Rare B and D decays

Youngjoon Kwon

Yonsei University
Seoul, Korea

Nov. 17, 2011

Acknowledgment, apology & disclaimer

- Thanks to my Belle colleagues as well as S. Robertson, T. Gershon, D. Tonnelli, R.v. Kooten. G. Raven, B. Casey, D. Asner and many others

- I tried my best to keep the experimental reference up to date, but theory reference is by no means complete. Any omission is my fault.
- I restricted my scope to *Rare decays*, hence not covering anything about CKM, mixing, exotic resonances and other beautiful/charming new results.

Rare B decays

Rare B decays for New Physics

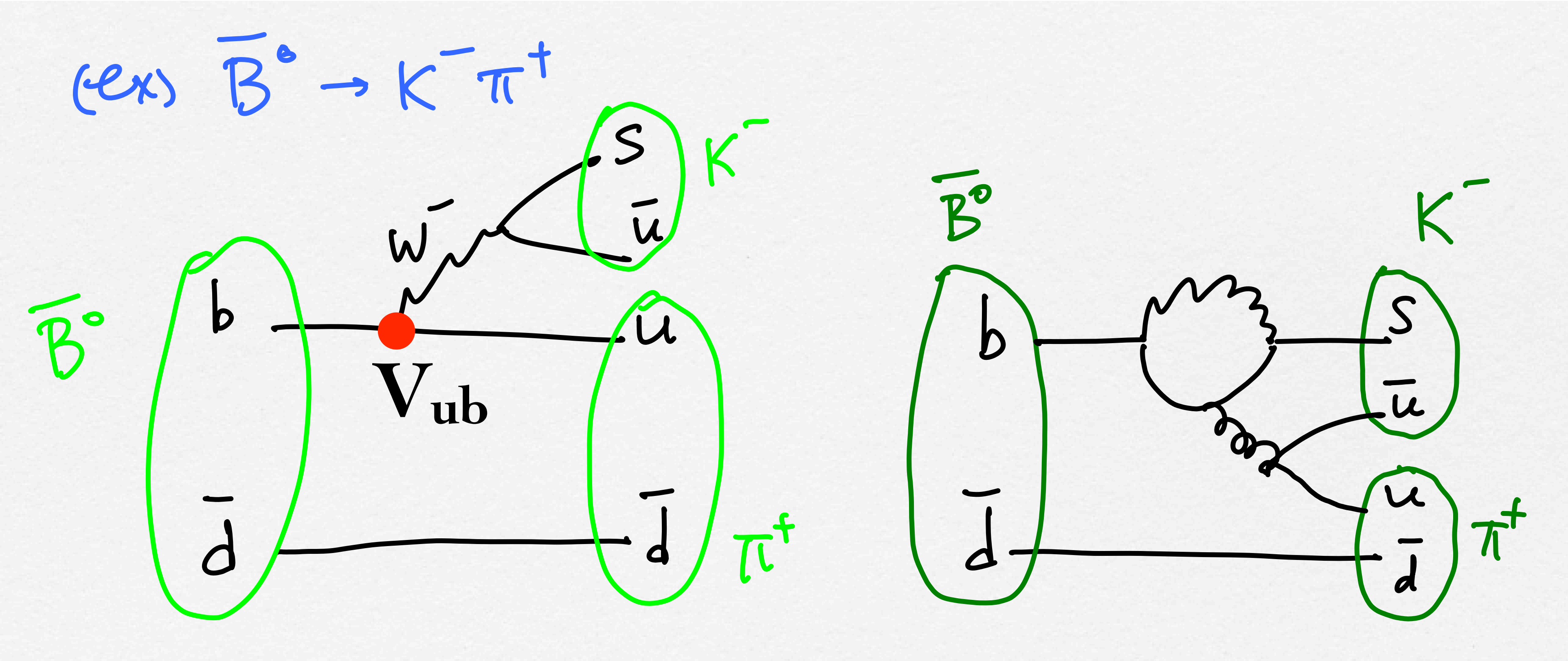
- SM is a very good approx. for reality
  i.e. $A_{\text{Nature}} \simeq A_{\text{SM}}$ for most processes
- Need to look where A_{SM} is small, in order to be sensitive to NP
  e.g. $b \to s$ penguins
- Compare A_{Nature} with A_{SM}, then
  Find new physics or learn new lessons!

- In particular, we will focus on:
  * the $K\pi$ puzzle
  * EWP and related
  * purely leptonic decays
  * invisible and semi-invisible decays

N.B. Some channels are experimentally clean (*e.g.* all-charged, low-multiplicity), while others are very difficult (*e.g.* invisible and semi-invisible modes).

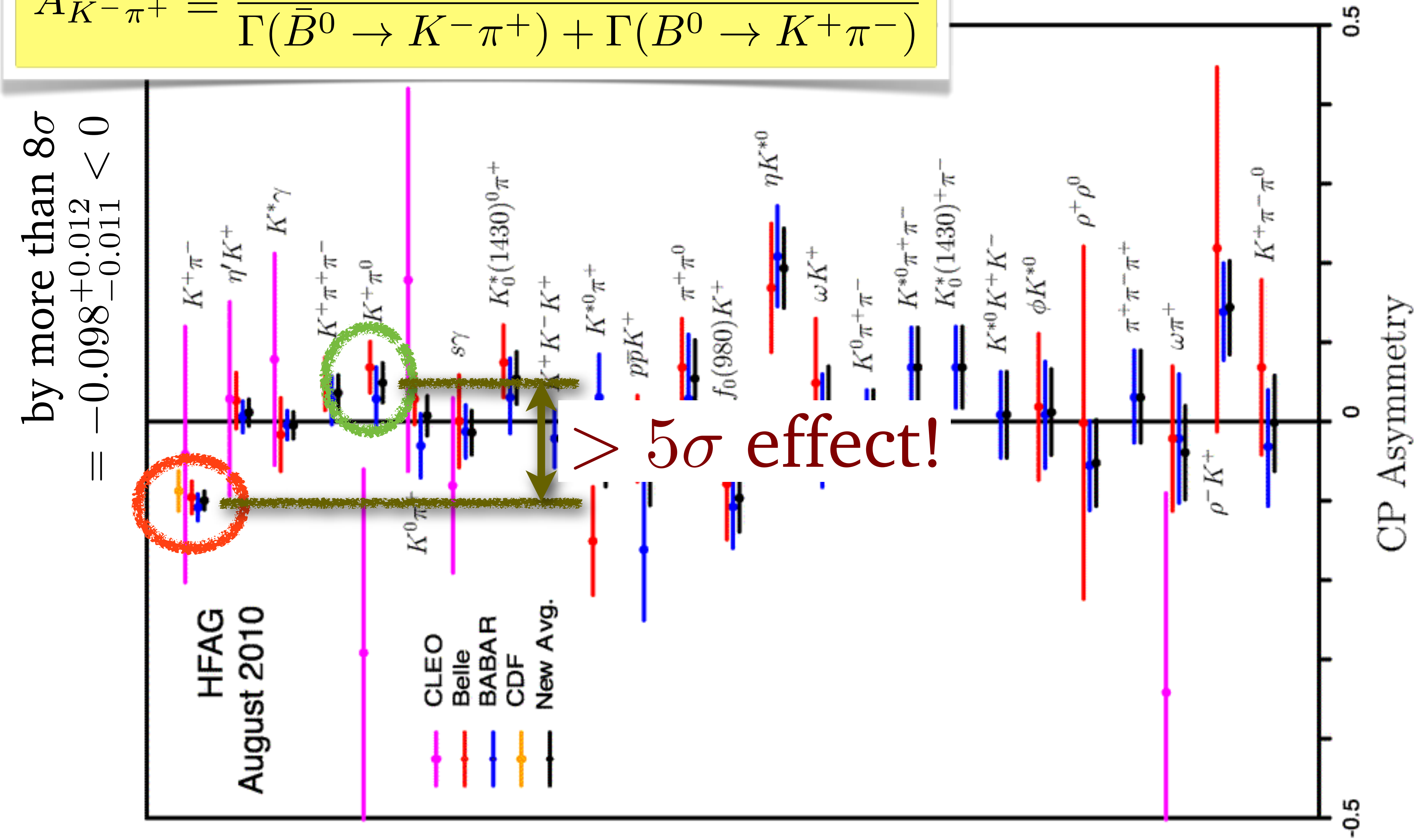
Charmless Hadronic B decays

Charmless hadronic B decays

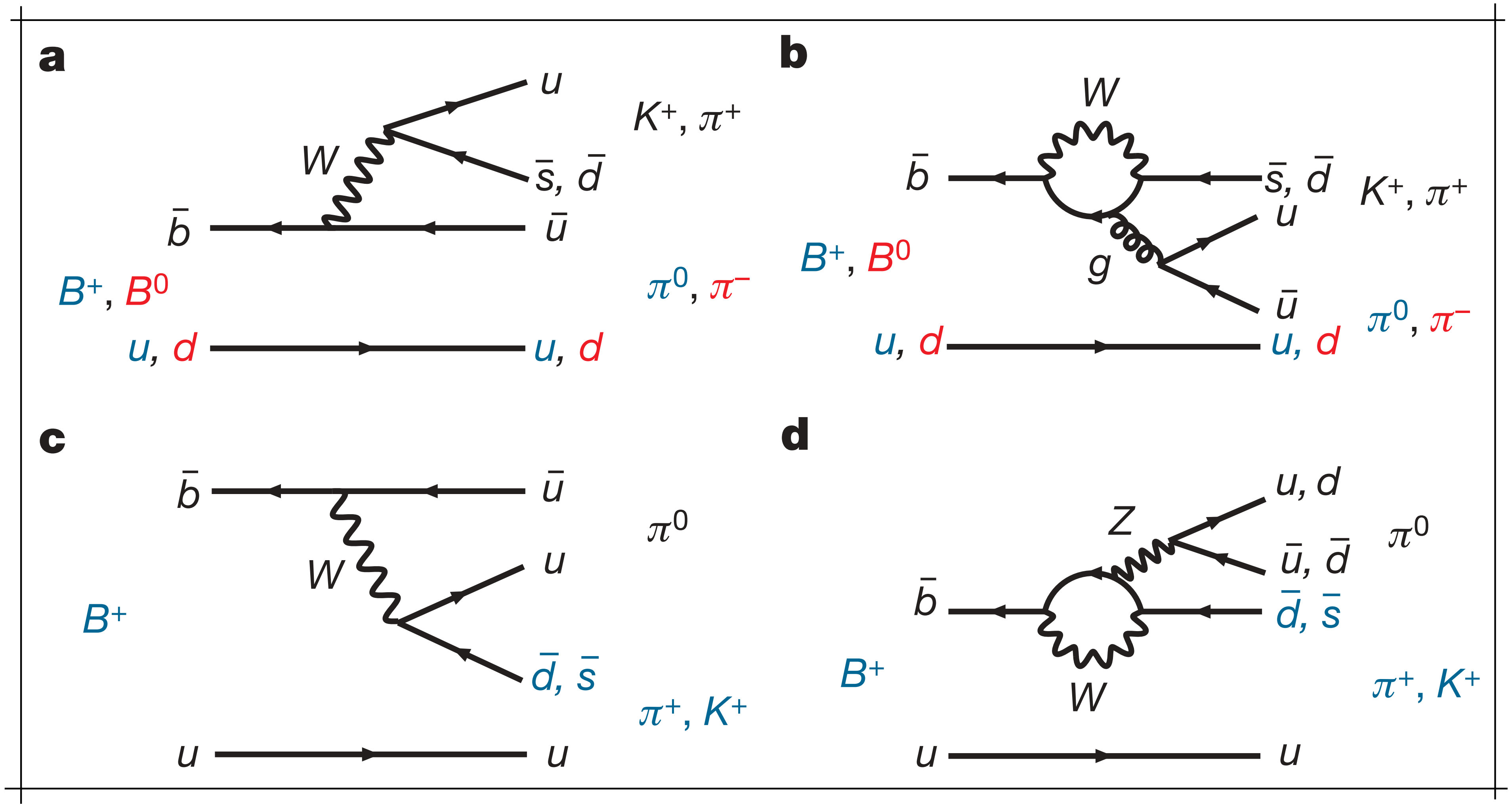


- $\exists$ tree-penguin interference $\Rightarrow$ a great place to look for DCPV
  - extract the CKM angle $\phi_3(\gamma)$
  - the "$K\pi$ puzzle": $\Delta A_{K\pi} \equiv A_{CP}(K^-\pi^0) - A_{CP}(K^-\pi^+) \neq 0$

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



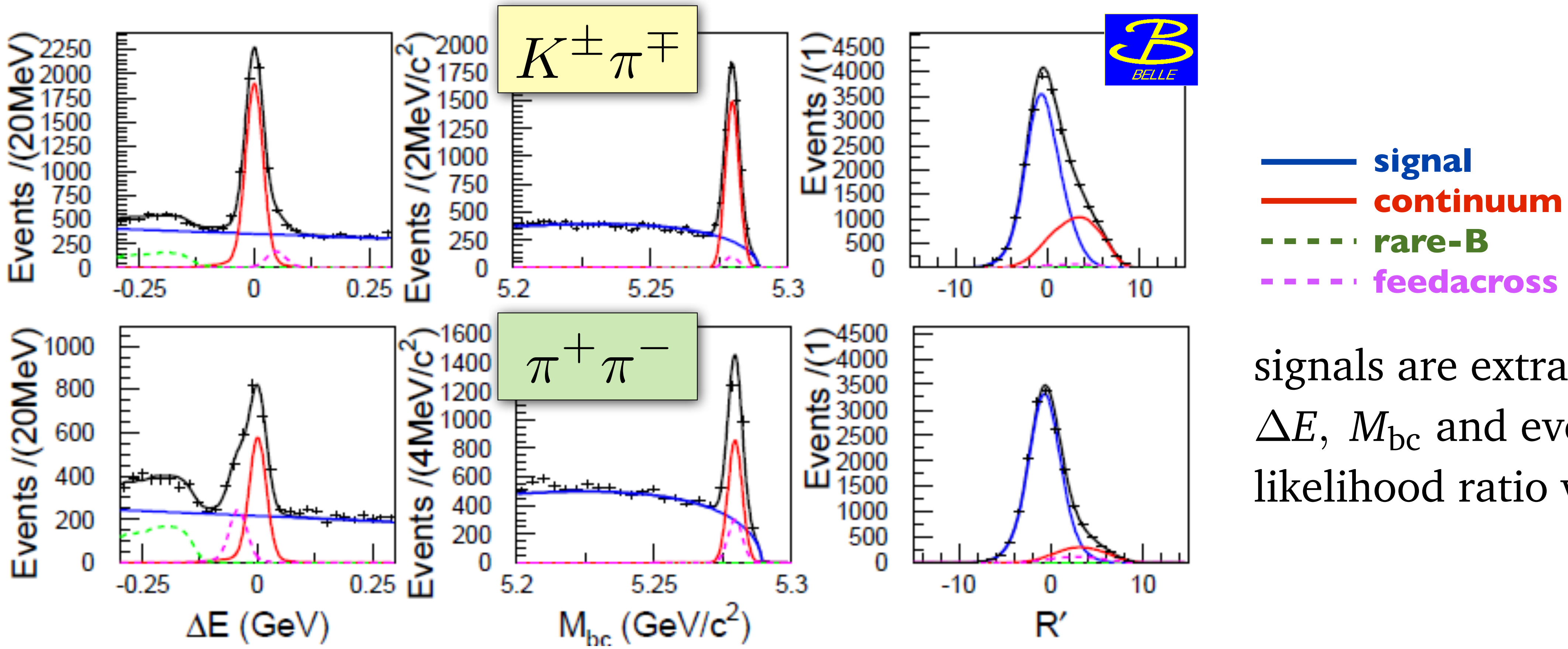
A_{CP} of hadronic rare *B* decays (HFAG 2010)



- enhanced color-suppressed tree?
  - Can it be bigger than color-favored tree?
- EW penguin?
  - negligible CP phase in SM $\Rightarrow$ cannot affect ΔA by much
  - perhaps, picking up a new phase from NP?

CWC, MG, JR, DS, PRD 70, 034020 (2004), YYC, HnL, PRD 71, 014036 (2005)
WSH, MN, AS, PRL 95, 141601 (2005), SB, PH, DL, DS, PRD 71, 057502 (2005), etc.

$B^0 \to K^\pm\pi^\mp$ and $\pi^+\pi^-$ (Belle, *prelim.*)



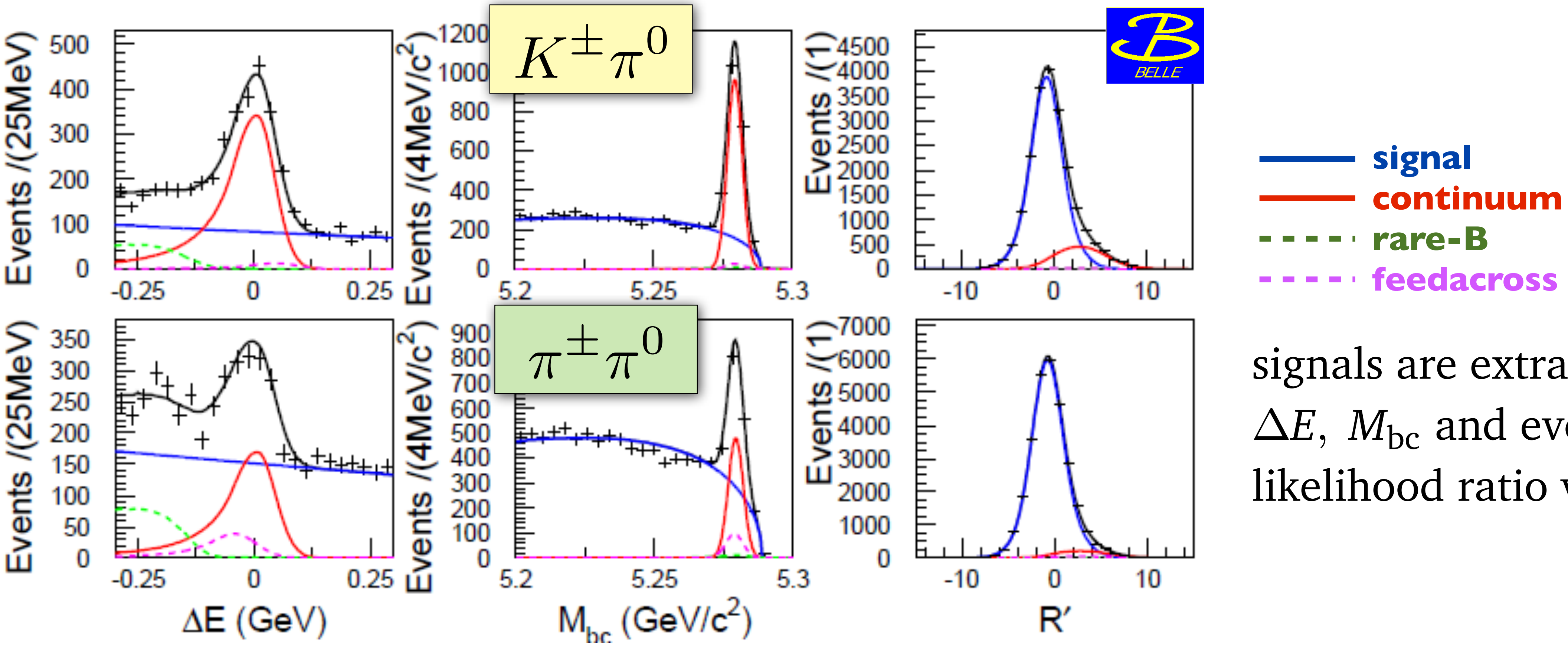
signals are extracted by 3D-fit on ΔE, $M_{\rm bc}$ and event shape likelihood ratio variables

$N_{B\bar{B}} = 772$M (full Belle sample)

$B^0 \to K^\pm\pi^\mp$
- $N = 7527 \pm 127$
- $\mathcal{B} = (20.00 \pm 0.34 \pm 0.63) \times 10^{-6}$
- $A_{CP} = (-0.069 \pm 0.014 \pm 0.007)$

$B^0 \to \pi^+\pi^-$
- $N = 2111 \pm 89$
- $\mathcal{B} = (5.04 \pm 0.21 \pm 0.19) \times 10^{-6}$

$B^\pm \to K^\pm\pi^0$ and $\pi^\pm\pi^0$ (Belle, *prelim.*)



signals are extracted by 3D-fit on ΔE, $M_{\rm bc}$ and event shape likelihood ratio variables

$N_{B\bar{B}} = 772$M (full Belle sample)

$B^\pm \to K^\pm\pi^0$

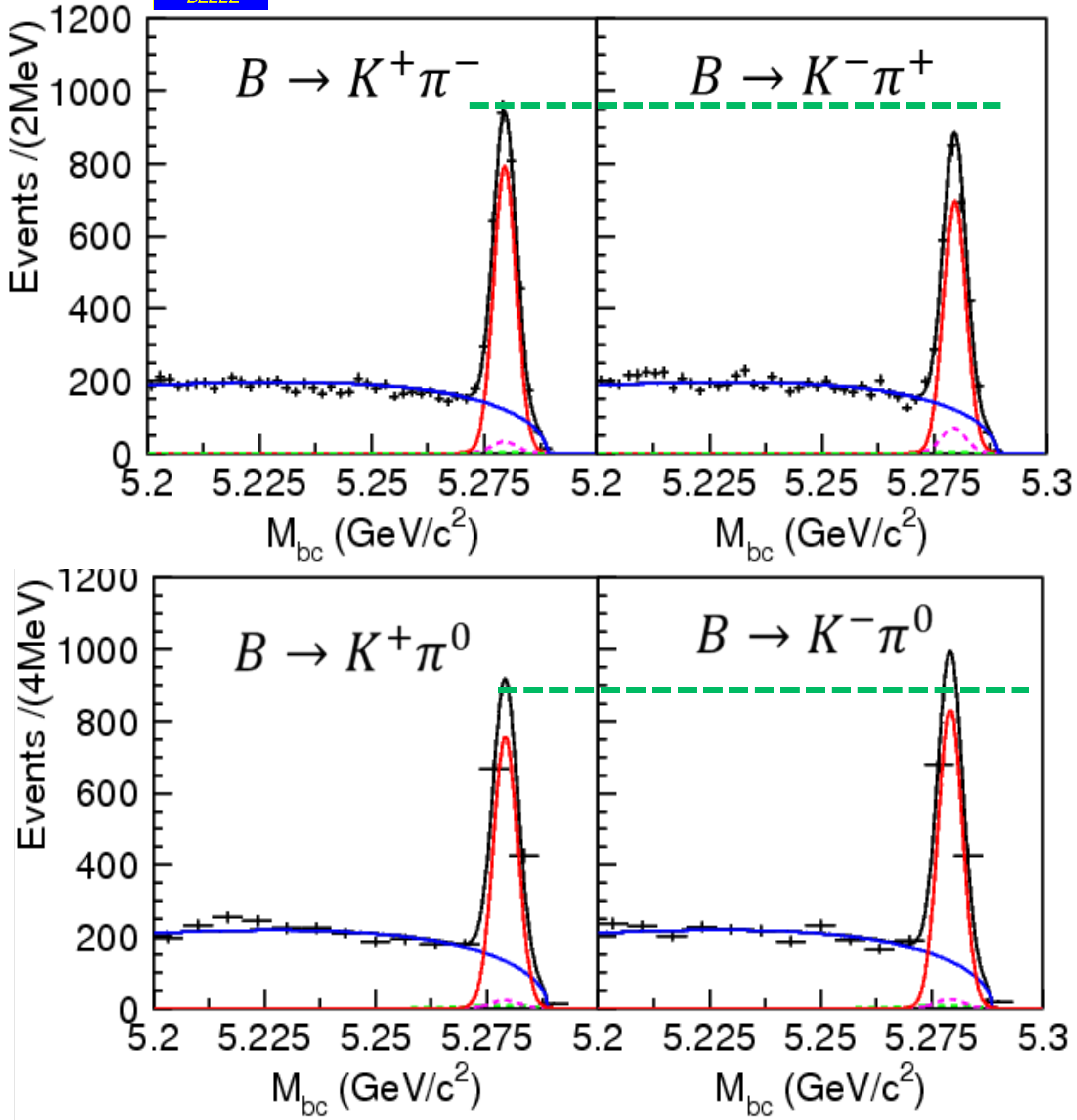
- $N = 3731 \pm 92$
- $\mathcal{B} = (12.62 \pm 0.31 \pm 0.56) \times 10^{-6}$
- $A_{CP} = (+0.043 \pm 0.024 \pm 0.002)$

