university of groningen / faculty of science and engineering / van swinderen institute for particle physics and gravity

Nikhef

# Lepton Universality Violation


Gerco Onderwater

*on behalf of the LHCb collaboration*


LHCb


CIPANP2018, Palm Springs, CA, USA, 29 May – 3 June 2018

# Outline

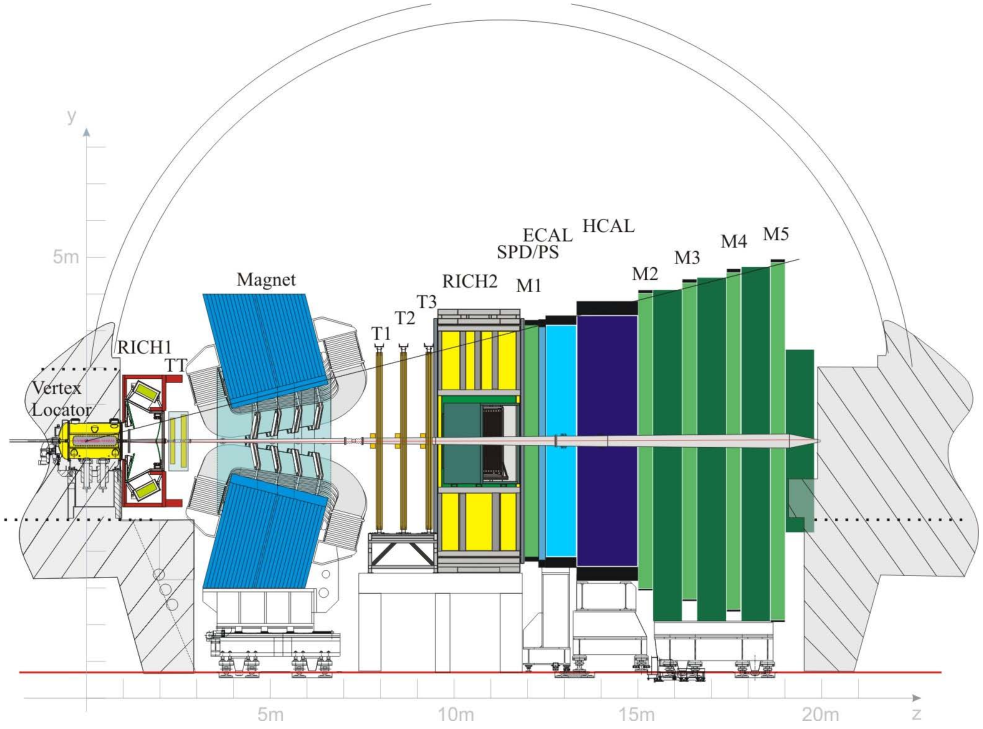
Introduction

EM interaction

NC weak interaction

CC weak interaction

Conclusion



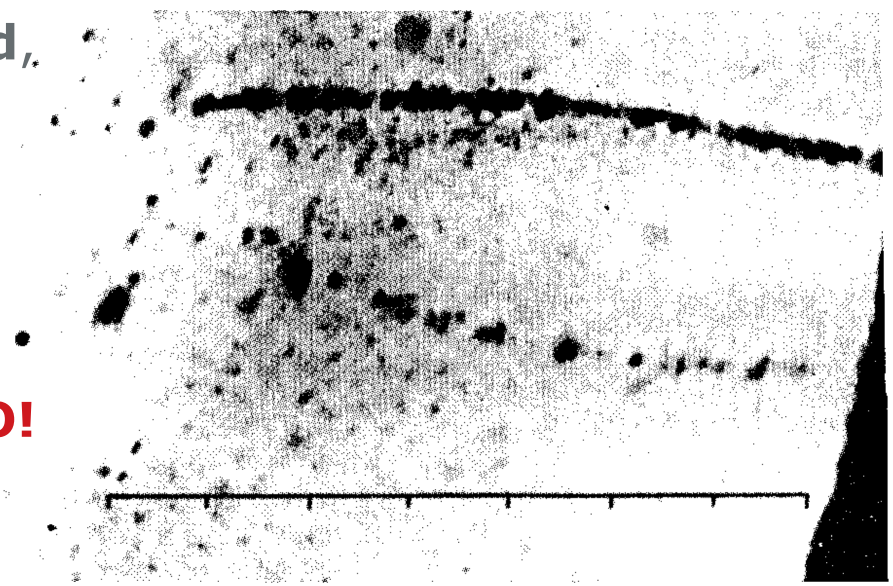
# Intro

# Discovery of leptons

Electron found by **Thomson**, **Townsend**, **Wilson** (1896)

Muon found by **Kunze** (1933), identified by **Neddermeyer** & **Anderson** (1937)

Mass between electron and proton → "mesotron" → **Yukawa's** particle? **NO!**



"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a ...osion".

Kunze, P., Z. Phys. 83, (1933) 1

**Rabi**[*]: "Who ordered that?!"

**What is it?**

**Note on the Nature of Cosmic-Ray Particles**

SETH H. NEDDERMEYER AND CARL D. ANDERSON
*California Institute of Technology, Pasadena, California*

(Received March 30, 1937)

# Lepton Numbers

**Konopinski** & **Mahmoud** (1953) propose conserved lepton number **L** to explain missing decays

Allows **$\mu \rightarrow e + \gamma$** → not observed …

**The Universal Fermi Interaction***

E. J. Konopinski and H. M. Mahmoud
*Physics Department, Indiana University, Bloomington, Indiana*
(Received July 24, 1953)

**Pontecorvo** (1959) : $L_\mu$ and $L_e$ different

$$\nu_\ell + n \rightarrow \ell^- + p$$

Muon neutrino discovered in 1962 by **Lederman**, **Schwartz**, & **Steinberger**, later τ **Perl et al.** (1975), and $\nu_\tau$ **DONUT** (2000)

$$L = L_e + L_\mu + L_\tau$$

**Electron, muon, tau differ by mass, otherwise identical**



doi.org/10.1103/PhysRev.92.1045
Schwartz, Nobel Lecture

# Lepton Flavor Universality

$$\begin{bmatrix} \nu_l & q_u \\ l^- & q_d \end{bmatrix}$$

3 families → many arbitrary SM variables

→ rich phenomenology (CPV, flavor oscillations, ...)

**Same gauge interactions for all flavors → UNIVERSALITY**

no fundamental reason for universality

only difference: mass & flavor quantum number

everything else determined by these two → precise predictions

**Understanding flavor might be key to understand nature**

**Leptons: no internal structure → easier analysis & theory**

# Charged Lepton Properties

| Particle | Mass [MeV] | Lifetime | Main Decay |
| --- | --- | --- | --- |
| e | 0.5109989461(31) | >6.6x10$^{28}$ yr | – |
| μ | 105.6583745(24) | 2.1969811(22) μs | $e^- \bar{\nu}_e \nu_\mu$ |
| τ | 1776.86(12) | 290.3(5) fs | $\mu^- \bar{\nu}_\mu \nu_\tau$ (17%)<br>$e^- \bar{\nu}_e \nu_\tau$ (18%)<br>$\pi^- \bar{\nu}_\tau$ (11%)<br>$\pi^-\pi^+\pi^- \bar{\nu}_\tau$ (9%) |

**How precisely do we know that the underlying interactions are identical for three lepton generation?**



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$$\gamma$$

# Lepton-photon coupling

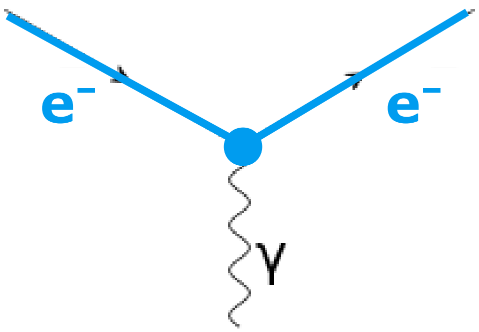
General description involves three form factors

$$T[l\bar{l}\gamma^*] = e\,\varepsilon_\mu(q)\,\bar{l}\left[F_1(q^2)\gamma^\mu + i\frac{F_2(q^2)}{2m_l}\sigma^{\mu\nu}q_\nu + \frac{F_3(q^2)}{2m_l}\sigma^{\mu\nu}\gamma_5 q_\nu\right] l$$

