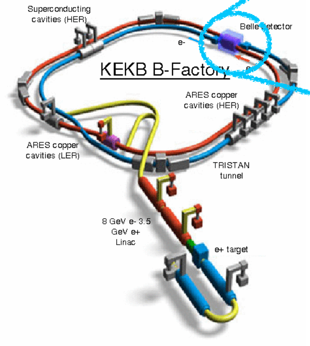
Recent highlights from Belle

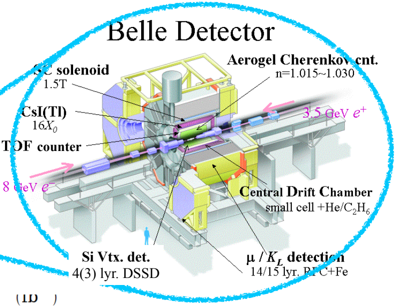
Youngjoon Kwon
Yonsei Univ. / Belle

Dec. 21, 2015
The 12th Saga-Yonsei Joint Workshop on HEP

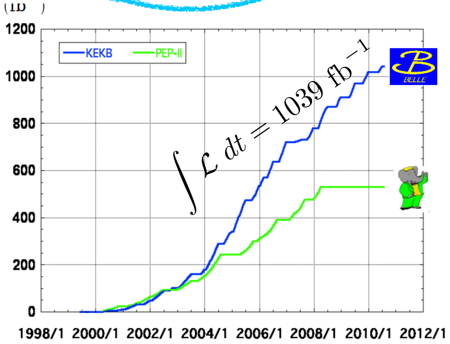
18 countries
84 institutes
~400 members

$$\mathcal{L}_{\text{peak}} = 21.1\ \text{nb}^{-1}\text{s}^{-1}$$



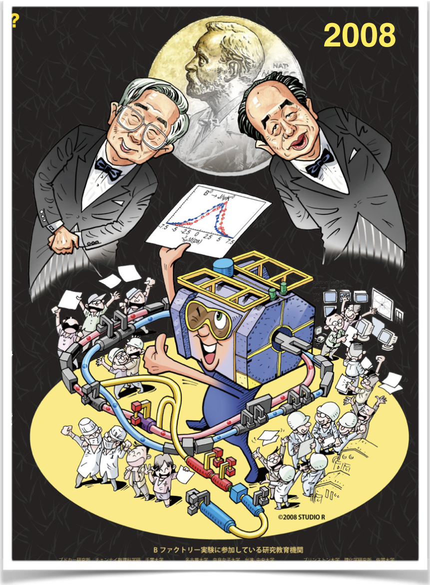


$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$



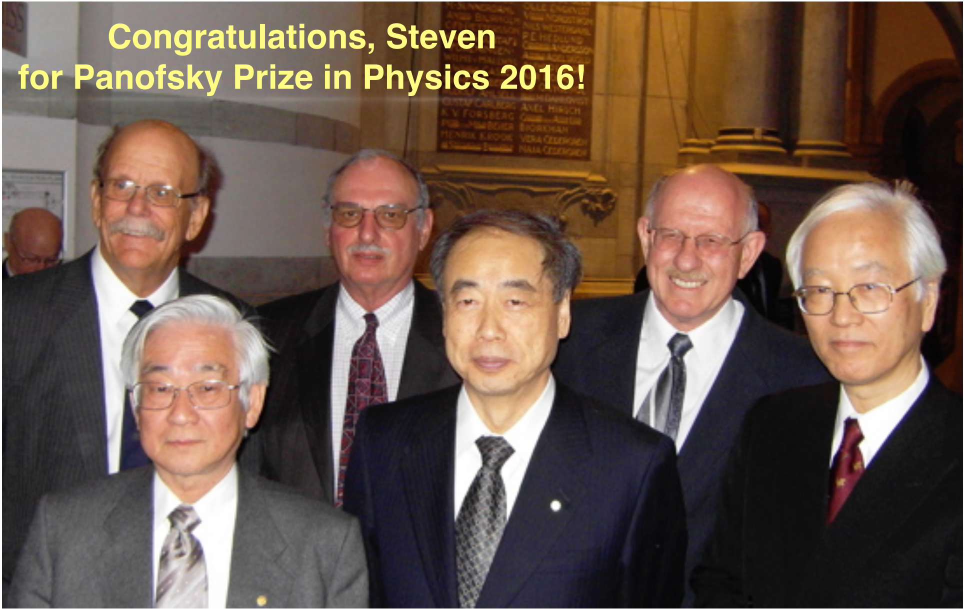
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}



Belle achievements include:

- CPV, CKM, and rare decays of B (and B_s, too)
- Mixing, CP, and spectroscopy of charm hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$
- Studies of τ and 2γ


Congratulations, Steven
for Panofsky Prize in Physics 2016!

