Semi-leptonic B decays with tau

$$B \to \overline{D}^{(*)} \tau^+ \nu_\tau$$

Anže Zupanc
Jožef Stefan Institute and University of Ljubljana

Physics Motivation

Semi-tauonic *B* decays are sensitive probes of New Physics. NP could impact:

- Branching fraction
- tau, D* polarisations
- Properties of NP can be inferred also by looking at various kinematic properties of the decay (momenta, …)

NP effects can be different for D and D modes.*

Effective Lagrangian for $b \to c\tau\bar{\nu}$

SM

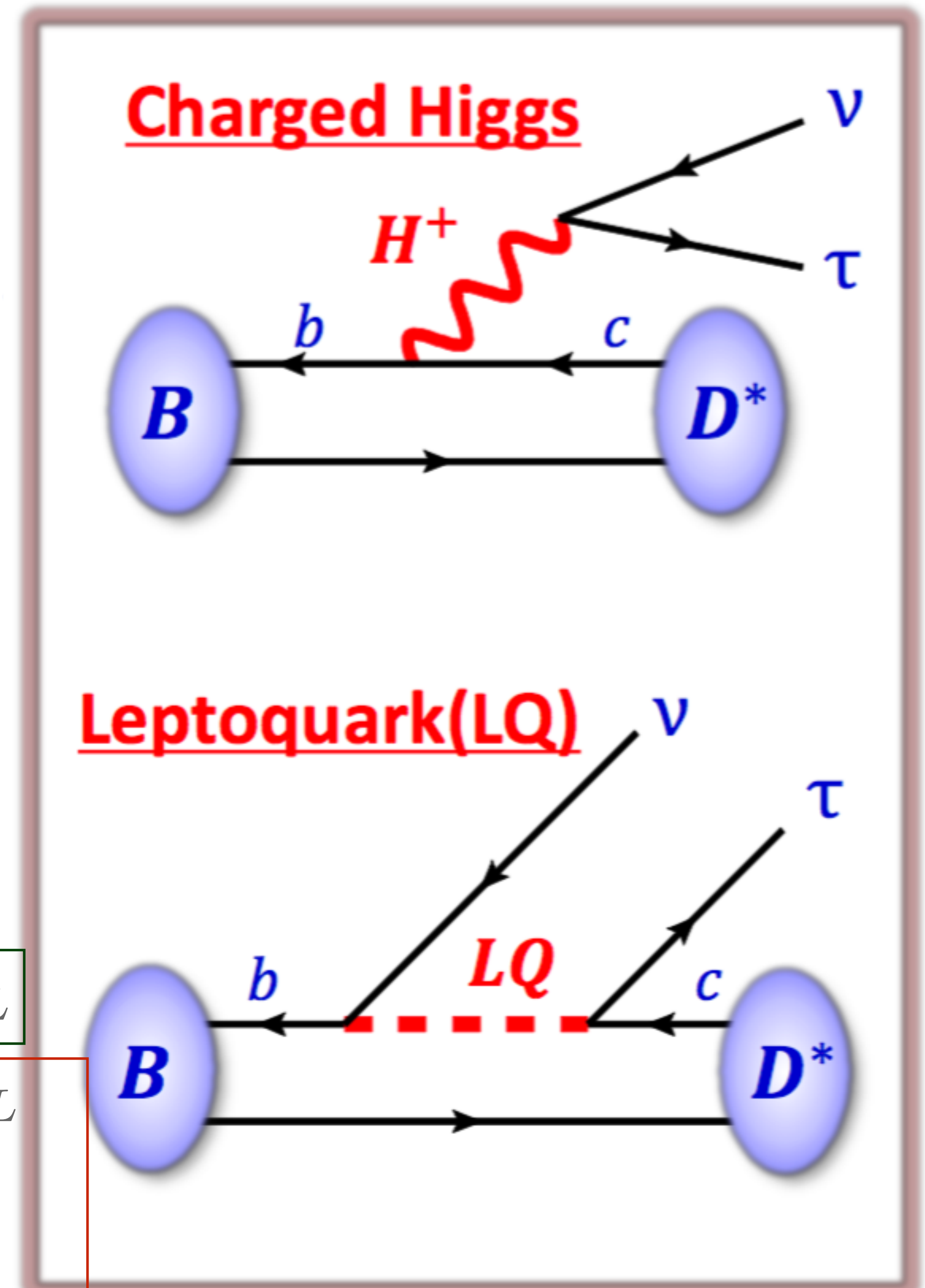
$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb}(1+C_{V_1})\mathcal{O}_{V_1} \qquad \mathcal{O}_{V_1} = \bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_L$$

$$+C_{V_2}\mathcal{O}_{V_2} \quad \textbf{RH-current} \qquad \mathcal{O}_{V_2} = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_L$$

$$+C_{S_1}\mathcal{O}_{S_1} \quad \textbf{2HDM (Type-II)} \qquad \mathcal{O}_{S_1} = \bar{c}_L b_R\,\bar{\tau}_R\nu_L$$

$$+C_{S_2}\mathcal{O}_{S_2} \quad \textbf{2HDM} \qquad \mathcal{O}_{S_2} = \bar{c}_R b_L\,\bar{\tau}_R\nu_L$$

$$+C_T\mathcal{O}_T \quad \textbf{Tensor} \qquad \mathcal{O}_T = \bar{c}_R\sigma^{\mu\nu}b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_L$$



Observables

Ratio of branching fractions

$$R_{D^{(*)}} := \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

- benefits from cancelations
  - Vcb
  - hadronic matrix elements (theory)
  - experimental systematics

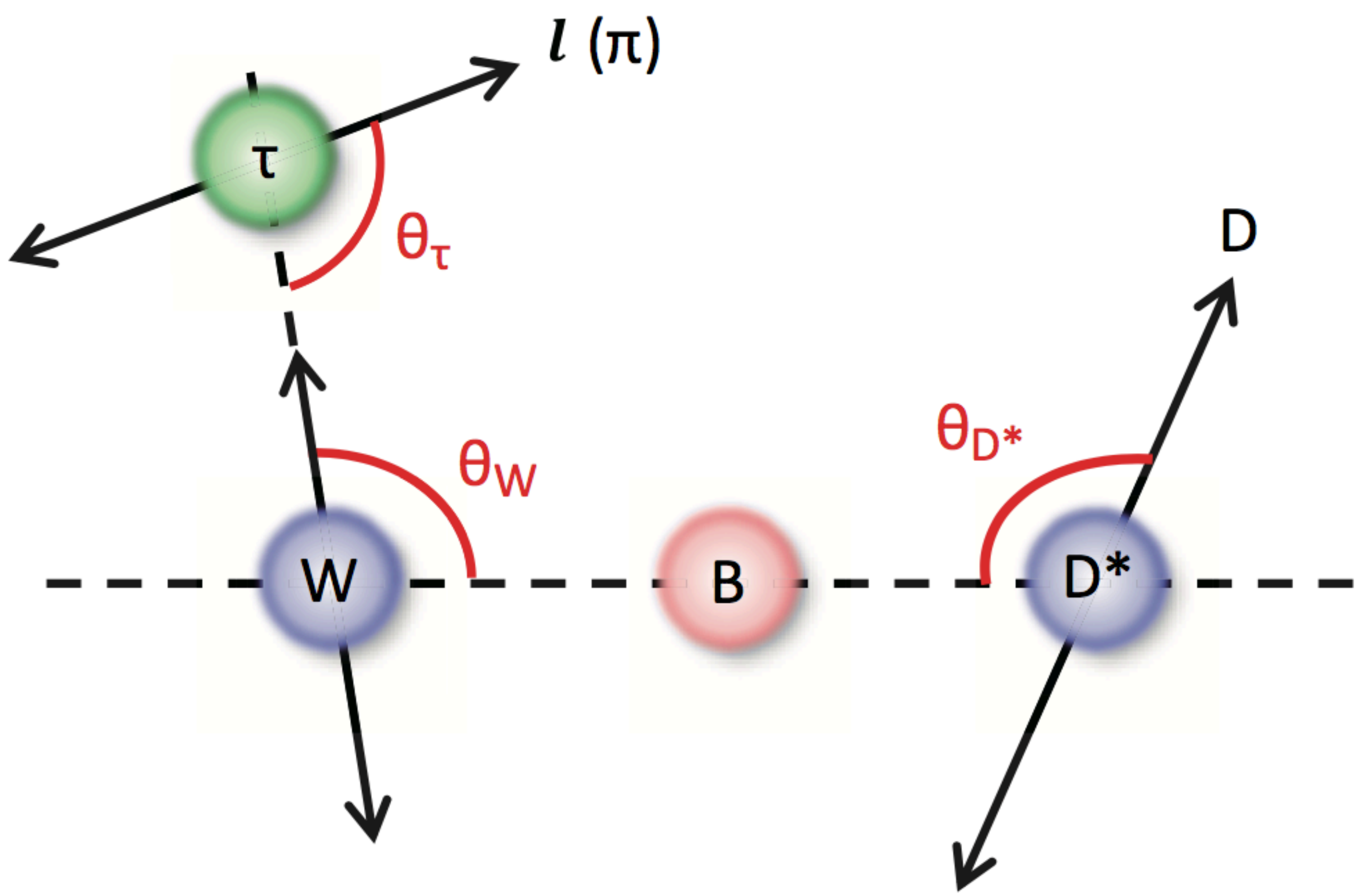
SM prediction

$$R(D) = 0.300 \pm 0.008$$
H. Na et al., Phys.Rev.D 92, 054410 (2015)

$$R(D^*) = 0.252 \pm 0.003$$
S.Fajfer, J.F.Kamenik, and I.Nisandzic, Phys.Rev.D85(2012) 094025

Observables

Kinematics of the decay



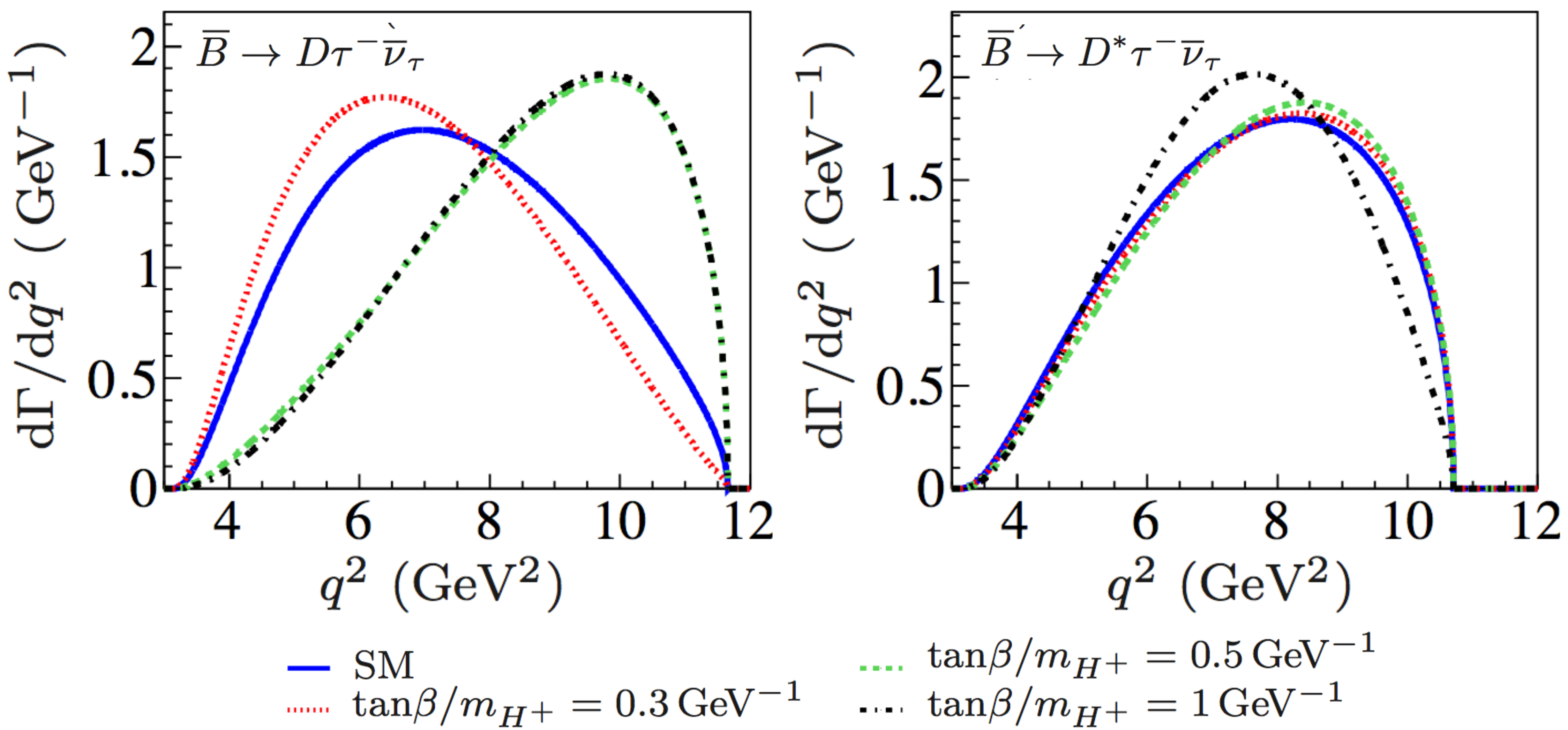
Kinematics of $B \to D^* \tau \nu$ can be described for example with

$$q^2, \quad \cos\theta_{D^*}, \quad \cos\theta_W, \quad \cos\theta_\tau$$

Observables

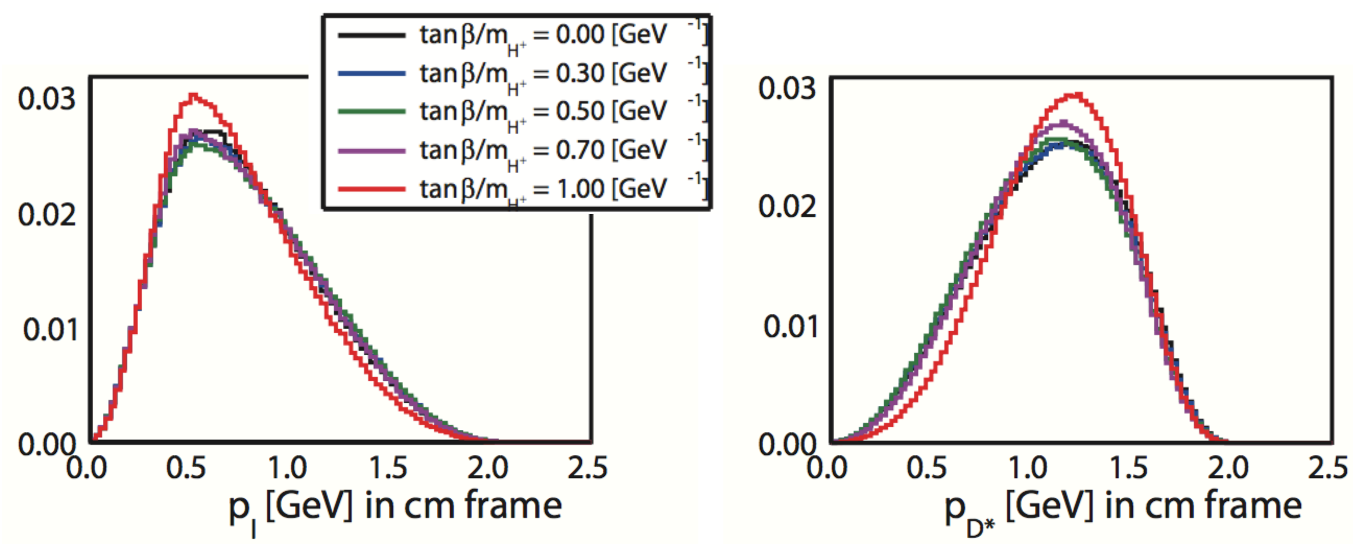
Kinematics of the decay $q^2 = (p_\tau + p_\nu)^2$

