SUSY-related Lepton and Hadron Flavor Results from Belle

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For the Belle Collaboration

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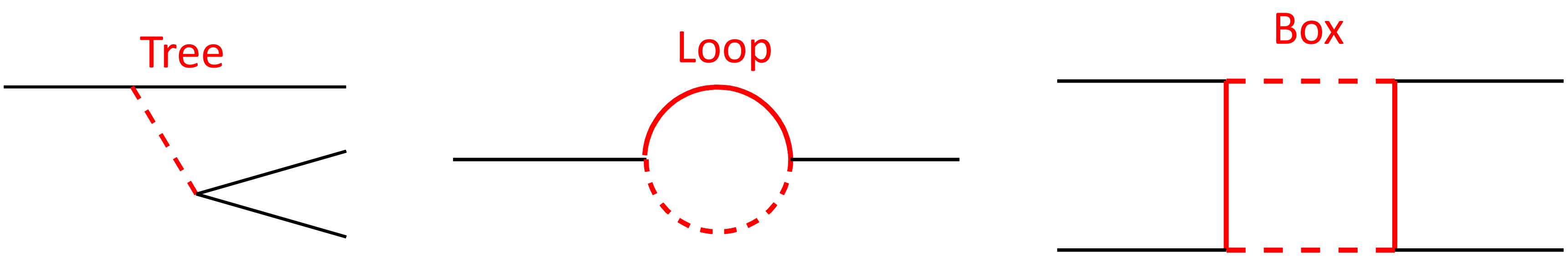
New physics search at Belle

- New particles (e.g. SUSY particles) could enter in the tree, loop, and box diagrams.
  - Observables (such as branching fraction or asymmetry) are modified.

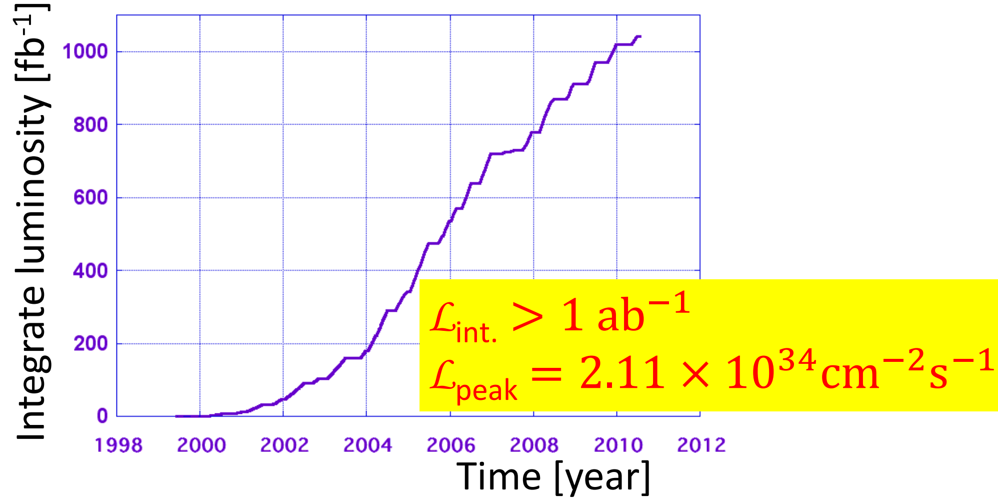


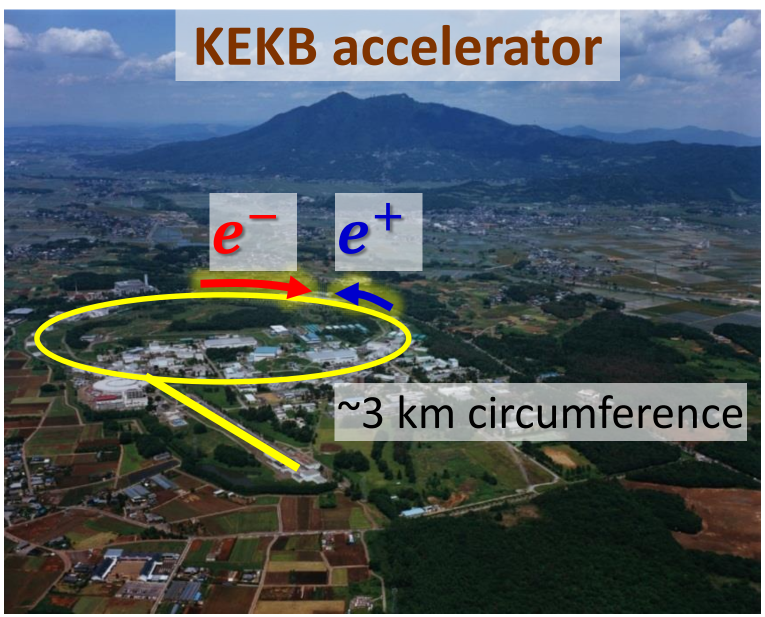
Topics covered in this talk :

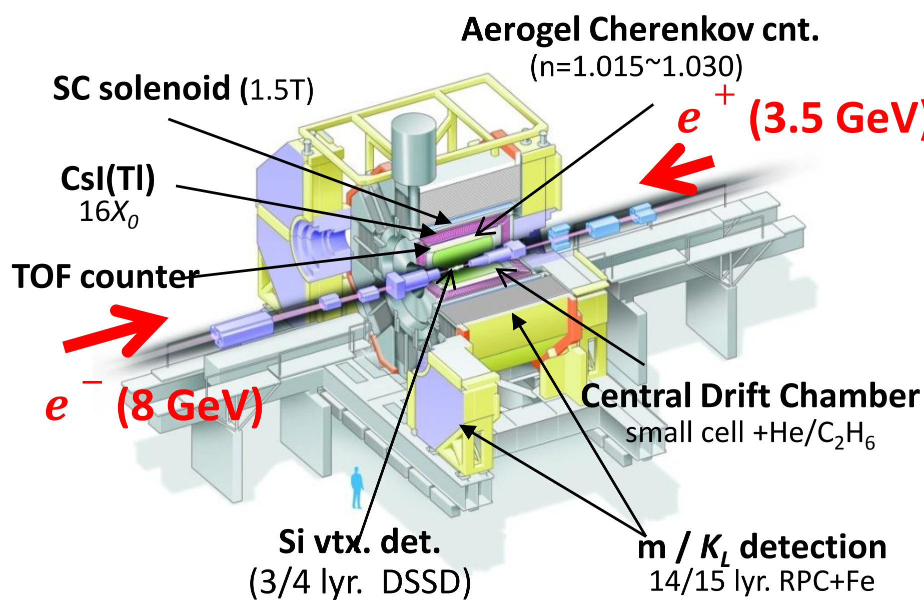
1. $B \to D^{(*)}\tau\nu$ with hadronic tag (arXiv:1507.03233, submitted to PRD)
2. $B \to \pi\tau\nu$ with hadronic tag
3. $B_s \to \phi\gamma, \gamma\gamma$ (PRD 91, 011101(R)(2015))
4. $A_{\mathrm{CP}}(B \to X_{s+d}\gamma)$ (PRL 114, 151601 (2015))

Belle Experiment

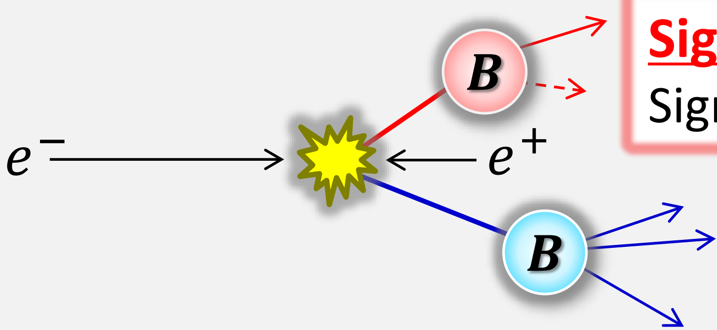
- KEKB accelerator and Belle detector at Tsukuba, Japan.
  - Asymmetric e^+e^- energy to boost B mesons
  - Data taking for 1999-2010
  - Good particle ID capability
    - $(p, \pi^\pm, K^\pm, \gamma, e, \mu, K_L^0)$
  - Good momentum resolution
    - $\frac{\sigma_{P_t}}{P_t} = 0.19P_t \oplus \frac{0.30}{\beta}\%$







Hadronic tagging with Neural Network



Signal side

Signal decay

Tag side

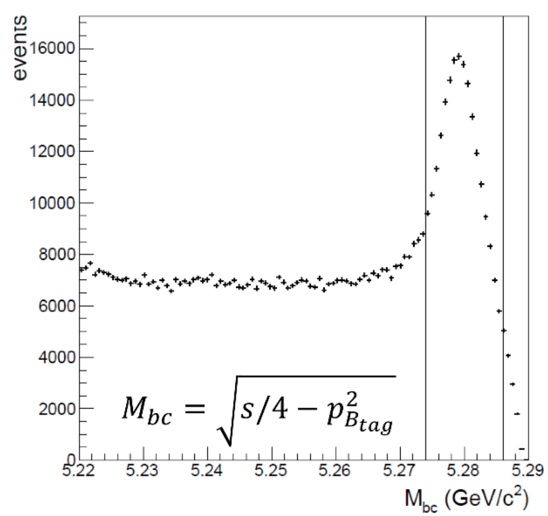
B_{tag} is completely reconstructed from hadronic decay ($B \to D^{(*)}X,\ J/\psi X, \ldots$).

