New Physics Searches in B Decays

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World Research Unit for Heavy Flavor Particle Physics
Symposium 2016
"Interplay between LHC and Flavor Physics"
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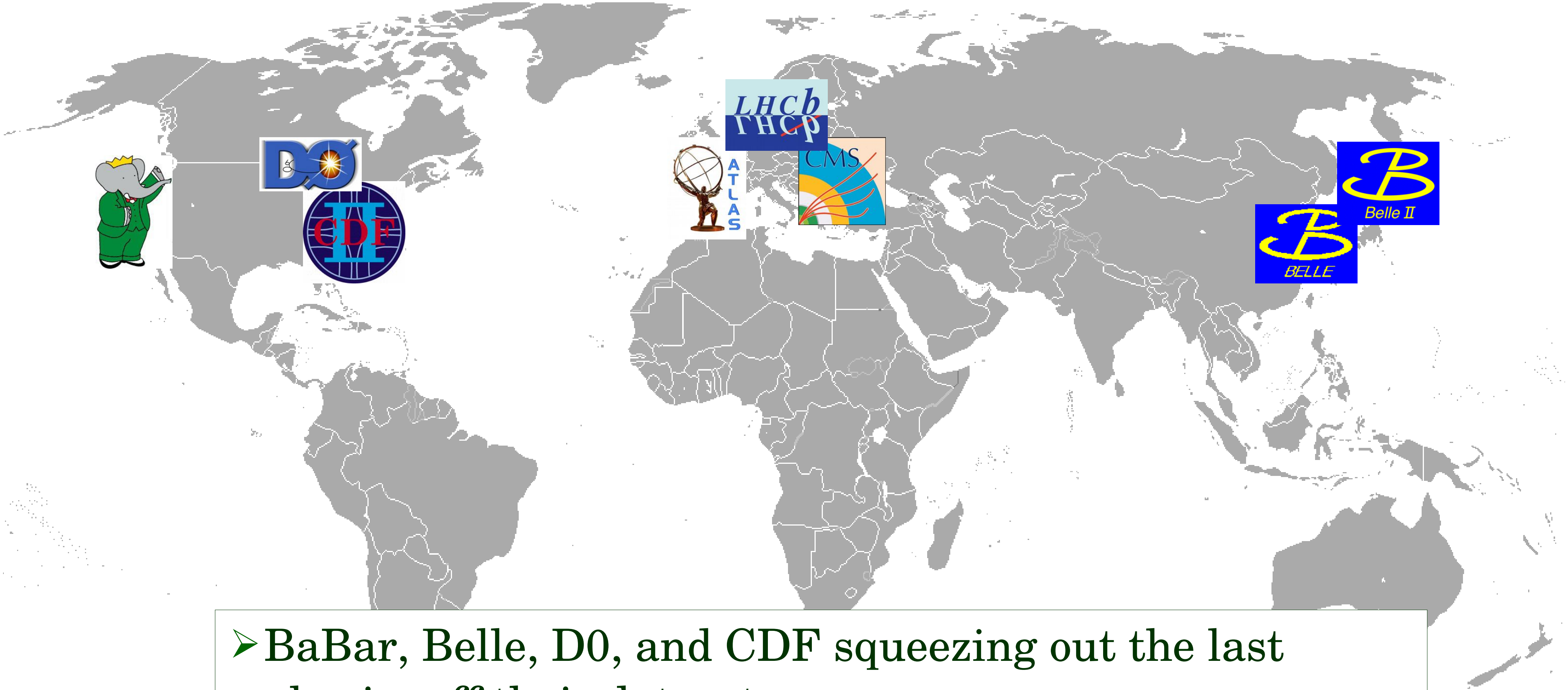
B Physics Experiments



- BaBar, Belle, D0, and CDF squeezing out the last physics off their datasets
- LHCb (+ATLAS and CMS) now dominating the scene…
- … while Belle II is preparing for data taking!

Competition and Complementarity

In the next years LHCb and Belle II will fiercely compete in some areas … in others, they will exploit their own strengths;

- LHCb:
  - ➔ Very high b-quark cross section (B^0, B^+, B_s, B_c, Λ_b, …);
  - ➔ Unbeatable in rare decays to charged final state particles;
  - ➔ Large boost, long flight lengths → can exploit it for kinematical constraints;
- Belle II:
  - ➔ Coherent $B\bar{B}$ production from Υ(4s) decays;
  - ➔ Very clean environment, great efficiency in final states with neutrals (π^0, $\eta^{(\prime)}$, ω, …);
  - ➔ Possibility to do energy scans above/below thresholds.

The Way to New Physics

- B decays offer unique opportunities to test the Standard Model, we can indirectly probe the existence of New Physics particles at masses well above the direct production capabilities of the LHC;
- Focus on the observables with theoretically clean predictions;
- Several tensions observed in the past have disappeared, some are still there;

- Hopefully we will get a glaring discrepancy, but New Physics could also manifest itself in a coherent pattern of small deviations...
- So, let's not leave any stone unturned!
- And also, let's not forget to improve the precision on our reference modes, where New Physics is not expected to enter.

Outline

A personal selection of “hot” topics in B Physics (and apologies if I am not covering your favorite modes):

- Rare (leptonic) decays;
- Semileptonic decays;
- CP violation in $B\bar{B}$ mixing;
- Radiative penguins;
- Measurement of the CKM UT angles and ϕ_s ;

In many of these areas the LHC experiments and Belle II can play complementary roles, so that a tight cooperation between the two experiments will be essential.

Rare decays: $B_{d,s} \to \mu^+\mu^-$

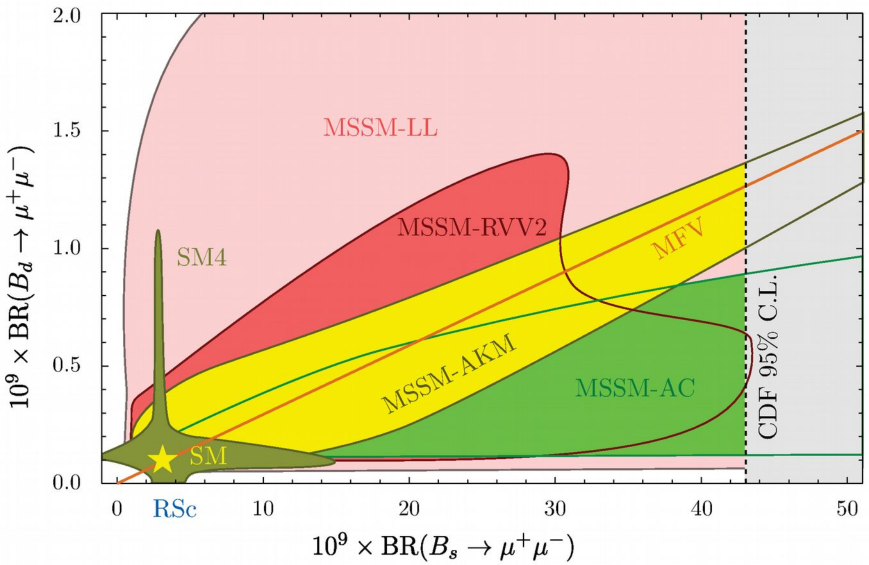
- Very popular channels to indirectly detect New Physics;
- Precise predictions from the SM:

$$BF\ (B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

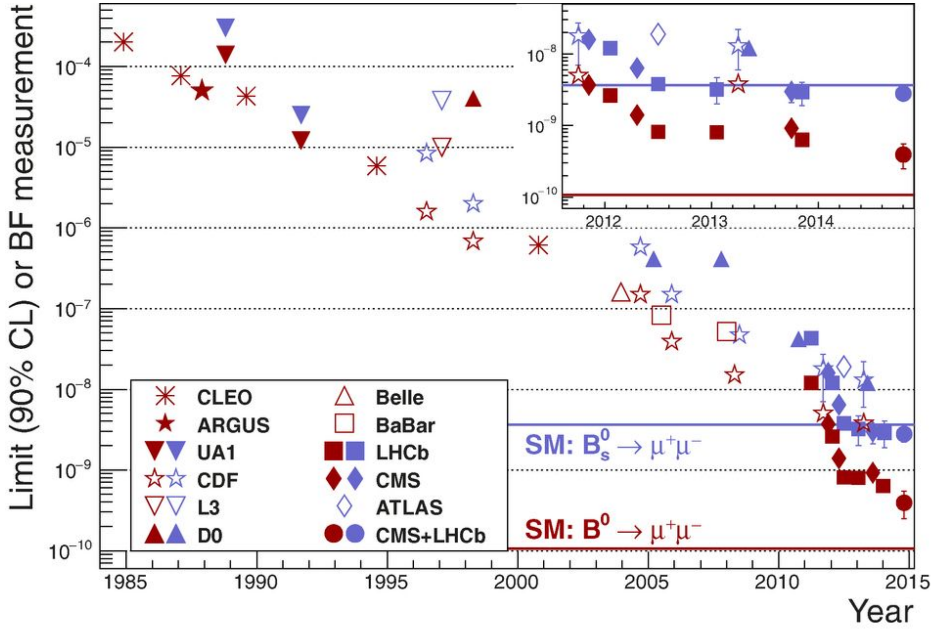
$$BF\ (B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.
PRL **112**, 101801 (2014)

- New Physics (e.g. SUSY, models with additional Higgs's, …) can produce sizable shifts wrt SM:



D. Straub,
CKM Workshop 2010



Rare decays: $B_{d,s} \to \mu^+\mu^-$

- Combined CMS+LHCb analysis on full RunI (7 and 8 TeV) dataset:

$$\mathrm{BF}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \quad (5.2\sigma)$$

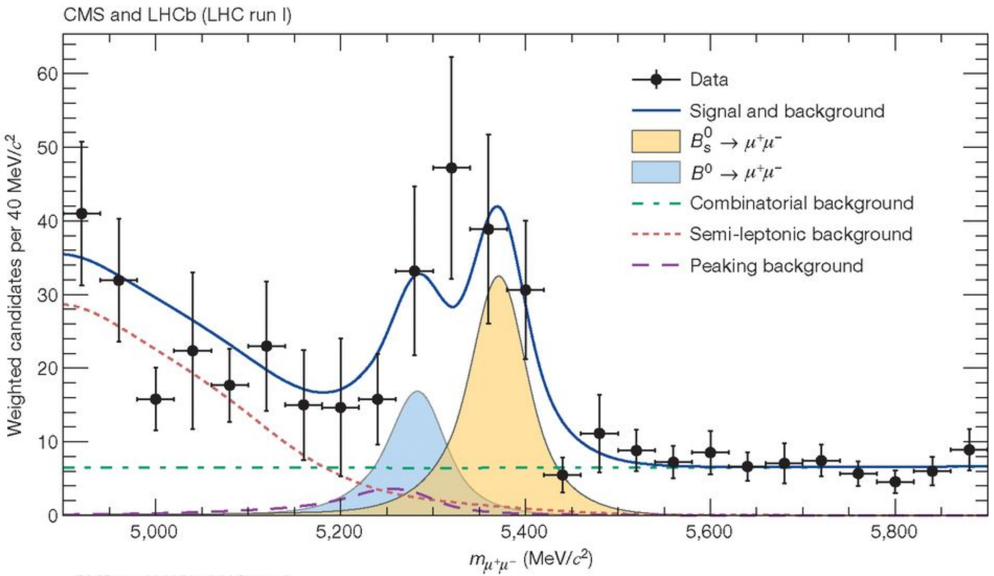
$$\mathrm{BF}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \quad (3.2\sigma)$$

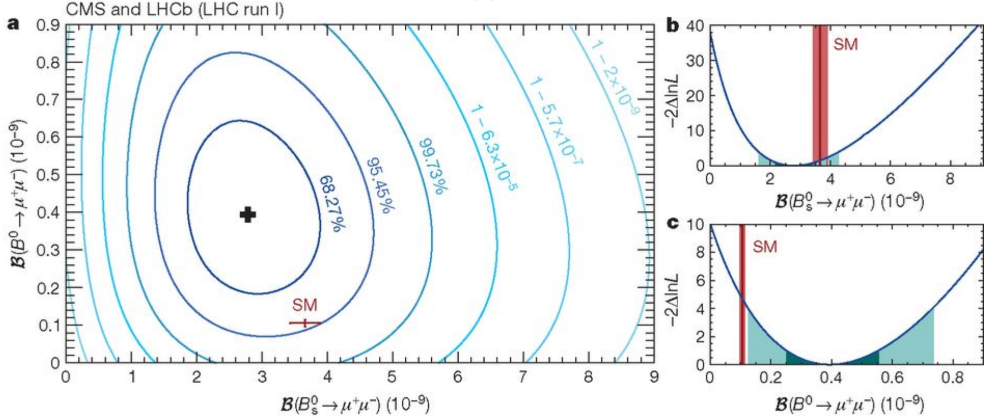
- Some tension with SM predictions, mostly driven by the B_d. This is particularly evident by the ratio:

$$R = \frac{\mathrm{BF}(B_d \to \mu^+\mu^-)}{\mathrm{BF}(B_s \to \mu^+\mu^-)} = 0.14^{+0.8}_{-0.6}$$

SM prediction is: $R = 0.0295^{+0.0028}_{-0.0025}$
(2.3σ tension)

CMS and LHCb Collaborations, Nature **522**, 68 (2015)

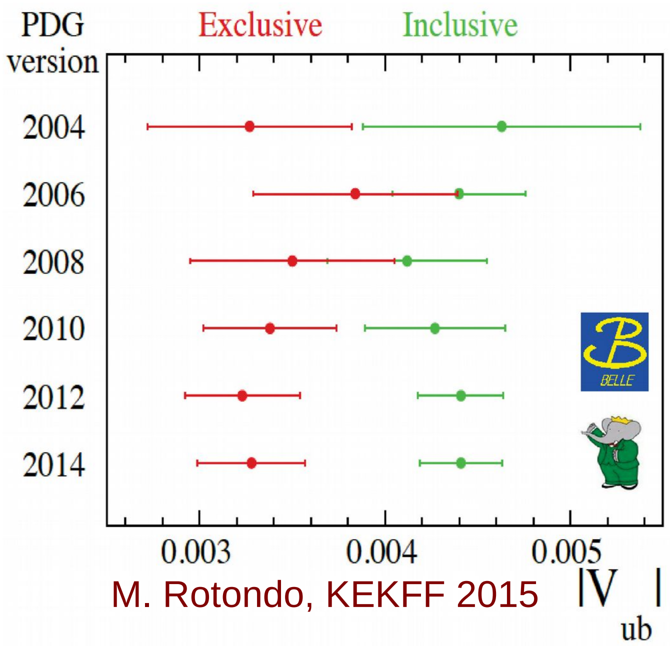




Semileptonic Decays

- $|V_{cb}|$ and $|V_{ub}|$ are fundamental inputs for the CKM fit;
- Semileptonic B decays allow for their extraction at tree level, their determination is crucial for New Physics searches;
- Tremendous progress in the last decade:

PDG 2014:	$\vert Vcb\vert$	$\vert Vub\vert$
Inclusive:	$(42.2 \pm 0.7) \times 10^{-3}$	$(4.41 \pm 0.21) \times 10^{-3}$
Exclusive:	$(39.5 \pm 0.8) \times 10^{-3}$	$(3.28 \pm 0.29) \times 10^{-3}$



M. Rotondo, KEKFF 2015

- Error on $|V_{cb}| < 2\%$, on $|V_{ub}| \sim 5$-9%;

… but the FNAL/MILC collaboration now obtains ~4% error on the exclusive determination of $|V_{ub}|$ from BaBar + Belle...

- Great improvement on the errors, but ~3σ tension between inclusive and exclusive determinations of both $|V_{cb}|$ and $|V_{ub}|$;
- LHCb entered the game with $\Lambda_b \to \Lambda_c/p\,\mu\,\nu$ (!).

