Physics Prospects at SuperKEKB / Belle II

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The 3rd KMI International Symposium
on "Quest for the Origin of Particles and the Universe"
(KMI2017)
Nagoya (Japan) January 5th-7th 2017

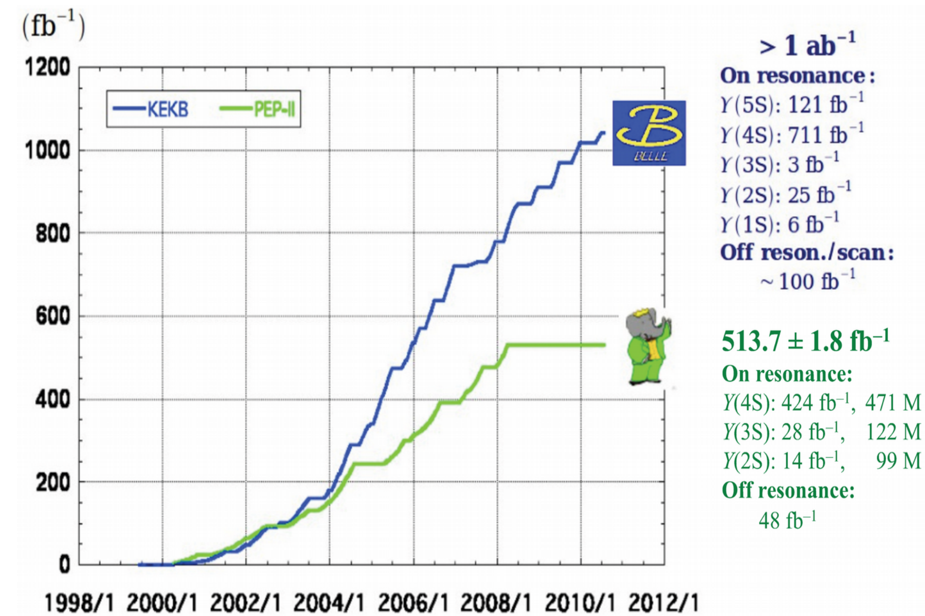
The B-factories heritage

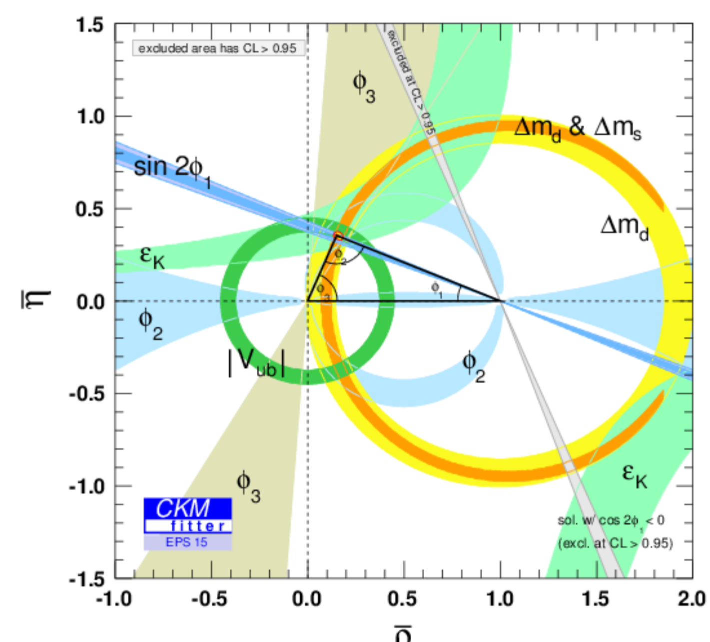
The B-factories operated for about a decade colliding e^+e^- at (or close to) the energy of the Y(4s) resonance;

Achievements (in > 1000 papers):

- Discovery of CP violation in B decays;
- Spectacular confirmation of the CKM paradigm of Flavor Physics;
- Discovery of several new particles;
- Stringent limits on New Physics scenarios;
- …

The SM is very healthy, but some intriguing tensions are there…





Searching for New Physics

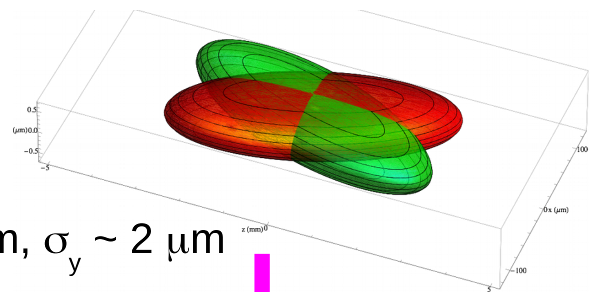
- Belle II: continue on the path set by the B-factories;
- Complementary strategy to LHC direct searches:
  - ➔ measure observables that can be predicted with small theoretical uncertainties: a significant discrepancy would be a clear sign of New Physics!
  - ➔ if New Physics particles are observed at the LHC, Belle II would be in a strong position to determine the flavor structure and weak phases of the New Physics;
- Exploit the clean environment and constrained kinematics to measure final states containing neutrals (π^0, $\eta^{(\prime)}$, K^0_L, …) and neutrinos;

Key to success: increase dataset size by ~2 orders of magnitude!

From KEKB to SuperKEKB

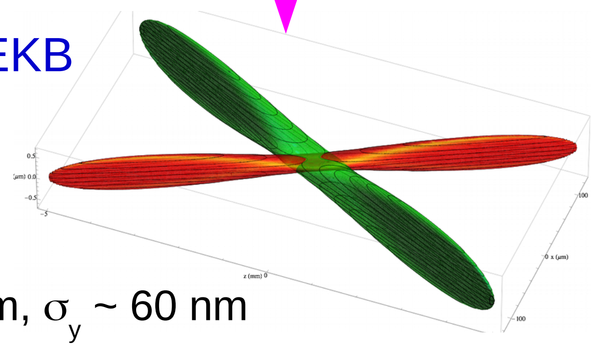
Crucial ingredient: nanobeams!

KEKB

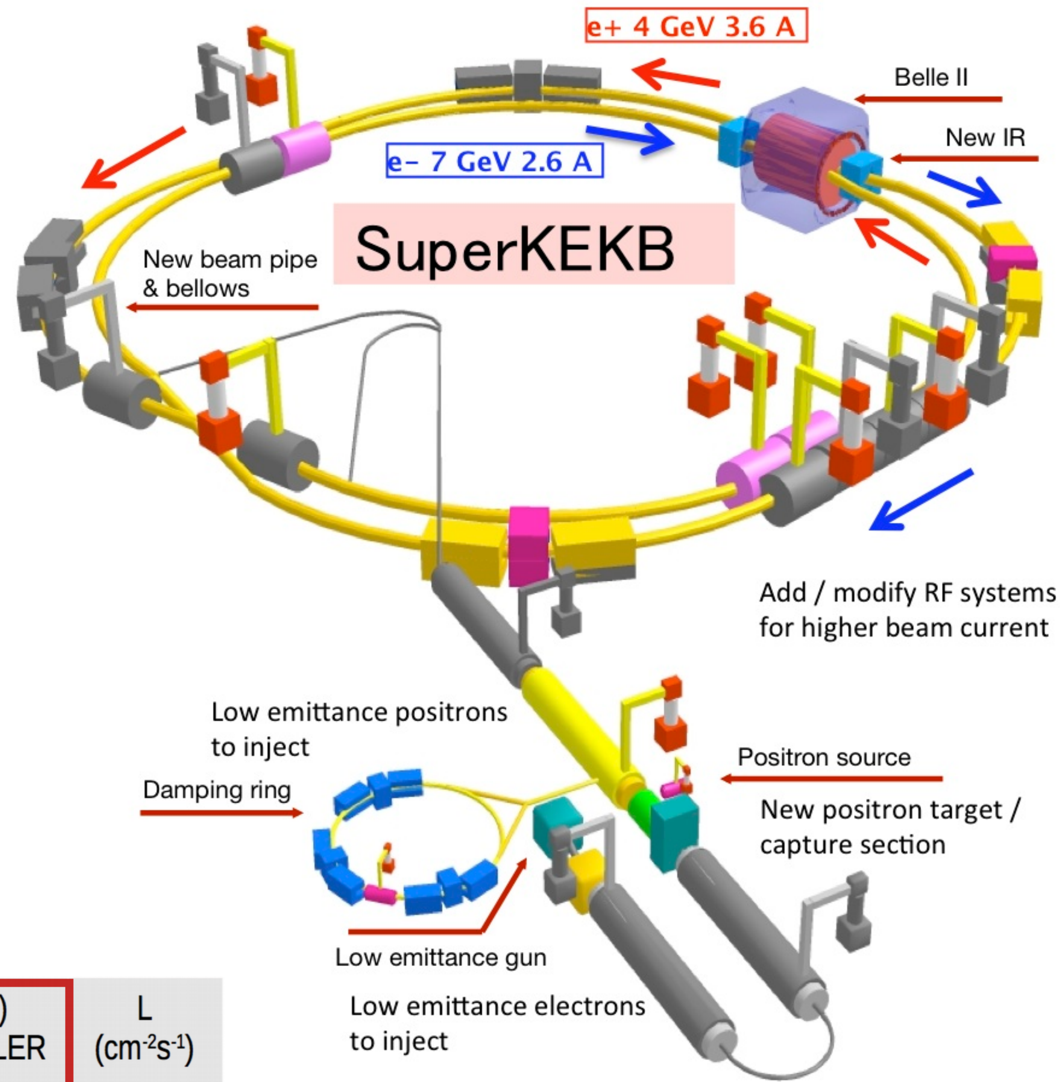


σ_x ~100 μm, σ_y ~ 2 μm

SuperKEKB



σ_x ~10 μm, σ_y ~ 60 nm

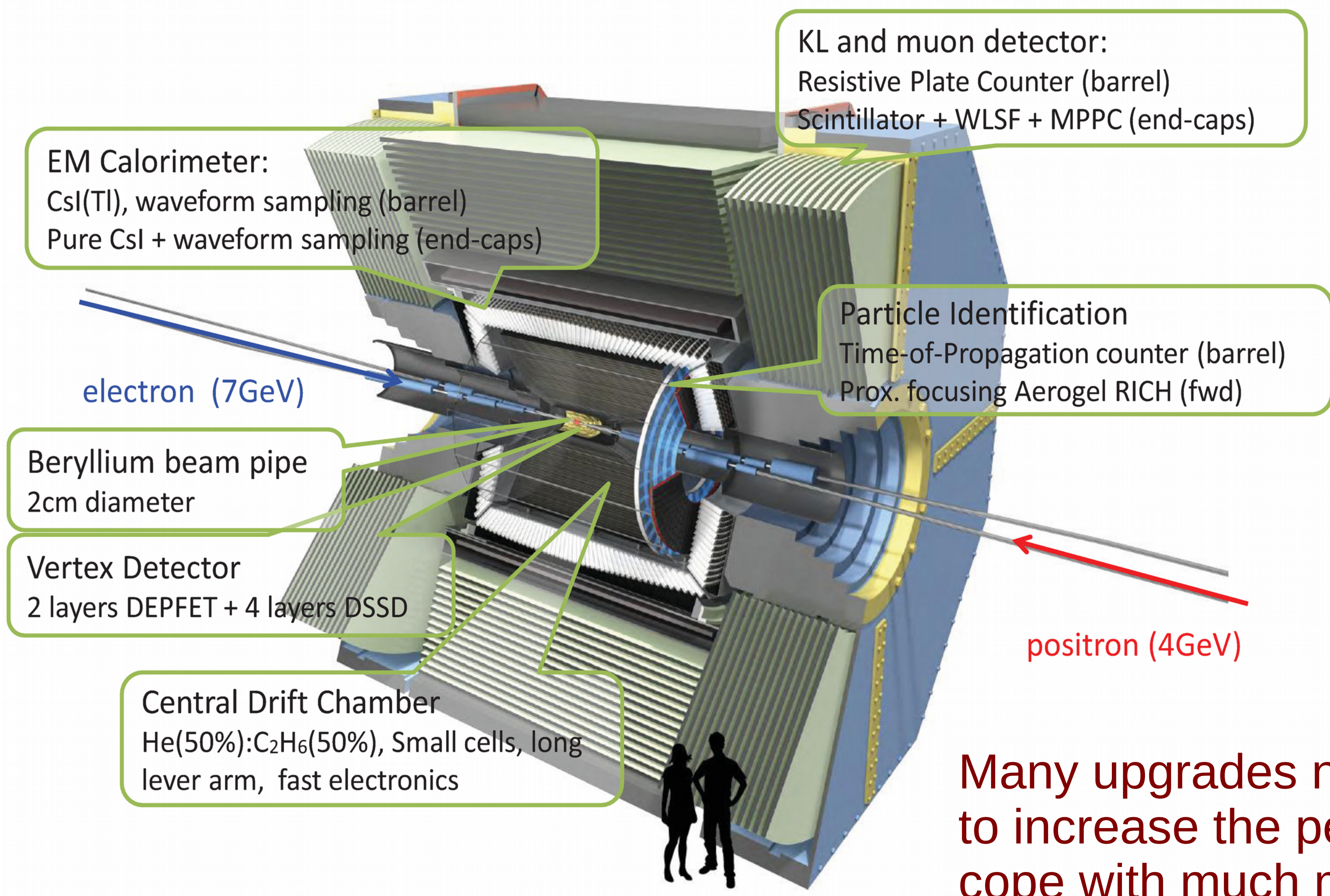


	E(GEV) HER/LER	β^*_y(mm) HER/LER	β^*_x(mm) HER/LER	2φ (mrad)	I(A) HER/LER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	22	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	83	3.6/2.6	80×10^{34}

x40 increase in instantaneous luminosity

The Belle II Detector

Structure from the old Belle... practically a brand new detector!



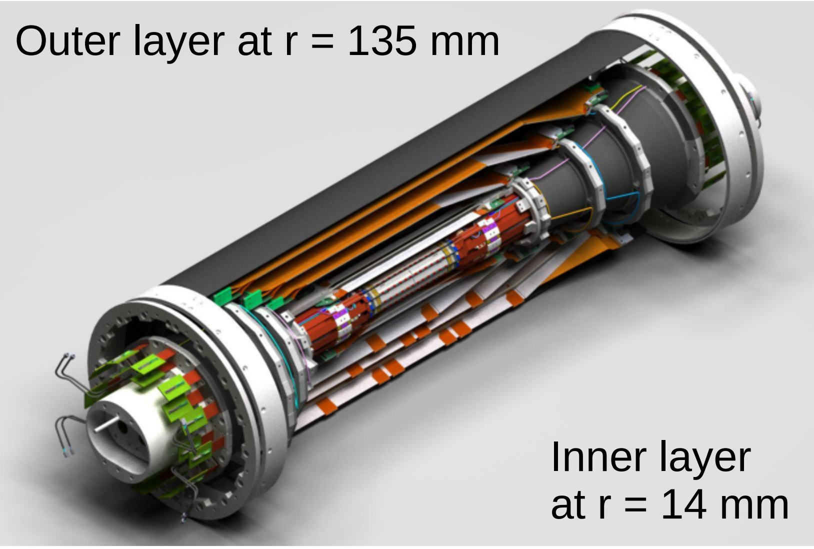
Many upgrades needed in order to increase the performance and cope with much more severe background conditions

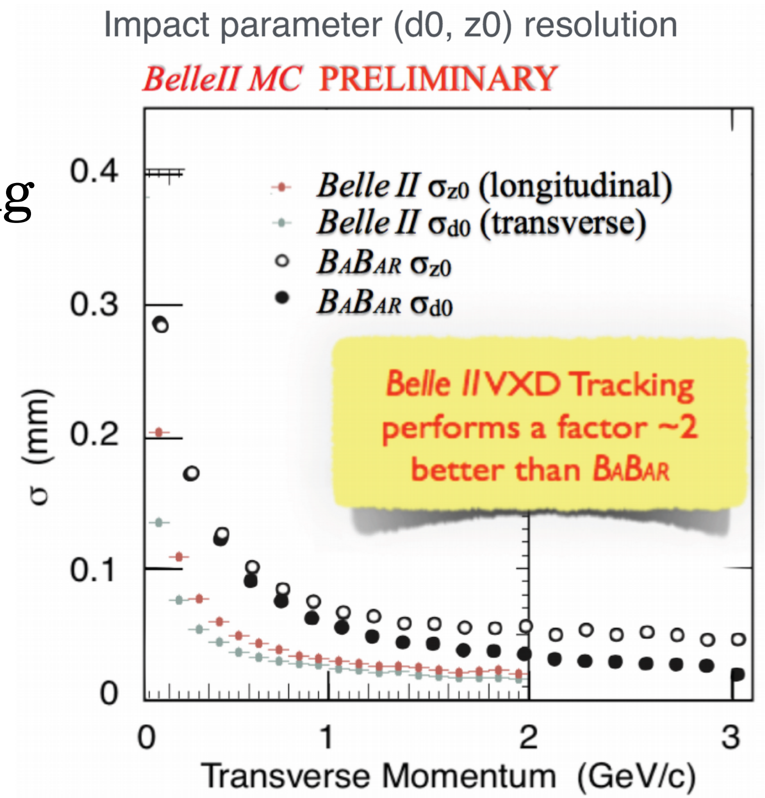
The Belle II Detector - highlights

Improvement in performance especially in two areas:

1) Tracking and vertexing:

new (and bigger) silicon vertex tracker using both pixel (PXD) and strips (SVD) sensors

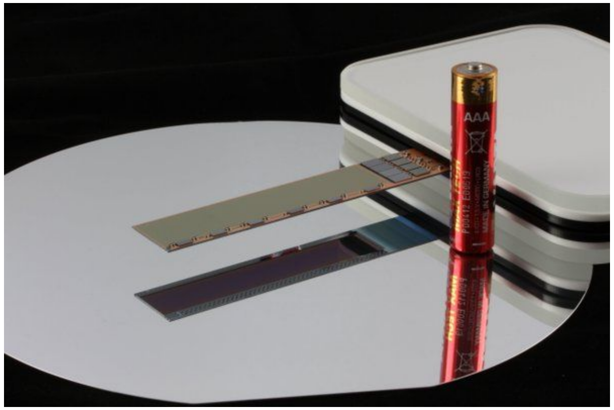




2) Particle Identification:

please see K. Matsuoka's talk on Friday

First built PXD module



The Physics Program

We plan to collect 50 ab^{-1} of e^+e^- collisions at (or close to) the Y(4s) resonance, so that we have:

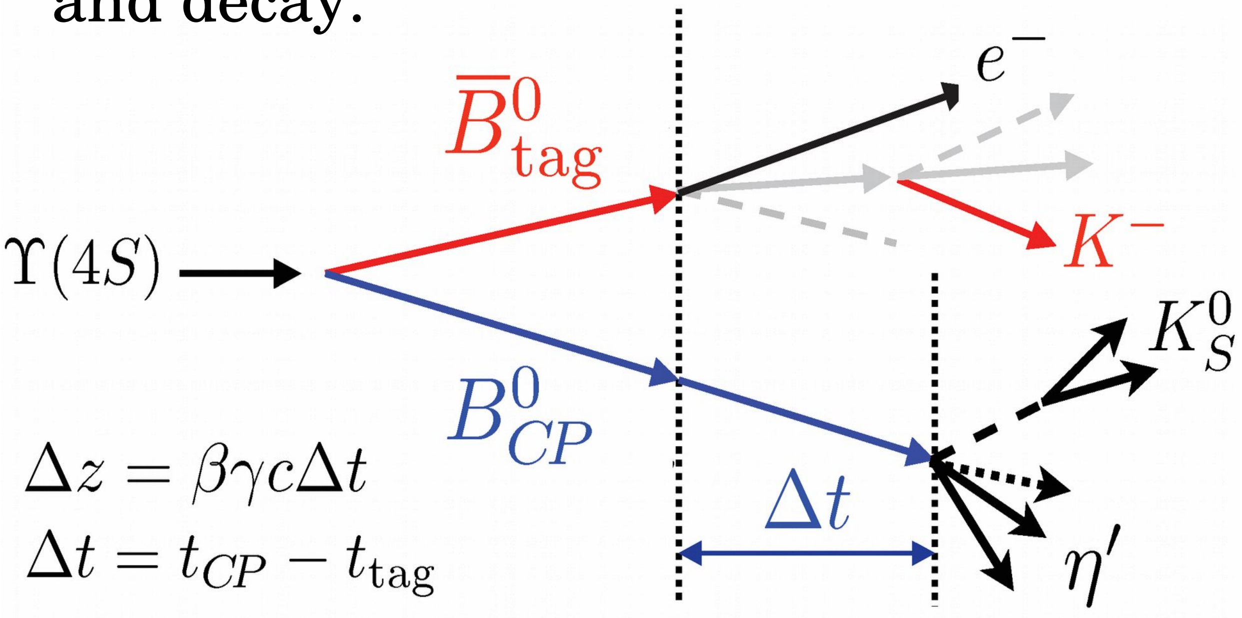
- a (Super) B-factory (~1.1 x 10^9 $B\overline{B}$ pairs per ab^{-1});
- a (Super) charm factory (~1.3 x 10^9 $c\overline{c}$ pairs per ab^{-1});
- a (Super) τ factory (~0.9 x 10^9 $\tau^+\tau^-$ pairs per ab^{-1});
- thanks to the Initial State Radiation, we can effectively scan the range [0.5 – 10] GeV and measure the $e^+e^- \rightarrow$ light hadrons cross-section very precisely;
- finally we can exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, …

I will give highlights on some of the processes that will be studied at Belle II.
This reflects (also) my personal tastes, apologies if I am neglecting your favorite topic!

