Lepton Flavor Universality Violation: the Experimental View.

PASCOS 2024, ICISE, Quy Nhon, Vietnam,

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Outline

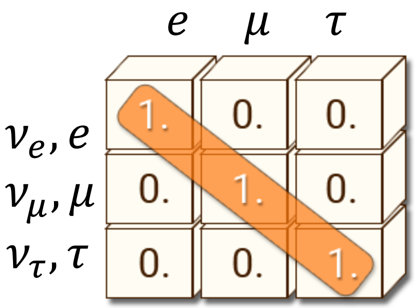
- What is LFUV and why it is relevant
- Experiments and data sets
- Low energy
  - Light mesons decays
  - Tau decays
- High energy:
  - W and Z decays
  - TeV scale
- Heavy flavour transitions
  - c->s l nu transitions
  - b->s l l transitions
  - b->c l nu transitions
- Conclusions

What is LFUV and why it matters

- SM: 3 generations of leptons with the same gauge couplings
  - Difference in masses and Higgs coupling

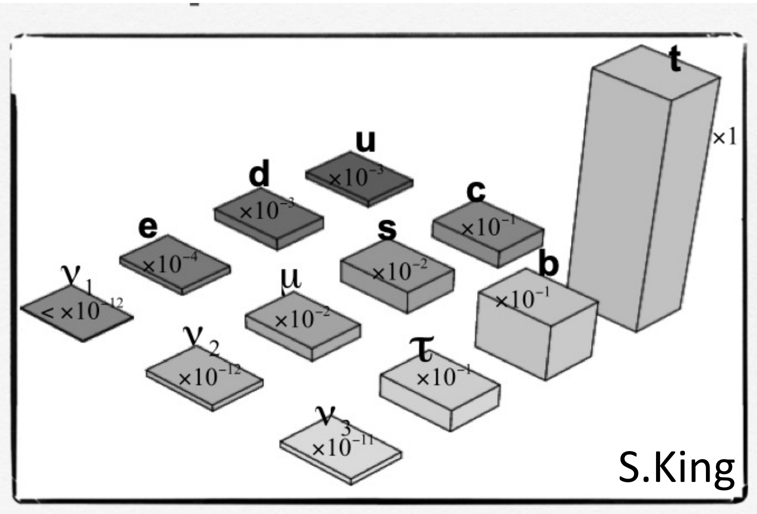
$$m_e \neq m_\mu \neq m_\tau$$

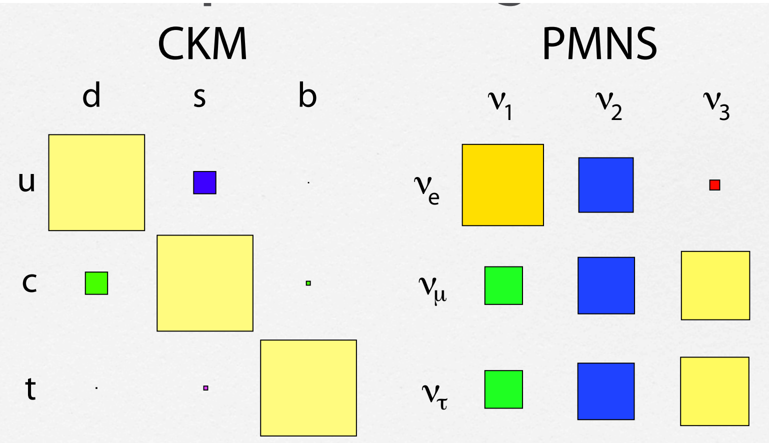
- SM fields do mix:
  - Quarks → CKM matrix
  - Neutrinos → PMNS matrix
- For charged leptons the matrix seems purely diagonal



$$\begin{array}{c|ccc} & e & \mu & \tau \\ \hline \nu_e, e & 1. & 0. & 0. \\ \nu_\mu, \mu & 0. & 1. & 0. \\ \nu_\tau, \tau & 0. & 0. & 1. \end{array}$$

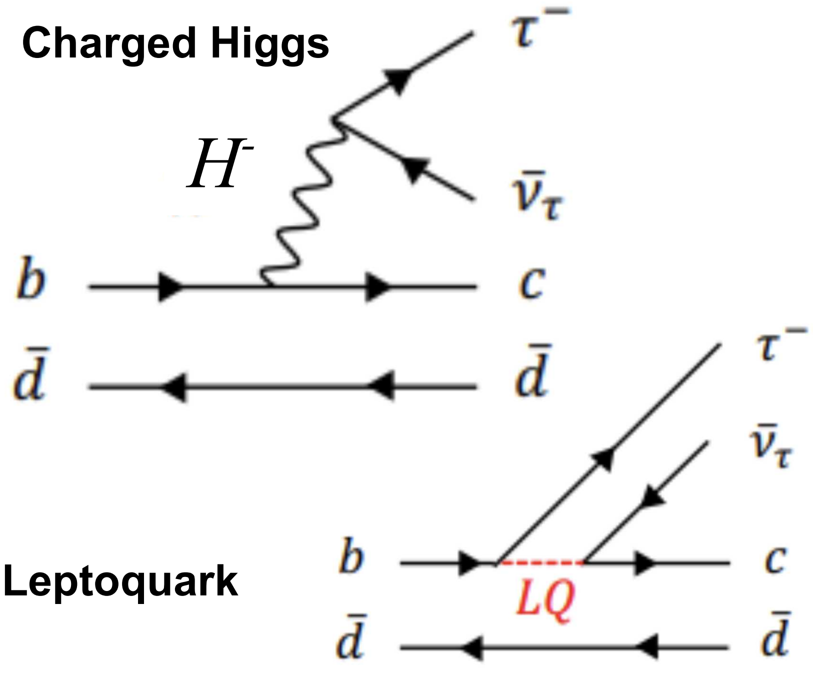
- Lepton Flavor Violation: out of diagonal term
- Lepton Flavor Universality Violation: diagonal terms not all equal
  - Sensitive to physics beyond the standard model
  - Tensions or anomalies observed in various channels
- Accidental symmetry, not coming from first principles





Possible sources of LFUV

- LFUV experimental bounds can be intepreted as constraints on New Physics
- Effective Field Theory
  - Modified $W\ell\nu$ couplings
  - Four-lepton operators
  - Two-quark-two-lepton operators
- Specific NP models
  - W' boson
  - Vector-like leptons
  - Additional SU(2)L scalars
  - Z' boson
  - Leptoquark
  - Charged Higgs



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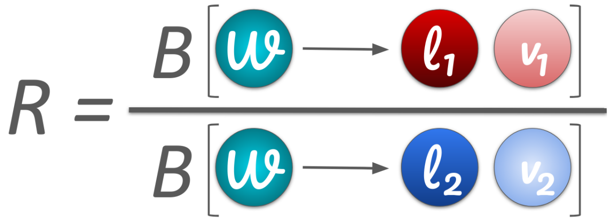
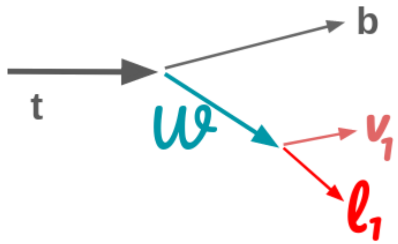
How can we observe LFUV

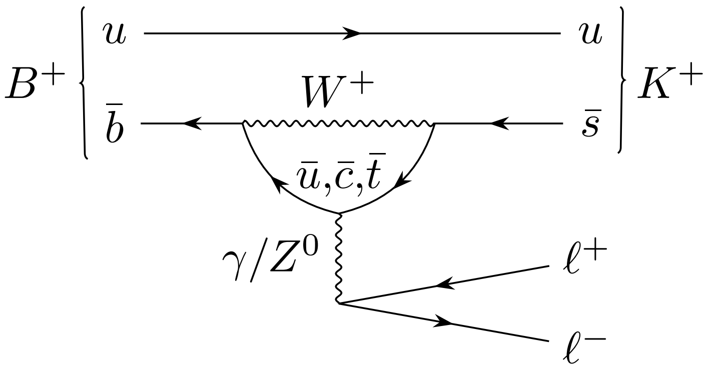
- Measure ratios of processes with different leptons to reduce systematics

A.Knue



$$R = \frac{B[W \to \ell_1 \nu_1]}{B[W \to \ell_2 \nu_2]}$$





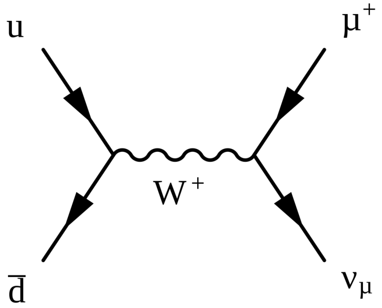
W and Z decays

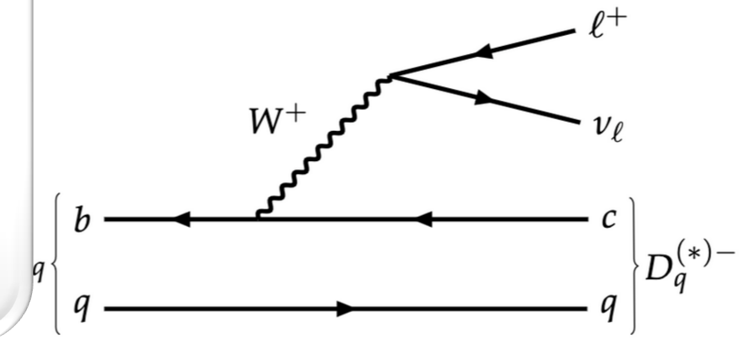
Leptonic decays of strange, charm, beauty hadrons, and tau

LFUV

Semileptonic decays of strange, charm and beauty hadrons

Rare decays of beauty hadrons





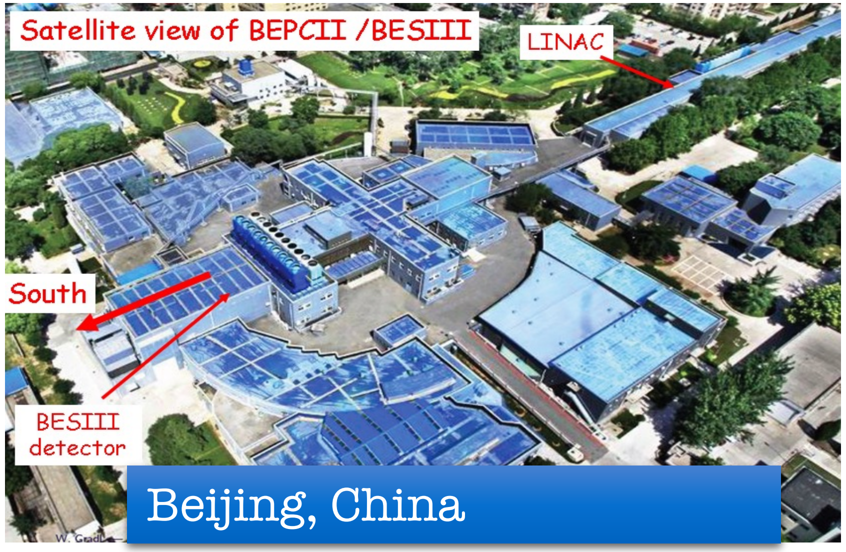
Charge conjugated processes implied

Experiments and data sets

Beam energy: 1.0-2.3 GeV
Optimum energy: 1.89 GeV
Designed luminosity: 1.00×10^{33} cm^{-2}s^{-1}
Data taken from: 2009
Achieved luminosity: 1.00×10^{33} cm^{-2}s^{-1}

CM energy	Data set
3.773 GeV	7.9 fb^{-1}
4.178 GeV	7.3 fb^{-1}
4.6 GeV	4.5 fb^{-1}

BESS III @ BEPCII: 2009--

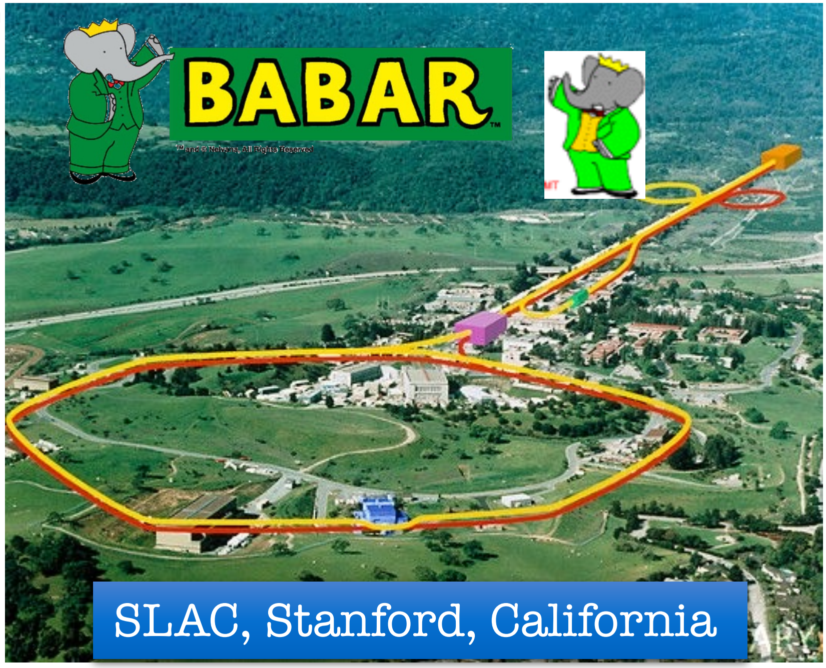


Beijing, China

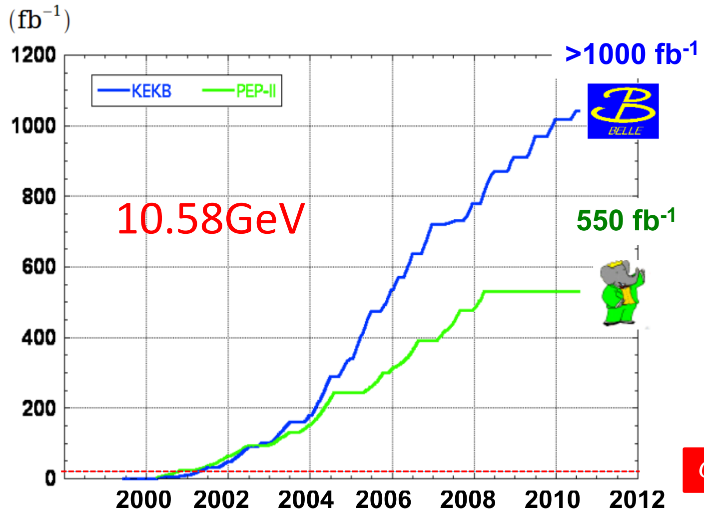
10.58GeV

Channel	Belle	BaBar
$B\bar{B}$	7.7×10^8	4.8×10^8
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–
$\Upsilon(1S)$	1.0×10^8	
$\Upsilon(2S)$	1.7×10^8	0.9×10^7
$\Upsilon(3S)$	1.0×10^7	1.0×10^8
$\Upsilon(5S)$	3.6×10^7	–
$\tau\tau$	1.0×10^9	0.6×10^9

BABAR @ PEP-II: 1999-2008

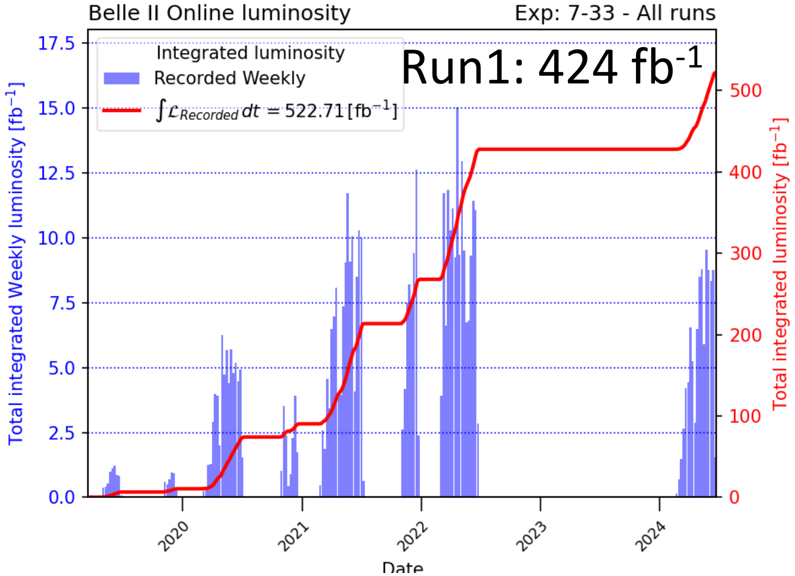


SLAC, Stanford, California

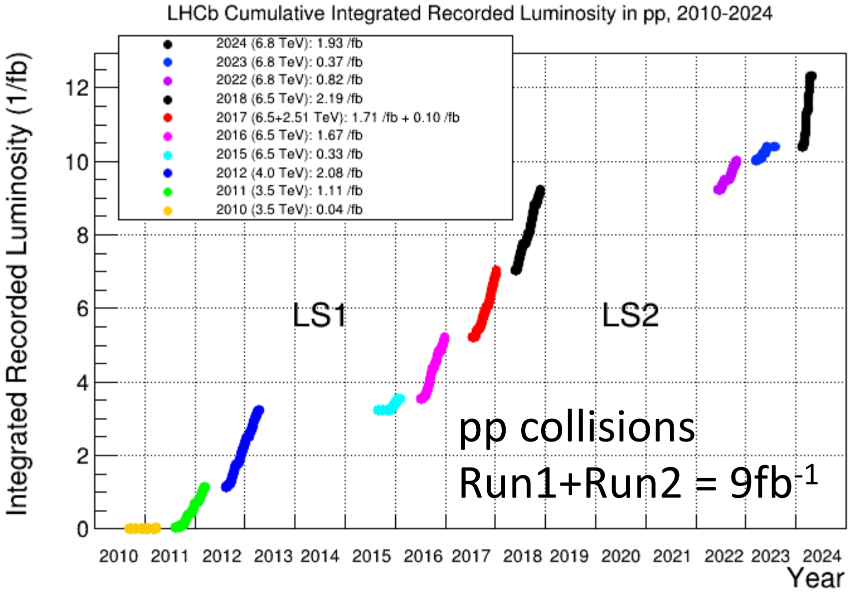


BELLE @ KEKB: 1999-2010

KEK, Tsukuba, Japan



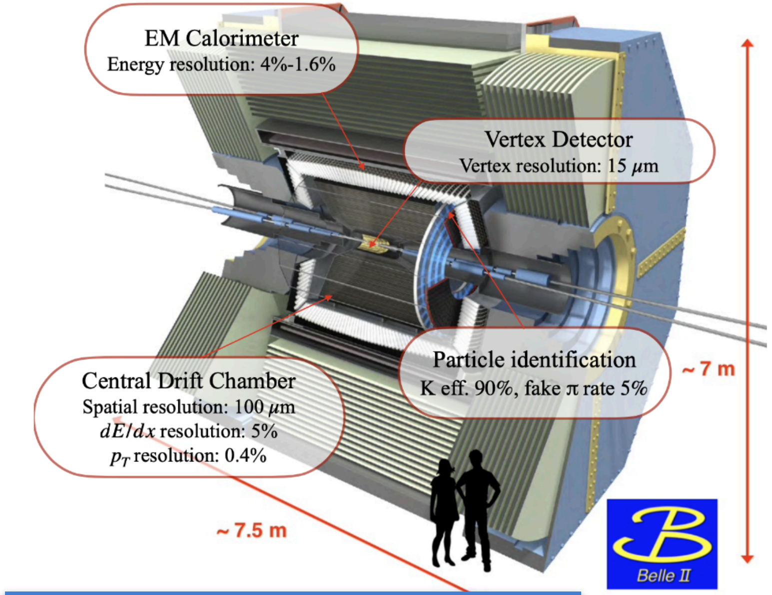
Run1: 424 fb^{-1}



pp collisions

Run1+Run2 = 9fb^{-1}

BELLE II @ SuperKEKB: 2019 -



EM Calorimeter
Energy resolution: 4%-1.6%

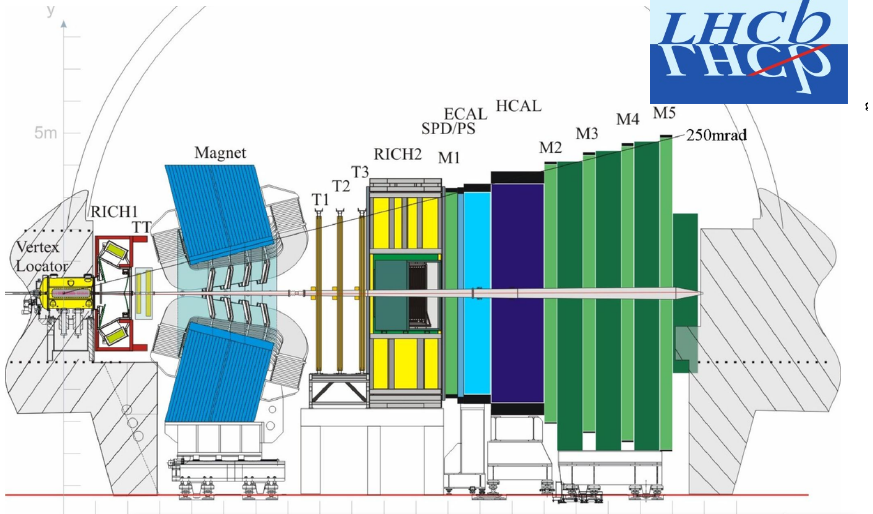
Vertex Detector
Vertex resolution: 15 μm

