HASCO Summer School 2021

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Flavour Physics: Precision Tests and Anomalies

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Heisenberg-Programm Deutsche Forschungsgemeinschaft DFG

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Quizz

Discoveries and precision measurements

What was the last discovery of a fuindamental particle / force that was not hinted at indirectly?

Discoveries and precision measurements

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1937

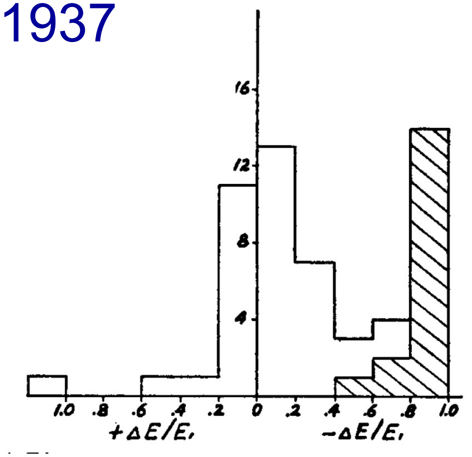
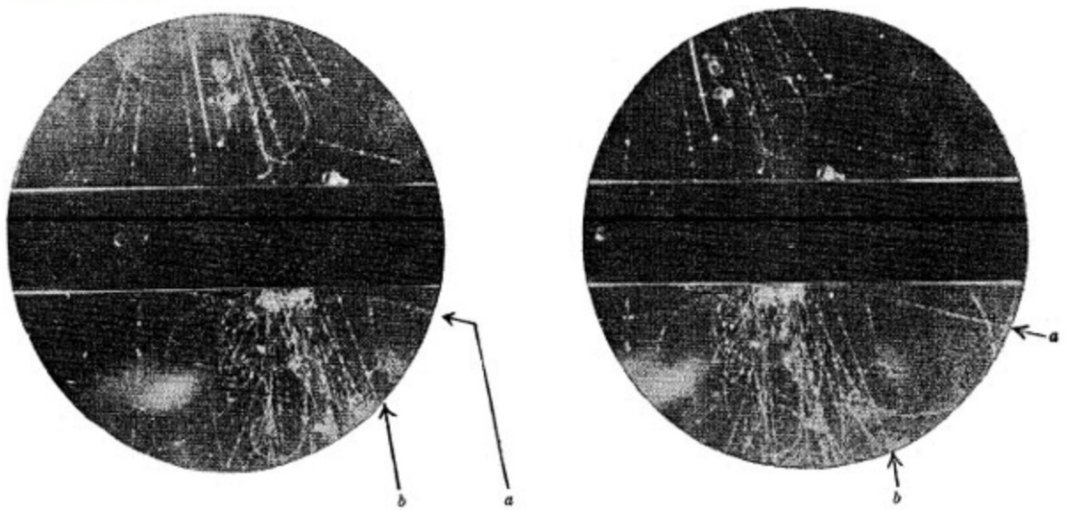
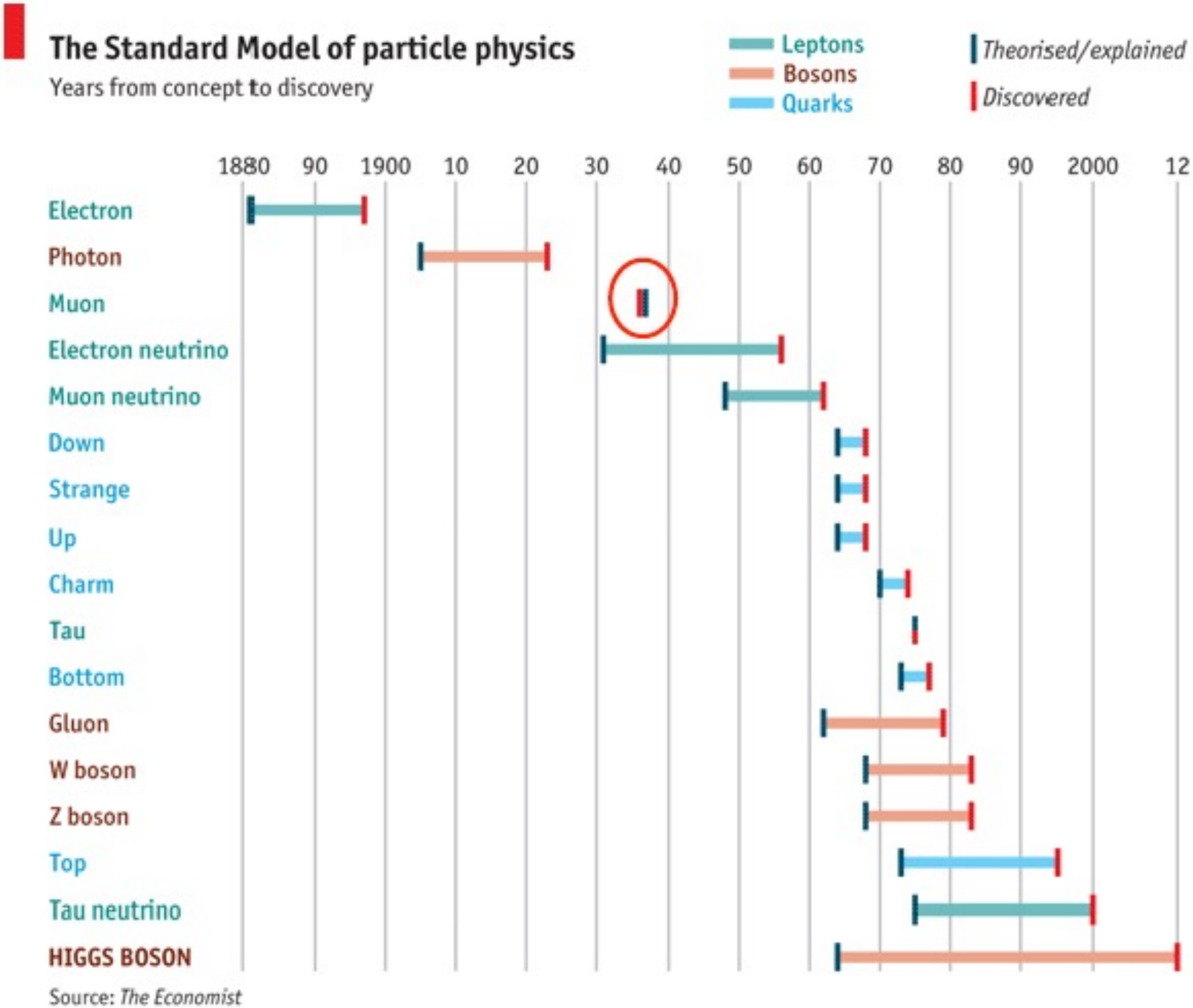


Figure 2: Distribution of fractional losses in 1 cm of platinum.

20 December 1947



Expected and unexpected discoveries



See also C. Doglioni

Indirect searches for New Physics

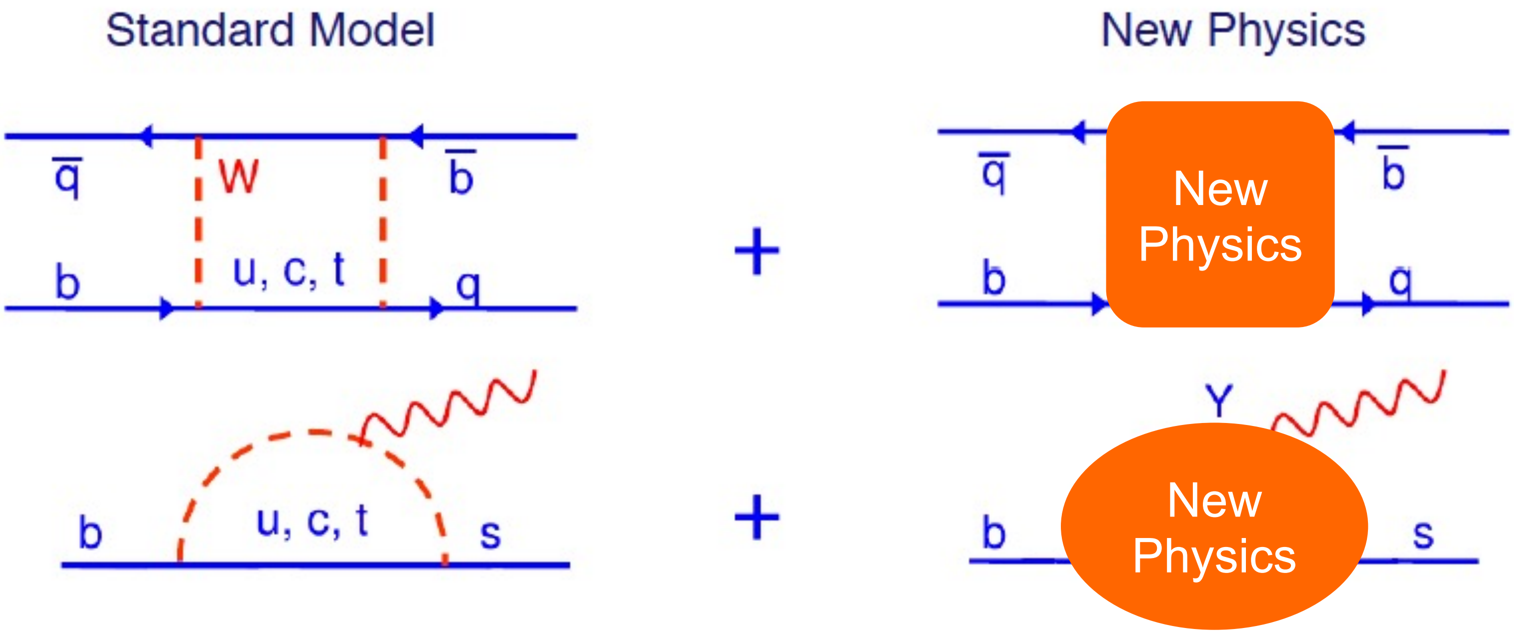
- High **energy**:
  "real" new particles can be produced and discovered via their decays
  - Discovery of the Higgs boson at the LHC → completion of the SM
  - **Tested scale : <10TeV**

- High **precision**:
  "virtual" new particles can be seen in quantum loops
  - Higher mass scale reachable (up to **~100TeV**)

Direct and indirect searches are both needed,
both equally important,
and complement each other

Searches for New Physics in Flavour

Contribution of New Physics as correction to the Standard Model



$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda^2}} \right)$$

What is the scale of λ_{NP}? What is its coupling C_{NP}?

GIM Mechanism

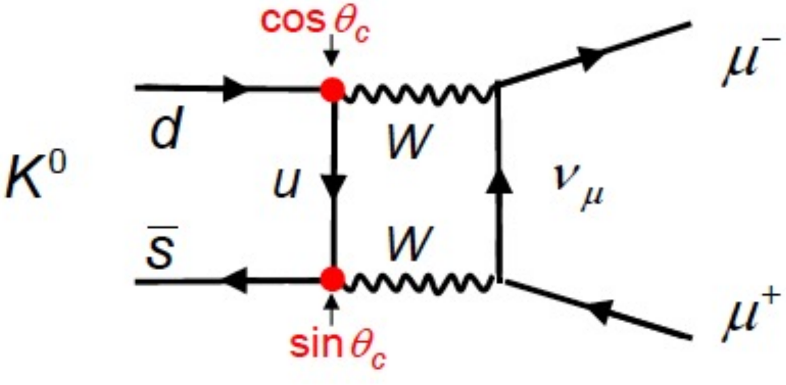
Observed branching ratio $K^0 \rightarrow \mu\mu$

$$\frac{BR(K_L \rightarrow \mu^+\mu^-)}{BR(K_L \rightarrow all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

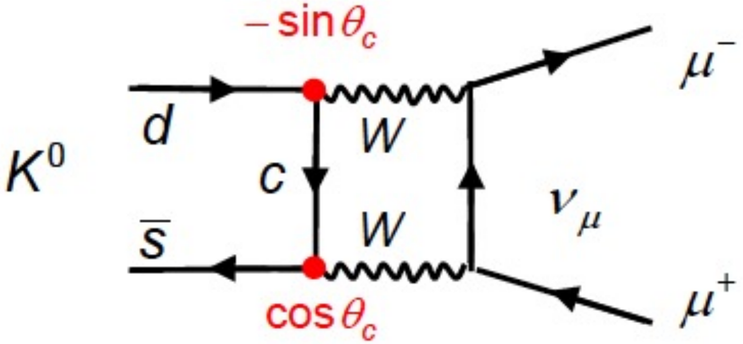
In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up-type quark, additional Feynman graph cancels the "u box graph".



$M \sim \sin\theta_c \cos\theta_c$

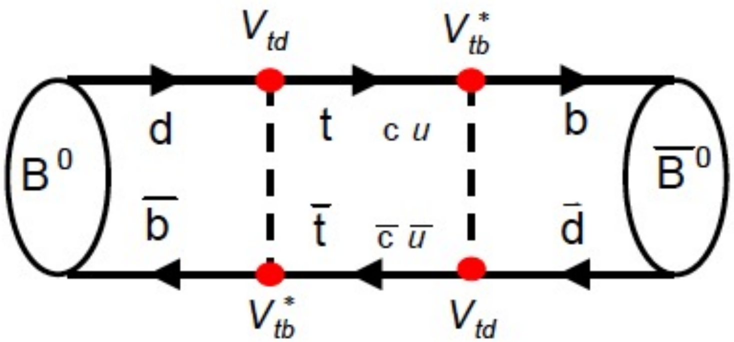


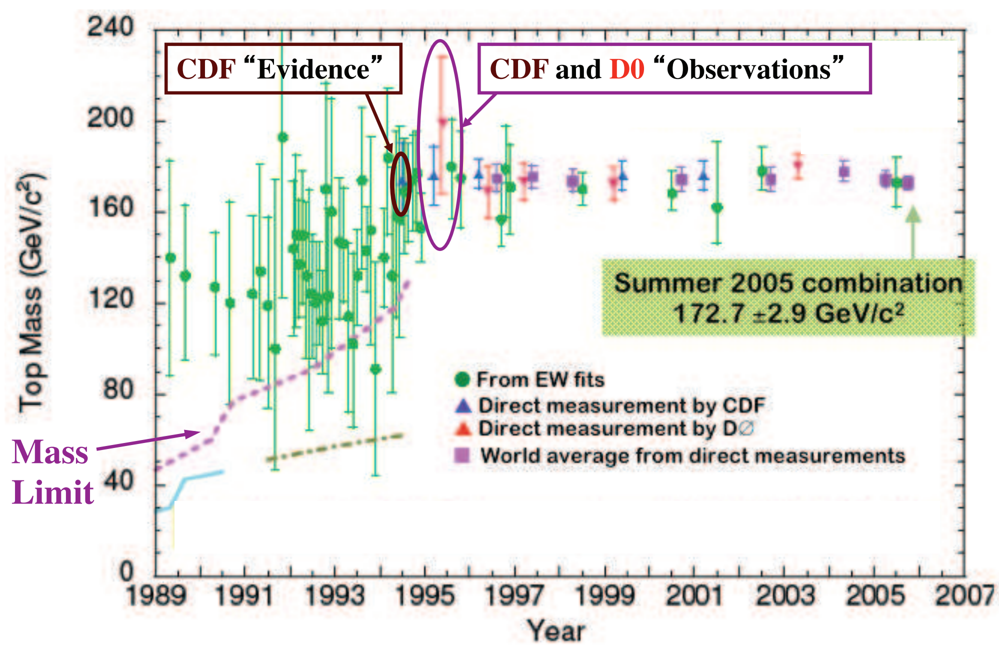
$M \sim -\sin\theta_c \cos\theta_c$

Examples from the past II

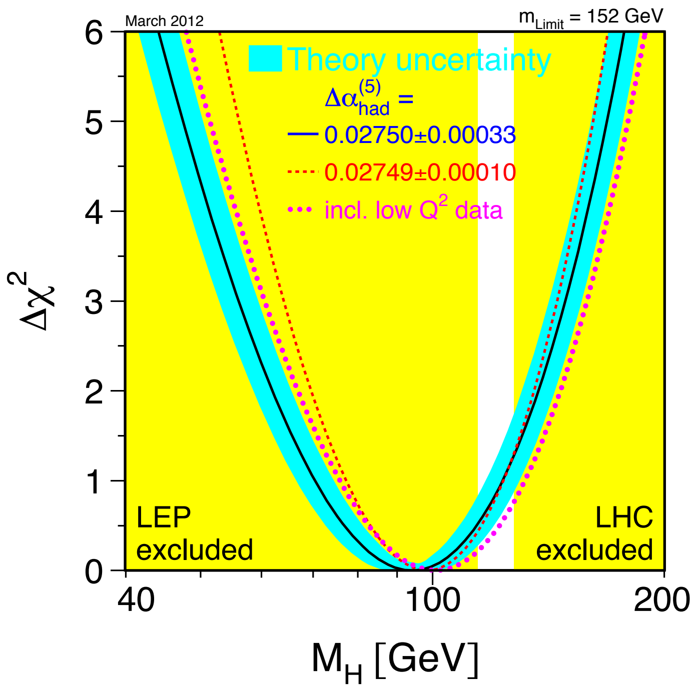
ARGUS Experiment, 1987:

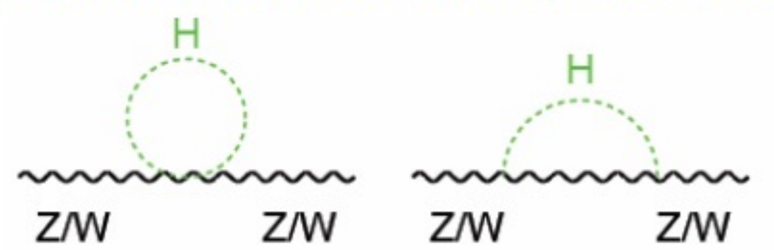
Observation of B^0-B^0 Oscillation → $m_t > 50$ GeV





- Higgs knowledge 2012:
  Electroweak precision measurements at Z-pole and direct searches at LEP, Tevatron & LHC

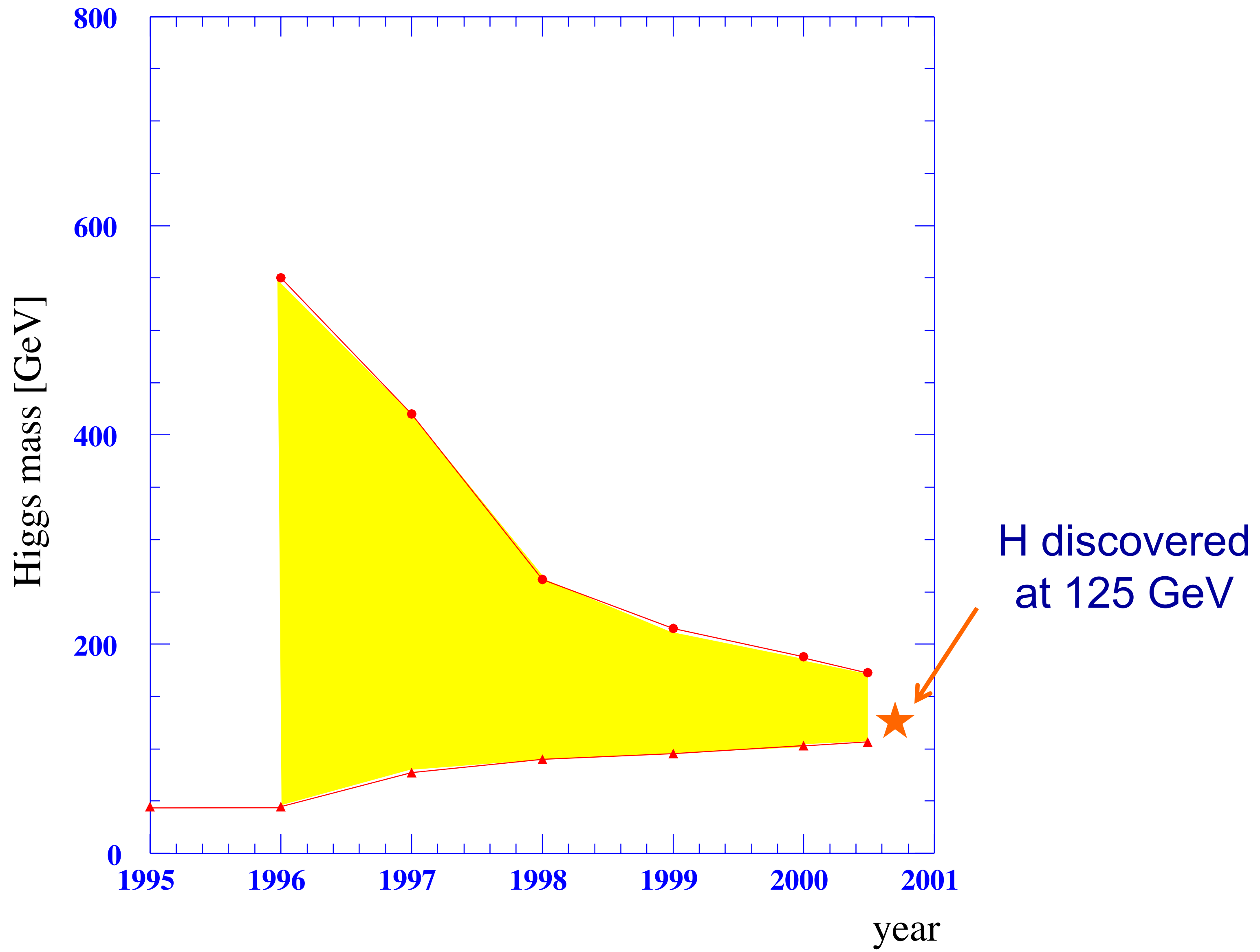




$$M_{\mathrm{H}} < 152\ \mathrm{GeV} \quad (95\%\mathrm{C.L.})$$

$$M_{\mathrm{H}} = 94^{+29}_{-24}\,\mathrm{GeV}$$

The way to the Higgs boson



What do we learn – process to discovery

- GIM: anomaly seen in data (too low $K^0 \to \mu^+\mu^-$ rate)
  → anomaly interpreted as "heavy new physics"
  → charm quark mass constrained to 1.5-2GeV
  → direct searches confirm predicted charm quark (1974, m_c~1.28GeV)

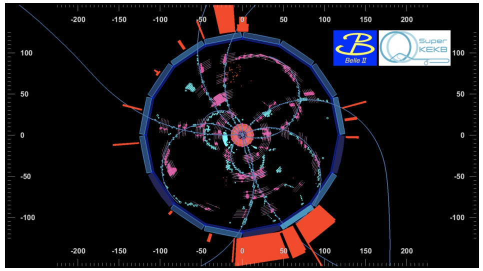
- Top: missing quark predicted by theory (CKM)
  → precision tests at DESY + LEP constrain mass m_t = 178±20 GeV
  → discovery at Fermilab 1995: m_t = 180±20 GeV

- Higgs postulated to explain fermion masses, prevent W scattering
  → precision measurements at LEP $m_H = 94\ ^{+29}_{-25}$
  → discovery at CERN (ATLAS, CMS) 2012: m_H = 125 ± 0.6

- Anomalies in data tend to show up first
  → with model assumptions theory predicts new physics / particles
  → these new particles need to be discovered to confirm model

Part 2: Heavy quark flavour physics

Flavour at electron and proton colliders



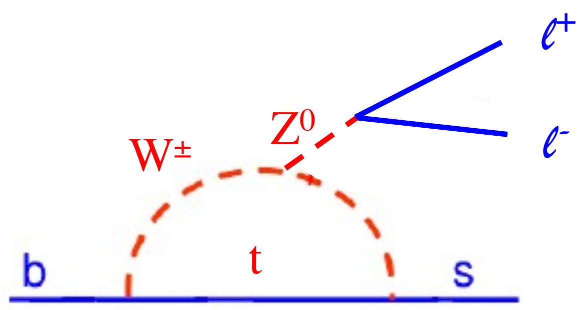
- Defined initial state:
  - Low trigger bias
  - Full event reconstruction, low multiplicity
  - Allows selection of inclusive and invisible decays
  - Experimentally: $e^- \cong \mu^-$
- Excellent for decays with difficult signatures
  - $B \rightarrow \tau^+\tau^-$, $B^- \rightarrow \tau^-\nu$, $B \rightarrow K^*\nu\nu$, ..
  - τ^- decays (LFV)

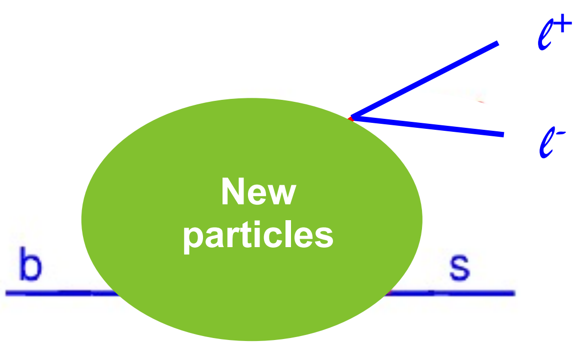
- Complex hadronic environment
- Very big $b\bar{b}$ (and $c\bar{c}$, $\tau^+\tau^-$) production rate
  - Specialized on (very) rare and clean final states
    → then cleaner than e^+e^-
  - Leading for decays with muons
    $B \rightarrow \mu^+\mu^-$, $B \rightarrow K^*\mu^+\mu^-$, $B_s \rightarrow J/\psi\phi$
- Trigger and reconstruction are significant challenges, specially for ATLAS / CMS

This talk

- Status of indirect searches
  - Electroweak precision observables
    → a lot to learn in Higgs couplings, consistency of the SM
  - **Flavour**

- This talk focuses on flavour physics:
  Search for new heavy particles in measurements of quantum effects





- Review of current flavour data:
  Where do we see inconsistencies between Standard Model prediction and measurement (=anomalies) ? Where not?

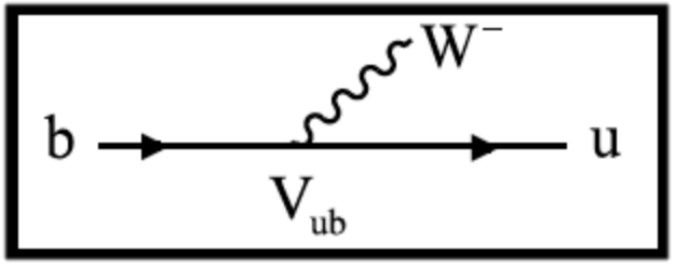
Outline of this talk: Search for anomalies

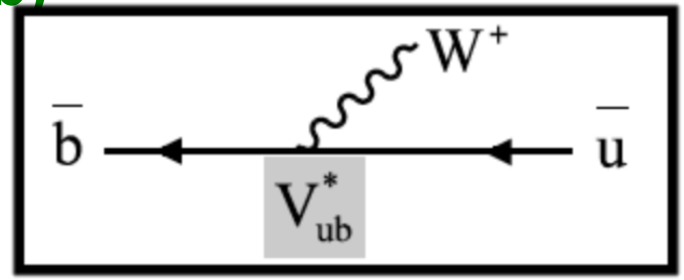
1. CP violation and CKM precision measurements

2. Charm physics – discovery of CPV in charm

3. Rare decays – an intruiging pattern of anomalies

V_{CKM} describes the rotation between weak (d’, s’, b’) and mass eigenstates (d, s, b)





Couplings of the charged current:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Magnitude:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{pmatrix}$$

Complex phases:

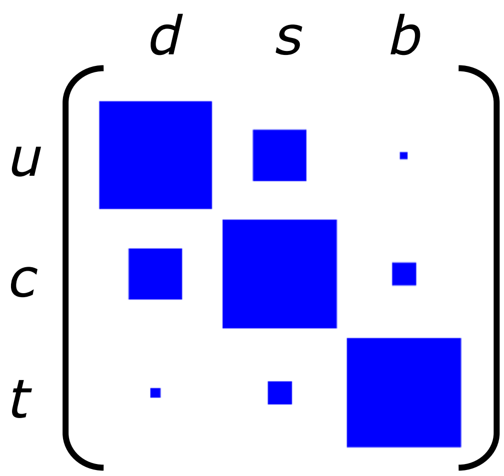
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

CKM matrix II

- CKM matrix is complex and unitary
- Four independent parameters
  - Fundamental constants of nature that must be measured

$$\hat{V}^{+}_{CKM}\hat{V}_{CKM} = 1$$

- Reflects hierarchy of quark transitions



$\lambda = \sin(\theta_c) = 0.23$

Why the ranking?
We don't know (yet)!

*If you figure this out, you **will** win the nobel prize*

Deriving the triangle interpretation

- Starting point: the 9 unitarity constraints on the CKM matrix

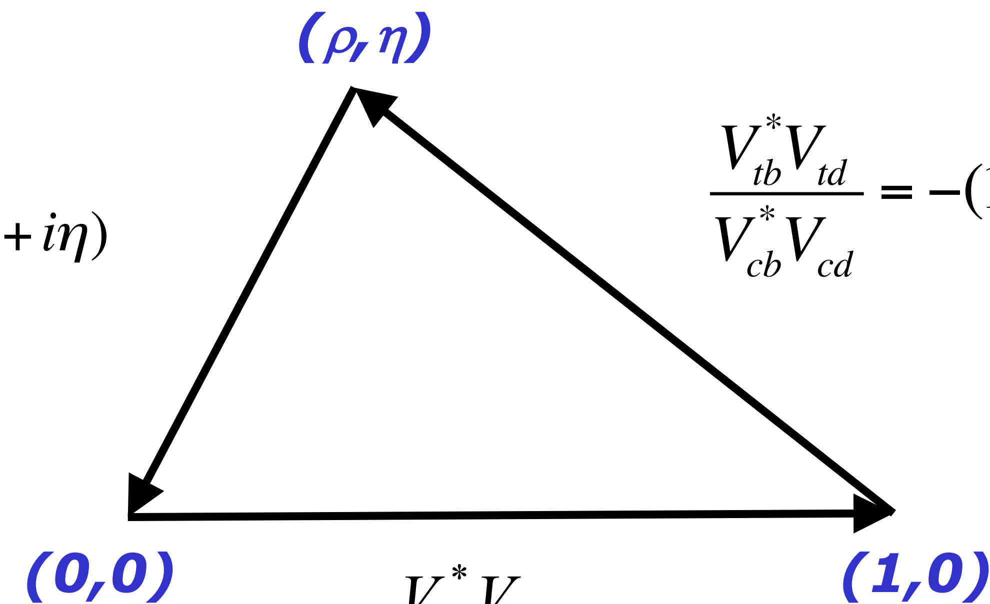
$$V^{+}V=\begin{pmatrix} V^{*}_{ud} & V^{*}_{cd} & V^{*}_{td} \\ V^{*}_{us} & V^{*}_{cs} & V^{*}_{ts} \\ V^{*}_{ub} & V^{*}_{cb} & V^{*}_{tb} \end{pmatrix}\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}=\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Pick (arbitrarily) orthogonality condition with (i,j)=(3,1)

