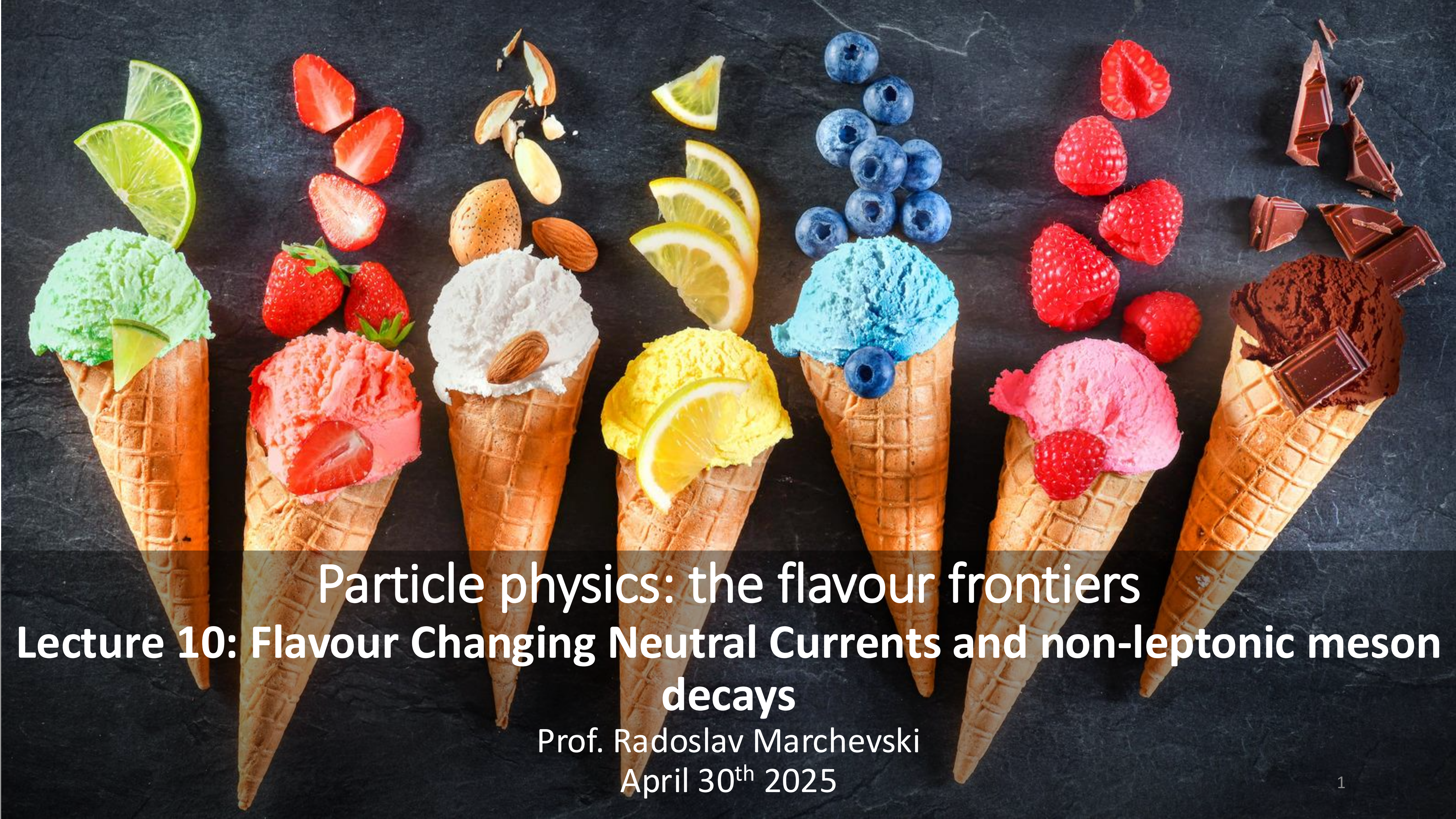


Particle physics: the flavour frontiers

Lecture 10: Flavour Changing Neutral Currents and non-leptonic meson decays

Prof. Radoslav Marchevski

April 30th 2025

Short recap and today's learning targets

Last time we discussed

- Tree-level semileptonic decays of mesons and how to measure their properties experimentally
- CKM tests and observed tensions in the data
- Types of Flavour Changing Neutral Currents in the Standard Model (GIM and CKM suppression)

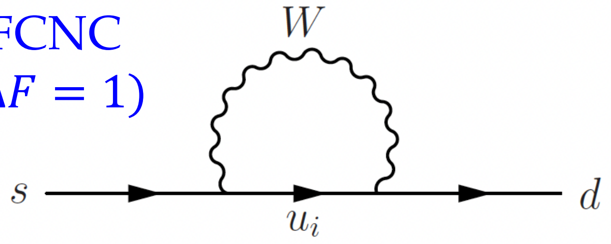
Today you will …

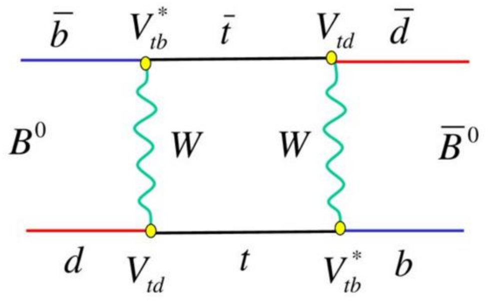
- learn how the measurements of the very rare $\Delta F = 1$ Flavour Changing Neutral Currents of B and K mesons are conducted
- learn about tests of Lepton Flavour Universality (accidental symmetry of the SM) using rare B decays
- analyse and classify the non-leptonic meson decays of B mesons

Flavour Changing Neutral Currents (FCNCs) reminder

- No fundamental symmetry forbids FCNCs in the quark sector
- FCNC can't be mediated at tree level by any of the neutral SM bosons (g, γ, Z, H) but can only appear via the exchange of an even number of $W^{\pm}$ bosons

FCNC
$(\Delta F = 1)$





Meson mixing
$(\Delta F = 2)$

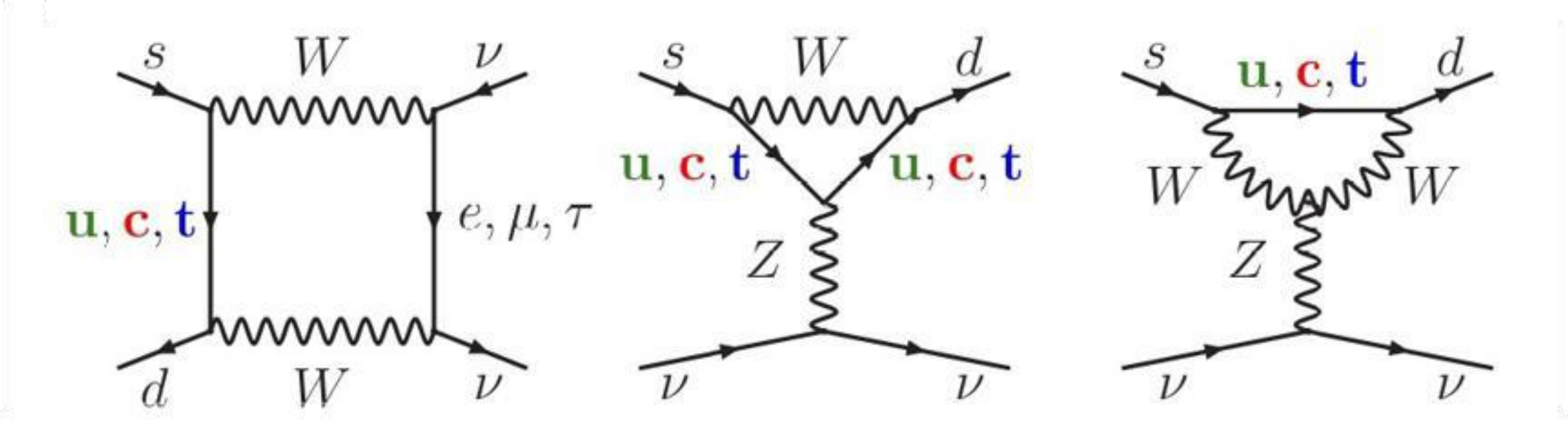
- Two classes of FCNCs based on the change in F (charge under the global $[U(1)]^6$ flavour symmetry of $\mathcal{L}_{\text{QCD}}$)
  - FCNC decays ($\Delta F = 1$ processes) have two insertions of W- boson couplings
  - Neutral meson mixings ($\Delta F = 2$ processes) have four insertions of W- boson couplings

Examples of golden rare $\Delta F = 1$ FCNC meson decays

- **Precise SM predictions necessary for a sensitive comparison between experiment and theory**
- Rare FCNC decays with precise SM predictions are often referred to as **golden** modes

Decay type	Decay mode	Branching ratio (~)
$B \to \mu\mu$	$B_d^0 \to \mu^+\mu^-$	10^{-10}
	$B_s^0 \to \mu^+\mu^-$	3×10^{-9}
$b \to sll \;\; [l = e, \mu]$	$B^+ \to K^+ l^+ l^-$	5×10^{-7}
	$B^+ \to K^{*+} l^+ l^-$	10^{-6}
	$B_d^0 \to K_S l^+ l^-$	3×10^{-7}
	$B_d^0 \to K^{*0} l^+ l^-$	10^{-6}
$K \to \pi\nu\nu$	$K^+ \to \pi^+ \nu\bar{\nu}$	8×10^{-11}
	$K_L \to \pi^0 \nu\bar{\nu}$	3×10^{-11}

The $K \to \pi\nu\bar{\nu}$ decay



$$\mathcal{A} \propto \overbrace{\underbrace{V_{ts}V_{td}^*}_{\text{complex}}X_t}^{\text{top}} + \overbrace{\underbrace{V_{cs}V_{cd}^*}_{\text{real}}X_c}^{\text{charm}}$$

$$X_q = f(m_q^2/M_W^2)$$

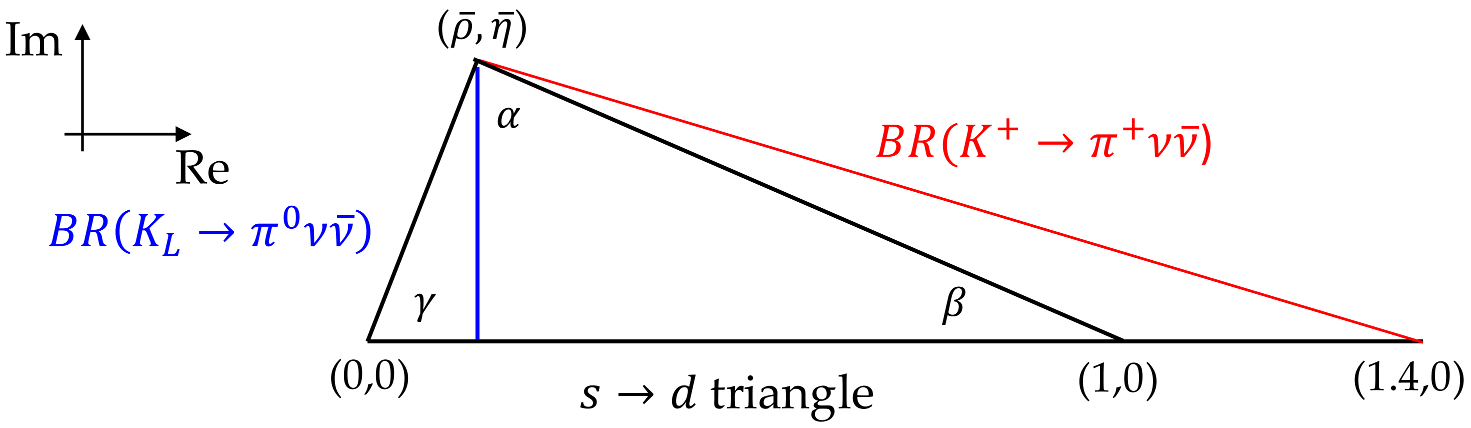
- Loop-level process (box – EW penguin)
- CKM factor $|V_{ts}V_{td}^*|^2, |V_{cs}V_{cd}^*|^2$
- Hadronic matrix element $\kappa \propto BR(K^+ \to \pi^0 e^+ \nu)$ precisely measured
  - few % theoretical uncertainty, Long Distance effects under control, largest uncertainty from CKM elements measurement

