Semileptonic and Leptonic *B* Decays

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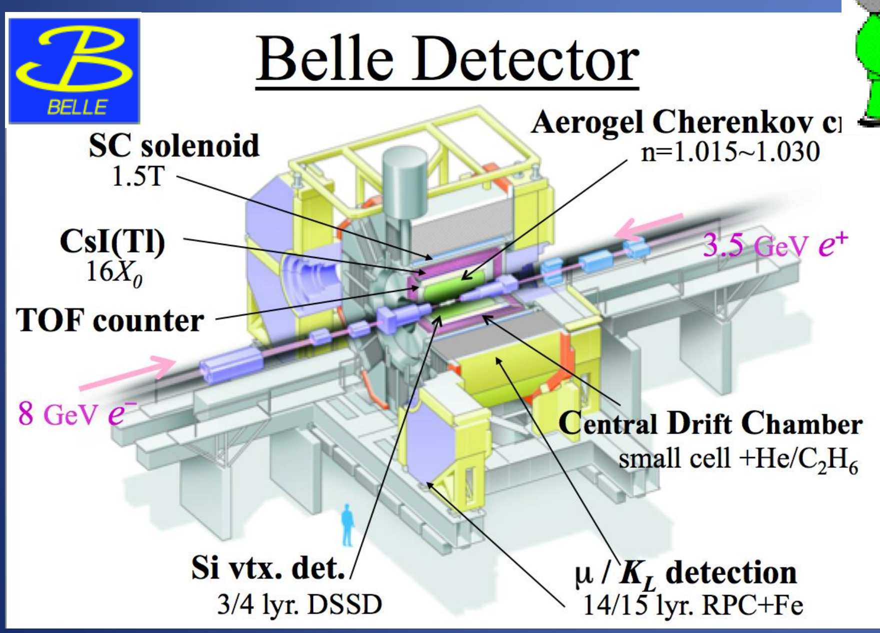
Introduction

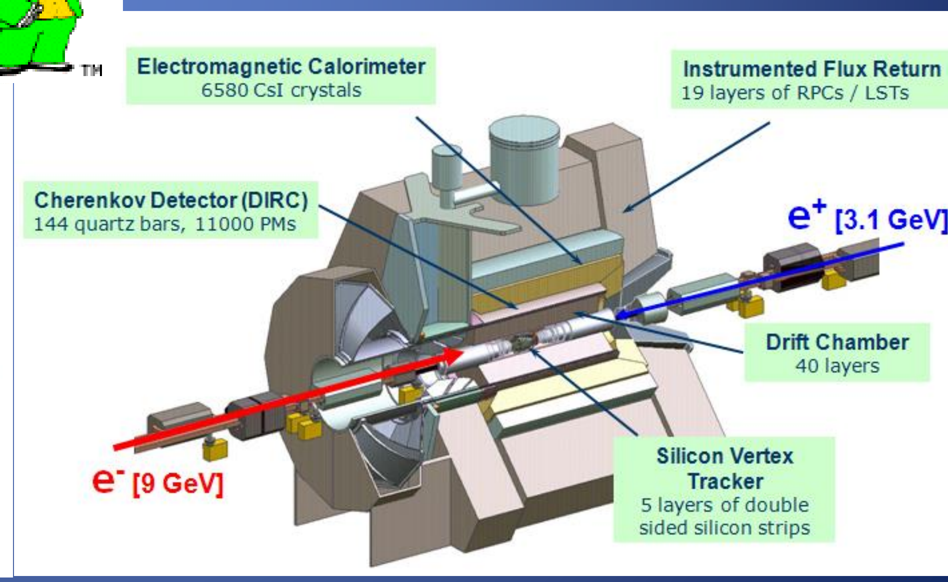
- Flavor physics is mainly to test CKM.
  - Measure CKM parameters using various ways
  - Check consistency and look for anomalies
- Probe new physics directly (low mass dark photons) or indirectly (off-mass contribution)
- Hadron collider and B factory are complementary.

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

Dual of two B Factories

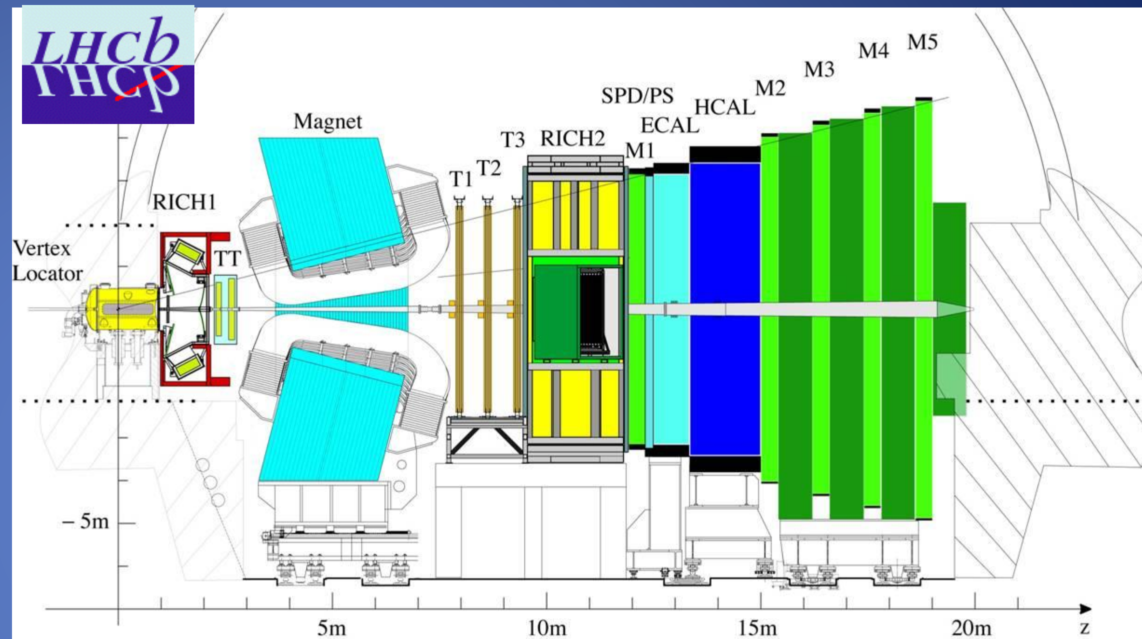
- Run at $\Upsilon(4S) \rightarrow B^0\bar{B}^0/B^+B^-$ and $\Upsilon(5S) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$
- Clean environment; active particle identification
- Good performance to detect neutrals and neutrinos

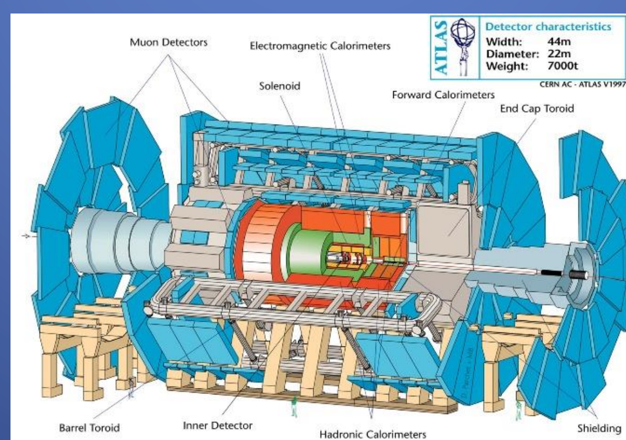


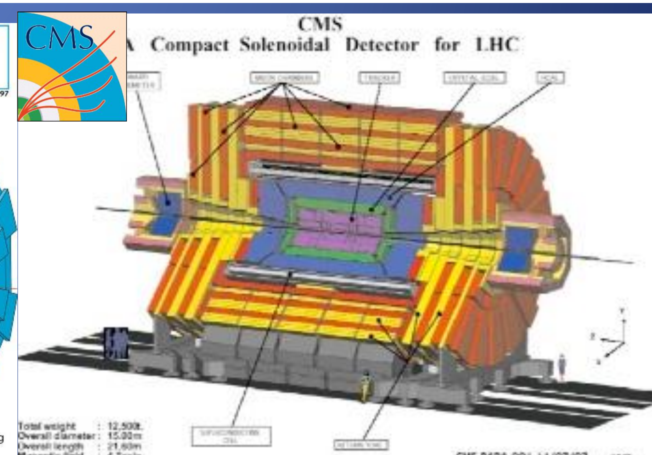


Large Hadron Collider

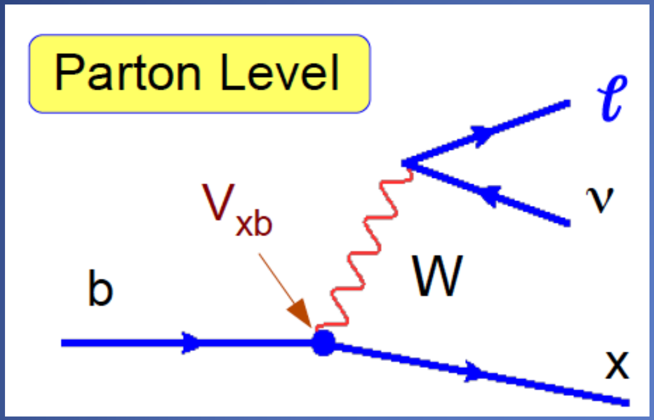
- Large $b\bar{b}$ cross section
- Decays with neutrals or neutrinos are difficult.
- Large boost & excellent vertex detector
- LHCb
  - Active PID
  - Fixed-target type
- CMS and ATLAS
  - General purpose detector
  - Di-muon trigger

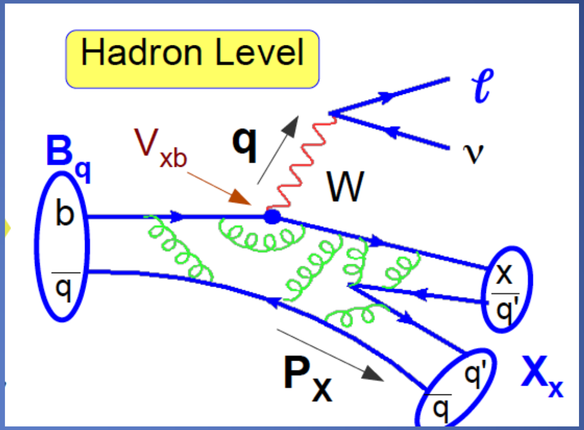






$|V_{cb}|$ and $|V_{ub}|$



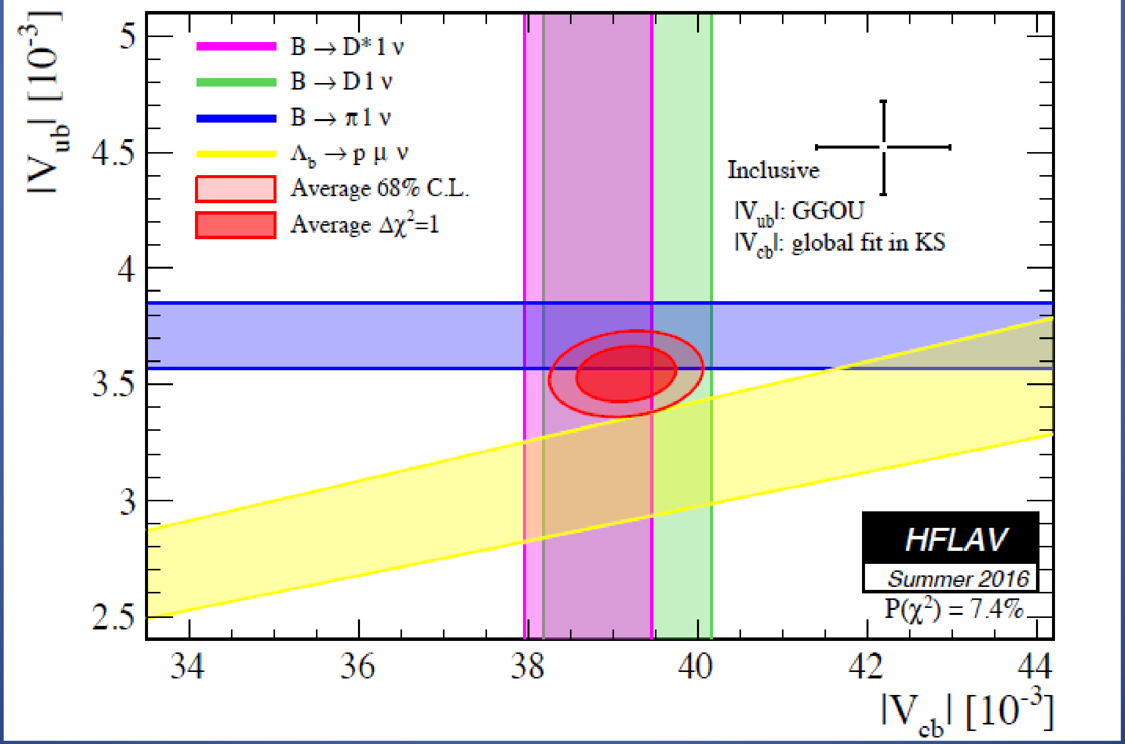


- Inclusive decays: $X_{c,u}\ell\boldsymbol{\nu}$
  - QCD correction for parton level decay rate.
  - Operator product expansion in α_s and Λ/m_b
- Exclusive decays: $D^{(*)}\ell\boldsymbol{\nu}, \pi\ell\boldsymbol{\nu}, \rho\ell\boldsymbol{\nu}$ …
  - QCD contributions parametrized in form factors
  - Lattice QCD for low q^2 and LCSR for high q^2

Puzzle

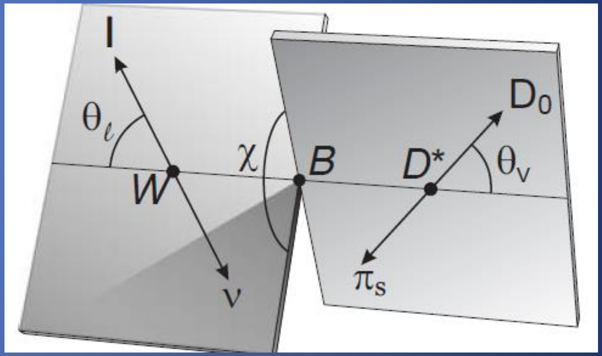
- $|V_{cb}| = (40.5 \pm 1.5) \times 10^{-3}$, 2.9σ discrepancy
  $|V_{ub}| = (4.09 \pm 0.39) \times 10^{-3}$, 2.6σ discrepancy

PDG 2016



New Measurements

- $|V_{cb}|$: $B \to D^* \ell \nu$ Belle 2018 Preliminary
- $|V_{ub}|$: Inclusive $B \to X_{\boldsymbol{u}} e \nu$ BaBar 2017
- $|V_{ub}|$: $B \to \eta^{(\prime)} \ell \nu$ Hadronic tag Belle 2017
- Exclusive $B^0 \to D^{*-} \ell^+ \nu_\ell$



$$w = \frac{M_B^2 + M_{D^*}^2 - q^2}{2M_B\, M_{D^*}}$$

Differential decay rate

$$\frac{d\Gamma(B \to D^{*-}\ell^+\nu_\ell)}{dw d\cos\theta_\ell d\cos\theta_\nu dx} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} F(w, \theta_\ell, \theta_\nu, x) G(w)$$

B to D^* form factor

Phase space

$B \to D^* \ell \nu$ untagged

- Form factors

1. Caprini, Lelouch, Neubert (CLN) arXiv: hep-ph/9712417

   Using theoretical assumptions to reduce number of free parameters that describe form factors. $\Rightarrow$ for small data set

   $F(w, \theta_\ell, \theta_\nu, x) \Rightarrow$ fit four parameter distributions to extract three variables, $R_1(w), R_2(w), \rho(w)$

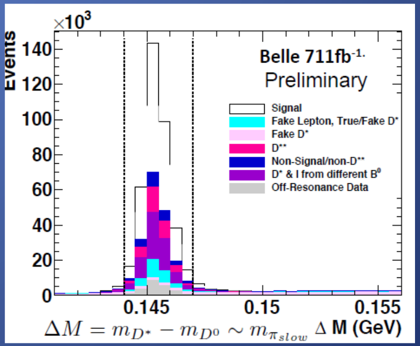
2. Buyd, Grinstein, Lebed (BGL) arXiv:hep-ph/9504235

   $F(w, \theta_\ell, \theta_\nu, x)$ is written in the most generic parameterization with minimal assumptions

- Data sample

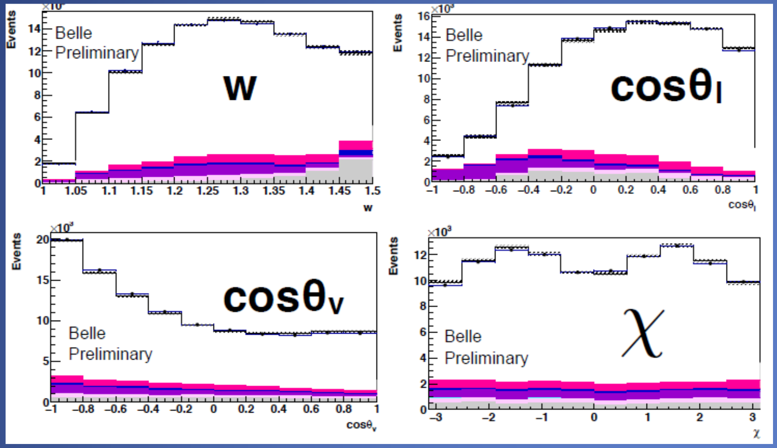
  $\mathrm{N}(D^* e\nu) = 91381$

  $\mathrm{N}(D^* \mu\nu) = 89965$



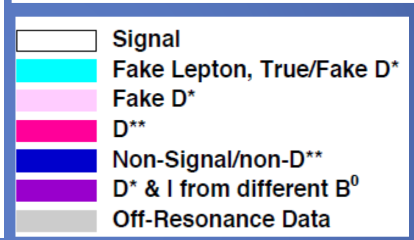
Fit Results

- $|V_{cb}|$ from CLN Fit to extract $\rho^2, R_1(1), R_2(1)$ and $F(1)|V_{cb}|$.

