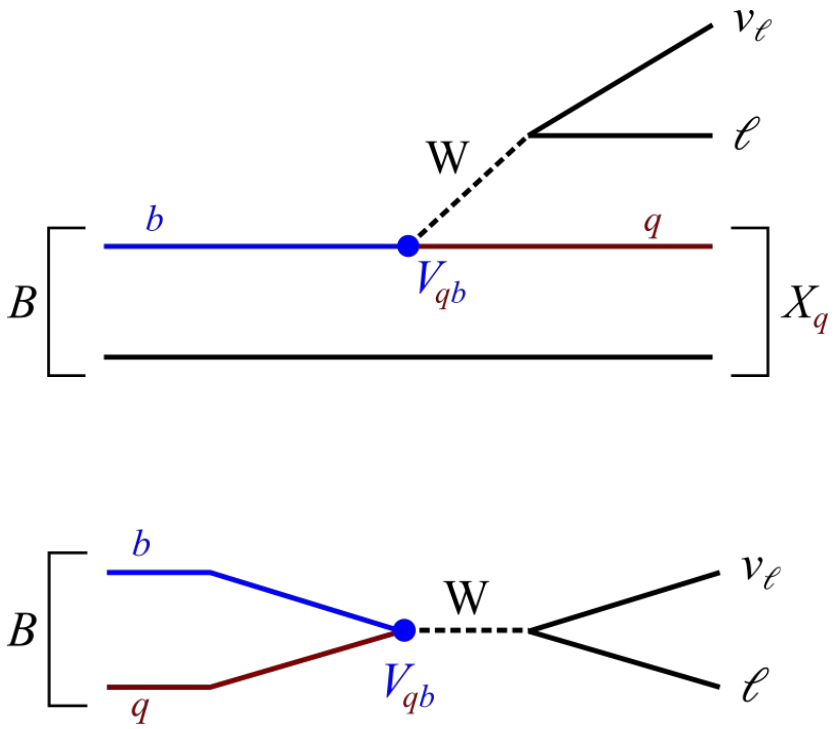

Semileptonic and Leptonic *B* decays

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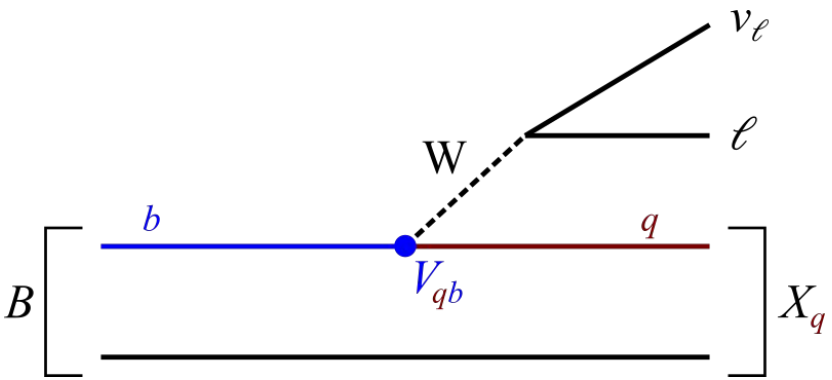
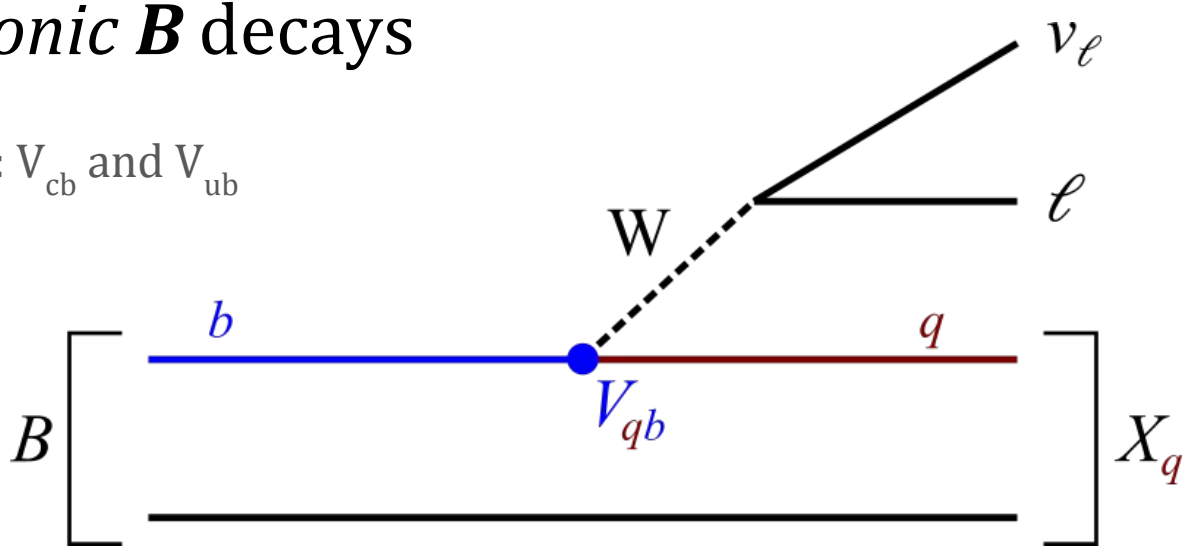
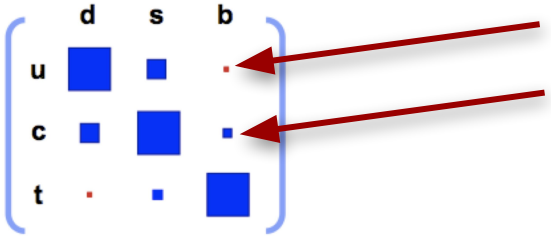


SEMILEPTONIC *B* DECAYS

*Semileptonic **B*** decays

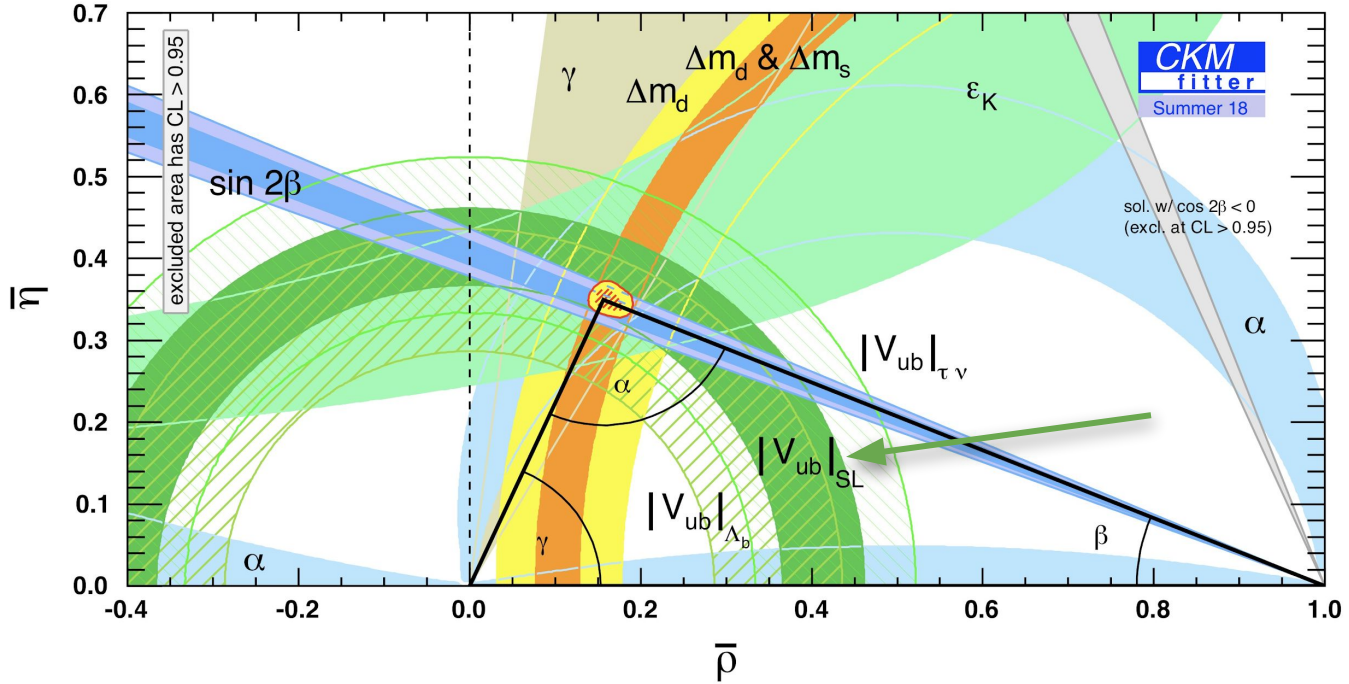
A **CKM** probe: V_{cb} and V_{ub}





*Semileptonic **B*** decays

A **CKM** probe: V_{cb} and V_{ub}



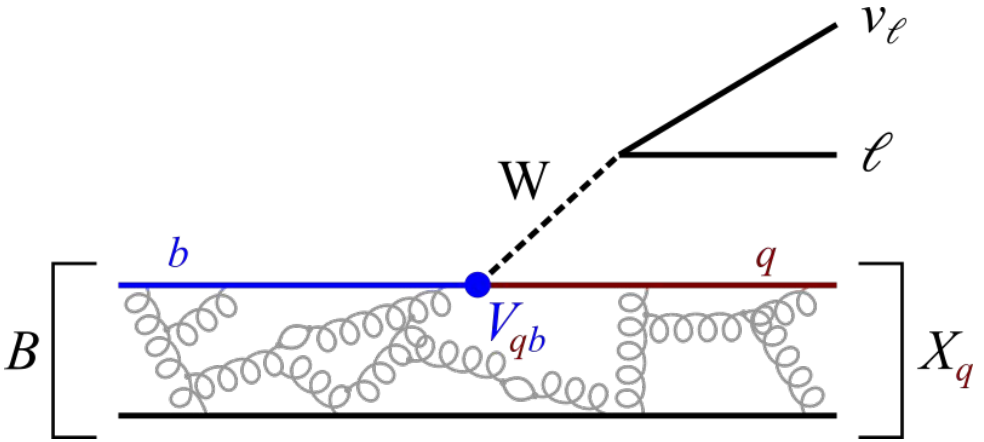
Semileptonic ***B*** decays

Theory: exclusive decays

- Tree-level diagram has **non-perturbative QCD muck**
- Parameterize in terms of the momentum transfer squared $q^2 = (p_\ell + p_\nu)^2$:

$$\frac{d\Gamma}{dq^2} \propto |V_{xb}|^2 |f(q^2)|^2$$

- Form factors tied to light cone sum rules (low q^2) or lattice calculations (high q^2)
- (three additional angular parameters needed in decays to vector mesons like ϱ, D^*)



