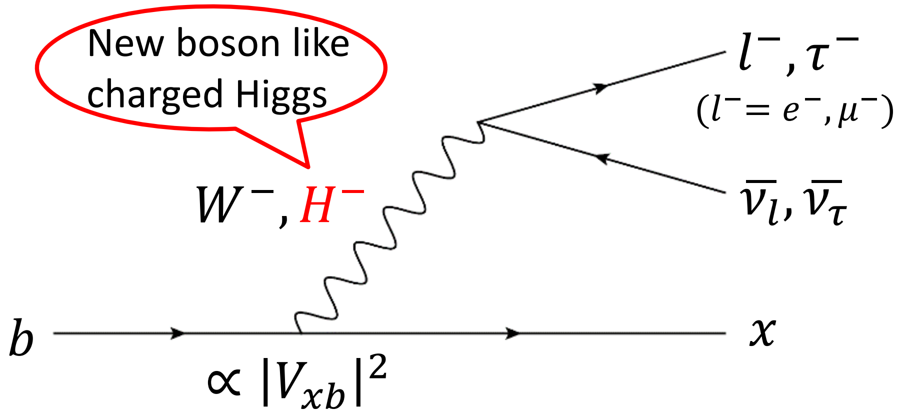
Recent Experimental Results for Semileptonic B decays

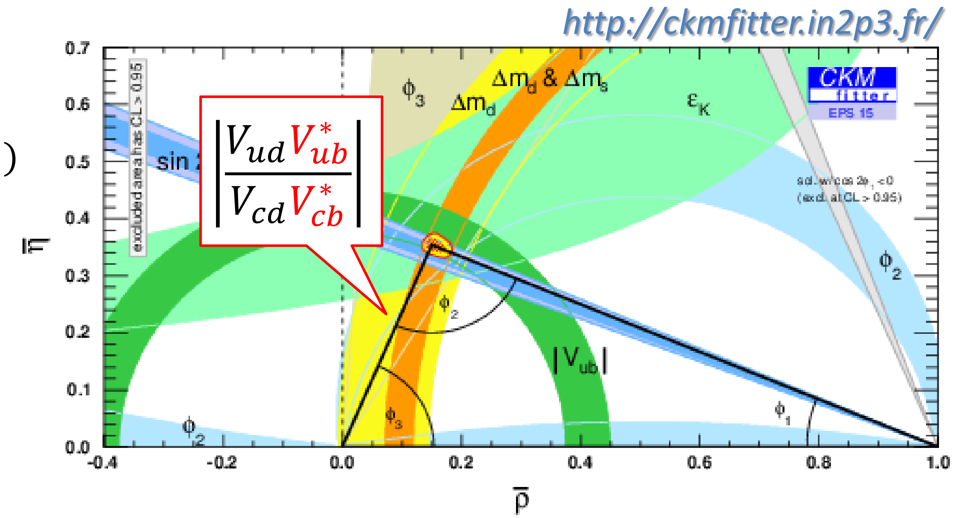
June 6, 2016 at FPCP 2016

Shigeki Hirose (Nagoya University)

For the Belle Collaboration

■ Semileptonic B Decays





- Good environment for $|V_{xb}|$ ($x = u, c$) extraction
  - Theoretically, cleaner than hadronic B decays; QCD contribution exists only in $b \to x$ transition part

- Semitauonic decays (e.g. $\bar{B} \to D^{(*)}\tau^-\overline{\nu_\tau}$) are good probe for indirect new physics searches

Recent Topics

- $\bar{B} \rightarrow X_c l^- \overline{\nu_l}$ $(l^- = e^-, \mu^-)$ measurements
  - $\bar{B} \rightarrow D l^- \overline{\nu_l}$ with hadronic tagging (Belle, 772M $B\bar{B}$)

    Presented at EPS 2015 → Phys. Rev. D 93, 032006 (2016)

  - $\bar{B} \rightarrow D^{(*)} \pi^- \pi^+ l^- \overline{\nu_l}$ with hadronic tagging (BaBar, 471M $B\bar{B}$)

    Presented at EPS 2015 → Phys. Rev. Lett. 116, 041801 (2016)

Hot topic!

- Semitauonic Decays
  - $\overline{B^0} \rightarrow D^{*+} \tau^- \overline{\nu_\tau}$ with semileptonic tagging (Belle, 772M $B\bar{B}$)

    Presented at Moriond EW 2016 (arXiv:1603.06711)

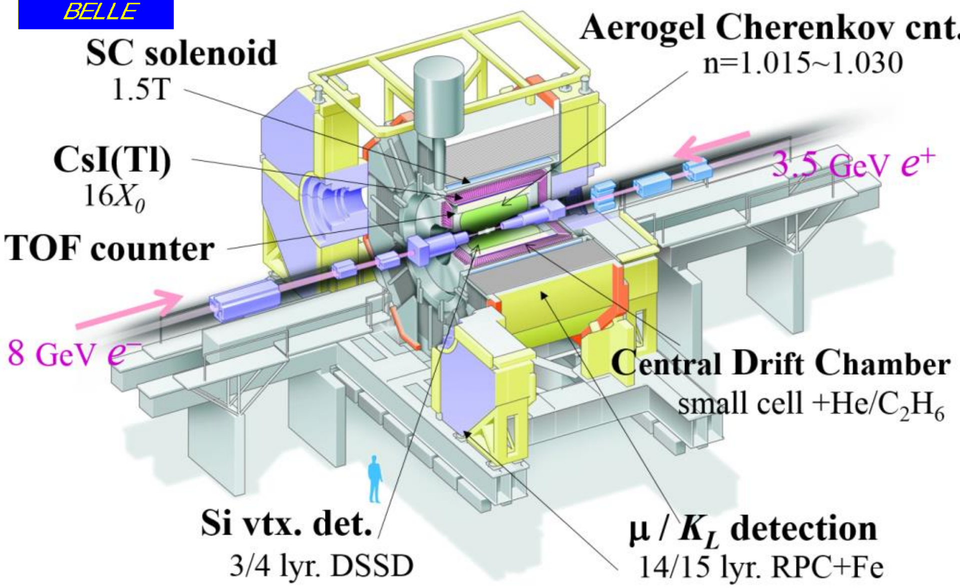
  - $\overline{B^0} \rightarrow \pi^+ \tau^- \overline{\nu_\tau}$ with hadronic tagging (Belle, 772M $B\bar{B}$)

    Presented at EPS 2015 → Phys. Rev. D 93, 032007 (2016)

All the results above are based on the full statistics of each experiment

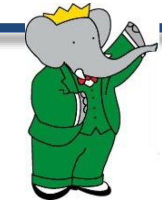
■ B Factories

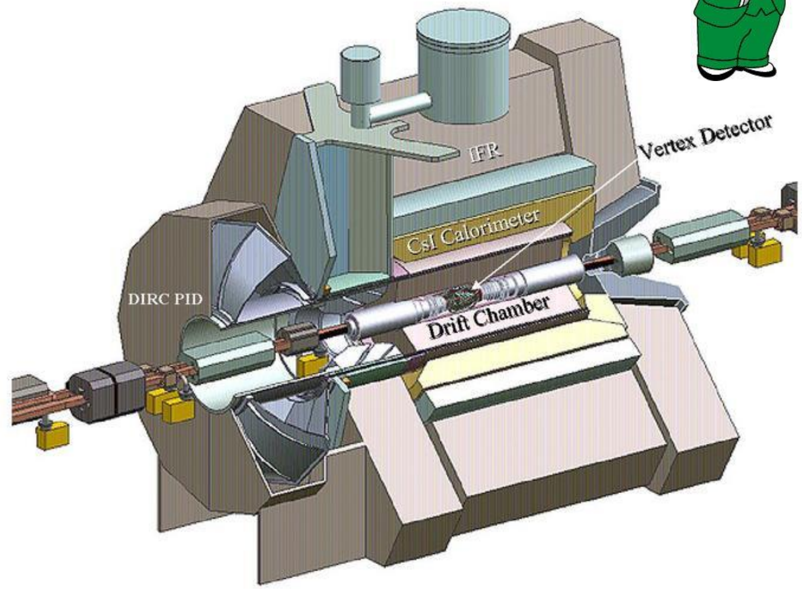
Belle @ KEKB (KEK)



Data take: 1999-2010
$N_{B\bar{B}}$ = 772M

BaBar @ PEP-II (SLAC)



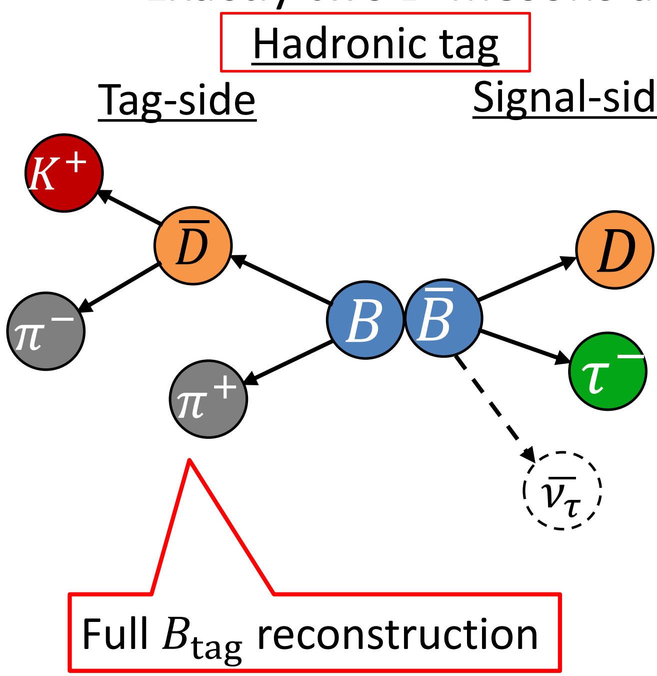


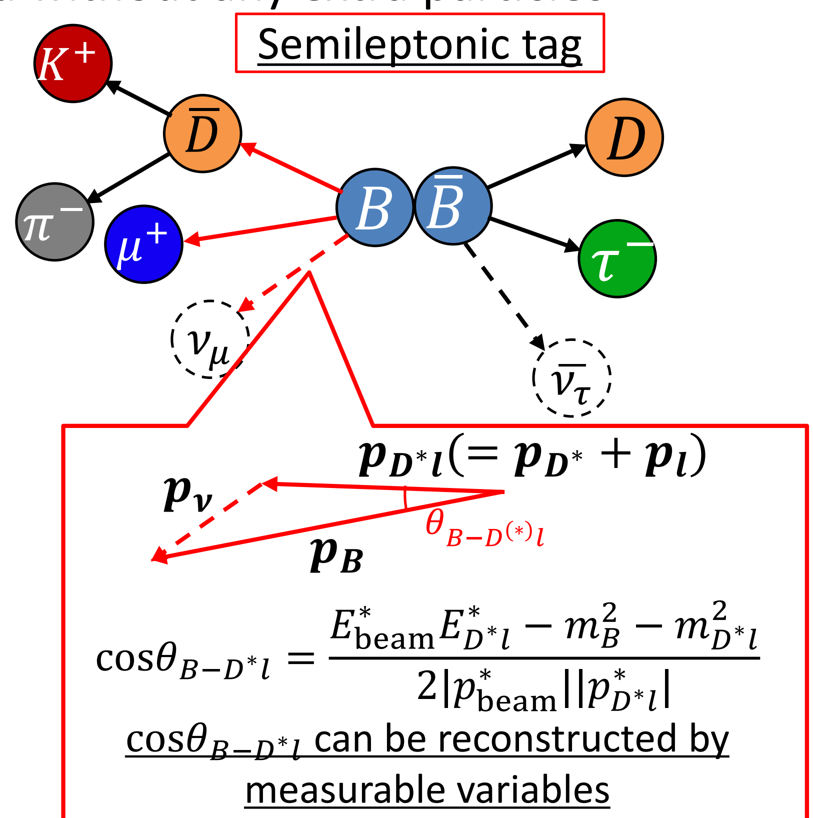
Data take: 1999-2008
$N_{B\bar{B}}$ = 471M

- B factories with e^+e^- colliders at $\sqrt{s}$ = 10.58 GeV
  - Produce B mesons via $\Upsilon(4S) \rightarrow B\bar{B}$
- Huge statistics: more than 1 billion $B\bar{B}$ have been accumulated at the two experiments

■ "Tagging" Analysis

- Reconstruct one B meson (B_{tag}) with specific decays
  - →Ensure all the remaining particles belong to the signal side
- Unique technique at B factories
  - Beam energy is precisely known
  - Exactly two B mesons are produced without any extra particles





"Tagging" Analysis

- Reconstruct one B meson (B_{tag}) with specific decays
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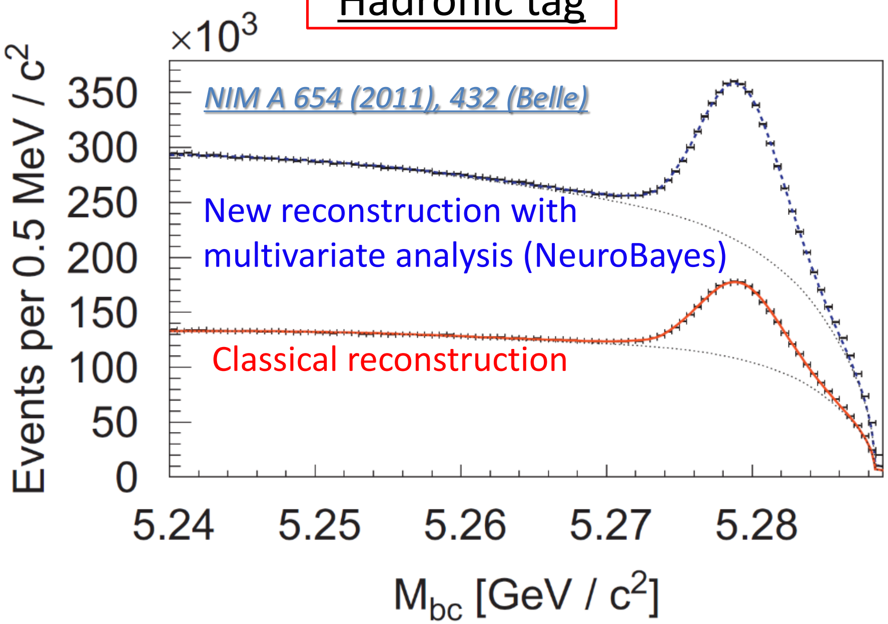
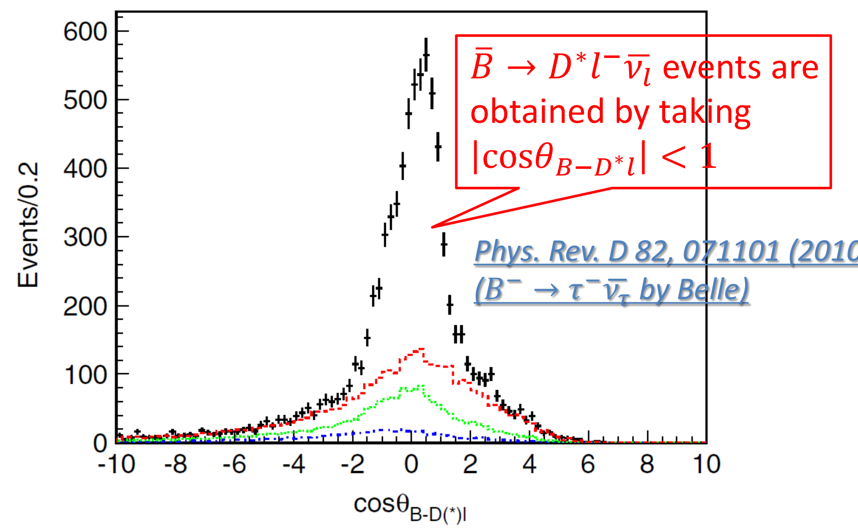
Hadronic tag