Menu

- *Appetizer*
  - * F_{L}, A_{FB} in $B \to K^* \ell^+ \ell^-$ (BaBar) arXiv:1508.07960
- *Plate of pastas*
  - * First Belle-BaBar joint analysis [CPV] PRL 115, 121604 (2015)
  - * A_{CP} in dileptons (BaBar) PRL 114, 081801 (2015)
- *Plate of meats*
  - * $B \to \overline{D}^{(*)} \tau^+ \nu_\tau$ (Belle) PRD 92, 072014 (2015)
  - * $B^+ \to \ell^+ \nu \gamma$ (Belle) PRD 91, 112009 (2015)
- *Dessert*
  - * Dark photon search (Belle) PRL 114, 211801 (2015)
  - * Dark photon search (BaBar) PRL 113, 201801 (2014)

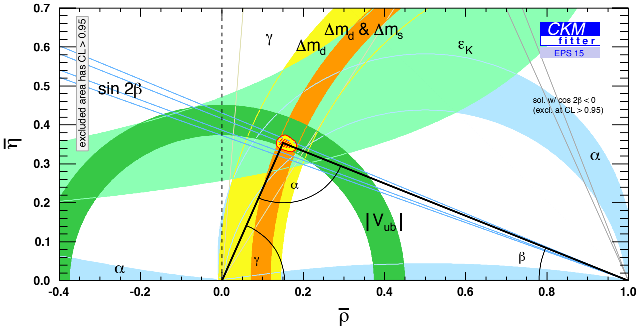
- First joint Belle-BaBar analysis

First Belle-BaBar joint analysis

PRL 115, 121604 (2015)

- Allows for combined use of all 1.25×10^9 $B\overline{B}$ pairs collected by both experiments at $\Upsilon(4S)$
- Systematic cross-checks between datasets, as well as for increased statistics
- A single analysis by a single group of analysts who have full access to both datasets
- Prospects for more joint analyses forthcoming.

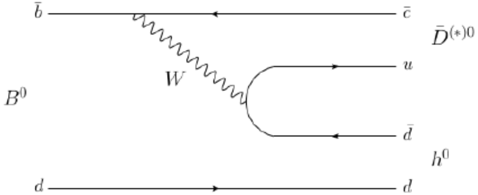
CKM unitarity triangle and $\sin 2\beta$

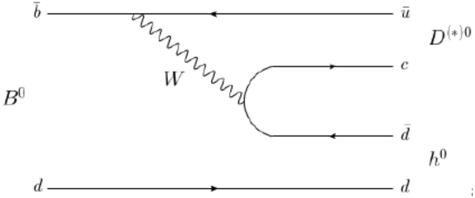


- $\sin 2\beta (= \sin 2\phi_1)$ is known with high precision, with $\delta\beta \lesssim 1°$.
  Yet, $\exists$ some tension between direct and indirect estimation of β.

Time-dependent *CP*-violation in $B^0 \to D^{*0}_{CP}\, h^0$

- $\sin 2\beta (= \sin 2\phi_1)$ is known with high precision, with $\delta\beta \lesssim 1^\circ$.
  Yet, $\exists$ some tension between direct and indirect estimation of β.
  - possibly related to penguin contributions to $b \to c\bar{c}s$ processes?





- $B^0 \to D^{*0}_{CP}\, h^0$ is very nearly clean $b \to c\bar{u}d$ color-suppressed tree, hence can be good cross-check for $\sin 2\beta$.
  - a nice confidence-builder, with *reasonably solid expectations*, for the first joint analysis

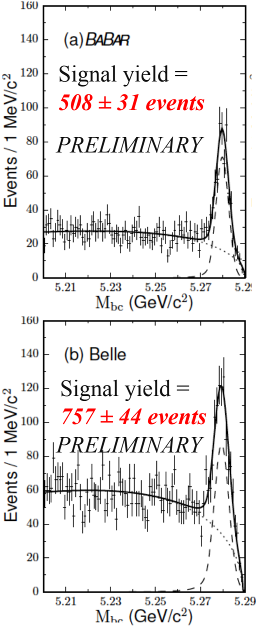
Principle of the combined analysis

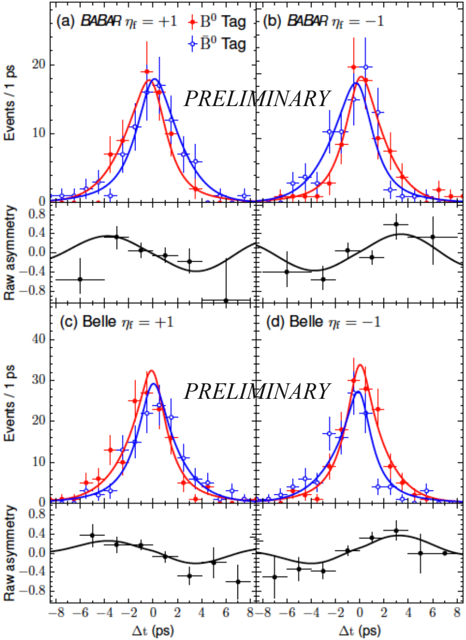
- Perform the CPV measurement by maximizing the combined log-likelihood function:

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{\text{B\scriptsize{A}B\scriptsize{AR}}} + \sum_j \ln \mathcal{P}_j^{\text{Belle}}$$

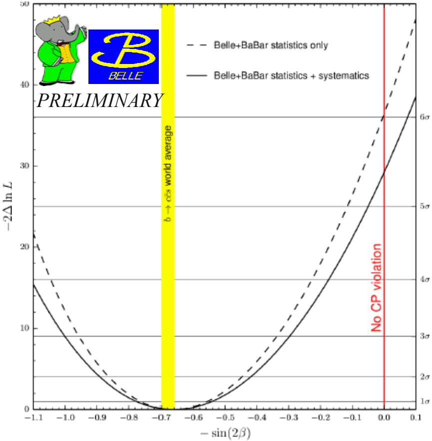
- Use the standard Belle and BaBar resolution functions and B flavor-tagging algorithms.

- The backgrounds and Δt resolution functions, used to fit the data from the two experiments share the same parametrizations, and those parameters are all precisely determined via the m_{ES} sidebands ($m_{\text{ES}} = M_{\text{bc}} < 5.26$ GeV).


