BEAUTY PHYSICS

Comparison of the discovery potential at Belle-II and at the LHCb

BEAUTY IN THE LHC ERA

❑ **if new physics found at LHC**

⇒ the effects in B/D/K/τ decays;

⇒ flavour structure of new physics

❑ **otherwise…**

⇒ search for deviations from SM in flavor physics will be one of the best ways to look for new physics.

❑ Long list of important measurements driven by theory and experimental results:

- Unitarity triangle with O(1%) precision: *tree* ($|V_{ub}|$, γ) *vs loop* ($|V_{td}|$, β)
- Inclusive measurements (preferred by theory): $b\to u$, $b\to s\gamma$, $b\to d\gamma$, $b\to s\, l\bar{l}$
- Charged Higgs searches in $B\to\tau\nu_\tau$ and $B\to D^{(*)}\tau\nu_\tau$;
- Non SM CP-phase: *high precision b→s studies*, β_s;
- Non SM right-handed currents: *CPV in* $B\to K^*\gamma$;
- Scalar interactions: $B_{s,d}\to\mu^+\mu^-$
- …
- Lepton Flavor Violation (LFV): *e.g.* $\tau\to\mu\gamma$
- …

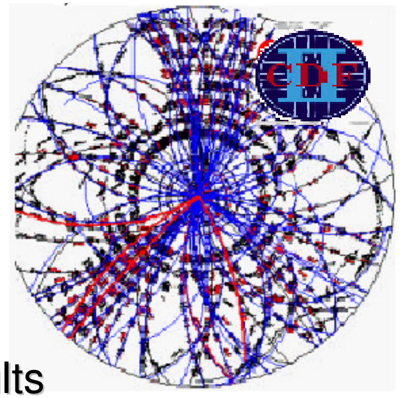
…most of them very challenging experimentally

Experimental opportunities

TEVATRON: CDF, D0

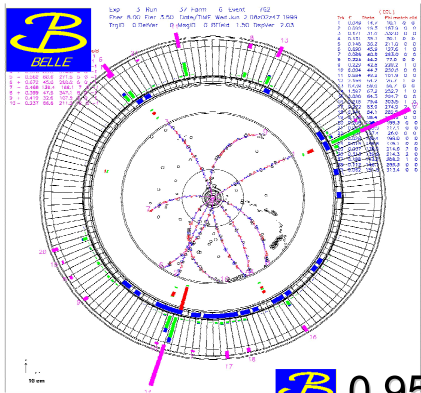
$\sigma(\bar{b}b)\approx 150\ \mu b$

$B^0 \to J/\psi K_s$



Typical data samples
used in published results
2–4 fb^{-1}

PEPII: BaBar, **KEKB**:Belle



$\sigma(\bar{b}b)\approx 1$ nb

$B^0 \to J/\psi K_s$

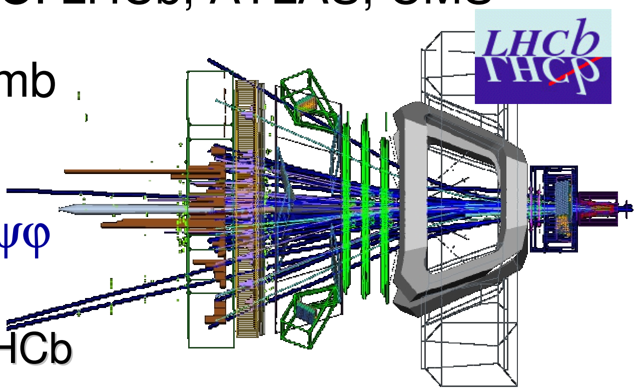
0.95(0.75) ab^{-1}(@Υ(4S))

0.57(0.4) ab^{-1}

LHC: LHCb, ATLAS, CMS

$\sigma(\bar{b}b)\approx 500$ mb

$B_s \to J/\psi \varphi$

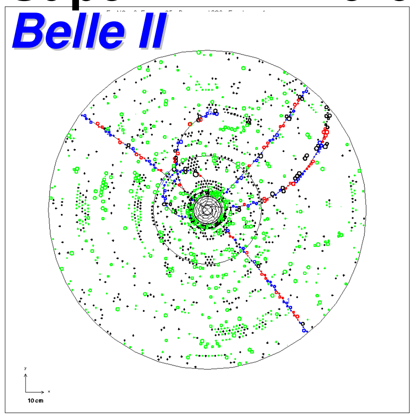


10 fb^{-1} @ LHCb

100 fb^{-1} @ SuperLHCb

SuperB-factories (SBF)

SuperKEKB: Belle II, **SuperB**



$\sigma(\bar{b}b)\approx 1$ nb

>50 ab^{-1}

(Super)B-factory vs LHC(b)

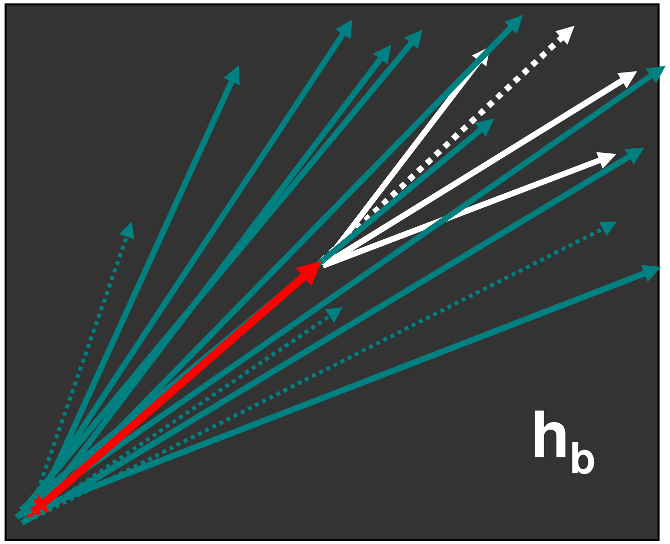
	$e^+e^- \to \Upsilon(4S) \to \bar{B}B$	$pp \to \bar{b}bX$ ($\sqrt{s}$=14TeV)
σ_{bb}	1 nb	500 mb
production rate	~10^{10} $\bar{B}B$/year	~10^{12} $\bar{b}b$/year
purity	$\sigma(\bar{B}B)/\sigma_{tot}$~ 0.25	$\sigma(\bar{b}b)/\sigma_{inel}$~ 0.006
b-hadron types	$\bar{B}^0B^0$(50%), B^+B^-(50%), B_s at $\Upsilon(5S)$	B^0(40%), B^+(40%), B_s(10%), B_c(<0.1%), b-baryons(10%)
event topology	$\bar{B}B$ w/o other particles $E_B = \sqrt{s}/2$	many additional particles
flavor tagging	coherent $\bar{B}^0B^0$ - mixing	Incoherent $B^0(B_s)$ – mixing
b-hadron boost	small ($\beta\gamma$=0.43)	large, p_{lab} 50÷100 GeV
p_{lab}-secondaries	up to ~4 GeV – background from soft photons	O(10) GeV – γ/π^0 separation
vertexing	$\bar{B}B$ – vertex separation ~ 200μm	secondary vertex ~ 3mm

Basic tools

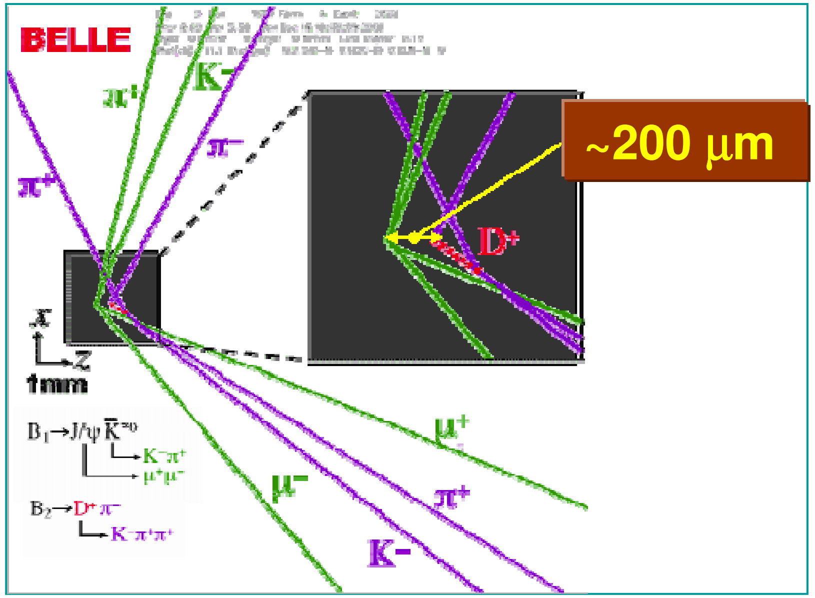
- ❑ **LHC(b)**

  $E_B \sim 50 \div 100$ GeV

  $\Rightarrow$ vertex displacement **~ few mm**



- ❑ **B-factory**



Sufficient to study time-evolution of B-system.

