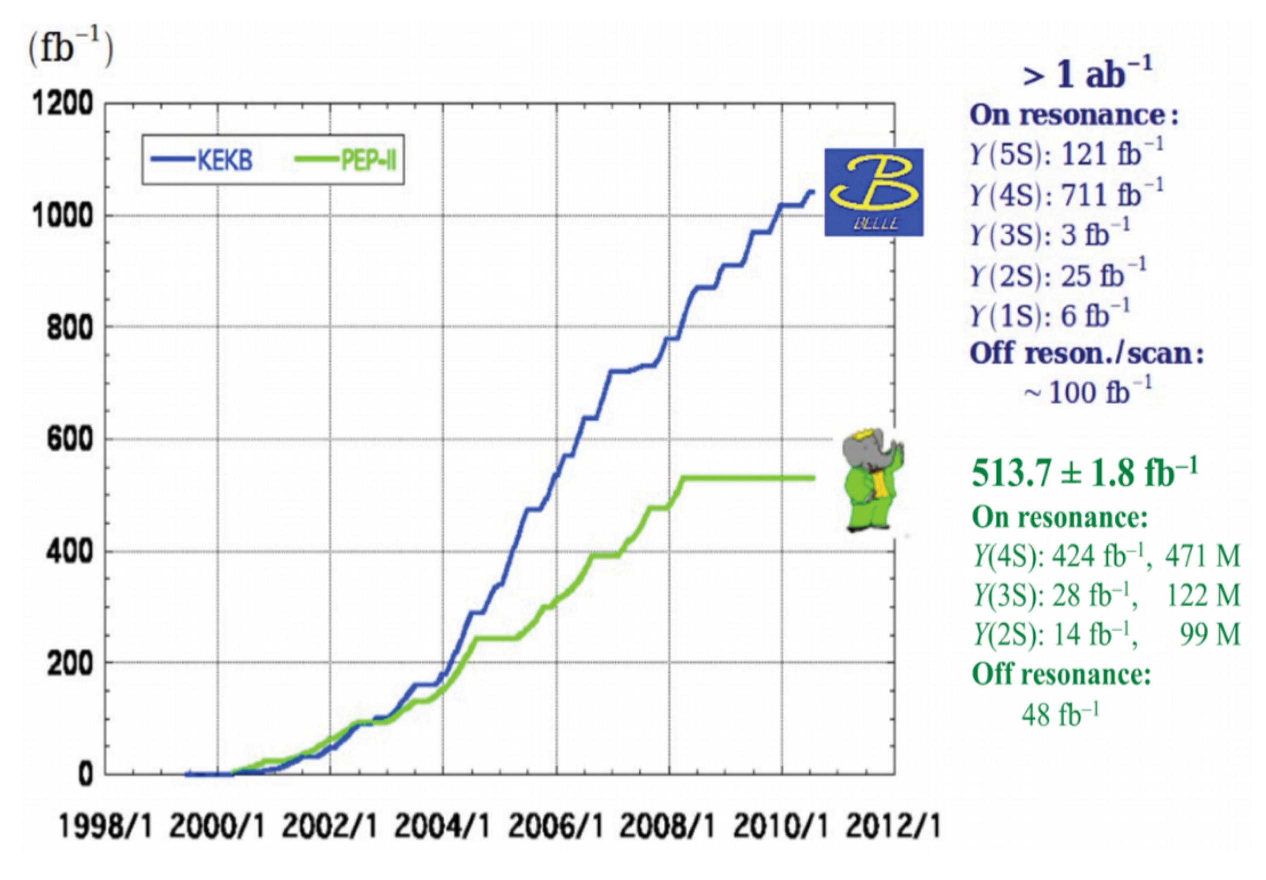
15th Conference on Flavor Physics and CP violation
9 June 2017, Prague

Belle II physics prospects

Elisa Guido
INFN Torino
(on behalf of the BELLE II Collaboration)

The B-factories legacy

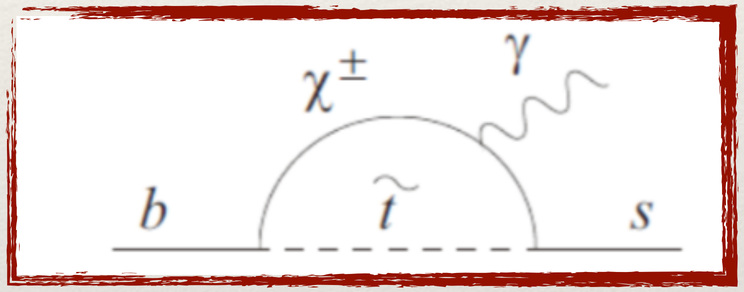
- The 1st generation of B-factories (BABAR+Belle) collected, in about a decade, more than 1.5 ab^{-1} of data, leaving a solid heritage to the future experiments:
  - discovery of CP violation, and confirmation of the CKM description of flavor physics
  - discovery of several new particles
  - precision tests of the SM → some interesting tensions



- Belle II at the SuperKEKB factory will collect 50 ab^{-1} by 2024
- Its purpose is:
  - to search for NP through precision study of rare and suppressed processes, confirming current anomalies and understanding their correlations
  - to further reveal the nature of QCD in describing matter

The intensity frontier

- Belle II will be an intensity frontier experiment
- Complementary to the energy frontier (LHC, direct searches)
  - if NP was detected at LHC, Belle II could provide determination of the flavor structure and weak phases of NP
  - if not, indirect searches could be the right path



- Advantages:
  - a full solid angle detector, within a clean environment, and with a constrained kinematics
  - missing-energy decays can be studied ($B \to \tau\nu$, $B \to D^{(*)}\tau\nu$)
  - inclusive measurements can be performed ($b \to s\gamma$, $b \to s\ell\ell$)
  - efficient reconstruction of neutrals (π^0, η, η', K_L^0)

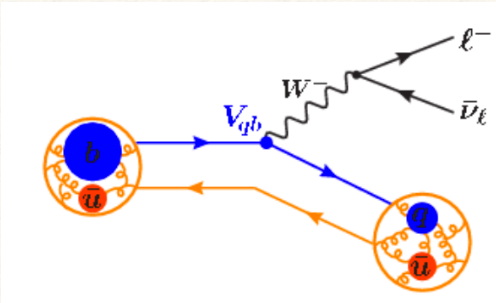
Highlights of the physics program

- The expected available physics program is wide:

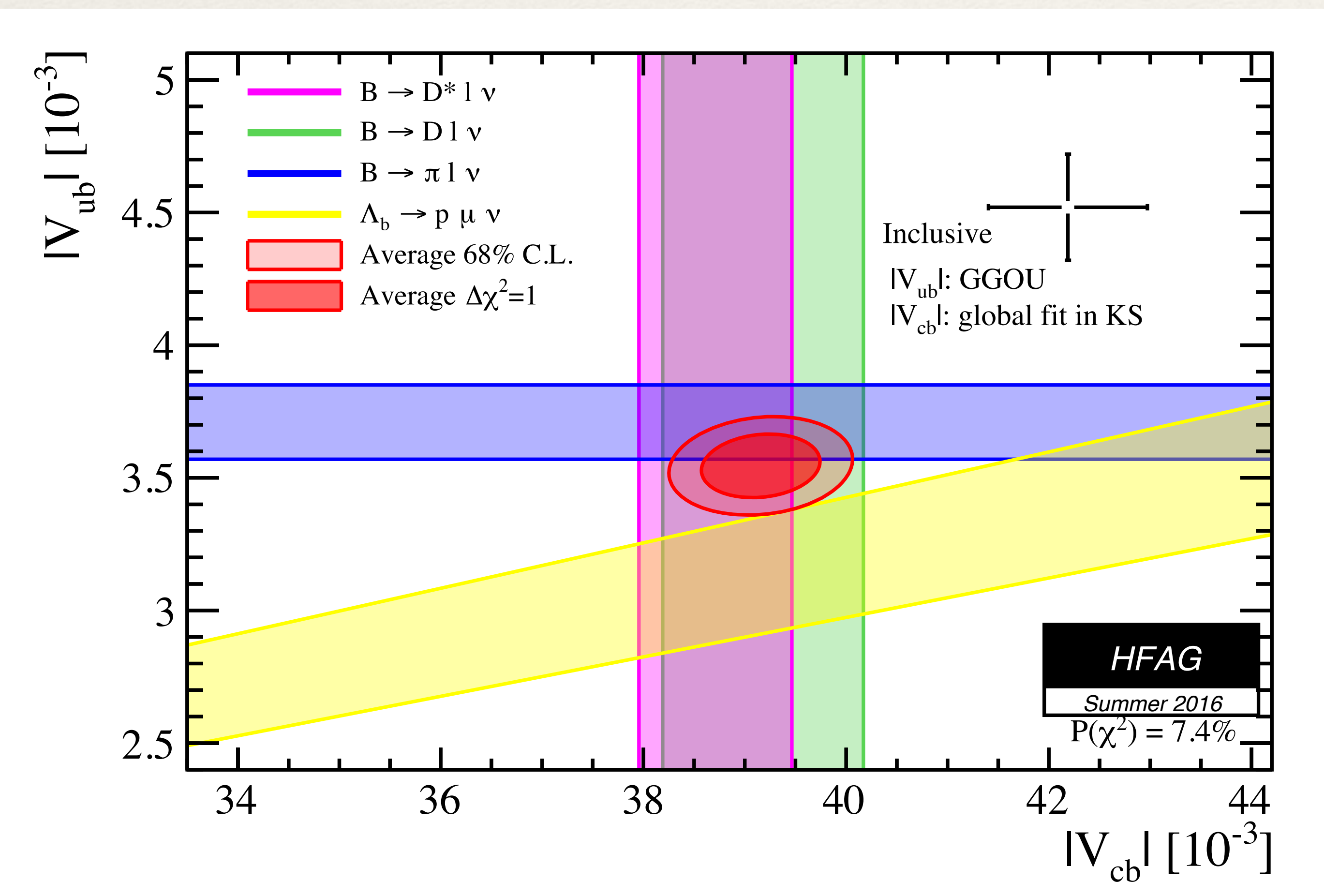
  - B physics [~1.1 x 10^9 $B\bar{B}$ pairs / ab^{-1}]: neutral B mixing, penguin B decays, semileptonic B decays
  - charm physics [~1.3 x 10^9 $c\bar{c}$ pairs / ab^{-1}]: mixing, CPV in charm, rare decays
  - τ-physics [~0.9 x 10^9 $\tau^+\tau^-$ pairs / ab^{-1}]: LFV beyond SM
  - Initial State Radiation: $e^+e^- \to$ light hadrons cross section
  - bottomonium spectroscopy and search for exotic states
  - direct searches of NP at the MeV-GeV scale (dark sector)

- A (not exhaustive) selection of topics will be presented in this talk
- Many details are available in the B2TiP report: detector, simulation, software, analysis tools, physics program (https://confluence.desy.de/display/BI/B2TiP+ReportStatus), to be published in 2017

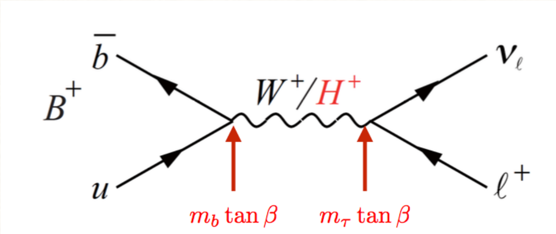
Semileptonic B decays



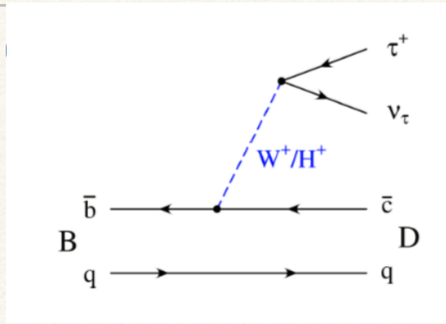
- Used at Belle+BABAR to precisely determine the CKM parameters $|V_{ub}|$ and $|V_{cb}|$
- At the end of the B-factories era, <u>tension between inclusive and exclusive measurements</u>