Central Drift Chamber
Spatial resolution: 100 μm
dE/dx resolution: 5%
p_T resolution: 0.4%

Particle identification
K eff. 90%, fake π rate 5%

KEK, Tsukuba, Japan

LHCb@LHC: 2011 -



CERN, Geneva, Switzerland

Low Energy

μ/e:Light meson decays

- Pseudo scalars leptonic decays
  - $P = \pi/K$

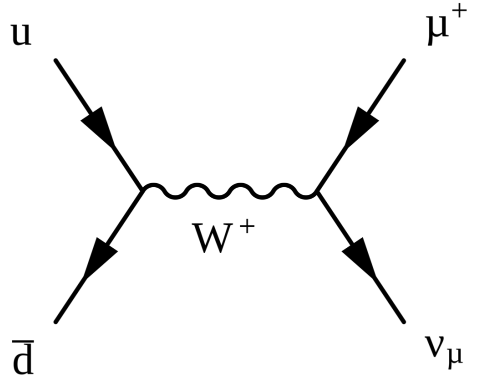
$$R^P_{e/\mu} = \frac{\Gamma[P \to e\bar{\nu}_e(\gamma)]}{\Gamma[P \to \mu\bar{\nu}_\mu(\gamma)]}, = \bar{R}^P_{e/\mu}\left[1 + \Delta^P_{e^2 Q0} + \dots\right.$$

- Helicity suppressed because of V-A
  - Can be calculated at 10^{-4} level with radiative corrections

$$\bar{R}^P_{e/\mu} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2}\right)^2$$

- Recast in terms of ratios of coupling constants

$$L_{CC} = A_\ell \bar{u}\gamma^\mu P_L d \bar{\nu}_\ell \gamma_\mu P_L \ell,$$



$$\left(\frac{A_\mu}{A_e}\right)_{R^\pi_{e/\mu}} = 1.0010 \pm 0.0009, \quad \left(\frac{A_\mu}{A_e}\right)_{R^K_{e/\mu}} = 0.9978 \pm 0.0018.$$

- Compatible with SM

PDG Averages, see
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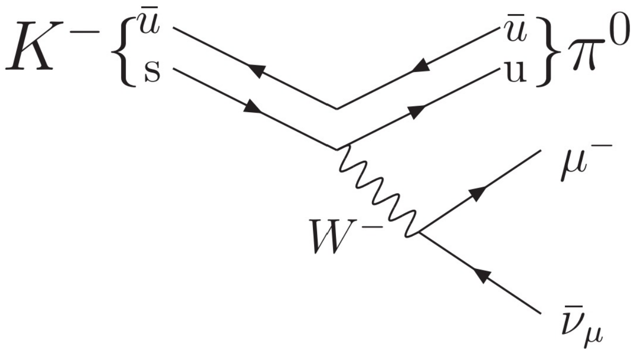
μ/e: semileptonic decays $s \to u\ell\nu$, $c \to s\ell\nu$

- The SM ratio is determined entirely by phase-space factors and long-distance radiative corrections



$$\left(\frac{A_\mu}{A_e}\right)_{R^{K\to\pi}_{e/\mu}} = 1.0009 \pm 0.0018.$$

K^0/K^{+-} average

PDG average see

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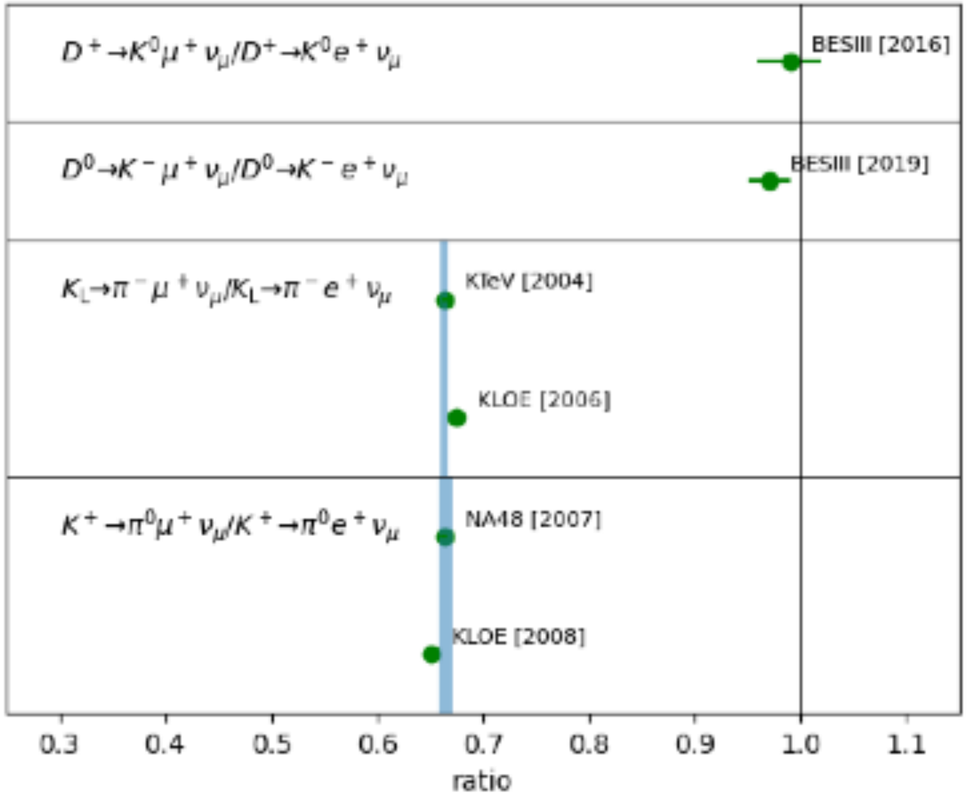


Ratios of Branching Fractions

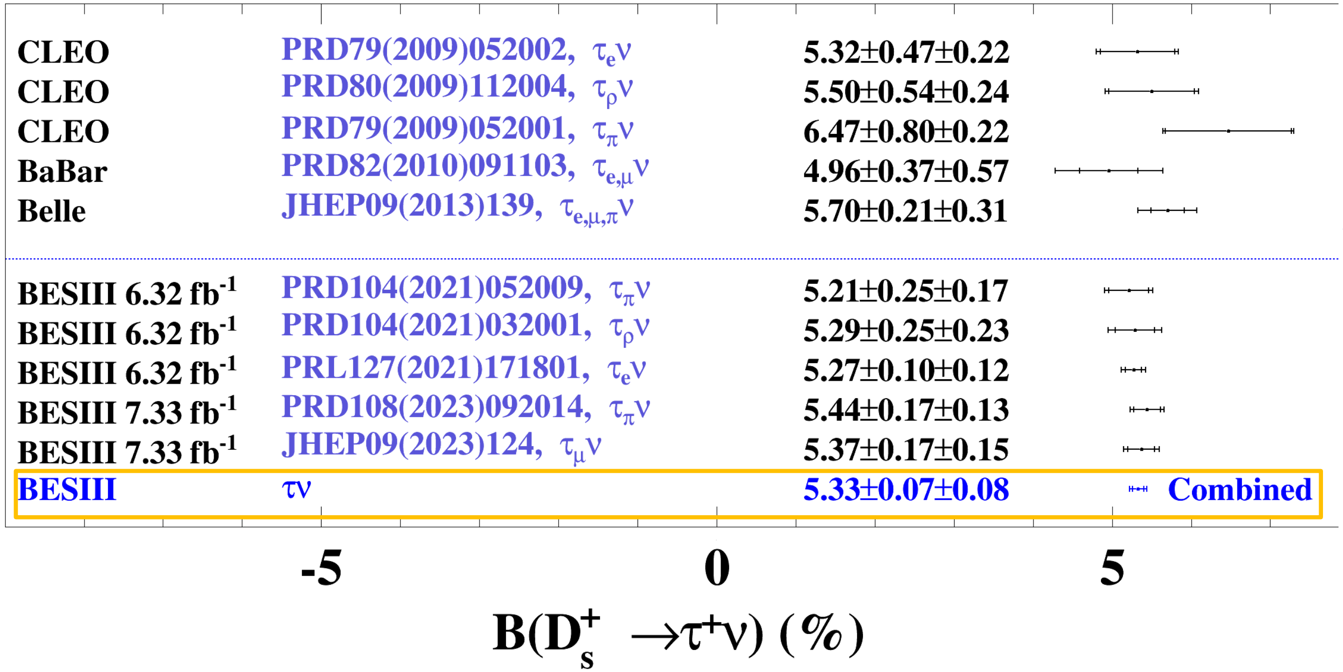
http://www.scholarpedia.org/article/Lepton_flavour_universality

CM energy	Data set
3.773 GeV	7.9 fb^{-1}
4.178 GeV	7.3 fb^{-1}
4.6 GeV	4.5 fb^{-1}

μ/e : more $c \to s\ell\nu$

D_s leptonic decays

BESIII PRD108(2023)11200, $\mu\nu$ $(5.29\pm0.11\pm0.09)\times 10^{-3}$



CLEO	PRD79(2009)052002,	$\tau_e\nu$	5.32±0.47±0.22
CLEO	PRD80(2009)112004,	$\tau_\rho\nu$	5.50±0.54±0.24
CLEO	PRD79(2009)052001,	$\tau_\pi\nu$	6.47±0.80±0.22
BaBar	PRD82(2010)091103,	$\tau_{e,\mu}\nu$	4.96±0.37±0.57
Belle	JHEP09(2013)139,	$\tau_{e,\mu,\pi}\nu$	5.70±0.21±0.31
BESIII 6.32 fb^{-1}	PRD104(2021)052009,	$\tau_\pi\nu$	5.21±0.25±0.17
BESIII 6.32 fb^{-1}	PRD104(2021)032001,	$\tau_\rho\nu$	5.29±0.25±0.23
BESIII 6.32 fb^{-1}	PRL127(2021)171801,	$\tau_e\nu$	5.27±0.10±0.12
BESIII 7.33 fb^{-1}	PRD108(2023)092014,	$\tau_\pi\nu$	5.44±0.17±0.13
BESIII 7.33 fb^{-1}	JHEP09(2023)124,	$\tau_\mu\nu$	5.37±0.17±0.15
BESIII		$\tau\nu$	5.33±0.07±0.08 Combined

$$R_{\tau/\mu} = \frac{\mathcal{B}[D_s^+\to\tau^+\nu]}{\mathcal{B}[D_s^+\to\mu^+\nu]} = \mathbf{10.05 \pm 0.35}$$, consistent with the SM prediction 9.75

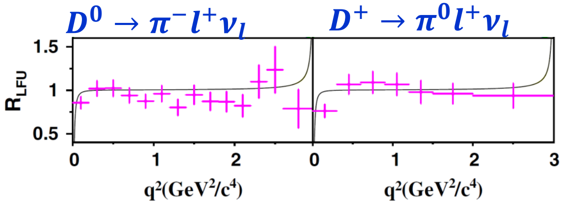
D semileptonic decays

- $\mathcal{R}_{\mu/e}$ **obtained by measuring BFs**

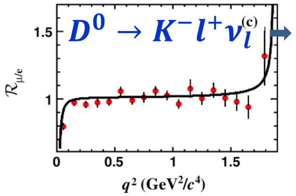
	Ref	$\mathcal{R}_{\mu/e}$	SM prediction
$D^+ \to \eta l^+ \nu_l$	PRL124(2020)231801	0.91 ± 0.13	0.97 – 1.00
$D^+ \to \omega l^+ \nu_l$	PRD101(2020)072005	1.05 ± 0.14	0.93 – 0.99
$D^+ \to \rho l^+ \nu_l$	PRD104(2021)L091103	0.90 ± 0.11	0.93 – 0.96

- $\mathcal{R}_{\mu/e}$ **in the full kinematic region**

PRL121(2018)171803

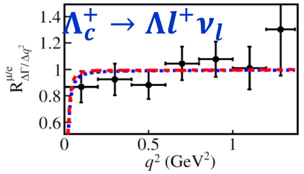


PRL122(2019)011804

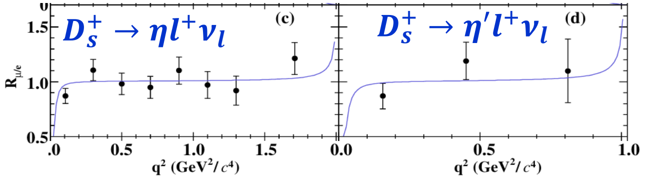


SM prediction

PRD108(2023)L031105



PRL132(2024)091802



Consistent with SM predictions

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LFUV, Beta Decays, and Cabibbo Angle Anomaly

- CKM Unitarity requires

$$\Delta_{\mathrm{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 - 1 = 0$$

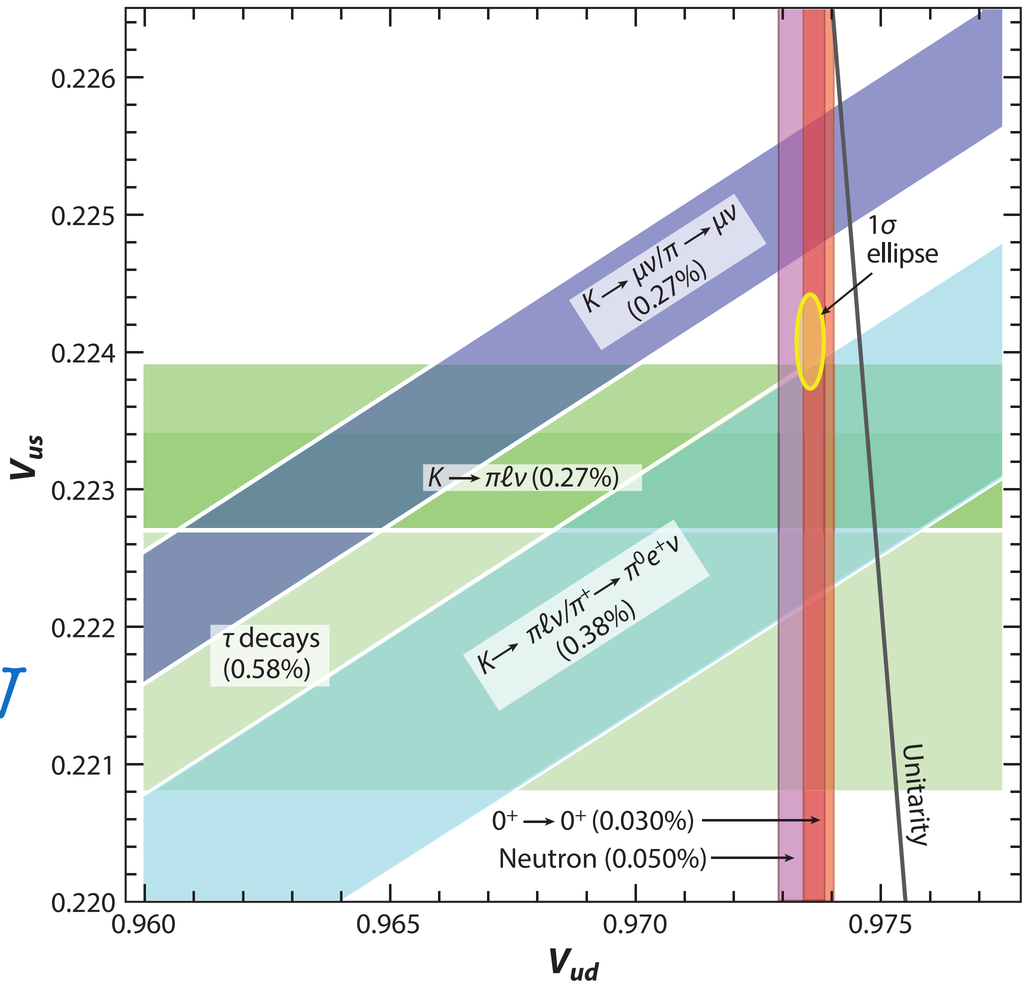
- Extraction of $V_{uD} (= V_{ud}, V_{us})$

$$\Gamma = G_{\mathrm{F}}^2 \times |V_{uD}|^2 \times |M_{\mathrm{had}}|^2 \times (1 + \delta_{\mathrm{IsoB}} + \delta_{\mathrm{RC}}) \times F_{\mathrm{kin}}$$

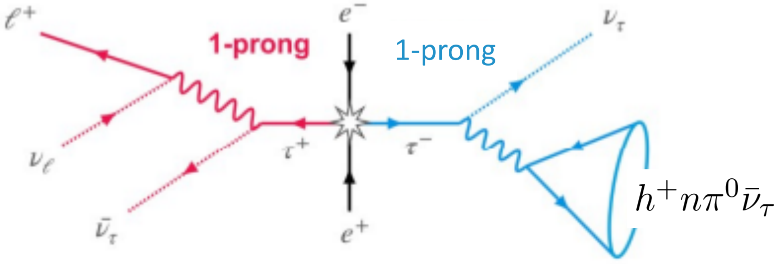
  - G_F from μ decay
  - V_{ud} from 0^+ nuclear β decays
  - V_{us} from $\Gamma(K \rightarrow \pi \ell \nu)$

