Searching for signal beyond the SM in flavour physics

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IN2P3 Les deux infinis

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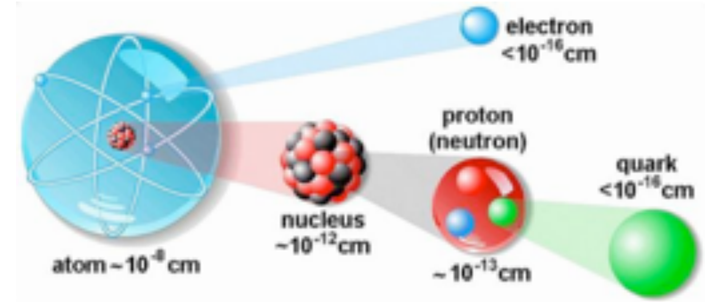
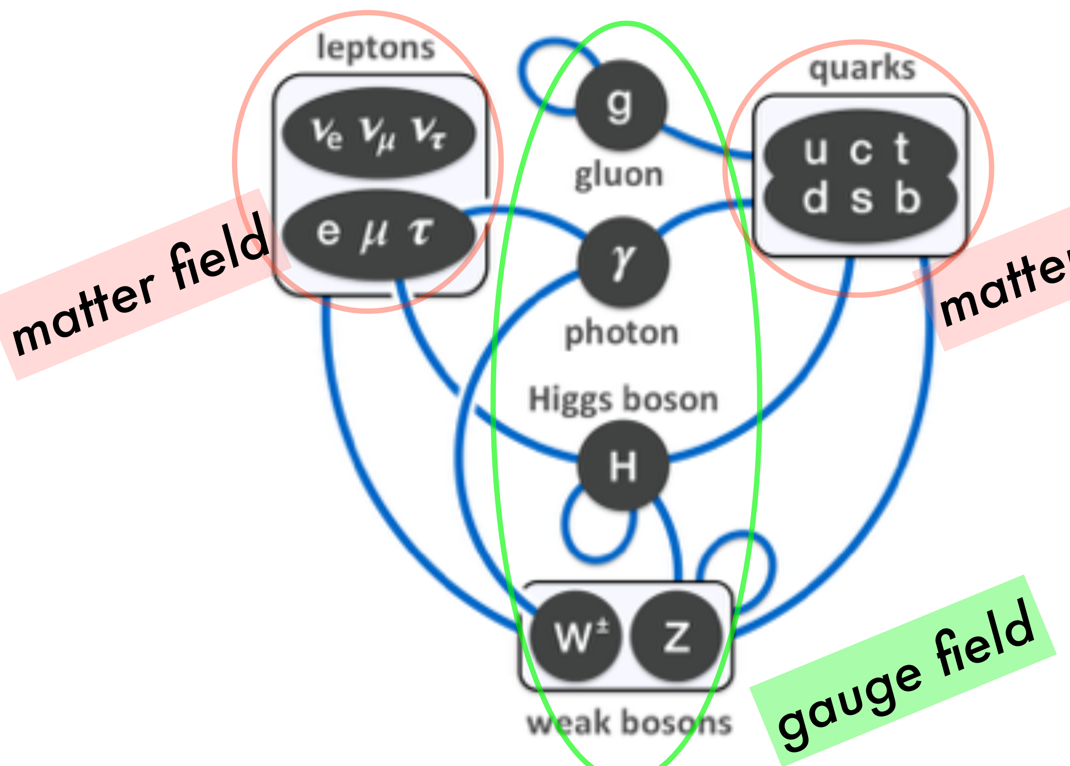
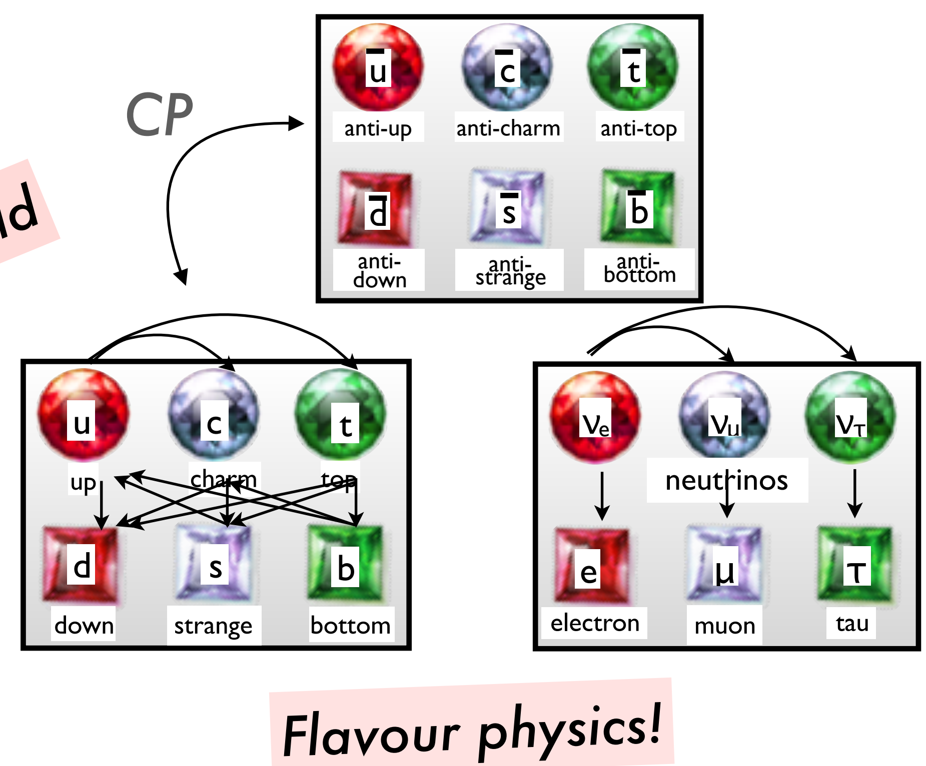
Introduction:
searching new physics in flavour physics

Flavour physics



- Investigating the fundamental interaction through transitions among different **quarks and leptons**
- **The CP violation** is one of the most interesting phenomena in flavour physics





Flavour Physics within SM

In SM, the difference between mass and interaction basis explains, the GIM mechanism, the CP Violation! Very concise!

$$\mathcal{L}_Y = \sum_{ij} Y^u_{ij} \overline{Q_{iL}} \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} u_{jR} + \sum_{ij} Y^d_{ij} \overline{Q_{iL}} \begin{pmatrix} -\phi^{-\dagger} \\ \phi^{0\dagger} \end{pmatrix} d_{jR} + h.c.$$

Yukawa coupling

Glashow, Illiopolous, Maiani '70

$$(U^u_{L,R})^\dagger U^u_{L,R} \equiv \mathbf{1}, \quad (U^d_{L,R})^\dagger U^d_{L,R} \equiv \mathbf{1}$$

Flavour changing neutral current suppression

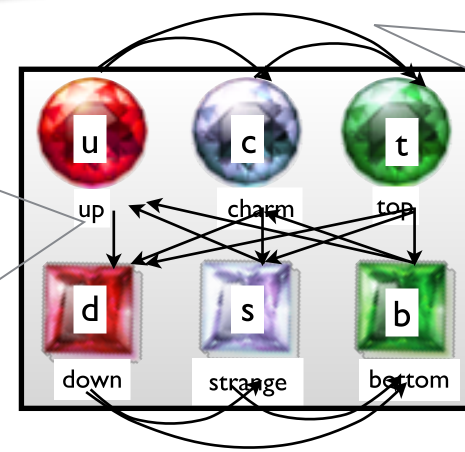
Cabibbo '63
Kobayashi, Maskawa '73

$$(U^u_L)^\dagger U^d_L \equiv V_{\mathrm{CKM}}$$

Charged current: CKM matrix
Origin of CP Violation (complex phase)!

