A critical look at the *B*-decay anomalies at the end of 2019

Vishal Bhardwaj
IISER Mohali

WHEPP XVI, IIT Guwahati
December 1-10, 2019

An experimental

~~A critical~~ look at the *B*-decay anomalies at the end of 2019

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Disclaimer

- Not a real expert, will try to summarize and introduce needed information for the anomalies.

- Hopeful that the material cover is sufficient for most of the people to follow the “discussions to follow” in the coming days.

- Apologies if some statement(s) is(are) wrong.

- Will introduce “*B-anomalies*” and their implications to be explained in detail by *Prof. R. Mohanta* “Combined explanation R_D/R_{D*} and R_K/R_{K*}” on Wednesday.

B decay anomalies

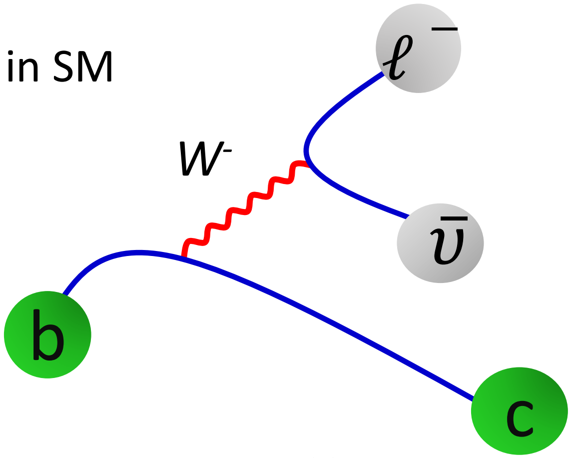
Two words are enough to wind up my presentation:

$\boldsymbol{R_{D,D^*}}$

$b \to c$ Charged current

$b \to c\tau\nu$

Tree-level in SM



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

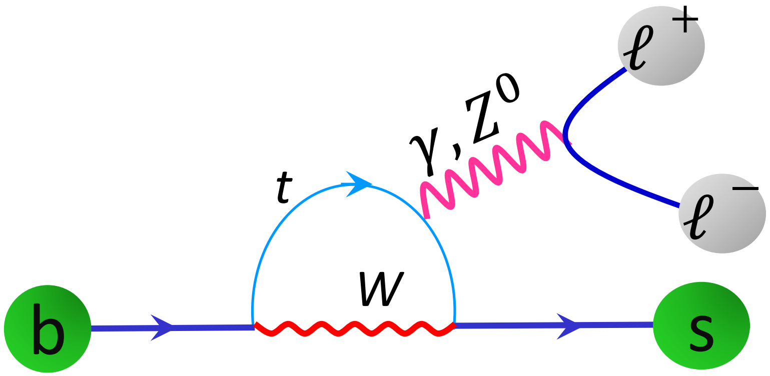
$$R_{D^{(*)}}^{exp} > R_{D^{(*)}}^{SM}$$

Scale of NP
must be “low”
$\Lambda \sim$TeV

$\boldsymbol{R_{K,K^*}}$

$b \to s$ Neutral current

$b \to s\ell\ell$ Loop-level in SM



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

$$R_{K^{(*)}}^{exp} < R_{K^{(*)}}^{SM}$$

Scale of NP
can be “high”
$\Lambda \sim$30-50 TeV

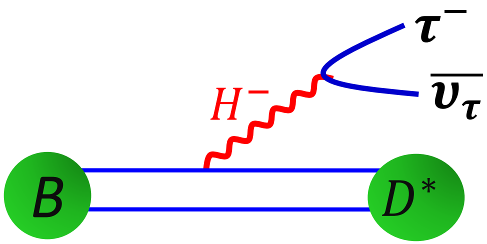
Lepton Flavor Universality Violation (LFUV) in B decays

$B \to D^{(*)}\tau\upsilon$

Not a rare decay, Branching fraction : 1-2 %

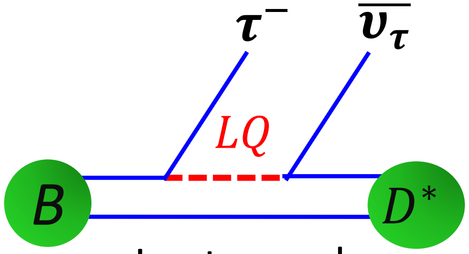
- ➢ Allow one to test theory of low-energy QCD, which contribute to $\bar{B} \to D^*$ transition.
- ➢ Weak interaction can be tested precisely.

$\bar{B} \to D^*\tau^-\overline{\upsilon_\tau}$ decays are sensitive to new scalar fields (New Physics at tree level)



Charged Higgs (2HDM-II)

Grossman, Ligeti, PLB332, 3 (1994)
Tanaka, Z. Phys. C 67, 321 (1995)



Leptoquark

Davidson *et al*, Z. Phys. C 61, 613 (1994)

What one looks for

$$R_{D^*} = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\overline{\upsilon_\tau})}{\mathcal{B}(\bar{B} \to D^*\ell^-\overline{\upsilon_\ell})}$$

← *Signal*

← $\ell = e, \mu$ *Normalization (background)*

Theory: cancels common factors : $|V_{cb}|$and hadronic FFs

Experiment: reduce experimental uncertainties (detector efficiencies)

$\mathcal{R}(D)_{SM} = 0.300 \pm 0.011$ Lattice, PRD92,034506 (2015)

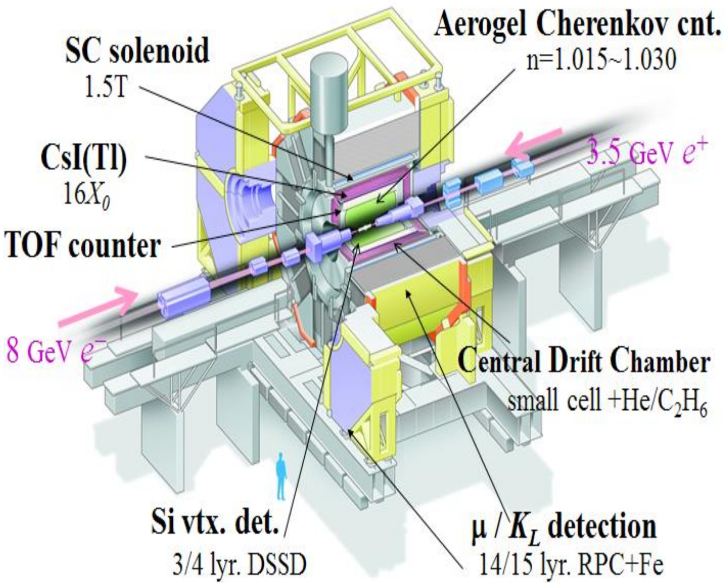
$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$ Fajfer *etal*PRD85.094025(2012)

Other variables :

τ and D^* polarization, q^2 distributions, lepton momentum

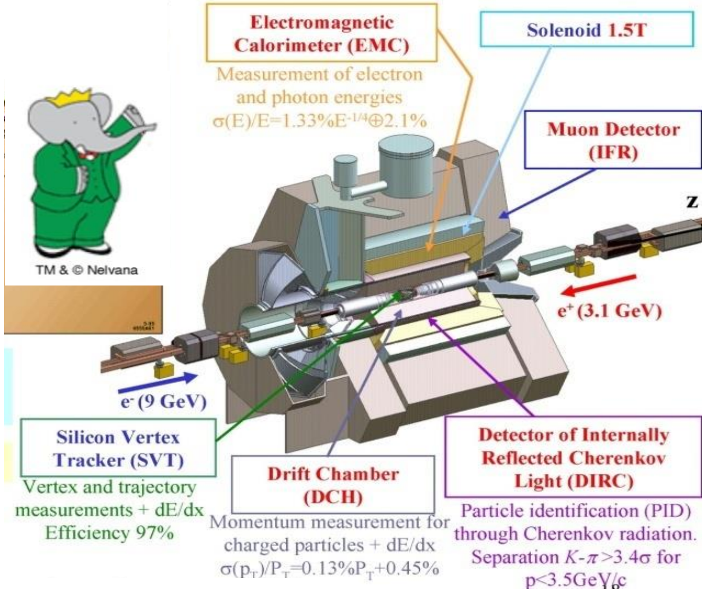
2007	2008	2010	2012
Observation of $B \to D^{*-}\tau^+\upsilon_\tau$ Belle, PRL99, 191807(2007)	*First $R_{D^{(*)}}$ measured* BaBar, PRL100, 021801(2008)	*Evidence of $B \to D^0\tau^+\upsilon_\tau$* Belle, PRD82, 072005(2010)	*Evidence of the excess* BaBar, PRL109, 101802 (2012)

e^+e^- colliders *for B physics*

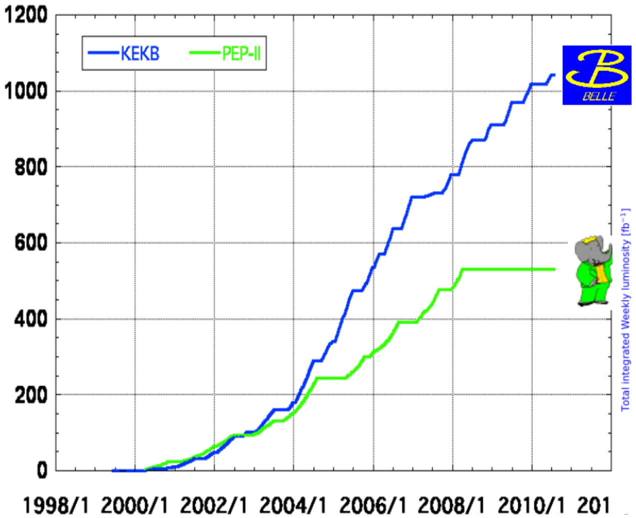


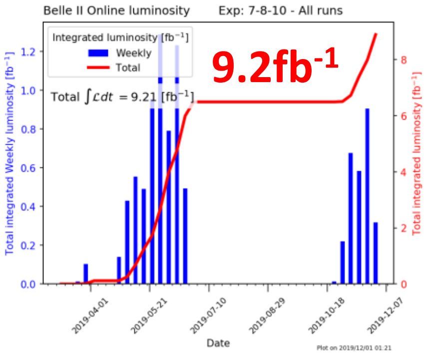
8 GeV e^- on 3.5 GeV e^+

Already data accumulated

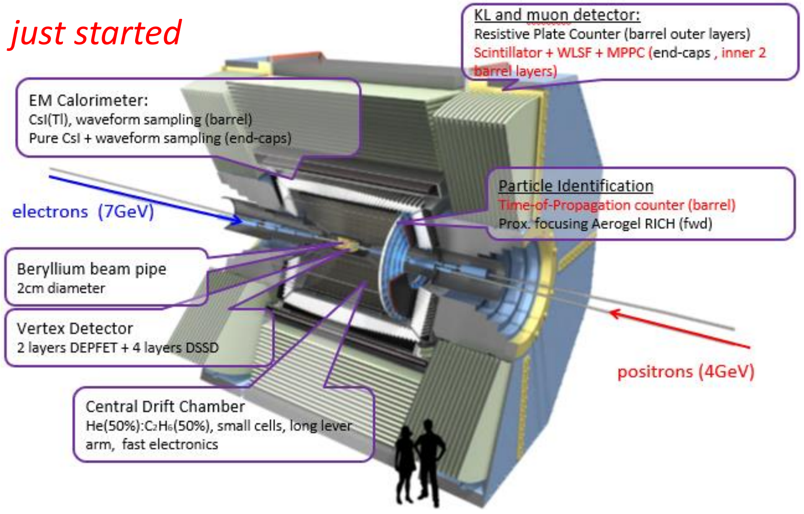


9 GeV e^- on 3.1 GeV e^+



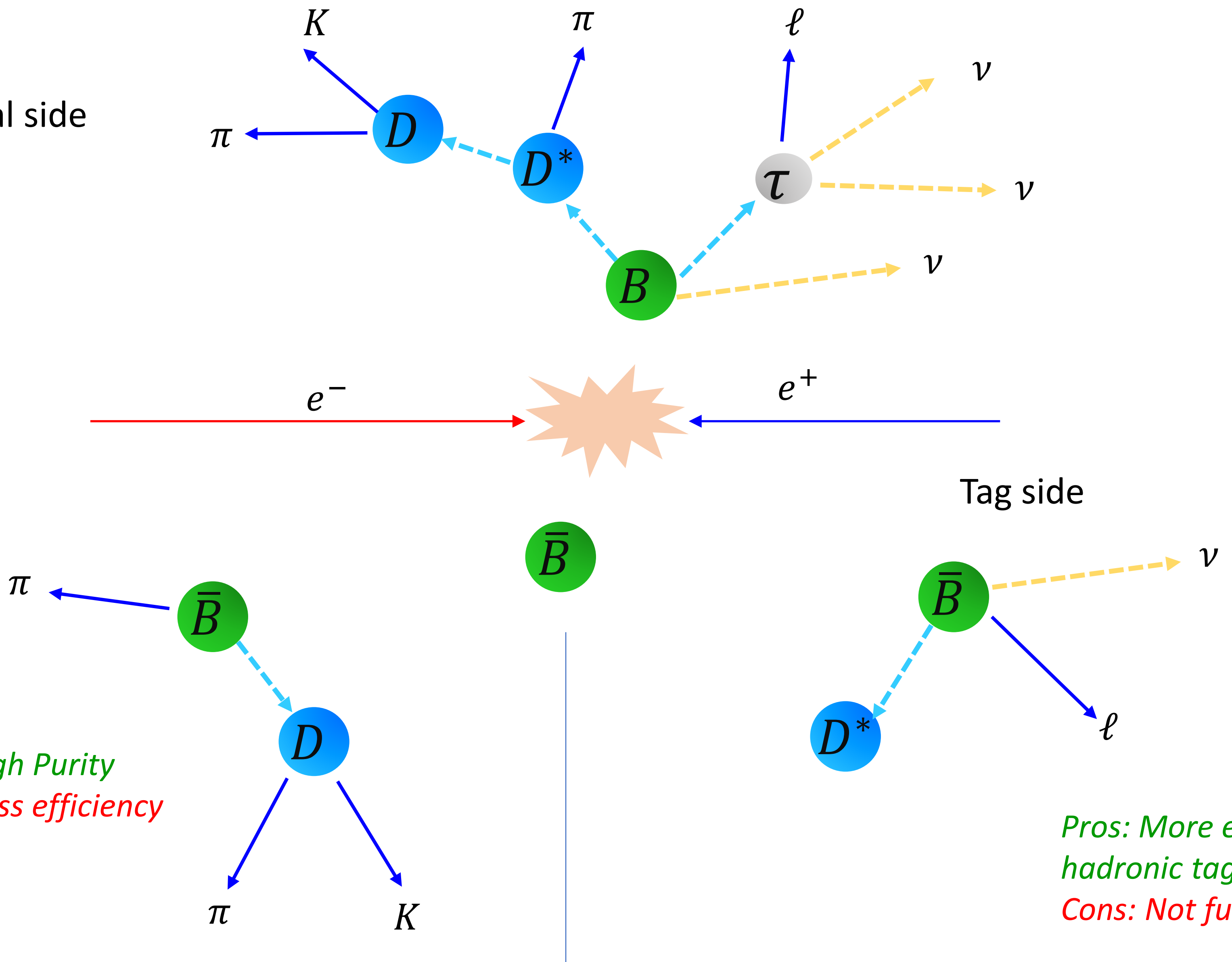


Data accumulation just started



7 GeV e^- on 4 GeV e^+

How one measures $R_{D^{(*)}}$ at e^+e^- colliders



Signal side

Tag side

Pros: High Purity
Cons: Less efficiency

Hadronic tag ($\varepsilon_{sig} \sim 0.2\%$)

Pros: More efficient than hadronic tag
Cons: Not full kinematics

Semileptonic tag ($\varepsilon_{sig} \sim 0.5\%$)

Hadronic tag

Beginning of “the R_{D^*} saga”

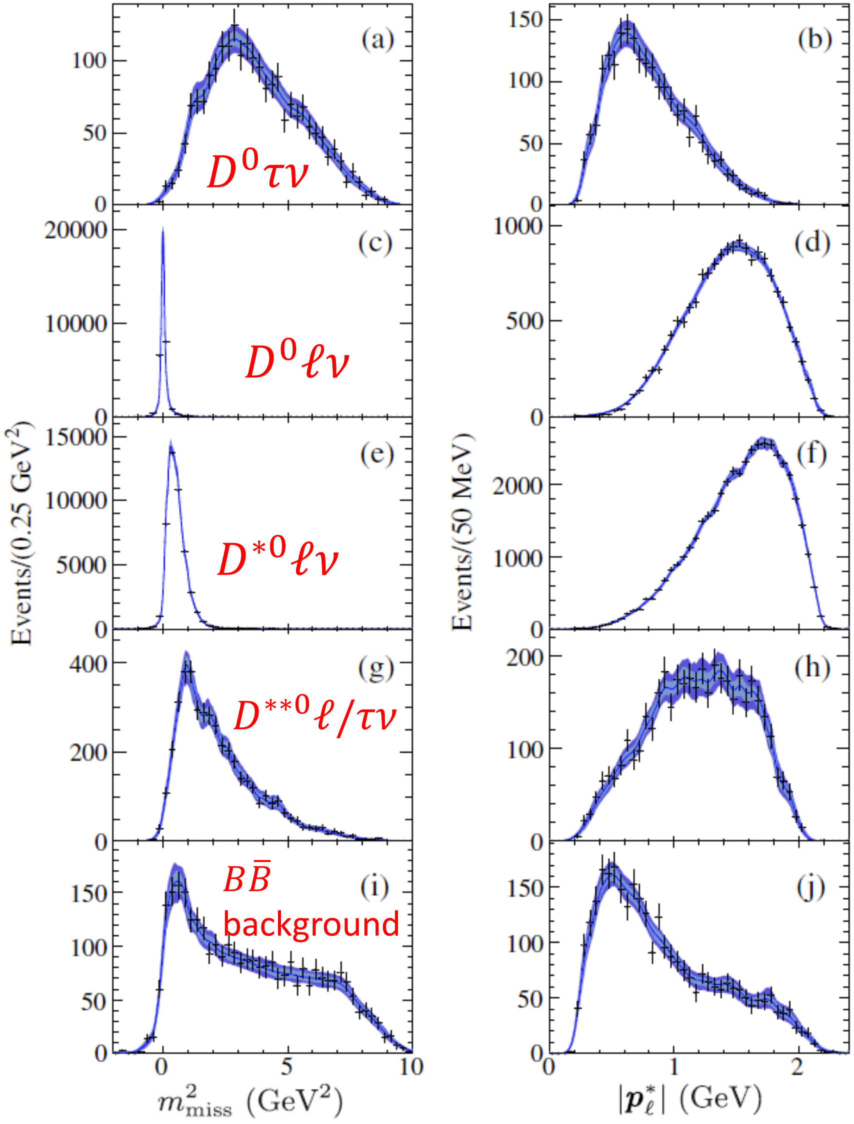
BaBar
PRL 109, 101802(2012)
PRD 88, 072012 (2013)

Simultaneous UML fit to
4 signal samples $D^0\ell$, $D^{*0}\ell$, $D^+\ell$ and $D^{*+}\ell$

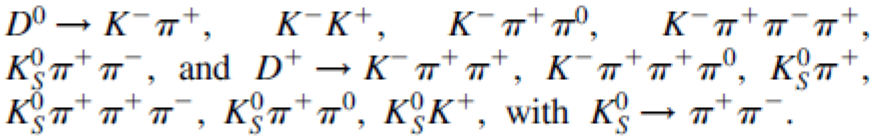
$\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$

Signal is identified by:

- ➢ $m^2_{miss} = (p_{e^+e^-} - p_{tag} - p_{D^{(*)}} - p_\ell)^{\,2}$
- ➢ $|p^*_\ell|$ in the B_{sig} rest-frame



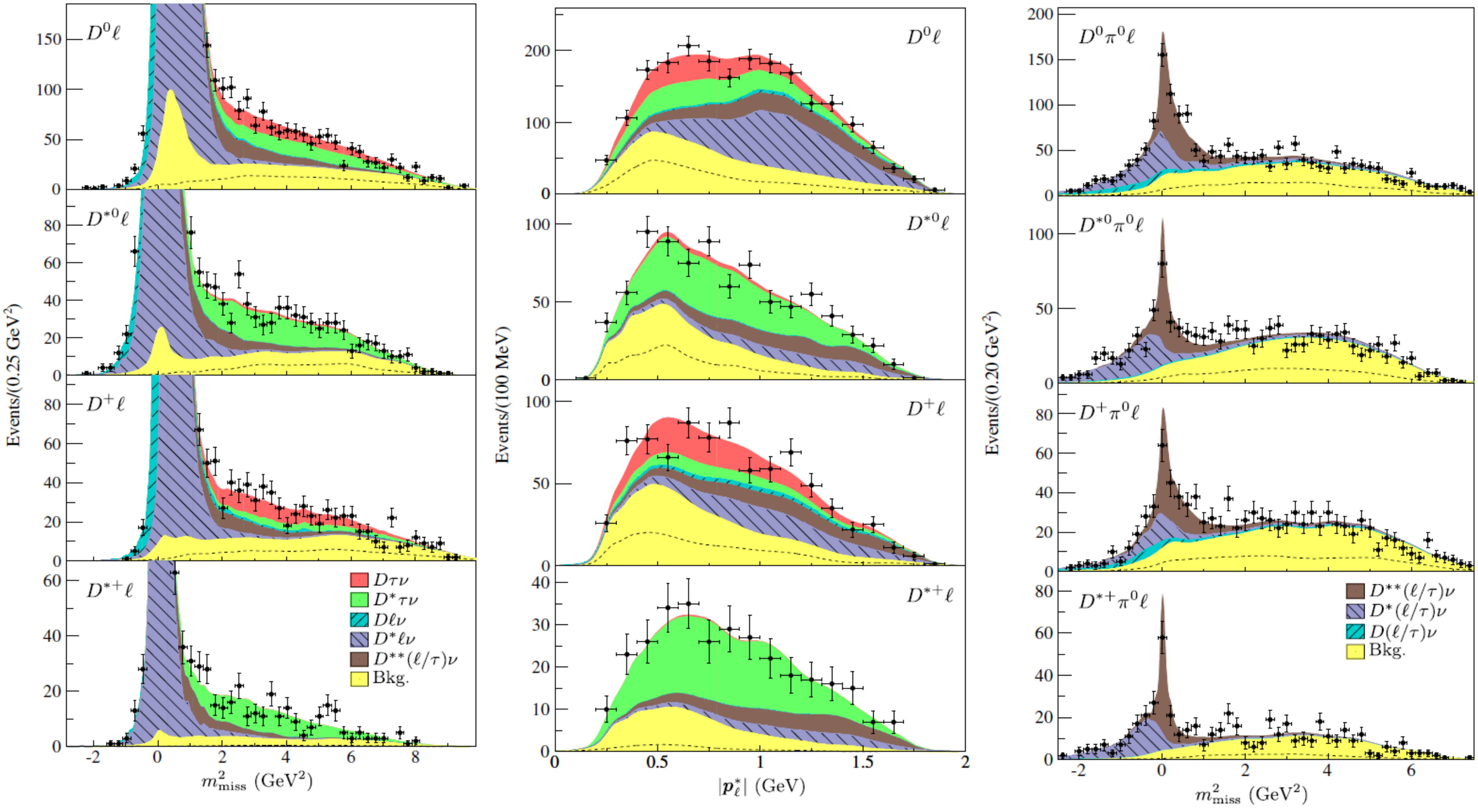
Signal extracted together with control sample of $B \to D^{**}\ell\nu$ (addition of an extra π^0)



$D^0 \to K^-\pi^+$, K^-K^+, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^0_S\pi^+\pi^-$, and $D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^+\pi^-$, $K^0_S\pi^+\pi^0$, $K^0_SK^+$, with $K^0_S \to \pi^+\pi^-$.

Results

BaBar
PRL 109, 101802(2012)
PRD 88, 072012 (2013)

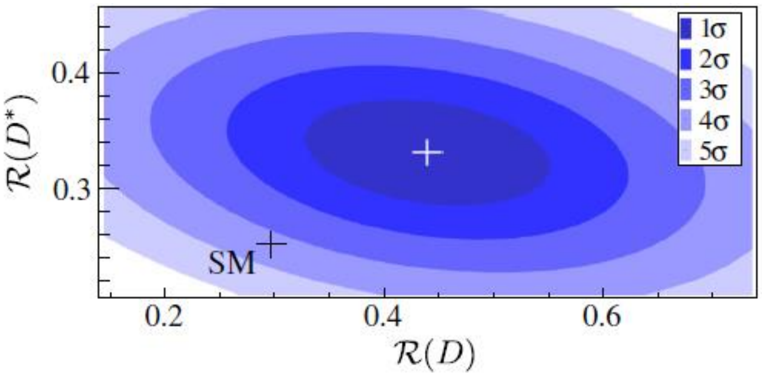


$$\mathcal{R}(D) \ \ = 0.440 \pm 0.058 \pm 0.042 \ \ (2.0\sigma \text{ from SM})$$
$$\mathcal{R}(D^*) = 0.332 \pm 0.024 \pm 0.018 \ (2.7\sigma \text{ from SM})$$

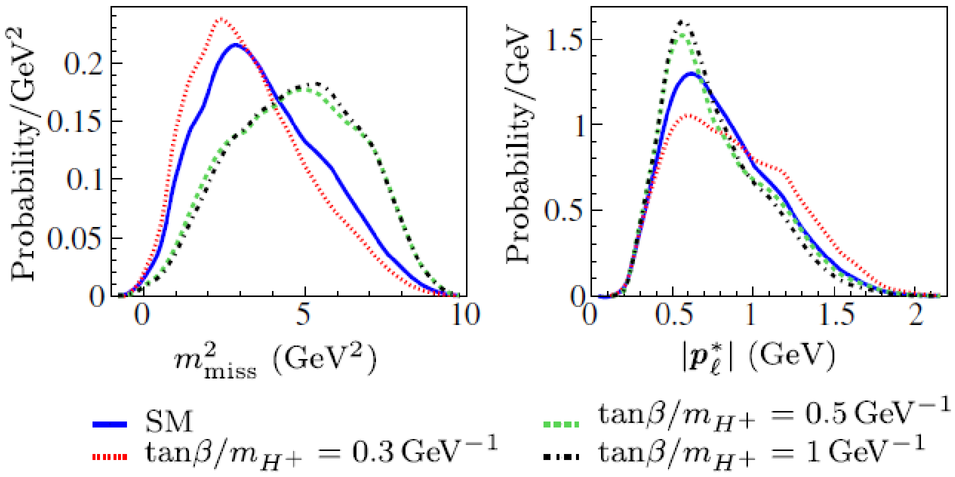
$$\mathcal{R}(D)_{SM} \ \ = 0.300 \pm 0.011$$
$$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$$

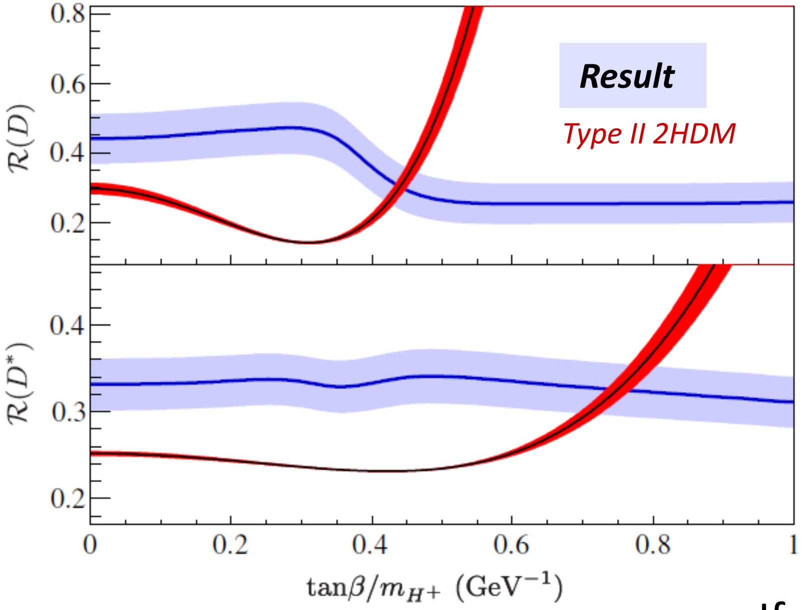
How one should interpret the result

BaBar
PRD 88, 072012 (2013)



Based on the mass and vacuum expectation (Signal PDF modifies)



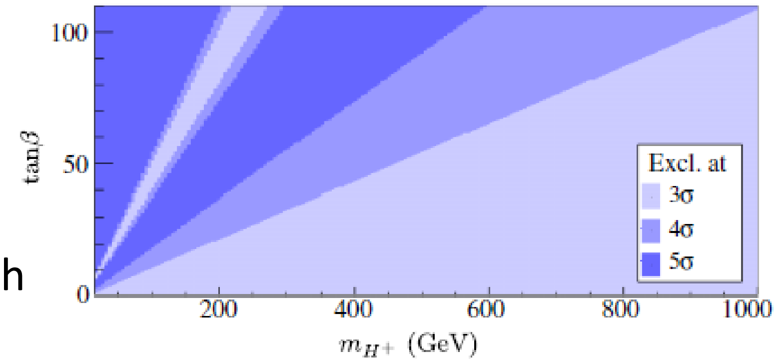


Matches value :

$$\mathcal{R}(D) \rightarrow \frac{\tan\beta}{m_{H^\pm}} = 0.44 \pm 0.02\ \mathrm{GeV}^{-1}$$

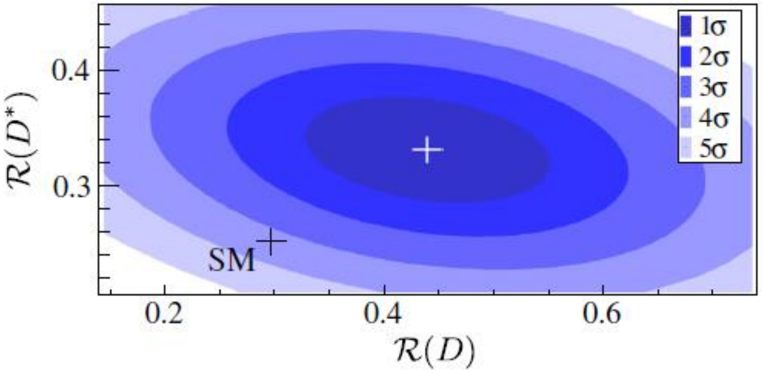
$$\mathcal{R}(D^*) \rightarrow \frac{\tan\beta}{m_{H^\pm}} = 0.75 \pm 0.04\ \mathrm{GeV}^{-1}$$

If one takes both

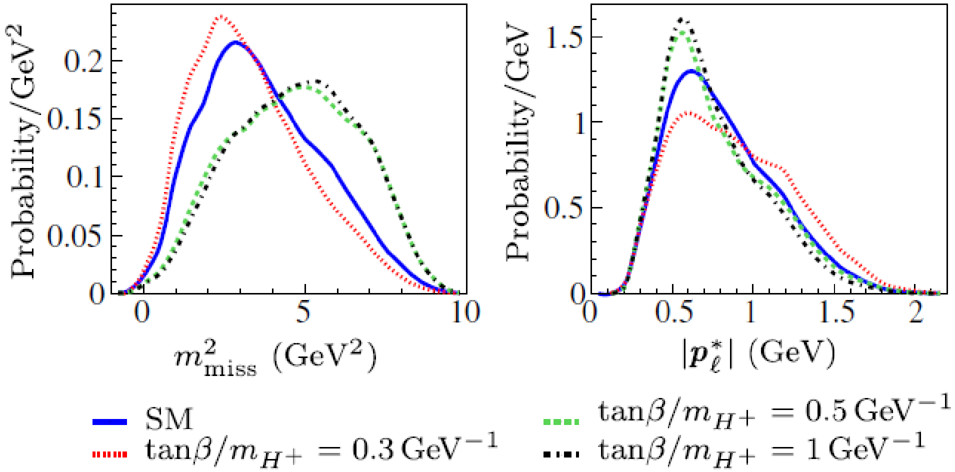


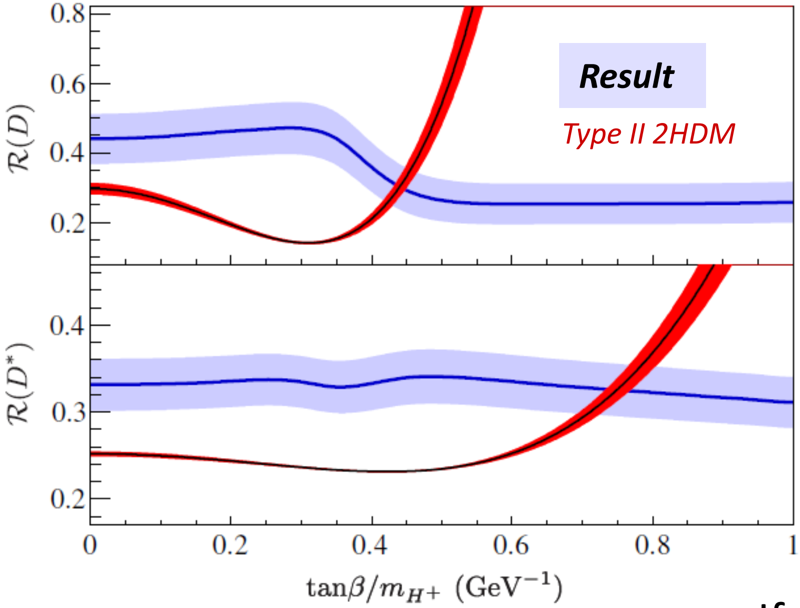
How one ~~should~~ can interpret the result

BaBar
PRD 88, 072012 (2013)



Based on the mass and vacuum expectation (Signal PDF modifies)





Matches value :