(a) BABAR
Signal yield =
508 ± 31 events
PRELIMINARY
(b) Belle
Signal yield =
757 ± 44 events
PRELIMINARY
Events / 1 MeV/c²
M_bc (GeV/c²)


(a) BABAR η_f = +1
B⁰ Tag
B̄⁰ Tag
(b) BABAR η_f = −1
PRELIMINARY
(c) Belle η_f = +1
(d) Belle η_f = −1
PRELIMINARY
Events / 1 ps
Raw asymmetry
Δt (ps)

t-CPV in $B^0 \to D^{*0}_{CP}\, h^0$, Results



$$-\eta_f \mathcal{S} = +0.66 \pm 0.10 \pm 0.06$$
$$\mathcal{C} = -0.02 \pm 0.07 \pm 0.03$$

* World average from $b \to c\bar{c}s$:

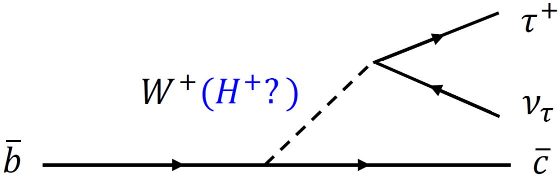
$$\sin 2\beta = 0.68 \pm 0.02$$

Excludes the hypothesis of no mixing-induced CPV in $B^0 \to D^{*0}_{CP}\, h^0$ at a significance of 5.4σ.

- $B \to D^* \tau \nu$

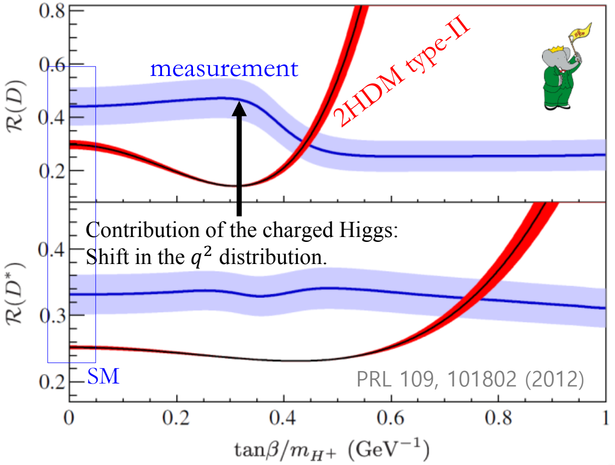
$B \to \overline{D}^{(*)}\tau^+\nu_\tau$, motivations

- New physics may show up $\because m_\tau \gg m_\mu,\ m_e$



- Existing measurements: $\mathcal{B}(B \to \overline{D}^{(*)}\tau^+\nu_\tau) \gtrsim \mathcal{B}_{SM}$
  - e.g. BaBar (2012), 3.4σ away from SM, and not compatible with 2HDM(II)

$R(R^*)$ each matches for
$\tan\beta/m_{H^+} = 0.44 \pm 0.02\ (0.75 \pm 0.04)\ GeV^{-1}$



$$R(D) = \frac{\mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)}$$
$$= 0.440 \pm 0.058 \pm 0.042$$

$$R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)}$$
$$= 0.332 \pm 0.024 \pm 0.018$$

Hadronic B tagging for $B \to \overline{D}^{(*)}\tau^+\nu_\tau$

- Exploit the unique feature of the e^+e^- B-factories

$$e^+e^- \to \Upsilon(4S) \to B_{\rm sig}B_{\rm tag}$$

- Full reconstruction of $B_{\rm tag}$ in hadronic B decay modes

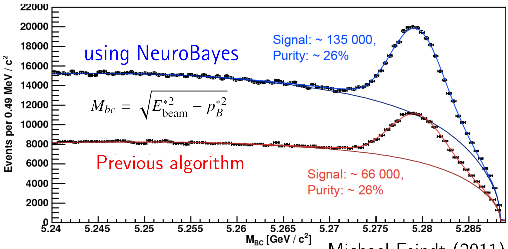
  ⇒ constrain the charge, flavor, & $(E,\vec{p})$ of $B_{\rm sig}$

  ⇒ resulting in very high-purity, but with low-efficiency ($\sim \mathcal{O}(0.1\%)$)

- **Neurobayes** M. Feindt, *et al.*, NIM A **654**, 432 (2011)
  - multivariate analysis using a neural network, for an improved full-recon of B mesons
  - The output of the network can be interpreted as Bayesian probability
  - provides a well-discriminating variable for intermediate cuts, *whose behaviors are under control*

Hadronic B tagging for $B \to \overline{D}^{(*)}\tau^+\nu_\tau$

- **Neurobayes** performance for hadronic B-tagging
  - multivariate analysis using a neural network
  - much improvement in B-tagging by adding more B_{tag} and D modes



Michael Feindt (2011)

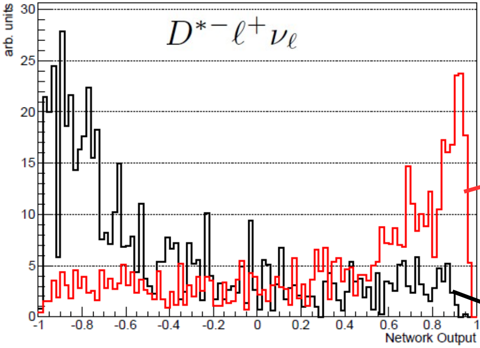
$\times(2 \sim 3)$ statistical gain over previous hadronic B tagging

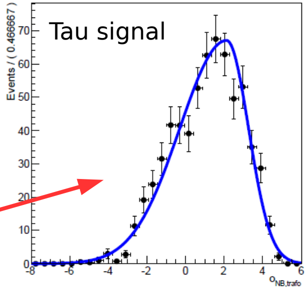
$\leftarrow$ Neurobayes + data re-processing in 2011