B Physics

Time Dependent CP Violation

- Flagship measurements of the B-factories: access the weak phase of the CKM Matrix by exploiting the interference between mixing and decay:



All aspects of the experiment crucially important:

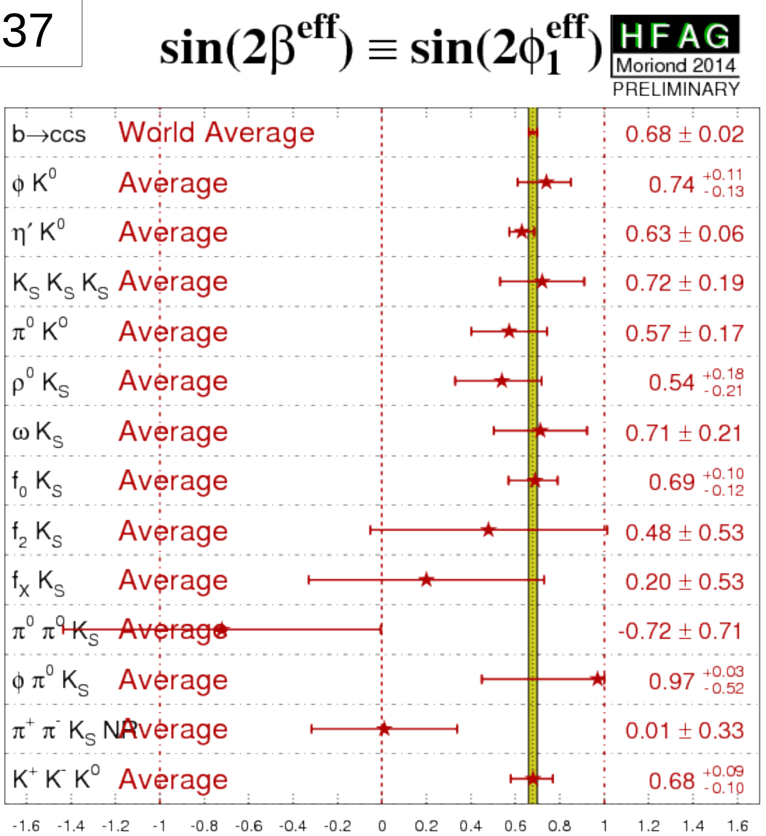
- tracking efficiency;
- neutrals reconstruction;
- vertexing;
- PID;
- B Flavor Tagging;
- background rejection;
- …

- Significant improvements over the previous generation of experiments:
  - Δt resolution ~0.77 ps (30% to a factor 2 better compared to Belle);
  - effective flavor tagging efficiency ~35.8% (was 30.1% at Belle).

Time Dependent CP Violation

- The measurement of $\sin 2\phi_1$ from $B \to c\bar{c} K^0$ with the full dataset will be dominated by systematic uncertainties:

	Belle	Belle II (50 ab^{-1})
S	0.667 ± 0.023 ± 0.012	x.xxxx ± 0.0027 ± 0.0044
A	0.006 ± 0.016 ± 0.012	x.xxxx ± 0.0033 ± 0.0037

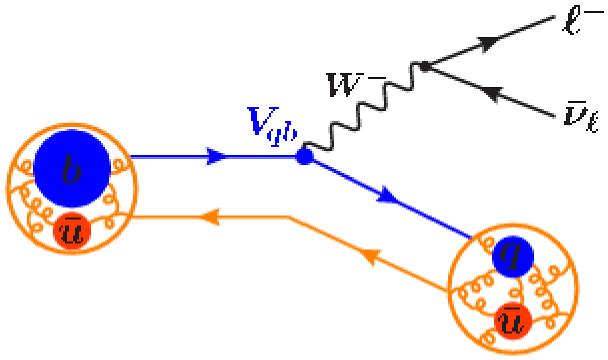


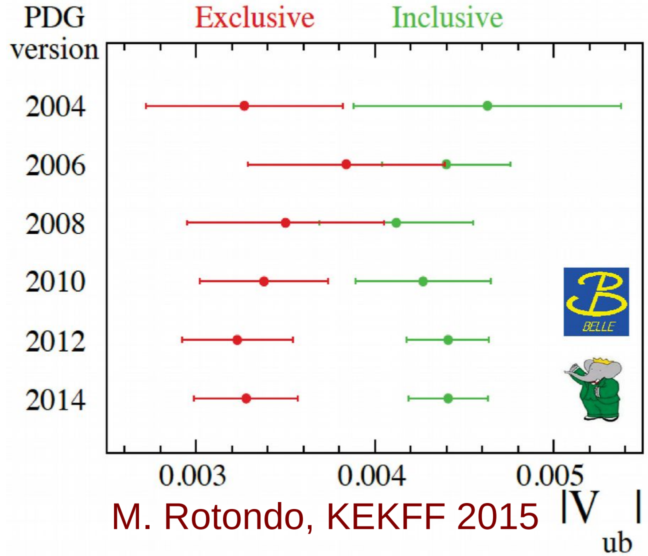
- Most gluonic penguin dominated modes will be limited by statistical uncertainties.
  Many of these modes are theoretically clean, and allow for precise tests for non-SM contributions.

Mode	QCDF [32]
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$
ηK_S	$0.10^{+0.11}_{-0.07}$
ϕK_S	$0.02^{+0.01}_{-0.01}$
ωK_S	$0.13^{+0.08}_{-0.08}$

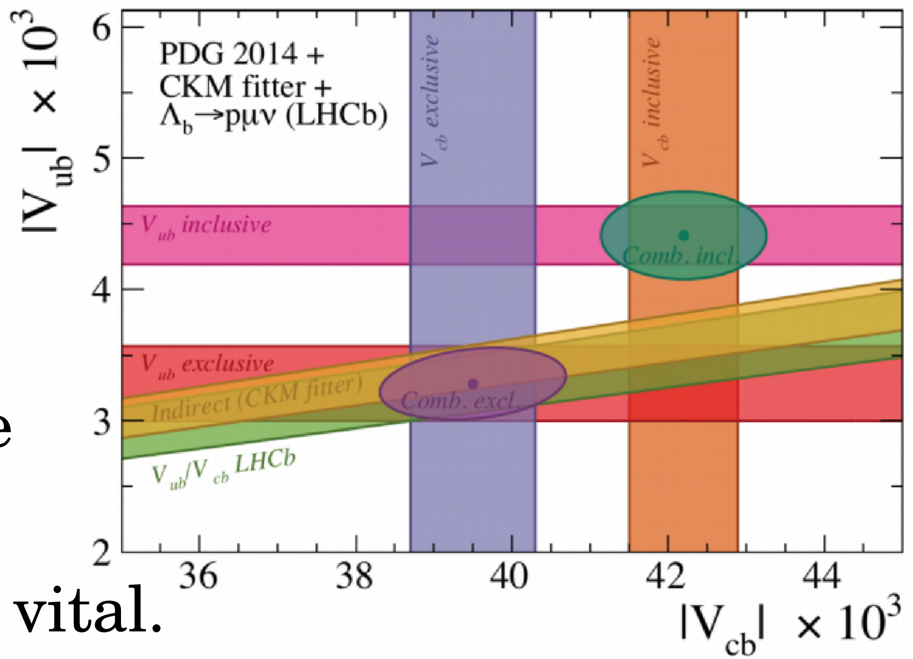
Semileptonic Decays

- Semileptonic B decays have been used at the B-factories to measure $|V_{cb}|$ and $|V_{ub}|$:





- Huge progress, but also tension between inclusive and exclusive determinations;
- LHCb can contribute to this field, but Belle II will have the advantage of more modes accessible;



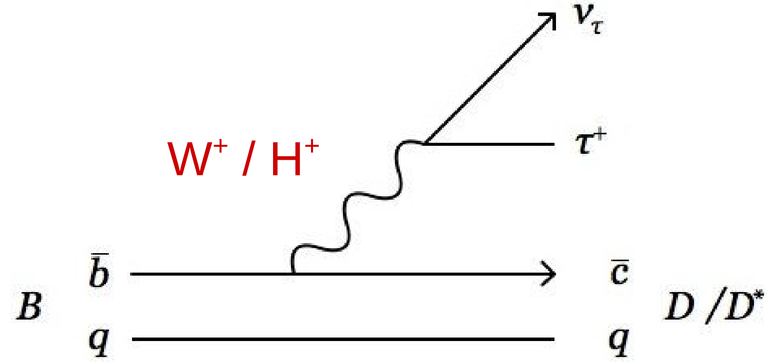
- Collaboration with theorists will be vital.

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

- A hot topic in B Physics comes from the measurement of:

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

l = e, μ

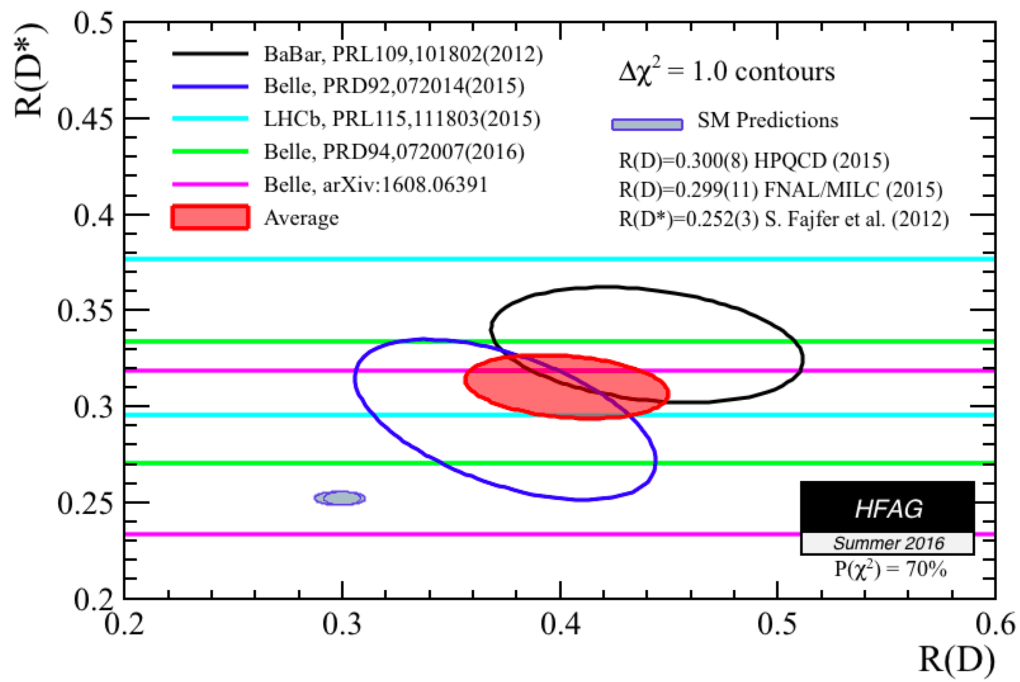


- Very clean prediction from the theory:

$$R(D) = 0.297 \pm 0.017$$
$$R(D^*) = 0.252 \pm 0.003$$

PRD **78**, 014003 (2008)
PRD **85**, 094025 (2012)

- Measured values seem to be consistently higher than SM prediction: level of discrepancy at 4σ now.



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

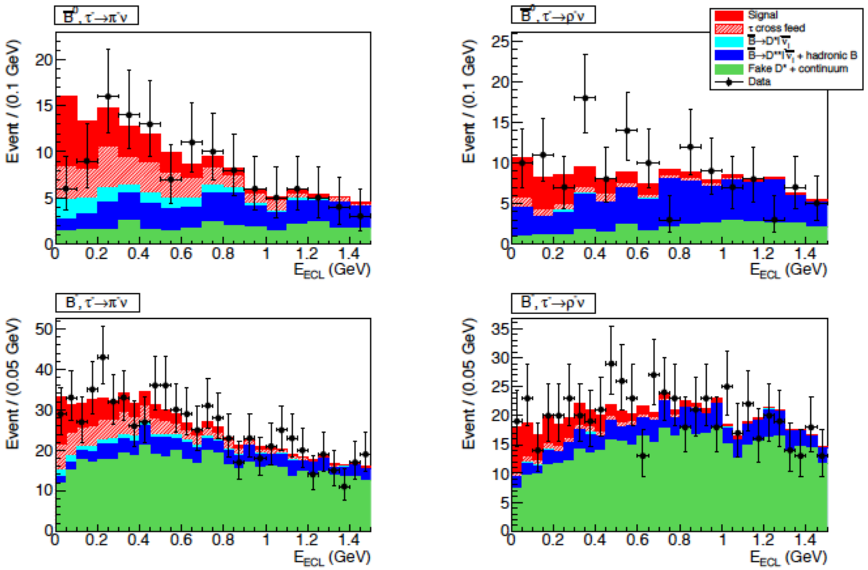
- The excess needs to be confirmed with more data:

	δR(D)/R(D)	δR(D*)/R(D*)
World Average	12%	5.5%
Belle II (50 ab^{-1})	3.4%	2.1%

The experimental precision will match the current theoretical uncertainty

- It will be important to look at more observables, measure τ and D^* polarization, measure rates as a function of q^2, … ;
- Belle already measured the τ polarization with the full dataset:

$$P(\tau) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

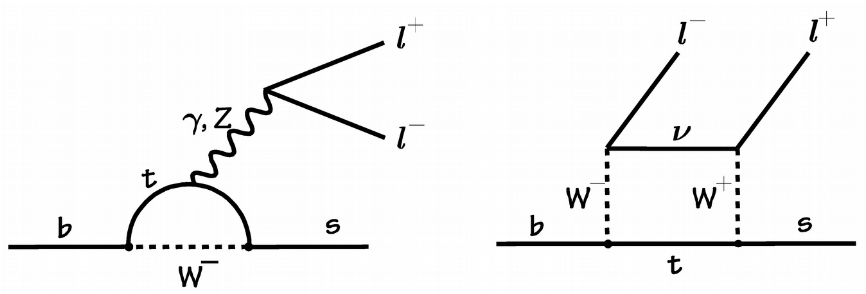


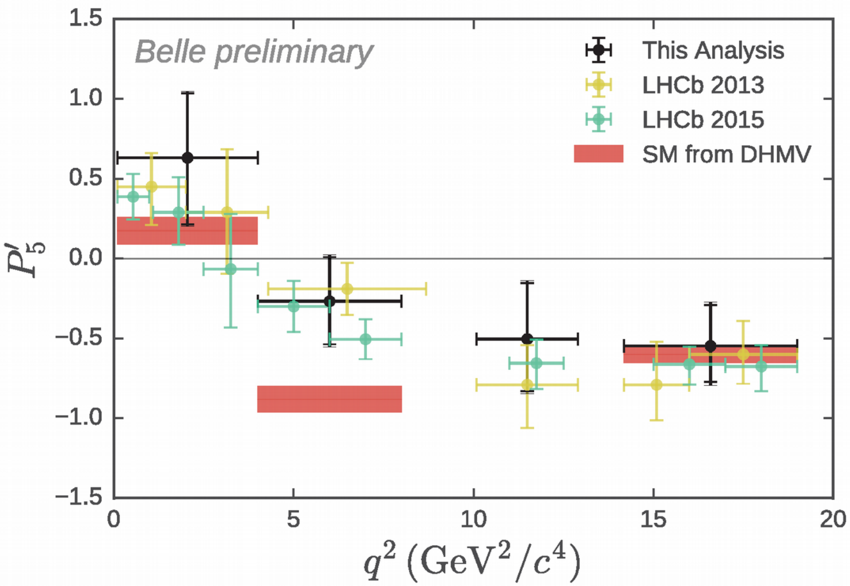
Belle Preliminary, submitted to PRL
see S. Hirose's poster tonight

- Possibly the anomaly is linked to other tensions we see in B physics.

Electroweak Penguins

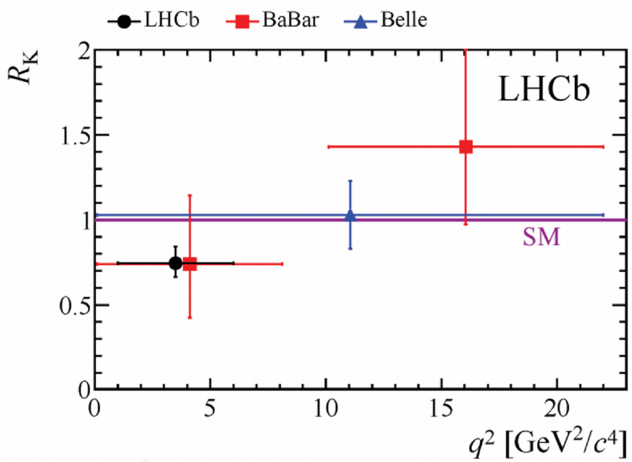
- Several tensions at the 2-3σ level from decays mediated by electroweak penguin amplitudes;





- Lepton Flavor Universality violation in $B^+ \to K^+ l^+ l^-$?

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



2.6σ tension from latest LHCb measurement

- LHCb will have the edge on many of these decays, but confirmation from Belle II will be crucial.

Electroweak Penguins

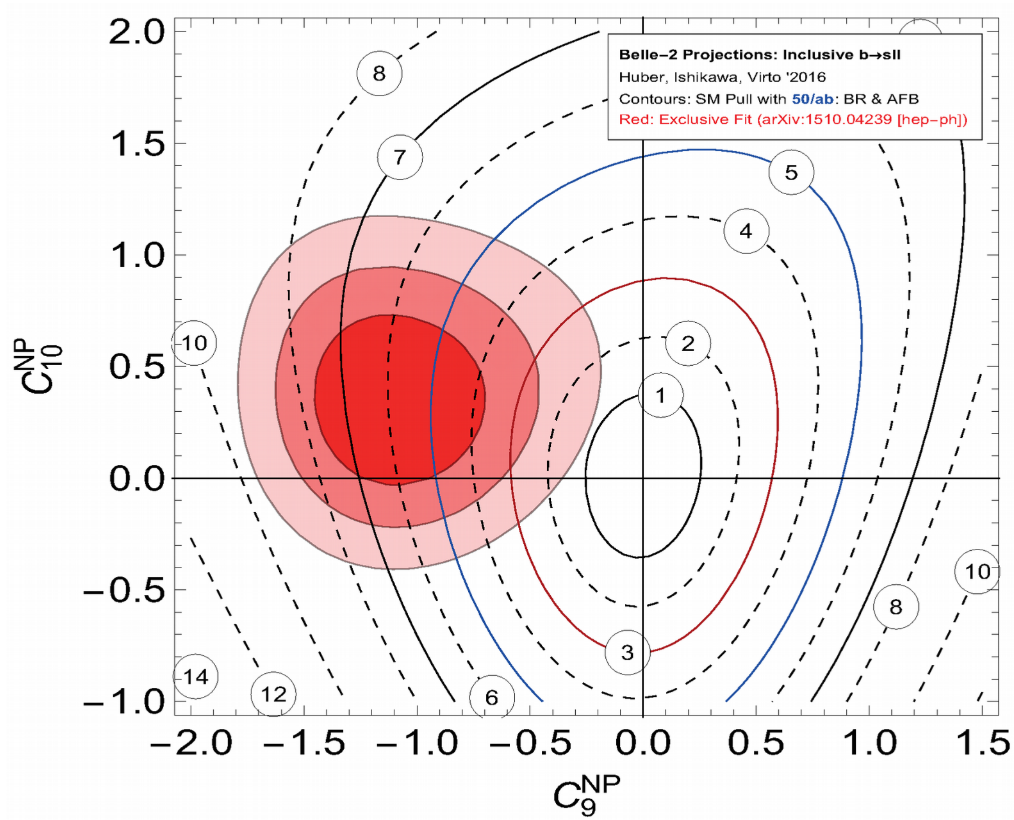
- Attempts to fit all the different anomalies in electroweak penguin dominated B decays have been made;

e.g. J. Virto at CKM2016

- Many observables are analyzed and NP contributions to the Wilson coefficients are studied;
- Negative C_9^{NP} seems a good candidate;

		R_K	$\langle P'_5 \rangle_{[4,6],[6,8]}$	$BR(B_s \to \phi\mu\mu)$	low recoil BR	Best fit now
$\mathcal{C}_9^{NP}$	+					
	−	✓	✓	✓	✓	X
$\mathcal{C}_{10}^{NP}$	+	✓		✓	✓	X
	−		✓			
$\mathcal{C}_{9'}^{NP}$	+			✓	✓	X
	−	✓	✓			
$\mathcal{C}_{10'}^{NP}$	+	✓	✓			
	−			✓	✓	X

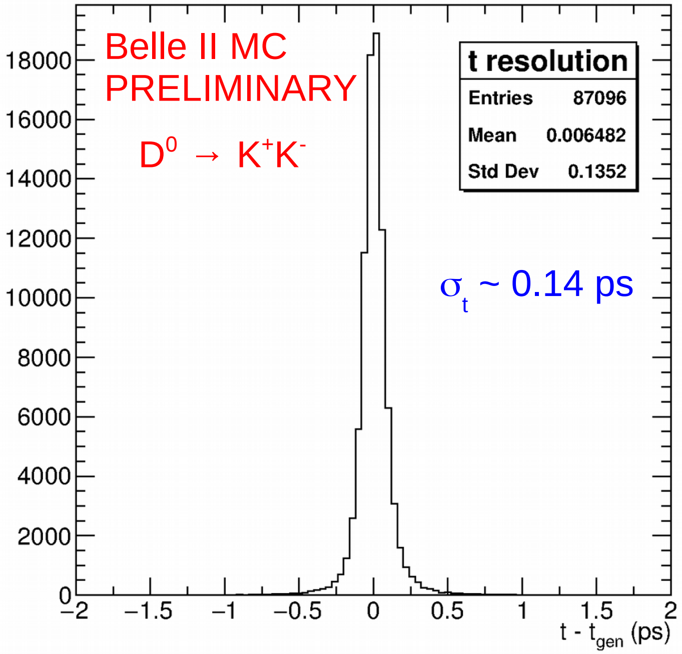
- If this is confirmed, Belle II will have the potential to discover New Physics with >5σ significance.



