Exclusive (Semi) Leptonic Decays at Belle

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On Behalf of the Belle Collaboration

EPS Grenoble
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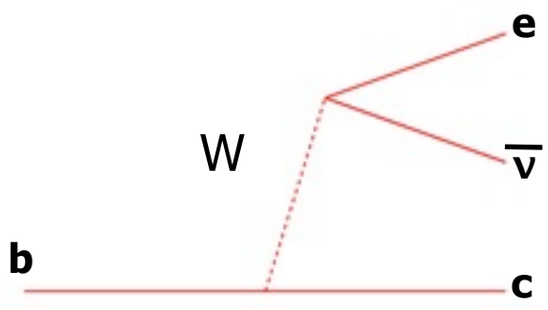
CKM Element Magnitudes

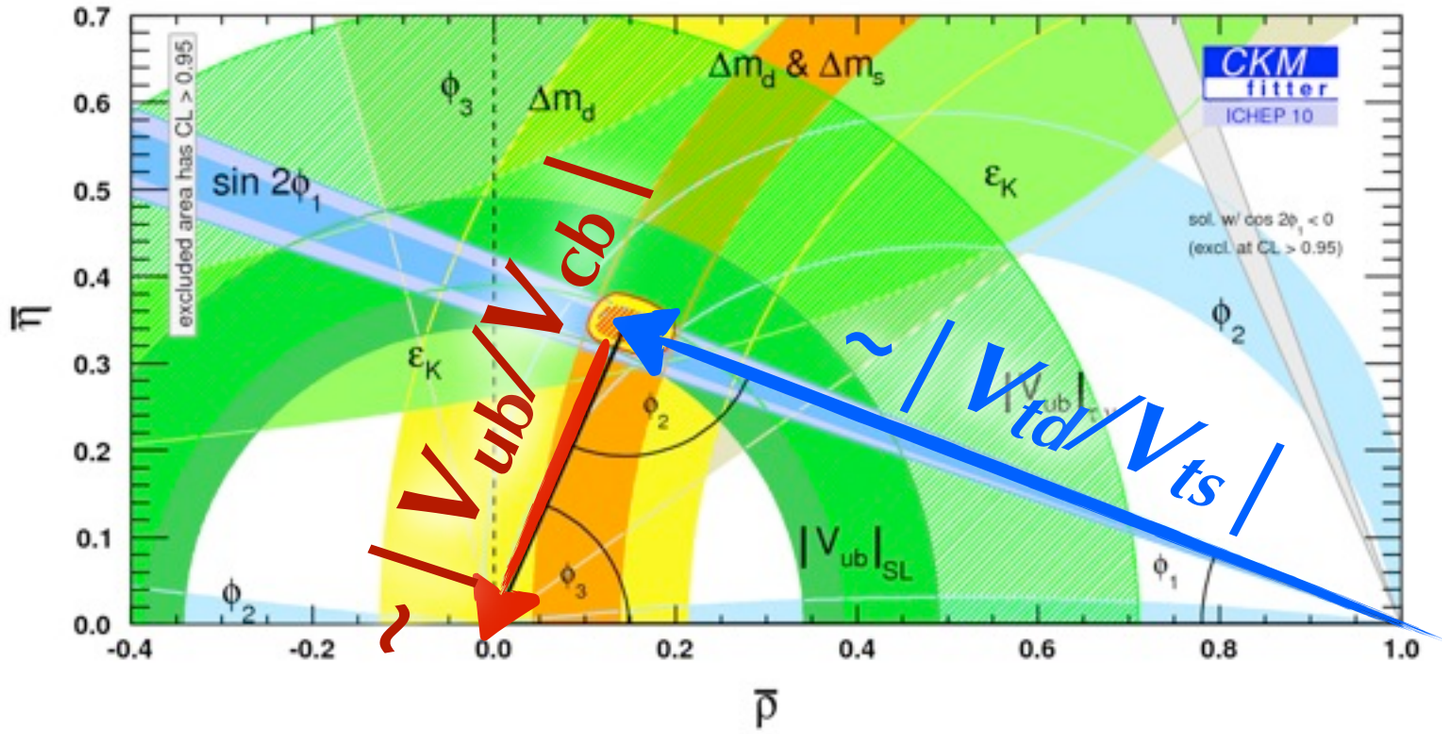
CKM matrix elements are **fundamental** parameters of the Standard Model and cannot be predicted.

Exploit unitarity constraint to look for new physics → angle from CP asymmetries and size from $|V_{CKM}|$.

$|V_{ub}|$ and $|V_{cb}|$ from semileptonic B decays

$b \rightarrow c\, e\, \nu$





Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b in perturbative regime (α_s^n).

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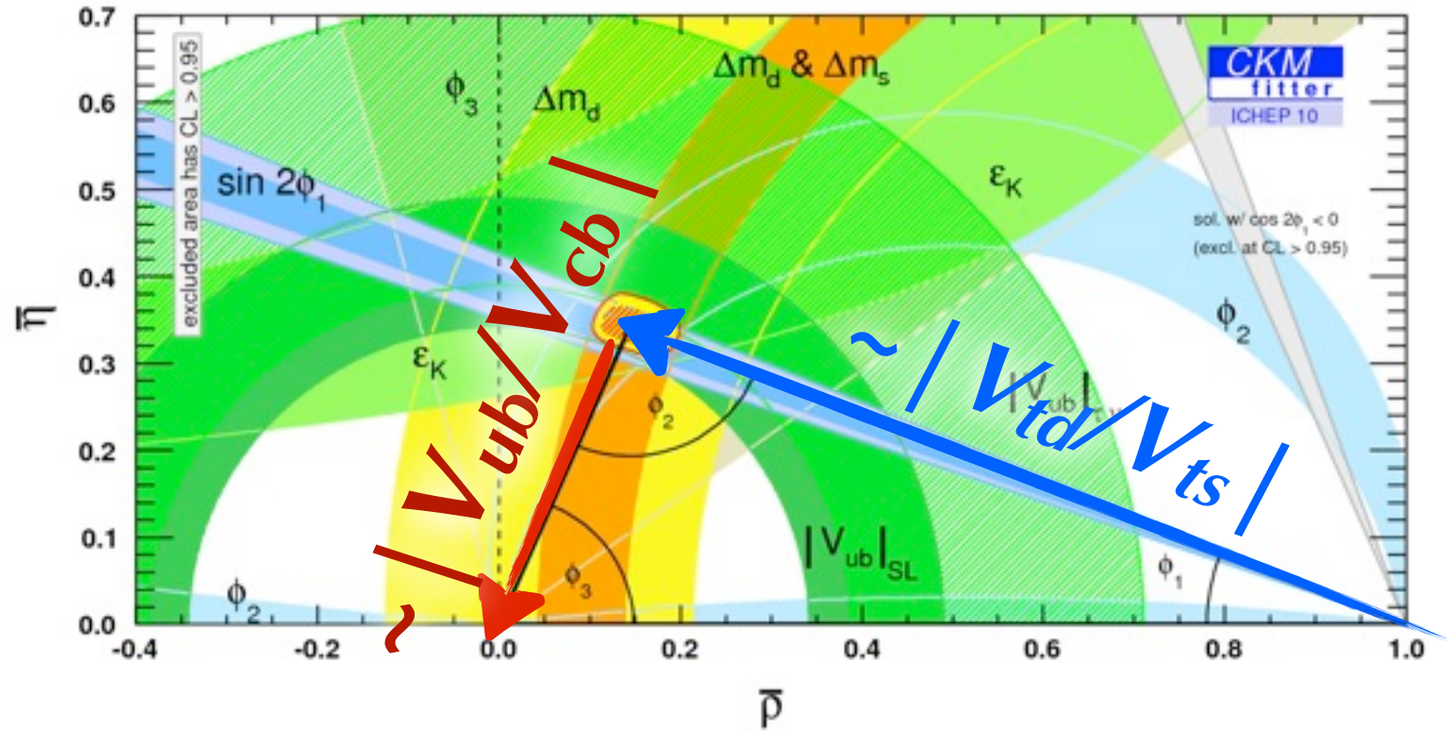
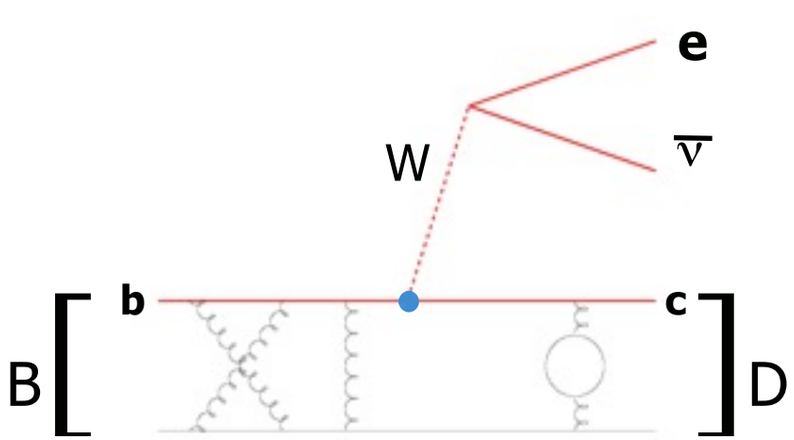


B → D e ν



Decay properties depend directly on $|V_{cb}|$ & $|V_{ub}|$ and m_b in perturbative regime (α_s^n).

But quarks are bound by soft gluons: non-perturbative long distance interactions of *b* quark with light quark.

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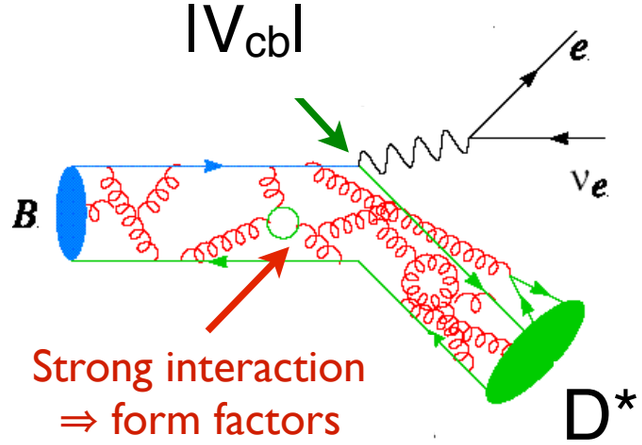
Exclusive decays: $B \to D^{(*)} l \nu$

- Differential decay rate proportional to $|V_{cb}|^2$ and form factors.

$$\frac{d\Gamma(B \to D^* \ell \nu)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 m_{D^*}^3 (w^2-1)^{1/2} P(w) \mathcal{F}(w,\ldots)^2$$

$$\mathcal{F}(w) \Rightarrow \mathcal{F}(w, \cos\theta_\ell, \cos\theta_V, \chi, R_1, R_2, \rho^2)$$

$$w \equiv v_B \cdot v_{D^{(*)}} = \frac{p_B \cdot p_{D^{(*)}}}{m_B \cdot m_{D^{(*)}}} : D^{(*)} \text{ boost}$$



- Fit angular distributions θ_{lep}, θ_V, χ to determine form factors R_1, R_2 ρ^2

From experiment

$|V_{cb}|$ x F.F. @w=1 (0 recoil)

ρ_D, ρ_{D^*} (F.F. slopes)

From Lattice (Non-perturbative input)