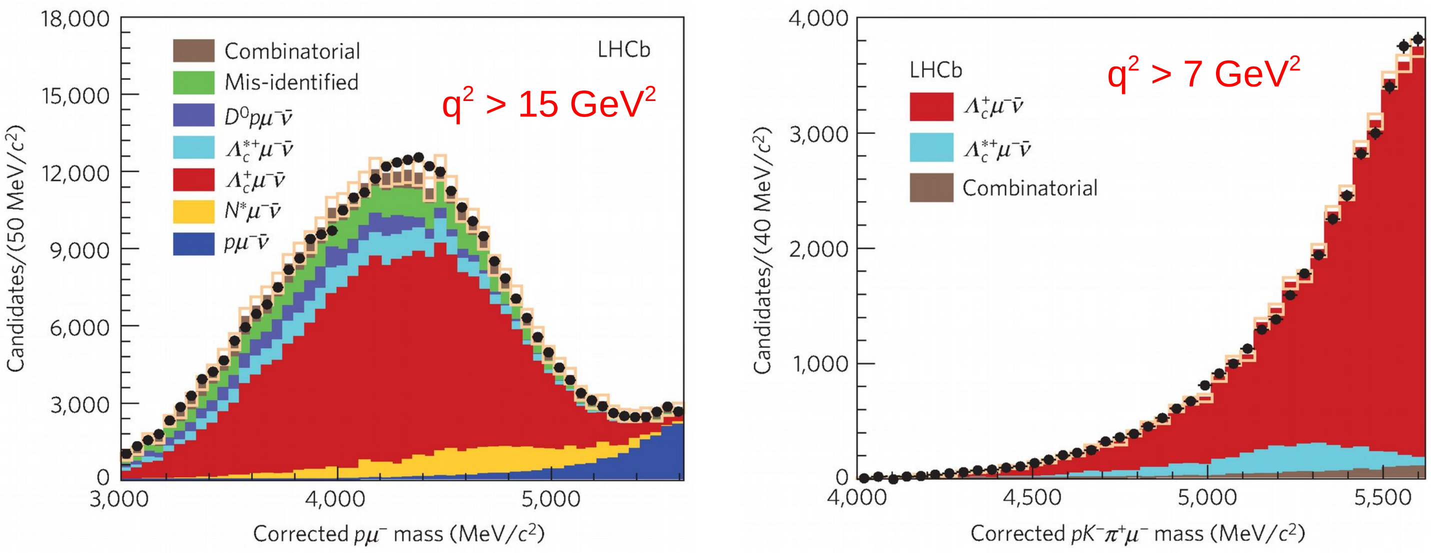
Semileptonic Decays

- LHCb determined $|V_{ub}|/|V_{cb}|$ by measuring the ratio:

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} \boxed{R_{\mathrm{FF}}} \longrightarrow$$

Ratio of form factors, provided by LQCD
W. Detmold et al., PRD **92** 034503 (2015)

- Exploit the copious Λ_b production at LHC and the excellent vertexing and PID of LHCb to reconstruct the two channels;
- LQCD predictions are reliable in the high q^2 part of spectrum:



LHCb Collaboration,
Nature Physics **11**, 743 (2015)

Semileptonic Decays

Result:

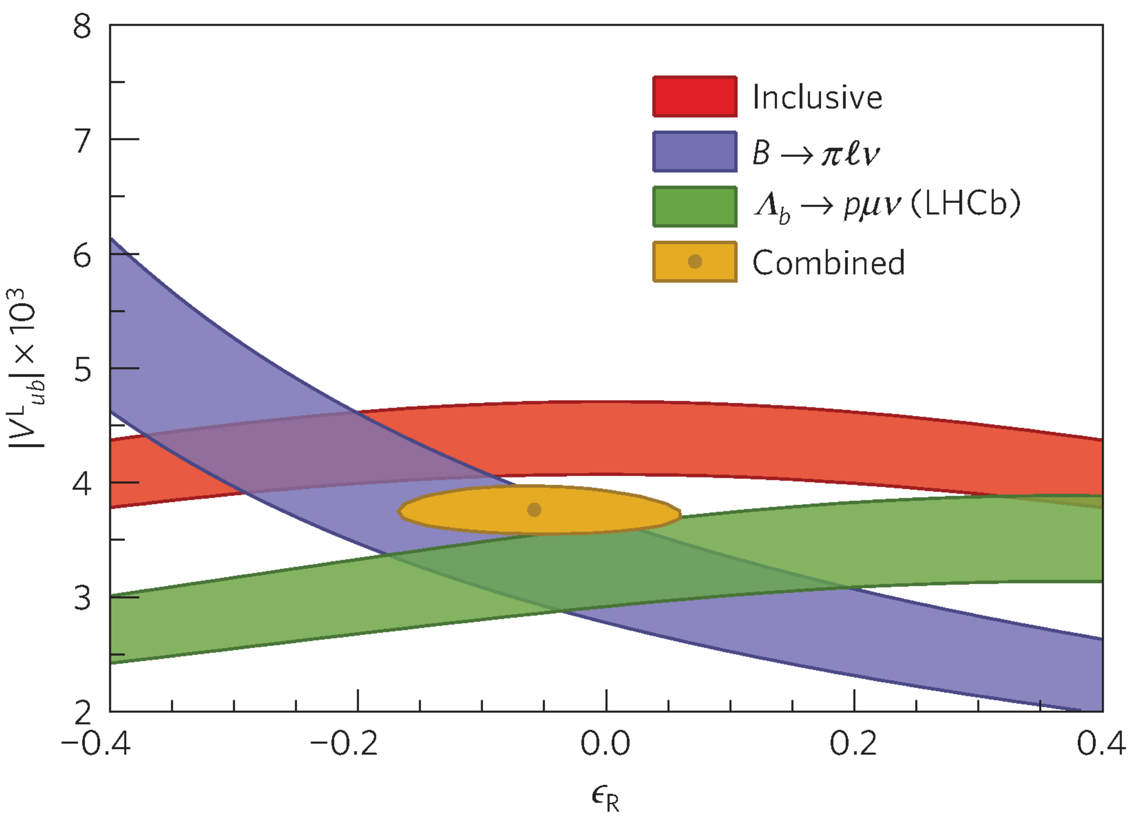
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

experimental

FF LQCD prediction

uncertainty from $|V_{cb}|$

- The presence of right-handed (V+A) currents could explain the discrepancy between inclusive and exclusive determinations;
- The Λ_b result from LHCb strongly disfavors this hypothesis.



$B \rightarrow D^{(*)}\tau\nu$

- One of the hot topics of the moment, potential charged Higgs-like particles can cant effects;
- Measure: $$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}\ell^+\nu_\ell)}$$ *l* = e, μ
- Clean predictions from SM, most uncertainties cancel in the ratio:

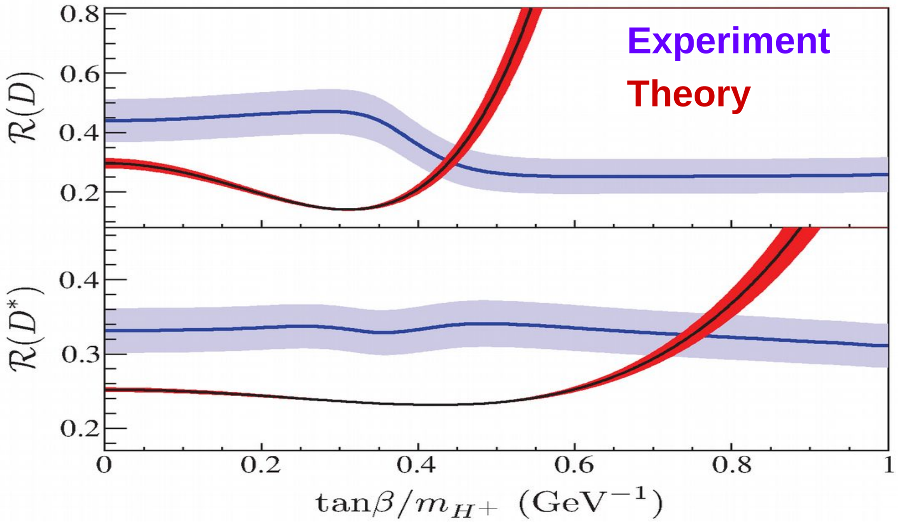
$$\begin{aligned} R(D) &= 0.297 \pm 0.017 \\ R(D^*) &= 0.252 \pm 0.003 \end{aligned}$$

PRD **78**, 014003 (2008)

PRD **85**, 094025 (2012)

- BaBar saw a 3.4σ discrepancy a few years ago;
- Type II 2HDM almost ruled out by this result.

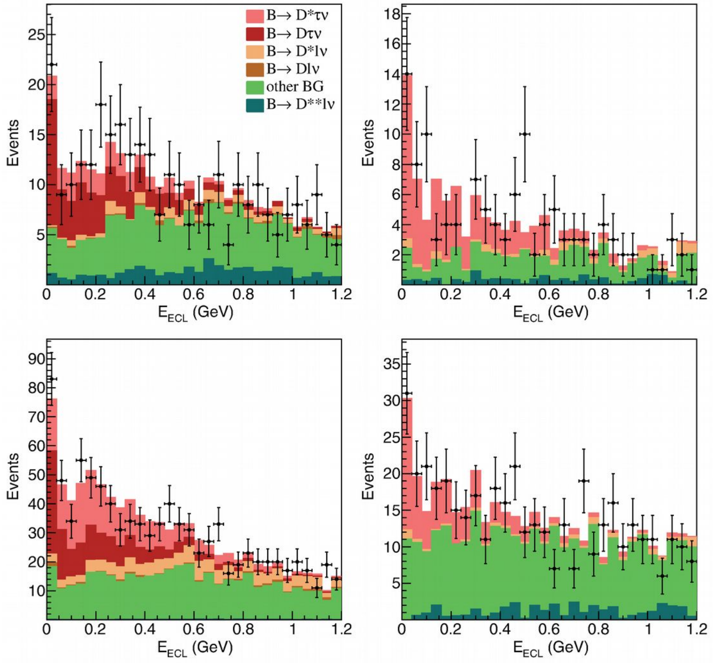
More about potential New Physics effects in M. Tanaka's talk tomorrow



BaBar Collaboration, PRD **88**, 072012 (2013)

$B \rightarrow D^{(*)}\tau\nu$

- In the last year, Belle and LHCb measured the same quantities:



Belle reconstructs signal events on the recoil of hadronic B_{tag}, using leptonic τ decays (similar to BaBar)

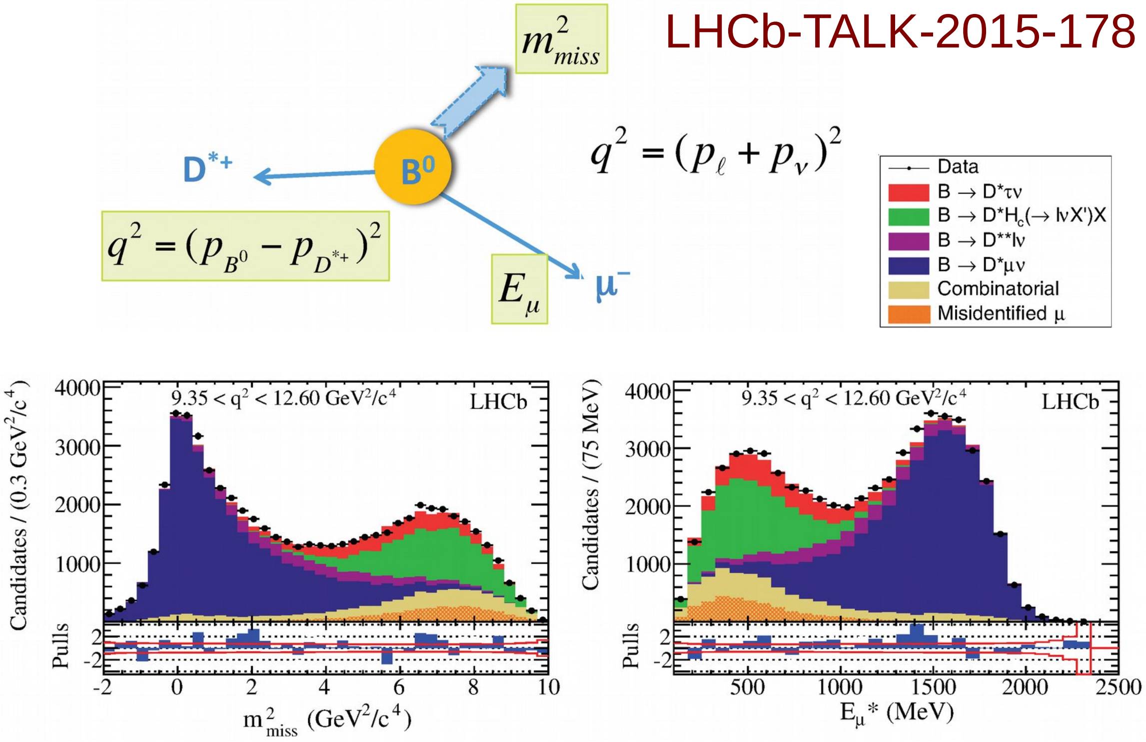
$$R(D) = 0.375 \pm 0.064 \pm 0.026 \quad \sim 1.4\sigma$$

$$R(D^*) = 0.293 \pm 0.038 \pm 0.015 \quad \sim 1.8\sigma$$

Belle Collaboration,
PRD **92**, 072014 (2015)

LHCb performs a template fit on the 3 kinematic variables:

LHCb-TALK-2015-178



$$R(D^*) = 0.336 \pm 0.027 \pm 0.030 \quad \sim 2.1\sigma$$

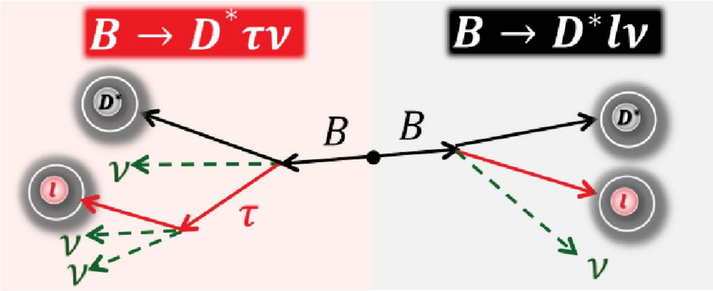
Still tension with SM

LHCb Collaboration,
PRL **115**, 111803 (2015)

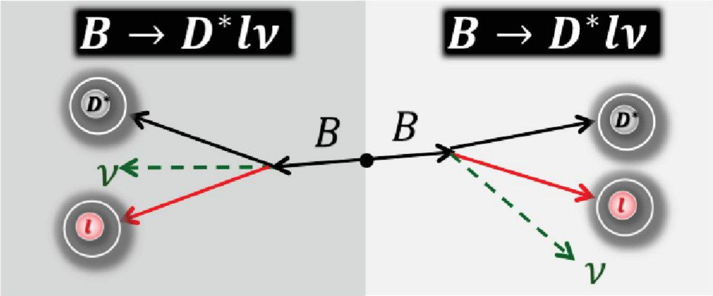
$B \to D^{(*)}\tau\nu$

NEW!!!

- New Belle result on $R(D^*)$ for $B^0 \to D^{*\mp}\tau^\pm\nu$;
- Analysis performed on the recoil of $B^0 \to D^{*\mp}l^\pm\nu$ mesons (statistically independent from previous Belle analysis);

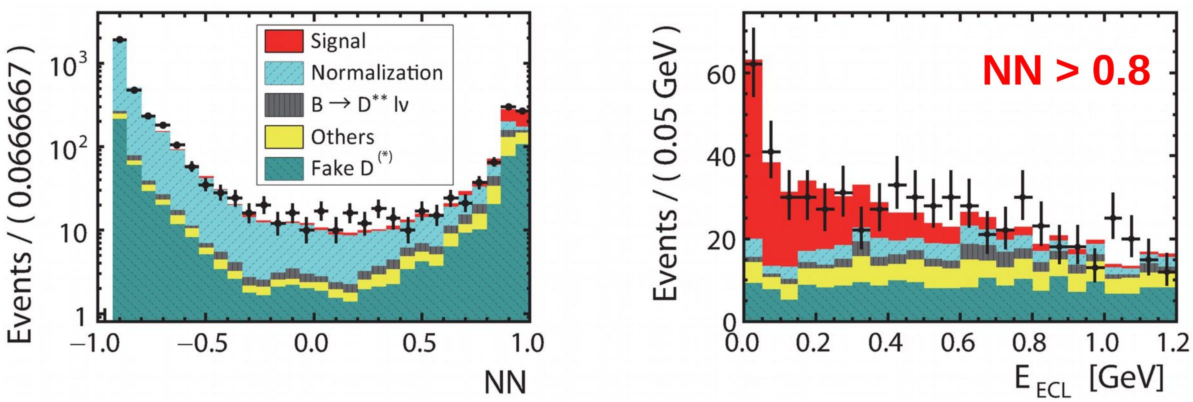


Numerator in $\mathcal{R}(D^*)$



Denominator in $\mathcal{R}(D^*)$

- Signal yield extracted by 2D fit on NN output (combining kinematic variables) and extra energy E_{ECL};



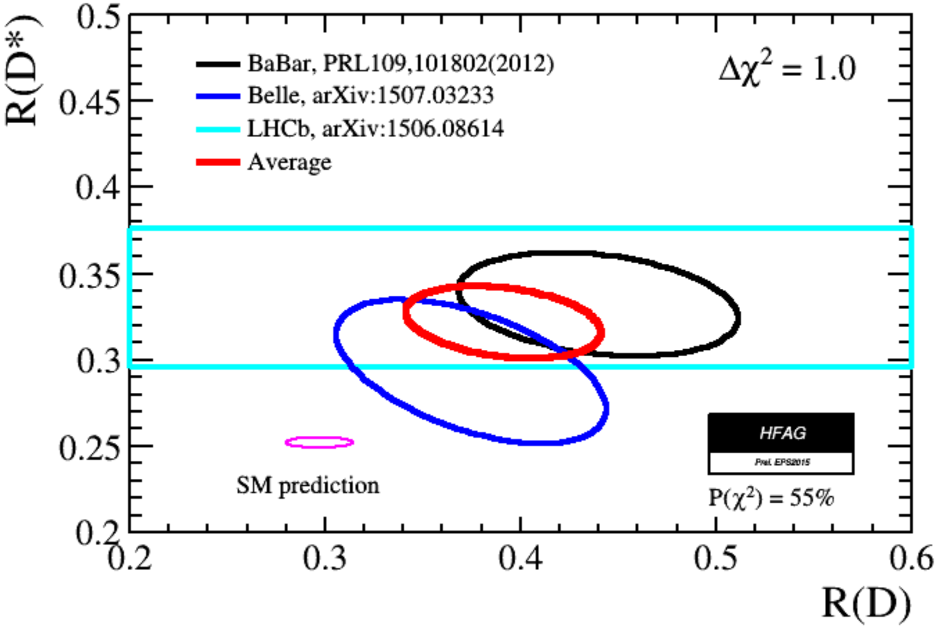
$$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$$

1.6σ above SM

$B \to D^{(*)}\tau\nu$: Outlook

- Global significance of the discrepancy at the 3.9σ level;
- Belle II eagerly awaited to confirm/disprove the excess, but in the meantime:
  - ➔ LHCb can improve the precision, and can also look at $\Lambda_b \to \Lambda_c\tau\nu$;

Latest Belle result non included



  - ➔ Belle can squeeze out some more from its dataset, e.g. looking at τ polarization in hadronic decays;

See S. Hirose's poster later today

- It will also be interesting to measure the inclusive $B \to X_c\, \tau\, \nu$: experimentally very challenging.