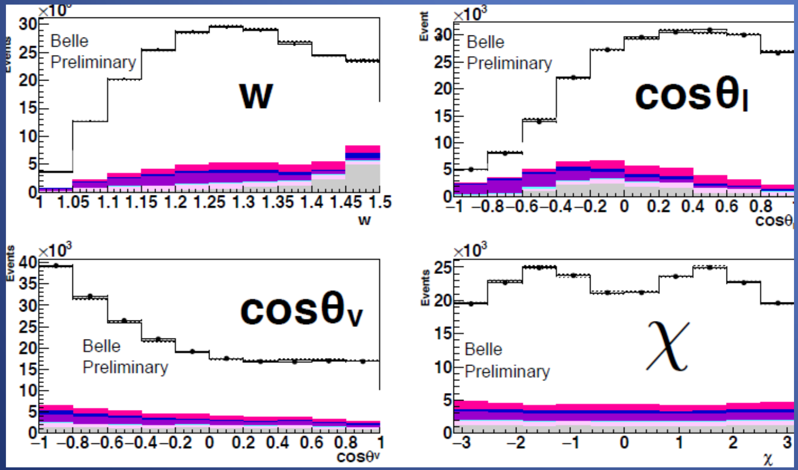


F(1)|Vcb|ηEW 10³= 35.1 ± 0.2 ± 0.5

$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.86 \pm 0.02 \pm 0.15)\%$



- $|V_{cb}|$ from BGL Fit to extract coefficients of expansions and $F(1)|V_{cb}|$.



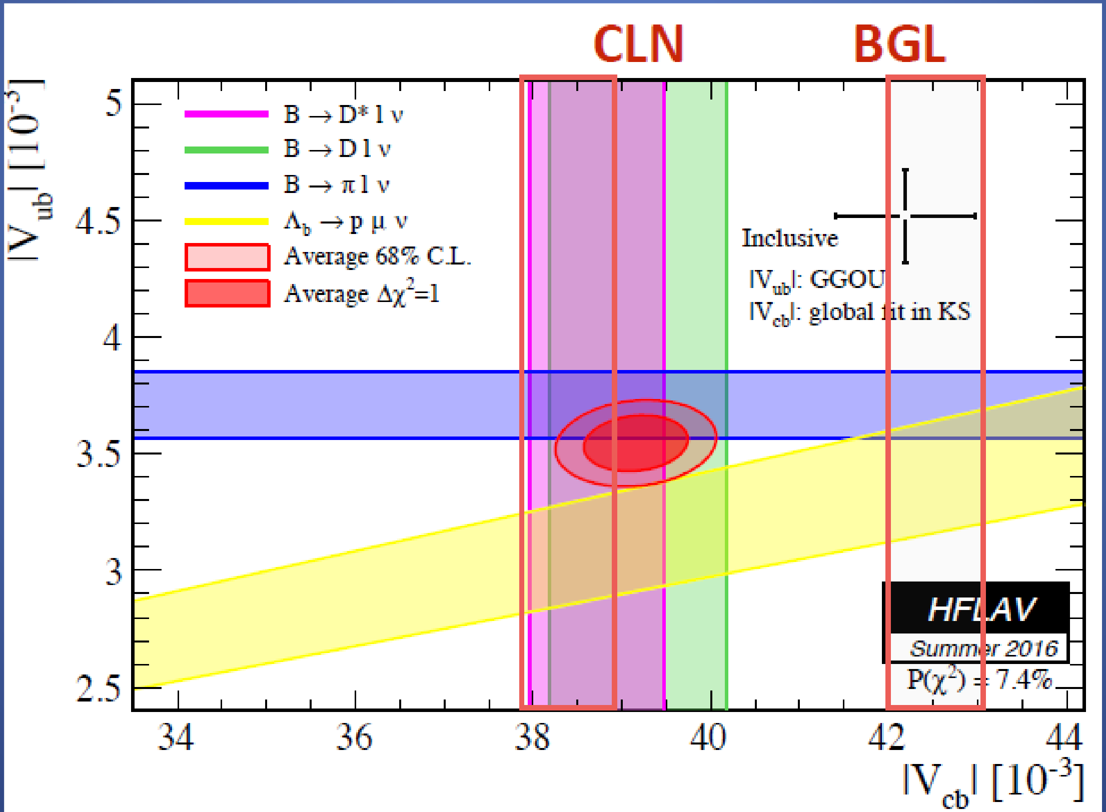
Parameters	Value
$\tilde{a}_0^f \times 10^2$	0.05635 ± 0.0004
$\tilde{a}_1^f \times 10^2$	-0.0701 ± 0.01834
$\tilde{a}_1^F \times 10^2$	-0.0276 ±0.0071
$\tilde{a}_2^F \times 10^2$	-0.3242 ±0.1388
$\tilde{a}_0^g \times 10^2$	-0.1037± 0.0020

F(1)|Vcb|ηEW 10³= 38.7 ± 0.3 ± 0.6

New $|V_{cb}|$ Results

Preliminary

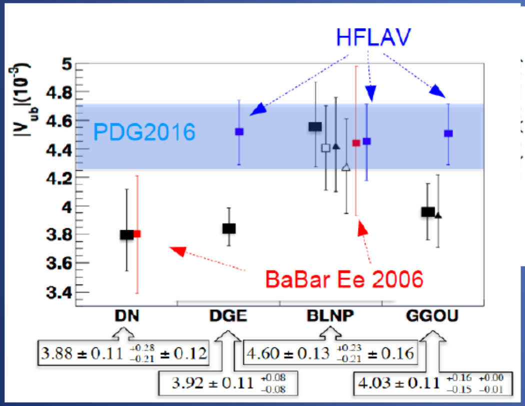
- $|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$ Inclusive
- $|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$ Exclusive (BGL)
- $|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$ Exclusive (CLN)

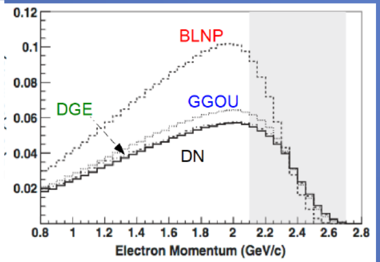


$|V_{ub}|$

PRD95, 072001 (2017)

- Untagged inclusive $X_u \ell \nu$
  - update of el. endpoint analysis
  - Use on- and off-resonance data
  - Fit on electron momentum with $X_u \ell \nu$ and $X_c \ell \nu$ compon.
  - 4 theoretical framework



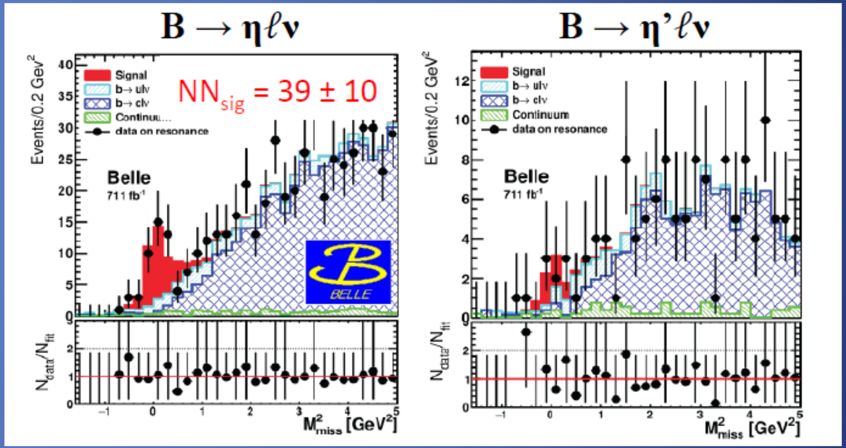


Lower $|V_{ub}|$ value except for BLNP

PRD96, 091102 (2017) b

- Search for $B \to \eta^{(\prime)} \ell \nu$
  - Understand $B \to X_u \ell \nu$
  - Hadronic tag

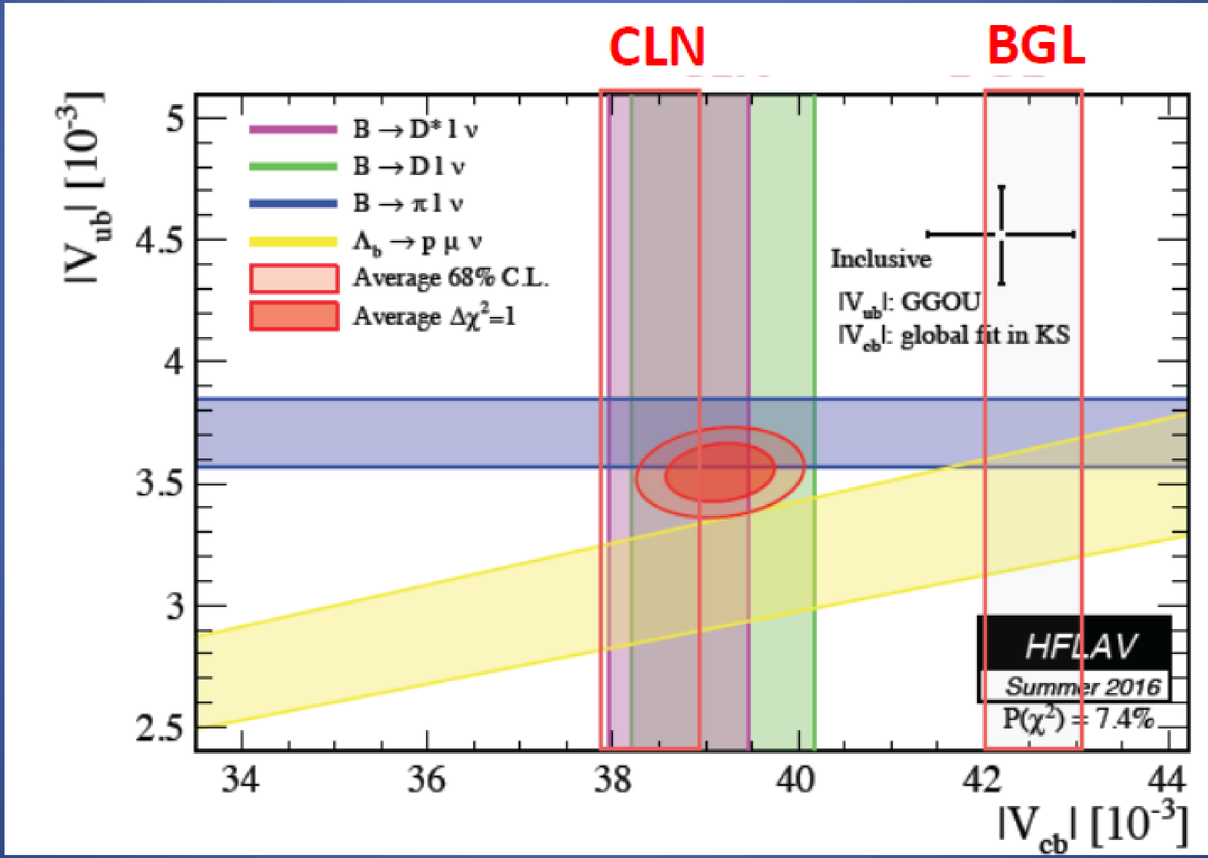
3.7σ



$$\mathcal{B}(B \to \eta \ell \nu) = (4.2 \pm 1.1 \pm 0.3) \times 10^{-5}$$
$$\mathcal{B}(B \to \eta' \ell \nu) < 0.72 \times 10^{-4} \text{@90\% C.L.}$$
$$|V_{ub}| = (3.59 \pm 0.58 \pm 0.13^{+0.29}_{-0.32}) \times 10^{-3}$$

Status of $|V_{ub}|$

- $|V_{ub}| = (4.52 \pm 0.15 \pm 0.22) \times 10^{-3}$ Inclusive average
- $|V_{ub}| = (3.65 \pm 0.09 \pm 0.11) \times 10^{-3}$ $B \to \pi \ell \nu$ average



3σ discrepancy persists.

Probe new Physics in $B \to D^*\tau\nu$

- Well understood in SM.
- Extract $|V_{cb}|$ and $|V_{ub}|$
- Probe physics beyond the SM.

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu, \ell = e \text{ or } \mu\right)}$$

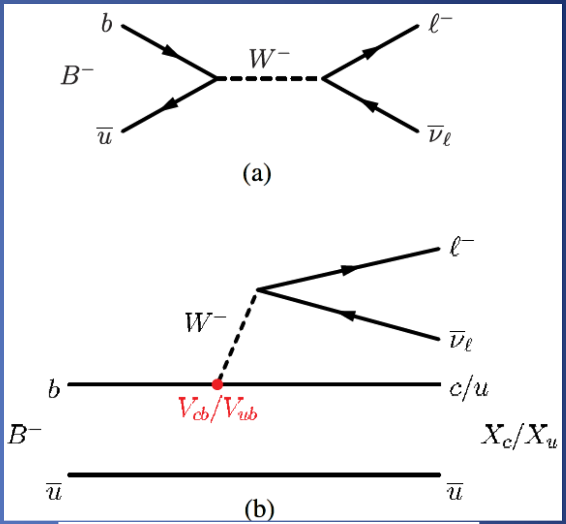
- Accurate theoretic SM predictions.