@ $q^2 = 0$ **Q** **aMDM** **EDM**

**Some explored avenues**

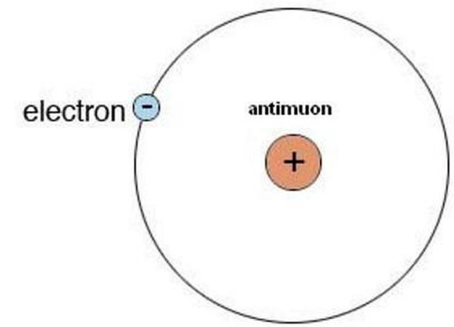
1. muonium $M(e^-\mu^+)$ 1s–2s
2. $^{e}H$ vs $^{\mu}H$ spectroscopy
3. MDM (**e**, **μ**)
4. EDM (**e**, **μ**)
5. $e^+e^- \to \gamma \to \ell^+\ell^-$ (**e**, **μ**, **τ**)
6. quarkonium decay $q\bar{q} \to \gamma \to \ell^+\ell^-$ (**e**, **μ**, (**τ**))





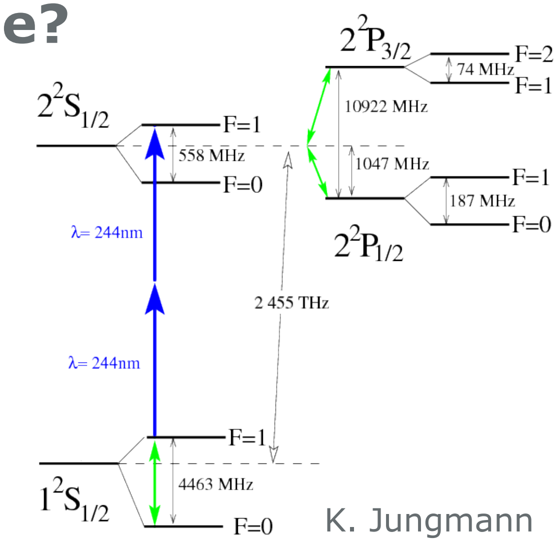

arXiv:hep-ph/9701263

# $F_1$ : Charge Equality




Electric charge : coupling to photon → EM coupling

**Are the electron and muon charge the same?**




K. Jungmann

Muonium **M($\mu^+e^-$)** 1s–2s interval **$\Delta\nu \sim [Q_\mu Q_e/n]^2$**

$\Delta\nu_{1s2s}(\text{expt}) = 2\ 455\ 528\ 941.0(9.8)$ MHz

$\Delta\nu_{1s2s}(\text{theo}) = 2\ 455\ 528\ 935.4(1.4)$ MHz

$$Q_\mu Q_e = -1 - 1.1(2.1)\cdot 10^{-9*}$$

***given $m_\mu/m_e$**

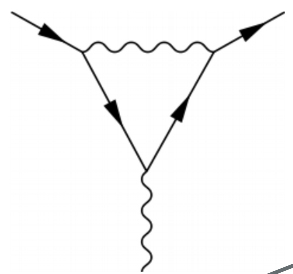

doi.org/10.1103/PhysRevLett.84.1136

# $F_2$ : Anomalous Magnetic Moment

$$a_e^{exp} \simeq a_e^{QED} = 0.001\ 159\ 652\ 180\ 73(28)$$

Recently 2x more precise measurement via 133-Cs recoil

$$\alpha$$

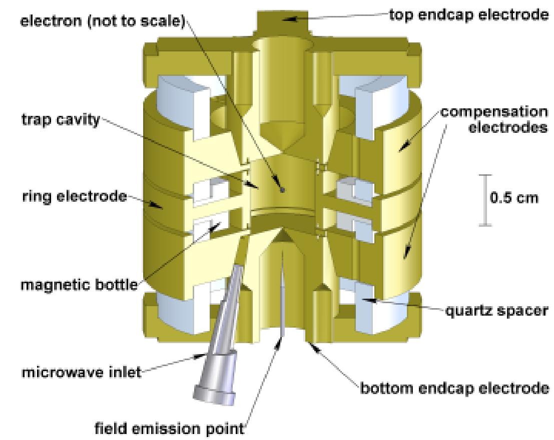


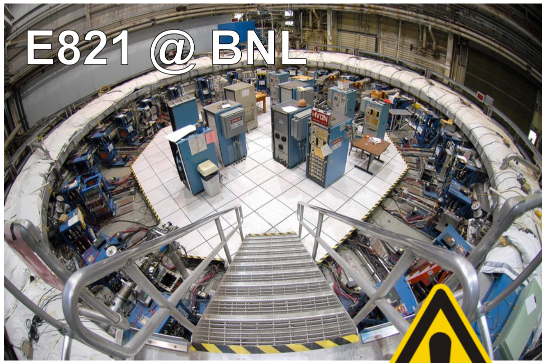
$\sim 10^6 : 10^2 : 1$

$$a_\mu^{th} \simeq a_\mu^{QED} + a_\mu^{QCD} + a_\mu^{QFD} = 0.001\ 165\ 917\ 93(68)$$

$$a_\mu^{exp} = 0.001\ 165\ 920\ 80(64)$$

$$\Delta a_\mu^{exp} = 0.000\ 000\ 002\ 87(91)$$




**Tests Lepton Universality @ $\sim 10^{-6*}$ level; 3σ discrepancy**

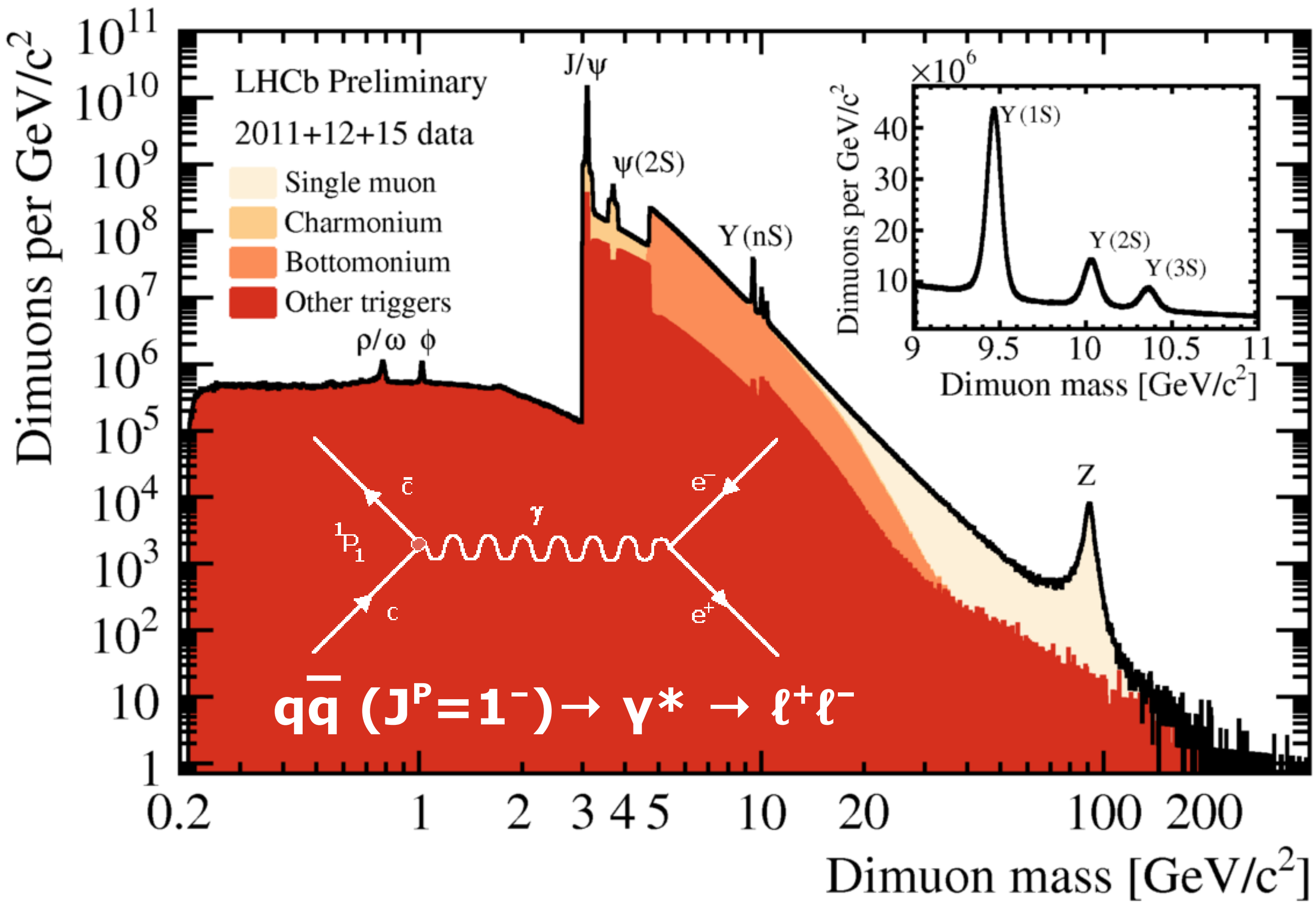
***assuming theory (QCD) understood**

**See Wed/Thu parallel sessions**



ge: doi.org/10.1103/PhysRevLett.100.120801
gmu: doi.org://10.1103/PhysRevD.73.072003
"The Anomalous Magnetic Moment of the Muon", F. Jegerlehner, Springer (2017)
133Cs :doi.org/10.1126/science.aap7706