$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto |\mathcal{A}|^2 \Longrightarrow \kappa_+[(\mathcal{Im}(V_{ts}V_{td}^*)X_t)^2 + (\mathcal{Re}(V_{cs}V_{cd}^*)X_c + \mathcal{Re}(V_{ts}V_{td}^*)X_t)^2] \approx (8.1 \pm 0.6) \times 10^{-11}$$

$$BR(K_L \to \pi^0\nu\bar{\nu}) \propto |p\mathcal{A}(K^0 \to \pi^0\nu\bar{\nu}) + q\mathcal{A}(\bar{K}^0 \to \pi^0\nu\bar{\nu})|^2 \Longrightarrow \kappa_L(\mathcal{Im}(V_{ts}V_{td}^*)X_t)^2 \approx (2.6 \pm 0.3) \times 10^{-11}$$

The rarest meson decays that can constrain the unitarity triangle with the smallest theoretical uncertainties

The $K \to \pi\nu\bar{\nu}$ decay



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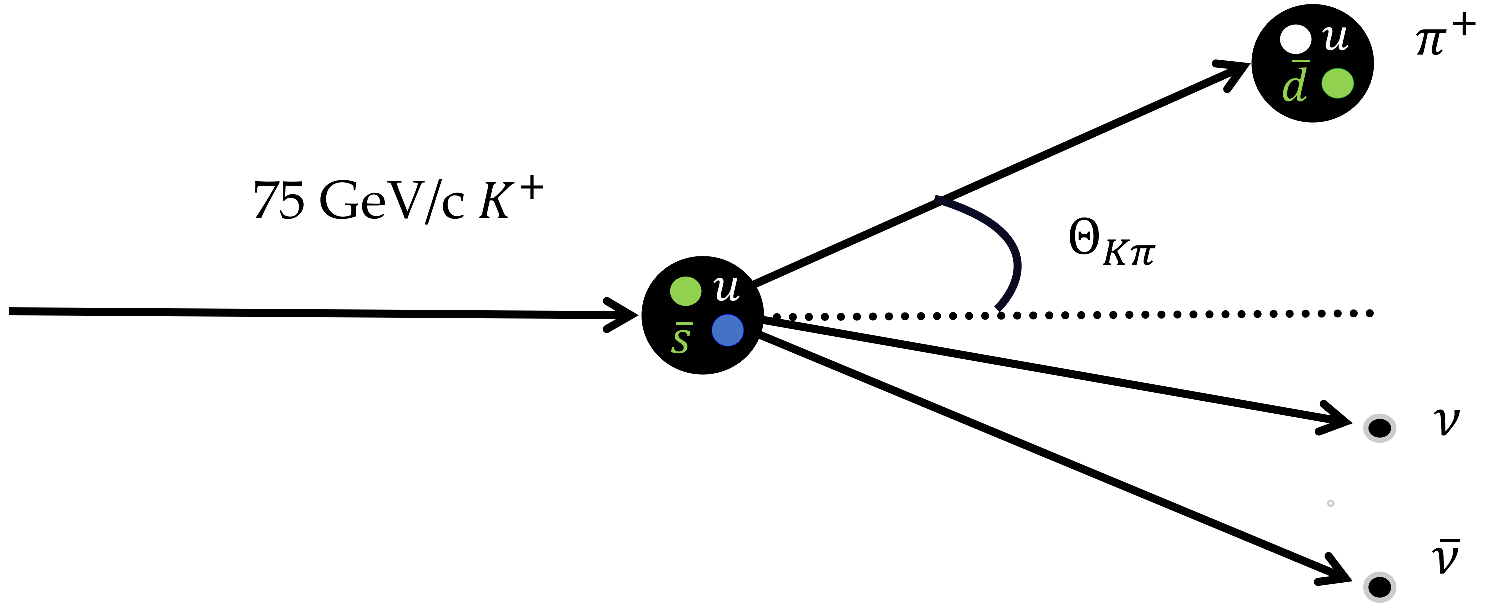
The rarest meson decays that can constrain the unitarity triangle with the smallest theoretical uncertainties

$K^+ \to \pi^+ \nu\bar{\nu}$: experimental method



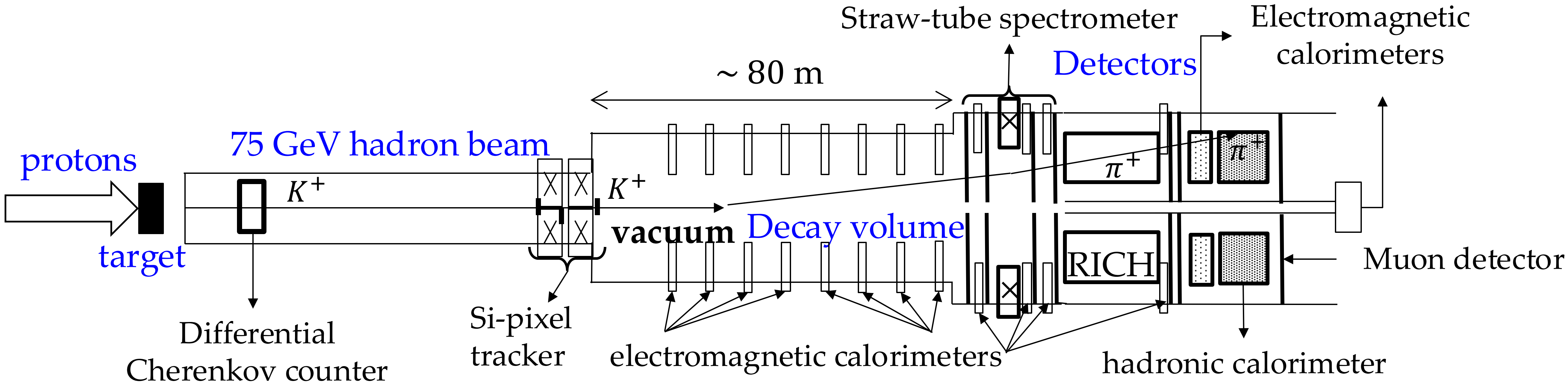
Squared missing mass
(mass of the $\nu\bar{\nu}$ pair):

$$m^2_{miss} = (P_K - P_\pi)^2$$

π^+ mass hypothesis

- Highly boosted decay: (75 ± 1) GeV/c K^+ ($\gamma \sim 150$)
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range 15 – 45 GeV/c ($E_{miss} > 30$ GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed

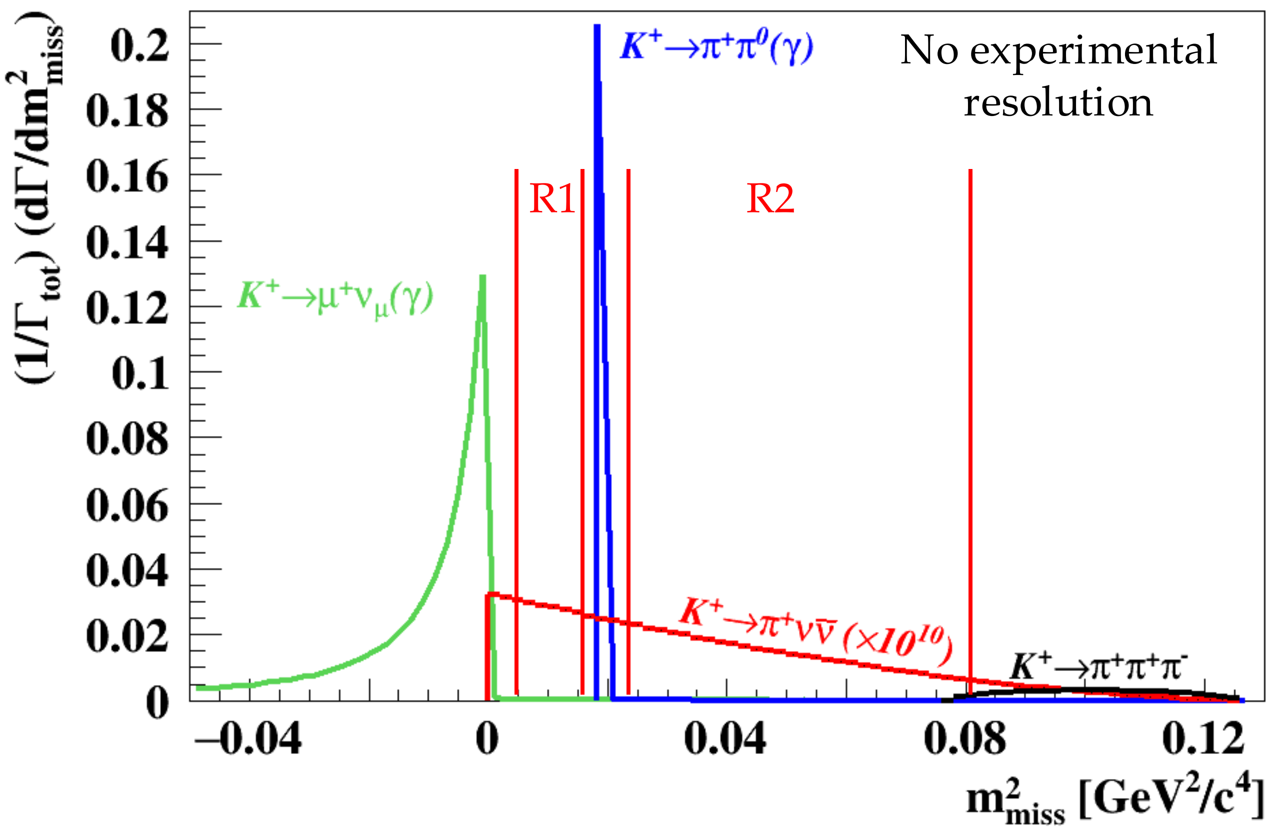
$K^+ \to \pi^+\nu\bar{\nu}$: NA62 experiment

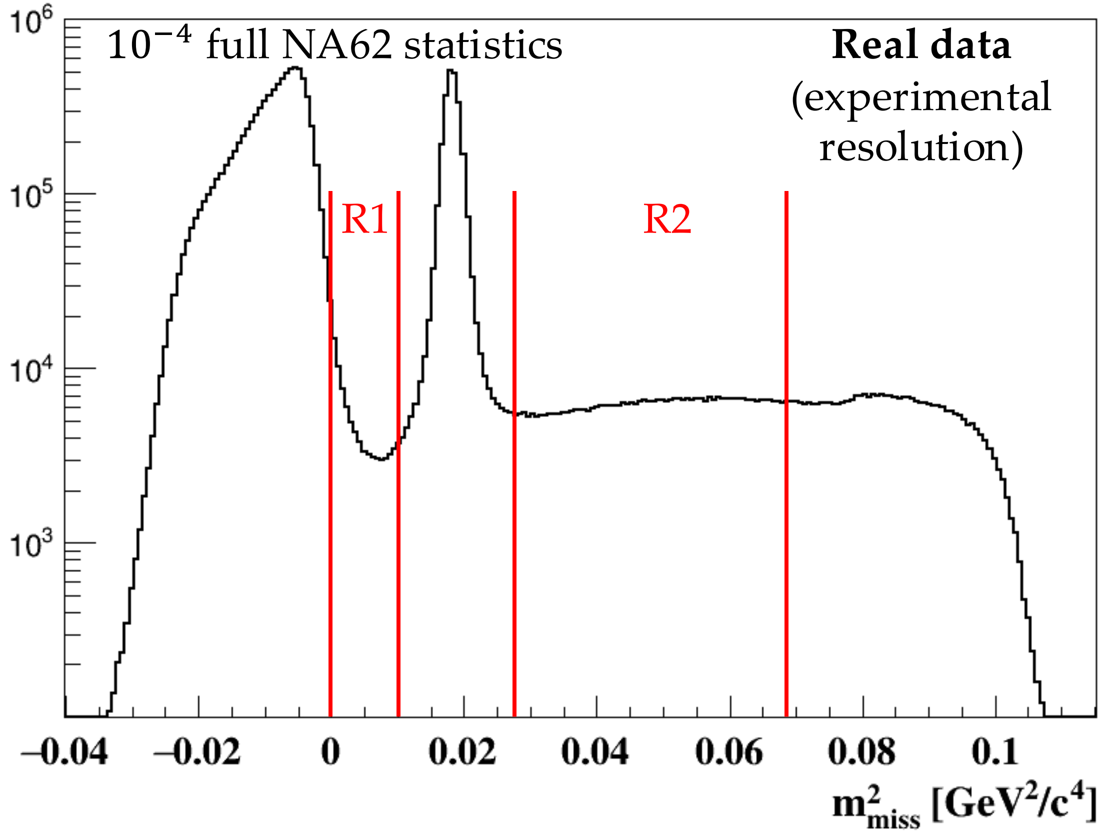


- K^+ are only 6% of the secondary beam created from the proton-target interactions
- ~10% of K^+ decay in the decay volume
- Beam energy defined by CERN-SPS proton energy (400 GeV) and optimisation of signal yield