Basic tools at B-factories

- **B-factory:** $\overline{B}B$ without additional particles $\Rightarrow$ $\mathbf{E_B} = \sqrt{s}/2$.

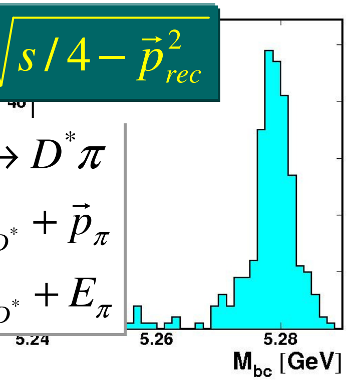
$$M_{bc} = \sqrt{s/4 - \vec{p}_{rec}^{\,2}}$$

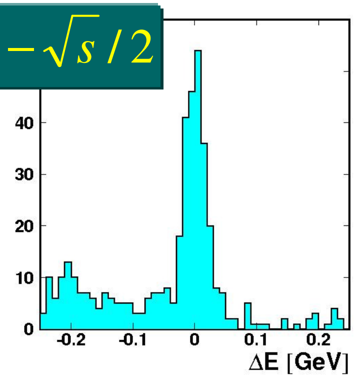
$$\Delta E = E_{rec} - \sqrt{s}/2$$

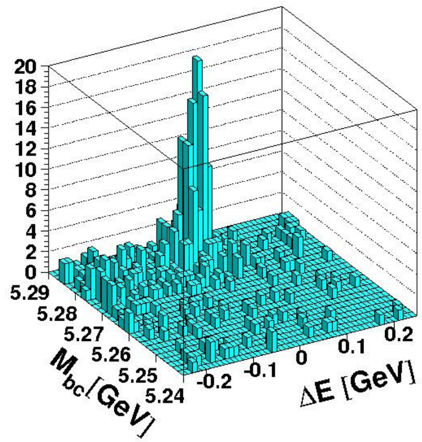
$e.g.: B \to D^* \pi$

$\vec{p}_{rec} = \vec{p}_{D^*} + \vec{p}_\pi$

$E_{rec} = E_{D^*} + E_\pi$

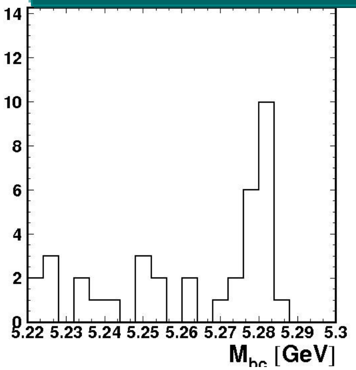


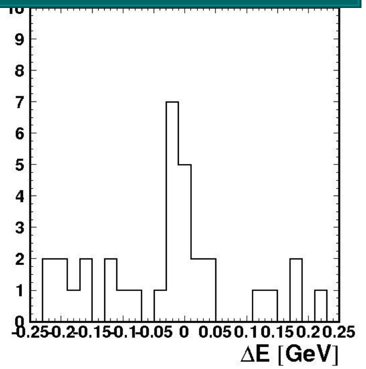




$\overline{B}^0 \to D_s^+ K^-,\ D_s^+ \to \varphi \pi^+$

$BF(\overline{B}^0 \to D_s^+ K^-) \times BF(D_s^+ \to \varphi \pi^+) \approx 10^{-7}$

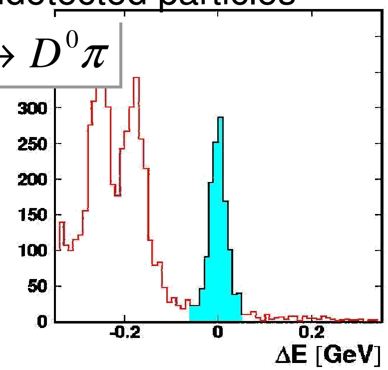




Provides information on very slow, undetected particles

helps to identify secondaries

$e.g.: B \to D^0 \pi$

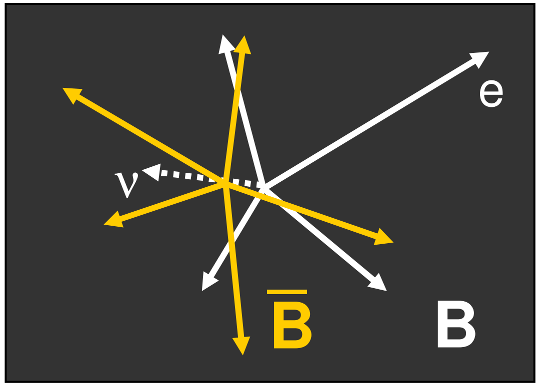


Basic tools at B-factories

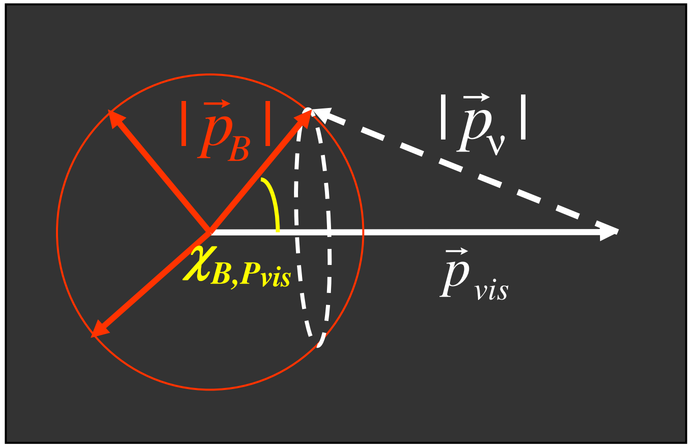
- semileptonic decays at B-factory

$$B \to h l \nu_l \qquad l = e, \mu \qquad X_h = D, D^*, D^{**}, \pi, \rho, \omega ...$$

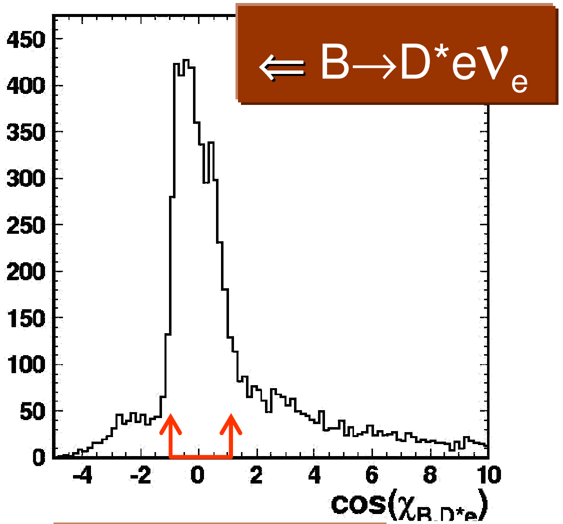
$$E_{vis} \equiv E_{X_h} + E_l \qquad \vec{p}_{vis} \equiv \vec{p}_{X_h} + \vec{p}_l$$



$$E_\nu = |\vec{p}_\nu| = E_B - E_{vis}$$



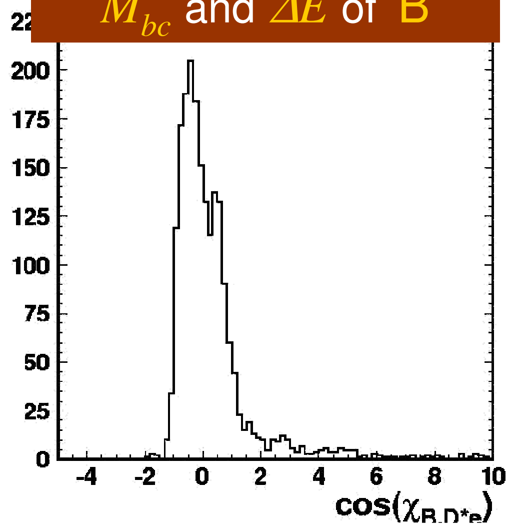
$$\cos \chi_{B,\vec{p}_{vis}} = f(E_{vis}, p_{vis})$$



