PHYSICS AT THE TERASCALE
Helmholtz Alliance

Latest News from Flavour Physics

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Introduction:
Searching new physics in B 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

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

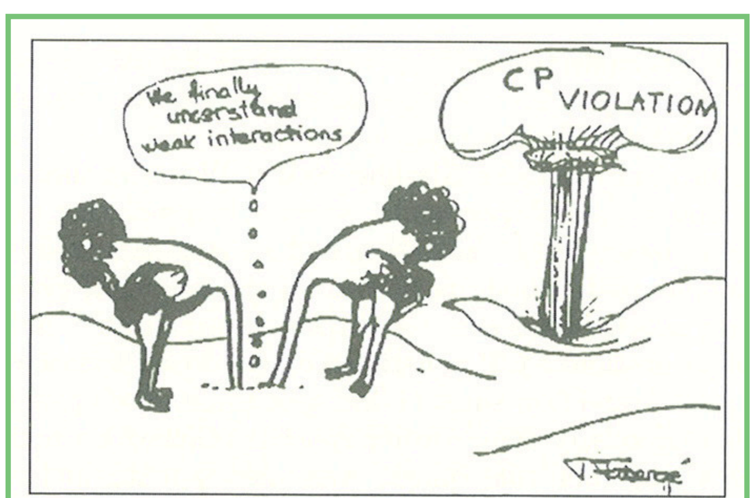
Flavour changing neutral current suppression

Cabibbo '63
Kobayashi, Maskawa '73

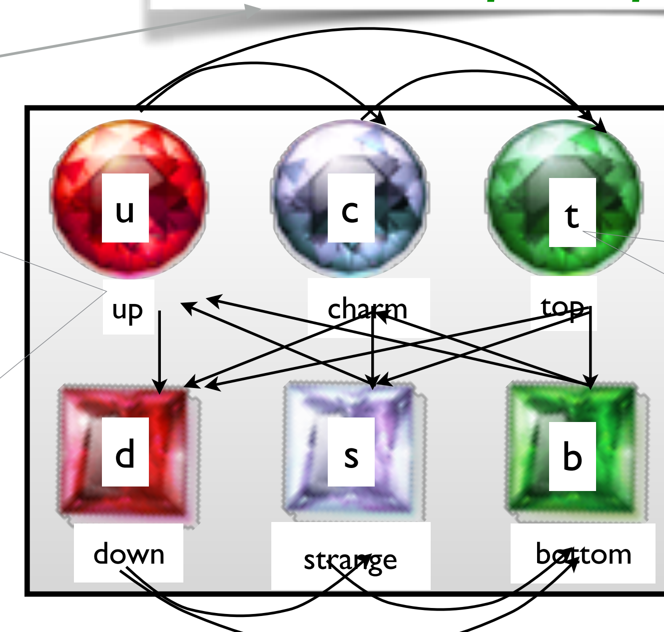
$$(U^u_L)^\dagger U^d_L \equiv V_{\rm CKM}$$

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

Cronin, Fitch, Christenson,Turlay '64



Vckm: Cabibbo-Kobayashi-Maskawa matrix



FCNC suppressed

What has been confirmed?

Observed Quark masses

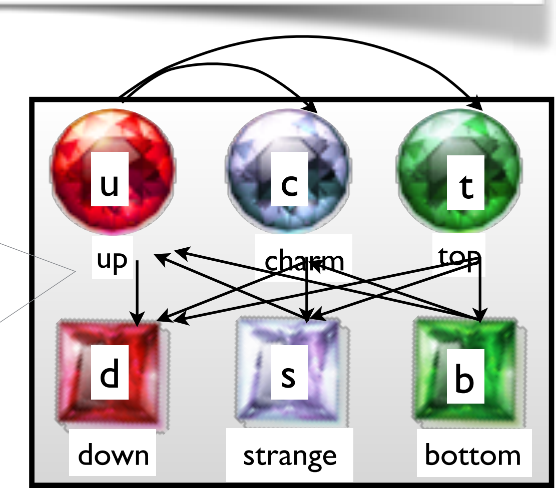
	1st generation	2nd generation	3rd generation
up type charge 2/3	up 2.2±0.5MeV	charm 1.27±0.03GeV	top 173.21±0.87GeV
down type charge -1/3	down 4.7±0.5MeV	strange 96±6MeV	bottom 4.18±0.04GeV
charged lepton charge -1	electron 0.511MeV	μ 105.7MeV	τ 1.78GeV
neutrinos charge 0	ν_e <2.0eV	ν_μ <0.17eV	ν_τ 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

Observed Quark mixing V_{CKM}

	down	strange	bottom
up	Vub 0.97370±0.00014	Vus 0.2245±0.0008	Vub 0.00382±0.00024
charm	Vcd 0.221±0.004	Vcs 0.997±0.011	Vcb 0.0410±0.0014
top	Vtd	Vts	Vtb 1.013 ± 0.030

- ✓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.

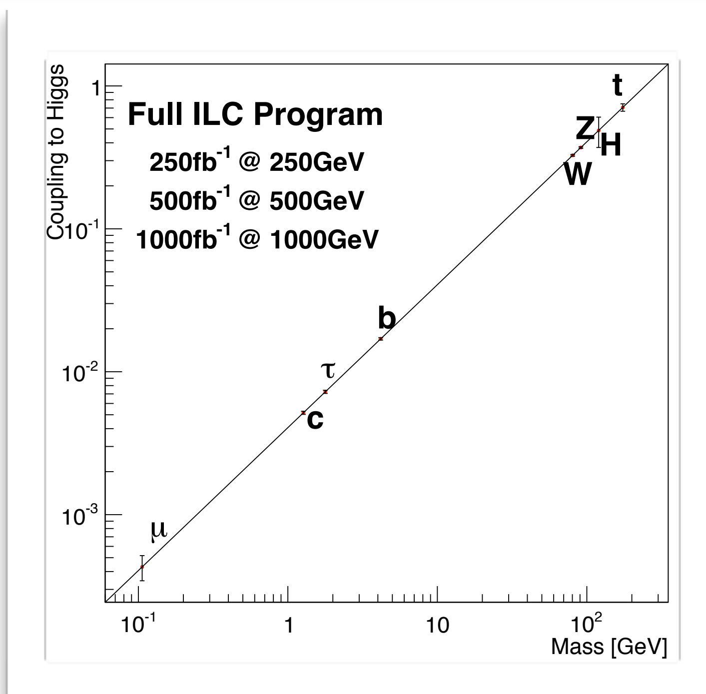
Vckm: Cabibbo-Kobayashi-Maskawa matrix



What has been confirmed?

Observed Quark masses

	1st generation	2nd generation	3rd generation
up type cha	up	charm	top
dov char			
ch l ch			
ne ch			
c			1.009 ± 0.031

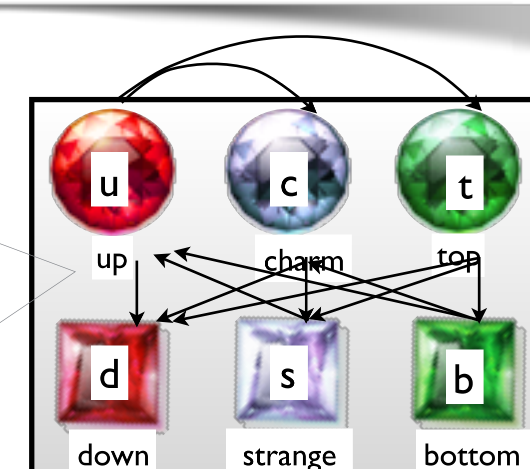


DBD 2012

Do fermion masses come entirely from the Yukawa coupling?

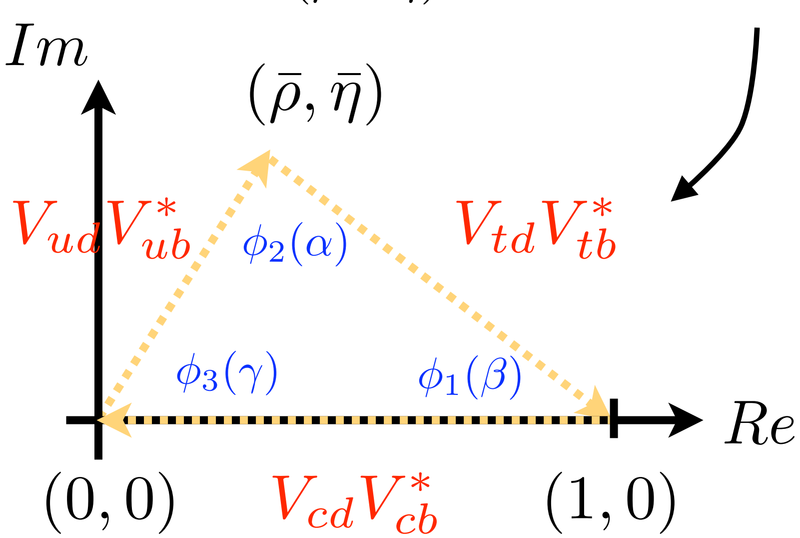
- ✓ SM does not say anything about the Yukawa coupling so the masses and the couplings are not predictable.
- ✓ **V_{CKM} has to be a 3x3 unitary matrix which includes only one complex phase.**
- ✓ N.B. LHC and LCs can tell us the linearity of the masse and the Higgs coupling.

Vckm: Cabibbo-Kobayashi-Maskawa matrix



What has been confirmed?

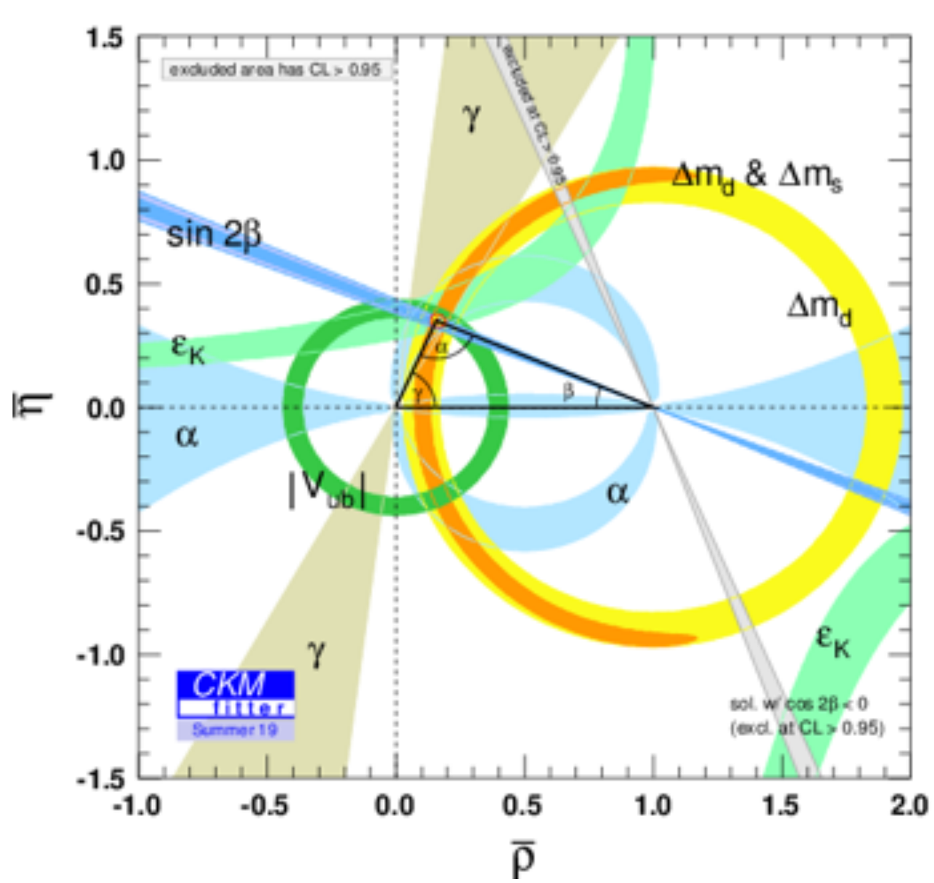
$$\underbrace{V_{ud}V_{ub}^*}_{A\lambda^3(\rho+i\eta)} + \underbrace{V_{cd}V_{cb}^*}_{-A\lambda^3} + \underbrace{V_{td}V_{tb}^*}_{A\lambda^3(1-\rho-i\eta)} = 0$$

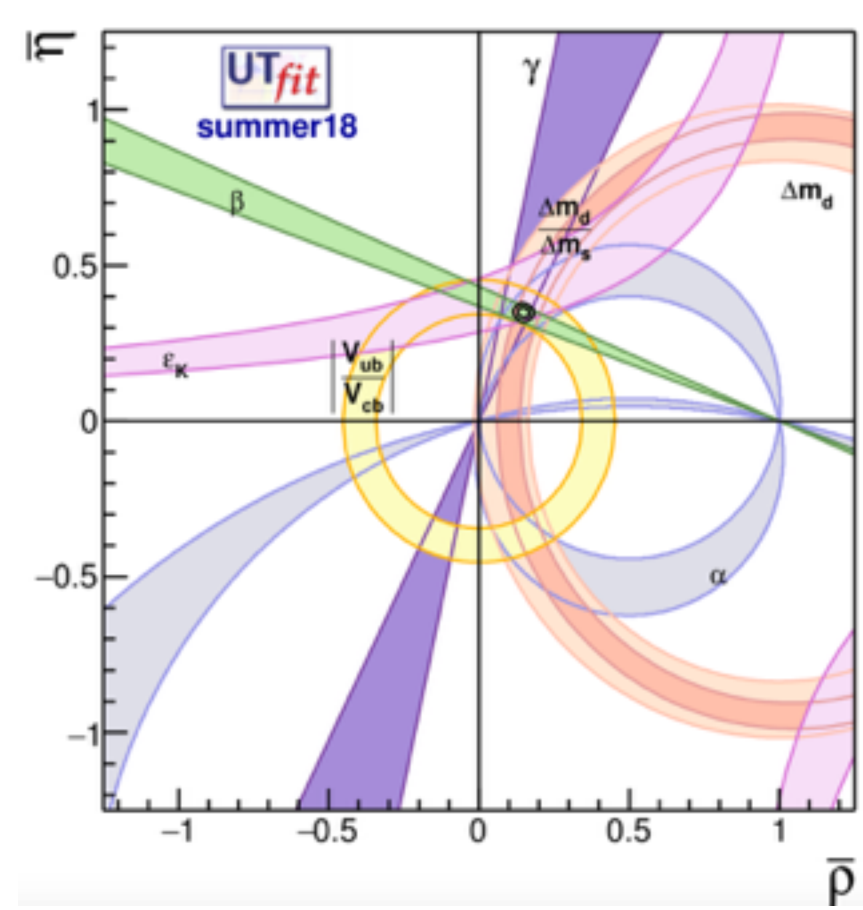


divide by $A\lambda^3$

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

- 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 extra CP violation parameters can appear.

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

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

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Existence of new particles $\Rightarrow$ Excessive occurring of FCNC & CP violation process

Flavour Physics beyond SM

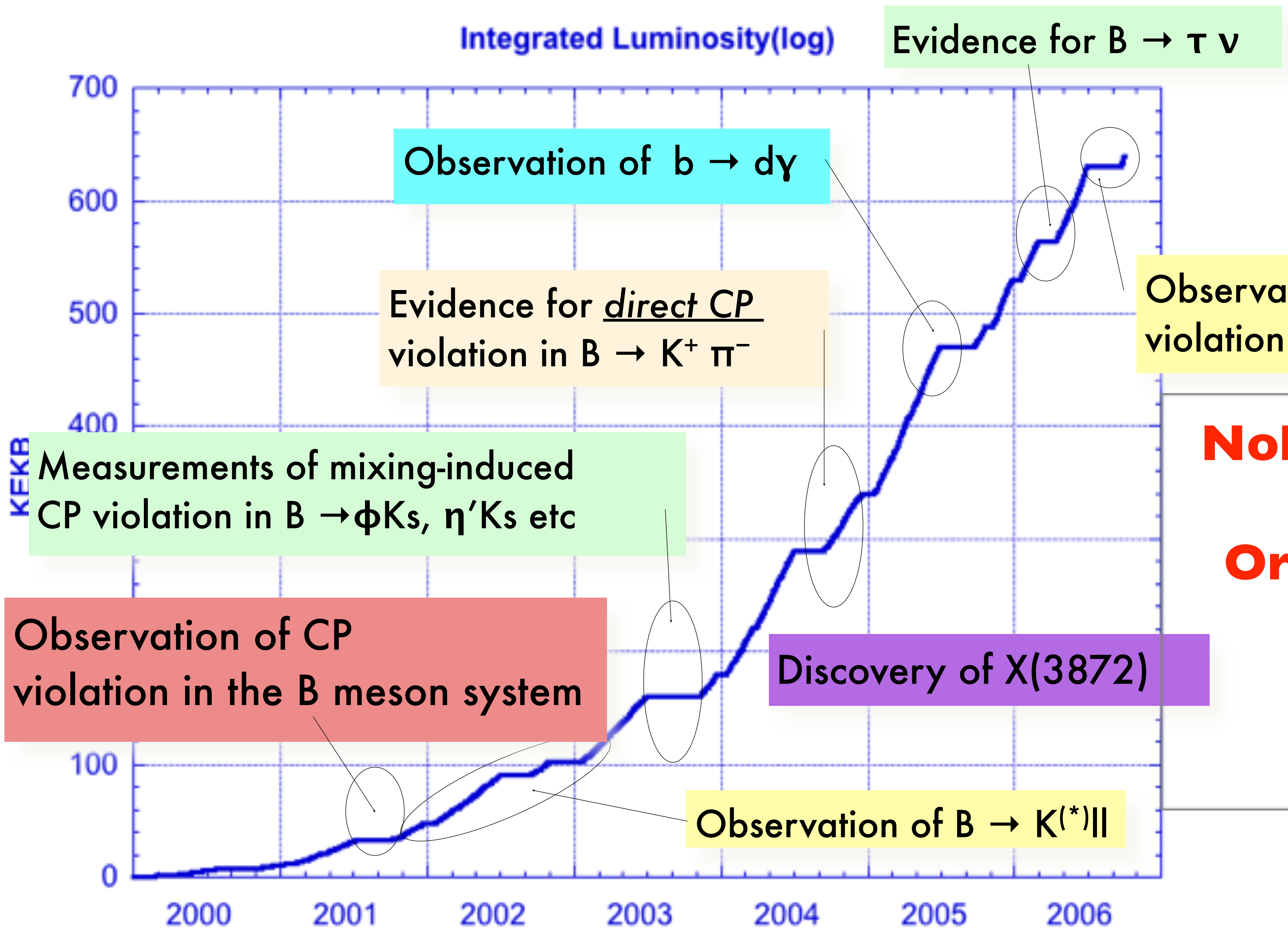
The indirect search of new physics through quantum effect: very powerful tool to search for new physics signal!

- This very simple picture does not exist in most of the extensions of SM: suppression of the FCNC is NOT automatic and also extra CP violation parameters can appear.