Charm Physics

Motivations

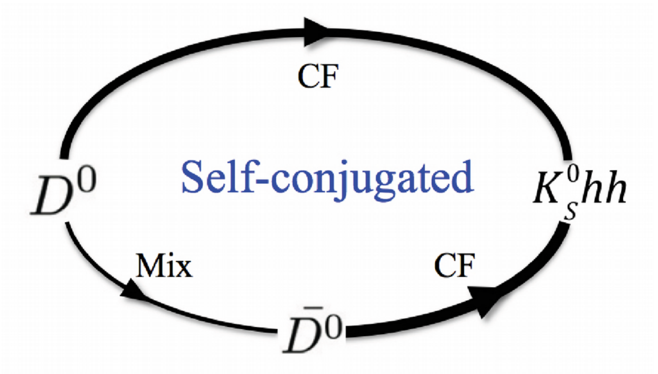
- B-factories discovered D^0-$\overline{D}^0$ mixing;
- Next: improve knowledge of mixing parameters, look for direct and indirect (in mixing) CP Violation, search for rare decays…;
- Clear advantage on LHCb on some important areas:
  - → semileptonic D decays (neutrinos in final state);
  - → rare decays ($D^0 \to \gamma\gamma$, $D^0 \to e^+e^-$, …);
- Substantial improvement over Belle/BaBar on:
  - → proper time resolution;
  - → flavor tagging: besides the D^{*+} self tagging decays, new methods, based on the analysis of the Rest Of Event (ROE) are being developed.



Prospects on Charm Physics

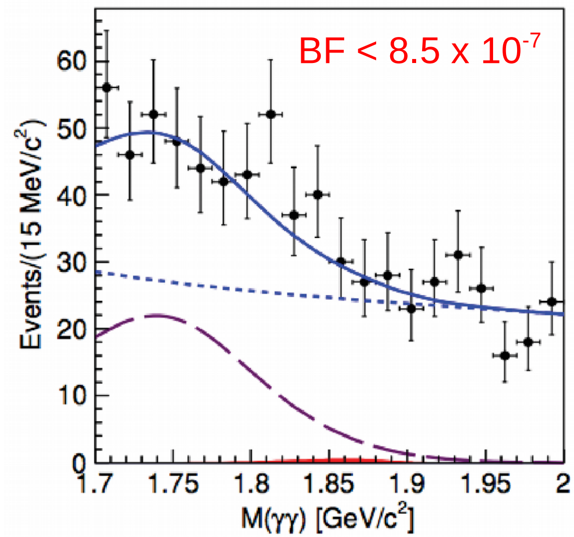
- Mixing/CPV in $D^0 \to K_s\pi^+\pi^-$:

	Belle	Belle II (50 ab^{-1})
$\sigma(x)$ (10^{-2})	0.20	0.11
$\sigma(y)$ (10^{-2})	0.16	0.05
$\sigma(\|q/p\|)$ (10^{-2})	17.8	7.4
$\sigma(\arg(q/p))$ (°)	12.2	4.2



(this is based on an extrapolation from Belle results – a large fraction of 'irreducible' systematic uncertainties will be reduced by moving to model-independent Dalitz Plot analysis)

- Sensitivity to $D \to \gamma\gamma$ (expected BF: a few 10^{-8});
- Belle II sensitivity with 50 ab^{-1}:
  - ➔ ~2 x 10^{-8} if sensitivity scales with $\mathcal{L}$;
  - ➔ ~10^{-7} if sensitivity scales with sqrt($\mathcal{L}$);
- Controlling beam backgrounds will be the key!

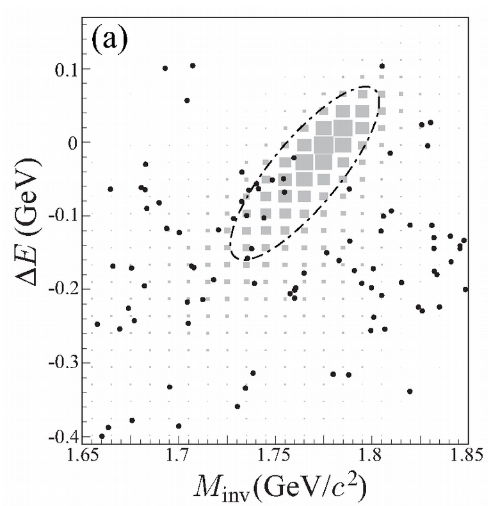


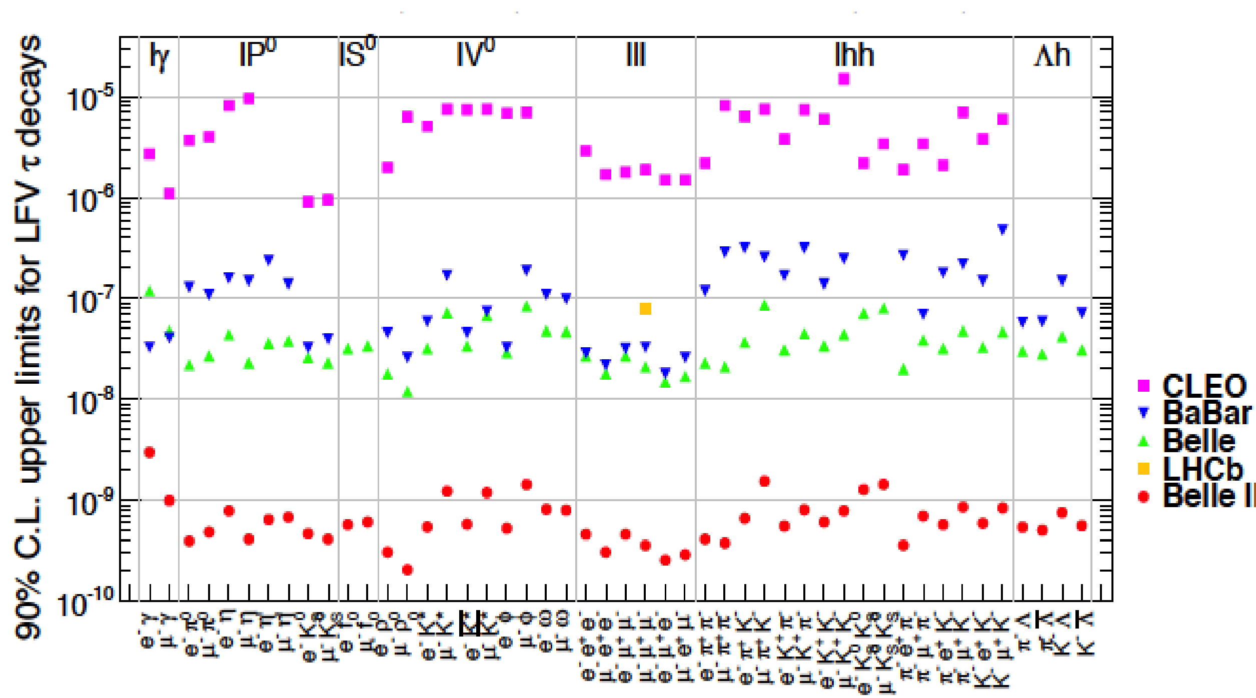
Belle Collaboration,
PRD 93, 051102 (2016)

τ Physics

Lepton Flavor Violation in τ decays

- In the SM, lepton flavor violating decays, like $\tau \to \mu\,\gamma$, are ~forbidden, while NP could enhance their BF's up to O(10^{-8});
- LHCb will be competitive with Belle II only on a very few channels (most notably $\tau \to \mu\mu\mu$);
- Belle II will be the only to access final states with neutrals (γ, π^0, $\eta^{(\prime)}$, …), control of the beam backgrounds will be crucial.

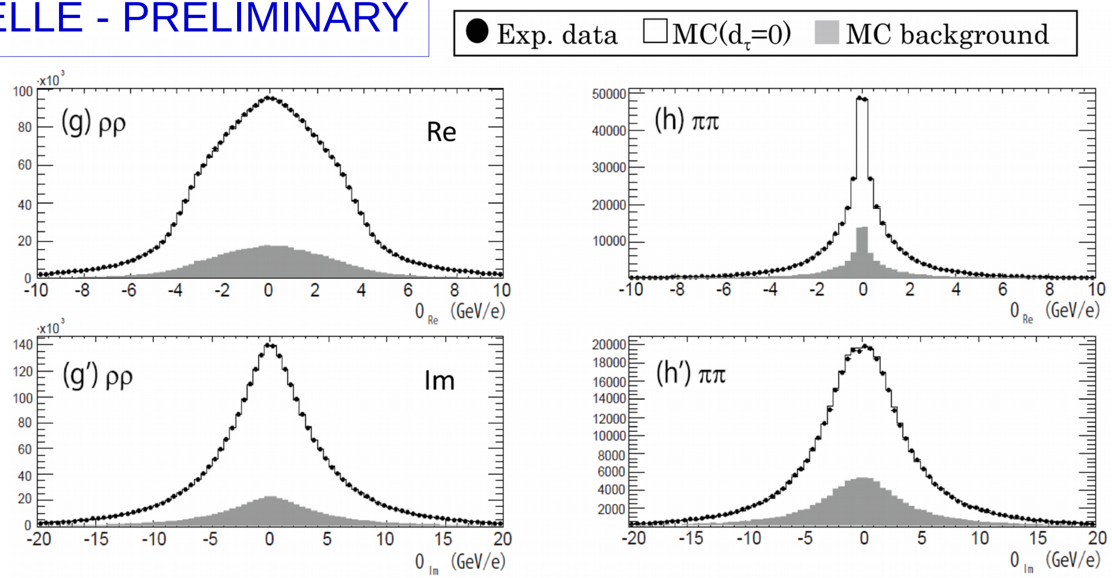


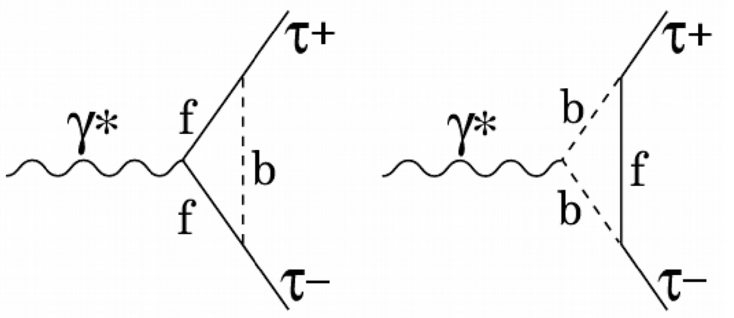


τ Electric Dipole Moment

- Other null test from the SM: τ EDM;

BELLE - PRELIMINARY





$Re(d_\tau)$: $(\pm 0.33) \times 10^{-17}$ecm

$Im(d_\tau)$: $(\pm 0.30) \times 10^{-17}$ecm

"Optimal observable" - PRD 45, 2405 (1992)

- Belle's limit reaches the region where some NP models predict potential enhancements;
- Good margin for improvement on $Re(d_\tau)$, $Im(d_\tau)$ is currently dominated by systematics. Better understanding of the detector will be needed for Belle II to continue making progress.

$e^+e^- \to$ light hadrons

Motivations

- Long standing discrepancy between theory and experiment in the $(g\text{-}2)_\mu$:

E821 Collaboration, PRL **92**, 1618102 (2004)

$$\vec{\mu} = g\frac{e\hbar}{2mc}\cdot\vec{S}$$

anomalous magnetic moment

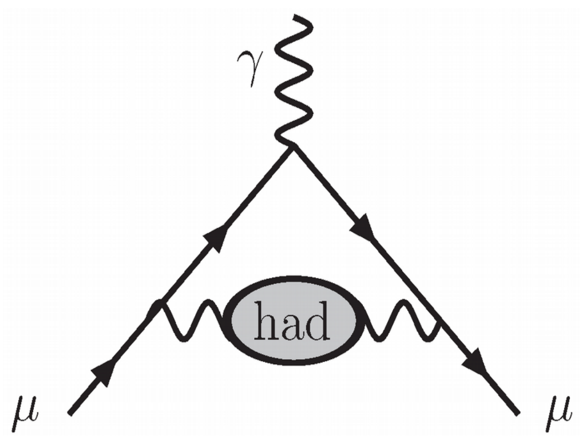
Experiment: $(g\text{-}2)_\mu/2 = 11659208.9\ (6.3) \times 10^{-10}$

Theory: $(g\text{-}2)_\mu/2 = 11659181.5\ (4.9) \times 10^{-10}$

Discrepancy : $(27.4 \pm 8.0) \times 10^{-10}$

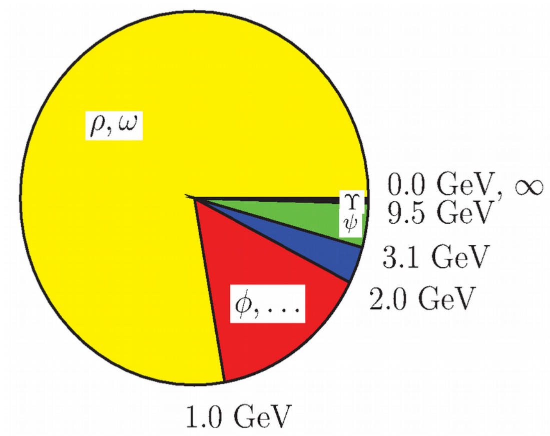
3.5σ discrepancy

- Most of the uncertainty in the theory prediction comes from the hadronic contribution:

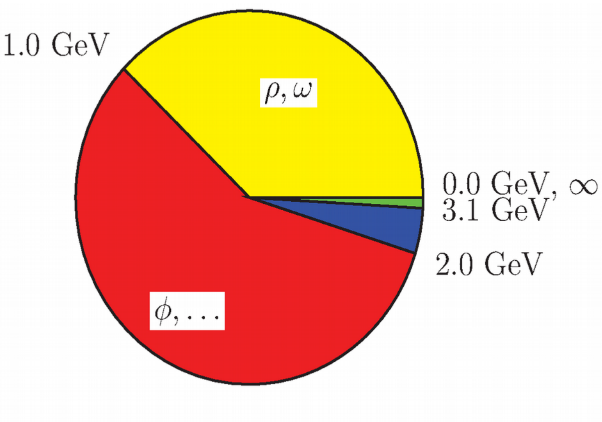


"hadronic vacuum polarization"

Phys. Rept. **447**, 1-110 (2009)



size



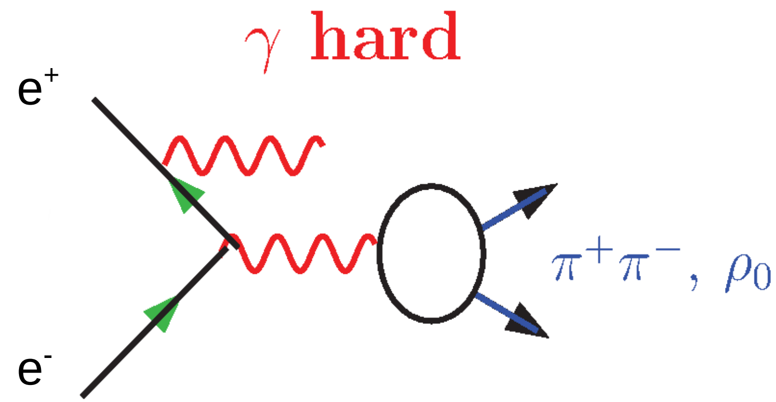
uncertainty

of the hadronic contribution

See next talk by Y. Sato on prospects for the measurement of $(g\text{-}2)_\mu$

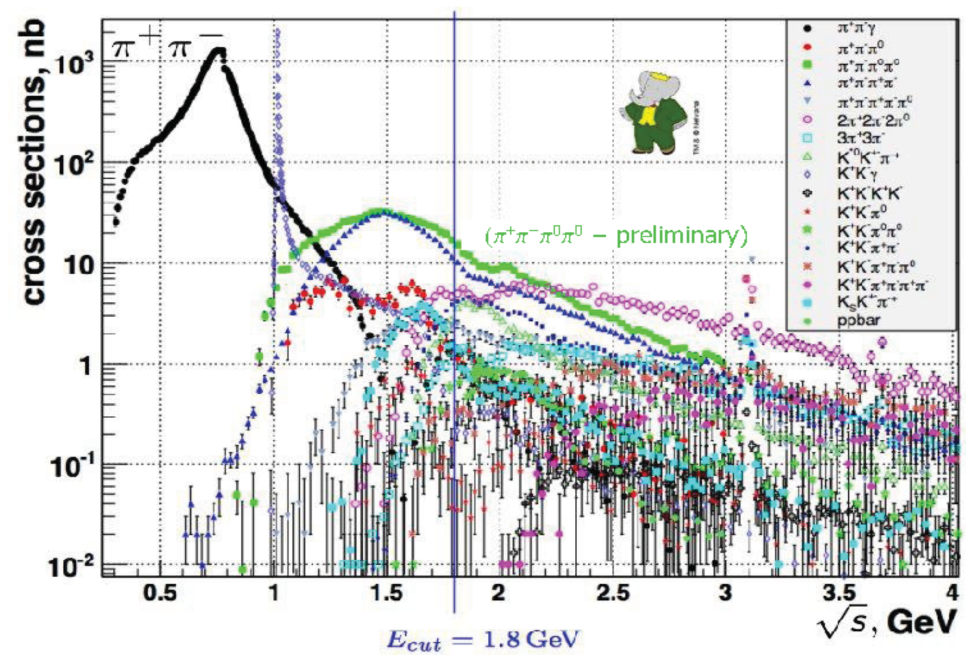
Prospects

- The vacuum polarization is connected to the $e^+e^- \rightarrow$ hadrons through the optical theorem;
- At the B-factories we can exploit the initial state radiation (ISR) and the large integrated luminosity to effectively have a “scan” at low invariant masses;
- A large number of exclusive final states has been investigated by BaBar;
- Due to trigger limitations, Belle could not participate to the campaign, but this will be an important topic at Belle II!



$$s = M_\phi^2;\ s' = s\,(1-k),\ k = E_\gamma / E_{\mathrm{beam}}$$

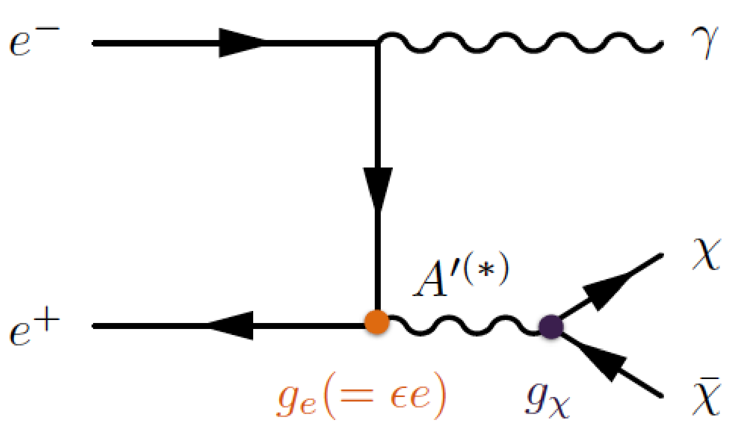
γ



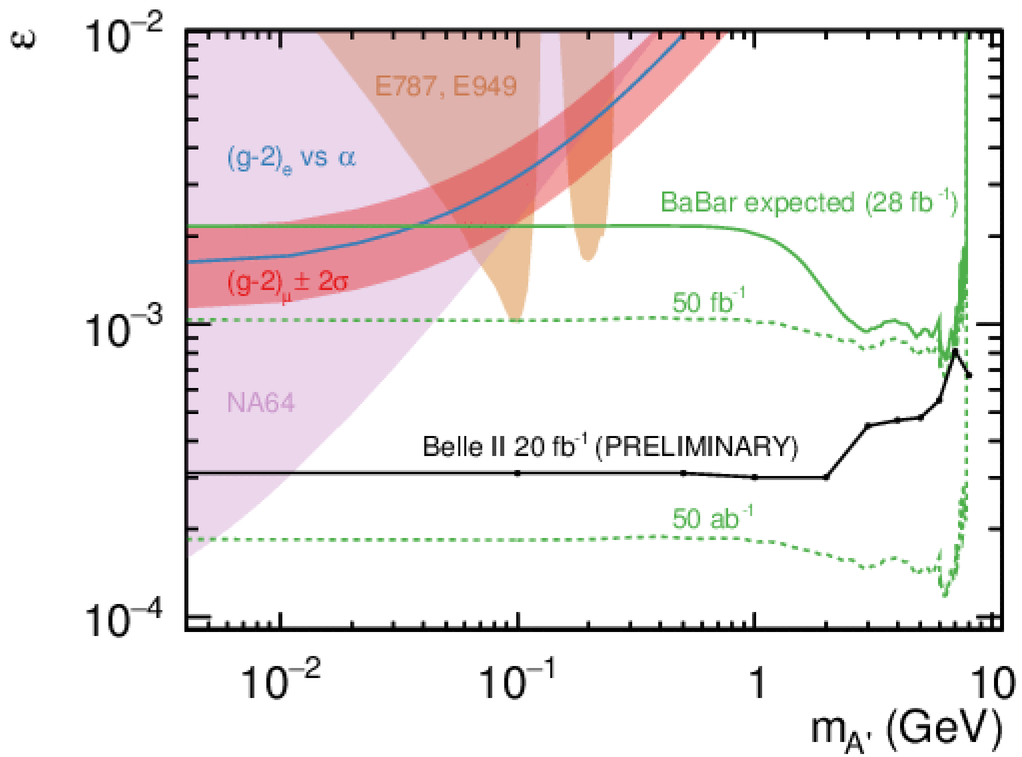
Searches for dark/exotic particles

Dark photons decaying to invisible

- Many BSM theories predict the existence of a Dark Sector;
- Common ingredient: a dark photon A' that mixes kinetically with the SM photon with strength ε;
- Several search strategies already pioneered at the B-factories;
- Only at Belle II:



mono-photon signal: this requires a special trigger (under development)



