Recent Progress in Heavy Quark Flavor Physics

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Outline

- Overview
- Experimental progress
- Puzzling results
- Theoretical progress
- Summary

Flavor Physics complements

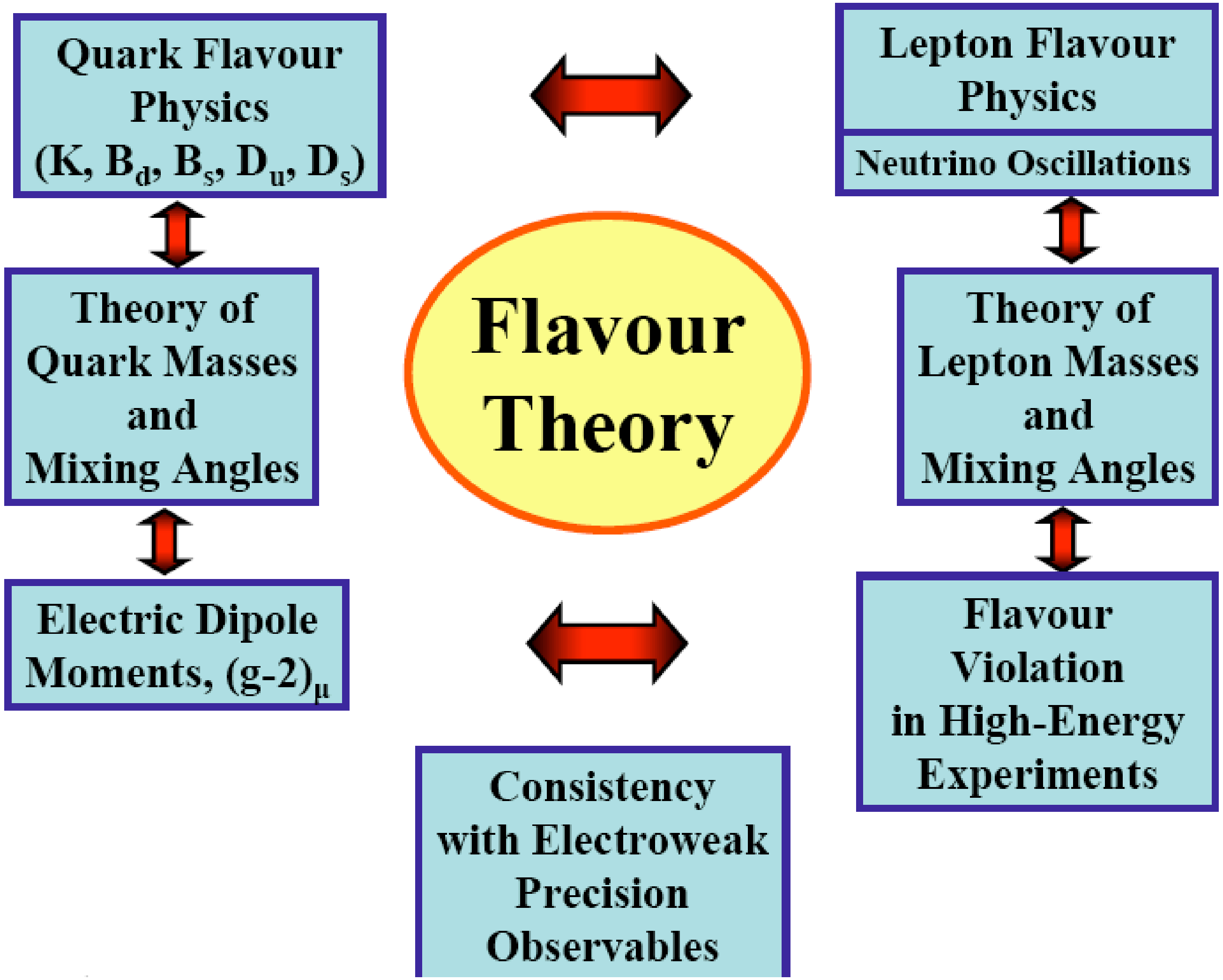
Frontiers of Elementary Particle Physics → Search for Physics Laws At very short distance

Heisenberg Principle → To test 10^{-18} m we need E ≅ 200 GeV

LHC E=7TeV → Test at 10^{-20}m

Flavor Physics via quantum fluctuations sensitive to **E≈200TeV** and even higher → Frontiers in testing very very short distance scales
→Flavor Physics
But require very high precision

Flavor Physics-



Lepton Flavor Physics

Xing's talk

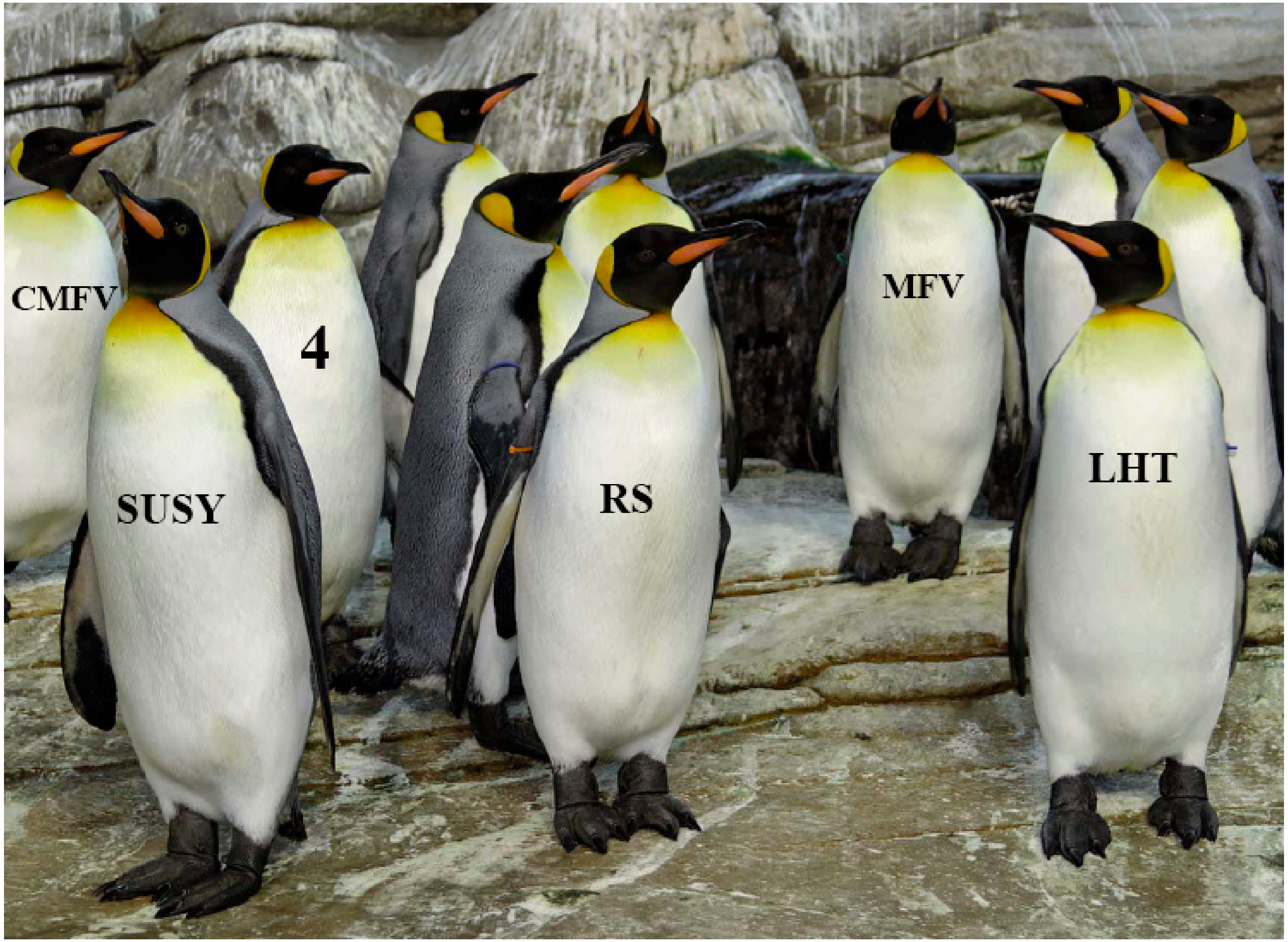
Quark Flavor Physics

So far, confirmed success of the CKM picture
of Flavor Changing Neutral Current of GIM picture

Yet

- ✔ Several tensions between the quark flavor data and the SM exist
- ✔ There is still a lot of room for New Physics(NP) contributions
- ✔ Hierarchies in Fermion mass and Mixing angles have to be understood with the help of Flavor Physics

NP scenarios dancing with Penguins

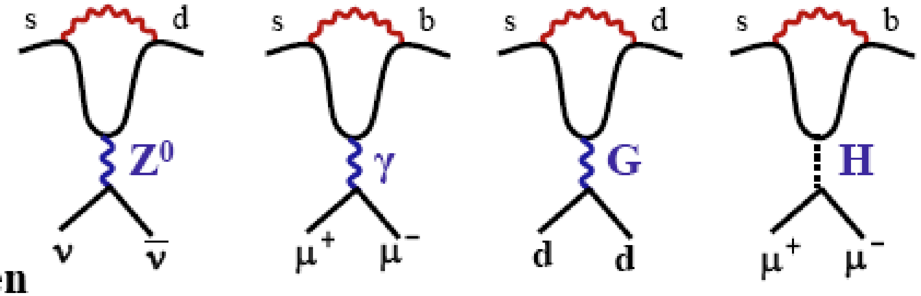


Their flavor structures, parameter spaces, new particles are constrained very much by Penguin processes

FCNC

FCNC cont..