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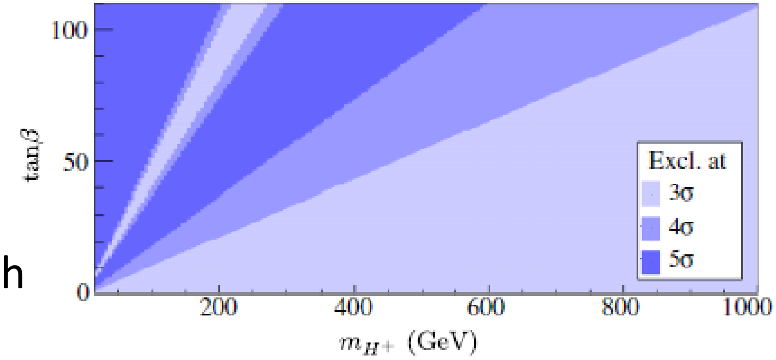
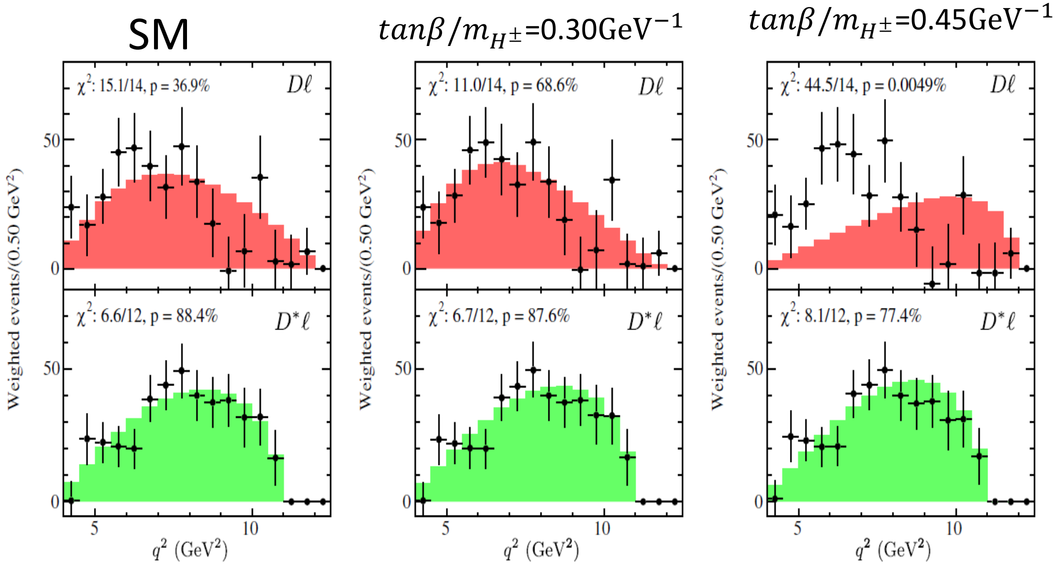
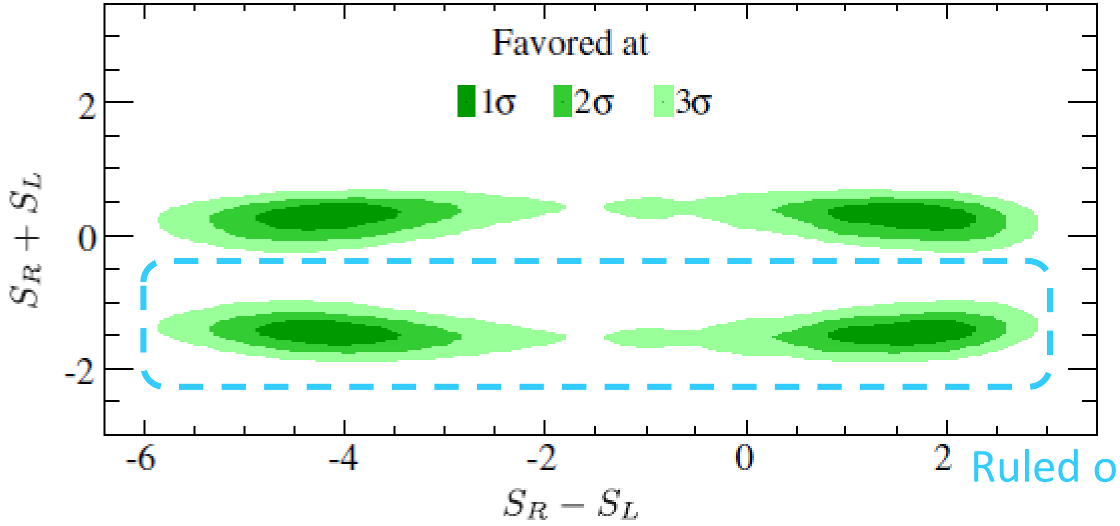
If one takes both





Type III 2HDM survives

$|S_R + S_L| < 1.4$



Ruled out by q^2 distribution

Favored regions of real values of the type III 2HDM parameters S_R and S_L

PS: Uncertainties in the extrapolation of type II 2HDM are not included

Hadronic tag

Belle turn

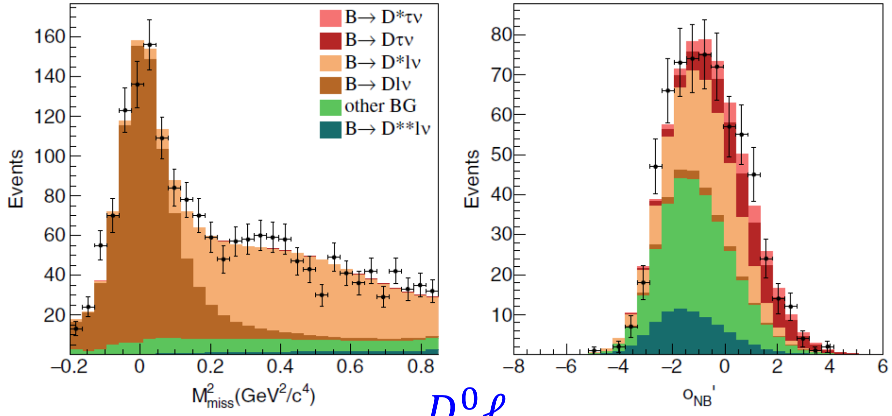
Belle PRD92, 072014 (2015)

Four signal sample $D^0\ell$, $D^{*0}\ell$, $D^+\ell$ and $D^{*+}\ell$

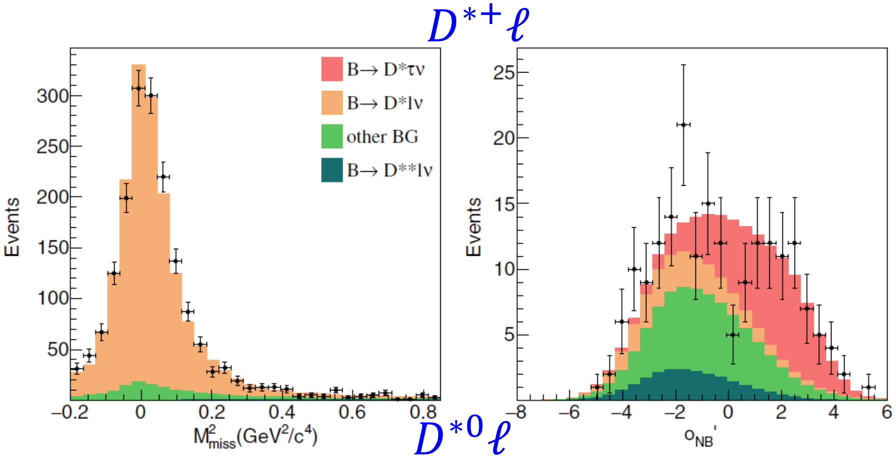
$\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$

We reconstruct D^+ mesons in the decays to $K^-\pi^+\pi^+$, $K^0_S\pi^+$, $K^0_S\pi^+\pi^0$, and $K^0_S\pi^+\pi^+\pi^-$; D^0 mesons to $K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0$, $K^0_S\pi^0$, and $K^0_S\pi^+\pi^-$; D^{*+} mesons to $D^0\pi^+$ and $D^+\pi^0$; and D^{*0} mesons to $D^0\pi^0$ and $D^0\gamma$.

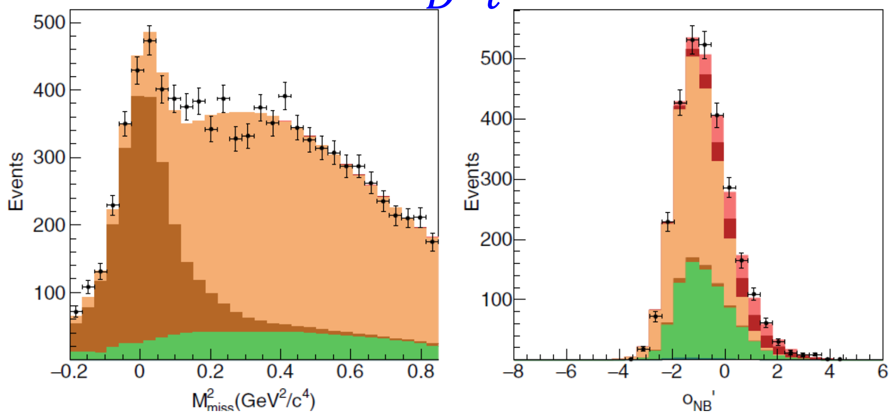
$D^+\ell$



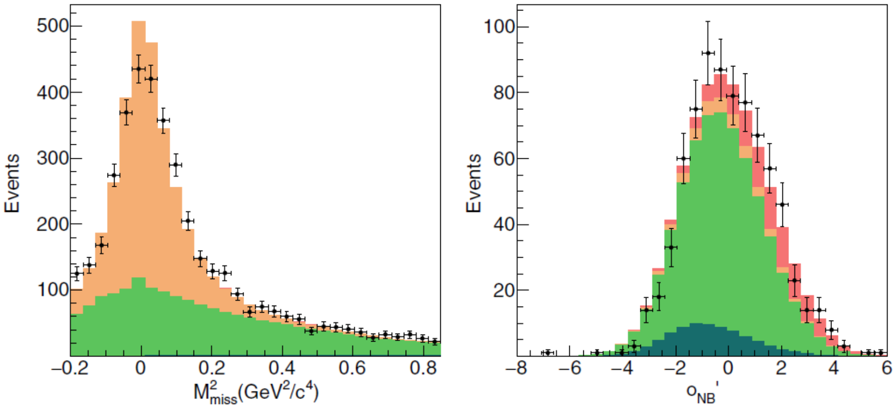
$D^{*+}\ell$



$D^0\ell$



$D^{*0}\ell$



$\mathcal{R}(D) \ = 0.375 \pm 0.064 \pm 0.026$ (1.4σ from SM)

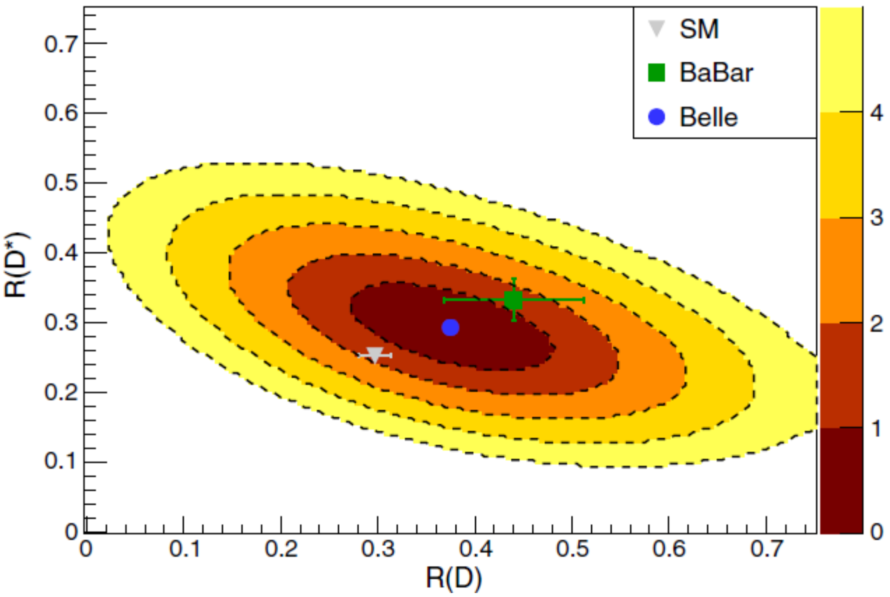
$\mathcal{R}(D^*) = 0.295 \pm 0.038 \pm 0.015$ (1.8σ from SM)

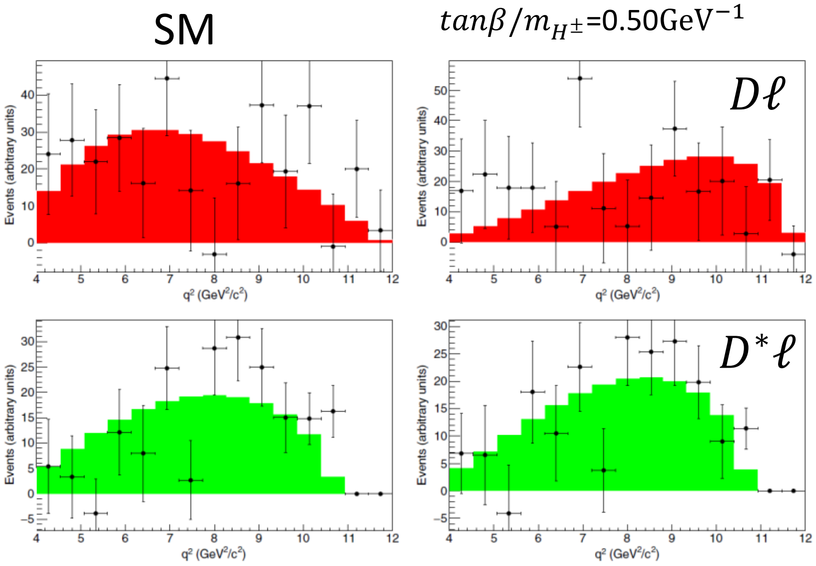
$\mathcal{R}(D)_{SM} \ = 0.300 \pm 0.011$

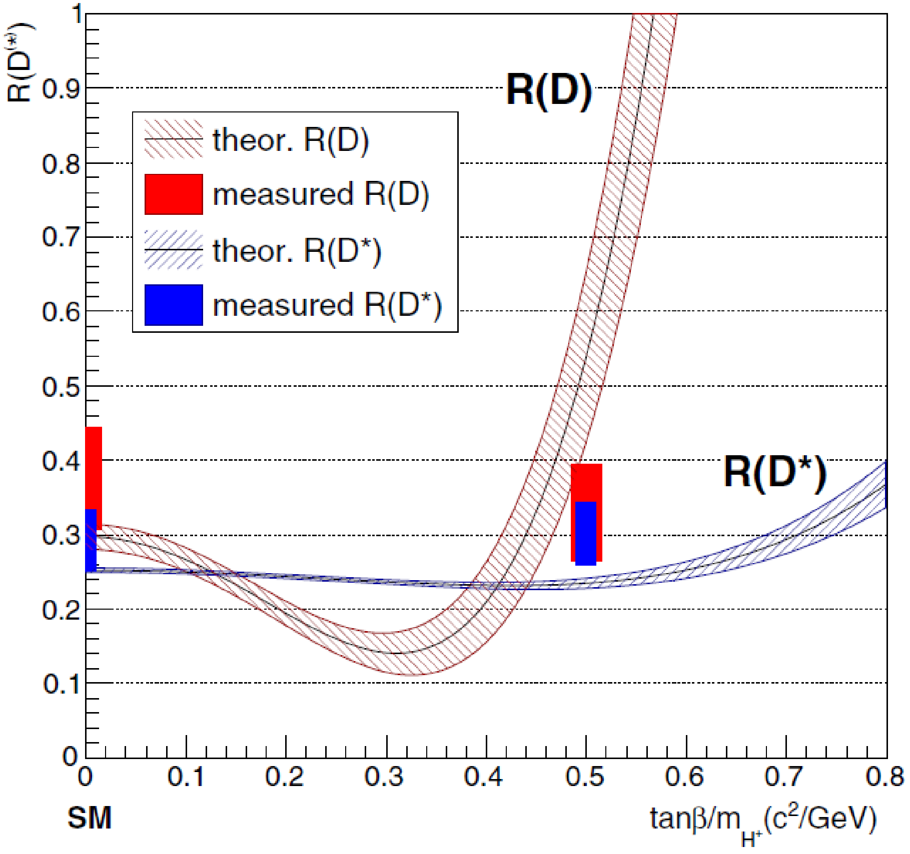
$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$

Interpretation

Belle PRD92, 072014 (2015)







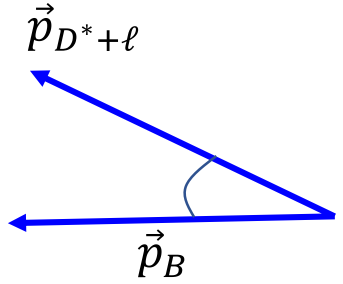
Belle result lies between SM expectation and the BaBar result (compatible with both).
Also compatible with 2HDM of type II around $tan\beta/m_{H^\pm}$=0.50GeV^{-1}

Semileptonic B tag

Different Method

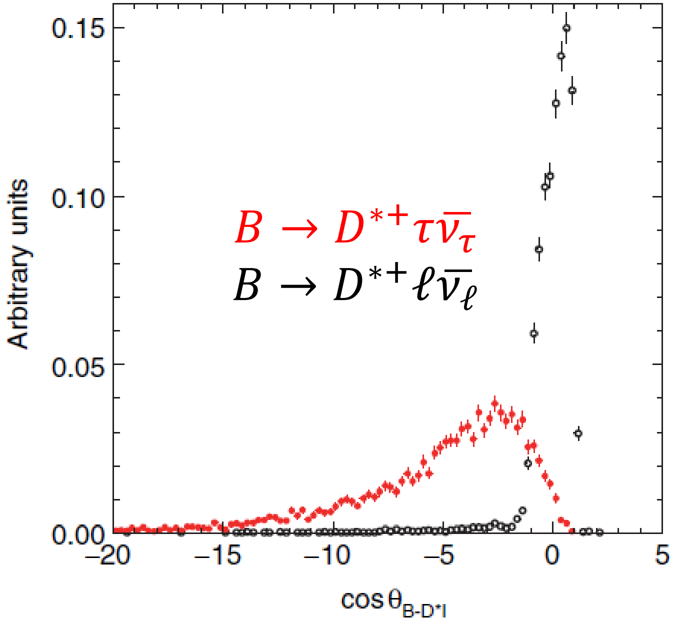
Belle PRD94, 072007 (2016)

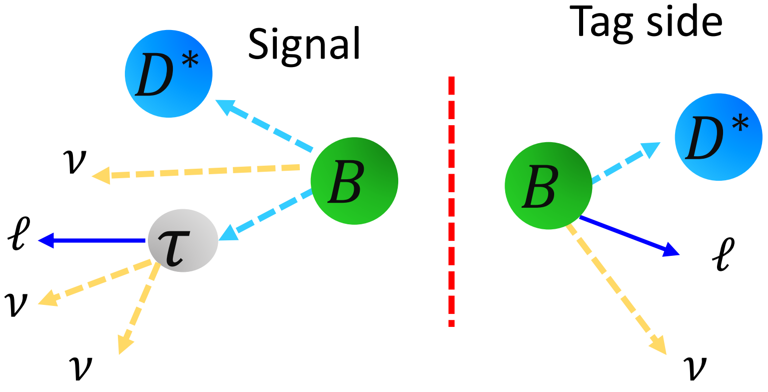
Independent analysis of previous Belle measurement.
Better efficiency in tagging *(somewhat double)*
✗ More background due to missing particle in tag side

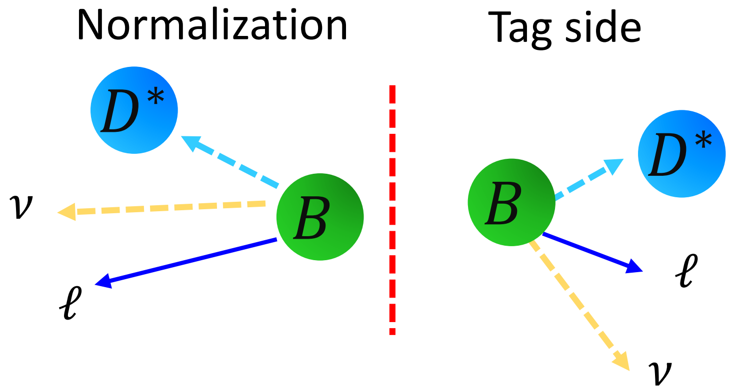


Analysis focus on $D^{*+}\tau\overline{\nu_\tau}$ $\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$

$$cos\theta_{B-D^*\ell} = \frac{E^*_{beam}E^*_{D^*\ell} - m_B^2 - m^2_{D^*\ell}}{2|p^*_{beam}||p^*_{D^*\ell}|}$$







2D fit to neural network output (O_{NB}) and E_{ECL}

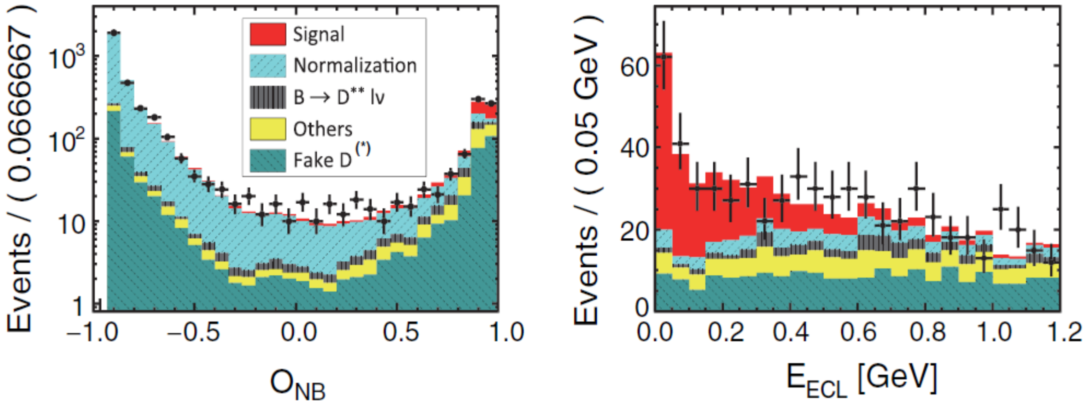
O_{NB} :
- $cos\theta_{B-D^*\ell}$
- M^2_{miss}
- Total energy of $B_{tag} + B_{sig}$

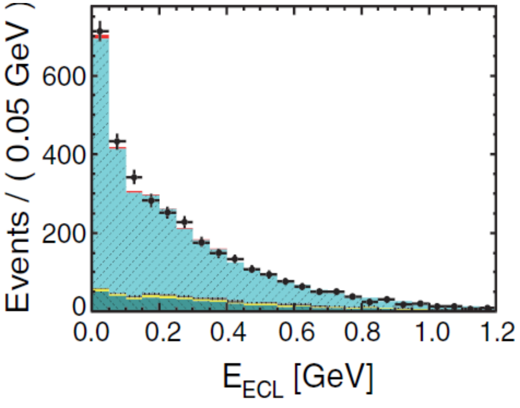
E_{ECL} : Sum of energy in ECL not associated with reconstruction

Result from semileptonic

Belle PRD94, 072007 (2016)

: $D^0 \to K^-\pi^+$, $K_S^0\pi^0$, K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, $K^-\pi^+\pi^0$, $\pi^+\pi^-\pi^0$, $K_S^0K^+K^-$, $K^-\pi^+\pi^+\pi^-$, and $K_S^0\pi^+\pi^-\pi^0$. Charged D mesons are reconstructed in the following modes: $D^+ \to K_S^0\pi^+$, $K^-\pi^+\pi^+$, $K_S^0\pi^+\pi^0$, $K^+K^-\pi^+$, and $K_S^0\pi^+\pi^+\pi^-$.

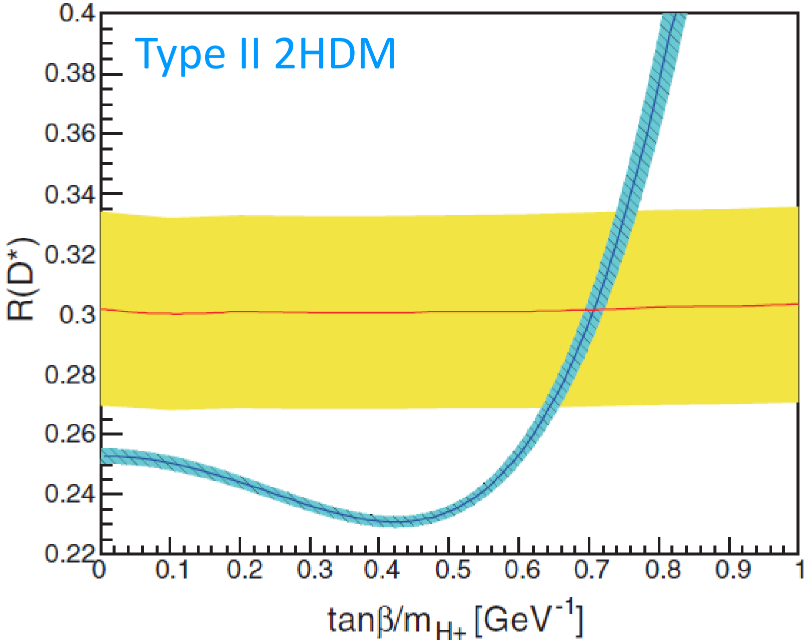


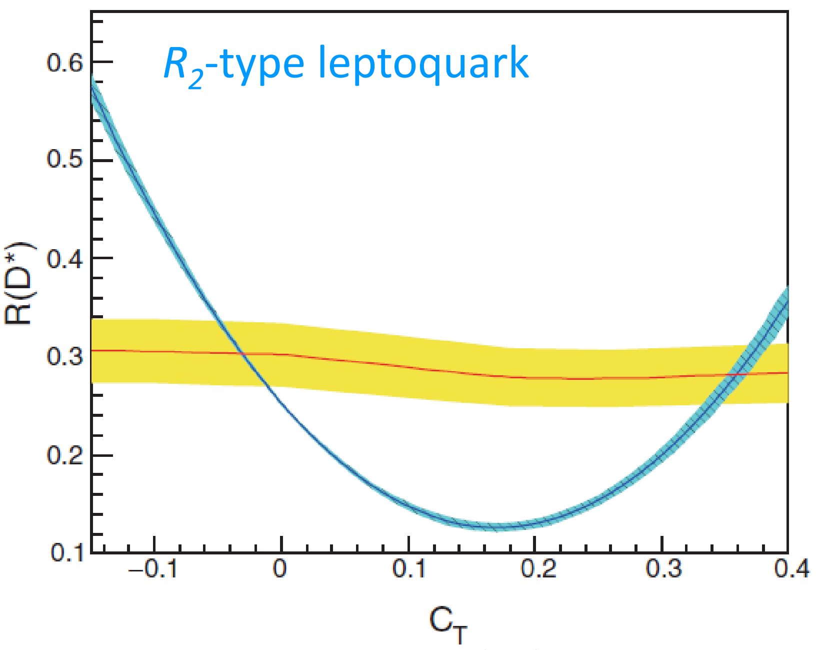


$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$ (1.6σ from SM)

$\mathcal{R}(D^*) = 0.295 \pm 0.038 \pm 0.015$

Previous from Hadron Tag





$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$

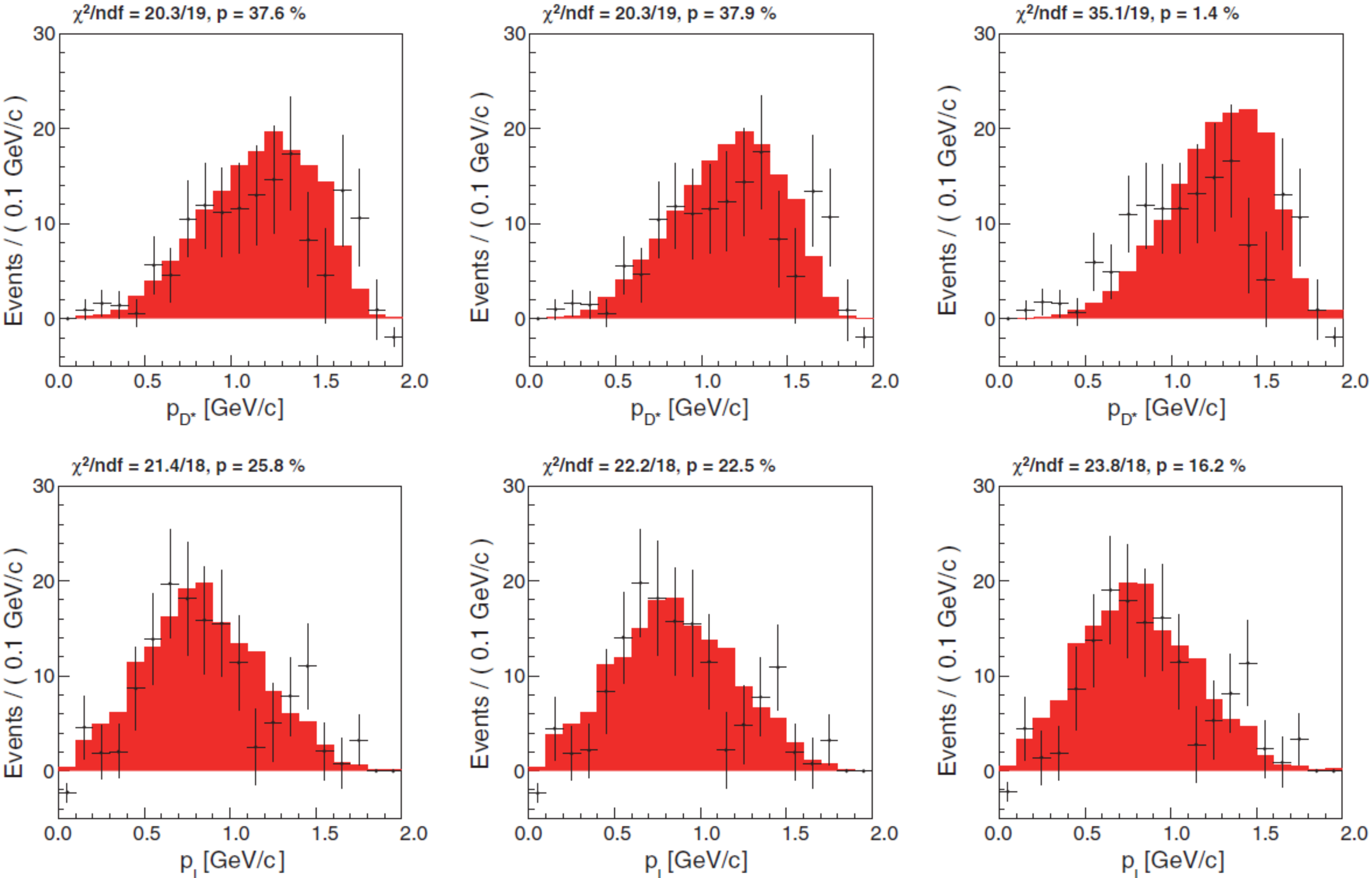
More distribution

Belle PRD94, 072007 (2016)

SM

$tan\beta/m_{H^\pm}$=0.7GeV^{-1}

R_2 −type leptoquark with $C_T = +0.36$



Allow additional contribution from scalar and vector operators while disfavouring large additional contributions from a tensor operator with $+0.34 < C_T < +0.39$, and R_2-type leptoquark model with $+0.34 < C_T < +0.38$, or an S_1-type leptoquark model with $+ 0.22 < C_T < +0.28$

Other variable : $P_\tau(D^*)$

Hadronic Tag

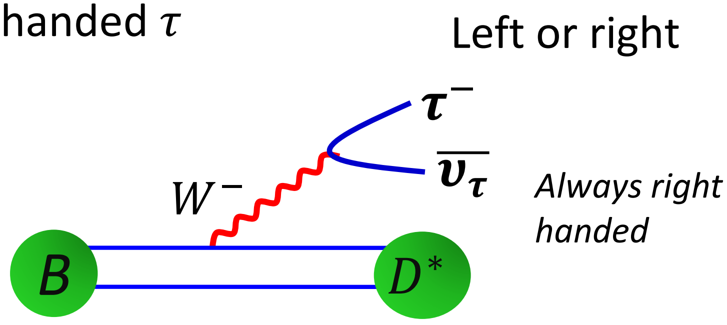
τ polarization :

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

Γ^+ for right handed τ
Γ^- for left handed τ

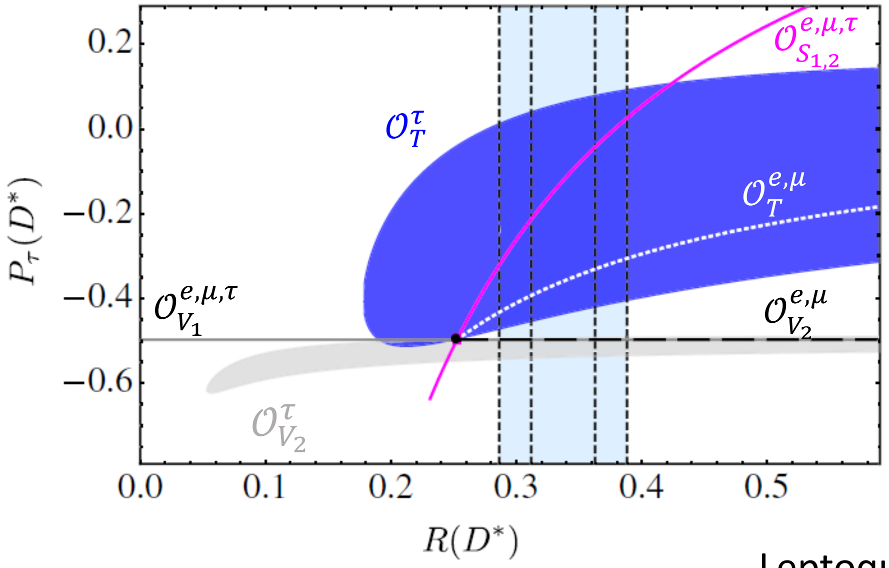
$$P_\tau(D^*)_{\rm SM} = -0.497 \pm 0.013$$

M. Tanaka and R. Watanabe PRD87, 034028 (2013)

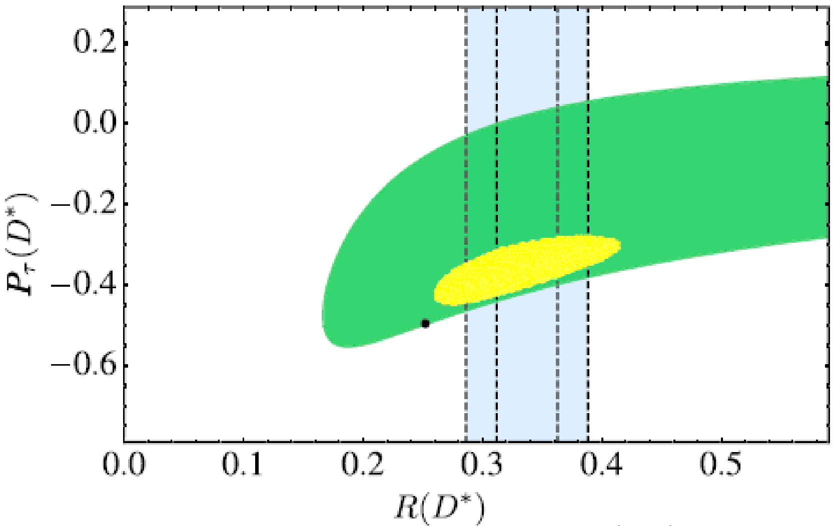


τ polarization is sensitive to the NP contribution.