Cronin, Fitch, Christenson,Turlay '64

Vckm: Cabibbo-Kobayashi-Maskawa matrix

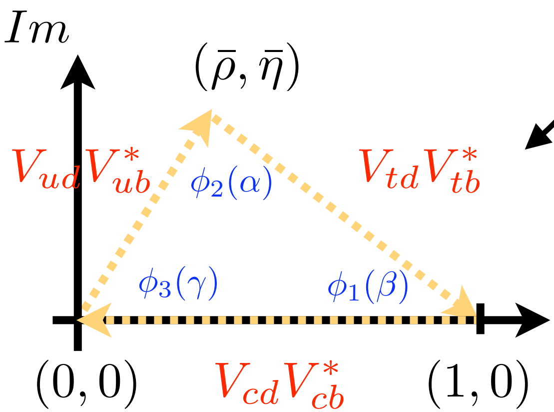


FCNC suppressed

The Unitarity triangle: test of Unitarity

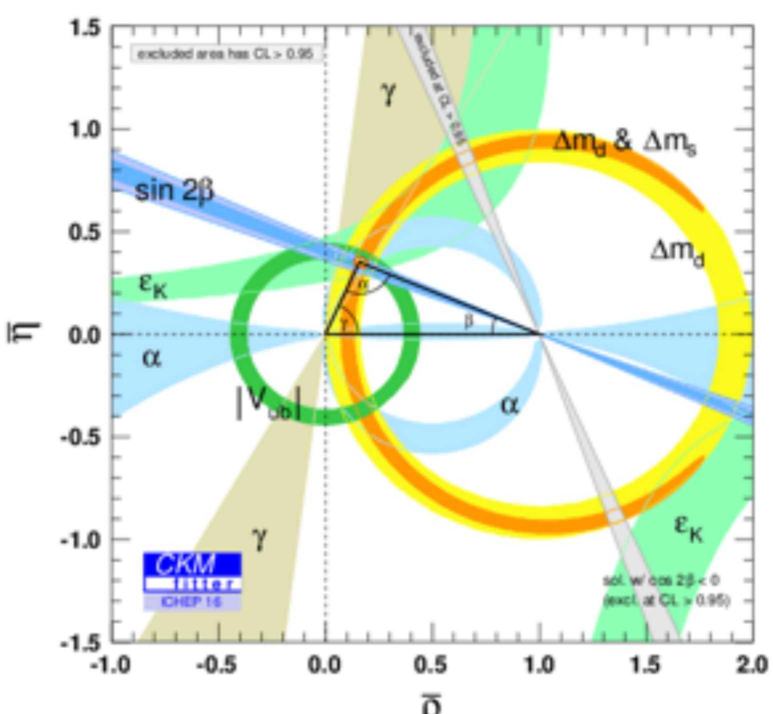
$$\underbrace{V_{ud}V_{ub}^*}_{A\lambda^3(\rho+i\eta)} + \underbrace{V_{cd}V_{cb}^*}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{A\lambda^3(1-\rho-i\eta)} = 0$$

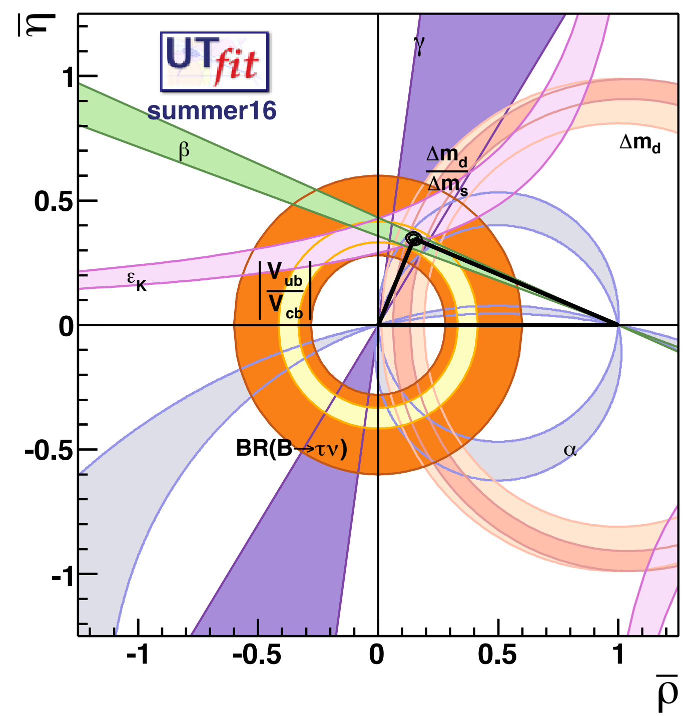
divide by $A\lambda^3$



$$arg\left(\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cs}}\right) \equiv -\phi_1$$
$$arg\left(\frac{V_{tb}^*V_{td}}{V_{ub}^*V_{ud}}\right) \equiv -\phi_2$$
$$arg\left(\frac{V_{cb}^*V_{cs}}{V_{ub}^*V_{ud}}\right) \equiv -\phi_3$$

- Successful explanation of flavour physics up to now! Hundreds of observables (including dozens of CPV) are explained by this single matrix.





Flavour Physics beyond SM

The indirect search of new physics through quantum effect: very powerful tool to search for new physics signal!

- This very simple picture does not exist in most of the extensions of SM: suppression of the FCNC is NOT automatic and also CP violation parameters can appear.
  N.B.: SM also has an "unwanted" CP parameter (strong CP problem).

SUSY: Quark and Squark mass matrices can not be diagonalized at the same time ---> FCNC and CP violation

Mutli-Higgs model, Left-Right symmetric model: Many Higgs appearing in this model ---> tree level FCNC and CP violation

Warped extra-dimension with flavour in bulk: Natural FCNC suppression though, K-K mixing might be too large due to the chiral enhancement

Flavour Physics beyond SM

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SUSY: Quark and Squark mass matrices can not be diagonalized at the same time ---> FCNC and CP violation

Mutli-Higgs model, Left-R... sy...

Warped extra- ... with

New particle introduces new source of flavour/CP violations. Then, if new physics exist, we should observe those phenomena at some point!

The strategies…

Strategy for discovery via precision

Discovery by the intensity frontier experiments.

WE WANT
5-7σ
DEVIATION !!

Reducing uncertainties = probing higher energies

Δ_{NP} = Deviation from SM

$= (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$

$= c/(M_{NP})^n$

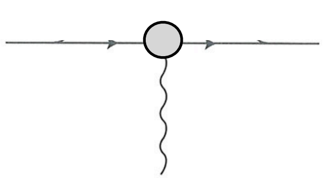
new physics coupling c, new physics scale M_{NP}

E.x. muon g-2

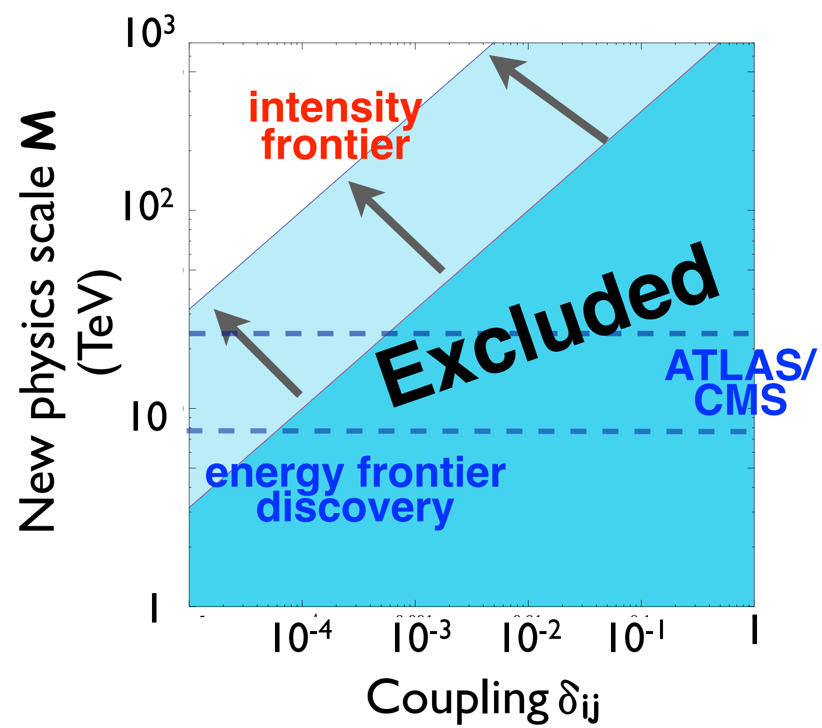
3.6σ effect!

$a_\mu^{exp.} = 116592091(54)(33) \times 10^{-11}$.

$a_\mu^{the.} = 116591803(1)(42)(26) \times 10^{-11}$



$$\frac{e}{M}\, \overline{\psi} \sigma_{\mu\nu} \psi F^{\mu\nu}$$



Reducing experimental uncertainties

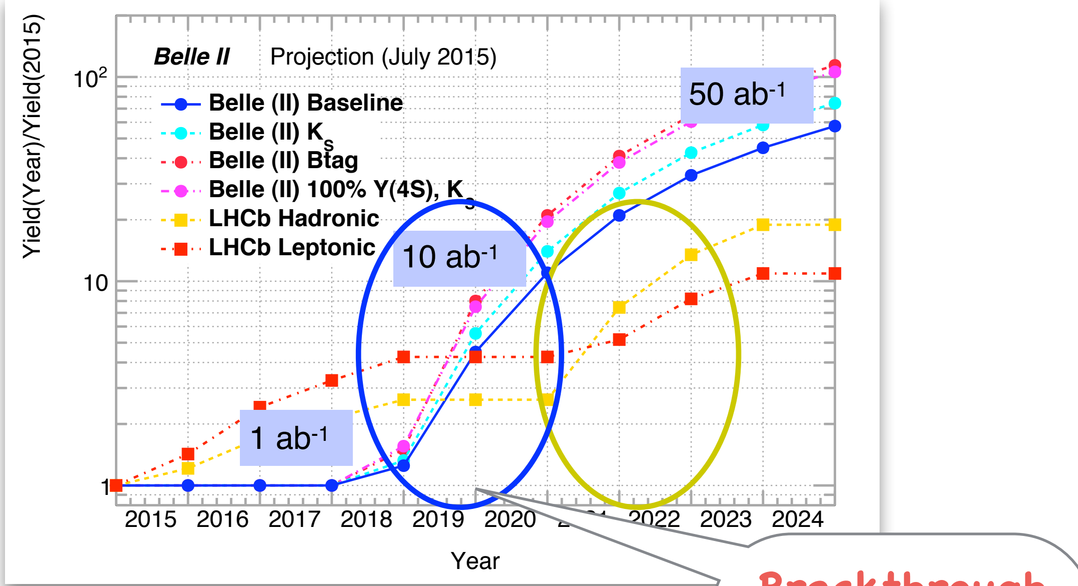
$$\Delta_{NP} = (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$$

