Searches for New Physics at BABAR

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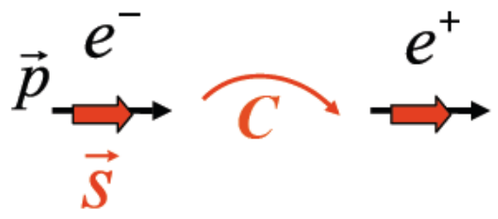
BROOKHAVEN NATIONAL LABORATORY

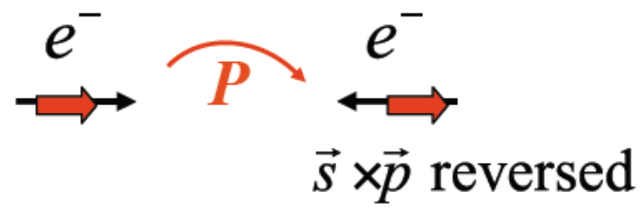
Particle Physics Seminar, 20th March 2008

Symmetries in Particle Physics

Charge Conjugation (C):



Parity Transformation (P):



Time Reversal (T):

Local QFT with Lorentz Invariance ⇒ CPT Conservation

Standard Model (SM): $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$

3 quark generations: 1 complex phase ⇒ CP Violation ✓

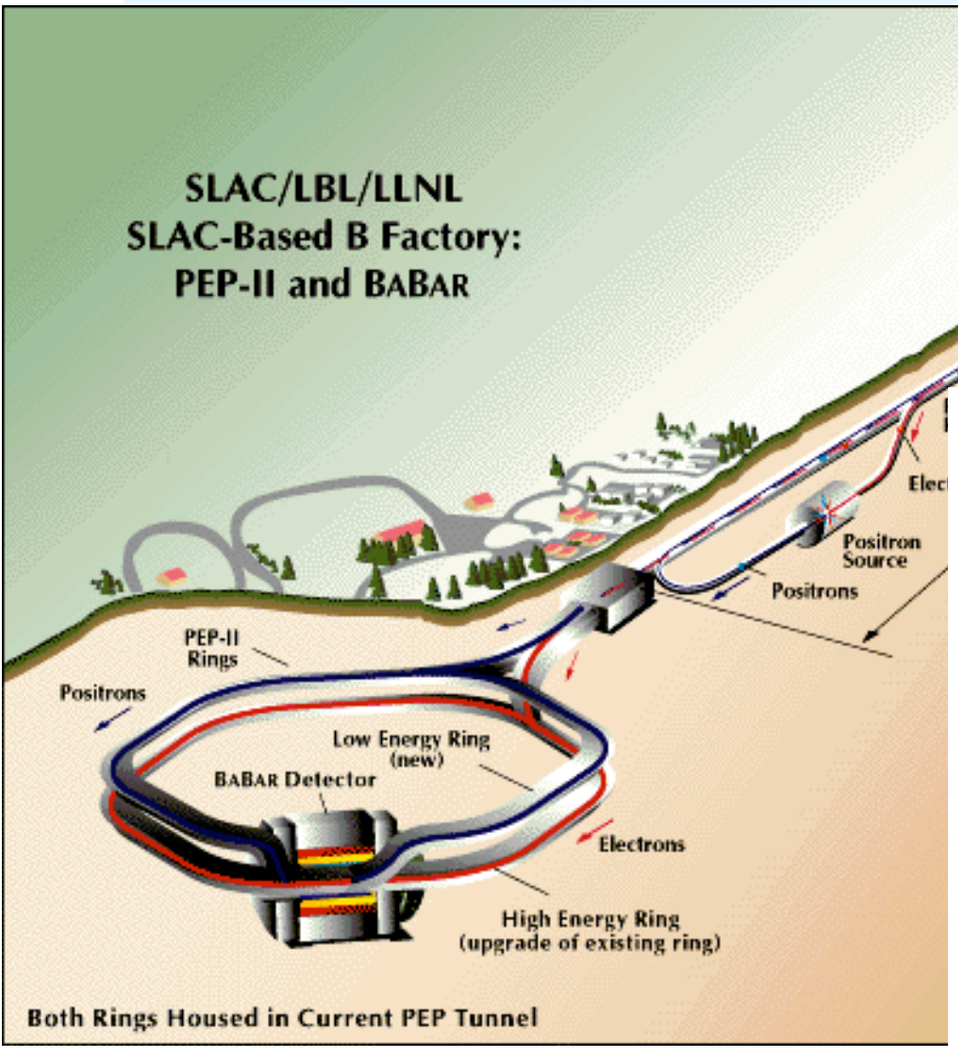
3 lepton generations: zero m_ν ⇒ Lepton Flavor Violation ✗

Signatures of New Physics

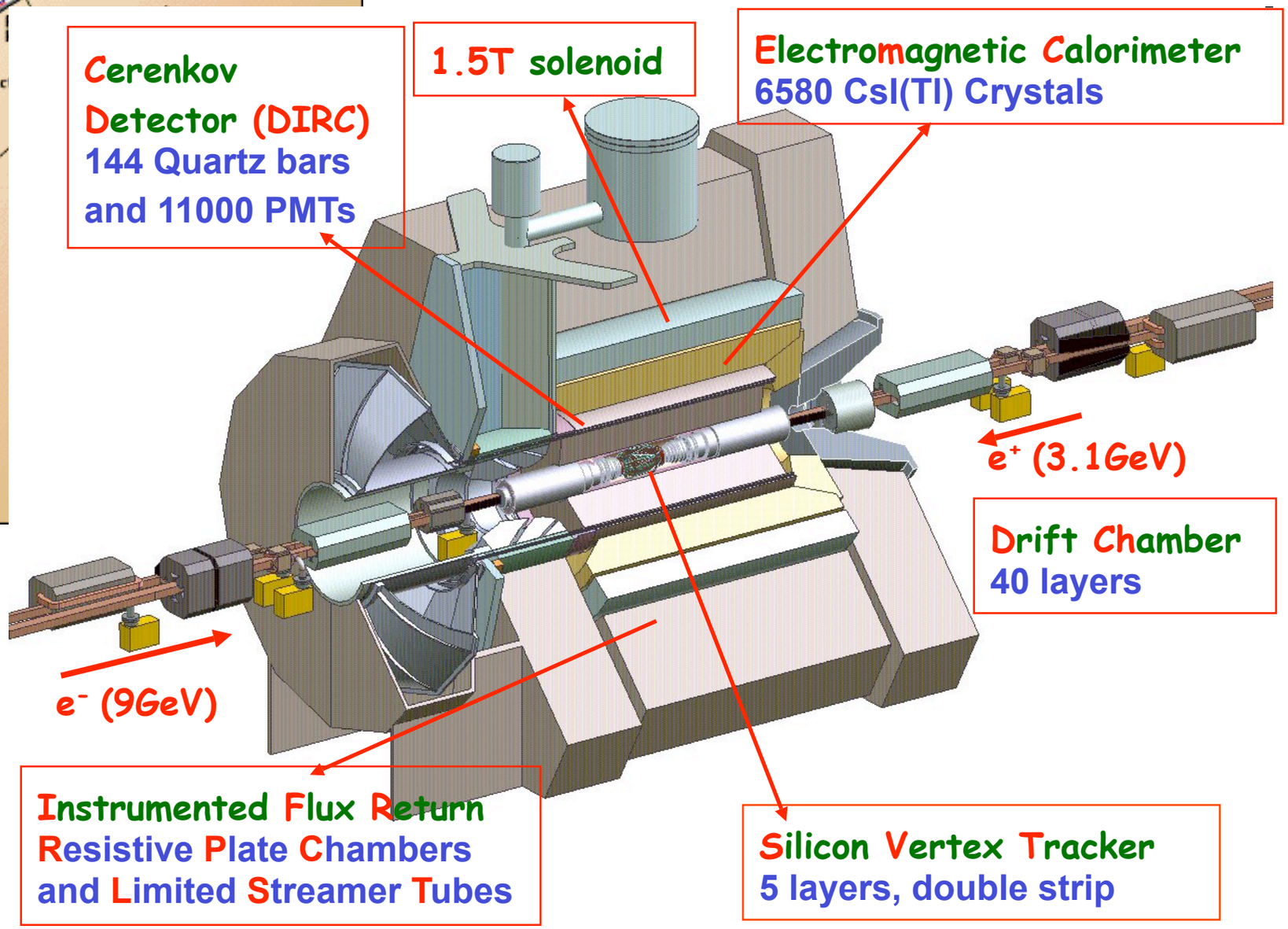
- CP Violation in K(1964), B(2001), D(?) decays
- CPT Violation: Sidereal time dependence in $B^0\overline{B^0}$ oscillations
- Excess in FCNC in $B \to X_{(s,d)}\gamma, K^*\ell\ell,$ NEW $K\nu\bar{\nu}$ decays
  - $X_s\gamma$: Isospin Asymmetry, CP Asymmetry NEW
  - $K^*\gamma$: Photon Polarization in Time Dependent CP Asymmetry
  - $(\rho/\omega)\gamma$: Isospin Asymmetry, $\mathcal{B}(\rho\gamma)/\mathcal{B}(K^\star\gamma)$ vs. B_s mixing
  - $K^*\ell\ell$: Longitudinal Polarization, Forward-Backward Asymmetry NEW
- Excess in helicity suppressed $B \to \ell\ell, \ell\nu$ $(\ell = e, \mu)$ decays
- Excess in helicity favored $B \to \ell\ell\gamma, \tau\nu, D^{(*)}\tau\nu$ decays
- Observation of LFV in $B \to e\mu, \ell\tau, K\tau\mu$ decays
- Observation of LFV in $\tau \to \ell\gamma, \ell\pi^0, \ell\eta, \ell\eta', \ell\omega, \ell\ell\ell, \ell hh$ decays

NEW journal draft to be submitted soon

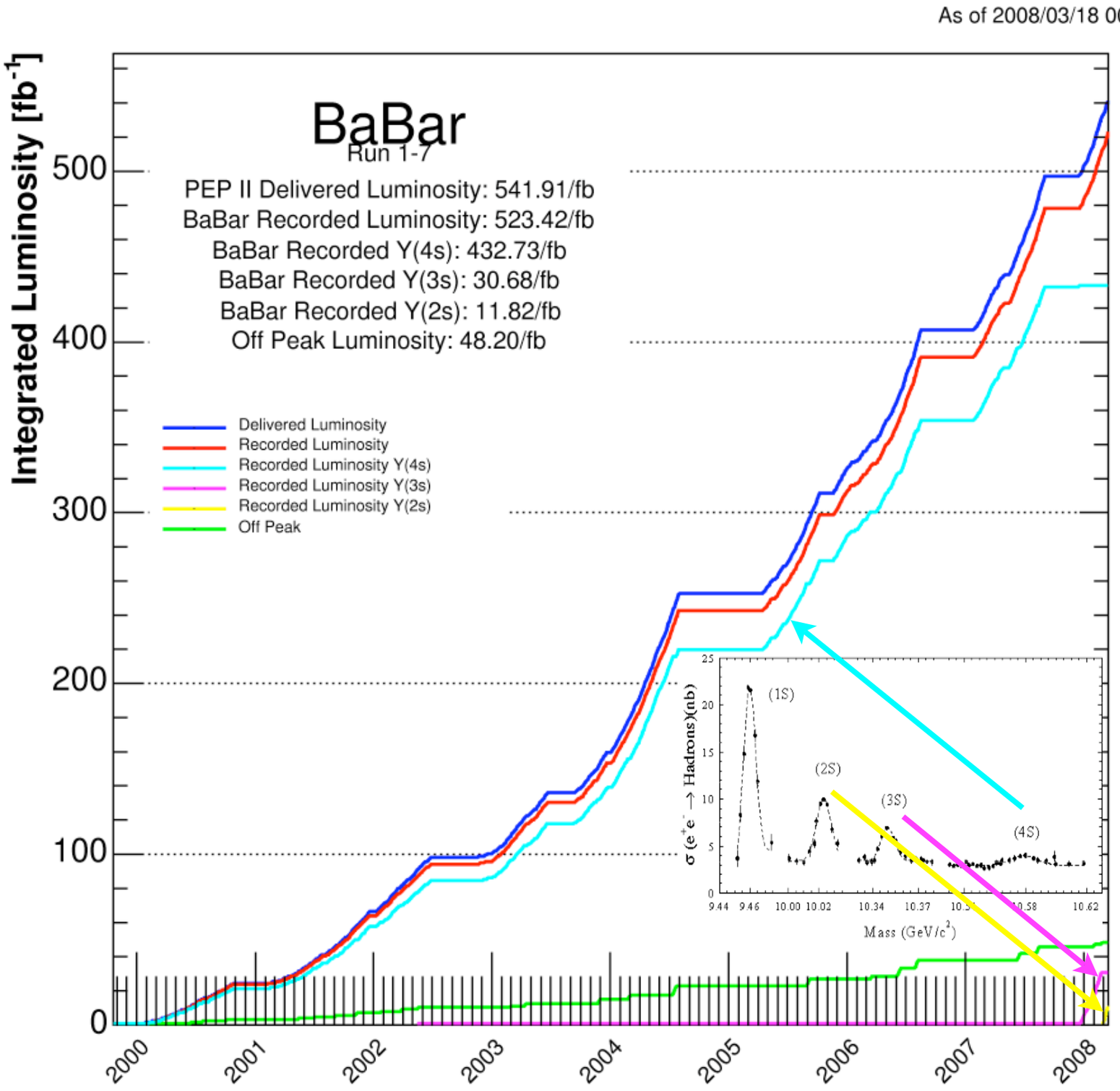
PEP II & BABAR



The BABAR Detector



History of Data Taking



Integrated luminosity > 500 fb^{-1}

- 433 fb^{-1} at Y(4S) (10.58 GeV)

$$\sigma(B\bar{B}) \approx 1.1nb \approx \sigma(c\bar{c}) \approx 1.3nb \approx \sigma(\tau^+\tau^-) \approx 0.9nb$$

Current Schedule:

- 30 fb^{-1} at Y(3S) (10.36 GeV)
- 20 fb^{-1} at Y(2S) (10.02 GeV)

Motivation:

- Y Invisible with sensitive to Dark Matter
- Lepton Universality in Y decays sensitive to Light Higgs

Results:

- Expected in Summer '08

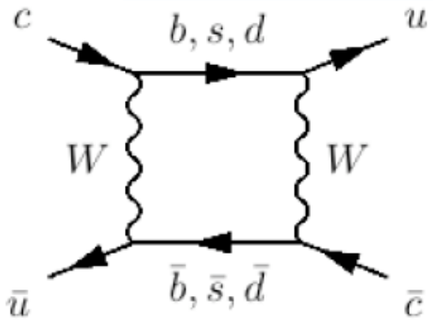
D^0-$\bar{D}^0$ Mixing

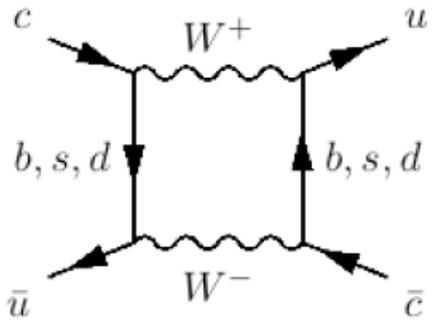
- $|D_{1,2}>= p|D^0> \pm q|\bar{D}^0>,\ |p|^2+|q|^2=1$
- Mixing parameters **x** and **y**: in SM $|\mathbf{x}|,\ |\mathbf{y}| \leq \mathcal{O}(\mathbf{10^{-2}})$

Falk, Grossman, Ligeti, Nir, Petrov PRD 69 114021 (2004)

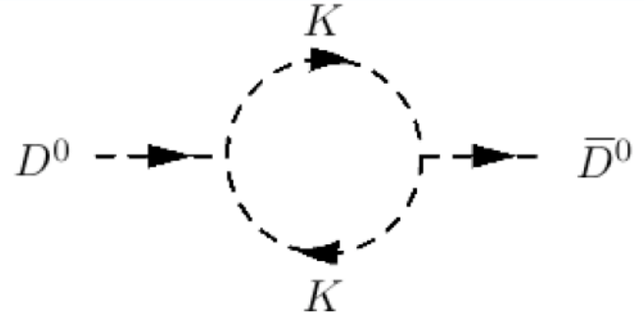
  - $x = \frac{m_1-m_2}{\Gamma},\quad y = \frac{\Gamma_1-\Gamma_2}{2\Gamma},\quad \Gamma = \frac{1}{2}(\Gamma_1+\Gamma_2)$
  - GIM, CKM suppressed but enhanced by long-distance effects

Short-range SM Contributions:



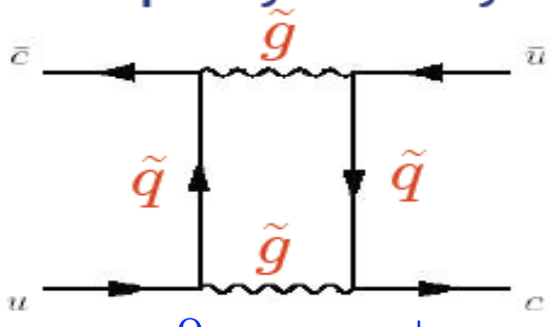


Long-range SM Contributions:

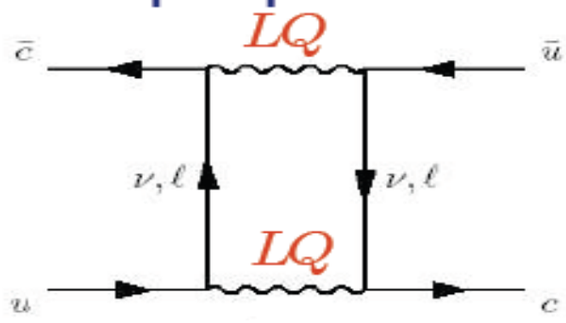


New Physics Contributions ⇒ |x| >> |y|, CP Violation, ...

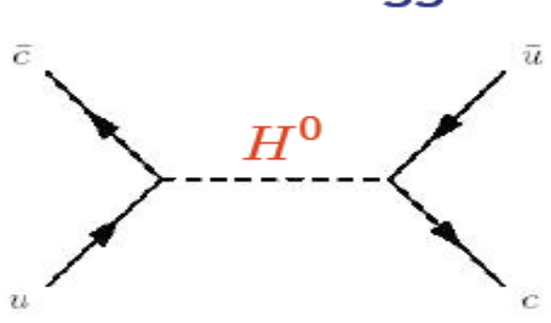
Supersymmetry:



Leptoquarks:



Extended Higgs:



Mixing in $D^0 \to K^+\pi^-$:

- BaBar: 3.9σ evidence $(\mathcal{L} = 384 fb^{-1})$ PRL 98, 211802 (2007)
- CDF: 3.8σ evidence $(\mathcal{L} = 1.5 fb^{-1})$ arXiv: 0712.1567 (subm. to PRL)

Lifetime: $D^0 \to K^-\pi^+$, K^-K^+, $\pi^-\pi^+$

Mixing parameters:

- $y_{CP} = \frac{\tau_{K\pi}}{\tau_{hh}} - 1 \xrightarrow[conserv.]{CP} y$
- $\Delta Y = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} A_\Gamma;\ A_\Gamma = \frac{\tau^+_{hh} - \tau^-_{hh}}{\tau^+_{hh} + \tau^-_{hh}} \xrightarrow[conserv.]{CP} 0$

arXiv:0712.2249 (subm. to PRD) $\mathcal{L} = 384$ fb^{-1}

Sample	y_{CP}	ΔY
K^-K^+	$(1.60 \pm 0.46 \pm 0.17)\%$	$(-0.40 \pm 0.44 \pm 0.12)\%$
$\pi^-\pi^+$	$(0.46 \pm 0.65 \pm 0.25)\%$	$(\ 0.05 \pm 0.64 \pm 0.32)\%$
Combined	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

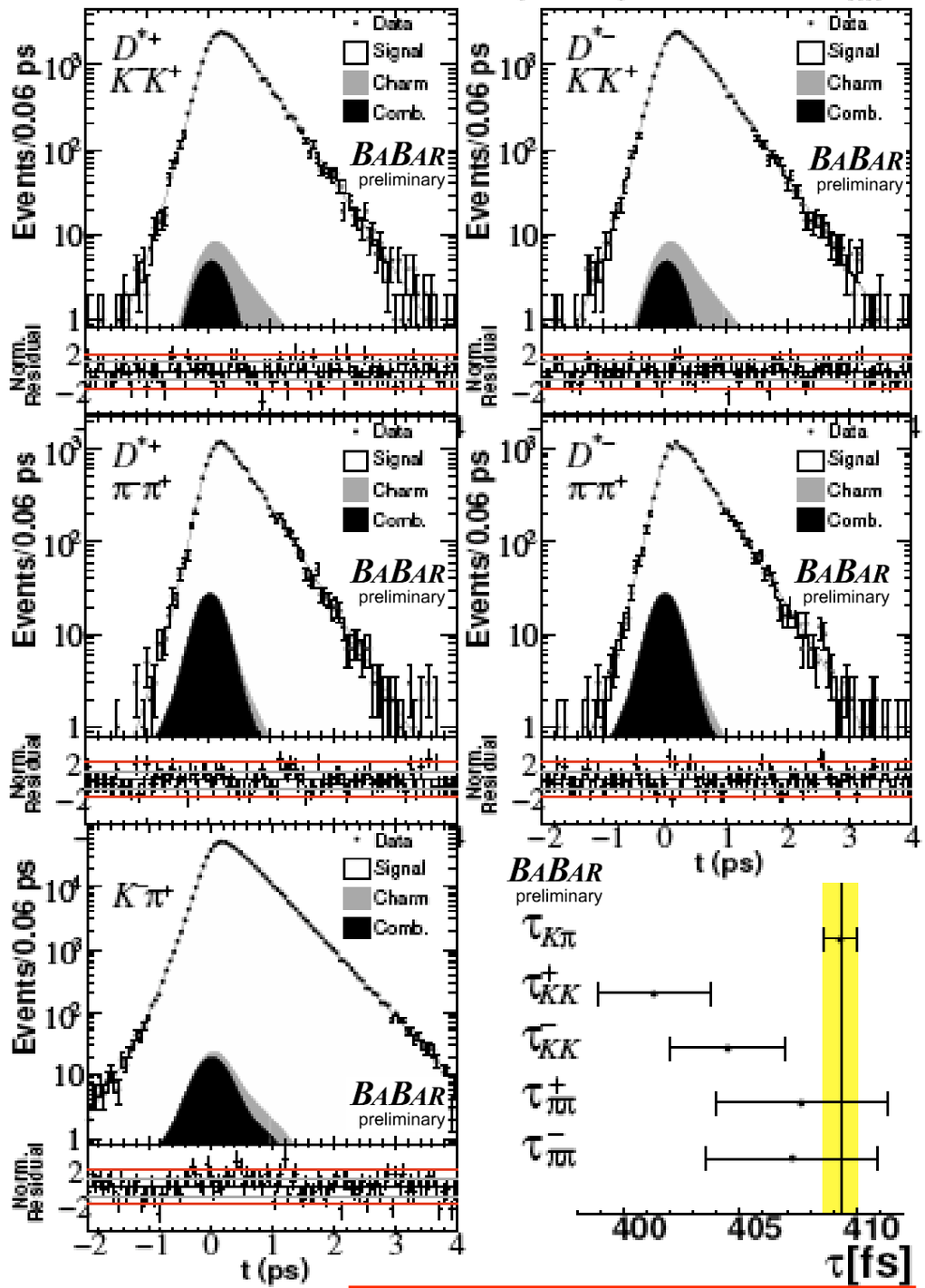
No mixing excluded at 3σ.

PRL 98, 211803 (2007) $\mathcal{L} = 540$ fb^{-1}

	y_{CP}	A_Γ
Combined	$(1.31 \pm 0.32 \pm 0.25)\%$	$(0.01 \pm 0.30 \pm 0.15)\%$

Evidence of charm mixing at 3.2σ level.
No evidence of CP violation

Unbinned likelihood fit to (t, σ_t) to obtain τ_{hh}



$K\pi$ and KK lifetimes differ!

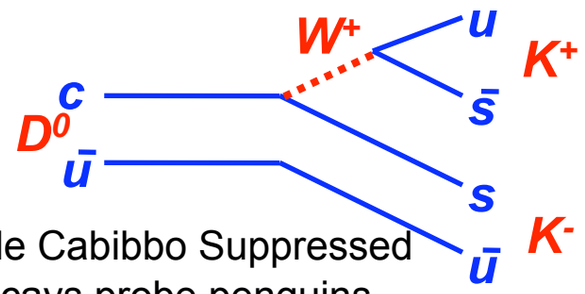
Direct CPV: 2-body Charm Decays

$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2\,\mathrm{Im}\, A_1 A_2^* \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2\,\mathrm{Re}\, A_1 A_2^* \cos(\delta_1 - \delta_2)}$$

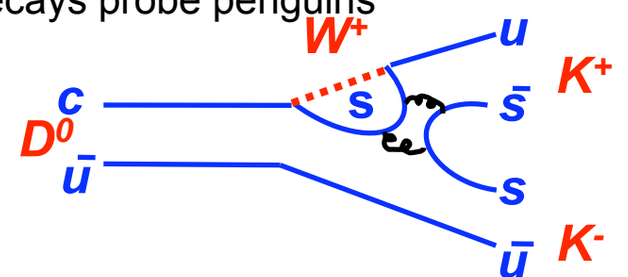
2 weak amplitudes with phase difference

strong phase difference

e.g., $D^0 \to K^+K^-$:



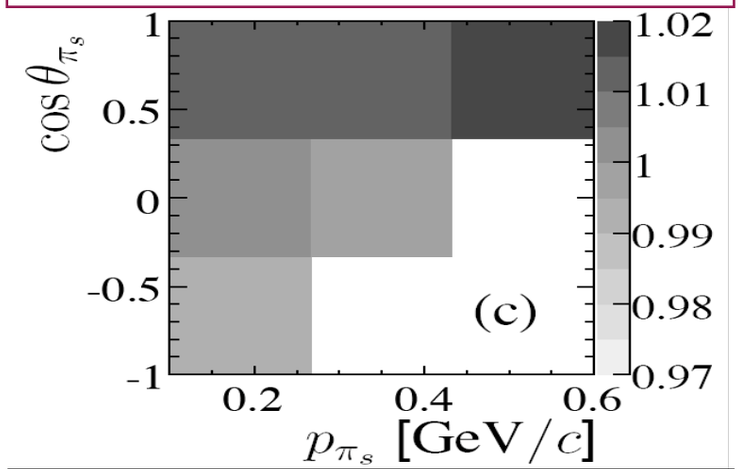
Single Cabibbo Suppressed decays probe penguins



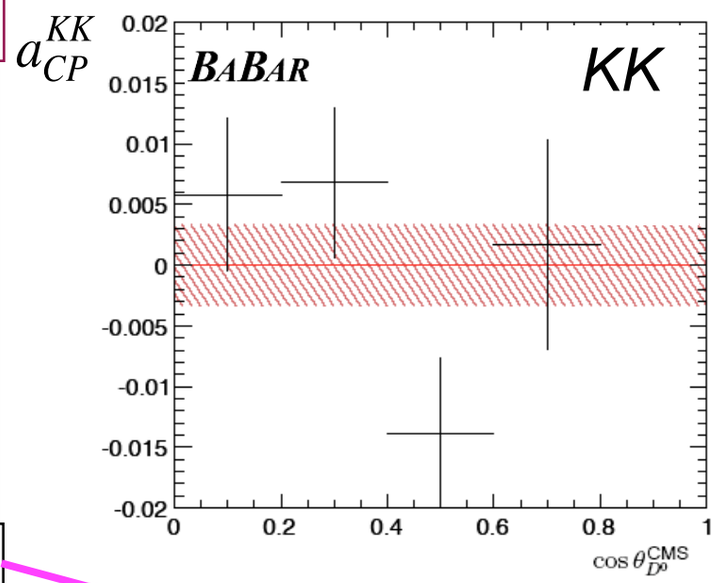
- for $f = K^-K^+, \pi^-\pi^+$: $A_{CP} \sim \mathcal{O}(10^{-5} - 10^{-4})$ PRD51,3478(1995); RNCIB,26N7,11(2003)

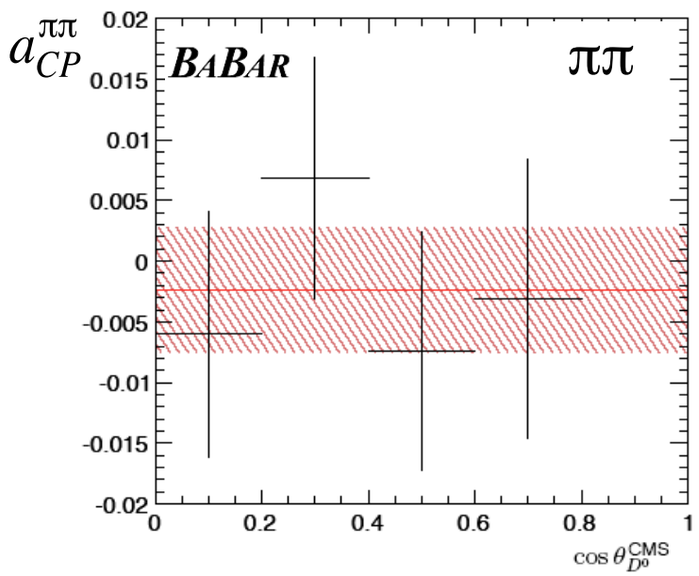
If direct CPV is at 1% level, its likely source is new physics in loop diagrams.