One can measure the τ polarization using its two-body decay



Relevant mass scale of leptoquark could be ~500GeV



Leptoquark having mass of 1 TeV will lead to $P_\tau(D^*)$ $[-0.5, 0]$

Sakaki *et al* PRD88, 094012 (2013).

Hadronic Tag

Belle measures $P_\tau(D^*)$

Belle
PRL118,211801 (2017)
PRD97, 012004 (2018)

New variable to search for NP
Provide independent study/confirmation of previous measurements

Angular distribution of τ decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\text{hel}}} = \frac{1}{2}[1 + \alpha P_\tau(D^*)\cos\theta_{\text{hel}}] \qquad \alpha = \begin{cases} 1 \text{ for } \tau \rightarrow \pi\nu \\ 0.45 \text{ for } \tau \rightarrow \rho\nu \end{cases}$$

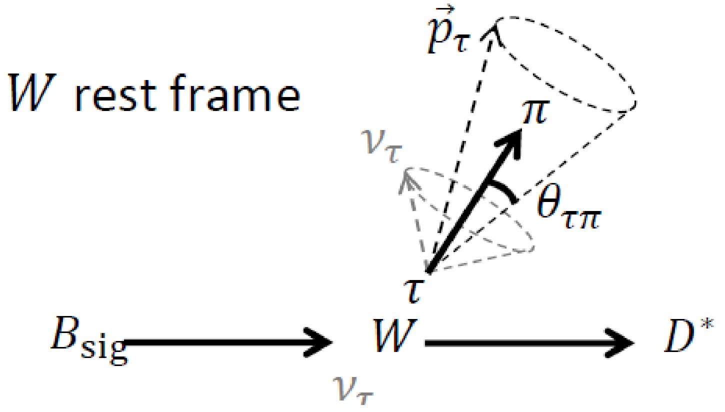
τ rest frame estimated

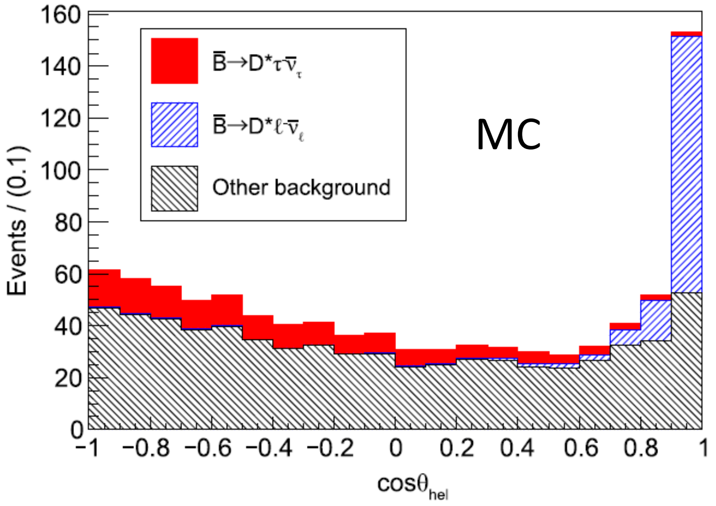
$q = p_{e^+e^-} - p_{tag} - p_{D^*}$

$$E_\tau = \frac{q^2 + m_\tau^2}{2\sqrt{q^2}} \qquad |\vec{p}_\tau| = \frac{q^2 - m_\tau^2}{2\sqrt{q^2}}$$

$$\cos\theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\vec{p}_\tau||\vec{p}_d|}$$

$$|\vec{p}_d^{\,\tau}|\cos\theta_{\text{hel}} = -\gamma|\vec{\beta}|E_d + \gamma|\vec{p}_d|\cos\theta_{\tau d},$$



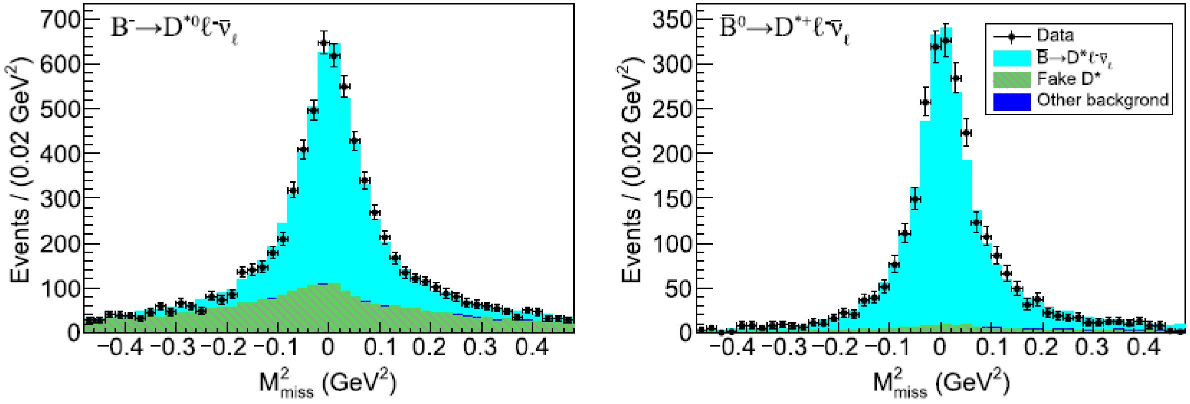


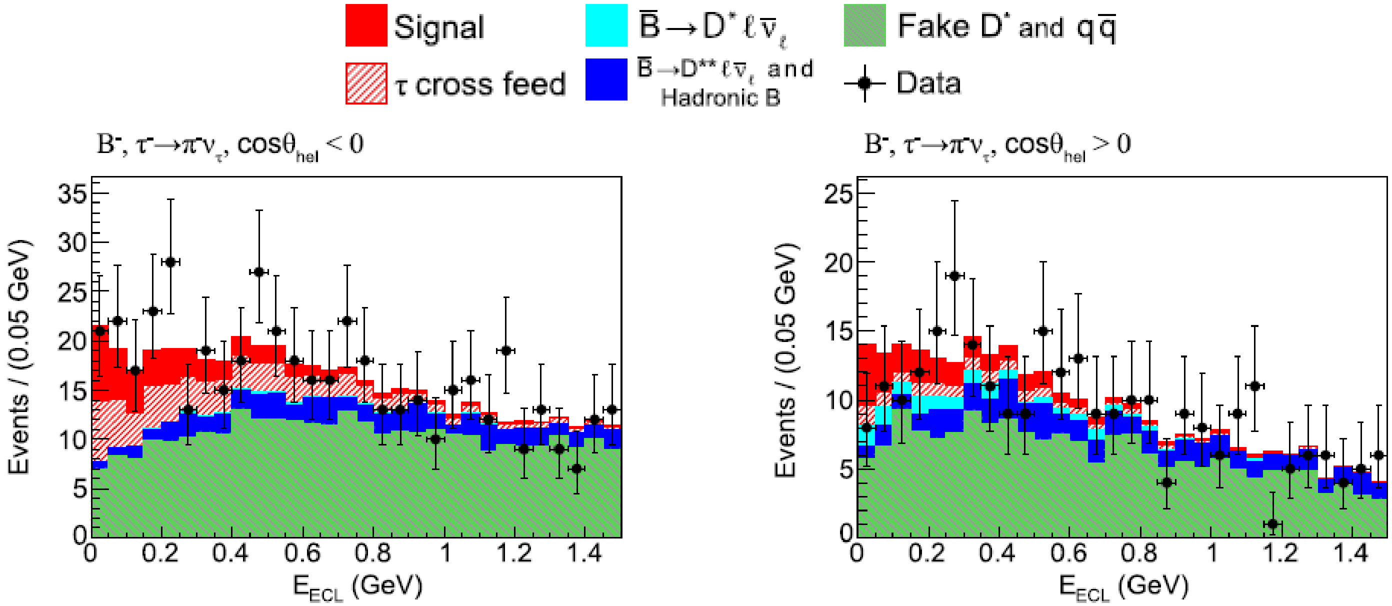
How the signal look

$$M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{\mathrm{tag}} - p_{D^*} - p_\ell)^2,$$

$D^{*0} \to D^0\gamma, D^0\pi^0, D^{*+} \to D^+\pi^0, D^0\pi^+$

$\tau \to \pi^+\nu, \rho^+\nu$





Simultaneous fit to 8 samples

$[B^0, B^+] \otimes [\pi^+, \rho^+] \otimes [\cos\theta_{\mathrm{hel}} > 0, \cos\theta_{\mathrm{hel}} < 0]$

$D^0 \to K^0_S\pi^0, \pi^+\pi^-, K^-\pi^+, K^+K^-, K^-\pi^+\pi^0, K^0_S\pi^+\pi^-, K^0_S\pi^+\pi^-\pi^0, K^-\pi^+\pi^+\pi^-, D^+ \to K^0_S\pi^+, K^0_S K^+, K^0_S\pi^+\pi^0, K^-\pi^+\pi^+, K^+K^-\pi^+, K^-\pi^+\pi^+\pi^0$, and $K^0_S\pi^+\pi^+\pi^-$

Result

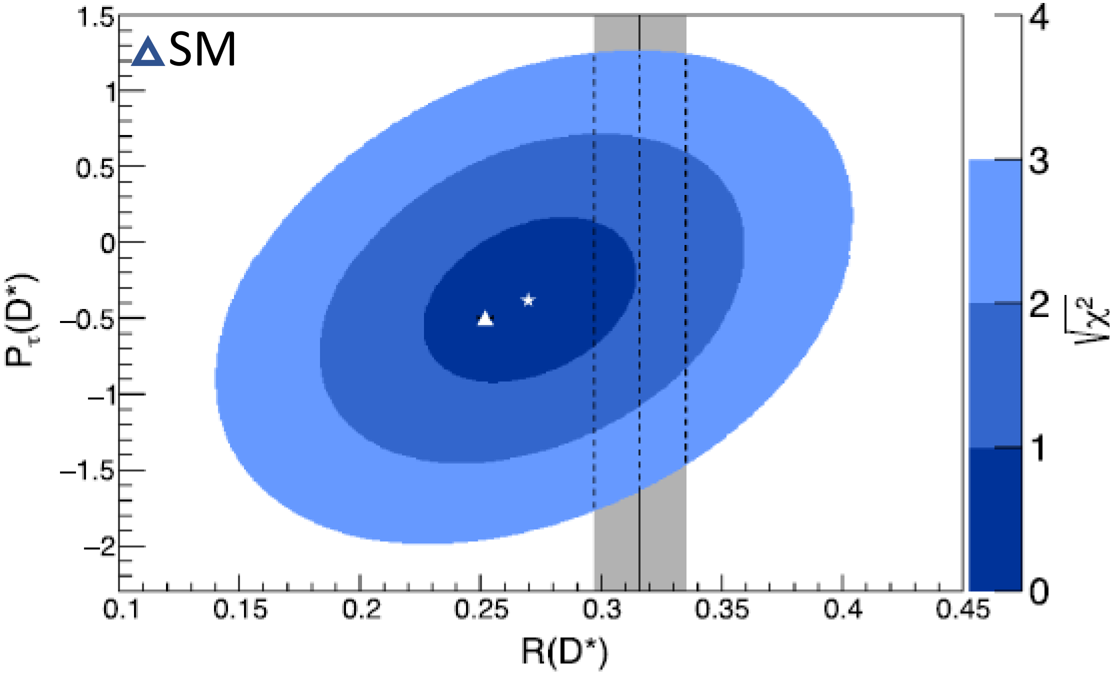
Belle
PRL118,211801 (2017)
PRD97, 012004 (2018)

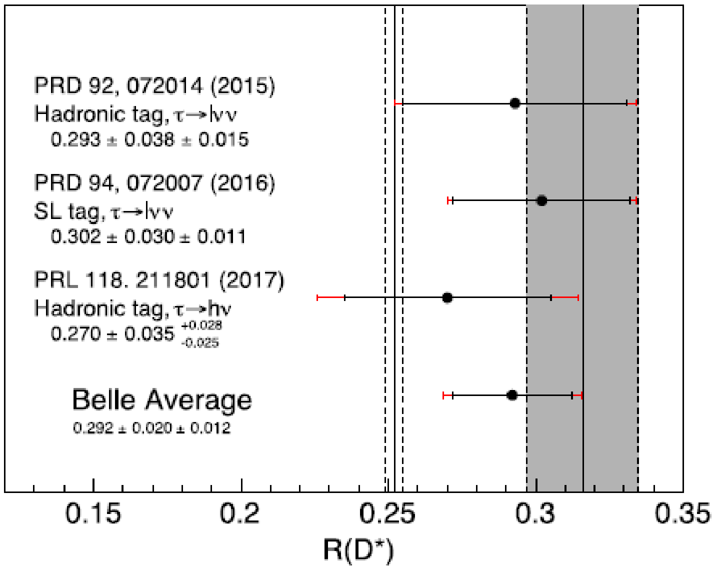
$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst}),$$

Signal significance of 7.1σ

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst}),$$

SM = -0.497±0.013



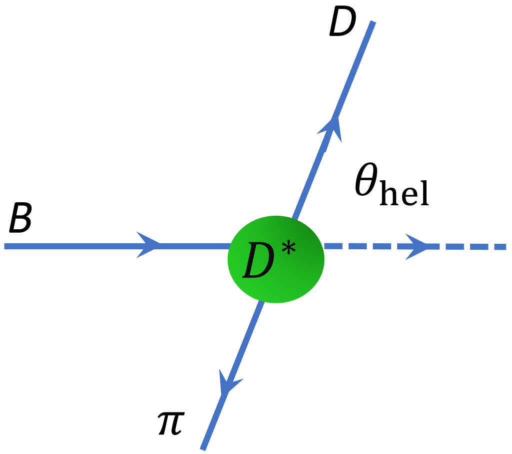


Measurement is consistent with the SM prediction
Excludes $P_\tau(D^*)$ larger than 0.5 at 90% CL.

$\mathcal{R}(D^*) = 0.295 \pm 0.038 \pm 0.015$
Previous from Hadron Tag

$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$

D^* polarization



D^* polarization can give clue about the NP signature

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{\rm hel} + (1-F_L^{D^*})\sin^2\theta_{\rm hel})$$

θ_{hel} = angle in D^*- rest frame between D0 and B0 flight

$F_L^{D^*}$ fraction of longitudinal polarization of D*

Evis and Xmiss

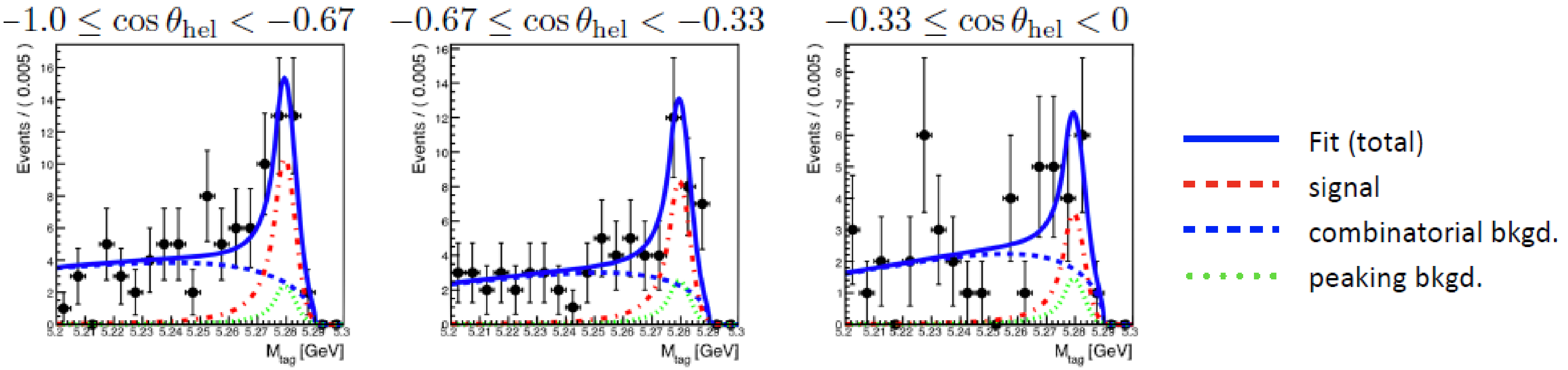
$$X_{miss} = \frac{E_{miss} - |p_{D^*} - p_{d_\tau}|}{\sqrt{E_{beam}^2 - m_{B^0}^2}}$$

Peaking background from $B \to D^*(X)\ell\nu$

- All τ decays are useful (cross-feed no effect)
- Strong dependence on $cos\theta_{hel}$ and q^2 due to slow π from D^* [softer at $(\cos\theta_{hel}) > 0$].

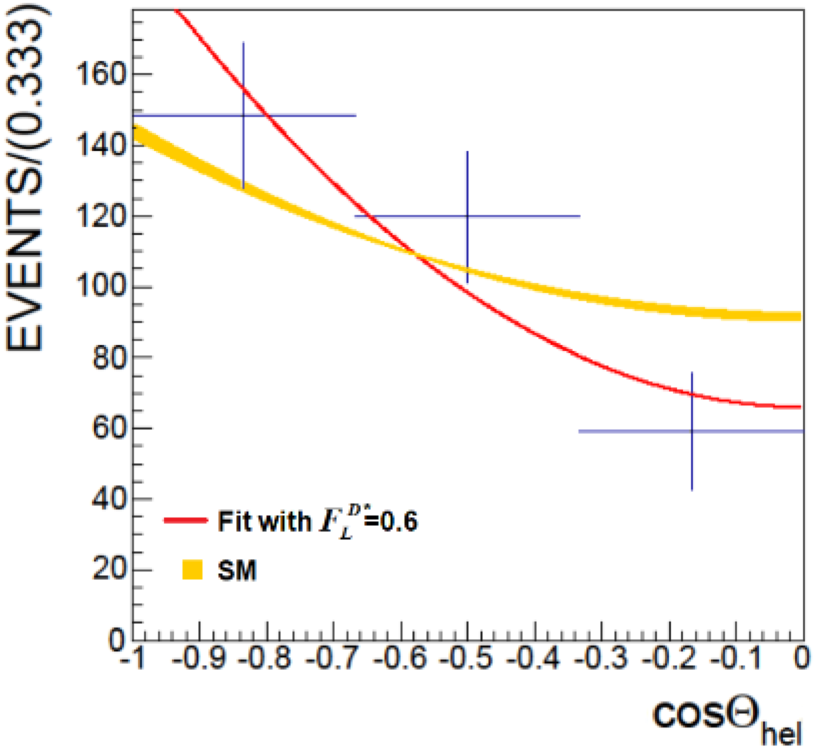
Measured F_L for $F_L^{D^*}(B \to D^{*-}e^+\nu) = 0.56 \pm 0.02$

SM : 0.54



First measurement of *D** polarization

Belle, arXiv:1903.03102



$$F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

$$\left(F_L^{D^*}\right)_{SM} = 0.457 \pm 0.010$$

Li et al PRD98, 095018(2018)

Agrees with SM within 1.6σ

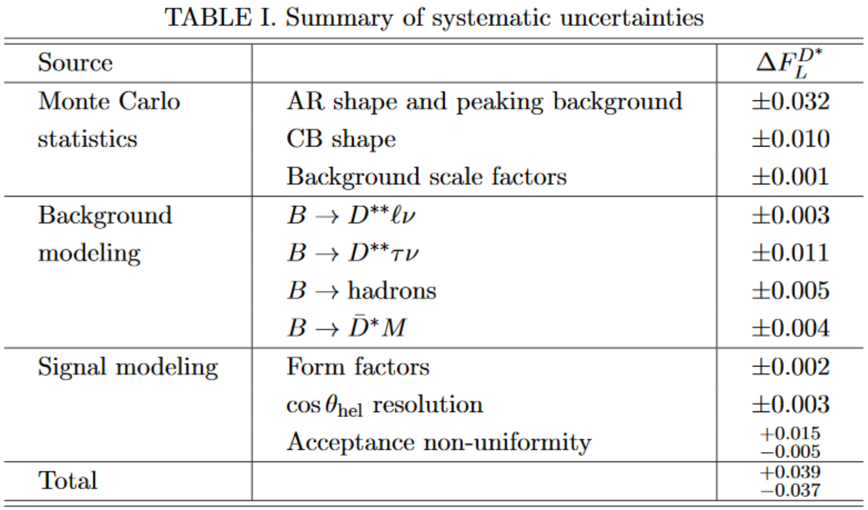
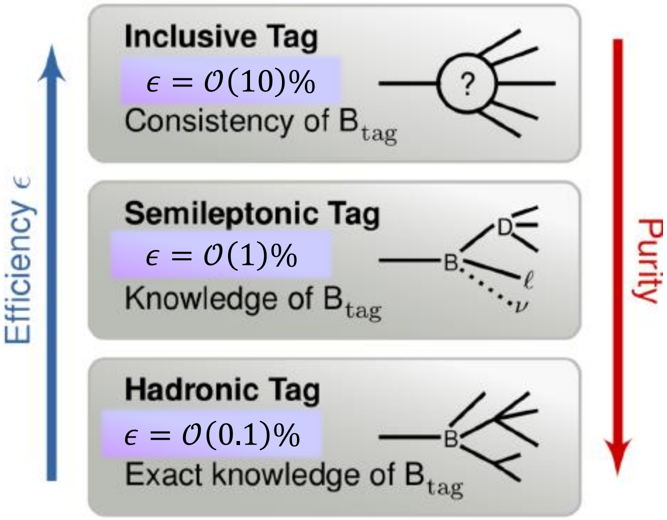


TABLE I. Summary of systematic uncertainties

Source		$\Delta F_L^{D^*}$
Monte Carlo	AR shape and peaking background	± 0.032
statistics	CB shape	± 0.010
	Background scale factors	± 0.001
Background	$B \to D^{**}\ell\nu$	± 0.003
modeling	$B \to D^{**}\tau\nu$	± 0.011
	$B \to$ hadrons	± 0.005
	$B \to \bar{D}^* M$	± 0.004
Signal modeling	Form factors	± 0.002
	$\cos\theta_{\rm hel}$ resolution	± 0.003
	Acceptance non-uniformity	$^{+0.015}_{-0.005}$
Total		$^{+0.039}_{-0.037}$

Update on semileptonic tagging by Belle

Previous	Updated
$\mathcal{R}(D^*)$ only	$\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$ simultaneously
B^0 only	B^0 and B^+
Semileptonic	Improved tagging, FEI

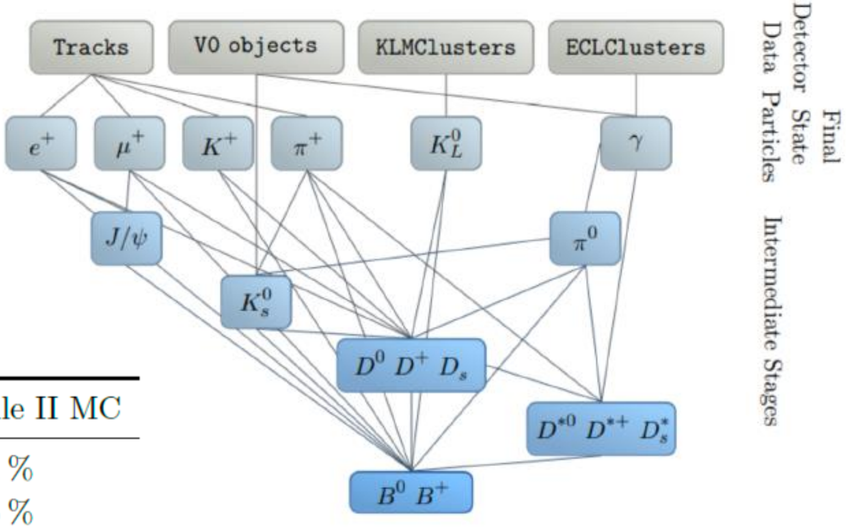


Tag	FR^4 @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %

FEI developed for Belle II; used in several Belle studies.

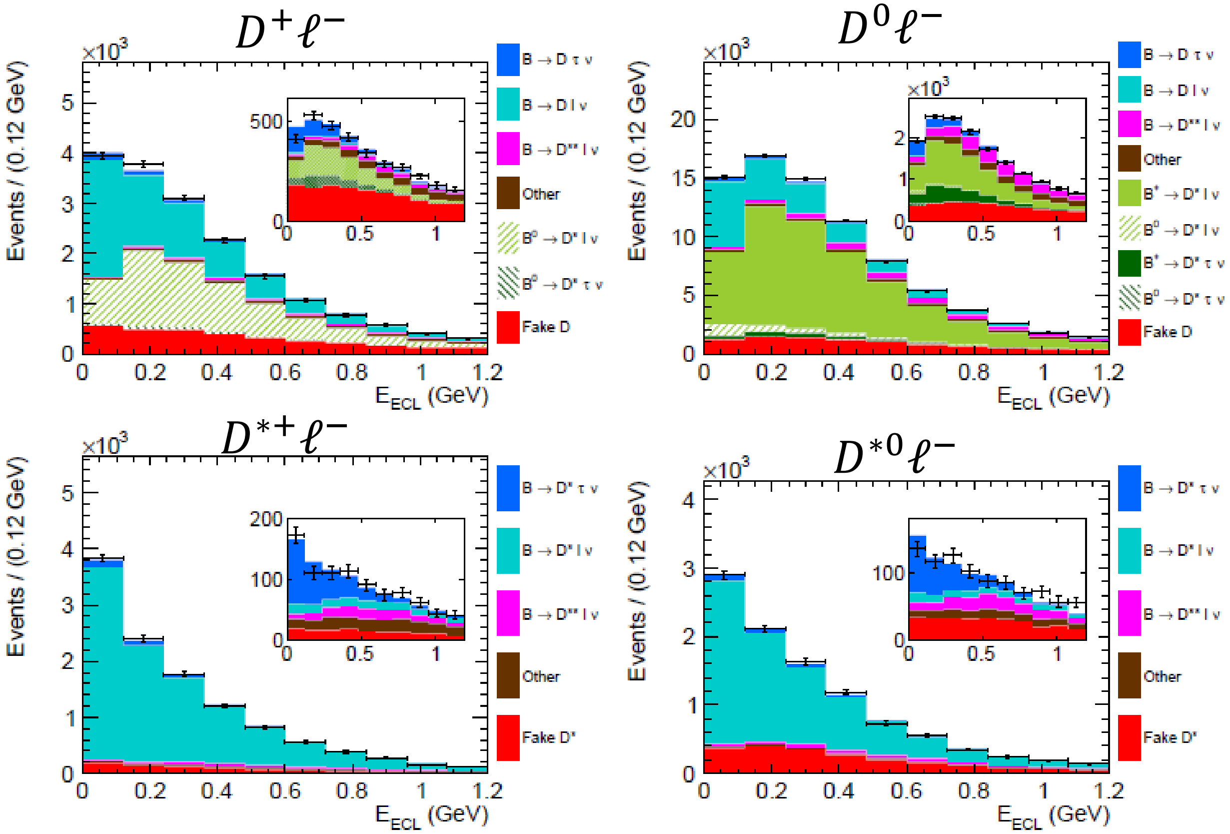
Exclusive Tagging:
The Full Event Interpretation (FEI)

Keck, T., et al. Comput Softw Big Sci (2019)



Updated result

Belle arXiv:1910.05864
submitted to PRL



Signal enhanced
$\mathcal{O}_{cls} > 0.9$ (inset)

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.282 \pm 0.018 \pm 0.014$$

Most precise measurement to date !

$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$
Previous semileptonic measurement

$\mathcal{R}(D)_{SM} = 0.300 \pm 0.011$
$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$

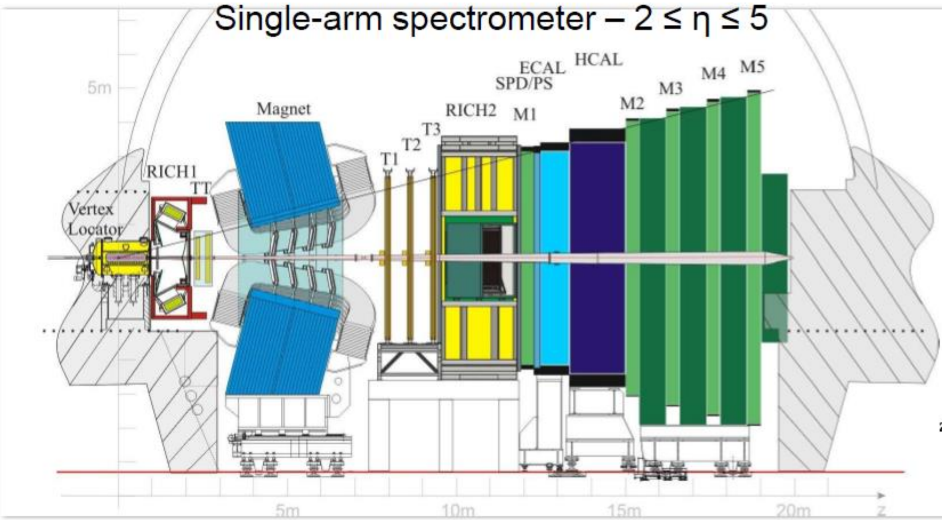
LHCb : beauty at the beast

LHCb is a single arm spectrometer optimized for beauty and charm physics at large η

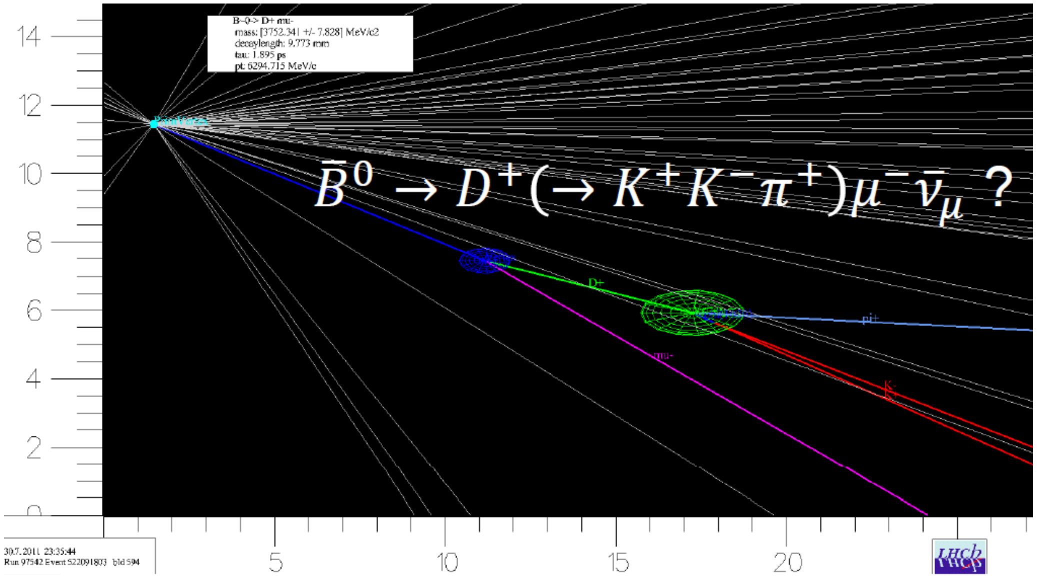
Excellent vertex resolution: 20μm resolution on impact parameter.

Excellent particle identification

Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

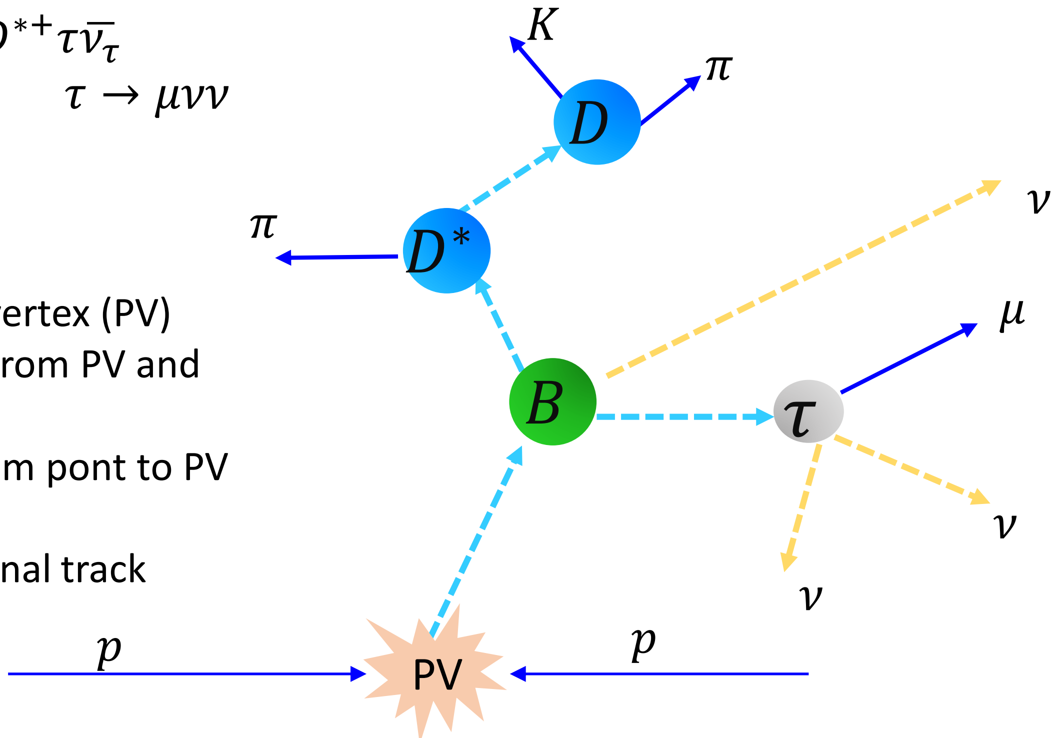


Semileptonic decays : High trigger efficiency



$\bar{B}^0 \rightarrow D^+(\rightarrow K^+K^-\pi^+)\mu^-\bar{\nu}_\mu$?