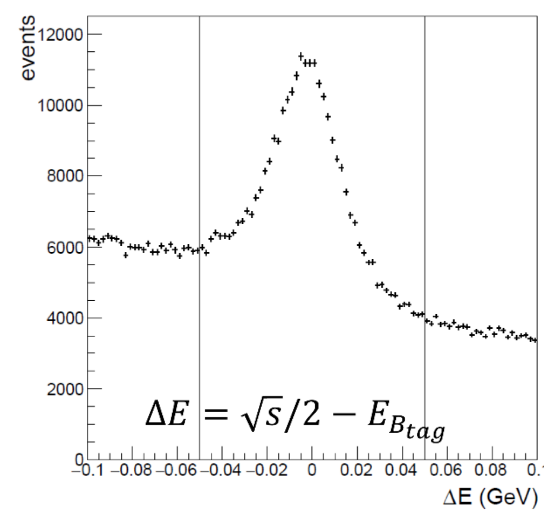
- Event selection by using NeuroBayes (neural network).
  - 1104 exclusive decays are used.

NIMA 654, 432 (2011)

- Especially, useful for final states with neutrinos.

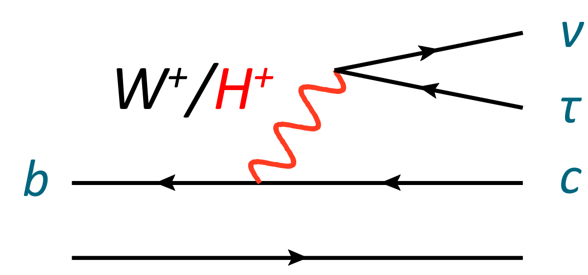
  (e.g.) $B \to D^{(*)}\tau\nu, \pi\tau\nu, \ldots$





before the selections are applied

$B \to D^{(*)}\tau\nu$ with Hadronic Tag



- Sensitive to charged Higgs.

Observables

- $R(D^{(*)}) = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to Dl\nu)}$ $(l = e, \mu)$
- Several systematic uncertainties mostly cancel out in the ratio.
  - V_{cb}, (part of) form factors, experimental efficiencies.
- All measurements indicate $R(D^{(*)})$ higher than SM.

Selection

- $B_{\rm tag}$ is reconstructed by hadronic tagging based on Neural network.
- Leptonic τ decays are used.
  - Same final state as $B \to D^{(*)}l\nu$
- 4 $D^{(*)}l$ final states ($D^{*+}l, D^{*0}l, D^{+}l, D^{0}l$)
- No further tracks or π^0
- $q^2 > 4\ \mathrm{GeV}^2$
- $-0.2\ \mathrm{GeV}^2 < M^2_{\rm miss} < 8.0\ \mathrm{GeV}^2$

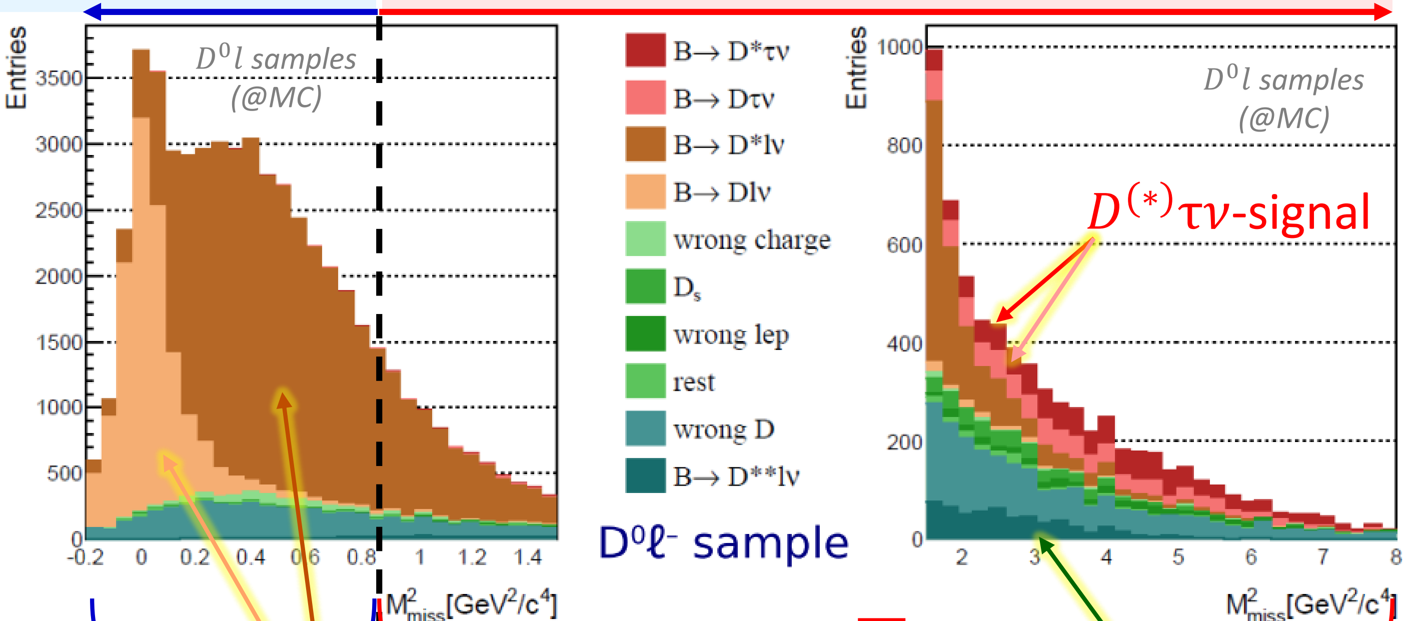
> - Virtual boson mass-squared
> $q^2 = (p_B - p_{D^{(*)}})^2$
> - Missing mass-squared
> $M^2_{\rm miss} = (p_{\rm Beam} - p_{B_{\rm tag}} - p_{D^{(*)}} - p_l)^2$

Fit Strategy

$B \to D^{(*)}\tau\nu$ with hadronic tag

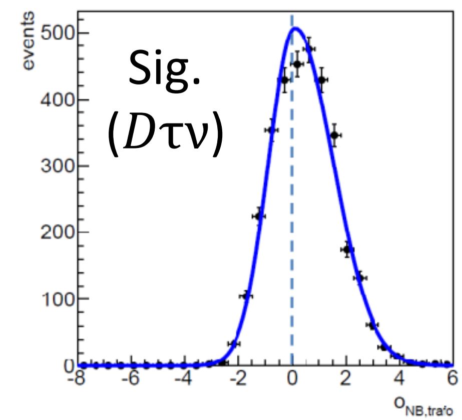
- Split sample at $M^2_{\text{miss}} = 0.85\ \text{GeV}^2/c^4$

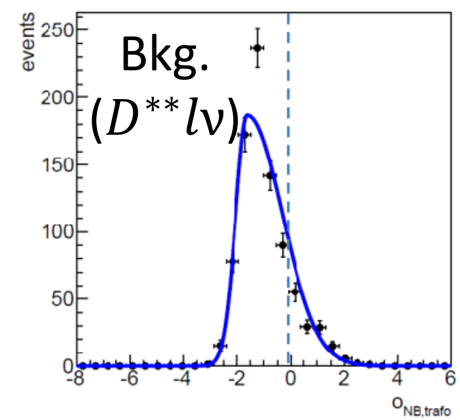
$D^{(*)}l\nu$ enhanced | $D^{(*)}\tau\nu$ enhanced



Fit in M^2_{miss} to determine $D^{(*)}l\nu$

Fit in Neural Network output to separate sig. from bkg. (mainly $D^{**}l\nu$)



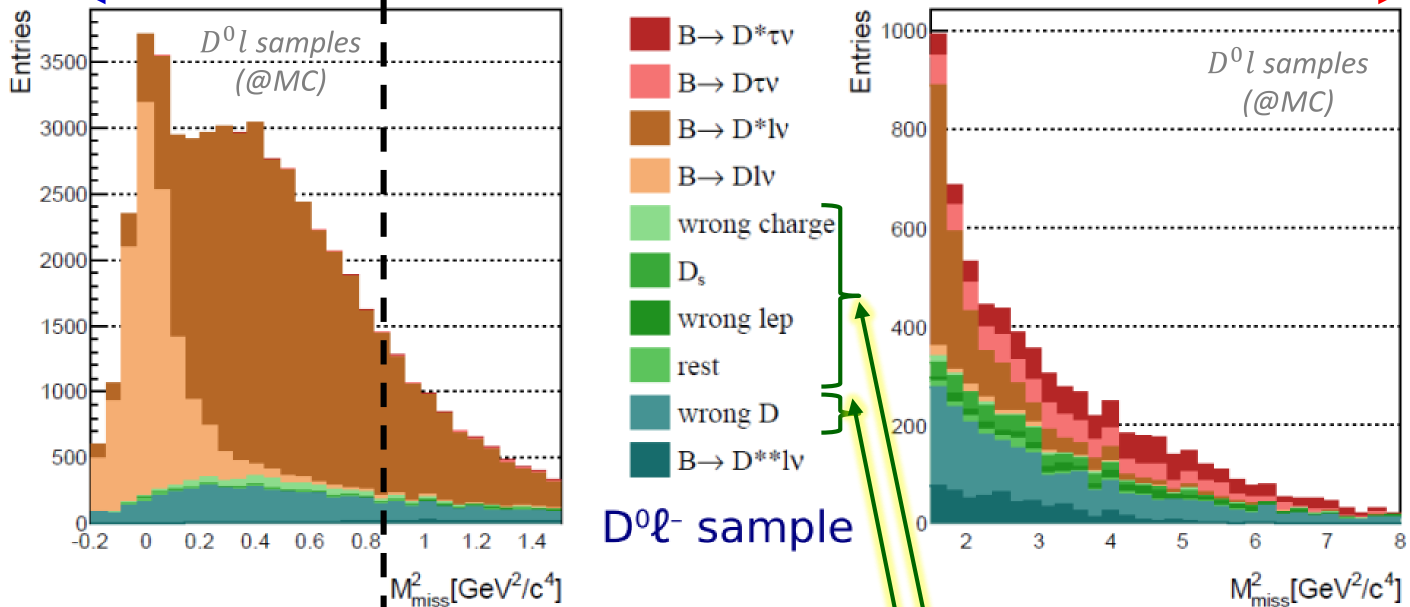


Fit Strategy

$B \to D^{(*)}\tau\nu$
with hadronic tag

- 4 $D^{(*)}l$ channels are simultaneously fitted.