Existence of new particles ⇐ Excessive occurring of FCNC & CP violation process

Legacy of B factories

B factories: e+e- circular collider with energy at $\Upsilon(4S)(\rightarrow B\bar{B})$



Nobel Prize to Kobayashi-Maskawa (2009)
Origin of CP violation in Standard Model

KEK (Japan) = Belle/KEKB

SLAC (US) = Babar/PEP-II

BABAR Collaboration Home Page

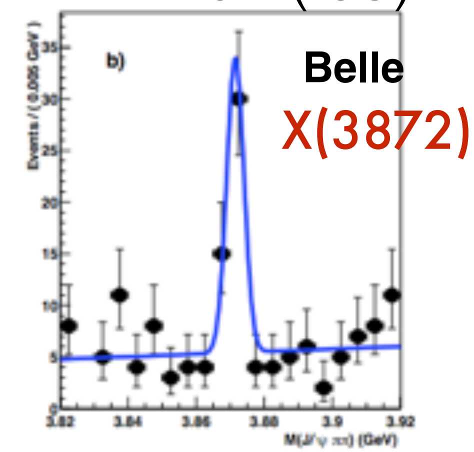
BELLE

Legacy of B factories

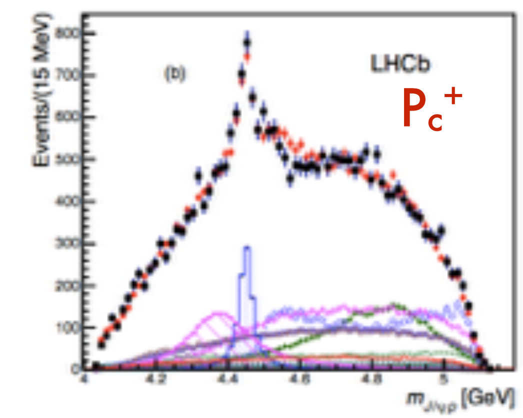
Discovery of charm/bottom exotic bound states

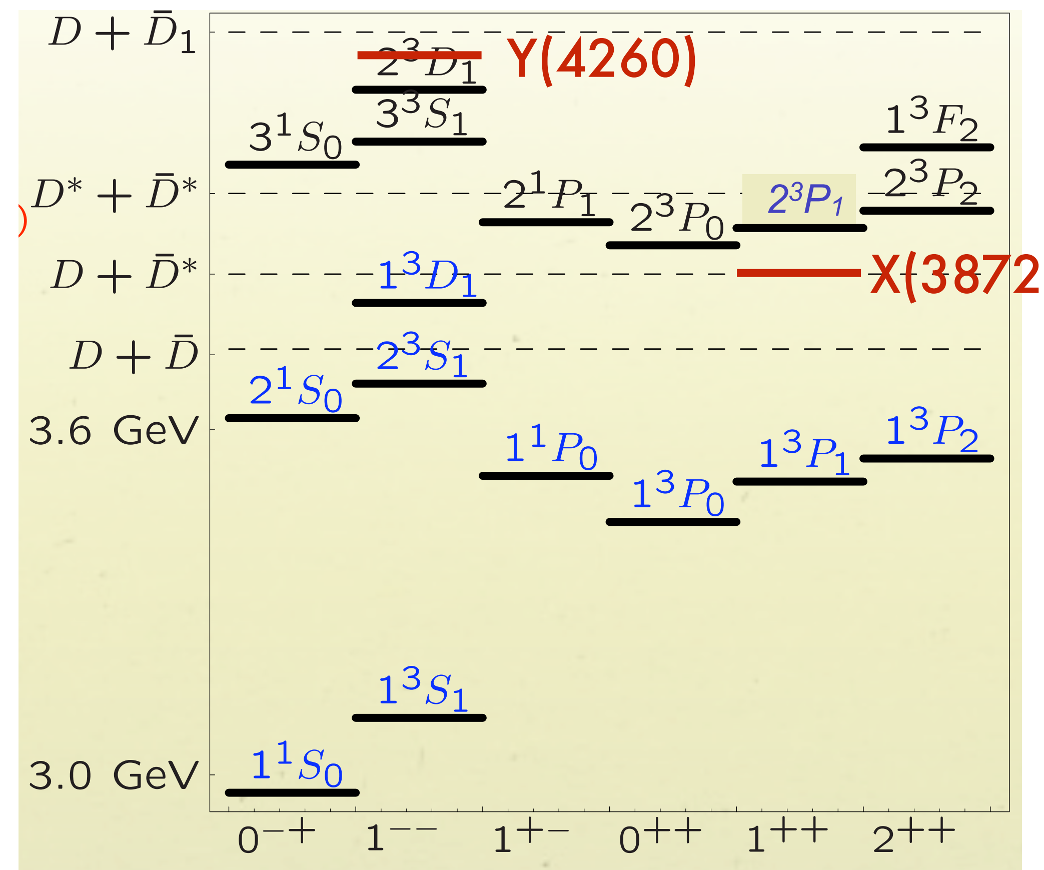
State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [1050, 1138] (>10), BaBar [1139] (8.6)	2003	Ok
X(3872)				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1140–1142] (11.6), D0 [1143] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [1144–1146] (np), CMS [1147] (np)	2012	Ok
				$Y(4260) \to \gamma(\pi^+\pi^- J/\psi)$	BESIII [1148] (6.3)	2013	NC!
				$B \to K(\omega J/\psi)$	Belle [1149] (4.3), BaBar [1150] (4.0)	2005	NC!
				$B \to K(\gamma J/\psi)$	Belle [1149, 1151] (5.5), BaBar [1152, 1153] (3.6), LHCb [1154] (> 10)	2005	Ok
				$B \to K(\gamma\psi(2S))$	BaBar [1153] (3.5), Belle [1151] (0.2), LHCb [1154] (4.4)	2008	NC!
				$B \to K(D^0\bar{D}^{*0})$	Belle [1155, 1156] (6.4), BaBar [1157] (4.9)	2006	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	1^{+-}	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BESIII [1158] (>8), Belle [1159] (5.2), CLEO data [1160] (>5)	2013	Ok
Zc(3900)$^+$				$Y(4260, 4360) \to \pi^0(\pi^0 J/\psi)$	CLEO data [1160] (3.5), BESIII [1161] (10.4)	2013	Ok
				$Y(4260, 4390) \to \pi^-(\pi^+ h_c)$	BESIII [1162] (2.1)	2013	NC!
				$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BESIII [1163, 1164] (18)	2013	Ok
				$Y(4260) \to \pi^0(D\bar{D}^*)^0$	BESIII [1165] (>10)	2015	Ok
$Y(4260)$	4221.1 ± 2.5	47.7 ± 4.0	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	BaBar [1210, 1211] (8), CLEO [1212, 1213] (11), Belle [1159, 1214] (15), BESIII [1158, 1215] (np)	2005	Ok
Y(4260)				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [1212] (5.1), BESIII [1161] (np)	2006	Ok
				$e^+e^- \to (K^+K^- J/\psi)$	CLEO [1212] (3.7)	2006	NC!
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1211] (np), Belle [1159] (np)	2012	Ok
				$e^+e^- \to (\pi^+\pi^- h_c)$	BESIII [1162, 1216] (10)	2013	NC!
				$e^+e^- \to (\pi^0\pi^0 h_c)$	BESIII [1166] (np)	2014	NC!
				$e^+e^- \to (\omega\chi_{c0})$	BESIII [1217] (>9)	2014	NC!
				$e^+e^- \to (\gamma X(3872))$	BESIII [1148] (6.3)	2013	NC!
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BESIII [1158, 1164] (>8), Belle [1159] (5.2)	2013	Ok
				$e^+e^- \to (\pi^0 Z_c(3900)^0)$	BESIII [1161, 1165] (10.4)	2015	Ok
				$e^+e^- \to (\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [1162, 1166, 1169, 1170] (>10)	2013	Ok

PRL91 ('03)



PRL115 ('15)





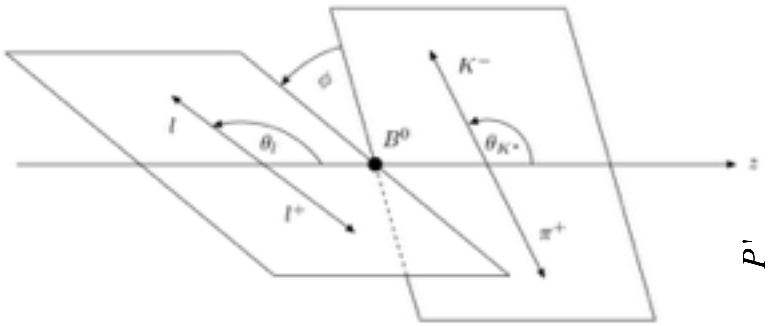
❖identified charmonium

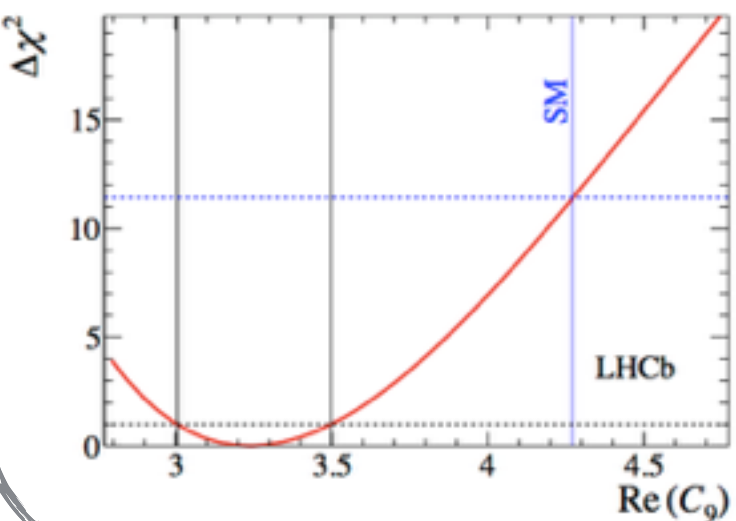
❖un-identified charmonium

❖Newly discovered state

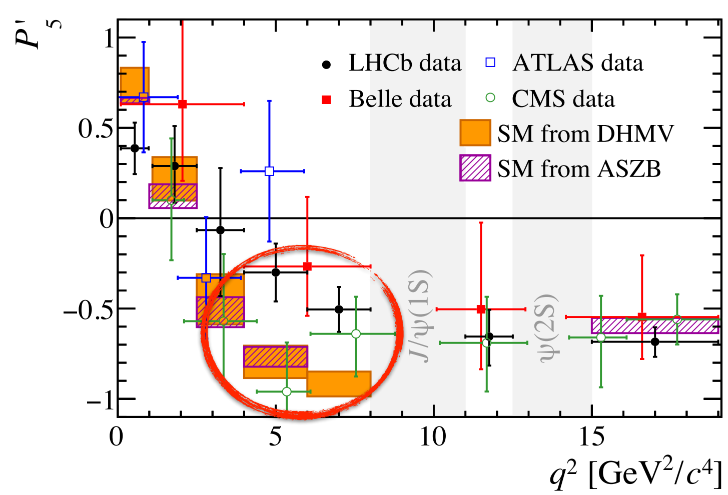
B Anomalies

B->K*μ+μ-: Re(C9) (~3-4σ)

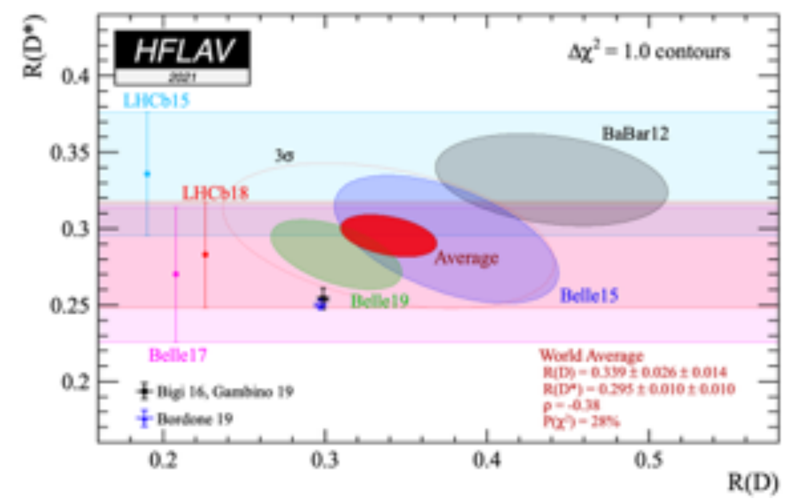




P5′

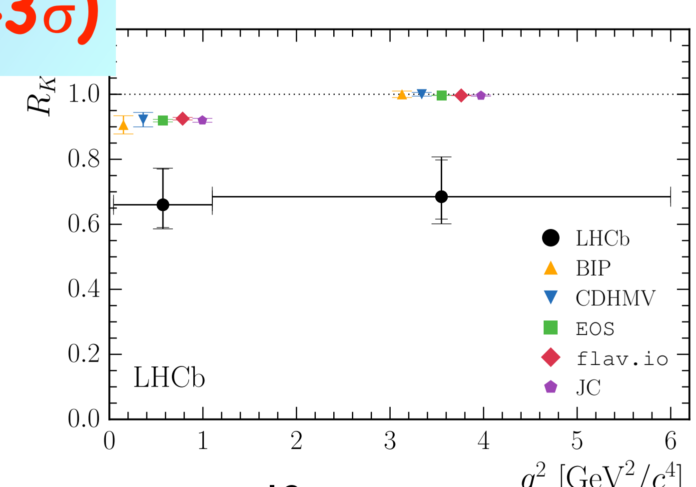


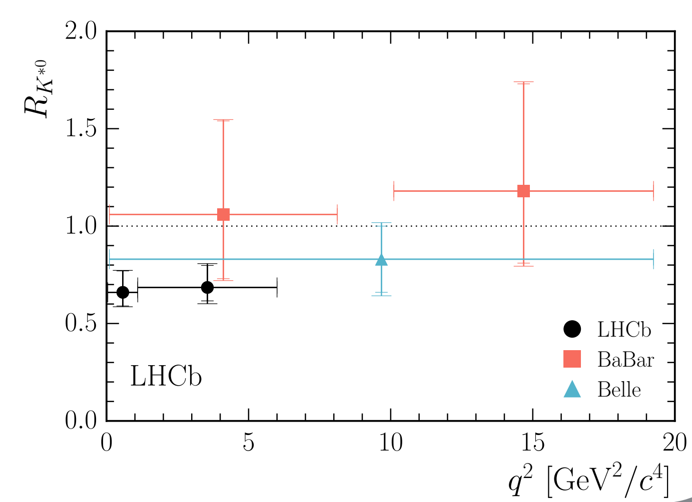
B->D*τν/B->D*μν: R(D*) (~3σ)



B->K*μ+μ-/K*e+e-: R(K*) (~2-3σ)

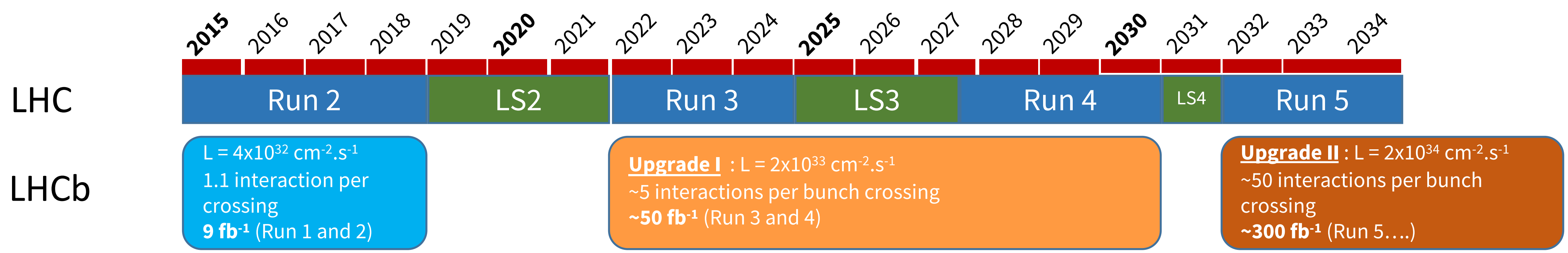
	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$



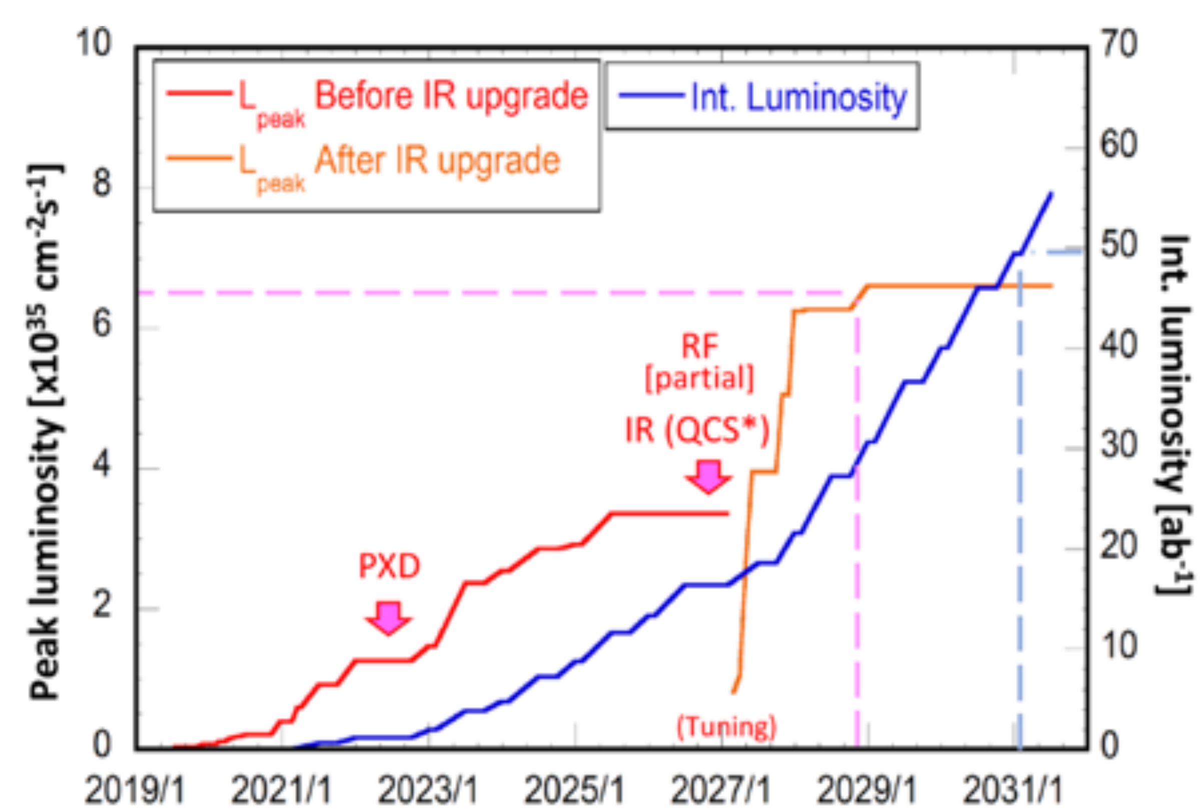


Coming years for B Physics

Competition/Complementarity between Belle II vs LHCb



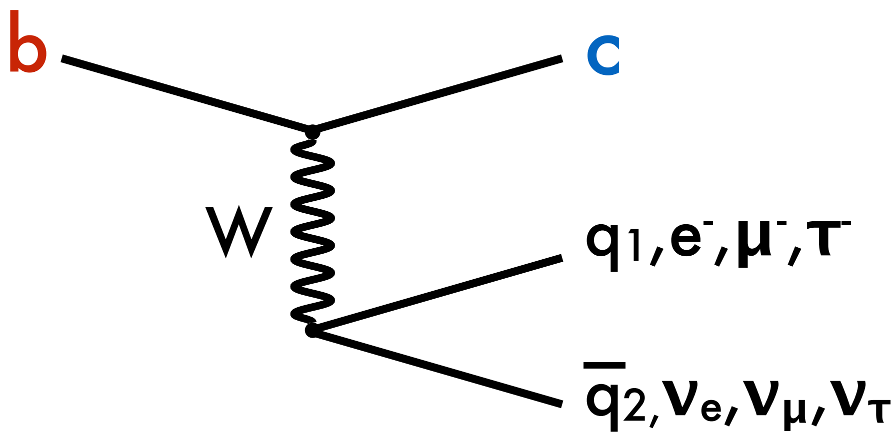
LHCb	Belle II
Higher number of B mesons	B production in a cleaner
Higher boost (Bs oscillation)	Full kinematics (e.g. ν channels)
B, Bs, Bc, Λb, Ξb…	Inclusive processes
Upgrade I: hadronic	First e+e- machine with nano beam



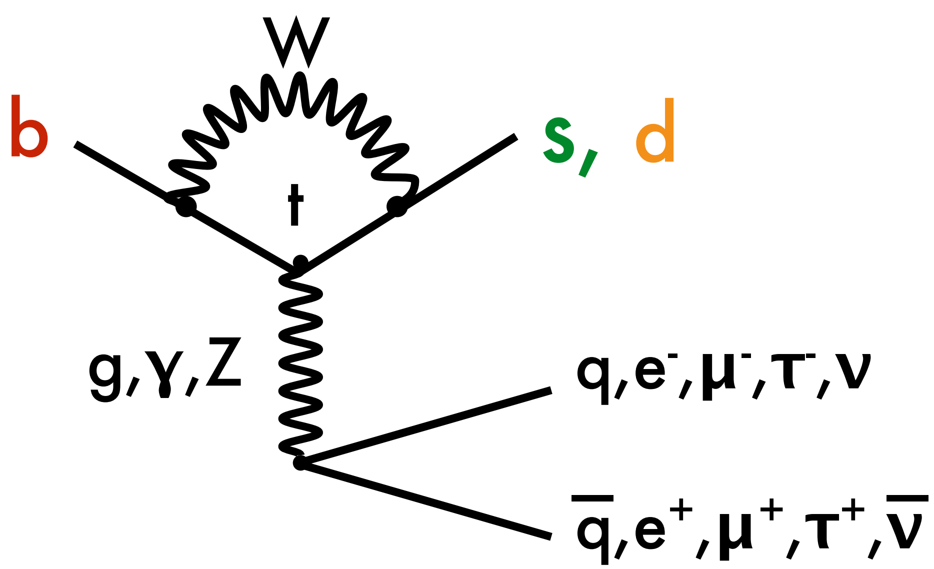
B physics in nutshell...

