Semileptonic tree-level B decays

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(On behalf of BaBar, Belle and LHCb)

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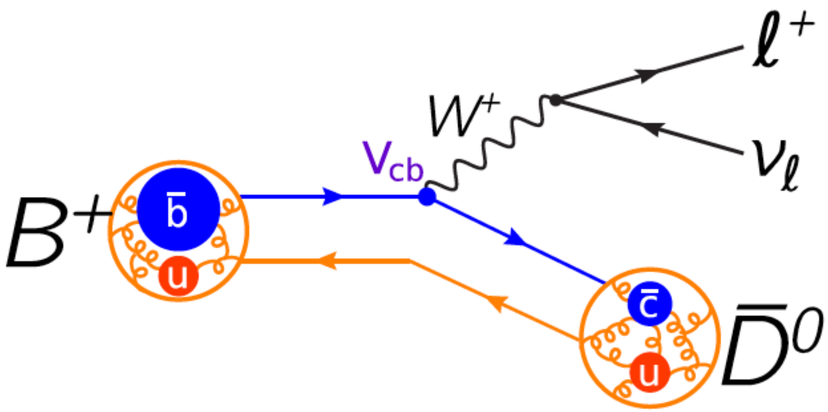
Why study these decays?

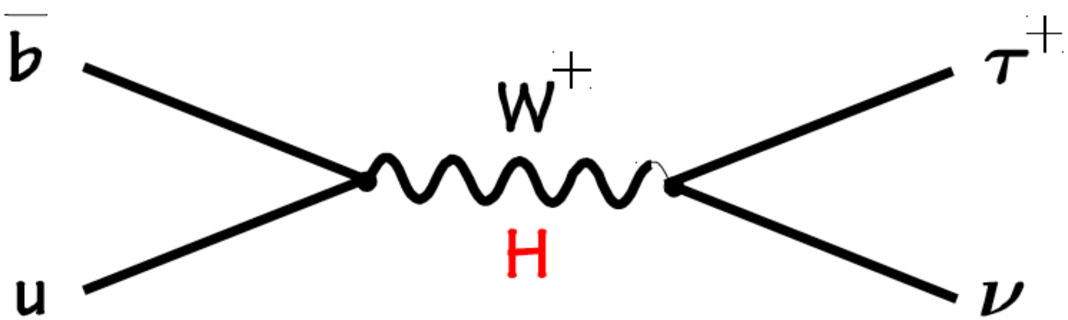
- ❑ Precision test of the quark-flavour sector of the standard model (SM)
- ✧ Measure elements of the CKM unitarity matrix

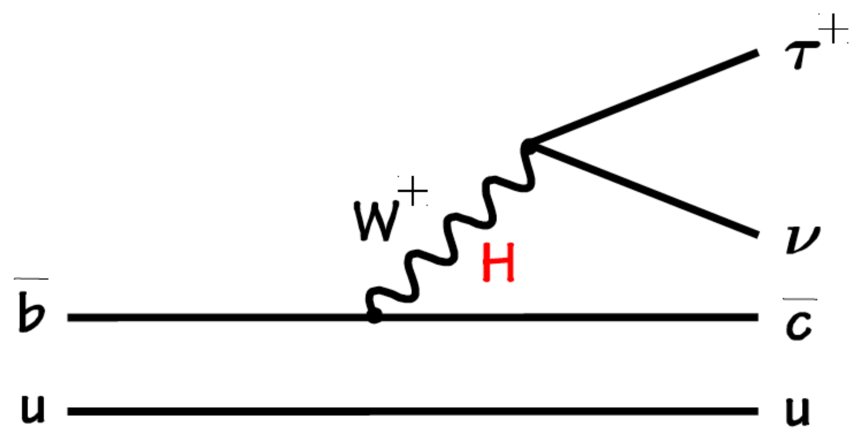
$\ell = e, \mu$



- ❑ Provide complementary information to test and validate QCD calculations

- ❑ Indirectly probe new physics e.g., the charged Higgs boson appearing in place of the W ➔ complementarity with searches at the energy frontier





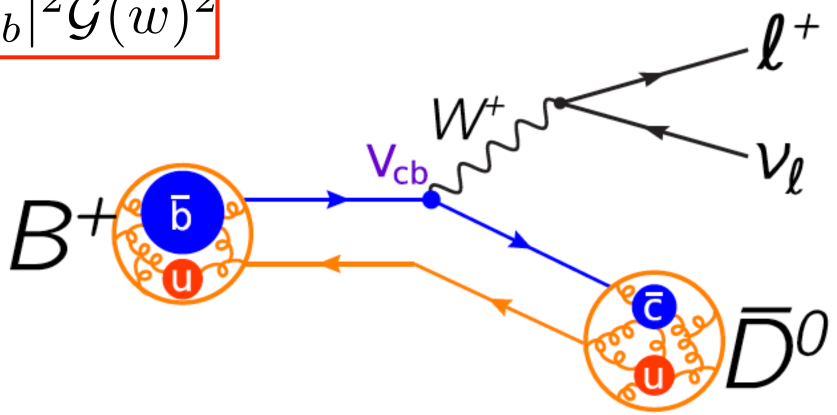
➢ Review some recent results from B-factories (BABAR and Belle) and LHCb

Measure the CKM matrix element V_{cb}

- Extract $|V_{cb}|$ from differential decay width

$$\boxed{\frac{d\Gamma}{d\omega} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 (w^2 - 1)^{\frac{3}{2}} \eta_{\rm EW}^2 |V_{cb}|^2 \mathcal{G}(w)^2}$$

$\ell = e, \mu$



- ✧ Kinematics: $w = v_B \cdot v_D$
- ✧ Electroweak correction: $\eta_{\rm EW}$
- ✧ Form factor: $\mathcal{G}(w)$

- Need inputs from Lattice QCD or Light Cone Sum Rules
- ✧ Until recently, Caprini-Lellouch-Neubert (CLN) parametrization was used

$$\mathcal{G}(w) = \mathcal{G}(1)[1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3] \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

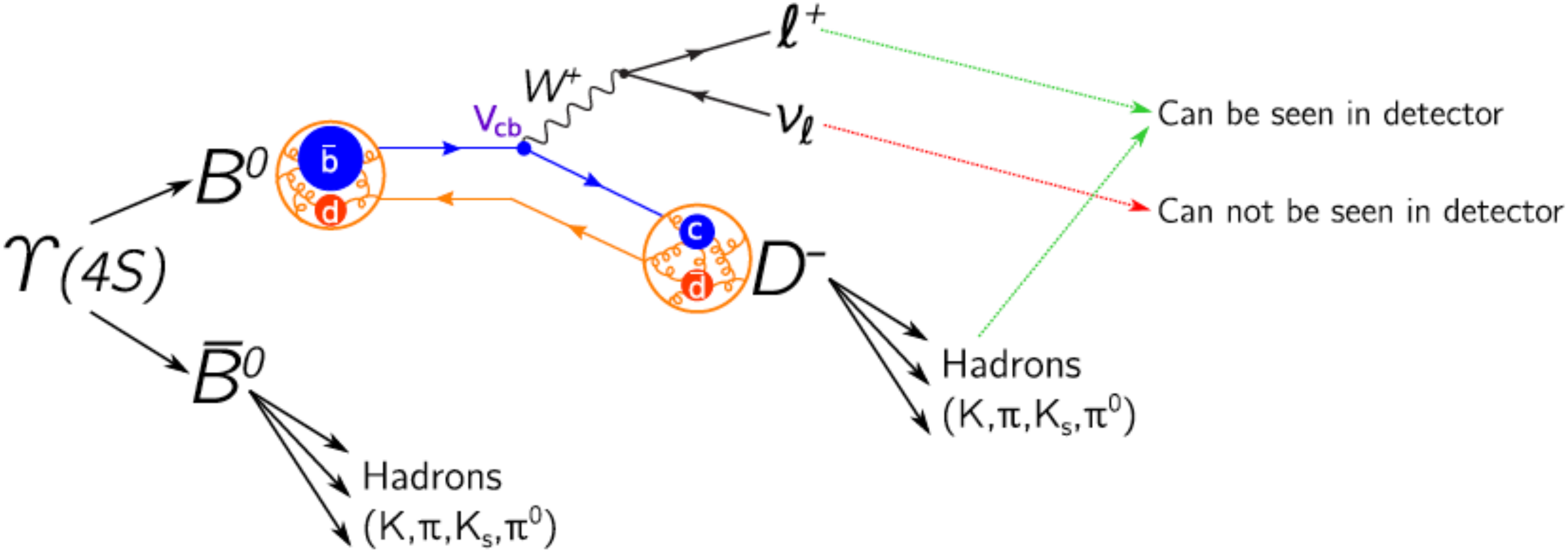
NPB 530 (1998) 153

- ✧ Meanwhile, Boyd-Grinstein-Lebed (BGL) parametrization is also available (less model assumptions)

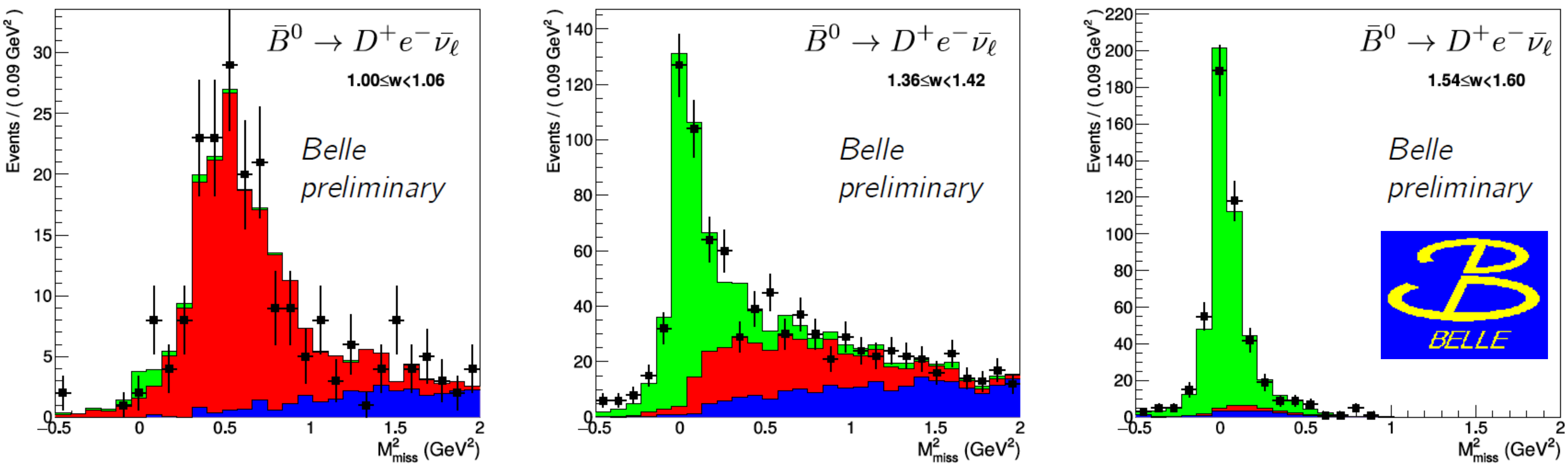
$$\mathcal{G}(w) = \frac{\sqrt{4M_D/M_B}}{1+M_D/M_B} \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n$$

NPB 461 (1996) 493

Analysis in a nutshell



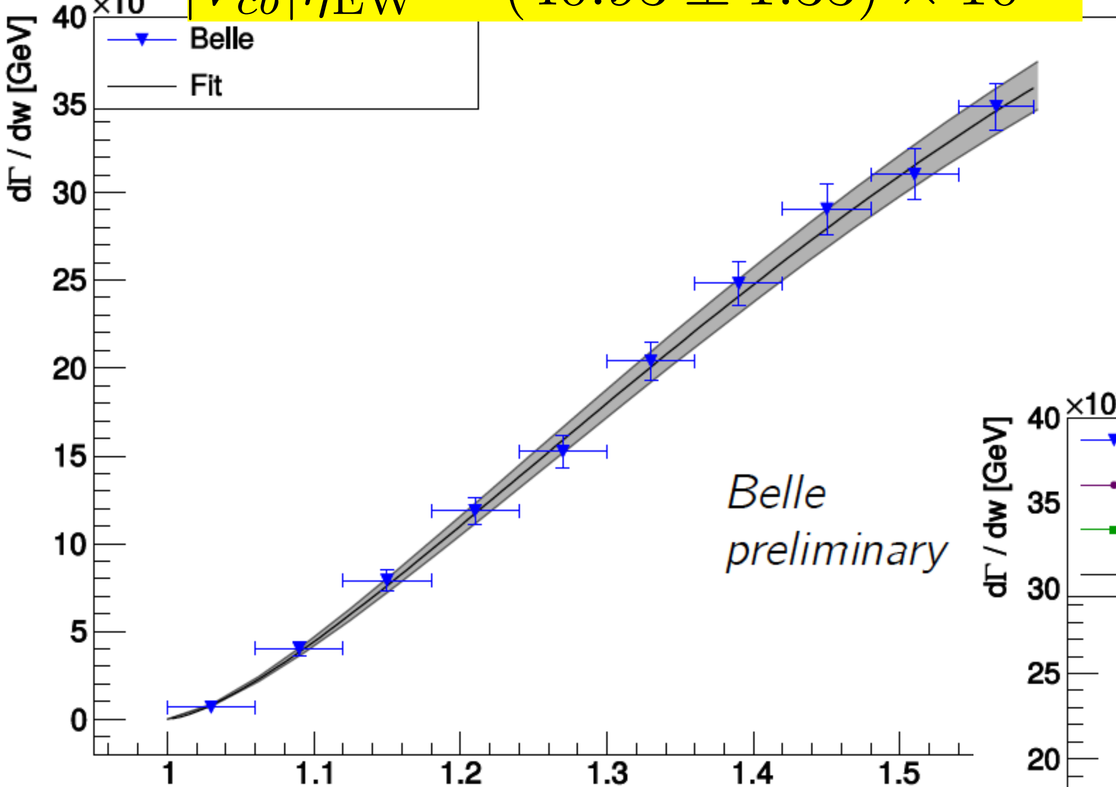
- Determine missing mass squared $\boxed{M^2_{\rm miss} = (p_{\rm beam} - p_{B_{\rm tag}} - p_D - p_\ell)^2}$
- Extract signal yield in 10 different w-bins (from 1.0 to 1.6)