$K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62

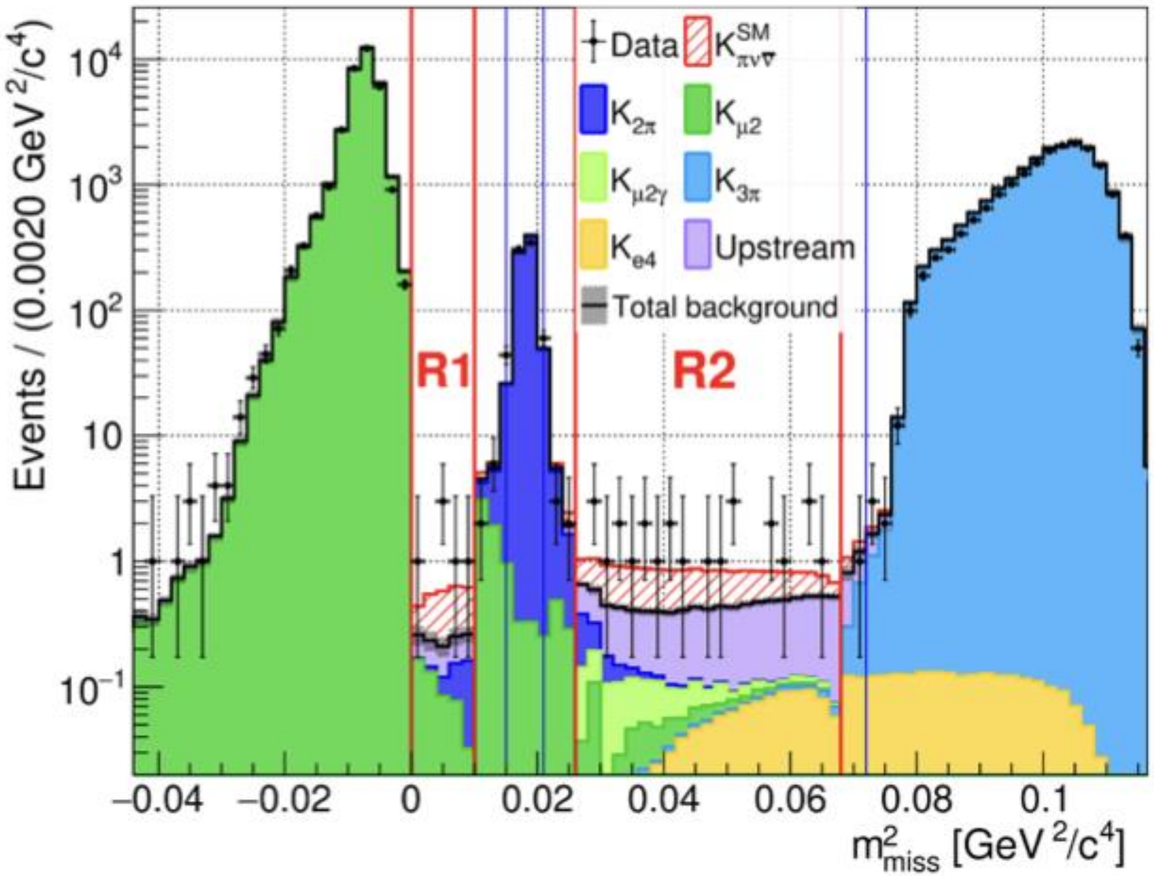
- Kinematics, timing → $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$ → $K - \pi$ association, low material-budget tracking systems

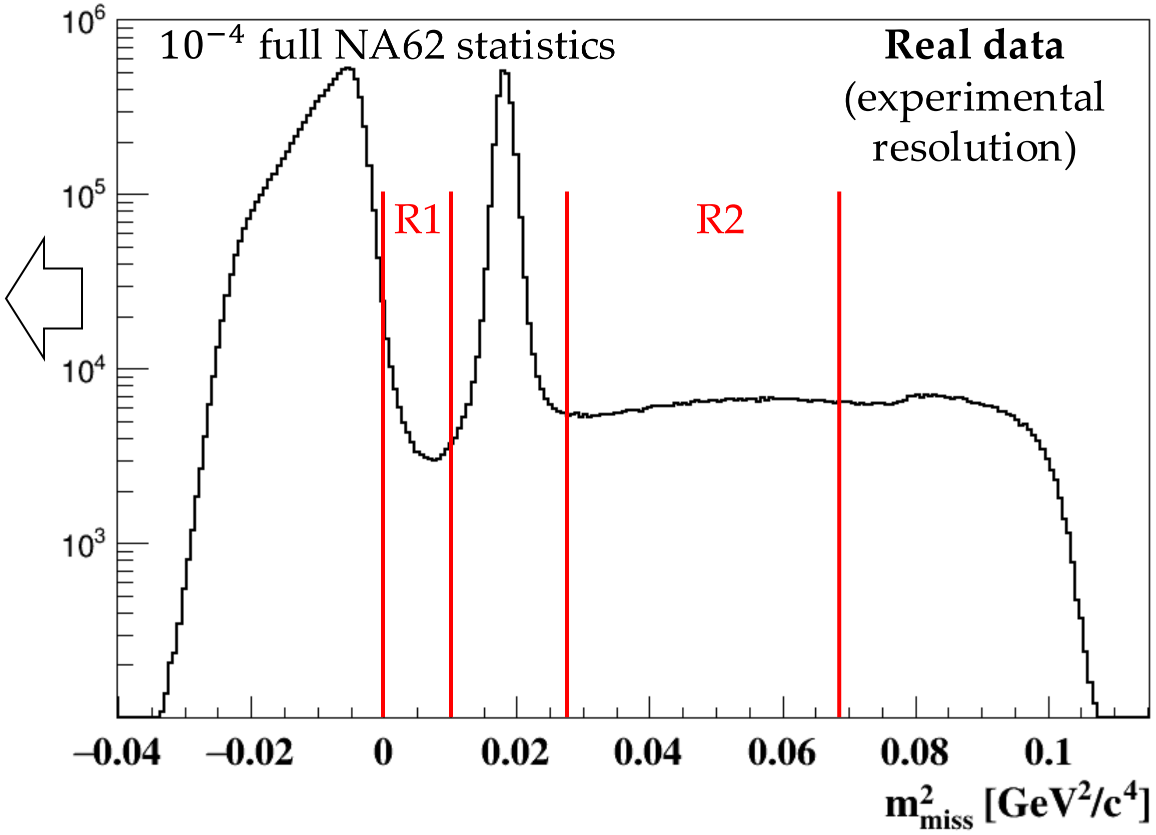




$K^+ \to \pi^+ \nu \bar{\nu}$ @ NA62: results

- Kinematics, timing cuts; tight cuts on additional in-time energy in detectors; BDT classifier for particle ID and to reduce beam-induced background





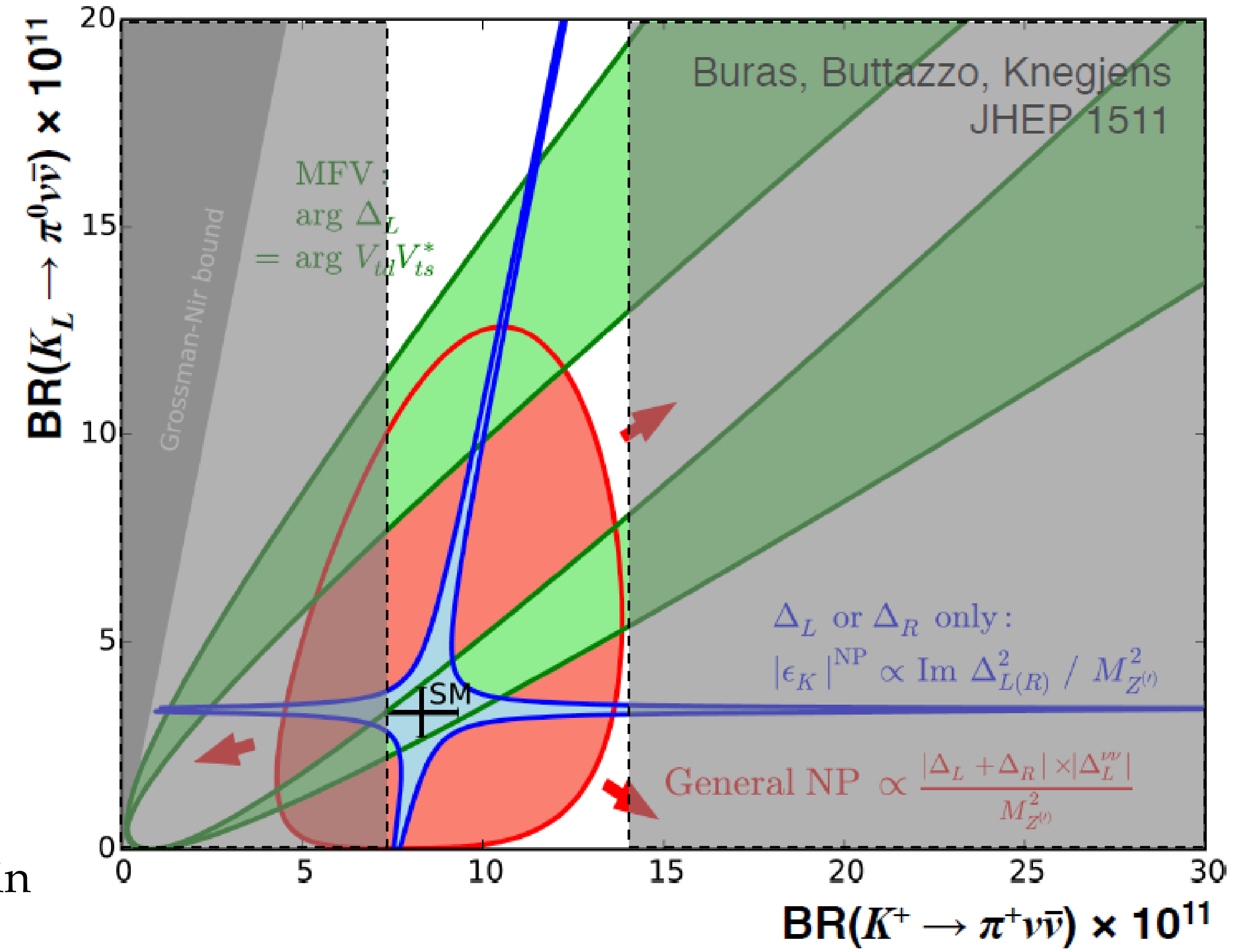
- $N_{obs} = 51$ events observed in signal region (Region 1 + Region 2)
- $\mathrm{BR}(\mathrm{K}^+ \to \pi^+ \nu \bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{stat} \pm 1.3_{syst}) \times 10^{-11}$ [JHEP 02 (2025) 191]