CP violation in $B\bar{B}$ mixing

- Some formalism of $B\bar{B}$ oscillations:

Time evolution of a B^0B^0 system

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

Mass eigenstates

$$|B_{H,L}\rangle = \frac{1}{\sqrt{2}}(p|B^0\rangle \mp q|\bar{B}^0\rangle)$$

If $|q/p| \neq 1$ the probability for a B^0 to oscillate to a $\bar{B}^0$ is different from the probability of a $\bar{B}^0$ going to B^0

- Experimentally we measure:

$$A_{SL} = \frac{\Gamma(\bar{B} \to B \to f) - \Gamma(B \to \bar{B} \to \bar{f})}{\Gamma(\bar{B} \to B \to f) + \Gamma(B \to \bar{B} \to \bar{f})} \approx 2\left(1 - \left|\frac{q}{p}\right|\right)$$

- The Standard Model predicts tiny CP violation in mixing:

$$\begin{aligned} A^d_{SL} &= (-4.1 \pm 0.6) \times 10^{-4} \\ A^s_{SL} &= (\ \ 1.9 \pm 0.3) \times 10^{-5} \end{aligned}$$

Experimental precision ~10^{-3}, still room for surprises…

A. Lenz, arXiv 1205.1444 [hep-ph]

CP violation in $B\bar{B}$ mixing

Different strategies to measure A_{SL}:

1) Tag two B^0's (at B-factories and D0):

Time integrated, exploiting symmetry in production of B^0 and B^0

$$A_{SL} = \frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)}$$

… can also use $l^{\pm}K^{\pm}$ pairs!

2) Untagged measurement (at LHCb):

Time dependent, complications from the asymmetric production at a pp collider

$$\frac{N(B,t) - N(\bar{B},t)}{N(B,t) + N(\bar{B},t)} = \frac{A_{SL}}{2}\left[1 - \frac{\cos \Delta M t}{\cosh \frac{\Delta\Gamma t}{2}}\right]$$

CP violation in B$\bar{\text{B}}$ mixing

- Experimental status:

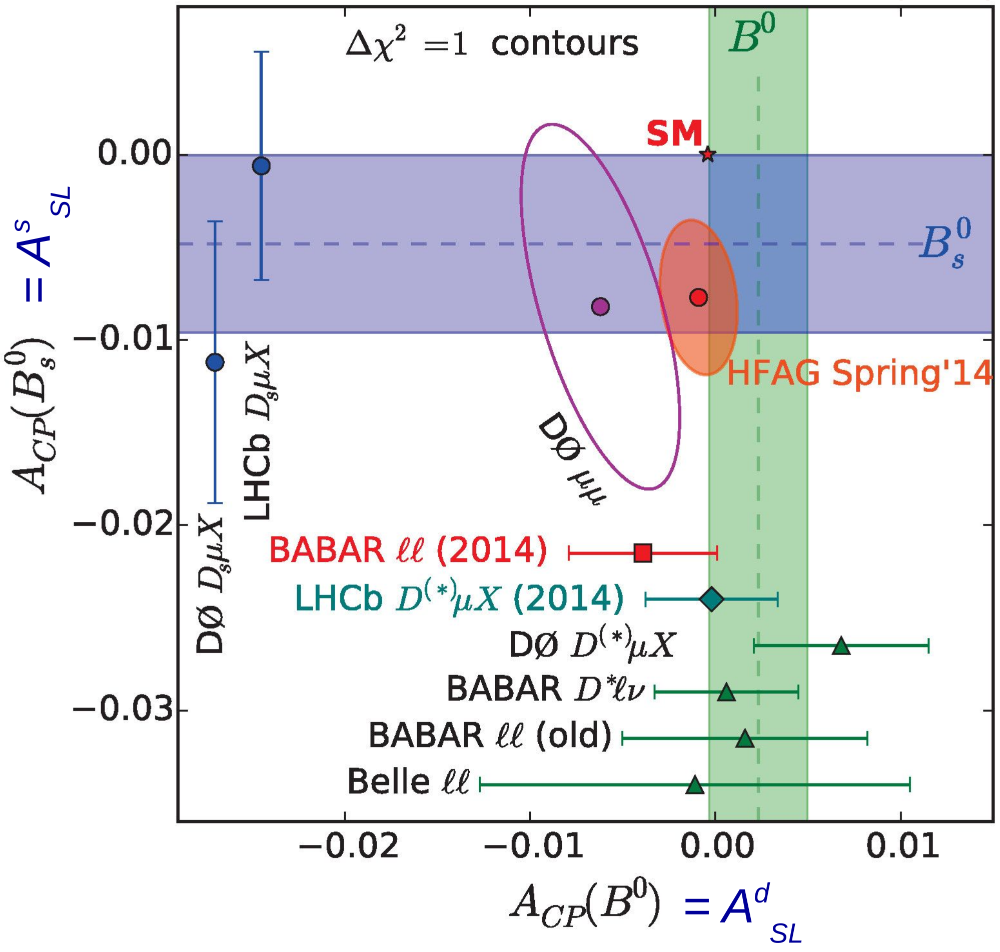
A^d_{SL}:

BaBar (*ll*):	(-0.39 ± 0.35 ± 0.19)%
BaBar (*D*lν*):	(0.06 ± 0.17 ± 0.35)%
D0 (*DμX*):	(0.68 ± 0.45 ± 0.14)%
LHCb (*DμX*):	(0.02 ± 0.19 ± 0.30)%

A^s_{SL}:

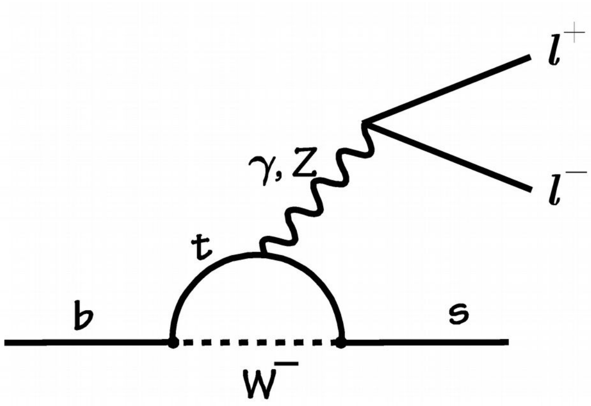
D0 ($D_s\mu X$):	(-1.12 ± 0.74 ± 0.17)%
LHCb ($D_s\mu X$):	(-0.06 ± 0.50 ± 0.36)%

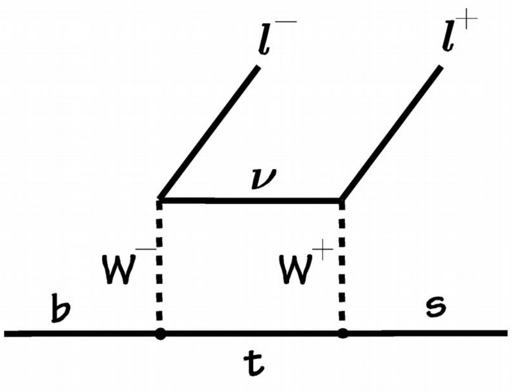
From PRL **114**, 081801 (2015)



- The next years will be quite interesting: still quite a bit of margin for improvement (many systematics depend on statistics of control samples).

Electroweak Penguins





Sensitive to the:

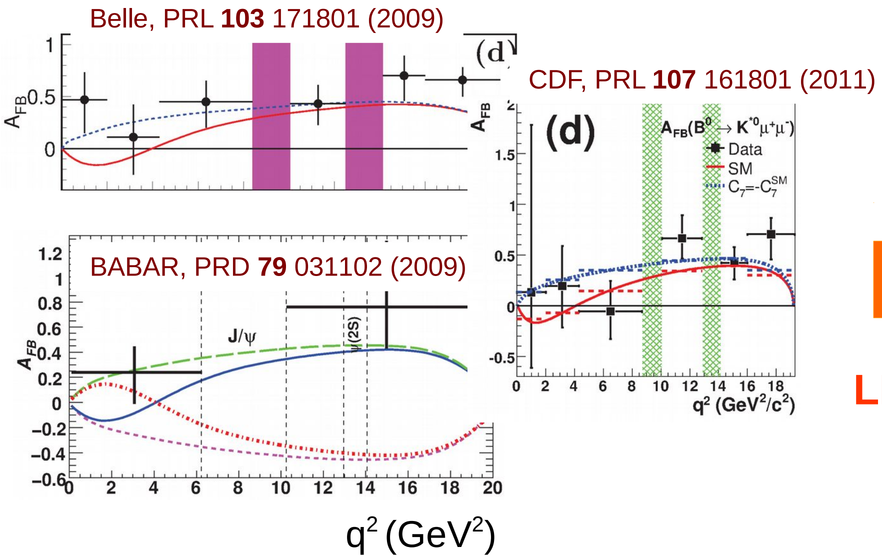
C_7: elctromagnetic penguin

C_9: vector electroweak

C_{10}: axial-vector electroweak

Wilson Coefficients

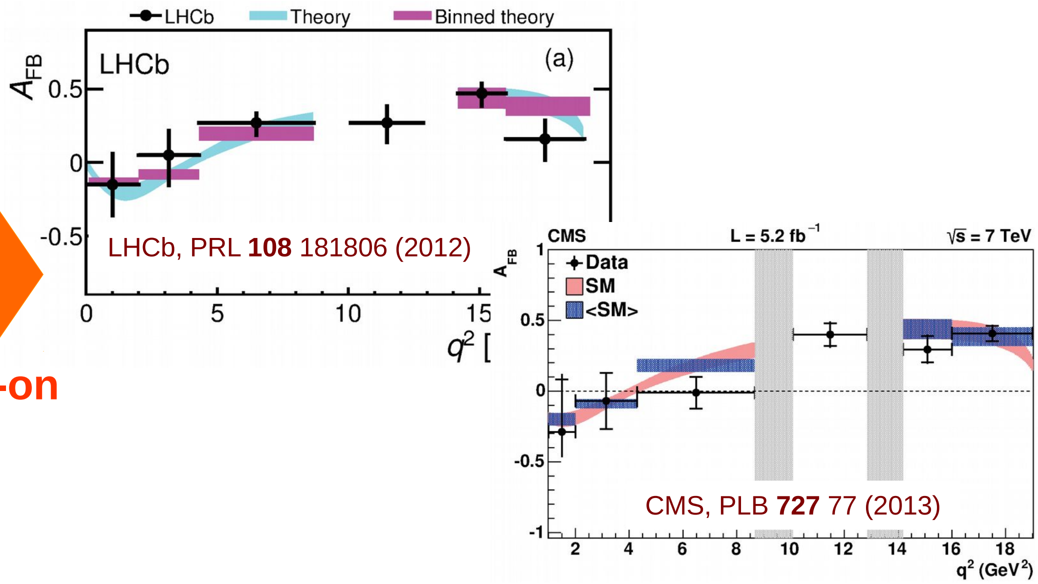
- Very suppressed in the SM (BF ~ 10^{-6});
- Many observables and often very precise predictions from theory;


Belle, PRL **103** 171801 (2009)

BABAR, PRD **79** 031102 (2009)

CDF, PRL **107** 161801 (2011)

LHC turn-on

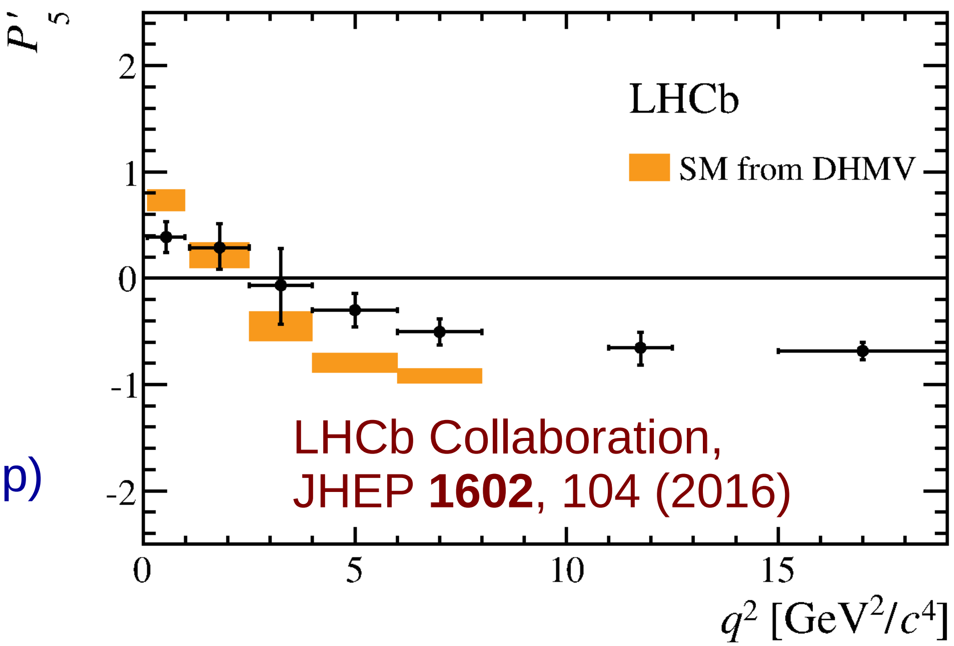

LHCb, PRL **108** 181806 (2012)

CMS, PLB **727** 77 (2013)

Electroweak Penguins: P'_5

- Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$;
- Many observables investigated, can cancel the leading uncertainty on hadronic form factor by defining “optimised” observables:
- Interesting discrepancy is observed in P'_5;

(full definitions of observables in backup)



DHMV: JHEP **1412**, 125 (2014)

LHCb Collaboration, JHEP **1602**, 104 (2016)

- Global fit to complete set of observables gives a 3.4σ tension with SM: New Physics or hadronic effects larger than expected?
- While the experiments improve the precision, input from theory is essential.

Electroweak Penguins: LUV?