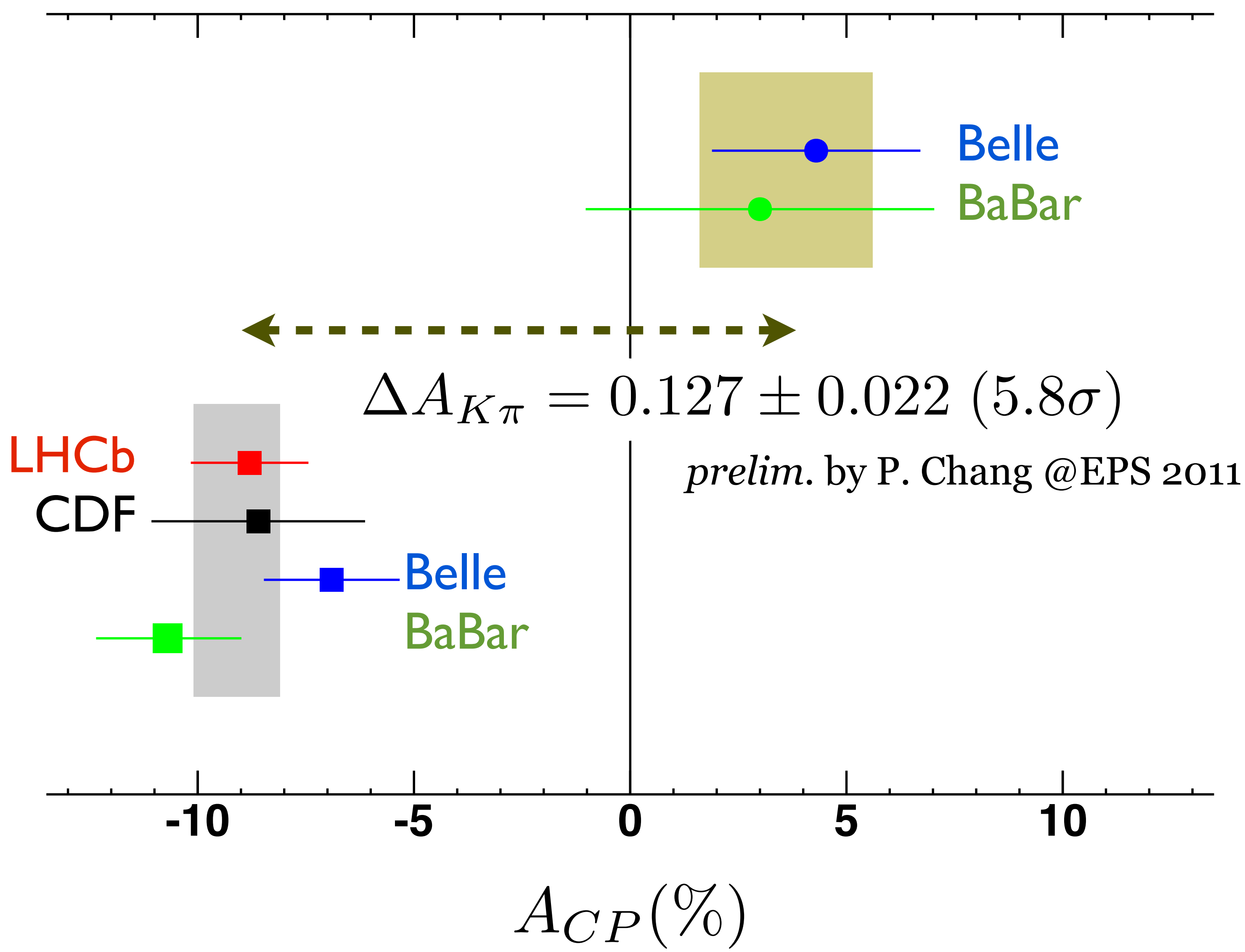
$B^\pm \to \pi^\pm\pi^0$

- $N = 1846 \pm 82$
- $\mathcal{B} = (5.86 \pm 0.26 \pm 0.38) \times 10^{-6}$
- $A_{CP} = (+0.025 \pm 0.043 \pm 0.007)$

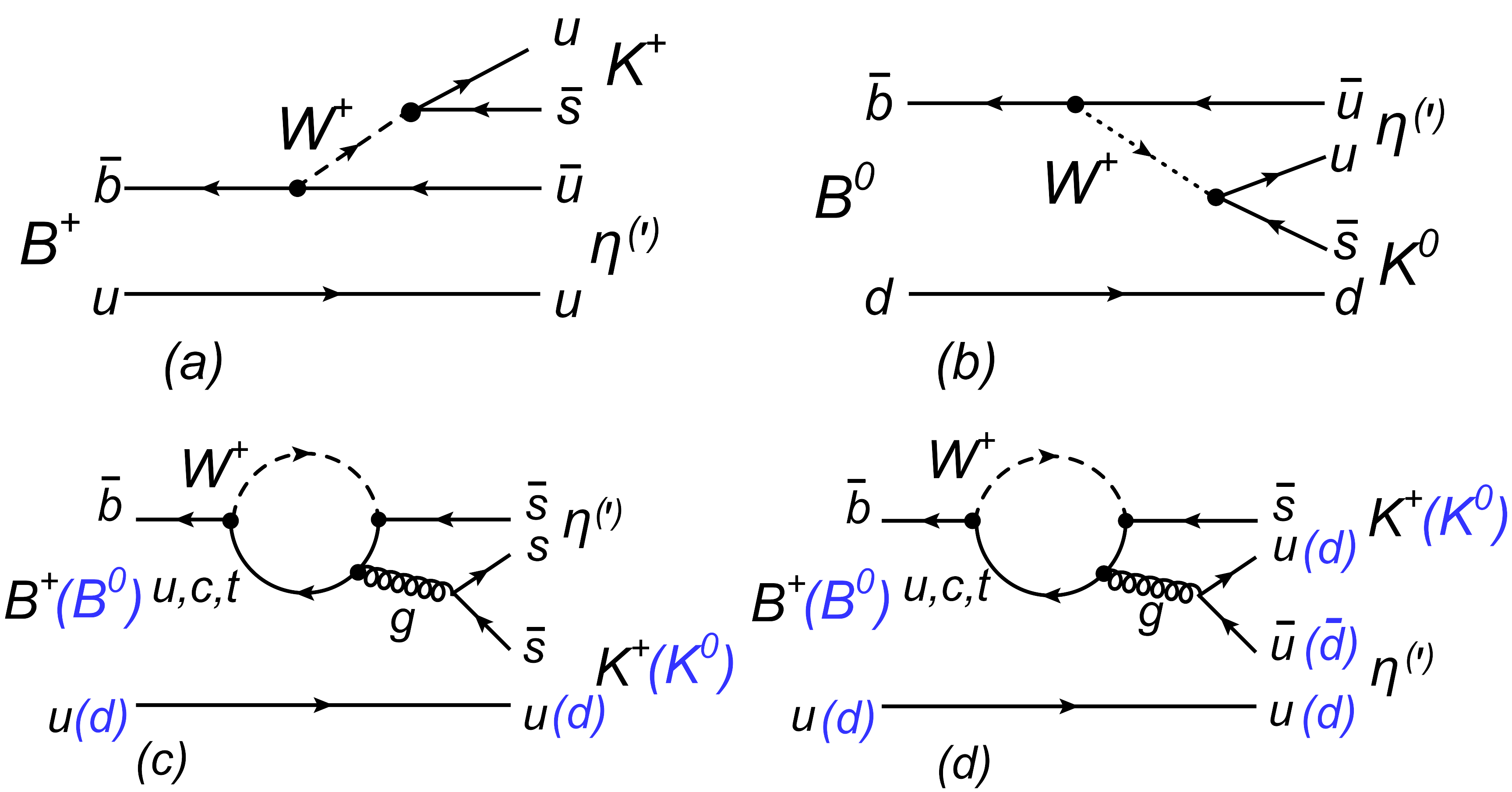
The $K\pi$ puzzle, *updated*

preliminary (EPS 2011)



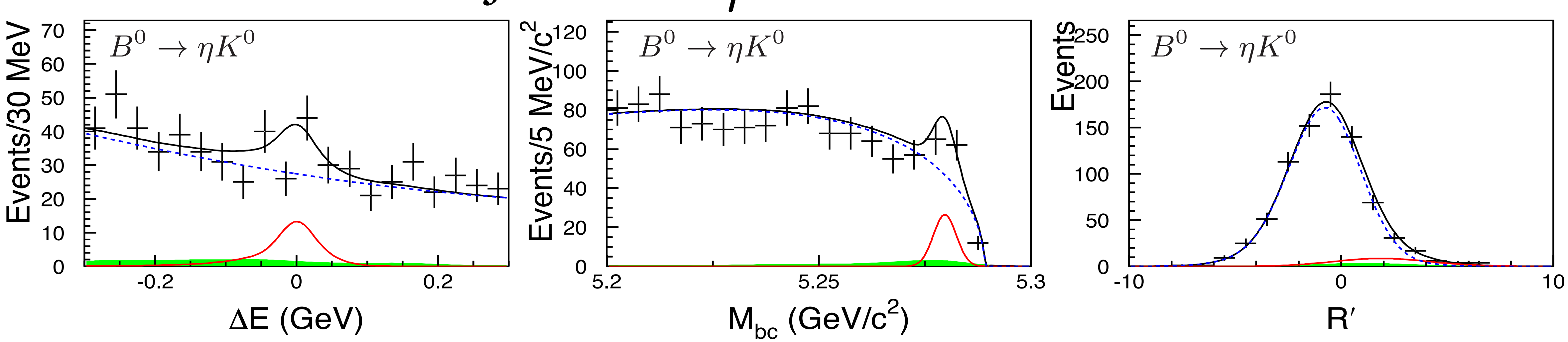


DCPV in $B^{\pm} \to \eta h^{\pm}$



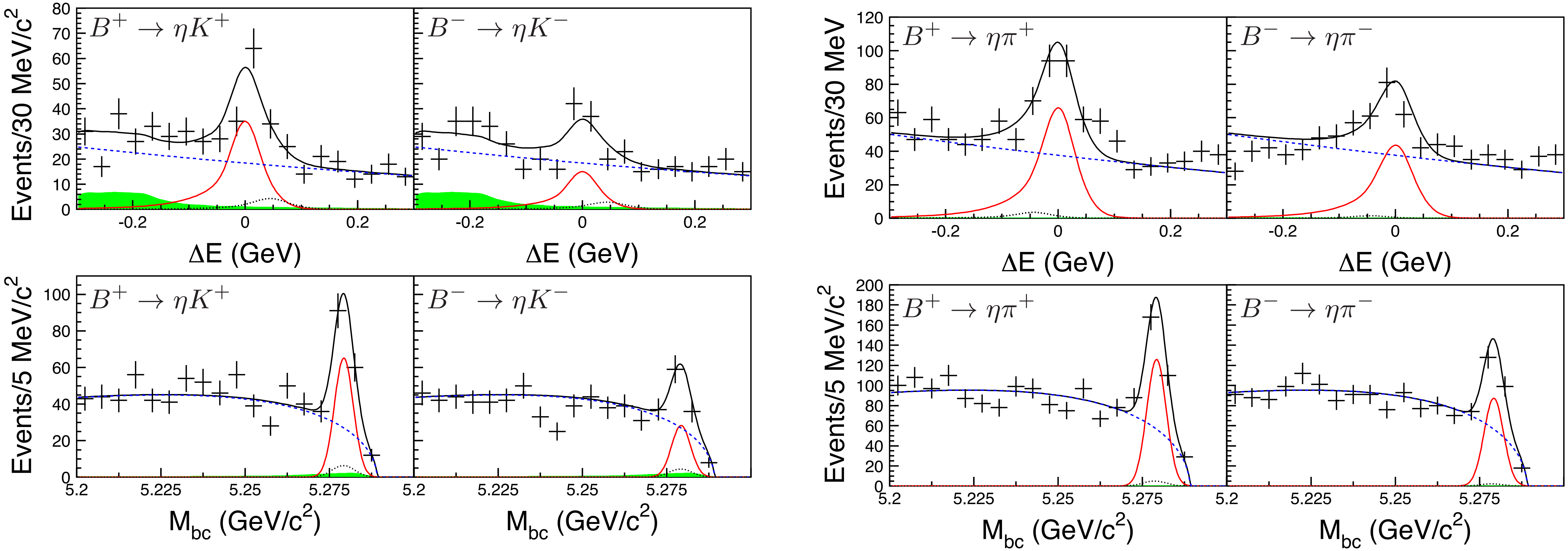
* intriguing BF's for $B \to \eta(') h^{(*)}$
* DCPV is expected
* details may depend on $\eta - \eta'$ mixing

First observaton of $B^0 \to \eta K^0$



1110.2000

DCPV in $B^\pm \to \eta h^\pm$



Mode	ϵ (%)	Yield	$\Sigma(\mathcal{Y})$	$\mathcal{B}$ (10^{-6})	A_{CP}	$\Sigma(A_{CP})$
$B^\pm \to \eta K^\pm$			13.2	$2.12 \pm 0.23 \pm 0.11$	$-0.38 \pm 0.11 \pm 0.01$	3.8
$\eta_{\gamma\gamma} K^\pm$	13.3	$201.9^{+27.1}_{-26.5}$	10.2	$2.07 \pm 0.27 \pm 0.10$	$-0.36 \pm 0.13 \pm 0.01$	2.9
$\eta_{3\pi} K^\pm$	4.9	$80.2^{+14.9}_{-13.9}$	8.6	$2.29^{+0.43}_{-0.40} \pm 0.15$	$-0.42 \pm 0.18 \pm 0.01$	2.4
$B^\pm \to \eta \pi^\pm$			22.4	$4.07 \pm 0.26 \pm 0.21$	$-0.19 \pm 0.06 \pm 0.01$	3.0
$\eta_{\gamma\gamma} \pi^\pm$	15.3	$480.6^{+35.1}_{-36.0}$	19.0	$4.24 \pm 0.32 \pm 0.19$	$-0.14 \pm 0.08 \pm 0.01$	1.8
$\eta_{3\pi} \pi^\pm$	5.4	$138.6^{+18.5}_{-17.5}$	12.2	$3.63 \pm 0.49 \pm 0.25$	$-0.31 \pm 0.13 \pm 0.01$	2.5
$B^0 \to \eta K^0$			5.4	$1.27^{+0.33}_{-0.29} \pm 0.08$		
$\eta_{\gamma\gamma} K^0$	4.2	$38.0^{+12.6}_{-11.4}$	4.0	$1.18^{+0.39}_{-0.35} \pm 0.06$		
$\eta_{3\pi} K^0$	1.5	$16.2^{+6.5}_{-5.4}$	4.1	$1.48^{+0.59}_{-0.49} \pm 0.10$		

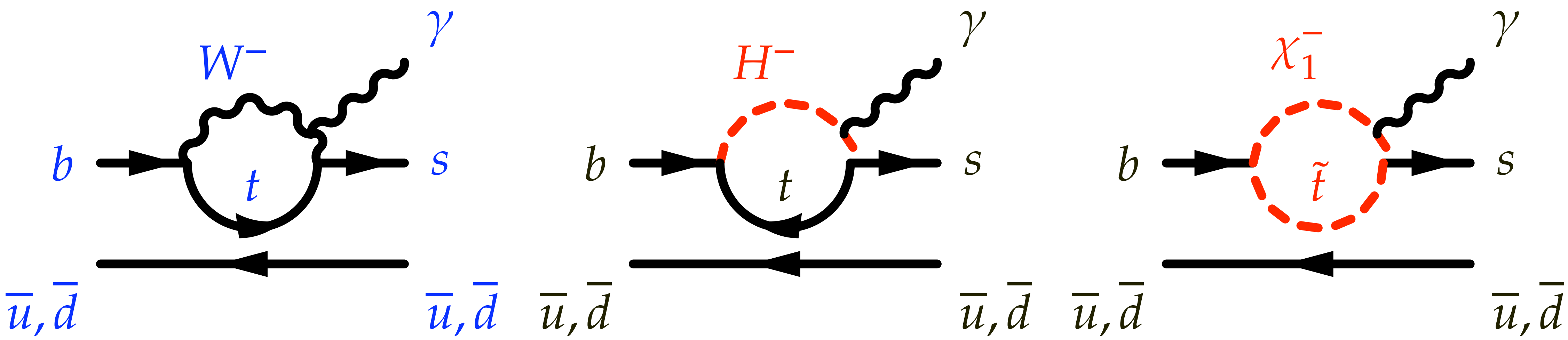
1st evidence!

1st observation!

Electroweak Penguin *B* decays

EW penguin B decays

- one-loop penguin
  - suppressed in SM, hence sensitive to NP
  - (ex) H^+ in place of W^+ in the loop



- CPV in radiative penguin can be a sensitive probe for NP
- Its cousin, $B \to X\ell^+\ell^-$ is interesting, too
  - rich structure
  - sensitive to several Wilson coeff's.

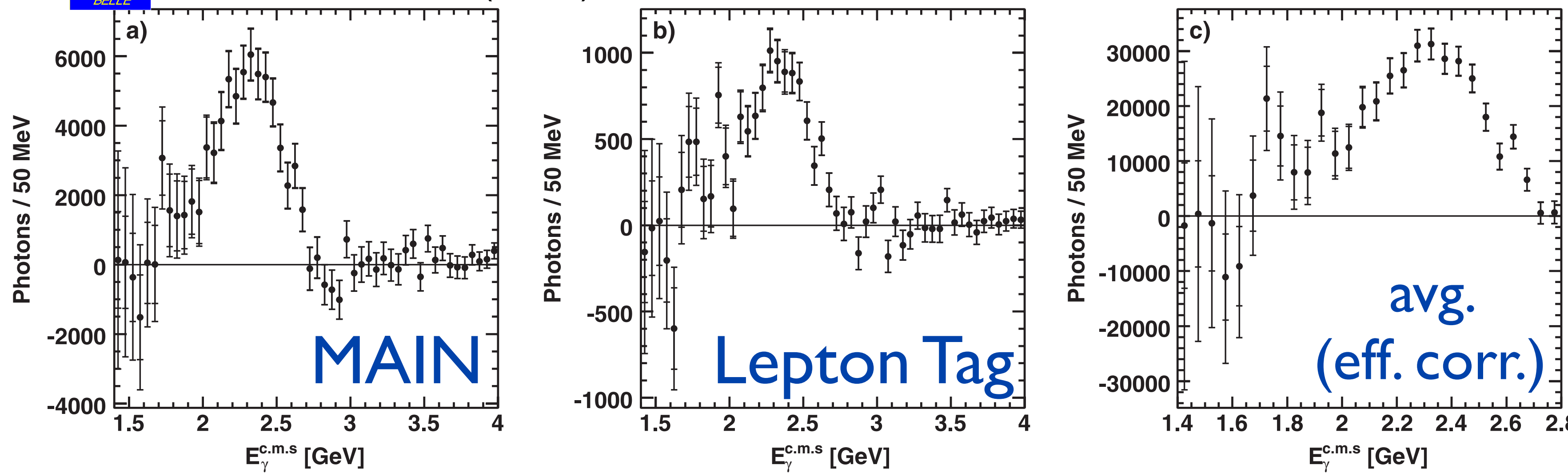
Belle's legacy on EWP

- First observation of $B \to K\ell^+\ell^-$ PRL **88**, 021801 (2002)
- First observation of $B \to K^*\ell^+\ell^-$ PRL **91**, 261601 (2003)
- First observation of $B \to X_s\ell^+\ell^-$ PRL **90**, 021801 (2003)
- First measurement of $A_{\rm FB}$ of $B \to K^*\ell^+\ell^-$ PRL **96**, 251801 (2006)

- First observations of several radiative modes, $\phi K\gamma$, $K_1\gamma$, etc.
- First observation of $B \to (\rho, \omega)\gamma$ PRL **96**, 221601 (2006)
- Most precise measurement of $B \to X_s\gamma$ covering the widest E_γ range PRL **103**, 241801 (2009)
- *and many more published results*

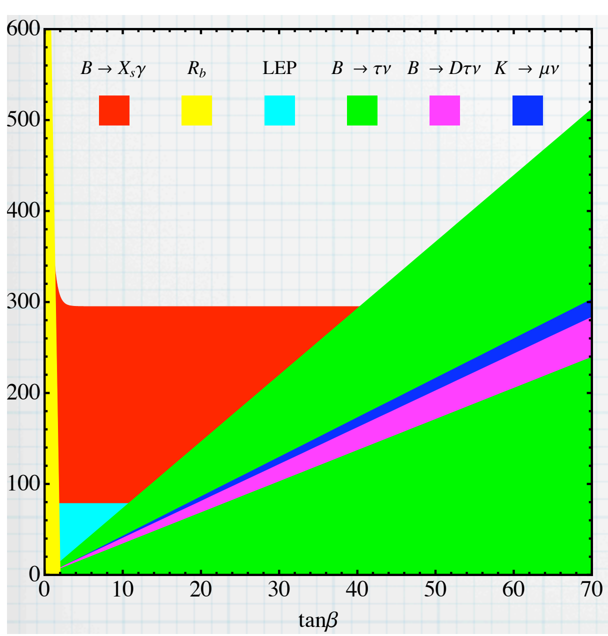
Inclusive $B \to X_s\gamma$

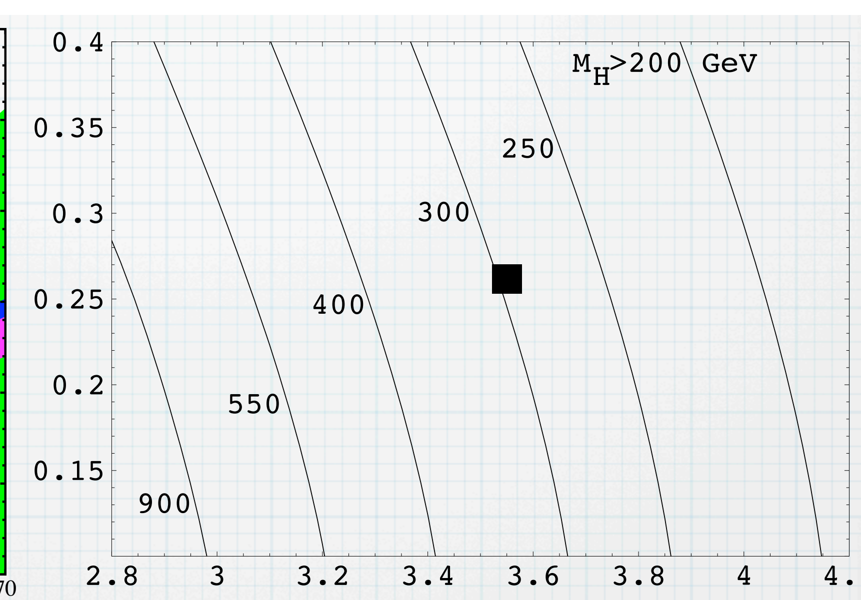
PRL 103, 241801 (2009)



$\mathcal{B}(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$ $(1.7 < E_\gamma < 2.8$ GeV$)$

$\mathcal{B}_{\rm SM} = (3.15 \pm 0.23) \times 10^{-4}$ $(E_\gamma > 1.6$ GeV$)$ NNLO by Misiak *et al.*, PRL 98, 022002 (2007)