SM and 2HDM predictions of q^2

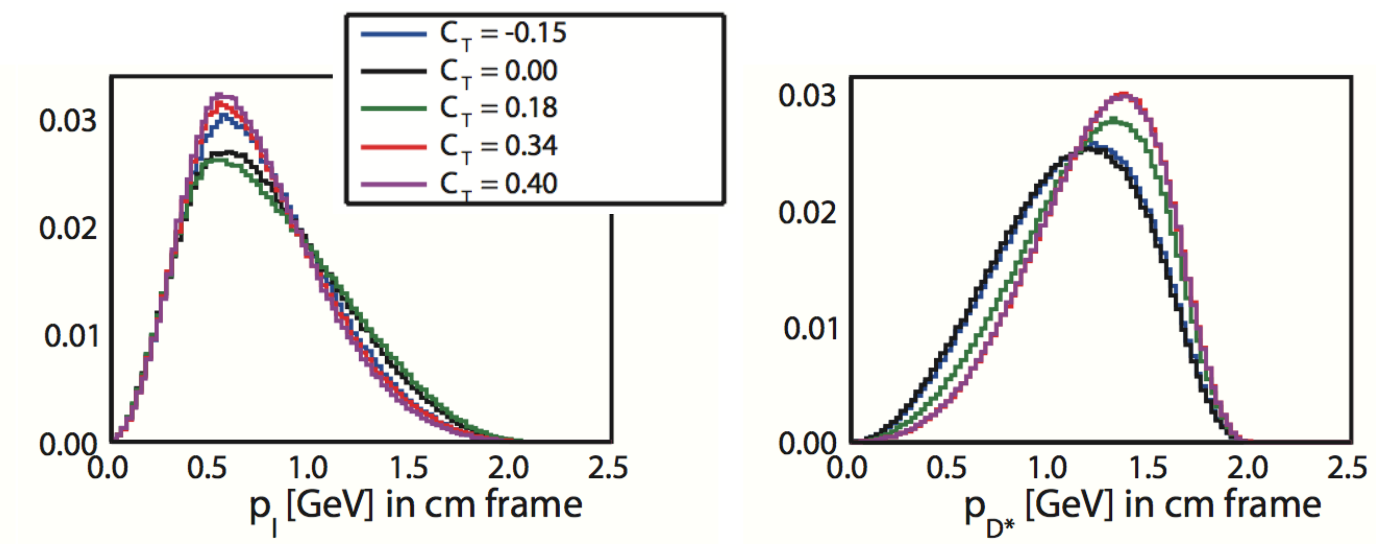


Observables

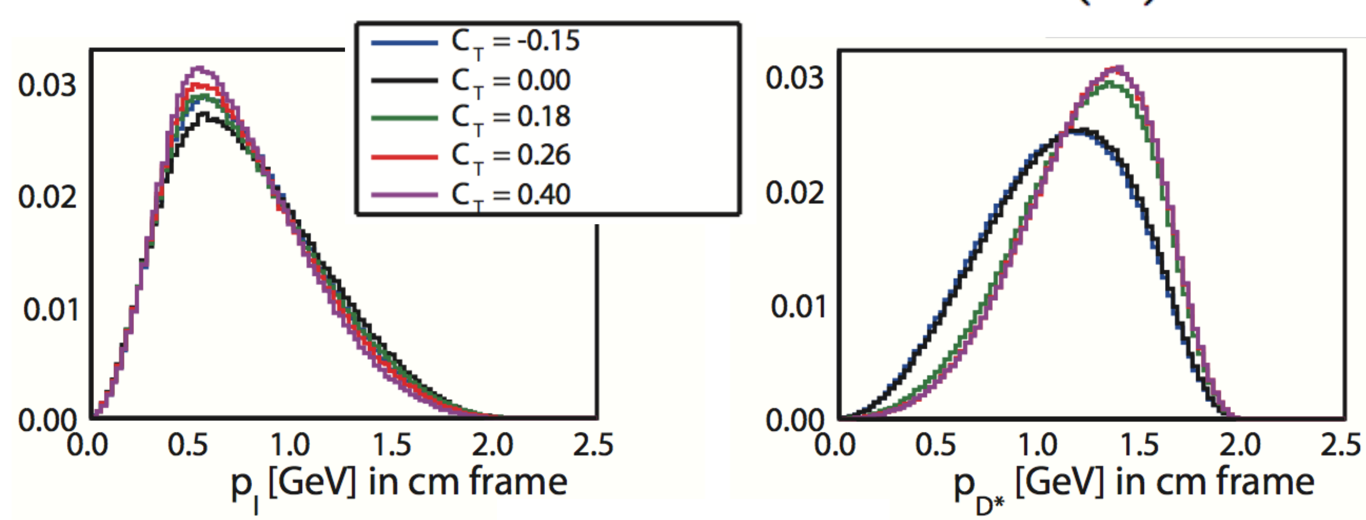
Kinematics of the decay $p^*_{\ell(\tau)}$, $p^*_{D^*}$



(a) Type-II 2HDM.



(b) R_2-LQ.

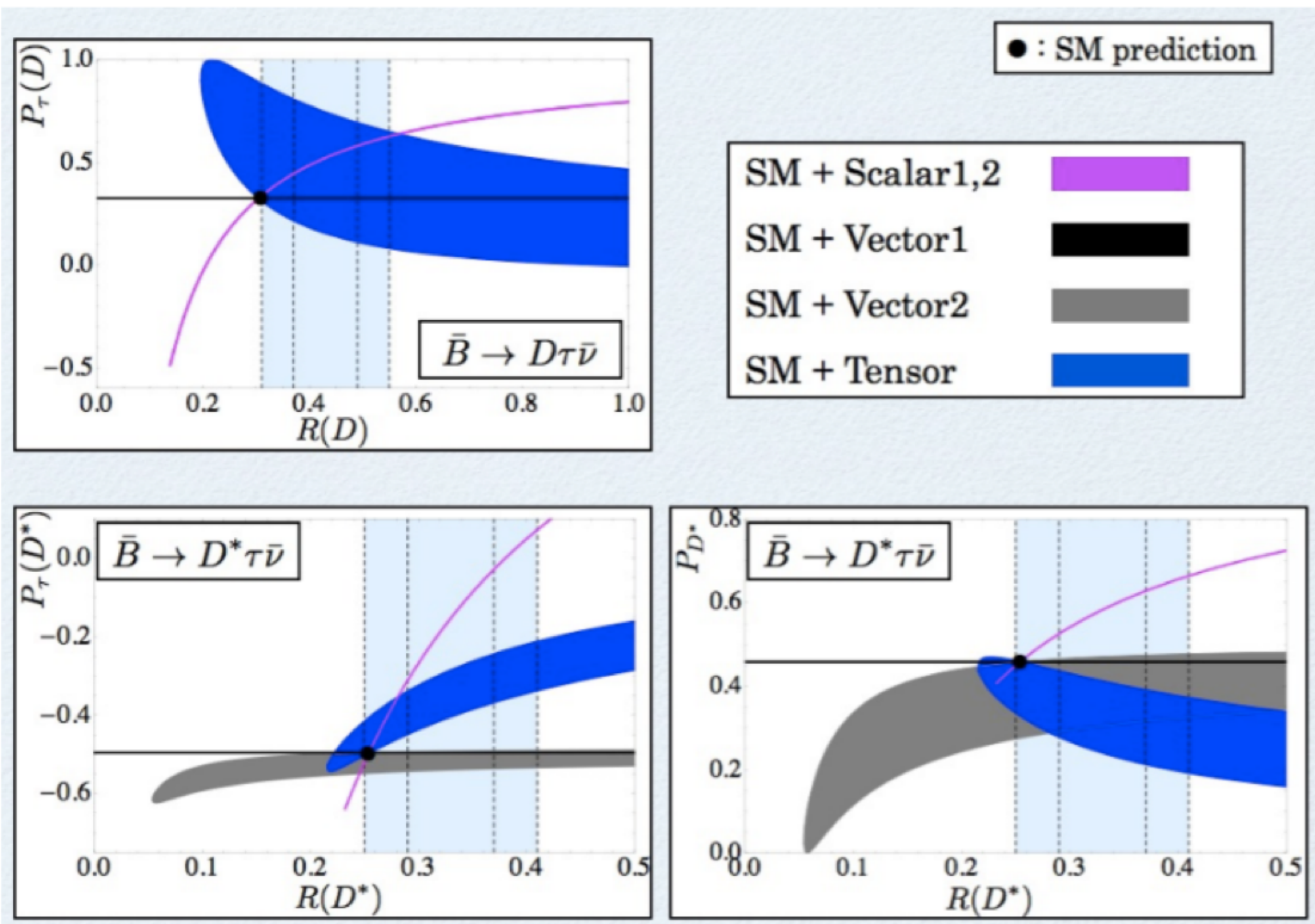


(c) S_1-LQ.

Observables

Tau polarisation

Examples of correlations between τ and D^* polarization and BF ratio (R(D$^{(*)}$));



$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^\pm$ denotes the decay rate of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with a τ helicity of $\pm 1/2$.

SM prediction

$$P_\tau = 0.325 \pm 0.009 \text{ for } \bar{B} \to D\tau^-\bar{\nu}_\tau$$

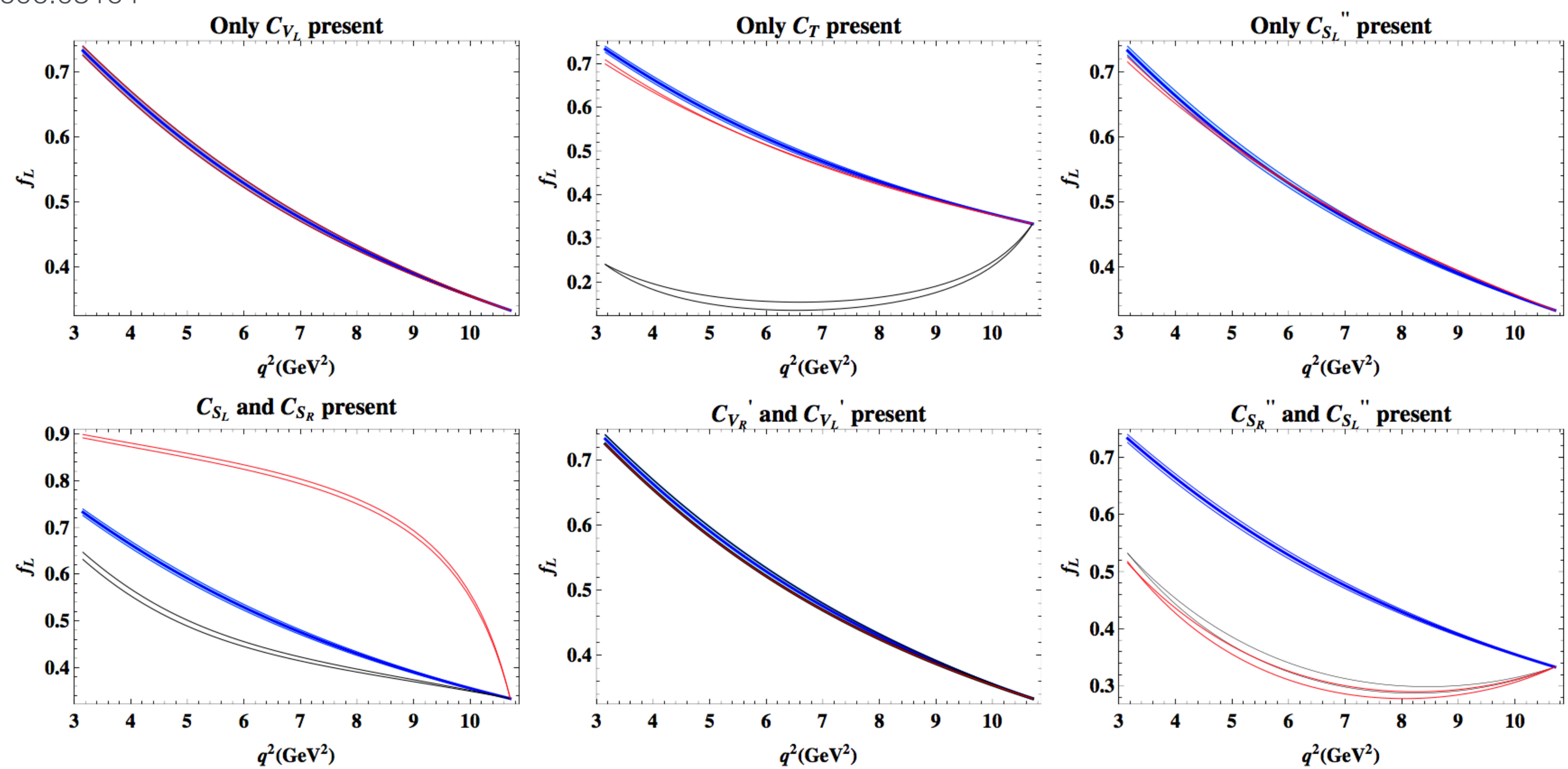
$$P_\tau = -0.497 \pm 0.013 \text{ for } \bar{B} \to D^*\tau^-\bar{\nu}_\tau$$

M.Tanaka, R.Watanabe Phys. Rev. D87 (2013), 034028

Observables

D^* polarisation fraction in $\overline{B} \to D^* \tau^- \overline{\nu}_\tau$ $\quad f_L(q^2)$

arxiv:1606.03164



SM contributions in all plots shown in BLUE, red and black show SM + various NP

Experimental strategies

B-factories

- multiple neutrinos prevent to fully measure/determine the decay's kinematics
- exploit unique experimental setup
  - detector hermetically encloses the interaction point
  - knowledge of initial state and known production process

$$e^+e^- \to \Upsilon(4S) \to B_{\mathrm{comp}}\overline{B}_{\mathrm{sig}}$$

The companion *B* meson reconstruction

- **Hadronic**: *sum of exclusive hadronic decays*

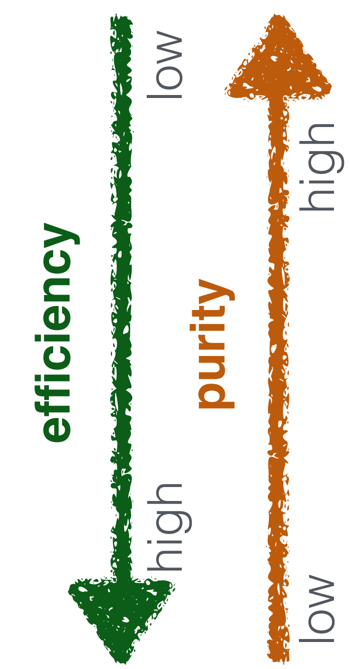
  $$B \to \overline{D}^{(*)}n\pi,\ \overline{D}^{(*)}D^{(*)}K,\ \overline{D}_s^{(*)}D^{(*)},\ J/\psi K n\pi$$

  provides $p(B_{sig})$

- **Semi-leptonic**: *sum of exclusive semi-leptonic decays*

  $$B \to \overline{D}^{(*)}\ell\nu_\ell$$

- ***Untagged/Inclusive***: *sum all tracks/clusters not used for B_{sig} reconstruction*