Future increase of the luminosity in Heavy Flavour physics

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

LHCb upgrade

BELLE2-NOTE-PH-2015-004



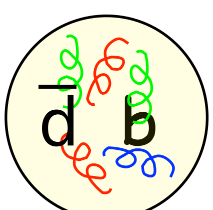
- Belle II increases the luminosity (50 times by 2025)
- We expect order of magnitude increase of sensitivity in LFV (mu-e), EDM, g-2 experiments.
- Hadronic channels become available after LHCb upgrade

Reducing theoretical uncertainties

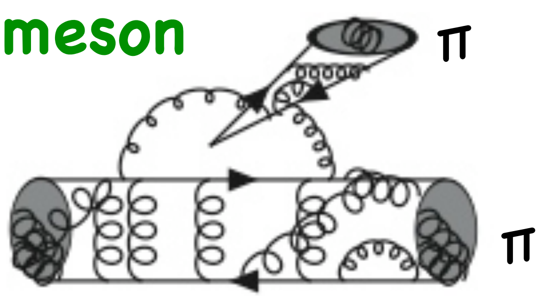
$$\Delta_{NP} = (\text{exp.} - \text{SM}) \pm \sqrt{(\sigma_{exp})^2 + (\sigma_{SM})^2}$$

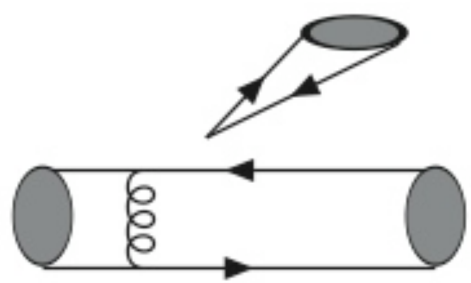
- Theoretical development in QCD higher order corrections, Lattice QCD etc allow to reduce the theoretical uncertainties.
- Improved measurements of "theoretical control channels" are very important to reduce the theoretical errors.

E.x. B meson

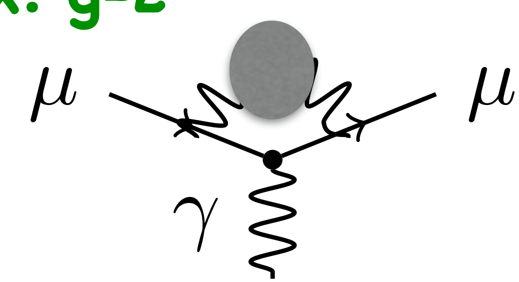


B





E.x. g-2



Lattice QCD, QCD sum rules, Large Nc QCD, HQET, Perturbative QCD etc...

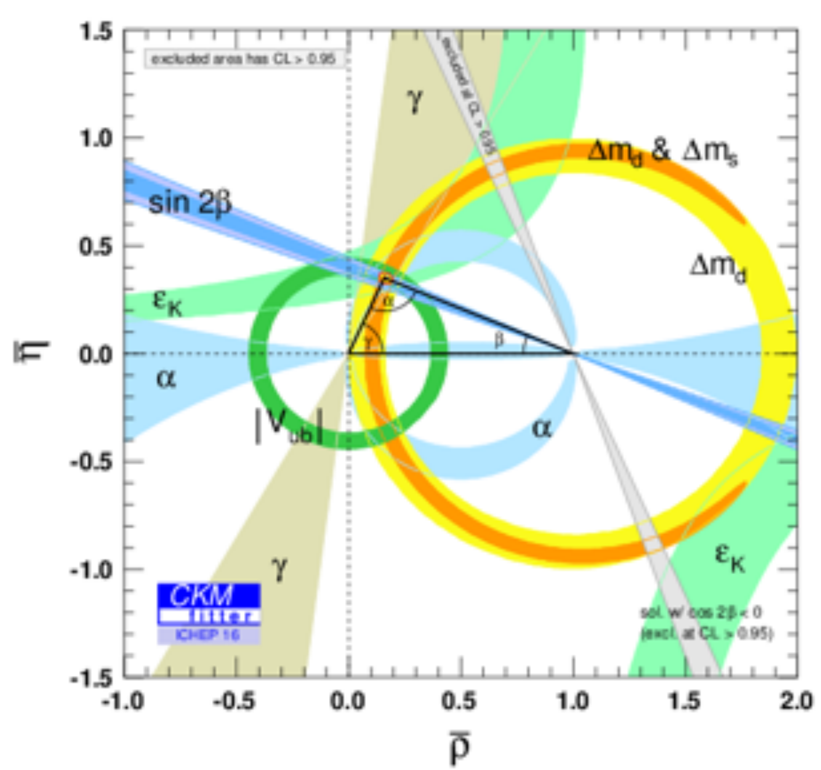
OR

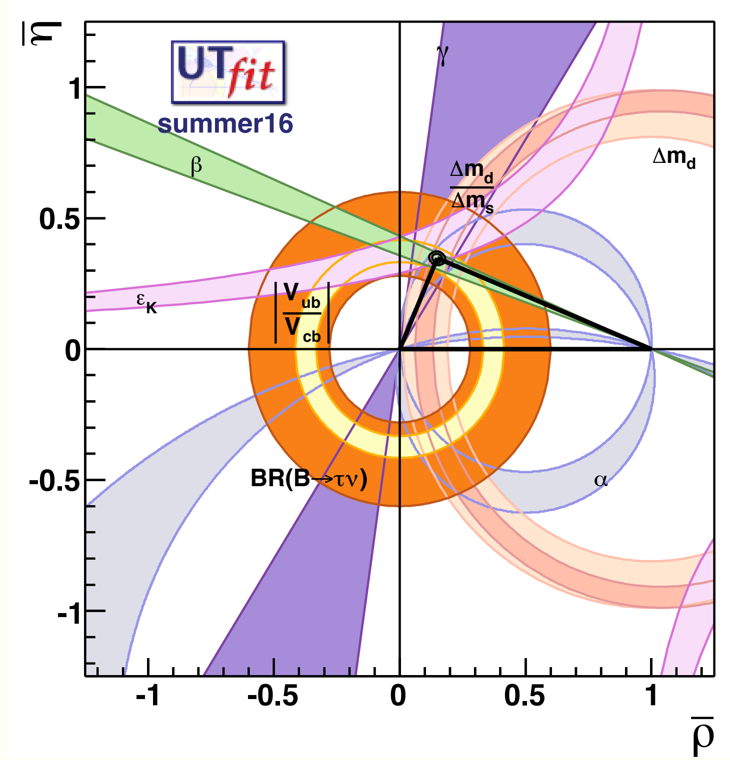
Data driven

What is the odds for discovery: example of CKM unitarity triangle

The Unitarity triangle: test of Unitarity?

Can we expect a discovery of New Physics with the Unitarity Triangle ?!

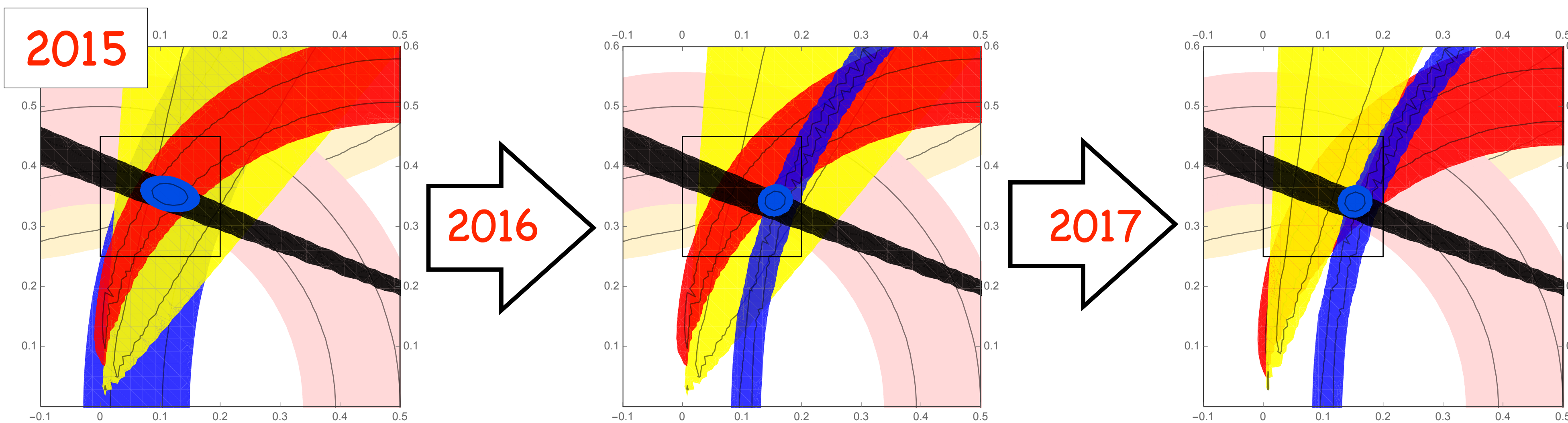




Future of the Unitarity Triangle

What do we expect to see in the future???