- Determine new techniques to understand this tension, exploiting a larger dataset
- Improvement of theoretical predictions is crucial
- LHCb can also contribute ($|V_{ub}|$ from barionic decays, **Nature Phys.11 (2015) 743**)
- Belle II will have access to more processes

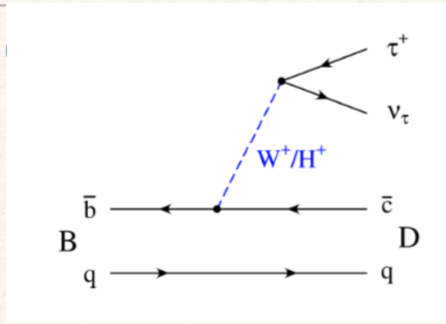


B→τν and B→D$^{(*)}$τν



- (Semi)leptonic modes with a τ lepton are also very sensitive to NP, in the form of a charged Higgs contribution

B→τν and B→D$^{(*)}$τν



- (Semi)leptonic modes with a τ lepton are also very sensitive to NP, in the form of a charged Higgs contribution

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

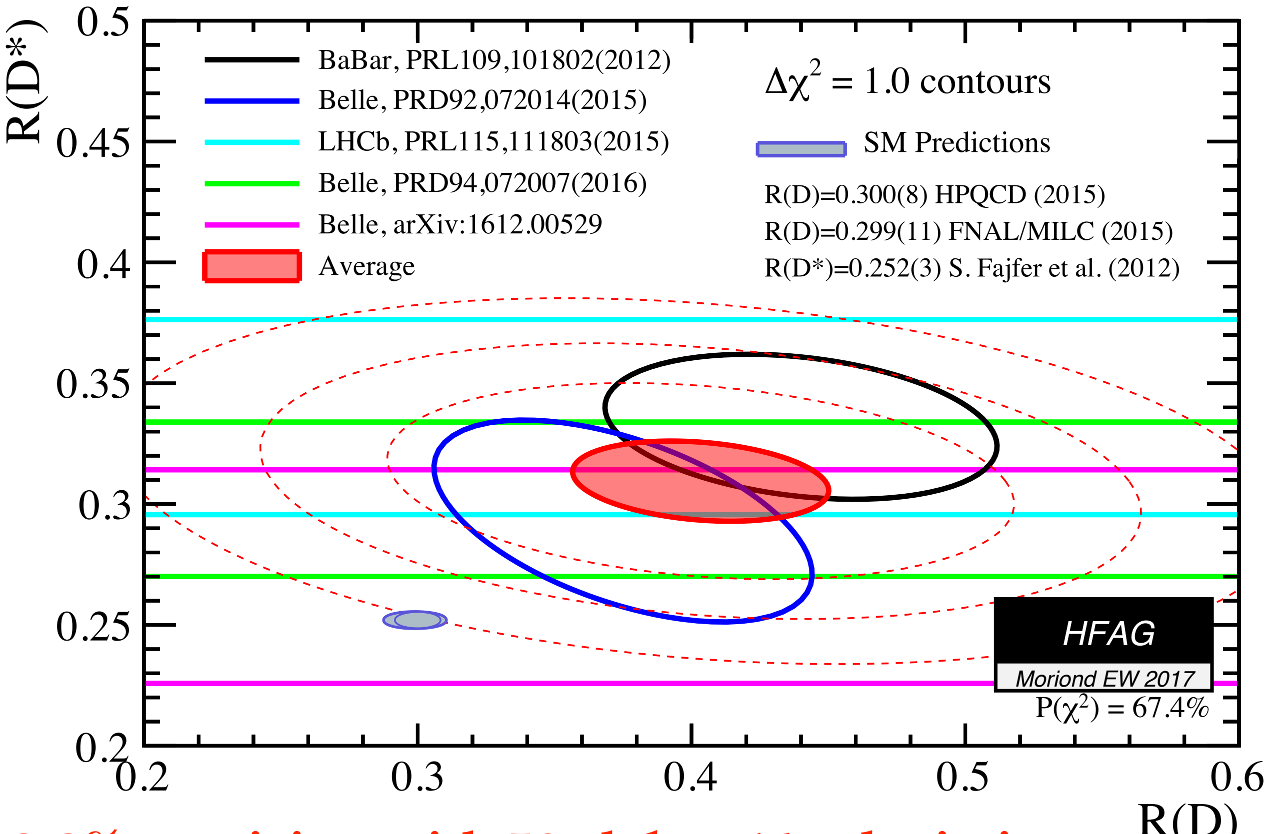
- 4σ deviation from the SM observed in B→D$^{(*)}$τν
  - Very clean theoretical predictions:

$R(D) = 0.300 \pm 0.008, 0.299 \pm 0.011$ **[HPQCD 2015, FNAL/MILC 2015]**

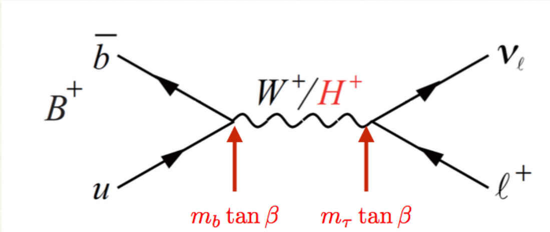
$R(D^*) = 0.252 \pm 0.003$ **[S. Fajfer et al. 2012]**

  - With 50 ab^{-1} the experimental sensitivity will be comparable to the current theoretical precision
  - interest in D* and τ polarizations:
    - τ polarization already measured by Belle **[arXiv:1612.00529, accepted by PRL]**

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



~2-3% precision with 50 ab^{-1} → 14σ deviation

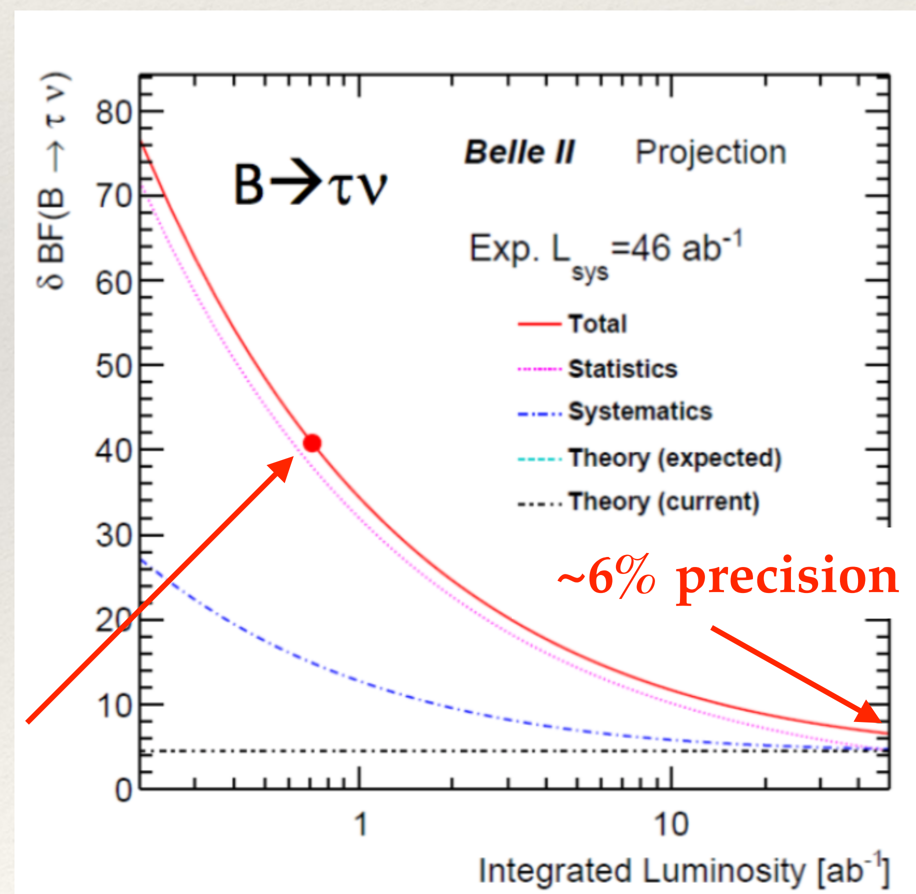


B→τν and B→D$^{(*)}$τν

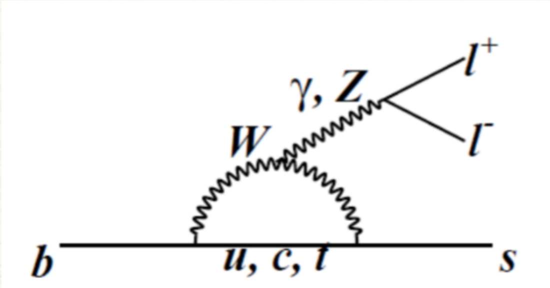
- (Semi)leptonic modes with a τ lepton are also very sensitive to NP, in the form of a charged Higgs contribution

- Current world average (hadronic and semileptonic tags) BF = (1.09 ± 0.24) 10^{-4}
- No deviation from the SM observed in B→τν so far

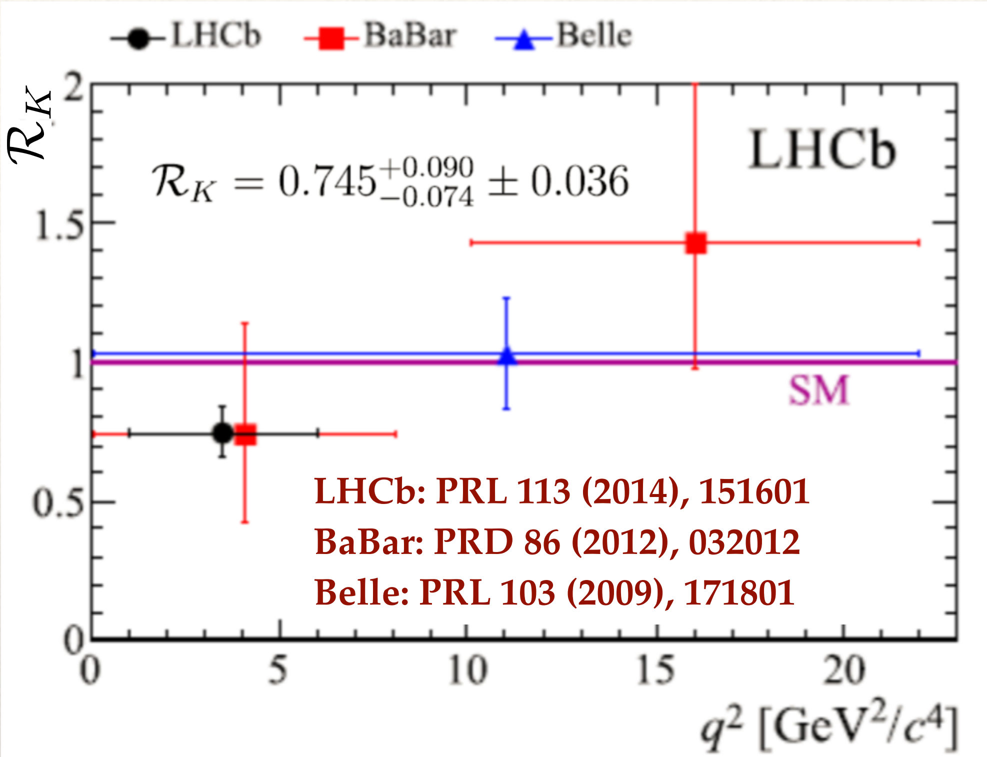
- With 50 ab^{-1} the experimental sensitivity will reach ~6%