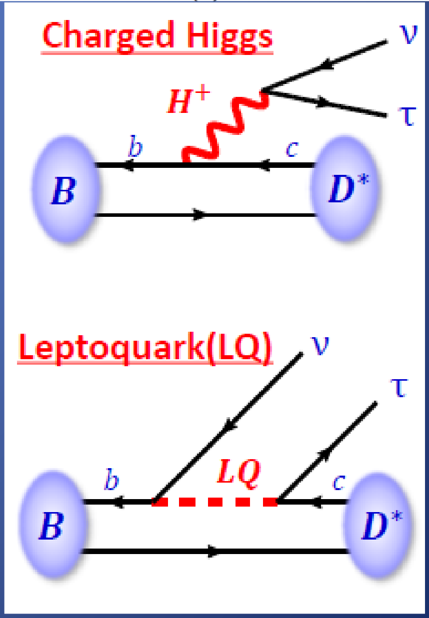
$R(D) = 0.299 \pm 0.003$

$R(D^*) = 0.258 \pm 0.005$

- Other observables

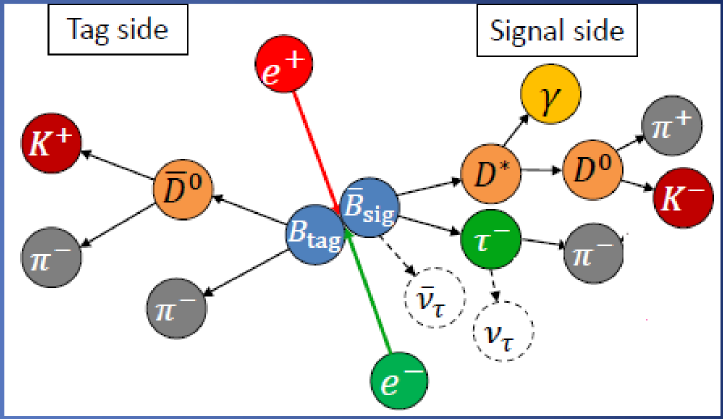
$P_\tau(D^{(*)})$ and P_{D^*}





Analysis Strategy for B Factories

- Tag accompanying B mesons
  - Hadronic tag
  - Semileptonic tag
  - Inclusive* (early Belle)

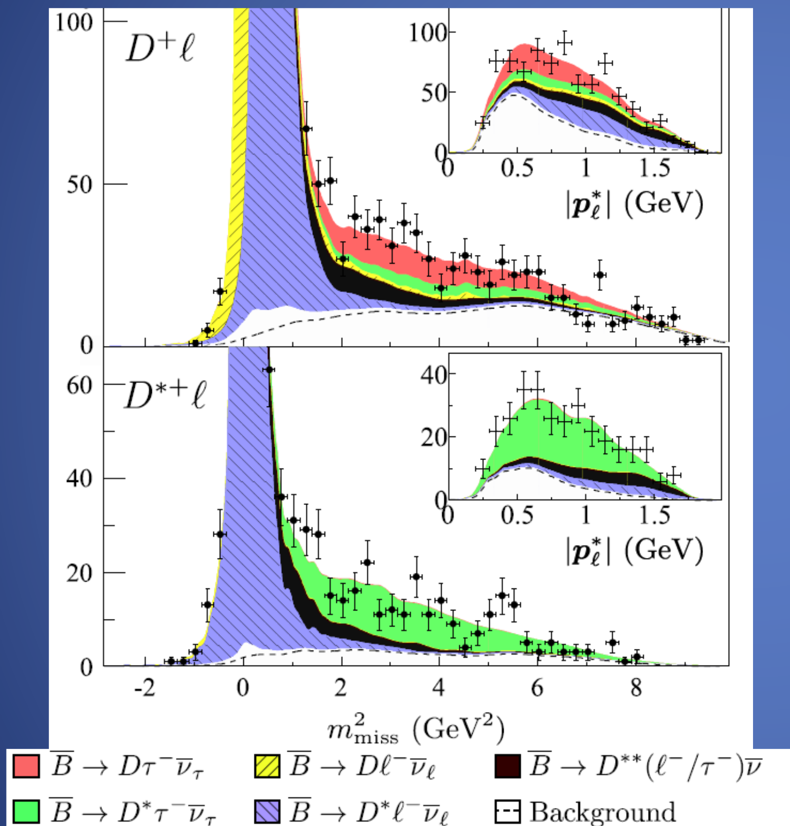


- Signal identification
  - $D^{*0} \to D^0\gamma,\ D^0\pi^0; D^{*-} \to \bar{D}^0\pi^-, D^-\pi^0$

    5~8 D^0 decay modes and 6~7 D^-modes
  - Identify $\tau^+ \to l^+\nu\bar{\nu}, \pi^+\bar{\nu}_\tau, \rho^+\bar{\nu}_\tau$
- Suppress backgrounds with various variables

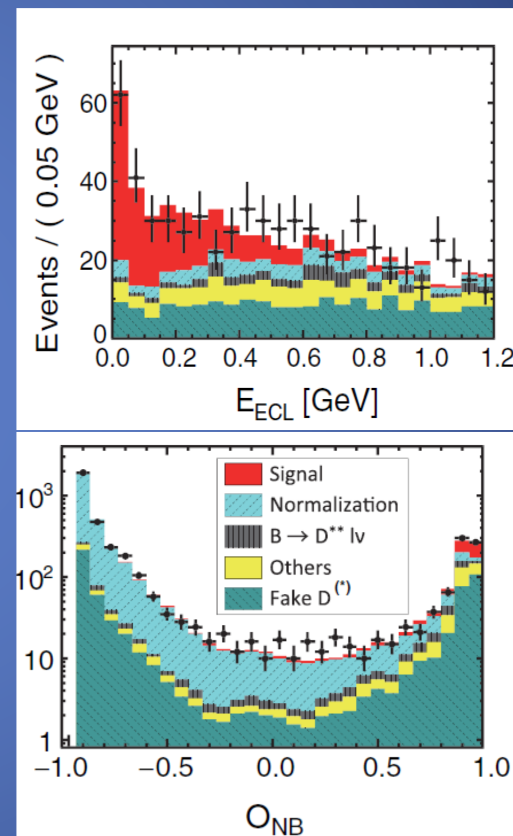
Signal Extraction, B Factories

Fit on m_{miss}^2 and p_ℓ^* / O_{NB}



$$m_{miss}^2 = \left(p_{e^+e^-} - p_{\rm tag} - p_{\rm D^{(*)}} - p_\ell\right)^2$$

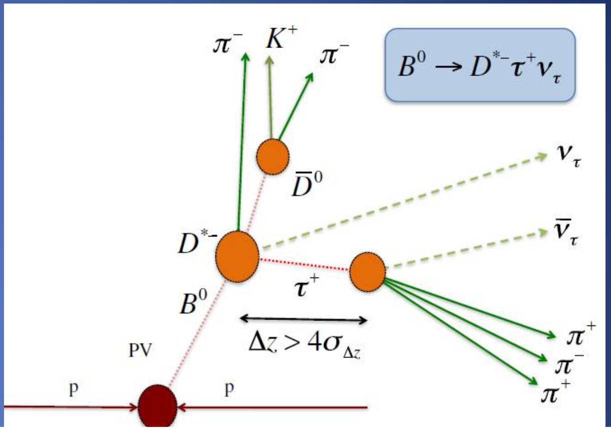
Fit on E_{ECL} and O_{NB}

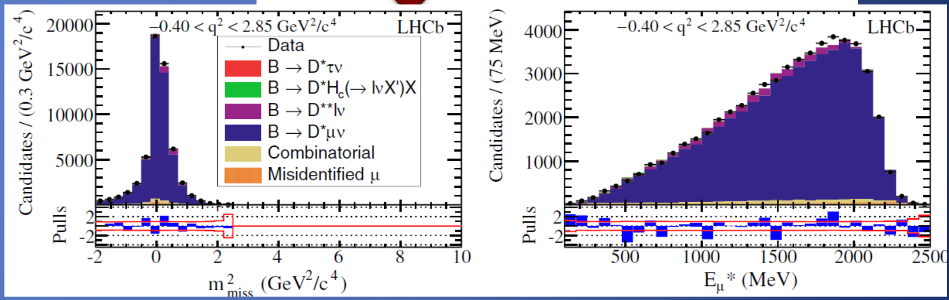


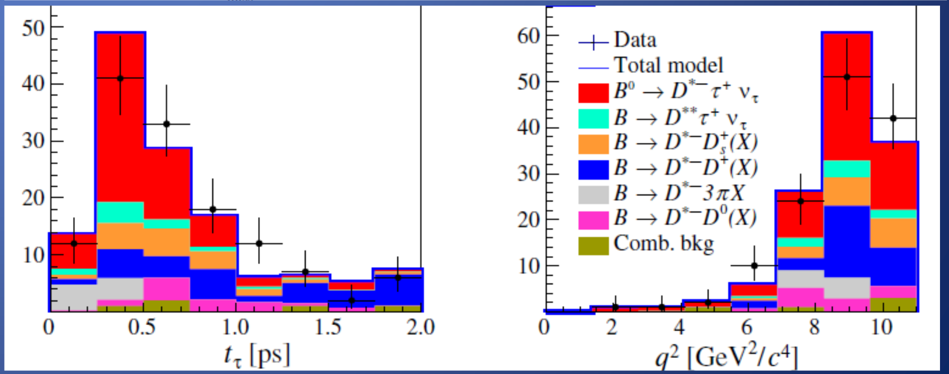
O_{NB} = Neural-network variable

Analysis Strategy, LHCb

- Identify $B^0 \to D^{*-}\tau^+\nu_\tau$
  - $D^{*-} \to \bar{D}^0\pi^- \to (K^+\pi^-)\,\pi^-$
- $\tau^+ \to \mu^+\nu_\mu\,\bar{\nu}_\tau$
  - $(p_B)_z = \frac{m_B}{m_{\text{rec}}}\,(p_{\text{rec}})_z$
  - Fit on m^2_{miss}, E^*_μ and q^2 Simultaneously obtain yields of $D^{*-}\tau^+\nu_\tau$ and $D^{*-}\mu^+\nu_\nu$
- $\tau^+ \to \bar{\nu}_\tau\pi^+\pi^-\pi^+(\pi^0)$
  - $B^0 \to D^{*-}3\pi$ as norm. sample
  - Require $\Delta Z > 4\sigma_{\Delta Z}$
  - Compute p_B use kinematics
  - Fit on t_τ, q^2 and a BDT output







Results of $R(D)$ and $R(D^*)$

EXP	Tag	τ decays	$R(D)$	$R(D^*)$
BaBar 12	Hadronic	$\ell\nu\bar{\nu}, \pi\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle 15	Hadronic	$\ell\nu\bar{\nu}$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
Belle 16	Semileptonic	$\ell\nu\bar{\nu}$	–	$0.302 \pm 0.030 \pm 0.011$
Belle 18	Hadronic	$\pi\nu, \rho\nu$	–	$0.270 \pm 0.035 \pm 0.027$
LHCb 15	–	$\ell\nu\bar{\nu}$	–	$0.336 \pm 0.027 \pm 0.030$
LHcb 18	–	$3\pi\nu$	–	$0.286 \pm 0.019 \pm 0.033$

- Averages from HFLAV

$R(D) = 0.407 \pm 0.039 \pm 0.024$

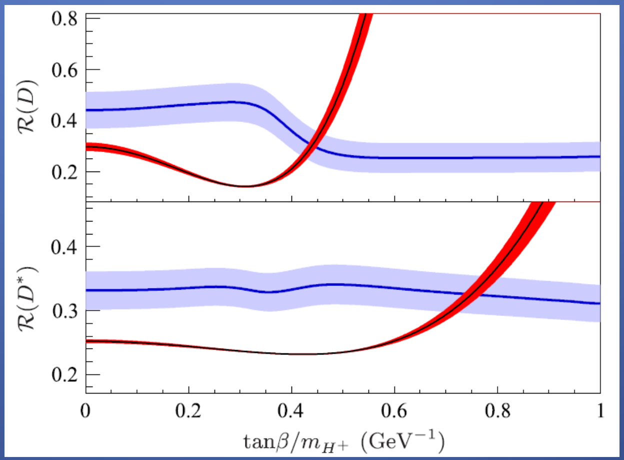
$R(D^*) = 0.306 \pm 0.013 \pm 0.007$

- Standard Model

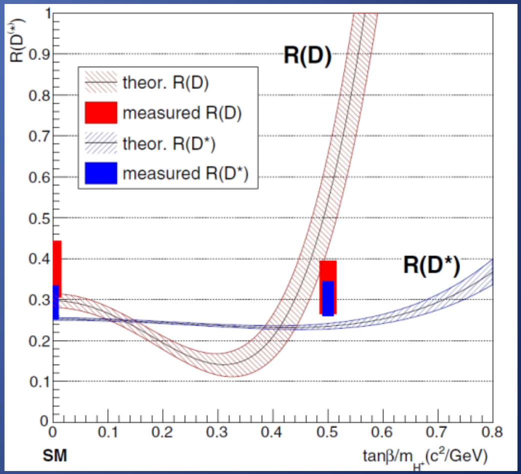
$R(D) = 0.299 \pm 0.003$

$R(D^*) = 0.258 \pm 0.005$

BaBar PRL109, 101802 (2012)



Belle PRD 92, 072014 (2015)



τ Polarization in $B \to D^* \tau \bar{\nu}_\tau$

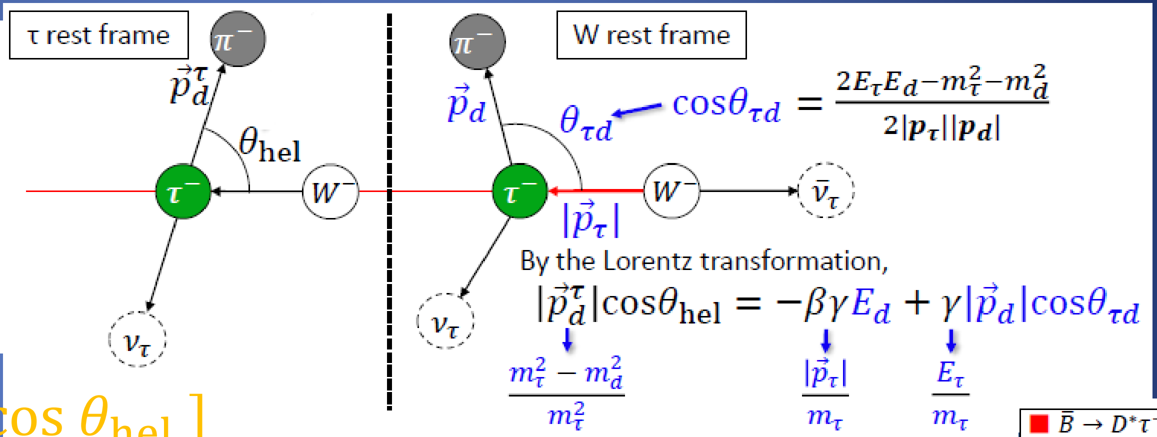
$p_W = p_{e^+e^-} - p_B - p_{D^*}$ $\qquad d = \pi$ or ρ

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

$\Gamma^{+(-)}$ for right-(left-)handed τ

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

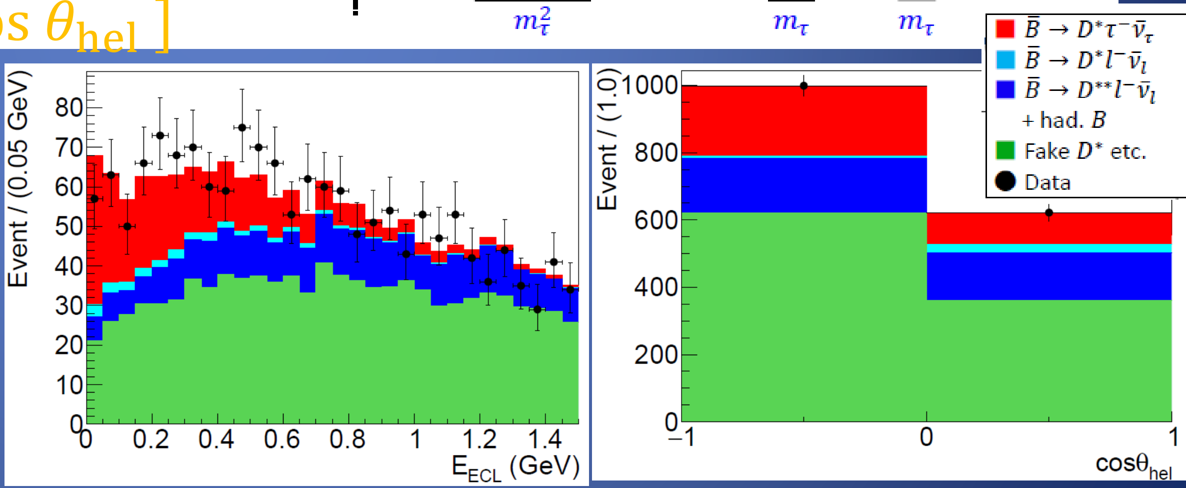
M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1}{2}\left[1 + \alpha\, P_\tau(D^*)\cos\theta_{\rm hel}\right]$$

$$\alpha = 1, \quad \tau^+ \to \pi^+\nu_\tau$$
$$= 0.45, \quad \tau^+ \to \rho^+\nu_\tau$$