Penguin Family :

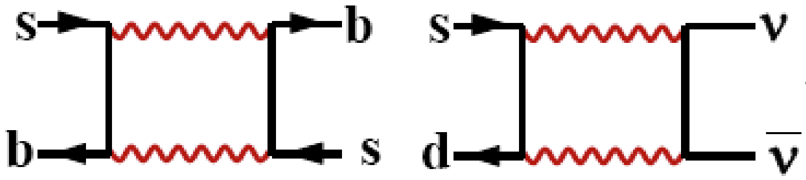


New Physics enters here

Similar diagrams in LFV and EDM´s

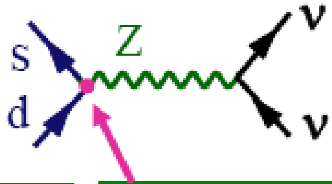
(GIM broken at one loop)

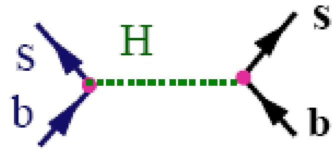
Box Diagrams



+ other box diagrams

Tree Diagrams





(GIM broken at tree level)

RS

Generated through mixing with New Gauge Bosons

Double Higgs Penguin in SUSY

FCNC cont. Master formula

Long Distance (Non-perturbative Lattice)

Flavour and CPV in SM and MFV enters only here

Short Distance Functions (Perturbation TH)

(real for MFV)

$$A(FCNC) = \sum_i B_i \eta_i^{QCD} V_i^{CKM} F_i(m_t, NP)$$

NP can add new B_i´s absent in SM

(New Operators with new Dirac Structures)

Renormalization Group (QCD) LD ↔ SD

Q_{LR} (right-handed currents, S, P)

NP can add new loops and trees with new flavour parameters and CPV phases

Only Loops if GIM works

non-MFV

FCNC cont.

- Rare but not so rare: precise measurement @BaBar, Belle, CDF, D0, LHCb
- Sensitive to New Physics, thus tough constraints on NP scenarios
- Strong correlated & complementary to the direct searches via high energy processes
- Hints for NP have been shown

Groups involved in Heavy Flavor Physics

From North China to South China

HIT, Dalian(LNNU+DLUT)
Tsinghua, PKU, ITP, IHEP,GUCAS Nankai,
Huabei, Yantai, Henan NU,
USTC

Chongqin U.,Nanjing Normal, Zhejiang U,
Shanghai, CCNU, Nanchang……

So, there is a big asymmetry

2: Overview of experimental progress

Now: ~10 years of B-factories BaBar & Belle

Step1

Discovery of CPV in B decay ← **2001 summer !**

Step2

Precise test of KM(CPV) and SM

→ Hints for NP ?

Step3

Search/Evidence for New Physics

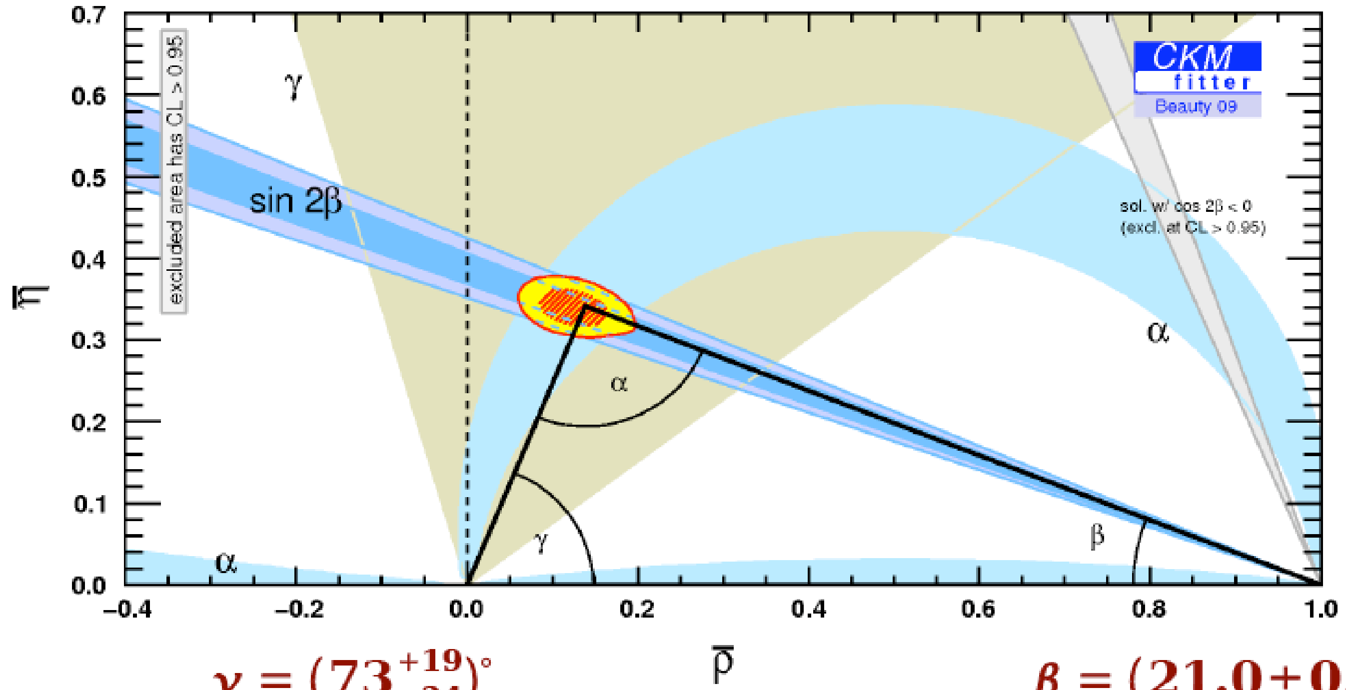
LHCb

Need >10^{12} B data

Super B (L ~10^{36}cm^{-2}s^{-1})

The unitary triangle

$\alpha = (89.0^{+4.4}_{-4.2})^\circ$
(WA, CKMfitter, Winter09)

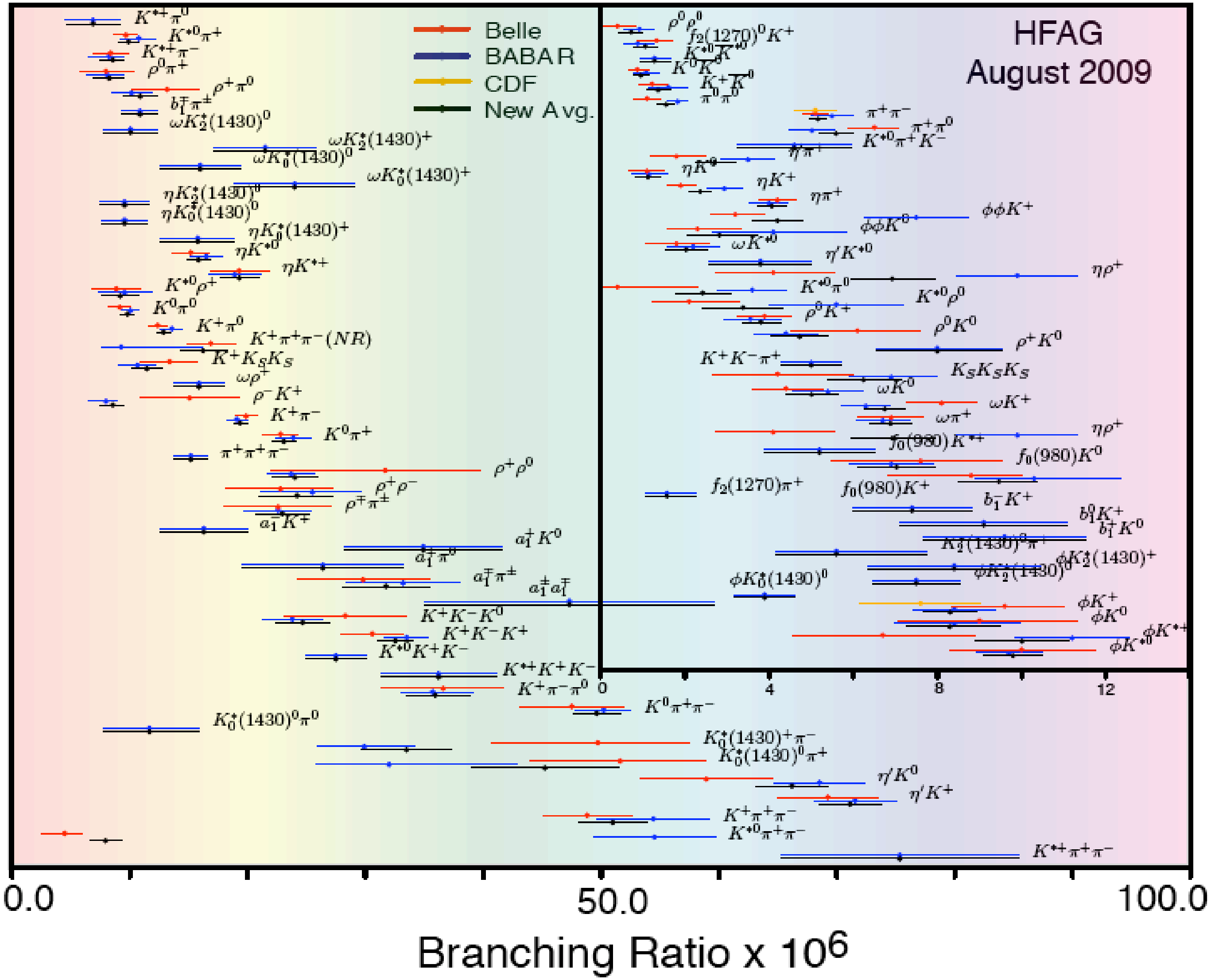


$\gamma = (73^{+19}_{-24})^\circ$
(WA, CKMfitter, Beauty09)

$\beta = (21.0 \pm 0.9)^\circ$
(WA, HFAG, Winter09)