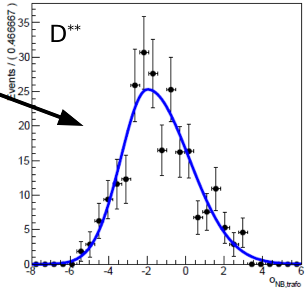
$B \to \overline{D}^{(*)}\tau^+\nu_\tau$, **analysis overview**

arXiv:1507.03233, submitted to PRD

- Hadronic B-tagging ($B_{\rm tag}$) using NeuroBayes
- Signal side ($B_{\rm sig}$): reconstructed in $D^{(*)}\ell$ ($\ell = e, \mu$) [$\tau \to e\nu\bar{\nu}, \mu\nu\bar{\nu}$ only]
  - * no extra tracks or π^0; total charge = 0
- $-0.2 < M^2_{\rm miss} < 8.0$ GeV^2 and $q^2 > 4$ GeV^2
  - * $M^2_{\rm miss}$ = (missing mass)^2 of the event
  - * q^2 = (momentum transfer to $\tau\nu(\ell\nu)$)$^2 = (p_B - p_{D^{(*)}})^2$
- Signal fitting in split regions
  - * $M^2_{\rm miss} < 0.85$ GeV^2 mostly $B \to D^{(*)}\ell\nu$ ($\ell = e, \mu$); fit $M^2_{\rm miss}$
  - * $M^2_{\rm miss} > 0.85$ GeV^2 $B \to \overline{D}^{(*)}\tau^+\nu_\tau$ enhanced; fit neural-net variable, $o'_{\rm NB}$
- Measure relative ratios $R(D)$, $R(D^*)$ $R(D^{(*)}) \equiv \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\ell\nu)$



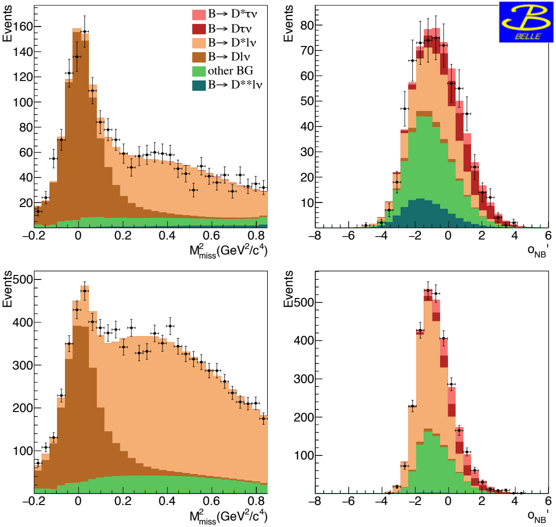




Transformation of the neural net output (o_{NB}) for easy parametrization:

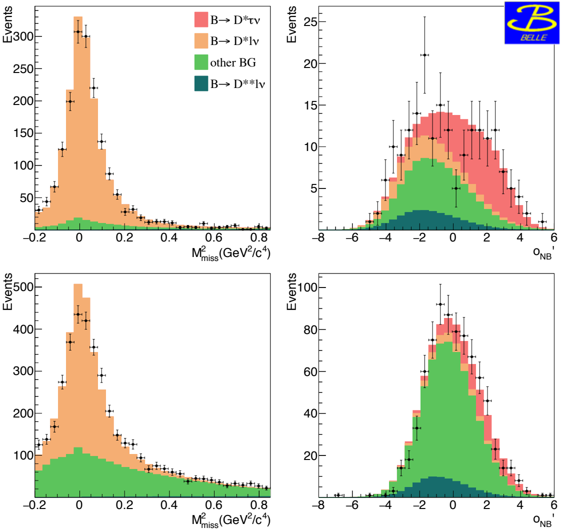
$$o'_{NB} \equiv \ln \frac{o_{NB} - o_{min}}{o_{max} - o_{NB}}$$

Fits for $B \to D\ell(X)$ final states



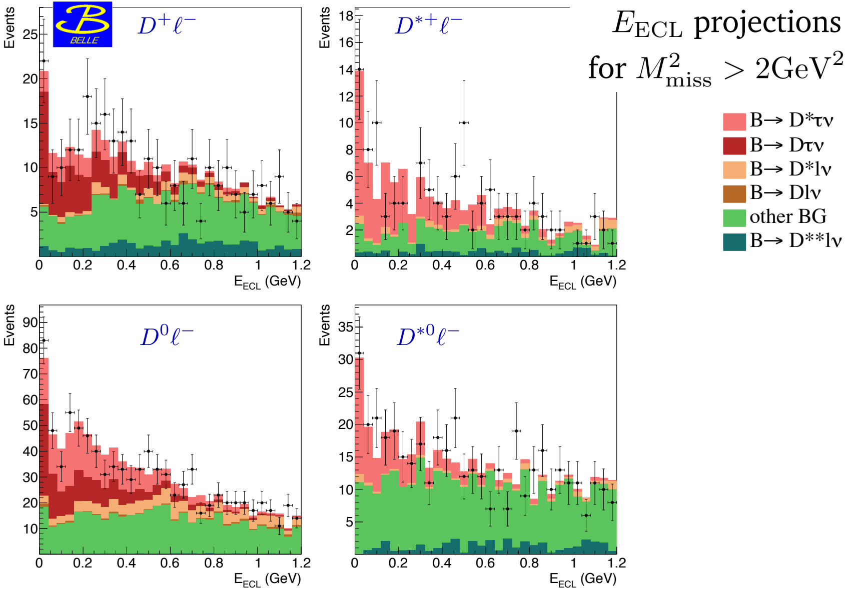
- (top) $D^+\ell^-$
  (bottom) $D^0\ell^-$
- (left) $M^2_{\rm miss} < 0.85$ GeV^2
  - $B \to D\ell\nu$ dominant
  - fit $M^2_{\rm miss}$ for backgr'd normalization
- (right) $M^2_{\rm miss} > 0.85$ GeV^2
  - $B \to D\tau\nu$ enhanced
  - fit $o'_{\rm NB}$