Results on V_{cb}

- Fit with the CLN parameterization

$$|V_{cb}|\eta_{\mathrm{EW}} = (40.93 \pm 1.33) \times 10^{-3}$$



$$\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.35 \pm 0.04 \pm 0.11)\%$$

$$\mathcal{B}(\mathrm{B}^+ \to \bar{D}^0\ell^+\nu_\ell) = (2.67 \pm 0.04 \pm 0.12)\%$$

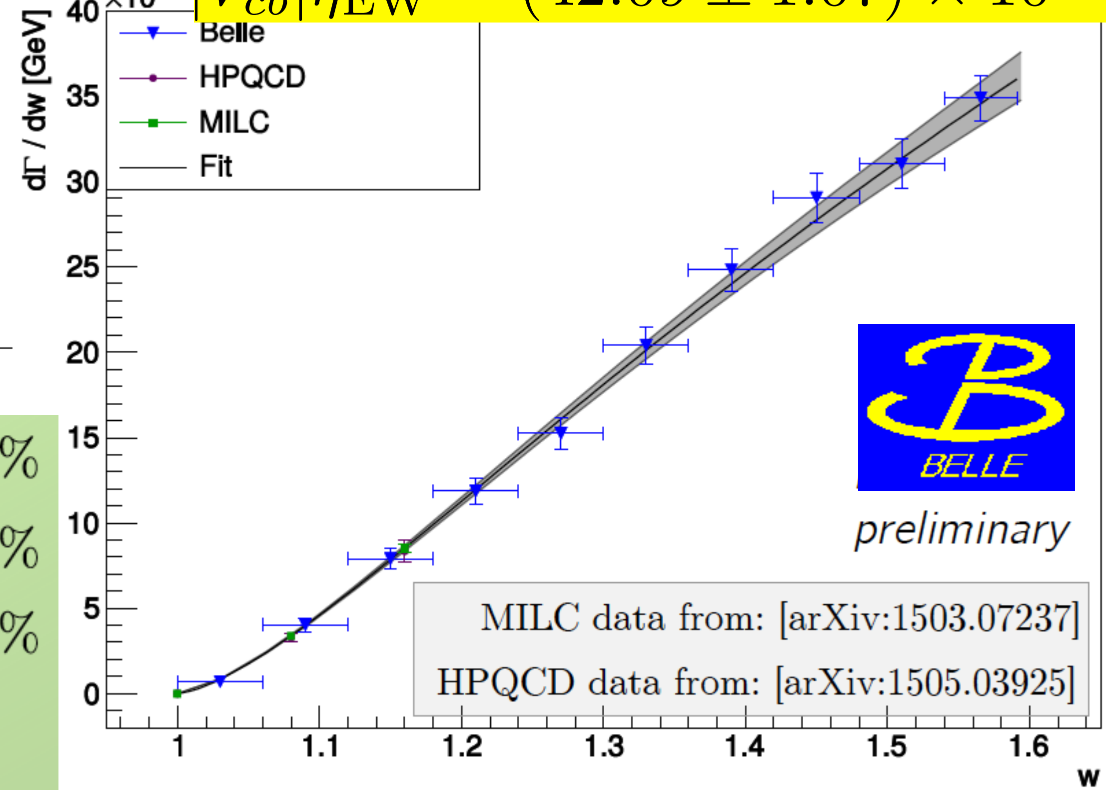
$$\mathcal{B}(B \to D\ell\nu_\ell) = (2.43 \pm 0.03 \pm 0.10)\%$$

(stat) (syst)

(in terms of B^0)

- Fit with the BGL parameterization

$$|V_{cb}|\eta_{\mathrm{EW}} = (42.09 \pm 1.07) \times 10^{-3}$$



Summary on V_{cb}

- Inclusive: $B \to X_c \ell \nu$
  - ✧ Heavy quark expansion

    |Vcb| = [42.42 ± 0.86] x 10^{-3}

- Exclusive: $B \to D^{(*)} \ell \nu$
  - ✧ $B \to D^* \ell \nu$ LQCD

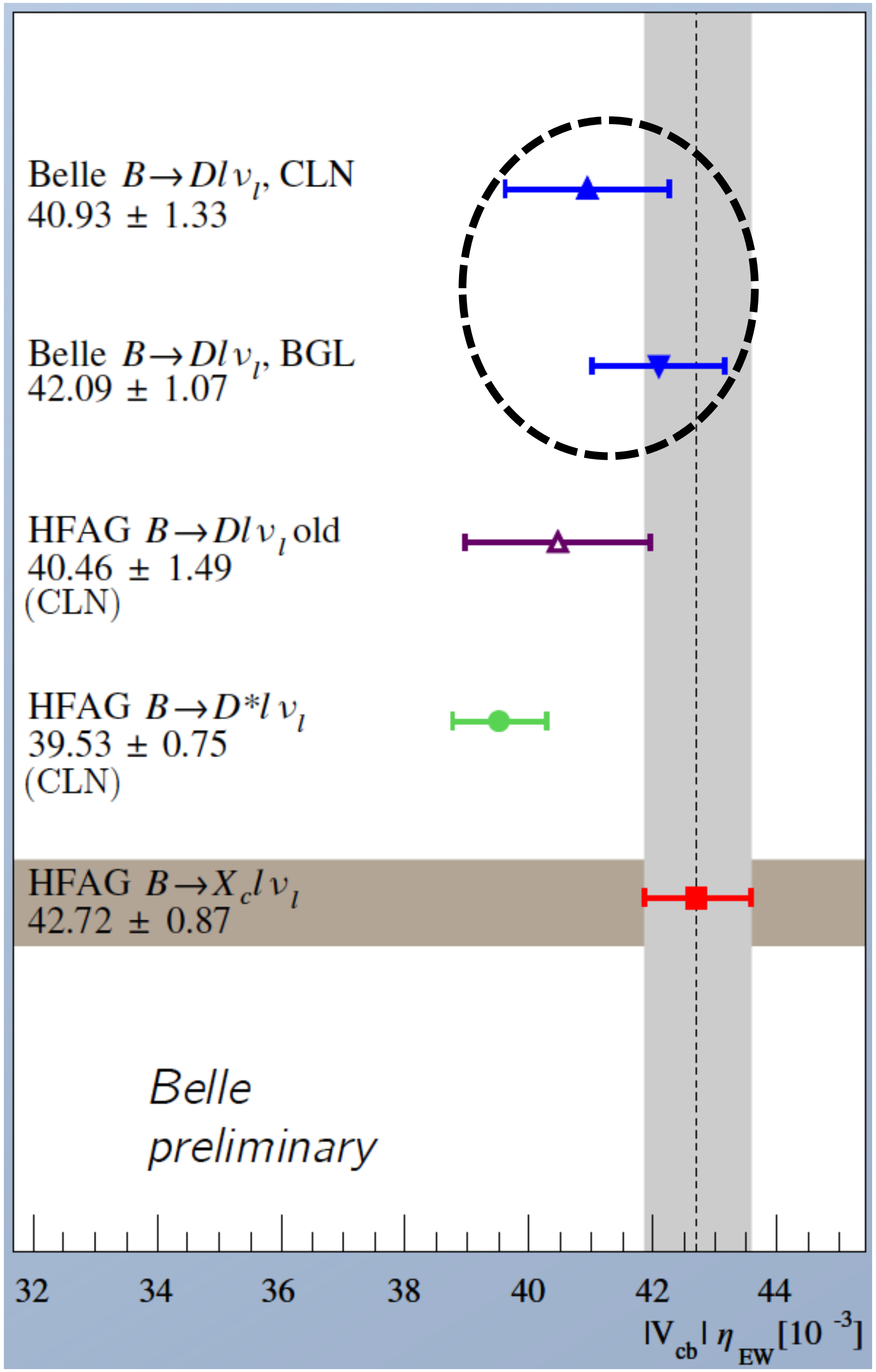
    |Vcb| = [39.27 ± 0.75] x 10^{-3}

  - ✧ $B \to D \ell \nu$ LQCD

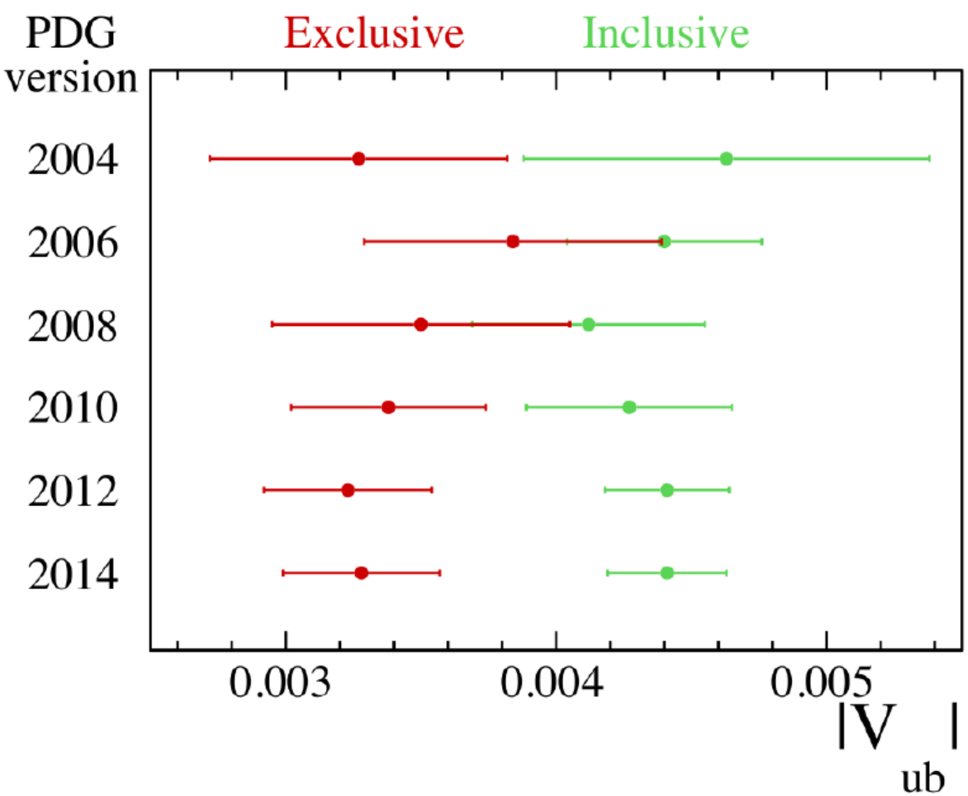
    |Vcb| = [40.19 ± 1.48] x 10^{-3}

- About 2-3σ discrepancy between the two approaches

➢ New measurement does not confirm inclusive vs. exclusive discrepancy



A bit of history on V_{ub}



- A longstanding discrepancy between the value of $|V_{ub}|$ determined using exclusive and inclusive decays

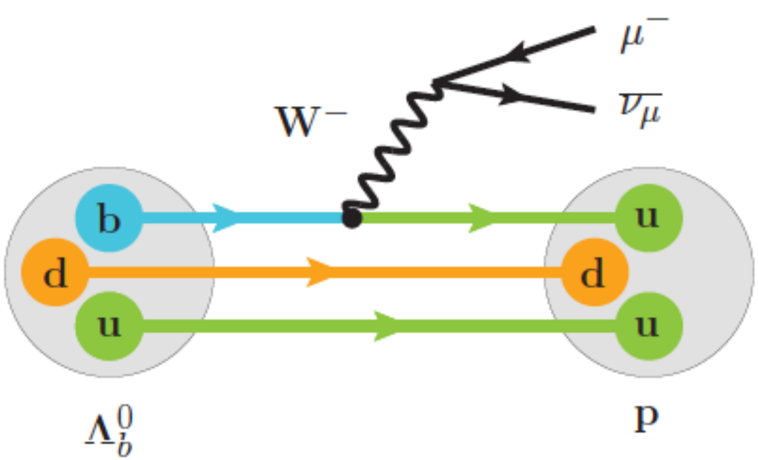
- According to PDG2014:

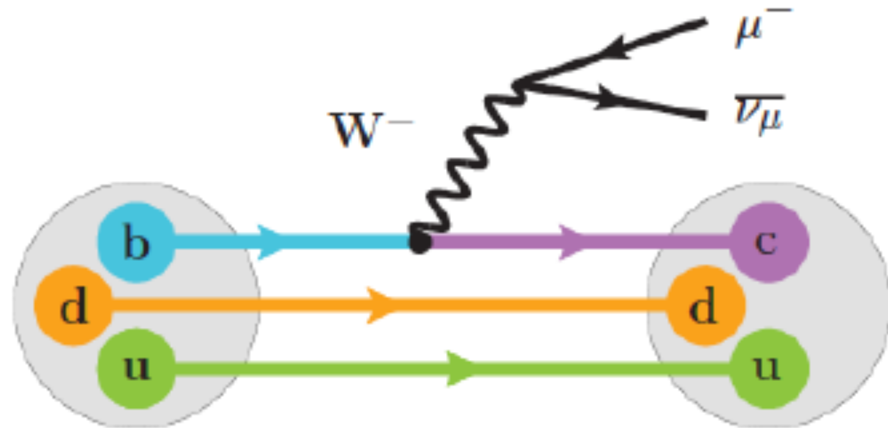
Inclusive: $(4.41 \pm 0.15^{+0.15}_{-0.10}) \times 10^{-3}$

Exclusive: $(3.28 \pm 0.29) \times 10^{-3}$

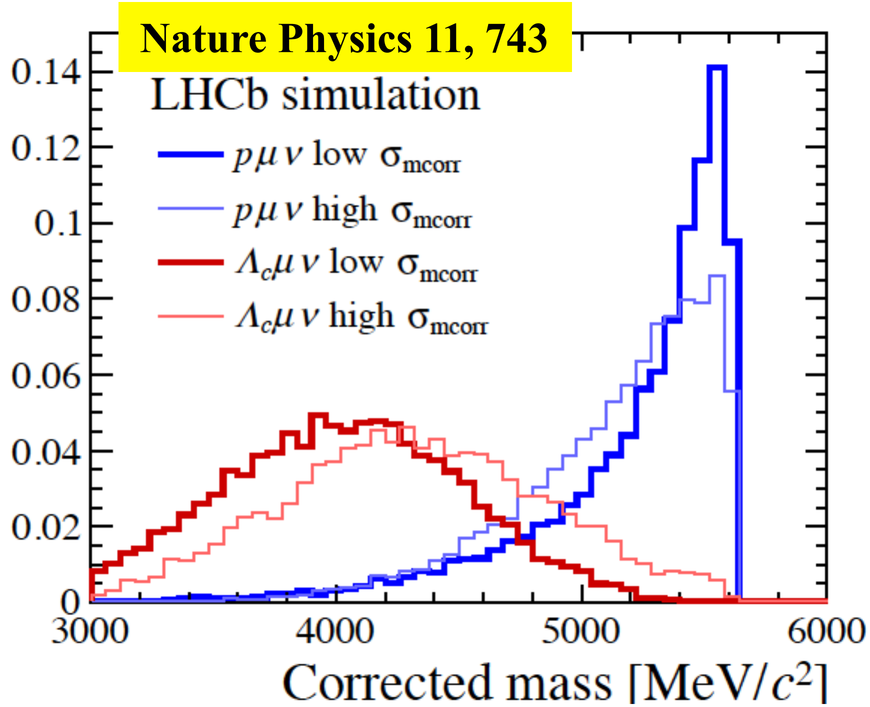
Average: $(4.13 \pm 0.49) \times 10^{-3}$

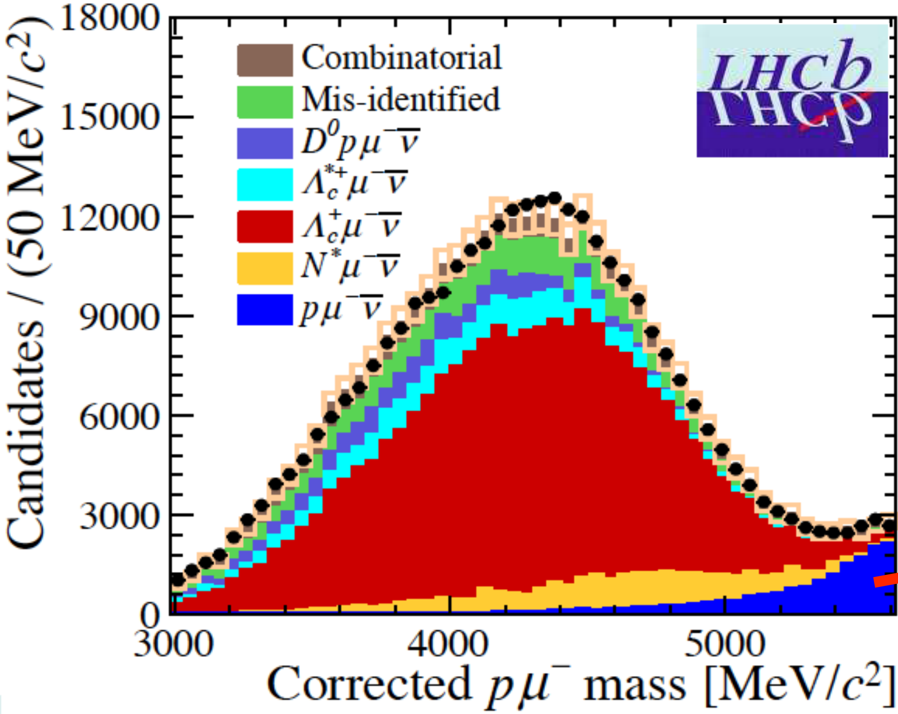
- Can semileptonic b-hadron decays help to resolve the paradox?





Observation of $\Lambda_b^0 \to p\mu^- \bar{\nu}_\mu$

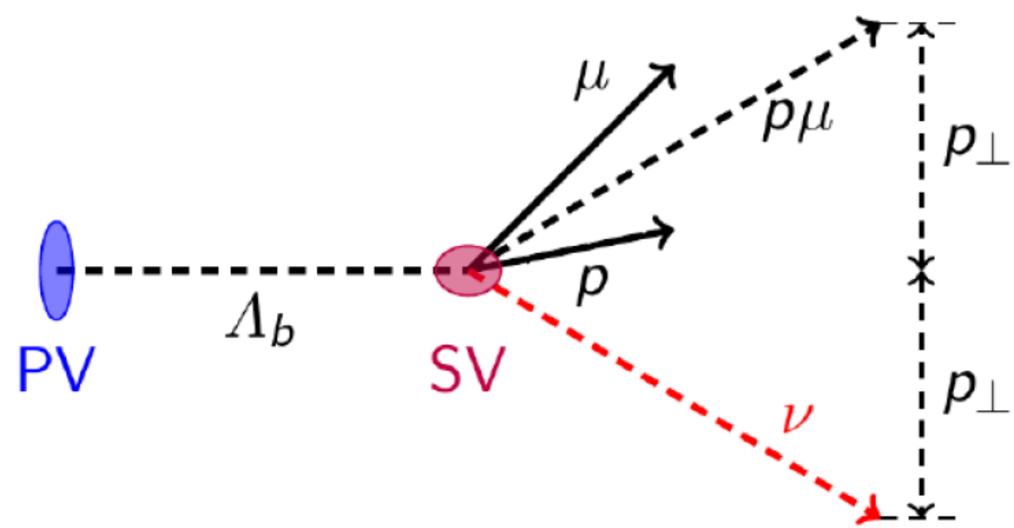




- LHC is a Λ_b factory as B^0:Λ_b:B_s ~ 4:2:1
- Key to find the signal is the corrected mass

$$m_{\rm corr} = \sqrt{m^2 + p_\perp^2} + p_\perp$$

(the minimal b-hadron mass compatible with its flight direction)

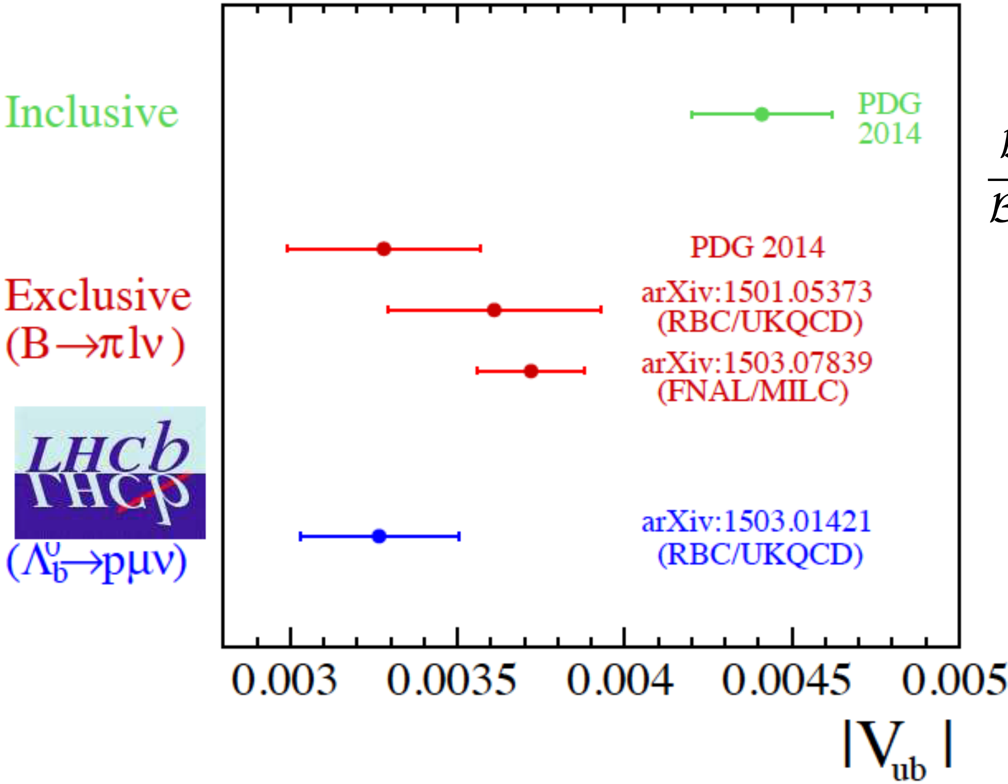


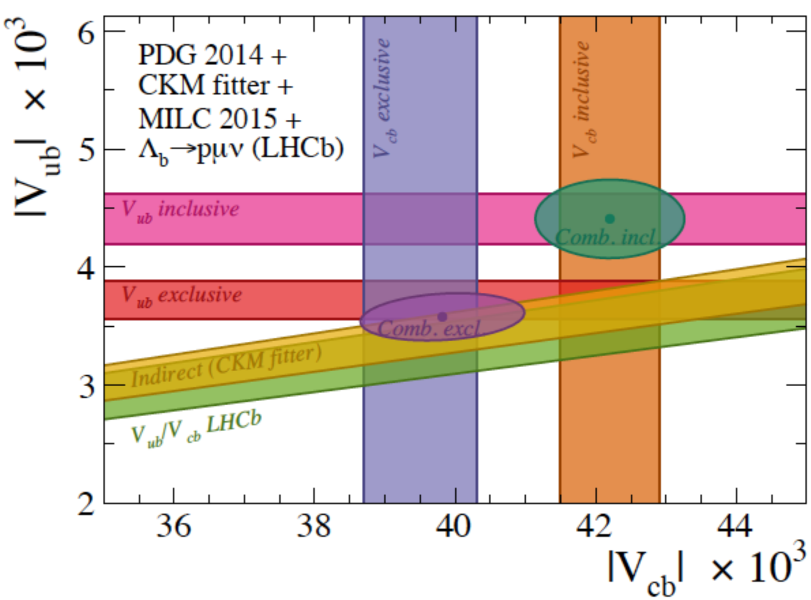
- Dominant background

$$\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}_\mu$$

First observation (17,687 ± 733)

$|V_{ub}/V_{cb}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$





- Measure the ratio of branching fraction

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)_{q^2>15\,\mathrm{GeV}}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\nu)_{q^2>7\,\mathrm{GeV}}} = (1.00 \pm 0.04 \pm 0.08)\%$$

- Based on lattice input, extract

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.083 \pm 0.004 \pm 0.008$$

Nature Physics 11, 743

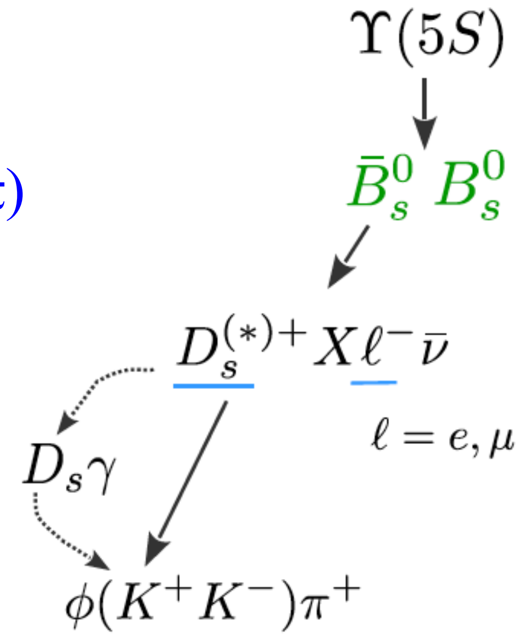
- Using the WA value for $|V_{cb}|$, we derive $|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$
- Agrees with the exclusive value but not with the inclusive measurement (3.5σ discrepancy)