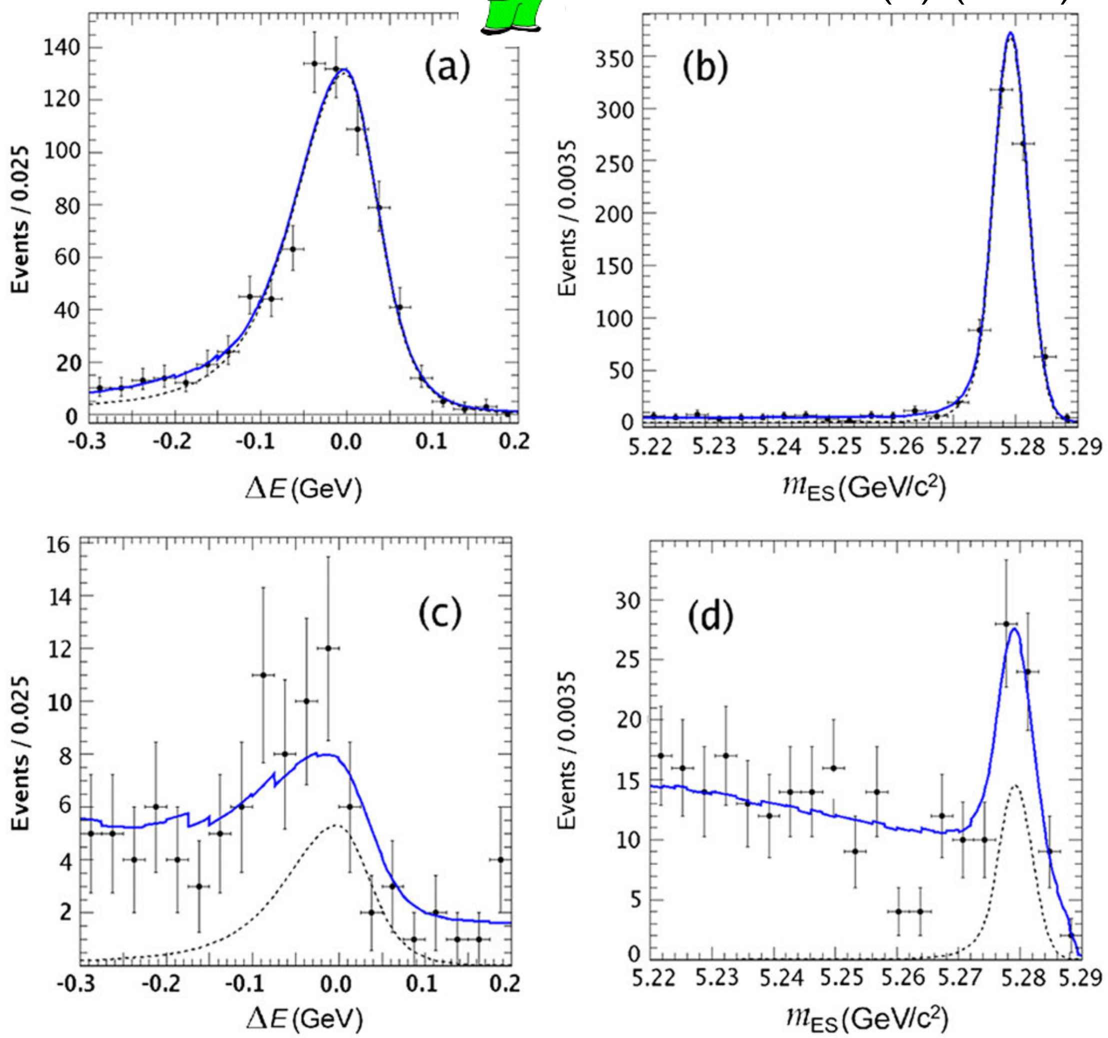


$m_{H^+} > 300$ GeV @ 95% CL for all $\tan\beta$

Complementary to direct constraints from ATLAS/CMS!

Inclusive $B \to X_{s(d)}\gamma$

PRD 82, 051101(R) (2010)



Projections of ΔE with $5.275 < m_{\rm ES} < 5.286$ GeV/c^2 and $m_{\rm ES}$ with $-0.1 < \Delta E < 0.05$ GeV for $B \to X_s\gamma$ (top) and $X_d\gamma$ (bottom) in the mass range $0.5 < M(X_{s(d)}) < 1.0$ GeV/c^2.

- separately studied for low- (0.5 – 1.0) and high-mass (1.0 – 2.0) regions of the hadronic states $X_{s(d)}$
- by a sum of 7 exclusive final states for each of $X_s\gamma$ and $X_d\gamma$

	$M(X_s) 0.5-2.0$	$M(X_s) 0.5-2.0$
$\mathcal{B}$ $(\times 10^6)$	$230 \pm 8 \pm 30$	$9.2 \pm 2.0 \pm 2.3$
$X_d\gamma/X_s\gamma$	$0.040 \pm 0.009 \pm 0.010$	

- The ratio $X_d\gamma/X_s\gamma$ is converted to give

$$|V_{td}/V_{ts}| = 0.199 \pm 0.022 \pm 0.024 \pm 0.002$$

3rd error is from theory uncertainty

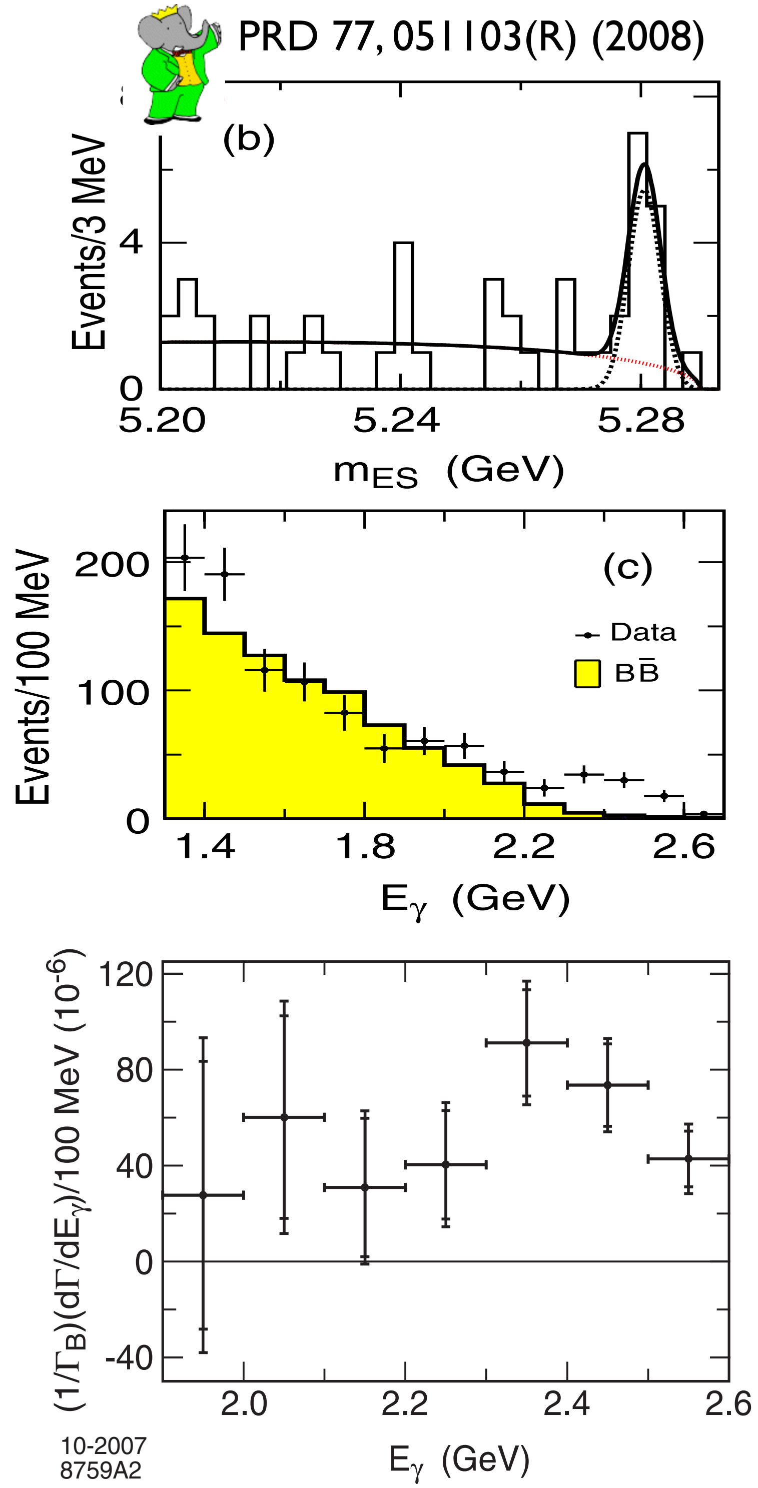
complementary to constraints from $B_s\overline{B}_s$ mixing

$$|V_{td}/V_{ts}| = 0.2061 \pm 0.0012^{+0.0080}_{-0.0060}$$

PDG (2010) mini-review on B mixing

Inclusive $B \to X_s\gamma$, *separately for* B^0 *&* B^+

PRD 77, 051103(R) (2008)

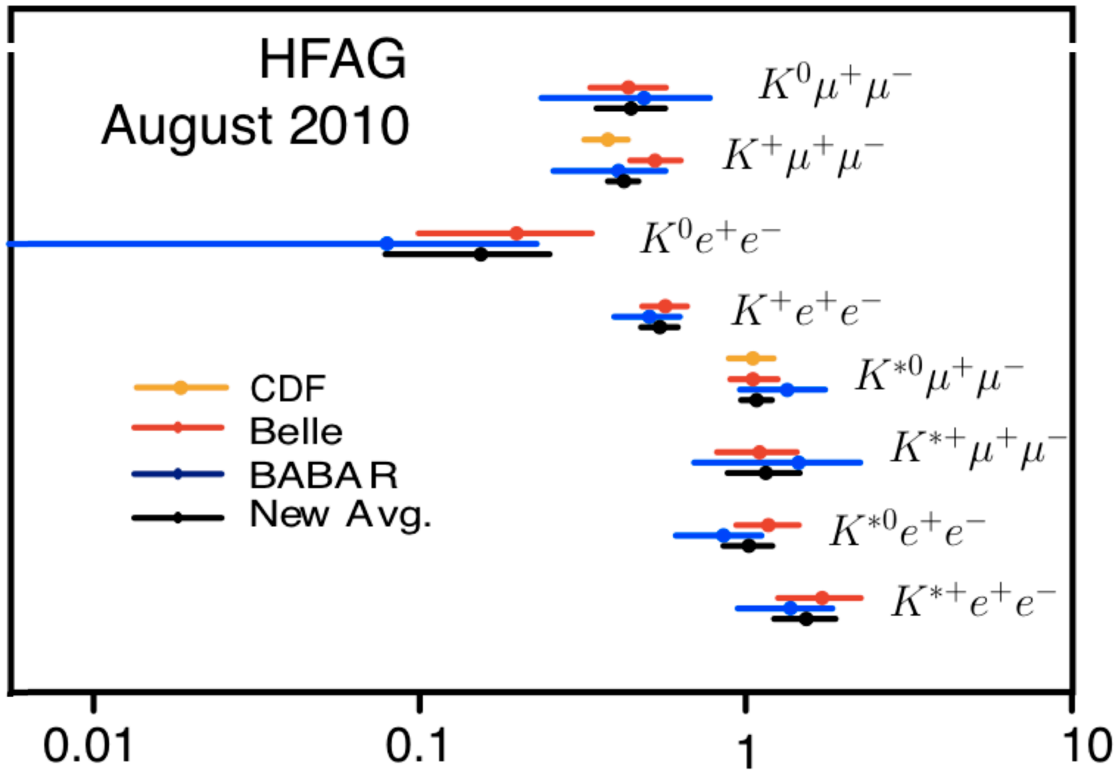


- Why separately for B^0 and B^+?
  - $\Delta A(K\pi)$ puzzle is, after all, about the difference btw B^+ and B^0
  - a possible explanation is in the EWP
  - so, it's important to study B^+/B^0 difference in the EWP
- How to do it, inclusively?
  - by full-recon. of the companion B
  - unique at e^+e^- B-factories

$$\mathcal{B} = (3.91 \pm 0.91 \pm 0.64) \times 10^{-4}$$
$$\Delta_{0-} = -0.06 \pm 0.15 \pm 0.07$$
$$A_{CP} = 0.10 \pm 0.18 \pm 0.05$$

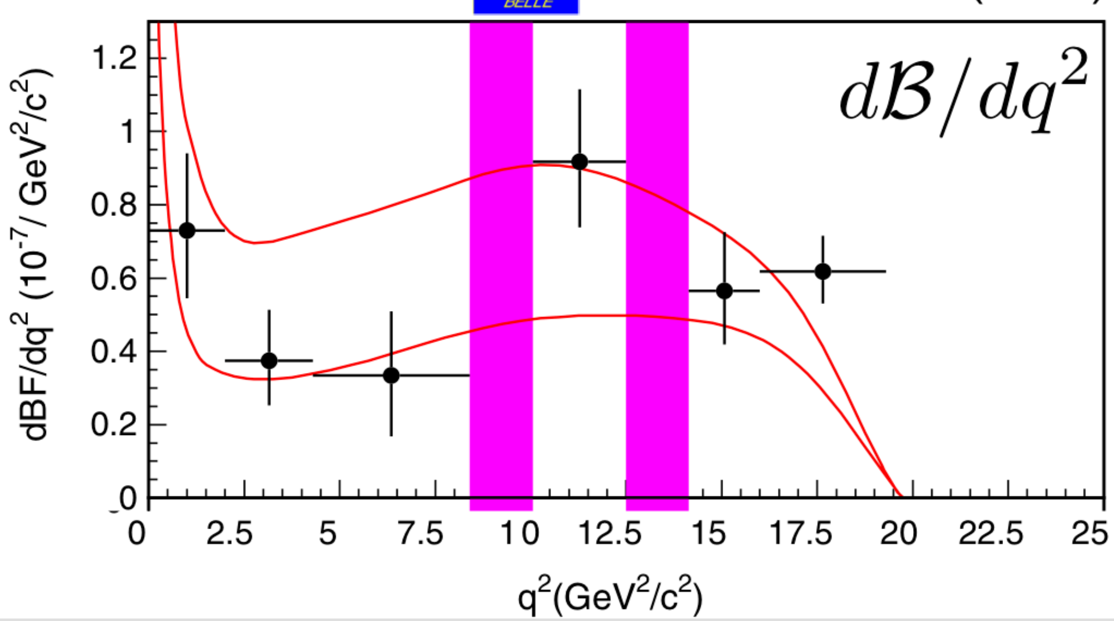
$B \to K^{(*)}\ell^+\ell^-$

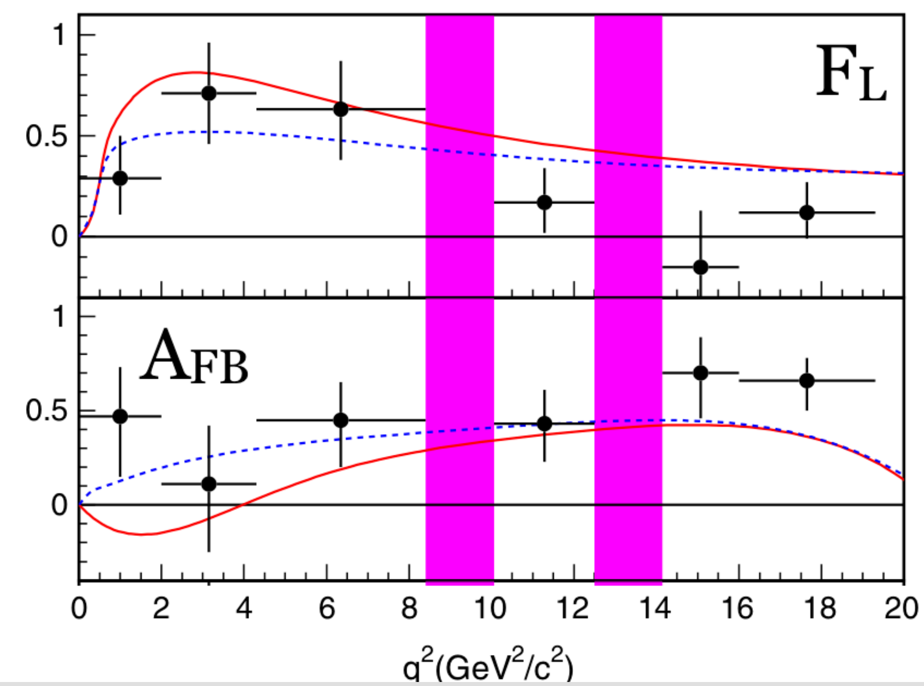
$\mathcal{B}(B \to X_s\ell^+\ell^-) \times 10^6$



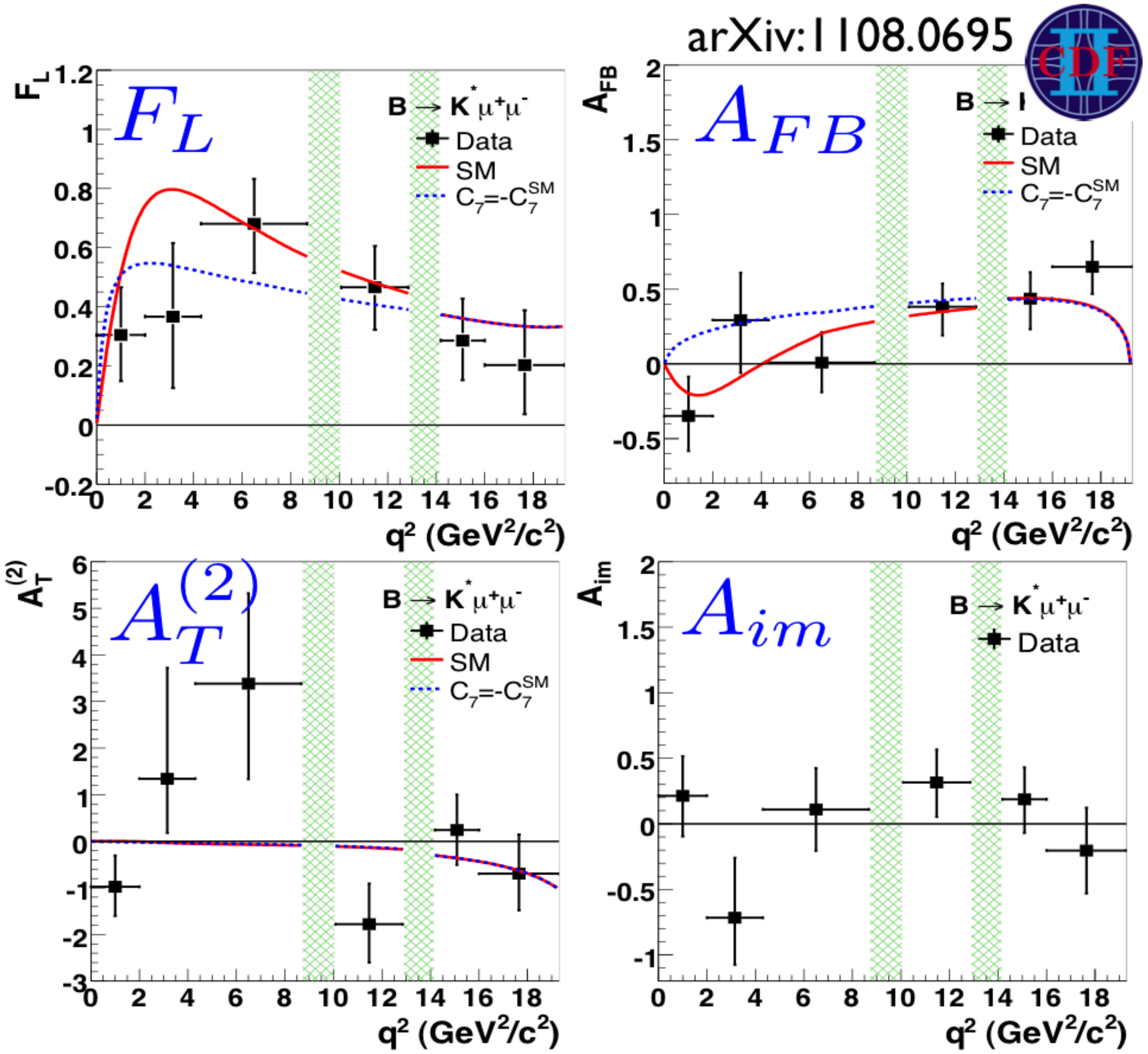
- first observed in 2002 ($K\ell^+\ell^-$) and 2003 ($K^*\ell^+\ell^-$) *both by Belle*
- branching fractions are pretty well measured
- 3-body decay $\Rightarrow$ provide rich observables ($d\mathcal{B}/dq^2, F_L, A_{FB}$, etc.) to study structure in detail
- no signals observed for CKM-suppressed $B \to X_d\ell^+\ell^-$

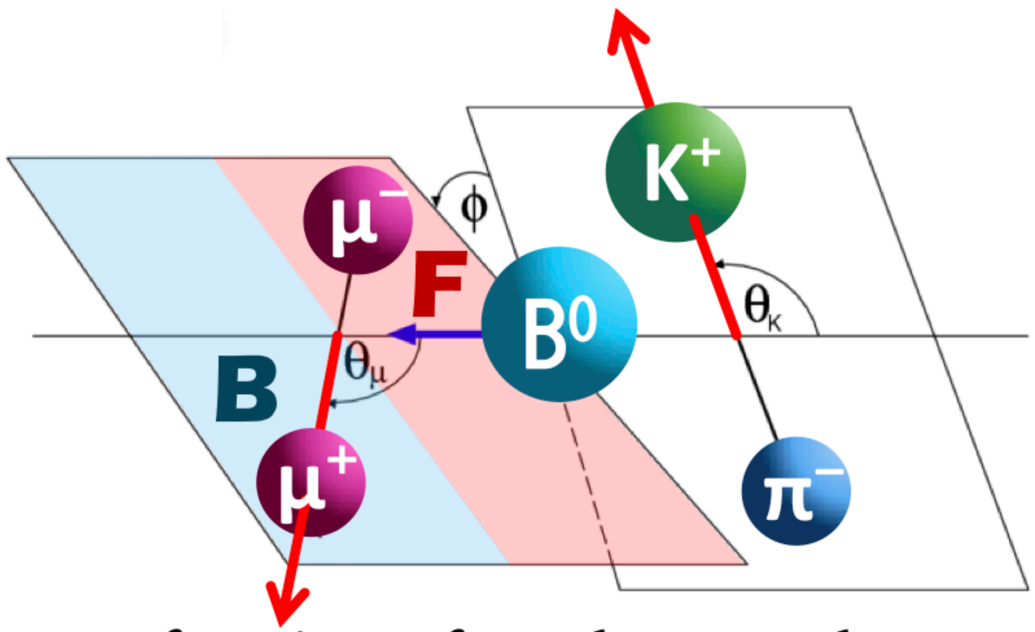
PRL 103, 171801 (2009)





$B \to K^* \mu^+ \mu^-$ CDF (6.8 fb^{-1})





F_L: fraction of K^* long. pol.
A_{FB}: μ forward-backward asym.
$A_T^{(2)}$: transverse pol. asym.
A_{im}: T-odd CP asym.