- Interplay between CAA and LFUV
  - 3.7σ tension (CAA)

$$\Delta_{\mathrm{CKM}} = (-19.5 \pm 5.3) \times 10^{-4}$$



$\mu/e; \tau/\mu : \tau$ decays



- In $e^+e^- \to \tau^+\tau^-$ one can separate the event in two hemispheres: tag τ and signal τ

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$$R^\tau_{\mu/e} = \frac{\mathrm{Br}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathrm{Br}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} \qquad \left(\frac{A_\tau}{A_\mu}\right)_\tau = 1.0010 \pm 0.0014,$$

$$R^{\tau\pi(K)}_{\tau/\mu} = \frac{\mathrm{Br}[\tau \to \pi(K)\nu_\tau]}{\mathrm{Br}[\pi(K) \to \mu\nu_\mu]}, \qquad \left(\frac{A_\tau}{A_e}\right)_\tau = 1.0029 \pm 0.0014,$$

$$R^\tau_{\tau/\mu} = \frac{\mathrm{Br}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}{\mathrm{Br}(\mu^- \to e^-\bar{\nu}_e\nu_\mu)}, \qquad \boxed{\left(\frac{A_\mu}{A_e}\right)_\tau = 1.0018 \pm 0.0014.}$$

$$\left(\frac{A_\tau}{A_\mu}\right)_\pi = 0.9964 \pm 0.0038,$$

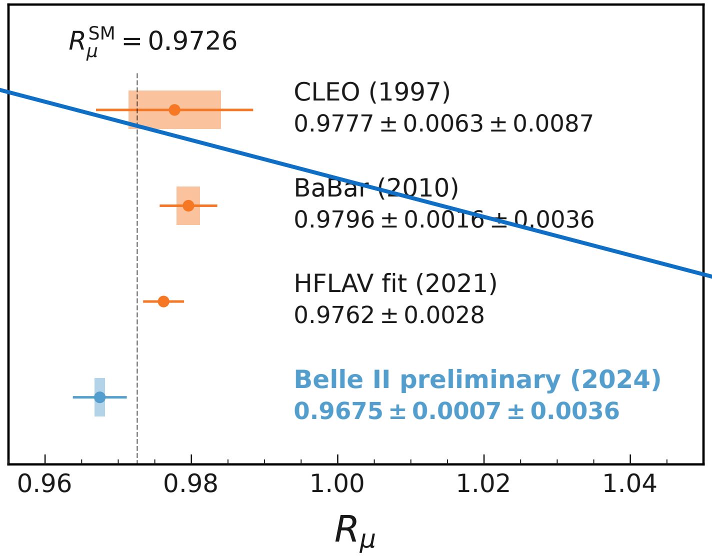
$$R^\tau_{\tau/e} = \frac{\mathrm{Br}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathrm{Br}(\mu^- \to e^-\bar{\nu}_e\nu_\mu)} \qquad \left(\frac{A_\tau}{A_\mu}\right)_K = 0.9857 \pm 0.0078.$$

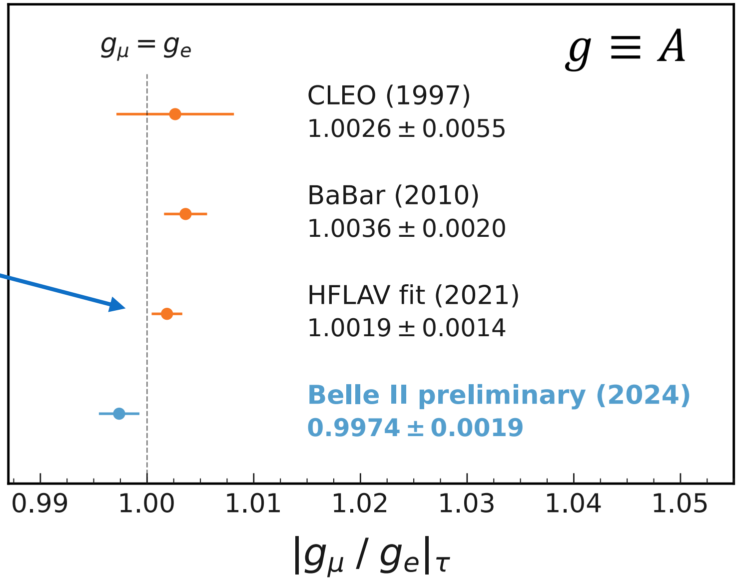
From BF to couplings $$\left(\frac{A_\mu}{A_e}\right)_\tau = \sqrt{R^\tau_{\mu/e}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

$$\boxed{f(x) = -8x + 8x^3 - x^4 - 12x^2 \log x.}$$

- New Belle II analysis
  - 362 fb−1
  - Purity 96% and 92% for electron and muon channel.
  - Systematics dominated by electron ID and trigger

arXiv:2405.14625
Submitted to JHEP





Consistent with the SM at 1.4 σ

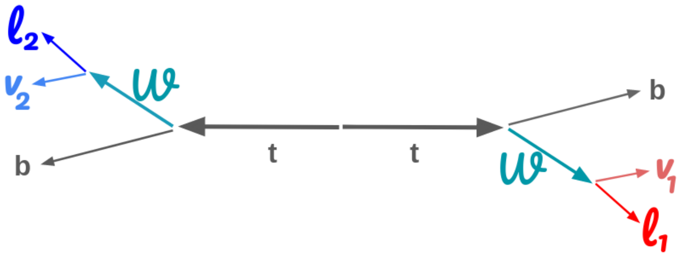
High Energy

A.Knue@Moriond2024

Atlas briefing

W/Z decays

- Existing tension from LEP in $W \to \tau\nu / W \to (e,\mu)\nu$
- Very precise Z measurements from LEP/SLD
- CMS and ATLAS can use tt events

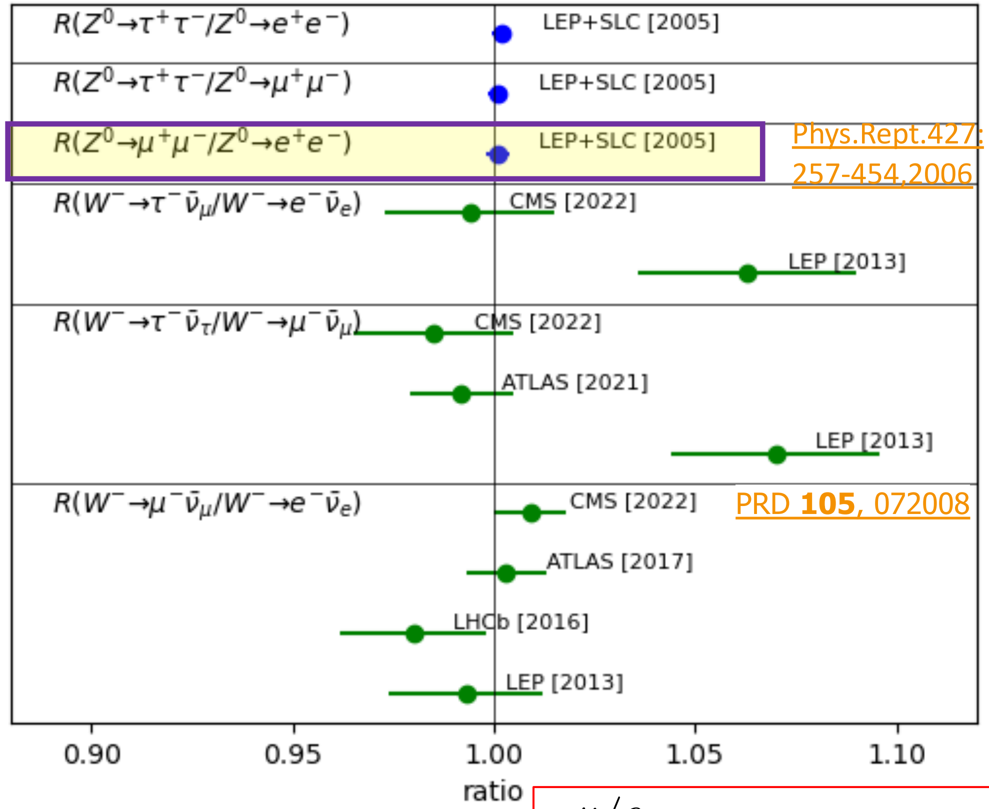


- New ATLAS analysis
  - Reduce lepton ID systematics with double ratio
  - Get final value using precise LEP/SLD measurement

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}}$$

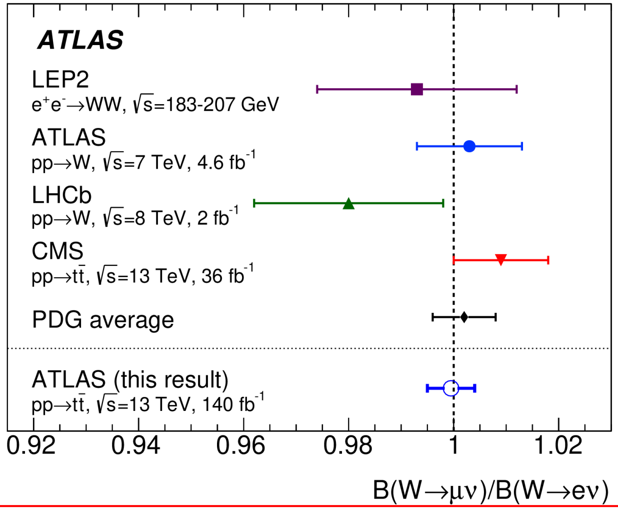
$$R_W^{\mu/e}(\text{ATLAS}) = R_{WZ}^{\mu/e}(\text{ATLAS}) \cdot \sqrt{R_Z^{\mu\mu/ee}(\text{LEP+SLD})}$$

Presented by H.Potti on Monday



Phys.Rept.427: 257-454,2006

PRD **105**, 072008



- Relative uncertainty of 0.45%
- Most precise single measurement
- Better than PDG average

arxiv.org/abs/2403.02133

Accepted in EPJC

$$R_W^{\mu/e}(\text{ATLAS}) = 0.9995 \pm 0.0022\,(\text{stat.}) \pm 0.0036\,(\text{syst.}) \pm 0.0014\,(\text{LEP+SLD})$$

JHEP **07** (2021) 208

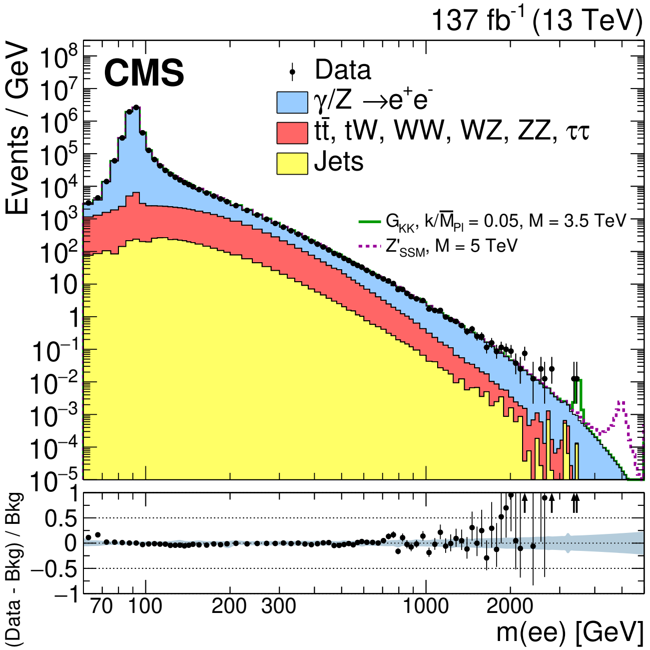
TeV-scale tests

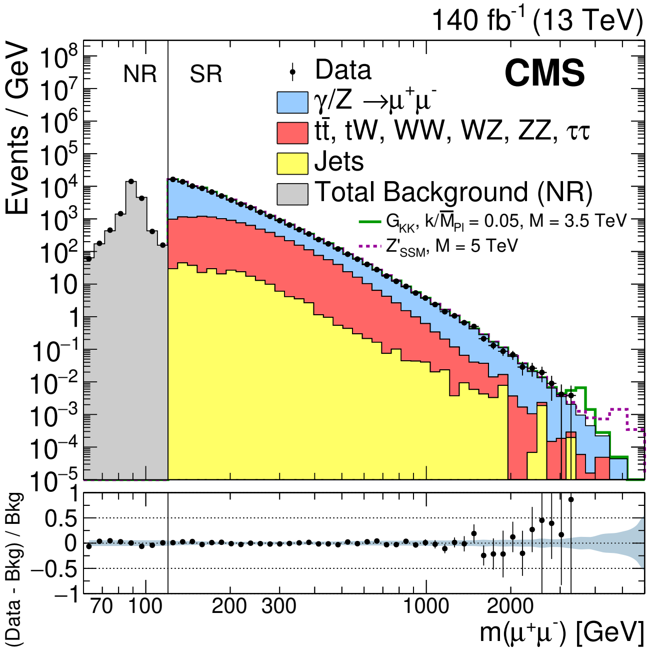
JHEP **11** (2020) 005

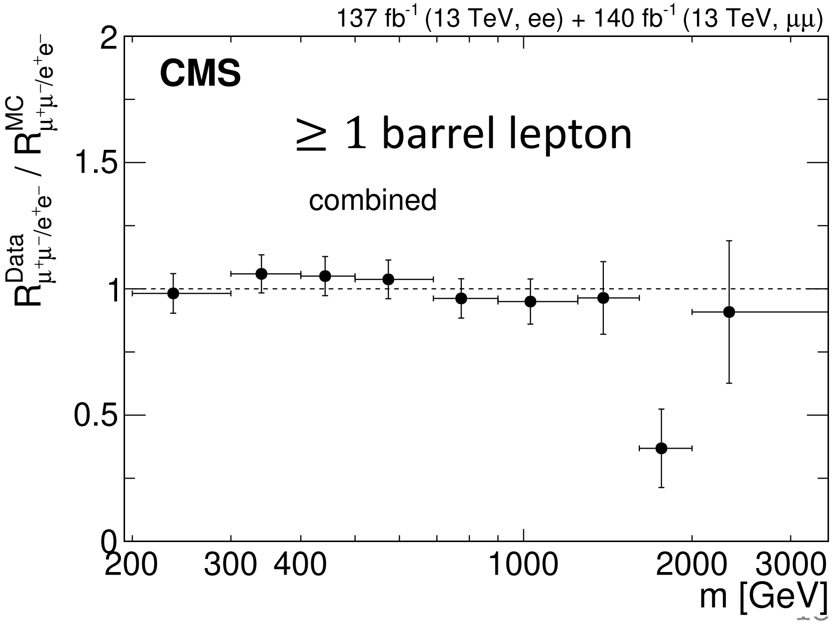
- Investigation in electron and muon pairs in *pp* collisions at 13TeV. Resonant and non resonant
- Experimental challenge: properly model lepton efficiency vs. momentum and angle
- Compare spectrum to MC $R^{\mathrm{Data}}_{\mu^+\mu^-/e^+e^-} / R^{\mathrm{MC}}_{\mu^+\mu^-/e^+e^-}$
- No significant deviation from LFU observed

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$

Source	Uncertainty
Electron selection efficiency	6–8%
Muon selection efficiency	1–2% (two-sided), 0–6.5% (one-sided)
Mass scale uncertainty	0–3%
Dimuon mass resolution uncertainty	8.5–15%





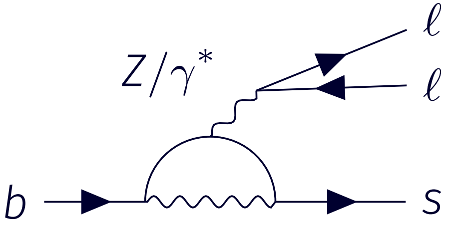


Heavy Flavor Transitions

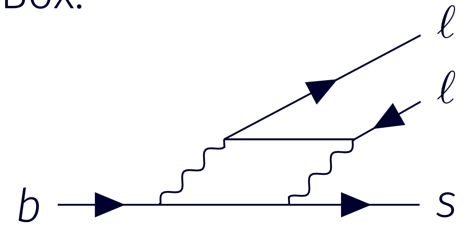
As D.Buttazzo explained, this is were the interesting stuff lies

$b \to s\ell\ell$ signals

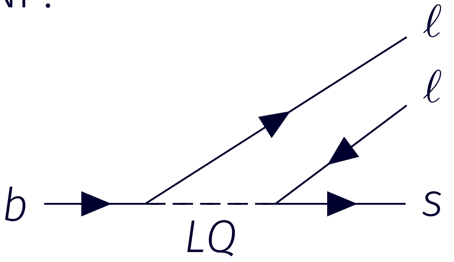
Penguin:



Box:



NP:



- Forbidden at tree level, very sensitive to New Physics signals

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}\ (B\to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}\ (B\to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \qquad \begin{array}{c} B = B^+, B^0, B_s, \Lambda_b \\ H = K^+, K^{*0}, K_S, pK^- \end{array}$$

- Measure double ratio using J/ψ resonance to reduce systematics

$$R_K = \frac{\mathcal{B}\ (B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}\ (B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}\ (B^+ \to K^+e^+e^-)}{\mathcal{B}\ (B^+ \to J/\psi(\to e^+e^-)K^+)}$$

- LHCB 2019 showed 2.4σ and 2.5σ for $R_{K^{*0}}$ in two bins (Run1: 3fb^{-1})

$$R_{K^{*0}} = \begin{cases} 0.66\ {}^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \ \text{GeV}^2/c^4 \\ 0.69\ {}^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1\ \ \ < q^2 < 6.0\ \ \text{GeV}^2/c^4 \end{cases}$$

JHEP 08(2017) 55

- LHB 2020 measured R_{pK} in $\Lambda_b \to pK^-\ell\ell$ $\quad R_{pK}|_{0.1<q^2<6\ \text{GeV}^2/c^4} = 0.86\,{}^{+0.14}_{-0.11} \pm 0.05$ JHEP 05(2020) 40

- LHCB 2022 result showed a 3.1σ tension for R_K and $1.4 - 1.5\sigma$ for $R_{K_S}, R_{K^{*+}}$

$$R_K(1.1 < q^2 < 6.0\,\text{GeV}^2\,c^{-4}) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

Nat. Phys. 18 (2022) 277-282

$$R_{K^0_S} = 0.66^{+0.20}_{-0.14}(\text{stat})^{+0.02}_{-0.04}(\text{syst}),$$

PRL 128 (2022) 191802

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst}).$$

$b \to s\ell\ell$ update

- LHCB 2023 update simultaneous measurement of R_K and R_{K^*} in two q^2 bins for full statistics (9fb^{-1})
- Now compatible with SM
    - R_{K^*}: increase in statistics
    - R_K: more stringent e-ID reducing contribution from processes not properly accounted for; modeling of residual background
- CMS 2024 also measured R_K, but statistical error still very large
    - Also verified universality of J/ψ and $\psi(2s)$ decays

Rep. Prog. Phys. 87 077802 (2024)