➢ Puzzle is still alive and kicking

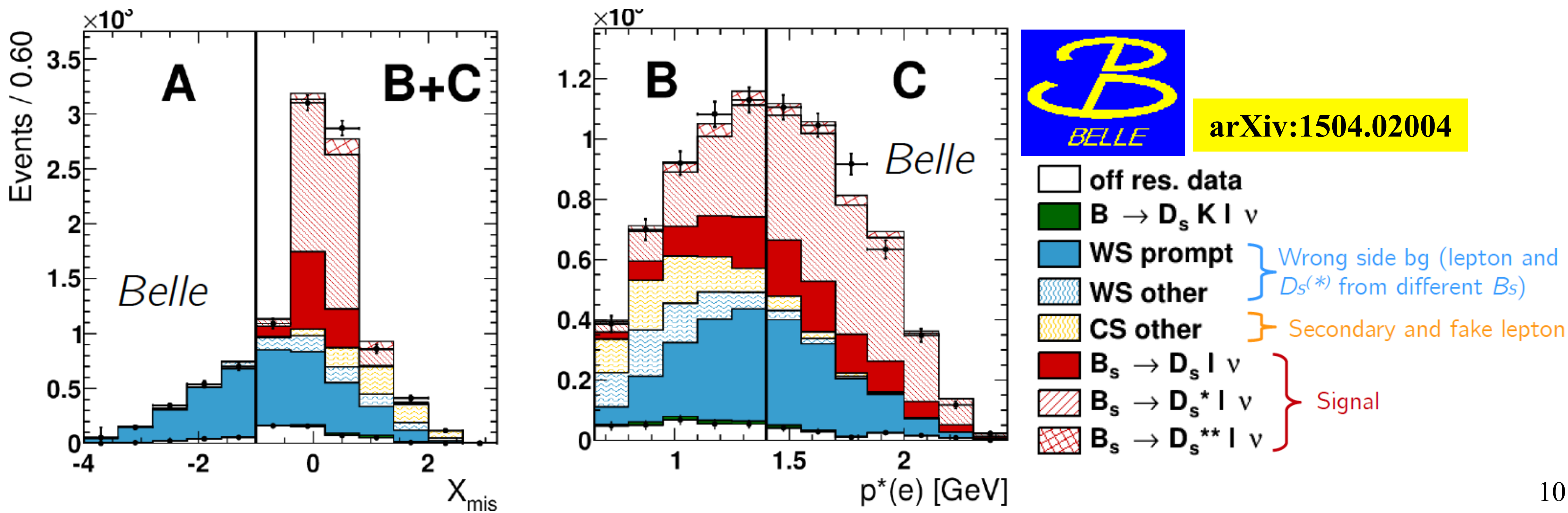
First measurement of $B_s \to D_s^{(*)} X \ell \nu$

- Reconstruct $D_s \to \phi(K^+K^-)\pi$ ➔ fit M(KKπ)
  $D_s^* \to D_s\gamma$ ➔ fit M(KKπγ)−M(KKπ)
- Combine with an oppositely charged lepton
- Determine the number of signal events in

$$X_{\text{miss}} = \frac{E^*_{B_s} - (E^*_{D_s\ell} + p^*_{D_s\ell})}{\sqrt{s/4 - m^2_{B_s}}}$$



- Use 3 counting regions (A,B,C) to extract signal and backgrounds



arXiv:1504.02004

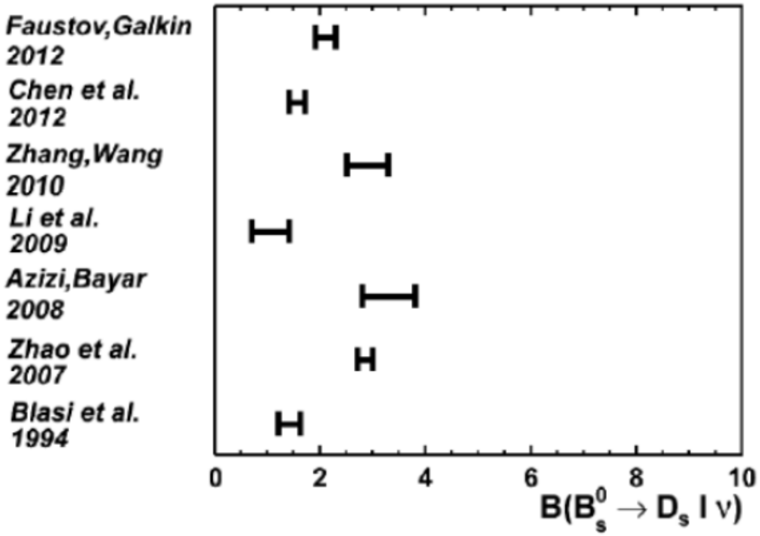
Results on $B_s \to D_s^{(*)} X \ell \nu$

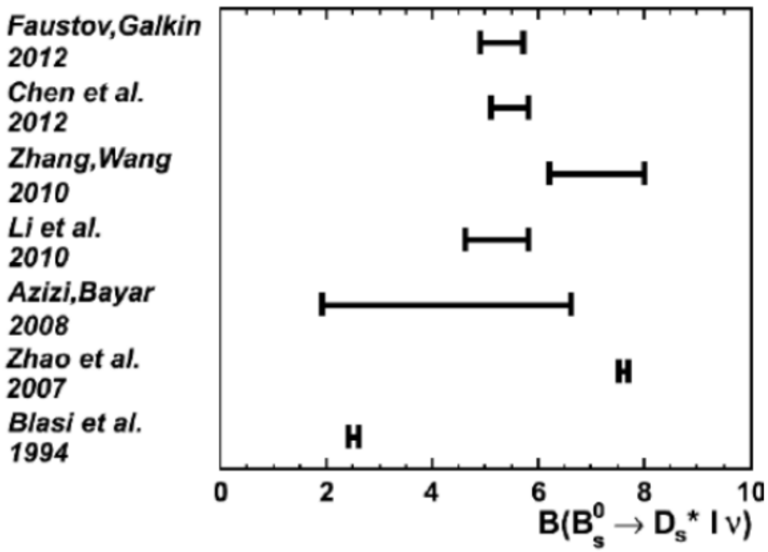
arXiv:1504.02004

$$\mathcal{B}(D_s X e\nu) = [8.1 \pm 0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 1.4(\text{ext})]\%$$
$$\mathcal{B}(D_s X \mu\nu) = [8.3 \pm 0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 1.5(\text{ext})]\%$$
$$\mathcal{B}(D_s^* X e\nu) = [5.2 \pm 0.6(\text{stat}) \pm 0.4(\text{syst}) \pm 0.9(\text{ext})]\%$$
$$\mathcal{B}(D_s^* X \mu\nu) = [5.7 \pm 0.6(\text{stat}) \pm 0.4(\text{syst}) \pm 1.0(\text{ext})]\%$$

$$\mathcal{B}(D_s X \ell\nu) = [8.2 \pm 0.2(\text{stat}) \pm 0.6(\text{syst}) \pm 1.4(\text{ext})]\%$$
$$\mathcal{B}(D_s^* X \ell\nu) = [5.4 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.9(\text{ext})]\%$$

Theory predictions:

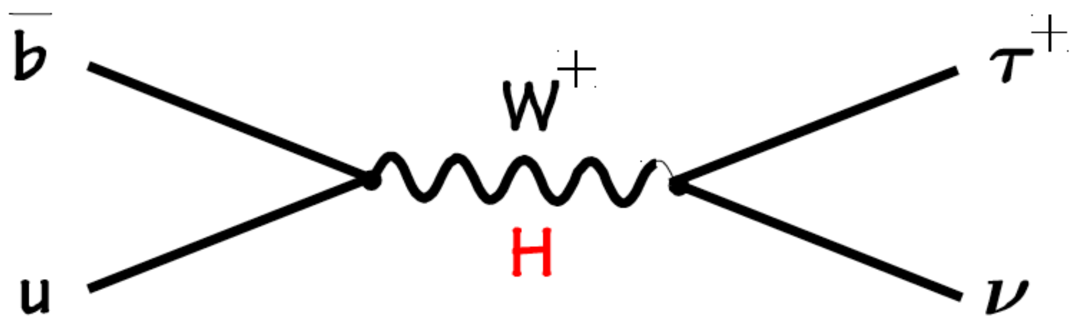


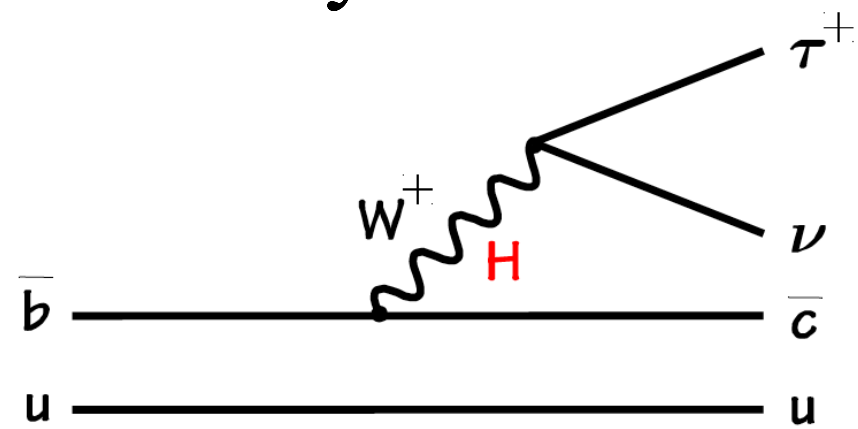


- ✧ '(ext)' is the error due to external measurements of $N(B_s\overline{B}_s)$ and secondary BF of $D_s^{(*)}$
- ❑ Theory predictions don't include the secondary BF ➔ should be lower than our results
- ❑ Provides the most precise estimate for:

$$\sigma[e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}] = [57.1 \pm 1.5(\text{stat}) \pm 4.3(\text{syst}) \pm 4.2(\text{ext})]\ \text{pb}$$

Enter the tauonic B decays





$B \to \tau\nu$

helicity suppression

$$\mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2$$

➔ 2HDM (type II): $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}_{\rm SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$

uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B and other CKM uncertainties by combining with precise Δm_d

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

➔ 2HDM (type II): $\mathcal{B}(B^+ \to D\tau^+\nu_\tau) = G_F^2 \tau_B |V_{\rm cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$

uncertainties from form factors F_V and F_S can be studied with $B \to D l \nu$ (more form factors in $B \to D^* \tau \nu$)

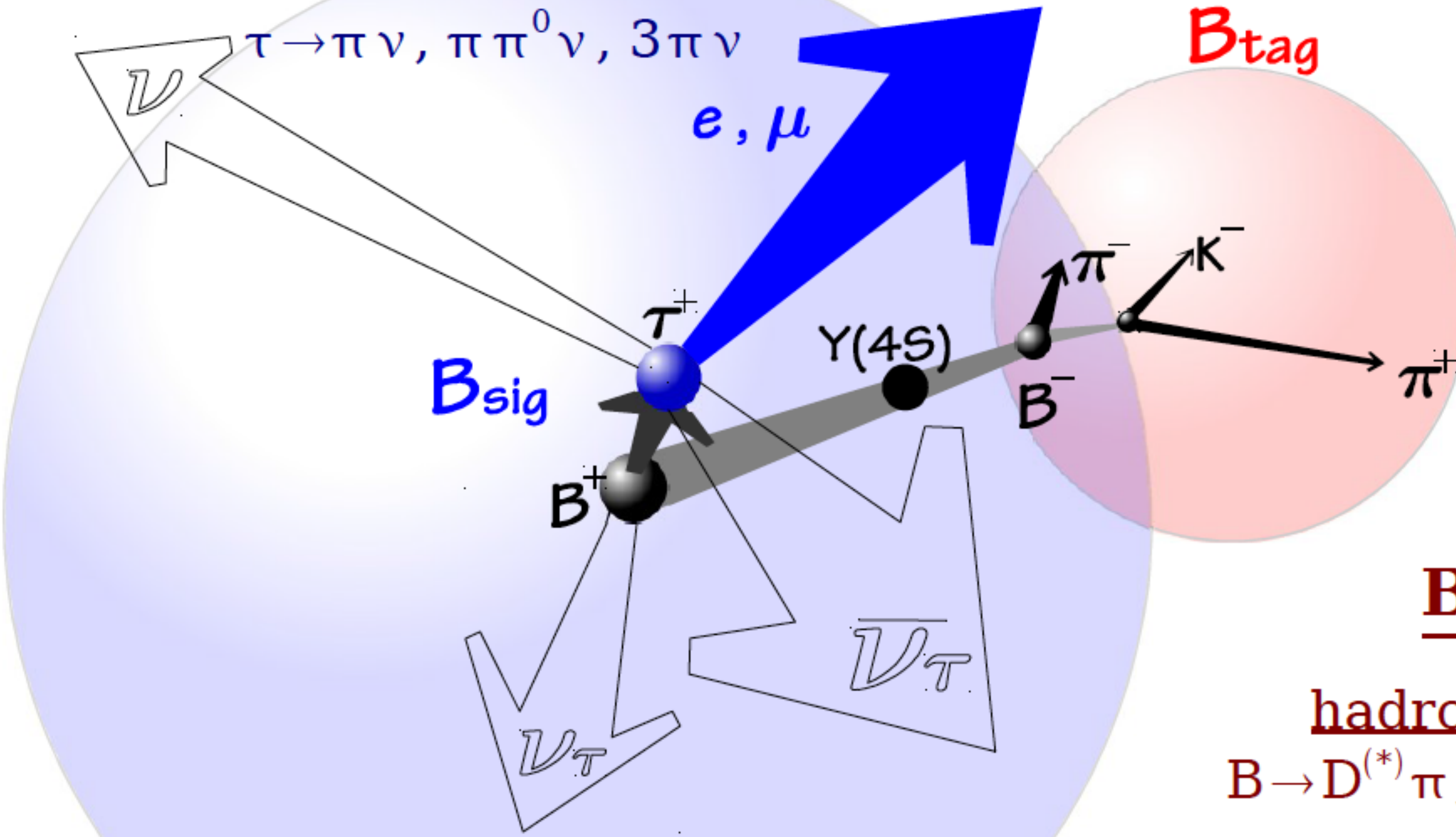
How to identify the signal?