F(1)=0.908±0.017, **PoS Lattice2010:311(2010)**

New lattice result reduces discrepancy with $|V_{cb}|$ inclusive

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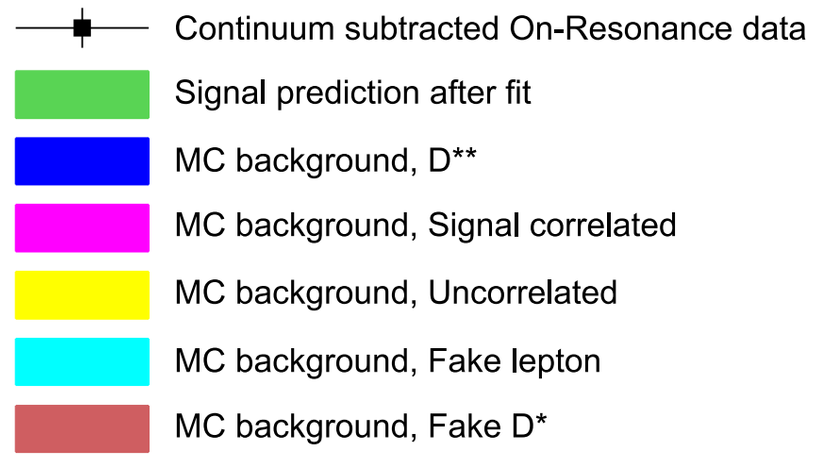
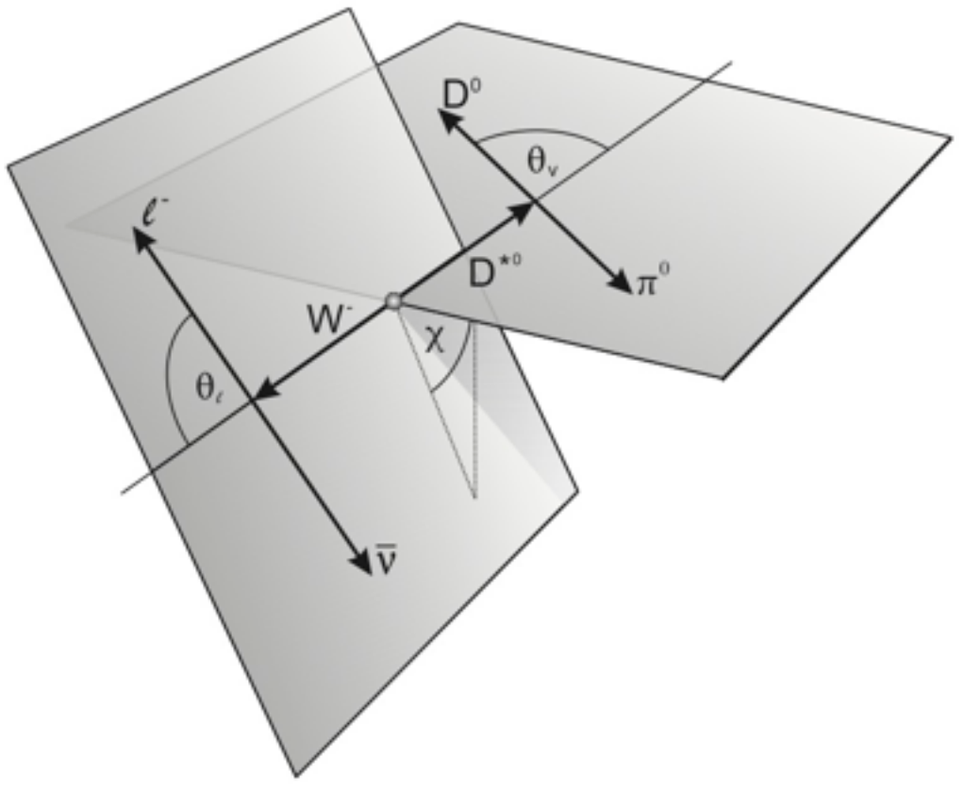
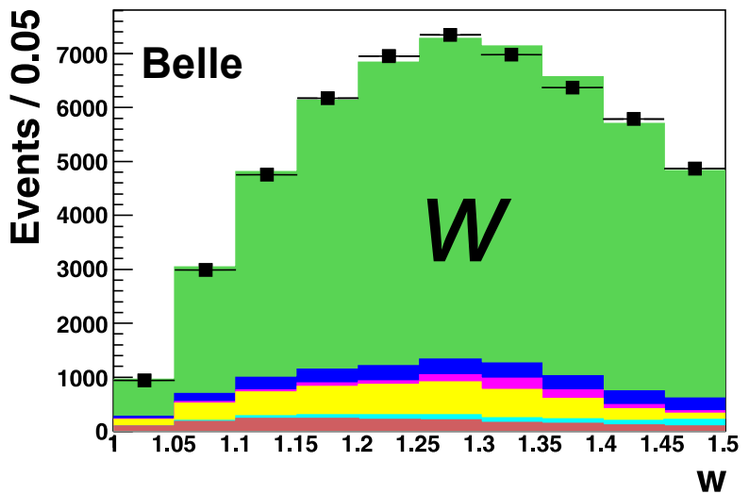
$B^0 \to D^{*-} l^+ \nu$

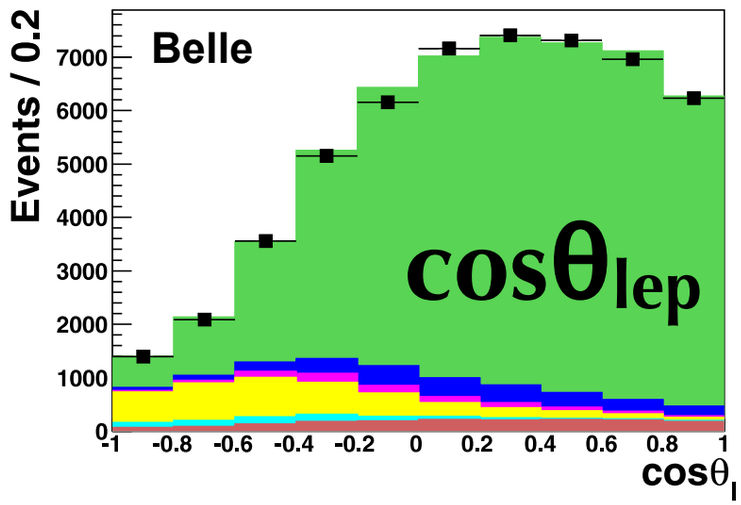
- **772M BBbar** events, **123K D^{*-} l^+** candidates
- FF pars determined from fit to 1D hists (10 bins) of ***w*, $\cos\theta_{lep}$, $\cos\theta_V$, χ**
- 40x40 covariance input to $F(1)|V_{cb}|$ fit

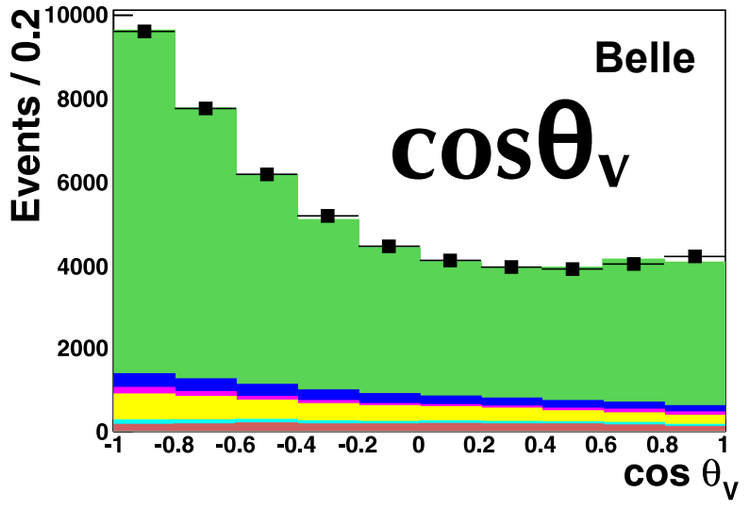


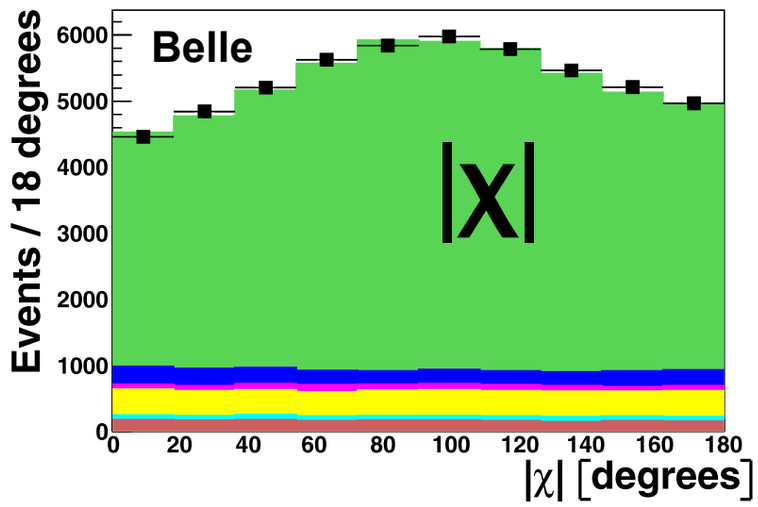
PRD 82, 112007 (2010)











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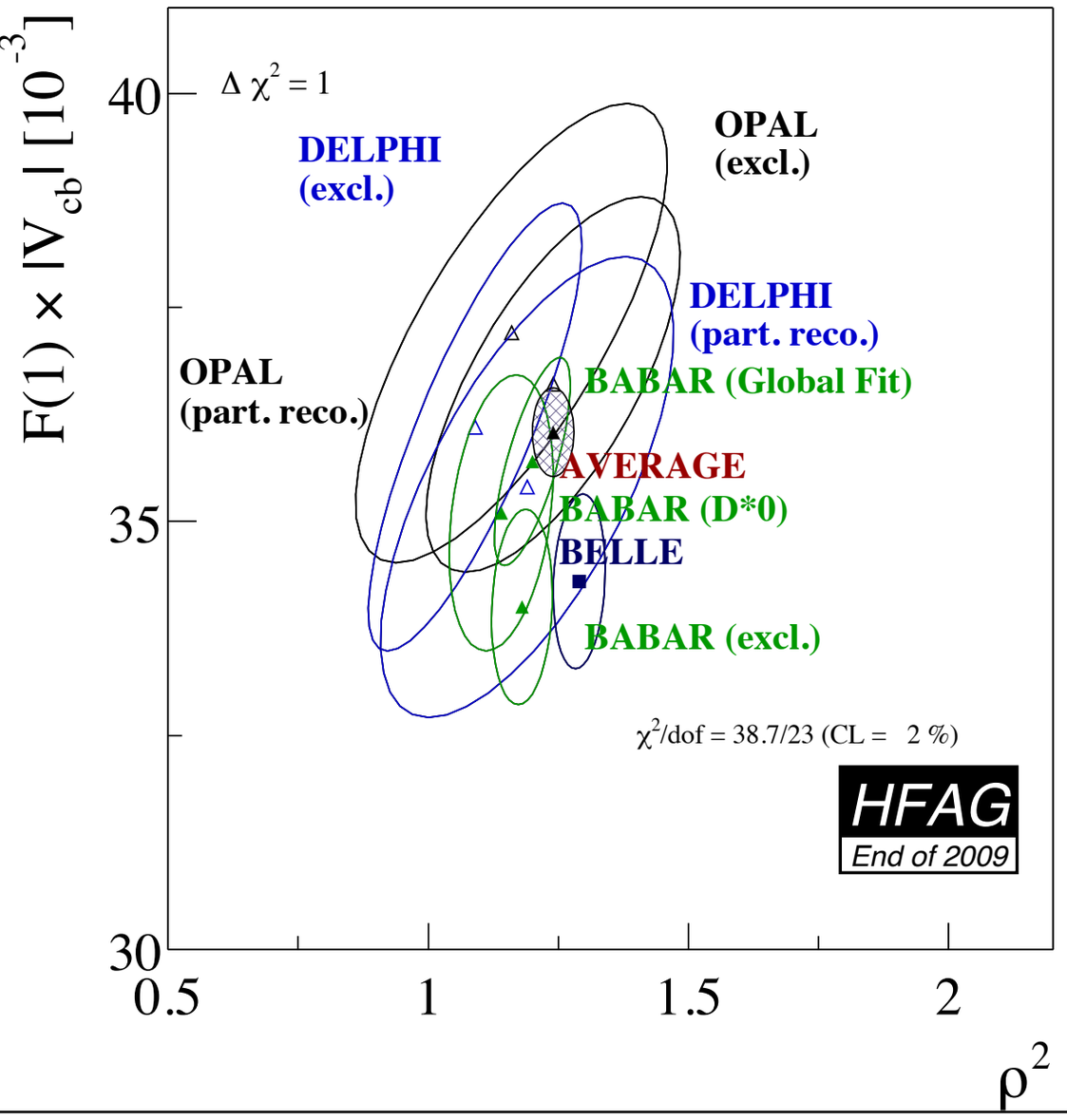
$B^0 \to D^{*-} l^+ \nu$