# Dimuon production @ LHCb






CERN-LHCb-CONF-2016-005

# Vector Meson Branching Ratios

| | e | μ | τ |
|---|---|---|---|
| $\rho^0(770)$ | $4.72(5)\cdot10^{-5}$ | $4.55(28)\cdot10^{-5}$ | – |
| $\varphi(1020)$ | $2.96(3)\cdot10^{-4}$ | $2.87(2)\cdot10^{-4}$ | – |
| $J/\Psi$ | $5.97(3)\cdot10^{-2}$ | $5.96(3)\cdot10^{-2}$ | – |
| $\Psi(2S)$ | $7.89(2)\cdot10^{-3}$ | $7.9(9)\cdot10^{-3}$ | $3.1(4)\cdot10^{-3}$* |
| $\Upsilon(1S)$ | $2.38(11)\cdot10^{-2}$ | $2.48(5)\cdot10^{-2}$ | $2.60(10)\cdot10^{-2}$ |
| $\Upsilon(2S)$ | $1.91(16)\cdot10^{-2}$ | $1.93(17)\cdot10^{-2}$ | $2.00(21)\cdot10^{-2}$ |
| $\Upsilon(3S)$ | $2.18(20)\cdot10^{-2}$ | $2.18(21)\cdot10^{-2}$ | $2.29(30)\cdot10^{-2}$ |

*phase space

**~theory free**

**Consistent with Lepton Universality @ ~$10^{-2}$ level**



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# $Z^0$

# Lepton-$Z^0$ coupling

Leptons w/ equal charge have identical coupling to Z boson

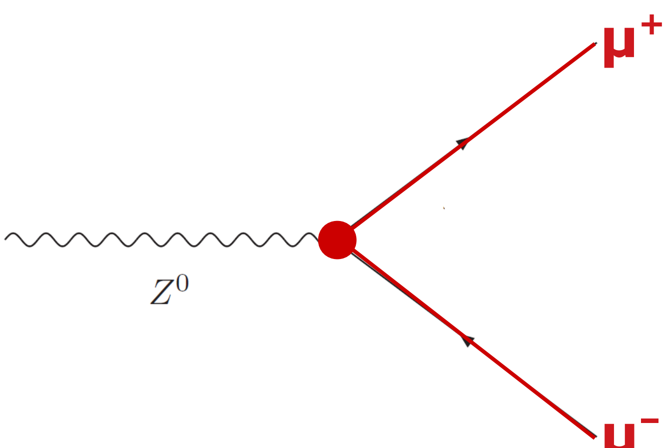
$$\mathcal{L}_{\mathrm{NC}}^{Z} = \frac{g}{2\cos\theta_W} Z_\mu \sum_l \bar{l}\gamma^\mu (v_l - a_l\gamma_5) l$$

with effective **vector** and **axial-vector** couplings

**Some explorations** (**e**, **μ**, **τ**, ***ν*** )

Z-production & decay @ LEP, SLC, LHC, ...

1. partial decay widths
2. forward-backward asymmetry $A_{FB}$
3. polarization asymmetry $A_{LR}$

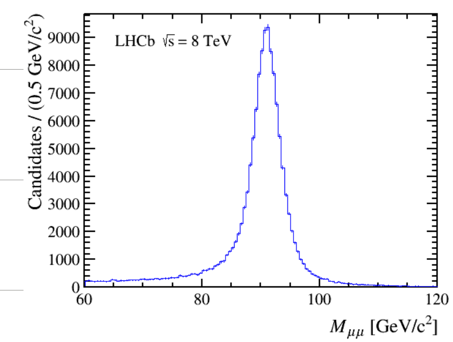




arXiv:hep-ph/9701263

# $Z^0$ line-shape parameters

| | e | μ | τ | ν |
|---|---|---|---|---|
| **Br** | 0.03363(4) | 0.03366(7) | 0.03370(8) | |
| **$A_{LR}$** | 0.1515(19) | 0.142(15) | 0.143(4) | |
| **$A_{FB}$** | 0.0145(25) | 0.0169(13) | 0.0188(17) | |
| **$g_V$** | -0.03817(47) | -0.0367(23) | -0.0366(10) | 0.502(17)* |
| **$g_A$** | -0.50111(35) | -0.50120(54) | -0.50204(64) | |




* from $\nu_\mu$e scattering

**~theory free**

**Consistent with Lepton Universality @ ~$10^{-3}$ level**



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doi.org/10.1007/JHEP01(2016)155

# $W^{\pm}$

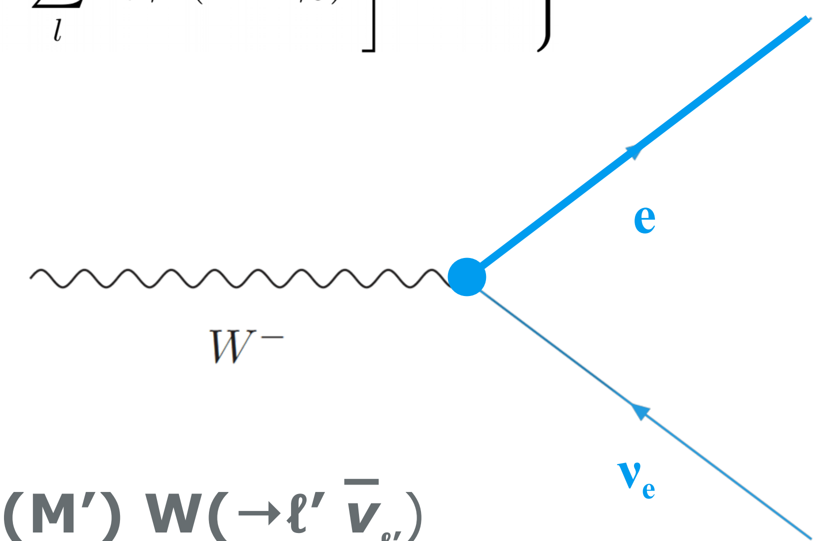
# Lepton-W$^{\pm}$ coupling

Charged current interaction governed by universal coupling *g*

$$\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} \left\{ W_\mu^\dagger \left[ \sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5) l \right] + \text{h.c.} \right\}$$

**Some explored avenues** (**e**, **μ**, **τ**)

1. W-decay partial decay widths
2. lepton decay $\ell \to \nu_\ell W(\to \ell' \bar{\nu}_{\ell'})$
3. (semi-)leptonic meson decay $M \to (M') W(\to \ell' \bar{\nu}_{\ell'})$






arXiv:hep-ph/9701263

# $W^{\pm}$ branching fractions

produced in pairs at $e^+e^-$ colliders or indirectly at hadron colliders
missing neutrinos complicate analysis

| | e | μ | τ |
|---|---|---|---|
| **Br** | 0.1071(16) | 0.1063(15) | 0.1138(21) |

**Universality tested @ ~$10^{-2}$ level**

**Br(τ) about 3σ above average of Br(e) & Br(μ)**

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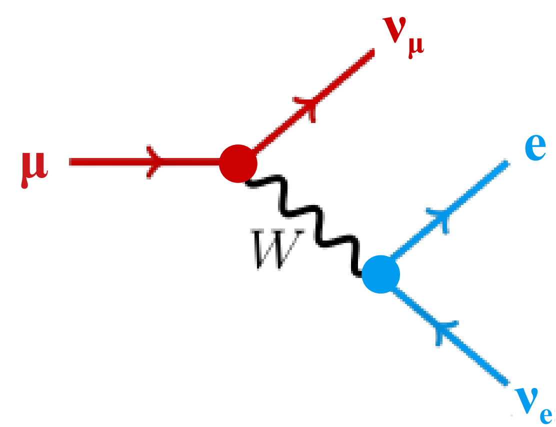
# Muon Decay