$K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62: new physics

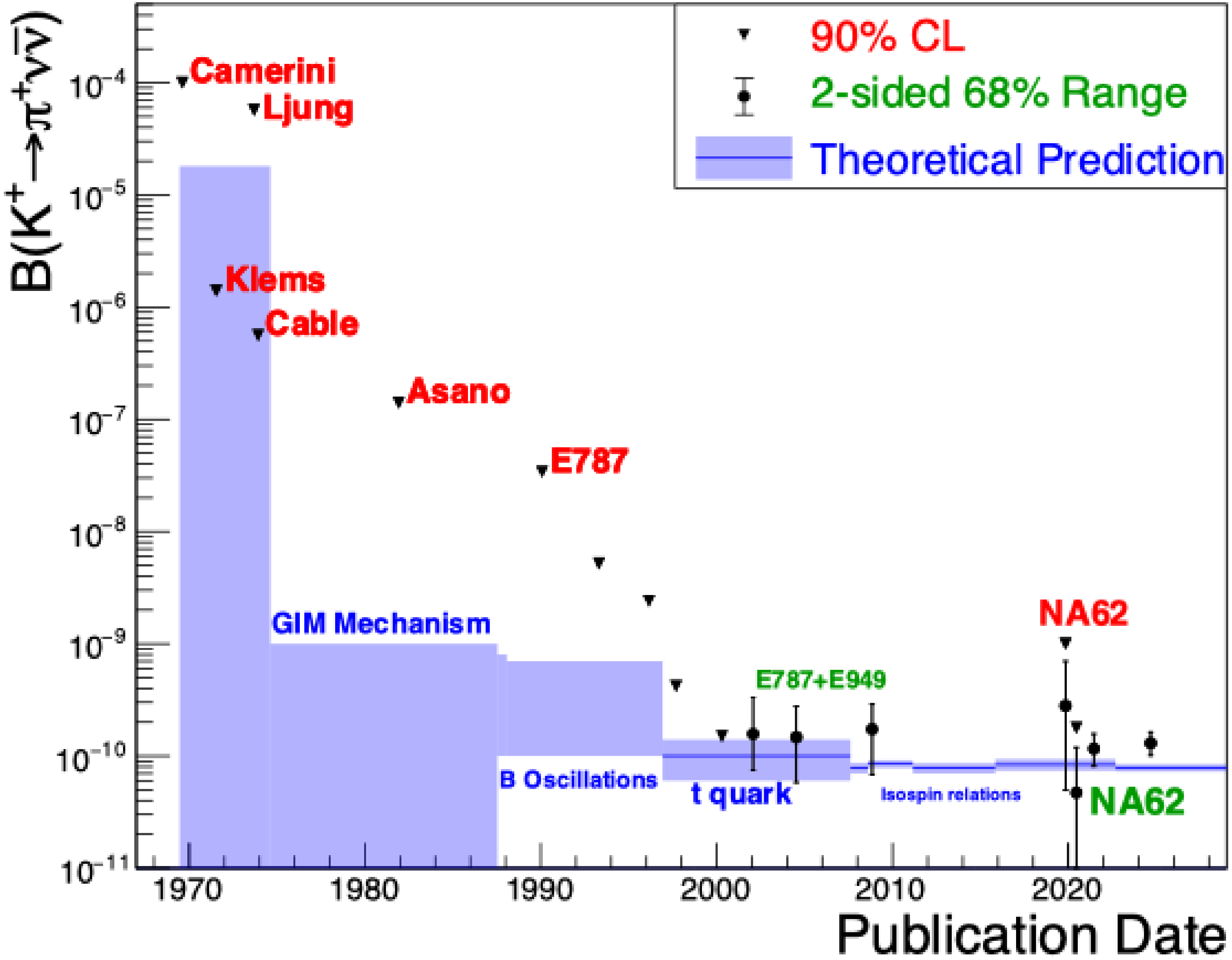
- Extremely sensitive to NP in several models depending on the NP flavour structure
  - Supersymmtery
  - Leptoquarks
  - Z' boson mediating tree-level FCNC
  - Non-SM Higgs boson

- NA62 is aiming at a $\mathcal{O}(15\%)$ measurement of $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ within the next few years

- $K_L \to \pi^0 \nu\bar{\nu}$ not yet observed: 1 experiment in Japan (KOTO @ JPARC) aiming to get an observation within the next decade years

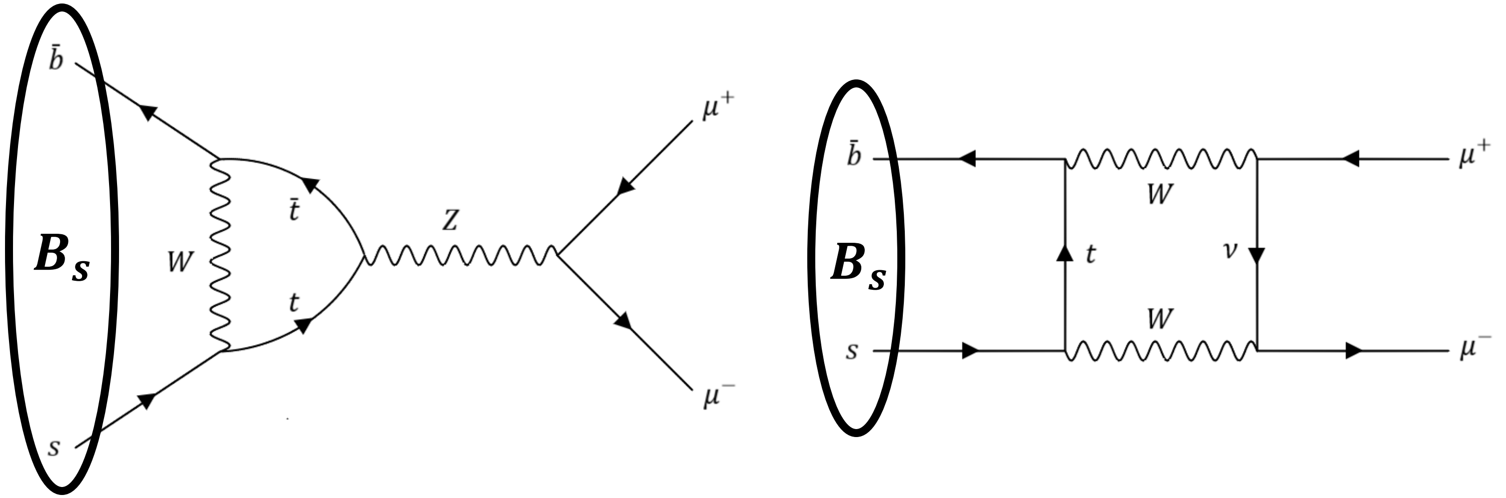


History of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay



The $B^0_{(s)} \to \mu^+\mu^-$ decay

- Loop-level process (box – EW penguin)
- CKM factor $|V_{tb}V^*_{td(s)}|^2$
- Helicity suppression $(m_\mu/m_B)^2$
- No γ penguin (Ward identity)
- Only top quark relevant in the loop



- SM prediction

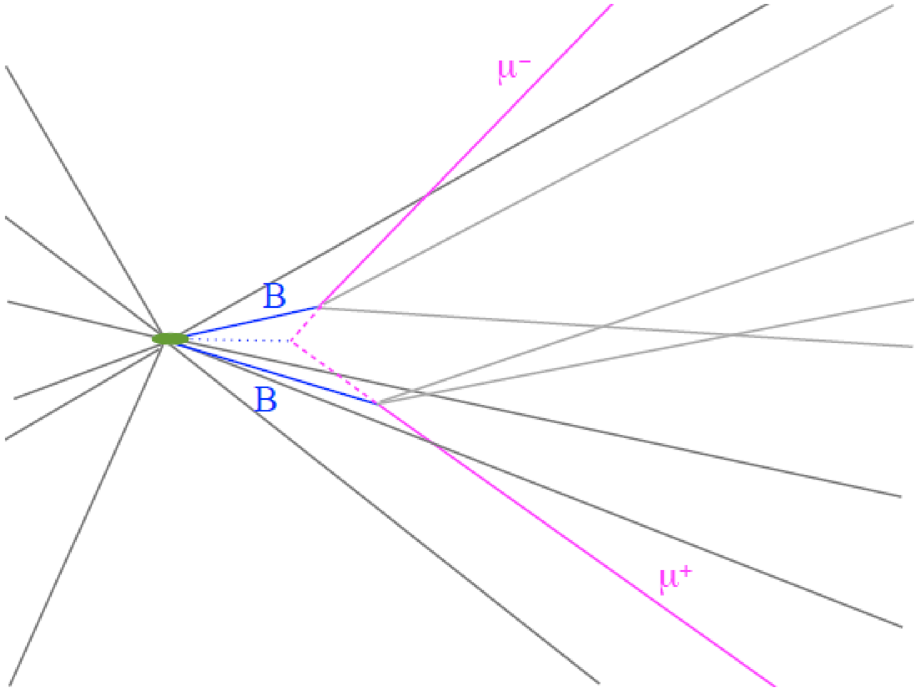
decay constant (lattice) — phase space — Wilson coefficient (diagram calculations)

$$BR(B^0_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2 f_{B_s}^2 \tau_{B_s} m_{B_s} m_\mu}{16\pi^3}|V_{tb}V^*_{ts}|^2 F(m_{\mu,B})|C_{10}|^2 \quad \begin{cases} BR(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14)\times 10^{-9} \\ BR(B^0_d \to \mu^+\mu^-) = (1.03 \pm 0.05)\times 10^{-10} \end{cases}$$

~5% theoretical uncertainty (precise measurement of CKM parameters crucial)

The $B^0_{(s)} \to \mu^+\mu^-$ @ LHCb

- **Signal signature**
  - 2 oppositely charged μ tracks originating from a vertex displaced from the primary vertex (PV), B coming from PV
- **Background**
  - combinatorial, μ from 2 semileptonic B decays
  - Machine learning methods to separate signal from background



- **Branching ratio measurement** (principle): $\mathrm{BR}\left(B^0_{(s)} \to \mu^+\mu^-\right) = \frac{\mathrm{BR}_{norm}\varepsilon_{norm}f_{norm}}{N_{norm}\varepsilon_{sig}f_{d(s)}} N\left(B^0_{(s)} \to \mu^+\mu^-\right)$
  - normalisation: $B^+ \to J/\psi\, K^+$, $B_d \to K^+\pi^-$, very well-known BR_{norm}, signal – like trigger/topology
  - normalisation (signal) efficiency $\varepsilon_{norm\,(sig)}$ from simulation and data-driven method (trigger, reco efficiency)
  - B fragmentation functions: f_s/f_d from LHCb measurement; f_d for both $B^+$and B^0

N.B. **time – integrated** $\mu\mu$ observed → effect of $\Delta\Gamma_s \neq 0$ can be different between SM and NP

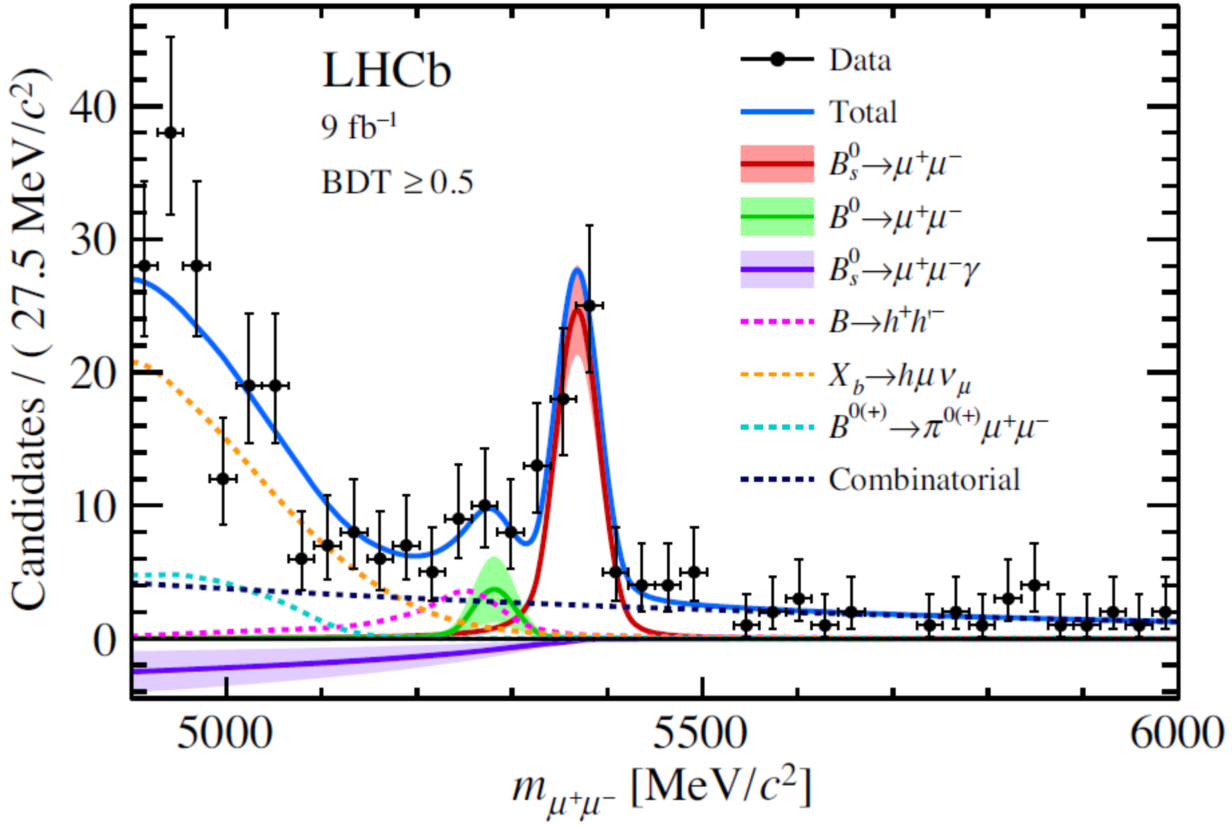
The $B^0_{(s)} \to \mu^+\mu^-$ @ LHCb: results