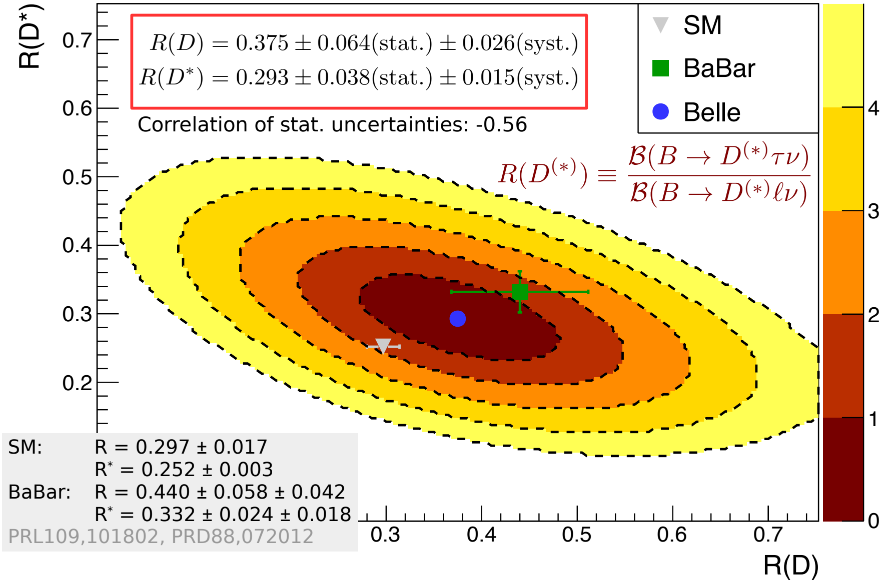
Fits for $B \to D^*\ell(X)$ final states



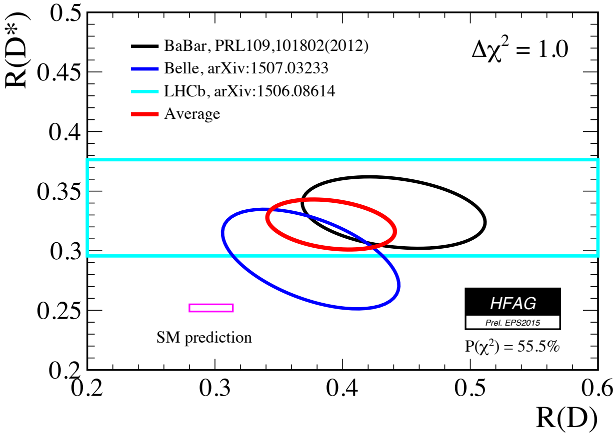
- (top) $D^{*+}\ell^-$
  (bottom) $D^{*0}\ell^-$
- (left) $M^2_{\rm miss} < 0.85$ GeV^2
  - * $B \to D^*\ell\nu$ dominant
  - * fit $M^2_{\rm miss}$ for backgr'd normalization
- (right) $M^2_{\rm miss} > 0.85$ GeV^2
  - * $B \to D^*\tau\nu$ enhanced
  - * fit $o'_{\rm NB}$

E_{ECL} projections for $M^2_{\mathrm{miss}} > 2\mathrm{GeV}^2$




$R(D) = 0.375 \pm 0.064(\text{stat.}) \pm 0.026(\text{syst.})$
$R(D^*) = 0.293 \pm 0.038(\text{stat.}) \pm 0.015(\text{syst.})$
Correlation of stat. uncertainties: -0.56
SM
BaBar
Belle
$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$
R(D*)
R(D)
0.7
0.6
0.5
0.4
0.3
0.2
0.3
0.4
0.5
0.6
0.7
4
3
2
1
0
SM: R = 0.297 ± 0.017
R* = 0.252 ± 0.003
BaBar: R = 0.440 ± 0.058 ± 0.042
R* = 0.332 ± 0.024 ± 0.018
PRL109,101802, PRD88,072012

HFAG average for $B \to \overline{D}^{(*)}\tau^+\nu_\tau$



The combined $R(D)$ and $R(D^*)$ result exceeds the SM predictions at 3.9σ level, with a p-value of 1.1×10^{-4}. The $R(D)$ vs. $R(D^*)$ correlation of -0.29 is considered.

www.scientificamerican.com/article/2-accelerators-find-particles-that-may-break-known-laws-of-physics1/

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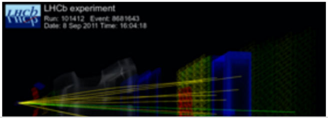
2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español

At the smallest scales, everything in the universe can be broken down into fundamental morsels called particles. The Standard Model of particle physics—the



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Democracy suffers a blow—in particle physics

Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

Steven K. Blau 17 September 2015

PREVIOUS POST | PHYSICS UPDATE | NEXT POST (1)

