



# *The Future of $|V_{ub}|$*

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# Motivation



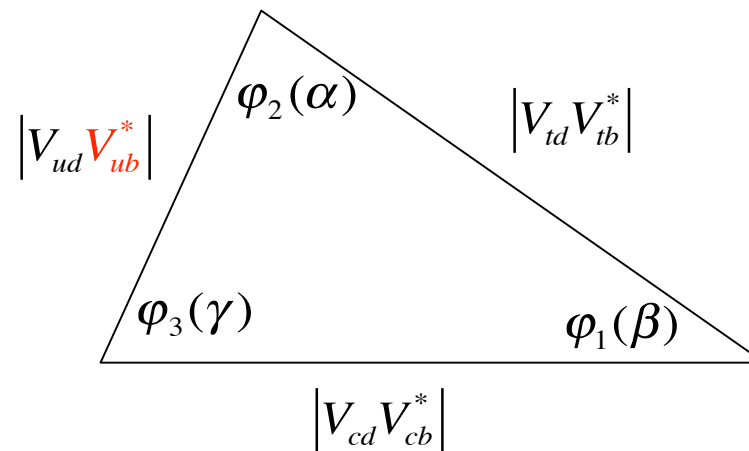
- *Fundamental parameter in SM*

$$\mathcal{L}_{SM} = \dots + g W_{\mu}^{+} \bar{b}_L \gamma^{\mu} V_{ub} u_L + \dots$$

- *CKM mixing matrix element*

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

- *Unitarity Triangle Side-length*



*Directly test the mechanism for CP Violation in SM*



# Measurement type - Inclusive

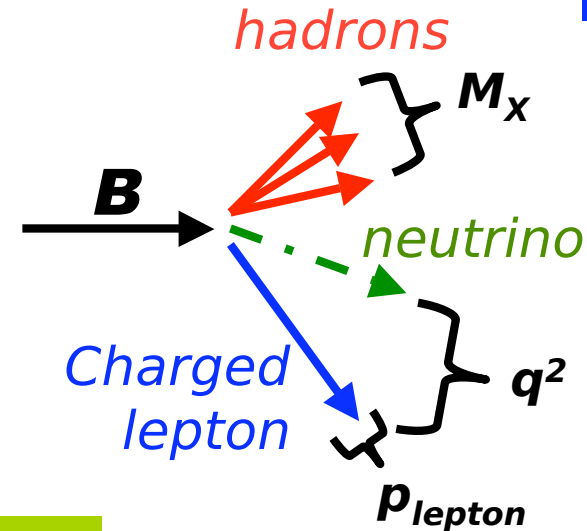


1. Cuts to avoid  $B \rightarrow X_c l \nu$

$$p_l > \frac{(M_B^2 - M_D^2)}{2M_B} \approx 2.3 \text{ GeV}/c \quad (\sim 10\% \text{ phase space})$$

$$q^2 > (M_B - M_D)^2 \approx 11 \text{ GeV}^2/c^2 \quad (\sim 30\%)$$

$$M_X < M_D \approx 1.8 \text{ GeV}/c^2 \quad (\sim 80\%)$$



2. Measure

$$\Delta\mathcal{B}(B \rightarrow X_u l \nu) = \frac{N_{\text{Selected}} - N_{\text{Background}}}{\epsilon}$$

3. Extract  $V_{ub}$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}}{\tau_B} \frac{1}{R}}$$

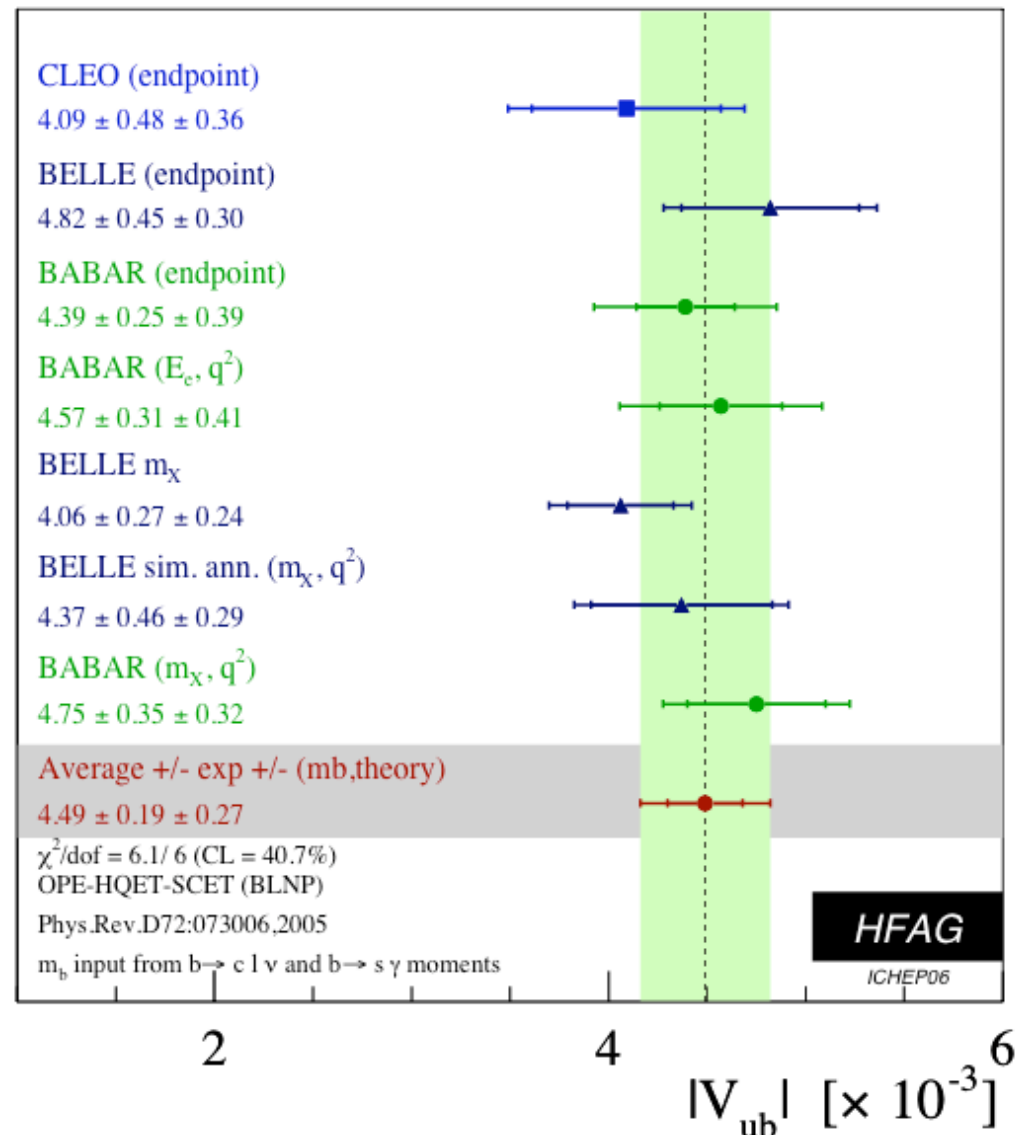
$\tau_B$       average  $B^{0\pm}$  lifetime  
 $\Delta\mathcal{B}$       Partial B.F.  
 $R$         Theory Prediction  
 $R = R_{\text{BLNP}}(m_b, \mu_\pi^2)$