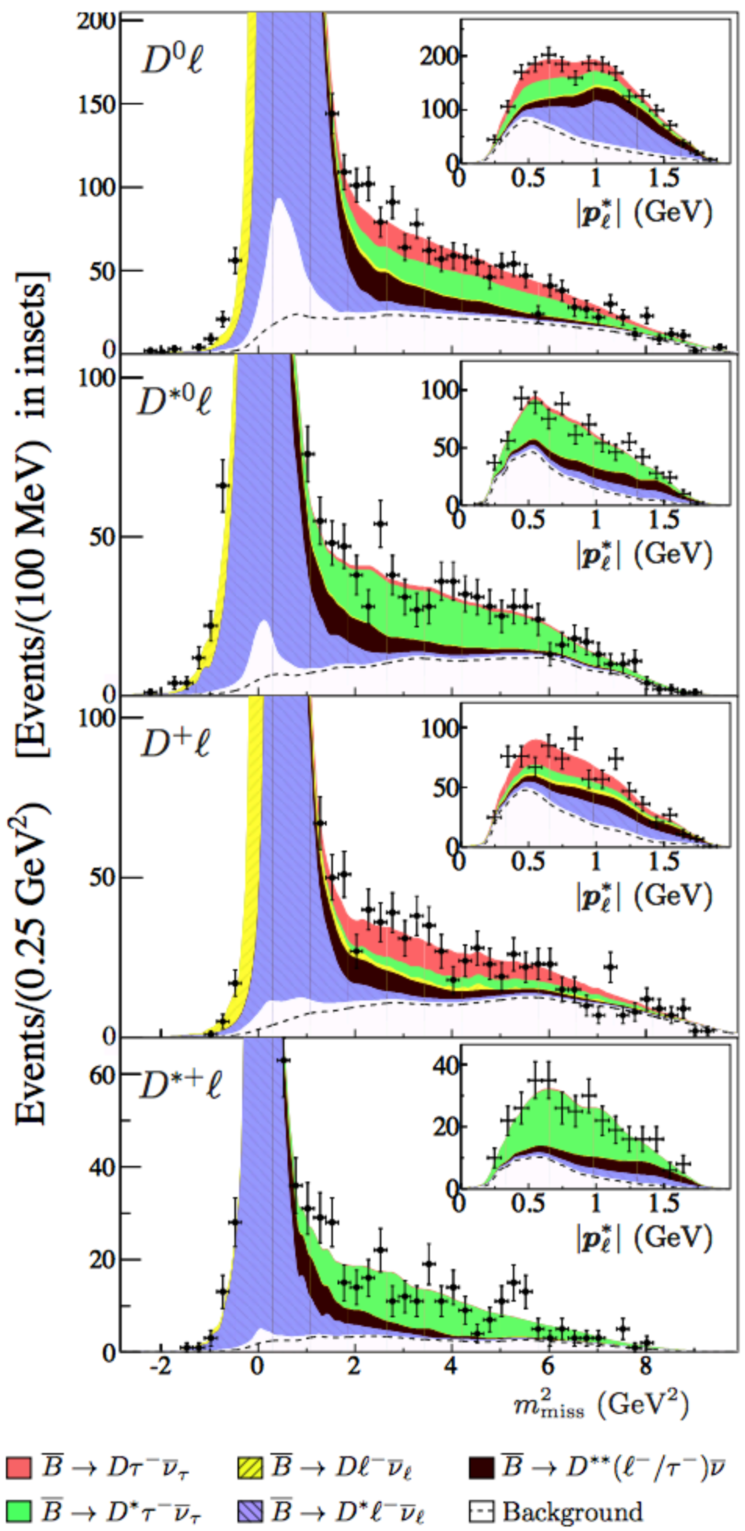


Experimental status

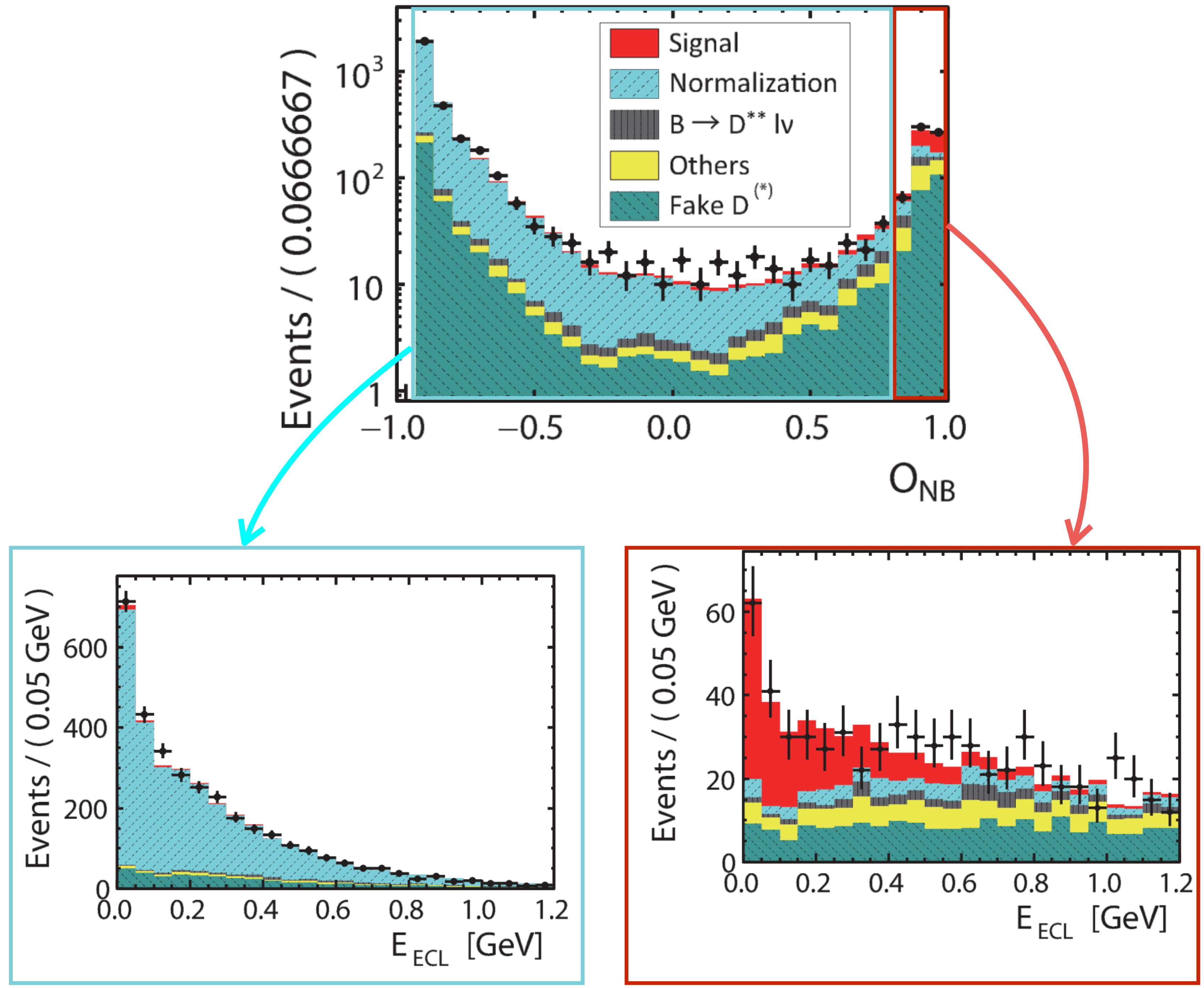
Experiment	Mode	Technique	Observables
BaBar [PRL109, 101802; PRD88, 072012]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Hadronic	R(D), R(D*), q^2
Belle [PRL99,191807; PRD82,072005;]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Inclusive	Br
Belle [PRD92,072014]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Hadronic	R(D), R(D*), q^2, $\lvert p_l^*\rvert$
Belle [PRD94, 072007]	$B^0 \to D^{*-}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Semi-leptonic	R(D*), $\lvert p^*_l\rvert$, $\lvert p^*_{D^*}\rvert$
Belle [arXiv:1608.06391]	$B \to \overline{D}^{*}\tau\nu_\tau$ $\tau \to \pi\nu_\tau,\ \rho\nu_\tau$	Hadronic	R(D*), P_τ
LHCb [PRL115,111803]	$B^0 \to D^{*-}\tau\nu_\tau$ $\tau \to \mu\overline{\nu}_\mu\nu_\tau$		R(D*)

Experimental results

BaBar@Hadronic(τ→l)

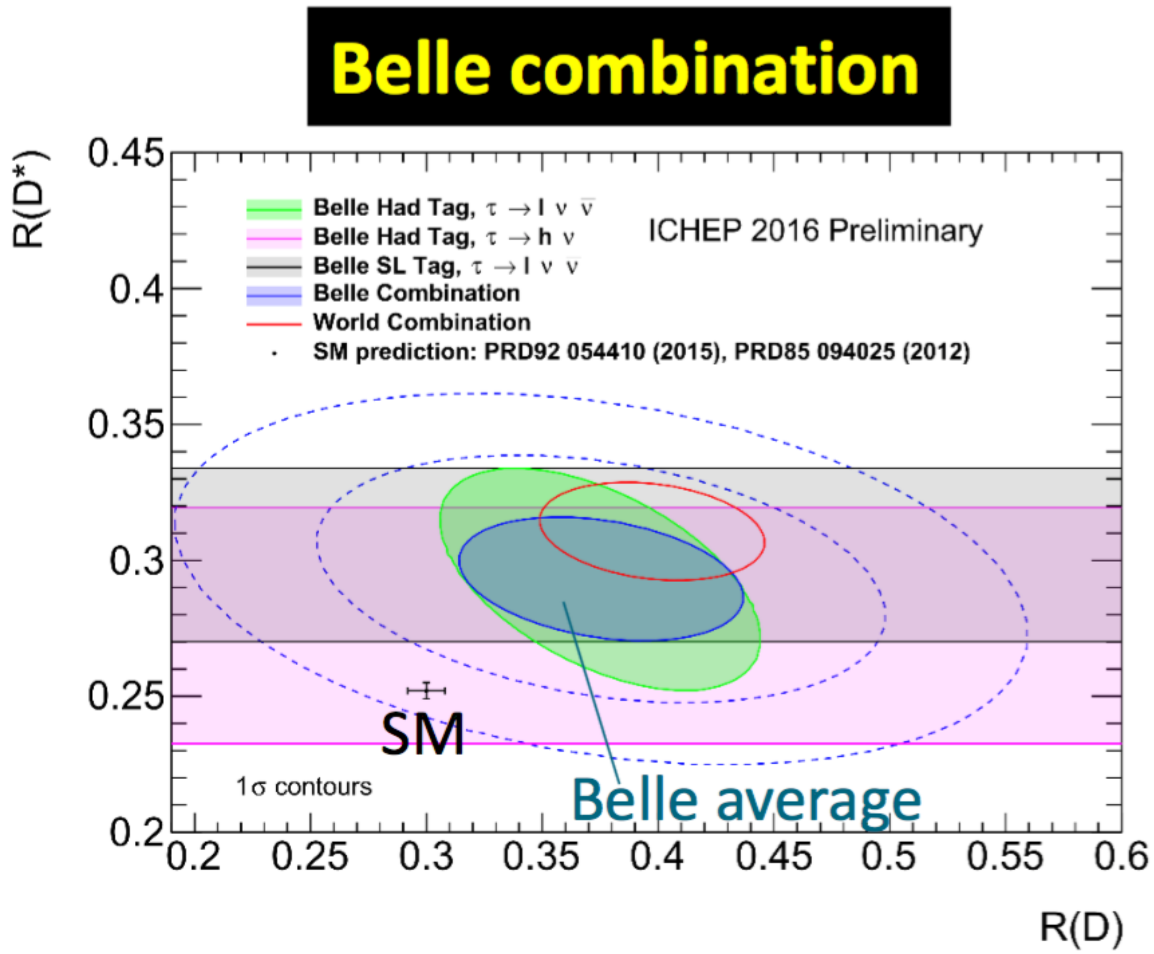


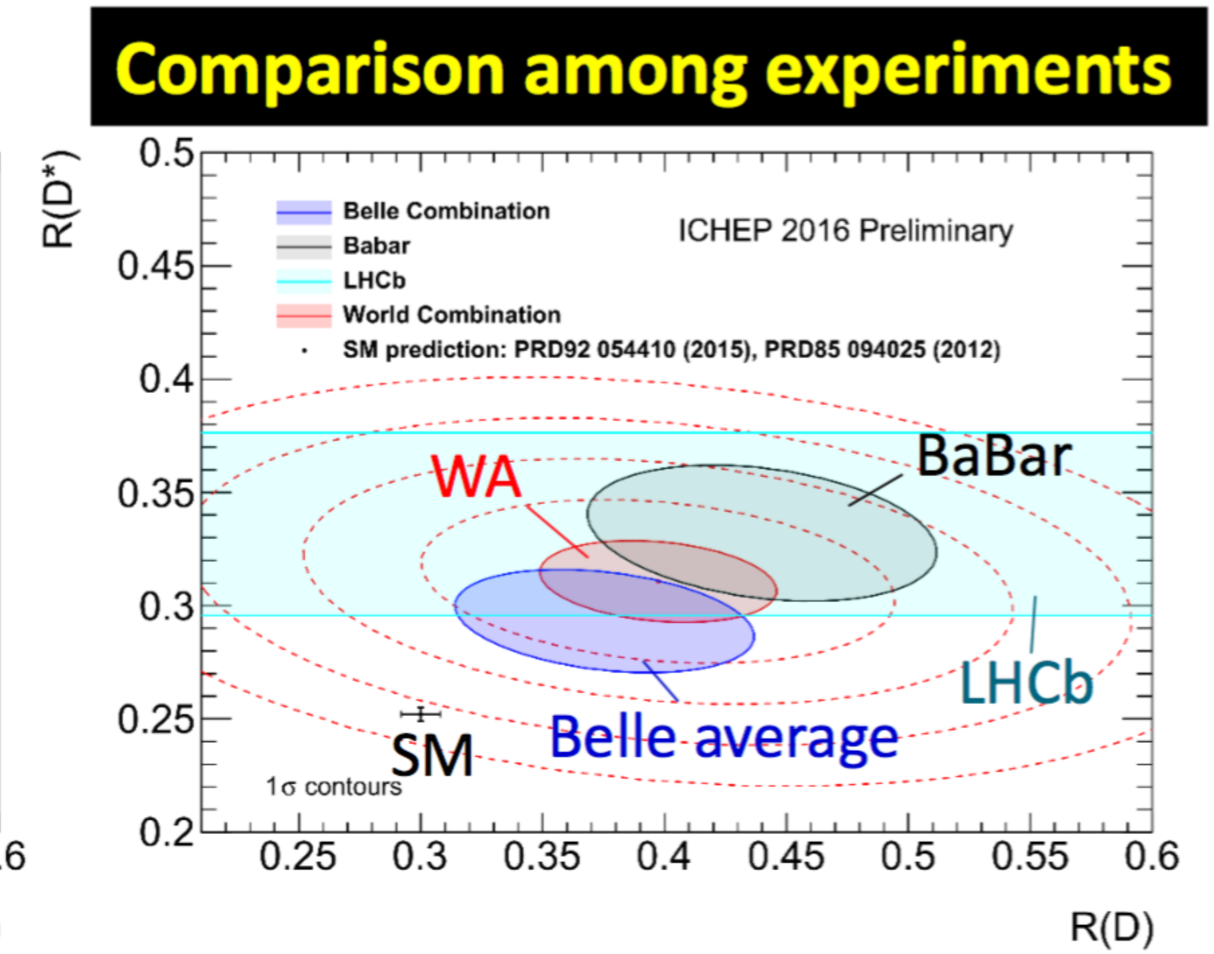
Belle@Semileptonic(τ→l)



