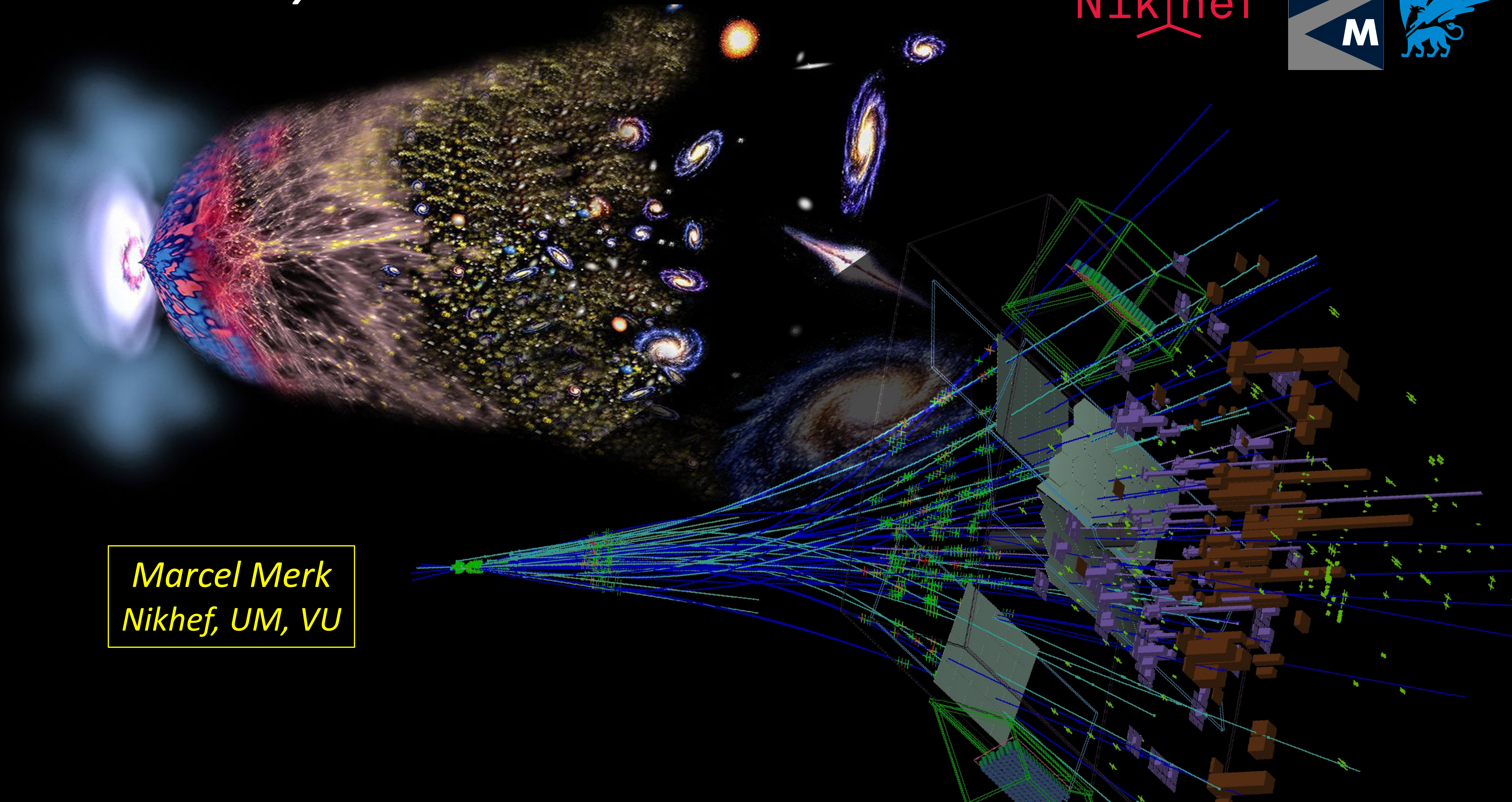
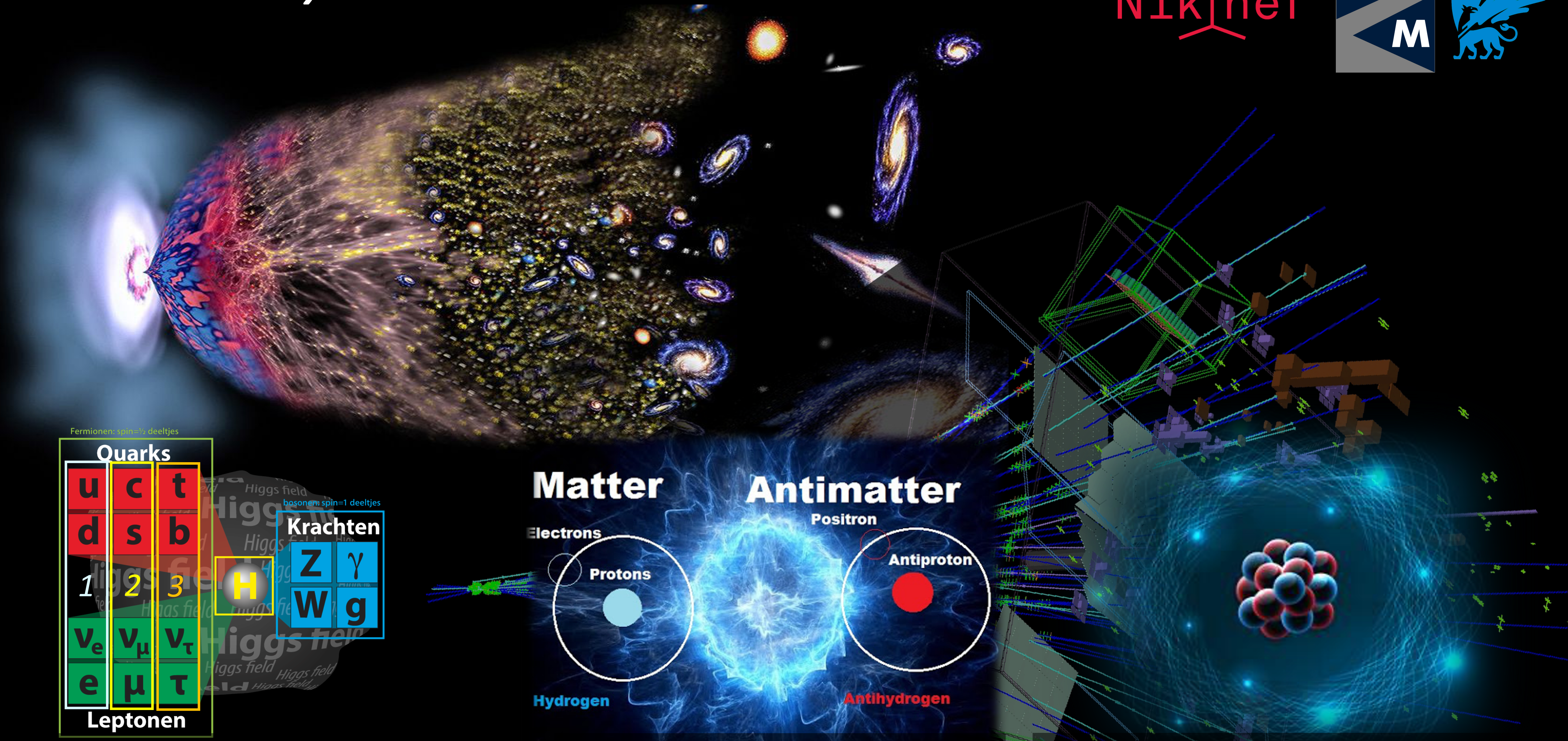
# *Flavour Physics and CP Violation*



*Marcel Merk*
*Nikhef, UM, VU*

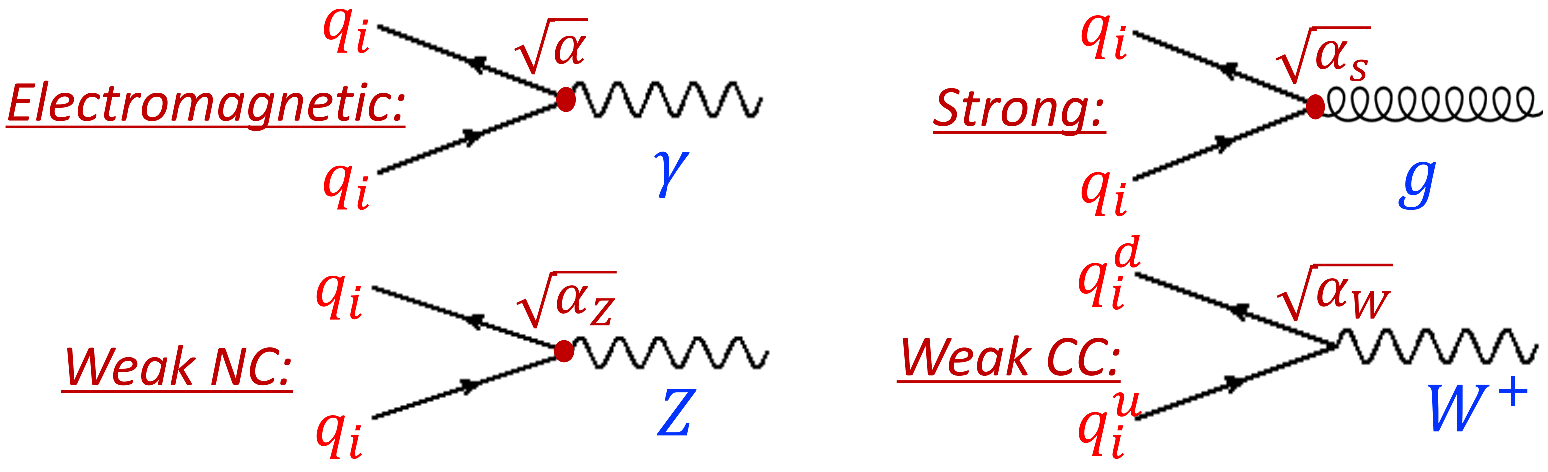
# Flavour Physics and CP Violation



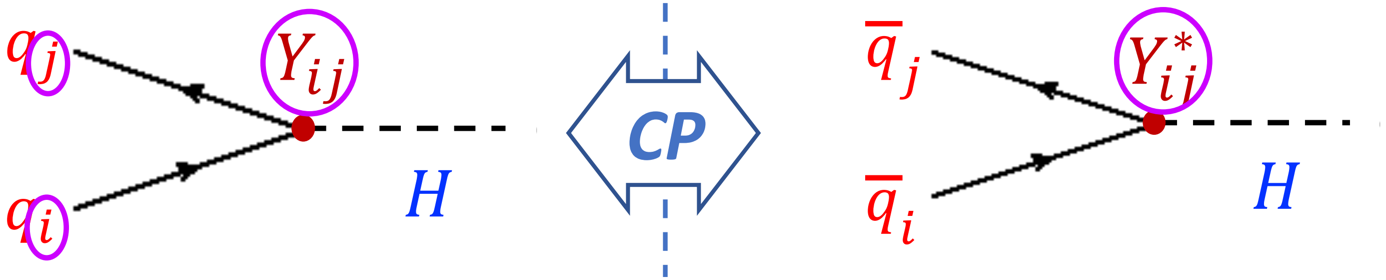

***Why three generations of particles?*** ***Why is there no antimatter?*** ***Why is an atom electric neutral?***

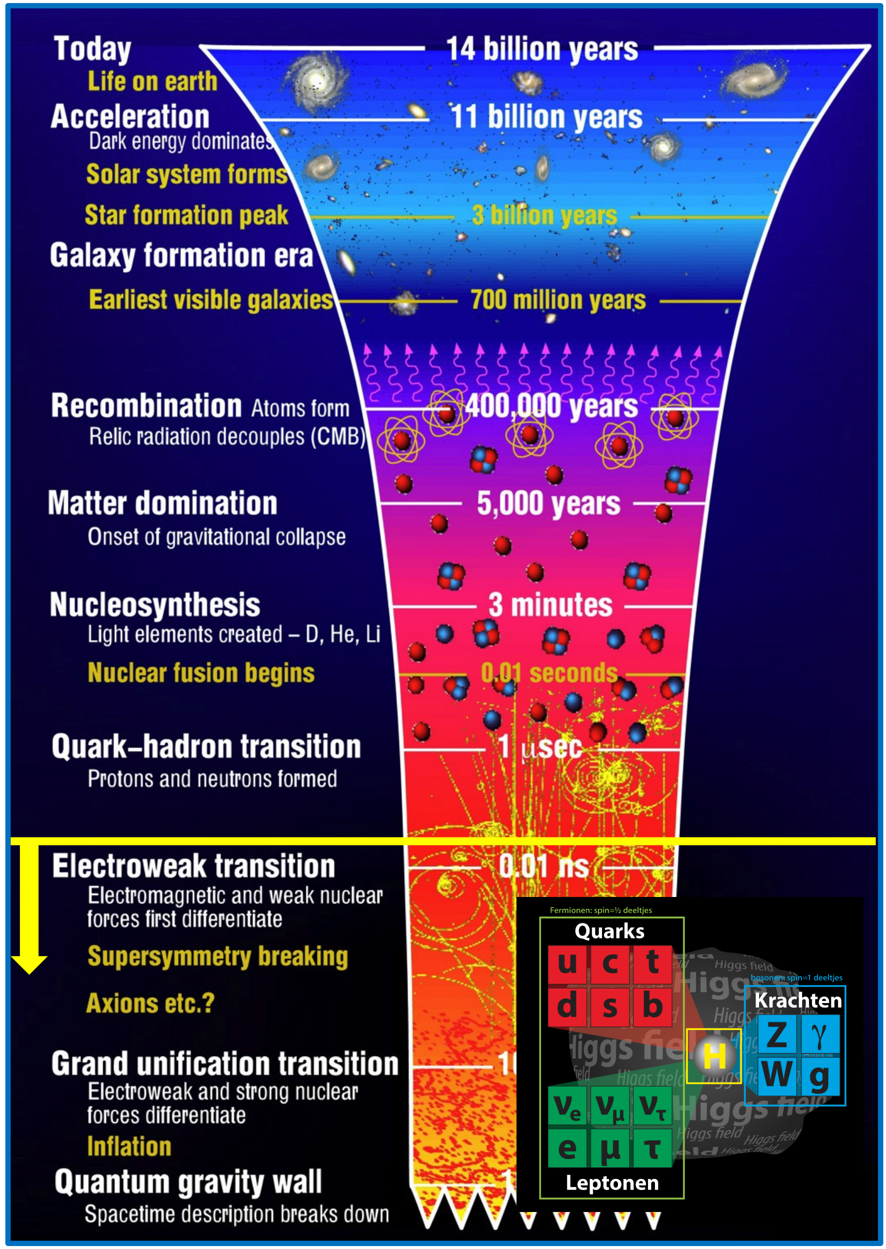
# Recap: Flavour Universality in very Early Universe

- Quark and lepton generations interact identically
  - No difference between particles of different generation?
  - No matter – antimatter asymmetry (CP Violation)?




- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!

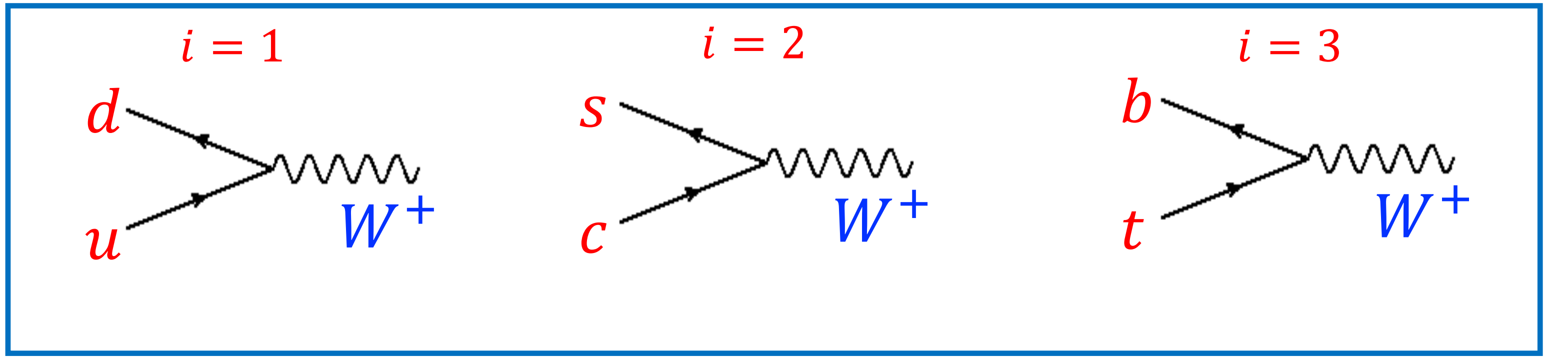


# Recap: Flavour Universality in very Early Universe



- Weak charged current interaction: $(i \leftrightarrow i)$

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  - Higgs coupling is *not universal*, and mixes generations
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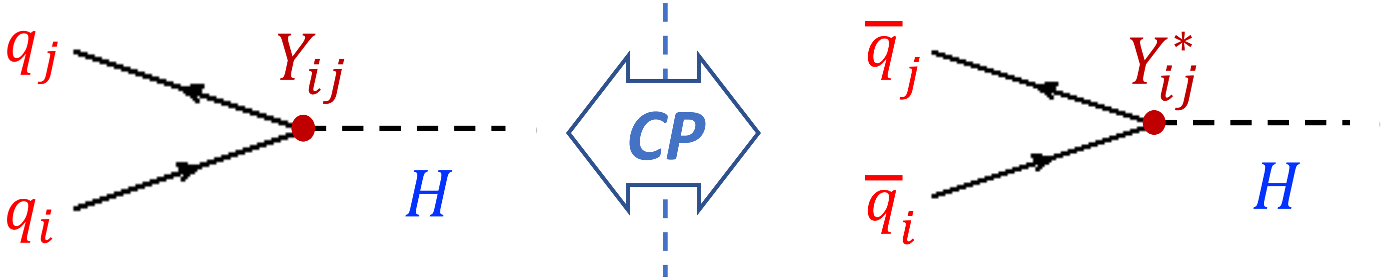
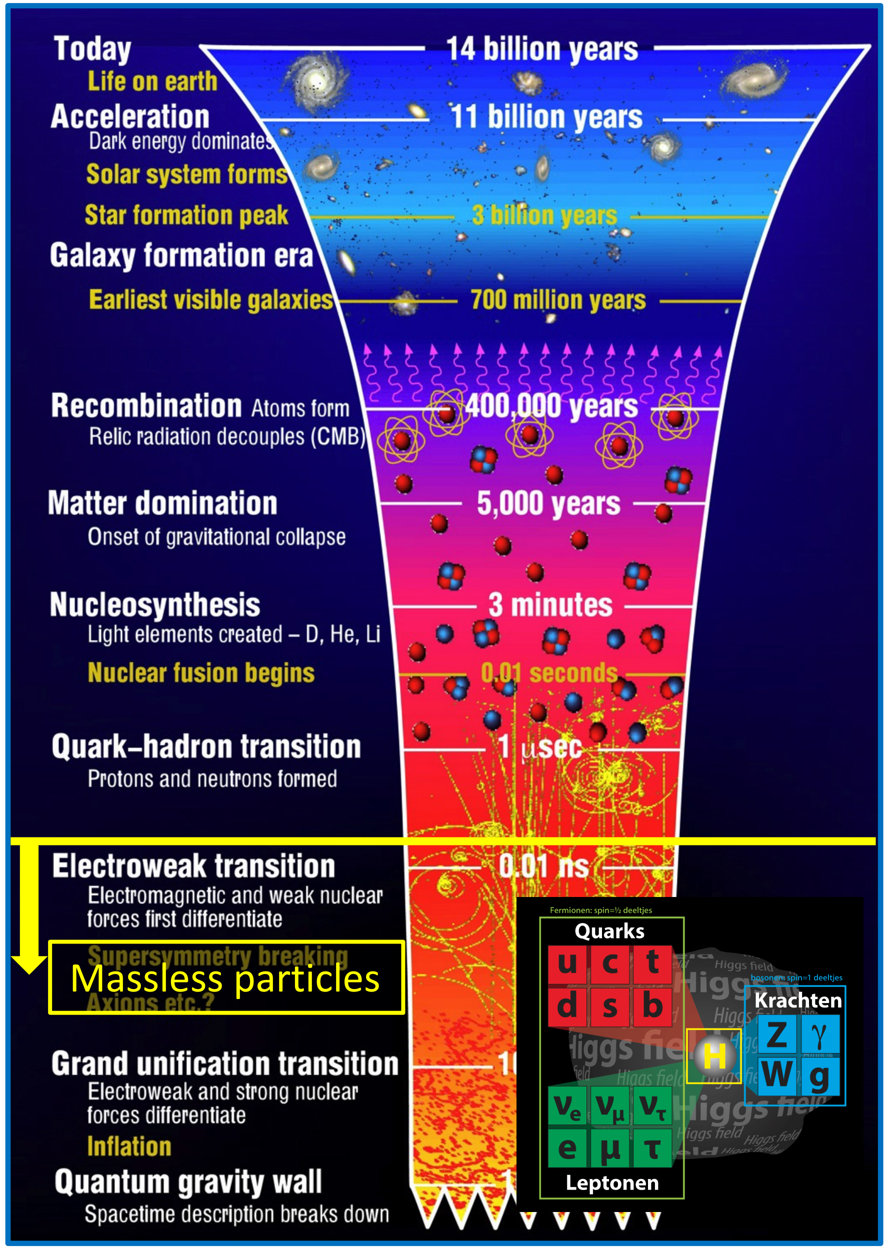
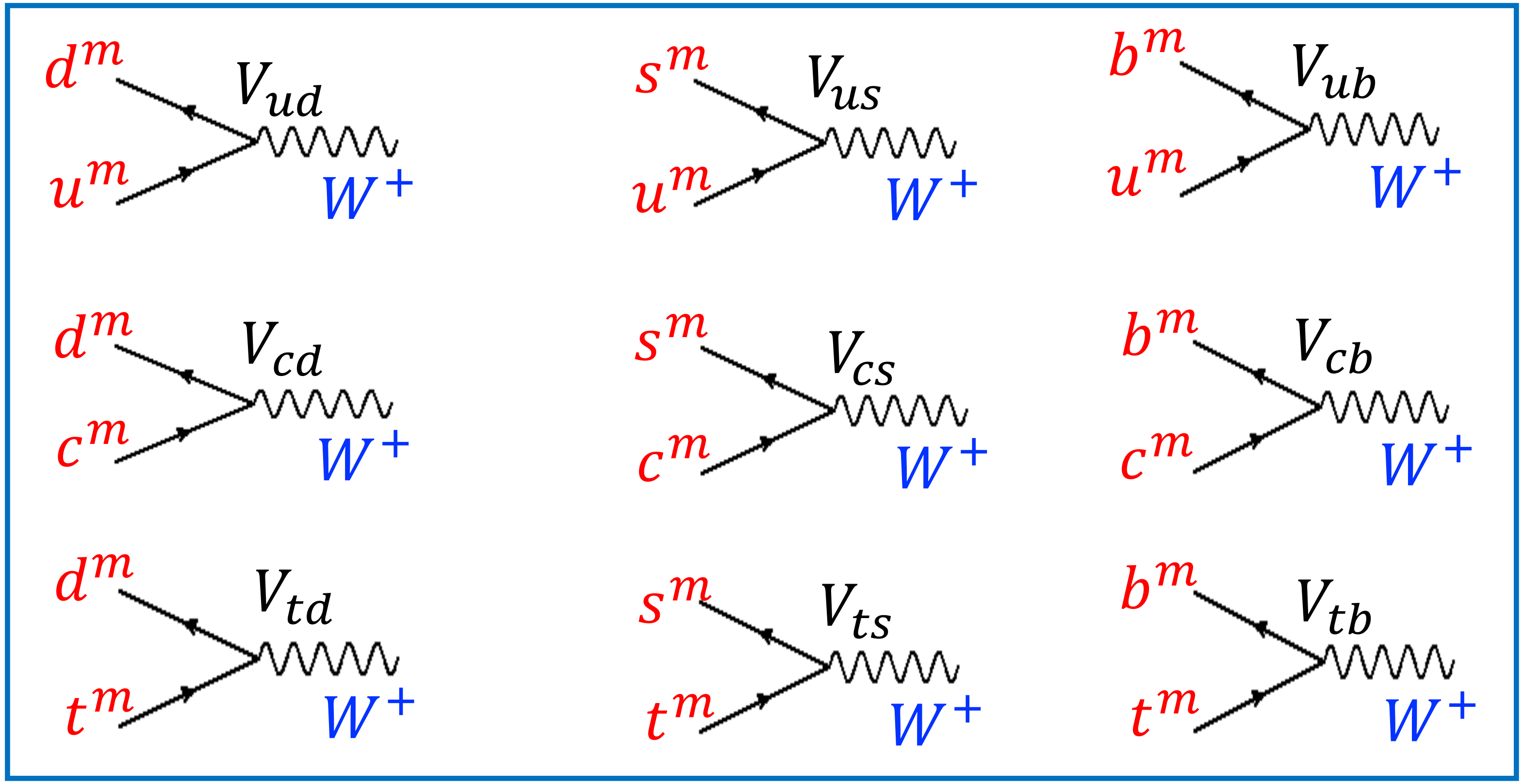
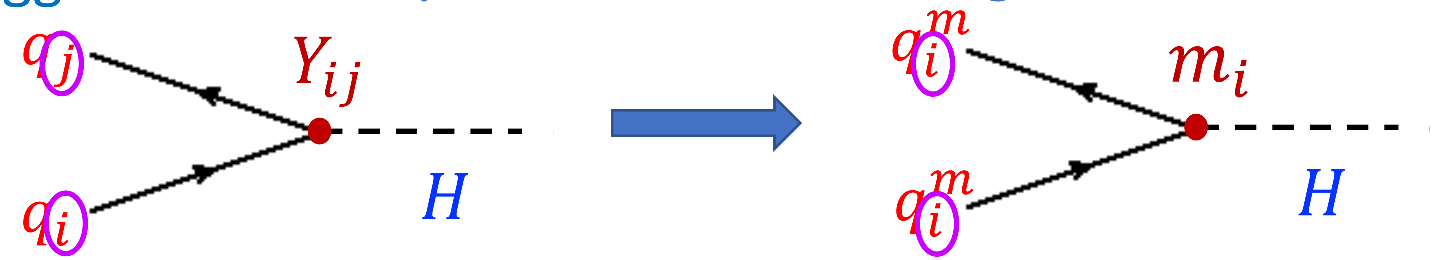


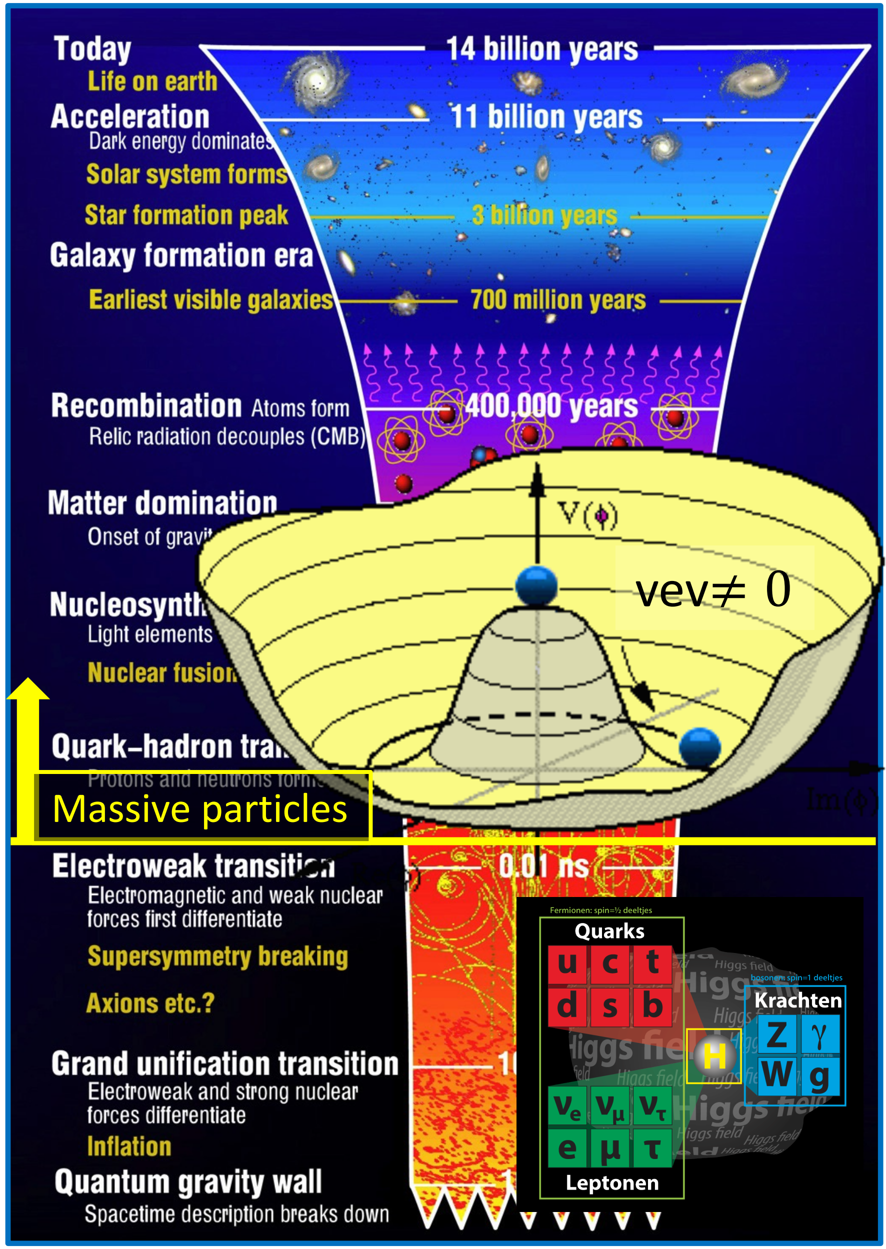



- Weak charged current interaction: $(i \leftrightarrow j)$



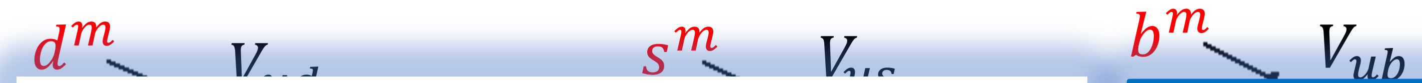

- Higgs: redefines quark states in mass eigenstates: $(i \leftrightarrow i)$



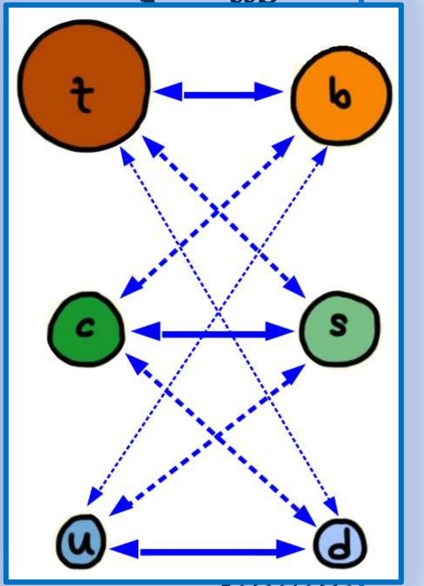



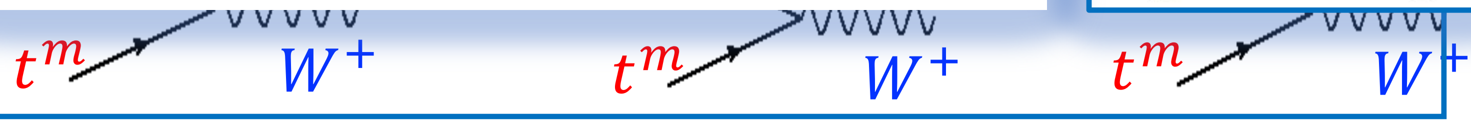
# Recap: Flavour Universality → Symmetry Breaking → Flavour Mixing

- Weak charged current interaction:

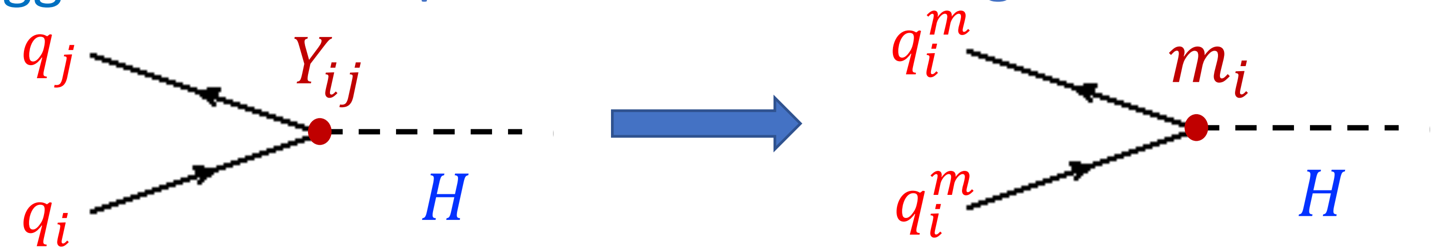


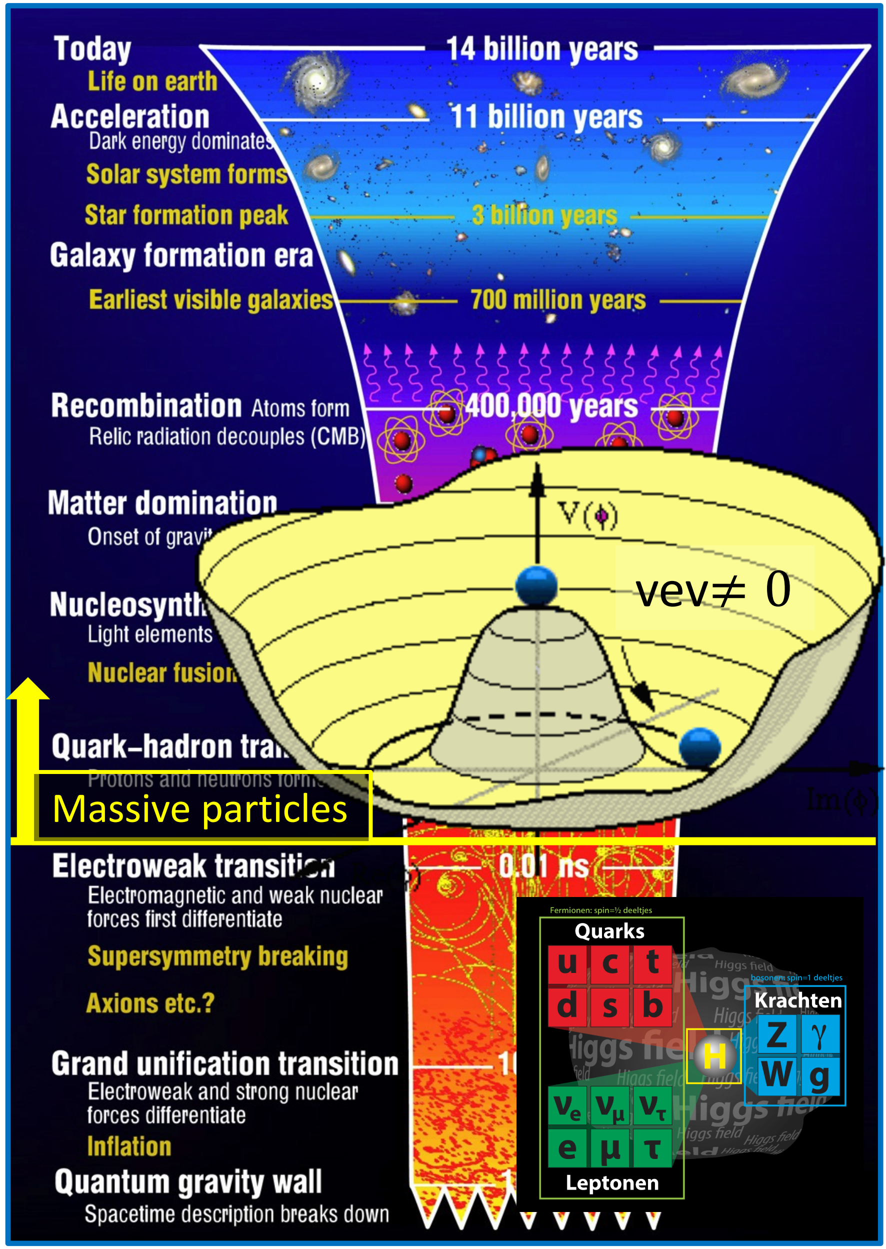

- Weak interactions mixes the generations of *mass eigenstates.*
- Complex couplings $V_{ij}$ allow for CP violating phenomena.
  - <u>*At least 3 generations required!*</u>




- Higgs: redefines quark states in mass eigenstates:



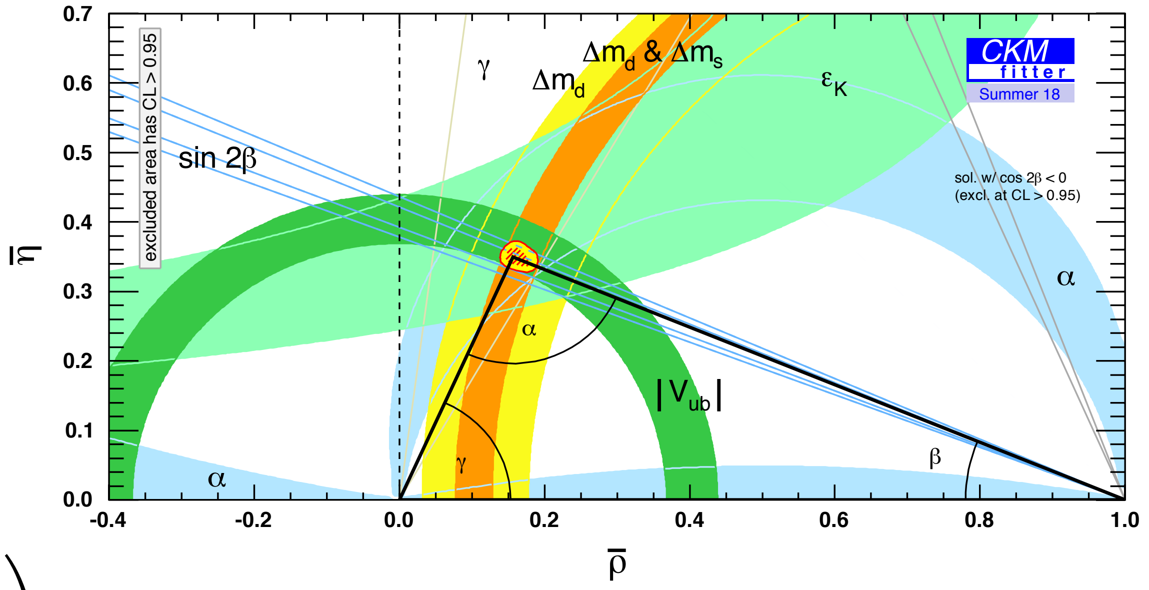
# Recap: The CKM matrix and unitarity triangle

- CKM in terms of ***phases***:

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Triangle in the complex plane:

$$V_{CKM}^{\dagger} V_{CKM} = 1$$



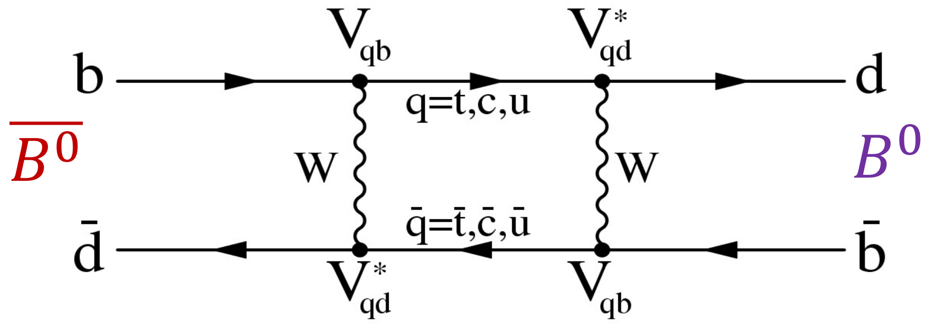

- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- CP Violation:
  - Non-zero unitary phases
  - Triangle surface $\neq 0$
    - Jarlskog invariant

# Recap: Flavor Oscillations

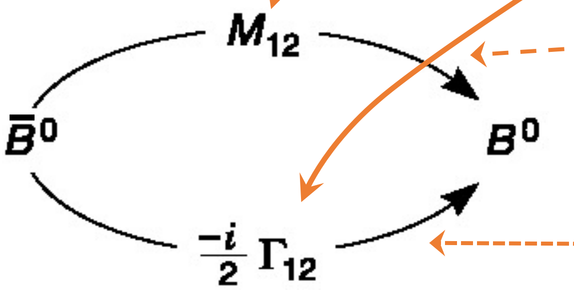
- Quantum mechanics with $\overline{B^0}$ and $B^0$ states: *"What is a particle?"*
  - Particle – antiparticle transitions $\overline{B^0} \leftrightarrow B^0$ mesons happen spontaneously.