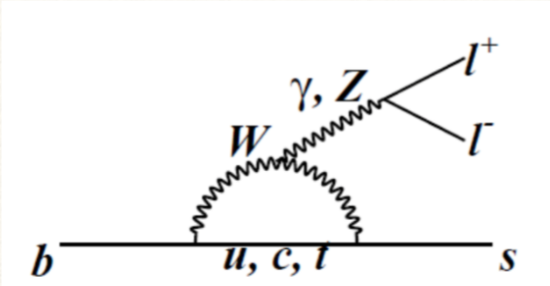
Electroweak penguins



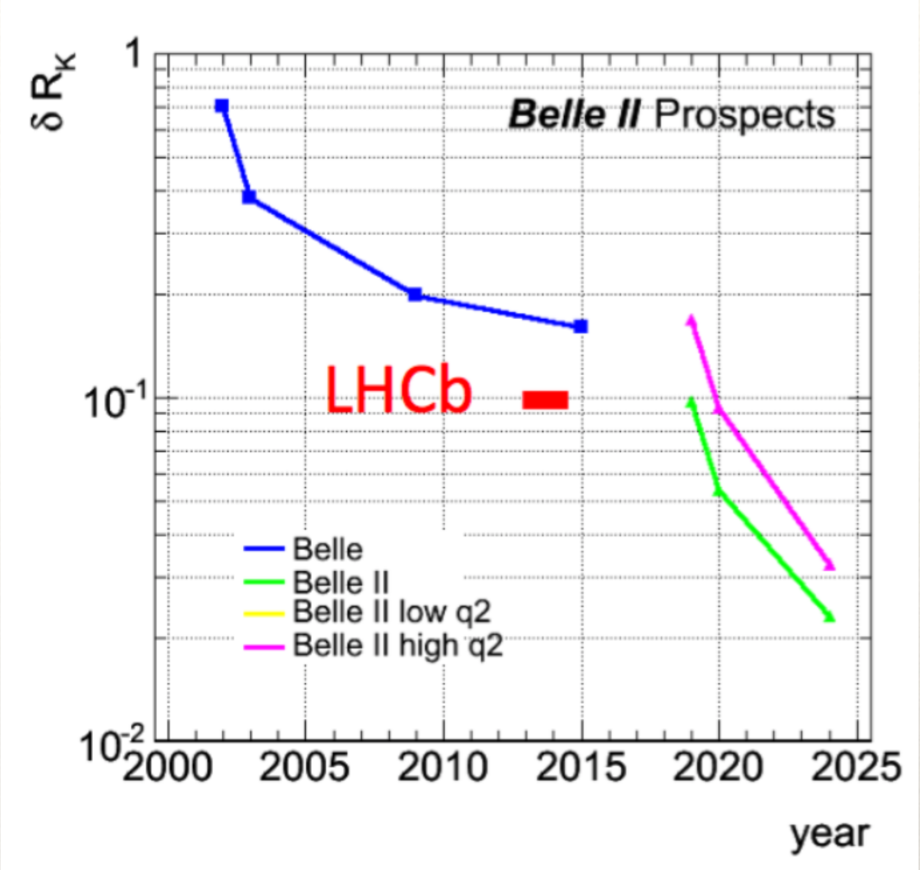
- B→Kℓℓ, for lepton universality: $\mathcal{R}_K = \frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)} \sim 1$
- LHCb reported a 2.6σ deviation from SM expectation
- b→see modes difficult at LHCb at high q²



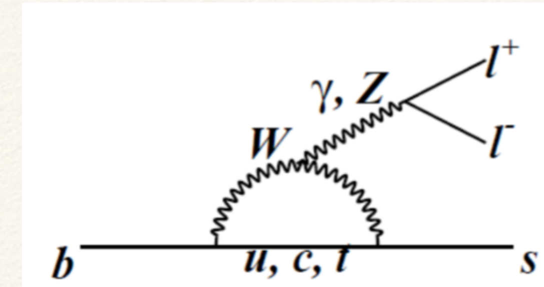
Electroweak penguins



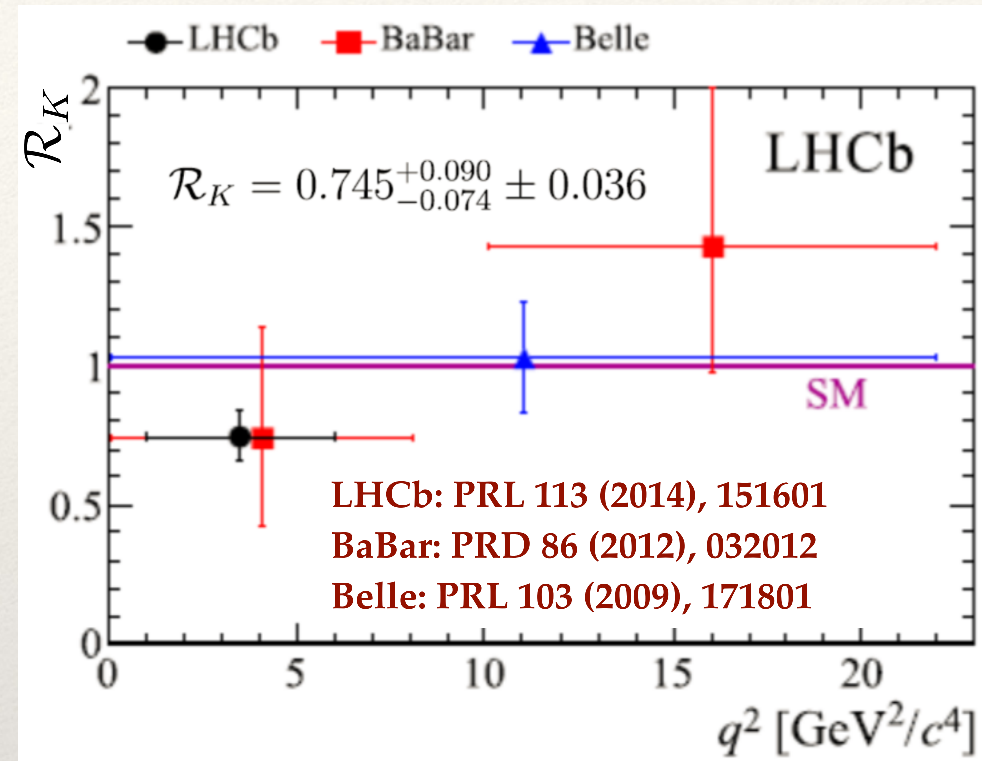
- B→Kℓℓ, for lepton universality: $\mathcal{R}_K = \frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)} \sim 1$
- LHCb reported a 2.6σ deviation from SM expectation
- b→see modes difficult at LHCb at high q^2
- At Belle II the same detection efficiency is expected for electrons and muons, at both low and high q^2



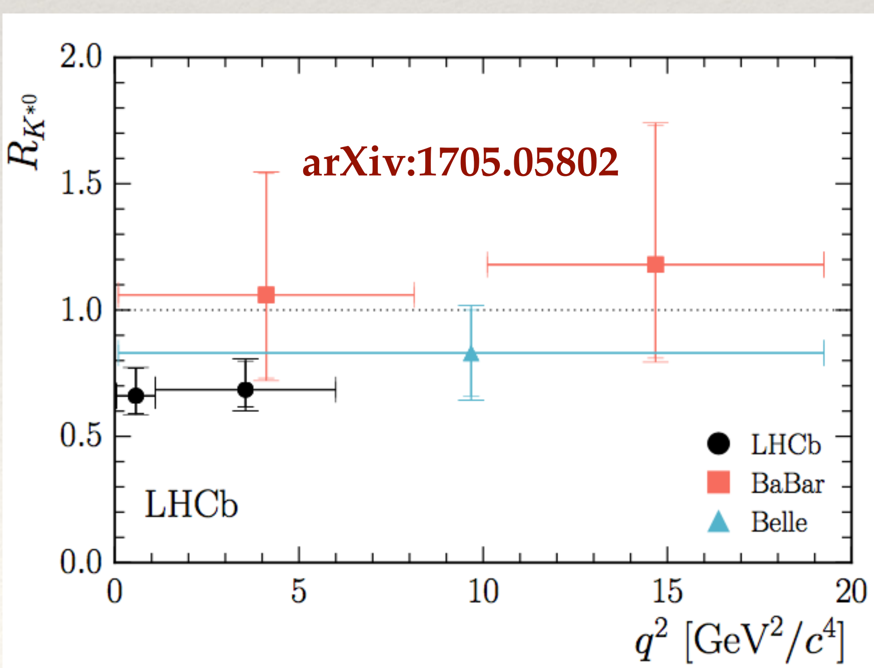
Electroweak penguins



- B→Kℓℓ, for lepton universality: $\mathcal{R}_K = \frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)} \sim 1$
- LHCb reported a 2.6σ deviation from SM expectation
- b→see modes difficult at LHCb at high q^2
- At Belle II the same detection efficiency is expected for electrons and muons, at both low and high q^2



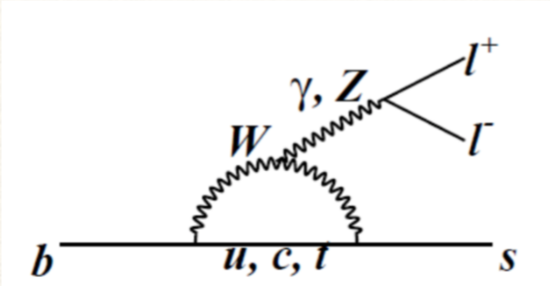
- Very recent result by LHCb $B^0 \to K^{*0}\ell\ell$:



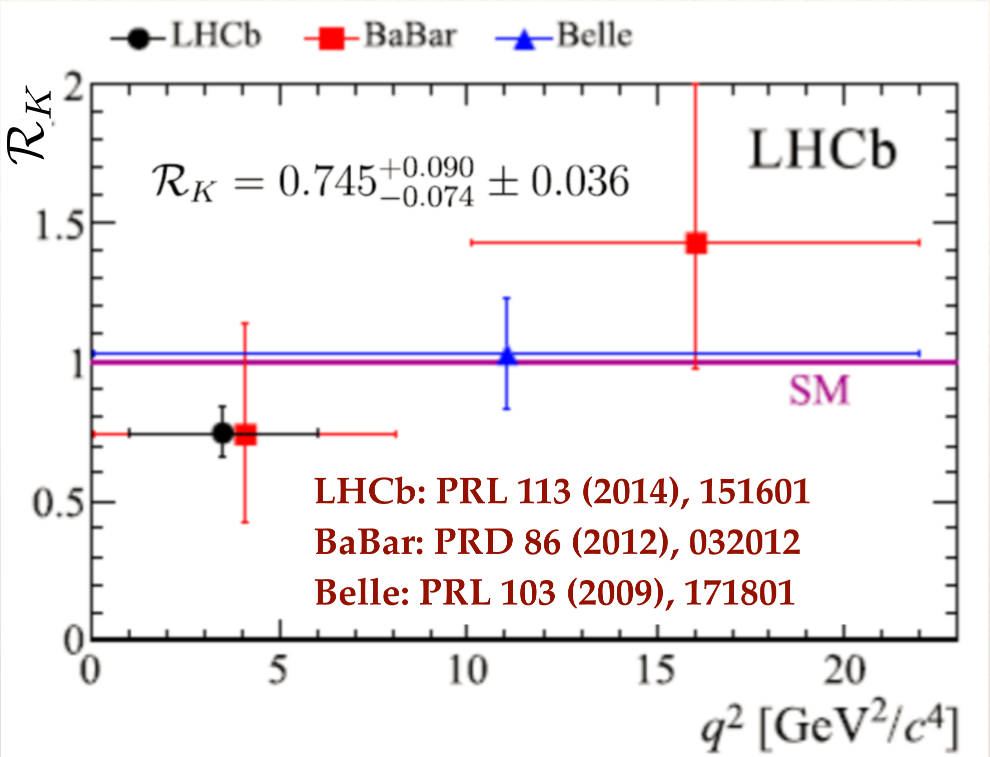
$$R_{K^{*0}} = \begin{cases} 0.66\ {}^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4\,, \\ 0.69\ {}^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1\ \ < q^2 < 6.0\ \text{GeV}^2/c^4\,. \end{cases}$$