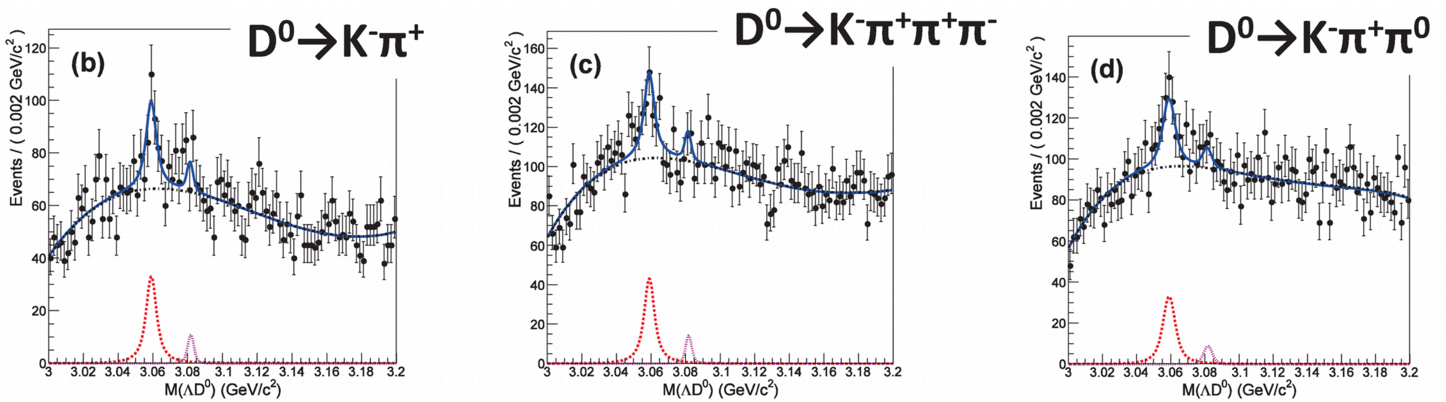
Enormous improvement wrt BaBar

Charmed Baryons

- Substantial progress at Belle in the study of charmed baryons;
- Several new states and decay modes have been observed for the first time;

Yuji Kato received JPS Young Scientist Award

First observation of $\Xi_c(3055)^0$



Belle Collaboration, PRD **94** 032002 (2016)

- The properties (spin-parity) of many of these states are not yet determined;
- Boost in statistics will allow the determination of the quantum numbers of the newly discovered states (and the discovery of more states).

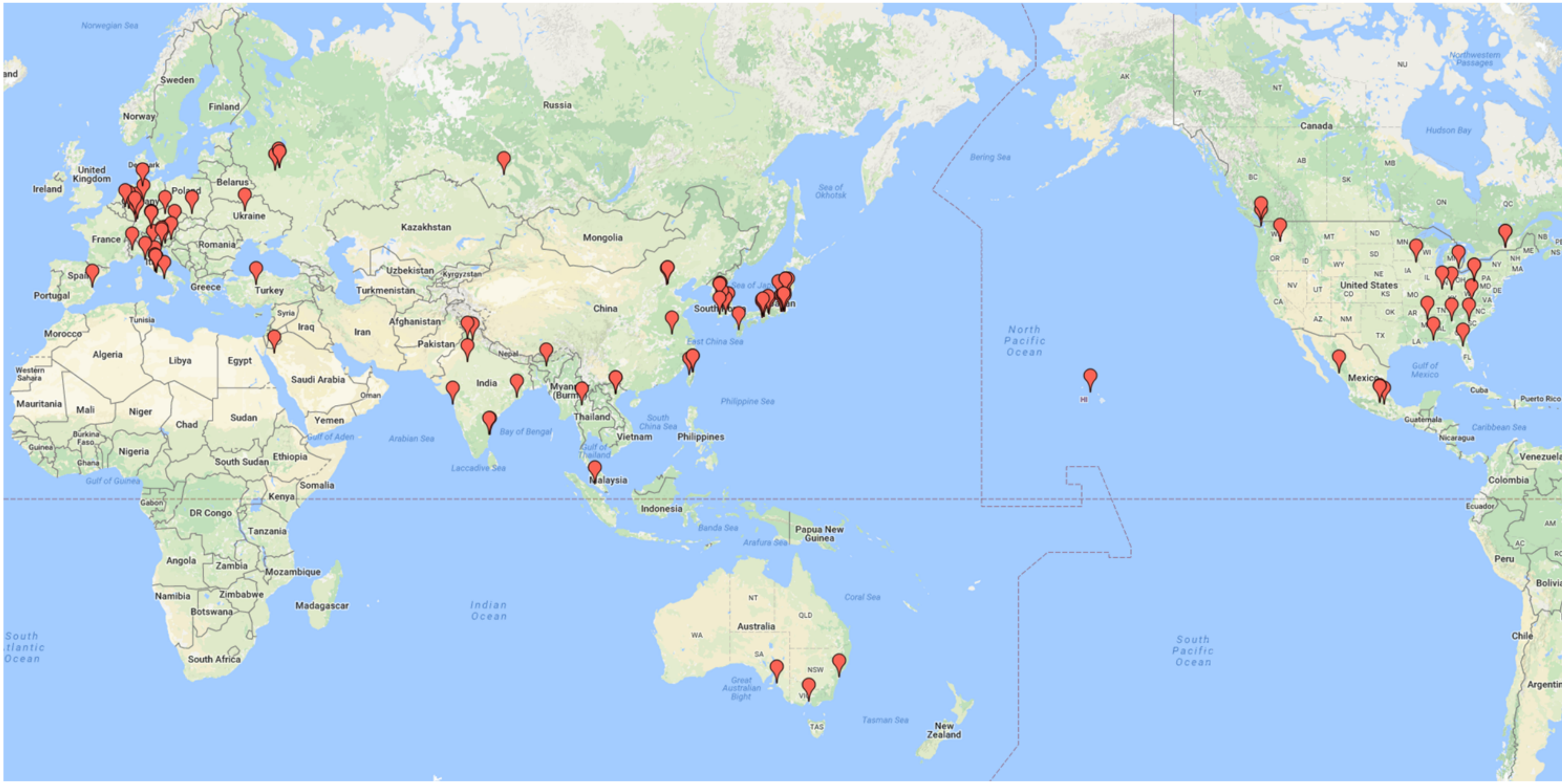
More exotic particles?

Belle top cited papers:

1) Observation of a narrow charmonium-like state in exclusive $B^+ \to K^+ J/\psi \pi^+ \pi^-$ decays – PRL 91, 262001 (2016); 1269 citations
2) Observation of large CP violation in the neutral B meson system – PRL 87, 091802 (2001); 831
3) Observation of a resonance-like structure in the $\pi^\pm\psi'$ mass distribution in exclusive $B \to K \pi^\pm\psi'$ decays – PRL 100, 142001 (2008); 489
4) A measurement for the branching fraction of inclusive $B \to X_s \gamma$ at Belle – PLB 511, 151 (2001); 427
5) Observation of a near-threshold $\omega J/\psi$ mass enhancement in exclusive $B \to K \omega J/\psi$ decays – PRL 94, 182002 (2005). 414

Several non-anticipated states have been found at Belle, whose nature has not yet been fully clarified. More surprises are likely to be in store for Belle II...

The Belle II Collaboration



700	Members
100	Institutions
23	Countries

Impressing computing infrastructure for data reconstruction/analysis and Monte Carlo generation.
See Y. Kato's talk on Belle II computing on Friday

World Research Unit for Heavy Flavor Particle Physics

"WPI-next" under "Program for Promoting the Enhancement of Research Universities"

SuperKEKB/
Belle II

Toru Iijima
- B, Tau Physics
- Exotic hadrons

LHC-ATLAS

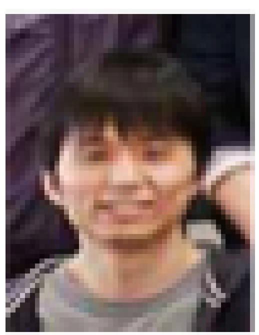
Makoto Tomoto
- Top physics
- Higgs

Peter Krizan
(Ljubljana)

Theory

Junji Hisano
- Flavor Physics
- Dark Matter

Alessandro Gaz

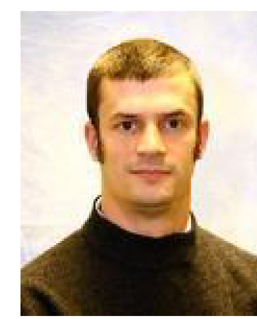


Kodai Matsuoka

Yuji Omura

Gino Isidori
(Zurich)

Yu Nakahama



Tim Gershon
(Warwick)

SuperKEKB commissioning

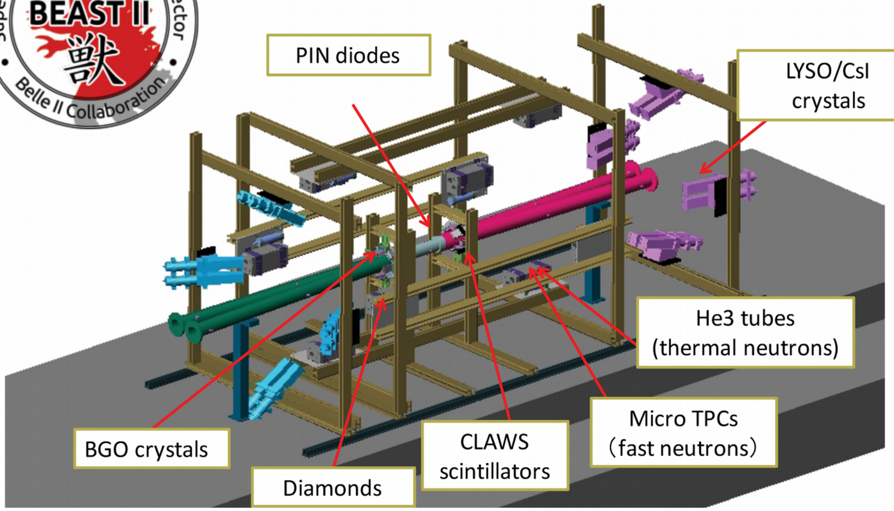
Feb-June 2016, PHASE1 commissioning (without Belle II):

- Basic machine tuning;
- Vacuum scrubbing;
- Background studies;

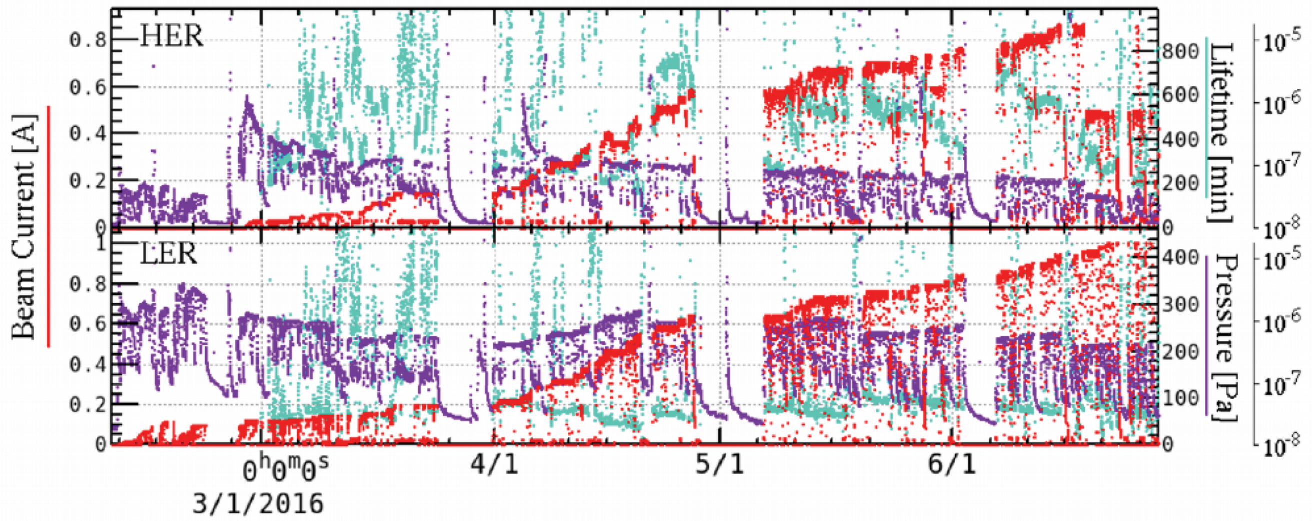
Achieved 1010 (870) mA in the LER (HER)

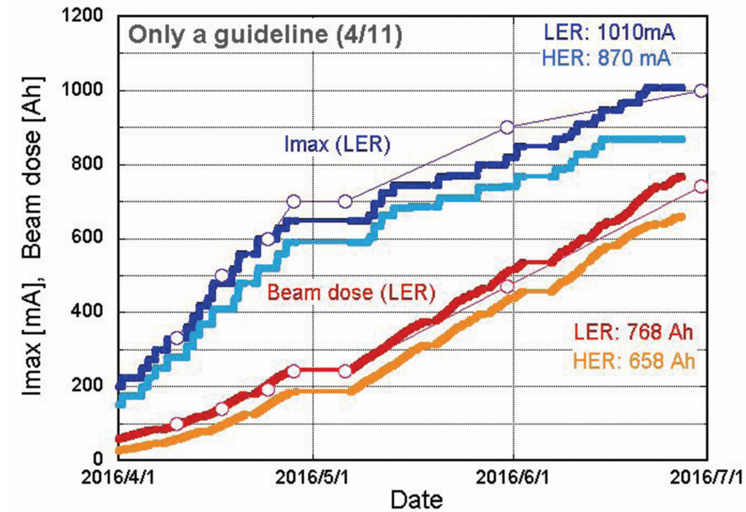
H. Nakayama

BEAST Phase1 sensors at IP



Various measurements (fast charged particle, high-energy photons, thermal/MeV neutron, dosimetry, etc..) to **validate beam loss simulation**

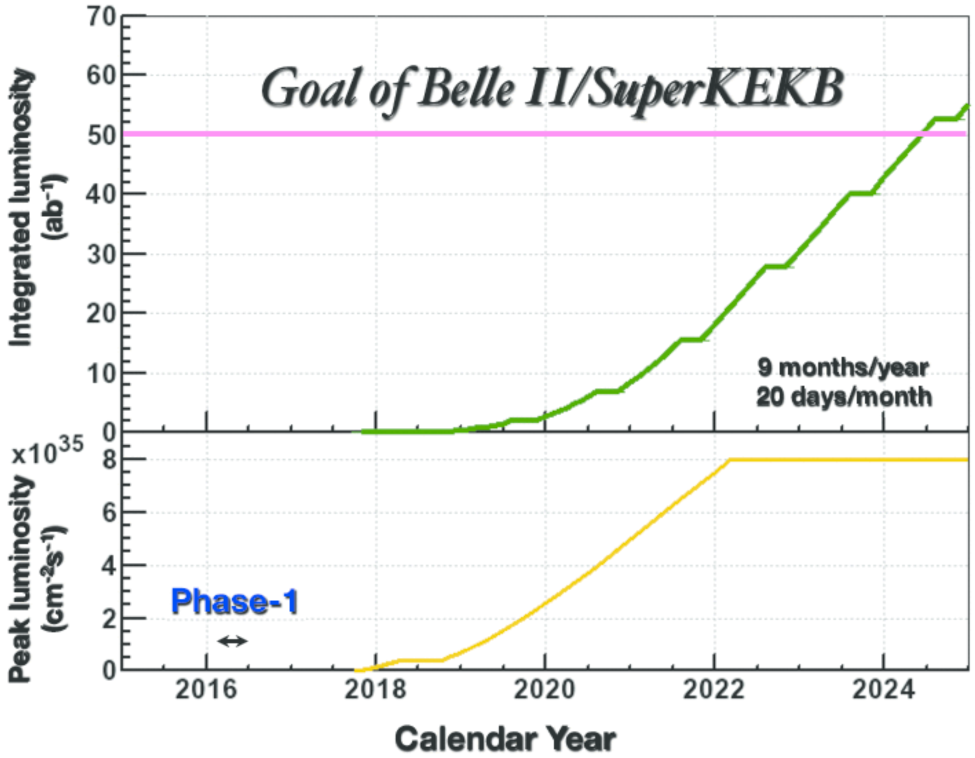




Road to Physics

PHASE 2: January 2018 – June 2018

Machine commissioning with the Belle II detector (w/o silicon vertex detectors);
More background studies and detector commissioning on e^+e^- collisions;
Target luminosity: 10^{34} $cm^{-2}s^{-1}$;
Some physics opportunities at the energy of the Y(6s).



PHASE 3: December 2018 –

Belle II detector complete;
Luminosity tuning;
Start of Physics Run!

Conclusions

- The Belle II detector is in its final stages of construction, roll-in to the beam line is scheduled for March 14th;
- Aim: discover Physics beyond the Standard Model exploring a very broad physics case, ranging from B physics to $(g-2)_\mu$;
- There will be competition with LHCb, but high degree of complementarity and many channels will be exclusive to Belle II;
- Several exciting anomalies need to be confirmed;
- First phase of SuperKEKB accelerator successfully completed;

- We are looking forward for the first physics papers in 2018;
- The B2TiP report on Belle II Physics Program and expected sensitivity is on track to be released this coming Spring.

Backup Slides

Competition and Complementarity

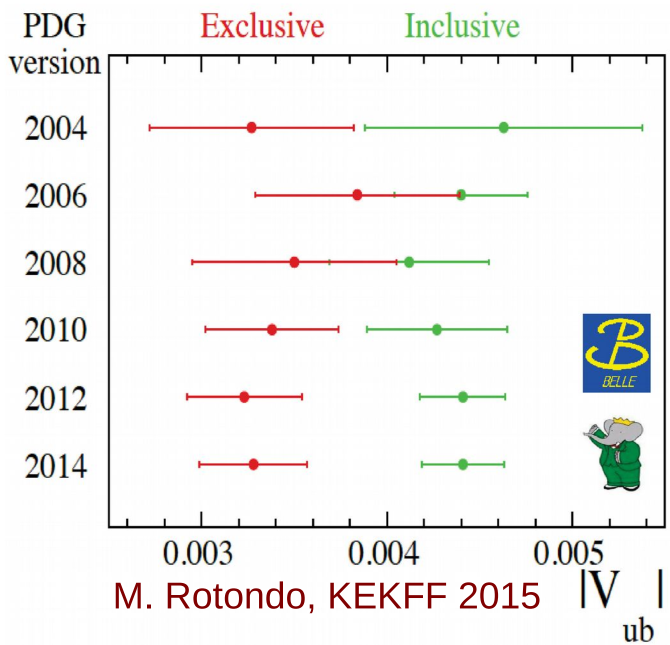
In the next years LHCb and Belle II will fiercely compete in some areas … in others, they will exploit their own strengths;

- 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.

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:	$|V_{cb}|$	$|V_{ub}|$
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 $|V_{ub}| \sim 5\text{-}9\%$;

… 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

Result:

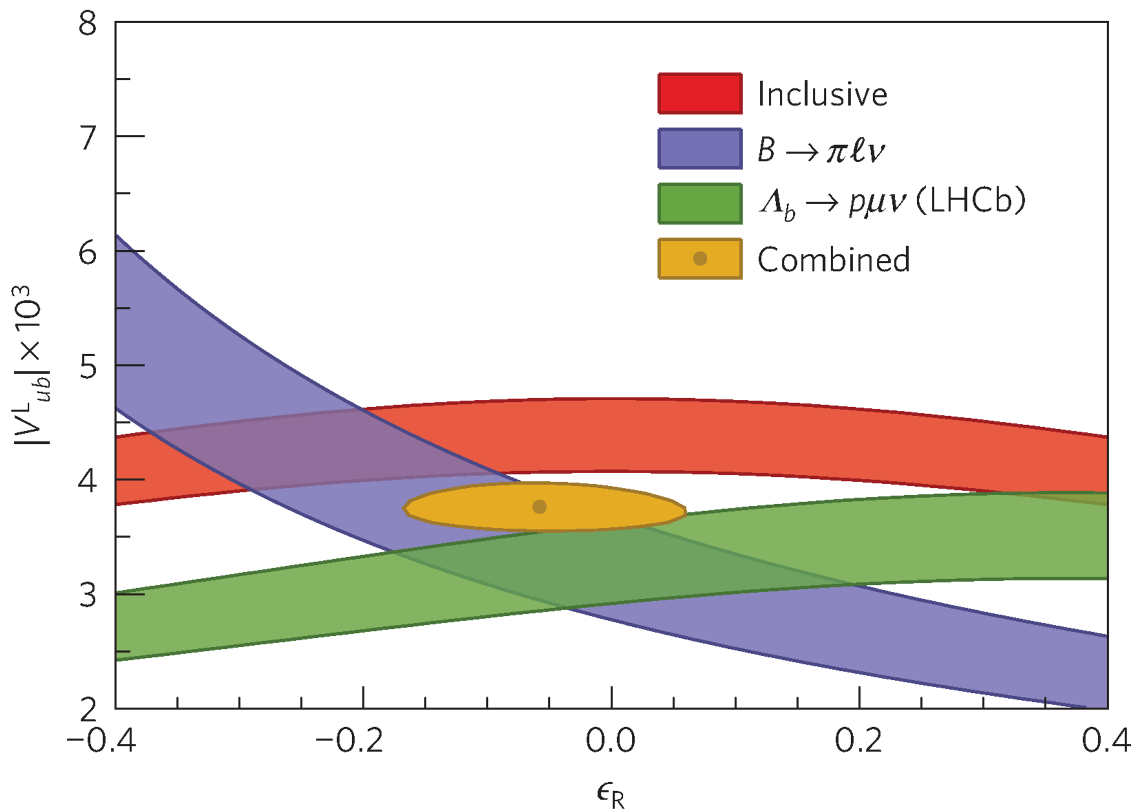
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

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.