$B_{sig} \rightarrow \tau\, \nu$

(70 % of all τ decays)

$\tau \rightarrow e\,\nu\nu,\ \mu\,\nu\nu,$

$\tau \rightarrow \pi\,\nu,\ \pi\,\pi^0\nu,\ 3\pi\,\nu$



Require no particle
and no energy left
after removing B_{tag}
and visible particles of B_{sig}

B_{tag}

hadronic tag

$B \rightarrow D^{(*)}\pi,\ D^{(*)}$rho...

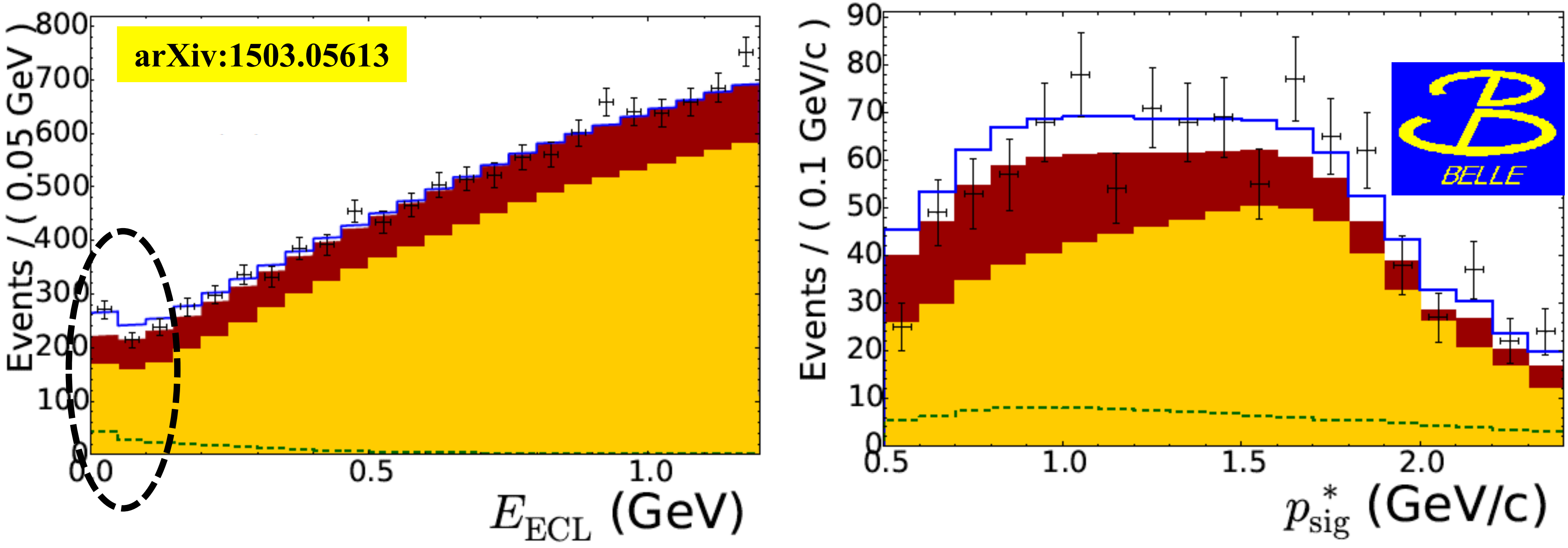
$\epsilon \sim 0.2\%$

semileptonic tag

$B \rightarrow D^{(*)} l \nu\ X$

Analysis in a nutshell

- Improvements with respect to previous measurement **PRD 82 (2010) 071101**
  - An improved 'semileptonic tagging' method
  - Additional tau decay channels: $\pi^+\pi^0\nu$ and $\pi^+\pi^0\pi^0\nu$
  - Robust background fighting (neural network based)
  - 20% more data
  - Inclusion of 2nd variable: visible momentum of the τ candidate in the centre-of-mass (CM) frame
- Extended maximum likelihood fit in E_{ECL} and p^*_{sig}



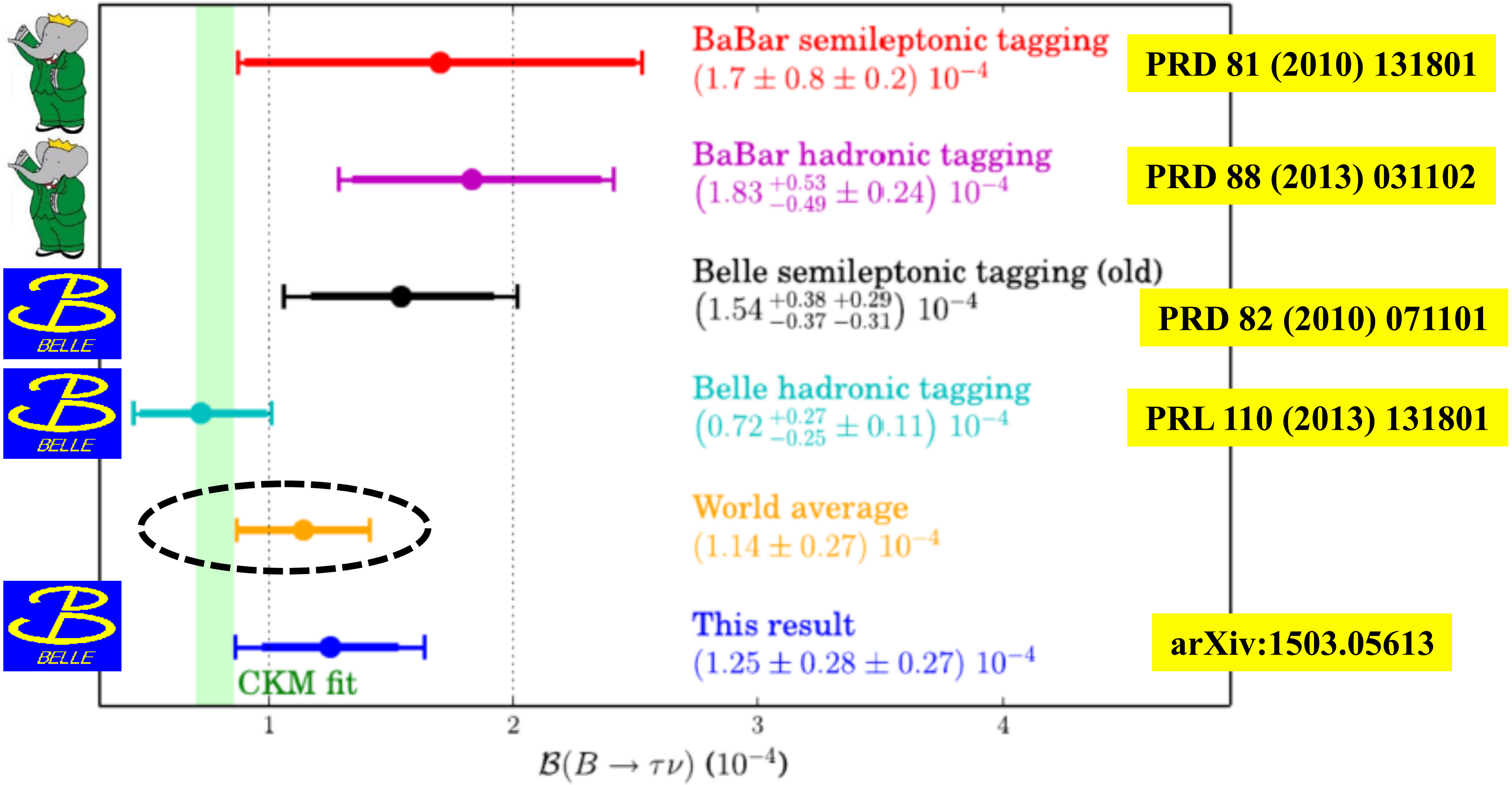
Summary on $B^+ \to \tau^+ \nu_\tau$

- Results of the presented semileptonic-tag measurement ➔ 3.8σ

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$$

- New Belle result combined with hadronic tag one ➔ 4.6σ

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (0.91 \pm 0.19 \pm 0.11) \times 10^{-4}$$



➢ Consistent with the SM expectation based on a global fit using other inputs

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

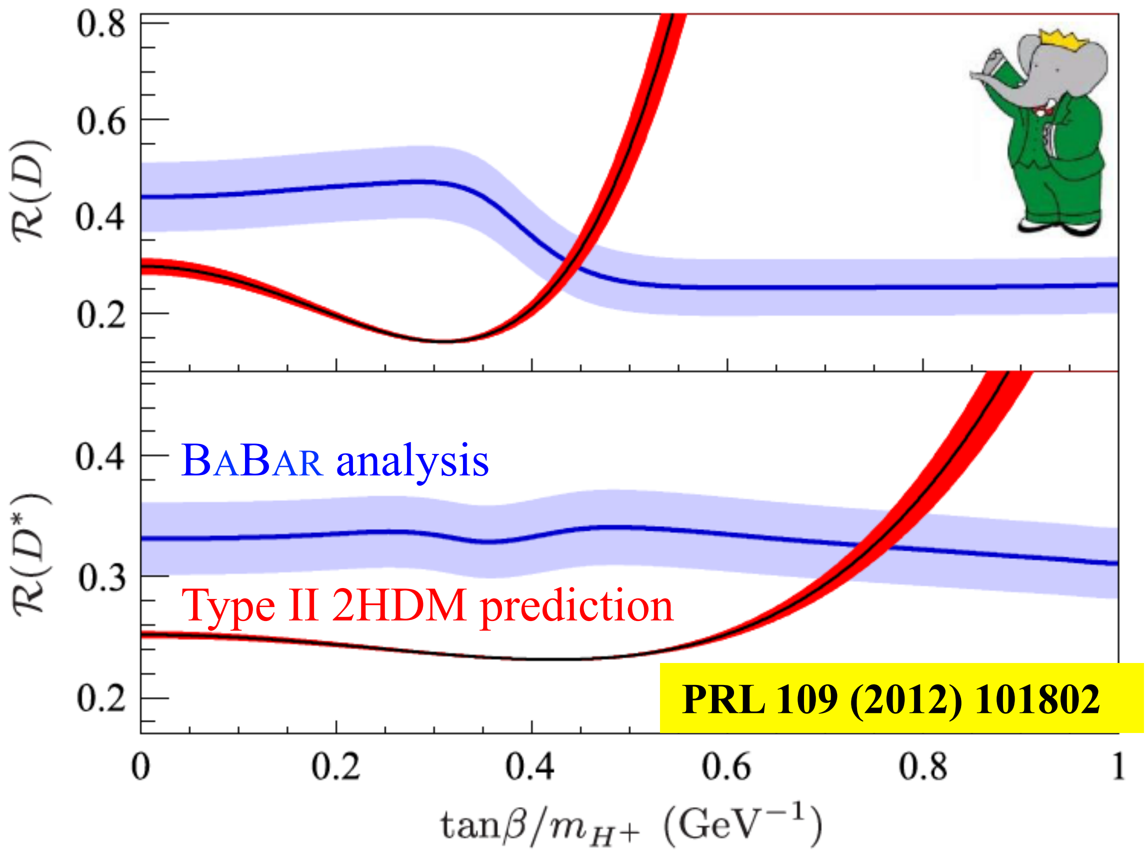
- Semileptonic decays are pretty well described in the SM
  - ✧ Charged lepton universality implies branching fraction to e,μ,τ differ only by phase-space and helicity suppression factor
- Measure the ratio of branching fractions ➔ dependence on FF and CKM matrix element cancels out

$$R(D) = \frac{\mathcal{B}(B \to D\tau^+\nu_\tau)}{\mathcal{B}(B \to D\ell^+\nu_\ell)}$$

$$R(D^*) = \frac{\mathcal{B}(B \to D^*\tau^+\nu_\tau)}{\mathcal{B}(B \to D^*\ell^+\nu_\ell)}$$

- Provides a good probe for NP, in particular to the possible charged Higgs boson contribution
- BABAR result

$$\boxed{\begin{aligned}\mathcal{R}(D) &= 0.440 \pm 0.058 \pm 0.042 \\ \mathcal{R}(D^*) &= 0.332 \pm 0.024 \pm 0.018\end{aligned}}$$