# HFAG $V_{ub}$ Average



Source	Error (%)
Stat	2.2
Exp	2.8
Bkgd model	1.9
Signal model	1.6
HQE: $m_b$	4.2
SSF/matching	3.8
WA	1.9
<b>Total</b>	<b>7.3</b>





# Fully reconstructed B sample



- Dedicated exclusive channels are searched for in reconstruction
  - 180 decay chains
  - Clean environment but small sample
  - Reconstruction Efficiency  $\sim 0.3\%$

## Reconstructed modes

$$B^0 \rightarrow D^{(*)-} \{ \pi^+, \rho^+, a_1^+, D_s^{(*)+} \}$$

$$B^+ \rightarrow D^{(*)0} \{ \pi^+, \rho^+, a_1^+, D_s^{(*)+} \}$$

$$D^{(*)0} \rightarrow D^0 \pi^0$$

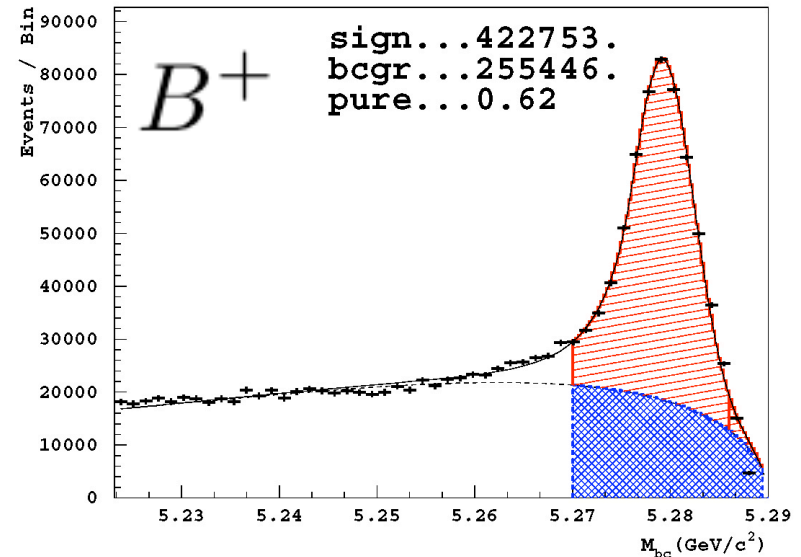
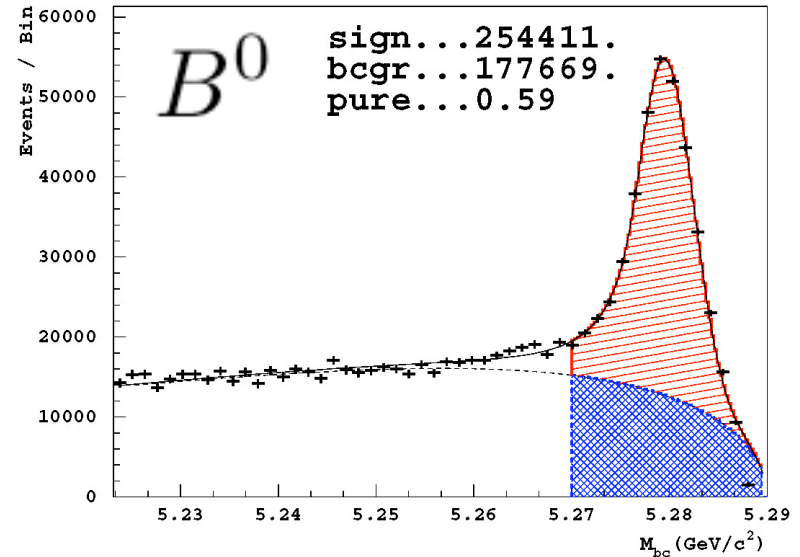
$$D^{(*)+} \rightarrow D^0 \pi^+ / D^+ \pi^0$$

