SUSY-related lepton and hadron flavour results from Belle

BELLE

OUTLINE

- Belle & SUSY
- selected results
  - prospects for BelleII
- summary

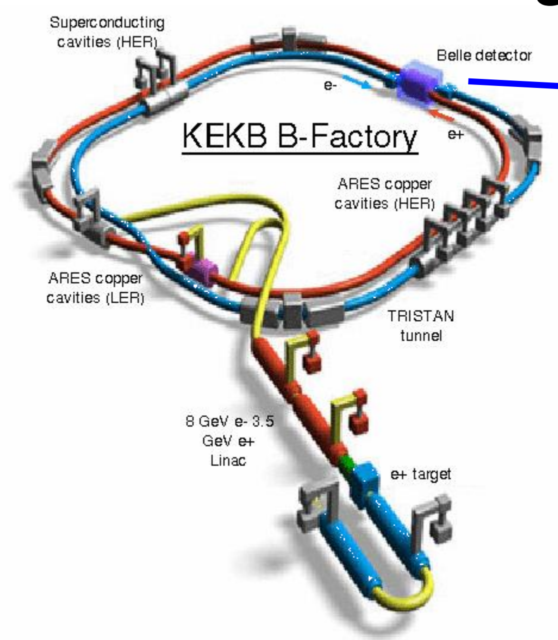
- $B^0 \to D^{*-}\tau^+\nu_\tau$
- $B^0 \to K^* l^+ l^-$
- $B_s^0 \to K_s^0 \overline{K}_s^0$

Maria Różańska for the Belle Collaboration
INP PAN, Kraków

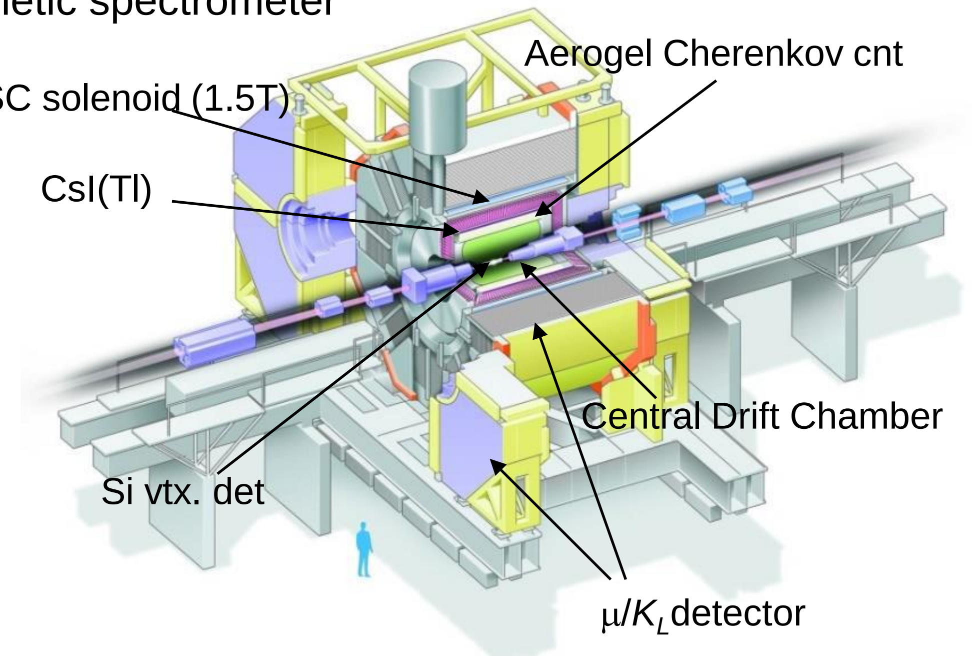
Belle experiment

KEKB B-factory at KEK (Japan): asymmetric energy e^+e^- collider

$$e^+e^- \to \Upsilon(4S) \to \bar{B}B$$



Belle detector:
multi-purpose, large-solid-angle magnetic spectrometer



Data taking: 1999-2010
$L_{int.} > 1\text{ab}^{-1}$
$L_{peak} = 2.11\times10^{34}\text{cm}^{-2}\text{s}^{-1}$

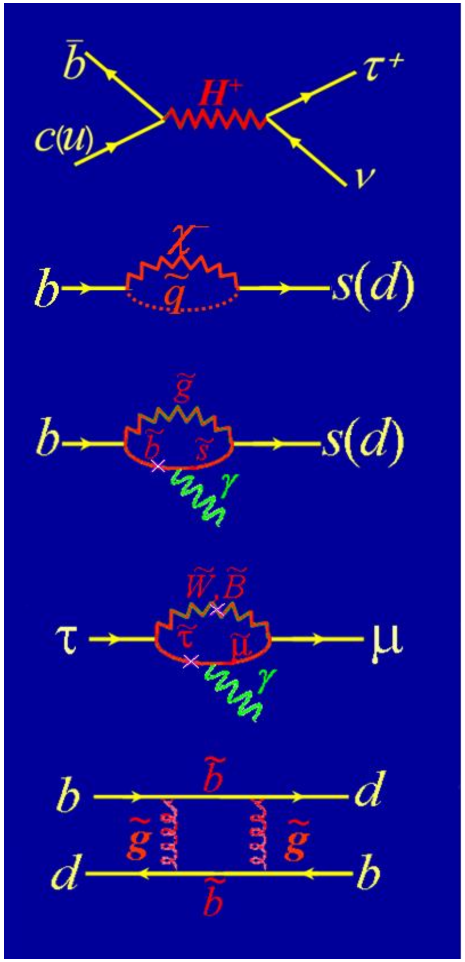
771 million $\bar{B}B$ events
>6 million $\bar{B}_s B_s$ events

few ten times more expected from BelleII

SUSY in flavour physics

Many places and ways to look for new physics effects in $B_{(s)}$ and lepton decays

Examples of SUSY contributions to tree, penguin and box diagrams



GOALS:

- get a hint of new physics,
- distinguish between different models based on pattern of deviations from the SM,
- determine the flavor structure of squark mass matrixes (new sources of flavor mixing and CP phases)...

…or constrain parameter space of various SM extensions

Need observables that are:

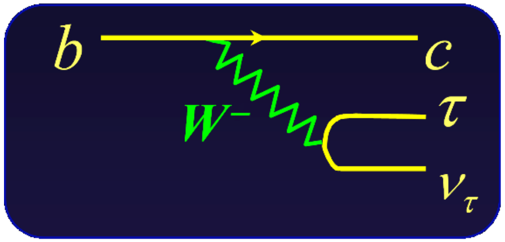
- sensitive to NP
- clean theoretically
- accessible experimentally

E.g.