- Results of 4-parameter HQET fit.
- First determination of G^L, and G^T (helicity functions)
- Sensitive to slow π reco. and **D**** modelling.

772M BBbar **PRD 82, 112007 (2010)**

ρ^2	1.214±0.034±0.009
$R_1(1)$	1.401±0.034±0.018
$R_2(1)$	0.864±0.024±0.008
$BR(\%)$	4.58±0.03±0.26
$F(1)\lvert V_{cb}\rvert$	34.6±0.2±1.0
χ^2/dof	138.8/155



⇨**Belle**

$|V_{cb}| = (38.0 \pm 0.2 \pm 1.1 \pm 0.7(FF)) \times 10^{-3}$

Δ ~3.5%

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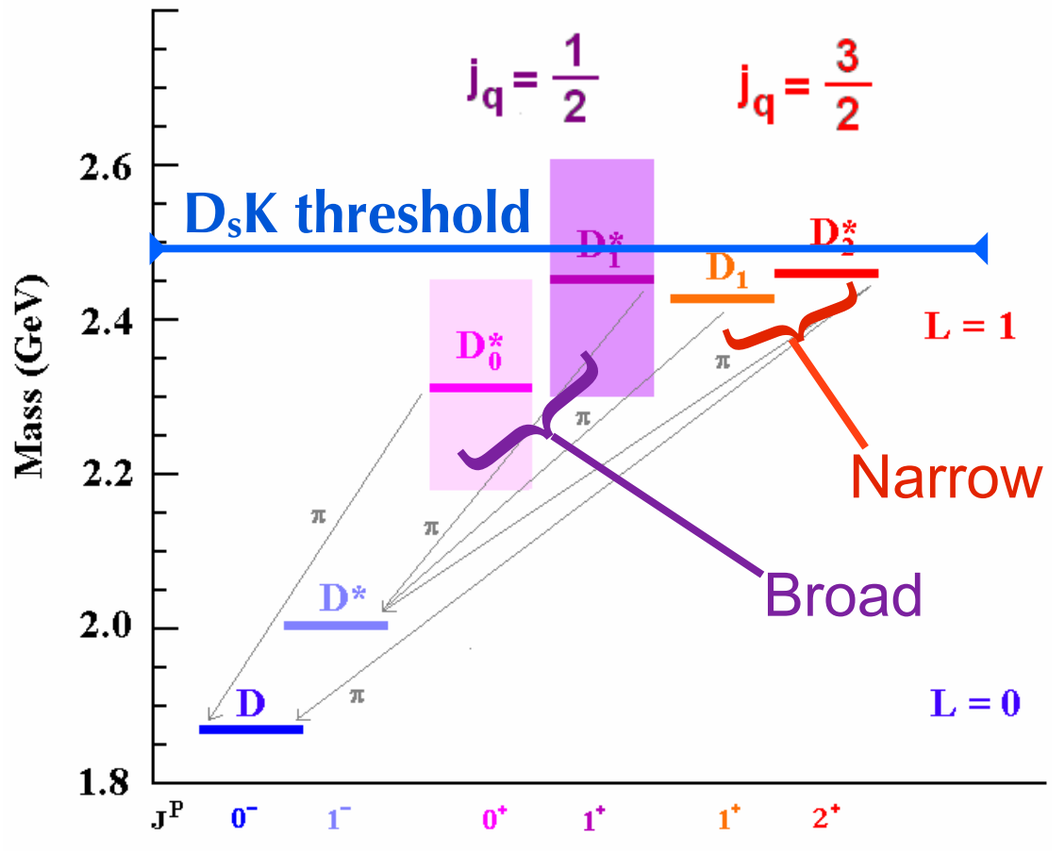
$B \to D_s K l \nu$

- Puzzle: *Measured* sum of exclusive mode BR's **X_c=D+D*+D**** doesn't match inclusive BR (10-15% unaccounted).
  - Explore mass region above $m(D_sK)$=2.46 GeV where **resonant** and **non-resonant** contributions are present.
  - Disentangling **$D_s K l \nu$** and **$D_s^* K l \nu$** gives new insights for modelling this region.
  - Background to **$B_s \to D_s X l \nu$** at Y(5S) and hadron colliders. e.g. at LHCb ***$(f_u+f_d)/f_s \sim 6$***



- *BR small due to kinematics, need efficient reco.*
  - Select B_{sig} in **$D_s(\gamma)K l^+$** (**$D_s \to \Phi\pi$**). Remaining particles must be consistent with B decay (**B_{tag} in semileptonic mode**)
  - Minimal signal side selection to limit model dependence.

$B \to D_s K l \nu$ Fit

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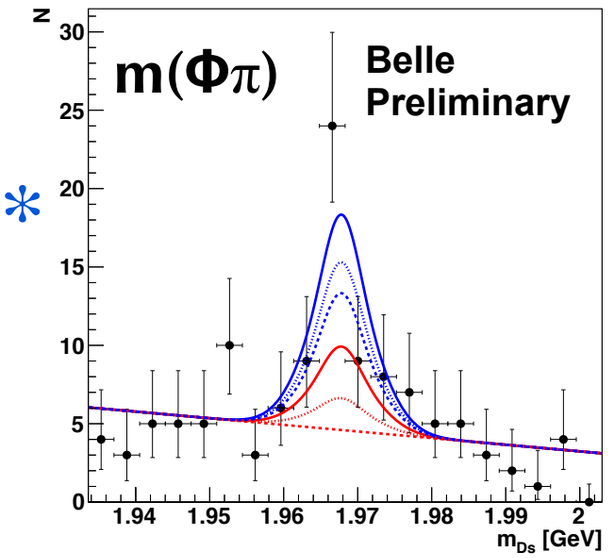
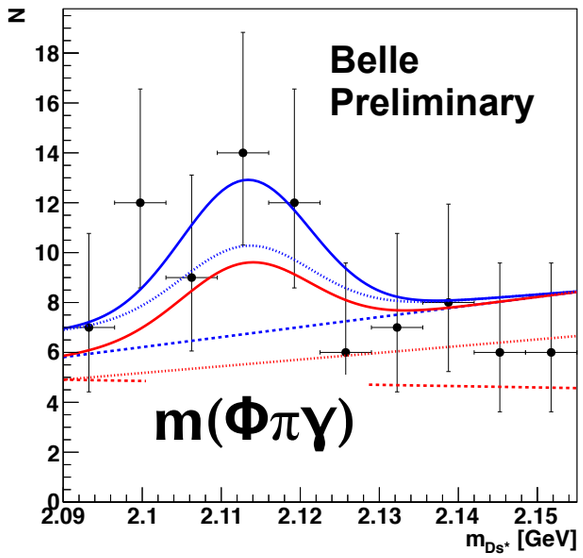
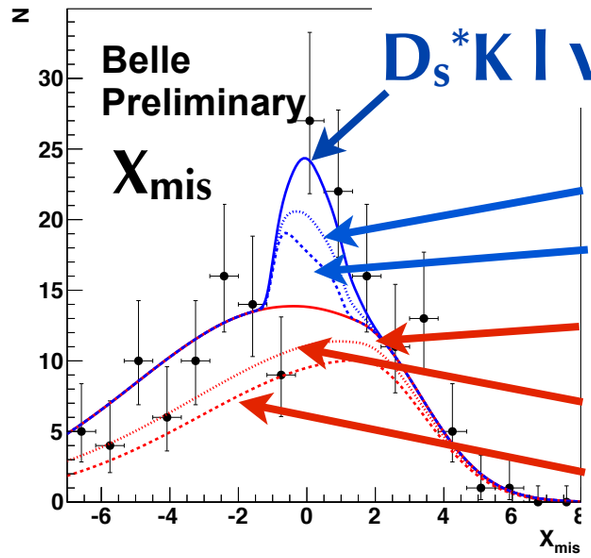
- Signal PDF parameterised from MC
- Background PDF derived from MC and data sidebands.
- Measure $D_s K$ and $D_s^* K$ modes simultaneously to measure cross feed.

$$X_{\mathrm{mis}} = \frac{(E_{beam} - E_{\mathrm{vis}}) - p_{\mathrm{vis}}}{\sqrt{E_{beam}^2 - M_B^2}}$$