First measurement of RH-sensitive observables: $A_T^{(2)}(q^2)$ and $A_{im}(q^2)$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_K} = \frac{3}{2} F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

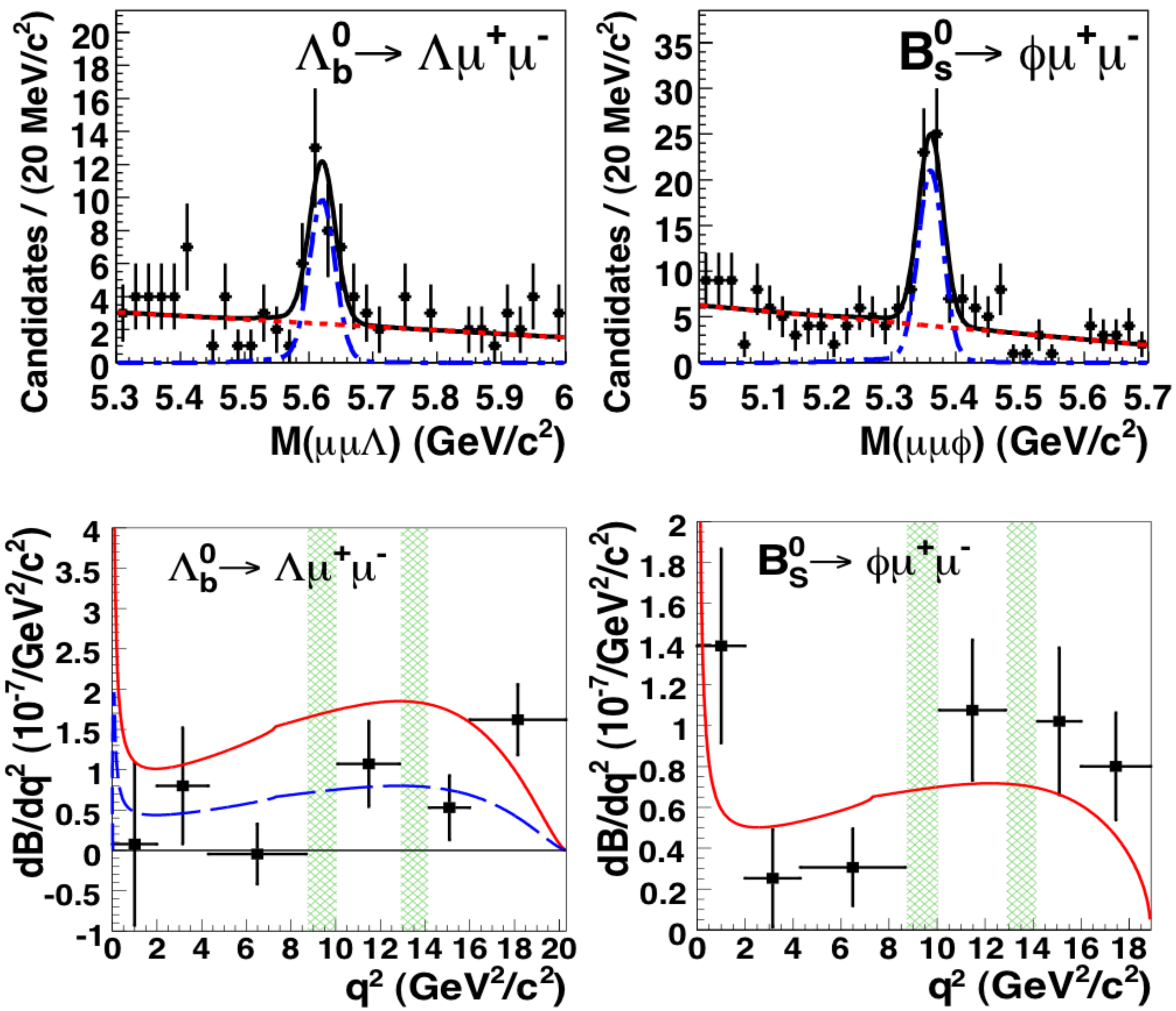
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\mu} = \frac{3}{4} F_L(1-\cos^2\theta_\mu) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\mu) + A_{FB}\cos\theta_\mu$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} = \frac{1}{2\pi}\left[1 + \frac{1}{2}(1-F_L)A_T^{(2)}\cos 2\phi + A_{im}\sin 2\phi\right]$$

$B \to K^* \mu^+ \mu^-$

- CDF also measured $\mathcal{B}(\Lambda_b^0 \to \Lambda \mu^+ \mu^-) = (1.73 \pm 0.42 \pm 0.55) \times 10^{-6}$ and $d\mathcal{B}/dq^2$ for $B_s^0 \to \phi \mu^+ \mu^-$ & $\Lambda_b^0 \to \Lambda \mu^+ \mu^-$

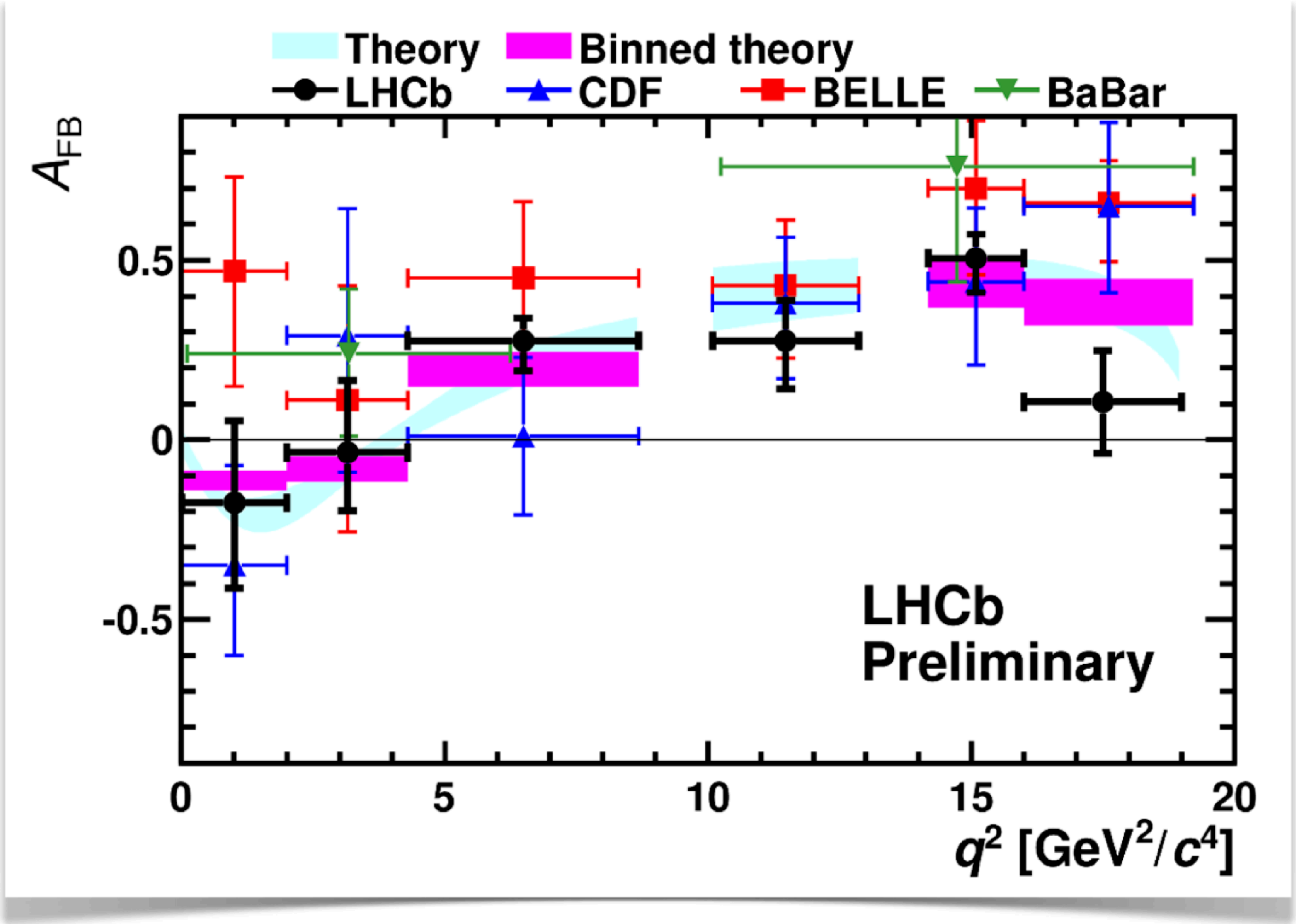
arXiv:1107.3753



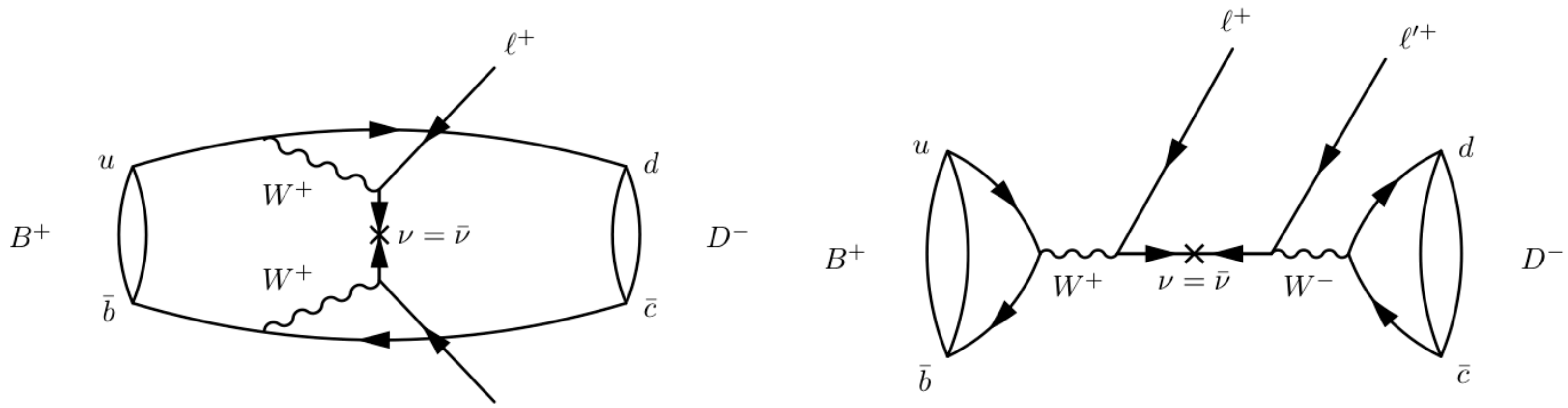
$B \to K^* \mu^+ \mu^-$

- *also available*: results from LHCb

  ⇒ See "Results from LHCb" by T. Nakada!



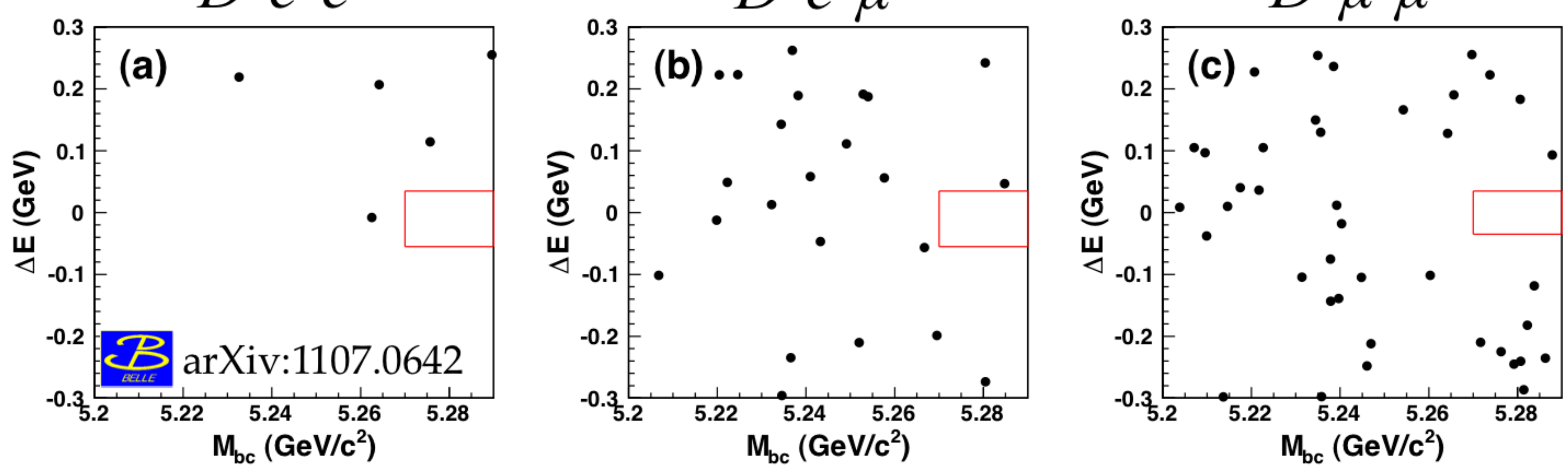
$B^+ \to D^- \ell^+ \ell^+$ *not really a penguin, but still interesting*



Feynman diagrams for $B^+ \to D^- \ell^+ \ell'^+$.

- $\Delta L = 2$ process, sensitive to Majorana-type ν
  "$0\nu 2\beta$ for B meson"
- expect $\mathcal{B} \sim \mathcal{O}(10^{-7})$
  if $\exists$ a sterile Majorana ν with $m \in (2-4)$ GeV/c^2
  Cvetic *et al.*, PRD 82, 053010 (2010)

$D^- e^+ e^+$ | $D^- e^+ \mu^+$ | $D^- \mu^+ \mu^+$



BF < 2.6x10^{-6} | BF < 1.8x10^{-6} | BF < 1.1x10^{-6}

- Belle search with full sample ($N_{B\bar{B}} = 772M$)
  PRD 84, 071106(R) (2011)

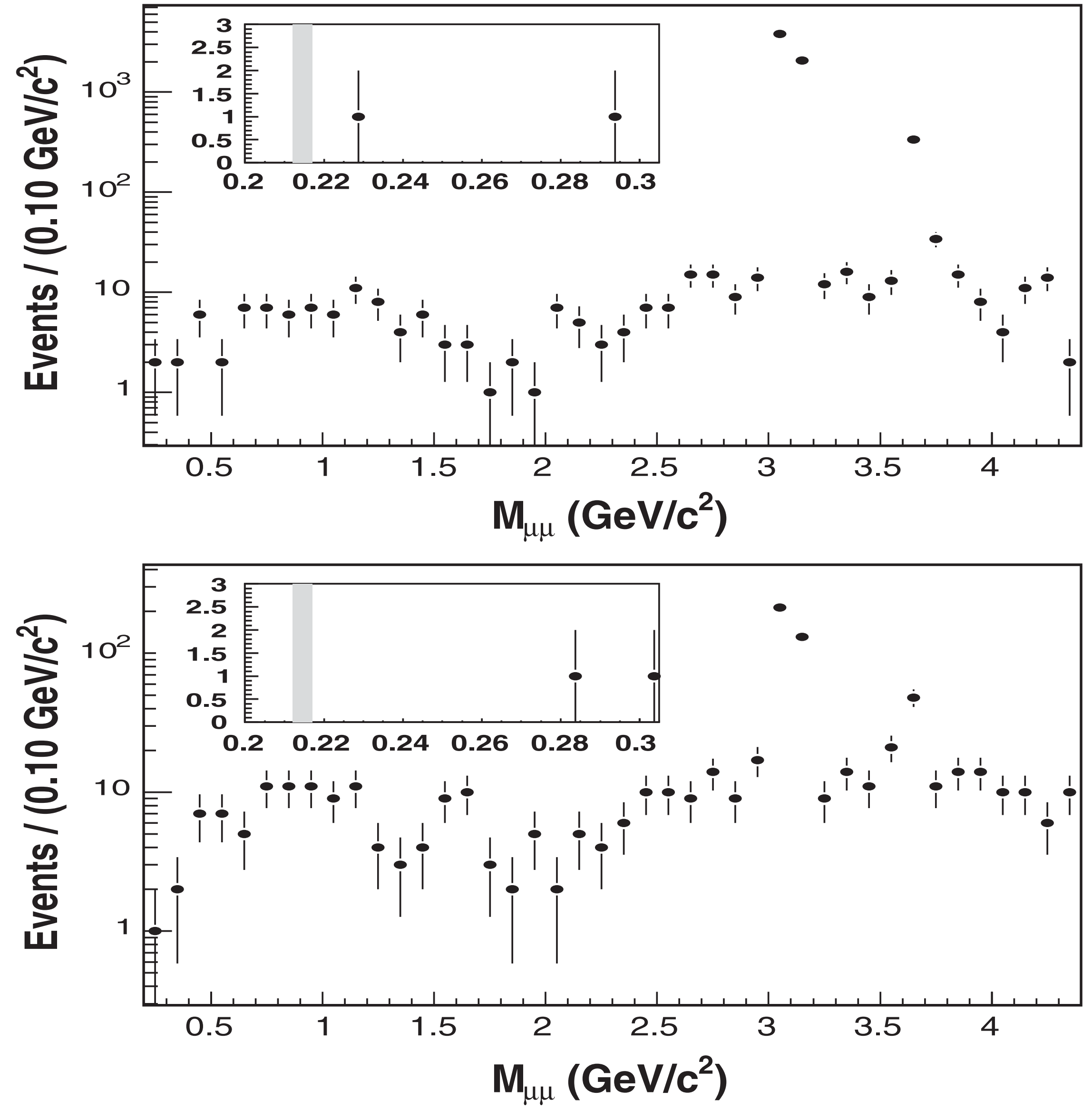
$\mathcal{B}(D^- e^+ e^+) < 2.6 \times 10^{-6}$
$\mathcal{B}(D^- e^+ \mu^+) < 1.8 \times 10^{-6}$
$\mathcal{B}(D^- \mu^+ \mu^+) < 1.1 \times 10^{-6}$

- ○ *c.f.* LHCb search (*preliminary*)
  $\mathcal{B}(B^+ \to K^- \mu^+ \mu^+) < 4.3 \times 10^{-8}$
  $\mathcal{B}(B^+ \to \pi^- \mu^+ \mu^+) < 4.5 \times 10^{-8}$

$X(214)$ search *not really a penguin, but still interesting*

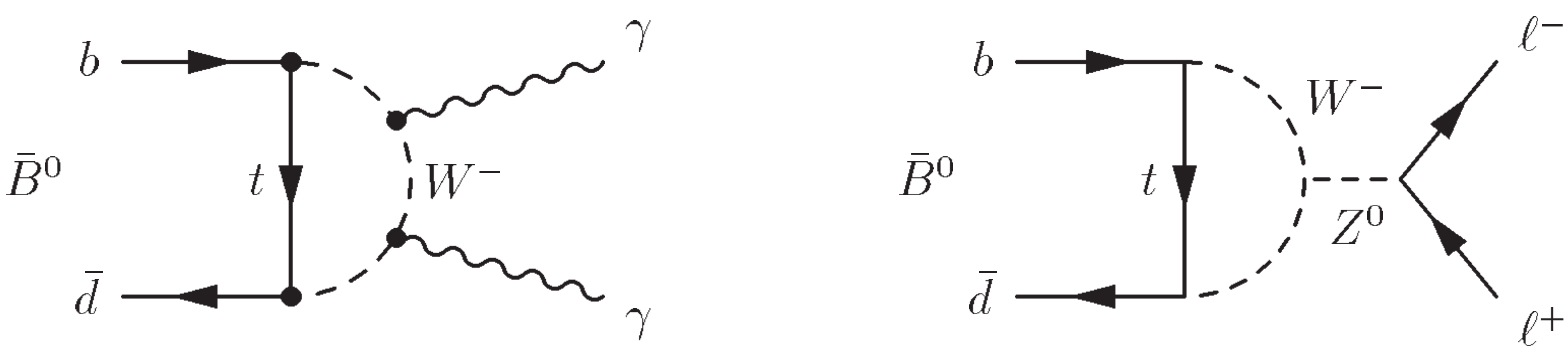
- Searching for $X(214) \to \mu^+\mu^-$, originally claimed by HyperCP collab. PRL **94**, 021801 (2005)
- modes to search for
  $B^0 \to V^0\, X(214)$
  where $V^0 = K^{*0},\ \rho^0$
- Not only $X(214)$, but generic search in $(212, 300)$ MeV/c^2 is made
  e.g. looking for GeV-scale dark sector

PRL, **105**, 091801 (2010)



$\mathcal{B}(B^0 \to K^{*0}X, K^{*0} \to K^+\pi^-, X \to \mu^+\mu^-) < 2.26 \times 10^{-8}$
$\mathcal{B}(B^0 \to \rho^0 X, \rho^0 \to \pi^+\pi^-, X \to \mu^+\mu^-) < 1.73 \times 10^{-8}$
rules out some models for the sgoldstino interpretation of the HyperCP result

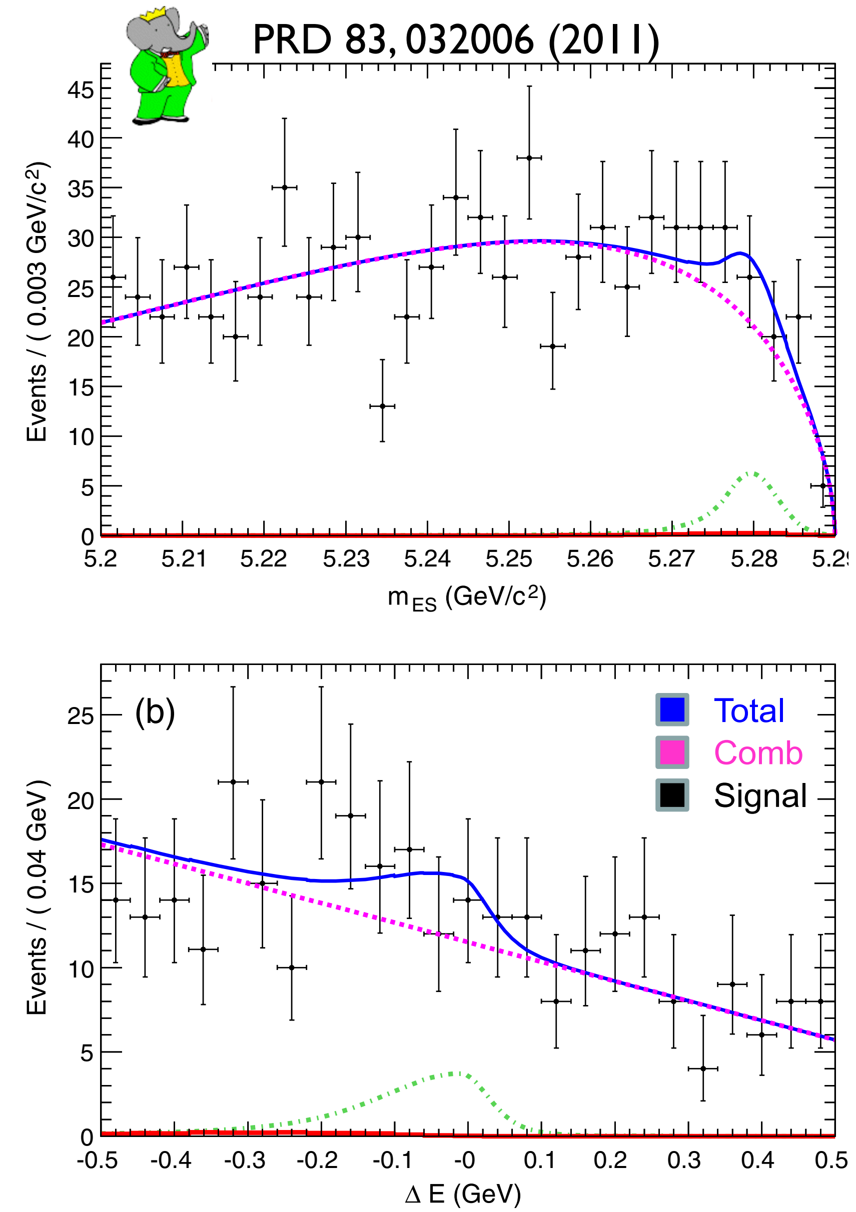
vertical penguins



- highly suppressed (compared to EWP), because of
  - $b \to d$ transition
  - the two quarks must "find" each other $\sim \mathcal{O}(f_B^2/m_B^2)$
  - $B^0 \to \gamma\gamma$: extra $\mathcal{O}(\alpha_{\text{QED}})$ suppression
  - $B^0 \to \ell^+\ell^-$: helicity-suppressed
- $\therefore$ observation of any signal with the current experimental sensitivity $\Rightarrow$ *NP*!