Relative $D^0/\bar{D}^0$ soft pion tagging efficiency from $D^0 \to K^-\pi^+$ data



➠ 0.08% systematic uncertainties





No evidence for CPV in either modes

$A_{CP}^{KK} = (\ 0.00 \pm 0.34(\mathrm{stat}) \pm 0.13(\mathrm{syst}))\%$
$A_{CP}^{\pi\pi} = (-0.24 \pm 0.52(\mathrm{stat}) \pm 0.22(\mathrm{syst}))\%$

PRL 100, 061803 (2008) $\mathcal{L} = 386\,\mathrm{fb}^{-1}$

$A_{CP}^{KK} = (-0.41 \pm 0.30(\mathrm{stat}) \pm 0.11(\mathrm{syst}))\%$
$A_{CP}^{\pi\pi} = (+0.41 \pm 0.52(\mathrm{stat}) \pm 0.12(\mathrm{syst}))\%$

Prelim. Moriond (2008) $\mathcal{L} = 540\,\mathrm{fb}^{-1}$

BELLE

Direct CPV: 3-body Charm Decays

Method I: Search for differences in Dalitz plots between D^0 and $\bar{D}^0$

$$\Delta = (N_{\bar{D}^0} - RN_{D^0})/\sqrt{\sigma^2_{N_{\bar{D}^0}} + R^2\sigma^2_{N_{D^0}}}$$

$$\chi^2/\nu = (\sum_{DP} \Delta^2)/\nu = \begin{cases} 1.020 & \pi^+\pi^-\pi^0 \\ 1.056 & K^+K^-\pi^0 \end{cases}$$

One Sided Gaussian CL for consistency with no CPV:
32.8%($\pi^+\pi^-\pi^0$) and 16.6%($K^+K^-\pi^0$)

Method II: Look for a phase space integrated asymmetry

$$A^{\rm reco}_{\rm corr}(cos\theta^*) = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)}$$

Phase space integrated A_{CP}:

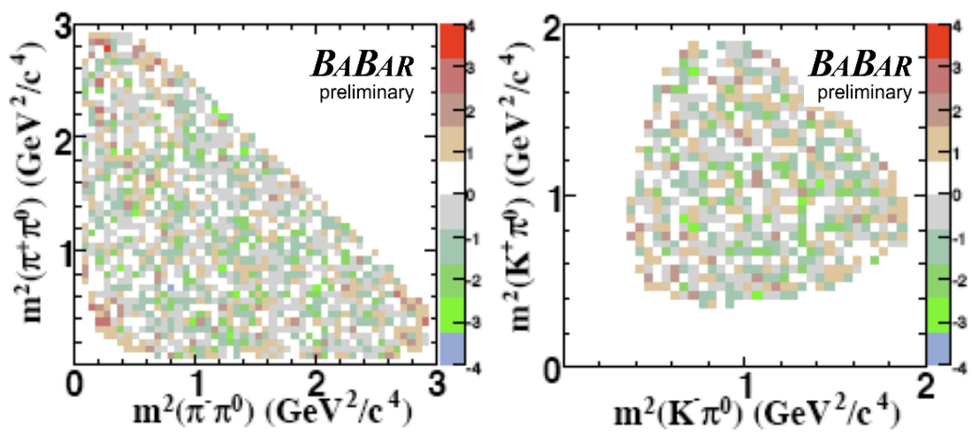
$$a_{CP}^{\pi^+\pi^-\pi^0} = (-0.31 \pm 0.41 \pm 0.17)\%$$

$$a_{CP}^{K^+K^-\pi^0} = (1.00 \pm 1.67 \pm 0.25)\%$$

Mode	Eff.	PID	Bkg.	Mistag	Total Syst.
$D^0 \to \pi^-\pi^+\pi^0$	0.06	0.05	0.11	0.10	0.17
$D^0 \to K^-K^+\pi^0$	0.11	0.08	0.19	0.10	0.25

arXiv:0802.4035 (subm. to PRL) $\mathcal{L}$ = 385fb^{-1}

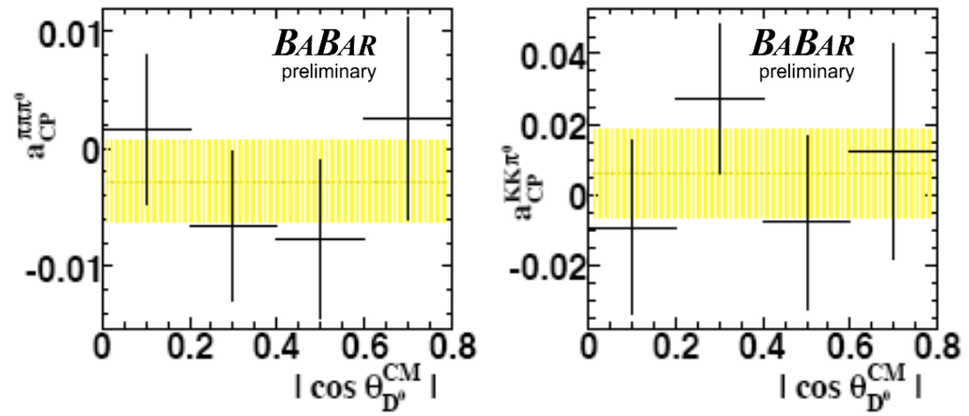
$\pi^+\pi^-\pi^0$ $\quad$ $K^+K^-\pi^0$



Normalized residuals.

No evidence for CPV in either modes

$\pi^+\pi^-\pi^0$ $\quad$ $K^+K^-\pi^0$



$$a_{CP}^{\pi^+\pi^-\pi^0} = (0.43 \pm 0.41 \pm 1.23)\%$$

Syst: Tracking=1.01%, Fit=0.58%, Others=0.40%

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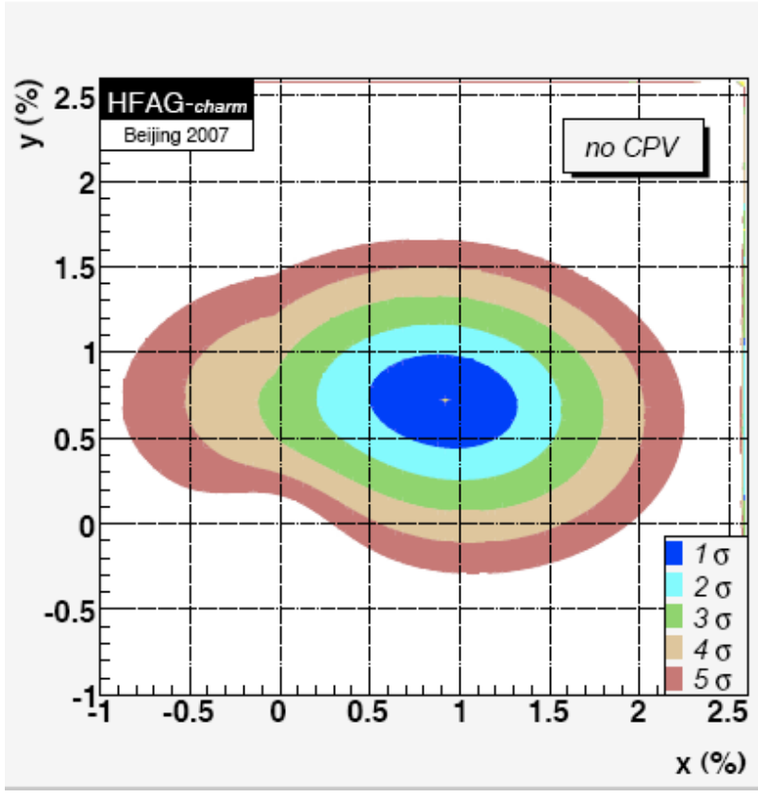
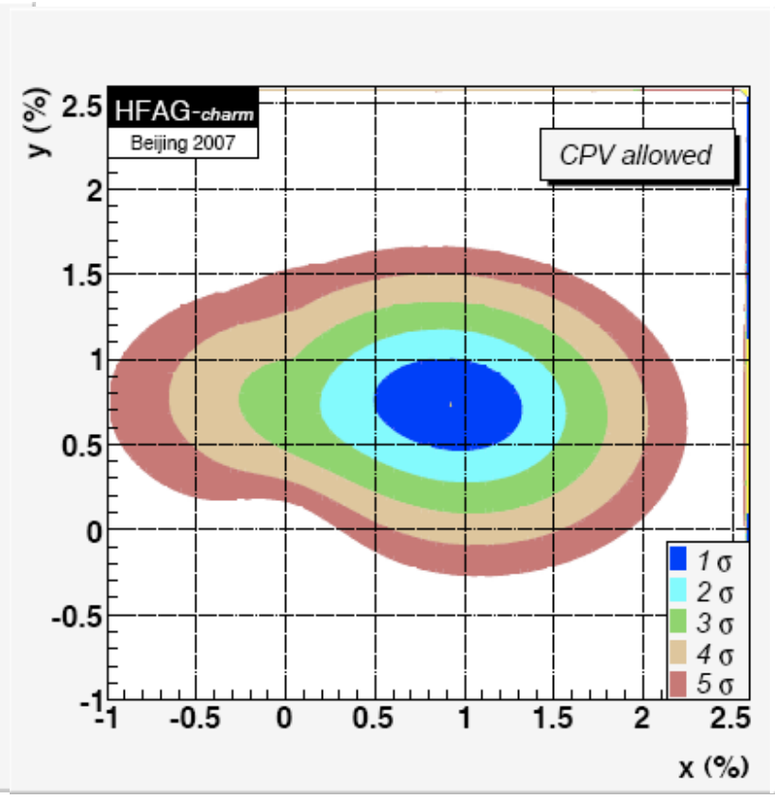
arXiv:0801.2439 (subm. to PLB) $\mathcal{L}$ = 532fb^{-1}

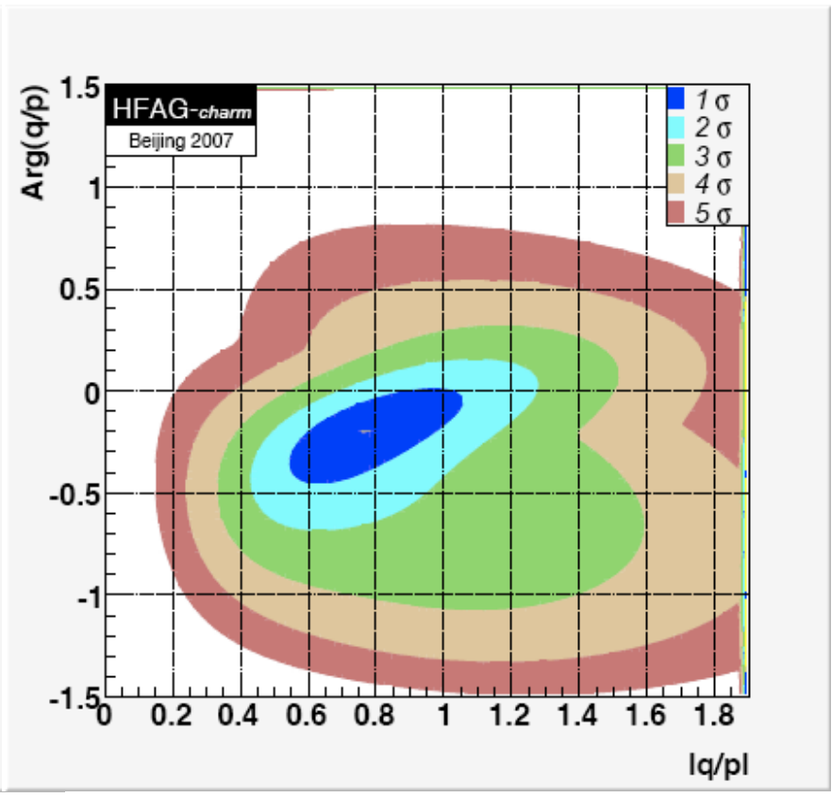
World Average of Charm Decays

HFAG (arXiv: 0803.0082, Submitted to Chin.Phys.C)

$$D^0 \to K^+\ell^-\nu,\ D^0 \to K^+K^-/\pi^+\pi^-,\ D^0 \to K^+\pi^-, D^0 \to K^+\pi^-\pi^0, D^0 \to K^+\pi^-\pi^+\pi^-, \text{and } D^0 \to K^0_S\pi^+\pi^-$$







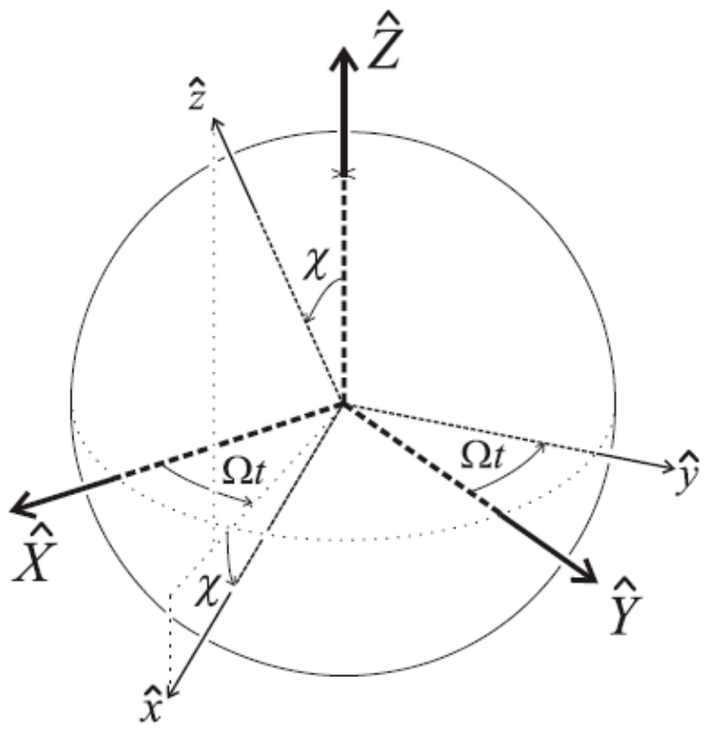
- Evidence of mixing: (x≠0) @ 3.0σ, (y≠0) @ 4.1σ, (x,y)≠(0,0) @ 6.7σ
- No evidence of CPV in decay, mixing and/or interference
- Strong Phase Difference < 45° @ 95% CL

CPT Violation

$$|B_L^0> = p\sqrt{1-z}\,|B^0> + q\sqrt{1+z}\,|\overline{B}^0>)$$
$$|B_H^0> = p\sqrt{1+z}\,|B^0> - q\sqrt{1-z}\,|\overline{B}^0>)$$

$$z \simeq \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

- Sign of Δt defines the type of transition.
- The sign of the leptons gives the flavor of the B^0



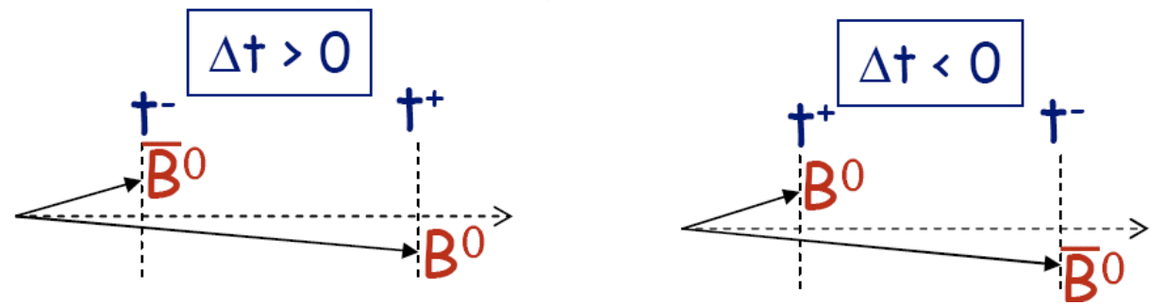
In BaBar: $\beta\gamma \approx 0.55 \Rightarrow \cos\chi = 0.607$

CPT symmetry

$$\text{Prob}(\overline{B}^0 \to \overline{B}^0)(\Delta t) = \text{Prob}(B^0 \to B^0)(\Delta t)$$

CP symmetry

$\Delta t = t^+ - t^-$



$$A_{CP/CPT}(|\Delta t|) = \frac{Prob(\overline{B}^0 \to \overline{B}^0)(|\Delta t|) - Prob(B^0 \to B^0)(|\Delta t|)}{Prob(\overline{B}^0 \to \overline{B}^0)(|\Delta t|) + Prob(B^0 \to B^0)(|\Delta t|)}$$
$$= \frac{N(\ell^+,\ell^-)(\Delta t < 0) - N(\ell^+,\ell^-)(\Delta t > 0)}{N(\ell^+,\ell^-)(\Delta t < 0) + N(\ell^+,\ell^-)(\Delta t > 0)}$$

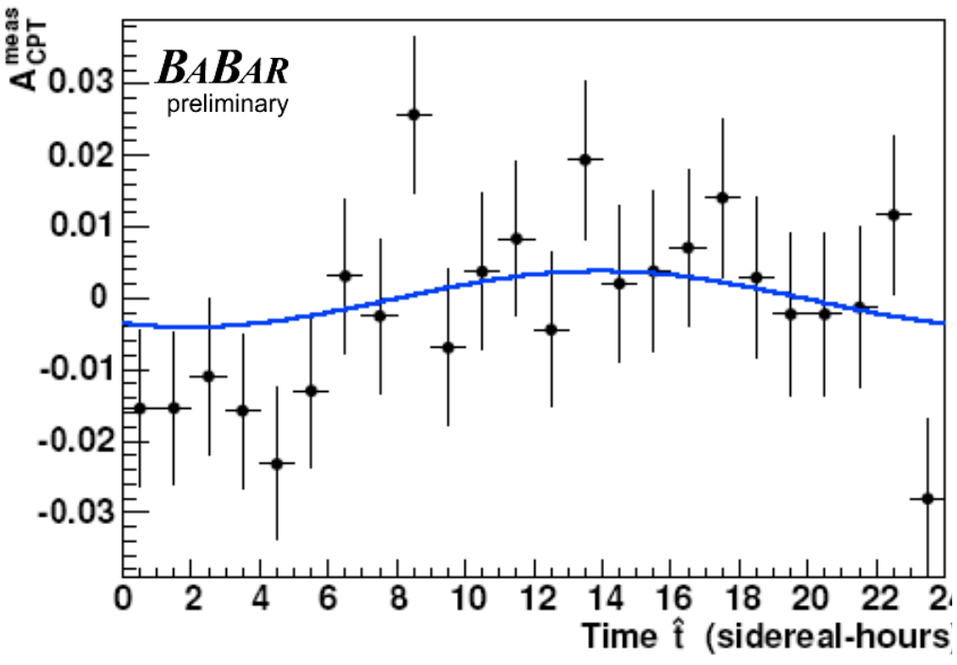
$$\Delta\Gamma \times \text{Re}(z) = \Delta\Gamma \times \text{Re}(z)_0 + \Delta\Gamma \times \text{Re}(z)_1 \cos(\Omega T + \varphi_r)$$
$$\text{Im}(z) = \text{Im}(z)_0 + \text{Im}(z)_1 \cos(\Omega T + \varphi_i)$$

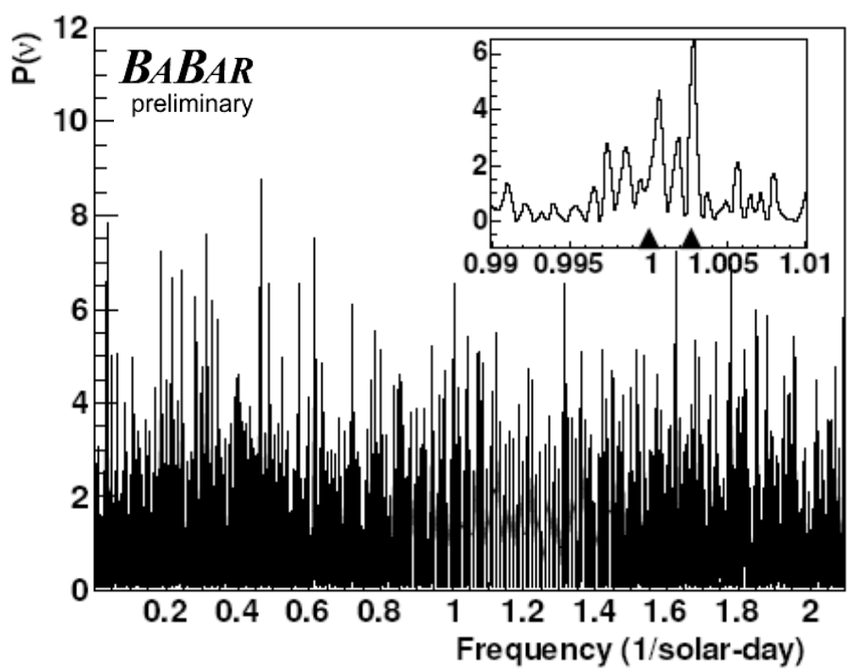
Sidereal frequency $\Omega \approx 1.0027$ solar-day^{-1}

$\varphi_i = \varphi_r$ (assumed in our fits to data)

Variation of z with a period of 1 sidereal day
⇒ Lorentz Violation ⇒ Proof of CPT Violation.

CPT Violation

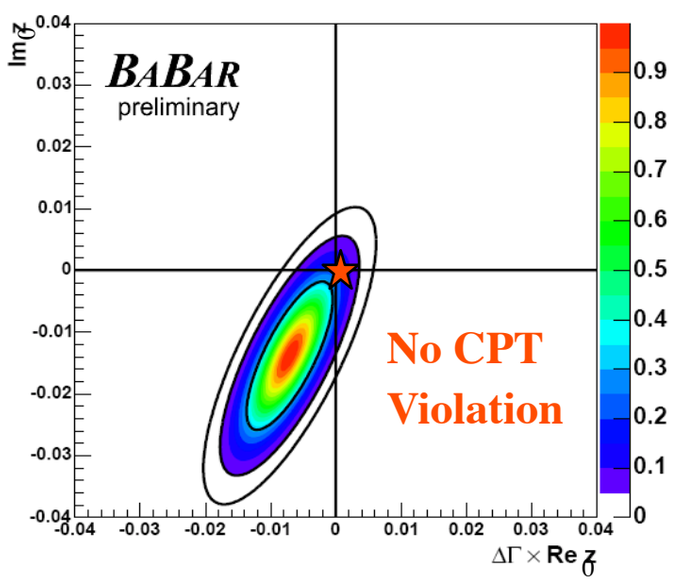


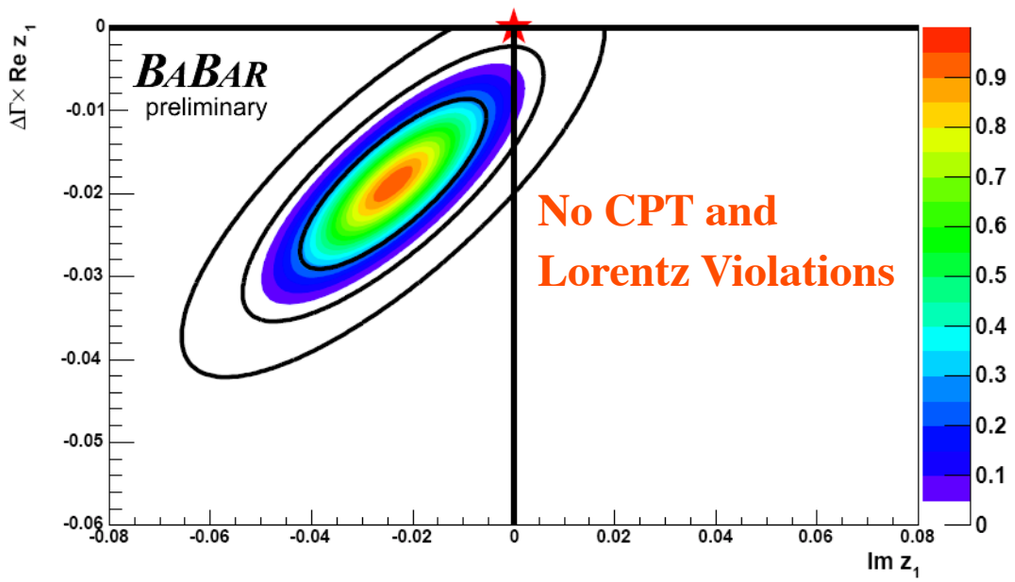


$$P(\nu) \equiv \frac{1}{N\sigma_w^{\,2}} \left| \sum_{j=1}^{N} w_j e^{2i\pi\nu T_j} \right|^2$$

$w_j \propto \Delta m \times \Delta t_j - \sin(\Delta m \times \Delta t_j)$

- P(ν) = 5.28 @ sidereal frequency exceeded at 78/20994 tests.