$$D_s^* \rightarrow D_s \gamma$$

$$D^0 \rightarrow K \{ \pi, \pi\pi^0, \pi\pi\pi \} / K_S^0 \{ \pi^0, \pi\pi, \pi\pi\pi^0 \} / KK$$

$$D^+ \rightarrow K \{ \pi\pi, \pi\pi\pi^0 \} / K_S^0 \{ \pi, \pi\pi^0, \pi\pi\pi \} / KK\pi$$

$$D_s \rightarrow K_S^0 K \pi / KK\pi$$





# Fully reconstructed B analysis



- Fully reconstruct the event  $\rightarrow$  4-momenta of both B's are known

$$P(B_{\text{sig}}) = P(\Upsilon(4S)) - P(B_{\text{reco}}) \quad b \rightarrow c$$

- Identify lepton from  $B \rightarrow X l \nu$  on the signal side

- Use Particle ID to reconstruct the hadronic system and calculate

$$P_X = \sum P_{\text{sig.rec.}} - P_{\text{lep}}$$

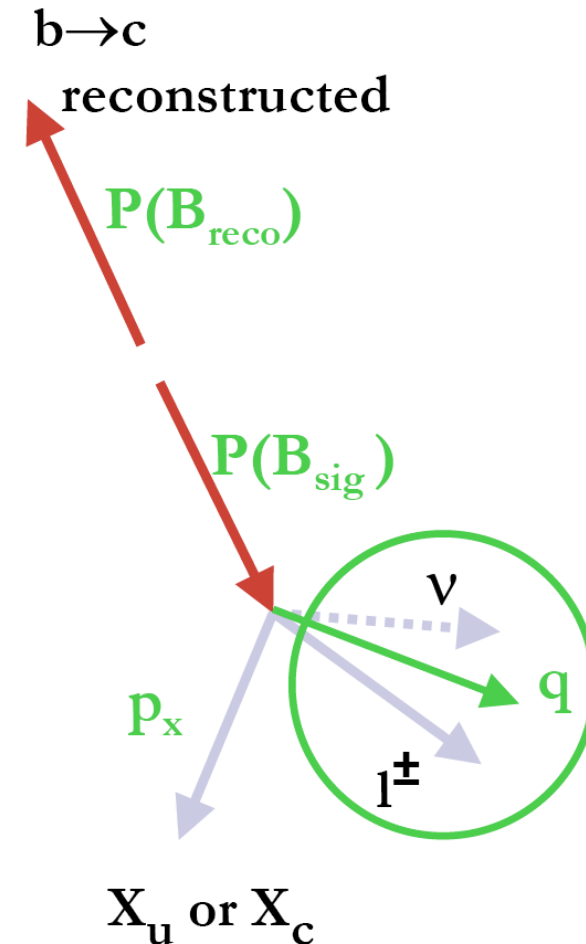
$$M_X^2 = P_X^2$$

$$q^2 \equiv (P_{\text{lep}} + P_\nu)^2 = (P(B_{\text{sig}}) - P_X)^2$$

$$P_+ = E_X - |\vec{p}_X|$$

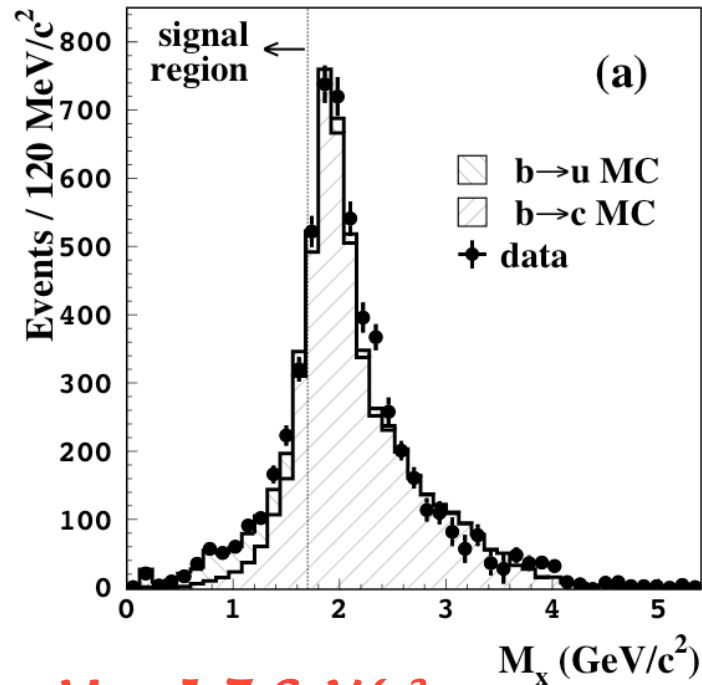
$$M_{\text{miss}}^2 = (q - P_{\text{lep}})^2$$