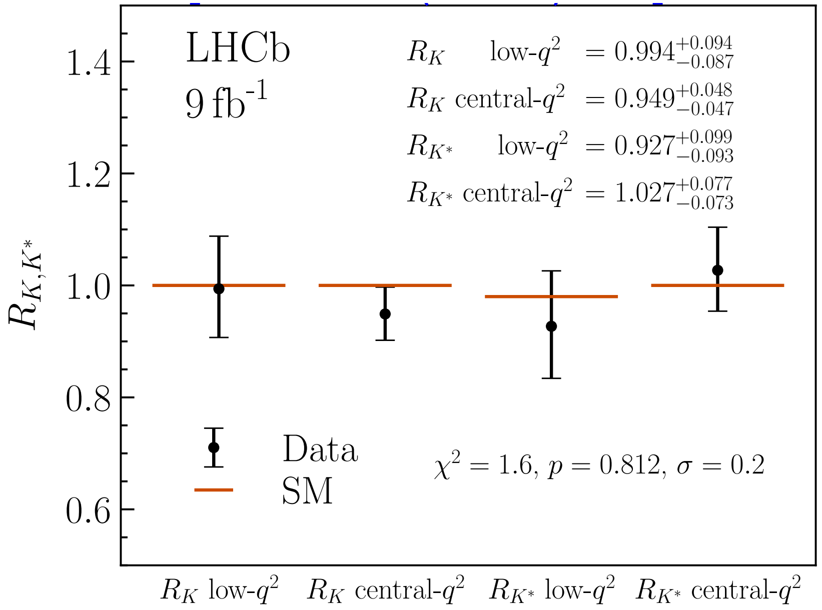
$$R_{J/\psi} = 1.006^{+0.020}_{-0.019},$$

$$R_{\psi(2S)} = 0.966^{+0.071}_{-0.066}$$

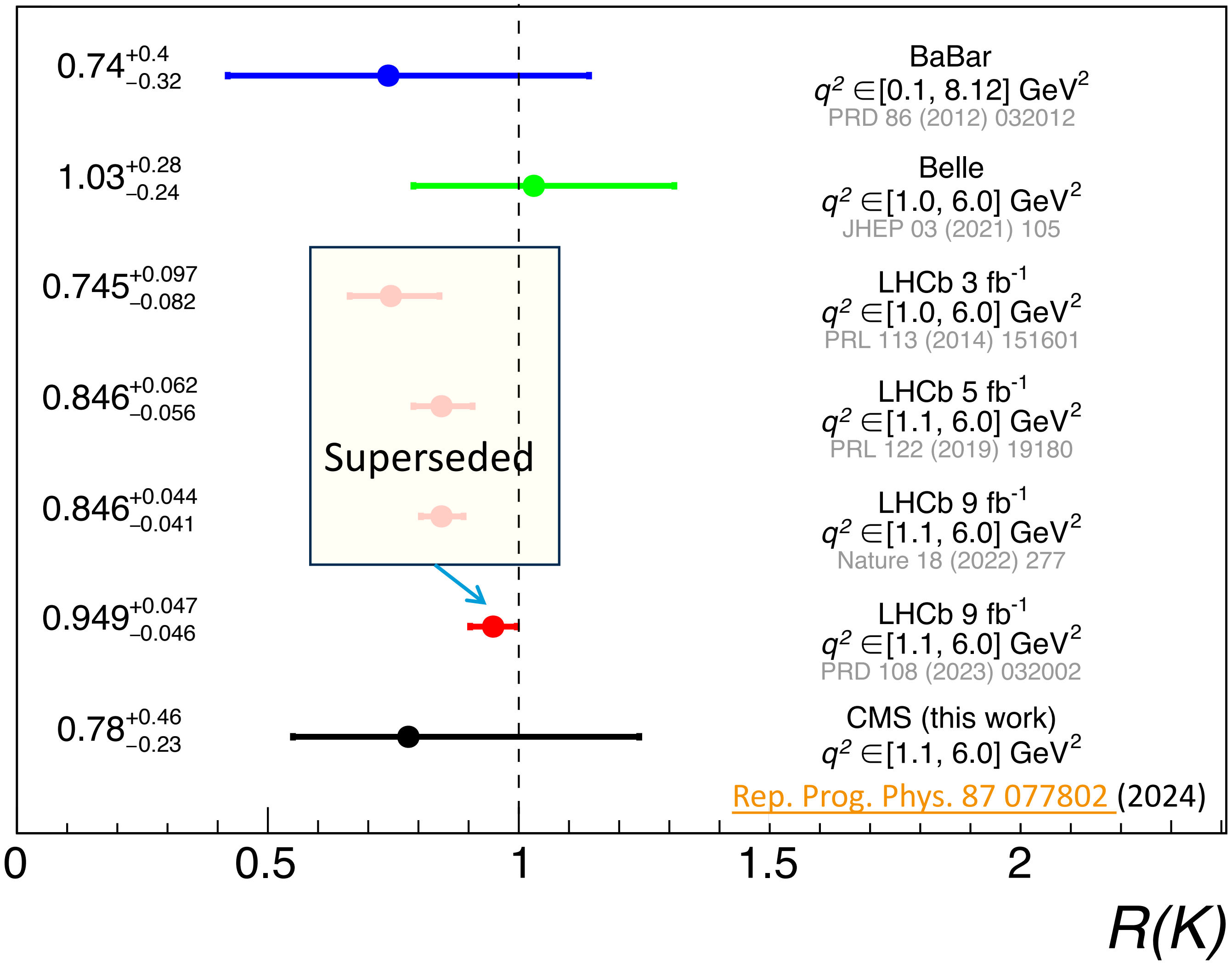
$$\text{low-}q^2 \begin{cases} R_K = 0.994^{+0.090}_{-0.082}(\text{stat})^{+0.029}_{-0.027}(\text{syst}), \\ R_{K^*} = 0.927^{+0.093}_{-0.087}(\text{stat})^{+0.036}_{-0.035}(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949^{+0.042}_{-0.041}(\text{stat})^{+0.022}_{-0.022}(\text{syst}), \\ R_{K^*} = 1.027^{+0.072}_{-0.068}(\text{stat})^{+0.027}_{-0.026}(\text{syst}). \end{cases}$$

PRL 131 (2023) 051803 and PRD 108 (2023) 032002



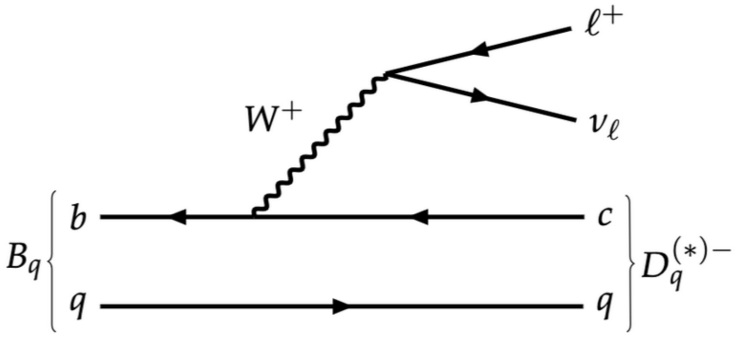
$b \to s\ell\ell$ status and history



Rep. Prog. Phys. 87 077802 (2024)

- $b \to s\ell\ell$ still very interesting
- Some tension in angular analysis
- precision regime is not yet reached for LFU tests:
    - need to go below 1% uncertainty

$b \to c\ell\nu$



- Measure the ratios of rates to different leptons
  - Hadronic uncertainties mostly cancel in the ratio
  - Reduced experimental systematic uncertainties

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu \nu_\mu)}$$

$$H_b = B^0, B^+_{(c)}, \Lambda^0_B, B^0_s, \ldots.$$

$$H_c = D^*, D^0, D^+, D_s, \Lambda_C^{(*)}, J/\psi, \ldots.$$

History of slight excess of semitauonic decays

- Angular analysis adds extra power and sensitivity

LHCB		BELLE / BELLE II	
$R(D) - R(D^*)$ with muonic τ	PRL 131, 111802 (2023)	$R(D^*)$ with leptonic τ had tag	arXiv:2401.02840 (2024) (Submitted to PRD)
$R(D^*)$ with hadronic τ	PRD 108, 012018 (2023)	$R(X_{\mu/e})$ with had tag	PRL 131, 051804 (2023)
$R(D^{+(*)})$ with muonic τ	arXiv:2406.03387 (2024) (Submitted to PRL)	$R(X_{\tau/\ell})$ with leptonic τ had tag	PRL 132, 211804 (2024)
$R(\Lambda_c)$	PRL 128, 191803 (2022)	Angular analysis in $B^0 \to D^*(e/\mu)\nu$	PRL 131, 181801 (2023)
$R(J/\psi)$	PRL 120, 121801 (2018)	Angular coefficients	arXiv: 2310.20286 (2023) (Accepted by PRL)

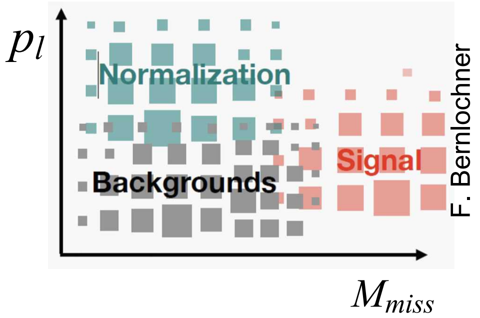
Complementary approaches

B Factories

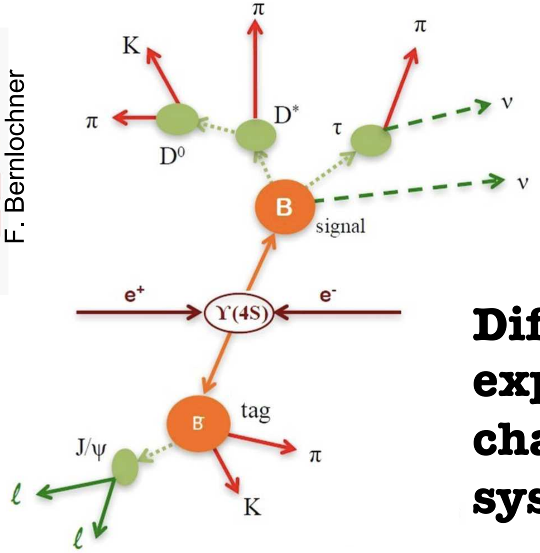
- Full reconstruction of both signal and tagging B meson (low efficiency)
- Closed event kinematics (missing energy)
- π^0 and neutrals reconstruction
- Simple normalization; high efficiency for both μ and e

LHCb

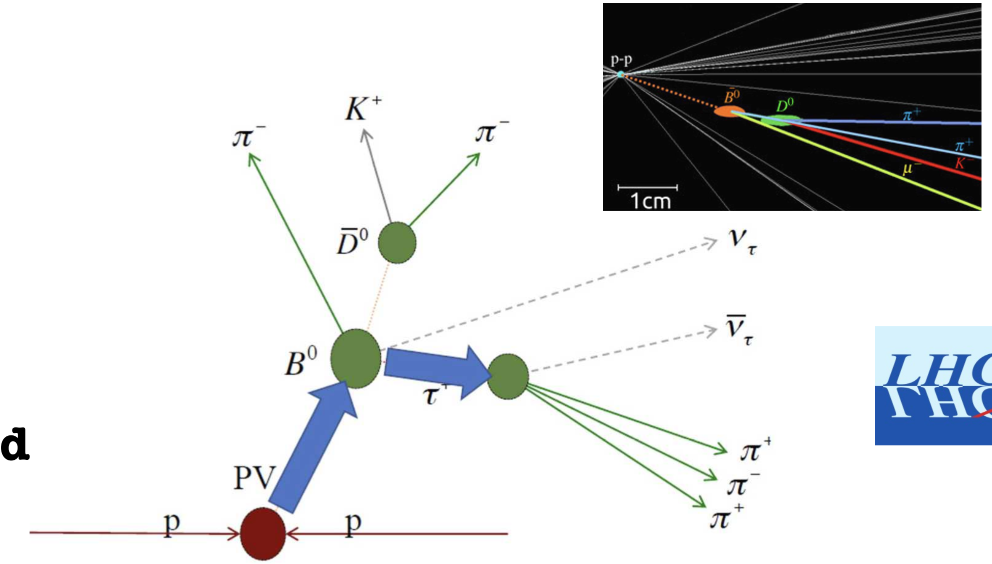
- Large cross section
- Exploit vertexing for B, D, τ reconstruction
- Reliance on all-charged modes and μ-ID
- Normalization of signal relative to similar decay processes



F. Bernlochner



Different experimental challenges and systematics



C. Bozzi

Charge conjugated processes implied

R(D) and R(D*) from LHCb

Leptonic τ decays $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

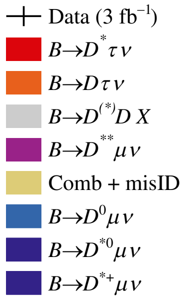
$$B^-/\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau$$

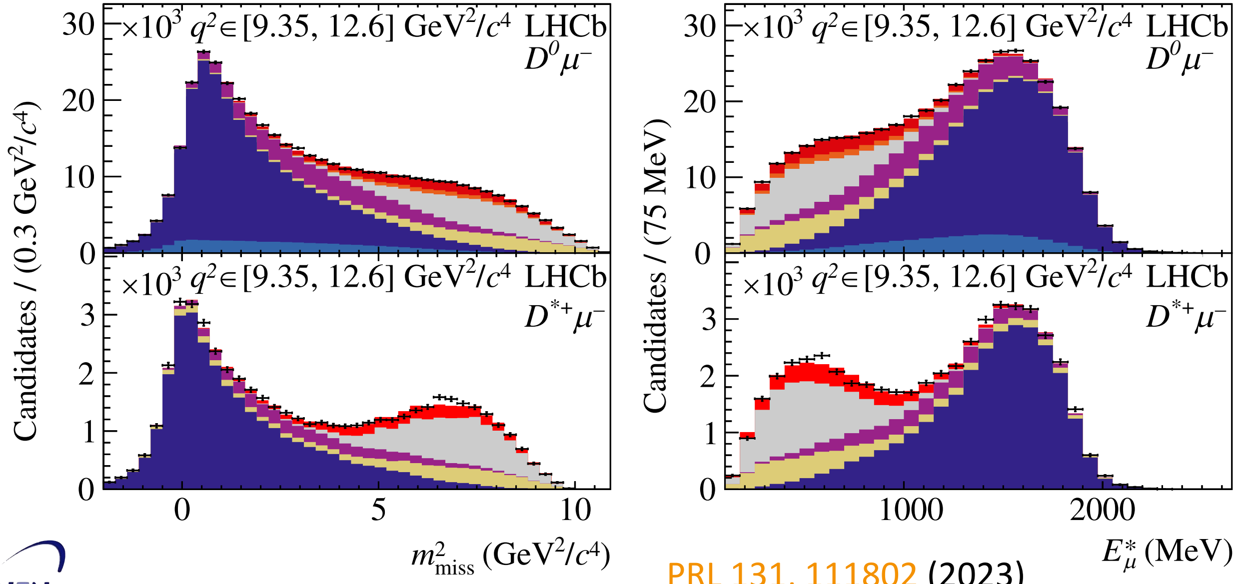
$D^{(*)} = D^0, D^{*+}, D^{*0}$

where $D^{*+} \to D^0\pi^+$ and $D^0 \to K^+\pi^-$

$$\mathcal{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$$

$$\mathcal{R}(D^0) = 0.441 \pm 0.060 \pm 0.066$$





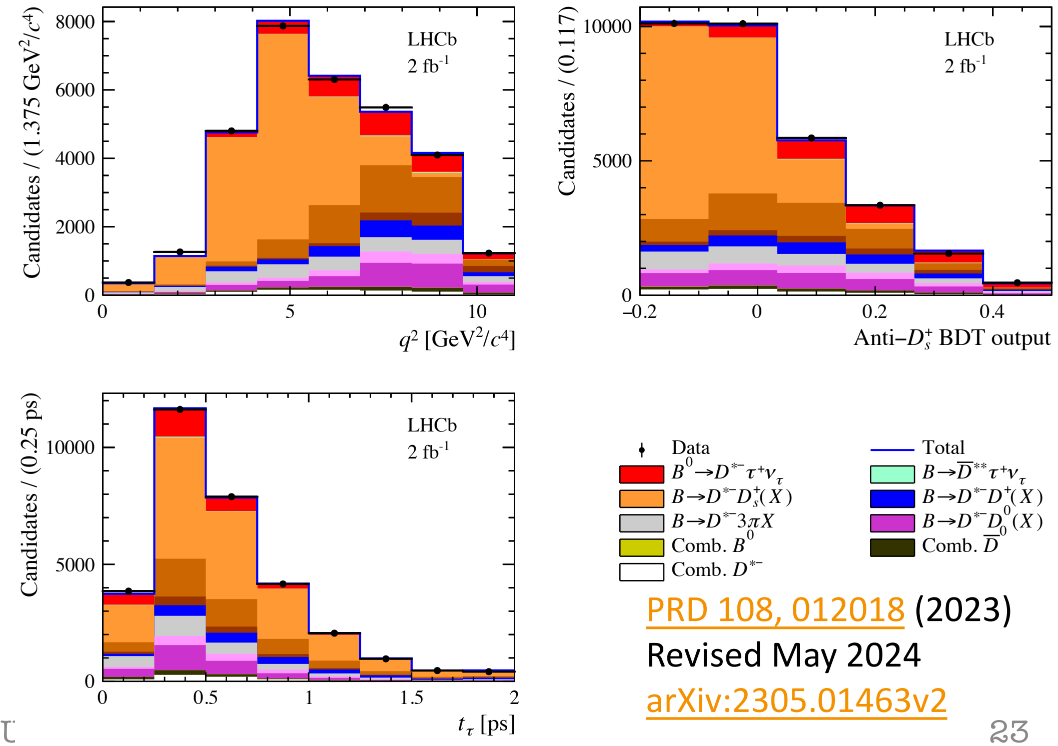
PRL 131, 111802 (2023)

Hadronic τ decays $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

$$B^0 \to D^{*-}\tau^+\nu_\tau \qquad D^{*-} \to \pi^-\bar{D}^0(\to K^+\pi^-)$$

Measure relative to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$, same visible final state, use known B.F.

$$\mathcal{R}(D^{*-}) = 0.260 \pm 0.015\,(\text{stat}) \pm 0.016\,(\text{syst}) \pm 0.012\,(\text{ext})$$