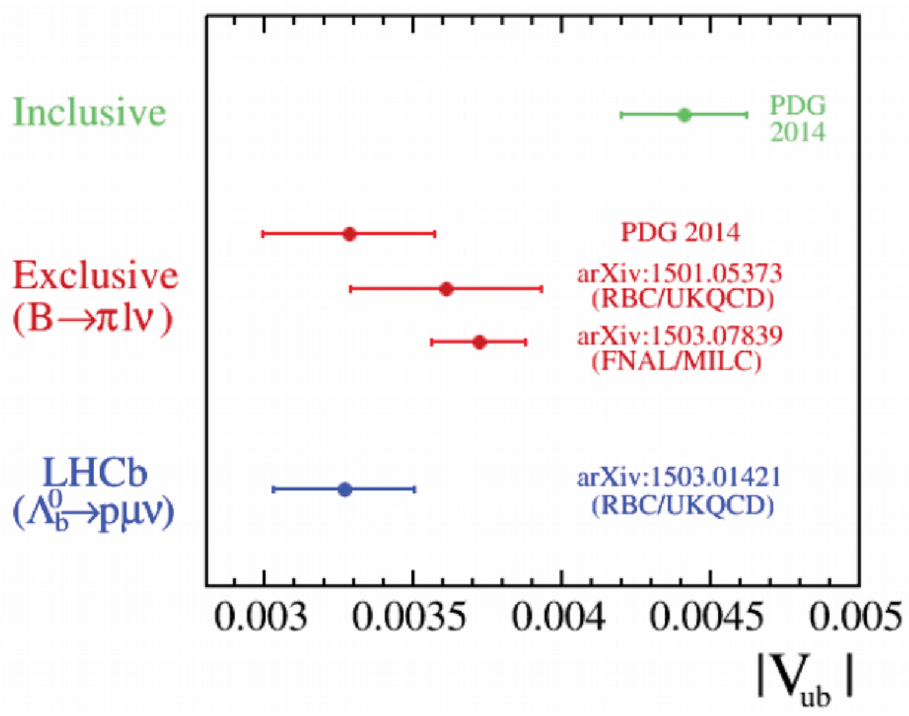


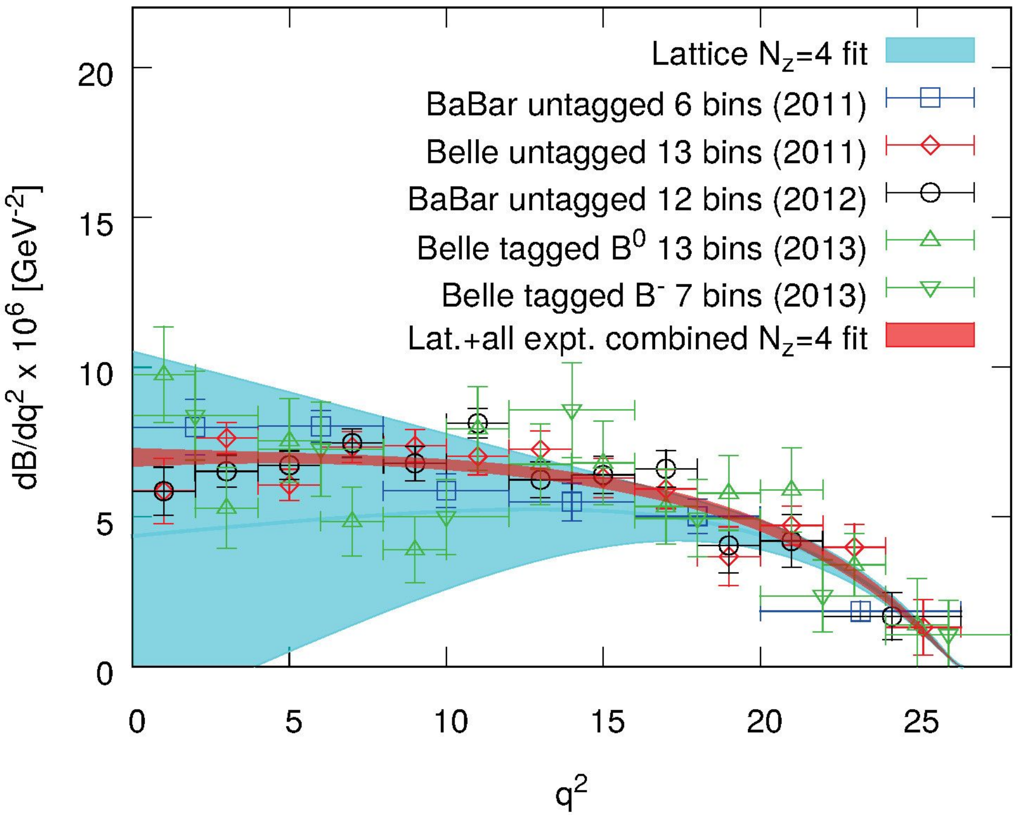
Semileptonic Decays

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

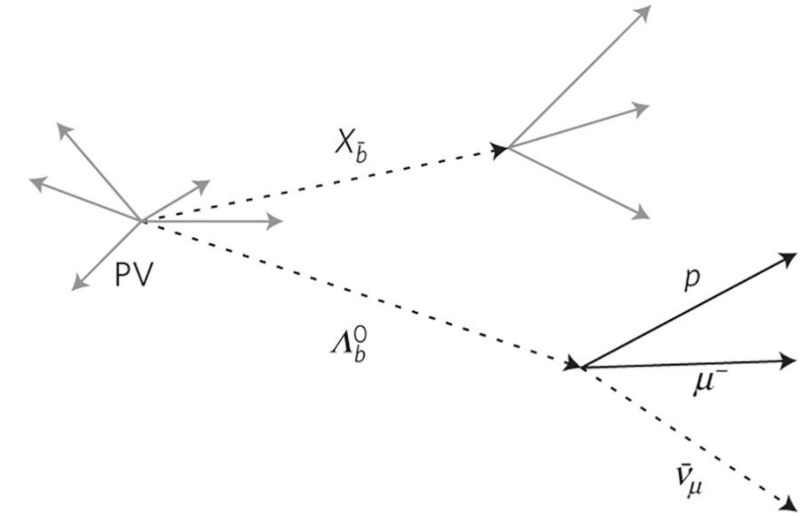
$$|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$$

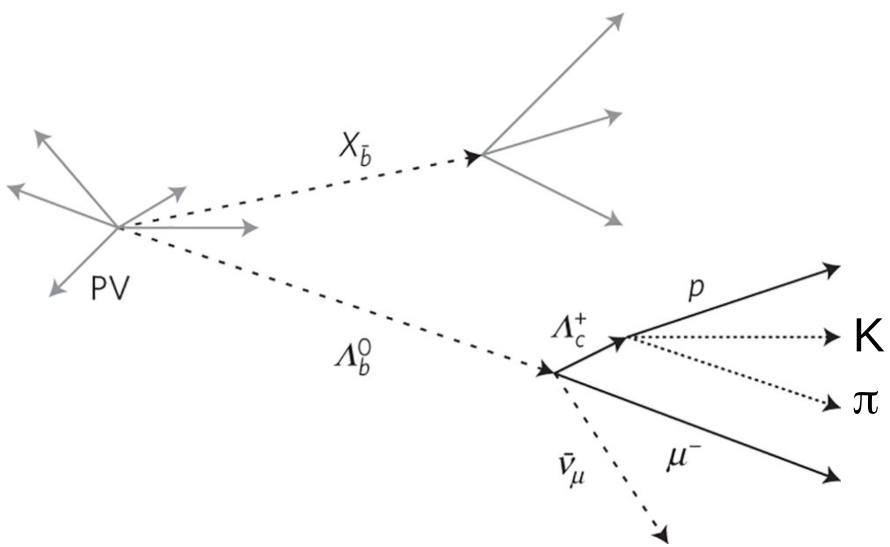
PRD **92**, 014024 (2015)





Semileptonic Decays





Corrected mass:

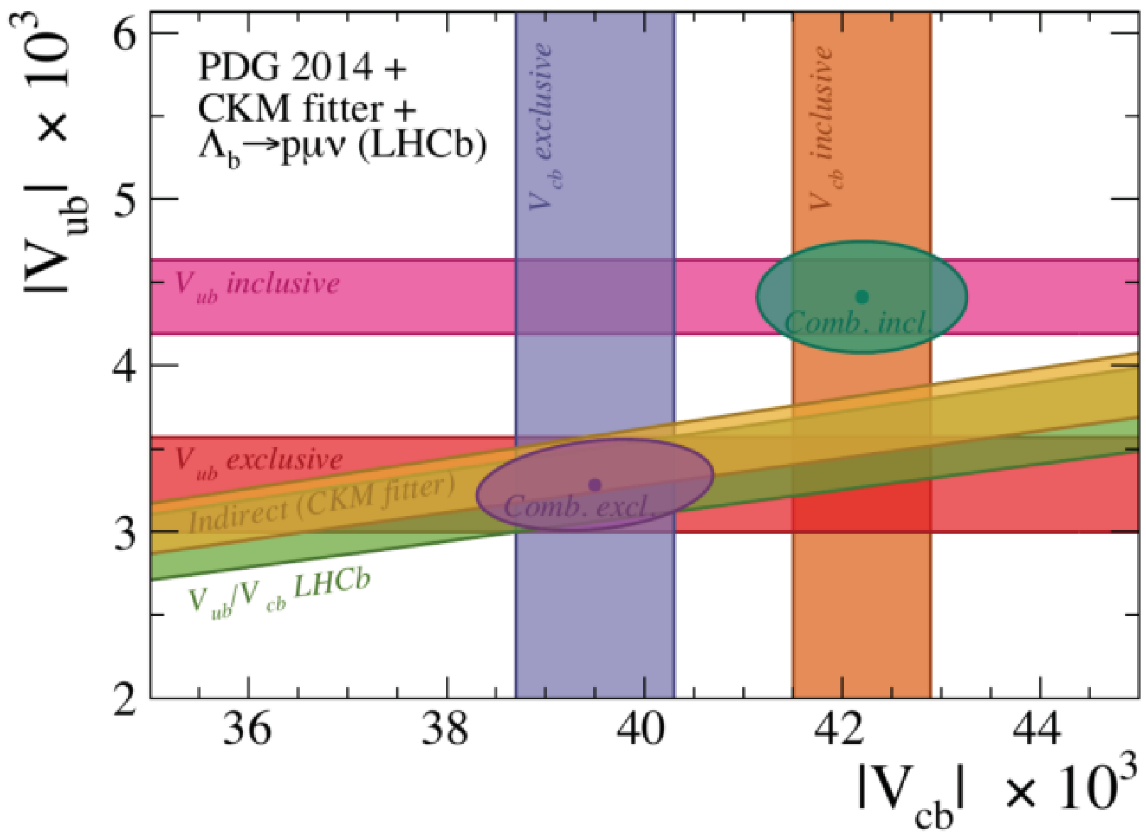
$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$

$m_{h\mu}$: 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

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



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

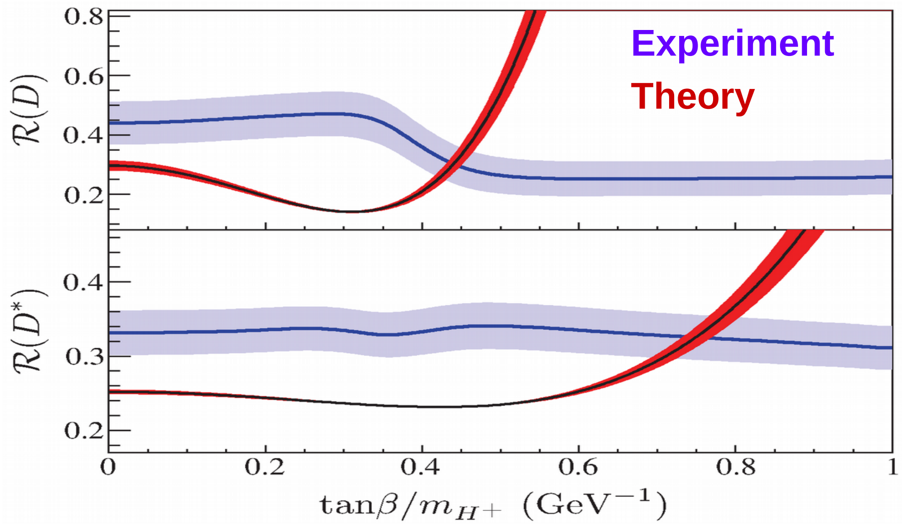
- One of the hot topics of the moment, potential charged Higgs-like particles can cant effects;
- Measure: $$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to \bar{D}^{(*)}\ell^+\nu_\ell)}$$ l = e, μ
- Clean predictions from SM, most uncertainties cancel in the ratio:

$$R(D) = 0.297 \pm 0.017$$ PRD **78**, 014003 (2008)

$$R(D^*) = 0.252 \pm 0.003$$ PRD **85**, 094025 (2012)

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

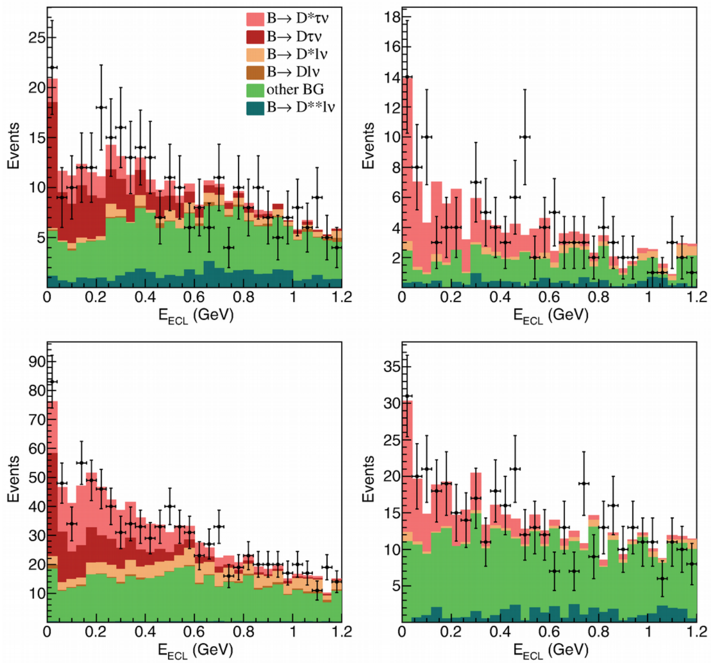
More about potential New Physics effects in M. Tanaka's talk tomorrow



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

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

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



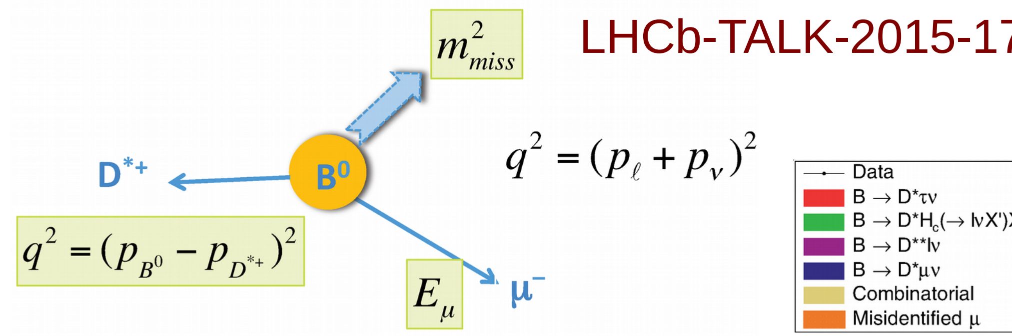
Belle reconstructs signal events on the recoil of hadronic B_{tag}, using leptonic τ decays (similar to BaBar)

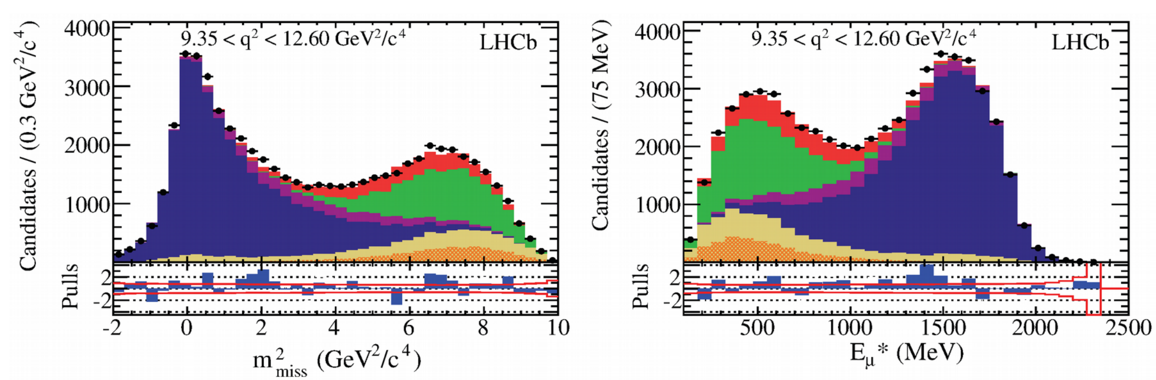
$$R(D) = 0.375 \pm 0.064 \pm 0.026 \quad \sim 1.4\sigma$$
$$R(D^*) = 0.293 \pm 0.038 \pm 0.015 \quad \sim 1.8\sigma$$

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

LHCb performs a template fit on the 3 kinematic variables:

LHCb-TALK-2015-178





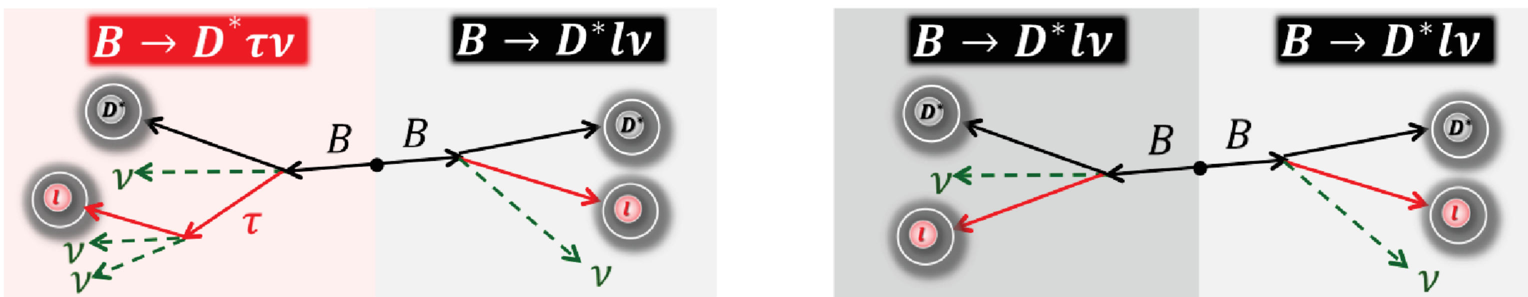
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030 \quad \sim 2.1\sigma$$

Still tension with SM

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

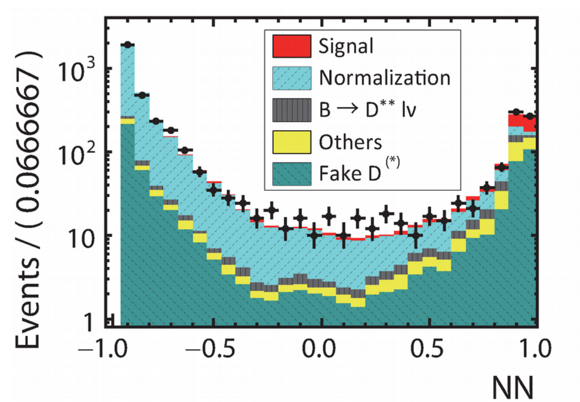
$B \to D^{(*)}\tau\nu$

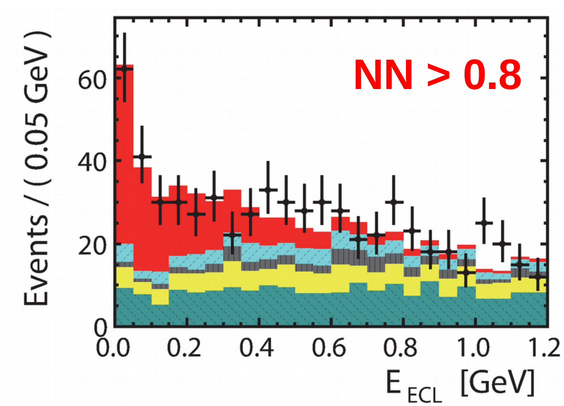
- New Belle result on $R(D^*)$ for $B^0 \to D^{*\mp}\tau^{\pm}\nu$;
- Analysis performed on the recoil of $B^0 \to D^{*\mp}l^{\pm}\nu$ mesons (statistically independent from previous Belle analysis);