- Full reconstruction of B_{tag} is possible
- Reconstruction efficiency = $O(10^{-3})$

Semileptonic tag



- Reconstruction efficiency is better: $O(10^{-2})$
- One neutrino exists in the tag-side

Exclusive $\bar{B} \rightarrow X_c l^- \overline{\nu_l}$ Measurements

$\bar{B} \rightarrow D l^- \overline{\nu_l}$ $(l^- = e^-, \mu^-)$ with hadronic tagging (Belle)
Phys. Rev. D 93, 032006 (2016)

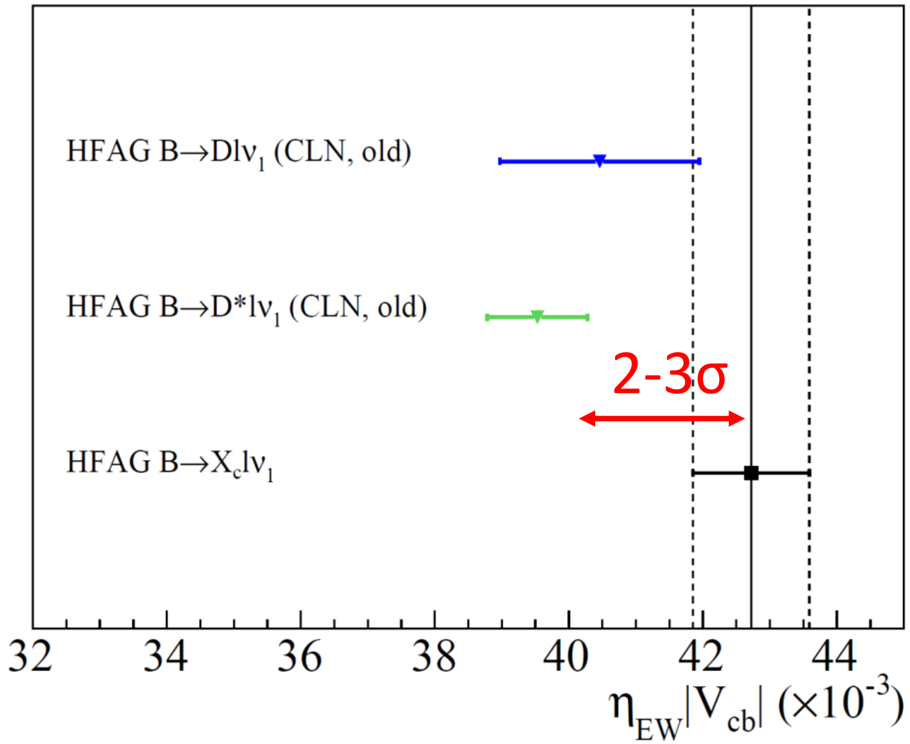
$\bar{B} \rightarrow D^{(*)} \pi^- \pi^+ l^- \overline{\nu_l}$ with hadronic tagging (BaBar)
Phys. Rev. Lett. 116, 041801 (2016)

$|V_{cb}|$ Determination

- Discrepancy between inclusive and exclusive $|V_{cb}|$ measurements
  - $|V_{cb}|$ determined by incl. measurements and by $\bar{B} \to D^{(*)} l^- \overline{\nu_l}$ decays show 2-3σ discrepancy

  →Belle updated $|V_{cb}|$ determination with $\bar{B} \to D l^- \overline{\nu_l}$ with full data

  x7 larger statistics than the previous Belle analysis: Phys. Lett. B 526, 258 (2002)



■ $\bar{B} \to D l^- \bar{\nu}_l$ by Belle

- Signal extraction with missing mass squared

$$M^2_{\rm miss} = \left(p_{\rm beam} - p_{B_{\rm tag}} - p_D - p_l\right)^2 \quad (l = e, \mu)$$

→ To be zero for signal with only one ν

- Signal reconstruction as a function of $w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$

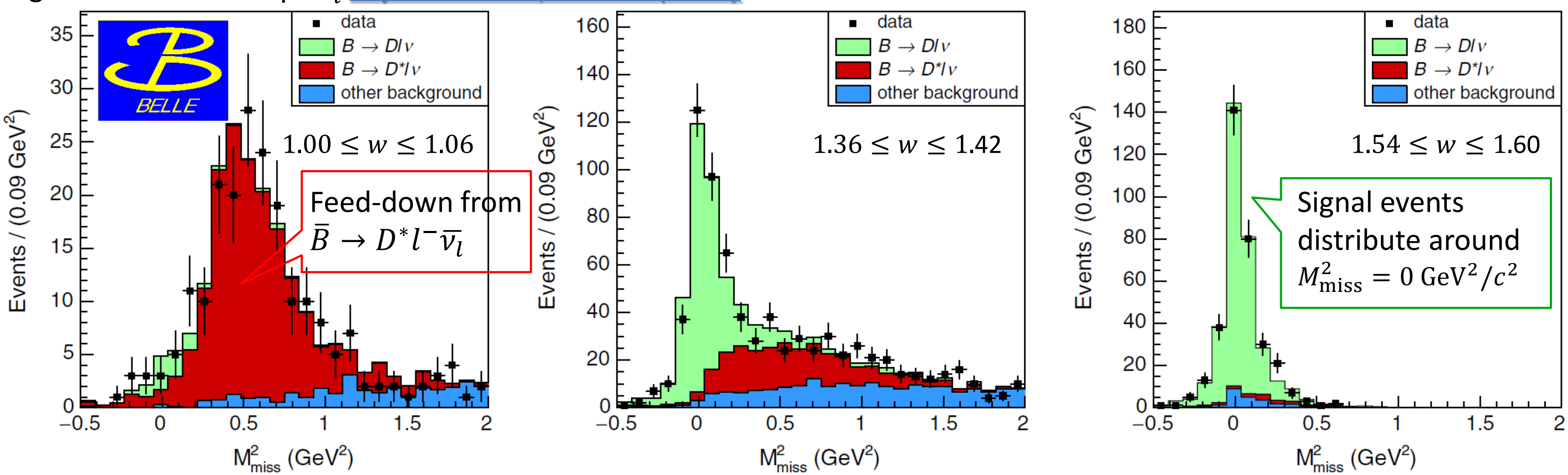
Differential decay rate

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2 - 1)^{\frac{3}{2}} \eta_{\rm EW}^2 |V_{cb}|^2 |g(w)|^2$$

Electroweak correction

Form factor for $\bar{B} \to D$

Figures for $\overline{B^0} \to D^{*+}\mu^-\bar{\nu}_l$ Phys. Rev. D 93, 032006 (2016)



■ $|V_{cb}|$ Determination

$$g(w) = g(1)(1 - 8\rho^2 + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$
$$\left(z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}\right)$$

With heavy-quark symmetry etc.

I. Caprini, et. al., Nucl. Phys. B 530, 153 (1998)

- Results:

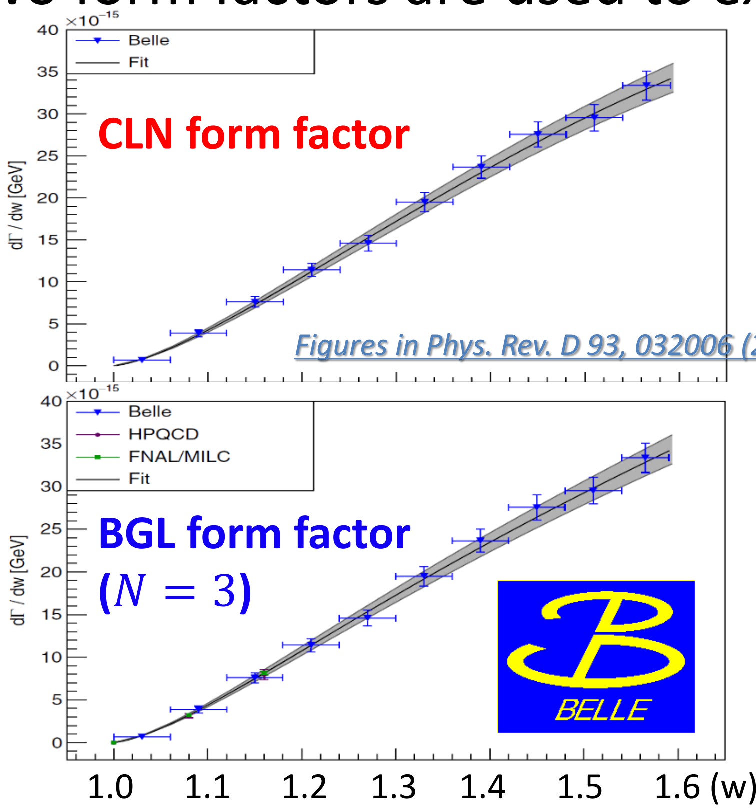
$$\eta_{\mathrm{EW}}|V_{cb}|^2 = (40.12 \pm 1.34) \times 10^{-3} \text{ (CLN form factor)}$$
$$\eta_{\mathrm{EW}}|V_{cb}|^2 = (41.10 \pm 1.14) \times 10^{-3} \text{ (BGL form factor)}$$

$$g(w) = \frac{\sqrt{\frac{4m_D}{m_B}}}{1 + \frac{m_D}{m_B}} \frac{1}{P_i(z)\varphi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n$$

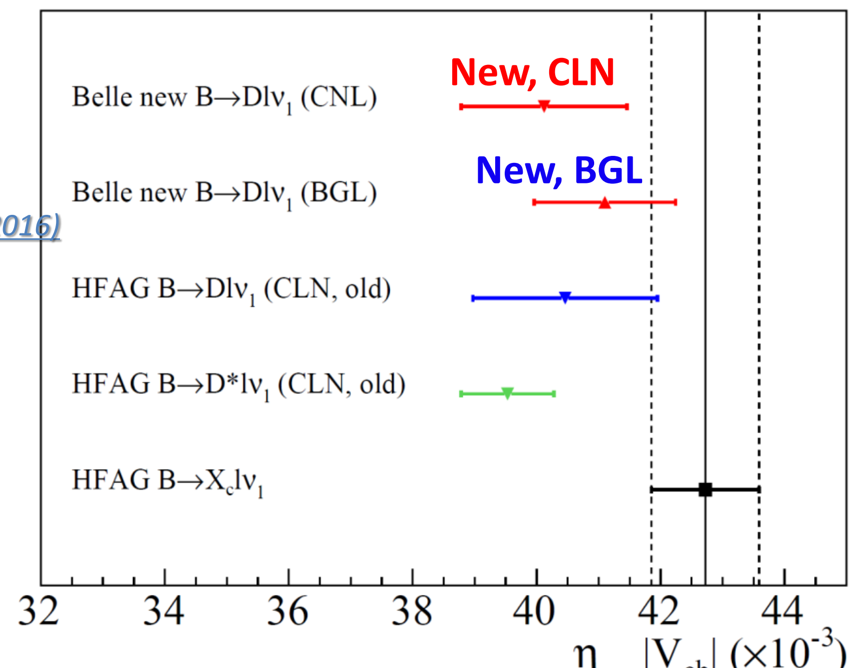
Model independent

C. G. Boyd, et. al., Phys. Rev. Lett. 74, 4603 (1995)

- Two form factors are used to extract $|V_{cb}|$



Figures in Phys. Rev. D 93, 032006 (2016)

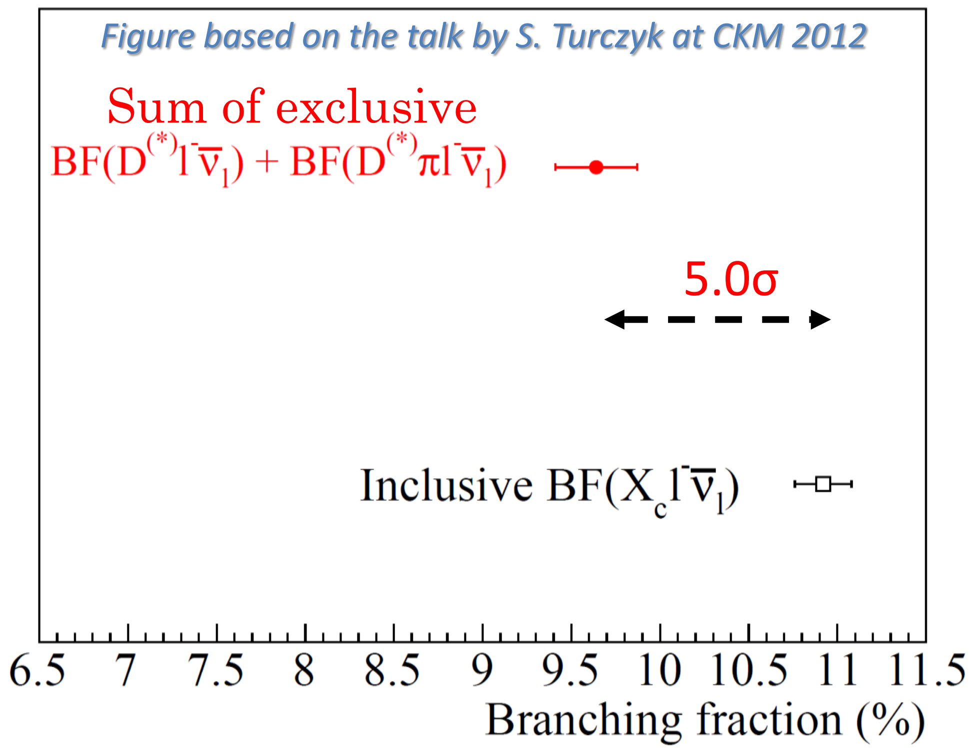


Two results agree with both $|V_{cb}|$ by inclusive and by $\bar{B} \to D^* l^- \bar{\nu}_l$