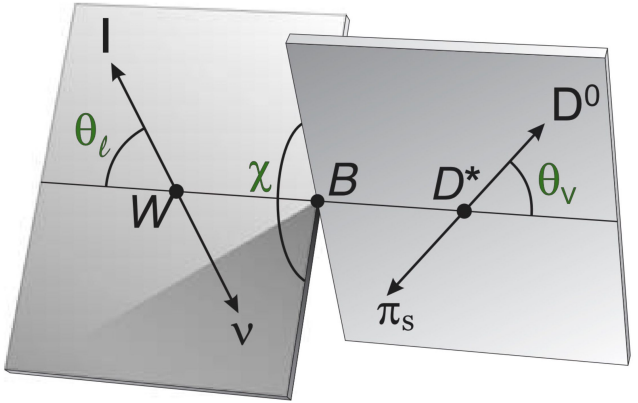
CLN, 1998
arXiv:9712417

BGL, 1997
arXiv:9508211

*Semileptonic **B*** decays

Theory: form factor parameterization

- (as an example: exclusive $B \to D^{*} l\nu$)
- Form factor *F*: terms for **three helicity amplitudes**
- **CLN**: (Caprini, Lellouch, Neubert)
  - **HQET** input to reduce number of free parameters to 3; extract from experiment
- **BGL**: (Boyd, Grinstein, Lebed)
  - Expand each FF in the most generic form, with minimal assumptions, in a power series
- **CLN** was standard for 20 years, but **BGL** is gaining favor due to **model-independent approach**
  - **Some implications for validity of HQET**

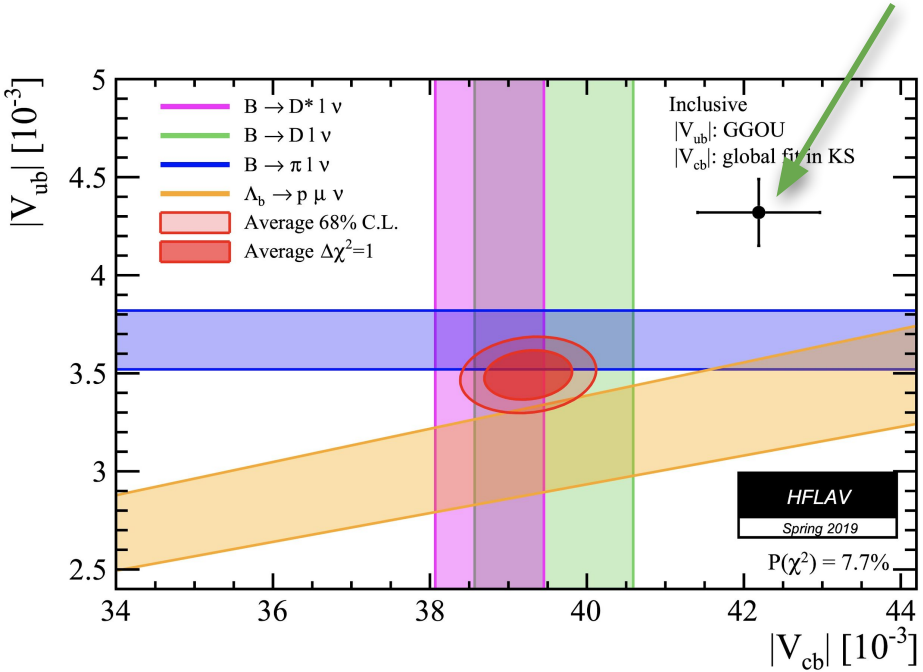


$$\frac{d\Gamma(B \to D^{*-}\ell^{+}\nu)}{dw\ d\cos\theta_\ell\ d\cos\theta_\nu\ d\chi} = \frac{G_F^2\,|V_{cb}|^2}{48\pi^3} F(w, \cos\theta_\ell, \cos\theta_\nu, \chi) G(w)$$

*Semileptonic **B*** decays

An interesting puzzle

- Tension in V_{cb} and V_{ub} between *inclusive* vs. *exclusive* reconstructions
- (exclusive results here use **CLN**)



Semileptonic ***B*** decays

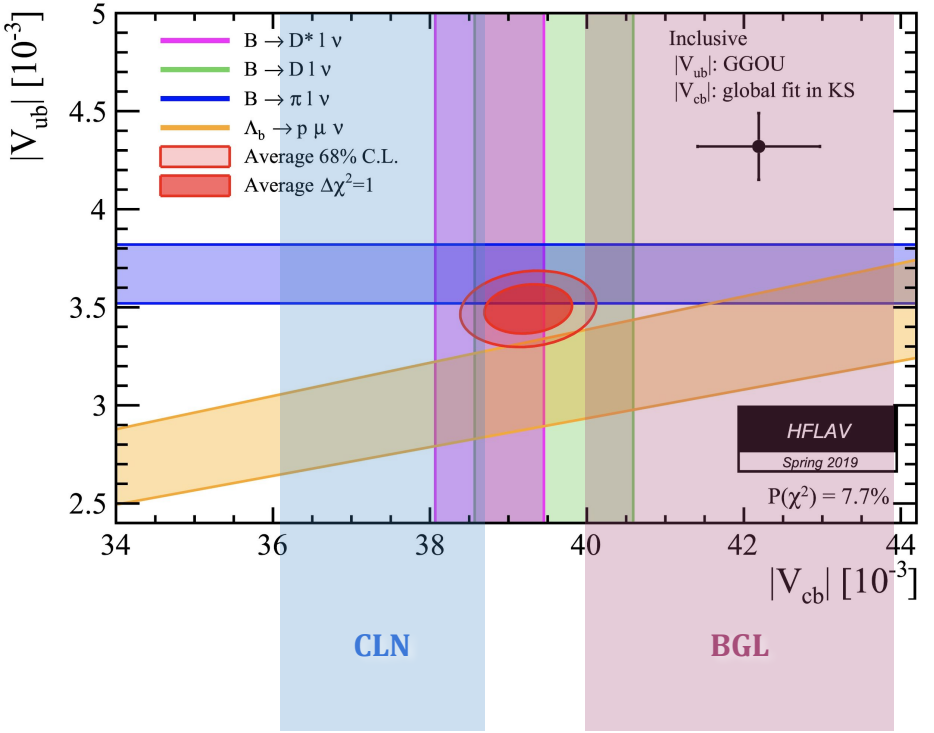
While our findings do not provide a clear resolution of the $|V_{cb}|$ puzzle, they strongly question the reliability of the current $B \to D^* \ell \nu$ averages [3] and call for a reanalysis of old experimental data before Belle-II comes into action.

Belle tagged $B \to D^* l \nu$, 2017
arxiv:1702.01521

Reparameterizations, 2017
arxiv:1703.06124
arxiv:1703.08170

An interesting puzzle: *a solution?*

- Two 2017 re-parameterizations of Belle's extraction of $|V_{cb}|$ in $B \to D^* l\nu$:
  - **CLN** consistent with HFLAV exclusive average
  - **BGL** more consistent with inclusive
- **Is exclusive/inclusive tension entirely a result of form factor parameterization?**
- New developments to be discussed!



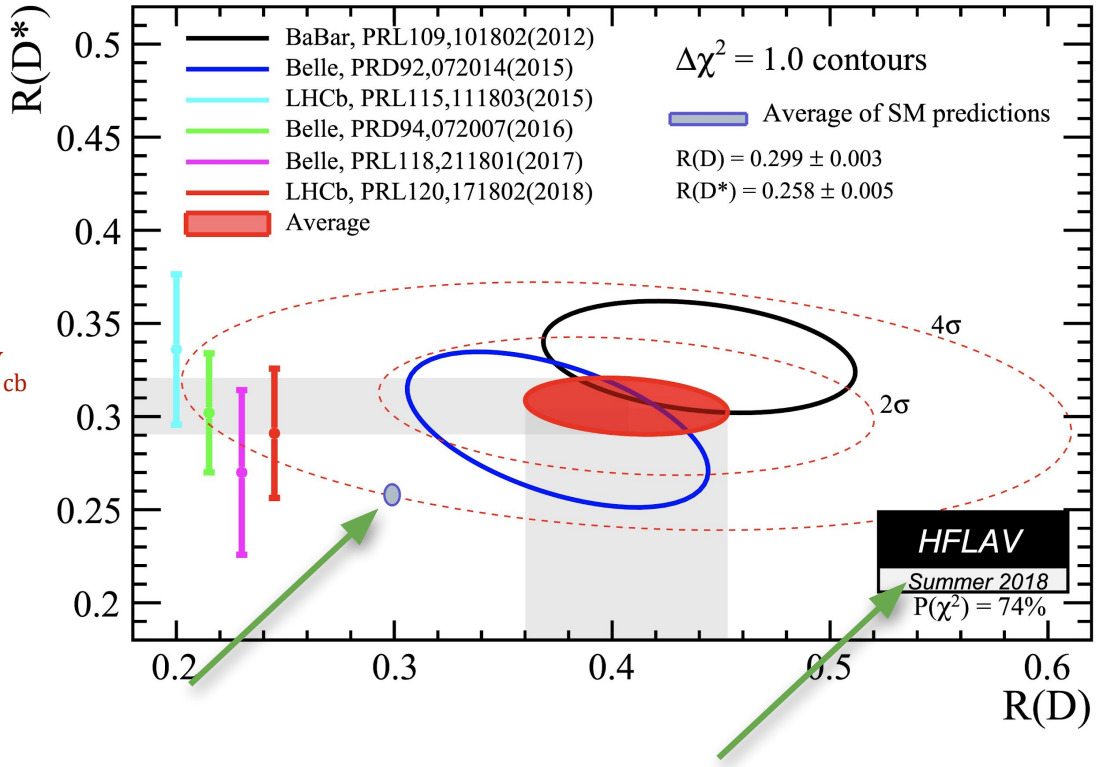
*Semileptonic **B** decays*

Another interesting puzzle

- Signs of lepton universality violation?