PRD 108, 012018 (2023)
Revised May 2024
arXiv:2305.01463v2

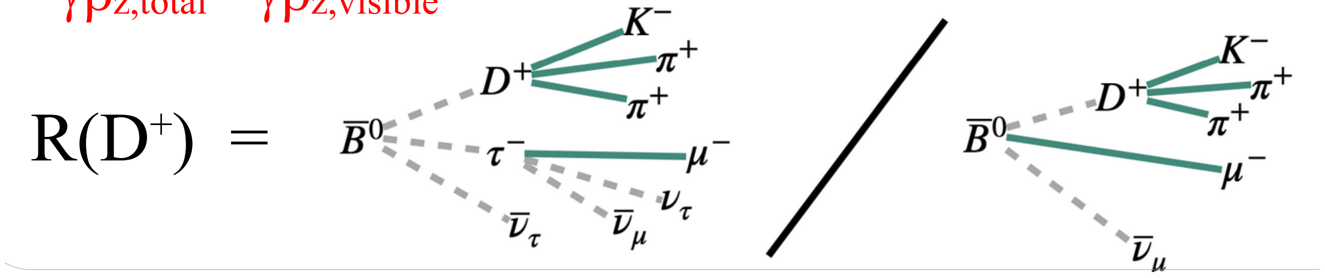
$R(D^{(*)+})$

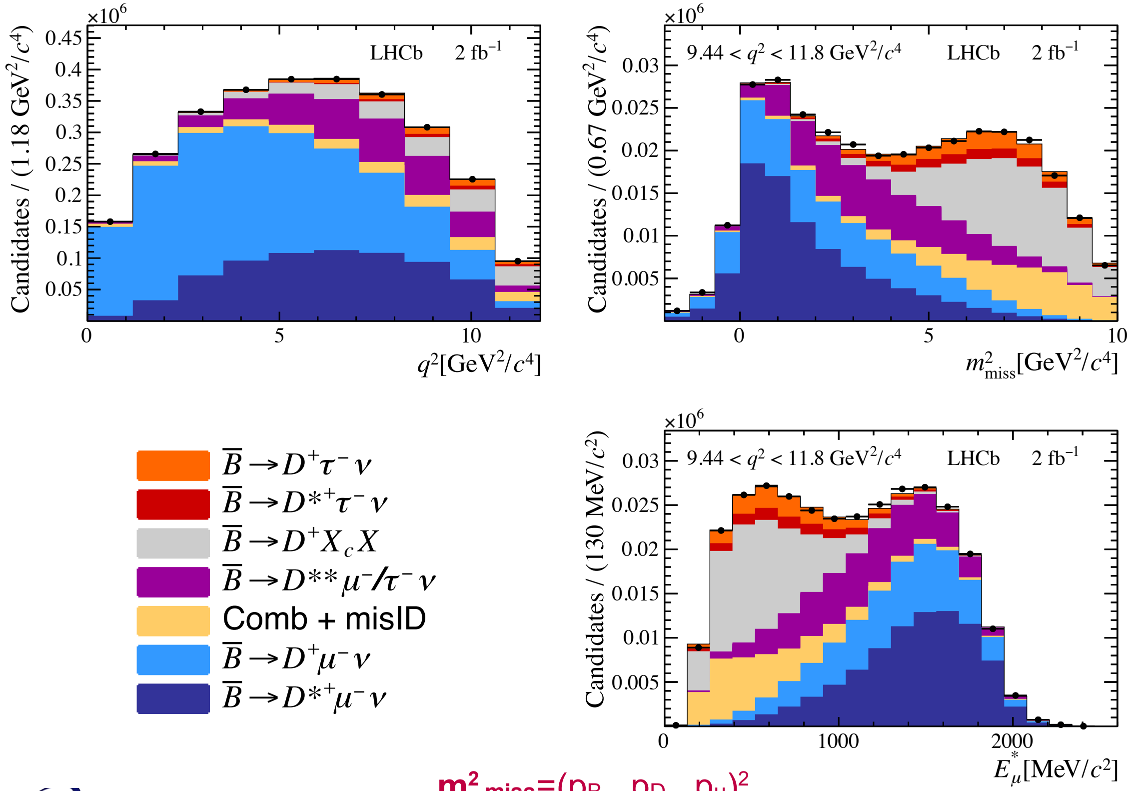
$$R(D^{(*)+}) = \frac{\mathcal{B}(B \to D^{(*)+}\tau^-\nu_{\tau^-})}{\mathcal{B}(B \to D^{(*)+}\mu^-\nu_{\mu^-})}$$

arXiv:2406.03387 (2024)
Submitted to PRL

- First LHCb measurement using the D^+ ground state
  - B momentum at LHC: exploit B flight direction and boost approximation

$\gamma\beta_{z,\text{total}} = \gamma\beta_{z,\text{visible}}$





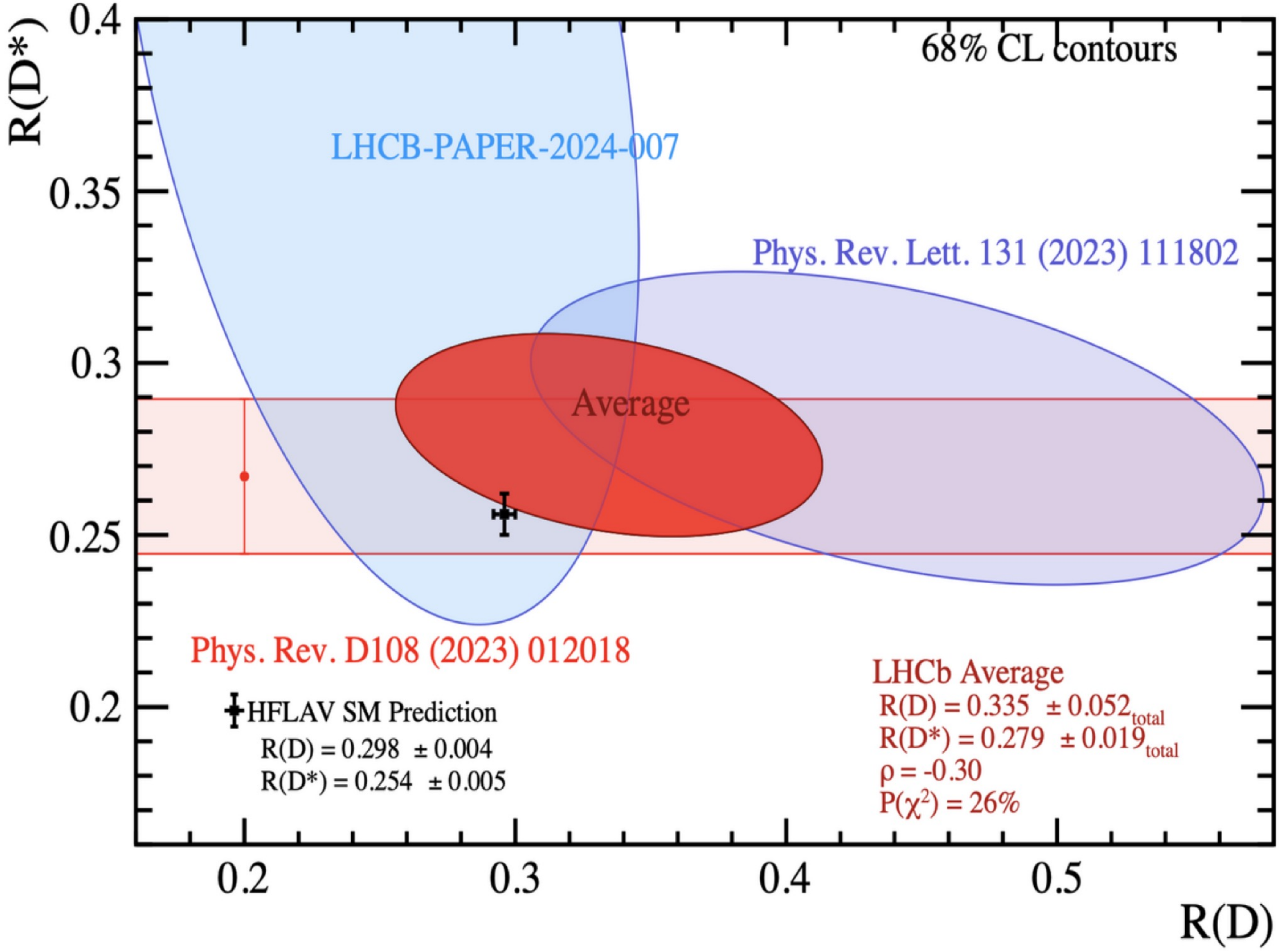
$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$
$$\rho = \text{-}0.39$$

Compatible with SM at 0.8σ and with World Average at ~1σ
Main systematic uncertainties from form factor parameters and background modeling
Uncertainty on ratio of efficiencies are sub-dominant

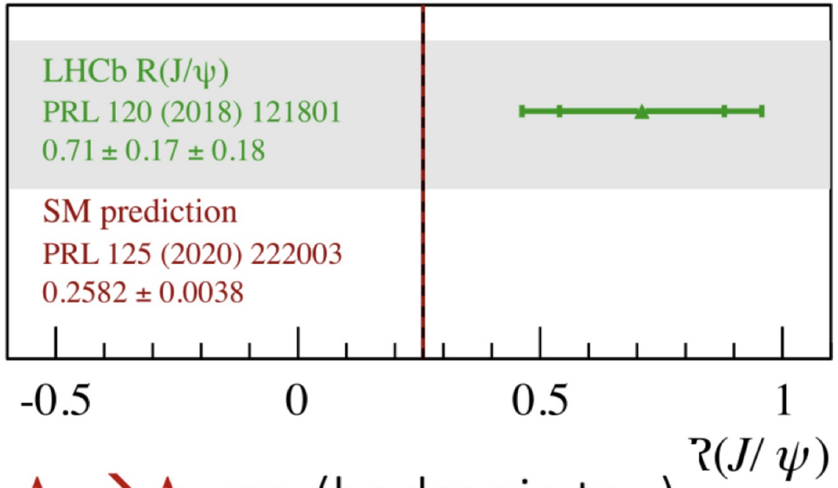
See also talk by Alex Fernez ,"Tests of Lepton Flavor Universality in tree-level B Meson Decays at LHCb" W1P4, Wed @ 8.30

$m^2_{\text{miss}} = (p_B - p_D - p_\mu)^2$
E_μ muon energy in B rest frame
$q^2 = (p_B - p_D)^2$

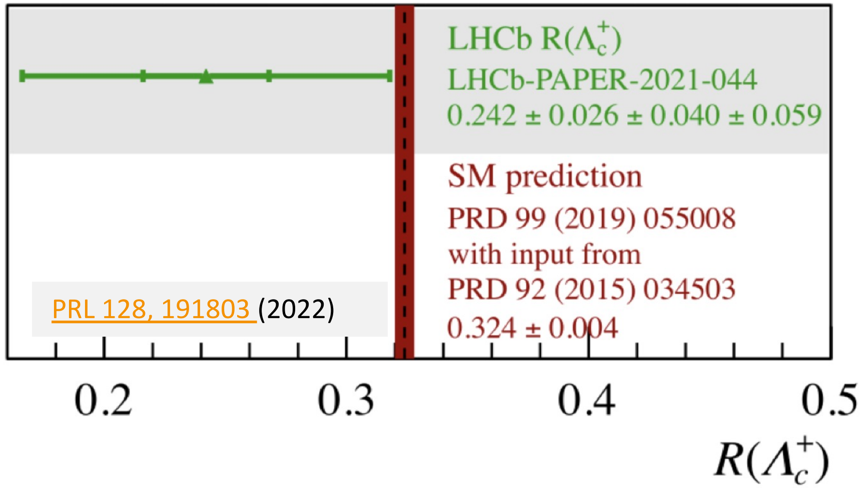
LHCb Measurements



$B_c \to J/\psi\ \tau\nu$ (muonic tau)



$\Lambda_b \to \Lambda_c\ \tau\nu$ (hadronic tau)



PRL 128, 191803 (2022)

M.Rotondo, FPCP 2024

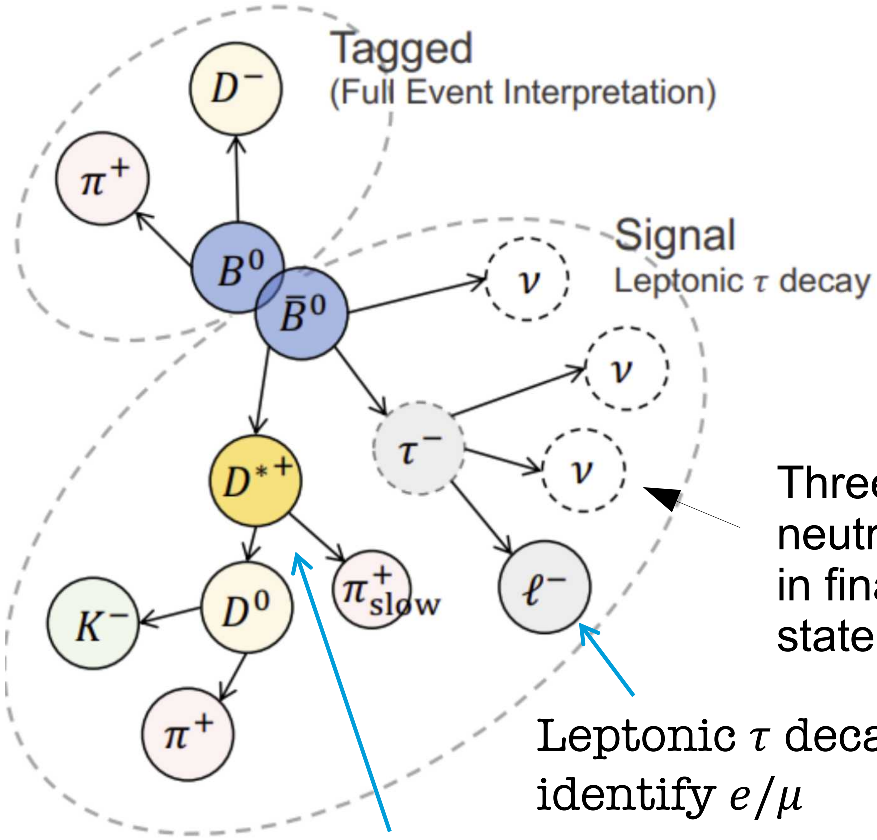
R(D*) from Belle II

- Exclusively reconstruct the hadronically-decaying tag B using “Full Event Interpretation” (FEI) method Comput Softw Big Sci 3, 6 (2019)
  - Similar methodology to previous BABAR and Belle publications
  - Fully reconstructed D*
  - Leptonic tau decay
  - Require that there are no additional charged tracks or π⁰ candidates left over
  - To extract the signal, use the residual calorimeter energy E_{ECL} and the beam-constrained missing mass

PRL 109,101802 (2012).
PRD 88, 072012 (2013).
PRL 118,211801 (2017).
PRD 97, 012004 (2018).

$$M_{\rm miss}^2 = (E^*_{\rm beam} - E^*_{D^*} - E^*_\ell)^2 - (-\vec{p}^{\,*}_{B_{\rm tag}} - \vec{p}^{\,*}_{D^*} - \vec{p}_\ell^{\,*})^2$$

  - Primary experimental challenge is to understand the significant (and poorly known) backgrounds from B → D**lν



Three neutrinos in final state

Leptonic τ decay, identify e/μ

$D^{*+} \to D^0\pi^+$ and $D^+\pi^0$
$D^{*0} \to D^0\pi^0$

arXiv:2401.02840 (subm. to PRD)

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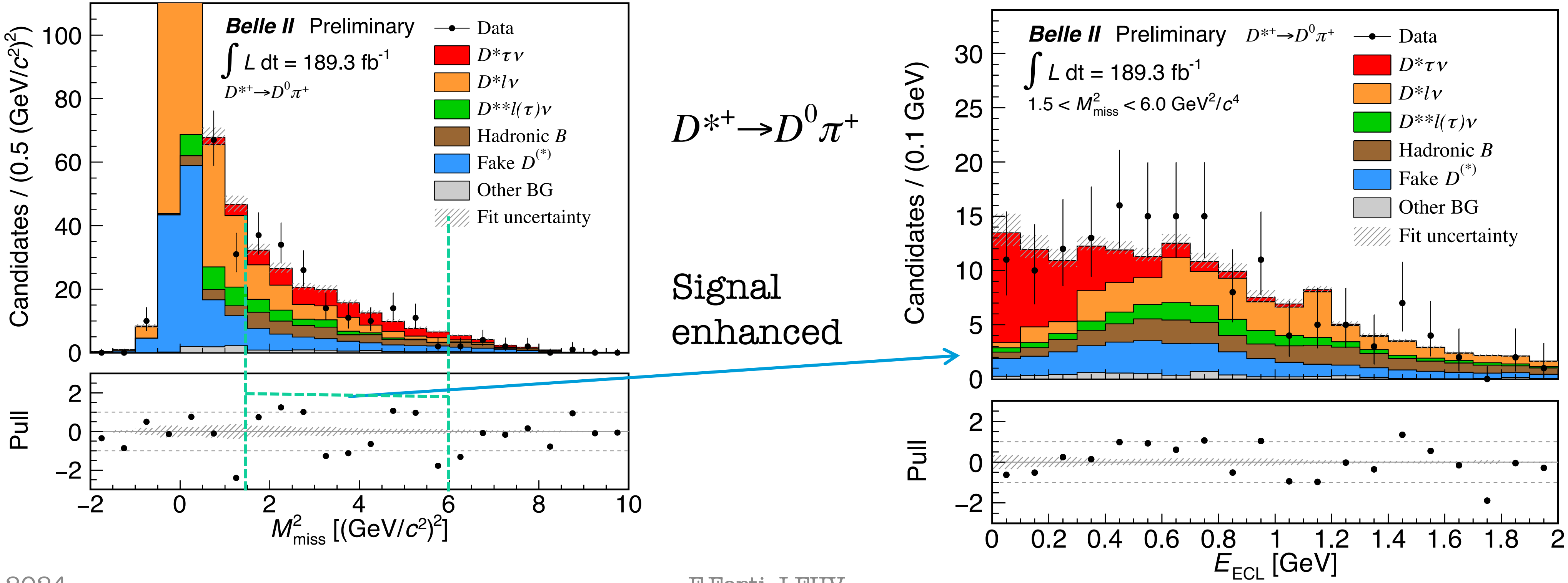
R(D*) from Belle II

- Signal extraction using 2d binned likelihood fit to E_{ECL} and M^2_{miss}.
- First R(D*) result from Belle II

$$R(D^*) = 0.262 \; {}^{+0.041}_{-0.039}(\text{stat}) \; {}^{+0.035}_{-0.032}(\text{syst})$$

  - Consistent with SM and previous results, but still fairly large statistical uncertainty