2.4σ away from SM and incompatible with type II 2HDM

➢ Would be interesting to see results from other experiments

Belle's analysis in a nutshell

- Exploit the uniqueness of e^+e^- B factories

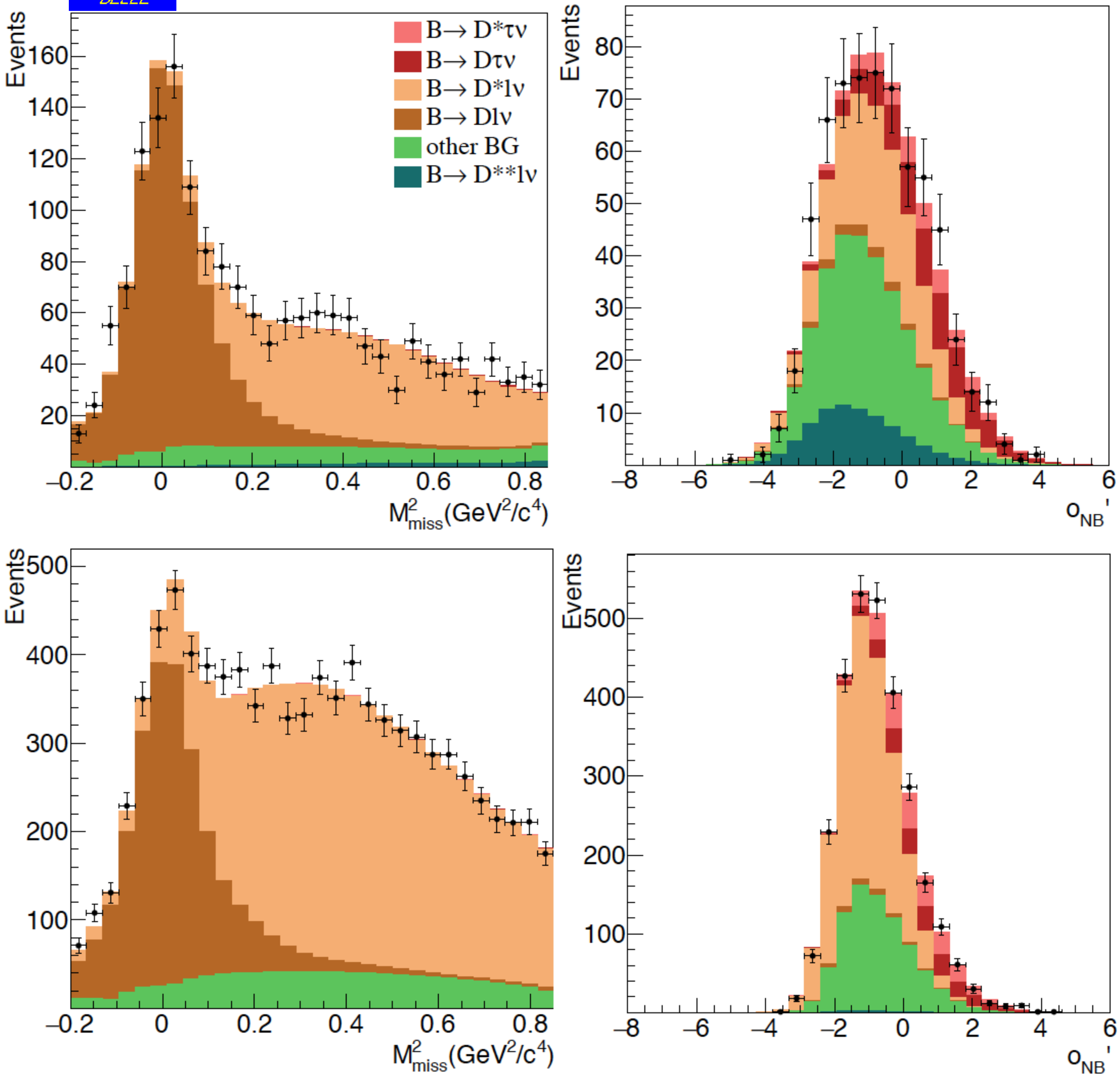
$$\boxed{e^+e^- \to \Upsilon(4S) \to B_{\rm sig}B_{\rm tag}}$$

- B_{tag} is identified with 'hadronic tag'
  - Constrain charge, flavour as well as (E,p) of B_{sig}
  - Results in a high purity but low efficiency
- Reconstruct B_{sig} in the $D^{(*)}$+lepton final state (lepton: electron/muon)
- No further tracks or π^0 are allowed

- Signal fitting in split regions
  - * $M^2_{\rm miss} < 0.85\ {\rm GeV}^2$ mostly $B \to D^{(*)}\ell\nu$ $(\ell = e, \mu)$; fit $M^2_{\rm miss}$
  - * $M^2_{\rm miss} > 0.85\ {\rm GeV}^2$ $B \to \overline{D}^{(*)}\tau^+\nu_\tau$ enhanced; fit neural-net variable, $o'_{\rm NB}$

- The above neural network variable comprises E_{ECL}, q^2 (momentum transfer) and the lepton momentum in the CM frame

Fits for $B \to D\ell X$



arXiv:1507.03233

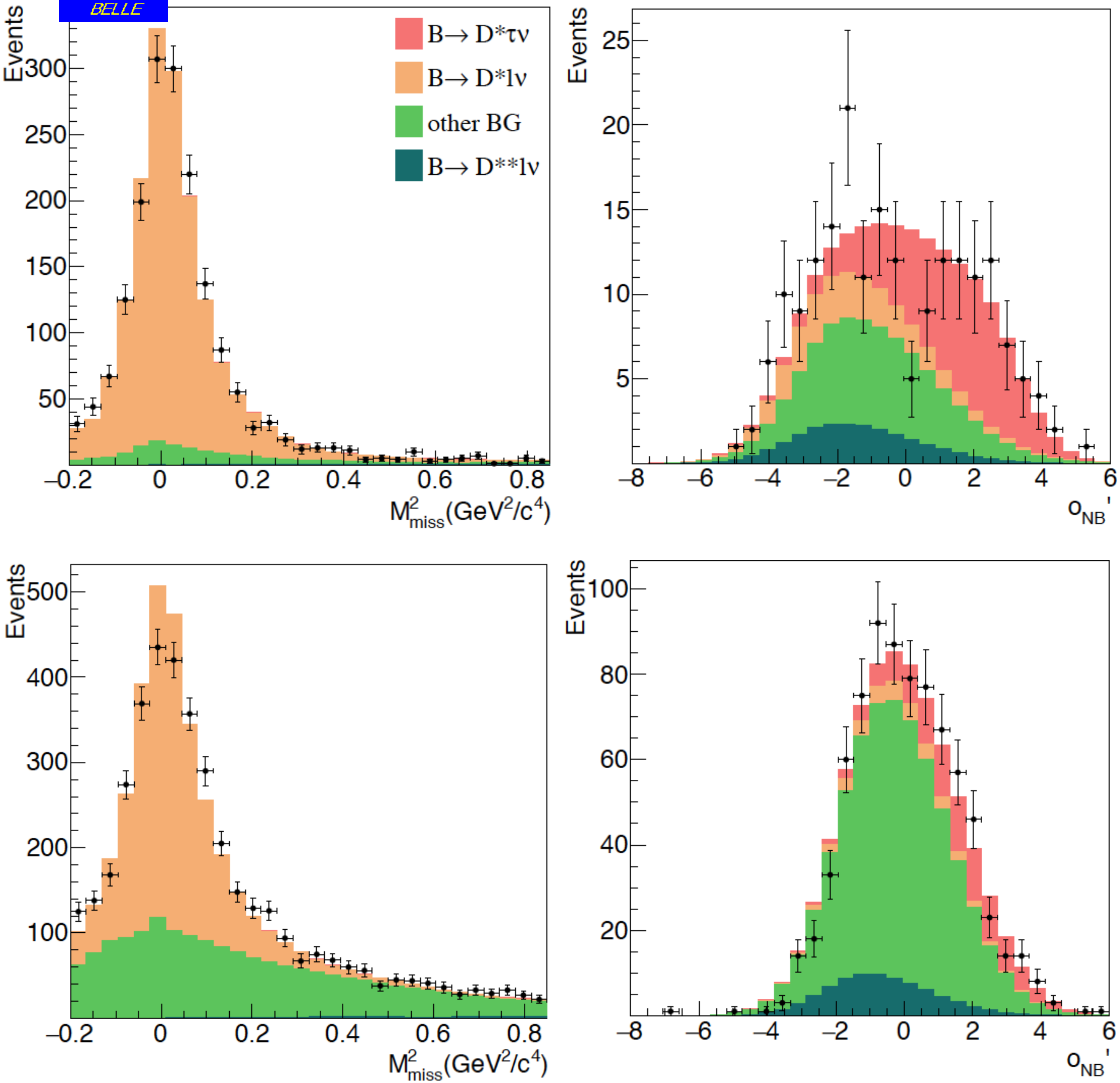
- (top) $D^+\ell^-$

  (bottom) $D^0\ell^-$

- (left) $M^2_{\rm miss} < 0.85$ GeV^2
  - * $B \to D\ell\nu$ dominant
  - * fit $M^2_{\rm miss}$ for backgr'd normalization

- (right) $M^2_{\rm miss} > 0.85$ GeV^2
  - * $B \to D\tau\nu$ enhanced
  - * fit $o'_{\rm NB}$

Fits for $B \to D^* \ell X$



arXiv:1507.03233

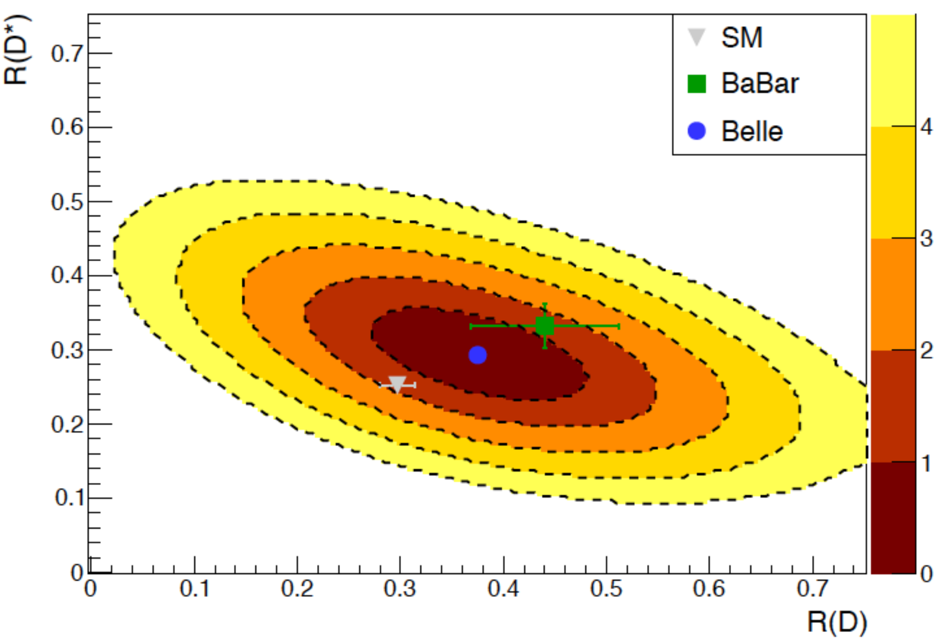
- (top) $D^{*+}\ell^-$
  (bottom) $D^{*0}\ell^-$
- (left) $M^2_{\text{miss}} < 0.85\ \text{GeV}^2$
  - $B \to D^* \ell \nu$ dominant
  - fit M^2_{miss} for backgr'd normalization
- (right) $M^2_{\text{miss}} > 0.85\ \text{GeV}^2$
  - $B \to D^* \tau \nu$ enhanced
  - fit o'_{NB}

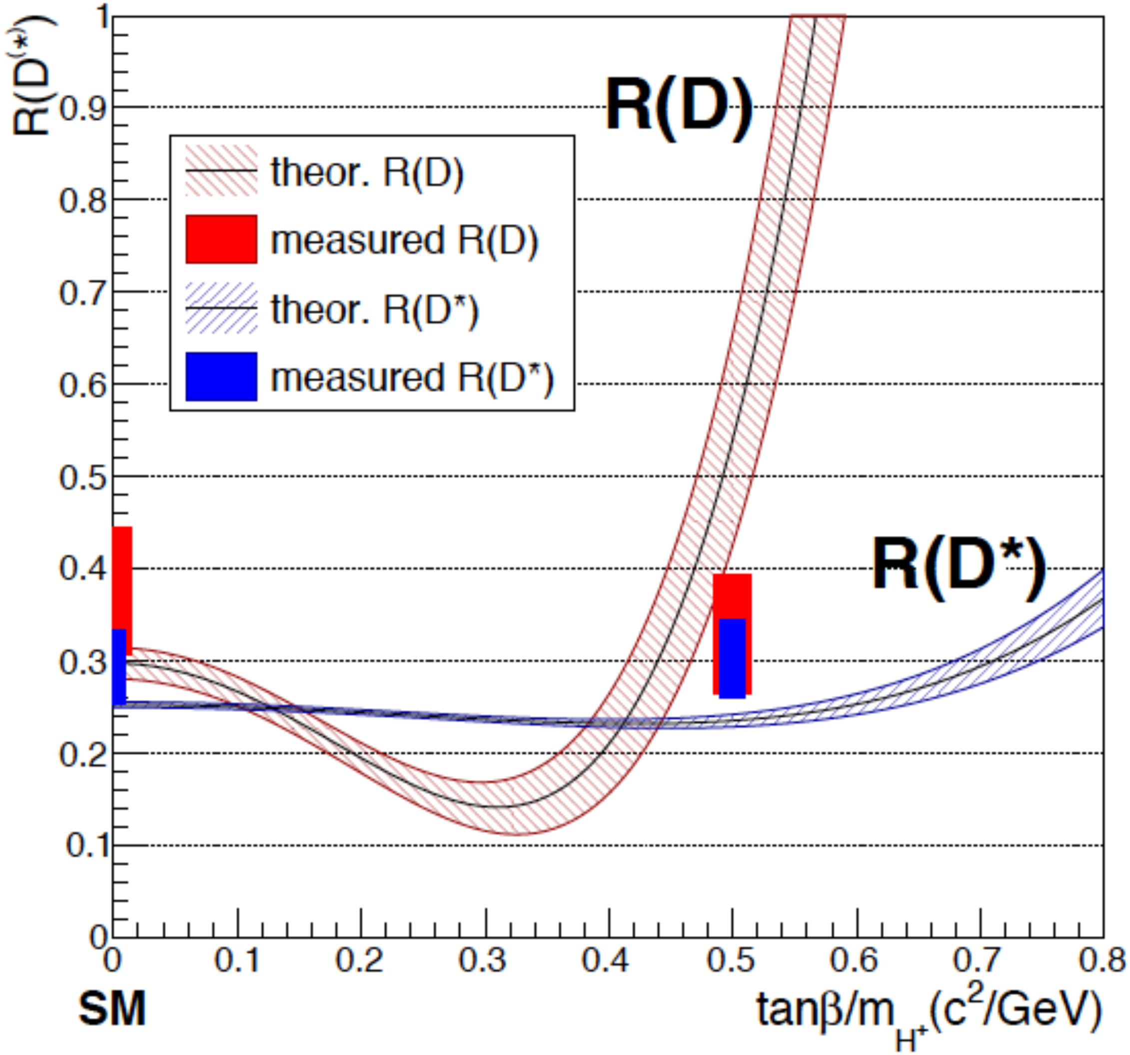
Results

- Fit is repeated with PDF generated for type II 2HDM of $\tan\beta/m_H = 0.5\ \mathrm{GeV}^{-1}$

arXiv:1507.03233

$$R(D) = 0.375 \pm 0.064 \pm 0.026$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015$$