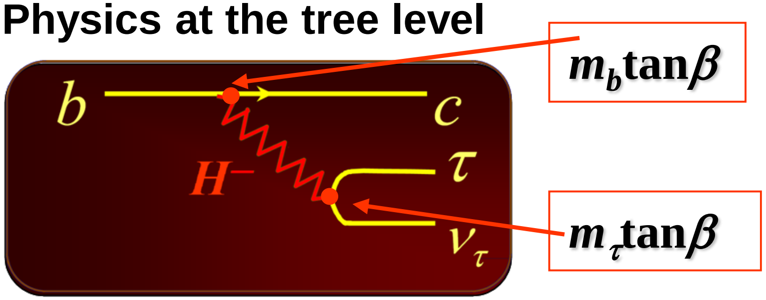
- Branching ratios and distributions in $B \to D^{(*)}\tau\nu$;
- Branching ratios and angular distributions of $b \to sll$
- Branching ratio and CP asymmetris in $B \to X\gamma$
- Mixing-induced and direct CP asymmetries in hadronic $B_{(s)}$ decays
- Lepton flavor violation in tau decays.

tensions with the SM

Semileptonic, tree-dominated decay



New Physics at the tree level



Sensitive to NP and theoreticaly clean observables:

$$R(D^{(*)}) = \frac{BF(B \to \overline{D}^{(*)}\tau\nu_\tau)}{BF(B \to \overline{D}^{(*)}l\nu_l)}, \; l = e, \mu$$

q^2 distributions
D^* and τ polarizations

$R(D)_{SM} = 0.299 \pm 0.003$

D. Bigi, P. Gambino, arXiv:1606.08030

$R(D)_{SM} = 0.297 \pm 0.017$

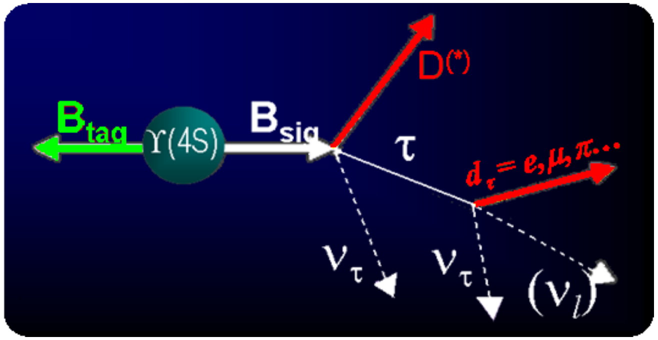
$R(D^*)_{SM} = 0.252 \pm 0.003$

S. Fajfer *et al.*, PRD **85**, 094025 (2012)

Common uncertainties (partly) cancel out

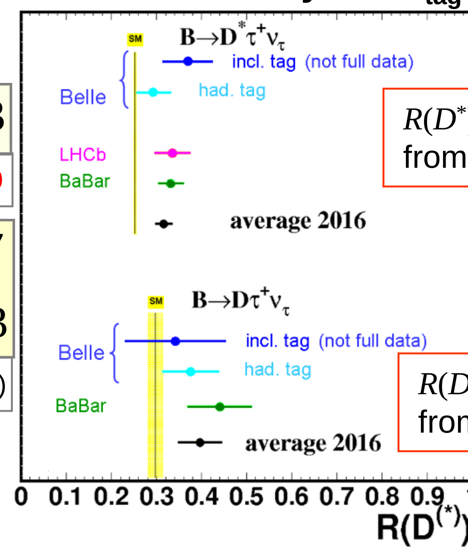
- Theoretical uncertainty of some form factors
- Uncertainty of $|V_{cb}|$
- Experimental uncertainty of efficiencies, partial BF etc…

Challenging experimentaly



At B-factories B decays to multiple ν's final states can be observed in recoil of fully reconstructed B_{tag}.

Till recently all B-factory results based on **hadronic decays of B_{tag}**



$R(D^*)$ 3σ away from the SM

$R(D)$ 1.9σ away from the SM

HFAG
Prel. Winter 2016

$R(D^*)$& $R(D)$ 3.9σ away from the SM

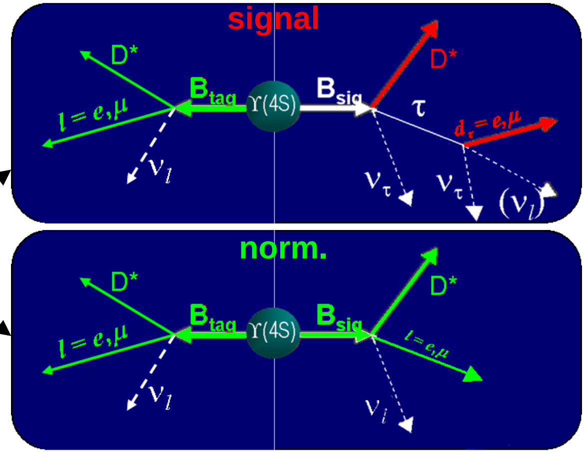
$B^0 \to D^{*-}\tau^+\nu_\tau$ with semileptonic tagging

Use the cleanest mode:

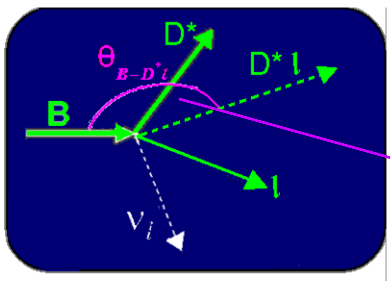
$B^0 \to D^{*-}\tau^+\nu_\tau$,

$\tau \to l\, \nu_l\, \nu_\tau$

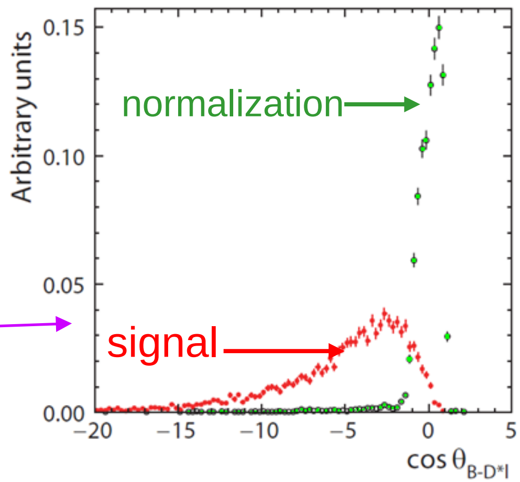
$$R(D^{(*)}) = \frac{BF(B \to \overline{D}^{(*)}\tau\nu_\tau)}{BF(B \to \overline{D}^{(*)}l\nu_l)}$$



Signal events can be separated from normalization events based on the kinematics - **two more ν's in the signal**



$$\cos\theta_{B-D^*l} = \frac{2E_{beam}E_{D^*l} - m_B^2 - M_{D^*l}^2}{2|\vec{p}_B||\vec{p}_{D^*l}|}$$



Variable	Signal	Norm
$\cos\theta_{B-D^*l}$	<0	[-1,1]
M^2_{mis} - missing mass squared	large	≈0
E_{vis} - sum of energies of secondary particles	small	large

Input variables to neural network

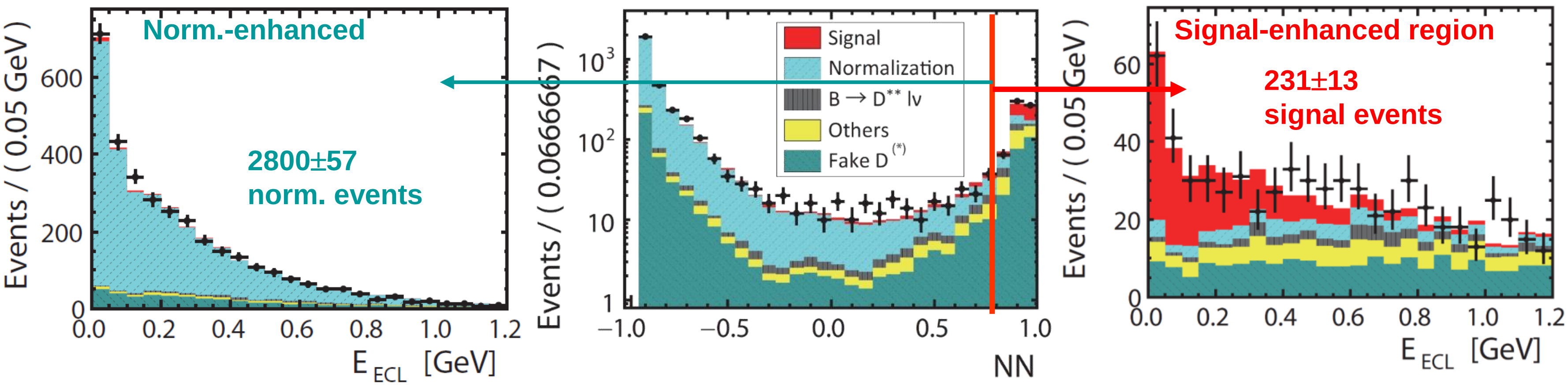
Use the full Belle data sample of 772×10^6 $\bar{B}$B-pairs

