Flavour Physics

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Outline

- Lecture 4
  - B physics
    - time-dependent CP violation
    - the B factories BaBar and Belle
    - measurements of UT angles β and α
    - the LHCb experiment (B physics at hadron machines)
    - searches for new physics in
      - B_s oscillations
      - rare B decays
  - Future flavour physics

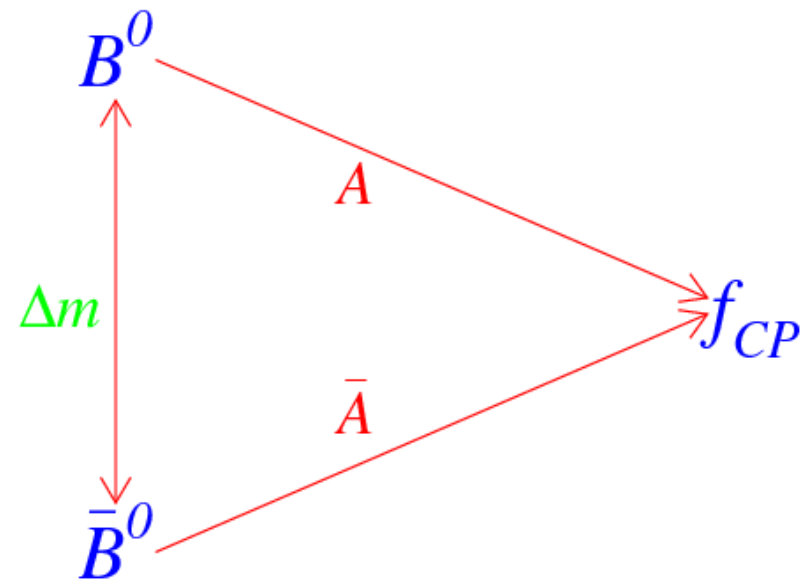
Some theory papers

- Ellis, Gaillard, Nanopoulos & Rudaz, NPB 131, 285 (1977)
- Bander, Silverman & Soni, PRL 43, 242 (1979)
  - CP violation may be large in the B system
- Carter & Sanda, PRD 23, 1567 (1981)
  - time-dependence in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\underline{B}^0$
- Bigi & Sanda, NPB 193, 85 (1981)
  - $B^0 \rightarrow J/\psi\ K_s$ and other possible decay modes

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$



$$\left|\frac{q}{p}\right| \neq 1$$ CP violation in mixing

$$\left|\frac{\overline{A}}{A}\right| \neq 1$$ CP violation in decay (direct CPV)

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$ CP violation in interference between mixing and decay

Neutral B mixing parameters

- Recall: $q/p = -(\Delta m - \frac{1}{2}i\Delta\Gamma)/2(M_{12} - \frac{1}{2}i\Gamma_{12})$

  $(\Delta m)^2 - \frac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \frac{1}{4}|\Gamma_{12}|^2)$ $\quad \Delta m\Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$

- In the neutral B system $\Delta m >> \Delta\Gamma$

  $\Delta m \sim 2|M_{12}|$ $\quad \Delta\Gamma \sim 2\mathrm{Re}(M_{12}\Gamma_{12}^*)/|M_{12}|$ $\quad q/p \sim -|M_{12}|/M_{12}$

- $|M_{12}|$ from mixing diagram

  $\Rightarrow$ $\boxed{q/p \sim e^{-2i\beta}}$ (in the usual phase convention)

Evolution with time

- Consider a B meson which is known to be B^0 at time t=0
- At later time t:

amplitudes

$B^0_{(phys)}(\Delta t) =$

$$e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m\Delta t/2)\, B^0 + i\,(q/p)\, e^{-iMt}e^{-\Gamma t/2}\sin(\Delta m\Delta t/2)\, \underline{B}^0$$

- Similarly

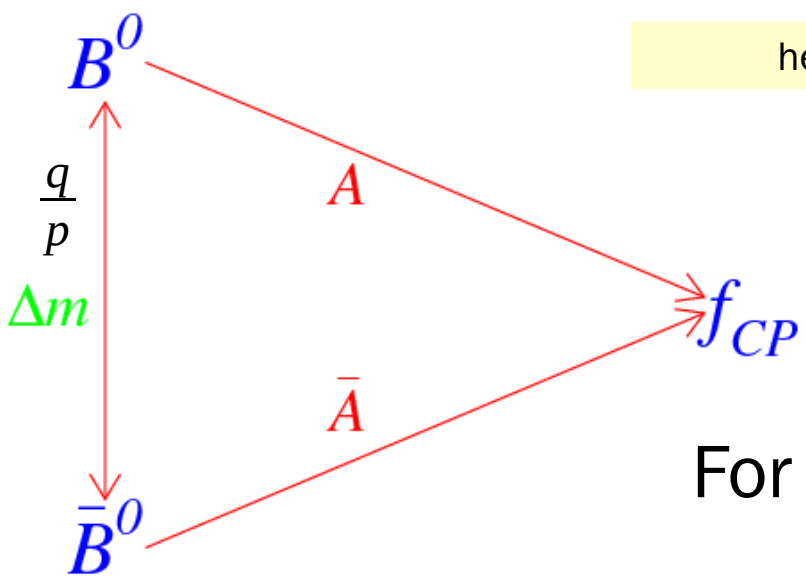
$\underline{B}^0_{(phys)}(\Delta t) =$

$$(p/q)\, i\, e^{-iMt}e^{-\Gamma t/2}\sin(\Delta m\Delta t/2)\, B^0 + e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m\Delta t/2)\, B^0$$