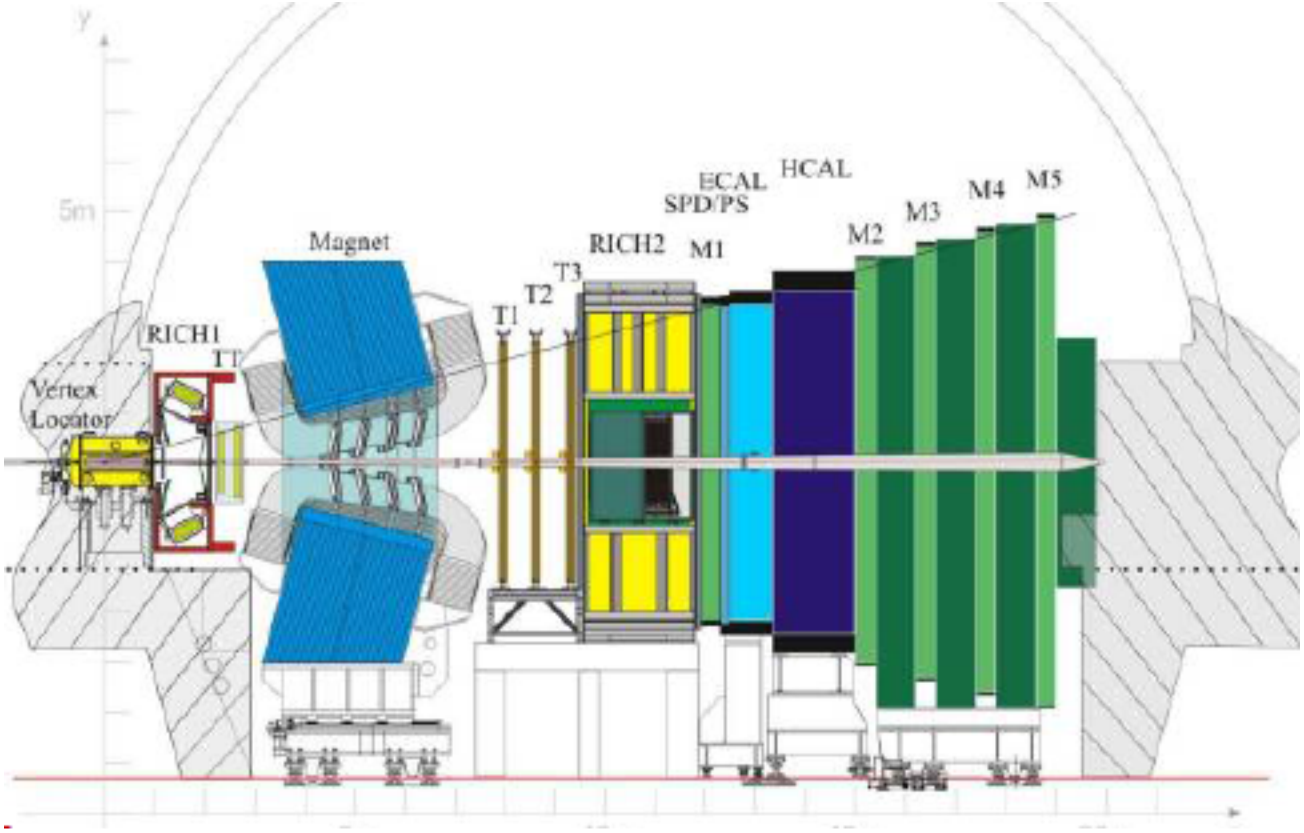
- Result lies between the SM prediction and BABAR value
- Compatible with type II 2HDM around $\tan\beta/m_H = 0.5\ \mathrm{GeV}^{-1}$

Now turn the page to LHCb

- So far, precise measurement of final state with multiple neutrinos are considered to be unfeasible at hadron colliders
  - No luxury of kinematic constraint and suffers from large background unlike the e^+e^- B factories
- Take the ratio of branching fractions for two modes with the same visible final state particles

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+(\mu^+\nu_\mu\bar{\nu}_\tau)\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

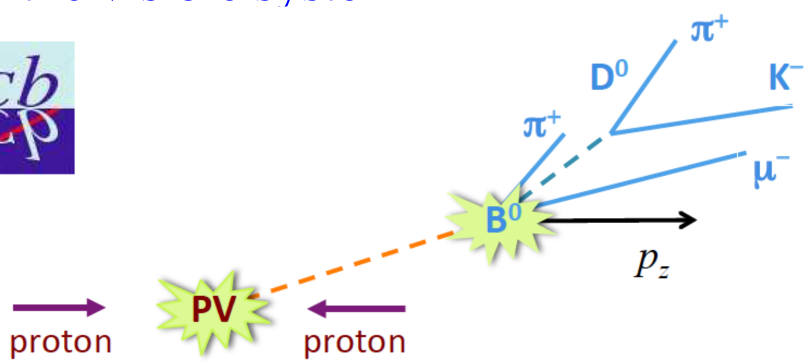
- 20 μm IP resolution
- Great muon detection capability (efficiency ~97% for 1-3% π➔μ mis-identification)
- Excellent charged pion and kaon separation



- Software trigger selects high p_T D(➔Kπ) with a displaced vertex

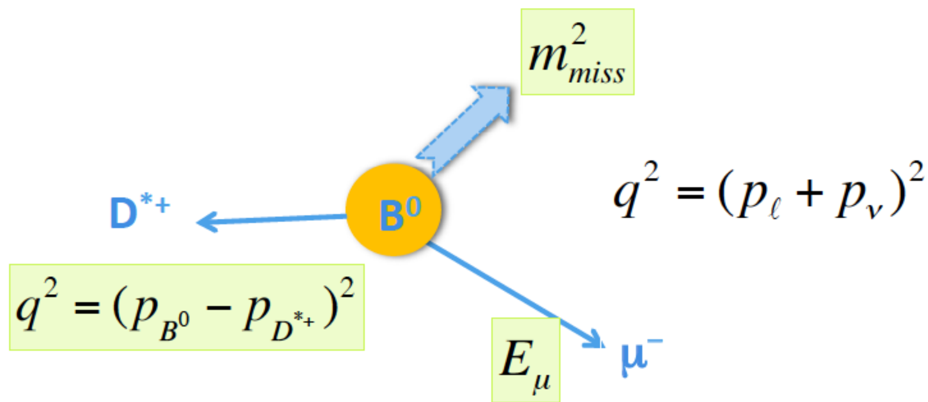
Find the B rest frame

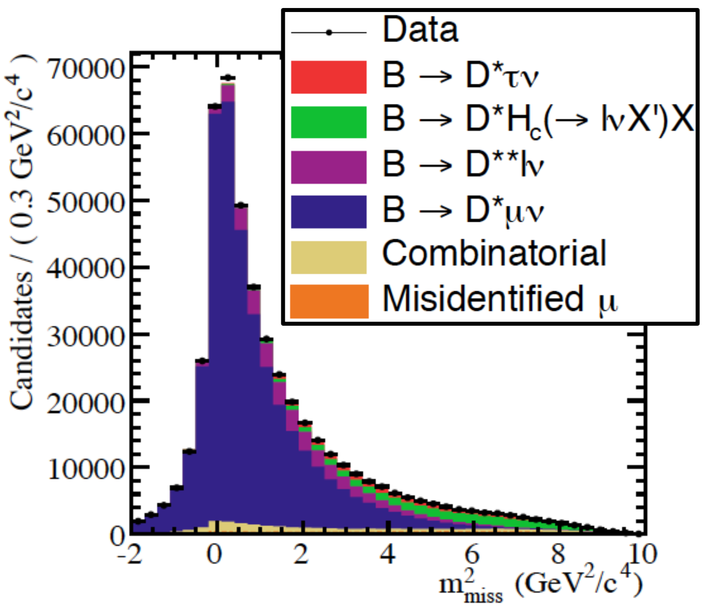
- ✧ B momentum is unknown at production from pp collisions
- ✧ B direction well determined by a vector from primary to decay vertex
- ✧ Boost along the z axis approximates the boost of the visible system

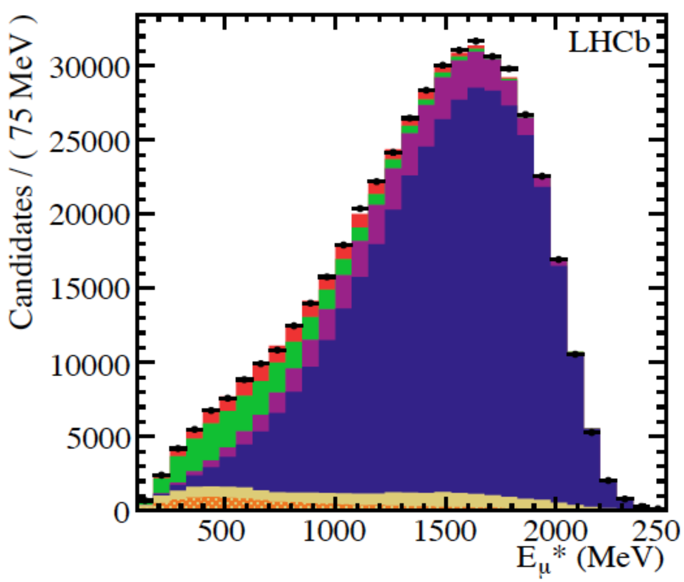


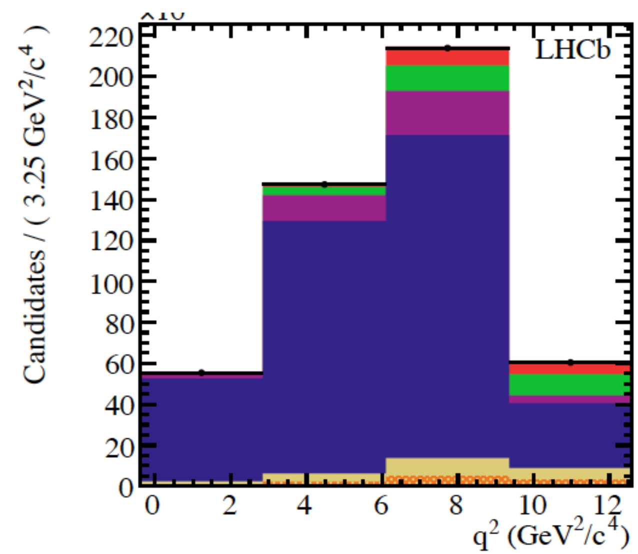
Separate the $D^*\tau\nu$ from $D^*\mu\nu$ mode