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};

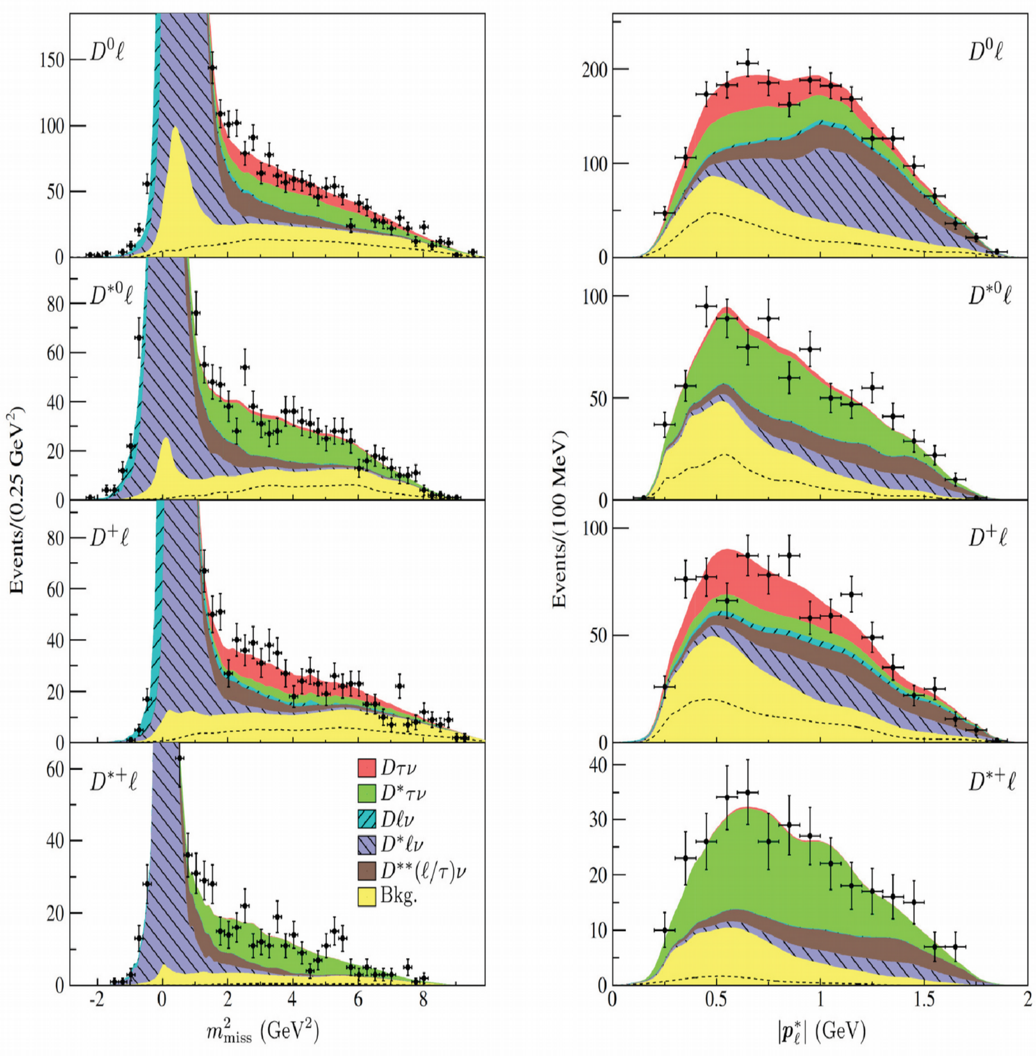




$$\mathcal{R}(D^*) = 0.302 \pm 0.030 \pm 0.011$$

1.6σ above SM

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

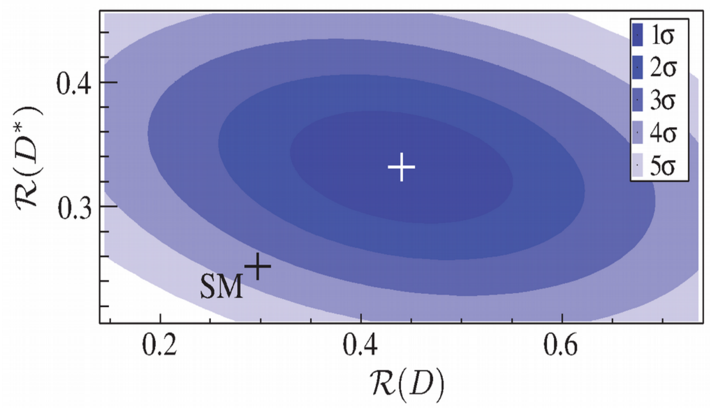


$$\mathcal{R}(D)_{\text{exp}} = 0.440 \pm 0.072$$
$$\mathcal{R}(D)_{\text{SM}} = 0.297 \pm 0.017$$

2.0σ

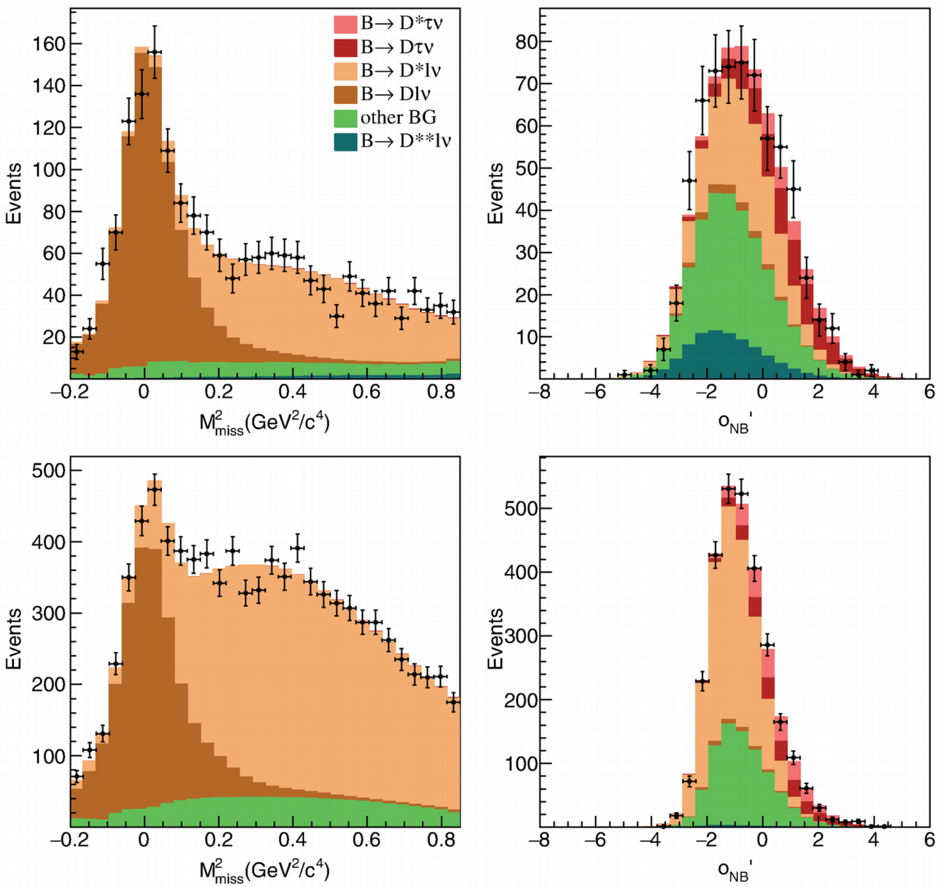
$$\mathcal{R}(D^*)_{\text{exp}} = 0.332 \pm 0.030$$
$$\mathcal{R}(D^*)_{\text{SM}} = 0.252 \pm 0.003$$

2.7σ

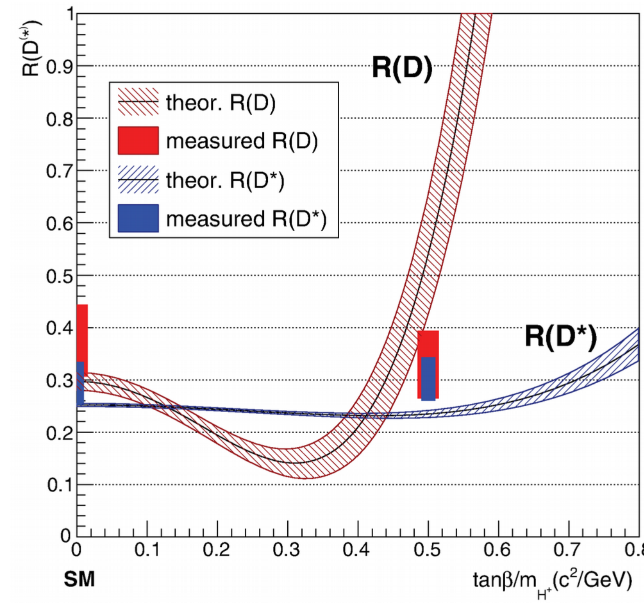


BaBar Collaboration,
PRD **88**, 072012 (2013)

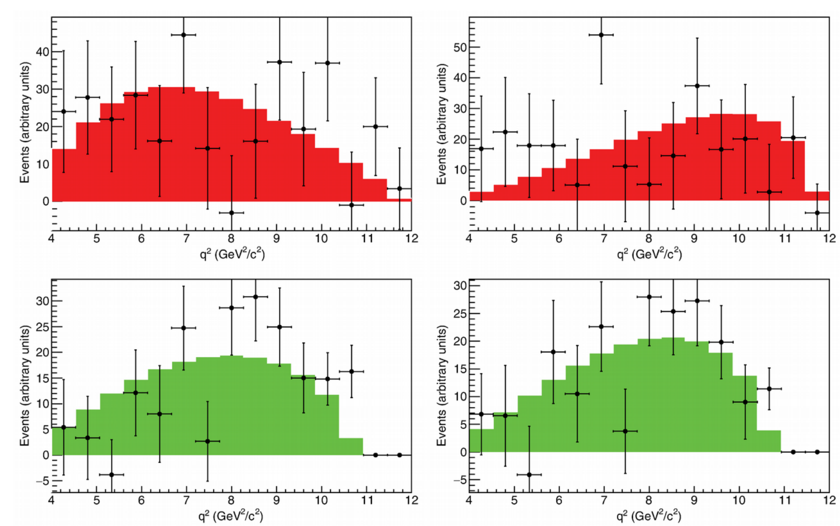
$B \to D^{(*)}\tau\nu$



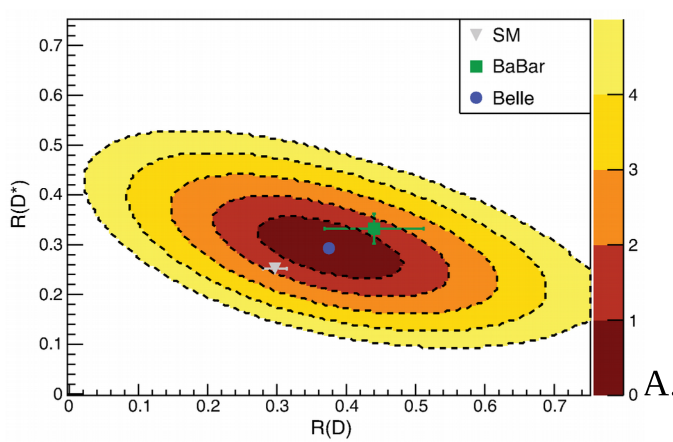
B→ D*τν
B→ Dτν
B→ D*lν
B→ Dlν
other BG
B→ D**lν
Events
$M^2_{miss}(GeV^2/c^4)$
o_{NB}'



R(D)
R(D*)
theor. R(D)
measured R(D)
theor. R(D*)
measured R(D*)
$R(D^{(*)})$
SM
$\tan\beta/m_{H^+}(c^2/GeV)$



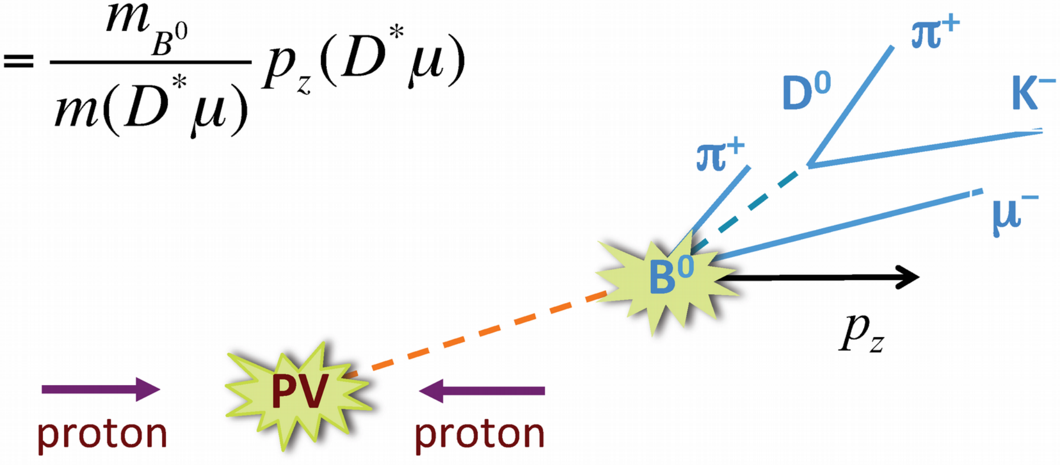
Events (arbitrary units)
q^2 (GeV^2/c^2)



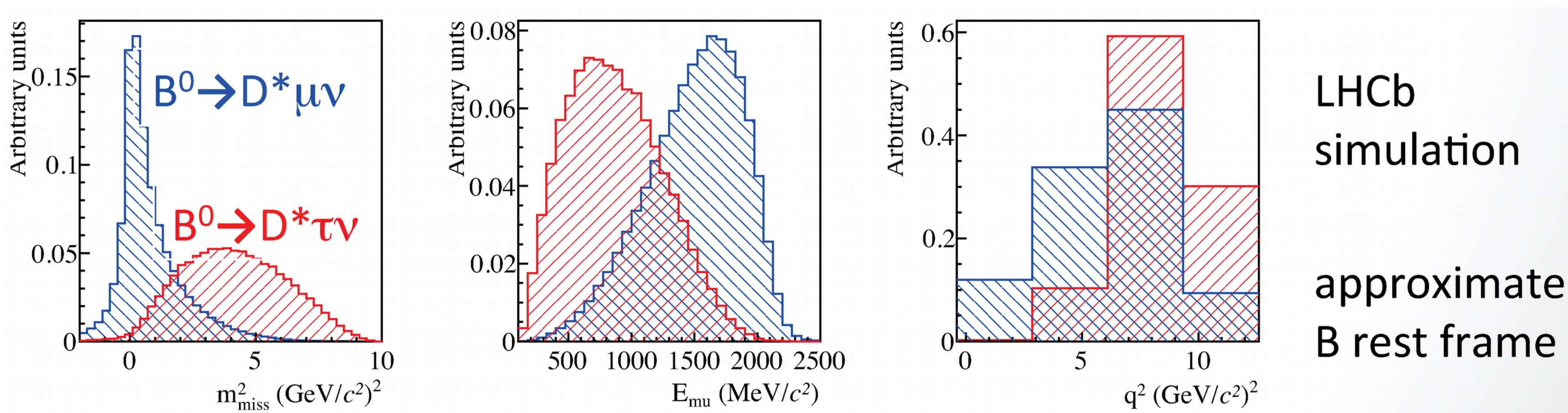
SM
BaBar
Belle
R(D*)
R(D)

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

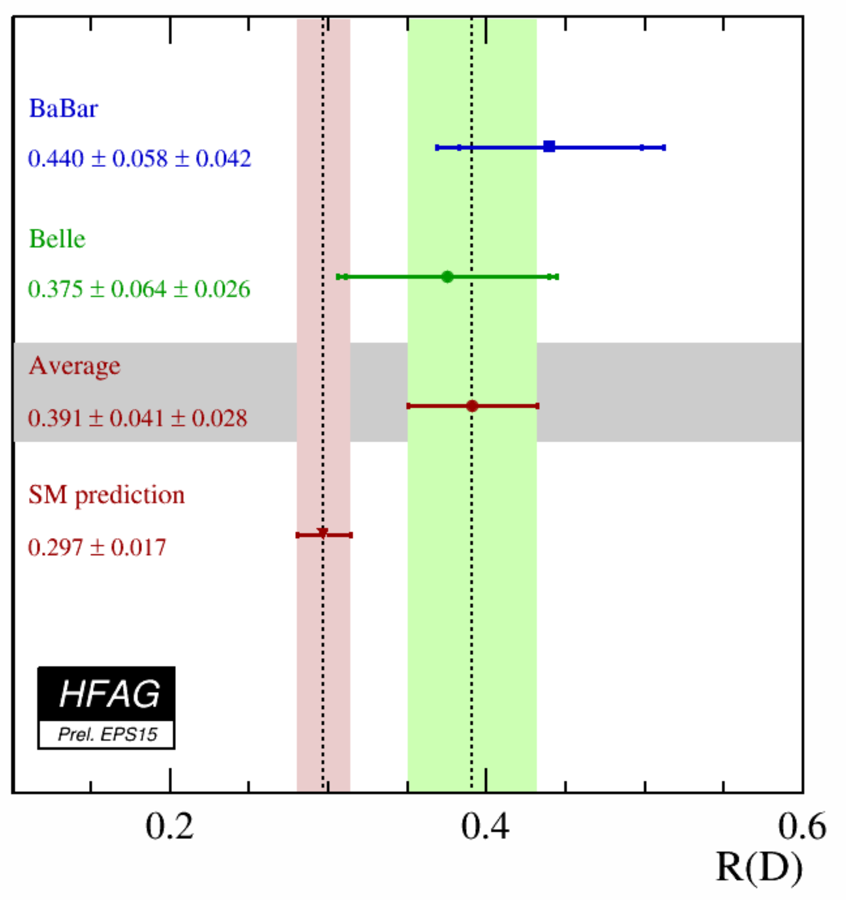
$$p_z(B^0) = \frac{m_{B^0}}{m(D^*\mu)} p_z(D^*\mu)$$

