Flavor Physics & CP Violation
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The tau lepton in B decays

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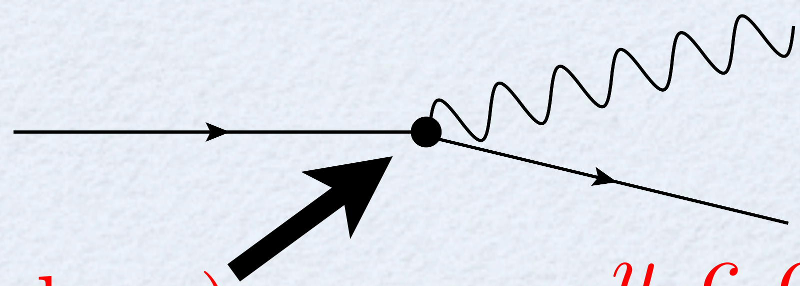
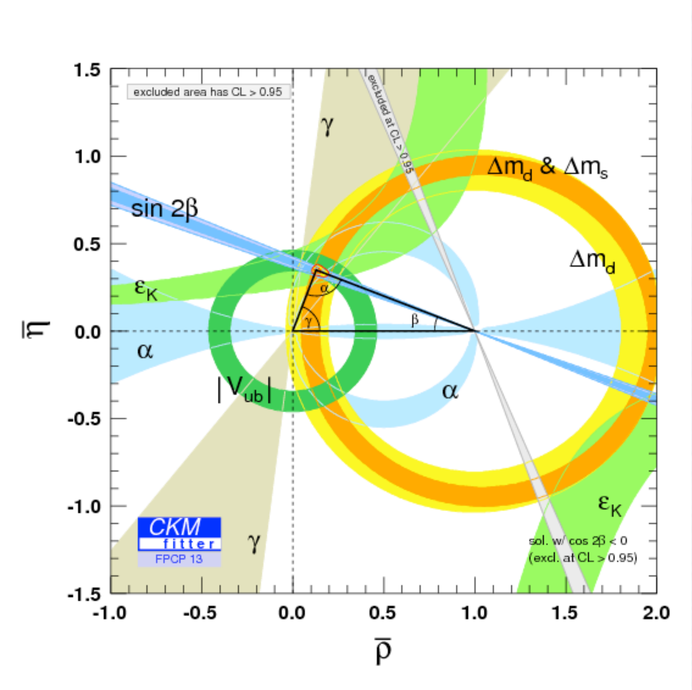
Prologue...

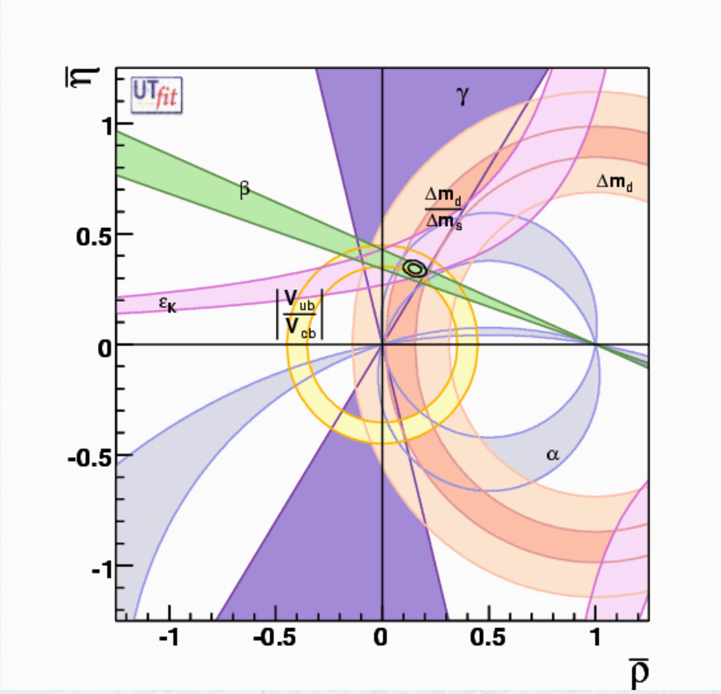
B meson decays have been used to investigate **the flavor structure** in the quark sector due to their various final states.



Structure: $V_{\mathrm{CKM}}\ (\times \mathrm{loop})$

Belle & BABAR have measured a lot of processes, studied them, and then found the validity of large part of **flavor structure in SM**.





Prologue...

Among them, **B decays with "tau lepton"** have special meanings.

Because...

- **3rd generation is important clue to new physics beyond SM**

  → **Potentially sensitive to new physics**

- **Some particular kind of analysis is required for the measurement**

  → **Challenging task to identify the tau lepton in the final state**

Conceivable decay modes:

- **Already measured:**

  $\bar{B} \to \tau\bar{\nu}, \quad \bar{B} \to D\tau\bar{\nu}, \quad \bar{B} \to D^*\tau\bar{\nu}$ **Today's topic**

- **Not (yet) measured:**

  $\bar{B} \to (\pi, D^{**})\tau\bar{\nu},\ B_c \to (X)\tau\bar{\nu},\ B_{(s)} \to (X)\tau\,\tau,$ ...etc.

[See, for example, Biancofiore et. al. arXiv:1302.1042]

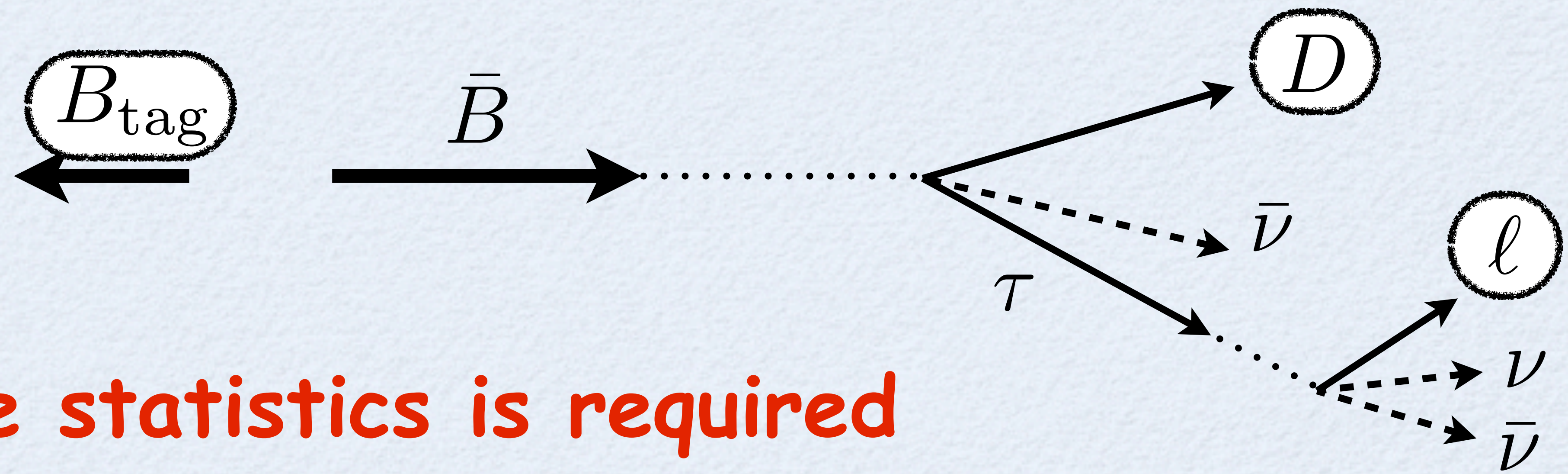
Content

- **Review on tauonic B decays**
  - Theory
  - Experiment
- **New physics**
  - Effective operator analysis
  - Several models
- **Observables**
  - Asymmetry, polarization
  - CP violation
- **Near future prospects**
  - q^2 distribution

Review on tauonic B decays

Tau in a final state

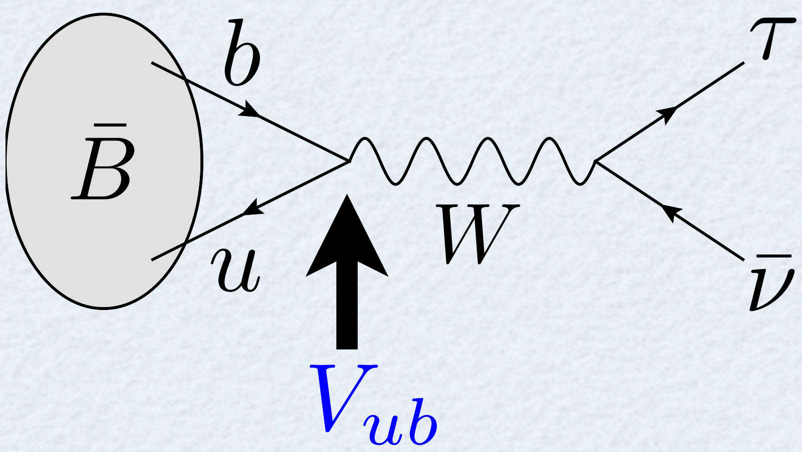
- It is challenging to measure tauonic B meson decays, because **more than 2 neutrinos go through the detector**.
- At B factory, however, reconstructing the opposite B mesons we can compare the properties of the remaining particles to those expected for signal and background: **"Full reconstruction"** .



Large statistics is required even for tree level process

Status on B→τν

- Tree level process via V_{ub} in the SM



$$\mathcal{B}(\bar{B} \to \tau\bar{\nu}) = \frac{|V_{ub}|^2 f_B^2}{8\pi\tau_B} G_F^2 m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2$$

* Latest average: $f_B = (190.5 \pm 4.2)\mathrm{MeV}$

[FLAG, arXiv:1310.8555]

- Experimental result & determination of $|V_{ub}|$ [BABAR2012, Belle2012]

	BABAR	Belle	CKM fit
$\mathcal{B}(\bar{B} \to \tau\bar{\nu}) \times 10^4$	1.79 ± 0.48	0.96 ± 0.26	1.14 ± 0.23
$\lvert V_{ub}\rvert \times 10^3$	5.28 ± 0.72	3.87 ± 0.53	3.38 ± 0.15

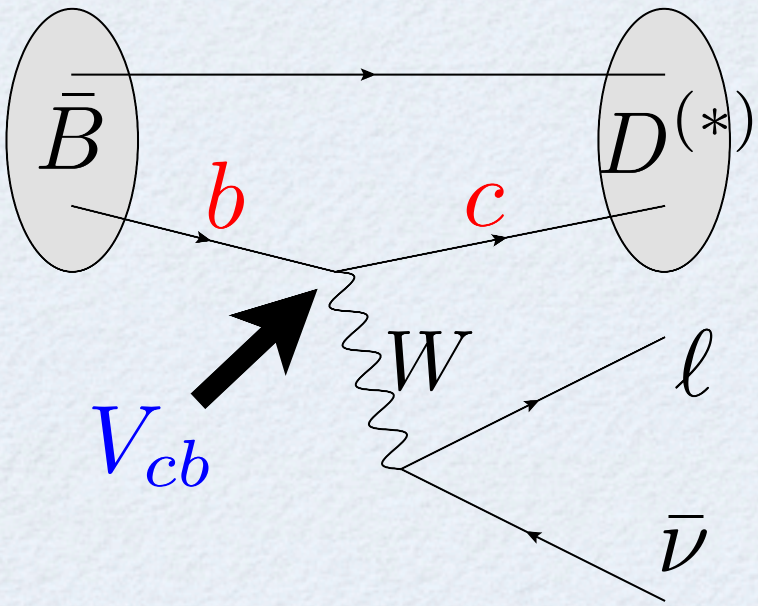
* Combination of "semi-leptonic tag" & "hadronic tag" for B_{tag}

* Discrepancy in determination of $|V_{ub}|$ is one of most important issues. But today, I don't go deeply into it.