- Time evolution of $B^0$ and $\overline{B^0}$ described by an effective Hamiltonian

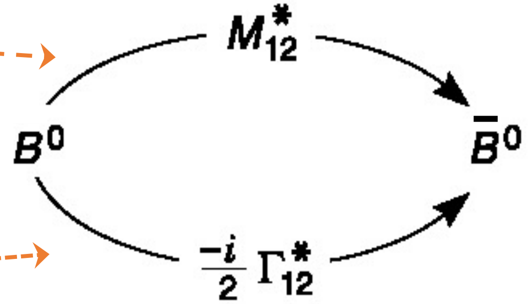
$$i\frac{\partial}{\partial t}\psi = H\psi \quad \rightarrow \quad \psi(t) = a(t)|B^0\rangle + b(t)|\overline{B^0}\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\textit{Hermitean Mass-matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\textit{Hermitean Decay-matrix}}$$



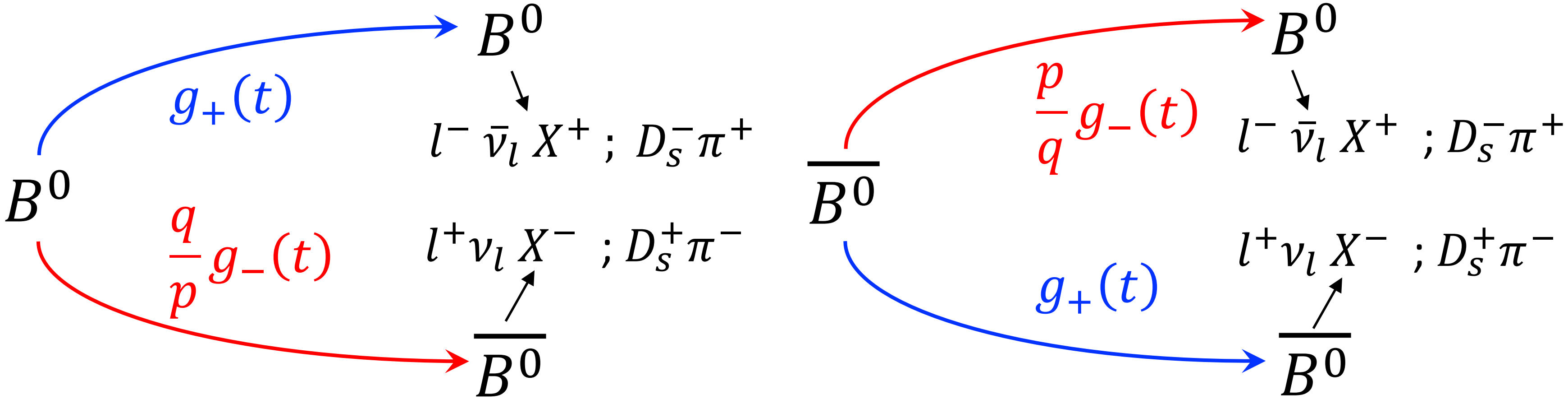

$M_{12}$ describes $B^0 \leftrightarrow \overline{B^0}$ via *off-shell* states, e.g. the weak box diagram ("dispersive")

$\Gamma_{12}$ describes $B^0 \leftrightarrow f \leftrightarrow \overline{B^0}$ via *on-shell* states, e.g. $f = \pi^+\pi^-$ ("absorptive")



# Recap: $B^0$ Oscillations : *flavour specific* final states






Calculate:

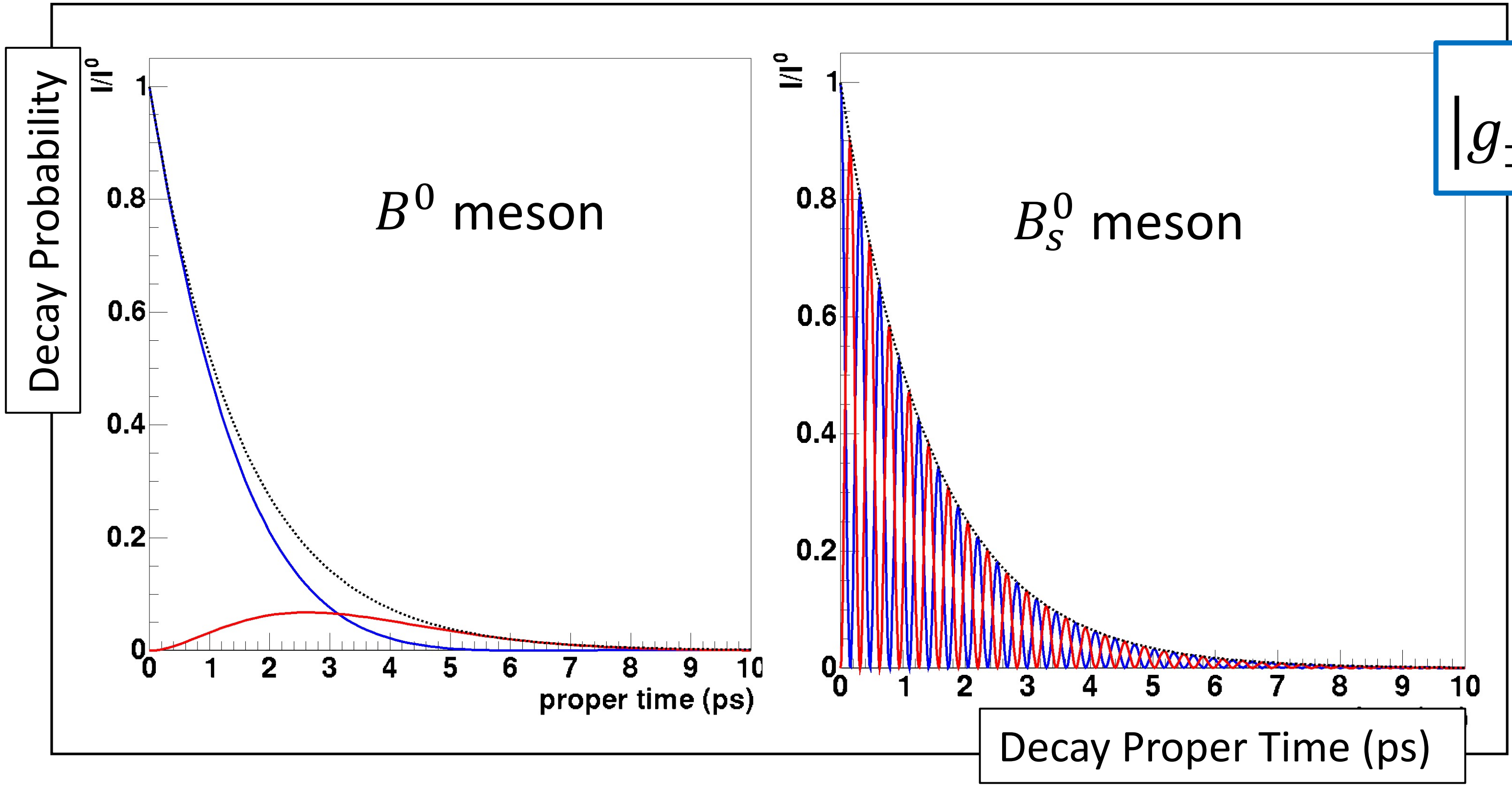
$|\langle B(t)|B^0\rangle|^2$

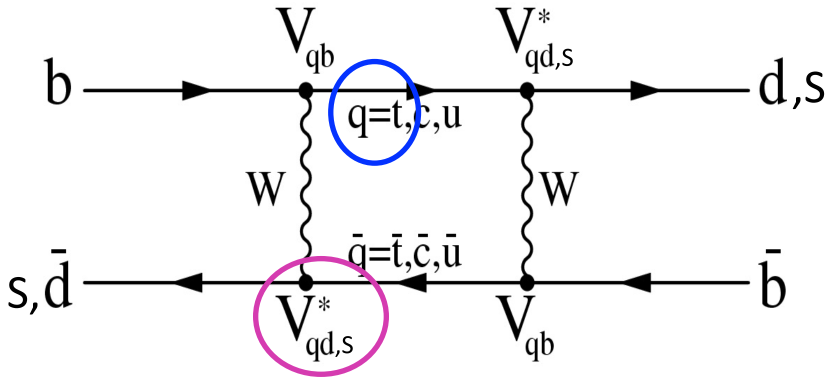
$|\langle \bar{B}(t)|B^0\rangle|^2$

For $B^0$, expect:
$\Delta\Gamma \sim 0$ , $|q/p| = 1$

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[1 \pm \cos(\Delta m \cdot t)\right]$$

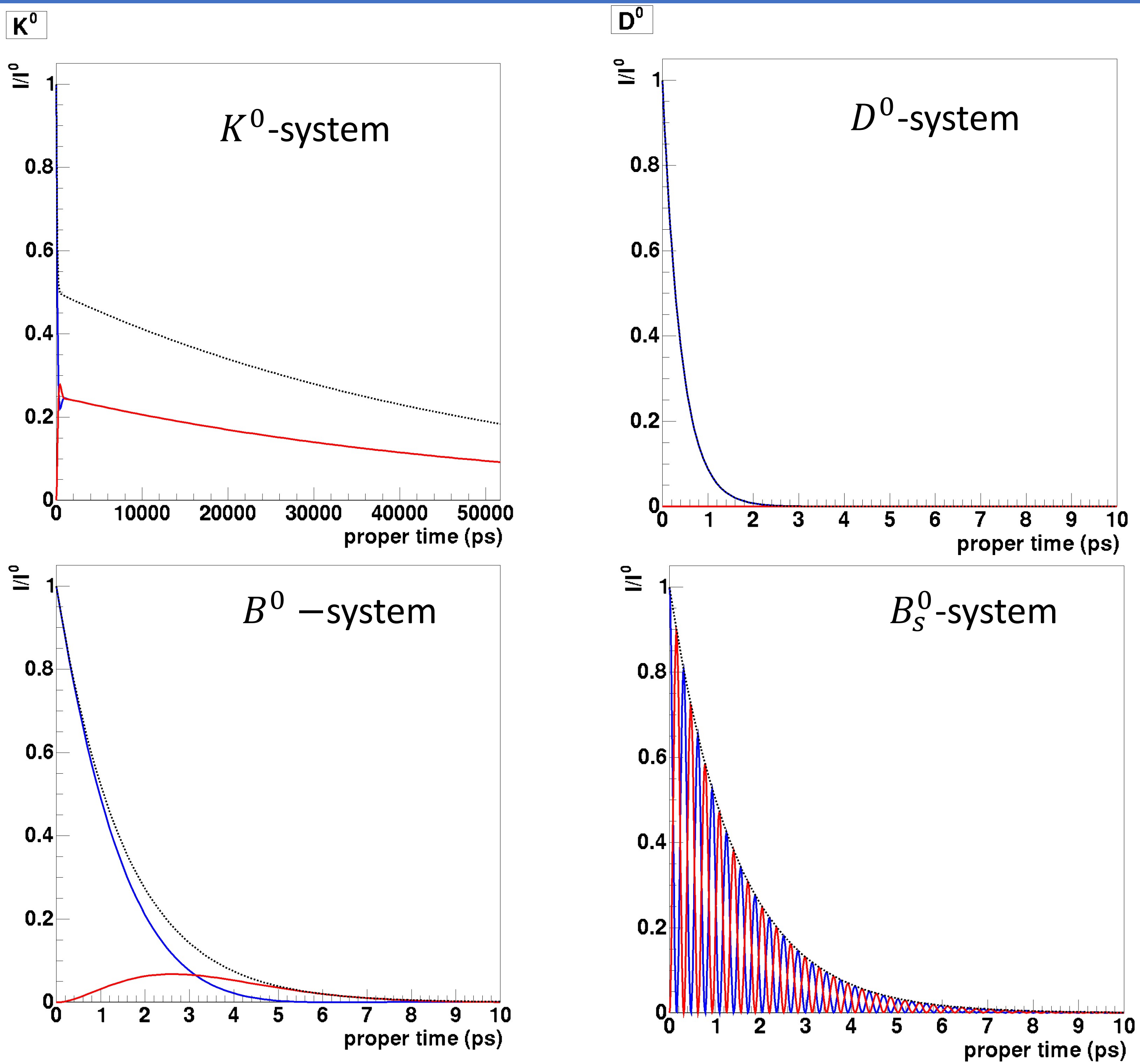
Flavour Oscillations!



# Meson Mixing: Summary for all mesons





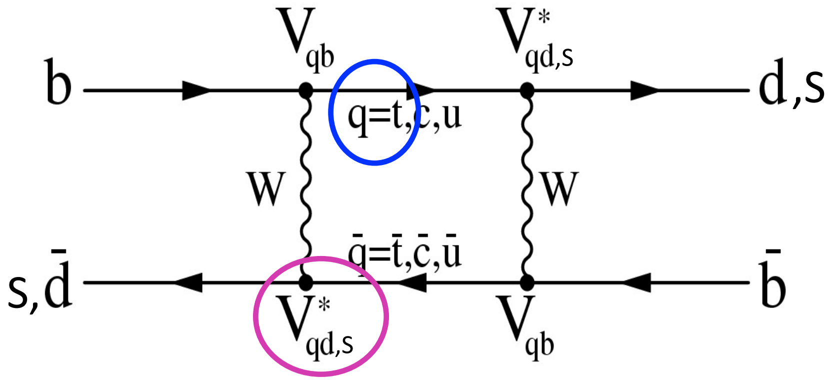

Blue line: given a $P^0$, at t=0, the probability of finding a $P^0$ at t.

Red Line: given a $P^0$, at t=0, the probability of finding a $P^0$ at t.

Q: Why does the $B_s$ oscillate so much faster than the $B^0$? (Vts/Vtd)

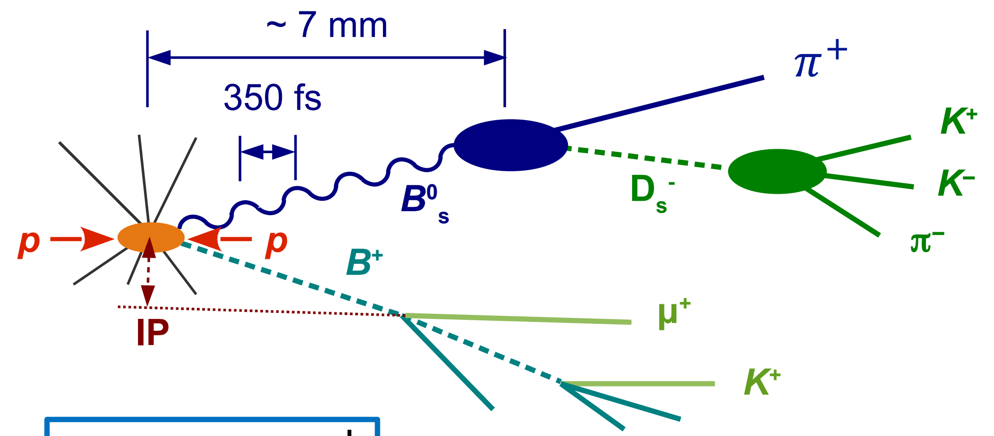
Q: why does the $D^0$ meson oscillate very slowly? (Box diagram: beauty mass << top mass)

Q: do you expect any other (neutral) mesons/baryons to mix? (Top decays too fast)



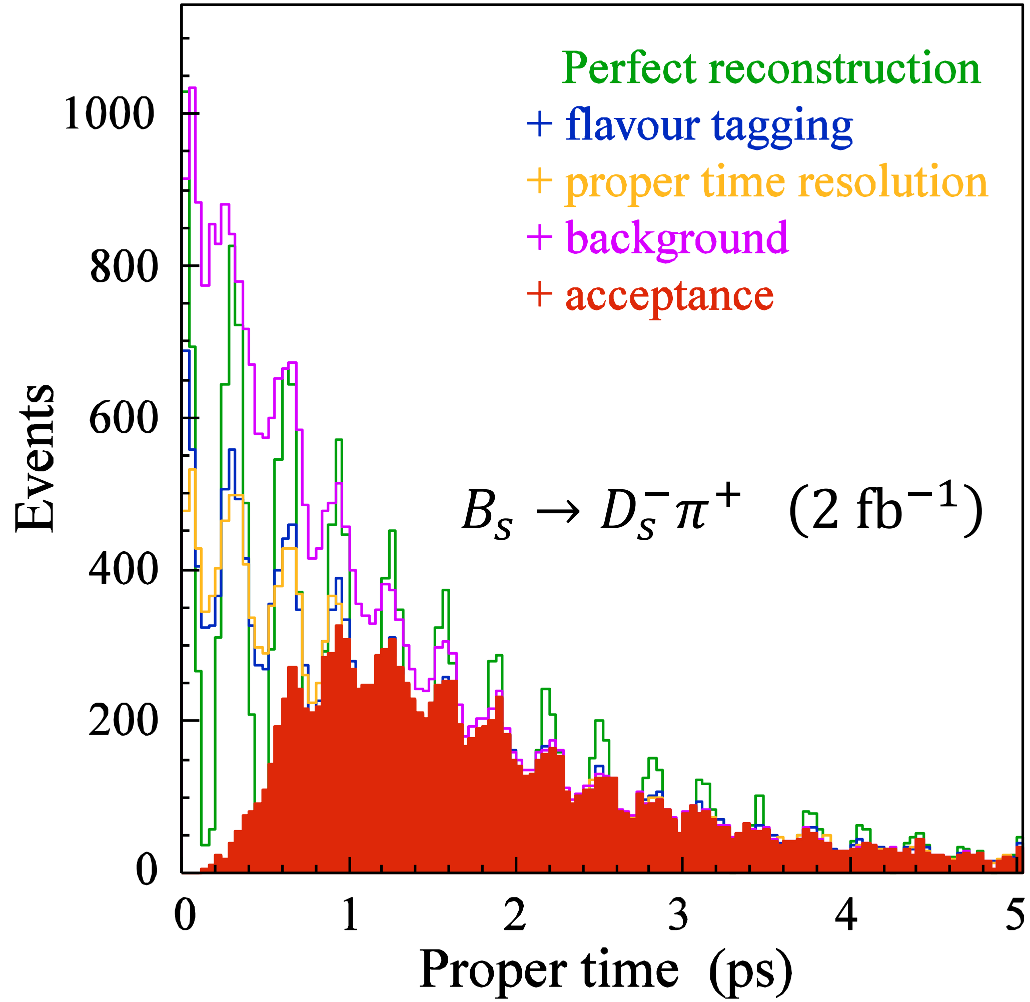
# Recap: Measuring $B_s$ - $\overline{B_s}$ Oscillations






$B_s \to D_s^- \pi^+$

Proper-time dependent decay rate:




***Experimental Situation:***

Ideal measurement (no dilutions)

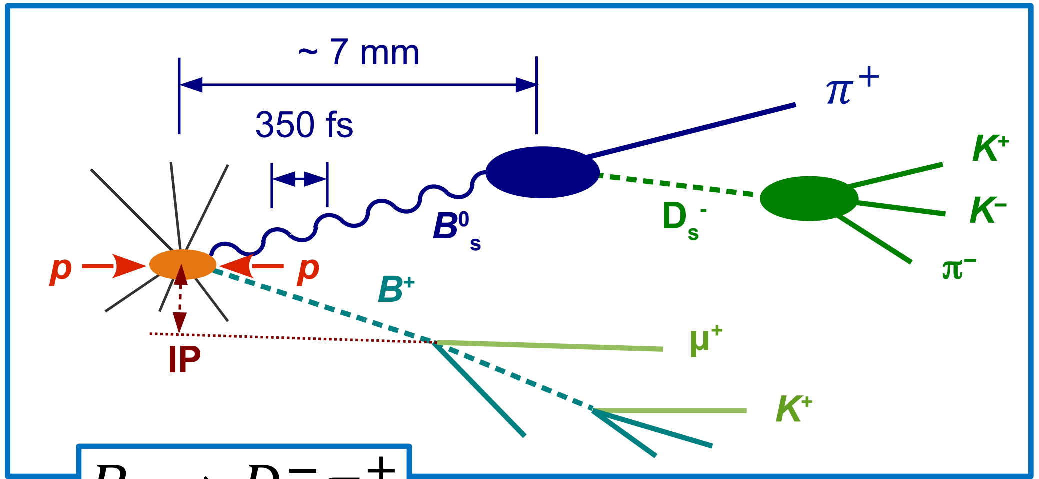
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

+ Background events

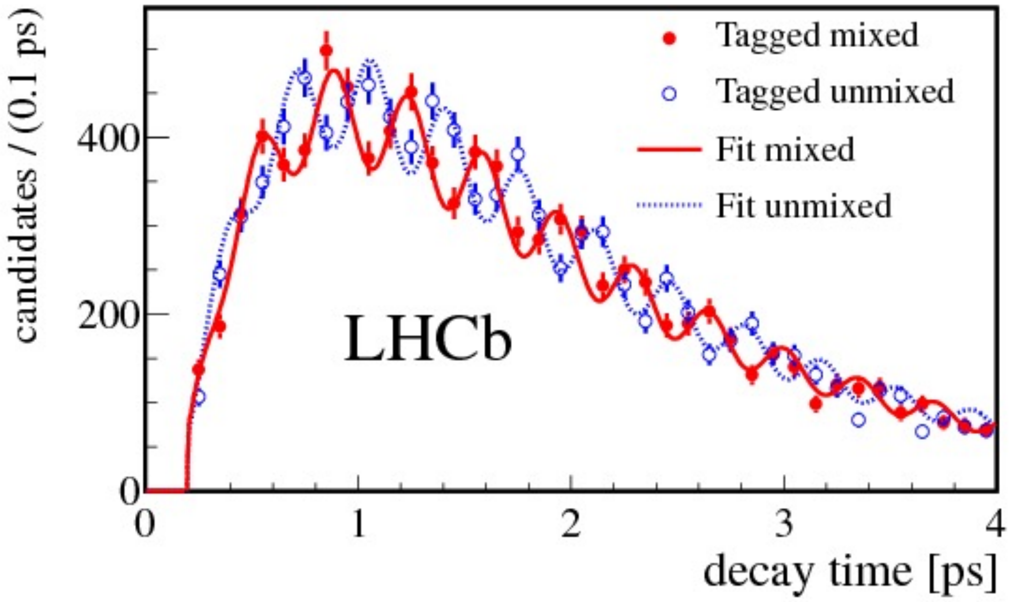
+ Trigger and selection acceptance

# Recap: Measuring $B_s$ - $\overline{B_s}$ Oscillations

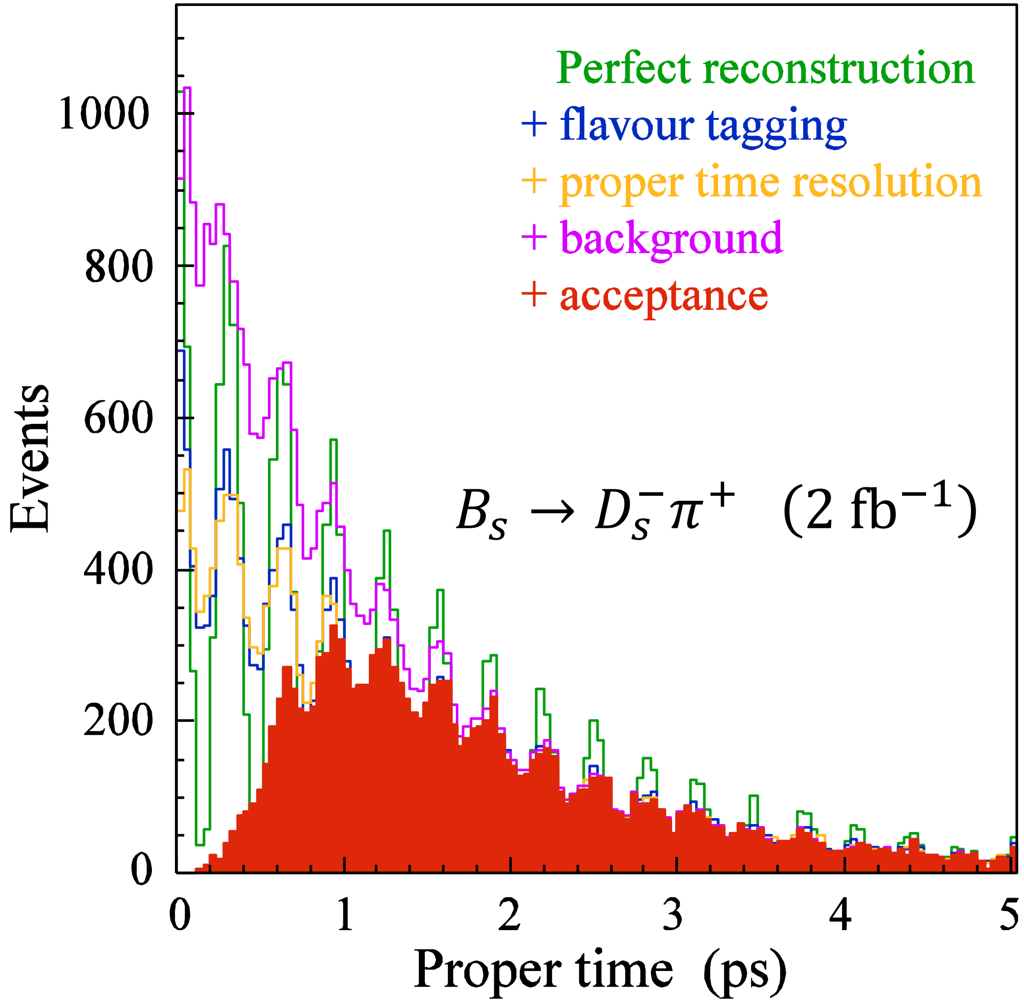



$B_s \to D_s^- \pi^+$

Proper-time dependent decay rate:




Measurement



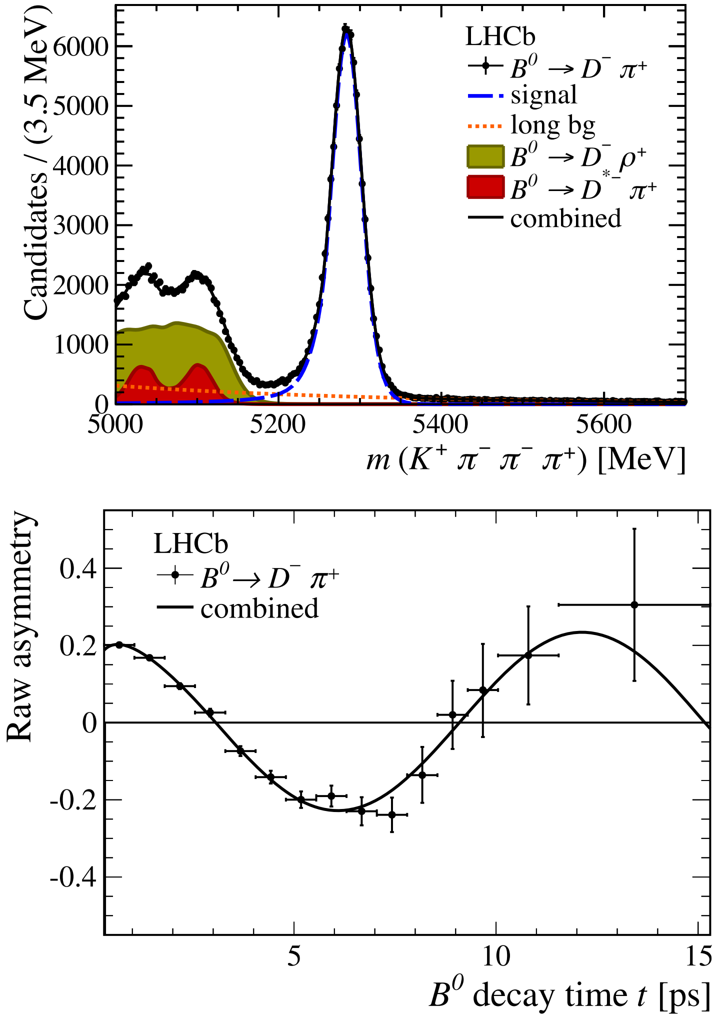

Prediction

# Meson mixing in LHCb: experiment works well



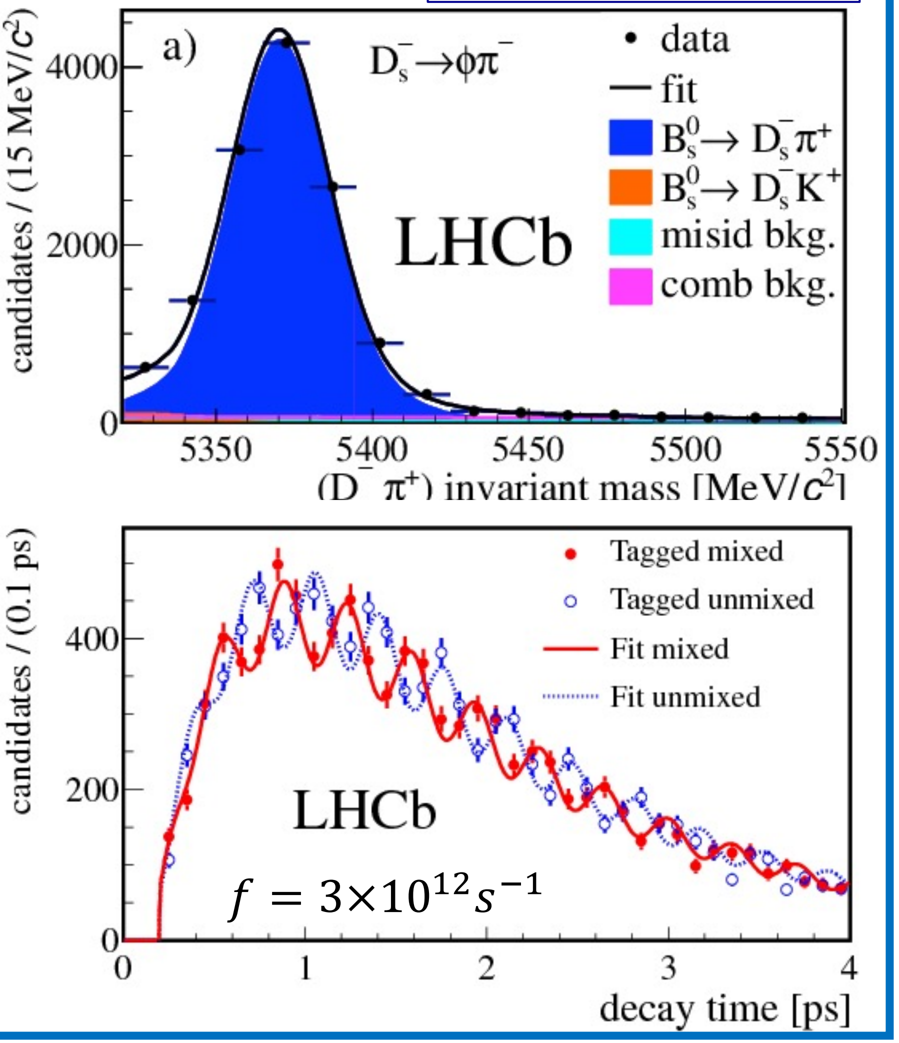
## $B^0 - \overline{B^0}$ mixing

$B^0 \to D^-\pi^+$ **Phys.Lett.B719 (2013) 318**




## $B_s^0 - \overline{B_s^0}$ mixing

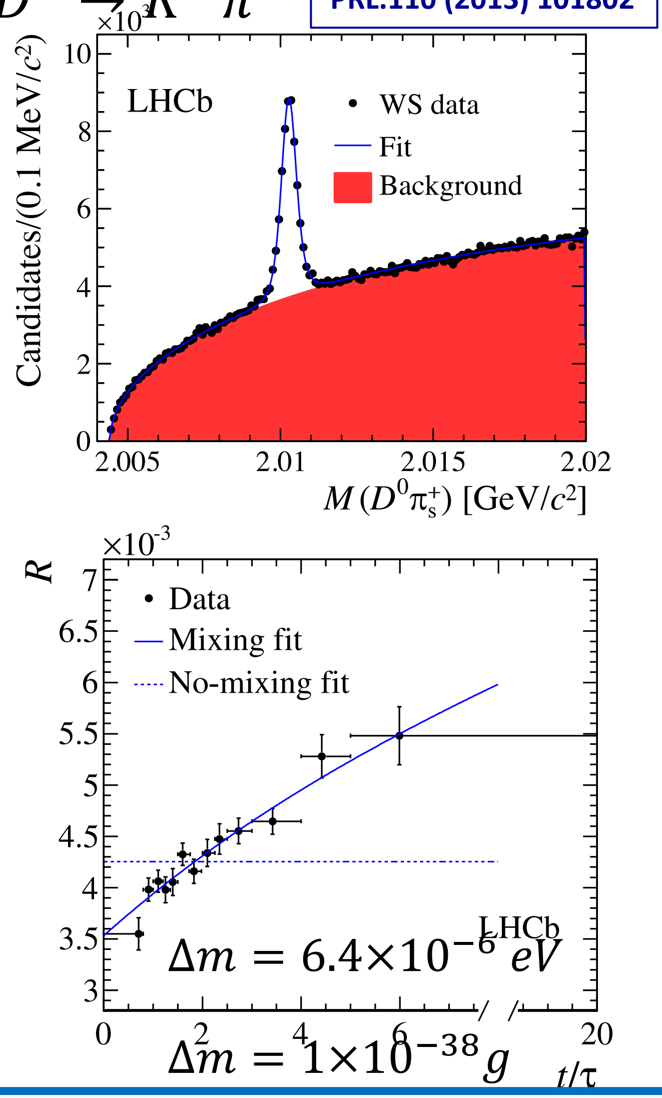
$B_s^0 \to D_s^-\pi^+$ **New.J.Phys.15 (2013) 053021**




