B physics

a probe to hunt for new physics

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2014 Working Month on the Frontier of Physics

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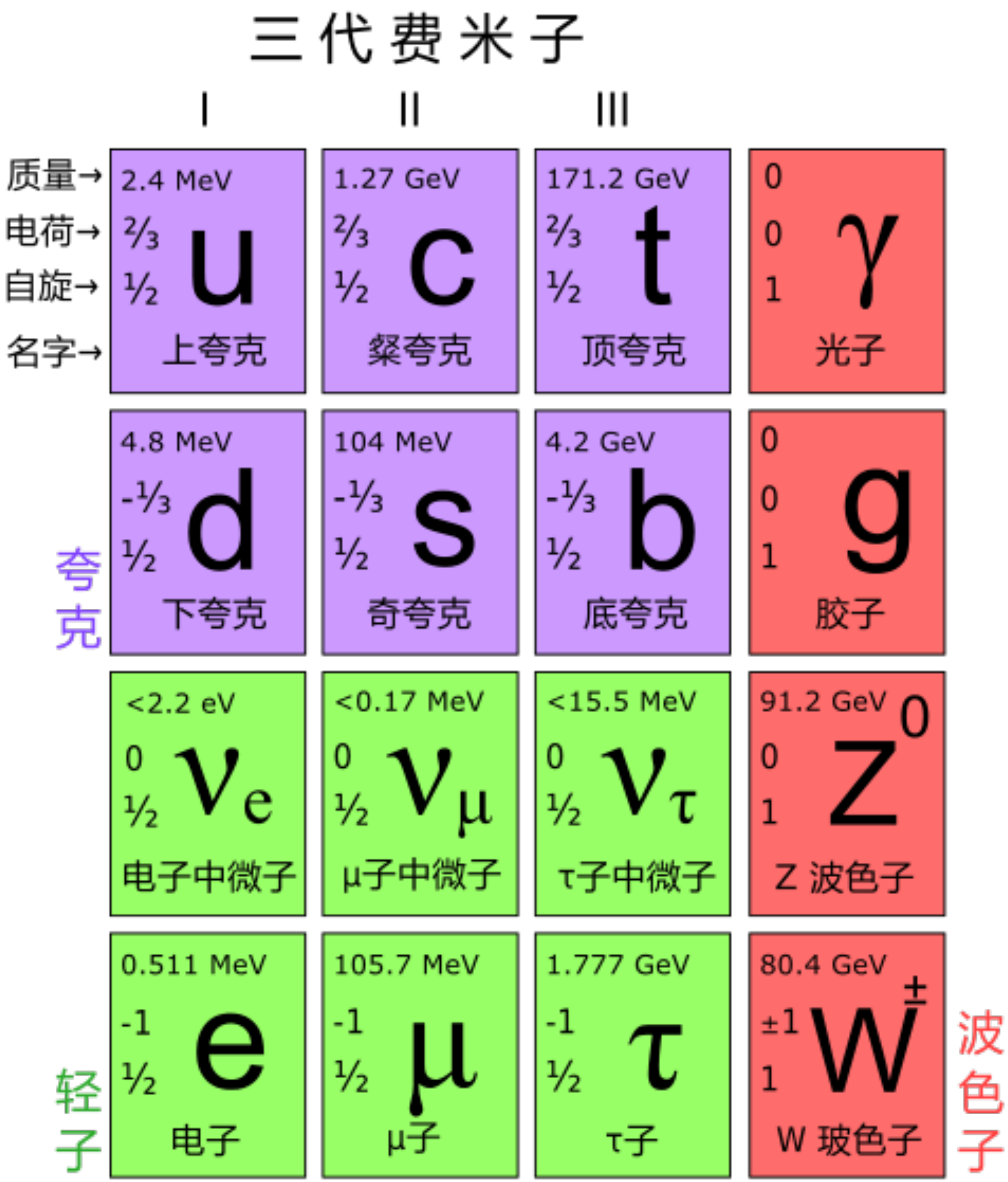
Content

- What is B physics?
- B experiments
- Why B physics?
- A few B decay modes
- Factorization in Effective field theory
  Heavy-Quark-Effective-Theory, SCET


三代费米子
I
II
III
质量→
电荷→
自旋→
名字→
2.4 MeV
⅔
½
u
上夸克
1.27 GeV
⅔
½
c
粲夸克
171.2 GeV
⅔
½
t
顶夸克
0
0
1
γ
光子
4.8 MeV
-⅓
½
d
下夸克
104 MeV
-⅓
½
s
奇夸克
4.2 GeV
-⅓
½
b
底夸克
0
0
1
g
胶子
夸克
<2.2 eV
0
½
νe
电子中微子
<0.17 MeV
0
½
νμ
μ子中微子
<15.5 MeV
0
½
ντ
τ子中微子
91.2 GeV
0
1
Z0
Z 波色子
0.511 MeV
-1
½
e
电子
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-1
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μ子
1.777 GeV
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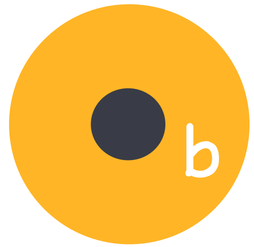
波色子