**Muon decay**

simplest flavor-changing process $\mu \rightarrow \nu_\mu\, e\, \bar{\nu}_e$



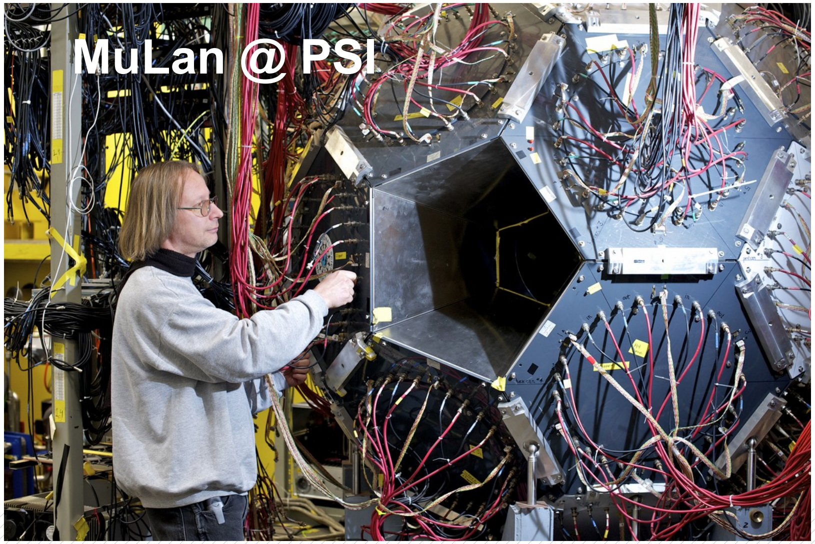

$$\tau_\mu = 2.1969811(22)\ \mu s$$

Determines weak interaction strength

$$1/\tau_\mu \approx G_F^2\, m_\mu^5 / 192\pi^3$$

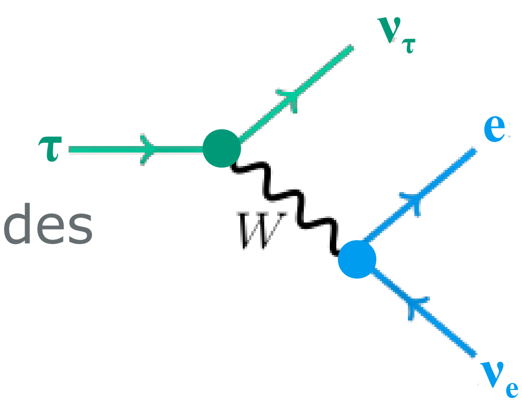
$$\downarrow$$

$$G_F = \sqrt{2} \cdot g_e \cdot g_\mu / 8M_W^2$$




doi.org/10.1016/j.nuclphysbps.2012.02.048

# Tau Decay




Several final states (e, μ, quarks) w/ equal amplitudes

$$\tau_\tau = 290.3(5)\ \text{fs} \approx \tau_\mu/5\cdot(m_\mu/m_\tau)^5$$

Branching fractions depend on coupling constants : $g_e$, $g_\mu$, $g_\tau$, $g_{u,d}$

$$\text{Br}(e) = \text{Br}(\mu)/0.972564(10) = \tau_\tau/1632.1(14)\ \text{fs}$$

0.1782(4) 0.1788(4) 0.1779(3)

**Consistent with Universality @ $3\cdot10^{-3}$ level**

| | e | μ |
|---|---|---|
| **Br** | 0.1782(4) | 0.1739(4) |



arXiv:hep-ph/9701263
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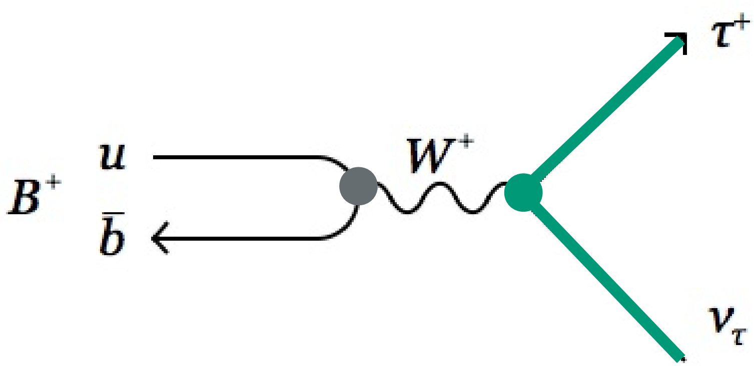
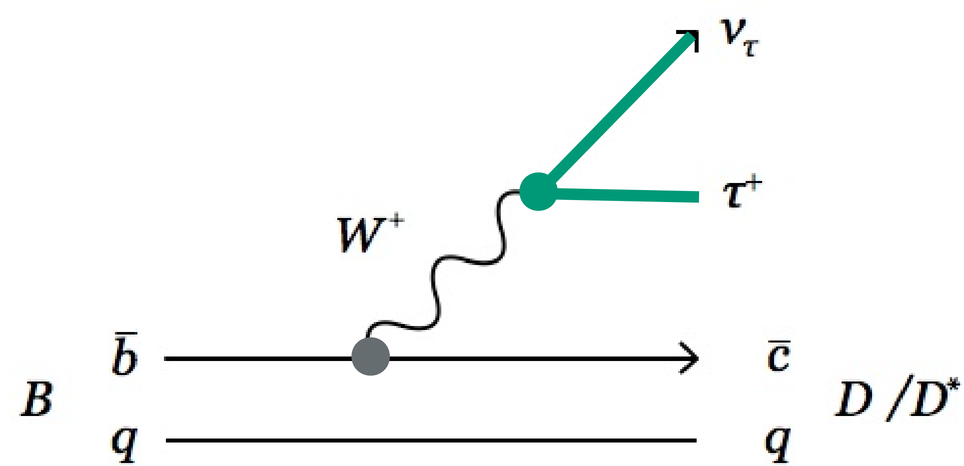
# Meson decay

Two basic processes: leptonic and semi-leptonic decay



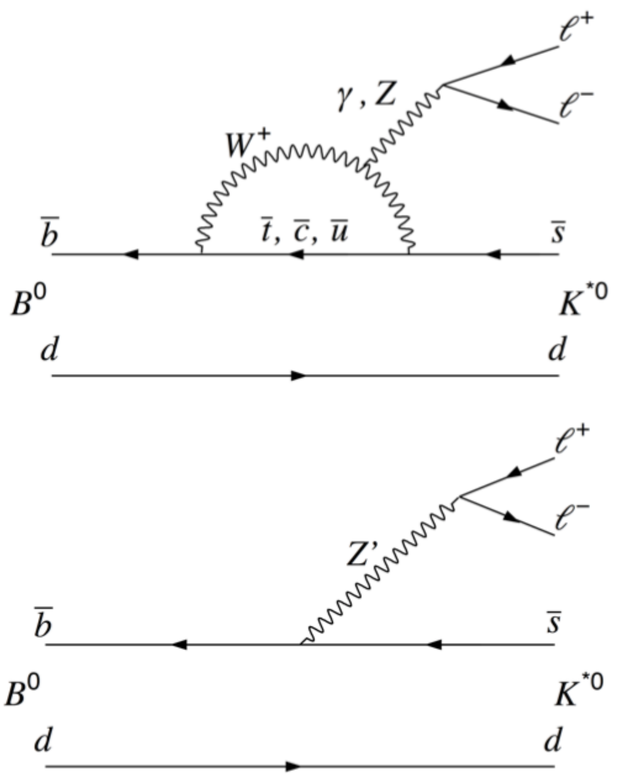

**Examples:**

$(\pi,K,D_s)^+ \to (e,\mu)^+\nu_{e,\mu}$
(helicity suppression)

$(K,D_s)^0 \to (\pi,K,K^*)^-(e,\mu,\tau)^+\nu_{e,\mu,\tau}$
$(K,D_s)^+ \to (\pi,K)^0(e,\mu,\tau)^+\nu_{e,\mu,\tau}$