E.K. for B2TiP working group



Consistent with SM

New lattice result on ΔMs/ΔMd hadronic parameter: Consistent with SM

Latest average of the γ measurement of LHCb: Consistent with SM

Future of the Unitarity Triangle

What do we expect to see in the future???

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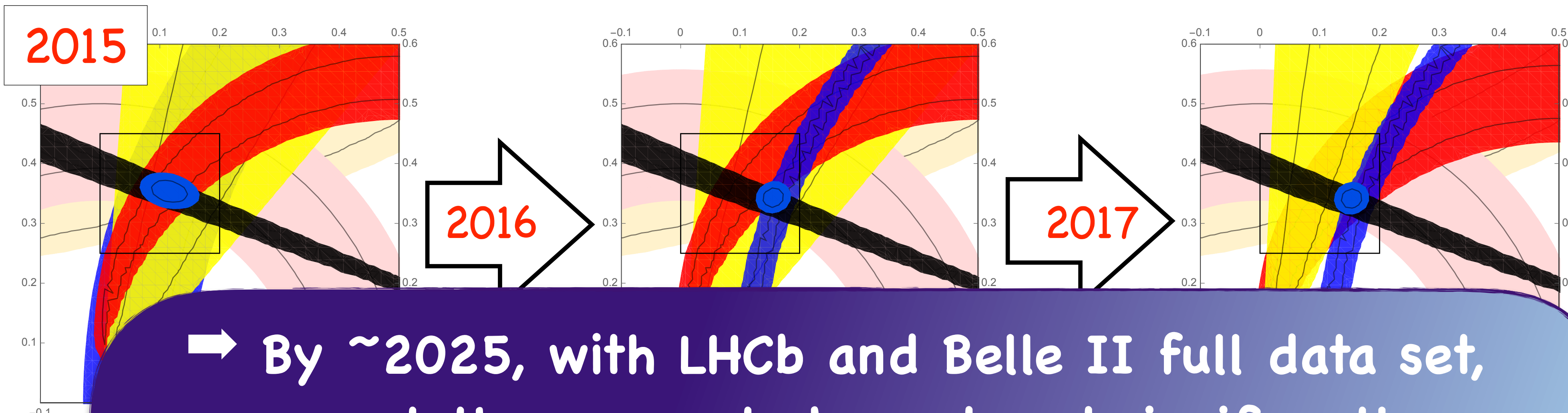


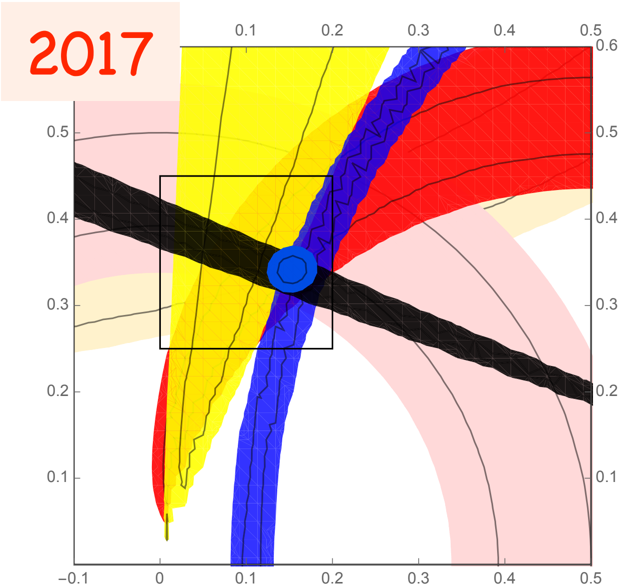
➡ By ~2025, with LHCb and Belle II full data set, we expect the errors to be reduced significantly.

➡ Let's see what could happen when the error will go down to

$$\delta\phi_1\ (\delta\beta)=0.4^\circ,\ \delta\phi_2\ (\delta\alpha)=1^\circ,\ \delta\phi_3\ (\delta\gamma)=1.5^\circ,$$

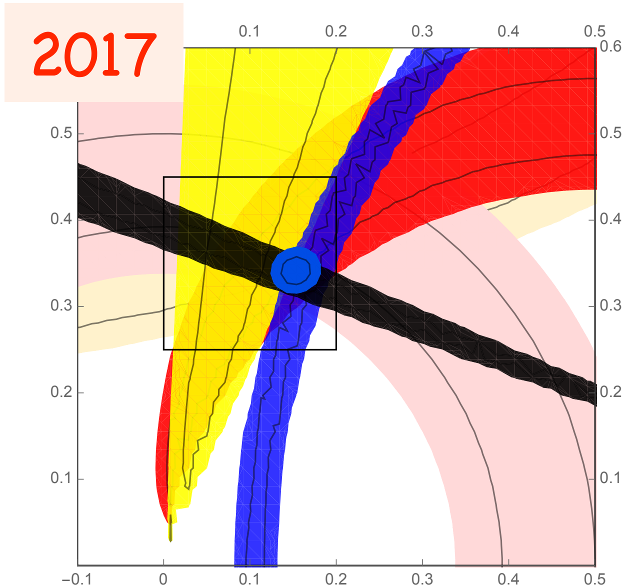
$$\delta V_{ub}^{today}/\delta V_{ub}=1/2$$

Future of the Unitarity Triangle



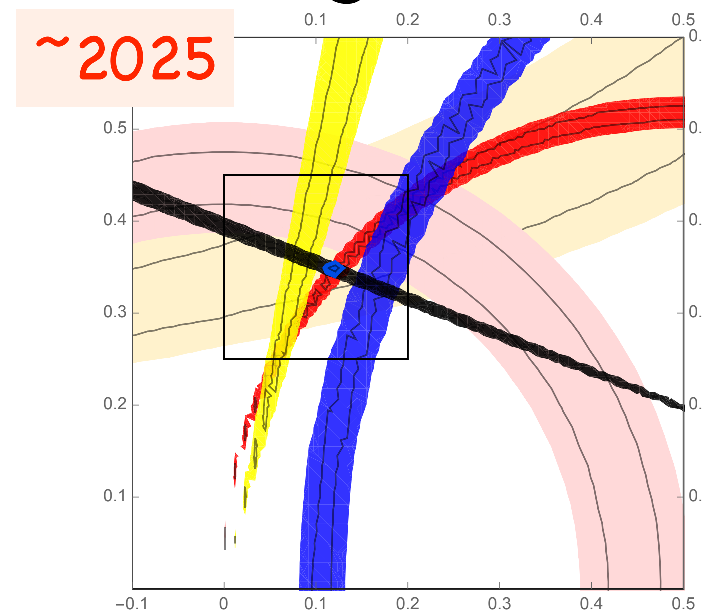
Consistent with SM

Future of the Unitarity Triangle



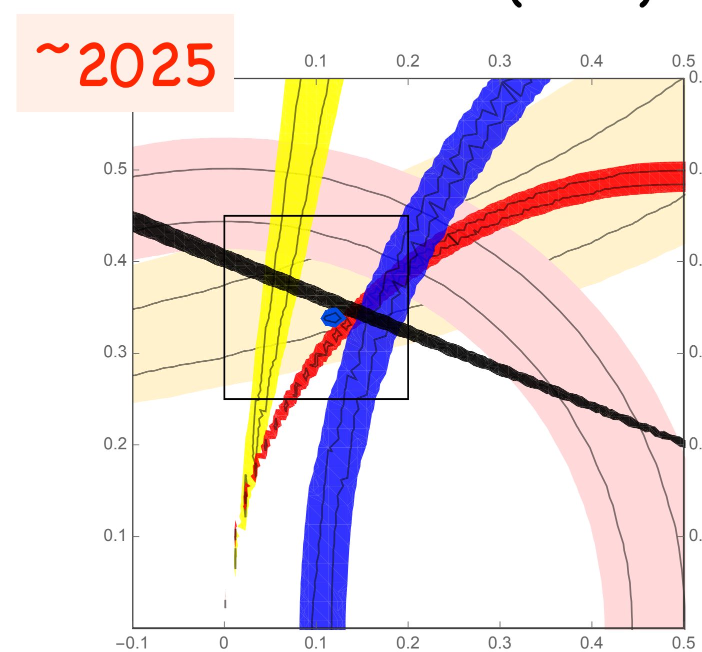
Consistent with SM

If the central value remains exactly the same (though unlikely)...