$$V^{*}_{ub}V_{ud}+V^{*}_{cb}V_{cd}+V^{*}_{tb}V_{td}=0$$

Visualizing the unitarity constraint

- Divide all sides by length of base



$$\frac{V_{ub}^{*}V_{ud}}{V_{cb}^{*}V_{cd}} = -(\rho + i\eta)$$

$$\frac{V_{tb}^{*}V_{td}}{V_{cb}^{*}V_{cd}} = -(1 - \rho - i\eta)$$

$$\frac{V_{cb}^{*}V_{cd}}{V_{cb}^{*}V_{cd}} \equiv 1$$

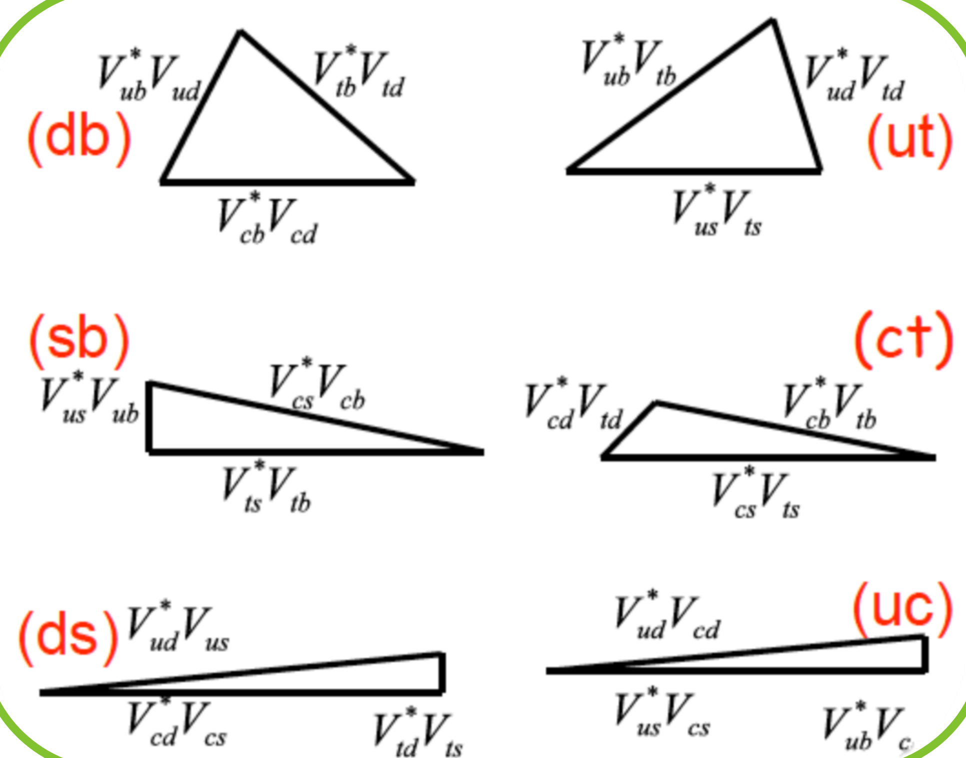
- Constructed a triangle with apex (ρ,η)

Unitarity triangles

CKM matrix is unitary:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{(db)}$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad \text{(sb)}$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad \text{(ds)}$$

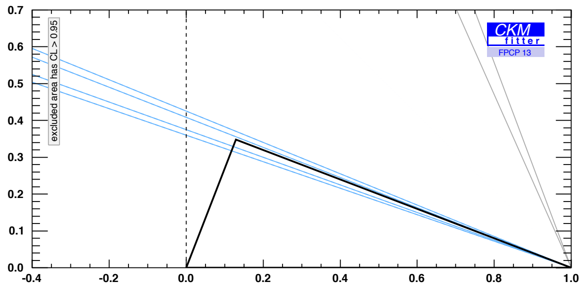
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \quad \text{(ut)}$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0 \quad \text{(ct)}$$
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad \text{(uc)}$$



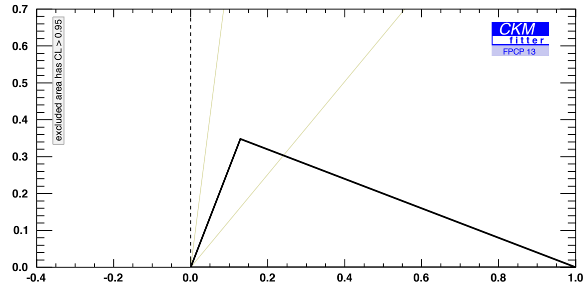
All 6 triangles have the same area, a measure of CPV in the SM

Summary of CKM measurements

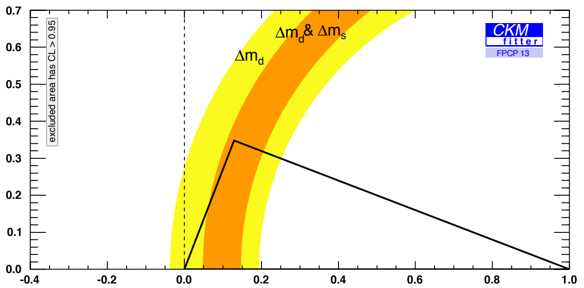
sin 2β



γ



Bs and Bd mixing



Summary of CKM measurements

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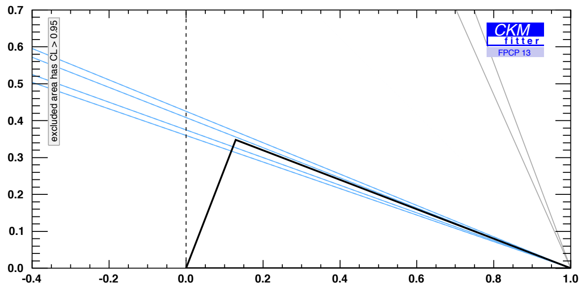
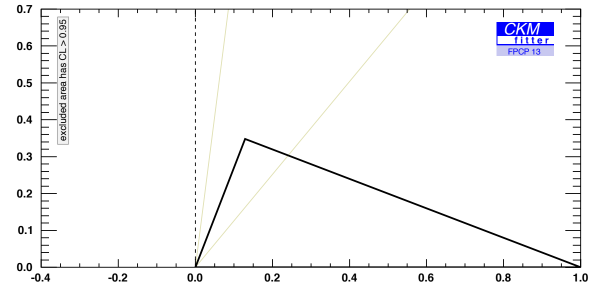
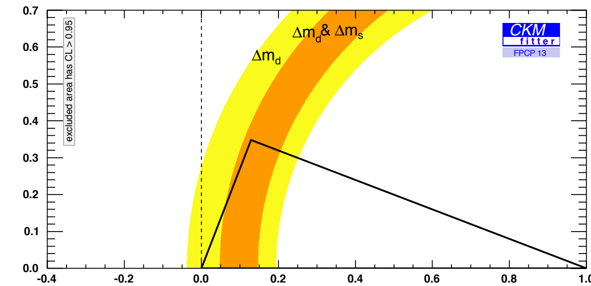


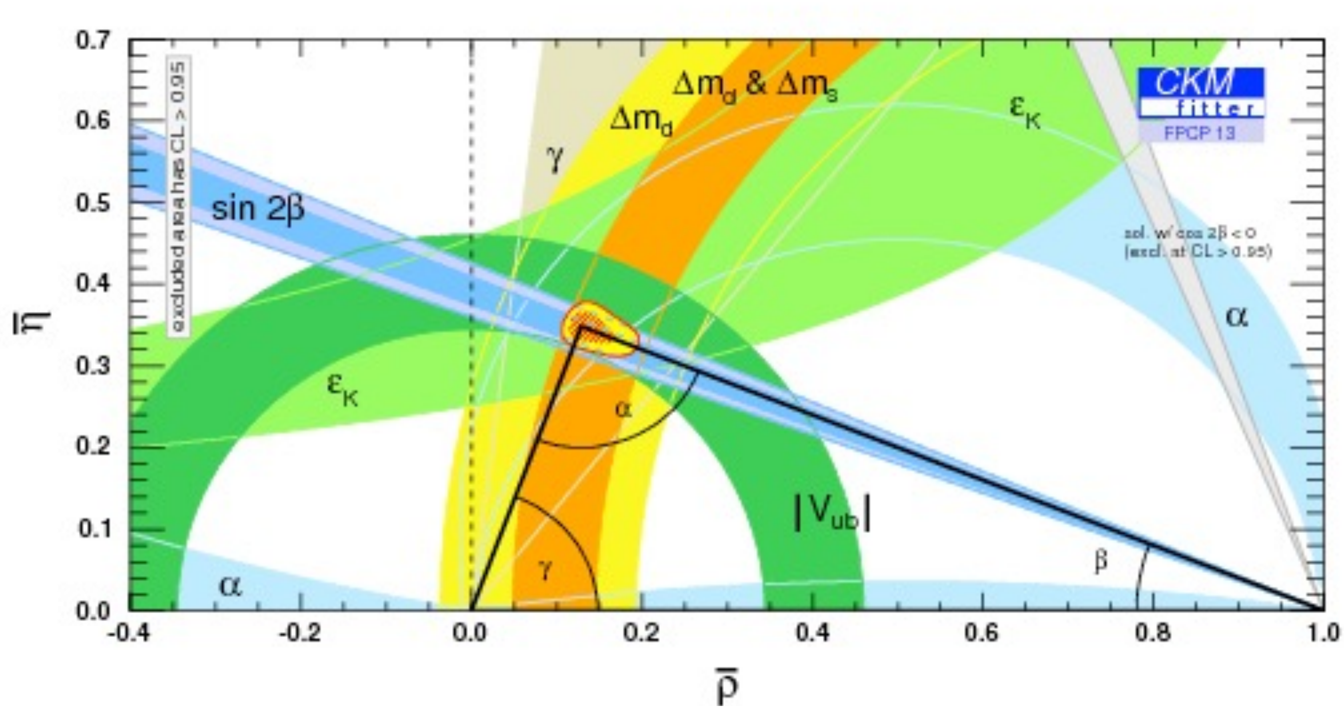
γ



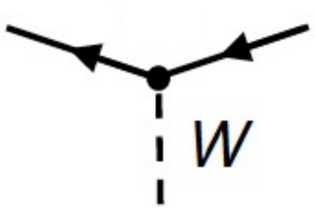
Bs and Bd mixing



Adding many complimentary measurements



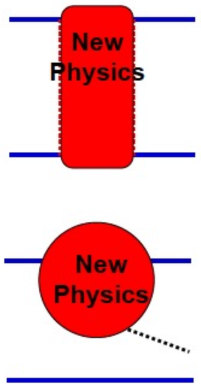
- Tree Processes only



SM dominant
→ no new effects expected

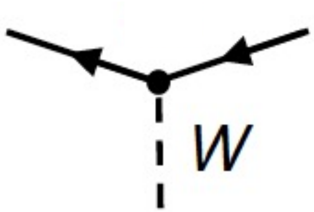
- Loop processes only

New Physics is expected to appear in loops



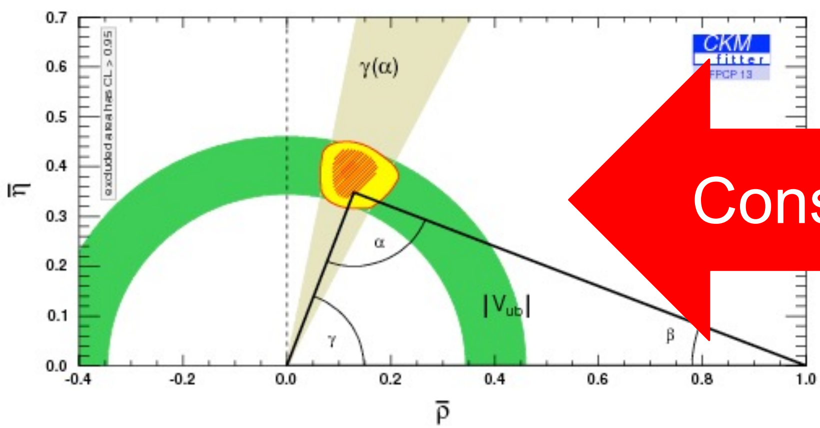
Tree vs loop

- Tree Processes only



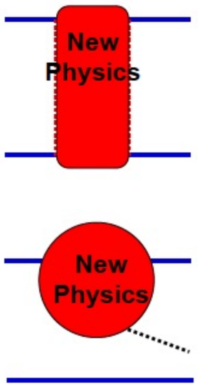
SM dominant
→ no new effects expected

$$|V_{ub}/V_{cb}|,\ B\to\tau\nu,\ \gamma,\ \pi-\alpha-\beta$$

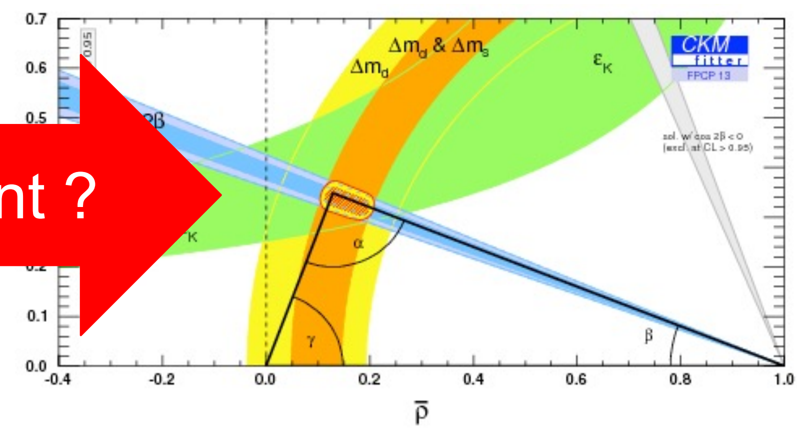


- Loop processes only

New Physics is expected to appear in loops



$$|\varepsilon_K|,\ \sin 2\beta,\ \Delta m_d,\ \Delta m_s$$



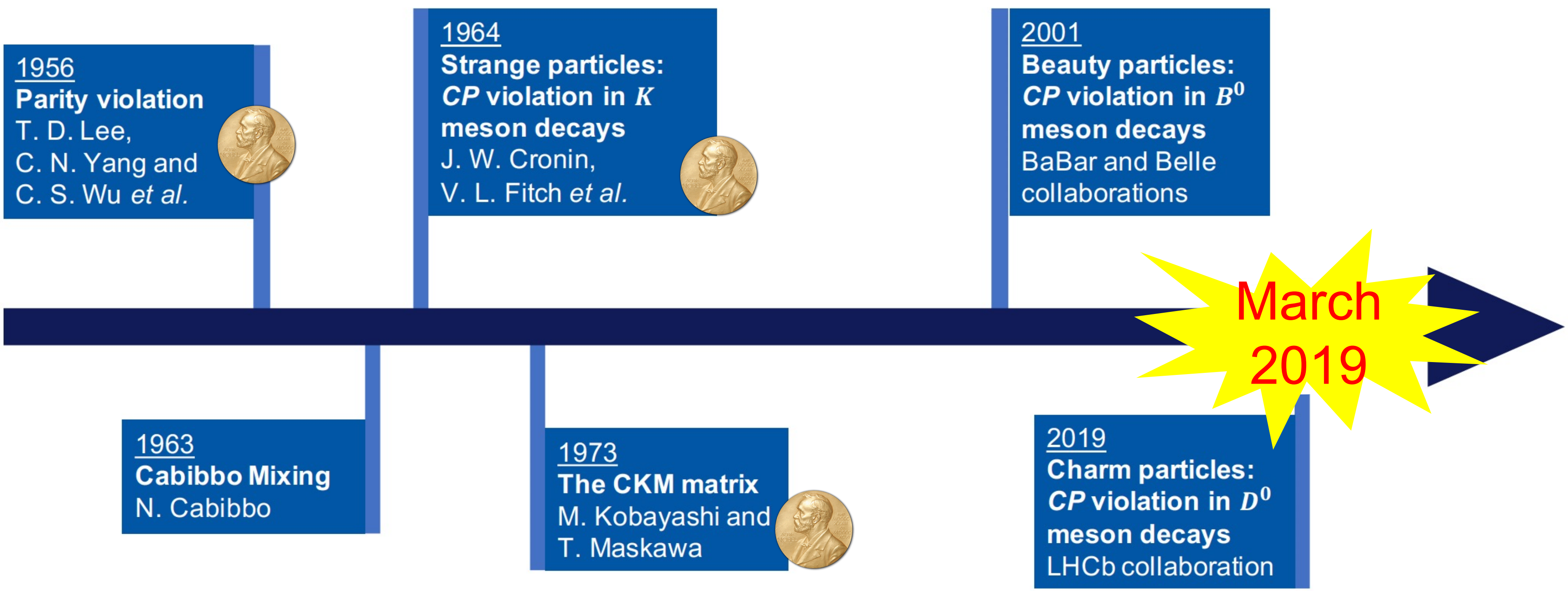
Consistent ?