- Estimate the signal  $B \rightarrow X_u l \nu$

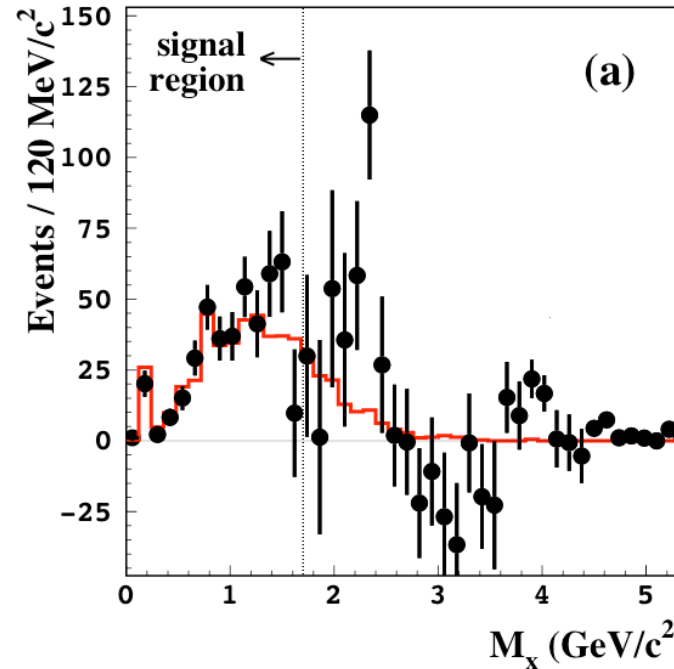




# Belle $M_x$ Analysis @ 253/fb



$M_x < 1.7 \text{ GeV}/c^2$



Phys.Rev.Lett.95:241801,2005 (hep-ex/0505088)

$$\Delta B = (1.24 \pm 0.11(\text{stat}) \pm 0.09(\text{sys}) \pm 0.08(b \rightarrow u) \pm 0.03(b \rightarrow c)) \times 10^{-3}$$

$$V_{ub} = 4.09 \times 10^{-3} (1 \pm 0.049(\text{stat}) \pm 0.035(\text{sys}) \pm 0.031(b \rightarrow u) \pm 0.011(b \rightarrow c) \pm 0.045(\text{SF}) \pm 0.038(\text{theory}))$$



# $M_x$ Analysis : Statistical Error projections



$$\Delta_{stat} = \frac{1}{2} \times \sqrt{\frac{1 + (S/B \times f_{S/B})^{-1}}{n_0 \times f_{freq} \times \epsilon_{b \rightarrow u} \times L}}$$

Luminosity(/ab)	0.25	1.0	5.0	50.0
Signal to Noise	0.65	1.5	2.0	2.0
B tag efficiency	0.3	0.4	0.6	0.6
$ V_{ub} $ stat %	4.9	2.0	0.7	0.2



# $M_x$ Analysis : Systematic & Theory Error projections



Luminosity(/ab)	0.25	1.0	5.0	50.0
Detector simulation	3.5	3.5	3.5	3.5
Background model (charm)	1.1	1.0	0.5	0.5
Signal model	Depends of HQE parameters : b-quark mass, $m_b$ , dominates			
Extrapolating to full branching fraction (SF)				
Theory $ V_{ub} $ : Matching scales, SSF				
Theory/Exp $ V_{ub} $ : Weak Annihilation				
$ V_{ub} $ stat %				



# $M_x$ Analysis : $b$ -quark mass



b-quark mass, $m_b$ (4.60 +/- 0.04) GeV/c <sup>2</sup>				
Luminosity(/ab)	0.25	1.0	5.0	50.0
Exp error: Moments data	0.025	0.02	0.01	0.01
Theory error Vary $\alpha_s, m_b, m_c$	0.03	0.03	0.03	0.03
Total error	0.04	0.04	0.03	0.03

Precision on  $m_b$  hits theory floor!



# $M_x$ Analysis : Systematic & Theory Error projections



Luminosity(/ab)	0.25	1.0	5.0	50.0
Detector simulation	3.5	3.5	3.5	3.5
Background model (charm)	1.1	1.0	0.5	0.5
Signal model	3.1	2.8	2.6	2.4
Extrapolating to full branching fraction (SF)	4.5	4.2	3.9	3.7
Theory $ V_{ub} $ : Matching scales, SSF	3.6	3.6	3.6	3.6
Theory/Exp $ V_{ub} $ : Weak Annihilation	3.0	2.0	1.0	1.0