Overall 95% consistency, KM mechanism is at work,

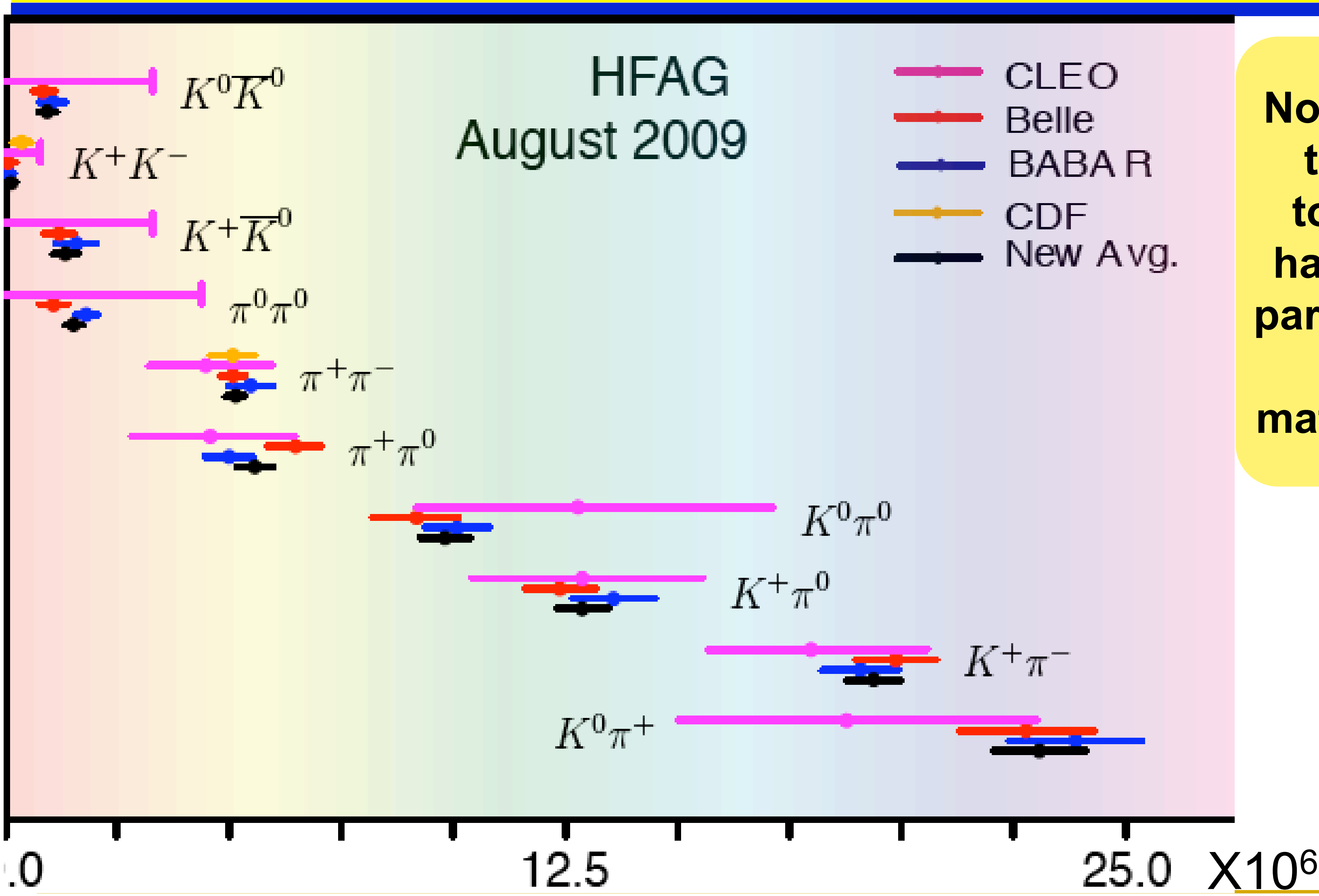
2.1 Charmless nonleptonic decays(exp)