R(D) and R(D*) combination

Y.SATO@ICHEP'16



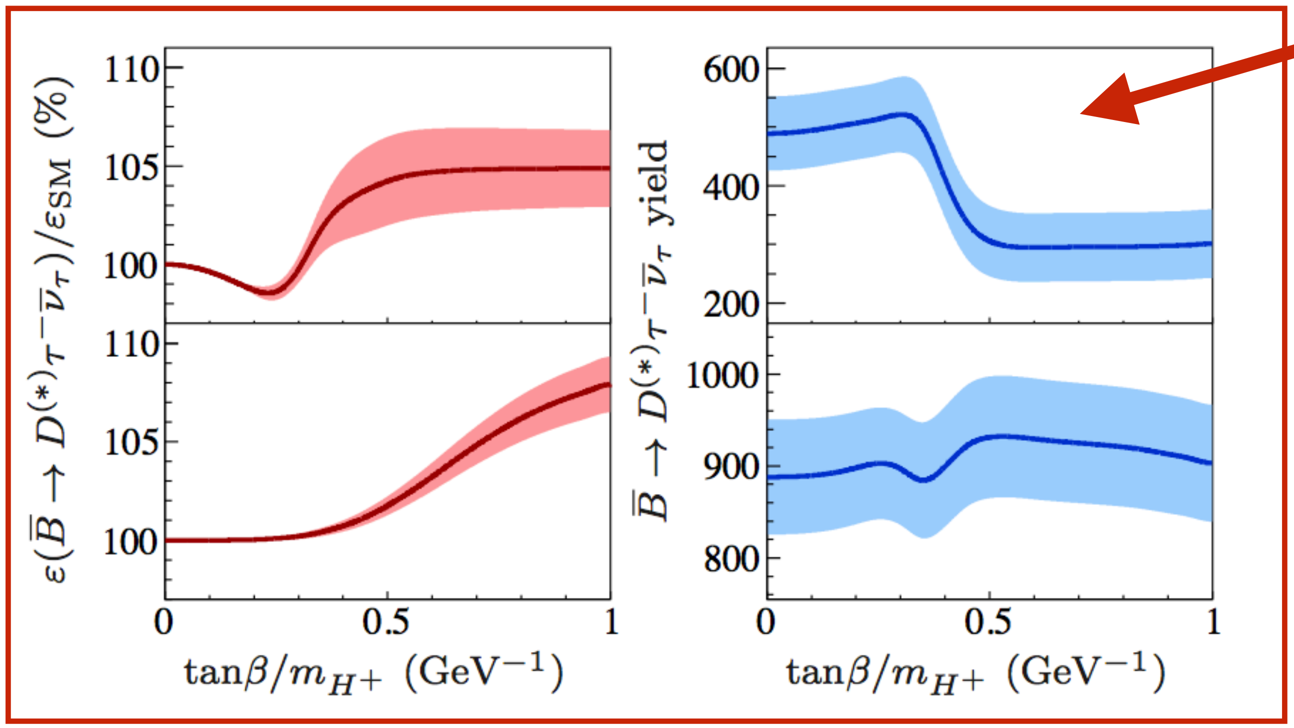


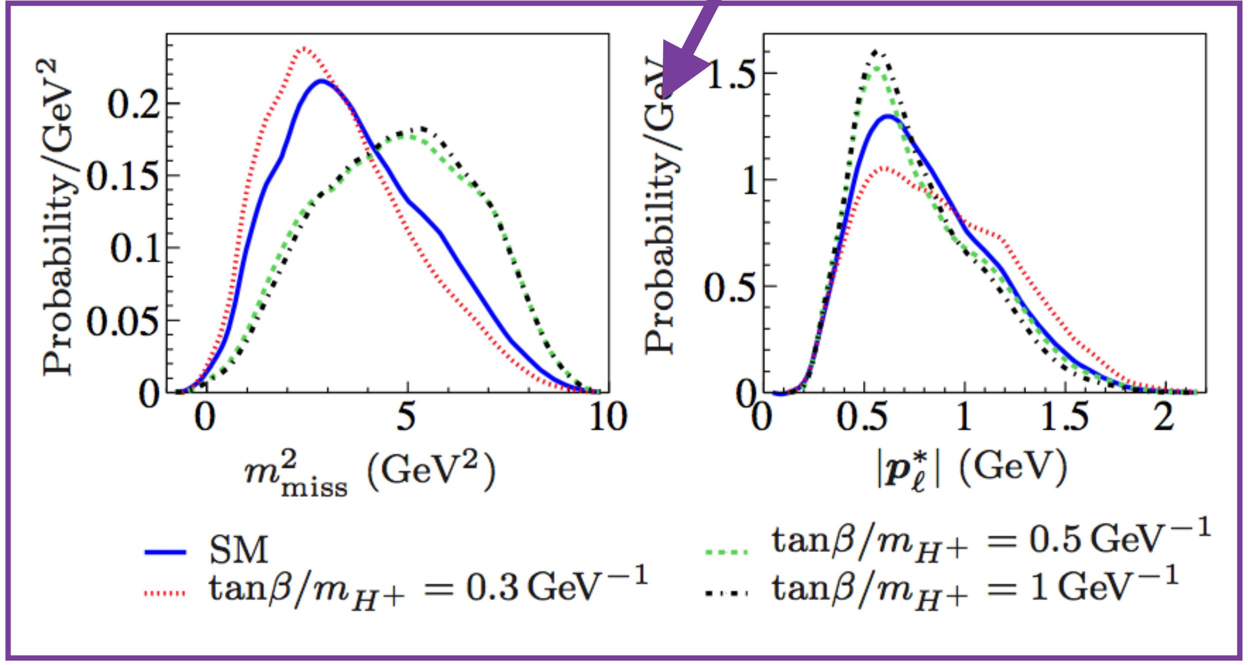
The difference with the SM predictions is at >4σ level!

New Physics contributions? $R(D^{(*)})$

Model dependent analysis (type-II 2HDM)

- kinematics of the decays depend on NP model and its free parameters
  - difference in kinematics → difference in efficiency and fitted distributions





BaBar@Hadronic(τ→l)

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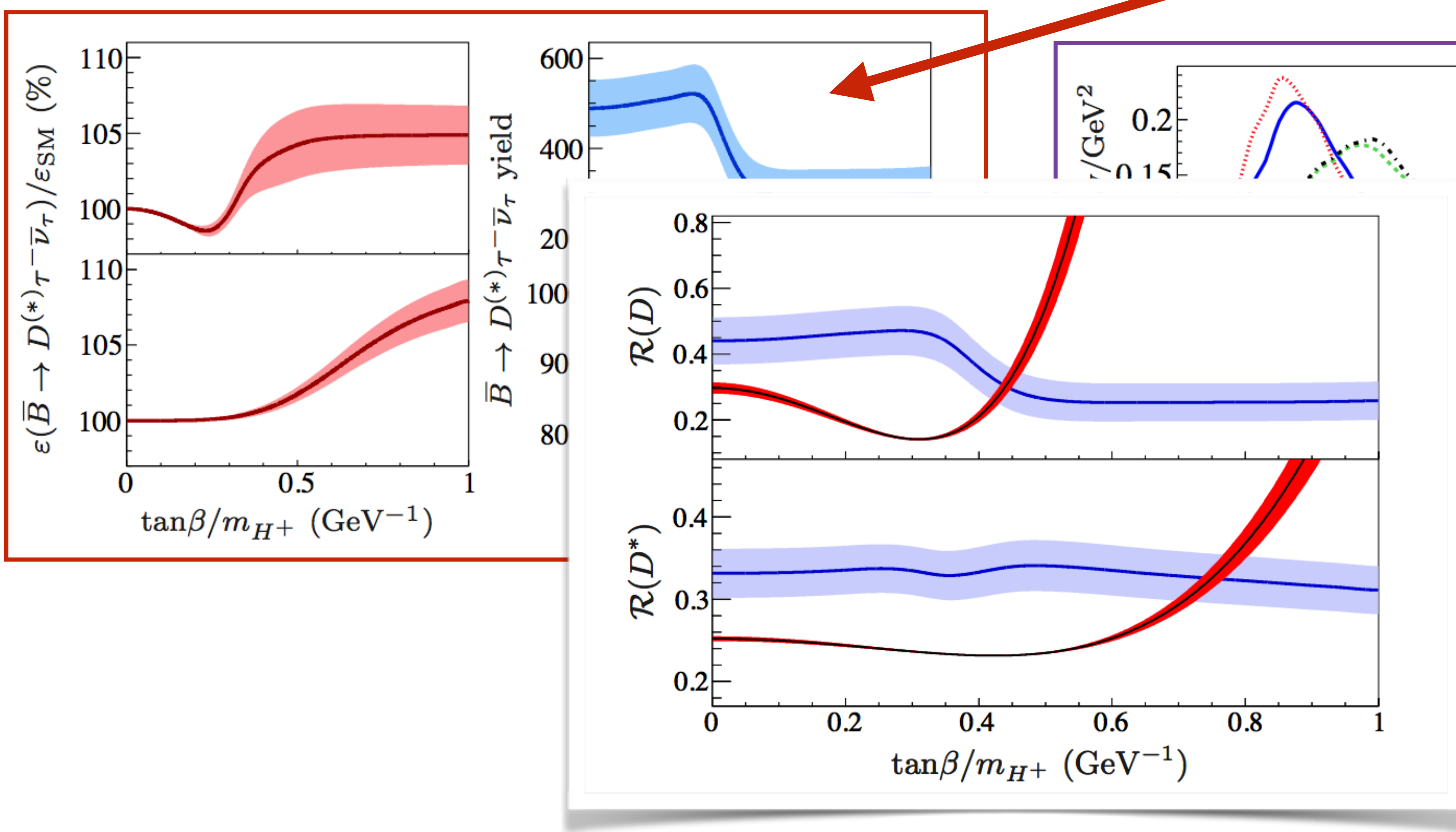
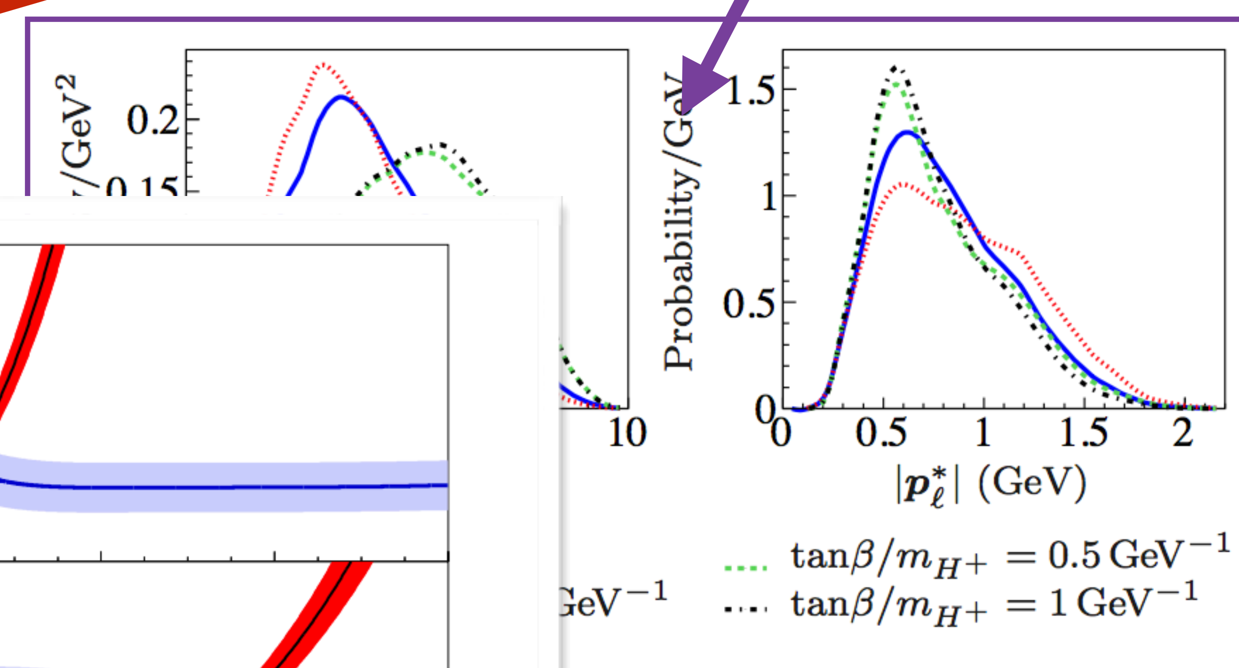


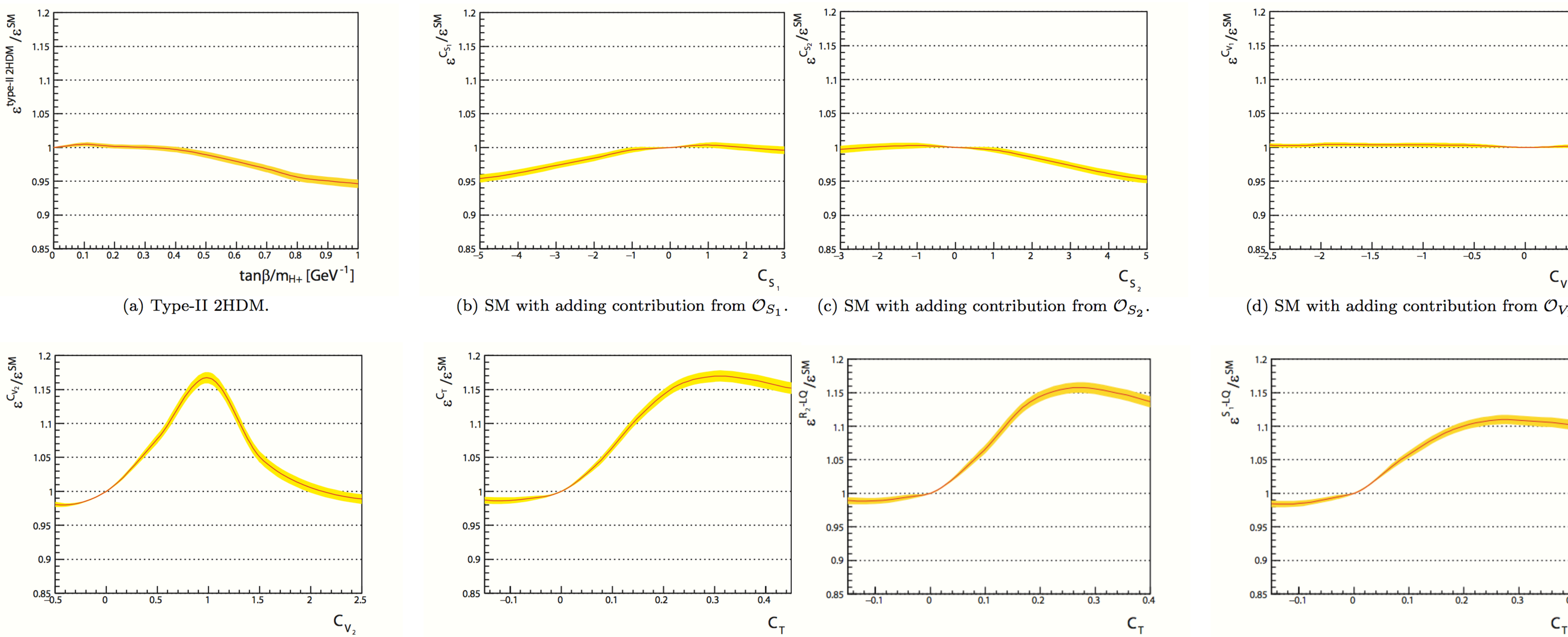


BaBar@Hadronic(τ→l)

New Physics contributions? $R(D^{(*)})$

Model independent analysis

- examine the impact of each operator
  - difference in kinematics ➔ difference in efficiency and fitted distributions



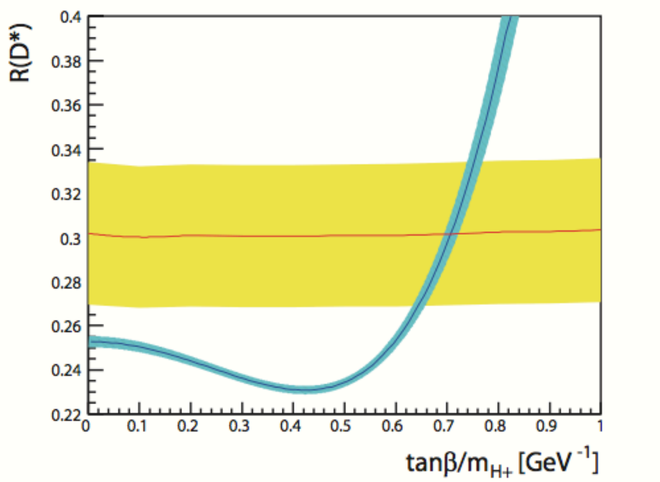
(a) Type-II 2HDM. (b) SM with adding contribution from $\mathcal{O}_{S_1}$. (c) SM with adding contribution from $\mathcal{O}_{S_2}$. (d) SM with adding contribution from $\mathcal{O}_{V_1}$. (e) SM with adding contribution from $\mathcal{O}_{V_2}$. (f) SM with adding contribution from $\mathcal{O}_{T}$. (g) R_2-type leptoquark model. (h) S_1-type leptoquark model.