■ Branching Fractions of $\bar{B} \to X_c l^- \overline{\nu_l}$

- $BF(\bar{B} \to X_c l^- \overline{\nu_l})$ by Inclusive and exclusive measurements are inconsistent
  - About 1.5% difference (5.0σ)
  - This indicates unmeasured exclusive $\bar{B} \to X_c l^- \overline{\nu_l}$ decays

    →BaBar measured additional exclusive decays: $\bar{B} \to D^{(*)}\pi^-\pi^+ l^- \overline{\nu_l}$



■ $\bar{B} \to D^{(*)}\pi^-\pi^+l^-\overline{\nu_l}$ by BaBar

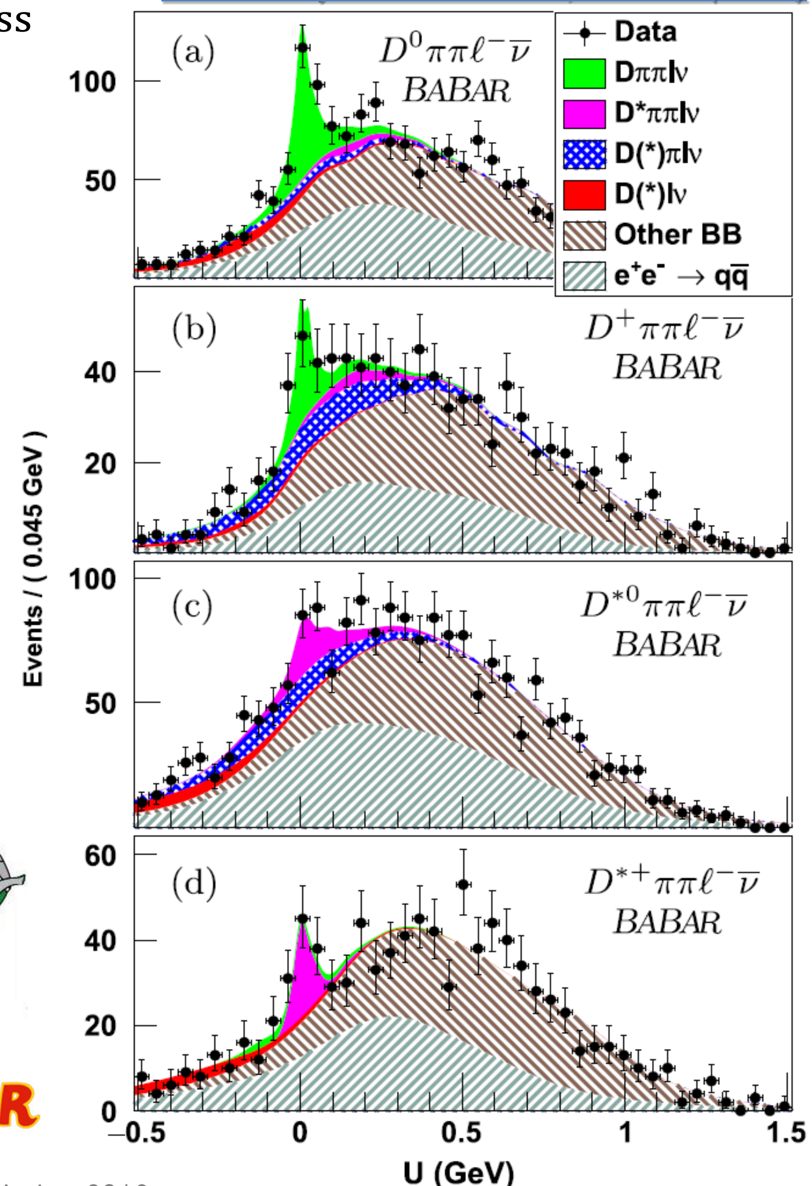
- Signal extraction with $U = E_{\text{miss}} - p_{\text{miss}}$
  - U has less dependence on modeling of decay dynamics than M_{miss}^2
- Significant signals were observed

Mode	Sig. (stat. only)	Sig. (stat.+syst.)
$D^0\pi\pi l^-\overline{\nu_l}$	5.4	5.0
$D^+\pi\pi l^-\overline{\nu_l}$	3.5	3.0
$D^{*0}\pi\pi l^-\overline{\nu_l}$	1.8	1.6
$D^{*+}\pi\pi l^-\overline{\nu_l}$	3.3	3.0

First observation for $D^0\pi\pi l^-\overline{\nu_l}$

First evidence for $D^{(*)+}\pi\pi l^-\overline{\nu_l}$

Plots in Phys. Rev. Lett. 116, 041801 (2016)



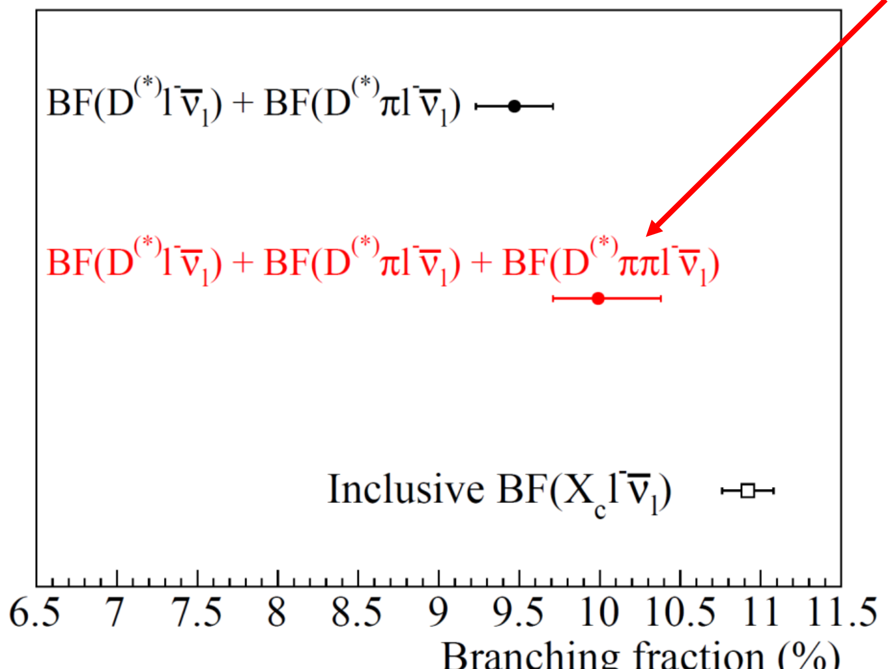
■ Incl. vs Excl. Gap with $\bar{B} \to D^{(*)}\pi\pi l^- \overline{\nu_l}$

- The obtained branching fractions

$$BF(\bar{B} \to D\pi^-\pi^+ l^- \overline{\nu_l}) = (0.152 \pm 0.023(\text{stat}) \pm 0.018(\text{syst}) \pm 0.007(\text{norm}))\%$$
$$BF(\bar{B} \to D^*\pi^-\pi^+ l^- \overline{\nu_l}) = (0.108 \pm 0.028(\text{stat}) \pm 0.023(\text{syst}) \pm 0.004(\text{norm}))\%$$

- Total BFs for $\bar{B} \to D^{(*)}\pi\pi l^- \overline{\nu_l}$ with isospin symmetry:

$$BF\left(\bar{B} \to D^{(*)}\pi^-\pi^+ l^- \overline{\nu_l}\right)/BF(\bar{B} \to D^{(*)}\pi\pi l^- \overline{\nu_l}) = (0.50 \pm 0.17)$$
$$\to BF(\bar{B} \to D\pi\pi l^- \overline{\nu_l}) + BF(\bar{B} \to D^*\pi\pi l^- \overline{\nu_l}) = (0.52^{+0.14+0.27}_{-0.07-0.13})\%$$



The incl.-excl. gap was reduced to 2-3σ

New Physics Search with Semitauonic Decays

$\overline{B^0} \rightarrow D^{*+}\tau^-\overline{\nu_\tau}$ with semileptonic tagging (Belle)

Presented at Moriond EW 2016 (arXiv:1603.06711)

$\overline{B^0} \rightarrow \pi^+\tau^-\overline{\nu_\tau}$ with hadronic tagging (Belle)

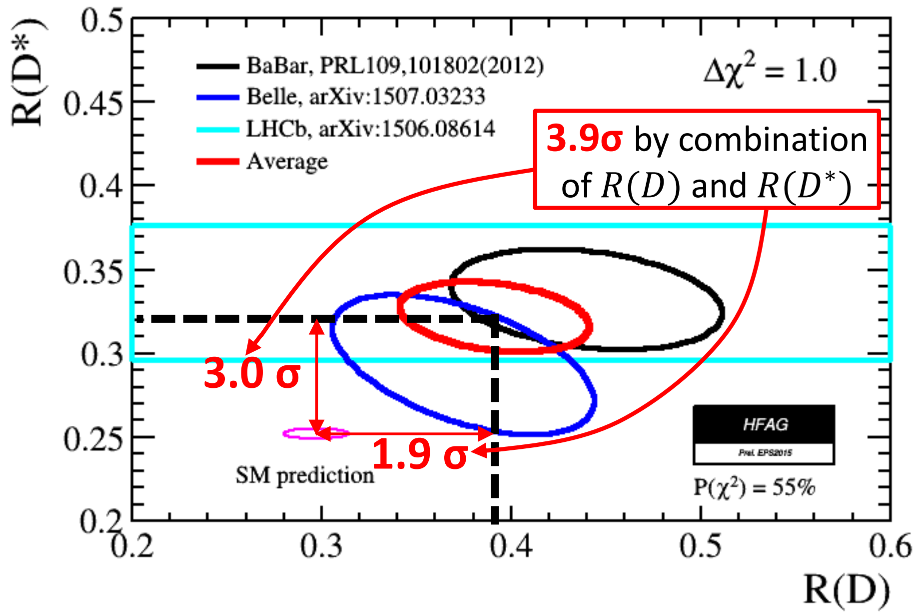
Phys. Rev. D 93, 032007 (2016)

■ $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ as of EPS 2015

- Experimental results from BaBar, Belle and LHCb show about 4σ discrepancy from SM prediction

$$R(D^{(*)}) = \frac{BF(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{BF(\bar{B} \to D^{(*)}l^-\bar{\nu}_l)}$$

Some common systematics are (partly) cancelled out
- Theoretical uncertainty of form factors
- Uncertainty of $|V_{cb}|$
- Experimental uncertainty of efficiencies etc.



http://www.slac.stanford.edu/xorg/hfag/semi/eps15/eps15_dtaunu.html

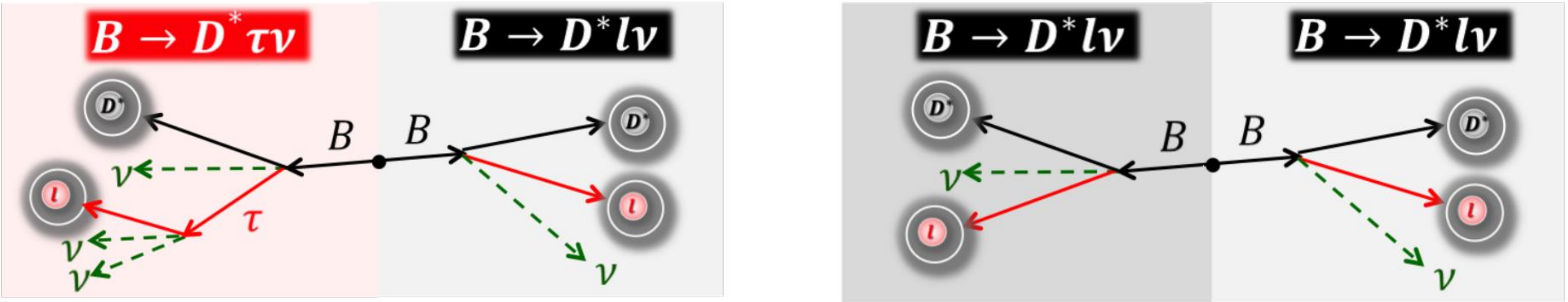
All the past results from B factories utilized hadronic decays for tagging

→Belle released a preliminary result of $R(D^*)$ with semileptonic tag

(First $R(D^{(*)})$ measurement with S.L. tag)

■ Signal Signature

Figures presented at Moriond EW 2016 by P.Goldenzweig
(Image credit: Y, Sato)



Numerator in $\mathcal{R}(D^*)$
→ Signal event

Denominator in $\mathcal{R}(D^*)$
→ Normalization event

- Only $\overline{B^0} \to D^{*+} \tau^- \overline{\nu_\tau}$ was measured as it is the cleanest
- Signal events can be separated from normalization events based on the kinematics: two more ν in the signal

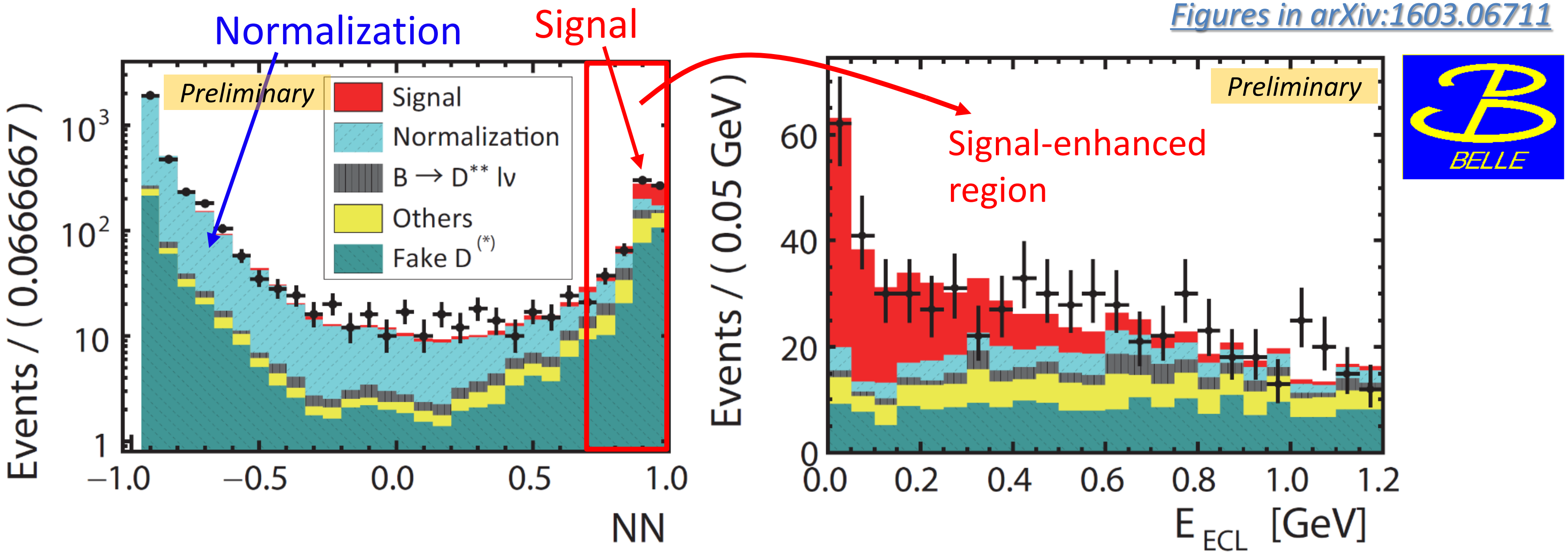
Variable	Signal	Norm.
Missing mass squared (M^2_{miss})	> 0	~ 0
Visible energy: sum of energy used for event recon.	Small	Large
$\cos\theta_{B-D^*l}$	< 0	$[-1, +1]$