2σ effect (=SM)

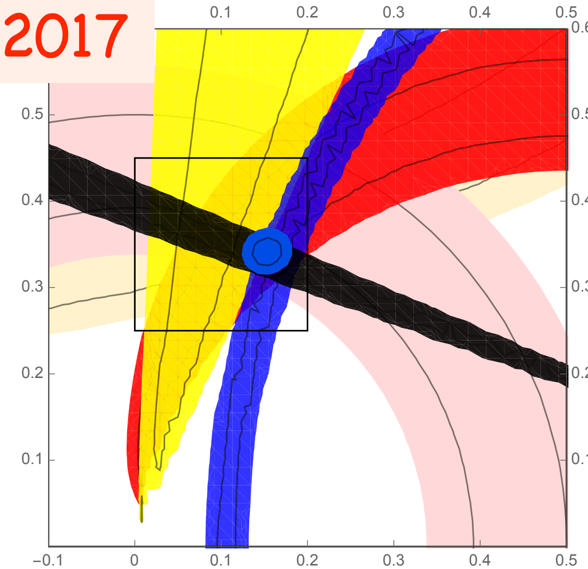
If all the central values move a little higher (within 1σ)...



8σ effect (≠SM)!

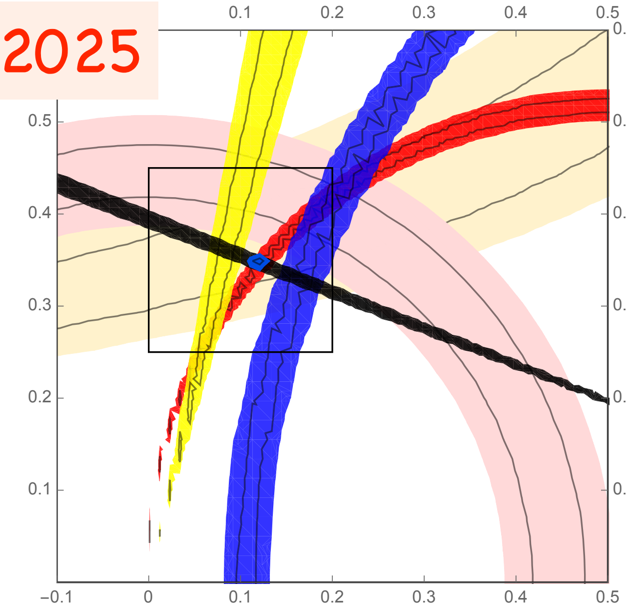
Future of the Unitarity Triangle

2017



Consistent with SM

~2025



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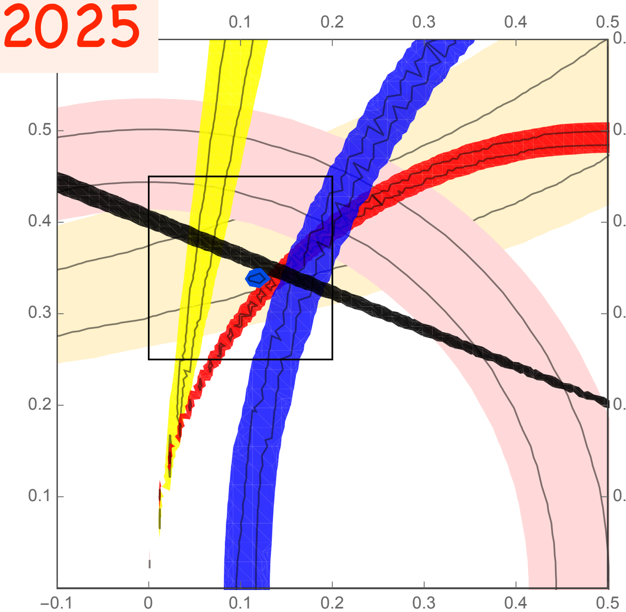
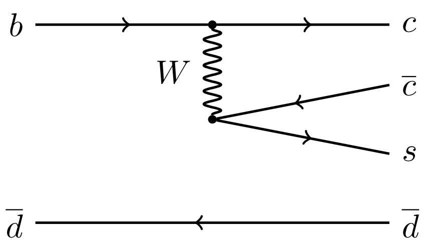
~2025



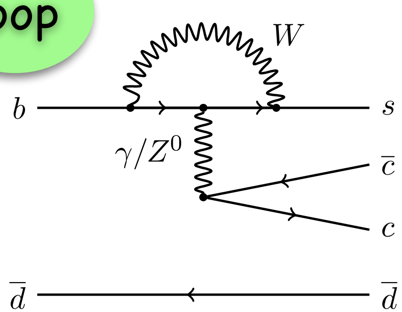
8σ effect (≠SM)!

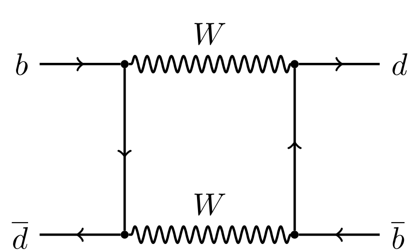
If all the central values move a little higher (within 1σ)...

tree

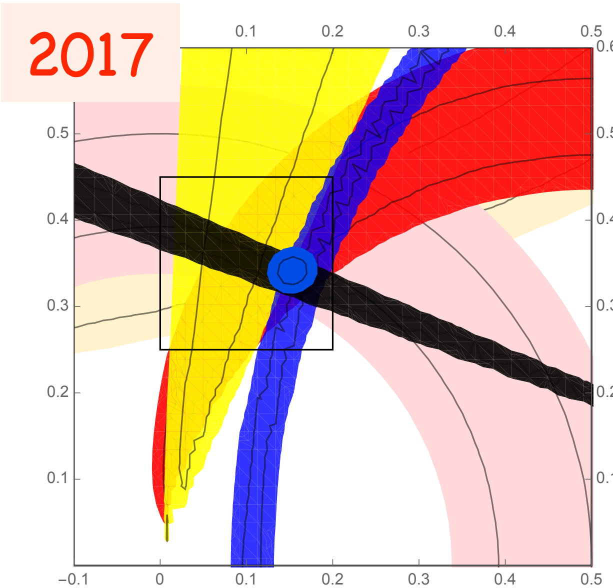


loop





Future of the Unitarity Triangle



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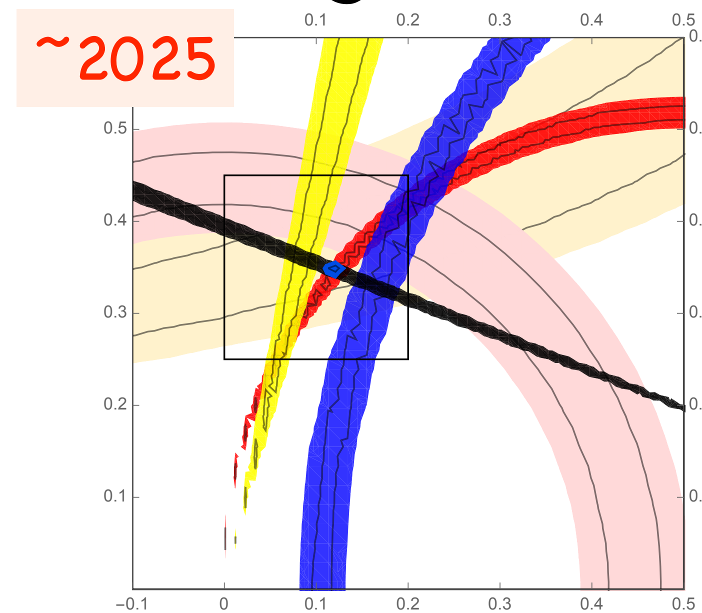

2σ effect (=SM)