$f = 3\times10^{12}s^{-1}$

## $D^0 \to \overline{D^0}$ mixing

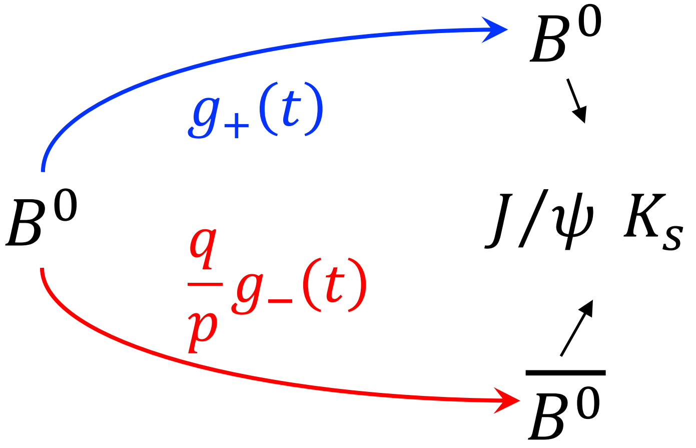
$D^0 \to K^+\pi^-$ **PRL.110 (2013) 101802**




$\Delta m = 6.4\times10^{-6}eV$

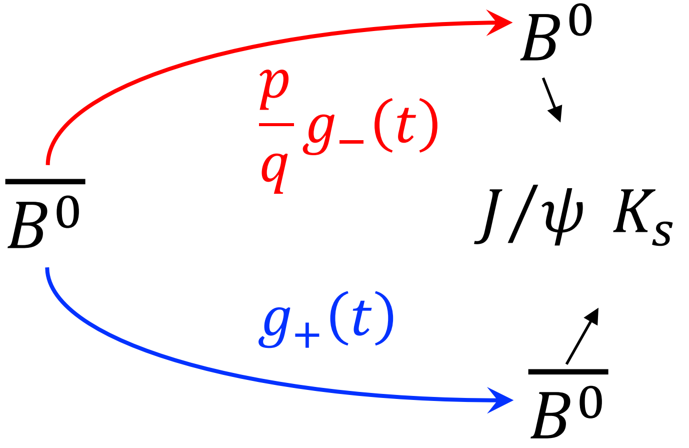
$\Delta m = 1\times10^{-38}g$

# Recap: $B$ Decays to ***common final states***: eg $CP$ eigenstates



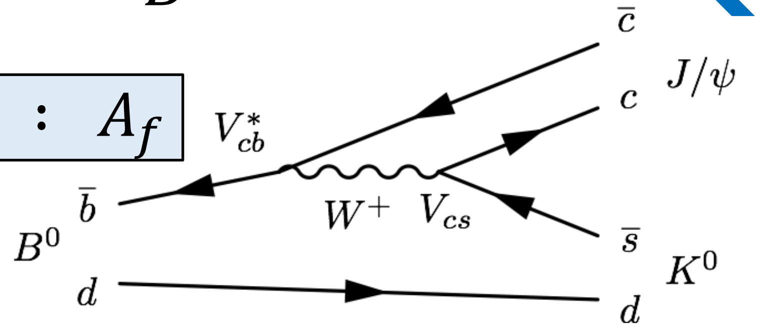

$B^0 \to J/\psi\, K_s$
+
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

$\overline{B^0} \to J/\psi\, K_s$
+
$\overline{B^0} \to B^0 \to J/\psi\, K_s$



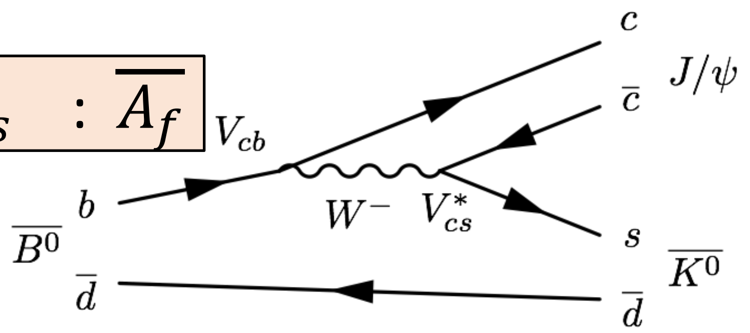

←CP→

$B^0 \to J/\psi\, K_s \quad : \quad A_f$



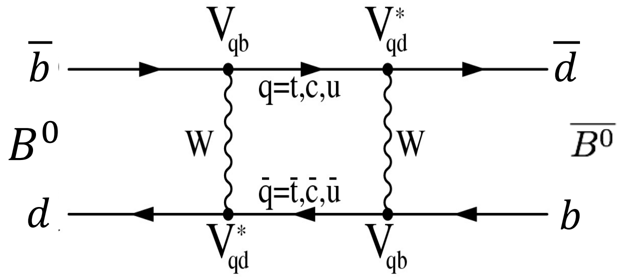
+

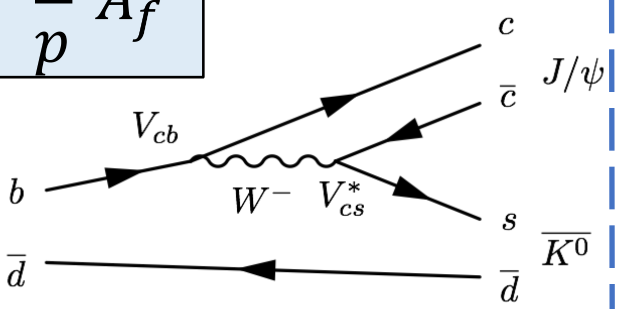
$\overline{B^0} \to J/\psi\, K_s \quad : \quad \overline{A_f}$



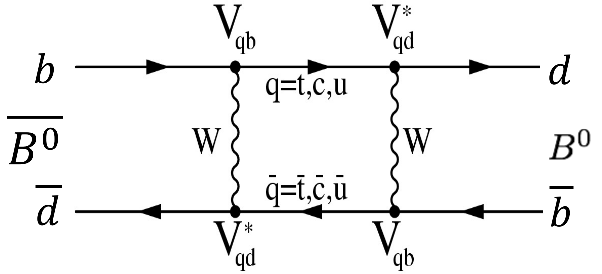
+

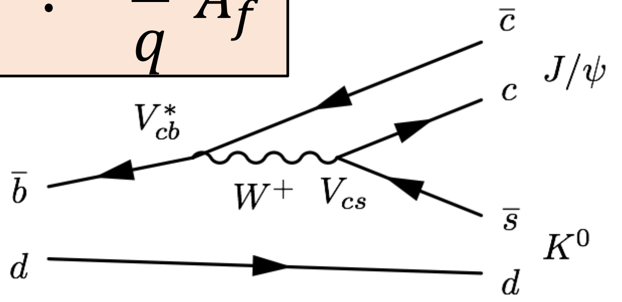
$B^0 \to \overline{B^0} \to J/\psi\, K_s \quad : \quad \frac{q}{p}\,\overline{A_f}$





$\overline{B^0} \to B^0 \to J/\psi\, K_s \quad : \quad \frac{p}{q}\,A_f$

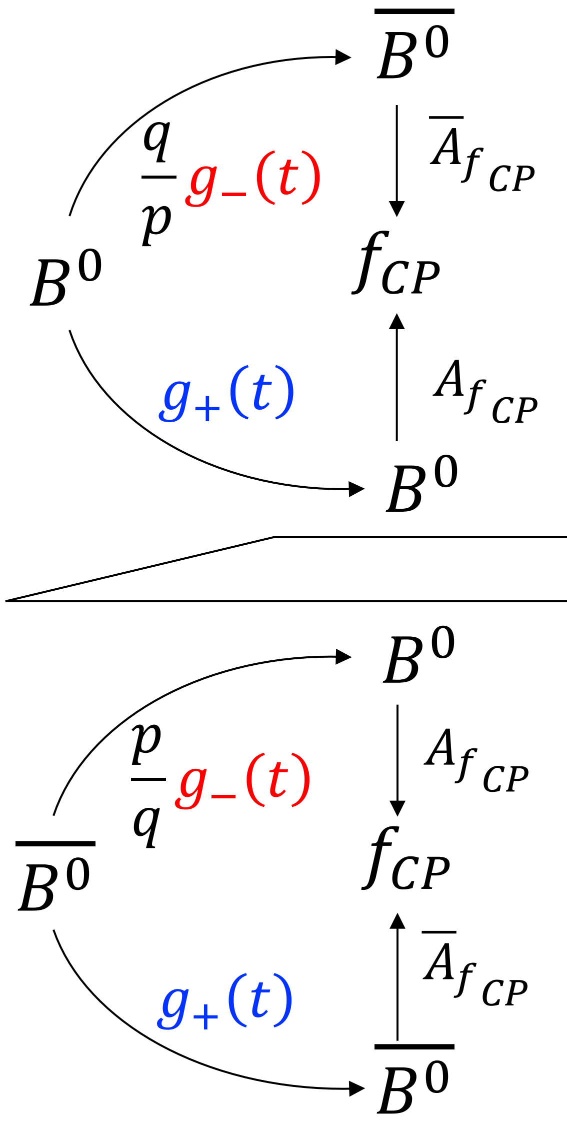




# Recap: How does it give CP violation?



$t=0$ | $t$ | Amplitude




$$A_{f_{CP}}\left(g_+(t)+\lambda g_-(t)\right)$$

$$\lambda_{f_{CP}}=\frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$\overline{A}_{f_{CP}}\left(g_+(t)+\frac{1}{\lambda}g_-(t)\right)$$

$$\overline{\lambda}_{f_{CP}}=\frac{p}{q}\frac{A_{f_{CP}}}{\overline{A}_{f_{CP}}}=\frac{1}{\lambda_{f_{CP}}}$$

$$g_\pm(t)=\frac{e^{-i\omega_1}\pm e^{-i\omega_2 t}}{2}$$

$$g_+(t)=\frac{e^{-i(m-\Delta m/2)t}\,e^{-\Gamma t/2}+e^{-i(m+\Delta m/2)t}\,e^{-\Gamma t/2}}{2}$$

$$=e^{-imt}\,e^{-\Gamma t/2}\cos\frac{\Delta mt}{2}$$

$$g_-(t)=\frac{e^{-i(m-\Delta m/2)t}\,e^{-\Gamma t/2}-e^{-i(m+\Delta m/2)t}\,e^{-\Gamma t/2}}{2}$$

$$=e^{-imt}\,e^{-\Gamma t/2}\,\boldsymbol{i}\,\sin\frac{\Delta mt}{2}$$

For neutral B mesons, $g_-$ has a 90° (= $i$) phase difference wrt. $g_+$

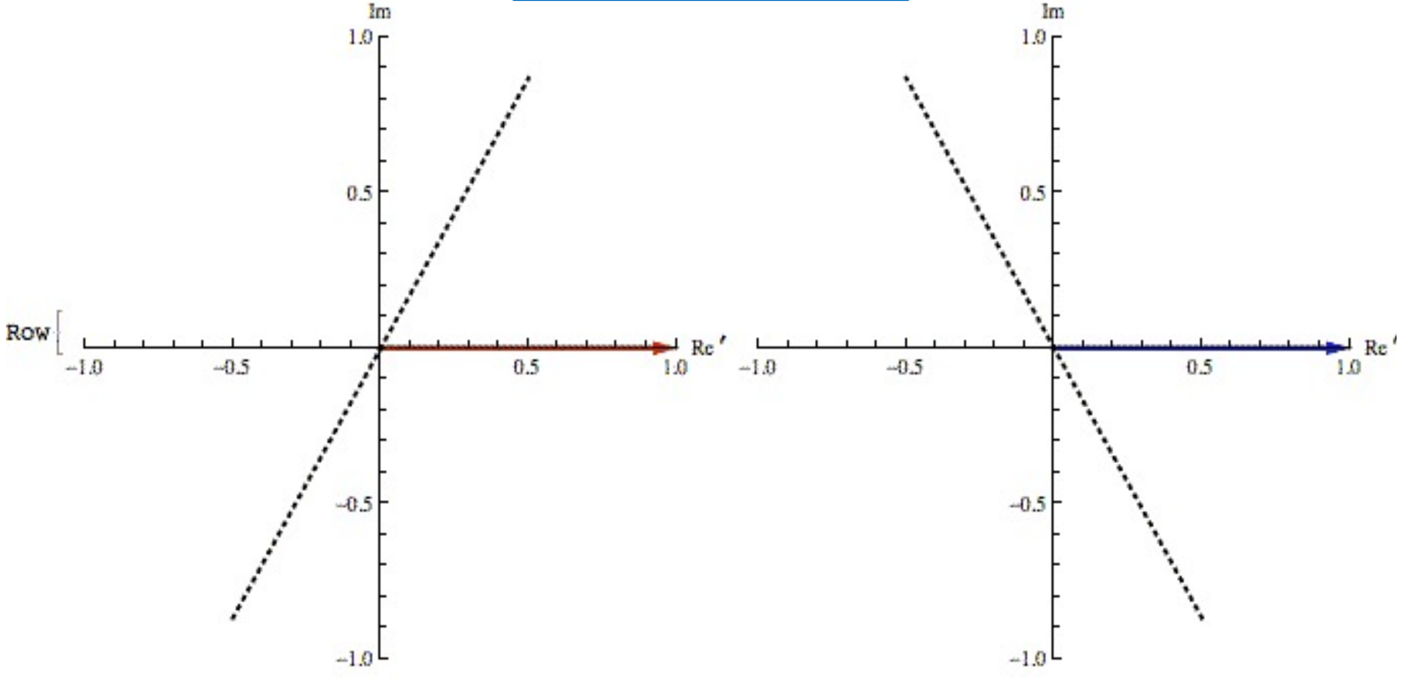
# Time Dependent CP violation



$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

| $t=0$ | | $t$ | Amplitude |
|---|---|---|---|
| $B^0$ | $\rightarrow$ | $f_{CP}$ | $A_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\, e^{-i\phi_{weak}} \sin\frac{\Delta mt}{2}\right)$ |
| $\overline{B^0}$ | $\rightarrow$ | $f_{CP}$ | $\bar{A}_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\, e^{+i\phi_{weak}} \sin\frac{\Delta mt}{2}\right)$ |

Decay Amplitudes



# Time Dependent CP violation

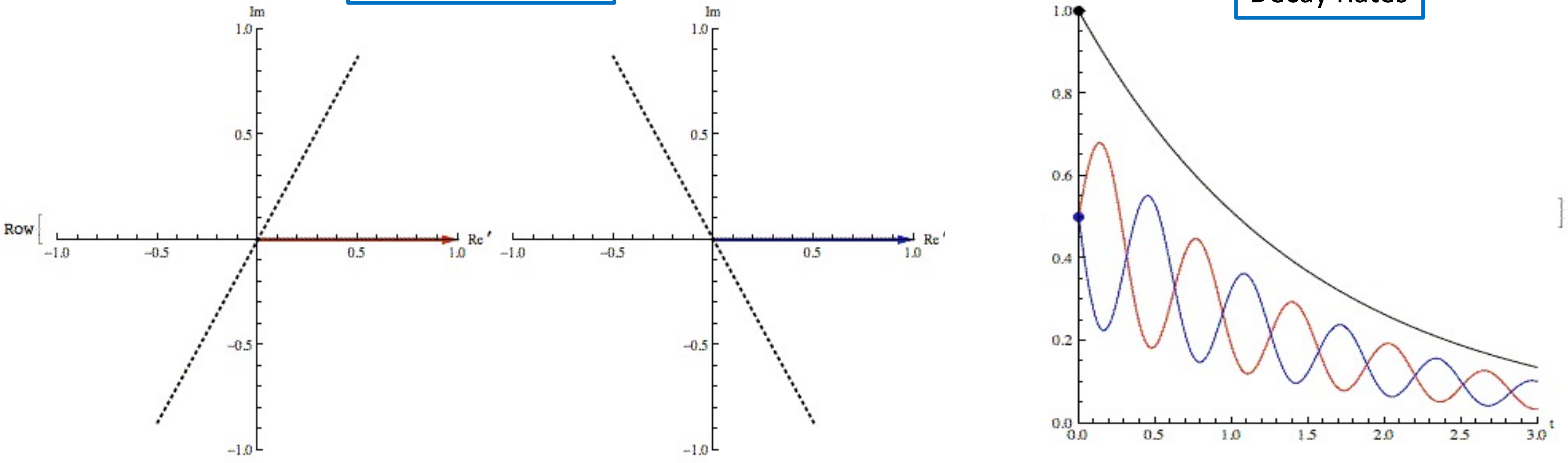


$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

| $t = 0$ | | $t$ | Decay Rate |
|---|---|---|---|
| $B^0$ | $\rightarrow$ | $f_{CP}$ | $\propto\ e^{-\Gamma t}\,[1 + \sin\phi_{weak}\sin\Delta m t]$ |
| $\overline{B^0}$ | $\rightarrow$ | $f_{CP}$ | $\propto\ e^{-\Gamma t}\,[1 - \sin\phi_{weak}\sin\Delta m t]$ |

Decay Amplitudes

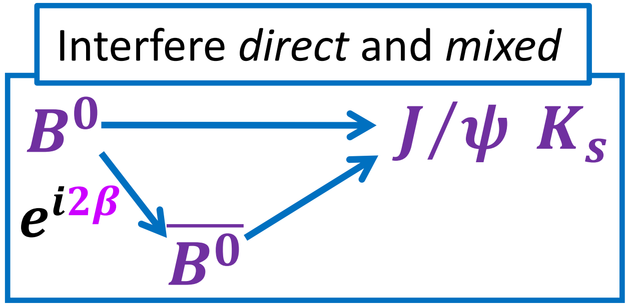
Decay Rates



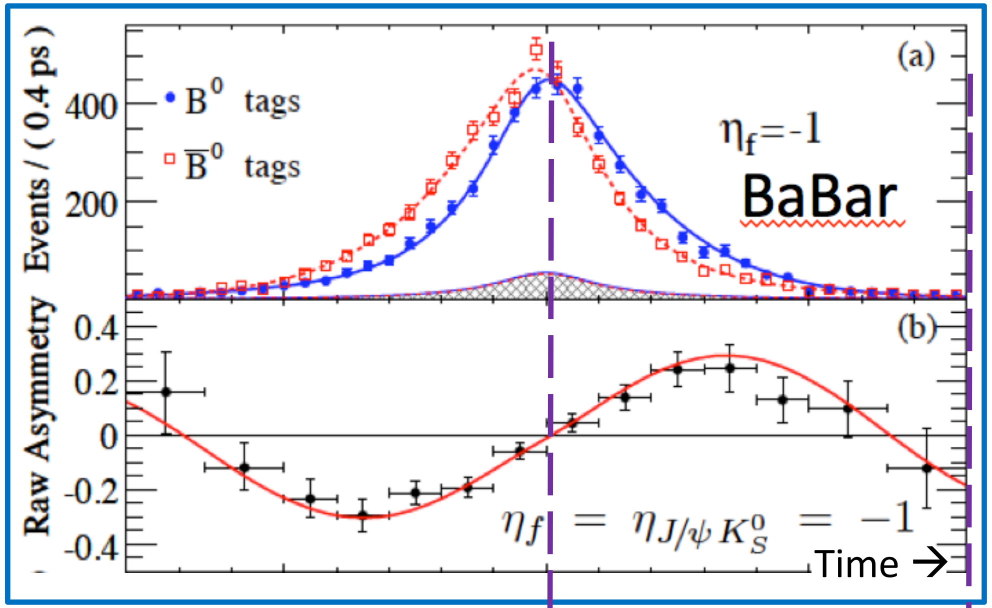
# Type-3: CP violation in *interference of mixing and decay*

- Interfere *direct* with *mixed* decay ("mixing induced"):

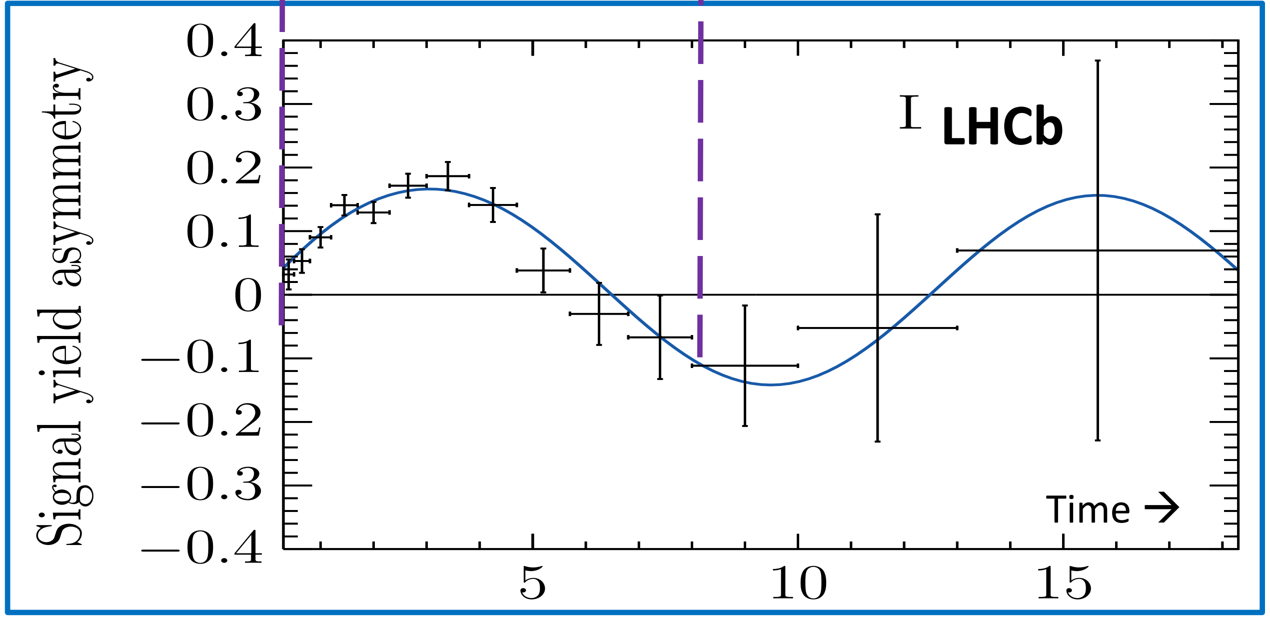
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



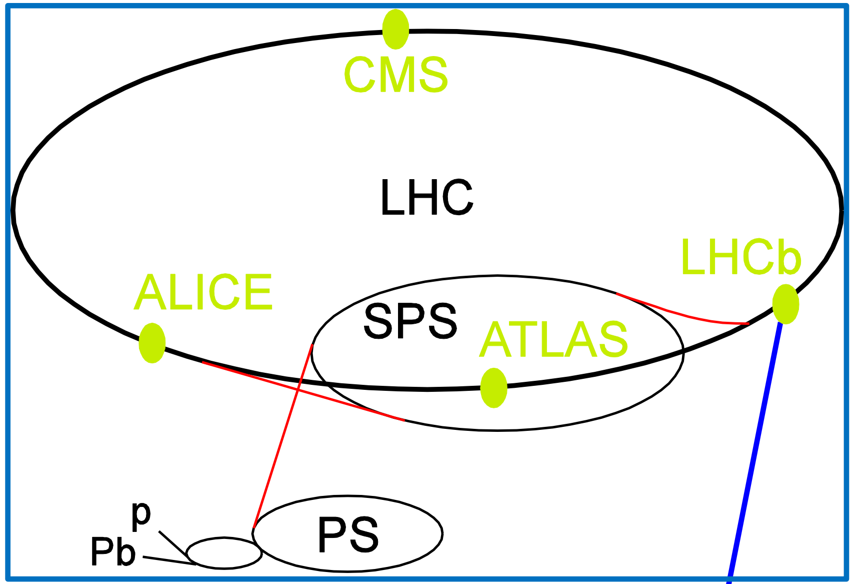

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$




*Decay-time dependent* CP violation



# $B_s \to D_s K$ : Quantum Interference Experiment @ LHCb

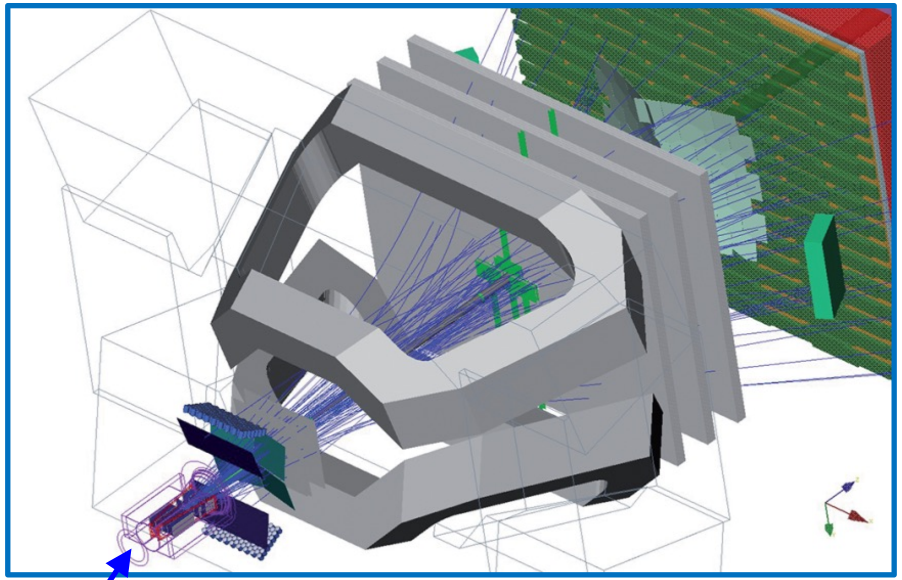


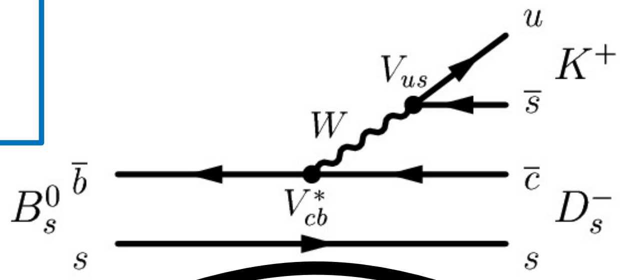

**Measure:**

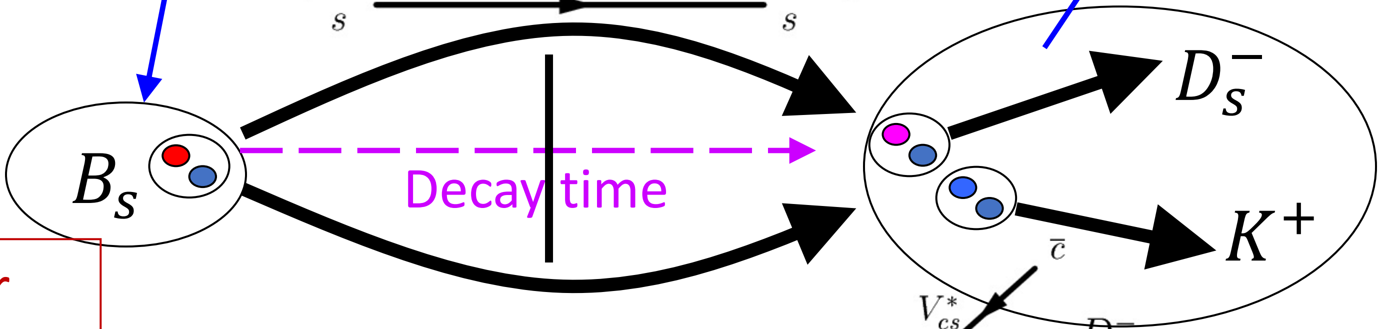
$B_s \to (\overline{B_s} \to) D_s^- K^+$

$\overline{B_s} \to (B_s \to) D_s^- K^+$

Repeat for $D_s^+ K^-$

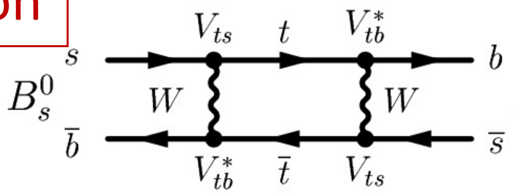


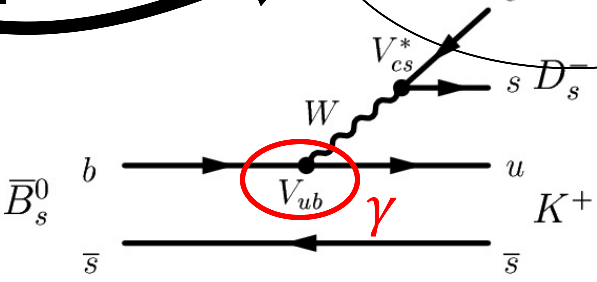



2) Measure decay rate as function of decay-time

1) Determine whether $B_s$ or $\overline{B_s}$ at production

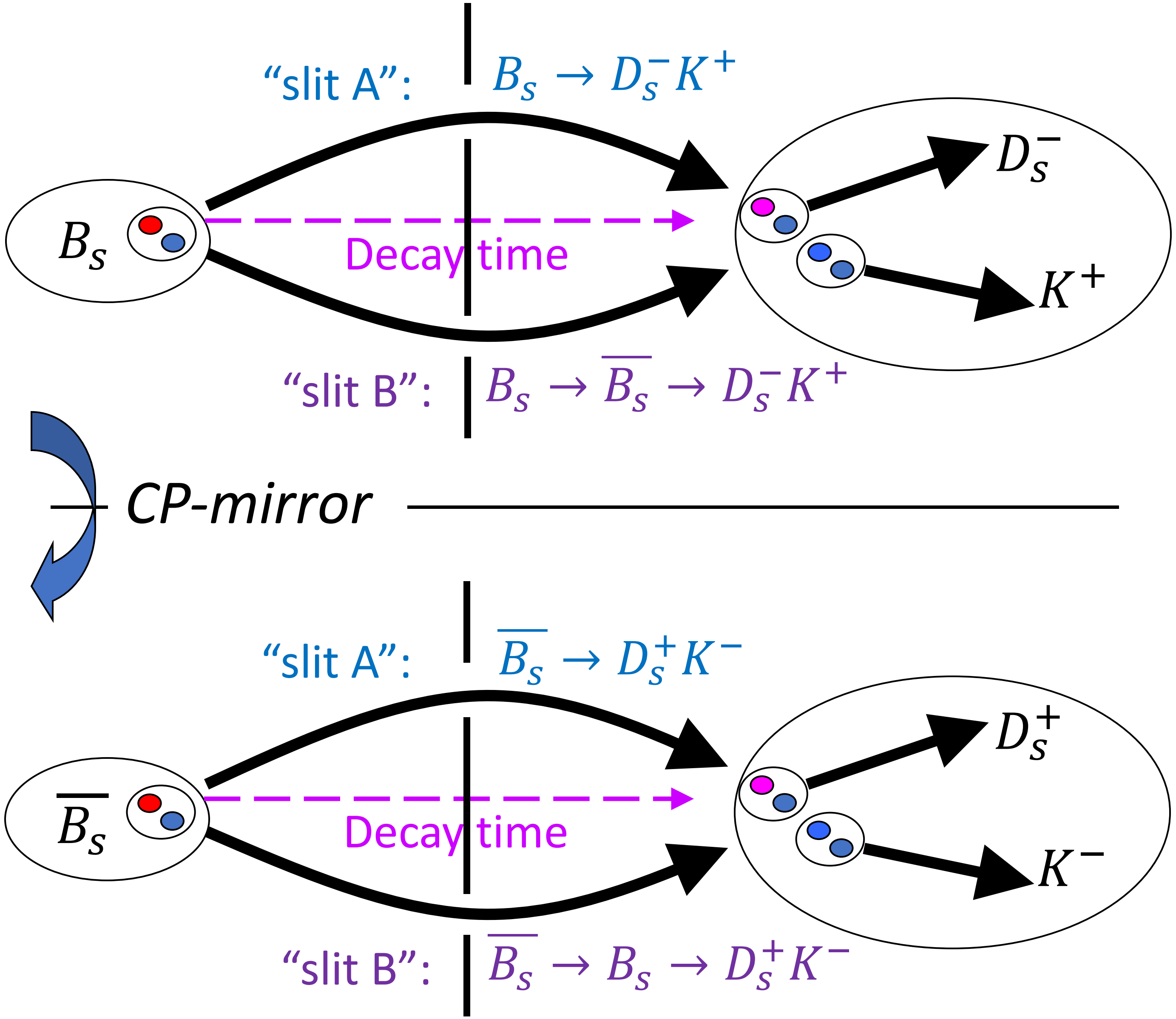


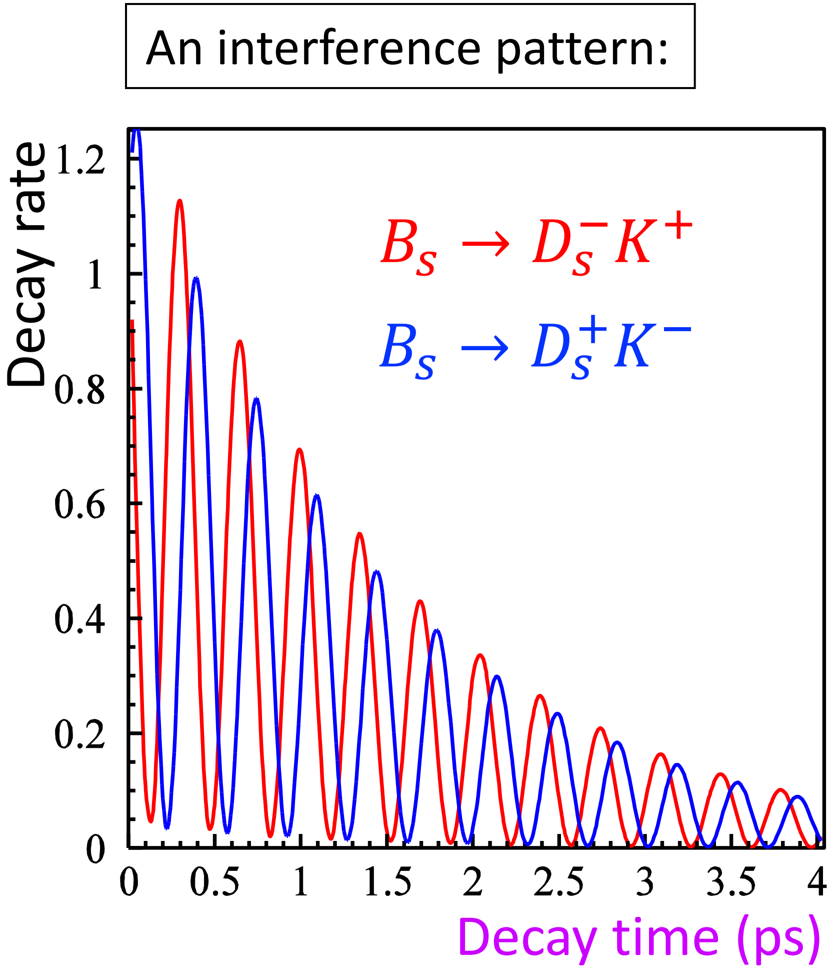




$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

# Recap: $B_s \to D_s K$ : Quantum Interference Experiment @ LHCb





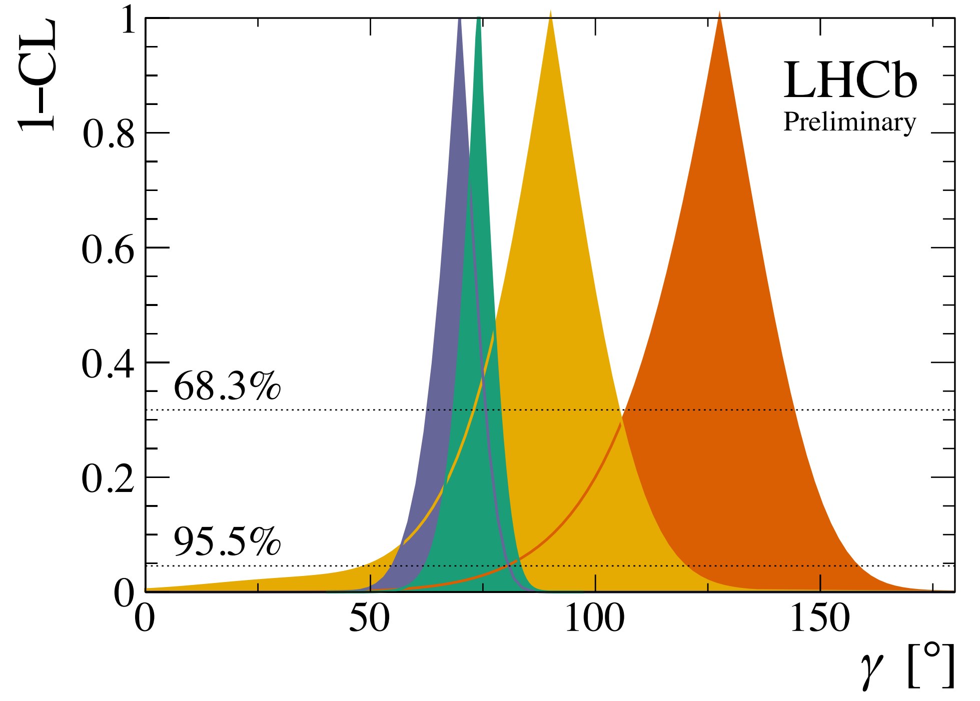



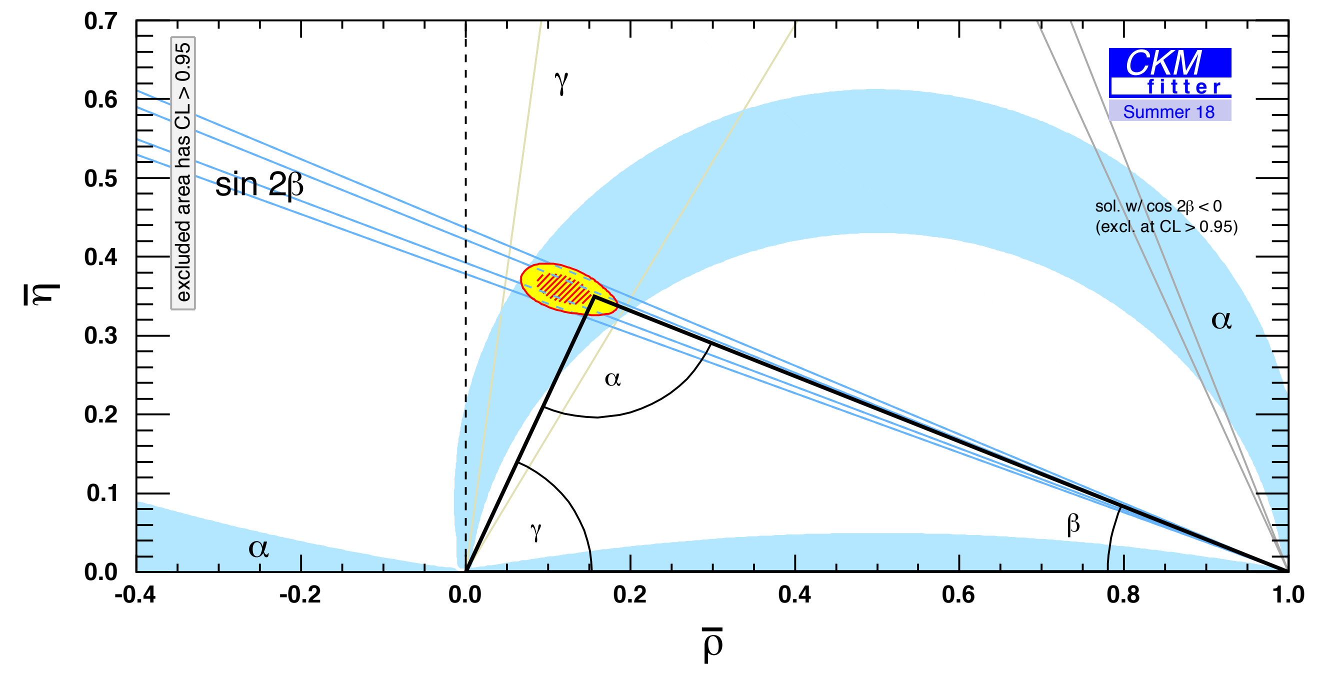

Time dependent $CP$ violation!