$D^{(*)}l\nu$ enhanced | $D^{(*)}\tau\nu$ enhanced



- Small backgrounds are fixed, relying MC expectation.
- Events with falsely reconstructed $D^{(*)}$ is determined by sideband of Δm (m_D).

- Total 12 free parameters
  - 4 parameters for $B \to D^{(*)}l\nu$
  - 2 parameters for $R\left(D^{(*)}\right)$ assuming isospin symmetry
  - 2 parameters for cross-feed from $D^{*}l$ to Dl
  - 4 parameters for $B \to D^{**}l\nu$

Fit for $D^* l$ Samples

$B \to D^{(*)}\tau\nu$
with hadronic tag

$D^* l\nu$-enhanced region ($M^2_{miss} < 0.85\ GeV^2/c^4$)

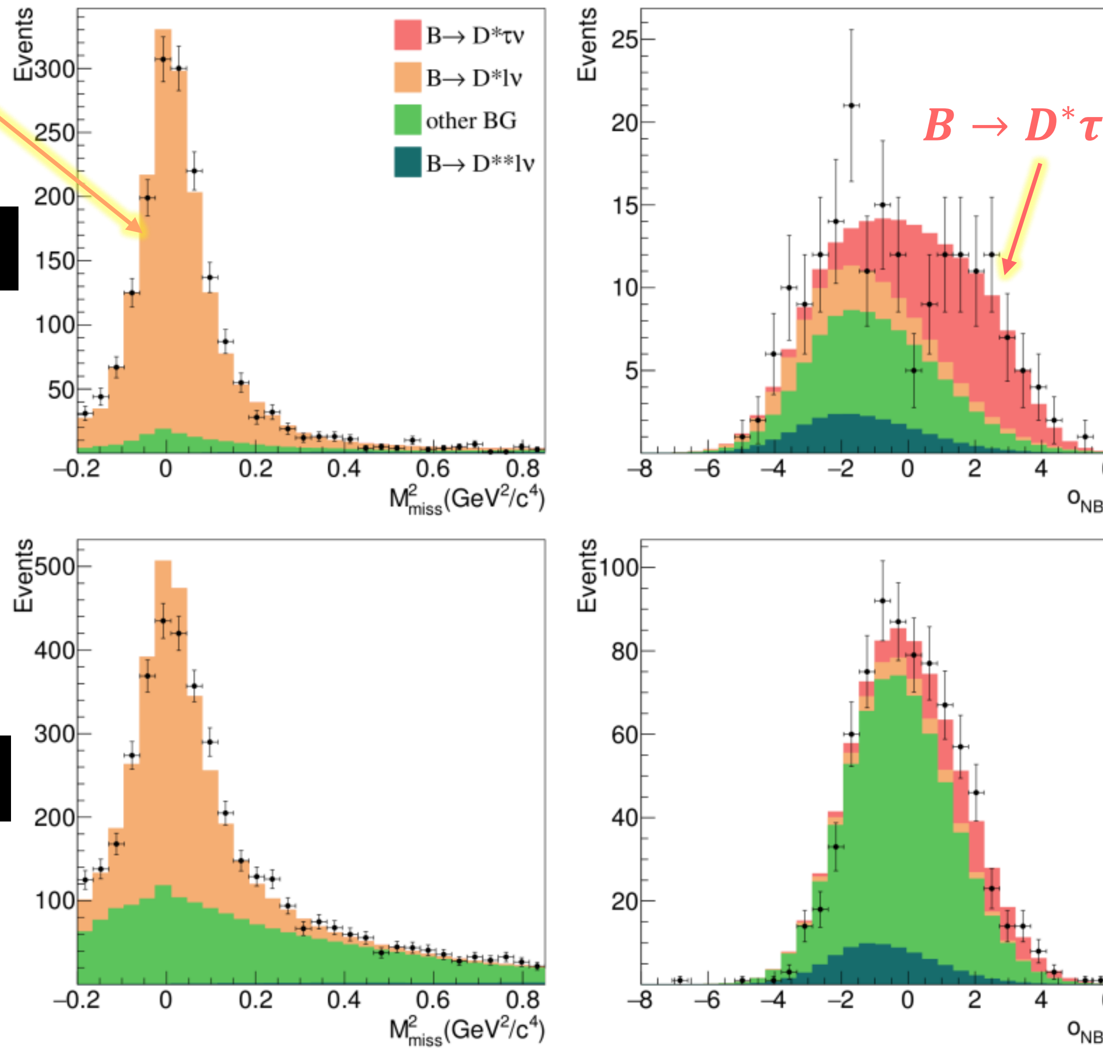
$D^* \tau\nu$-enhanced region ($M^2_{miss} > 0.85\ GeV^2/c^4$)

$B \to D^* l\nu$ (normalization)

$B \to D^* \tau\nu$ (signal)

$D^{*+} l$

$D^{*0} l$



Fit for Dl Samples

$B \to D^{(*)}\tau\nu$
with hadronic tag

$Dl\nu$-enhanced region ($M^2_{miss} < 0.85\ GeV^2/c^4$)

$D\tau\nu$-enhanced region ($M^2_{miss} > 0.85\ GeV^2/c^4$)

$B \to D^* l\nu$ (normalization, CF)

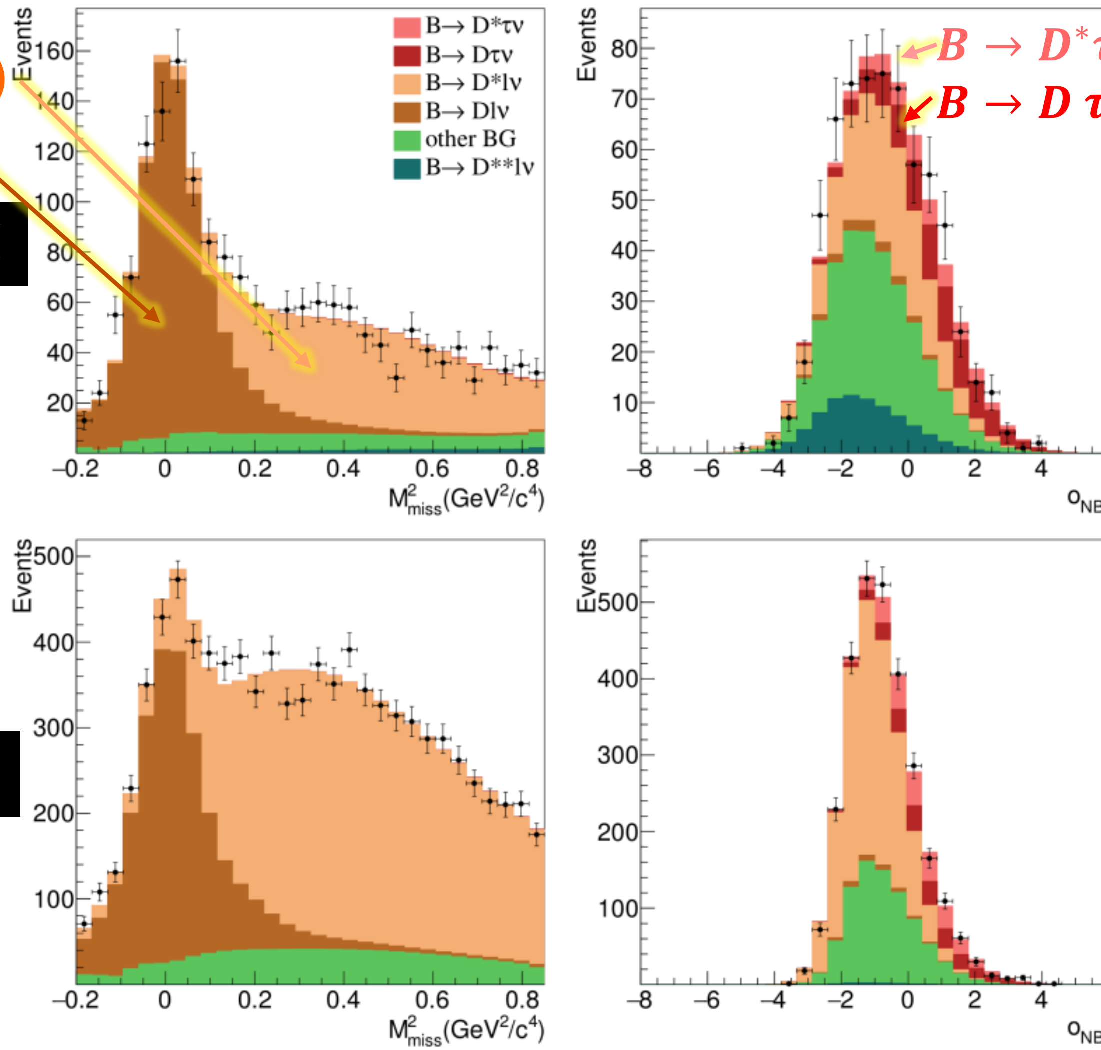
$B \to D\ l\nu$ (normalization)