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

  - (ratio removes dependence on V_{cb} and cancels some theoretical+experimental uncertainties)



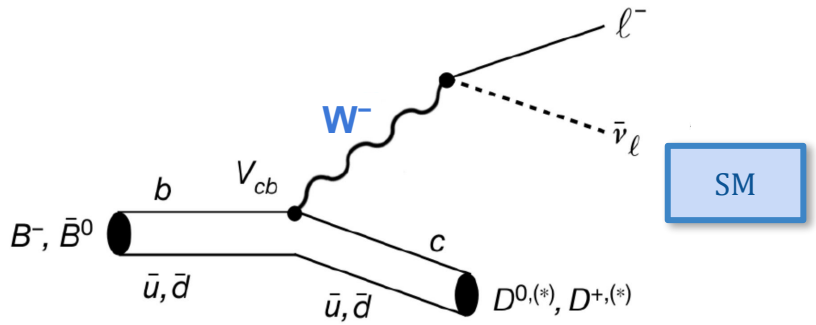
Semileptonic ***B*** decays

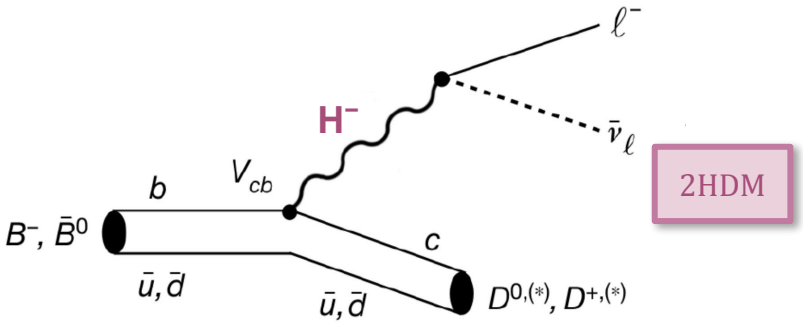
Another interesting puzzle: $R(D^{(*)})$

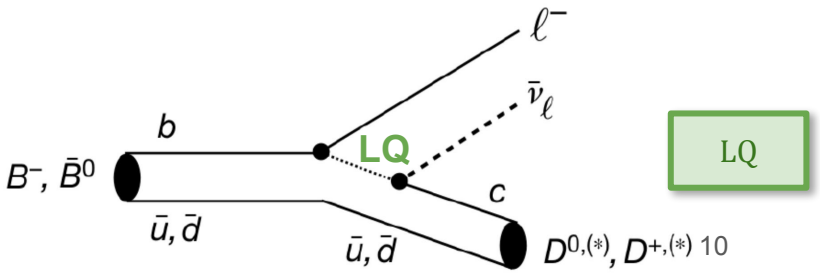
- $R(D^{(*)})$ Sensitive to NP (for example, **charged Higgs**):

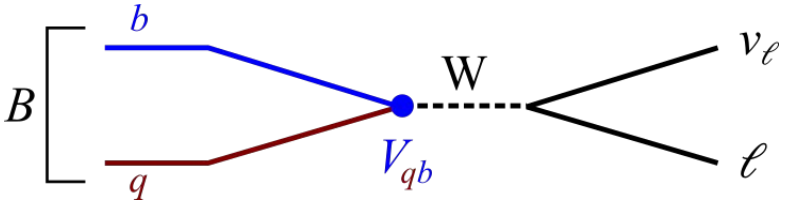
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \left\{ [\bar{c}\gamma^\mu(1-\gamma_5)b][\bar{\tau}\gamma_\mu(1-\gamma_5)\nu_\tau] - \frac{m_b m_\tau}{m_B^2}\bar{c}[g_S + g_P\gamma_5]b[\bar{\tau}(1-\gamma_5)\nu_\tau] \right\} + h.c.$$

- Could be sensitive to **leptoquark** models too (additional tensor operator)
- New developments to be discussed!





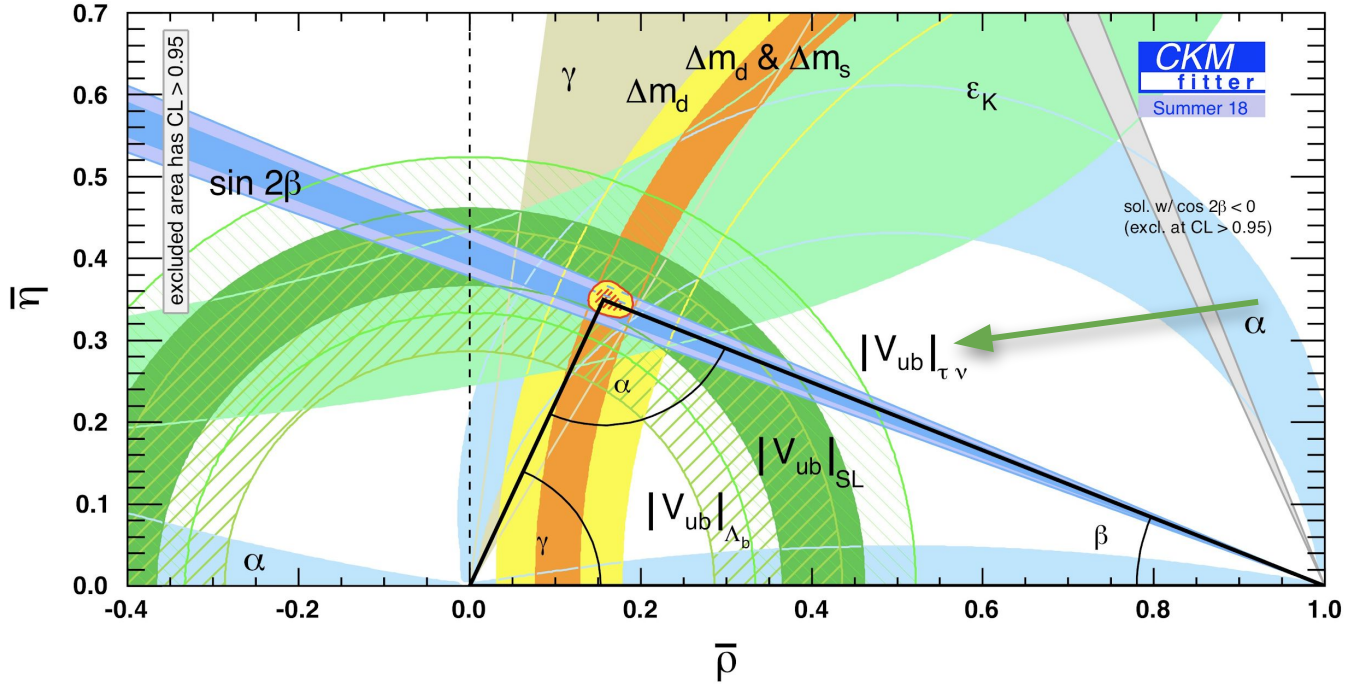




LEPTONIC *B* DECAYS

Leptonic ***B*** decays

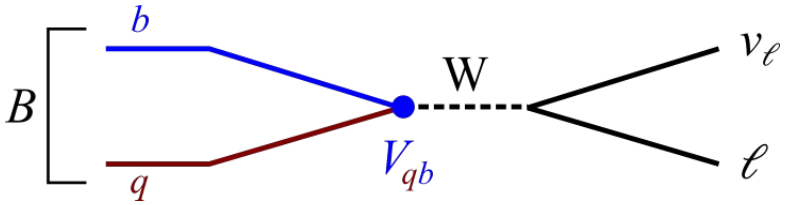
A **CKM** probe: V_{ub}



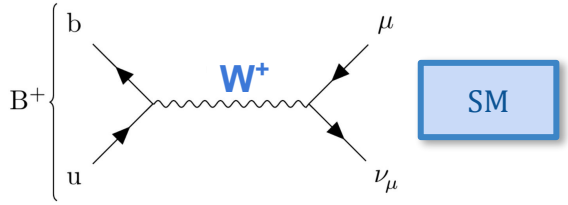
Leptonic ***B*** decays

Theory (exclusive)

- Decay rate (leading-order):
  - Theoretically very clean; precise SM prediction
  - $\Gamma(B \to \ell\nu) \propto f_B^2 |V_{ub}|^2 x^2 (1-x)^2$
  - Decay constant f_B from QCD sum rules or lattice calculations
  - Helicity suppression factor ($x = m_\ell / m_B$) favors tau mode



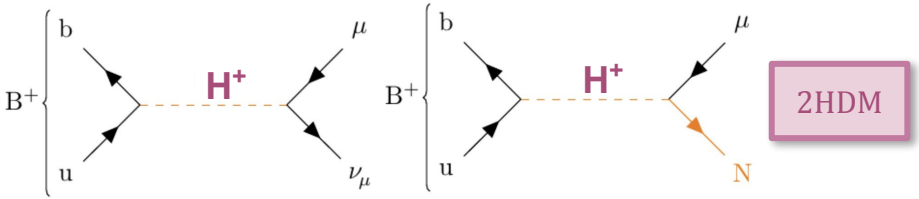
*Leptonic **B*** decays



Theory: NP potential

- Sensitive to NP (for example, **charged Higgs**):

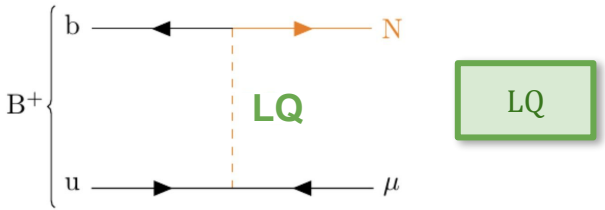
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{ub} \left\{ [\bar{u}\gamma^\mu(1-\gamma_5)b][\bar{l}\gamma_\mu(1-\gamma_5)\nu_l] - \tan^2\beta \frac{m_b m_l}{m_H^2}[\bar{u}(1+\gamma_5)b][\bar{l}(1-\gamma_5)\nu_l] \right\} + h.c.$$



  - Lepton flavor-independent BF enhancement:

$$\mathcal{B}(B^- \to l^- \bar{\nu}) = \mathcal{B}_{\text{SM}} \left[1 - \tan^2\beta \frac{m_B^2}{m_H^2}\right]^2$$

- Could be sensitive to **leptoquark** models and/or reveal **sterile neutrinos**



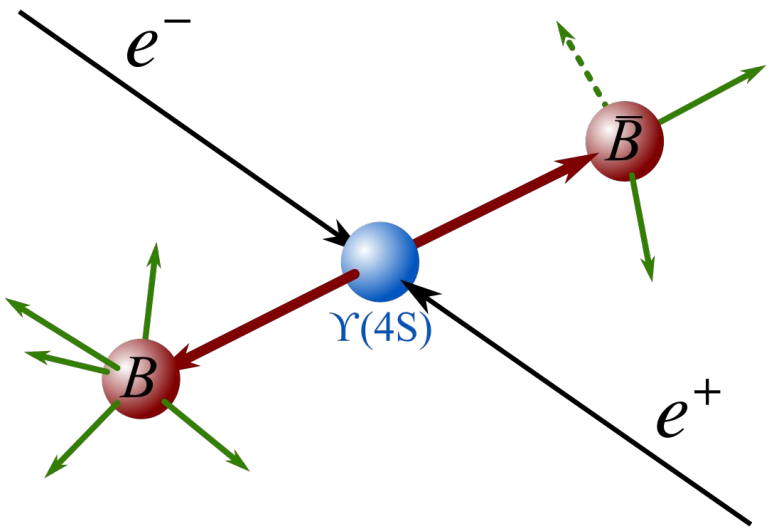
- New developments to be discussed!