Trees, Boxes and Penguins

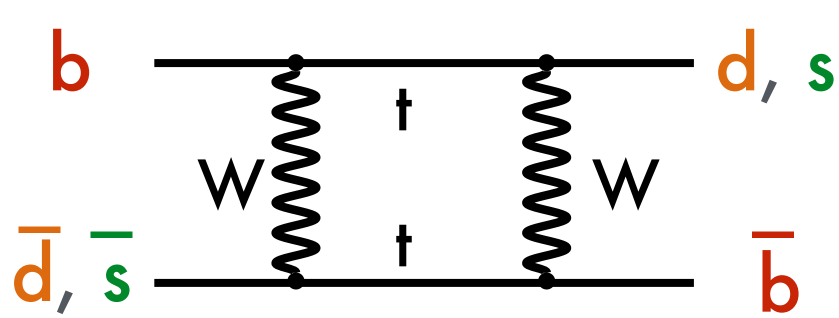
Basic quark level interactions in SM for B physics



- ✦ CKM elements $V_{cb,ub}$ measurement*
- ✦ New physics in the tree



- ✦ FCNC process (rare decay)
- ✦ New physics in the loop
- ✦ CKM elements $V_{tb,ts}$ measurement



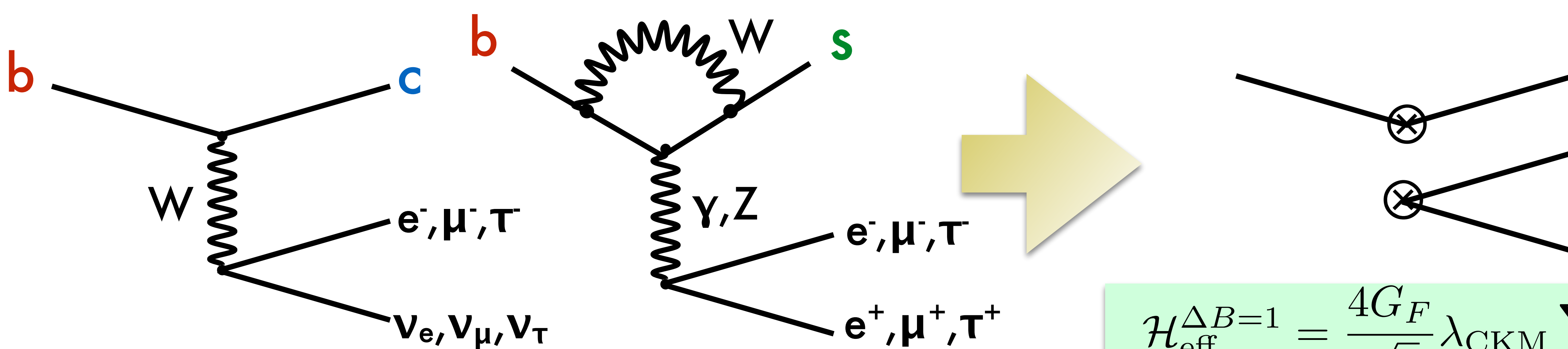
- ✦ FCNC process (oscillation)
- ✦ New physics in the loop
- ✦ CKM element $V_{td,ts}$ measurement*

** Including its phase*

SM Effective Hamiltonian

Basic quark level interactions in SM for B physics

- All the four fermi interactions are described Effective Hamiltonian.
- The Wilson Coefficient includes the QCD correction and its renormalisation running from m_W to m_b scale.



$$\mathcal{H}_{\text{eff}}^{\Delta B=1} = \frac{4G_F}{\sqrt{2}}\lambda_{\text{CKM}}\sum_i C_i O_i$$

$$O = \bar{\ell}_L\gamma_\mu\nu_L\bar{c}_L\gamma^\mu b_L$$

$$O_9 = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_\mu\ell\bar{s}_L\gamma^\mu b_L$$

$$O_{10} = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_\mu\gamma_5\ell\bar{s}_L\gamma^\mu b_L$$

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Basic quark level interactions in SM for B physics

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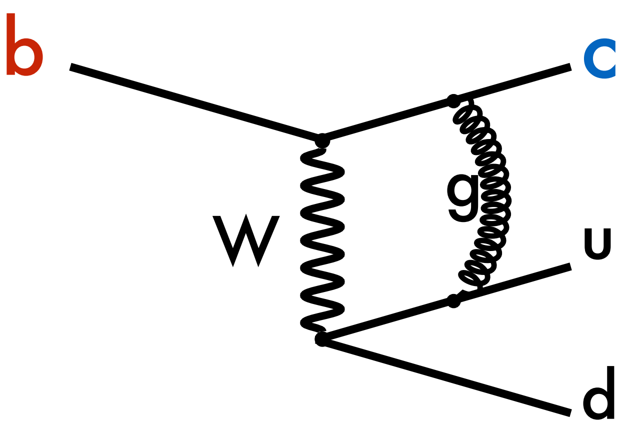
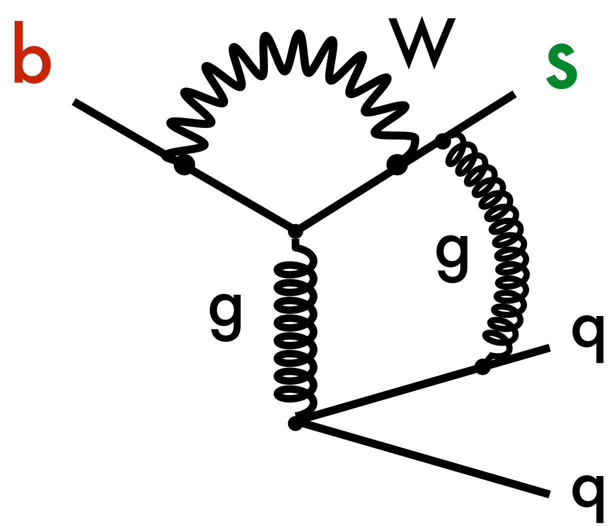
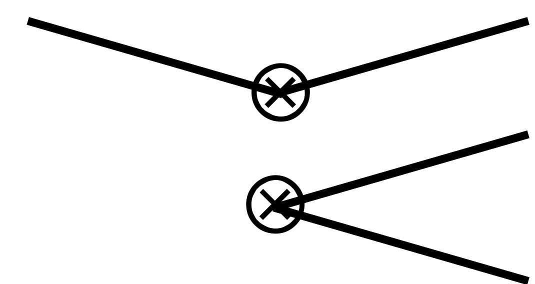






$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \frac{4G_F}{\sqrt{2}} \lambda_{\rm CKM} \sum_i C_i O_i$$

$$O_1 = \bar{d}_L^\alpha \gamma_\mu u_L^\beta \bar{c}_L^\beta \gamma^\mu b_L^\alpha$$

$$O_2 = \bar{d}_L \gamma_\mu u_L \bar{c}_L \gamma^\mu b_L$$

$$O_3 = \sum_{u,d,s,c} \bar{q}_L \gamma_\mu q_L \bar{s}_L \gamma^\mu b_L$$

$$O_4 = \sum_{u,d,s,c} \bar{q}_L^\alpha \gamma_\mu q_L^\beta \bar{s}_L^\beta \gamma^\mu b_L^\alpha$$

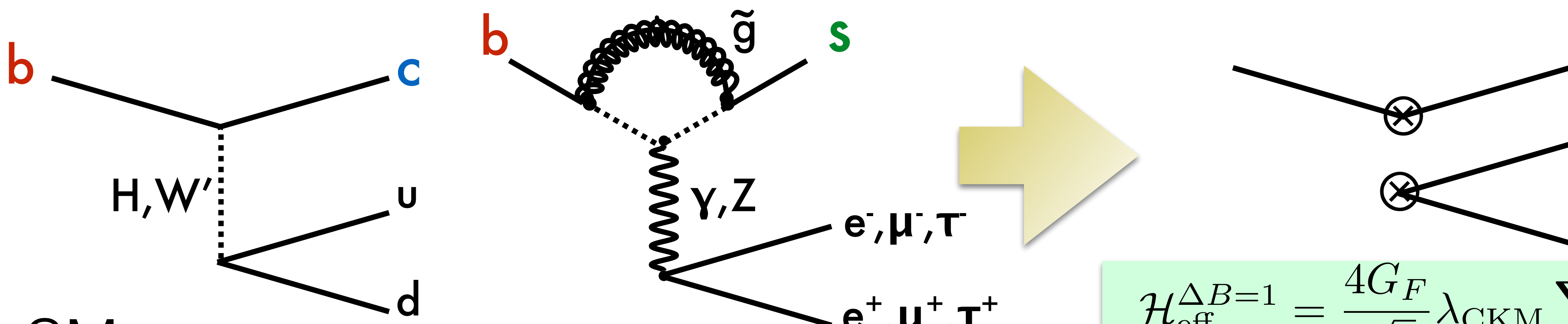
$$O_5 = \sum_{u,d,s,c} \bar{q}_R \gamma_\mu q_R \bar{s}_L \gamma^\mu b_L$$

$$O_6 = \sum_{u,d,s,c} \bar{q}_R^\alpha \gamma_\mu q_R^\beta \bar{s}_L^\beta \gamma^\mu b_L^\alpha$$

BSM Effective Hamiltonian

Extending the SM Effective Hamiltonian to BSM

- New physics induces new types of operator beyond SM ones.
- The Wilson Coefficient includes renormalisation running from new physics scale to electroweak scale and to m_b scale.



$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \frac{4G_F}{\sqrt{2}}\lambda_{\rm CKM}\sum_i C_i O_i$$

SM

$$O_{V-A} = \bar{d}_L\gamma_\mu u_L\ \bar{c}\gamma^\mu b_L$$

$$O_9 = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_\mu\ell\bar{s}_L\gamma^\mu b_L$$

$$O_{10} = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_\mu\gamma_5\ell\bar{s}_L\gamma^\mu b_L$$

$$O'_9 = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_\mu\ell\bar{s}_R\gamma^\mu b_R$$

$$O'_{10} = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_\mu\gamma_5\ell\bar{s}_R\gamma^\mu b_R$$

$$O_{V+A} = \bar{d}_R\gamma_\mu u_R\ \bar{c}_R\gamma^\mu b_R$$

$$O_{S+P} = \bar{d}_R u_R\ \bar{c}_R b_R$$

$$O_{S-P} = \bar{d}_L u_L\ \bar{c}_L b_L$$

$$O_S = \frac{e^2}{16\pi^2}\bar{\ell}\ell\bar{s}_R b_R$$

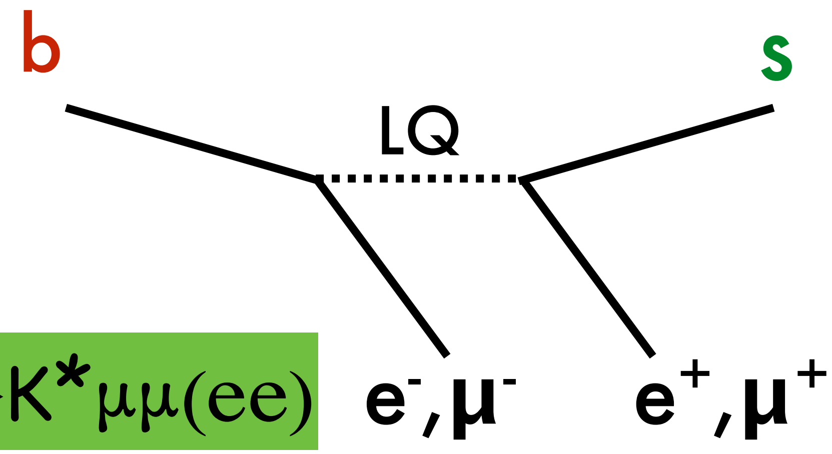
$$O_P = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_5\ell\bar{s}_R b_R$$

$$O'_S = \frac{e^2}{16\pi^2}\bar{\ell}\ell\bar{s}_L b_L$$

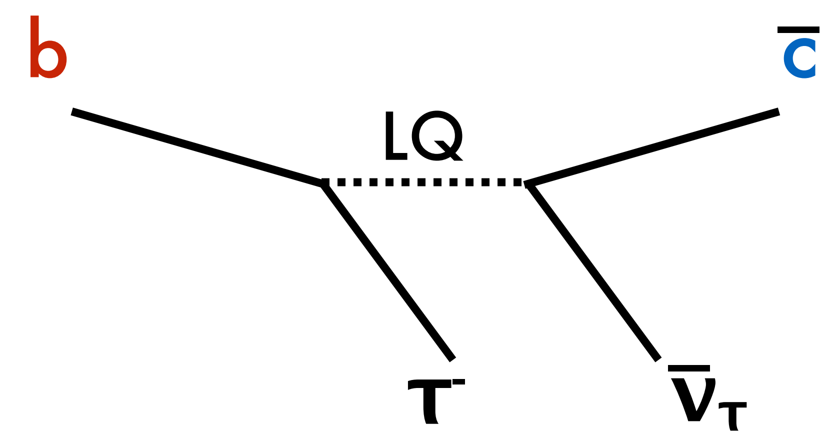
$$O'_P = \frac{e^2}{16\pi^2}\bar{\ell}\gamma_5\ell\bar{s}_L b_L$$

Leptoquark as solution of anomalies?

Tree level LQ diagrams seem to explain the patterns of anomaly



B→K*μμ(ee)



B→D*τν

Scalar leptoquark

$$\begin{aligned}\mathcal{L} \supset &+ y^{LL}_{3\,ij}\bar{Q}^{C\,i,a}_L \epsilon^{ab}(\tau^k S^k_3)^{bc} L^{j,c}_L - \\ &- y^{RL}_{2\,ij}\bar{u}^i_R R^a_2 \epsilon^{ab} L^{j,b}_L + y^{LR}_{2\,ij}\bar{e}^i_R R^{a\,*}_2 Q^{j,a}_L - \\ &- \tilde{y}^{RL}_{2\,ij}\bar{d}^i_R \tilde{R}^a_2 \epsilon^{ab} L^{j,b}_L + \tilde{y}^{\overline{LR}}_{2\,ij}\bar{Q}^{i,a}_L \tilde{R}^a_2 \nu^j_R \\ &+ \tilde{y}^{RR}_{1\,ij}\bar{d}^{C\,i}_R \tilde{S}_1 e^j_R + \\ &+ y^{LL}_{1\,ij}\bar{Q}^{C\,i,a}_L S_1 \epsilon^{ab} L^{j,b}_L + y^{RR}_{1\,ij}\bar{u}^{C\,i}_R S_1 e^j_R + y^{\overline{RR}}_{1\,ij} \\ &+ \bar{y}^{\overline{RR}}_{1\,ij}\bar{u}^{C\,i}_R \bar{S}_1 \nu^j_R + \text{h.c.}\end{aligned}$$

Vector leptoquark

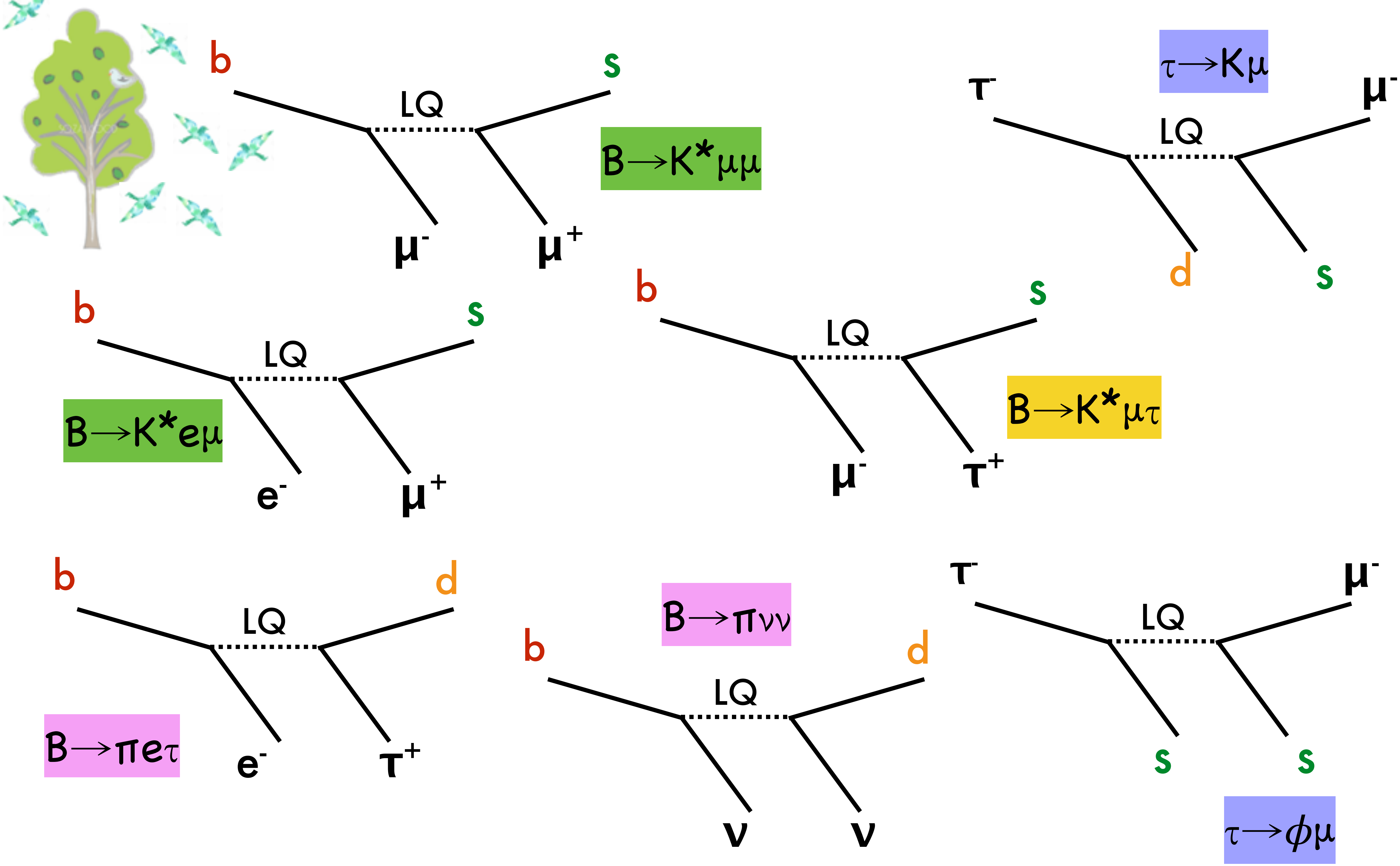
$$\begin{aligned}\mathcal{L} \supset &+ x^{LL}_{3\,ij}\bar{Q}^{i,a}_L \gamma^\mu (\tau^k U^k_{3,\mu})^{ab} L^{j,b}_L + \\ &+ x^{RL}_{2\,ij}\bar{d}^{C\,i}_R \gamma^\mu V^a_{2,\mu} \epsilon^{ab} L^{j,b}_L + x^{LR}_{2\,ij}\bar{Q}^{C\,i,a}_L \gamma^\mu \epsilon^{ab} V^b_{2,\mu} e^j_R + \\ &+ \tilde{x}^{RL}_{2\,ij}\bar{u}^{C\,i}_R \gamma^\mu \tilde{V}^b_{2,\mu} \epsilon^{ab} L^{j,a}_L + \tilde{x}^{\overline{LR}}_{2\,ij}\bar{Q}^{C\,i,a}_L \gamma^\mu \epsilon^{ab} \tilde{V}^b_{2,\mu} \nu^j_R + \\ &+ \tilde{x}^{RR}_{1\,ij}\bar{u}^i_R \gamma^\mu \tilde{U}_{1,\mu} e^j_R + \\ &+ x^{LL}_{1\,ij}\bar{Q}^{i,a}_L \gamma^\mu U_{1,\mu} L^{j,a}_L + x^{RR}_{1\,ij}\bar{d}^i_R \gamma^\mu U_{1,\mu} e^j_R + x^{\overline{RR}}_{1\,ij}\bar{u}^i_R \gamma^\mu U_{1,\mu} \nu^j_R + \\ &+ x^{\overline{RR}}_{1\,ij}\bar{d}^i_R \gamma^\mu \bar{U}_{1,\mu} \nu^j_R + \text{h.c.}\end{aligned}$$

I. Doršner et.al, Phys.Rept. 641 (‘16)

x and y are the flavour coupling

Leptoquark as solution of anomalies?

All possible leptoquark couplings are explored in B and tau decays!



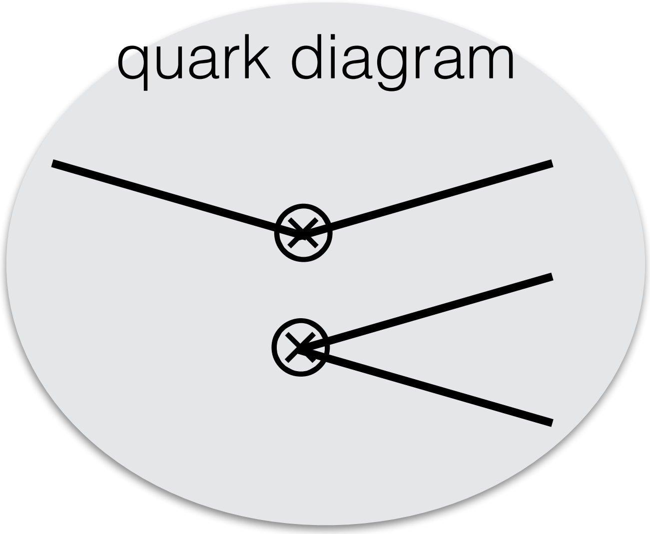
B physics and strong interaction

Basic hadronic level interactions in BSM for B physics

- Form factors include the non-perturbative QCD effect.
- Non-factorisable effect for hadronic decays: QCD effect between m_b and Λ_{QCD} scale.