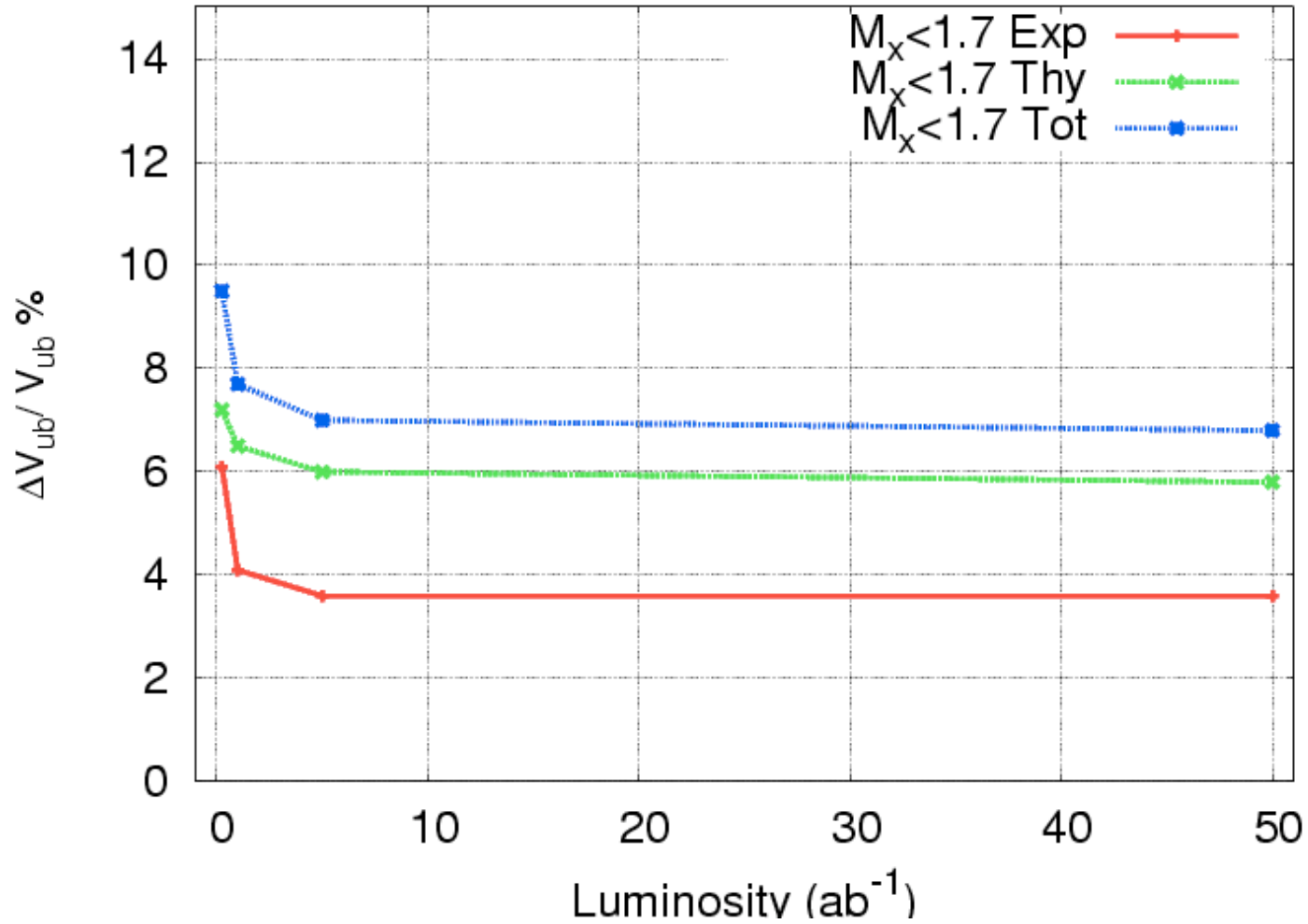
# $M_x$ Analysis : Total Error projections



Luminosity(/ab)	0.25	1.0	5.0	
$ V_{ub} $ total %	9.4	7.7	7.0	6.8
$ V_{ub} $ exp %	6.1	4.1	3.6	3.6
$ V_{ub} $ theory %	7.2	6.5	6.0	5.8



# $M_x$ Analysis : Total Error projections

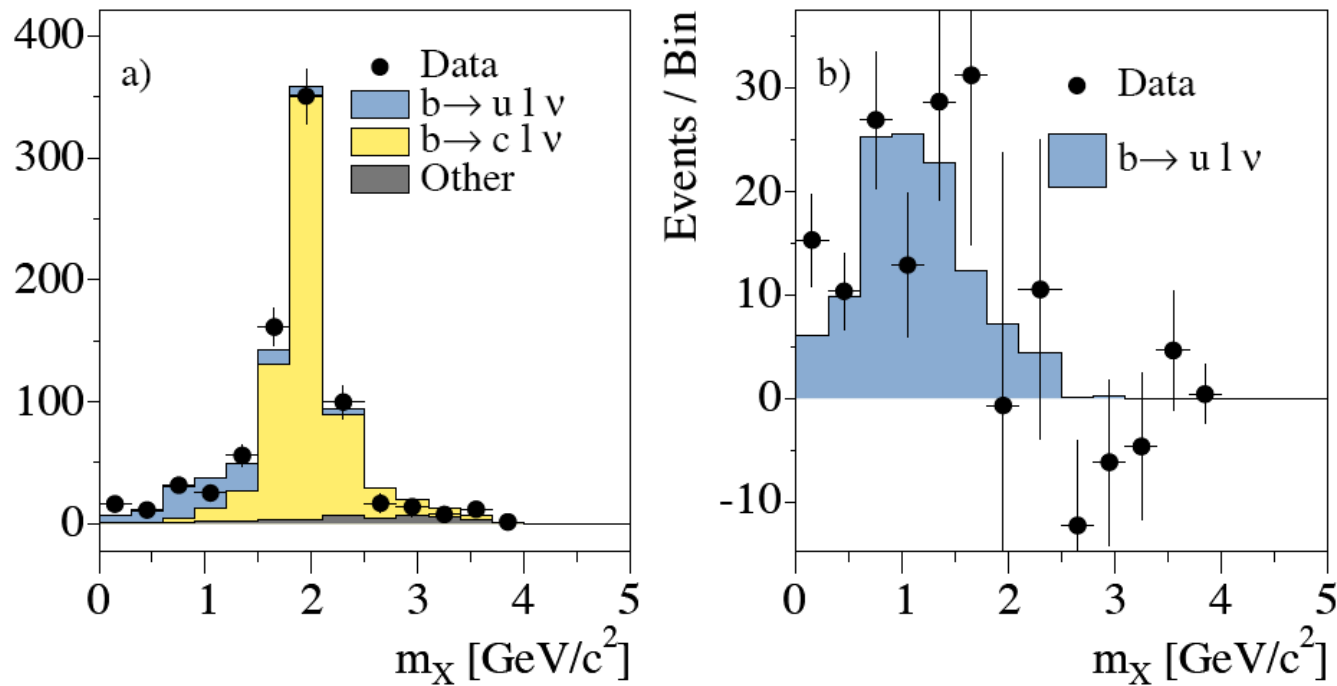




# $V_{ub}$ with Reduced Model dependence



Phys.Rev.Lett. 96 (2006) 221801 (hep-ex/0601046) (BABAR Collaboration)