B Physics

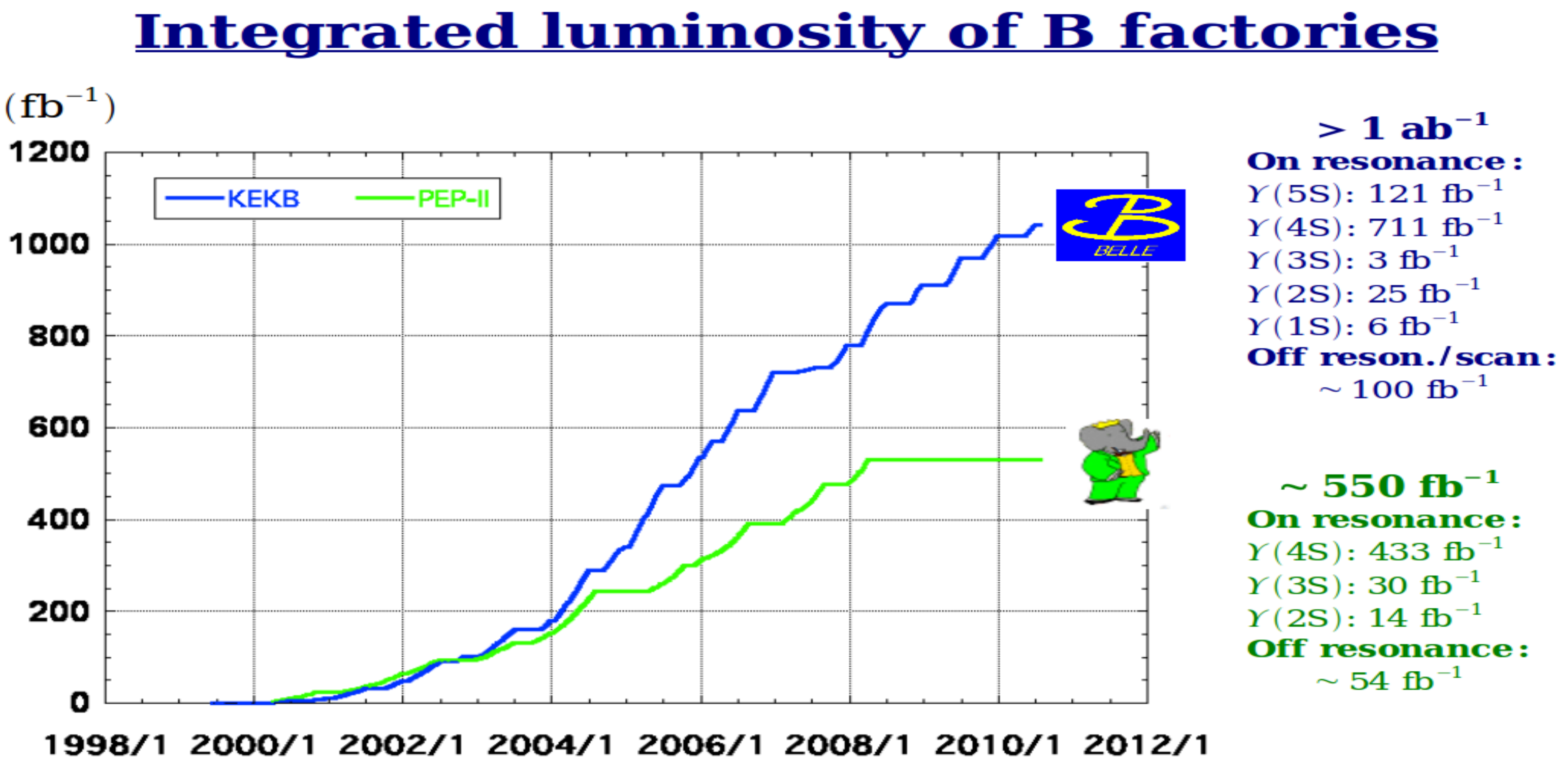


- Bound states of b and light quarks
  - mesons (B^-, B^0, B_s)
  - baryons $(\Lambda_b, \Xi_b^-, \Xi_b^0)$
- Heaviest stable bound states in QCD $(\geq 5.28\ \mathrm{GeV})$
- Rich spectrum, many decay channels
- Important source of information about CP violation, CKM parameters, new physics

B Experiments

B factories

- B factories， Starting in 1999， asymmetric collision
- KEKB (Belle)， e^+ energy 8GeV, e^- energy 3. 5GeV
- PEP-II (BaBar), e^+ energy 9GeV, e^- energy 3. 1GeV



Super B and LHCb

- Super B(Italy)
- Super KEKB (Belle II)
- LHC-b@CERN
- … …

SuperKEKB luminosity projection

Prospect: B experiments in future

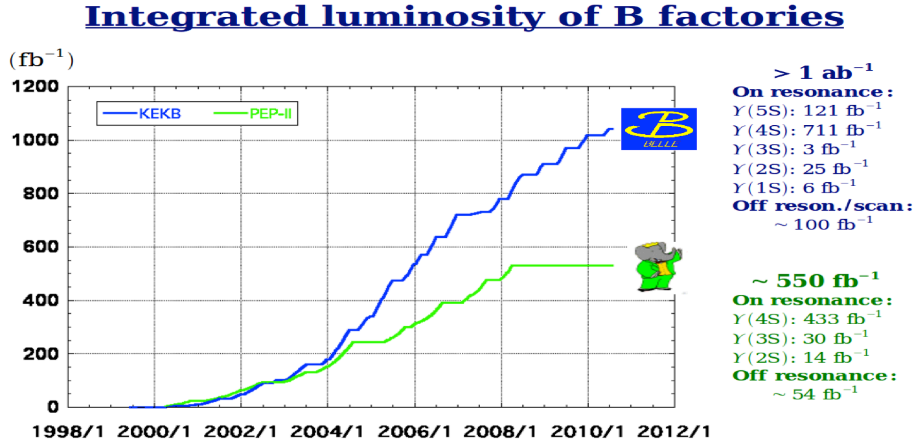
Experiments providing most of analyses today

3.1 GeV e^+
9 GeV e^-

3.5 GeV e^+
8 GeV e^-

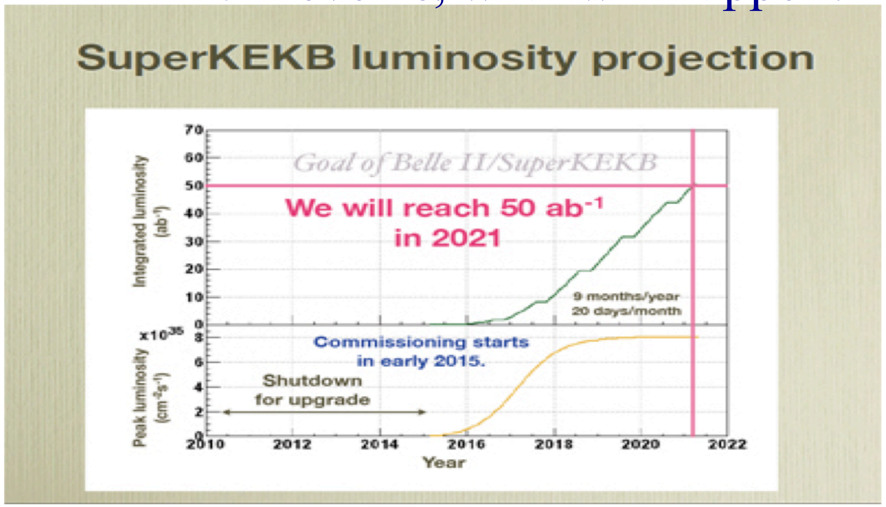
Experiments that start collecting results recently

Planned facilities



10^9 events, leading to Nobel in 2008

10^{11} events, what will happen?

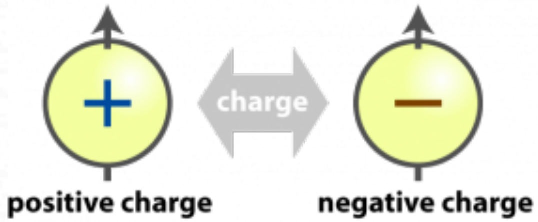


Experimental prospect is very promising!

Why B physics?

What is the origin for matter-antimatter asymmetry in our universe?

C:Matter-AntiMatter



CP

We need C and CP asymmetry!

Quark mixing and CKM

Mass Eigenstates $\neq$ Weak Eigenstates $\Rightarrow$ Quark Mixing

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

CKM Matrix

Complex matrix described by
4 independent real parameters

Wolfenstein parametrization:

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

phase

CP Violation:

$$J = \mathrm{Im}\left(V_{ik}\, V^*_{jk}\, V_{j\ell}\, V^*_{i\ell} \right) \neq 0$$

$$J \approx A^2\lambda^6\eta$$

$\eta = 0 \Rightarrow$ no CPV from SM

CP violation (matter-antimatter asymmetry) **in the kaon-system**
→ prediction of third quark family

1973: M. Kobayashi, T. Maskawa,
theoretical mechanism for CP-violation in the Standard Model requires b- and t-quark

M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

before J/Psi was discovered in 1974

2001: experimental proof of **CP violation in B-system** by B-factories (BELLE & BaBar)

B. Aubert *et al. (BaBar Collab.), Phys. Rev. Lett.* **87**, 091801 (2001).
K. Abe *et al. (Belle Collab.), Phys. Rev. Lett.* **87**, *091802* (2001).