$-1 \le \cos\chi_{B,\vec{p}_{vis}} \le 1$

for channel with single neutrino

requirements on M_{bc} and ΔE of B̄



Basic tools at B-factories

- reconstruct one of B-mesons (B_{tag}) in a clean hadronic or semi-leptonic mode:

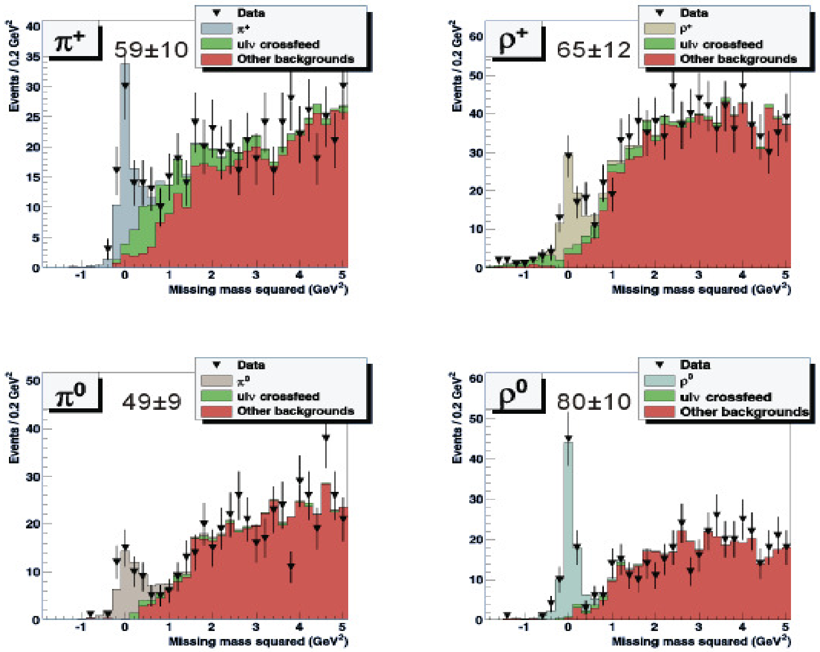
all remaining particles associated with 2nd B (B_{sig}) $p_{sig} = (E_{beam}, -\vec{p}_{tag})$

$\Rightarrow$ study decays of B_{sig}:

- inclusive,
- with unknown missing mass (*e.g.* multiple neutrinos),
- with large non- $\bar{B}B$ background…

e.g. $B_{tag} \to$ hadrons

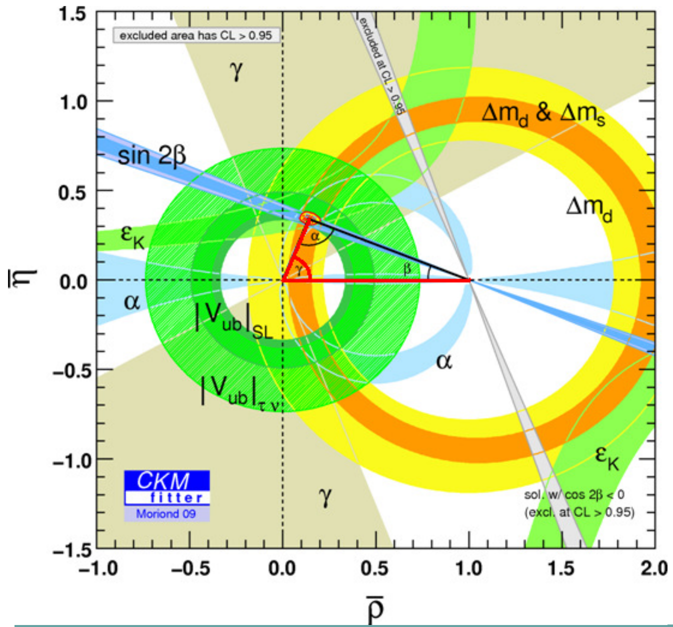
$B_{sig} \to h\, l\, \nu,\ h = \pi, \rho, \omega \ldots$



605 fb^{-1}

UNITARITY TRIANGLE

- Unitarity triangle with O(1%) precision: *tree* ($|V_{ub}|$, γ) *vs loop* ($|V_{td}|$, β)



"$|V_{ub}|$ - tension"

CKM fitter: $\sin(2\beta)=0.798\ +0.027/-0.036$

HFAG (FPCP 2009, PRELIMINARY): 0.655 ± 0.0244 ($J/\psi K_s$)

$\sim 0.58\pm0.06$ ("clean" penguin)

$> 2.5\sigma$ deviation

CKM fitter: no $\sin(2\beta)$ measurements used

HFAG (FPCP 2009, PRELIMINARY): direct measurements

$|V_{ub}|\times10^{-3}$

- CKMFitter $3.51^{+0.14}_{-0.16}$
- $B\to\pi l\nu$ $3.5^{+0.6}_{-0.5}$
- $B\to ul\nu$ $4.12\pm0.15\pm0.40$

PDG 2008

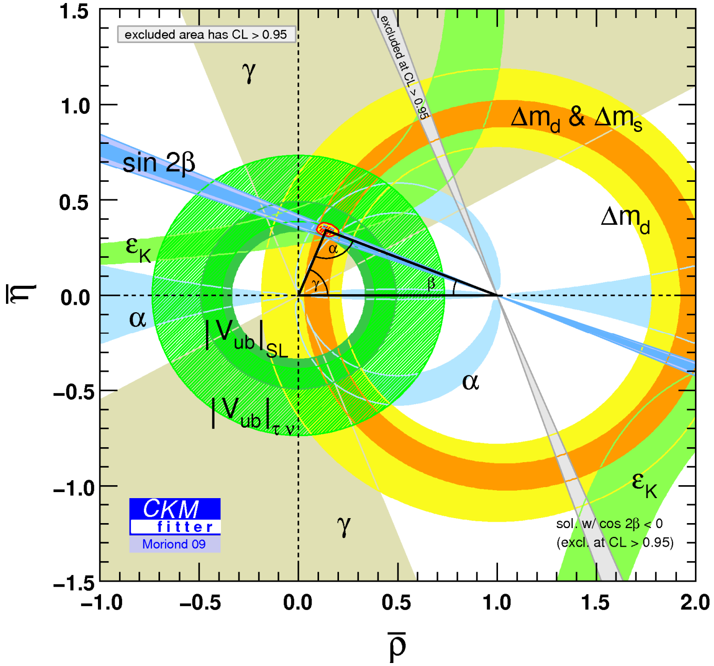
$|V_{cb}|\times10^{-3}$

- CKMFitter $43.9^{+0.66}_{-0.40}$
- $B\to D^{*}l\nu$ 38.6 ± 1.3
- $B\to cl\nu$ 41.6 ± 0.6

2.7σ

The effort required to further improve the knowledge of $|V_{ub}|$ and $|V_{cb}|$ is well motivated.

Unitarity triangle from tree amplitudes



γ

- CKMFitter $(66.8^{+5.4}_{-3.8})°$
- measured $(70\ ^{+27}_{-29})°$

CKMFitter:
from measurements in $B \to D^{(*)}K^{(*)}$ decays, using several methods

Numbers in the Table:

T. Browder *et al.*,
New Physics at a Super Flavor Factory,
arXiv:0802.3201 [hep-ph]

Expression of Interest for an LHCb Upgrade
CERN/LHCC/2008-007

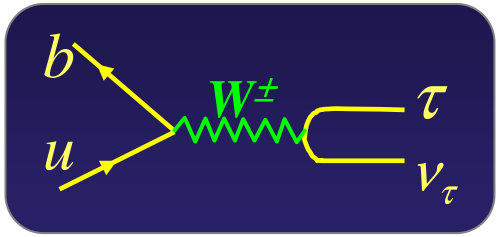
observable	current sensitivity	superBF ($50\ ab^{-1}$)	superLHCb ($100\ fb^{-1}$)
$\|V_{cb}\|$ *(incl)*	1.5÷2%	0.7÷1%	—
$\|V_{cb}\|$ *(excl)*	4÷5%	2÷3%	—
$\|V_{ub}\|$ *(incl)*	~ 8%	3÷5%	—
$\|V_{ub}\|$ *(excl)*	~18%	3÷5%	—
γ ($B \to D^{(*)}K^{(*)}$)	~30°(CKMFitter) ~15°(UTfit)	1÷2°	<1°