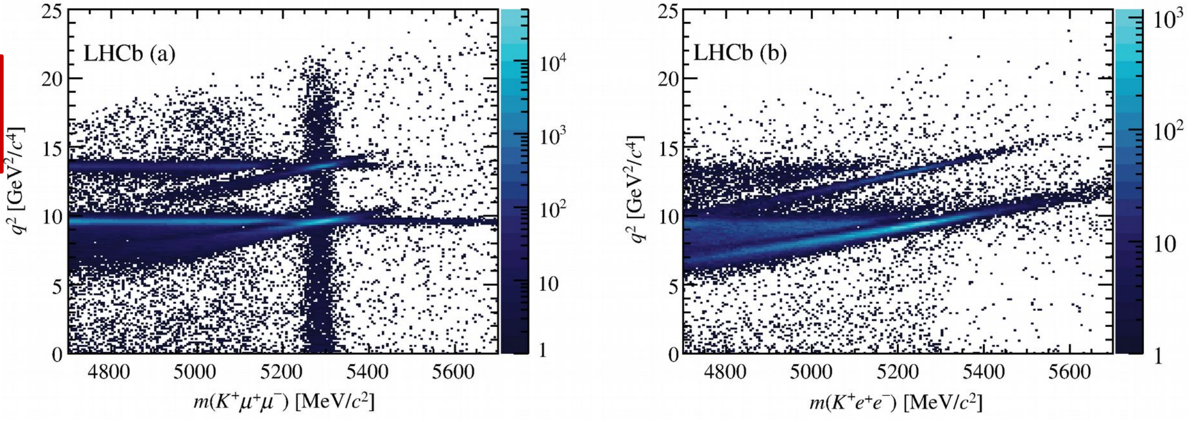
- Tests of Lepton Universality in b → sl^+l^- decays can reveal the presence of Higgs-like particles;
- LHCb measured the ratio R_K in $B^+ \rightarrow K^+ l^+ l^-$:

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2}\, dq^2} \approx 1 \text{ (modulo tiny corrections)}$$

- Challenging analysis, need to correct for Bremstrahlung;
- In $1 < q^2 < 6$ GeV^2:

$$\boxed{R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})}$$

- 2.6σ tension wrt expectation: this needs confirmation!



LHCb Collaboration,
PRL **113**, 151601 (2014)

Electroweak Penguins: Outlook

- Quite a few channels where LHCb will improve a lot in the next couple years:
  - $B \to \pi l^+l^-$;
  - $B_s \to \phi l^+l^-$;
  - $\Lambda_b \to \Lambda l^+l^-$;
  - …

Keep refining precision on differential BF's, CP asymmetries, angular observables, Lepton Universality...

- … and quite a few more where we need to wait for Belle II:
  - $B \to K^{(*)} \tau^+\tau^-$; current limit ~2 orders of magnitude above predictions
  - $B \to K^{(*)} \nu \nu$;
  - $B \to \gamma\gamma$;

    might see a signal with full dataset but it is crucial to control the machine backgrounds
  - (semi-)inclusive $b \to d/s\ \gamma$;
  - Time dependent CPV in $B^0 \to K_S\pi^0\gamma$, $B^0 \to \rho^0 \gamma$;
  - …

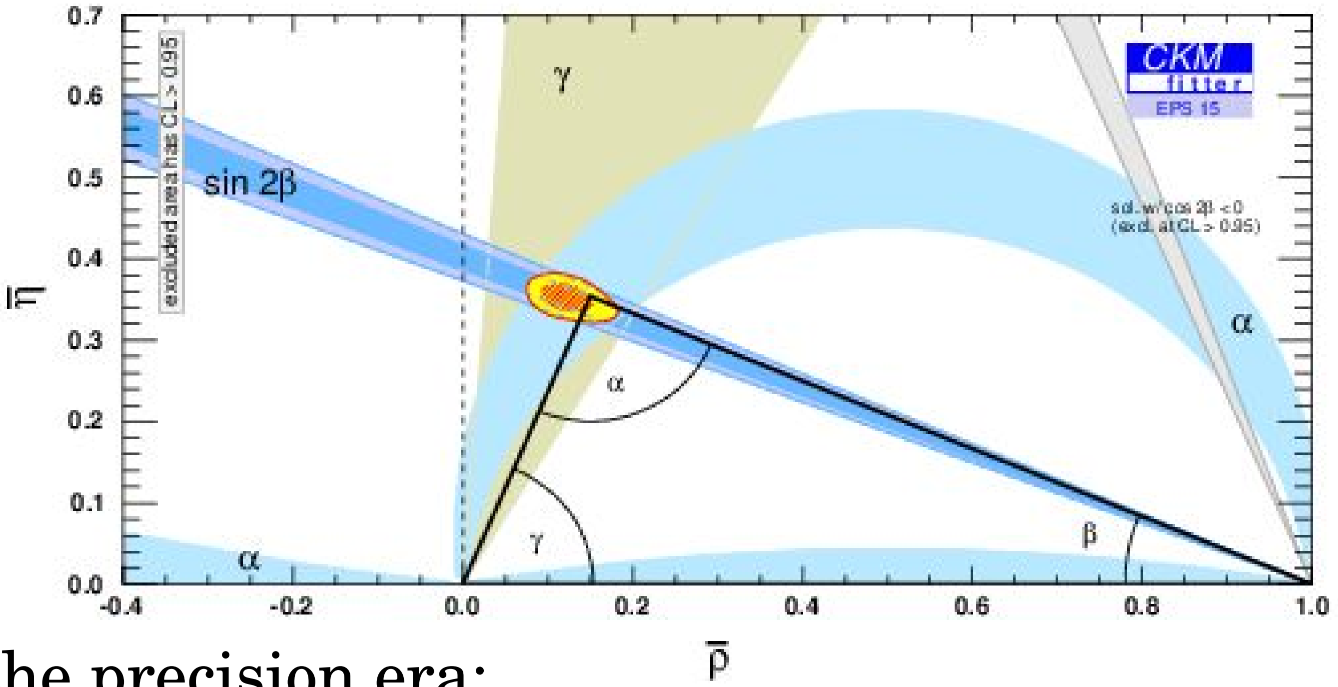
The Angles of the UT

- One of the main goals of the B-factories: still a lot to do!

$$\alpha = \phi_2 \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

$$\beta = \phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma = \phi_3 \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

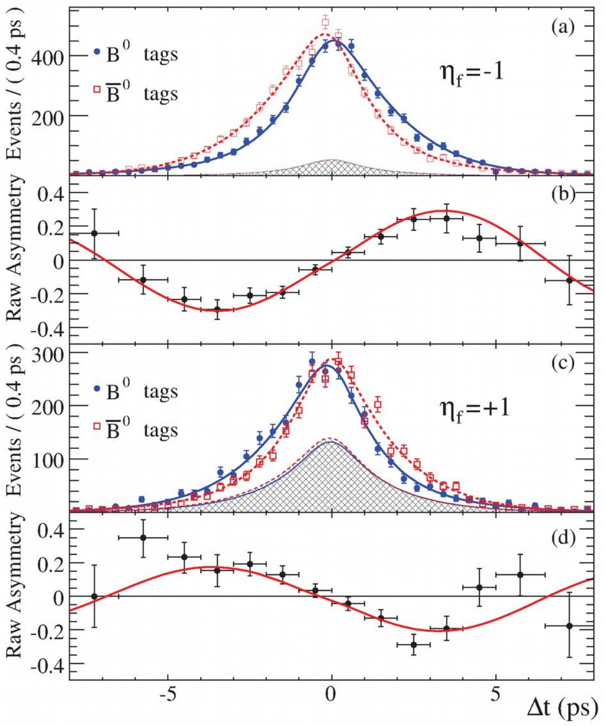


→ ϕ_1/β: now well into the precision era;

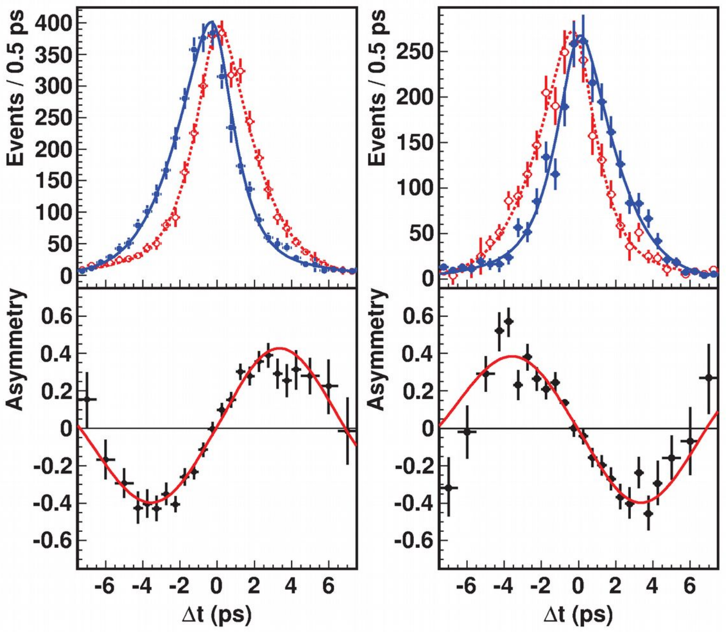
→ ϕ_2/α: larger theoretical and experimental uncertainties, will need to combine several modes;

→ ϕ_3/γ: measured through tree level amplitudes: crucial input for the CKM fit.

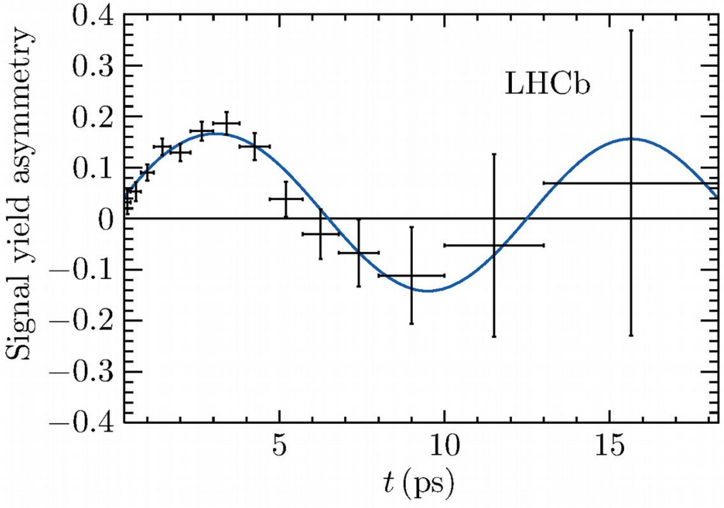
ϕ_1/β from charmonium K^0



BaBar Collaboration
PRD **79**, 072009 (2009)



Belle Collaboration
PRL **108**, 171802 (2012)



LHCb Collaboration
PRL **115**, 031601 (2015)

$$\begin{aligned} S &= 0.687 \pm 0.028 \pm 0.012 \\ C = -A &= 0.024 \pm 0.020 \pm 0.016 \end{aligned}$$

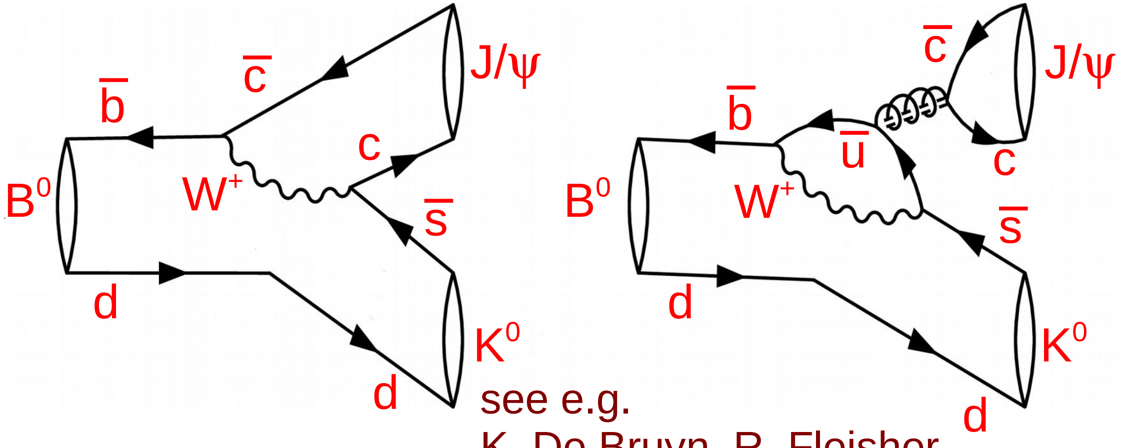
$$\begin{aligned} S &= 0.667 \pm 0.023 \pm 0.012 \\ C = -A &= -0.006 \pm 0.016 \pm 0.012 \end{aligned}$$

$$\begin{aligned} S &= 0.731 \pm 0.035 \pm 0.020 \\ C = -A &= -0.038 \pm 0.032 \pm 0.005 \end{aligned}$$

So far we assumed that penguin pollution played a negligible role in these measurements: we cannot afford this luxury any longer...

ϕ_1/β – Penguin Pollution

- Penguin diagrams carrying different weak phases contribute to these decays and can shift the measured value of the phase by as much as 1°;



see e.g.
K. De Bruyn, R. Fleisher
JHEP **1503**, 145 (2015)

- Those contributions cannot be reliably computed by QCD;
- Need a coherent plan to constrain these effects experimentally, measuring weak phases of SU(3) or U-spin related decays:

$B_d \to J/\psi\, K^0$ $\quad$ $B_d \to J/\psi\, \pi^0$, $B_s \to J/\psi\, K^0$

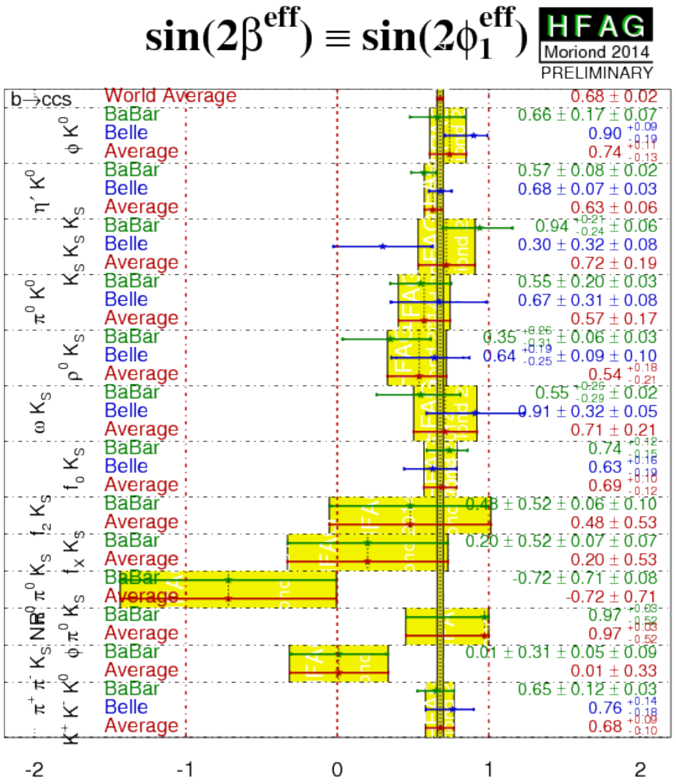
$B_s \to J/\psi\, \phi$ $\quad$ $B_s \to J/\psi\, K^{*0}$, $B_d \to J/\psi\, \rho^0$

Recent measurements from LHCb:
JHEP 1506, **131** (2015)
PLB 742, **38** (2015)

- Already got useful constraints, but need more precision;
- Strong interplay between LHCb and Belle II!