On average, data is in (good) agreement with SM

Status on B→Dτν & B→D*τν

- **Tree level process via V_{cb} in the SM**



$$\mathcal{B}(\bar{B} \to D\tau\bar{\nu}) \propto |V_{cb}|^2 \mathcal{G}(1)^2 \times \{\text{function of } \rho_1^2\ \}$$

$$\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu}) \propto |V_{cb}|^2 \mathcal{F}(1)^2$$
$$\times\{\text{func. of } \rho_{A_1}^2,\ R_1(1),\ R_2(1)\ \}$$

* D=pseudo-scalar, D*=vector

* $\mathcal{G}$, $\mathcal{F}$, ρ^2, R are FF parameters

- **Hadronic uncertainty and measurement**

V_{cb} & FF parameters are obtained by a fit to distributions of $\bar{B} \to D^{(*)}\ell\bar{\nu}$ for $\ell = e$ or μ. For an observable of $\bar{B} \to D^{(*)}\tau\bar{\nu}$, normalized decay rate;

$$R(D) = \frac{\Gamma(\bar{B} \to D\tau\bar{\nu})}{\Gamma(\bar{B} \to D\ell\bar{\nu})} \qquad R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau\bar{\nu})}{\Gamma(\bar{B} \to D^*\ell\bar{\nu})}$$

is used in order to cancel $|V_{cb}|\mathcal{G}(1)$, $|V_{cb}|\mathcal{F}(1)$ and reduce FF uncertainties.

Status on $B \to D\tau\nu$ & $B \to D^*\tau\nu$

- **Experimental result** [Belle private combination, BABAR in arXiv:1205.5442]

Normalized decay rate: $R(D) = \frac{\Gamma(\bar{B} \to D\tau\bar{\nu})}{\Gamma(\bar{B} \to D\ell\bar{\nu})}$ $R(D^*) = \frac{\Gamma(\bar{B} \to D^*\tau\bar{\nu})}{\Gamma(\bar{B} \to D^*\ell\bar{\nu})}$

	Belle	BABAR	SM
$R(D)$	0.430 ± 0.091	$0.440 \pm 0.058 \pm 0.042$	0.297 ± 0.017
$R(D^*)$	0.405 ± 0.047	$0.332 \pm 0.024 \pm 0.018$	0.252 ± 0.003
correlation	neglected	-0.27	-

Status on B→Dτν & B→D*τν

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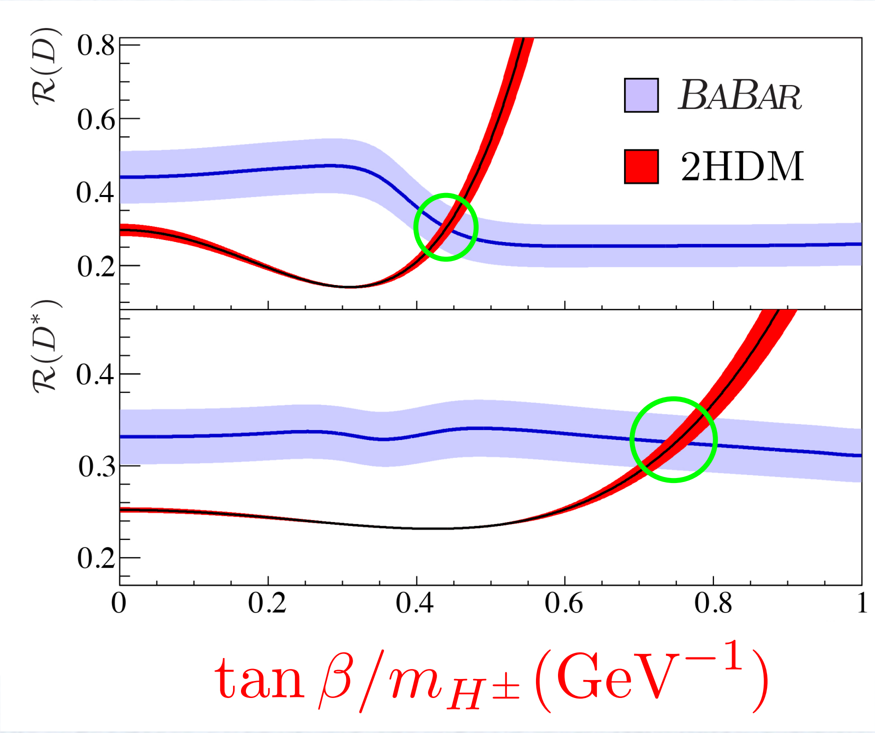
BABAR analysis:



3.4σ deviation from SM!

* reported by BABAR
* 2.0σ for R(D), 2.7σ for R(D*)

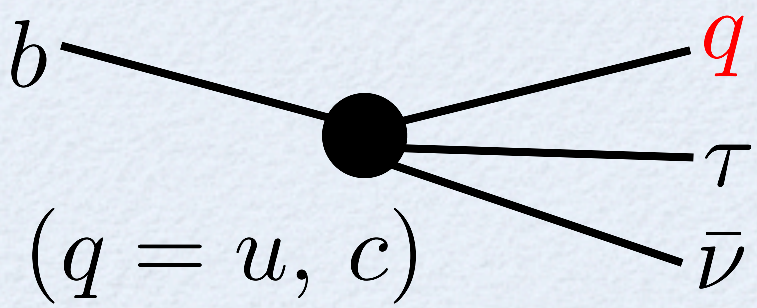
Type-II 2HDM is disfavored

* Charged Higgs can contribute
* cannot explain data at the same time

New physics

(Very quick review)

Model independent analysis



$$\mathcal{L}_{\rm eff} = -2\sqrt{2} G_F V_{qb} \Big[(1 + C^q_{V_1}) \mathcal{O}^q_{V_1} + C^q_{V_2} \mathcal{O}^q_{V_2} + C^q_{S_1} \mathcal{O}^q_{S_1} + C^q_{S_2} \mathcal{O}^q_{S_2} + C^q_T \mathcal{O}^q_T \Big]$$

- **Effective operators**

Vector1: $\mathcal{O}^q_{V_1} = \bar{q}_L \gamma^\mu b_L\, \bar{\tau}_L \gamma_\mu \nu_L$

Vector2: $\mathcal{O}^q_{V_2} = \bar{q}_R \gamma^\mu b_R\, \bar{\tau}_L \gamma_\mu \nu_L$

Tensor: $\mathcal{O}^q_T = \bar{q}_R \sigma^{\mu\nu} b_L\, \bar{\tau}_R \sigma_{\mu\nu} \nu_L$

Scalar1: $\mathcal{O}^q_{S_1} = \bar{q}_L b_R\, \bar{\tau}_R \nu_L$

Scalar2: $\mathcal{O}^q_{S_2} = \bar{q}_R b_L\, \bar{\tau}_R \nu_L$

- **Wilson coefficients**

Cx represent "New Physics" contribution normalized by SM contribution

No right-handed neutrino is assumed.

- **Bound on operator $\mathcal{O}_X^u$ from Br(B→τν)** [RW, in my PhD thesis]

NP contribution: $\mathcal{B}(\bar{B} \to \tau\bar{\nu}) = \left|1 + r_{\rm NP}\right|^2 \cdot \mathcal{B}(\bar{B} \to \tau\bar{\nu})_{\rm SM}$

Allowed range: $|1 + r_{\rm NP}|^2 = 1.24 \pm 0.16$

where $r_{\rm NP} = C_{V_1}^u - C_{V_2}^u + \dfrac{m_B^2}{m_b m_\tau}\left(C_{S_1}^u - C_{S_2}^u\right)$

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NP contribution is limited,

but large error (~13%) is still involved

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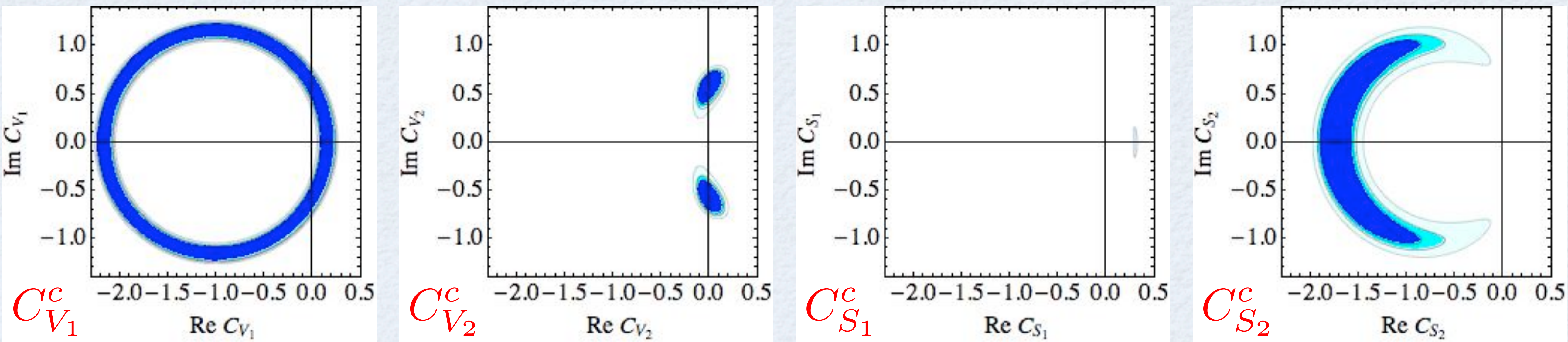
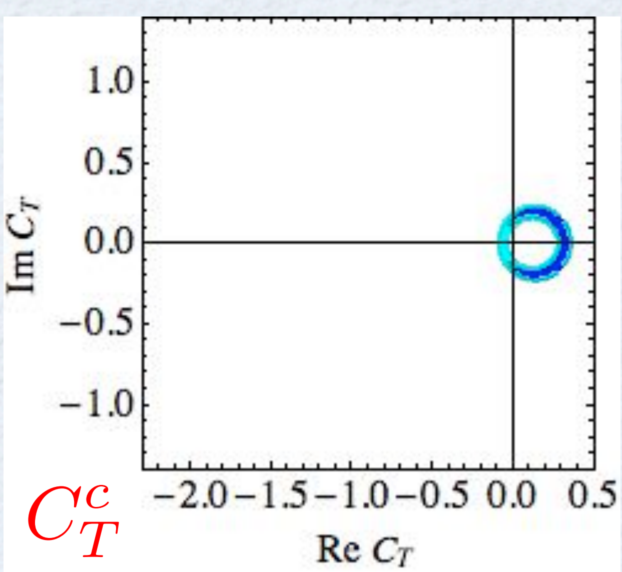
- **Bound on operator $\mathcal{O}_X^c$ from R(D) & R(D*)** [M.Tanaka&RW, arXiv:1212.1878]





* assuming one operator dominance (ex: $C_{S_2} \neq 0, \ \text{others} = 0$)

* using the data which is the average of Belle & BABAR

* allowed at 90%(Light blue), 95%(Cyan), 99%(Dark blue)

- **Bound on operator $\mathcal{O}_X^u$ from Br(B→τν)** [RW, in my PhD thesis]

NP contribution: ...