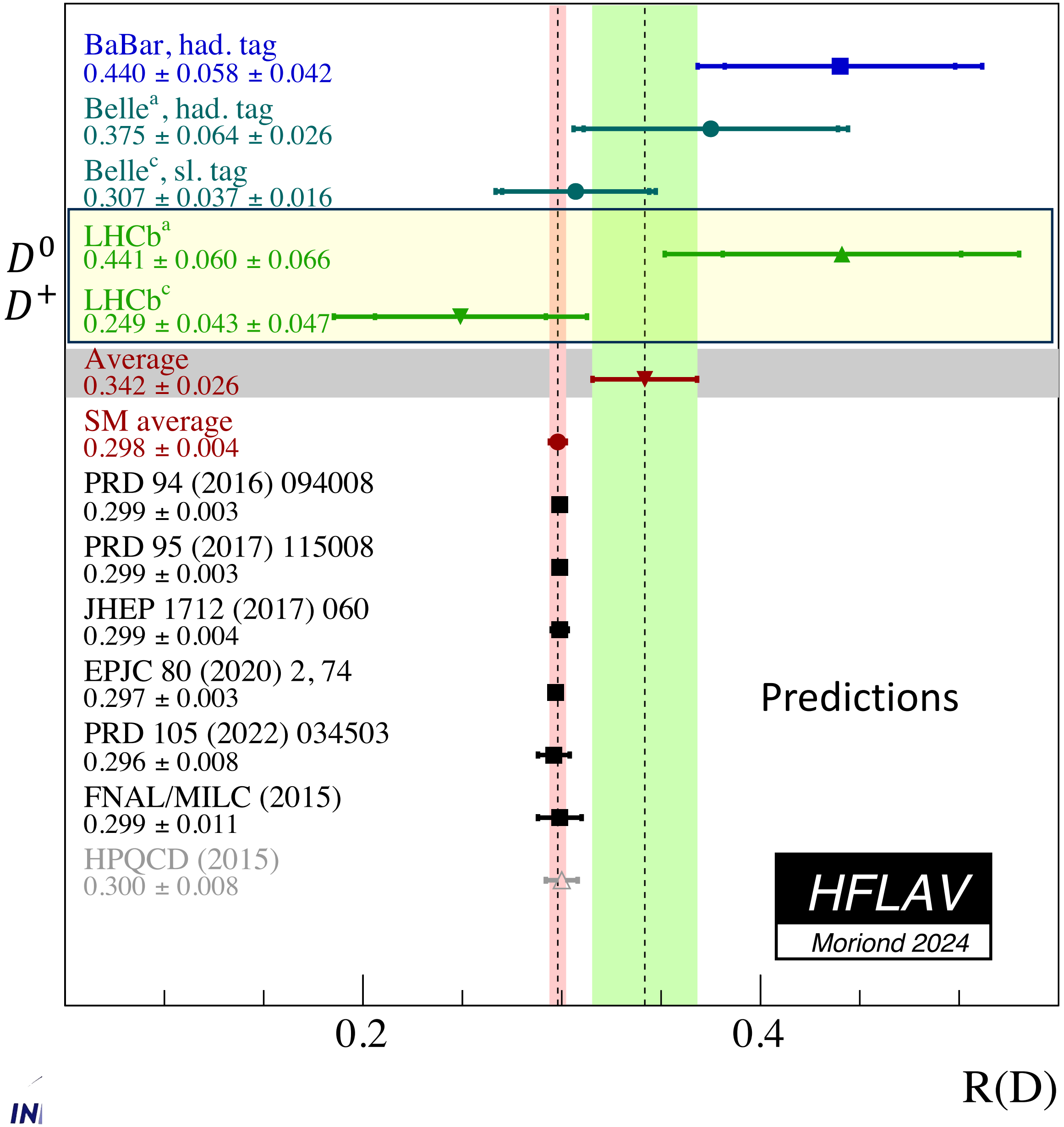
$$1.5 < M^2_{\text{miss}} < 6.0 \text{ GeV}^2/c^4$$