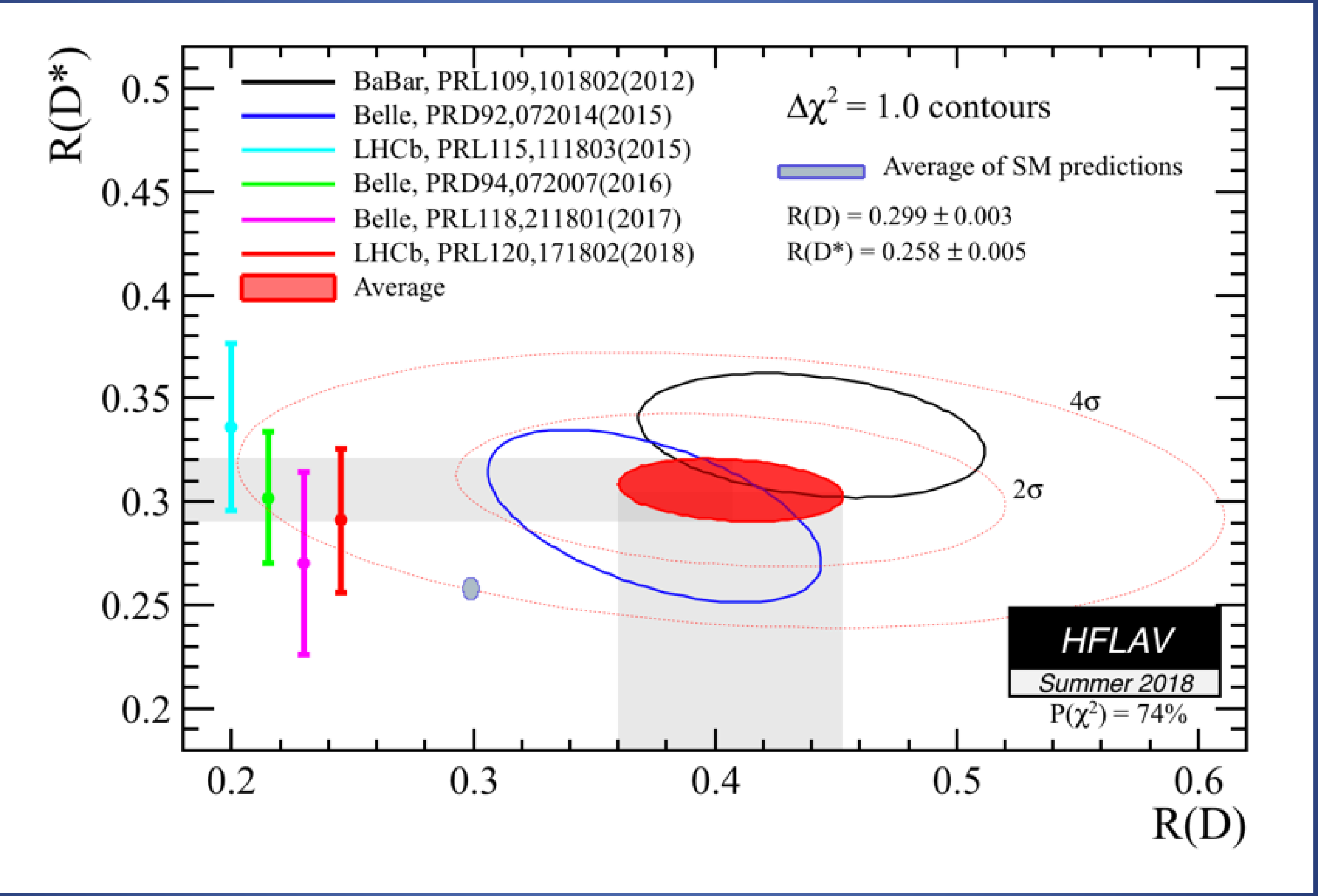
$$P_\tau(D^*) = \frac{[2(N^F - N^B)]}{[\alpha(N^F + N^B)]}$$



Perform fits in forward and backward regions $\Rightarrow$ $P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$

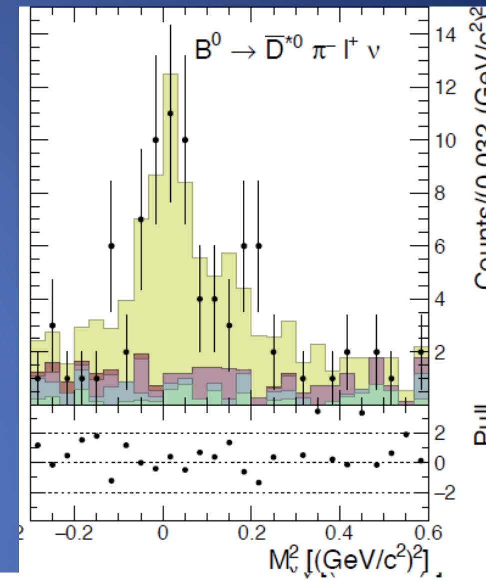
Summary of $R(D)$ and $R(D^*)$

The average is 3.8σ deviation from the SM



$B \to D^{(*)}\pi\,\ell\nu$, Hadronic Tagged

- Important background for $B \to D^{*}\ell\nu$
  $D^{**} \to D^{*}\pi$
- Fit on missing mass squared.

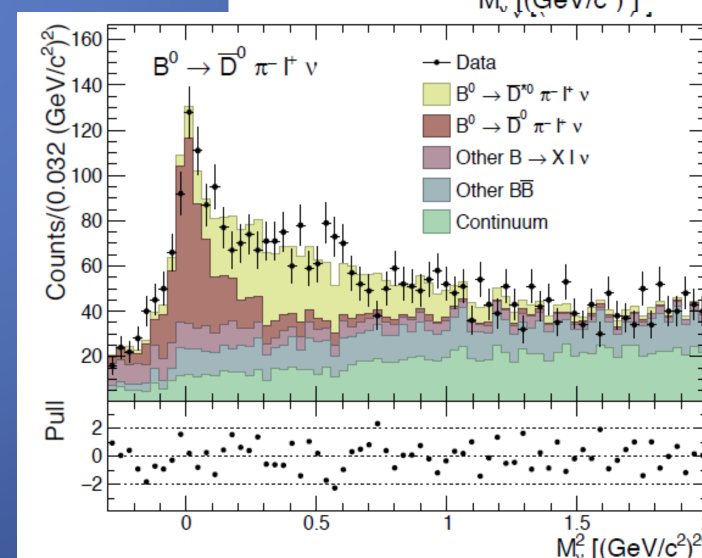


$\mathcal{B}(B^+ \to D^-\pi^+\ell^+\nu)$
$= [4.55 \pm 0.27\ (\text{stat.}) \pm 0.39\ (\text{syst.})] \times 10^{-3}$,

$\mathcal{B}(B^0 \to \bar{D}^0\pi^-\ell^+\nu)$
$= [4.05 \pm 0.36\ (\text{stat.}) \pm 0.41\ (\text{syst.})] \times 10^{-3}$,

$\mathcal{B}(B^+ \to D^{*-}\pi^+\ell^+\nu)$
$= [6.03 \pm 0.43\ (\text{stat.}) \pm 0.38\ (\text{syst.})] \times 10^{-3}$,

$\mathcal{B}(B^0 \to \bar{D}^{*0}\pi^-\ell^+\nu)$
$= [6.46 \pm 0.53\ (\text{stat.}) \pm 0.52\ (\text{syst.})] \times 10^{-3}$.



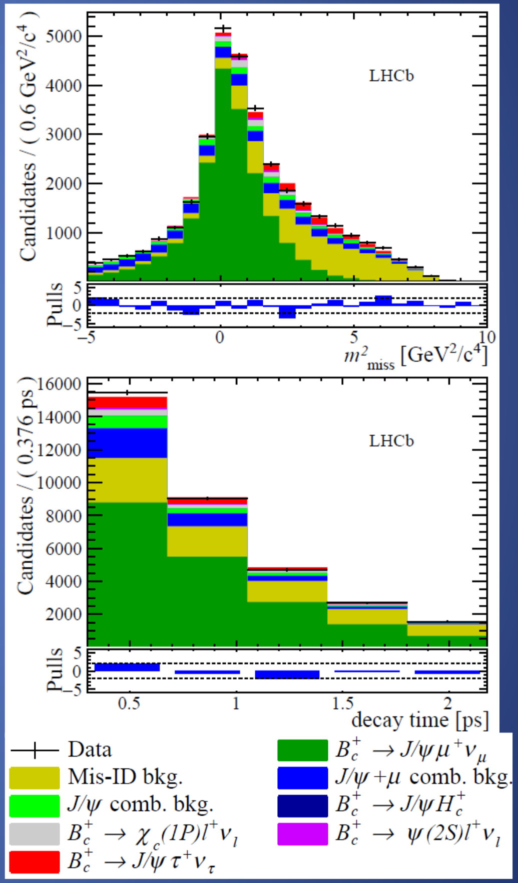
arXiv: 1803.06444, submitted to PRD

LFU on B_c : $J/\psi\tau\nu$ vs $J/\psi\mu\nu$

- Similar strategy

  Fit on m^2_{miss} , τ_{B_c} and q^2

$$R(J/\psi) = \frac{\mathcal{B}(B \to J/\psi\tau\nu)}{\mathcal{B}(B \to J/\psi\mu\nu)}$$



- LHCb 3 fb^{-1} (Run1)
  - $\tau^+ \to \ell^+ \nu \bar{\nu}$

  $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$

  PRL 120, 121801 (2018)

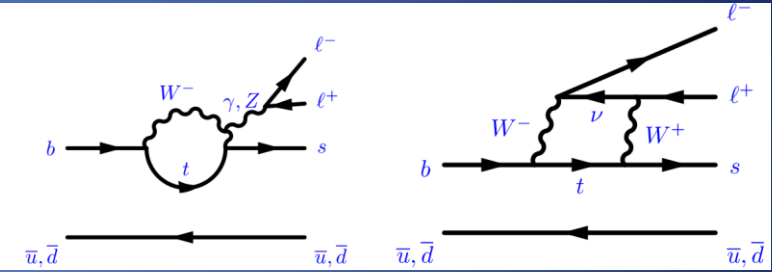
  - SM prediction: 0.25~0.28

  Compatible within 2σ

Rare Semileptonic Decays

- B decays in $b \to s/d\ \ell^+\ell^-$ transition provides good probe for new physics in the penguin loop.
  - Small SM branching fraction ($\mathcal{B}$)
  - More precise theoretical predictions
  - Many observables: $\mathcal{B}$, A_{cp}, A_{FB}, P_5', $A_{iso\text{-}spin}$, *RK*, *RK**...

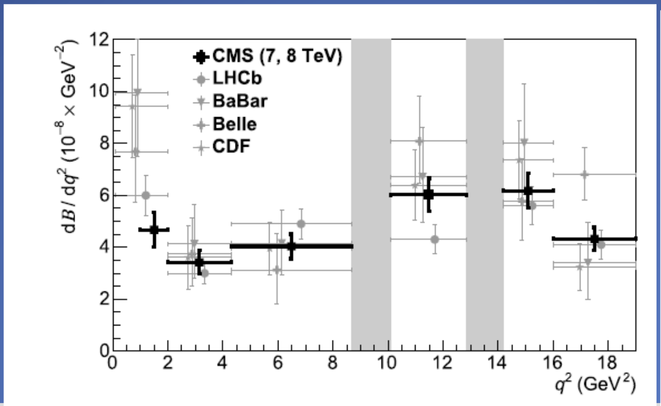
    Decay amplitudes depend on $q^2 = (p_{\ell^+} + \boldsymbol{p}_{\ell^-})^2$



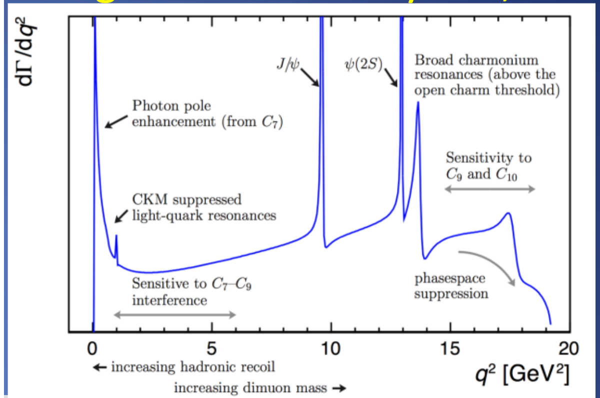
- Exclusive modes
  - Belle, BaBar, LHCb, CMS, ATLAS
- Inclusive modes
  - Belle and BaBar

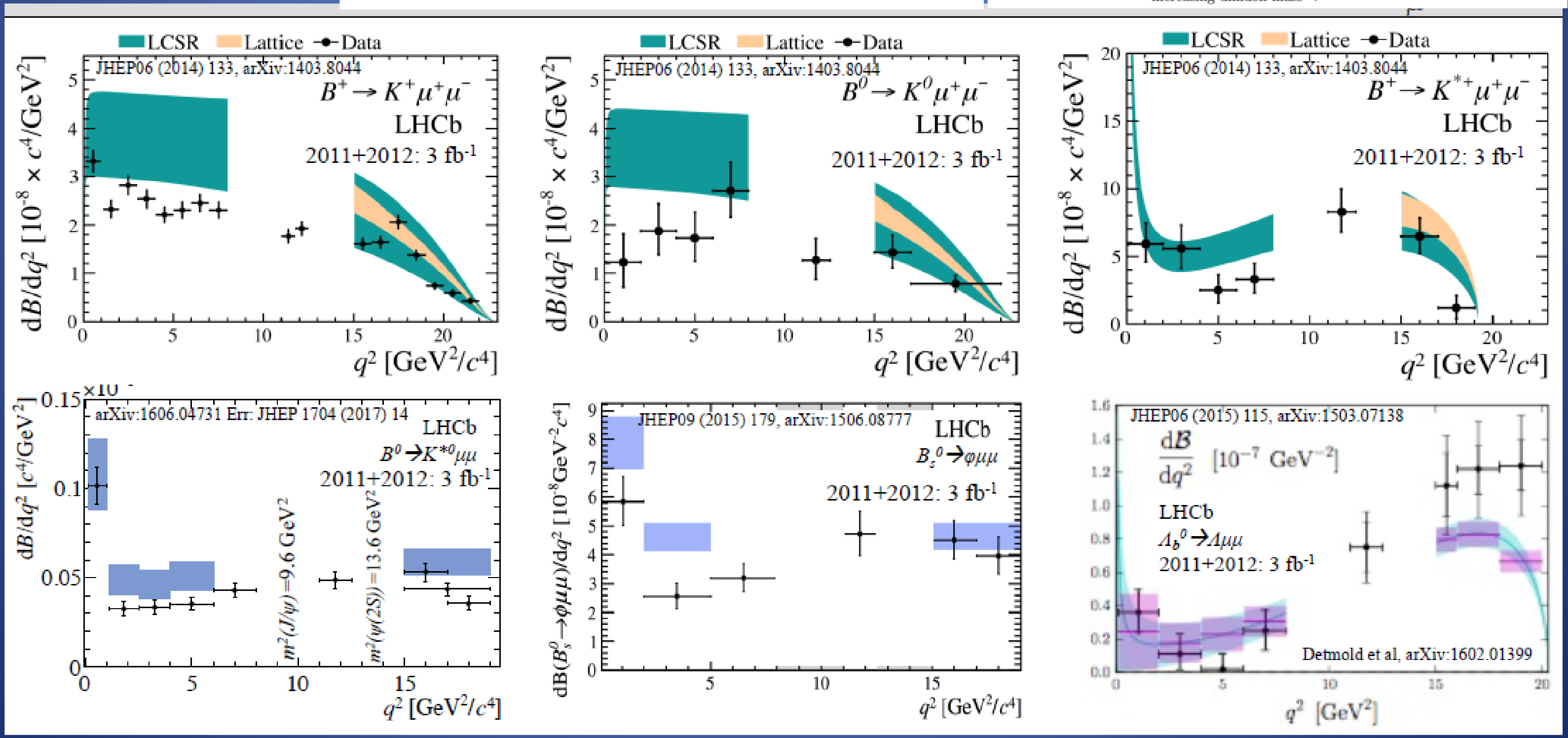
Decay Branching Fractions

- BFs consistently low.
- Consistent Exp. results



Prog. Part. Nucl. Phys 92, 50



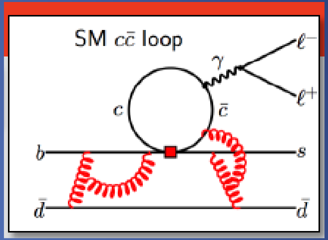


Contributions from Charm

EPJ C77, 161 (2017)

- Phase difference between short- ($b \to s\ell\ell$) and long-distance ($b \to scc$) contribution.

