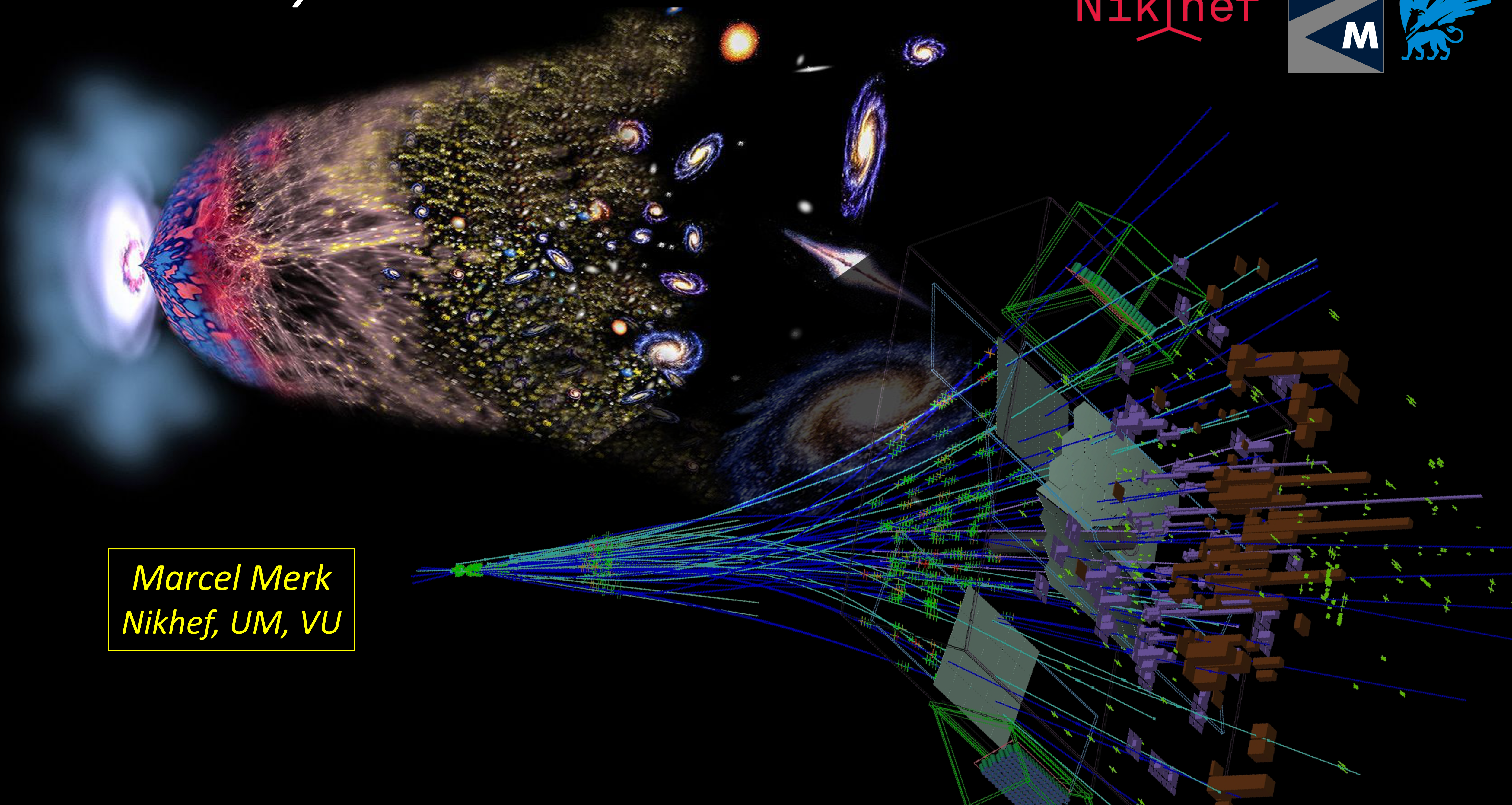
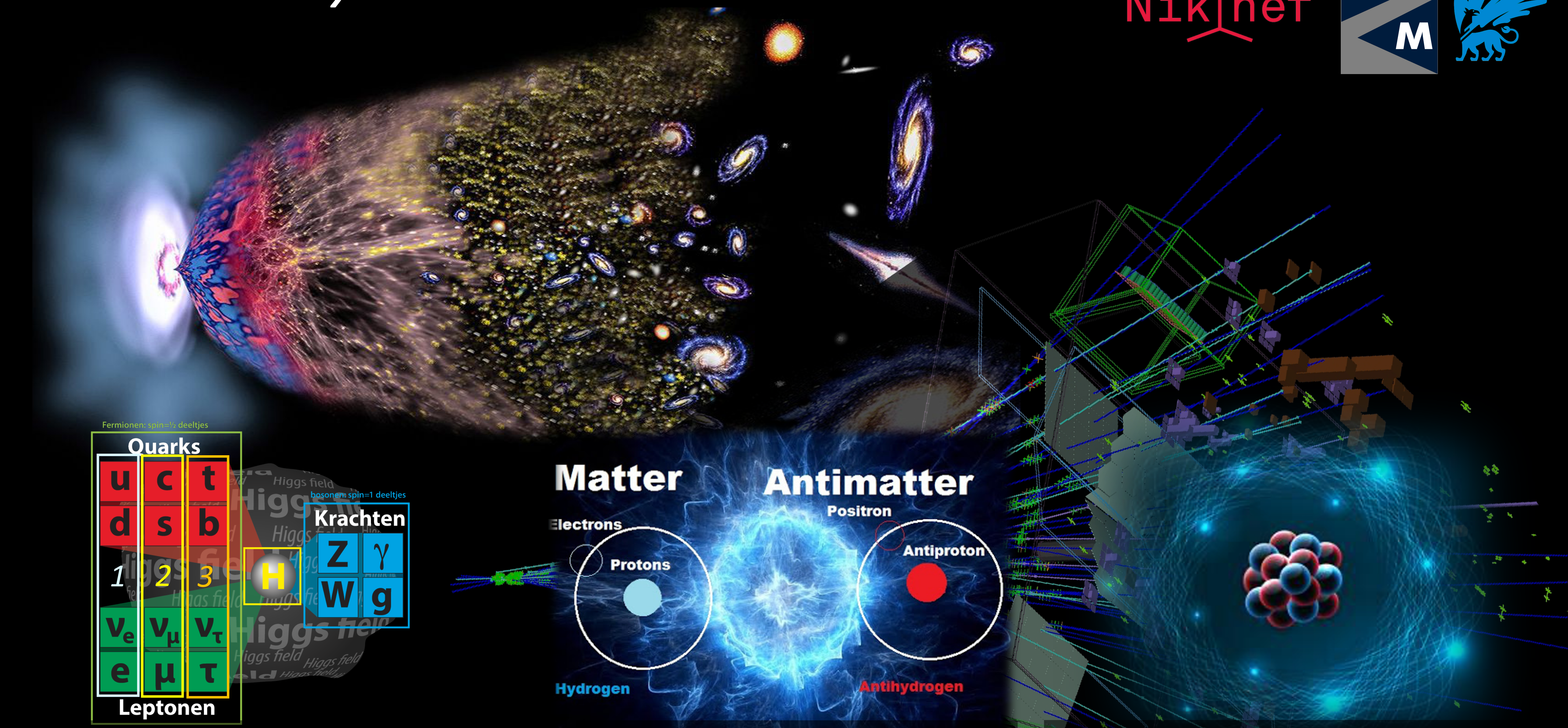
# *Flavour Physics and CP Violation*



*Marcel Merk*
*Nikhef, UM, VU*

Nikhef

# *Flavour Physics and CP Violation*



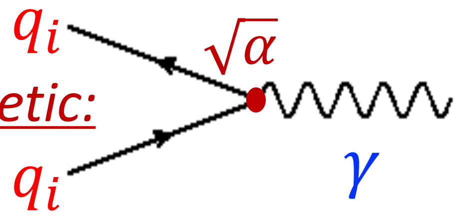

***Why three generations of particles?*** ***Why is there no antimatter?*** ***Why is an atom electric neutral?***

# Recap: Flavour Universality in very Early Universe

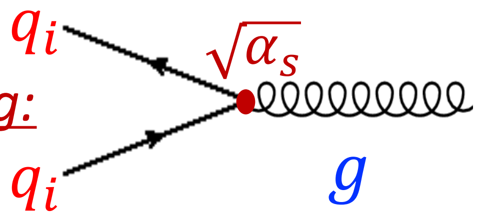


- Quark and lepton generations interact identically
  - No difference between particles of different generation?
  - No matter – antimatter asymmetry (CP Violation)?

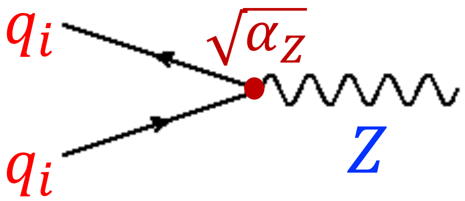
<u>*Electromagnetic:*</u>



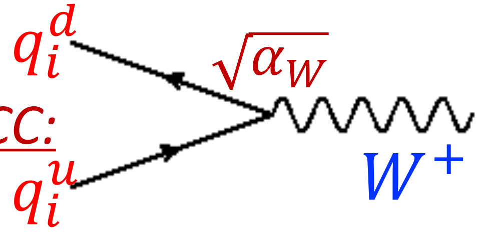

<u>*Strong:*</u>



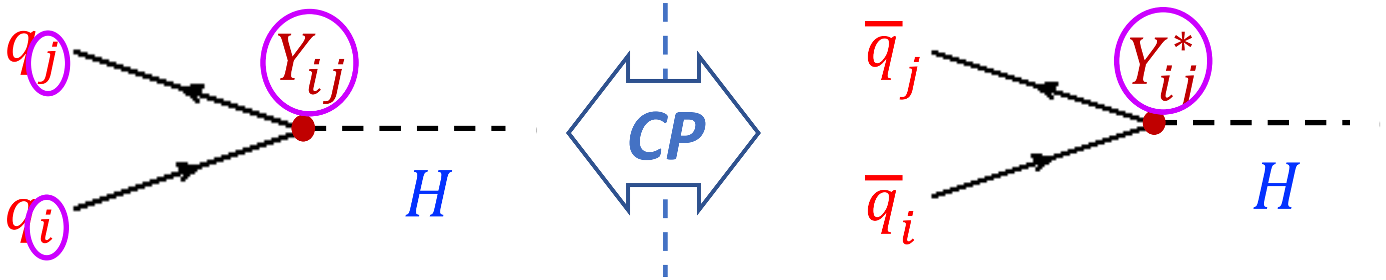

<u>*Weak NC:*</u>

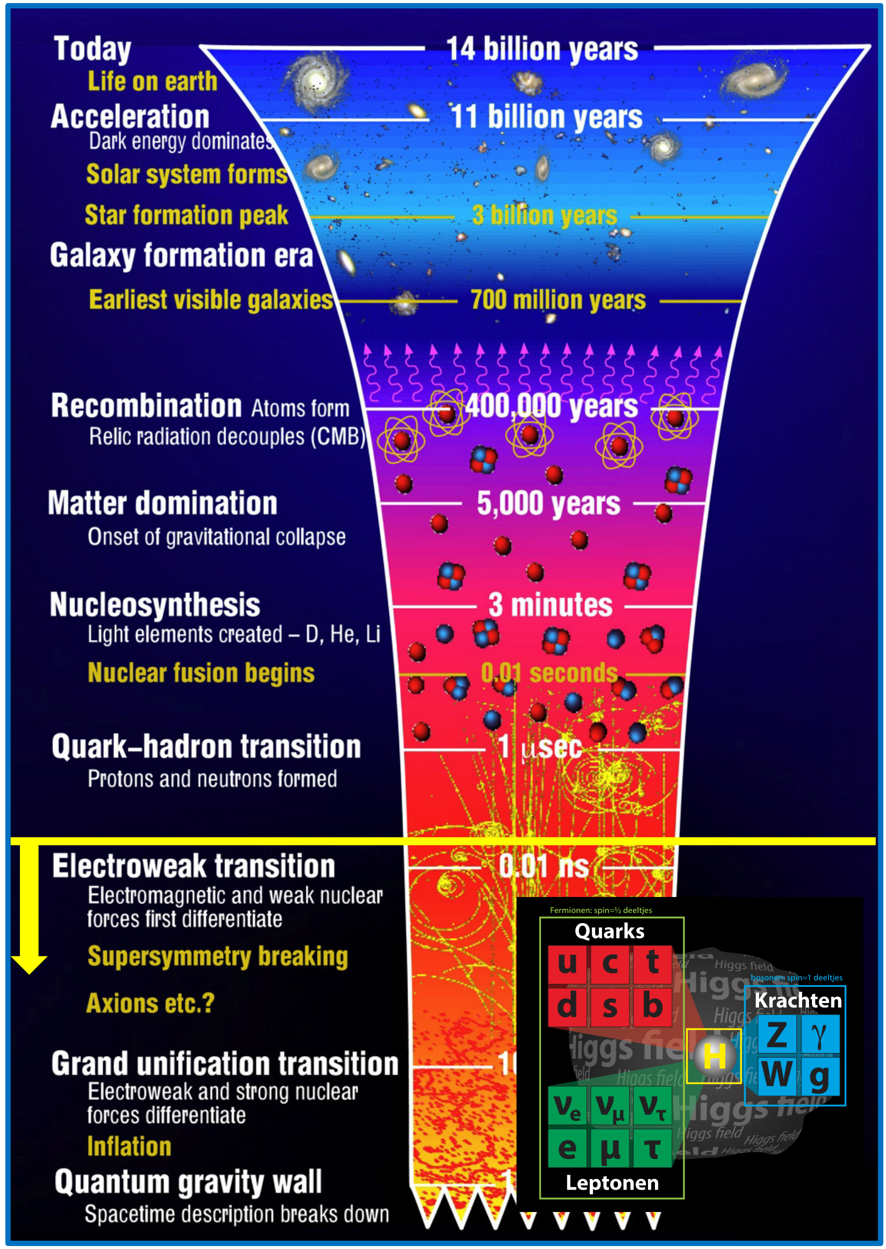



<u>*Weak CC:*</u>



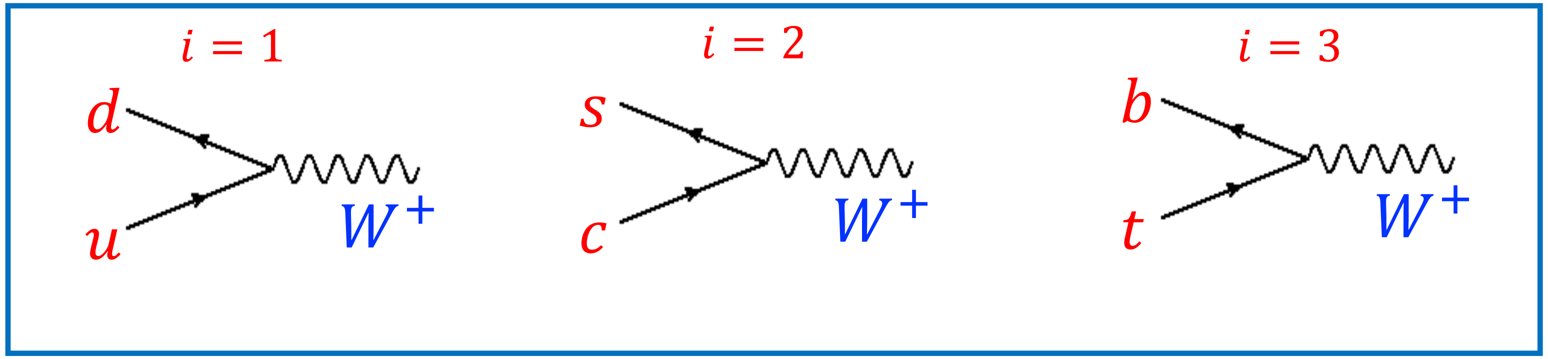

- Universality violation: Higgs !
  - Higgs coupling is *not universal*, and mixes generations
  - Complex couplings: allows for CP Violation!



# Recap: Flavour Universality in very early universe

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




- Universality violation: Higgs ! $(i \leftrightarrow j)$
  - Higgs coupling is *not universal*, and mixes generations
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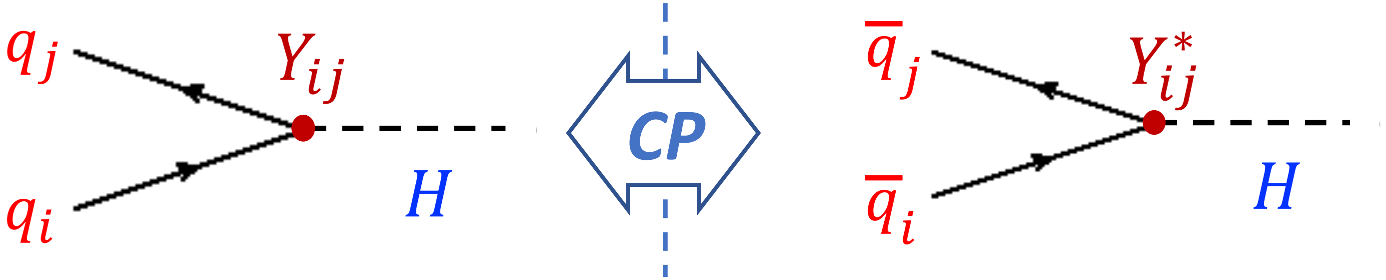
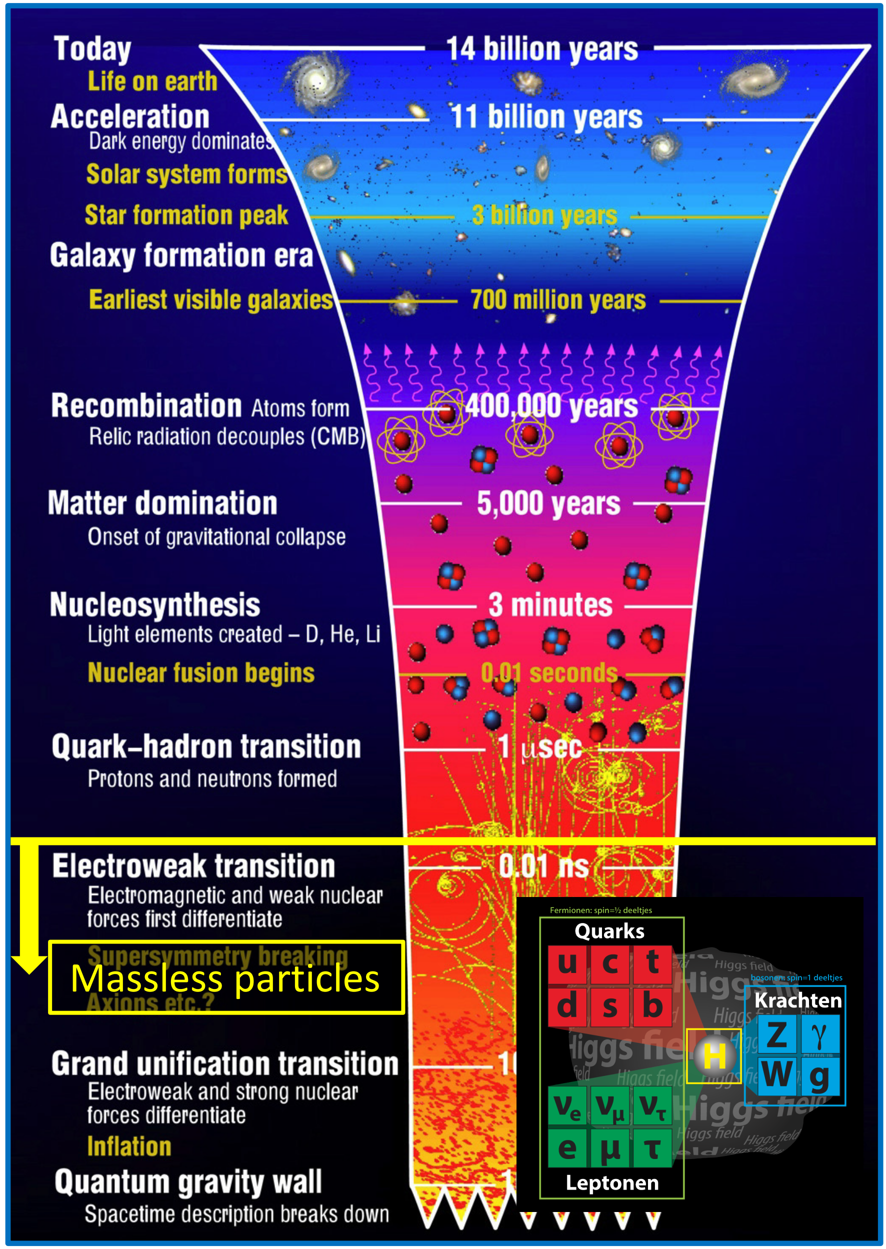
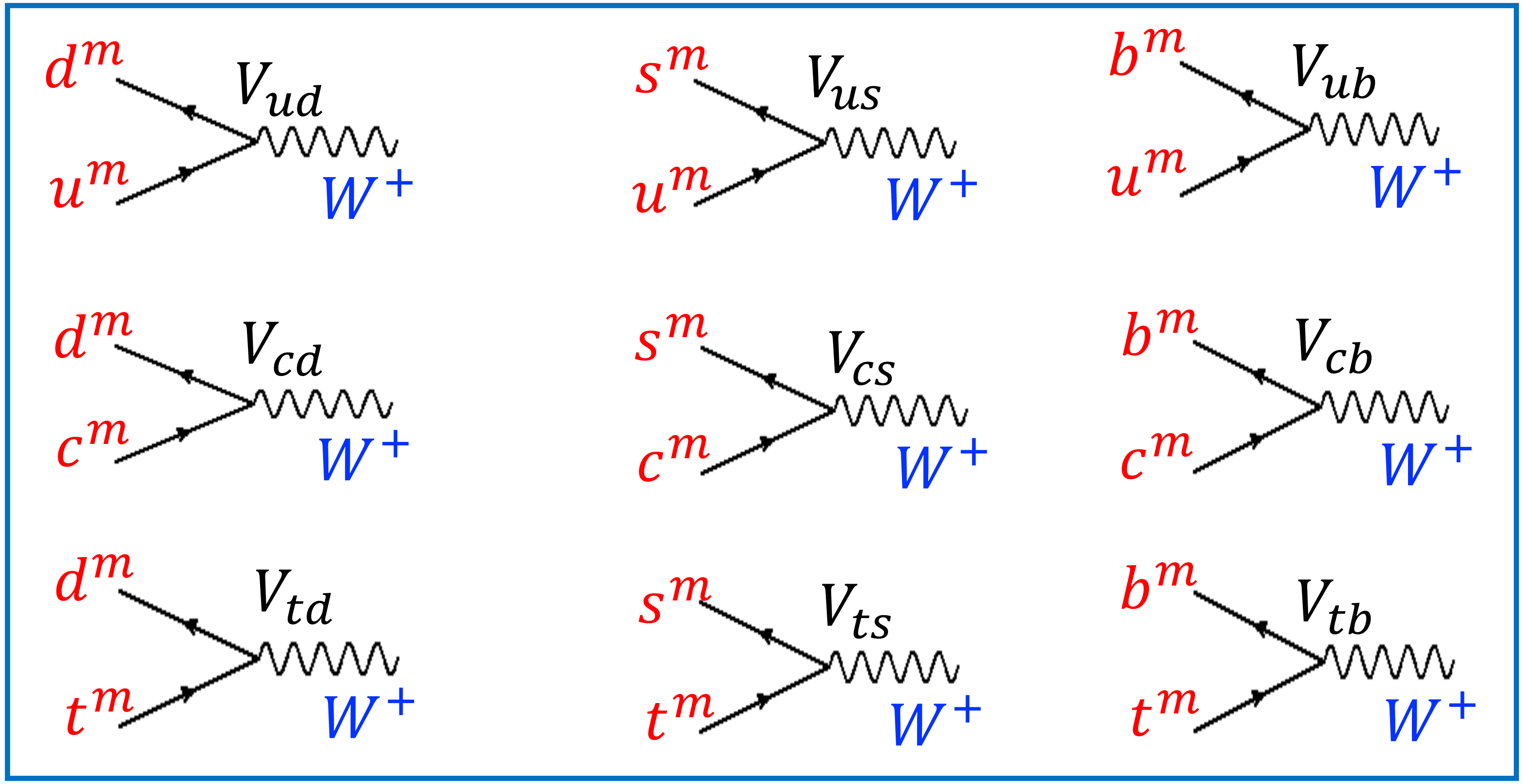


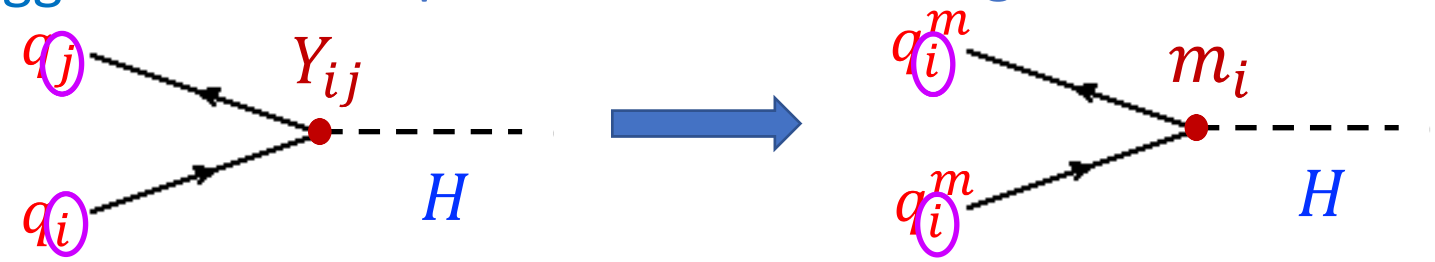



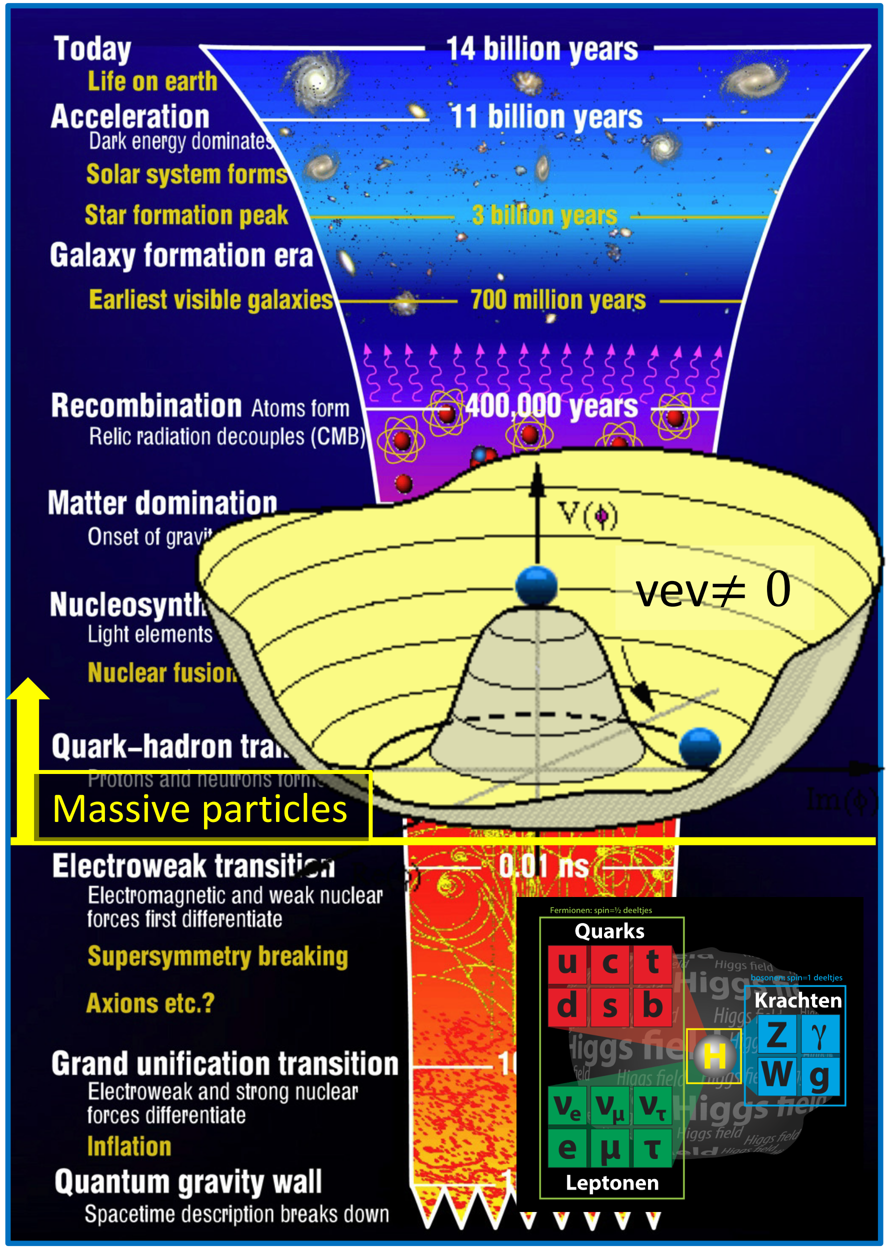
# Recap: Flavour Universality → Symmetry Breaking → Flavour Mixing 