$M_x < 2.5 \text{ GeV}/c^2$

$$V_{ub} = 3.84 \times 10^{-3} (1 \pm 0.182 \text{ (stat)} \pm 0.036 \text{ (sys)} \\ \pm 0.056 \text{ (b} \rightarrow \text{u)} \pm 0.038 \text{ (b} \rightarrow \text{c)} \\ \pm 0.000 \text{ (SF)} \pm 0.026 \text{ (theory)})$$



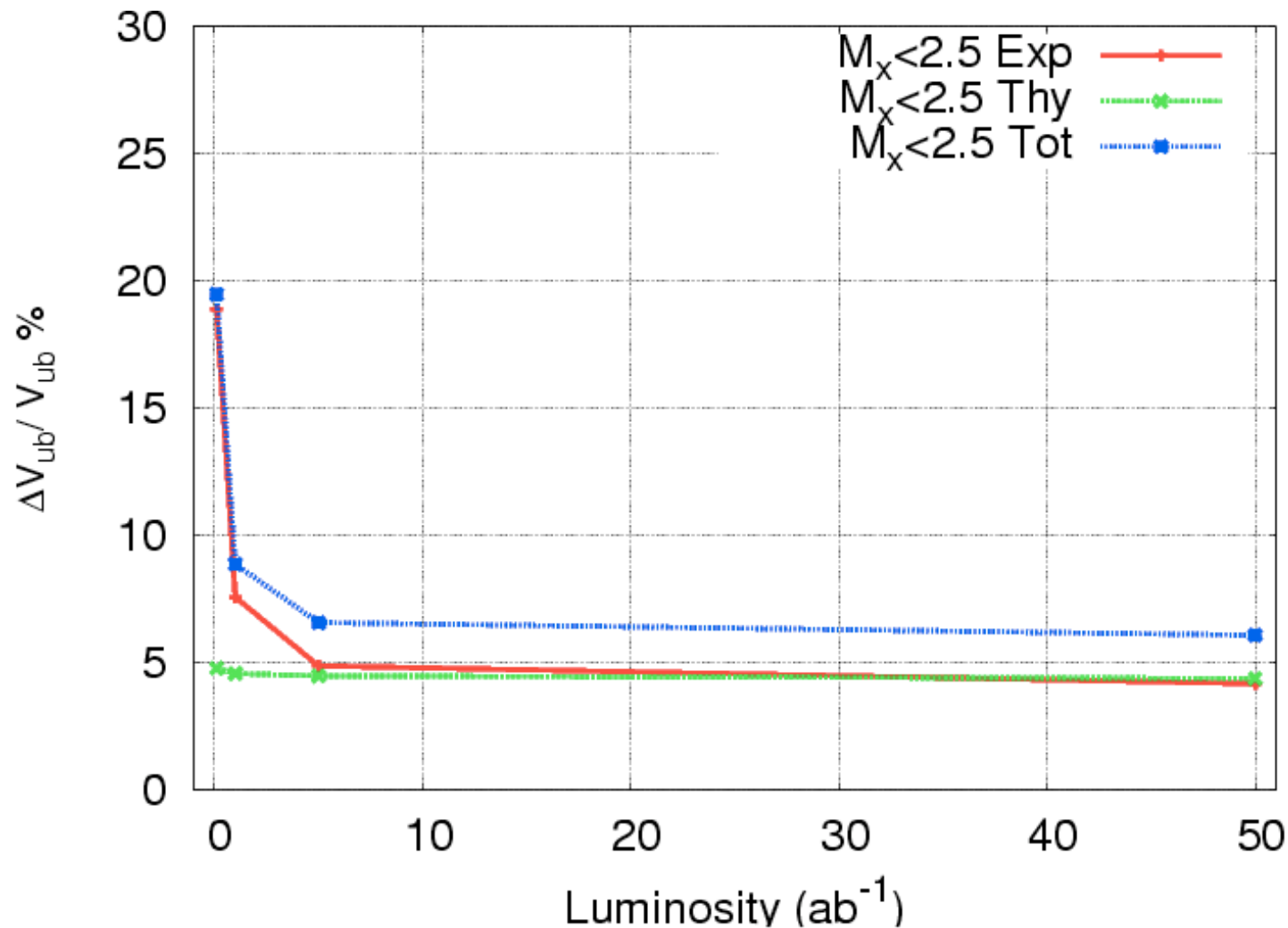
# Error projections



Luminosity(/ab)	0.1	1.0	5.0	50.0
Statistics	18.2	5.7	2.6	0.8
Detector simulation	3.6	3.6	3.6	3.6
Background model (charm)	3.8	3.5	2.0	2.0
Signal model	3.1	2.9	2.7	2.5
Extrapolating to full branching fraction (SF)	0.0	0.0	0.0	0.0
Theory $ V_{ub} $ : Perturbative	3.6	3.6	3.6	3.6
Total	19.5	8.9	6.6	6.1