2

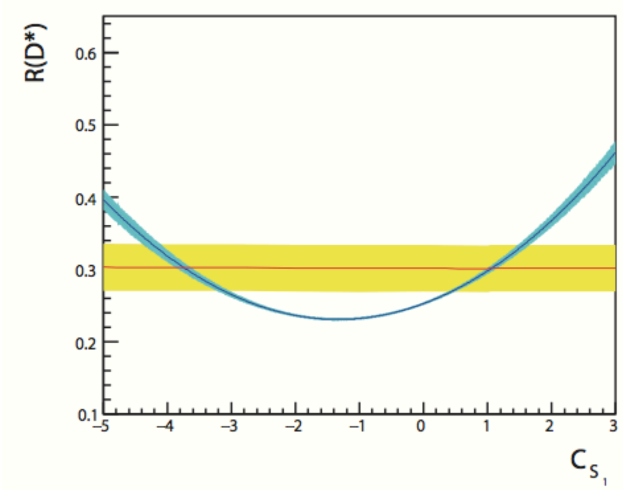
New Physics contributions? $R(D^{(*)})$

Model independent analysis

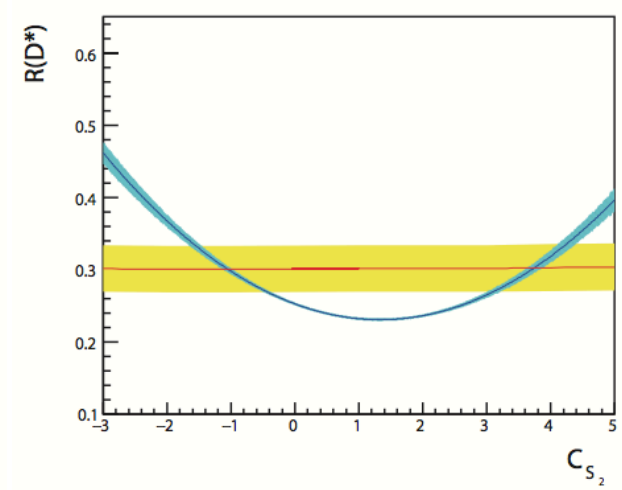
- examine the impact of each operator
    - difference in kinematics ➔ difference in efficiency and fitted distributions



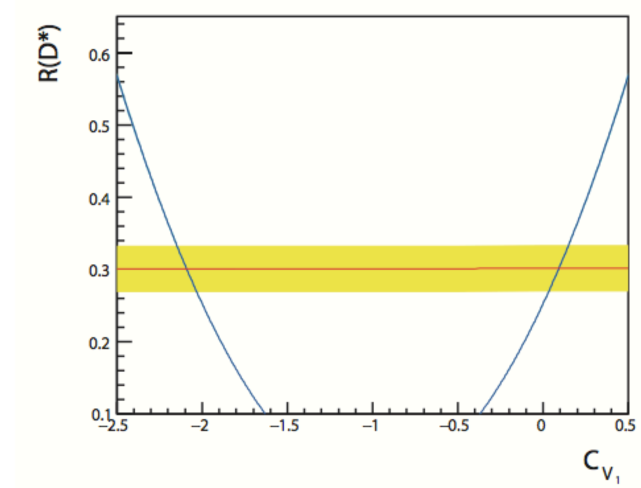
(a) Type-II 2HDM.



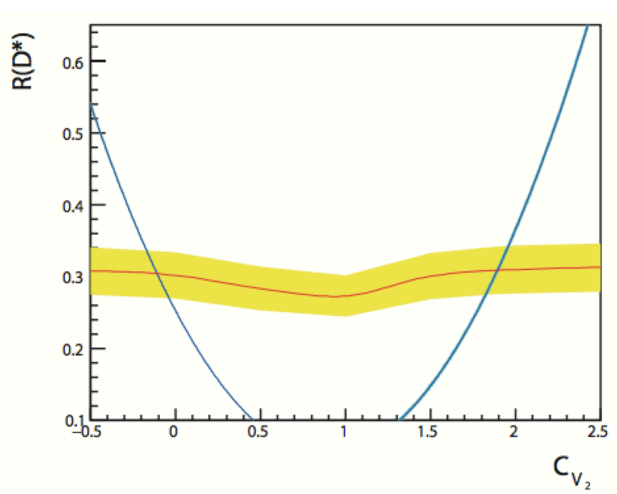
(b) SM with adding contribution from $\mathcal{O}_{S_1}$.



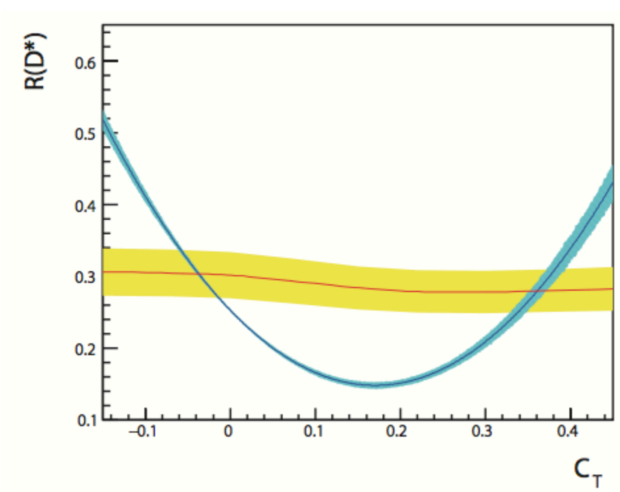
(c) SM with adding contribution from $\mathcal{O}_{S_2}$.



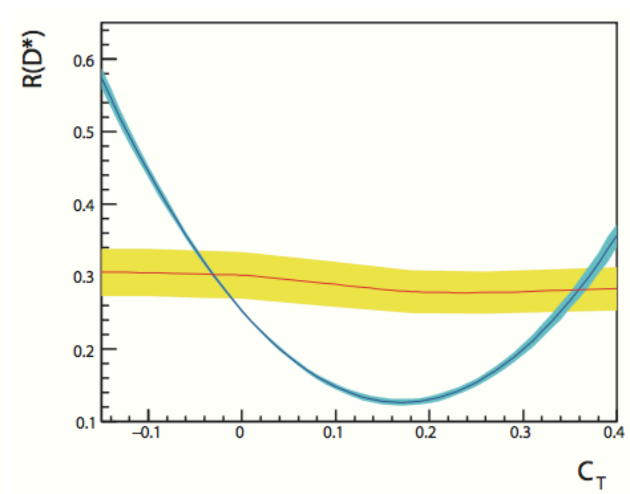
(d) SM with adding contribution from $\mathcal{O}_{V_1}$.



(e) SM with adding contribution from $\mathcal{O}_{V_2}$.

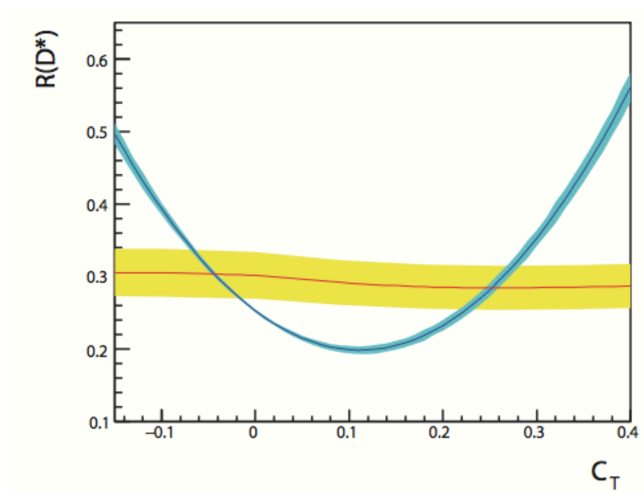


(f) SM with adding contribution from $\mathcal{O}_T$.



(g) R_2-type leptoquark model.

3

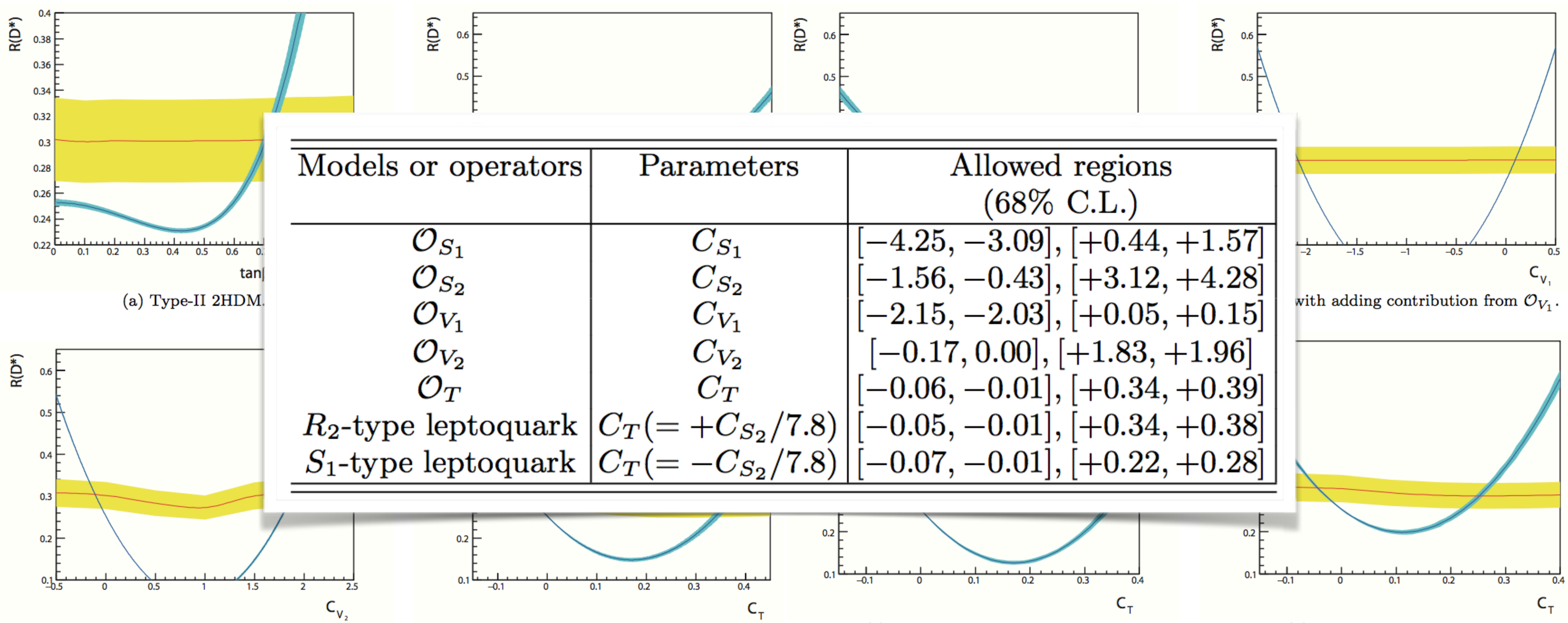


(h) S_1-type leptoquark model.

New Physics contributions? $R(D^{(*)})$

Model independent analysis

- examine the impact of each operator
  - difference in kinematics ➞ difference in efficiency and fitted distributions



(a) Type-II 2HDM.

with adding contribution from $\mathcal{O}_{V_1}$.

(e) SM with adding contribution from $\mathcal{O}_{V_2}$.

(f) SM with adding contribution from $\mathcal{O}_T$.

(g) R_2-type leptoquark model.

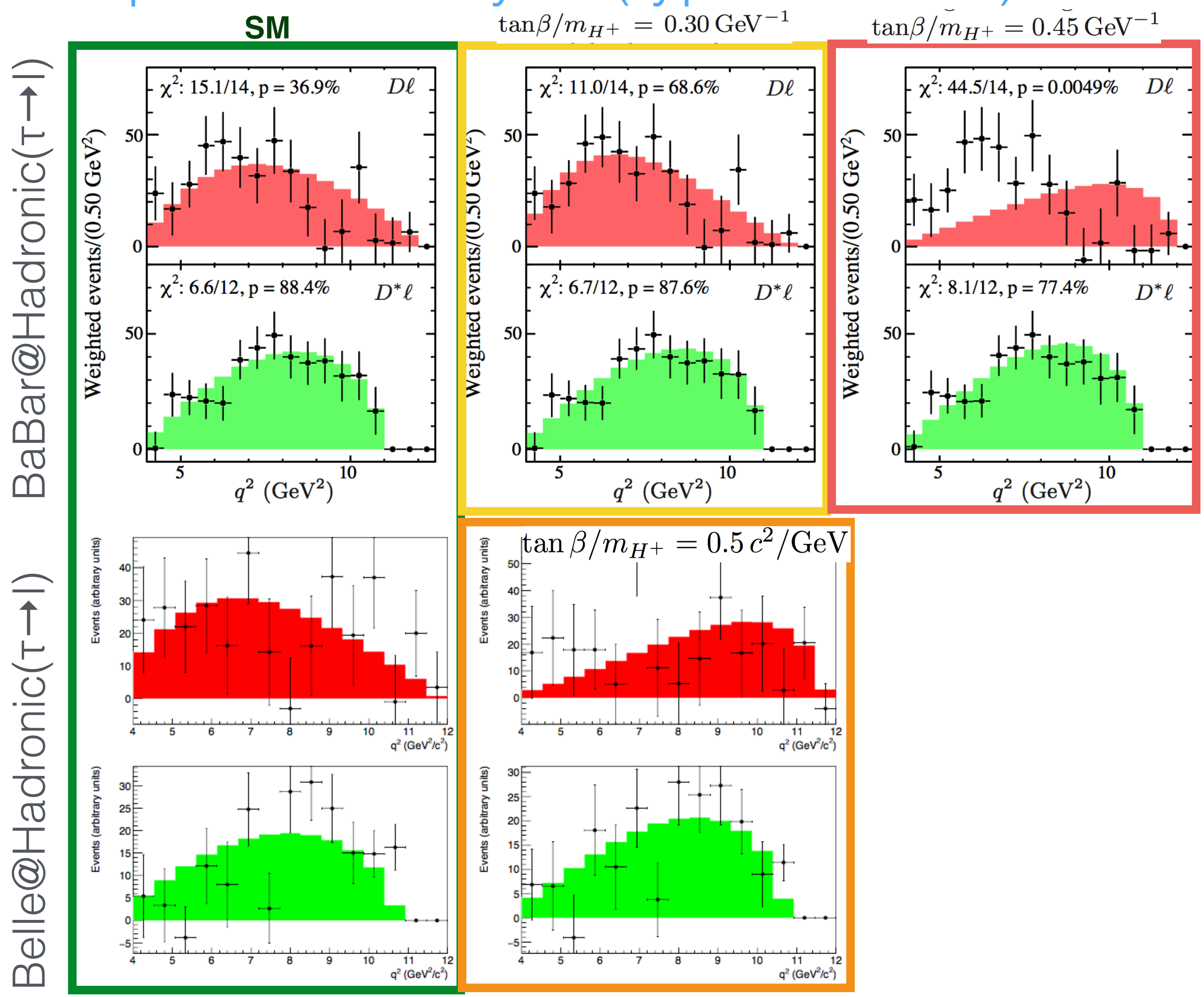
3

(h) S_1-type leptoquark model.