→input for multivariate analysis with NeuroBayes

■ Signal Extraction

- Two-dimensional fit to NN and E_{ECL}
  - E_{ECL} = sum of energies on the electromagnetic calorimeter, unused for signal reconstruction → Background tends to be higher

Figures in arXiv:1603.06711



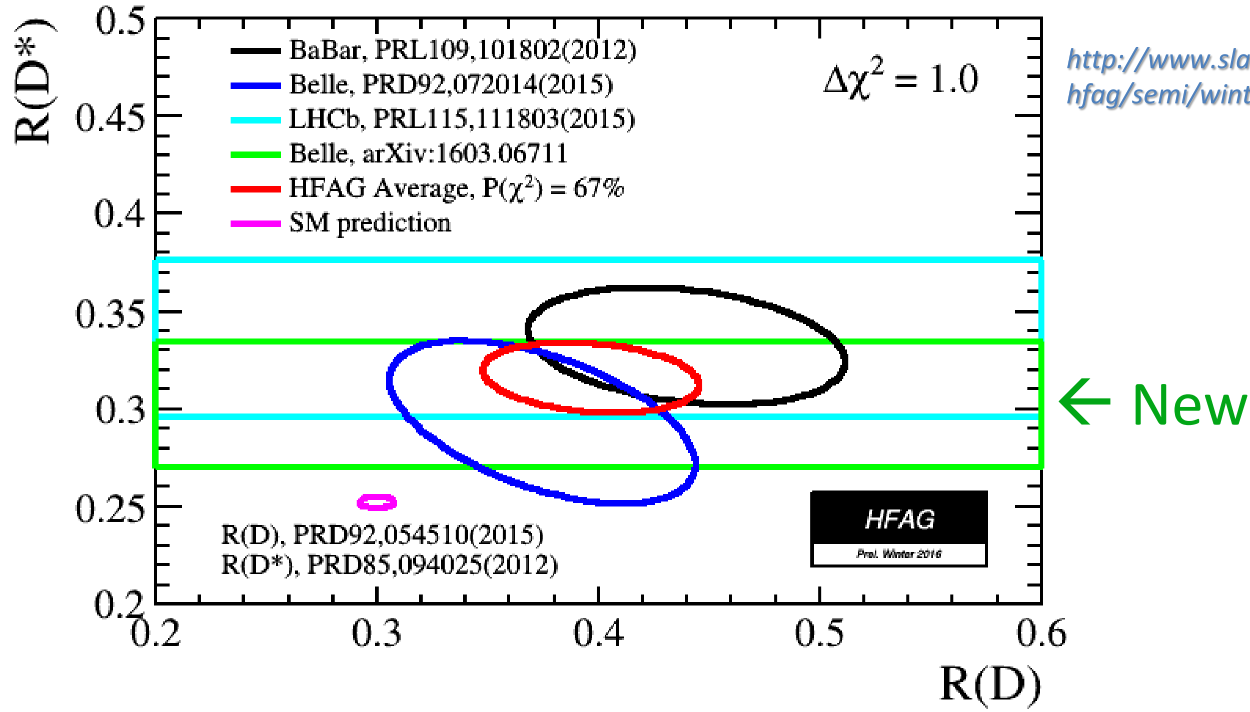
$$R(D^*) = 0.302 \pm 0.030\,(\mathrm{stat}) \pm 0.011(\mathrm{syst})$$

Preliminary

MC stat. for PDF shape
PDF shape of $\bar{B} \rightarrow D^{**} l^- \overline{\nu_l}$
etc.

New $R(D^{(*)})$ Average by HFAG

- HFAG updated the $R(D^{(*)})$ summary
  - The new Belle result is 1.6σ larger than the SM prediction



http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

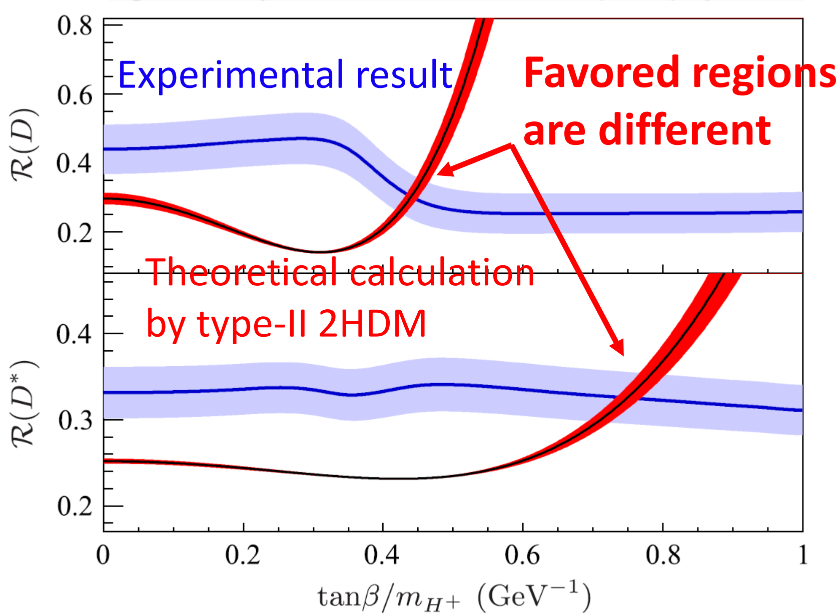
Discrepancies with SM for $\begin{cases} R(D^*) \text{ slightly increased: } 3.0\sigma \rightarrow 3.3\sigma \\ R(D^{(*)}) \text{ slightly increased: } 3.9\sigma \rightarrow 4.0\sigma \end{cases}$

■ NP Test

- NP tests with $R(D^*)$ + D^* and lepton momenta
  - Efficiency was corrected as a function of the model parameter

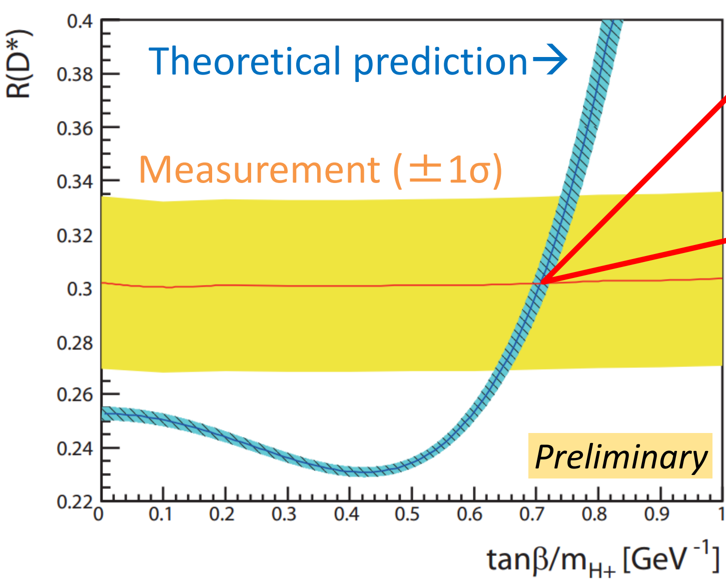
1. Type-II 2 Higgs Doublet Model (Type-II 2HDM)
   - Some SUSY models have the same structure as Type-II 2HDM
   - BaBar excluded the model at 99.8% C.L. → Independent test by Belle
2. Leptoquark as another scenario
   - Part of the phase space is compatible with the results from BaBar

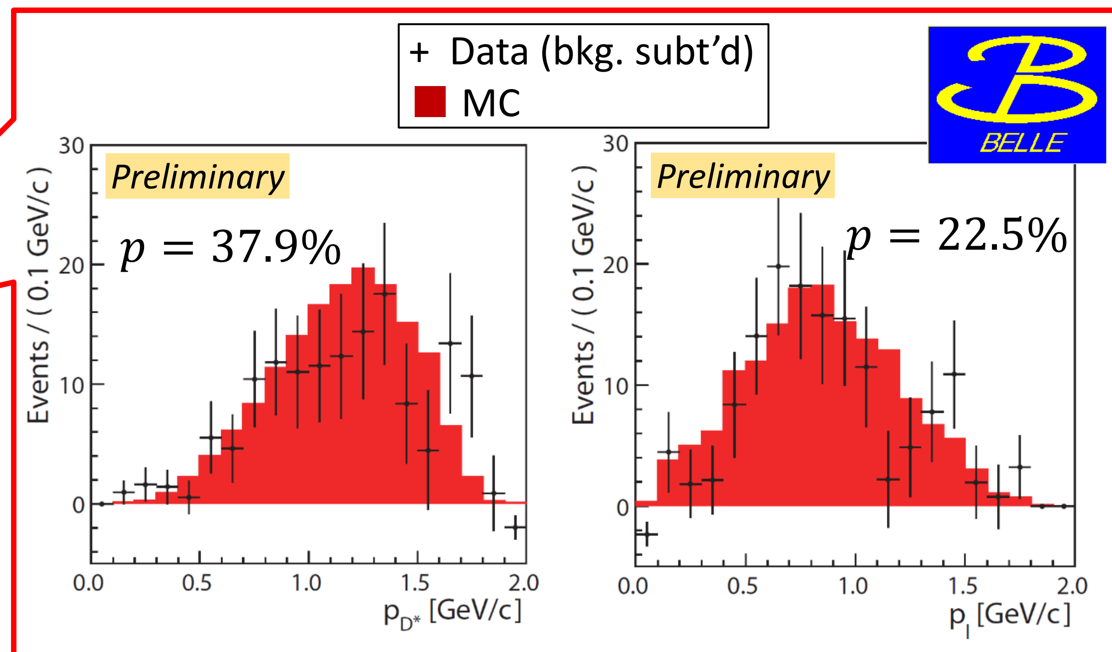
Figure in Phys. Rev. Lett. 109, 101802 (2012) by BaBar



■ NP Model: Type-II 2HDM

- Type-II 2HDM
  - Parameter $\tan\beta/m_{H^+}$
    - $\tan\beta$ = VEV ratio of two Higgs doublets, m_{H^+} = charged Higgs mass
- Our result
  - $R(D^*)$ favors around $\tan\beta/m_{H^+} = 0.7$
  - At $\tan\beta/m_{H^+} = 0.7$, $\boldsymbol{p_{D^*}}$ and $\boldsymbol{p_l}$ distributions are compatible with type-II 2HDM





Figures in arXiv:1603.06711

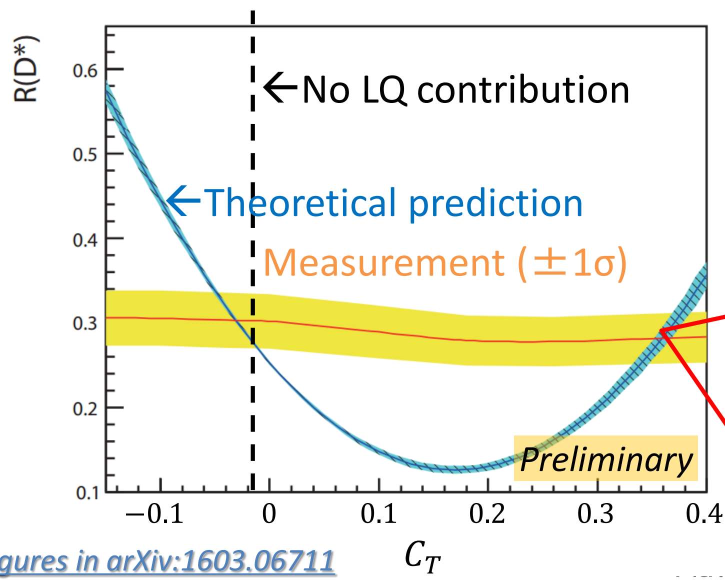
■ NP Model: Leptoquark Model

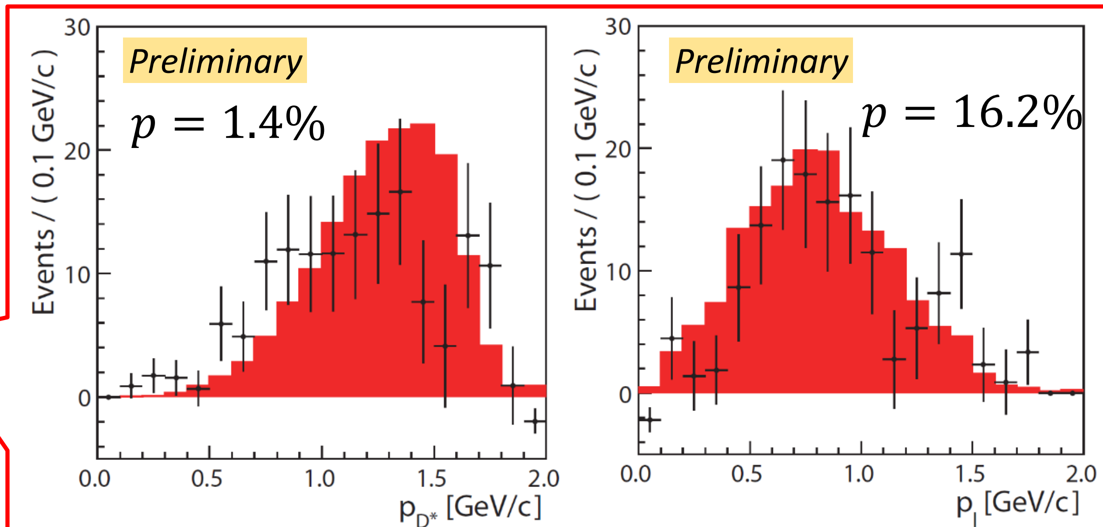
- R_2-type leptoquark model with m_{LQ} = 1 TeV
  - The model is constructed by [Y. Sakaki et al., Phys. Rev. D. 88, 094012 (2013)]
  - Scalar-type (S_2 in the PRD paper) and Tensor-type operators contribute with the relation