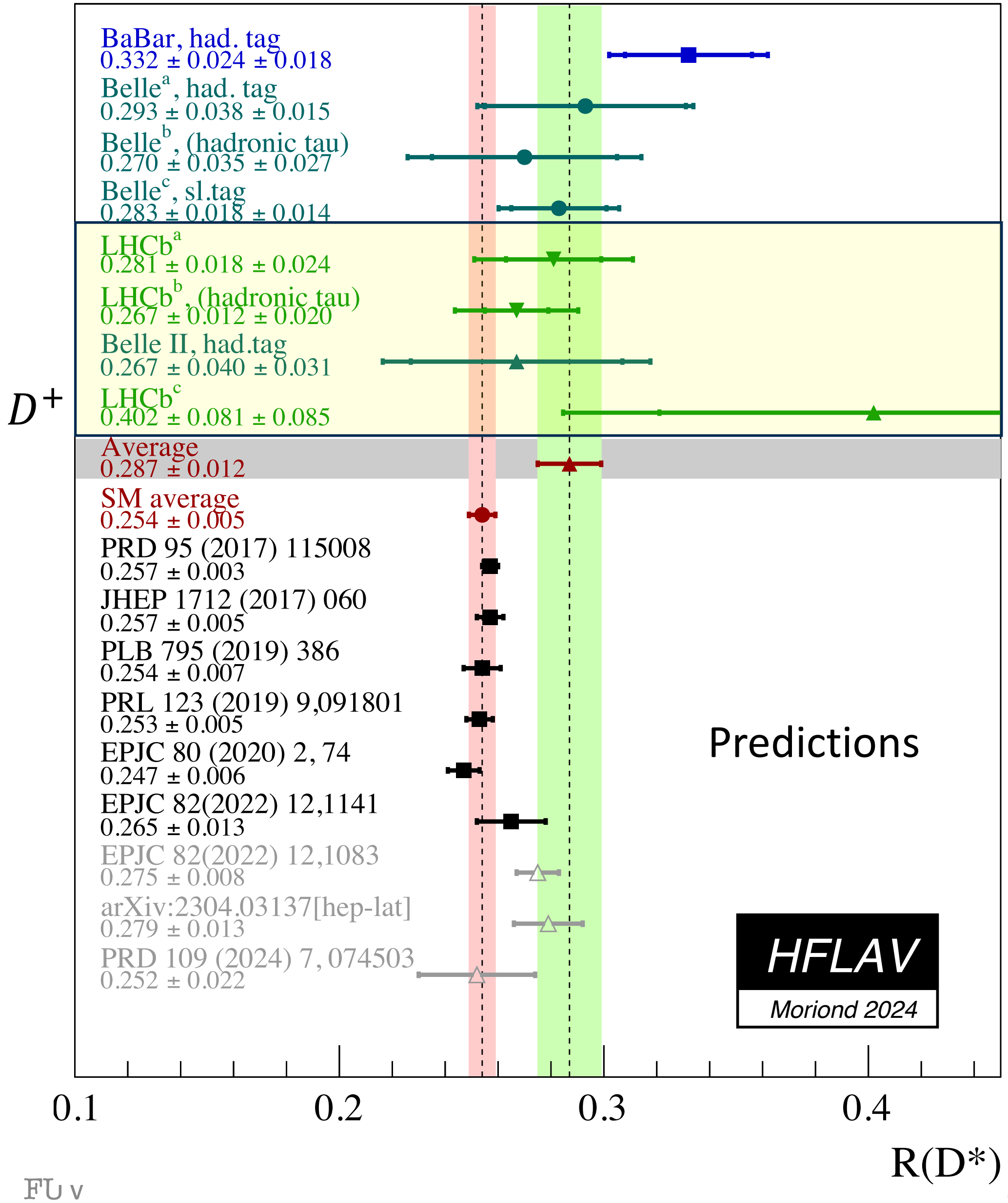


$D^{*+}\to D^0\pi^+$

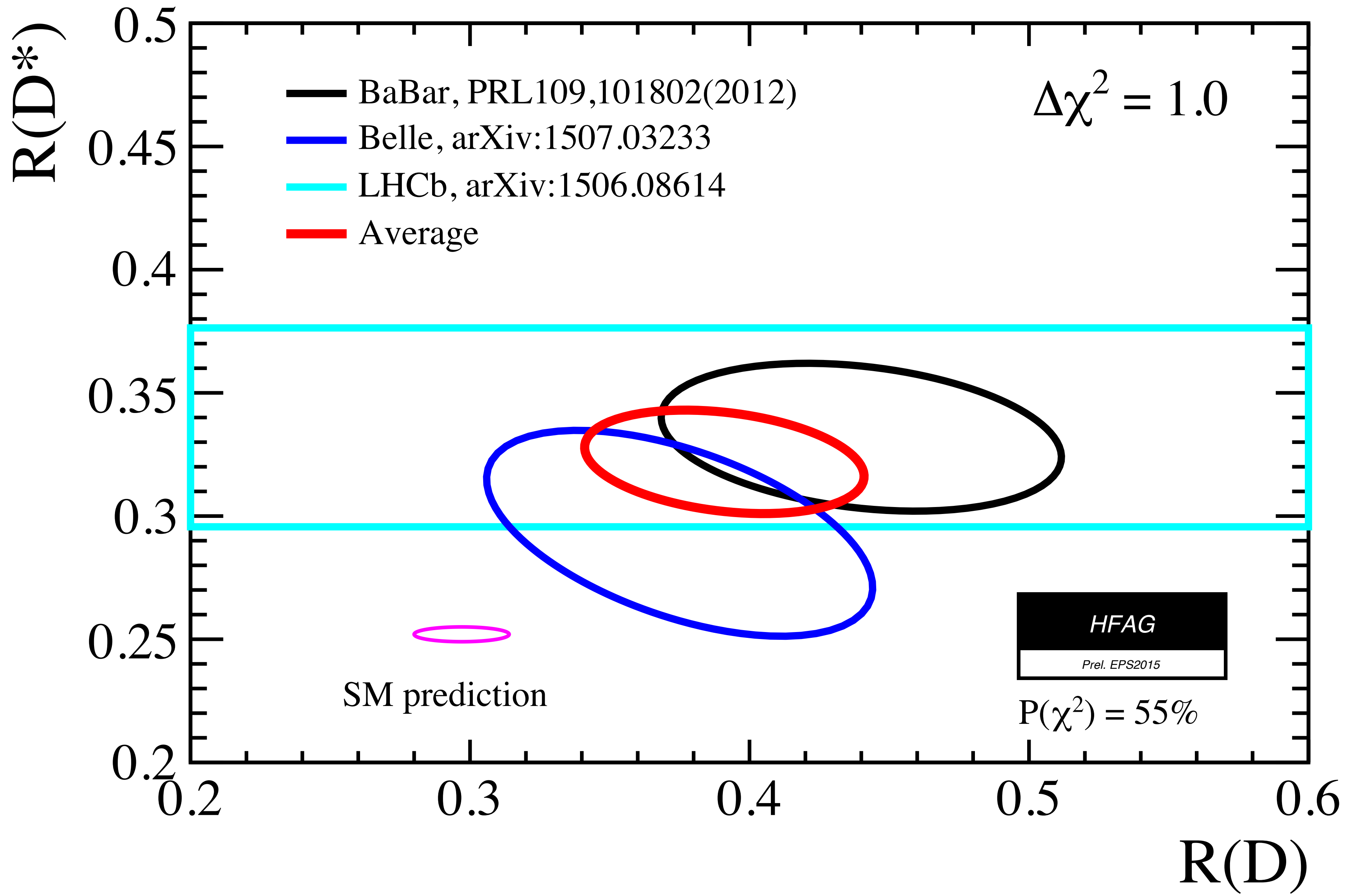
Signal enhanced

$R(D)$ & $R(D^*)$ measurements and predictions

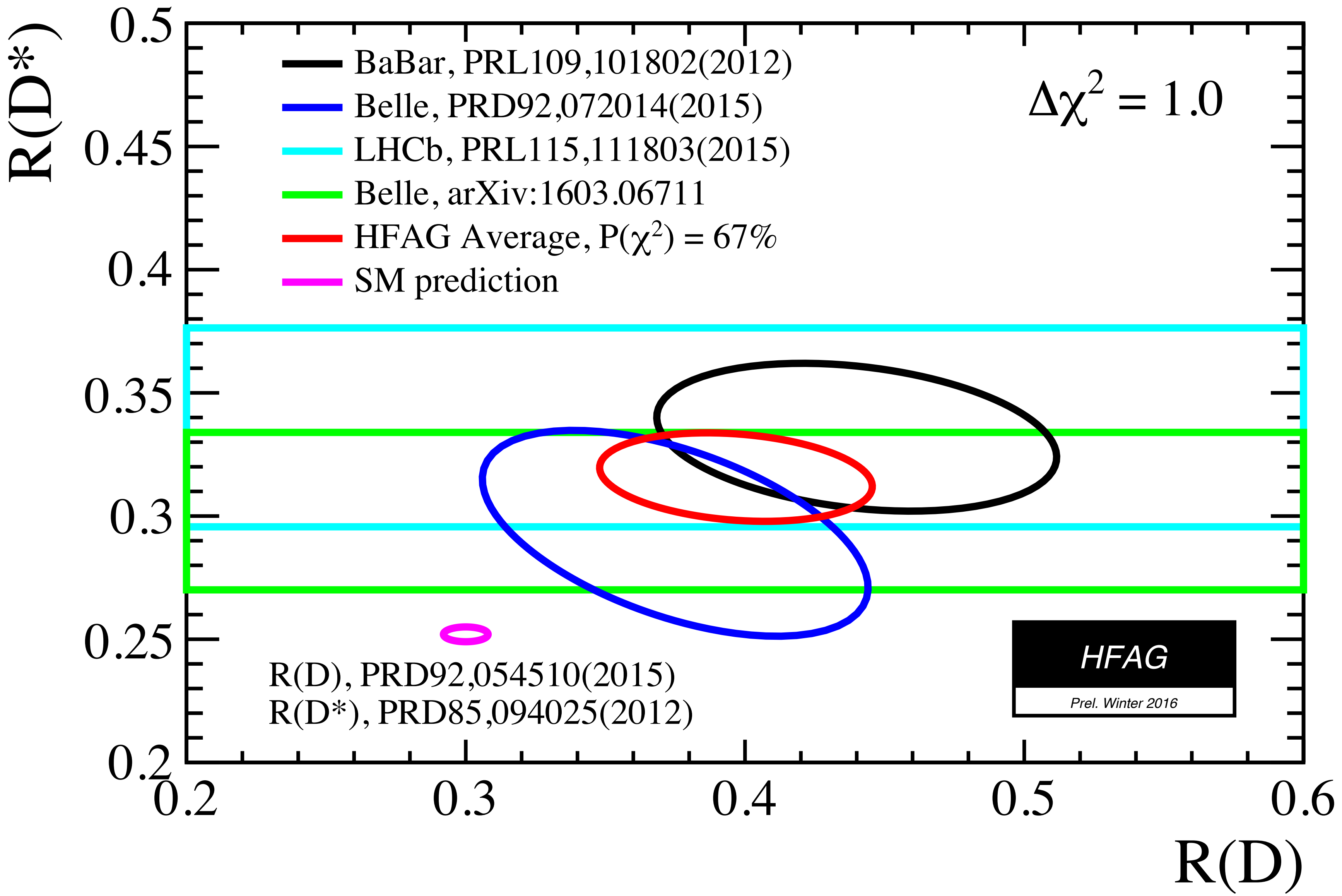




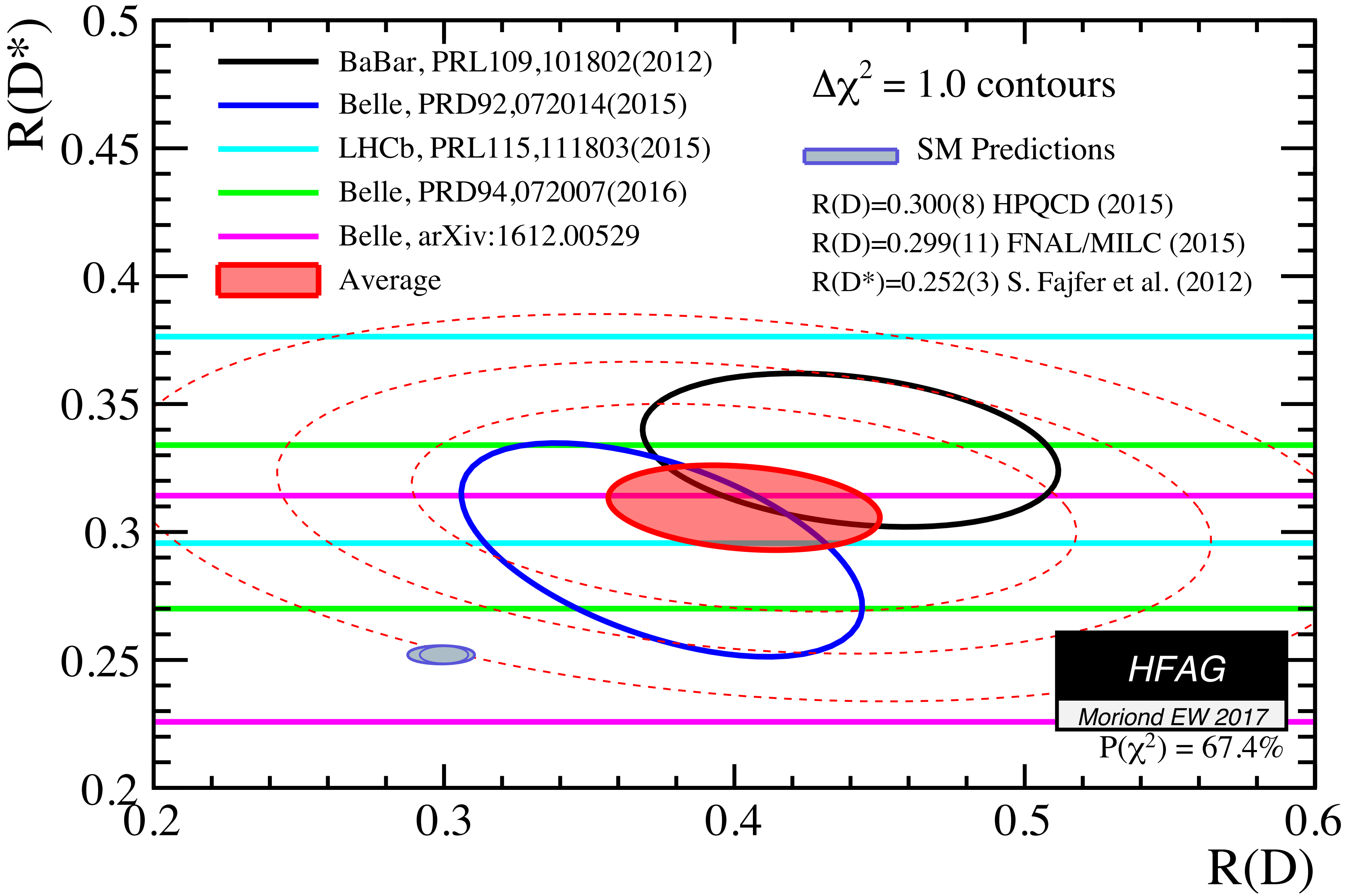
$R(D)$ & $R(D^*)$ EPS 2015



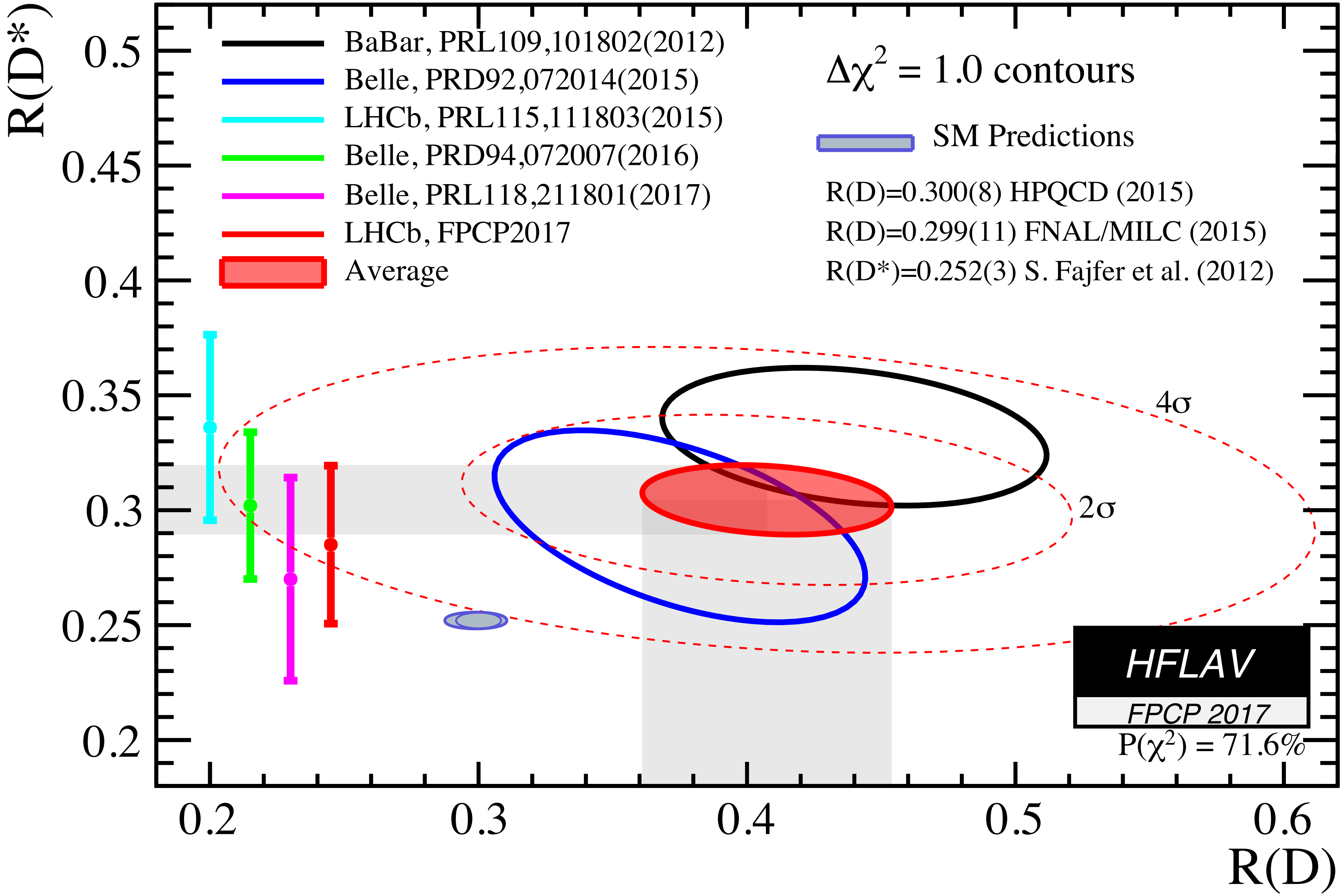
$R(D)$ & $R(D^*)$Winter 2016



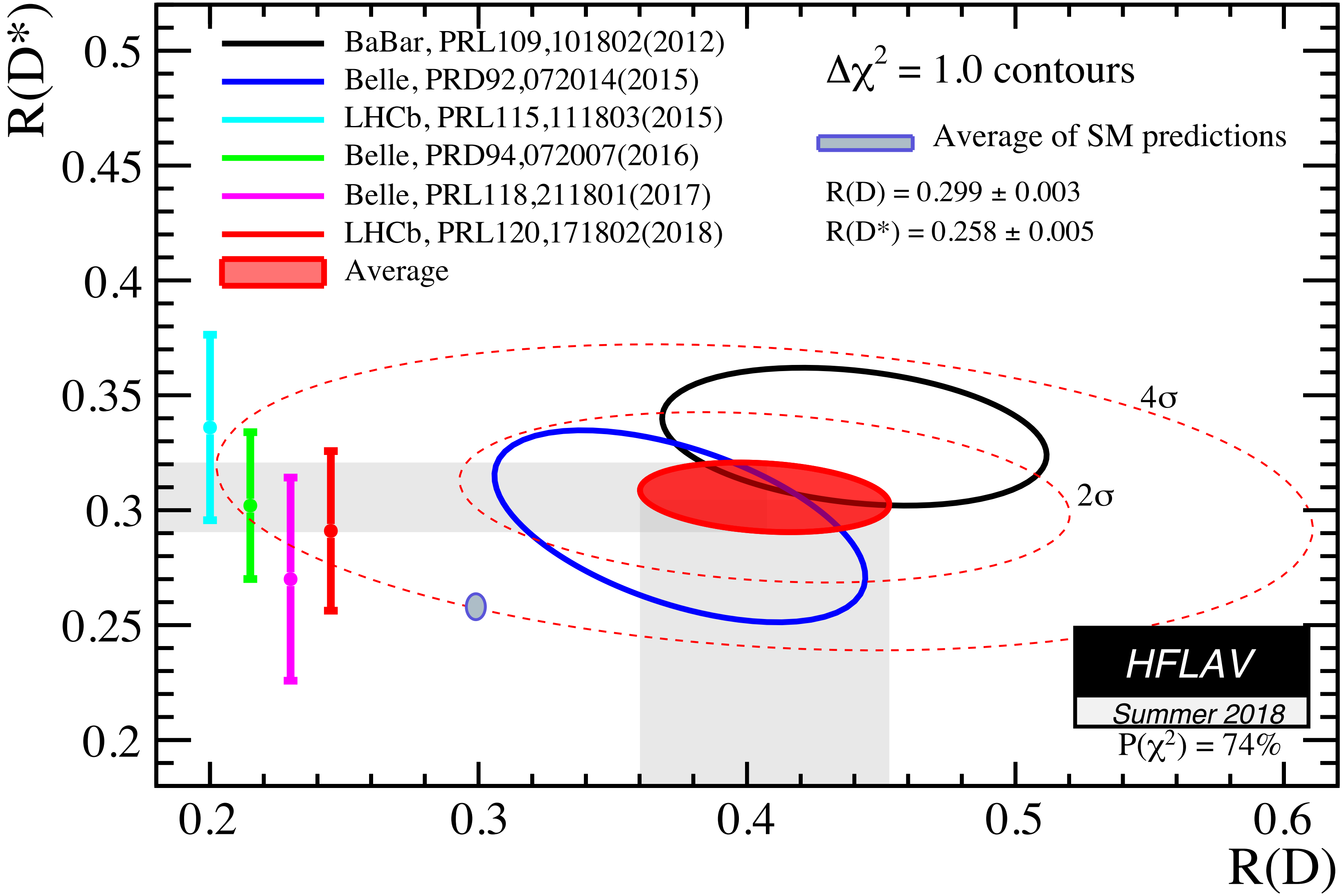
$R(D)$ & $R(D^*)$ Moriond 2017



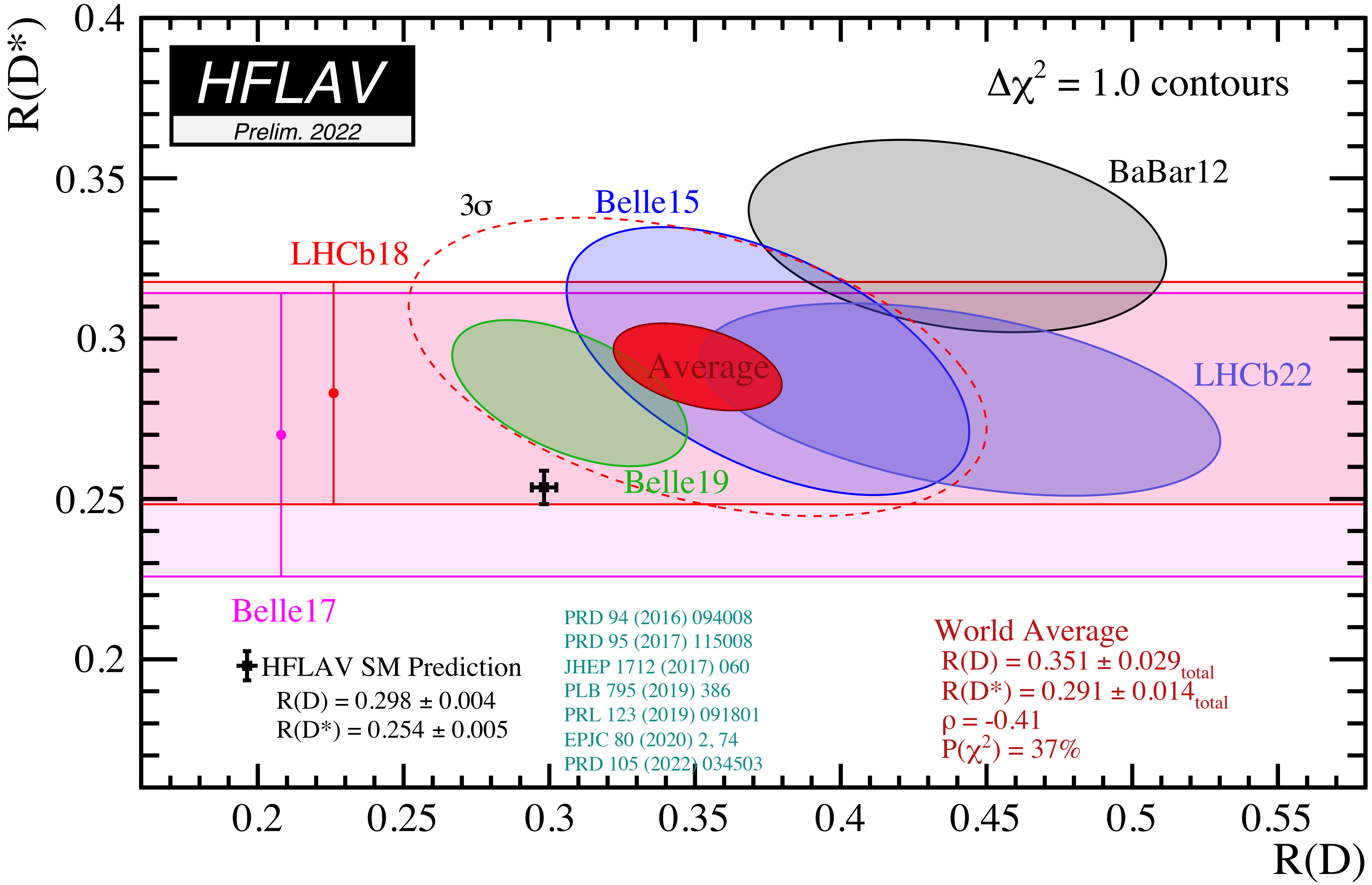
$R(D)$ & $R(D^*)$ FPCP 2017



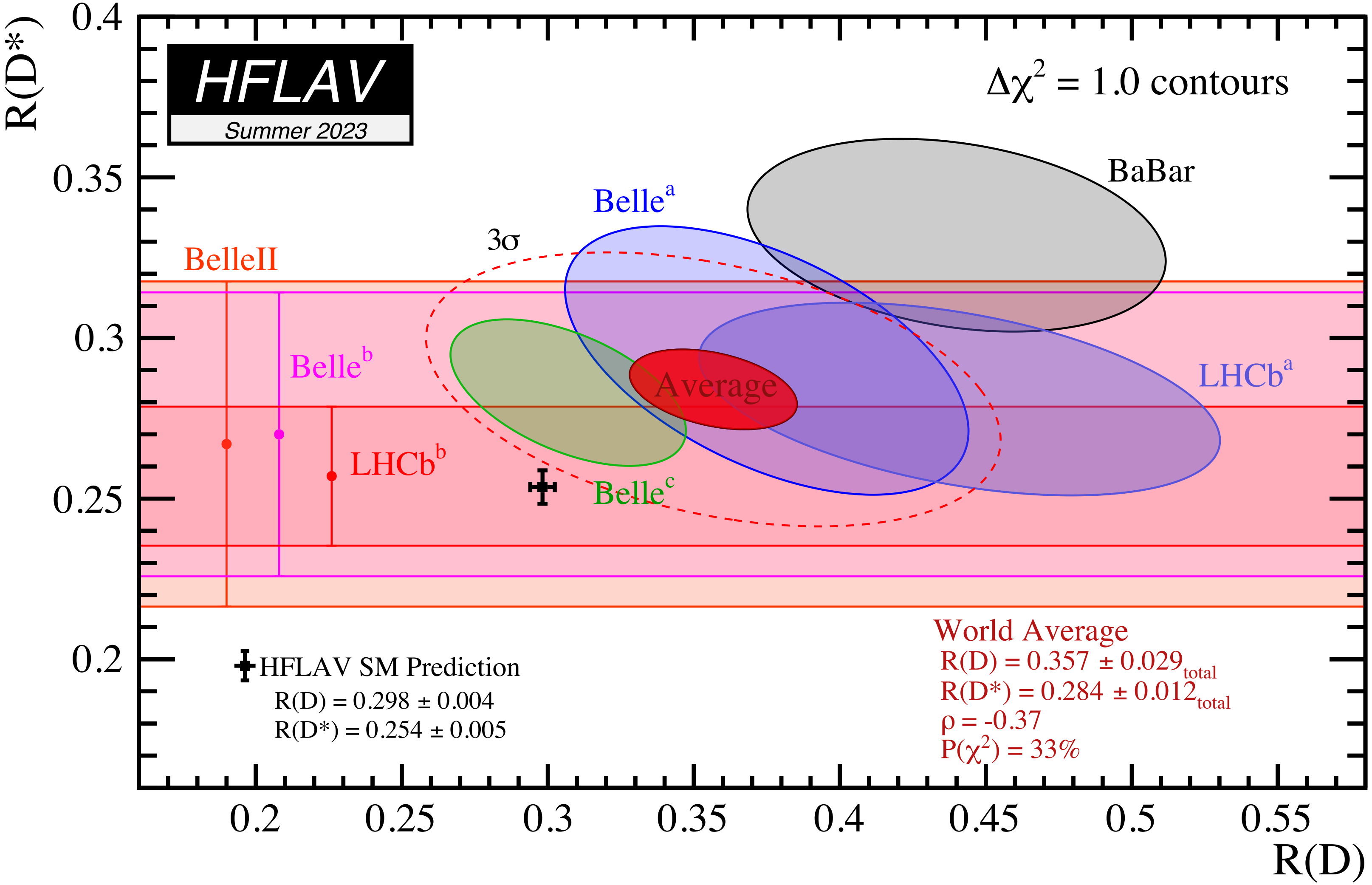
$R(D)$ & $R(D^*)$ Summer 2018



$R(D)$ & $R(D^*)$ Fall 2022



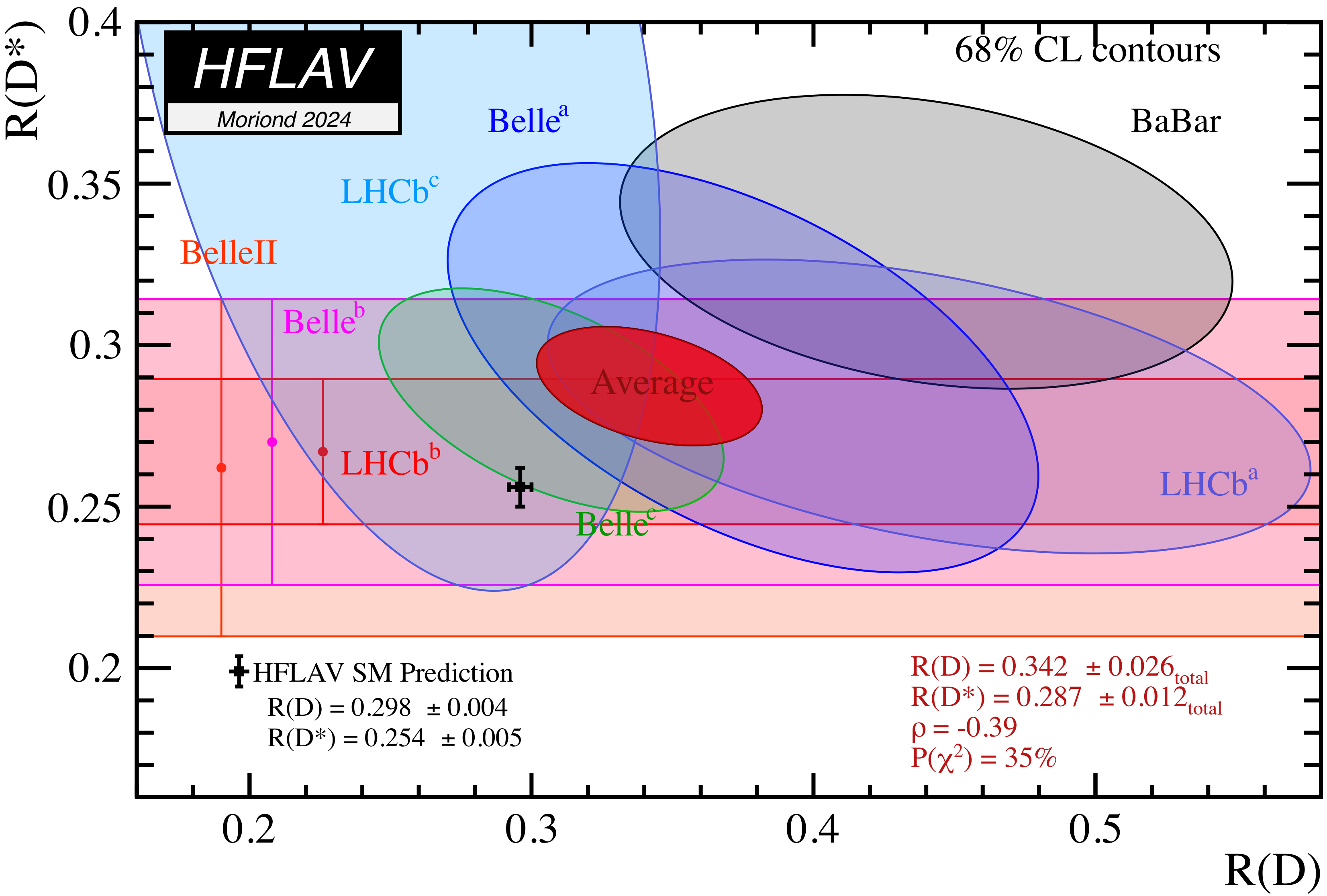
$R(D)$ & $R(D^*)$ Summer 2023



$R(D)$ & $R(D^*)$

HFLAV

- R(D) and R(D*) combined average
  - 3.31 σ tension with the SM prediction considering the correlation
- Is the SM prediction stable?
  - R(D): predictions consistent
  - R(D*): tensions between some of the calculations



Inclusive R(X)

PRL 131, 051804 (2023) e/μ
PRL 132, 211804 (2024) τ/ℓ

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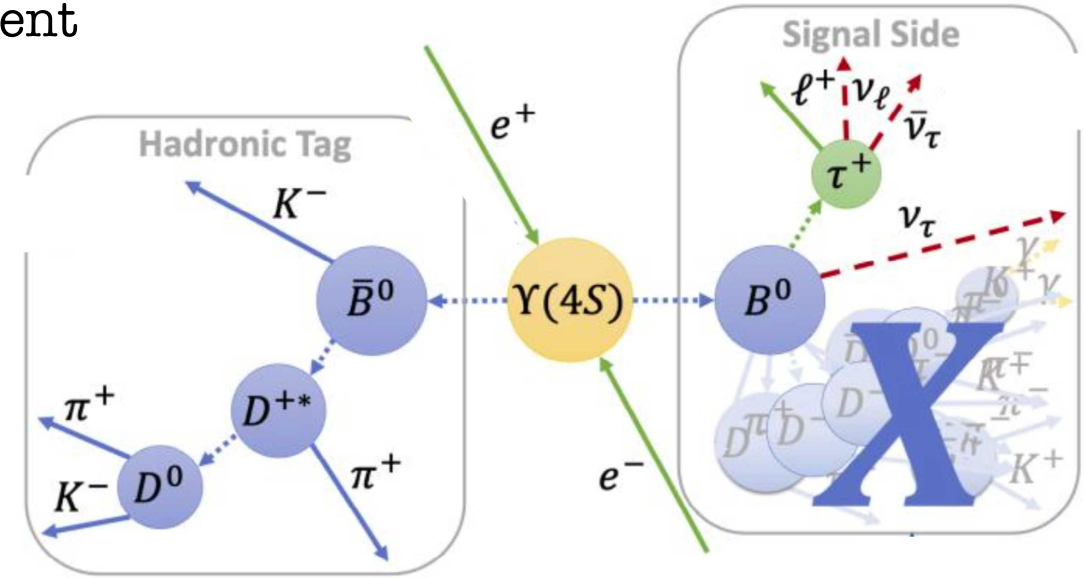
- Possible to compare the inclusive rates
- Tag B reconstructed using FEI method
- Search for the signal B in the rest of the event
  - Leptonic $\tau \to e/\mu\bar{\nu}\nu$ decay
  - Remaining reconstructed particles in the event form the hadronic system “X”
  - Additional experimental challenge due to unspecified hadronic “X” system
- Primary experimental challenge is modelling/ characterizing backgrounds:
  - B→Xlν (l=e,μ)decays
  - Generic $B\bar{B}$ events with mis-reconstruction
  - Continuum $q\bar{q}$ events