# Current situation on angle $\gamma$

- The situation for angle $\gamma$ :

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$




**Average:**

$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^{o}$$

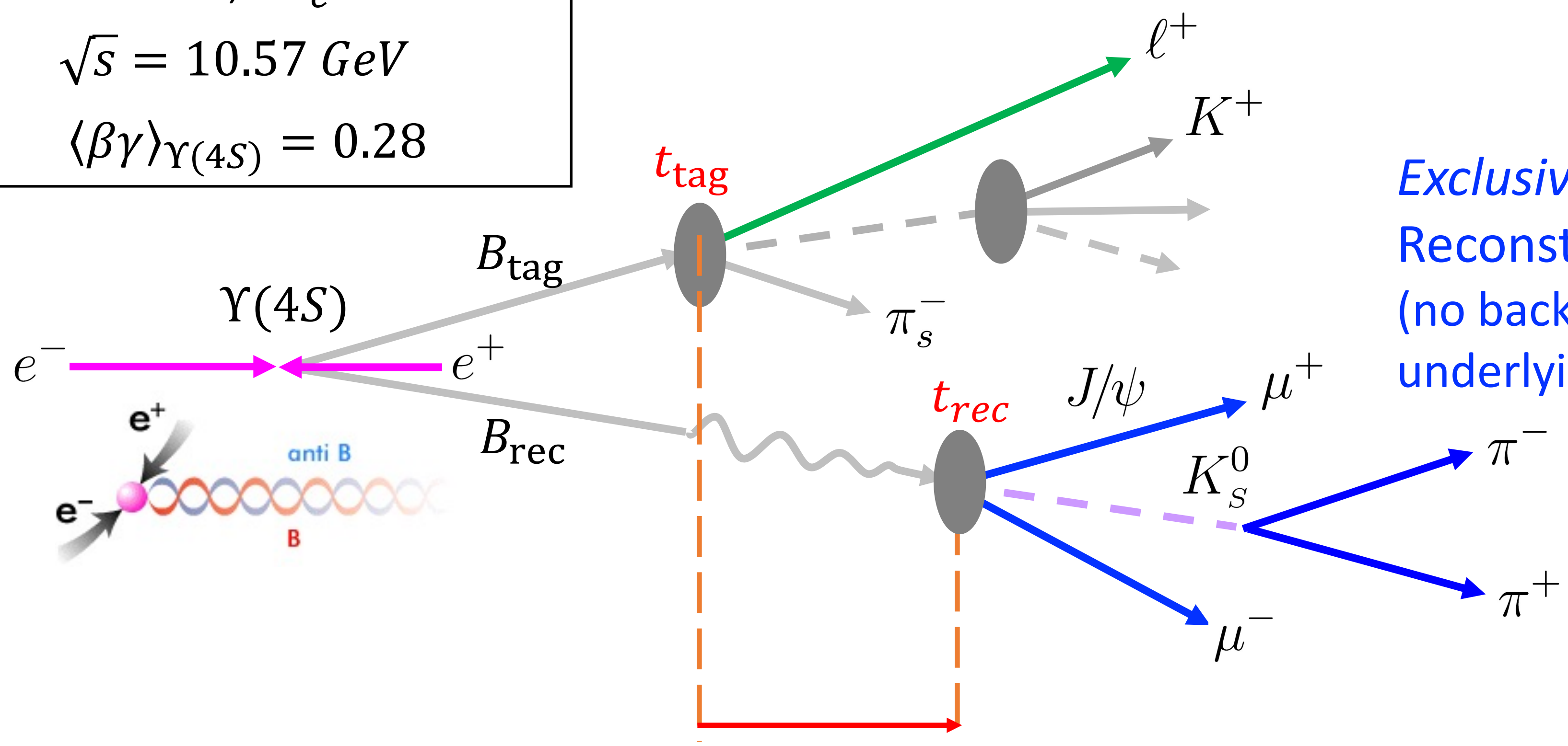
# $\Upsilon(4S)$ : ***Coherent*** $B$ - $\overline{B}$ production (Babar & Belle) 

## Belle II @ Super KEKB

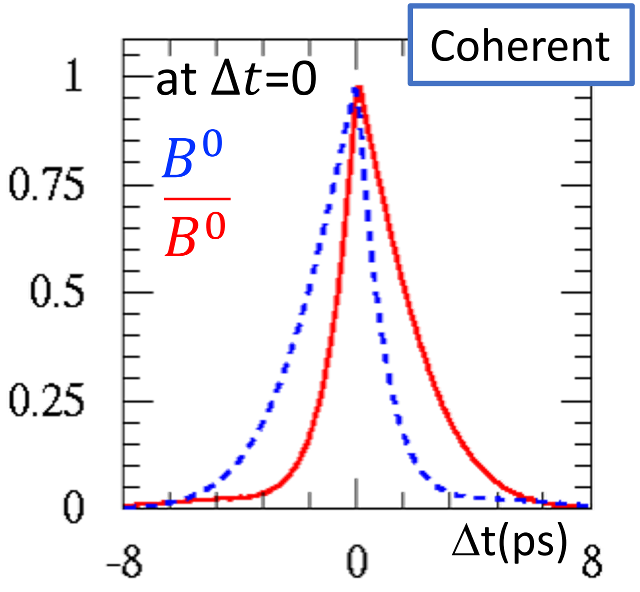
$$E_{e^-} = 7\ GeV \quad ; \quad E_{e^-} = 4\ GeV$$
$$\sqrt{s} = 10.57\ GeV$$
$$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.28$$

Flavour tagging of *other* $B$
(can be 100% pure)

*Exclusive* $B$ meson Reconstruction
(no backgrounds from underlying event)




$\Delta t \equiv t_{rec} - t_{tag}$



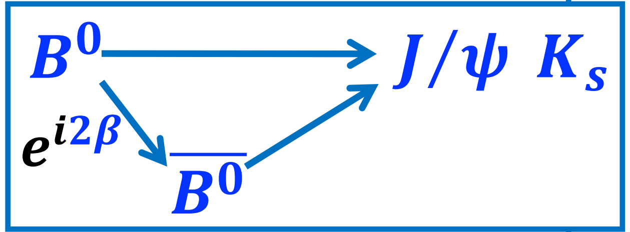

Vertexing and time reconstruction

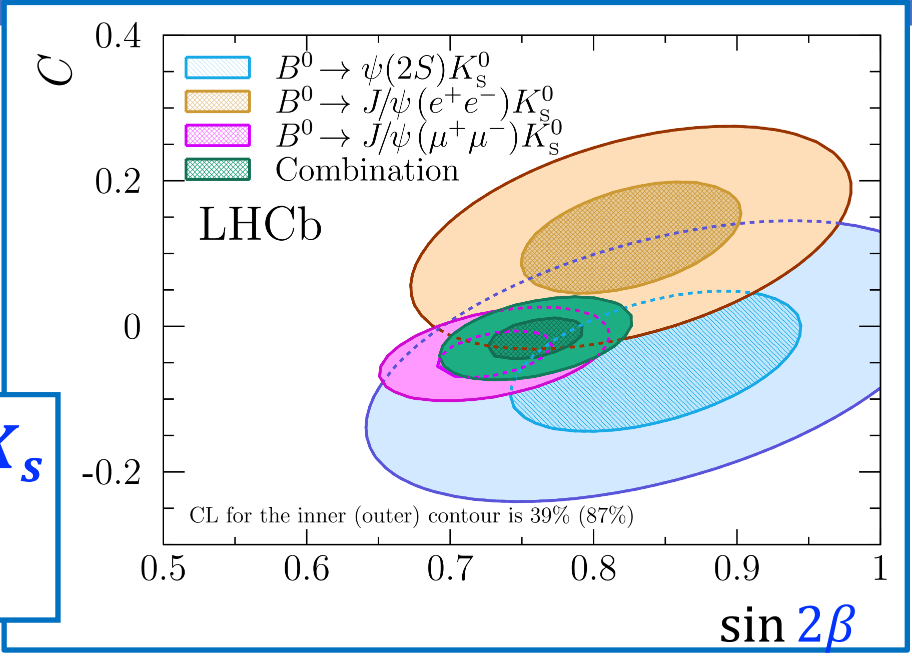
$\Delta t \approx {}^{\Delta z}/_{c\ \beta\gamma\Upsilon(4S)}$ ; ($\langle \Delta z \rangle \approx 130\ \mu m$)

# Decay time dependent $CP$ violation

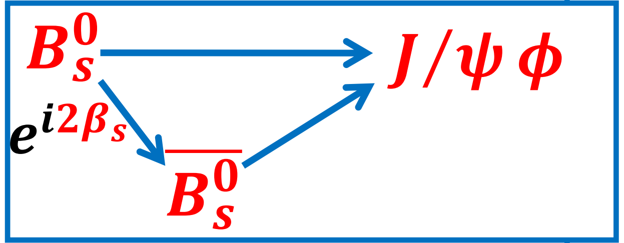
- $B^0 \to J/\psi\, K_s$ and $B_s^0 \to J/\psi\, \phi$

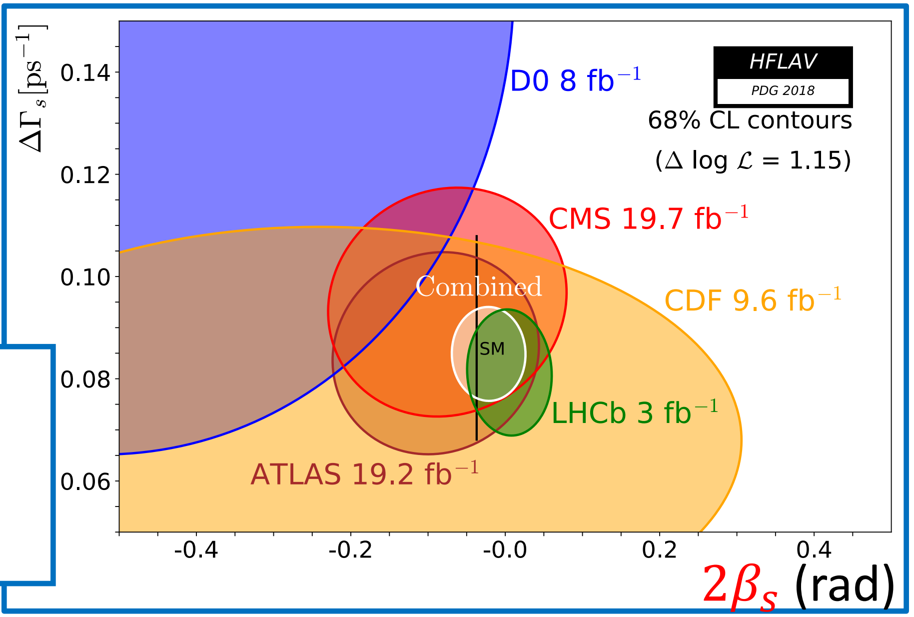
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_{(s)}\to f}(t) - \Gamma_{B_{(s)}\to f}(t)}{\Gamma_{B_{(s)}\to f}(t) + \Gamma_{B_{(s)}\to f}(t)}$$




$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

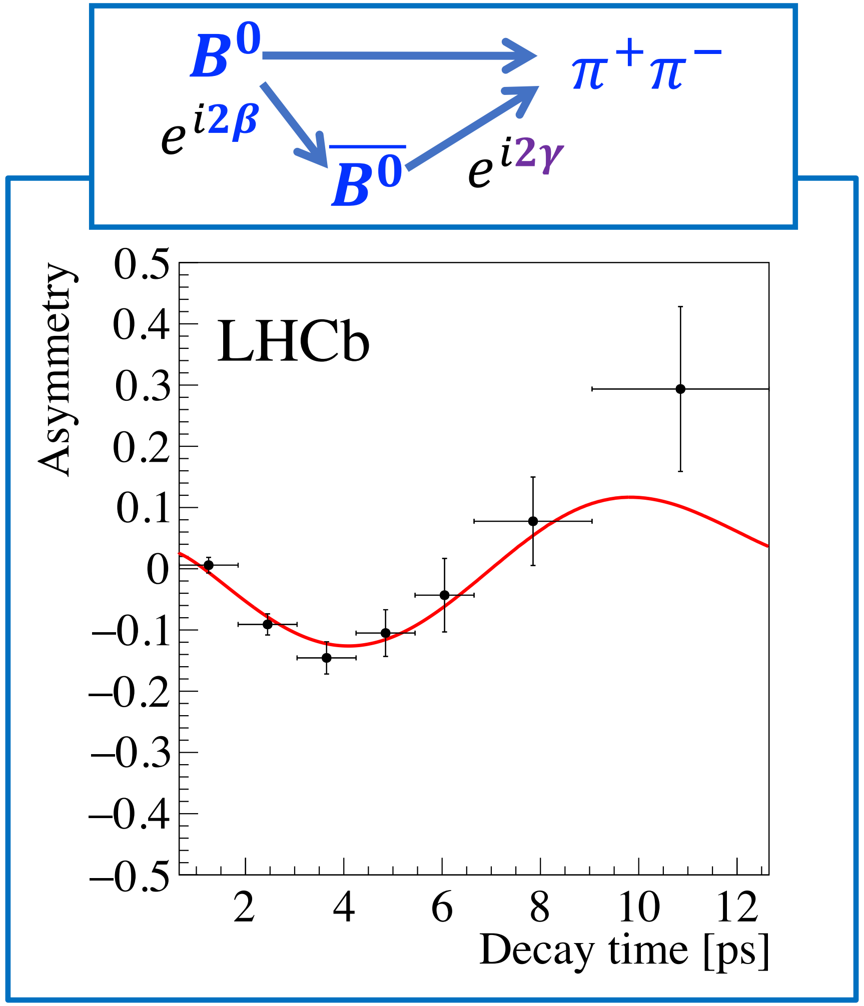


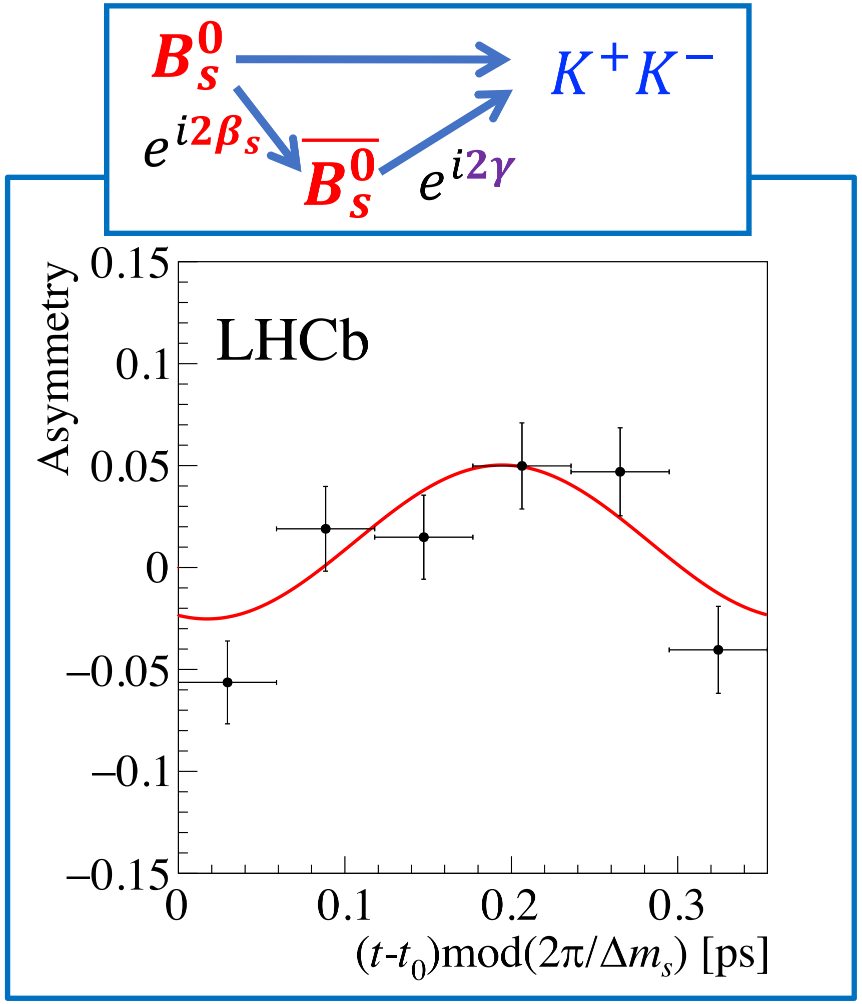



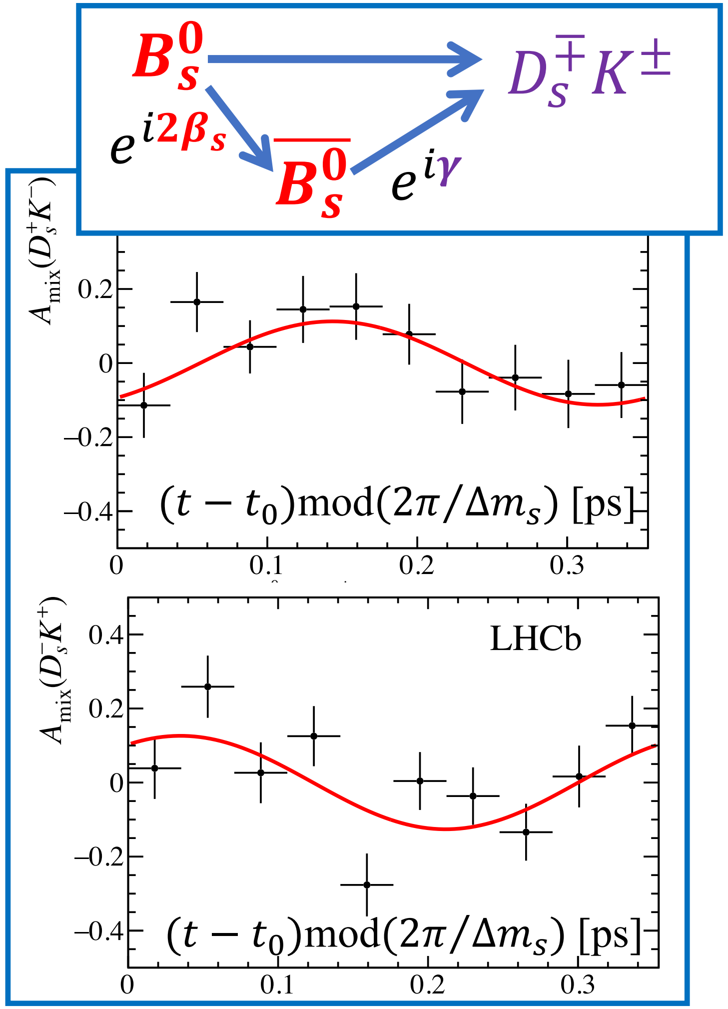
- *Hadronic decay modes (LHCb)*:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Note: $\alpha = \pi - (\beta + \gamma)$



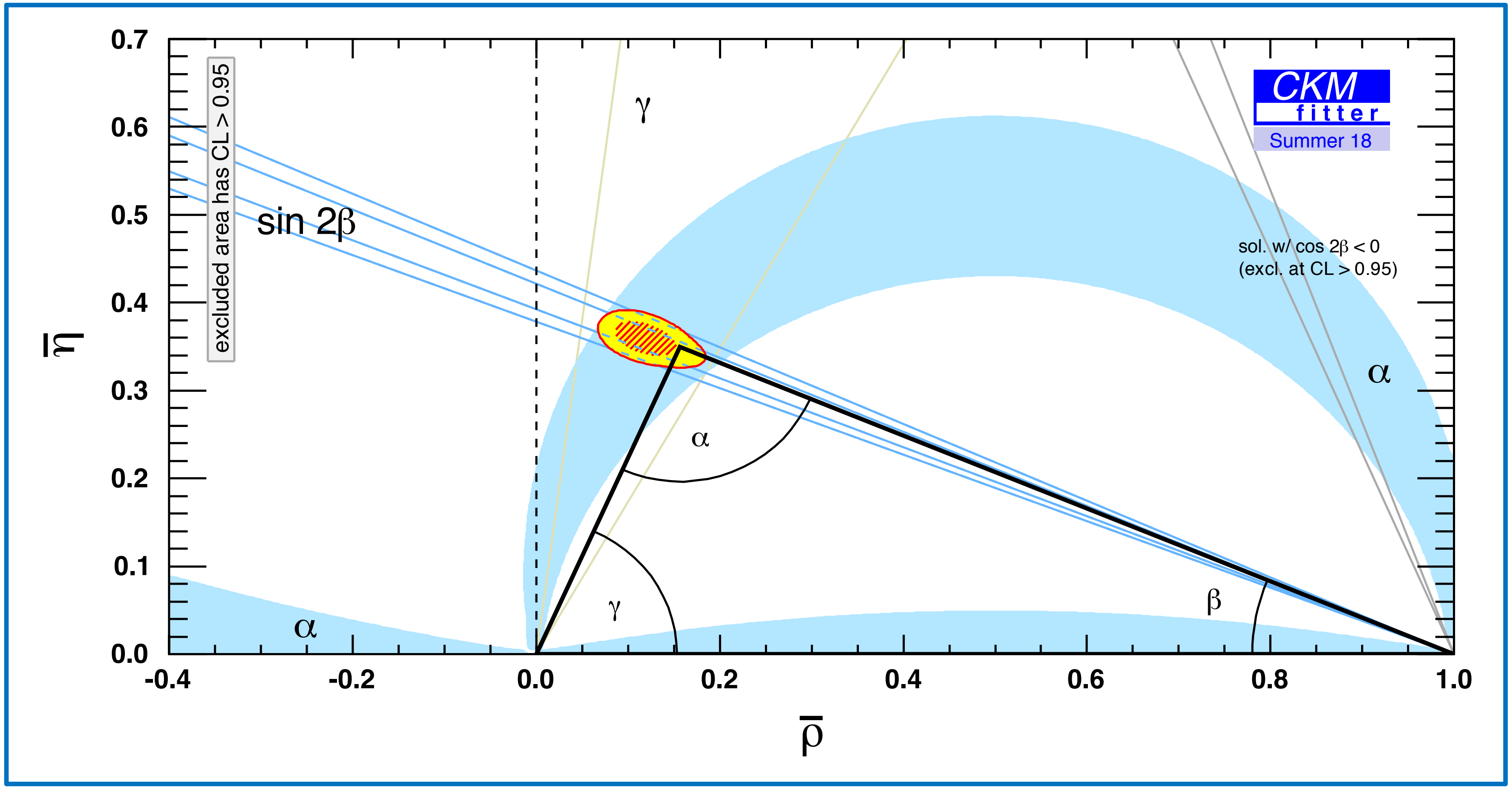



# CKM triangle: putting all measurements together



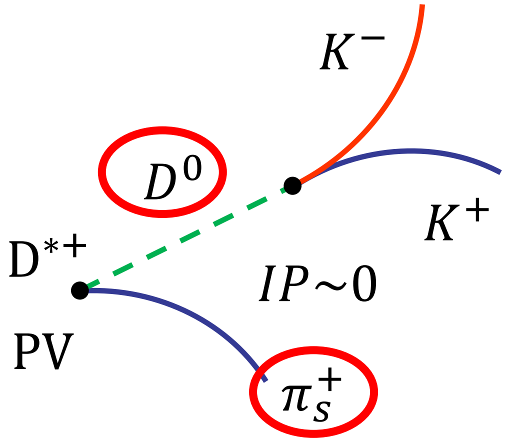
| | Measured | CKMfitter prediction | UTfit prediction |
|---|---|---|---|
| β | 22.7 ± 0.7 | $23.7^{+1.1}_{-1.0}$ | 23.8 ± 1.4 |
| γ | 70.0 ± 4.2 | $65.3^{+1.0}_{-2.5}$ | 65.8 ± 2.2 |
| α | 93.1 ± 5.6 | $92.1^{+1.5}_{-1.1}$ | 90.1 ± 2.2 |

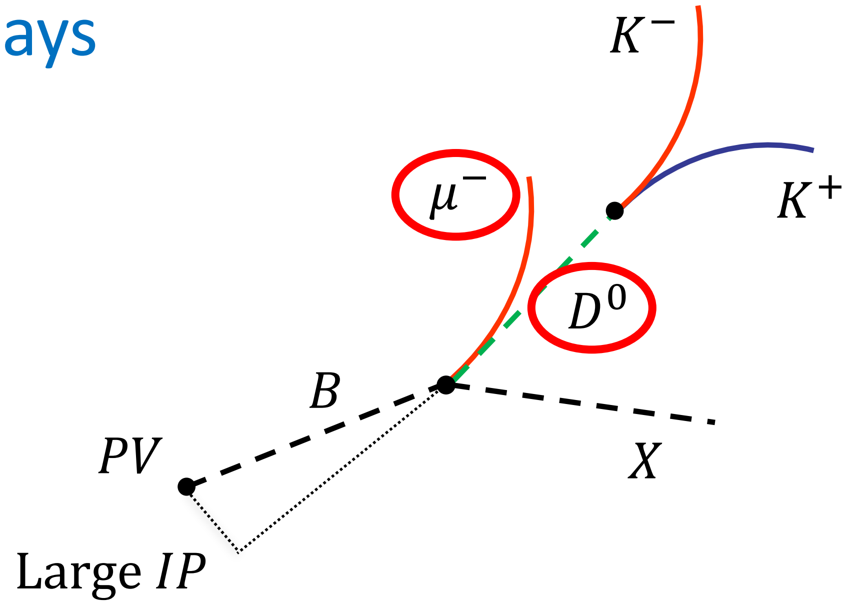


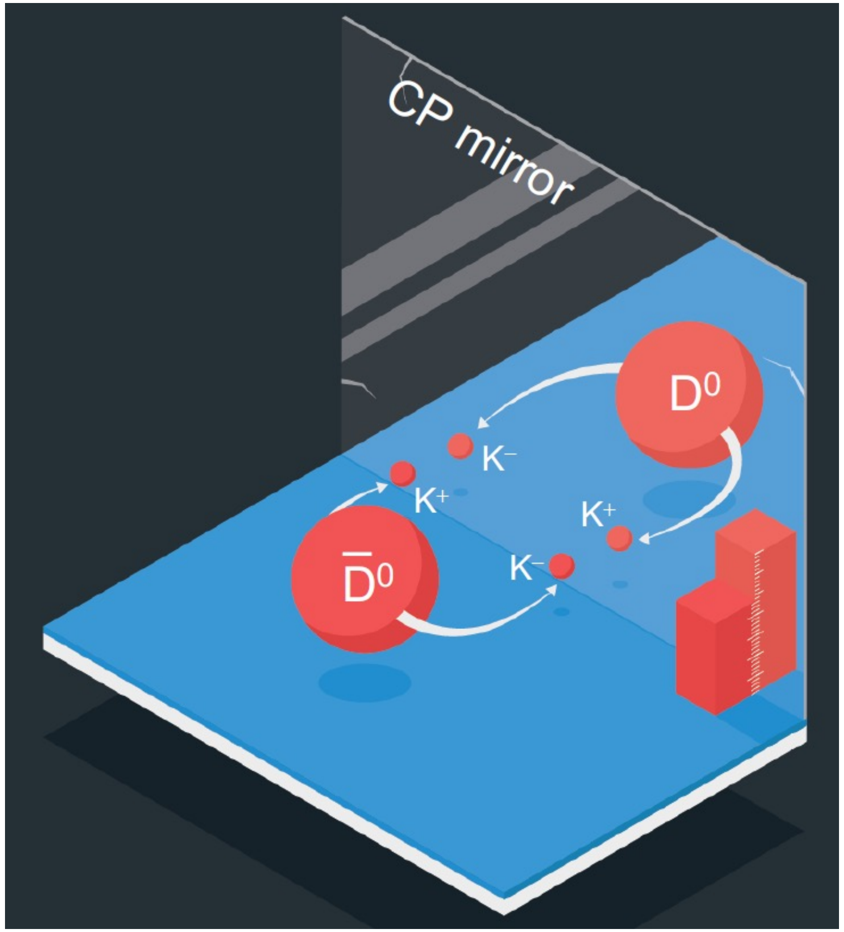
# CPV in Kaons (K) and Beauty (B): How about Charm (D)?



- $D^0 \to K^+K^-$ decays



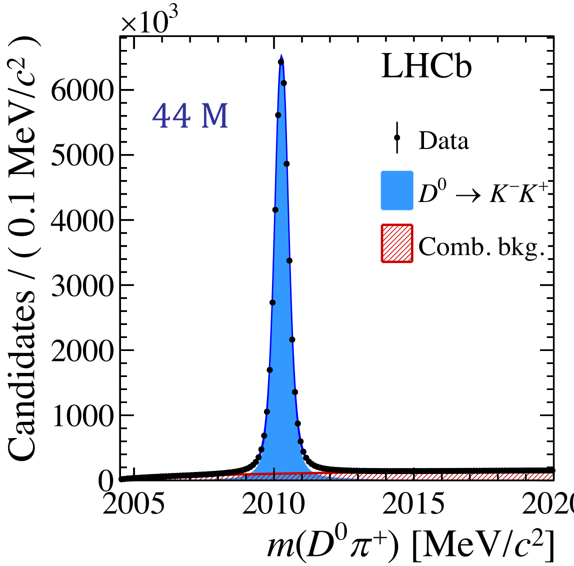

$$A_{raw}(K^+K^-) = \frac{N(D^0 \to K^+K^-) - N(\bar{D}^0 \to K^+K^-)}{N(D^0 \to K^+K^-) + N(\bar{D}^0 \to K^+K^-)}$$

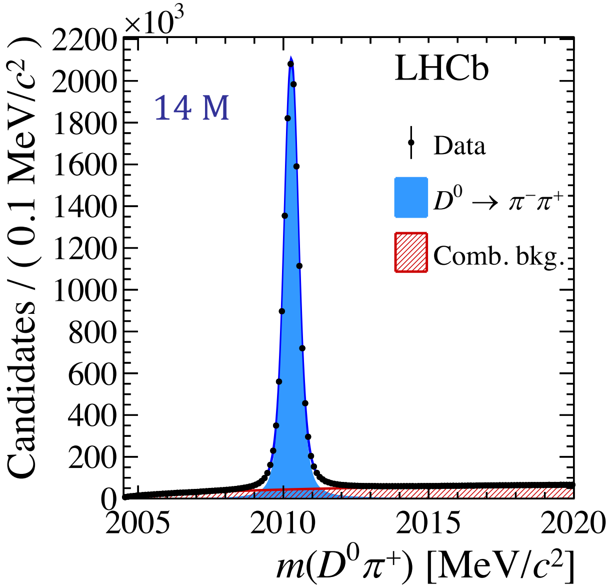
$$A_{raw}(K^+K^-) = A_{CP}(K^+K^-) + A_D(K^+K^-) + A_D(\pi_s) + A_P(D^{*+})$$

- Look at: $\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$
  - ⇒ All detection and production asymmetries cancel
  - ⇒ Directly observe CP asymmetry!

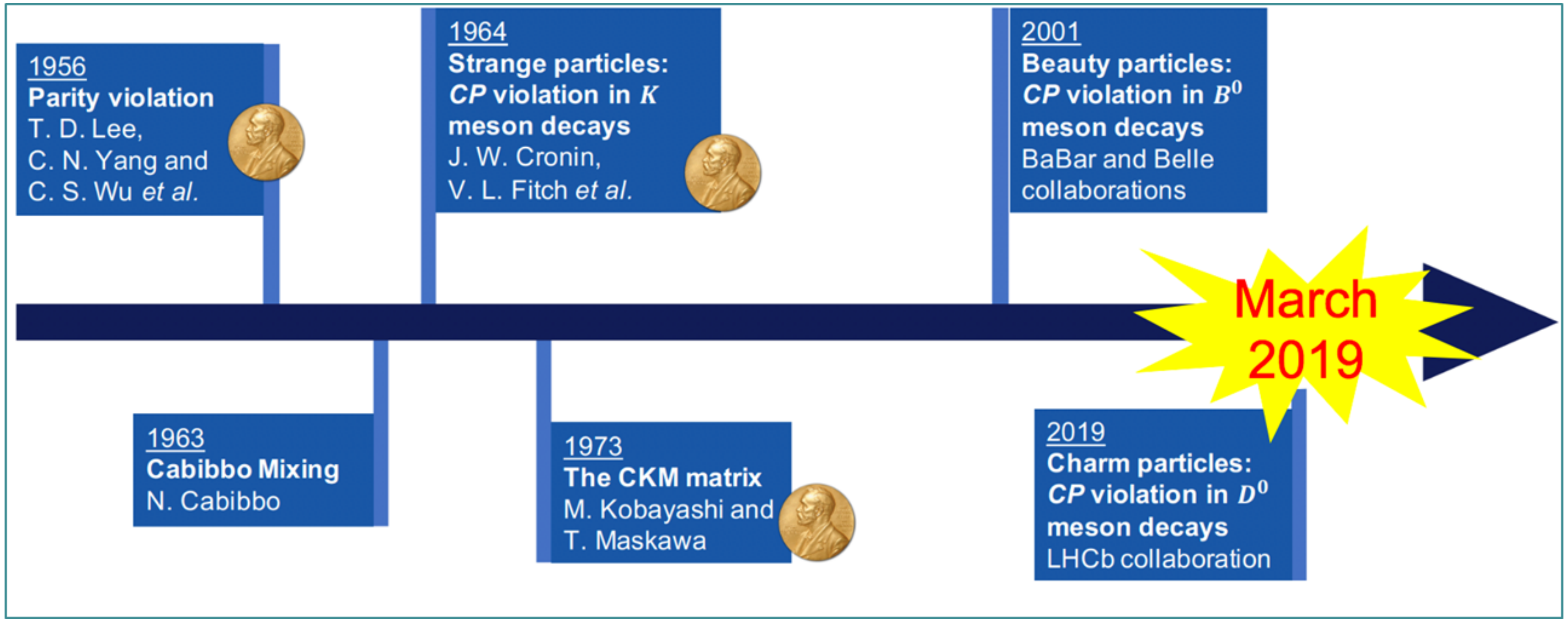
# 2019: Discovery of CP violation in charm mesons!