Semi-leptonic, Leptonic B meson decays

Hadronic B meson decays



$$\mathcal{H}_{\text{eff}}^{\Delta B=1} = \frac{4G_F}{\sqrt{2}} \lambda_{\text{CKM}} \sum_i C_i O_i$$

B physics and strong interaction

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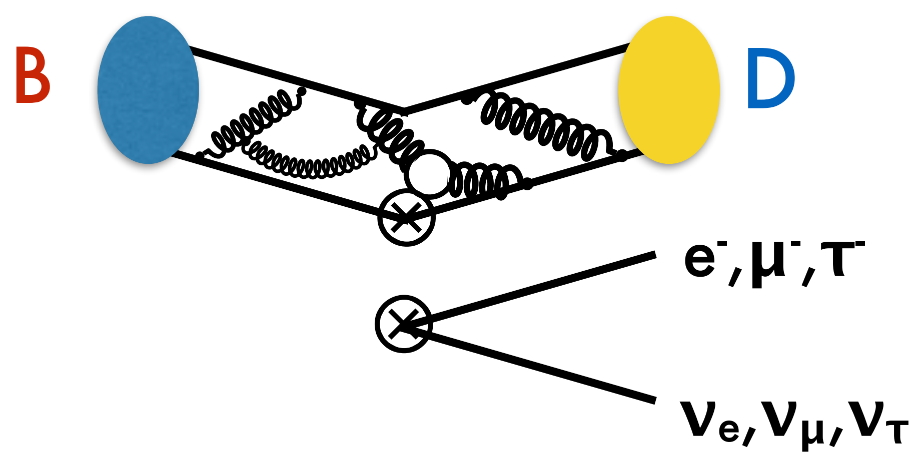

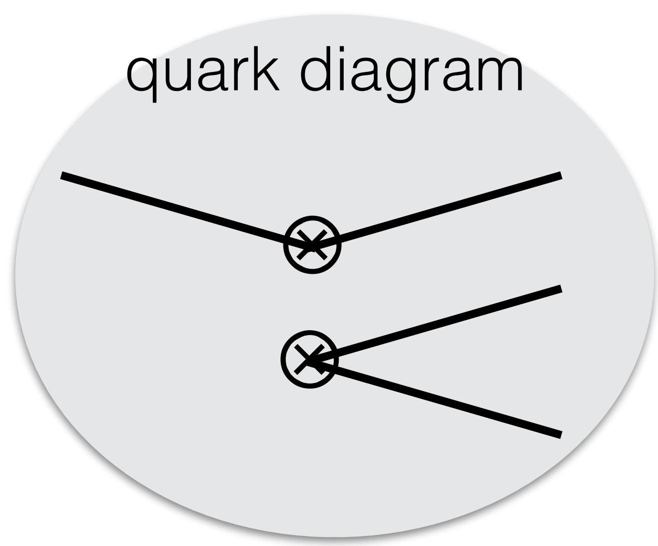

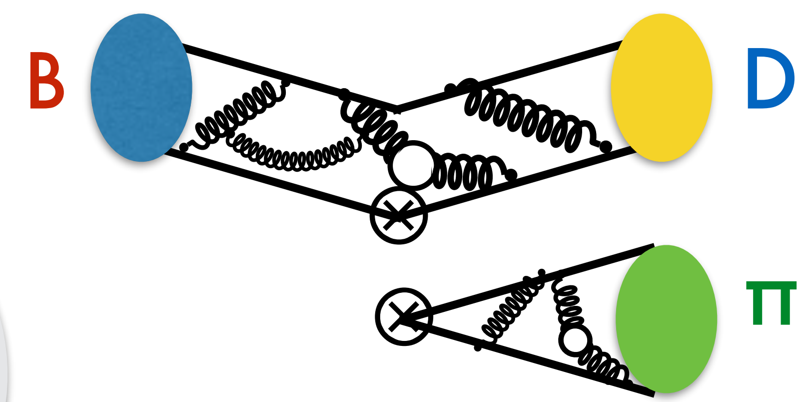

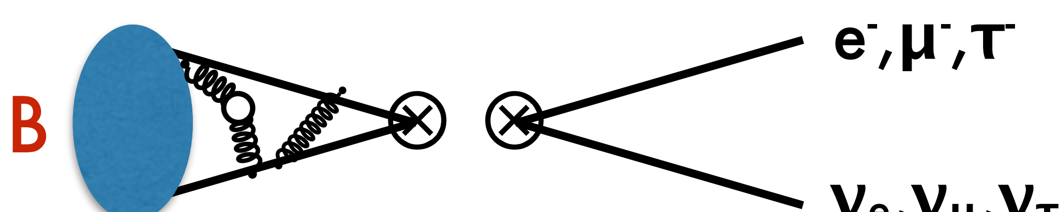

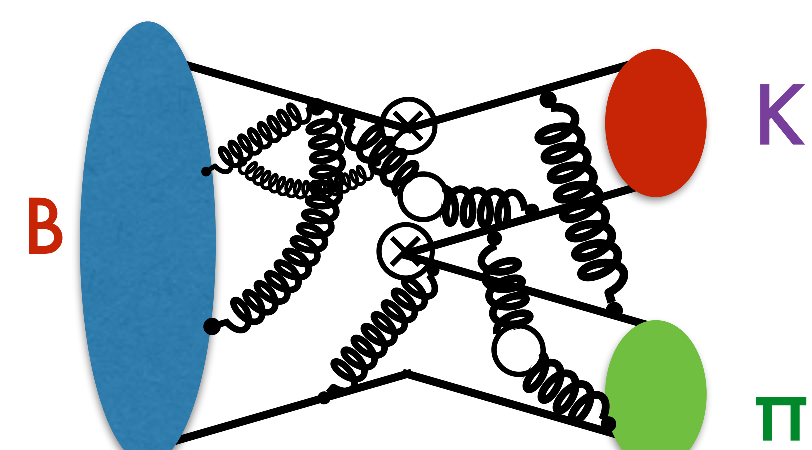

B physics and strong interaction

Basic hadronic level interactions in BSM for B physics

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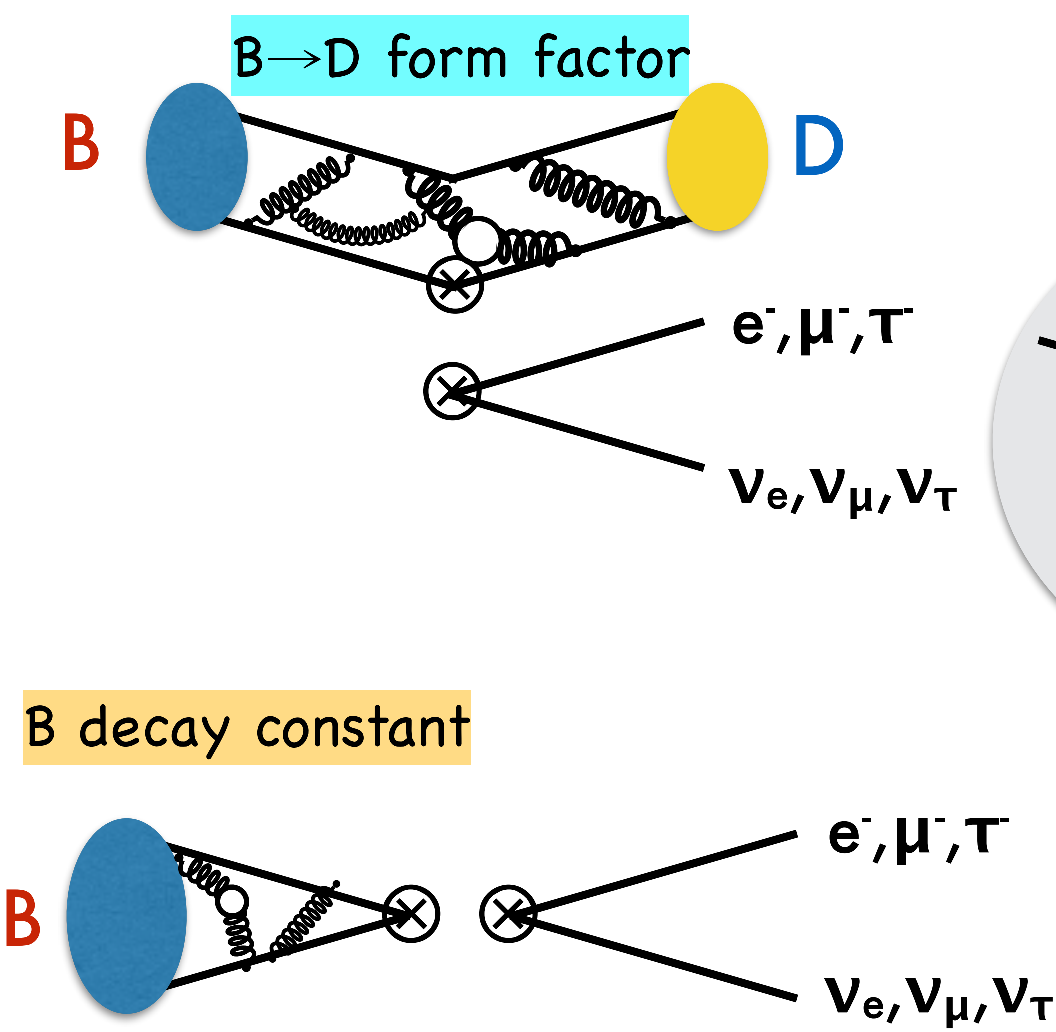
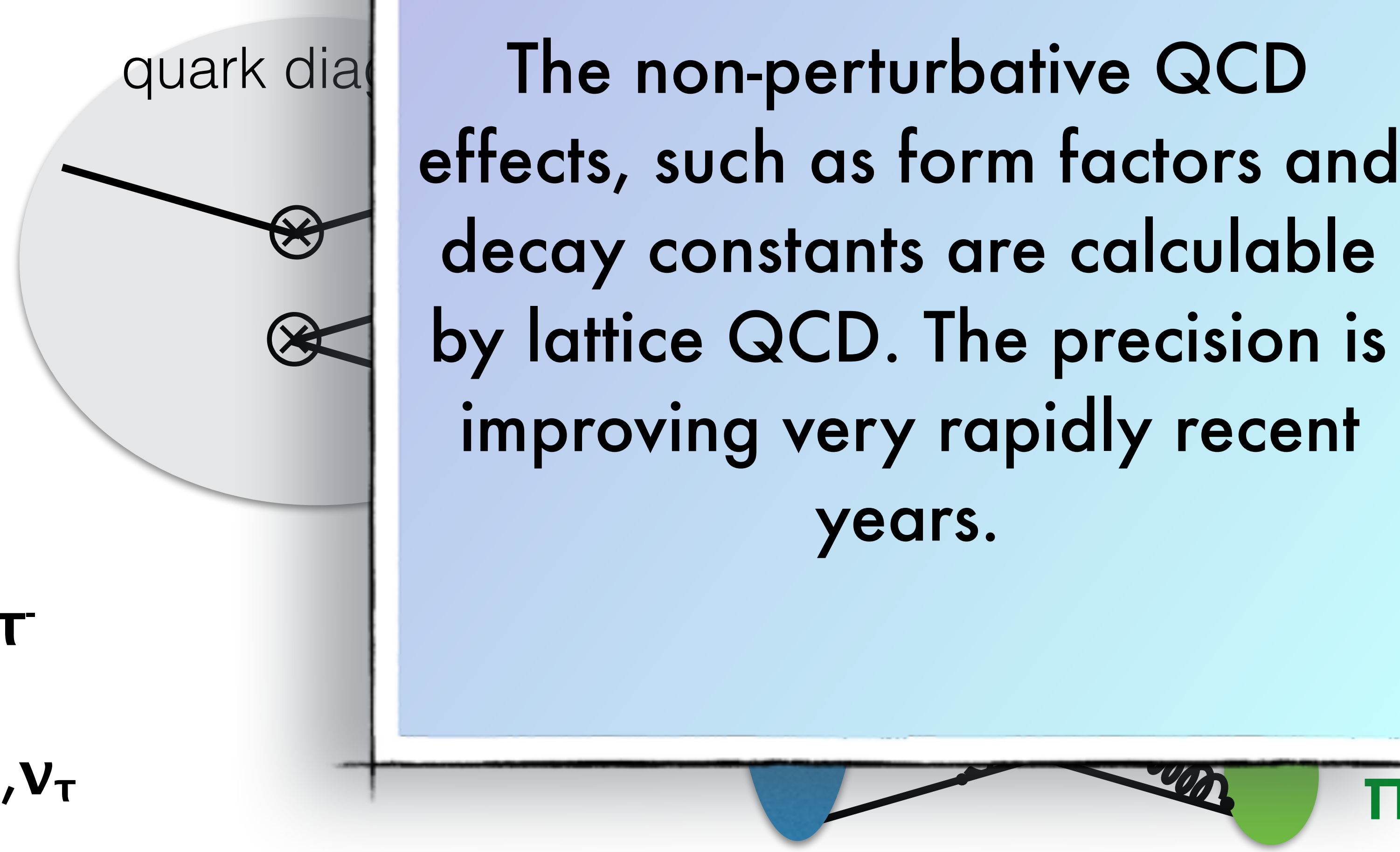
Semi-leptonic, Leptonic B meson decays



Hadronic B meson decays



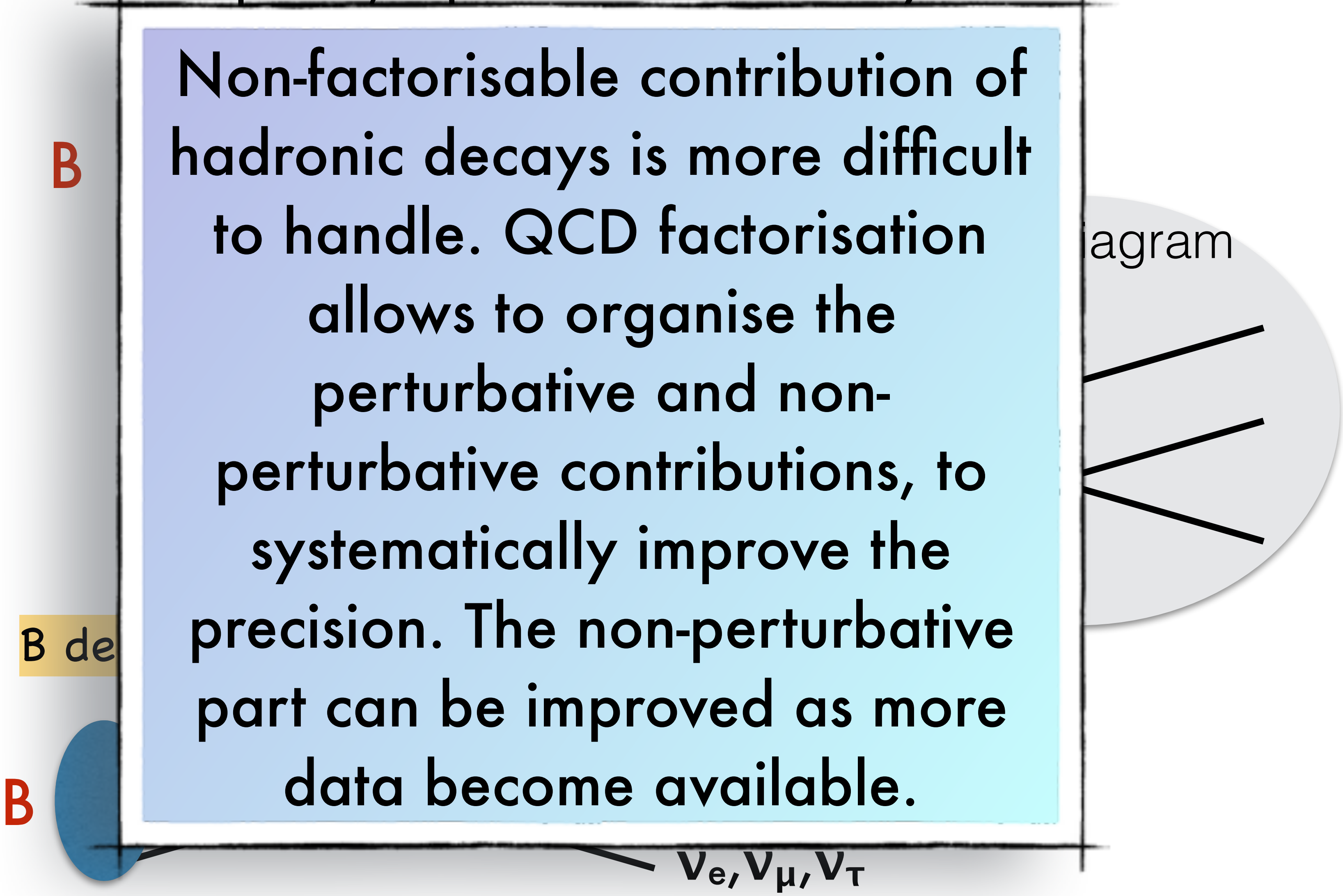
The non-perturbative QCD effects, such as form factors and decay constants are calculable by lattice QCD. The precision is improving very rapidly recent years.

B physics and strong interaction

Basic hadronic level interactions in BSM for B physics

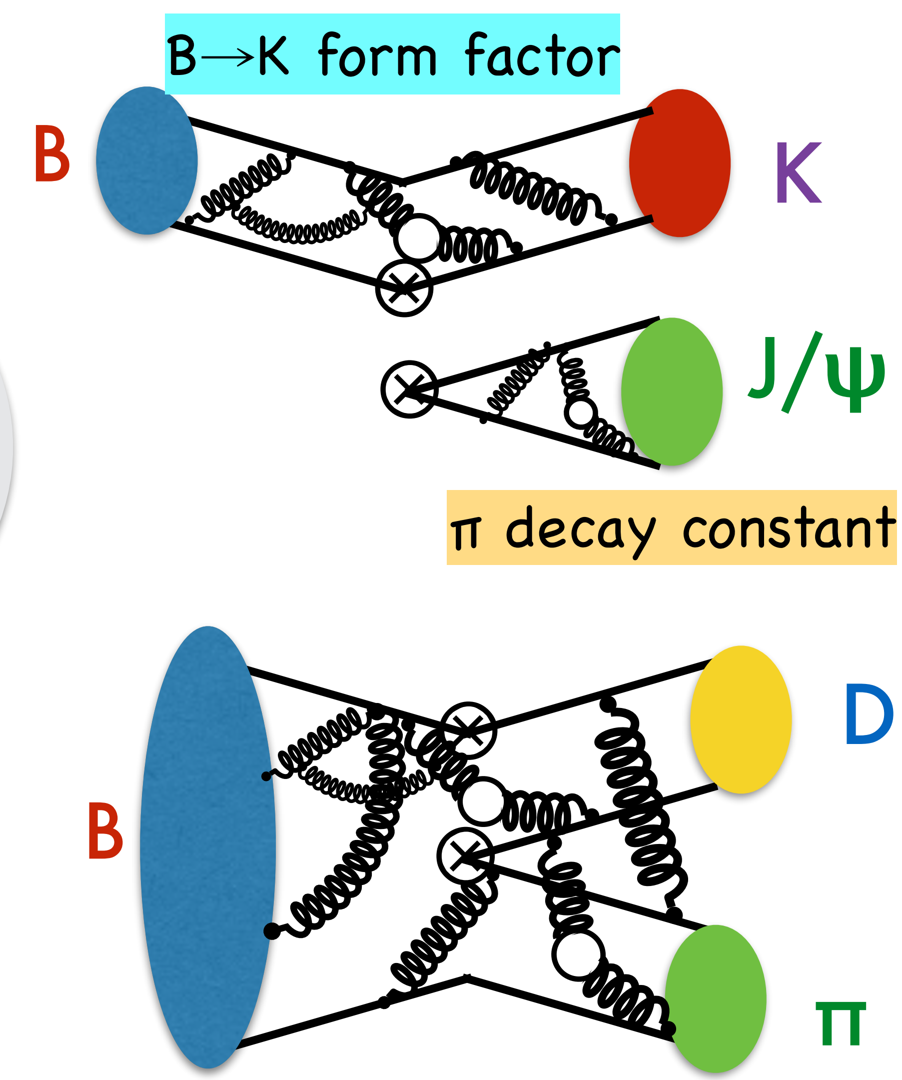
- ✦ Form factors include the non-perturbative QCD effect
- ✦ Non-factorisable effect for hadronic decays: QCD effect between m_b and Λ_{QCD} scale

Semi-leptonic, Leptonic B meson decays



Non-factorisable contribution of hadronic decays is more difficult to handle. QCD factorisation allows to organise the perturbative and non-perturbative contributions, to systematically improve the precision. The non-perturbative part can be improved as more data become available.

Hadronic B meson decays



B physics and strong interaction

An observation of CP violation requires a complex phase from strong interaction!

$$|A(B \to f)| \neq |A(\overline{B} \to \overline{f})|$$

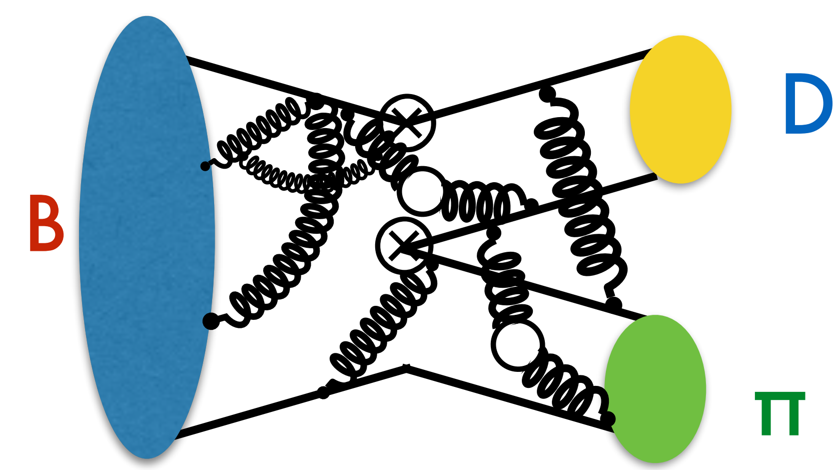
is the condition to have CP violation.