2008: Nobel prize in physics

" for the discovery of the **origin of the broken symmetry** which predicts the existence of at least three families of quarks in nature"

CP violation in K,D,B

- In Kaon CP violation is about 0.2%
- In D meson decays, CPA at 1% (LHCb and CDF) is argued to be New physics.
- In B decays $\sin(2\beta)$ =0.672! Large CPA

Good test of SM from B physics.

Where is New Physics?

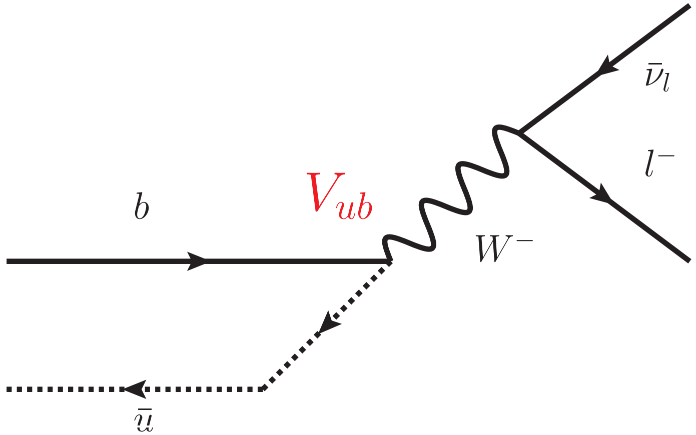
Physics Goal

NP found	NP not found
- determine the FV and CPV couplings of the NP Lagrangian - look for the effect of heavier states	- look for any deviation from the SM signaling NP in the multi-TeV energy region

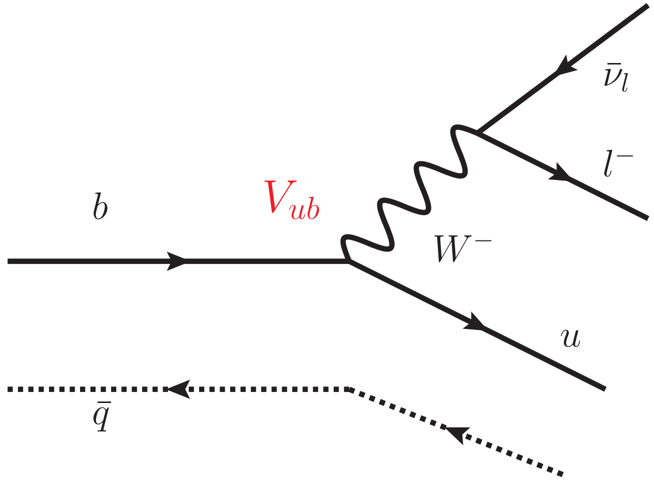
- probe regions of the NP parameter space

Tree-level B decays: extract SM parameters

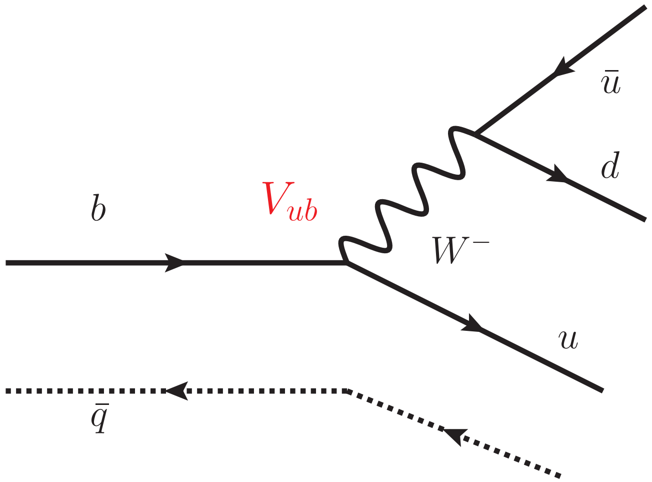
$|V_{ub}|$



Leptonic

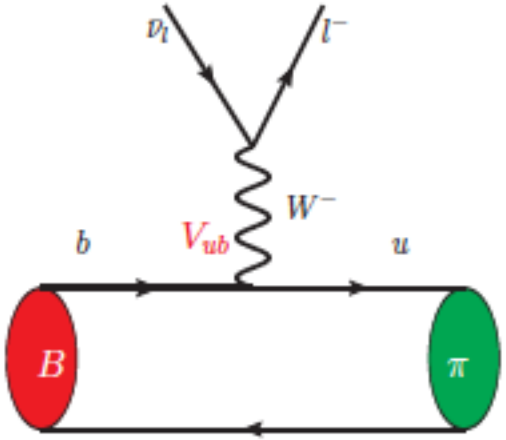


Semi-Leptonic



Non-Leptonic

B->pi lnu



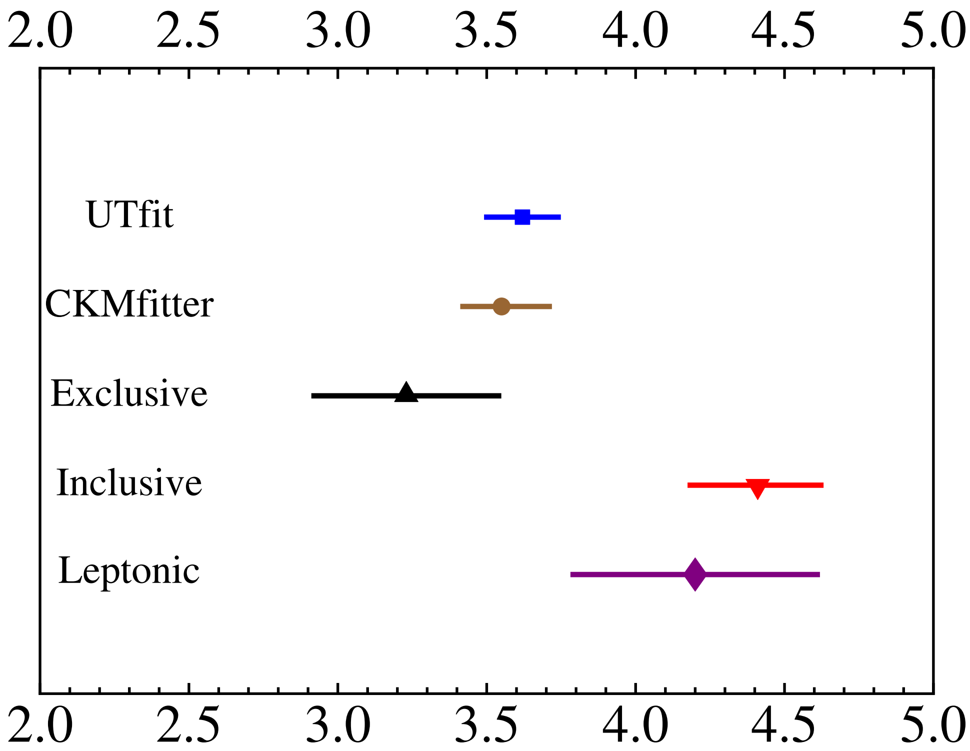
m_B=5.28 GeV

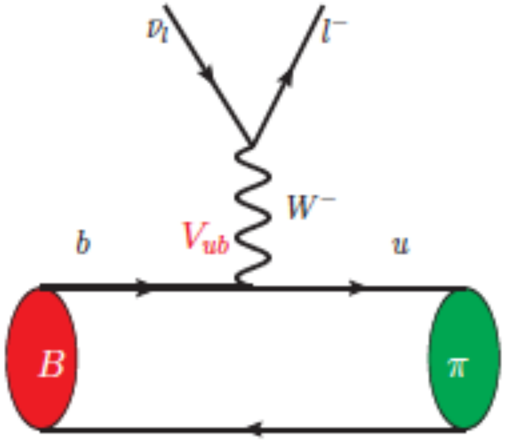
Hadronic Form factors:

Lattice QCD: pion has a soft momentum

Light-Cone Sum Rules: pion has to move fast

3σ Tension in $|V_{ub}|$

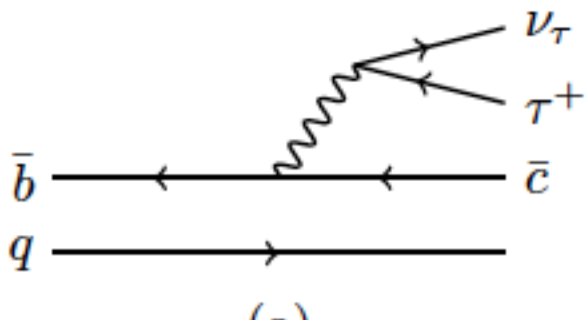




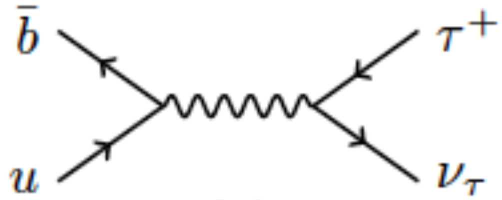
$$|V_{ub}| = (4.41 \pm 0.15 \,{}^{+\,0.15}_{-\,0.17}) \times 10^{-3} \qquad \text{(inclusive)},$$

$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \qquad \text{(exclusive)}.$$

B->Dlnu for V_{cb}

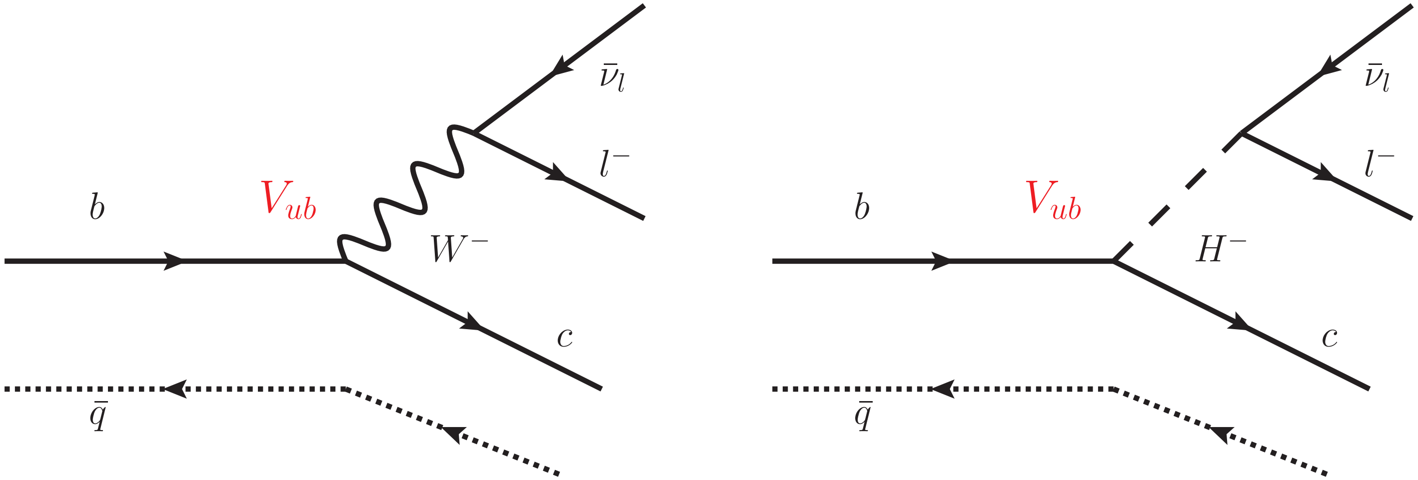


(a)



(b)

B->Dlnu



$$\begin{aligned}\mathcal{H}_{\text{eff}} = \ & \frac{4G_F V_{cb}}{\sqrt{2}}\Big[(1+V_L)\left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{\tau}\gamma^\mu P_L \nu_\tau\right) + V_R\left(\bar{c}\gamma_\mu P_R b\right)\left(\bar{\tau}\gamma^\mu P_L \nu_\tau\right) \\ & + S_L\left(\bar{c}P_L b\right)\left(\bar{\tau}P_L\nu_\tau\right) + S_R\left(\bar{c}P_R b\right)\left(\bar{\tau}P_L\nu_\tau\right) \\ & + T_L\left(\bar{c}\sigma^{\mu\nu}P_L b\right)\left(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau\right)\Big] + H.c.,\end{aligned}$$

$$S_L = 0, S_R = -m_b m_\tau \tan^2\beta / m_{H^\pm}^2$$

Charged Higgs to B->D\tau\nu

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}\ell^+\nu_\ell)}.$$

Decay amplitudes

$$H_s = H_s^{\rm SM}\left[1 + (S_R \pm S_L)\frac{q^2}{m_\tau(m_b \mp m_c)}\right]$$

where the upper sign is for $B \to \bar{D}\tau^+\nu_\tau$ and the lower is for $B \to \bar{D}^*\tau^+\nu_\tau$.

Theory

$$R_{\rm SM}(D) = 0.297 \pm 0.017,$$
$$R_{\rm SM}(D^*) = 0.252 \pm 0.03.$$

Table 2. Results of the $B \to \bar{D}^{(*)}\tau^+\nu_\tau$ analysis from BABAR[13,14], showing for each mode the number of signal events, the ratio $R(D^{(*)})$, the branching fraction, and the signal significance.