ϕ_1/β from Gluonic Penguins

- Measuring ϕ_1/β on modes dominated by gluonic penguins allows for the detection of NP effects;
- Despite the fact that now the averages look more consistent with SM than 10 years ago, this remains one of the best places to look for NP;
- As with the charmonium modes, it will be crucial to measure SU(3) related modes, to evaluate the impact of amplitudes carrying the “wrong” phase;
- On most channels Belle II will have best sensitivity and will be statistics limited.



evaluation of the sensitivity of Belle II in realistic MC simulation ongoing, to be included in the B2TiP report at the end of the year

ϕ_s at the LHC

- The “classic” Unitarity Triangle does not tell the whole story:

$\phi_s = -0.098 \pm 0.084 \pm 0.040$

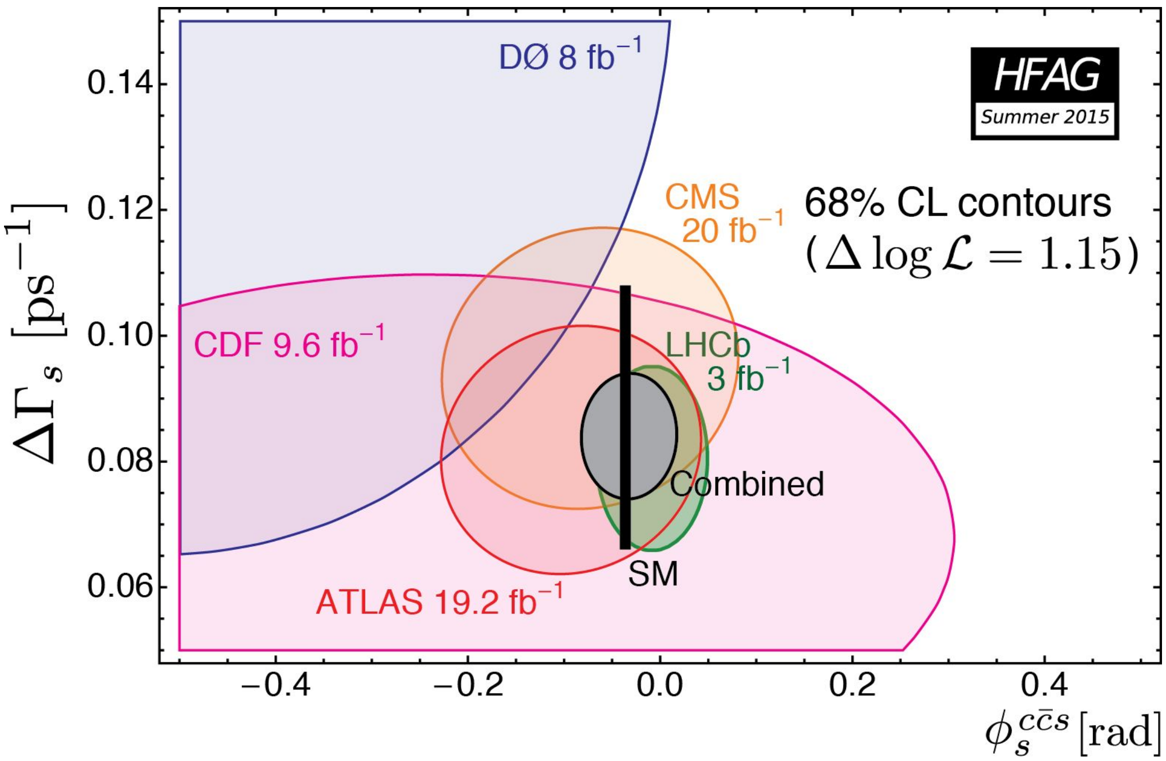
ATLAS Collaboration,
arXiv 1601.03297, submitted to JHEP

$\phi_s = -0.075 \pm 0.097 \pm 0.031$

CMS Collaboration,
arXiv 1507.07527, submitted to PLB

$\phi_s = -0.058 \pm 0.049 \pm 0.006$

LHCb Collaboration,
PRL 114, 041801 (2015)

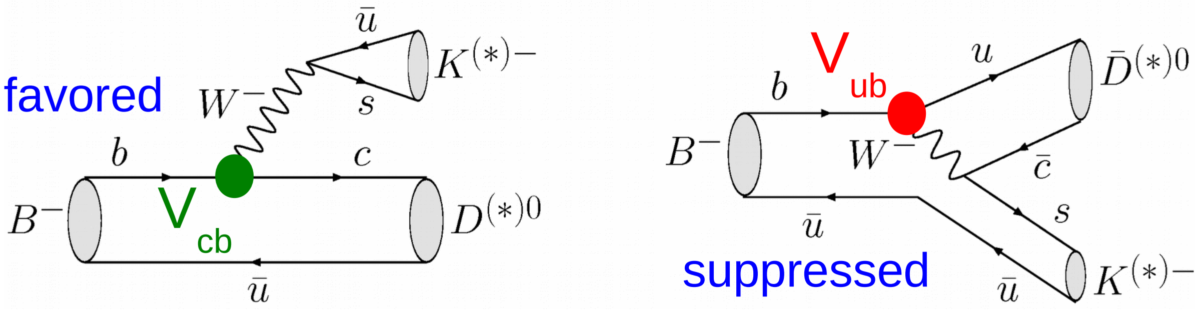


- No sign of discrepancy wrt SM… still quite some margin for improvement, given that the measurements are still statistics limited.

ϕ_3/γ status

- Methods exploiting the interference between tree level B → $DK^{(*)}$ amplitudes pioneered at the B-factories:

GLW - Phys. Lett. B**253**, 483 (1991)
ADS – Phys. Rev. D**63**, 036005 (2001)
GGSZ – Phys. Rev. D**68**, 054018 (2003)

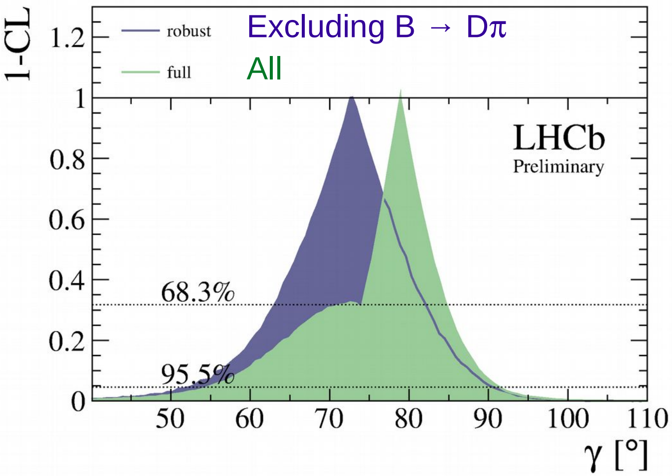


~11° uncertainty from the B-factories

- LHCb is now dominating the scene:

B decay	D decay	lumi	type
$B^\pm \to D\,h^\pm$	$D \to h\,h$	$1\,\text{fb}^{-1}$	GLW/ADS
$B^\pm \to D\,h^\pm$	$D \to K\,\pi\,\pi\,\pi$	$1\,\text{fb}^{-1}$	ADS
$B^\pm \to D\,K^\pm$	$D \to K_s K\,\pi$	$3\,\text{fb}^{-1}$	ADS
$B^\pm \to D\,K^\pm$	$D \to K_s h\,h$	$3\,\text{fb}^{-1}$	GGSZ
$B^0 \to D\,K^{\star 0}$	$D \to h\,h$	$3\,\text{fb}^{-1}$	GLW/ADS
$B^0_s \to D_s^\mp\,K^\pm$	$D \to h\,h\,h'$	$1\,\text{fb}^{-1}$	TD

LHCb-CONF-2014-004



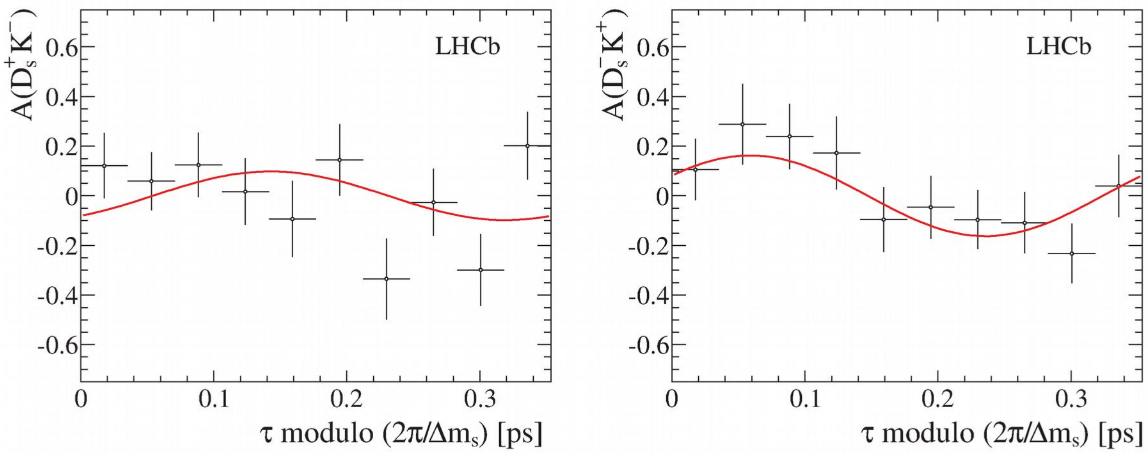
$$\gamma = (72.9^{+9.2}_{-9.9})^\circ$$

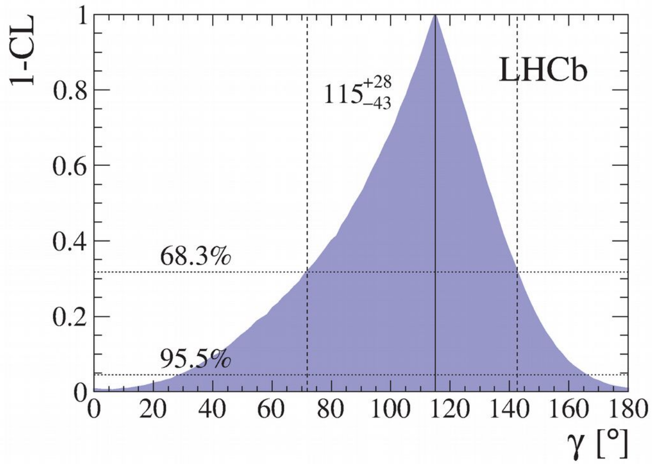
$$\gamma = (78.9^{+5.8}_{-7.4})^\circ$$

$$\gamma = (72.8^{+11.9}_{-1.3})^\circ$$

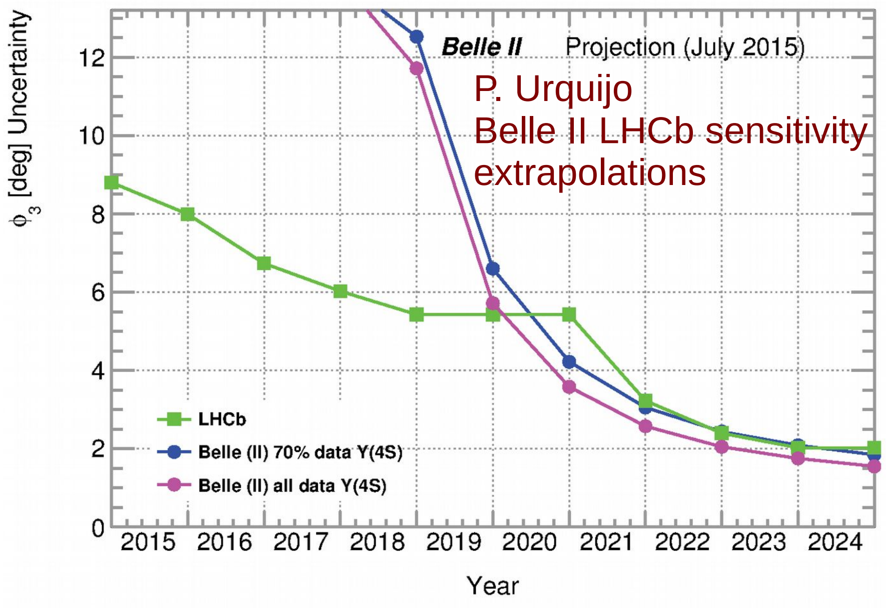
ϕ_3/γ outlook

- LHCb also measures it from time dependent $B_s \to D_s^{\mp}K^{\pm}$ decays:





LHCb Collaboration,
JHEP **1411**, 60 (2014)

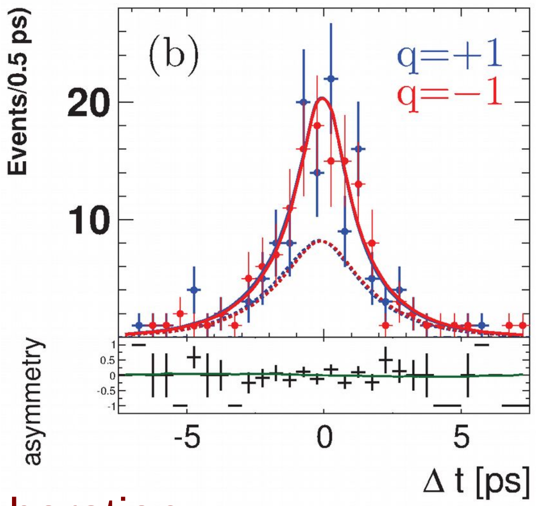


P. Urquijo
Belle II LHCb sensitivity extrapolations

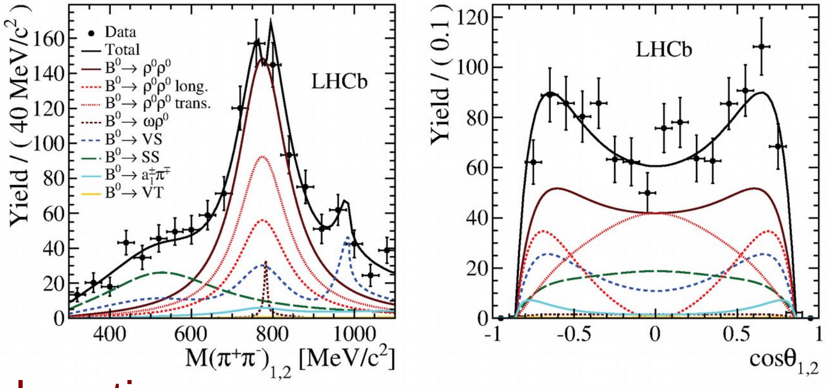
- Enormous progress expected in the next decade, the competition between LHCb and Belle II will be tight!

ϕ_2/α status

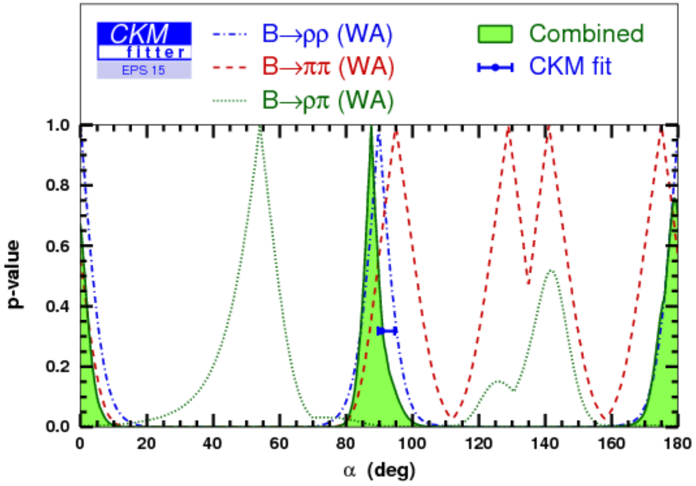
- Can be extracted in a way conceptually similar to ϕ_1/β from $B^0 \to \pi\pi$, $B^0 \to \rho\rho$, but sizable penguin pollution requires isospin analysis (and leads to ambiguities);



$B \to \rho^+\rho^-$
Belle Collaboration,
PRD **93** 032010 (2016)



$B \to \rho^0\rho^0$
LHCb Collaboration,
PLB **747** 468 (2015)

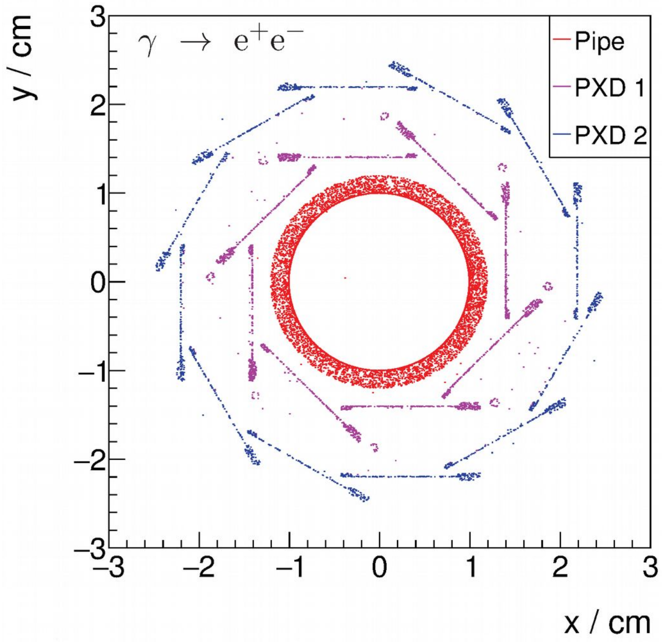


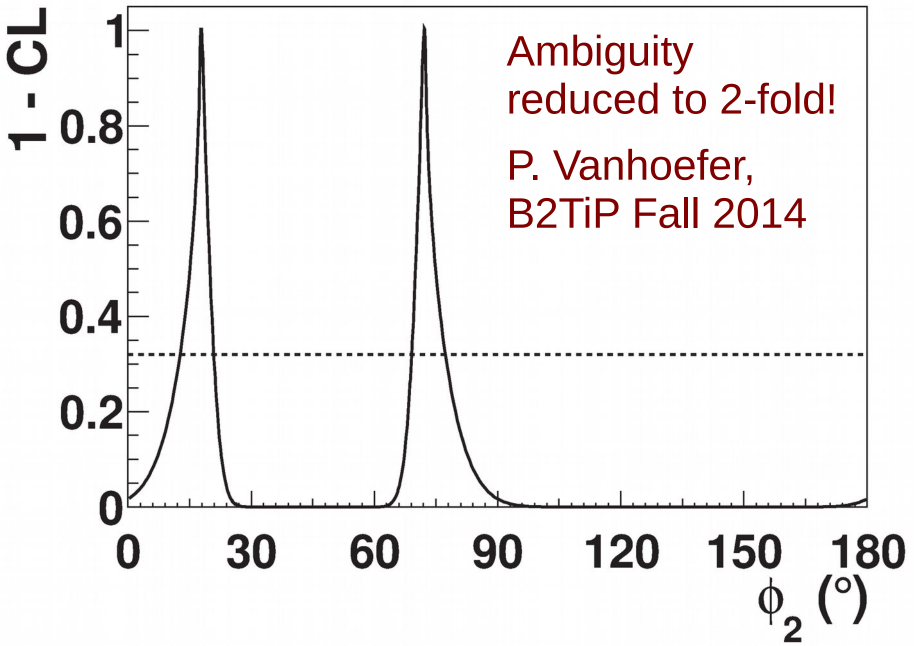
- Current precision ~8°;
- LHCb will dominate on $\rho^0\rho^0$, Belle II on $\rho^+\rho^-$, $\rho^+\rho^0$. Expected precision ~3° from both ππ and ρρ by the end of Belle II.