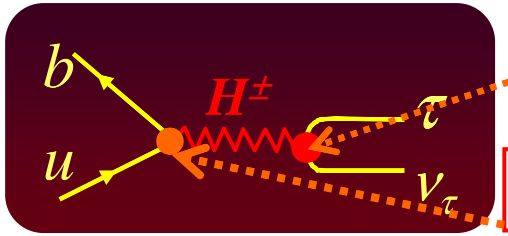
(Semi)tauonic B decays

- Charged Higgs searches in $B \to \tau\nu_\tau$ and $B \to D^{(*)}\tau\nu_\tau$;

$B \to \tau\nu_\tau$

W-mediated annihilation



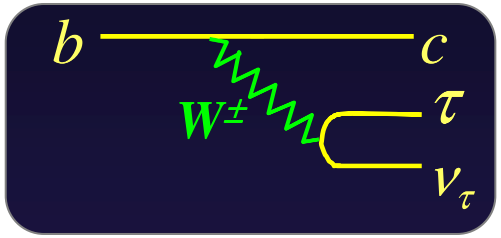


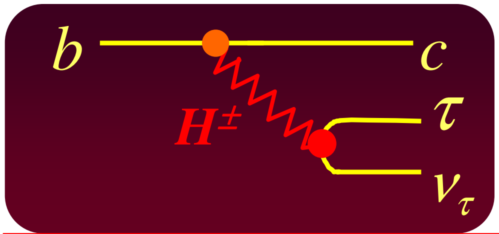
$m_\tau \tan\beta$

$m_b \tan\beta + m_u \cot\beta$

Decay amplitude $\propto\ m_b\, m_\tau \tan^2\beta$

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





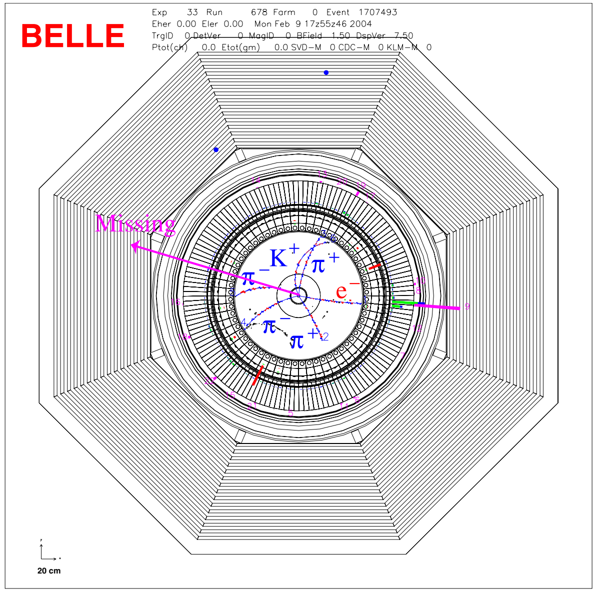
sensitive observables *e.g.* τ polarization

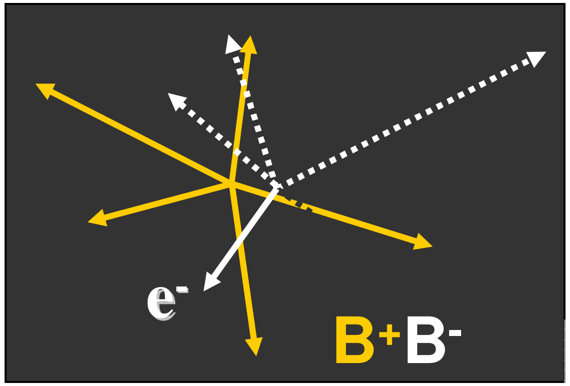
New Physics at tree level.

multiple neutrinos in final states

$B\to\tau\nu_\tau$

difficult signature:
$e/\mu/\pi/\rho\ldots \oplus$ invisible





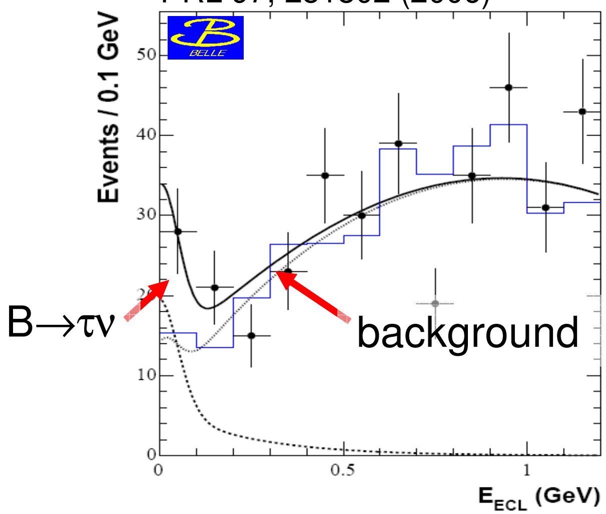
$B^+ \to \overline{D}^0\,\pi^+$

$\quad\hookrightarrow K^+\,\pi^-\,\pi^+\,\pi^-$

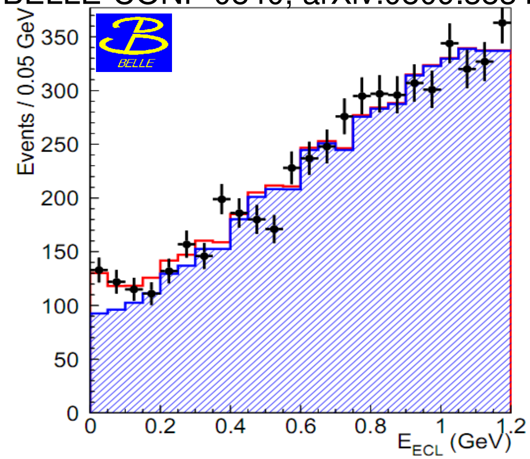
$B^- \to \tau^-\,\nu$

$\quad\hookrightarrow e^-\nu\nu$

Hadronic Tag (449M $\bar{B}B$)
PRL 97, 251802 (2006)



Semileptonic Tag (657M $\bar{B}B$)
BELLE-CONF-0840, arXiv:0809.3834



$B \to \tau \nu_\tau$

Belle+BaBar: $BF(\tau\nu_\tau)_{exp} = [1.73 \pm 0.35] \times 10^{-4}$

CKMFitter: $BF(\tau\nu_\tau)_{fit} = [0.786^{+0.179}_{-0.083}] \times 10^{-4}$

BF(τν) is not included in the fit

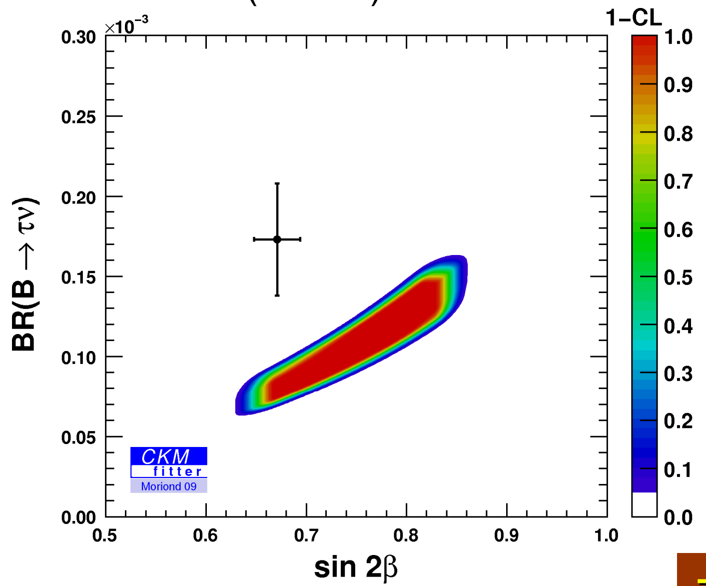
2.5σ deviation

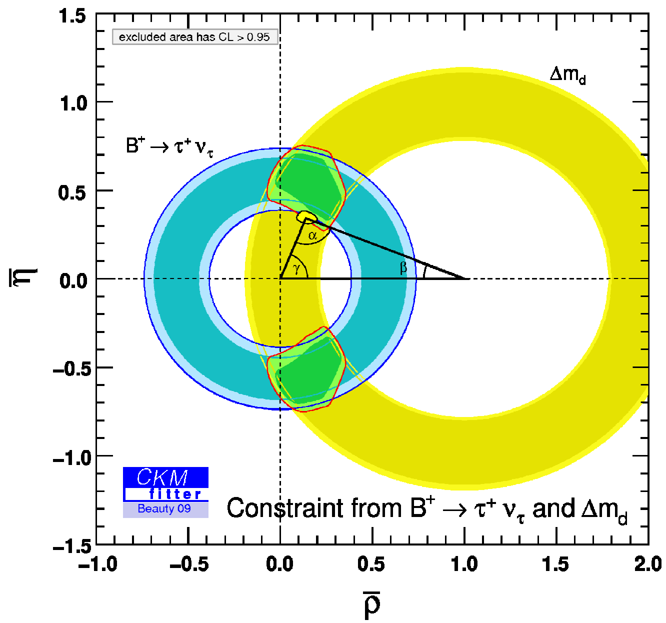
$$\mathcal{B}(B^- \to \ell^- \bar{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

The decay constant f_B cancels in the ratio $BF(B \to \tau\nu_\tau)/\Delta m_d$, leaving limited theoretical uncertainties

$$\frac{BF(B^- \to \tau^- \bar{\nu}_\tau)}{\Delta m_d} \propto \left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

CKM fitter: prediction from the global fit; measurements of sin(2β) and BF(B→τν) not used





The tension is not driven by the decay constant f_B.