88 modes
$> 4\sigma$

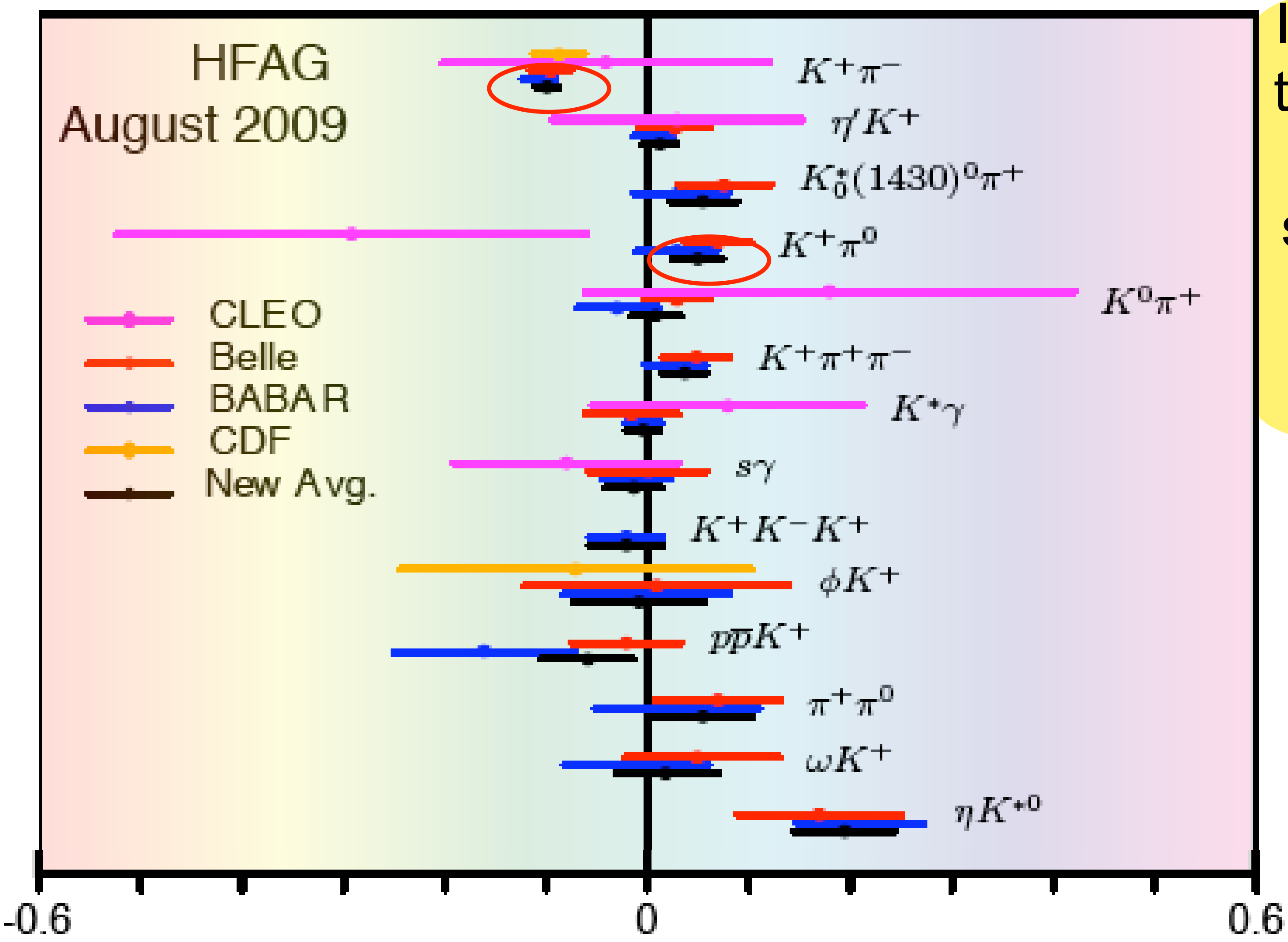
From HFAG

2.1 Precise measurements



Now, it is tough to tune hadronic parameters to match data

2.1 cont. The CP Asymmentries

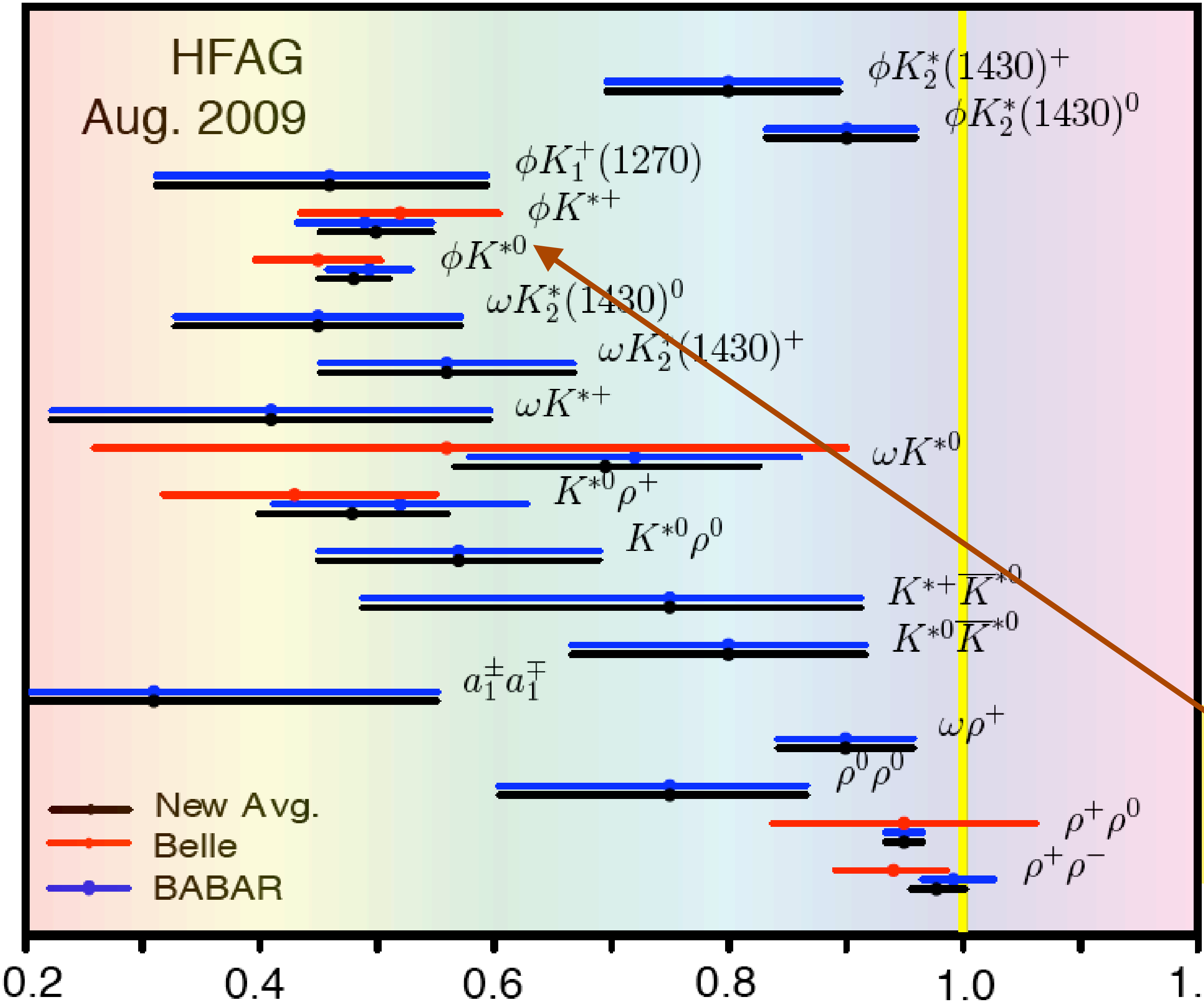


It's much more tough to match A_{CP} &Br simultaneously with hadronic parameters

Say, the 5σ direct CP difference

πK CP puzzle

2.1 cont. Polarizations in B→VV

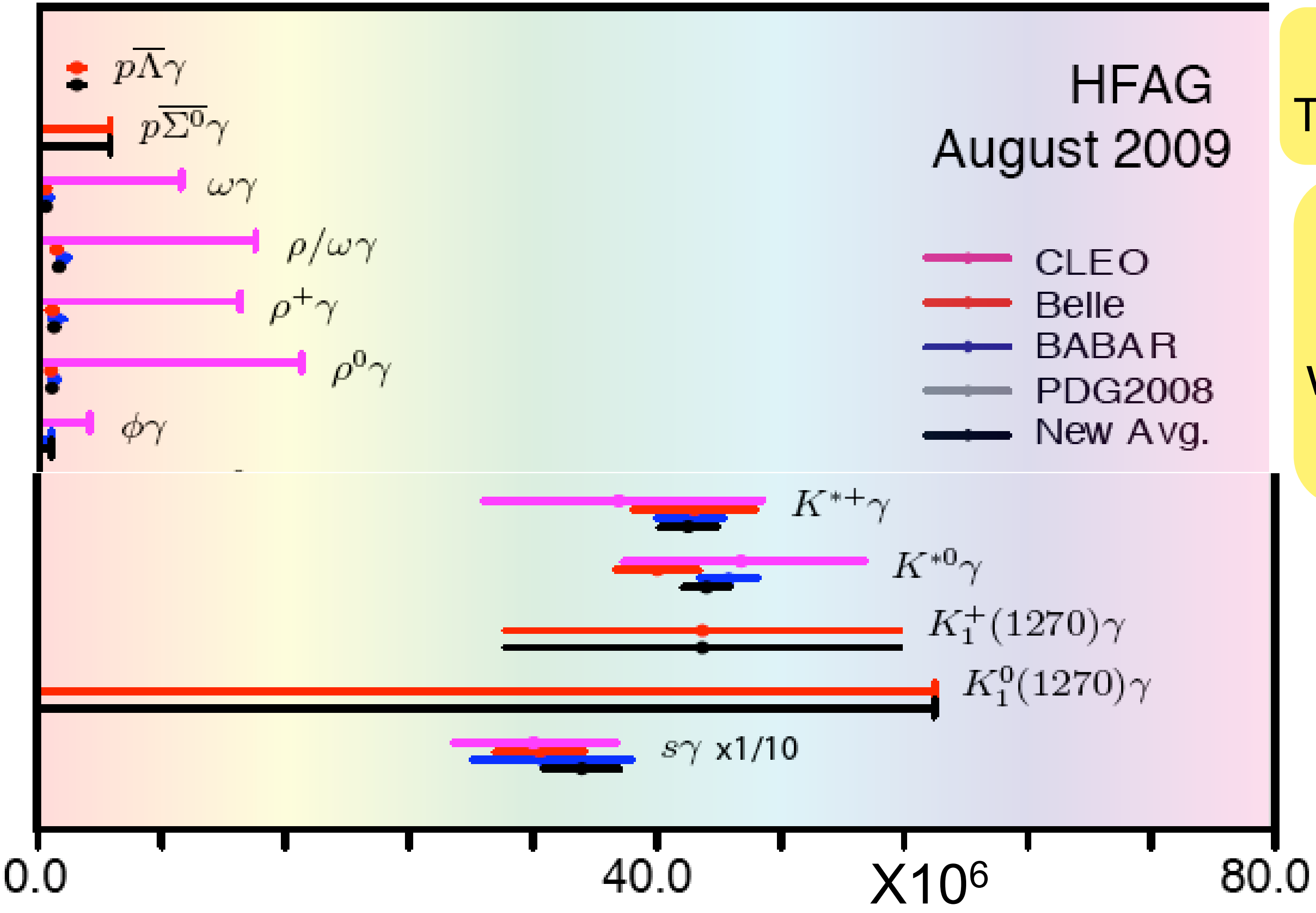


In the SM
$f_L=1-O(M_V/M_B)$

Polarization "puzzle"

For exp detail,
Pls ask J.Z.Zhang

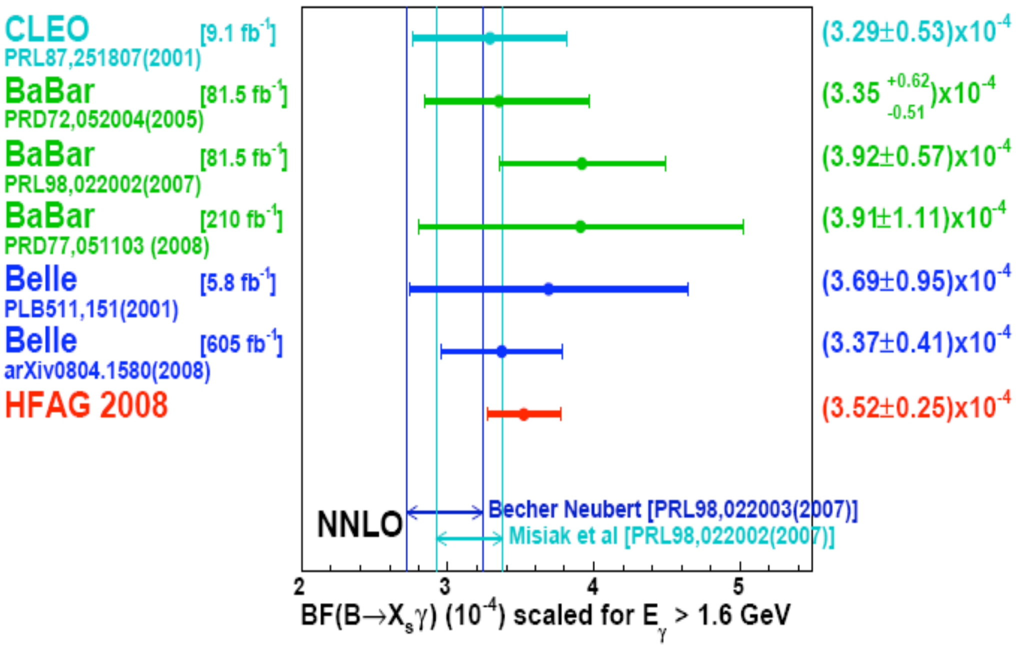
2.2 The radiative B decays

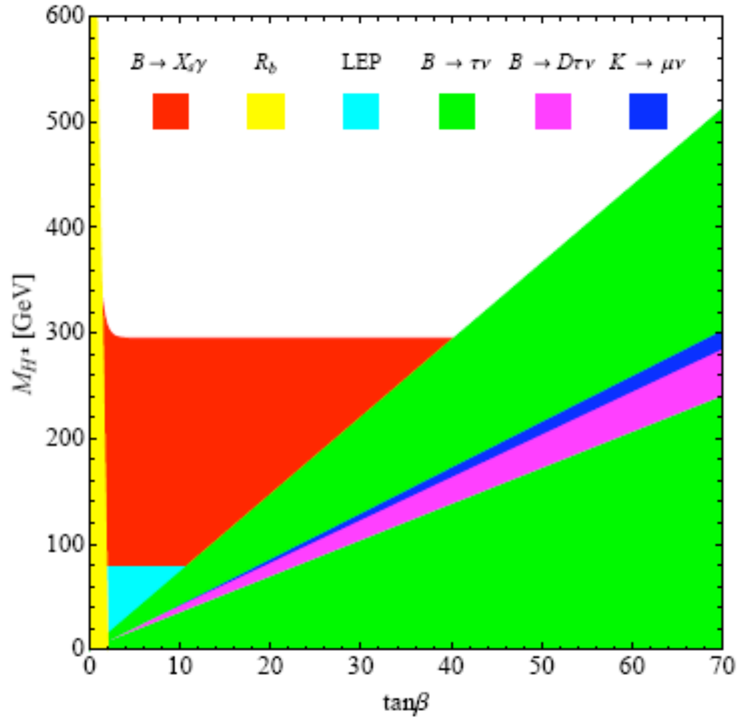


A very long Th.&Exp story

In good agreement with the SM @NNL

$B \to X_s\gamma$

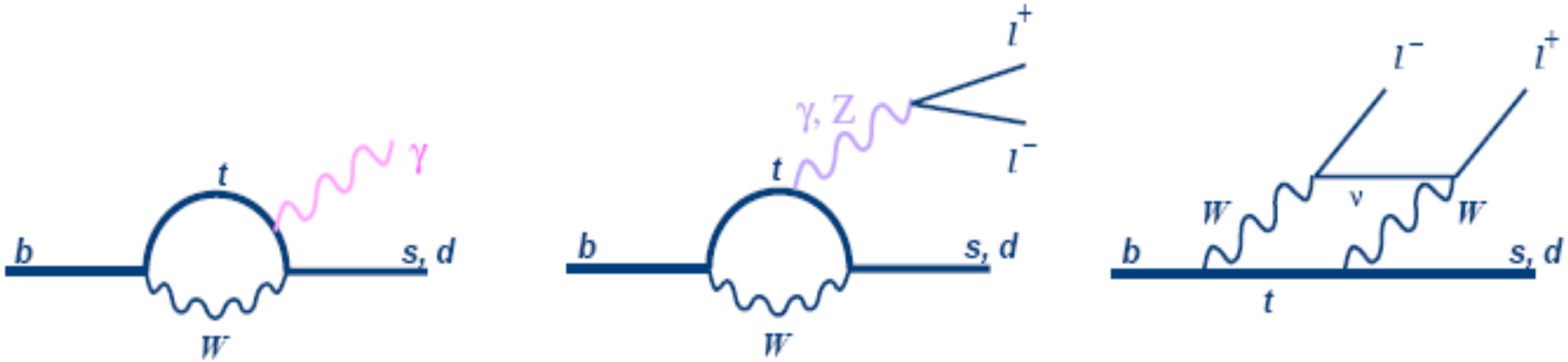




Ulrich Haisch, arXiv:0805.2141v2

Together with $(g-2)_{\mu}$, $B\to X_s\ \gamma$ serve as strong constraints on NP