D_s^*

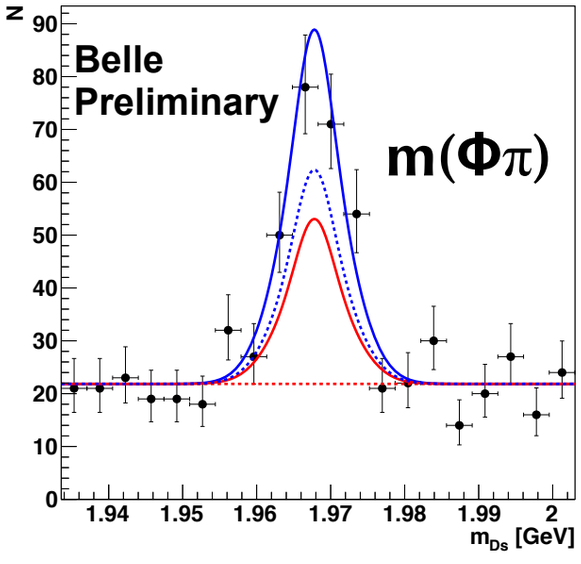


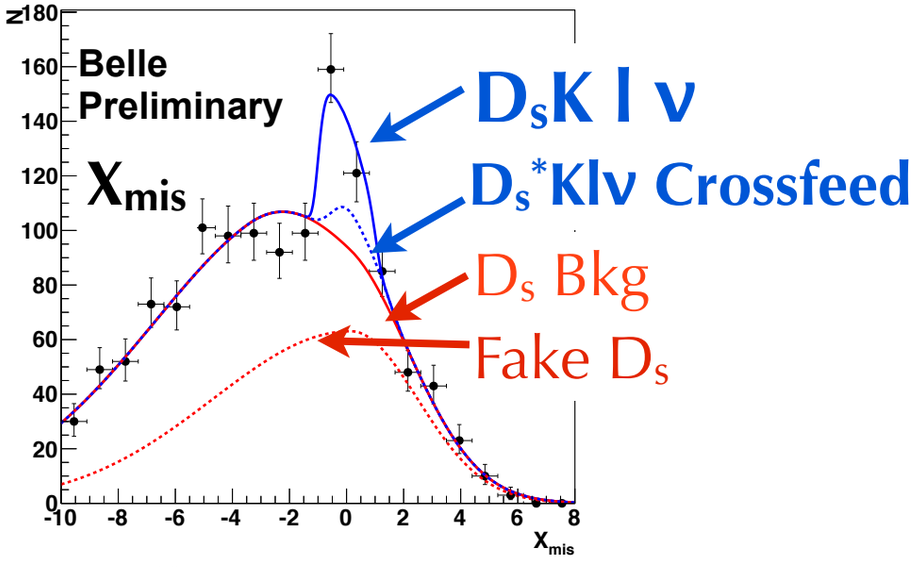




New@EPS

D_s





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$B \to D_s K l \nu$ BR

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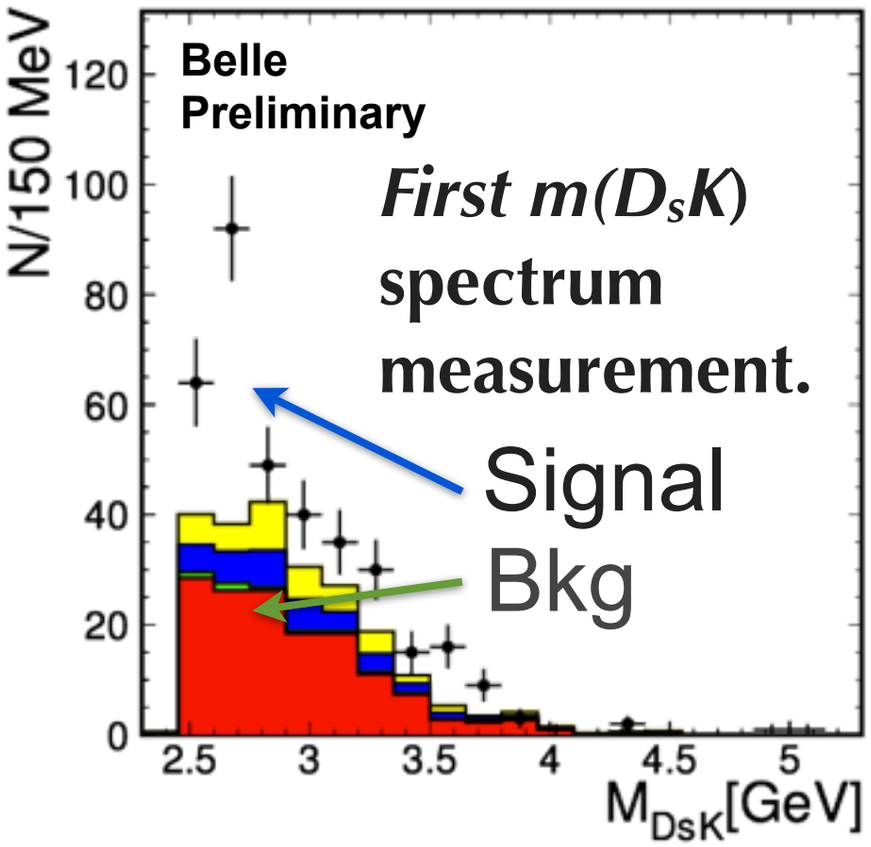
- *First* time measured separately.
- *Systematics highly correlated: combined has high signif.*
- Only a small part of $B \to X_c l \nu$

Mode	BR: Belle Preliminary
$D_s K l \nu$	$(3.0 \pm 1.2_{stat}{}^{+1.1}_{-0.8\ sys}) 10^{-4}$
$D_s^* K l \nu$	$(2.9 \pm 1.6_{stat}{}^{+1.1}_{-1.0\ sys}) 10^{-4}$
Combined	6 σ significance



Systematic Error	ΔBR (D_sK)%	ΔBR (D_s^*K)%
Tracking,KID,LeptID	8	
BR($D_s \to \varphi\pi$)	6	
Signal Efficiency	**21**	
$N(B^+B^-)$	2	
Signal PDF (MC)	**+27, -7**	**+17, -22**
BKG PDF (MC)	+6, -8	**+20,-17**
BKG PDF (Data)	+5, -1	3
Cross Feed	1	2

Efficiency determined with data: reduced model dependence.

- Consistent with prev. measurement (Babar) arXiv:1012.4158 [hep-ex]

$$\mathcal{B}(B^- \to D_s^{(*)+} K^- \ell^- \overline{\nu}_\ell) = [6.13^{+1.04}_{-1.03}(\text{stat.}) \pm 0.43(\text{syst.}) \pm 0.51(\mathcal{B}(D_s))]\ 10^{-4}$$ **>5 σ**

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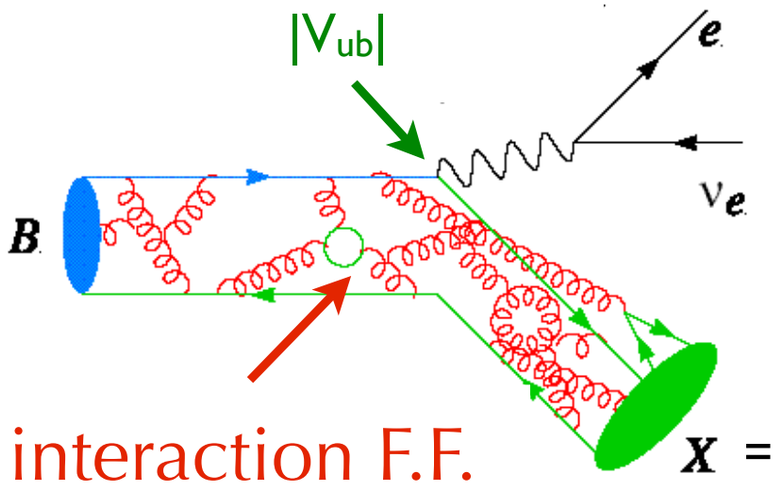
$|V_{ub}|$ from $B \to \pi l \nu$



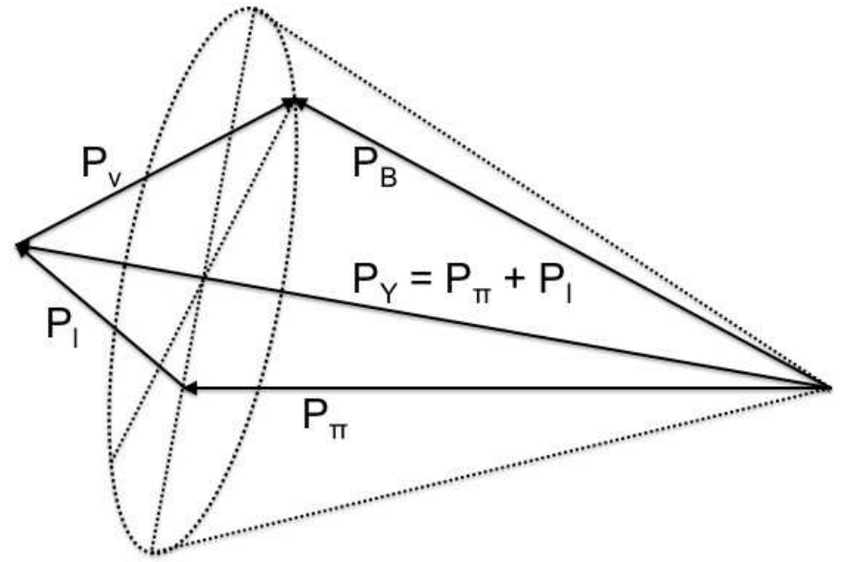
Strong interaction F.F.

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

Method: Untagged (with ν reconstruction)

- Identify π^+ and l^+ on **signal** side
- Neutrino 4-momentum from missing 3-momentum

$$p_\nu = (|\vec{p}_{\text{miss}}|, \vec{p}_{\text{miss}}) \qquad q^2 = (p_\ell + p_\nu)^2 = (p_B - p_\pi)^2$$



Form-factor calculations using different methods

- Measure in bins of q^2 → **reduces model dependence**
- Compare to **Lattice**, **LCSR**, **Quark** model

q^2 is calculated as the weighted average along the cone (Y-average q^2).