$B \to D^{*+}\tau\overline{\nu_\tau}$
$\tau \to \mu\nu\nu$



Signal identify

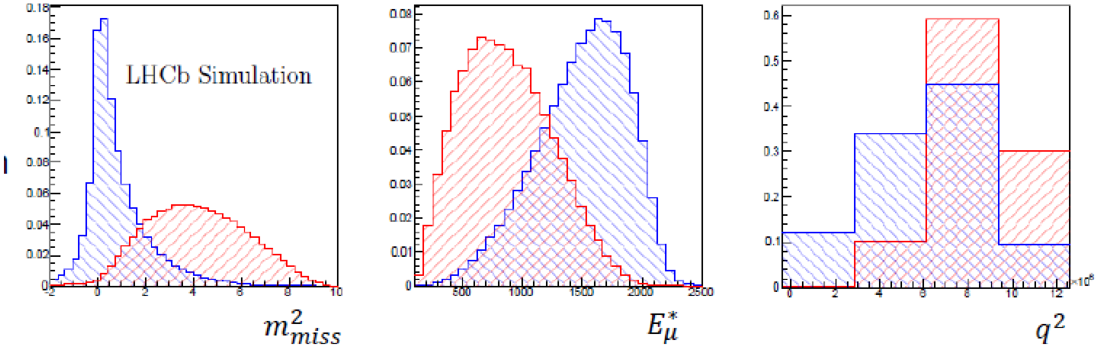
- Identify D^* with ΔM
- D0 decay vertex separate from primary vertex (PV)
- μ candidate 3< p < 100 GeV/c, separate from PV and form good vertex with D^0
- $M(D^*\mu) < 5.280\ \mathrm{GeV}/c^2$ and momentum pont to PV location.
- $D^*\mu$ required to be isolated from additional track

Separate signal from the normalization channel

- E^* , muon energy in the B rest frame
- $m^2_{miss} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$ where p^μ is four momentum.
- $q^2 = (p^\mu_B - p^\mu_{D^*})^2$

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

3 missing vs, analysis seems to look impossible for LHCb. Thanks to the boost and vertex capability of LHCb, they made it possible

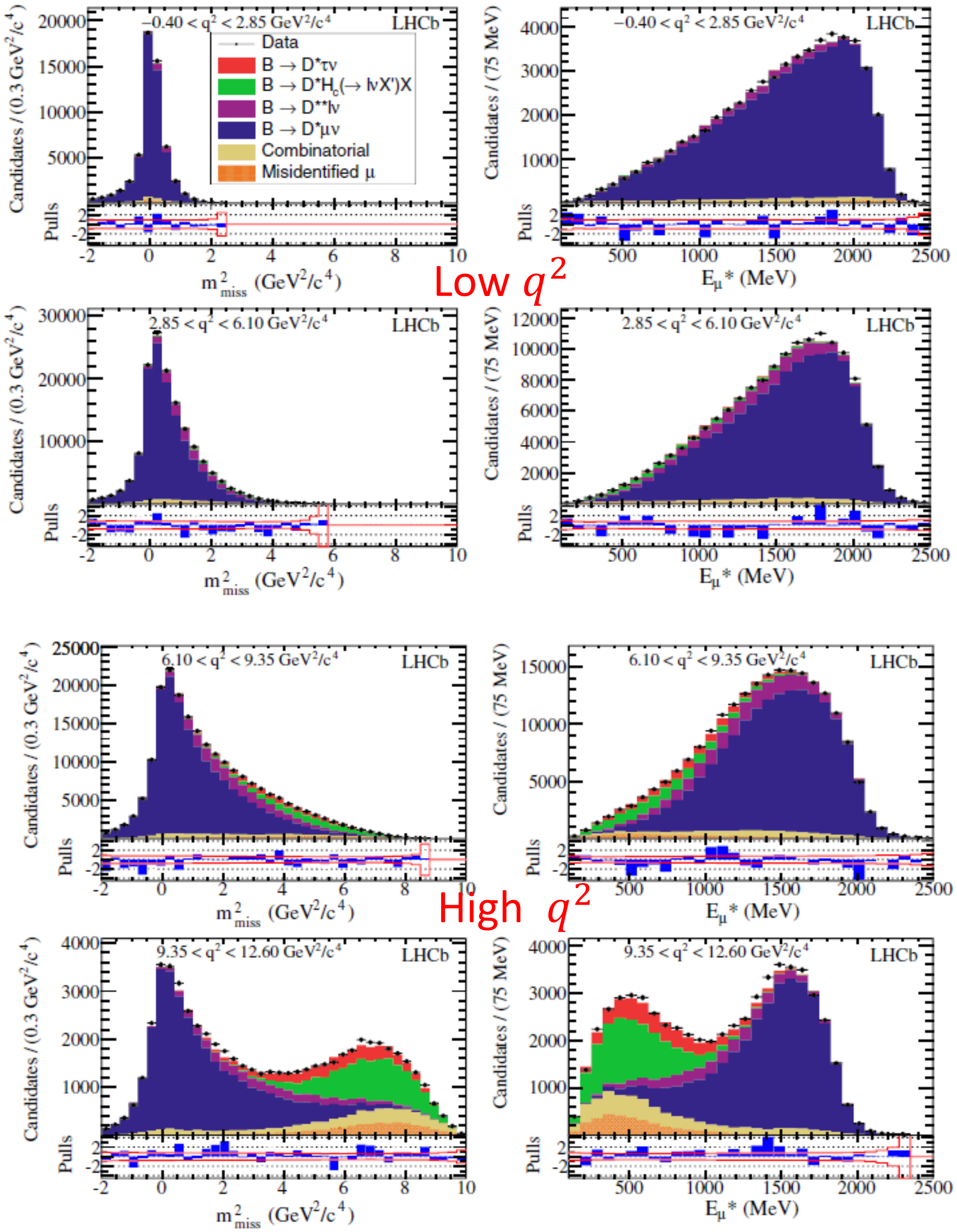


B momentum direction is determined from unit vector to B decay vertex from the associated PV.
Component of B momentum along the B momentum along the beam axis is approximated using $(p_B)_z = (^{m_B}/_{m_{reco}})(p_{reco})_z$

Deviate from SM

LHCb, PRL 115, 111803 (2015)

$3fb^{-1}$ 2011-2012 data



Low q^2

High q^2

- Data
- 🟥 $B \rightarrow D^{*}\tau\nu$
- 🟩 $B \rightarrow D^{*}H_c(\rightarrow l\nu X')X$
- 🟪 $B \rightarrow D^{**}l\nu$
- 🟦 $B \rightarrow D^{*}\mu\nu$
- 🟨 Combinatorial
- 🟧 Misidentified μ

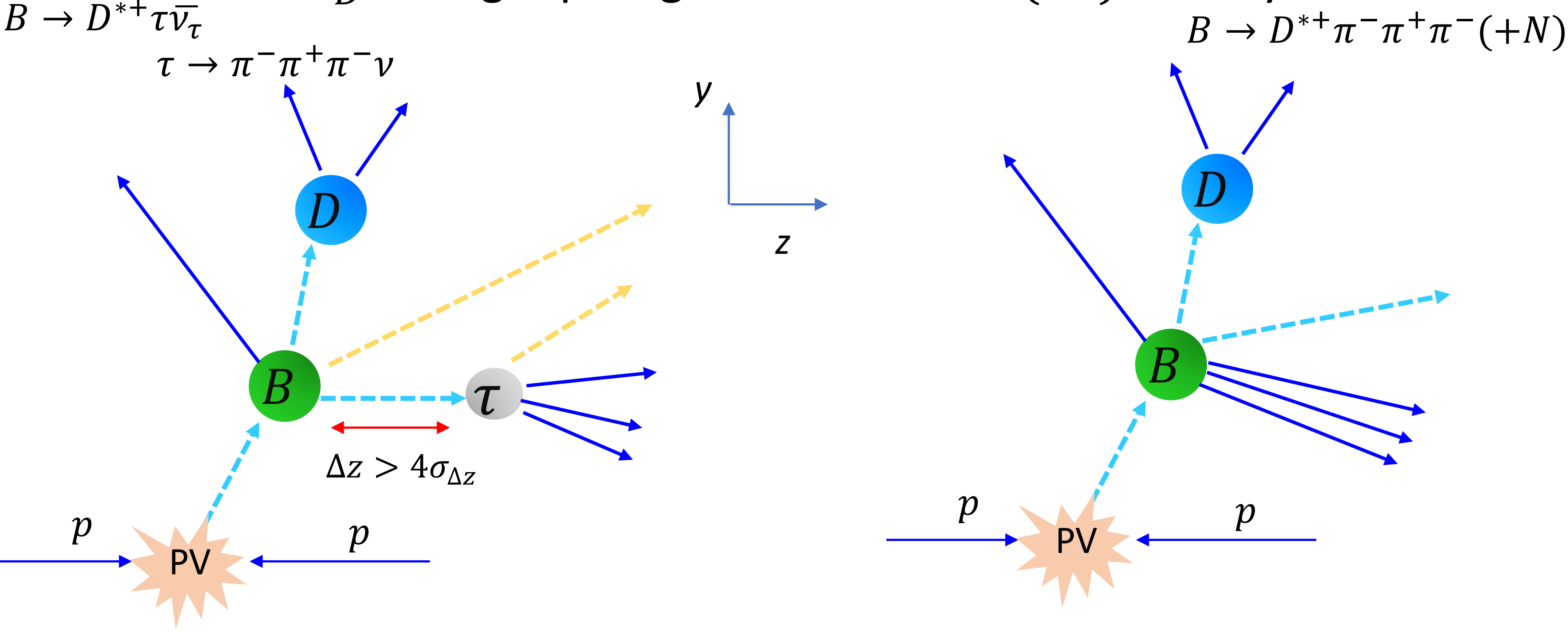
~16400 events for $\overline{B^0} \rightarrow D^{*+}\tau^{-}\overline{\upsilon_\tau}$

$$\mathcal{R}(D^{*}) = 0.336 \pm 0.027 \pm 0.030$$

(2.1σ from SM)

$$\mathcal{R}(D^{*})_{SM} = 0.252 \pm 0.003$$

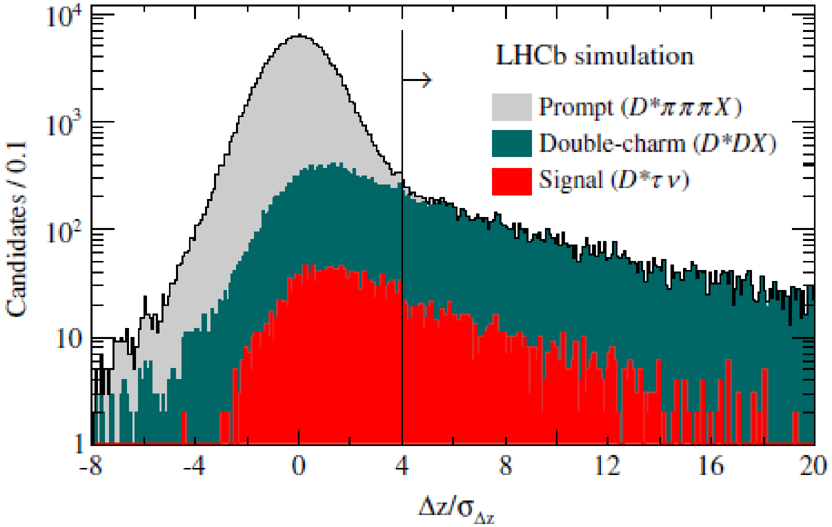
R_{D^*} using 3-prong $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$ decays



- Absence of charged lepton avoids background from semileptonic $b \to c$ decays
- Three prong helps in getting precise τ decay vertex.
- Only one ν emitted at the τ vertex.
- Background $B \to D^{*-}DX$ leads to nice mass peaks and not the signal. Provide handle to control various background.

R_{D^*} using 3-prong $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$ decays

Signal candidates are required to be well isolated.
Events with extra charged particles pointing to B and/or τ vertices are vetoed.



$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \quad = \frac{N_{\rm sig}}{N_{\rm norm}}\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}\frac{1}{\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau)}$$

Most of the systematic cancel in this ratio.

$$\mathcal{R}(D^*) = \mathcal{K}(D^{*-}) \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

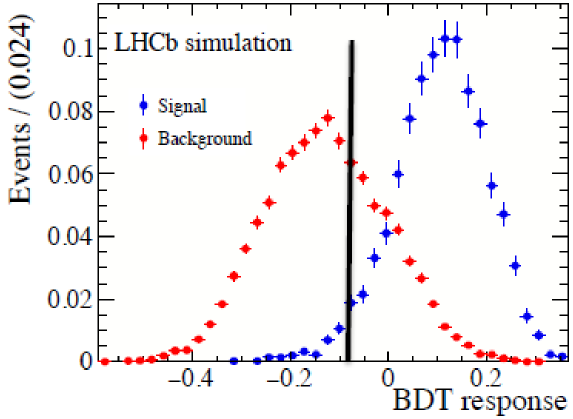
$N_{\rm sig}$ from a 3D fit to q^2 (8 bins), 3π decay time (8 bins) and BDT (4 bins)
$N_{\rm sig}$ from a fit to $M(D^{*-}\pi^+\pi^-\pi^+)$

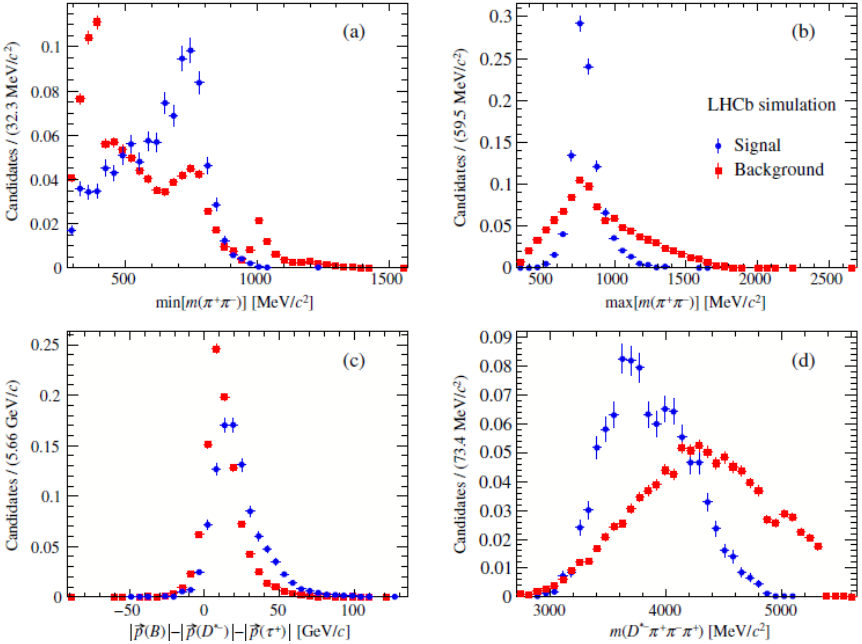
LHCb,PRD 97, 072013 (2018)

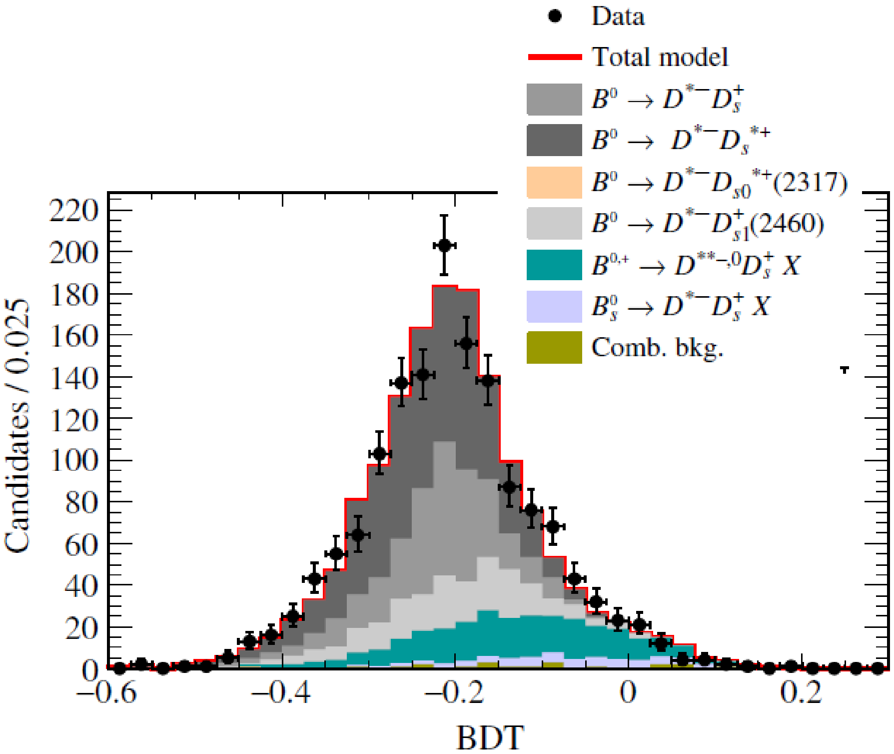
R_{D^*} using 3-prong $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$ decays

BDT trained to suppress main background from $D^{*-}D_s^+X$ events

Input variables:
3π dynamics, $D^*3\pi$ dynamics, neutrals isolation

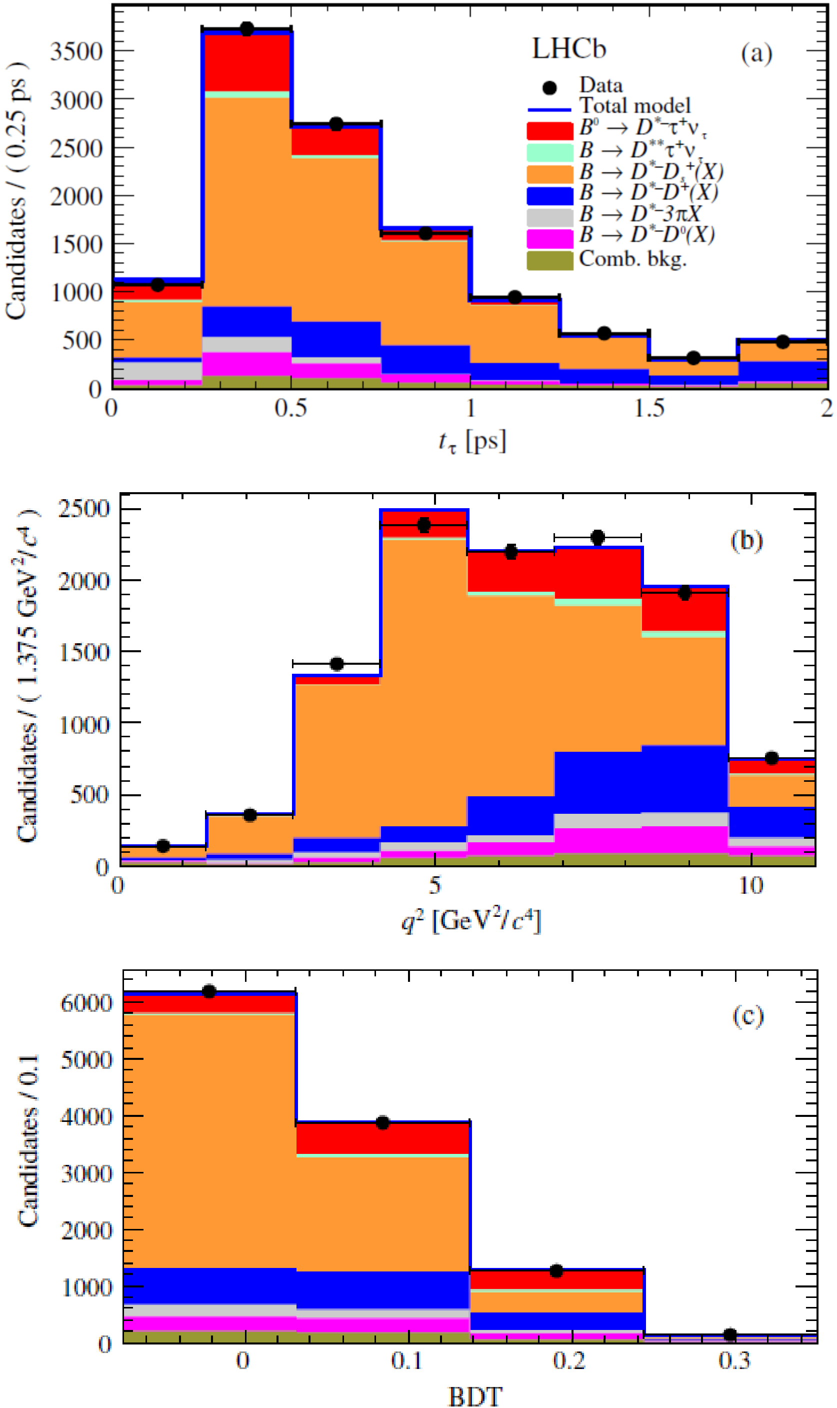


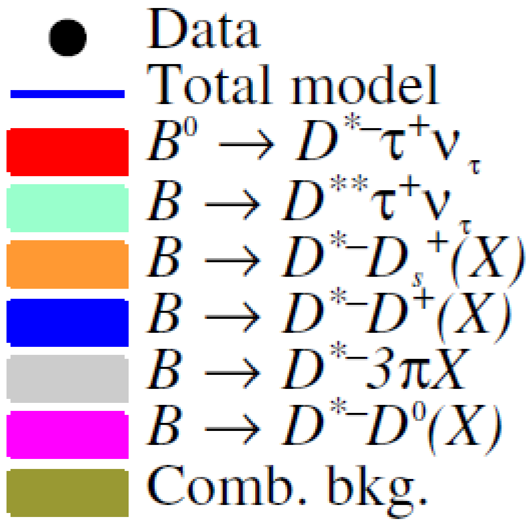


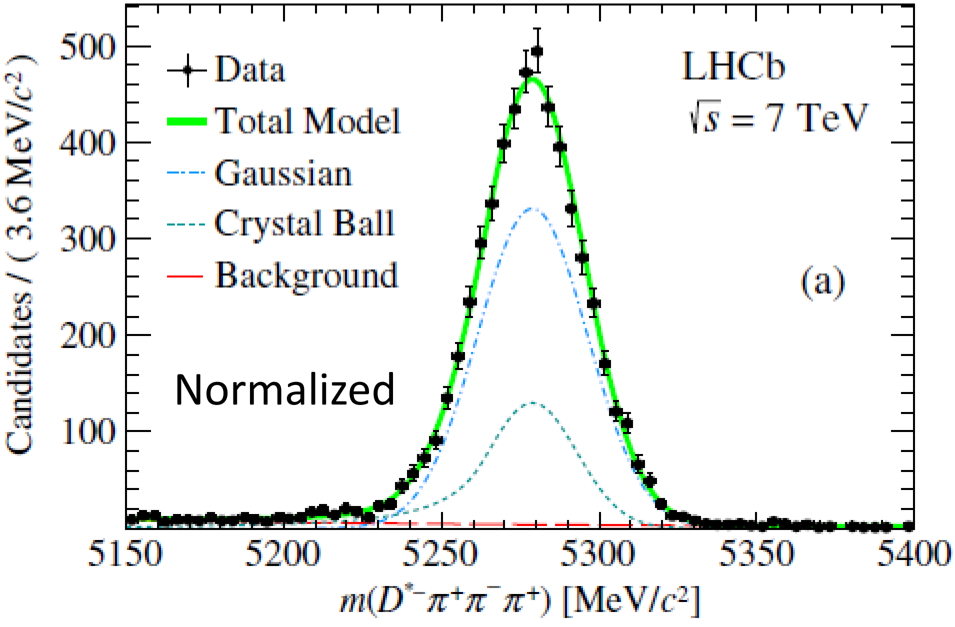


R_{D^*} using 3-prong

LHCb,PRD 97, 072013 (2018)







Normalized

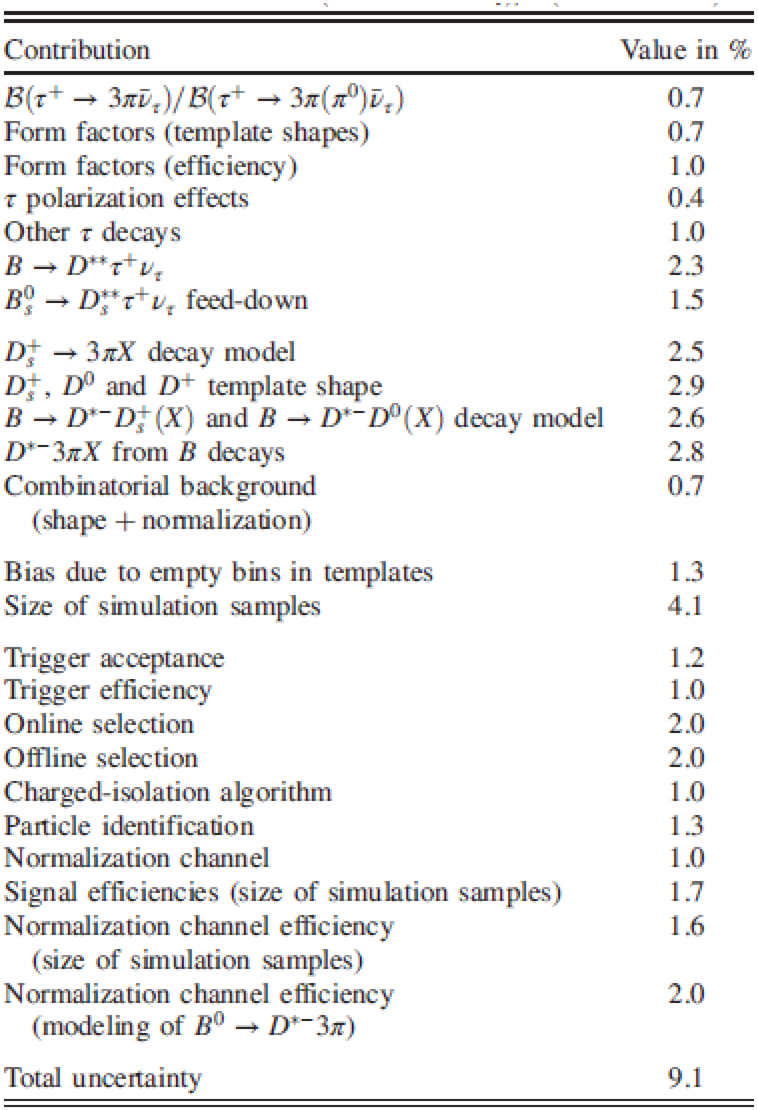
Result by 3 prong

LHCb,PRD 97, 072013 (2018)

$3fb^{-1}$ data

$$\mathcal{R}(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

(1.1σ from SM)



Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Particle identification	1.3
Normalization channel	1.0
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

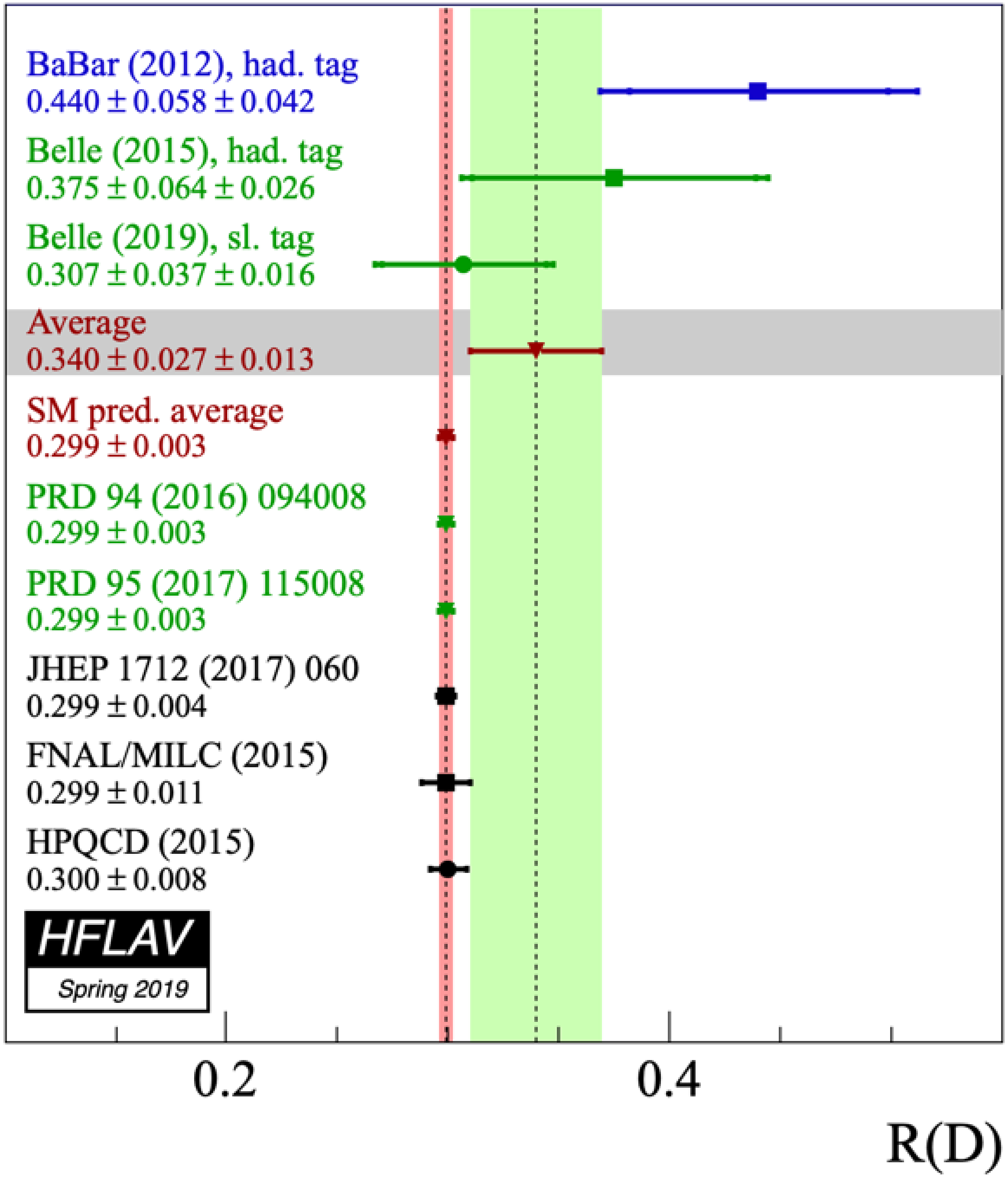
Previous one prong result

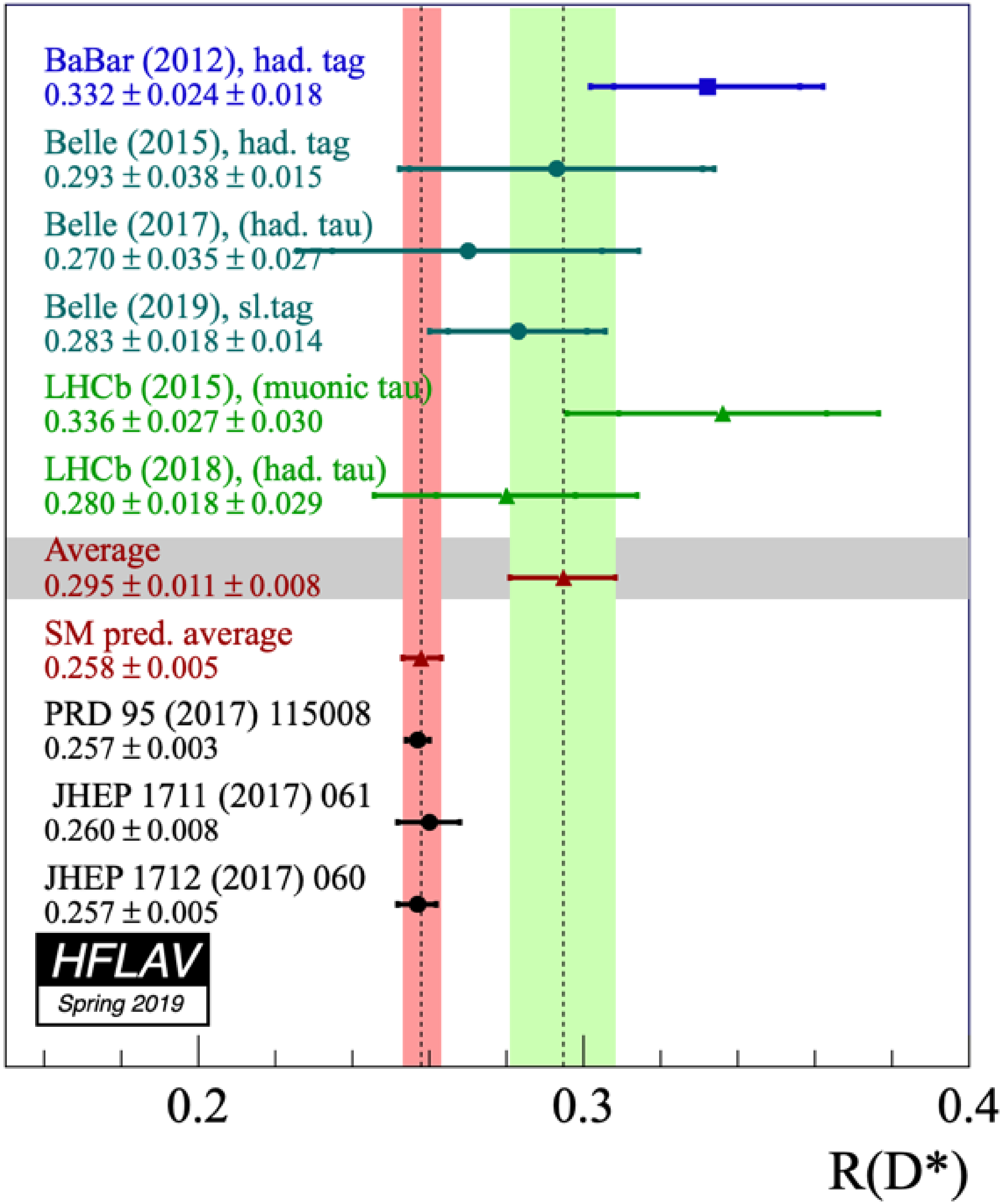
$$\mathcal{R}(D^*) = 0.336 \pm 0.027 \pm 0.030$$