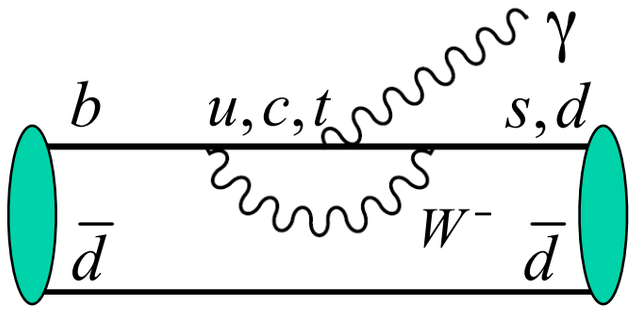


- Correlations between $\mathrm{Im}z_0/\Delta\Gamma \times \mathrm{Re}z_0$ and $\mathrm{Im}z_1/\Delta\Gamma \times \mathrm{Re}z_1$ are 76% and 79%.
- Minima are only 1.5σ / 2.2σ away from (0.0).

No evidence of CPT Violation observed in 2D likelihood or Periodogram method

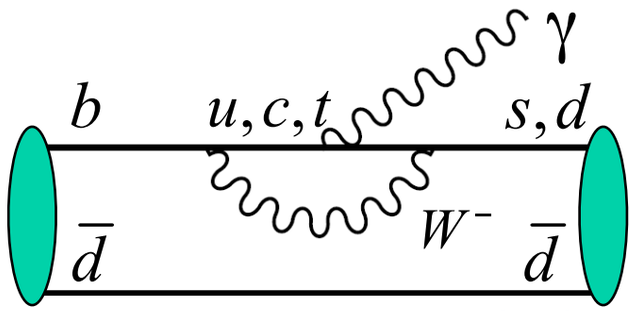
arXiv:0711.2713 (subm. to PRL)
$\mathcal{L} = 211 fb^{-1}$

Electromagnetic



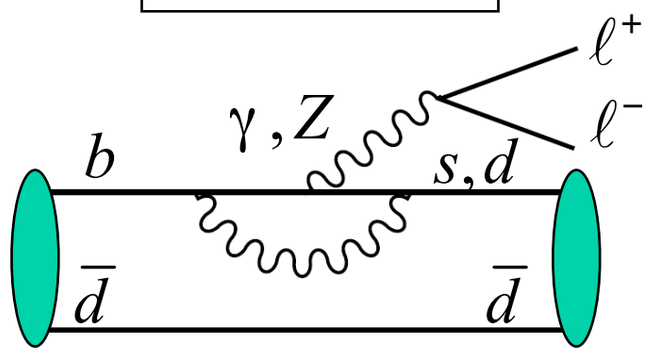
- EM penguin encoded in C7
- $|C7| \approx 0.33$ from $\mathcal{B}(b \to s\gamma)$

Electromagnetic

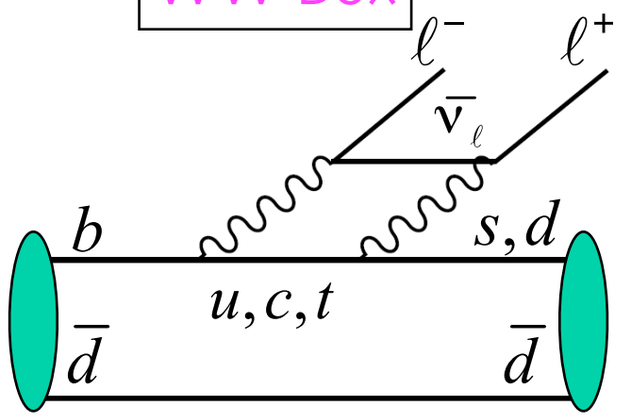


- EM penguin encoded in C7
- |C7|≈0.33 from $\mathcal{B}(b\to s\gamma)$
- Sign from $b\to s\ell^+\ell^-$
  - ☞ Longitudinal Polarization, FB Asymmetry in $B\to K^*ll$

Electroweak



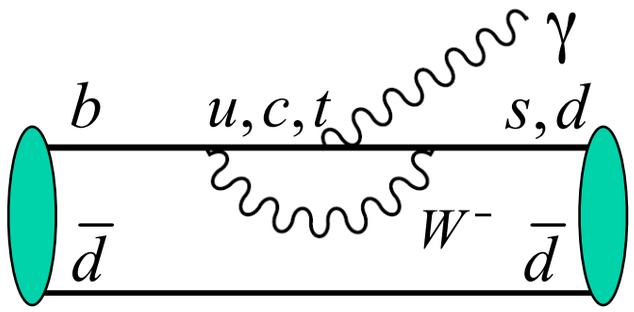
WW Box



- Vector/Axial-Vector part of EW encoded in C9/C10
- SM: V-A (Left-handed)
- Sign-flip in C9C10: V+A

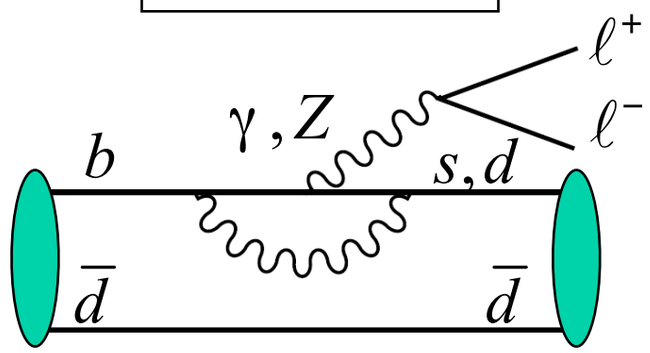
Flavor Changing Neutral Current

Electromagnetic

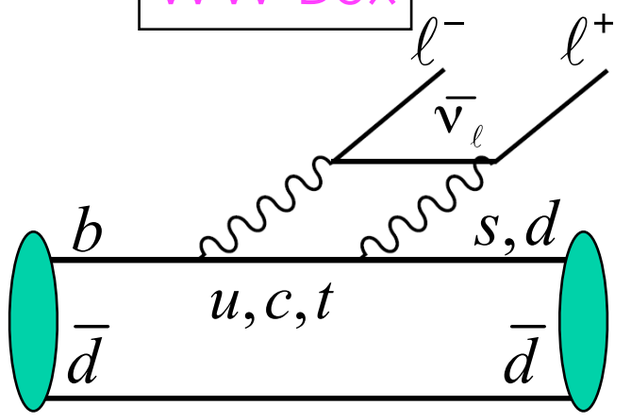


- EM penguin encoded in C7
- |C7|≈0.33 from $\mathcal{B}(b\to s\gamma)$
- Sign from $b\to s\ell^+\ell^-$
  - ☞ Longitudinal Polarization, FB Asymmetry in $B\to K^*ll$ [=0 in $B\to Kll$, as $J^P(K)=0^-$]

Electroweak

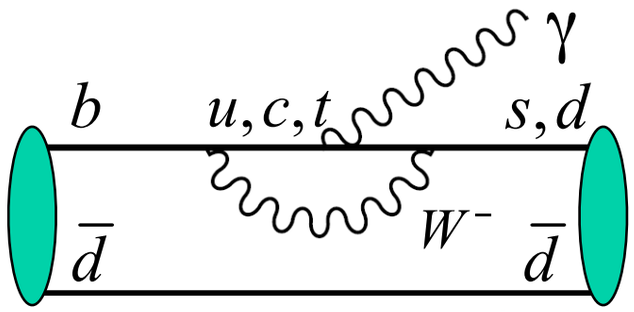


WW Box



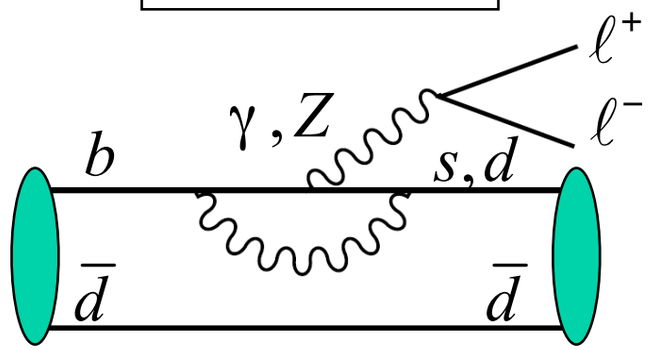
- Vector/Axial-Vector part of EW encoded in C9/C10
- SM: V-A (Left-handed)
- Sign-flip in C9C10: V+A

Electromagnetic

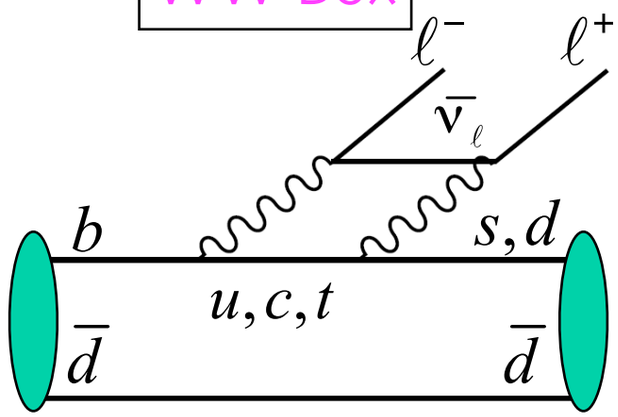


- EM penguin encoded in C7
- |C7|≈0.33 from $\mathcal{B}(b\to s\gamma)$
- Sign from $b\to s\ell^+\ell$
  - ☞ Longitudinal Polarization, FB Asymmetry in B→K*ll [=0 in B→Kll, as $J^P(K)=0^-$]
- EM penguin absent in $b\to s\nu\bar{\nu}$

Electroweak



WW Box



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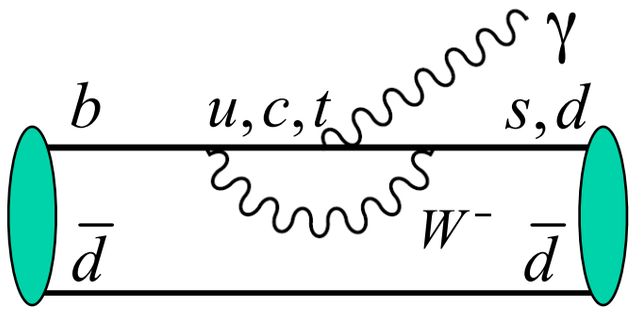
Electromagnetic



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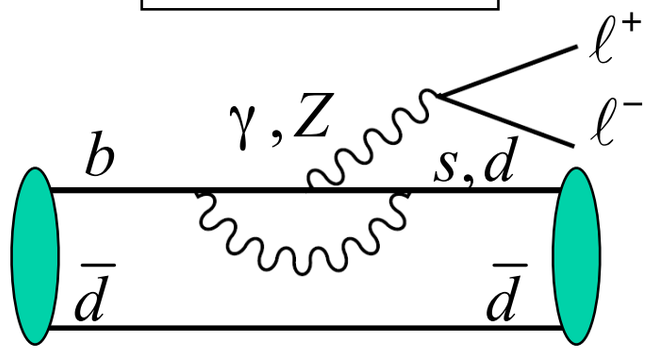
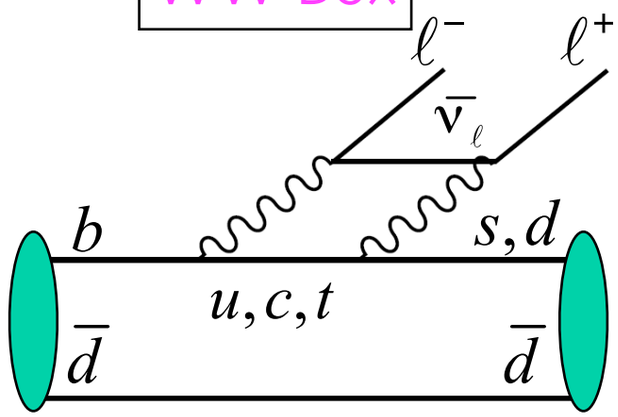
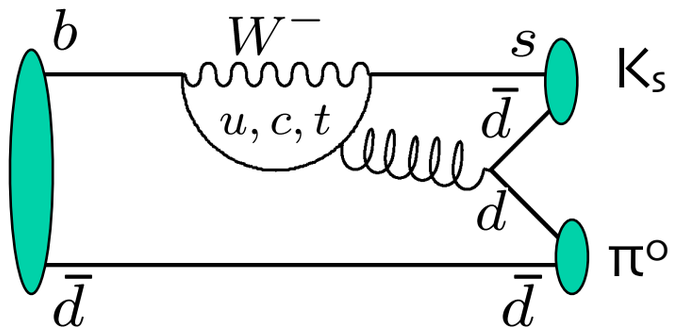
Electroweak



WW Box



Gluonic



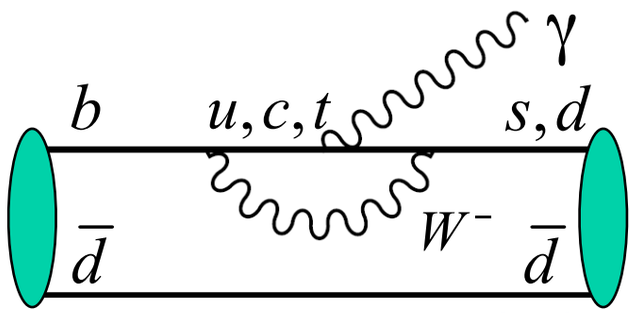
- Vector/Axial-Vector part of EW encoded in C9/C10
- SM: V-A (Left-handed)
- Sign-flip in C9C10: V+A

☞ Photon Polarization in B→K*(KsπO)γ

AS TOLD BY

Flavor Changing Neutral Current

Electromagnetic



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- Sign from $b\to s\ell^+\ell$
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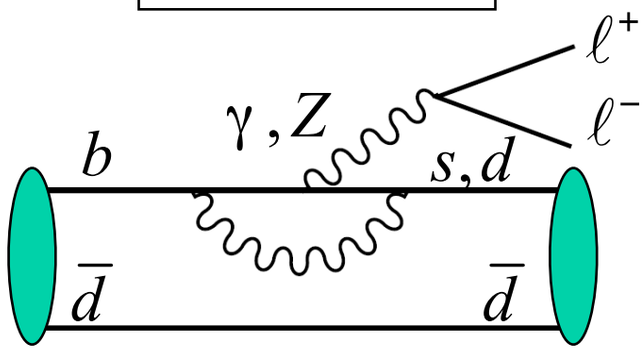
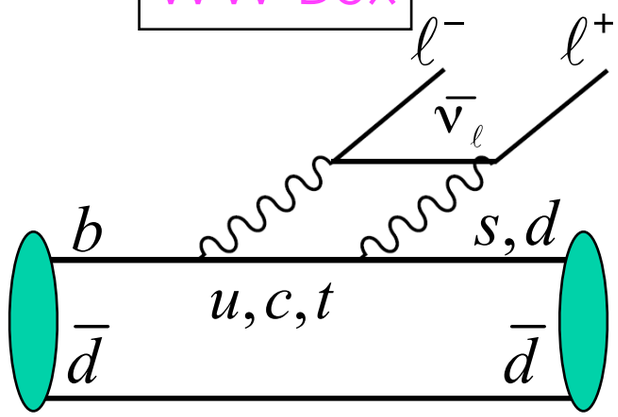
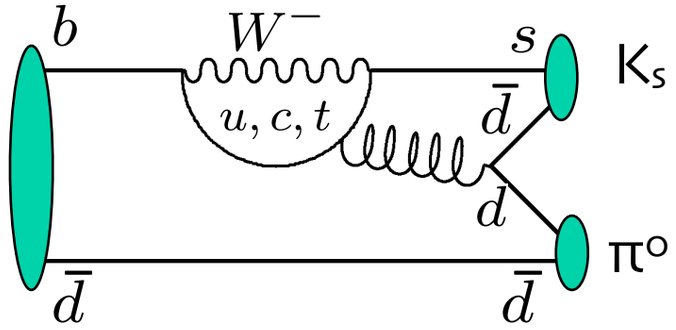
Electroweak



WW Box



Gluonic



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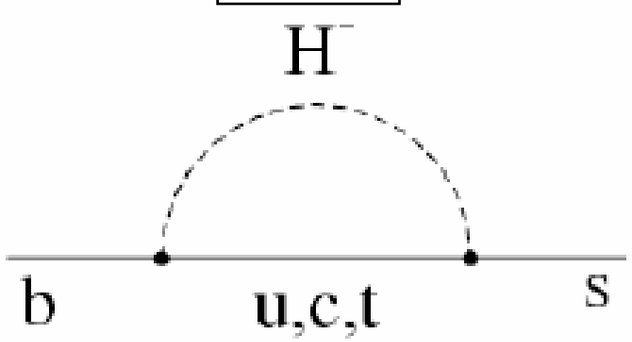
- SM: V-A (Left-handed)
- Sign-flip in C9C10: V+A

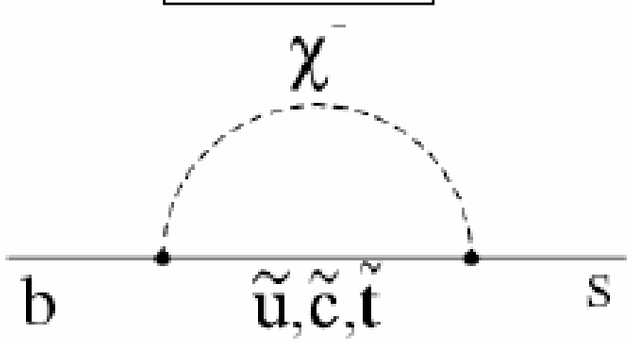
☞ Photon Polarization in B→K*(KsπO)γ

Higgs



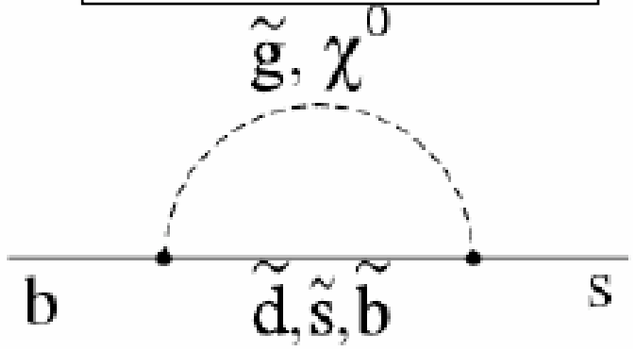
- New particles in loop may enhance $\mathcal{B}(b\to s\gamma)$

Chargino



- Affects mostly EW penguins (C7 & C9)

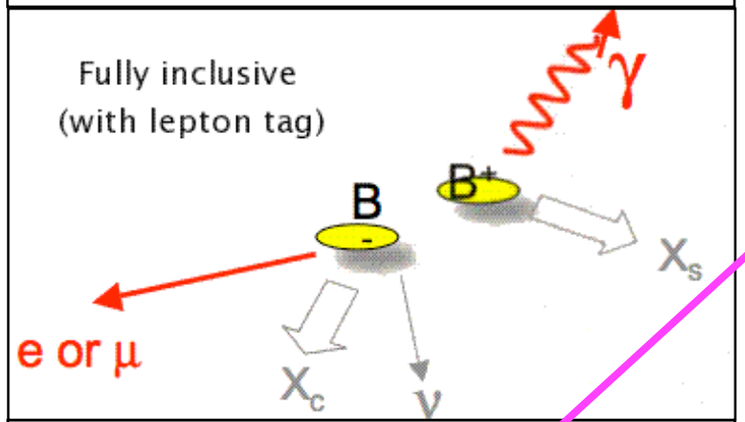
Gluino/Neutralino

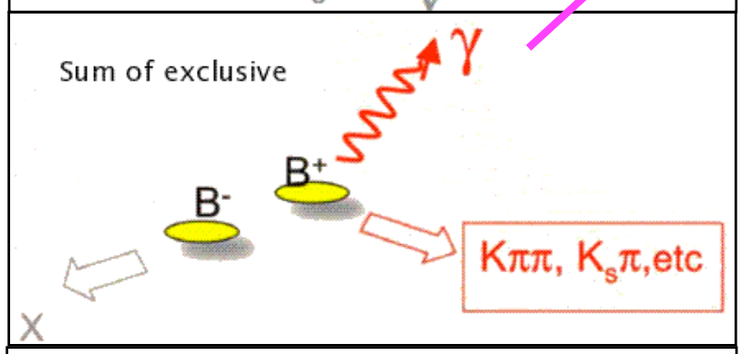


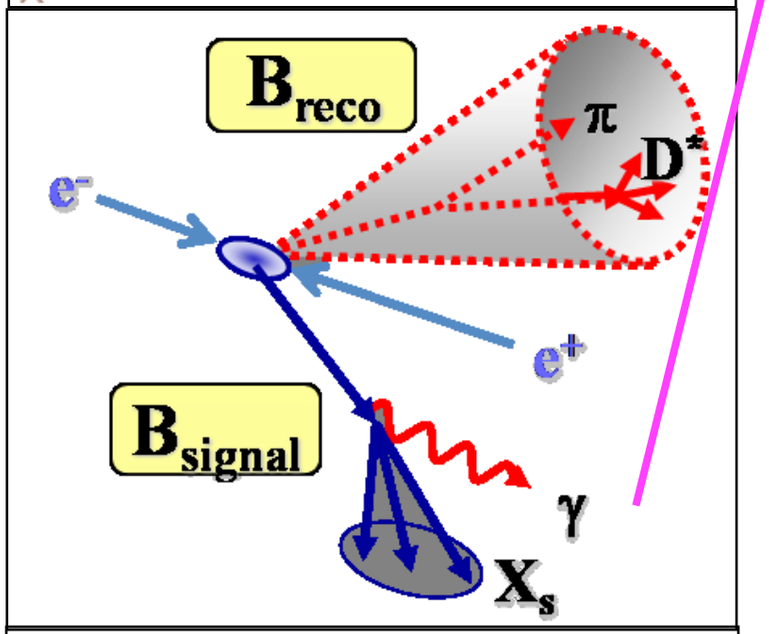
- EM penguins (C7) enhanced by $m_{\tilde{g}}/m_b$

MARCH OF THE PENGUINS AS TOLD BY $B \to X_s\gamma$

Theoretically cleanest

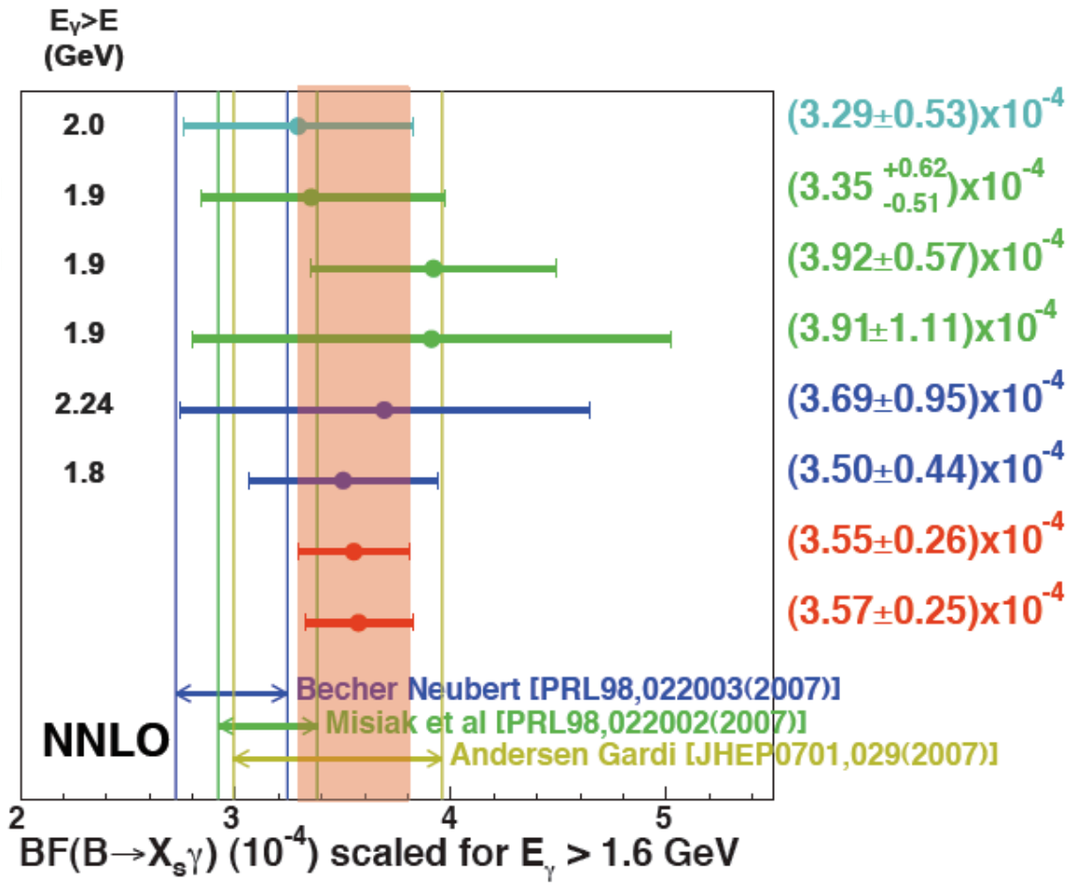


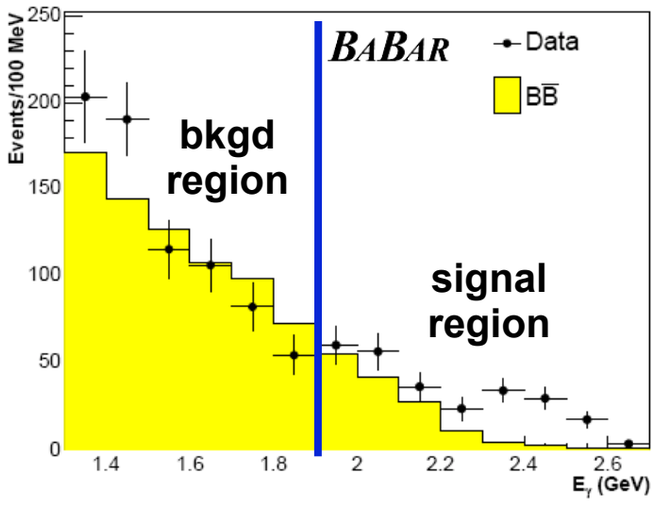




Experimentally cleanest

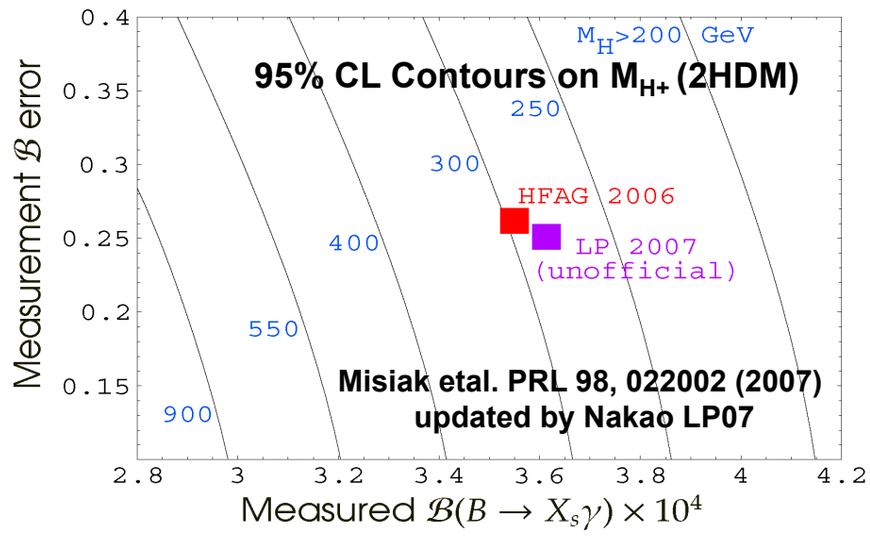
CLEO PRL87,251807(2001)	[9.1 fb^{-1}]	$(3.29\pm0.53)\times10^{-4}$
BaBar PRD72,052004(2005)	[81.5 fb^{-1}]	$(3.35\ ^{+0.62}_{-0.51})\times10^{-4}$
BaBar PRL98,022002(2007)	[81.5 fb^{-1}]	$(3.92\pm0.57)\times10^{-4}$
BaBar PRD-RC new	[210 fb^{-1}]	$(3.91\pm1.11)\times10^{-4}$
Belle PLB511,151(2001)	[5.8 fb^{-1}]	$(3.69\pm0.95)\times10^{-4}$
Belle PRL93,061803(2004)	[140 fb^{-1}]	$(3.50\pm0.44)\times10^{-4}$
HFAG 2006 hep-ex/0603003		$(3.55\pm0.26)\times10^{-4}$
(* simple minded average)		$(3.57\pm0.25)\times10^{-4}$