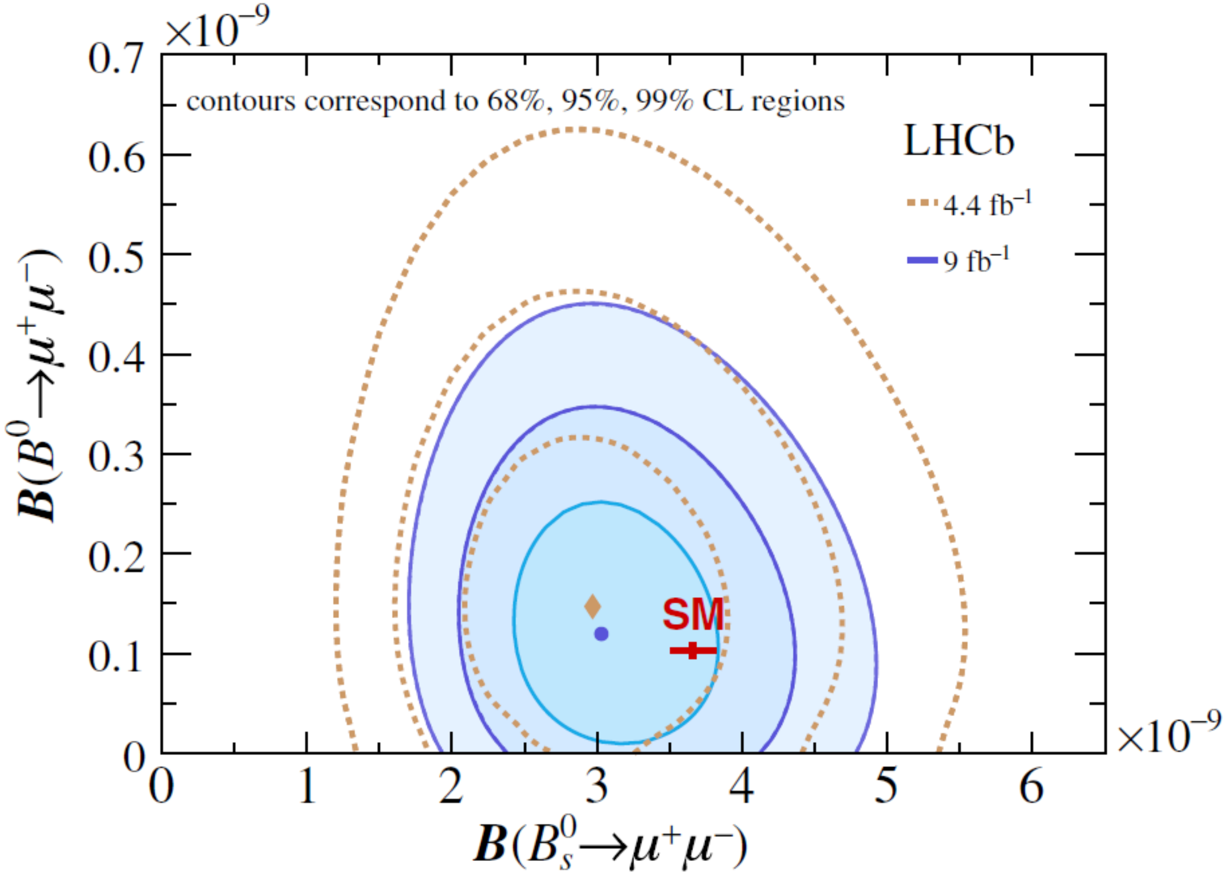
Phys. Rev. D **105**, 012010

- Data collected during Run1 (2011-2012) + Run2 (2015-2018)
- Luminosity 9 fb^{-1}

$$\text{BR}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}{}^{+0.13}_{-0.11}) \times 10^{-9}$$

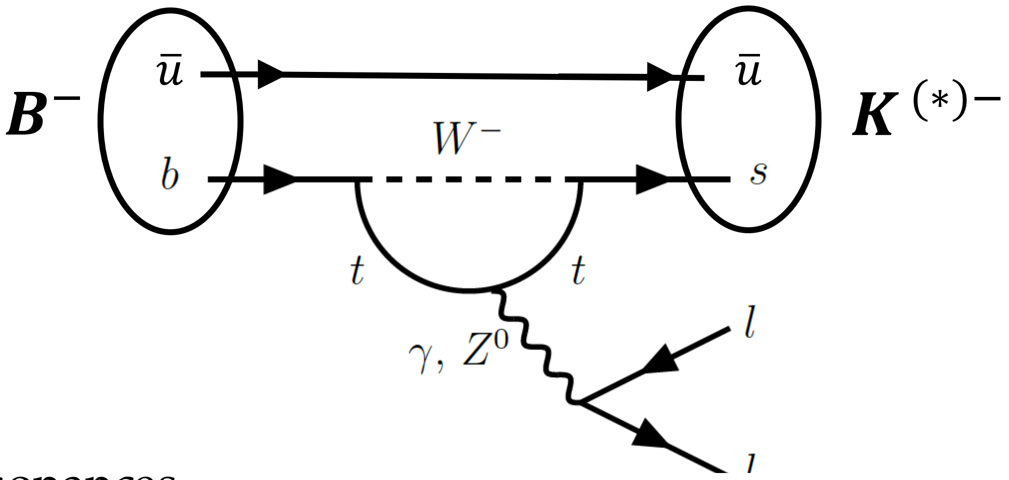
$$\text{BR}(B^0_d \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ @ 95\% CL}$$



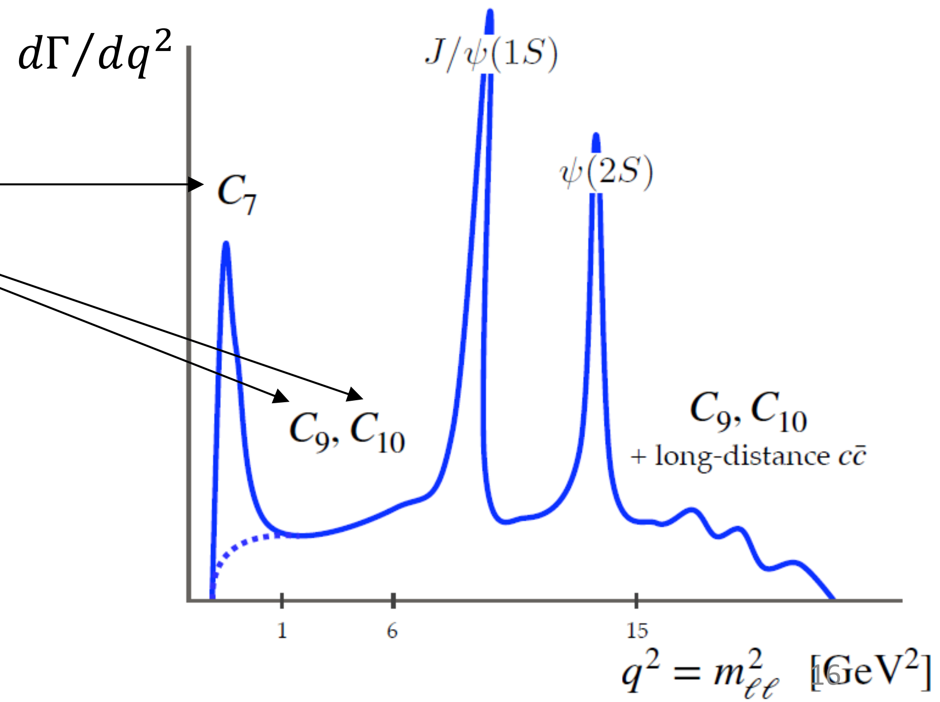


$b \to sl^+l^-$ decays

- Similar short distance structure as $B \to \mu\mu$
- Loop-level process (box – EW penguin)
- Z penguin: GIM suppression, CKM factor $|V_{tb}^* V_{ts}|^2$
- No protection from Ward identity: γ penguin possible
- Sizable hadronic uncertainties: form factors
- Non – perturbative long-distance effects: loop $c\bar{c}$ giving rise to resonances



- Effective field theory approach: $\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$
- Long-distance contributions **affect**:
  - Branching ratio (fully)
  - Angular distributions (partially)
- Long-distance contributions **does not affect**:
  - Lepton flavour universality ratios (e.g. $b \to s\mu^+\mu^- / b \to se^+e^-$)



Lepton Flavour Universality (LFU)

- **Accidental symmetries** of the SM $\mathcal{L}$ involving leptons

Symmetry (conservation law)	Type	Limit of validity	Observed violation
Total lepton number (LN)	Exact	$m_\nu = 0$ & ν Dirac particle	Never
Lepton flavour [individual lepton number] (LF)	Exact	$m_\nu = 0$	ν oscillation
Lepton flavour universality (LFU)	Almost exact	$y^2_{e,\mu,\tau} \ll g^2_i$	Maybe ?

- **LFU = universality* of decay amplitudes involving different leptons**
- Exact accidental symmetry of the gauge sector (+ quark Yukawa sector) of the SM
- Broken in the lepton Yukawa sector → $m_e \ll m_\mu \ll m_\tau$ → Yukawa couplings $y_e \ll y_\mu \ll y_\tau$
- Almost valid because $y^2_{e,\mu.\tau} \ll g^2_i$ with $g_i = e, g$ gauge couplings (EM, weak charges)

NP can easily violate LFU: non-universal coupling to the three lepton families

* *excluding pure kinematical effects*

Lepton Flavour Universality (LFU)

- **LFU observables:** any comparison between classes of decays involving different pairs of leptons

Tree level

Experiment	Observable	Measured value	SM prediction	
PIENU	$R^{\pi}_{e/\mu} = \frac{\text{BR}\left(\pi^+ \to e^+\nu_e(\gamma)\right)}{\text{BR}\left(\pi^+ \to \mu^+\nu_e(\gamma)\right)}$	$1.2327(23) \times 10^{-4}$	$1.23524(15) \times 10^{-4}$	Helicity suppression
NA62 KLOE	$R^{K}_{e/\mu} = \frac{\text{BR}\left(K^+ \to e^+\nu_e(\gamma)\right)}{\text{BR}\left(K^+ \to \mu^+\nu_e(\gamma)\right)}$	$2.488(9) \times 10^{-5}$	$2.477(1) \times 10^{-5}$	Helicity suppression
BESIII	$R_{J/\psi} = \frac{\text{BR}(J/\psi \to e^+e^-)}{\text{BR}(J/\psi \to \mu^+\mu^-)}$	$1.0016(31)$	1	

Lepton Flavour Universality (LFU)

- **LFU observables:** any comparison between classes of decays involving different pairs of leptons

- **Loop level** (B-factories, LHCb)

$$R_h = \frac{\mathrm{BR}(B \to h\mu^+\mu^-)}{\mathrm{BR}(B \to he^+e^-)} \qquad \begin{matrix} B = B^+ & h = K^+, K^{*+} \\ B = B^0 & h = K_S\,, K^{*0} \end{matrix}$$