Models or operators	Parameters	Allowed regions (68% C.L.)
$\mathcal{O}_{S_1}$	C_{S_1}	$[-4.25, -3.09]$, $[+0.44, +1.57]$
$\mathcal{O}_{S_2}$	C_{S_2}	$[-1.56, -0.43]$, $[+3.12, +4.28]$
$\mathcal{O}_{V_1}$	C_{V_1}	$[-2.15, -2.03]$, $[+0.05, +0.15]$
$\mathcal{O}_{V_2}$	C_{V_2}	$[-0.17, 0.00]$, $[+1.83, +1.96]$
$\mathcal{O}_T$	C_T	$[-0.06, -0.01]$, $[+0.34, +0.39]$
R_2-type leptoquark	$C_T(= +C_{S_2}/7.8)$	$[-0.05, -0.01]$, $[+0.34, +0.38]$
S_1-type leptoquark	$C_T(= -C_{S_2}/7.8)$	$[-0.07, -0.01]$, $[+0.22, +0.28]$

New Physics contributions? q^2

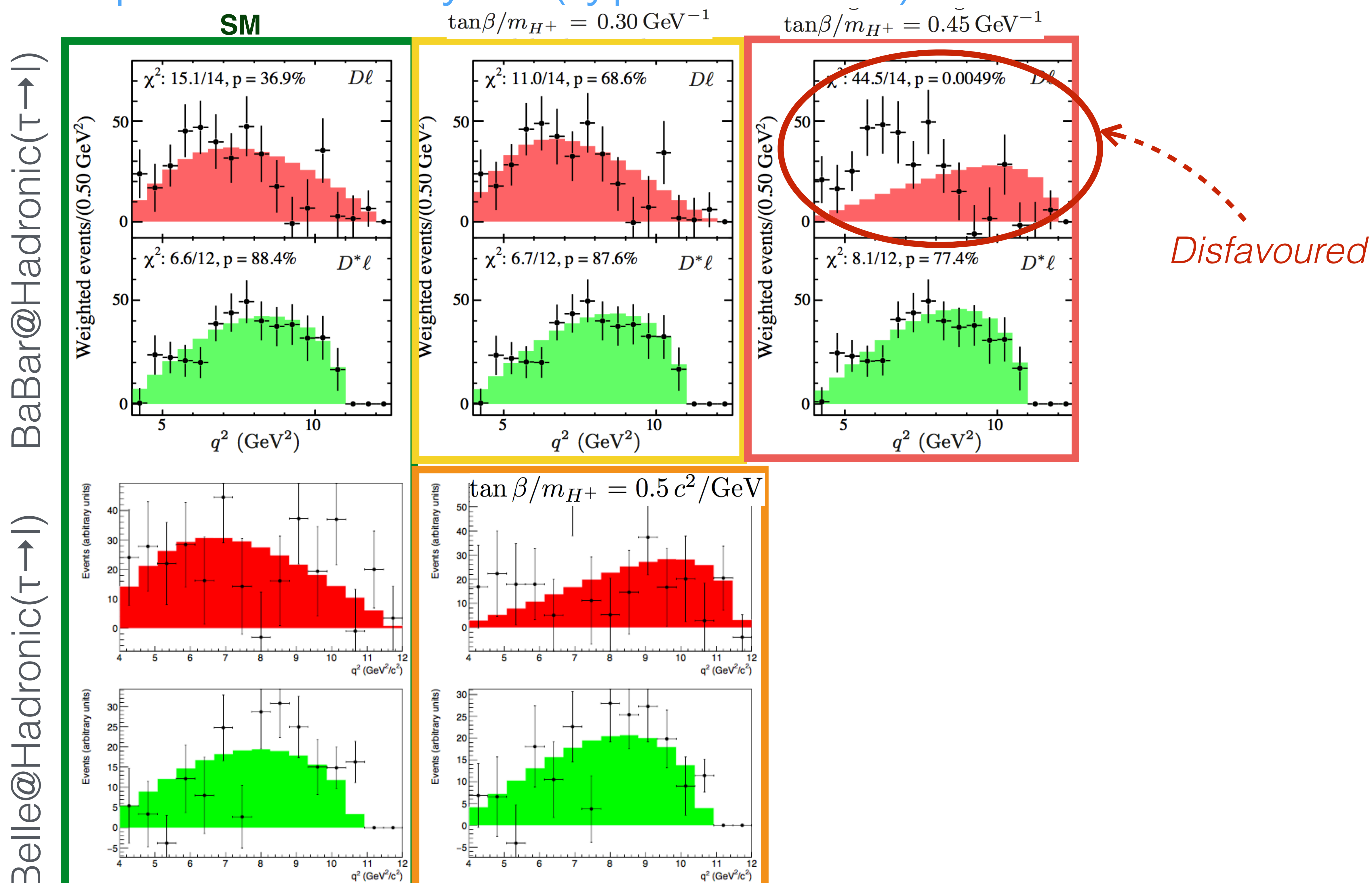
Model dependent analysis (type-II 2HDM)



New Physics contributions?

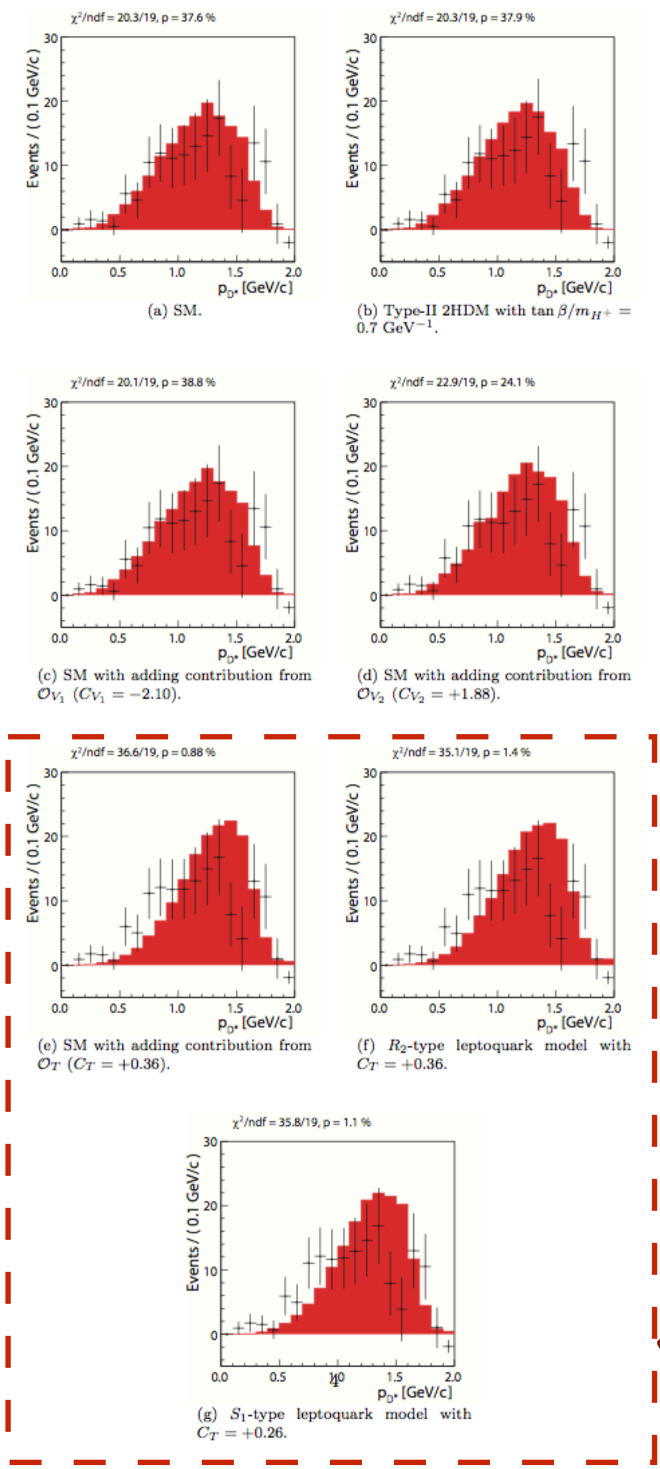
q^2

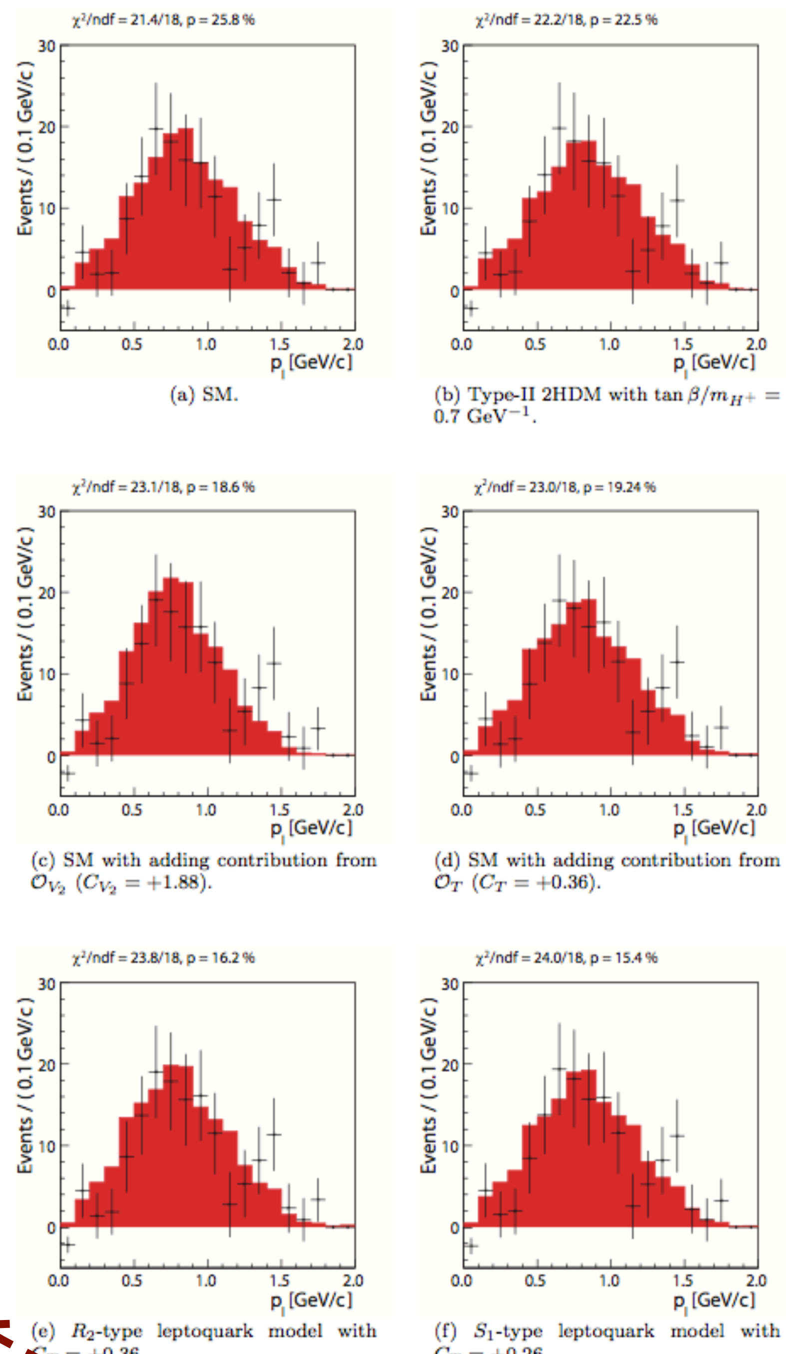
Model dependent analysis (type-II 2HDM)



New Physics contributions? $|p_\ell^*|, \ |p_{D^*}^*|$

Model independent analysis





Belle@Semileptonic(τ→l)

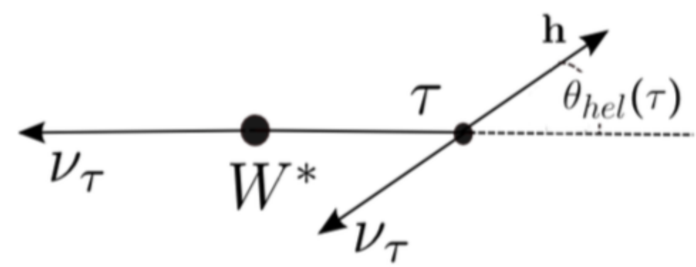
Model or operator	Parameter	p values [%]	
		p_{D^*}	p_ℓ
SM		37.6	25.8
Type-II 2HDM	$\frac{\tan\beta}{m_{H^+}} = 0.7$ GeV^{-1}	37.9	22.5
$\mathcal{O}_{V_2}$	$C_{V_2} = +1.88$	24.1	18.6
$\mathcal{O}_T$	$C_T = +0.36$	0.9	19.2
R_2-type leptoquark model	$C_T = +0.36$	1.4	16.2
S_1-type leptoquark model	$C_T = +0.26$	1.1	15.4

Large additional contributions from tensor operator or R2-(S1)-type leptoquark models are disfavoured.

Tau Polarimeters (hadronic decays)

- $\cos\theta_{hel}(\tau)$ distribution in (quasi)2-body decays $\tau \to M\nu_\tau$
- τ polarization measurment based on $\cos\theta_{hel}(\tau)$ distribution:

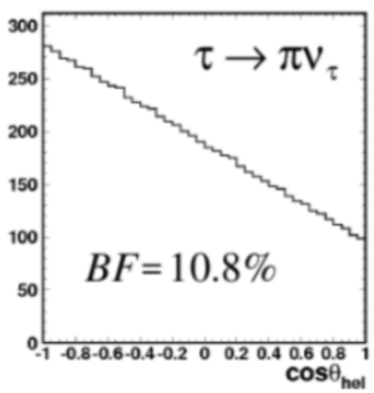
$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} \sim \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$

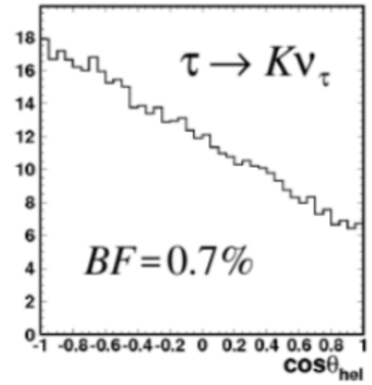


- **SM: $P_\tau \approx$ -0.5**
- leptonic τ decays not useful;

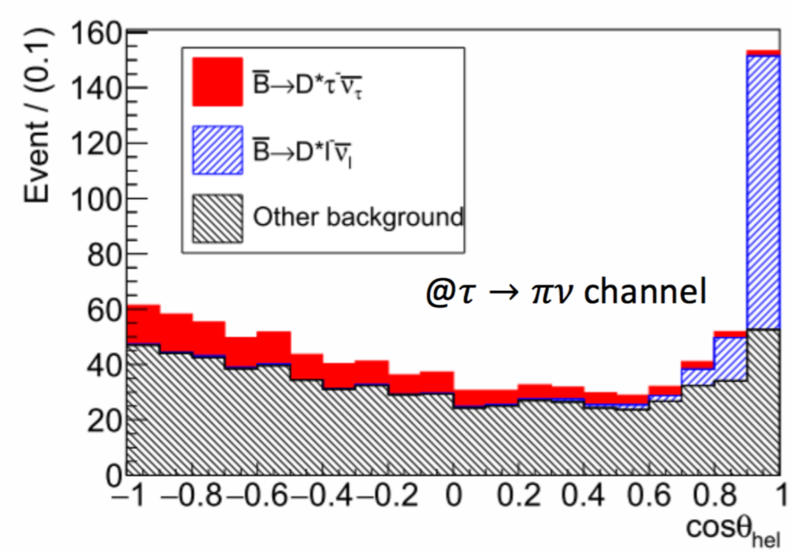
for $J_M = 0$

$\alpha = 1$





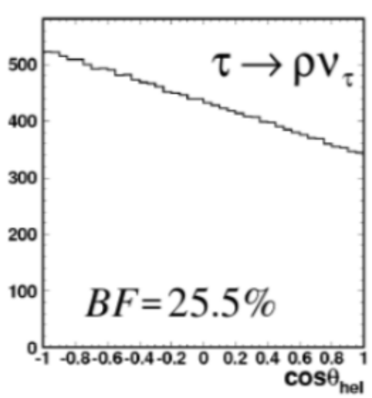
Belle MC

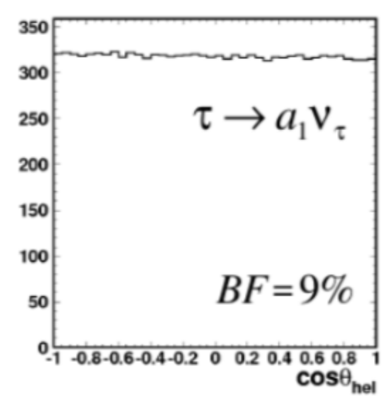


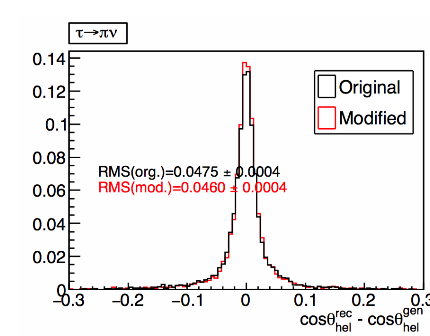
best sensitivity

for $J_M = 1$

$$\alpha = \frac{m_\tau^2 - m_M^2}{m_\tau^2 + m_M^2}$$







$\alpha = 0.45$ for $\tau \to \rho\nu$

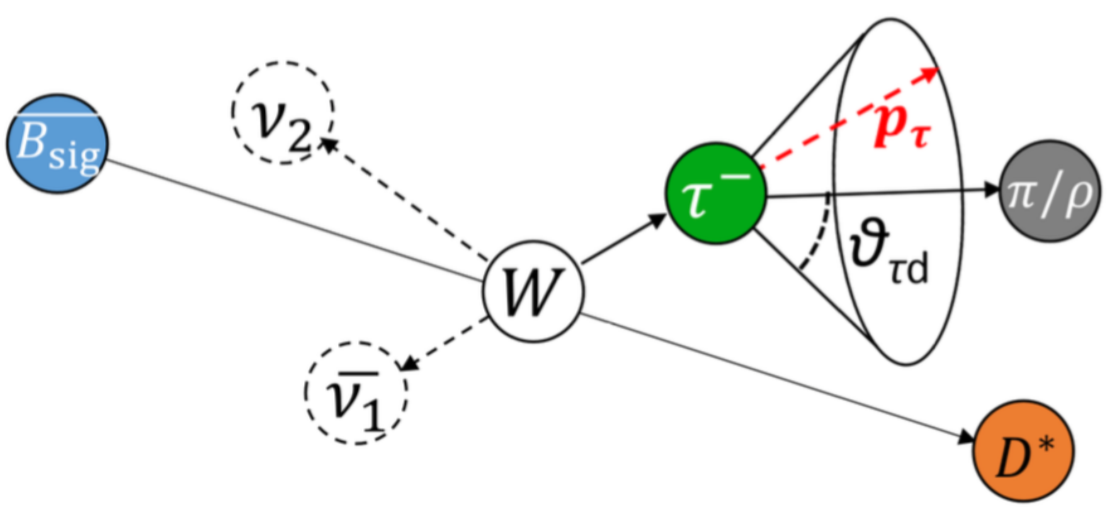
$\alpha = 0.12$ for $\tau \to a_1\nu$

Tau Polarimeters (hadronic decays)