We can measure $\cancel{CP}$ *only* through an interference of two amplitudes with different CP conserving and CP violating phases.

$$\begin{aligned} A(\overline{B}^0 \to \overline{f}) &= A_1 e^{+i\theta_1} e^{+i\delta_1} + A_2 e^{+i\theta_2} e^{+i\delta_2} \\ A(B^0 \to f) &= A_1 e^{-i\theta_1} e^{+i\delta_1} + A_2 e^{-i\theta_2} e^{+i\delta_2} \end{aligned}$$

$\theta_{1,2}$: CP the violating phase, $\delta_{1,2}$: the CP conserving phase.

$$\frac{\Gamma(\overline{B}^0 \to \overline{f}) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to \overline{f}) + \Gamma(B^0 \to f)} = \frac{2(A_2/A_1)\sin(\theta_1 - \theta_2)\sin(\delta_1 - \delta_2)}{1 + 2(A_2/A_1)\cos(\theta_1 - \theta_2)\cos(\delta_1 - \delta_2)}$$



Complex phase coming from strong interaction is NEEDED to be able to observe the complex phase coming from CP violation!

Challenges and progresses in B physics

Challenge of Flavour Physics

BSM information is hidden in the strong interaction effects

Rough stone

Theoretical computation

eliminate the effects of
strong interaction

- Perturbative QCD
  factorisation approach...
- Non-perturbative QCD
  lattice QCD, QCD sum rule...
- Effective theory
  ChPT, HQET, SCET...

Discovery!

Difficult to **precisely** estimate the uncertainties associated to each assumption behind

Challenge of Flavour Physics

Amplitude Analysis : new paradigm in the high statistics era?

Rough stone

Theoretical computation

Data driven method

extract the hadronic information from data

Discovery!

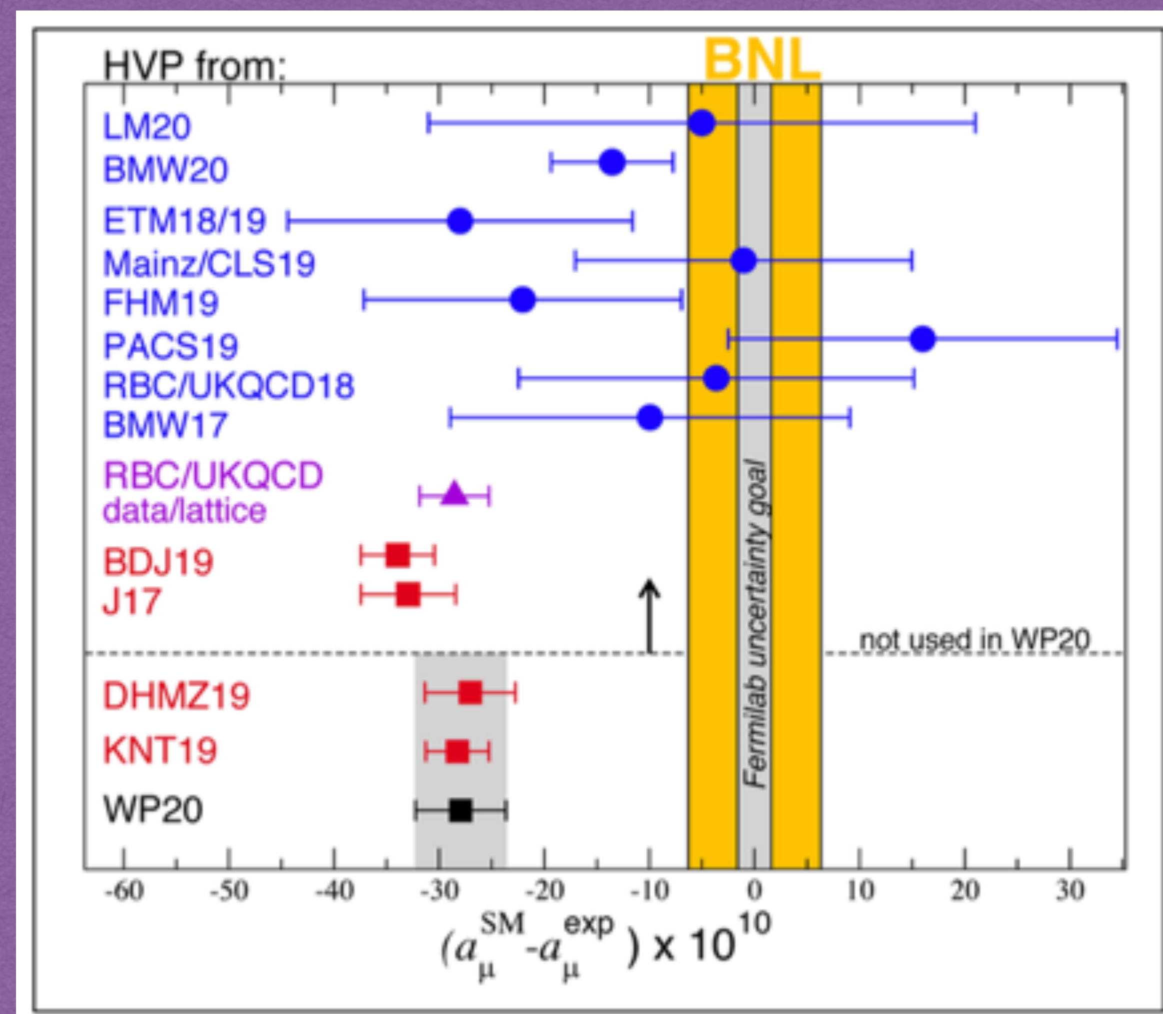
Parametrise the strong interaction and fit those parameters from data (either the same data or from the others). **Cross check with theory computation** is essential.

Challenge of Flavour Physics

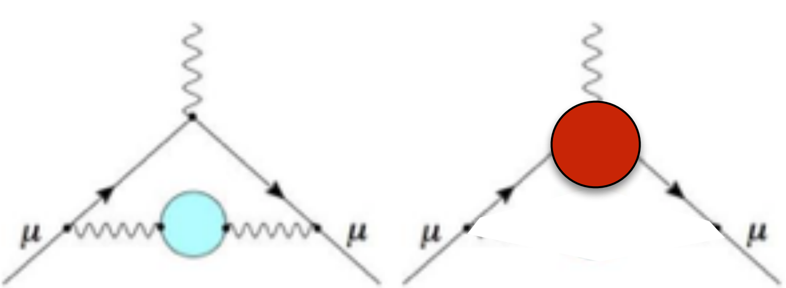
Amplitude Analysis : new paradigm in the high statistics era?

Rough stone

Famous example : muon g-2



Discovery!



SM BSM

and fit those parameters from data (either the same data or from the others). **Cross check with theory computation** is essential.

Data driven method for UT precision test

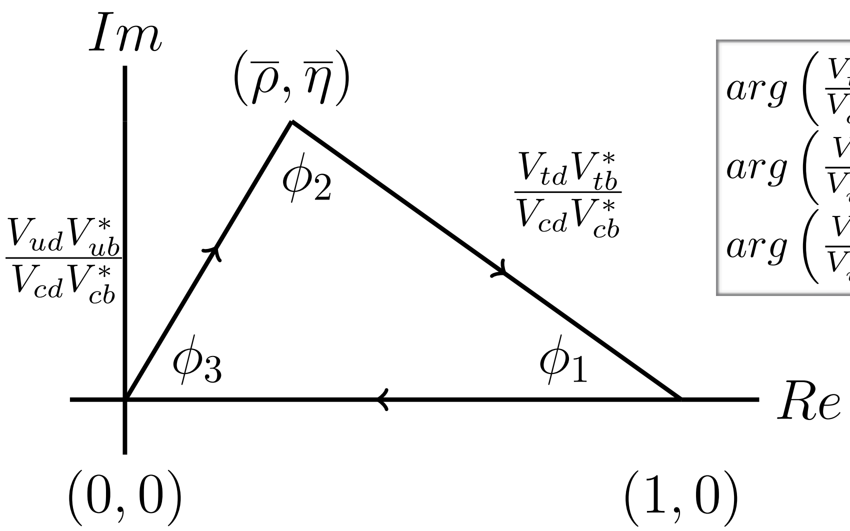
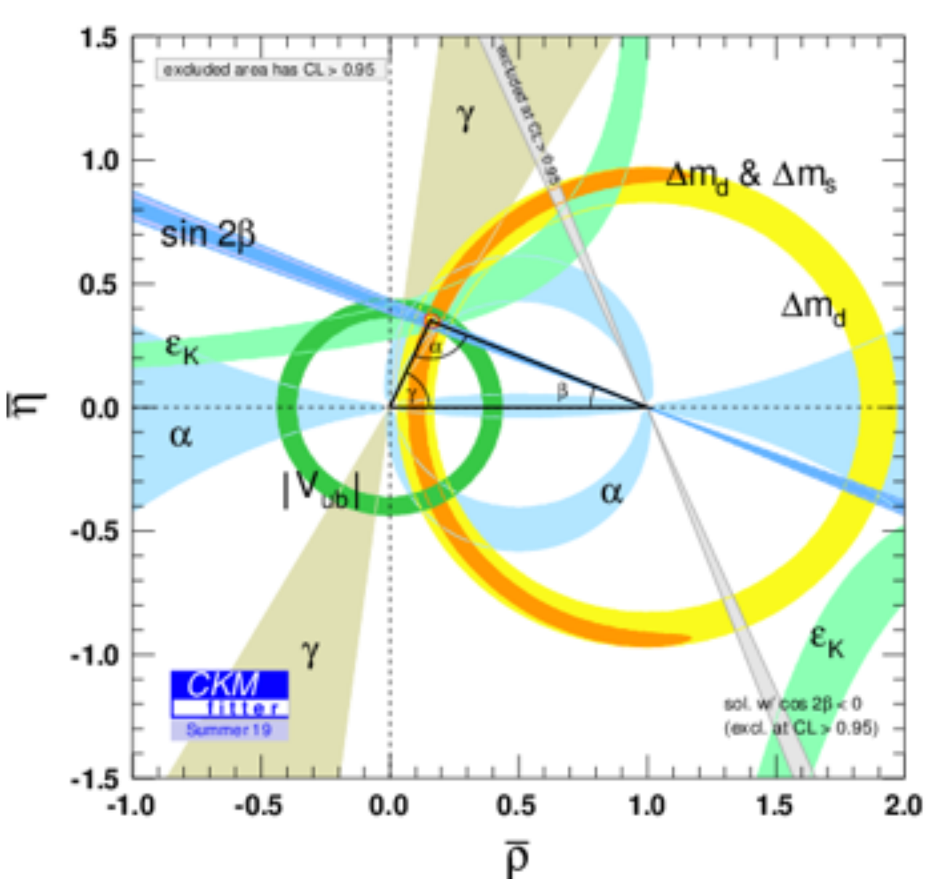


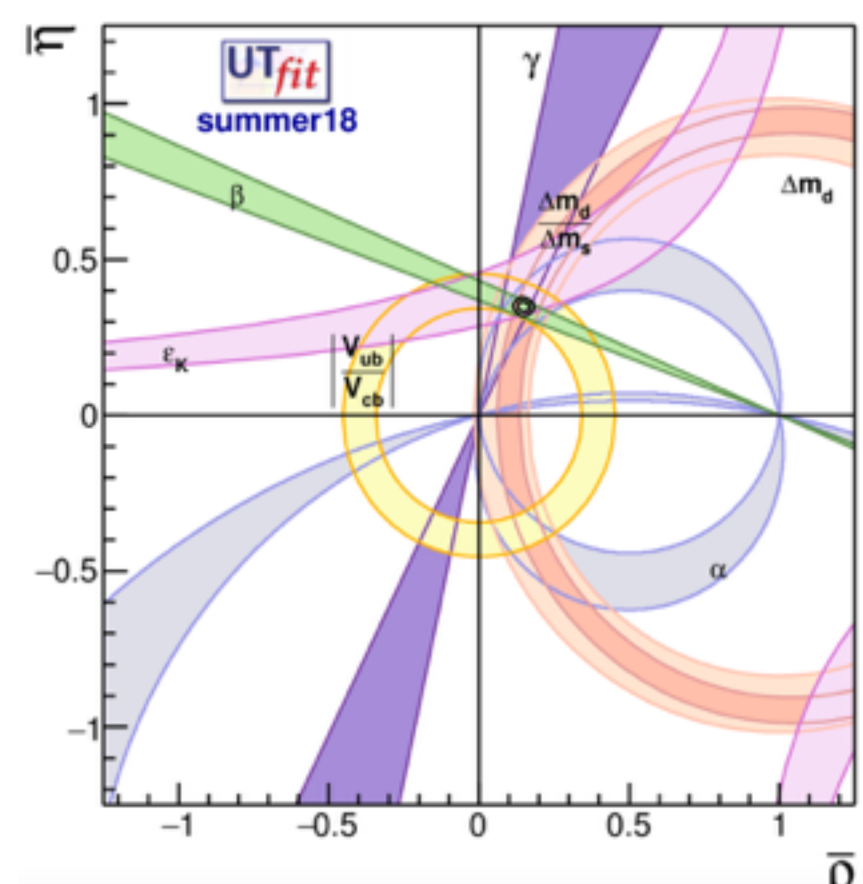
Fig. 3: The unitarity triangle.

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

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad \mathbf{V}\mathbf{V}^\dagger = 1,$$

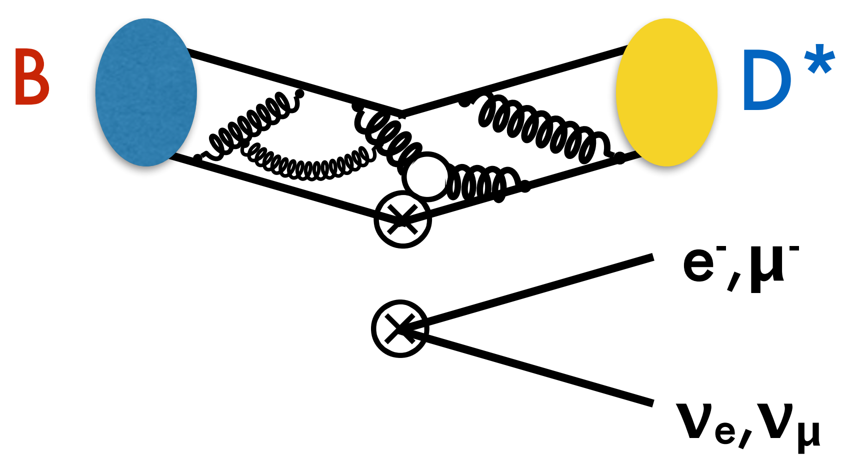
$$\mathbf{V} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\sqrt{\rho^2+\eta^2}e^{-i\delta}\lambda^3 \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A(1-\sqrt{\rho^2+\eta^2}e^{i\delta})\lambda^3 & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

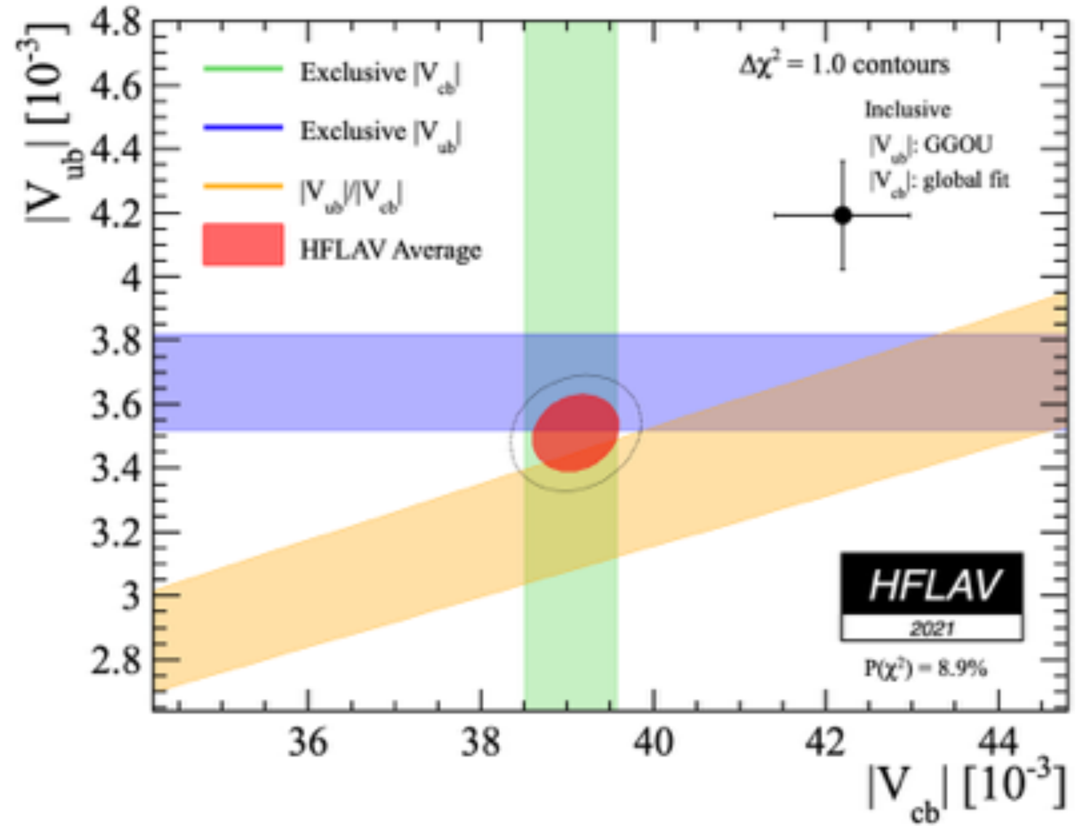




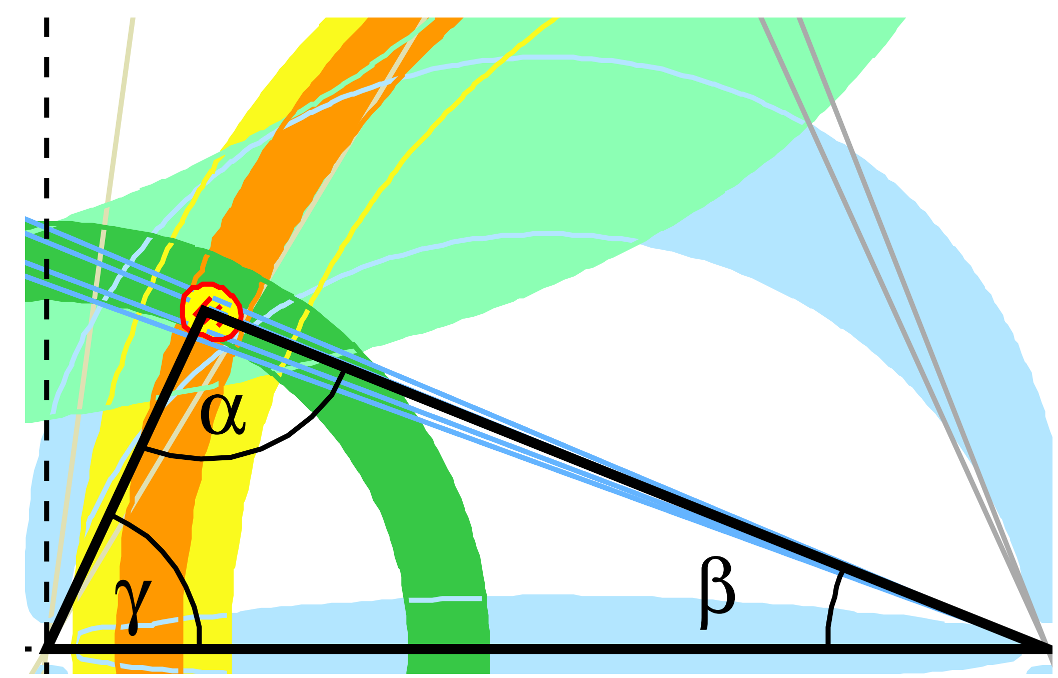
$B \to D^* l\, \nu$ $(l = e, \mu)$

Determining the CKM element Vcb and form factors simultaneously





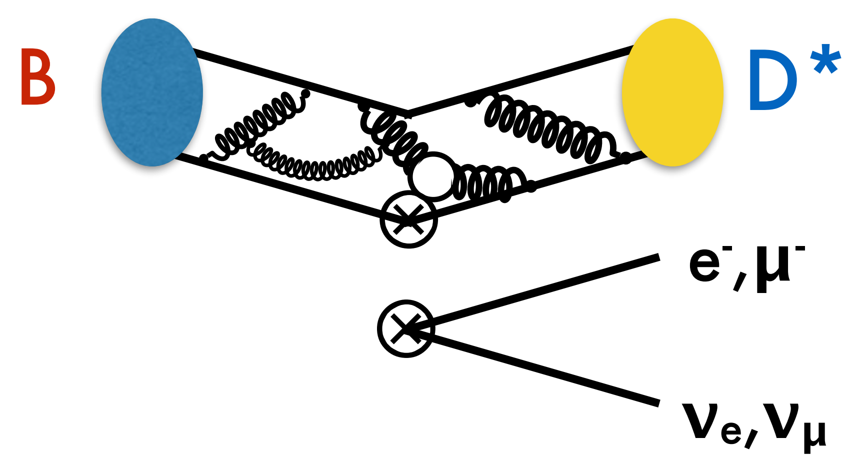
Exclusive determination relies heavily on the form factor values determined by the lattice QCD.