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




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

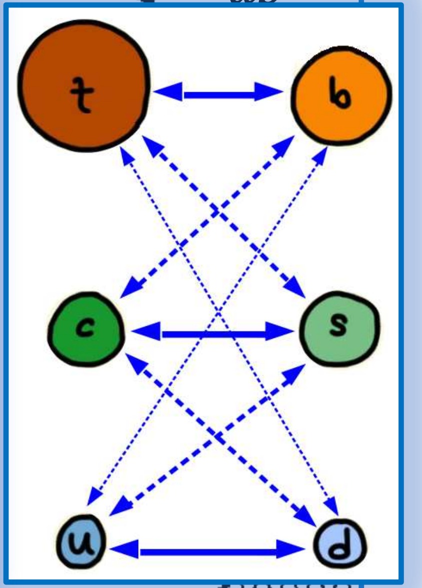


- Weak charged current interaction:

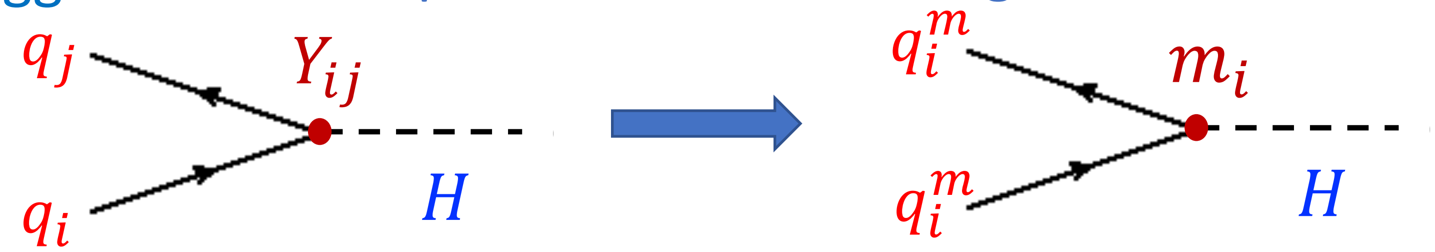
$d^m$ $V_{ud}$ $s^m$ $V_{us}$ $b^m$ $V_{ub}$

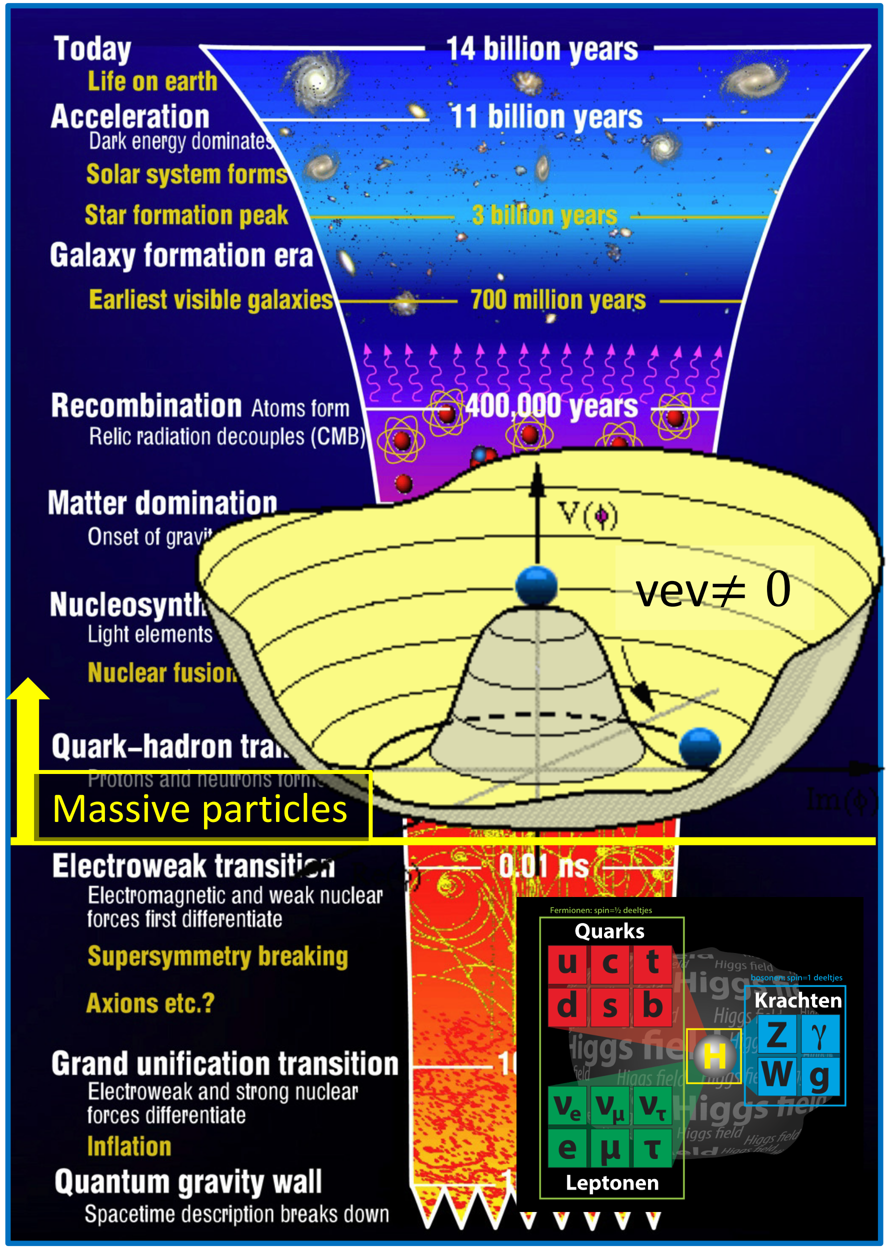
- Weak interactions mixes the generations of *mass eigenstates.*
- Complex couplings $V_{ij}$ allow for CP violating phenomena.
  - *At least 3 generations required!*



$t^m$ $W^+$ $t^m$ $W^+$ $t^m$ $W^+$

- Higgs: redefines quark states in mass eigenstates:



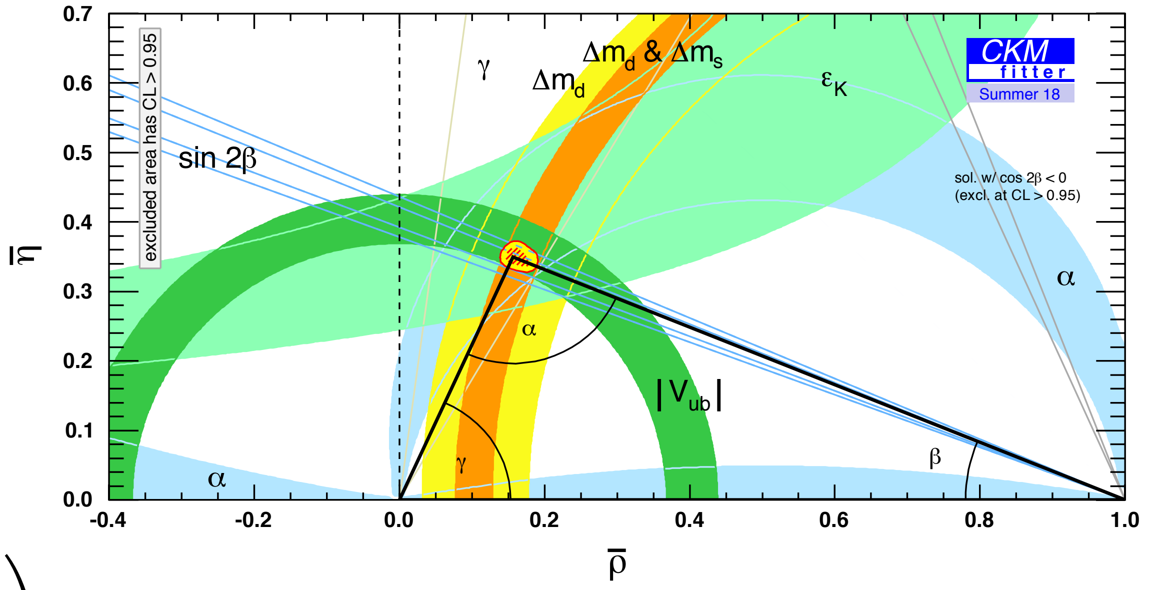
# Recap: The CKM matrix and unitarity triangle

- 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:

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



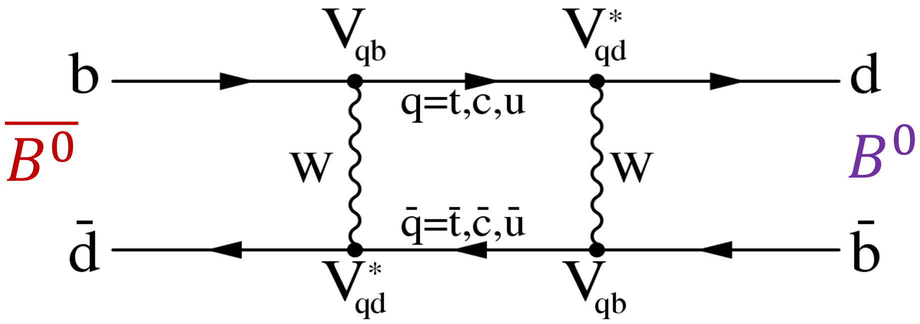

- Wolfenstein parametrization:

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

- 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.

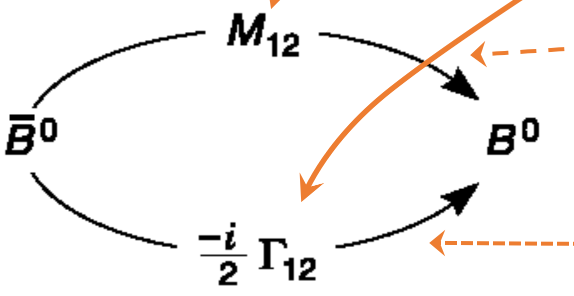



- Time evolution of $B^0$ and $\overline{B^0}$ described by an effective Hamiltonian

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

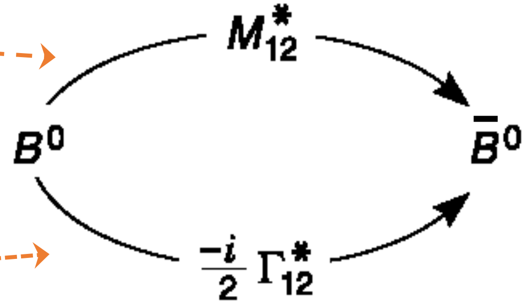
$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{Hermitean Mass-matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{Hermitean Decay-matrix}}$$

*Hermitean Mass-matrix* *Hermitean Decay-matrix*



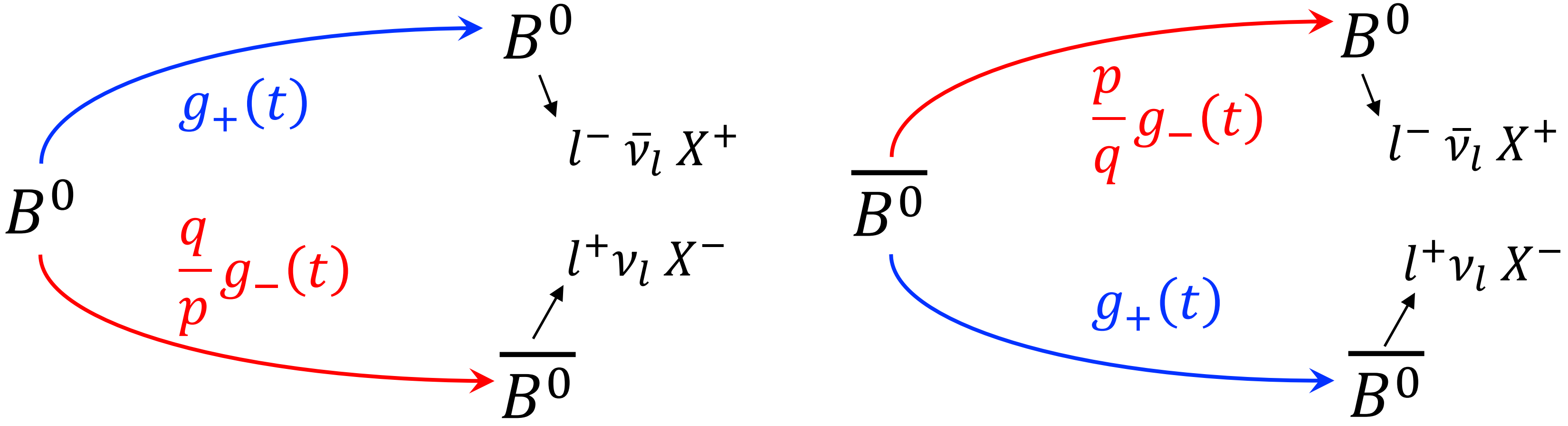

$M_{12}$ describes $B^0 \leftrightarrow \overline{B^0}$ via *off-shell* states, e.g. the weak box diagram (“dispersive”)

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



# Recap: $B^0$ Oscillations






Calculate:

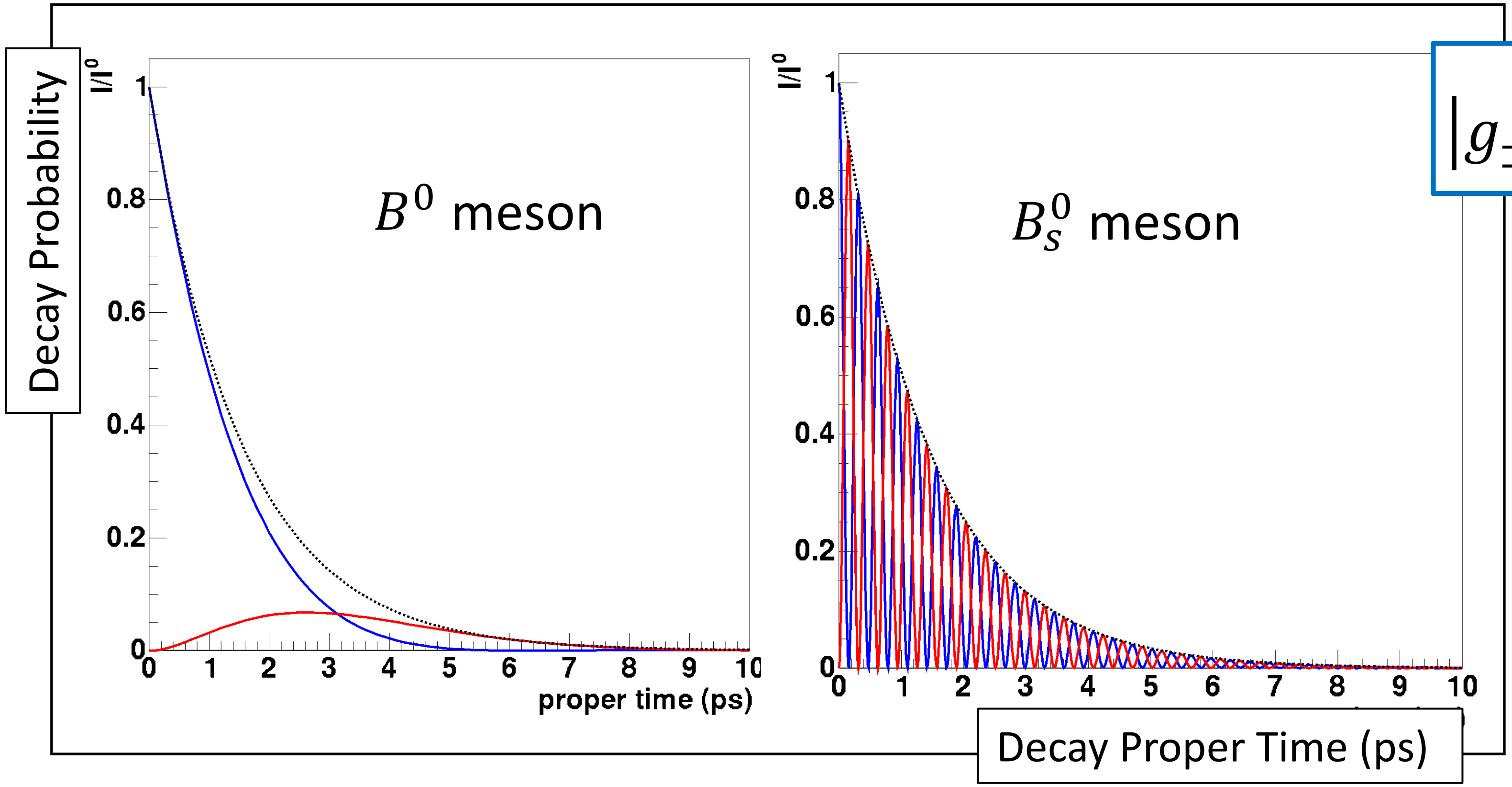
$|\langle B(t)|B^0\rangle|^2$

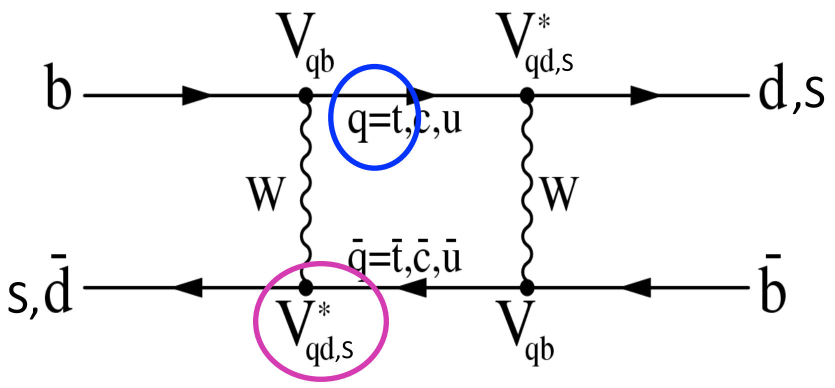
$|\langle \bar{B}(t)|B^0\rangle|^2$

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

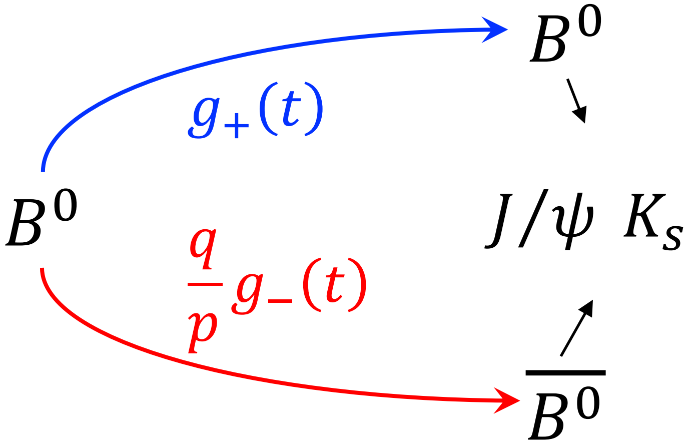
$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[1 \pm \cos(\Delta m \cdot t)\right]$$

Flavour Oscillations!



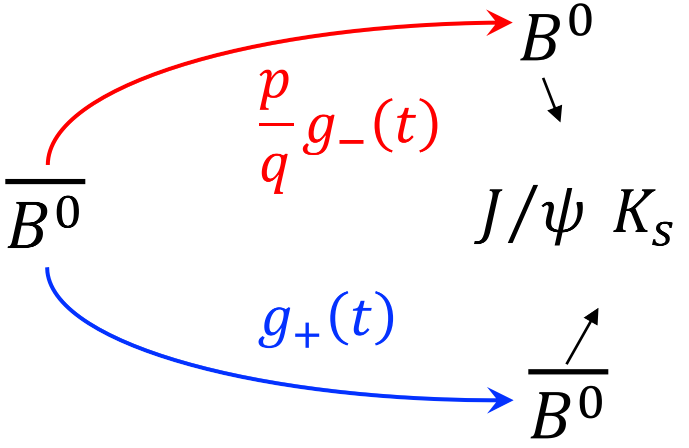



# Recap: $B$ Decays to common final states: $CP$ eigenstates



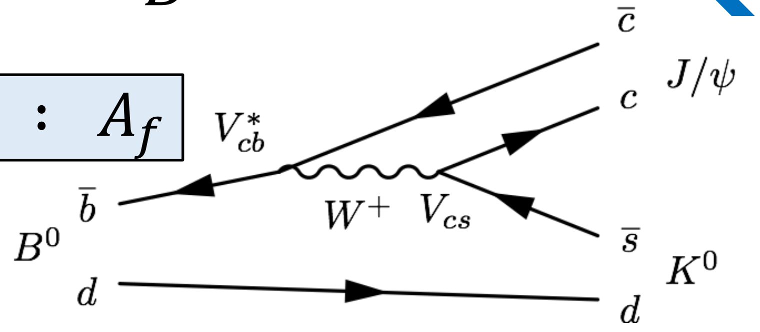

$B^0 \to J/\psi\, K_s$
+
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

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



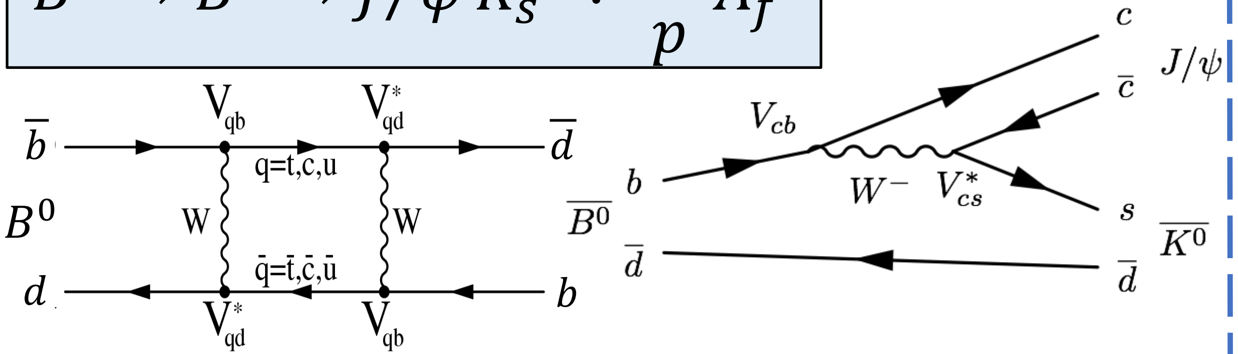

CP

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

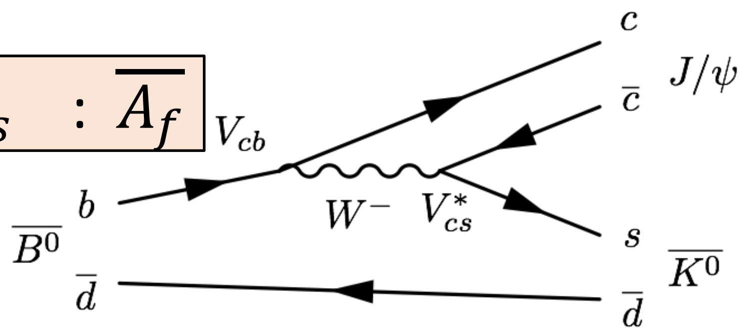



+

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

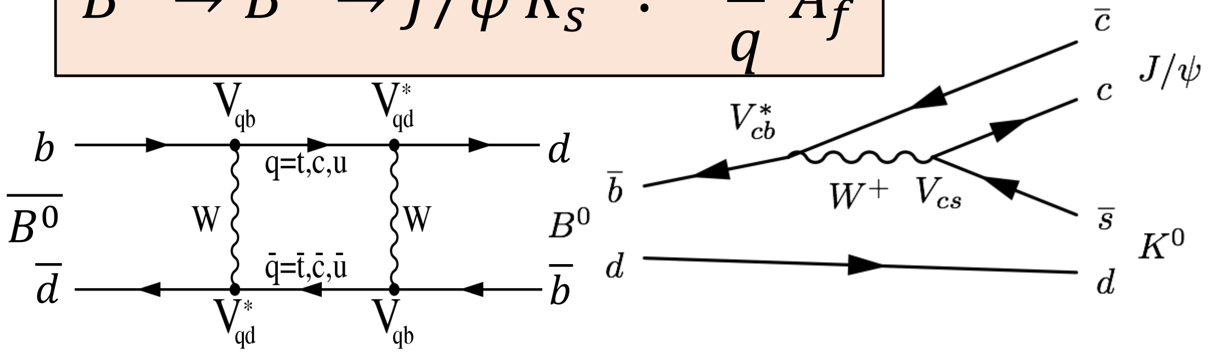



$\overline{B^0} \to J/\psi\, K_s \quad : \quad \overline{A_f}$




+

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

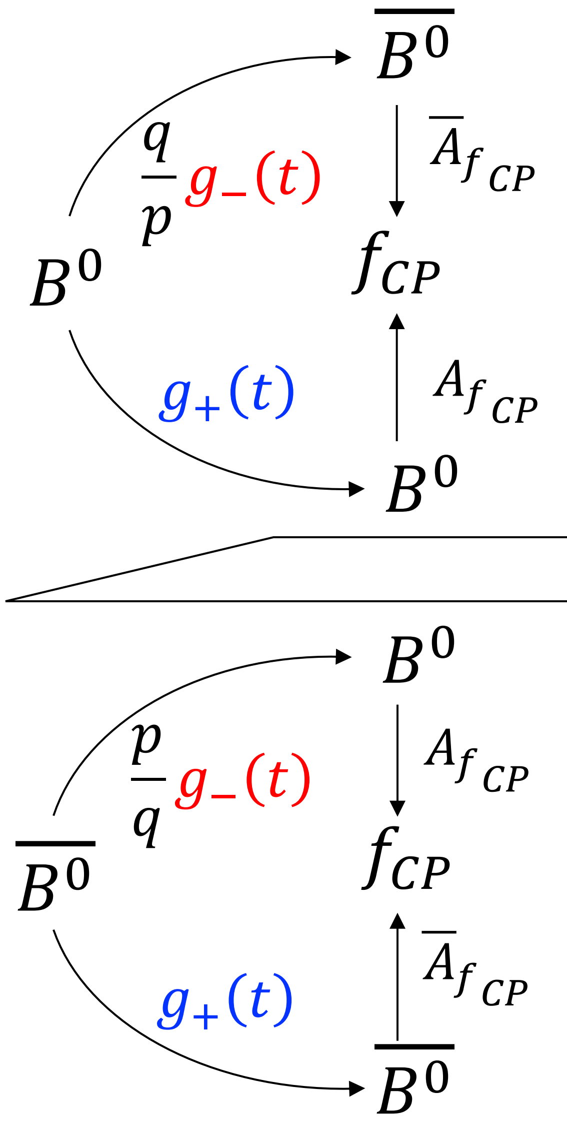


# Recap: How does it give CP violation?



$t = 0$ | $t$ | Amplitude

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




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

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

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

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

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

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

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

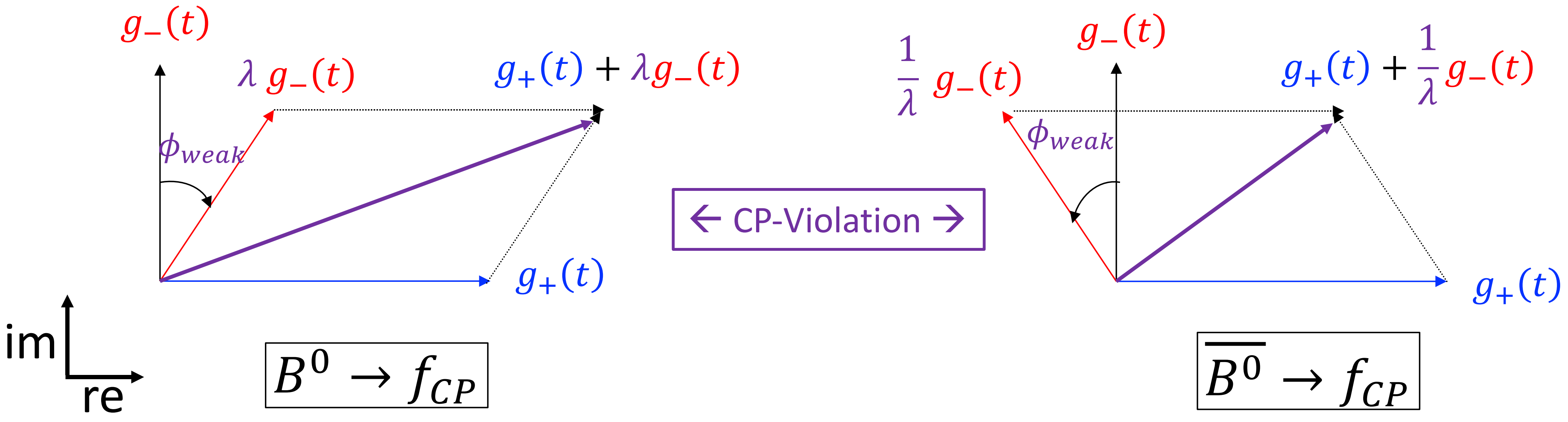
# Recap: Interfering Amplitudes: CP violation!