"New" BaBar Technique
E_γ extracted from fits to

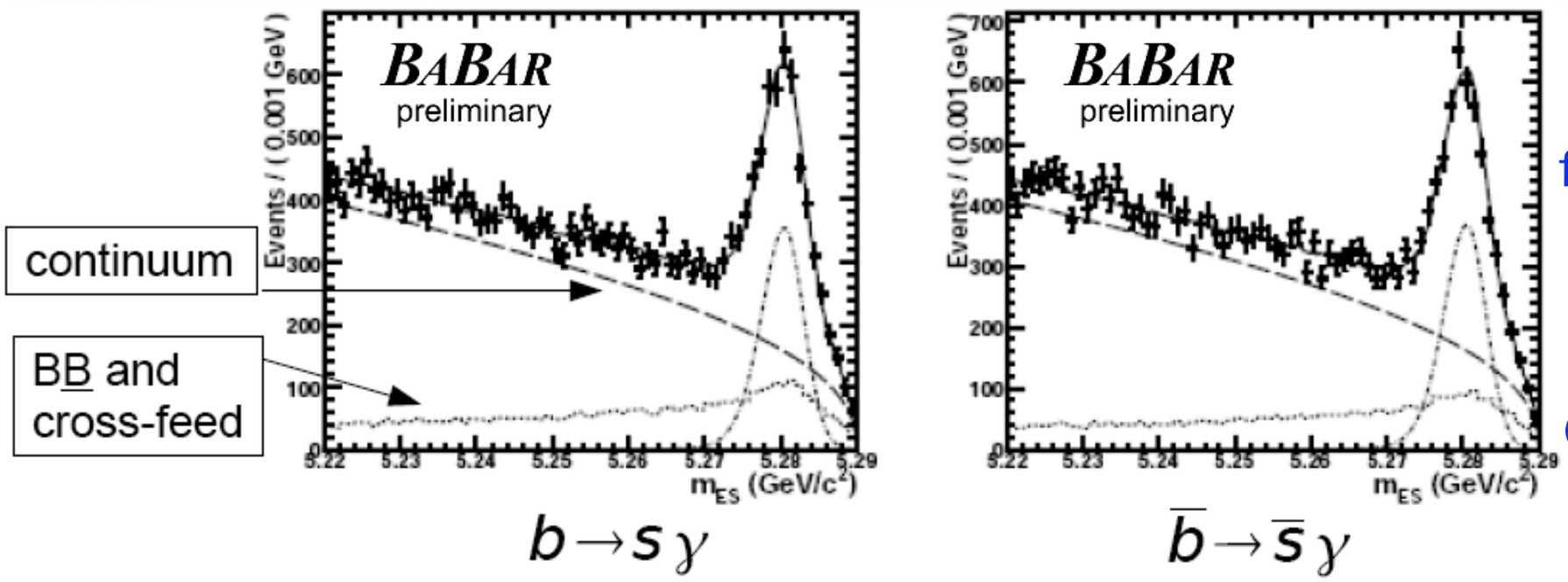
$$m_{ES} = \sqrt{(E^*_{beam})^2 - P^2_{Breco}}$$



M_{H+} > 295 GeV (95%CL)
M_{H+} ~ 650 GeV

AS TOLD BY

CP, Isospin Asymmetry in $B \to X_s \gamma$



$b \to s\gamma$ $\quad$ $\bar{b} \to \bar{s}\gamma$

Sum of 16 exclusive (self) flavor-tagging final states: 1 or 3 K, ≤3π, ≤2π° [eg, Kππ, $K_S\pi$, etc.] with Eg > 1.9 GeV, $0.6 < m(X_s) < 2.8$ GeV (Data sample: 383M $B\bar{B}$)

NEW

$$A_{CP} = \frac{\mathcal{B}(B \to X_{s,d}\gamma) - \mathcal{B}(\overline{B} \to X_{s,d}\gamma)}{\mathcal{B}(B \to X_{s,d}\gamma) + \mathcal{B}(\overline{B} \to X_{s,d}\gamma)} = -0.012 \pm 0.030(stat.) \pm 0.018(syst.)$$

(most precise measurement to date)

Previous Measurements:

Experiment/Method	A_{CP}
CLEO/Inclusive (10M $B\overline{B}$)	$-0.079 \pm 0.108 \pm 0.022$
Belle/Pseudoreconstruction (140M $B\overline{B}$)	$0.002 \pm 0.050 \pm 0.030$
BaBar/Inclusive (89M $B\overline{B}$)	$-0.110 \pm 0.115 \pm 0.017$
BaBar/Semi (89M $B\overline{B}$)	$0.025 \pm 0.050 \pm 0.015$

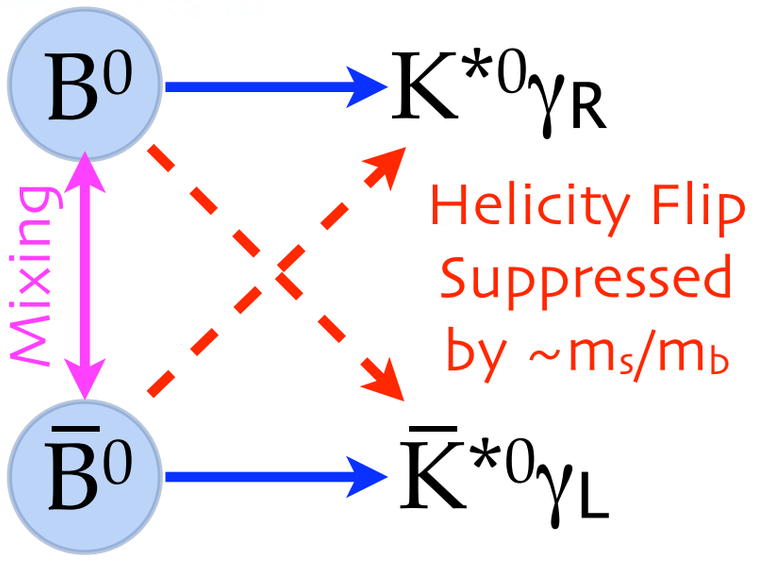
$$\Delta_{0-} = \frac{\Gamma(\overline{B}^0 \to X_{s,d}\gamma) - \Gamma(B^- \to X_{s,d}\gamma)}{\Gamma(\overline{B}^0 \to X_{s,d}\gamma) + \Gamma(B^- \to X_{s,d}\gamma)}$$

Recoil Analysis (PRD77, 051103 (R) 2008)

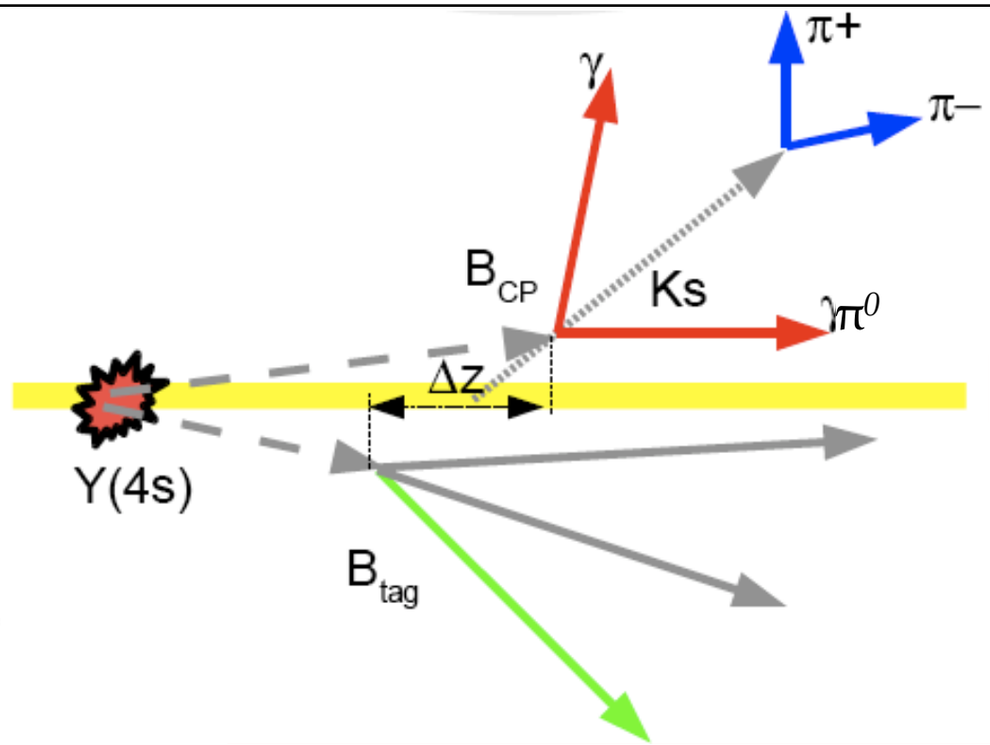
- Isospin: $\Delta_{0-} = -0.06 \pm 0.15 \pm 0.07$
- CP: $A_{CP} = +0.10 \pm 0.18 \pm 0.05$

Time Dependent CP Asymmetry in $B \to K^{*0}\gamma$

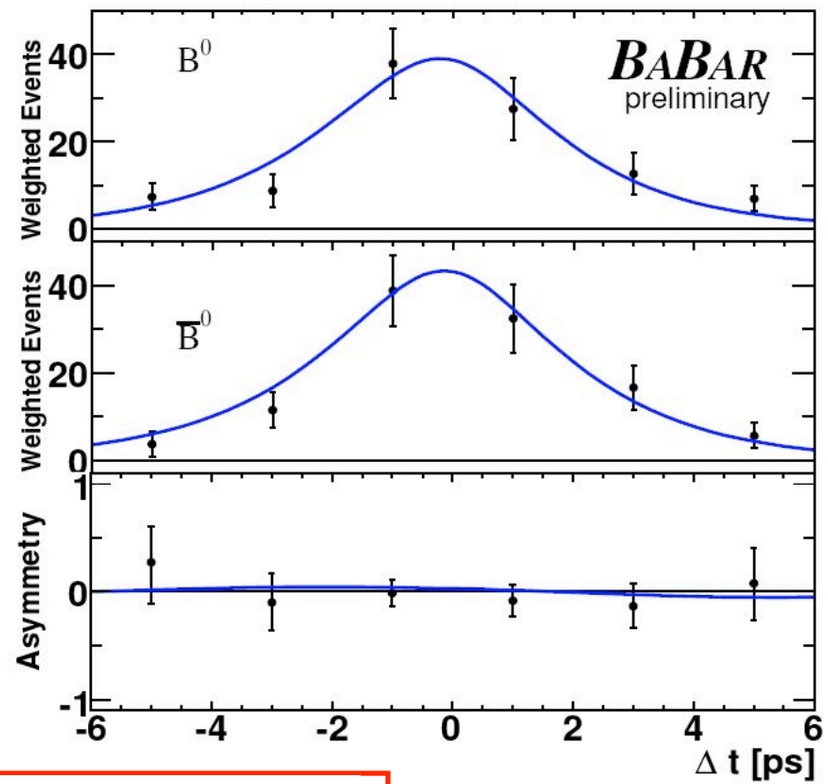
- The photon in $b \to s\,\gamma$ decays is polarized in SM (V-A)
- Final states almost flavor specific ⇒ Interference between direct and mixing-induced decay only by helicity flip allowed by non-zero quark masses
- Large mixing-induced CPV indication of New Physics



$$\mathcal{P}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \times [1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)]$$



$\Delta t \approx \Delta z / < \beta\gamma > c$



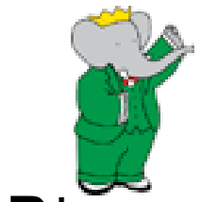
arXiv:0708.1614

431M $B\bar{B}$ pairs

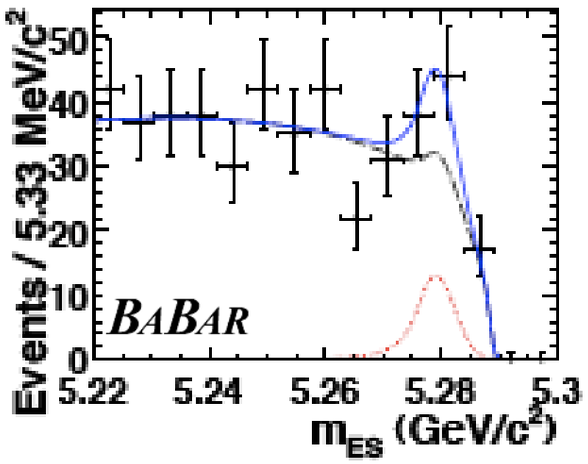
$$S_{K^*\gamma} \propto \frac{m_s}{m_b}\sin 2\beta = 0.07 \pm 0.03 \qquad C_{K^*\gamma} \approx 0.01 \quad \text{(SM)}$$
$$S_{K^*\gamma} = -0.08 \pm 0.31 \pm 0.05 \; C_{K^*\gamma} = -0.15 \pm 0.17 \pm 0.03$$

$B \to (\rho/\omega)\gamma$, Isospin Asymmetry

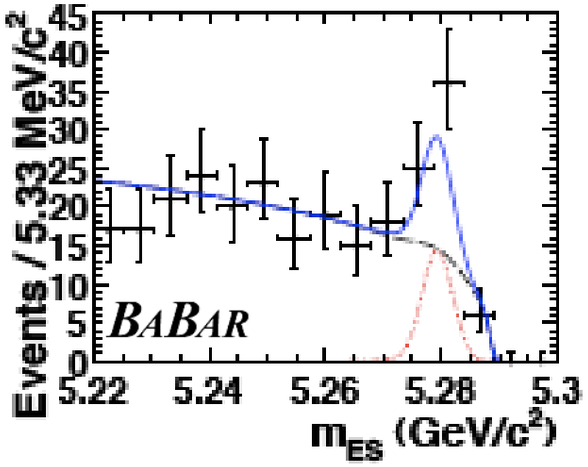
PRL 98, 151802 (2007) $\mathcal{L} = 316 fb^{-1}$



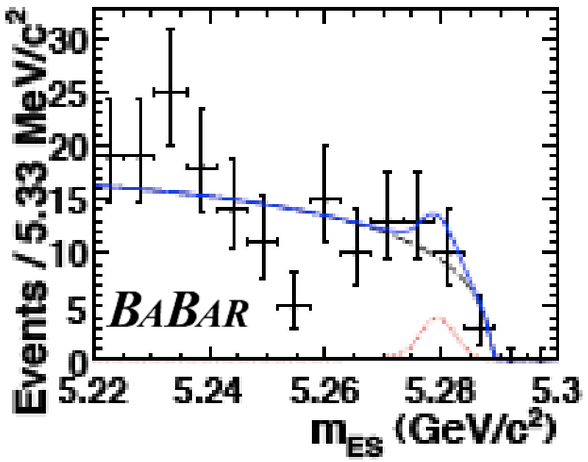
$B^+ \to \rho^+\gamma$

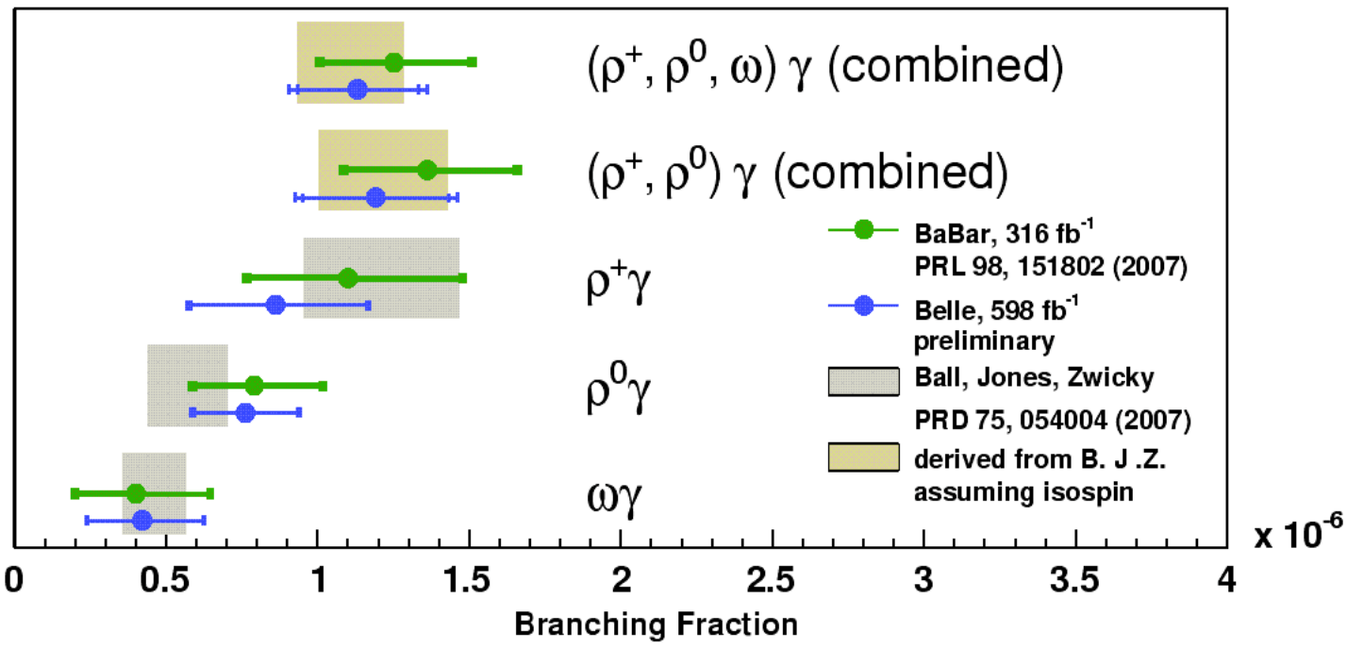


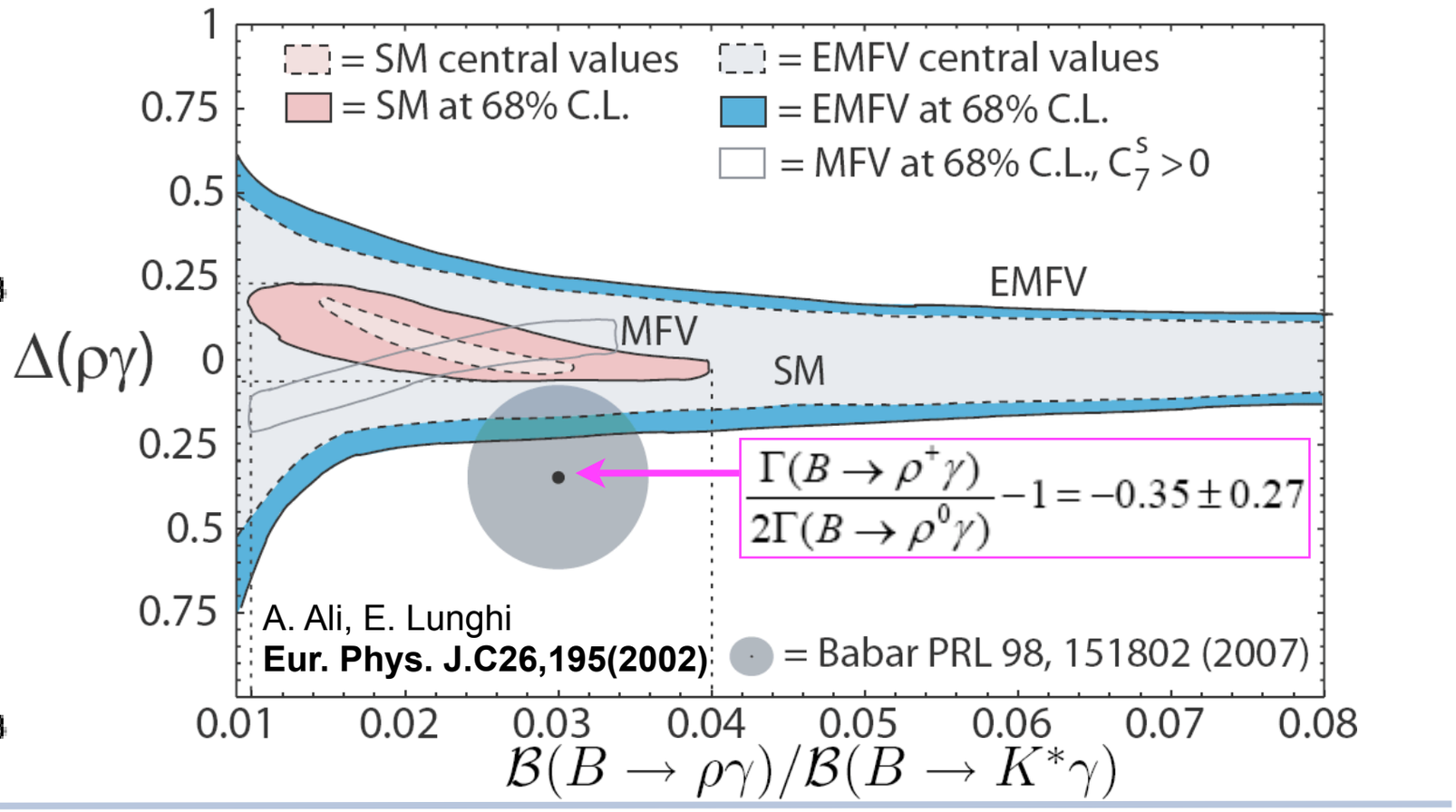
$B^0 \to \rho^0\gamma$



$B^0 \to \omega\gamma$





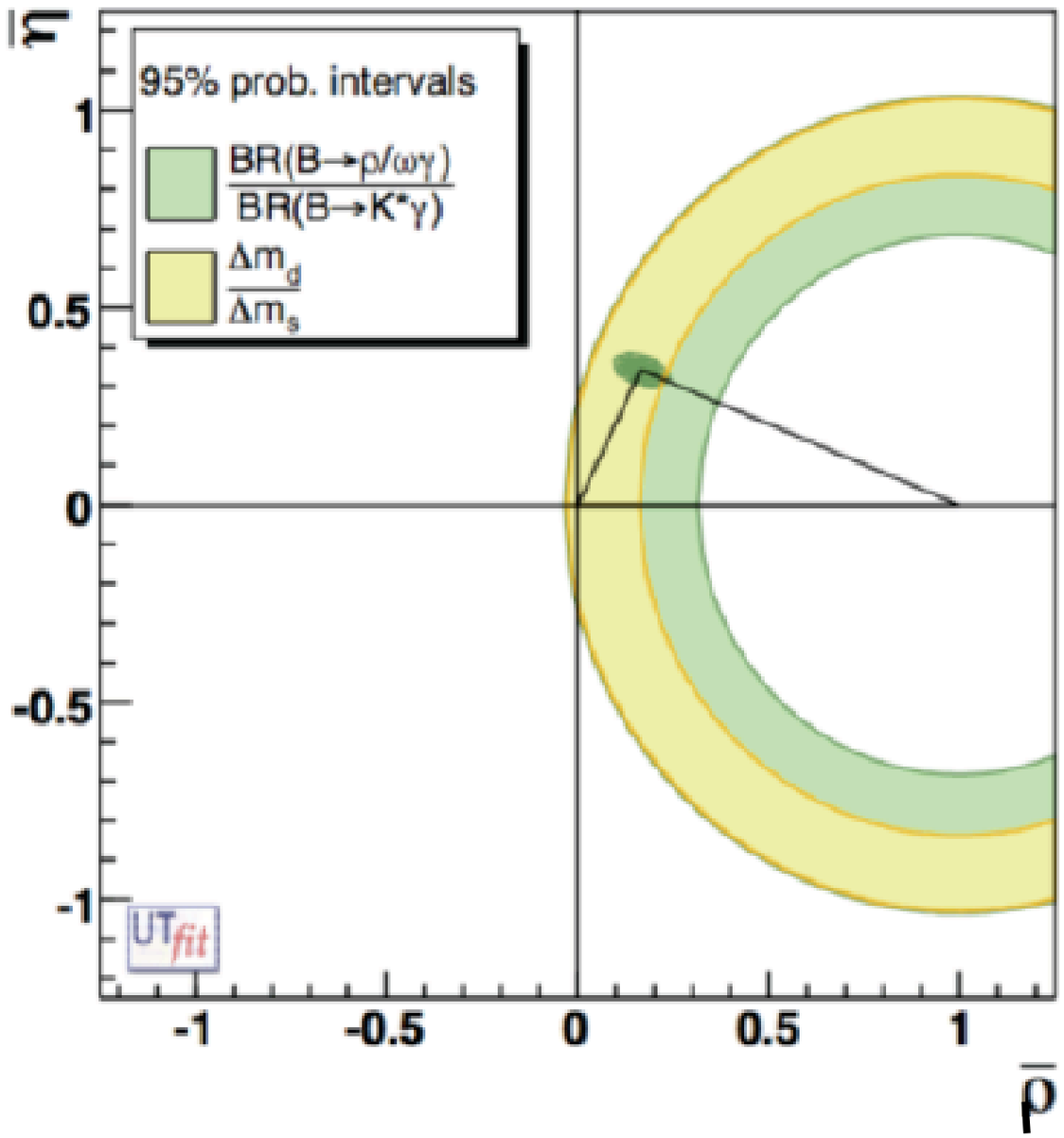


Constraints on The Unitarity Triangle

$$\frac{BF(B \to \rho\gamma)}{BF(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1 - m_\rho^2/m_B^2)^3}{(1 - m_{K^*}^2/m_B^2)^3}\zeta^2[1 + \Delta R]$$