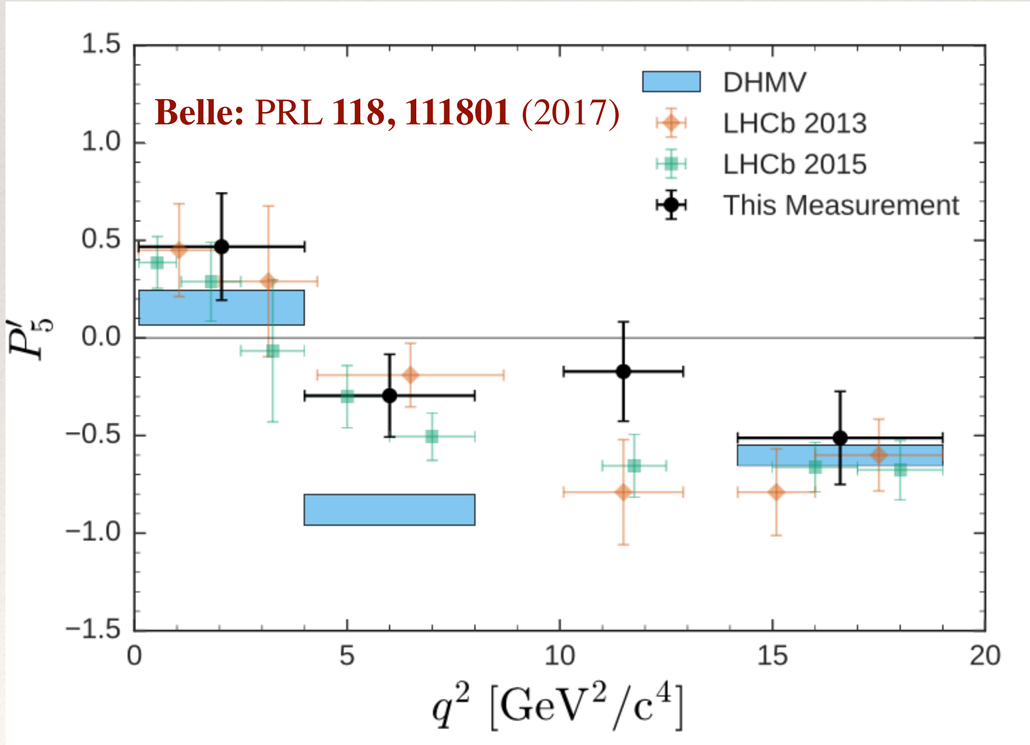
- 2.1-2.5σ deviation from SM expectation, depending on the q^2 region and prediction considered

Electroweak penguins



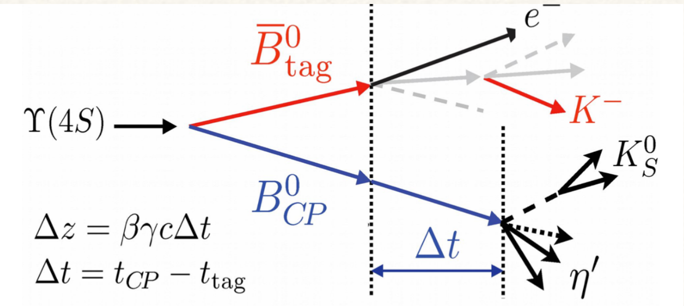
- B→Kℓℓ, for lepton universality: $\mathcal{R}_K = \frac{\mathcal{B}(B\to K\mu\mu)}{\mathcal{B}(B\to Kee)} \sim 1$
- LHCb reported a 2.6σ deviation from SM expectation
- b→see modes difficult at LHCb at high q^2
- At Belle II the same detection efficiency is expected for electrons and muons, at both low and high q^2





- 2.6σ tension with the SM also in the angular distribution of B→K*ℓℓ
- Can these anomalies be fit together? NP contributions to the Wilson coefficients
- Confirmation of these measurements by Belle II will be important

Time-dependent CPV



- Among the benchmark measurements at the B-factories
- Access to the weak phase of the CKM matrix, through interference between mixing and decay

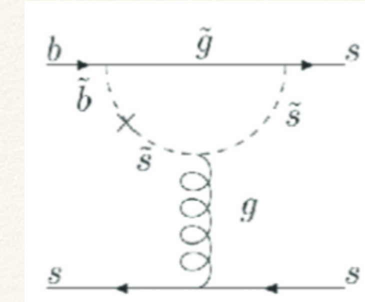
- Precise determination of sin2β still important at Belle II:
  - check consistency of unitarity triangle
  - search for new CP violating phases in b→s by testing the SM prediction:

$$\sin 2\beta(b \to s q\bar{q}) = \sin 2\beta(J/\psi K)$$

- Involve all the aspects of the detector:
  - tracking
  - neutrals reconstruction
  - vertexing
  - PID
  - flavor tagging
  - background rejection

- Significant improvements expected at Belle II:
  - improved Δt resolution (30% wrt Belle)
  - enhanced flavor tagging efficiency

Time-dependent CPV



- Belle result on full dataset from $B \to c\bar{c}K^0$ (**PRL 108 (2012), 171802**):

$$\mathcal{S} = (0.667 \pm 0.023 \pm 0.012)$$
$$\mathcal{A} = (0.006 \pm 0.016 \pm 0.012)$$

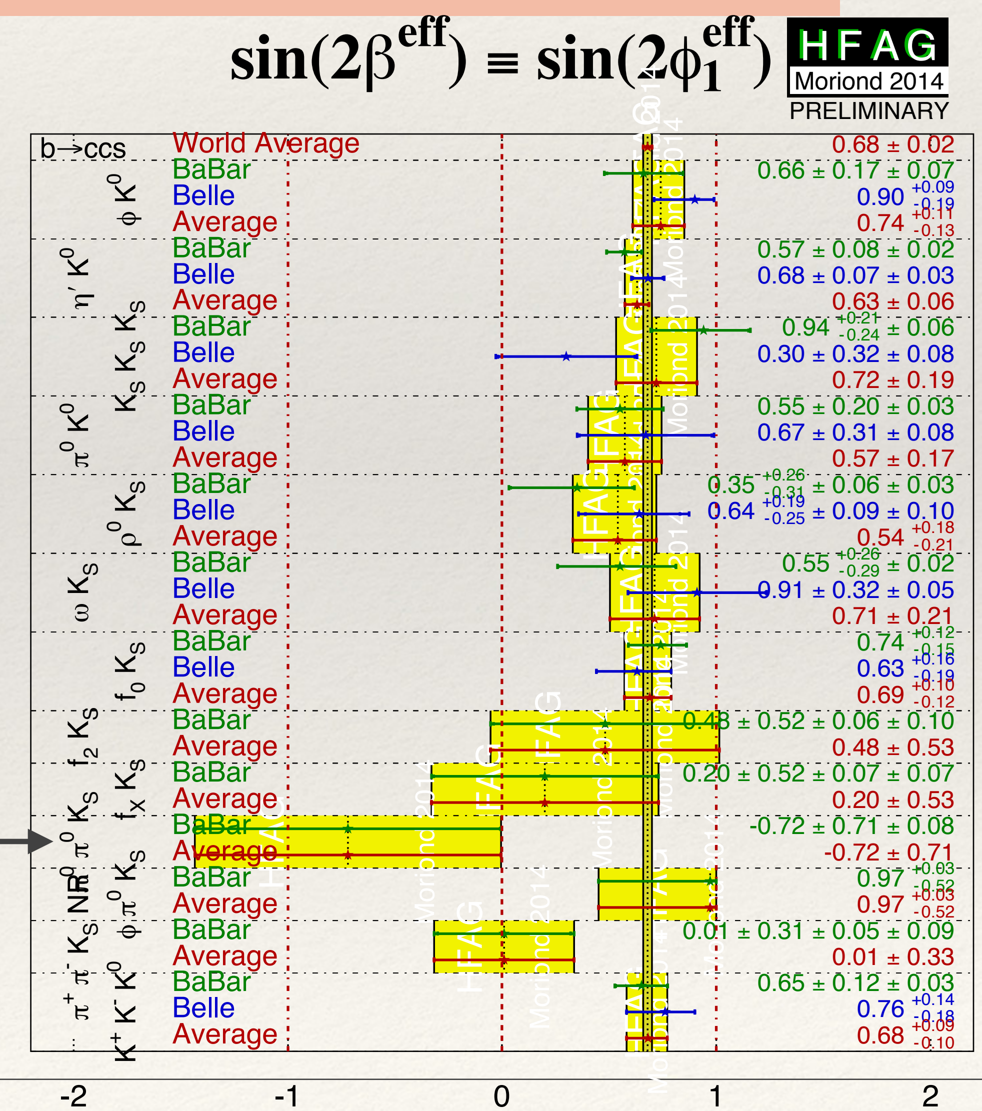
- Belle II expected sensitivity on 50 ab^{-1}:
  → **dominated by systematic uncertainties!**

$$\mathcal{S} = (x.xxxx \pm 0.0027 \pm 0.0044)$$
$$\mathcal{A} = (x.xxxx \pm 0.0033 \pm 0.0037)$$

- Several golden modes to search for additional CP-violating phases, given by particles beyond the SM entering the loop
  - $B \to \phi K_S$
  - $B \to \eta' K_S$
  - $B \to K_S K_S K_S$

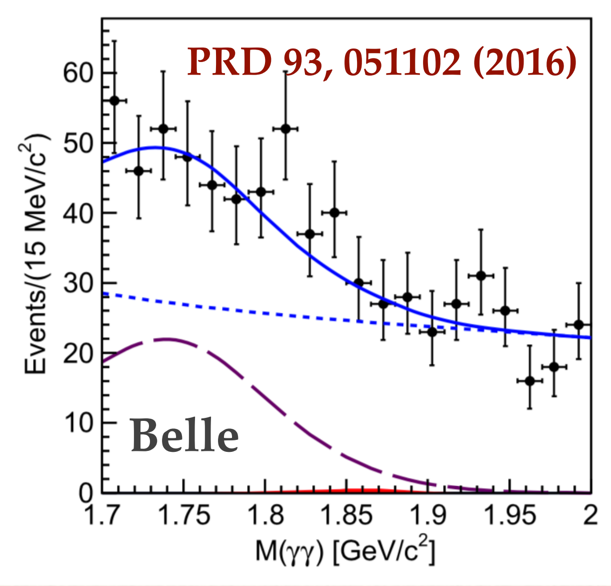
Mode	50 ab^{-1}	
	$\sigma(\mathcal{S})$	$\sigma(\mathcal{A})$
$\eta' K^0$	0.011	0.009
ϕK^0_S	0.018	0.023
$K_S K_S K_S$	0.033	0.021

- Theoretically clean (~2%)
- Current measurements consistent with $J/\psi K_S$
- Expected errors at Belle II at the same level of the theoretical ones