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |\boldsymbol{k}| \beta \left\{ \frac{2}{3} |\boldsymbol{k}|^2 \beta^2 \left| \mathcal{C}_{10} f_+(q^2) \right|^2 + \frac{4m_\mu^2 (m_B^2 - m_K^2)^2}{q^2 m_B^2} \left| \mathcal{C}_{10} f_0(q^2) \right|^2 + |\boldsymbol{k}|^2 \left[1 - \frac{1}{3}\beta^2 \right] \left| \mathcal{C}_9 f_+(q^2) + 2\mathcal{C}_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right|^2 \right\},$$

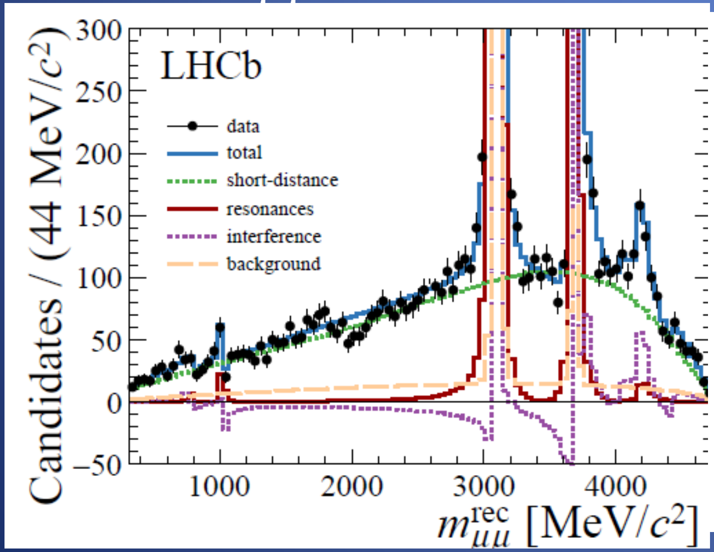


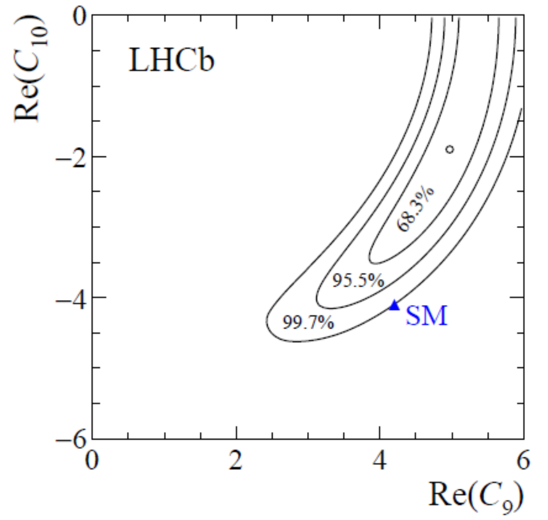
$$C_9^{eff} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2)$$

j = 9 (mesons)

$\rho, \omega, \phi, J/\psi, \psi(2S) \ldots$

- Fit to $m_{\mu\mu}$ with 980000 $B^+ \to K^+\mu^+\mu^-$



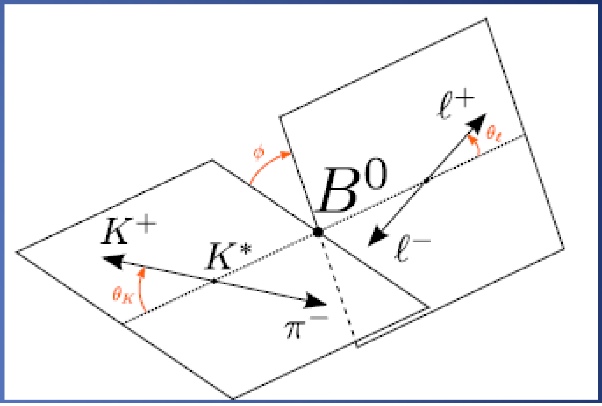


- Default fit: $|C_{10}| < |C_{10}^{SM}|$ $|C_9| > |C_9^{SM}|$
- Fix $|C_{10}| = |C_{10}^{SM}|$ $|C_9| < |C_9^{SM}|$

Short distance $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$

Angular Analysis on $B \to K^{*}\ell^{+}\ell^{-}$

- $K^{*} \to K^{+}\pi^{-}, K^{+}\pi^{0}, K_{S}^{0}\pi^{+}$ and $\ell = e, \mu$ for B factories; $K^{+}\pi^{-}\mu^{+}\mu^{-}$ for collider
- Background suppression
- Veto candidates in J/ψ and ψ' regions
- Perform angular fits in several q^{2} bins



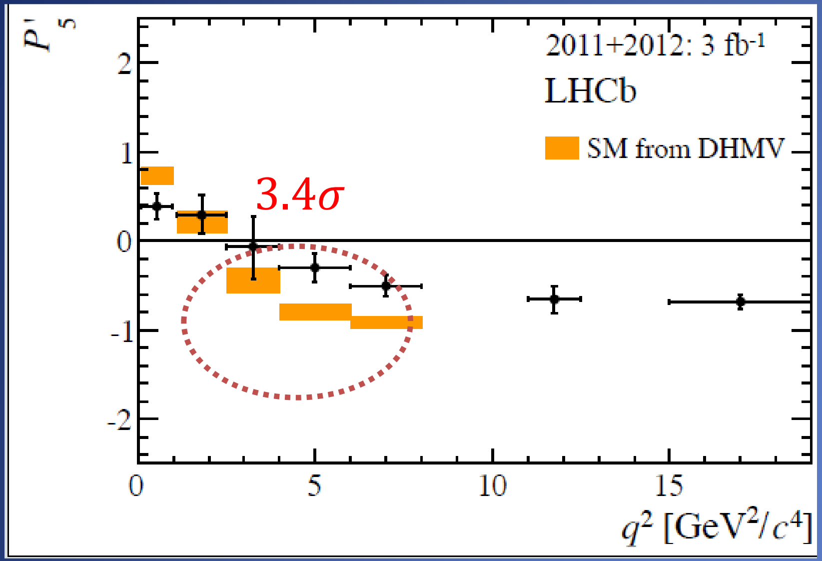
$$\frac{1}{d\Gamma/dq^{2}}\frac{d^{4}\Gamma}{d\cos\theta_{\ell}\,d\cos\theta_{K}\,d\phi\,dq^{2}} = \frac{9}{32\pi}\Bigg[\frac{3}{4}(1-F_{L})\sin^{2}\theta_{K} + F_{L}\cos^{2}\theta_{K} + \frac{1}{4}(1-F_{L})\sin^{2}\theta_{K}\cos 2\theta_{\ell}$$
$$- F_{L}\cos^{2}\theta_{K}\cos 2\theta_{\ell} + S_{3}\sin^{2}\theta_{K}\sin^{2}\theta_{\ell}\cos 2\phi + S_{4}\sin 2\theta_{K}\sin 2\theta_{\ell}\cos\phi$$
$$+ S_{5}\sin 2\theta_{K}\sin\theta_{\ell}\cos\phi + S_{6}\sin^{2}\theta_{K}\cos\theta_{\ell} + S_{7}\sin 2\theta_{K}\sin\theta_{\ell}\sin\phi$$
$$+ S_{8}\sin 2\theta_{K}\sin 2\theta_{\ell}\sin\phi + S_{9}\sin^{2}\theta_{K}\sin^{2}\theta_{\ell}\sin 2\phi\Bigg],$$

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

$P'_{i} \Rightarrow$ Largely free from form-factor uncertainties. JHEP 05, 137 (2013)

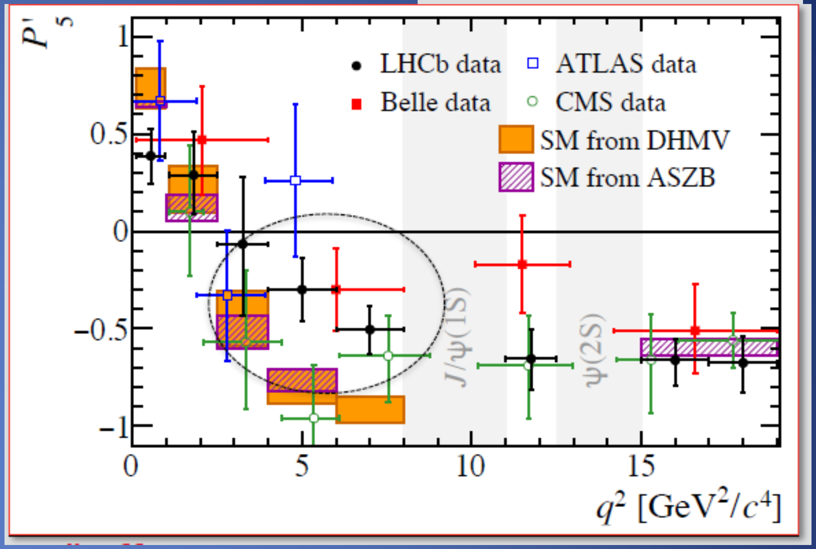
P_5' Measurements

- LHCb, JHEP02 (2016) 104
- Belle, PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS, PLB 81 (2018) 517



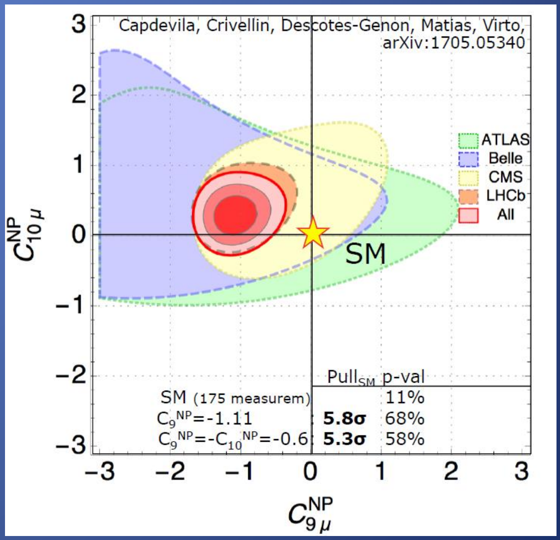
LHCb, JHEP02, 104 (2016)

⇒



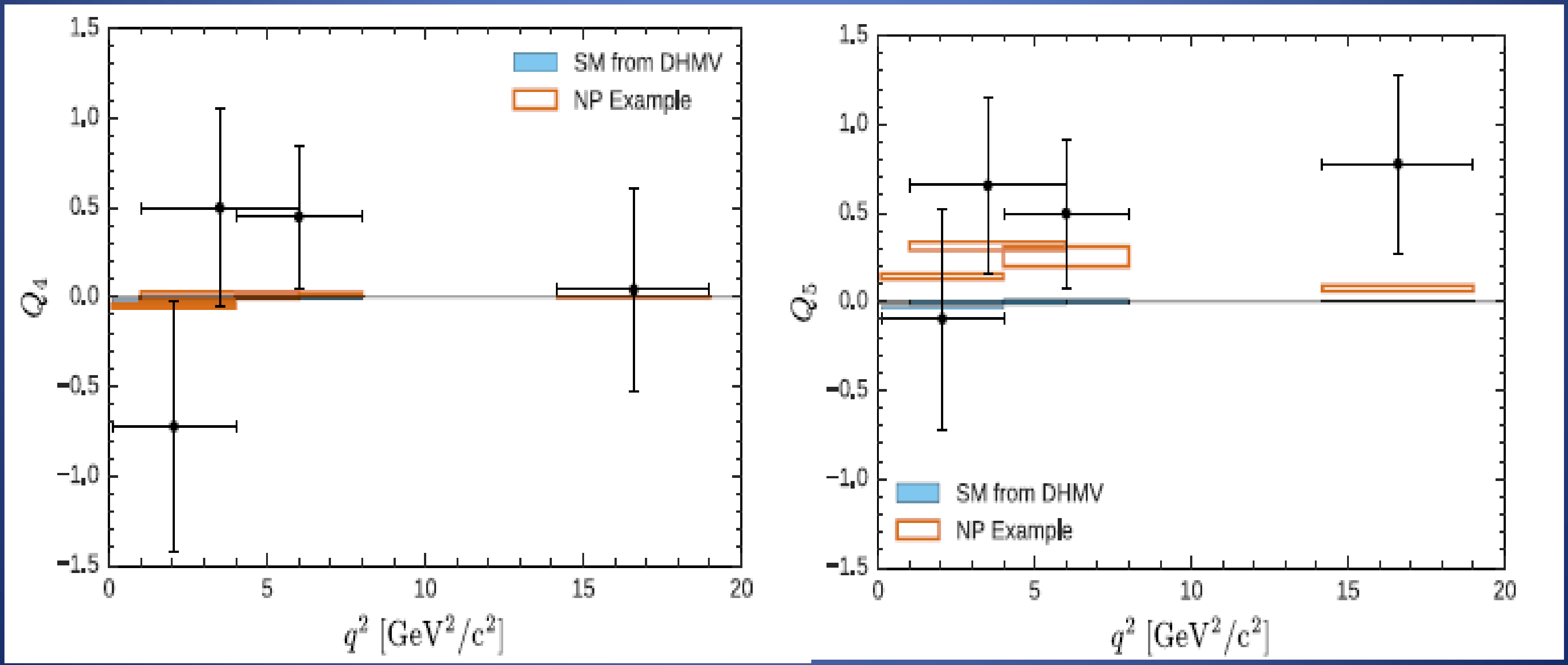
- Tension in $q^2 = 4\sim 8\ \mathrm{Gev}^2$ range
- Need to have precise measurements
- CMS has compatible accuracy.
- Global fit to $K^{(*)}\ell^+\ell^-$ results assuming new physics scenario.

⇒



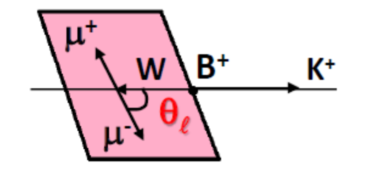
Separate Lepton Flavor

- $Q_i = P_i^{\mu} - P_i^{e}$
- Deviations from zero are sensitive to new physics.
- First presentation of Q_4 and Q_5



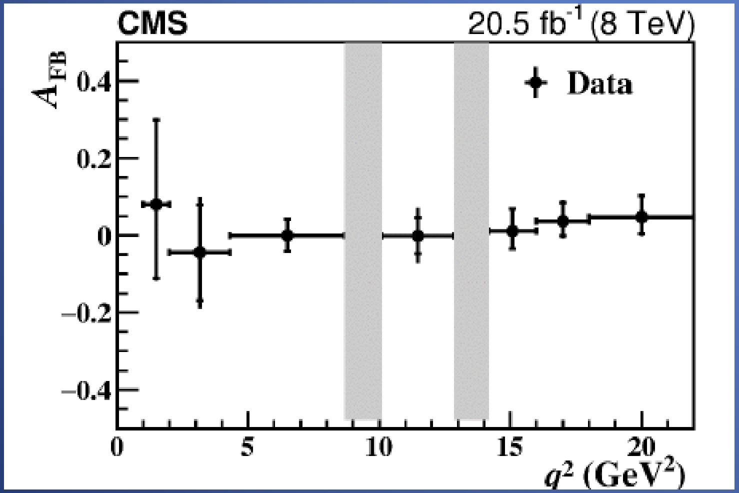
Angular analysis on $K^+\mu^+\mu^-$

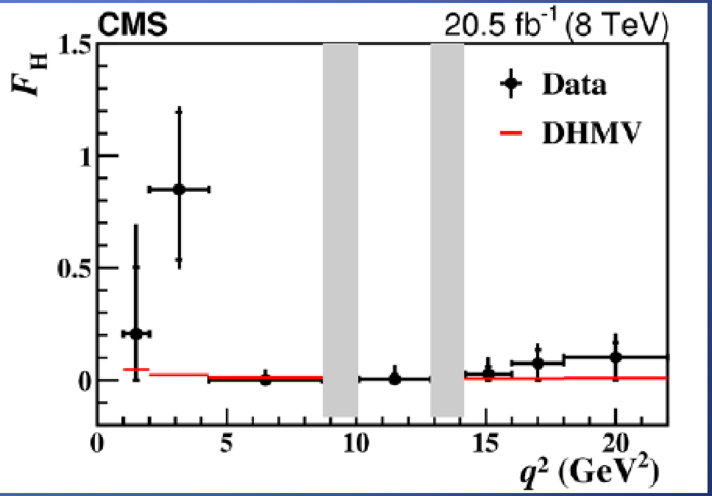
- CMS recent analysis using run 1 data.



$$\frac{1}{\Gamma_\ell}\frac{d\Gamma_\ell}{dcos\theta_\ell} = \frac{3}{4}(1-F_H)(1-\cos^2\theta\,) + \frac{1}{2}F_H + A_{FB}\,cos\theta_\ell$$

A_{FB}: Forward-backward asymmetry of the di-muon system.
F_H: Contribution of pseudo scalar, scalar and tensor amplitudes to decay width





$\Rightarrow$ Consistent with SM expectations

arXiv: 1806.00636

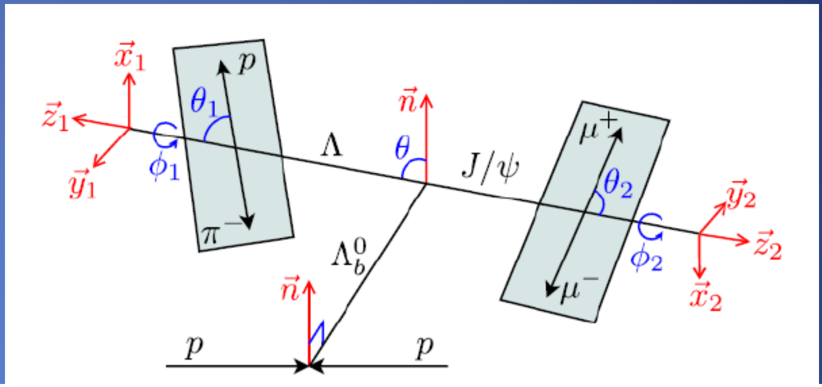
Angular analysis on $\Lambda\mu^+\mu^-$

LHCb-2018-019, submitted to JHEP

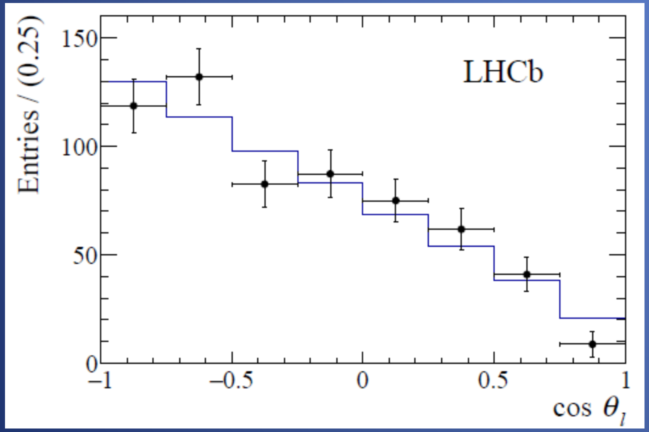
- LHCb angular analysis on $\Lambda_b \to \Lambda\mu^+\mu^-$. $\Rightarrow$ 5 fb^{-1}