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B→π l ν Fit

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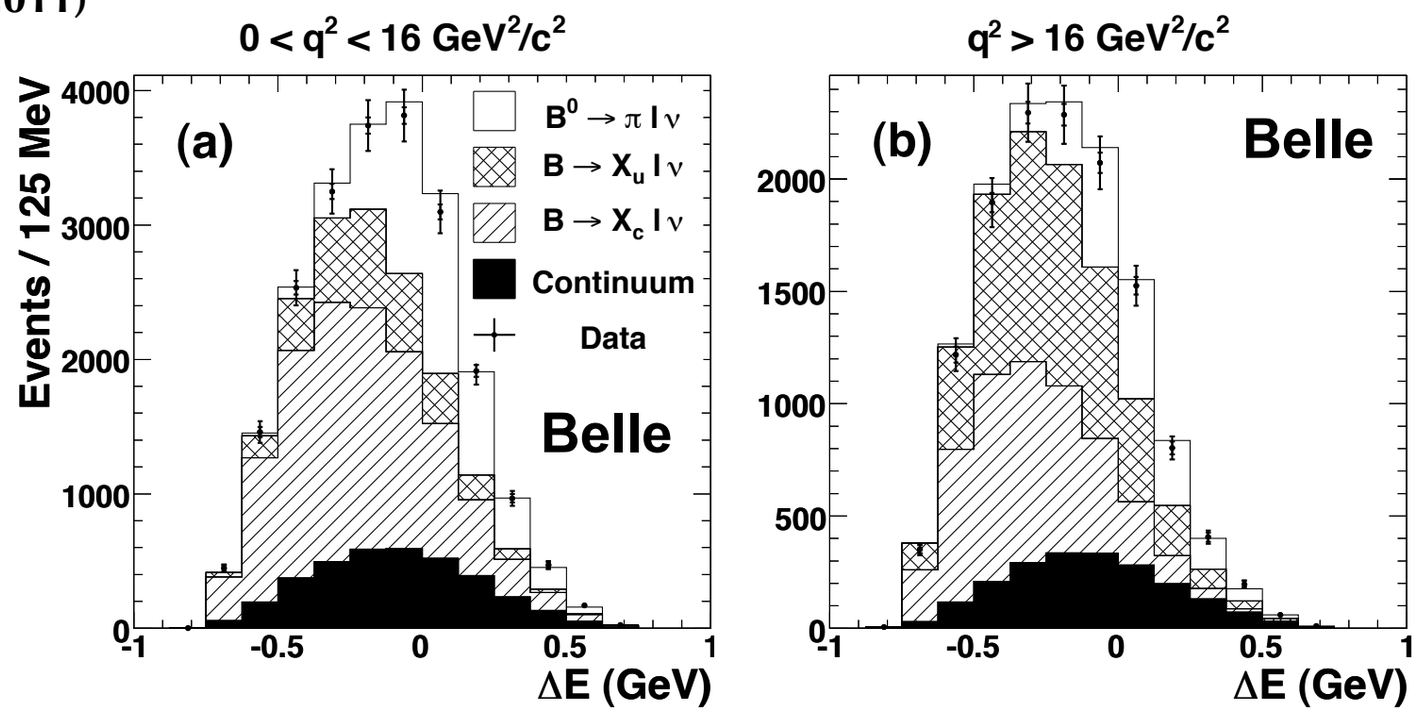
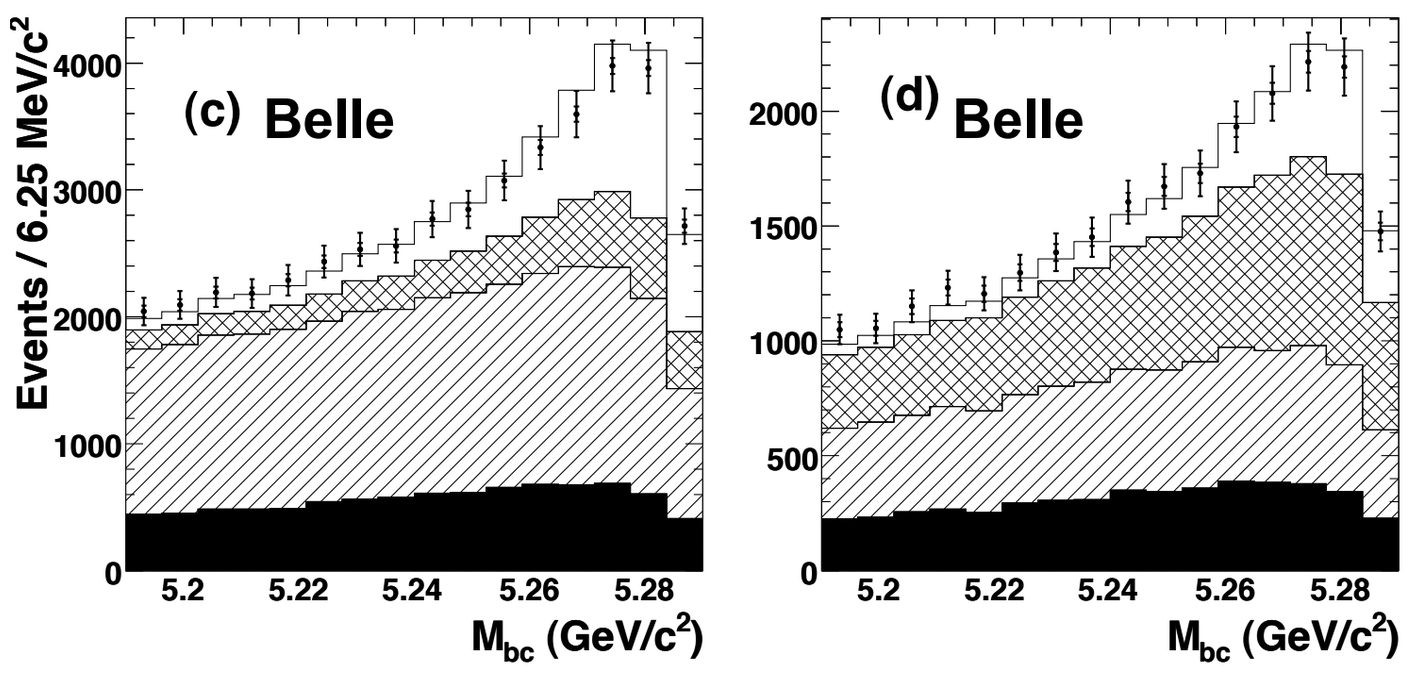
PRD 83, 071101(R) (2011)

- Estimate B yield by fitting

$$m_{\rm bc} = \sqrt{E^2_{\rm beam} - \left|\vec{p_\pi} + \vec{p_\ell} + \vec{p_\nu}\right|^2}$$
$$\Delta E = E_{\rm beam} - (E_\pi + E_\ell + E_\nu)$$

- Components in q^2 bins
  - 13 bins for π l ν
  - 3 bins for X_u l ν
  - 4 bins for X_c l ν
  - fixed continuum
- Large Bkg at high q^2





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Exclusive $|V_{ub}|$

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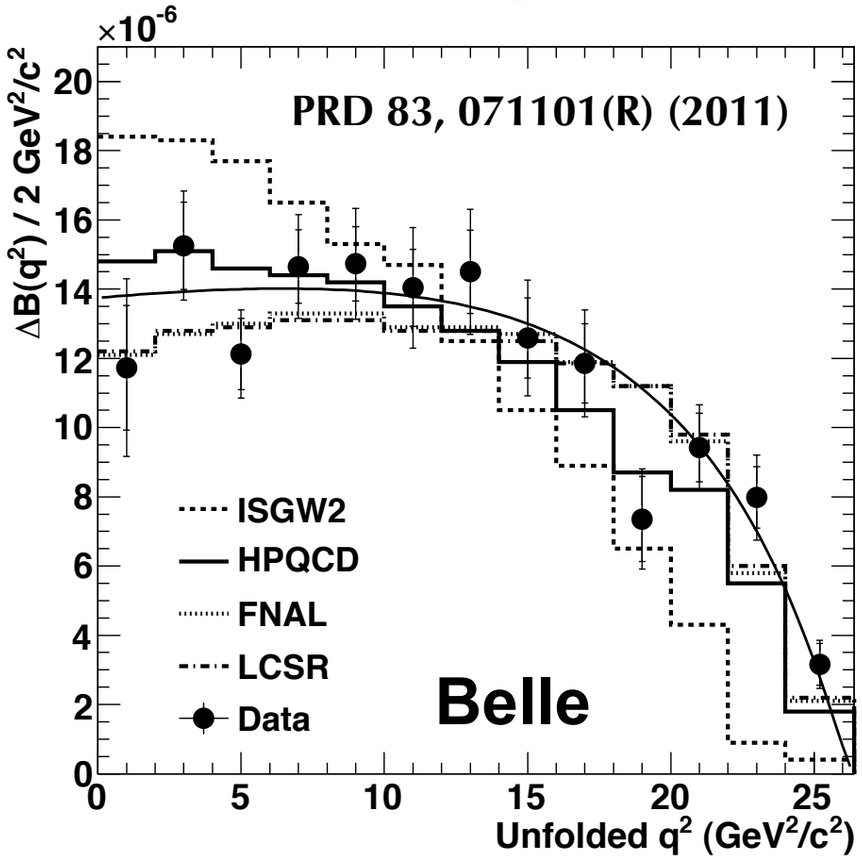
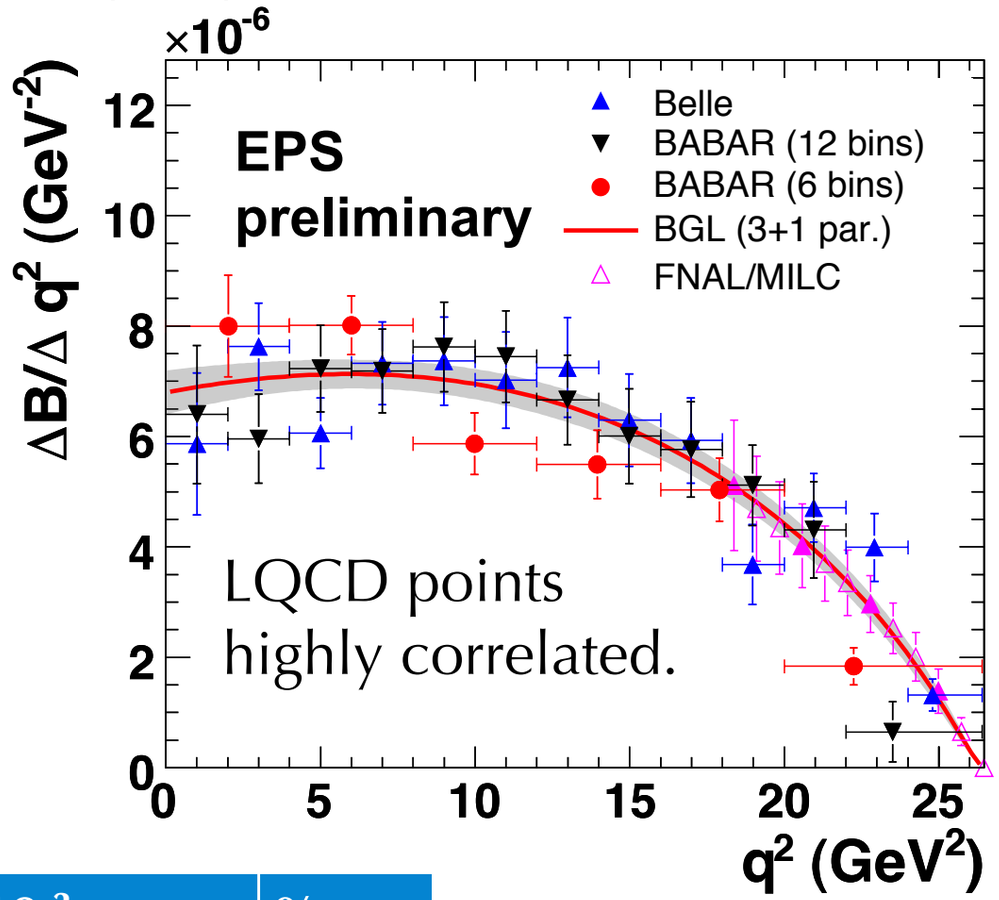
1. Extract $|V_{ub}|$ from integrated q^2 regions with **FF** (depending on theory).