A. Abdesselam, *et al.*, (Belle Collaboration), arXiv:1603.006711

$B^0 \to D^{*-}\tau^+\nu_\tau$ with semileptonic tagging

Signal extraction:

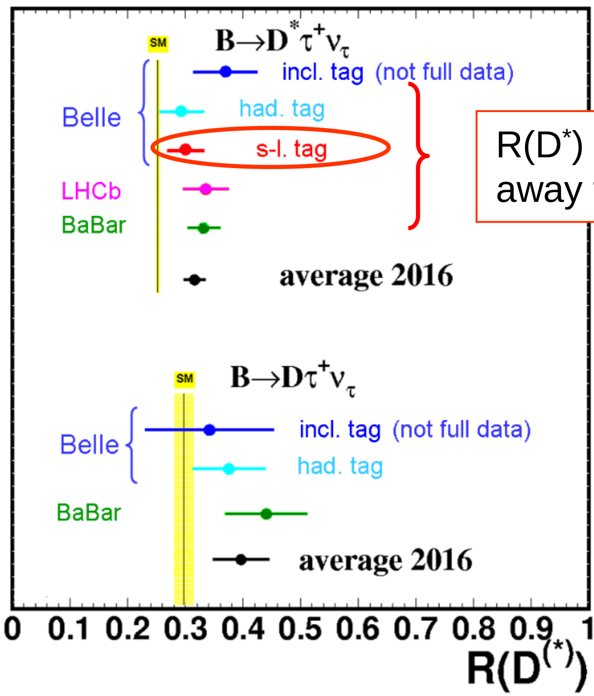
- Two-dimensional fit to neural network clasifier output NN, and E_{ECL}, residual energy in the electromagnetic calorimeter; $E_{ECL} \approx$ for signal, tends to be higher for background.
- Signal, $B \to D^* l\nu$ (normalization) and $B \to D^{**} l\nu$ yields are floated in the fit, other components are fixed to MC expectation.



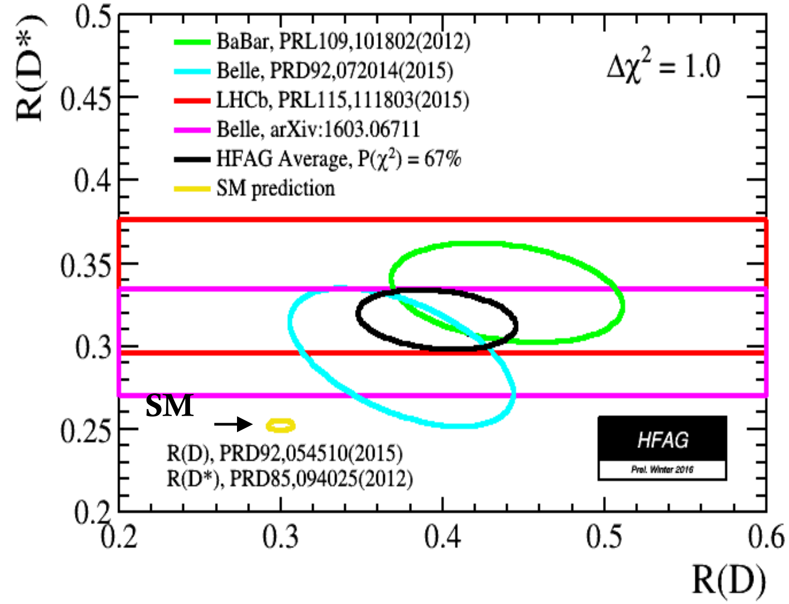
231±13 signal events with the significance of 13.8σ

$B^0 \to D^{*-}\tau^+\nu_\tau$ with semileptonic tagging

Result: $R(D^*)=0.302\pm0.030(stat)\pm0.011(syst)$ 1.6σ larger than the SM prediction



R(D*) 3σ ⇒ 3.3σ away from the SM



HFAG Prel. Winter 2016 — R(D*)& R(D) 3.9σ ⇒ 4σ away from the SM

Consistent with eariler measurements;
precission better than for other Belle and LHCb measurements

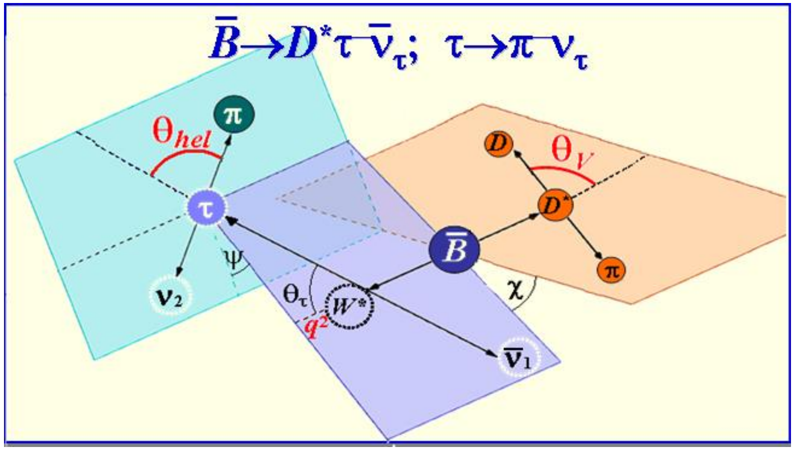
(BaBar result $R(D^*)$=0.332±0.024(stat)±0.018(syst) combines B^0 and B^+ decays)

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

Tantalizing but inconclusive hints of a deviation from the Standard Model in $b \to c\tau\nu_\tau$ transitions:

- ***R(D^{(*)})*** systematically above the SM expectations, surprisingly large effect for $R(D^*)$;
- Measured distributions of q^2 [BaBar PRD **88**,072012(2013), Belle, PRD **92**,072014(2015)], p_{D*} and p_l [arXiv:1603.06711] consistent with SM, but statistically limited;
- More observables with more data needed to clarify the situation;

Angular observables not yet explored experimentally.



cosθ$_V$ and **cosθ$_{hel}$** can be reconstructed at B-factories with hadronic decays of $B_{\rm tag}$
⇒ polarization of D^* ($F^{D*}_{L(T)}$) and τ (P_τ)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_V} = \frac{3}{4}[2F_L^{D^*}\cos^2\theta_V + F_T^{D^*}\sin^2\theta_V], \quad F_L^{D^*} + F_T^{D^*} = 1$$

all τ decays

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{hel}} = \frac{1}{2}[1+\alpha P_\tau \cos\theta_{hel}]$$

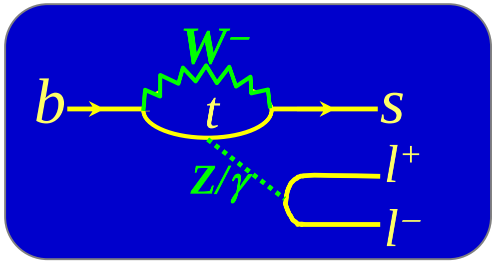
only $\tau \to M\nu_\tau$ decays,
α=1 for $M = \pi$

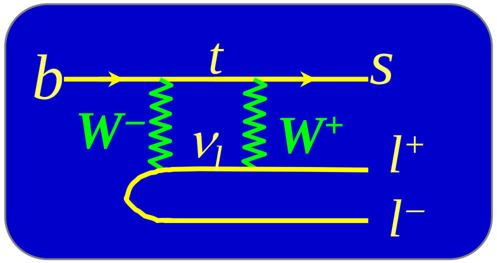
Important topics for Belle II

some constraints on $F^{D*}_{L(T)}$ and P_τ feasible with the Belle data
(N.B. the $\tau \to \pi\nu_\tau$ mode was used in two Belle analyses of $B \to D^{(*)}\tau^+\nu_\tau$ PRL **99**, 191807 (2007), PRD **82**, 072005 (2010))

Flavor-changing neutral current (FCNC) decays that are forbidden in the SM at tree level, and proceed at higher orders via penguin loops & box diagrams.