(2.1σ from SM)

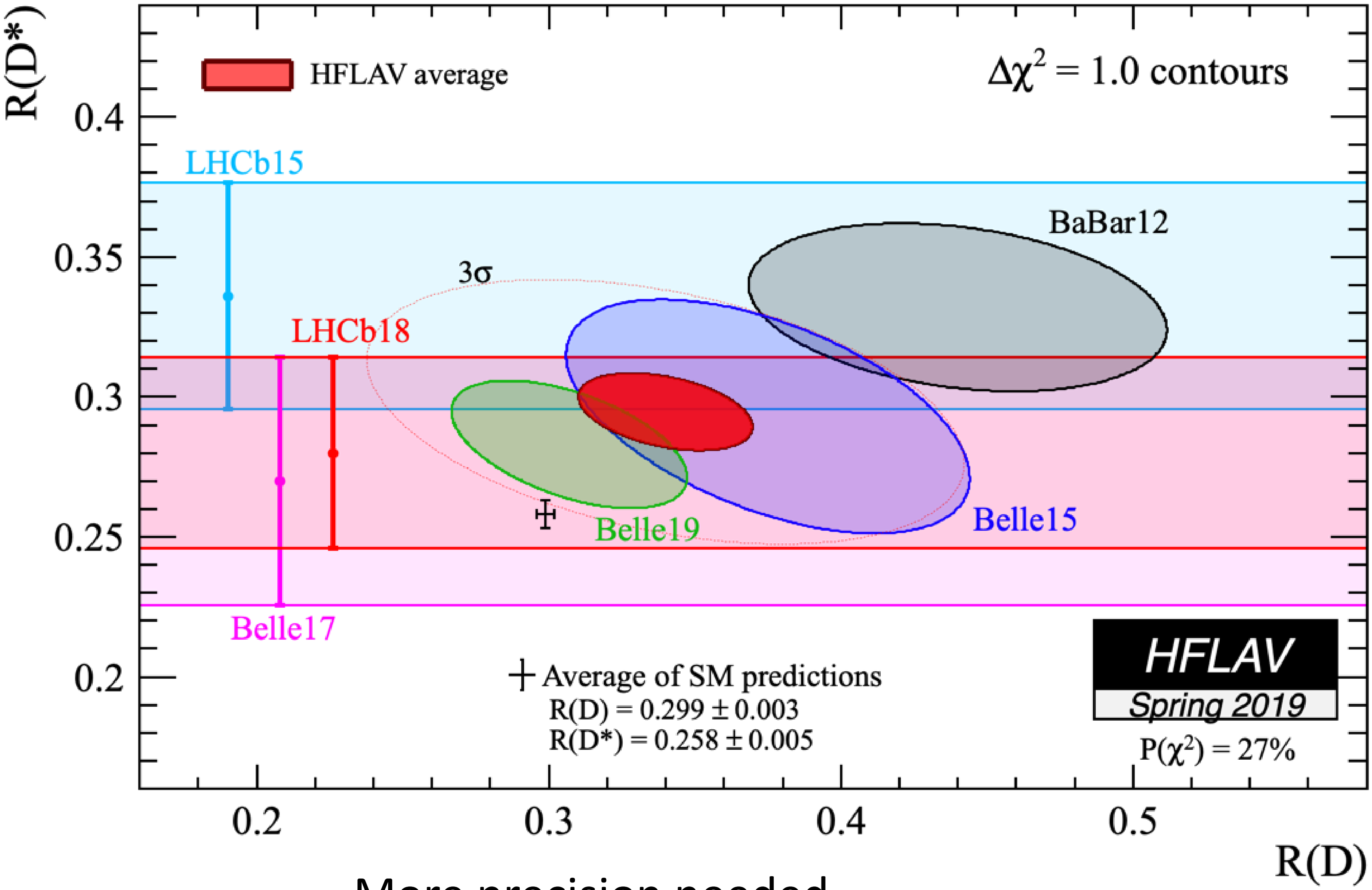
LHCb, PRL 115, 111803 (2015)

$$\mathcal{R}(D^*)_{SM} = 0.252 \pm 0.003$$


BaBar (2012), had. tag
0.440 ± 0.058 ± 0.042
Belle (2015), had. tag
0.375 ± 0.064 ± 0.026
Belle (2019), sl. tag
0.307 ± 0.037 ± 0.016
Average
0.340 ± 0.027 ± 0.013
SM pred. average
0.299 ± 0.003
PRD 94 (2016) 094008
0.299 ± 0.003
PRD 95 (2017) 115008
0.299 ± 0.003
JHEP 1712 (2017) 060
0.299 ± 0.004
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
Spring 2019
0.2
0.4
R(D)


BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018
Belle (2015), had. tag
0.293 ± 0.038 ± 0.015
Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027
Belle (2019), sl.tag
0.283 ± 0.018 ± 0.014
LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030
LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029
Average
0.295 ± 0.011 ± 0.008
SM pred. average
0.258 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005
HFLAV
Spring 2019
0.2
0.3
0.4
R(D*)

Current scenario

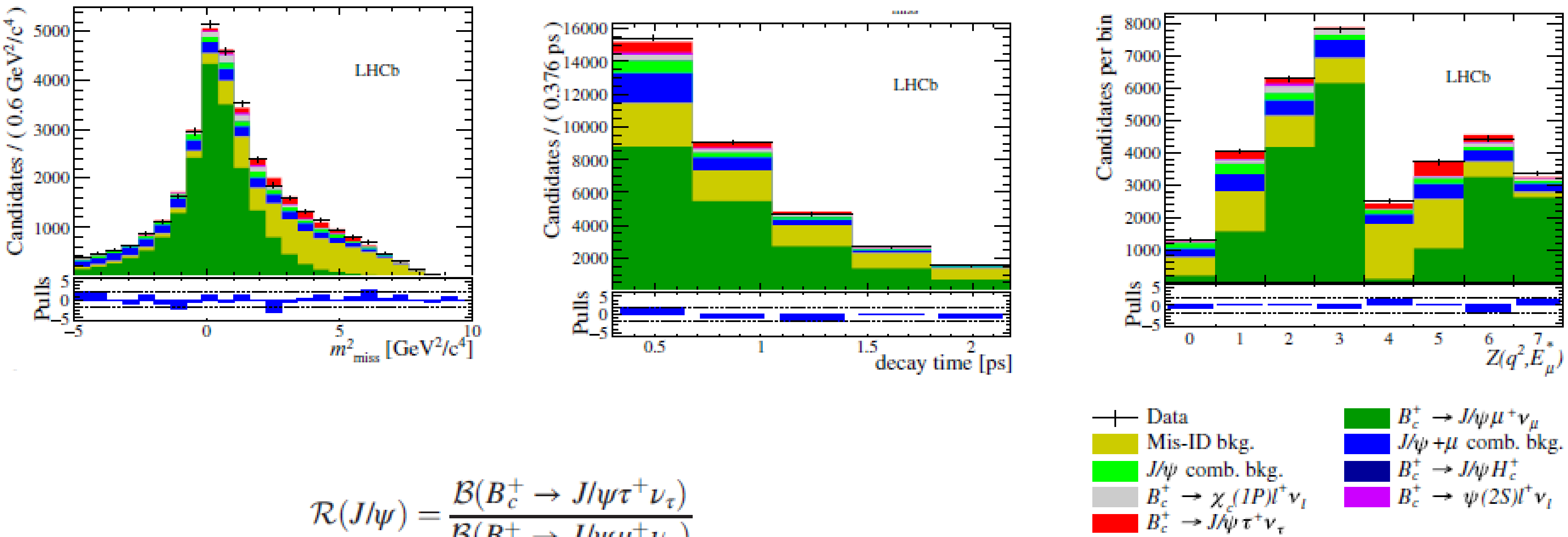


More precision needed.
Picture more clear by 202X

Skip

Anomaly $\mathcal{R}_{J/\psi}$

LHCb,PRL120, 121801 (2018)



$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$
$$= 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}).$$

SM predicts within range: 0.25-0.28

Source of uncertainty	Size ($\times 10^{-2}$)
Finite simulation size	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Mis-ID background strategy	5.6
combinatorial background cocktail	4.5
combinatorial J/ψ background scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
$\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$	0.2
Systematic uncertainty	17.7
Statistical uncertainty	17.3

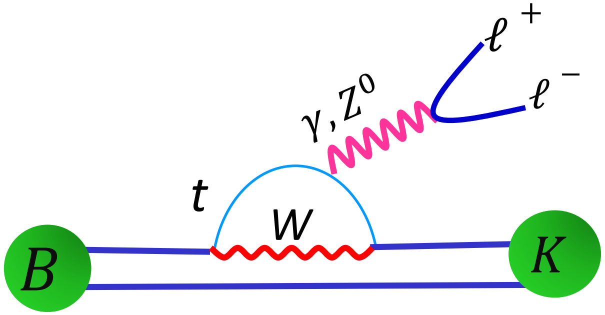
$b \to s\ell\ell$

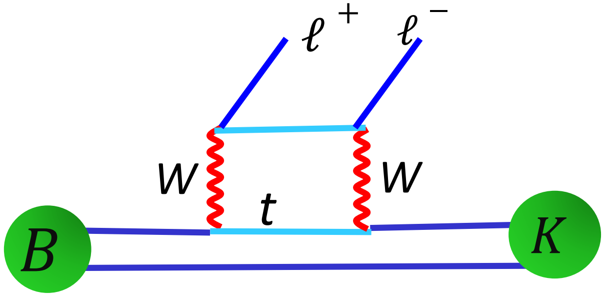
Rare decays, FCNC

Small branching fraction : $\mathcal{O}(10^{-6})$

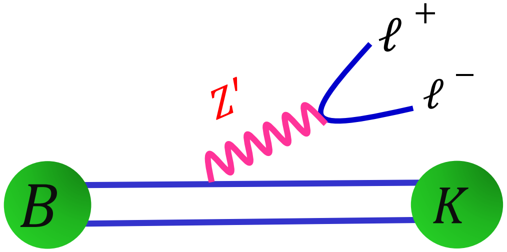
- Decays are sensitive to NP
- Modify the decay rate and the angular distribution of final state

- Give strong constraints on many BSM by probing energy scales higher than direct searches
- Experimentally: full reconstruction but background dominated

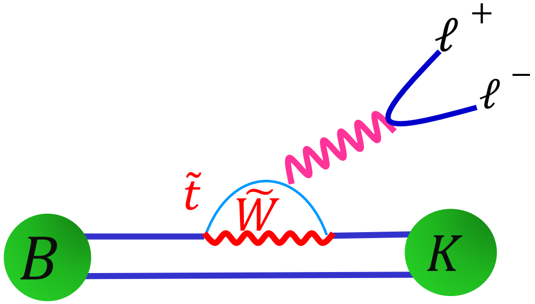




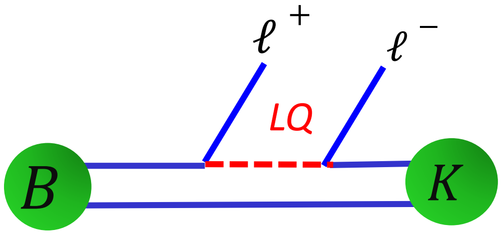
Processes which are suppressed or even forbidden in the SM, one expect the NP effect to be relatively large.



New Heavy Gauge Bosons



Supersymmetry



Leptoquarks

Amplitude of a hadron decay process is described as

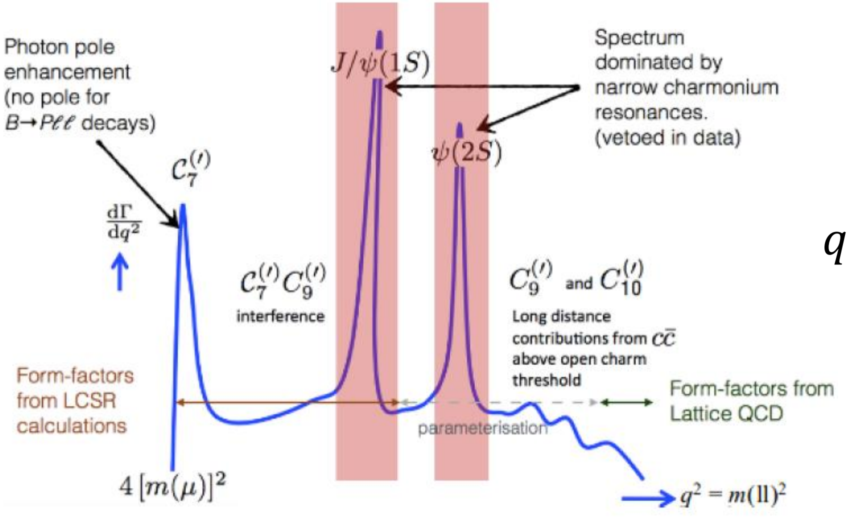
$$\mathcal{A}(I \to F) = \langle F|\mathcal{H}_{eff}|I\rangle = \frac{G_F}{\sqrt{2}}\sum_i V^i_{CKM}\, C_i(\mu)\langle F|O_i(\mu)|M\rangle$$

CKM couplings Wilson coefficients Hadronic Matrix Elements

At μ scale

Wilson Coefficients C_i = Perturbative short distance effects
Operators O_i = non-perturbative long distance effects
i = 7 : Photon penguin
i =9,10 : Electroweak penguin

NP modify the SM operator contribution (C_i) and /or enter through new operators



Contribution of C_7, C_9 and C_{10} depends on q^2 (invariant mass of two leptons)

In the SM, couplings of the gauge bosons to leptons are independent of lepton flavour
Any sign of lepton non-universal interaction would be a direct sign of new physics

What we observe is effect of the particle involved affecting the $\mathcal{B}$

To give an idea from an old plot

Hou, Willey, and Soni PRL 58, 1608 (1987)

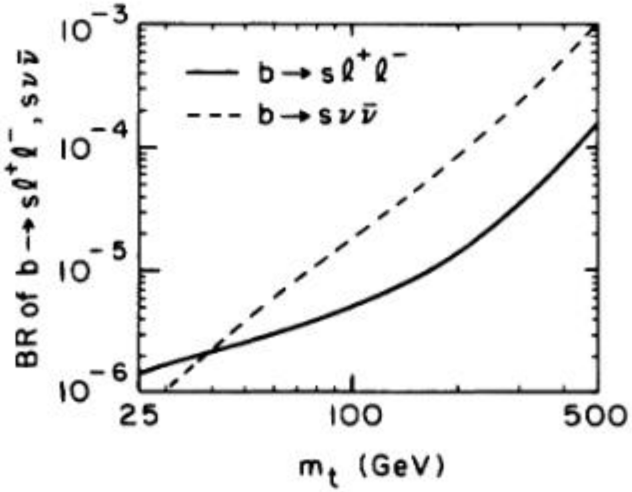
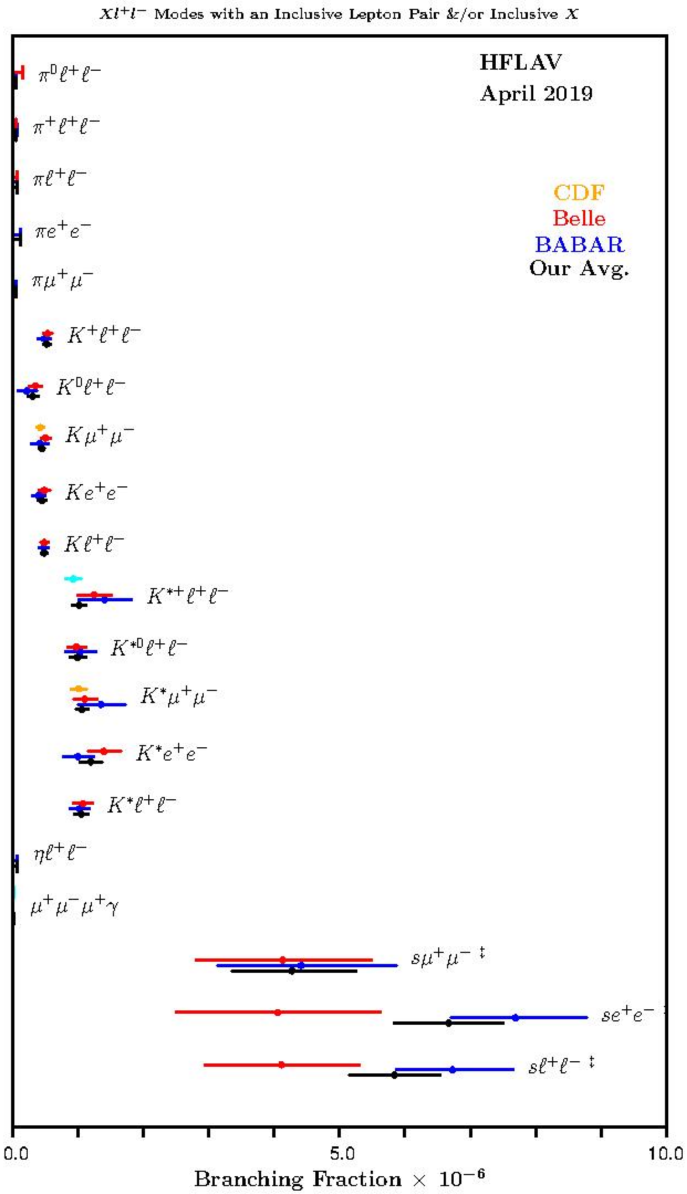


FIG. 2. Branching ratios for the processes $b \to se^+e^-$, $s\nu\bar{\nu}$ in the three-generation case. For $b \to s\nu\bar{\nu}$ the three neutrino species have been summed over. For $b \to s\mu^+\mu^-$ the rate is slightly smaller (see Refs. 15 and 16).



$$m_t = 173.0 \pm 0.4 \text{ GeV}/c^2$$

Provide unique way to look for the (new) physics

Forward-backward Asymmetry in $B \to K^*\ell\ell$

A.Ali et al PLB 273, 505 (1991)

Interference between γ and weak coupling in $b \to s\ell^+\ell^-$production give rise to a forward-backward asymmetry

$$\frac{N_F - N_B}{N_F + N_B} = \qquad A_{FB}(B \to K^*\ell^+\ell^-) = -C_{10}\xi(q^2)\left[Re(C_9)F_1 + \frac{1}{q^2}C_7F_2\right]$$

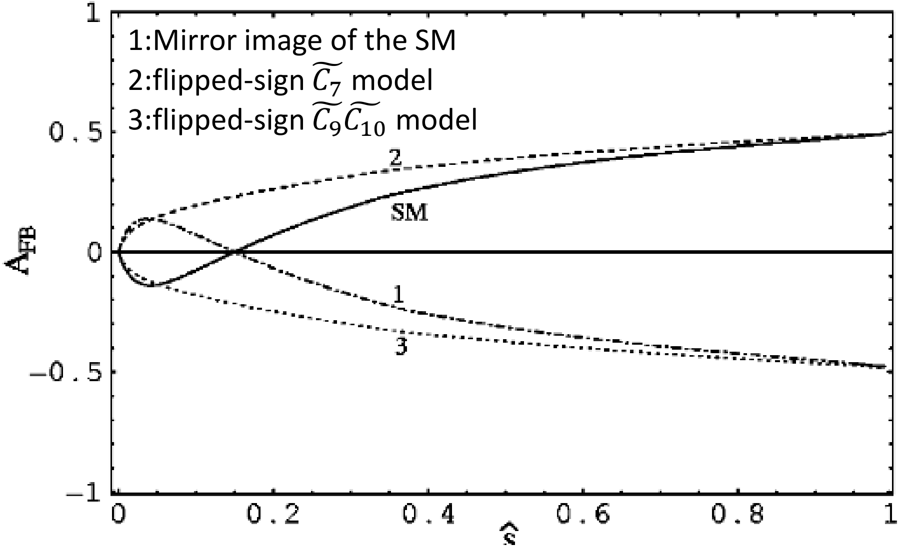
F_1, F_2 are form factors

$q^2 = m^2_{\ell^+\ell^-}$

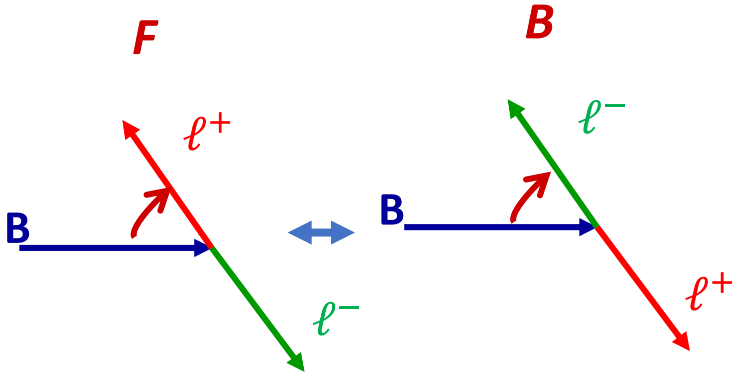
Z contribution

Effective photon contribution

A.Ali et al PRD66,034002 (2002)



SM predictions are not sensitive to QCD corrections



$\ell^+\ell^-$rest frame

Measurement of $\mathcal{A}_{FB}$

Belle, PRL96, 251801(2006)

$B \to K^{*0}\ell^+\ell^-, K^{*+}\ell^+\ell^-, K^+\ell^+\ell^-$

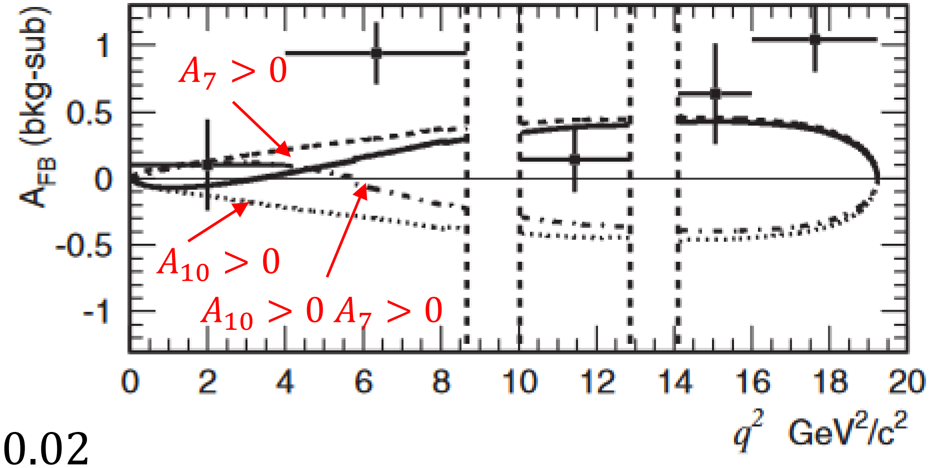
$K^{*0} \to K^+\pi^-,$

$K^{*+} \to K_S^0\pi^+, K^+\pi^0$

357fb^{-1}

SM (solid line)

$A_7 = -0.330;\ A_9 = 4.069;\ A_7 = -4.213;$



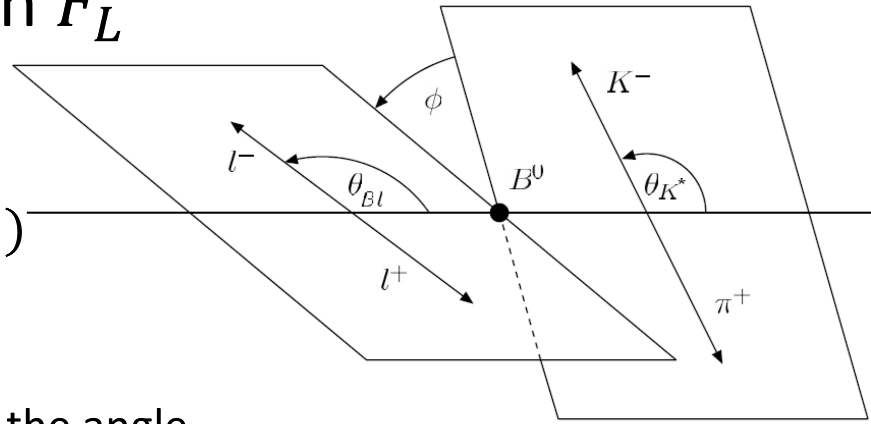
$$\mathcal{A}_{FB}(B \to K^*\ell^+\ell^-) = 0.50 \pm 0.15 \pm 0.02$$
$$\mathcal{A}_{FB}(B \to K^+\ell^+\ell^-) = 0.10 \pm 0.14 \pm 0.01$$

It seems $C_7 = -C_7^{SM}$ preferred the $\mathcal{A}_{FB}$ data

Flipping the sign of photonic penguin, would turn on the large rate of $B \to X_s\ell\ell$ (then what seen in experiments) Cite19

Addition to measuring $\mathcal{A}_{FB}$ one can also measure K* longitudinal polarization F_L

$\mathcal{A}_{FB}$ along with F_L



$$\frac{d\Gamma}{dcos\theta_{K^*}} = \frac{3}{4} F_L cos^2_{\theta_{K^*}} + \frac{3}{4}(1 - F_L)(1 - cos^2_{\theta_{K^*}})$$

$\mathcal{A}_{FB}$ is extracted from the fit to cosθ$_{Bl}$, where θ$_{Bl}$ is the angle between l$^+$ and B^0(B$^+$) in dilepton rest frame.

$$\frac{d\Gamma}{dcos\theta_{B\ell}} = \frac{3}{4} F_L(1 - cos^2_{\theta_{B\ell}}) + \frac{3}{8}(1 - F_L)\left(1 + cos^2_{\theta_{K^*}}\right) + \mathcal{A}_{FB} cos_{\theta_{B\ell}}$$

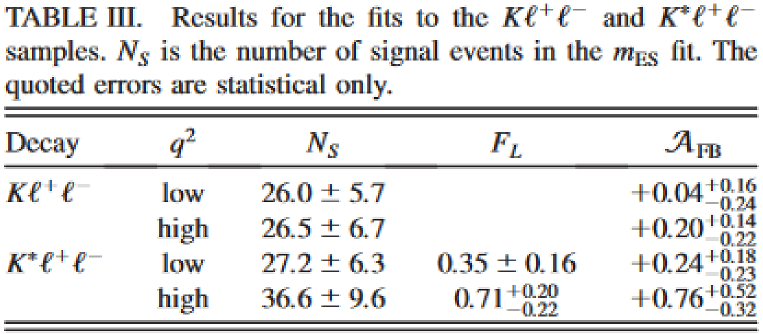
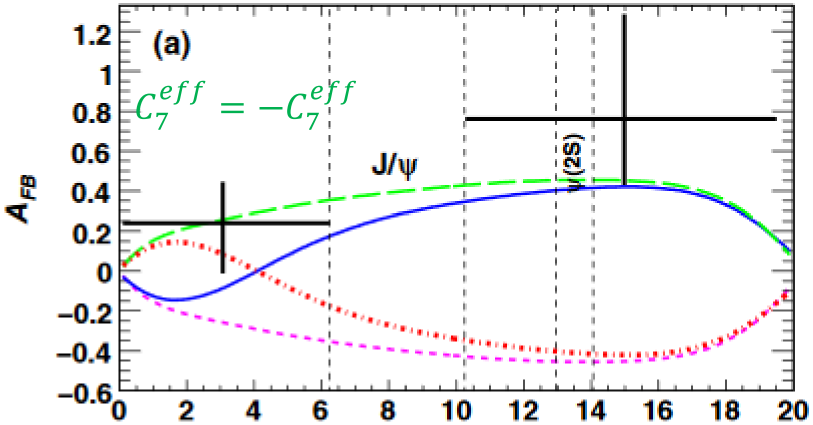


TABLE III. Results for the fits to the $K\ell^+\ell^-$ and $K^*\ell^+\ell^-$ samples. N_S is the number of signal events in the m_{ES} fit. The quoted errors are statistical only.

Decay	q^2	N_S	F_L	$\mathcal{A}_{FB}$
$K\ell^+\ell^-$	low	26.0 ± 5.7		$+0.04^{+0.16}_{-0.24}$
	high	26.5 ± 6.7		$+0.20^{+0.14}_{-0.22}$
$K^*\ell^+\ell^-$	low	27.2 ± 6.3	0.35 ± 0.16	$+0.24^{+0.18}_{-0.23}$
	high	36.6 ± 9.6	$0.71^{+0.20}_{-0.22}$	$+0.76^{+0.52}_{-0.32}$

SM (solid line) $C_9^{eff} C_{10}^{eff} = -C_9^{eff} C_{10}^{eff}$



$C_7^{eff} = -C_7^{eff}$

$C_7^{eff} = -C_7^{eff}$ and $C_9^{eff} C_{10}^{eff} = -C_9^{eff} C_{10}^{eff}$

$A_i \simeq C_i$ A_i are q^2 independent real term of C_i
$C_7 C_9 C_{10}$ are real up to higher order corrections.

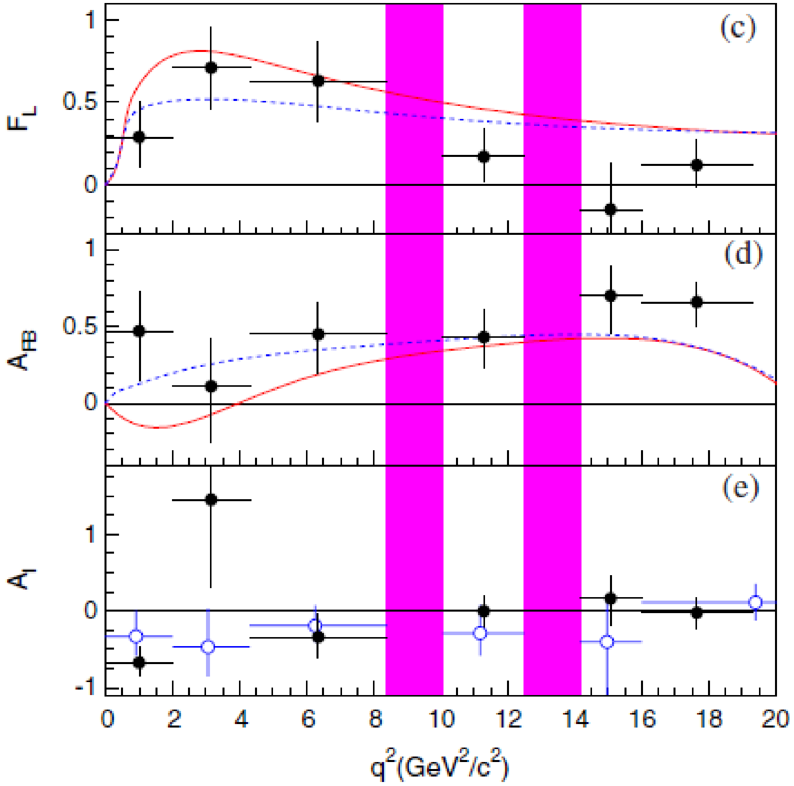
One need to use Wilson coefficient complex (not only for NP, but also for SM)
Wou, Hovhannisyan, Mahajan PRD 77, 014016 (2008)

BaBar, PRD79, 031102 (R) (2009).

$\mathcal{A}_{FB}$ in $B \to K^{*}\ell^{+}\ell^{-}$

Belle updated the study and found the opposite sign again

Belle PRL103,171801 (2009)

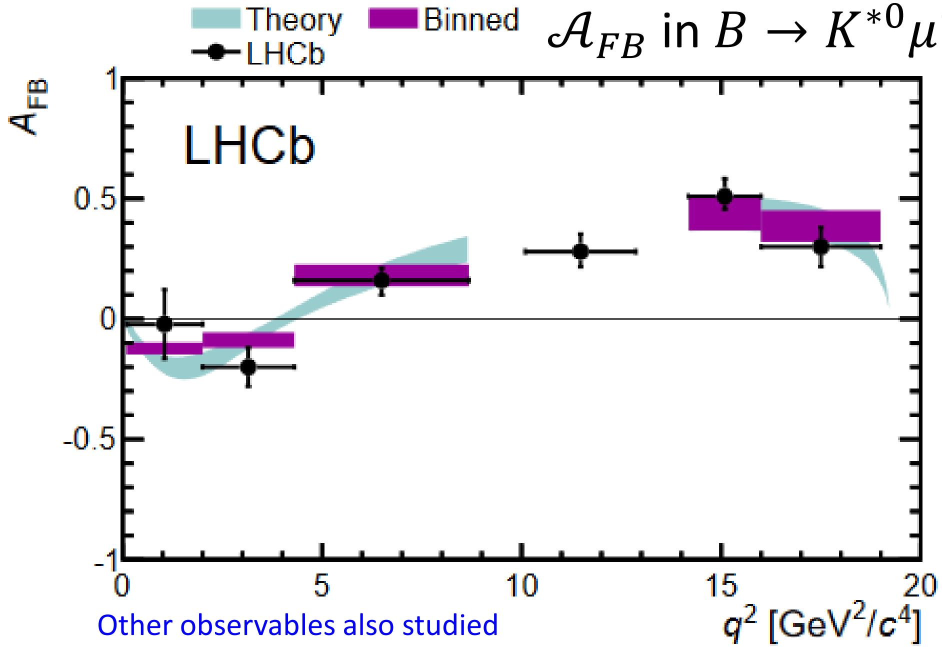


Both e and μ modes are included

$C_7 = -C_7^{SM}$ seems to be favourable. If then data favoured 4th generation case.