2.3 The A_{FB} in $B \to X_s\, l^+ l^-$, $K^{(*)} l^+ l^-$



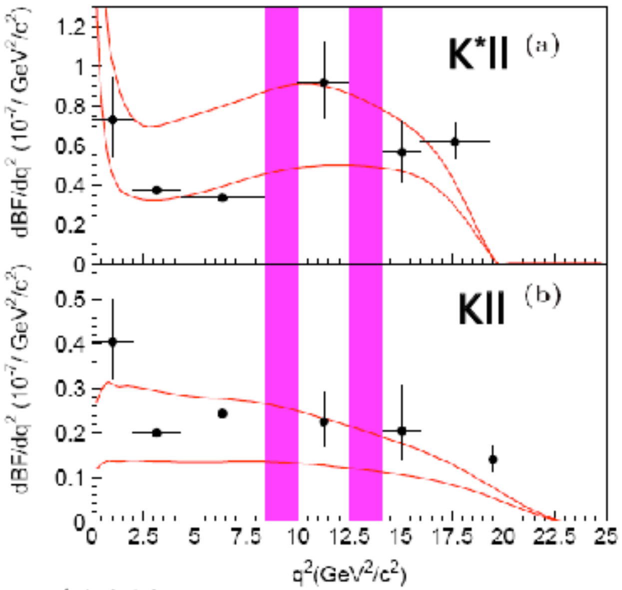
- Wilson coefficients
  - C_7 : from electromagnetic penguin diagram
    C_9 : from vector electroweak
  - C_{10}: from axial vector electroweak
- Differential branching fraction (B.F.) and Forward-backward asymmetry (A_{FB}) in $B \to K^* l^+ l^-$

$$\frac{dA_{FB}}{dq^2} \propto -\Re e[\widetilde{C}_9 \widetilde{C}_{10} V A_1 + \frac{M_B m_b}{q^2} \widetilde{C}_7 \widetilde{C}_{10} (V T_2 \cdot (1 - \frac{m_{K^*}}{M_B}) + A_1 T_1 \cdot (1 + \frac{m_{K^*}}{M_B}))]$$

2.3 Rare electroweak B decays

657M BB
PRL **103**, 171801 (2009)

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (10.7^{+1.1}_{-1.0} \pm 0.9) \times 10^{-7}$$
$$\mathcal{B}(B \to K\ell^+\ell^-) = (4.8^{+0.5}_{-0.4} \pm 0.3) \times 10^{-7}$$

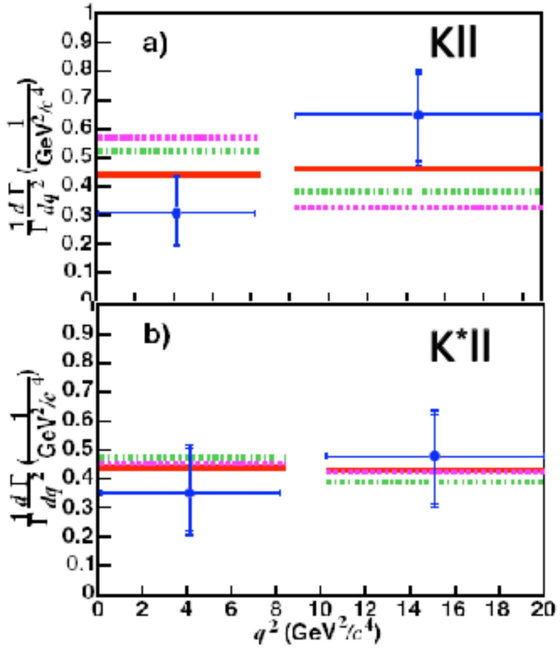


: J/ψ (ψ') veto regions

: SM expectation w/ min. & max. form factors from[Ali et al. PRD 66, 034002 (2002)]

383M BB
PR **D73**, 092001 (2009)

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (7.8^{+1.9}_{-1.7} \pm 1.1) \times 10^{-7}$$
$$\mathcal{B}(B \to K\ell^+\ell^-) = (3.4 \pm 0.7 \pm 0.2) \times 10^{-7}$$



Lines are SM predictions w/ various form factor models.

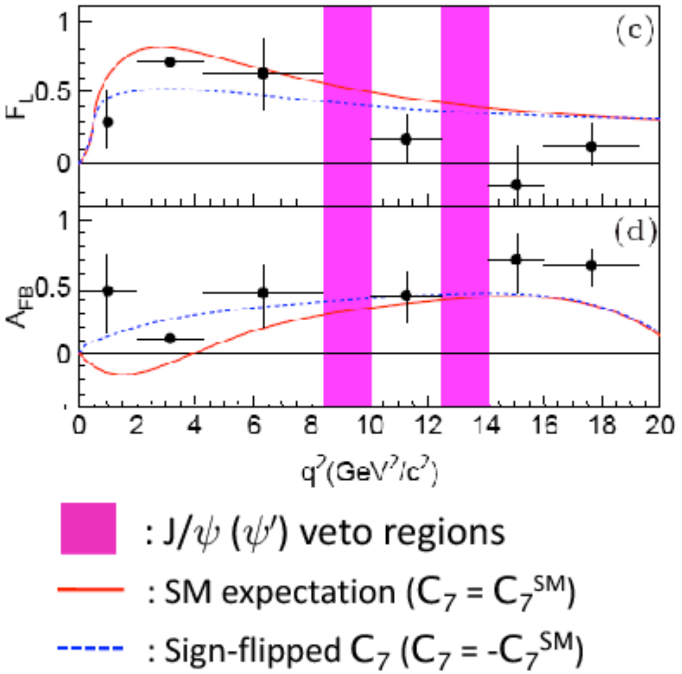
2.3 A_{FB} "puzzle"

$$\frac{d\Gamma}{d\cos\theta_{K^*}} = \frac{3}{2}F_L\cos^2\theta_{K^*} + \frac{3}{4}(1-F_L)(\sin^2\theta_{K^*})$$

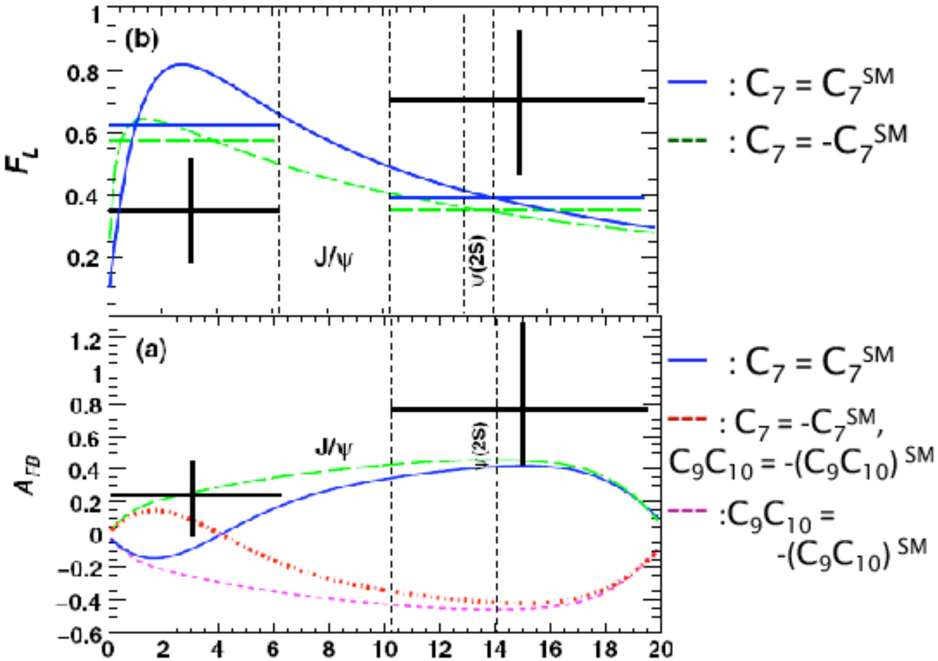
$$\frac{d\Gamma}{d\cos\theta_{B\ell}} = \frac{3}{4}F_L\sin^2\theta_{B\ell} + \frac{3}{8}(1-F_L)(1+\cos^2\theta_{B\ell}) + A_{FB}\cos\theta_{B\ell}$$

Wrong sign C_7 ??