D^+l

D^0l

$B \to D^*\tau\nu$ (signal, CF)

$B \to D\ \tau\nu$ (signal)

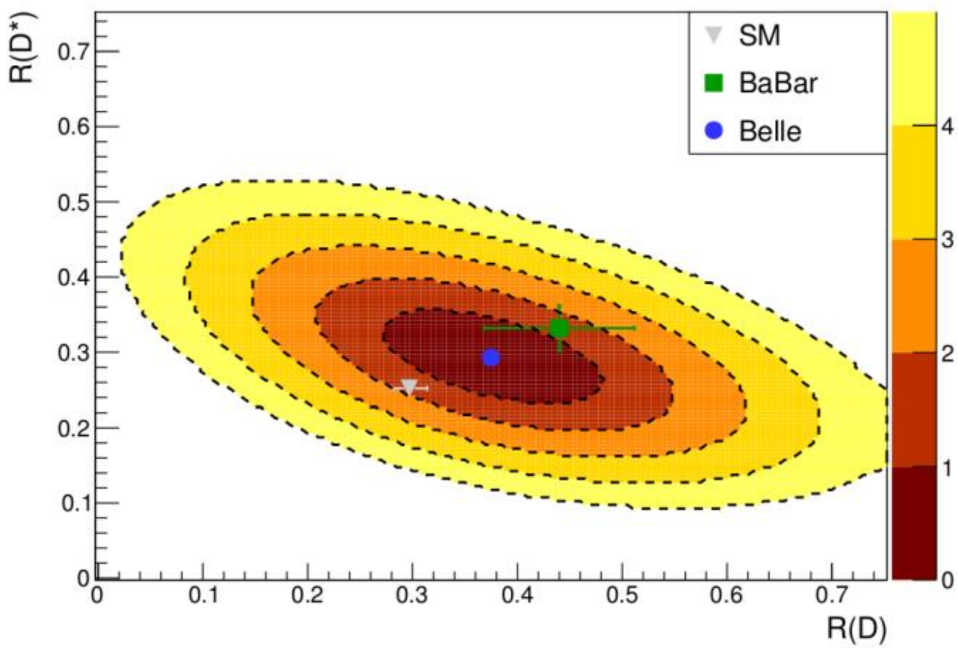


Results

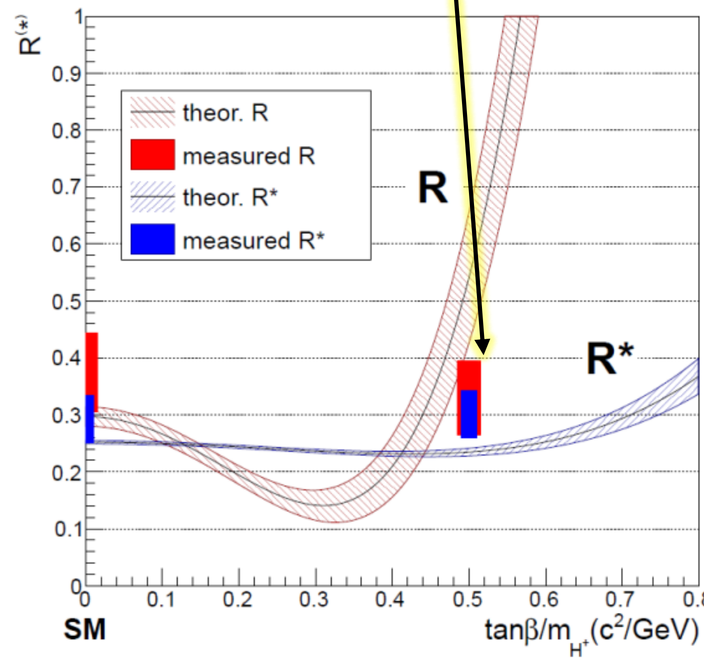
$B \to D^{(*)}\tau\nu$
with hadronic tag

Result

$$R(D) = 0.375^{+0.064}_{-0.063}(\text{stat.}) \pm 0.026(\text{syst.})$$
$$R(D^*) = 0.293^{+0.039}_{-0.037}(\text{stat.}) \pm 0.015(\text{syst.})$$

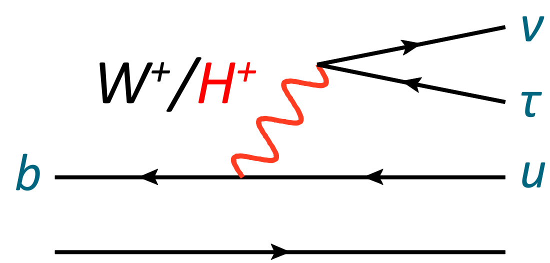


Analysis is repeated for type-II 2HDM with $\tan\beta/m_{H+} = 0.5\ \text{GeV}^{-1}$



- Belle result is consistent with SM and BaBar result within 2σ.

Search for $B \to \pi\tau\nu$



Motivation

- Deviation from SM in $B \to D^{(*)}\tau\nu$ decay.
- $B \to \pi\tau\nu$ can be also used for SM test.
  - Decay amplitude

Vector FF

$$\langle \pi^+(p)|\bar{u}\gamma_\mu b|\bar{B}^0(p+q)\rangle = f^+_{B\pi}(q^2)\left[2p_\mu + \left(\frac{1-m_B^2-m_\pi^2}{q^2}\right)q_\mu\right] + f^0_{B\pi}(q^2)\frac{m_B^2-m_\pi^2}{q^2}q_\mu$$

Scalar FF

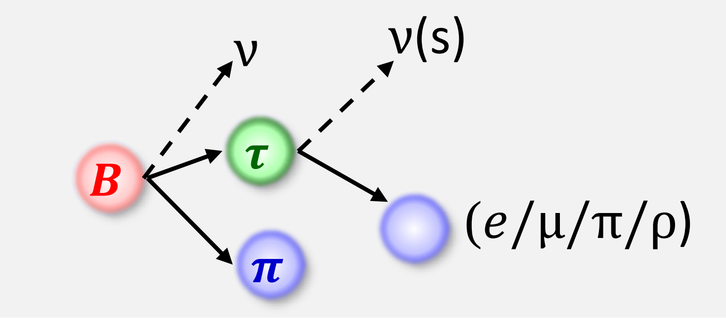
  - $\frac{B(B\to\pi\tau\nu)/dq^2}{B(B\to\pi l\nu)/dq^2}$ only depends on the ratio of form factors : $f^0(q^2)/f^+(q^2)$.

→ Search for first evidence of $B \to \pi\tau\nu$

Analysis

$B \to \pi\tau\nu$
with hadronic tag

Analysis



- B_{tag} is reconstructed by hadronic tag based on Neural network.
- Four one-prong τ decays are used
  - $\tau \to e\nu\nu, \mu\nu\nu, \pi\nu, \rho\nu$
    ($\tau \to \mu\nu\nu$ is only used as veto due to less significance)
- Signal signature
  - exactly 2 oppositely charged tracks in signal side
  - large missing momentum by (two or three) neutrinos

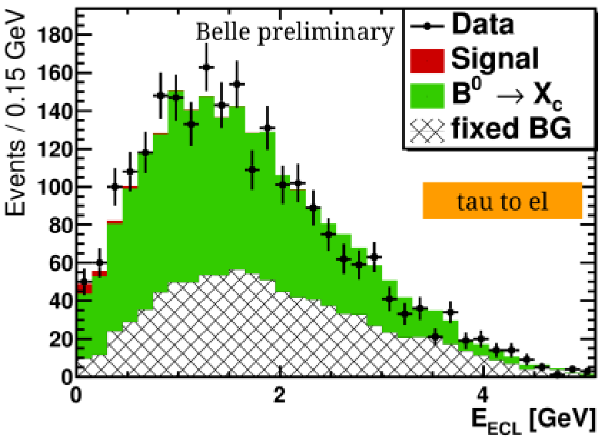
Backgrounds

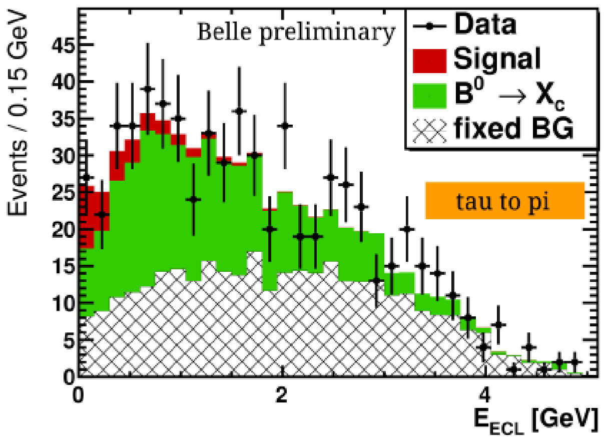
- No remaining tracks and K_L^0 veto.
- $B \to \pi l\nu$ is removed by selection on M_{miss}^2.
- Backgrounds are suppressed using Boosted Decision Trees.
  - Main backgrounds in signal region : $B \to Dl\nu, B \to D\pi$ with $D \to K_L^0\pi$
- Signal is extracted from extra energy on ECL (E_{ECL})

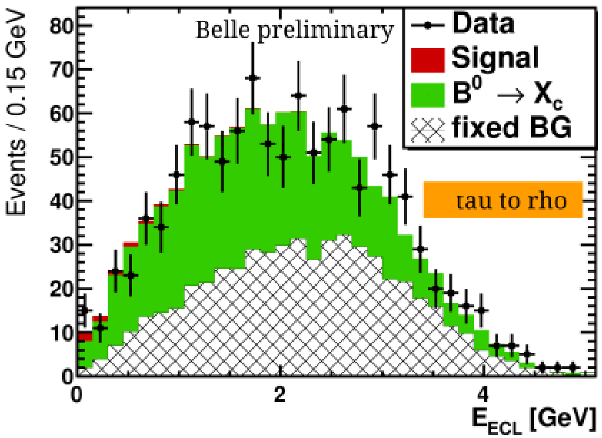
Result

$B \to \pi\tau\nu$
with hadronic tag

- Fit is simultaneously performed in all three modes.
  - 4 fit parameters : 1 parameter for Sig. and 3 parameters for $b \to c$ Bkg.
  - Other background is fixed and systematic uncertainty is estimated.