Allowed ...

where $r_{NP} = C_{V_1} - C_{V_2} + \frac{\cdots}{m_b m_\tau}(C_{S_1} - C_{S_2})$

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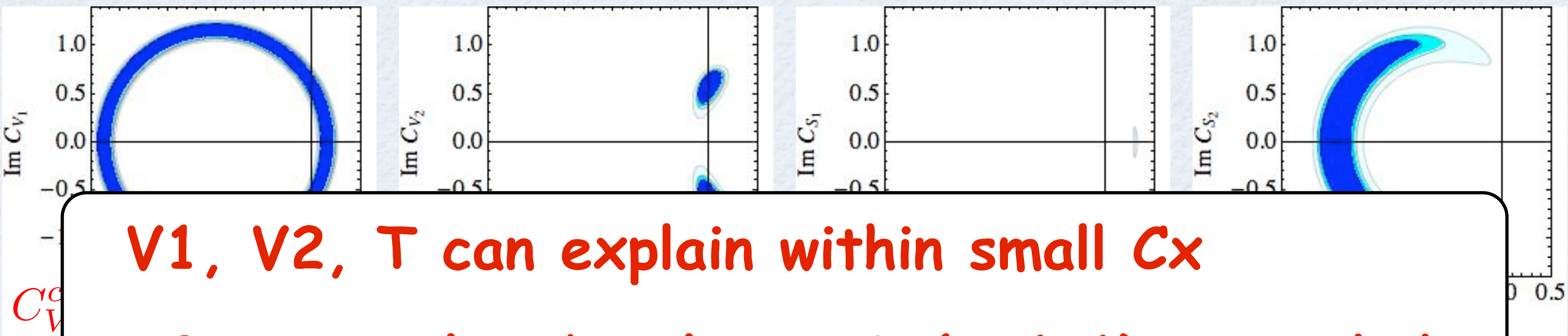
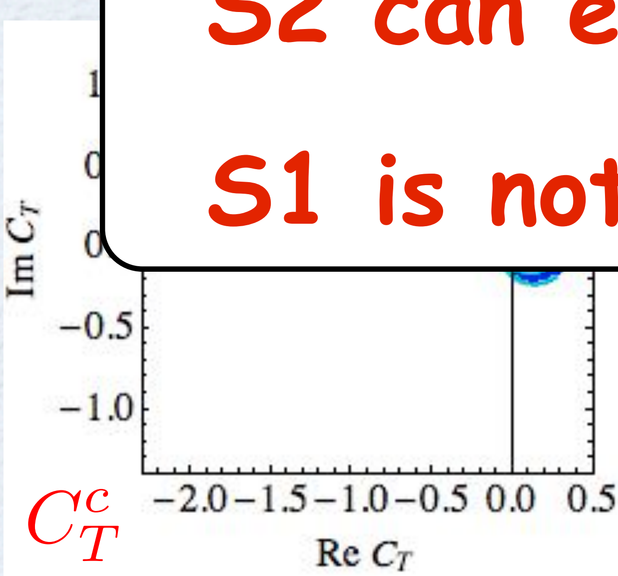




V1, V2, T can explain within small Cx

S2 can explain but large C_{S_2}(~-1.6) is needed

S1 is not preferred

* using the data which is the average of Belle & BABAR

* allowed at 90%(Light blue), 95%(Cyan), 99%(Dark blue)

2 Higgs Doublet Models

- **Type of 2HDM**

In order to forbid **tree level FCNC**,

only one of two Higgs doublets couples to each fermion doublet:

$$\mathcal{L}_{\text{yukawa}} = -\bar{Q}_L Y_u \tilde{H}_u u_R - \bar{Q}_L Y_d H_d d_R - \bar{L}_L Y_\ell H_\ell \ell_R + \text{h.c.}$$

*** H_1 or H_2 is assigned to H_u, H_d, and H_l one by one**

As a result, there are 4 distinct types for Yukawa structure:

Type I : $H_2 = H_u = H_d = H_\ell$

Type II : $H_2 = H_u,$ $\qquad H_1 = H_d = H_\ell$

Type X : $H_2 = H_u = H_d,$ $\qquad H_1 = H_\ell$

Type Y : $H_2 = H_u = H_\ell,$ $\qquad H_1 = H_d$

[X,Y is named by Kanemura et. al. arXiv0902.4665]

2 Higgs Doublet Models

- **Corresponding Wilson coefficients**

$$C^u_{S_1} = C^c_{S_1} = -\frac{m_b m_\tau}{m^2_{H^\pm}}\xi_1\,, \quad C^u_{S_2} = -\frac{m_u m_\tau}{m^2_{H^\pm}}\xi_2\,, \quad C^c_{S_2} = -\frac{m_c m_\tau}{m^2_{H^\pm}}\xi_2$$

* Charged Higgs contributes

* ξ depends on the type:

	Type I	Type II	Type X	Type Y
ξ_1	$\cot^2\beta$	$\tan^2\beta$	-1	-1
ξ_2	$-\cot^2\beta$	1	1	$-\cot^2\beta$

* For S1, "u"&"c" have the same contribution

* For S2, "u" is suppressed, and thus "c" has independent contribution

- **Bound**

For S1, same contribution in "u"&"c" is apparently not favored according to model independent analysis.

For S2, Best fit $C^c_{S_2}$~-1.6 from R(D) & R(D*) then,

TypeI & Y are unlikely, because they cannot have negative C_{S_2}

TypeII & X are disfavored, because $\xi_2 = 1,\ m_{H^\pm} \sim \mathcal{O}(1)\,\mathrm{GeV}$

2HDM with tree level FCNC

V_1 V_2 S_1 S_2 T

"S2 enhancement" can be realized allowing FCNC : [Crivellin et. al. arXiv:1206.2634]

ex.) $$\mathcal{L}_{\rm yukawa} = -\bar{Q}_L Y_u \tilde{H}_2 u_R - \bar{Q}_L Y_d H_1 d_R - \bar{L}_L Y_\ell H_1 \ell_R + {\rm h.c.}$$
$$-\bar{Q}_L \epsilon'_u \tilde{H}_1 u_R - \bar{Q}_L \epsilon'_d H_2 d_R + {\rm h.c.}$$

* ε is coupling that control FCNC in the weak basis
* Constraint on FCNC in up-quark sector εu is rather weak

S2 type contribution to B→D(*) τ ν : $C^c_{S_2} \simeq \frac{V_{tb}}{\sqrt{2}V_{cb}} \frac{v m_\tau}{m^2_{H^\pm}} (\epsilon^*_u)^{tc} \sin\beta \tan\beta$

Best fit value is $\epsilon^{tc}_u \sim -0.7$ **with** $m_{H^\pm} = 500{\rm GeV},\ \tan\beta = 50$

We may predict top FCNC decay such as t→ch

* $\mathrm{Br}(t \to ch) \simeq 0.12 \times |\epsilon^{tc}_u|^2 \cos^2(\alpha - \beta) \simeq 0.06 \times \cos^2(\alpha - \beta)$
* **Observed limit at 14TeV LHC of 100fb^-1:** $\mathrm{Br}(t \to ch) < 4.1 \times 10^{-5}$

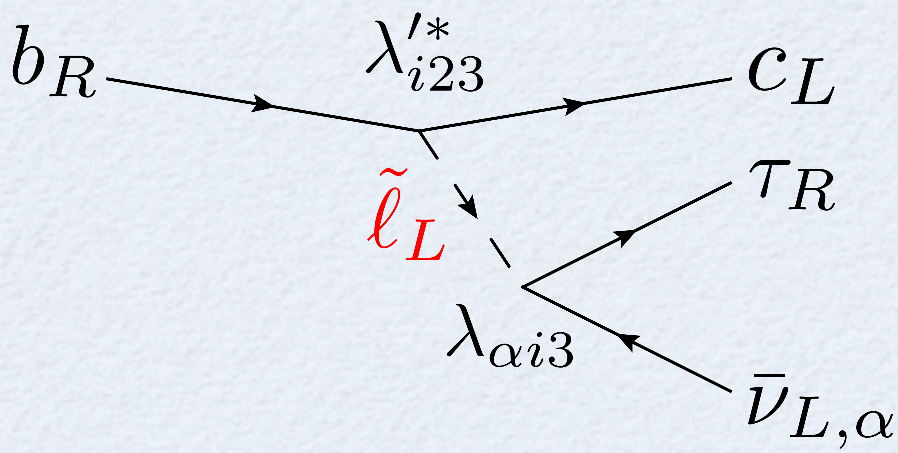
[J. Aguilar-Saavedra, hep-ph/0409342]

R Parity Violation

V_1 V_2 S_1 S_2 T

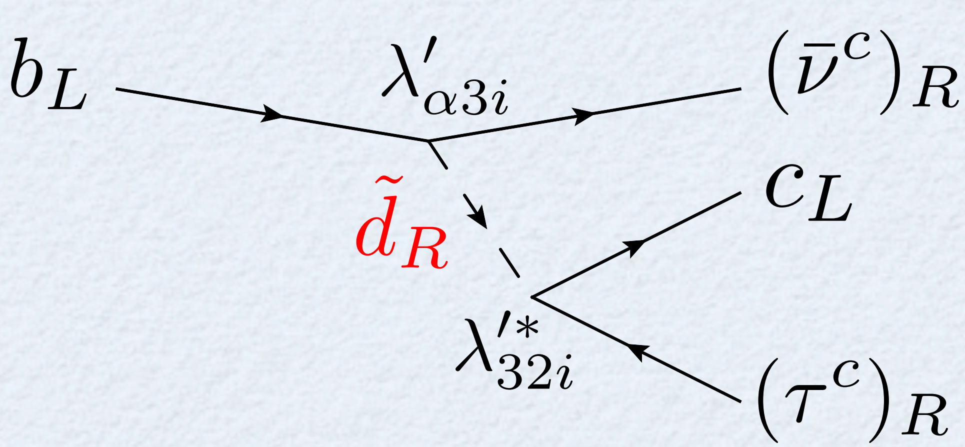
Only considering a contribution to B→D(*) τ ν

Superpotential: $W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k$



correspond to S1,

then this is disfavored



correspond to V1,

It is likely to explain the results,

but incompatible with B→X$_s$νν:

$$\mathcal{B}(B \to X_s \nu \bar{\nu}) < 6.4 \times 10^{-4}$$

[ALEPH collaboration, hep-ex/0010022]

Lepto Quark

$V_1 \quad V_2 \quad S_1 \quad S_2 \quad T$

Only considering a contribution to B→D(*) $\tau\ \nu$

Classification of interaction: **4 independent types generated**

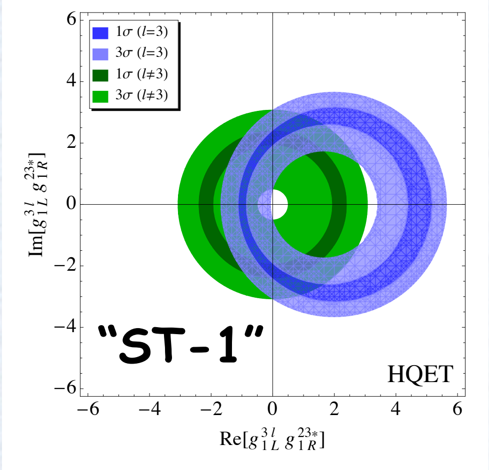
[Tanaka et. al. arXiv:1309.0301]

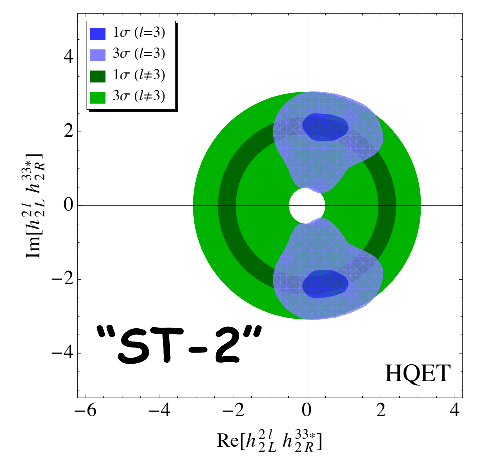
Scalar1: disfavored according to model indep. analysis

Vector1: incompatible with B→X_sνν, as well as RPV

Scalar2-Tensor: both C_{S_2}&C_T appear at the same time

"ST-1" $C^c_{S_2} = 4C^c_T$ "ST-2" $C^c_{S_2} = -4C^c_T$ @LQ scale





* Green: $\nu_{\ell\neq\tau}$ Blue: ν_τ
* No other constraint

They are likely to explain the data

New physics: summary

2 Higgs Doublet Model: V_1 V_2 S_1 S_2 T

- Usual 2HDM cannot explain the recent R(D)&R(D*)
- FCNC induced S2 can explain them

R Parity Violation: V_1 V_2 S_1 S_2 T

- S1 type is generated, and is disfavored
- V1 type is generated, but it is incompatible with $B \to X_s \nu\nu$

Lepto Quark: V_1 V_2 S_1 S_2 T

- S1&V1 type are generated and disfavored as well as RPV
- S2-T types are generated and likely to explain the results

Observables

New physics analyzer

- Compared with two body decay; $B\to\tau\nu$,
  many more observables are available in three body decays; $B\to D^{(*)}\tau\nu$

- Actually, there are several studies for NP search using such observables
  (q^2 distributed and/or integrated)

Asymmetry:

Pick up

for CP violation
in $B\to D\tau\nu$ [Sakaki et. al. arXiv:1403.5892]
in $B\to D^*\tau\nu$ [Duraisamy et. al. arXiv:1302.7031, arXiv:1405.3719]

for Tensor operator [Biancofiore et. al. arXiv:1302.1042]

to distinguish NP operators [Sakaki, arXiv:1205.4908; Datta et. al. arXiv1206.3760]

Polarization:

to distinguish NP operators [Tanaka&RW, arXiv:1212.1878; Datta et. al. arXiv1206.3760]

Multi-pion tau decays

[Sakaki, Hagiwara, Nojiri, arXiv:1403.5892]

Successive decay involving **vector resonance**;

$$\left.\begin{array}{l}\bar{B} \to D\tau\bar{\nu}_\tau \\ \qquad \tau \to V\nu_\tau \\ \qquad\qquad V \to 2\pi, \text{ or } 3\pi\end{array}\right\}$$

* **vector mesons:** $V = \rho,\ \rho',\ a_1,\ \cdots$
* **Br ~ 44% of tau decay**

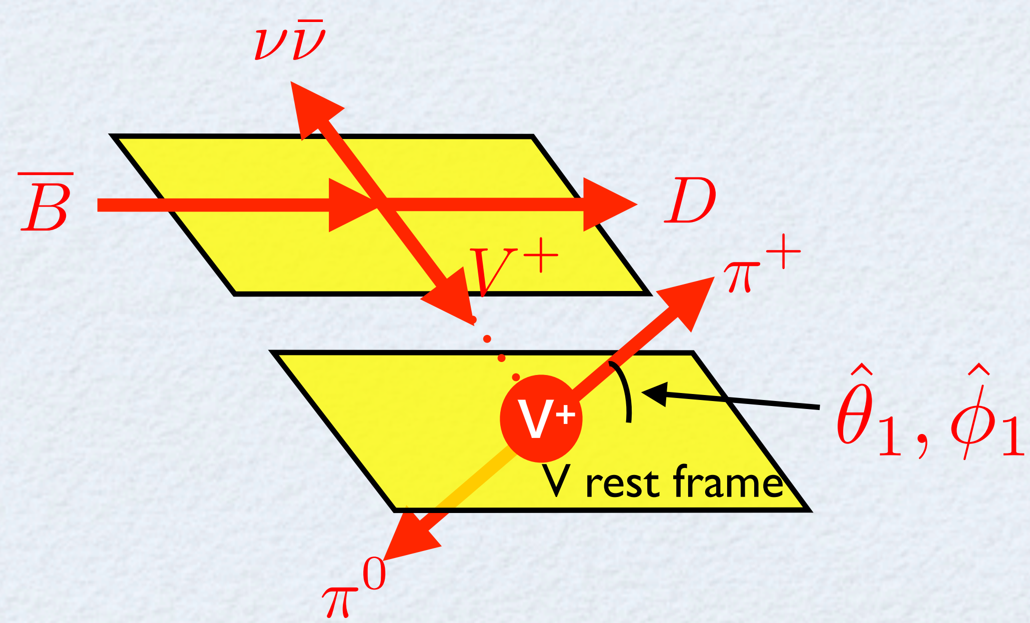
can provide CP violated observable $d\Gamma - d\Gamma^{CP} \neq 0$;

$$A(q^2) \equiv \frac{1}{\Gamma + \Gamma^{CP}} \int dE_V dQ^2 d\cos\theta_V \cdot \left(\int_0^1 - \int_{-1}^0\right) d\cos\hat{\theta}_1 \cdot \left(\int_0^\pi - \int_\pi^{2\pi}\right) d\hat{\phi}_1 \frac{d\Gamma - d\Gamma^{CP}}{d\Phi}$$

$$d\Phi = dq^2 dE_V d\cos\theta_V dQ^2 d\cos\hat{\theta}_1 d\hat{\phi}_1$$

* $q^2 = (p_{\bar{B}} - p_D)^2$

where $(\hat{\theta}_1,\ \hat{\phi}_1)$ are angles which represent charged pion direction;



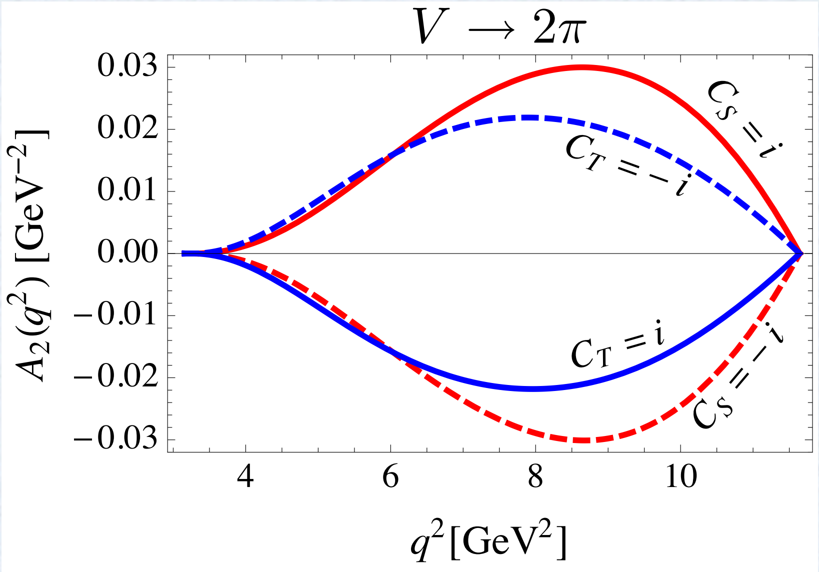
* **Similar to CP conjugate mode**

Multi-pion tau decays

[Sakaki, Hagiwara, Nojiri, arXiv:1403.5892]

Accessibility to CP violation:

ImCx, including its sign, affects the shape of the quantity



*** could distinguish NP including CP violation**

*** Same distribution is obtained in V→3π**

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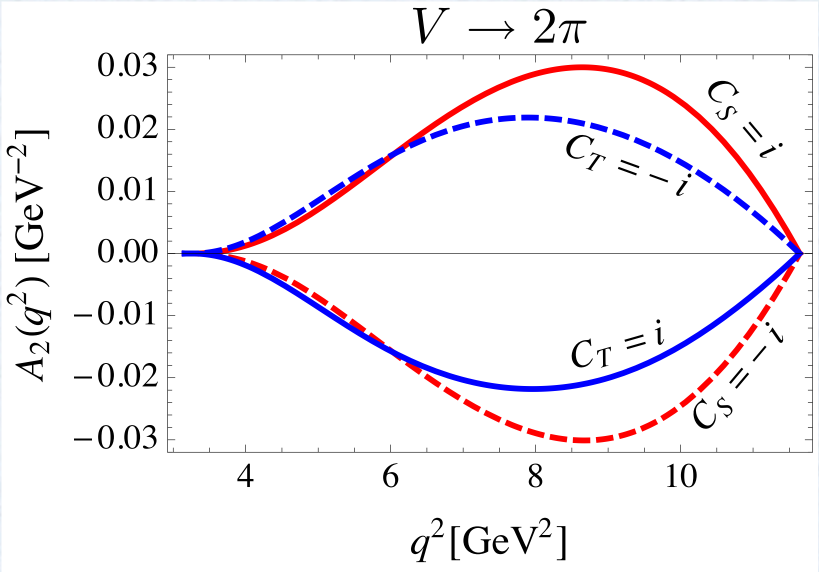

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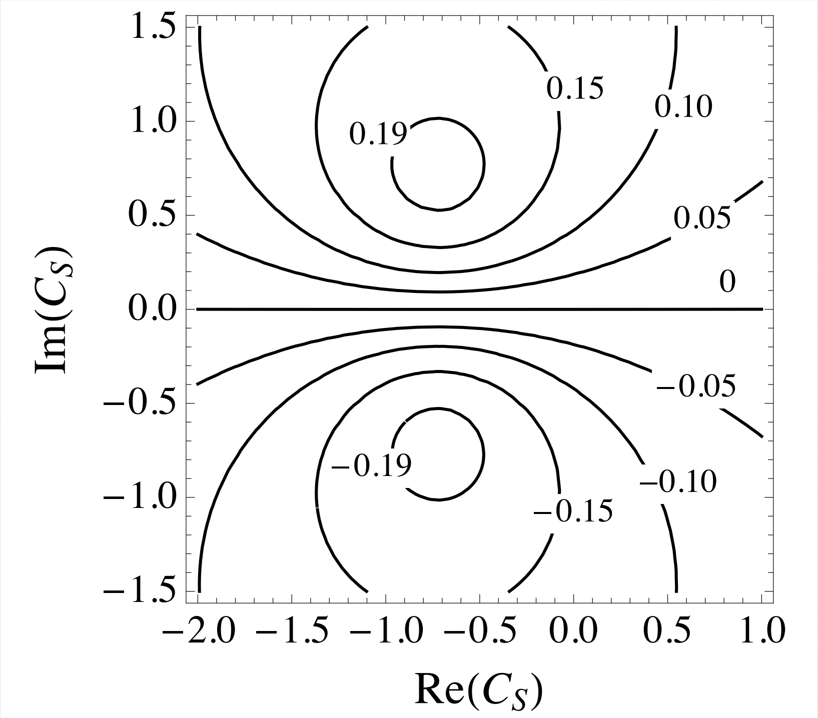
Reach of integrated asymmetry



* In the case of scalar operator: $C_S = C^c_{S_1} - C^c_{S_2}$

* Contour plot of $\int dq^2 A(q^2)$

on the plane of (ReCx, ImCx)

* Typical upper reach ~ O(0.1)

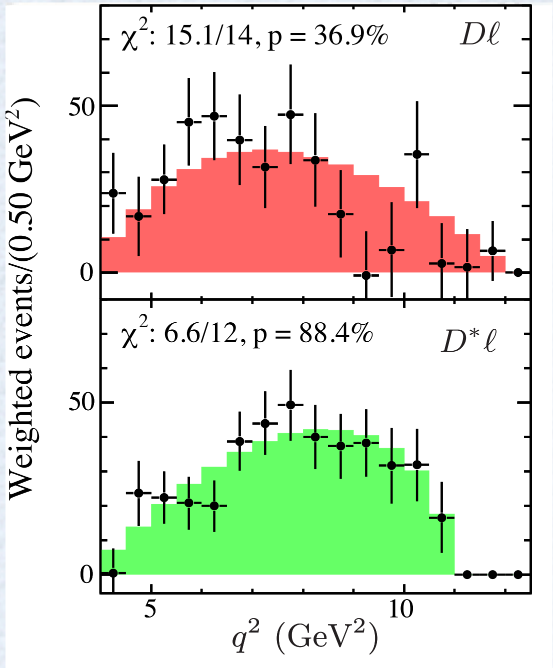
Near future prospect

[Work in progress
by Sakaki, Tayduganov, Tanaka &RW]

Already measured "distribution" [BABAR, arXiv:1303.0571]

BABAR has studied **q^2 distribution**: $d\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})/dq^2$

*** will be obtained more precisely at Belle2 in early year of running**



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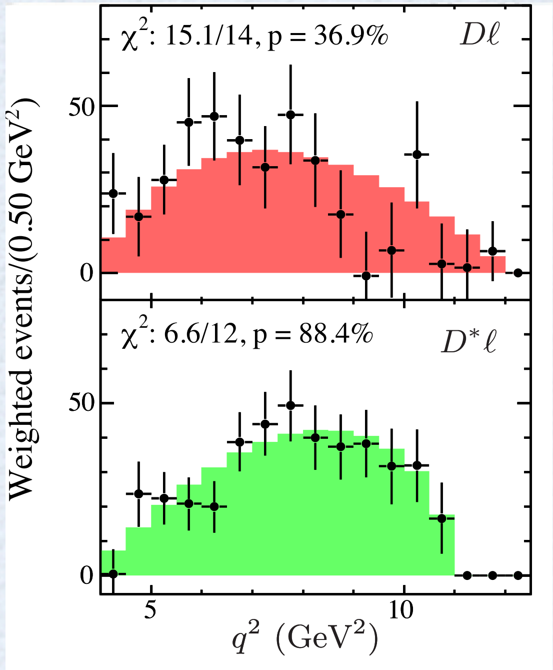