SM examples

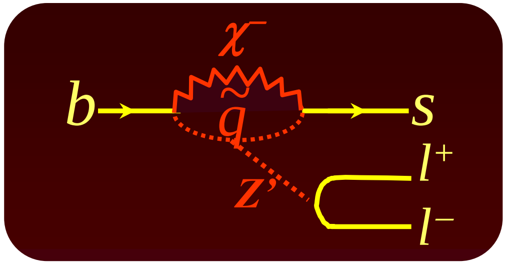


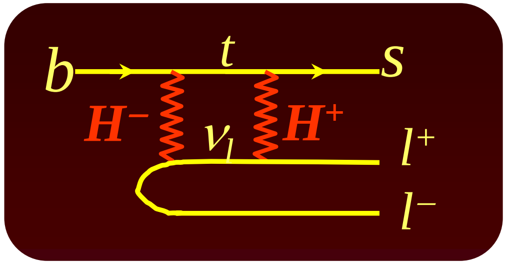


Main contributions from: semi-leptonic operators O_9 (V current), O_{10} (A current) and EM dipol operator O_7

New physics adds new loops with new particles

NP examples



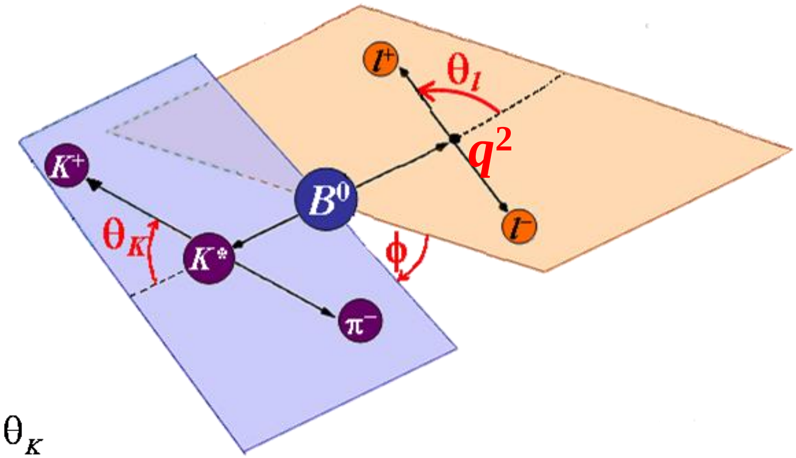


NP modifies SM values of the Wilson coefficients $C_{\mathrm{i}}^{\mathrm{eff}}$ and may introduce new terms, e.g. scalar & pseudoscalar couplings C_{S} & $C_{\mathrm{P}}^{\mathrm{eff}}$;
angular observables bear high sensitivity to NP.

$\Rightarrow$ probes of new physics at a scale of few TeV.

Angular variables

The $B \to K^* l^+ l^-$ decay is described by 4 variables:
q^2 - effective mass squared of the $l^+ l^-$ system,
θ_l - angle between $l^+(l^-)$ & $B(\bar{B})$ in $l^+ l^-$ rest frame
θ_K - angle between K & B in K^* rest frame
ϕ - angle between the di-lepton and $K\pi$ decay planes



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

$F_L - K^*$ longitudinal polarization

F_L, S_i – functions of q^2

form factor independent observables, P_i':

$$P'_{i'=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Notation consitent with the LHCb paper. LHCb Collab, arXiv:1308.1707

folding method:

$$e.g.\ \text{for } S_5:\ \begin{cases}\phi \to -\phi & \text{for } \phi < 0\\ \theta_l \to \pi - \theta_l & \text{for } \theta_l > \pi/2\end{cases}$$

all S_i terms except for S_3 and S_5 vanish

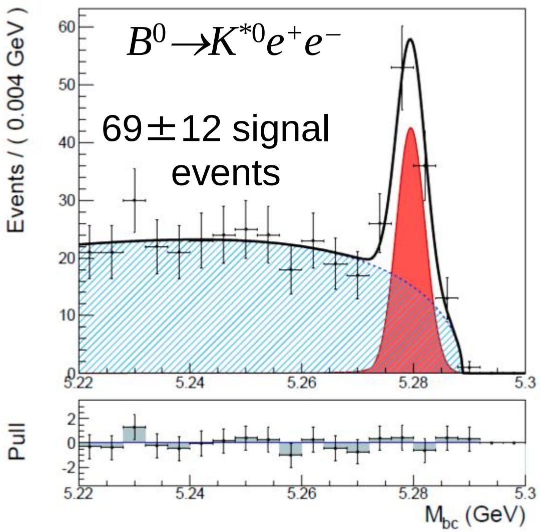
Number of free parameters reduced from 8 to 3: F_L, S_3 and $S_{5(4,7,8)}$

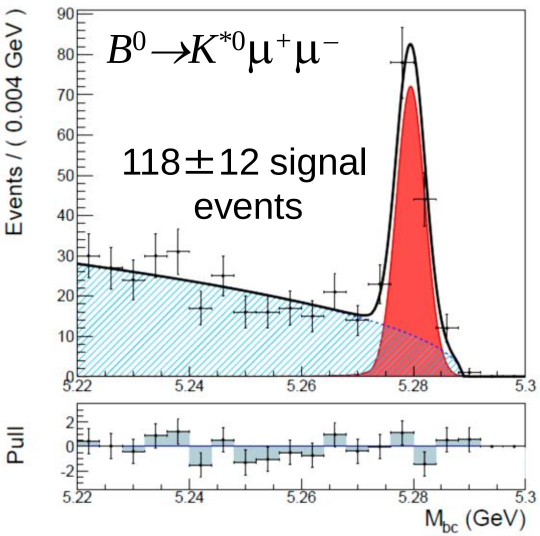
LHCb reported 3.4σ deviation from the SM prediction in P_5' for $4 < q^2 < 8$ GeV² from full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb Collab., JHEP **02**, 104 (2016)

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

full range of q^2





Only B^0 used

Challenges:

- $BF(B^0 \to K^*(892) l^+ l^-) \approx 10^{-7}$
- irreducible background from $B \to K^* J/\psi$ and $B \to K^* \psi(2S)$
- expect $\mathcal{O}(100)$ candidates in the Belle data-sample

Experimental approach:

- use both, di-electron and di-muon modes
- Neural Network based selections adopted to improve the sensitivity;
- Robust fitting technique, suitable for low statistics;
- Signal and background yields from fits to M_{bc} distribution;

$$M_{bc} = \sqrt{(E_{beam})^2 - |\vec{p}_B|^2}$$

- 3-dim UML fits to angular distributions in the region of M_{bc} >5.27 GeV to exctract F_L, P'_3 and P'_i (i=4,5,6,8)
- The fits are performed in bins of q^2