ϕ_2/α from TD $B^0 \to \pi^0\pi^0$

- Precision on ϕ_2/α from $B \to \pi\pi$ is limited by small $B^0 \to \pi^0\pi^0$ branching ratio and the fact that we could not measure the $S^{\pi0\pi0}$ parameter;
- A TD analysis, exploiting photon conversion and Dalitz decays can be attempted at Belle II (need high integrated luminosity and clean environment!);

F. Abudinen
B2TiP Fall 2015





Ambiguity
reduced to 2-fold!

P. Vanhoefer,
B2TiP Fall 2014

- Estimate of the sensitivity with 50 ab^{-1} currently in progress.

Conclusions

- B decays offer great opportunities to probe energy scales beyond the direct production capabilities of the LHC!
- A lot has been done in the recent past, still quite a bit of space for New Physics to show up;
- LHCb and Belle II will be complementary in many areas: a tighter cooperation between the two experiments (with theorists also) is desirable;
- While construction and commissioning is ongoing, Belle II is now studying its expected sensitivity on the key channels;
- B2TiP(*) report should be ready by the end of 2016;
- A few exciting years are ahead of us!

See S. Mishima's talk tomorrow

(*) Belle II Theory interface Platform

Backup Slides

Rare decays: $B_{d,s} \rightarrow \mu^+\mu^-$

Other leptonic branching fractions:

$BF(B_s \rightarrow \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$

$BF(B_d \rightarrow \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$

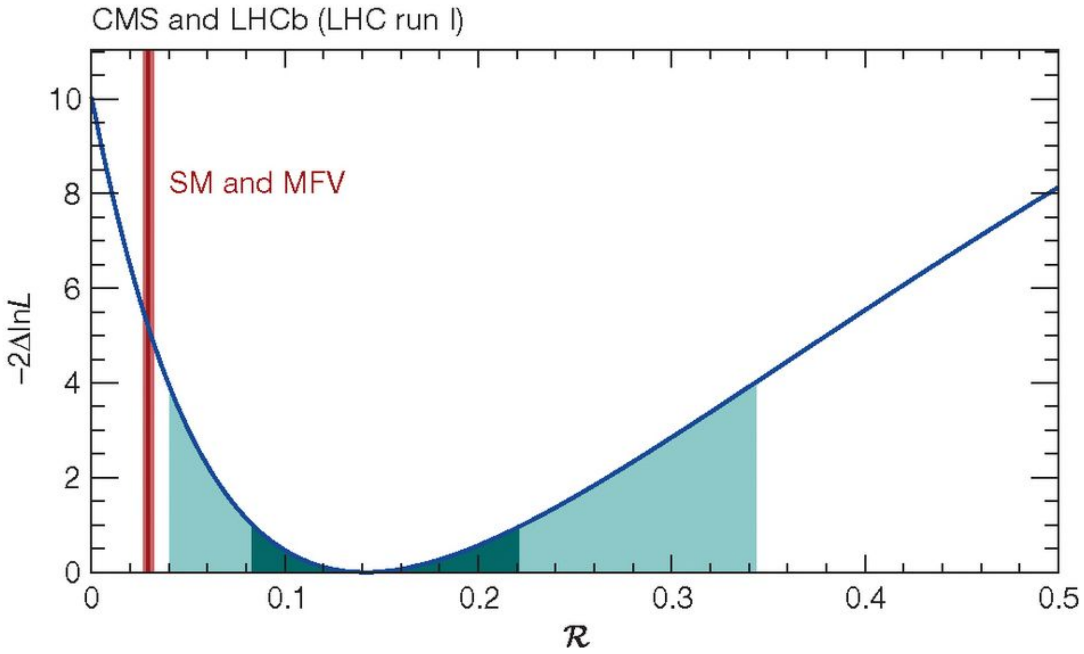
$BF(B_s \rightarrow e^+e^-) = (8.54 \pm 0.55) \times 10^{-14}$

$BF(B_d \rightarrow e^+e^-) = (2.48 \pm 0.21) \times 10^{-15}$

Bobeth et al.
PRL 112, 101801 (2014)

Likelihood scan for the ratio:

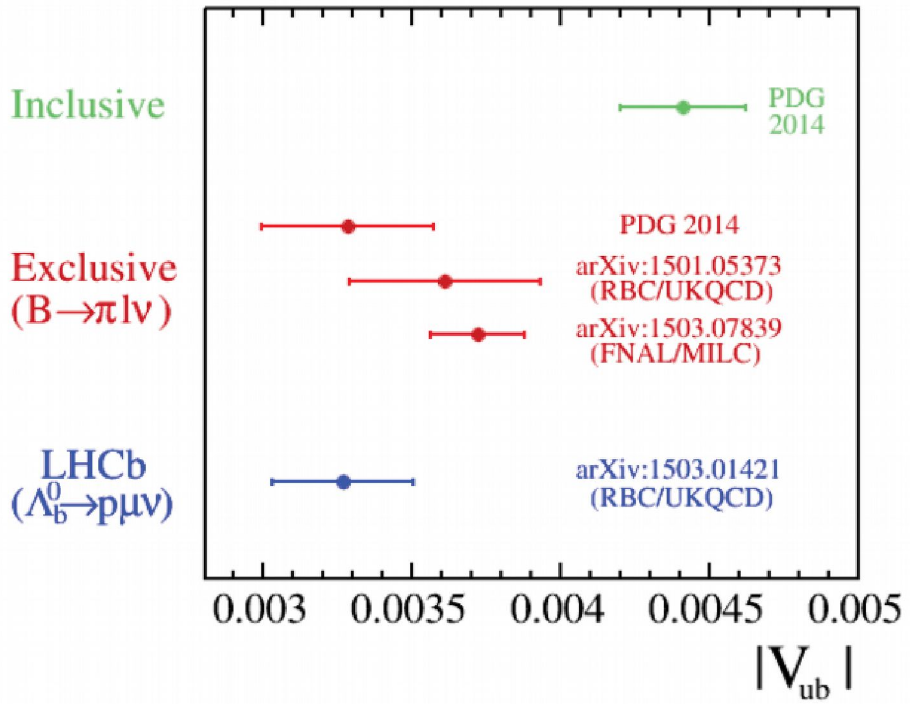
$$R = \frac{BF(B_d \rightarrow \mu^+\mu^-)}{BF(B_s \rightarrow \mu^+\mu^-)} = 0.14$$



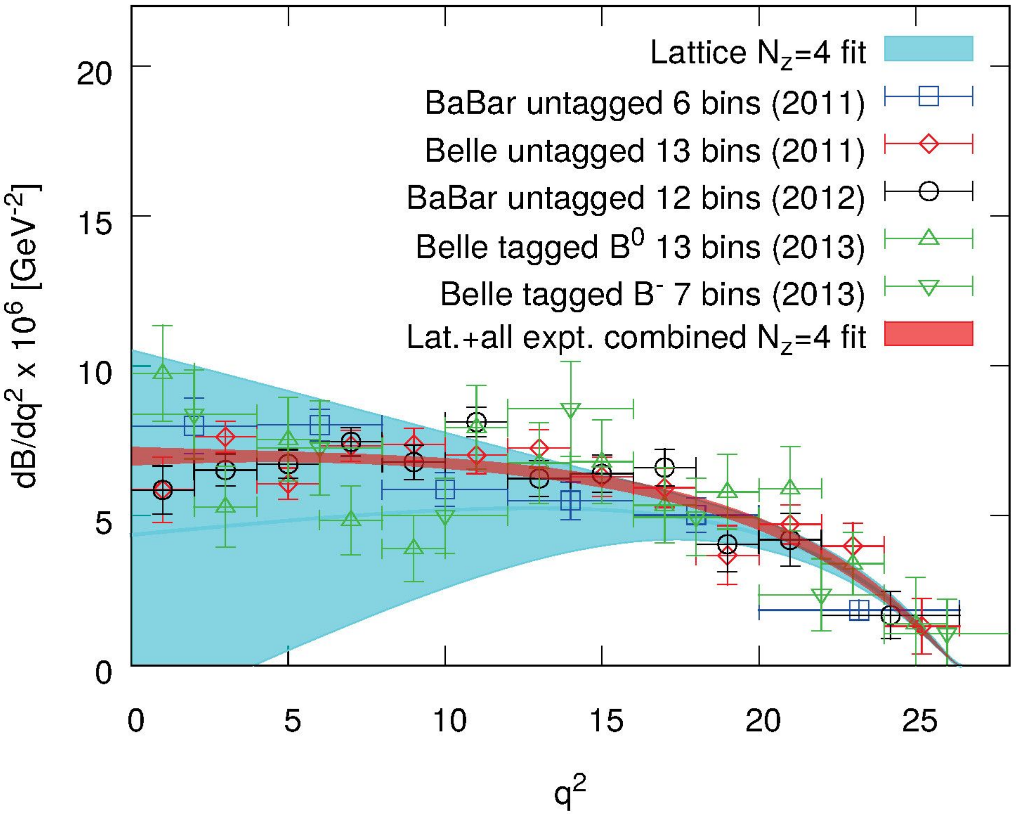
Semileptonic Decays

- Exclusive |V_{ub}| determination from $B \rightarrow \pi l \nu$ data (BaBar + Belle) from the FNAL/MILC Collaboration (2015):

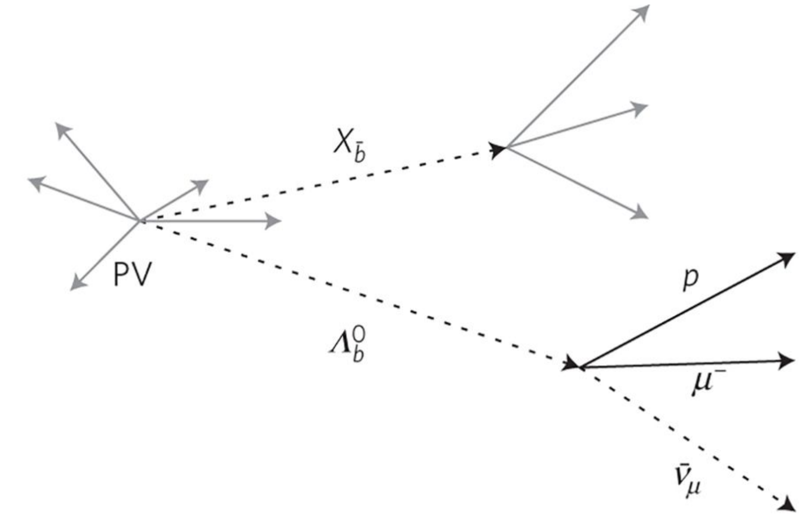
$$|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$$

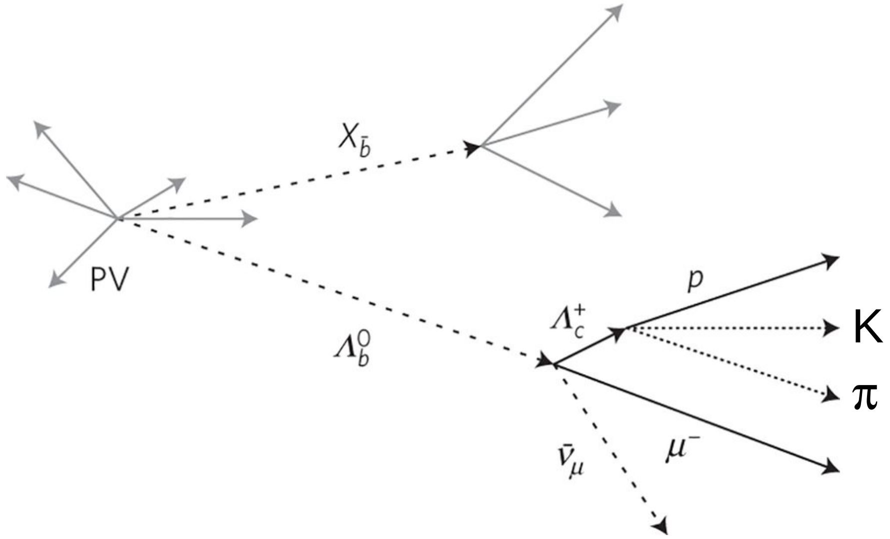


PRD **92**, 014024 (2015)



Semileptonic Decays





Corrected mass:

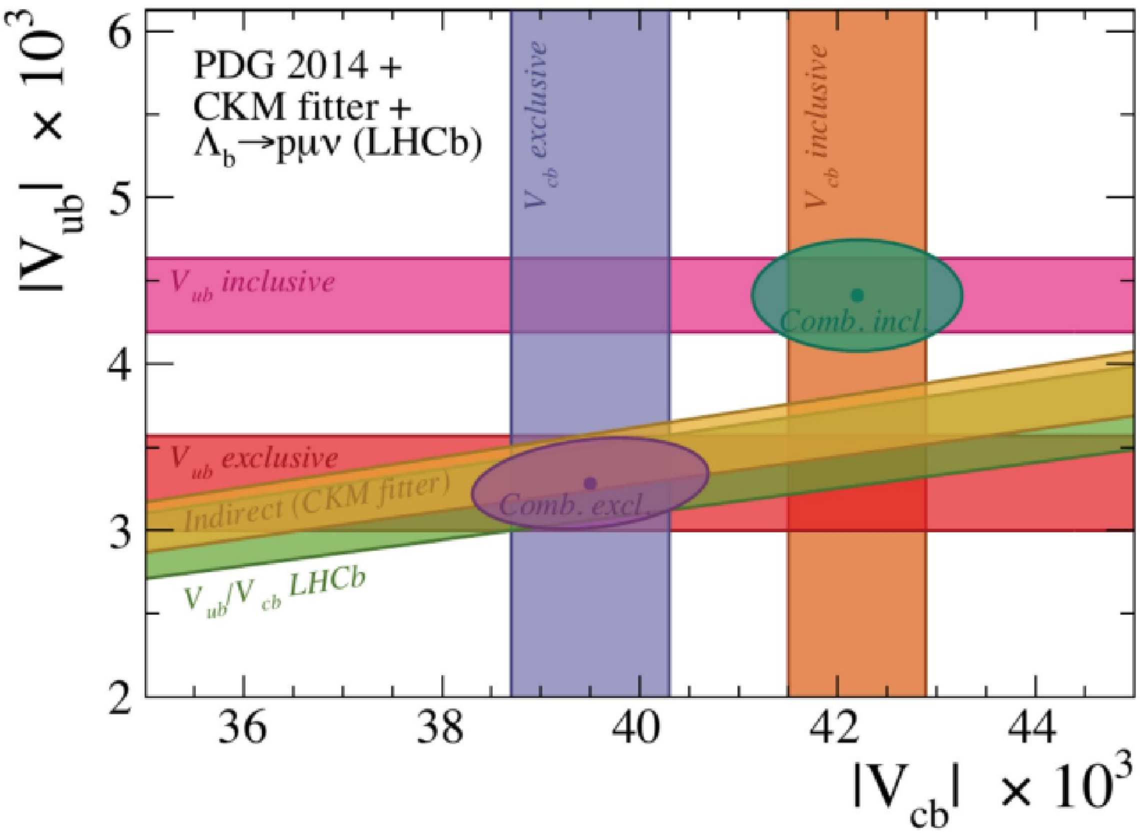
$$m_{\text{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$