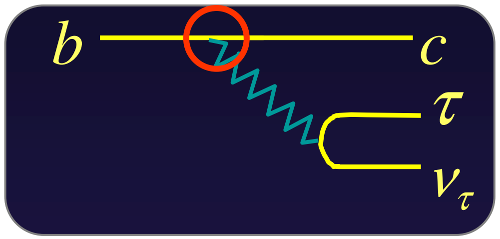
$B \to D^{(*)}\tau\nu_\tau$

530 fb^{-1}

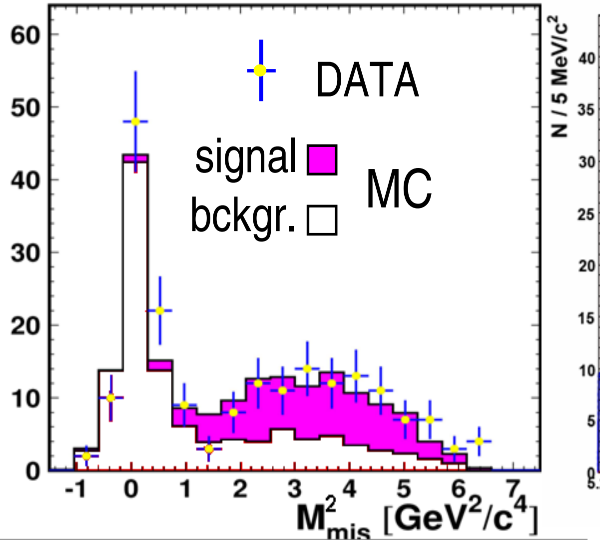
PRL **99**, 251802 (2007)

FIRST OBSERVATION, significance 5.2σ

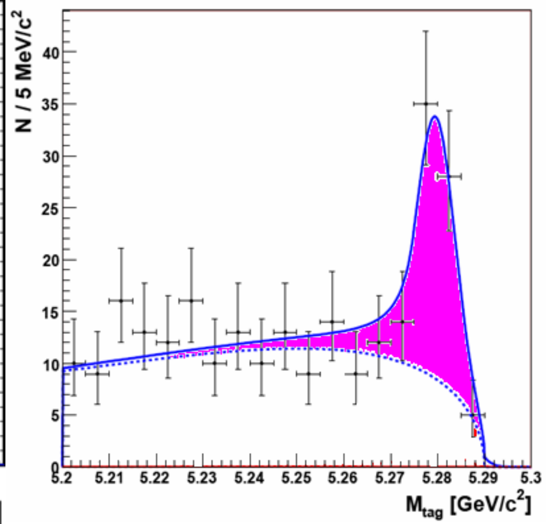
$$BF(B^0 \to D^{*-}\tau^+\nu_\tau) = (\mathbf{2.02}^{+0.40}_{-0.37}(stat) \pm 0.37(syst)) \times \mathbf{10}^{-2}$$



(missing mass)^2



M_{bc} of the tagging side



observable	current sensitivity	superFF (50 ab^{-1})	superLHCb (100 fb^{-1})
BF(B→τν)	30%	3÷4%	—
BF(B→μν)	not measured	5÷6%	—
BF(B→Dτν)	31%	2÷3% transverse τ polarization	—

T. Browder *et al.*, New Physics at a Super Flavor Factory, arXiv:0802.3201 [hep-ph]

Charmless, hadronic B decays

- measurements of α from time dependent CP violation (TCPV) in $B^0 \to \pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $\rho\rho$; important ingredients to extract α: $B^\pm \to \pi^\pm\pi^0$, $B^0 \to \pi^0\pi^0$

- search for non-SM amplitudes in B decays with $b \to s(d)$ transitions

"B →Kπ puzzle"

$A_{CP} \equiv \Gamma(B \to f) - \Gamma(B \to f) / \Gamma(B \to f) + \Gamma(B \to f)$

Belle, BaBar, CDF⇒ $A_{CP}(K^+\pi^-) = -0.098 \pm 0.012$

$A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) = -0.147 \pm 0.028 \quad 5.3\sigma$

$A_{CP}(K^+\pi^0) = 0.050 \pm 0.025$

Belle, BaBar

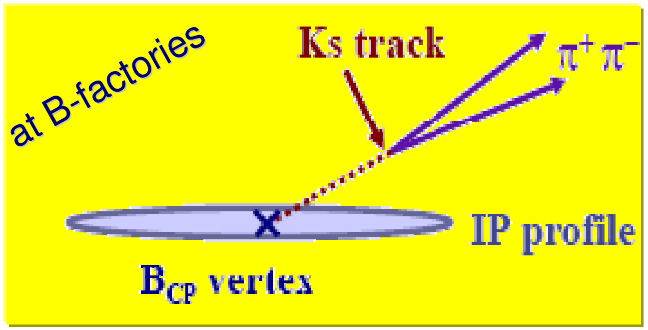
$A_{CP}(K^0\pi^+) = 0.009 \pm 0.025$

$A_{CP}(K^0\pi^0) = -0.01 \pm 0.10$

$S_{CP}(K^0\pi^0) = 0.57 \pm 0.17$ ⇐***TCPV***⇒

needed for a data driven solution with sum rules

$S_{CP} \equiv \sin(2\beta_{eff})$



- search for non-SM CP-violating phases in TCPV violation in $B \to f_{CP}$ with FCNC B decays, *e.g.* $B^0 \to \varphi K_S, \varphi K_L$, $B_s \to \varphi\varphi$

B-factories superior for the modes with neutrals

(Charmless) hadronic B decays

observable	current sensitivity	superFF (50 ab^{-1})	superLHCb (100 fb^{-1})
$\alpha(\pi\pi,\rho\pi,\rho\rho)$	15°(CKMFitter)	1÷2°	—
$S(\varphi K^0)$	0.17	0.02÷0.03	0.025÷0.035
$S(K_S K_S K^0)$	0.20	0.02÷0.03	0.025÷0.035
$S(\eta' K^0)$	0.07	0.01÷0.02	—
$S(\varphi\varphi)$	not measured	—	0.01÷0.02
$\sin(2\beta)$ $(J/\psi K)$	0.025	0.005÷0.012	0.003÷0.010
β_s $(J/\psi\varphi)$	1.1÷1.2	0.14	0.0015
β_s $(K^0 K^0)$		0.19	—

$b \to c\,\bar{c}\,s$

superFF (30 ab^{-1})@$\Upsilon(5S)$

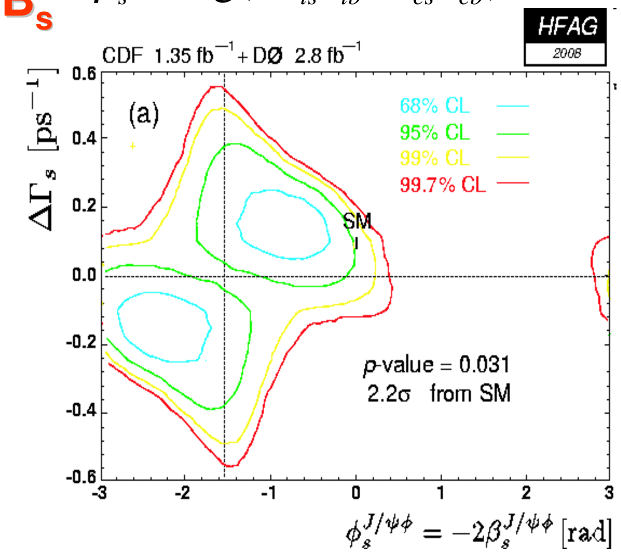
B. Di Ruzza @ DPF 2009

2.9 fb^{-1}

$BF(B_s \to \varphi\varphi) = (24 \pm 8.9) \times 10^{-6}$

B_s

$\beta_s = \arg(-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*)$



Numbers from:

PDG, HFAG,

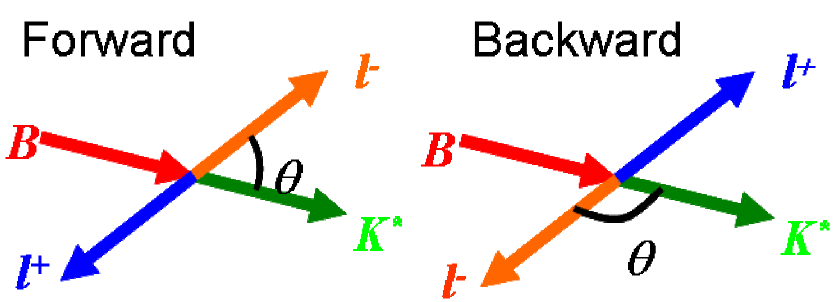
T. Browder *et al.*, New Physics at a Super Flavor Factory, arXiv:0802.3201 [hep-ph]

Expression of Interest for an LHCb Upgrade CERN/LHCC/2008-007

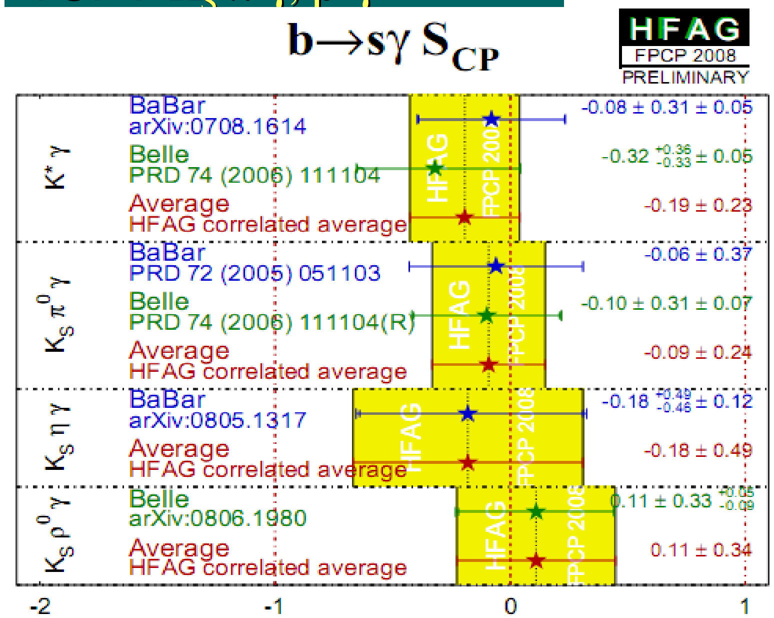
Radiative and semileptonic decays with b→s(d)

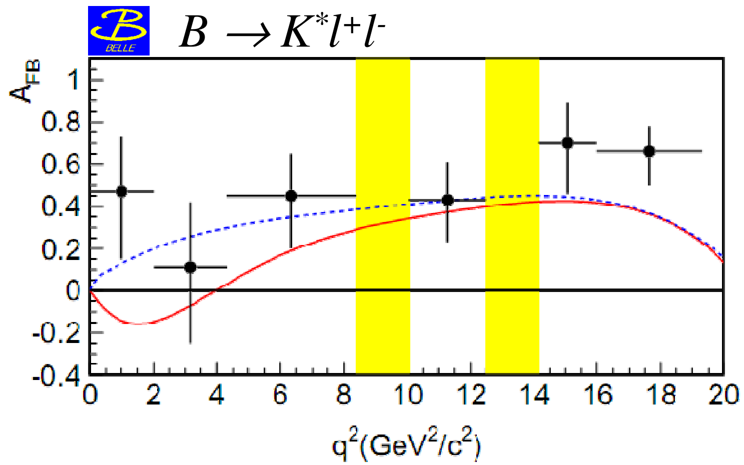
- inclusive b→s
  - $B \to X_s \gamma$
  - $B \to X_s l^+ l^-$
  - $B \to X_s \bar{\nu}\nu$
- exlusive b→s
  - $B \to K^* \gamma$
  - $B \to K^{(*)} l^+ l^-$
  - $B \to K^{(*)} \bar{\nu}\nu$
- inclusive b→d
  - $B \to X_d \gamma$
- exlusive b→d
  - $B \to \rho\gamma$

A_{FB} (forward-backward asymmetry) in b→s $l^+ l^-$ arises from the interference between γ and Z^0 contributions



TCPV $K_S \pi^0\gamma$, $\rho^0\gamma$





Radiative and (semi)leptonic decays

observable	current sensitivity	superFF (50 ab^{-1})	superLHCb (100 fb^{-1})
$A_{CP}(b\to s\gamma)$	0.028	0.004÷0.005	—
$A_{CP}(b\to s\gamma + d\,\gamma)$	0.12	0.01	—
$BF(B\to X_d\gamma)$	~ 40%	5÷10%	—
$BF(B\to\rho\gamma)/BF(B\to K^*\gamma)$	~16%	3÷4%	—
$S(B^0\to K_S\pi^0\gamma)$	0.24	0.02÷0.03	—
$S(B^0\to\rho^0\gamma)$	0.67	0.08÷0.12	—
$S(B_s\to\varphi\gamma)$			0.016 ÷0.025
$BF(B\to X_s l^+ l^-)$	23%	4÷6%	
$A_{FB}(B\to X_s l^+ l^-) s_0$		4÷6%	
$A_{FB}(B\to K^{*0}\mu^+\mu^-) s_0$			0.07 GeV^2
$BF(B\to K\,\nu\bar{\nu})$		16÷20%	
$BF(B_s\to\mu^+\mu^-)$			5÷10%
$BF(B_d\to\mu^+\mu^-)$			3σ

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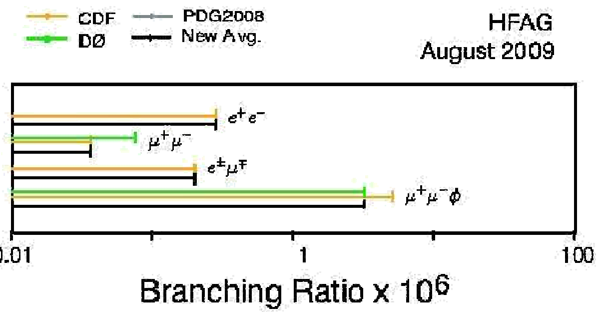
$BF(B_s\to\varphi\gamma) = (57^{+18\,+12}_{-15\,-11})\times 10^{-6}$



…many interesting opportunities for non-b physics:

- charm — mixing and CPV are a unique handle to test FCNC of u-like quarks
- τ — LFV: $\tau\to\mu\gamma$, $\tau\to\mu\mu\mu$

Summary

The flavor sector of the Standard Model passed fundamental tests;
yet there are several measurements that are uncomfortable for the Standard Model:

CDF and D0 demonstrated the power of hadron colliders in b-physics.

The needed decay modes & techniques established at B-factories.