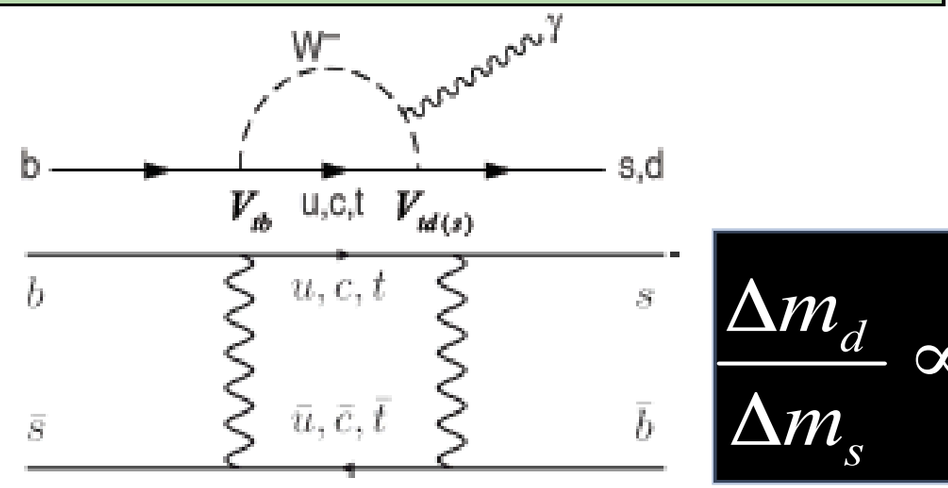
ζ allows for SU(3) breaking in the form factors

ΔR allows for isospin breaking (weak annihilation)



$|V_{td}/V_{ts}|$ from $B \to \rho/\omega\gamma$

$0.202 \pm 0.017_{(exp)} \pm 0.015_{(theo)}$



$$\frac{\Delta m_d}{\Delta m_s} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

$|V_{td}/V_{ts}|$ from B_s mixing

$0.2060 \pm 0.0007_{(exp)} \pm 0.008_{(theo)}$

PRL 97, 242003 (2006)

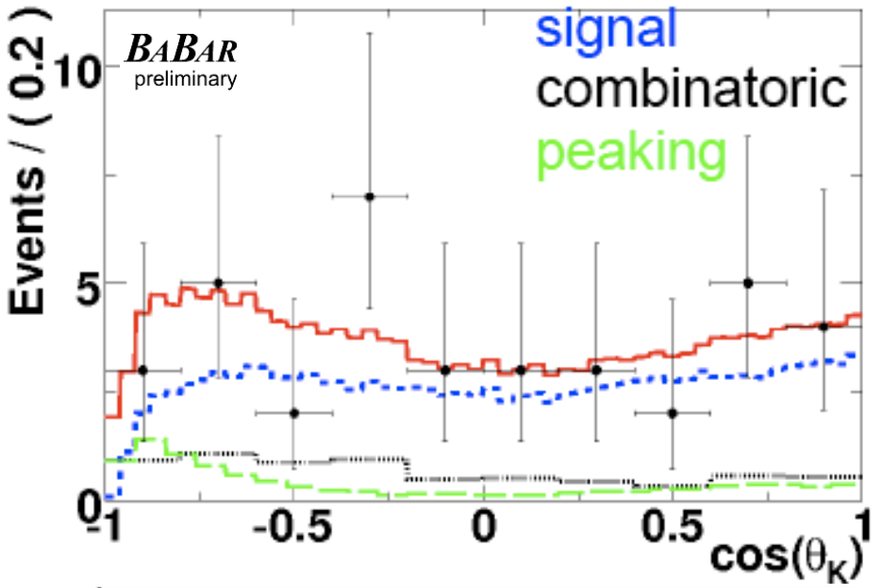
- Extract F_L from a fit to $\cos(\theta_k)$, extract A_{FB} from $\cos(\theta_l)$

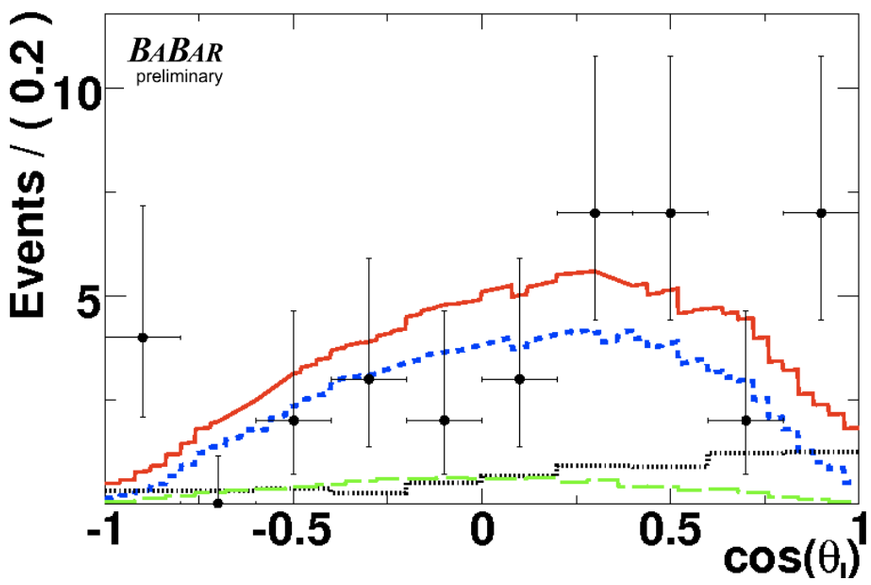
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos(\theta_K)} = \frac{3}{2}F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

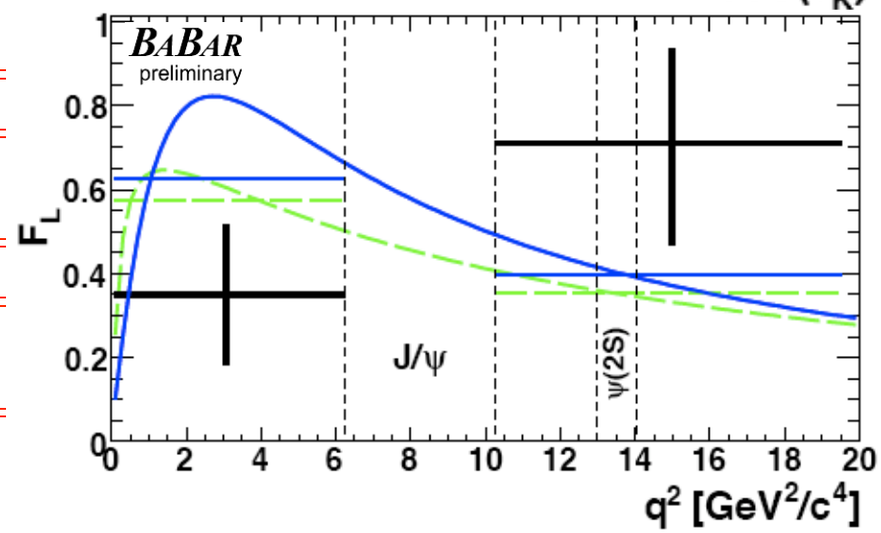
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos(\theta_l)} = \frac{3}{4}F_L(1-\cos^2\theta_l) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_l) + A_{FB}\cos\theta_l$$

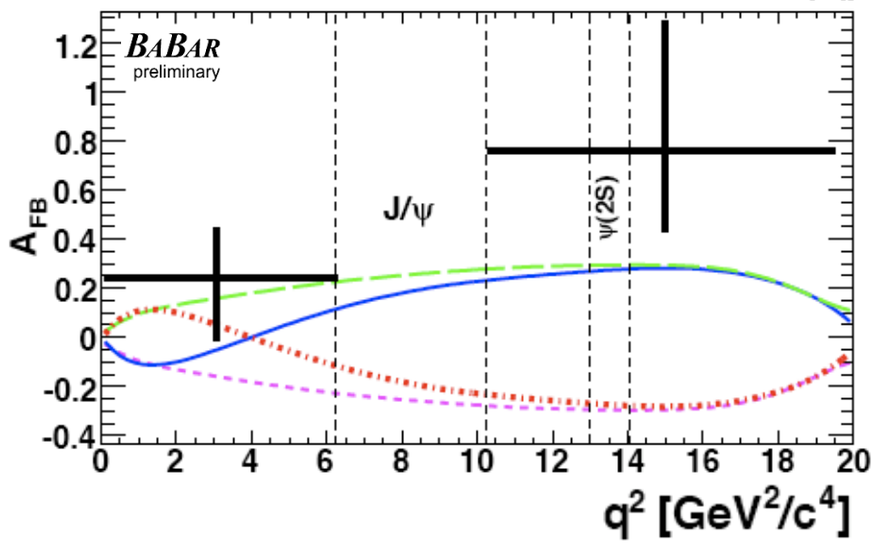
θ_k: between K and B in K* rest frame

θ_l: between l and B in l+l- rest frame









q^2	F_L
$< 6.25\ \text{GeV}^2/c^4$	$0.35 \pm 0.16 \pm 0.04$
$> 10.24\ \text{GeV}^2/c^4$	$0.71^{+0.20}_{-0.22} \pm 0.04$
q^2	A_{FB}
$< 6.25\ \text{GeV}^2/c^4$	$+0.24^{+0.18}_{-0.23} \pm 0.05$
$> 10.24\ \text{GeV}^2/c^4$	$+0.76^{+0.52}_{-0.32} \pm 0.07$

NEW

(Data sample: 384M $B\bar{B}$)

solid: Standard Model (SM)

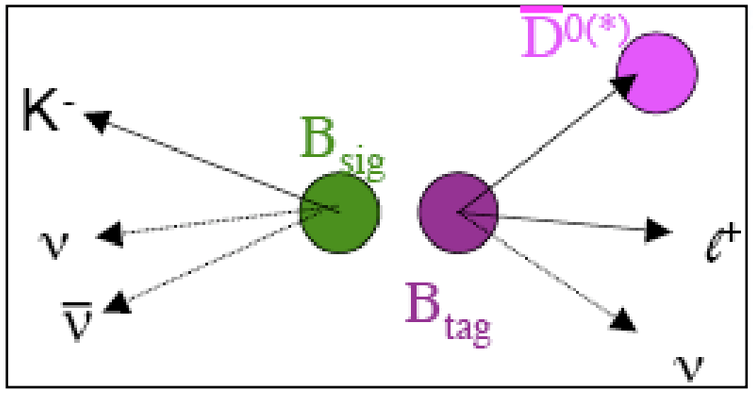
dash: $C_7 = -C_7^{SM}$

short dash: $C_9C_{10} = -C_9C_{10}^{SM}$ ✗

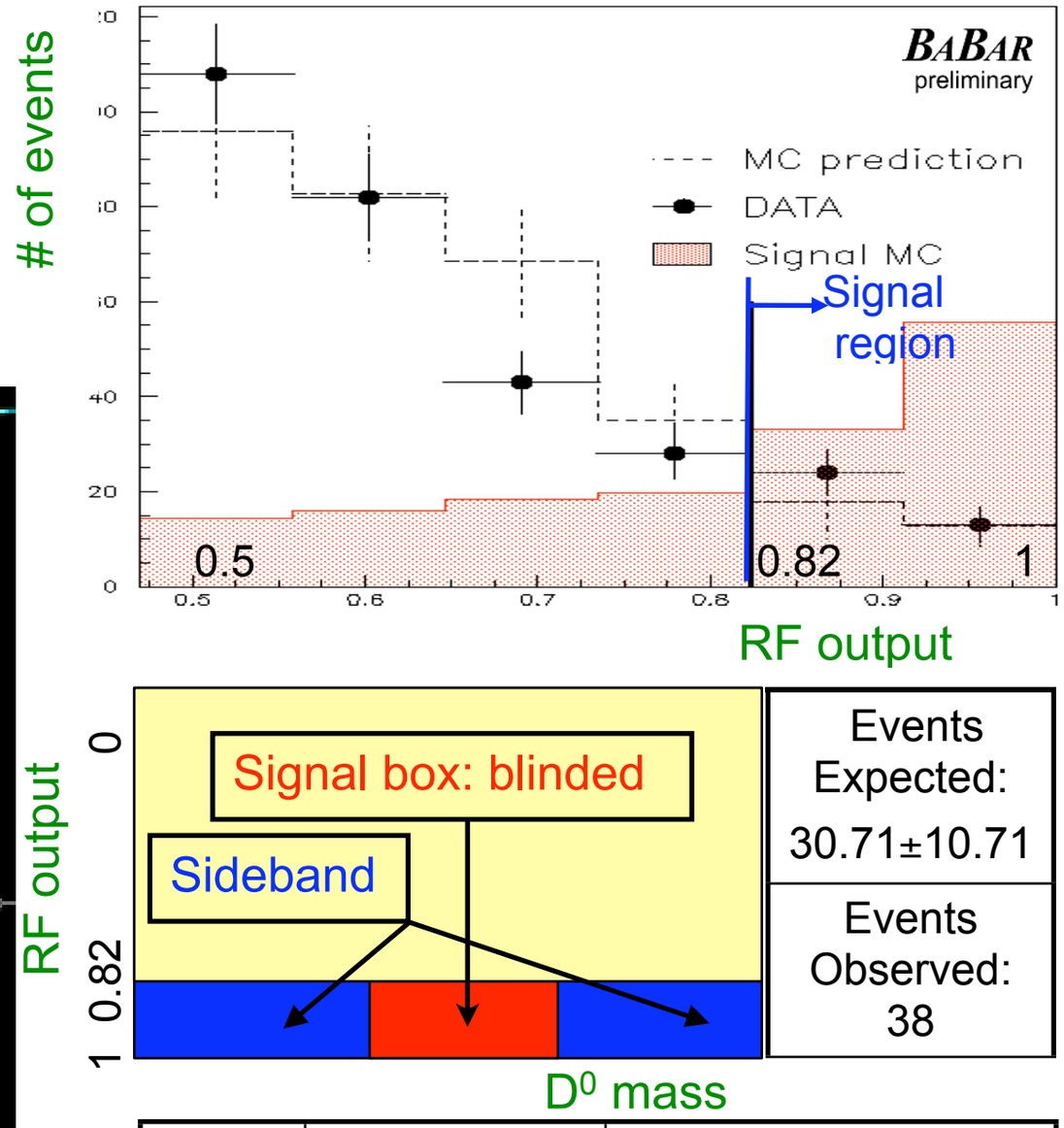
dot dash: $C_7C_{10} = -C_7C_{10}^{SM}$

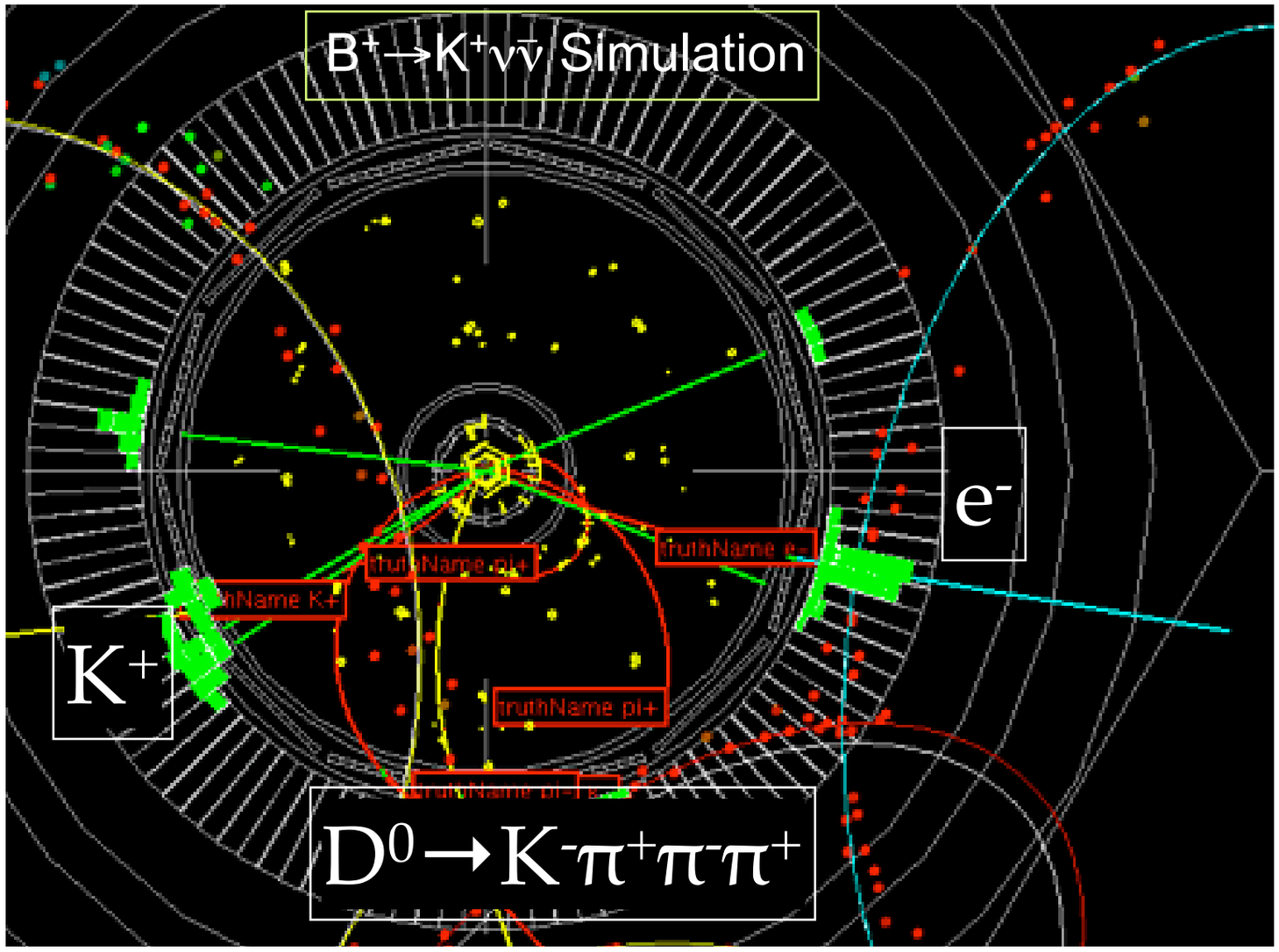
Search for $B \to K \nu\bar{\nu}$ (semi-leptonic tags)

NEW



22 variables in Random Forest method (except D^0 mass)

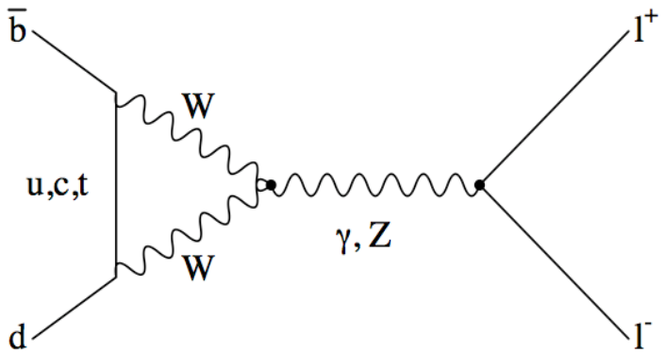




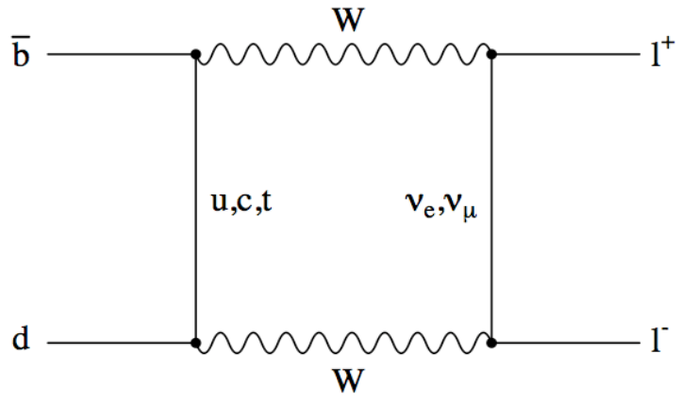
	# $B\bar{B}$ events	$B^+ \to K^+ \nu\bar{\nu}$
SM	-	3.8×10^{-6}
Belle	535 M	1.4×10^{-5} @ 90% CL
BaBar	351 M	4.2×10^{-5} @ 90% CL

$B \to ll,\ l\nu,\ D^{(*)}l\nu$

Electroweak Penguin

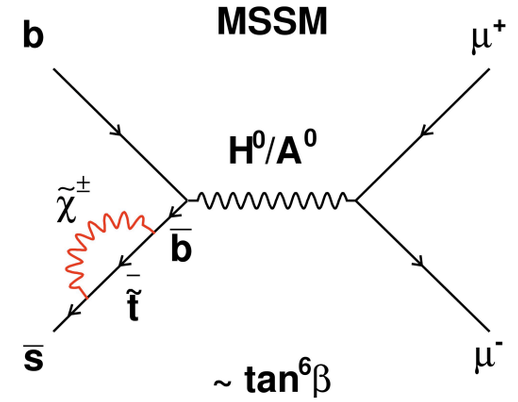


WW Box



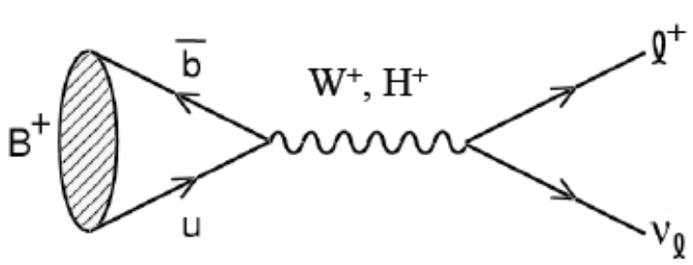
Annihilation Diagram

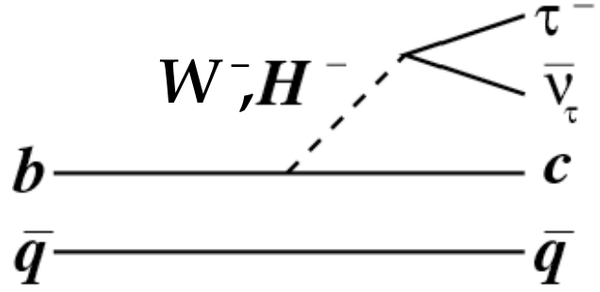
New Physics at leading order



Exchange Diagram

Charged Higgs at Tree Level :

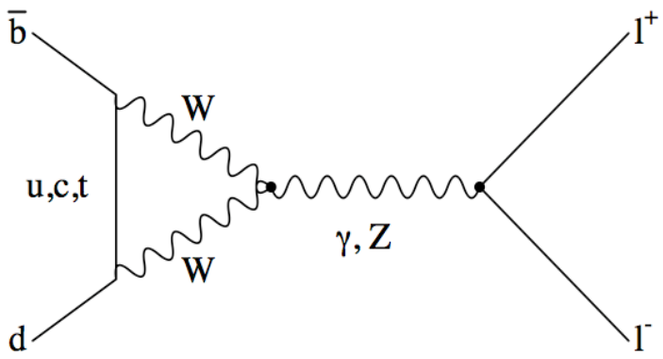




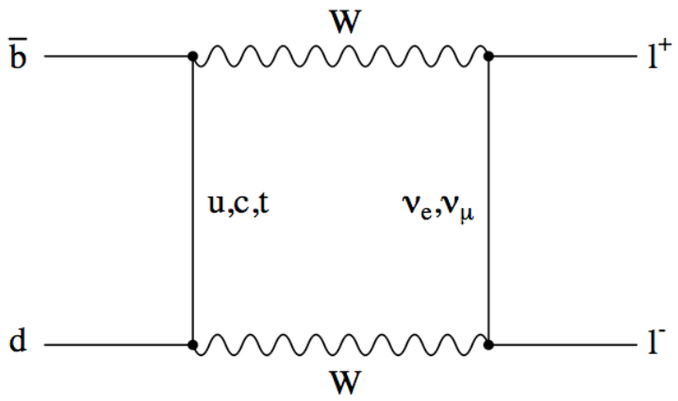
CONTINUES ...