Upon learning of the discovery of the muon, I. I. Rabi famously quipped, "Who ordered that?" After all, the muon appeared to be identical to the electron except for its mass. Indeed, in the standard model of particle physics, the charged leptons—electron, muon, and tau—interact in the same way with the model's gauge bosons, the particles that transmit force. As a consequence of that lepton democracy, the standard model prescribes the relative probabilities, or branching ratios, for a heavy particle to decay into one or another of the charged leptons plus other particles in common. Three years ago the BaBar collaboration at SLAC measured the branching ratios for B-meson decay to produce either a muon or a tau. For two slightly different decays, they found 2σ or greater deviations from the democratic standard-model expectation. Now the LHCb collaboration at CERN has confirmed the BaBar result for one of the decays. In a preprint, the Belle group at KEK in Japan has also announced

Physics Upc

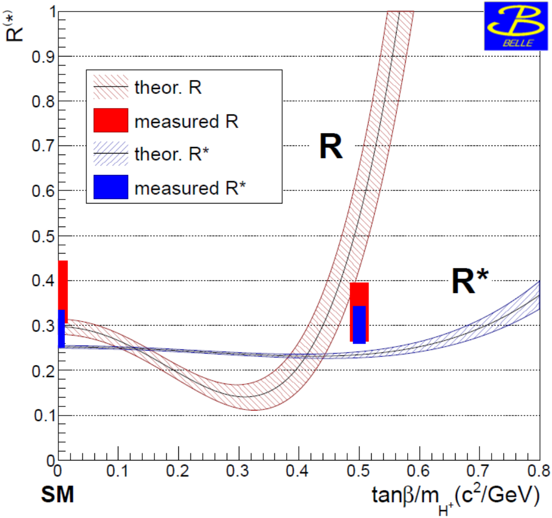
History matters fo

A two-in-a-million nuclear decay

Enceladus's subs wraps the moon

A study in contras surface frost

Testing 2HDM(II) for $B \to \overline{D}^{(*)}\tau^+\nu_\tau$



- Analysis repeated for 2HDM(II) with $\tan\beta/m_{H^+} = 0.5/\mathrm{GeV}$

  $R(D) = 0.329 \pm 0.060 \pm 0.022$
  $R(D^*) = 0.301 \pm 0.039 \pm 0.015$

- Belle results, consistent with 2HDM(II) for $0 < \tan\beta/m_{H^+} \lesssim 0.45/\mathrm{GeV}$

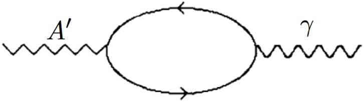
- Dark sector searches

Dark photon and dark higgs

Dark photon & kinetic mixing

- First proposed by P. Fayet, PL B 95, 285 (1980)
- (Holdom, 1986) A boson A' belonging to $U(1)'$ of dark sector particles would mix kinetically with γ

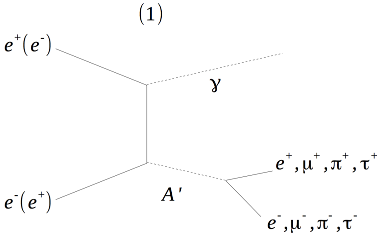
$$\frac{1}{2}\,\epsilon\,F_{\mu\nu}F'^{\mu\nu}$$

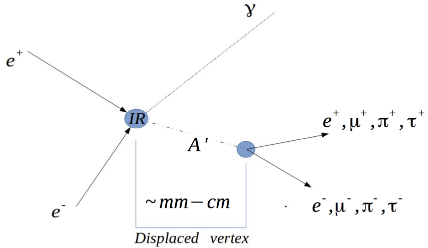


Dark higgs

- For A' to acquire mass, an extended Higgs sector is required in order to break this $U(1)'$.

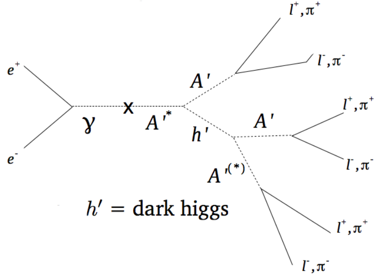
Dark photon searches at e^+e^- B-factory





- low-multiplicty final state
- $A' \to \ell^+\ell^-$ or $\pi^+\pi^-$ with prompt or displaced vertex
- also study invisible final state, e.g. $e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$
  $\Leftarrow$ need special single-γ trigger (BaBar did; Belle did not)