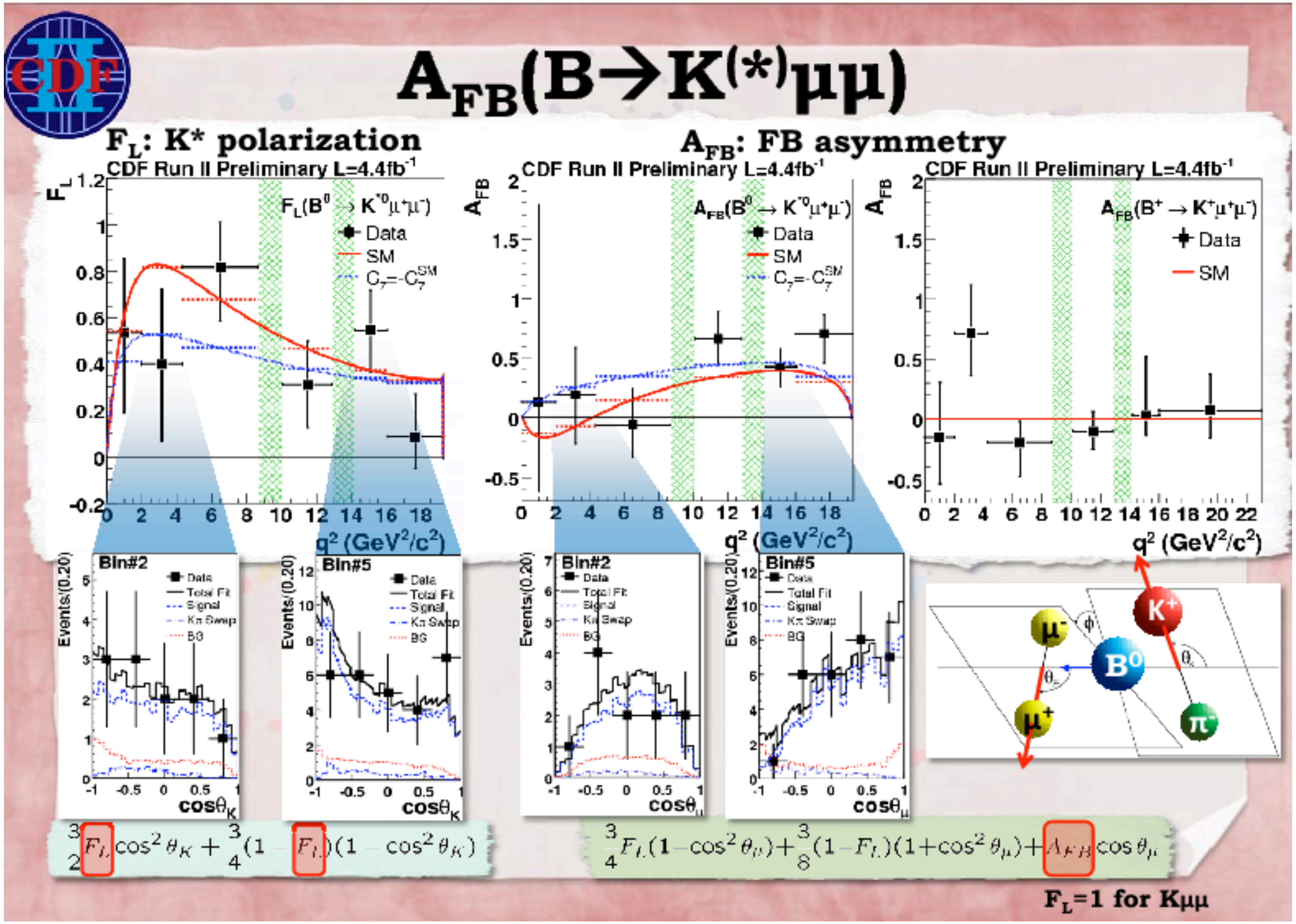
BELLE
657M BB
PRL **103**, 171801 (2009)



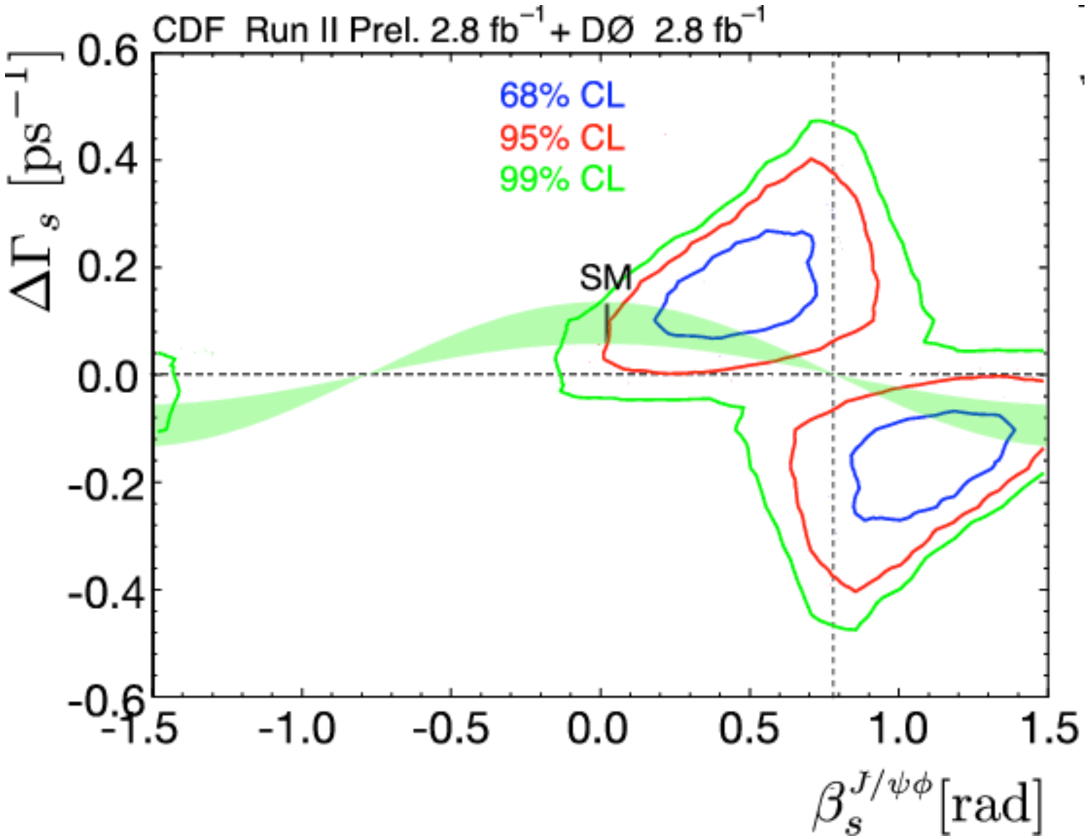
383M BB
PR **D79**, 031102 (2009)



2.3 A_{FB} "puzzle" contd



2.4 $B_s - \overline{B}_s$ mixing



B_s unitarity triangle

$$\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*} + 1 + \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = 0$$

$$O(\lambda^2) + O(1) + O(1)$$

CP-violation for B_s meson

$$\bar{\rho}_s + i\bar{\eta}_s = -\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}$$

$$\beta_s = \arg\left(\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right)$$

The SM weak phase in the Bs mixing is very well predicted:

$$\beta_s = (1.035\ ^{+0.049}_{-0.046})\ \text{deg} \qquad \left[\beta_s = 22.3^{+10.2}_{-8.0}\ \text{deg (Tevatron)}\right]$$

2.X

- There are so many interesting pro
- X, Y, Z states [S.Zhu, Q. Zhao, K.T. Chao, X.Liu, Z.G. Wang…]
- Charmonium production [state of the art calculations by K.T.Chao, J.X.Wang; C.Qiao, Y.Jia, D.Yang……]
- f_{Ds} puzzle [X.Q.Li, Z.Wei, H.b.Li…….]

I will skip charm physics, since there is a nice review

Charm Physics:
A Field Full with Challenges and Opportunities
[X.Q.Li, Z.T.Wei, Front.Phys.China 4:49-74,2009]

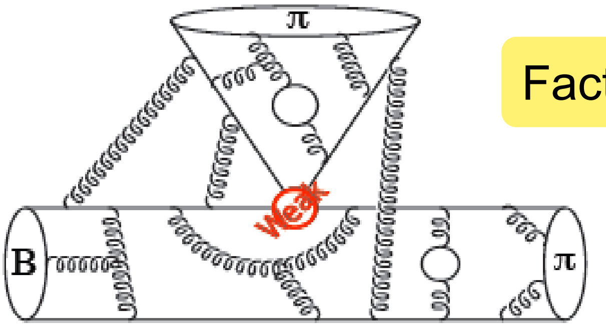
3. Theories.

- Hadronic dynamics (nonperturbative QCD) complicated and hindered precise Th estimations from QCD very very much.
- We rely on Factorization to separate long and short distance effects
- **LD**: modeled, extracted from exp., Lattice
- **SD**: well defined, EW phys, QCD loop corrections, RGE……

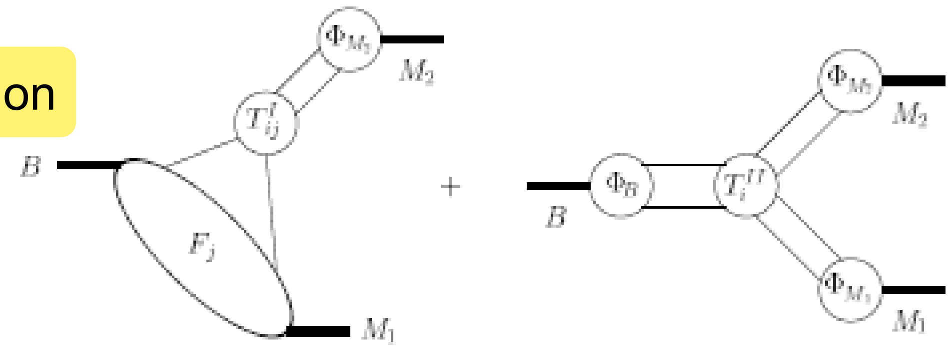
3. Charmless B decays: Theory shopping list

- QCD Factorizations [BBNS, PRL'99, NPB'00]
- pQCD [Y.Y.Keum,H.n.Li,A.Sanda, PRD'01, C.Lu, K.Ukai, M.Z.Yang, PRD'01]
- Soft Collinear Effective Theory[SCET]
  [C.W.Bauer et al., PRD'01, '02, '04. J.Chay&C.Kim, PRD'03, NPB'04]
- Transverse momentum dependent [TMD]
  [J.P.Ma,Q.Wang,PLB613(05)39, JHEP0601, PLB674(09)176]
- Six Quark H_{eff} QCDF
  [Y.L.Wu, et al., Int.J.Mod.Phys.A25:69-111,2010.]
- etc

Theory continued [QCDF]