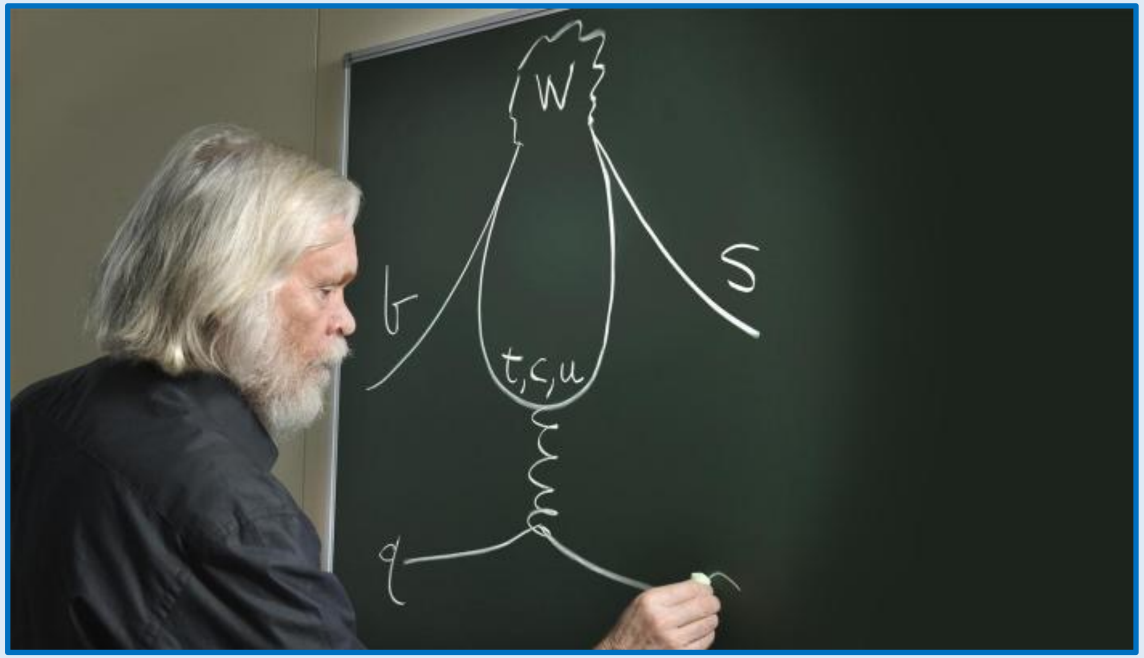




- Result: $\Delta A_{CP} = (-15.8 \pm 2.9)\times 10^{-4}$
- $5.3\sigma$ Observation!
- Is it consistent with CKM in Standard Model?



## Contents:

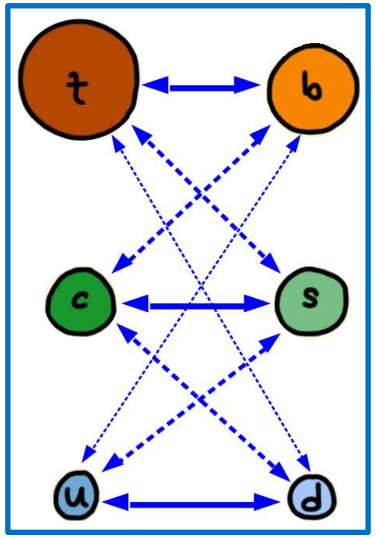




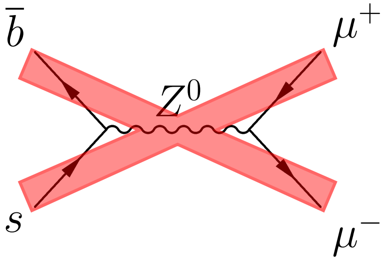
# S.M.: No Flavour Changing Neutral Currents (FCNC)

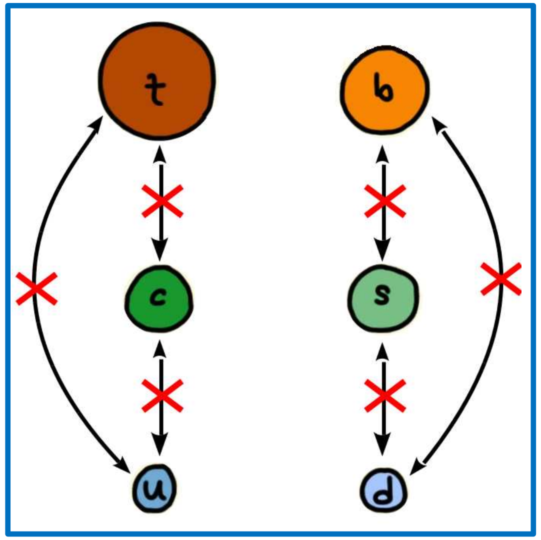


- CKM: Flavour changing *charged* currents



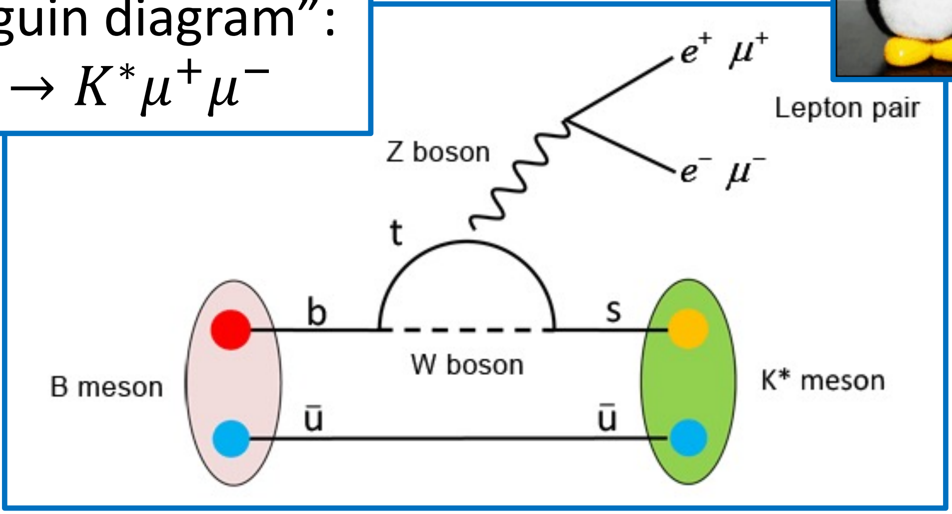

- SM does *not* have Flavour changing *neutral* currents



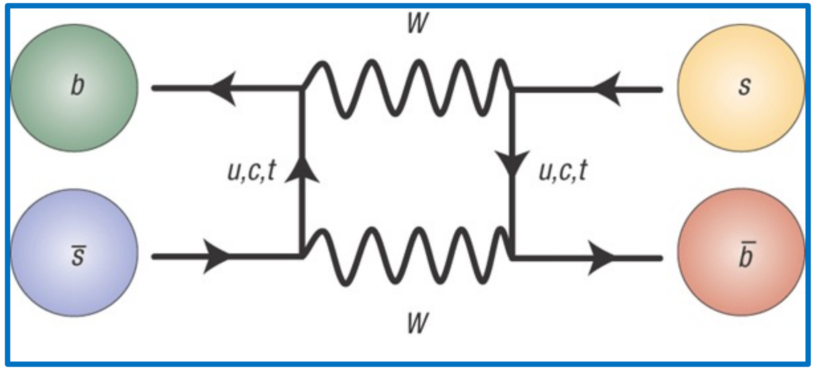




- Neutral currents are possible via higher order processes:

Decay via "Penguin diagram":
$B \to K^* \mu^+ \mu^-$



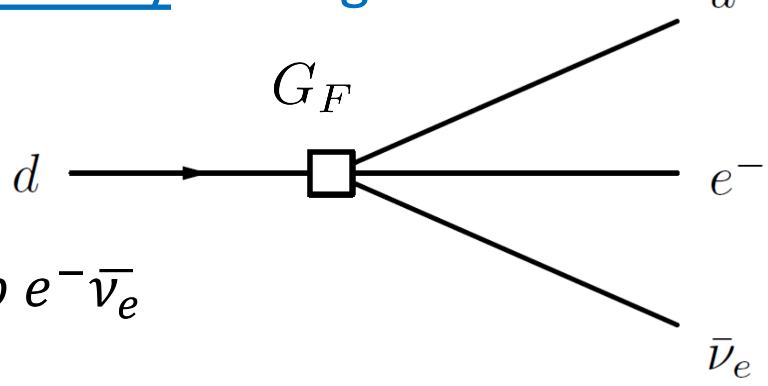

Flavour Oscillation via "Box diagram":
$\overline{B_s} \to B_s$



# $B$-decays and effective couplings

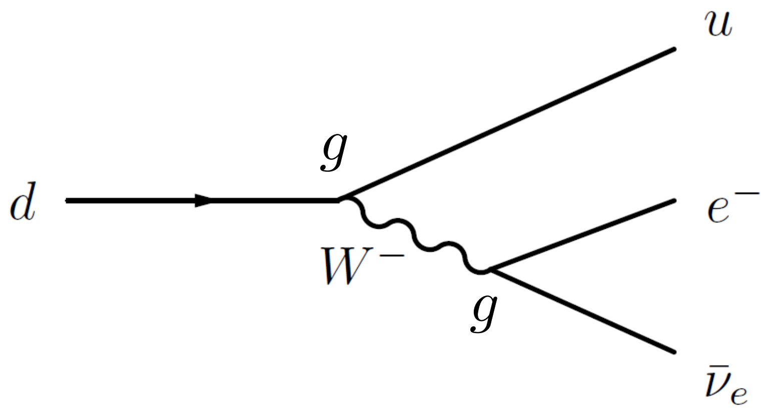


- Beta decay: "charged current":

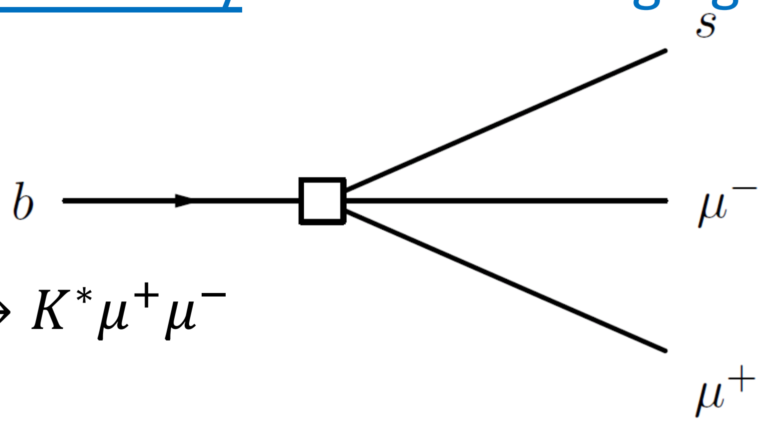



$n \to p\, e^- \bar{\nu}_e$

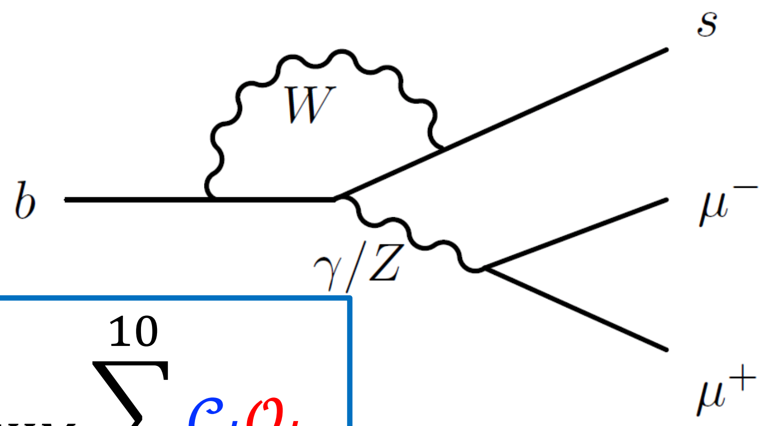
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$




- Rare B decay: "Flavour changing neutral current":




$B^0 \to K^* \mu^+ \mu^-$



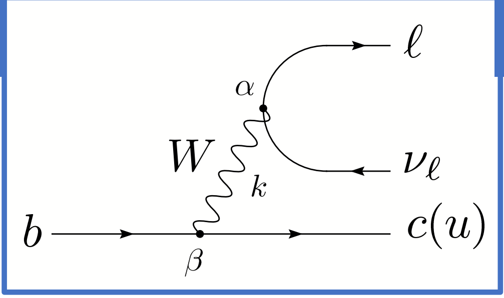

Eff Hamiltonian:

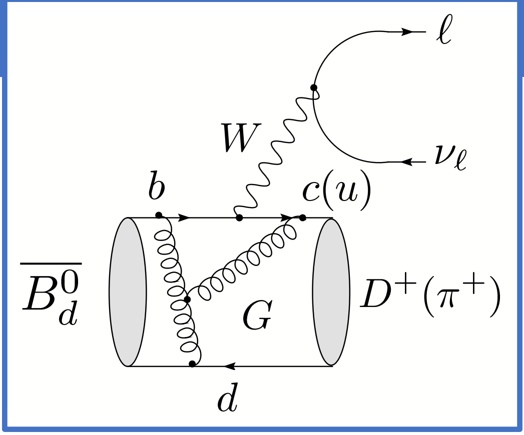
$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i$$

Effective Operators $\mathcal{O}_i$ with Wilson coefficients $\mathcal{C}_i$ predicted by the Standard Model.

# Strong Interaction causes trouble

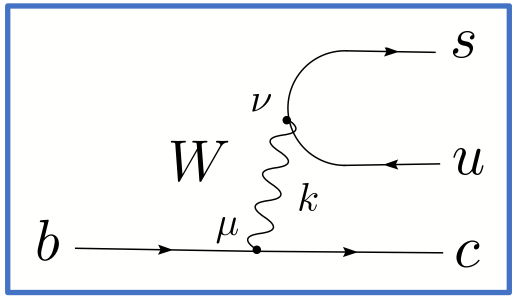


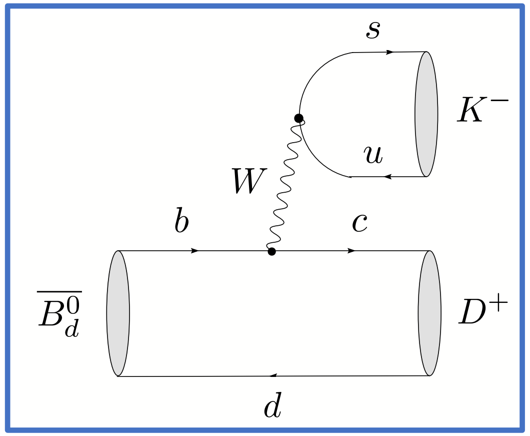



- Semileptonic decays
  - Factorization!

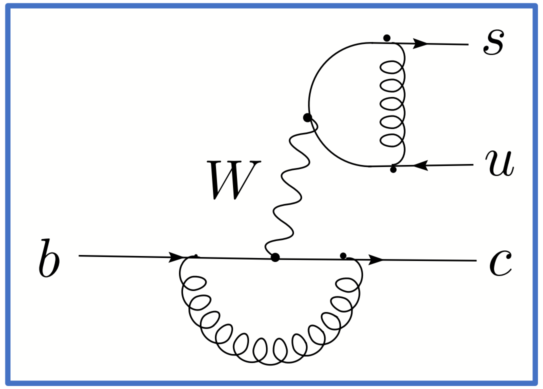
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \underbrace{[\overline{u}_l\, \gamma^\alpha (1-\gamma_5)\, u_\nu]}_{\textit{Dirac spinors}} \underbrace{\left[D^+ \middle| \overline{c}\, \gamma^\beta (1-\gamma_5)\, b \middle| \overline{B_d^0}\right]}_{\textit{hadronic ME}}$$



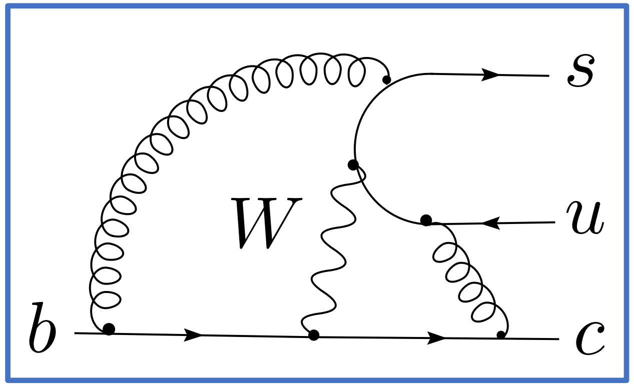




- $\mathcal{H}$adronic decays
  - Factorization?

*Factorizable* QCD:



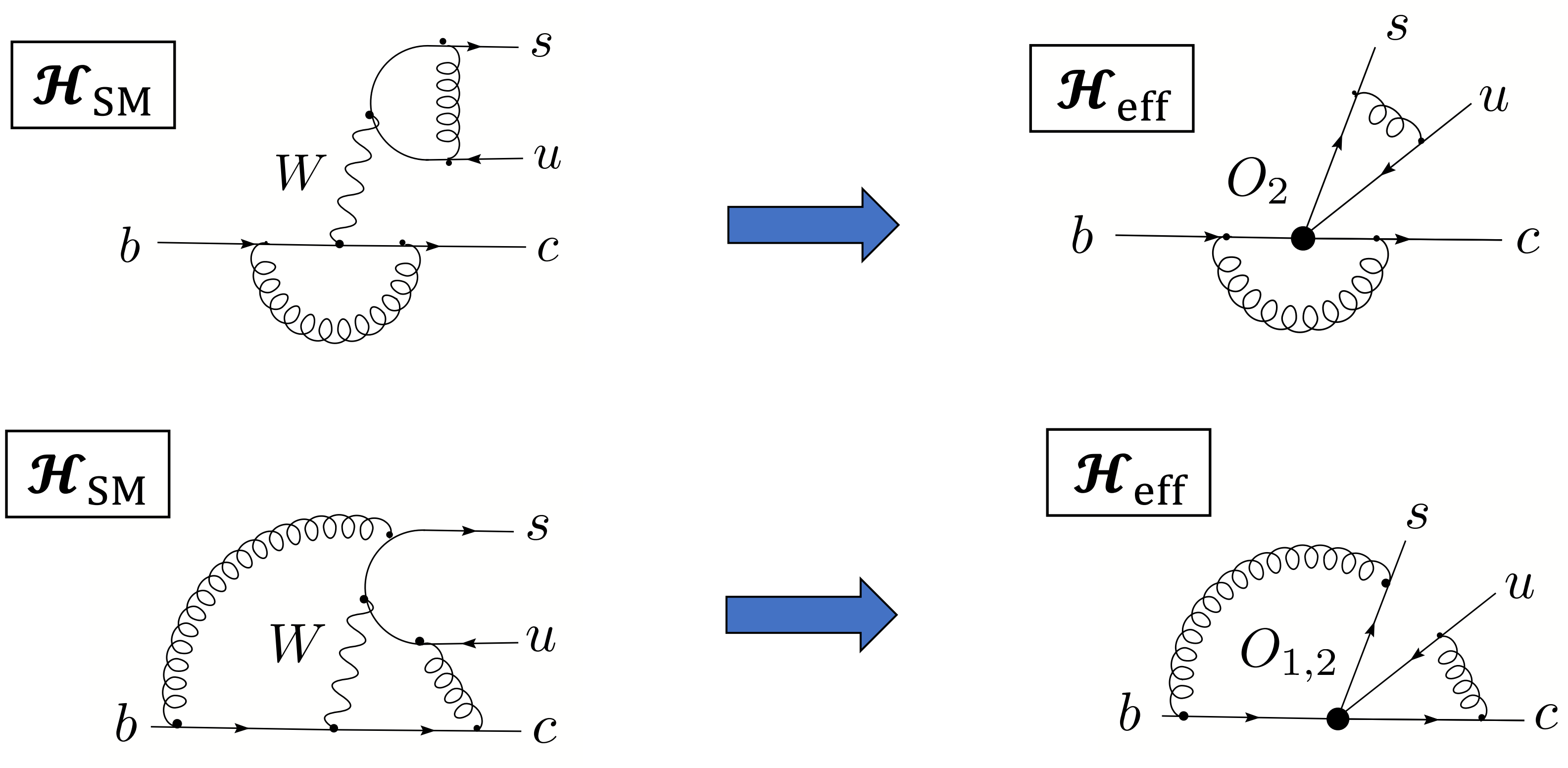

*Non-Factorizable* QCD:



# Solution: Effective couplings



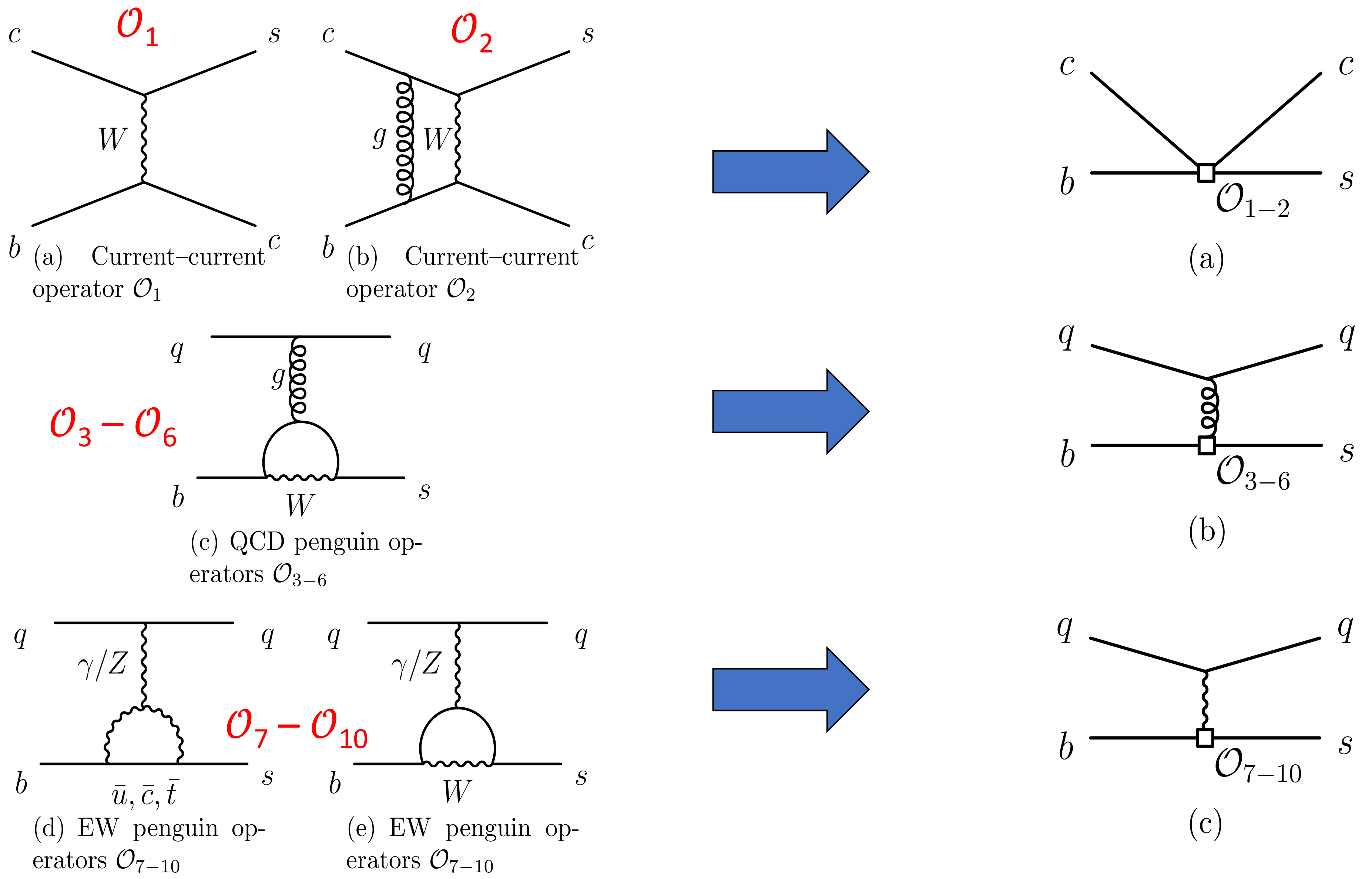
- Operator Product Expansion:
  - Integrate out heavy fields
  - Separate *perturbative* Wilson coefficients $\mathcal{C}_{\mathrm{i}}$ from *non-perturbative* local operators $\mathcal{O}_{\mathrm{i}}$




$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} V_{us}^{*} V_{cb} \left[\mathcal{C}_1 \mathcal{O}_1 + \mathcal{C}_2 \mathcal{O}_2\right]$$

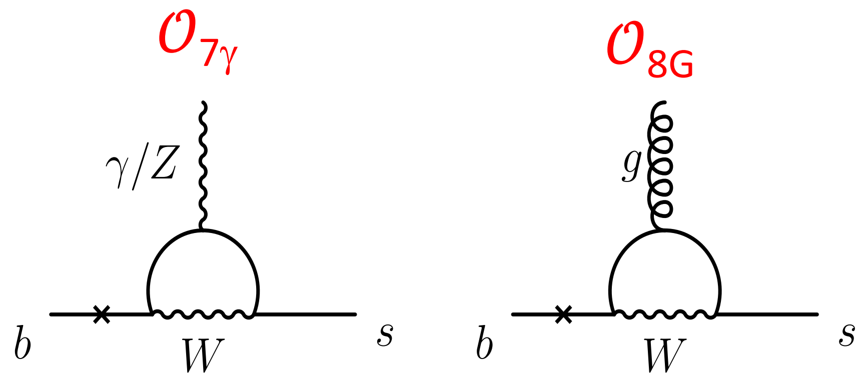
# Rare $B$-decays and effective couplings: $b \to s q \bar{q}$





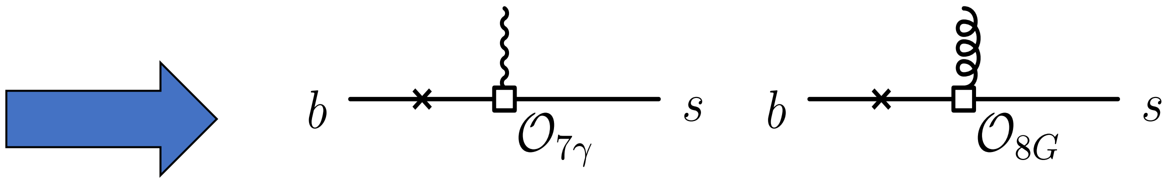
# Rare $B$-decays and effective couplings: $b \to sl^+l^-$



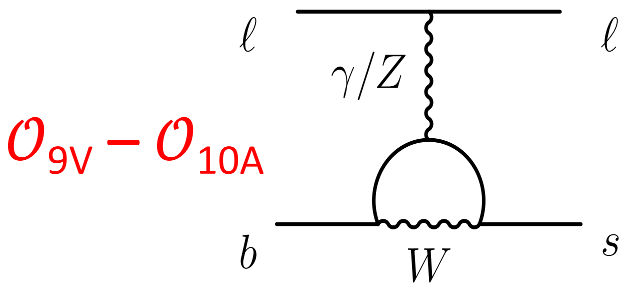



(f) Electromagnetic penguin operator $\mathcal{O}_{7\gamma}$

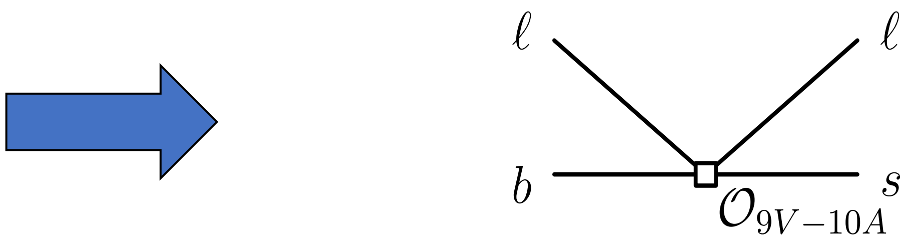
(g) Chromomagnetic penguin operator $\mathcal{O}_{8G}$




(d) (e)




(h) Semi-leptonic operators $\mathcal{O}_{9V-10A}$

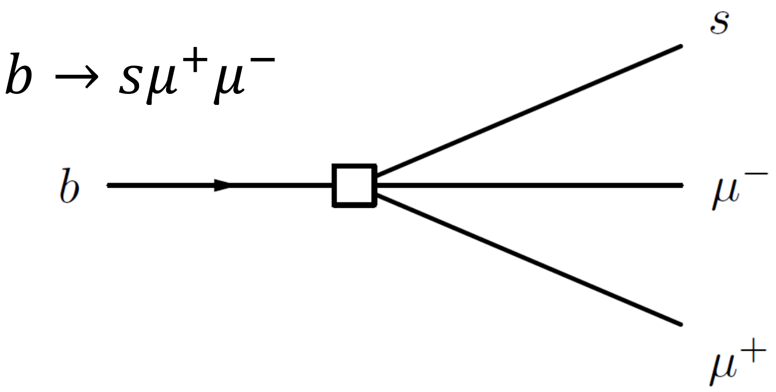



(f)

# Rare $B$-decays and effective couplings: $b \to s\mu^+\mu^-$

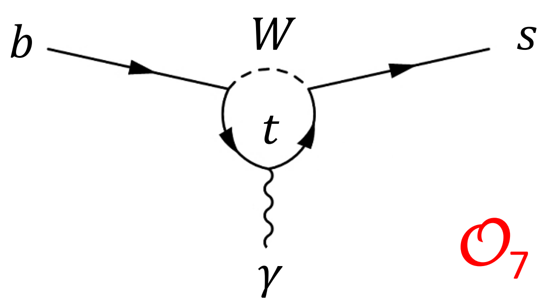
- Effective 4-fermion coupling:

$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i$$

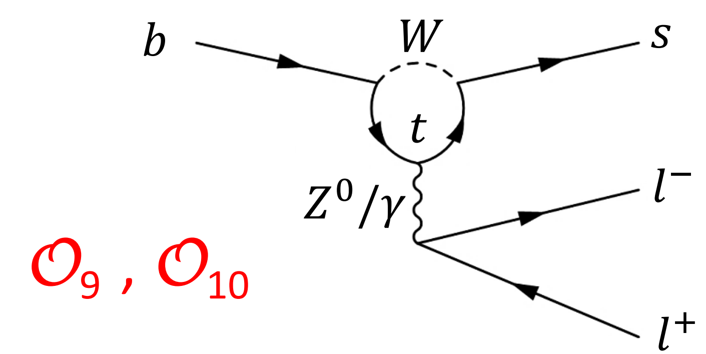



- Standard Model diagrams:

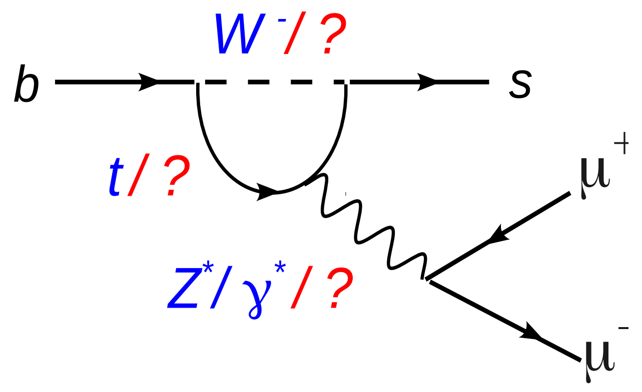
Photon penguin:




Vector, Axial vector:




- Beyond Standard Model:




- Experimental test: Compare calculable $C_i$ coefficients to experimental data
  - Sensitivity for NP in Wilson coefficients $C_7$, $C_9$, $C_{10}$

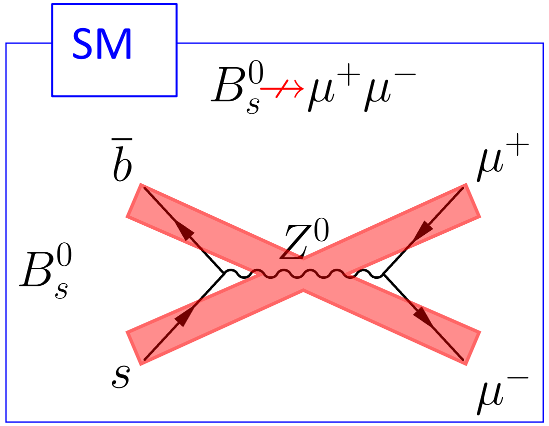
# Very Rare $B$-Decays

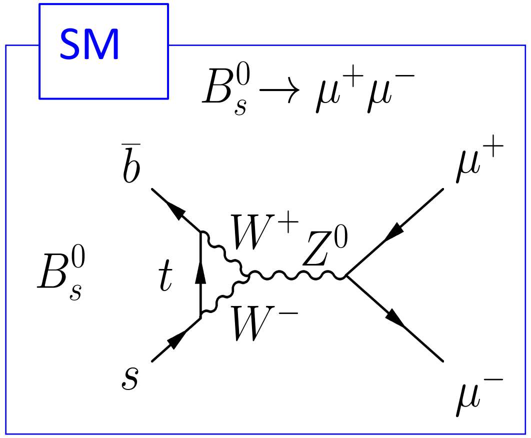


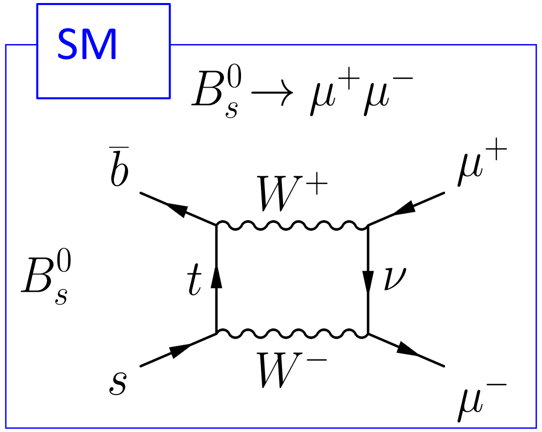
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\, V_{CKM} \sum_i C_i\, \mathcal{O}_i$$

$$B_s^0 \to \mu^+\mu^-$$
$$B_d^0 \to \mu^+\mu^-$$

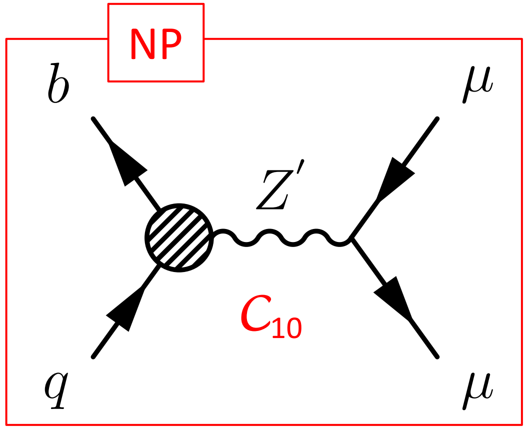
**SM**: CKM and helicity suppressed: very small B.R.
→ Axial vector coupling $C_{10}$