$B \to ll,\ l\nu,\ D^{(*)}l\nu$

Electroweak Penguin

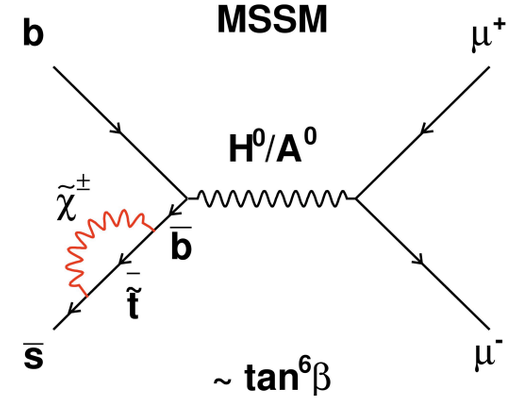


WW Box



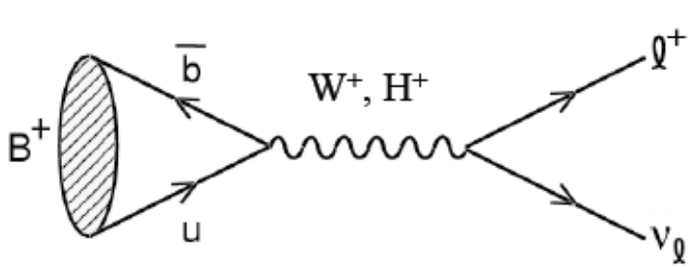
Annihilation Diagram

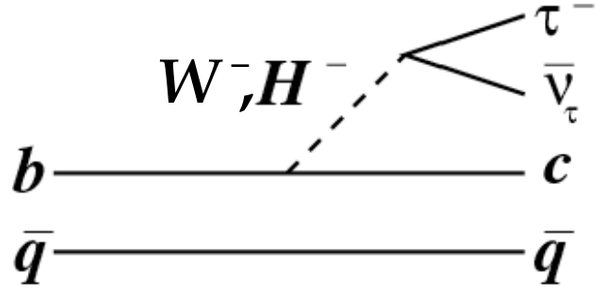
New Physics at leading order



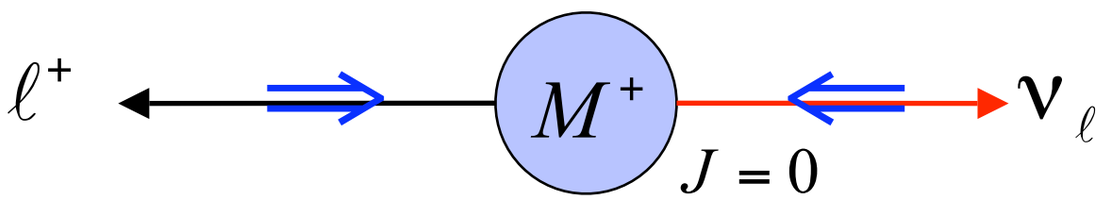
Exchange Diagram

Charged Higgs at Tree Level :

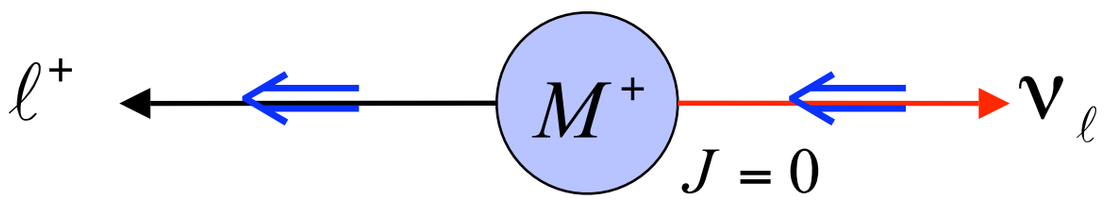




✓ Angular Momentum Conservation

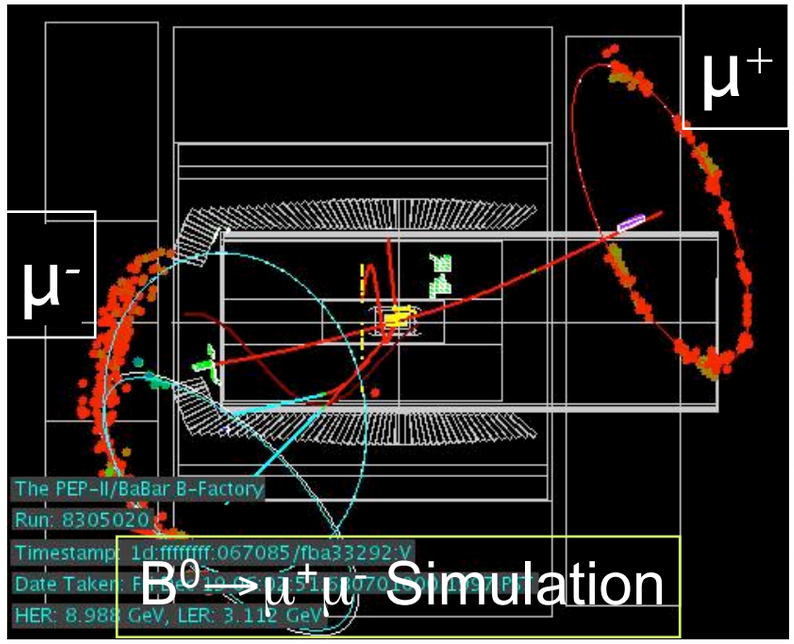


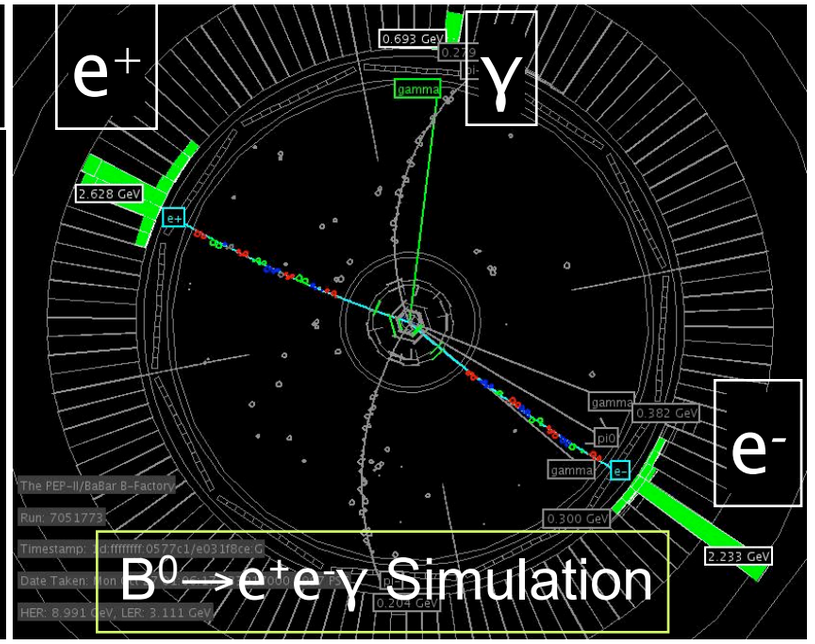
✗ Angular Momentum Conservation



- Helicity suppressed decays: $B \to \ell\ell, \ell\nu\ (\ell = e, \mu)$
- Helicity favored decays: $B \to \ell\ell\gamma, \tau\nu, D^{(*)}\tau\nu$

$B \to ll(\gamma)$, $l\nu$, $l\tau$

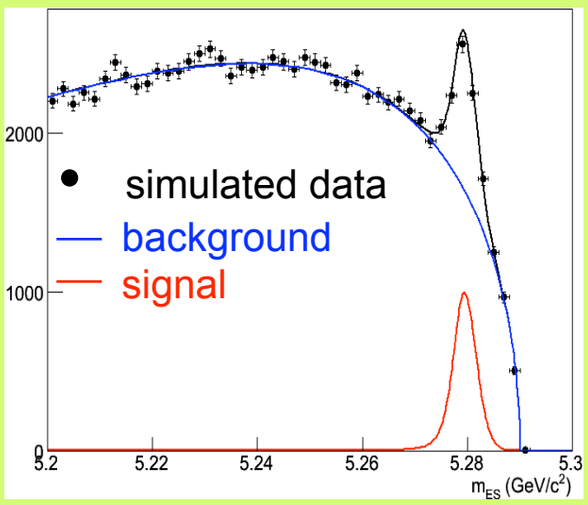




- Construct B^0 from oppositely charged tracks (& photon)
- Use Kinematic Variable (m_{ES}, ΔE)

$$m_{\mathrm{ES}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$$

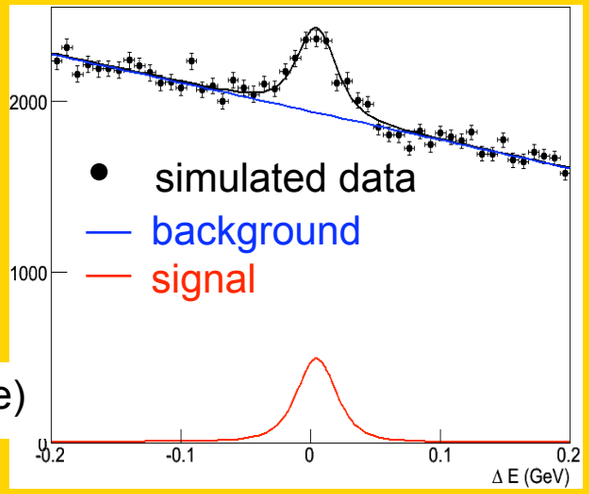
Peaks at B mass for signal



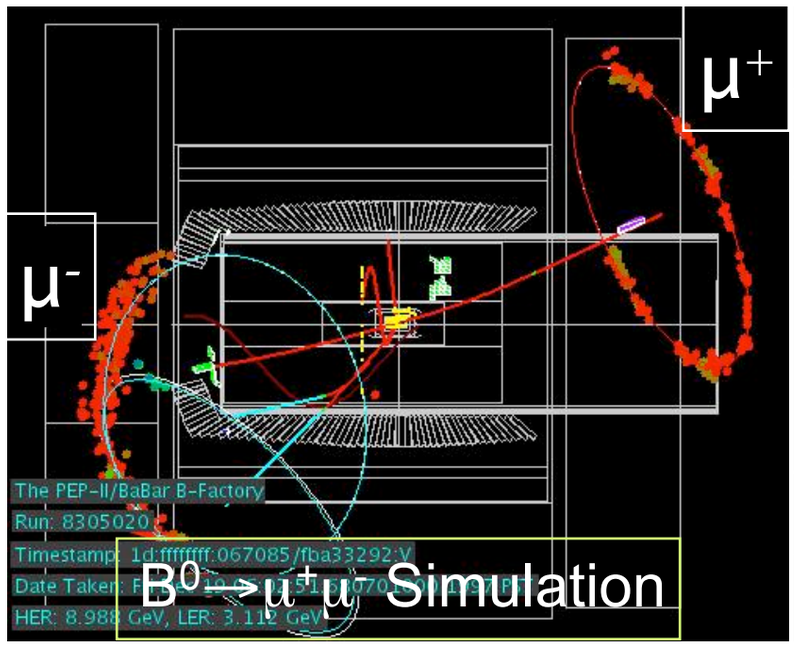
(*: CM frame)

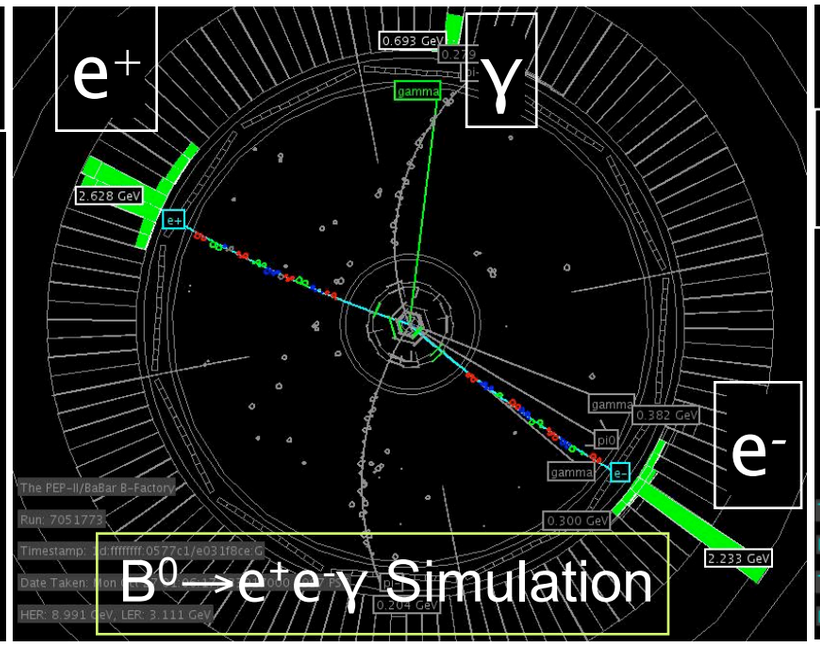
$$\Delta E^{*} = E^{*}_{B} - E^{*}_{\mathrm{beam}}$$

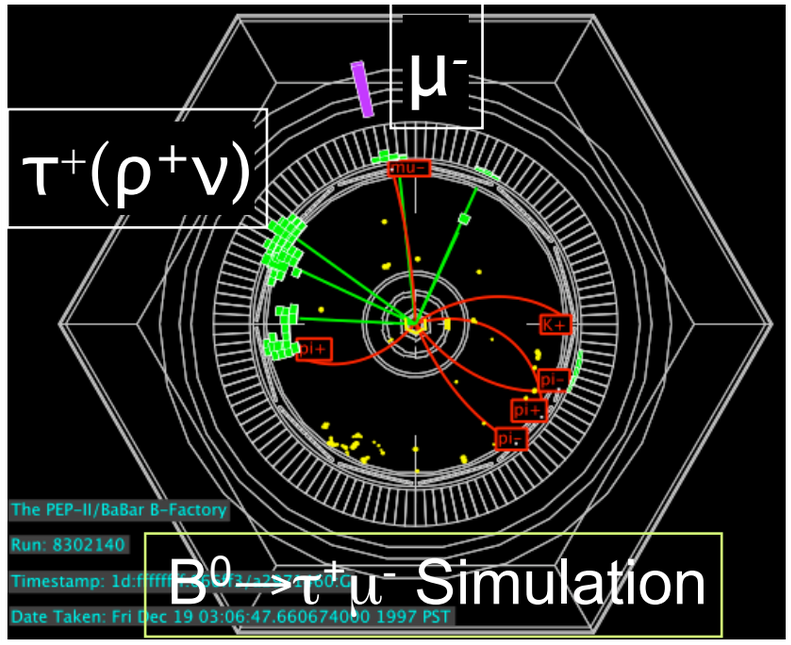
Peaks at zero for signal



$B \to ll(\gamma)$, $l\nu$, $l\tau$



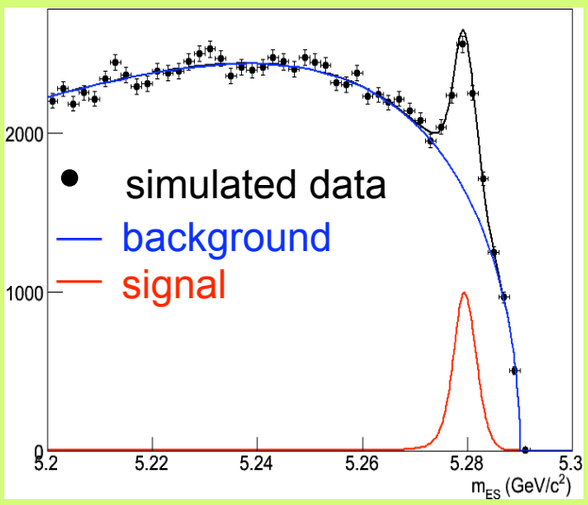




- Construct B^0 from oppositely charged tracks (& photon)
- Use Kinematic Variable (m_{ES}, ΔE)

$$m_{\mathrm{ES}} = \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_{B}}$$

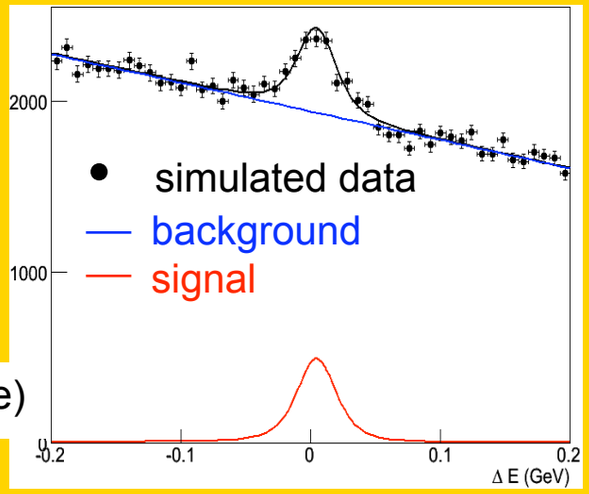
Peaks at B mass for signal



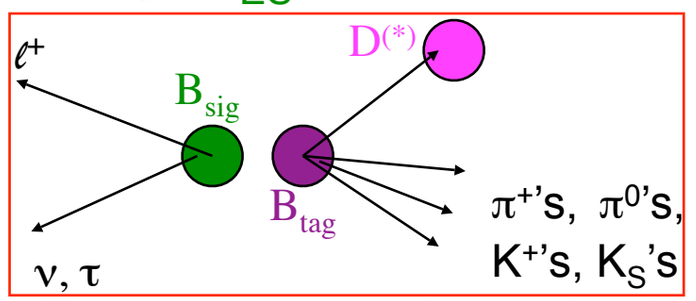
(*: CM frame)

$$\Delta E^{*} = E^{*}_{B} - E^{*}_{\mathrm{beam}}$$

Peaks at zero for signal



- Lepton Momentum is mono-energetic in B_{sig} rest frame
- Reconstruct hadronic decays on other side (B_{tag}: m_{ES}, ΔE)



- Extra energy deposited in Calorimeter $E_{Extra} \approx 0$

$B \to ll(\gamma)$, $l\nu$, $l\tau$

Mode (SM Expectation)	# $B\bar{B}$ events	Upper Limit @ 90% CL	Previous Best Limit BaBar, CDF, Belle, CLEO
$B^0 \to e^+e^-$ (2×10^{-15})	384 M	11.3×10^{-8}	6.1×10^{-8}
$B^0 \to \mu^+\mu^-$ (9×10^{-11})		5.2×10^{-8}	1.8×10^{-8}
$B^0 \to e^+\mu^-$ LFV		9.2×10^{-8}	18×10^{-8}
$B^0 \to e^+e^-\gamma$ ($2\text{–}8 \times 10^{-10}$)	320 M	1.2×10^{-7}	None
$B^0 \to \mu^+\mu^-\gamma$ ($1\text{–}6 \times 10^{-10}$)		1.6×10^{-7}	None
$B^+ \to e^+\nu$ (1.2×10^{-11})	378 M	5.2×10^{-6}	9.8×10^{-7}
$B^+ \to \mu^+\nu$ (5.2×10^{-7})		5.6×10^{-6}	1.7×10^{-6}
$B^0 \to e^+\tau^-$ LFV		2.8×10^{-5}	1.4×10^{-4}
$B^0 \to \mu^+\tau^-$ LFV		2.2×10^{-5}	3.8×10^{-5}

PRD 77, 032007 (2008)

PRD 77, 011104(R) (2008)

arXiv: 0801.0697 submitted to PRD-RC

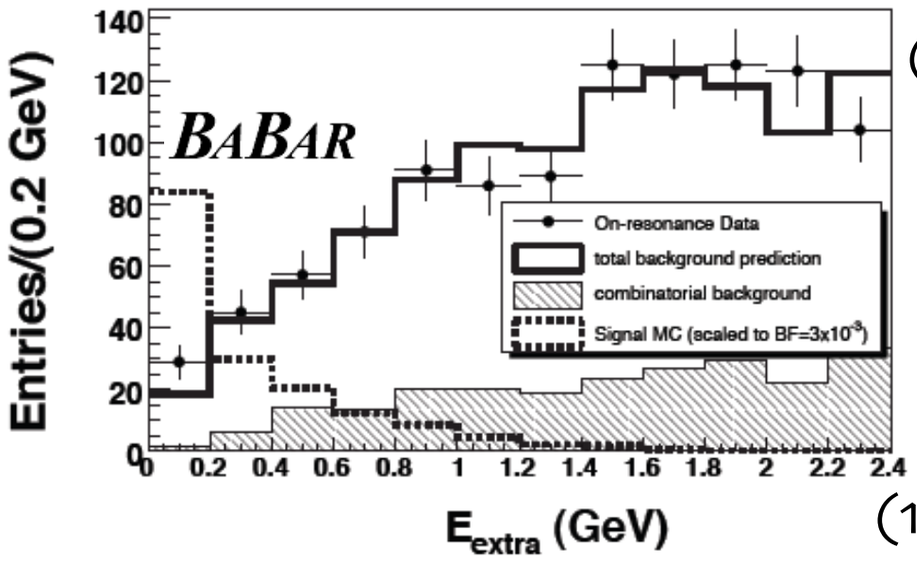
Lepton Flavor Violation

Motivated by neutrino oscillations, a model-independent framework for flavor changing neutral current has been proposed by Black, Han, He and Sher, PRD 66, 053002 (2002).

$B^0 \to e/\mu\tau$ limits moves lower limit from 8.2 TeV to 11.6 TeV for Λ_{bd} operator

$B^+ \to \tau^+\nu$

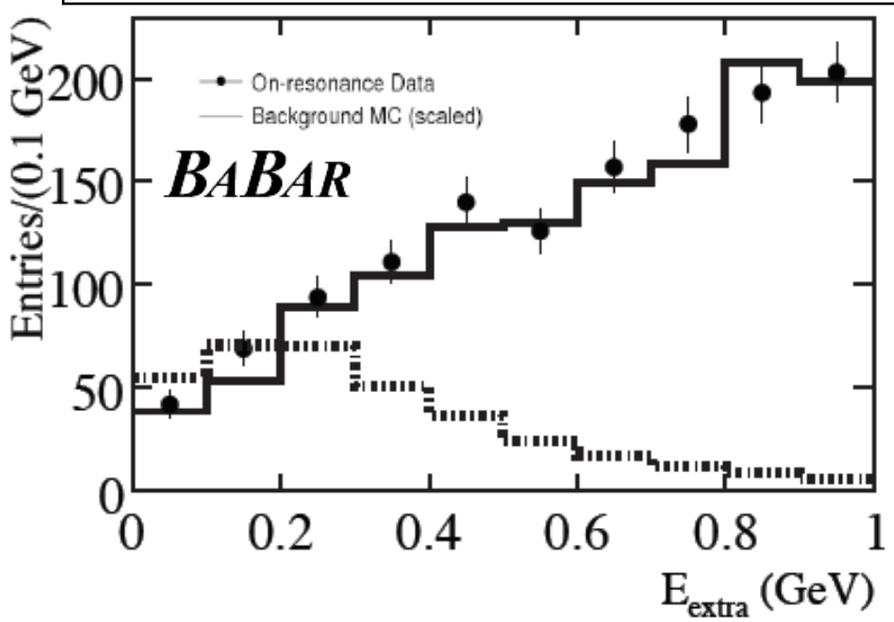
Hadronic Tags in 383M $B\bar{B}$
PRD77, 011107(R) (2008)



(2.2σ)

(1.3σ)

Semi-Leptonic Tags in 383M $B\bar{B}$
PRD 76, 052002 (2007)



$$\mathcal{B}(B^+ \to l^+\nu_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1-\frac{m_l^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

f_B: Lattice QCD ~ 10% error $|V_{ub}|$: b → u$l\nu$ ~ 8% error

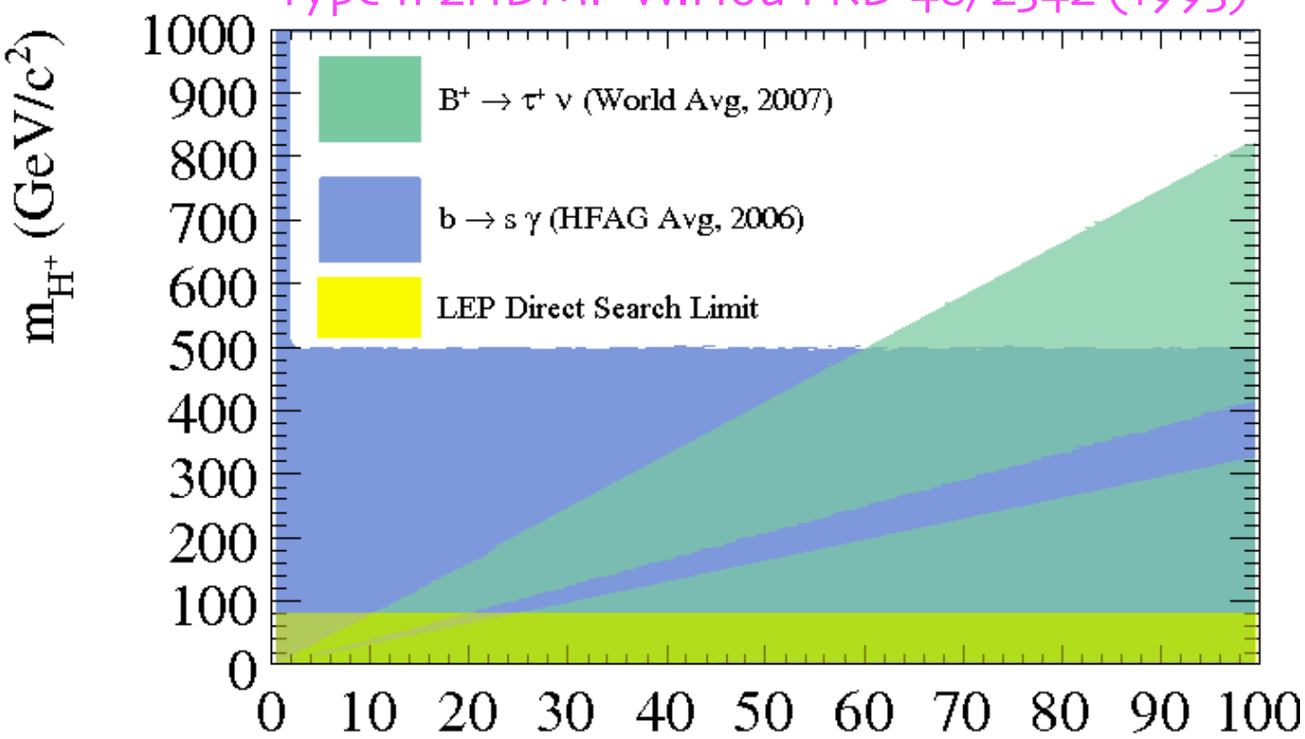
SM prediction: $\mathcal{B} = (1.6 \pm 0.4)\times 10^{-4}$

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.39 \pm .37)\times 10^{-4} (2.6\sigma)$$

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = 1.79\,^{+0.56\ +0.39}_{-0.49\ -0.46}\times 10^{-4} \quad (3.5\sigma)$$

$$BF(B^+ \to \tau^+\nu_\tau) = BF_{SM}\times\left(1-\left(\frac{m_B^2}{m_{H^\pm}^2}\right)\tan^2\beta\right)$$

Type II 2HDM: W.Hou PRD 48, 2342 (1993)



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

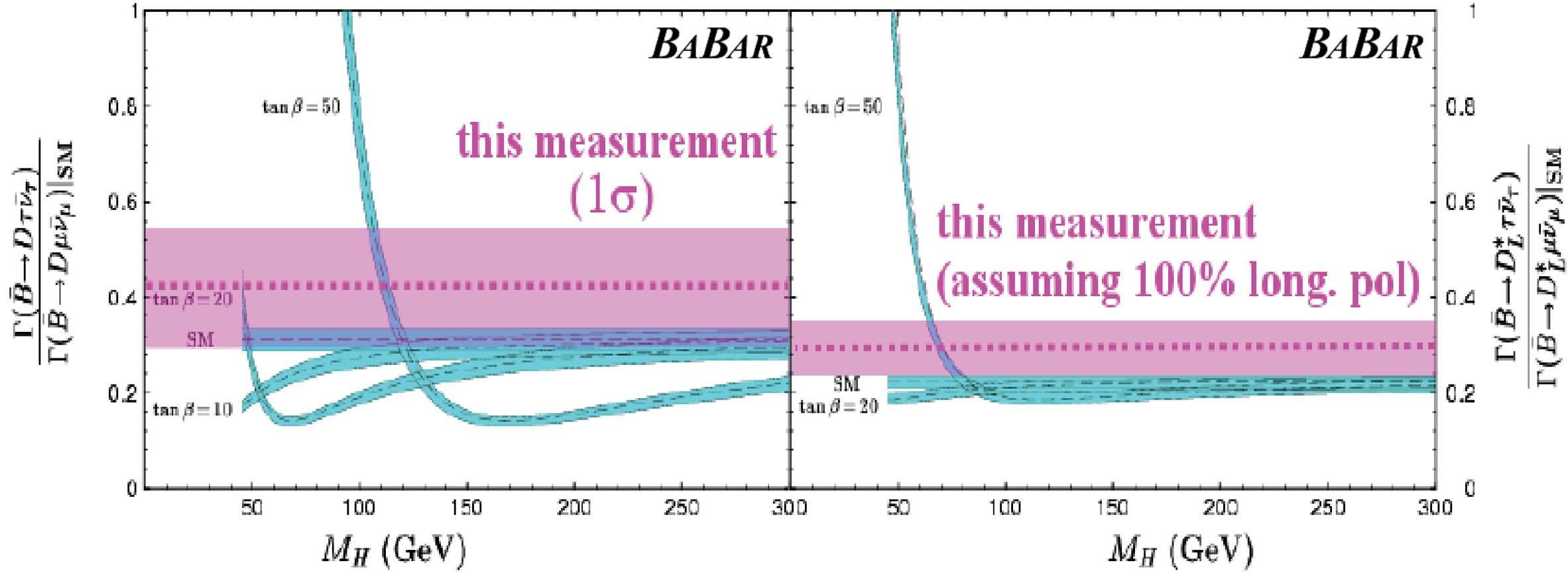
Mode		$\mathcal{B}$ [%]
B^-	$\to D^0\tau^-\overline{\nu}_\tau$	$0.67 \pm 0.37 \pm 0.11 \pm 0.07$
B^-	$\to D^{*0}\tau^-\overline{\nu}_\tau$	$2.25 \pm 0.48 \pm 0.22 \pm 0.17$
$\overline{B}^0$	$\to D^+\tau^-\overline{\nu}_\tau$	$1.04 \pm 0.35 \pm 0.15 \pm 0.10$
$\overline{B}^0$	$\to D^{*+}\tau^-\overline{\nu}_\tau$	$1.11 \pm 0.51 \pm 0.04 \pm 0.04$
B	$\to D\tau^-\overline{\nu}_\tau$	$0.86 \pm 0.24 \pm 0.11 \pm 0.06$
B	$\to D^*\tau^-\overline{\nu}_\tau$	$1.62 \pm 0.31 \pm 0.10 \pm 0.05$