MEASUREMENT

The *B* factories

High luminosity, low cross-section, low background, high efficiency

- Experiments
  - Babar (1999-2008): 471 million *BB* (424 fb^{-1})
  - Belle (1999-2010): 771 million *BB* (711 fb^{-1})
  - Belle II (2019-): target **50 ab^{-1}**

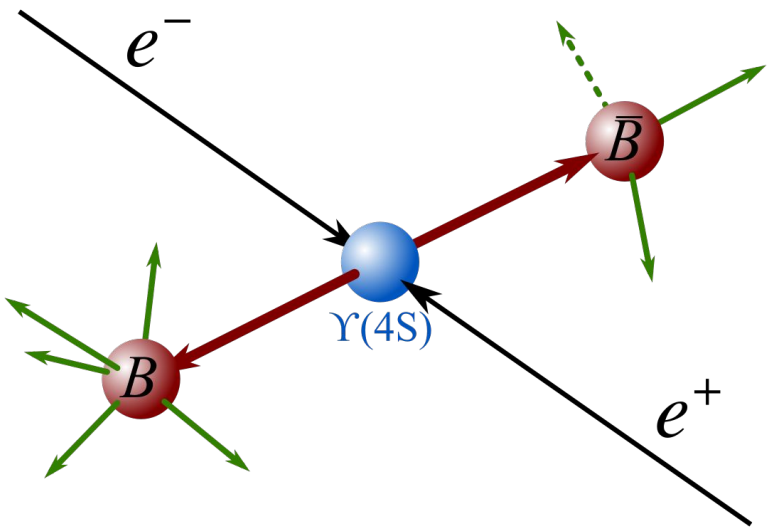


See **Shuji Tanaka**'s talk tomorrow for Belle II status

The *B* factories

High luminosity, low cross-section, low background, high efficiency

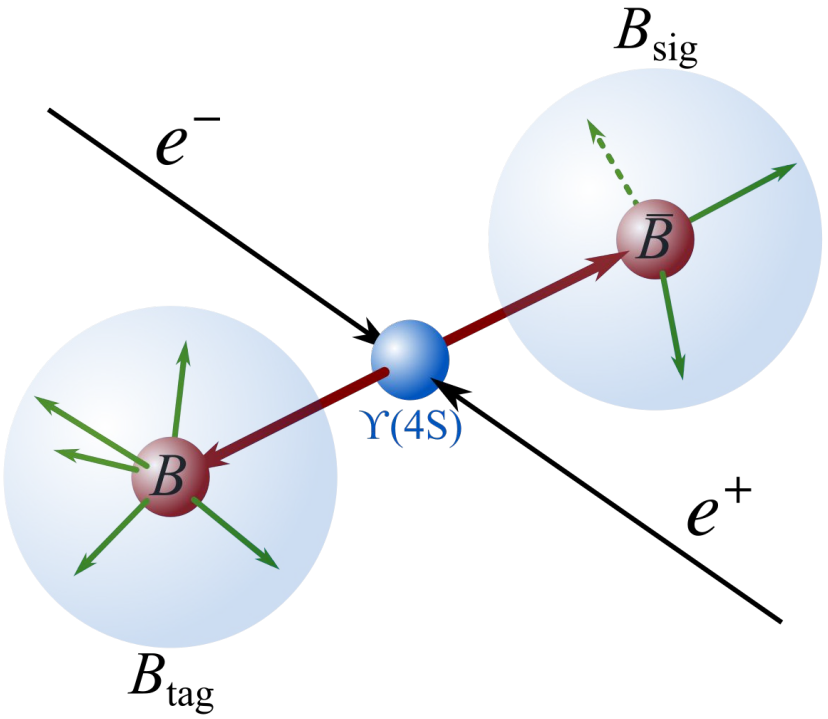
- The essentials
  - Electron/positron collision at $\Upsilon(4S)$ [or higher] *bb* resonance (10.58 GeV)
    - Decays ~100% of time to ~at-rest *BB* pairs
    - **Kinematics completely known**
  - $\sim 4\pi$ detector coverage
  - Efficient reconstruction of neutrals
  - Very clean environment

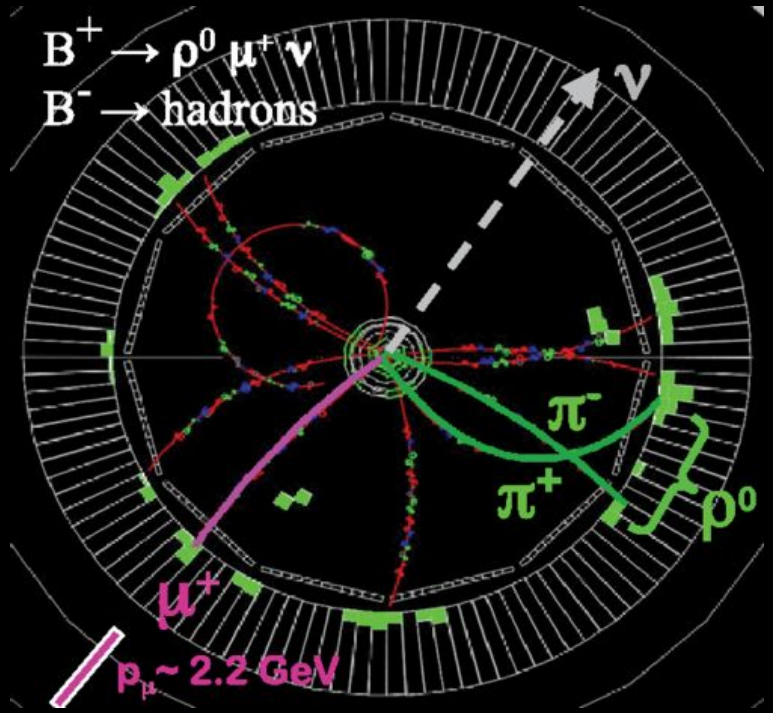


The *B* factories

Tagging

- Full (hadronic) tagging
  - Reconstruct B_{tag} in one of >10,000 hadronic modes
  - p_{tag} now known; thus p_{sig} is too
  - p_{ν} now recoverable
  - Tight kinematic constraints now possible; very pure signal selection
  - Downside: tagging efficiency ~0.1%
- Semileptonic tagging
  - Higher tagging efficiency (~1%)
  - Weaker kinematic constraints (B_{tag} not fully recovered)

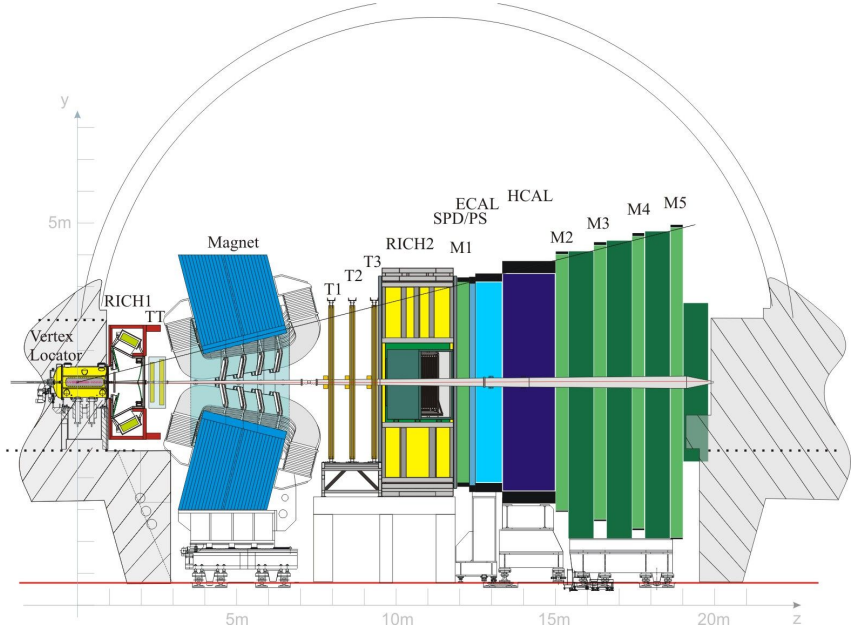



$B^+ \to \rho^0 \mu^+ \nu$
$B^- \to$ hadrons
ν
π^-
π^+
ρ^0
μ^+
$p_\mu \sim 2.2$ GeV

LHCb

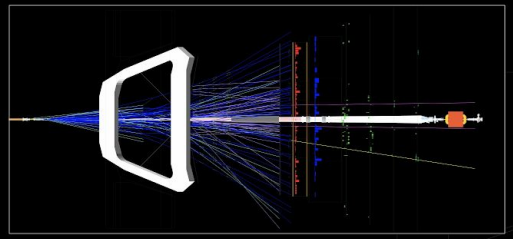
Low luminosity, high cross-section

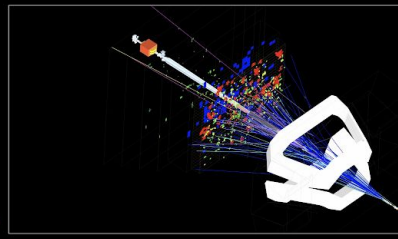
- The essentials
  - Proton/anti-proton collision at ~10*T*eV
  - To date: 9 fb^{-1}
  - Forward coverage only; **large boost**
  - Excellent vertexting (~cm displacement)
  - Access to *strange* B mesons/baryons
- A generalization:
  - *B*-factories best for final states with neutrals or missing energy (*e.g.* $B^+ \to \pi^0 l^+ \nu$)
  - LHCb best for charged final states (*e.g.* $B^0_s \to \mu\mu$)
  - **Competitive and complementary**