See PEN in Tuesday parallel session

# Semi-leptonic meson decay




**Tree level, b → c ℓ *ν***

abundant

well known in SM

**possible new physics in 3rd gen.**

**Loop level, b → s ℓ ℓ**

FCNC forbidden at tree-level in SM

**sensitive to new physics in loops**

**Approach : determine ratio of branching fractions**

experimentally clean → many systematics cancel

theoretically clean → many QCD effects cancel

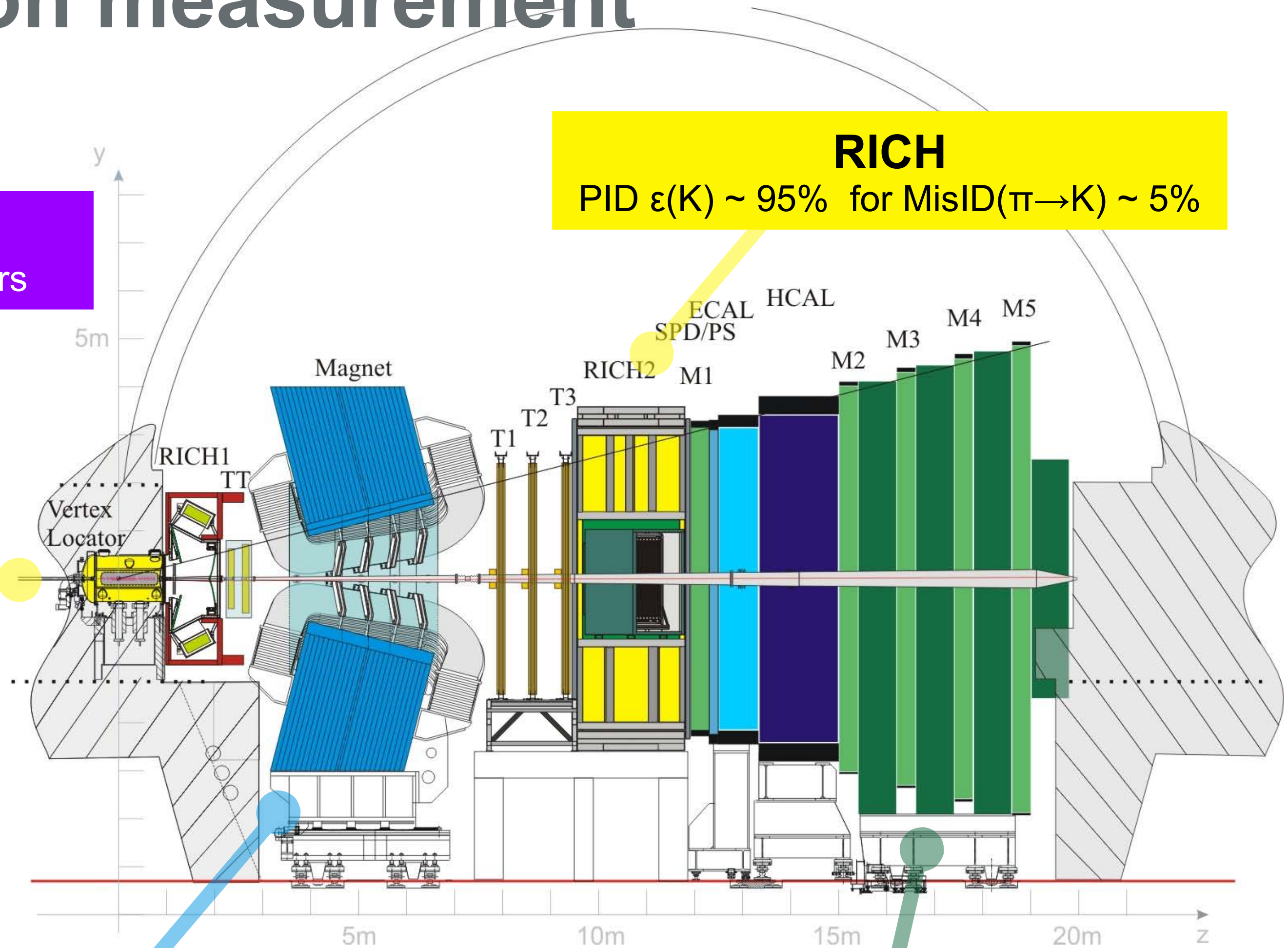
# LHCb

# LHCb : precision measurement

**Trigger**
high efficiency *esp.* muon triggers

**RICH**
PID ε(K) ~ 95% for MisID(π→K) ~ 5%

**VELO**
IP resolution 15+29/($p_T$/GeV) μm

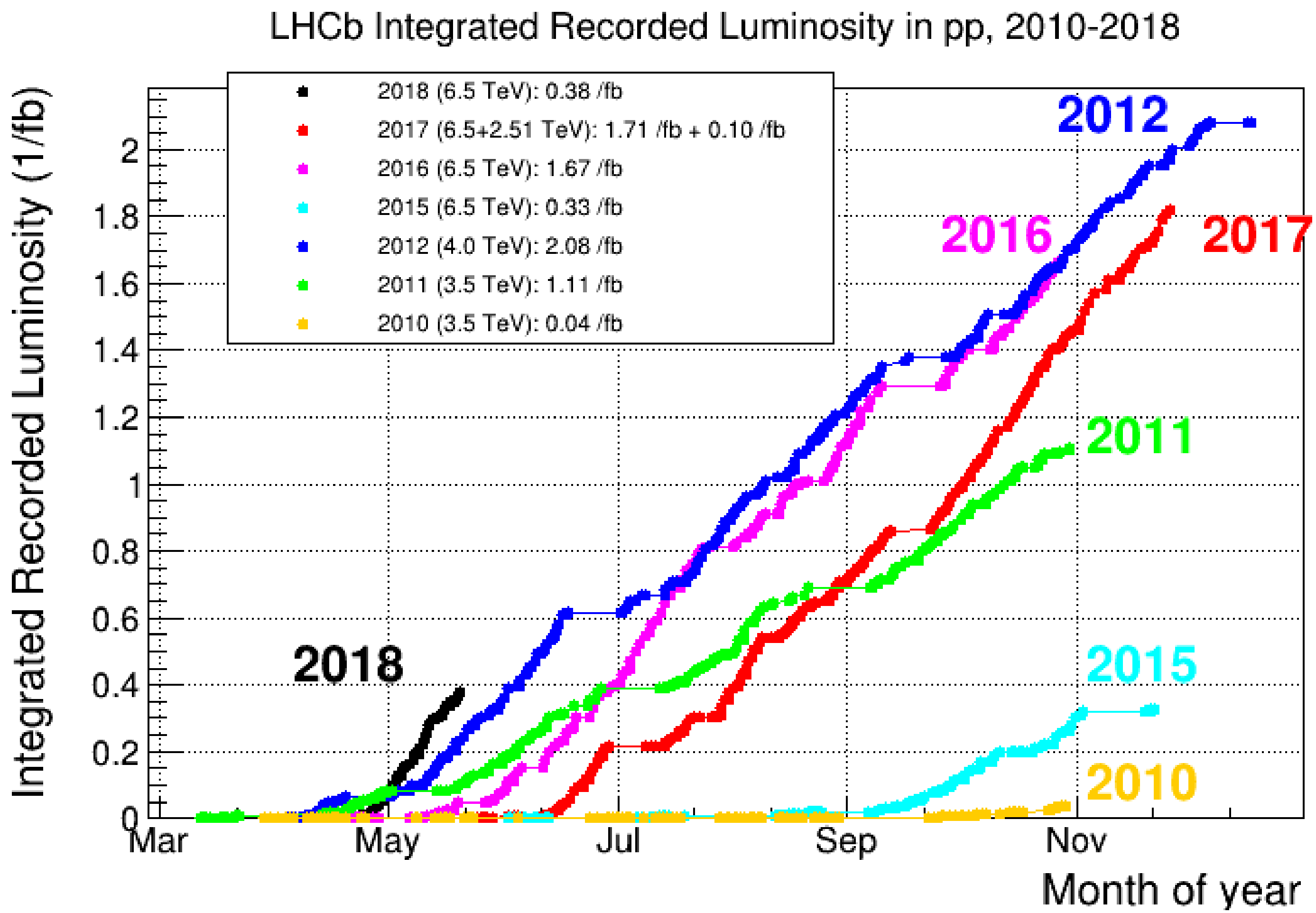



**Tracking Δp/p**
0.4% @ 5 GeV/*c* – 1.0% @ 200 GeV/*c*

**Muon ID**
identification ε ~ 97% misID ~ 2%

Int. J. Mod. Phys. A 30, 1530022 (2015)