Attempt: determining the various form factors, including its momentum dependence, from the data to learn some aspects of form factor behaviour.

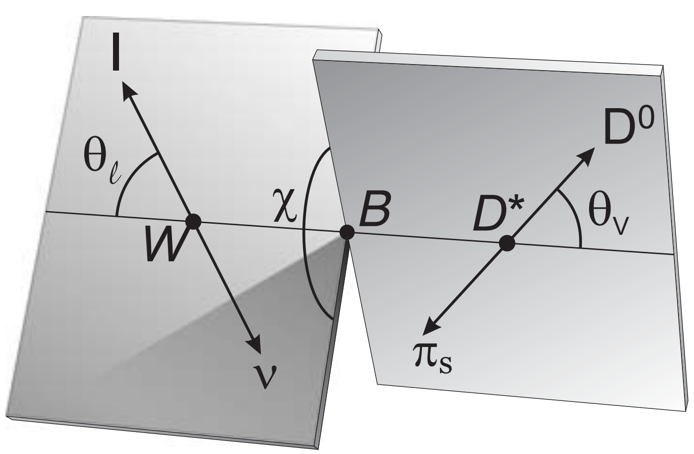
B→D*l ν (l=e,μ)

Determining the CKM element Vcb and form factors simultaneously



B→D* form factor

$$\langle D^*(p_{D^*},\epsilon)|\bar{c}\gamma_\mu(1-\gamma_5)b|\bar{B}(p_B)\rangle =$$
$$\frac{2iV(q^2)}{m_B+m_{D^*}}\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p^\alpha_{D^*}p^\beta_B - 2m_{D^*}A_0(q^2)\frac{\epsilon^*\cdot q}{q^2}q_\mu$$
$$-(m_B+m_{D^*})A_1(q^2)\left(\epsilon^*_\mu - \frac{\epsilon^*\cdot q}{q^2}q_\mu\right)$$
$$+A_2(q^2)\frac{\epsilon^*\cdot q}{m_B+m_{D^*}}\left[(p_B+p_{D^*})_\mu - \frac{m_B^2-m_{D^*}^2}{q^2}q_\mu\right]$$



Form factors including its momentum dependence are fitted to the experimental data (3 angles, 1 momentum) along with the Vcb.

Belle arXiv:1809.03290

Results in CNL parameterisation

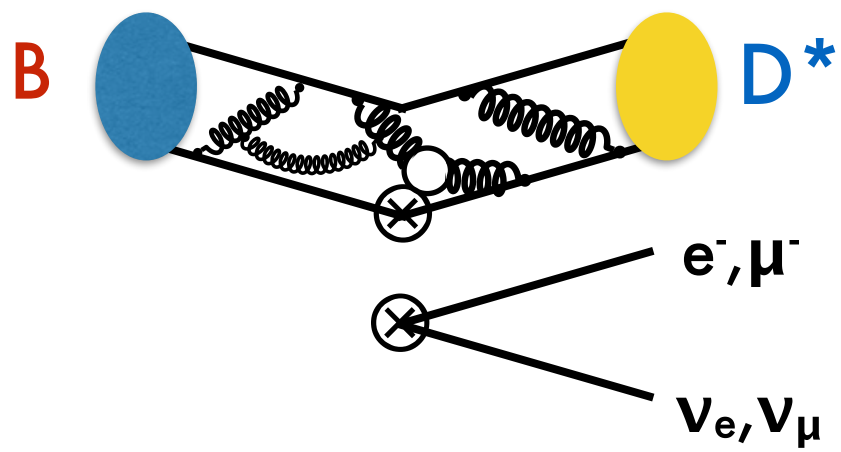
$$\rho^2 = 1.106 \pm 0.031 \pm 0.007,$$
$$R_1(1) = 1.229 \pm 0.028 \pm 0.009,$$
$$R_2(1) = 0.852 \pm 0.021 \pm 0.006,$$
$$\mathcal{F}(1)|V_{cb}|\eta_{\rm EW} \times 10^3 = 35.06 \pm 0.15 \pm 0.56,$$

Results in BGL parameterisation

$$\tilde{a}_0^f \times 10^3 = -0.506 \pm 0.004 \pm 0.008,$$
$$\tilde{a}_1^f \times 10^3 = -0.65 \pm 0.17 \pm 0.09,$$
$$\tilde{a}_1^{F_1} \times 10^3 = -0.270 \pm 0.064 \pm 0.023,$$
$$\tilde{a}_2^{F_1} \times 10^3 = +3.27 \pm 1.25 \pm 0.45,$$
$$\tilde{a}_0^g \times 10^3 = -0.929 \pm 0.018 \pm 0.013,$$
$$\mathcal{F}(1)|V_{cb}|\eta_{\rm EW} \times 10^3 = 34.93 \pm 0.23 \pm 0.59,$$

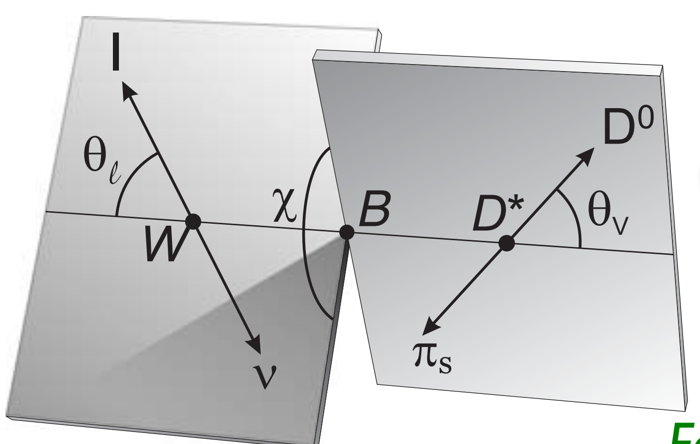
B→D*l ν (l=e,μ)

Determining the CKM element Vcb and form factors simultaneously



B→D* form factor

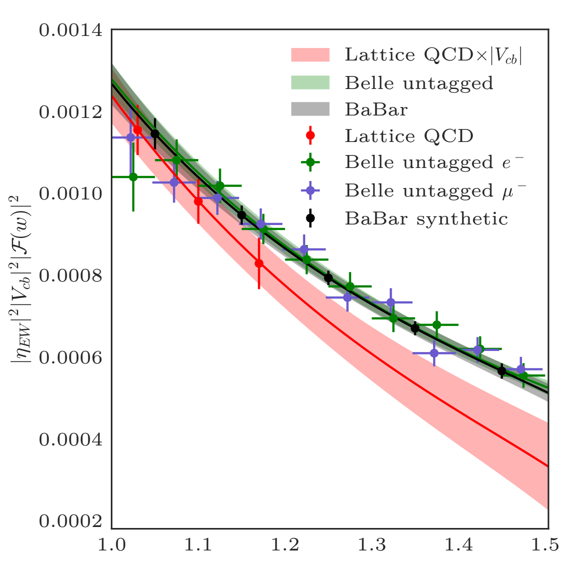
$$\langle D^*(p_{D^*},\epsilon)|\bar{c}\gamma_\mu(1-\gamma_5)b|\bar{B}(p_B)\rangle =$$
$$\frac{2iV(q^2)}{m_B+m_{D^*}}\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}p^\alpha_{D^*}p^\beta_B - 2m_{D^*}A_0(q^2)\frac{\epsilon^*\cdot q}{q^2}q_\mu$$
$$-(m_B+m_{D^*})A_1(q^2)\left(\epsilon^*_\mu - \frac{\epsilon^*\cdot q}{q^2}q_\mu\right)$$
$$+A_2(q^2)\frac{\epsilon^*\cdot q}{m_B+m_{D^*}}\left[(p_B+p_{D^*})_\mu - \frac{m_B^2-m_{D^*}^2}{q^2}q_\mu\right]$$

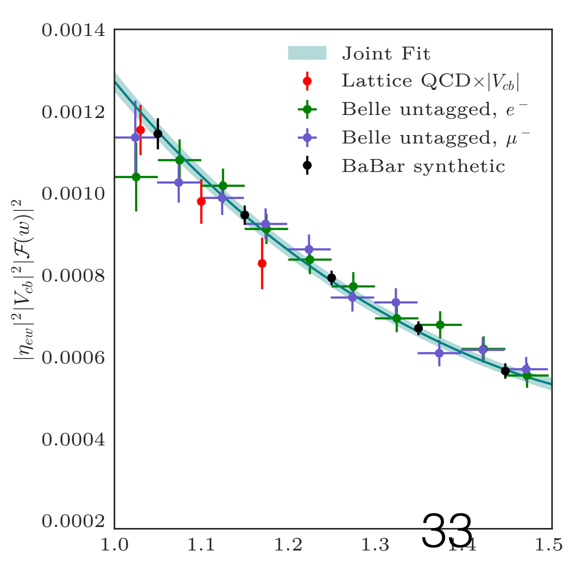


Cross check!

Most recently, two lattice QCD group have presented their results on the form factor!

Fermilab-MILK arXiv:2105.14019

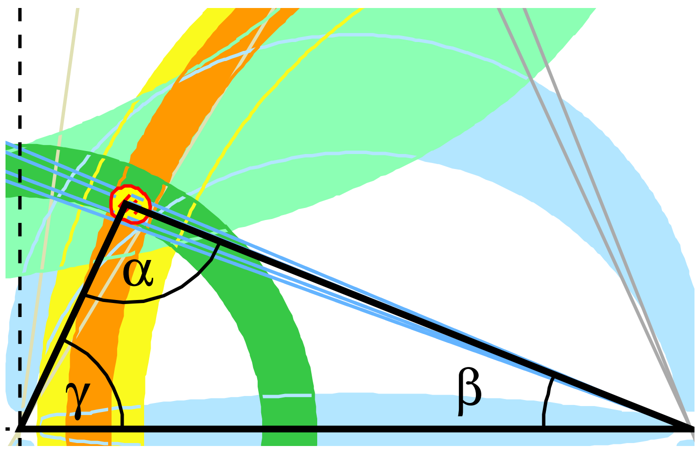




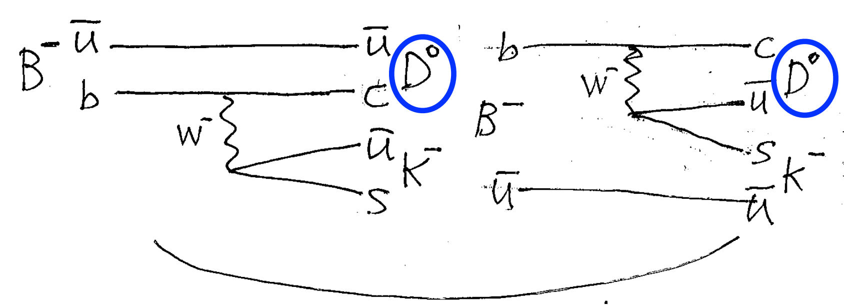
	Linear	Quadratic	Cubic
a_0	0.0330(12)	0.0330(12)	0.0330(12)
a_1	−0.157(52)	−0.155(55)	−0.155(55)
a_2		−0.12(98)	−0.12(98)
a_3			−0.004(1.000)
b_0	0.01229(23)	0.01229(24)	0.01229(23)
b_1	−0.002(10)	−0.003(12)	−0.003(12)
b_2		0.07(53)	0.05(55)
b_3			−0.01(1.00)
c_1	−0.0057(22)	−0.0058(25)	−0.0057(25)
c_2		−0.013(91)	−0.02(10)
c_3			0.10(95)
d_0	0.0508(15)	0.0509(15)	0.0509(15)
d_1	−0.317(59)	−0.327(67)	−0.327(67)
d_2		−0.03(96)	−0.02(96)
d_3			−0.0006(1.0000)
χ^2/dof	0.83/5	0.64/3	0.64/3
$\sum_i^N a_i^2$	0.026(16)	0.04(24)	0.04(24)
$\sum_i^N (b_i^2+c_i^2)$	0.000193(69)	0.005(70)	0.01(18)
$\sum_i^N d_i^2$	0.103(37)	0.110(61)	0.110(52)

Strong phase for ϕ_3(γ) measurement

Determining the CKM phase ϕ_3 using external input for strong phase

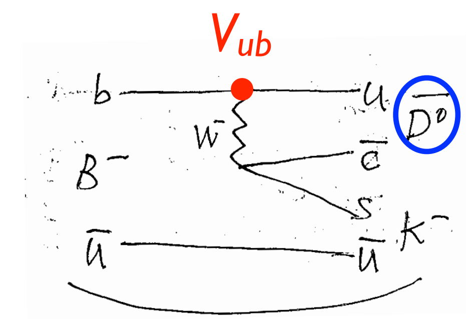


We need to measure interference to extract a complex phase



color-allowed

A_B



color-suppressed

$A_B r_B e^{i(\delta_B - \phi_3)}$

To have interference, we need the D and D decay into the same final state, e.g. Ksπ+π-

$$A(B^- \to (K_S\pi^-\pi^+)_{D,\overline{D}}K^-) = A_B\left[A_D(s_{12},s_{13})e^{i\delta_D(s_{12},s_{13})} + r_B e^{i(\delta_B-\phi_3)}A_{\overline{D}}(s_{12},s_{13})e^{i\delta_{\overline{D}}(s_{12},s_{13})}\right]$$

Strong phase for ϕ_3(γ) measurement

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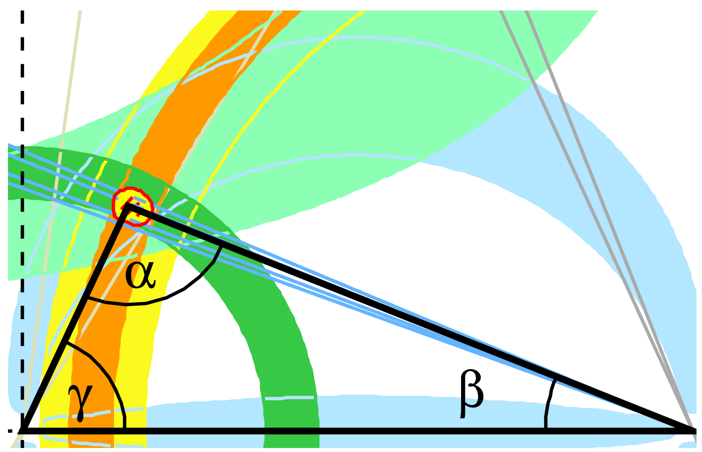

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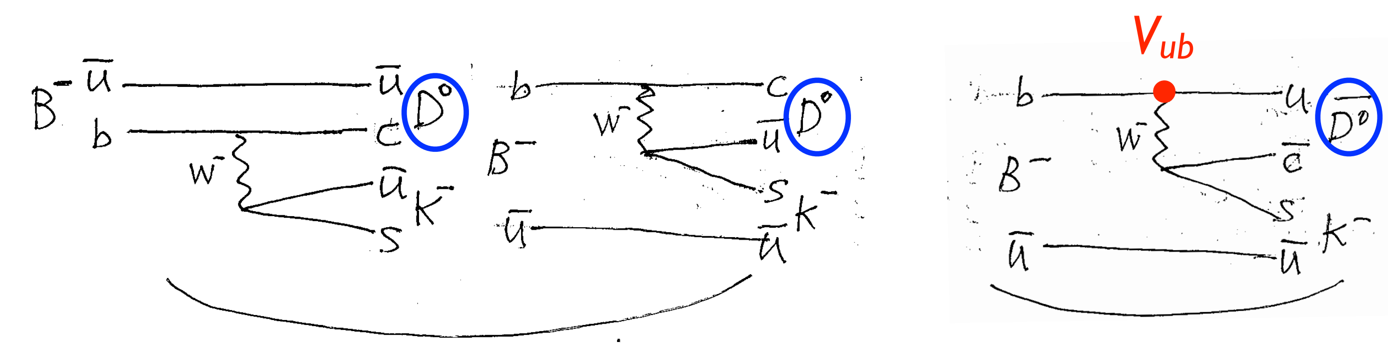

color-allowed

A_B

color-suppressed

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Since strong interaction is CP conserving, we have relation between D and D amplitudes

$$\boxed{A_{\overline{D}}(s_{12},s_{13})e^{i\delta_{\overline{D}}(s_{12},s_{13})} = A_D(s_{13},s_{12})e^{i\delta_D(s_{13},s_{12})}}$$

$$= A_B\left[\underline{A_D(s_{12},s_{13})}e^{i\underline{\delta_D}(s_{12},s_{13})} + r_B e^{i(\delta_B-\phi_3)} \underline{A_D}(s_{13},s_{12})e^{i\delta_D(s_{13},s_{12})}\right]$$

Strong phase for $\phi_3(\gamma)$ measurement

Determining the CKM phase ϕ_3 using external input for strong phase

Belle hep-ex/0303187

Although, now it boils down to only one strong phase (in 2D space), there have been difficulties to obtain it from the Dalitz plot.

BPGGSZ idea: obtain the strong phase from D meson experiments (CLEO, BESIII) and copy them!

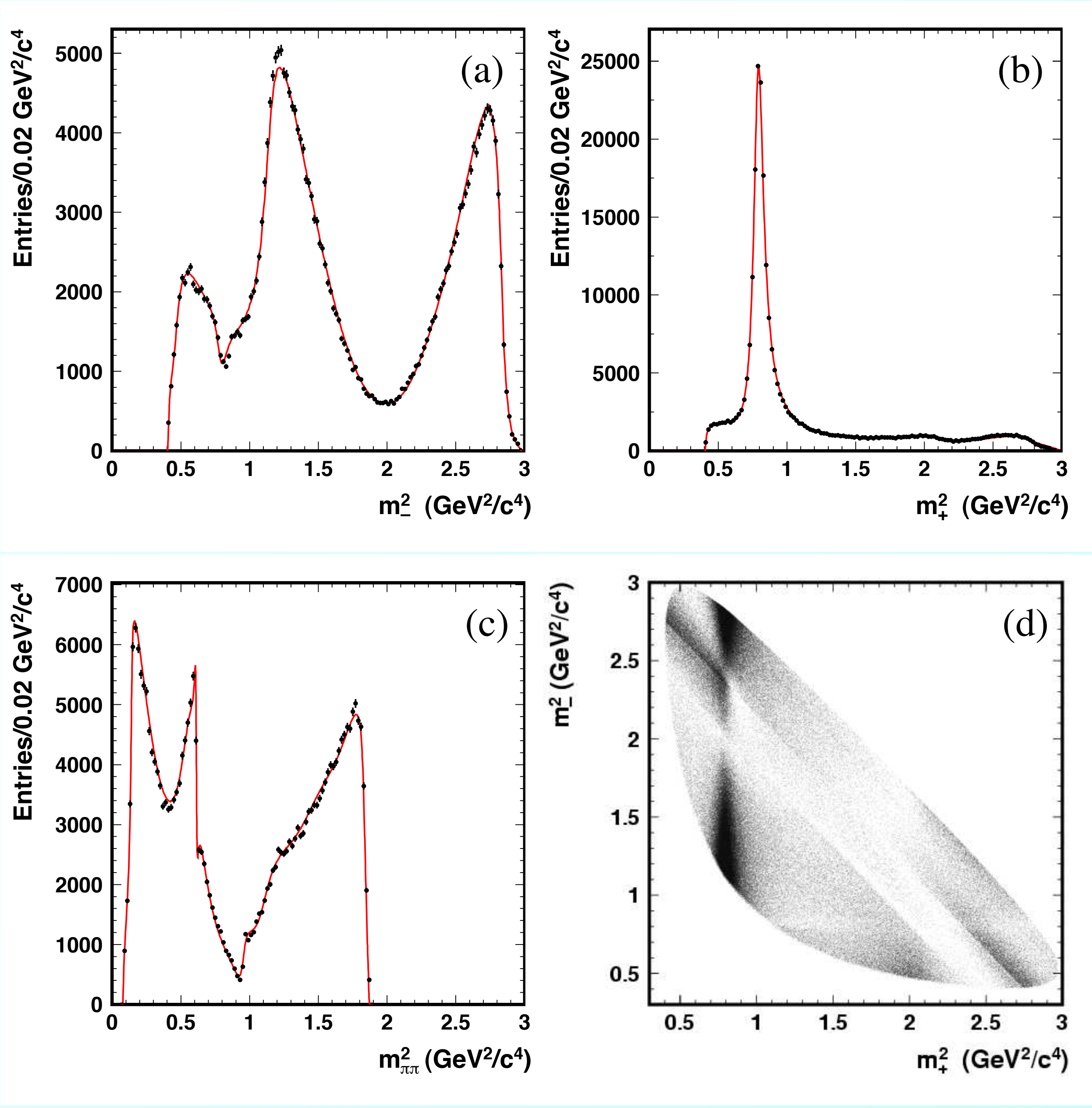


FIG. 2: (a) m_-, (b) m_+, (c) $m_{\pi\pi}$ and (d) Dalitz plot distribution for $D^{*-} \to \overline{D}^0\pi_s^-$, $\overline{D}^0 \to K_S^0\pi^+\pi^-$ decays from the $e^+e^- \to c\bar{c}$ continuum process. The points with error bars show the data; the smooth curve is the fit result.