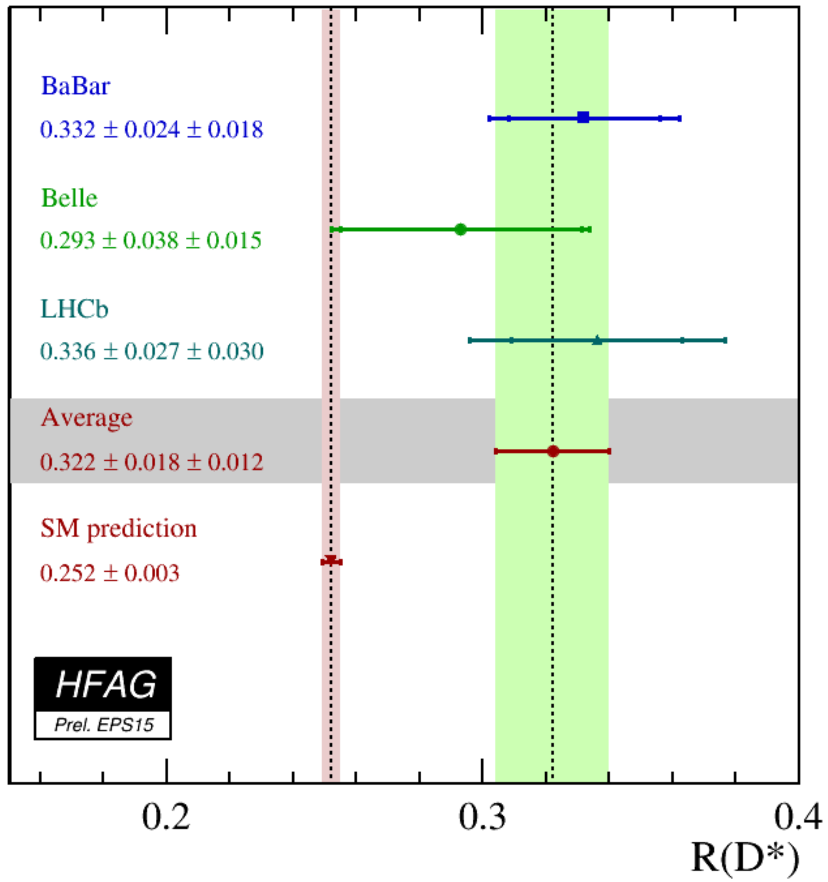


LHCb-TALK-2015-178



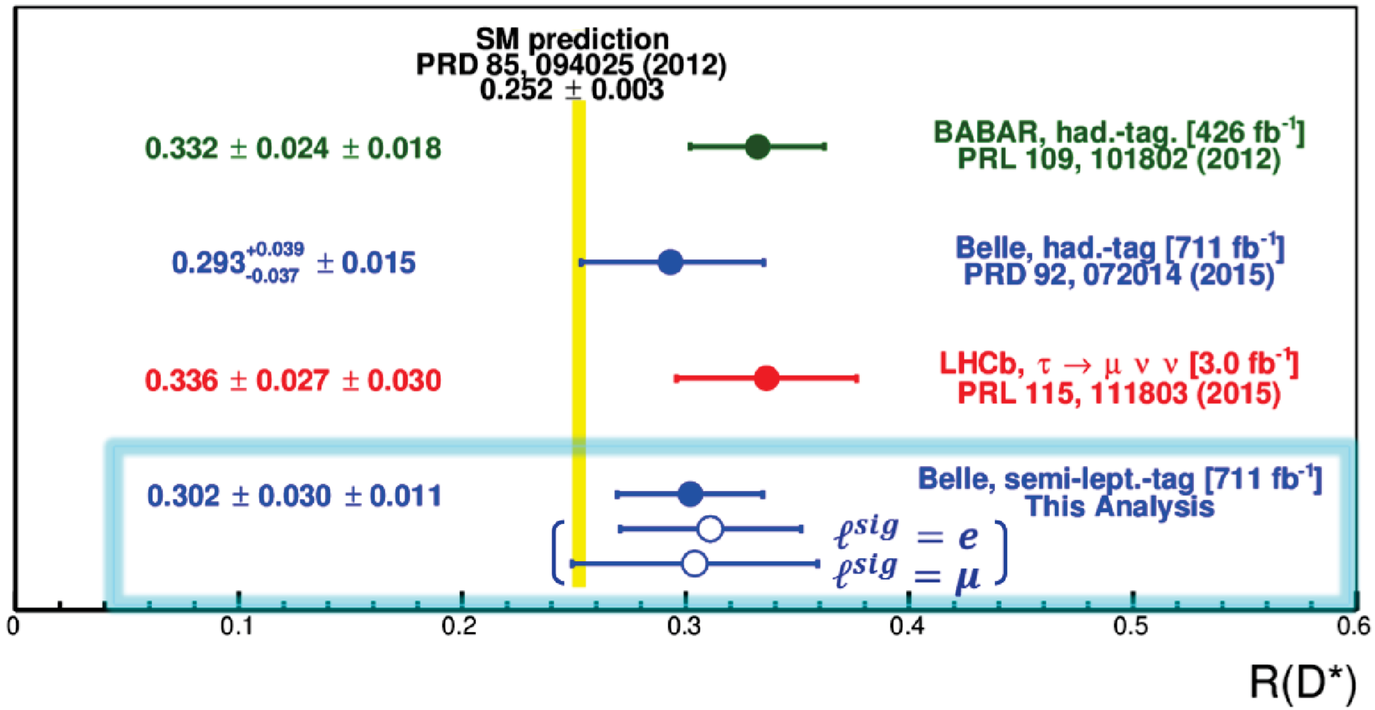
$B \to D^{(*)}\tau\nu$


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*)

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

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



PRELIMINARY – from P. Goldenzweig @ Moriond EW 2016

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

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

Time evolution of a $B^0\bar{B}^0$ 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:

$$\begin{aligned} A_{SL}^d &= (-4.1 \pm 0.6) \times 10^{-4} \\ A_{SL}^s &= (\ \ 1.9 \pm 0.3) \times 10^{-5} \end{aligned}$$

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:

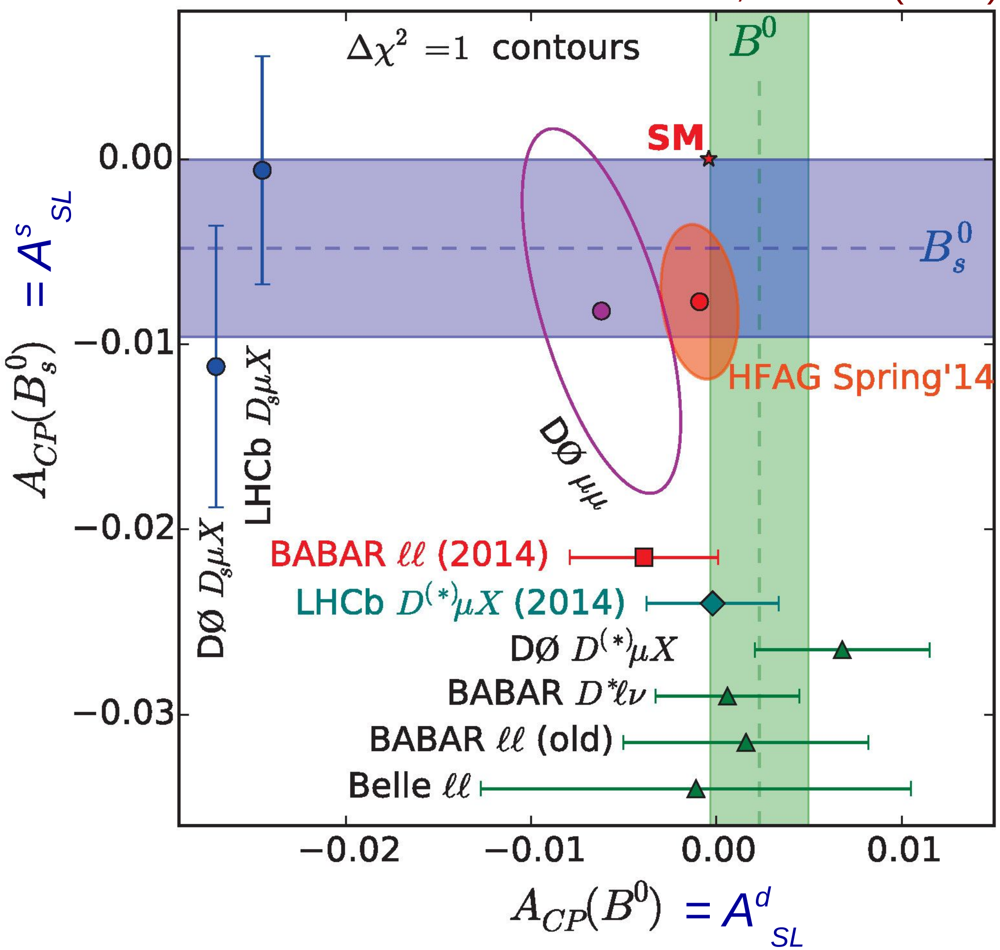
A^d_{SL}:

BaBar (ll):	(-0.39 ± 0.35 ± 0.19)%
BaBar ($D^*l\nu$):	(0.06 ± 0.17 ± 0.35)%
D0 ($D\mu X$):	(0.68 ± 0.45 ± 0.14)%
LHCb ($D\mu X$):	(0.02 ± 0.19 ± 0.30)%

A^s_{SL}:

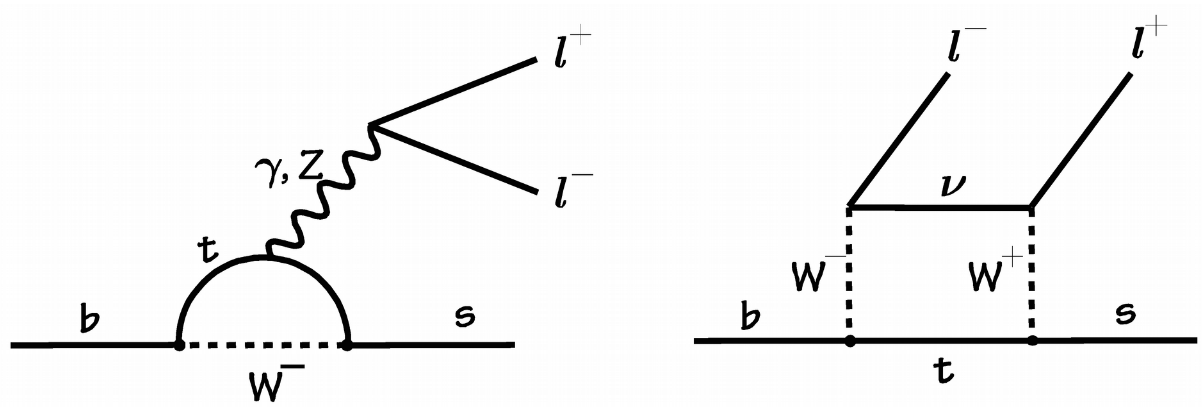
D0 ($D_s\mu X$):	(-1.12 ± 0.74 ± 0.17)%
LHCb ($D_s\mu X$):	(-0.06 ± 0.50 ± 0.36)%

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:

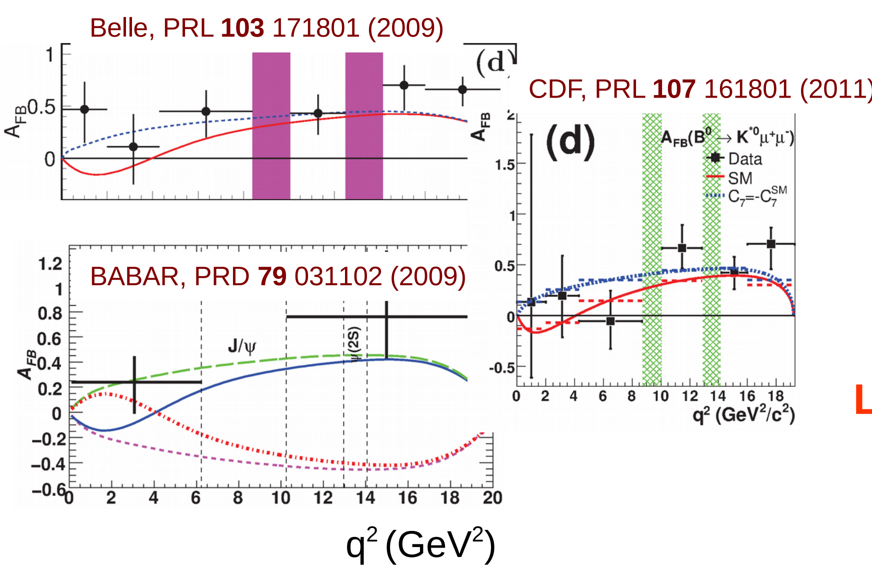
C_7: elctromagnetic penguin

C_9: vector electroweak

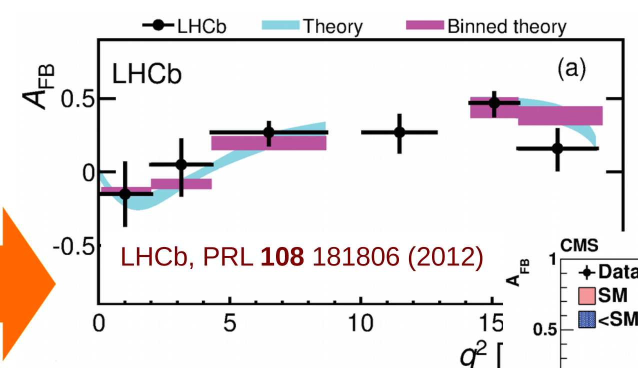
C_{10}: axial-vector electroweak

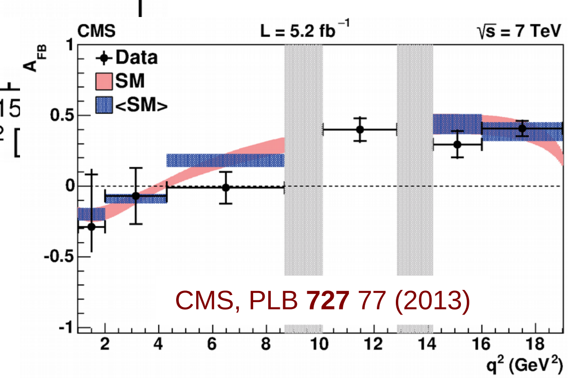
Wilson Coefficients

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



LHC turn-on

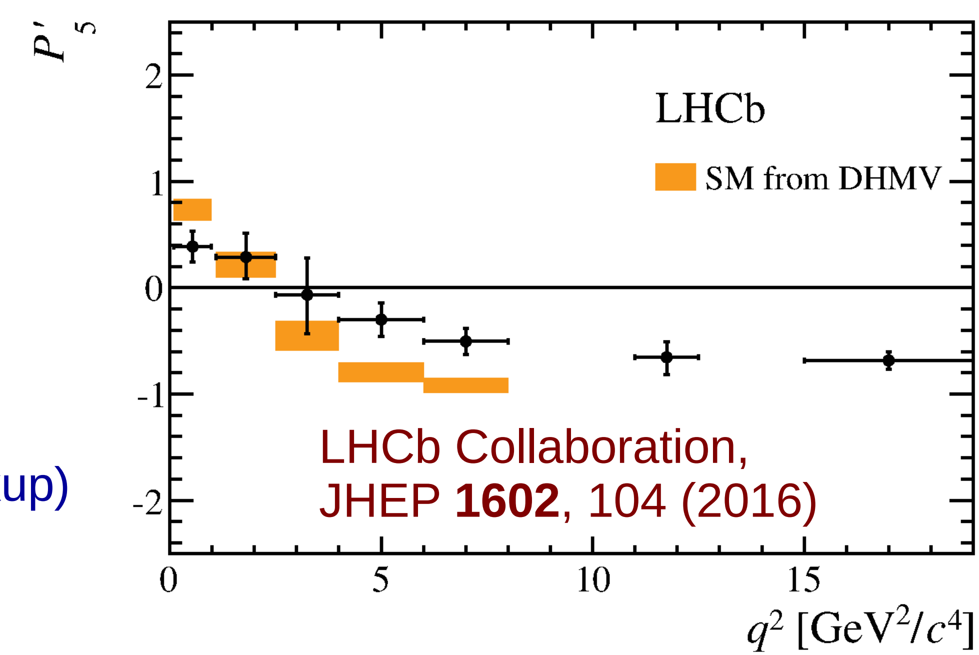




Electroweak Penguins: P'_5

- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$;
- 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)

- 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 $b \to s l^+ l^-$ decays can reveal the presence of Higgs-like particles;
- LHCb measured the ratio R_K in $B^+ \to K^+ l^+ l^-$:

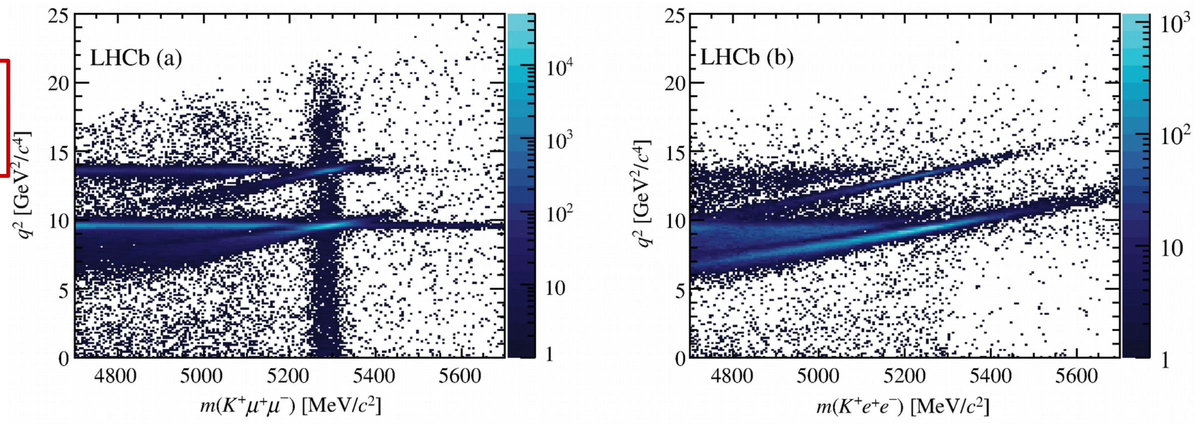
$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

≈ 1 (modulo tiny corrections)

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

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

- 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 $B^0 \to K_S\pi^0\gamma$, $B^0 \to \rho^0\ \gamma$;
  - …

Electroweak Penguins

- Definitions of main observables:

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

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

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

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

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

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

$$P_1 = \frac{2\,S_3}{(1-F_L)} = A_T^{(2)}$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)}$$

$$P_3 = \frac{-S_9}{(1-F_L)}$$

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

$$P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}$$

Electroweak Penguins: A_{FB}

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

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

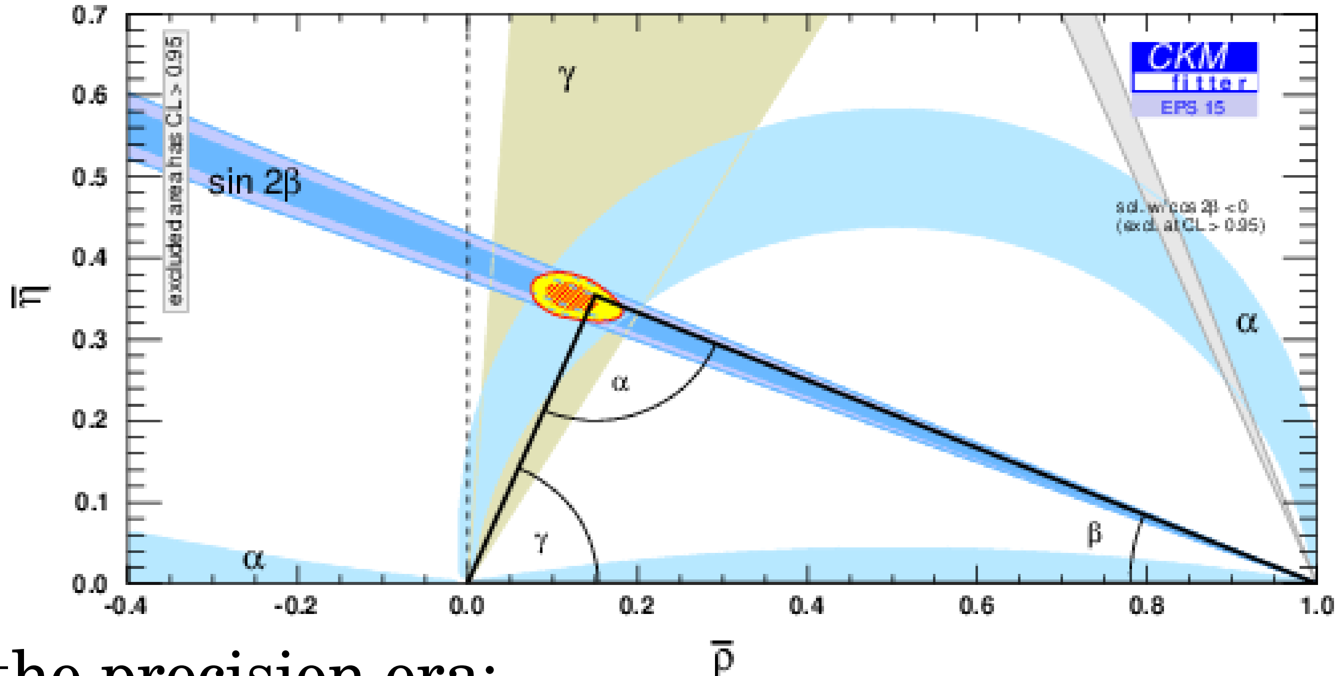
The Angles of the UT

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

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

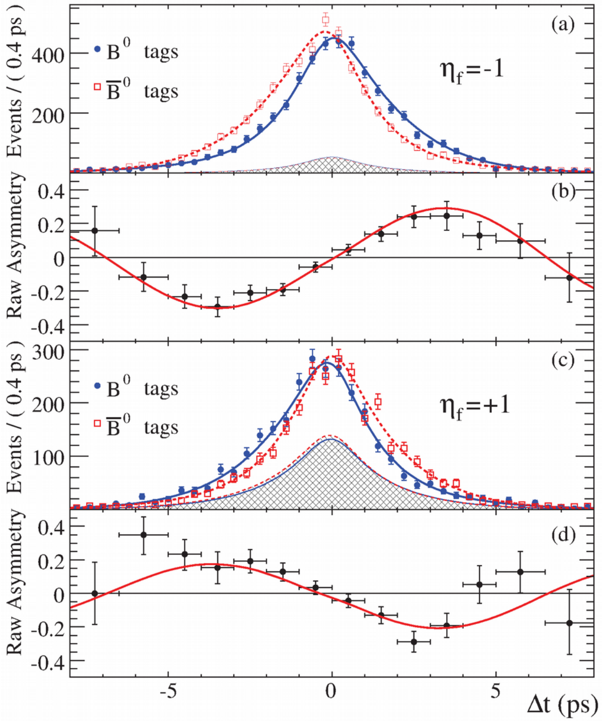
$$\beta = \phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

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



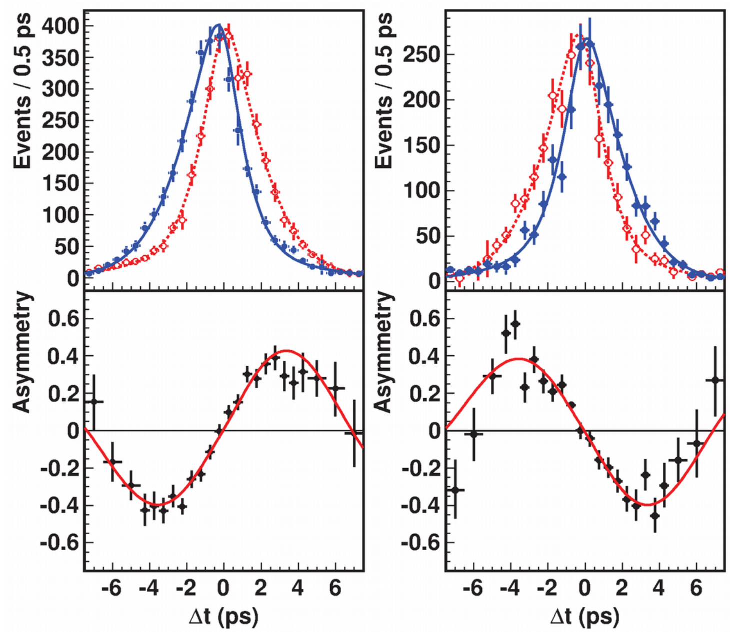
- ϕ_1/β: now well into the precision era;
- ϕ_2/α: larger theoretical and experimental uncertainties, will need to combine several modes;
- ϕ_3/γ: measured through tree level amplitudes: crucial input for the CKM fit.