# Successful data taking



# Recent LHCb results – Run-I, 3 fb$^{-1}$

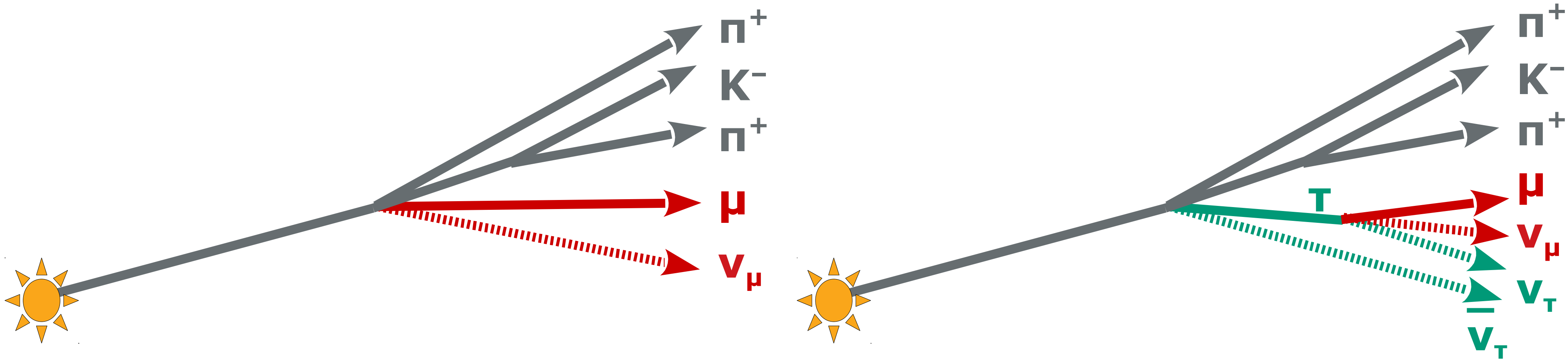
| | | |
|---|---|---|
| $B^0_{(s)} \to e\mu$ | JHEP 1803 (2018) 078 | **LFV** |
| $\bar{B}^0 \to D^{*+} \tau\bar{\nu}_\tau / \mu\bar{\nu}_\mu$ | PRD 97, 072013 (2018) | LNU |
| $B^0 \to K^{0*}\mu\mu / ee$ | JHEP 08 (2017) 055 | LNU |
| $D^0 \to e\mu$ | PLB 754 (2016) 167 | **LFV** |
| $\bar{B}^0 \to D^{*+} \tau\bar{\nu}_\tau / \mu\bar{\nu}_\mu$ | PRL 115, 111803 (2015) | LNU |
| $\tau \to \mu\mu\mu$ | JHEP 02 (2015) 121 | **LFV** |
| $B^+ \to K^+\mu\mu / ee$ | PRL 113, 151601 (2014) | LNU |
| $B^- \to \pi^+\mu^-\mu^-$ | PRL 112, 131802 (2014) | *LNV* |
| $\tau^- \to p\mu^-\mu^-$ | PLB 724 (2013) 36 | *BLNV* |
| $D^+ \to \pi^-\mu^+\mu^+$ | PLB 724 (2013) 203 | *LNV* |

# $R_{D^*}$

# $\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$ / $D^{*+}\mu^-\overline{\nu}_\mu$ @ LHCb

$\tau \rightarrow \mu\nu\nu$ $D^{*+} \rightarrow D^0\pi^+$

$\hookrightarrow K^-\pi^+$

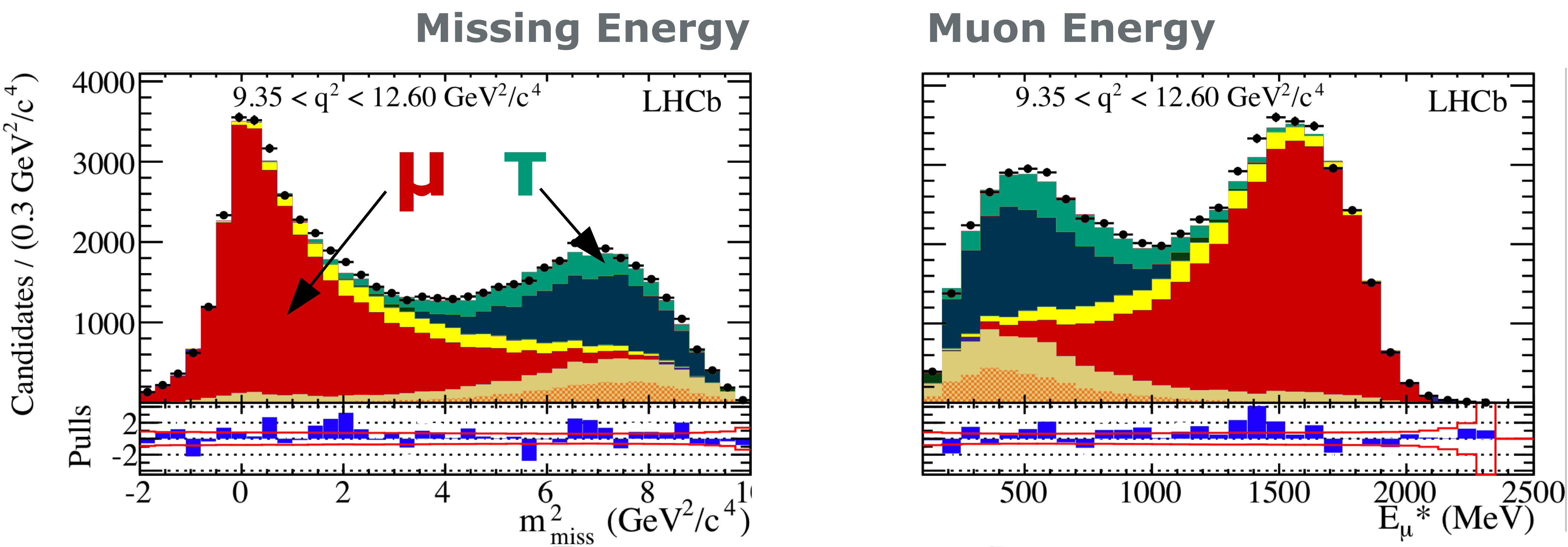



**Cannot reconstruct B mass because of missing ν's**



Nature 546, 227–233 (2017)
PRL 115, 111803 (2015)