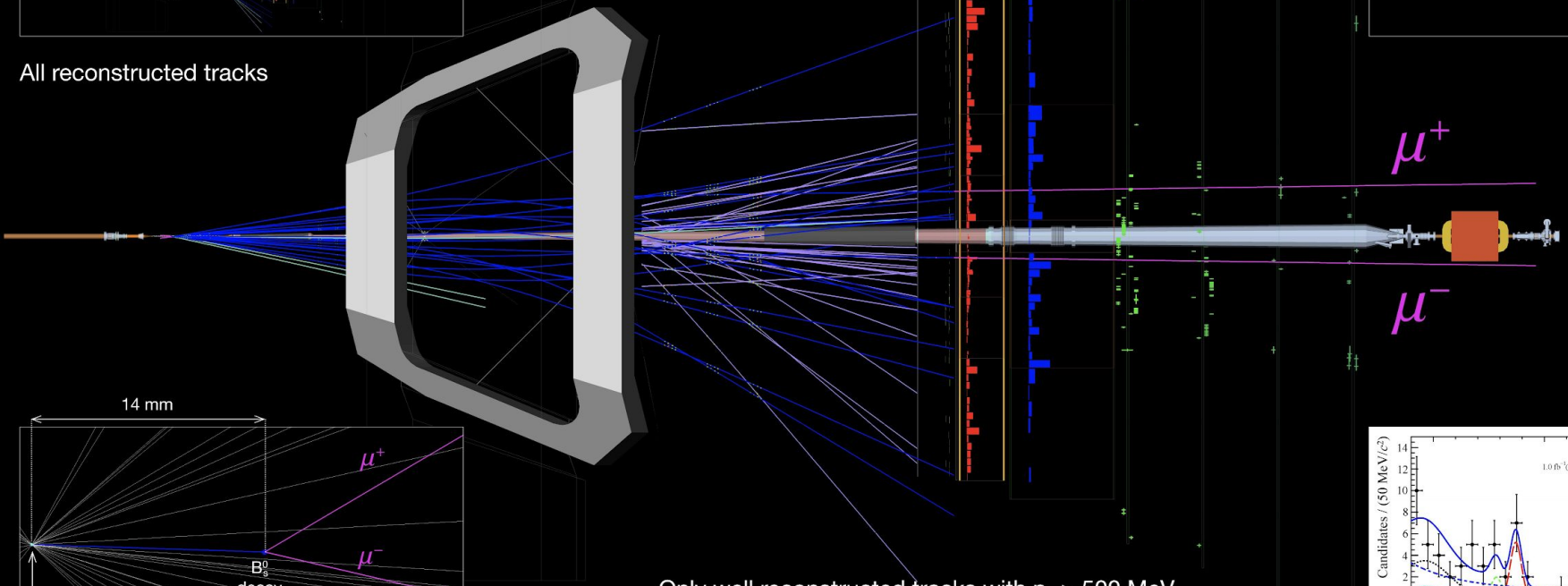
See **Mark Smith**'s talk tomorrow for recent LHCb results

$B_s^0 \longrightarrow \mu^+\mu^-$

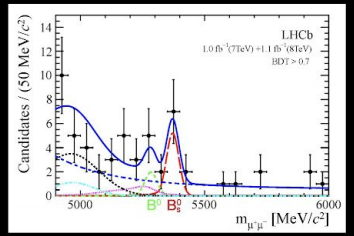


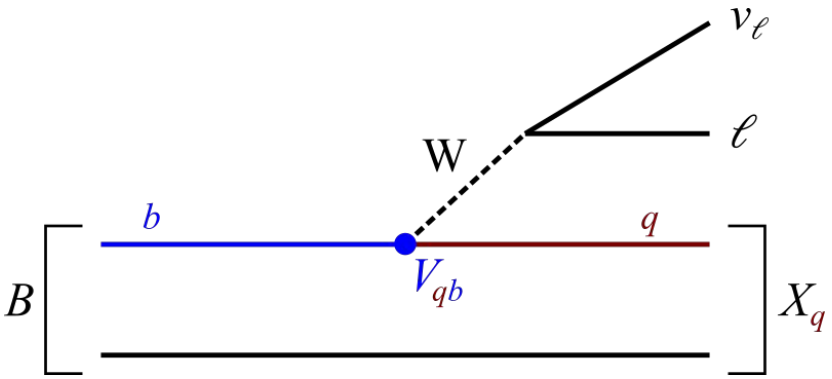


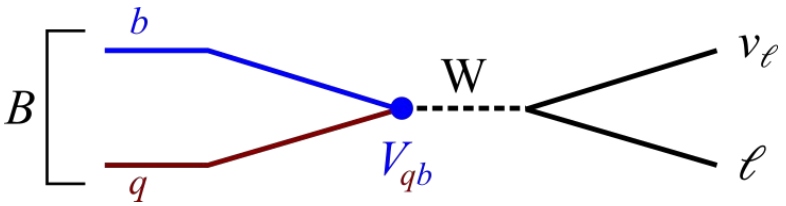
All reconstructed tracks



Only well reconstructed tracks with $p_T > 500$ MeV







RECENT DEVELOPMENTS

Belle SL-tagged R($D^{(*)}$), 2019
arXiv:1904.08794

Belle: update to R(D) and R(D*)

Using *semileptonic* tagging

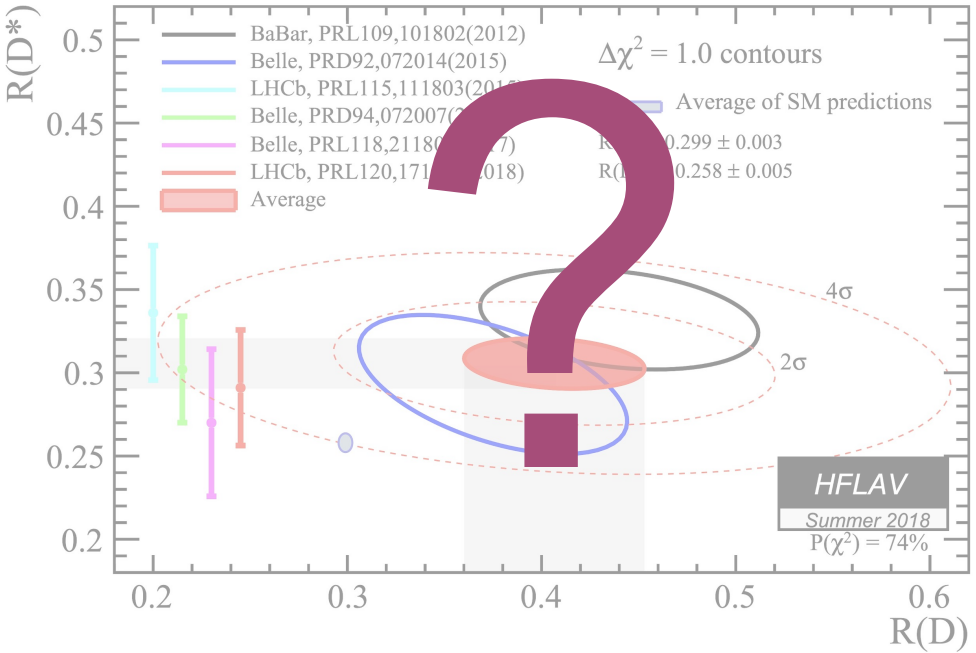
- (posted to arXiv Apr. 2019)

Belle SL-tagged R(D$^{(*)}$), 2019
arXiv:1904.08794

Belle: update to R(D) and R(D*)

Using *semileptonic* tagging

- (posted to arXiv Apr. 2019)
- **First R(D) measurement using SL tag**
- Improvements vs. older analysis
  - R(D*) only → R(D) and R(D*) simultaneously
  - For R(D*), B^0 only → $B^\pm$, B^0
  - Improved tagging algorithm ("Full Event Interpretation" from Belle II, arXiv:1807.08680)

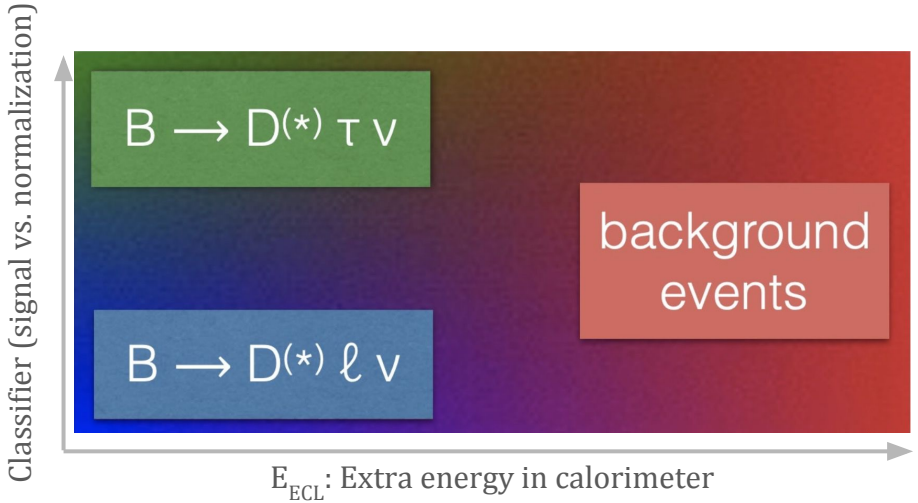


Belle SL-tagged R(D$^{(*)}$), 2019
arXiv:1904.08794

Belle: update to R(D) and R(D*)

Using *semileptonic* tagging

- Simultaneous extraction of all $B \to D^{(*)}\, l/\tau\, \nu$
  - Use $B \to D^{(*)} l\nu$ as "normalization" mode
- Extraction: 2D fit to:
  - $\mathbf{E_{ECL}}$: *extra energy* in calorimeter (not associated with tag or signal, right)
  - Signal **class**ifier from a BDT trained on *signal against normalization* mode

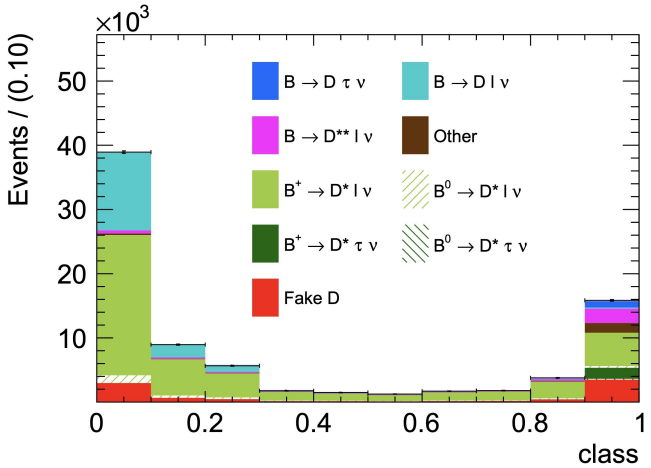


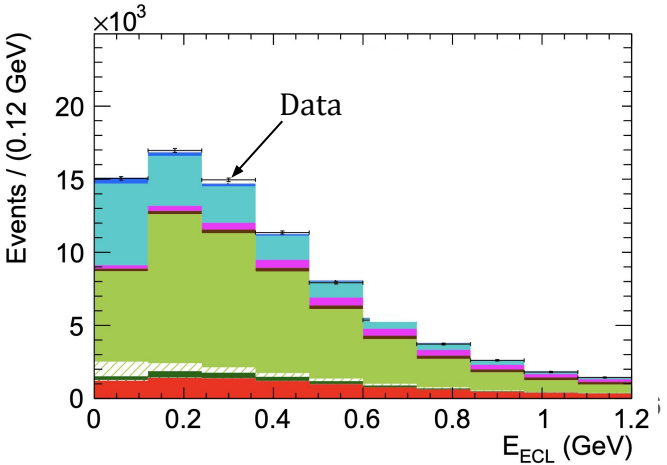
Belle SL-tagged R(D$^{(*)}$), 2019
arXiv:1904.08794