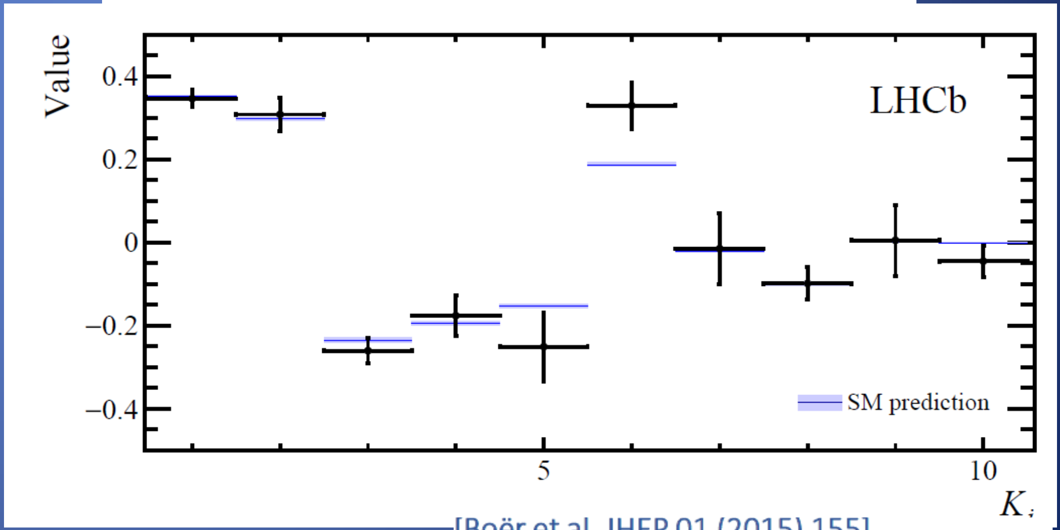
$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{5}{32\pi^2}\sum_i^{34} K_i f_i(\vec{\Omega})$$

- 5 angles and 1 normal direction observables K_i



$15 < q^2 < 20\ \mathrm{GeV}/c^2$





[Boër et al, JHEP 01 (2015) 155],
[Detmold et al. Phys.Rev. D93 (2016) 074501]

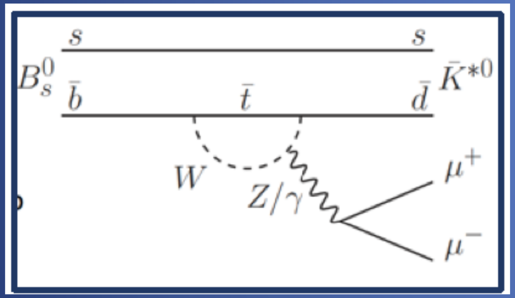
Compatible with SM expectations

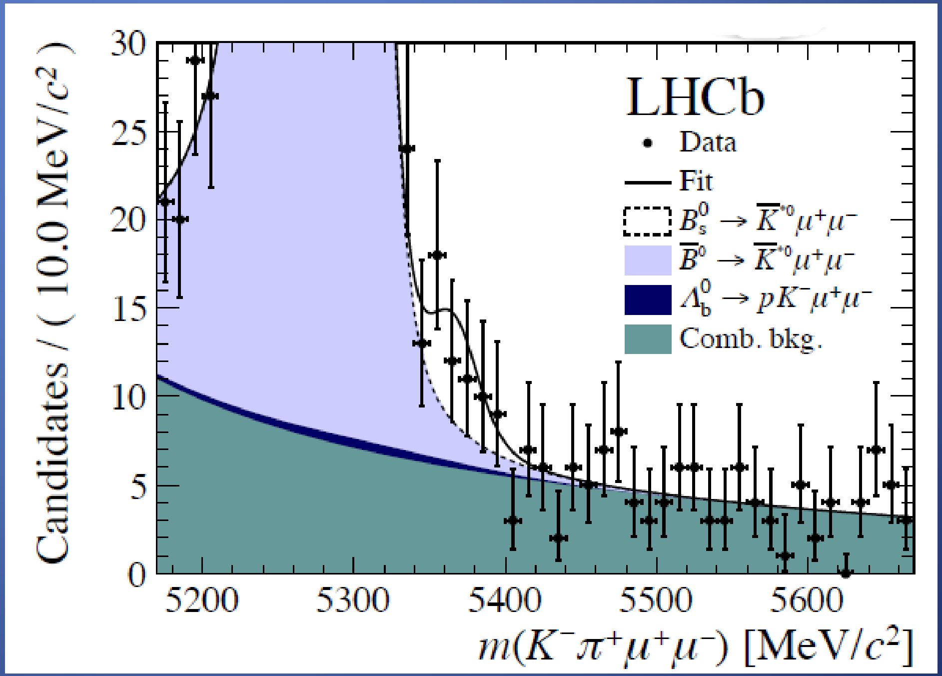
Evidence of $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$

- $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ proceeds through $b \to d\ell^+\ell^-$ transition, similar to $B_d^0 \to \rho^0\mu^+\mu^-$. $\Rightarrow$ Low decay rate.
- 38 ± 12 events with 3.4σ significance

arXiv:1804.07167
Run 1+2: 4.6 fb^{-1}

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0 \pm 0.2 \pm 0.3\,) \times 10^{-8}$$



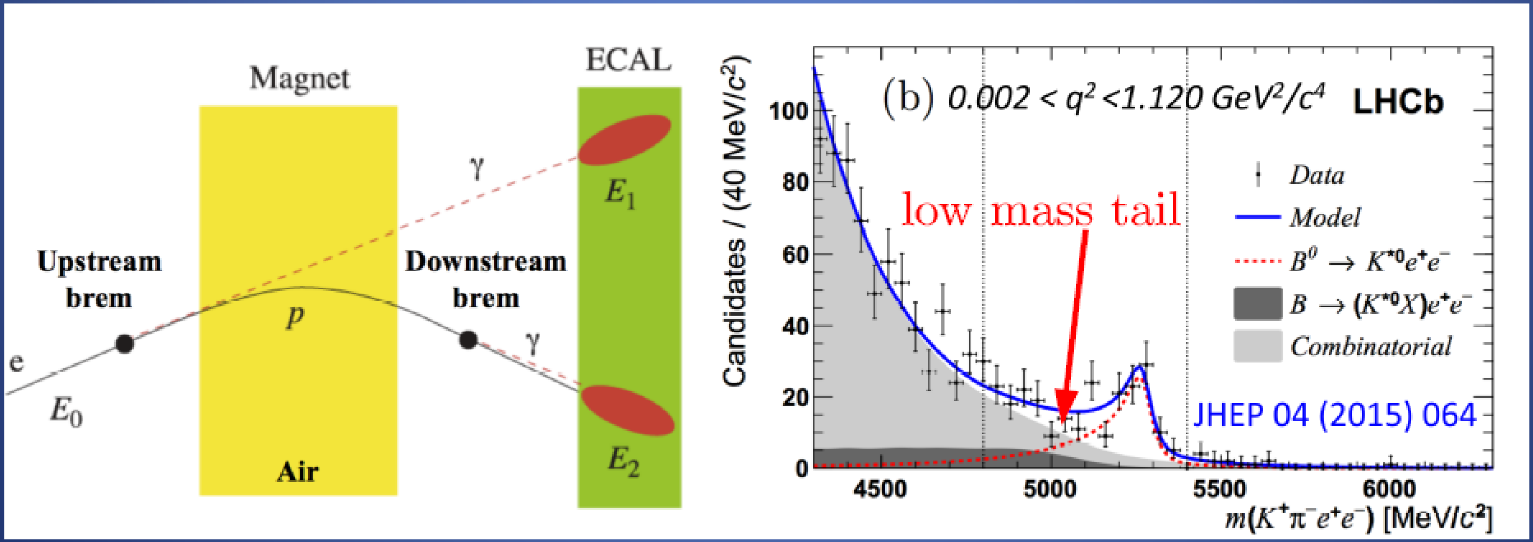


Test Lepton Universality

- Weak couplings are the same for leptons in SM.

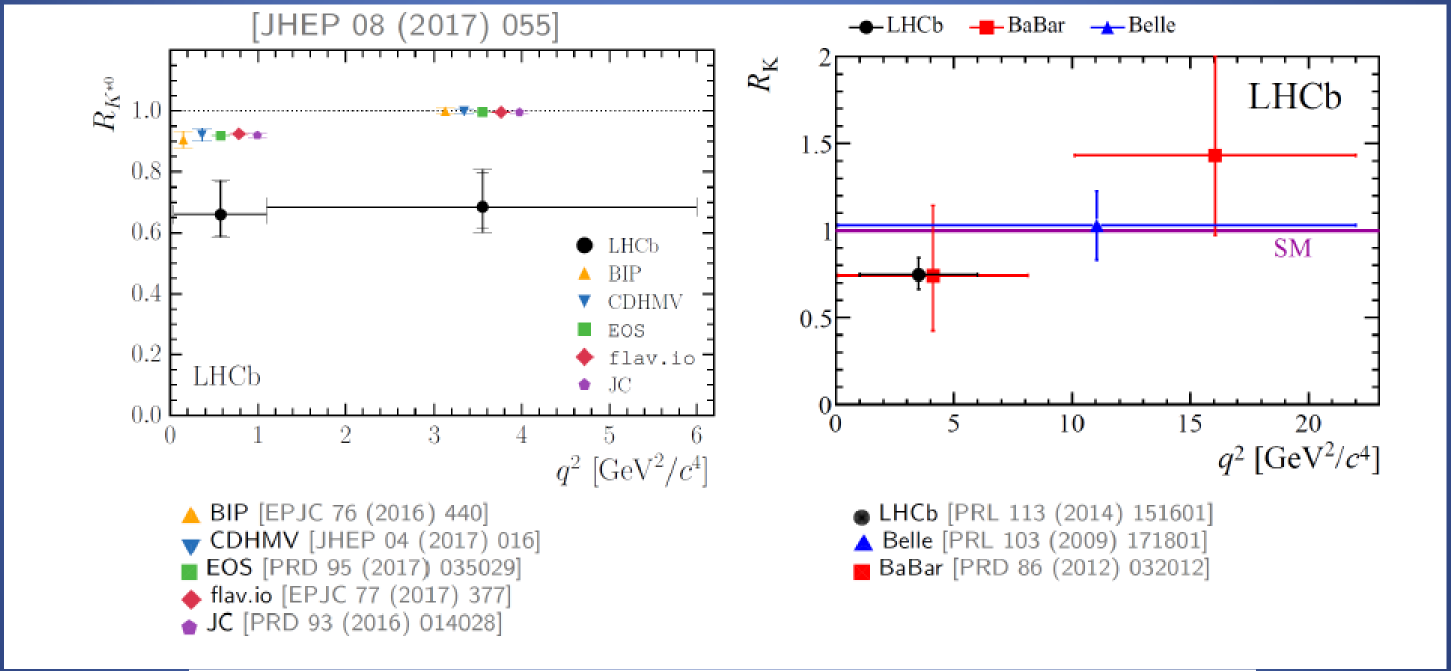
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)} \quad \text{(in } q^2 \text{ bins)}$$

Identifying electrons are challenging in LHCb.



LHCb Run1 Results on $R_{K^{(*)}}$

Double ratio: $\frac{\mathcal{B}(B\to(K^{(*)}\mu^+\mu^-))}{\mathcal{B}(B\to(K^{(*)}e^+e^-))} \Big/ \frac{\mathcal{B}(B\to(J\psi\,\mu^+\mu^-))}{\mathcal{B}(B\to(J/\psi\,e^+e^-))}$

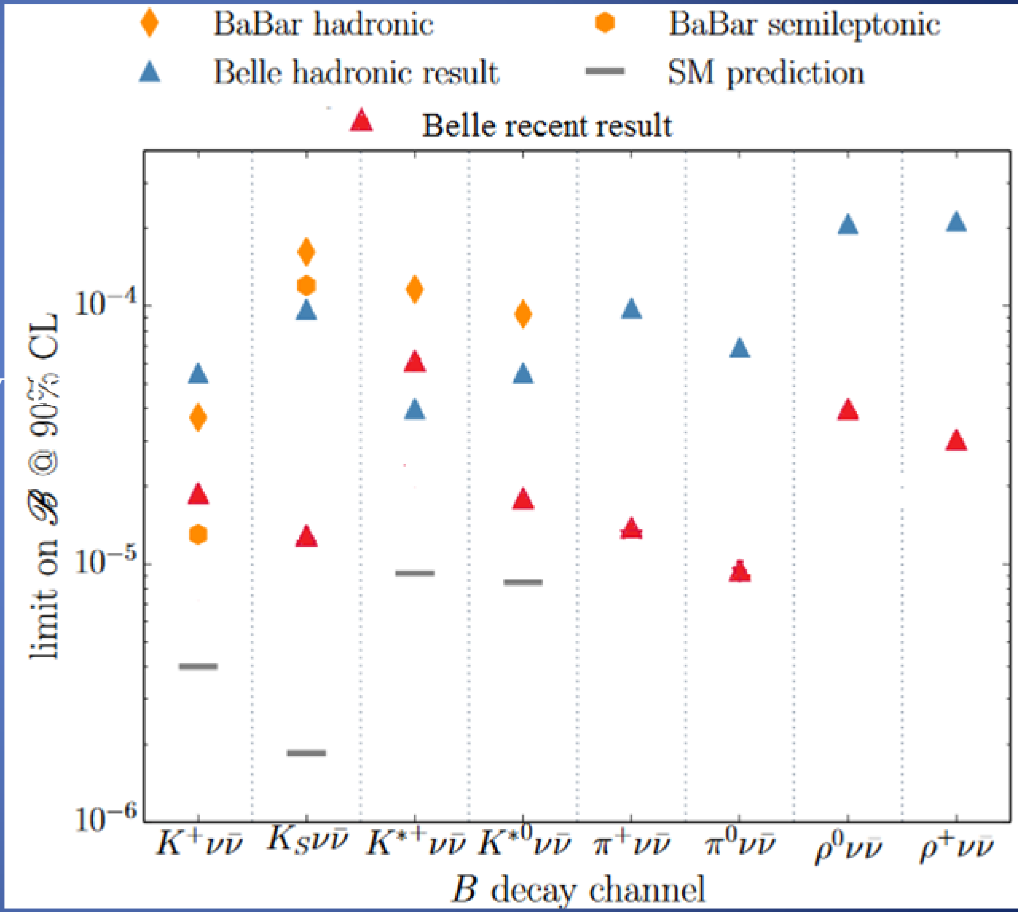


- $R_{K^*}(0.045 < q^2 < 1.1\ \text{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$: $2.1-2.3\sigma$
- $R_{K^*}(1.1 < q^2 < 6.0\ \text{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$: $2.4-2.5\sigma$
- $R_K\ (1 < q^2 < 6.0\ \text{GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$: 2.6σ

Search for $B \to h\nu\bar{\nu}$

- $h = K^{*+}, K^{*0}, K^+, K_S^0, \pi^+, \pi^0,$
  π^+, ρ^0, ρ^+
- Clean SM expectation on B.F.
  $\mathcal{B}(\mathrm{B}^+ \to K^{*+}\nu\bar{\nu}) = 9.2 \times 10^{-6}$
  $\mathcal{B}(\mathrm{B}^0 \to \pi^0\nu\bar{\nu}) = 1.2 \times 10^{-7}$
- Need a B tag to perform the analy
  Signals are identified in $\mathrm{E}_{\mathrm{ECL}}$
- References:

Exp.	Tag	Ref.erence
BaBar	Hadronic	PRD 87, 112005
BaBar	Semilep.	PRD 82, 112002
Belle	Hadronic	PRD 87, 111103
Belle	Semilep.	PRD 92, 091101