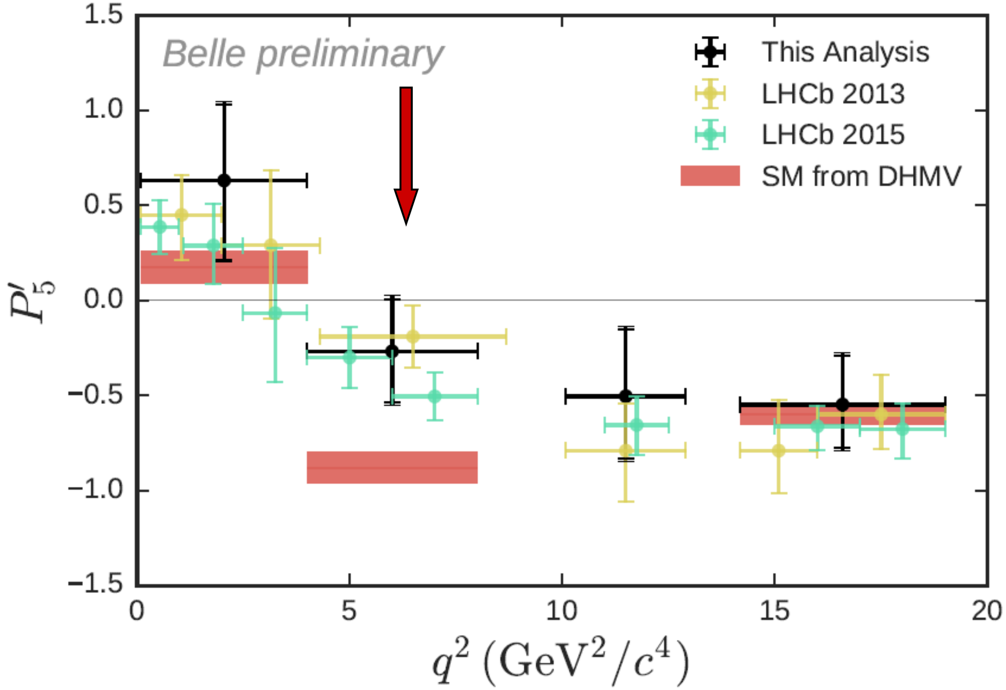
Use the full Belle data sample of 772×10^6 $\bar{B}$B-pairs

A. Abdesselam, et al (Belle Collaboration), arXiv:1604.04042

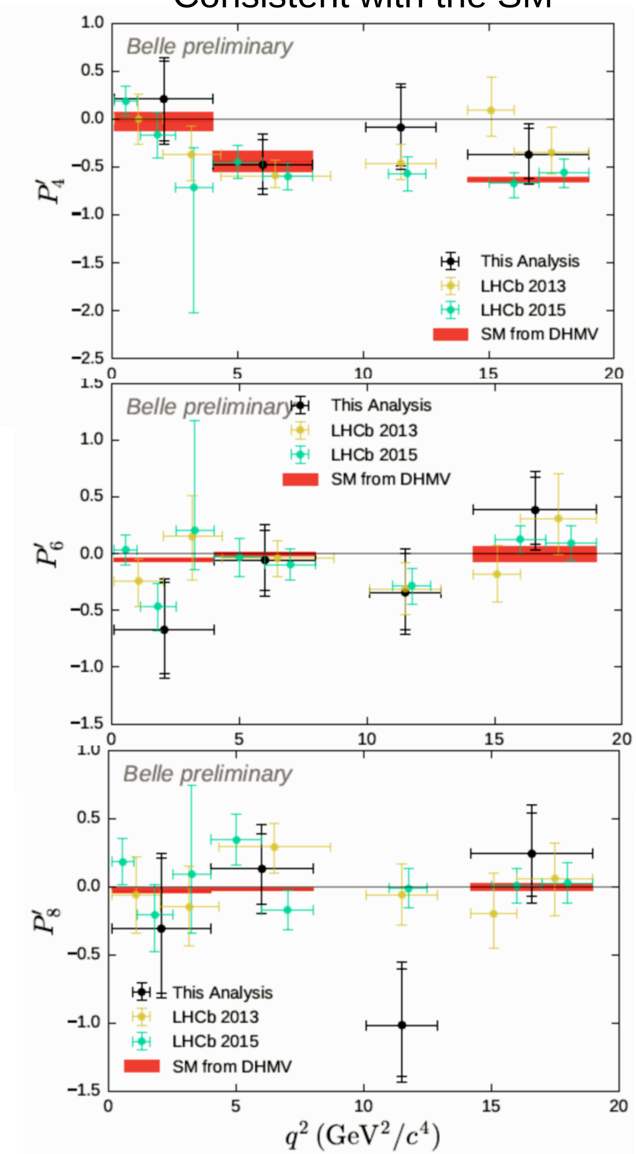
Consistent with the SM

Results:

The measurements are compatible with the SM predictions and the LHCb measurements



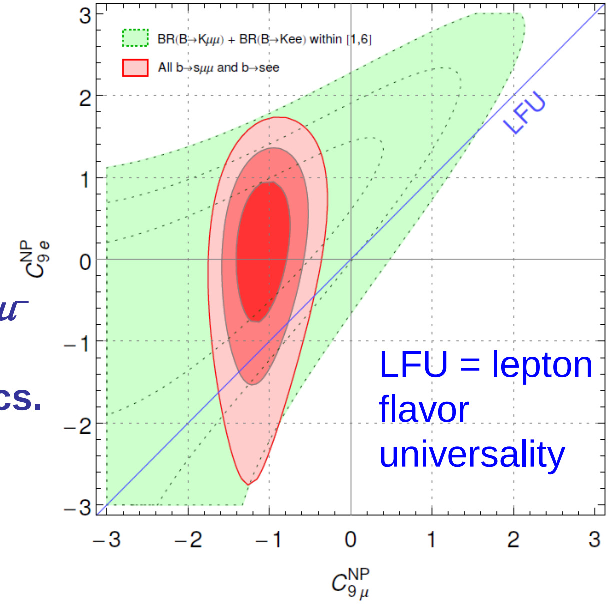
The result for 4< q^2 < 8 GeV^2 is 2.1σ away from the theoretical prediction in the same direction as observed by LHCb.



A. Abdesselam, et al (Belle Collaboration), arXiv:1604.04042

$B \to K^{(*)} l^+ l^-$

S. Descotes-Genon *et al.*, arXiv:1605.06059[hep-ph]



Global analyses of the deviations in EW $b \to s$ transitions point towards a large additional contribution to the Wilson coefficient C_9^μ of the semi-leptonic operator in the efective Hamiltonian for $b \to s\mu^+\mu^-$ (significance over 4σ).
On the other hand, $B \to K^{(*)}e^+e^-$ observables suggest that $b \to se^+e^-$ transitions agree well with the SM.

A full angular analysis of $B \to K^*e^+e^-$ and its comparison with $B \to K^* \mu^+\mu^-$ could improve our understanding of these anomalies and help confirming their interpretation in terms of short-distance New Physics.

S. Descotes-Genon *et al.*, arXiv:1603.03156[hep-ph]

There is a significant difference in the theoretical accuracy of the inclusive and exclusive $b \to sl^+l^-$ decays in the low-q^2 region (theoretical description of power corrections exists only in the inclusive case). This issue makes it rather difficult or even impossible to separate new physics effects from such potentially large hadronic power corrections within these exclusive angular observables. **These tensions might stay unexplained until Belle-II will clarify the situation by measuring the corresponding inclusive $b \to sl^+l^-$ observables.**

T. Hurth, F. Mahmoudi and S. Neshatpour, arXiv:1603.00865[hep-ph]

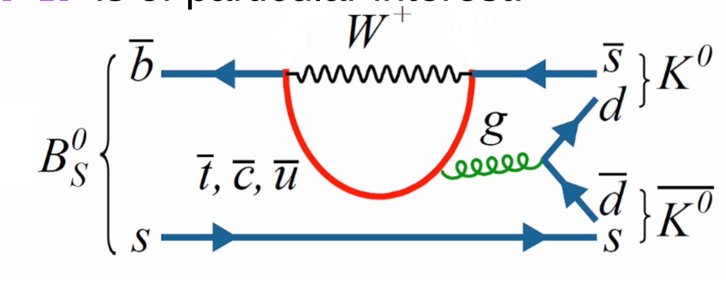
The deviations in EW $b \to s$ transitions can be explained either by new particles or by unexpectedly large hadronic effects (charm loops).