Experimental challenges:

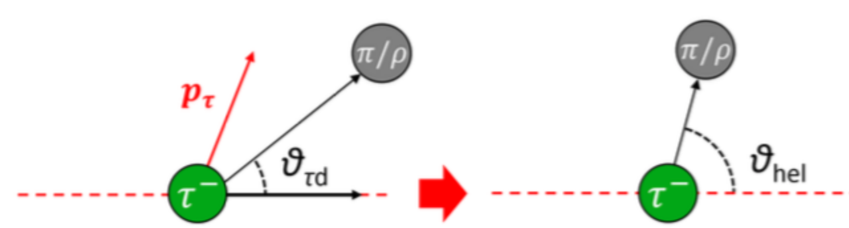
- due to multiple neutrinos in the final state the tau momentum can not be completely determined
- go to W rest frame, where $p_W = p_{Bsig} - p_{D^*} = 0$
- in W rest frame the tau and neutrino from B decay are back-to-back, therefore:
  - magnitude of tau momentum ($|p_\tau|$) can be determined $|\vec{p}_\tau| = \frac{q^2 - m_\tau^2/c^2}{2\sqrt{q^2}}$
  - direction of the tau momentum is constrained to lie on the cone around the hadron daughter momentum

$$\cos\theta_{\tau d} = \frac{2E_\tau E_{\mathrm{da}} - m_\tau^2 - m_{\mathrm{da}}^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_{\mathrm{da}}|}$$



Decay kinematics of the $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ decay in the W rest frame

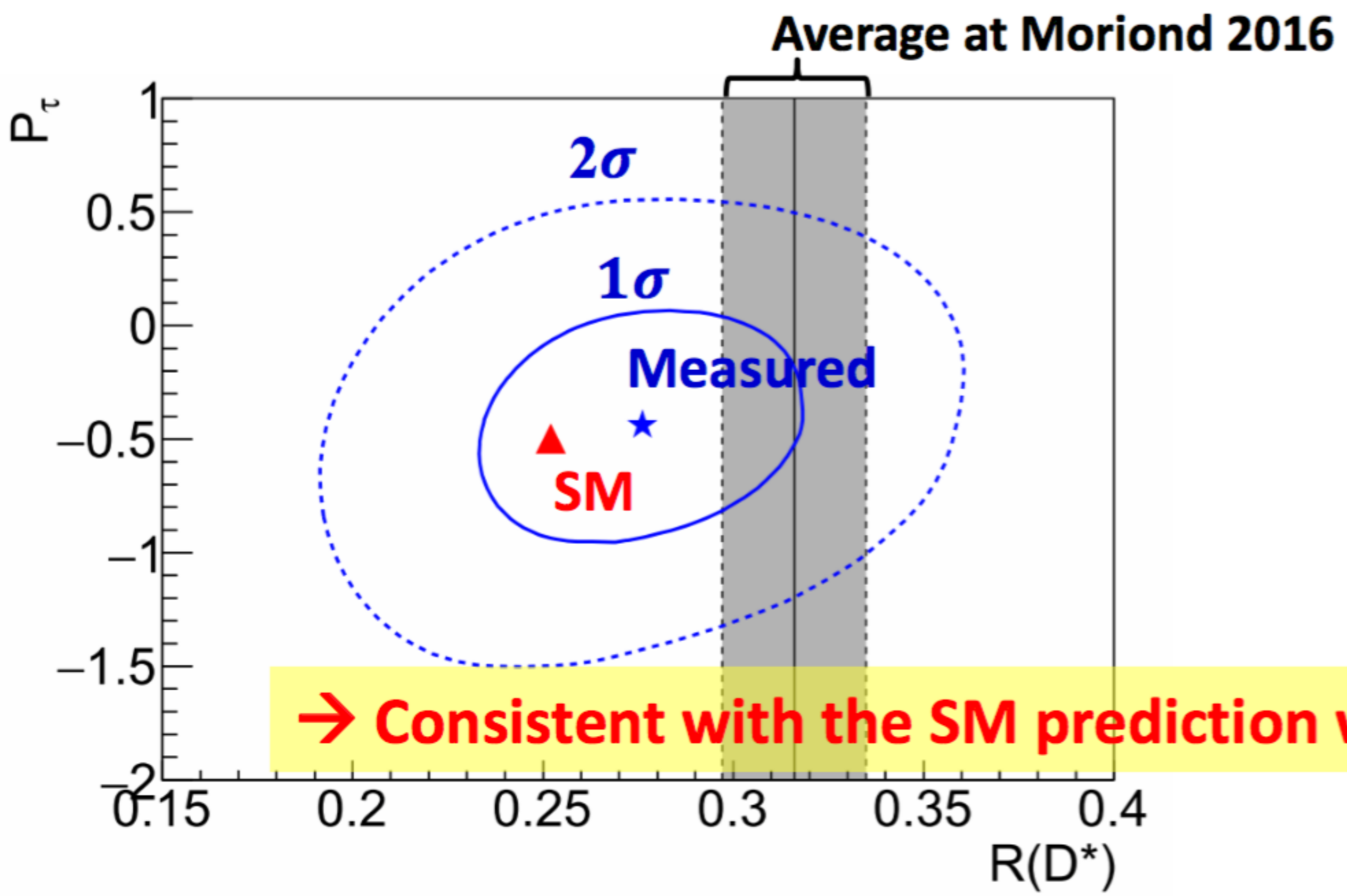
Boost in arbitrary direction on the cone to get into the tau rest frame



Results

$\mathcal{R}(D^*)$ and $\mathcal{P}_\tau$ with Had-tag

- $\mathcal{R}(D^*) = 0.276 \pm 0.034(\text{stat})^{+0.029}_{-0.026}(\text{syst})$ ***Preliminary***
  - 7.1σ significance including systematic uncertainty.
  - Consistent with SM prediction and other measurements.
- $\mathcal{P}_\tau = -0.44 \pm 0.47(\text{stat})^{+0.20}_{-0.17}(\text{syst})$ ***Preliminary***
  - **First $\mathcal{P}_\tau$ measurements !**
  - Consistent with SM prediction (-0.497 ± 0.014) within uncertainty. *M. Tanaka, R. Watanabe, PRD 87, 034028 (2013)*
- Systematics arises mainly from hadronic B bkg, MC statistics.



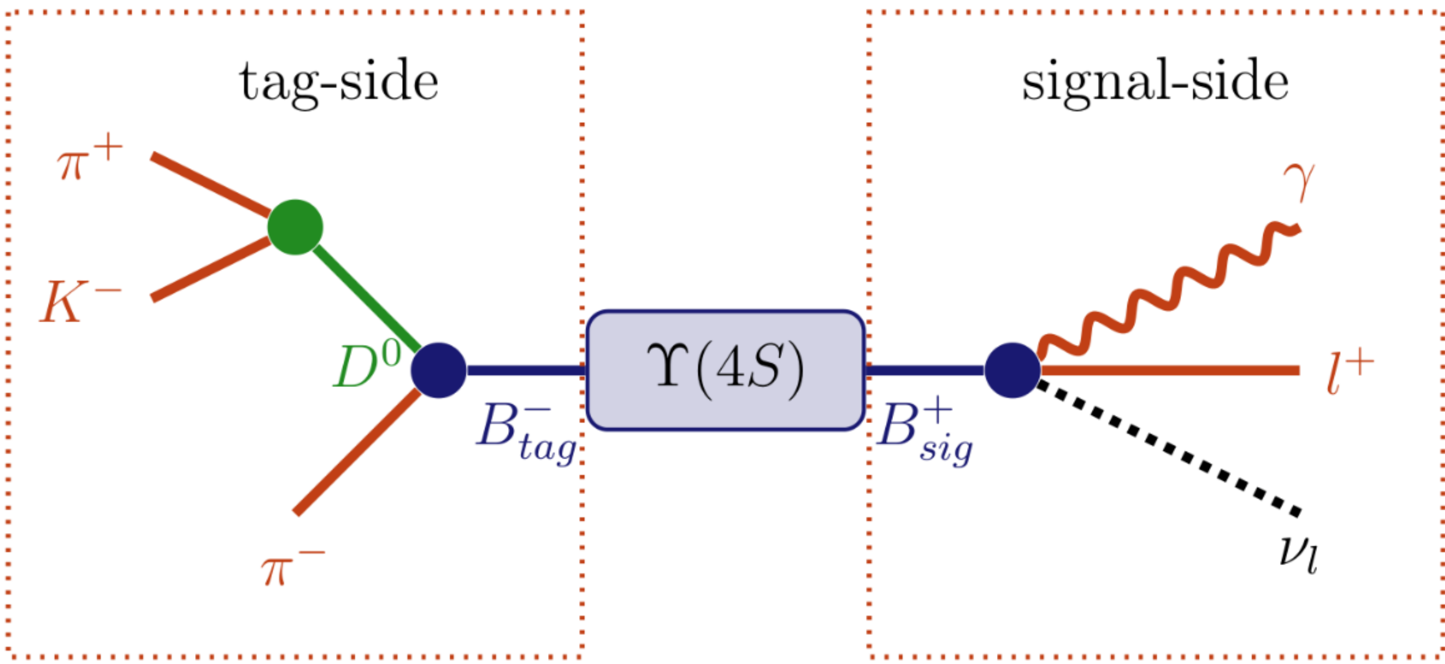
→ Consistent with the SM prediction within 0.6σ

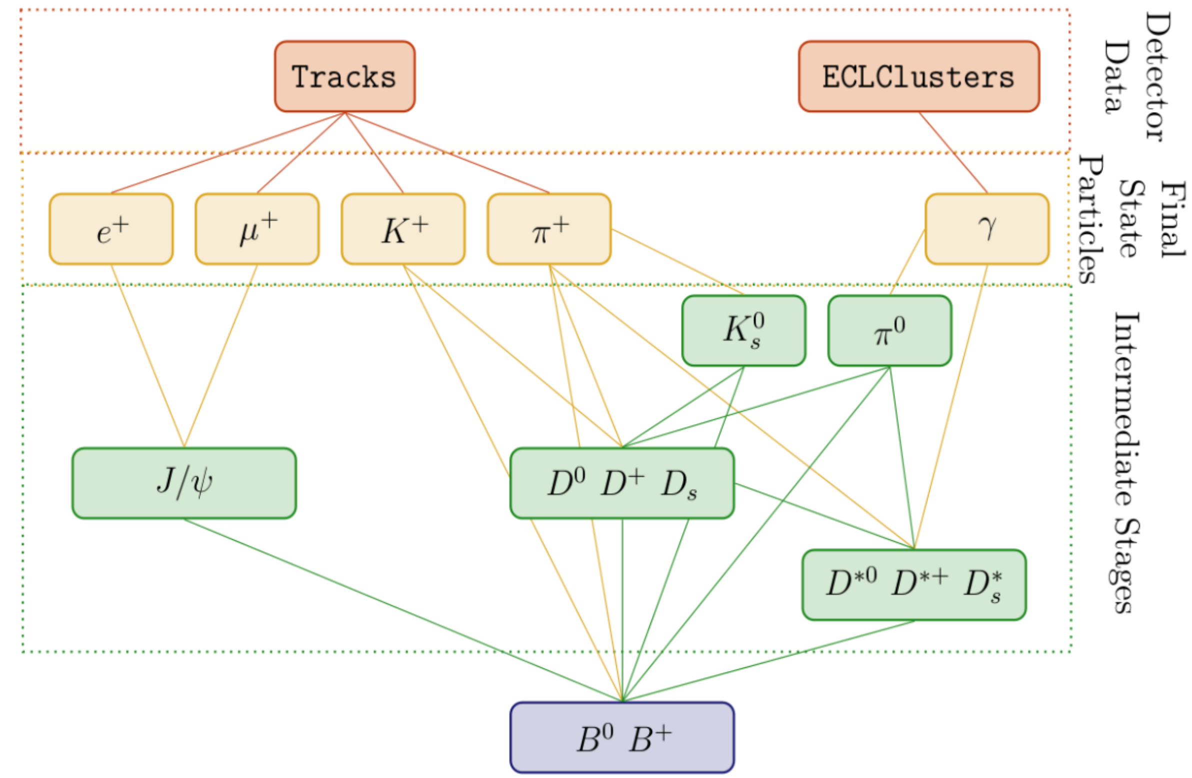
Belle II prospects

- Measurements are currently statistically limited
- Several (at the moment dominant) sources of systematic uncertainty are also statistical in nature
  - estimations of backgrounds with control samples on data, MC statistics

Experiment	Technique	R(D)	R(D*)
BaBar [PRL109, 101802; PRD88, 072012]	Hadronic	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle [PRD92,072014]	Hadronic	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
Belle [PRD94, 072007]	Semi-leptonic		$0.302 \pm 0.030 \pm 0.011$
Belle [arXiv:1608.06391]	Hadronic		$0.276 \pm 0.034^{+0.029}_{-0.026}$

Hadronic B$_{tag}$ Reconstruction at Belle II



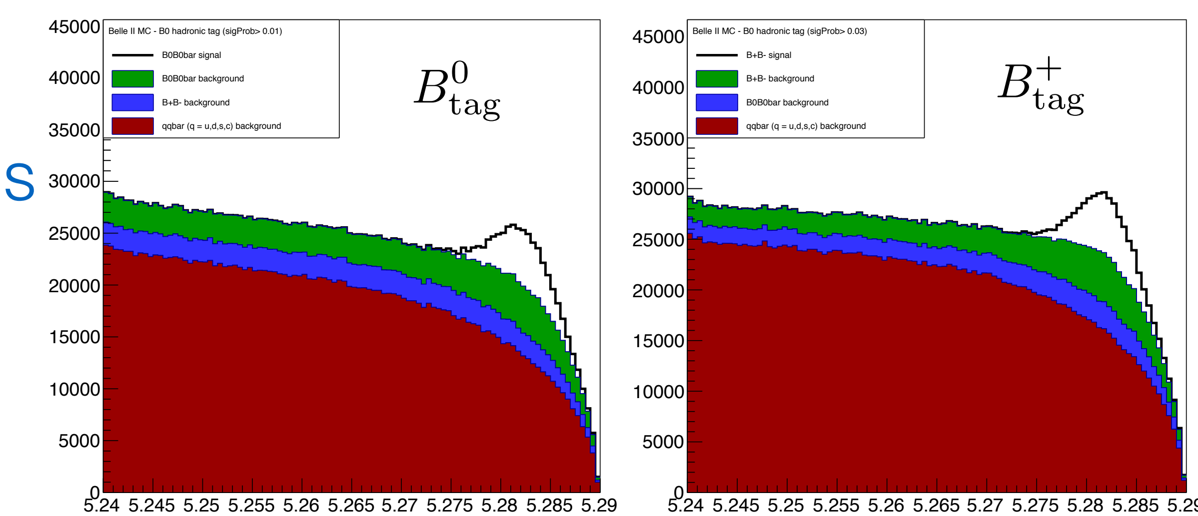


$$\varepsilon(B_{\text{tag}}) = \sum_i \mathcal{B}(B \to i)\varepsilon_i$$

Full Event Interpretation algorithm:

- includes considerably more B decay modes
- training of the classifiers (one per decay mode) is fully automated
- validation with Belle data is ongoing

Expect significantly higher tagging reconstruction efficiency at Belle II!