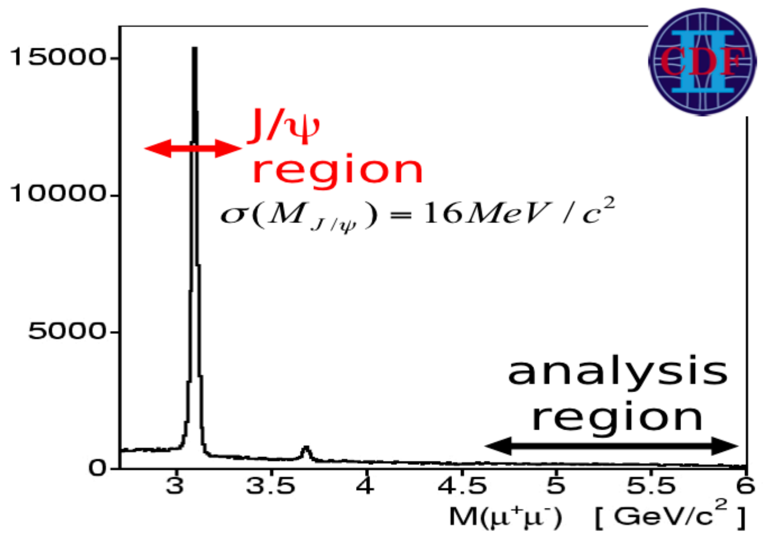
$B^0 \to \gamma\gamma$

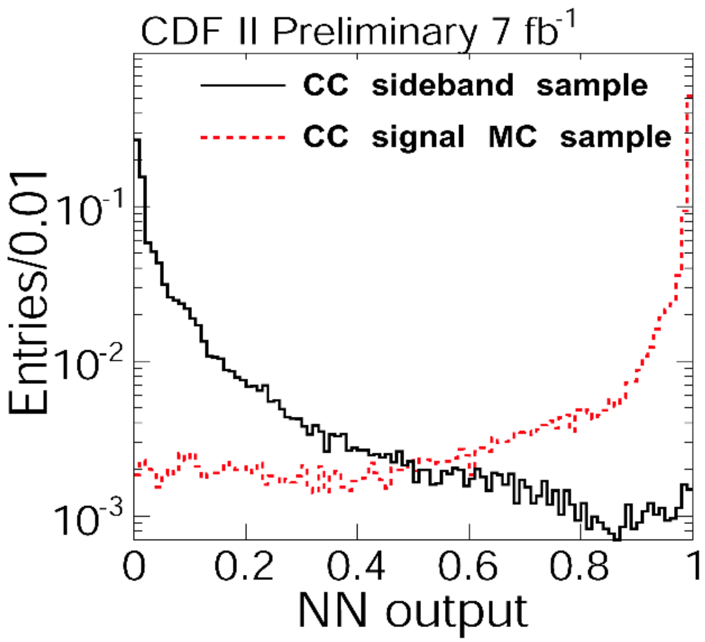
- (SM) $\mathcal{B} \sim 3 \times 10^{-8}$ Bosch & Buchalla, JHEP 0208:054
- Analysis procedure
  * dominant background: γ's from π^0 and η decays
  * signal extraction by 2D fit on $m_{\rm ES} \otimes \Delta E$
- Result
  * $N_{\rm sig} = 20.8^{+12.8}_{-11.8}$ (1.8σ) *corrected for fit bias*
  * $\mathcal{B} < 3.2 \times 10^{-7}$ (90% CL)

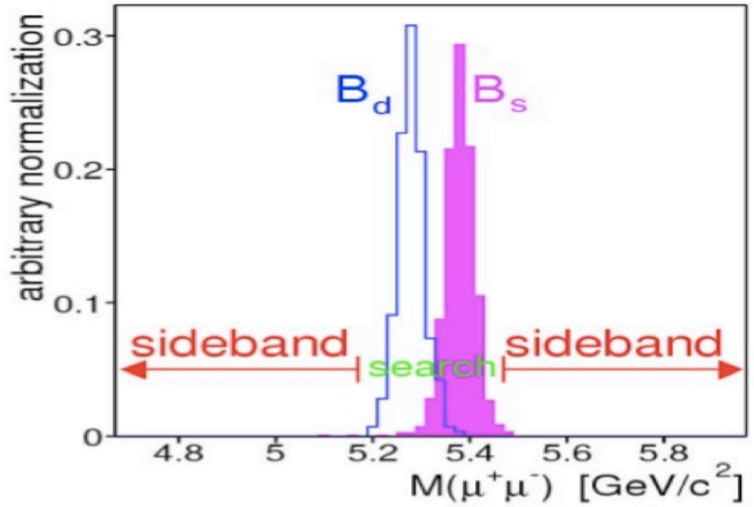


$B^0_{(s)} \to \mu^+\mu^-$

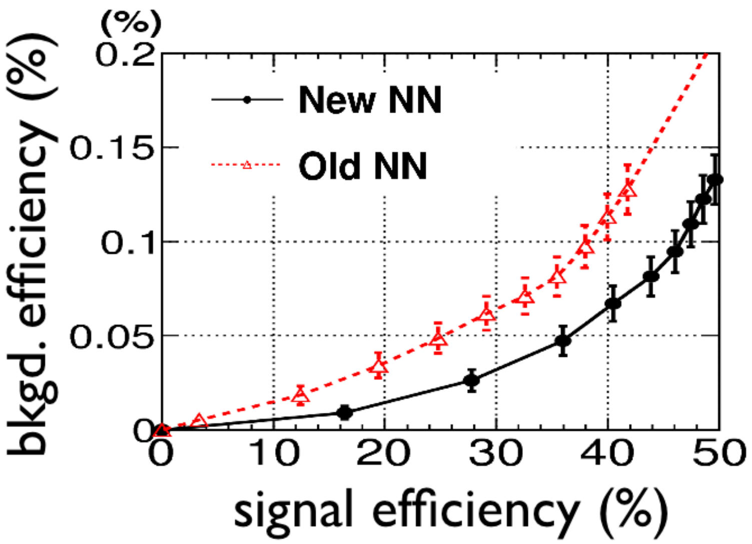
- (SM) Buras *et al.*, JHEP 1010:009
  $\mathcal{B}(B^0) = (1.0 \pm 0.1) \times 10^{-10}$
  $\mathcal{B}(B^0_s) = (3.2 \pm 0.2) \times 10^{-9}$
- Many NP models predict enhanced $\mathcal{B} \gg \mathcal{B}(\text{SM})$
- CDF analysis (7 fb^{-1})
  - μ in the central and forward regions: CC & CF
  - loose cut on $M_{\mu^+\mu^-}$, then neural-net (ν_N)
  - $B^+ \to J/\psi K^+$ as a normalization mode





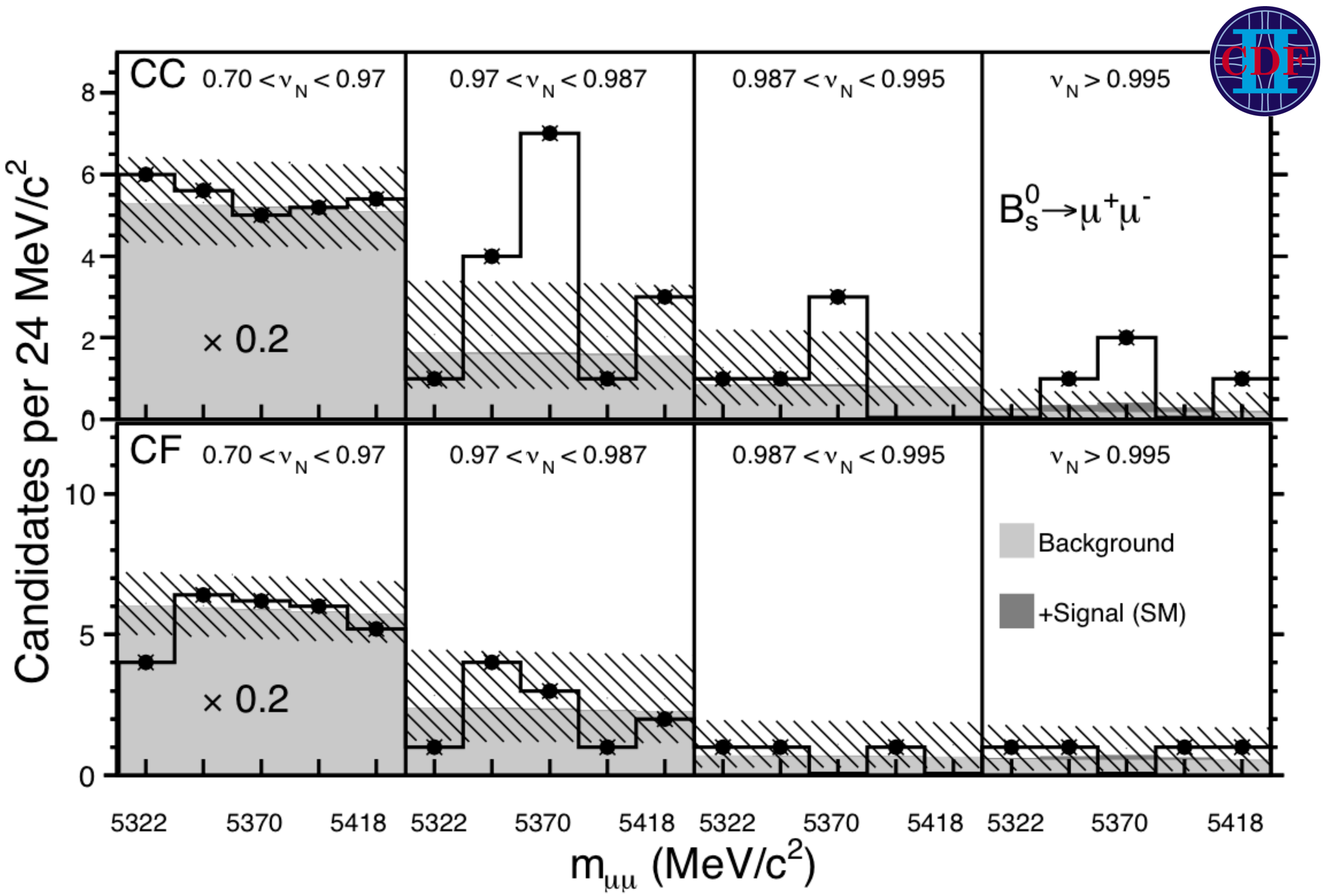


$(5.169, 5.469)$ GeV$/c^2$
blinded region



$B_s^0 \to \mu^+\mu^-$

arXiv:1107.2304



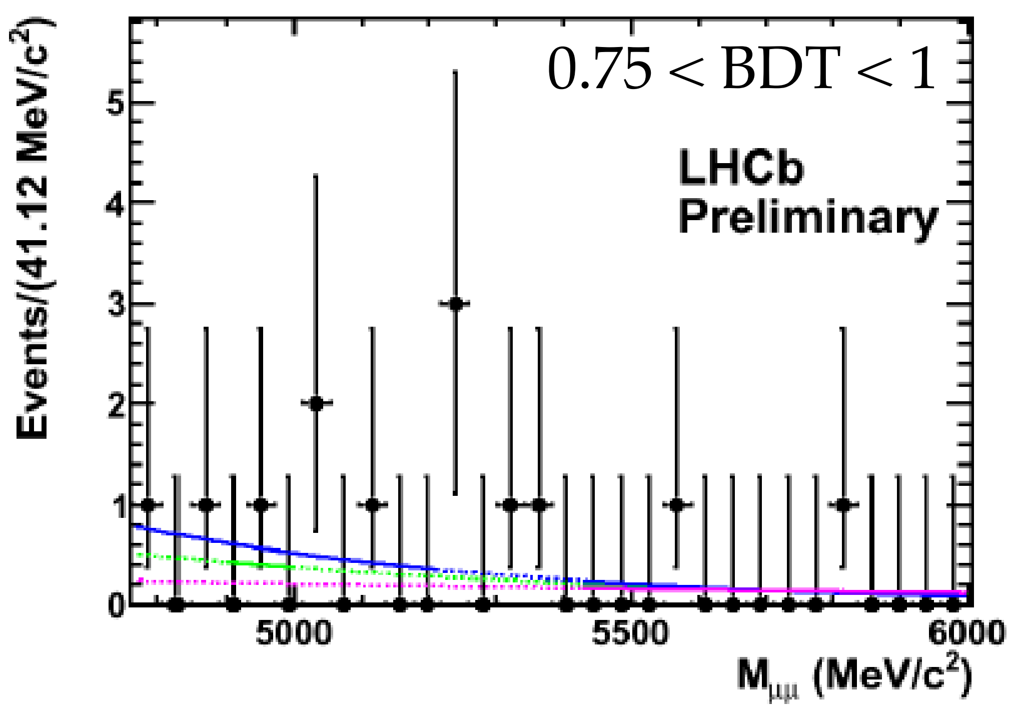
- consistency check (*top 2 bins*)
  - * $p = 0.66\%$ for bkgd.-only
  - * $p = 4.3\%$ for bkgd.+SM
- $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (*all bins*)
  - * obtained with modified frequentist approach
  - * $4.6\times10^{-9} < \mathcal{B} < 3.9\times10^{-8}$
    First double-sided
    90% CL region
    $\mathcal{B} = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$
  - * results cross-checked with Bayesian approach

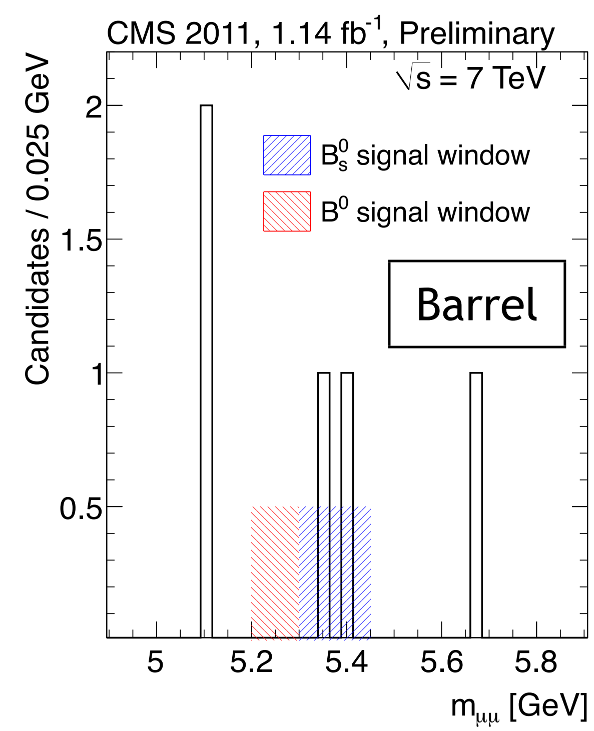
- D0 result: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.2 \times 10^{-8}$ (90% CL) PLB 693, 539 (2010)
- CDF also obtained $\mathcal{B}(B^0 \to \mu^+\mu^-) < 5.0 \times 10^{-9}$ (90% CL)

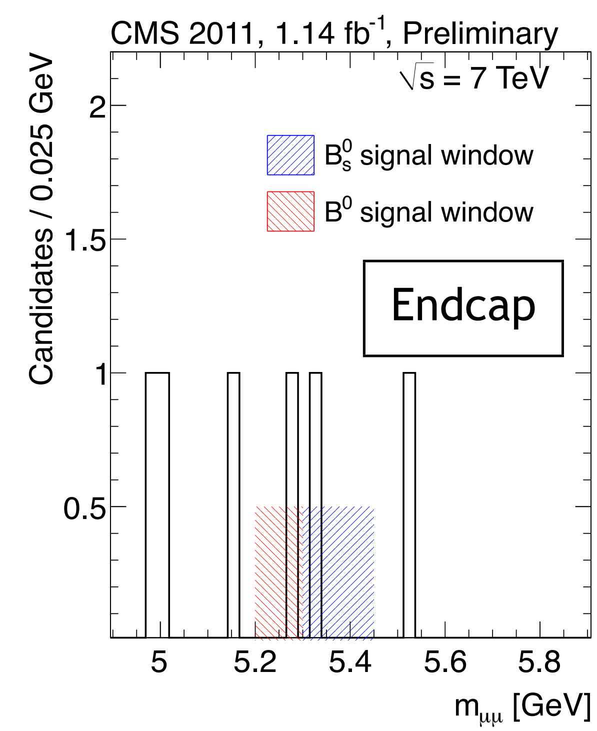
$B^0_{(s)} \to \mu^+\mu^-$

- *also available*: results from LHCb, CMS, etc.

  $\Rightarrow$ See "Results from LHCb" by T. Nakada!





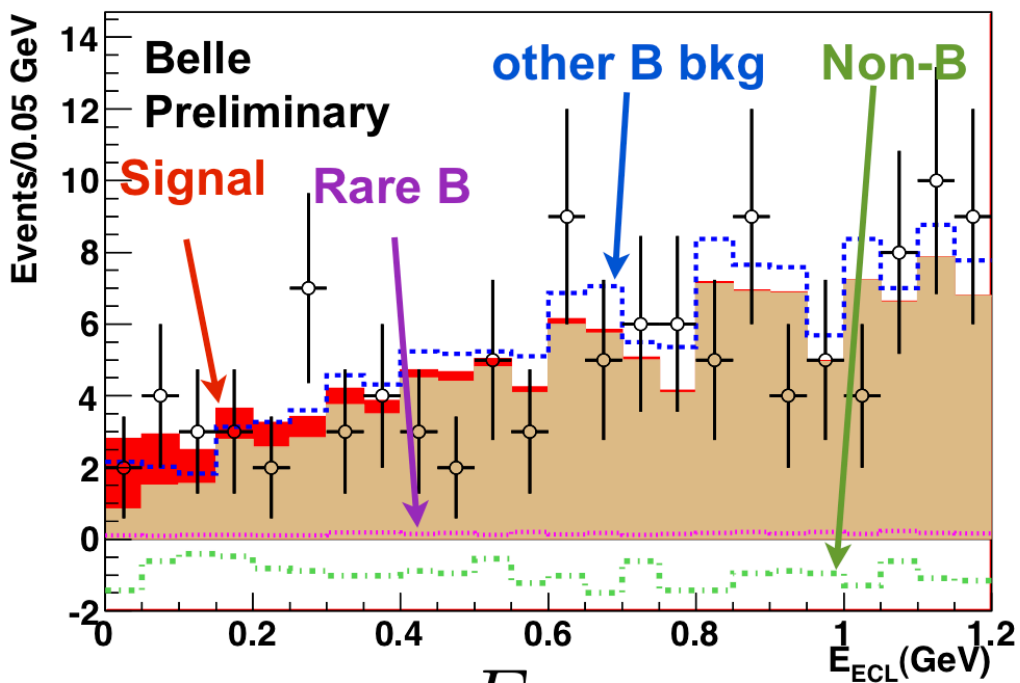


$B^0 \to \nu\overline{\nu}$ *invisible vertical* penguin

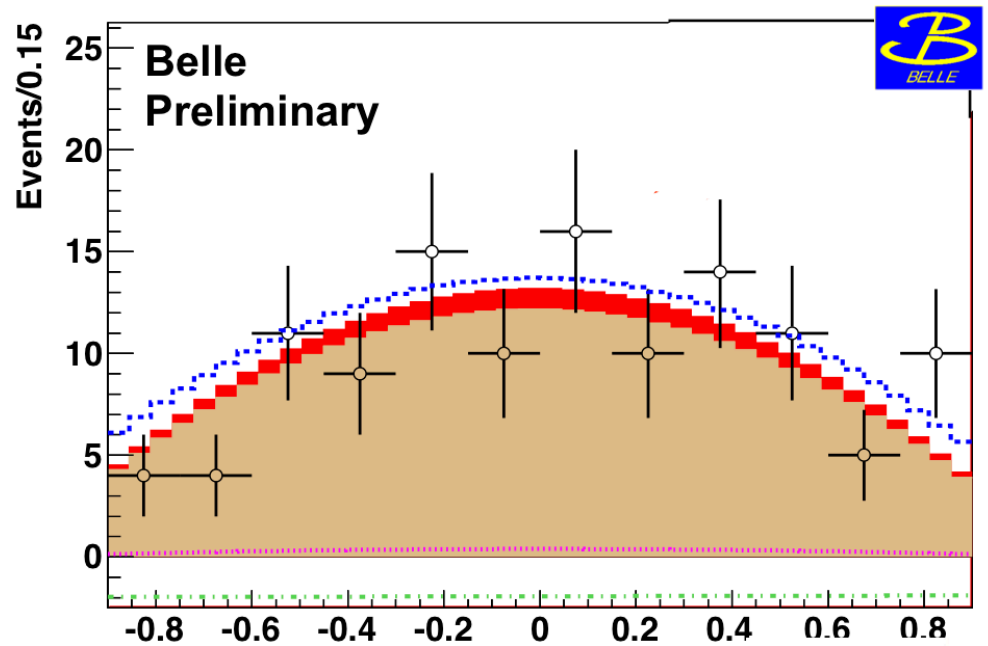
- strongly helicity-suppressed by $\mathcal{O}(m_\nu^2/m_B^2)$

$$\mathcal{B}(B^0 \to \nu\overline{\nu}) = \tau_{B^0} \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2 \Theta_W} \right)^2 F_{B^0}^2 m_\nu^2 m_{B^0} \sqrt{1 - 4m_\nu^2/m_{B^0}^2} |V_{tb}^* V_{td}|^2 Y^2(x_t)$$

- NP models predict significant branching fractions, e.g.
  $10^{-7} < \mathcal{B}(B^0 \to \overline{\nu}\tilde{\chi}_1^0) < 10^{-6}$
- with Full-recon tagging, Belle searched for $B^0 \to \nu\overline{\nu}$ by 2D-fitting to $(E_{\rm ECL}, \cos\theta_B)$



$E_{\rm ECL}$



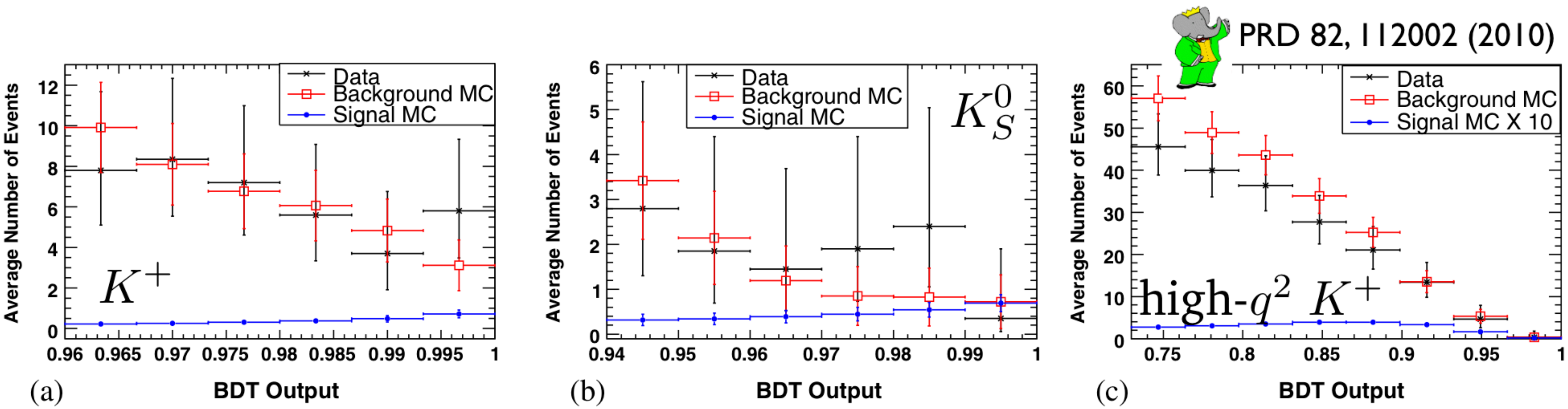
$\cos\theta_B$

$\mathcal{B}(B^0 \to \nu\overline{\nu}) < 1.3 \times 10^{-4}$ (90% CL)

c.f. (BaBar) $\mathcal{B} < 2.2 \times 10^{-4}$, PRL 93, 091802 (2004)