Wilson coefficients

$$C_{S_2} = 7.8 C_T$$

- The result favors around $C_T = -0.03$ and $C_T = +0.36$
  - However, at $C_T = +0.36$, $\boldsymbol{p_{D^*}}$ and $\boldsymbol{p_l}$ distributions disfavor the leptoquark model





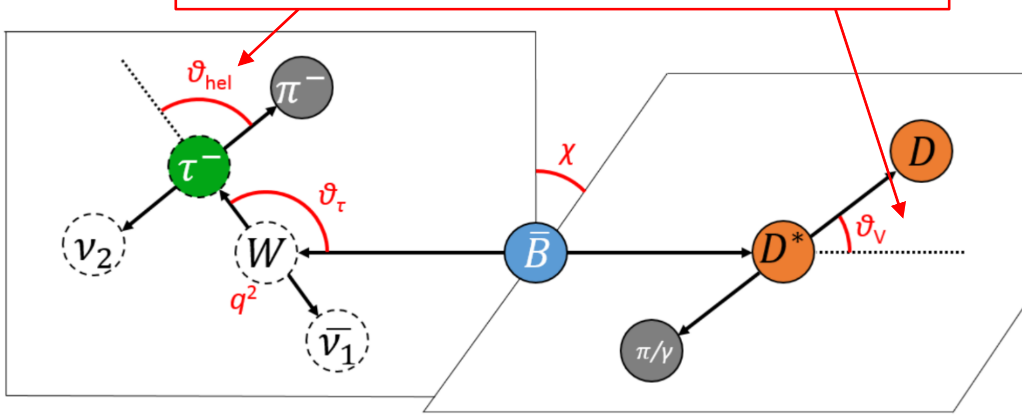
[Figures in arXiv:1603.06711]

■ $\bar{B} \to D^{(*)}\tau^-\overline{\nu_\tau}$ Status at Belle

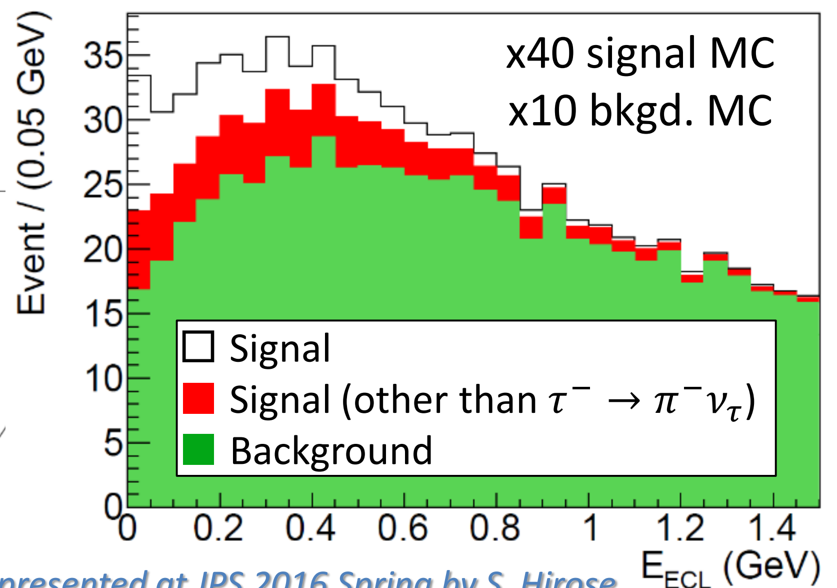
- $\overline{B^0} \to D^{*+}\tau^-\overline{\nu_\tau}$ result with semileptonic tagging is going to be published soon with further NP studies
- Two more $\bar{B} \to D^{*}\tau^-\overline{\nu_\tau}$ analysis are ongoing for summer
  - Hadronic tagging + hadronic τ decays $(\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau)$
  - Inclusive tagging + $\tau^- \to l^-\overline{\nu_l}\nu_\tau, \pi^-\nu_\tau$

→ Both analyses aim at polarization measurement of τ/D^*, which provide additional probes to NP [Theoretical studies in M. Tanaka and R. Watanabe, Phys. Rev. D. 87, 034028 (2013)]

Measure these angular distributions to extract polarizations

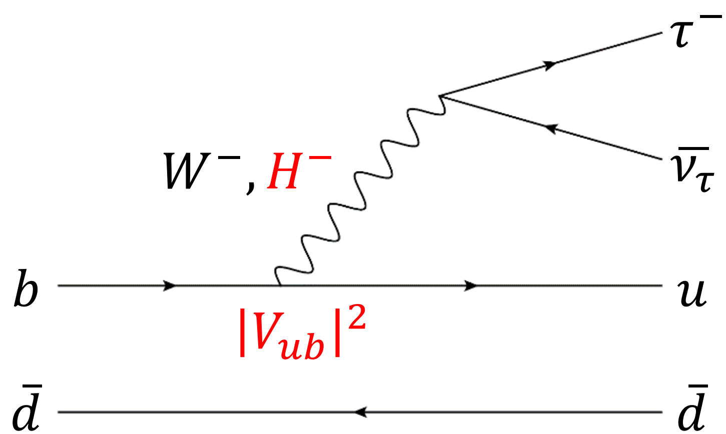


E.g. $(B^-, \tau^- \to \pi^-\nu_\tau)$ for had. τ^- decay analysis



Plot presented at JPS 2016 Spring by S. Hirose

■ $\overline{B^0} \to \pi^+ \tau^- \overline{\nu_\tau}$



- $\overline{B^0} \to \pi^+ \tau^- \overline{\nu_\tau}$ contains b quark and τ^- lepton like $\bar{B} \to D^{(*)} \tau^- \overline{\nu_\tau}$
  - May provide hints to the 4σ discrepancy between experiments and SM prediction in $\bar{B} \to D^{(*)} \tau^- \overline{\nu_\tau}$
- Branching fraction is suppressed by $|V_{ub}/V_{cb}|^2$ compared to $\bar{B} \to D^{(*)} \tau^- \overline{\nu_\tau}$

$$BF\left(\overline{B^0} \to \pi^+ \tau^- \overline{\nu_\tau}\right) = (9.35 \pm 0.38) \times 10^{-5}$$

→ This may be enhanced/diminished by NP effects

Belle performed the first measurement of $\overline{B^0} \to \pi^+ \tau^- \overline{\nu_\tau}$

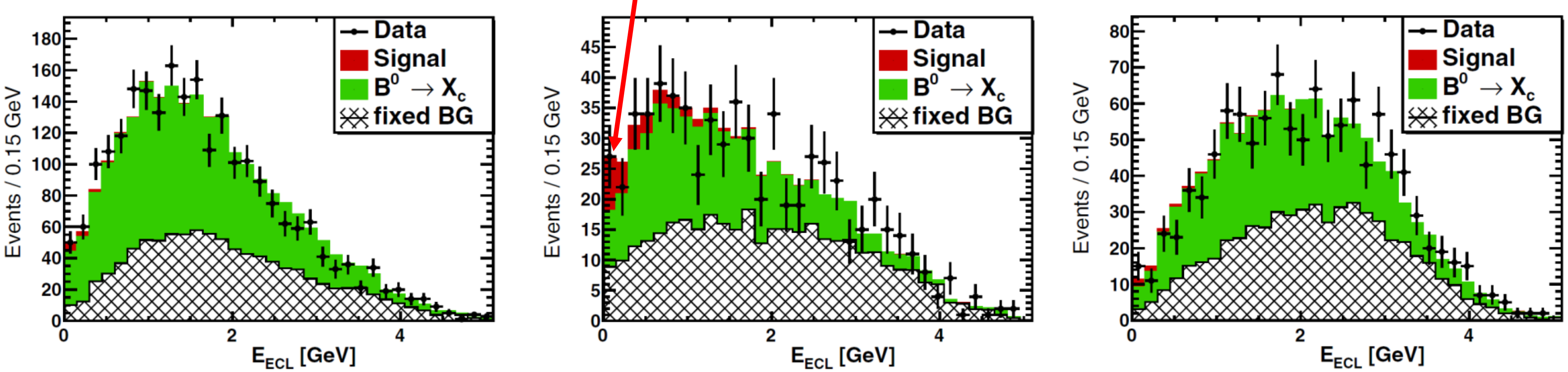
■ $\overline{B^0} \to \pi^+\tau^-\overline{\nu_\tau}$

- Use $\tau^- \to e^-\overline{\nu_e}\nu_\tau, \pi^-\nu_\tau$ and $\rho^-\nu_\tau$ for signal reconstruction
  - Oppositely-charged two particles (and π^0) in the signal side are the sign of the signal
- Signal extraction with E_{ECL}

Signal component: 2.4σ including systematics

(combination of all the τ^- final states)

Figures in Phys. Rev. D 93, 032007 (2016)



$\tau^- \to e^-\overline{\nu_e}\nu_\tau$ $\tau^- \to \pi^-\nu_\tau$ $\tau^- \to \rho^-\nu_\tau$

$$BF\left(\overline{B^0} \to \pi^+\tau^-\overline{\nu_\tau}\right) < 2.8 \times 10^{-4} \text{ @ 95\% C.L.}$$

c.f. $BF\left(\overline{B^0} \to \pi^+\tau^-\overline{\nu_\tau}\right) = (9.35 \pm 0.38) \times 10^{-5}$ for SM

U.L. is not so far from the SM prediction, interesting topic at the early stage of Belle II

Summary and Prospects

- Results for tree-level semileptonic B decays
  - $|V_{cb}|$ determination with $\bar{B} \to D l^- \overline{\nu_l}$ by Belle
  - First observation/evidence of a few $\bar{B} \to D^{(*)} \pi^- \pi^+ l^- \overline{\nu_l}$ decays by BaBar
  - New $\overline{B^0} \to D^{*+} \tau^- \overline{\nu_\tau}$ result by Belle; Semileptonic tag was used for the first time to the semitauonic decay analysis

    → Combined $R(D^{(*)})$ by HFAG show 4.0σ discrepancy with SM
  - Belle set U.L. for $\overline{B^0} \to \pi^+ \tau^- \overline{\nu_\tau}$ for the first time

Belle and BaBar are still active for semileptonic B decays

- Prospects for near future
  - Belle and BaBar continue releasing interesting results at the era that Belle II is starting soon
  - Also, LHCb is a great competitor as they have shown their capability for semileptonic B decay analyses; Interesting news must be provided soon

Hadronic Tagging

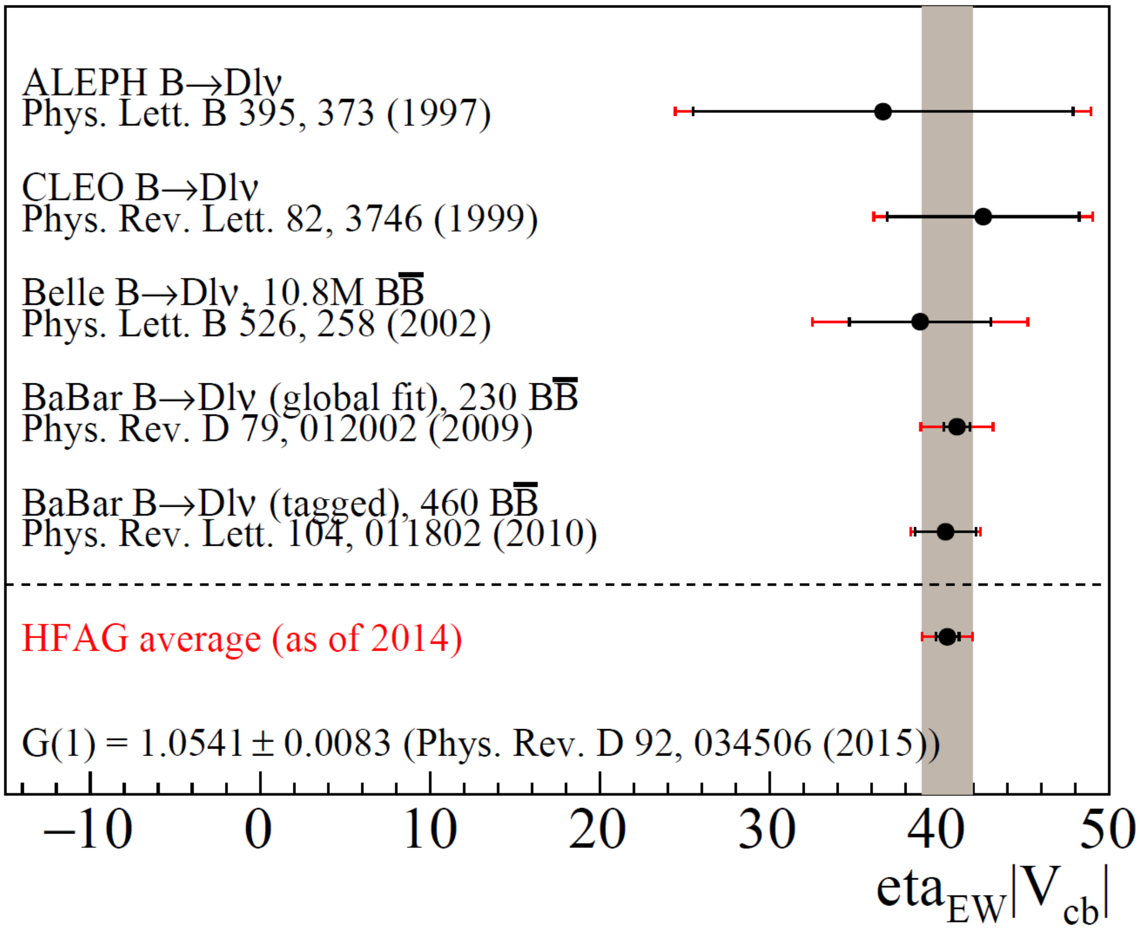
- Comparison between Belle and BaBar

	Belle	BaBar
# of decay chains	1104	1768
Algorithm	Exclusive recon. with NeuroBayes	Semi-inclusive recon.
Recon. eff. (typ.)	0.2% (B^0) 0.3% (B^+)	0.2% (B^0) 0.4% (B^+)