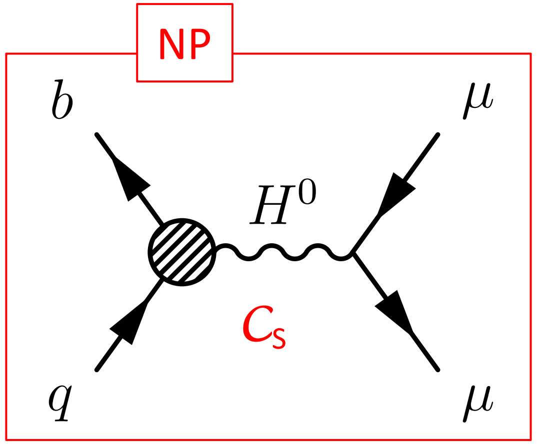


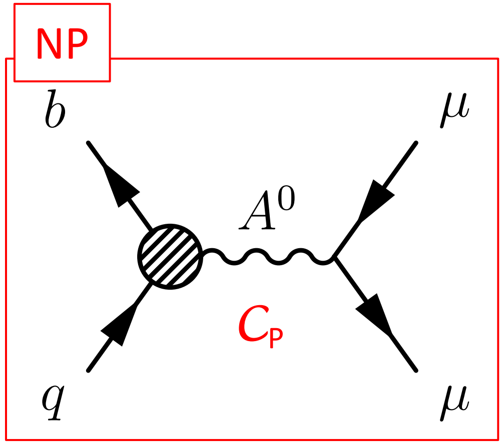




**NP**: Sensitive to new particles via additional ($C_{10}$, $C_S$, $C_P$) couplings.
→ eg.: Z' , (pseudo-)scalars, …

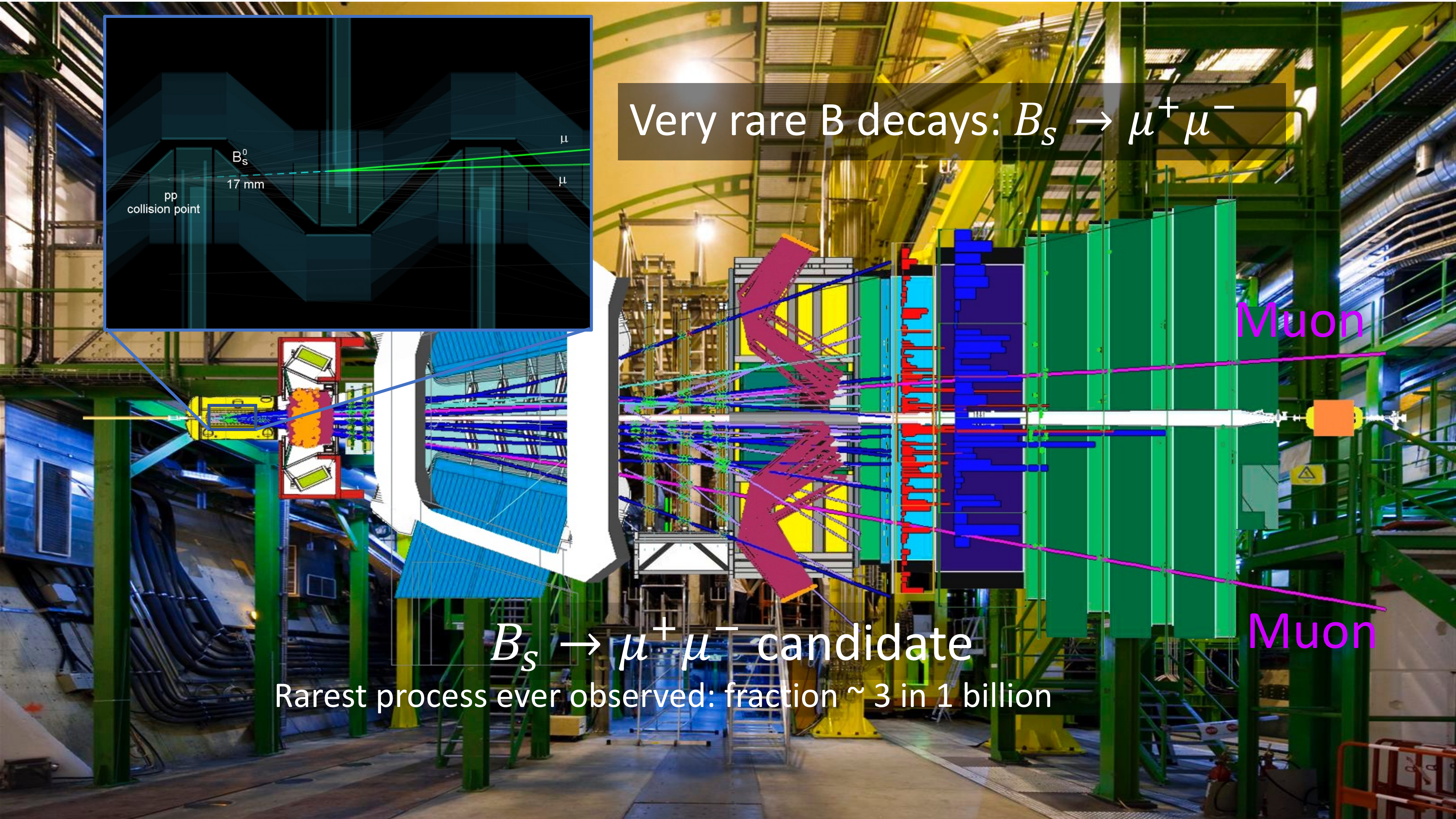



$$BR \propto |V_{tb}V_{tq}|^2 \left[ \left(1 - \frac{4m_\mu^2}{M_B^2}\right) |C_S - C_S'|^2 + |(C_P - C_P') + \frac{2m_\mu}{M_B^2}(C_{10} - C_{10}')|^2 \right]$$

# Very rare B decays: $B_s \to \mu^+\mu^-$



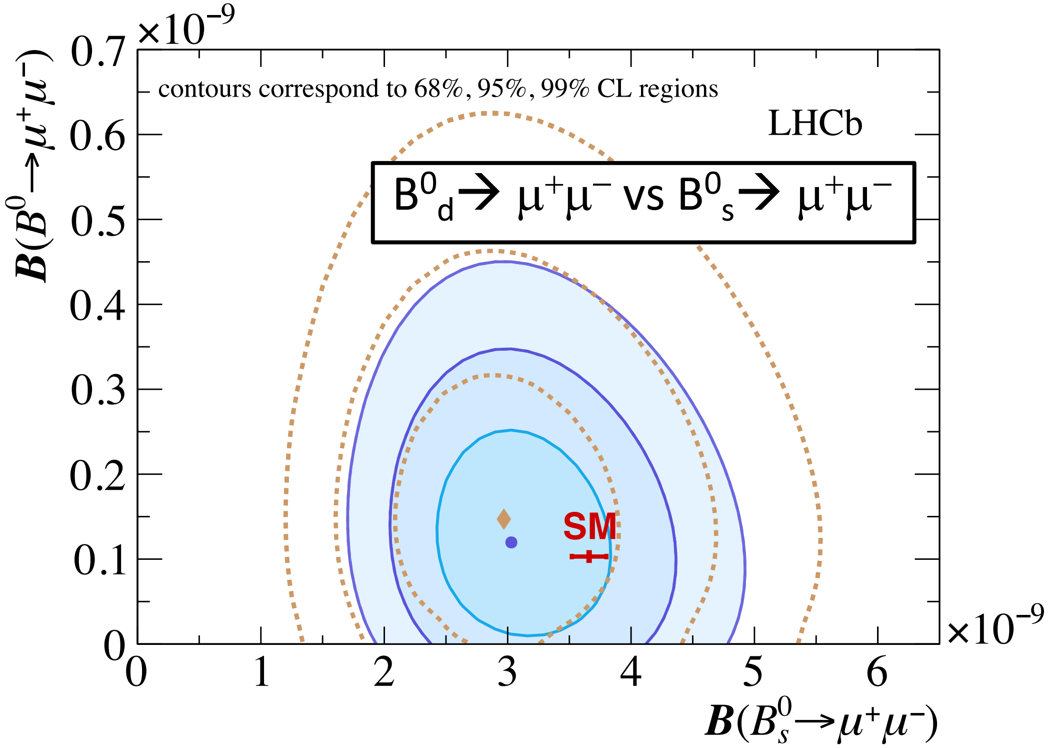

$B_s \to \mu^+\mu^-$ candidate

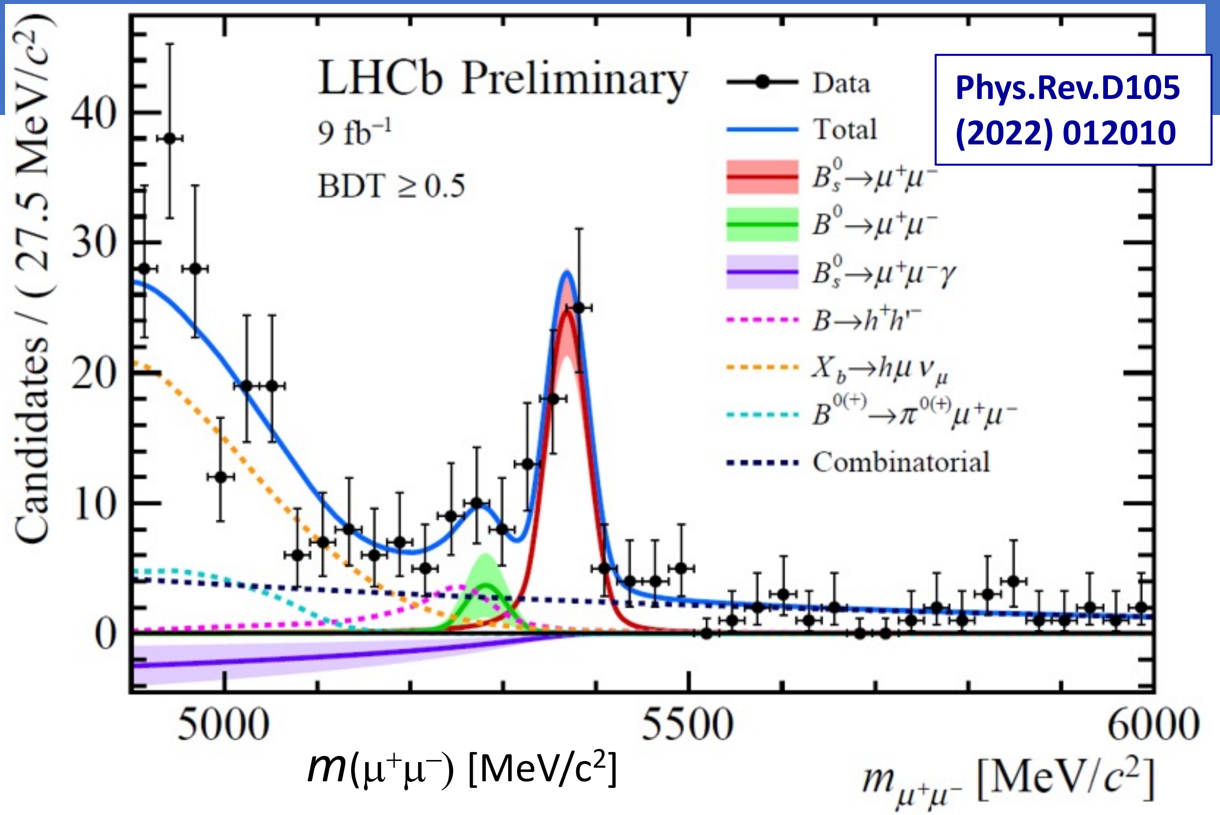
Rarest process ever observed: fraction ~ 3 in 1 billion

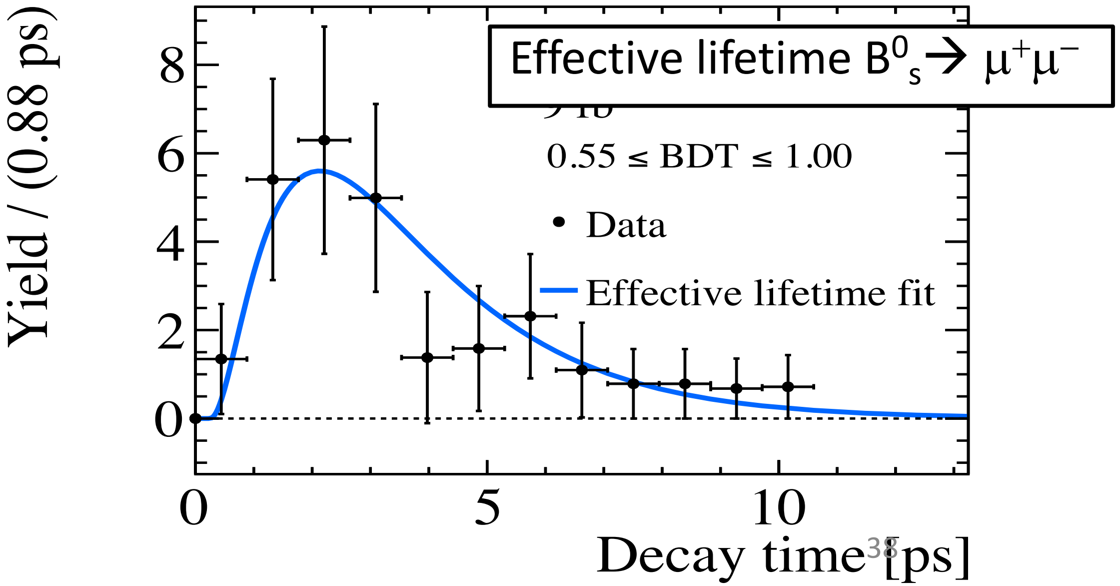
# Very Rare $B$-Decays

$$B^0_{s,d} \to \mu^+\mu^-$$

- Very strongly suppressed in the SM
- High sensitivity for physics beyond SM
- Hot topic for LHCb

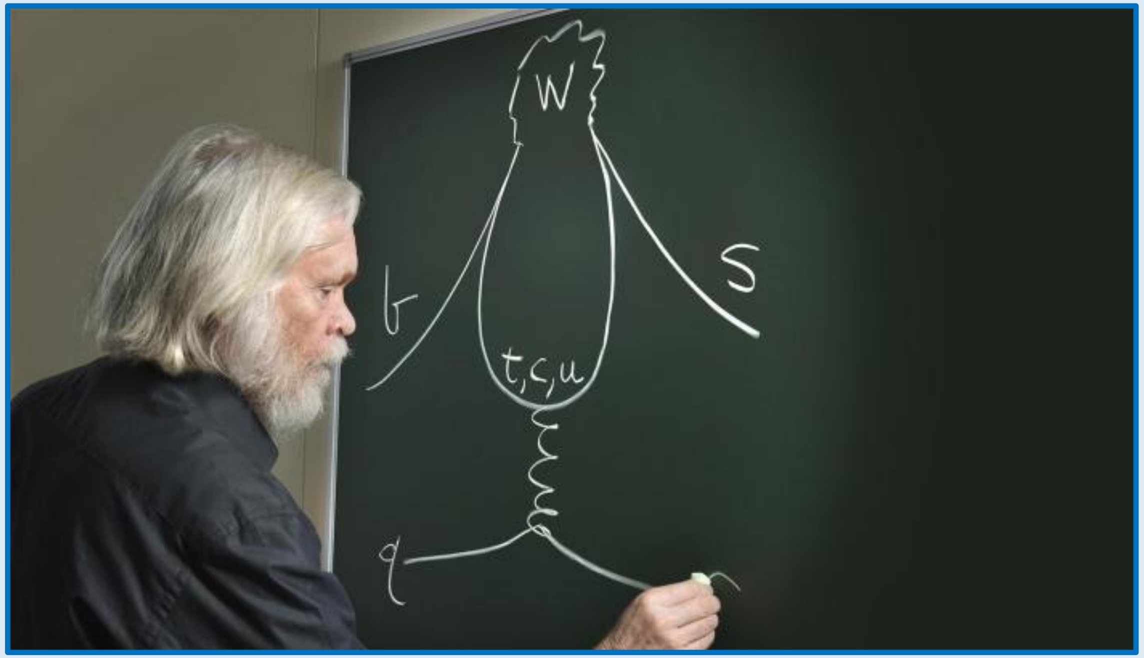


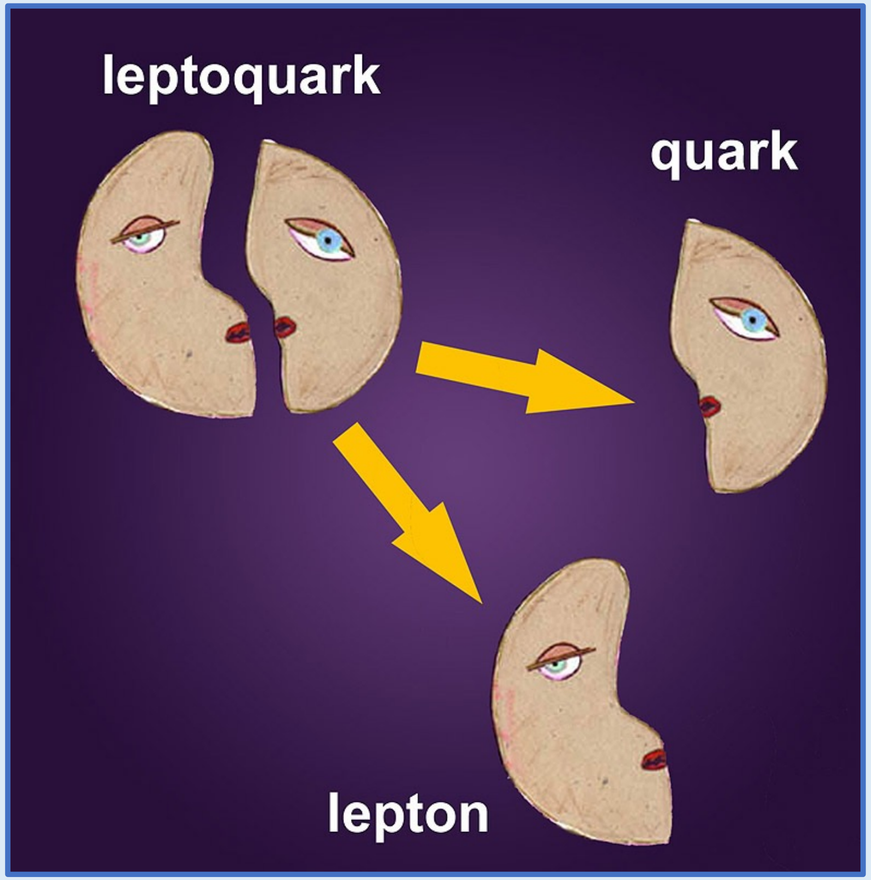
Contents:





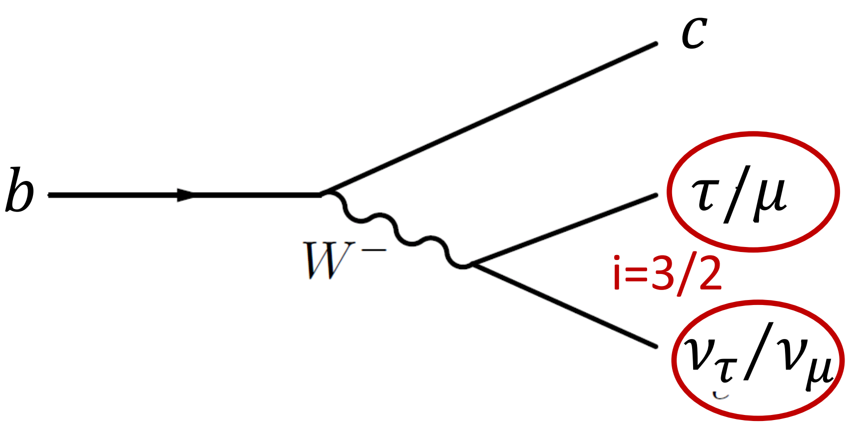
## Contents:





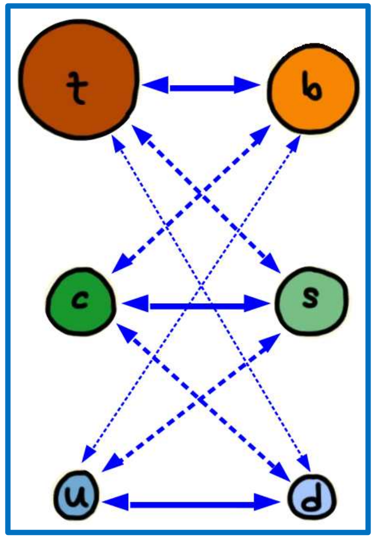
# $B$-decays and lepton universality

1) $b \rightarrow c\, l\, \nu$ charged current: "Allowed" → large decay rates

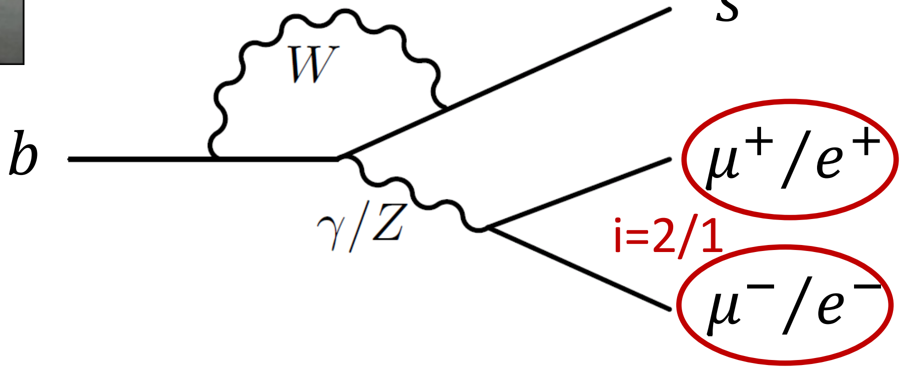



$$R_D = \frac{B \rightarrow D\tau\nu}{B \rightarrow D\mu\nu}$$

$$R_{D^*} = \frac{B \rightarrow D^*\tau\nu}{B \rightarrow D^*\mu\nu}$$

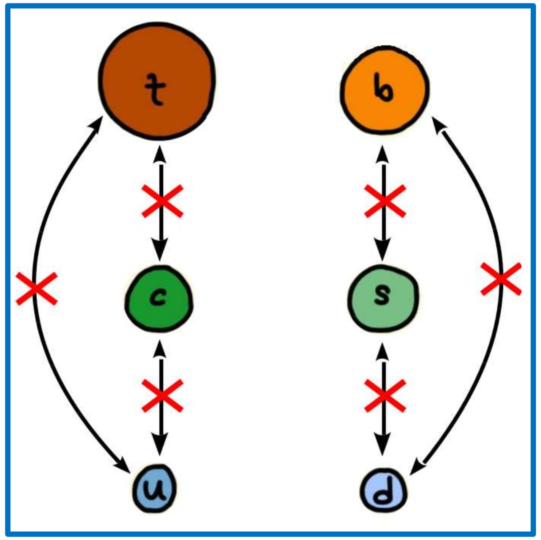



2) $b \rightarrow s l^+ l^-$ neutral current: "Suppressed" → rare decays




$$R_K = \frac{B^+ \rightarrow K^+\mu^+\mu^-}{B^+ \rightarrow K^+e^+e^-}$$

$$R_{K^*} = \frac{B^0 \rightarrow K^{*0}\mu^+\mu^-}{B^0 \rightarrow K^{*0}e^+e^-}$$



# $R_D$ and $R_{D^*}$

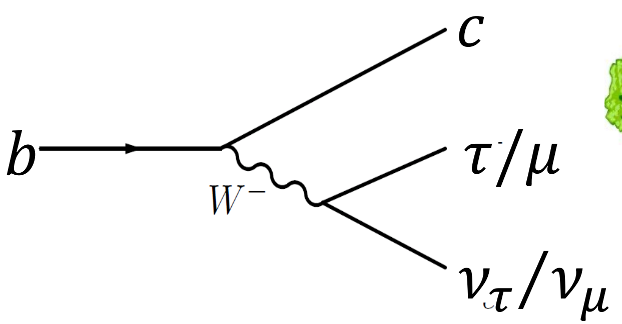


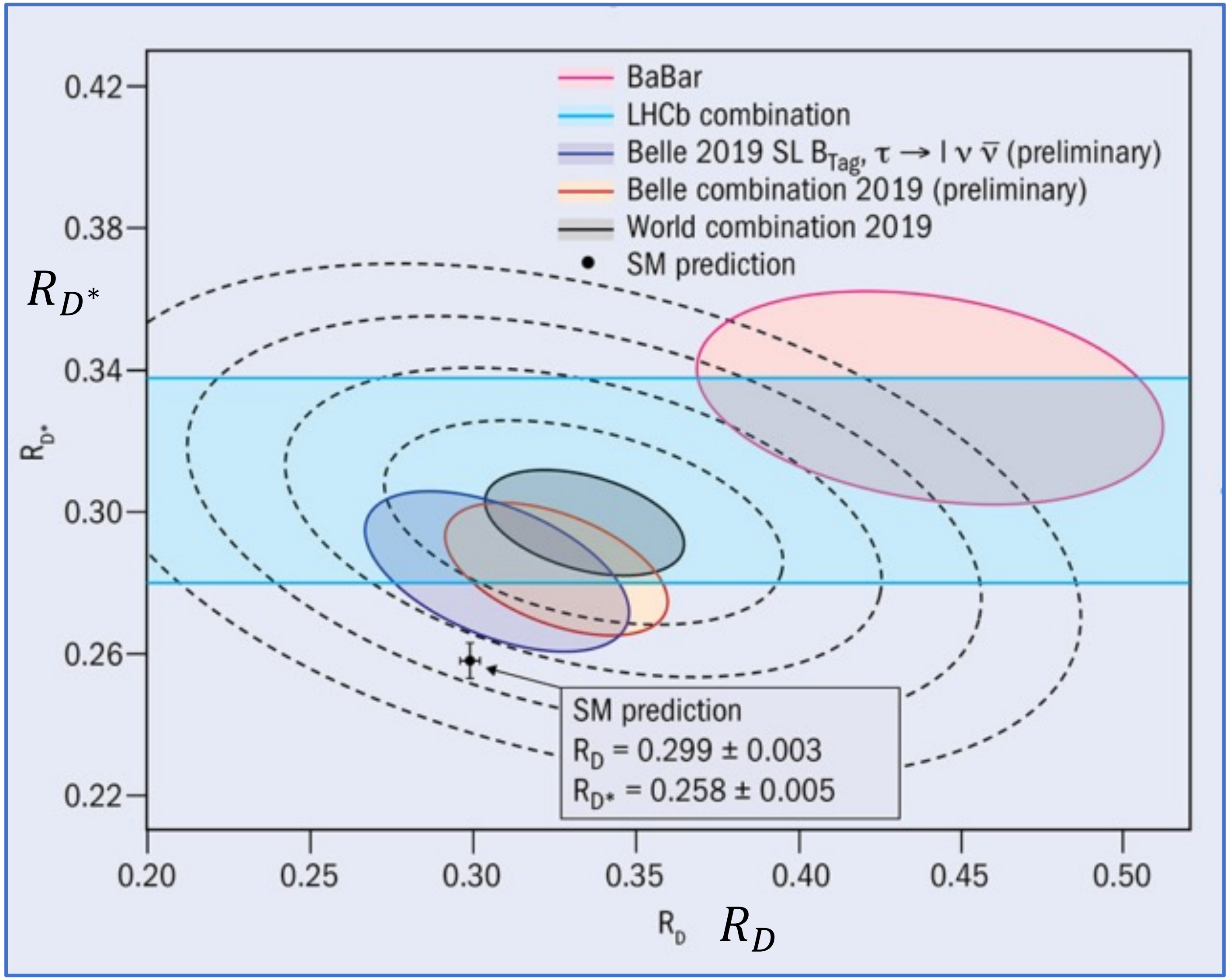
1) $b \rightarrow c\, l\, \nu$:

allowed charged current

$$R(D^{(*)}) = \frac{BR(B \rightarrow D^{(*)}\tau\nu)}{BR(B \rightarrow D^{(*)}\mu\nu)}$$

~ 3 – 4 σ deviation



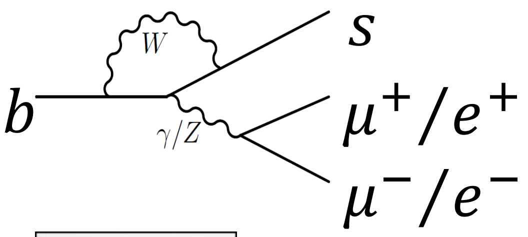

Potential *large* effect ➔ Involves particles of 2nd and 3rd generation

# $R_K$ and $R_{K^*}$



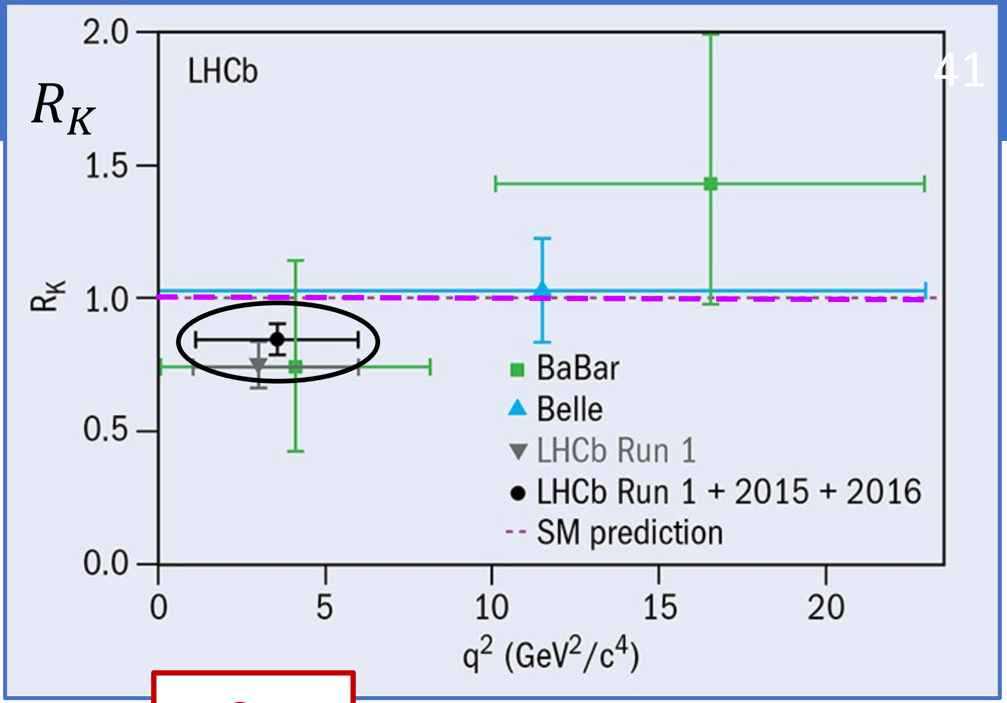
2) $b \to s\, l^+ l^-$

Suppressed neutral current

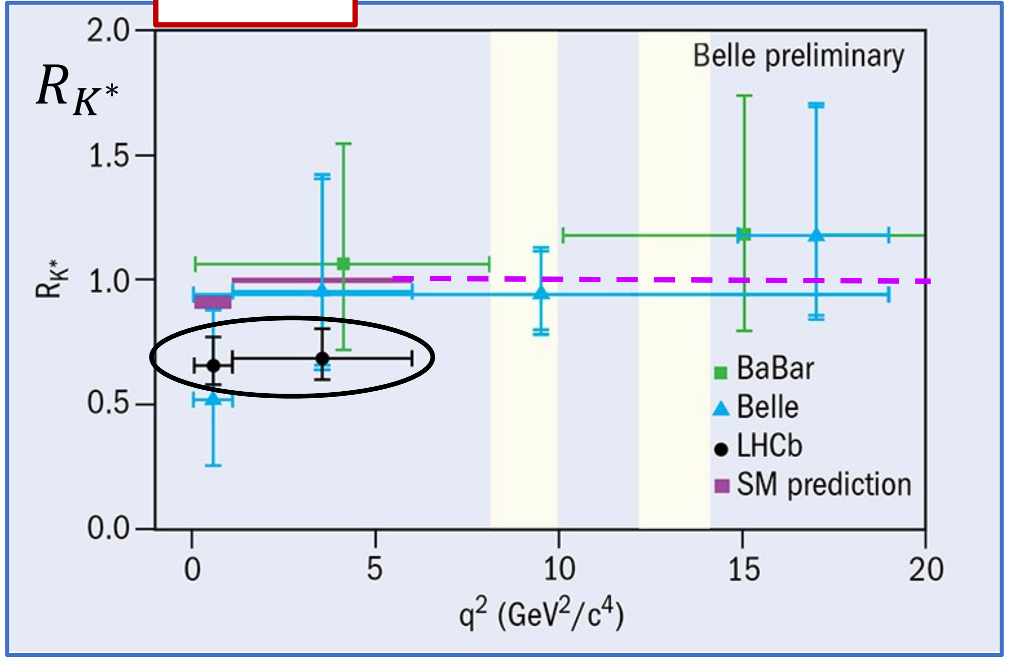



$$R(K) = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

$$R(K^*) = \frac{BR(B^0 \to K^* \mu^+ \mu^-)}{BR(B^0 \to K^* e^+ e^-)}$$




~ 3 $\sigma$

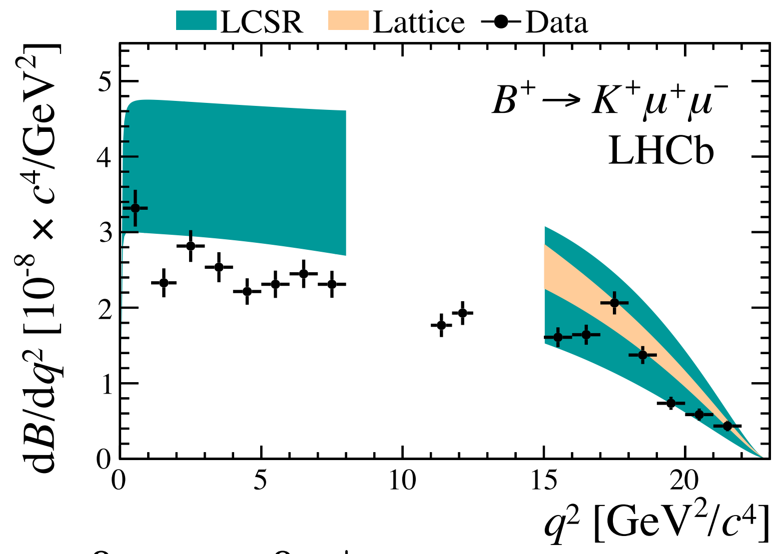



*Small* effect ➔ Particles of 1st and 2nd generation

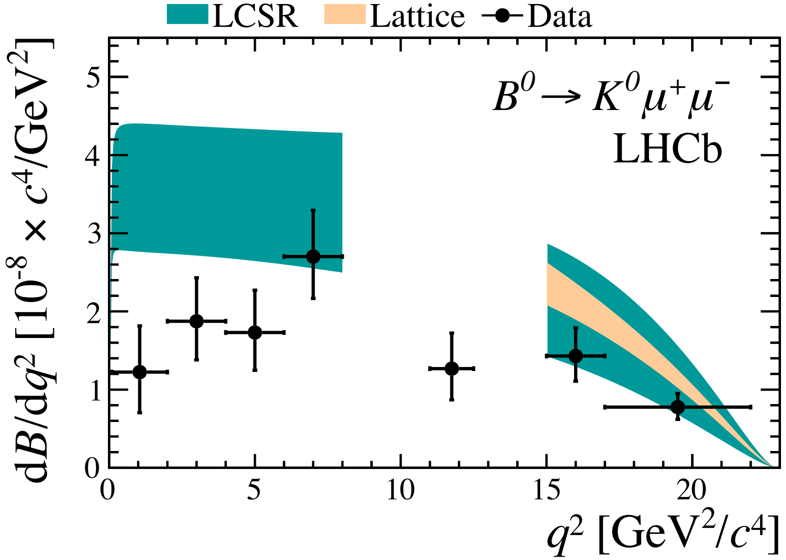
# Branching fractions of Rare Decays: $b \to s\,\mu^+\mu^-$



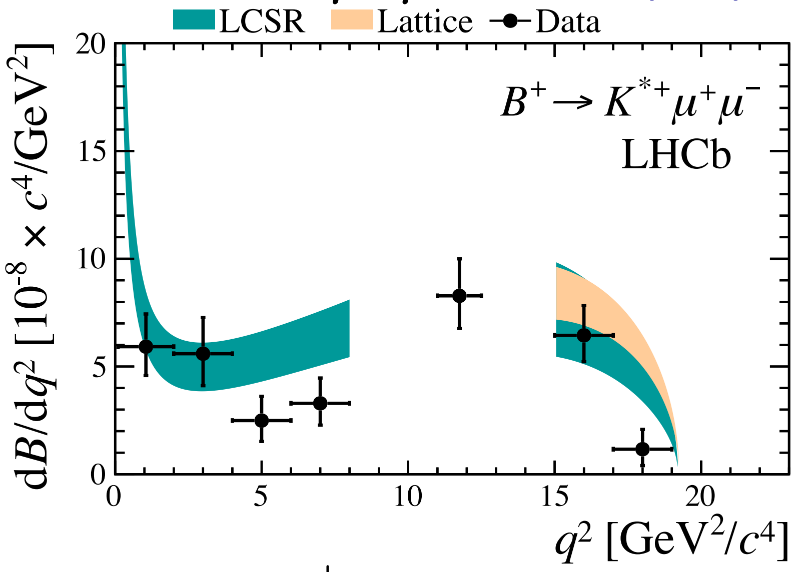
$B^+ \to K^+\mu^+\mu^-$ **JHEP 06 (2014) 133**