Things to be improved (in addition to rate/radiation tolerance)

- Better particle identification;
- Larger radial size of vertex detector to accept more K_S;
- Innermost sensor closer to the IP to improve Δz resolution;
- More hermetic detector to help reconstruction of *invisible* modes (w/ ν);
- Reduce material;
- …

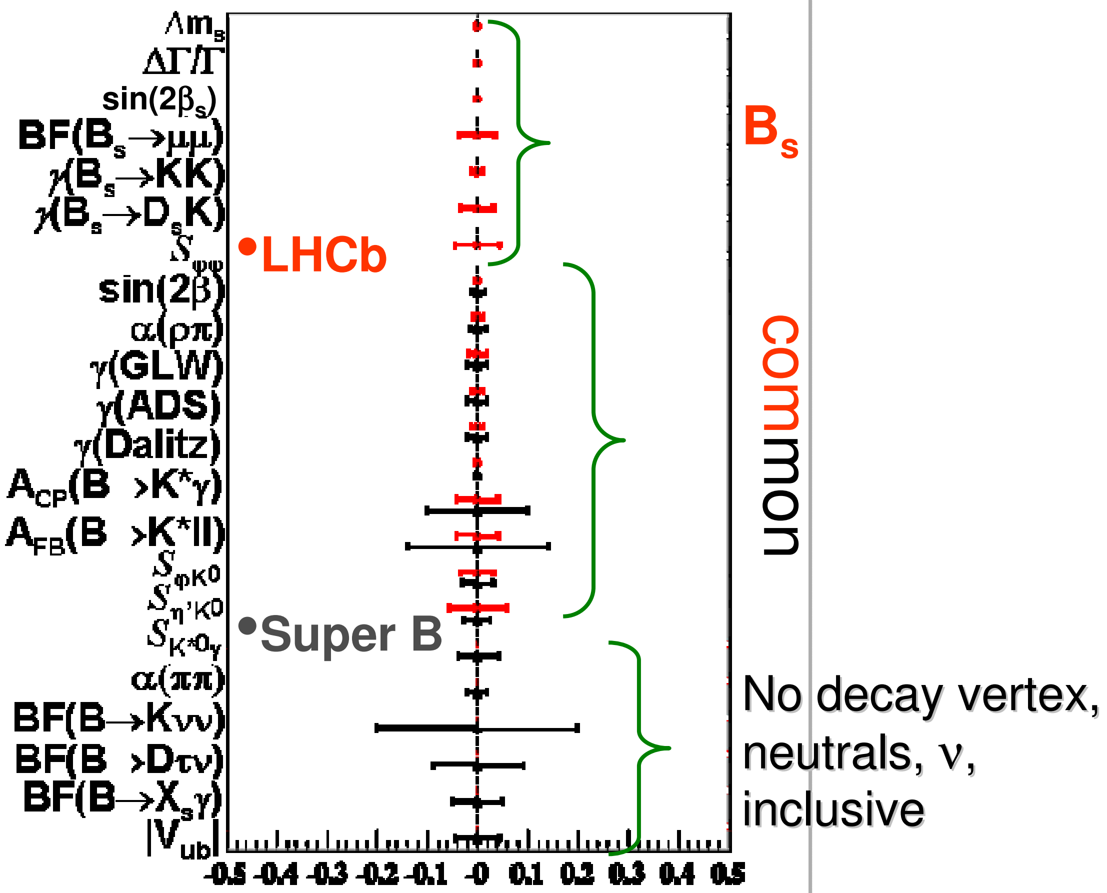
(Super)B-factories and LHC(B) quite complementary to each other.