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

$$e : p_T/p_{\mathrm{lab}} > 0.3\,\mathrm{GeV}/0.5\,\mathrm{GeV}$$
$$\mu : p_T/p_{\mathrm{lab}} > 0.4\,\mathrm{GeV}/0.7\,\mathrm{GeV}$$

To reject misidentifed lepton

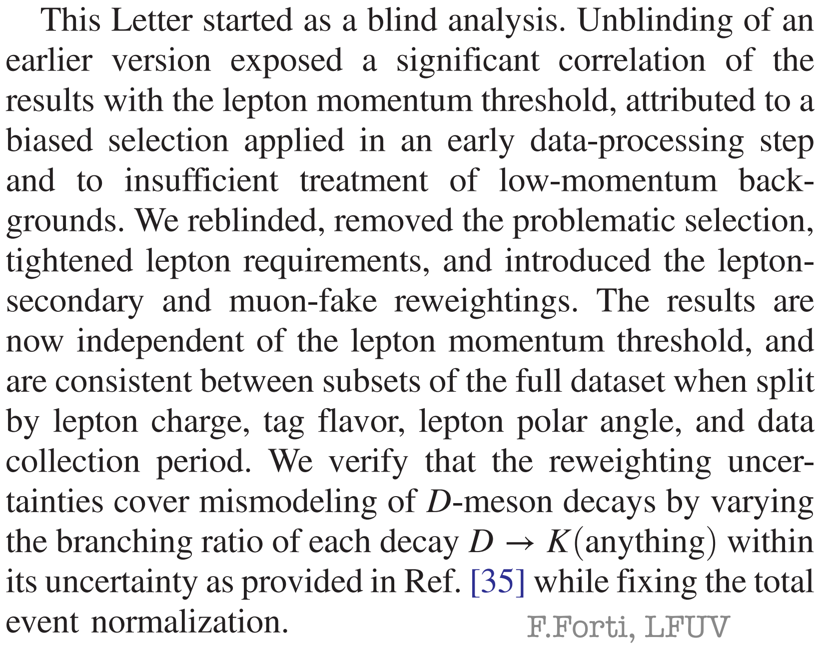


Inclusive R(X)

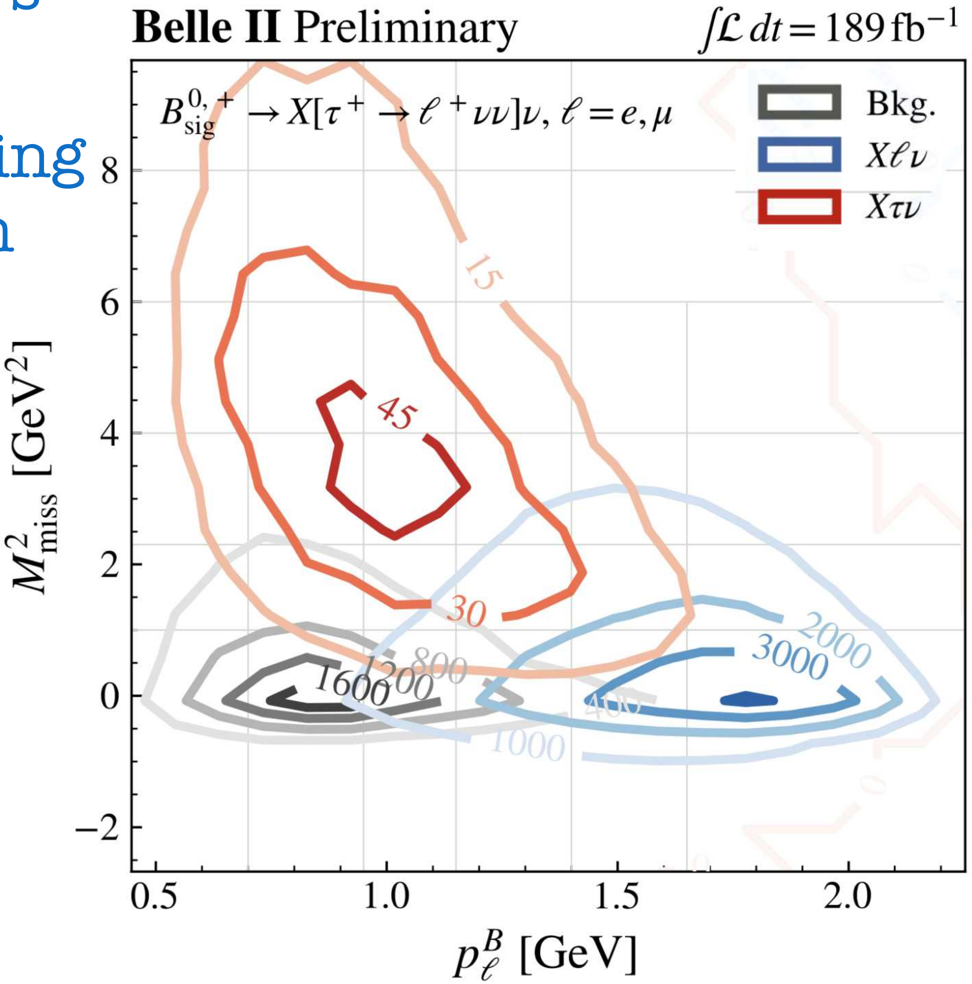
PRL 131, 051804 (2023) e/μ
PRL 132, 211804 (2024) τ/ℓ

189 fb^{-1}

- Signal determined from 2D distribution of p_ℓ^B vs M^2_{miss}
- Data-driven $X\ell\nu$ modelling and reweighting using M_X distribution in $p_\ell^B > 1.4\ GeV$ sideband region
- Systematics dominated by data-driven corrections to background and signal modelling
- Life is hard:



This Letter started as a blind analysis. Unblinding of an earlier version exposed a significant correlation of the results with the lepton momentum threshold, attributed to a biased selection applied in an early data-processing step and to insufficient treatment of low-momentum backgrounds. We reblinded, removed the problematic selection, tightened lepton requirements, and introduced the lepton-secondary and muon-fake reweightings. The results are now independent of the lepton momentum threshold, and are consistent between subsets of the full dataset when split by lepton charge, tag flavor, lepton polar angle, and data collection period. We verify that the reweighting uncertainties cover mismodeling of D-meson decays by varying the branching ratio of each decay $D \to K(\text{anything})$ within its uncertainty as provided in Ref. [35] while fixing the total event normalization.



Inclusive R(X) results

PRL 131, 051804 (2023) e/μ
PRL 132, 211804 (2024) τ/ℓ

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$$R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat}) \pm 0.019(\text{syst})$$

$$\boxed{\begin{aligned} R(X_{\tau/e}) &= 0.232 \pm 0.020(\text{stat}) \pm 0.037(\text{syst}), \\ R(X_{\tau/\mu}) &= 0.222 \pm 0.027(\text{stat}) \pm 0.050(\text{syst}), \end{aligned}}$$

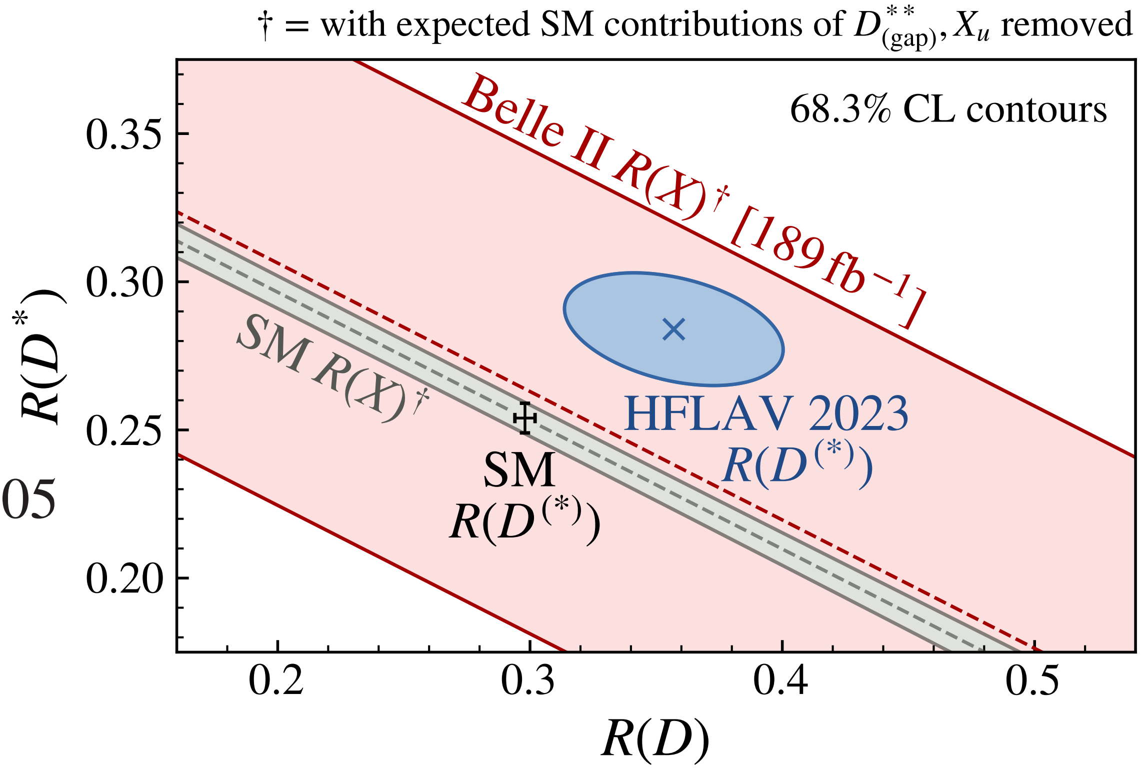
Combined

$$\boxed{R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst})}$$

Average of SM expectation: 0.223 ± 0.005

PRD 105, 073009 (2022)
JHEP 11 007 (2022)

Limited by systematics, even with smallish data set



Main sources of syst. uncertainties: $X_c\ell\nu$ M_X shape: 7.1%, $\mathscr{B}(B \to X\ell\nu)$:7.7%, $X_c\tau(\ell)\nu$ form factors: 7.8%

PRL 131, 181801 (2023)

Angular analysis

189 fb-1

- Rich phenomenology due to different decay amplitudes encoded in angular distributions (3 angles) as a function of the recoil energy of the D^*
- measure 5 angular asymmetries and **compare them for e/μ** in 2 bins of w ($1 \leq w_{low} \leq 1.275, 1.275 < w_{high} \leq 1.503$)

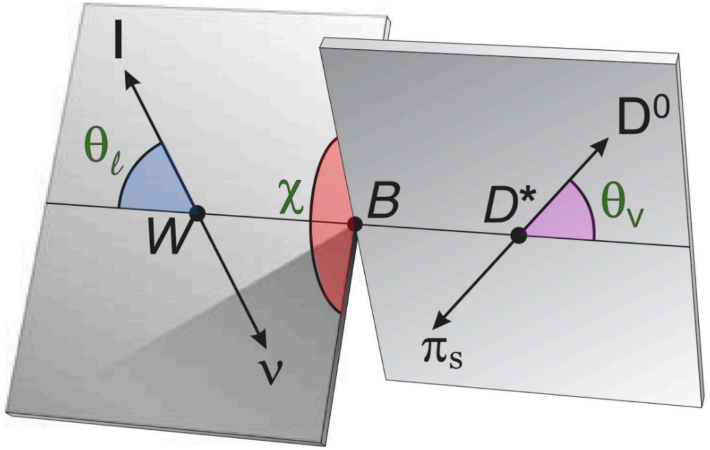
$$\mathcal{A}_x(w) \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}w}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right]\mathrm{d}x\,\frac{\mathrm{d}^2\Gamma}{\mathrm{d}w\mathrm{d}x}$$

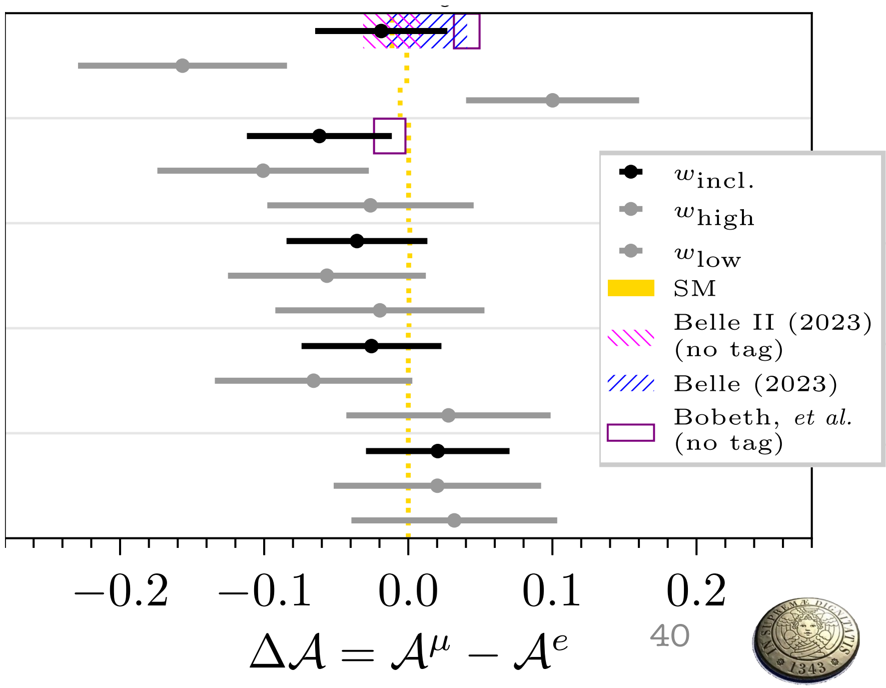
$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

with $x = \cos\theta_\ell$ for A_{FB}, $\cos 2\chi$ for S_3, $\cos\chi\cos\theta_V$ for S_5, $\sin\chi\cos\theta_V$ for S_7, and $\sin 2\chi$ for S_9, as illustrated in the

A_{FB}: tendency of the lepton to travel along the W direction
S_3, S_9 : sensitive to alignment of lepton and D* direction
S_5, S_7 : measure coupled alignments in the orientation of the D wrt the D*

- All asymmetry measurements are statistics limited.
- Compatible with SM, no evidence for LFU violation.





Angular coefficients

arXiv: 2310.20286 (2023)
Accepted by PRL

711 fb^{-1}

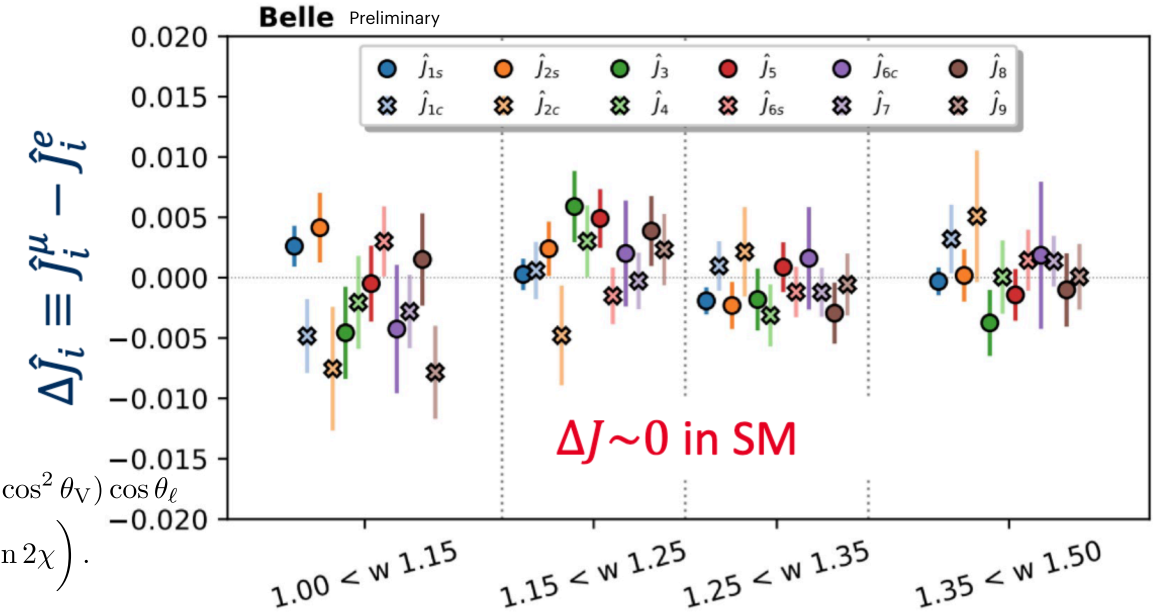
- The differential decay rate can be decomposed in a basis of angular functions with 12 coefficients J_i all dependent on w
  - Measure J_i in four bins of w
  - Reconstruct D meson in different modes: , D → KK D → KK(n)π, D → K(n)π

Difference between electron and muon sensitive to LFU: $\Delta J_i = J_i^{\mu} - J_i^{e}$.

Difference between electron and muon sensitive to LFU: $\Delta J_i = J_i^{\mu} - J_i^{e}$

No significant deviation from the SM

$$\frac{\mathrm{d}\Gamma(\bar{B} \to D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w\, \mathrm{d}\cos\theta_\ell\, \mathrm{d}\cos\theta_\mathrm{V}\, \mathrm{d}\chi} = \frac{2G_\mathrm{F}^2 \eta_\mathrm{EW}^2 |V_\mathrm{cb}|^2 m_B^4 m_{\mathrm{D}^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_\mathrm{V} + J_{1c} \cos^2\theta_\mathrm{V}$$
$$+ (J_{2s} \sin^2\theta_\mathrm{V} + J_{2c} \cos^2\theta_\mathrm{V}) \cos 2\theta_\ell + J_3 \sin^2\theta_\mathrm{V} \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s} \sin^2\theta_\mathrm{V} + J_{6c} \cos^2\theta_\mathrm{V}) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_\mathrm{V} \sin^2\theta_\ell \sin 2\chi \Big).$$



Conclusions

- Lepton Flavour Universality Violation provides powerful tools for exploration of physics beyond standard model
- Experimentally challenging analyses, many channels tried
- Many new results, and more analyses ongoing, just scratching the surface
- Common effort with theory to improve the interpretation of the results and the SM expectations
- Tension with SM has been shrinking with more data and improved analysis

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