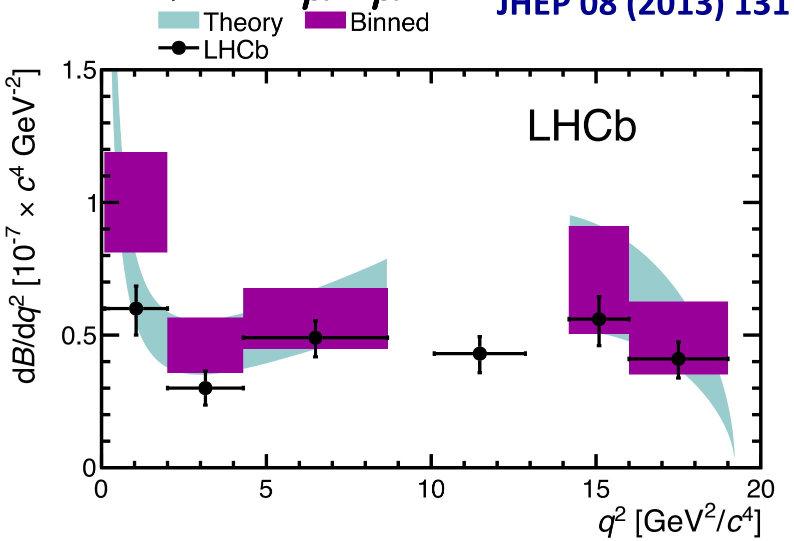

$B^0 \to K^0\mu^+\mu^-$ **JHEP 06 (2014) 133**



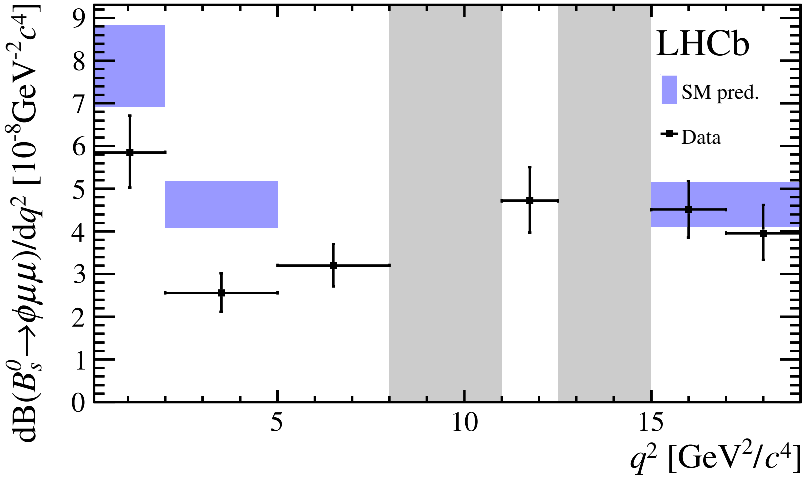

$B^+ \to K^{*+}\mu^+\mu^-$ **JHEP 06 (2014) 133**



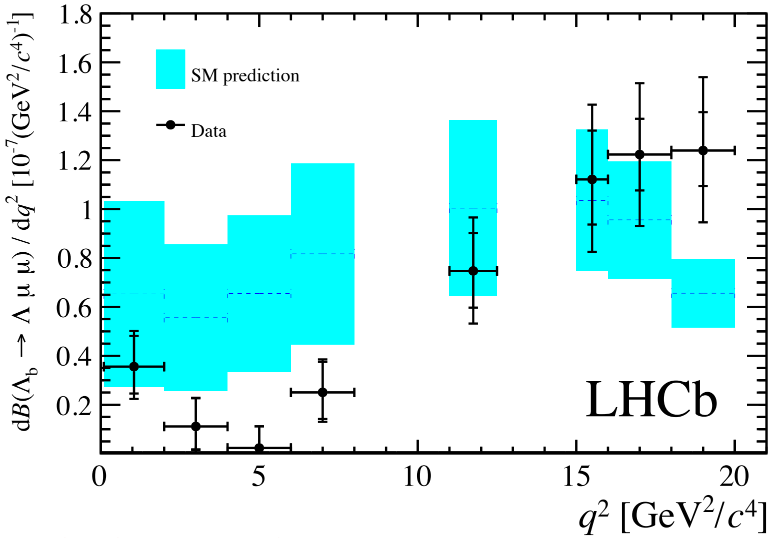

$B^0 \to K^{*0}\mu^+\mu^-$ **JHEP 08 (2013) 131**




$B_s \to \phi\mu^+\mu^-$ **JHEP 09 (2015) 179**

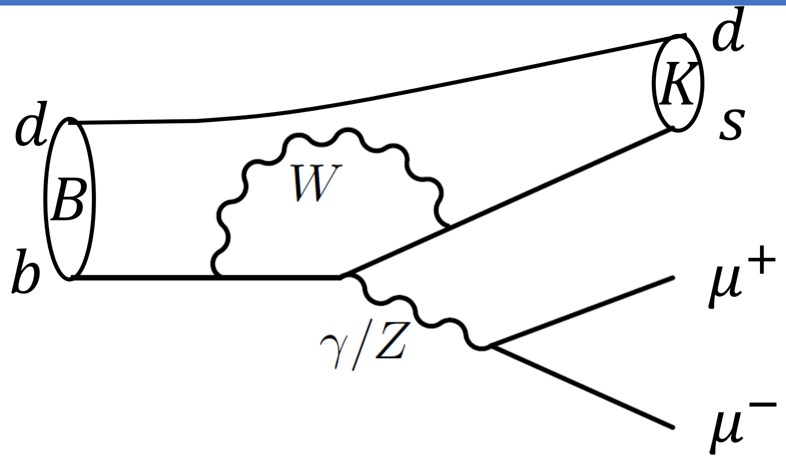


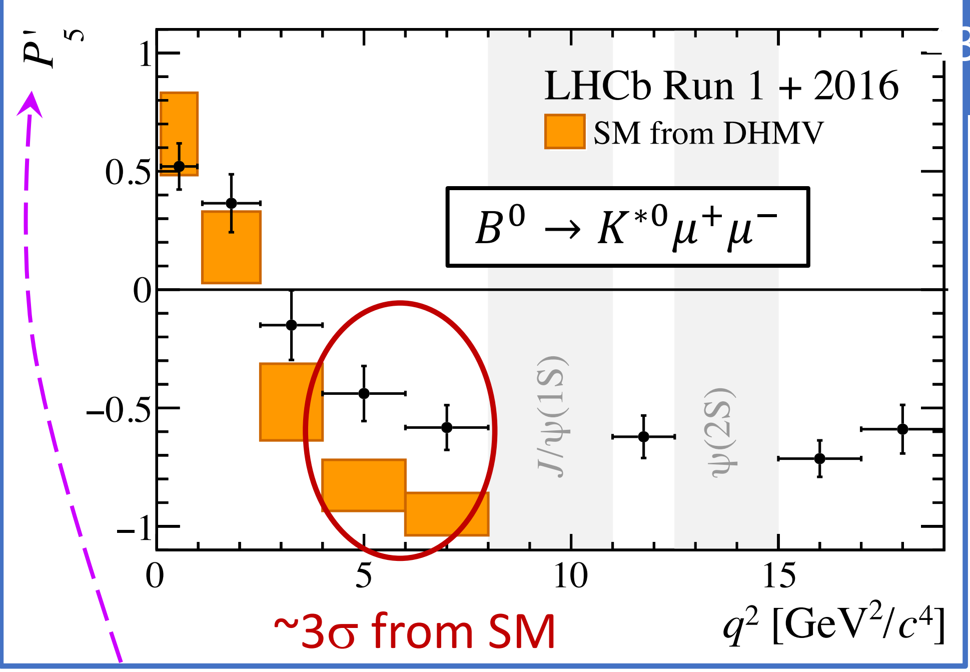

$\Lambda_b \to \Lambda\mu^+\mu^-$ **JHEP 06 (2015) 115**



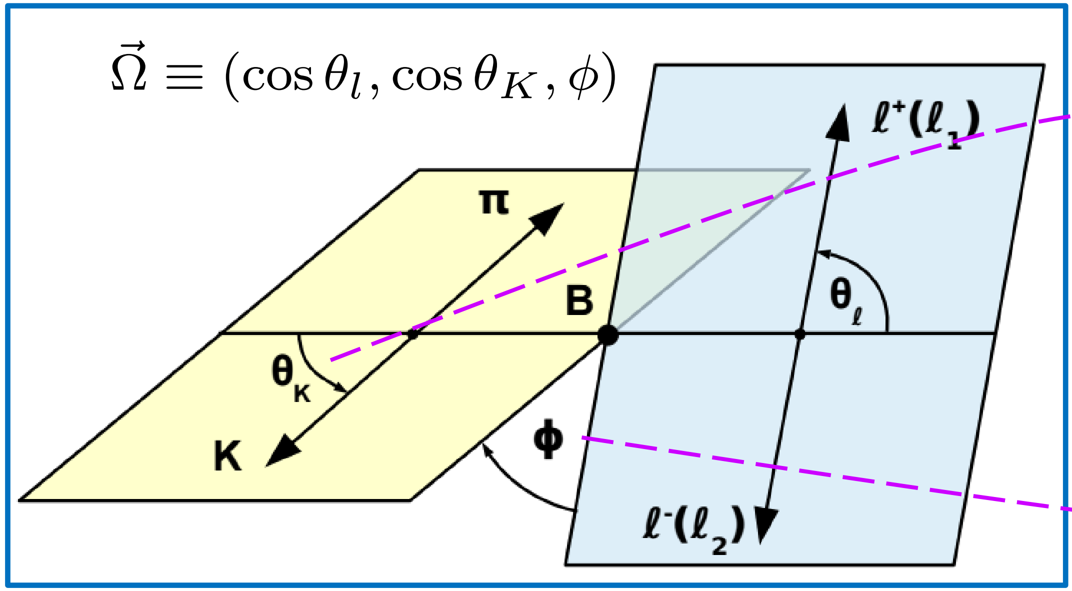

- Branching fractions related to $b \to s\,\mu^+\mu^-$ transition *consistently lower* than predicted.

# Variable $P'_5$ in $B^0 \to K^{*0}\mu^+\mu^-$

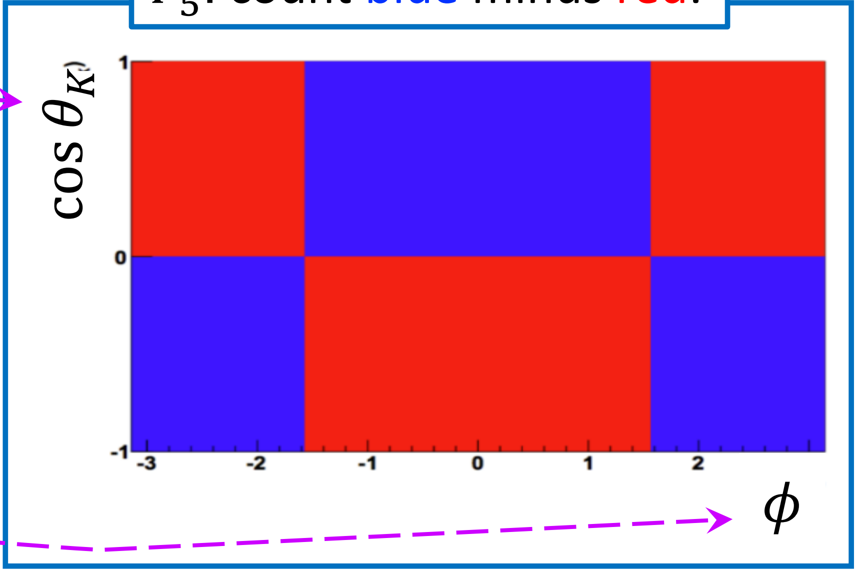



- LHCb: Study angular distribution of the produced particles




$P'_5$: count blue minus red:

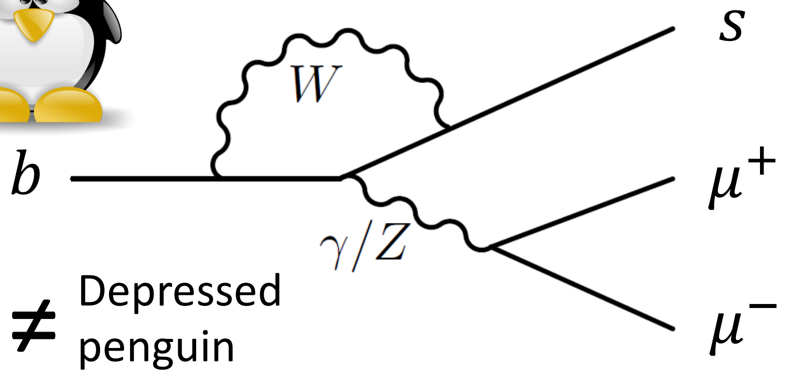


# Global Fit of $b \to s\,\mu^+\mu^-$



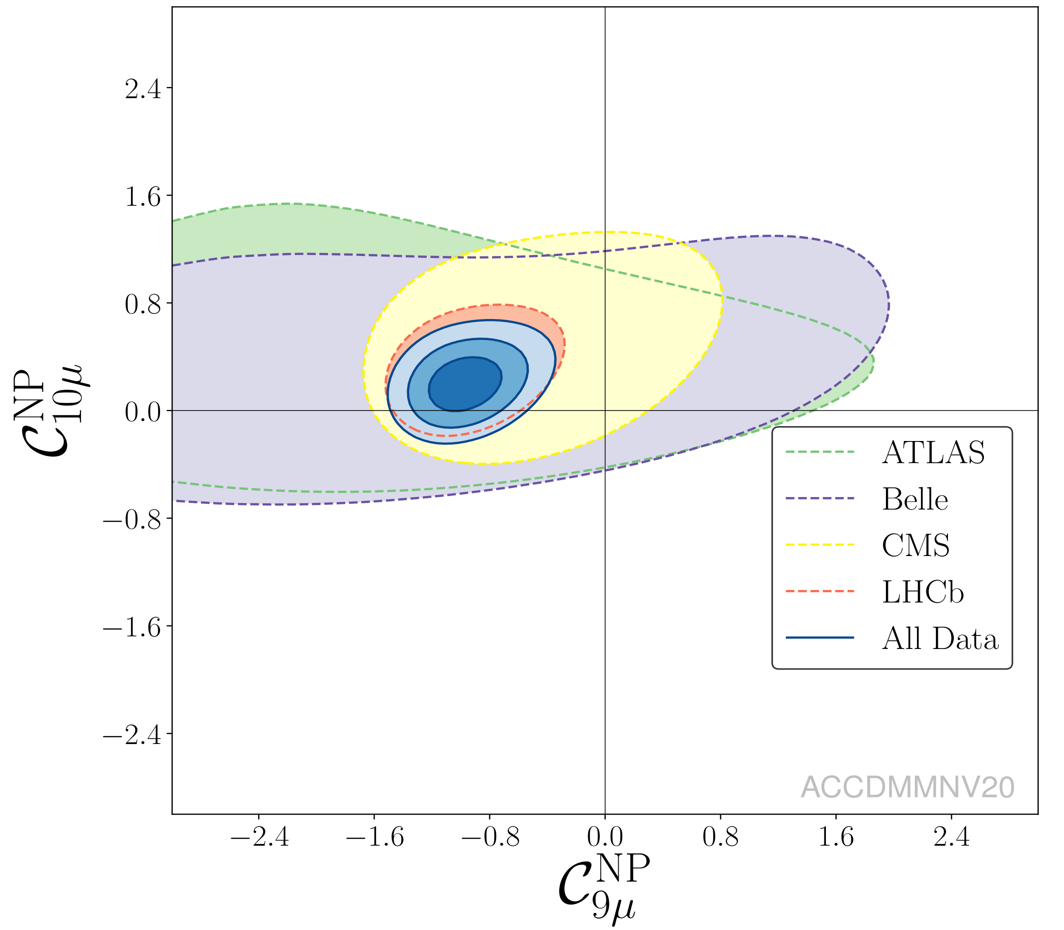
$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} C_i O_i$$

- Semileptonic Penguin operators: $O_9, O_{10}$
- Good fit for: $C_9^{NP} = -C_{10}^{NP} \simeq -1$
  - New effective $V - A$ contribution
  - Suppressed $b \to s\,\mu^+\mu^-$ penguin




Note: Suppressed penguin ≠ Depressed penguin

Weak Effective couplings: $C_9^{NP}$ , $C_{10}^{NP}$

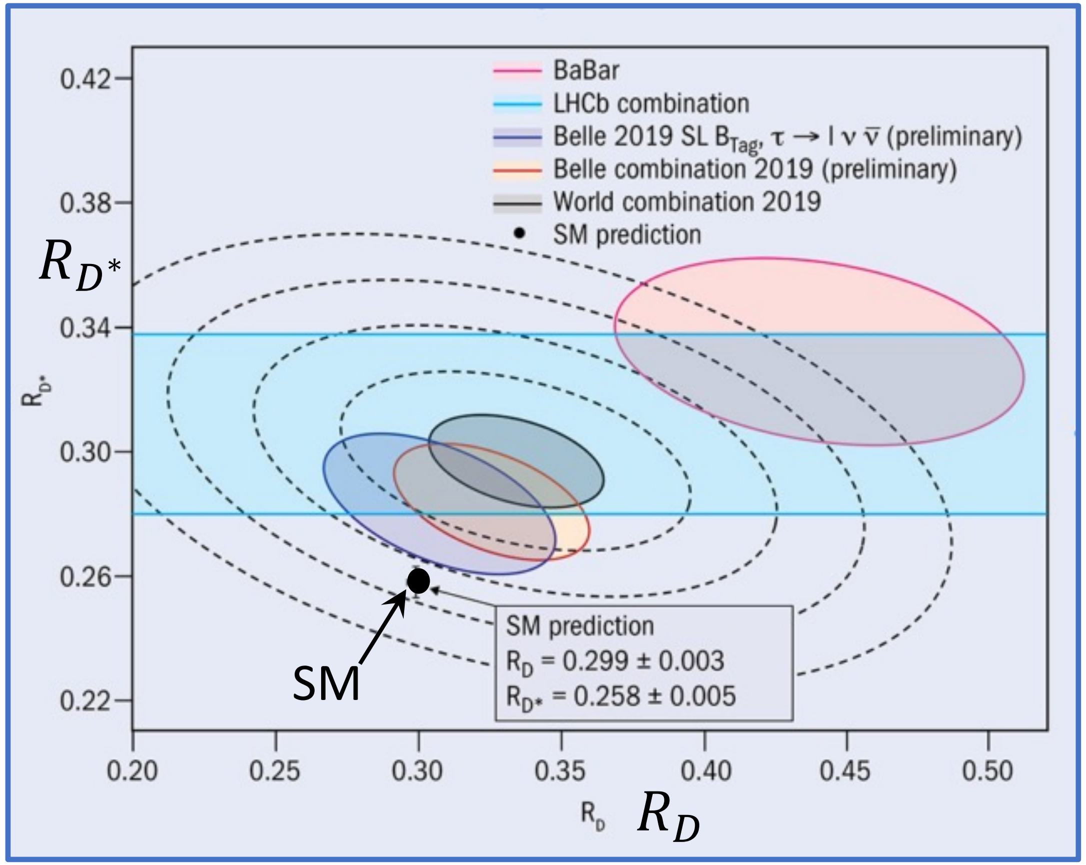


# Interpretation as a single cause: contradicting effects?



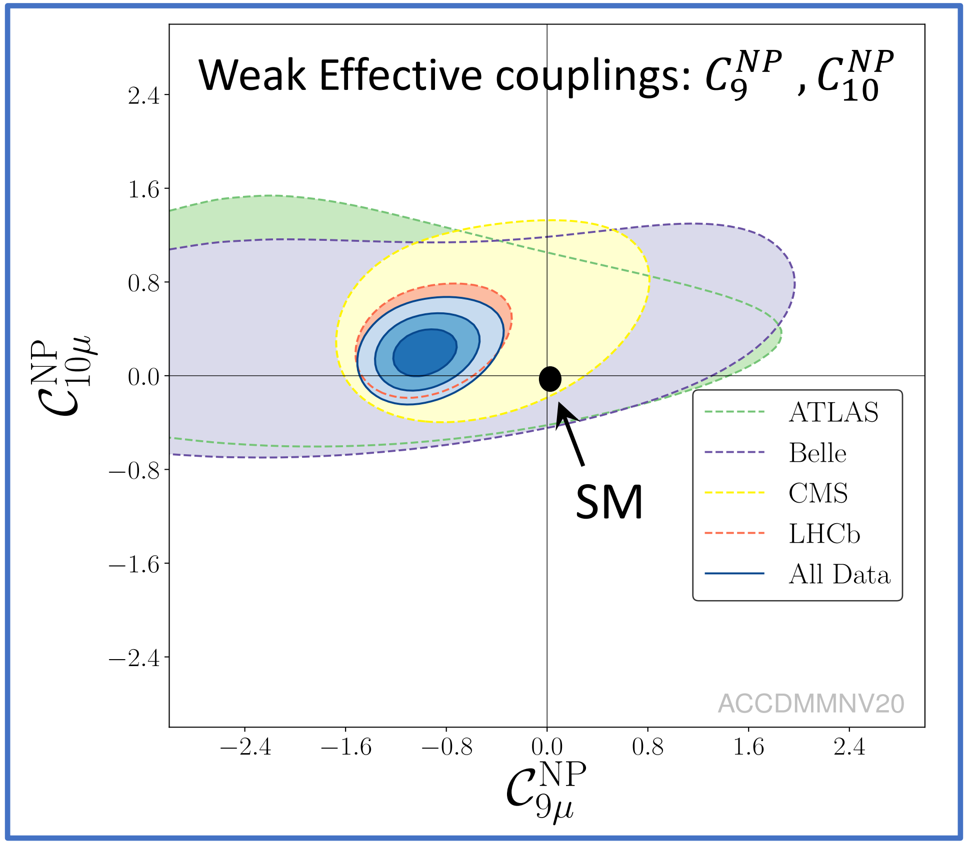
1) $b \to c\, l\, \nu$: $R_D, R_{D^*}$

- ~ 25% effect at ***enhanced tree*** level
  - ***Large*** effect → Large ***3rd*** generation couplings




2) $b \to s\, l^+ l^-$: $R_K, R_{K^*}$

- ~ 25% effect at ***suppressed penguin*** level
  - ***Small*** effect; Small ***2nd*** generation couplings



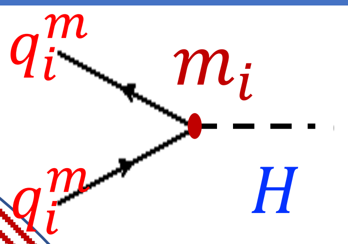

Similar to Higgs couplings: *large* for 3rd generation, *small* for 2nd generation, *tiny* for 1st generation.

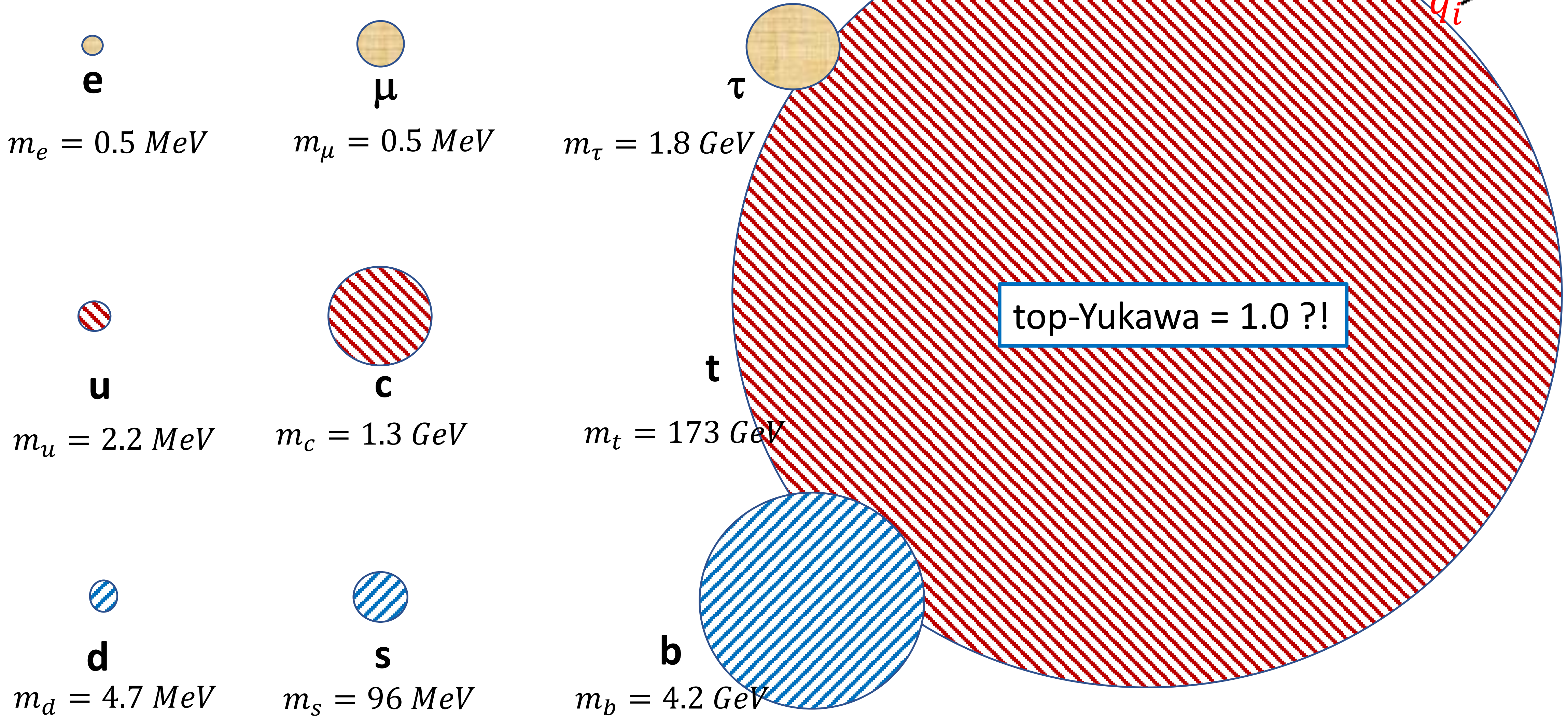
➔ New particle perhaps has similar flavour structure as the Higgs?

# Flavour Puzzle: particle masses? Origin Yukawa couplings?

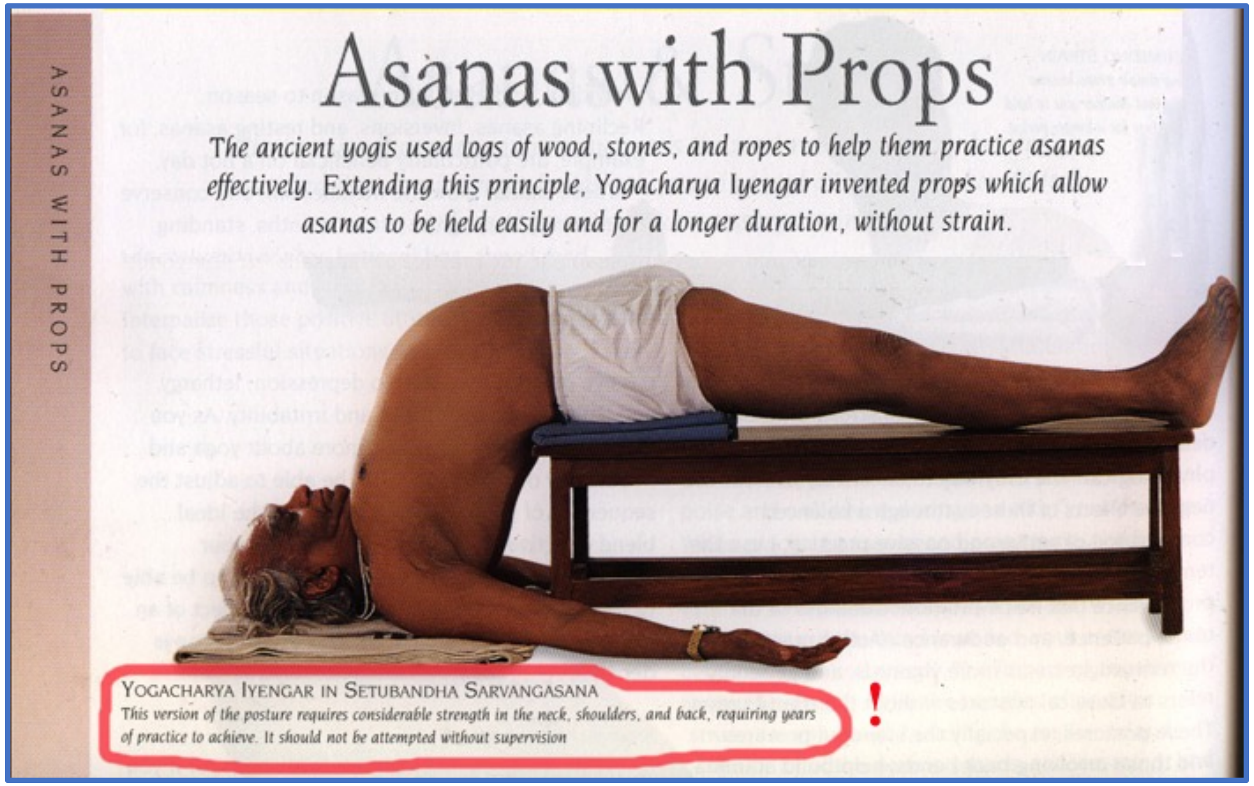


- Weak interaction flavour universal
- Higgs interaction almost purely 3rd generation



# Universality?

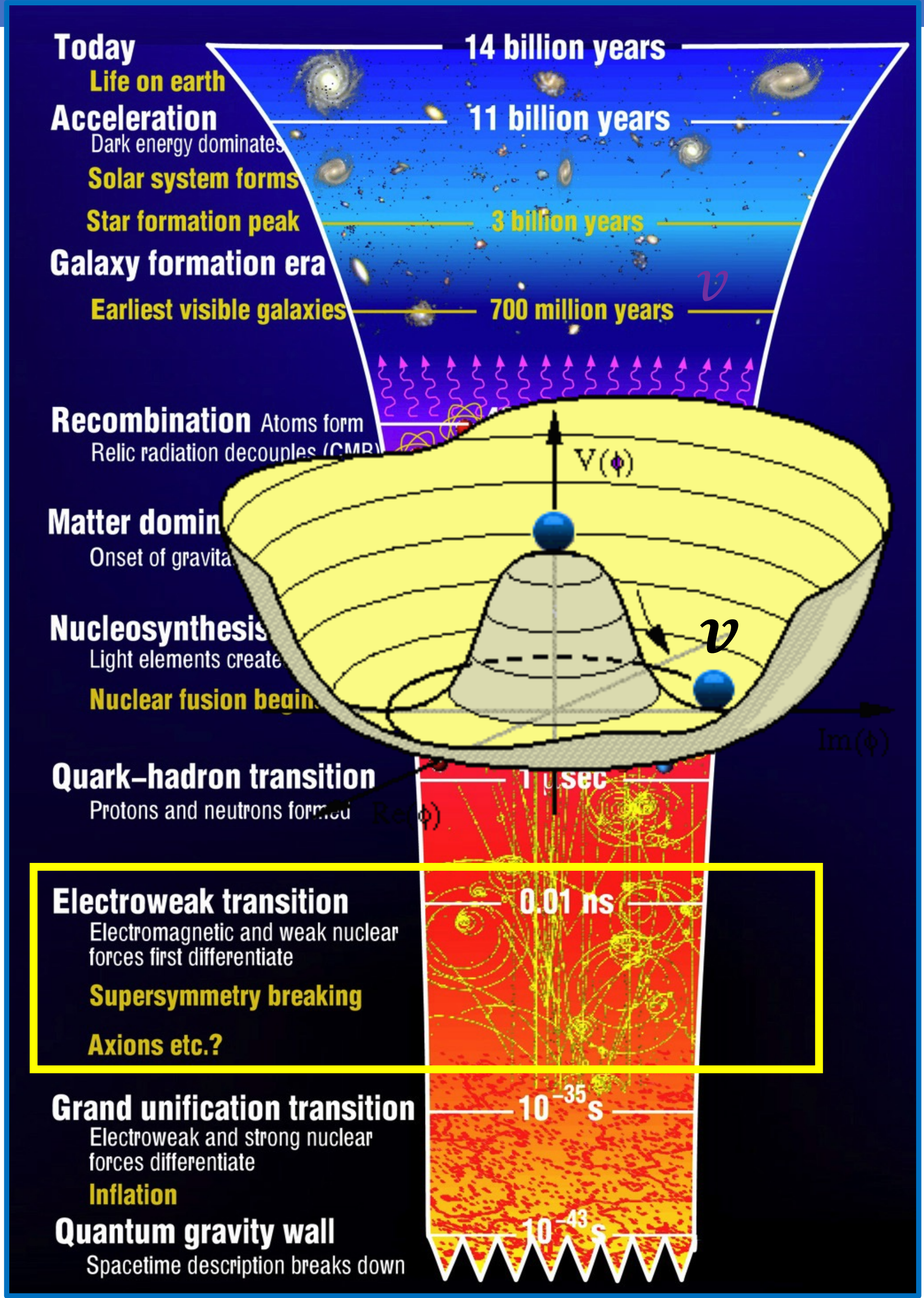



…Indian Yoga

Russian Yoga…

# Flavour Physics at high mass: GGL model

- Effective New Physics operators point at *left-handed vector* coupling
- New physics occurs above weak scale (~TeV)
  - Before EWSB: physics that is invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - *Operates on massless interaction states*
- $3^{rd}$ generation is special (eg. $Y_{top}$ = 1)
- Glashow, Guagdagnoli, Lane (GGL) model: Operator for NP in $3^{rd}$ generation:
  - $G\,(\overline{b'}_L\,\gamma_\mu\,b'_L)\,\,(\overline{\tau'}_L\,\gamma^\mu\,\tau'_L)$



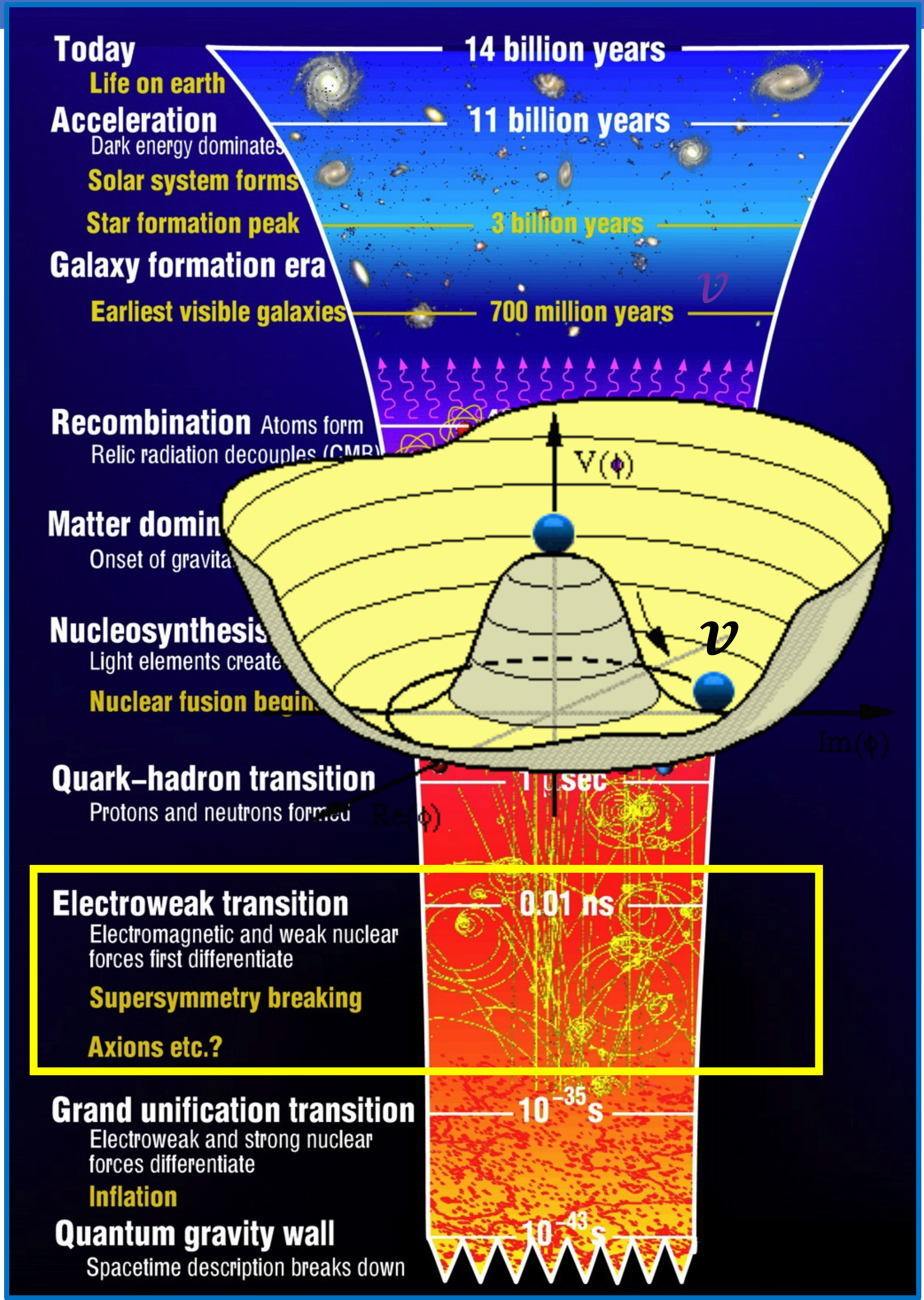
# Where does GGL operator come from?