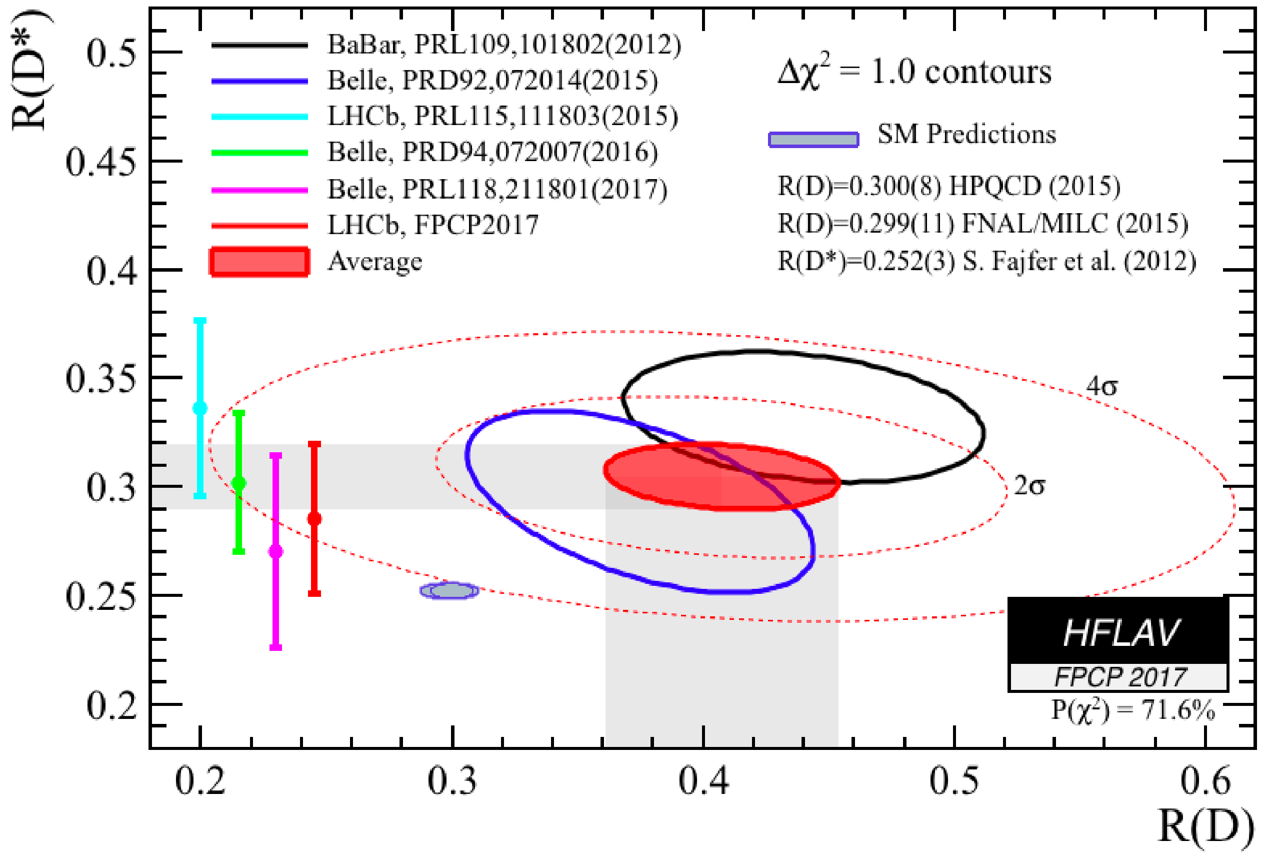
# Maximum likelihood fitting




**Fit data using simulated kinematic distributions**

PRL 115, 111803 (2015)

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




**Violates Universality @ $10^{-2}$ level by 4.1σ**

# $R_K$

# b → sℓ⁺ℓ⁻ (ℓ=e,μ)

requires FCNC → rates suppressed

Ratio close to unity in SM

$$R_H = \frac{\int \frac{d\Gamma(B \to H \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to H e^+ e^-)}{dq^2} dq^2}$$

for range of squared di-lepton invariant mass ($q^2$)

**Ratio sensitive to possible new particles**


doi.org/10.1140/epjc/s10052-016-4274-7

# $B^0 \rightarrow K^{*0}\ell^+\ell^-$ ($\ell$=e,μ)

Measured as double ratio → **many systematics reduced**

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

**LNU-free**

$K^{*0}$ from $K^{*0} \rightarrow K^+\pi^-$

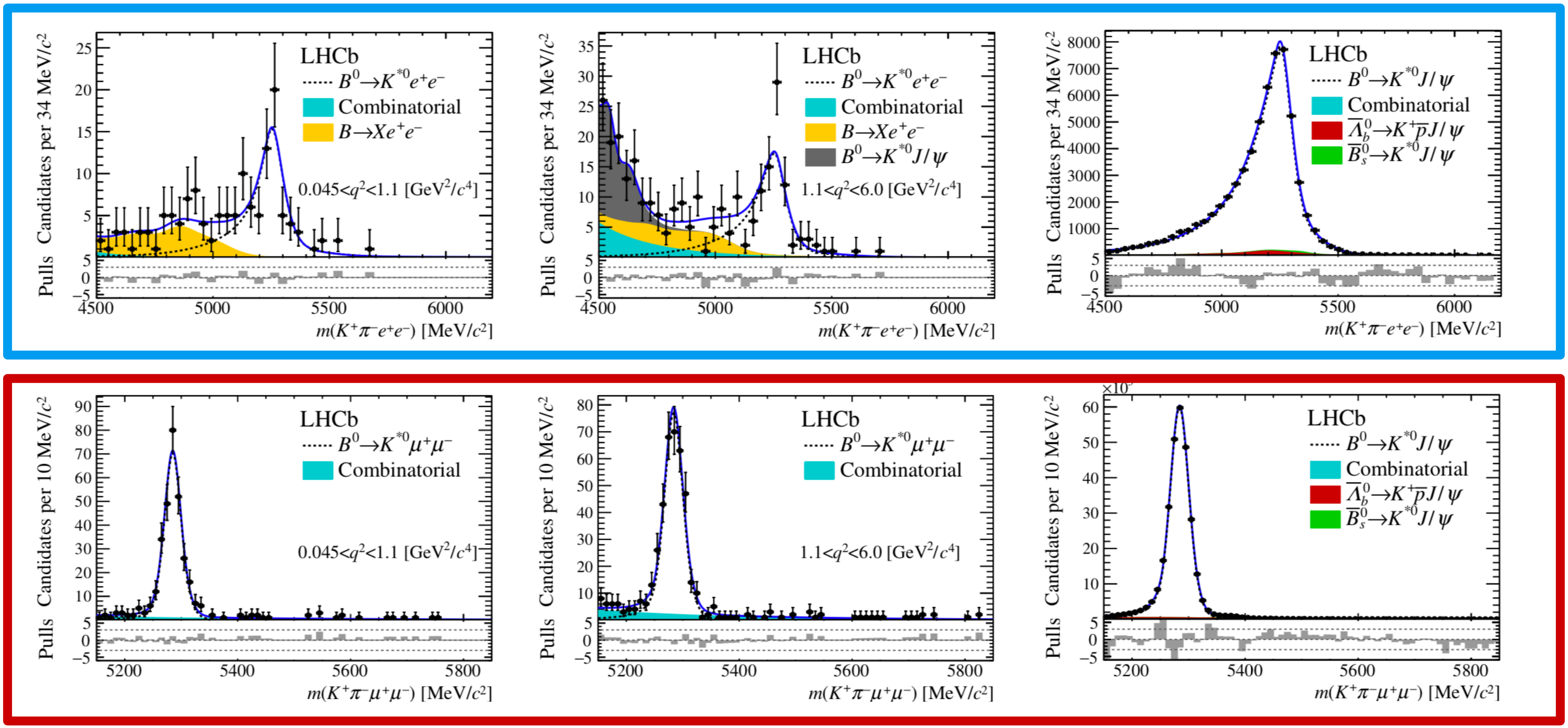
**$q^2 = m(\ell^+\ell^-)$ ranges used**

| | | |
|---|---|---|
| $B^0 \rightarrow K^{*0}\ \ell^+\ell^-$ | [0.045–1.1] | incl. φ(1020) |
| $B^0 \rightarrow K^{*0}\ \ell^+\ell^-$ | [1.1–6] | |
| $B^0 \rightarrow K^{*0}\ J/\psi(\rightarrow \ell^+\ell^-)$ | [6-11] | |



JHEP 08 (2017) 055

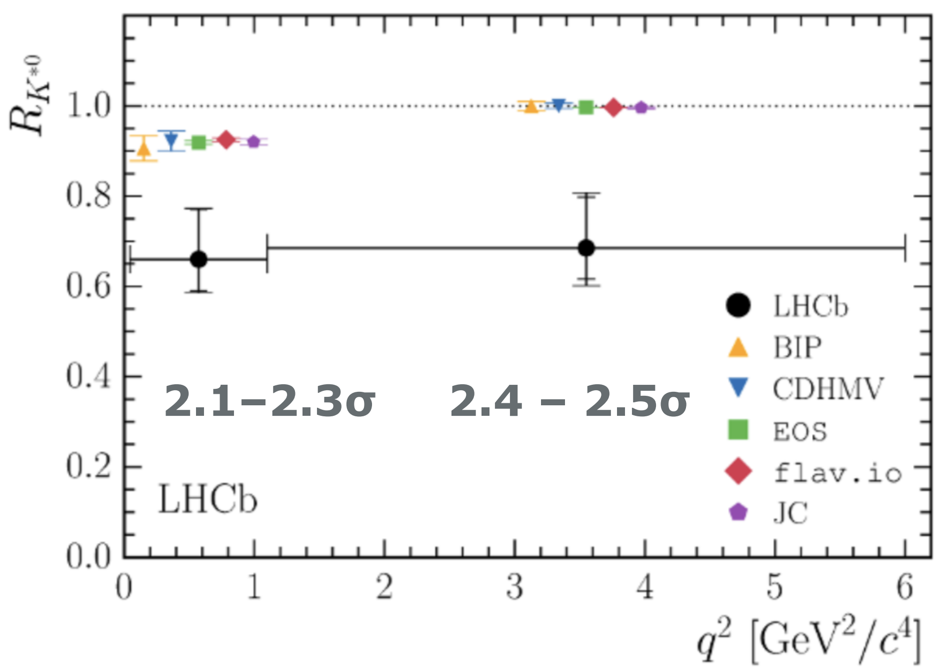
# $B^0 \rightarrow K^{*0}\ell^+\ell^-$ ($\ell$=e,μ)