Tasks for Belle II (~2000 events of $B^0 \to K^* e^+e^-$ and ~5000 events of $B^0 \to K^* \mu^+\mu^-$):
measurements of angular observables in $B \to K^*e^+e^-$ and in inclusive $B \to sl^+l^-$ decays.

$B_s \to K^0 \bar{K}^0$

The two-body decays $B_s \to h_1^+ h_2^-$, where $h_{1(2)}^{\pm} = K^{\pm}$, or $\pi^{\pm}$ have now all been observed, in contrast to the neutral-daughter decays $B_s \to h_1^0 h_2^0$.

The decay $B_s \to K^0 \bar{K}^0$ is of particular interest:



only down-type quarks – gluon penguin amplitude dominates

- Predicted branching fraction $BF(B_s \to K^0 \bar{K}^0)$ is in the range (1.6-2.7)×10^{-5}
- The presence of non-standard particles or couplings such as model with Z' coupling may enhance the branching fraction up to 3.0×10^{-5}

  [Q. Chang, X. Q. Li and Y. D. Yang, J. Phys. G 41, 105002 (2014)]
- The direct CP asymmetry, A_{CP} is not more than 1% in SM, can be 10% larger in the presence of SUSY without changing the branching ratio.

  [A. Hayakawa *et al*., PTEP 2014, no. 2, 023B04 (2014); S. Baek *et al*., JHEP 0612, 019 (2006)]

➢ Previous searches by Belle with 23.6 fb^{-1} gave an upper limit of
$BF(B_s \to K^0 \bar{K}^0)<6.6\times10^{-5}$ at 90% CL.

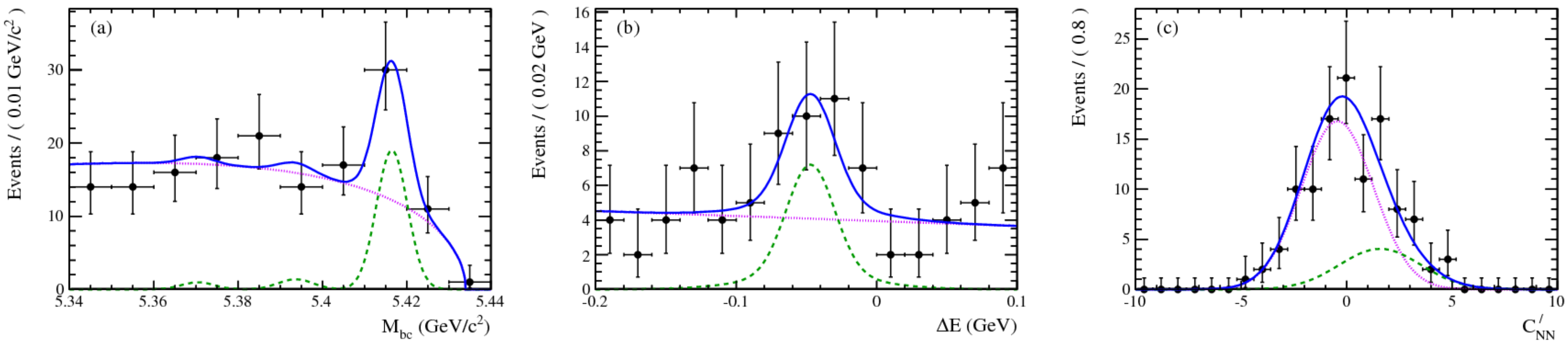
➢ The new analysis uses 121.4 fb^{-1} of Belle data collected at $\Upsilon(5S)$ resonance;
The data set corresponds to $(6.53 \pm 0.66)\times10^6$ $\bar{B}_s B_s$ pairs produced in three $\Upsilon(5S)$ decay channels: $\bar{B}_s B_s$, $\bar{B}_s^* B_s$ or $\bar{B}_s B_s^*$, and $\bar{B}_s^* B_s^*$
The latter two channels dominate, with production fractions: $f_{B_s^* \bar{B}_s} = (7.3 \pm 1.4)\%$ $f_{B_s^* \bar{B}_s^*} = (87.0 \pm 1.7)\%$

Belle Collab., Phys. Rev. Lett **116**, 161801 (2016)

$B_s \to K^0 \bar{K}^0$

- K^0 mesons are reconstructed only via the decay $K_S \to \pi^+\pi^-$;
- 3D fit is performed to extract the signal yield;

$$M_{bc} = \sqrt{(E_{beam})^2 - |\vec{p}_B|^2} \qquad \Delta E = E_B - E_{beam} \qquad C'_{NN} = \ln \frac{C_{NN} - C_{NN}^{min}}{C_{NN}^{max} - C_{NN}}$$



- The three peaks in M_{bc} arise from $\Upsilon(5S) \to B_s\bar{B}_s,\ (B_s\bar{B}_s^* + B_s^*\bar{B}_s),\ B_s^*\bar{B}_s^*$

$29.0^{+8.5}_{-7.6}$ signalevents significance 5.1σ (*syst. included*)

first observation

$$BF(B_s^0 \to K^0\bar{K}^0) = [19.6^{+5.8}_{-5.1}(\text{stat}) \pm 1.0(\text{syst}) \pm 2.0(N_{B_s\bar{B}_s})] \times 10^{-6}$$

in good agreement with the Standard Model expectations

- in Belle II (~5 ab^{-1} of data) ~1200 events expected
  ⇒ much higher sensitivity search for new physics, including CP violation study.

Summary and prospects

- **New measurements at Belle confirm the existing tensions:**
  - The result for $\boldsymbol{R(D^*)}$ obtained with semileptonic tagging $\boldsymbol{R(D^*)} = 0.302 \pm 0.030(\text{stat}) \pm 0.011(\text{syst})$ confirms the excess seen by other measurements and brings to tension with the SM to 4.0σ;
    - we need more data and more observables on $b \to c(u)\tau\nu_\tau$ transitions, e.g. inclusive $BF(B \to X_c\tau\nu_\tau)$, polarizations of τ and D^*…
  - The P_5' value for $4 < q^2 < 8$ GeV^2 from angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ is 2.1σ away from the theoretical prediction and supports the anomaly seen by LHCb; The deviations in EW $b \to s$ transitions can be explained either by new particles or by unexpectedly large hadronic effects (charm loops).
    - measurements of angular observables in inclusive $b \to sl^+l^-$ and $B \to K^*e^+e^-$ decays are needed to clarify the situation.
- First observation of of a charmless two-body B_s decay involving only neutral hadrons in the channel $B_s^0 \to K^0\overline{K}^0$
  - good place to look for NP in gluonic penguins