Summary

Sensitivity Comparison ~2020 *(preliminary)*

Super-LHCb 100 fb^{-1} vs

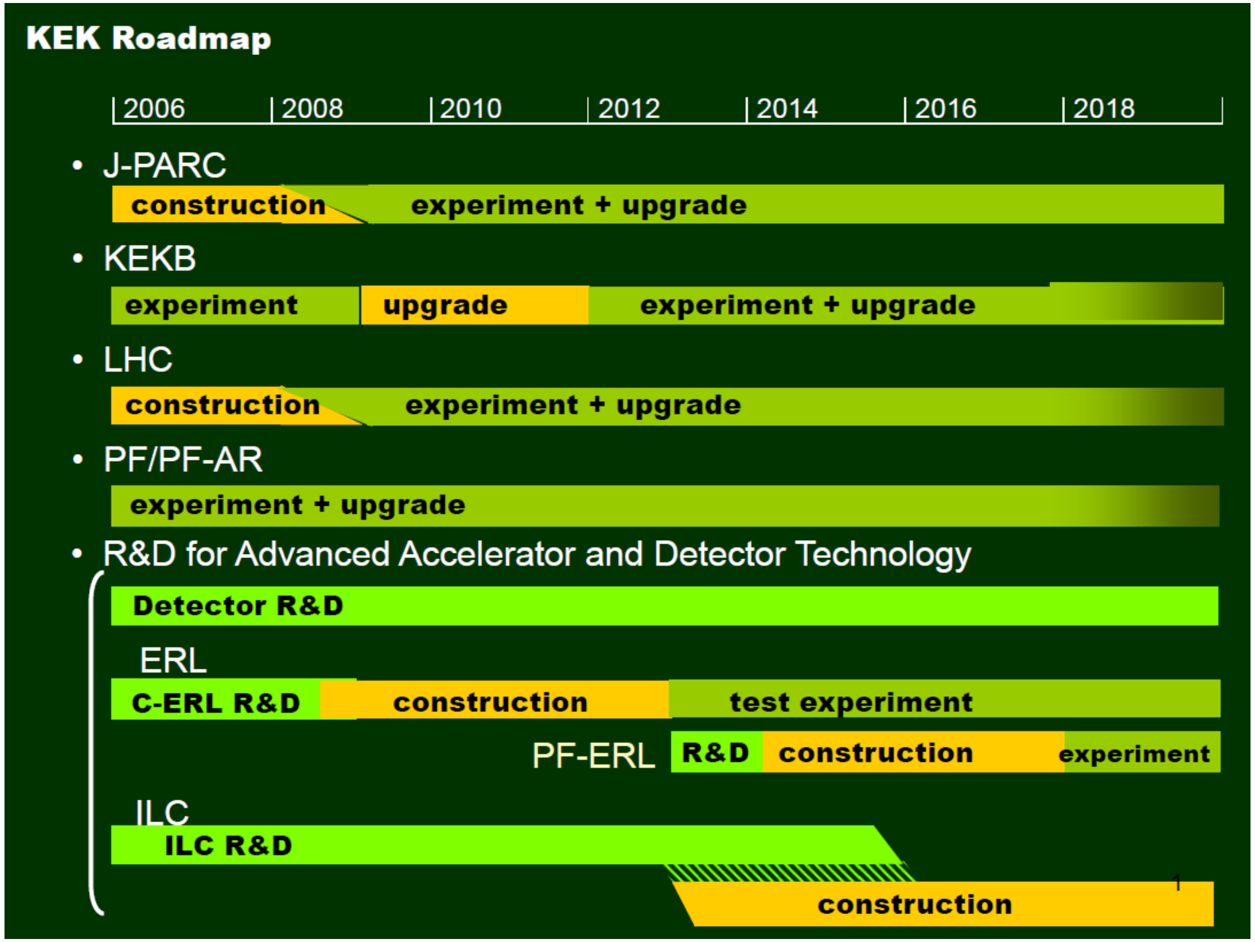
Super-B factory 50 ab^{-1}



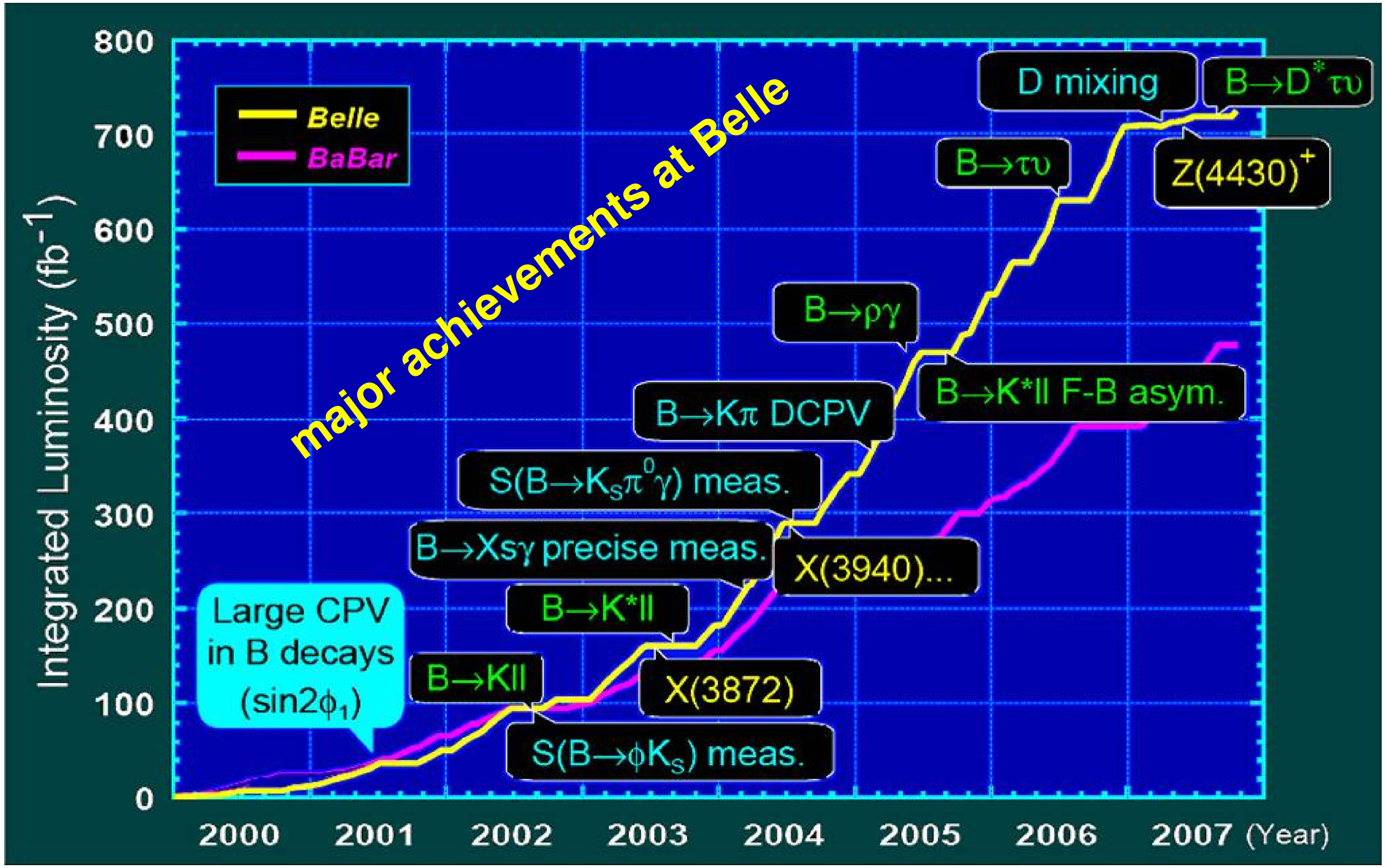
Plot by S. Stone,

SuperBF-numbers from M. Hazumi

KEK-Roadmap


KEK Roadmap
2006
2008
2010
2012
2014
2016
2018
J-PARC
construction
experiment + upgrade
KEKB
experiment
upgrade
experiment + upgrade
LHC
construction
experiment + upgrade
PF/PF-AR
experiment + upgrade
R&D for Advanced Accelerator and Detector Technology
Detector R&D
ERL
C-ERL R&D
construction
test experiment
PF-ERL
R&D
construction
experiment
ILC
ILC R&D
construction

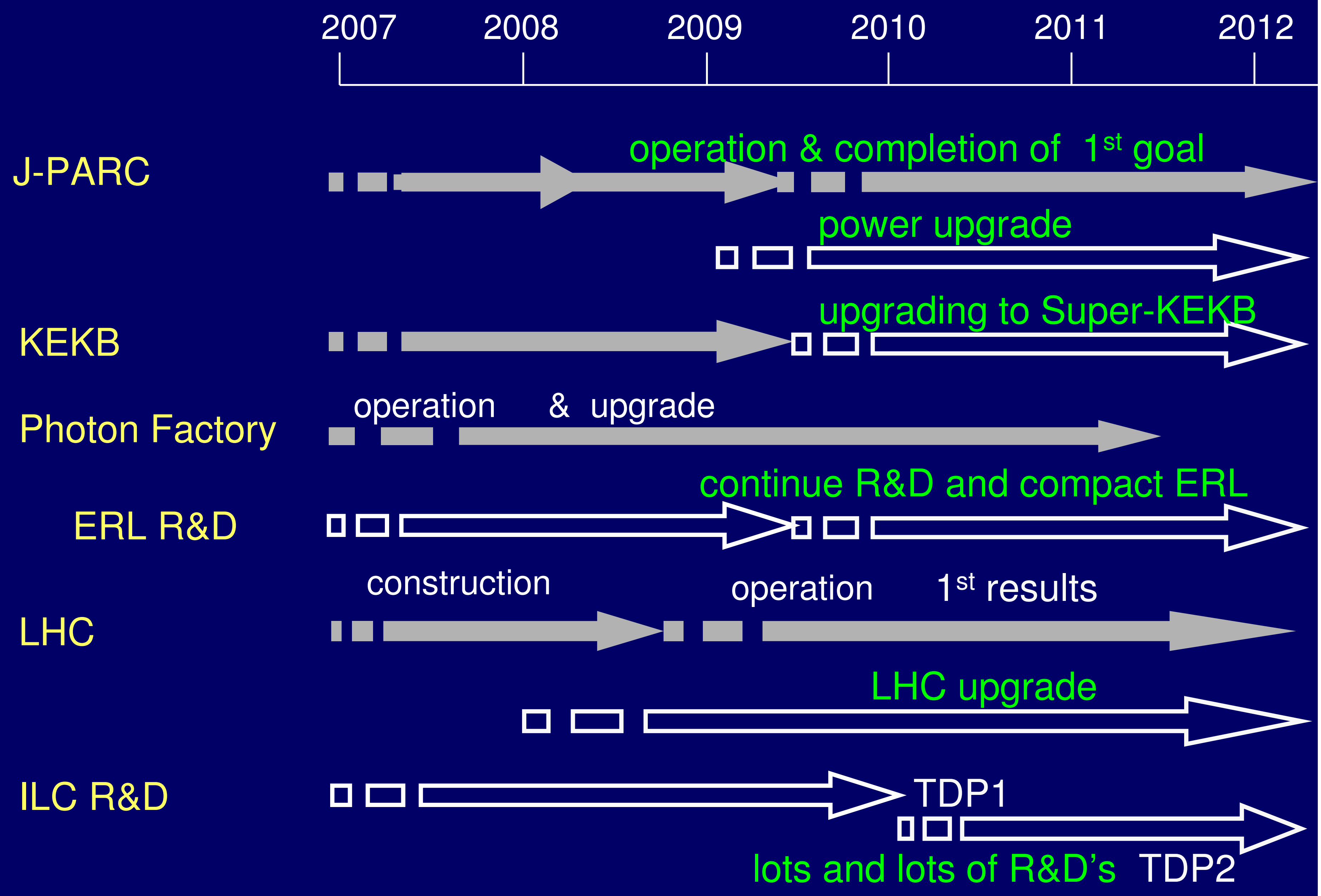
TOWARDS SuperB-factory

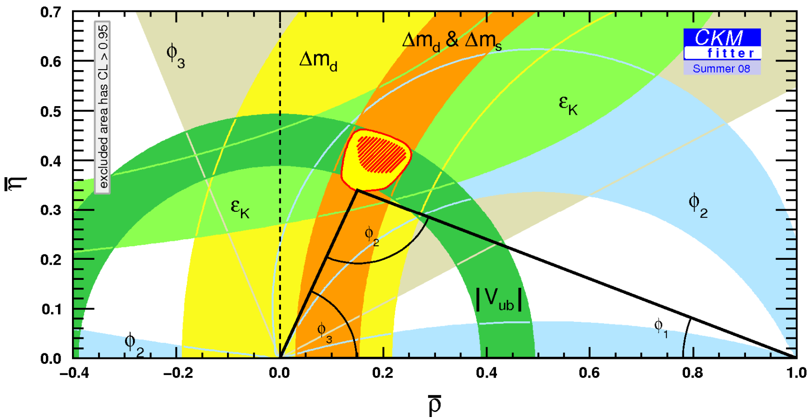


The needed decay modes & techniques established at B-factories

Summary of KEK Roadmap

(A.Suzuki)





$$A_{FB}(B \to K^{*}\ell^{+}\ell^{-}) = -C_{10}\xi(q^{2})\left[Re(C_{9})F_{1} + \frac{1}{q^{2}}C_{7}F_{2}\right]$$

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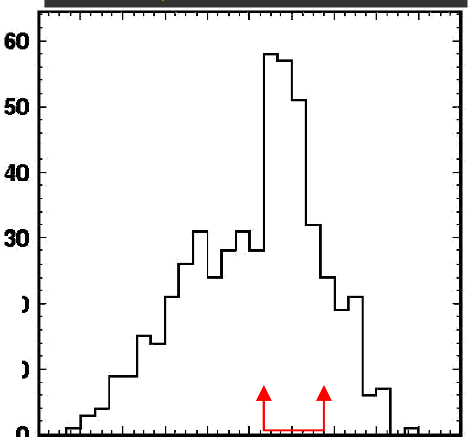
$$BF(B_s \to D_s^{-}\pi^{-}) = (3.67^{+0.35}_{-0.33}(stat)^{+0.43}_{-0.42}(syst) \pm 0.49(norm)) \times 10^{-3}$$

requirements on $\cos\chi_{B,hl}$ $\overline{\mathrm{B}}$



Observed signal from a rare semileptonic B decay