| $t=0$ | | $t$ | Amplitude |
|---|---|---|---|
| $B^0$ | $\rightarrow$ | $f_{CP}$ | $A_{f_{CP}}\left(g_+(t) + \lambda g_-(t)\right)$ |
| $\overline{B^0}$ | $\rightarrow$ | $f_{CP}$ | $\bar{A}_{f_{CP}}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)$ |

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

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

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



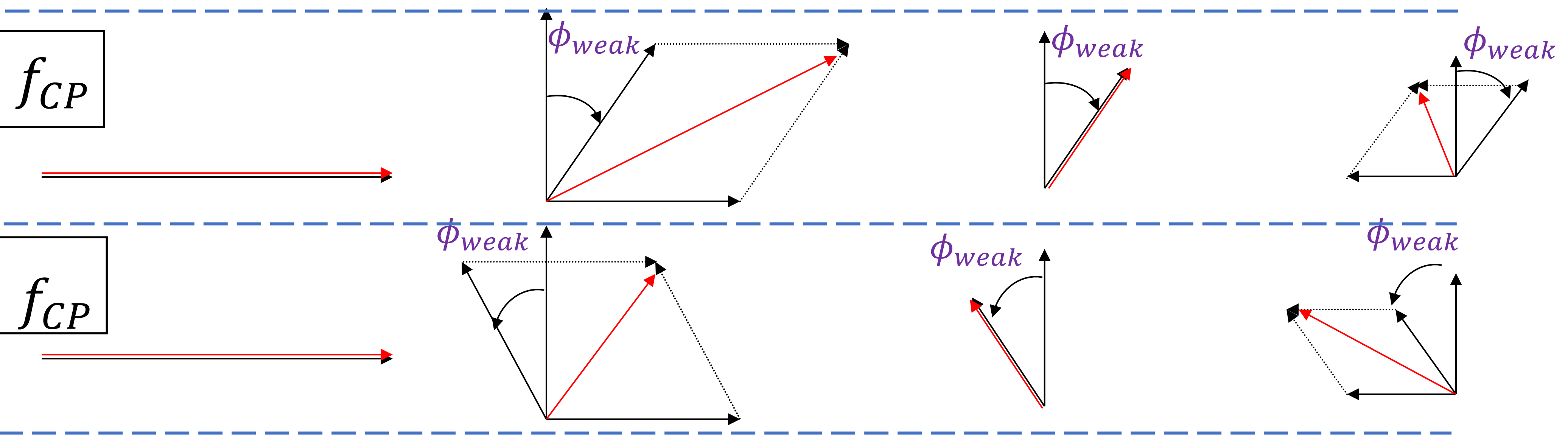
# Recap: Interfering Amplitudes: time dependent CP violation!



| $t = 0$ | | $t$ | Amplitude |
|---|---|---|---|
| $B^0$ | $\rightarrow$ | $f_{CP}$ | $A_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2} \left( \cos\frac{\Delta m t}{2} + i\,\lambda\, \sin\frac{\Delta m t}{2} \right)$ |
| $\overline{B^0}$ | $\rightarrow$ | $f_{CP}$ | $\bar{A}_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2} \left( \cos\frac{\Delta m t}{2} + i\,\frac{1}{\lambda}\, \sin\frac{\Delta m t}{2} \right)$ |

$B^0 \rightarrow f_{CP}$

$\overline{B^0} \rightarrow f_{CP}$




$\Delta m t/2 = 0$ — *No CPV*

$\Delta m t/2 = \pi/4$

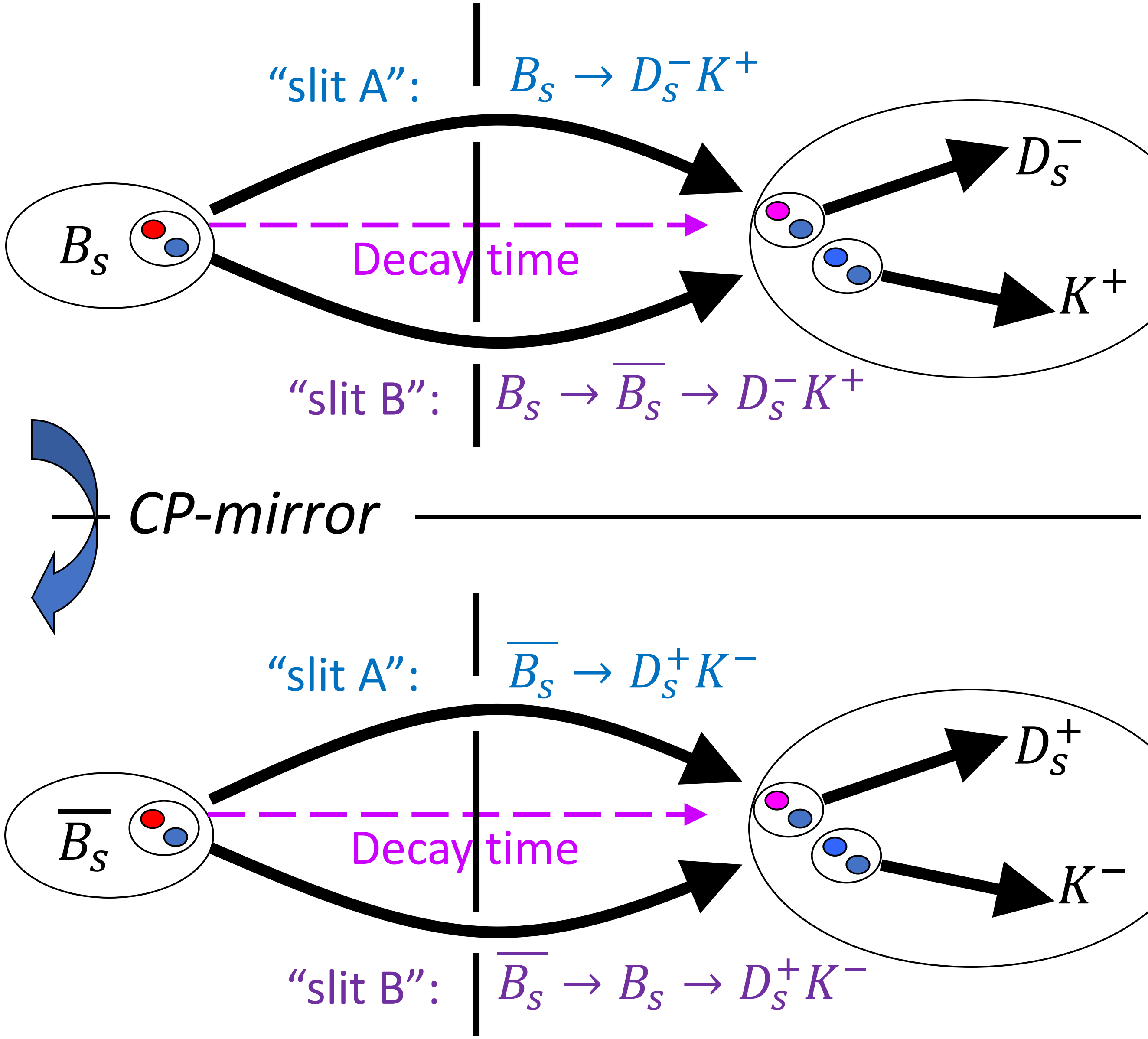
$\Delta m t/2 = \pi/2$

$\Delta m t/2 = 3\pi/4$ — *CPV!*

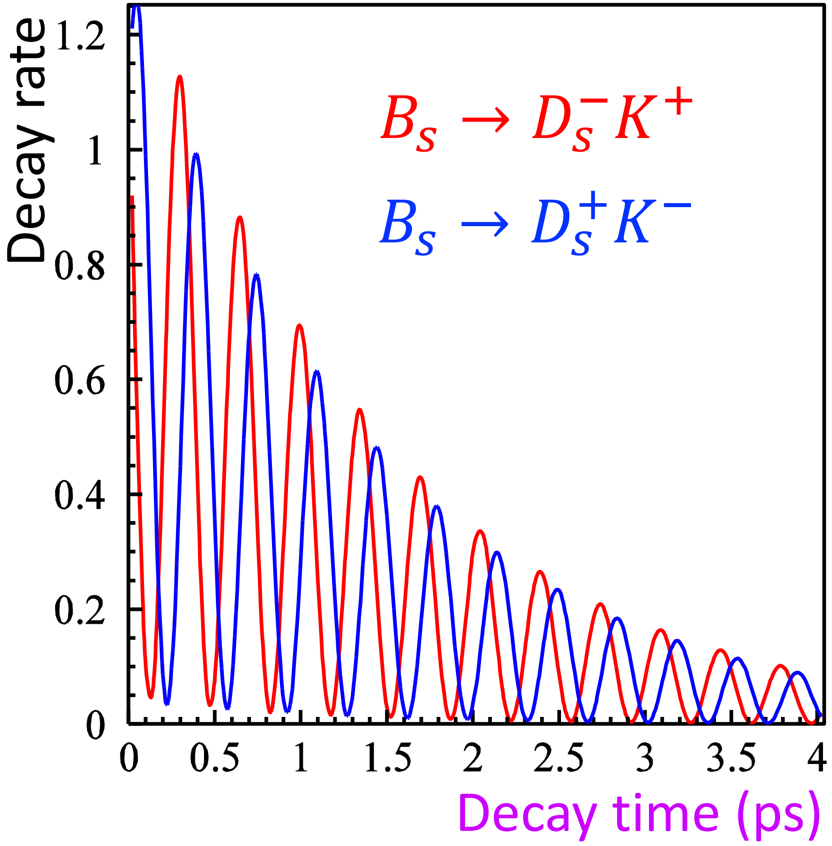
➔ Decay-Time Dependent CP Asymmetry!

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



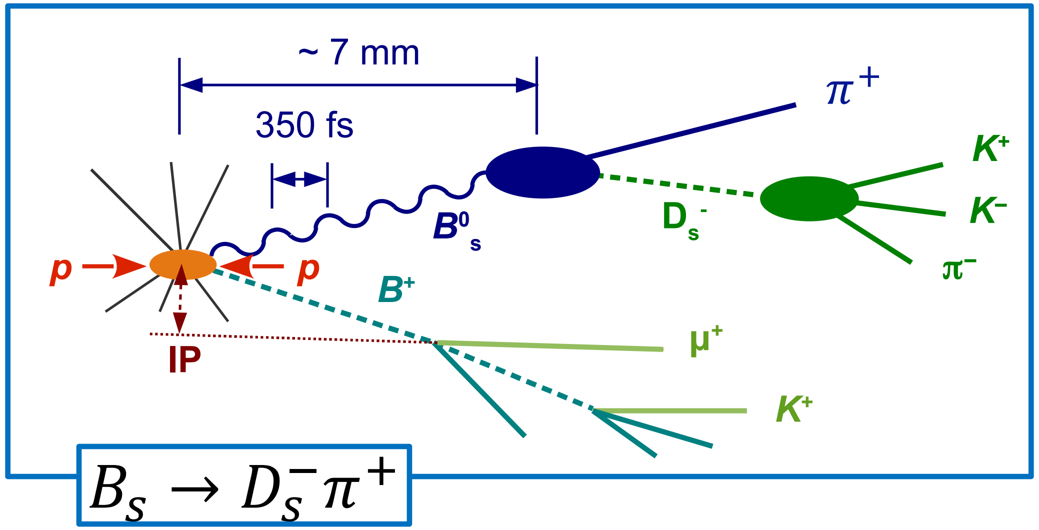



An interference pattern:

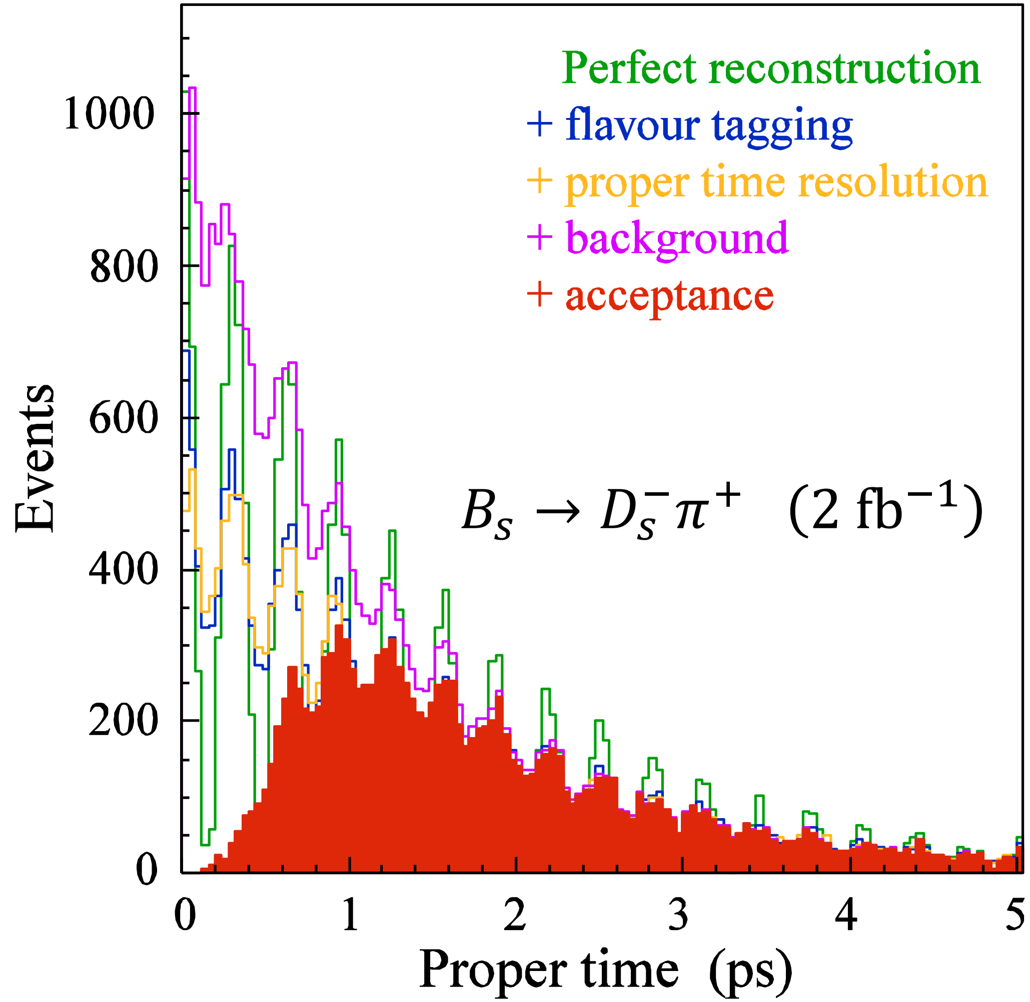



Time dependent $CP$ violation!

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




Proper-time dependent decay rate:




***Experimental Situation:***

Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

+ Realistic decay time resolution

+ Background events

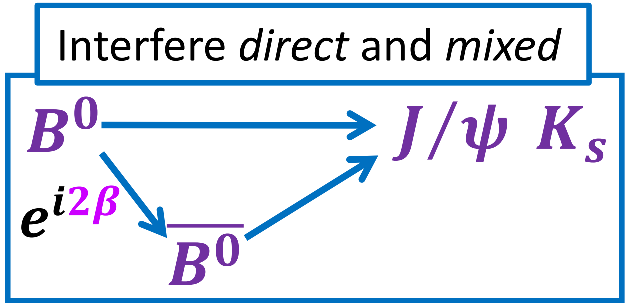
+ Trigger and selection acceptance

# Recap: Compare LHC with B-factory for $B^0 \to J/\psi\ K_S$

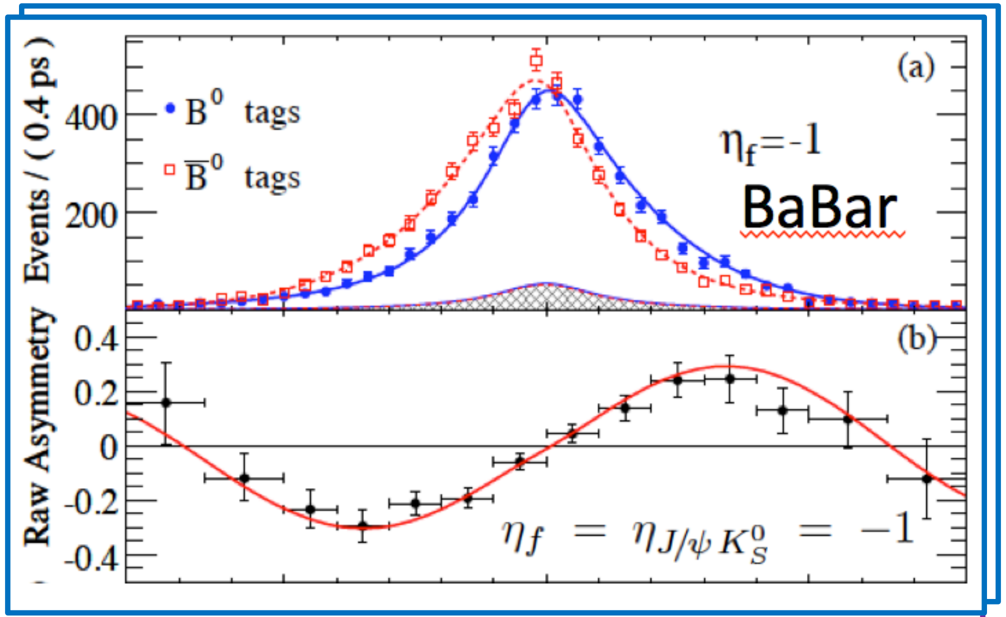
- *Decay-time dependent*

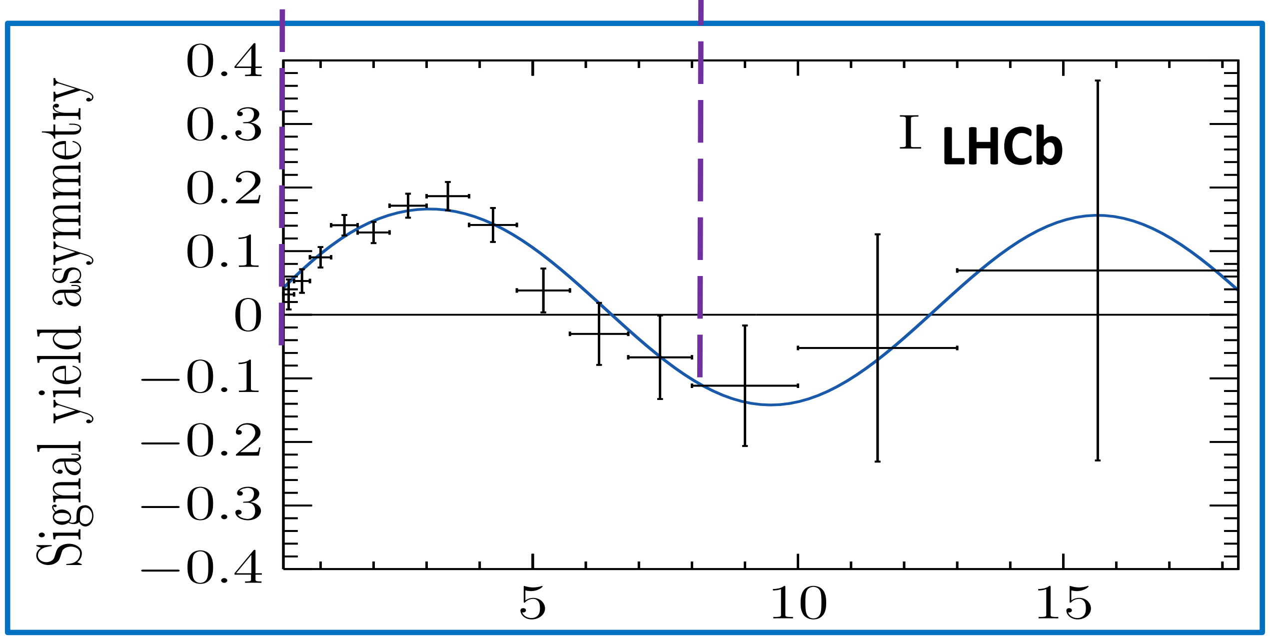
  $CP$ violation:

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



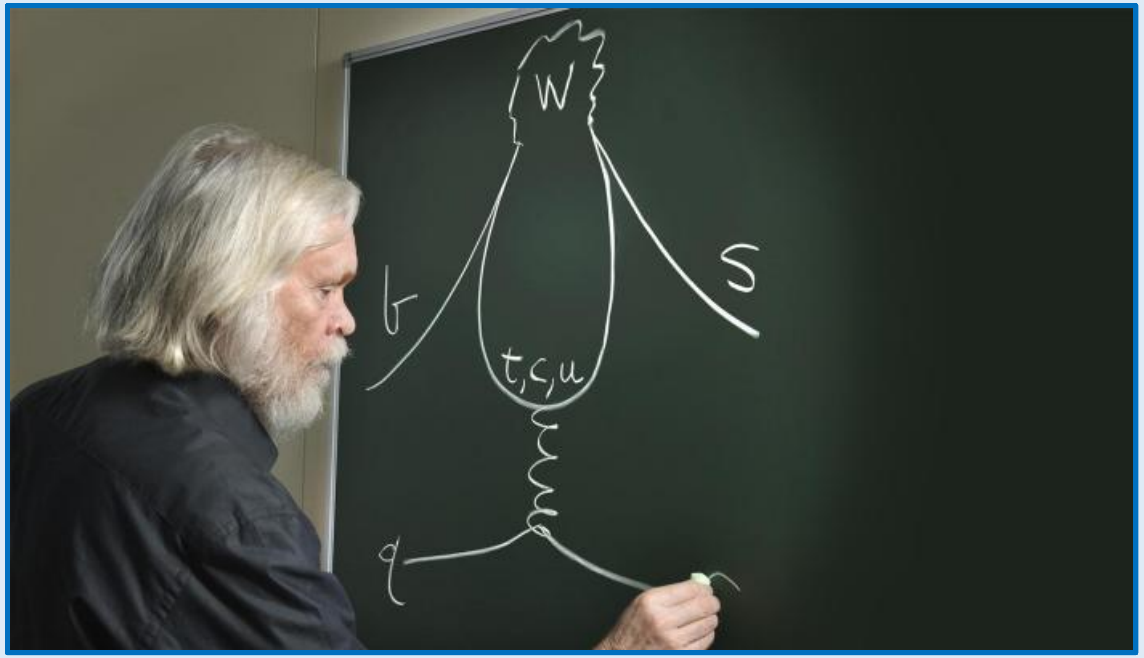

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



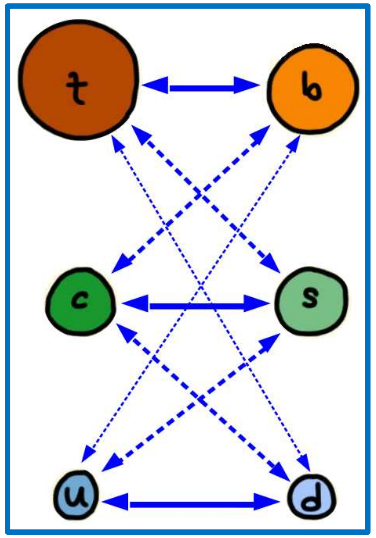
## Contents:



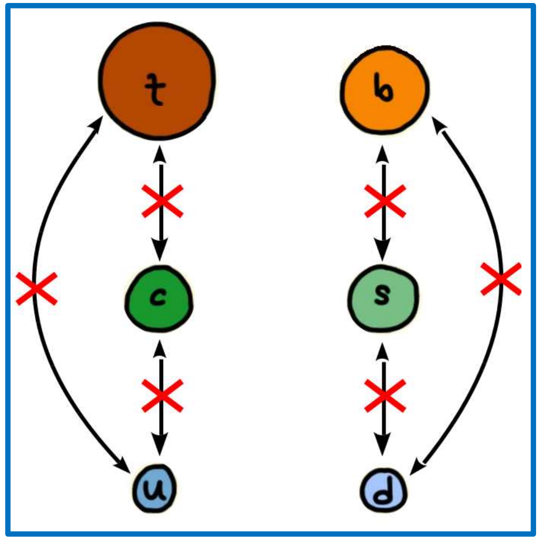


# S.M.: No Flavour Changing Neutral Currents (FCNC)

- CKM: Flavour changing *charged* currents

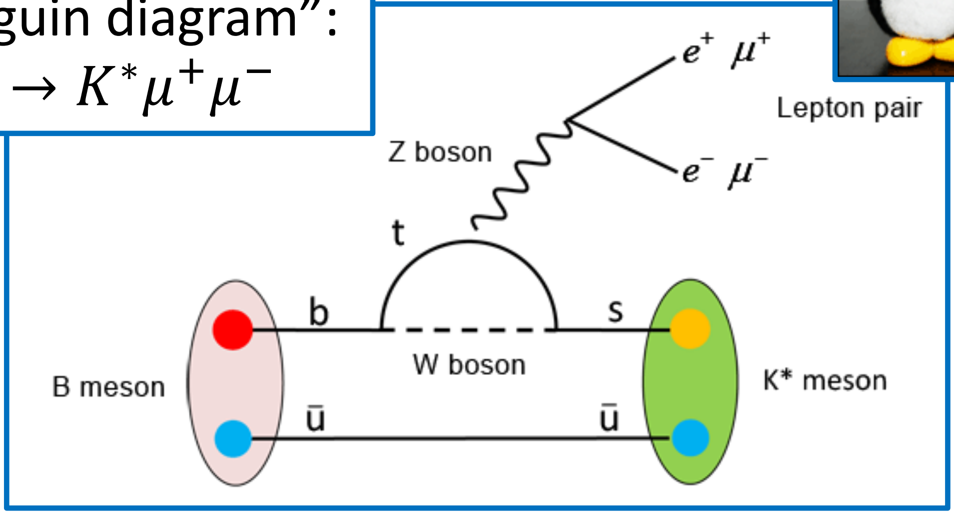



- SM does *not* have Flavour changing *neutral* currents

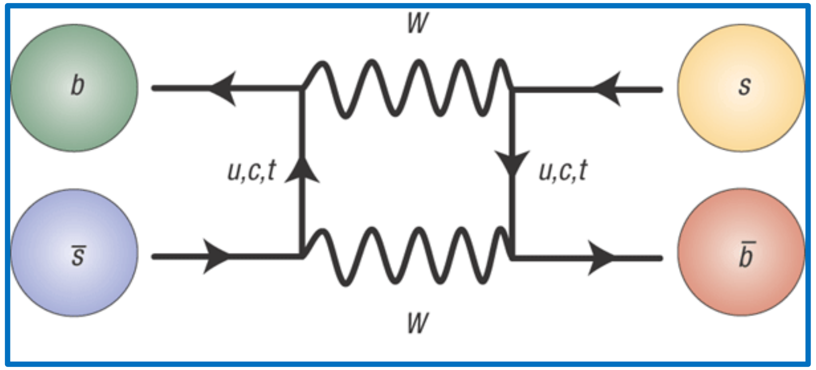



- Neutral currents are possible via higher order processes:

Decay via "Penguin diagram":
$B \rightarrow K^{*}\mu^{+}\mu^{-}$

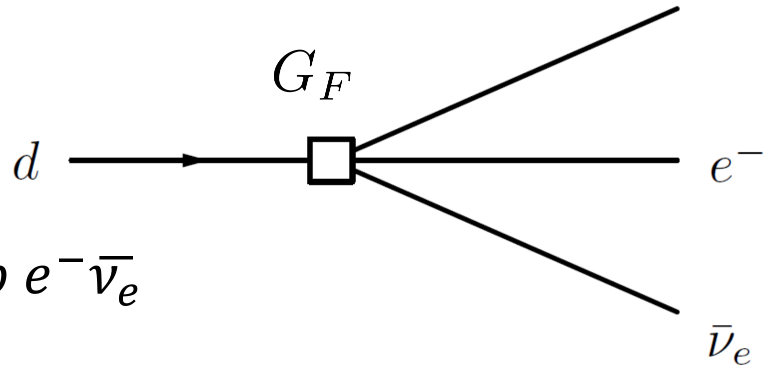



Flavour Oscillation via "Box diagram":
$\overline{B_s} \rightarrow B_s$



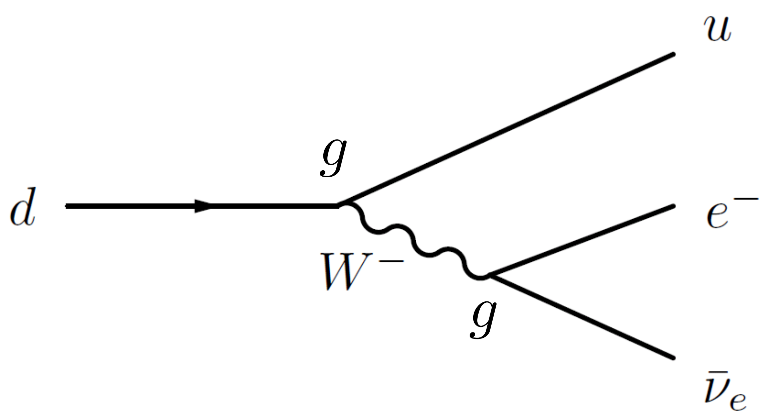
# $B$-decays and effective couplings

- Beta decay: "charged current":

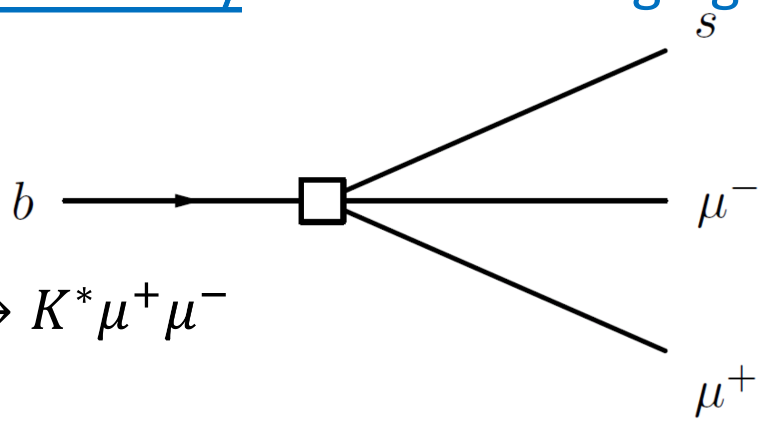



$n \to p\, e^- \overline{\nu}_e$

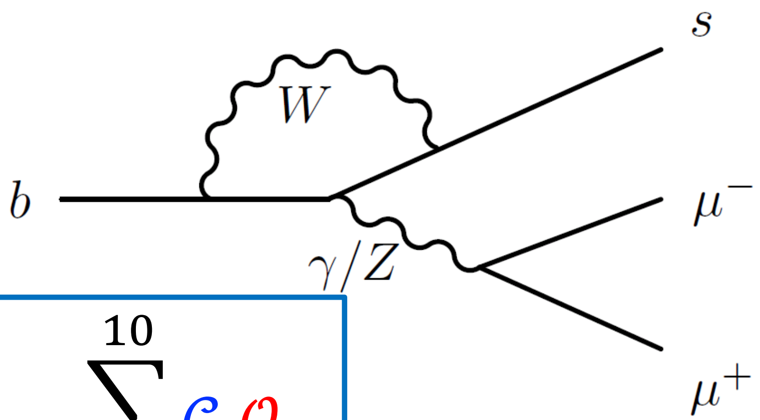
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$




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




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



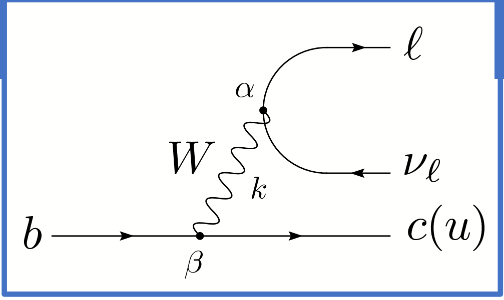

Eff Hamiltonian:

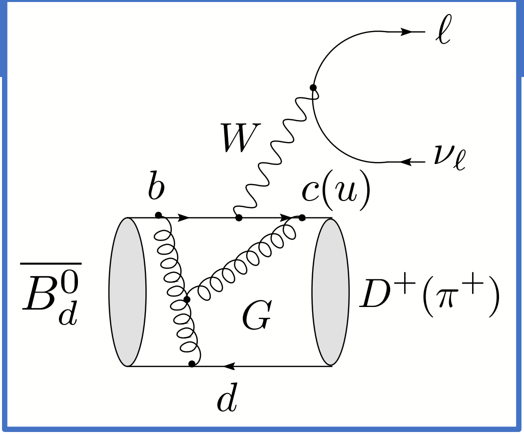
$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i$$

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

# Strong Interaction causes trouble

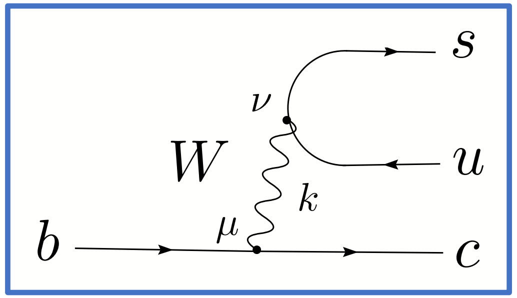


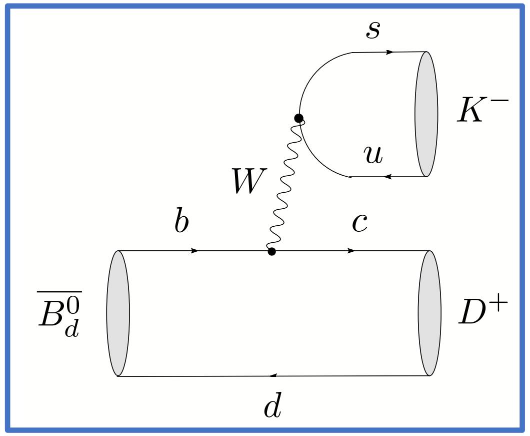



- Semileptonic decays
  - Factorization!

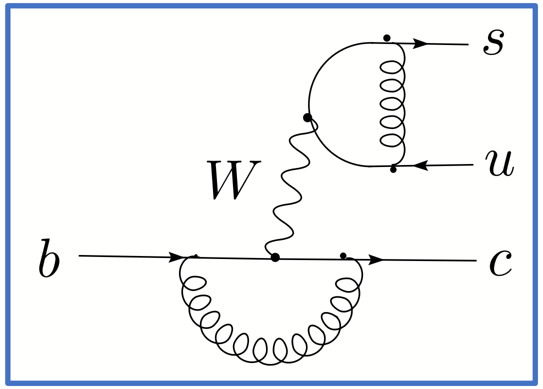
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \underbrace{[\overline{u}_l\, \gamma^\alpha (1-\gamma_5)\, u_\nu]}_{\textit{Dirac spinors}} \underbrace{\left[D^+ \middle| \overline{c}\, \gamma^\beta (1-\gamma_5)\, b \middle| \overline{B}^0_d\right]}_{\textit{hadronic ME}}$$



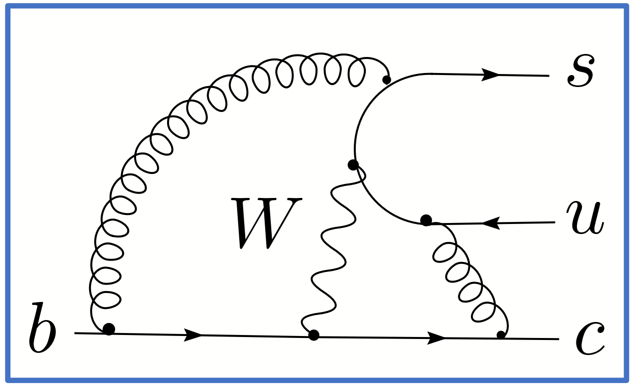




- $\mathcal{H}$adronic decays
  - Factorization?

*Factorizable* QCD:

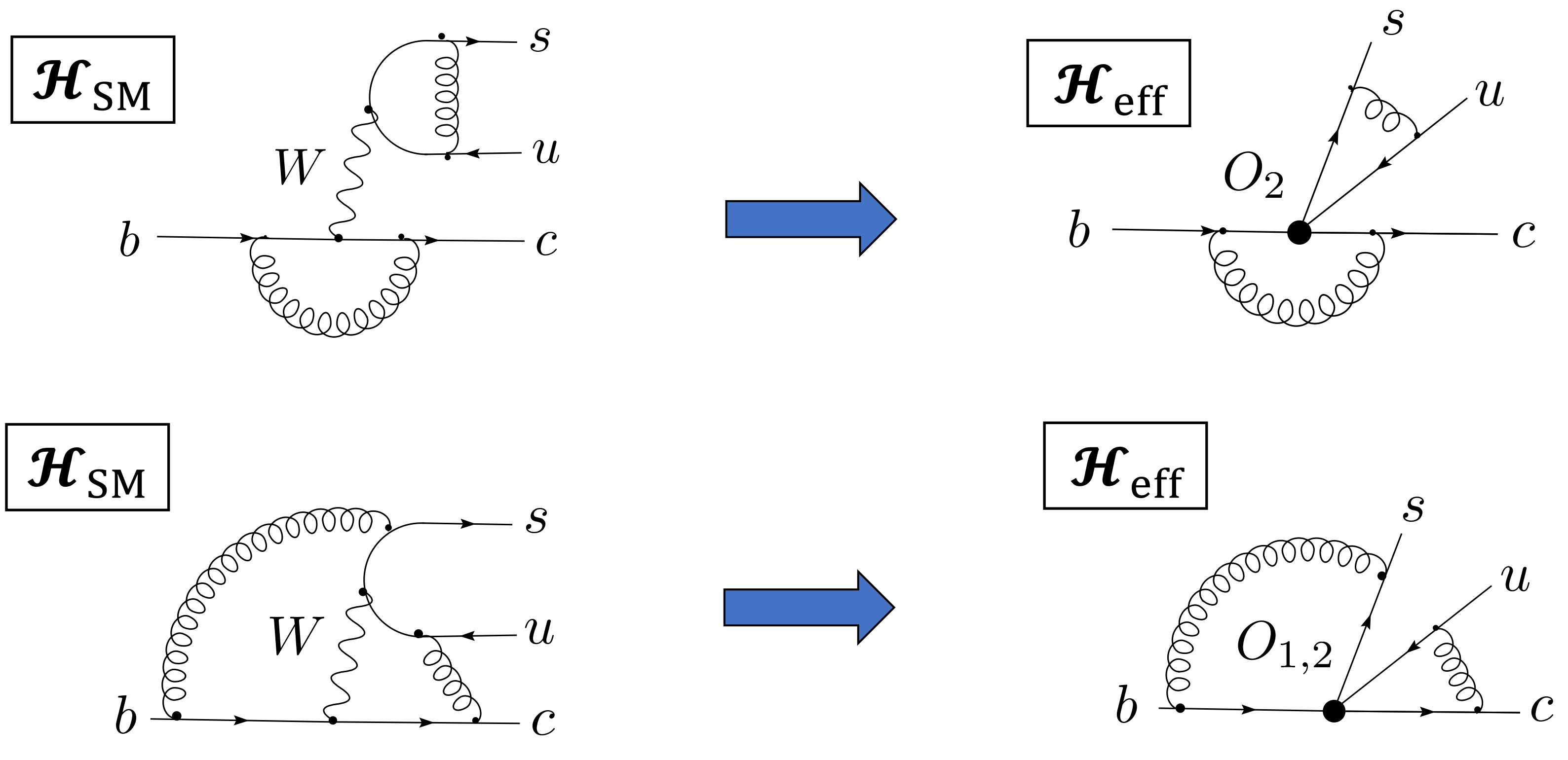



*Non-Factorizable* QCD:



# Solution: Effective couplings

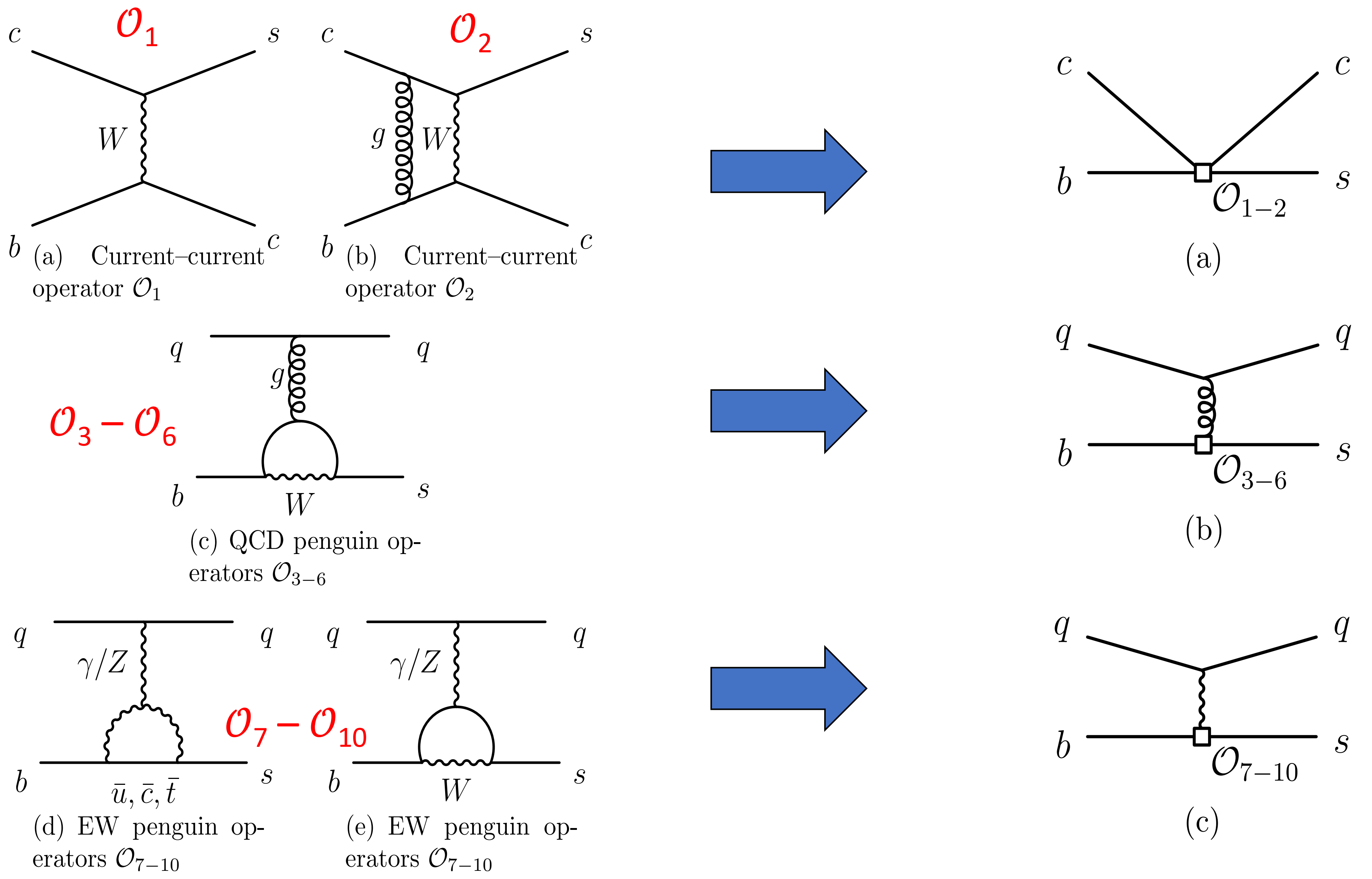
- Operator Product Expansion:
  - Integrate out heavy fields
  - Separate *perturbative* Wilson coefficients $\mathcal{C}_\mathrm{i}$ from *non-perturbative* local operators $\mathcal{O}_\mathrm{i}$



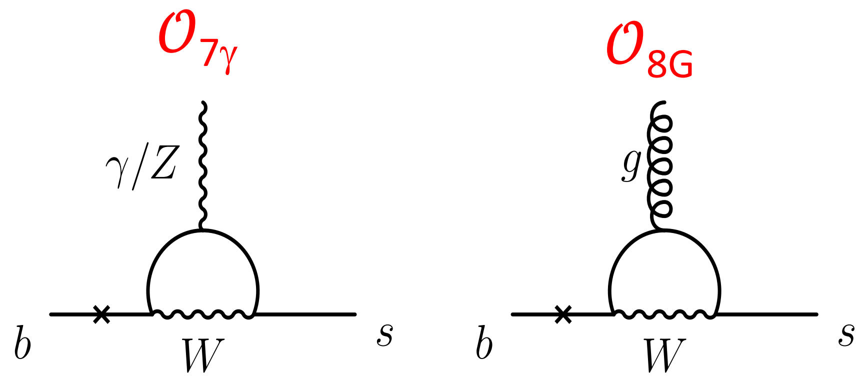

$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} V_{us}^{*} V_{cb} \left[\mathcal{C}_1 \mathcal{O}_1 + \mathcal{C}_2 \mathcal{O}_2\right]$$

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



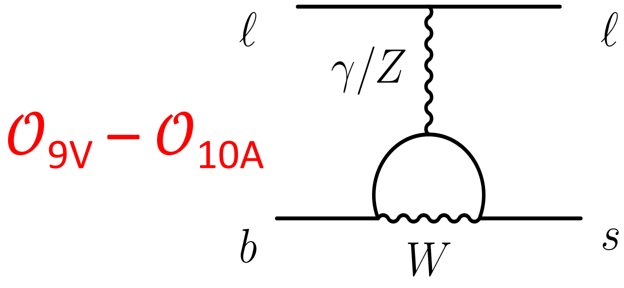


# Rare $B$-decays and effective couplings: $b \to sl^+l^-$

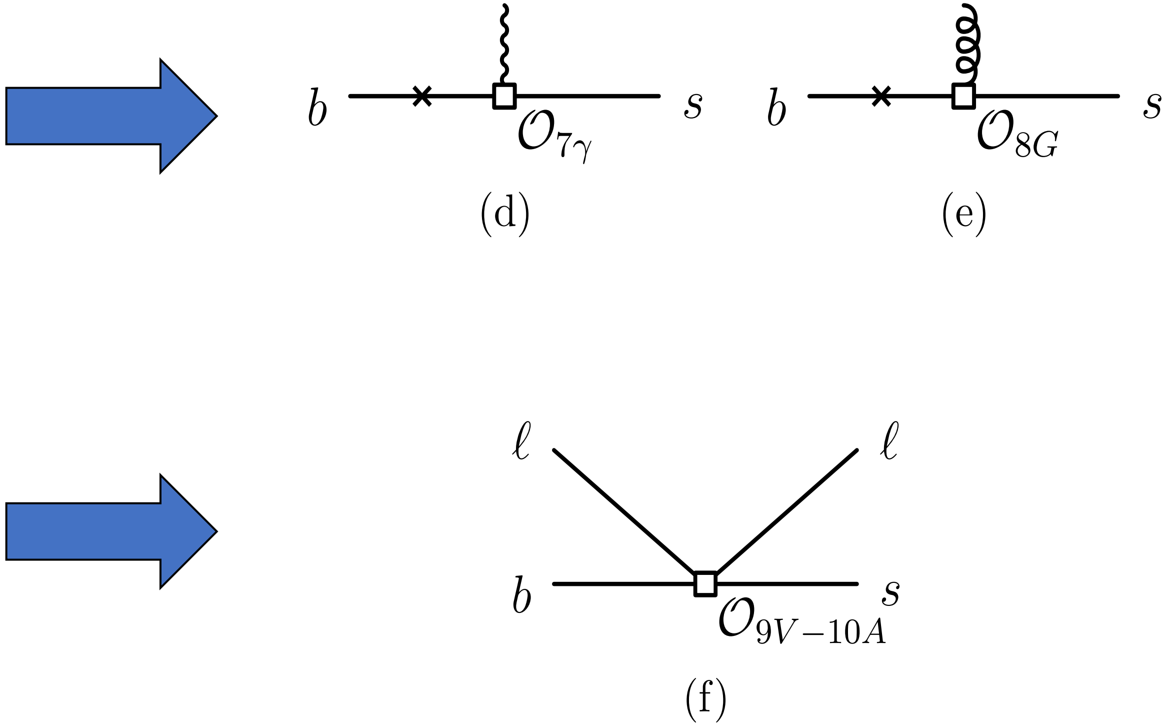



(f) Electromagnetic penguin operator $\mathcal{O}_{7\gamma}$

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




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

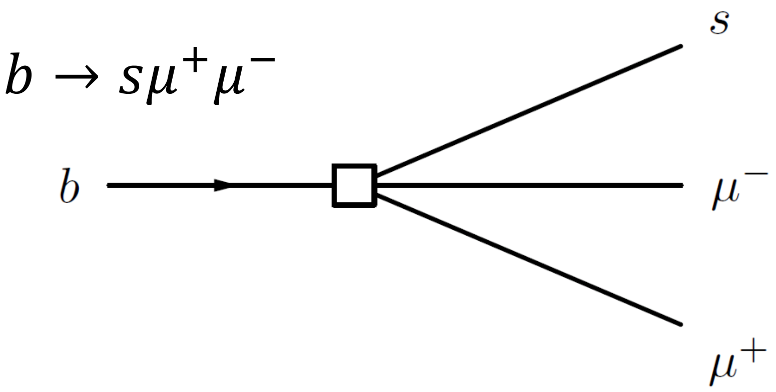


# Rare $B$-decays and effective couplings: $b \to s\mu^+\mu^-$

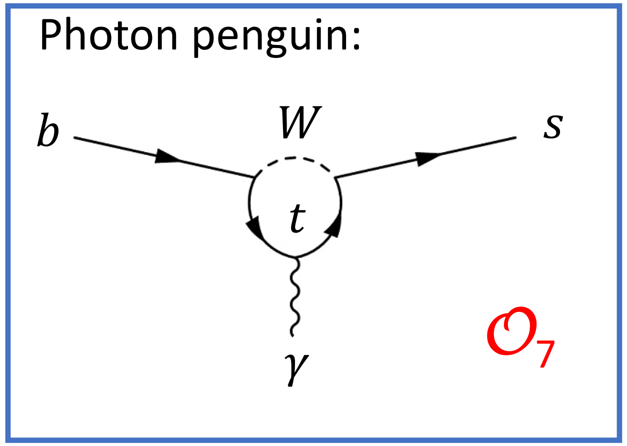


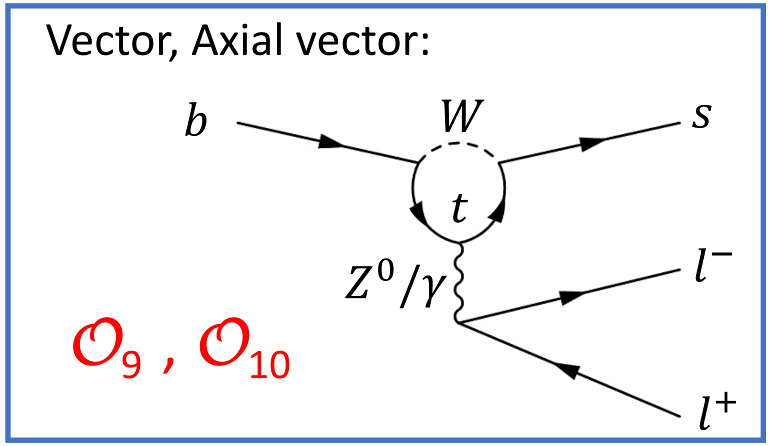
- Effective 4-fermion coupling:

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

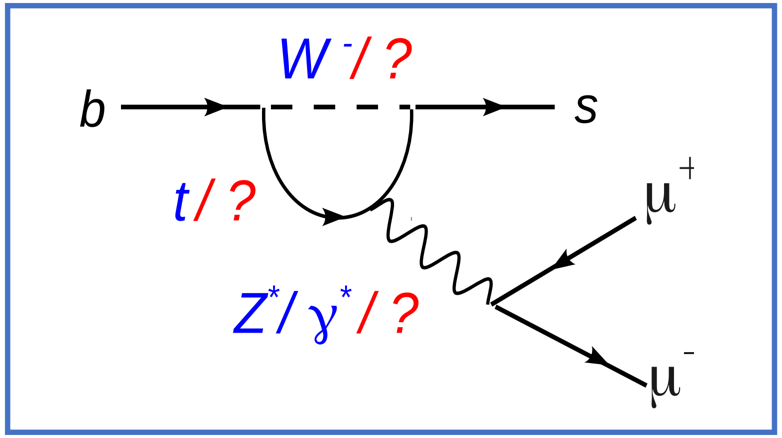



- Standard Model diagrams:




- Beyond Standard Model:




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

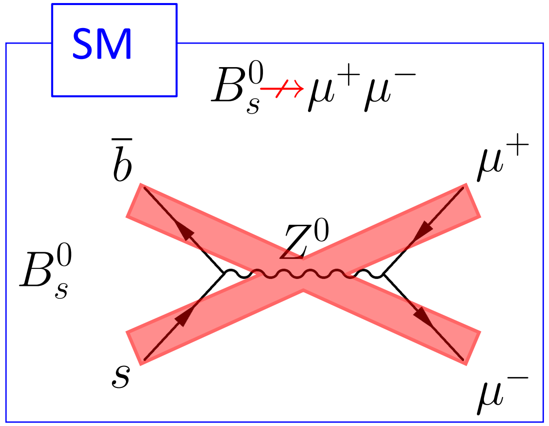
# Very Rare $B$-Decays

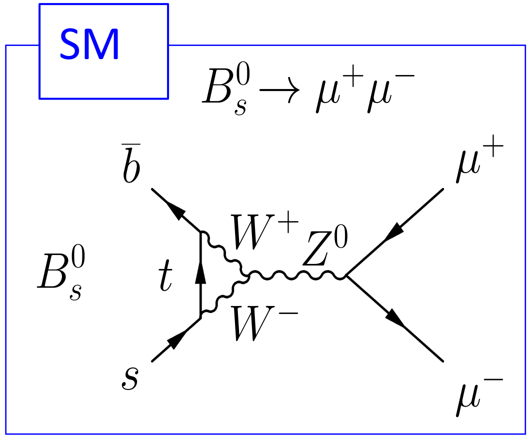


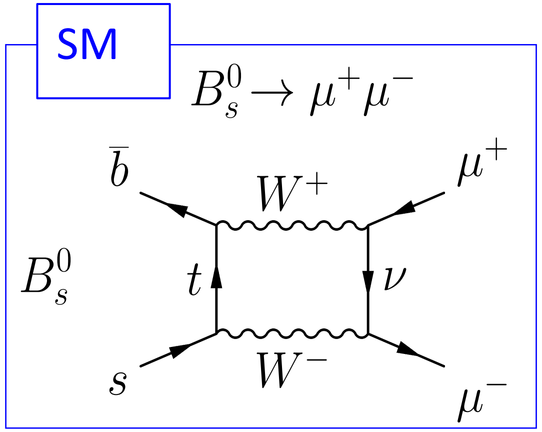
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_i C_i \, \mathcal{O}_i$$

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

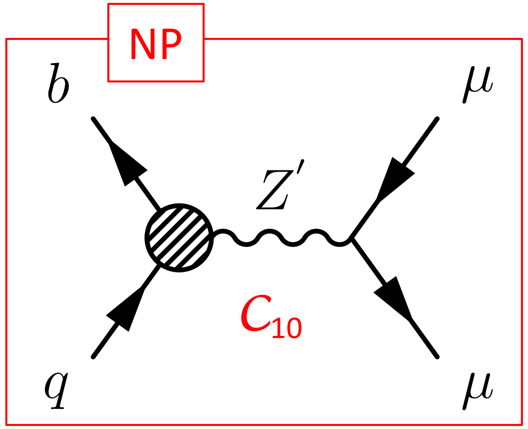
**SM**: CKM and helicity suppressed: very small B.R.
→ Axial vector coupling $C_{10}$

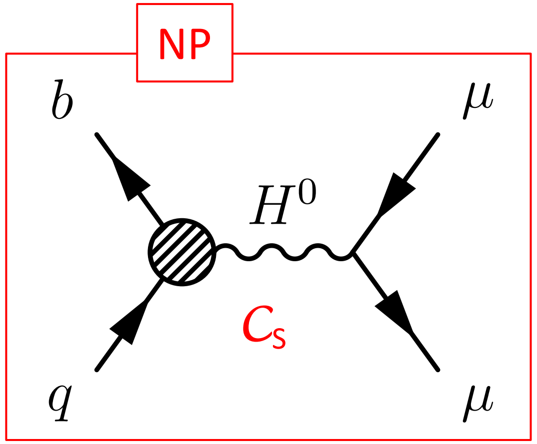


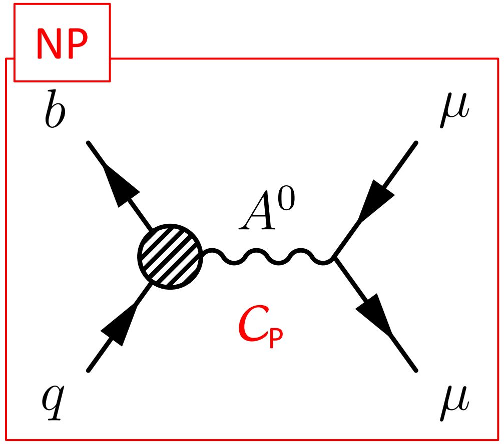




**NP**: Sensitive to new particles via additional ($C_{10}$, $C_S$, $C_P$) couplings.
→ eg.: Z' , (pseudo-)scalars, …

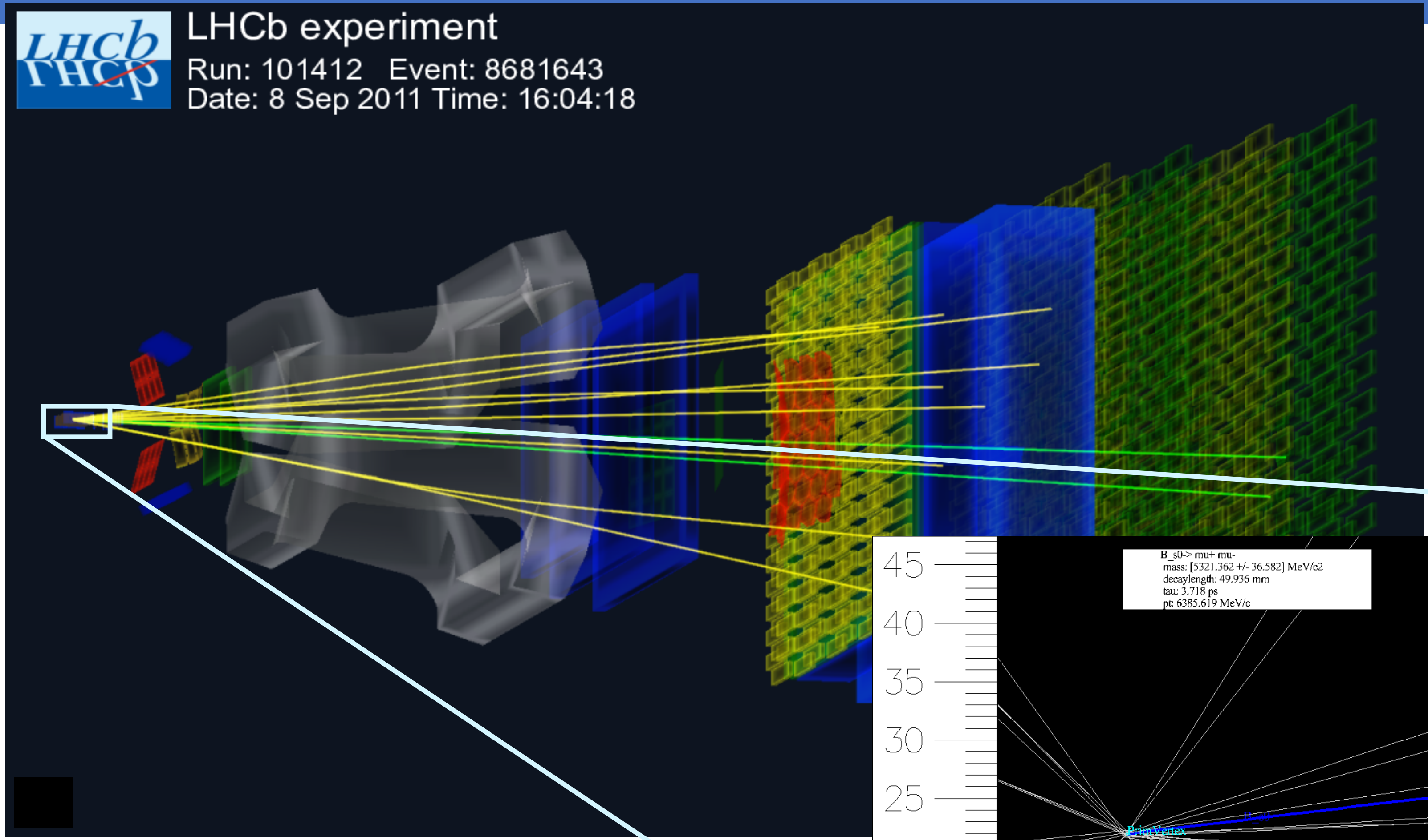


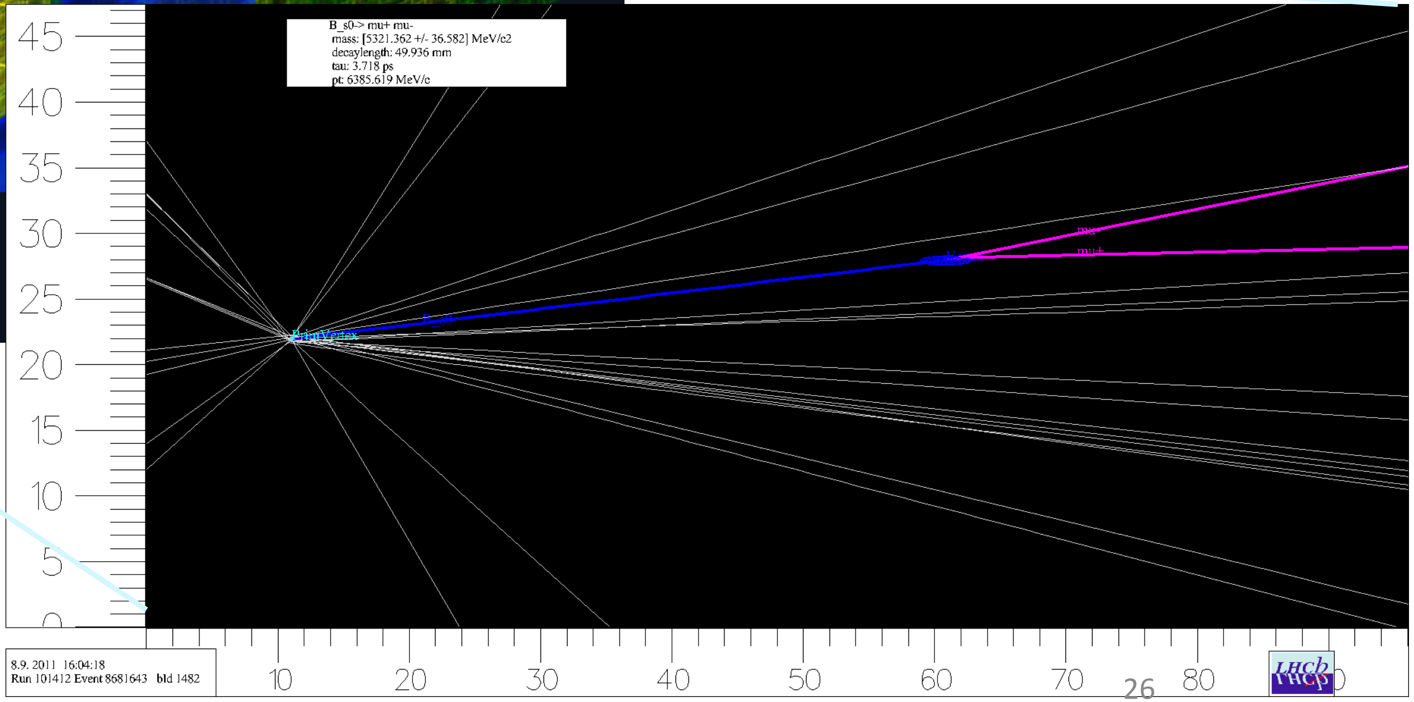




$$BR \propto |V_{tb}V_{tq}|^2 \left[ \left(1 - \frac{4m_\mu^2}{M_B^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + \frac{2m_\mu}{M_B^2}(C_{10} - C_{10}')\right|^2 \right]$$

# Very Rare $B$-Decays




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



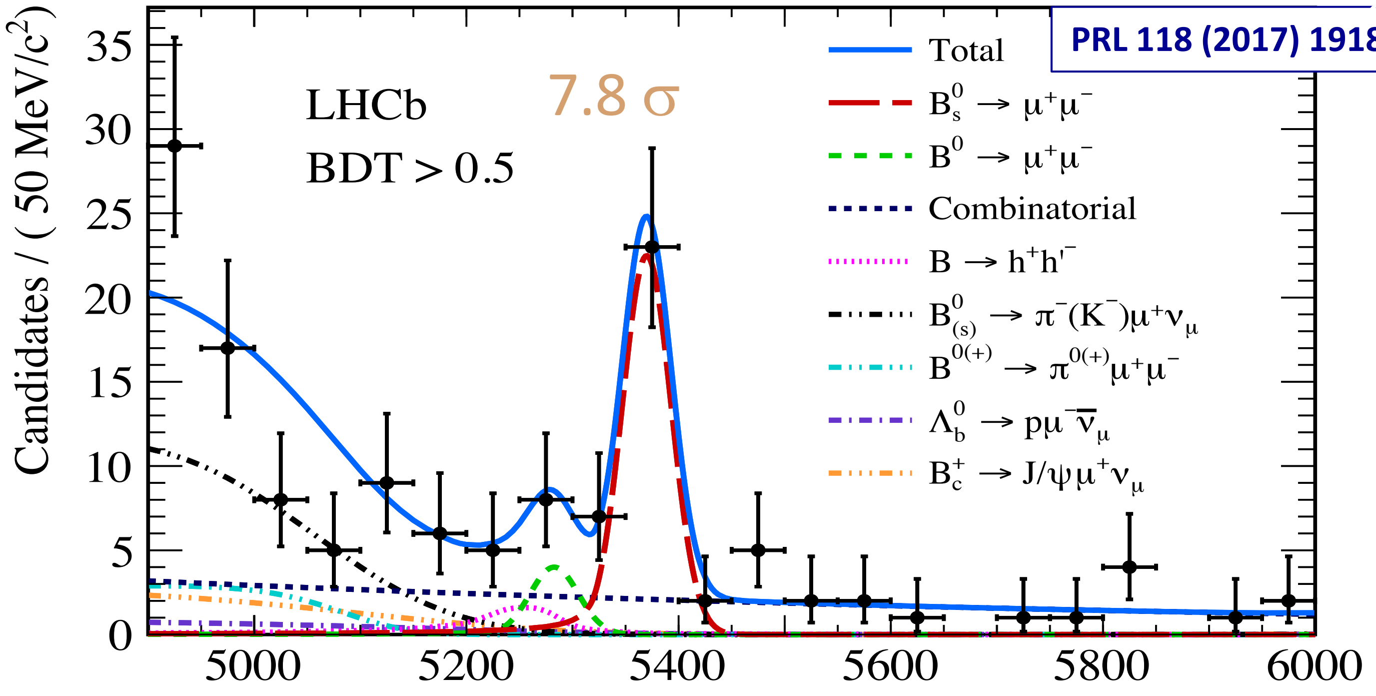

Multivariate technique to suppress Backgrounds.

- Detached vertex
- Muon identification

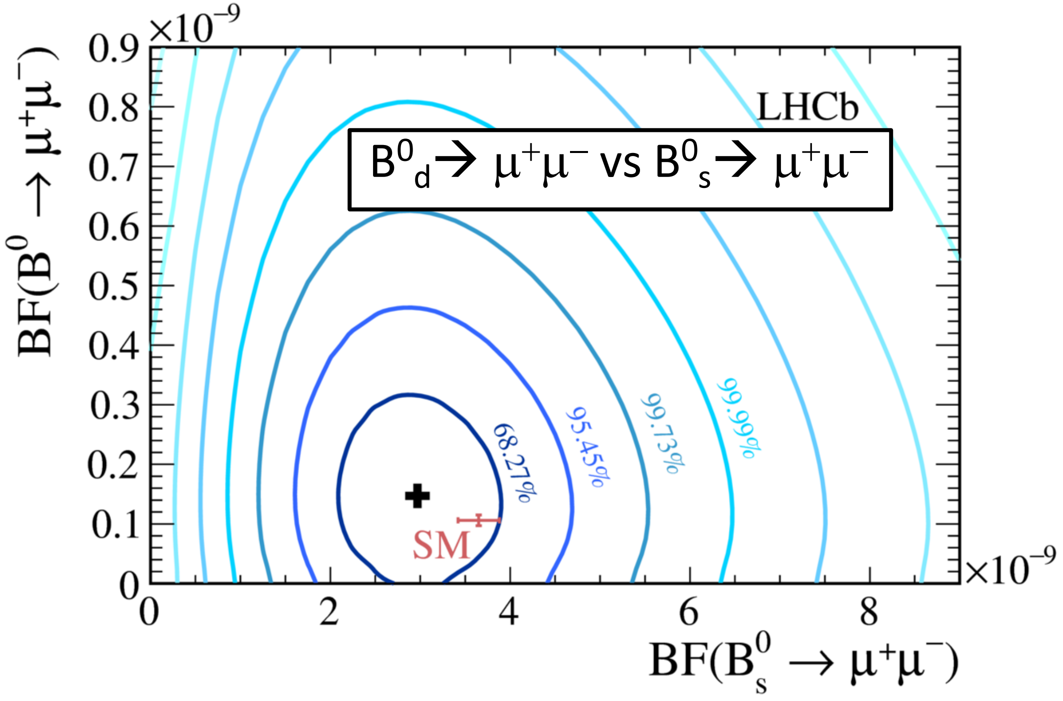
# Very Rare $B$-Decays

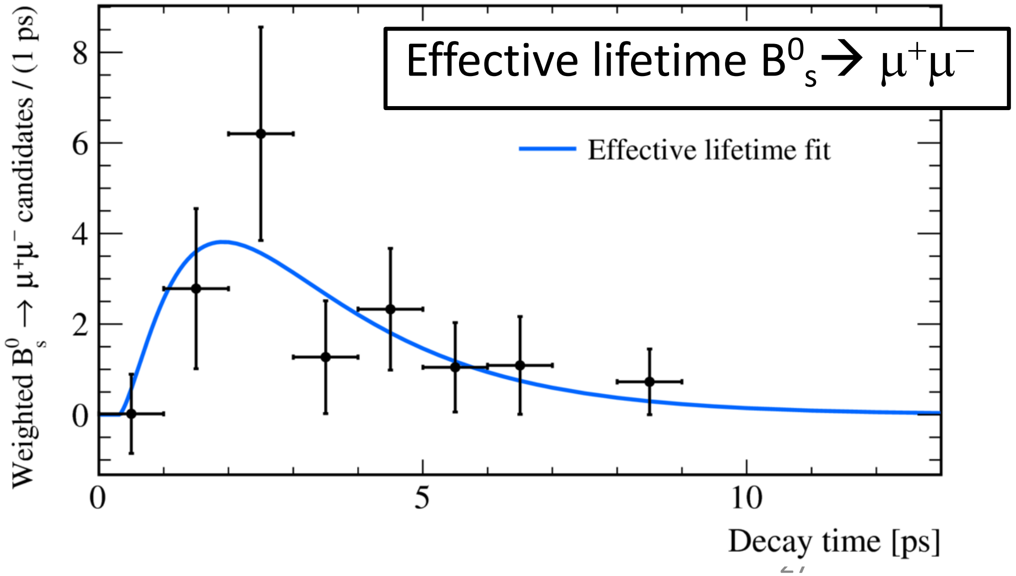
$$B^0_{s,d} \to \mu^+\mu^-$$

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



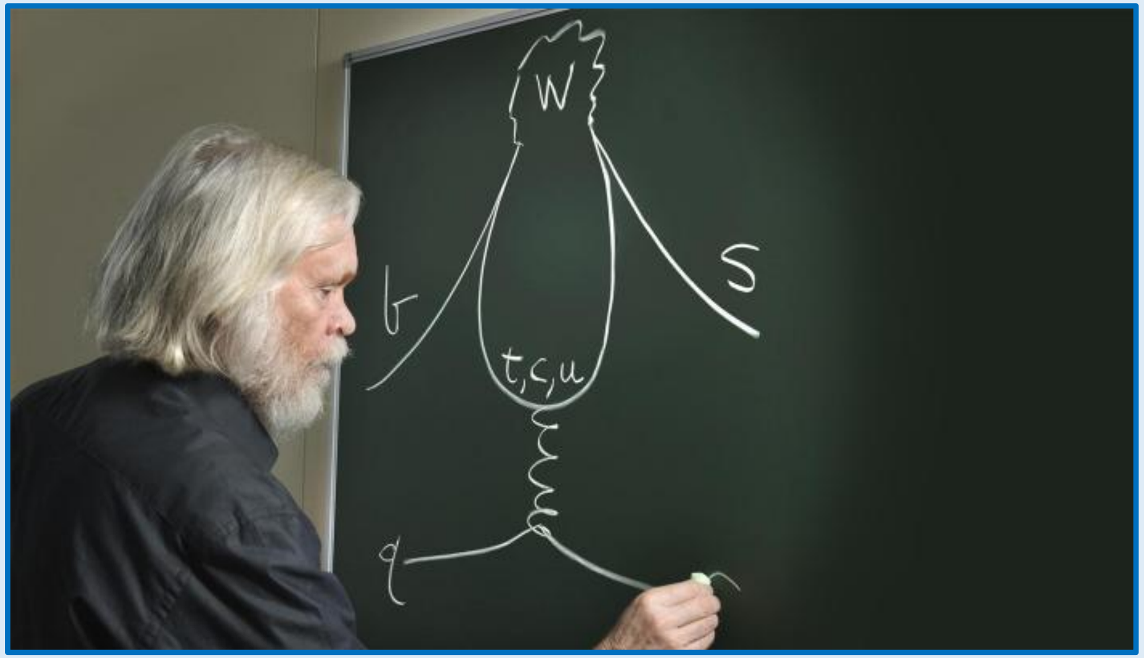

PRL 118 (2017) 191801



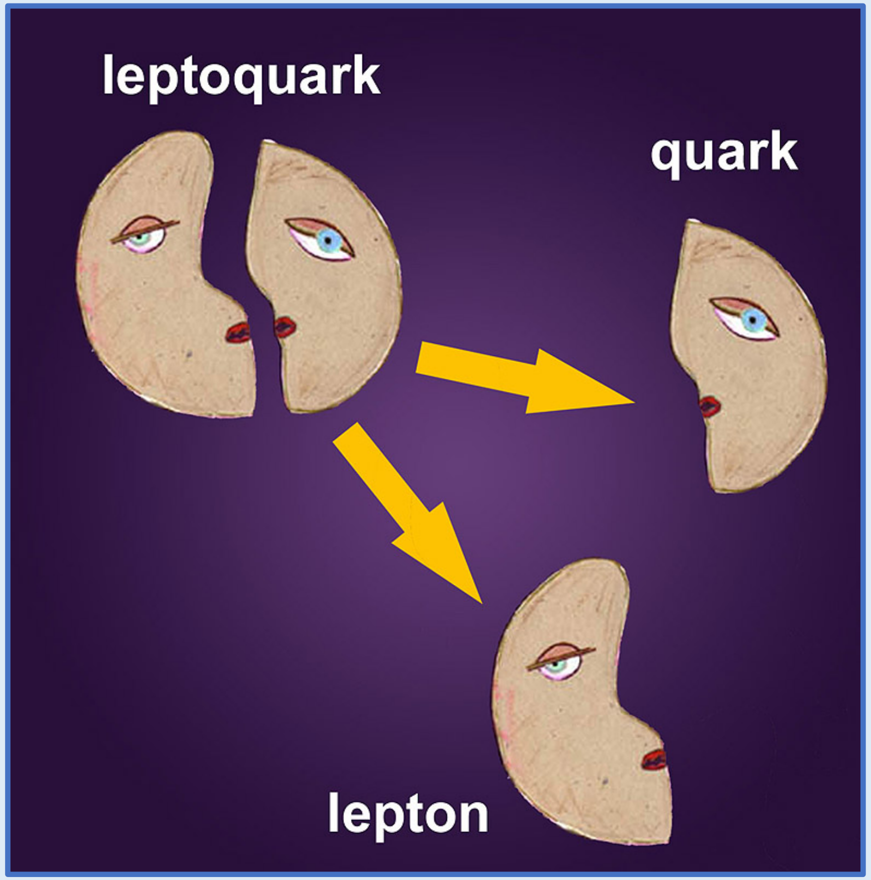
## Contents:





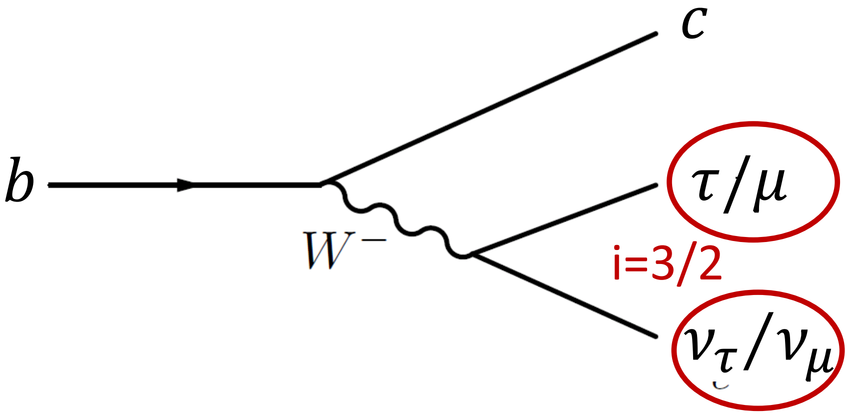
## Contents:





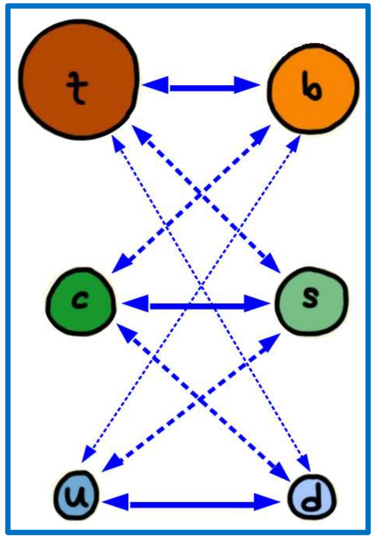
# $B$-decays and lepton universality 

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

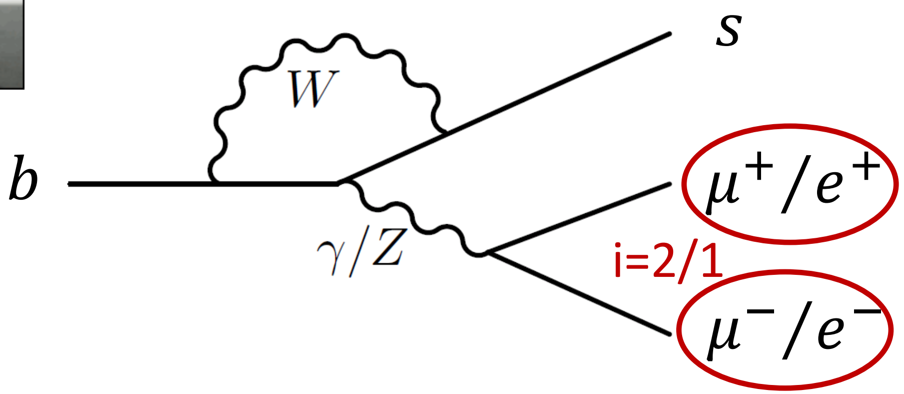



$$R_D = \frac{B \to D\tau\nu}{B \to D\mu\nu}$$

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

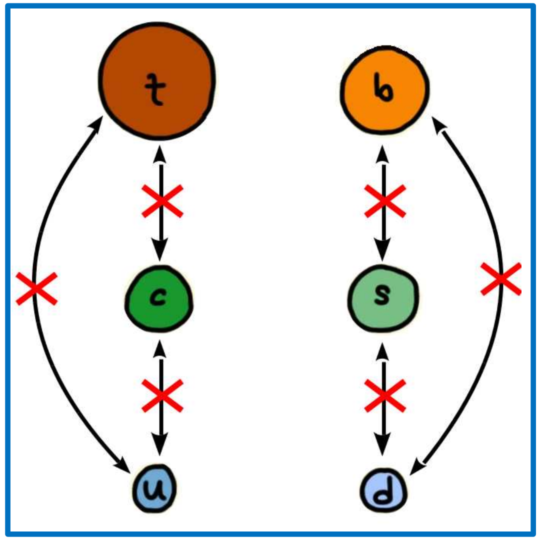



2) $b \to s l^+ l^-$ neutral current: "Suppressed" → rare decays




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

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

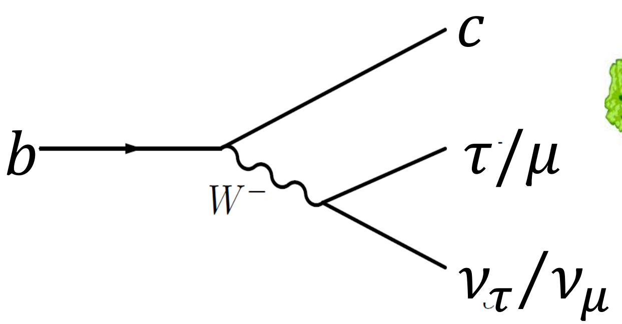


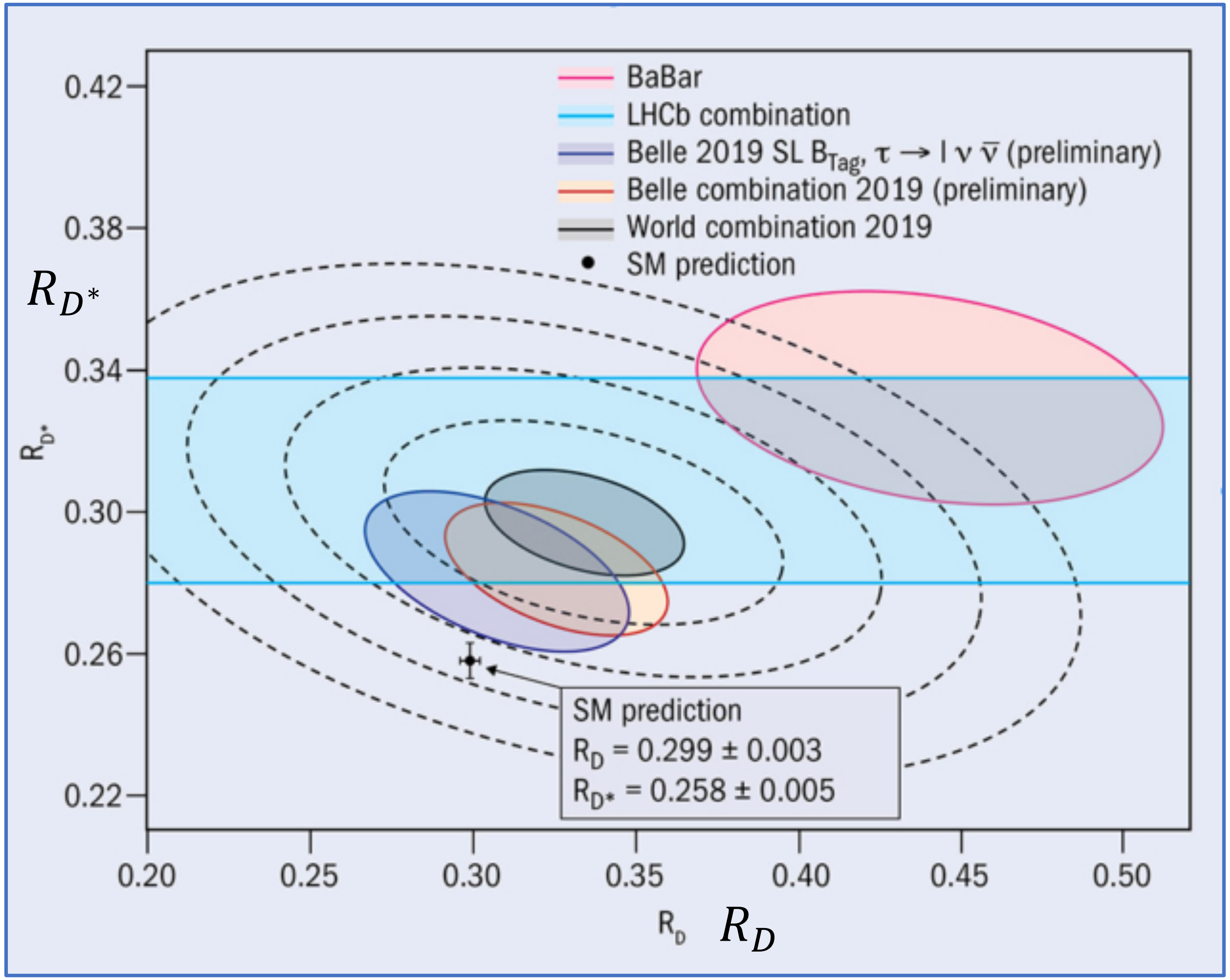
# $R_D$ and $R_{D^*}$

1) $b \to c\, l\, \nu$:
allowed charged current

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

~ 3 – 4 σ deviation



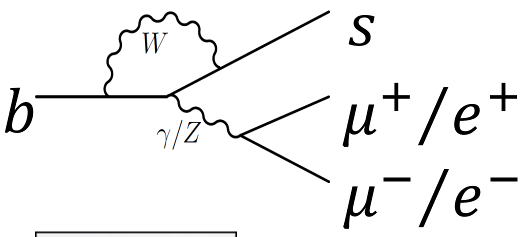

Potential *large* effect ➔ Involves particles of 2nd and 3rd generation

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



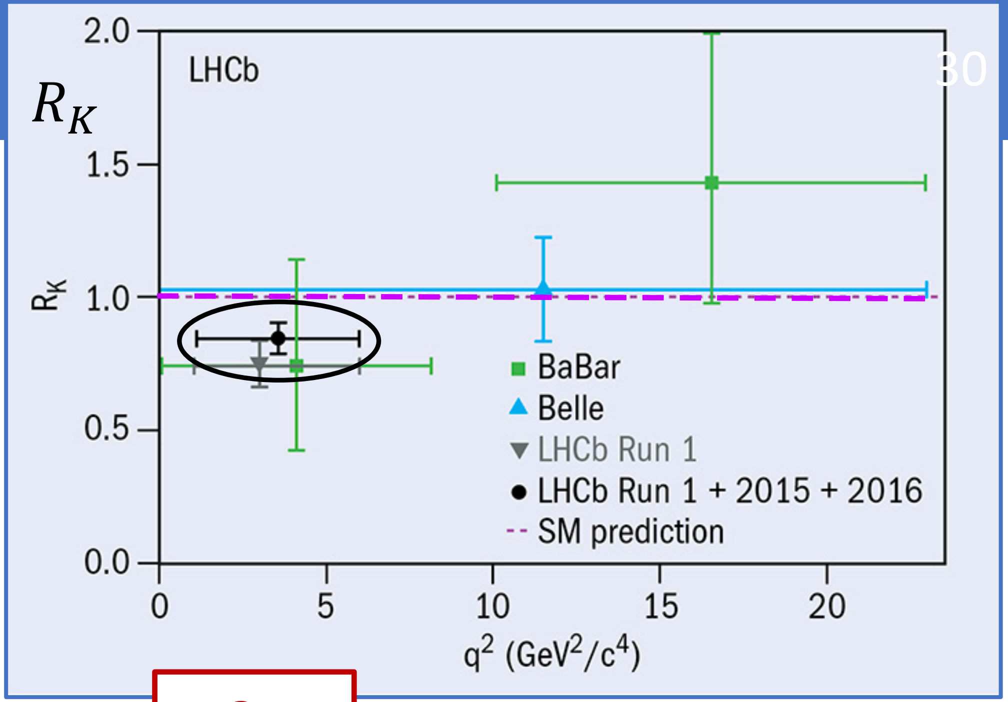
2) $b \to s\, l^+ l^-$

Suppressed neutral current

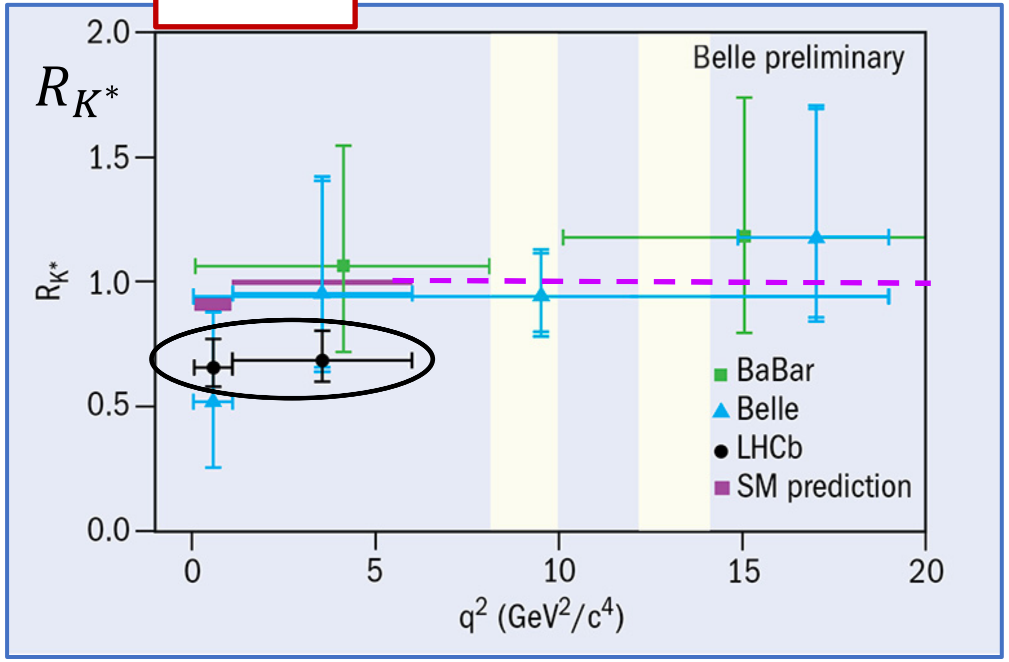



$$R(K) = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

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




~ 3 $\sigma$

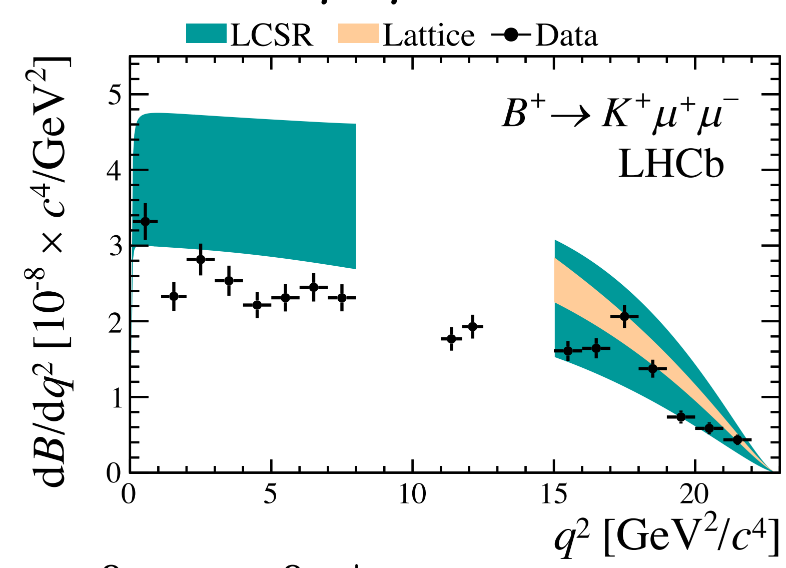



*Small* effect ➔ Particles of 1st and 2nd generation

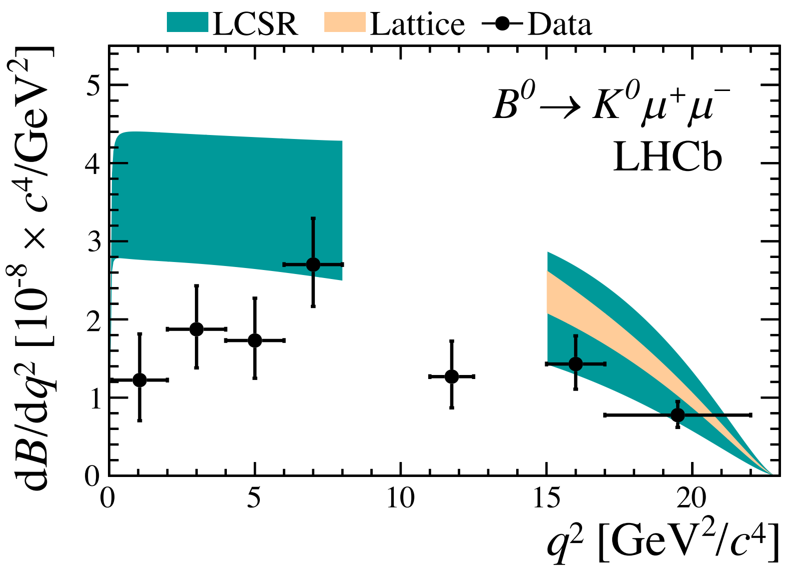
# Branching fractions of Rare Decays: $b \to s\,\mu^+\mu^-$



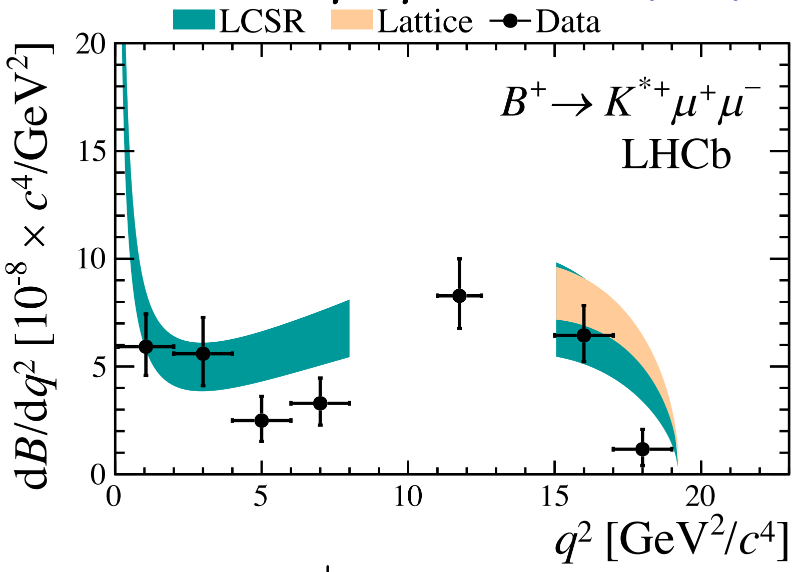
$B^+ \to K^+\mu^+\mu^-$ JHEP 06 (2014) 133



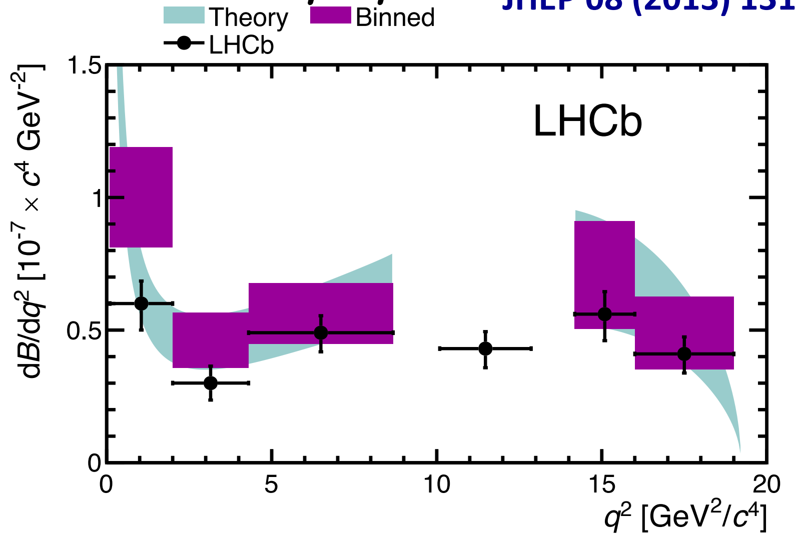

$B^0 \to K^0\mu^+\mu^-$ JHEP 06 (2014) 133



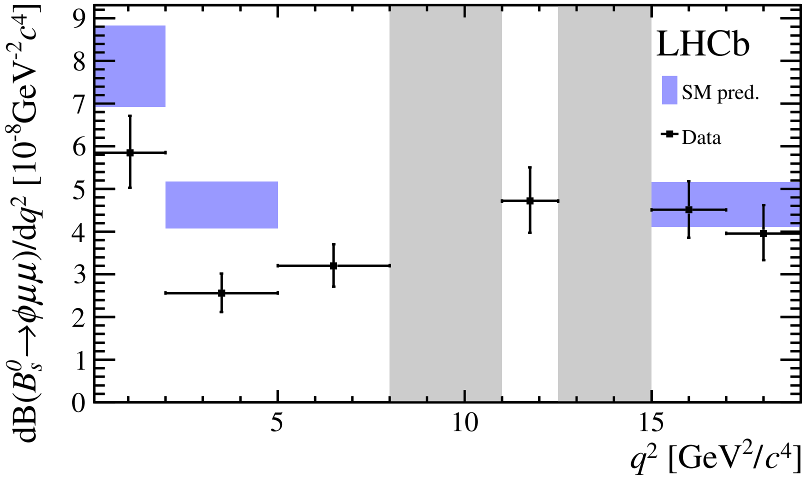

$B^+ \to K^{*+}\mu^+\mu^-$ JHEP 06 (2014) 133



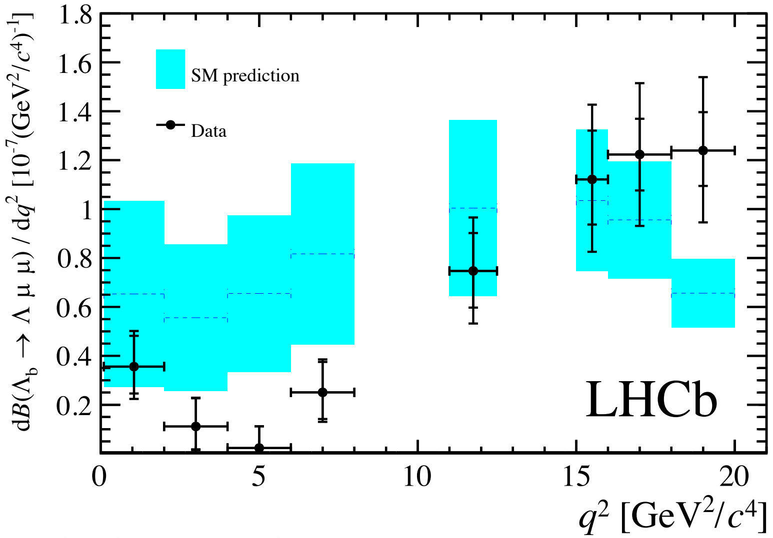

$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 08 (2013) 131




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

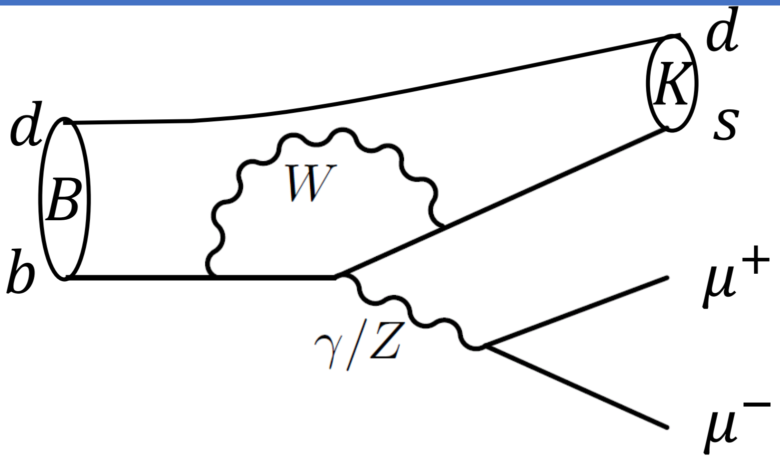


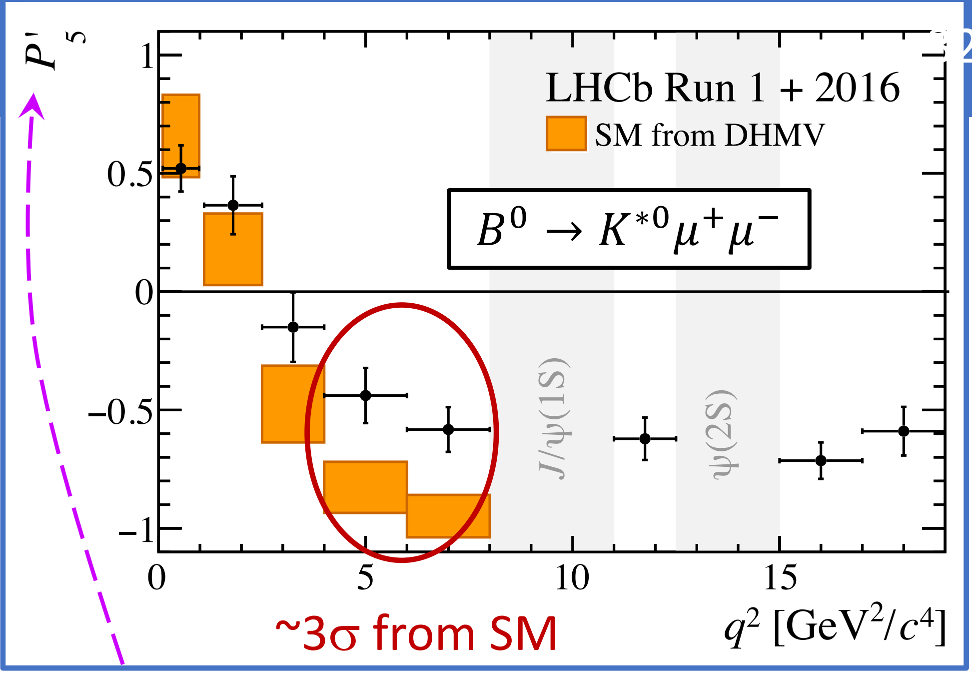

$\Lambda_b \to \Lambda\mu^+\mu^-$ JHEP 06 (2015) 115




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

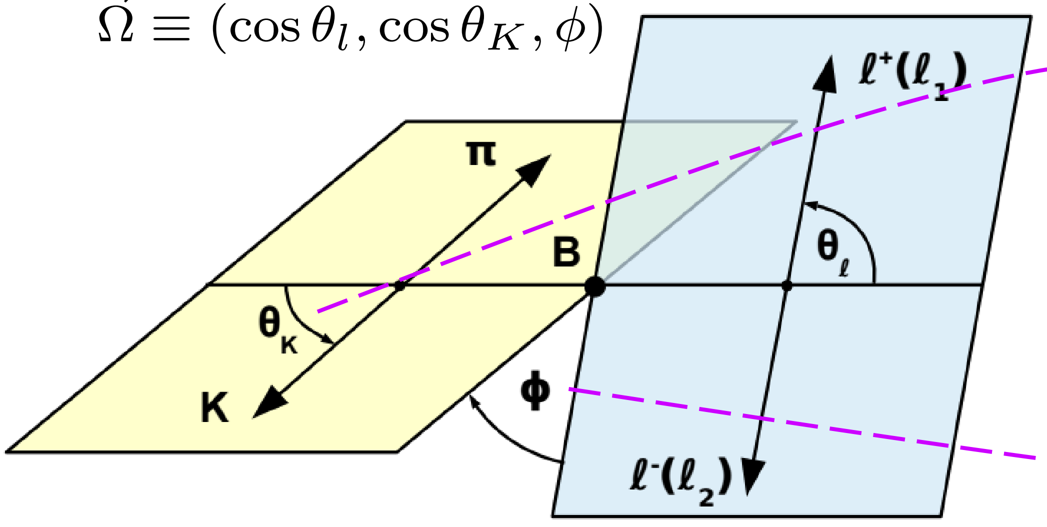
# Variable $P_5'$ in $B^0 \to K^{*0}\mu^+\mu^-$



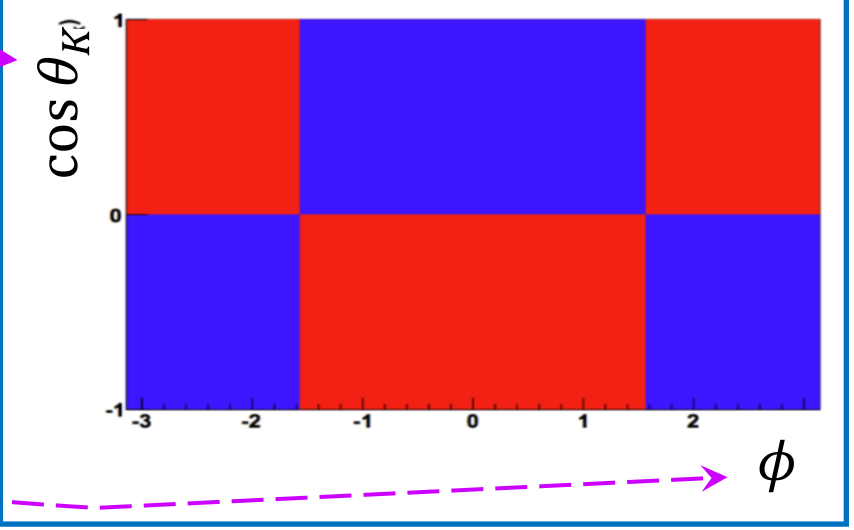




- LHCb: Study angular distribution of the produced particles

$$\vec{\Omega} \equiv (\cos\theta_l, \cos\theta_K, \phi)$$




$P_5'$: count blue minus red:

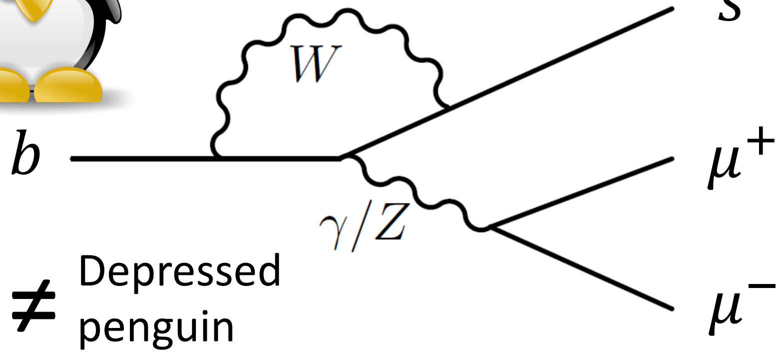


# Global Fit of $b \to s\,\mu^+\mu^-$



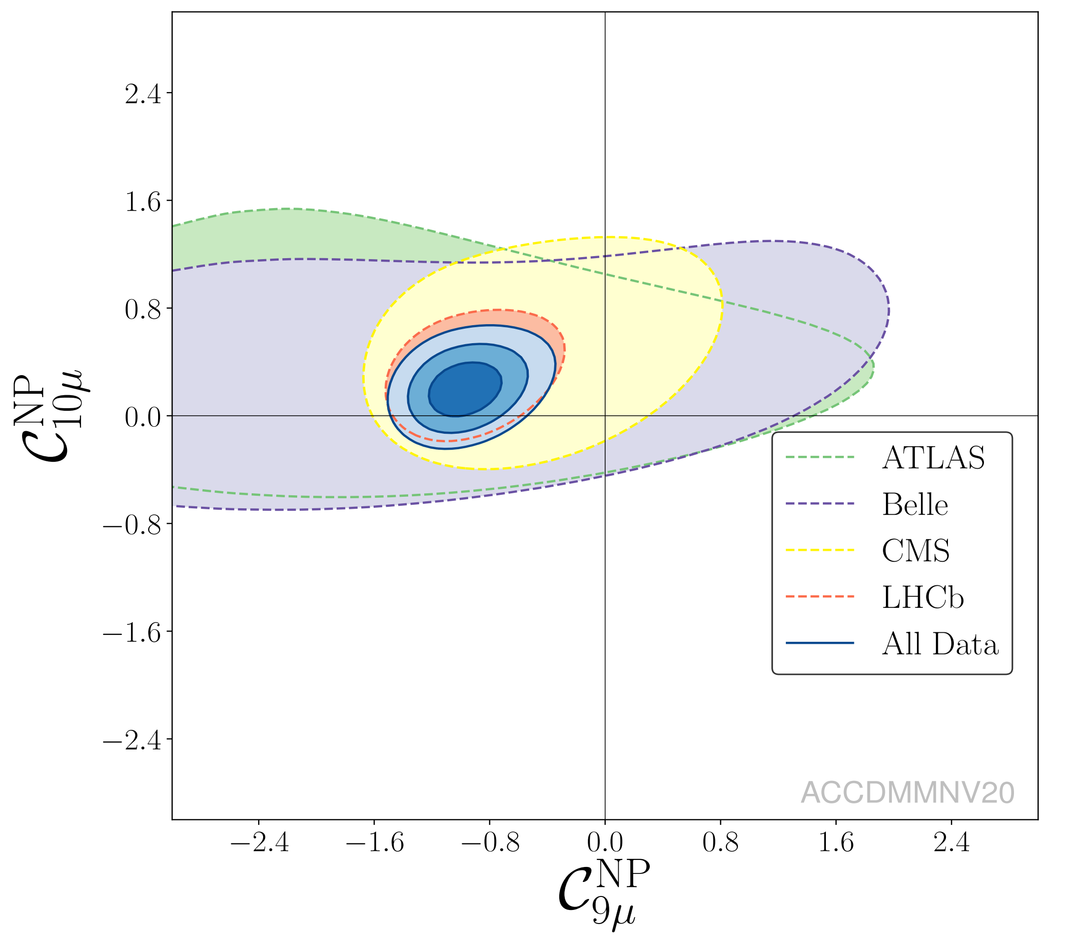
$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} C_i O_i$$