Should be visible else where ($\sin 2\phi_{B_s}$ negative)

LHCb, JHEP08, 131 (2013)

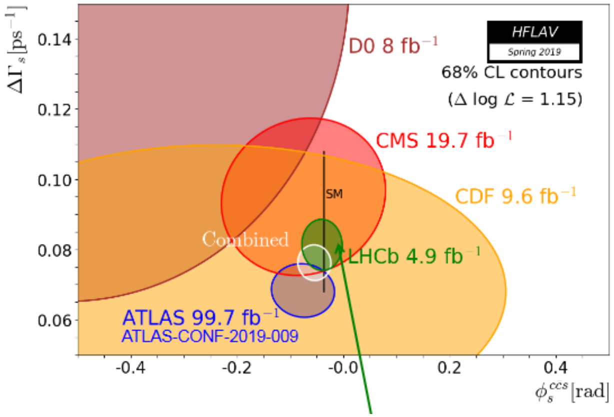


$\mathcal{A}_{FB}$ in $B \to K^{*0}\mu^{+}\mu^{-}$

Other observables also studied

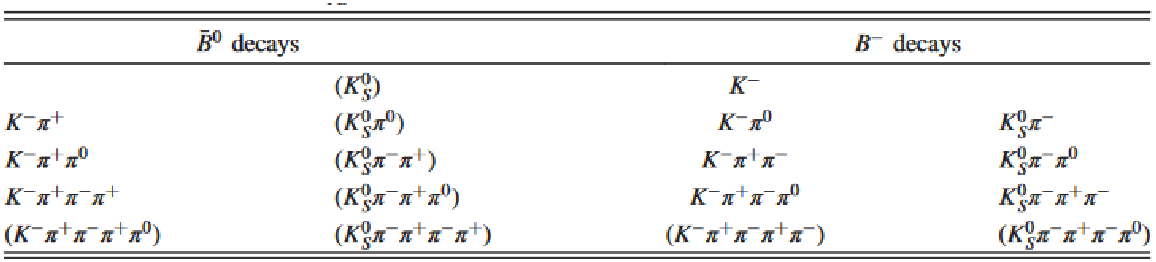
First measurement of zero-crossing point of $\mathcal{A}_{FB}: q_0^2 = 4.9 \pm 0.9 \mathrm{GeV}^2/c^4$

Consistent with SM



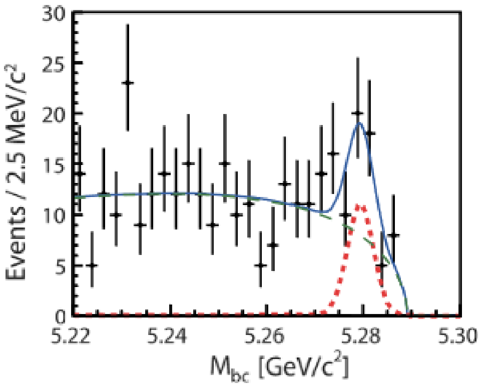
$\mathcal{A}_{FB}$ in Sum of Exclusive

Inclusive measurement is theoretically cleaner than exclusive, but experimentally challenging

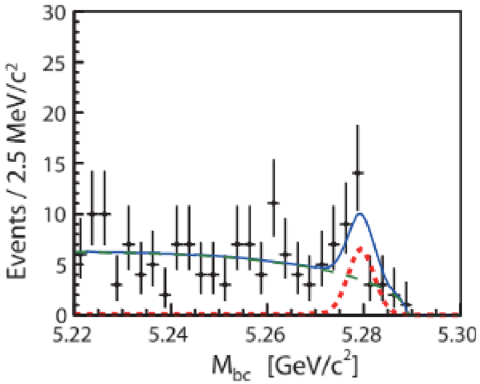


$\bar{B}^0$ decays		B^- decays	
	(K_S^0)	K^-	
$K^-\pi^+$	$(K_S^0\pi^0)$	$K^-\pi^0$	$K_S^0\pi^-$
$K^-\pi^+\pi^0$	$(K_S^0\pi^-\pi^+)$	$K^-\pi^+\pi^-$	$K_S^0\pi^-\pi^0$
$K^-\pi^+\pi^-\pi^+$	$(K_S^0\pi^-\pi^+\pi^0)$	$K^-\pi^+\pi^-\pi^0$	$K_S^0\pi^-\pi^+\pi^-$
$(K^-\pi^+\pi^-\pi^+\pi^0)$	$(K_S^0\pi^-\pi^+\pi^-\pi^+)$	$(K^-\pi^+\pi^-\pi^+\pi^-)$	$(K_S^0\pi^-\pi^+\pi^-\pi^0)$

$M(X_s) < 2.0$ GeV/c^2

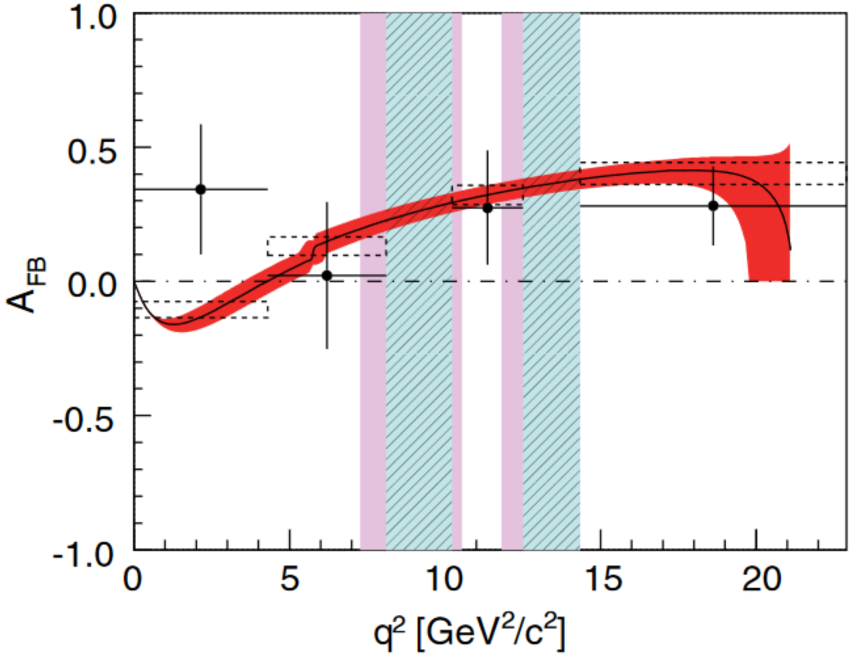


(a)$B \to X_s e^+ e^-$ candidates with $\cos\theta > 0$



(b)$B \to X_s e^+ e^-$ candidates with $\cos\theta < 0$

Belle, PRD 93, 032008 (2016)



Result is consistent with SM prediction within error

1.8σ tension in low q^2

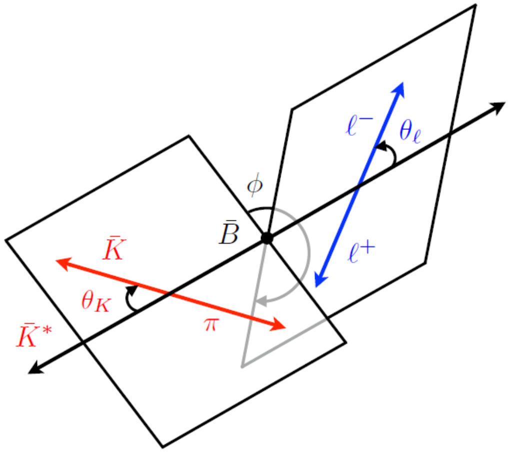
Need more data points for this study

P_5' anomaly Continuing with $B \to K^*\ell^+\ell^-$

Angular analysis of $B \to \ell^+\ell^- K^*(892)(\to K^-\pi^+)$.
One can simply measure the angles between the direction of flight of all the different particles as function of q^2

Differential Angular distribution can be written as

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin2\theta_K\sin2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big],$$



F_L is the longitudinal polarization fraction
One has additional angular observables $S_n (n = 3,4,5,7,8,9)$ from the decay amplitude, which are functions of the Wilson coefficients and form factors
Suggested by Decoste-Genon etal JHEP 2013, 137 (2013)

$$P'_{4,5,6,8} = \frac{S_{4,5,6,8}}{\sqrt{F_L(1-F_L)}}$$

These observables are largely free from form factor uncertainties (especially at low q^2)

Each transformation preserves the first five terms and corresponding S_i term.
Resulting angular distribution depend only on F_L, S_3 *and one of the observables* $S_{4,5,7,8}$

$$P'_4, S_4: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_5, S_5: \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

$$P'_6, S_7: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2, \end{cases}$$

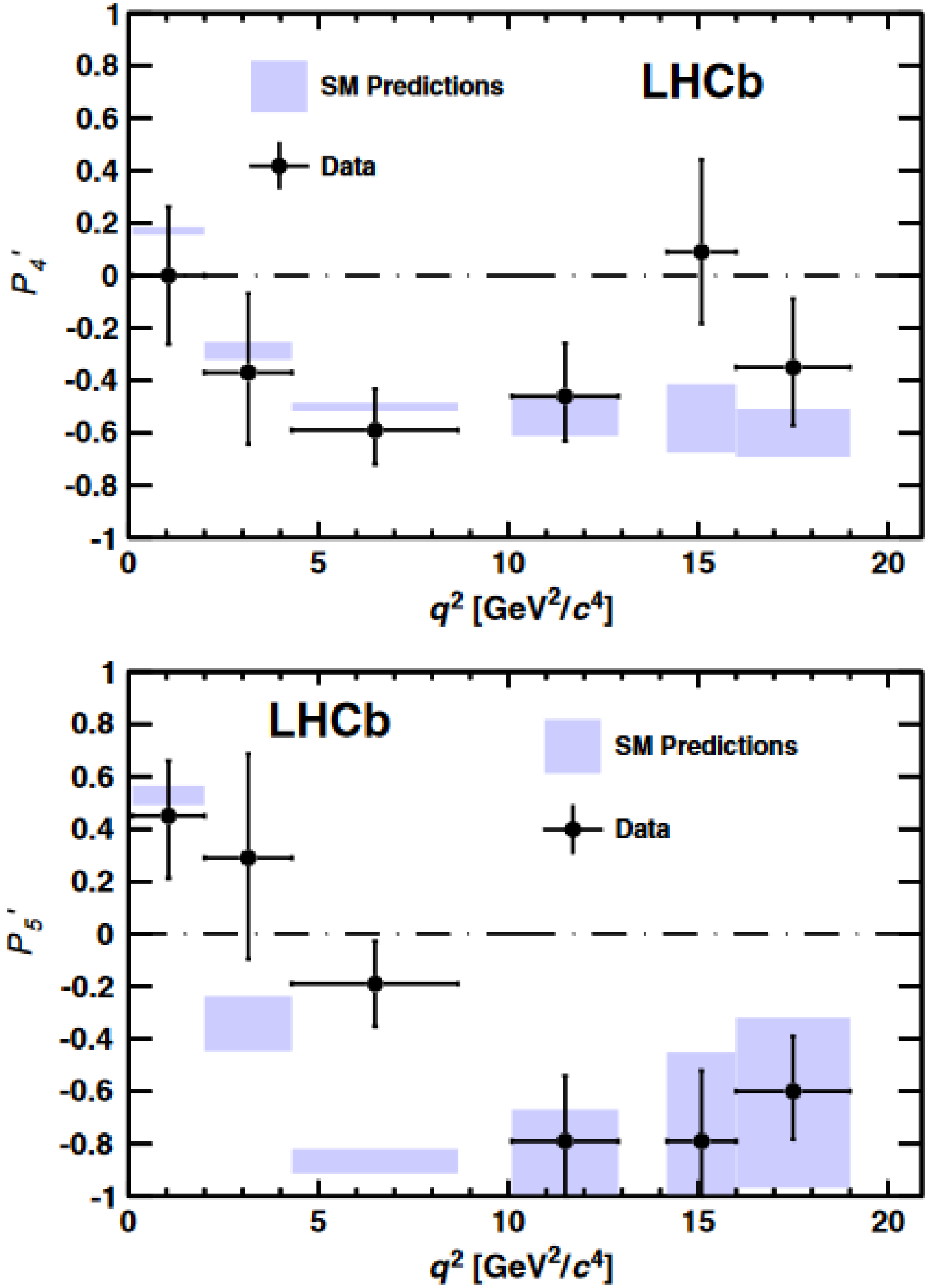
$$P'_8, S_8: \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \to \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2. \end{cases}$$

First anomaly observed in P_5'

LHCb,PRL111, 191801 (2013)

$$B \to K^*(892)\mu^+\mu^-$$

$$K^*(892) \to K^-\pi^+$$



Local discrepancy of 3.7σ is observed in the interval $4.30 < q^2 < 8.68$ GeV^2 for P_5'

Integrating over 1-6 , is 2.5σ

Belle data support similar trend

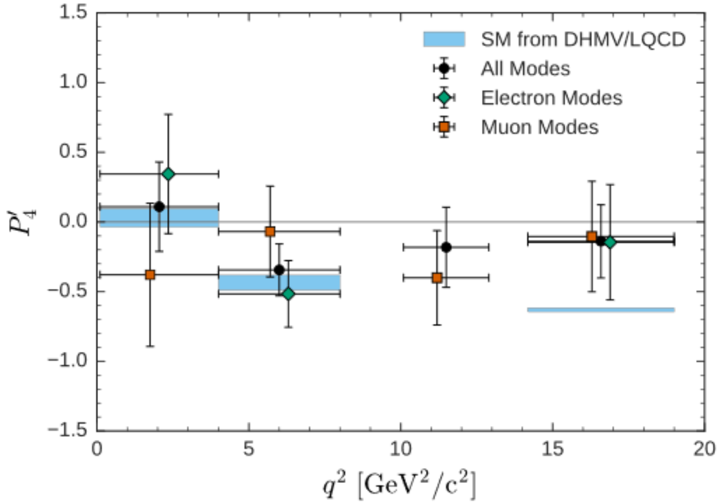
Bernat *et al* JHEP 10,075 (2016)

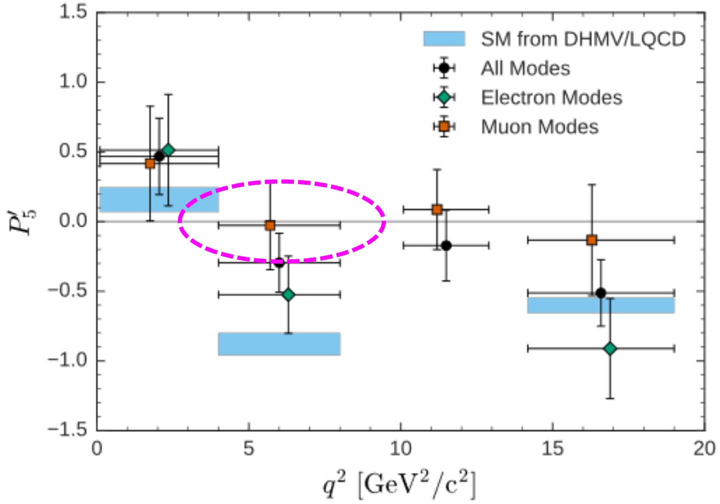
$B \to K^*(892)\ell^+\ell^-$ ℓ for e and μ

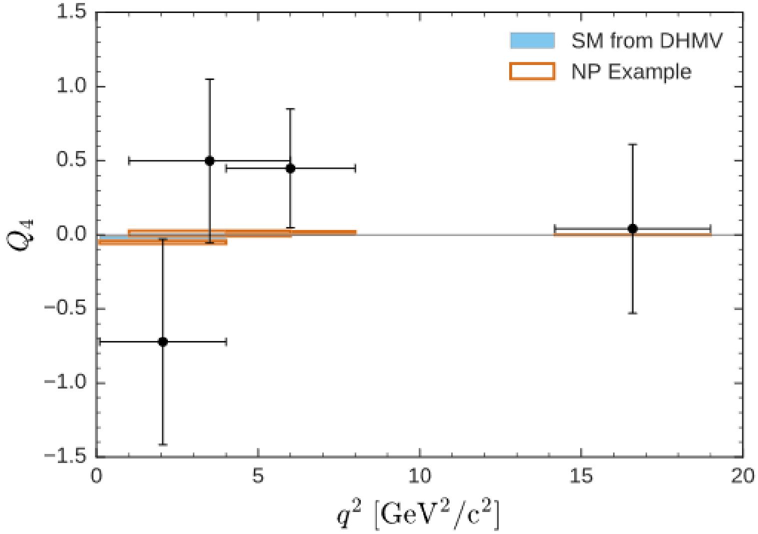
$K^*(892) \to K^-\pi^+, K_s\pi^+, K^+\pi^0$

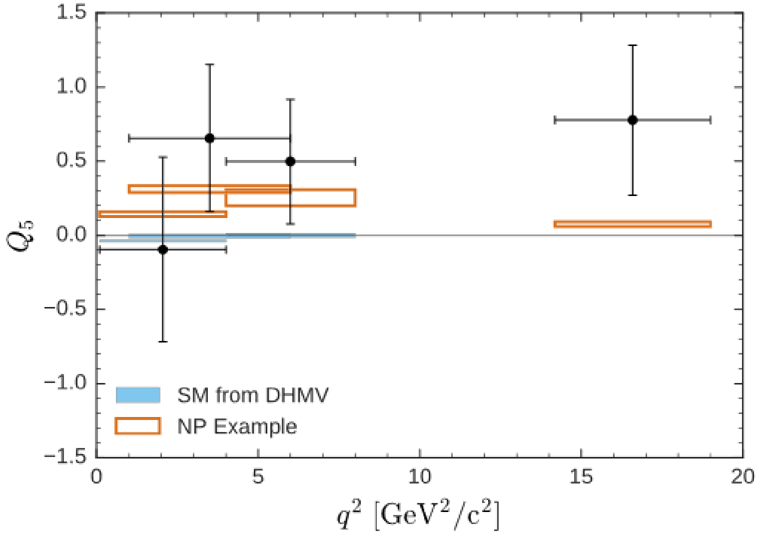
Observable to test LFU, $Q_i = P_i'^{\mu} - P_i'^{e}$

Deviation from zero test of SM.









Q_i provide unambiguous signal of NP, as in P_i hadronic uncertainties were argued.

Belle,PRL 118, 111801 (2017)

First lepton-flavour-dependent measurement for P_5' is reported

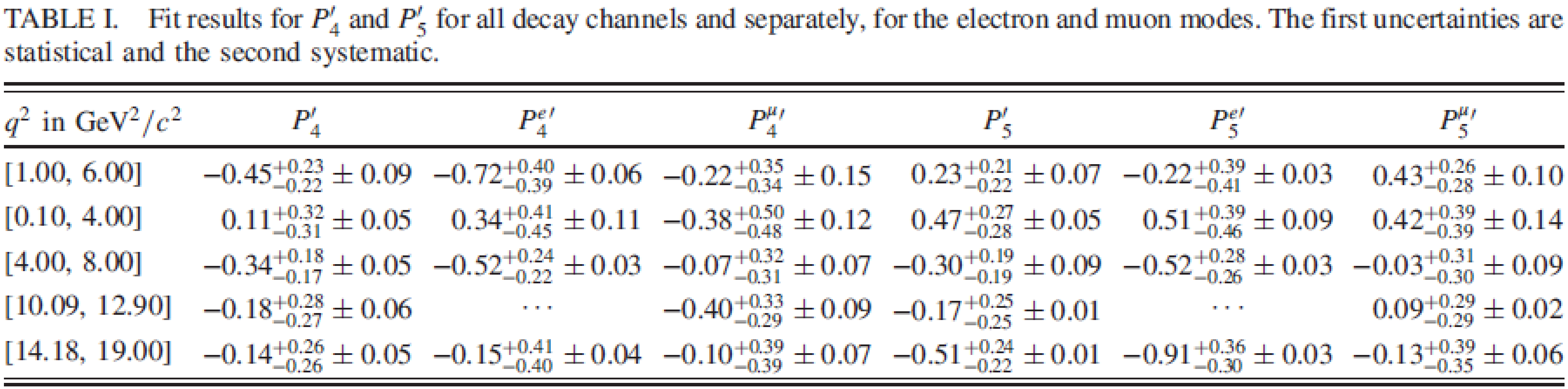


TABLE I. Fit results for P_4' and P_5' for all decay channels and separately, for the electron and muon modes. The first uncertainties are statistical and the second systematic.

q^2 in GeV$^2/c^2$	P_4'	$P_4^{e\prime}$	$P_4^{\mu\prime}$	P_5'	$P_5^{e\prime}$	$P_5^{\mu\prime}$
[1.00, 6.00]	$-0.45^{+0.23}_{-0.22} \pm 0.09$	$-0.72^{+0.40}_{-0.39} \pm 0.06$	$-0.22^{+0.35}_{-0.34} \pm 0.15$	$0.23^{+0.21}_{-0.22} \pm 0.07$	$-0.22^{+0.39}_{-0.41} \pm 0.03$	$0.43^{+0.26}_{-0.28} \pm 0.10$
[0.10, 4.00]	$0.11^{+0.32}_{-0.31} \pm 0.05$	$0.34^{+0.41}_{-0.45} \pm 0.11$	$-0.38^{+0.50}_{-0.48} \pm 0.12$	$0.47^{+0.27}_{-0.28} \pm 0.05$	$0.51^{+0.39}_{-0.46} \pm 0.09$	$0.42^{+0.39}_{-0.39} \pm 0.14$
[4.00, 8.00]	$-0.34^{+0.18}_{-0.17} \pm 0.05$	$-0.52^{+0.24}_{-0.22} \pm 0.03$	$-0.07^{+0.32}_{-0.31} \pm 0.07$	$-0.30^{+0.19}_{-0.19} \pm 0.09$	$-0.52^{+0.28}_{-0.26} \pm 0.03$	$-0.03^{+0.31}_{-0.30} \pm 0.09$
[10.09, 12.90]	$-0.18^{+0.28}_{-0.27} \pm 0.06$	$\cdots$	$-0.40^{+0.33}_{-0.29} \pm 0.09$	$-0.17^{+0.25}_{-0.25} \pm 0.01$	$\cdots$	$0.09^{+0.29}_{-0.29} \pm 0.02$
[14.18, 19.00]	$-0.14^{+0.26}_{-0.26} \pm 0.05$	$-0.15^{+0.41}_{-0.40} \pm 0.04$	$-0.10^{+0.39}_{-0.39} \pm 0.07$	$-0.51^{+0.24}_{-0.22} \pm 0.01$	$-0.91^{+0.36}_{-0.30} \pm 0.03$	$-0.13^{+0.39}_{-0.35} \pm 0.06$

First time

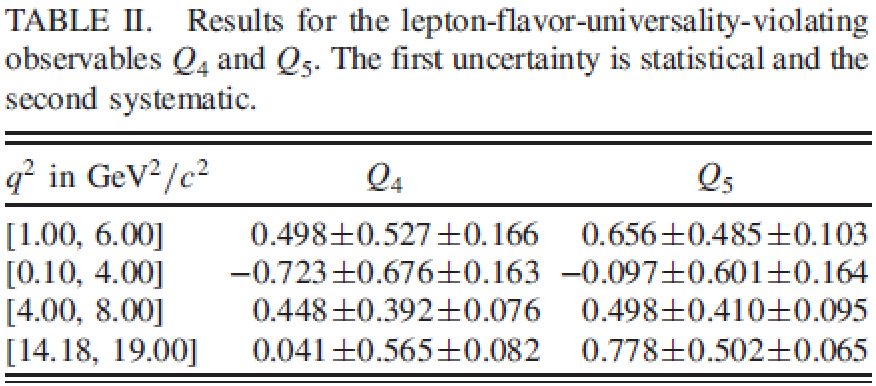


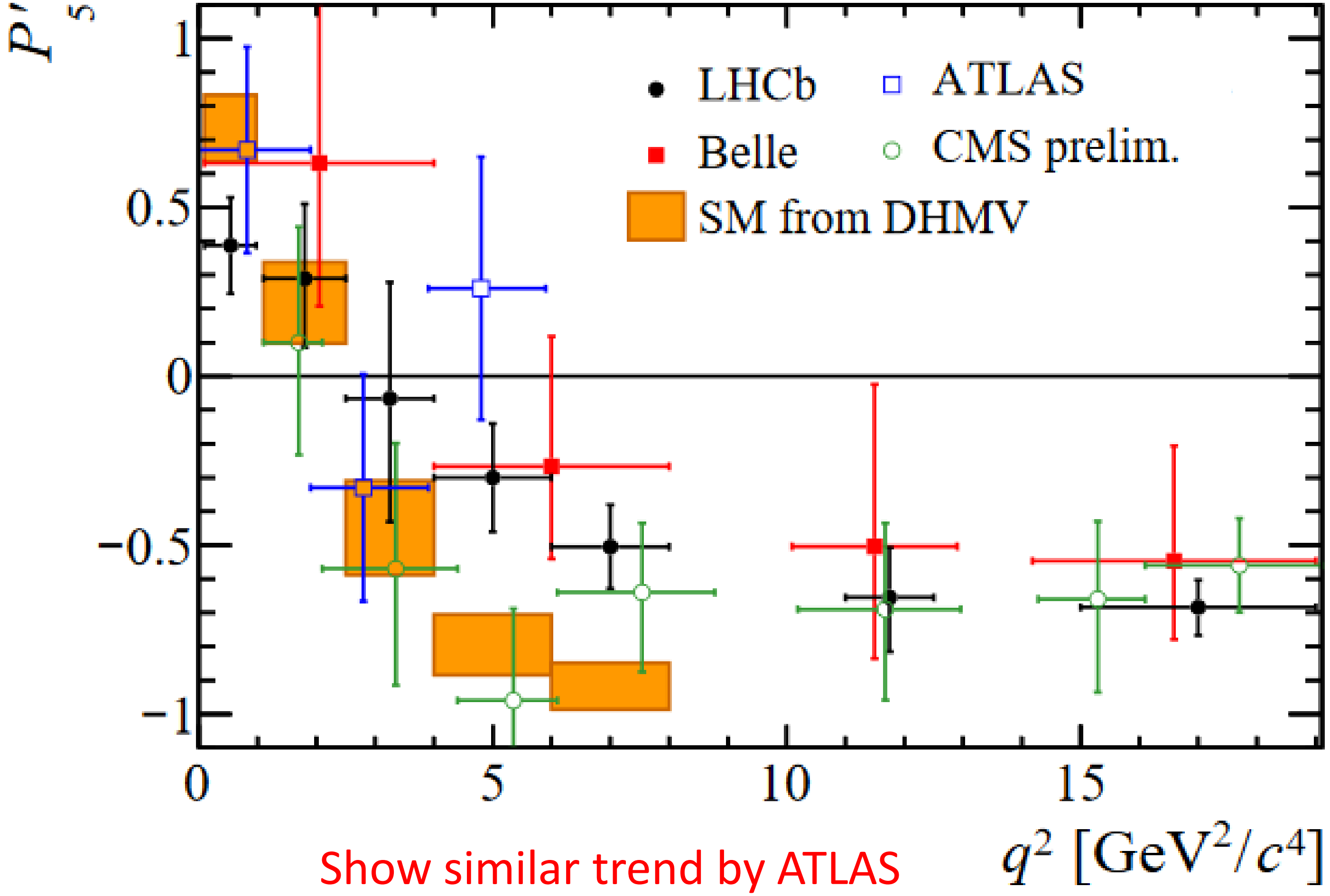
TABLE II. Results for the lepton-flavor-universality-violating observables Q_4 and Q_5. The first uncertainty is statistical and the second systematic.

q^2 in GeV$^2/c^2$	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

Results are compatible with SM within statistical uncertainty.

Largest discrepancy is 2.6σ in P_5' for the muon channel

Results from ATLAS and CMS on P_5'



Show similar trend by ATLAS

Differential branching fraction in $B \rightarrow K\mu\mu, B_s \rightarrow \phi\mu\mu, B \rightarrow K^*\mu\mu\ , \Lambda_b \rightarrow \Lambda\mu\mu$ consistently lower than SM prediction

JHEP06,133(2014), JHEP09,179(2015), JHEP06,115(2015)

$R_{K^*} R_K$ anomaly

Lepton flavour universality (LFU): electroweak couplings treat all flavours of leptons same *(observed difference are due to their mass differences)*

LFU can be tested very precisely

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

In ratio, hadronic uncertainties cancel and SM prediction is near unity.

$$R_K^{SM} = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-4})$$

C. Bobeth et al, JHEP 07, 040 (2004)

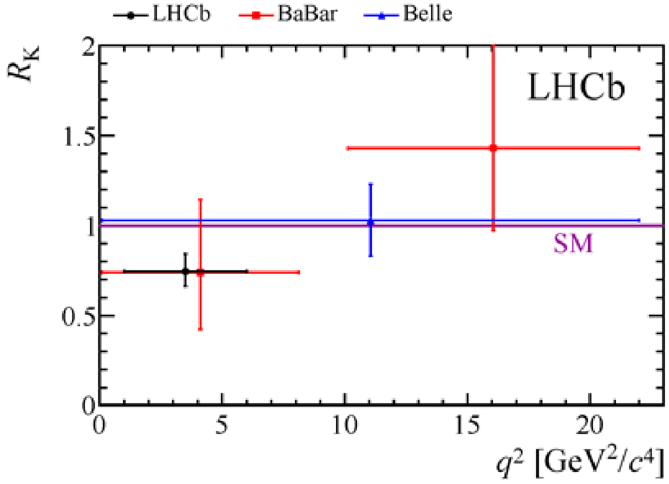
HPQCD, PRL111, 162002 (2013)

$R_H, H = K, K^*, X_s$ provides constraint to the New Physics

G. Hiller, F. Kruger PRD69. 074020 (2004)

0.001 typical error

In 2014, LHCb measured R_K and saw 2.6σ hint of deviation from the SM.

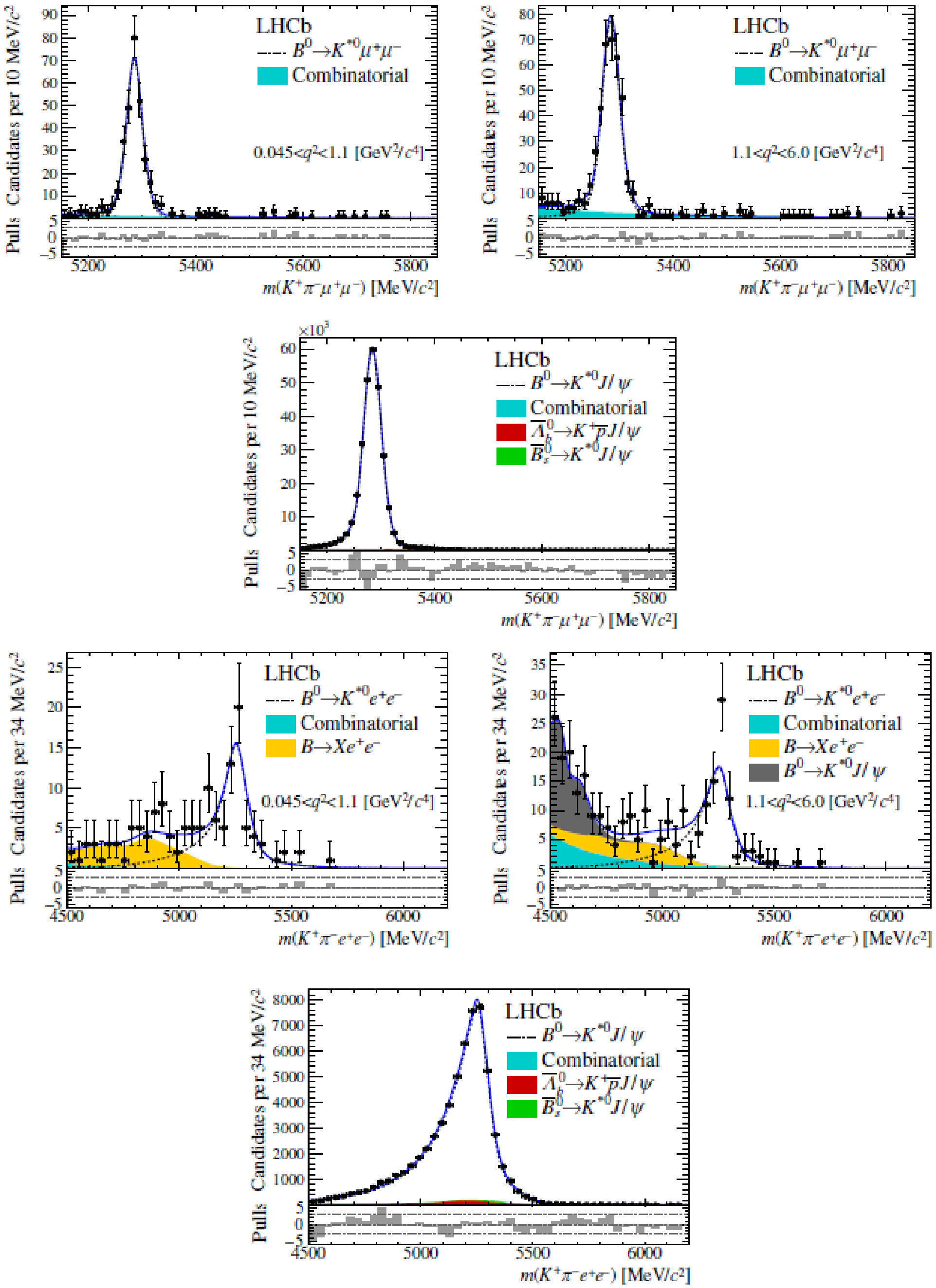


Both BaBar and LHCb seems to favour a value below one.
Belle result didn't contradict q^2 dependent.

$$R_K[1.0 < q^2 < 6.0\ GeV^2] = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb, PRL113, 151601(2014) BaBar, PRD86, 032012(2012) Belle, PRL103, 171801(2009)