Belle: update to R(D) and R(D*)

Using *semileptonic* tagging

- Fit projections, right, for $D^0 l$ samples



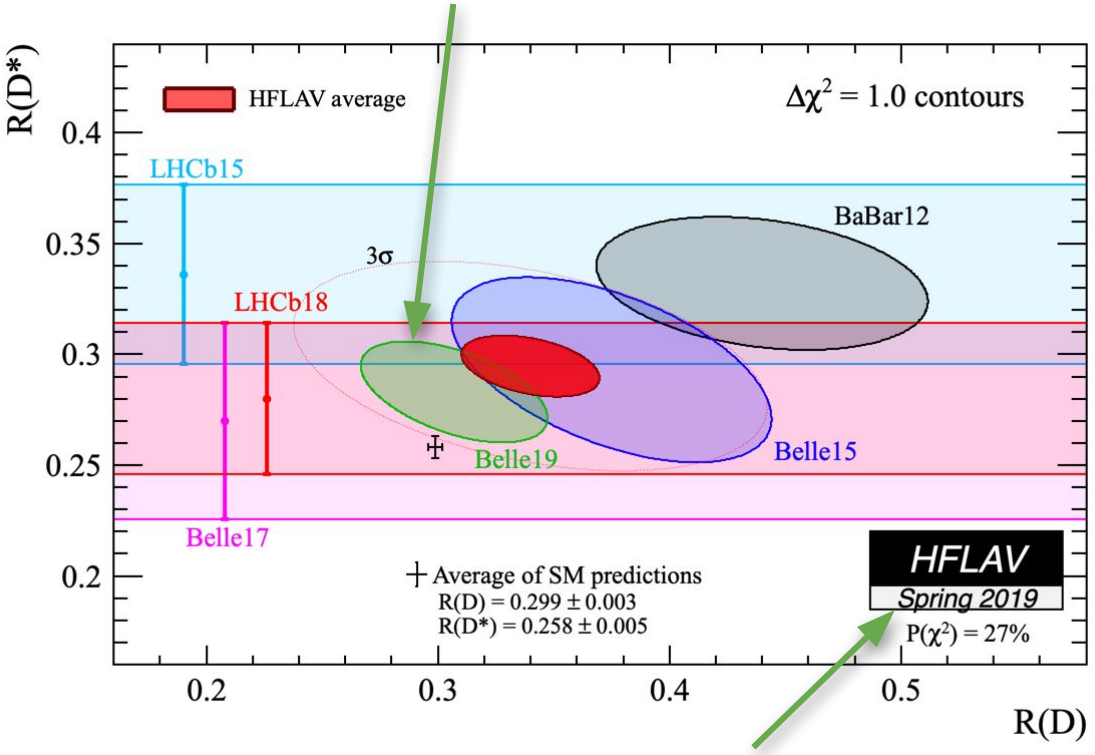


Belle SL-tagged R(D(*)), 2019
arXiv:1904.08794

Belle: update to R(D) and R(D*)

Preliminary findings

- Most-precise R(D)/R(D*) measurement to date
  - (final word from Belle?)
- Compatible with SM at 1.2σ
  - (possibly decreasing before publication)
- **Belle II results eagerly awaited**



Belle D^* polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$ 2019
arxiv:1903.03102

Belle: D^* polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$

A new angle on $R(D^*)$

- (**preliminary**)

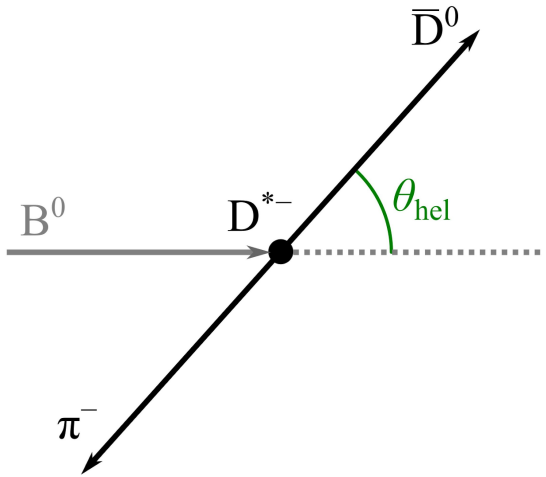
Belle D^* polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$, 2019
arxiv:1903.03102

Belle: D^* polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$

A new angle on R(D^*)

- (**preliminary**)
- Probe of **NP** signature in angular distributions
- Target the *fraction of D* longitudinal polarization*, $F_L^{D^*}$

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



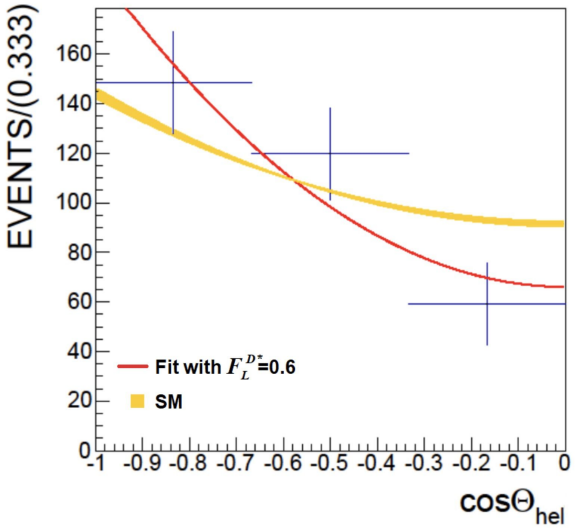
Belle D^* polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$, 2019
arxiv:1903.03102

Belle: D^* polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$

Analysis/results

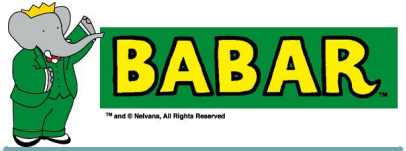
- *Inclusive* tag
- In each of three $\cos\theta_{\text{hel}}$ bins, yield comes from fit to **tag** kinematic distributions
- Result agrees with SM within 1.6σ:

$$F_L^{D^*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$$



BaBar: tagged $B \to D^* l \nu$

New analysis probing HQET



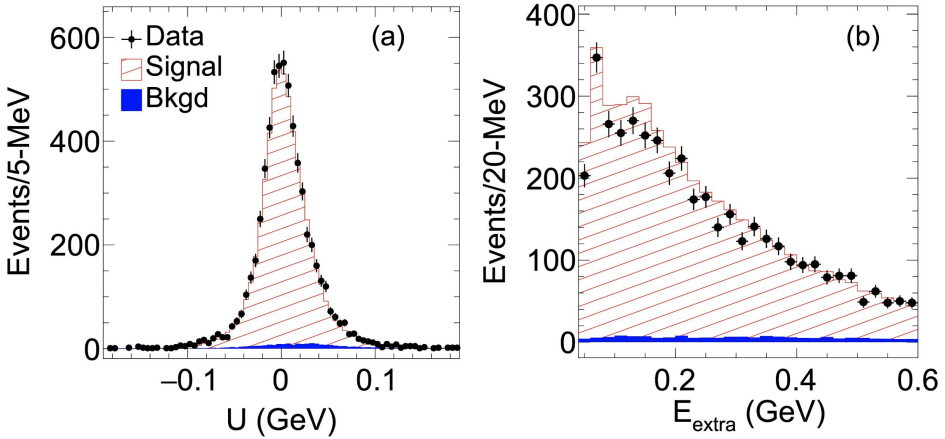
Babar hadronic tagged $B \to D^* l \nu$, 2019
PRL:123.091801

BaBar: tagged $B \to D^* l \nu$

Babar hadronic tagged $B \to D^* l \nu$, 2019
PRL:123.091801

New analysis probing HQET

- Hadronic-tagged full angular analysis
- Unbinned 4D fit to the 4 kinematic parameters
- A clean probe to HQET assumptions that differentiate **CLN** and **BGL**
- Tight kinematic constraints lead to ultra-pure sample, *right*



$$U = E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$$

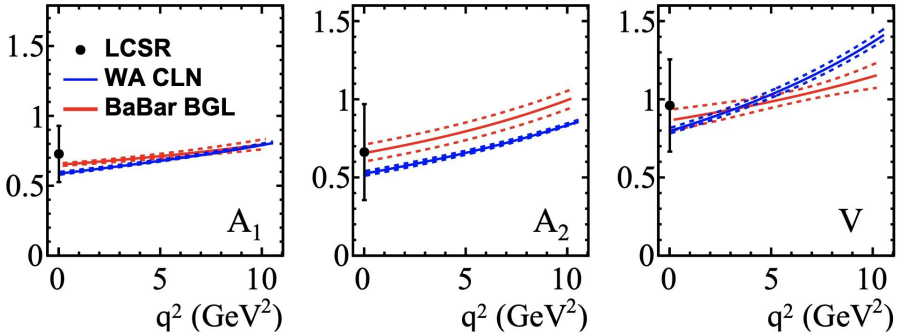
(inferred neutrino mass)

BaBar: tagged $B \to D^* l \nu$

Babar hadronic tagged $B \to D^* l \nu$, 2019
PRL:123.091801

Results

- Form factor shapes with BGL
  - Comparison with world-average CLN
  - Slightly better agreement with zero-recoil (q^2=0) LCSR
  - Significant tension in extrapolations to higher q^2
  - **BGL is in tension with HQET**