$\boldsymbol{R_{K,K^*} = 1}$ **SM prediction**

Ratios very clean theoretically (few permille precision, uncertainty due to treatment of radiative corrections)

- **Tree level Cabibbo suppressed** (B-factories, LHCb)

$$R\left(D^{(*)}\right) = \frac{\mathrm{BR}\left(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathrm{BR}(\bar{B} \to D^{(*)}l^-\bar{\nu}_l)} \qquad \begin{matrix} B = B^- & D^0, D^{*0} \\ B = \bar{B}^0 & D^+, D^{*+} \end{matrix}$$

$l = e, \mu$ average

$\boldsymbol{R(D) = 0.299 \pm 0.003}$

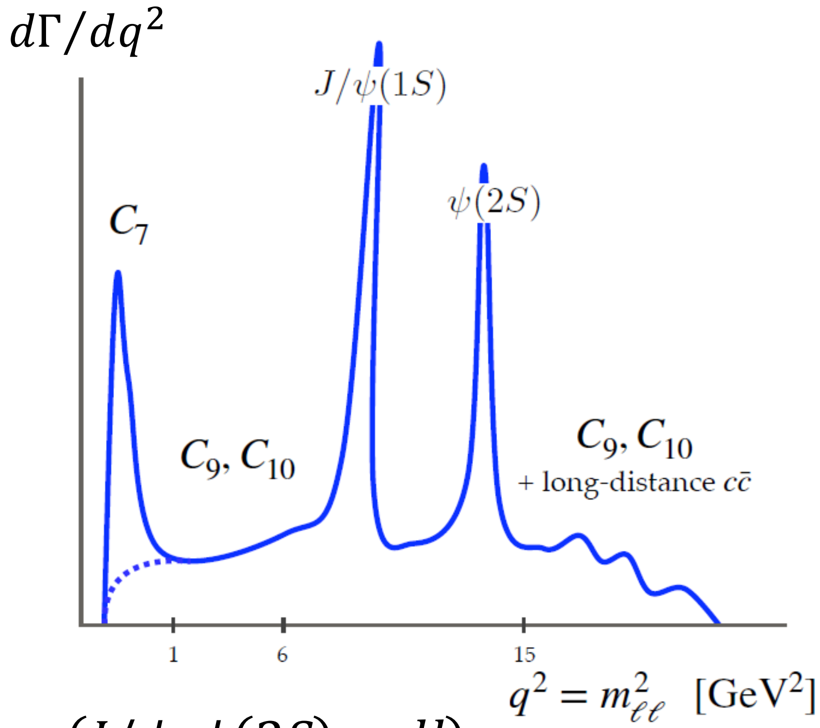
$\boldsymbol{R(D^*) = 0.2483 \pm 0.0016}$

SM prediction

LFU test: R_h

- **Experimental definition**

$$R_h[q^2_{min}, q^2_{max}] = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to h\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(B \to he^+e^-)}{dq^2} dq^2}$$



- Experiments measure R_h in q^2 regions away from charm resonances ($J/\psi, \psi(2S) \to ll$)
  - *B-factories:* full spectrum except for the regions around the peaks
  - *LHCb:* $B^+ \to K^+l^+l^-$ (R_K), $B^0 \to K^{*0}l^+l^-$ (R_{K^*})

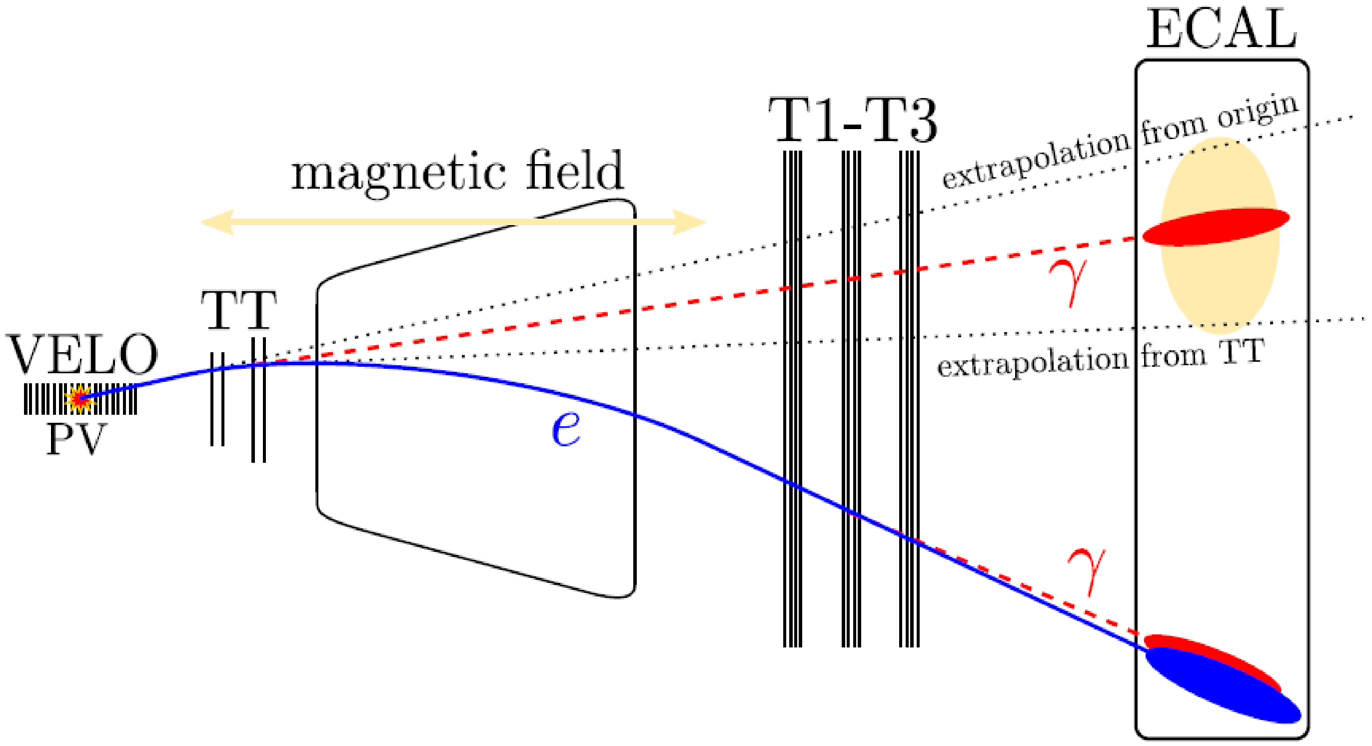
    $q^2 \in [1.1, 6.0]$ GeV^2 (central q^2), $q^2 \in [0.1, 1.1]$ GeV^2 (low q^2)

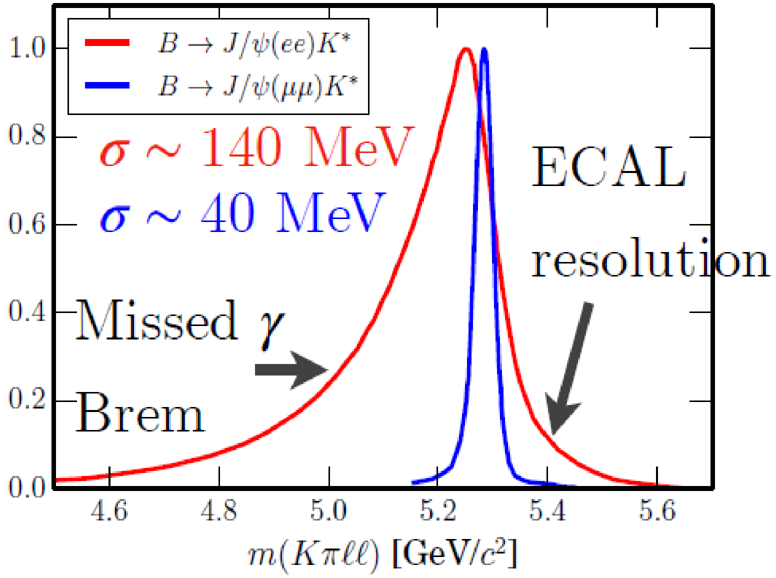
1

  - Different lepton pair kinematics in different regions
  - New Physics can affect different regions differently

LFU test: R_h (LHCb)

- **Experimental challenge:** different behaviour of e and μ
  - Bremsstrahlung → reconstruction efficiency, energy loss, kinematic resolution
  - Different energy release in calorimeters → trigger, particle identification efficiency
  - Muon particle identification → muon detector efficiency





LFU test: R_h (LHCb)

- **Experimental observable** (double ratio)**:**

$$R_h^{exp} = \frac{\text{BR}(B \to h\mu^+\mu^-)}{\text{BR}(B \to he^+e^-)} \cdot \frac{\text{BR}\big(B \to h\,J/\psi\,(e^+e^-)\big)}{\text{BR}\big(B \to h\,J/\psi\,(\mu^+\mu^-)\big)} = \frac{N_{\mu\mu}/\varepsilon_{\mu\mu}}{N_{\mu\mu}^{J/\psi}/\varepsilon_{\mu\mu}^{J/\psi}} \cdot \frac{N_{ee}^{J/\psi}/\varepsilon_{ee}^{J/\psi}}{N_{ee}/\varepsilon_{ee}}$$

- $\text{BR}(B \to hl^+l^-)$ restricted to a q^2 region $\propto N_{ll}/\varepsilon_{ll}$ (number of selected signal events / signal efficiency)
- $\text{BR}\big(B \to h\,J/\psi\,(l^+l^-)\big)$ charm resonance $\propto N_{ll}^{J/\psi}/\varepsilon_{ll}^{J/\psi}$

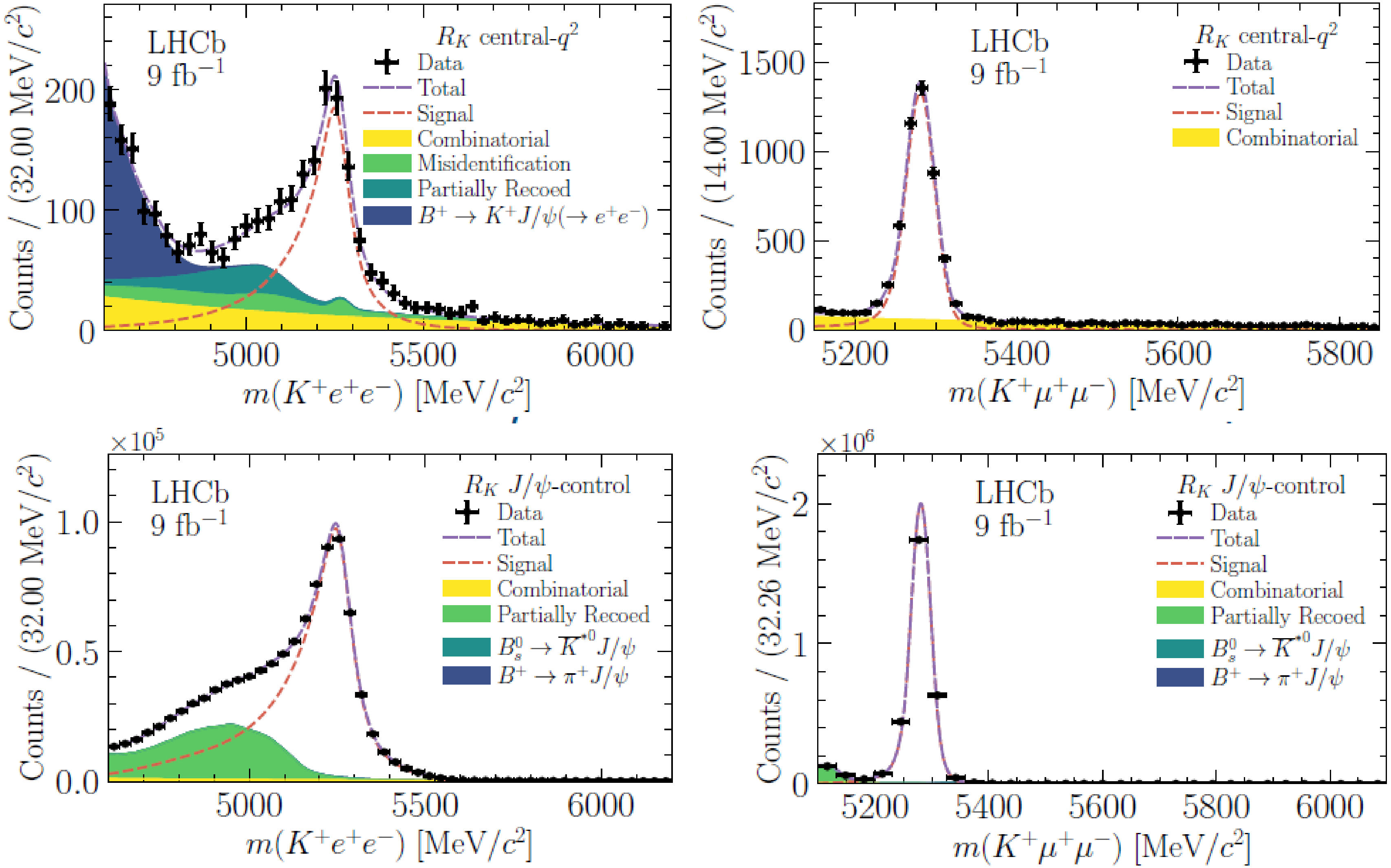
- Double ratio to mitigate $\mu - e$ differences:
  - “first-order” cancellation of systematics uncertainties of $\varepsilon_{\mu\mu}$ and ε_{ee} separately
  - residual difference from different ll kinematics between hll and $h\,J/\psi\,(ll)$
  - Cancellation does not apply to background: very different background in the 4 samples