*** will be obtained more precisely at Belle2 in early year of running**

We are studying **q^2 distribution** as a NP analyzer:

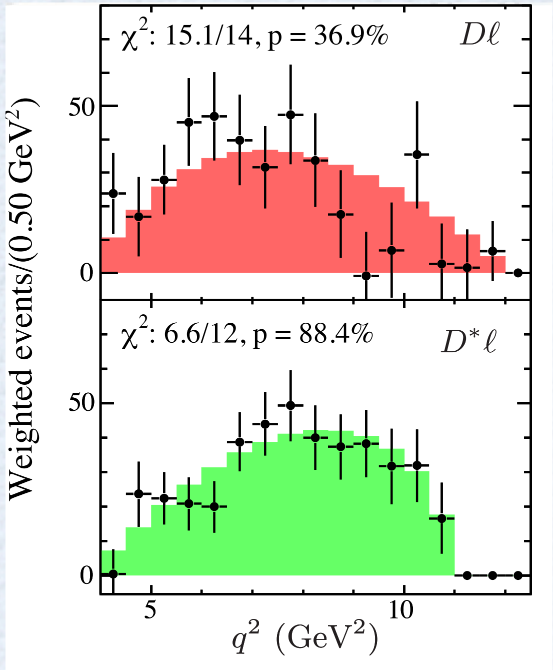
Ex. $$R_{D^*}(q^2) \equiv \frac{d\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu})/dq^2}{d\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})/dq^2} \cdot \left(1 - \frac{m_\tau^2}{q^2}\right)$$

*** Additional factor is imposed for our convenience**

Near future prospect

[Work in progress
by Sakaki, Tayduganov, Tanaka &RW]

Already measured "distribution" [BABAR, arXiv:1303.0571]



BABAR has studied **q^2 distribution**: $d\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})/dq^2$

*** will be obtained more precisely at Belle2 in early year of running**

We are studying **q^2 distribution** as a NP analyzer:

Ex. $R_{D^*}(q^2) \equiv \dfrac{d\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu})/dq^2}{d\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})/dq^2} \cdot \left(1 - \dfrac{m_\tau^2}{q^2}\right)$

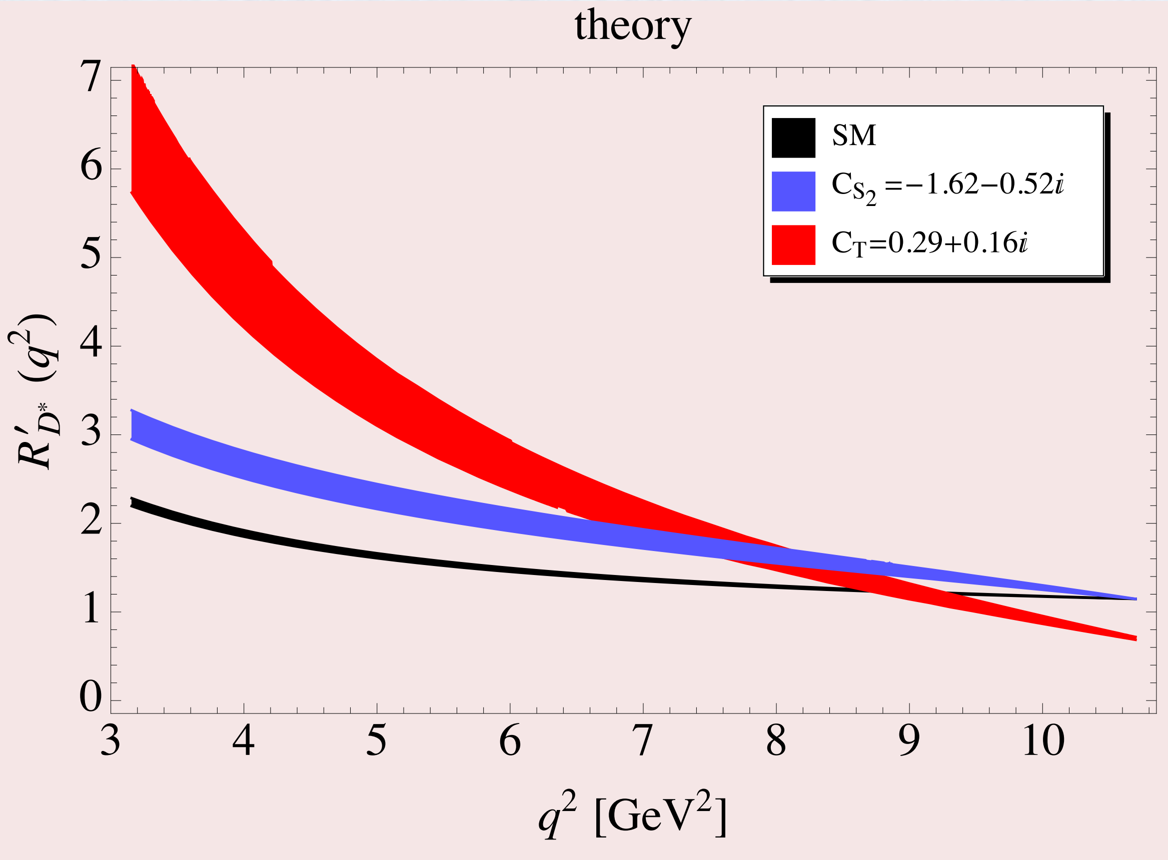
*** Additional factor is imposed for our convenience**

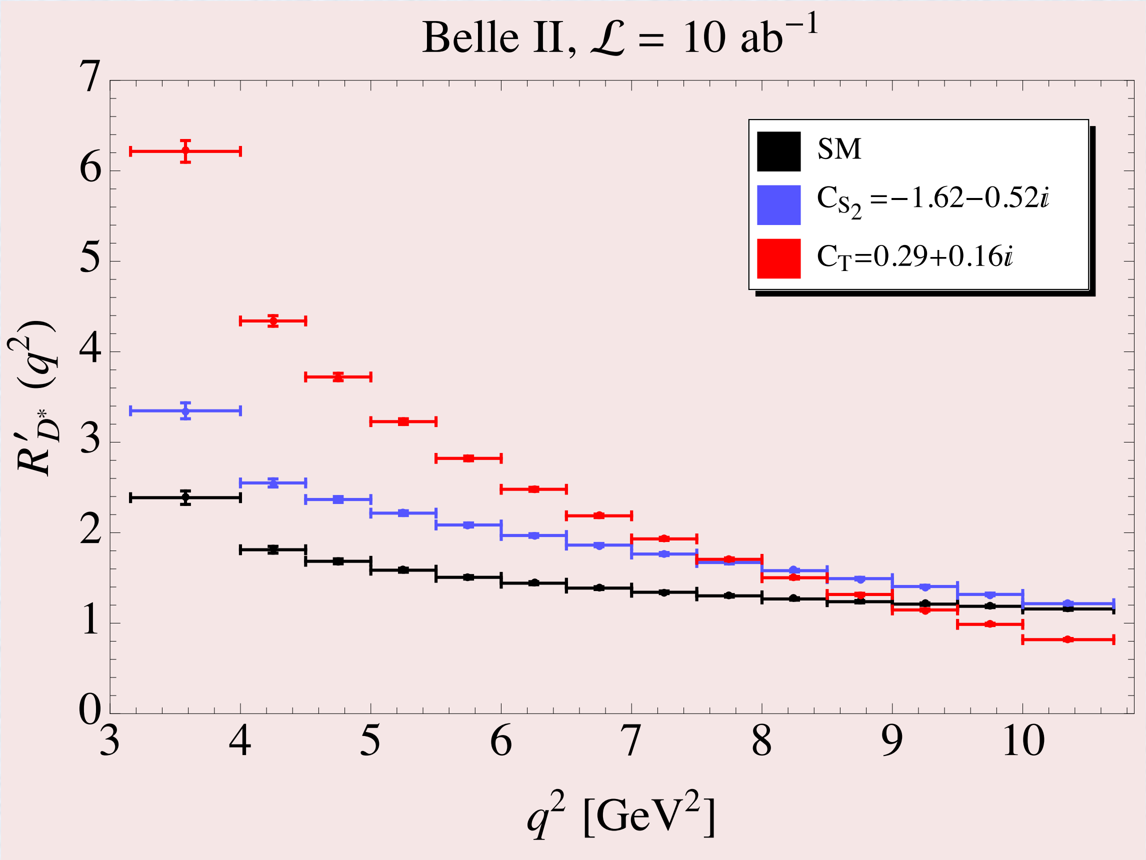
Suppose the central experimental value of R(D) & R(D*) from recent data, then the best fit value of Cx is obtained as follows:

$$C_{S_2} = -1.62 \pm 0.52i\,, \quad \text{with } C_{X\neq S_2} = 0$$

$$C_T = 0.29 \pm 0.16i\,, \quad \text{with } C_{X\neq T} = 0$$

- **Best fit value predict different shape of distribution** Preliminary



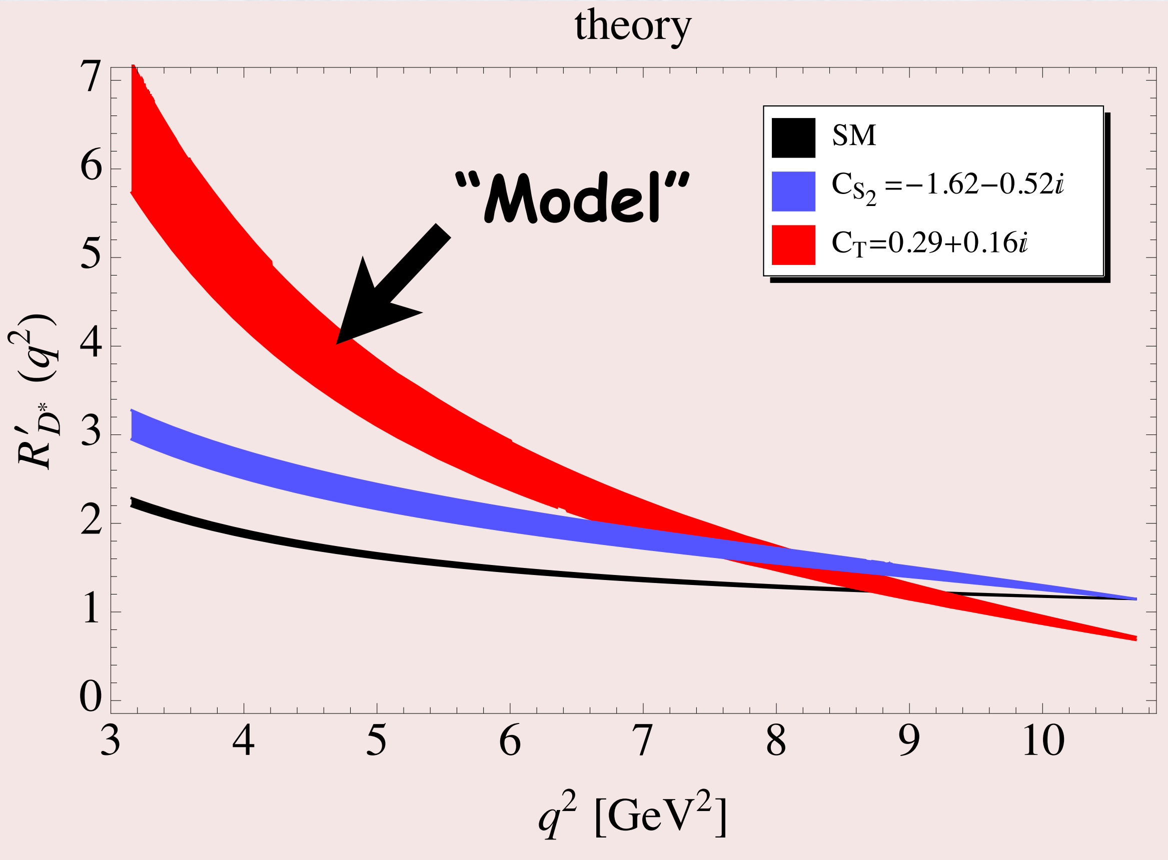


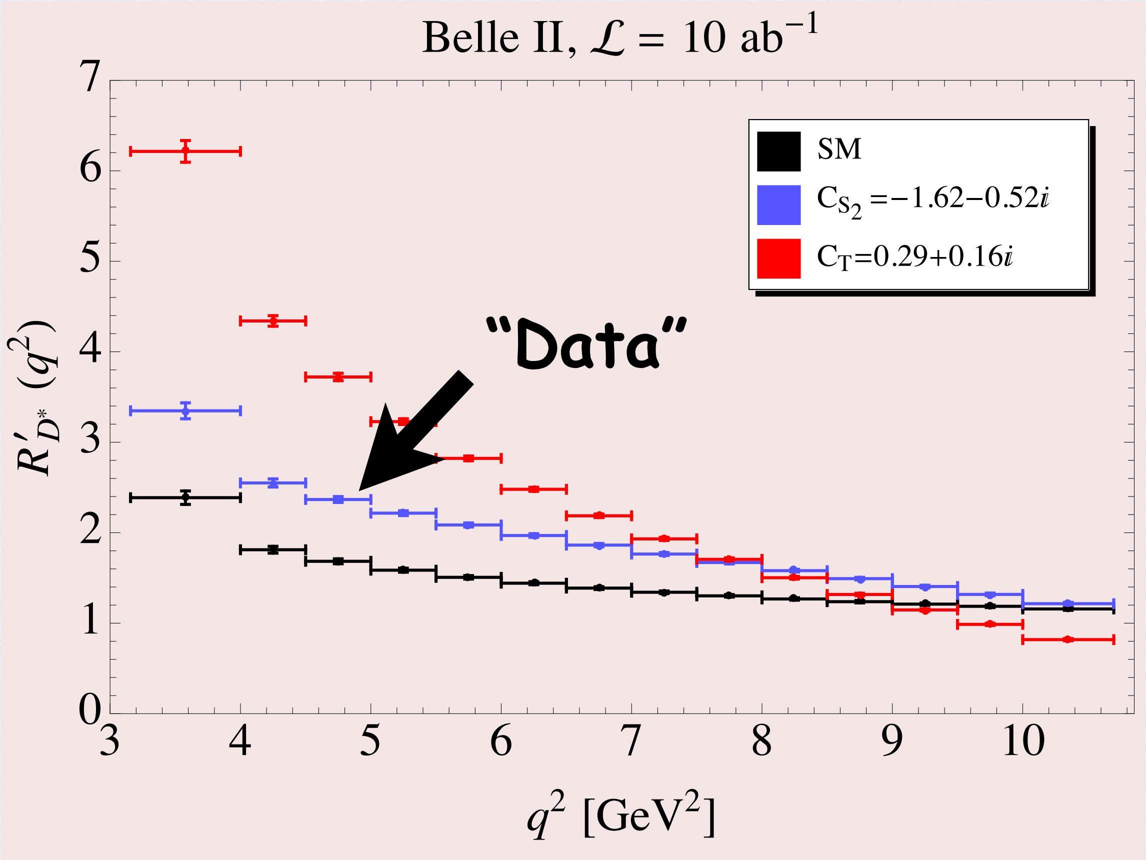
Theoretical uncertainty

Expected error at $10\ \mathrm{ab}^{-1}$ **with** $\varepsilon_{\mathrm{efficiency}} \sim \mathcal{O}(10^{-4})$

• **Best fit value predict different shape of distribution**

Preliminary





Theoretical uncertainty

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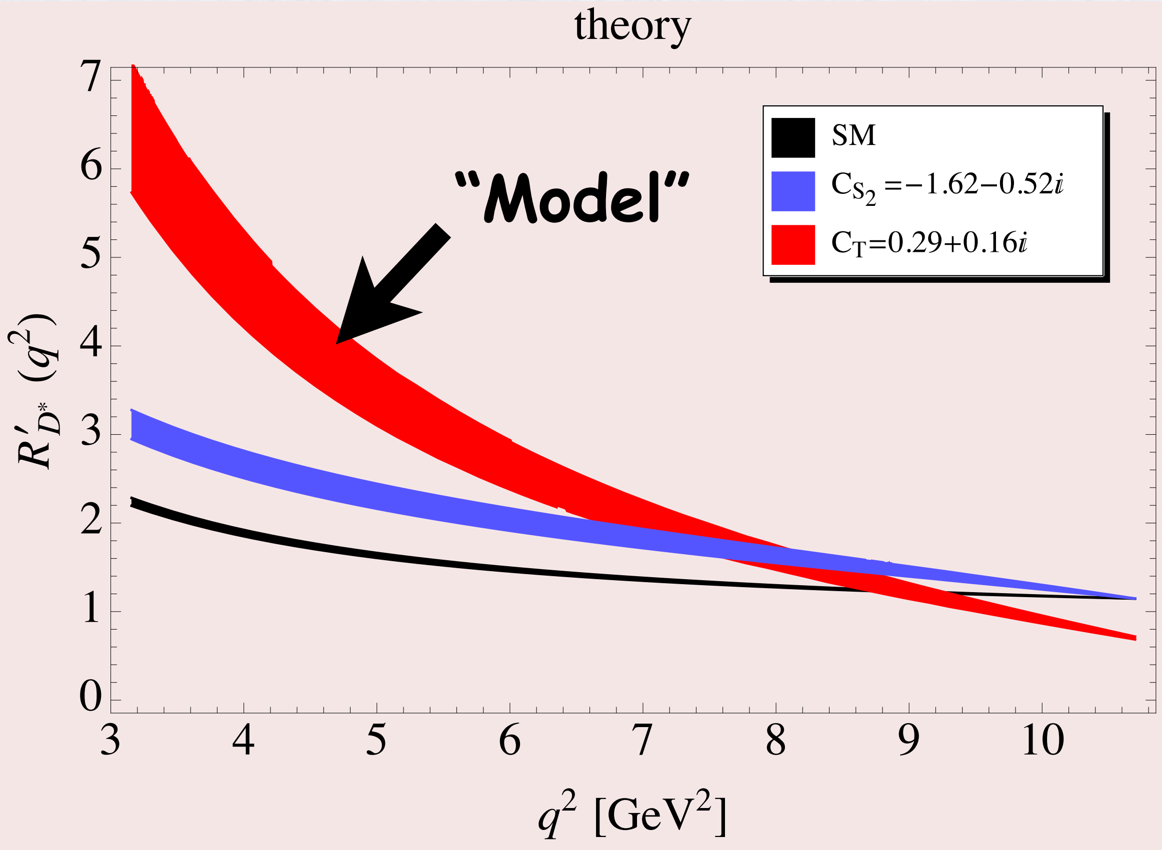
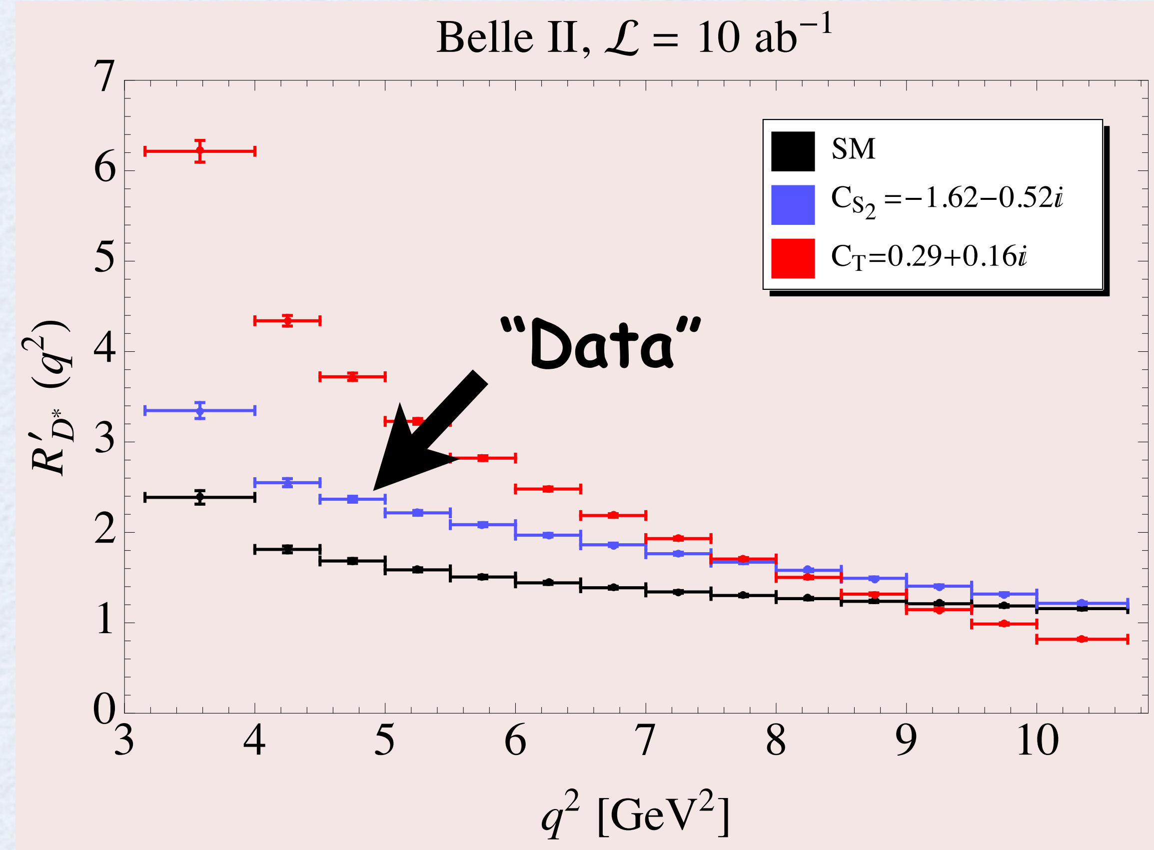
• Best fit value predict different shape of distribution

Preliminary





Theoretical uncertainty

Expected error at $10\ \mathrm{ab}^{-1}$ with $\varepsilon_{\mathrm{efficiency}} \sim \mathcal{O}(10^{-4})$

• R(q^2) distribution can distinguish between scalar- & tensor-like contribution

Integrated luminosity	χ^2/N_{bins}
$426\,\mathrm{fb}^{-1}$	10
$10\,\mathrm{ab}^{-1}$	225

* Simulation of fake "data" vs "model"

Summary

- **Review on tauonic B decays**
  - $B \to D(*) \tau \nu$: Large deviation from SM & type2-2HDM prediction
  - $B \to \tau \nu$: Good agreement with SM
- **New physics**
  - Several effective operators (vector, scalar, tensor) can explain data
  - "Unusual" 2HDM & LQM are in good agreement with data in $B \to D(*) \tau \nu$
- **Observables**
  - Asymmetry, polarization, distribution are useful to test NP contribution
  - CP violation is available using asymmetry
- **Near future prospects**
  - q^2 distribution will be obtained in relatively near future and sensitive to NP contributions

Back up

$|V_{cb}|$ determination

$\bar{B} \to D\ell\bar{\nu}$

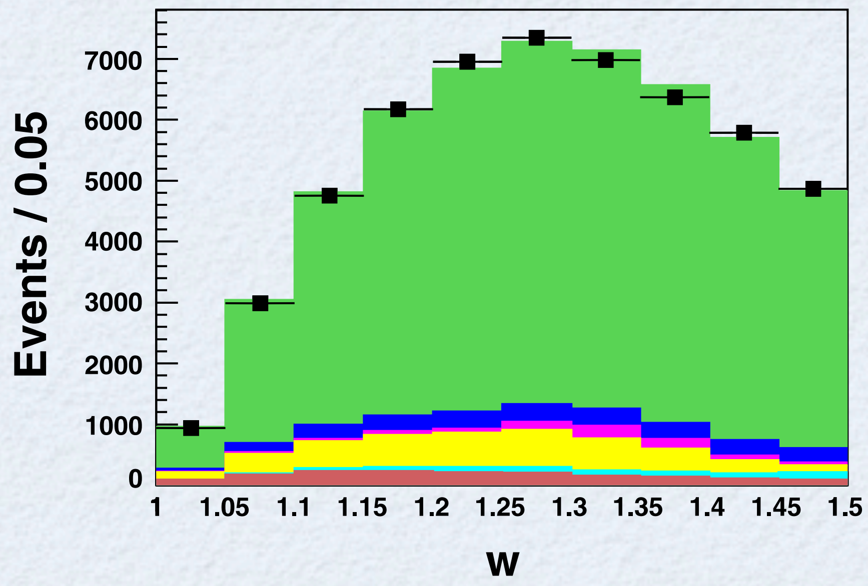
$$\frac{d\Gamma}{dw}(\bar{B} \to D\ell\bar{\nu}) = \frac{G_F m_B^5}{48\pi^3} r^3 (1+r)^2 (w^2-1)^{3/2} V_1(w)^2 |V_{cb}|^2$$