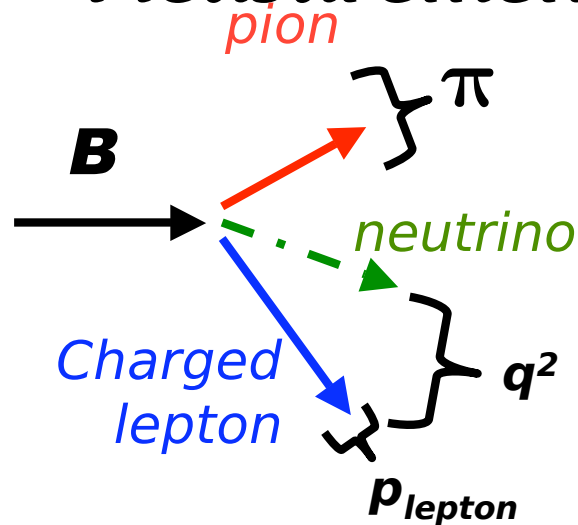


# Error projections





# Measurement types - Exclusive



Experimentally less ambiguous than the inclusive decay

Theoretical description parameterised by a single form factor

$$\frac{dB(B^0 \rightarrow \pi^- l^+ \nu)}{dq^2 d(\cos \theta_{wl})} = |V_{ub}|^2 \tau_{B^0} \frac{G_F^2 k_\pi^3}{32\pi^3} \sin^2 \theta_{wl} |f(q^2)|^2$$

$$|V_{ub}| = \sqrt{\frac{B(B \rightarrow (\pi / \rho) l \nu)}{\tilde{\Gamma}_{thy} \tau_B}},$$

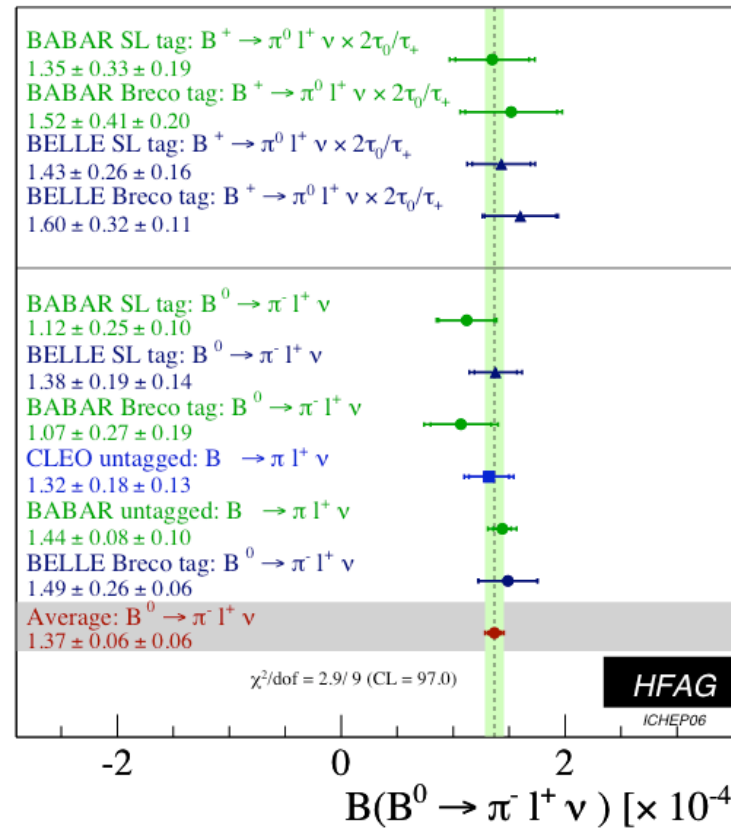
Determine  $\Gamma$  using unquenched lattice QCD calculations.

- Model independent
- Limited to  $q^2 > 16 \text{ GeV}^2/c^2$

$\tilde{\Gamma}_{thy}$  – Form factor normalisation



# Current status - Exclusive



FF calculation	$V_{ub}$ [ $10^{-3}$ ]	$q^2$ range	FF norm ( $\text{ps}^{-1}$ )	Reference
Ball-Zwicky <16 GeV	$3.38 \pm 0.12 +0.56-0.37$	<16 $\text{GeV}^2$	$5.44 \pm 1.43$	<a href="#">Phys. Rev. D71:014015 (2005)</a>
HPQCD >16 GeV	$3.93 \pm 0.26 +0.59-0.41$	>16 $\text{GeV}^2$	$1.46 \pm 0.35$	<a href="#">Phys. Rev. D73:074502 (2006)</a>
FNAL >16 GeV	$3.51 \pm 0.23 +0.61-0.40$	>16 $\text{GeV}^2$	$1.83 \pm 0.50$	<a href="#">hep-lat/0409116</a>
APE >16 GeV	$3.54 \pm 0.23 +1.36-0.63$	>16 $\text{GeV}^2$	$1.80 \pm 0.86$	<a href="#">Nucl. Phys. B 619 (2000) 565-587</a>