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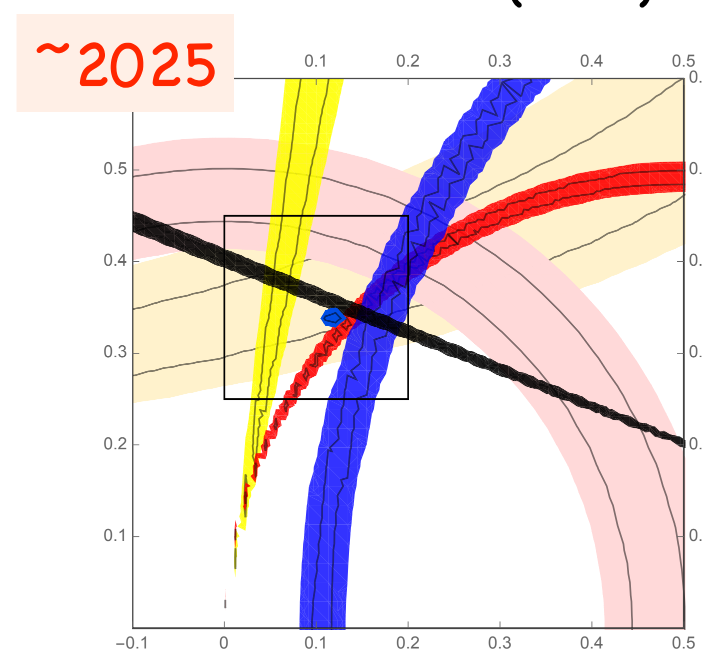
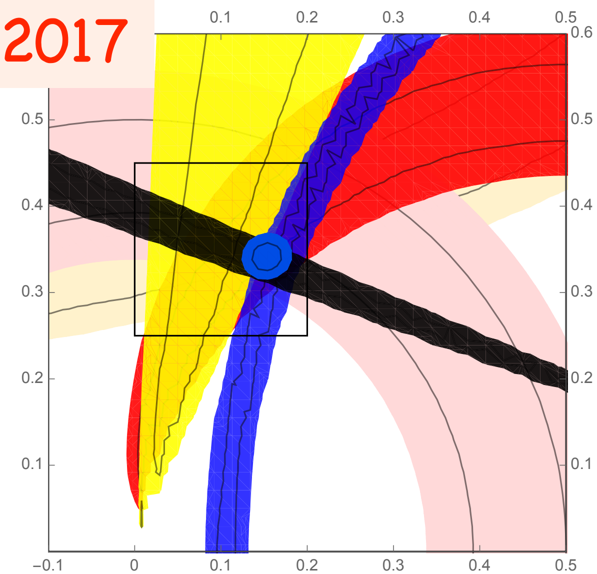


8σ effect ($\neq$SM)!

Is this 8σ
an "odd case" ???
(the answer is NO!)

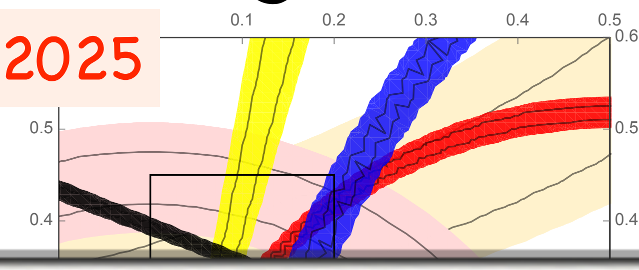
Future of the Unitarity Triangle

2017



Consistent with SM

~2025



If the central

Is this 8σ
an "odd case" ?
(the answer is N

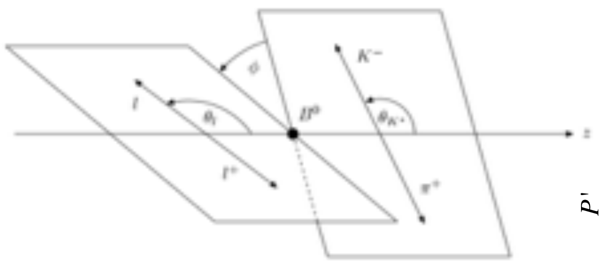
- To understand this "8σ" effect better, we have run a Monte Carlo simulation.
- We randomly sample the central values (1000 trials) assuming Gaussian measurements and compute the significance.
- The result shows that **the chance to observe deviation more than 5σ (8σ) significance is currently 60% (20%) !**

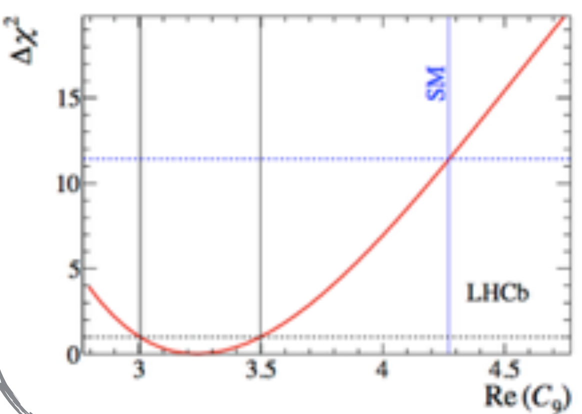
E.K. & F. Le Diberder for B2TiP working group

Near future of flavour physics…

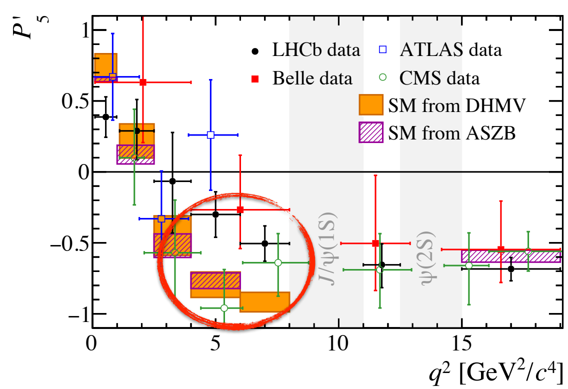
LHCb Run-II anomalies and theory?

B->K*μ+μ-: Re(C9) (3.4σ)

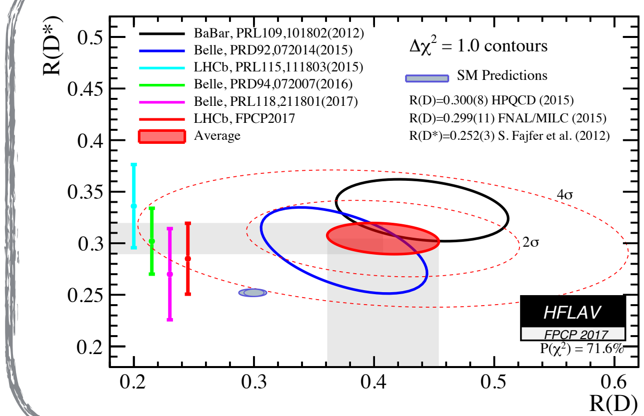




P5′

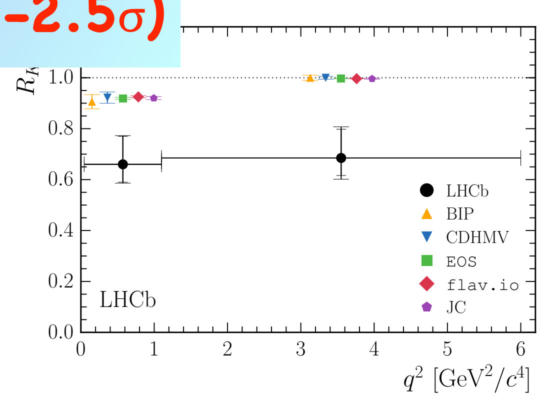


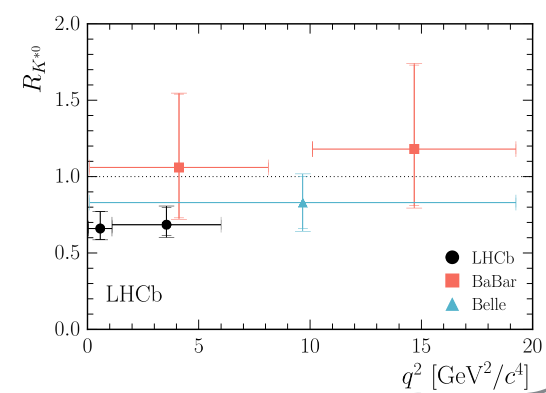
B->D*τν/B->D*τν: R(D*) (4.1σ)



B->K*e+e-/K*μ+μ-: R(K*) (2.1-2.5σ)

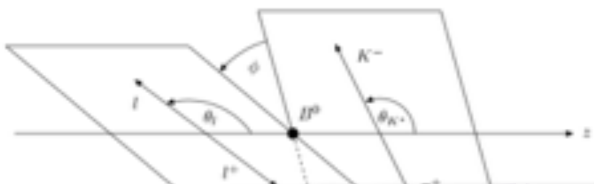
	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\ ^{+\,0.11}_{-\,0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]





LHCb Run-II anomalies and theory?

B->K*μ+μ-: Re(C9) (3.4σ)



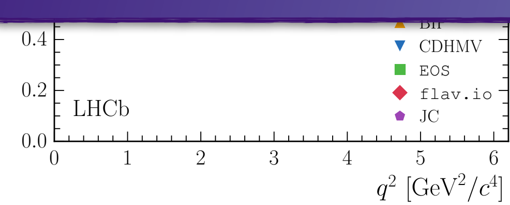
P5′

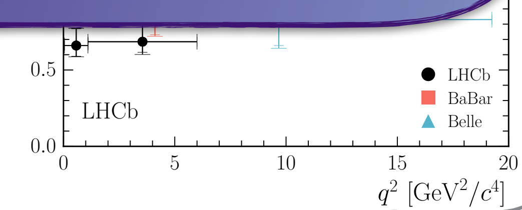
B->D*τν/B->D*τν: R(D*) (4.1σ)

B-

- Very convincing signals.
- SM uncertainties in B->K*μ+μ- to be further scrutinised.
- Many model independent studies (e.g. global fit of the effective couplings) are ongoing.
- The appearance of the anomaly implies a very "flavour/Dirac structure specific" new physics.