$B \to K^{*0}\ell\ell$



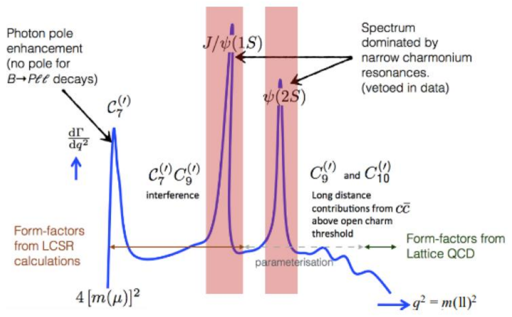
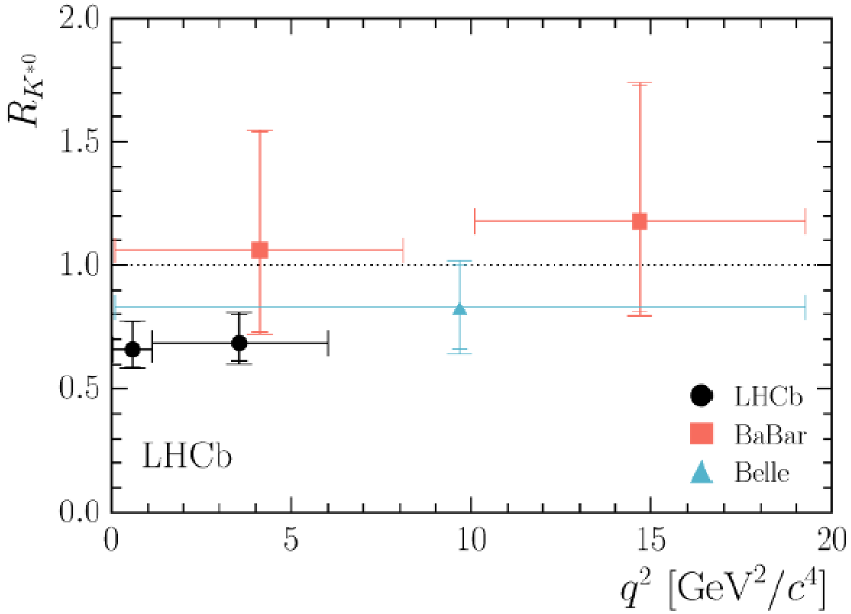
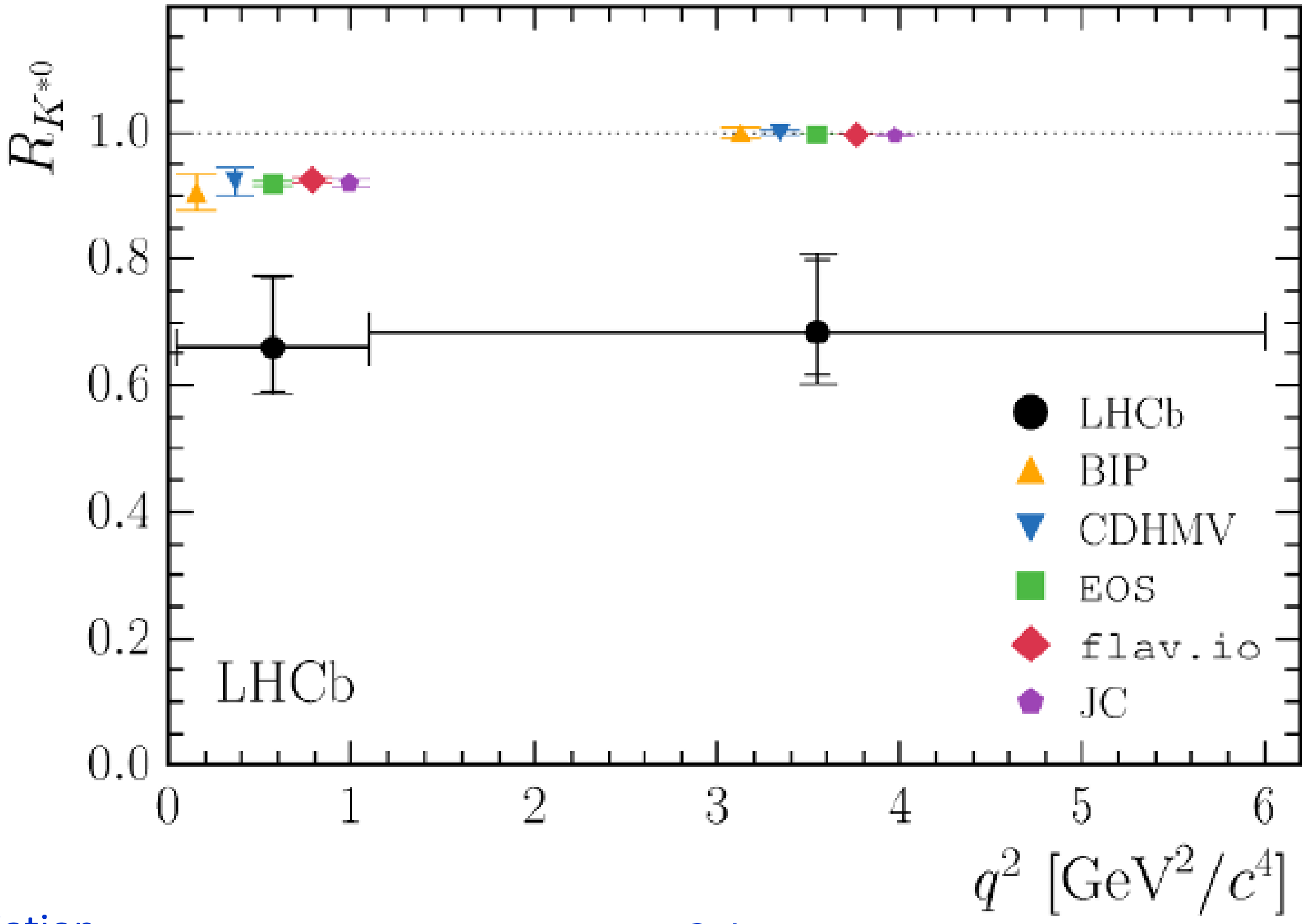


Photo peak, *missing in R_K*, allow for enough statistics in low q^2



R_{K^*} anomaly

LHCb, JHEP08, 055 (2017)



Deviation
From SM

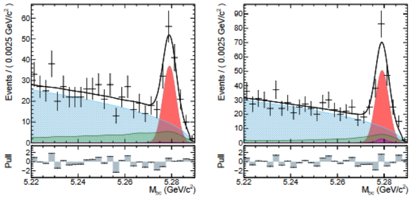
2.1σ

2.4σ

Trend similar to R_K

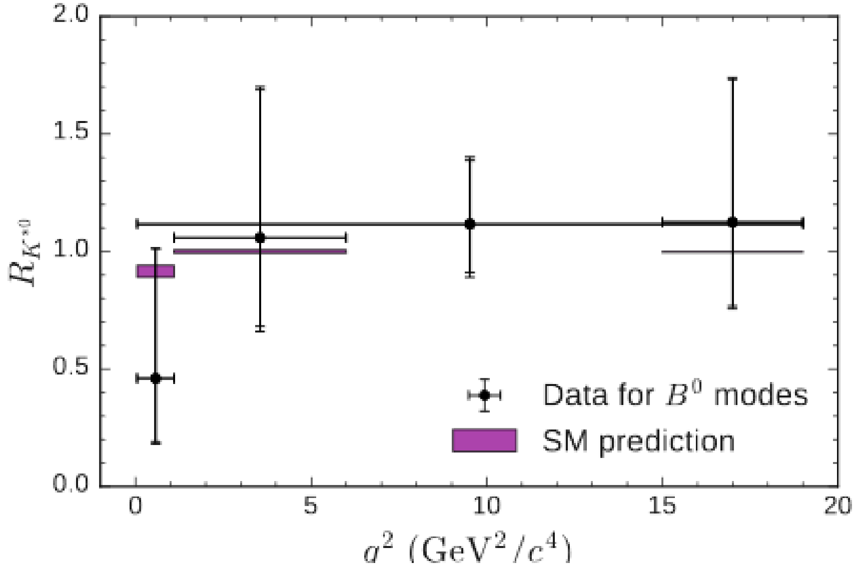
Belle result on R_{K^*}

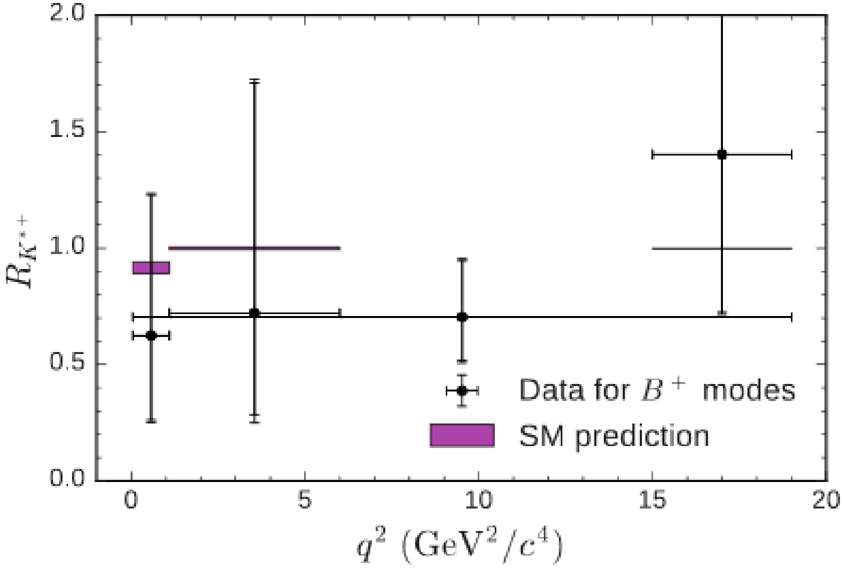
Belle, arXiv1904.02440

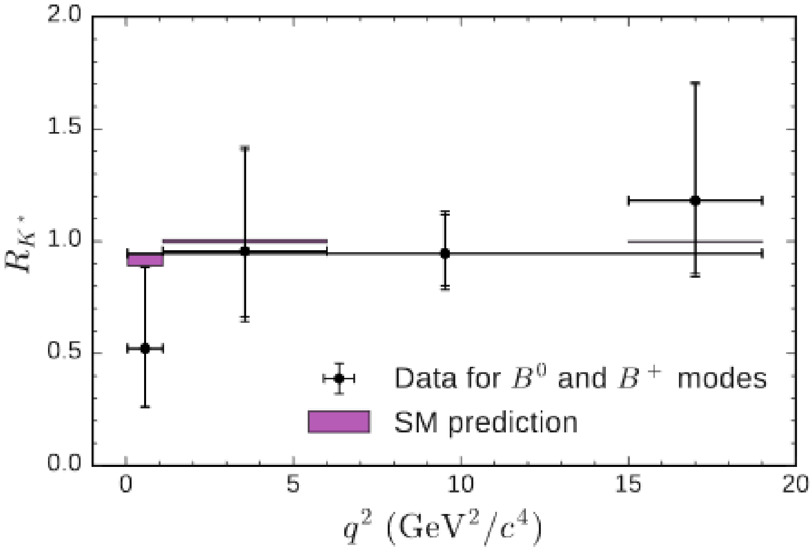


K^* from $K^+\pi^-$, $K^+\pi^0$, and $K_S^0\pi^+$

$B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$ and $B^+ \to K^{*+}e^+e^-$







First measurement of $R_{K^{*+}}$

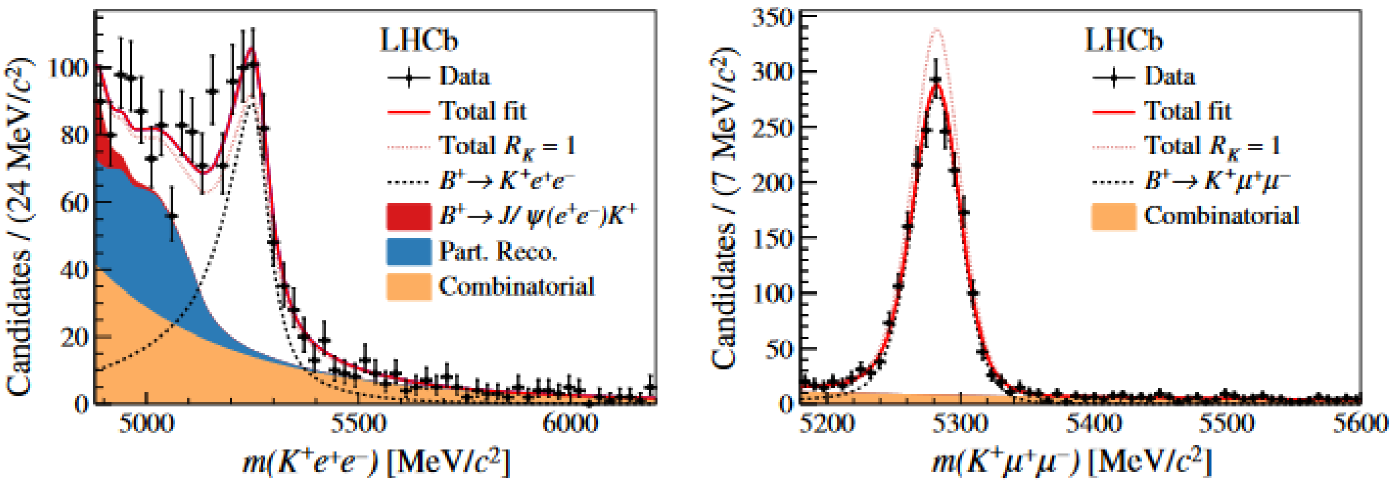
Consistent with SM, large uncertainty.
Need more statistics !

Trend similar to LHCb

$B \to K^+ \ell\ell$

2019 LHCb R_K update

LHCb, PRL122, 191801 (2019)



$$R_{K,\mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083}_{-0.071}\,(\mathrm{stat})^{+0.017}_{-0.016}\,(\mathrm{syst})\,,$$
$$R_{K,\mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}\,(\mathrm{stat}) \pm^{+0.020}_{-0.017}\,(\mathrm{syst})\,.$$

$$R_K[1.1 < q^2 < 6.0\ \mathrm{GeV}^2] = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

Most precise measurement to data
Consistent with SM at the level of 2.5 σ deviation

$$R_K[1.0 < q^2 < 6.0\ GeV^2] = 0.745^{+0.090}_{-0.074} \pm 0.036$$ LHCb, PRL113, 151601(2014)

$B \to K\ell\ell$

R_K result from Belle

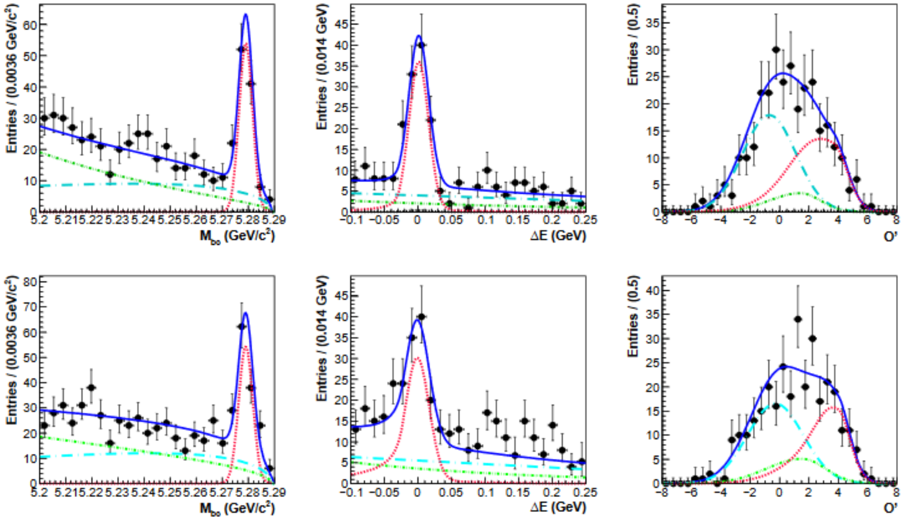
Belle, arXiv:190801848

Here K can be K^+ and K_S^0

Background and signal strength similar.

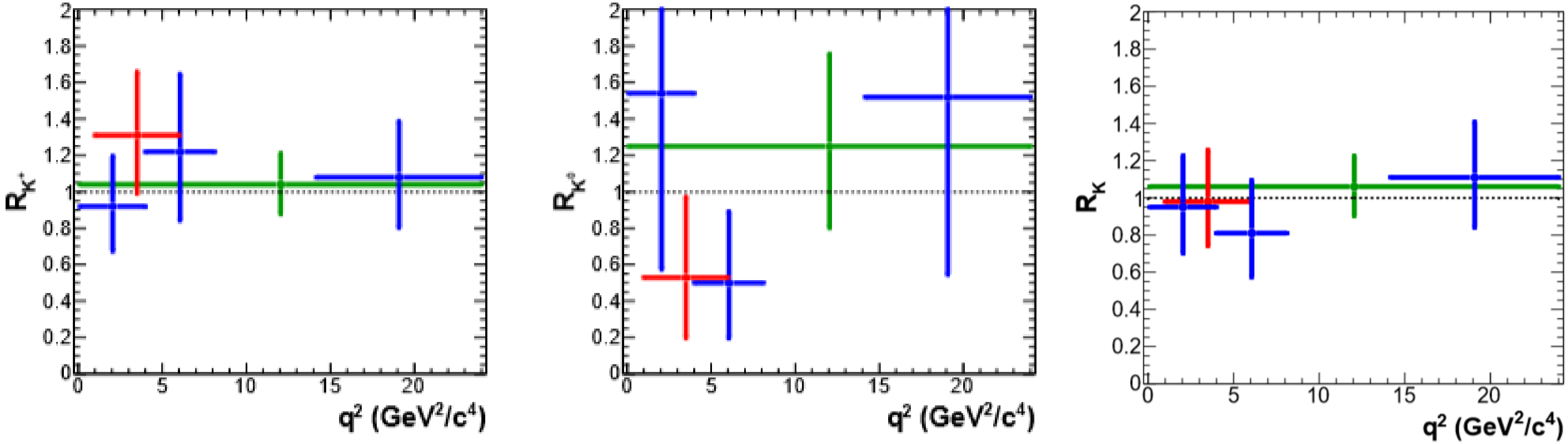
$B \to K^+\mu^+\mu^-$

$B \to K^+e^+e^-$



$1 < q^2 < 6 \text{ GeV}^2/c^4$

$0.1 < q^2 < 4 \text{ GeV}^2/c^4$



Result is consistent with LHCb as well as SM

More precision at Belle II

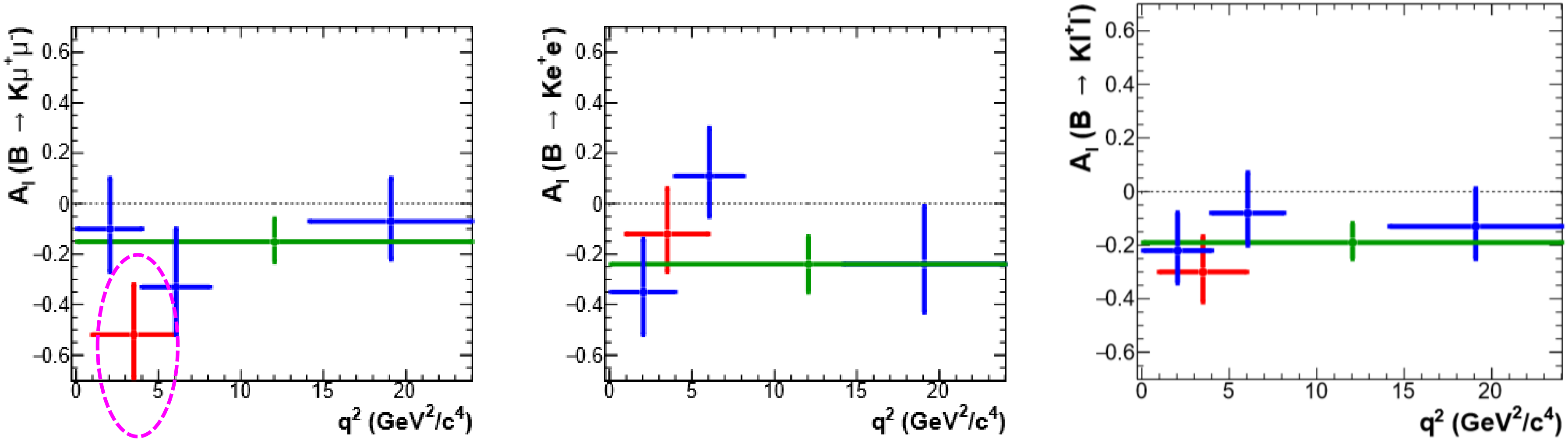
Belle, arXiv:190801848

R_K result from Belle

Lifetime ratio of B^+ to B^0

Isospin asymmetry

$$A_I = \frac{\boxed{(\tau_{B^+}/\tau_{B^0})}\mathcal{B}(B^0 \to K^0\ell^+\ell^-) - \mathcal{B}(B^+ \to K^+\ell^+\ell^-)}{(\tau_{B^+}/\tau_{B^0})\mathcal{B}(B^0 \to K^0\ell^+\ell^-) + \mathcal{B}(B^+ \to K^+\ell^+\ell^-)}$$



$0.1 < q^2 < 4\ \mathrm{GeV}^2/c^4$

$1 < q^2 < 6\ \mathrm{GeV}^2/c^4$

A_I for all bins have negative asymmetry.

For bin $1 < q^2 < 6\ \mathrm{GeV}^2/c^4$ deviates from zero by 2.7σ for muon final state.

First time provided by Belle

Anomalies leading SM

https://www.inc.com/peter-economy/10-powerful-habits-of-highly-effective-leaders.html

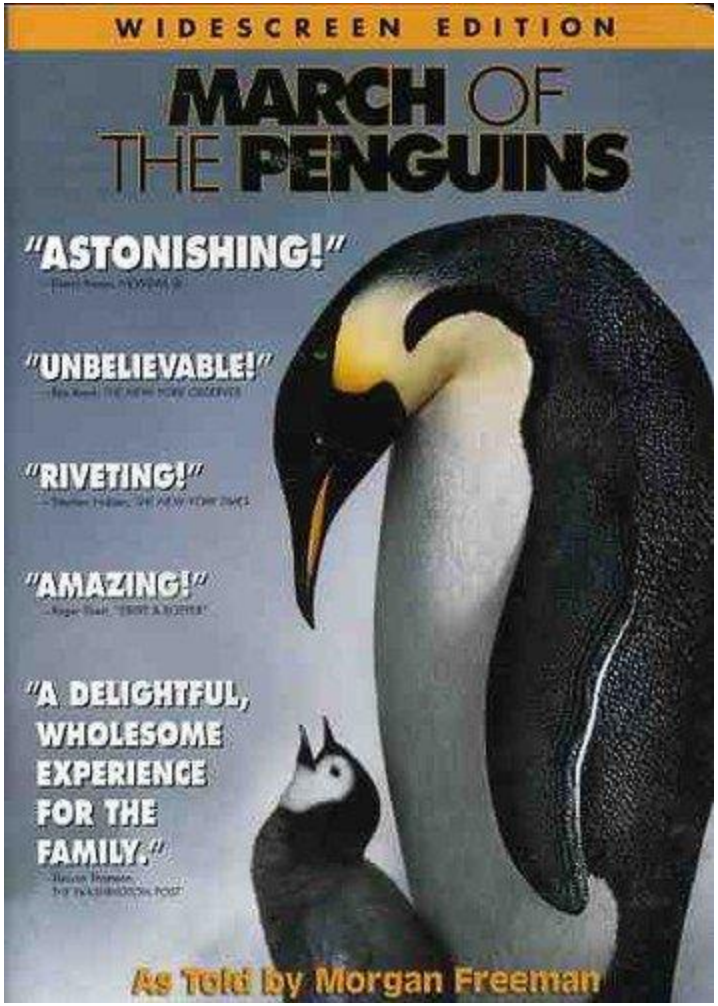
or

https://www.mycustomer.com/experience/engagement/how-can-leaders-create-conditions-for-all-employees-to-deliver-outstanding-cx

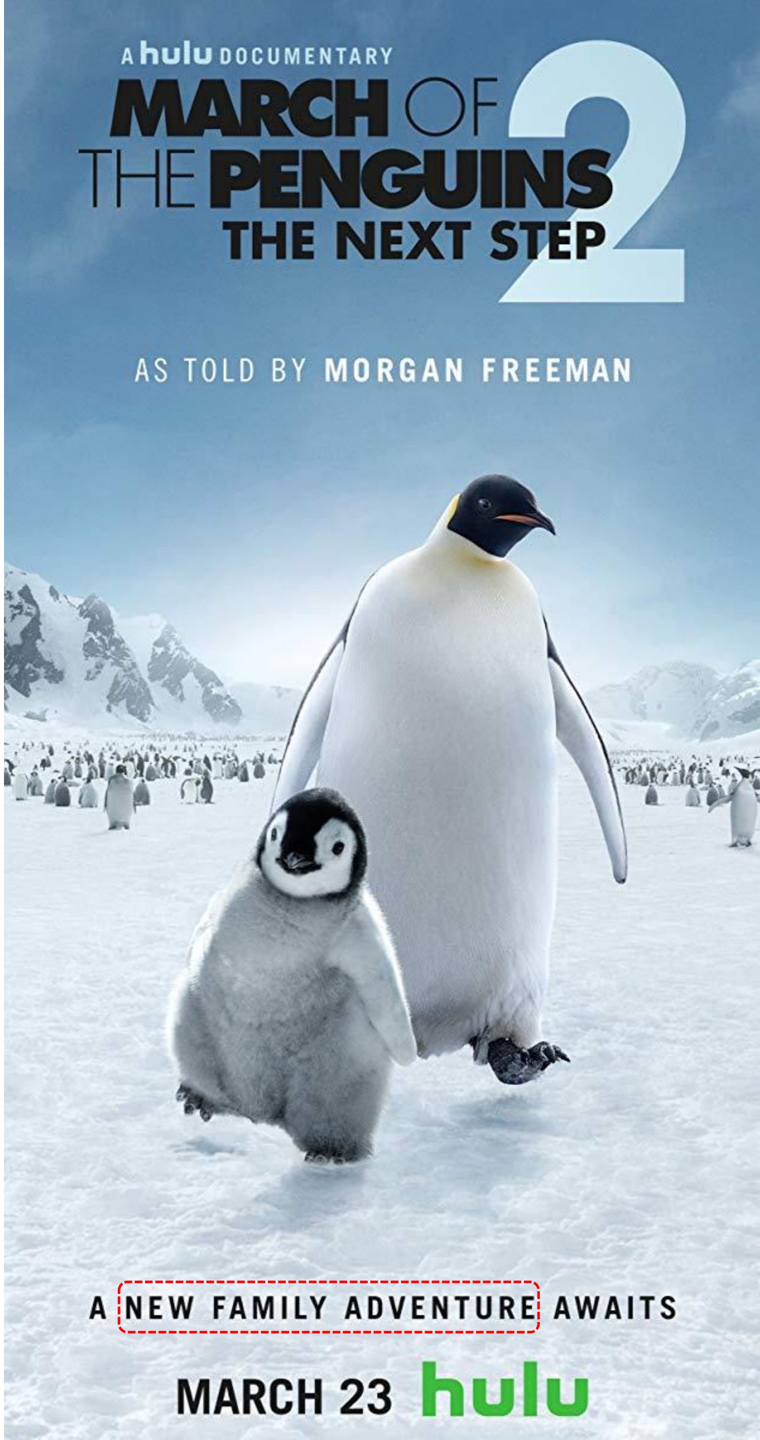
SM leading anomalies

SM itself an anomaly (?)

ttps://www.mckinsey.com/featured-insights/leadership/lead-at-your-best

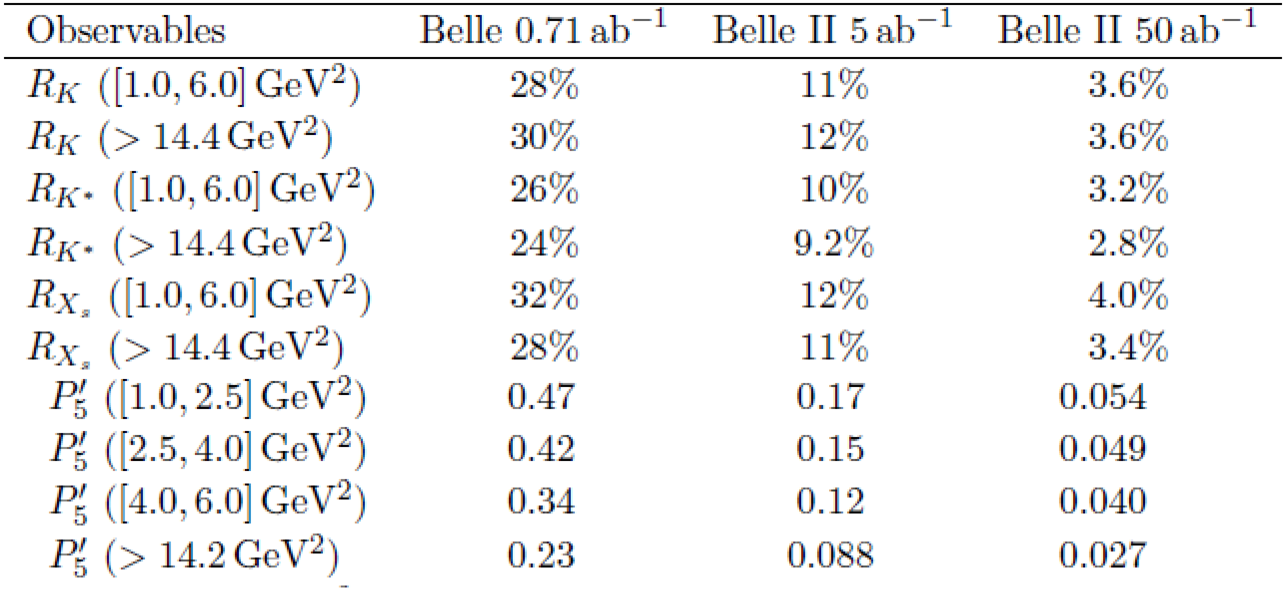


https://images-na.ssl-images-amazon.com/images/I/51fvLhfOxVL.jpg

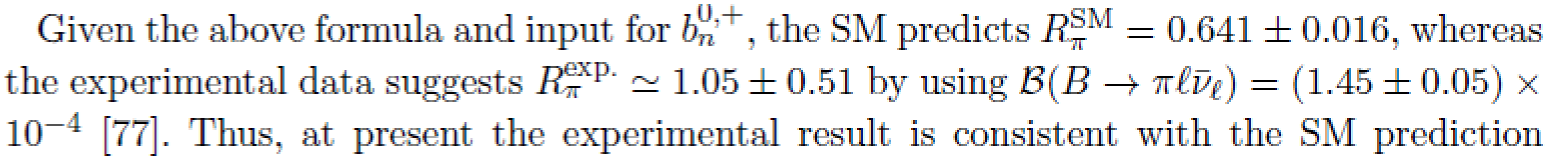


Thank you

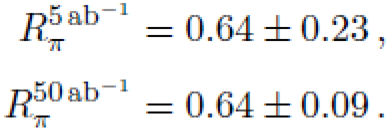
B2TiP report
arXiv:1808.10567



Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
R_K ($[1.0, 6.0]\,\mathrm{GeV}^2$)	28%	11%	3.6%
R_K ($> 14.4\,\mathrm{GeV}^2$)	30%	12%	3.6%
R_{K^*} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	26%	10%	3.2%
R_{K^*} ($> 14.4\,\mathrm{GeV}^2$)	24%	9.2%	2.8%
R_{X_s} ($[1.0, 6.0]\,\mathrm{GeV}^2$)	32%	12%	4.0%
R_{X_s} ($> 14.4\,\mathrm{GeV}^2$)	28%	11%	3.4%
P_5' ($[1.0, 2.5]\,\mathrm{GeV}^2$)	0.47	0.17	0.054
P_5' ($[2.5, 4.0]\,\mathrm{GeV}^2$)	0.42	0.15	0.049
P_5' ($[4.0, 6.0]\,\mathrm{GeV}^2$)	0.34	0.12	0.040
P_5' ($> 14.2\,\mathrm{GeV}^2$)	0.23	0.088	0.027

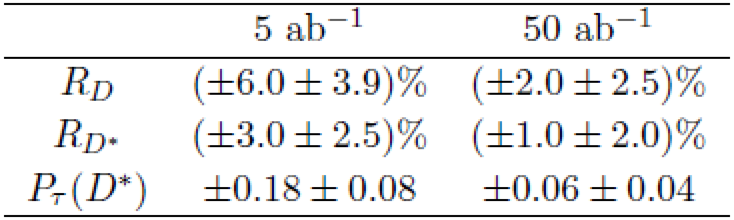


Given the above formula and input for $b_\pi^{0,+}$, the SM predicts $R_\pi^{\mathrm{SM}} = 0.641 \pm 0.016$, whereas the experimental data suggests $R_\pi^{\mathrm{exp.}} \simeq 1.05 \pm 0.51$ by using $\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell) = (1.45 \pm 0.05) \times 10^{-4}$ [77]. Thus, at present the experimental result is consistent with the SM prediction

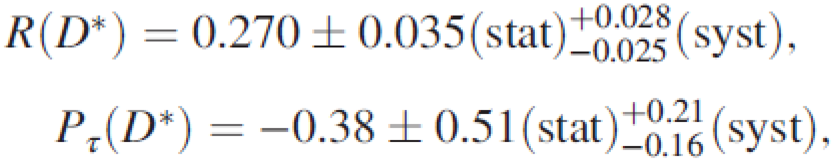


$$R_\pi^{5\,\mathrm{ab}^{-1}} = 0.64 \pm 0.23\,,$$

$$R_\pi^{50\,\mathrm{ab}^{-1}} = 0.64 \pm 0.09\,.$$



	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$P_\tau(D^*)$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