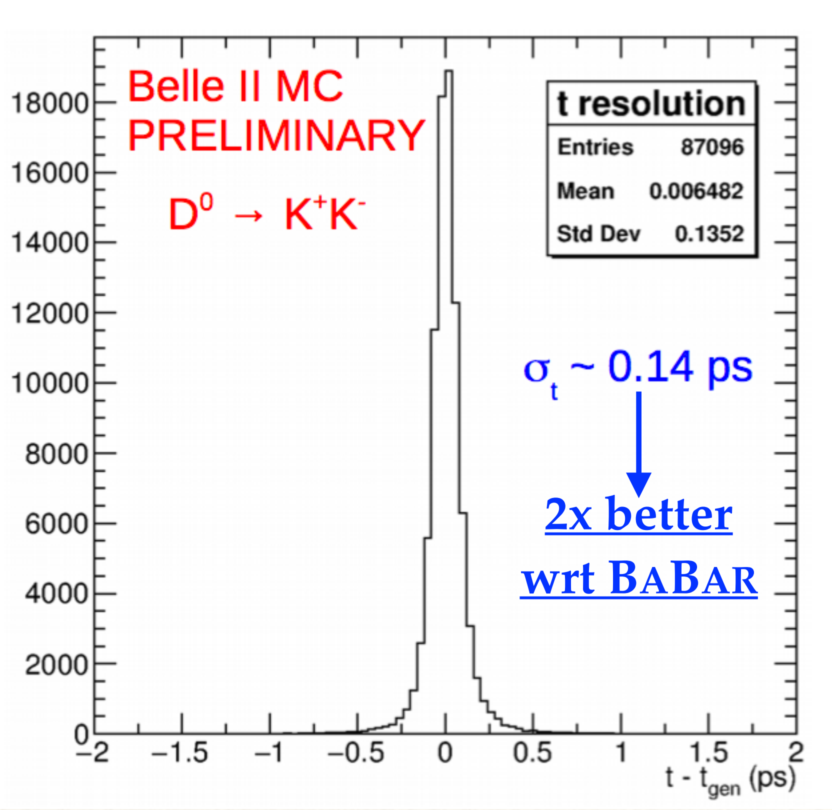


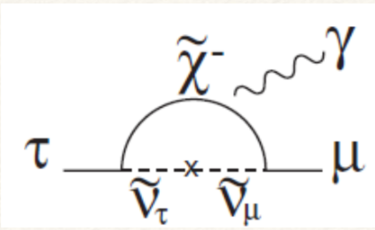
Charm physics

- B-factories discovered D^0-$\bar{D}^0$ mixing
- To-do-list for Belle II:
  - improve the measurements of mixing parameters
  - look for direct and indirect CPV
  - search for rare decays
  - …
- Advantages with respect to LHCb:
  - semileptonic decays (neutrinos in the final states)
  - rare decays:
    - FCNC mode $D^0 \to \gamma\gamma$ expected BF ~ 10^{-8}
    - Belle: BF < 8.5 10^{-7} @90% CL
    - Belle II sensitivity on 50 ab^{-1}: BF ~10^{-7} - 10^{-8}

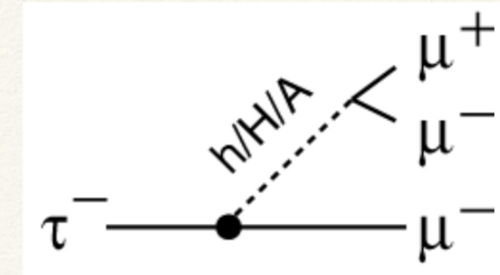


- Substantial improvements with respect to the B-factories:
  - proper time resolution
  - flavor tagging: new method based on the study of the rest of event are being developed



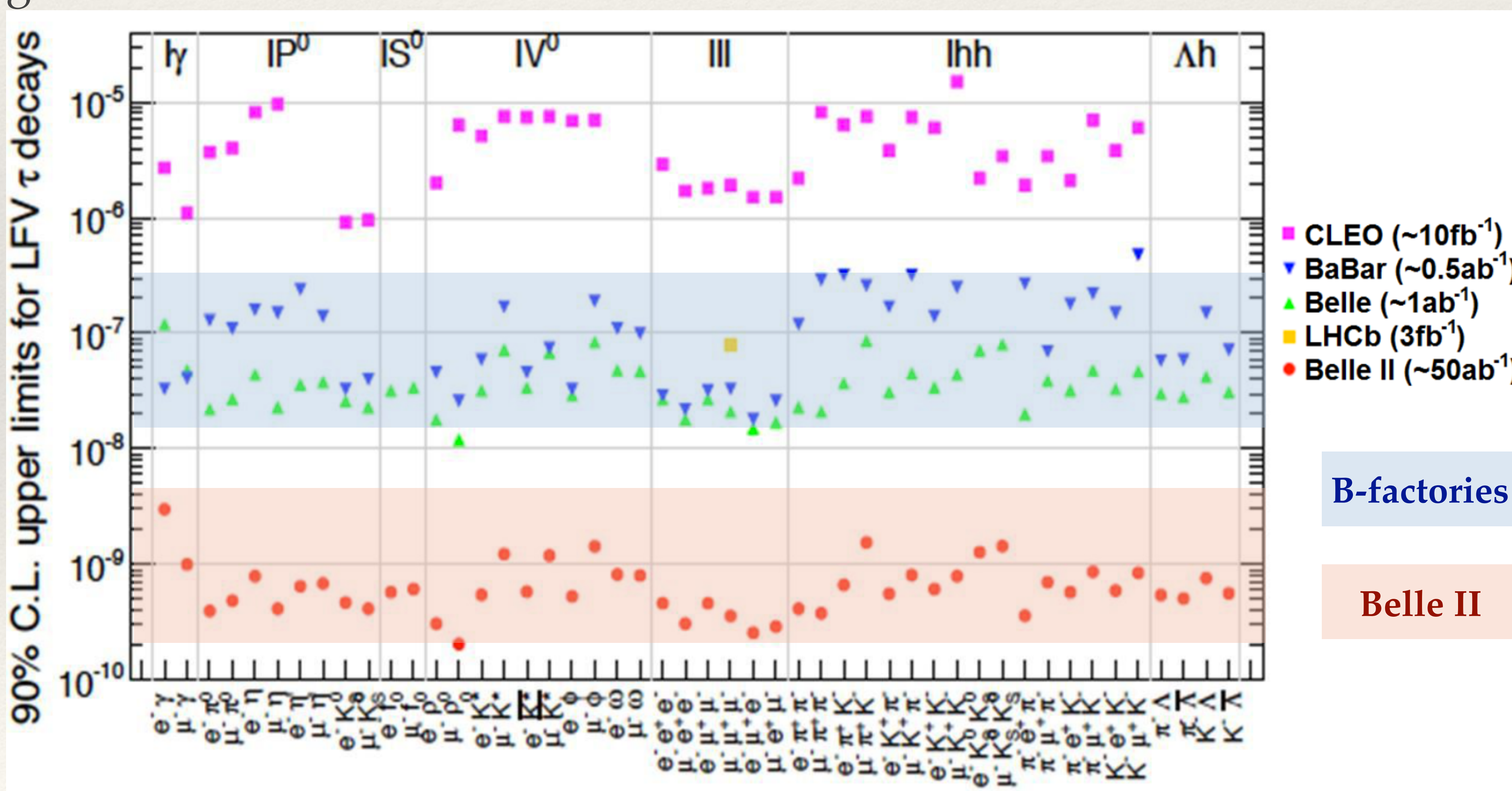


LFV in τ decays



- Forbidden in the SM, while possibly enhanced in NP models up to $O(10^{-8})$
- A field where LHCb competition is possible in few channels ($\tau\to\mu\mu\mu$)
- Belle II will uniquely access final states with neutrals (γ, π^0, η, η')
- Control of beam backgrounds will be crucial

- 1-2 orders of magnitude improvement from B-factories to Belle II

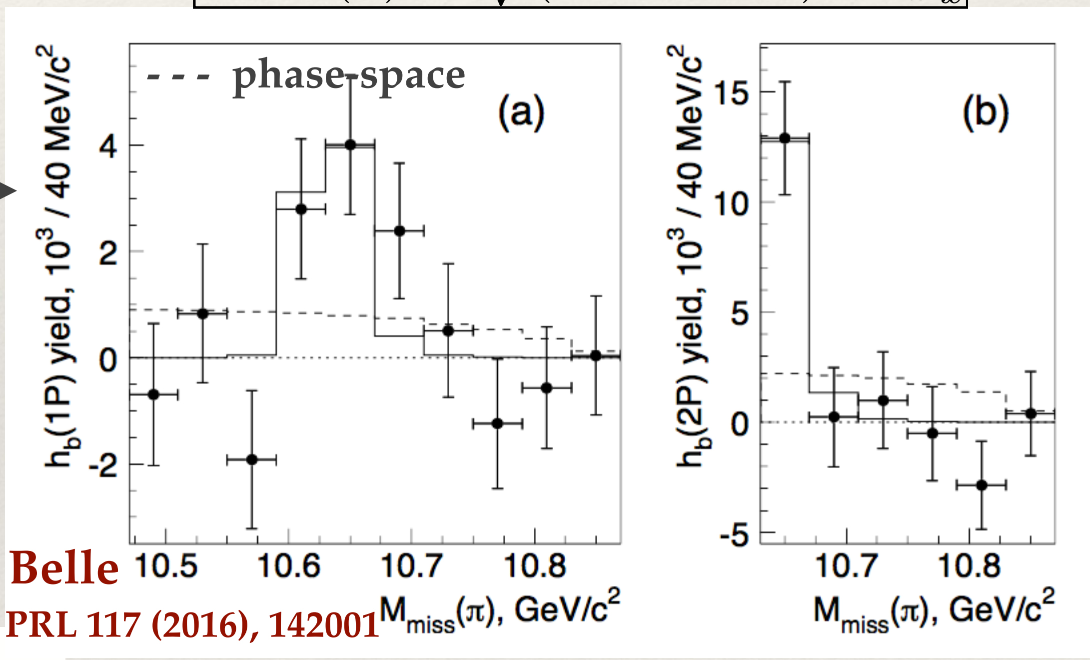


Bottomonium physics

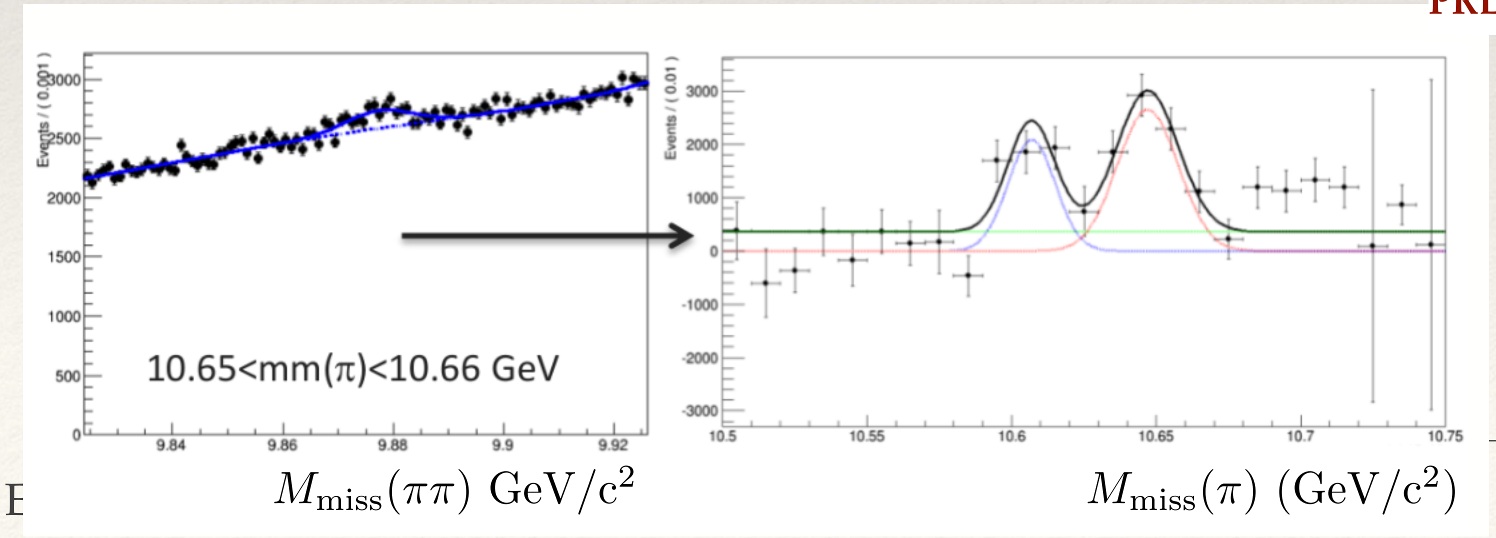
- The B-factories made great contributions to the knowledge of charmonium and bottomonium
- Several unexpected quarkonium-like states (from X(3872), to Z_b(10610,10650))
- Bottomonium physics at Belle II can achieve important results, through some golden modes based on a possibly **unique data sample** to be collected at the **Υ(6S)** energy

$$M_{\rm miss}(x) = \sqrt{(E_{\rm CM} - E_x)^2 - p_x^2}$$

- **$\Upsilon(6S) \to \pi Z_b$, $Z_b \to \pi h_b(nP)$**
  - not sufficient statistics at Belle to clearly separate the Z_b contribution
  - possibility for a data acquisition at the Υ(6S) energy during Phase 2 (2018)
  - according to MC studies, separation is possible already with 10 fb^{-1} of data