→ **Ineteresting program for Belle II**

BACKUP SLIDES

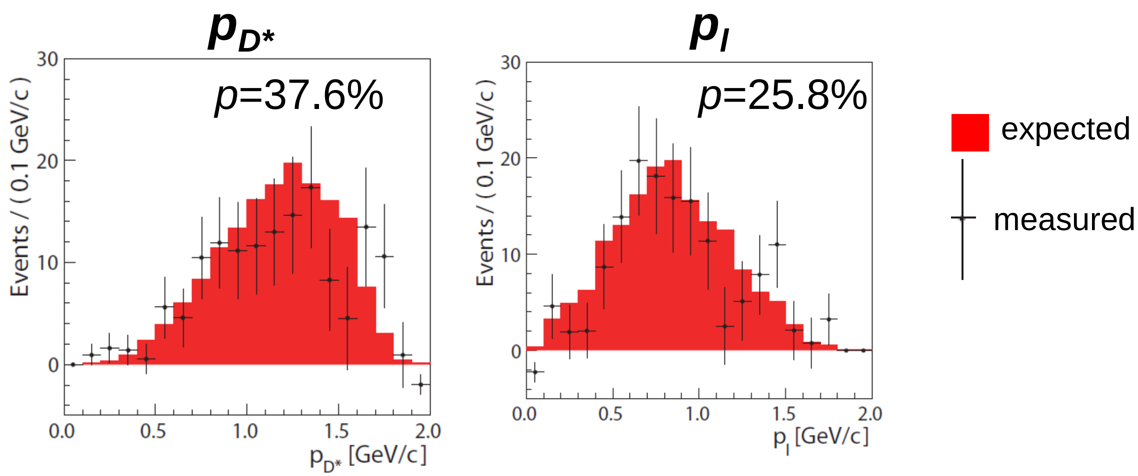
$B^0 \to D^{*-}\tau^+\nu_\tau$ with semileptonic tagging

compatibility tests with D* and lepton momenta

$q^2=(p_B-p_{D^*})^2$ cannot be calculated with semileptonic tags

Standard Model

Background-subtracted D* and lepton spectra in the Υ(4S) rest frame, in the signal enhanced region: **NN>0.8, E_{ECL}<0.5 GeV**.



New Physics compatbility tests

$$-\mathcal{L}_{\text{eff}} = 2\sqrt{2}G_F V_{cb}[O_{V1} + \sum_{X=S1,S2,V1,V2,T} C_X O_X]$$

added one by one:

$$O_{S1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_L)$$
$$O_{S2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_L)$$
$$O_{V1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$
$$O_{V2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L)$$
$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_R)(\bar{\tau}_L \sigma_{\mu\nu} \nu_L)$$

efficiency corrections applied as a function of C_X

Type-II 2 Higgs Doublet Model

$$C_{S1} = -m_b m_\tau \tan^2\beta / m_{H^+}^2$$

$\tan\beta$ - ratio of the vacuum expectation values of the 2 Higgs doublets

– excluded by BaBar at 99.8% C.L. based on combined R(D) & R(D*)

Models with scalar leptoquarks

R_2-type – compatible with data in some regions of parameter space

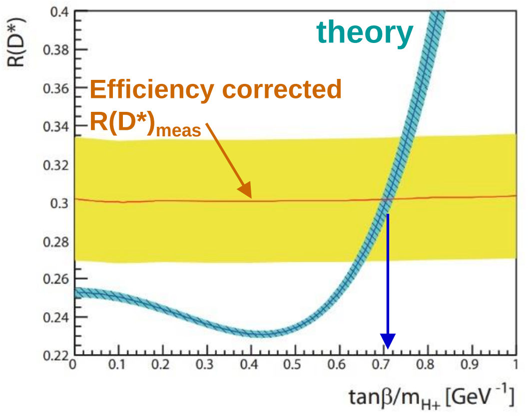
$$m_{LQ} = 1\ \text{TeV} \quad C_{S1} = +7.8 C_T$$

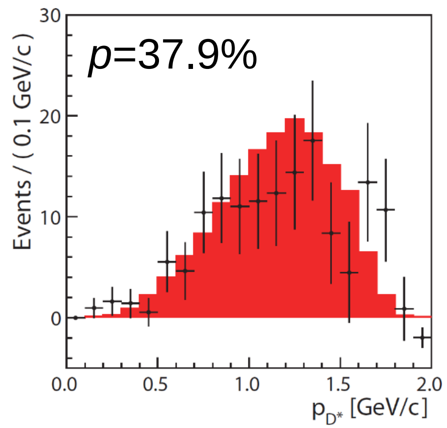
Y. Sakaki *et al*., Phys. Rev. D. **88**, 094012 (2013)

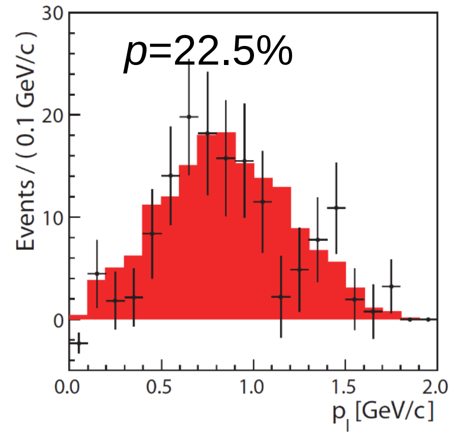
$B^0 \to D^{*-}\tau^+\nu_\tau$ with semileptonic tagging

compatibility tests with D* and lepton momenta

2HDM-II

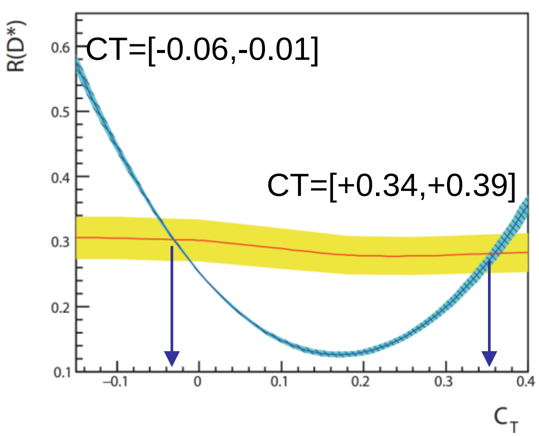




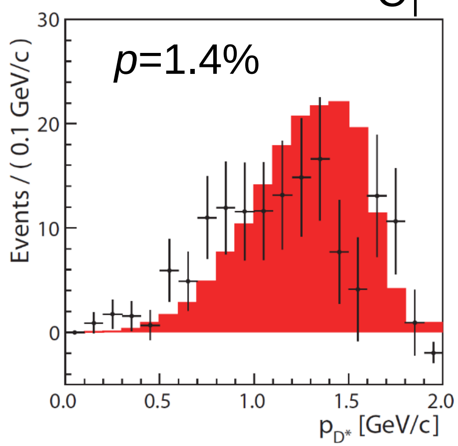


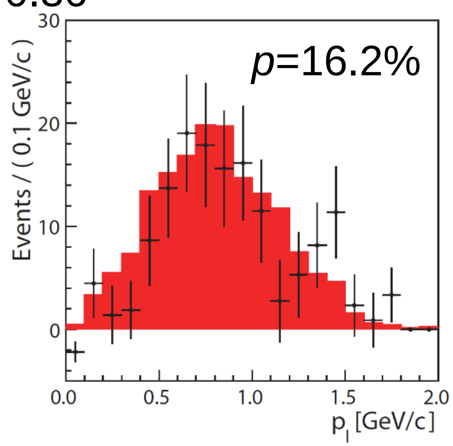
$R(D^*)_{meas}$ matches the $R(D^*)_{th}$ at $\tan\beta/m_{H+} \approx 0.7\ GeV^{-1}$; *p*-values of p_{D^*} and p_l similar to the SM case