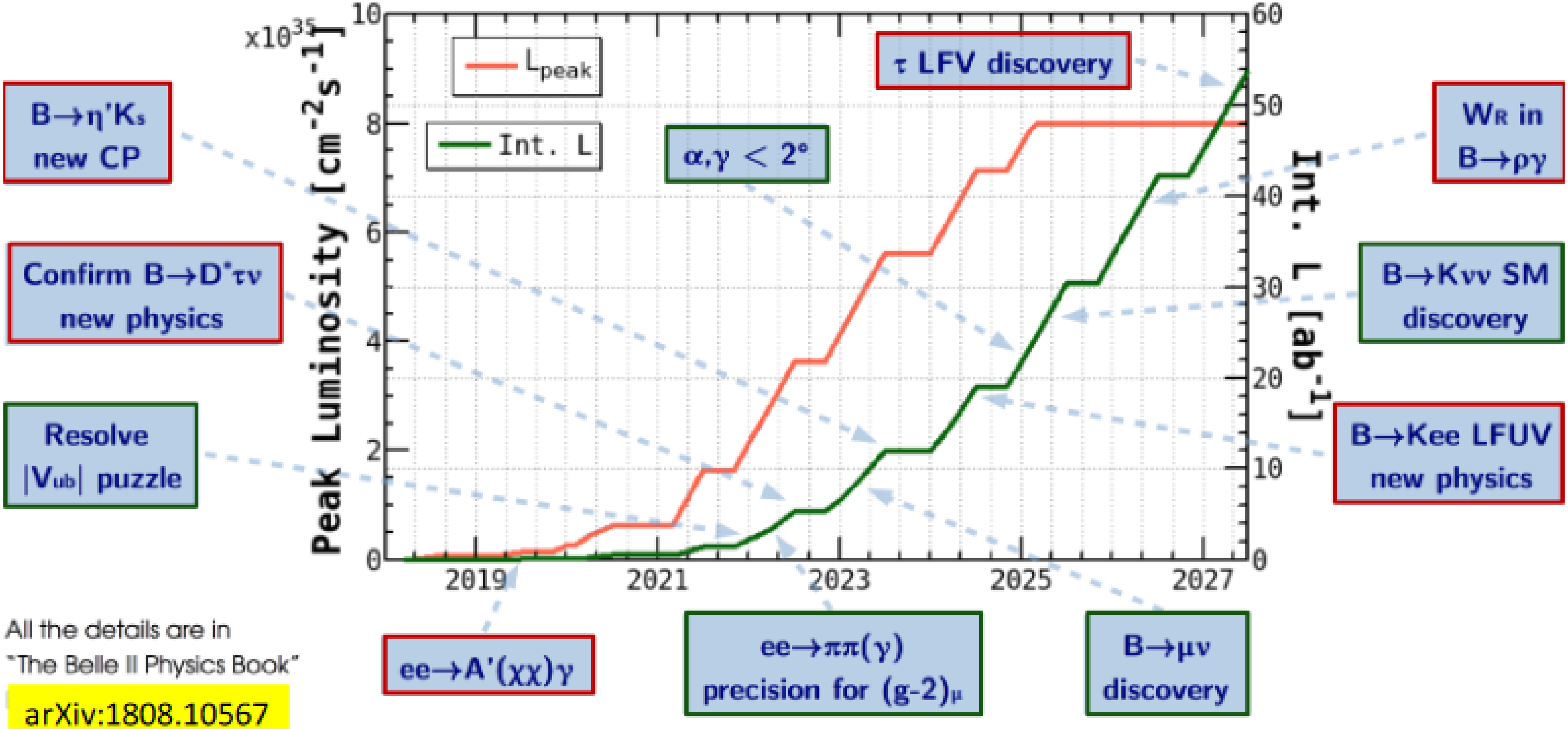


$$R(D^*) = 0.270 \pm 0.035(\mathrm{stat})^{+0.028}_{-0.025}(\mathrm{syst}),$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{syst}),$$

Slide taken from G. Mohanty

Prospects for data & physics harvesting



$B\to\eta' K_s$ new CP

Confirm $B\to D^*\tau\nu$ new physics

Resolve $|V_{ub}|$ puzzle

$ee\to A'(\chi\chi)\gamma$

$ee\to\pi\pi(\gamma)$ precision for $(g\text{-}2)_\mu$

$B\to\mu\nu$ discovery

τ LFV discovery

$\alpha,\gamma < 2°$

W_R in $B\to\rho\gamma$

$B\to K\nu\nu$ SM discovery

$B\to Kee$ LFUV new physics

All the details are in "The Belle II Physics Book"

arXiv:1808.10567

- 1 ab^{-1} (= Belle) in 2021
- 5 ab^{-1} in 2022
- 10 ab^{-1} by mid 2023

🟩 Sure shot

🟥 Wish list

Courtesy: Giacomo De Pietro

LHCb Upgrade II Physics Case

Taken from Eugeni Graugés

Summary of Results:

[LHCB-PUB-2018-009] arXiV:1808.08865

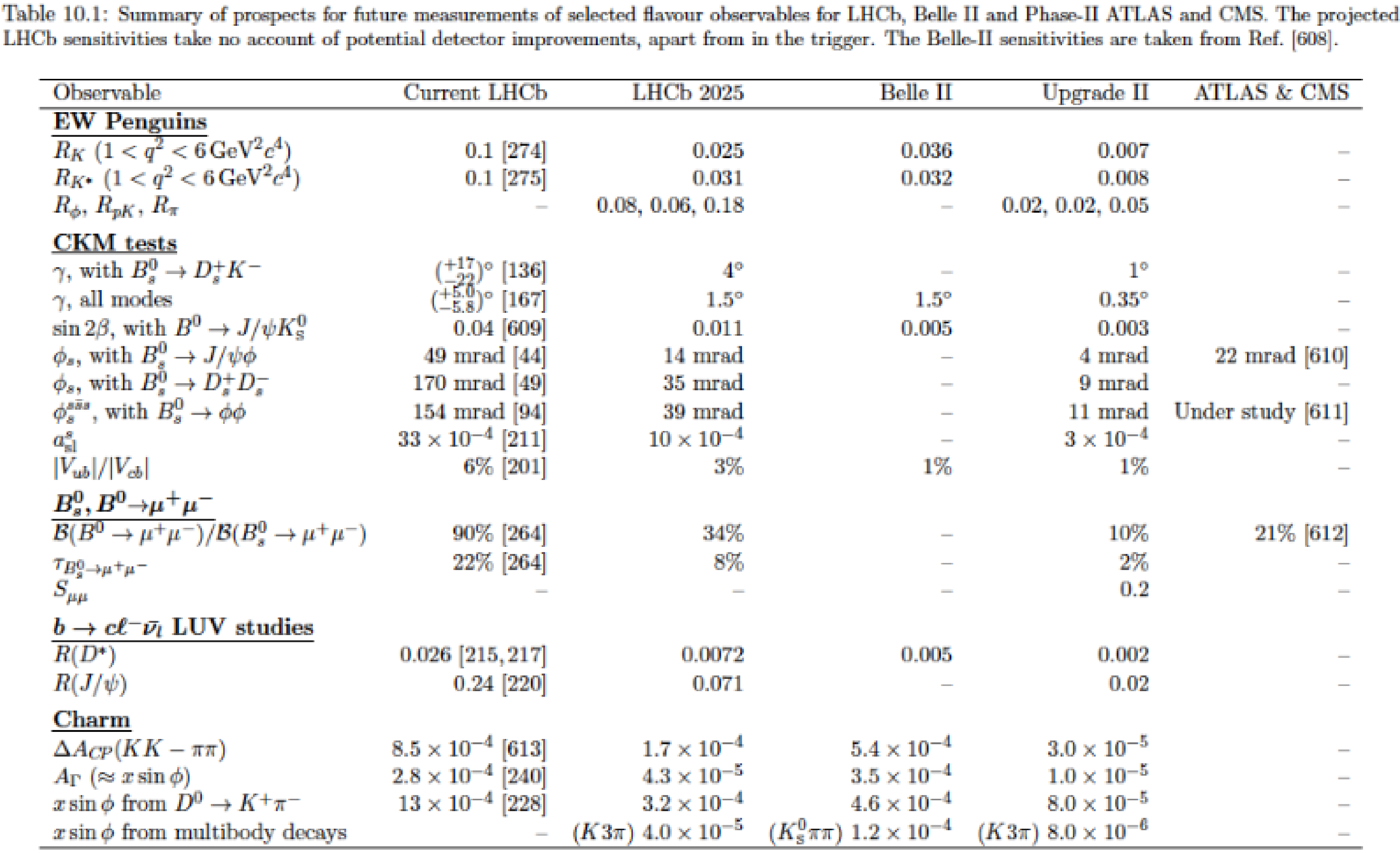
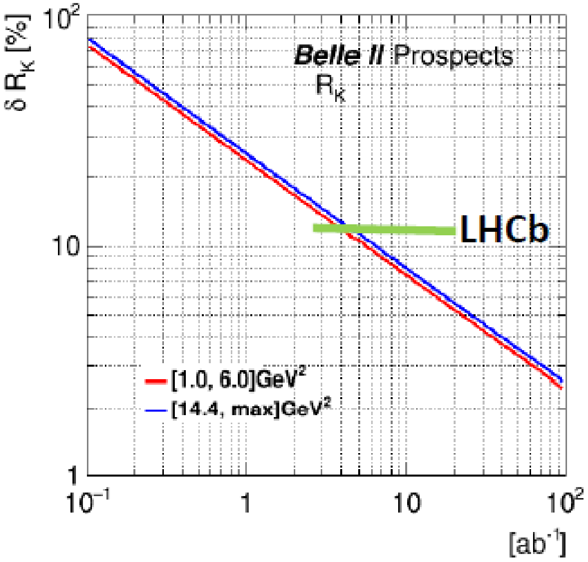


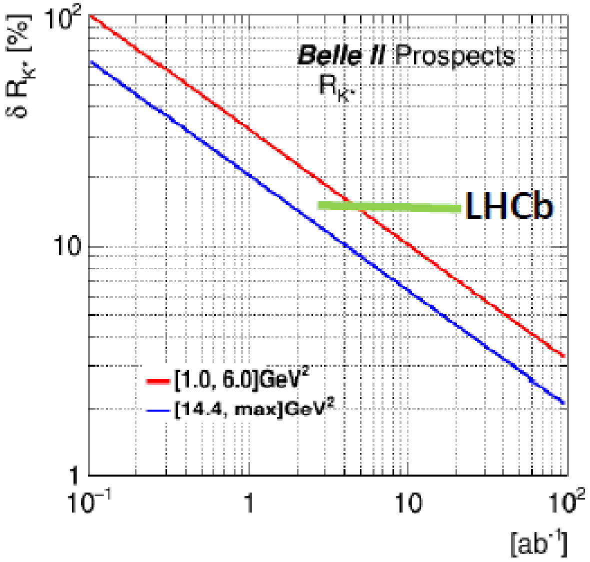
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

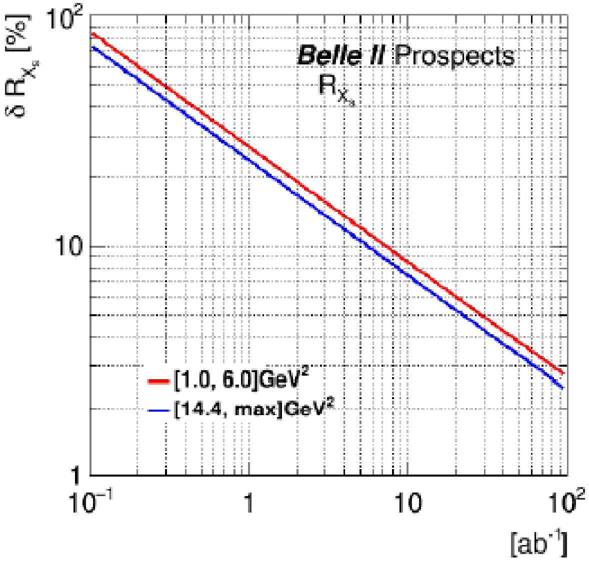
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

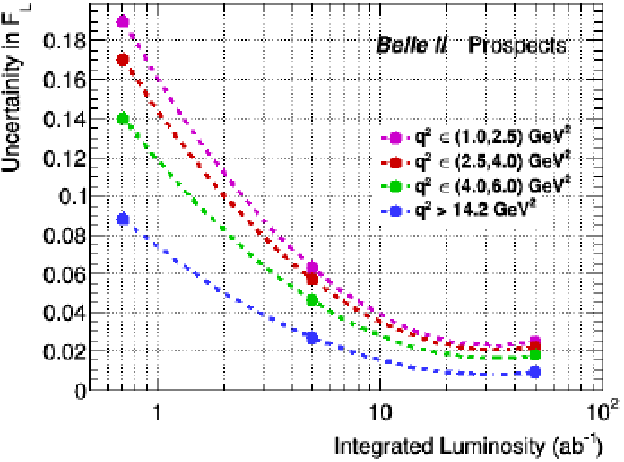
Integrated Lumi	9/fb	23/fb		300/fb

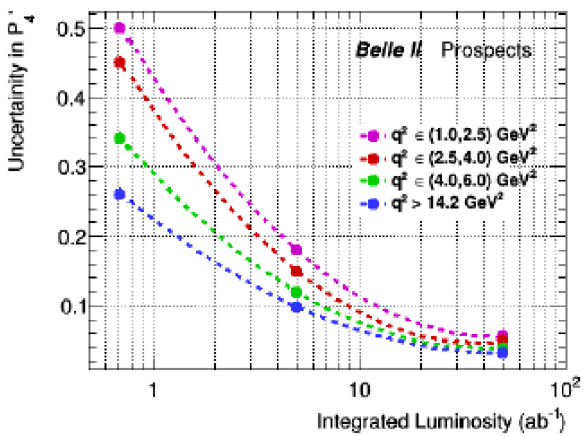
B2TIP report | arXiv:1808.10567

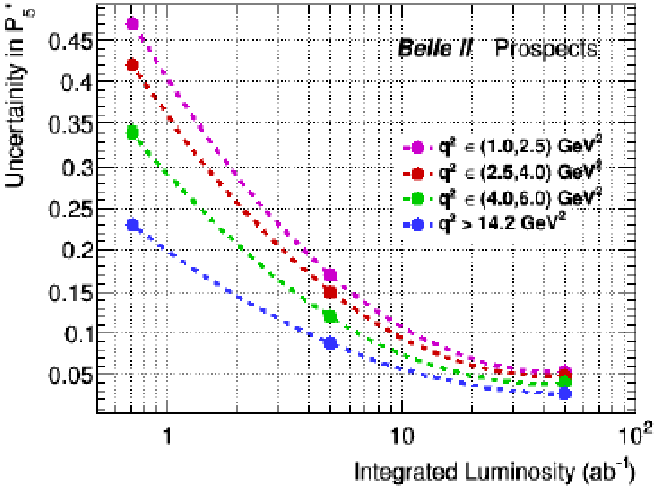












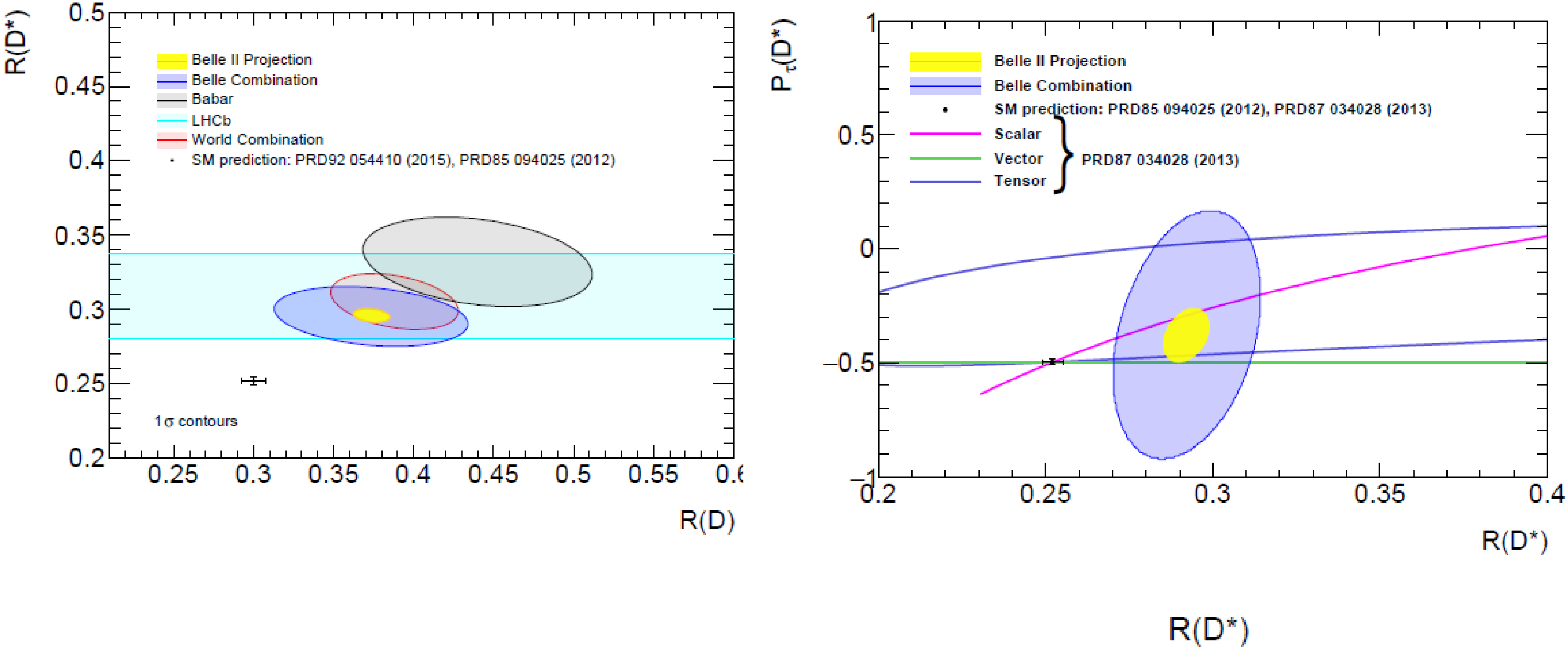


Fig. 72: Expected Belle II constraints on the R_D vs R_{D^*} plane (left) and the R_{D^*} vs $P_\tau(D^*)$ plane (right) compared to existing experimental constraints from Belle. The SM predictions are indicated by the black points with theoretical error bars. In the right panel, the NP scenarios "Scalar", "Vector" and "Tensor" assume contributions from the operators $\mathcal{O}_{S_1}$, $\mathcal{O}_{V_1}$ and O_T, respectively.

Observables	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.3.1)	compositeness (§17.7)	dark sector (§16.1)
$B \to D^{(*)}\tau\bar{\nu}$:											
Branching ratio	⋆⋆	⋆⋆	×	×	×	×	×	⋆	⋆⋆⋆	⋆	⋆
q^2	⋆⋆	⋆⋆⋆	×	×	×	×	×	⋆⋆	⋆⋆⋆	⋆	⋆
τ properties	⋆⋆⋆	⋆⋆⋆	×	×	×	×	×	⋆⋆	⋆⋆⋆	⋆	⋆
$B \to \pi\tau\bar{\nu}$:											
Branching ratio	⋆⋆	⋆⋆	×	×	×	×	×	⋆	⋆⋆⋆	□	⋆
q^2	⋆⋆	⋆⋆⋆	×	×	×	×	×	⋆⋆	⋆⋆⋆	□	⋆
τ properties	⋆⋆⋆	⋆⋆⋆	×	×	×	×	×	⋆⋆	⋆⋆⋆	□	⋆
Leptonic B Decays:											
$\mathcal{B}(B^+ \to \tau^+\nu)$	⋆⋆⋆	⋆⋆⋆	×	⋆	×	×	×	⋆	⋆⋆	□	⋆⋆
$\mathcal{B}(B^+ \to \mu^+\nu)$	⋆⋆⋆	⋆⋆	×	⋆	×	×	×	⋆	⋆⋆⋆	×	⋆⋆⋆
$\mathcal{B}(B^0_{d,s} \to \tau\tau)$	⋆⋆⋆	⋆⋆	⋆⋆	⋆	⋆	×	⋆	×	⋆⋆⋆	□	×
$\mathcal{B}(B^0_{d,s} \to \tau^\pm\ell^\mp)$	□	⋆	⋆	×	⋆	×	⋆	×	⋆⋆⋆	□	×

Observables	Experimental Sensitivity	Multi-Higgs Models (§17.2)	generic SUSY	MFV (§17.3)	Z' models (§17.6.1)	gauged flavour (§17.6.2)	3-3-1 (§17.6.3)	left-right (§17.6.4)	leptoquarks (§18.3.1)	compositeness (§17.7)	dark sector (§16.1)
Semileptonic $b \to s$ Penguin Decays:											
$B \to K^{(*)}\ell\ell$ angular	★★	×	×	★★	★★	×	★★	×	★★★	★★	×
$R(K^*)$, $R(K)$	★★	×	×	×	★★	×	★★	×	★★★	★★	×
$\mathcal{B}(B \to X_s\ell\ell)$	★★★	×	×	★★★	★★	×	★★	×	★★★	★★	×
$R(X_s)$	★★★	×	×	×	★★	×	★★	×	★★★	★★	×
$\mathcal{B}(B \to K^{(*)}\tau\tau)$	★★★	★★★	×	★	★	×	★	×	★★★	★	×
$\mathcal{B}(B \to X_s\tau\tau)$	☐	★★★	×	★	★	×	★	×	★★★	★	×
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	★★★	×	×	★	★	×	★	×	★★★	★	×
$\mathcal{B}(B \to X_s\nu\nu)$	☐	×	×	★	★	×	★	×	★★★	★	×
Semileptonic $b \to d$ Penguin Decays:											
$B \to \pi\ell\ell$ angular	★★	×	×	★★	★★	×	★★	×	★★★	★	×
$R(\rho)$, $R(\pi)$	★★	×	×	×	★★	×	★★	×	★★★	★	×
$\mathcal{B}(B \to X_d\ell\ell)$	★★★	×	×	★★★	★★	×	★★	×	★★★	★	×
$R(X_d)$	★★★	×	×	×	★★	×	★★	×	★★★	★	×
$\mathcal{B}(B \to \pi\tau\tau)$	☐	★★★	×	★	★	×	★	★	★★★	★	×
$\mathcal{B}(B \to \pi\nu\nu)$	★★★	×	×	★	★	×	★	×	★★★	★	×

TABLE II. The systematic uncertainties in $R(D^*)$ and $P_\tau(D^*)$, where the values for $R(D^*)$ are relative errors. The group "common sources" identifies the common systematic uncertainty sources in the signal and the normalization modes, which cancel to a good extent in the ratio of these samples. The reason for the incomplete cancellation is described in the text.

Source	$R(D^*)$	$P_\tau(D^*)$
Hadronic B composition	$^{+7.7\%}_{-6.9\%}$	$^{+0.134}_{-0.103}$
MC statistics for PDF shape	$^{+4.0\%}_{-2.8\%}$	$^{+0.146}_{-0.108}$
Fake D^*	3.4%	0.018
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.4%	0.048
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.001
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$	2.3%	0.007
τ daughter and ℓ^- efficiency	1.9%	0.019
MC statistics for efficiency estimation	1.0%	0.019
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau)$	0.3%	0.002
$P_\tau(D^*)$ correction function	0.0%	0.010
Common sources		
Tagging efficiency correction	1.6%	0.018
D^* reconstruction	1.4%	0.006
Branching fractions of the D meson	0.8%	0.007
Number of $B\bar{B}$ and $\mathcal{B}(\Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0)$	0.5%	0.006
Total systematic uncertainty	$^{+10.4\%}_{-9.4\%}$	$^{+0.21}_{-0.16}$

R(D)* systematics

LHCb one prong 2015

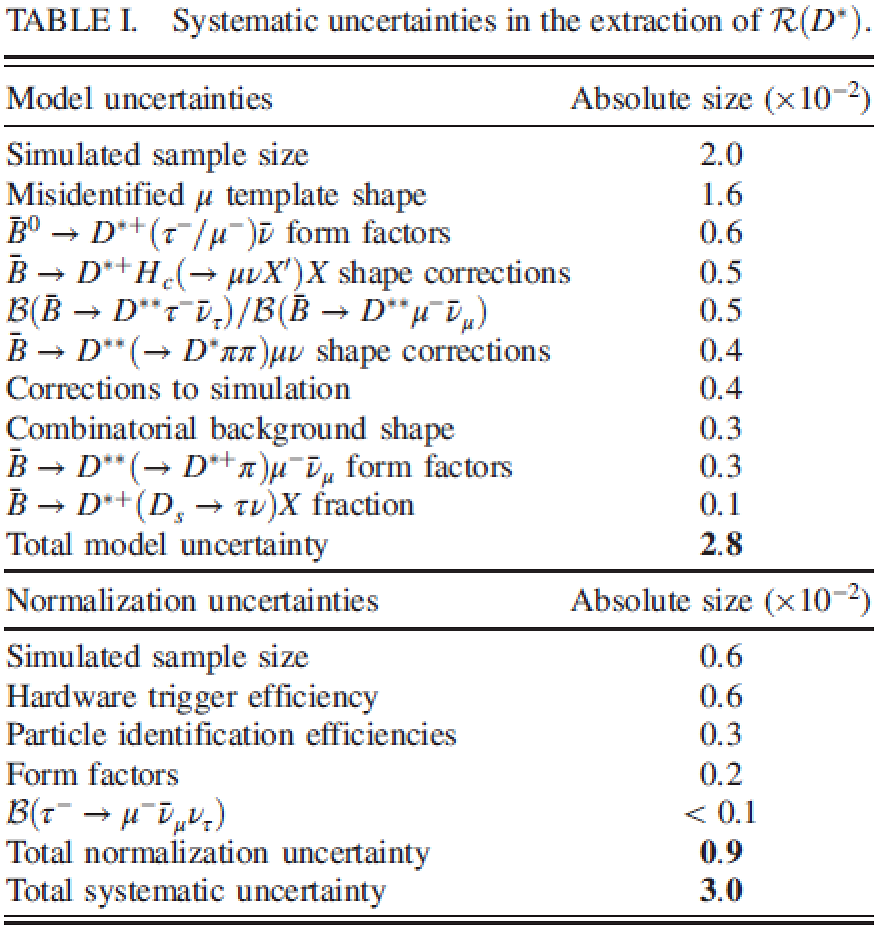


TABLE I. Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

LHCb three prong 2017

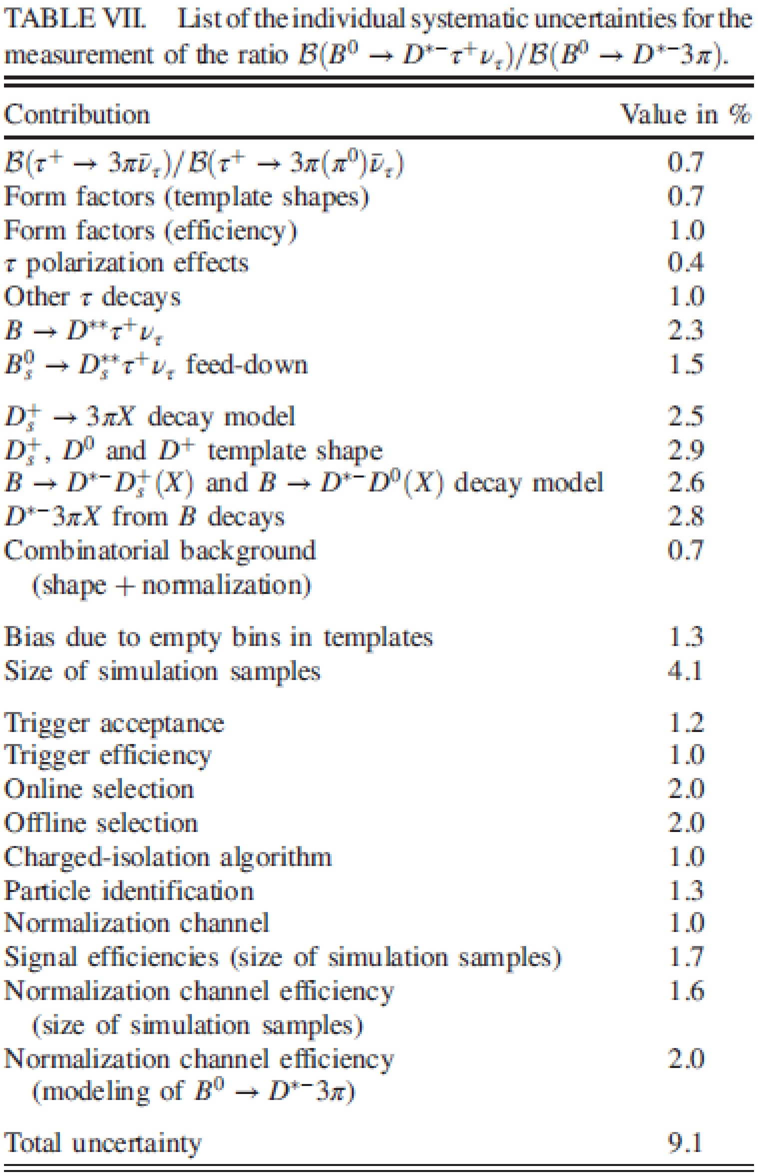


TABLE VII. List of the individual systematic uncertainties for the measurement of the ratio $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}3\pi)$.

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Particle identification	1.3
Normalization channel	1.0
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

Belle 2019 semileptonic

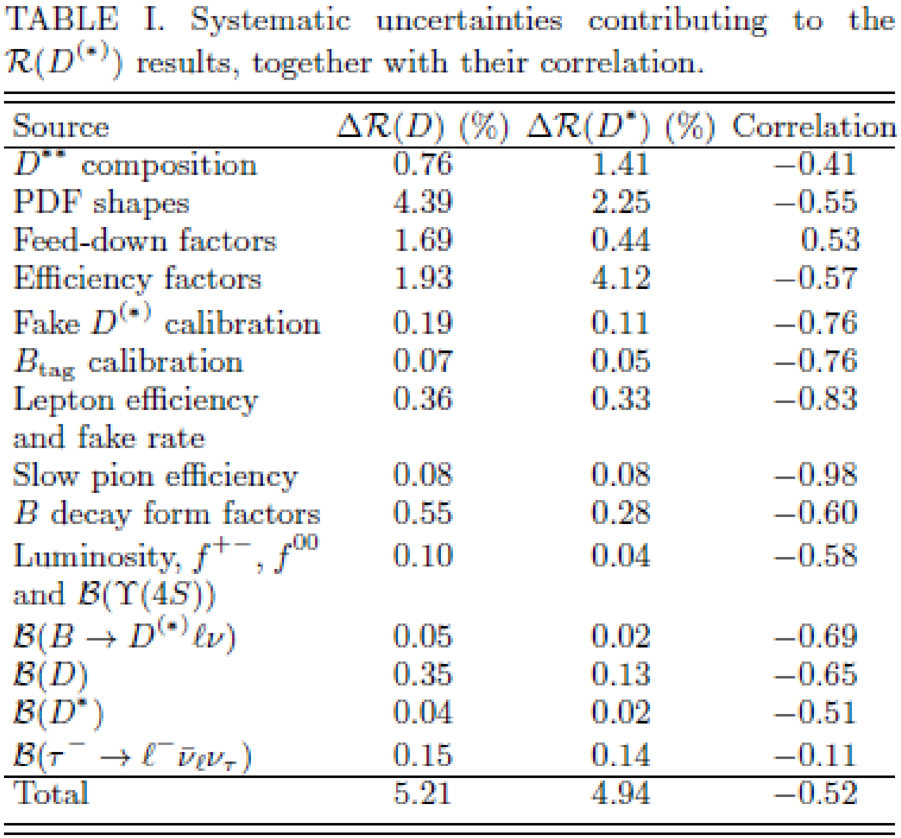


TABLE I. Systematic uncertainties contributing to the $\mathcal{R}(D^{(*)})$ results, together with their correlation.

Source	$\Delta\mathcal{R}(D)$ (%)	$\Delta\mathcal{R}(D^*)$ (%)	Correlation
D^{**} composition	0.76	1.41	−0.41
PDF shapes	4.39	2.25	−0.55
Feed-down factors	1.69	0.44	0.53
Efficiency factors	1.93	4.12	−0.57
Fake $D^{(*)}$ calibration	0.19	0.11	−0.76
B_{tag} calibration	0.07	0.05	−0.76
Lepton efficiency and fake rate	0.36	0.33	−0.83
Slow pion efficiency	0.08	0.08	−0.98
B decay form factors	0.55	0.28	−0.60
Luminosity, f^{+-}, f^{00} and $\mathcal{B}(\Upsilon(4S))$	0.10	0.04	−0.58
$\mathcal{B}(B \to D^{(*)}\ell\nu)$	0.05	0.02	−0.69
$\mathcal{B}(D)$	0.35	0.13	−0.65
$\mathcal{B}(D^*)$	0.04	0.02	−0.51
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.15	0.14	−0.11
Total	5.21	4.94	−0.52

Belle 2016 semileptonic

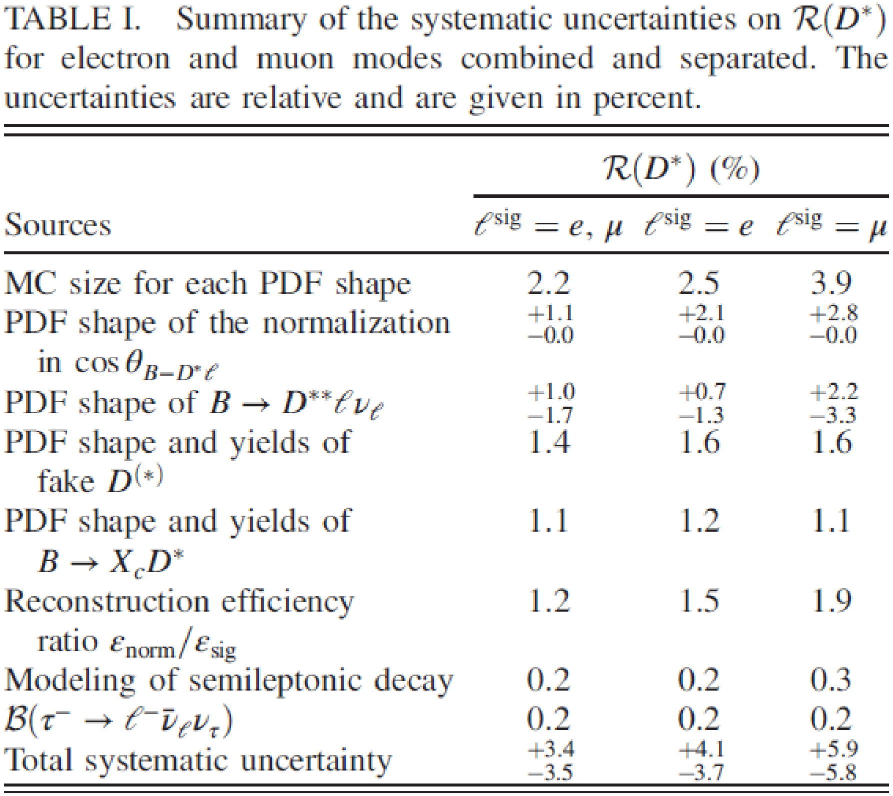


TABLE I. Summary of the systematic uncertainties on $\mathcal{R}(D^*)$ for electron and muon modes combined and separated. The uncertainties are relative and are given in percent.

	$\mathcal{R}(D^*)$ (%)		
Sources	$\ell^{\text{sig}} = e, \mu$	$\ell^{\text{sig}} = e$	$\ell^{\text{sig}} = \mu$
MC size for each PDF shape	2.2	2.5	3.9
PDF shape of the normalization in $\cos\theta_{B-D^*\ell}$	$^{+1.1}_{-0.0}$	$^{+2.1}_{-0.0}$	$^{+2.8}_{-0.0}$
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 $\varepsilon_{\text{norm}}/\varepsilon_{\text{sig}}$	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 uncertainty	$^{+3.4}_{-3.5}$	$^{+4.1}_{-3.7}$	$^{+5.9}_{-5.8}$