- 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

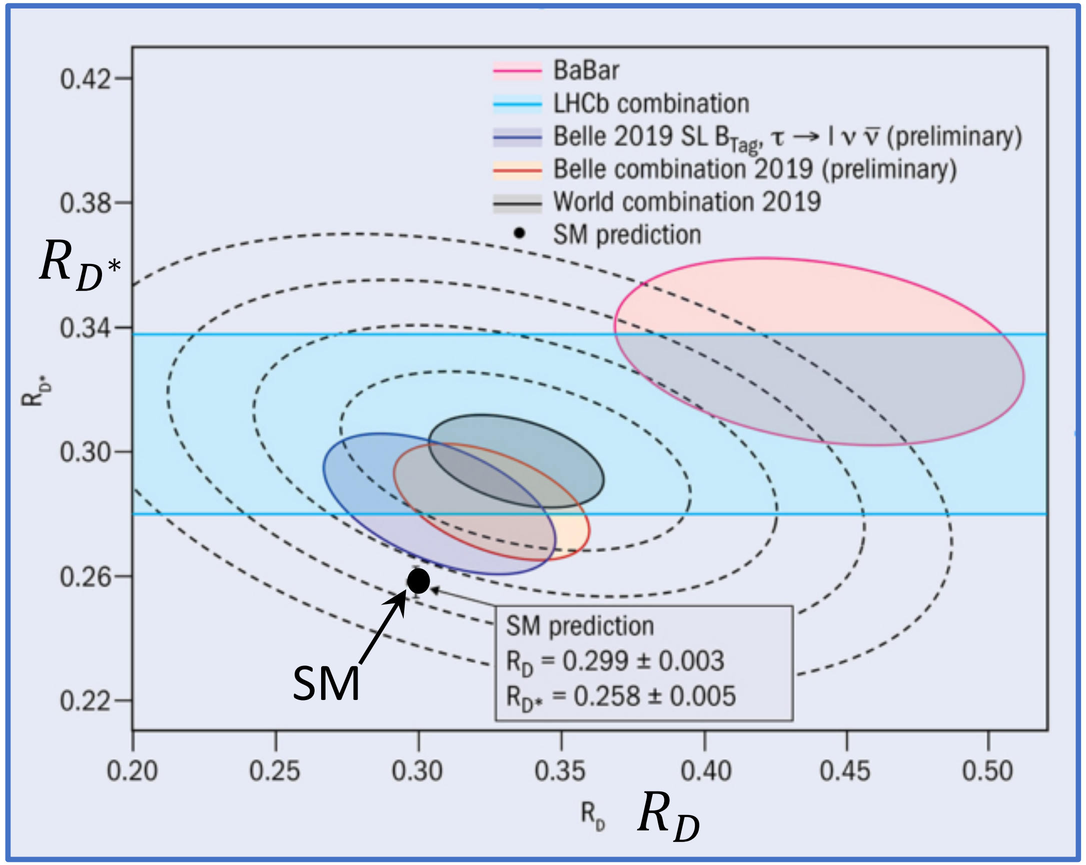
Weak Effective couplings: $C_9^{NP}$ , $C_{10}^{NP}$



# Interpretation as a single cause: contradicting effects?

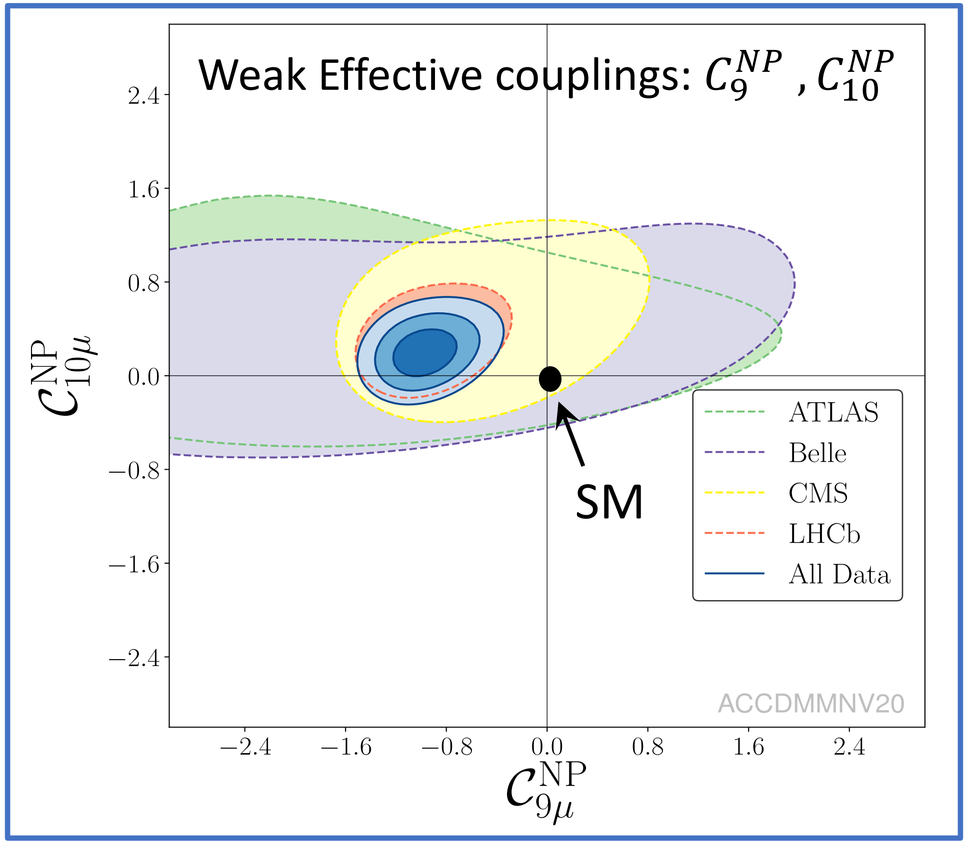
1) $b \to c\, l\, \nu$: $R_D\,, R_{D^*}$

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




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

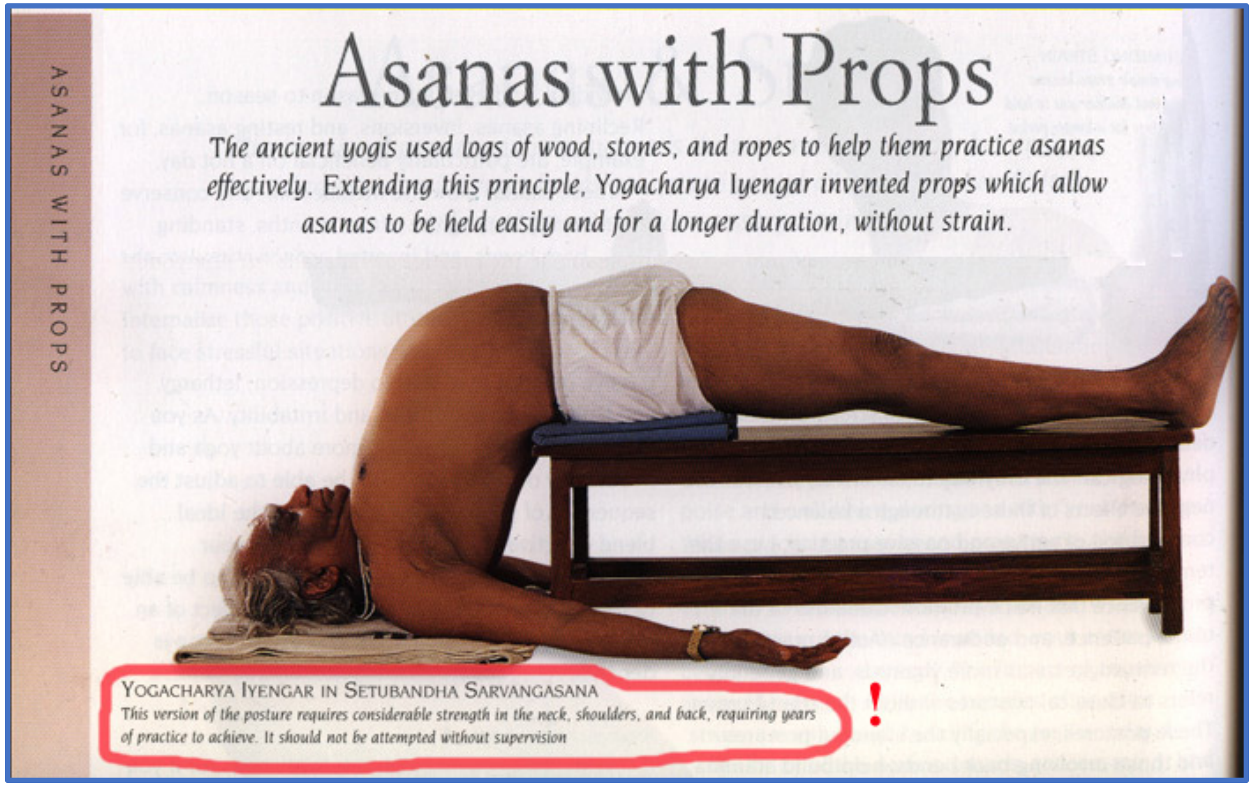
- ~ 25% effect at ***suppressed penguin*** level
  - ***Small*** effect; Small ***2nd*** generation couplings




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?

# Universality?


ASANAS WITH PROPS

Asanas with Props

*The ancient yogis used logs of wood, stones, and ropes to help them practice asanas effectively. Extending this principle, Yogacharya Iyengar invented props which allow asanas to be held easily and for a longer duration, without strain.*

YOGACHARYA IYENGAR IN SETUBANDHA SARVANGASANA

*This version of the posture requires considerable strength in the neck, shoulders, and back, requiring years of practice to achieve. It should not be attempted without supervision*

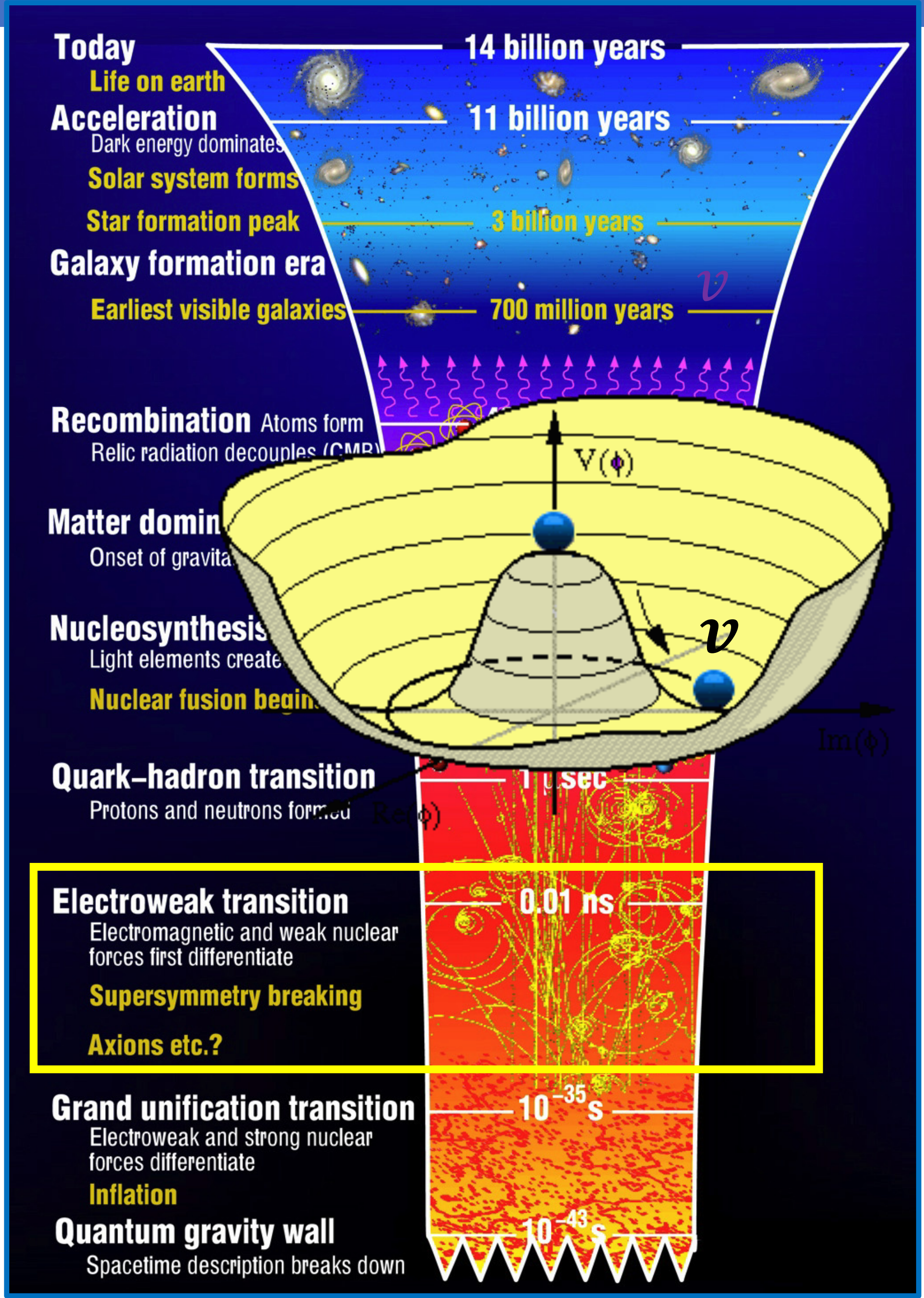
!

…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:
  - $G\,(\overline{b'}_L\,\gamma_\mu\,b'_L)\;(\overline{\tau'}_L\,\gamma^\mu\,\tau'_L)$



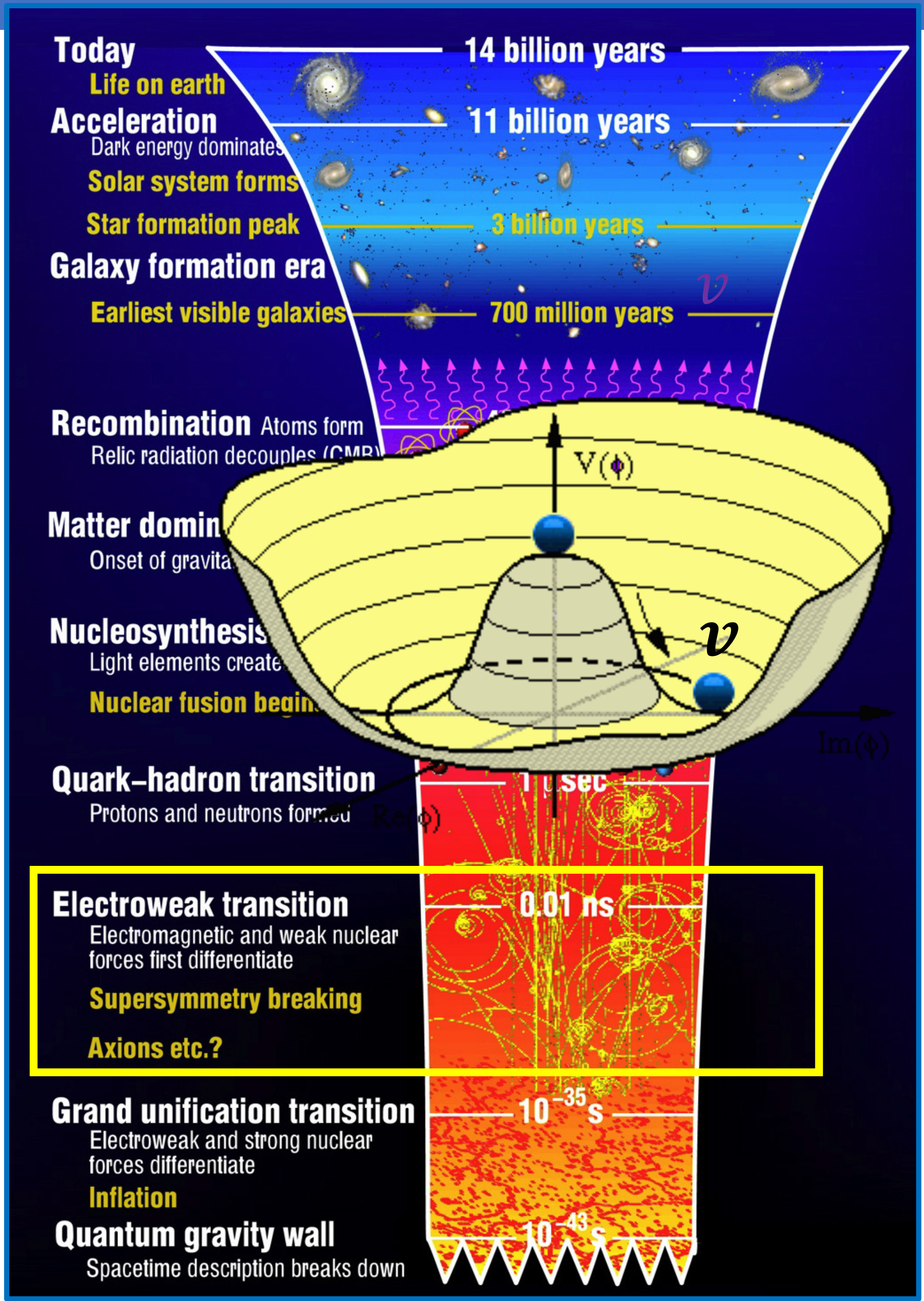
# Where does GGL operator come from?



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

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

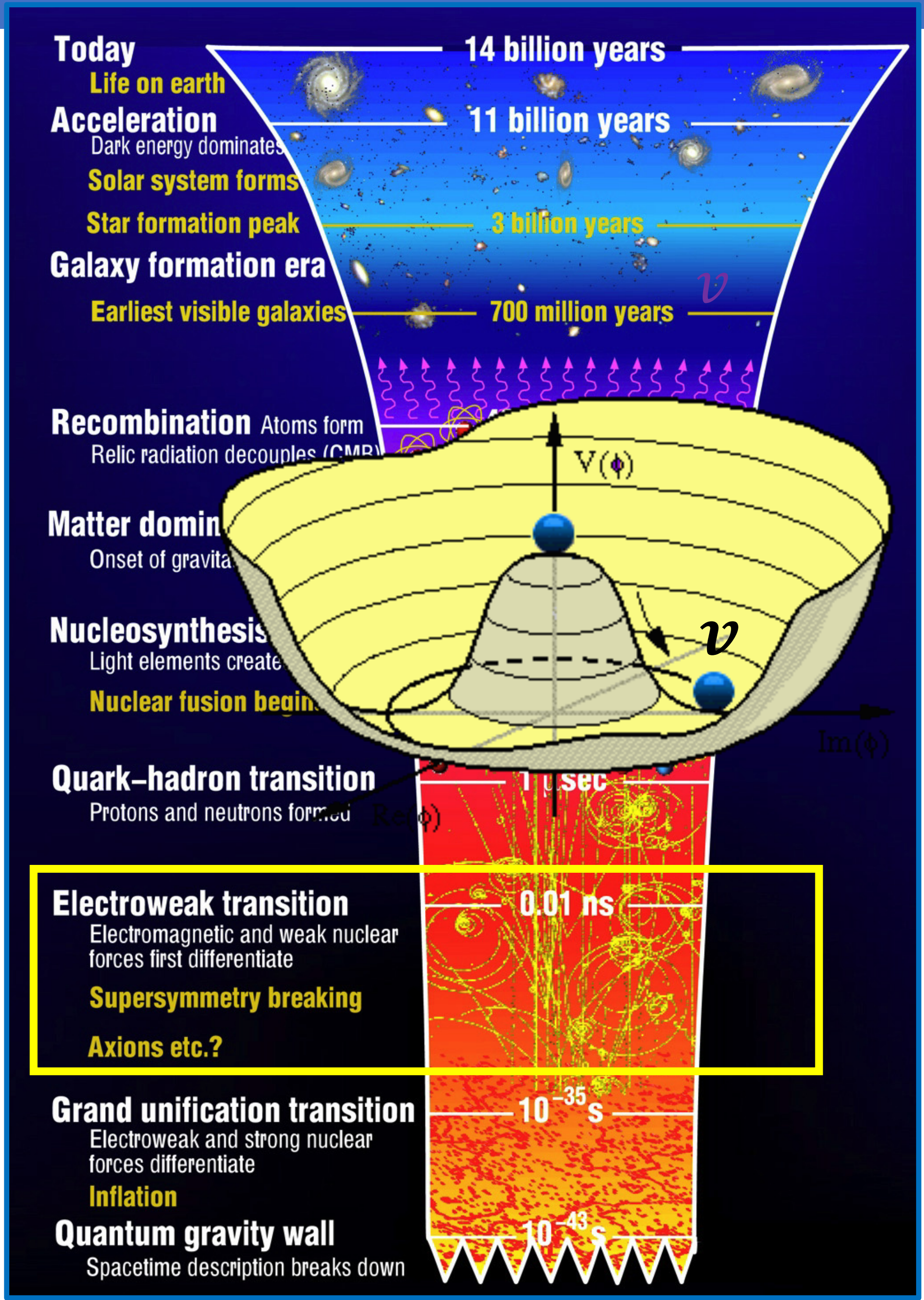
- CKM Hierarchy suggests:
  - $V^d_{33} \simeq V^l_{33} \simeq 1$ and $V^{d,l}_{31} \ll V^{d,l}_{32} \ll 1$
- GGL operator becomes:
  - $G\,\left[V^d_{33}\,V^{*d}_{32}\,|V_{32}|^2\right]\,(\bar{b}_L\,\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L\,)$
- *Large* effect in 3$^{rd}$ generation, *small* effect in 2$^{nd}$ 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:
    - $O_S^{NP} = G_S\,(\overline{Q'}_L\,\gamma_\mu\,Q'_L)\;(\overline{L'}_L\,\gamma^\mu\,L'_L)$
  - Triplet neutral current + two charged currents:
    - $O_T^{NP} = G_T\,(\overline{Q'}_L\,\gamma_\mu\,\sigma^I Q'_L)\;(\overline{L'}_L\,\gamma^\mu\,\sigma^I L'_L)$

- 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

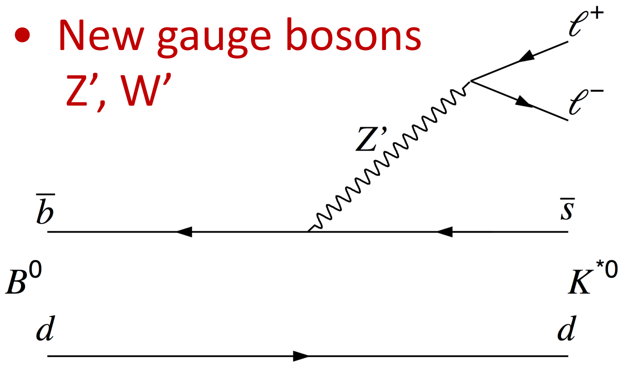


# Which particle/field could it be?

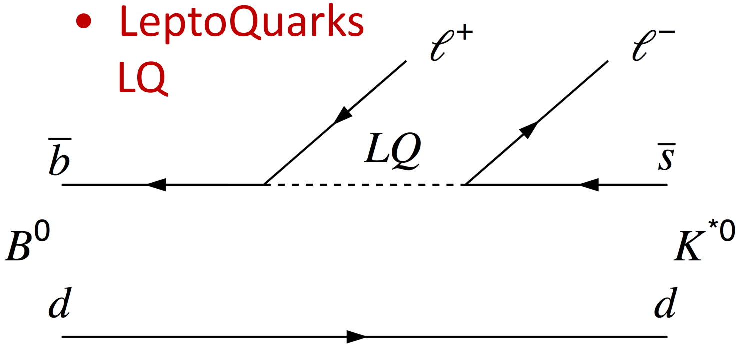


- LFNU is currently a hot topic, many theory papers, see eg. arXiv:1706.07808 for overview.