Decay mode	$N_{\rm signal}$	$R(D^{(*)})$	$\mathcal{B}(\%)$	Significance (σ)
$B^+ \to \bar{D}^0\tau^+\nu_\tau$	314 ± 60	$0.429 \pm 0.082 \pm 0052$	$0.99 \pm 0.19 \pm 0.13$	4.7
$B^0 \to D^-\tau^+\nu_\tau$	177 ± 31	$0.469 \pm 0.084 \pm 0053$	$1.01 \pm 0.18 \pm 0.12$	5.2
$B^+ \to \bar{D}^{*0}\tau^+\nu_\tau$	639 ± 62	$0.322 \pm 0.032 \pm 0022$	$1.71 \pm 0.17 \pm 0.13$	9.4
$B^0 \to D^{*-}\tau^+\nu_\tau$	245 ± 27	$0.355 \pm 0.039 \pm 0021$	$1.74 \pm 0.19 \pm 0.12$	10.4
$B \to \bar{D}\tau^+\nu_\tau$	489 ± 63	$0.440 \pm 0.058 \pm 0042$	$1.02 \pm 0.13 \pm 0.11$	6.8
$B \to \bar{D}^*\tau^+\nu_\tau$	888 ± 63	$0.332 \pm 0.024 \pm 0018$	$1.76 \pm 0.13 \pm 0.12$	13.2

Table 1. Results of the preliminary $B \to \bar{D}^{(*)}\tau^+\nu_\tau$ analysis from Belle[43], showing for each mode the number of signal events, the ratio $R(D^{(*)})$, the branching fraction, and the signal significance. Where given, the third uncertainty is due to the branching fraction $\mathcal{B}(B \to \bar{D}^{(*)}\ell^+\nu_\ell)$.

Decay mode	$N_{\rm signal}$	$R(D^{(*)})$	$\mathcal{B}(\%)$	Significance
$B^+ \to \bar{D}^0\tau^+\nu_\tau$	$98.6^{+26.3}_{-25.0}$	$0.70^{+0.19}_{-0.18}{}^{+0.11}_{-0.09}$	$1.51^{+0.41}_{-0.39}{}^{+0.24}_{-0.19} \pm 0.15$	3.8
$B^0 \to D^-\tau^+\nu_\tau$	$17.2^{+7.7}_{-6.9}$	$0.48^{+0.22}_{-0.19}{}^{+0.06}_{-0.05}$	$1.01^{+0.46}_{-0.41}{}^{+0.13}_{-0.11} \pm 0.10$	2.6
$B^+ \to \bar{D}^{*0}\tau^+\nu_\tau$	$99.8^{+22.2}_{-21.3}$	$0.47^{+0.11}_{-0.10}{}^{+0.06}_{-0.07}$	$3.04^{+0.69}_{-0.66}{}^{+0.40}_{-0.47} \pm 0.22$	3.9
$B^0 \to D^{*-}\tau^+\nu_\tau$	$25.0^{+7.2}_{-6.3}$	$0.48^{+0.14}_{-0.12}{}^{+0.06}_{-0.04}$	$2.56^{+0.75}_{-0.66}{}^{+0.31}_{-0.22} \pm 0.10$	4.7

Theory

$$R_{\rm SM}(D) = 0.297 \pm 0.017,$$
$$R_{\rm SM}(D^*) = 0.252 \pm 0.03.$$

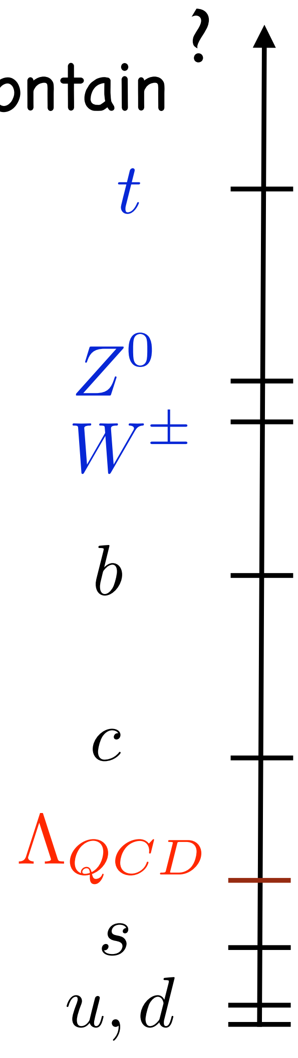
Flavor Changing Neutral Current: hunt for/constrain New Physics

How do we study B decays?

Separation of long-distance and short-distance physics: EFT

Effective field theories

The weak and strong interactions of the SM contain many disparate scales



The good success of the SM -> low energy predictions must be insensitive to the high-energy theory

Effective theory approach:

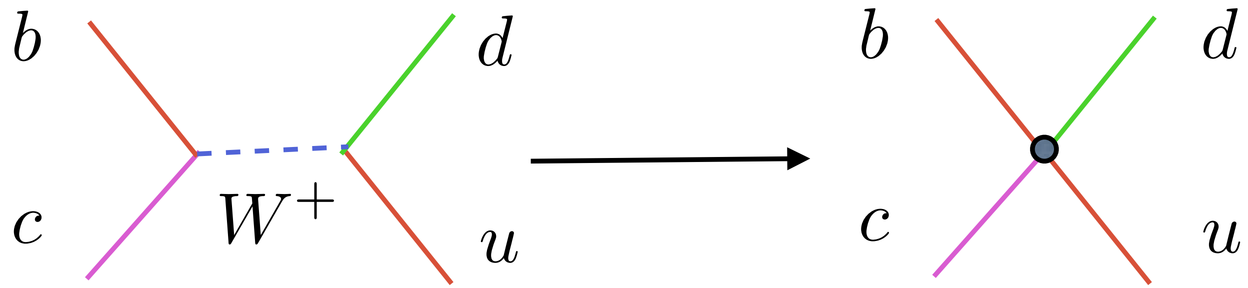
identify small expansion parameters.

- $m_{u,d,s,c,b} \ll m_{W,Z,t}$ — Effective theory of weak interactions
- $\Lambda_{QCD}/m_{b,c} \ll 1$ — Heavy quark effective theory

Above m_b

Weak interactions

Fermi 4-quark interaction



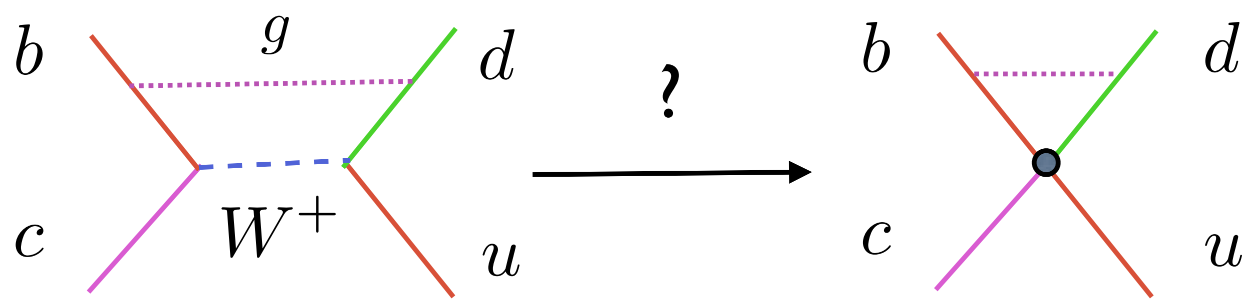
$$A = [\bar{d}\gamma_\mu P_L u]\frac{g^2}{M_W^2 - q^2}[\bar{c}\gamma^\mu P_L b] \to \frac{g^2}{M_W^2}[\bar{d}\gamma_\mu P_L u][\bar{c}\gamma^\mu P_L b] + O(p_q^2/M_W^2)$$