95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]





Many contributions from theorists!!

Belle II physics book

arXiv:1808.10567 (689 pages, submitted to PTEP)
Belle II collaboration + B2TiP theory community
Editor: E.K. & P. Urquijo

B2TiP acknowledges JENNIFER supports

- **B physics** : CKM UT measurement, rare decays, CP violation, QCD-based computation
- **D physics** : CP violation, rare decays, multi-body decays

Belle II(/LHCb) precision vs theory uncertainties

» UT angle measurements (very clean): Belle II+LHCb will reduce the errors significantly $\delta\phi_1(\delta\beta)=0.2°$, $\delta\phi_2(\delta\alpha)=1°$, $\delta\phi_3(\delta\gamma)=1.5°$, ⇨ theory can achieve about the same precision.

» Rare decays, hadronic B decays... ⇨ more difficult but data driven, more measurements could give us a guide.

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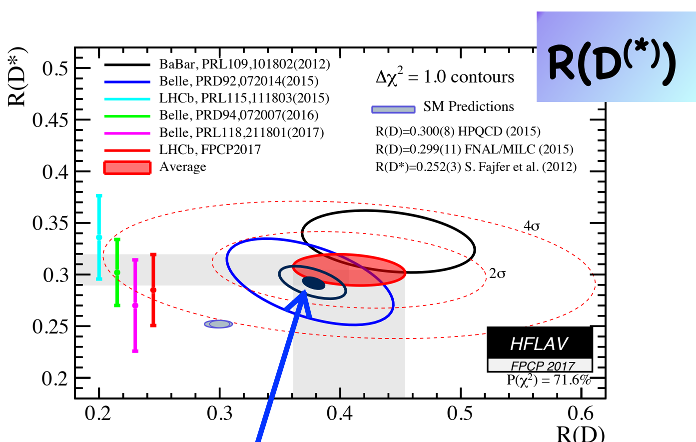
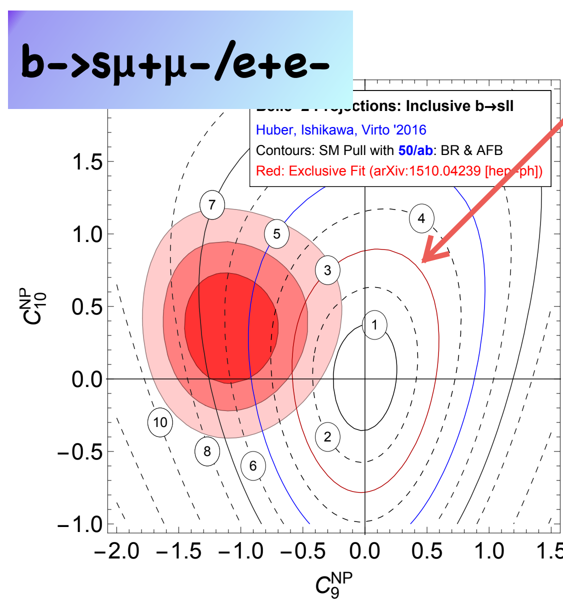
Will Belle II tell us something about LHCb anomalies?

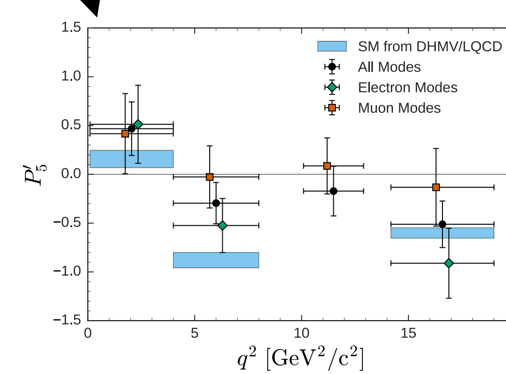


Belle II prospect
(with the current Belle central value)
14(6)σ deviation with 50(10)ab^{-1} of data!



Belle II confirmation via inclusive channel.

A high sensitivity to e+e- channel



» Also observation of B->γγ, K(*)νν̄ in a few years!

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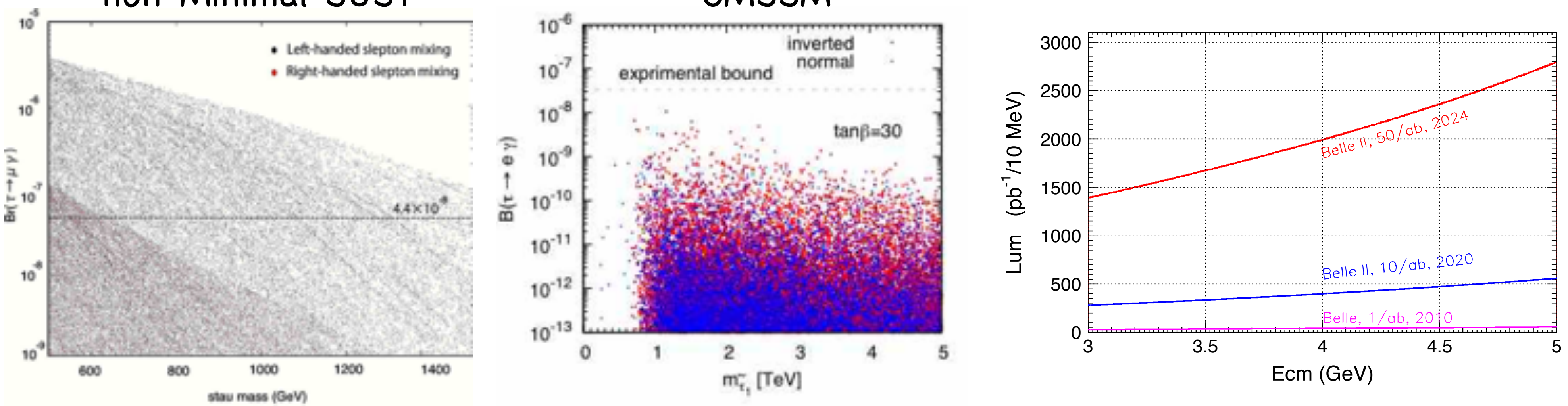
- **tau physics** : LFV, CP violation, a "wish list"...
- **g-2 related measurement** : hadronic cross section, two photon processes
- **quarkonium and exotics** : missing quarkonium (below threshold), pros and cons of the exotic interpretations

non-Minimal SUSY

CMSSM



LFV τ-> μγ sensitivity to SUSY-GUT

ISR luminosity at Belle II

Many contributions from theorists!!

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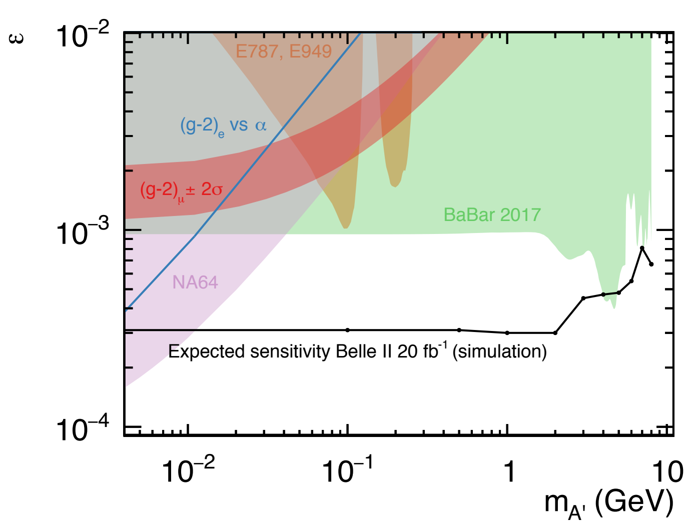
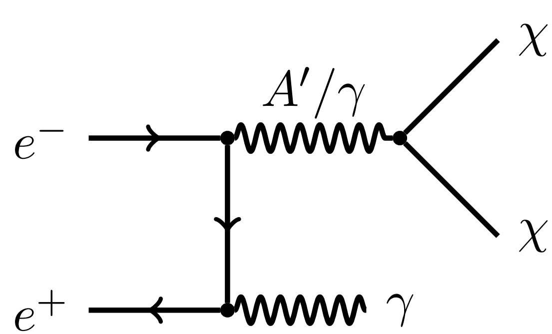
arXiv:1808.10567 (689 pages, submitted to PTEP)
Belle II collaboration + B2TiP theory community
Editor: E.K. & P. Urquijo

B2TiP acknowledges JENNIFER supports

- **Dark matter and Higgs** : dark photon search in phase II (2018), light Higgs search from quarkonium decays
- **Theory**: lattice "forecast", flavour benchmark models (and their "DNA test"), global fit packages

Dark Photon search at Belle II





Lattice forecast for Vub

$\mathcal{L}$ [ab^{-1}]	$\sigma_{\mathcal{B}}$ (stat±sys)	$\sigma_{LQCD}^{forecast}$	$\sigma_{V_{ub}}$
1	3.6 ± 4.4 1.3 ± 3.6	current	6.2, 6.2 3.6, 3.6
5	1.6 ± 2.7 0.6 ± 2.2	in 5 yrs	3.2, 3.0 2.1, 1.9
10	1.2 ± 2.4 0.4 ± 1.9	in 5 yrs	2.7, 2.6 1.9, 1.7
50	0.5 ± 2.1 0.2 ± 1.7	in 10 yrs	1.7, 1.4 1.3, 1.0

upper/down number: wo/w EM correction

Many contributions from theorists!!