- **Fit the shape (=interaction type) and the hight (=coupling)**
- **Shape is parametrized by HQET** **[Caprini et.al. (1996)]**

Shape : $V_1(w) = V_1(1)\left[1 - 8\rho_1^2 z + (51\rho_1^2 - 10)z^2 - (252\rho_1^2 - 84)z^3\right]$

Hight : $V_1(1)|V_{cb}|$

$$\left(z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}\right)$$

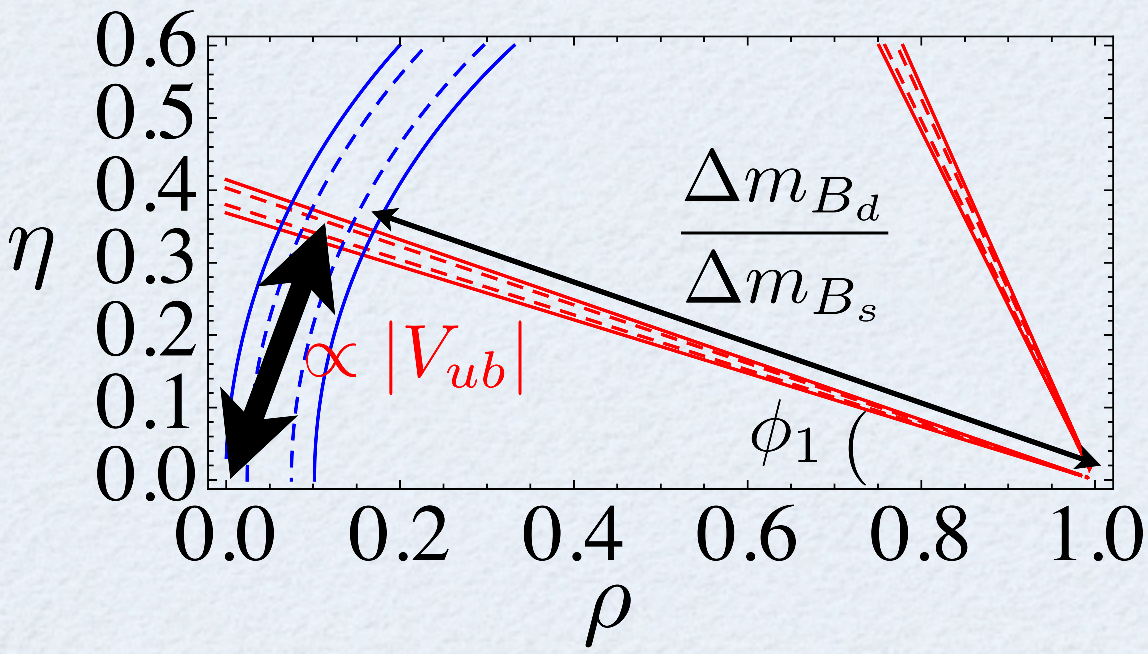


Fit result:

$$V_1(1)|V_{cb}| = (4.26 \pm 0.07 \pm 0.14) \times 10^{-2}$$

$$\rho_1^2 = 1.186 \pm 0.055$$

$|V_{ub}|$ determination from a fit to CKM unitarity



$$|V_{ub}| = (3.38 \pm 0.15) \times 10^{-3}$$

Average values

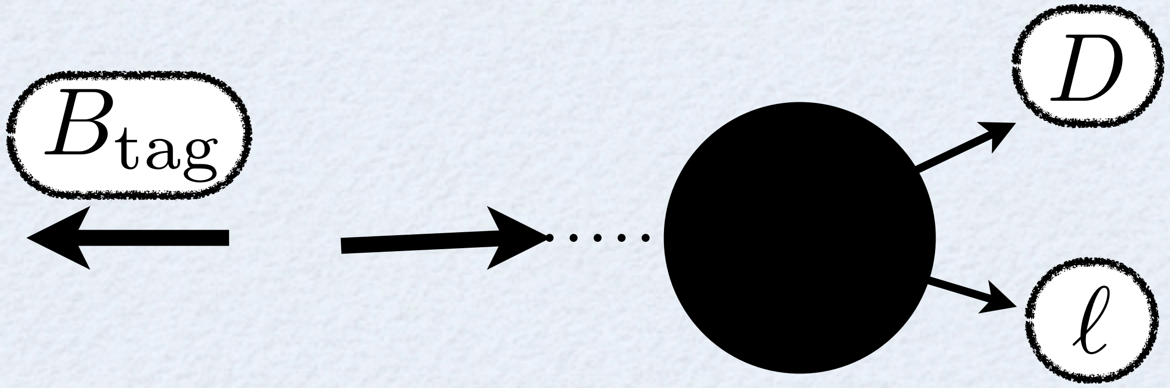
	Average	CKM fit
$\mathcal{B}(\bar{B} \to \tau\bar{\nu}) \times 10^4$	1.41 ± 0.23	1.14 ± 0.23
$|V_{ub}| \times 10^3$	4.18 ± 0.53	3.38 ± 0.15

	Average	SM
$R(D)$	0.421 ± 0.058	0.297 ± 0.017
$R(D^*)$	0.337 ± 0.025	0.252 ± 0.003
correlation	-0.19	-

* Belle result is obtained by our private calculation
* So, Belle result here is different from that shown in main slide

Experimental analysis @BABAR

[BABAR, arXiv:1205.5442]

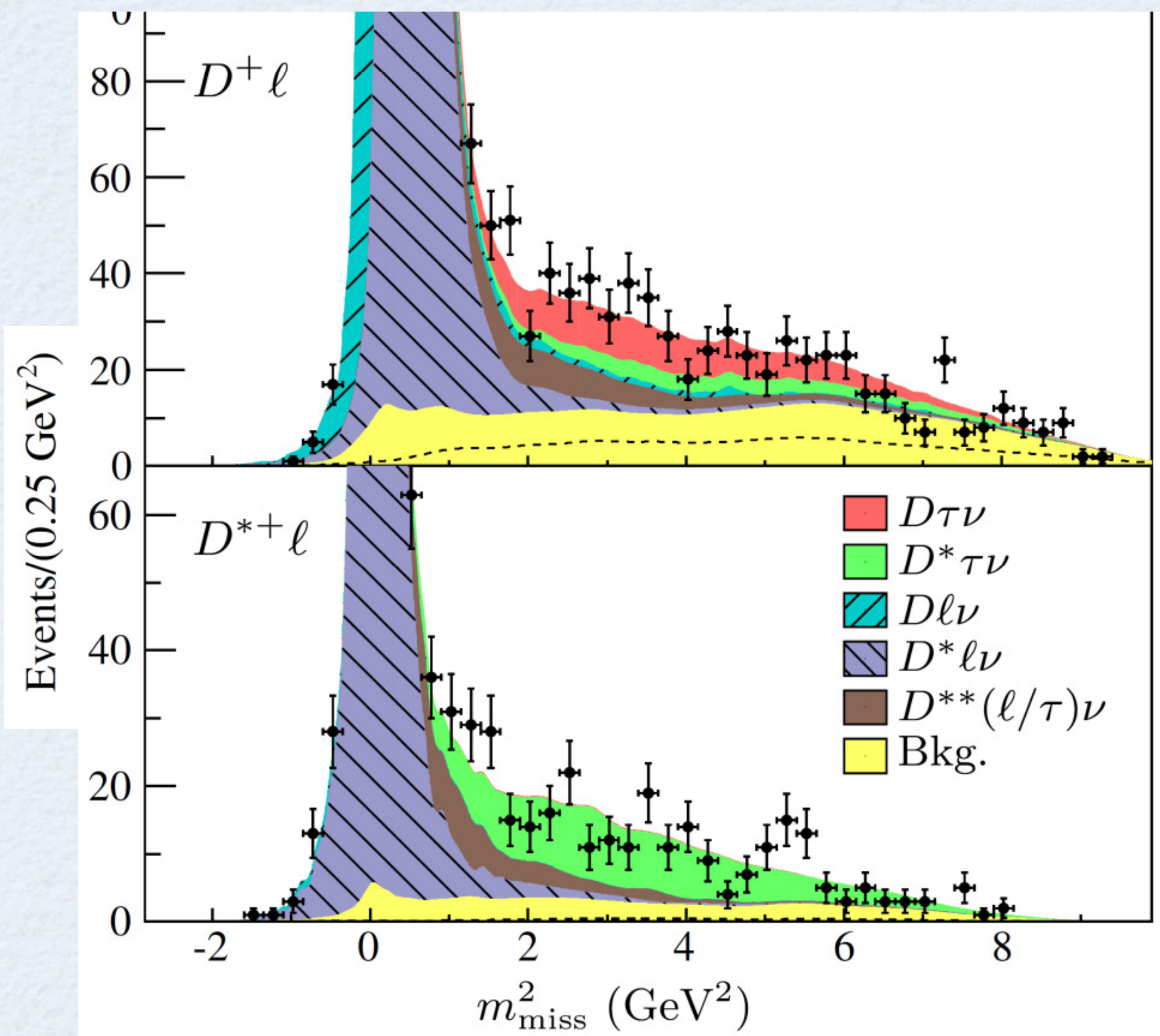


* Decay channel BABAR analyzed:

$$\bar{B} \to D^{(*)}(\tau \to \ell\bar{\nu}\nu)\bar{\nu}$$

* inv. mass of missing particles:

$$m^2_{\rm miss} = (p_{e^+e^-} - p_{\rm tag} - p_{D^{(*)}} - p_\ell)^2$$



1. $B_{\rm tag}$, $D^{(*)}$, ℓ are identified

2. $m^2_{\rm miss}$ distribution is measured

3. Comparing total event data with expected signal & background, signal event is extracted

Belle & Belle2

Belle...

- Belle result was reported, but it is not fully completed...
  We are now waiting for the upgrade.

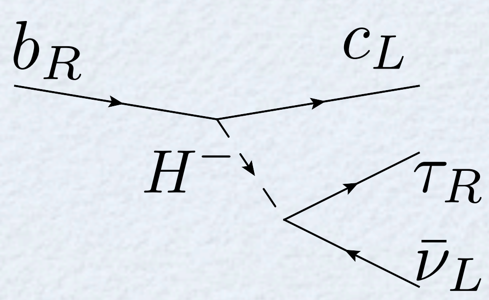
Super KEKB

- Tauonic B meson decay is one of the golden modes in future super B factory, due to its large statistics.
- Large statistics enable us to measure not only total rate, but also some distributions & polarizations

BABAR result for 2HDM of type II

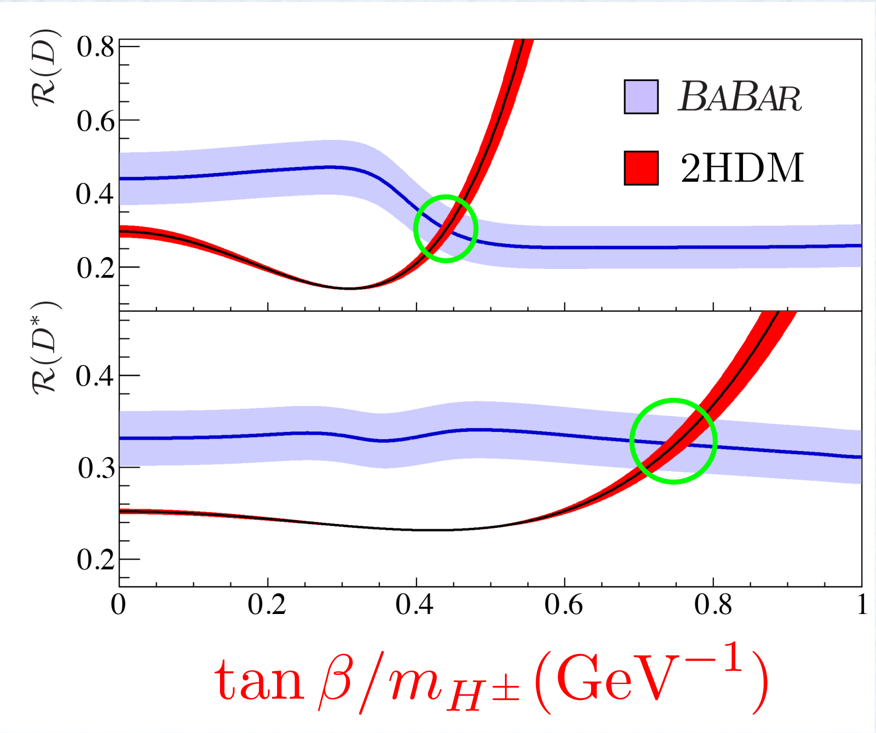
Type-II 2HDM is ruled out at 99.8% CL!