# $V_{ub}$ from $\Delta B(B \rightarrow \pi l \nu: q^2 > 16)$



## Three methods

1. *Untagged: Systematic error 4% @ 0.2ab<sup>-1</sup> (BABAR)*
  - *Previous to this study consensus was one couldn't get lower than 8%*
2. *Semileptonic tag : Systematic error 10% @ 0.25ab<sup>-1</sup> (Belle)*
  - *Systematic dominated by statistics of control sample*
  - *Total error 2.9% @ 5ab<sup>-1</sup> and 2.1% @ 50ab<sup>-1</sup>*
3. *Full B reconstruction tag : Systematic error 2.1% @0.5ab<sup>-1</sup> (Belle)*
  - *Total error : 40% @0.5ab<sup>-1</sup> (statistics dominated)*
  - *Total error : 27% @1.0ab<sup>-1</sup>*
  - *Total error : 15% @5.0ab<sup>-1</sup> (improvement in full recon efficiency)*
  - *Total error : 5% @50ab<sup>-1</sup>*

## Theoretical uncertainties (Lattice QCD)

[Phys. Rev. D73:074502 \(2006\)](#)

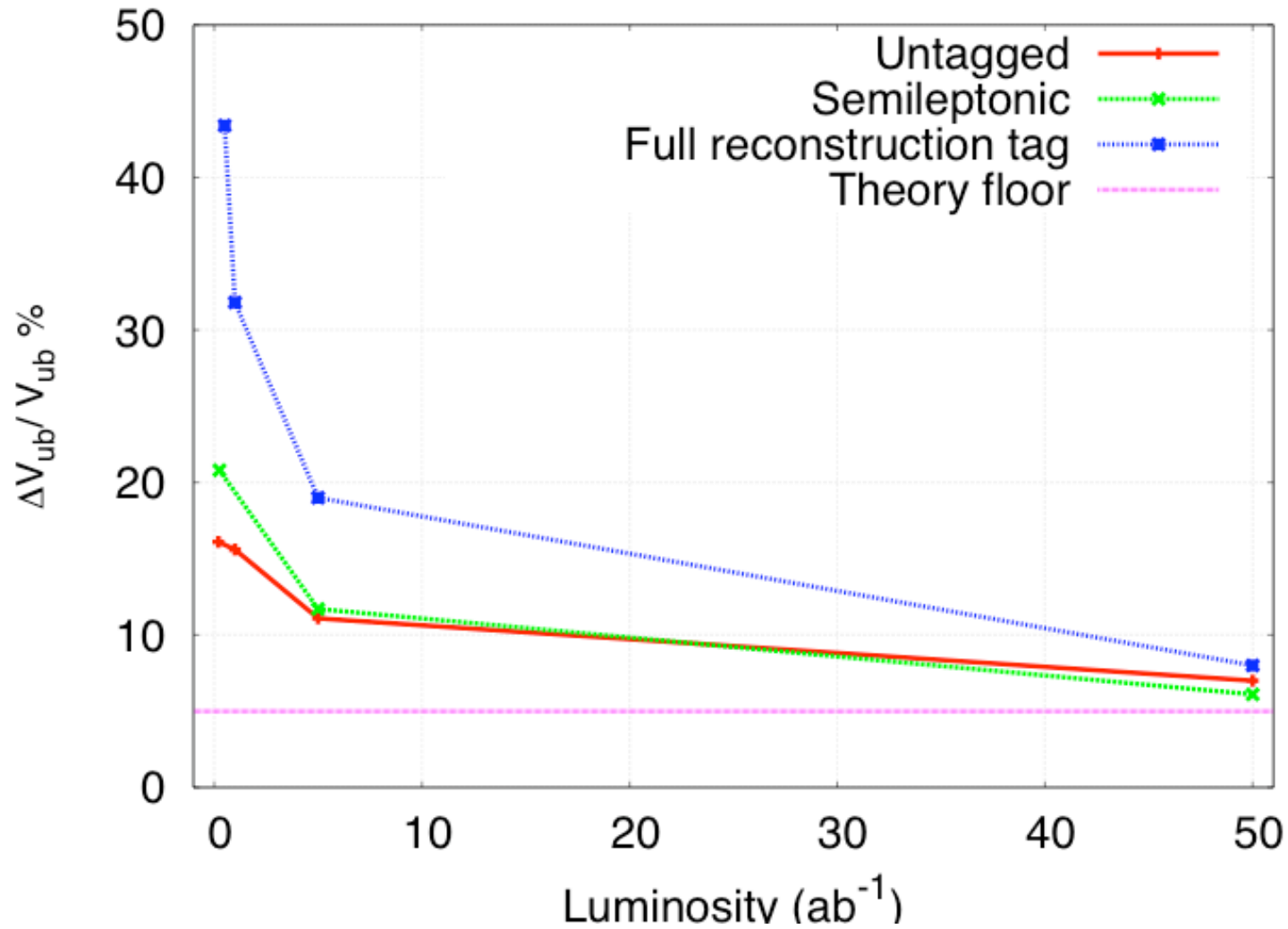
*Currently error is at 12%, but it's anticipated that it will reach 5%.*

TABLE VI. Estimate of percentage errors in  $f_+(q^2)$  for  $q^2 > 16 \text{ GeV}^2$ .

Source of error	Size of error (%)
Statistics + chiral extrapolations	8
Two-loop matching	9
Discretization	3
Relativistic	1
Total	12



# Future of Exclusive $V_{ub}$





# *Future of $V_{ub}$*



- Tagged analyses are essential
- At logged luminosities of  $5/\text{ab}$  and  $50/\text{ab}$  precision is limited by systematic and theoretical uncertainties  $\sim 5\%$
- Co-ordinated experimental and theory studies are needed to reduce this error further
  - b-quark mass



# *Backup Slides*