Apex known with 10-20%, aim at <1%

Outline of this talk: Search for anomalies

- CP violation and CKM precision measurements
- Charm physics – discovery of CPV in charm
- Rare decays – an intruiging pattern of anomalies

History of CP violation



A. Carbone, CERN seminar, March 19

Charm physics

- Charm mesons $D^0 = (c\bar{u})$ only first two generations
  → in Standard Model no CP violation in lowest order

- CP violation in charm sector (was) not observed
  - Only way to test CP violation in up-type mesons
  - complementary to K and B mesons

- LHCb has recorded huge charm samples, eg. *1billion* $D^0 \to K^+\pi^-$

- **Recent:**
  Search for direct CP violation with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ events
  - SM expectation small: $O(10^{-3} - 10^{-4})$
  - LHCb measurement with full dataset → ~100M signal events

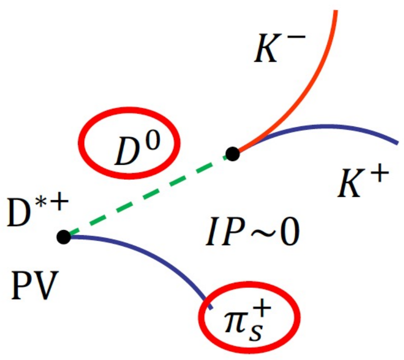
$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$ with $f = K^-K^+$ and $f = \pi^-\pi^+$

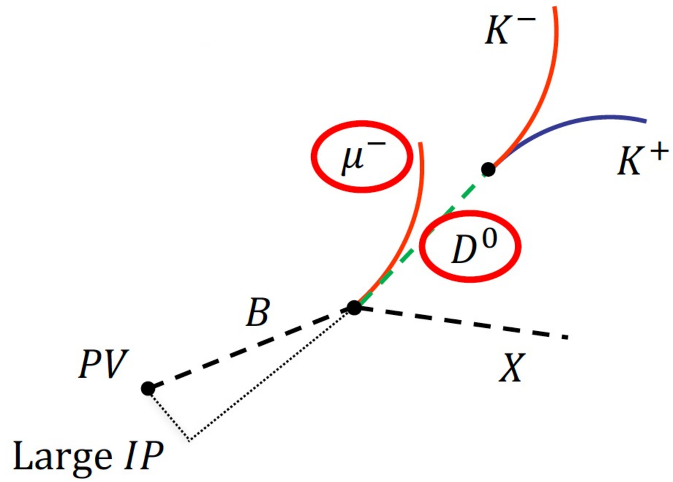
Measurement of CP violation in charm

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$ with $f = K^-K^+$ and $f = \pi^-\pi^+$

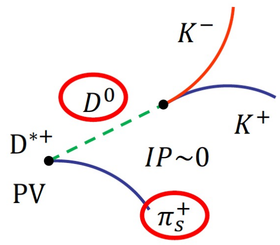
- Need to determine the initial flavour of the D0 / D0bar = Tagging

Tag the D^0 flavour at production with the charge of the soft pion or the muon

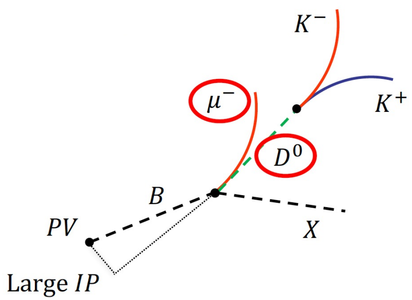




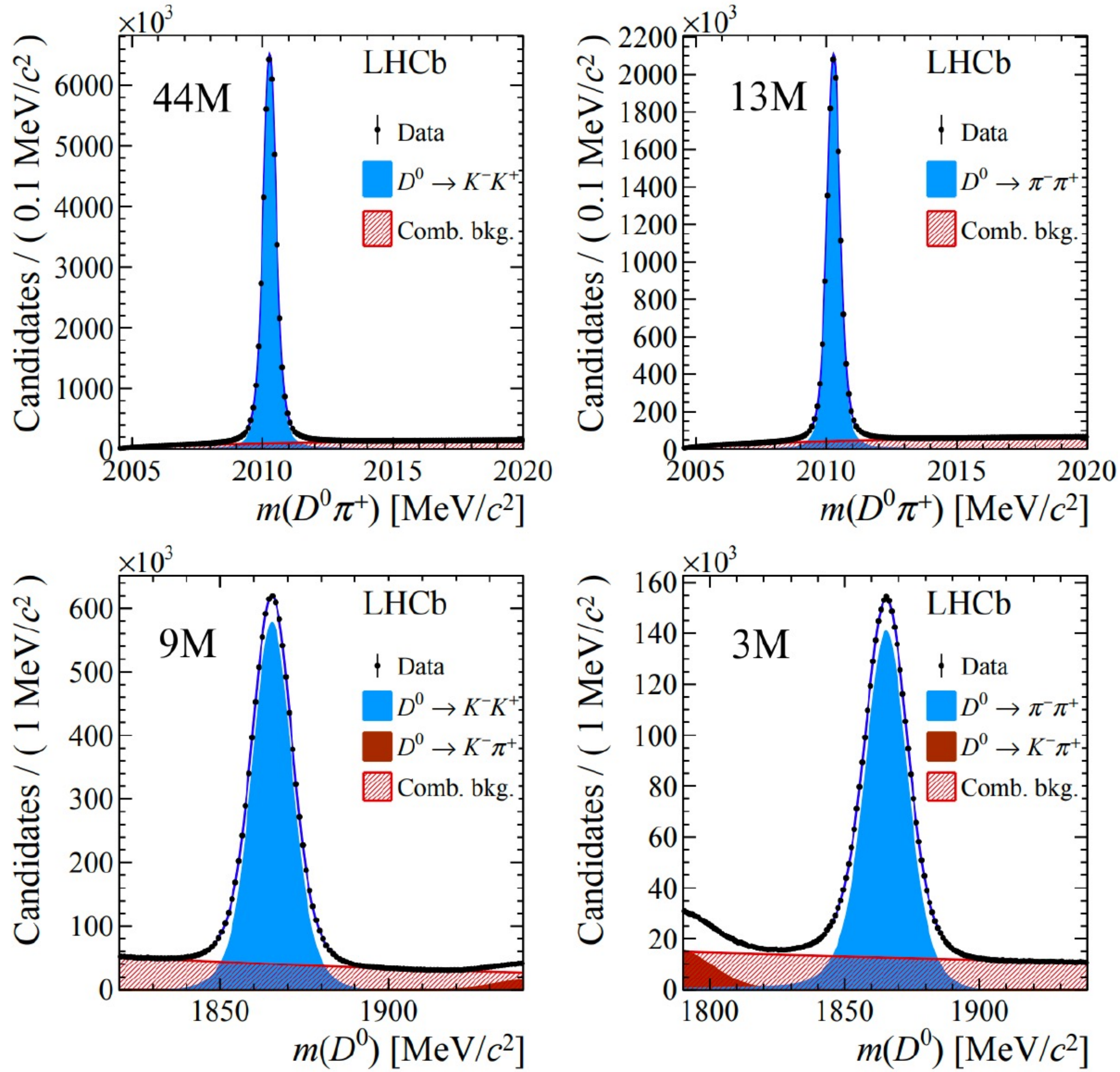
Reconstructed charm peaks



pion tag



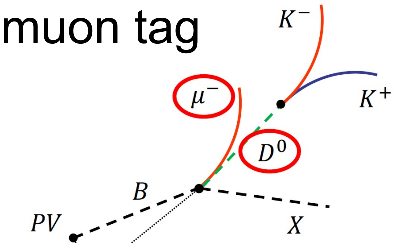
muon tag



Observable

- Experimentally:

muon tag



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

Valid up to $\mathcal{O}(10^{-6})$

$$A_{\mathrm{raw}}(f) \simeq A_{CP}(f) + A_{\mathrm{D}}(f) + A_D(\mu^-) + A_P(\bar{B})$$

- $A_{CP}(f)$: Physical *CP* asymmetry
- $A_{\mathrm{D}}(f)$: D^0 detection asymmetry ➔ equal to 0, since K^-K^+ and $\pi^-\pi^+$ are symmetric final states
- $A_D(\mu^-)$: μ^- detection asymmetry → Independent on the final state
- $A_P(\bar{B})$: $\bar{B}$ production asymmetry → Independent on the final state

- Difficult to control to the level of 10^{-3}-10^{-4}

- ΔA_{CP} is a robust combination of two asymmetries:

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+)$$

Discovery of CP violation

- Recent Run 2 analysis measures:

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

Compatible with previous LHCb results and WA

- Combination with LHCb Run 1:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

CP violation in charm observed at 5.3σ

Discovery of CPV in charm – Anomaly ??

- SM prediction broadly compatible: 10^{-3}–10^{-4}

Golden et. al., PLB 222 (1989) 501
Buccella et al., PRD 51 (1995) 3478
Bianco et al., Riv. Nuovo Cim . 26N7 (2003) 1
Grossman et al, PRD 75 (2007) 036008
Artuso et al., AR Nucl. Part. Sci. 58 (2008) 249
Khodjamirian et al., PLB 774 (2017) 235
Pirtskhalava et al. , PLB 712 (2012) 81
Cheng et al., PRD 85 (2012) 034036

Feldmann et al., JHEP 06 (2012) 007
Li et al., PRD 86 (2012) 036012
Franco et al., JHEP 05 (2012) 140
Brod et al., JHEP 10 (2012) 161
Atwood et al., PTEP 2013 (2013) 093B05
Hiller et al., PRD 87 (2013) 014024
Grossman et al., JHEP 04 (2013) 067
Müller et al., PRL 115 (2015) 251802
Buccella et al., arXiv:1902.05564 (2019)

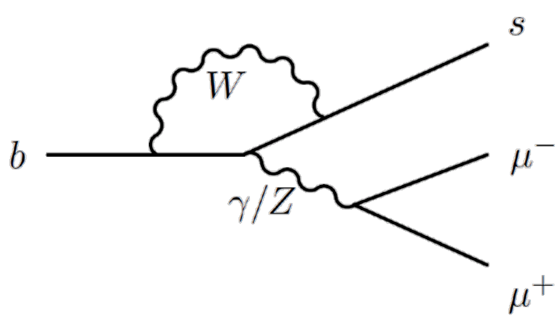
- But no agreement amongst different SM predictions
  → More theoretical work needed to understand
  if this is anomalous or SM like ..

Outline of this talk: Search for anomalies

- CP violation and CKM precision measurements
- Charm physics – discovery of CPV in charm
- Rare decays – an intruiging pattern of anomalies

Testing $b \to s\, \ell^+ \ell^-$ transitions

<u>$b \to s\, \mu^+\mu^-$ base diagram</u>



- Purely leptonic
  - "add nothing"

- Semileptonic
  - add d quark as spectator
    → $B^0 \to K^{*0}\, \mu^+\mu^-$
  - add s quark as spectator
    → $B_s \to \phi\, \mu^+\mu^-$
  - add u quark as spectator
    → $B^+ \to K^+\, \mu^+\mu^-$

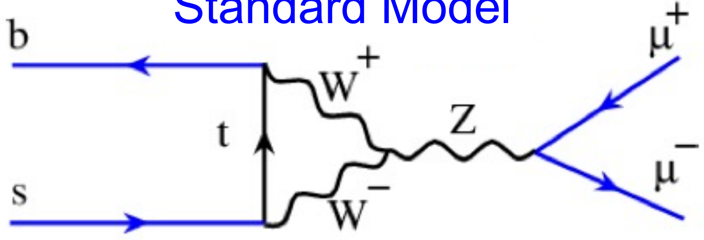
- Ratios:
  - Compare muons to electrons

Theory prediction: Standard Model

decay	SM
$B_s \to \mu^+\mu^-$	$3.5\pm0.3 \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$1.1\pm0.1 \times 10^{-10}$

SM: Buras, Isidori et al: EPJC72(2012) 2172
Mixing effects: Fleischer et al, PRL109(2012)041801

Standard Model

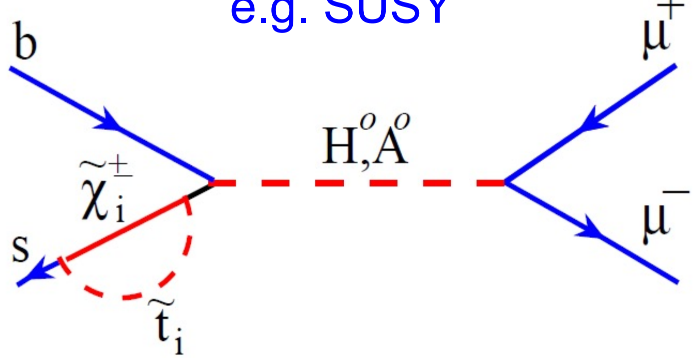


Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

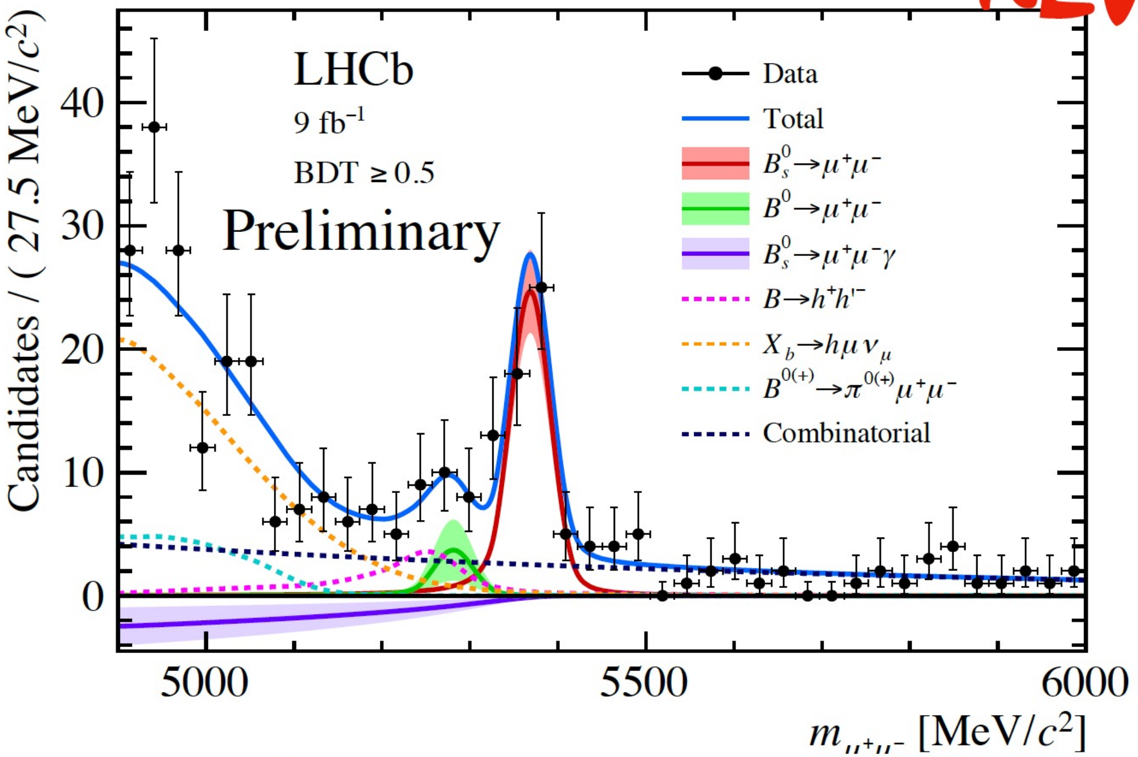
➔ Very **sensitive to an extended scalar sector**
(e.g. extended Higgs sectors, SUSY, etc.)

e.g. SUSY



LHCB-PAPER-2021-007

NEW!



