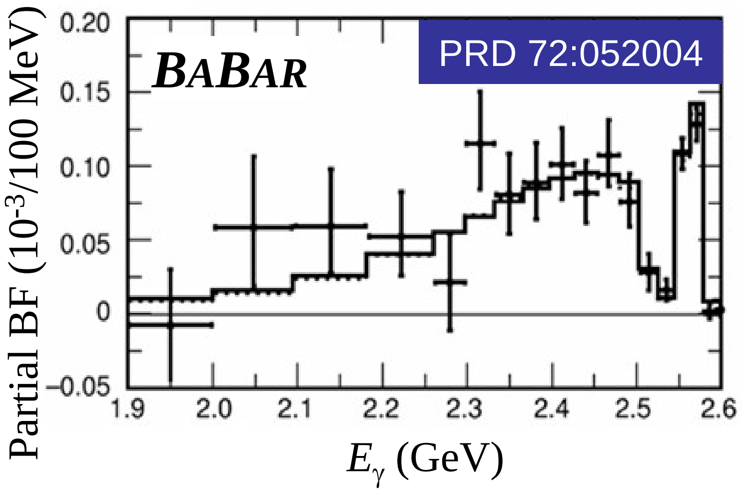
Backup Slides

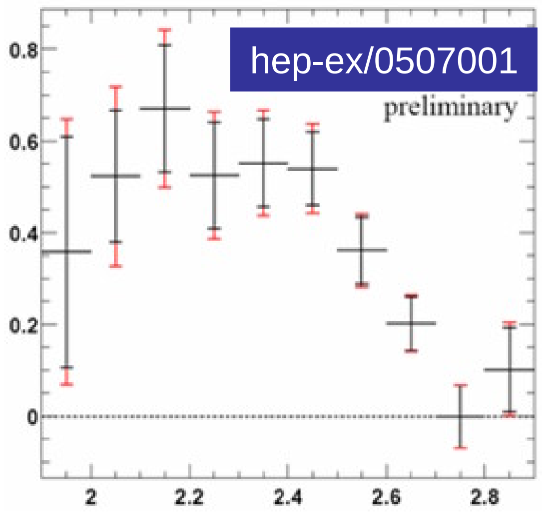
Semileptonic B decays: the "Big Picture"



Global OPE fit

- OPE predicts total rate Γ_c and moments $\langle E_\lambda{}^n \rangle$, $\langle m_X{}^n \rangle$ as functions of $|V_{cb}|$, m_b, m_c, and several non-perturb. params
  - Each observable has different dependence
    ➔ Can determine all parameters from a global fit
- E_γ spectrum in $B \to X_s \gamma$ decays connected directly to the SF
  - Small rate and high background makes it tough to measure
  - Measured by *BABAR*, Belle, CLEO





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	EPJ C45:35

- Buchmüller & Flächer (hep-ph/0507253) fit data from 10 measurements with an OPE calculation by Gambino & Uraltsev (Eur. Phys. J. C34 (2004) 181)
  - Fit parameters: $|V_{cb}|$, m_b, m_c, μ_π^2, μ_G^2, ρ_D^3, ρ_{LS}^3, $BR(B \to X_c \lambda \nu)$

±2% → $$|V_{cb}| = (41.96 \pm 0.23_{\text{exp}} \pm 0.35_{\text{OPE}} \pm 0.59_{\Gamma_{sl}}) \times 10^{-3}$$

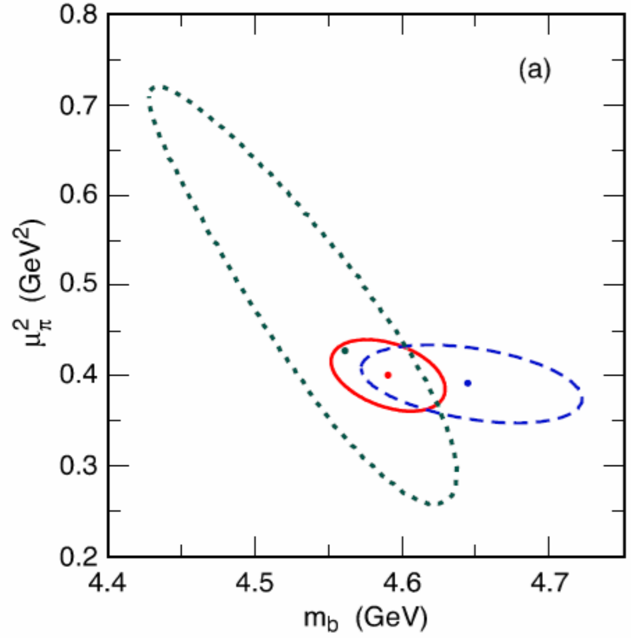
±1% → $$m_b = 4.590 \pm 0.025_{\text{exp}} \pm 0.030_{\text{OPE}}\ \text{GeV}$$

$$m_c = 1.142 \pm 0.037_{\text{exp}} \pm 0.045_{\text{OPE}}\ \text{GeV}$$

$$\mu_\pi^2 = 0.401 \pm 0.019_{\text{exp}} \pm 0.035_{\text{OPE}}\ \text{GeV}^2$$

$$BR = 10.71 \pm 0.10_{\text{exp}} \pm 0.08_{\text{OPE}}\ \%$$

Needed for $|V_{ub}|$



  - Goodness of the fit and the consistency between $X_c \lambda \nu$ and $X_s \gamma$ add confidence to the theory