$B \to K\nu\bar{\nu}$ *semi-invisible* penguin

- (SM) $\mathcal{B}(B \to K\nu\bar{\nu}) = (4.5 \pm 0.7) \times 10^{-6}$ (ABSW) JHEP 0904:022 (2009)
  or, $(3.8^{+1.2}_{-0.6}) \times 10^{-6}$ (BHI) PRD 63, 014015 (2000)
- many NP models (e.g. unparticle, SUSY at large tan β, models with scalar WIMP, etc.) predict $\mathcal{B} \sim \mathcal{O}(10) \times \mathcal{B}_{\rm SM}$
- BaBar's new search in two q^2 bins ($p_K^* \gtrsim 1.5$ GeV/c) with semileptonic tagging
  high-q^2 region is more sensitive to NP

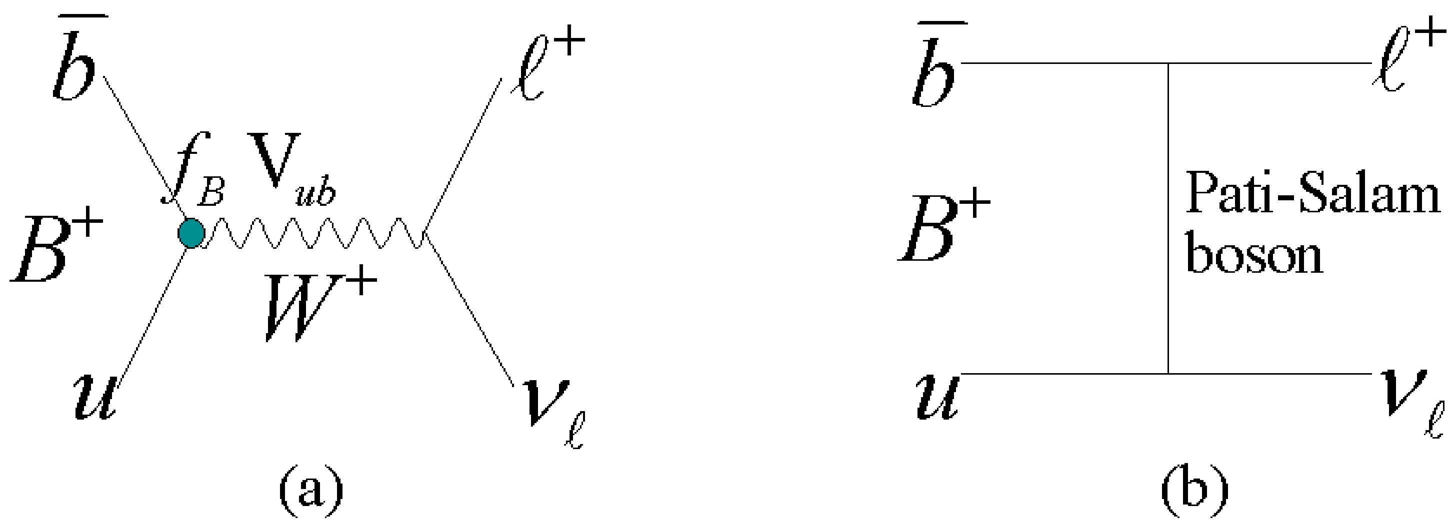


$$\mathcal{B}(K^+) < 1.3 \times 10^{-5}, \quad \mathcal{B}(K_S^0) < 5.6 \times 10^{-5} \text{ (90\% CL)}$$

- For many other modes, ∃ upper limits from Belle & BaBar using full-reconstruction tagging PRL 99, 221802 (2007), PRD 78, 072007 (2008)

$B^+ \to \ell^+\nu_\ell$ a different kind of rare *B*

$B^+ \to \ell^+ \nu_\ell$

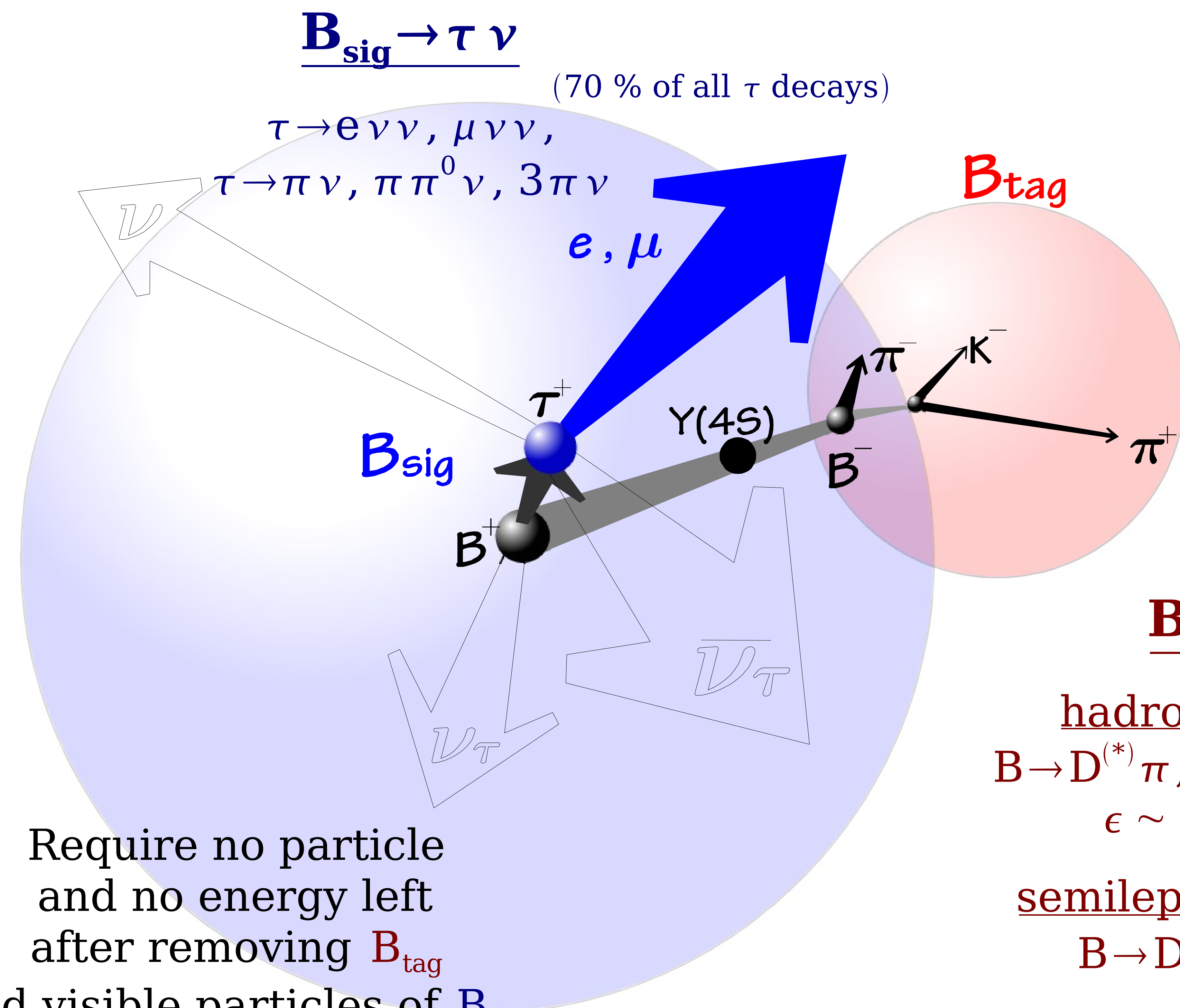


$$\Gamma(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

- very clean place to measure f_B (or V_{ub}?) and/or search for new physics (e.g. H^+, LQ)
- but, helicity-suppressed: $\Gamma(B^+ \to e^+ \nu_e) \ll \Gamma(B^+ \to \mu^+ \nu_\mu) \ll \Gamma(B^+ \to \tau^+ \nu_\tau)$
- First evidence for $B^+ \to \tau^+ \nu_\tau$ by Belle using hadronic tagging ("Full reconstruction")

PRL 97, 251802 (2006)

Tagging methods (for $B^+ \to \tau^+\nu_\tau$ and others)



Require no particle
and no energy left
after removing B_{tag}
and visible particles of B_{sig}

B_{tag}

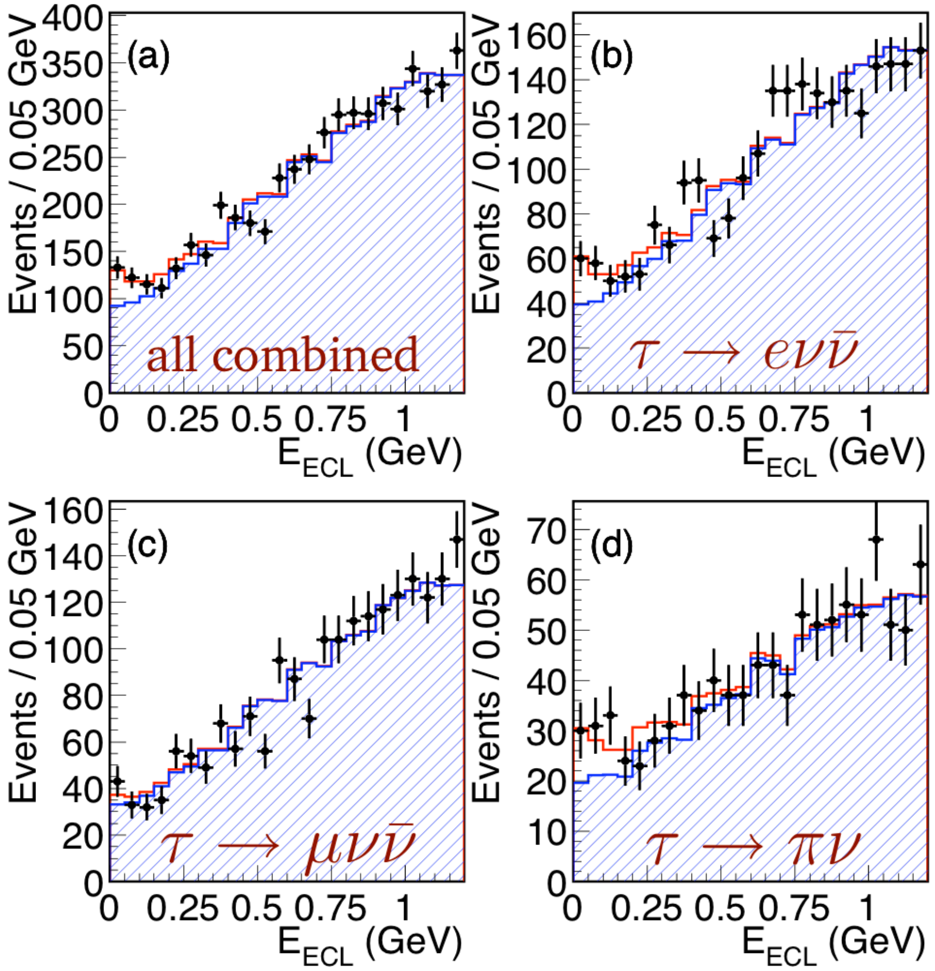
hadronic tag
$B \to D^{(*)}\pi,\ D^{(*)}$rho....
$\epsilon \sim 0.2\%$

semileptonic tag
$B \to D^{(*)} l \nu\ X$

slide from K. Trabelsi @ ICHEP 2010

$B^+ \to \tau^+\nu_\tau$ some recent results

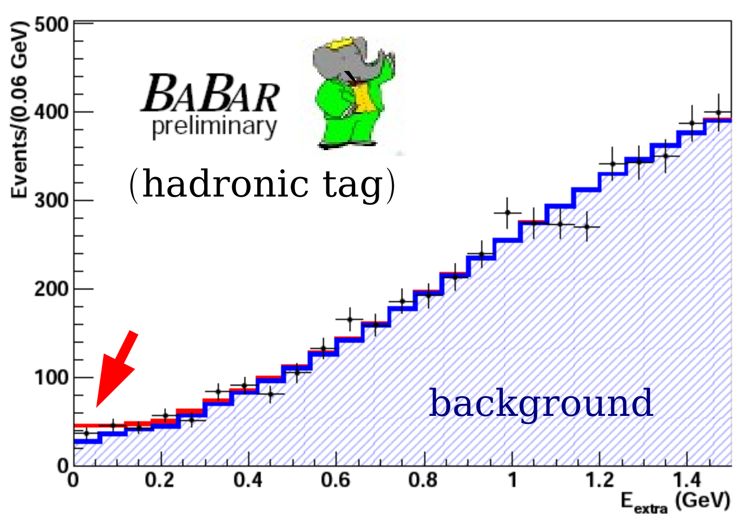
PRD 82, 071101(R) (2010)



- tagged by $B^+ \to \overline{D}^{(*)}\ell^+\nu_\ell$
  - *statistically independent from hadronic tagging analysis*
- signal side
  - Use *1-prong* τ^- modes: $\ell^-\bar{\nu}\nu$, $\pi^-\nu$
  - $E_{\rm ECL}$ to extract $N_{\rm sig}$
- Significance: 3.6σ incl. syst. err.

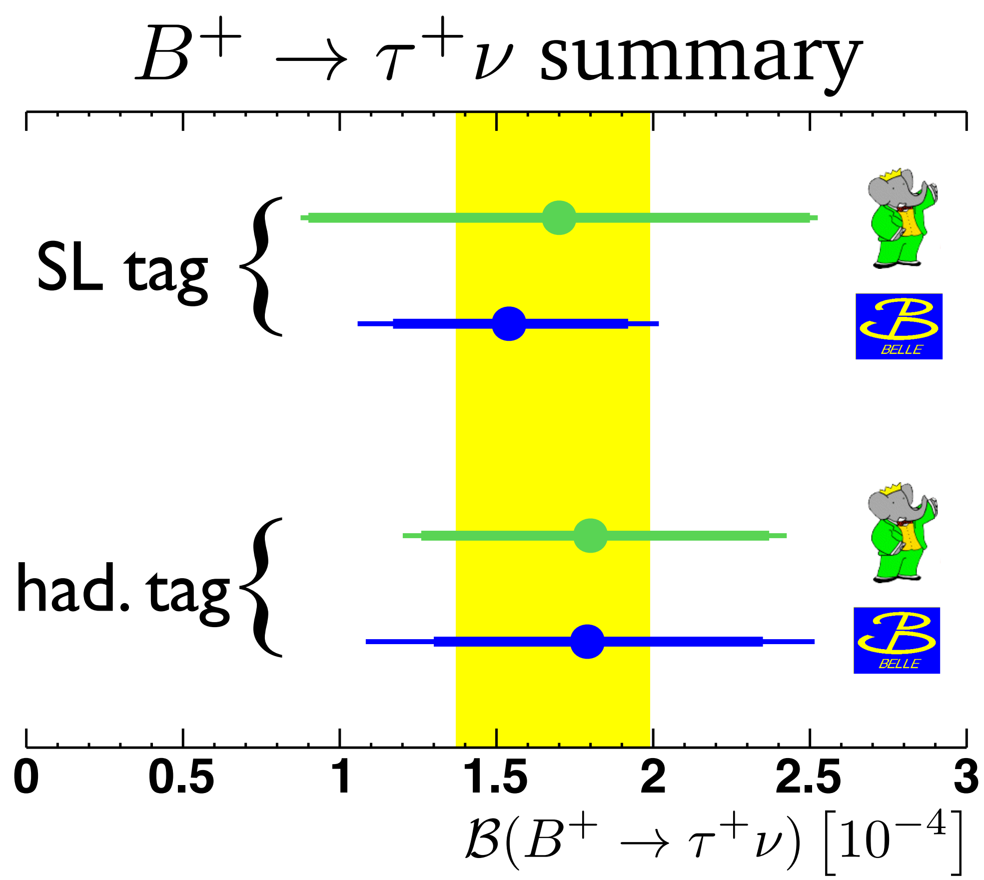
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31}) \times 10^{-4}$$

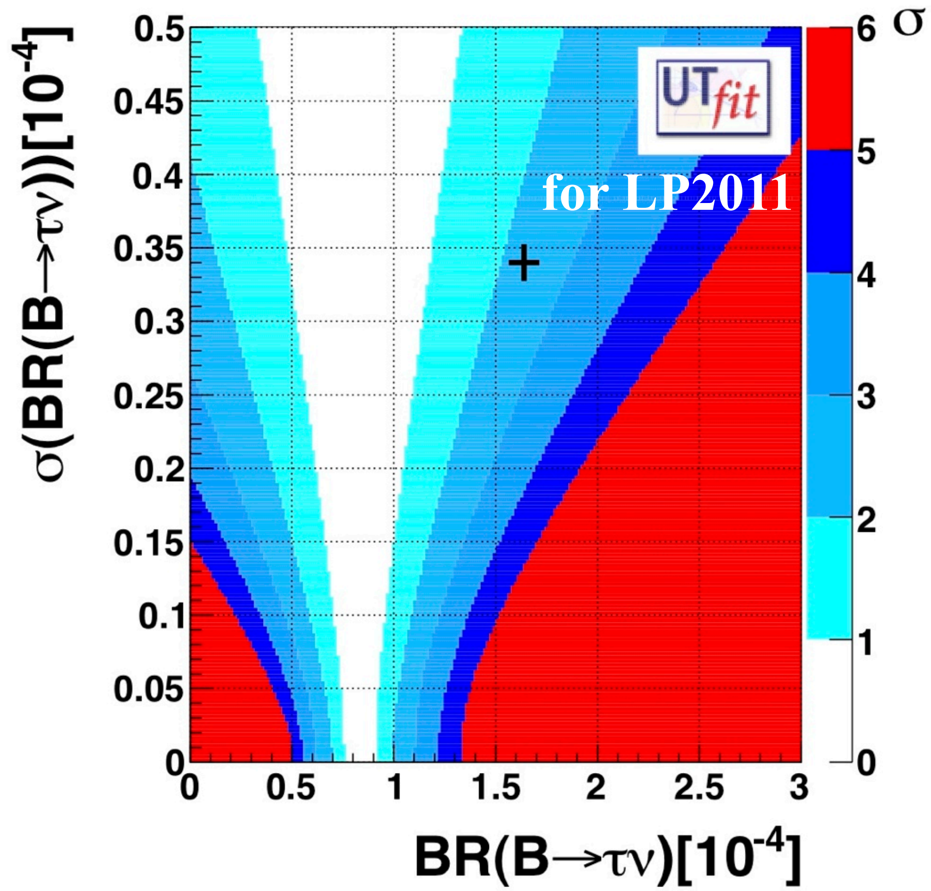
$$f_B|V_{ub}| = (9.3^{+1.2}_{-1.1} \pm 0.9) \times 10^{-4}\ \text{GeV}$$

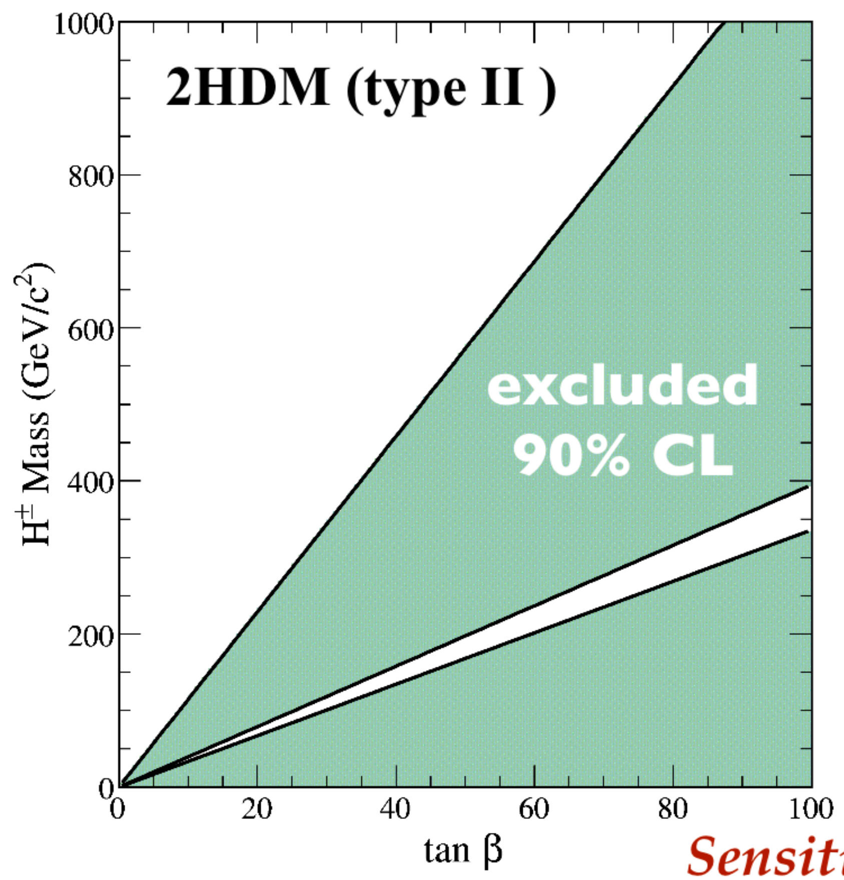


- BaBar *hadronic tagging* *preliminary* (2010)

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}\ (3.6\sigma)$$







W. Hou, PRD 48, 2342 (1993)

$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{\rm SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

for this plot, we use

$$B_{\rm SM}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$$

using f_B (HPQCD), $|V_{ub}|$ (HFAG)

Note:

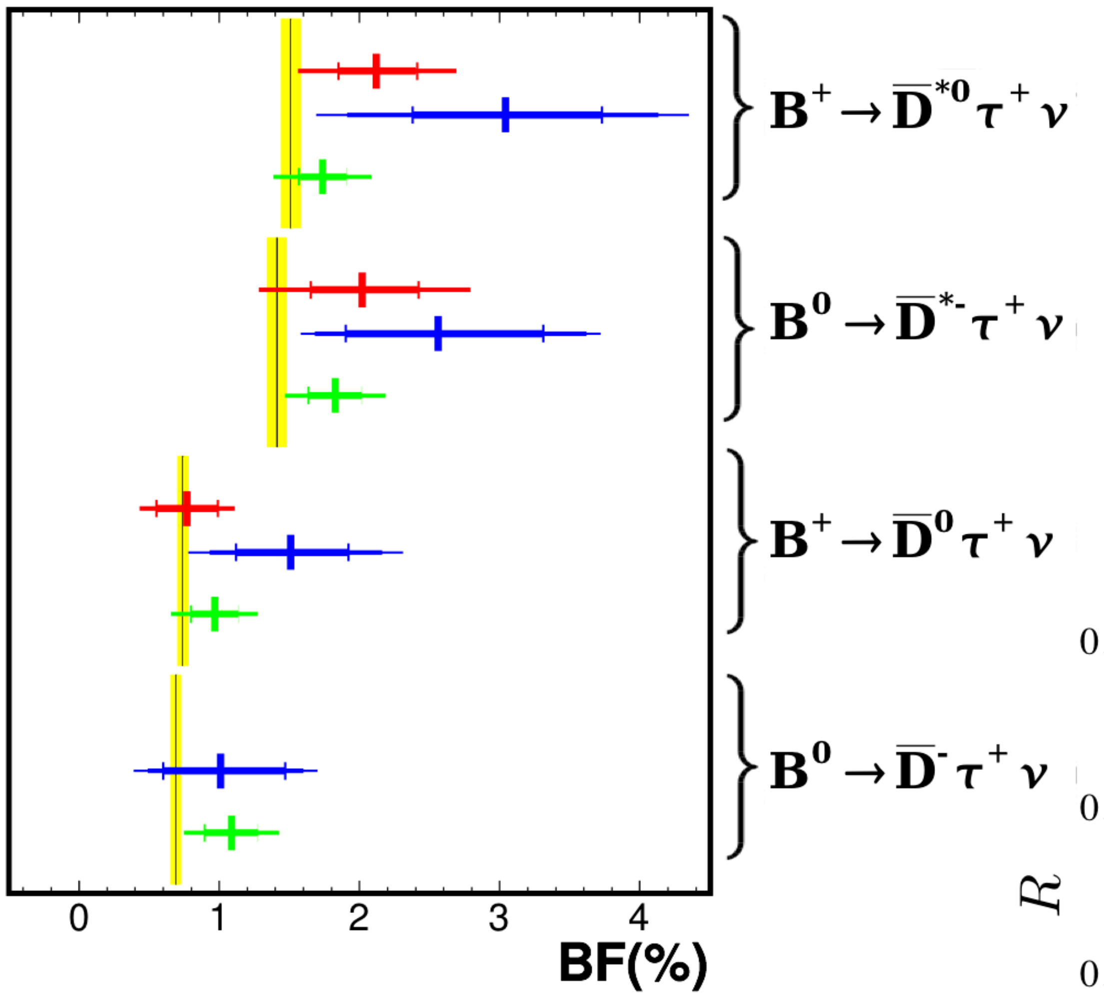
$$\mathcal{B}_{\rm SM} = 0.83 \pm 0.08 \text{ (UTfit)}$$

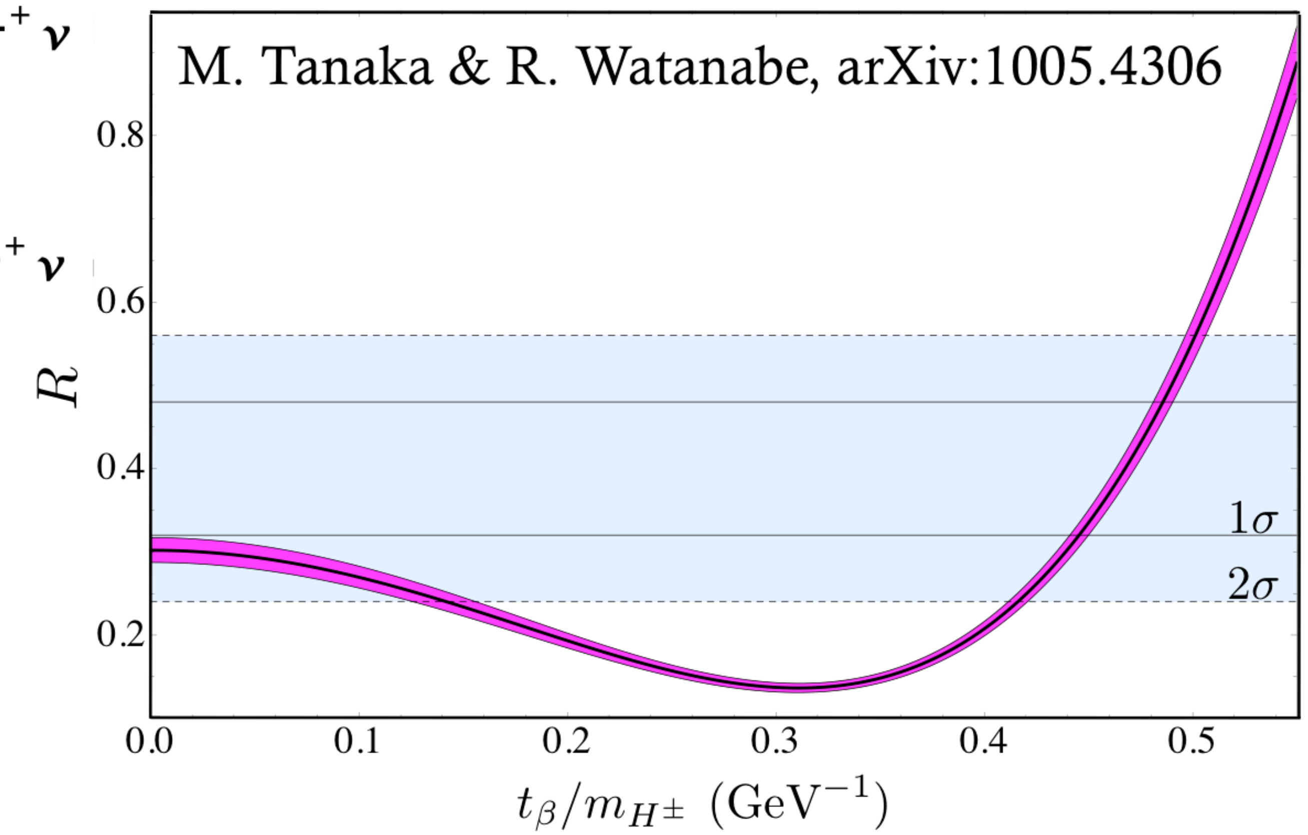
$$\mathcal{B}_{\rm SM} = 0.763^{+0.114}_{-0.061} \text{ (CKMfitter)}$$

Sensitivity to H^+ is complementary to LHC direct searches

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

- Not so rare, but addresses similar NP issues with $B^+ \to \tau^+ \nu_\tau$





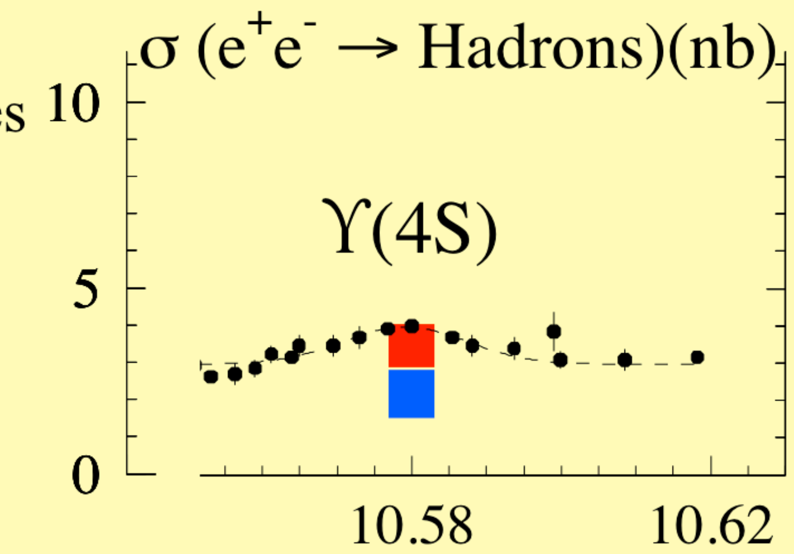
Rare D decays

Rare D decays

... reason to visit the Sistine Chapel, namely to see Michelangleo's frescoes. ... there are wonderful frescoes by other famous masters, namely Botticelli ...

Of course, Botticelli is still Botticelli, i.e. a first-rate artist, but what about charm?

by I. Bigi, *"Charm Physics - Like Botticelli in the Sistine Chapel (2001)"*



- D meson is the only place to study FCNC and related couplings in the *up*-type quarks

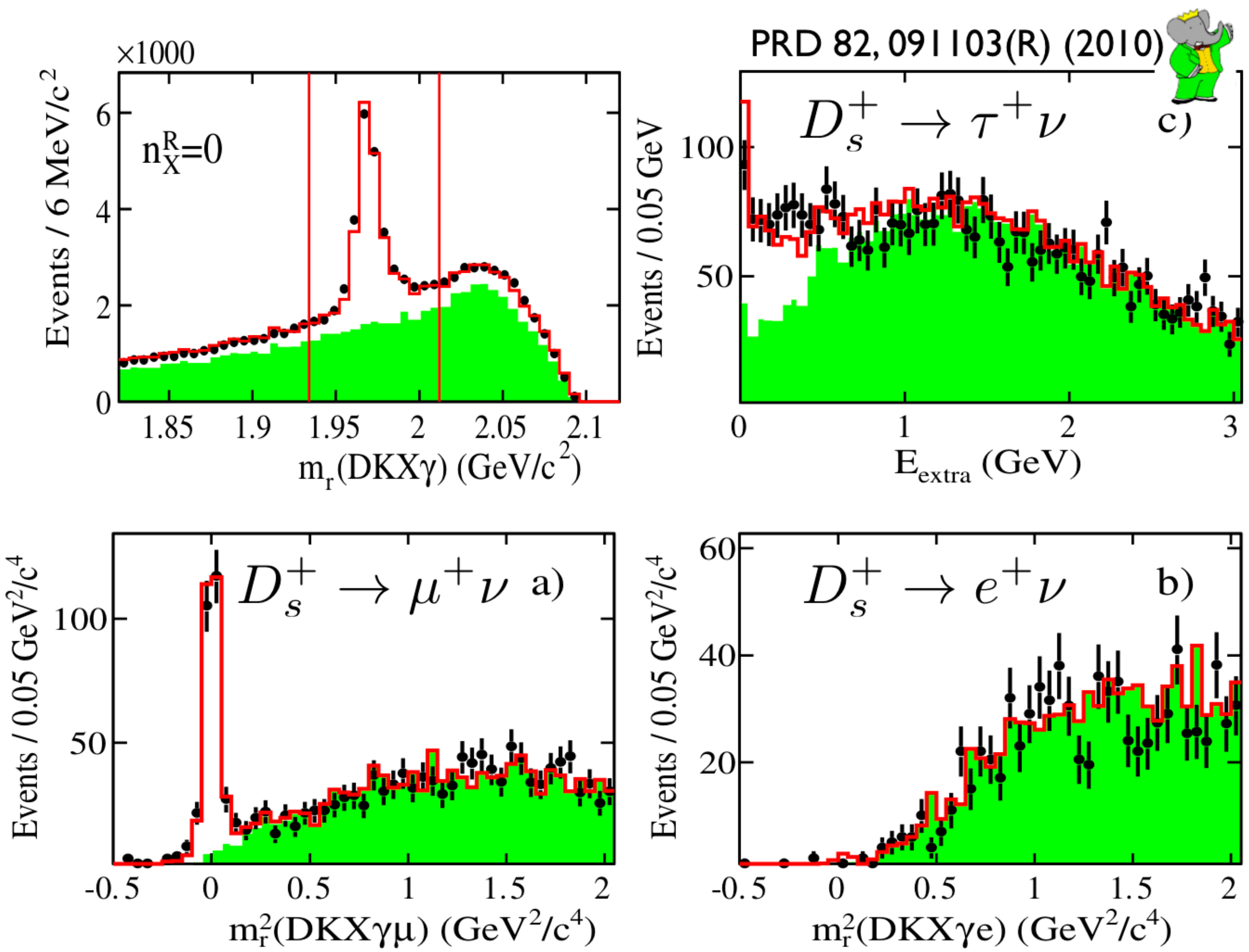
  (SM) FCNC is more highly suppressed than in B. But long distance effects are large.

- In this talk, we will focus on:

  * $D^+_{(s)} \to \ell^+ \nu_\ell$ and f_{D_s}
  * $D^0 \to \ell^+ \ell^-$
  * $D \to X\, \ell^\pm \ell^-$

$D_s^+ \to \ell^+ \nu_\ell$

- a clean probe for f_{D_s}
- $\exists \gtrsim 2\sigma$ tension between exp. avg. and the most precise L-QCD result HPQCD/UKQCD, PRL 100, 062002 (2008)



BaBar update (2010)

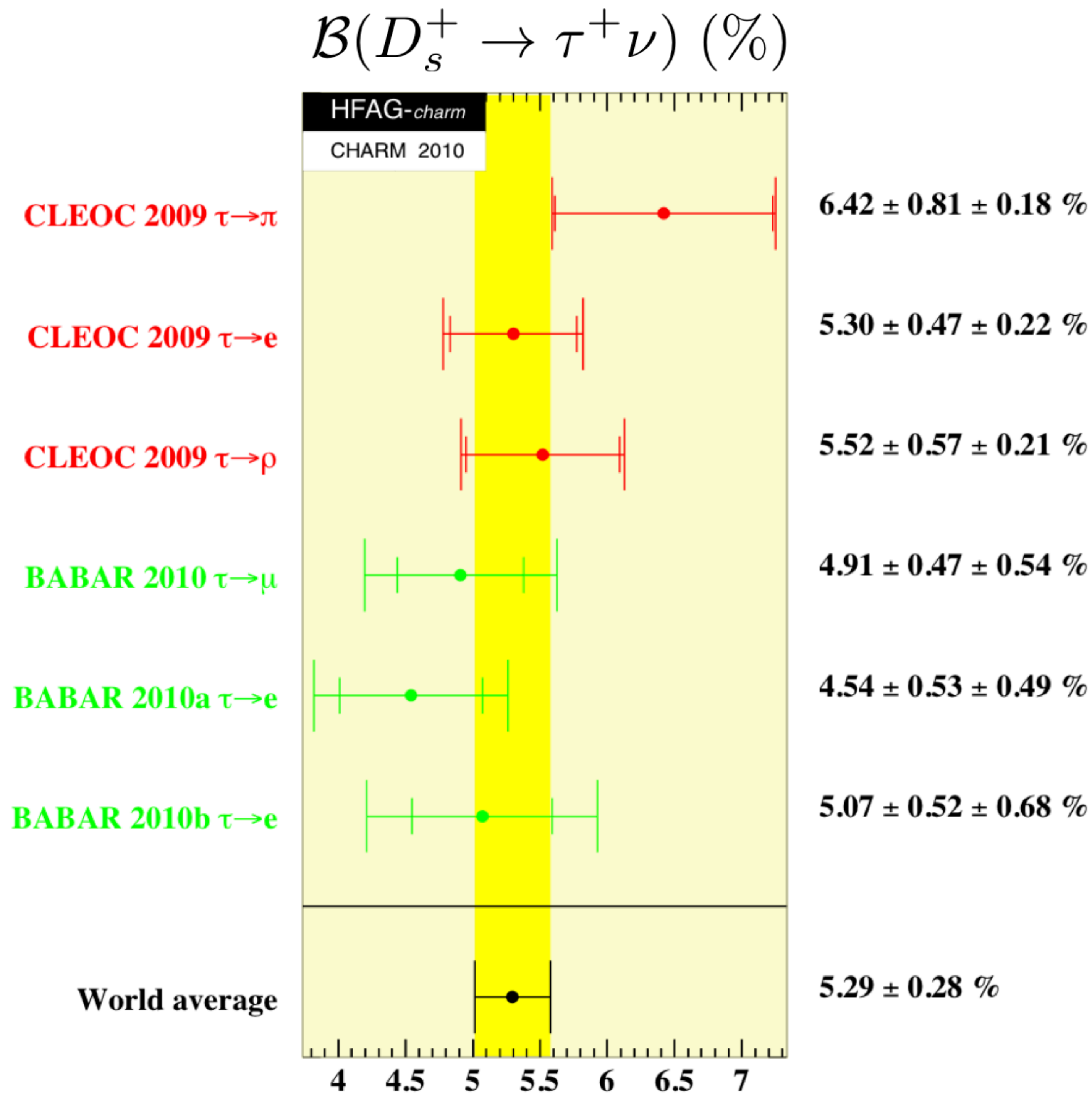
- Search for $D_s^- \to \ell^- \overline{\nu}$ in the $DKX\ D_s^{*-}\ (\to D_s^- \gamma)$ final state in the $e^+e^- \to c\bar{c}$ process
- Select candidates with $m_r(DKX\gamma)$
- Look for $\ell^+\nu$ ($\ell = e, \mu$) signals with $m_r^2(DKX\gamma\ell)$ and $\tau^+\nu$ signals with $E_{\rm ECL}$

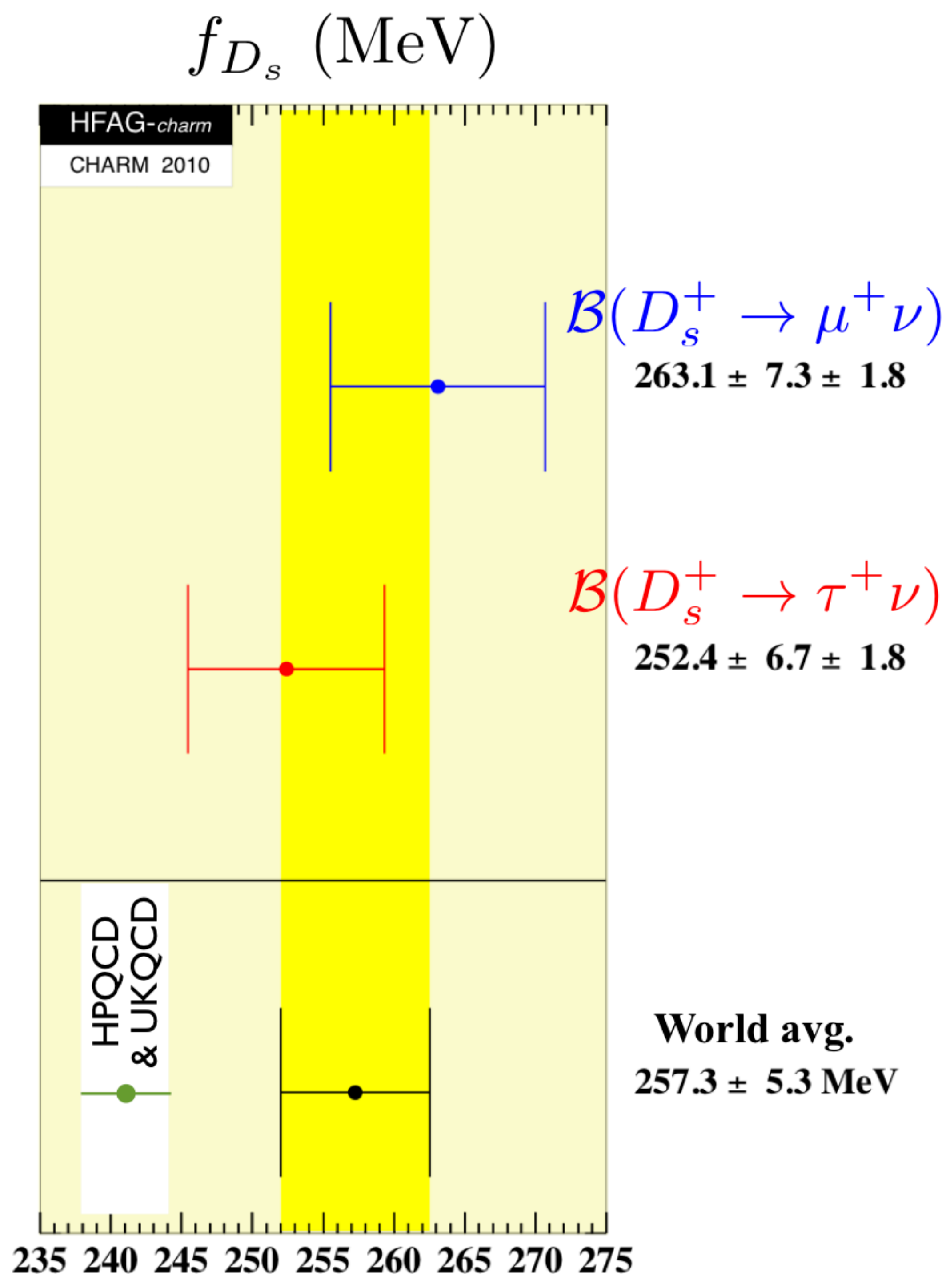
$\mathcal{B}(e^+\nu) < 2.3 \times 10^{-4}$ (90% CL)
$\mathcal{B}(\mu^+\nu) = (6.02 \pm 0.38 \pm 0.34) \times 10^{-3}$
$\mathcal{B}(\tau^+\nu) = (5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$

averaging over the modes, $f_{D_s} = (258.6 \pm 6.4 \pm 7.5)$ MeV

test of lepton universality: $\mathcal{B}(\tau^+\nu)/\mathcal{B}(\mu^+\nu) = 8.27 \pm 0.77 \pm 0.85$, consistent with 9.76 (SM)

$D_s^+ \to \ell^+ \nu_\ell$





$D^0 \to \ell^+\ell^-$

- (SM) highly suppressed

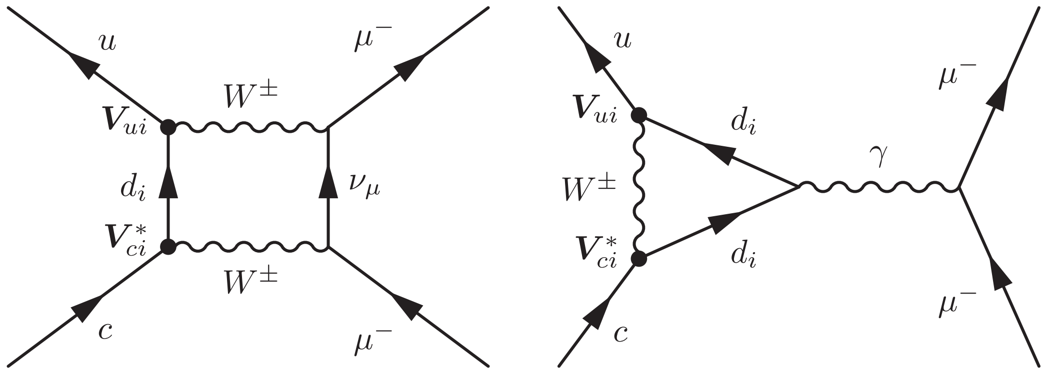
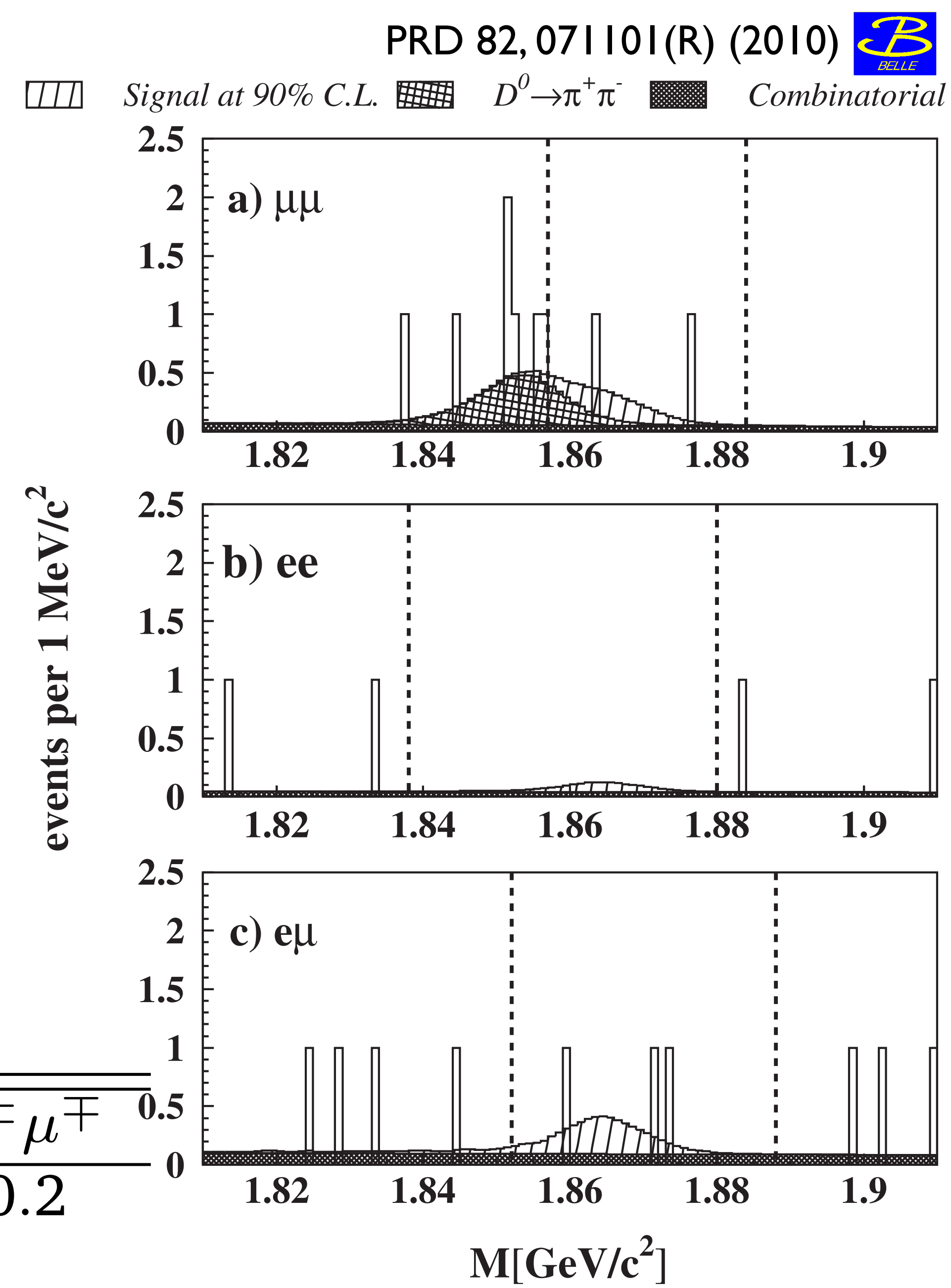


FIG. 1. The SM short distance Feynman diagrams for the $D^0 \to \mu^+\mu^-$ decay.