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9} \quad > 10\sigma$$

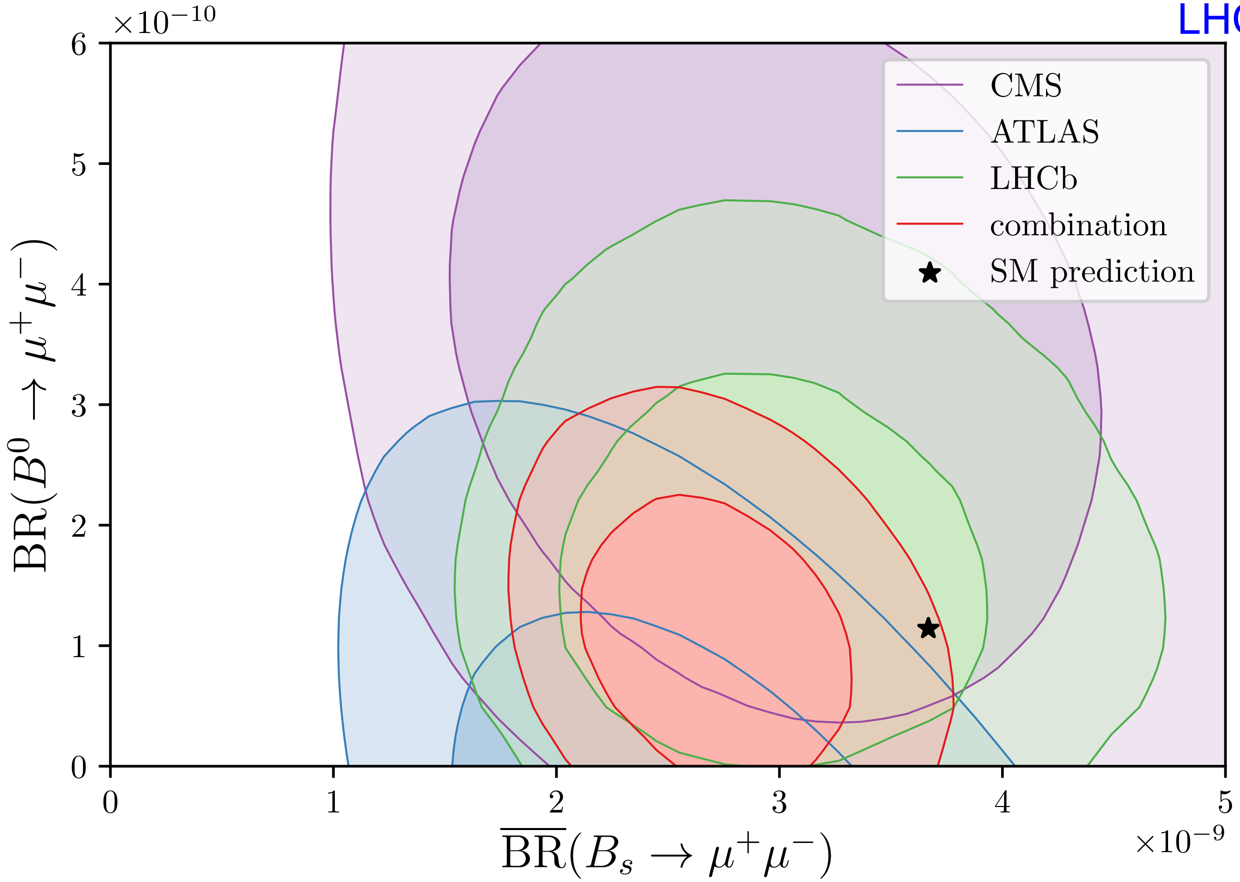
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10} \text{ at } 95\,\%\text{ CL}$$

First order: No sign of large New Physics effect!
Also very competitive results from ATLAS & CMS → combine

$B \to \mu^+\mu^-$: Combination from LHC

- Combination of LHCb, CMS & ATLAS

ATLAS: 1812.03017
CMS: PRL111(2013)101804
LHCb: PRL118(2017)191801



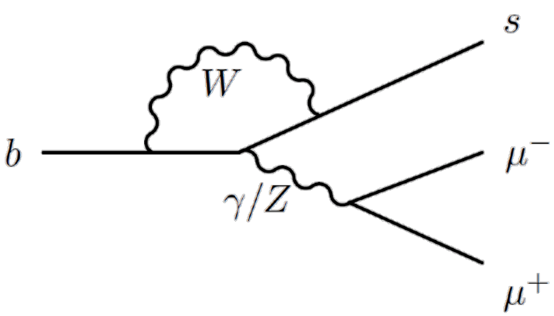
Combining all three LHC experiments

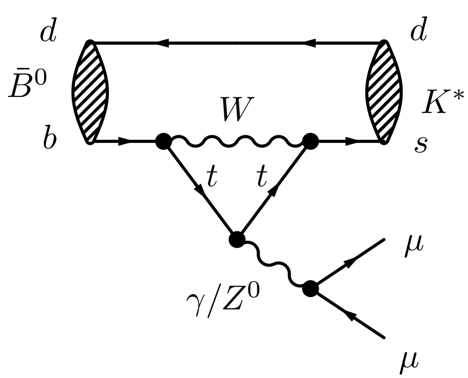
$$BR(B_S \to \mu^+\mu^-) = (2.71 \pm 0.4) \times 10^{-9}$$

~2σ from SM

D. Straub, Moriond EW 2019 & 1903.10434 & DPG 2019

$b \rightarrow s\, \mu^+\mu^-$ base diagram





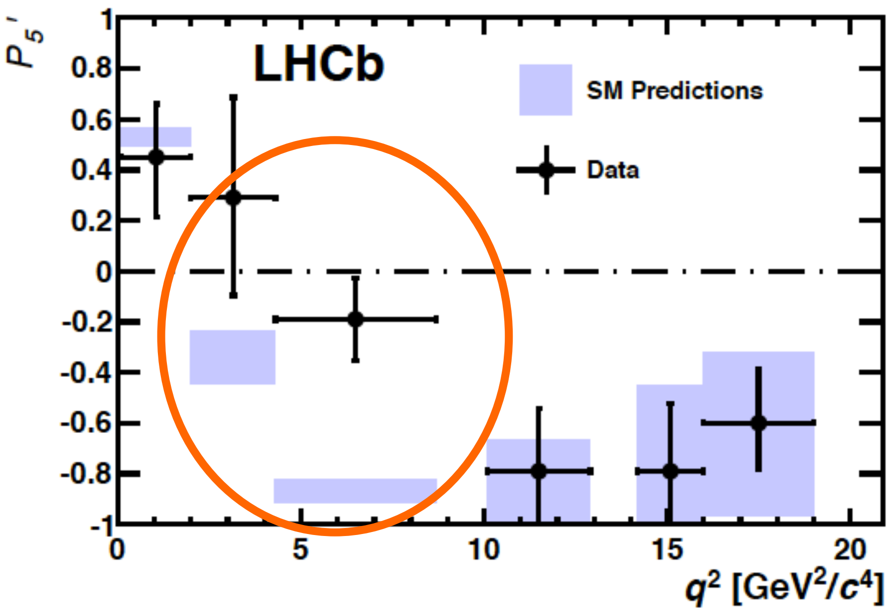
- Purely leptonic
  - "add nothing"

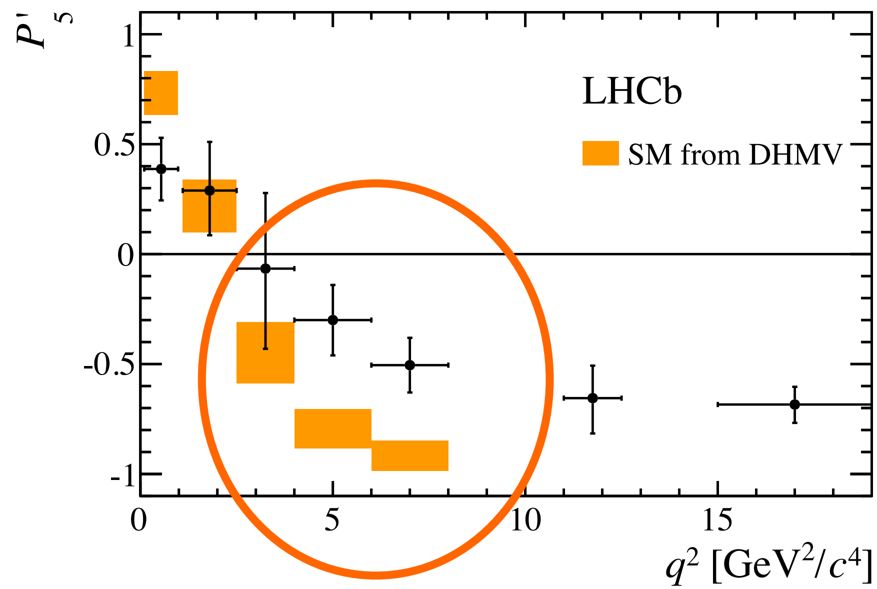
- Semileptonic
  - add d quark as spectator
    → $B^0 \rightarrow K^{*0}\, \mu^+\mu^-$
  - add s quark as spectator
    → $B_s \rightarrow\ \phi\, \mu^+\mu^-$
  - add u quark as spectator
    → $B^+ \rightarrow\ K^+\, \mu^+\mu^-$

- Ratios:
  - Compare muons to electrons

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0}\mu^+\mu^-$ decays

LHCb, Phys.Rev.Lett. 111 (2013) 191801





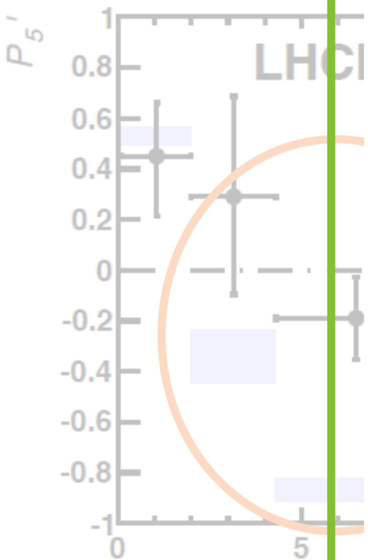
[LHCb, JHEP 02 (2016) 104]

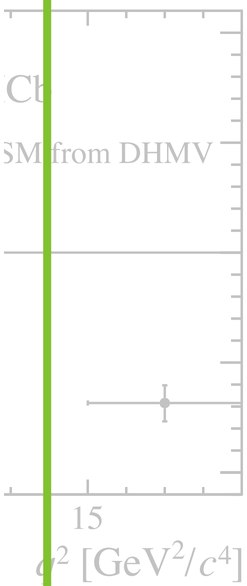
- Full Run 1 analysis confirms effect
  Run 2 update coming

Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

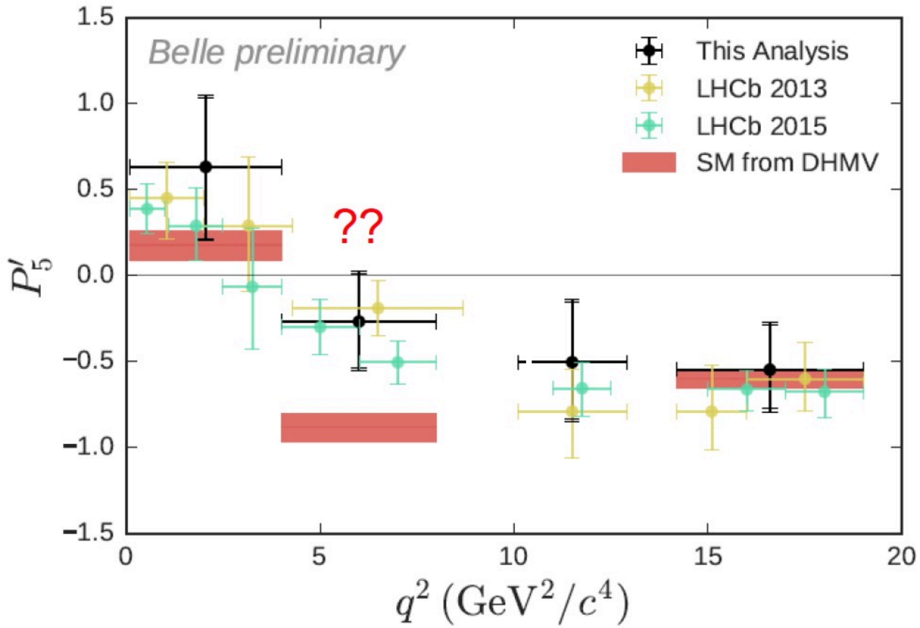
LHCb, Phys.





[LHCb, JHEP 02 (2016) 104]

Belle still has a word to say



Belle PRL118(2017)111801

Lower statistical power, but very consistent

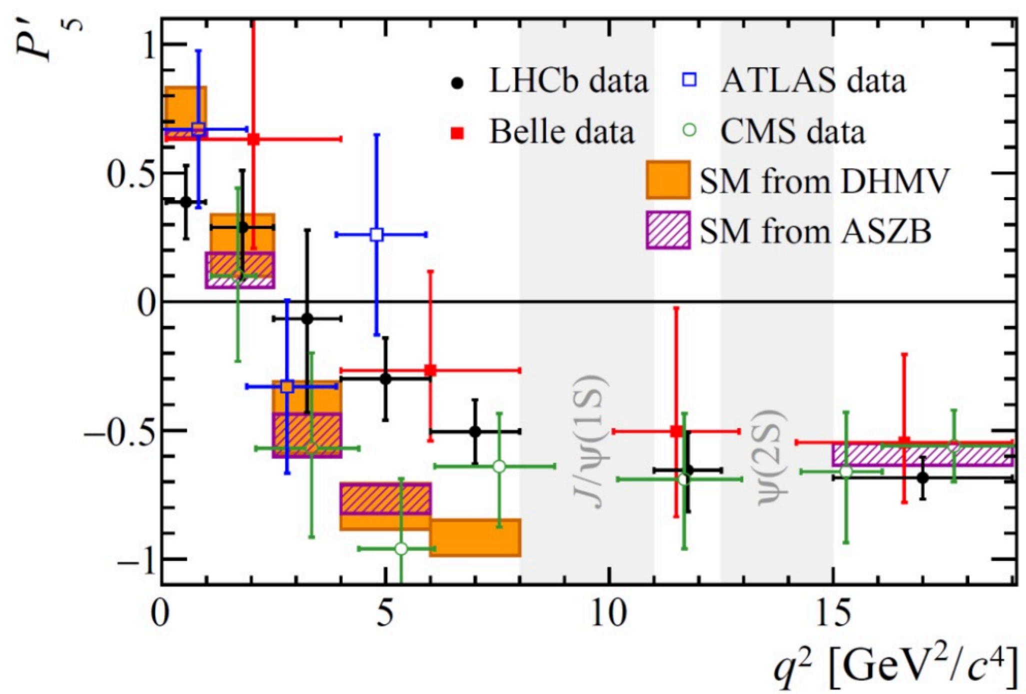
- Full Run

Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys.