- BaBar uses "semi-inclusive" reconstruction
  - Require $B_{\text{tag}} \to SX^{\pm}$
    - S = Seed meson with a charm ($D, D^*, D_s, D_s^+, J/\psi$)
    - $X^{\pm}$ = charged state with up to five hadrons (K_S^0, $\pi^{\pm}$ and up-to two π^0)
  - Analysis-dependent efficiency/purity adjustment by selecting decay chains

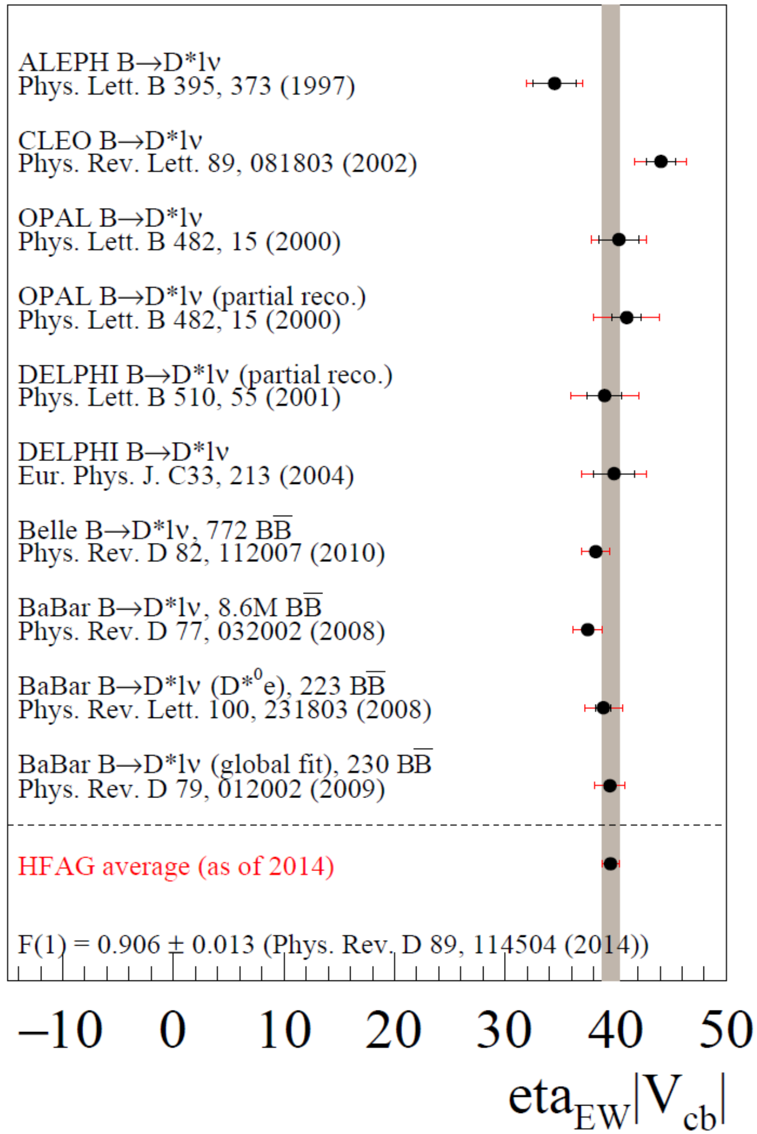
■ $|V_{cb}|$ Measurement by $\bar{B} \to D l^- \bar{\nu}_l$

- Average by HFAG



■ $|V_{cb}|$ Measurement by $\bar{B} \to D^* l^- \overline{\nu_l}$

- Average by HFAG



■ Old vs New $\bar{B} \to D l^- \overline{\nu_l}$ by Belle

- Old analysis in 2002
  - Use missing mass squared by

$$E_{\rm miss} = 2E_{\rm beam} - \Sigma E_i$$
$$\boldsymbol{p}_{\bf miss} = -\Sigma \boldsymbol{p}_i$$
$$M^2_{\rm miss} = E^2_{\rm miss} - |\boldsymbol{p}_{\bf miss}|^2$$

  - Not but hadronic tagging, so systematic error was large while statistical error is small

Large uncertainty arose from imperfection of detector simulation

Table 3
Summary of the relative systematic errors.

Source of uncertainty	$\Delta\|V_{cb}\|F_D(1)$ (%)	$\Delta\hat{\rho}^2_D$ (%)	$\Delta\Gamma$ (%)
ν reconstruction simulation	10.6	9.7	15.5
Correlated background normalization	2.4	4.4	1.9
D^* form factor	1.5	2.8	0.9
Other background normalization	0.6	1.8	0.4
D^+ vertexing efficiency	4.7	5.8	5.3
Lepton finding efficiency	1.5	-	3.0
$N_{B\bar{B}}$	0.5	-	1.0
$Br(D^+ \to K^-\pi^+\pi^+)$	3.3	-	6.7
$\tau_{\bar{B}^0}$	1.0	-	2.1
Total	12.5	12.6	18.2

Phys. Lett. B 526, 258 (2002)

Phys. Rev. D 93, 032006 (2016)

TABLE IV. Itemization of the systematic uncertainty in $\Delta\Gamma_i/\Delta w$ in each w bin. Refer to the main text for more details on the systematic error components.

	$\sigma(\Delta\Gamma_i/\Delta w)(\%)$									
	0	1	2	3	4	5	6	7	8	9
Tag correction	3.0	3.2	3.3	3.4	3.4	3.4	3.4	3.3	3.3	3.2
Charged tracks	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
$\mathcal{B}(D \to \text{hadronic})$	2.0	1.8	1.8	1.8	1.8	1.8	1.8	1.9	1.9	1.9
$\mathcal{B}(B \to D^{*(*)}\ell\nu)$	1.3	0.8	0.8	0.9	0.8	0.7	0.5	0.2	0.2	0.4
$\mathcal{B}(B \to X_u\ell\nu)$	0.4	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
$\text{FF}(B \to D^*\ell\nu)$	0.4	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2
$\text{FF}(B \to D^{**}\ell\nu)$	2.5	1.2	0.9	0.7	0.5	0.5	0.7	0.5	0.1	0.4
Signal shape	5.0	0.8	0.6	0.5	0.5	0.4	0.3	0.3	0.2	0.1
Lifetimes	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
π^0 efficiency	0.9	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7
K/π efficiency	1.1	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0
K_S efficiency	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Luminosity	1.4	1.4	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Total	7.3	4.7	4.7	4.7	4.7	4.6	4.7	4.6	4.5	4.5

BFs by New $\bar{B} \to D l^- \overline{\nu_l}$ Measurement

Sample	Signal yield	$\mathcal{B}$ (%)
$B^0 \to D^- e^+ \nu_e$	$2848 \pm 72 \pm 17$	$2.44 \pm 0.06 \pm 0.12$
$B^0 \to D^- \mu^+ \nu_\mu$	$2302 \pm 63 \pm 13$	$2.39 \pm 0.06 \pm 0.11$
$B^+ \to \bar{D}^0 e^+ \nu_e$	$6456 \pm 126 \pm 66$	$2.57 \pm 0.05 \pm 0.13$
$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$5386 \pm 110 \pm 51$	$2.58 \pm 0.05 \pm 0.13$
$B^0 \to D^- \ell^+ \nu_\ell$	$5150 \pm 95 \pm 29$	$2.39 \pm 0.04 \pm 0.11$
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	$11843 \pm 167 \pm 120$	$2.54 \pm 0.04 \pm 0.13$
$B \to D \ell \nu_\ell$	$16992 \pm 192 \pm 142$	$2.31 \pm 0.03 \pm 0.11$

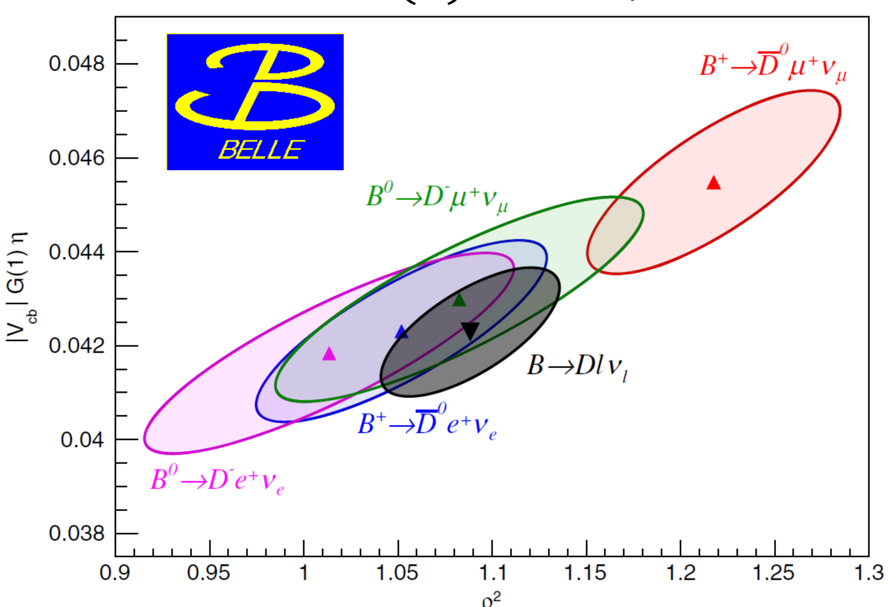
HFAG 2014: $(2.13 \pm 0.03 \pm 0.09)\%$

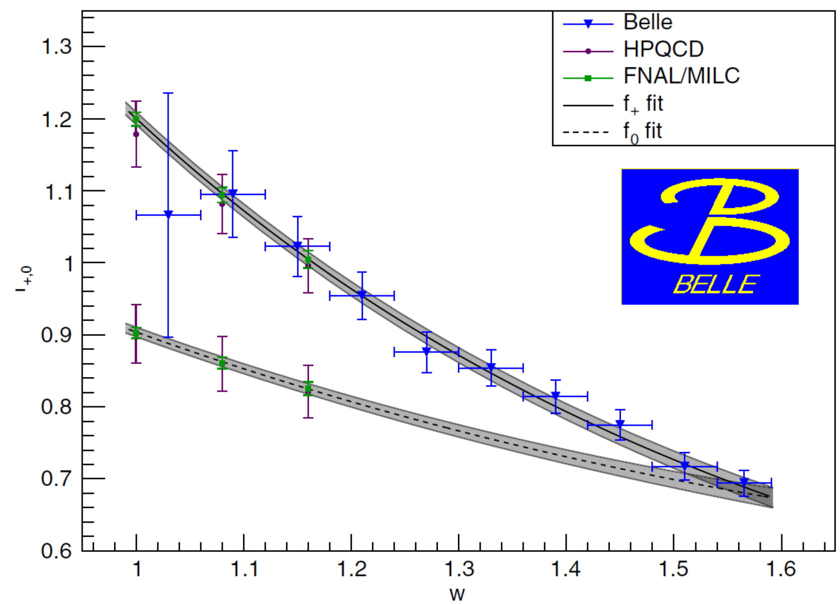
Fit

- Fit parameters are $\eta_{\mathrm{EW}}^2 |V_{cb}|^2 g(1)$ and form factor parameters
- Form factor parameters
  - CLN: ρ for $g(w) = g(1)(1 - 8\rho^2 + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$
  - BGN: $g(w) = \frac{\sqrt{\frac{4m_D}{m_B}}}{1+\frac{m_D}{m_B}} \frac{1}{P_i(z)\varphi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n$

$i = 0, 1, 2$ are determined by LQCD calculation
(Fermilab Lattice and MILC Collaboration, Phys. Rev. D 92, 034506 (2015); HPQCD Collaboration, Phys. Rev. D 92, 054510 (2015))

→ $N = 3(4)$ is used; Combined fit to Belle data and Lattice data





Phys. Rev. D 93, 032006 (2016)

■ Correlation between R(D) and R(D*)

- Because of huge feed-down from B→D*τν to B→Dτν, there is a negative correlation between R(D) and R(D*)
  - If R(D*) looks large, feed-down from B→D*τν to B→Dτν also looks large. Then R(D) looks small.