- Glashow, Guagdagnoli, Lane (GGL) model: operator for NP:
  - $G\left(\bar{b}'_L\,\gamma_\mu\,b'_L\right)\ \left(\bar{\tau}'_L\,\gamma^\mu\,\tau'_L\right)$
- Relate massive particles to massless states:
  - $b'_L = V^d_{31}\,d + V^d_{32}\,s + V^d_{33}\,b$ and
  - $\tau'_L = V^l_{31}\,e + V^l_{32}\,\mu + V^l_{33}\,\tau$

$$V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$$
$$V_{MNS} = \left(V^\nu V^{l\dagger}\right)_{ij}$$

- CKM Hierarchy suggests:
  - $V^d_{33} \simeq V^l_{33} \simeq 1$ and $V^{d,l}_{31} \ll V^{d,l}_{32} \ll 1$
- GGL operator becomes:
  - $G\left[V^d_{33}\,V^{*d}_{32}\,|V_{32}|^2\right]\left(\bar{b}_L\,\gamma_\mu s_L\right)\left(\bar{\mu}_L\gamma^\mu\mu_L\right)$
- *Large* effect in 3rd generation, *small* effect in 2nd generation



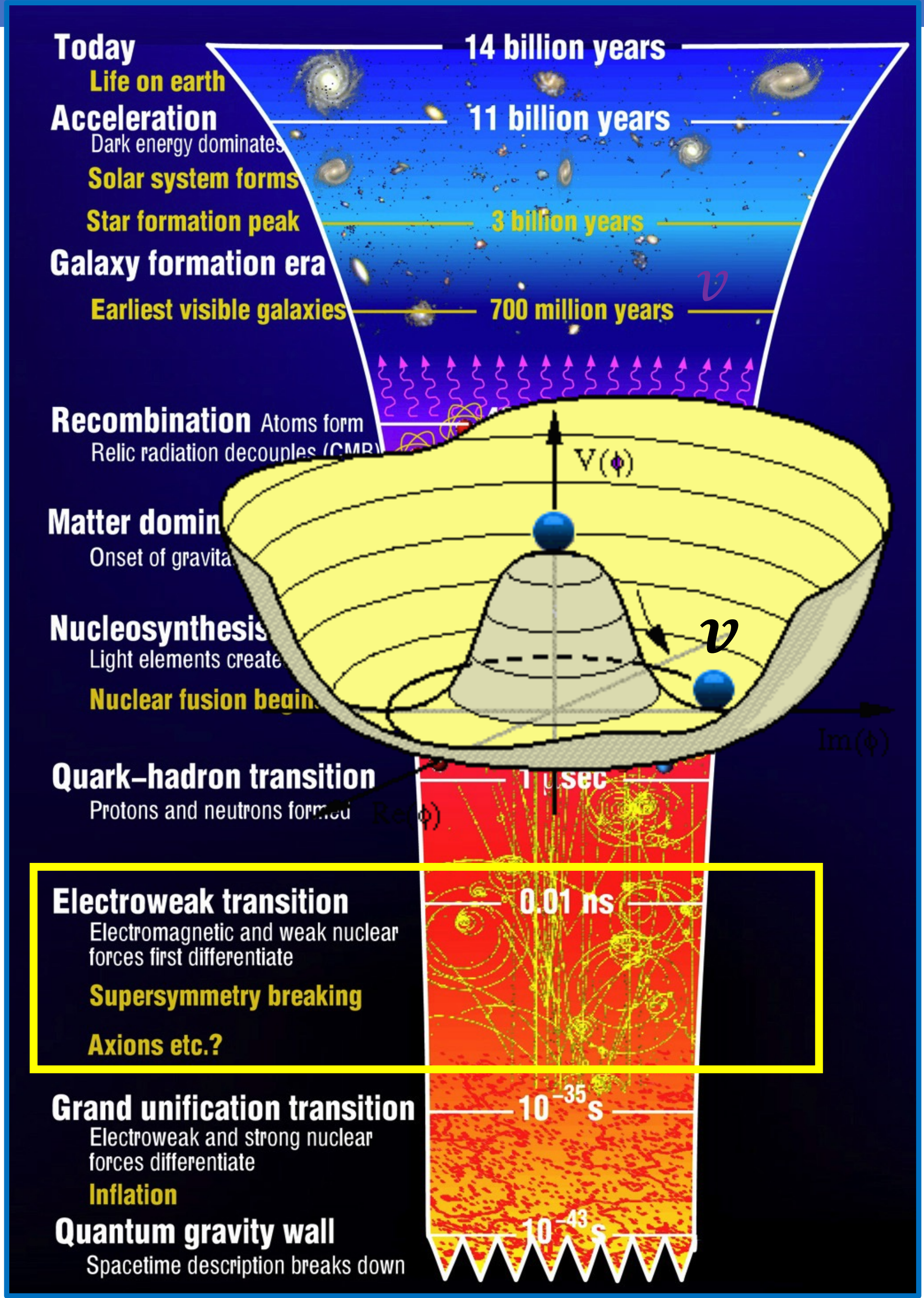
# GGL operator – more general

- Allow effective operators that are SU(2) x U(1) invariant:

  $Q' = \binom{t'}{b'}$ and $L' = \binom{\nu_\tau{}'}{\tau'}$

  - Singlet neutral current:
    - $O_S^{NP} = G_S \left(\overline{Q'}_L \gamma_\mu Q'_L\right) \left(\overline{L'}_L \gamma^\mu L'_L\right)$
  - Triplet neutral current + two charged currents:
    - $O_T^{NP} = G_T \left(\overline{Q'}_L \gamma_\mu \sigma^I Q'_L\right) \left(\overline{L'}_L \gamma^\mu \sigma^I L'_L\right)$

- These operators with CKM hierarchy "naturally" give simultaneous explanation of:
  - $R_D$ , $R_{D^*}$, charged current, 3rd generation
    - → large effect
  - $R_K$ ,$R_{K^*}$ , $b \to s\, \mu^+\mu^-$,neutral current, 2nd generation
    - → small effect

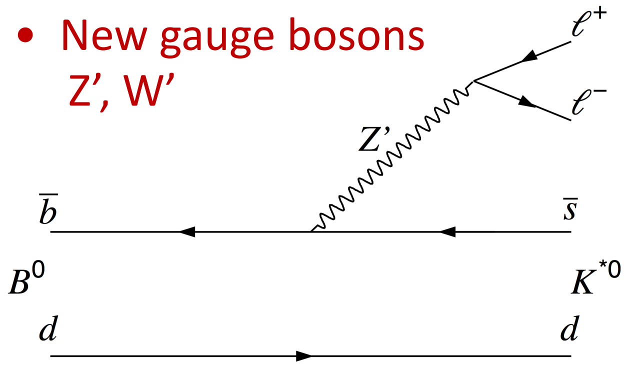


# Which particle/field could it be?

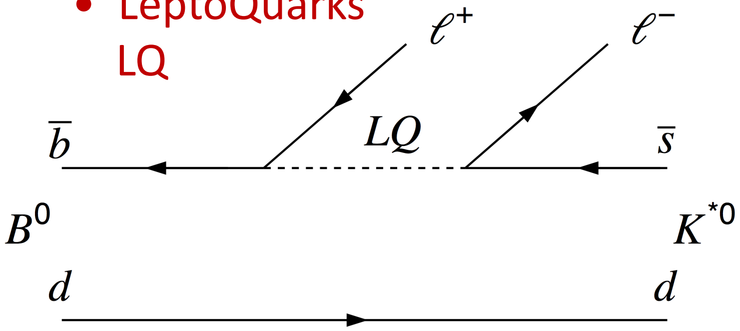


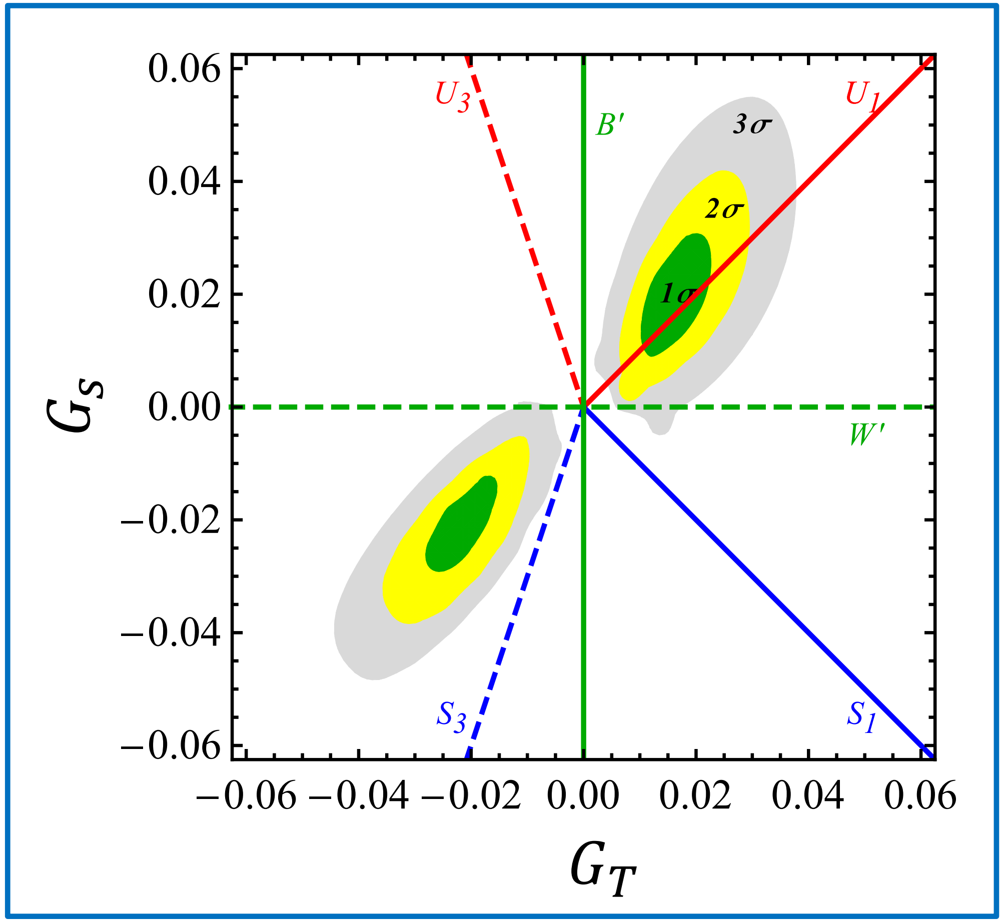
- LFNU is currently a hot topic, many theory papers, see eg. arXiv:1706.07808 for overview.

- New gauge bosons Z', W'

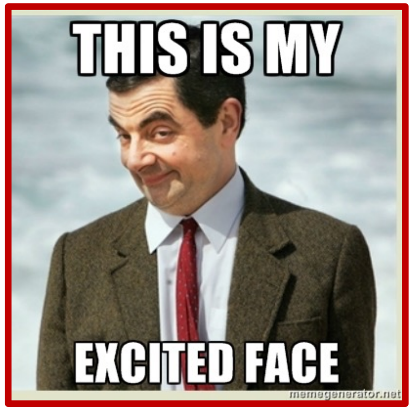



- LeptoQuarks LQ




- Best Single LQ model:
  - Vector LQ U1(3,1,2/3)
  - Scale of NP should be ~2 TeV
  - Possible UV completions:
    - Pati-Salam models SU(4)
      - Lepton←→4-th color
    - SU(5) GUT
    - 4321 model
    - $S_1$ & $S_3$, etc., etc.
  - Shine light on flavour puzzles?!

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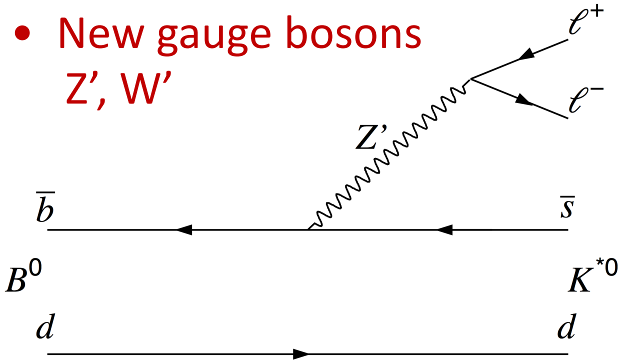
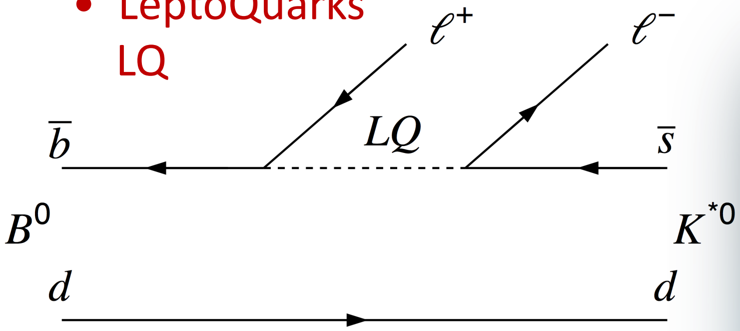



- LeptoQuarks
  LQ

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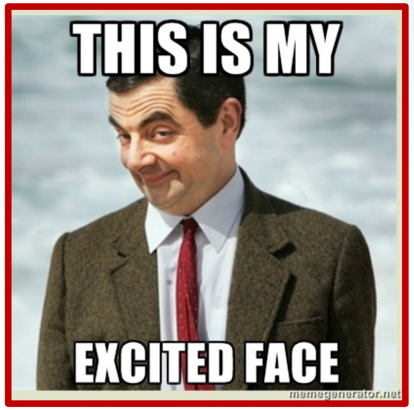
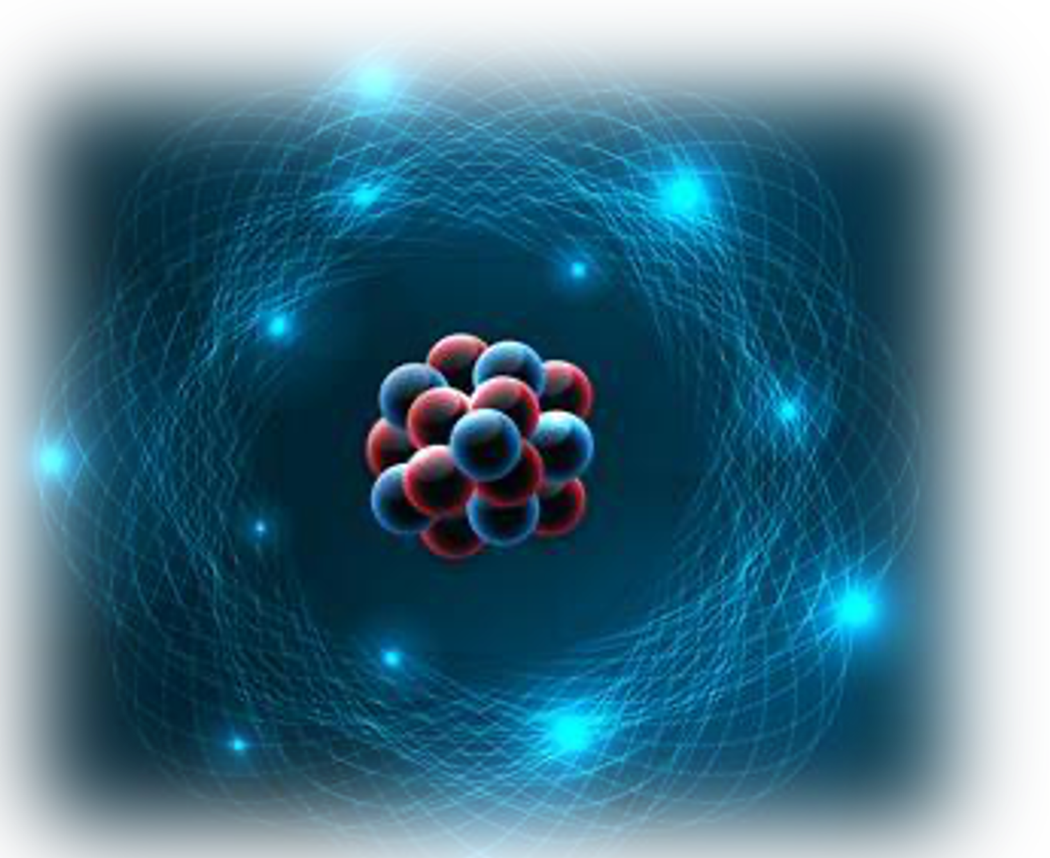


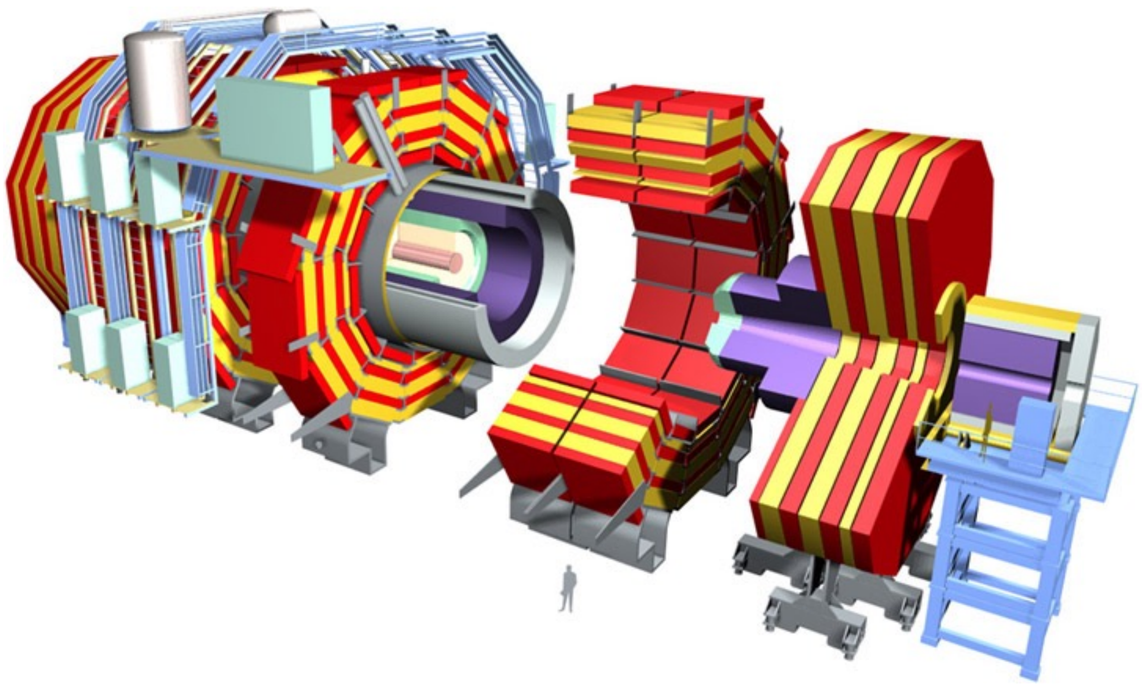
LQ relates charge of leptons to quarks!
Towards an understanding why
atoms are electrically neutral?

# Recent: direct search for specific 3rd generation leptoquarks

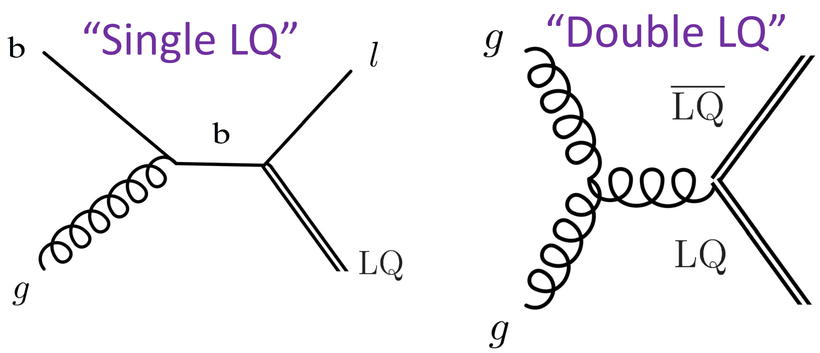
- CMS search for direct LQ production, arXiv:2012.04178, 7 Dec 2020

  Exclusion limit (98%): $M_{LQ} < 0.98$ - $1.73$ TeV

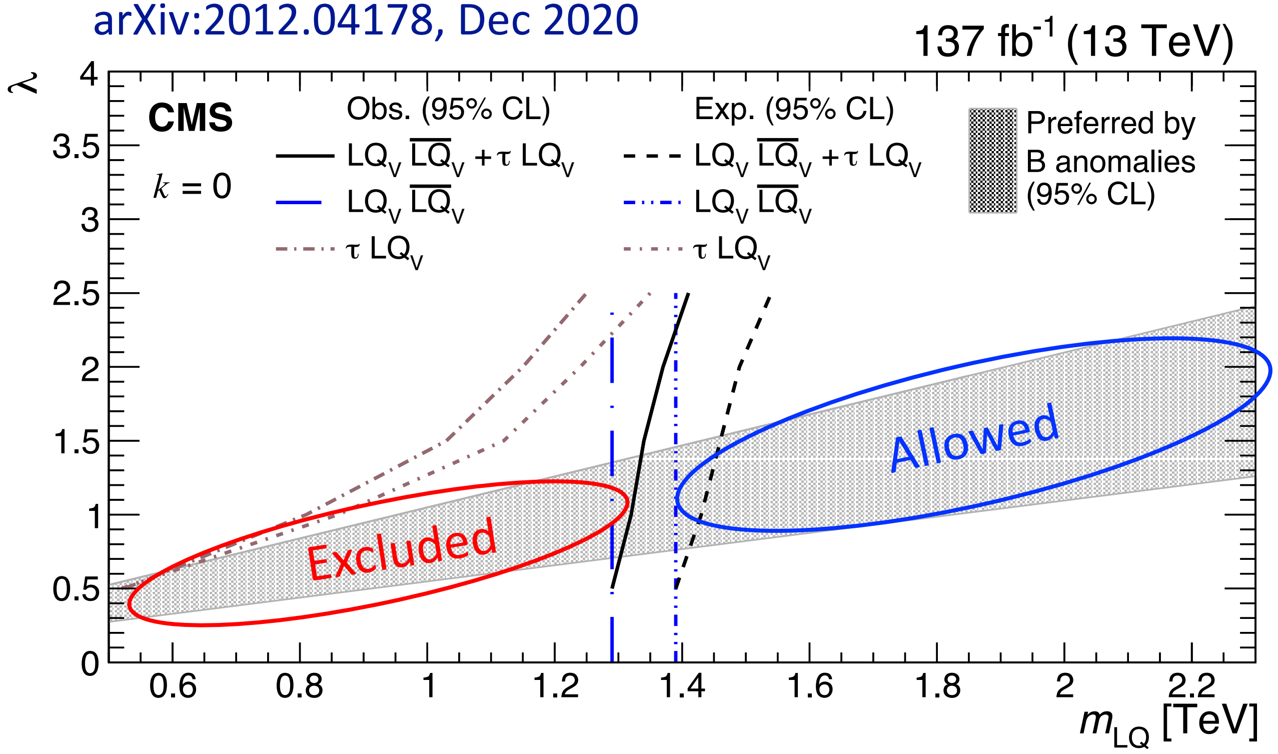
  (depending on the model parameters)



- LQ production at LHC:



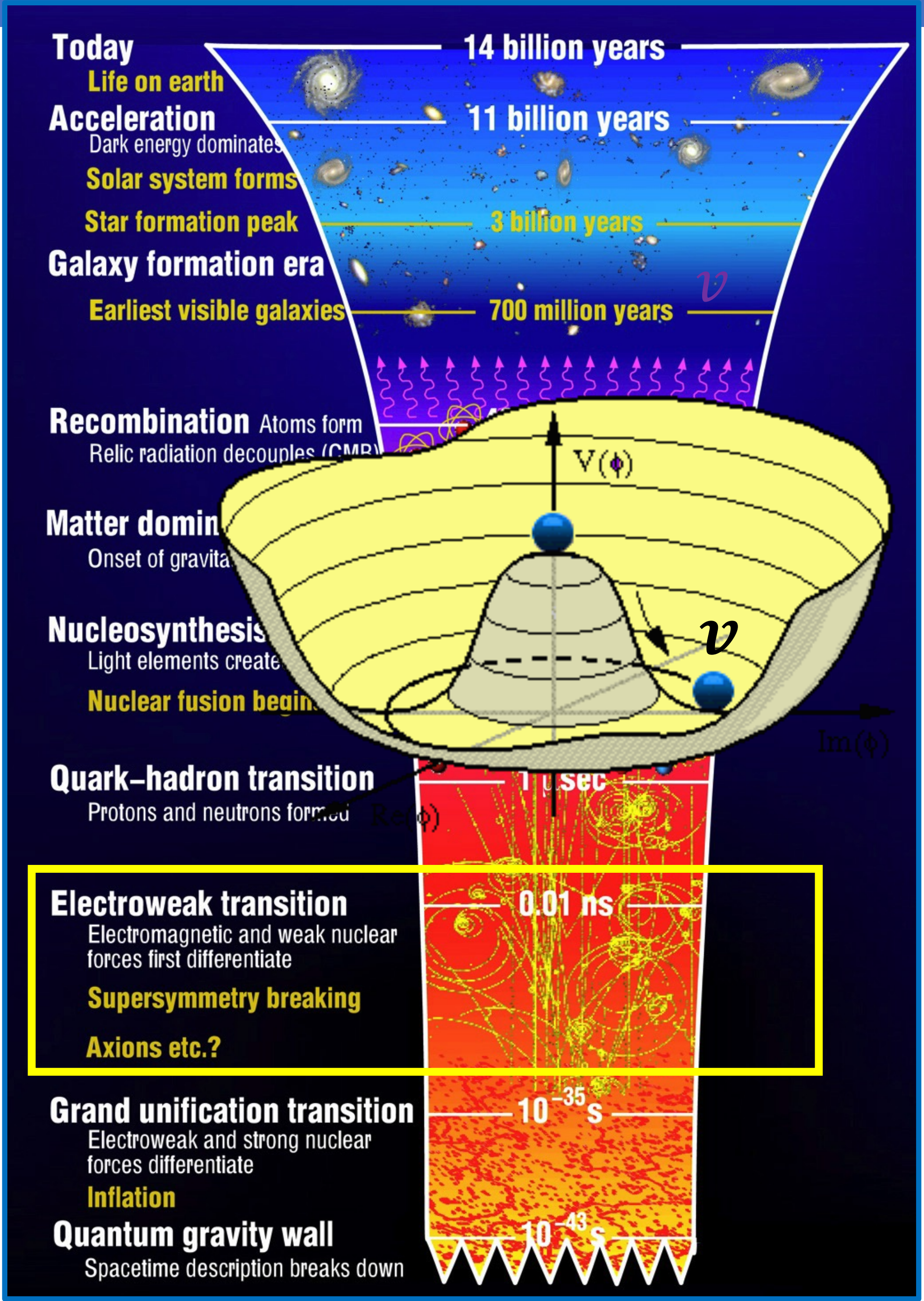

arXiv:2012.04178, Dec 2020

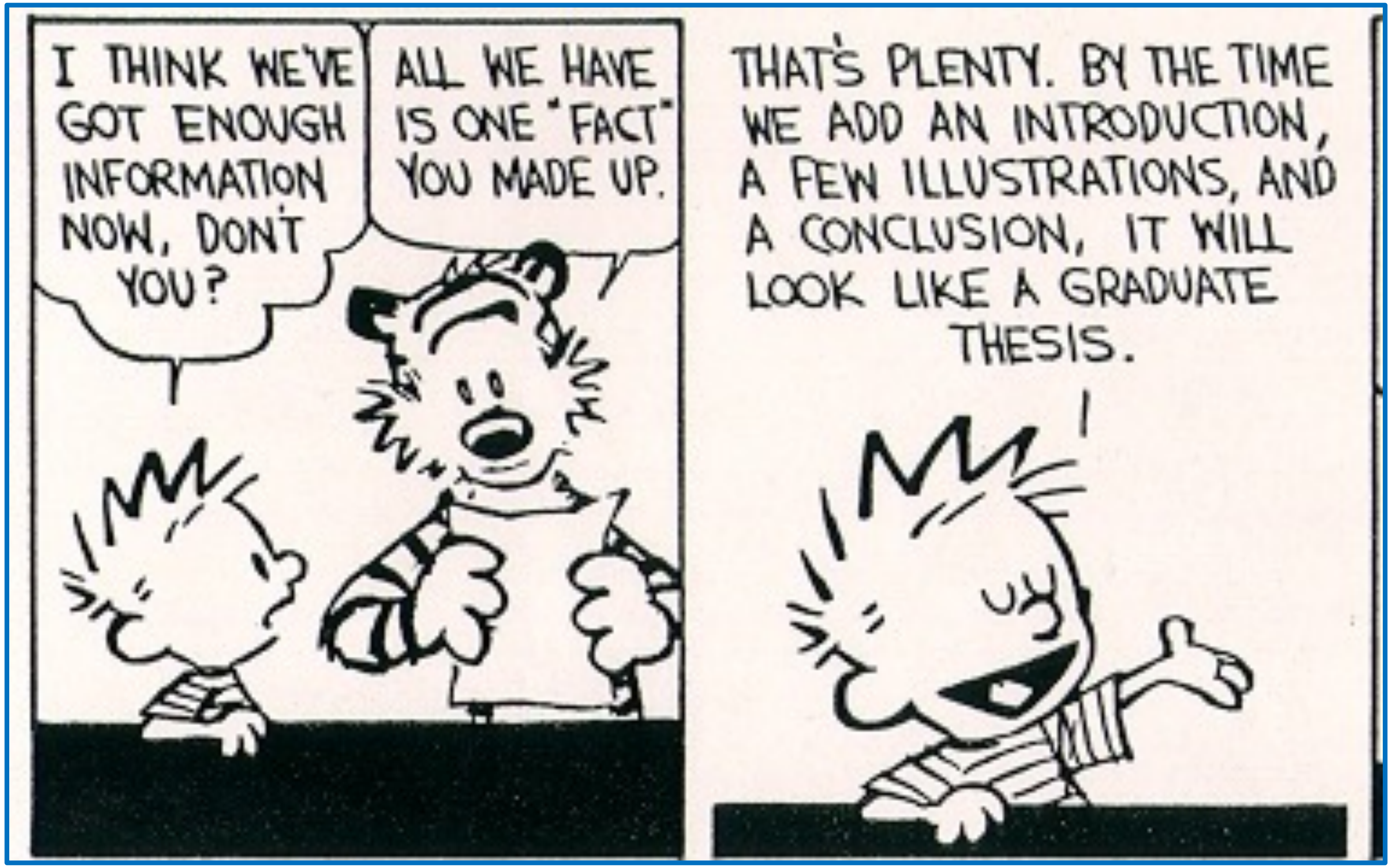


# Conclusions

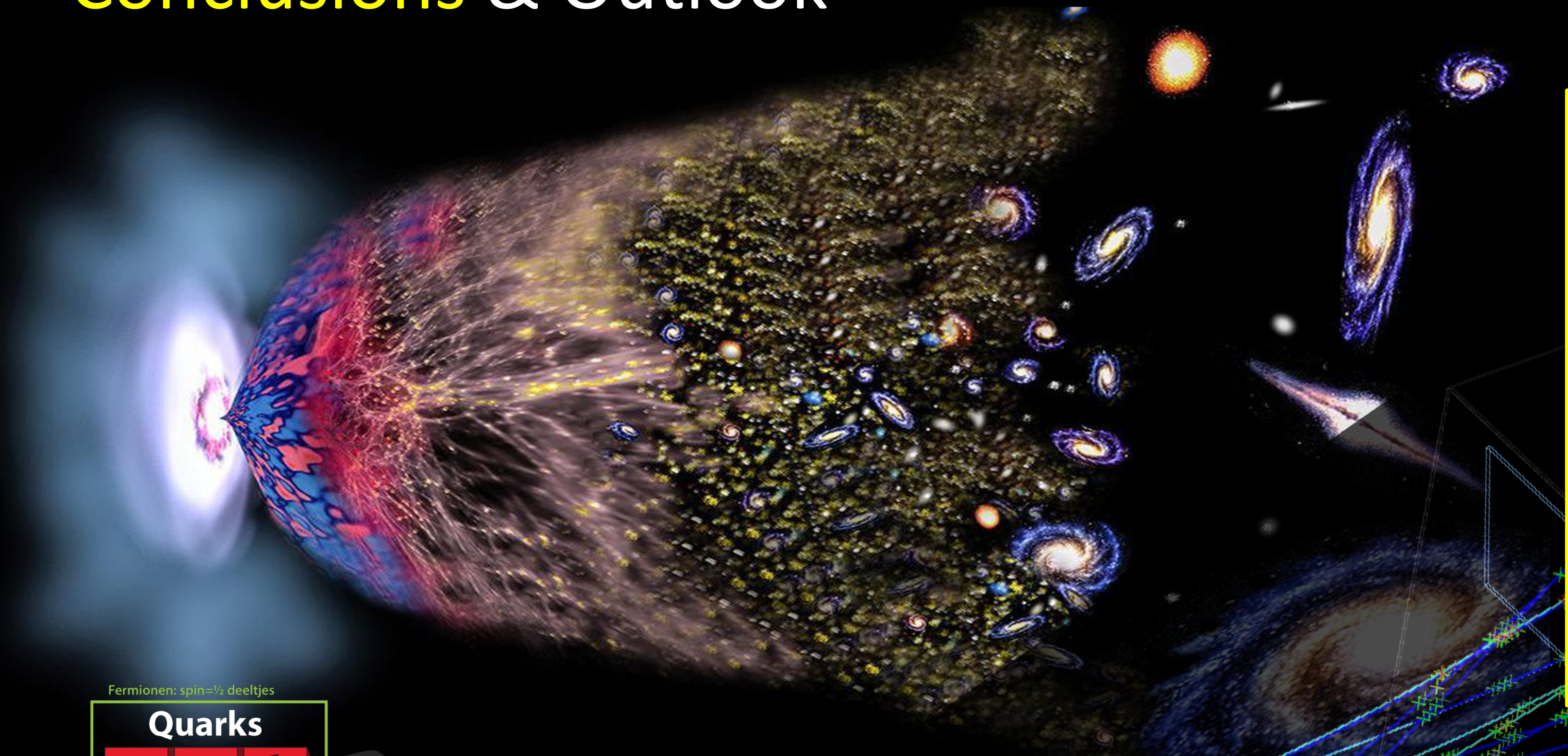


- CP Violation requires three generations of particles.
  - Does ***not*** explain the matter antimatter asymmetry in the universe.
  - LHC has ***not yet directly*** observed new massive particles.
- Forces are flavour universal across particle generations.
- Higgs is strongly non-universal, coupling mainly to 3rd generation.
- Precision measurements ***hint*** at the existence of new particles with non-universal couplings:
  - LeptoQuark candidate; couples to quarks and leptons
  - LeptoQuarks are a long sought particles that may address:
    - The matter - antimatter asymmetry of the universe,
    - Why proton has equal but opposite charge wrt electron.
- Updates expected in winter conferences.

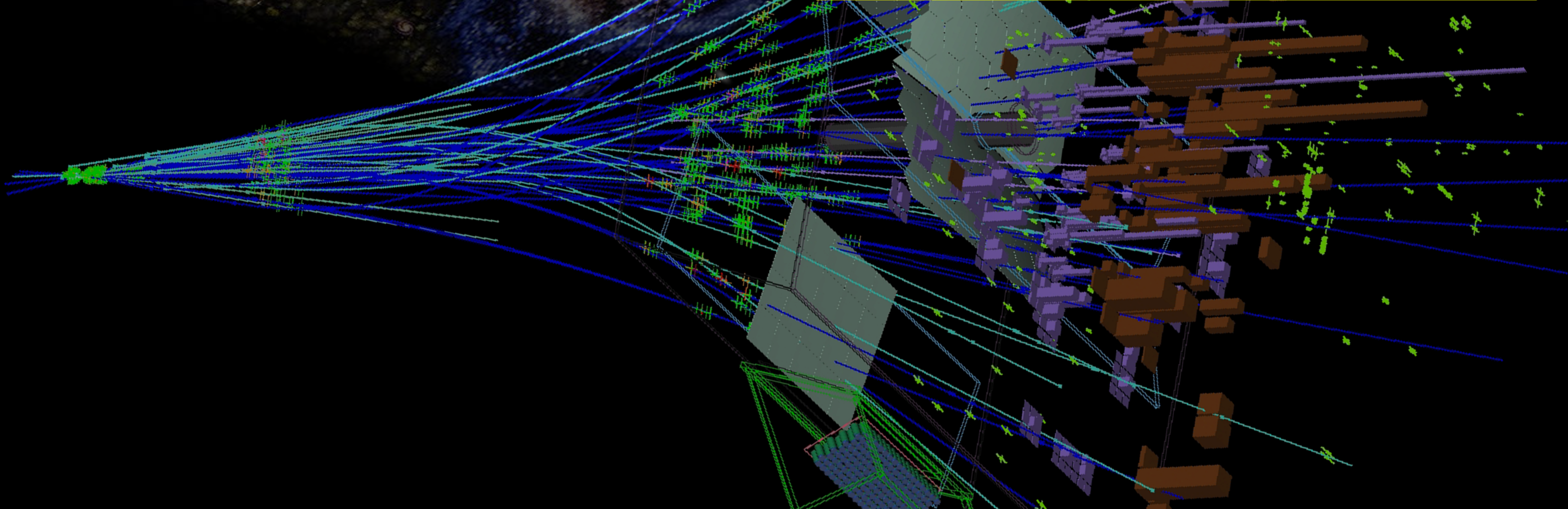


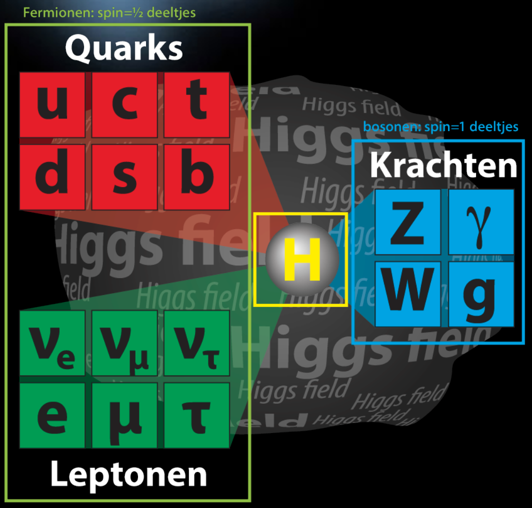

I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

# Conclusions & Outlook



- Why 3? → no antimatter?
- Non Universality → why 3?
- EWSB super interesting
- Flavour probes deeply into quantum (CP, rare decays)
- LHCb→Upgrade1→Upgrade2
- Belle2, …





# Thank You

Don’t be afraid to ask questions…