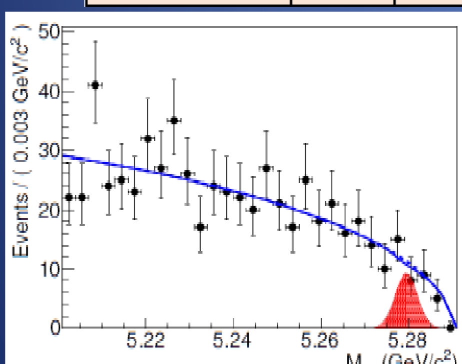


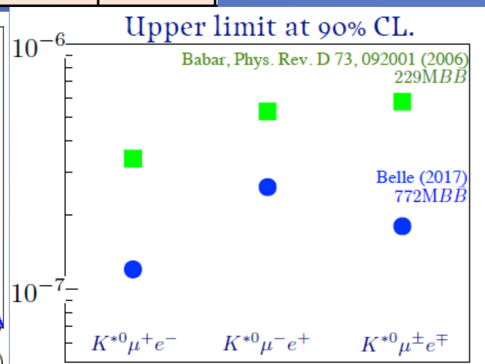
Good topics for Belle II

Search for $B^+ \to K^+\tau^+\tau^-$ and $B^0 \to K^{*0}\mu^\pm e^\mp$

- Violation of LFU $\Rightarrow$ LFV
- Veto $K^{*0}\, J/\psi$ events

Mode	ε (%)	N_{sig}	B^{UL} (10^{-7})
$B^0 \to K^{*0}\mu^+e^-$	8.8	$-1.5^{+4.7}_{-4.1}$	1.2
$B^0 \to K^{*0}\mu^-e^+$	9.3	$0.40^{+4.8}_{-4.5}$	1.6
$B^0 \to K^{*0}\mu^\pm e^\mp$	9.0	$-1.2^{+6.8}_{-6.2}$	1.8

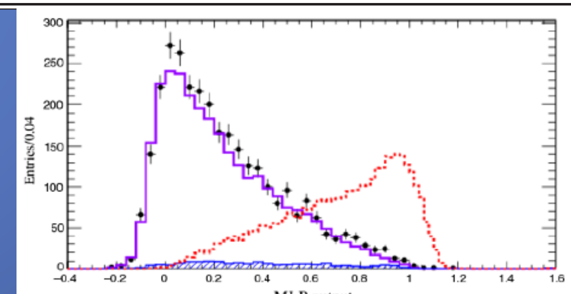




arXiv:8307.03267; submitted to PRD

- Possible new physics particles couple to $\tau^+\tau^-$
- Hadronic tags with $\tau^+ \to \ell^+\nu\nu$

	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
$N^i_{\rm bkg}$	$49.4 \pm 2.4 \pm 2.9$	$45.8 \pm 2.4 \pm 3.2$	$59.2 \pm 2.8 \pm 3.5$
$\epsilon^i_{\rm sig}$ ($\times 10^{-5}$)	$1.1 \pm 0.2 \pm 0.1$	$1.3 \pm 0.2 \pm 0.1$	$2.1 \pm 0.2 \pm 0.2$
$N^i_{\rm obs}$	45	39	92
Significance (σ)	-0.6	-0.9	3.7



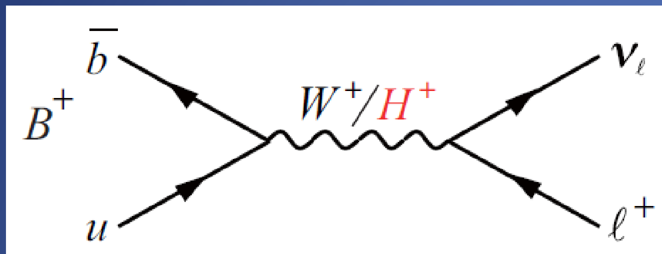
PRL 118, 031802 (2018)

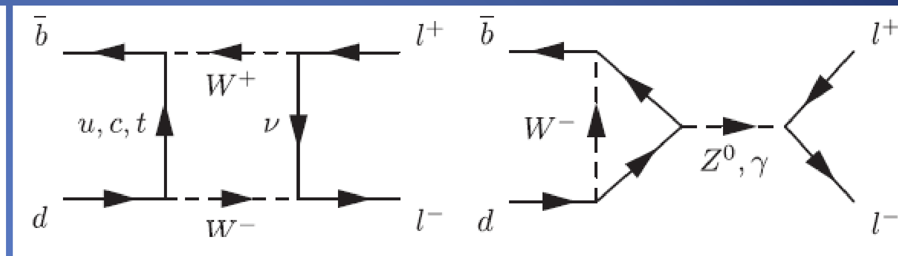
90% C.L.

$\mathcal{B}\,(B^+ \to K^{*0}\tau^+\tau^-) < 2.25 \times 10^{-3}$

$\mathcal{B}_{\rm SM}\,(B^+ \to K^{*0}\tau^+\tau^-) = (1-2) \times 10^{-7}$

Leptonic B Decays





$$\mathcal{B}\left(B^+ \to \ell^+ \nu_\ell\right)_{\mathrm{SM}} = \frac{G_F^2\, M_b M_\ell^2}{8\pi}\left(1 - \frac{M_\ell^2}{M_B^2}\right)^2 \times f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}\left(B^0 \to \ell^+ \ell^-\right)_{\mathrm{SM}} = \frac{G_F^2\, \alpha^2}{63\pi^3 \sin^4\theta_W} |V_{tb}^* V_{td}|^2 \tau_B M_B^3\, f_B^2 \times \sqrt{1 - \frac{4m_\ell^2}{M_B^2}}\ \frac{2m_\ell{}^2}{M_B^2}\ Y^2\left(\frac{m_t^2}{M_W^2}\right)$$

arXiv: 1712.04123

ℓ	$B^+\ \mathcal{B}_{\mathrm{SM}}$
τ	$(8.45 \pm 0.70) \times 10^{-5}$
μ	$(3.80 \pm 0.31) \times 10^{-7}$
e	$(8.89 \pm 0.73) \times 10^{-12}$

- Clean processes with accurate theoretical branching fractions.
- Diagram involved in *W* is helicity suppressed.
- Small SM BFs. enable good probe for new physics.

New physics in tree for B^+ and in loop for B^0

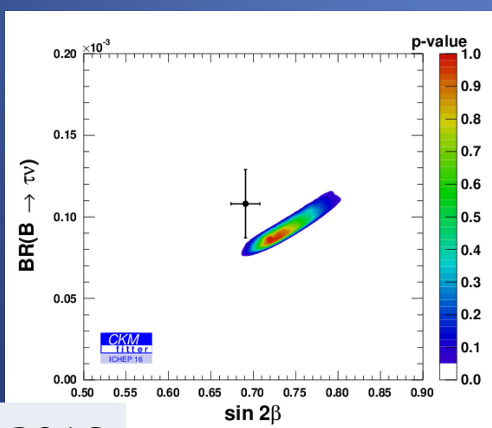
$B^+ \to \tau^+ \nu_\tau$

Exp.	Tag	B.F.$\times 10^4$	Reference
Belle	Hadronic	$0.72^{+0.27}_{-0.25} \pm 0.11$	PRL 110, 131801 (2013)
Belle	Semilept.	$1.25 \pm 0.28 \pm 0.27$	PRD 92, 051102 (2015)
BaBar	Hadronic	$1.83^{+0.53}_{-0.49} \pm 0.41$	PRD 88, 031102 (2013)
BaBar	Semilept.	$1.7 \pm 0.8 \pm 0.2$	PRD 81, 051101 (2010)

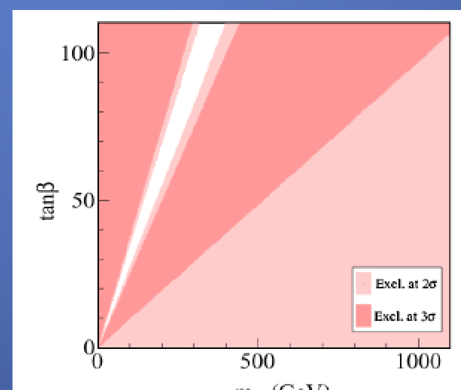
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\text{avg}} = (1.09 \pm 0.24) \times 10^{-4}$ PDG

$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\text{SM}} = (0.845 \pm 0.70) \times 10^{-4}$ arXiv: 1712.04123

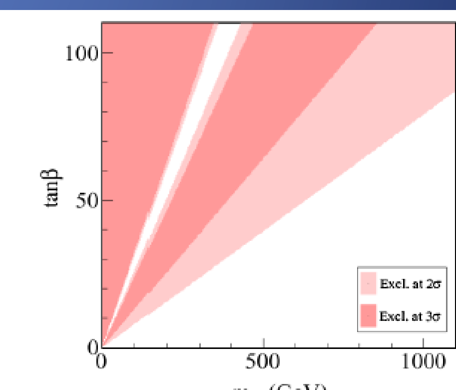
Test CKM



CKM fitter 2016



Exclusive $|V_{ub}|$



Inclusive $|V_{ub}|$

$B^+ \to \mu^+ \nu_\mu$

- Belle New analysis
  - Full data sample 772M $B\bar{B}$
  - Loose kinematic selections
  - Combine 14 variables in to O_{nn}
  - Fit to extract yield ratio of signals and $B \to \pi \ell \nu$

- Unique feature $p^*_\mu \approx \frac{M_B}{2}$
- BaBar $\mathcal{B} < 1.0 \times 10^{-6}$ (no tag)
- Belle $\mathcal{B} < 1.7 \times 10^{-6}$ (no tag)

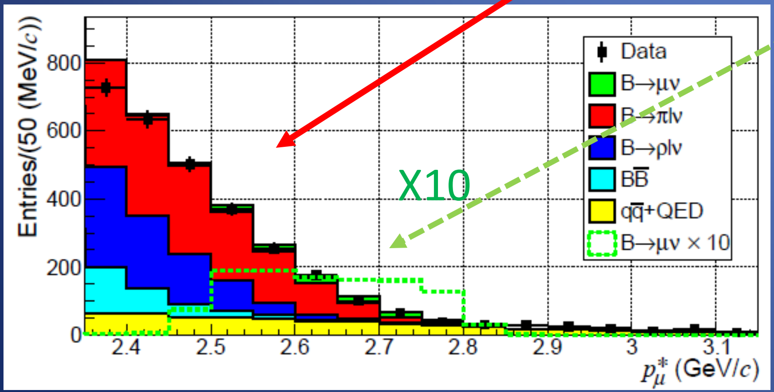
With tags $\Rightarrow$ large upper limits

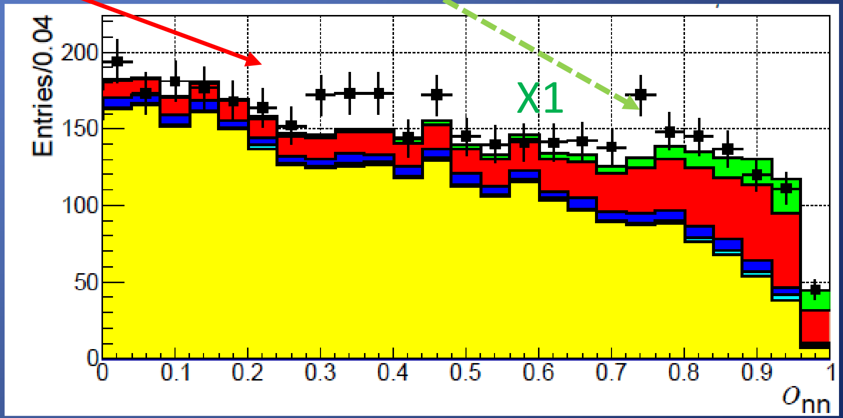
$\Rightarrow$ Yield = 195 $\pm$ 67, $\mathcal{B}$ =(6.46 $\pm$ 2.22 $\pm$ 1.60) $\times 10^{-7}$ @ 2.4σ

$\Rightarrow \mathcal{B}$ ($B^+ \to \tau^+ \nu_\tau$) =[2.9, 10.7] $\times 10^{-7}$ @ 90% CL. interval.

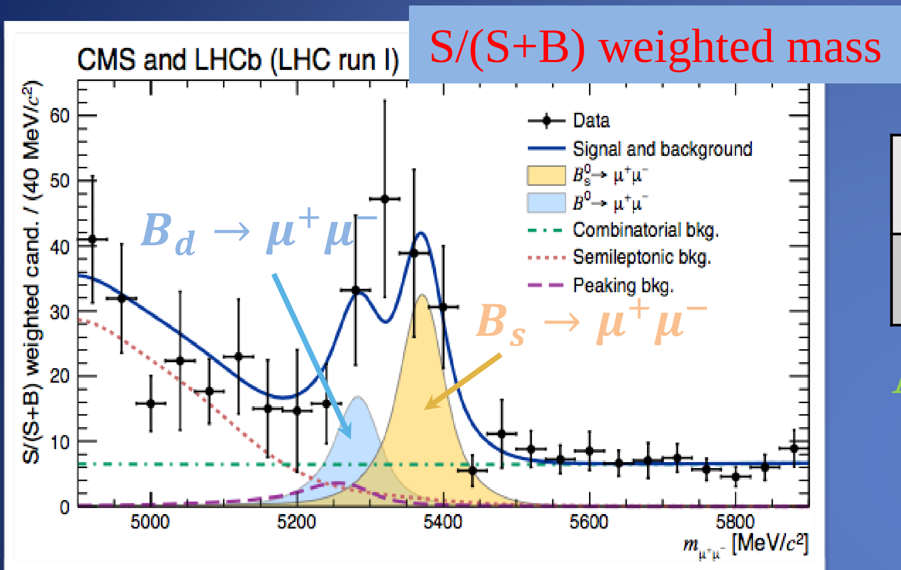
$\pi \ell \nu$ bkg

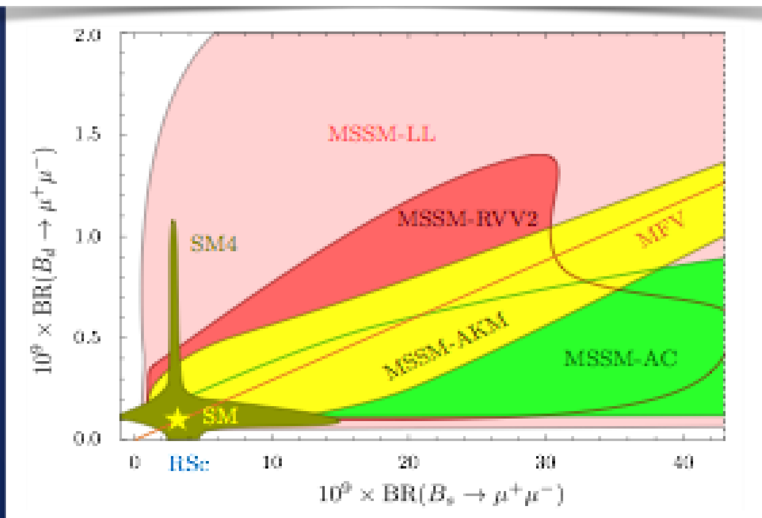
$\mu\nu$ signal





$B_{s,d} \to \mu^+\mu^-$





CMS + LHCb Nature 522, 68-72

6.2σ (7.4σ expected) for $B_s \to \mu^+\mu^-$

$B_s \to \mu^+\mu^-$	$\left(3.0^{+1.0}_{-0.9}\right) \times 10^{-9}$
$B_d \to \mu^+\mu^-$	$< 1.1 \times 10^{-9}$@95% CL

ATLAS: $(0.9^{+1.1}_{-0.8}) \times 10^{-9}$ for B_s

$< 4.2 \times 10^{-10}$ for B_d

SM: Robeth et al., PRL 112, 101801 (2014)

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

- Some new physics models may boost the branching fractions of $B \to \mu^+\mu^-$
- Stringent test MFV hypothesis
- When can we have Run II results?

A Few Remarks

- $B^0_{(s)} \to \tau^+\tau^-,\ B^0_{(s)} \to$ invisible ($\nu\bar{\nu}$)
  - Need a breakthrough in analysis technique to reach SM values for $\tau^+\tau^-$.
  - Looking for surprises.

$\mathcal{B}(B_s \to \tau^+\tau^-) = (2.2 \pm 0.2) \times 10^{-7}$
$\mathcal{B}(B_d \to \tau^+\tau^-) = (2.2 \pm 0.2) \times 10^{-7}$

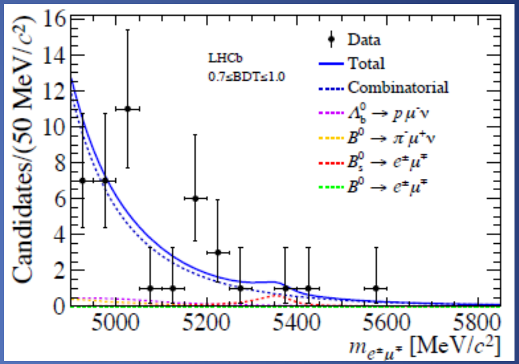
- $B \to \gamma\ell^+\ell^-,\ \gamma\ell^+\nu_\ell$ and $\gamma\nu\bar{\nu}$
  - Experimental results give limits at 10^{-5}~10^{-7}. Theoretical uncertainties may be large.