$\varepsilon(B^0_{\text{tag}}) = 0.33\%$	**Belle II**	$\varepsilon(B^+_{\text{tag}}) = 0.36\%$
$\varepsilon(B^0_{\text{tag}}) = 0.19\%$	**Belle**	$\varepsilon(B^+_{\text{tag}}) = 0.28\%$

Systematic errors

BaBar@Hadronic(τ→l)

Source of uncertainty	$\mathcal{R}(D)$ (%)	$\mathcal{R}(D^*)$ (%)
Additive uncertainties		
PDFs		
MC statistics	4.4	2.0
$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5
$\mathcal{B}(\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell)$	0.8	0.3
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6
Cross-feed constraints		
MC statistics	2.4	1.5
$f_{D^{**}}$	5.0	2.0
Feed-up/feed-down	1.3	0.4
Isospin constraints	1.2	0.3
Fixed backgrounds		
MC statistics	3.1	1.5
Efficiency corrections	3.9	2.3
Multiplicative uncertainties		
MC statistics	1.8	1.2
$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	1.6	0.4
Lepton PID	0.6	0.6
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1
Detection/Reconstruction	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2
Total syst. uncertainty	9.6	5.5
Total stat. uncertainty	13.1	7.1
Total uncertainty	16.2	9.0

Belle@Semileptonic(τ→l)

Sources	$\mathcal{R}(D^*)$ [%] $\ell^{sig} = e, \mu$
MC size for each PDF shape	2.2
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$
PDF shape and yields of fake $D^{(*)}$	1.4
PDF shape and yields of $B \to X_c D^*$	1.1
Reconstruction efficiency ratio $\varepsilon_{norm}/\varepsilon_{sig}$	1.2
Modeling of semileptonic decay	0.2
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$

Scales with MC statistics

Scales with DATA statistics

Theory/External

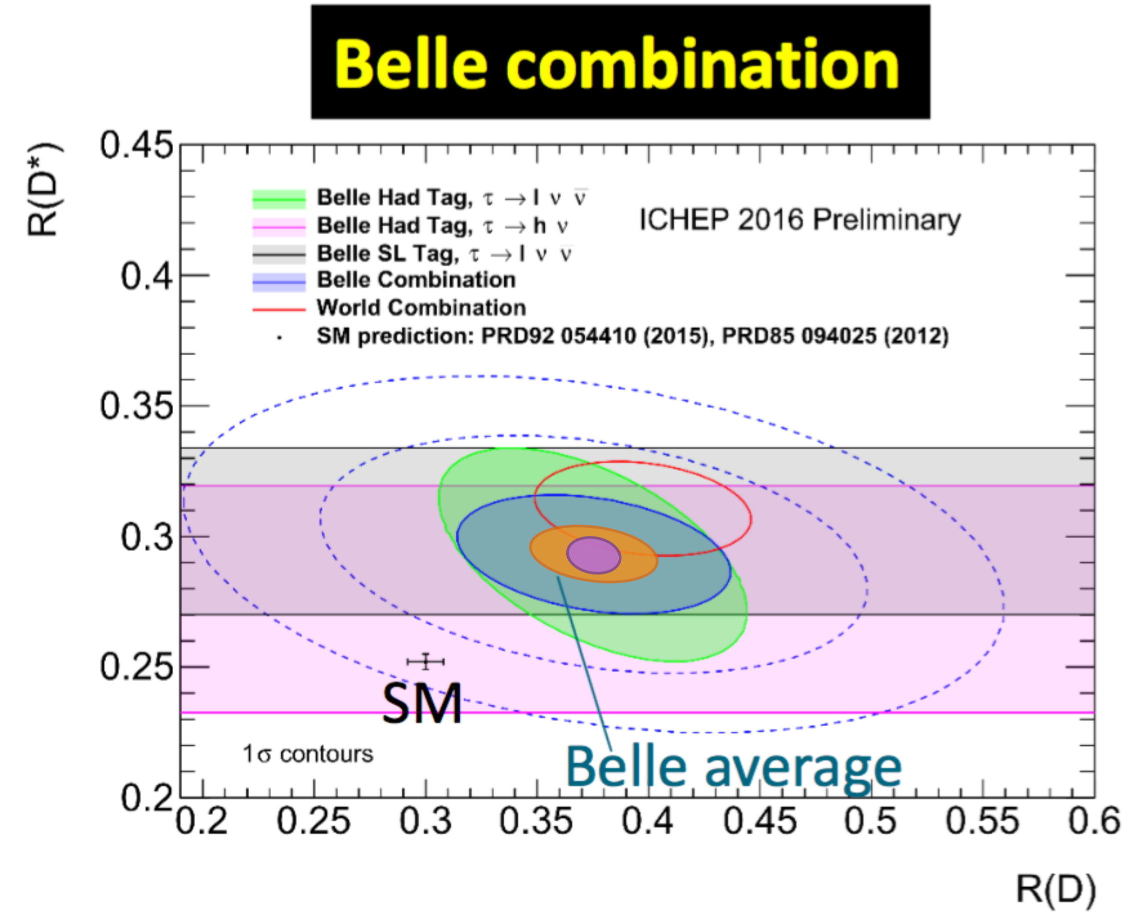
Irreducible
Requires additional studies

Belle@Hadronic(τ→h)

Source	$R(D^*)$	P_τ
Hadronic B composition	$^{+7.8\%}_{-6.9\%}$	$^{+0.14}_{-0.11}$
MC statistics for each PDF shape	$^{+3.5\%}_{-2.8\%}$	$^{+0.13}_{-0.11}$
Fake D^* PDF shape	3.0%	0.010
Fake D^* yield	1.7%	0.016
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.1%	0.051
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.003
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$	2.4%	0.008
τ daughter and ℓ^- efficiency	2.1%	0.018
MC statistics for efficiency calculation	1.0%	0.018
EvtGen decay model	$^{+0.8\%}_{-0.0\%}$	$^{+0.016}_{-0.000}$
Fit bias	0.3%	0.008
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \to \rho^-\nu_\tau)$	0.3%	0.002
P_τ correction function	0.1%	0.018
Common sources		
Tagging efficiency correction	1.4%	0.014
D^* reconstruction	1.3%	0.007
D sub-decay branching fractions	0.7%	0.005
Number of $B\bar{B}$	0.4%	0.005
Total systematic uncertainty	$^{+10.4\%}_{-9.5\%}$	$^{+0.20}_{-0.17}$

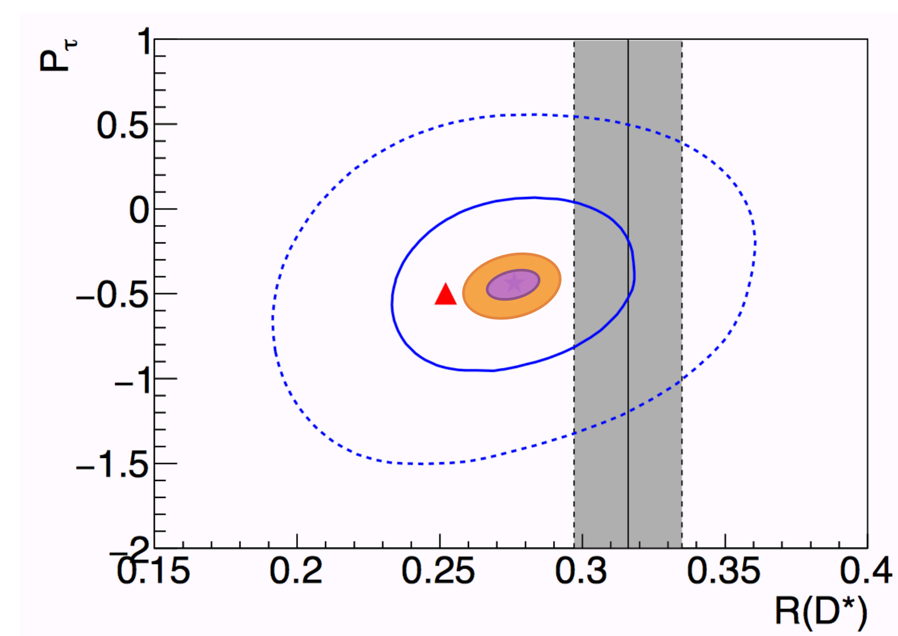
Belle II prospects

- At least 3 independent measurements of R(D*) with similar statistical and systematic uncertainties $R(D^*)$
  - **5 ab^{-1}: 3% (stat.) ± 2.5% (syst.)**
  - **50 ab^{-1}: 1% (stat.) ± 2.0% (syst.)**
- At least 1 measurement of R(D) $R(D)$
  - **5 ab^{-1}: 6% (stat.) ± 3.9% (syst.)**
  - **50 ab^{-1}: 2% (stat.) ± 2.5% (syst.)**
- At least 1 measurement of P_τ P_τ
  - **5 ab^{-1}: 0.18 (stat.) ± 0.08 (syst.)**
  - **50 ab^{-1}: 0.06 (stat.) ± 0.04 (syst.)**
- And measurements of various kinematic spectra



Belle II 5 ab^{-1}

Belle II 50 ab^{-1}



Belle II prospects

- At least 3 independent measurements of R(D*) with similar statistical and systematic uncertainties
  - **5 ab^{-1}: 3% (stat.) ± 2.5% (syst.)**
  - **50 ab^{-1}: 1% (stat.) ± 2.0% (syst.)**

$R(D^*)$

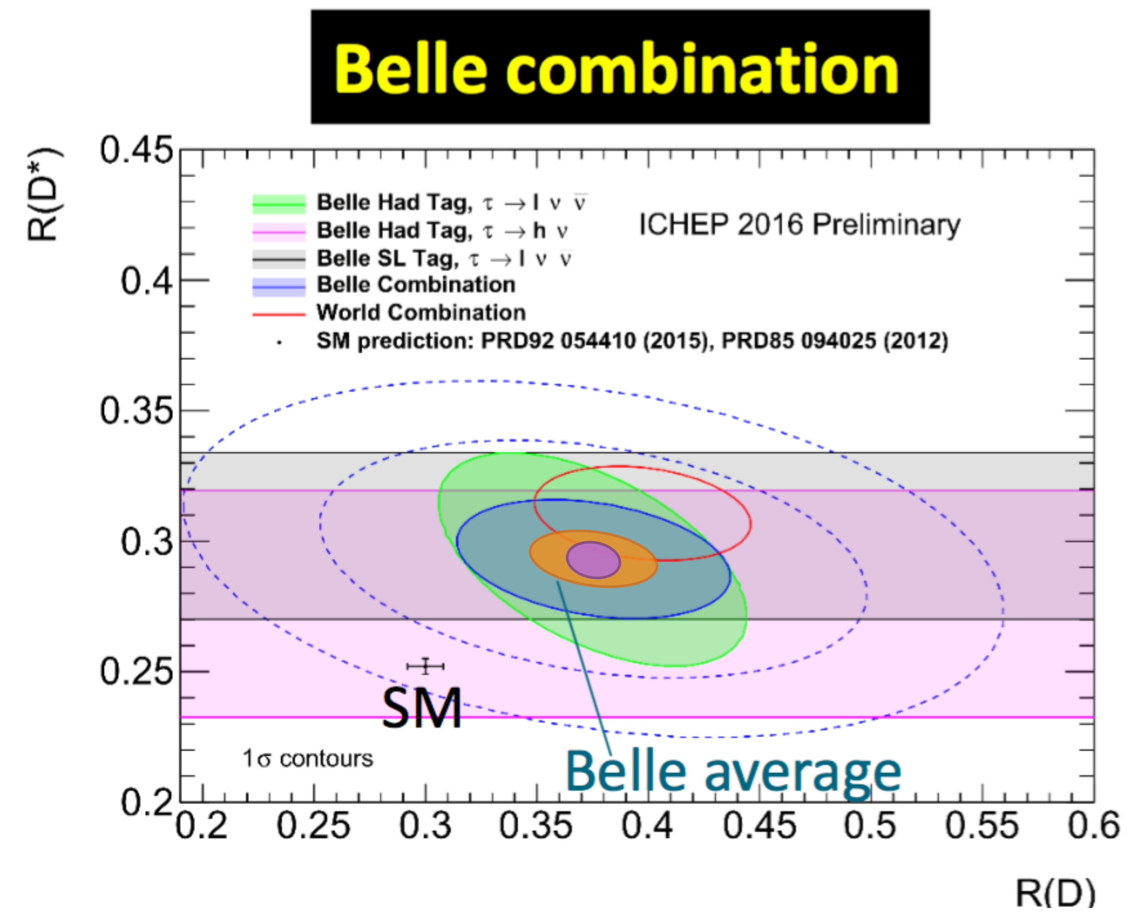
- At least 1 measurement of R(D)
  - **5 ab^{-1}: 6% (stat.) ± 3.9% (syst.)**
  - **50 ab^{-1}: 2% (stat.) ± 2.5% (syst.)**

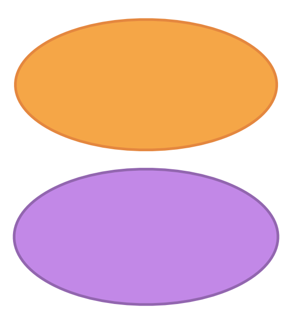
$R(D)$

- At least 1 measurement of P_τ
  - **5 ab^{-1}: 0.18 (stat.) ± 0.08 (syst.)**
  - **50 ab^{-1}: 0.06 (stat.) ± 0.04 (syst.)**

P_τ

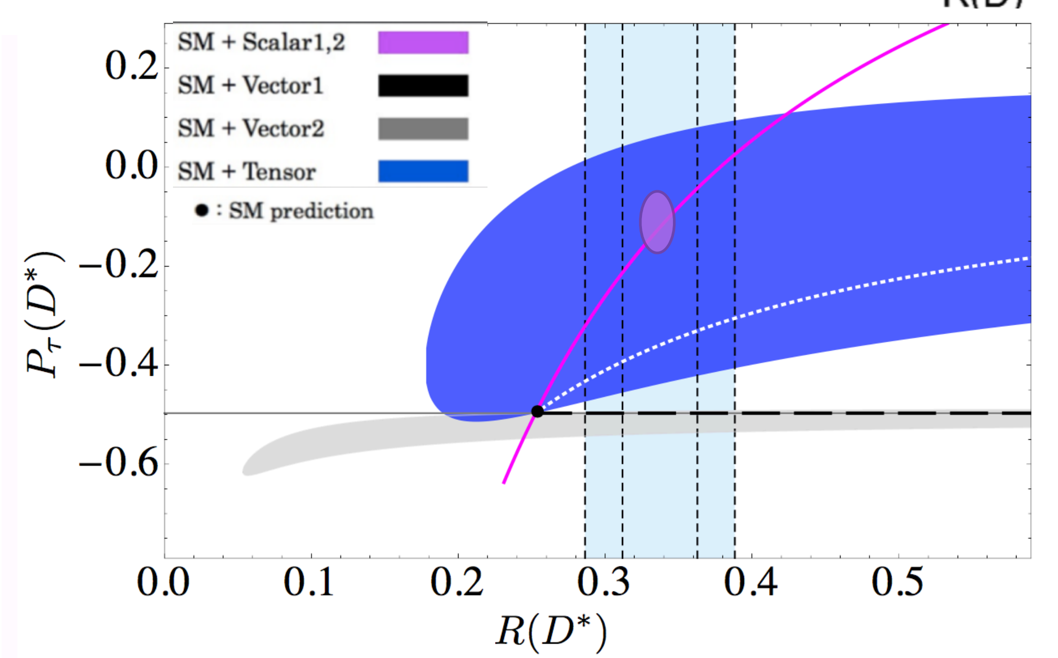
- And measurements of various kinematic spectra





Belle II 5 ab^{-1}

Belle II 50 ab^{-1}



Conclusions

Semi-tauonic B decays are sensitive probes of New Physics

- Rich laboratory not only to find but also to probe properties of NP
  - Close collaboration between experimentalists and theorists needed to discern NP properties
- Experimental setup of B-factories enables very rich physics program

Technique	D & τ→l	D* & τ→l	D & τ→h	D* & τ→h
Hadronic	✔	✔	(✔)	✔
Semileptonic	?	✔	?	?

- Can LHCb contribute even more?

$$\Lambda_b \to \Lambda_c \tau \nu_\tau,\ B_s \to D_s^{(*)} \tau \nu_\tau,\ B_c \to J/\psi \tau \nu_\tau$$