* $\mathcal{B}$(short distance) $\sim 10^{-18}$
* $\mathcal{B}$(long distance) $\sim 10^{-13}$
* NP models (e.g. $\not{R}$-SUSY) may enhance the branching fraction up to $\mathcal{O}(10^{-8})$



- Belle (2010) with 660 fb^{-1}

	$D^0 \to \mu^+\mu^-$	$D^0 \to e^+e^-$	$D^0 \to e^\pm\mu^\mp$
N_{bkg}	3.1 ± 0.1	1.7 ± 0.2	2.6 ± 0.2
N	2	0	3
$\epsilon_{\ell\ell}[\%]$	7.02 ± 0.34	5.27 ± 0.32	6.24 ± 0.27
UL $[10^{-7}]$	1.4	0.79	2.6

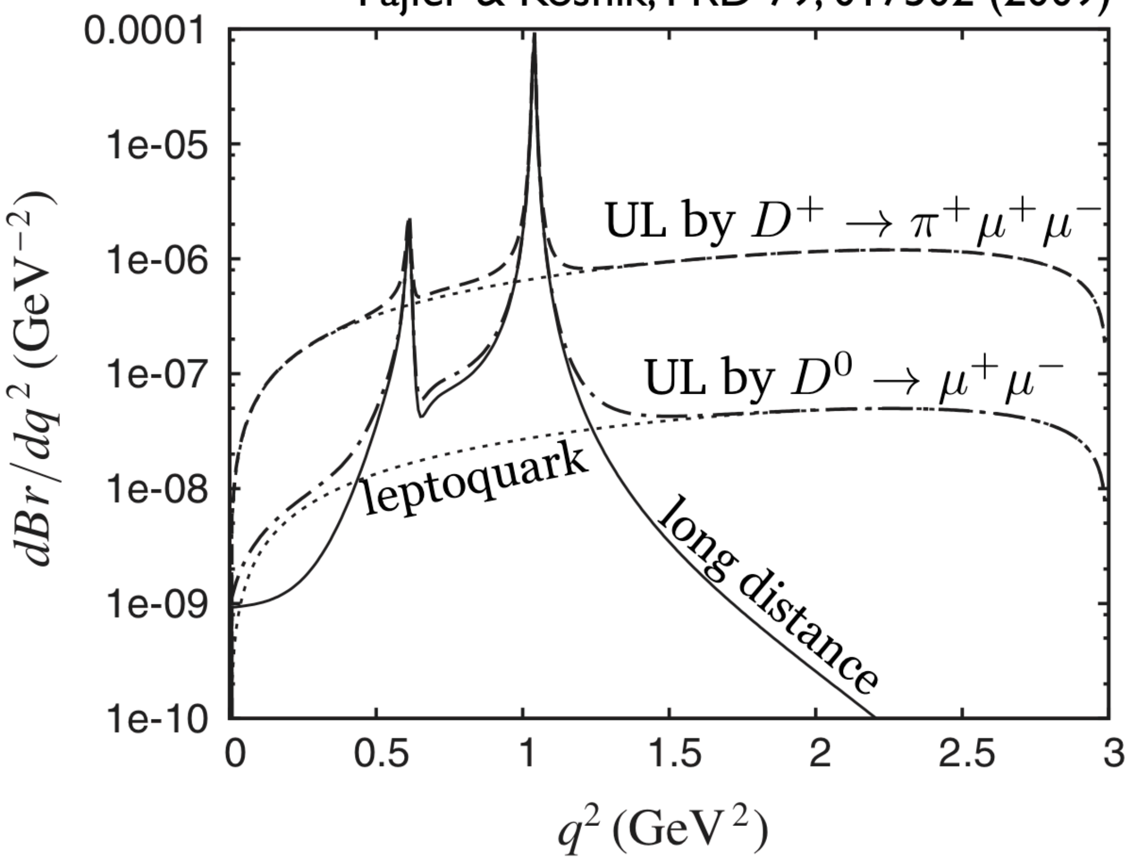
$D \to X\, \ell^+\ell^-$

- Radiative D decays such as $D \to \rho\gamma$, in contrast to $B \to K^*\gamma$, are not very useful for NP search.

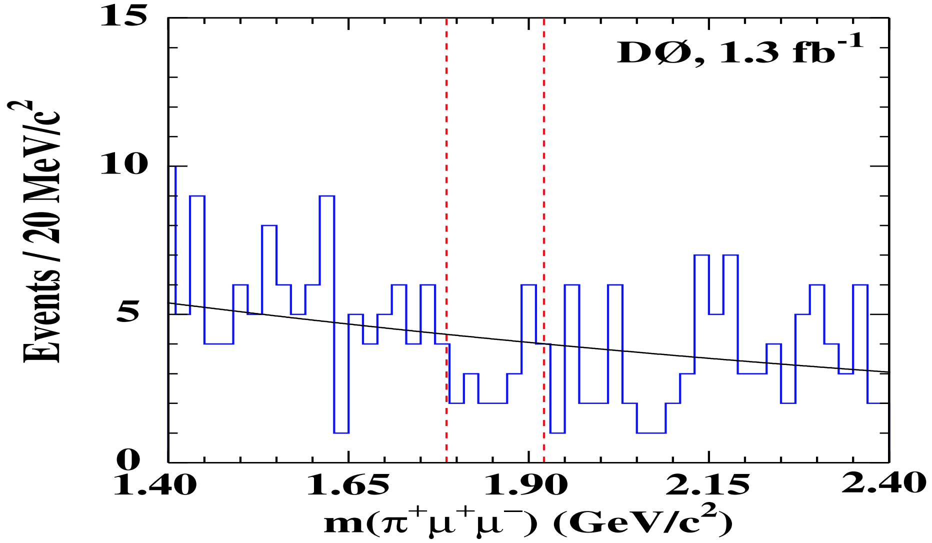
  $\because$ large long-distance effects

- In $D \to X\, \ell^+\ell^-$, long-distance effects may be avoided in certain regions of $M(\ell^+\ell^-)$.

Fajfer & Kosnik, PRD 79, 017502 (2009)

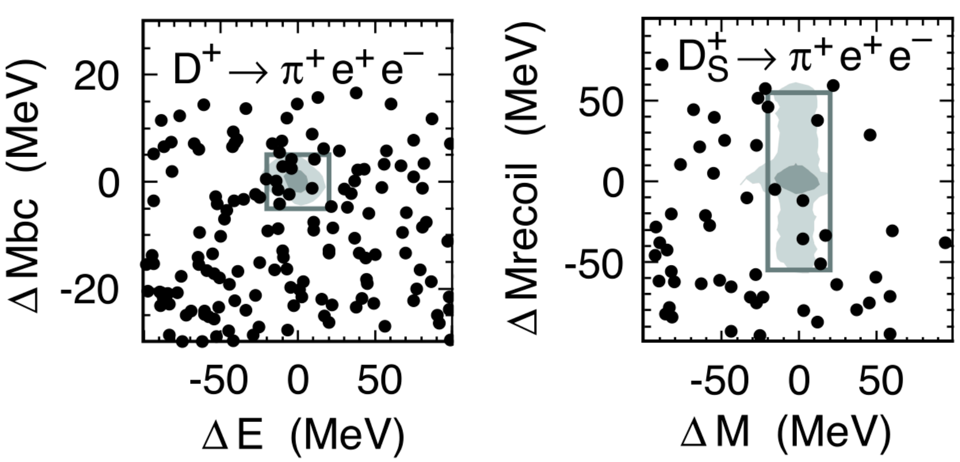


- $D^+ \to \pi^+\mu^+\mu^-$ by D0



$\mathcal{B} < 3.9 \times 10^{-6}$ (90% CL)

- $D_{(s)} \to h^\pm e^+e^-$ by CLEO



results $\Rightarrow$ next slide

$D \to h^{\pm}e^{\mp}e^{+}$

- CLEO's search for $D \to h^{\pm}e^{\mp}e^{+}$

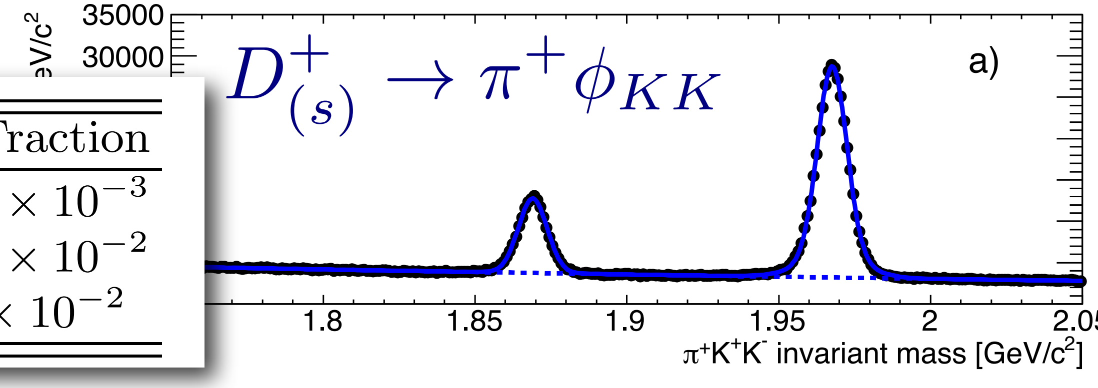
PRD 82, 092007 (2010)

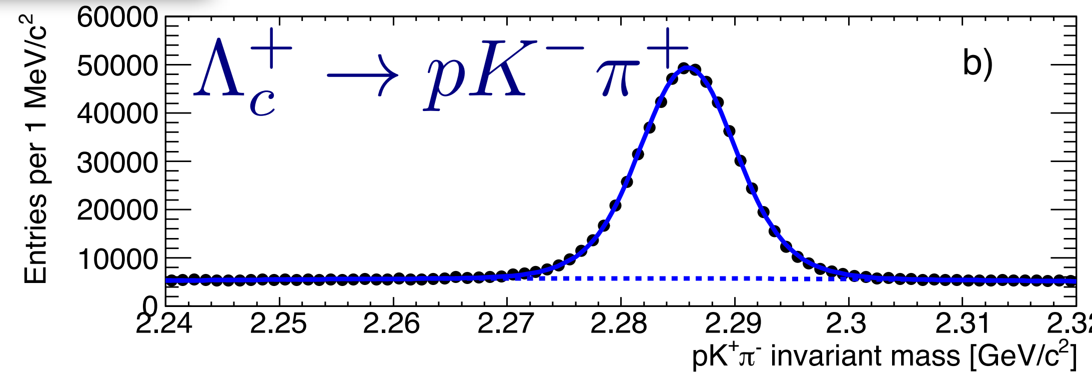
Channel	$N_{\rm exp}$	$N_{\rm obs}$	$\mathcal{C}(N_{\rm obs}\|N_{\rm exp})$	$\mathcal{B}$
$D^+ \to \pi^+e^+e^-$	5.7	9	9.3	$< 5.9 \times 10^{-6}$
$D^+ \to \pi^-e^+e^+$	1.3	0	2.3	$< 1.1 \times 10^{-6}$
$D^+ \to K^+e^+e^-$	4.9	2	3.2	$< 3.0 \times 10^{-6}$
$D^+ \to K^-e^+e^+$	1.2	3	5.8	$< 3.5 \times 10^{-6}$
$D^+ \to \pi^+\phi(e^+e^-)$	0.3	4		$(1.7^{+1.4}_{-0.9} \pm 0.1) \times 10^{-6}$
			7.9	$< 3.7 \times 10^{-6}$
$D_s^+ \to \pi^+e^+e^-$	6.7	6	5.6	$< 2.2 \times 10^{-5}$
$D_s^+ \to \pi^-e^+e^+$	2.2	4	6.2	$< 1.8 \times 10^{-5}$
$D_s^+ \to K^+e^+e^-$	3.0	7	9.3	$< 5.2 \times 10^{-5}$
$D_s^+ \to K^-e^+e^+$	4.1	4	5.0	$< 1.7 \times 10^{-5}$
$D_s^+ \to \pi^+\phi(e^+e^-)$	0.7	3		$(0.6^{+0.8}_{-0.4} \pm 0.1) \times 10^{-5}$
			6.2	$< 1.8 \times 10^{-5}$

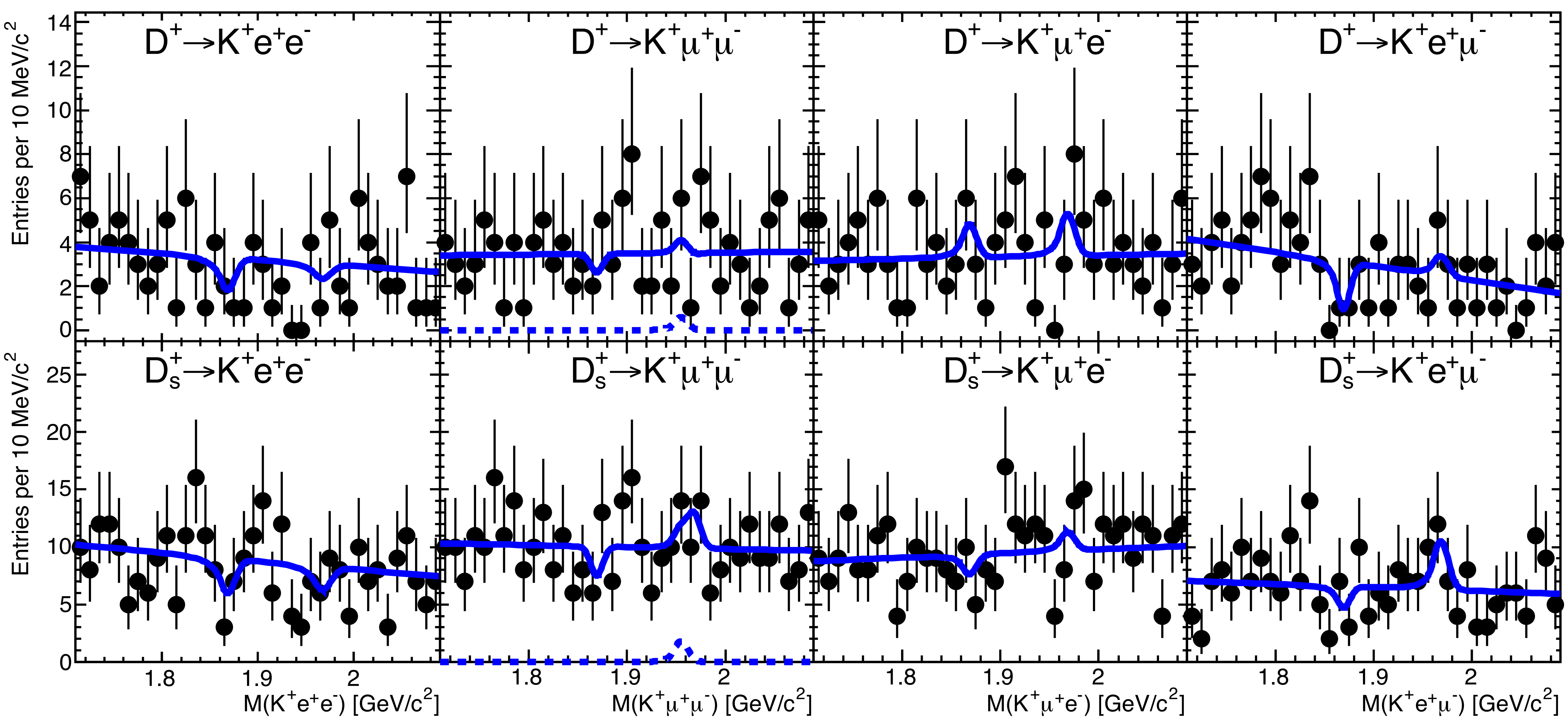
$D \to h^{\pm}\ell^{\mp}\ell^{+}$

1107.4465

Decay mode	N_{sig}	Efficiency	Branching Fraction
$D^+ \to \pi^+\phi_{KK}$	$106\,800 \pm 500$	$(15.44 \pm 0.07)\%$	$(2.72{\pm}0.13) \times 10^{-3}$
$D_s^+ \to \pi^+\phi_{KK}$	$338\,900 \pm 900$	$(15.29 \pm 0.07)\%$	$(2.32{\pm}0.14) \times 10^{-2}$
$\Lambda_c^+ \to pK^-\pi^+$	$488\,700 \pm 2\,100$	$(11.99 \pm 0.04)\%$	$(5.0{\pm}1.3) \times 10^{-2}$







$D \to h^{\pm}\ell^{\mp}\ell^{+}$

1107.4465

Decay mode	Yield (events)	Eff. (%)	BR UL 90% CL (10^{-4})	BF UL 90% CL (10^{-6})
$D^+ \to \pi^+ e^+ e^-$	$-3.9 \pm 1.6 \pm 1.7$	1.56	3.9	1.1
$D^+ \to \pi^+ \mu^+ \mu^-$	$-0.2 \pm 2.8 \pm 0.9$	0.46	24	6.5
$D^+ \to \pi^+ e^+ \mu^-$	$-2.9 \pm 3.4 \pm 2.4$	1.21	11	2.9
$D^+ \to \pi^+ \mu^+ e^-$	$3.6 \pm 4.3 \pm 1.3$	1.54	13	3.6
$D_s^+ \to \pi^+ e^+ e^-$	$8 \pm 34 \pm 8$	6.36	5.4	13
$D_s^+ \to \pi^+ \mu^+ \mu^-$	$20 \pm 15 \pm 4$	1.21	18	43
$D_s^+ \to \pi^+ e^+ \mu^-$	$-3 \pm 11 \pm 3$	2.16	4.9	12
$D_s^+ \to \pi^+ \mu^+ e^-$	$9.3 \pm 7.3 \pm 2.8$	1.50	8.4	20
$D^+ \to K^+ e^+ e^-$	$-3.7 \pm 2.9 \pm 3.3$	2.88	3.7	1.0
$D^+ \to K^+ \mu^+ \mu^-$	$-1.3 \pm 2.8 \pm 1.1$	0.65	16	4.3
$D^+ \to K^+ e^+ \mu^-$	$-4.3 \pm 1.8 \pm 0.6$	1.44	4.3	1.2
$D^+ \to K^+ \mu^+ e^-$	$3.2 \pm 3.8 \pm 1.2$	1.74	9.9	2.8
$D_s^+ \to K^+ e^+ e^-$	$-5.7 \pm 5.8 \pm 2.0$	3.20	1.6	3.7
$D_s^+ \to K^+ \mu^+ \mu^-$	$4.8 \pm 5.9 \pm 1.2$	0.85	9.1	21
$D_s^+ \to K^+ e^+ \mu^-$	$9.1 \pm 6.0 \pm 2.8$	1.74	5.7	14
$D_s^+ \to K^+ \mu^+ e^-$	$3.4 \pm 6.4 \pm 3.5$	2.08	4.2	9.7
$\Lambda_c^+ \to p e^+ e^-$	$4.0 \pm 6.5 \pm 2.8$	5.52	0.8	5.5
$\Lambda_c^+ \to p \mu^+ \mu^-$	$11.1 \pm 5.0 \pm 2.5$	0.86	6.4	44
$\Lambda_c^+ \to p e^+ \mu^-$	$-0.7 \pm 2.9 \pm 0.9$	1.10	1.6	9.9
$\Lambda_c^+ \to p \mu^+ e^-$	$6.2 \pm 4.6 \pm 1.8$	1.37	2.9	19

Decay mode	Yield (events)	Eff. (%)	BR UL 90% CL (10^{-4})	BF UL 90% CL (10^{-6})
$D^+ \to \pi^- e^+ e^+$	$4.7 \pm 4.7 \pm 0.5$	3.16	6.8	1.9
$D^+ \to \pi^- \mu^+ \mu^+$	$-3.1 \pm 1.2 \pm 0.5$	0.70	7.5	2.0
$D^+ \to \pi^- \mu^+ e^+$	$-5.1 \pm 4.2 \pm 2.0$	1.72	7.4	2.0
$D_s^+ \to \pi^- e^+ e^+$	$-5.7 \pm 14. \pm 3.4$	6.84	1.8	4.1
$D_s^+ \to \pi^- \mu^+ \mu^+$	$0.6 \pm 5.1 \pm 2.7$	1.05	6.2	14
$D_s^+ \to \pi^- \mu^+ e^+$	$-0.2 \pm 7.9 \pm 0.6$	2.23	3.6	8.4
$D^+ \to K^- e^+ e^+$	$-2.8 \pm 2.4 \pm 0.2$	2.67	3.1	0.9
$D^+ \to K^- \mu^+ \mu^+$	$7.2 \pm 5.4 \pm 1.6$	0.80	37	10
$D^+ \to K^- \mu^+ e^+$	$-11.6 \pm 4.0 \pm 3.1$	1.52	6.8	1.9
$D_s^+ \to K^- e^+ e^+$	$2.3 \pm 7.9 \pm 3.3$	4.10	2.1	5.2
$D_s^+ \to K^- \mu^+ \mu^+$	$-2.3 \pm 5.0 \pm 2.8$	0.98	5.3	13
$D_s^+ \to K^- \mu^+ e^+$	$-14.0 \pm 8.4 \pm 2.0$	2.26	2.4	6.1
$\Lambda_c^+ \to \overline{p} e^+ e^+$	$-1.5 \pm 4.2 \pm 1.5$	5.14	0.4	2.7
$\Lambda_c^+ \to \overline{p} \mu^+ \mu^+$	$-0.0 \pm 2.1 \pm 0.6$	0.94	1.4	9.4
$\Lambda_c^+ \to \overline{p} \mu^+ e^+$	$10.1 \pm 5.8 \pm 3.5$	2.50	2.3	16

Closing words

- Rare meson decays (esp. $B_{(s)}$ and D) have been very powerful tools to search for NP
- The "$K\pi$ puzzle" remains, and has not been fully understood yet
- Great advances have been made in understanding the EW penguin and other related decays
  - including invisible & semi-invisible decays and final states with one (or more) neutral particles
  - the strengths of the e^+e^- flavor-factories shine here
- Let's stay tuned for, with great anticipation,
  - SuperB & Belle-II
  - as well as upgrade plans for LHCb