*3.5*σ
*6.2*σ

Confirmation of Belle observation in D^{*+}, first observation of D^{*0} and first evidence for the D modes

$\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$

Belle 535M $B\bar{B}$, PRL 99 191807 (2007)
BaBar 232M $B\bar{B}$, PRL 100 021801 (2008)

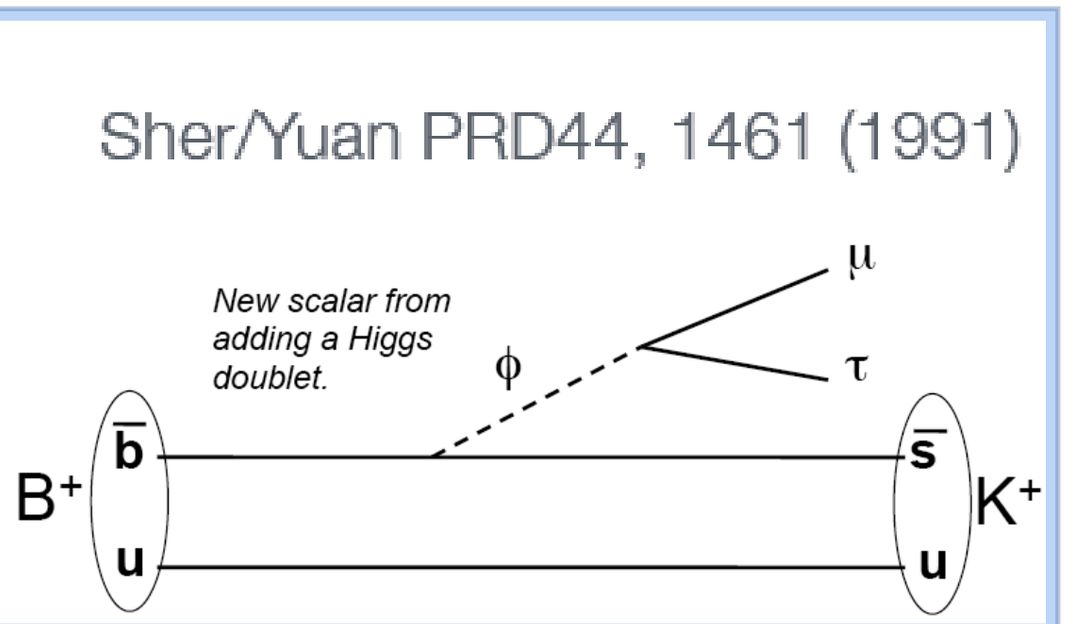


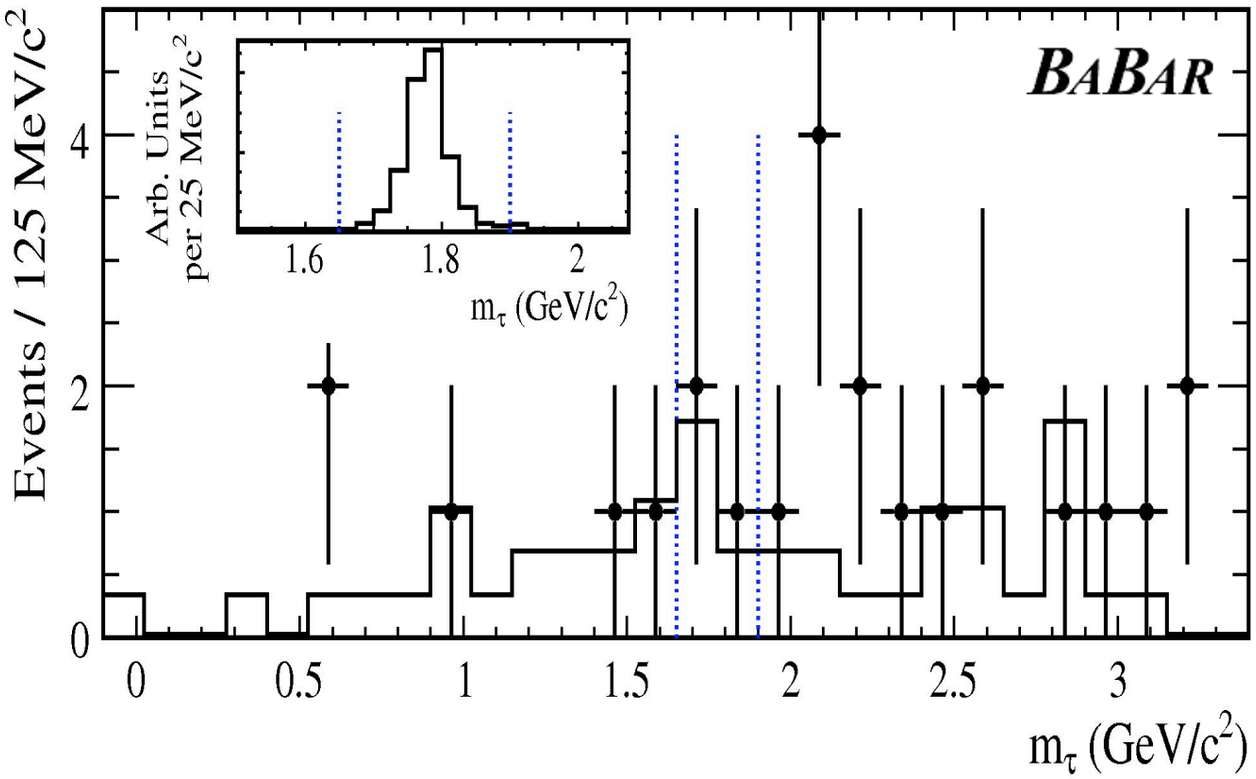
$B^+ \to K^+\tau\mu$

- Violates not one but *two* rules of the standard model!
  - Flavor changing neutral current (FCNC) [b→s].
  - Lepton flavor violation (note *no neutrinos* from B decay).

➢ ***Fully-reconstruct $B^+ \to K^+\tau\mu$ in recoil of other B***

Sher/Yuan PRD44, 1461 (1991)





PRL 99, 201801 (2007)
Data Sample : 383M $B\bar{B}$

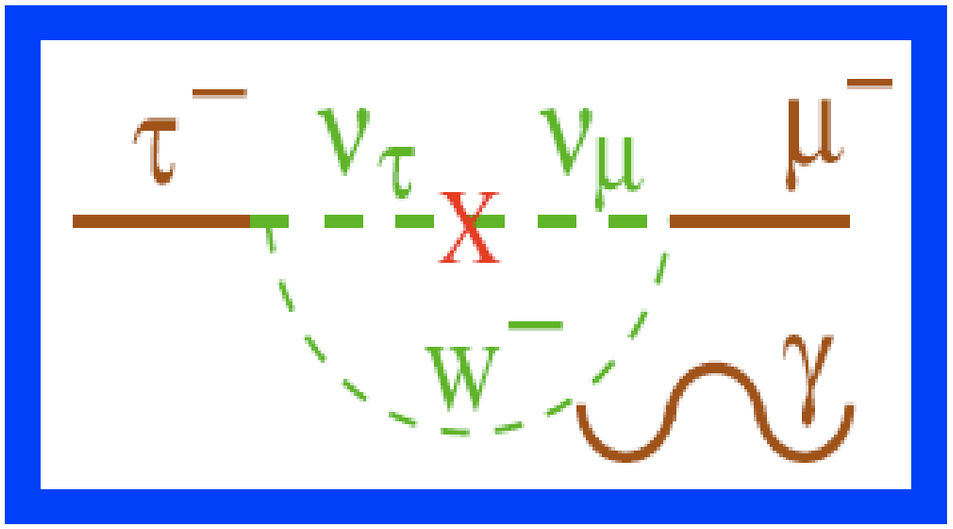
$$Br(B^+ \to K^+\tau^\pm\mu^\mp) < 7.7\times10^{-5} \text{ at } 90\% \text{ C.L.}$$

moves lower limit from 2.6 TeV to 13 TeV for Λ_{bs} operator

Lepton Flavor Violation in τ decays

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν's have finite mass
  $\Rightarrow$ Lepton Flavor is violated in Nature: but by how much?

- SM extended to include finite ν mass and mixing predicts LFV



$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma)$ [Lee-Shrock, Phys. Rev. D 16, 1444 (1977)]

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

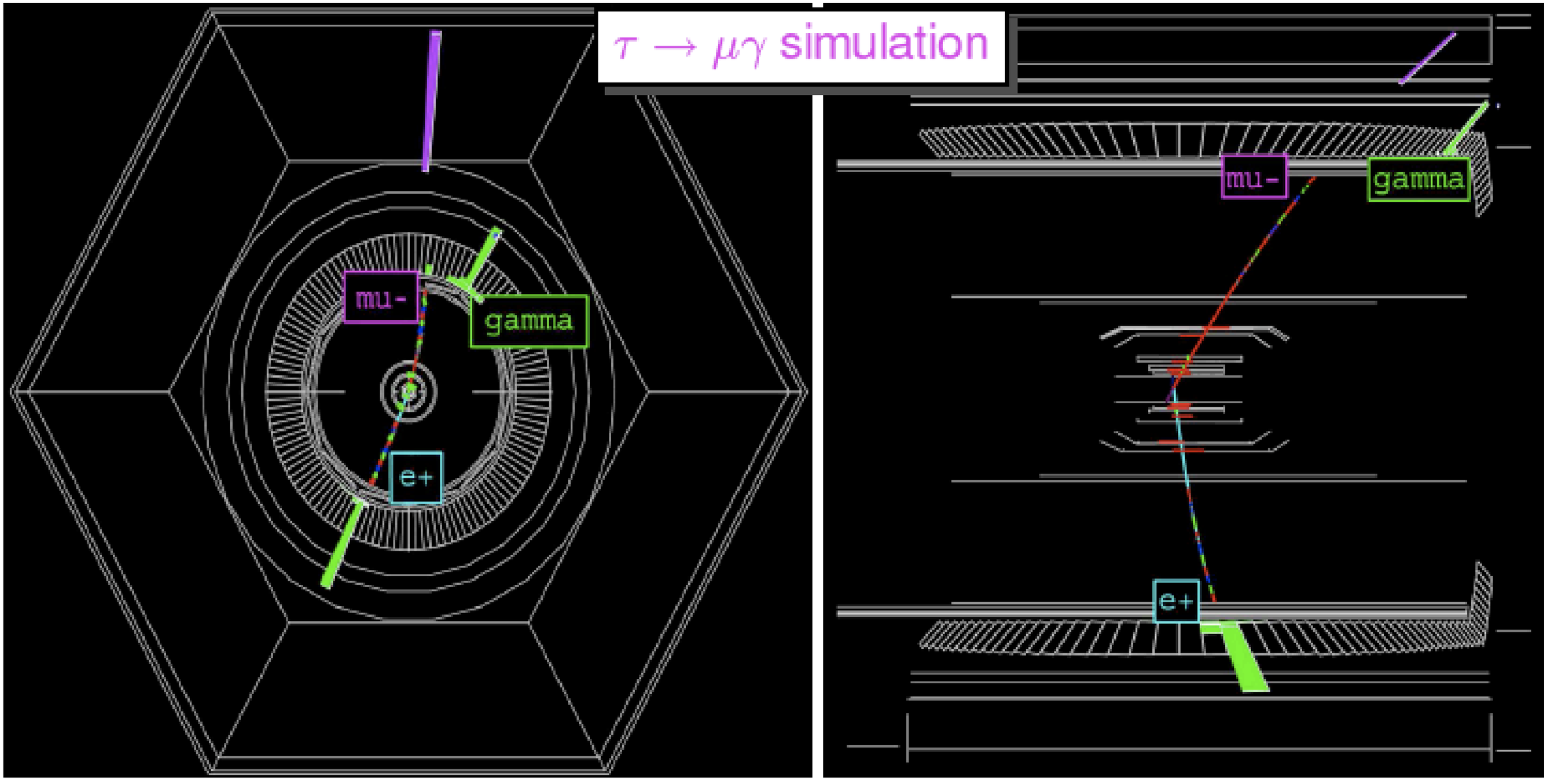
With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

... many orders below experimental sensitivity!

If we saw ...

- (Energy, Mass)$_{\tau-\mathrm{daughters}} \sim (\frac{\sqrt{s}}{2}, m_\tau)$ (upto resolution & radiation)



...unambiguous signature of new physics!

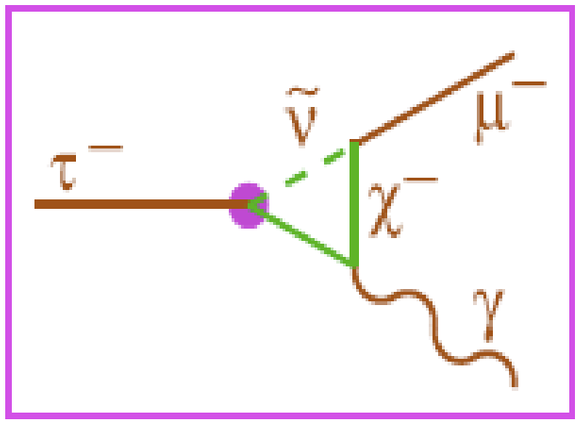
Lepton Flavor Violation in τ decays

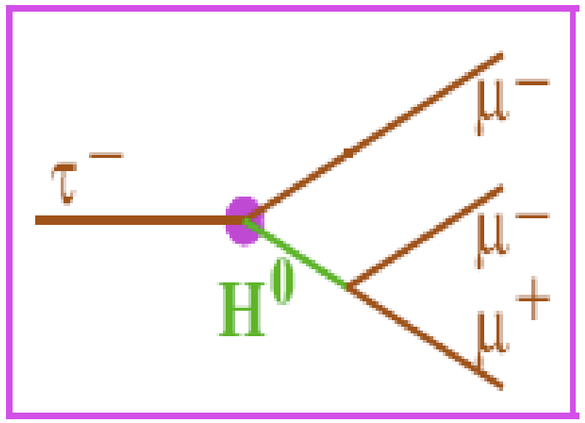
- Some models predict LFV upto existing experimental bounds

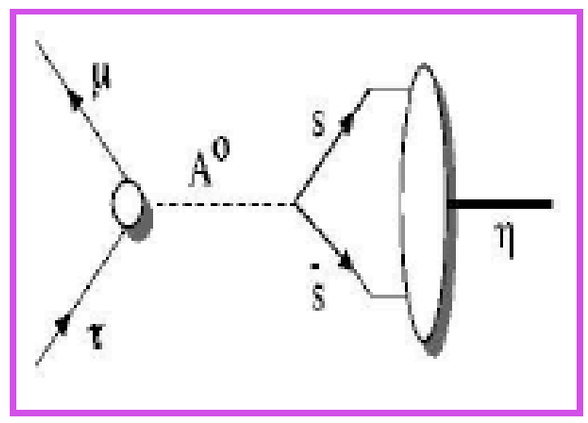
	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
SM+ν-mixing (PRL95(2005)41802,EPJC8(1999)513)	10^{-54}	10^{-14}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}	10^{-8}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}

MSSM+seesaw (PRD66 (2002) 057301) $\mathcal{B}(\tau \to \mu\gamma) : \mathcal{B}(\tau \to \mu\mu\mu) : \mathcal{B}(\tau \to \mu\eta) = 1.5 : 1 : 8.4$

Illustrations:

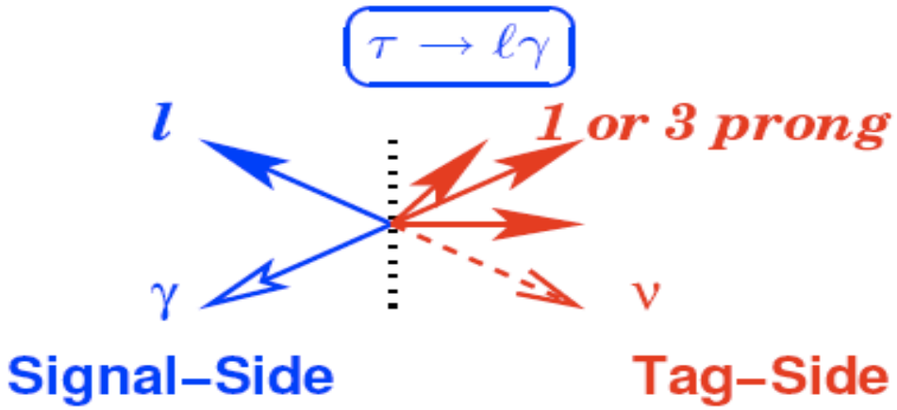






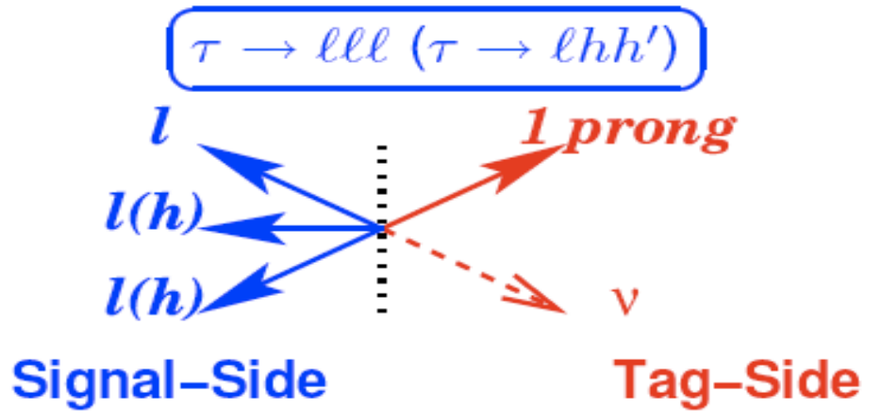
☞ Search for $\tau \to \ell\gamma/\pi^0/\eta/\eta', \tau \to \ell\ell\ell, \tau \to \ell hh' \ (\ell = e, \mu; h = \pi, K)$

$e^+e^- \to \tau^+\tau^-$ (Clean Environment)



Backgrounds:

- $\tau \to e\gamma\ (\tau \to \mu\gamma)$:
  - Radiative Bhabha (di-muon)
  - $\tau^+\tau^-\gamma(\tau \to \ell\nu\overline{\nu})$
  - $q\overline{q}\ (\gamma)$



Backgrounds:

- $\tau^- \to \ell'^-\ell^+\ell^-$:
  - Bhabha, di-muon
- $\tau^- \to \ell^+\ell'^-\ell'^-$, $\tau \to \ell hh'$:
  - $\tau^+\tau^-$, $q\overline{q}$

$\tau \to \mu\gamma$ simulation

$\Delta E = E_{rec} - \frac{\sqrt{s}}{2} \sim 0$

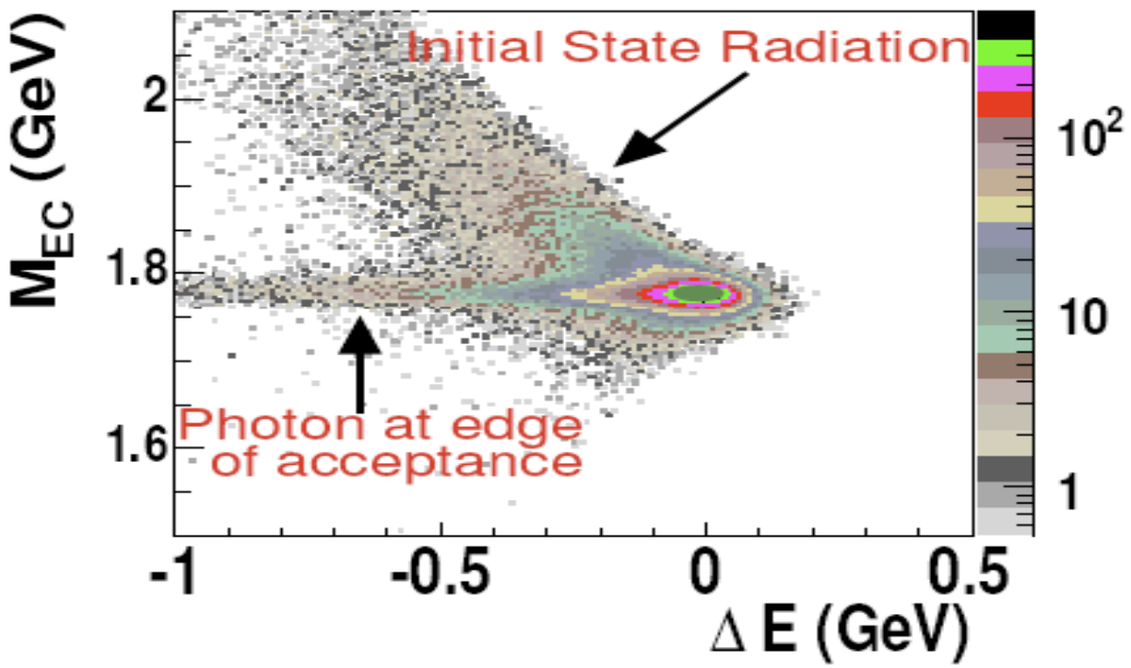
$\sigma(\Delta E) \sim 50\,MeV$

M_{EC} ($\sigma \sim 9$ MeV)

Beam energy constrained mass after vertexing

γ at μ POCA(XY)

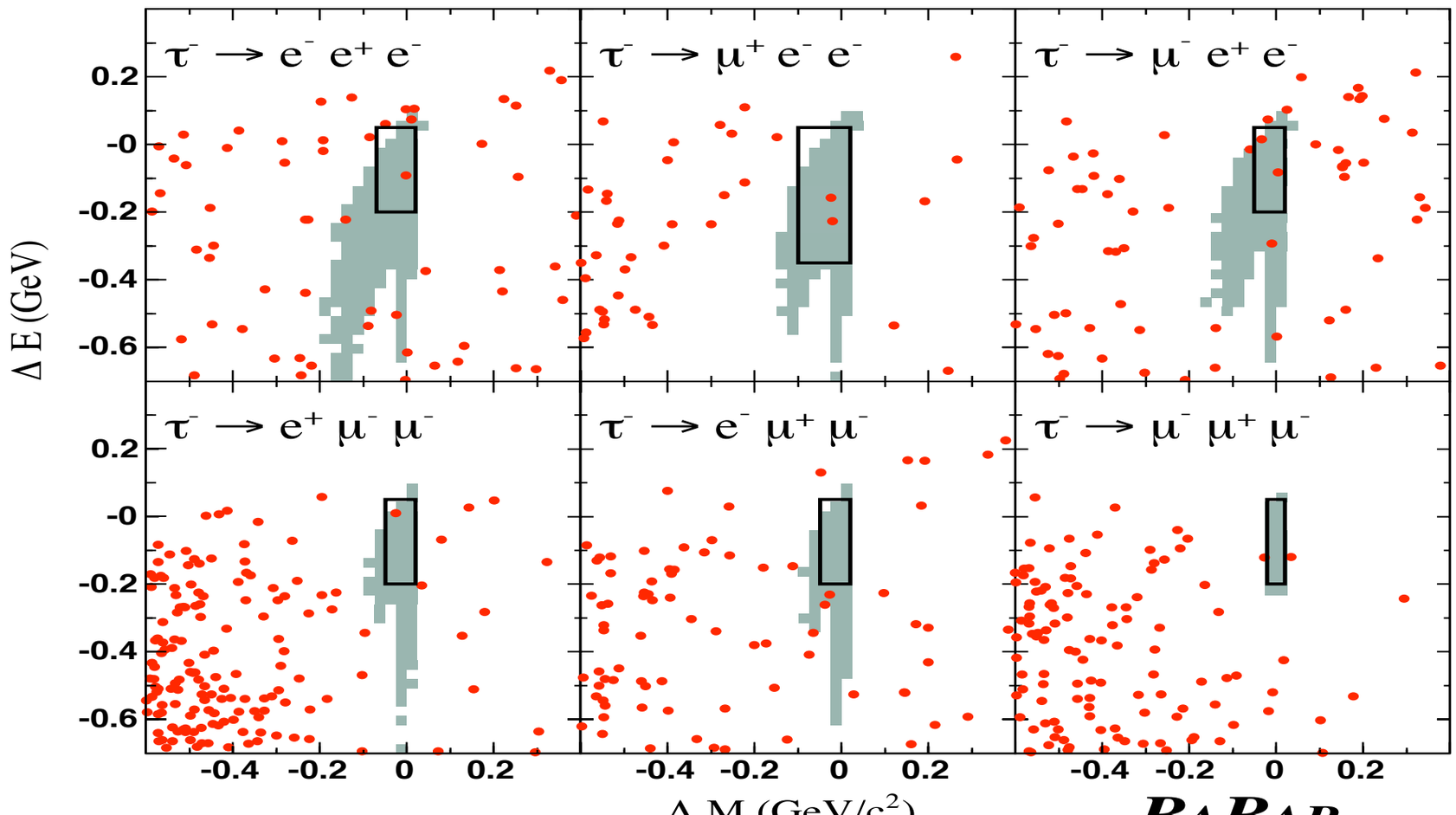
[Inv. mass: $\sigma \sim 24\,MeV$]



$\tau \to lll$, $\tau \to l\omega(\to \pi^+\pi^-\pi^0)$

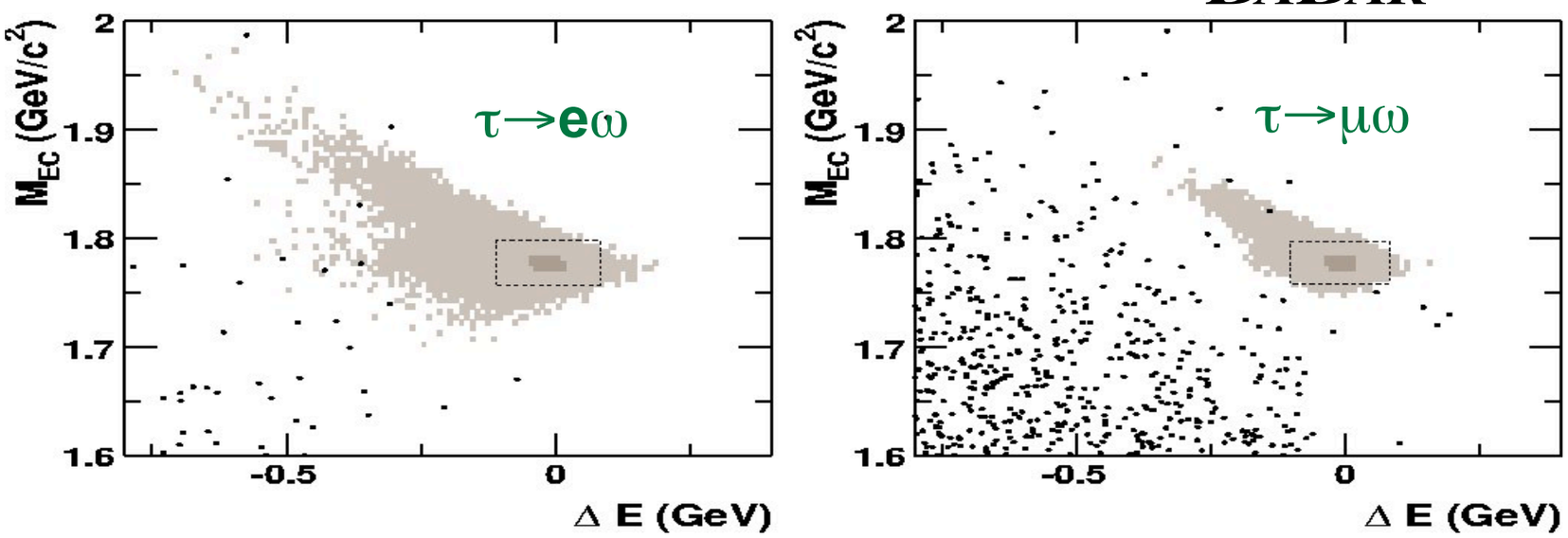
$\mathcal{B}(\tau \to \ell\ell\ell) < (3.7 - 8.0) \times 10^{-8}$
@ 90% C.L.