- **LHCb: simultaneous measurements of R_K and R_{K^*}**

LFU test: R_h (LHCb)

Phys. Rev. D 108 (2023) 032002

- Background from particle misidentification critical
  - modeled using data-driven approach
- Different background depending on q^2 and B^+, B^0 modes (not shown here)
- Fit to the B^+, B^0 mass spectra to extract the number of signal $K^+l^+l^-$, $K^{*0}l^+l^-$ events

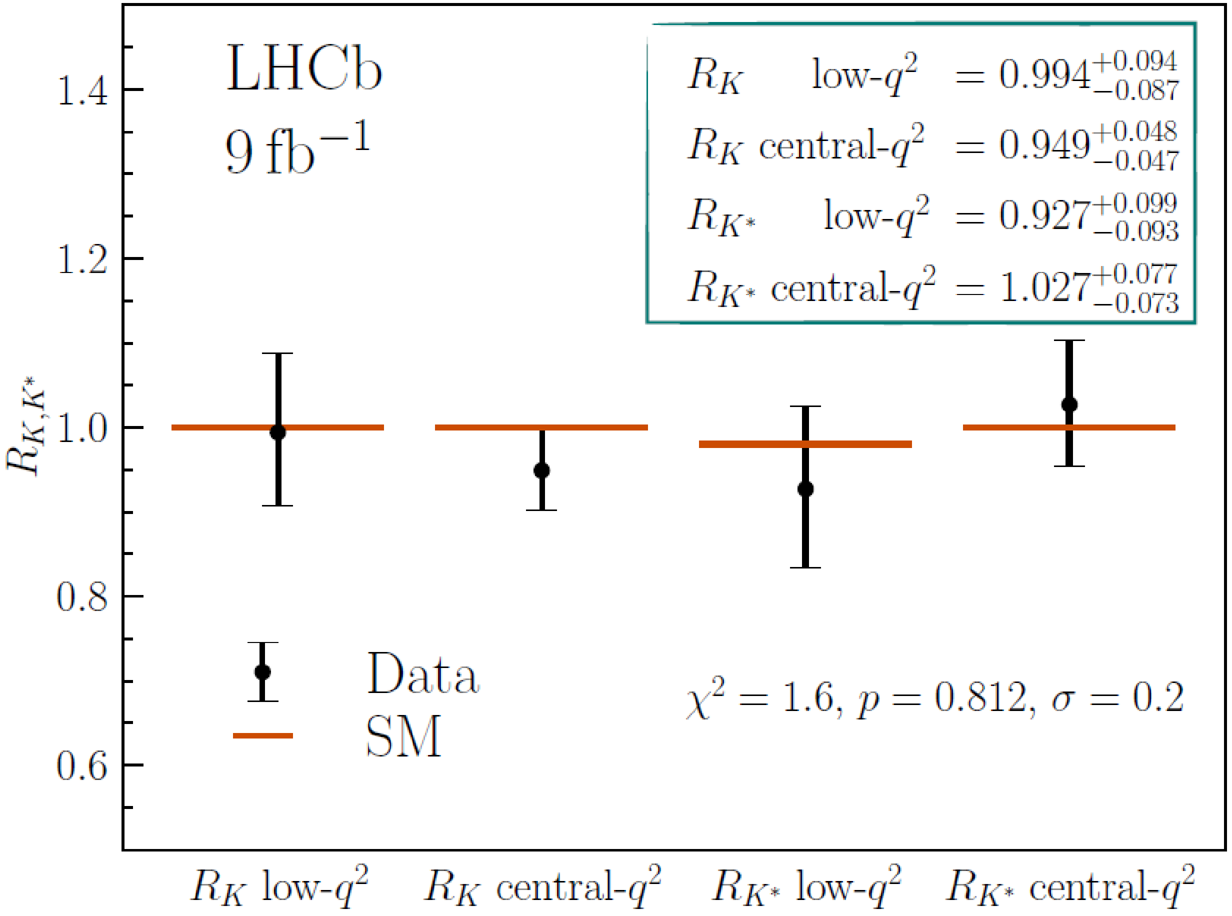


LFU test: R_K (LHCb)

Phys. Rev. D 108 (2023) 032002

$$\text{low-}q^2 \begin{cases} R_K = 0.994\,^{+0.090}_{-0.082}\,(\text{stat})\,^{+0.027}_{-0.029}\,(\text{syst}), \\ R_{K^*} = 0.927\,^{+0.093}_{-0.087}\,(\text{stat})\,^{+0.034}_{-0.033}\,(\text{syst}) \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\,^{+0.042}_{-0.041}\,(\text{stat})\,^{+0.023}_{-0.023}\,(\text{syst}), \\ R_{K^*} = 1.027\,^{+0.072}_{-0.068}\,(\text{stat})\,^{+0.027}_{-0.027}\,(\text{syst}). \end{cases}$$



Results compatible with SM

(older, less precise) results from Belle – Babar also compatible with SM

Non-leptonic meson decays

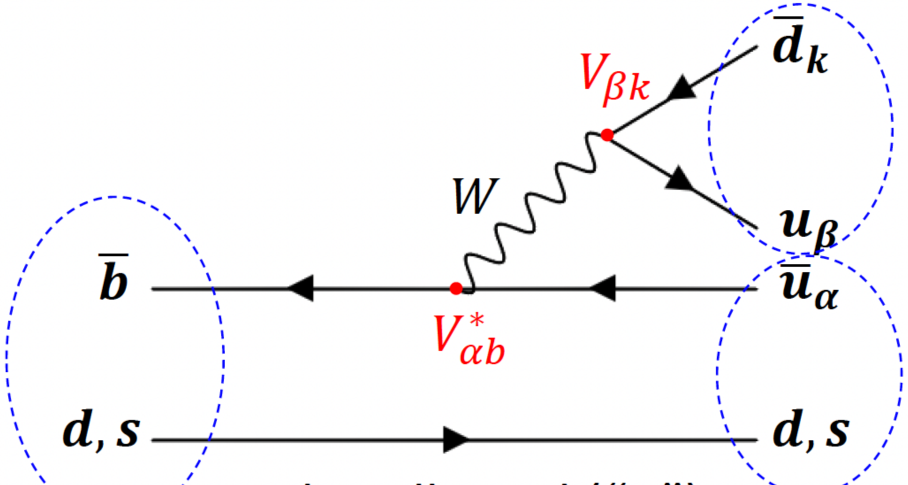
- **Decay to mesons** (+ possible photons)
  - Kaons: $\pi\pi, \pi\pi\pi$
  - $D-$mesons: $\underbrace{K, \pi, \eta, \eta'}, \underbrace{K^*, \rho, \phi, \omega}$ + excited states
  - $B-$mesons: $\underbrace{D, D_s, K, \pi, \eta, \eta', \eta_c}_{pseudoscalar}, \underbrace{D^*, D_s^*, K^*, \rho, \phi, \omega, J/\psi, \psi}_{vector}$ + excited states

- **Theoretical treatment**
  - Short Distance (SD): ≥ 1 amplitudes can contribute to the same final state
  - Long Distance (LD): hadronisation crucial (EFT), gives rise to large theoretical uncertainties

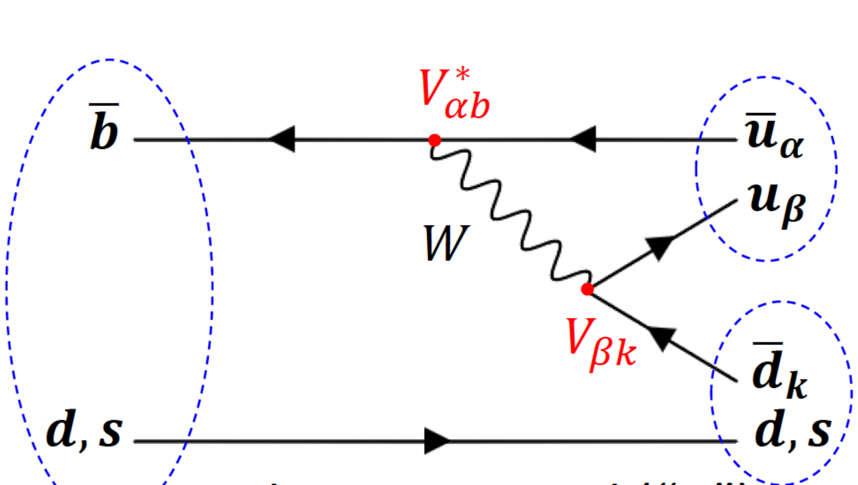
- **Experimental signature**
  - cascade of decays (B, D mesons), several particles in the final states (including leptons)
  - different timings in the decay depending on the final-state mesons (resonances, $D-$mesons, kaons)

$B^0_{d,s}$ decays to two mesons

- **Tree-level** amplitudes (quark spectator approximation)



color-allowed (“T”)



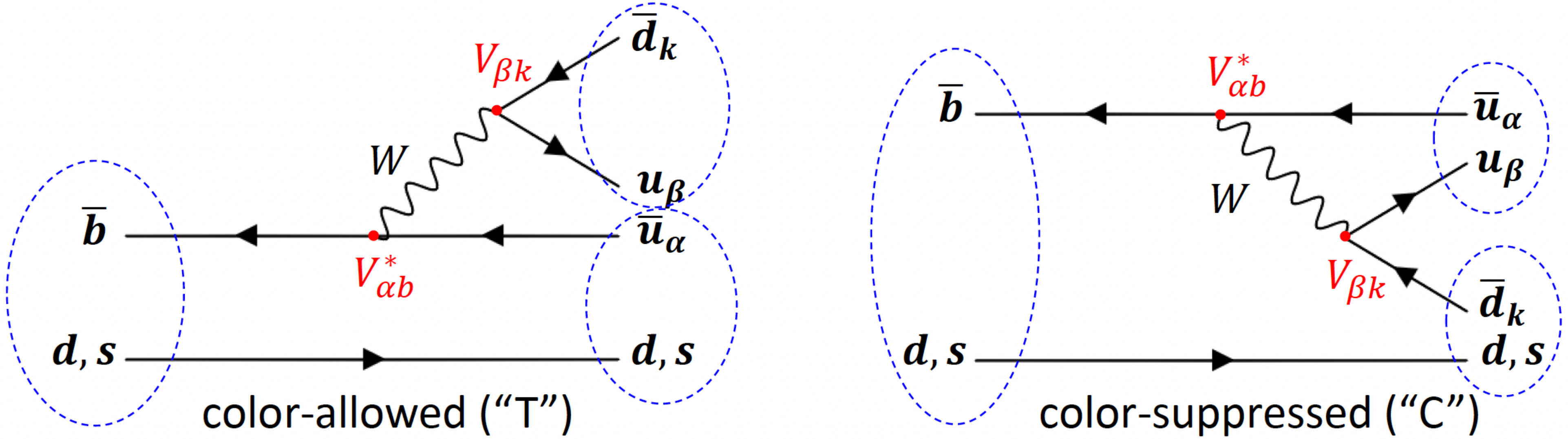
color-suppressed (“C”)