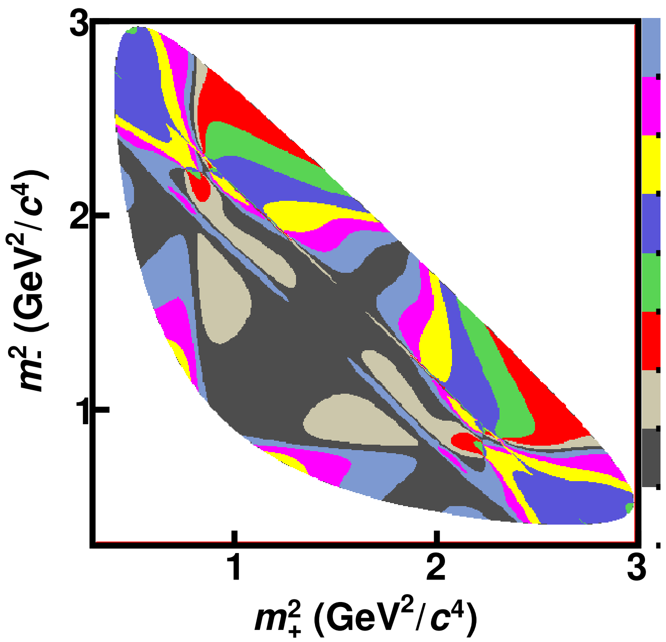
$$= A_B \left[\underline{A_D(s_{12}, s_{13})} e^{\underline{i\delta_D}(s_{12},s_{13})} + r_B e^{i(\delta_B - \phi_3)} \underline{A_D(s_{13}, s_{12})} e^{i\delta_D(s_{13},s_{12})} \right]$$

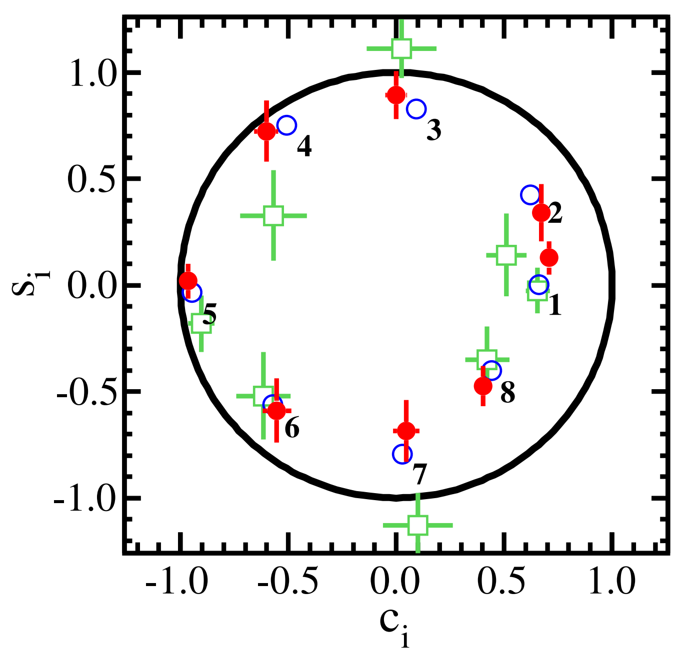
Strong phase for $\phi_3(\gamma)$ measurement

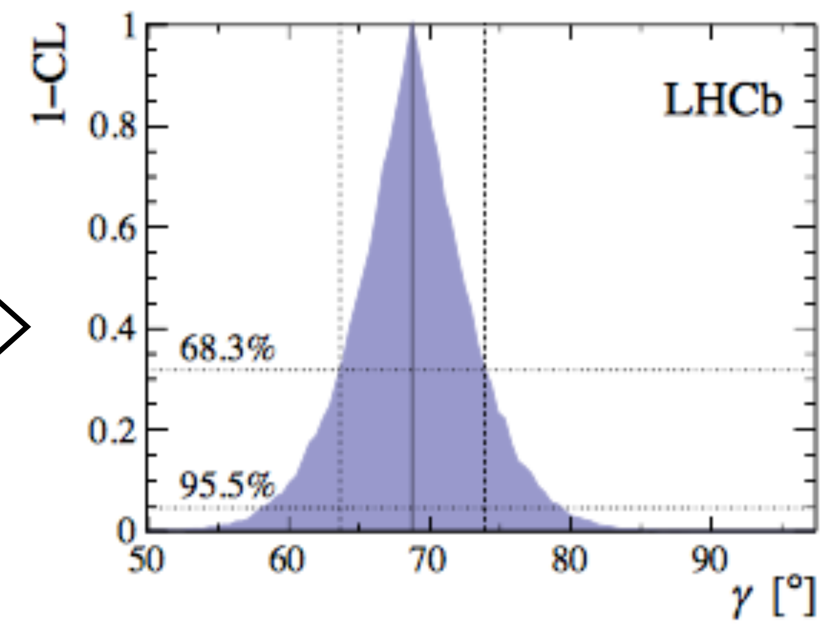
Determining the CKM phase ϕ_3 using external input for strong phase

$$\begin{aligned} c(s_{12}, s_{13}) &= A_D(\underline{s_{12}, s_{13}})A_D(\underline{s_{13}, s_{12}}) \cos[\delta_D(\underline{s_{12}, s_{13}}) - \delta_D(\underline{s_{13}, s_{12}})] \\ s(s_{12}, s_{13}) &= A_D(\underline{s_{12}, s_{13}})A_D(\underline{s_{13}, s_{12}}) \sin[\delta_D(\underline{s_{12}, s_{13}}) - \delta_D(\underline{s_{13}, s_{12}})] \end{aligned}$$

arXiv:2010.08483

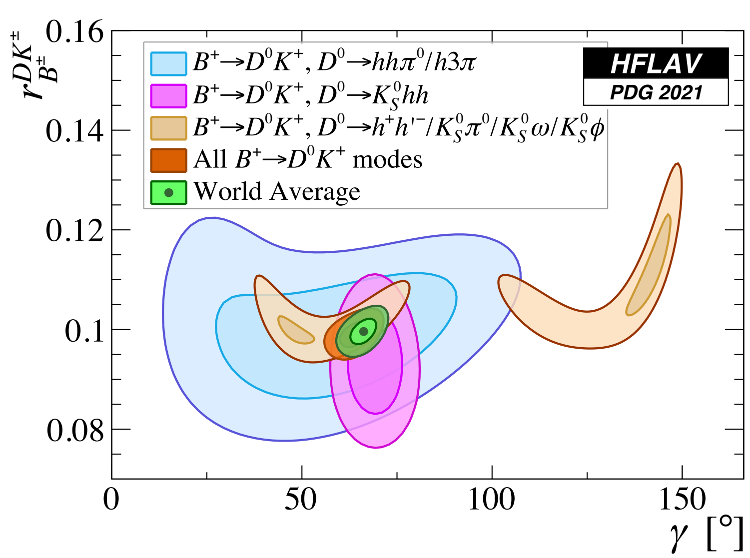




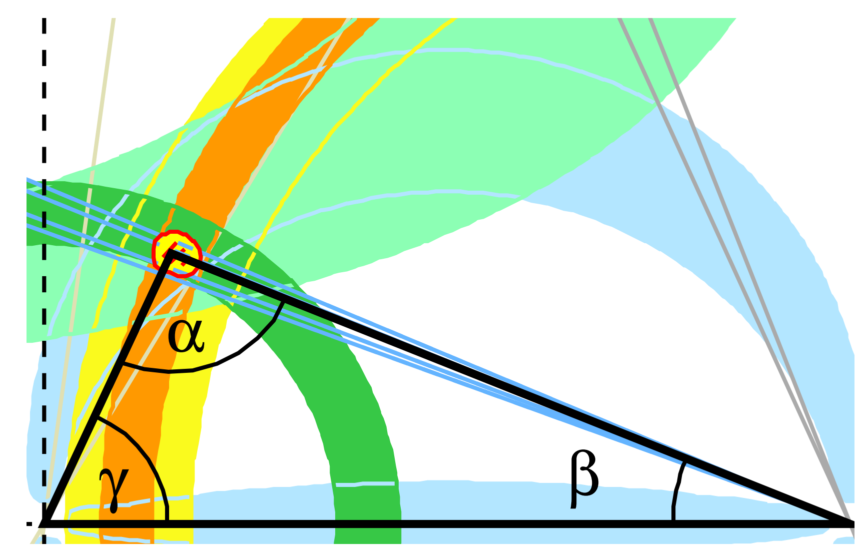


Strong phase from BESIII *arXiv:2003.00091*

LHCb γ measurement

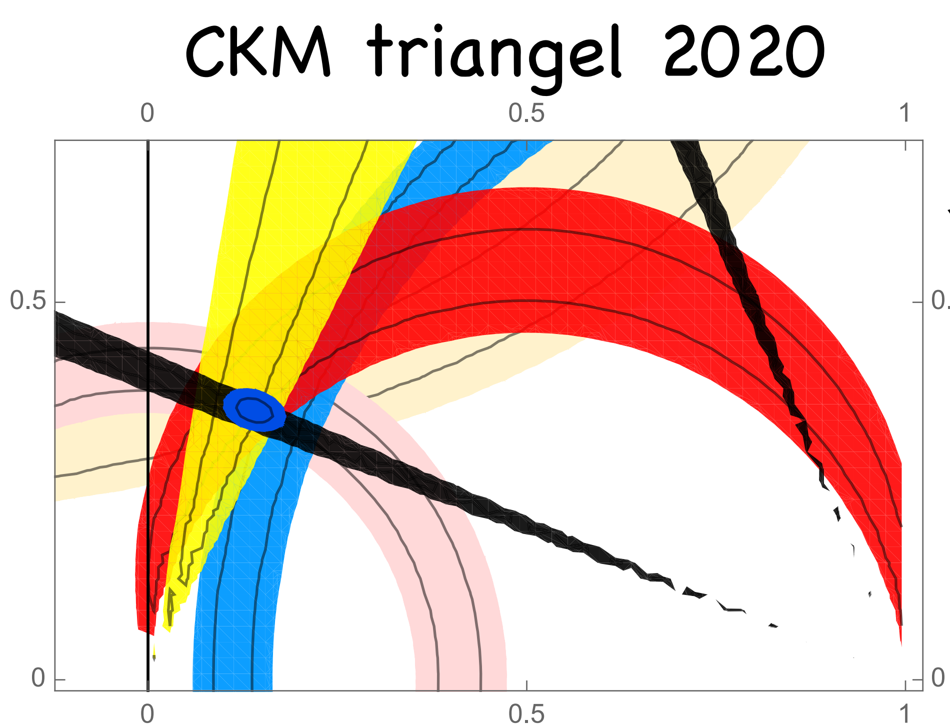


$$\begin{aligned} \gamma &= (68.7^{+5.2}_{-5.1})^\circ, \\ r_B^{DK^\pm} &= 0.0904^{+0.0077}_{-0.0075}, \\ \delta_B^{DK^\pm} &= (118.3^{+5.5}_{-5.6})^\circ, \\ r_B^{D\pi^\pm} &= 0.0050 \pm 0.0017, \\ \delta_B^{D\pi^\pm} &= (291^{+24}_{-26})^\circ. \end{aligned}$$

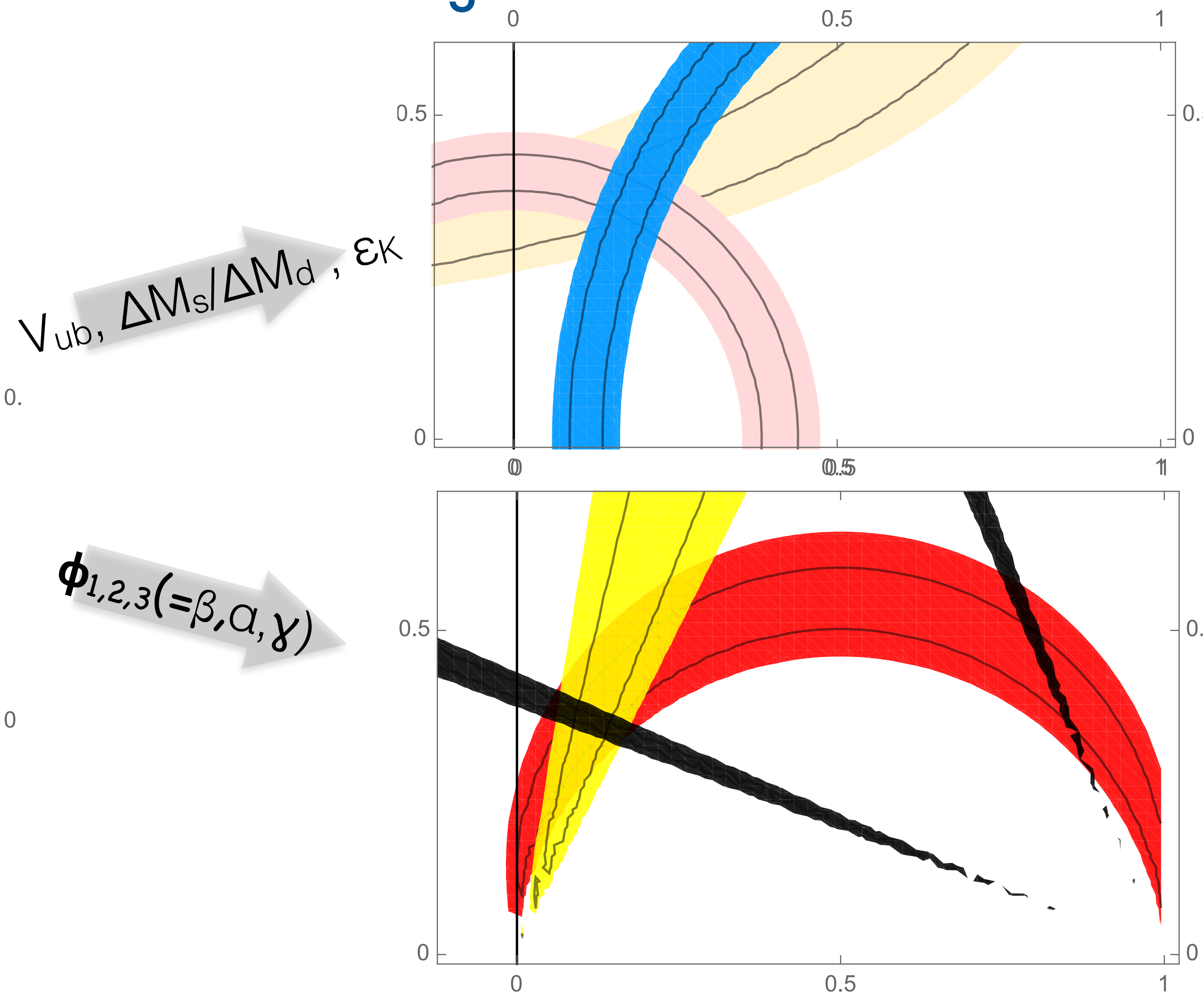


CKM unitarity triangle 2020 ⇨ 2030

Illustration of CKM triangle 2020



Input: PDG review on CKM ‘20

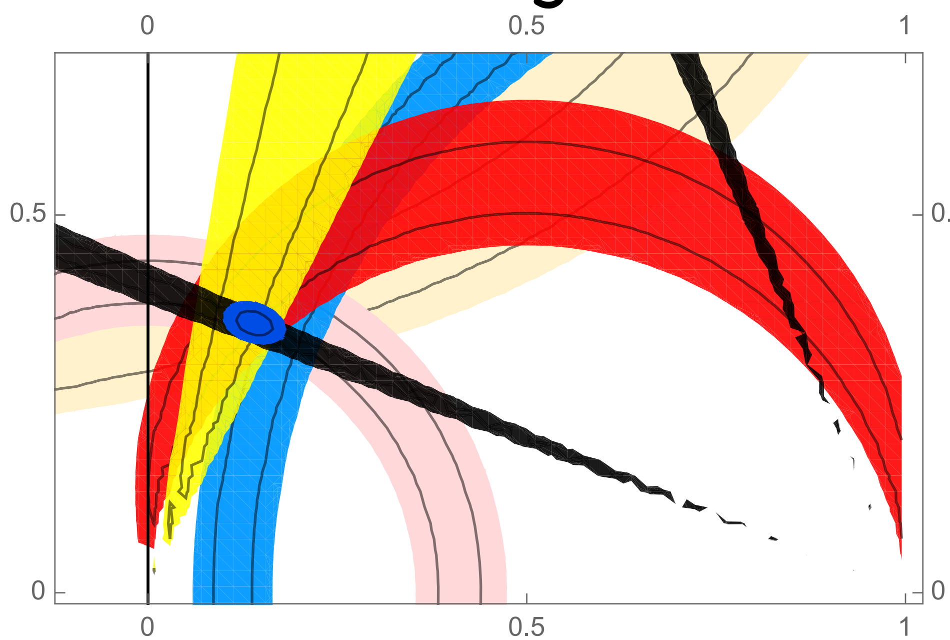


- V_{cb}: Exclusive (inclusive) measurements point to lower (higher) values. Individual uncertainties are much smaller.
- $\Delta M_s/\Delta M_d$: The latest lattice QCD ξ value has about a half uncertainty.
- α,β,γ : Experimental error dominant. The uncertainties will go down to $\delta\phi_1$ $(\delta\beta)$=~0.4°, $\delta\phi_2$ $(\delta\alpha)$=~1°, $\delta\phi_3$ $(\delta\gamma)$=~1.5°

CKM unitarity triangle 2020 ⇨ 2030

Illustration of CKM triangle 2030

CKM triangel 2020

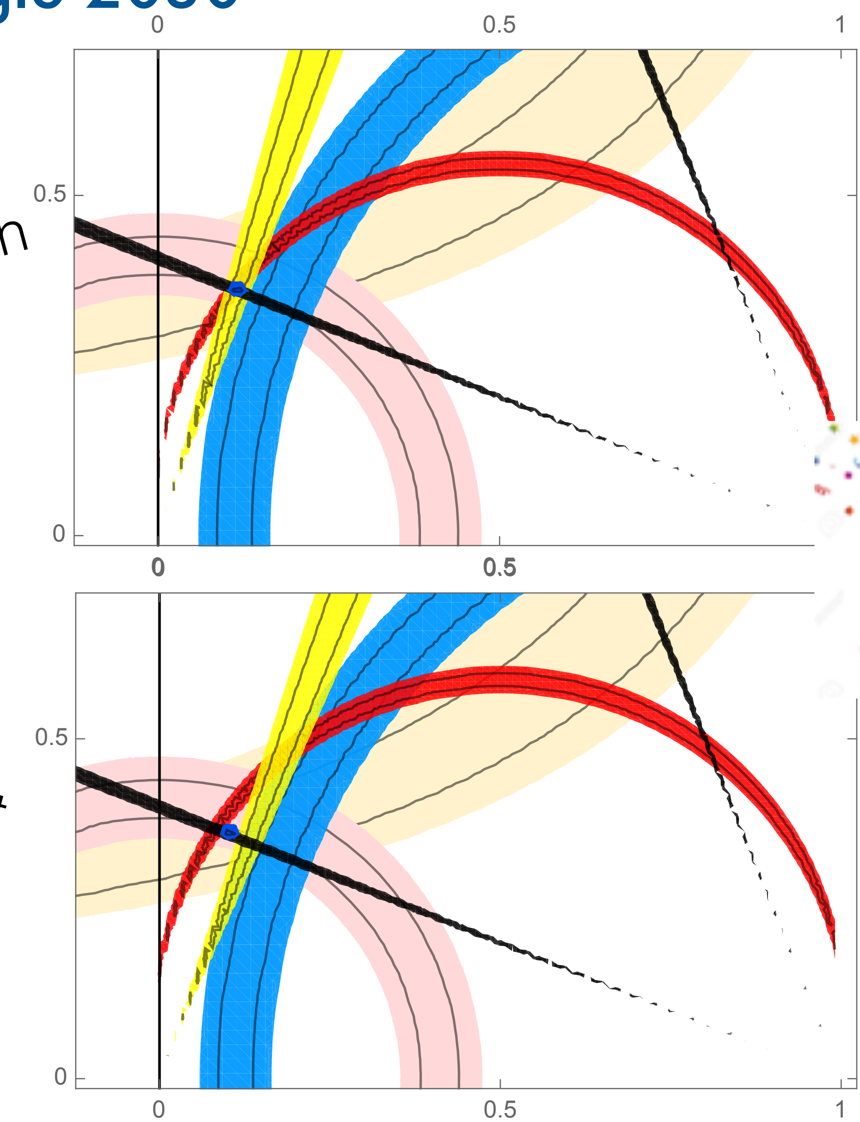


Input: PDG review on CKM ‘20

Central values remain the same

2030

Central values shift to lower side (within 1σ)

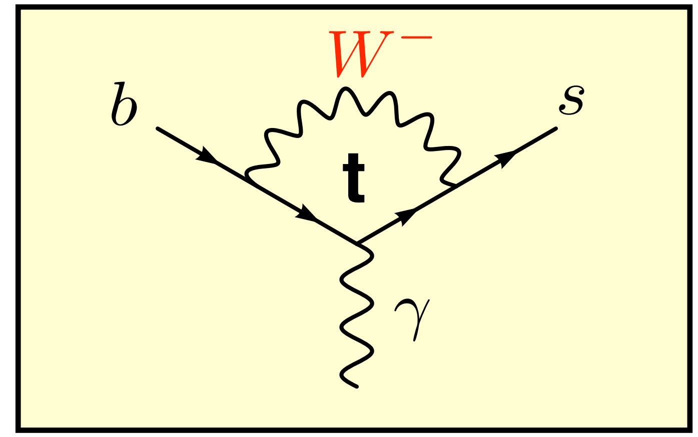


- Curiously, the current central values indicate α+β+γ very close to 180 degree.
- But by varying them within 1 sigma range, we find that a significant deviation from α+β+γ≠180° is still quite possible.
- Solving the side measurement issues is very important to pin down the new physics!