Figure in Phys. Rev. D 92, 072014 (2015) by Belle

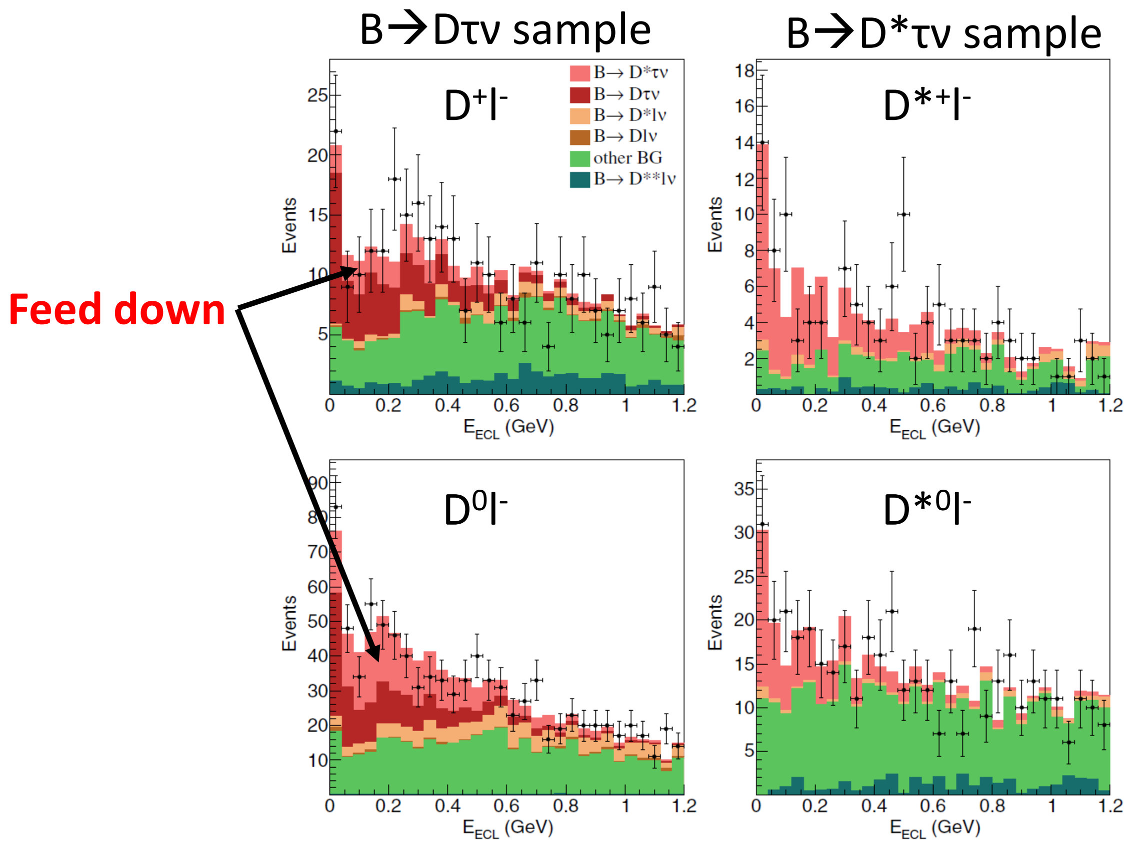
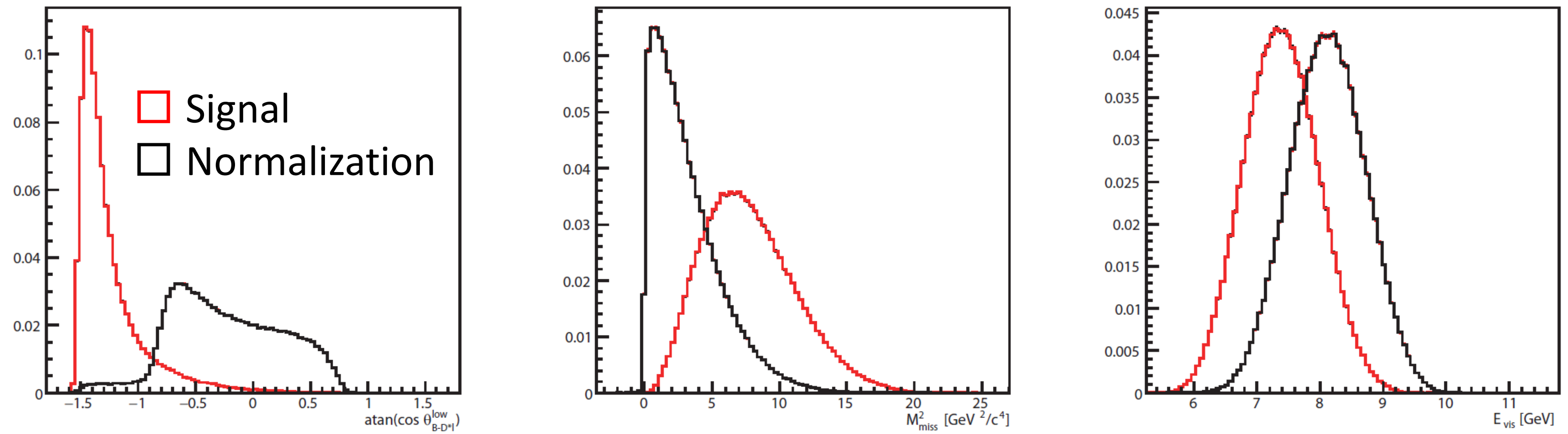


FIG. 4 (color online). Projections of the fit results and data points with statistical uncertainties in a signal-enhanced region of $M^2_{\rm miss} > 2.0\ {\rm GeV}^2/c^4$ in the $E_{\rm ECL}$ dimension. Top left: $D^+\ell^-$; top right: $D^{*+}\ell^-$; bottom left: $D^0\ell^-$; bottom right: $D^{*0}\ell^-$.

■ Distributions to Separate Sig. vs Norm.



Signal Extraction

- Two-dimensional fit to NN and E_{ECL}

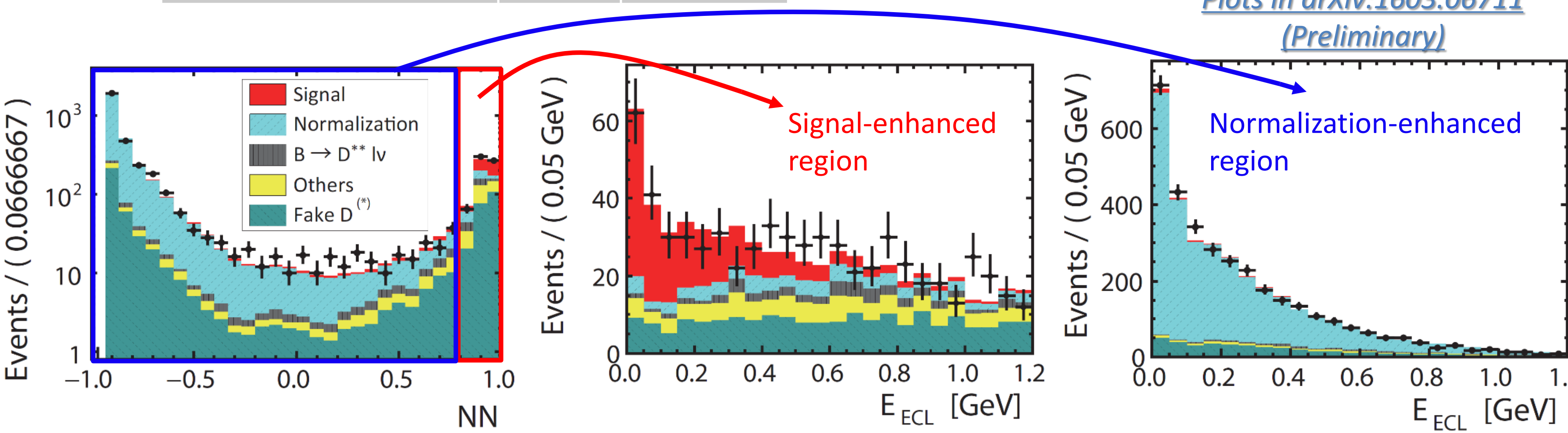
Component	Yield	Shape
Signal	Float	1D x 1D
Normalization	Float	2D
$\bar{B} \to D^{**} l^- \bar{\nu}_l$	Float	2D
Others	Fix	2D
Falsely-recon'd D^*	Fix	2D

Formula for R(D*):

$$R(D^*) = \frac{1}{BF(\tau^- \to l^- \bar{\nu}_l \nu_\tau)} \frac{\varepsilon_{\mathrm{norm}}}{\varepsilon_{\mathrm{sig}}} \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}}$$

$\varepsilon_{\mathrm{norm}}/\varepsilon_{\mathrm{sig}} = 1.289 \pm 0.015$ (by MC)

Plots in arXiv:1603.06711 (Preliminary)



$$R(D^*) = 0.302 \pm 0.030\ (\mathrm{stat})$$

Systematics

- Limited MC statistics caused uncertainties of PDF shapes
  - Evaluated with toy MC studies with changing PDF shapes within their statistical errors
- PDF shape uncertainty for $\bar{B} \to D^{**} l^- \overline{\nu_l}$ arises from poorly known $\bar{B} \to D^{**} l^- \overline{\nu_l} / D^{**}$ branching fractions
  - Varied composition within their uncertainties

Figure presented at Moriond EW 2016 by P.Goldenzweig

	$\mathcal{R}(D^*)$ [%]		
Sources	$\ell^{\rm sig} = e, \mu$	$\ell^{\rm sig} = e$	$\ell^{\rm sig} = \mu$
MC statistics for PDF shape	2.2%	2.5%	3.9%
PDF shape of the normalization	$^{+1.1}_{-0.0}\%$	$^{+2.1}_{-0.0}\%$	$^{+2.8}_{-0.0}\%$
PDF shape of $B \to D^{**} \ell \nu_\ell$	$^{+1.0}_{-1.7}\%$	$^{+0.7}_{-1.3}\%$	$^{+2.2}_{-3.3}\%$
PDF shape and yields of fake $D^{(*)}$	1.4%	1.6%	1.6%
PDF shape and yields of $B \to X_c D^*$	1.1%	1.2%	1.1%
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2%	1.5%	1.9%
Modeling of semileptonic decay	0.2%	0.2%	0.3%
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.2%	0.2%	0.2%
Total systematic uncertainties	$^{+3.4}_{-3.5}\%$	$^{+4.1}_{-3.7}\%$	$^{+5.9}_{-5.8}\%$

$$R(D^*) = 0.302 \pm 0.030\ (\text{stat}) \pm 0.011\ (\text{syst})\ \ (13.8\sigma)$$

(preliminary)

■ NP Model: Leptoquark Model

- Belle also tested the R_2-type leptoquark model

M. Tanaka and R. Watanabe, Phys. Rev. D. 87, 034028 (2013)

Y. Sakaki et al., Phys. Rev. D. 88, 094012 (2013)

TABLE I. Quantum numbers of scalar and vector leptoquarks with $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant couplings.

	S_1	S_3	V_2	R_2	U_1	U_3
spin	0	0	1	0	1	1
$F = 3B + L$	−2	−2	−2	0	0	0
$SU(3)_c$	3^*	3^*	3^*	3	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	1/3	1/3	5/6	7/6	2/3	2/3

Effective Lagrangean for $b \to c\tau^- \overline{\nu_\tau}$ transition

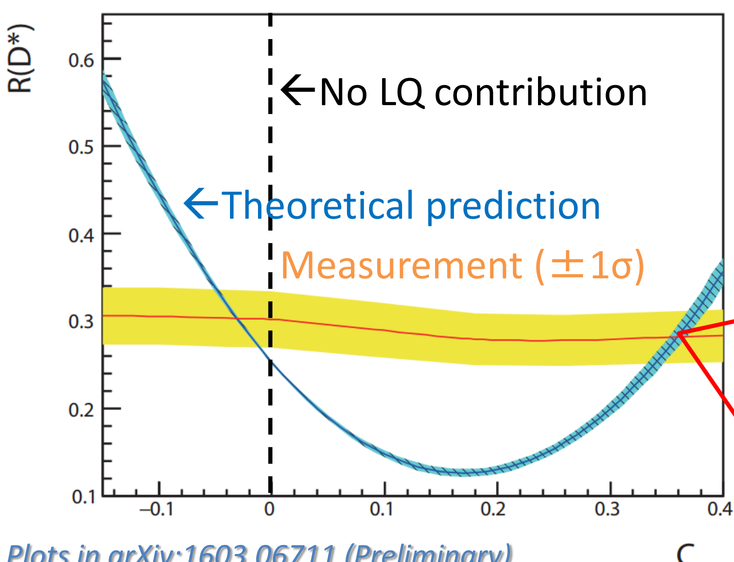
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{cb} \Sigma_{l=e,\mu,\tau}\left[\delta_\tau O_{V_1} + \Sigma_{i=V_1,V_2,S_1,S_2,T} C_i O_i\right]$$

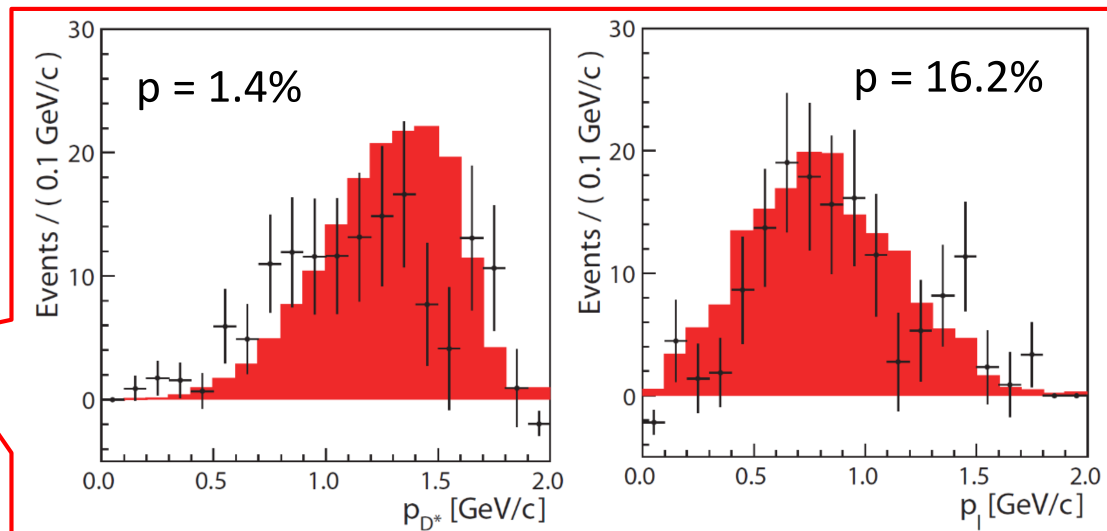
R_2-type LQ model has contribution to S_1 and T currents

$$O_{S_2} = \overline{c_R} b_L \overline{\tau_R} \nu_L$$
$$O_T = \overline{c_R} \sigma^{\mu\nu} b_R \overline{\tau_R} \sigma_{\mu\nu} \nu_L$$

$C_{S_2} = 7.8 C_T$ at m_b scale

- The result supports around $C_T = -0.03$ and $C_T = +0.36$
  - At $C_T = +0.36$, $\boldsymbol{p_{D^*}}$ and $\boldsymbol{p_l}$ distribution look inconsistent



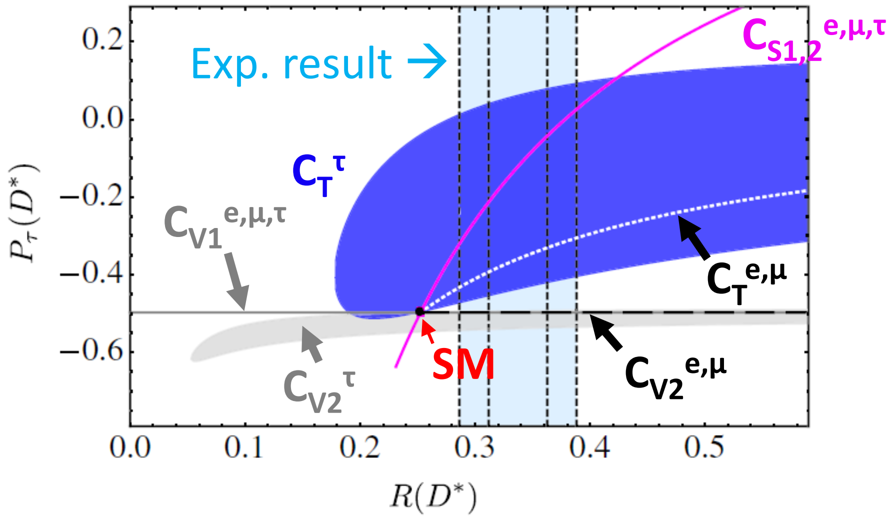


Plots in arXiv:1603.06711 (Preliminary)