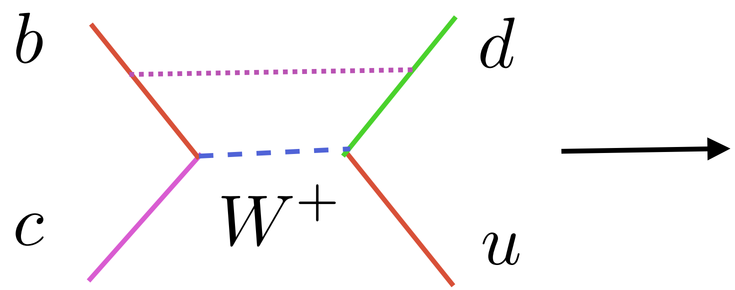
$$G_F = \frac{g^2}{M_W^2}$$ Fermi constant

Local interaction

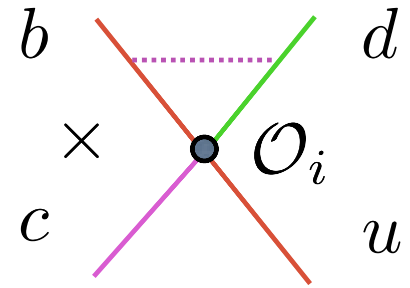
Radiative corrections

Does this picture survive the introduction of radiative corrections?





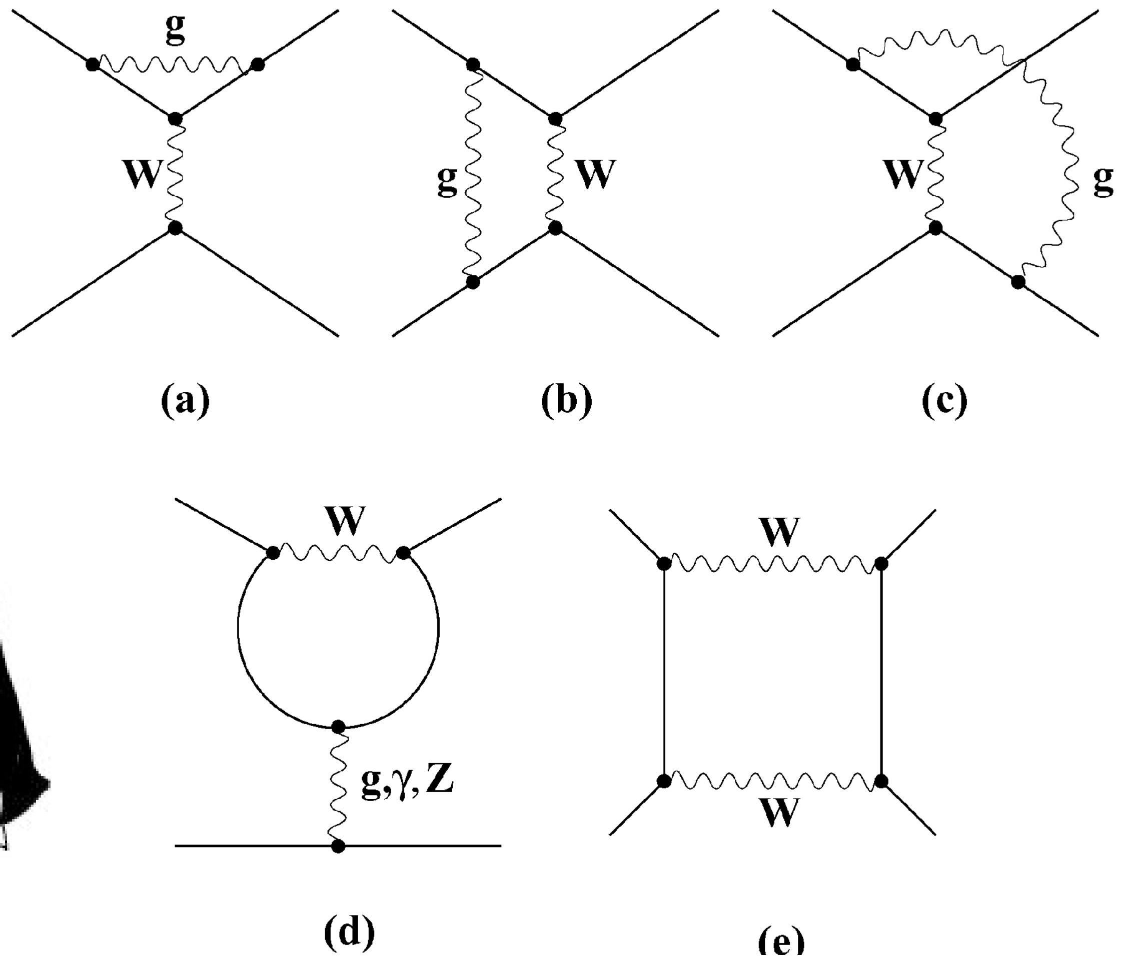
$$\longrightarrow \quad \Sigma_i \, C_i\left(\frac{\mu}{M_W}\right) \times \mathcal{O}_i$$

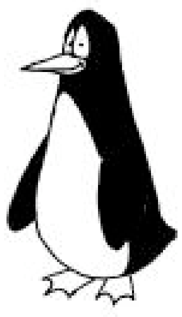


$C(\mu/M_W)$ = Wilson coefficient containing the contributions of the hard loop momenta

Can be computed in perturbation theory at any order in $\alpha_s(M_W)$ ⟹ Matching

Typical diagrams contributing to matching beyond tree level



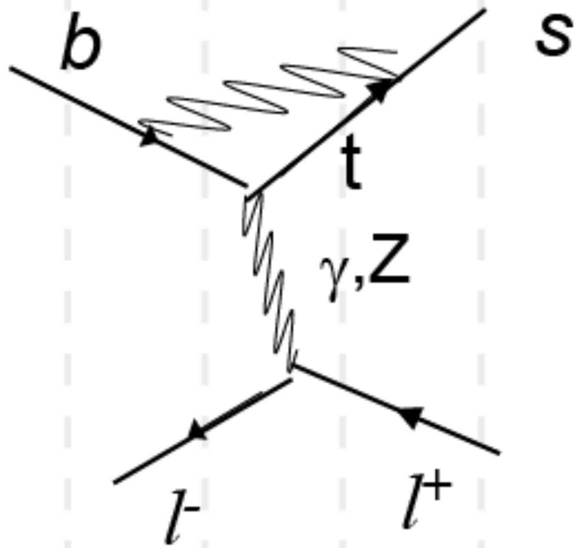


Flavor changing Electroweak penguin operators

$$O_7 = \frac{em_b}{8\pi^2}\bar{s}\sigma^{\mu\nu}(1+\gamma_5)bF_{\mu\nu} + \frac{em_s}{8\pi^2}\bar{s}\sigma^{\mu\nu}(1-\gamma_5)bF_{\mu\nu}$$

$$O_9 = \frac{\alpha_{em}}{2\pi}(\bar{l}\gamma_\mu l)(\bar{s}\gamma^\mu(1-\gamma_5)b),$$

$$O_{10} = \frac{\alpha_{em}}{2\pi}(\bar{l}\gamma_\mu\gamma_5 l)(\bar{s}\gamma^\mu(1-\gamma_5)b)$$