ϕ_1/β from charmonium K^0



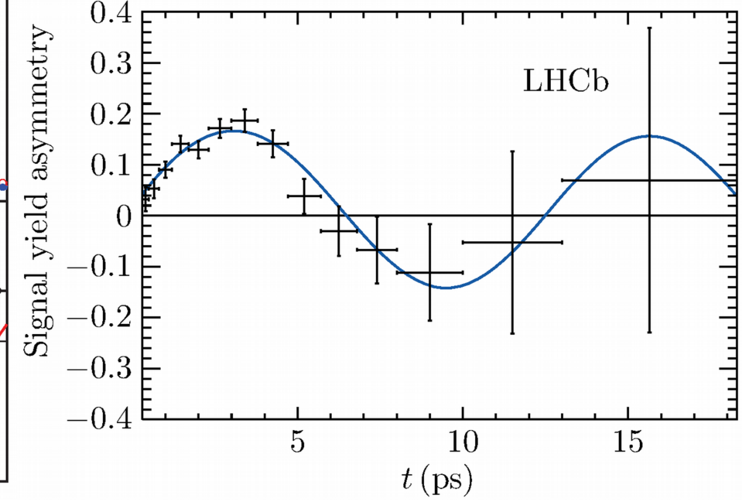
BaBar Collaboration
PRD **79**, 072009 (2009)

$$S = 0.687 \pm 0.028 \pm 0.012$$
$$C = -A = 0.024 \pm 0.020 \pm 0.016$$



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

$$S = 0.667 \pm 0.023 \pm 0.012$$
$$C = -A = -0.006 \pm 0.016 \pm 0.012$$



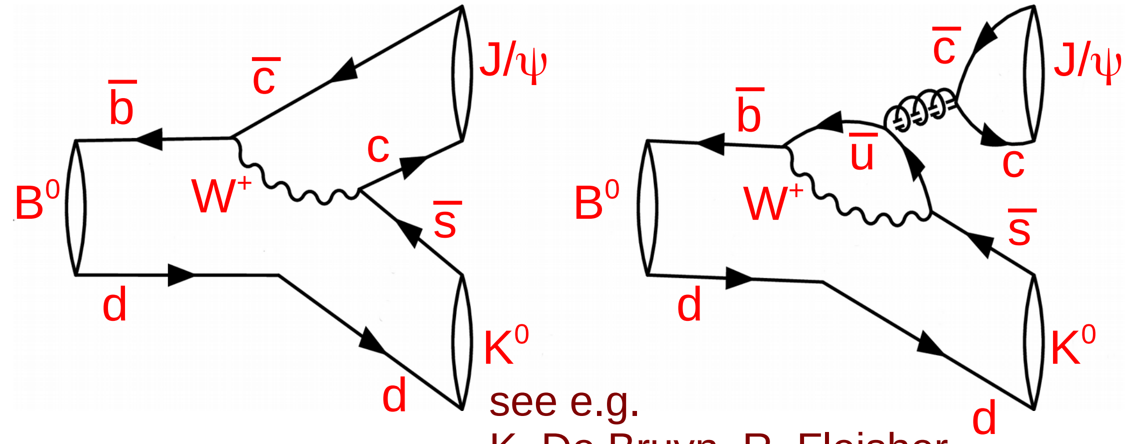
LHCb Collaboration
PRL **115**, 031601 (2015)

$$S = 0.731 \pm 0.035 \pm 0.020$$
$$C = -A = -0.038 \pm 0.032 \pm 0.005$$

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:

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

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

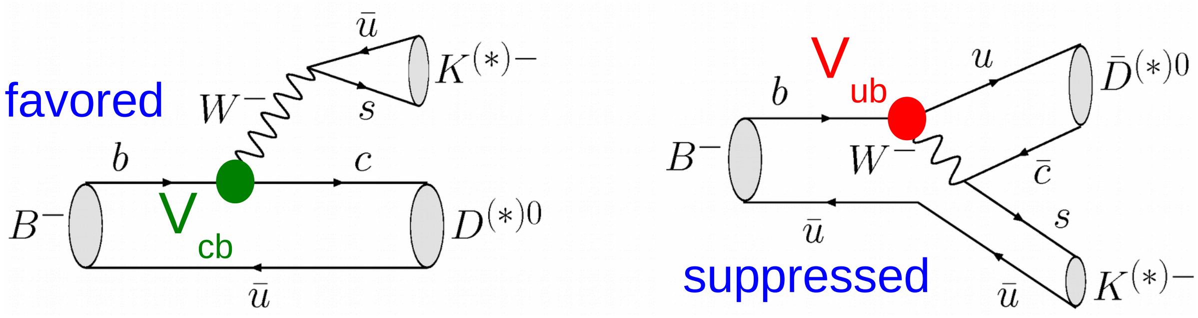
Recent measurements from LHCb:
JHEP 1506, **131** (2015)
PLB 742, **38** (2015)

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

ϕ_3/γ status

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

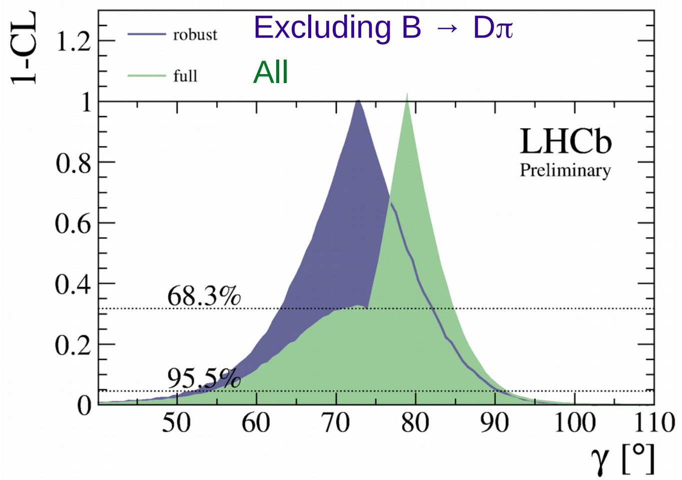
GLW - Phys. Lett. B**253**, 483 (1991)
ADS – Phys. Rev. D**63**, 036005 (2001)
GGSZ – Phys. Rev. D**68**, 054018 (2003)



~11° uncertainty from the B-factories

- LHCb is now dominating the scene:

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



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

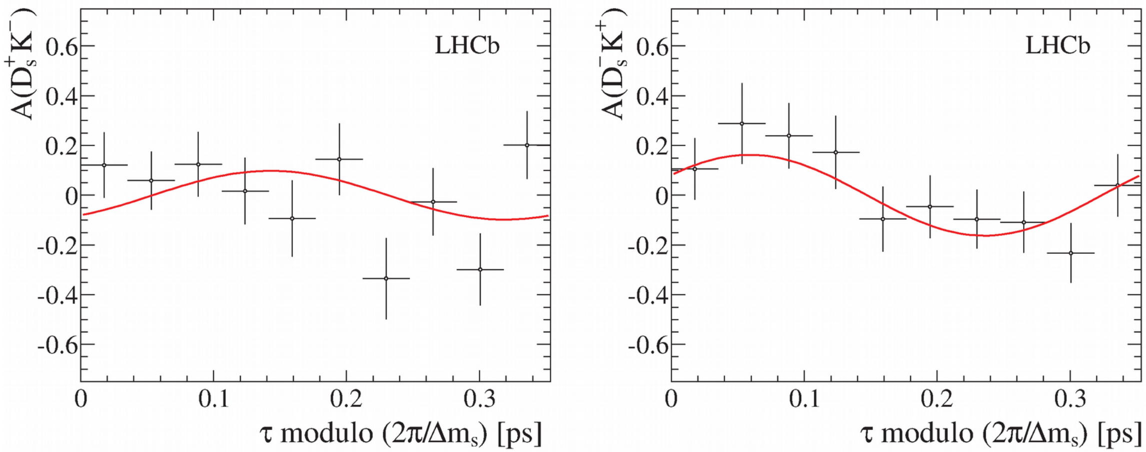
$$\gamma = (78.9^{+5.8}_{-7.4})^\circ$$

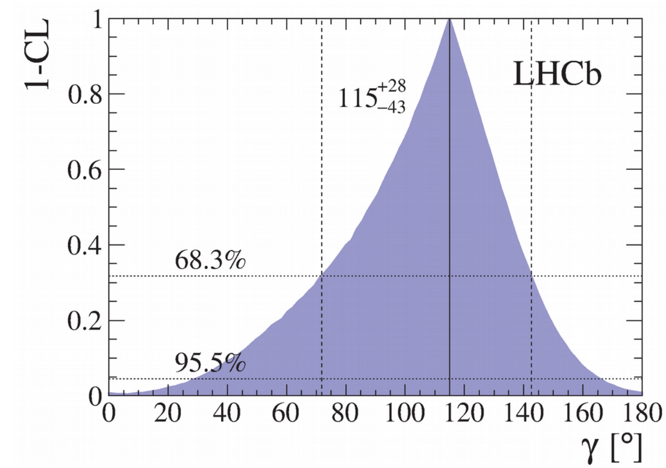
$$\gamma = (72.8^{+11.9}_{-1.3})^\circ$$

LHCb-CONF-2014-004

ϕ_3/γ outlook

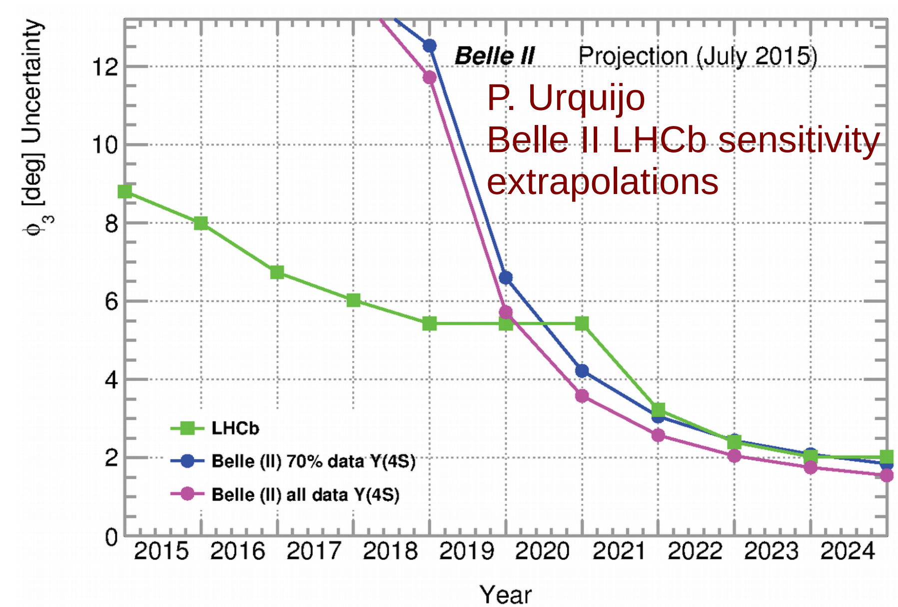
- LHCb also measures it from time dependent $B_s \to D_s^{\mp}K^{\pm}$ decays:





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

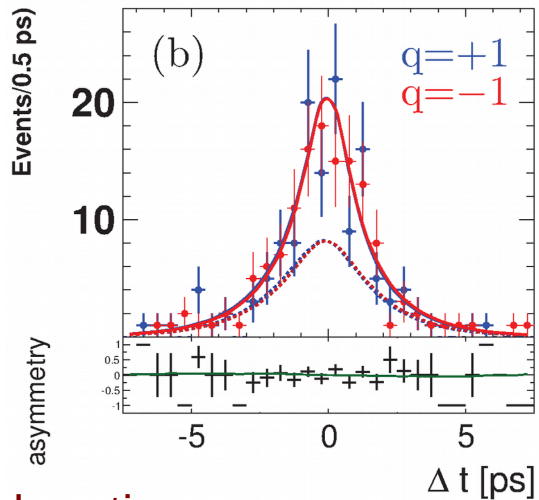
- Enormous progress expected in the next decade, the competition between LHCb and Belle II will be tight!



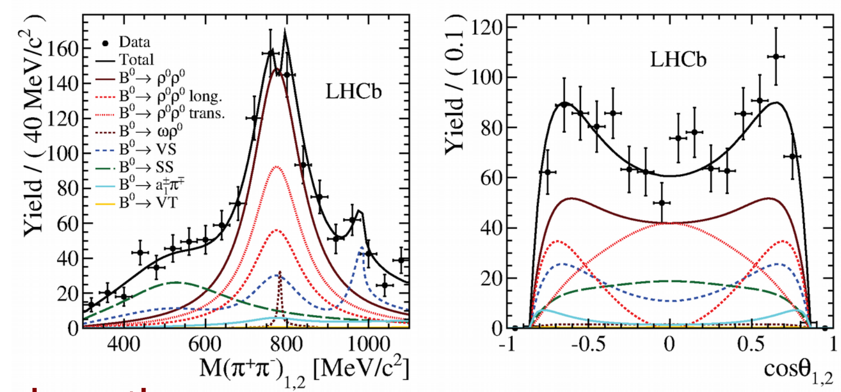
P. Urquijo
Belle II LHCb sensitivity extrapolations

ϕ_2/α status

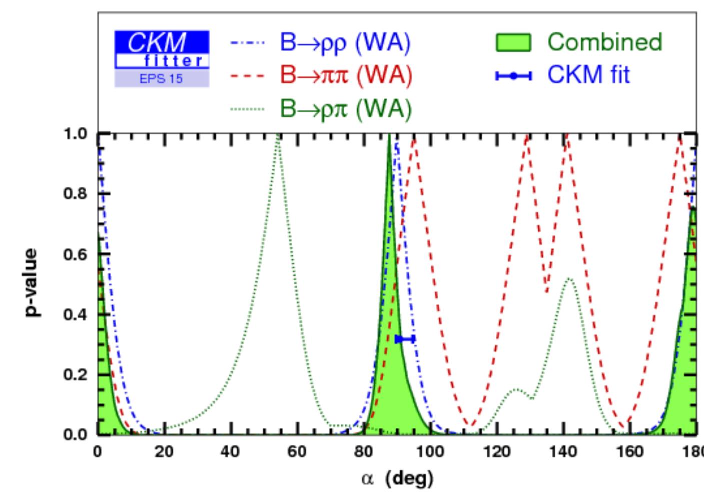
- Can be extracted in a way conceptually similar to ϕ_1/β from $B^0 \to \pi\pi$, $B^0 \to \rho\rho$, but sizable penguin pollution requires isospin analysis (and leads to ambiguities);



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



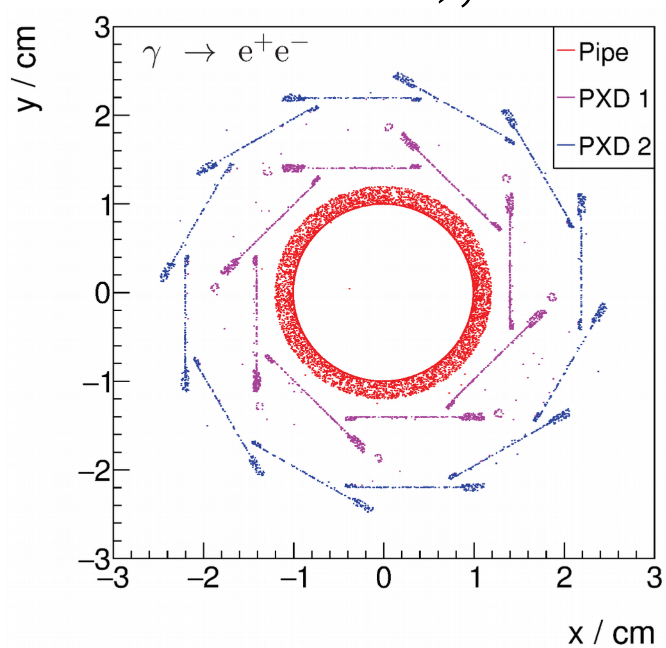
$B \to \rho^0\rho^0$
LHCb Collaboration,
PLB **747** 468 (2015)



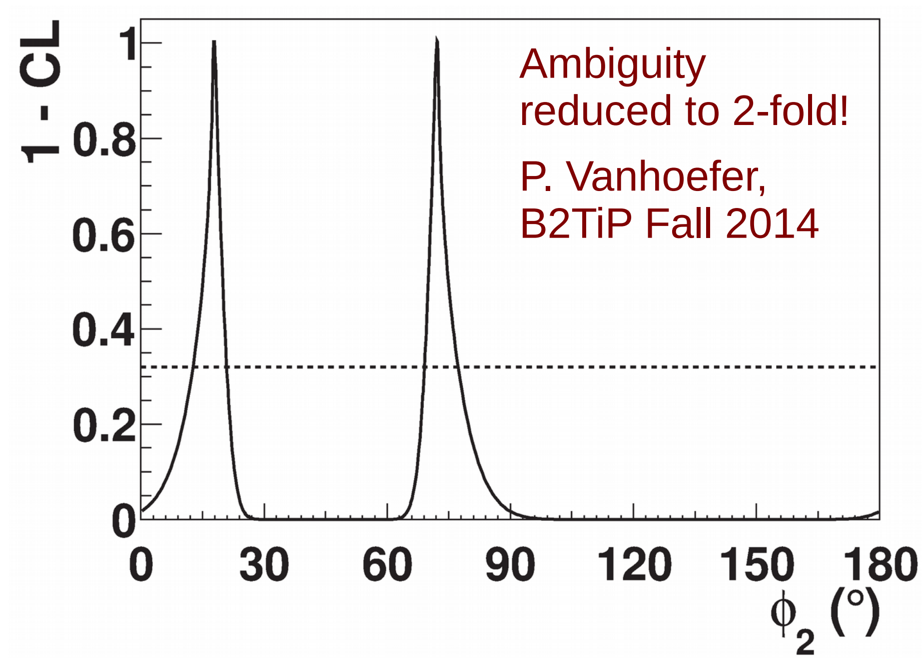
- Current precision ~8°;
- LHCb will dominate on $\rho^0\rho^0$, Belle II on $\rho^+\rho^-$, $\rho^+\rho^0$. Expected precision ~3° from both $\pi\pi$ and $\rho\rho$ by the end of Belle II.

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 $S^{\pi^0\pi^0}$ 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



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

ϕ_3/γ determinations

Decay amplitudes:

$$A(B^+) = \left[(\bar{D}^0 K^+) + r_b e^{+i\gamma + i\delta_b}(D^0 K^+)\right]$$

Weak phase changes sign

Strong phase (measured from the data) stays the same

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

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):

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

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

- 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:

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

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

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 γ through:

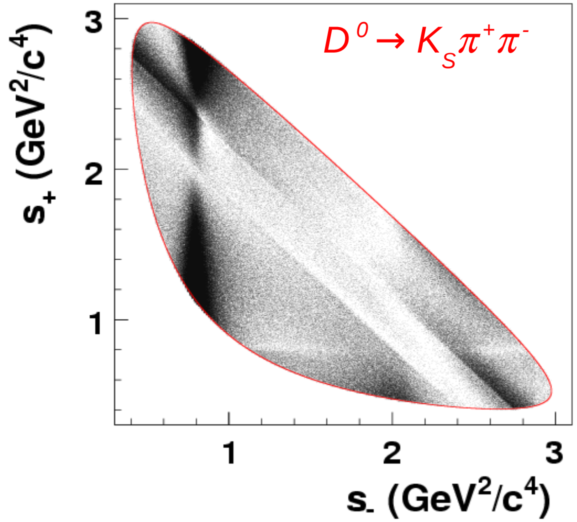
$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$$

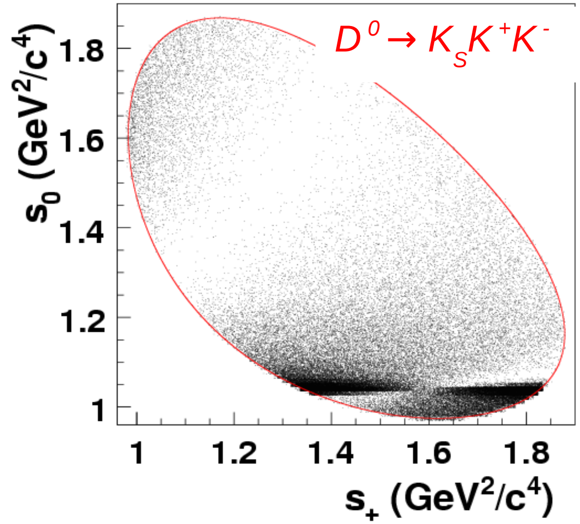
$$\mathcal{A}_{CP\pm} = \pm 2r_B \sin\delta_B \sin\gamma / \mathcal{R}_{CP\pm}$$

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;





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

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