Dark photon search via Higgs-strahlung



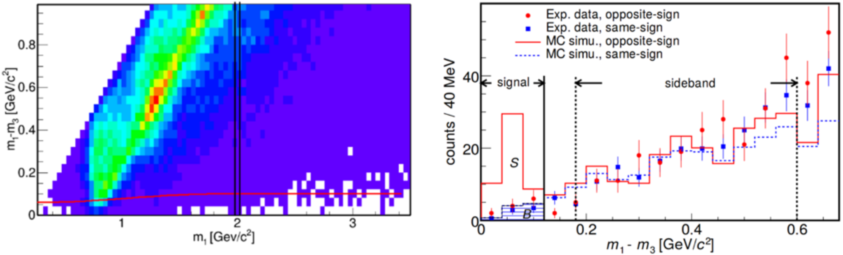
h' = dark higgs

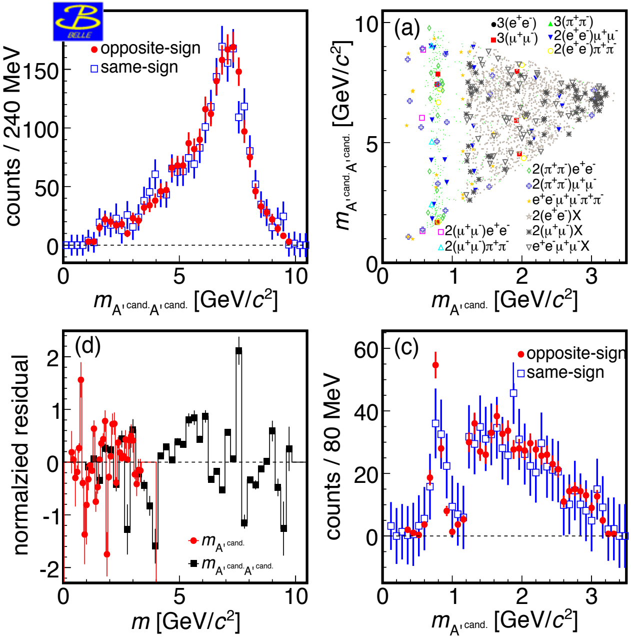
- Search mode depends on $M_{h'}$ and $M_{A'}$
- In this talk, only $M_{h'} > 2M_{A'}$ is considered $\Rightarrow h' \to A'A'$ is used
  - * $A' \to \ell^+\ell^-$ or $\pi^+\pi^-$ with prompt or displaced vertex
  - * 'exclusive': 3 charged-track pairs, each with the same invariant mass
  - * 'inclusive': 2 charged-track pair, each with the same invariant mass, and missing $(E, \vec{p})$

Background

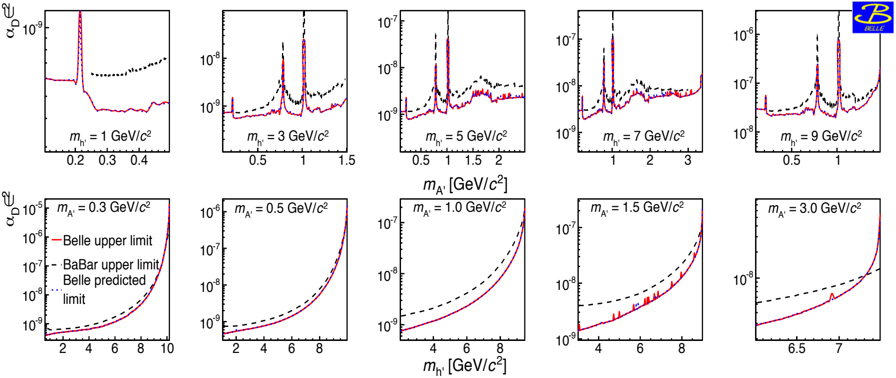
- estimated using "same-sign" pairs from $e^+e^- \to (\ell^+\ell^+)(\ell^+\ell^-)(\ell^-\ell^-)$
- Sort the pairs by invariant mass, $m_1 > m_2 > m_3$
  then plot $m_1 - m_3$ vs. m_1
- For each $M_{\ell^+\ell^-}$ region, scale same-sign yield to $\ell^+\ell^-$ in the side-band, then extrapolate into the $M_{\ell^+\ell^-}$ signal region.

for 6π mode, with $m_1 = 2\ \mathrm{GeV}/c^2$




opposite-sign
same-sign
counts / 240 MeV
$m_{A'^{cand.}A'^{cand.}}$ [GeV/c^2]
(a)
3(e+e-)
3(μ+μ-)
3(π+π-)
2(e+e-)μ+μ-
2(e+e-)π+π-
2(π+π-)e+e-
2(π+π-)μ+μ-
e+e-μ+μ-π+π-
2(e+e-)X
2(μ+μ-)X
e+e-μ+μ-X
2(μ+μ-)e+e-
2(μ+μ-)π+π-
$m_{A'^{cand.}}$ [GeV/c^2]
(d)
normalzied residual
$m_{A'^{cand.}}$
$m_{A'^{cand.}A'^{cand.}}$
m [GeV/c^2]
(c)
opposite-sign
same-sign
counts / 80 MeV
$m_{A'^{cand.}}$ [GeV/c^2]

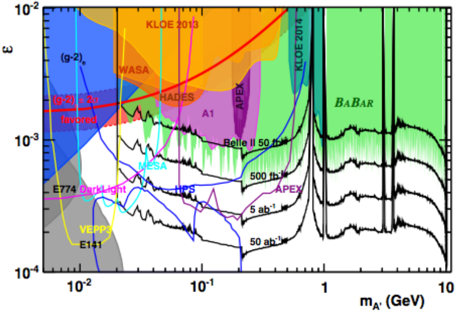
Limits on kinetic mixing parameters



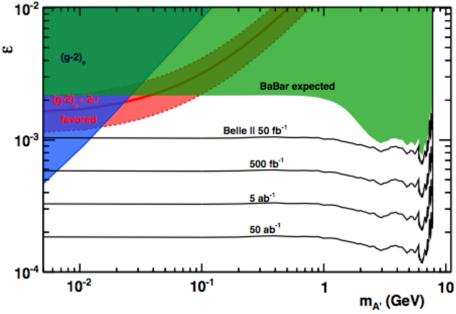
- $\epsilon \lesssim 8 \times 10^{-4}$ for $\alpha_D = 1/137$, $M_{h'} < 8$ GeV/c^2, $M_{A'} < 1$ GeV/c^2
- first limits (by any experiment) on $3(\pi^+\pi^-)$ and $2(e^+e^-)X$
- For Belle II, the improvement will be nearly linear (almost background-free for many modes)