$\bar{b} \to \bar{u}_\alpha u_\beta \bar{d}_k$			B^0_d
$\bar{c}c\bar{s}$	$V^*_{cb}V_{cs}$	$A\lambda^2$	$D^+_s D^-, J/\psi K^0,$
$\bar{c}u\bar{s}$	$V^*_{cb}V_{us}$	$A\lambda^3$	$K^+D^-, \bar{D}^0 K^0,$
$\bar{u}c\bar{s}$	$V^*_{ub}V_{cs}$	$A\lambda^3 R_b e^{i\gamma}$	$D^+_s\pi^-, D^0K^0,$
$\bar{u}u\bar{s}$	$V^*_{ub}V_{us}$	$A\lambda^4 R_b e^{i\gamma}$	$K^+\pi^-, K^0\pi^0,$

			B^0_d
$\bar{c}c\bar{d}$	$V^*_{cb}V_{cd}$	$A\lambda^3$	$D^+D^-, J/\psi\pi^0,$
$\bar{c}u\bar{d}$	$V^*_{cb}V_{ud}$	$A\lambda^2$	$\pi^+D^-, \bar{D}^0\pi^0,$
$\bar{u}c\bar{d}$	$V^*_{ub}V_{cd}$	$A\lambda^4 R_b e^{i\gamma}$	$D^+\pi^-, D^0\pi^0,$
$\bar{u}u\bar{d}$	$V^*_{ub}V_{ud}$	$A\lambda^3 R_b e^{i\gamma}$	$\pi^+\pi^-, \pi^0\pi^0,$

$B^0_{d,s}$ decays to two mesons

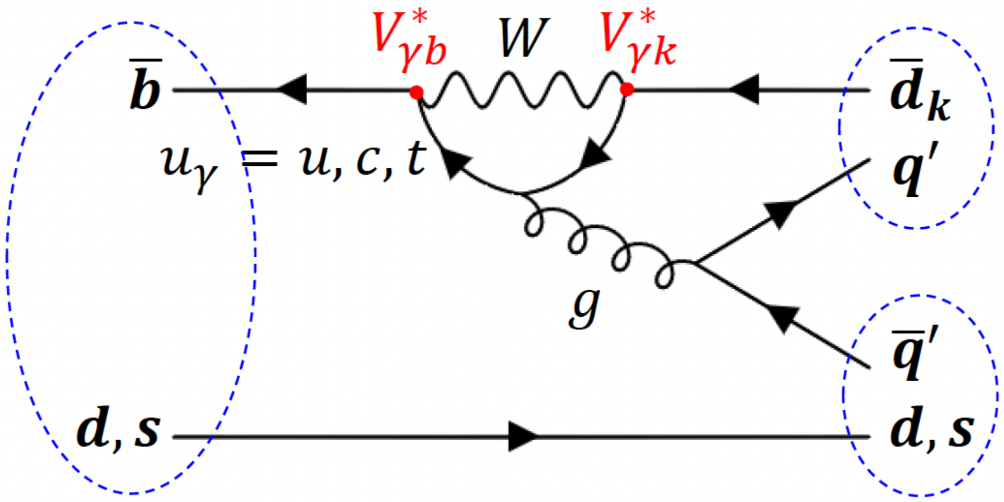
- **Tree-level** amplitudes (quark spectator approximation)



- Color suppression ~ 1/3: u_β $(\bar{d}_k)$ color must create a color singlet with u_α (d, s)
- Final states common to both $B^0_{d,s}$ and $\bar{B}^0_{d,s}$ $(e.g\ D^+D^-, \pi^0\pi^0, J/\psi, K^0_{S,L}, \ldots)$
- Final states CP-eigenstates $\bar{B}^0_{d,s}$ $(e.g\ D^+D^-, \pi^0\pi^0, J\psi, K^0_{S,L}, D_{f_{CP}}K^0_{S,L}, D_{f_{CP}}\pi^0\ \ldots)$
- Final states with 2 tree-level amplitudes $(D_{f_{CP}}K^0_{S,L}, D_{f_{CP}}\pi^0, \ldots)$

NB: not all mesons have a single $q\bar{q}'$ component ($e.g. \pi^0 \propto d\bar{d} - u\bar{u}$)

$B^0_{d,s}$ decays to two mesons



- **Gluonic-penguin** amplitudes $\bar{b} \to \bar{d}_k q' \bar{q}'$
  - $q'\bar{q}'$ can not form a meson because g carries color
  - can only form a meson if more than one gluon in the diagram ("singlet penguin")
  - flavour suppression (CKM factors)
  - loop suppression + GIM enhancement of $t \sim \frac{\alpha_s}{12\pi} \ln\frac{m_t^2}{m_b^2} \sim 0.04$

Intermediate quark

$\bar{s}q'\bar{q}'$

t	$V^*_{tb}V_{ts}$	$A\lambda^2$
c	$V^*_{cb}V_{cs}$	$A\lambda^2$
u	$V^*_{ub}V_{us}$	$A\lambda^4 R_b e^{i\gamma}$

$q' = c, u$ $\quad D_s^+ D^-, K^+\pi^-$
s, d $\quad \phi K^0, K^0\pi^0$ $\quad \boldsymbol{B^0_d}$

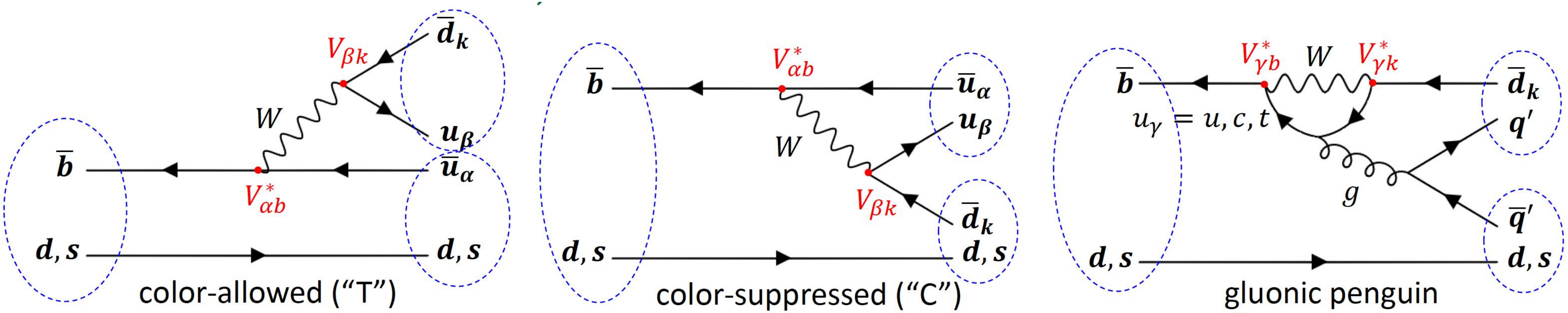
Intermediate quark

$\bar{d}q'\bar{q}'$

t	$V^*_{tb}V_{td}$	$A\lambda^3 R_t e^{-i\beta}$
c	$V^*_{cb}V_{cd}$	$A\lambda^3$
u	$V^*_{ub}V_{ud}$	$A\lambda^3 R_b e^{i\gamma}$

$q' = c, u$ $\quad D^+ D^-, \pi^+\pi^-$
s, d $\quad \bar{K}^0 K^0, \pi^0\pi^0$ $\quad \boldsymbol{B^0_d}$

$B^0_{d,s}$ decays to two mesons



Several combinations of amplitudes to the same final state*

- only tree $\bar{b} \to [\bar{c}u]\bar{s}, [\bar{u}c]\bar{s}, [\bar{c}u]\bar{d}, [\bar{u}c]\bar{d}$ $\bar{b} \to \bar{c}[u\bar{s}], \bar{u}[c\bar{s}], \bar{c}[u\bar{d}], \bar{u}[c\bar{d}]$
- only penguins $\bar{b} \to [\bar{s}s]\bar{s}, [\bar{d}s]\bar{s}, [\bar{s}d]\bar{d}, [\bar{d}d]\bar{d}$
- tree & penguins [charged] $\bar{b} \to [\bar{s}c]\bar{c}, [\bar{d}c]\bar{c}, [\bar{s}u]\bar{u}, [\bar{d}u]\bar{u}$
- tree & penguins ** [neutral] $\bar{b} \to \bar{s}[c\bar{c}], \bar{d}[c\bar{c}]$ $\bar{b} \to \bar{s}[u\bar{u}], \bar{d}[u\bar{u}]$

* [ ] Quarks forming a meson ** $[c\bar{c}]$ singlet penguins

$B_{d,s}^0$ decays to two mesons (examples)

B_d^0	Tree level (color supp)	Penguin	Singlet Penguin	"Final state"
$\bar{b}d \to [\bar{d}c][\bar{c}d]$	$A\lambda^3$ (T)	$A\lambda^3 R_t e^{-i\beta}$	–	D^+D^-
$\bar{b}d \to [\bar{d}u][\bar{u}d]$	$A\lambda^3 R_b e^{i\gamma}$ (T)	$A\lambda^3 R_t e^{-i\beta}$	–	$\pi^+\pi^-$
$\bar{b}d \to [\bar{c}u][\bar{s}d]$	$A\lambda^3$ (C)	–	–	$\bar{D}^0K^0$
$\bar{b}d \to [\bar{u}c][\bar{s}d]$	$A\lambda^3 R_b e^{i\gamma}$ (C)	–	–	D^0K^0
$\bar{b}d \to [\bar{c}u][\bar{d}d]$	$A\lambda^2$ (C)	–	–	$\bar{D}^0\pi^0$
$\bar{b}d \to [\bar{u}c][\bar{d}d]$	$A\lambda^4 R_b e^{i\gamma}$ (C)	–	–	$D^0\pi^0$
$\bar{b}d \to [\bar{s}d][\bar{u}u]$	$A\lambda^4 R_b e^{i\gamma}$ (C)	–	–	$K^0\pi^0$
$\bar{b}d \to [\bar{s}d][\bar{d}d]$	–	$A\lambda^2$	–	
$\bar{b}d \to [\bar{d}d][\bar{u}u]$	$A\lambda^3 R_b e^{i\gamma}$ (C)	–	–	$\pi^0\pi^0$
$\bar{b}d \to [\bar{d}d][\bar{d}d]$	–	$A\lambda^3 R_t e^{-i\beta}$	–	
$\bar{b}d \to [\bar{s}d][\bar{c}c]$	$A\lambda^2$ (C)	–	$A\lambda^2$	$J/\psi K^0$
$\bar{b}d \to [\bar{d}d][\bar{c}c]$	$A\lambda^3$ (C)	–	$A\lambda^3 R_t e^{-i\beta}$	$J/\psi\pi^0$
$\bar{b}d \to [\bar{s}s][\bar{s}d]$	–	$A\lambda^2$	$A\lambda^2$	ϕK^0
$\bar{b}d \to [\bar{d}s][\bar{s}d]$	–	$A\lambda^3 R_t e^{-i\beta}$	$A\lambda^3$	$K^0\bar{K}^0$

Non-leptonic meson decays

- Experimentally relevant for the study of CP violation and therefore to the measurement of the angles of the unitarity triangle!

- $K \to \pi\pi$ $\implies$ CP violation in kaons
- $B \to J/\psi K^0$ $\implies$ Measurement of β
- $B \to \pi\pi$
- $B \to \rho\rho$

  } Measurement of α
- $B \to DK$
- $B \to K\pi$

  } Measurement of γ

Summary of Lecture 10

Main learning outcomes

- How measurements of the very rare $\Delta F = 1$ Flavour Changing Neutral Currents of B and K mesons are conducted
- How to test Lepton Flavour Universality (accidental symmetry of the SM) using meson decays
- Classification of the non-leptonic meson decays of B mesons