R_2-type scalr LQ



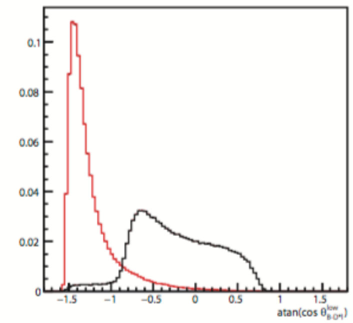
$C_T = 0.36$

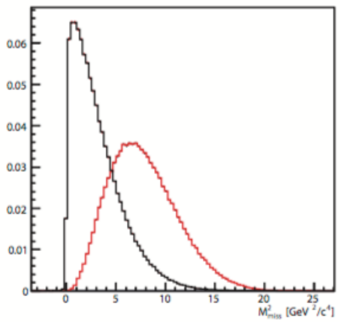


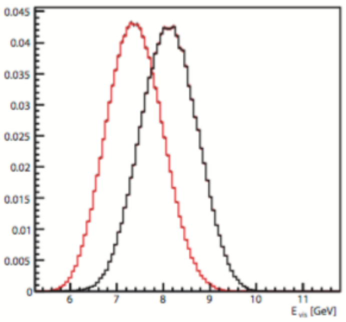


$R(D^*)_{meas}$ matches the $R(D^*)_{th}$ at $C_T \approx -0.03$ and $C_T \approx +0.36$; p_{D^*} distribution disfavors the $C_T = 0.36$ case

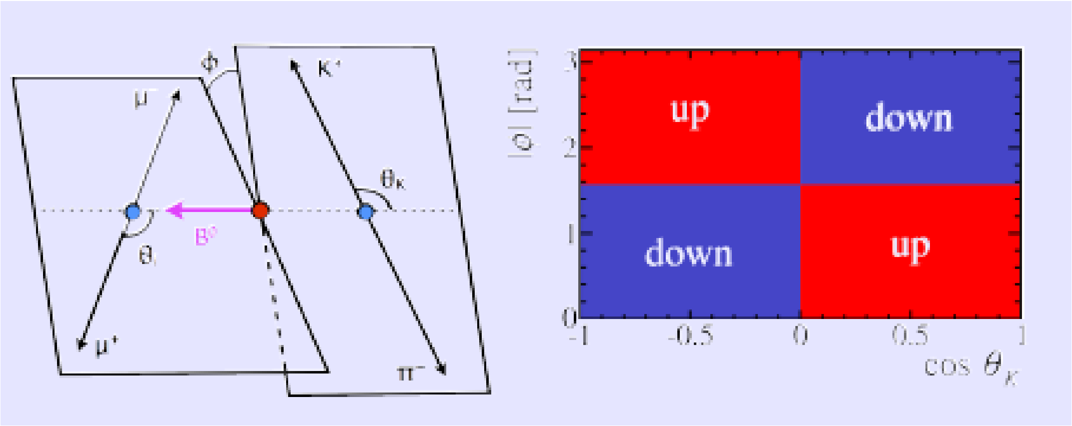
Input variables to neural network







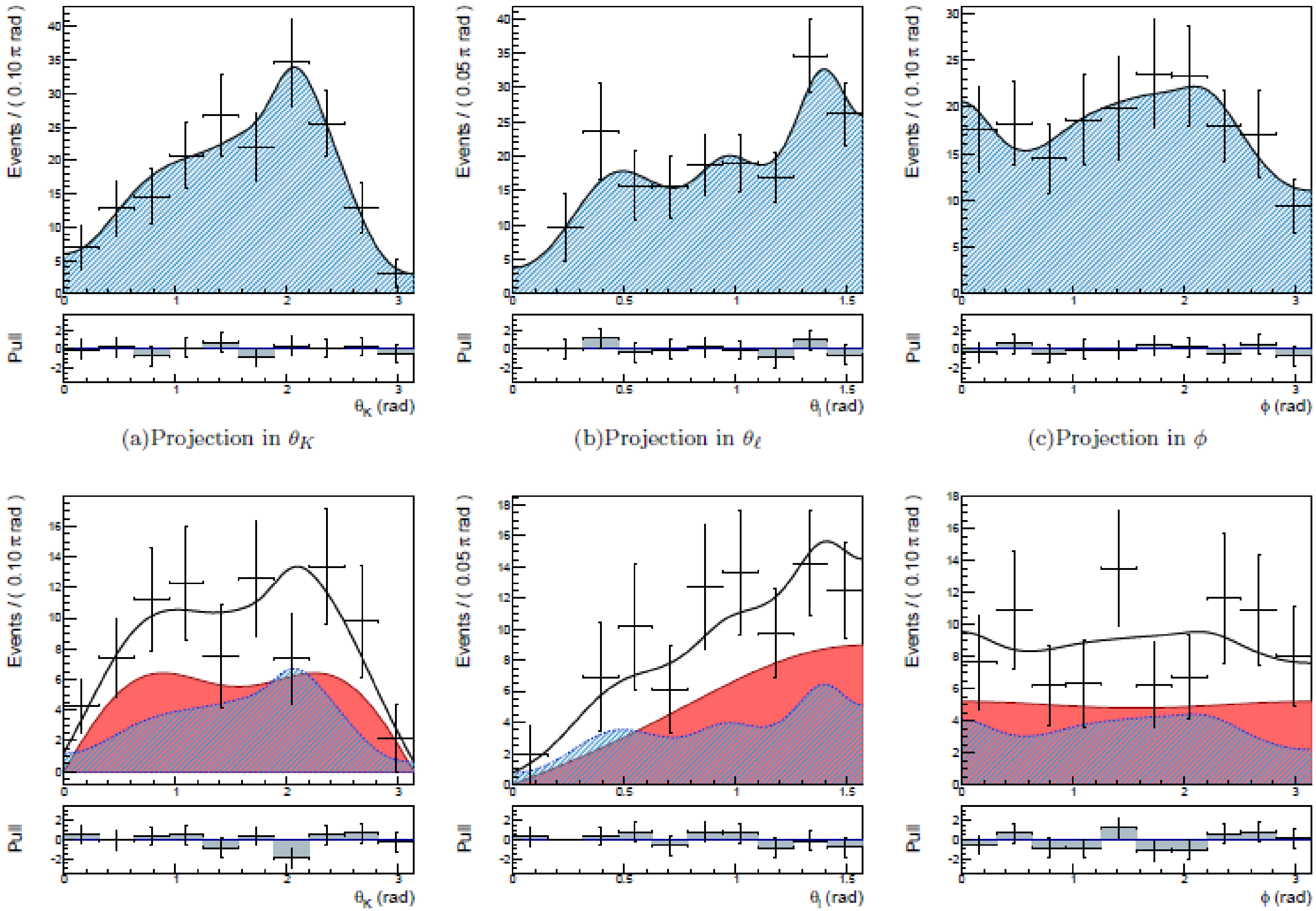
$B^0 \to K^{*0} l^+ l^-$



The P_5' asymmetry suggested by Ref. [99] is based on the angles θ_K and ϕ. It is defined as the relative difference between the number of decays in the regions in red and blue in Fig. 12 (right), divided by $\sqrt{F_L(1-F_L)}$. Quantities based on several angles are more difficult to measure than single-angle ones as they require a better understanding of the reconstruction efficiencies depending on the kinematics of the outgoing particles.

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

BELLE



(a)Projection in θ_K (b)Projection in θ_ℓ (c)Projection in ϕ

(d)Projection in θ_K (e)Projection in θ_ℓ (f)Projection in ϕ

FIG. 4. Projections for the fit result of P_5' in bin 2. Fit to the $M_{\rm bc}$ sideband for the determination of the background shape (top) and signal region (bottom) are displayed. Combinatorial (dashed blue), signal (red filled) and total (solid) fit distributions are superimposed on the data points.