OR

2. **Fit** data&theory in q^2(2-3 shape pars+ $|V_{ub}|$, data & LQCD correlations)



Method	Theory&Exp.	q^2	$\|V_{ub}\|/10^{-3}$	%
1. Form factor	HPQCD Belle	>16	$3.60\pm0.13^{+0.61}_{-0.41}$	$^{+17}_{-12}$
	FNAL Belle	>16	$3.44\pm0.13^{+0.38}_{-0.32}$	$^{+12}_{-10}$
	LCSR Belle	<12	$3.44\pm0.10^{+0.37}_{-0.32}$	$^{+11}_{-10}$
2. Fit	FNAL/MILC,Belle	Full	3.51±0.34	10
	FNAL/MILC,Belle+Babar	Full	3.26±0.30	9

Methods are compatible.
$|V_{ub}|$ Results for EPS from J. Dingfelder

c.f. $|V_{ub}|$ Inclusive (GGOU)
$\sim(4.34\pm0.16^{+0.15}_{-0.22})10^{-3}$

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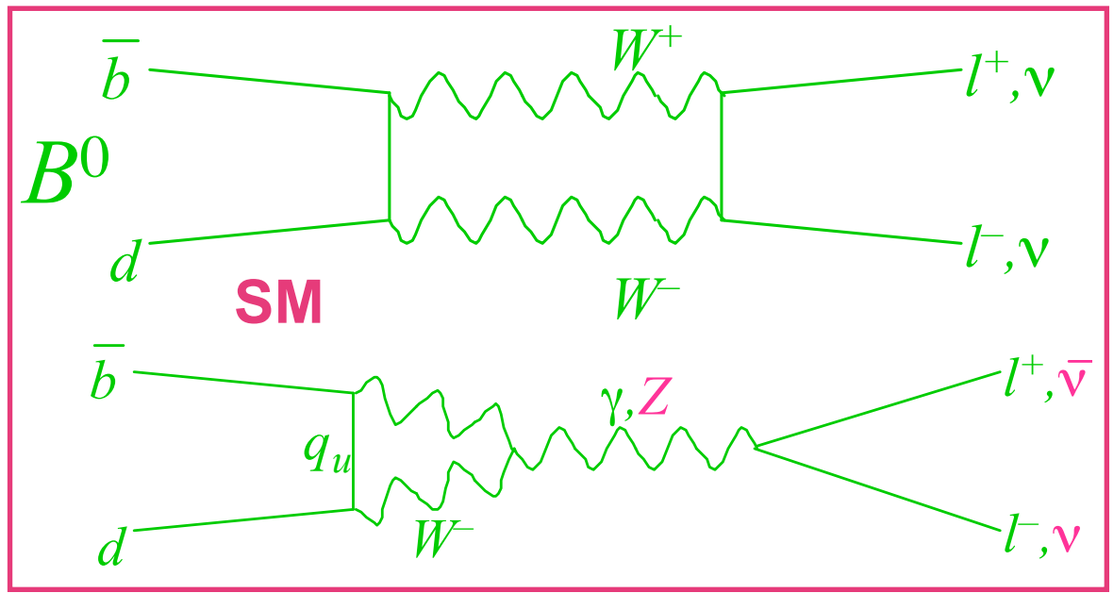
Leptonic B decays: B→νν̄

- **SM** strongly helicity suppressed by factor of order $(m_\nu/m_B)^2$

$$\mathcal{B}(B^0 \to \nu\overline{\nu}) = \tau_{B^0} \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2 \Theta_W} \right)^2 F_{B^0}^2 m_\nu^2 m_{B^0} \times \sqrt{1 - 4m_\nu^2/m_{B^0}^2} |V_{tb}^* V_{td}|^2 Y^2(x_t),$$

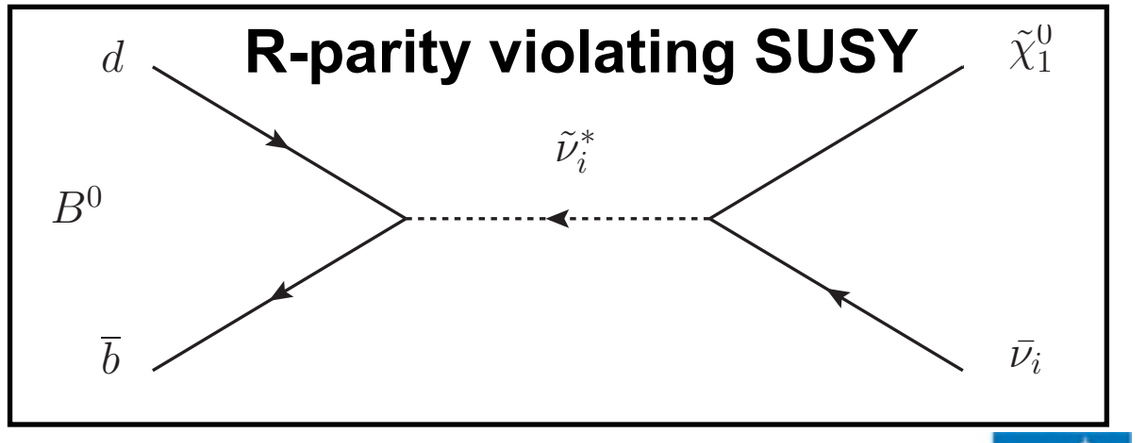
G. Buchalla, A.J. Buras, Nucl. Phys. B 400,225(1993)



- **Any signal is a sign of New physics**
- Several New Physics models predict significant BRs for invisible decay of B^0
  - e.g. **R-parity** violating models:

$$10^{-7} < \mathcal{B}(B^0 \to \bar{\nu}\tilde{\chi}_1^0) < 10^{-6}$$

NuTeV Collab., T. Adams et al., PRD 65, 015001
A. Dedes, H. Dreiner, and P. Richardson, PRL 87 41801



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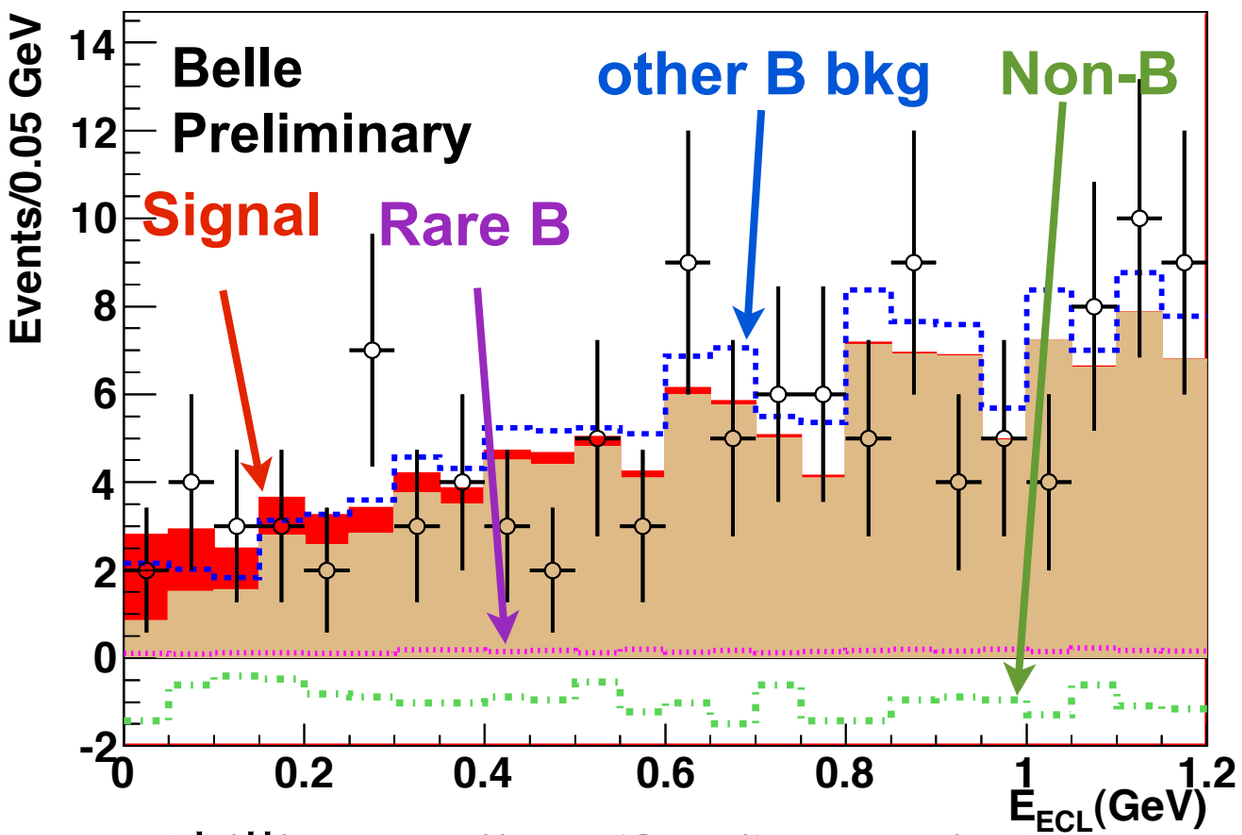
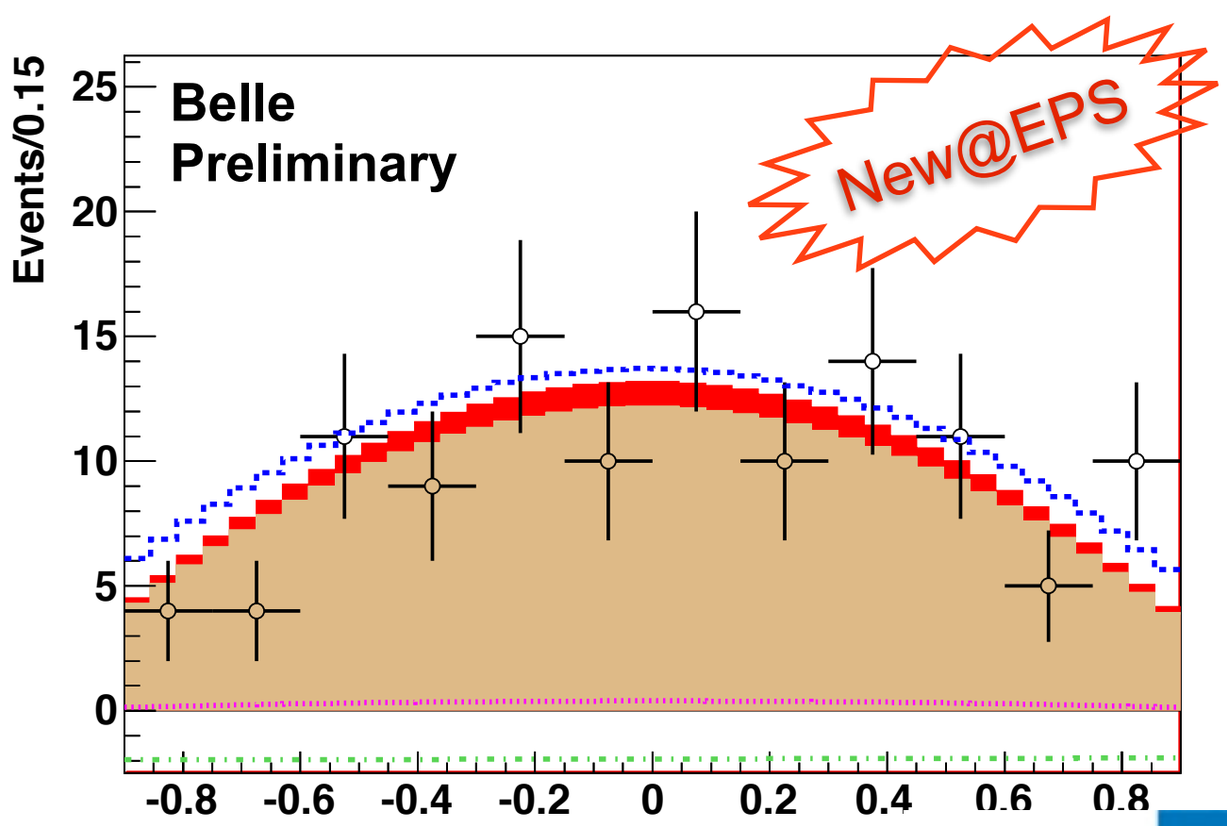
$B \to \nu\bar{\nu}$ Fit

- Reconstruct one *B* in hadronic mode, **veto** extra **tracks**, π^0 or K_L
- Clean up some E_{ECL}**~0** Bkg. from non-B with $\cos\theta_T$ (Angle of B_{tag} thrust axis w.r.t. beam axis)
  - Non-B more likely to "lose" energy in beam pipe.
- **2-D [E_{ECL},$\cos\theta_B$]** un-binned Max.-Likelihood fit
  - non-B **shape** from off-resonance **data**

657M BBbar **Belle Preliminary**

Results	Yield(±stat)
Signal	9±6
Other BB	132^{+22}_{-23}
Rare B	~4
Non-B	-23^{+22}_{-17}





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B→νν̄ Limit

- Obtain likelihood L(N_{sig}) distribution for the signal yield in fit. (Small) systematic added by smearing likelihood function.