- Signal yields : 52 ± 24 events
- $\mathcal{B}(B^0 \to \pi\tau\nu) = (1.52 \pm 0.74) \times 10^{-4}$ (stat. only)

→ Close to SM prediction : $(9.35 \pm 0.38) \times 10^{-5}$

→ 2.4 σ significance including systematic uncertainties.

Dominant syst. sources :

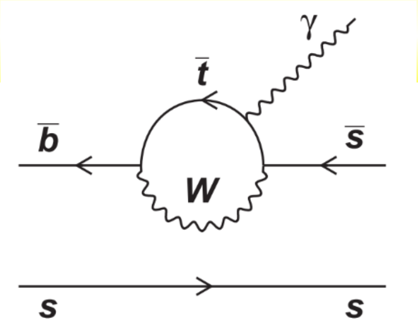
- Tag side efficiency
- K_L^0 veto efficiency

Upper Limits ***Preliminary***

$\mathcal{B}(B^0 \to \pi\tau\nu) < 2.5 \times 10^{-4}$ @ 90% C.L.

$\mathcal{B}(B^0 \to \pi\tau\nu) < 2.8 \times 10^{-4}$ @ 95% C.L.

$B_s \to \phi\gamma, \gamma\gamma$



$B_s \to \phi\gamma$

- First observation by Belle *PRL 100, 121801 (2008) (23.6 fb^{-1})*

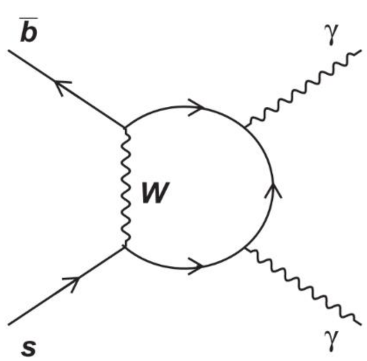
→ Update with full Belle data (121.4 fb^{-1})

- Theoretical prediction is 4×10^{-5} with 30% uncertainty *Eur. Phys. J.C 55, 577 (2008)* *PRD 75, 054004 (2007)*
- Most precise measurement by LHCb : $(35.1 \pm 3.5 \pm 1.2) \times 10^{-6}$ *Nucl. Phys. B867, 1 (2013)*

$B_s \to \gamma\gamma$

- Current best upper limits : 8.7×10^{-6} @ 90% C.L. by Belle. *PRL 100, 121801 (2008) (23.6 fb^{-1})*
- Theoretical predictions
  - $(2 - 8) \times 10^{-7}$ *PRD 56, 5805 (1997)*
  - $(1.8 \pm 0.4) \times 10^{-7}$ *PRD 85, 014008 (2012)*
  - 1.23×10^{-6} *JHEP 08, 054 (2002)*
- In R-parity violating model, it may be enhanced.

→ Search for first evidence with full Belle data (121.4 fb^{-1})



Result of $B_s \to \phi\gamma$

$B_s \to \phi\gamma$

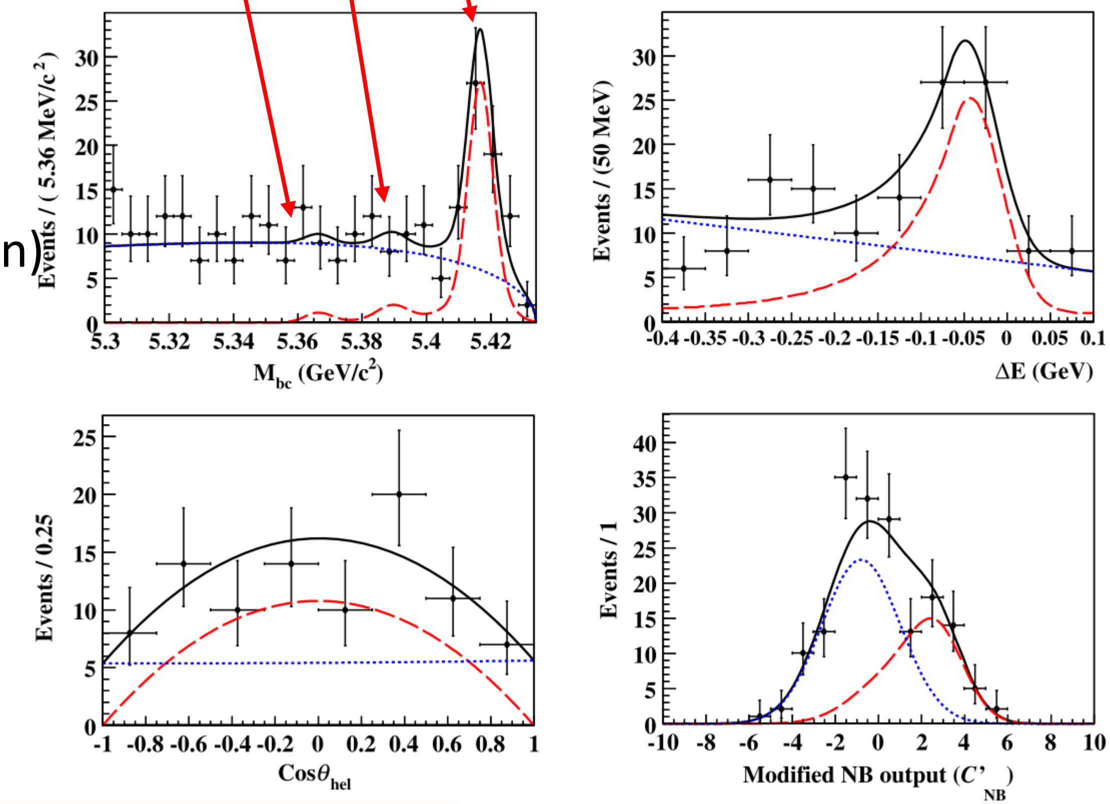
- 4-dimensional fit
  - $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{B_S}|^2}$
  - $\Delta E = E_{B_S} - E_{\text{beam}}$
  - C'_{NB}
    (Neural network output
    for continuum suppression)
  - $\cos\theta_{\text{hel}}$ (ϕ helicity angle)

- $N_{\text{sig}} = 91^{+14}_{-13}$

Three signal peaks

$(B_s B_s,\ B_s^* B_s,\ B_s^* B_s^*)$

$f_s = (17.2 \pm 3.0)\%$,
$f_{B_s^* \bar{B}_s^*} = (87.0 \pm 1.7)\%$
$f_{B_s^* \bar{B}_s} = (7.3 \pm 1.4)\%$



Result

$\mathcal{B}(B_s \to \phi\gamma) = (36 \pm 5(\text{stat.}) \pm 3(\text{syst.}) \pm 6(f_s)) \times 10^{-6}$

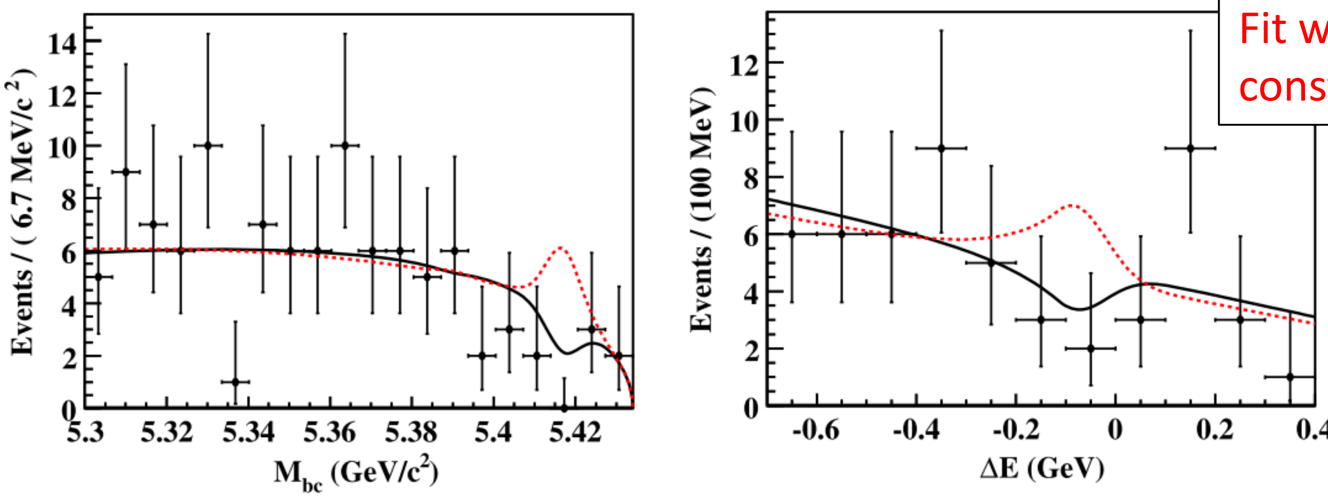
(10.7σ significance including systematics)

Consistent with theoretical prediction and LHCb result.