■ Motivation of τ Polarization Analysis

M. Tanaka and R. Watanabe, Phys. Rev. D. 87, 034028 (2013)

$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb}\sum_{l=e,\mu,\tau}[(\delta_{l\tau}+C^l_{V_1})\mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T],$$



- Polarizations may give us additional information for 4.0σ discrepancy of R(D(*))

■ Analysis procedure for P τ

- Measure $\cos\theta_{\mathrm{hel}}$ distribution at τ-rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{\mathrm{hel}})$$

τ polarization

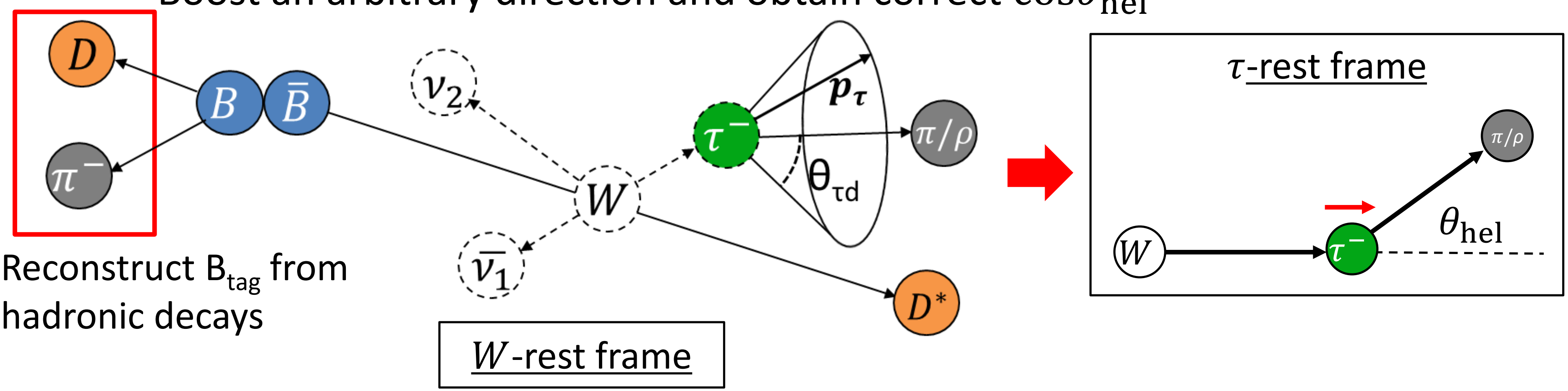
ex. A. Rouge, "Tau decays as polarization analysers" (1990)

- Utilize the W-rest frame instead of the τ-rest frame
  - Where $\boldsymbol{p}_W = \boldsymbol{p}_{B_{\mathrm{sig}}} - \boldsymbol{p}_{D^*} = 0$

    $\boldsymbol{p}_{B_{\mathrm{sig}}} = \boldsymbol{p}_{\mathrm{beam}} - \boldsymbol{p}_{B_{\mathrm{tag}}}$

    $\boldsymbol{p}_{B_{\mathrm{tag}}}$ is obtained by full reconstruction
  - On this frame, τ and $\bar{\nu}_\tau$ fly back-to-back therefore $|\boldsymbol{p}_\tau|$ is fixed

    $\rightarrow \cos\theta_{\tau d} = \frac{2E_\tau E_\pi - m_\tau^2 - m_\pi^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_\pi|}$ can be calculated
- The cone on $\boldsymbol{p}_\tau$ is rotation-symmetric around the direction of π/ρ
  - Boost an arbitrary direction and obtain correct $\cos\theta_{\mathrm{hel}}$



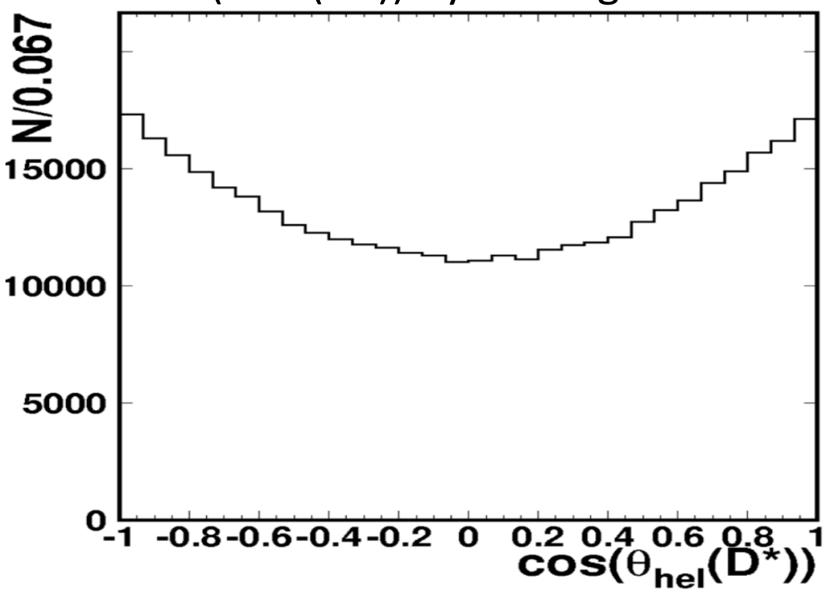
Inclusive Tagging Analysis

- Firstly, reconstruct D* and τ in the signal side → collect all the remaining particle and calculate an invariant mass
  - If the event is signal, the particles except for D* and τ daughter are associated with Btag→ The invariant mass must be equal to m_B

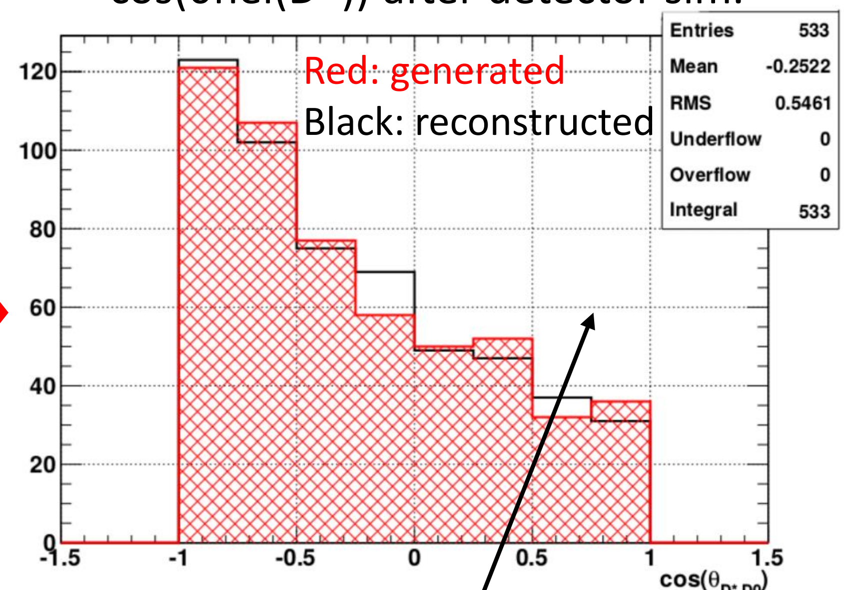
Exploited in two analyses by Belle: PRL 99, 191807 (2007, 535M BB) and PRD 82, 072005 (2010, 657M BB)

- τ polarization and D* measurements with inclusive tagging

cos(θhel(D*)) by event generator



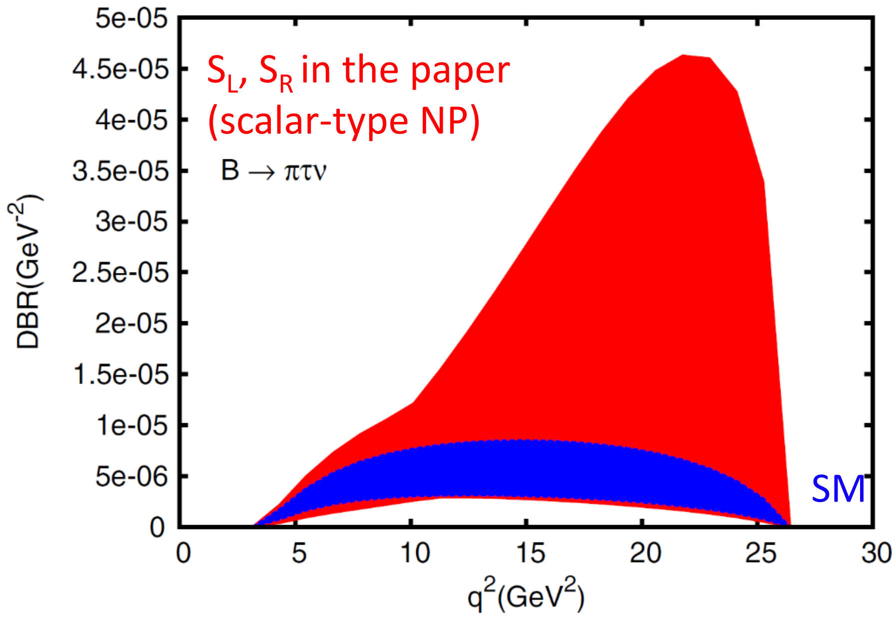
cos(θhel(D*)) after detector sim.



Huge distortion due to inefficiency of slow π+ from D*+→D0π+

Image credit: K. Adamczyk (Belle)

■ NP Example for B→ $\pi\ \tau\ \nu$



- Scalar-type NP can enhance the branching fraction
  - (1.69, 119.66) × 10^{-5}

  →It can reach 10 x BF_{SM} at the max. (= partly the parameter space was excluded by Belle)

R. Dutta et al., PRD 88, 114023 (2013)

■ Two Higgs Doublet Model

	up type	down type	charged lepton
type-I	ϕ_2	ϕ_2	ϕ_2
type-II	ϕ_2	ϕ_1	ϕ_1
type-X	ϕ_2	ϕ_2	ϕ_1
type-Y	ϕ_2	ϕ_1	ϕ_2

Same structure

type-II 2 Higgs Doublet Mode

$$C_{S_1}^{\tau} = -\frac{m_b m_\tau}{m_{H^\pm}^2}\tan^2\beta, C_{S_2}^{\tau} = -\frac{m_c m_\tau}{m_{H^\pm}^2}$$

TABLE II. Parameters $\xi_{d,u}$ in each type of 2HDMs.

	Type I	Type II	Type X	Type Y
ξ_d	$\cot^2\beta$	$\tan^2\beta$	-1	-1
ξ_u	$-\cot^2\beta$	1	1	$-\cot^2\beta$

M. Tanaka and R. Watanabe, PRD 87, 034028 (2013)

■ Leptoquark

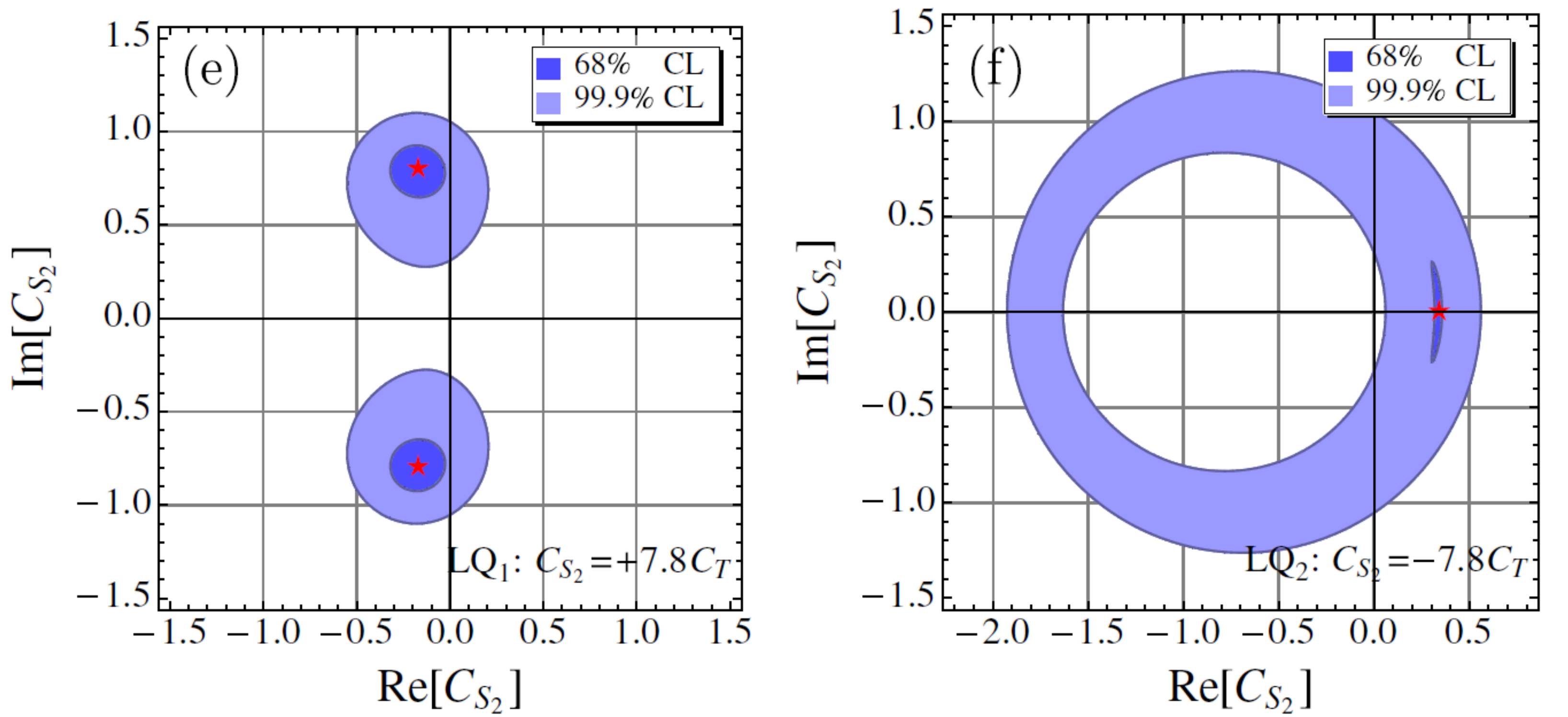
- Leptoquark
  - $C^l_{S_1} \cong \pm 7.8 C^l_T$
  - Some phase spaces are compatible with BaBar results

$$(SU(3)_c \times SU(2)_L \times U(1)_Y) = \begin{cases} (3,2,7/6) & (R_2) \\ (3^*,1,1/3) & (S_1) \end{cases}$$

Y. Sakaki et al., PRD 88, 094012 (2013)

R_2 type

S_1 type
→Might cause instability of protons



Y. Sakaki et al., PRD 91, 114028 (2015)