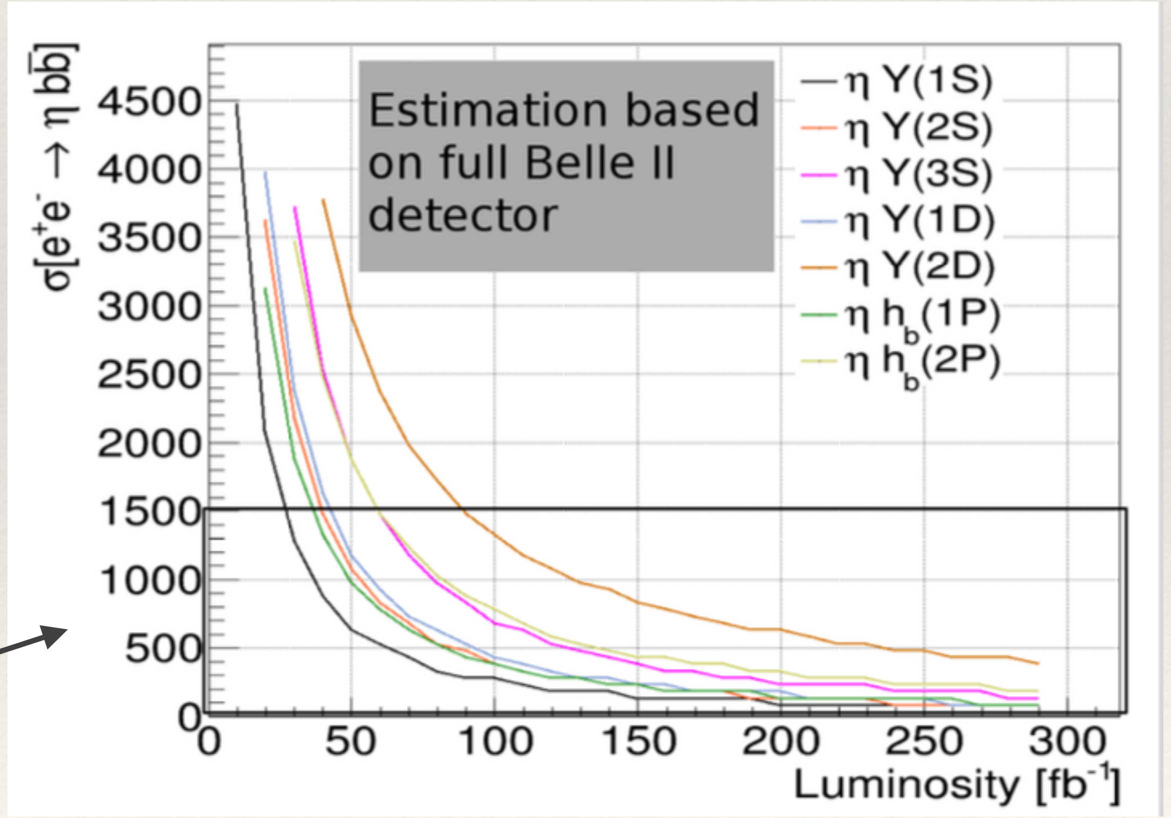


Belle
PRL 117 (2016), 142001



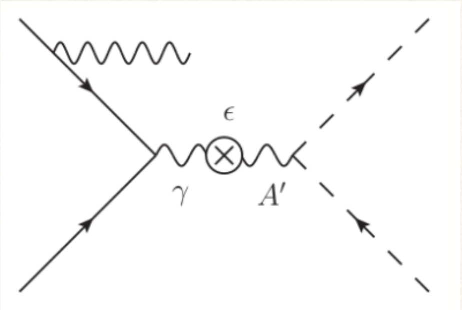
Bottomonium physics

- The B-factories made great contributions to the knowledge of charmonium and bottomonium
- Several unexpected quarkonium-like states (from X(3872), to Z_b(10610,10650))
- Bottomonium physics at Belle II can achieve important results, through some golden modes based on a possibly **unique data sample** to be collected at the **Υ(6S)** energy
- **η transitions from Υ(6S)**
  - could be used to access missing states below $B\bar{B}$ threshold (in particular Υ(2D) triplet)
  - heavy quark spin symmetry violating —> comparison with QCD multipole expansion calculations
  - results with 50 fb^{-1}, but more statistics will be needed for Υ(2D) discovery



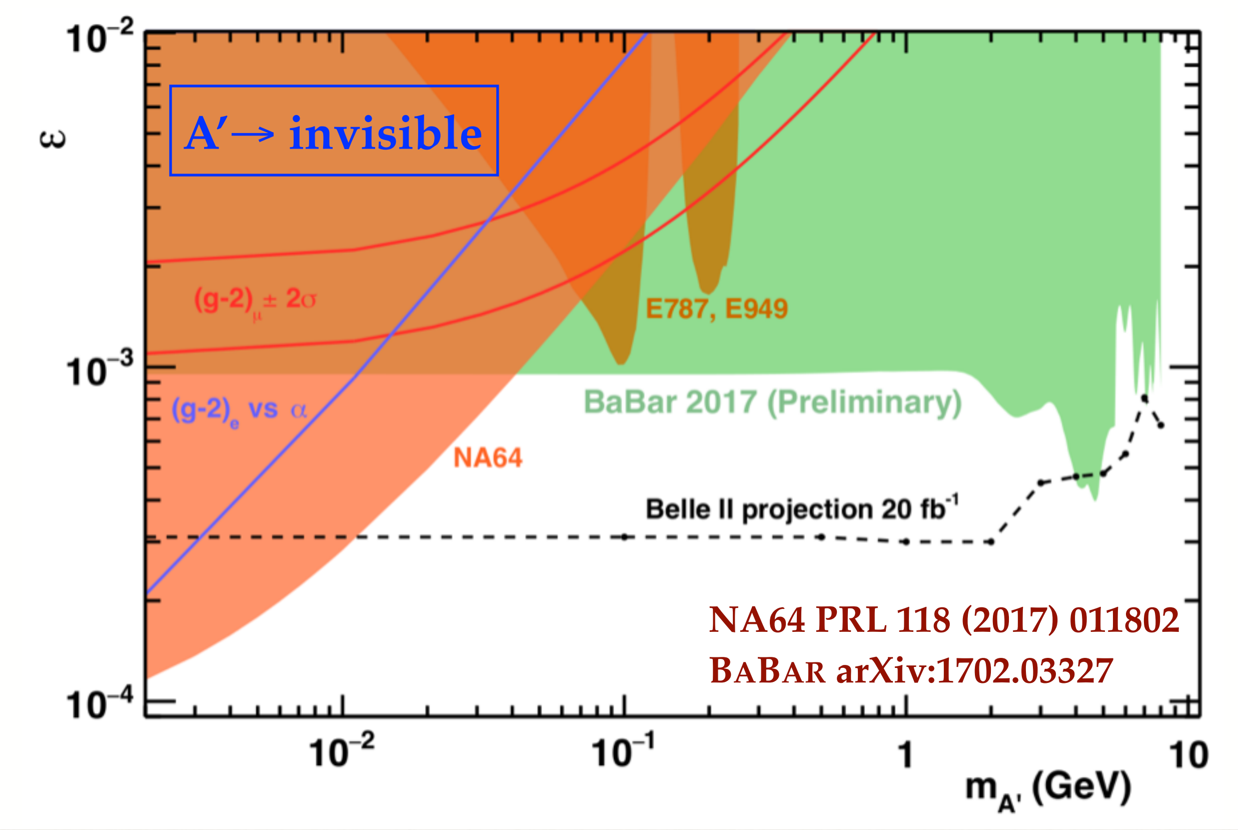
from similar transitions from Υ(5S) , it is reasonable to expect cross-sections < 1500 fb

Dark sector searches



- Hypothetical dark photon (A′) production in e^+e^- annihilations
- BABAR and NA64 ruled out the possibility to fully explain the g-2 anomaly introducing a dark photon
- But can still partially explain it (+ other NP), and it is still an important portal to light DM
- Preliminary projection with <u>20 fb^{-1} of data in Phase 2</u> shows a big exclusion potential for Belle II on invisible decays

More details: Search for dark forces in flavour experiments, T.Czank



- Very challenging signature: <u>A′(→ invisible)+γ</u>
  - special single photon trigger required
  - using KLM cluster information to reject events falling into the ECL gaps
  - excellent tracking efficiency to reject events containing tracks
  - studies on-going

Conclusions

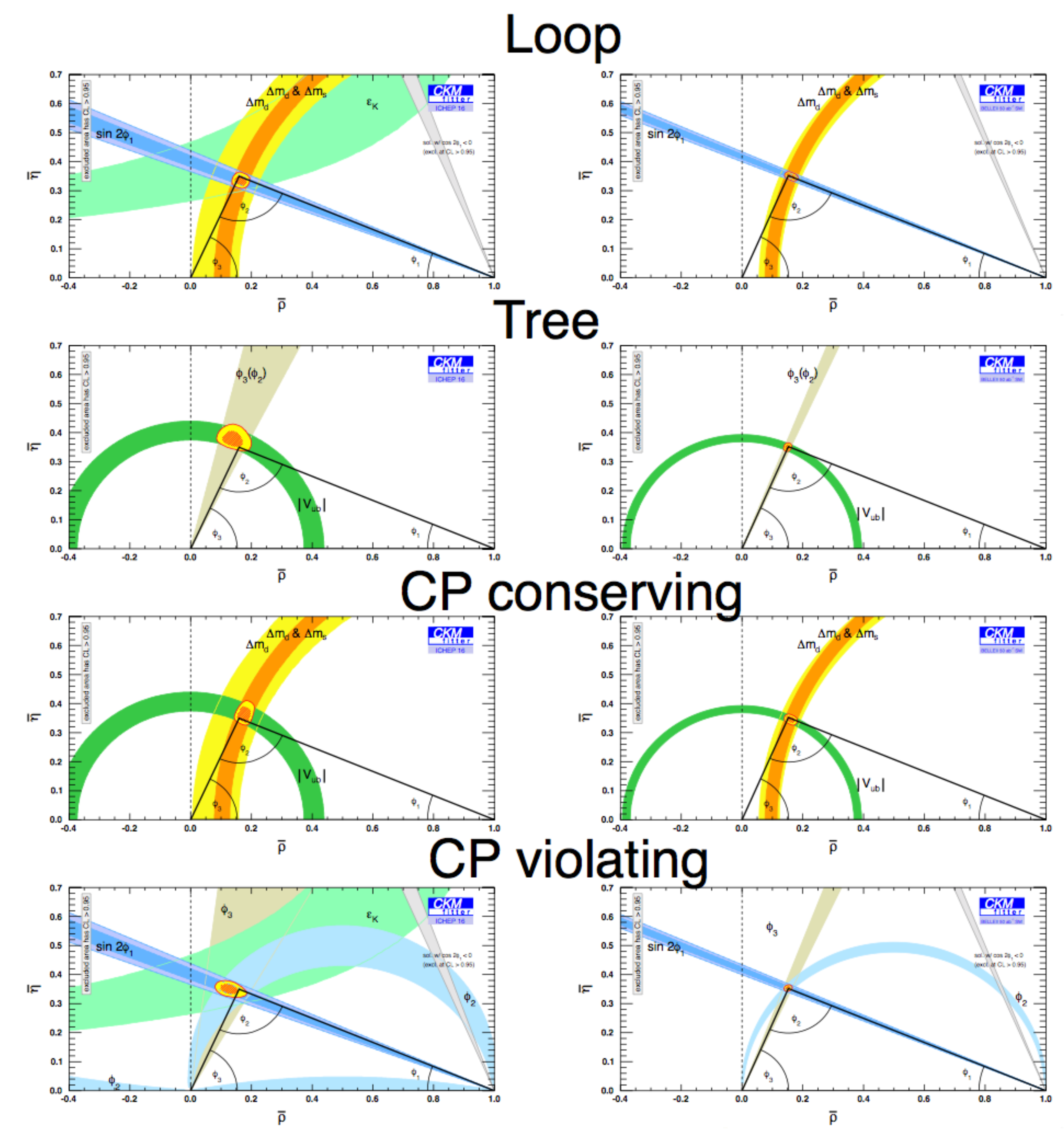
- **Belle II** is ready to collect the legacy of the 1st generation of B-factories, and to continue on the path set by them
- Its main purpose will be the search for NP signatures at the intensity frontier, along with a deeper knowledge of the nature of QCD in describing matter
- Complementarity with LHC (NP searches at the intensity vs. energy frontier, complementarity and competition with LHCb)
- The physics program will be wide:
  - some highlights have been summarized in this talk
  - many other possibilities and developing ideas behind the corner
- Possibility of obtaining the first physics results in the very next future, even during Phase 2 (2018)