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$$\mathcal{L}_{smear}(N_{sig}) = \int \mathcal{L}(N'_{sig}) \frac{e^{-\frac{(N_{sig}-N'_{sig})^2}{2\Delta N^2_{sig}}}}{\sqrt{2\pi\Delta N_{sig}}} dN'_{sig}$$

90% C.L. BR < 1.3 x 10^{-4}

Belle Preliminary 657M BBbar

c.f. (Babar) BR < 2.2 x 10^{-4}

- **K_L, π^0, track** veto efficiencies calibrated with **$B \to D^{(*)} l\nu$** in **low E_{ECL}** region.
- Conservative tagging efficiency systematic uncertainty.

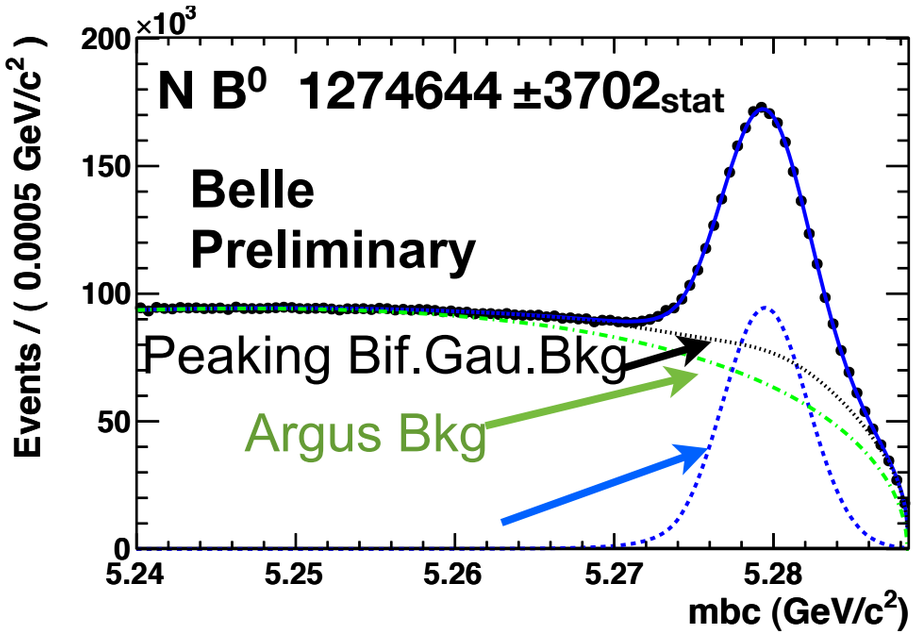
Systematics: Belle Preliminary

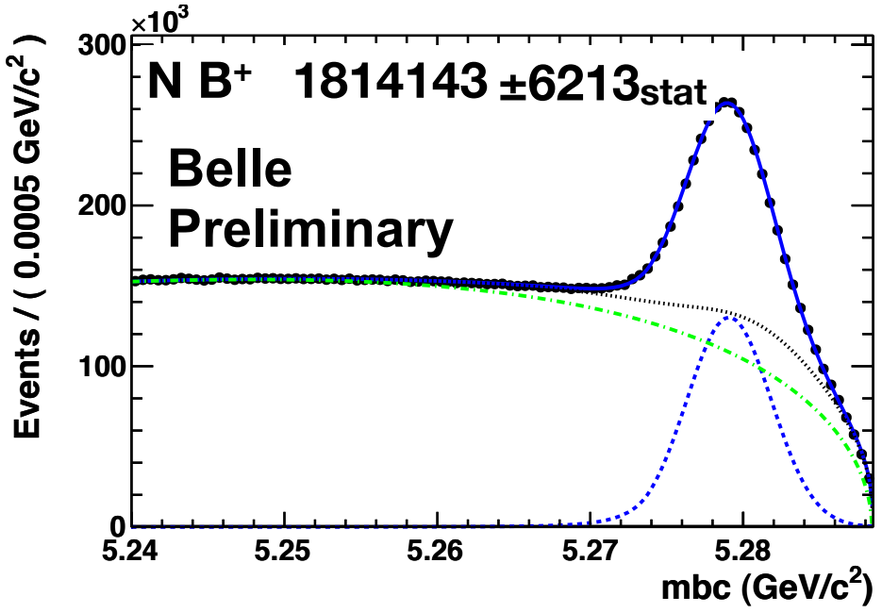
N (B^0B^{0bar})		1.4%
Tagging Efficiency		8.3%
Veto Efficiency	Track	1.6%
	π^0	2.0%
	K_L	2.0%
Sum		9.0%

Uncertainty of PDF modeling	Signal	±0.2
	OtherB	+1.6/-1.4
	Non B	+1.9/-2.2
	RareB	±0.1
Sum(unit:events)		+2.5/-2.6

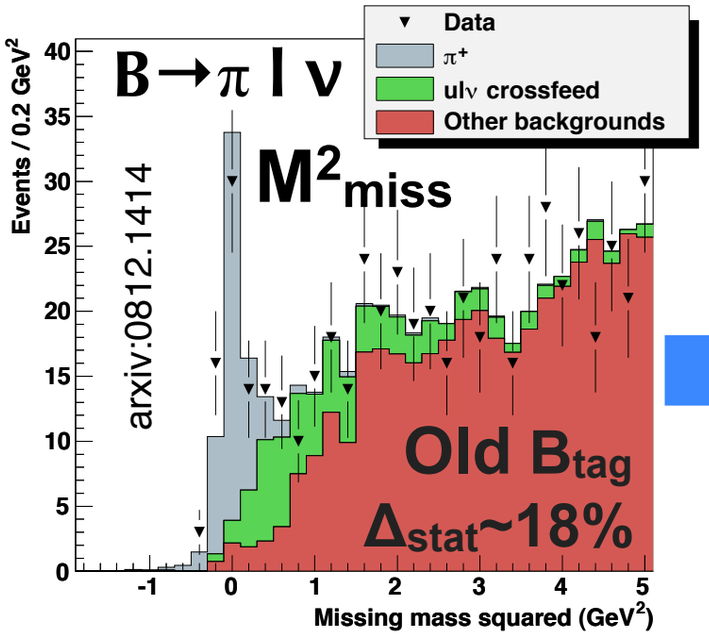
New full reconstruction

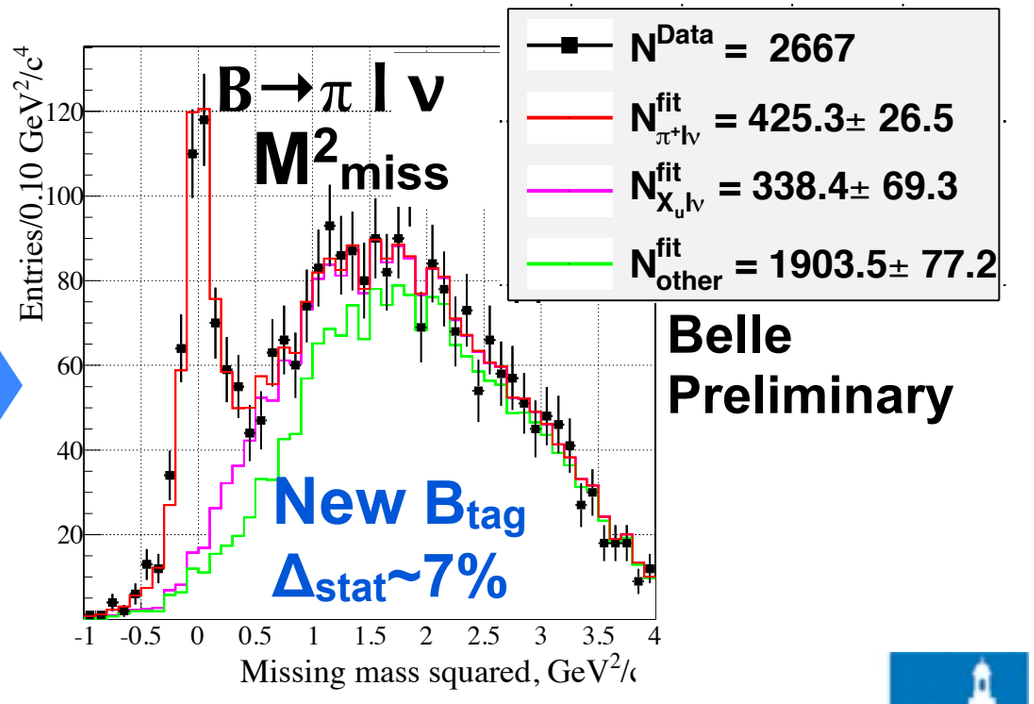
- *New* Neurobayes (neural network) tag B reconstruction in hadronic modes.
- >~3 x statistical gain over previous tagged analyses, with improved S/B.





- **All hadron tag B analyses** (leptonic and semileptonic decays) **are being reviewed.**
  - **e.g. B→π l ν**





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Summary of Belle (Semi)Leptonic Results

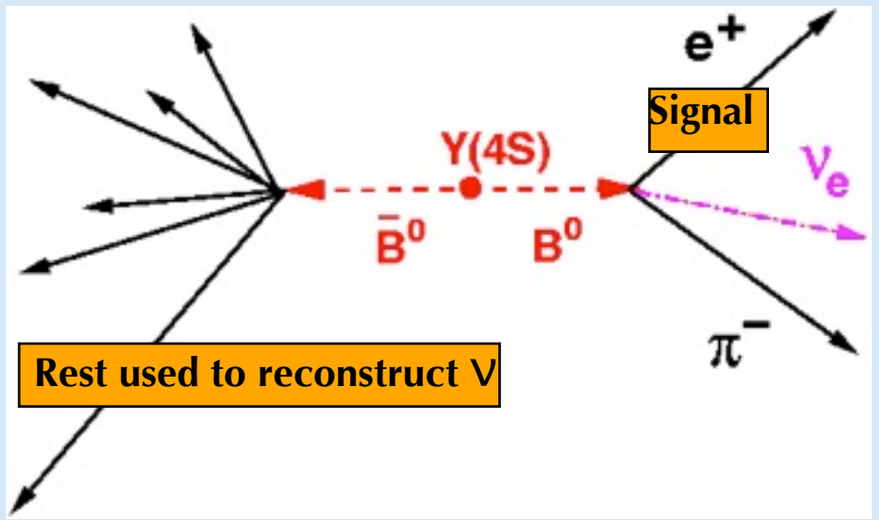
- Exclusive $|V_{cb}| = (38.0 \pm 0.2 \pm 1.1 \pm 0.7(FF)) \times 10^{-3}$ (Belle)
- Exclusive $|V_{ub}| = (3.51 \pm 0.34) \times 10^{-3}$ (Belle&LQCD fit)
  - tension with inclusive measurements ~2-3σ
- **BR($B \to D_s K l \nu$** & **$B \to D_s^* K l \nu$)** measured separately for the first time, key for $B_s \to D_s$ l ν X measurements.
  - **$BR(D_s K l \nu) = 3.0 \pm 1.2^{+1.1}_{-0.8} \times 10^{-4}$** (Belle preliminary)
  - **$BR(D_s^* K l \nu) = 2.9 \pm 1.6^{+1.1}_{-1.0} \times 10^{-4}$** (Belle preliminary)
- $B \to$ *invisible final states*: **New** limit:
  - **$BR < 1.3 \times 10^{-4}$** (Belle preliminary)
- New B tagging technique developed. Increases statistical power of all missing energy (ν) decay analyses that use hadron tag ~3x. Results coming.