Factorization →

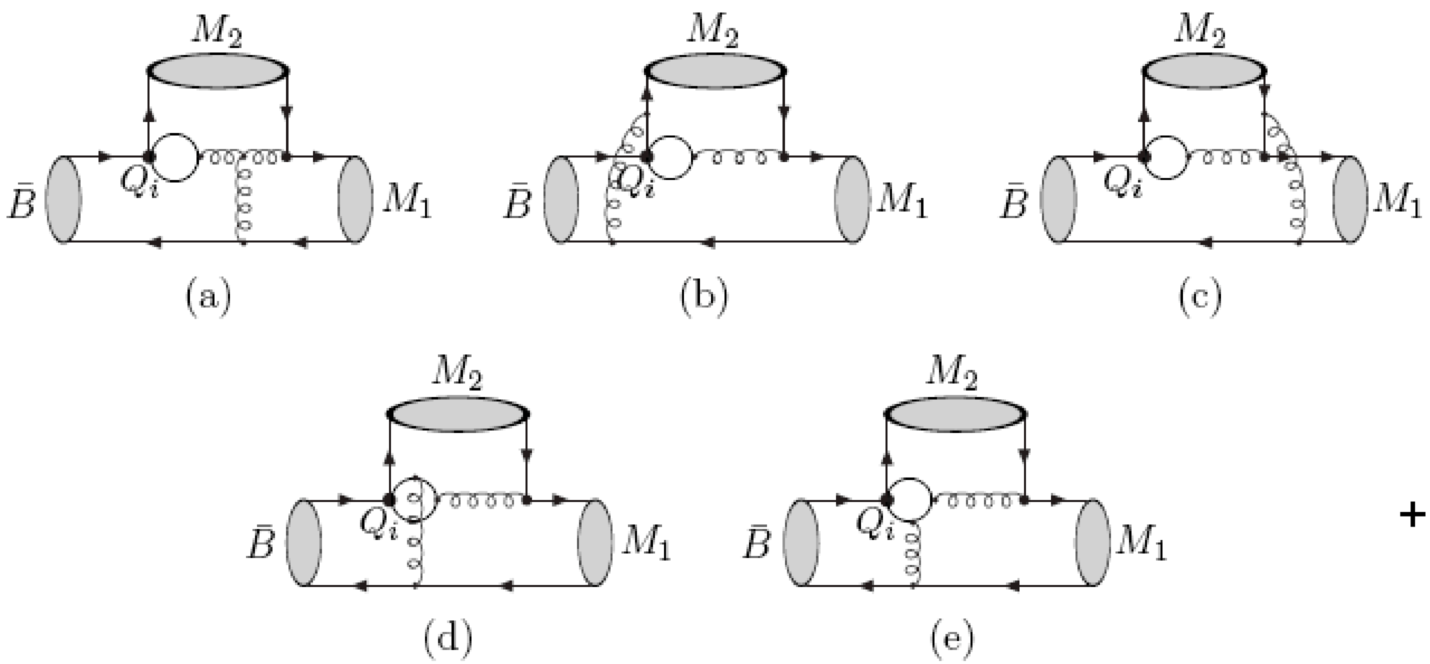


→
$$\langle M_1 M_2 | C_i O_i | \bar{B} \rangle_{\mathcal{L}_{\rm eff}} = \sum_{\rm terms} C(\mu_h) \times \Big\{ F_{B\to M_1} \times \underbrace{T^{\rm I}(\mu_h, \mu_s)}_{1+\alpha_s+\ldots} \star f_{M_2} \Phi_{M_2}(\mu_s)$$

$$+ f_B \Phi_B(\mu_s) \star \Big[\underbrace{T^{\rm II}(\mu_h, \mu_I)}_{1+\ldots} \star \underbrace{J^{\rm II}(\mu_I, \mu_s)}_{\alpha_s+\ldots} \Big] \star f_{M_1} \Phi_{M_1}(\mu_s) \star f_{M_2} \Phi_{M_2}(\mu_s) \Big\}$$

$$+ 1/m_b\text{-suppressed terms}$$

Theory continued [QCDF NNLO]



+ bsg ones

- Strong Penguin [partially by X.Q.Li YD, PRD72(05) 074007, 73(06)114027]

Theory continued [QCDF NNLO]

SCET was embedded in QCDF

Spectator -scattering

- One loop J^{II}: Becher et al.'04, Beneke, D.S.Yang'05
- One loop T^{II} tree amplitudes: Beneke, Jager'05, Pilipp'07
- One loop T^{II} penguin amplitudes: Beneke, Jager'06

Vertex term

- Two loop T^{II} tree amplitudes: G.Bell, NPB 822(09)172.
  Beneke, Huber,,X.Q.Li,NPB832(10)109
- Two loop T^{II} penguin amplitudes: Beneke+Li+? In progress

Steady progresses!

Theory continued [QCDF NNLO]

- Approx 70 two-loop vertex diagrams

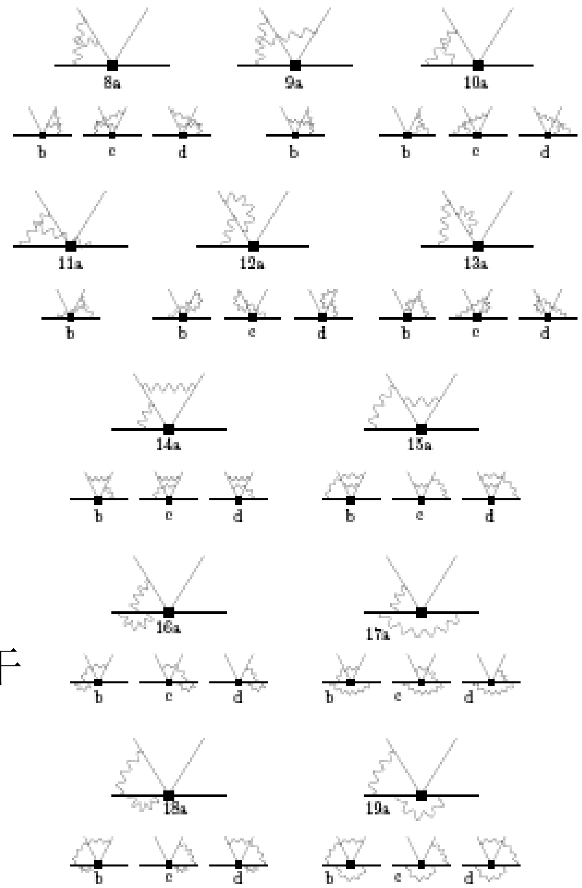
QCD to SCET matching calculation

$$Q_i = \sum_a \tilde{H}_{ia} \tilde{O}_a$$

with non-local $\mathrm{SCET_I}$ operators $\tilde{O}_a$.

2-loop techniques: Xinqiang's talk@ 18上午

See also Beneke, Huber, Li, NPB811(2009)77



Theory continued [QCDF NNLO]

Numerical result (tree amplitudes)

$$\begin{aligned} a_1(\pi\pi) &= 1.009 + [0.023 + 0.010i]_{\rm NLO} + [0.026 + 0.028i]_{\rm NNLO} \\ &\quad - \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.015]_{\rm LOsp} + [0.037 + 0.029i]_{\rm NLOsp} + [0.009]_{\rm tw3}\right\} \\ &= 1.00 + 0.01i \quad \longrightarrow \quad 0.93 - 0.02i \quad (\text{if } 2 \times r_{\rm sp}) \end{aligned}$$

$$r_{\rm sp} = \frac{9 f_{M_1} \hat{f}_B}{m_b f_+^{B\pi}(0) \lambda_B}$$

$$\begin{aligned} a_2(\pi\pi) &= 0.220 - [0.179 + 0.077i]_{\rm NLO} - [0.031 + 0.050i]_{\rm NNLO} \\ &\quad + \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.123]_{\rm LOsp} + [0.053 + 0.054i]_{\rm NLOsp} + [0.072]_{\rm tw3}\right\} \\ &= 0.26 - 0.07i \quad \longrightarrow \quad 0.51 - 0.02i \quad (\text{if } 2 \times r_{\rm sp}) \end{aligned}$$

- The NNLO corrections to the vertex term and spectator scattering are significant individually (about 25% for a_2). But both tend to cancel – too bad!
- Largest uncertainty is input parameter dependence: Allows $|C/T|_{\pi\pi} \approx 0.7$, if λ_B is small. The colour-suppressed amplitudes are probably dominated by spectator-scattering. But $\arg\left(C/T_{\pi\pi}\right) \lesssim 15°$.
- Perturbation theory works at scale m_b and $\sqrt{m_b\Lambda}$. No indication of further large radiative corrections.

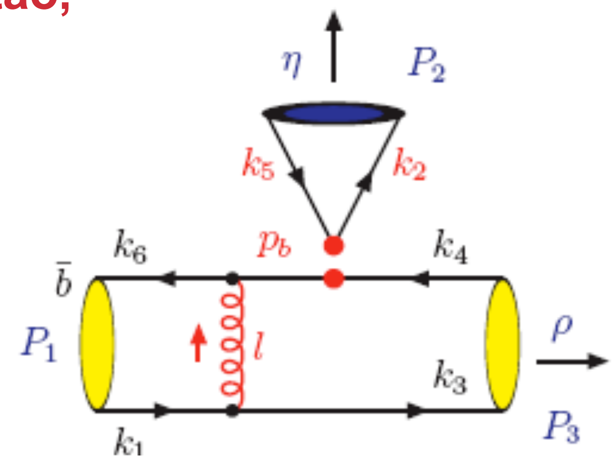
Theory continued [pQCD]

- Introduce K_T to kill end-point divergence in spectator-scattering kernel
- Sudakov factor to suppress long distance contributions

Many works by: Caidian, Maozhi, Xiao, Zhentao,

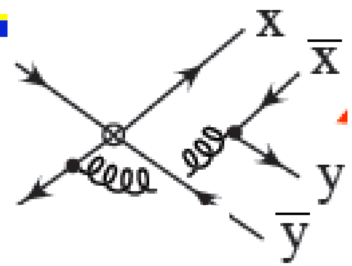
- One loop QCD corrections are in progress

Z.Xiao, PRD08+…



$$\frac{1}{M_B^4 x_1 x_3 (1-x_3)} \to \frac{1}{((1-x_3)M_B^2 + \mathbf{k}_{3T}^2)(x_1 x_3 M_B^2 + (\mathbf{k}_{1T} - \mathbf{k}_{3T})^2)}$$

Comparison: QCDF-pQCD-SCET



The end-point issue

pQCD: $$\frac{1}{m_b^2\bar{x} - k_T^2 + i0}$$ singularity regulated by k_T

BBNS: Introduce hadronic parameters $\int_0^1 dx/x \to X_A$

$$X_A = (1 + \rho_A e^{i\phi_A}) \ln(m_B/500\,\text{MeV})$$

SCET:

The annihilation singularity has to do with a potential double counting

Arnesen et.al.