Testing left-handedness of W

The b→sγ processes can be used to test left-handedness of W!

- ✍ $b \to s\ \gamma_L$ (left-handed polarisation)
- ✍ $\bar{b} \to \bar{s}\ \gamma_R$ (right-handed polarisation)



▸ Time dependent CP asymmetry

Atwood, Gronau, Soni PRL79
Atwood, Gershon, Hazumi, Soni PRD 05

- ✓ $B_d \to K_S \pi^0 \gamma$, $B_d \to \rho\gamma$ (Belle II)
- ✓ $B_d \to K_S \pi^+ \pi^- \gamma$ (Belle II)
- ✓ $B_d \to K_S \phi\gamma$, $K_S \eta\gamma$
- ✓ $B_s \to \phi\gamma$ (LHCb)

▸ Angular distribution (require more than 4 body final state)

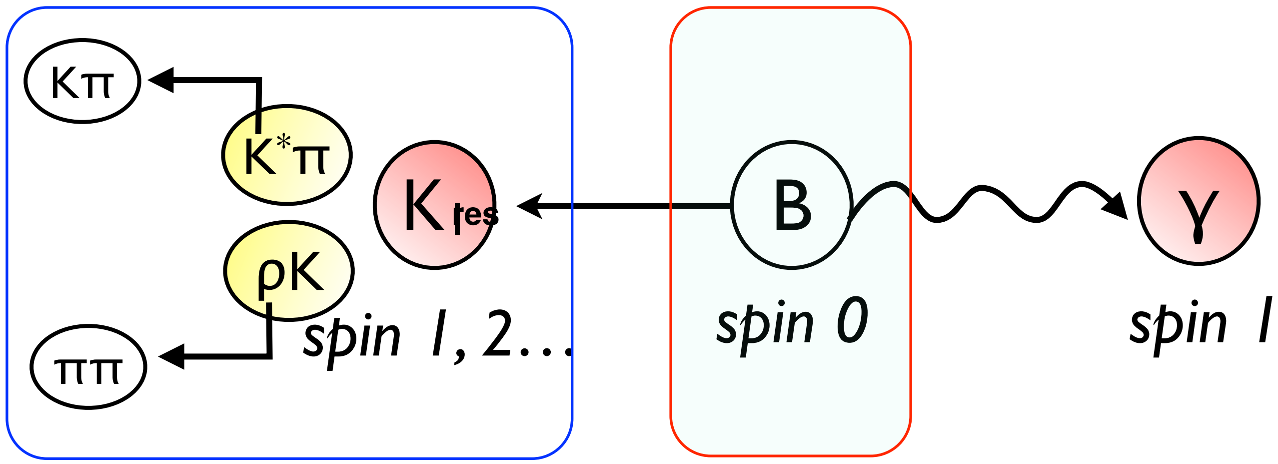
Kruger, Matias PRD71
Becirevic, Schneider, NPB854

- ✓ Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$) (LHCb)
- ✓ $B \to K_{res} (\to K\pi\pi)\gamma$ (called λ_γ) (Belle II/LHCB)
- ✓ $\Lambda_b \to \Lambda^{(*)}\gamma$ (LHCb)

Gronau et al PRL88
E.K. Le Yaouanc, Tayduganov PRD83

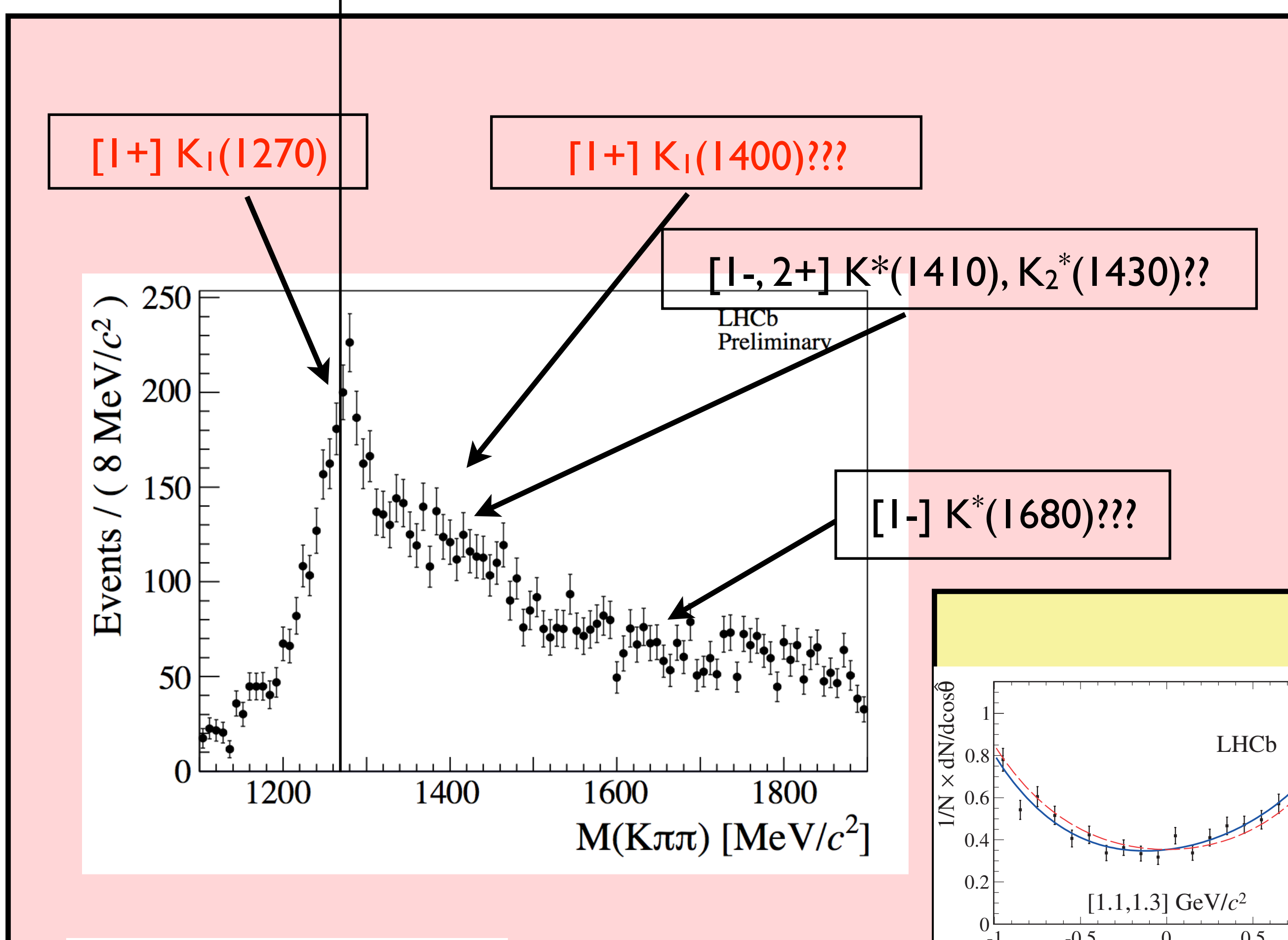
Testing left-handedness of W

The b→sγ processes can be used to test left-handedness of W!

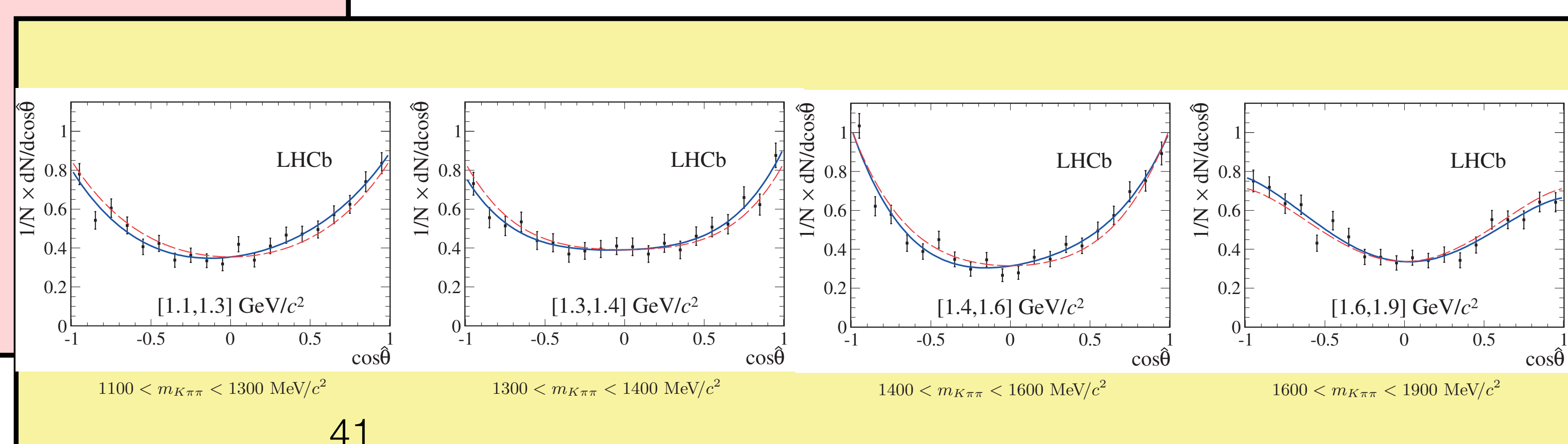


We have been working on the method utilising the $B \to K_{res}\gamma \to K\pi\pi\gamma$ final states. Photon polarisation is measured via the polarisation measurement of the recoiling hadrons, which can be obtained through amplitude analysis (2 angles and 2 Dalitz variables)

B. Knysh, EK, F. Le Diberder in preparation



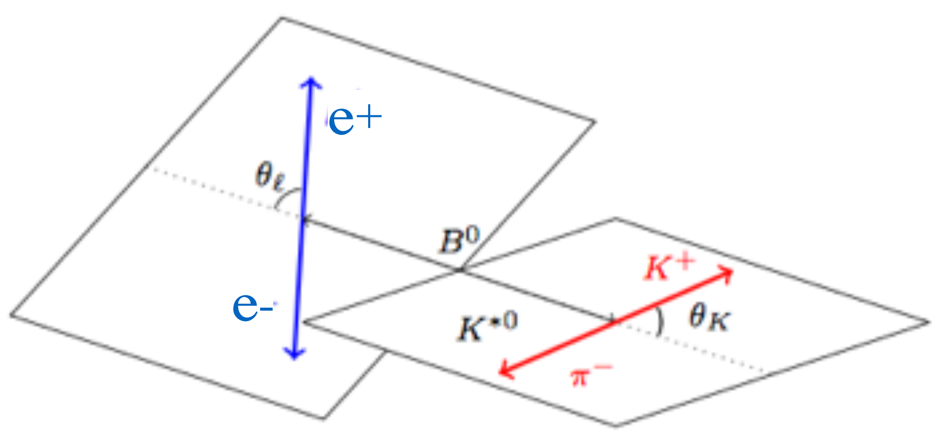
LHCb PRL ('14)



Testing left-handedness of W

The b→sγ processes can be used to test left-handedness of W!

Update from LHCb



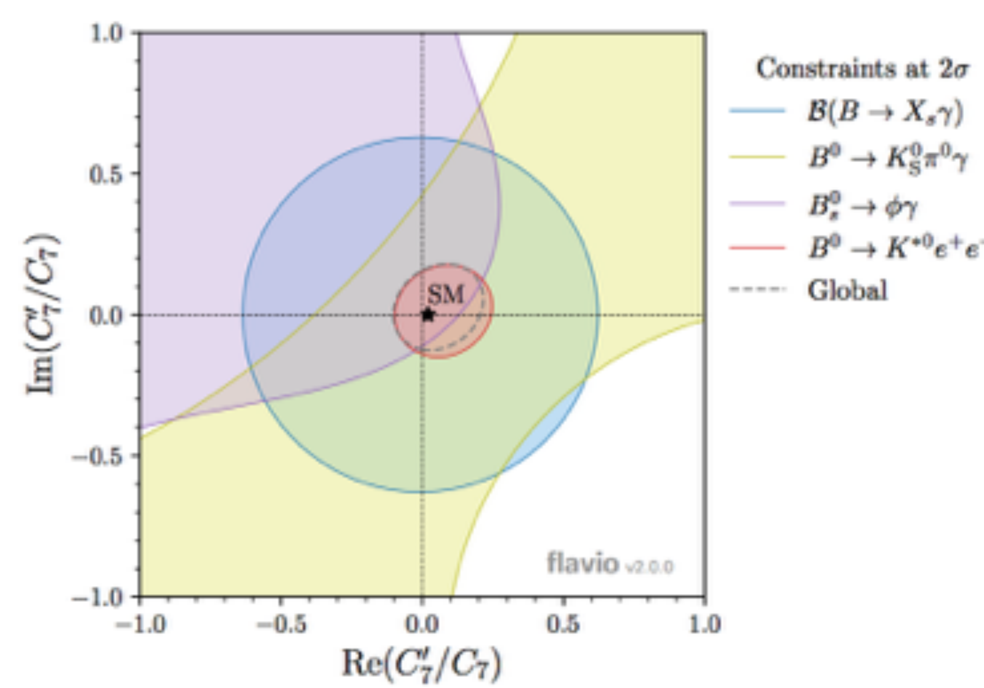
The B→K*e+e- process is dominated by the B→K*γ at low q^2 (e+e- mass) region. Using 3 angle distribution, one can determine the photon polarisation.

The observed signal ($0.0008 < q^2 < 0.257$ GeV^2) at LHCb: ~450 @9fb^{-1}

$$\lim_{q^2\to 0} \mathcal{A}_T^{(2)}(q^2) = \frac{2\mathcal{R}e[C_{7\gamma}C_{7\gamma}'^*]}{|C_{7\gamma}|^2 + |C_{7\gamma}'|^2}$$

$$\lim_{q^2\to 0} \mathcal{A}_T^{(\mathrm{im})}(q^2) = \frac{2\mathcal{I}m[C_{7\gamma}C_{7\gamma}'^*]}{|C_{7\gamma}|^2 + |C_{7\gamma}'|^2}$$

$$A_{\mathrm{T}}^{(2)} = +0.11 \pm 0.10 \pm 0.02$$
$$A_{\mathrm{T}}^{\mathrm{Im}} = +0.02 \pm 0.10 \pm 0.01$$



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Testing left-handedness of W

The b→sγ processes can be used to test left-handedness of W!

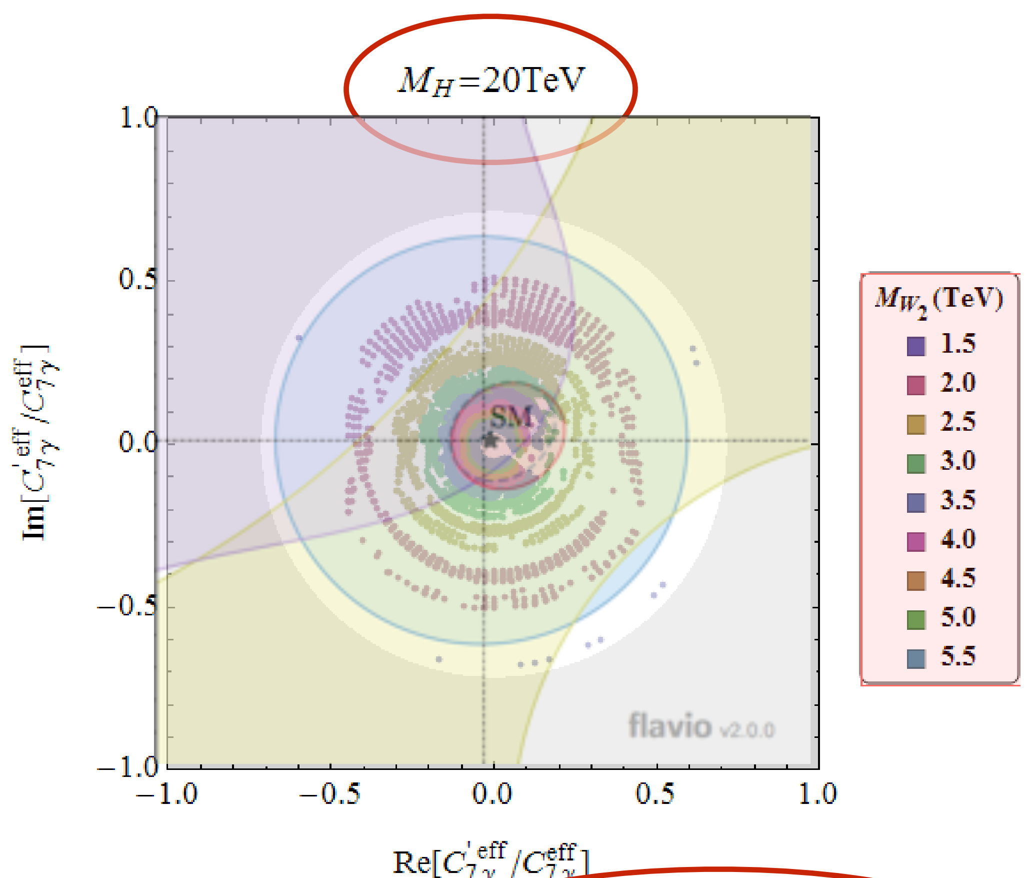
$$SU(2)_L \times SU(2)_R \times U(1)_{\tilde{Y}} \to SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}.$$

Pati,Salam,1974;Mohapatra,Pati,1975; Mohapatra,Sejanovic,1975,
See also M. Blanke et al. JHEP1203 for flavour studies

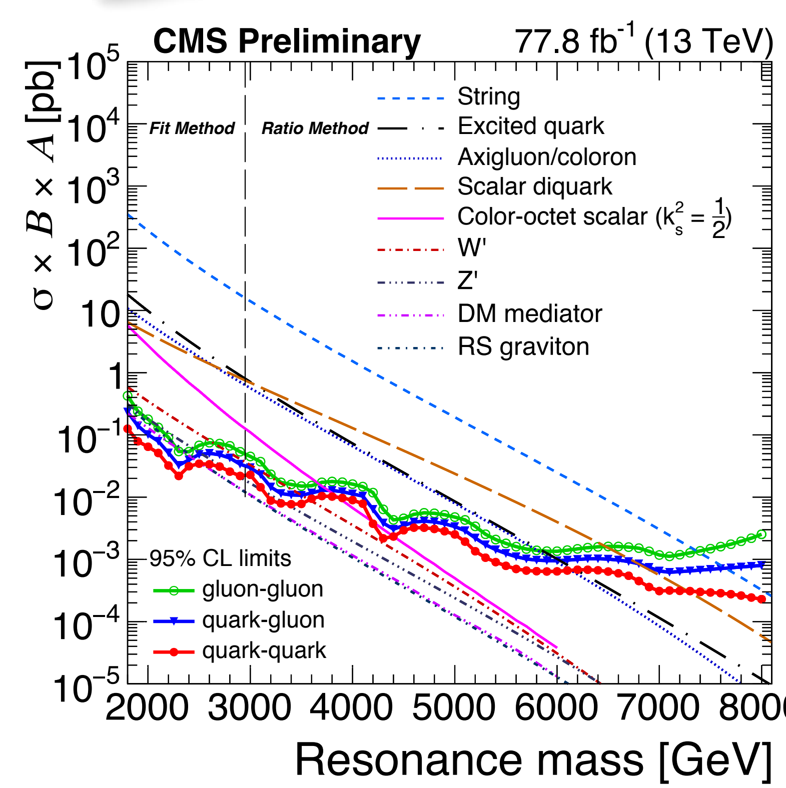
$$V^R_{(A)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\alpha & \pm s_\alpha \\ 0 & s_\alpha & \mp c_\alpha \end{pmatrix},$$

EK, C.-D. Lu and F.-S. Yu (JHEP 2013)

LHCb result indicates $m_{W2} \gtrsim$ 3 TeV, which is close to the limit at high P_T search.



Model parameters; g_R/g_L=1, tan beta=10



Generic resonance search with dijets
(sequential model i.e. g_R/g_L=1)

Conclusions

- The coming years are very exciting for flavour physics: the Belle II and the upgrades of LHCb will improve the sensitivity to new physics drastically.
- Searching new physics through FCNC/CPV is sensible as introducing a new particle immediately induces FCNC and extra freedoms for CP violating phase.
- The challenge of B physics comes from the strong interaction effects, which hide the new physics information.
- Lattice QCD is one of the the most powerful tools to overcome this issue.
- Data driven method is becoming more and more available and it will open possibilities to reduce the uncertainties coming from the strong interactions.

backup