End

B-factory Approaches to Measuring B→Xlν

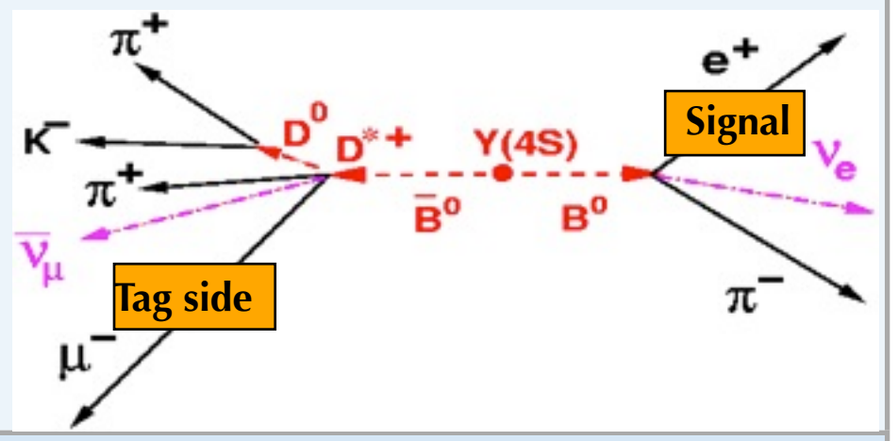
Untagged

Initial 4-momentum known
missing 4-momentum = one ν
Reconstruct B → X_q l ν
using m_B (beam-constrained)
and **Δ**E = E_B-E_{beam}



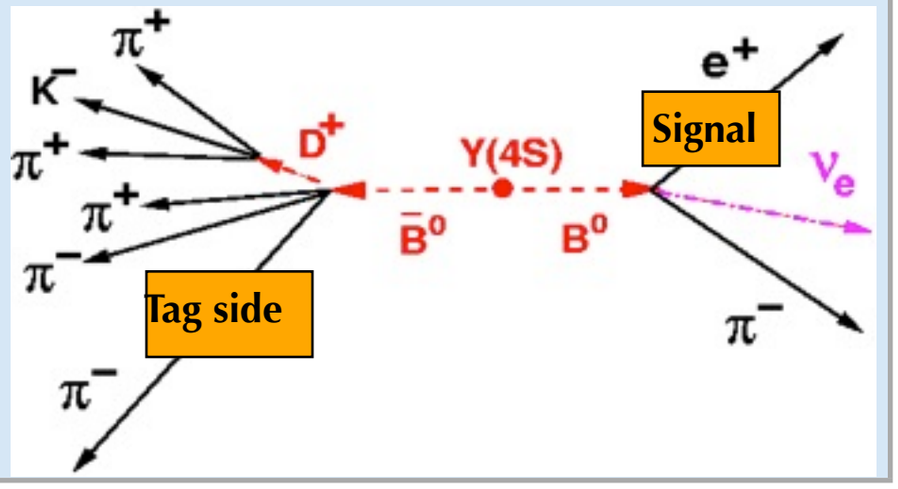
Semileptonic Tag

One B reconstructed in $D^{(*)}$ l ν modes.
Two missing ν in event.



Full Reconstruction Tag

One B reconstructed completely in a known b → c mode without ν.



Eff.	Purity	Lumi.
High	Low	< 0.5 ab^{-1}
		< 1 ab^{-1}
Low	High	> 1 ab^{-1}

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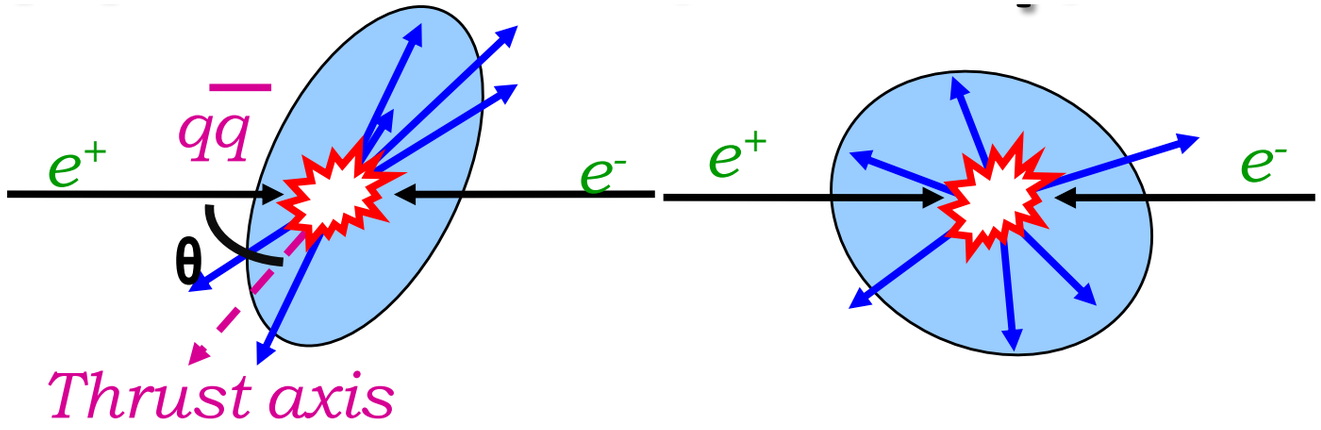
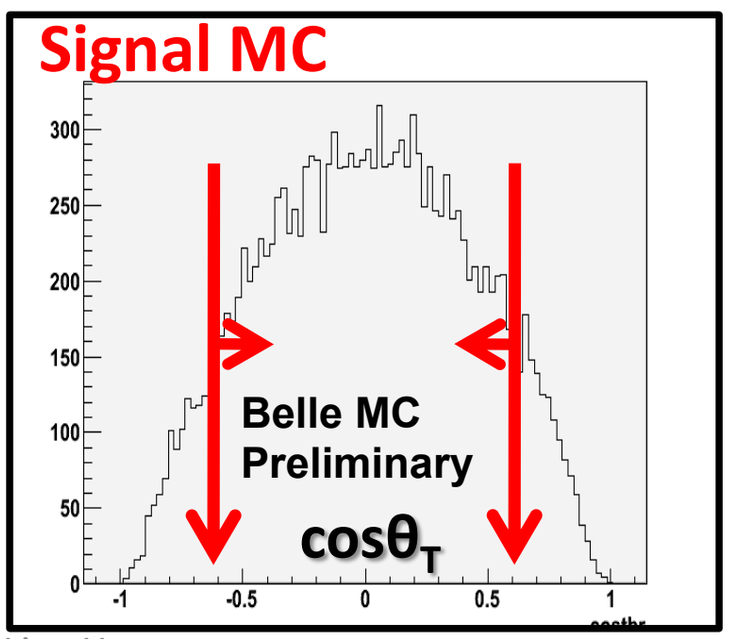
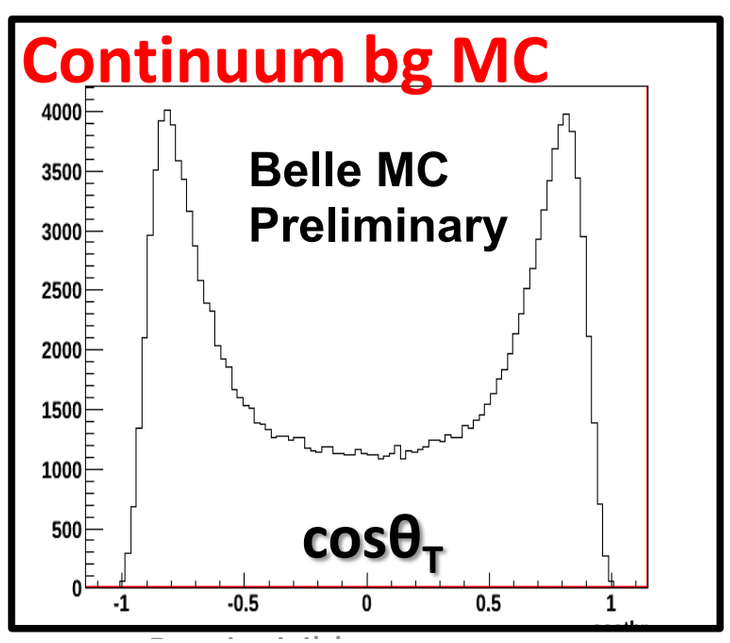
B→νν̄ Reconstruction

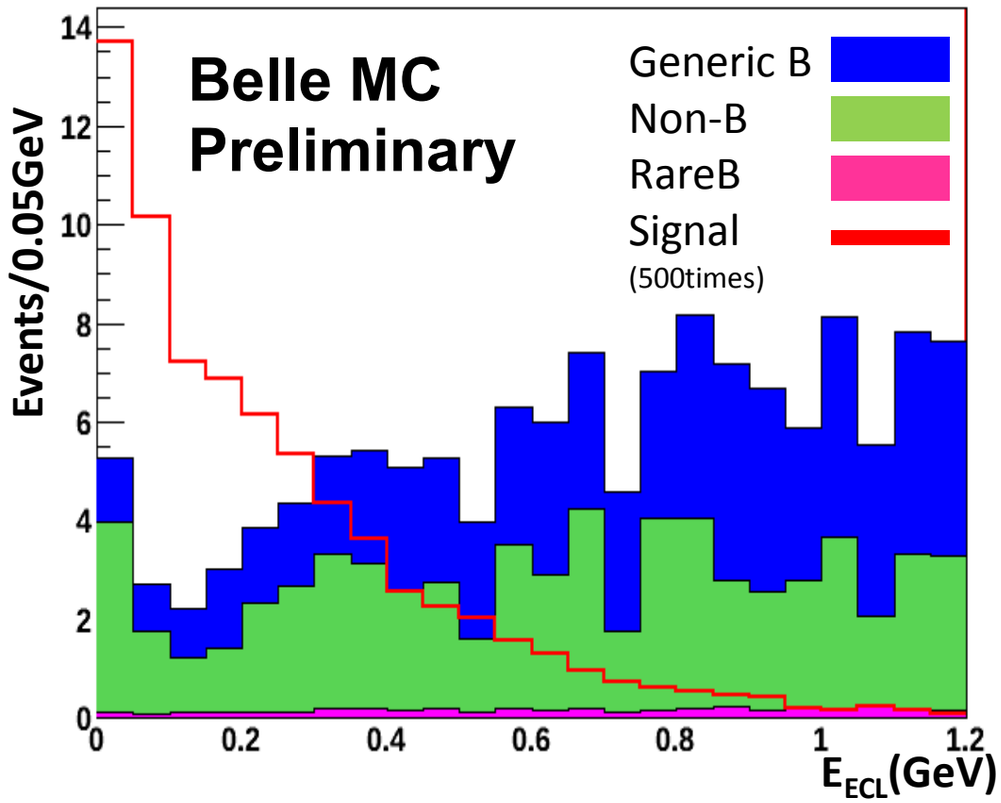
$\cos\theta_T$ Criteria







Calorimeter energy



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