$m_{h\mu}$: visible mass of the hμ pair

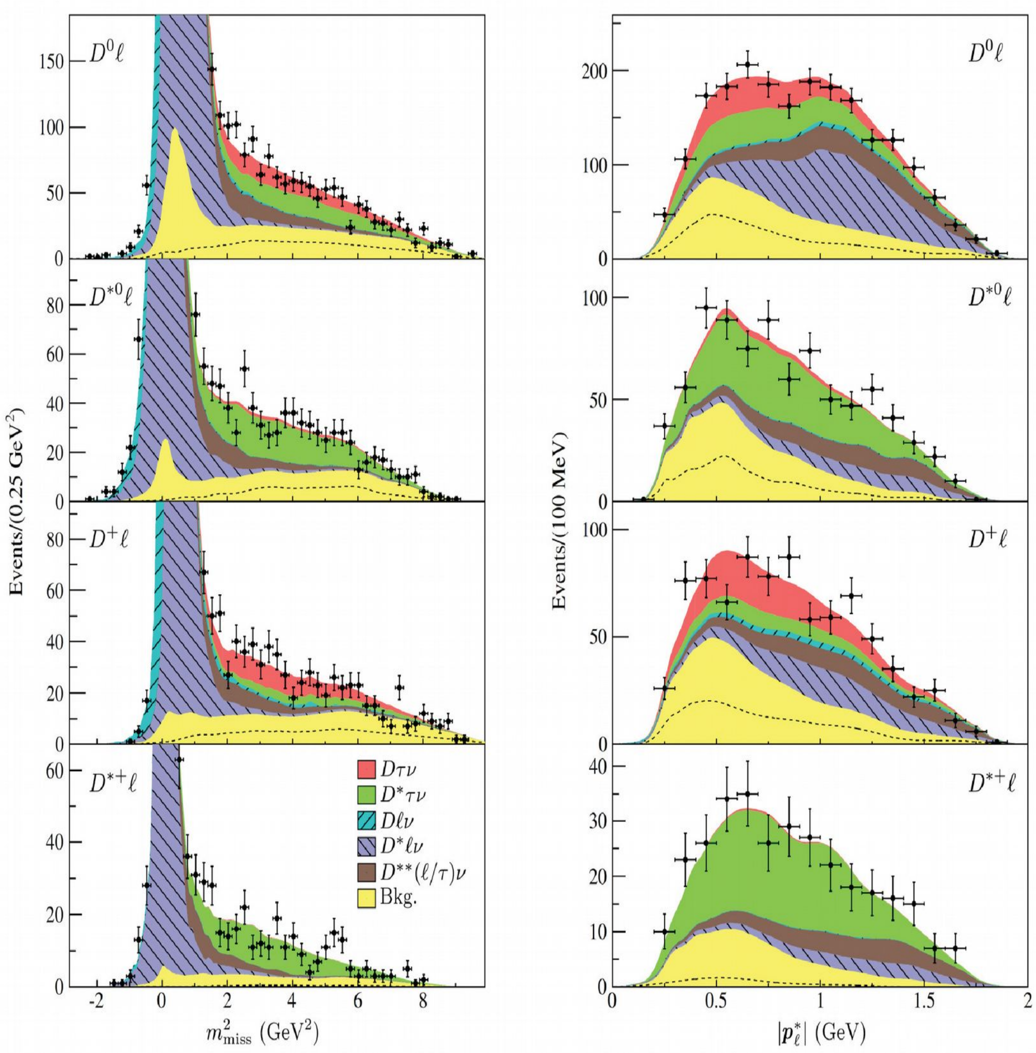
$p_\perp$: transverse momentum wrt the Λ_b flight direction (which is determined from the position of the decay vertex wrt the primary vertex)

Semileptonic Decays

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\exp) \pm 0.004(lattice)$$



$B \to D^{(*)}\tau\nu$



$$\mathcal{R}(D)_{\rm exp} = 0.440 \pm 0.072$$

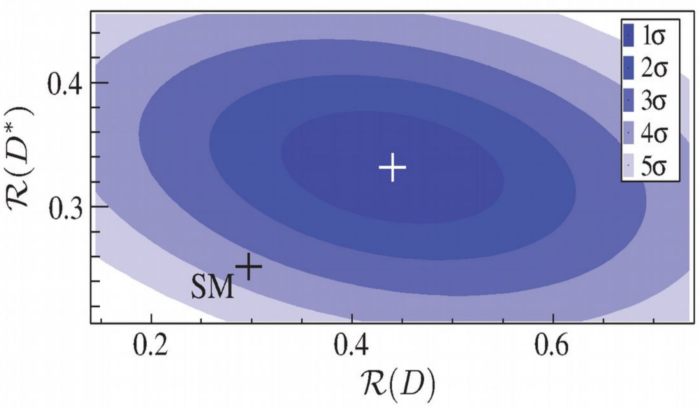
$$\mathcal{R}(D)_{\rm SM} = 0.297 \pm 0.017$$

2.0σ

$$\mathcal{R}(D^*)_{\rm exp} = 0.332 \pm 0.030$$

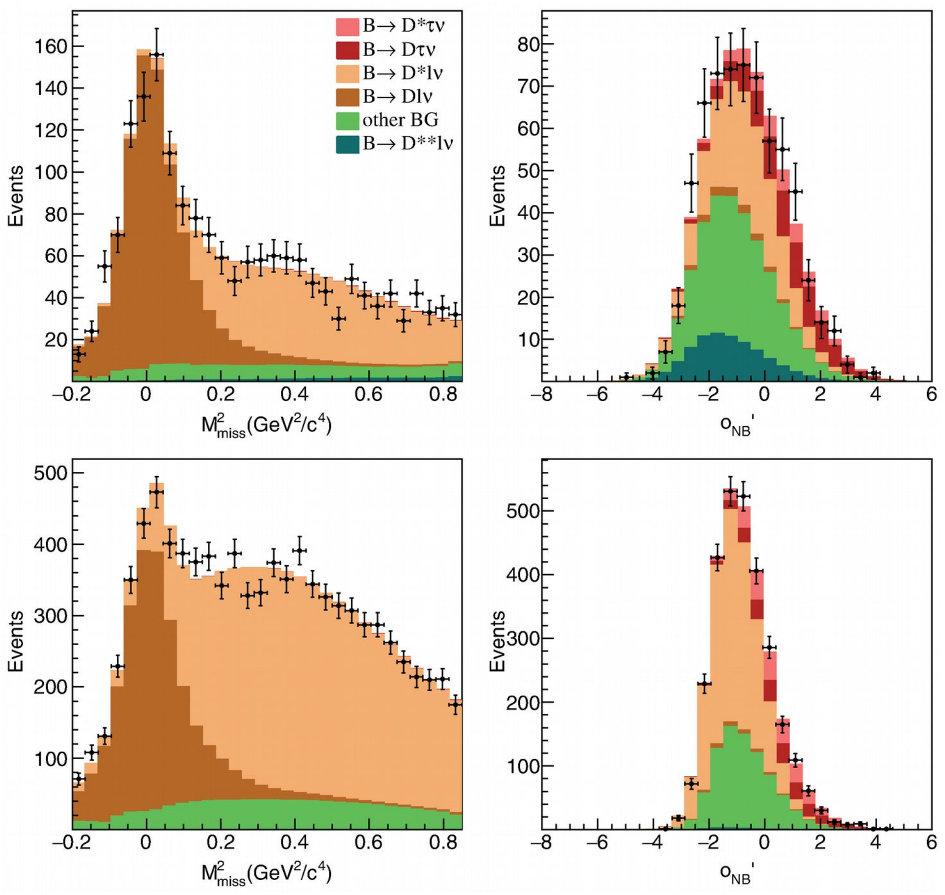
$$\mathcal{R}(D^*)_{\rm SM} = 0.252 \pm 0.003$$

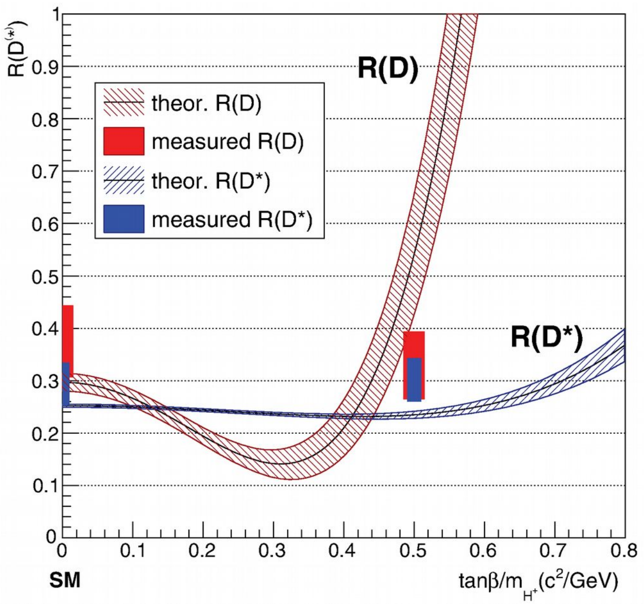
2.7σ

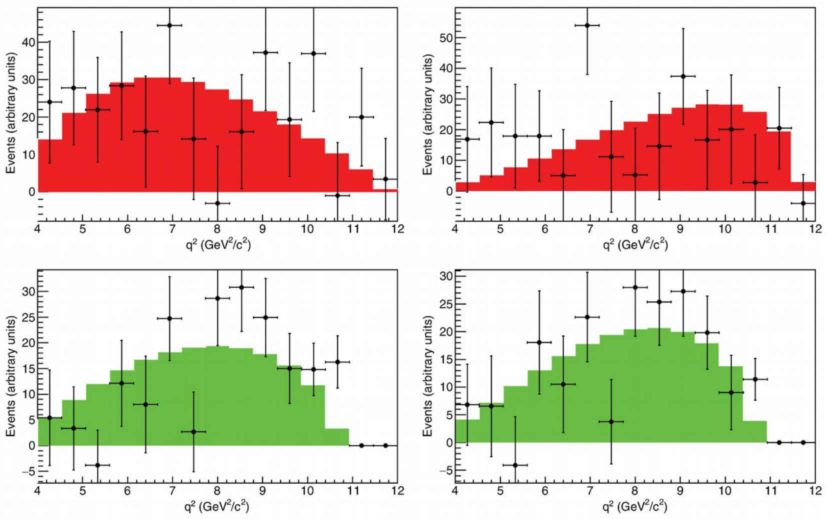


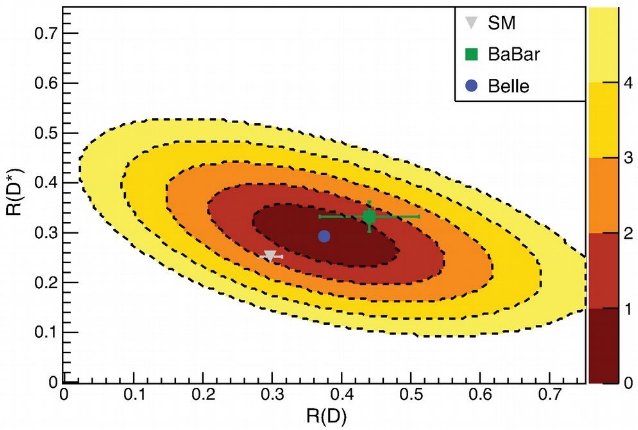
BaBar Collaboration,
PRD **88**, 072012 (2013)