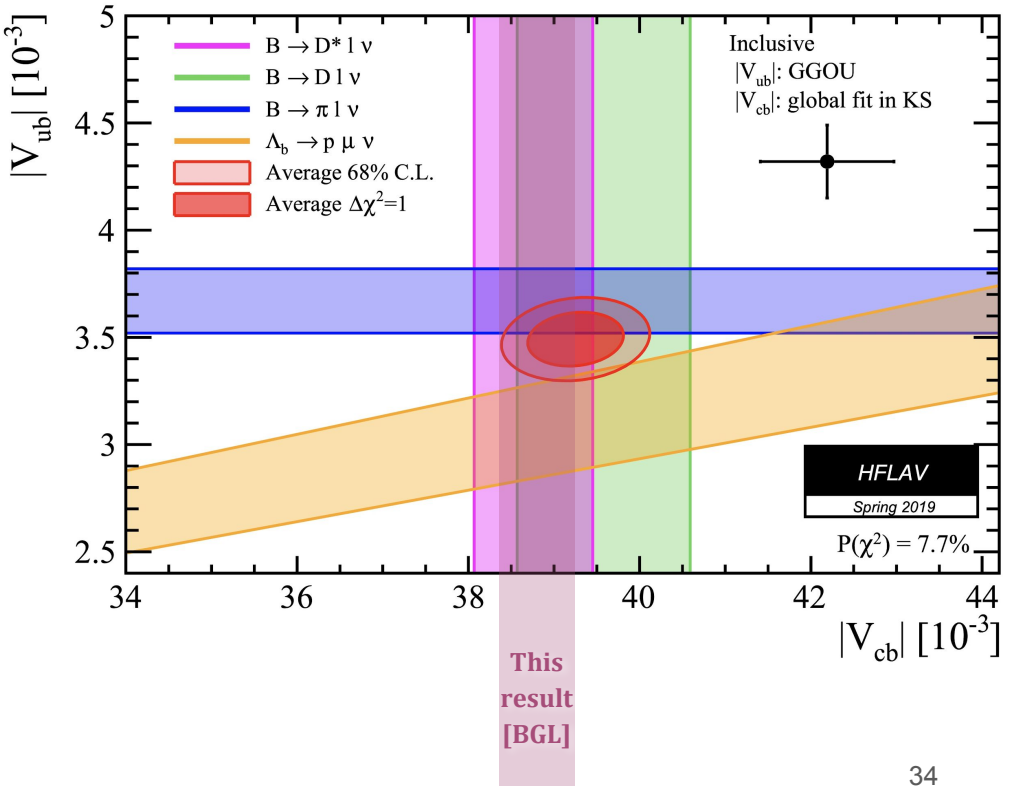


BaBar: tagged $B \to D^* l \nu$

Babar hadronic tagged $B \to D^* l \nu$, 2019
PRL:123.091801

Results

- Updated V_{cb} with **BGL**
  - Consistent with CLN world average
  - Parameterization with BGL **does not appear to solve** the inclusive/exclusive tension



Belle untagged $B \to D^* l \nu$, 2019
arxiv:1809.03290

Belle: untagged $B \to D^* l \nu$

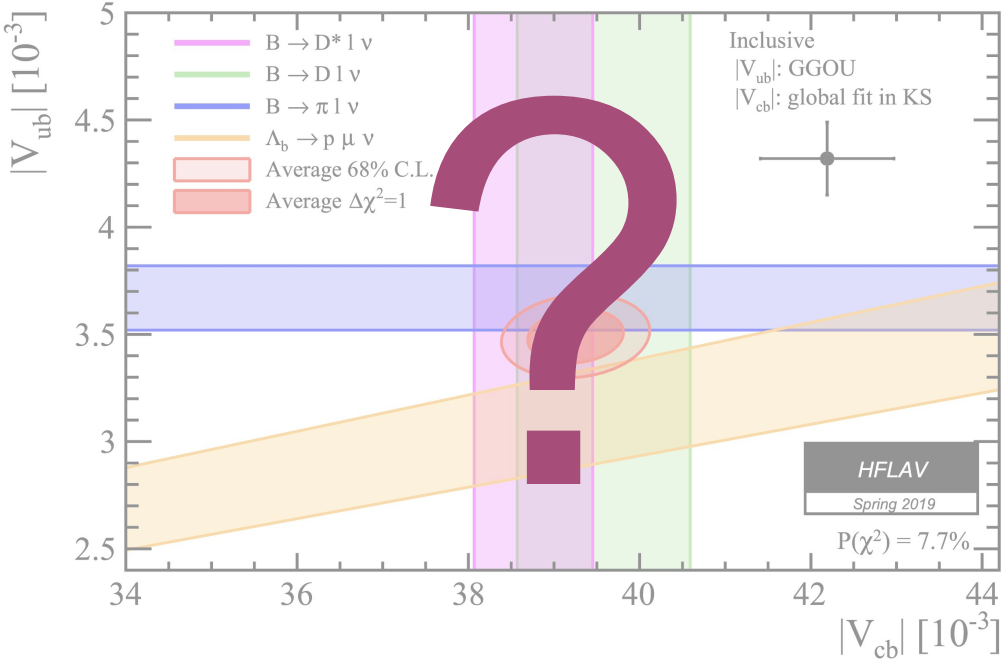
New analysis comparing CLN and BGL

Belle untagged $B \to D^* l \nu$, 2019
arxiv:1809.03290

Belle: untagged $B \to D^* l \nu$

New analysis comparing CLN and BGL

- **Highest-precision |Vcb| determination yet**
  - Systematics improvements over prior Belle result
- **First direct measurement using BGL**



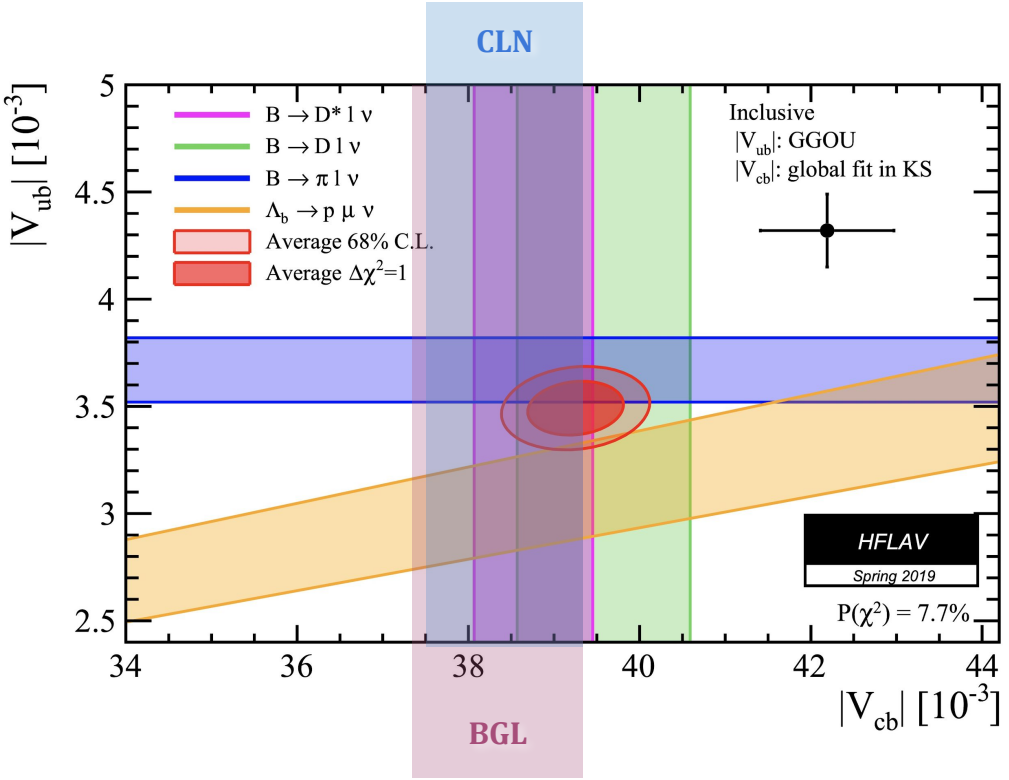
Belle untagged $B \to D^* l \nu$, 2019
arxiv:1809.03290

Belle: untagged $B \to D^* l \nu$

Quick summary

- The inclusive/exclusive question is **unresolved**

See **Eiasha Waheed**'s talk tomorrow for the details!



Belle $B^- \to \mu^- \nu$, 2018
PRL:121.031801
arxiv:1906.06871

Belle: update to $B^- \to \mu^- \nu$

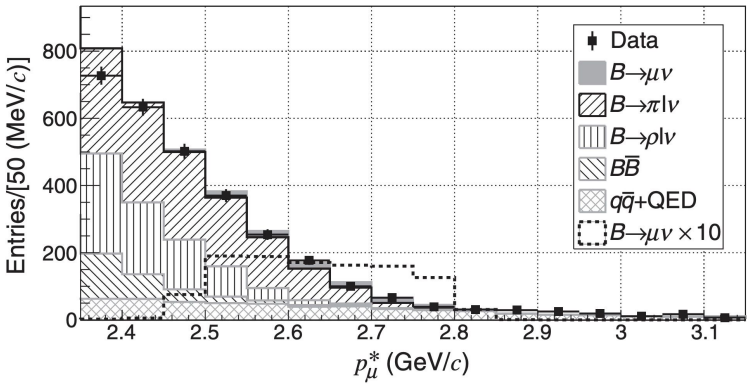
Preliminary update to Belle 2018 PRL

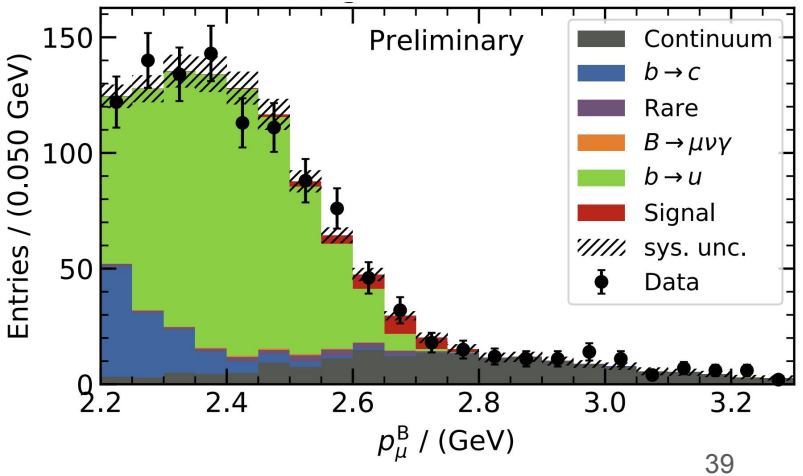
Belle $B^- \to \mu^- \nu$, 2018
PRL:121.031801
arxiv:1906.06871