Result of $B_s \to \gamma\gamma$

$B_s \to \gamma\gamma$

- 2-dimensional fit $(M_{bc}, \Delta E)$
- Dominant backgrounds of continuum $(ee \to qq\ (q = u, d, s, c))$ are suppressed by neural network output
  - Modified Fox-Wolfram moments and thrust angle are used.



Best fit line ($N_{sig} = -3.9^{+3.7}_{-2.6}$)

Fit with the signal yield constrained to U.L. (90% C.L.)

Upper Limits

$\mathcal{B}(B_s \to \gamma\gamma) < 3.1 \times 10^{-6}$ @ 90% C.L.

$A_{CP}(B \to X_{s+d}\gamma)$

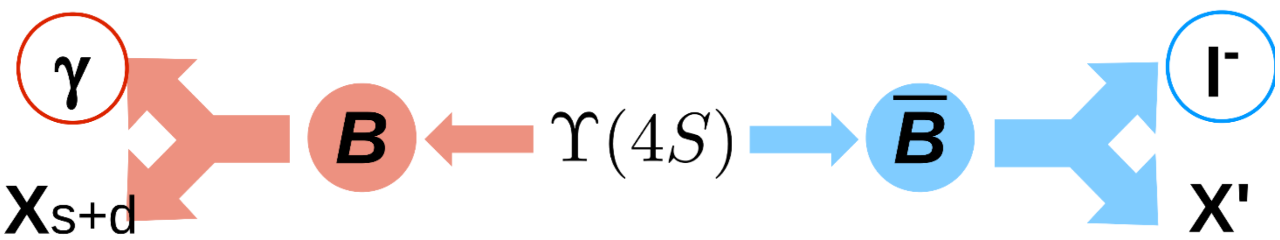
- $A_{CP} = \frac{\Gamma(\bar{B}\to X_{\bar{s}+\bar{d}}\gamma)-\Gamma(B\to X_{s+d}\gamma)}{\Gamma(\bar{B}\to X_{\bar{s}+\bar{d}}\gamma)+\Gamma(B\to X_{s+d}\gamma)}$
  - Cancellation due to CKM unitarity,
  - Negligible theory error

channel	$A_{CP}(SM)$
$B \to X_s\gamma$	$[-0.6\%, +2.8\%]$
$B \to X_d\gamma$	$[-62\%, +14\%]$
$B \to X_{s+d}\gamma$	0

@ PRL 106, 141801 (2011)

Inclusive analysis

- Only reconstruct photon and charged lepton for tagging.
  - $1.7 < E^*_\gamma < 2.8$ GeV
  - $1.10 < p^*_l < 2.25$ GeV/c



- $A_{CP} = \frac{N^+-N^-}{N^++N^-}$ (using tag-lepton)

Wrong Tag Fraction and Corrections

$A_{CP}(B \to X_{s+d}\gamma)$

- Measured A_{CP}^{meas} is corrected for various effects.

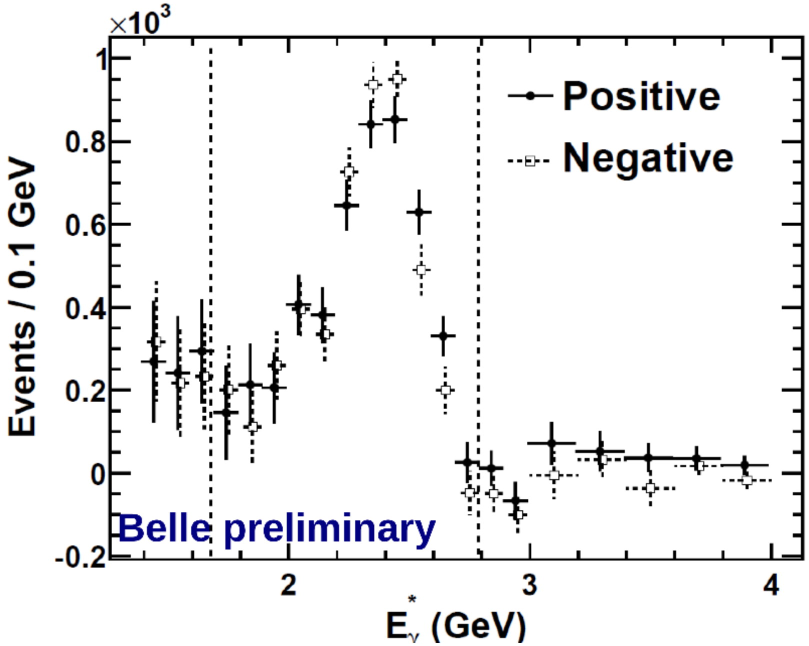
$$A_{CP}^{\text{true}} = \frac{1}{1-2w}\left(A_{CP}^{\text{meas}} - A_{\text{bkg}} - A_{\text{det}}\right)$$

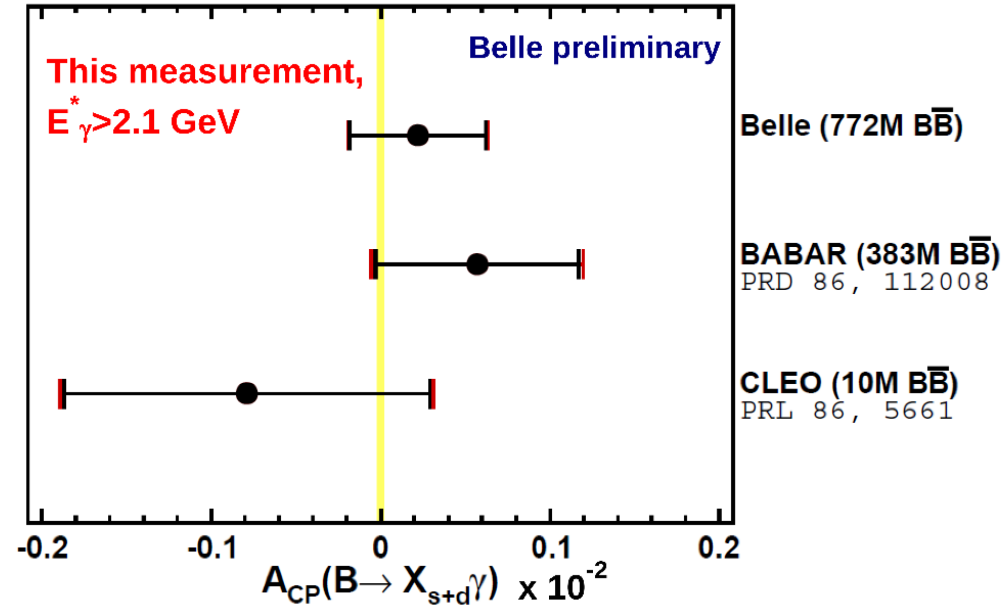
1. **Wrong tag factor** : $w = 0.1332 \pm 0.0052$
   - $B\bar{B}$ mixing
   - lepton from D decays
   - K/π miss-identified as lepton
2. **Asymmetry from detector** : $A_{\text{det}} = (0.10 \pm 0.22)\%$
   - Lepton ID, tracking
3. **Asymmetry from BB bkg** : $A_{\text{bkg}} = (-0.14 \pm 0.78)\%$
   - Low E_γ region (E_γ < 1.7 GeV) in data

Result

$A_{CP}(B \to X_{s+d}\gamma)$

Spectrum after bkg subtraction





- Measure as function of E_γ threshold.

  $A_{CP}(B \to X_{s+d}\gamma) = (2.23 \pm 4.02 \pm 0.78)\%$ with $E_\gamma^* > 2.1$ GeV

  – Consistent with SM.

  – Most precise measurement of $A_{CP}(B \to X_{s+d}\gamma)$.

  – Statistically dominated

  – Leading systematic comes from BB bkg asymmetry

Summary

- Various B decays are sensitive to new physics.
  - New particles such as SUSY particles might enter in the loop diagrams.
  - Charged Higgs might contribute in addition to the W boson.

1. $B \to D^{(*)}\tau\nu$ with hadronic tag (arXiv:1507.03233, submitted to PRD)
2. $B \to \pi\tau\nu$ with hadronic tag
3. $B_s \to \phi\gamma, \gamma\gamma$ (PRD 91, 011101(R)(2015))
4. $A_{\mathrm{CP}}(B \to X_{s+d}\gamma)$ (PRL 114, 151601 (2015))

- There are many SUSY-related results not covered in this talk an a lot of ongoing analysis.