- ❑ 3 key variables are computed in the B rest frame for the purpose



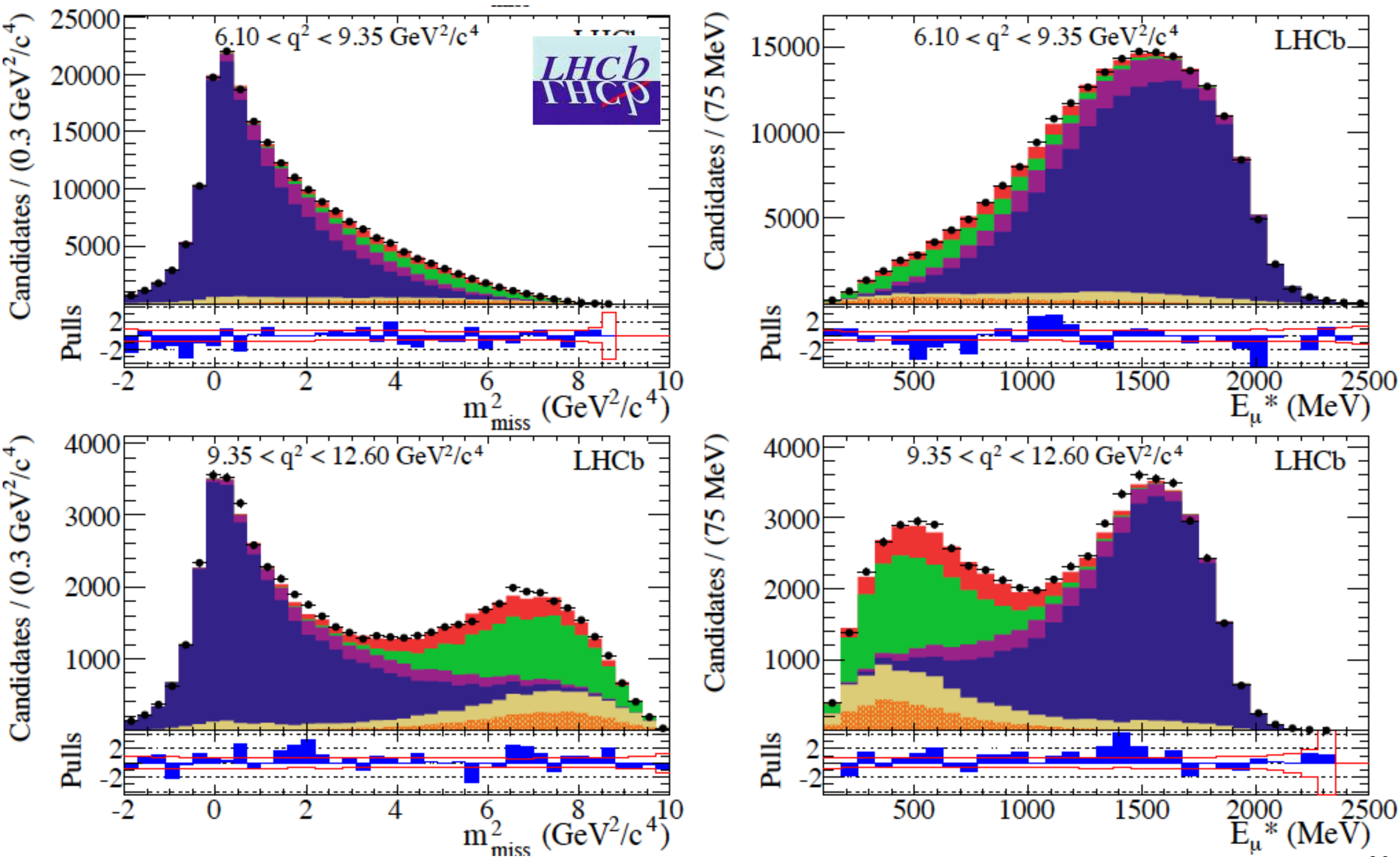






Results

- Below are the projections in m^2_{mass} and E^*_μ in two most sensitive q^2 bins



LHCb results and HFAG average

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

arXiv:1506.08614

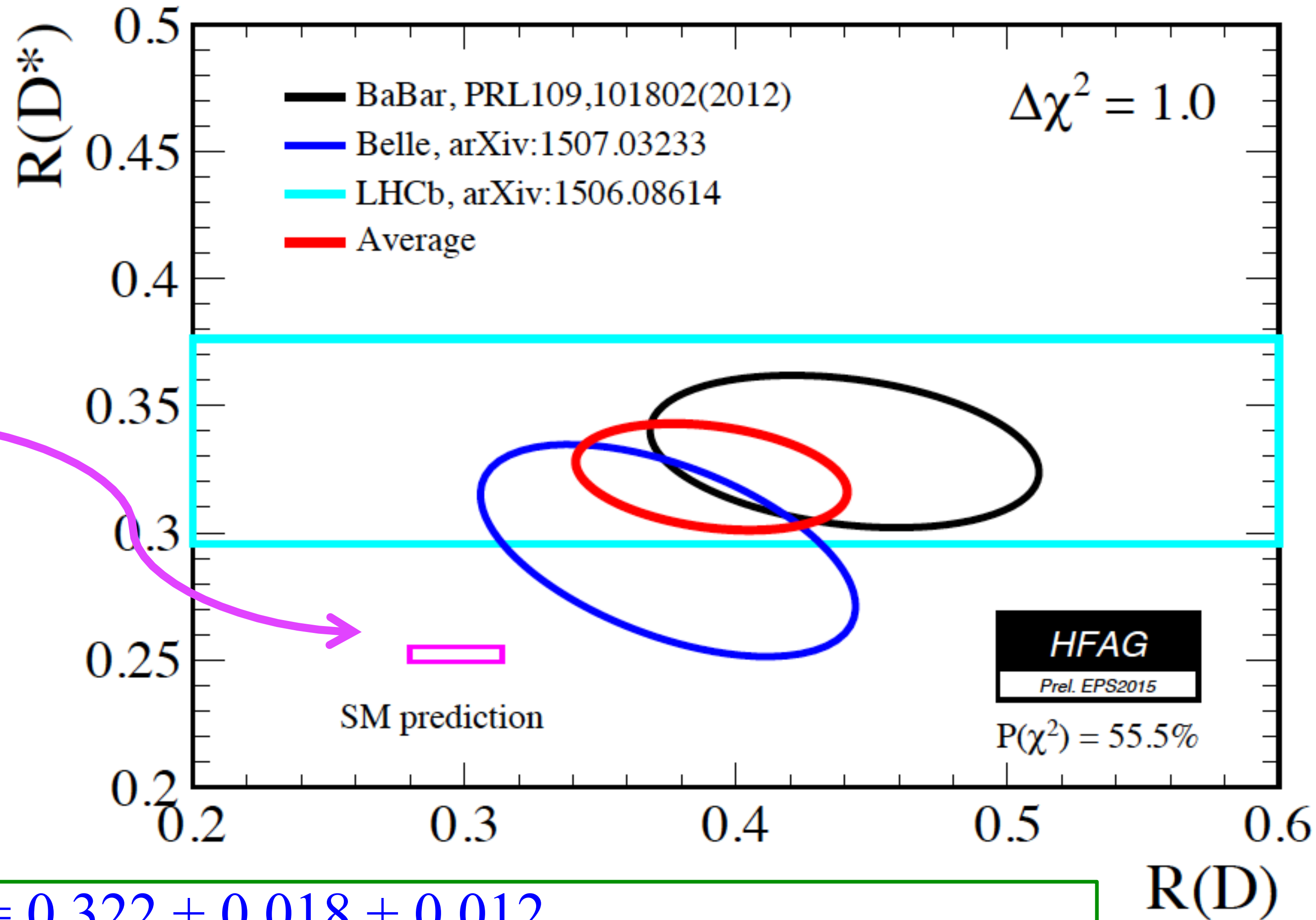
SM predictions

$R(D^*)=0.252 \pm 0.003$

*PRD **85** (2012) 094025*

$R(D) = 0.297 \pm 0.017$

*PRD **78** (2008) 014003*

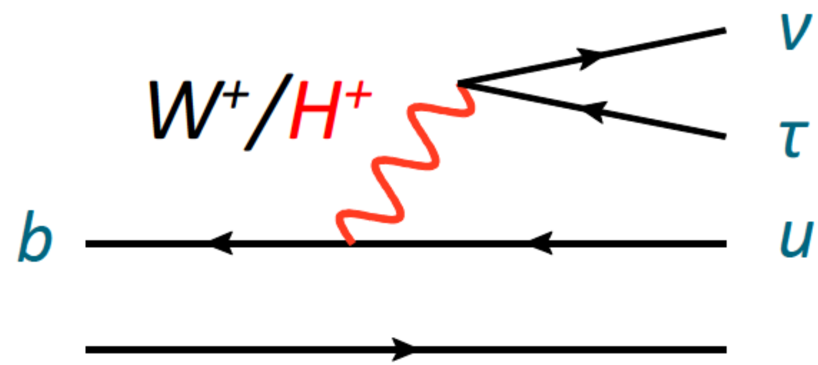


$R(D^*) = 0.322 \pm 0.018 \pm 0.012$
$R(D) = 0.391 \pm 0.041 \pm 0.028$

$\mathrm{Corr}[R(D^*),R(D)] = -0.29$

- All three experiments see similar trend for R(D*)
- 3.9σ difference with respect to the SM prediction

Motivation and strategy for $B \to \pi\tau\nu$



- The decay has never been probed before
- Check possible ramification of the tension surrounding $D^{(*)}\tau\nu$ in other related modes
- $\frac{d\Gamma(B\to\pi\tau\nu)/dq^2}{d\Gamma(B\to\pi\ell\nu)/dq^2}$ depends only on $f^0(q^2)/f^+(q^2)$
  ➔ nice probe for NP

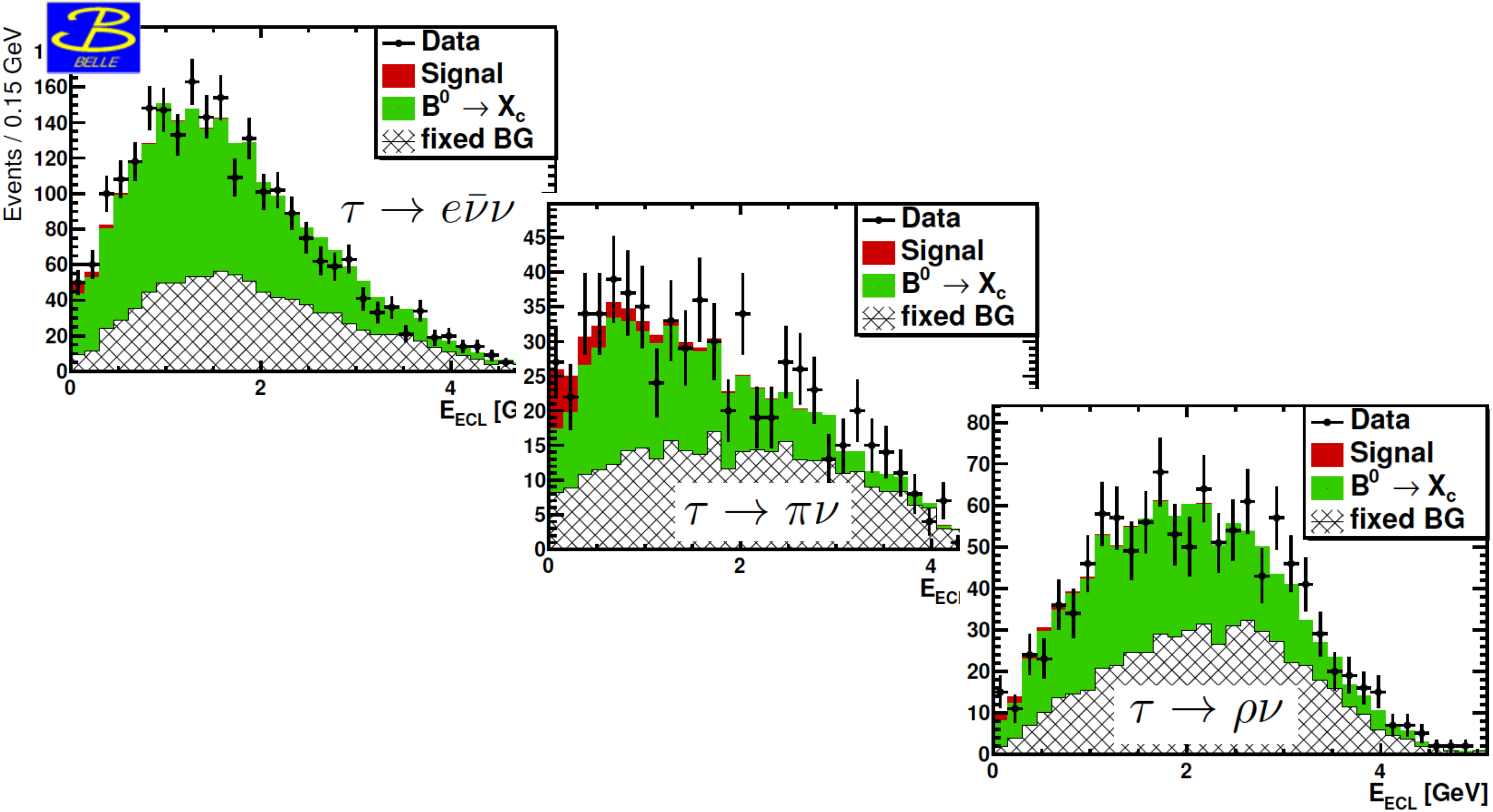
$$< \pi^+|\bar{u}\gamma_\mu b|\bar{b}^0(p+q)> = f^+_{B\pi}(q^2)\left[2p_\mu + \left(\frac{1-m_B^2-m_\pi^2}{q^2}\right)q_\mu\right] \quad \text{Vector FF}$$

$$+ f^0_{B\pi}(q^2)\frac{m_B^2-m_\pi^2}{q^2}q_\mu \quad \text{Scalar FF}$$

- ✧ Reconstruction of B_{tag} is similar to $D^*\tau\nu$: neural network based
- ✧ Tau candidate is reconstructed in $e\nu\nu$ (no $\mu\nu\nu$), $\pi\nu$ and $\rho\nu$ decays
- ✧ Simultaneously fit the E_{ECL} distribution for the above three channels

Results on $B \to \pi\tau\nu$

- Find a signal yield of 52 ± 24 events with 2.4σ significance
- Upper limit on branching fraction 2.5(2.8)×10−4 at 90(95)% CL



Summary and Outlook

- Presented a suite of recent results on semileptonic tree level B decays
- Measurements from Belle and BABAR based on their full data sample
- Not only more data, but also the analysis sophistication reached a new height
  - An example, what we thought to be impossible earlier (measuring B➔X$\tau\nu$ at hadron colliders) is now reality
- Among the important results, BABAR, Belle and LHCb observe similar deviation in R(D*) leading to a combined average 3.9σ over the SM

  - Is history going to repeat itself? Only, time will tell.

Bonus Materials