Belle: update to $B^- \to \mu^- \nu$

Preliminary update to Belle 2018 PRL

- 2018 result (*top*):
  - Untagged
  - Hunt for bump in p_μ
  - World's best BF (2.4σ significance)
- 2019 extension (**preliminary**; Moriond EW, *bottom*):
  - Inclusive tagging
  - Systematics improvements
  - Investigate type-II and -III 2HDM
  - Sterile neutrino scan



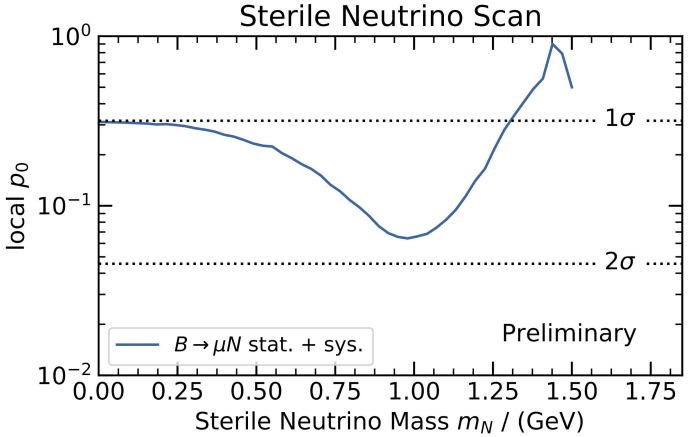


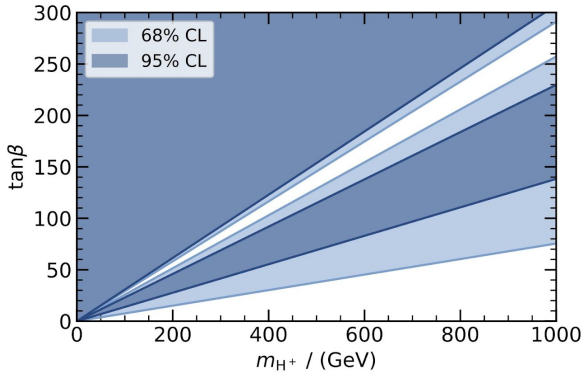
Belle $B^- \to \mu^- \nu$, 2018
PRL:121.031801
arxiv:1906.06871

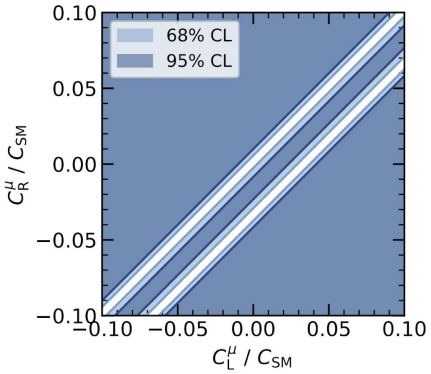
Belle: update to $B^- \to \mu^- \nu$

Preliminary update to Belle 2018 PRL

- Preliminary results:
  - Improved significance: **2.8σ**
  - Sterile neutrino scan
  - 2HDM limits







Prospects

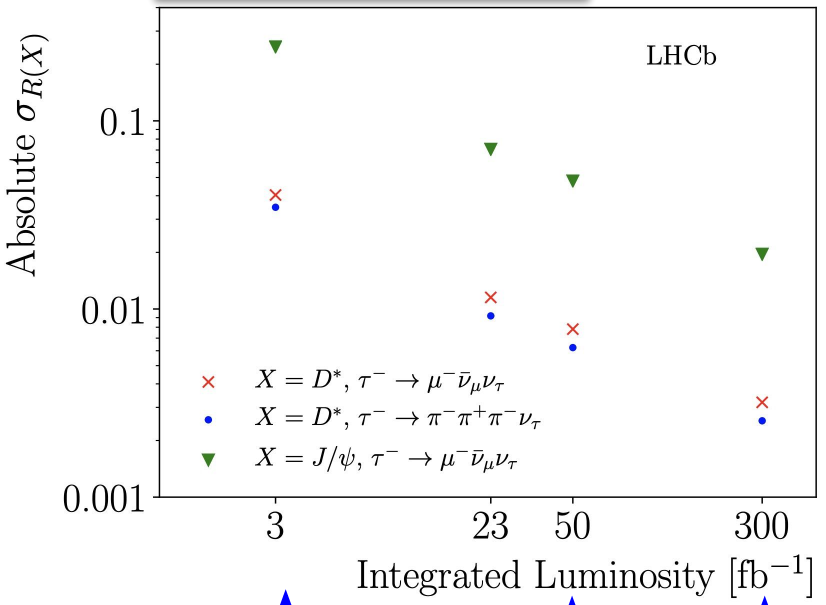
What can we expect in the future?

Belle II physics book, 2018
arxiv:1808.10567

	Process	Observable	Theory	Sys. dom. (Discovery) [ab^{-1}]	vs LHCb	vs Belle	Anomaly	NP
●	$B \to \pi \ell \nu_\ell$	$\lvert V_{ub}\rvert$	⋆⋆⋆	10-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆
●	$B \to X_u \ell \nu_\ell$	$\lvert V_{ub}\rvert$	⋆⋆	2-10	⋆⋆⋆	⋆⋆	⋆⋆⋆	⋆
●	$B \to \tau \nu$	$Br.$	⋆⋆⋆	>50 (2)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to \mu \nu$	$Br.$	⋆⋆⋆	>50 (5)	⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆
●	$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb}\rvert$	⋆⋆⋆	1-10	⋆⋆⋆	⋆⋆	⋆⋆	⋆
●	$B \to X_c \ell \nu_\ell$	$\lvert V_{cb}\rvert$	⋆⋆⋆	1-5	⋆⋆⋆	⋆⋆	⋆⋆	⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	⋆⋆⋆	5-10	⋆⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
●	$B \to D^{(*)} \tau \nu_\tau$	P_τ	⋆⋆⋆	15-20	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
●	$B \to D^{**} \ell \nu_\ell$	$Br.$	⋆	-	⋆⋆	⋆⋆⋆	⋆⋆	-

50ab^{-1} 2027

Physics case for an LHCb Upgrade II, 2018
arxiv:1808.08865

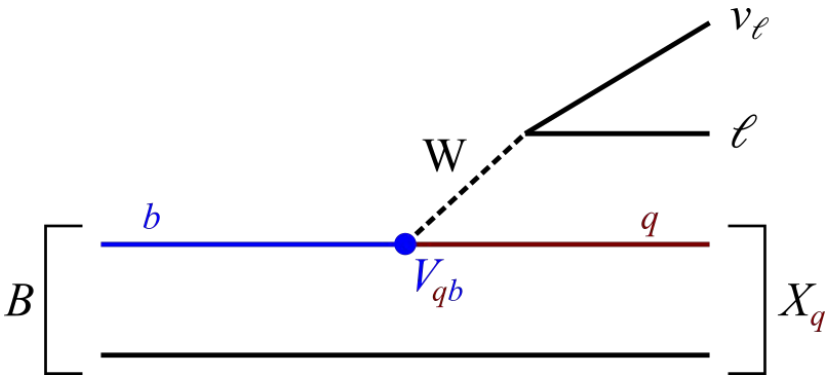


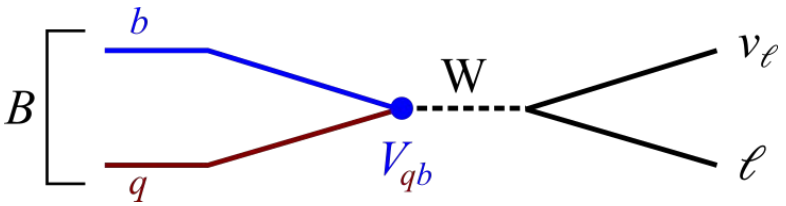
LHCb 2019 | **LHCb U1 2030** | **LHCb U2 2037**

Summary

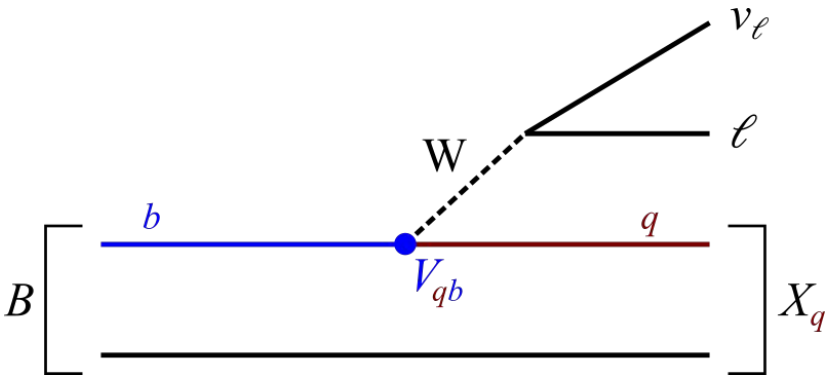
Mysteries still mysterious

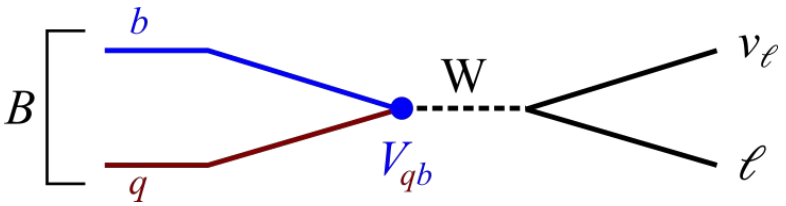
- Inclusive/exclusive tension in V_{ub}/V_{cb}
  - Form factor dependence (probably) won't save us
  - Tension still at $\sim 3\sigma$
- Excess in $R(D^{(*)})$
  - World average tension with SM still at $\sim 3\sigma$, but decreasing
- Semileptonic and leptonic B decays remain **excellent probes** of SM and BSM physics
- **Eagerly awaiting Belle II and upgraded LHCb results!**





THANK YOU!





ADDITIONAL SLIDES

The *B* factories

Kinematics

- We know the beam energy ($m_{\Upsilon(4S)}$)
- Define two ~independent kinematic quantities
  - $\Delta E = E^{\star}_{B} - E^{\star}_{\text{beam}}$ (~ 0 for true B)
  - $m_{\text{bc}} = \sqrt{E^{\star 2}_{\text{beam}} - \boldsymbol{p}^{\star 2}_{B}}$ ($\sim m_{B}$ for true B)
  - *Kinematic consistency* of reconstructed B with B meson
- For single-neutrino decays, define Y as the visible mass in the decay. Then this quantity should be in [-1, 1]
  - $\cos\theta_{BY} = \dfrac{2E_B E_Y - m_B^2 - m_Y^2}{2p_B p_Y}$