More on Belle II:
- SuperKEKB & Belle II status, R.de Sangro
- Alignment and Calibration Framework for the Belle II detector (poster), J.Kandra

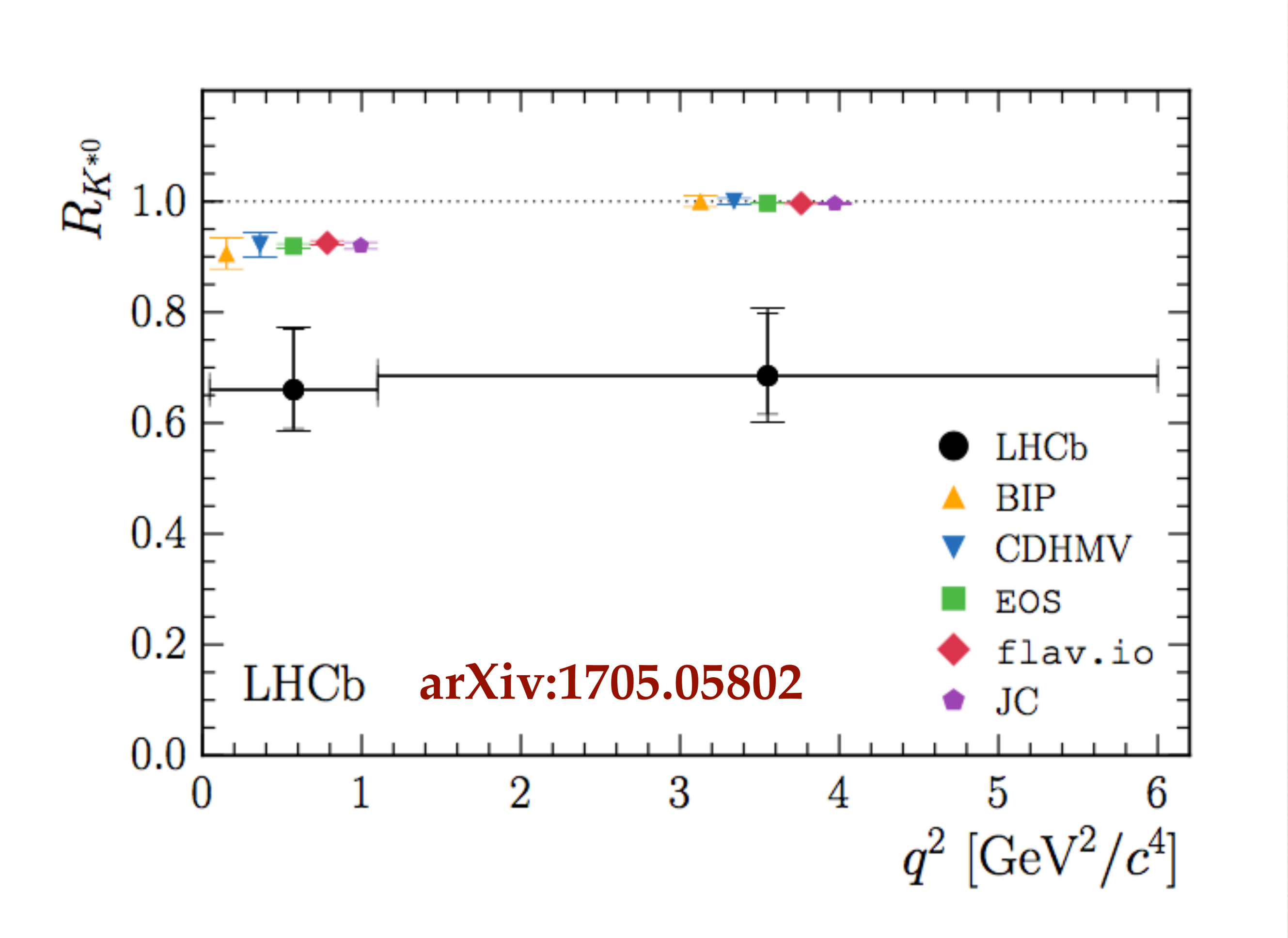
Backup

CKMFitter: 2016 vs. 2025

Input	World average 2016	Belle II (+LHCb) 2025
$\lvert V_{ub}\rvert$(semileptonic)$[10^{-3}]$	$4.01 \pm 0.08 \pm 0.22$	± 0.10
$\lvert V_{cb}\rvert$(semileptonic)$[10^{-3}]$	$41.00 \pm 0.33 \pm 0.74$	± 0.57
$\mathcal{B}(B \to \tau\nu)$	1.08 ± 0.21	± 0.04
$\sin 2\beta$	0.691 ± 0.017	± 0.008
$\gamma[^\circ]$	$73.2^{+6.3}_{-7.0}$	± 1.5 (± 1.0)
$\alpha[^\circ]$	$87.6^{+3.5}_{-3.3}$	± 1.0
Δm_d	0.510 ± 0.003	-
Δm_s	17.757 ± 0.021	-
$\mathcal{B}(B_s \to \mu\mu)$	$2.8^{+0.7}_{-0.6}$	(± 0.5)
f_{B_s}	$0.224 \pm 0.001 \pm 0.002$	0.001
B_{B_s}	$1.320 \pm 0.016 \pm 0.030$	0.010
f_{B_s}/f_{B_d}	$1.205 \pm 0.003 \pm 0.006$	0.005
B_{B_s}/B_{B_d}	$1.023 \pm 0.013 \pm 0.014$	0.005



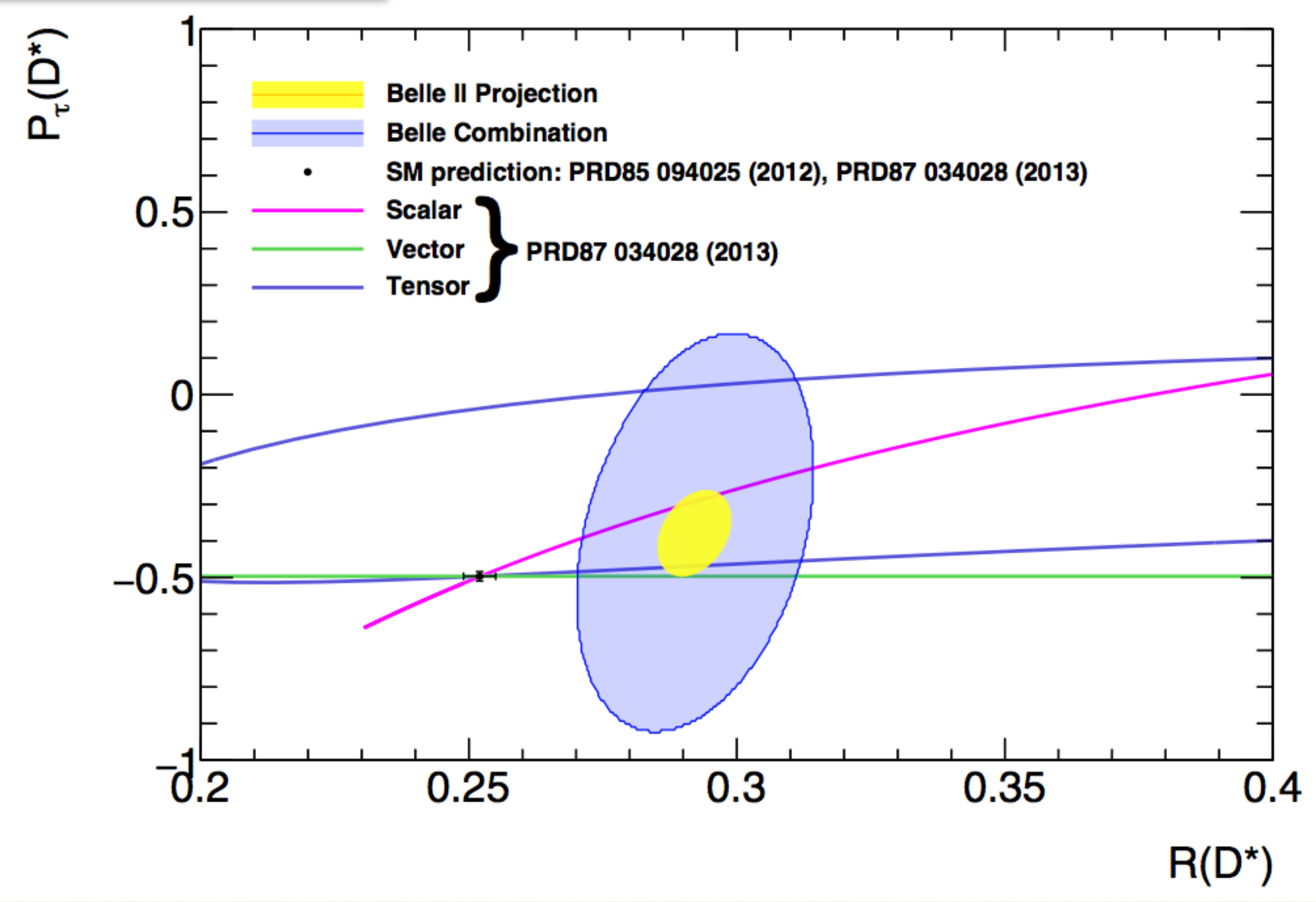
Electroweak penguins



- Comparison with theoretical predictions in bins of q^2:
  - BIP: EPJC 76 (2016) 440
  - CDHMV: JHEP 06 (2016) 092, JHEP 10 (2016) 075, JHEP 04 (2017) 016
  - EOS: PRD 95 (2017) 035029
  - flav.io: JHEP 08 (2016) 098
  - JC: PRD 93 (2016) 014028