Backup

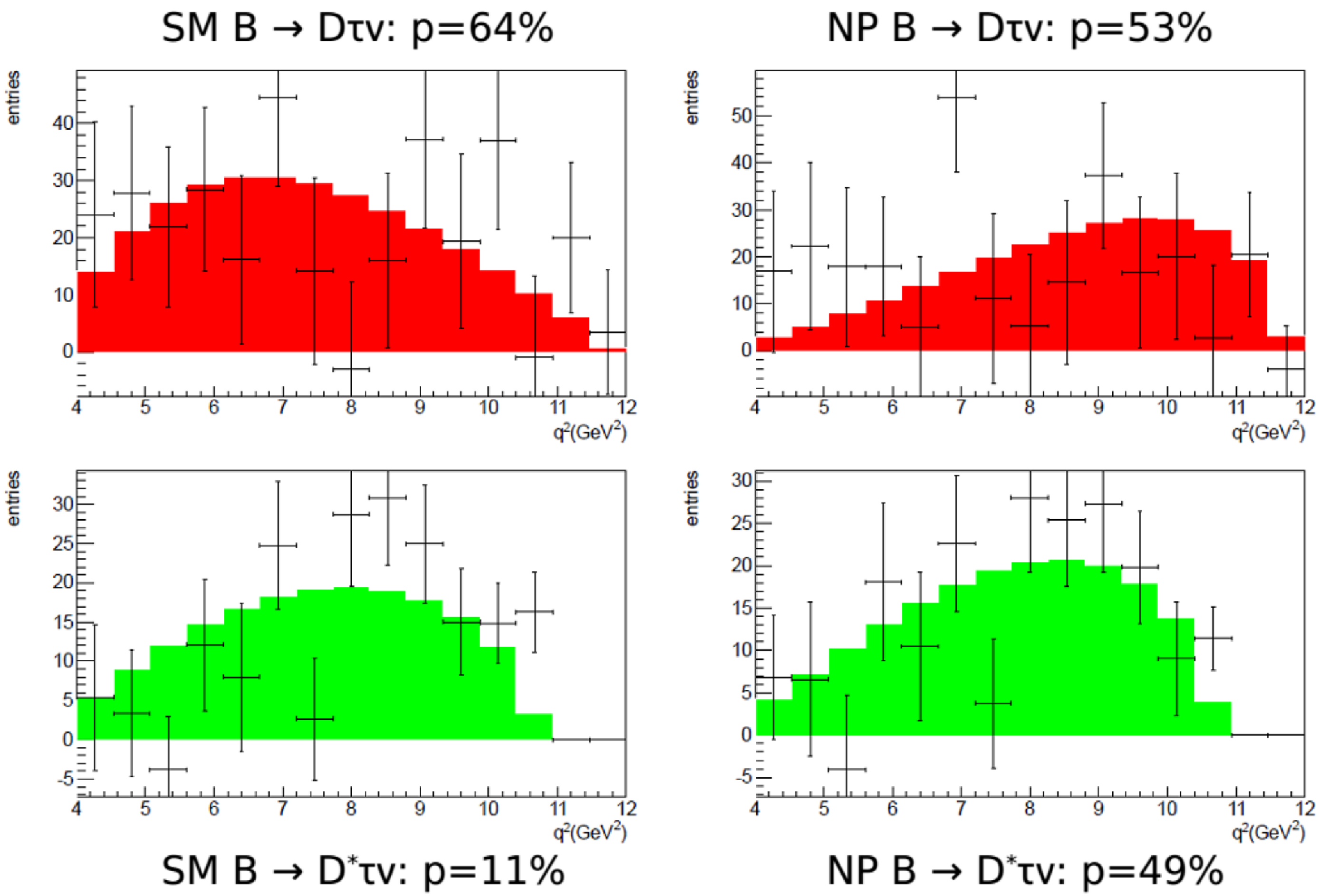
$B \to D^{(*)}\tau\nu$ with Hadronic Tag

- Neurobayes input
  - M_{miss}^2
  - E_{ECL}
  - q^2, p_l^{CM}
  - # of unused π^0 with $|S_{\gamma\gamma}| < 5$
  - Angle between $D^{(*)}$ momentum and vertex direction
  - $B/D^{(*)}$ decay channel identifiers

$B \to D^{(*)}\tau\nu$ with Hadronic Tag

$B \to D^{(*)}\tau\nu$ Hadronic tagging

q^2 distributions in SM and in 2HDM type-II

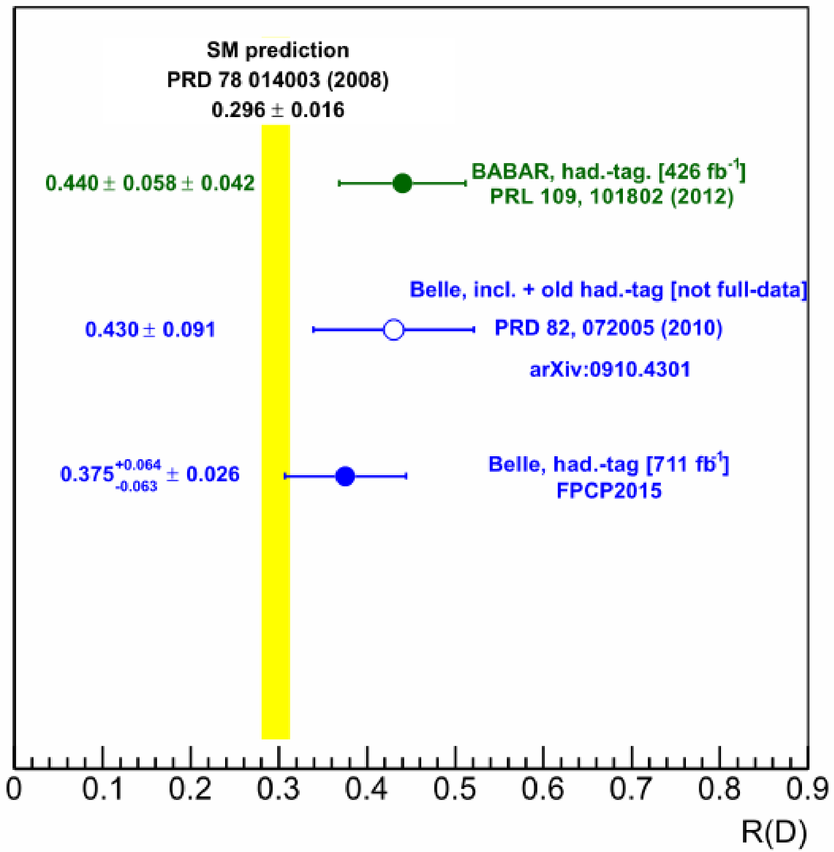


$B \to D^{(*)}\tau\nu$ with Hadronic Tag

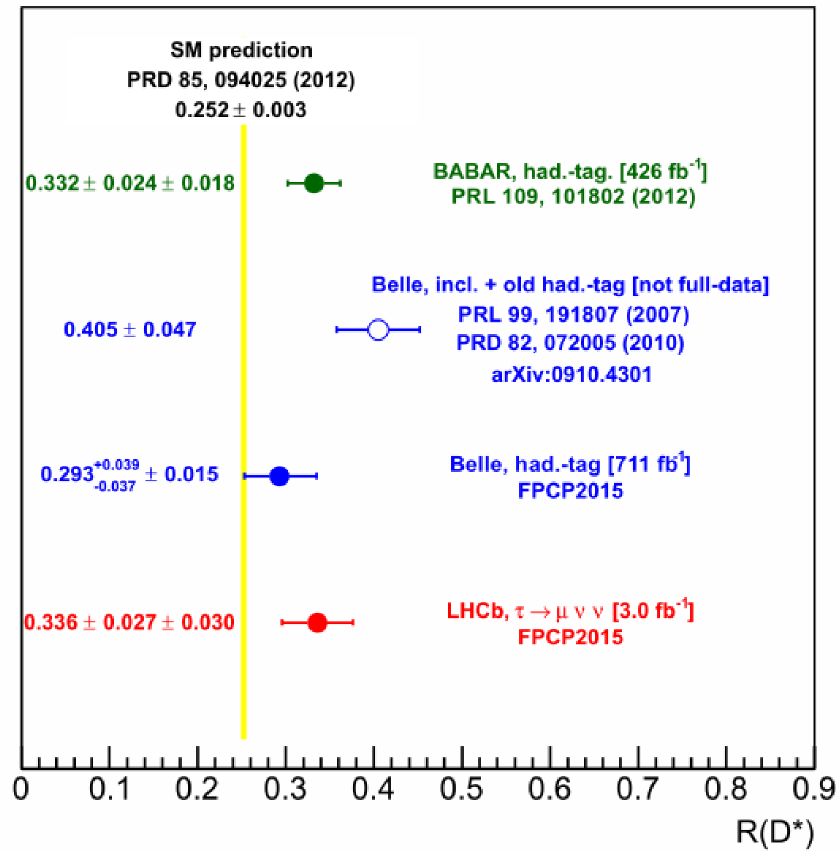
	R [%]	R^* [%]	correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
wrong charge factor	0.0	0.0	0.84
$Y_{D^+\ell^-,D_s}$	0.1	0.0	-0.95
$Y_{D^+\ell^-,\mathrm{rest}}$	0.1	0.0	-0.92
$Y_{D^+\ell^-,\mathrm{wrong}D}$	0.4	0.1	-0.99
$Y_{D^+\ell^-,\mathrm{wrong}\ell}$	0.3	0.1	-0.99
$Y_{D^0\ell^-,D_s}$	0.0	0.0	0.81
$Y_{D^0\ell^-,\mathrm{rest}}$	0.0	0.0	0.60
$Y_{D^0\ell^-,\mathrm{wrong}D}$	0.3	0.2	0.96
$Y_{D^0\ell^-,\mathrm{wrong}\ell}$	0.2	0.1	0.98
$Y_{D^{*+}\ell^-,D_s}$	0.1	0.1	-1.00
$Y_{D^{*+}\ell^-,\mathrm{rest}}$	0.0	0.0	-0.99
$Y_{D^{*+}\ell^-,\mathrm{wrong}D^*}$	0.1	0.1	-1.00
$Y_{D^{*+}\ell^-,\mathrm{wrong}\ell}$	0.3	0.5	-1.00
$Y_{D^{*0}\ell^-,D_s}$	0.0	0.0	-0.99
$Y_{D^{*0}\ell^-,\mathrm{rest}}$	0.0	0.0	-0.96
$Y_{D^{*0}\ell^-,\mathrm{wrong}D^*}$	0.1	0.1	-0.83
$Y_{D^{*0}\ell^-,\mathrm{wrong}\ell}$	0.1	0.2	-1.00
g_{B^0}	2.2	2.0	-1.00
g_{B^+}	1.7	1.0	-1.00
f_{R,B^0}	2.5	0.7	-0.98
f_{R,B^+}	1.8	0.4	0.86
f^*_{R,B^0}	1.3	2.5	-0.99
f^*_{R,B^+}	0.7	1.1	0.94
M^2_{miss} shape	0.6	1.0	0.00
$o_{\mathrm{NB,trafo}}$ shape	3.2	0.8	0.00
lepton PID efficiency	0.5	0.5	1.00
Σ	7.1	5.2	-0.32

state	uncertainty in %
D_2^*	42.3
D_0^*	34.6
D_1	14.9
D_1'	36.2
$D(2S)$	100.0
$D^*(2S)$	100.0