.. and ATLAS and CMS



[ATLAS-CONF-2017-023, CMS-PAS-BPH-15-007]

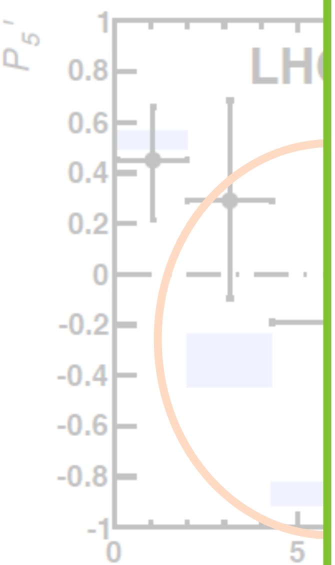
[LHCb, JHEP 02 (2016) 104]

- Full Ru

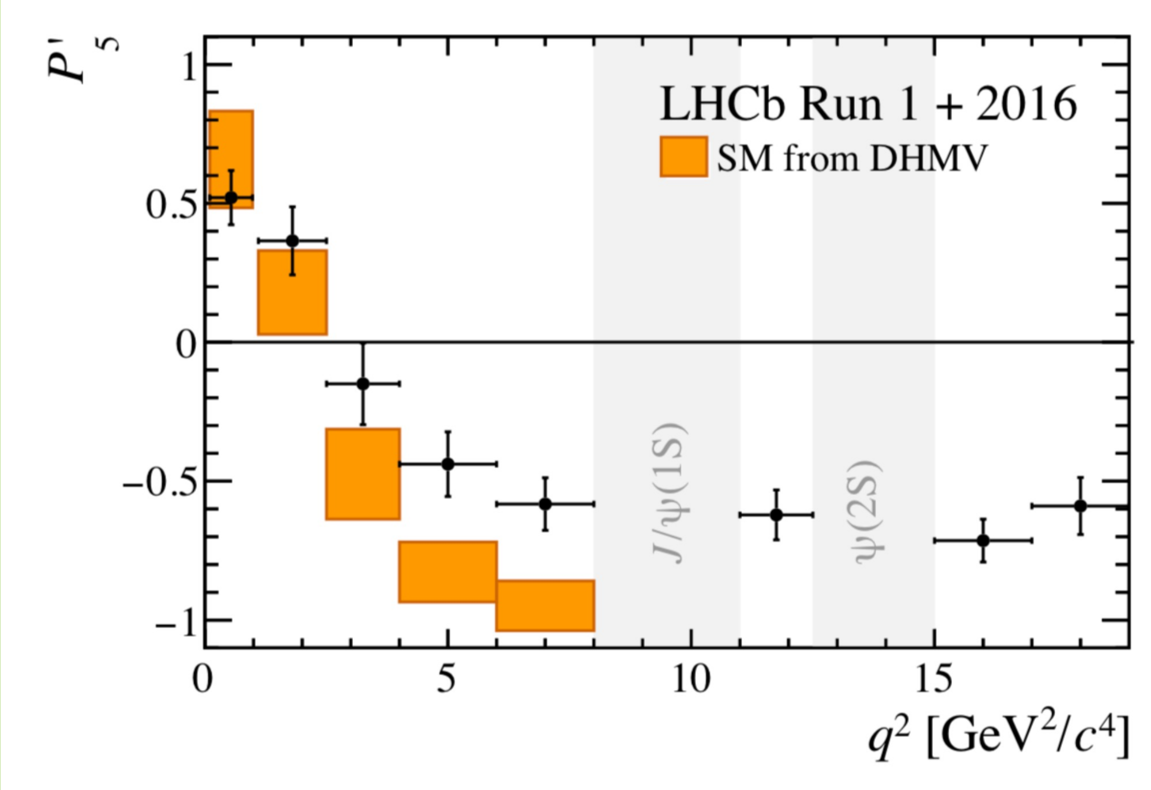
Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

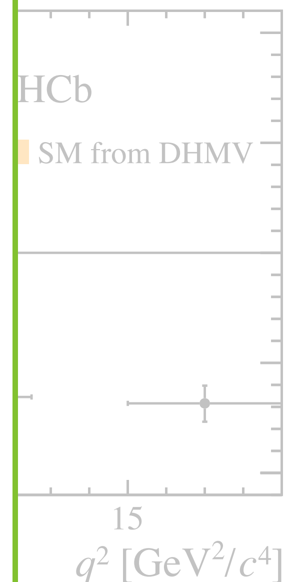
- 2013, LHCb has observed a deviation in angular observa

LHCb, Phys.



.. LHCb 2020 (doubling of dataset)





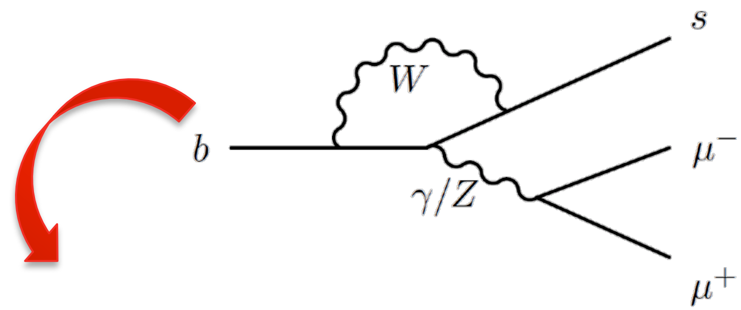
[LHCb, JHEP 02 (2016) 104]

- Full Rur

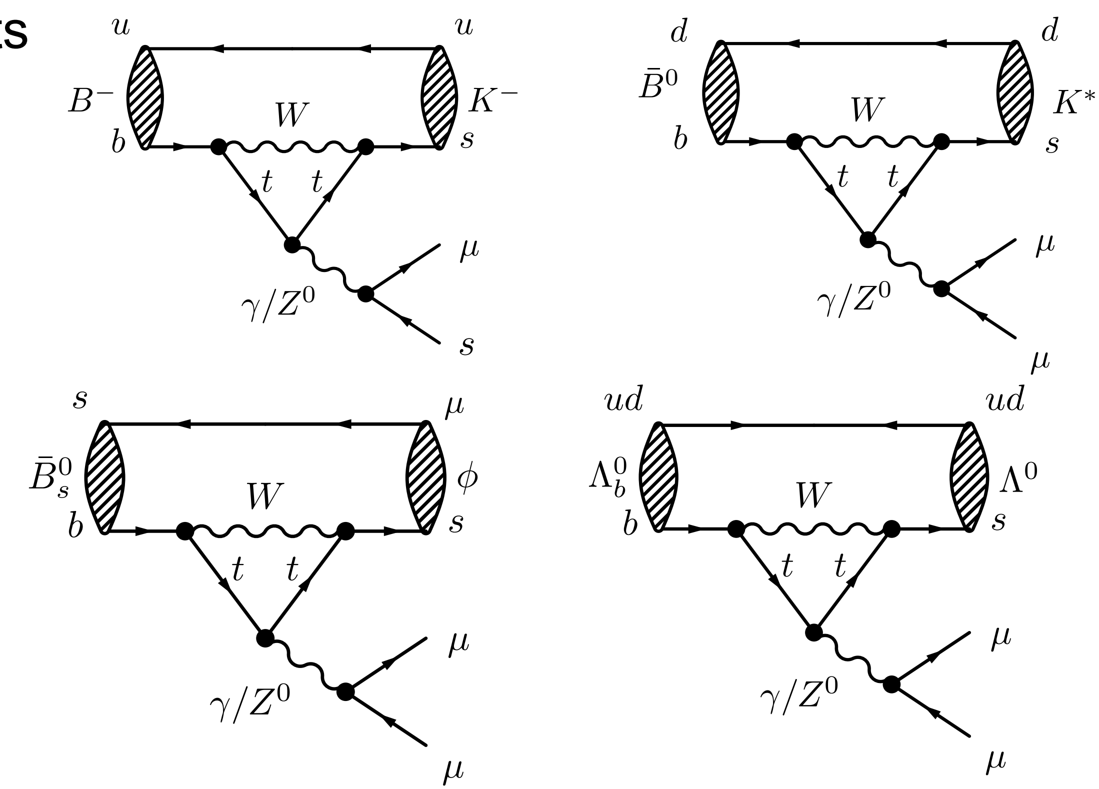
Situation unclear…. If real, expect discrepancies in **other $b \to s$ decays** ..

Other b → s $\mu^+\mu^-$ decays

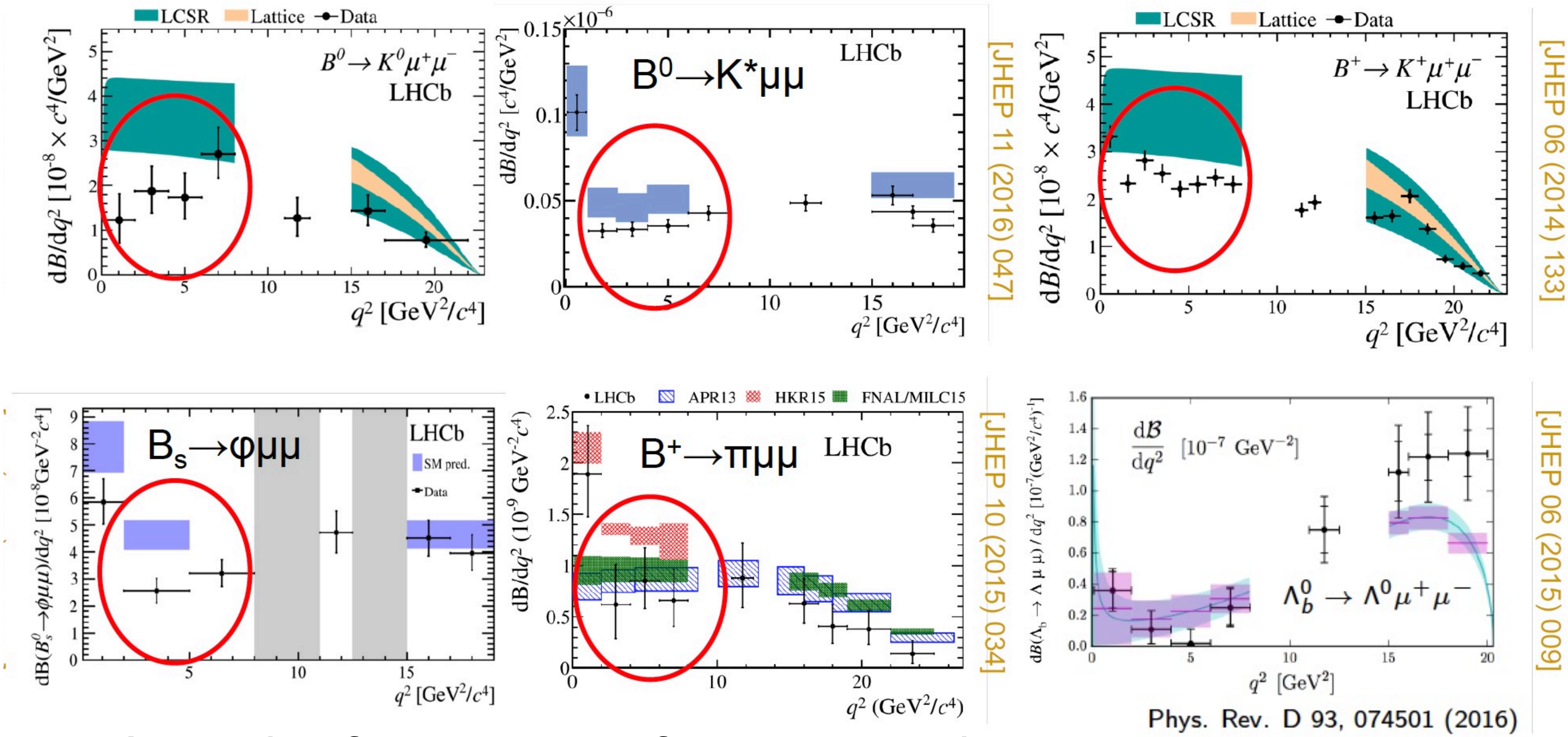
- Decay modes with same effective Feynman diagram accessible
  → different spectator quarks



- Test for same new effects
  → expect suppressed branching fractions

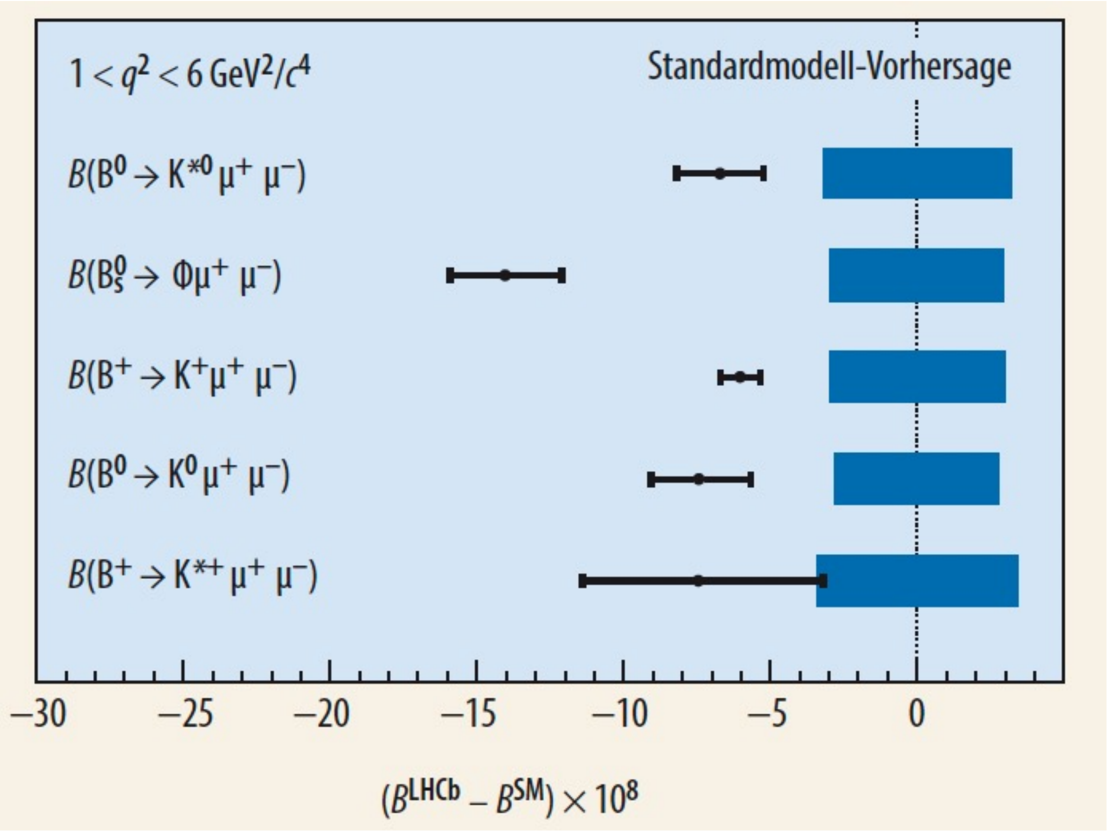


Branching fractions of $b \to s\ \mu^+\mu^-$



- Analysis of large class of $b \to s,d\ \mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate

Branching fractions of $b \to s\, \mu^+\mu^-$



J.A. & C. Langenbruch, Physik Journal 10/2018

- Analysis of large class of $b \to s,d\, \mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - Tendency to undershoot prediction of differential x-sections
    → **intriguing hint or theoretical issue in prediction?**

→ **We need cleaner tests …**

Flavour changing currents: Leptons

- Couplings of $W^{\pm}$ and Z^0 are equal for all lepton families
- Confirmed many times, e.g. in decays

g_τ : "weak coupling constant for taus"

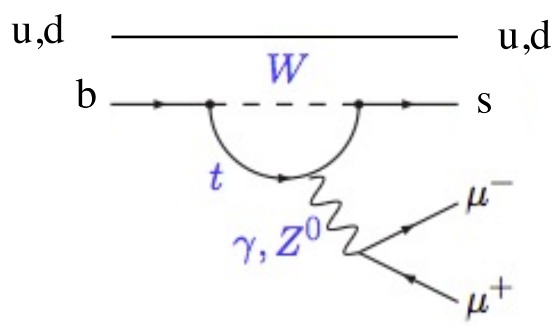
Compare decays	Measured ratio
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ und $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$	$g_\tau / g_\mu = 0.999 \pm 0.003$
$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ und $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$	$g_\mu / g_e = 1.001 \pm 0.004$
$\pi^+ \to e^+ \nu_e$ und $\pi^+ \to \mu^+ \nu_\mu$	$g_\mu / g_e = 1.001 \pm 0.002$

in $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$, $Z^0 \to \tau^+\tau^-$

- **Standard model: All leptons carry same weak**
  → Lepton-Flavour Universality

- Lepton universality almost untested in loop decays
  → test this in ratios of semileptonic decays

electrons / muons [**b → s**]

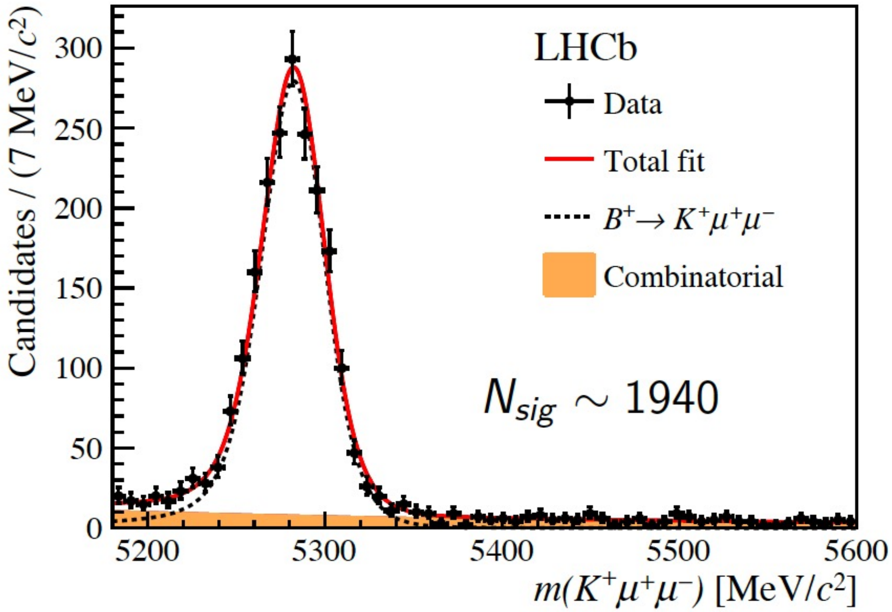


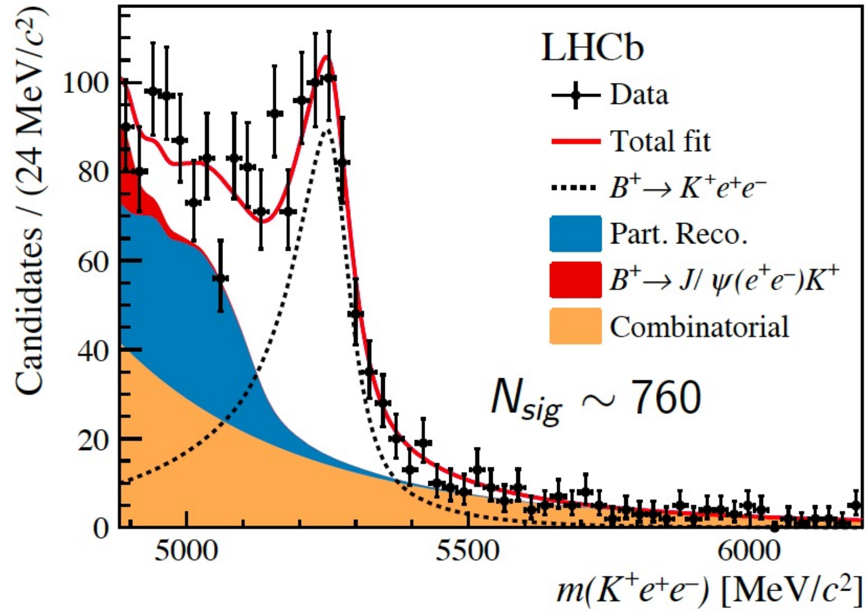
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \stackrel{\mathrm{SM}}{=} 1.0$$

- Very low hadronic uncertainties, electroweak corrections O(1%)

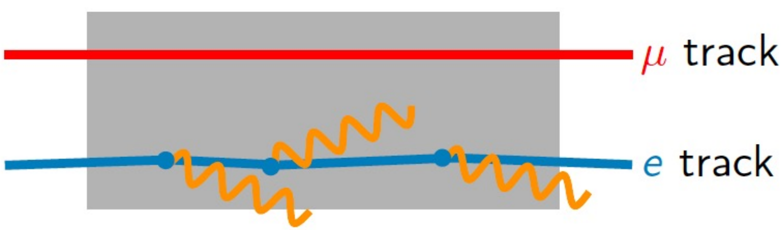
- Any significant deviation from 1 is a clear sign for New Physics

$B^+ \to K^+ \ell^+\ell^-$ mass distributions





$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} = \frac{N(K^+\mu\mu)}{N(K^+ee)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+\mu\mu)}$$



- Measurement as double ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(ee))}$$
$$= \frac{N(K^+\mu\mu)}{N(K^+J/\psi(\mu\mu))} \cdot \frac{N(K^+J/\psi(ee))}{N(K^+ee)} \cdot \frac{\varepsilon(K^+J/\psi(\mu\mu))}{\varepsilon(K^+\mu\mu)} \cdot \frac{\varepsilon(K^+ee)}{\varepsilon(K^+J/\psi(ee))}$$

- PID specific uncertainties cancel to first order

- Test consistency with resonances
  - $r_{J/\psi}$ = 1.014±0.035$^{(\text{stat+syst})}$ (known to be 1 at 0.4%)
  - $R_{\psi(2S)}$=0.986±0.013$^{(\text{stat+syst})}$

$$r_{J/\psi} = \frac{\mathcal{B}(B \to K^+J/\psi(\mu\mu))}{\mathcal{B}(B \to K^+J/\psi(ee))}$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

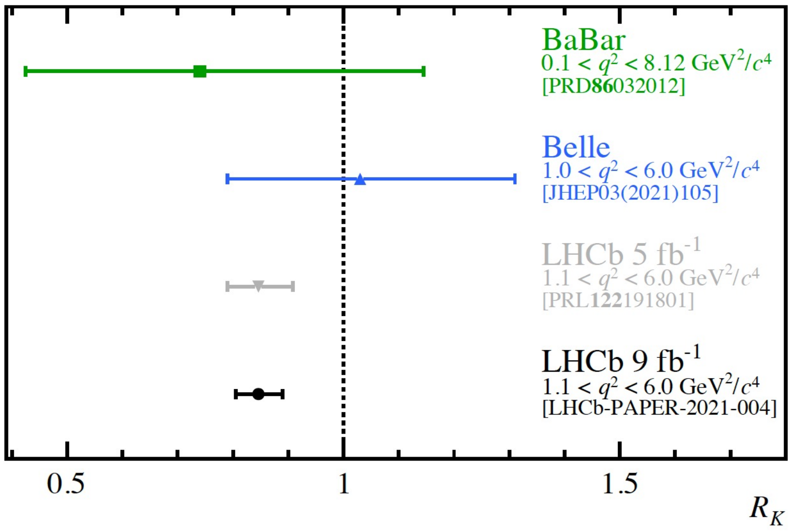
- First evidence of violation of LFU

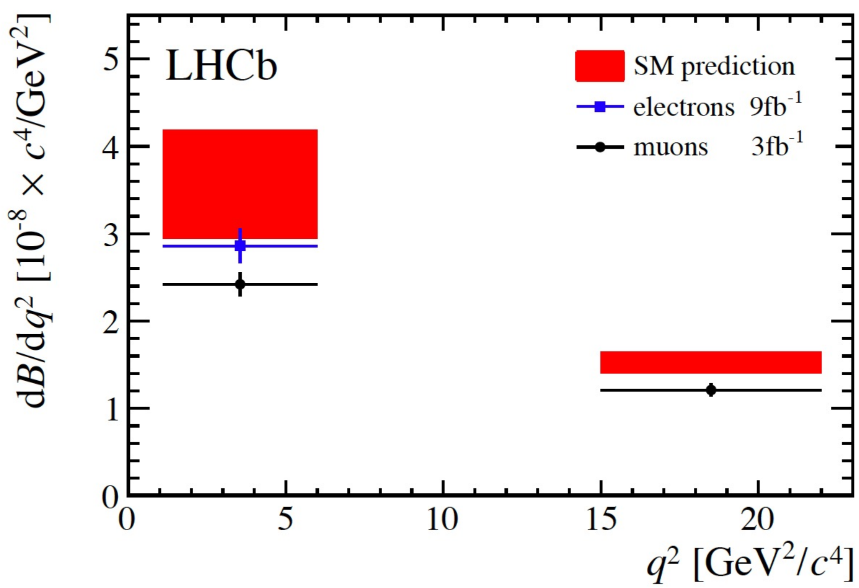
$$R_K = 0.846^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$

  – SM hypothesis: p-value = 0.0010
  – Evidence of LFU violation at 3.1σ

- Indication: Muons show issue with SM, Electrons seem consistent

- More channels to confirm or disprove measurement under study

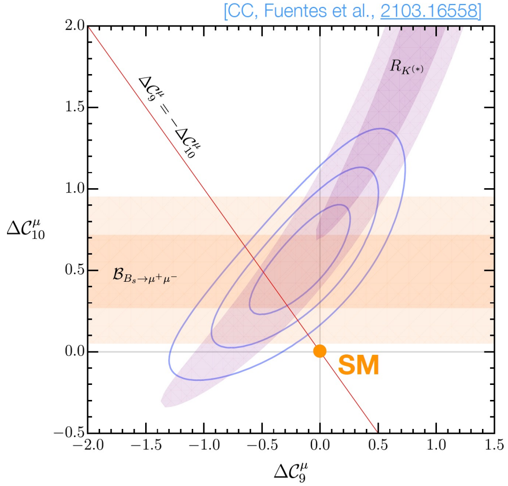




Interpretation LFU

- Global analysis of all observables & fit to Wilson coefficients

[CC, Fuentes et al., 2103.16558]



$$\mathscr{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i \mathcal{O}_i$$
$$\mathcal{O}_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu)$$
$$\mathcal{O}_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \gamma_5 \mu)$$

Significance between 3.9σ and >> 5σ, depending on fine print

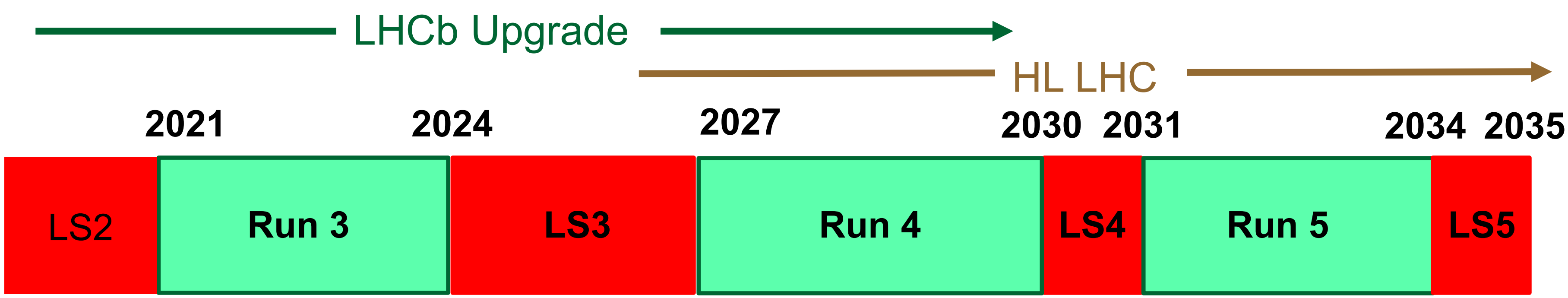
- Intriguing: a coherent picture seems to emerge.
  Some analyses: large significances which has lead to excited discussions of Z's, Leptoquarks, etc

- **Experimentalists view: Hypotheses non fingo**
  Excitement premature: we need significant individual measurements

LHC long term plan

- Results shown here (mostly) use ¼ - ½ of the already recorded datasets
  → updates are progressing well

- Beyond that: Excellent future landscape for flavour @ LHC :