Belle II physics book

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B2TiP continues!

1st Physics Week held (22-26 Oct. 2018)

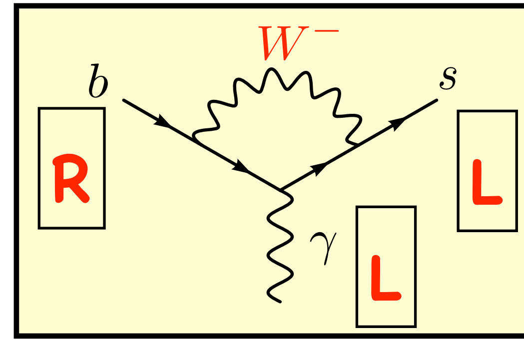
supported by Theory group of KEK

https://kds.kek.jp/indico/event/27330/

Last but not least...

Photon polarization of $b \to s\gamma$ modes

- The photon polarization of $b \to s\gamma$ process has an unique sensitivity to BSM with right-handed couplings.
- However, the photon polarization has never been measured at a hight precision so far: an important challenge for future experiments such as LHCb and Belle II.



In SM

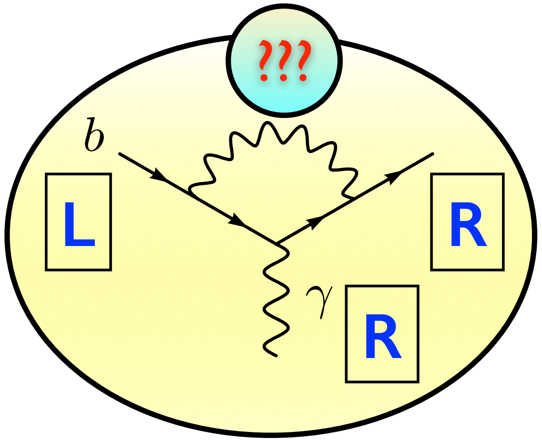
W-boson couples only left-handed ⟺ γ of $b \to s\,\gamma$ should be circularly-polarized

✍ $b \to s\,\gamma_L$ (left-handed polarization)

✍ $\bar{b} \to \bar{s}\,\gamma_R$ (right-handed polarization)

Last but not least...

Right-handed: which NP model?



- **What types of new physics models?**
  For example, models with right-handed neutrino, or custodial symmetry in general induces the right handed current.

Left-Right symmetric model (W_R)	SUSY GUT model δ_{RR} mass insertion
Blanke et al. JHEP1203	*Girrbach et al. JHEP1106*

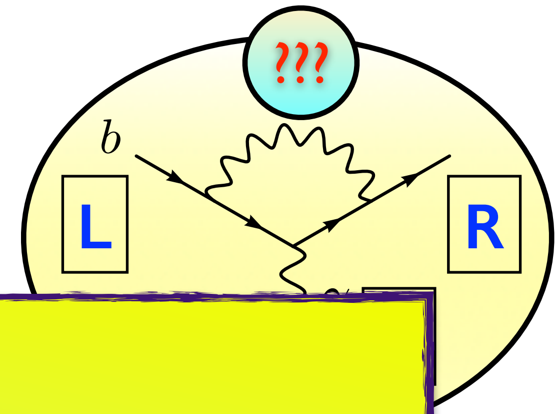
- **Which flavour structure?**
  The models that contain new particles which change the chirality inside of the $b \to s\gamma$ loop can induce a large chiral enhancement!

Left-Right symmetric model: m_t/m_b	SUSY with δ_{RL} mass insertions: m_{SUSY}/m_b
Cho, Misiak, PRD49, '94 *Babu et al PLB333 '94*	*Gabbiani, et al. NPB477 '96* *Ball, EK, Khalil, PRD69 '04*

NP signal beyond the constraints from Bs oscillation parameters possible.

Last but not least...

Right-handed: which NP model?



- What types of new physics models?

For example, models with right-handed

The new physics which are hinted (and which we are looking for) might have a strong connection to the neutrino sector...

This JENNIFER community could offer a great framework to investigate further such possibilities!

Cho, Misiak, PRD49, '94
Babu et al PLB333 '94

Gabbiani, et al. NPB477 '96
Ball, EK, Khalil, PRD69 '04

Conclusions

- The coming years are very exciting: the upgrades of several experiments in flavour physics will improve the sensitivity to new physics drastically. A breakthrough is possible!
- The LHCb anomalies are very intriguing. A confirmation by Belle II experiment is possible even in a few years time (e.g. at ~10 ab^{-1}).
- Theoretically, what we are looking for seems to be "Flavour/Dirac structure specific", which may need be postulated to further construct new physics models.
- Connection to neutrino physics might offer an interesting possibility of top-down model building. We will certainly investigate it in the framework of JenniferII.

Backup

What has been confirmed?

Observed Quark masses

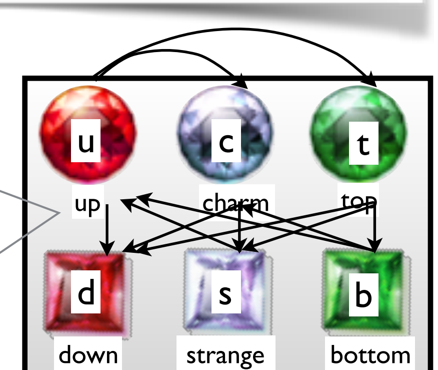
	1st generation	2nd generation	3rd generation
up type charge 2/3	up 2.2±0.5MeV	charm 1.27±0.03GeV	top 173.21±0.87GeV
down type charge -1/3	down 4.7±0.5MeV	strange 96±6MeV	bottom 4.18±0.04GeV
charged lepton charge -1	electron 0.511MeV	μ 105.7MeV	τ 1.78GeV
neutrinos charge 0	ν_e <2.0eV	ν_μ <0.17eV	ν_τ <18.2eV

Observed Quark mixing V_{CKM}

	down	strange	bottom
up	Vub 0.97417±0.00021	Vus 0.2248±0.0006	Vub 0.00409±0.0003
charm	Vcd 0.220±0.005	Vcs 0.995±0.016	Vcb 0.0405±0.0015
top	Vtd	Vts	Vtb 1.009 ± 0.031

- ✓ SM does not say anything about the Yukawa coupling so the masses and the couplings are not predictable.
- ✓ **V_{CKM} has to be a 3x3 unitary matrix which includes only one complex phase.**
- ✓ N.B. LHC and LCs can tell us the linearity of the masse and the Higgs coupling.

Vckm: Cabibbo-Kobayashi-Maskawa matrix



What has been confirmed?

Observed Quark masses

	1st generation	2nd generation	3rd generation
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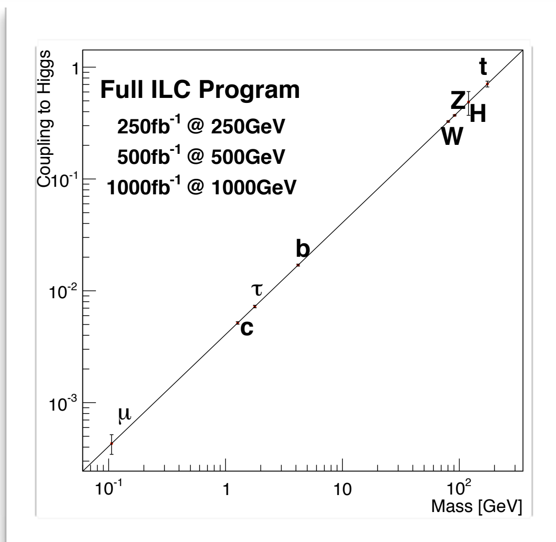
dov chai			
ch l ch			
ne ch			
c			1.009 ± 0.031



DBD 2012

Do fermion masses come entirely from the Yukawa coupling? (c.f. eta' for light mesons!)

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