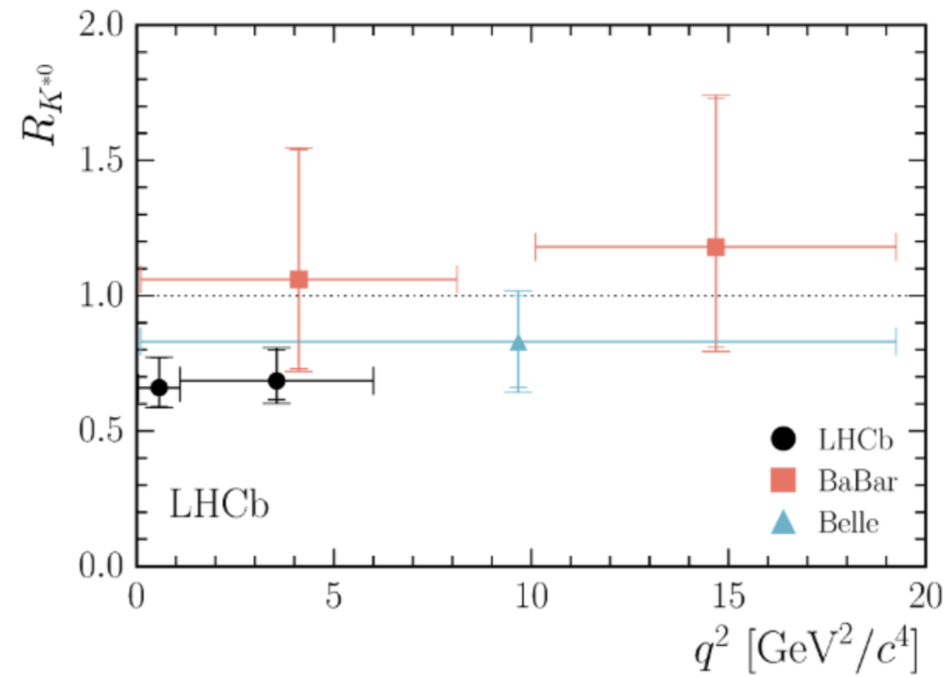





JHEP 08 (2017) 055

# $B^0 \rightarrow K^{*0}\ell^+\ell^-$ ($\ell$=e,μ)




**also $B^0 \rightarrow K^{*0}\ell^+\ell^-$: 0.745(96), 2.6σ**

**Violates Universality @ 30% level by combined ~4σ**



JHEP 08 (2017) 055
doi.org/10.1103/PhysRevLett.113.151601

# Finale

# Need for new physics?

## Required: $g_e \neq g_\mu \neq g_\tau$

**New vector Boson $W'^{\pm}$, $m_{W'} > m_W$**
constrained by $W' \rightarrow tb$, precision $\mu$, $\tau$ measurements

**Charged Higgs w/ S=0**
affects angular distributions

**Leptoquarks**
unified description of flavors, allows quark-lepton transitions

**Model 'independent' via EFT**
link various measurements, guide fundamental theories



Nature 546, 227–233 (2017)
arXiv:1805.05399

# What does it all mean?

## Lepton Universality is tested in various ways

**EM** coupling @ $10^{-9}$ ($Q_{e\mu}$) & $10^{-6}$ ($a_{e\mu}$) : **2.6σ tension**

**NC** couplings @ $10^{-3}$ (**e**,**μ**,**τ**) : **consistent**

**CC** coupling tested @ $10^{-3}$ (**e**,**μ**), $10^{-2}$ (**τ**)

- RD(*) (**e**,**μ**,**τ**) > prediction : **4.1σ tension**
- RK(*) (**e**,**μ**) < prediction : **~4σ tension**

**Linked** to many other observables: **LFV, direct searches, …**

Several theoretical speculations about **NP interpretation**

**Look for progress in the (near) future!**

# Thank you for your attention!

# Leptonic meson decay

Branching ratios strongly affected by helicity suppression
→ universality not obvious, $\Gamma_\ell \sim g_\ell^2 \cdot m_M \cdot [m_\ell (1-(m_\ell/m_M)^2)]^2$

| | e | μ | τ |
|---|---|---|---|
| $\pi^+$ | $1.230(4)\cdot10^{-4}$ | 99.98770(4)% | – |
| $K^+$ | $1.582(7)\cdot10^{-5}$ | 63.58(11)% | – |
| $D_s^+$ | $<8.3\cdot10^{-5}$ | $5.50(23)\cdot10^{-3}$ | 5.48(23)% |
| $B^-$ | $<9.8\cdot10^{-7}$ | $<1.0\cdot10^{-6}$ | $1.06(19)\cdot10^{-4}$ |

**Consistent with Universality @ $3\cdot10^{-3}$ level**

Particle Data Group
arXiv:1701.05254

# $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ ($\ell$=e,μ,τ) @ BaBar & Belle

**Tau** over **electron** or **muon** : $\mathcal{R}(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)}$

Combine $B^0 \to D^+$ … & $B^+ \to D^0$ … (spectator differs)
Combine **electron** & **muon** (both light)

R(D) : 2.0σ @ BaBar
E: 0.440 ± 0.058 ± 0.042 T: 0.297 ± 0.017

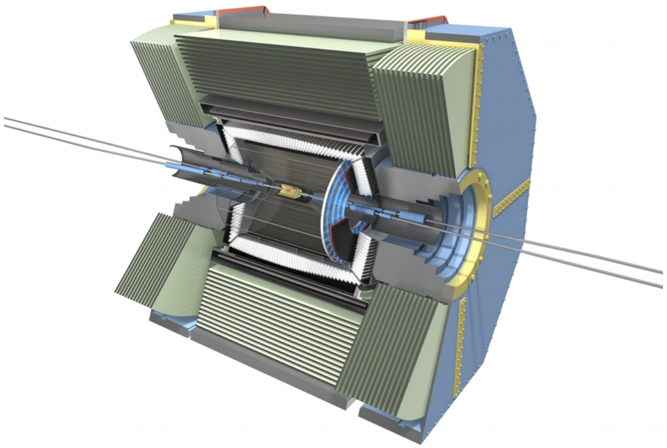
R(D*) : 2.7σ @ BaBar
E: 0.332 ± 0.024 ± 0.018 T: 0.252 ± 0.003

R(D*) : 1.6σ @ Belle
E: 0.302 ± 0.030 ± 0.011 T: 0.252 ± 0.003



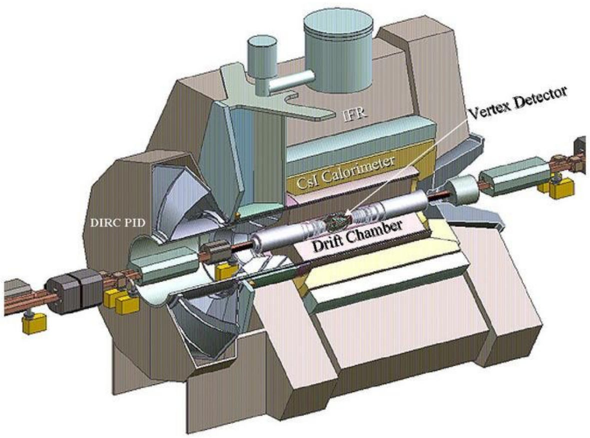
PRD 88, 072012 (2013)
PRD 94, 072007 (2016)

# B → $K^{(*)}\ell^+\ell^-$ ($\ell$=e,μ)



## Many options

- $B^0 \rightarrow K^0\ell^+\ell^-$
- $B^0 \rightarrow K^{*0}\ell^+\ell^-$
- $B^\pm \rightarrow K^\pm\ell^+\ell^-$
- $B^\pm \rightarrow K^{*\pm}\ell^+\ell^-$




## Previous from BaBar, Belle, LHCb

- BaBar $R_K$ = 1.00±0.29 , $R_{K^*}$ = 1.13±0.31
- Belle $R_K$ = 1.03±0.20 , $R_{K^*}$ = 0.83±0.19
- LHCb $R_{K+}$ = 0.75±0.10 → **2.6σ**



Babar: doi.org/10.1103/PhysRevD.86.032012
Belle: doi.org/10.1103/PhysRevLett.103.171801
LHCb: doi.org/10.1103/PhysRevLett.113.151601