EXP.	Mode	Data	BF.	Reference
BaBar	$\tau^+\tau^-$	232M $B\bar{B}$	< 4.1×10^{-3}	PRL 96 241802
LHCb	$B^0_d \to \tau^+\tau^-$	3 fb^{-1}	< 2.1×10^{-3}	PRL 118 251802
LHCb	$B^0_s \to \tau^+\tau^-$	3 fb^{-1}	< 6.8×10^{-3}	PRL 118 251802
BaBar	invisible	471M $B\bar{B}$	< 2.4×10^{-5}	PRD 86 051105
Belle	invisible	657M $B\bar{B}$	< 13×10^{-5}	PRD 86 032002

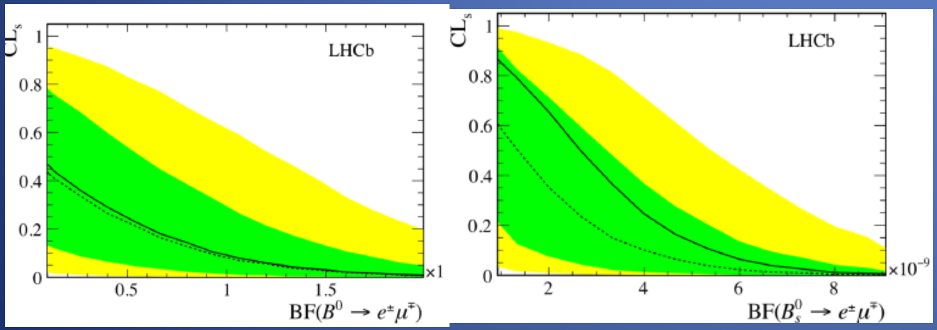
Search for $B^0_{(S)} \to e^\pm e^\mp$

- Data sample: 3 fb^{-1}
- Control samples:
  – $B^+ \to J/\psi K^+$
  – $B^+ \to K^+\pi^-$ (peaking background)
- Improvement since last measurement
  – Improved electron ID
  – Fit perform in different Bram. cate.
  – Better BDT calibration

JHEP 1803, 078 (2018)



- Fit to $e\mu$ mass and no signals are seen.



(1) Light (left) and (2) heavy (right) dominant

$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3(1.0) \times 10^{-9}$

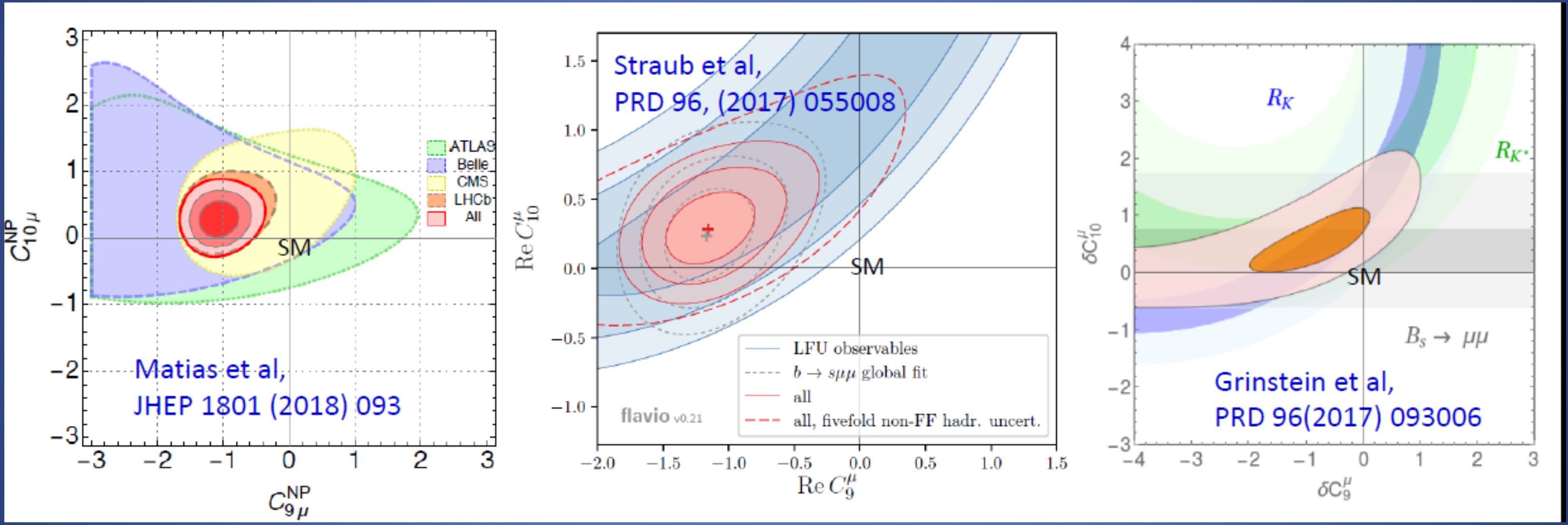
$\mathcal{B}_1(B^0_s \to e^\pm\mu^\mp) < 6.3(5.4) \times 10^{-9}$

$\mathcal{B}_2(B^0_s \to e^\pm\mu^\mp) < 7.2(6.0) \times 10^{-9}$

at 90 (95)% C.L.

Global Fits to Current Observables

- Extract Wilson coefficients and compare with their SM values
- Observables could be more than 100.



- Some of the global fits show new physics contribution with σ.
- Most of the fits point out that $C_9^{\rm NP}$ is the reason.

Hadronic B Decays

- Hadronic B decays provide rich samples for physics.
  - 3 CKM angles, ϕ_s, CP violations, spectroscopy
  - testing KM mechanism, probing new physics …
- Large hadronic uncertainties in the theoretical decay rates.
  - Ratio of branching fractions, A_{CP}, A_{CP}, polarization

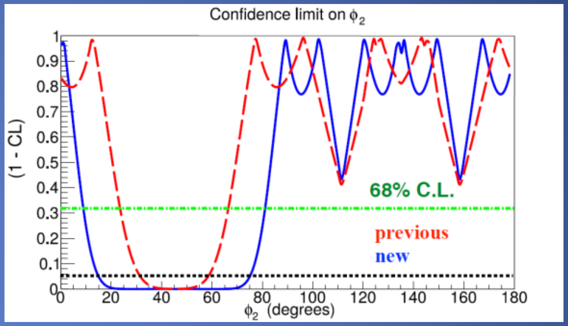
    Sometimes even A_{CP} has large theoretical uncertainty.
- Hadronic decays and CP violations ⇒ See Barsuk's talk
- Recent results:
  - 2-body charmless decays
  - 3-body charmless decays

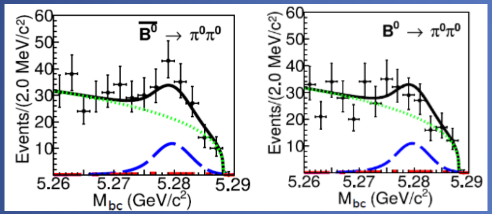
Charmless Two-body Decays

771 M $B\bar{B}$

- Update on $B^0 \to \pi^0\pi^0$
  - Apply B tagging
  - Fit on M_{bc}, ΔE and T_c
    T_c for continuum suppression

PRD 92, 032007 (2017)

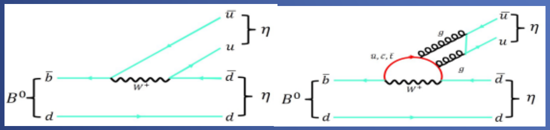


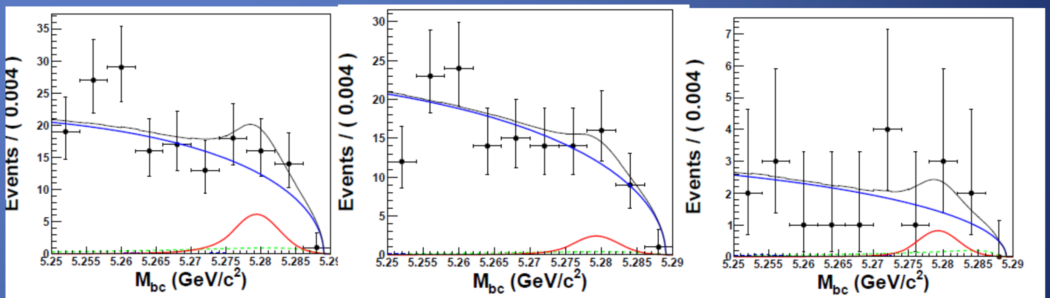


$$A_{CP} = +0.14 \pm 0.36 \pm 0.10$$

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$$

- Update on $B^0 \to \eta\eta$
  $\eta \to \gamma\gamma, \eta \to \pi^+\pi^-\pi^0$





(a) $B^0 \to \eta_{\gamma\gamma}\eta_{\gamma\gamma}$ (b) $B^0 \to \eta_{\gamma\gamma}\eta_{3\pi}$ (c) $B^0 \to \eta_{3\pi}\eta_{3\pi}$

$$\mathcal{B}(B^0 \to \eta\eta) = (7.6^{+2.7+1.4}_{-2.3-1.6}) \times 10^{-7} \ @ \ 3.7\sigma$$

First evidence, arXiv:1609.03267

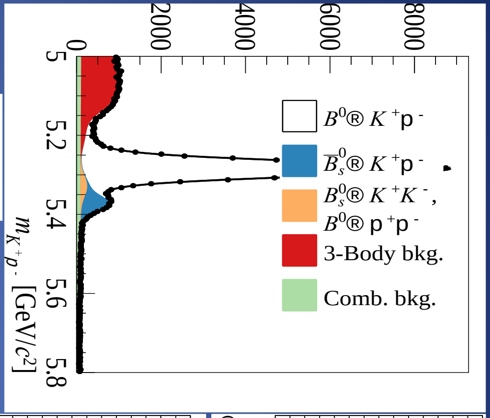
CP Violation for Two-body

- Direct CPV for $B^0_{(s)} \to K^+\pi^-$ arXiv:1805.06759

$A_{cp}^{B^0} = -0.084 \pm 0.004 \pm 0.003$
$A_{cp}^{B_s^0} = +0.213 \pm 0.015 \pm 0.007$

$\Rightarrow$ Most precise

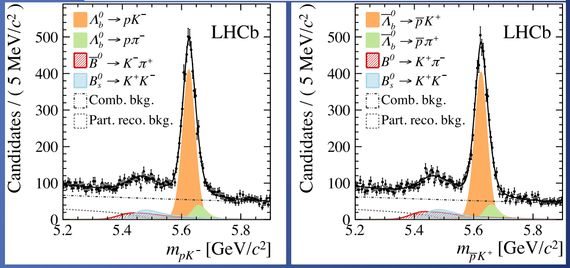
$$\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B_s^0}} + \frac{\mathcal{B}(B_s^0 \to \pi^+K^-)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = -0.11 \pm 0.04 \pm 0.03$$



- Direct CPV for $\Lambda_b^0 \to PK(\pi)$ preliminary

$A_{cp}^{PK} = -0.020 \pm 0.013 \pm 0.019$
$A_{cp}^{P\pi} = -0.035 \pm 0.017 \pm 0.020$

$\Rightarrow$ Most precise

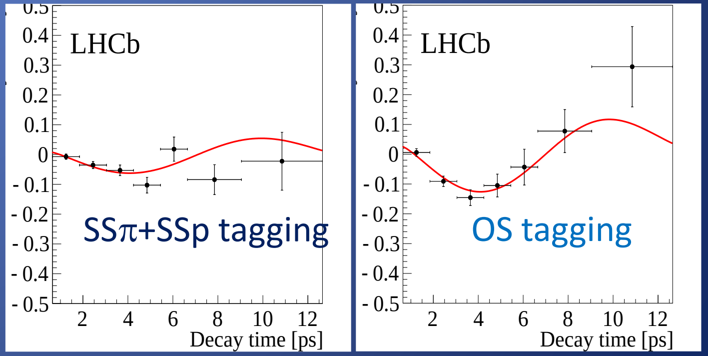


- CPV for $B_d^0 \to \pi^+\pi^-, B_s^0 \to K^+K^-$

$C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01$
$S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01$

$C_{K^+K^-} = +0.20 \pm 0.06 \pm 0.02$
$S_{K^+K^-} = +0.18 \pm 0.06 \pm 0.02$

arXiv:1805.06759

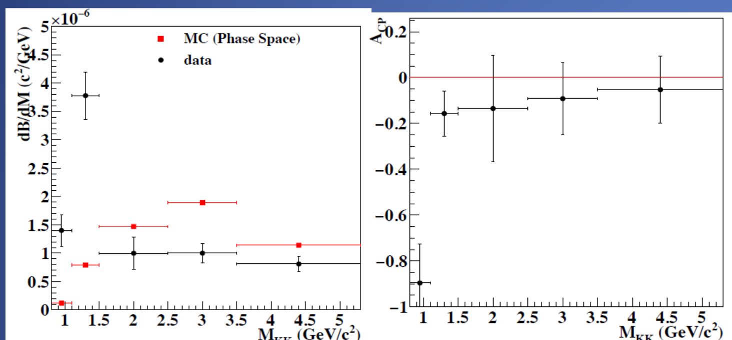


Charmless Three-body Decays

771 M $B\bar{B}$

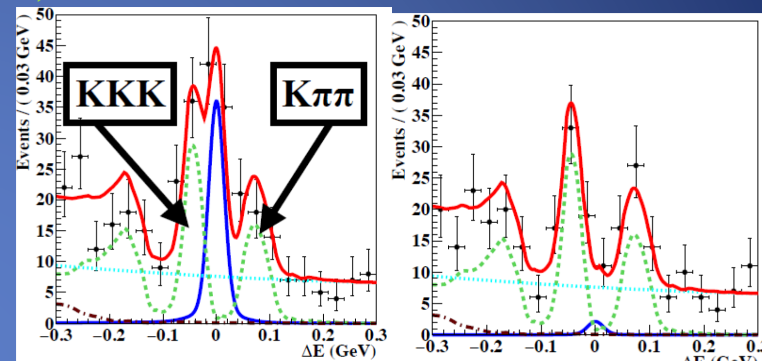
- $B^+ \to K^+K^-\pi^+$ PRD 96, 031101 (2017)

First bin: $0.8 < M_{KK} < 1.1$ Gev/c^2



M_{KK} <1.1: $A_{cp} = -0.90 \pm 0.17 \pm 0.03$ @4.8σ

$K^+K^-\pi^+$ $K^+K^-\pi^-$

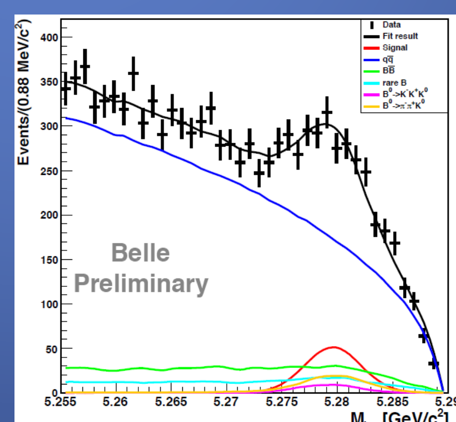


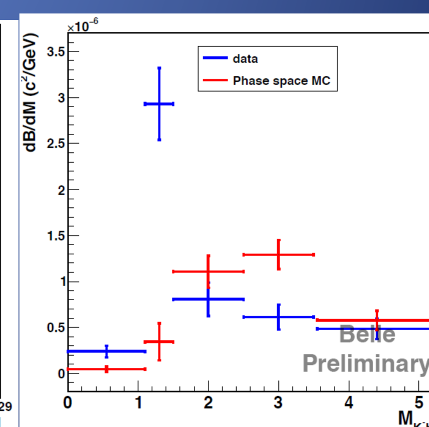
$Br(B^+ \to K^+K^-\pi^+) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$

$A_{CP} = -0.170 \pm 0.073 \pm 0.017$

PDG: Br = $(5.0 \pm 0.5 \pm 0.5) \times 10^{-6}$
$A_{CP} = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$

- $B^+ \to K^+\pi^-K^0_S$
  - ICHEP preliminary
  - Observe 490^{+50}_{-49} events
  - $\mathcal{B} = (3.60 \pm 0.33 \pm 0.15) \times 10^{-6}$
    $A_{CP} = (-8.5 \pm 8.9 \pm 0.2)\%$
  - Structure at $M_{KK} = 1.5$ GeV





Summary

- Many profound results from B decays have been reported. No striking new physics evidence is seen but several measurements show possible anomalies or tensions,

  $R(D^{(*)}), R(J/\psi)$, $S\ell^+\ell^-$ branching fractions, $R_{K^{(*)}}$, P_5'
- Converging $|V_{cb}|$ inclusive and exclusive is a triumph. Need more effort and ideas for $|V_{ub}|$. Close communication with theorists.
- Precise measurements and excess of rare decays are achieved with more data. However sometimes new ideas matter.

  $\Rightarrow$ Detecting B decays with neutrinos in the final states in LHCb.
- Looking for the era of Belle II and LHC Run 3.