* Charged Higgs can contribute to the processes



$$\propto m_\tau m_b \frac{\tan^2\beta}{m_{H^\pm}^2}$$

* However, it cannot explain the results at the same time



Note:
As explained, we must expect the signal event, to extract from the total event including the background event.
Thus, this result depends on the model parameters.

Lepto Quark model

- LQs are particles, carrying both baryon & lepton number. Thus, they couple to quark-lepton pair.

- LQ particles are expected to exist in various NP models; (ex: SU(5)-GUT, SO(10)-GUT, composite models, and so on)

Mass bounds on LQs from LHC

Scalar LQ: $M_{\mathrm{SLQ}_3} \gtrsim 530\mathrm{GeV}$ [ATLAS & CMS (2013)]

Vector LQ: $M_{\mathrm{VLQ}_3} \gtrsim 760\mathrm{GeV}$ [CMS (2013)]

Lagrangian relevant for b->cτν, with general dimensionless SU(3)xSU(2)xU(1) invariant couplings of scalar & vector LQs:

$$\mathcal{L}^{\mathrm{LQ}}_{F=0} = \left(h^{ij}_{1L}\,\overline{Q}_{iL}\gamma^\mu L_{jL} + h^{ij}_{1R}\,\overline{d}_{iR}\gamma^\mu \ell_{jR}\right) U_{1\mu} + h^{ij}_{3L}\,\overline{Q}_{iL}\boldsymbol{\sigma}\gamma^\mu L_{jL}\boldsymbol{U}_{3\mu}$$
$$+ \left(h^{ij}_{2L}\,\overline{u}_{iR} L_{jL} + h^{ij}_{2R}\,\overline{Q}_{iL} i\sigma_2 \ell_{jR}\right) R_2\,,$$

$$\mathcal{L}^{\mathrm{LQ}}_{F=-2} = \left(g^{ij}_{1L}\,\overline{Q}^c_{iL} i\sigma_2 L_{jL} + g^{ij}_{1R}\,\overline{u}^c_{iR}\ell_{jR}\right) S_1 + g^{ij}_{3L}\,\overline{Q}^c_{iL} i\sigma_2 \boldsymbol{\sigma} L_{jL}\boldsymbol{S}_3$$
$$+ \left(g^{ij}_{2L}\,\overline{d}^c_{iR}\gamma^\mu L_{jL} + g^{ij}_{2R}\,\overline{Q}^c_{iL}\gamma^\mu \ell_{jR}\right) V_{2\mu}\,,$$

S,R: scalar LQ
U,V: vector LQ

Tau polarization

- Tau has rich features compared with light leptons.
  Its helicity can vary depending on the type of the interaction.

  *** In SM,** $P_\tau = \dfrac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \simeq 0.325$

  *** NP can influence the tau helicity in B→D(*)τν**

  *** Pτ is measurable without knowing τ momentum**
  & we estimated expected error δPτ~0.04 at super KEKB

  [Tanaka & RW, arXiv:1005.4306]

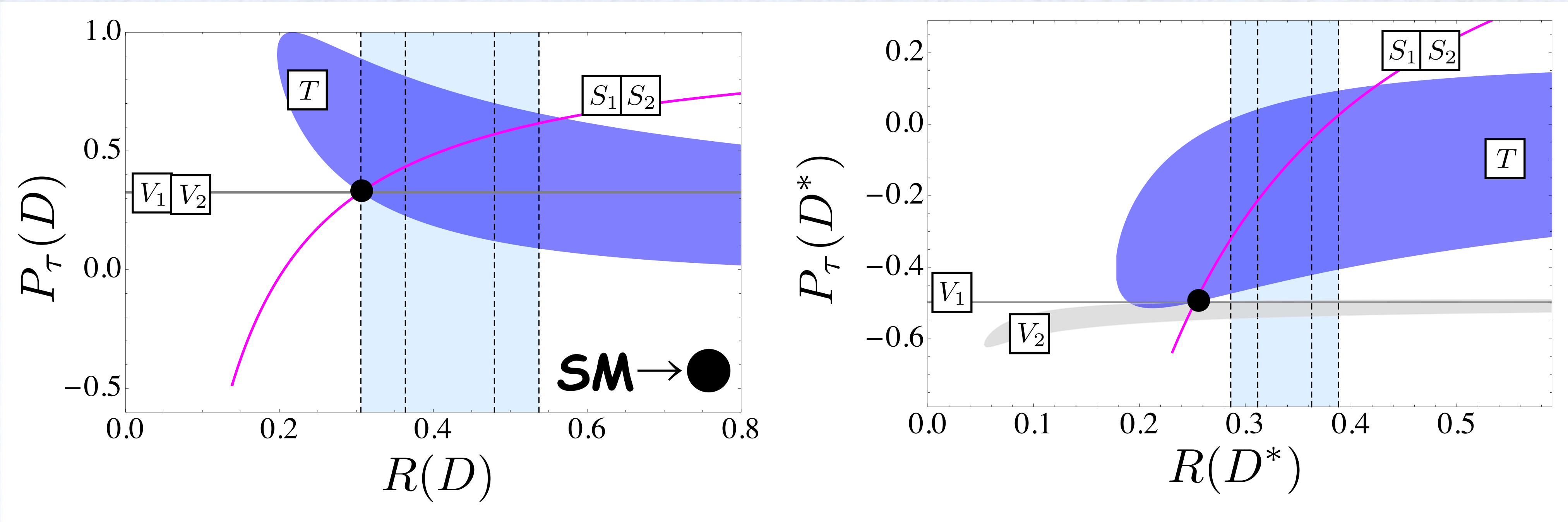
- Definition:

$$P_\tau(D) = \frac{\Gamma^+(D) - \Gamma^-(D)}{\Gamma^+(D) + \Gamma^-(D)} \qquad P_\tau(D^*) = \frac{\Gamma^+(D^*) - \Gamma^-(D^*)}{\Gamma^+(D^*) + \Gamma^-(D^*)}$$

$\Gamma^\pm(D)$ **is decay rate of B->Dτν with tau helicity to be** $\pm\frac{1}{2}$

Tau polarization

Correlation of R(D) & Pτ:



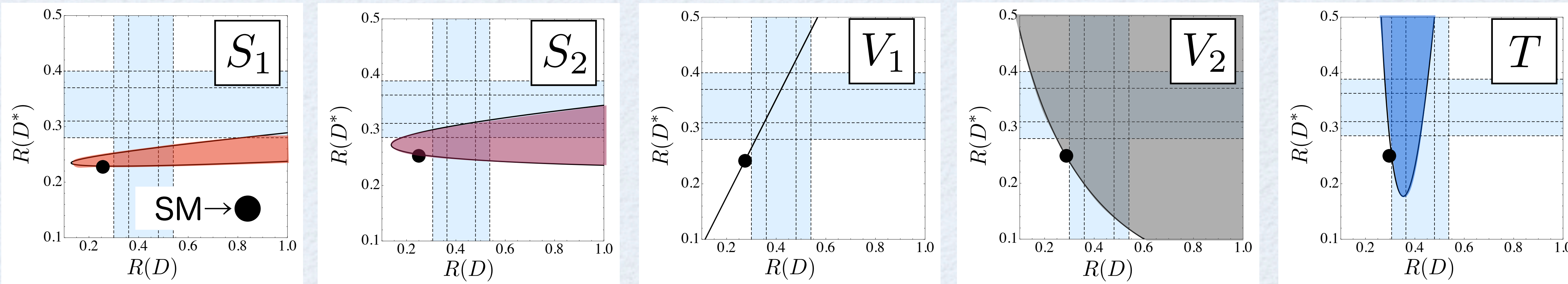
* Pτ & R are correlated
* Nontrivial strong correlation for S1,2 due to spin conservation

How to distinguish NP:

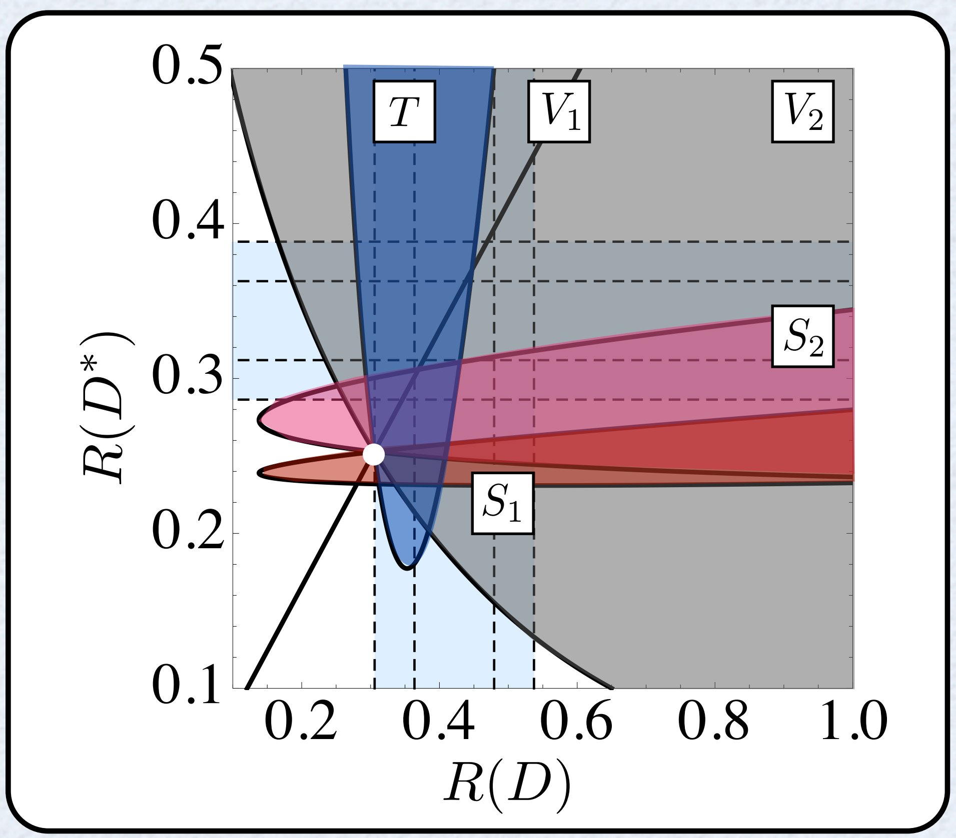
#. If R(D)&R(D*) are precisely measured, we can predict Pτ in each NP case

$(R(D), R(D^*))$	$(0.37, 0.28)$		
X	S_2	V_2	T
C_X	$-0.81 \pm i\,0.87$	$0.03 \pm i\,0.40$	$0.16 \pm i\,0.14$
$P_\tau(D)$	0.44	0.33	0.22
$P_\tau(D^*)$	−0.35	−0.50	−0.26

Correlations



Sensitive to R(D) Same to R(D*)



We can distinguish the type in part if we measure them more precisely.

Kinematics in multi-pion decay of tau