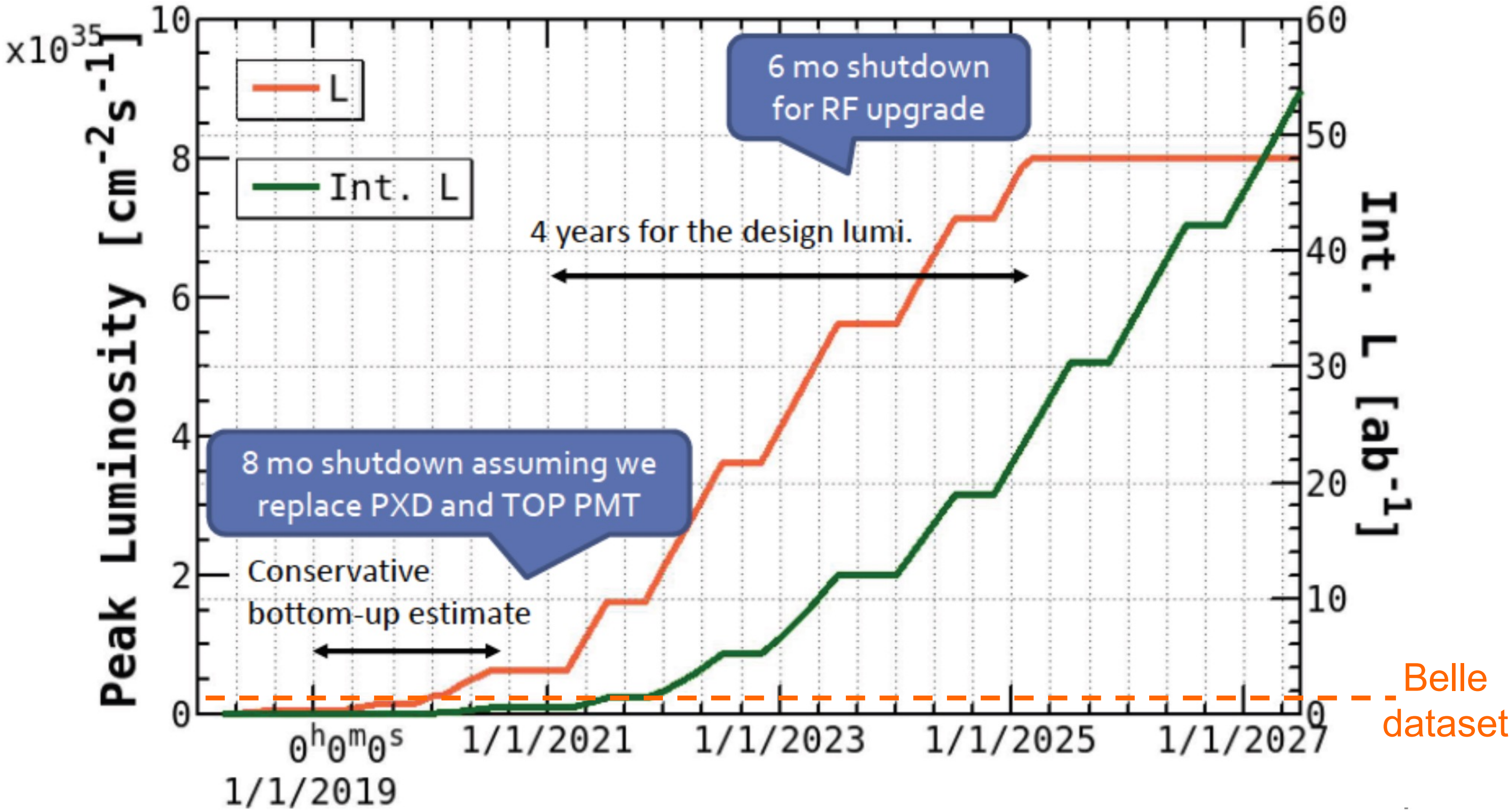
- HL-LHC funded until 2035!

- LHCb: significant detector upgrade in LS2 (now), GPDs follow in LS3

- LHCb also plans upgrade 2 for LS4

	Integrated luminosity	
	LHCb	GPD
Run 1	3	25
Run 2	9	100
Run 3	23	300
Run 4	50	+300+/a
Run 5,6	300+	+300+/a

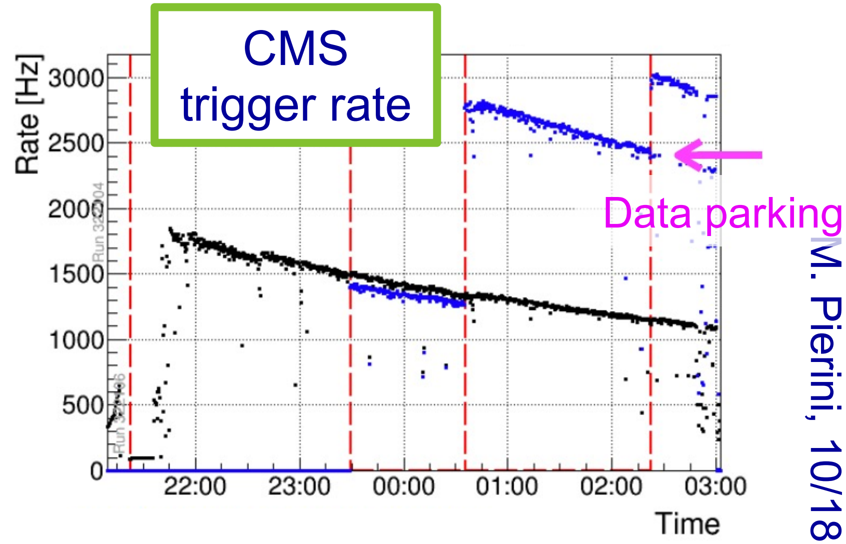
A new player coming up: Belle 2



- Physics run of Belle 2 started
  - First results published
  - Significant luminosity (for LFU tests) ~2024

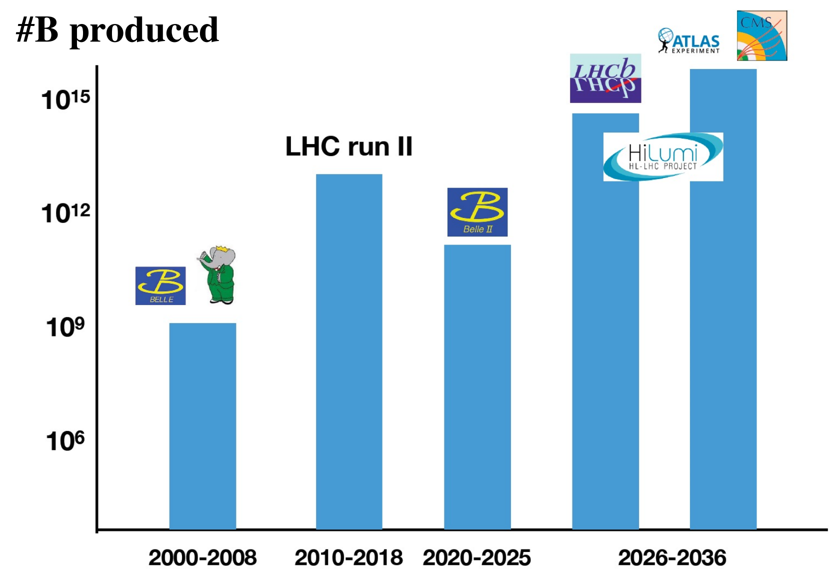
New ideas to exploit flavour

- Trigger & reconstruction are the main bottlenecks to exploit huge GPD flavour samples
  - New 2018: CMS “parks” ~10^9 unbiased B decays
  - Studies on low-PT electron reconstruction ongoing
  - Interesting sensitivity expected



M. Pierini, 10/18

- At HL-LHC: 10^{11} B-hadrons (Belle2 dataset) will be produced every ~30 min
  → is it possible to exploit this dataset?

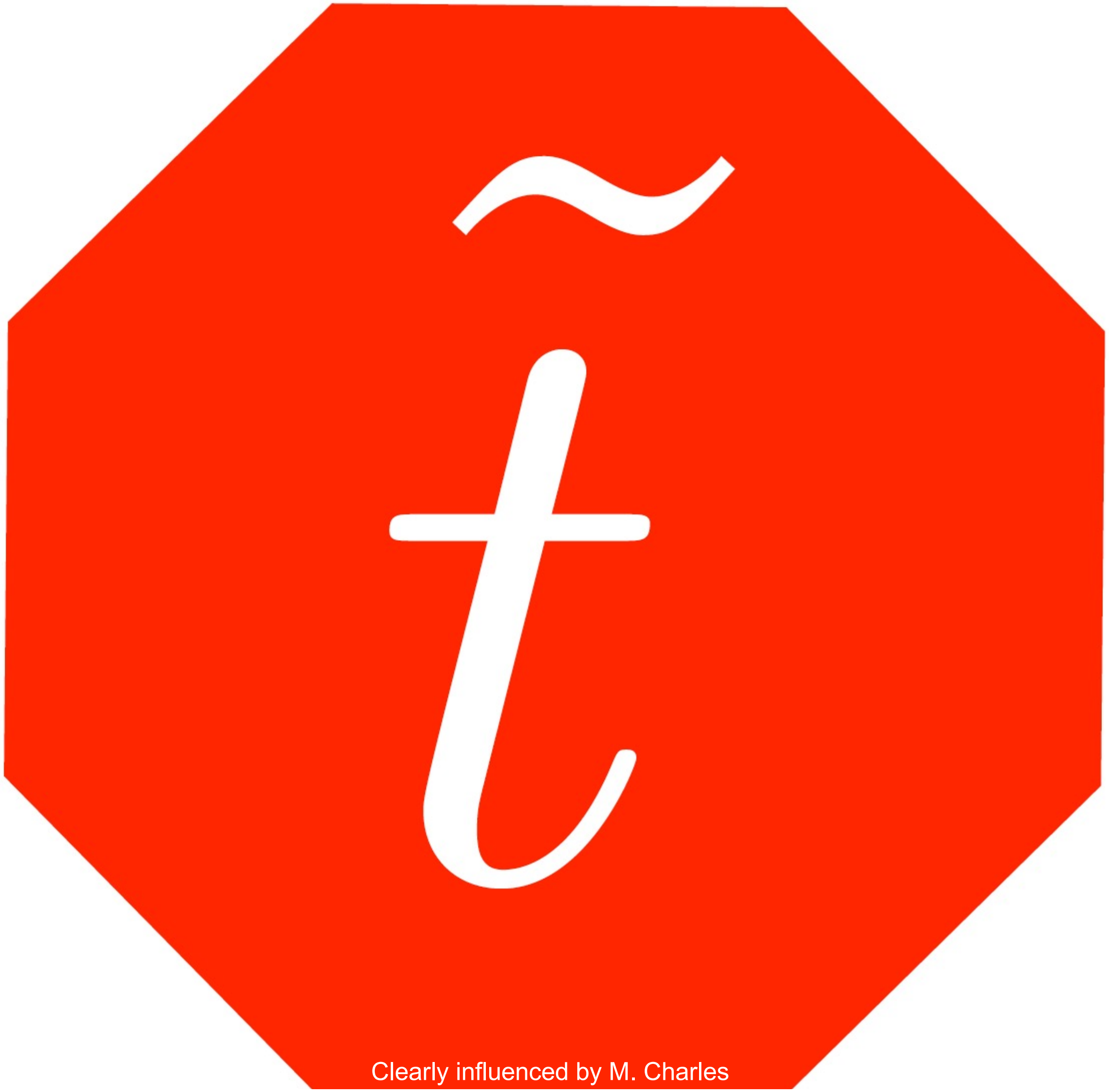


Summary

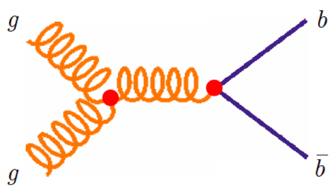
- Flavour physics is a great way to challenge Standard Model
  - CP violation and CKM sector: many sensitive tests,
    CKM picture consistent on ~10% level
  - Charm physics: experiment driven, CPV observed 2019
  - Special area of interest: $b \to s\, \ell^+ \ell^-$: flavour anomalies

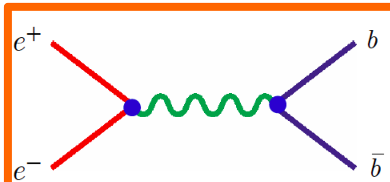
- Intriguing pattern: flavour anomalies
  - BR and angular observables
  - Lepton flavour universality

- Intense experimental program ongoing to verify anomalies


$\tilde{t}$
Clearly influenced by M. Charles

Complementarity LHCb – Belle 2





- Time dependent B_s physics
  - CPV in $B_s \to J/\psi\ \phi$, $B_s \to \phi\phi$
- $B_s \to \mu^+\mu^-$
- CKM angle γ
- CPV in B_d
- $B \to X_s\ \ell^+\ell^-$ (exclusive) → **LFU**
- $B \to X_s\ \gamma$ (exclusive)
- Charm physics
- Semileptonic B decays
- $B \to D\ \tau^-\ \nu$, $B \to D^*\ \tau^-\ \nu$
- Dark matter
- τ – physics: LFV
- $B \to \tau^-\ \nu$, $B \to \mu^-\ \nu$
- $B \to K^*\ \nu\nu$, $B \to \nu\nu$
- $B \to X_s\ \ell^+\ell^-$ (inclusive)
- $B \to X_s\ \gamma$ (inclusive)

"B_s & charged tracks"

Important overlap: sporty competition!

"inclusive & neutrals "

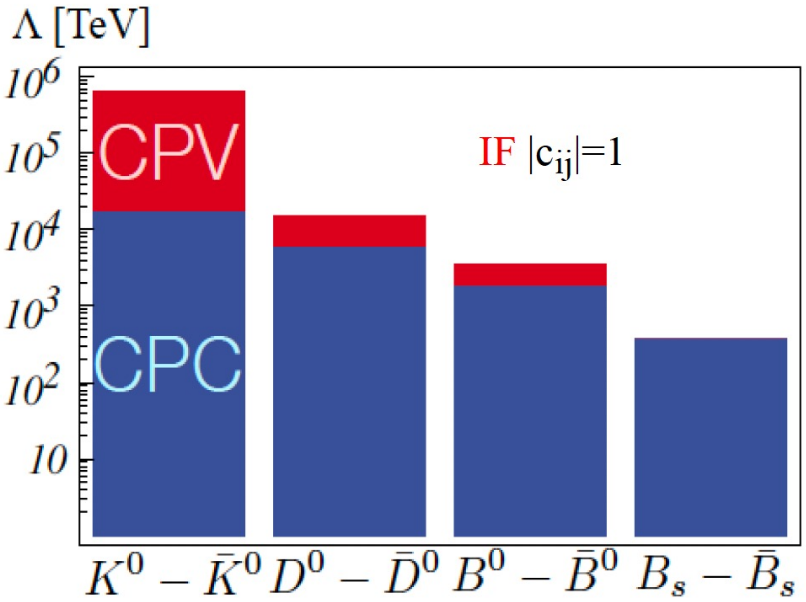
Accessible energy scales

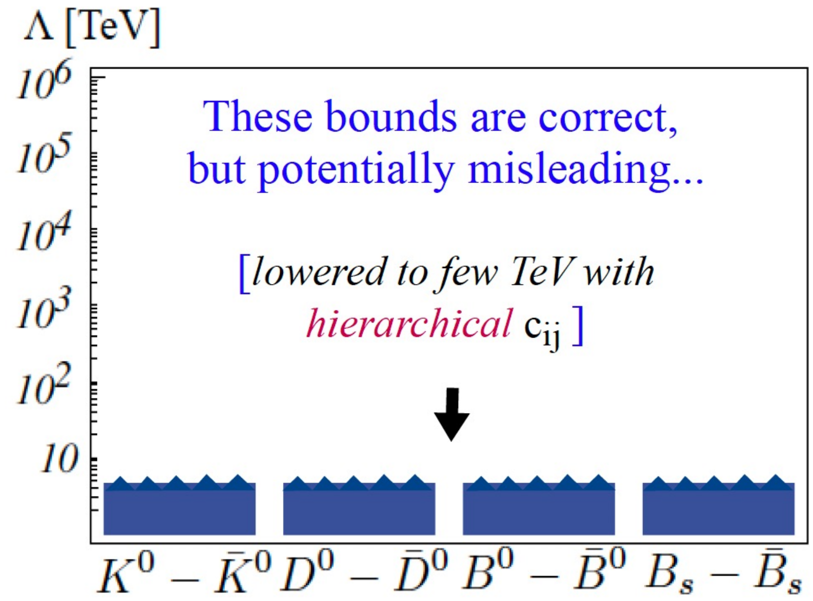
$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

trivial kinematical factors (A_0)

(a-dimensional) effective couplings (c_{SM}, c_{NP})

Very general decompositions: valid for both for forbidden processes (e.g.: $\mu \to e\gamma$) and precision meas. (e.g.: $B_s \to \mu\mu$)





G. Isidori, HL/HE-LHC workshop, March 19