Same QCD topology appears twice.

Comparison: QCDF-pQCD-SCET

	SCET	QCDF	pQCD
Expansion in $\alpha_s(\mu_i)$?	No	Yes	Yes
T, P if Singular convolution	N/A	New parameters	uses k_T
Annihilation	Real at "LO", complex "NLO"	Complex, new parameters	perturbative, large phases
Charm Loop?	Non-perturbative	Perturbative	Perturbative
Number of fit parameters	Most	Middle	N/A

Symmetry approaches

To reduce parameters, one has

- SU(2) isospin symmetry for pions
- SU(3) flavor symmetry for pions+kions

to relate relevant decay modes.

Sometime, uncertainties could be cancelled

Guohuai Zhu, aXiv:1002.4518[hep-ph]

However, $SU(3)_F$ broken effect f_K/f_π sizable

For SU(3) symmetry broken effects,
eg, Y.L.Wu,Y.F.Zhou, PRD72(2005)034037

Nonperturbative Alternatives

- QCD sumrules: [P.Ball,R.Zwicky, PRD'05,
  T.Huang, Z.Li, F.Zuo, EPJC'09]
- Light Front Quark Model
  [W.Jaus,PRD'90, H.Y.Cheng et al,PRD'97]
  Renewed with SCET[C.D.Lu.W.Wang, Z.T.Wei, PRD'07]
  Recently Extended to baryons:
  Zentao,H.W.Ke, X.Q.Li,PRD'09,
  Y.M.Wang, Y.L.Sheng, C.D.Lu, PRD'09
- Lattice QCD [to be reviewed by C.Liu]

Pursue New Physics

So far, the best we can do:

- Use as much form factor information from semileptonic decays as possible
- Use global fits which combine Factoriztion and SU(3) to look for interesting channels with large deviations from the SM
- Include THEORY uncertainties when discussing any deviations(model parameters and so on)
- Diagnose a new physics model if all the correlated deviations explained→ constrained flavor structure → if it is accessible at LHC

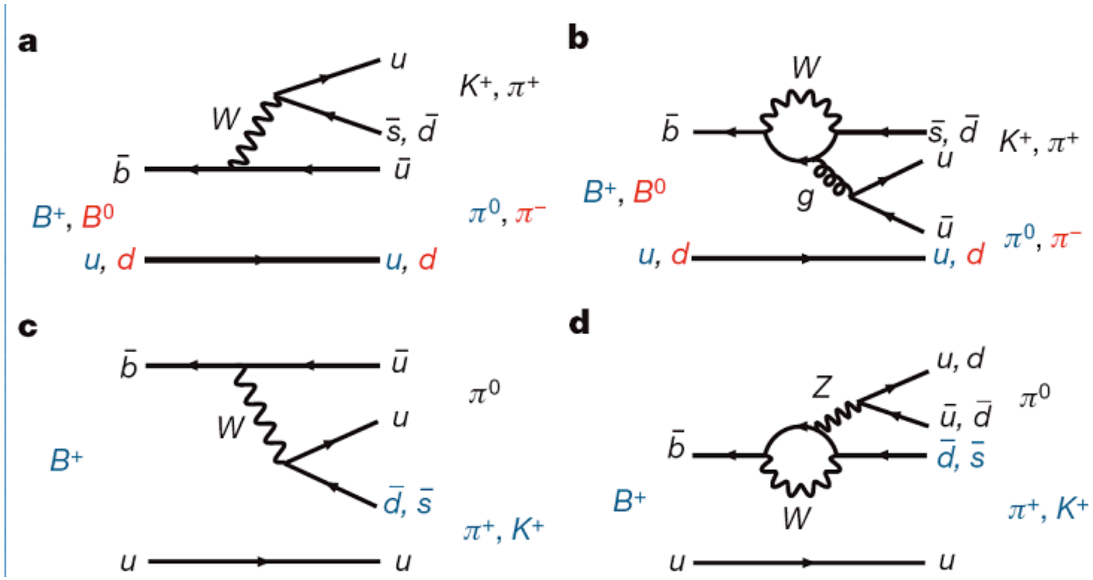
Examples: The π K -CP puzzle

In the SM, the direct CP asymmetries in charge and neutral B decays

$$A_{CP}(B^- \to K^-\pi^0) \equiv \frac{\Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^- \to K^-\pi^0) + \Gamma(B^+ \to K^+\pi^0)}$$

$$A_{CP}(\bar{B}^0 \to K^-\pi^+) \equiv \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$

Should be very close



However, the measurements:

$$A_{K^\pm\pi^\mp} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.094 \pm 0.018 \pm 0.008$$

$$A_{K^\pm\pi^0} = +0.07 \pm 0.03 \pm 0.01$$

Nature 452(2008) 332. (March)

which established the difference:

$$\Delta A \equiv A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+) = 0.164 \pm 0.037$$

at 4.5σ

The average of BABAR, Belle, CDF & CLEO

$$A_{CP}(B^- \to K^-\pi^0) = 0.050 \pm 0.025,$$
$$A_{CP}(\bar{B}^0 \to K^-\pi^+) = -0.097 \pm 0.012,$$

$$\Delta A = 0.147 \pm 0.028$$

at 5σ !

Possible Implications

The mismatch may be due to:

Our limited understanding of QCD so far, say, strong phase.

Equally, new physics.

M. Peskin, Nature 452(2008)334

Model independent approach

The possible new physics effects termed

$$\mathcal{H}_{\rm eff}^{\rm NP} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} |V_{tb}V_{ts}^*| e^{i\delta_S^q} \left[C_{S1}^q O_{S1}^q + C_{S8}^q O_{S8}^q \right] + {\rm h.c.}\,,$$

$$O_{S1}^u = \bar{s}(1+\gamma_5)b \otimes \bar{u}(1+\gamma_5)u\,, \qquad O_{S8}^u = \bar{s}_i(1+\gamma_5)b_j \otimes \bar{u}_j(1+\gamma_5)u_i\,,$$

$$O_{S1}^d = \bar{s}(1+\gamma_5)b \otimes \bar{d}(1+\gamma_5)d\,, \qquad O_{S8}^d = \bar{s}_i(1+\gamma_5)b_j \otimes \bar{d}_j(1+\gamma_5)d_i,$$

i.e., scalar FCNCs

Scanning 12 correlated channels (CPA+Brs)

all theoretical inputs and exp uncertainties included

Application continued

Constrained parameter space:

NP para.	Case I	Case II	Case III	Case IV	Case V
$C^u_{S1}(\times 10^{-3})$	-41.6 ± 13.4	—	—	25.8 ± 8.4	-6.7 ± 10.5
$C^u_{S8}(\times 10^{-3})$	38.7 ± 18.2	—	—	—	16.0 ± 7.1
δ^u_S	$99.5^\circ \pm 6.1^\circ$	—	—	$107.0^\circ \pm 11.5^\circ$	$73.0^\circ \pm 23.8^\circ$
$C^d_{S1}(\times 10^{-3})$	—	23.0 ± 5.1	22.8 ± 2.3	50.3 ± 12.8	17.5 ± 10.1
$C^d_{S8}(\times 10^{-3})$	—	-0.8 ± 13.7	—	—	10.5 ± 9.4
δ^d_S	—	$100.0^\circ \pm 8.7^\circ$	$99.3^\circ \pm 9.2^\circ$	$106.6^\circ \pm 7.3^\circ$	$114.7^\circ \pm 18.6^\circ$

Color singlet b→sqq dominated + a nontrivial weak phase!

We leave the mixing induced CPA in $B \to \pi^0 K_S$ and $B \to \rho^0 K_S$ as our prediction

Prediction(continued)

Decay Mode	Experiment data	SM	NP Case I	Case II	Case III	Case IV	Case V
$\overline{B}_d^0 \to \pi^0 K_S$	38 ± 19	77 ± 4	45 ± 11	56 ± 5	57 ± 3	59 ± 9	62 ± 8
$\overline{B}_d^0 \to \rho^0 K_S$	61^{+25}_{-27}	66 ± 3	—	61 ± 6	61 ± 3	56 ± 3	57 ± 4

Old data at that time

ICHEP08

BABAR $A_{\rm CP}^{\rm mix}(\bar{B}^0 \to \pi^0 K_S) = 0.55 \pm 0.20 \pm 0.03$

Belle $A_{\rm CP}^{\rm mix}(\bar{B}^0 \to \pi^0 K_S) = 0.67 \pm 0.31 \pm 0.08$

0.58 ± 0.17

Compared with the new data, unexpected match!

For details: Qin Chang, X.Q.Li, Yadong, JHEP0809:038,JHEP0706
Chang Qin's talk @5:40PM, 18April

Pursue in specified NP scenarios I

✔ Invisible Higgs in $B \to K\ \nu\nu$-bar[Guohai et al, PRD'10]

✔ Family Non-universal Z' Models

To tackle $A_{FB}(q^2)$ puzzle:
C.W.Chiang, R.H.Li, C.D.Lu, arXiv:0911.2399
Q.Chang, X.Q. Li, Y.D.Yang JHEP in production

To tackle $B_s - \overline{B}_s$, $B_s \to \mu^+\mu^-$, $B_s \to X_s\,\mu^+\mu^-$
Q.Chang, X.Q. Li, Y.D.Yang, JHEP1002(2010)

To tackle the abnormal large $B \to \pi^0\,\pi^0$
Q.Chang, X.Q. Li, Y.D.Yang,aXiv:1003.6051

P. Langacker, V.Barger… JHEP0912(2009)04, PRD80(09)055008

Pursue in specified NP scenarios II

- Most extensive studies from A.J. Buras grou

SUSY: AJB, Altmannshofer, S. Gori, P.Paradisi,D. Straub

LHT: AJB, M. Blanke, B. Duling, S. Recksiegel, C.Tarantino

RS: AJB Abrecht, K.Gemmler, A.Weiler

Munich gang

Summary

Flavor Physics enters the precision era

Hints for New Physics need to be confirmed

Inter-play

Direct searches @LHC, Tevatron, ILC,

Correlations among various Observables can distinguish NP scenarios

Great discoveries are just ahead of us

Which guy is the promised? Who will fly?