PRL 99, 251803 (2007)
$\mathcal{L}$ = 376 fb^{-1}



$\mathcal{B}(\tau \to e\omega) < 11 \times 10^{-8}$
$\mathcal{B}(\tau \to \mu\omega) < 10 \times 10^{-8}$
@ 90% C.L.

PRL 100, 071802 (2008)
$\mathcal{L}$ = 384 fb^{-1}



Status of LFV τ decays

W.J. Marciano, T. Mori and J.M. Roney, Annu. Rev. Nucl. Part. Sci. 2008 58

Channel	Belle		Babar		Combined BF	
	$N_{\rm obs}(N_{\rm bkg})$	BF	$N_{\rm obs}(N_{\rm bkg})$	BF	Freq.	Bayes.
	events	(10^{-8})	events	(10^{-8})	(10^{-8})	(10^{-8})
$\tau \to \mu\gamma$	$10\ (13.9^{+6.0}_{-4.8})$	4.5	$4\ (6.2 \pm 0.5)$	6.8	2.3	5.9
$\tau \to e\gamma$	$5\ (5.14^{+3.86}_{-2.81})$	12	$1\ (1.9 \pm 0.4)$	11	7.2	8.5
$\tau \to \mu e^+e^-$	$0\ (0.04\pm0.04)$	2.7	$2\ (0.89\pm0.27)$	8.0	3.0	3.0
$\tau \to \mu\mu^+\mu^-$	$0\ (0.07\pm0.05)$	3.2	$0\ (0.33\pm0.19)$	5.3	1.7	2.0
$\tau \to e\mu^+\mu^-$	$0\ (0.05\pm0.03)$	4.1	$0\ (0.81\pm0.31)$	3.7	1.4	2.2
$\tau \to ee^+e^-$	$0\ (0.40\pm0.30)$	3.6	$1\ (1.33\pm0.25)$	4.3	1.8	2.6

Status of LFV τ decays

W.J. Marciano, T. Mori and J.M. Roney, Annu. Rev. Nucl. Part. Sci. 2008 58

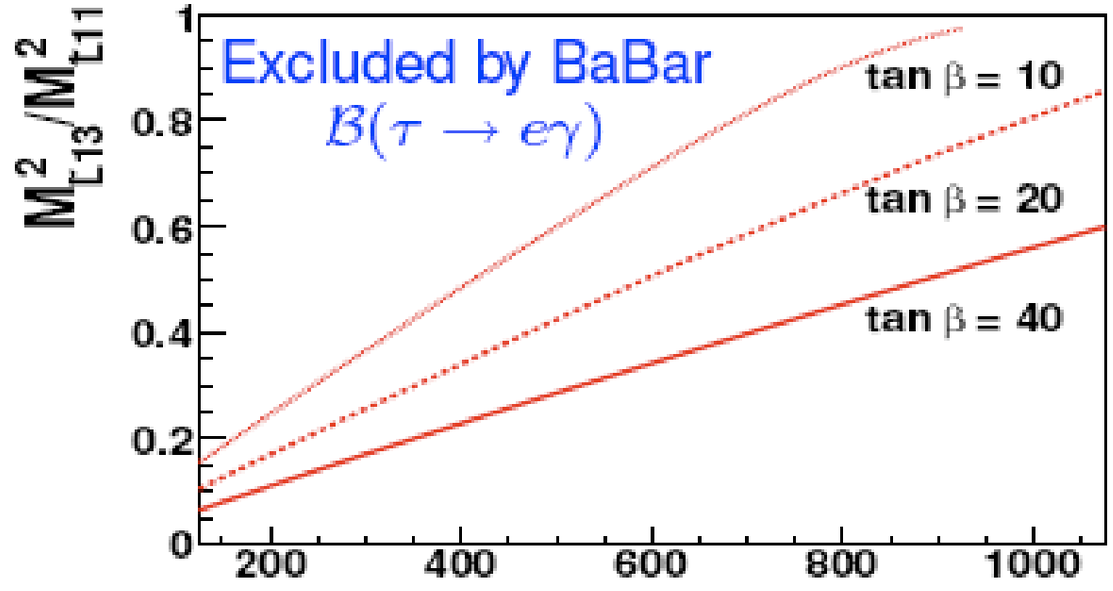
Channel	$\ell = e$ (10^{-8})				$\ell = \mu$ (10^{-8})			
	Belle	Babar	Combined		Belle	Babar	Combined	
			Freq.	Bayes.			Freq.	Bayes.
$\tau \to \ell\pi^0$	8	13	4.2	5.0	12	11	5.5	6.4
$\tau \to \ell\eta$	9.2	16	4.3	6.8	6.5	15	4.9	6.1
$\tau \to \ell\eta'$	16	24	8.9	9.7	13	14	5.2	7.3
$\tau \to \ell K_S^0$	5.6		5.6		4.9		4.9	
$\tau \to \ell\phi$	7.3		7.3		13		13	
$\tau \to \ell\rho^0$	6.3		6.3		6.8		6.8	
$\tau \to \ell\omega$	18	10	8.3	8.5	8.9	11	3.4	5.6
$\tau \to \ell K^{*0}$	7.8		7.8		5.9		5.9	
$\tau \to \ell\overline{K^{*0}}$	7.7		7.7		10		10	

New Physics Constraints

- mSUGRA mixing at GUT scale: $\mathcal{L} = -M^2_{\tilde{L}}\tilde{L}^*\tilde{L} - M^2_{\tilde{E}}\tilde{E}^*\tilde{E}$

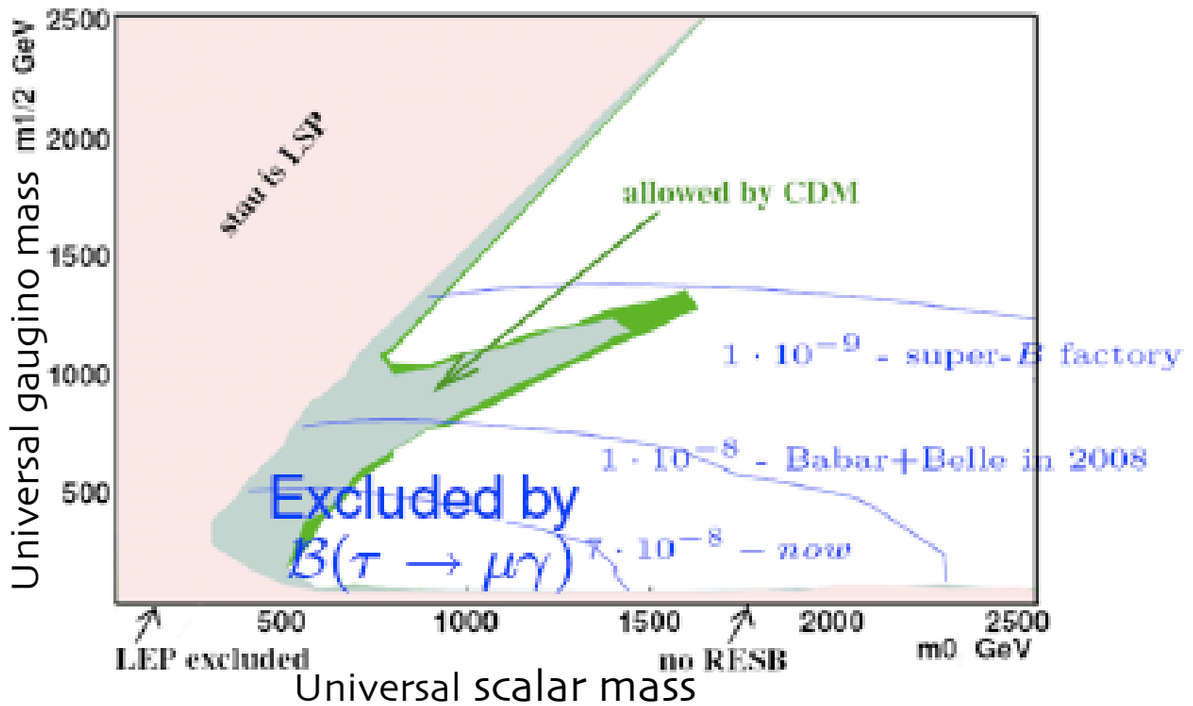
  - Model-independent calculation
    (A.Brignole, A.Rossi,
    NPB701(2004)3)

  - $m_{GUT} = 5 \cdot 10^{15}$ GeV
    $\mu > 0, A_0 = 0$



- mSUGRA + Seesaw: ν-mixing induces LFV at EW scale via RGE

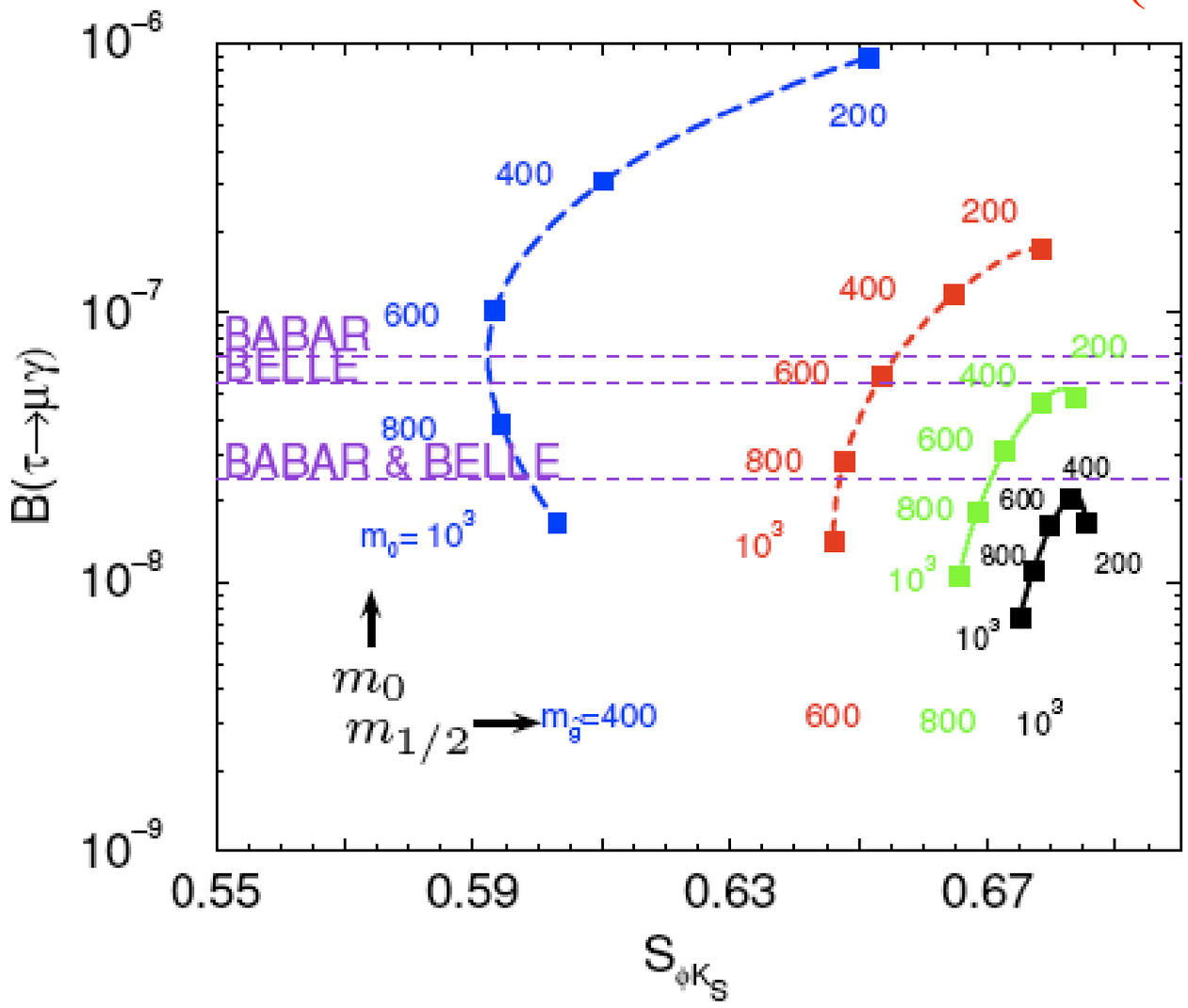
  - RGE using SPheno
    (W. Porod, CPC153(2003)275)
  - Cold Dark Matter: WMAP Data
    Simulation with micrOMEGAs
    (CPC149(2002)103)
  - $m_{\nu_R} = 5 \times 10^{14}$ GeV, $\tan\beta = 55$,
    $\mu > 0, A_0 = 0$, $m_0, m_{1/2}$,
    $M^2_{\tilde{L}}, M^2_{\tilde{E}}$: Diagonal



$\tau \to \mu\gamma$ & $S_{\varphi K_S}$

- SUSY SU(5) GUT: Flavor changing right-handed currents ⇒
  Correlations between CP asymmetry in b-s penguins and $\tau \to \mu\gamma$

$$(m^2_{\tilde{d}_R})_{23} \approx (m^2_{\tilde{l}_L})^*_{32} e^{i\varphi_{23}}$$



J. Hisano, Y. Shimizu

(PLB565(2003)183)

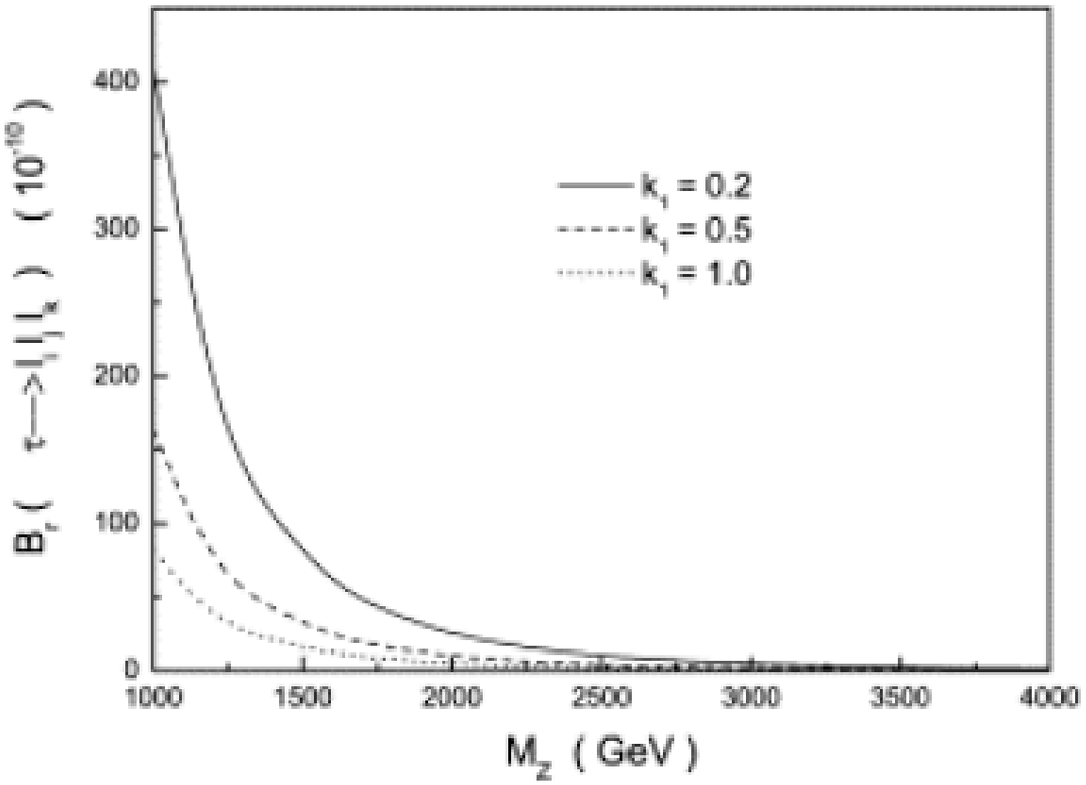
$$\tan\beta = 10,\ A_0 = 0,$$
$$m_{\nu_R} = 5 \times 10^{14}\,\mathrm{GeV},$$
$$m_{\nu_\tau} = 5 \times 10^{-2}\,\mathrm{eV}$$

- Current measurement: $S(B \to \phi K^0) = (0.39 \pm 0.17)$ (HFAG, 2007)
  More sensitive $\mathcal{B}(\tau^\pm \to \mu^\pm\gamma) < 2 \times 10^{-8}$ exclude some regions.

$\tau \to lll$ Implications

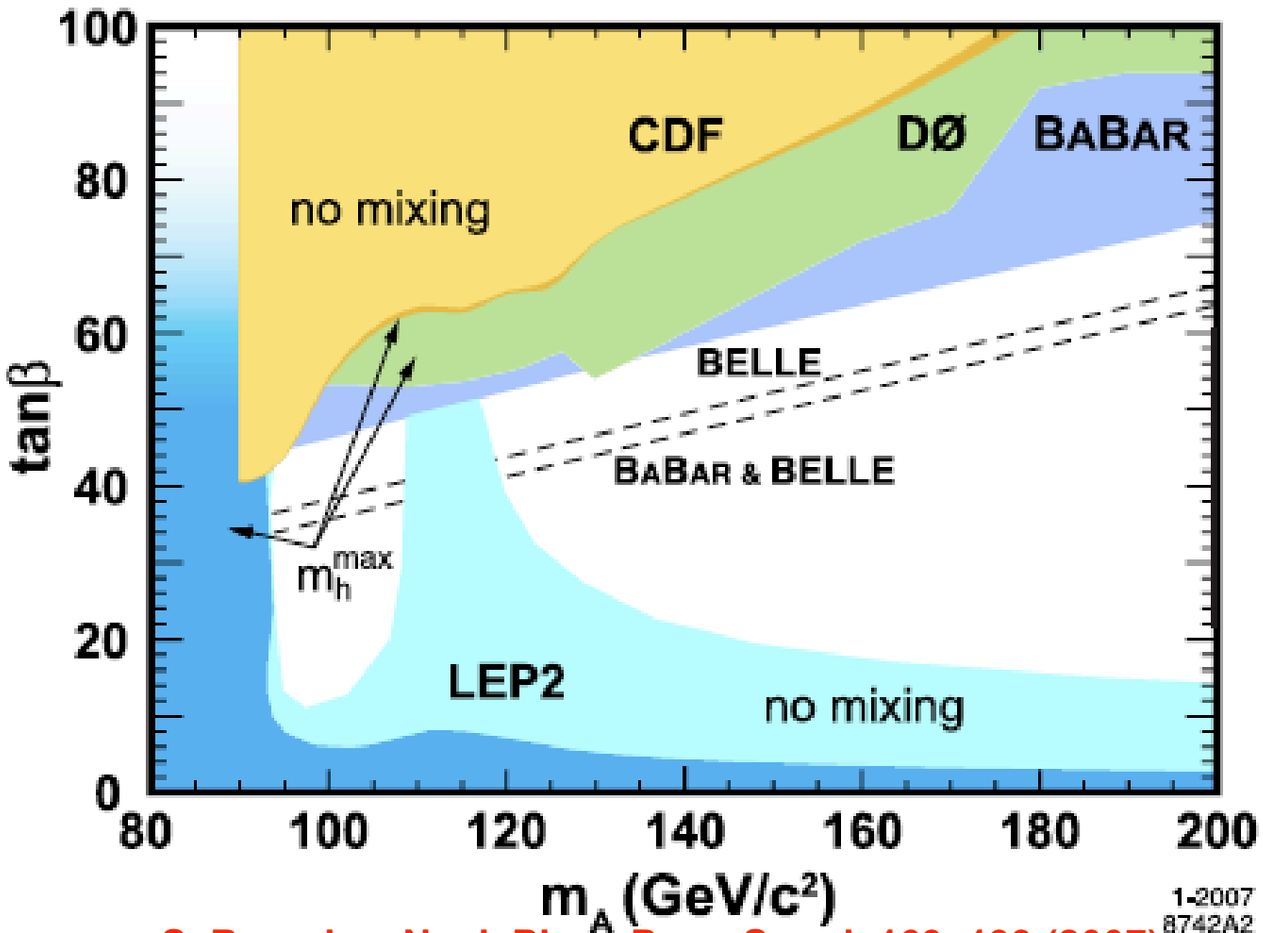
- SUSY + Higgs (A.Brignole, A.Rossi, PLB566(2003)217)
  - $\mathcal{B}(\tau \to 3\mu) \simeq 10^{-7} \times (\frac{\tan\beta}{50})^6 \times (\frac{100GeV}{m_A})^4 \times (\frac{|50\Delta_L|^2+|50\Delta_R|^2}{10^{-3}})$
  - If Higgs light, s-particles $\sim \mathcal{O}(\mathrm{TeV})$, $\tan\beta \sim 50$
    - No direct observation, but $\tau \to \mu\mu\mu$ observable (?)
    - Sensitivity $\sim 10^{-8} - 10^{-10}$ at B-Factories, LHC

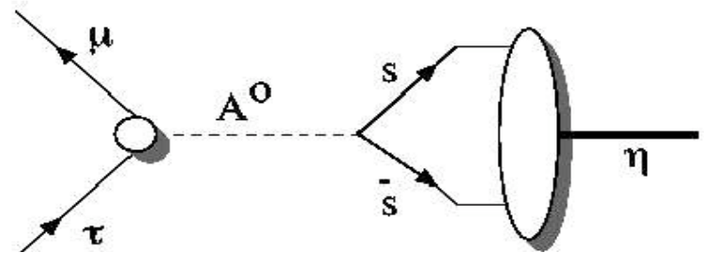
- Non Universal Z' (Technicolor) (C.Yue, Y.Zhang, L.Liu, PLB547(2002)252)
  - $\tau \to \ell\ell\ell$ most sensitive
  - Flavor mixing $(k_1) = 0.2$, $\mathcal{B}(\tau \to \ell\ell\ell) < 10^{-8}$ $\Rightarrow m_{Z'} < 1.2$ TeV



Search for CP-odd Higgs

- Mixing between left-handed smuons and staus with $m_{\nu_R} = 10^{14}\,\mathrm{GeV}$ via seesaw $\Rightarrow \tau^{\pm} \to \mu^{\pm}\eta$ limit translates into exclusion plot in $\tan\beta$ vs. m_A plane (M.Sher, PRD66 (2002) 057301)





$$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\eta) = 0.84 \times 10^{-6} \times \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100\ \mathrm{GeV}}{m_A}\right)^4$$

where m_A is the pseudoscalar Higgs mass and $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$

Light and dark shade: m_h^{max} and no-mixing stop mixing benchmark models (M. Carena et.al, hep-ph/9912223)

S. Banerjee, Nucl. Phys. Proc. Suppl. 169, 199 (2007)

- 95% C.L. from BABAR-BELLE competitive with direct searches at CDF: Higgs $\to \tau^+\tau^-$ (310 pb^{-1}), D0: Higgs $\to b\bar{b}$ (260 pb^{-1}), $\tau^+\tau^-$ (325 pb^{-1}); complementary to region excluded by LEP2

Summary & Outlook

Flavor Factories are more than precision machine: Discovery of New Physics hopeful...

	H^+ high tanβ	Minimal FV	Non-Minimal FV (1-3)	Non-Minimal FV (2-3)	NP Z-penguins	Right-Handed currents
BR($B \to X_s\gamma$)		X		o		o
$A_{CP}(B \to X_s\gamma)$				X		o
BR($B \to \tau\nu$)	X-CKM					
BR($B \to X_s l^+ l^-$)				o	o	o
BR($B \to K\nu\overline{\nu}$)				o	X	
$S(K_S\pi^0\gamma)$						X
β		X-CKM				X

Mode	Sensitivity		
	Current	Expected (10 ab^{-1})	Expected (75 ab^{-1})
BR($B \to X_s\gamma$)	7%	5%	3%
$A_{CP}(B \to X_s\gamma)$	0.037	0.01	0.004–0.005
BR($B^+ \to \tau^+\nu$)	30%	10%	3–4%
BR($B^+ \to \mu^+\nu$)	not measured	20%	5–6%
BR($B \to X_s l^+ l^-$)	23%	15%	4–6%
$A_{FB}(B \to X_s l^+ l^-)_{s_0}$	not measured	30%	4–6%
BR($B \to K\nu\overline{\nu}$)	not measured	not measured	16–20%
$S(K_S\pi^0\gamma)$	0.24	0.08	0.02–0.03