$B \rightarrow D^{(*)}\tau\nu$



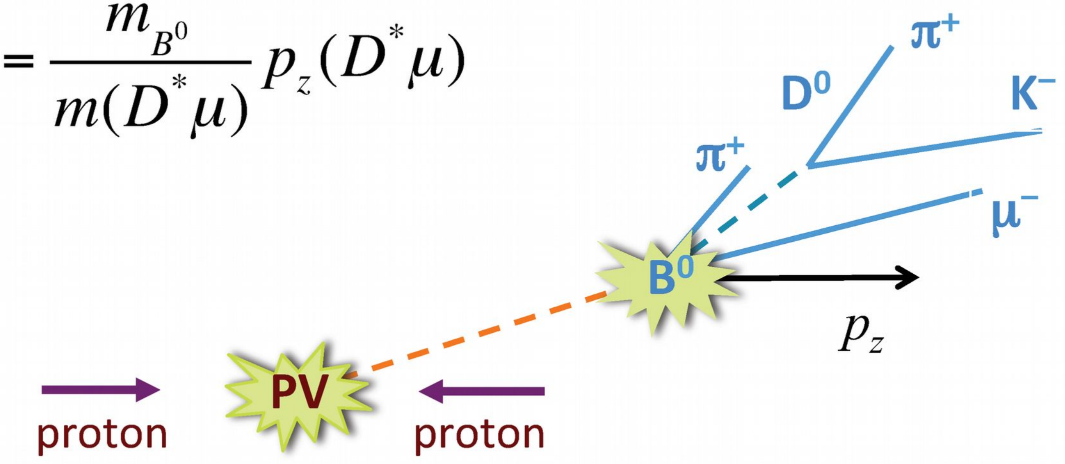




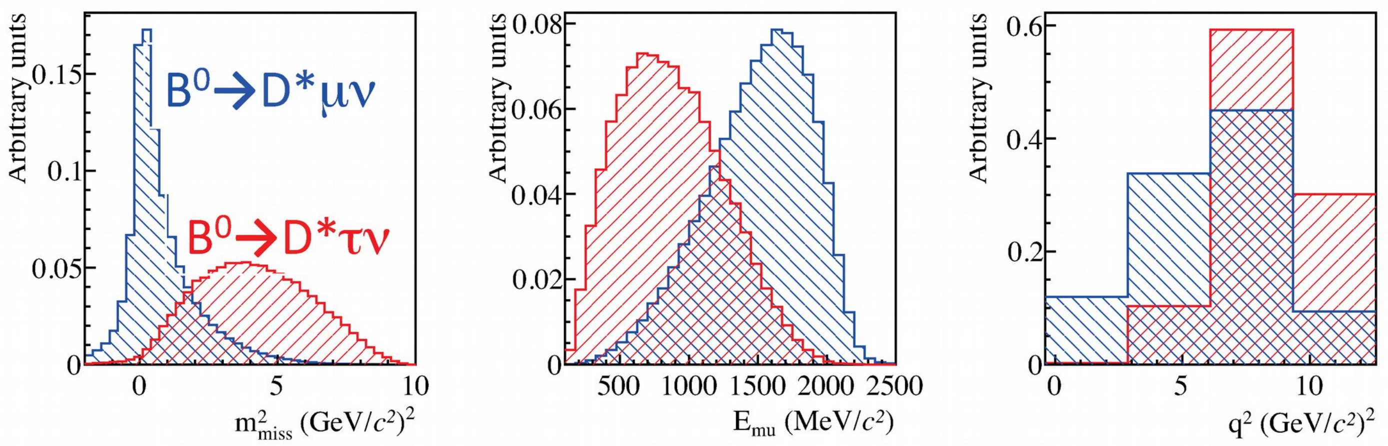


$B \to D^{(*)}\tau\nu$

$$p_z(B^0) = \frac{m_{B^0}}{m(D^*\mu)}\, p_z(D^*\mu)$$



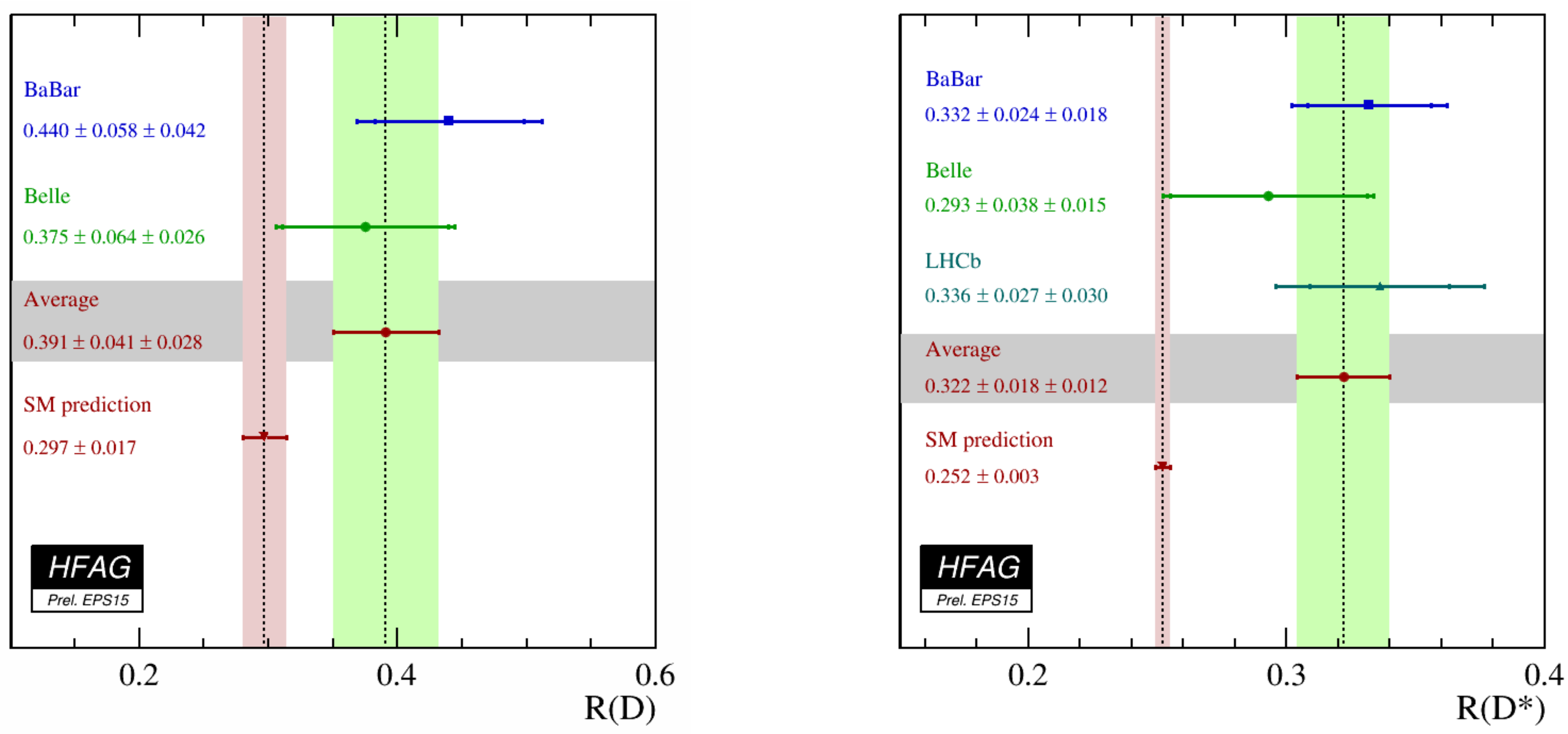
LHCb-TALK-2015-178



LHCb simulation

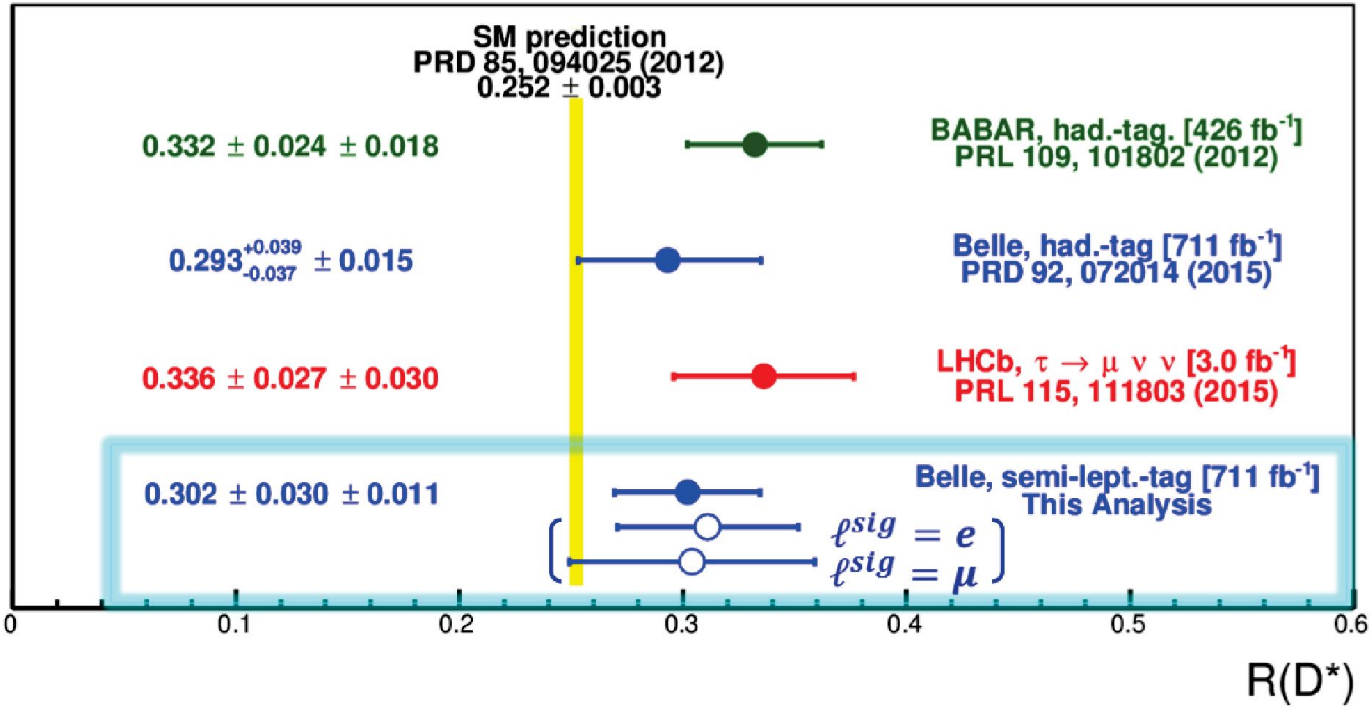
approximate B rest frame

$B \to D^{(*)}\tau\nu$


BaBar
0.440 ± 0.058 ± 0.042
Belle
0.375 ± 0.064 ± 0.026
Average
0.391 ± 0.041 ± 0.028
SM prediction
0.297 ± 0.017
HFAG
Prel. EPS15
0.2
0.4
0.6
R(D)
BaBar
0.332 ± 0.024 ± 0.018
Belle
0.293 ± 0.038 ± 0.015
LHCb
0.336 ± 0.027 ± 0.030
Average
0.322 ± 0.018 ± 0.012
SM prediction
0.252 ± 0.003
HFAG
Prel. EPS15
0.2
0.3
0.4
R(D*)

$B \to D^{(*)}\tau\nu$

$$\cos\theta_{B\text{-}D^*\ell} \equiv \frac{2E_{\mathrm{beam}}E_{D^*\ell} - M_B^2 - M_{D^*\ell}^2}{2|\vec{p}_B|\cdot|\vec{p}_{D^*\ell}|}$$



PRELIMINARY – from P. Goldenzweig @ Moriond EW 2016

Electroweak Penguins

- Definitions of main observables:

$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{\mathrm{d}^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

$$S_i = (I_i + \bar{I}_i) \bigg/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

$$A_i = (I_i - \bar{I}_i) \bigg/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

$I(q^2)$: q^2 dependent angular observables. They are expressed as a combination of 6 decay amplitudes (3 transversity states x 2 chirality states of the μμ system)

$$F_{\mathrm{L}} = S_{1c} = \frac{|\mathcal{A}_0^{\mathrm{L}}|^2 + |\mathcal{A}_0^{\mathrm{R}}|^2}{|\mathcal{A}_0^{\mathrm{L}}|^2 + |\mathcal{A}_0^{\mathrm{R}}|^2 + |\mathcal{A}_\parallel^{\mathrm{L}}|^2 + |\mathcal{A}_\parallel^{\mathrm{R}}|^2 + |\mathcal{A}_\perp^{\mathrm{L}}|^2 + |\mathcal{A}_\perp^{\mathrm{R}}|^2}$$

$$P_1 = \frac{2\,S_3}{(1 - F_{\mathrm{L}})} = A_{\mathrm{T}}^{(2)}$$

$$P_2 = \frac{2}{3}\frac{A_{\mathrm{FB}}}{(1 - F_{\mathrm{L}})}$$

$$P_3 = \frac{-S_9}{(1 - F_{\mathrm{L}})}$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}}$$

$$P'_6 = \frac{S_7}{\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}}$$

Electroweak Penguins: A_{FB}

$$\mathcal{A}_{\mathrm{FB}}(q^2_{\mathrm{min}}, q^2_{\mathrm{max}}) = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} dq^2 \int_{-1}^{1} d\cos\theta \, \mathrm{sgn}(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta}}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} dq^2 \int_{-1}^{1} d\cos\theta \frac{d^2\Gamma}{dq^2 d\cos\theta}}$$

θ : angle between the l^+ (l^-) momentum and the $\overline{B}$ (B) momentum in the l^+l^- rest frame

ϕ_3/γ determinations

Decay amplitudes:

$$A(B^+) \quad = \quad \Big[(\bar{D}^0 K^+) \; + \; r_b e^{+\,i\gamma\,+\,i\delta_b}(D^0 K^+)\Big]$$

Weak phase changes sign

Strong phase (measured from the data) stays the same

$$A(B^-) \quad = \quad \Big[(D^0 K^-) \; + r_b\, e^{-\,i\gamma\,+\,i\delta_b}(\bar{D}^0 K^+)\Big]$$

ϕ_3/γ : ADS method

- Select events where the (anti)D^0 from the favored amplitude decays to a DCS final state (and the (anti)D^0 from the suppressed amplitude decays to the same Cabibbo favored final state):

$$B^+ \;\to\; \overset{(-)}{D}{}^0\,K^+,\ \overset{(-)}{D}{}^0 \to K^-\pi^+$$

$$B^- \;\to\; \overset{(-)}{D}{}^0\,K^-,\ \overset{(-)}{D}{}^0 \to K^+\pi^-$$

- We define the two observables…

$$\mathcal{R}_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^{*-}) + \Gamma(B^+ \to [K^-\pi^+]_D K^{*+})}{\Gamma(B^- \to [K^-\pi^+]_D K^{*-}) + \Gamma(B^+ \to [K^+\pi^-]_D K^{*+})}$$

$$\mathcal{A}_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^{*-}) - \Gamma(B^+ \to [K^-\pi^+]_D K^{*+})}{\Gamma(B^- \to [K^+\pi^-]_D K^{*-}) + \Gamma(B^+ \to [K^-\pi^+]_D K^{*+})}$$

…related to γ:

$$\mathcal{R}_{ADS} = r_D^2 + r_B^2 + 2 r_D r_B \cos(\delta_B + \delta_D)\cos\gamma,$$
$$\mathcal{A}_{ADS} = 2 r_D r_B \sin(\delta_B + \delta_D)\sin\gamma/\mathcal{R}_{ADS}.$$

$$r_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right|$$

δ_D: strong phase difference between the above amplitudes (provided by CLEO)

ϕ_3/γ : GLW method

- Both D^0 and $\bar{D}^0$ decay to the same CP eigenstate;
- The four (only three independent) GLW observables are:

$$\mathcal{R}_{CP\pm} = 2\frac{\Gamma(B^- \to D^0_{CP\pm} K^{*-}) + \Gamma(B^+ \to D^0_{CP\pm} K^{*+})}{\Gamma(B^- \to D^0_{K\pi} K^{*-}) + \Gamma(B^+ \to \overline{D}^0_{K\pi} K^{*+})}$$

$$\mathcal{A}_{CP\pm} = \frac{\Gamma(B^- \to D^0_{CP\pm} K^{*-}) - \Gamma(B^+ \to D^0_{CP\pm} K^{*+})}{\Gamma(B^- \to D^0_{CP\pm} K^{*-}) + \Gamma(B^+ \to D^0_{CP\pm} K^{*+})}$$

- They are sensitive to *g* through:

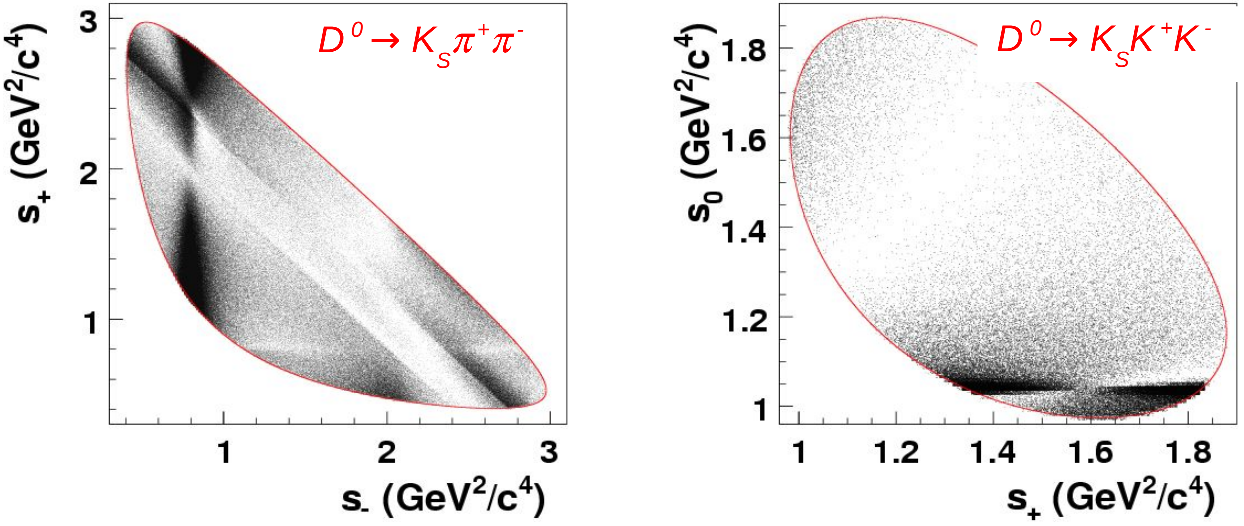
$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma$$

$$\mathcal{A}_{CP\pm} = \pm 2 r_B \sin\delta_B \sin\gamma / \mathcal{R}_{CP\pm}$$

no need of external inputs

ϕ_3/γ : GGSZ method

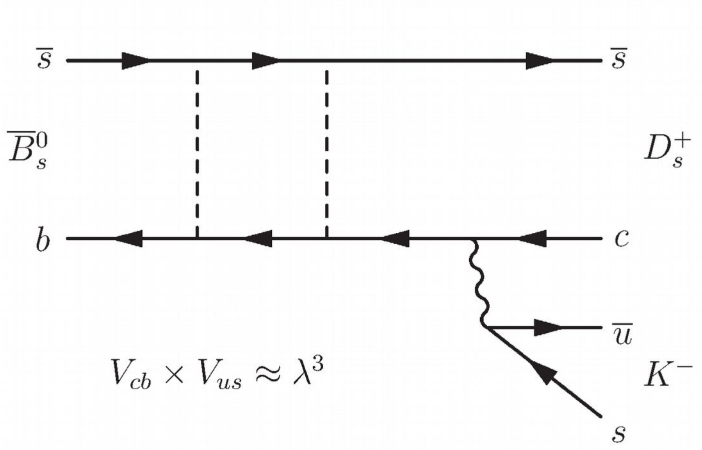
- Dalitz plot analysis: exploit the variation of the strong phase across the DP to increase sensitivity on γ;

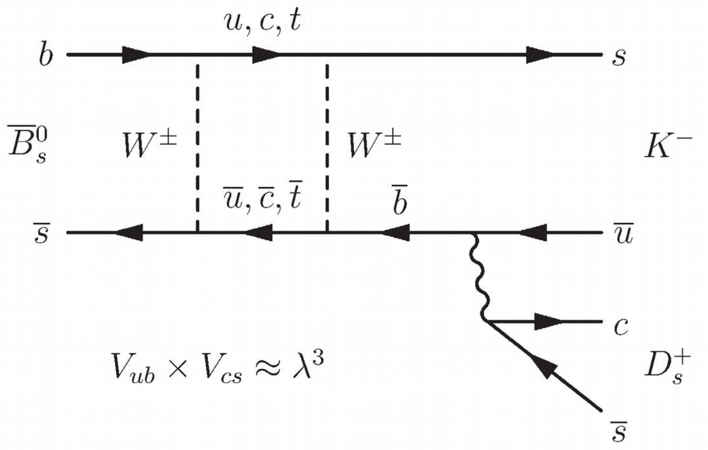


$$\boxed{\Gamma^{(*)}_{\mp}(s_-, s_+) \propto |\mathcal{A}_{\mp}|^2 + r_B^{(*)\,2}|\mathcal{A}_{\pm}|^2 + 2\lambda z^{(*)}_{\mp} A_{\mp}A^*_{\pm}}$$

$$z^{(*)}_{\mp} = r^{(*)}_{B\mp}\ e^{i(\delta_B^{(*)} \mp \gamma)}$$

ϕ_3/γ : from TD $B_s \rightarrow D_s^{\mp}K^{\pm}$





$$\frac{\mathrm{d}\Gamma_{B_s^0 \to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. + C_f\cos(\Delta m_s t) - S_f\sin(\Delta m_s t)\right]$$

$$\frac{\mathrm{d}\Gamma_{\overline{B}_s^0 \to f}(t)}{\mathrm{d}t} = \frac{1}{2}|A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. - C_f\cos(\Delta m_s t) + S_f\sin(\Delta m_s t)\right]$$

$$C_f = \frac{1 - r_{D_sK}^2}{1 + r_{D_sK}^2}$$

$$A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \qquad A_{\overline{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$

$$S_f = \frac{2r_{D_sK}\sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_sK}^2} \qquad S_{\overline{f}} = \frac{-2r_{D_sK}\sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}$$