No tree level flavor changing neutral current in SM

$B_{d,s}$->$\mu^+\mu^-$

$$\langle 0|\bar{d}\gamma_\mu\gamma_5 b|\bar{B}(p)\rangle = i f_B p_\mu,$$

V-A: proportional to lepton mass!

sensitive to Scalar/Pseudo-Scalar interaction

$$Q_S = (\bar{b}\gamma_5 s)(\bar{\mu}\mu)\,, \qquad Q_P = (\bar{b}\gamma_5 s)(\bar{\mu}\gamma_5\mu)\,.$$

Data:

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = \left(2.9^{+1.1}_{-1.0}\right) \times 10^{-9}, \qquad \text{LHCb [2]},$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = \left(3.0^{+1.0}_{-0.9}\right) \times 10^{-9}, \qquad \text{CMS [3]},$$

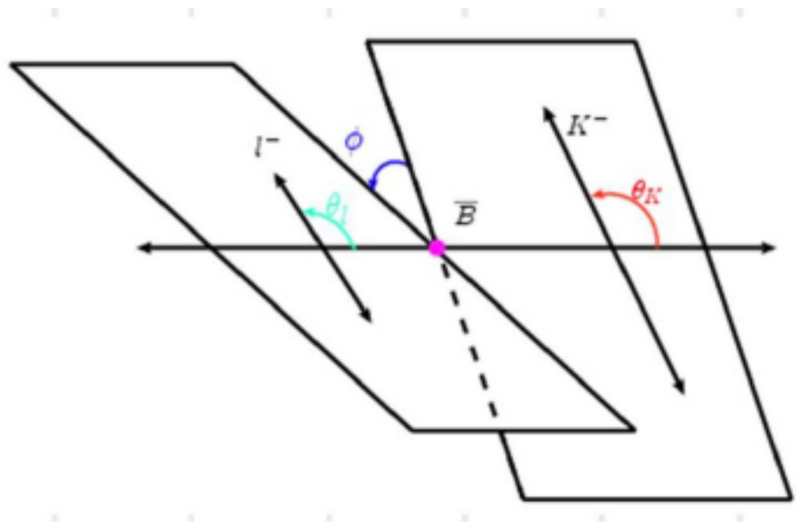
SM: 3-Loops

$$\overline{\mathcal{B}}_{s\mu} \times 10^9 = (3.65 \pm 0.06)\, R_{t\alpha}\, R_s = 3.65 \pm 0.23,$$

$B \rightarrow K^* l^+ l^-$ & NP

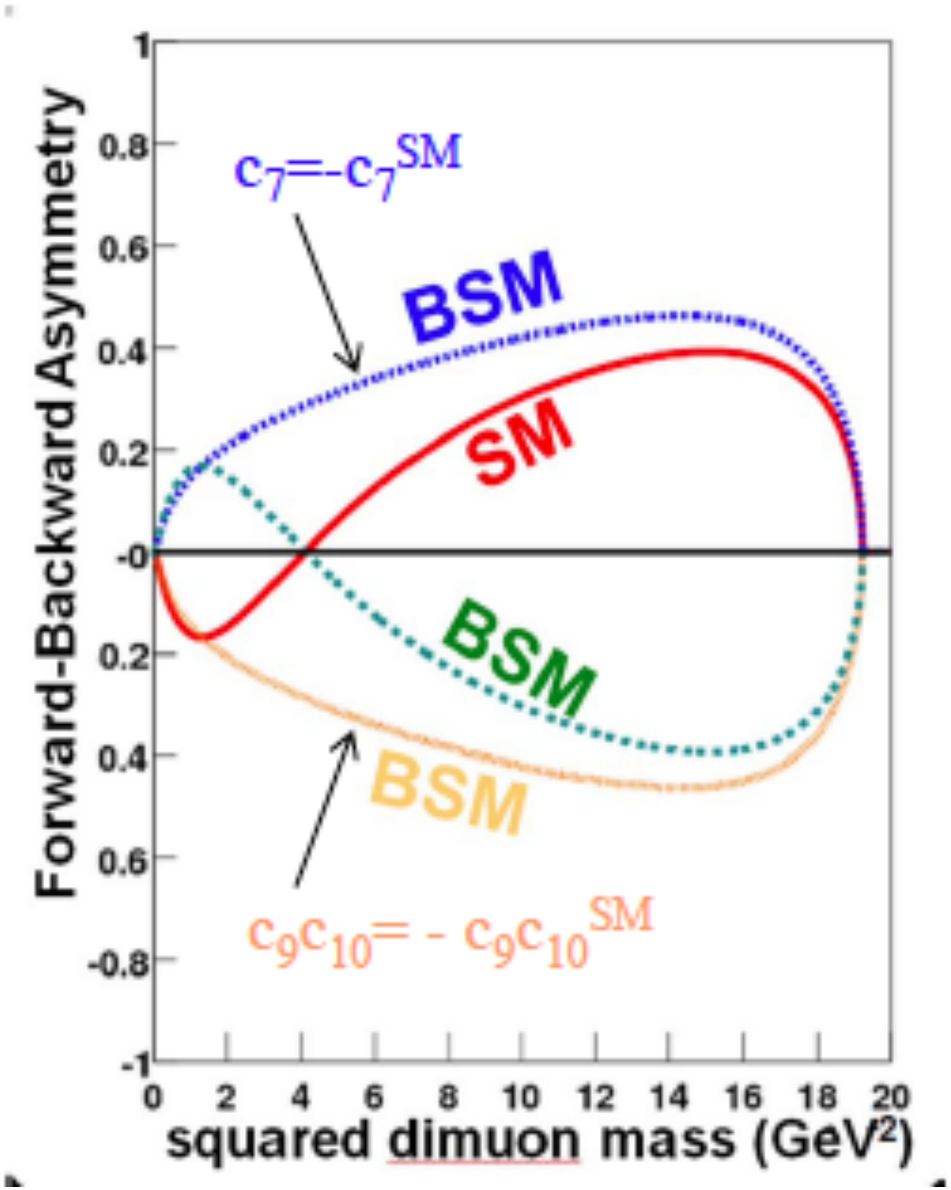
1. V/A interference: forward-backward asymmetry

$Tr[VpAp] \sim \cos(\theta_K)$

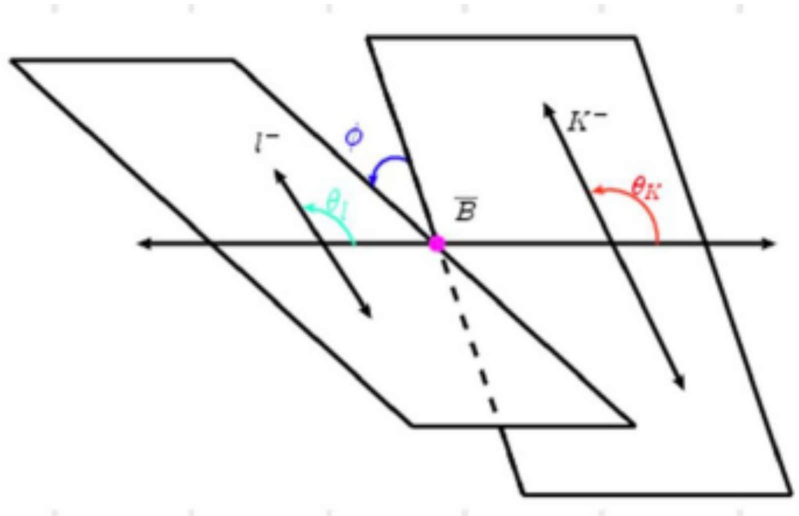


2. q^2 dependence:

$A - B/q^2$

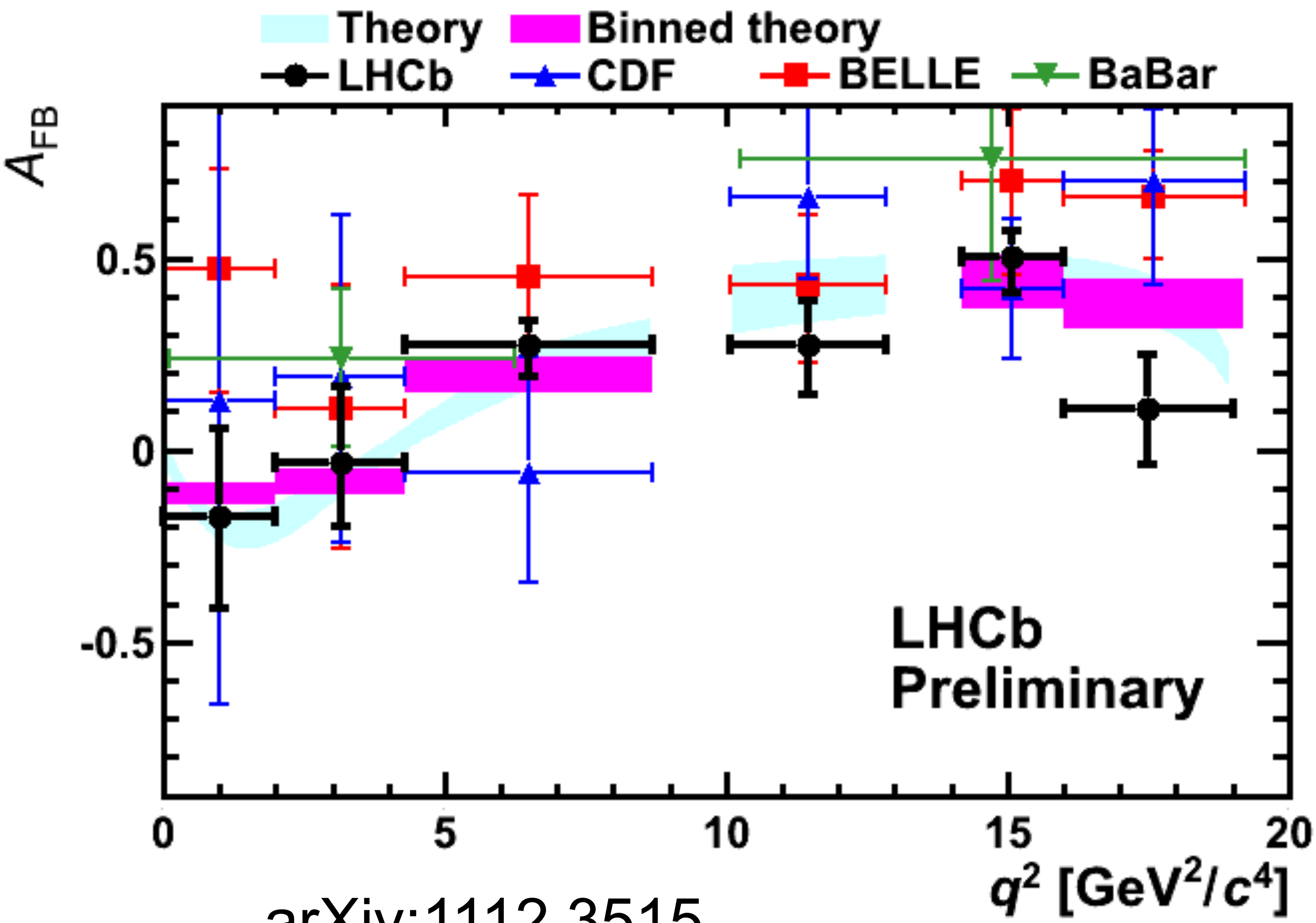


B➔K*l⁺l⁻ & NP



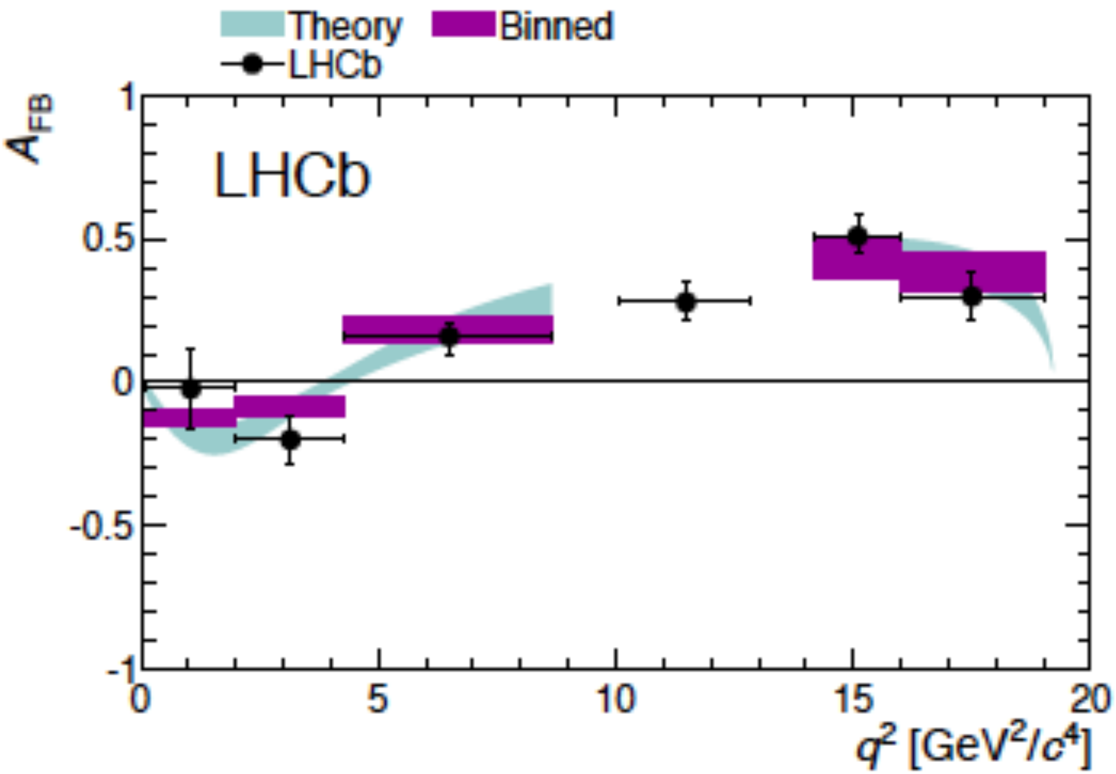
in high precision frontier

Comparison of data and theory



arXiv:1112.3515

Comparison of data and theory



1304.6325 LHCb

$B_{d,s}$ mixing

Bs->J/psi phi