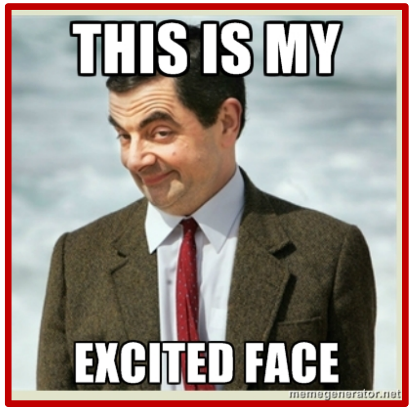
- New gauge bosons Z', W'

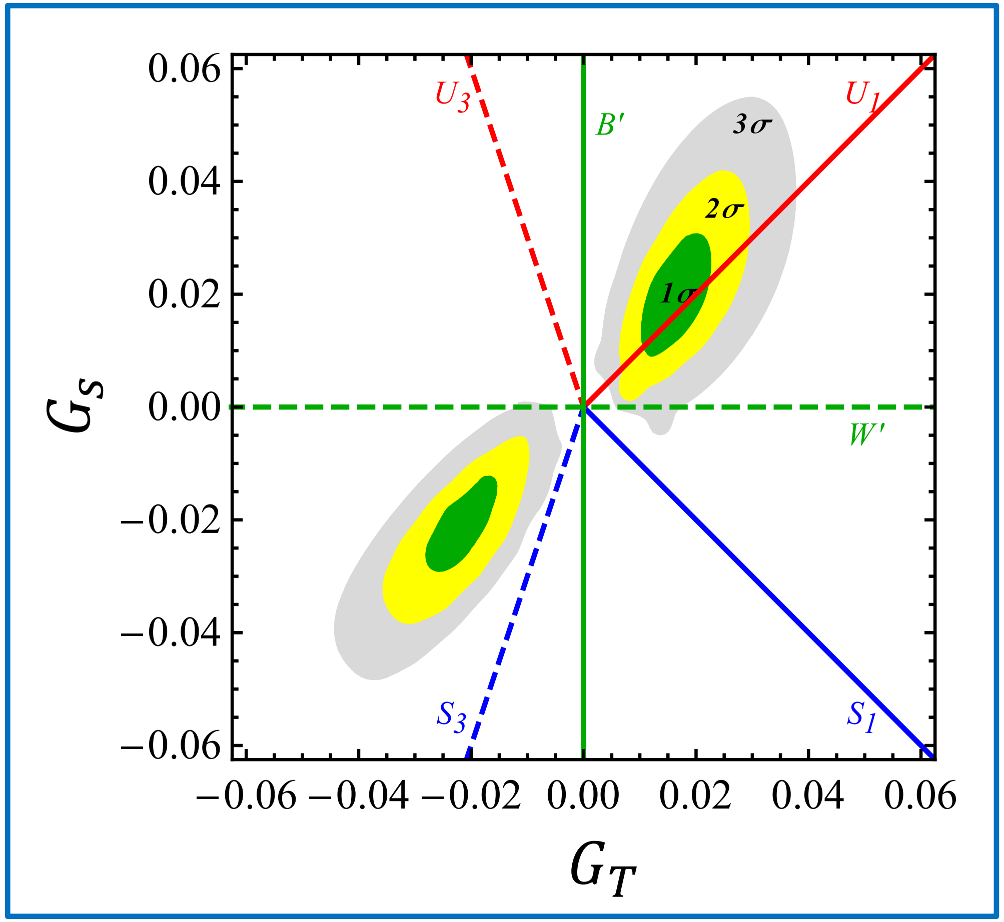



- LeptoQuarks LQ




- 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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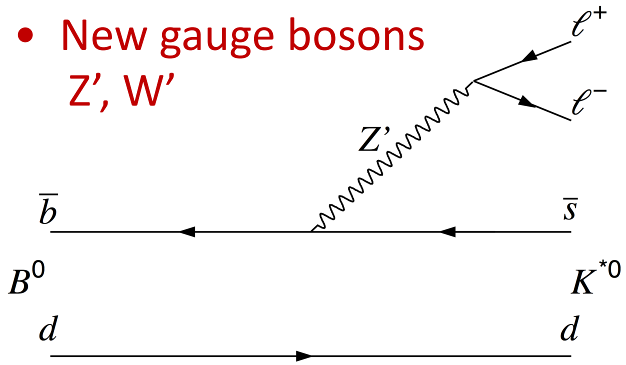
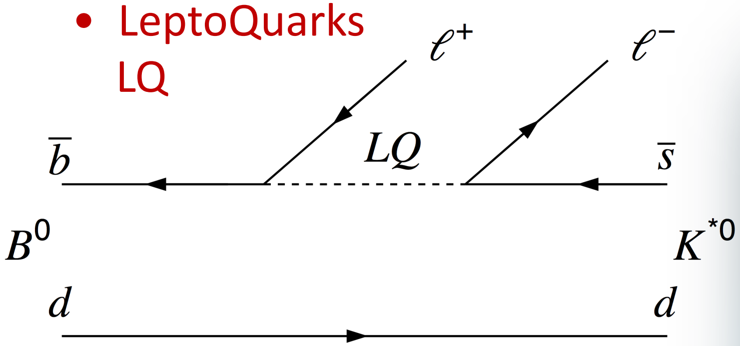



- LeptoQuarks
  LQ

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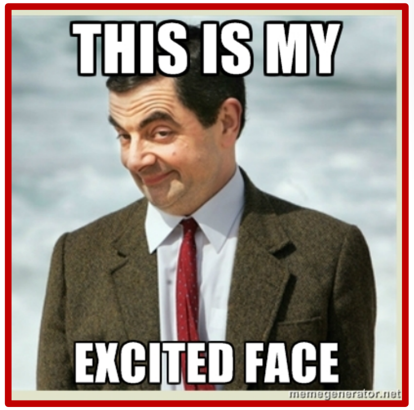
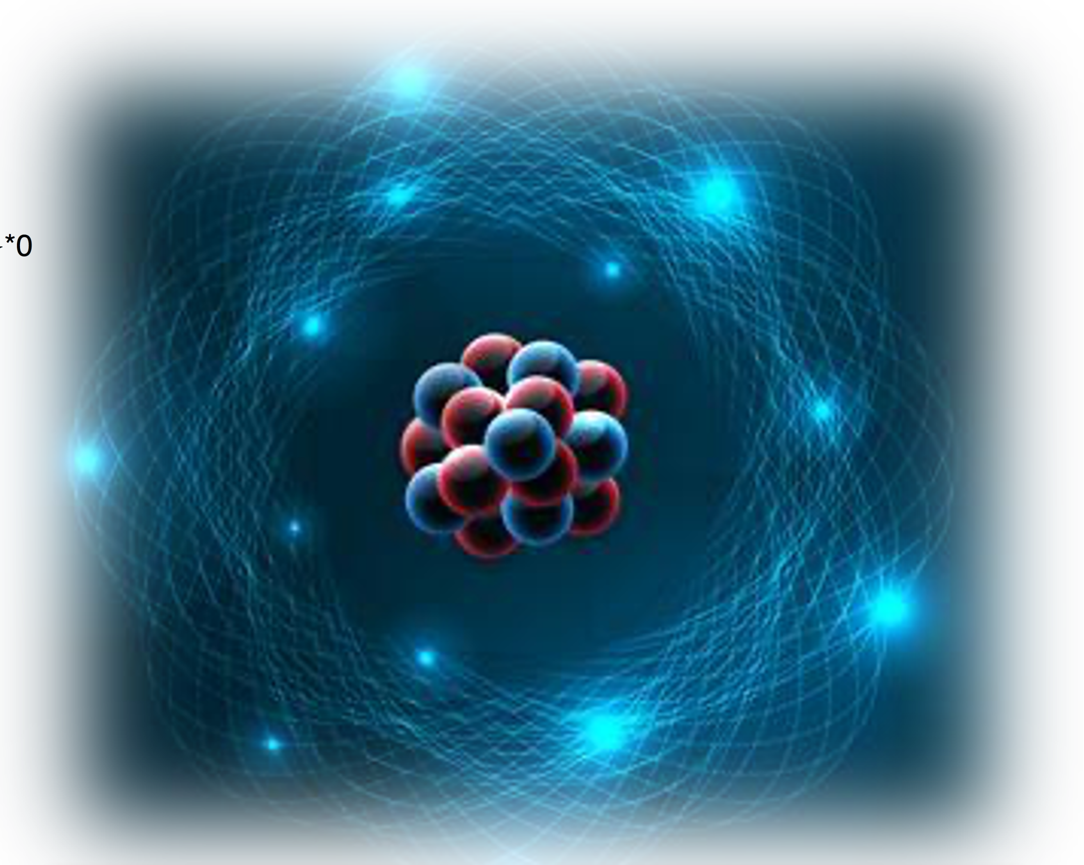


LQ relates charge of leptons to quarks!
Towards an understanding why atoms are electrically neutral?

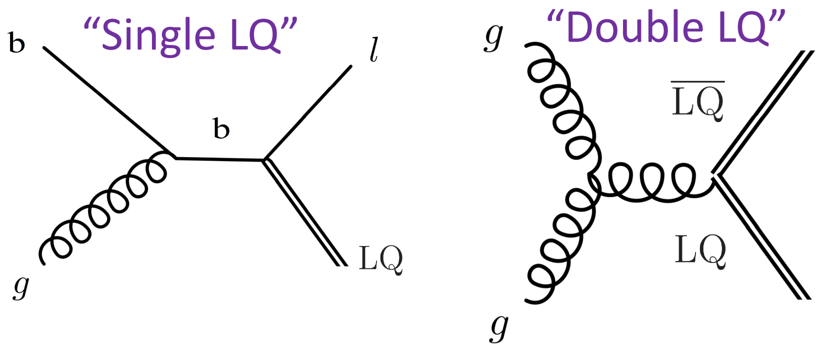
# Recent: direct search for specific 3rd generation leptoquarks

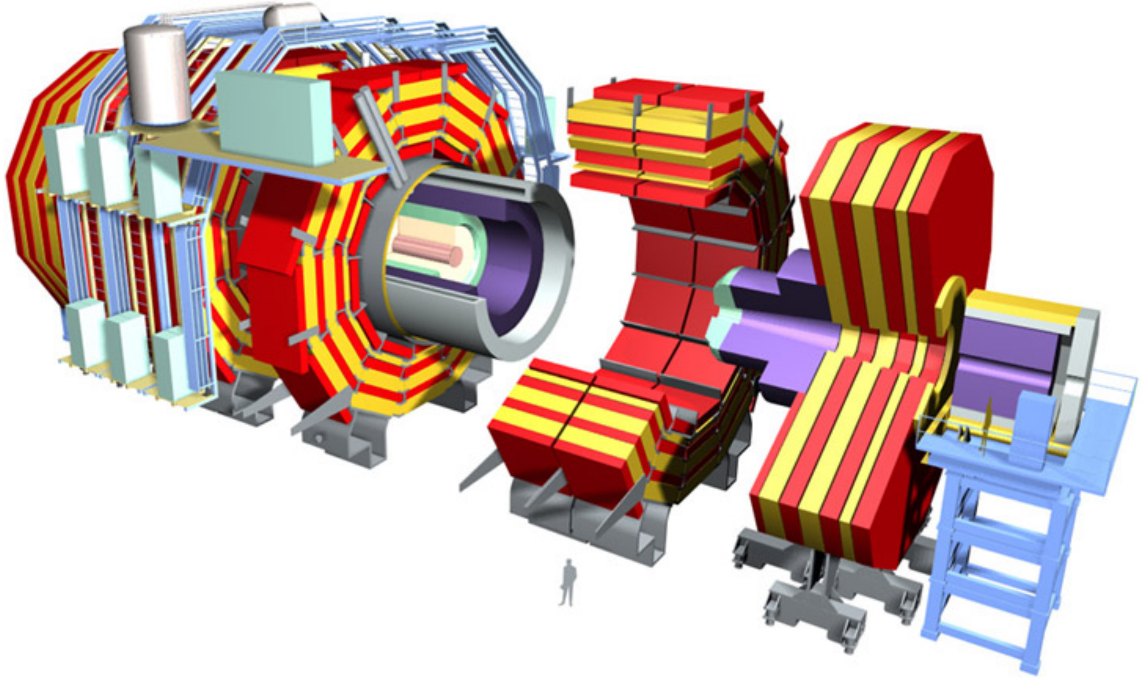
- CMS search for direct LQ production, arXiv:2012.04178, 7 Dec 2020

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

  (depending on the model parameters)

- LQ production at LHC:



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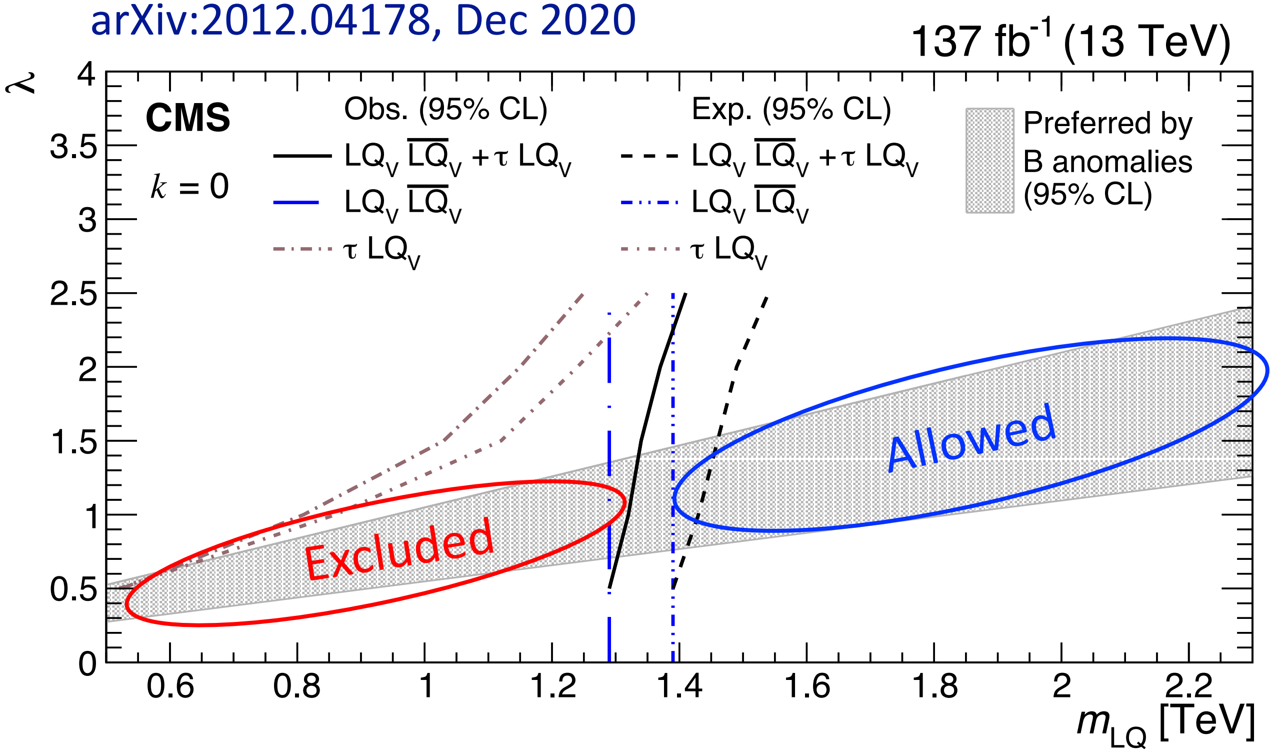


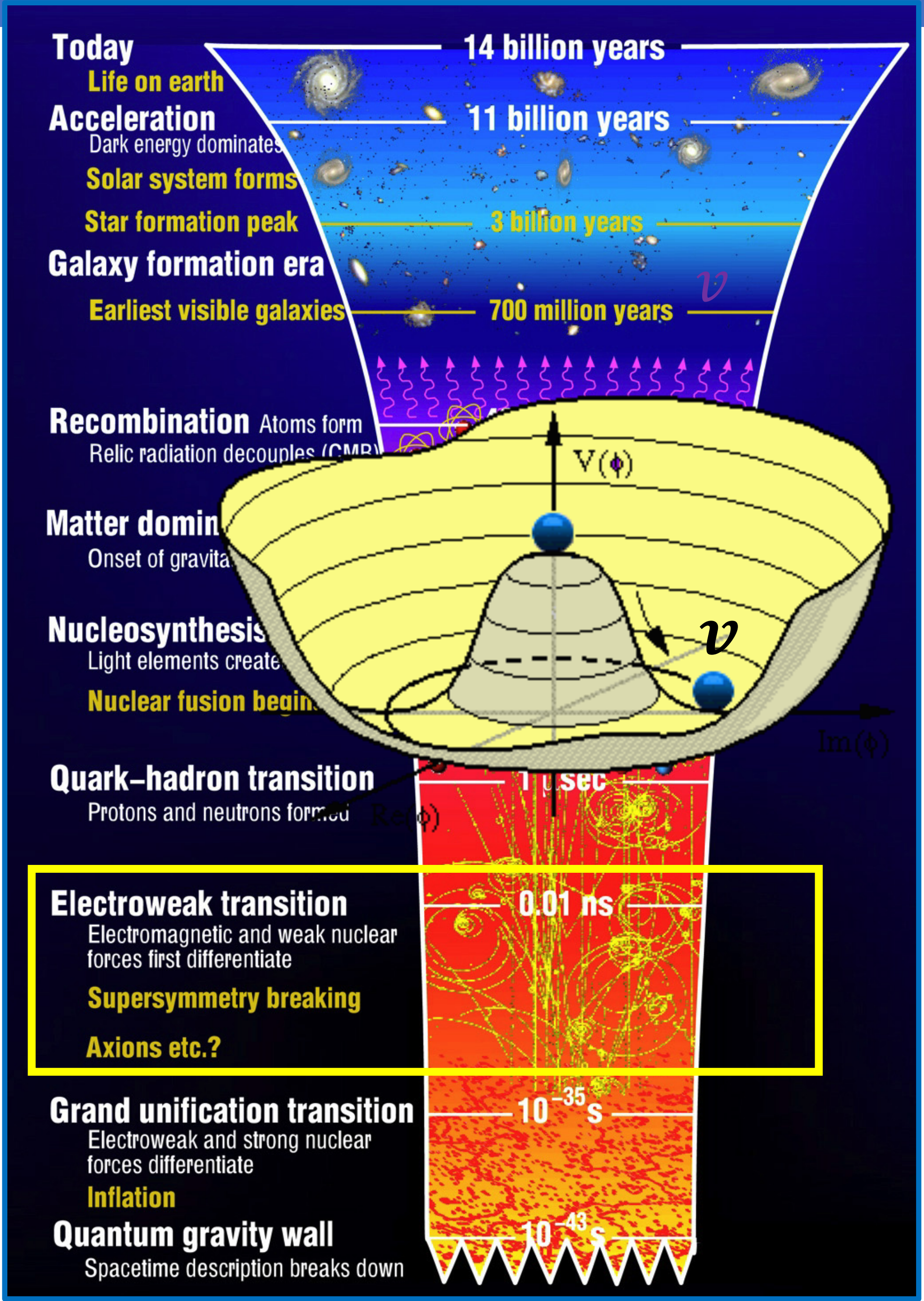
# Soon more news in Winter conferences…("Moriond")

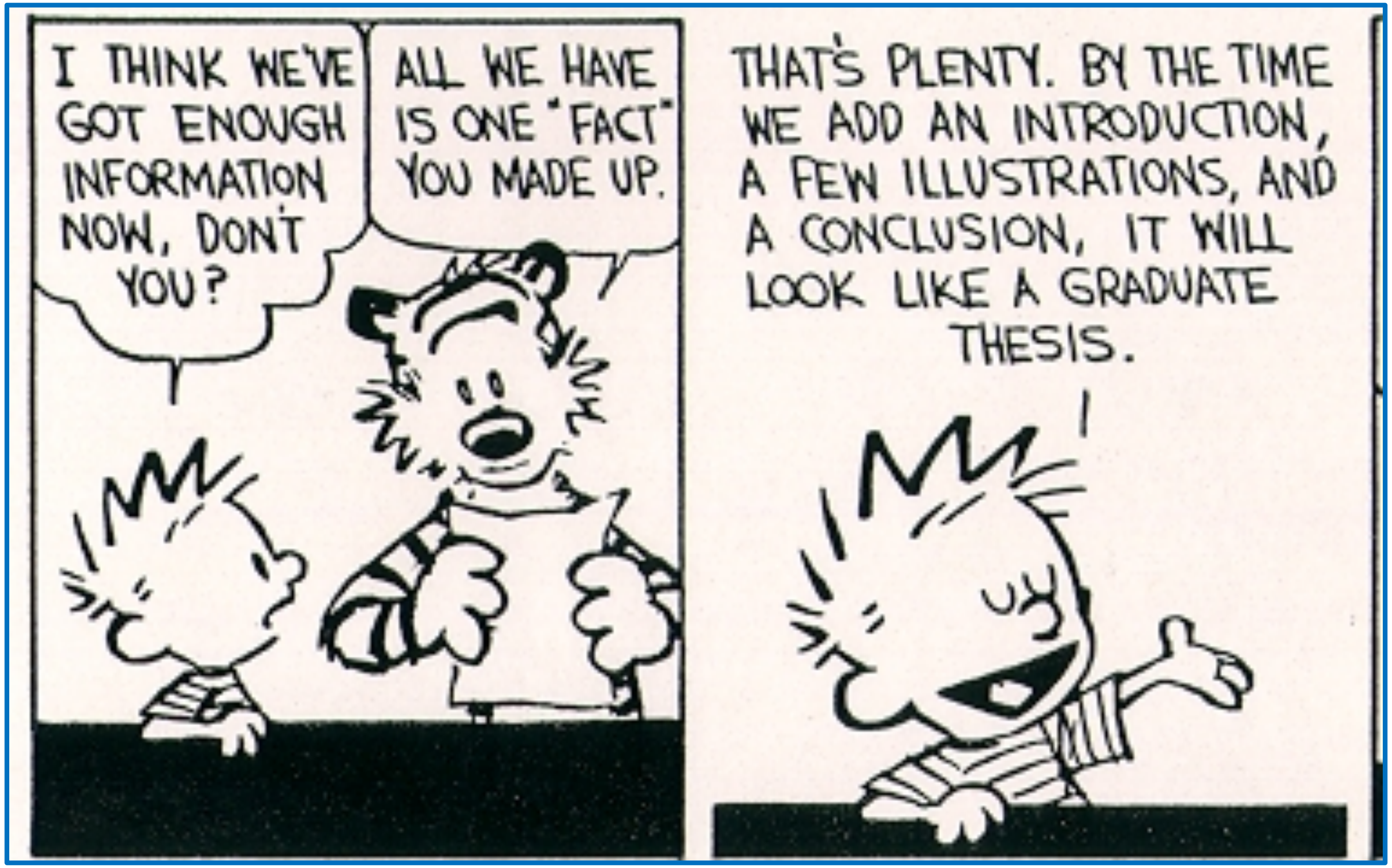


# Conclusions

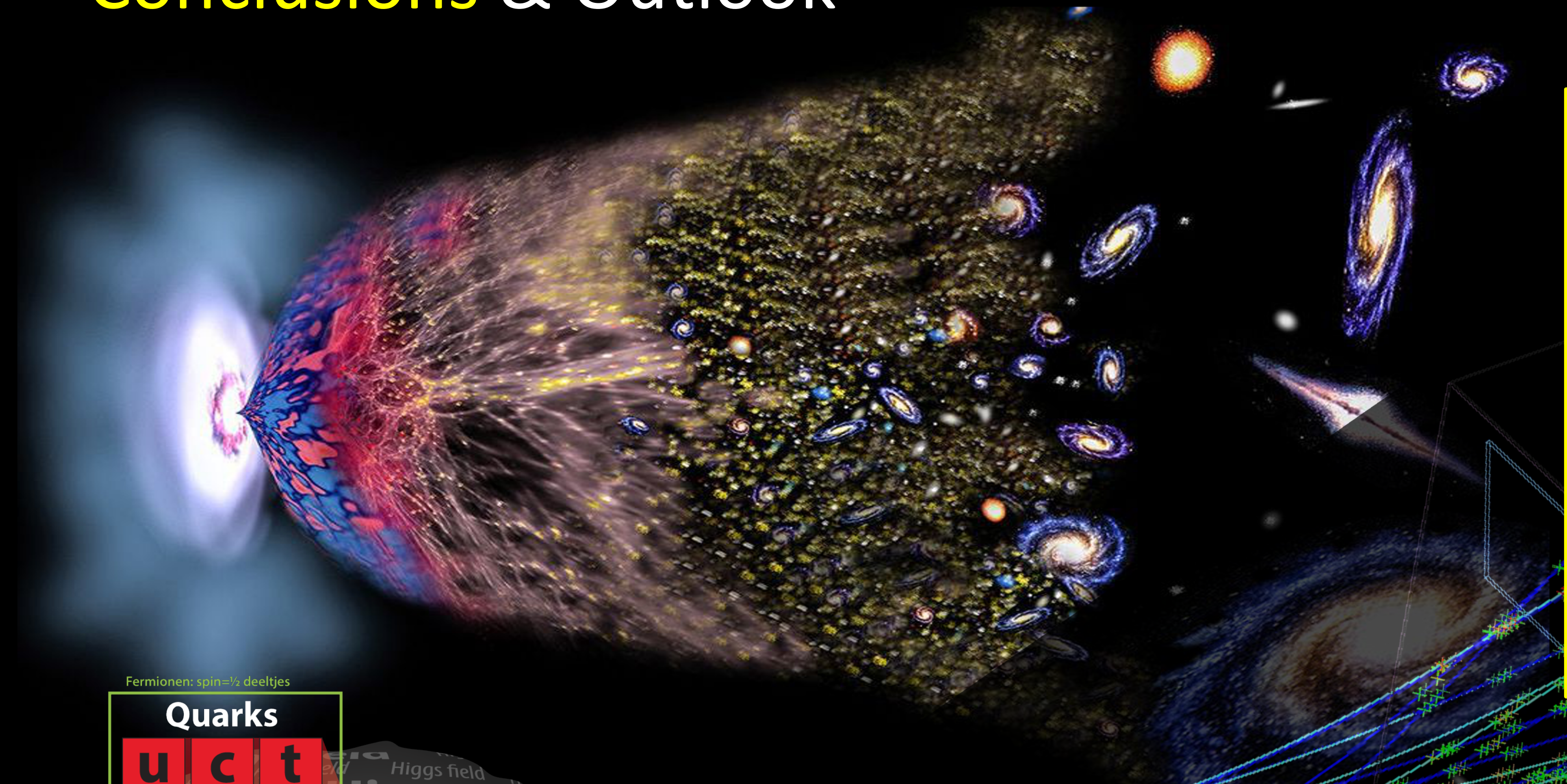


- CP Violation requires three generations of particles.
  - Does ***not*** explain the matter antimatter asymmetry in the universe.
  - LHC has ***not yet directly*** observed new massive particles.
- Forces are flavour universal across particle generations.
- Higgs is strongly non-universal, coupling 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.

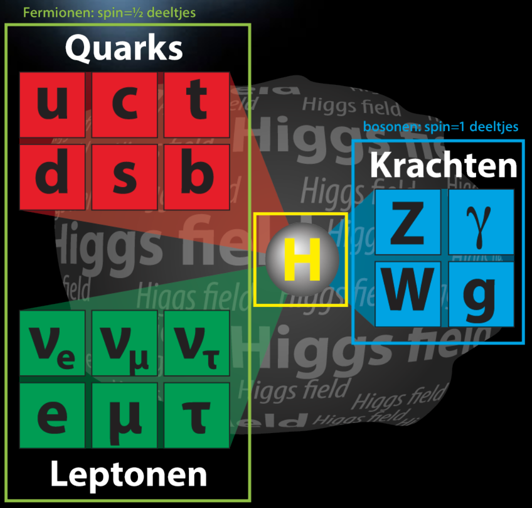


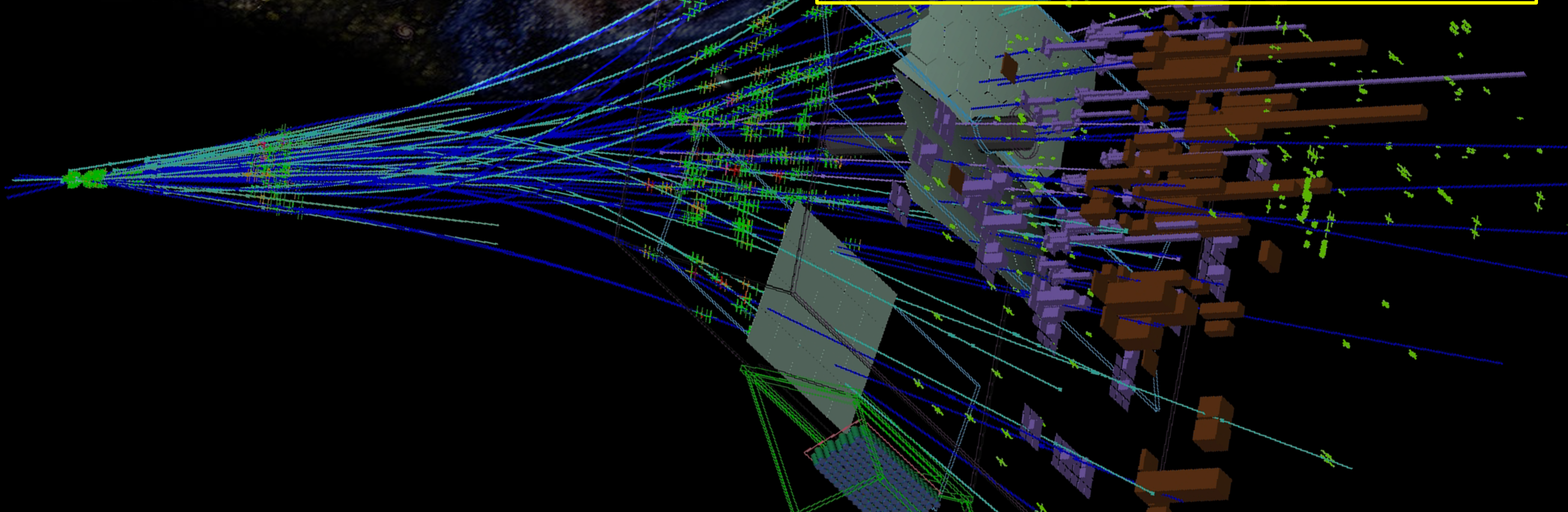

I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

# 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…