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

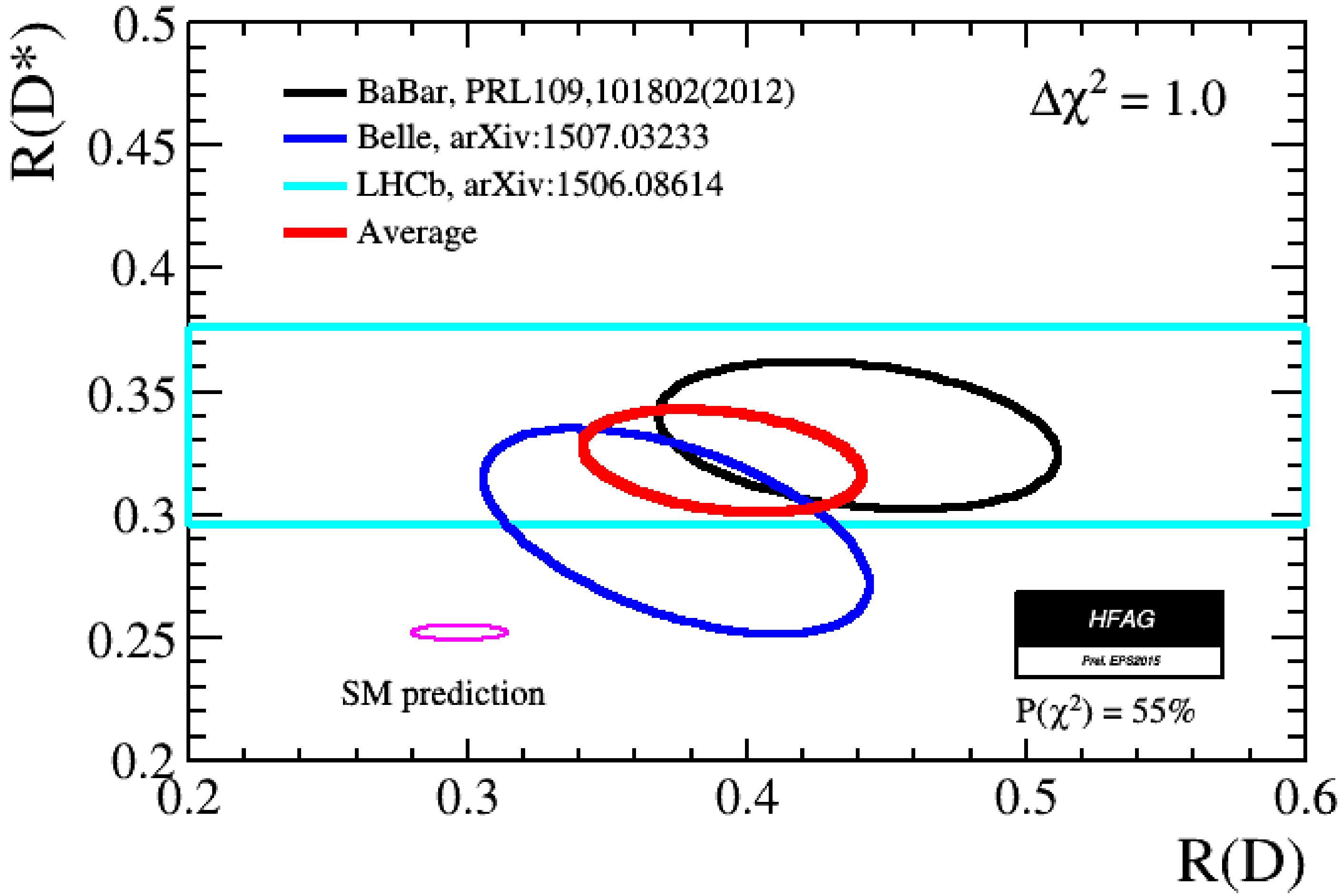


SM prediction
PRD 78 014003 (2008)
0.296 ± 0.016
0.440 ± 0.058 ± 0.042
BABAR, had.-tag. [426 fb-1]
PRL 109, 101802 (2012)
Belle, incl. + old had.-tag [not full-data]
0.430 ± 0.091
PRD 82, 072005 (2010)
arXiv:0910.4301
0.375 +0.064 -0.063 ± 0.026
Belle, had.-tag [711 fb-1]
FPCP2015
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
R(D)



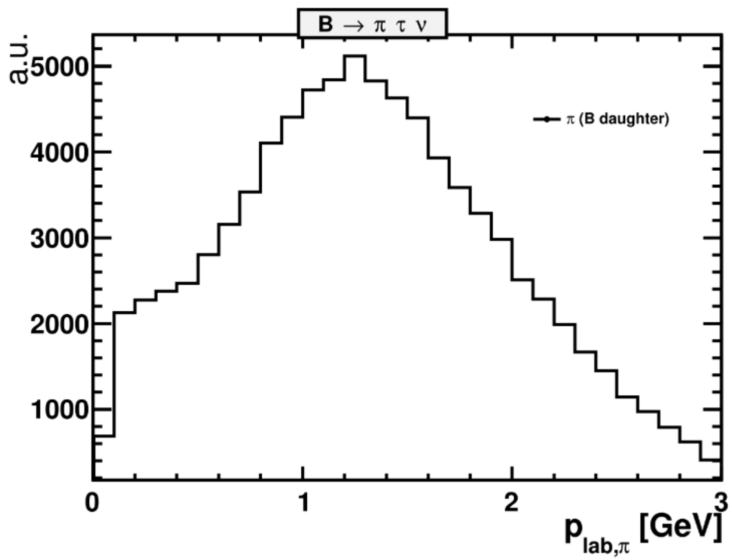
SM prediction
PRD 85, 094025 (2012)
0.252 ± 0.003
0.332 ± 0.024 ± 0.018
BABAR, had.-tag. [426 fb-1]
PRL 109, 101802 (2012)
Belle, incl. + old had.-tag [not full-data]
0.405 ± 0.047
PRL 99, 191807 (2007)
PRD 82, 072005 (2010)
arXiv:0910.4301
0.293 +0.039 -0.037 ± 0.015
Belle, had.-tag [711 fb-1]
FPCP2015
0.336 ± 0.027 ± 0.030
LHCb, τ → μ ν ν [3.0 fb-1]
FPCP2015
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
R(D*)

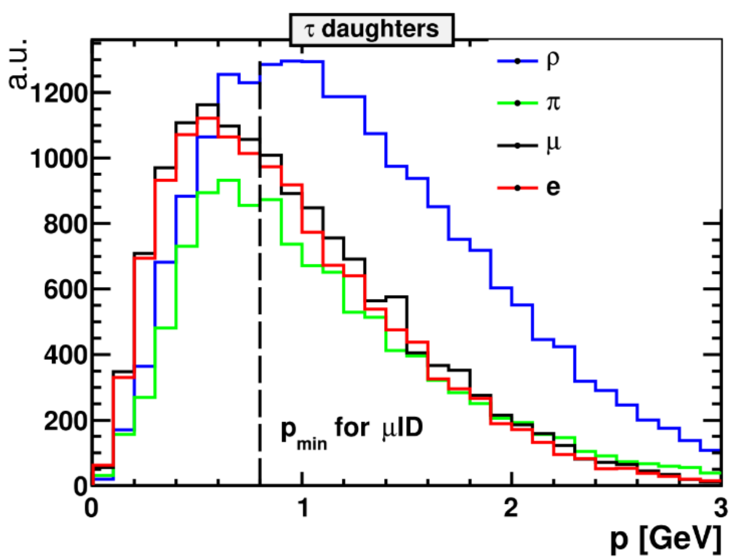
$B \to D^{(*)}\tau\nu$



R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
R(D)
BaBar, PRL109,101802(2012)
Belle, arXiv:1507.03233
LHCb, arXiv:1506.08614
Average
Δχ² = 1.0
SM prediction
HFAG
Prel. EPS2015
P(χ²) = 55%

$B \to \pi\tau\nu$ with Hadronic Tag





Mode	Signal Yield
e	13.2 ± 6.2
π	30.6 ± 14.3
ρ	8.1 ± 3.8
Total	51.9 ± 24.3

systematic	σ	$\Delta\sigma = \sigma_{\rm none} - \sigma_{\rm syst}$	$\lvert\Delta\sigma\rvert$ [%]
none	2.74		
eID	2.69	−0.05	1.81
πID	2.55	−0.19	6.87
π^0 ID	2.67	−0.07	2.47
slow π^0	2.77	+0.03	1.22
K_L veto	2.68	−0.06	2.15
track efficiency	2.60	−0.14	5.11
slow tracks	2.48	−0.25	9.25
finite MC	2.43	−0.31	11.31
background fit	2.46	−0.28	10.22
BG $\mathcal{B}$	2.43	−0.30	11.13
V_{ub}	2.51	−0.22	8.22
signal model	2.54	−0.20	7.33
$D^{(*)}\ell\nu$ model	2.60	−0.14	5.11
tagside	2.57	−0.17	6.14
$B \to X_u\tau\nu$	2.60	−0.13	4.84
$\sqrt{\sum(\Delta\sigma)^2}$		0.74	27.18