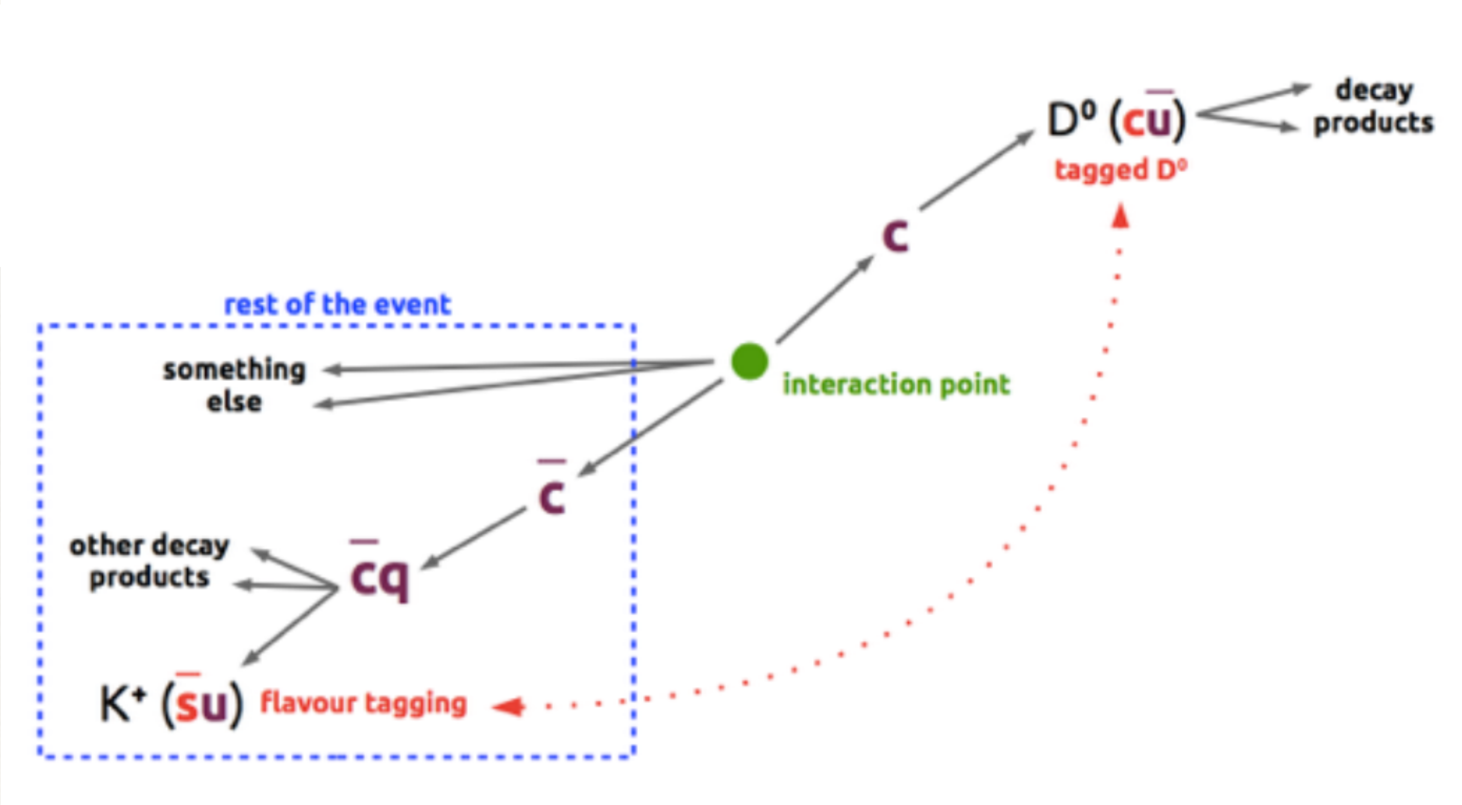
$B \to D^{(*)} \tau \nu$ - τ polarization

P. Urquijo, XIIth Meeting on B Physics, Naples 2017

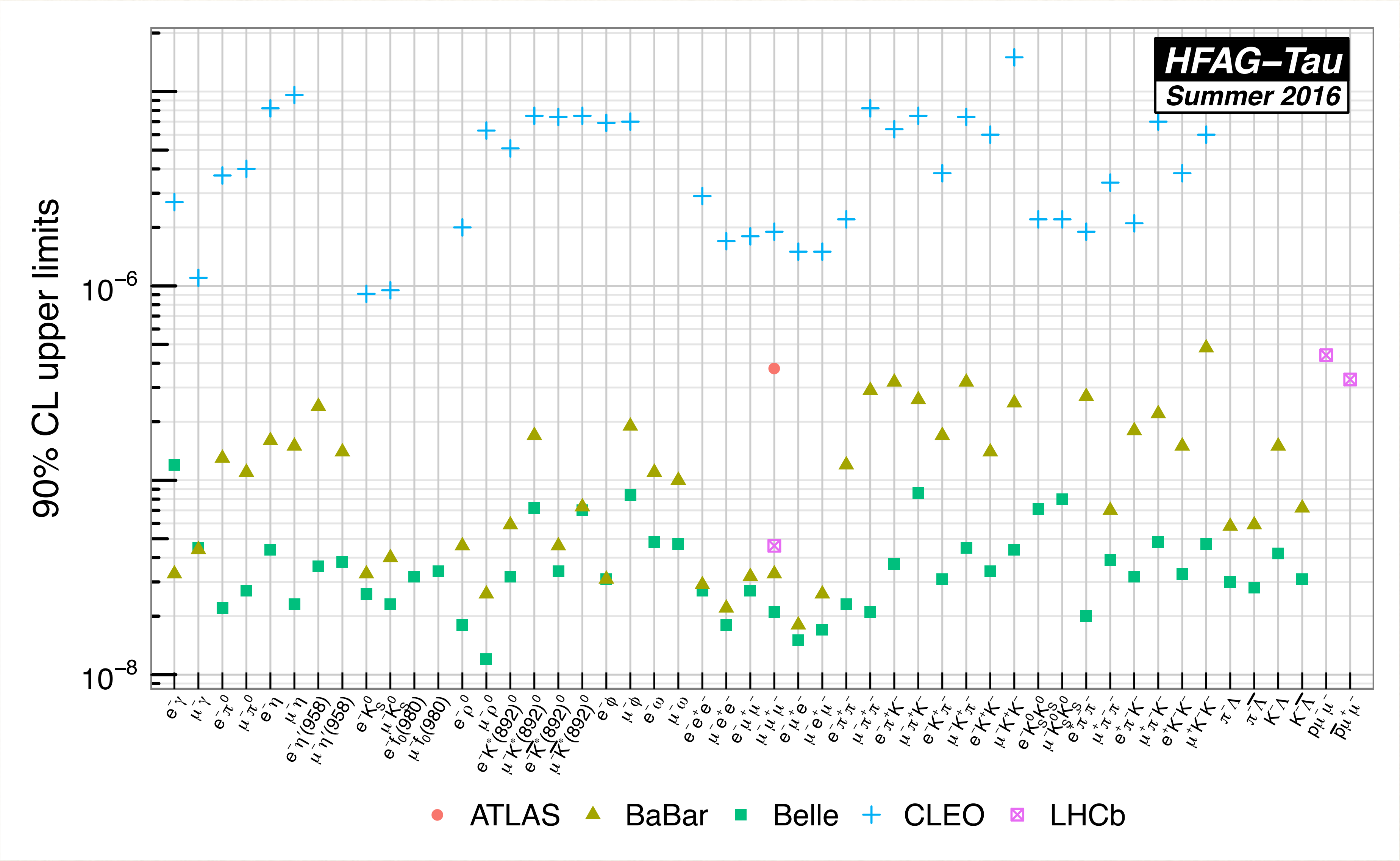


Rest Of Event (ROE)

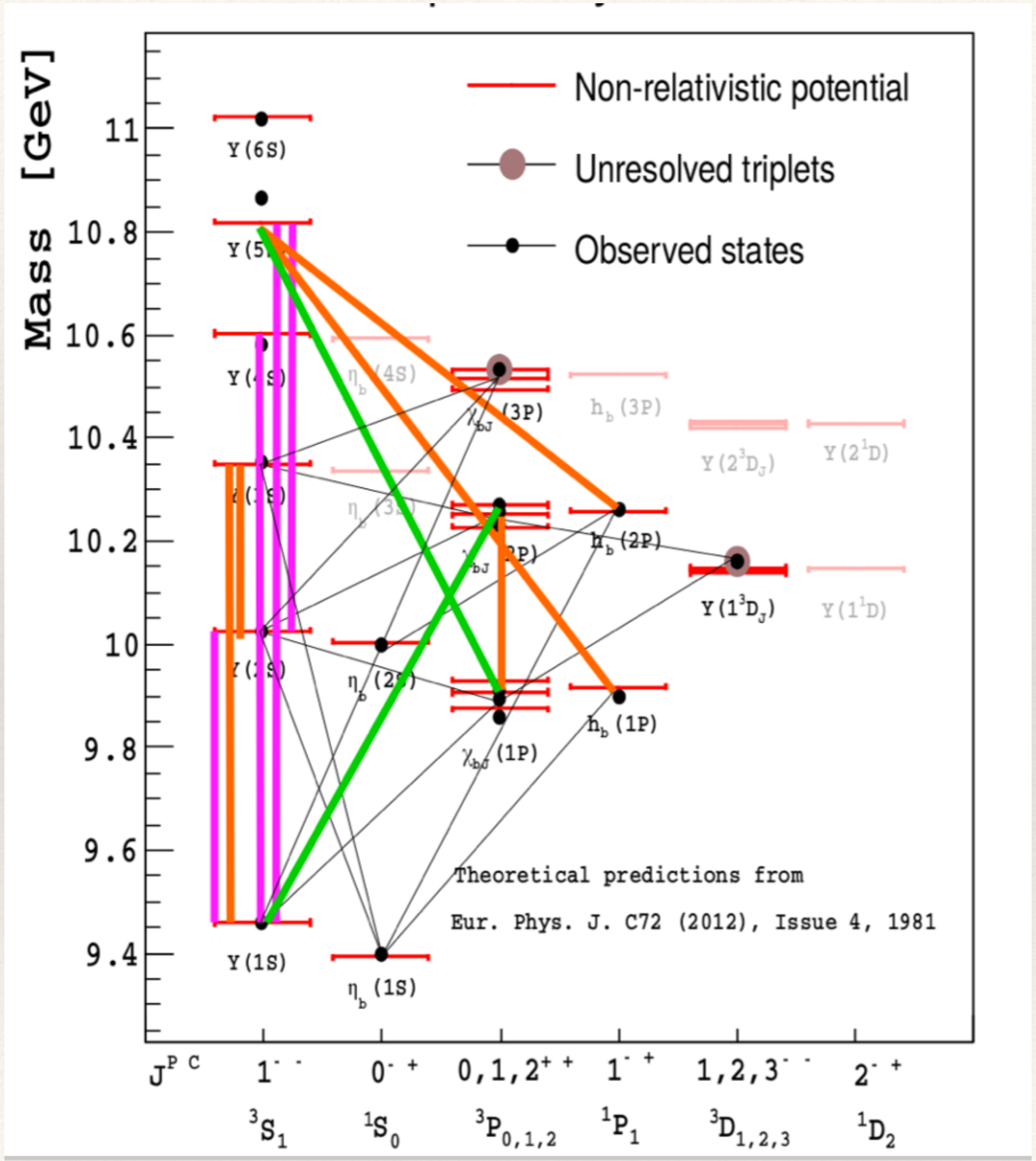
- Selection of events with only 1 $K^{\pm}$ in the ROE to tag the flavor of D^0 at production
- Expected performances:
  - tag efficiency ~27%
  - mistag level ~13%



LFV in τ decays - state of the art



Bottomonium



$\Upsilon(nS) \to \pi Z_b$, $Z_b \to \pi h_b(mP)$ transitions

- Missing mass for either the 2 pion system, or each pion individually
- One of the pions' missing mass must be within [10.55,10.70] GeV/c^2 to select the pion from $\Upsilon(nS) \to \pi Z_b$ transition
    - missing mass used to deduce the Z_b properties
- Additional requirements to suppress background:
    - tight PID for pion hypothesis
    - pions must originate from the interaction point
- Fit to the $M_{miss}(\pi)$ distribution with a Gaussian + 4th-order Chebyshev polynomial