Getting $|V_{ub}|$ from the partial rate

"traditional" theoretical calculations

- Take your favorite theory calculation and convert the partial rates into $|V_{ub}|$:

OPE gives good results for full phase space but break down in the "SF region" (low M_X and low q^2)

$$BR(B \to X_u l \nu) = \frac{\Delta BR}{f_u(m_b, \Lambda^{SF}, \lambda_1^{SF})}$$

$$|V_{ub}| = \sqrt{\frac{\Delta BR}{\Delta\zeta(\Lambda^{SF}, \mu_\pi^{2\,SF}) \cdot \tau_B}}$$

Predicted rate

various approaches to solve the problem

- **DFN** (De Fazio, Neubert) → **HQE with ad-hoc inclusion of SF** **JHEP9906:017(1999)**
- **BLNP** (Bosch, Lange, Neubert, Paz) → **HQE with systematic incorporation of SF** **PRD72:073006(2005)**

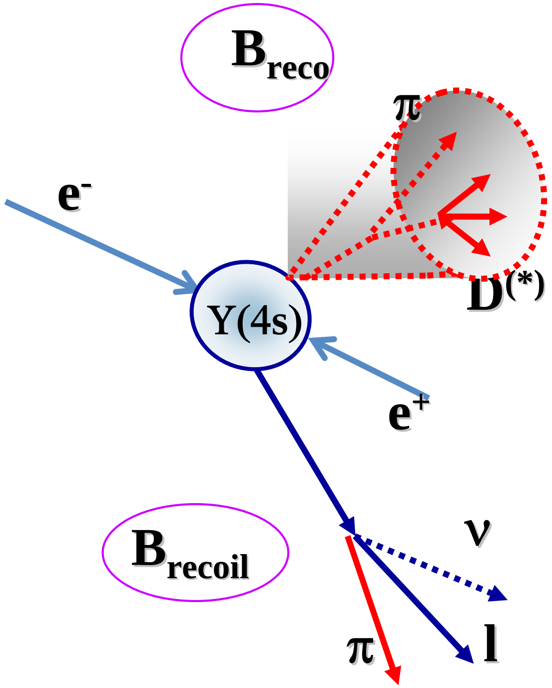
  Handle SF region by introducing a parameterization
  - Shape function form is unknown -> assume form
  - Shape function moments are related to HQE parameters (m_b, μ_π^2) -> can be measured
  - Leading shape functions universal in b->clv, b->ulv, b->sγ
  - Subleading shape functions depend on decay
- **BLL** (Bauer, Ligeti, Luke) → **HQE for $m_X < m_D$ and $q^2 > 8$ ('non SF region') to minimize SF effect**
  - Residual dependence on SF effects
  - Only depend on m_b

  PRD64:113004(2001)
- **DGE** (Anderson,Gardi) → **use "Dressed Gluon Exponentiation" to convert on-shell b quark calculation into meson decay spectra**
  - Only depend on m_b

  JHEP0601:097(2006)

Fully hadronic tag

Aim is to collect as many as possible fully reconstructed B mesons in order to study the property of the recoil.

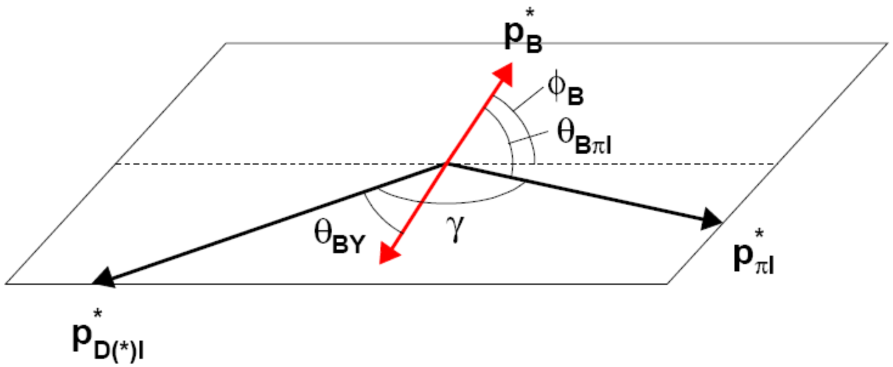


$\varepsilon_{\text{had. tag}} \sim 0.4\%$

- one B fully reconstructed in hadronic channels :
  $B_{reco} \rightarrow D^{(*)} + (n\pi\ mK\ pK_s\ q\pi^0) \rightarrow$ study the remaining of event
- B_{reco} kinematics well known → constraints for signal B
- B^0 and B^+ decays can be studied separately → reduce combinatorial background / cross-feed
- all visible particles on the events are reconstructed → only one missing ν in the event
- low level of background
  - loose cuts : theoretical extrapolation errors reduced
  - high multiplicity channels and large resonances can be studied
- **clean signal but low statistics**

Definition of $\cos^2\phi_B$

$$\cos^2\phi_B = \frac{\cos^2\theta_{BD^{(*)}l} + \cos^2\theta_{B\pi l} + 2\cos\theta_{BD^{(*)}l}\cos\theta_{B\pi l}\cos\gamma}{\sin^2\gamma}$$



ϕ_B is the angle between the directions of the two B mesons.
Well-reconstructed events with $B_{sig} \rightarrow \pi l \nu$ and $B_{tag} \rightarrow D(*) l \nu$ will have $\cos^2\phi_B \leq 1$.