Dark photon prospects with Belle II

$e^+e^- \to \gamma\, A'(\to \ell^+\ell^-)$

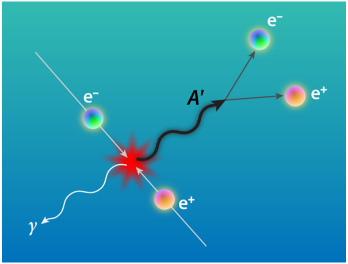


$e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$



Search for dark photon decaying to $\ell^+\ell^-$ (BaBar)

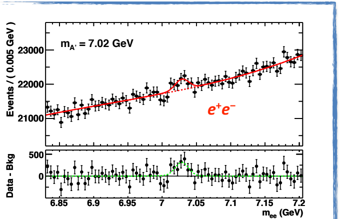
PRL **113**, 201801 (2014)



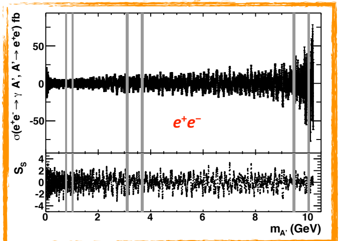
a slide taken from a talk
by G. Finnochiario (INFN) @ ICNFP 2015

Search for dark photon decaying to $\ell^+\ell^-$ (BaBar)

- Fit signal peak over smooth background
  - background: 3rd/4th order polynomial + Crystal Ball + interference
  - signal mass shape from MC, tuned on data using $e^+e^- \to J/\psi\ \gamma$; $J/\psi \to \ell^+\ell^-$
  - $\sigma_m(A')$ from 1.5 to 8 MeV
  - about 5500 fits to scan the A' mass spectrum from 0.02/0.212 GeV ($e^+e^-/\mu^+\mu^-$) up to 10.2GeV in steps of 1/2 $\sigma_m(A')$



The most significant e^+e^- signal fit

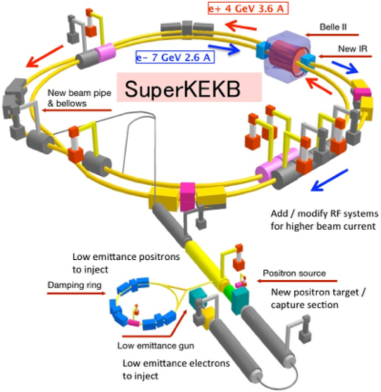


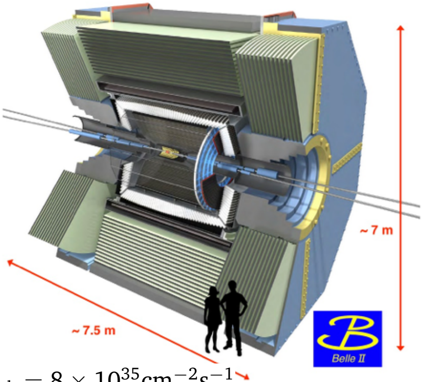
- $\sigma(e^+e^- \to A'\ \gamma;\ A' \to \ell^+\ell^-)$ vs A' mass; regions around known resonances (grey bands) excluded from fits
- Calculate (signed) signal significance with respect to background-only hypothesis

$$S = \mathrm{sign}[N(\mathrm{signal})]\sqrt{2\log[L(\mathrm{signal}+\mathrm{bkg})/L(\mathrm{bkg})]}$$

  - Largest significance at 7.02 GeV for electrons (3.4 σ → 0.6 σ with trial factor)

SuperKEKB & Belle II



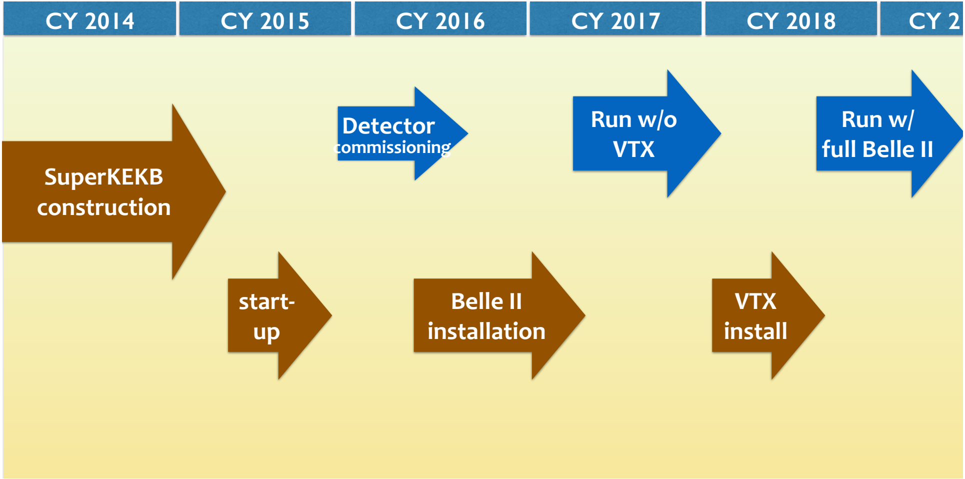


$$e^- \xrightarrow{\text{7 GeV}} (\star) \xleftarrow{\text{4 GeV}} e^+$$

$$\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

$$\int^{\text{goal}} \mathcal{L}\, dt = 50 \text{ ab}^{-1}$$

SuperKEKB & Belle II - current plan



Belle II Collaboration
September 29 at 11:25pm · Edited ·

On Sept. 18th, the Belle II solenoid magnet was fully excited to its nominal magnetic field strength of 1.5T for the first time since the end of the Belle experiment (The top left photograph shows the Belle II solenoid power supply and members of the solenoid group). Charged particles produced in the experiment have curved paths due to the interaction with the magnetic field - the curvature of the charged particle tracks enable identification of the particles' momentum and ch... See More