Time-Dependent CP Violation in the B^0–$\overline{B}^0$ System

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, that at later time t decays to the CP eigenstate f_{CP} :

$$\Gamma\left(B^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$
$$\Gamma\left(\overline{B}^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$



here assume ΔΓ negligible – will see full expressions later

$$S = \frac{2\,\Im(\lambda_{CP})}{1+\left|\lambda^2_{CP}\right|} \qquad C = \frac{1-\left|\lambda^2_{CP}\right|}{1+\left|\lambda^2_{CP}\right|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

For $B^0 \to J/\psi\, K_S$, $S = \sin(2\beta)$, $C=0$

NPB 193 (1981) 85

The golden mode – $B^0 \to J/\psi\ K_S$

- Dominated by $b \to c\underline{c}s$ tree diagram
  - subleading $b \to sc\underline{c}$ penguin has (predominantly) the same weak phase
- $|\underline{A}| = |A| \Rightarrow$ no direct CP violation
- $C = 0$ & $S = -\eta_{CP} \sin(2\beta)$
- Reasonable branching fraction & experimentally clean signature

Problem

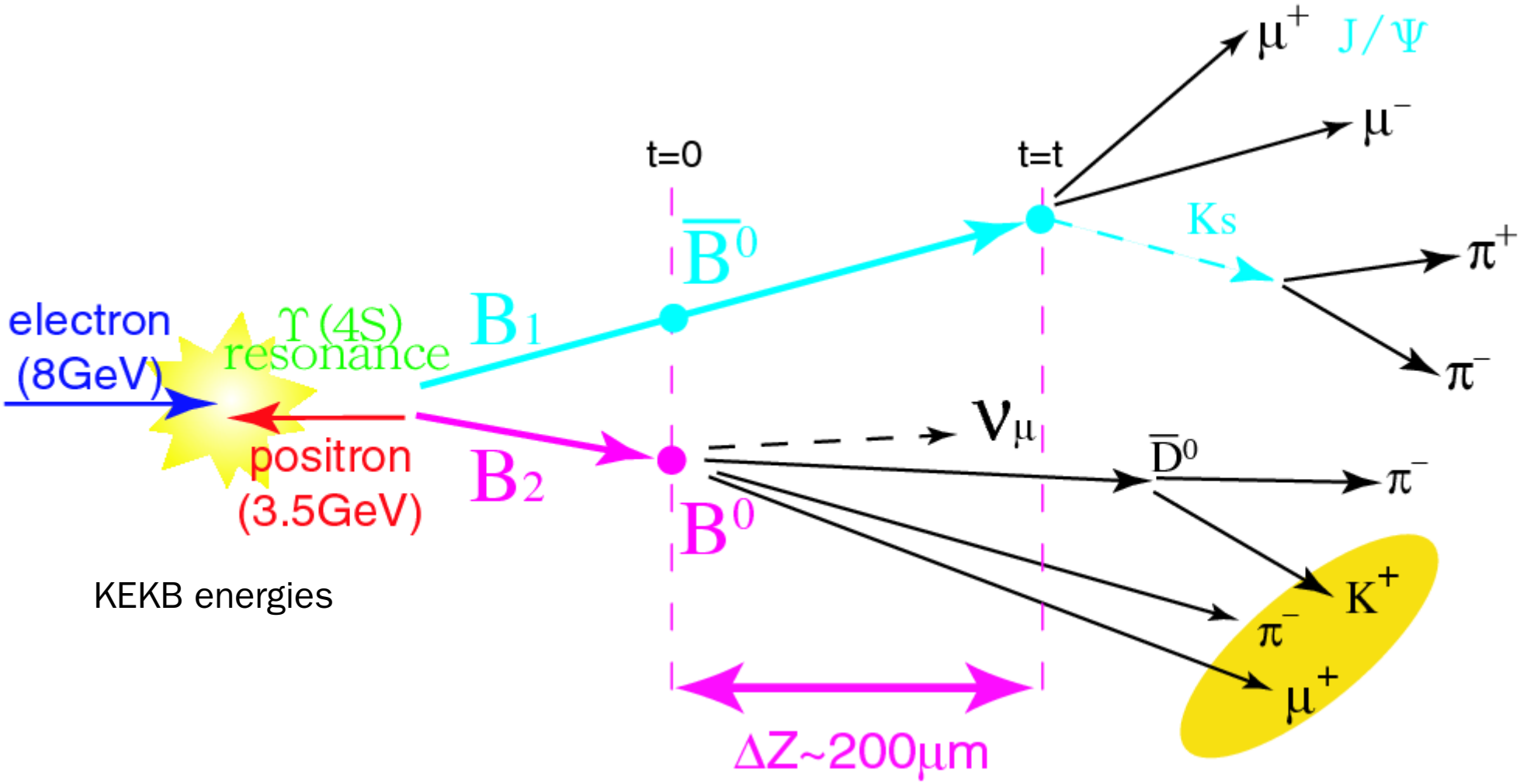
- How can we measure decay time in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\underline{B}^0$?

- The answer: (P.Oddone)

  <u>asymmetric-energy</u> B factory

- Key points
  - $\Upsilon(4S) \rightarrow B^0\underline{B}^0$ produces coherent pairs
  - B mesons are moving in lab frame

Asymmetric B factory principle

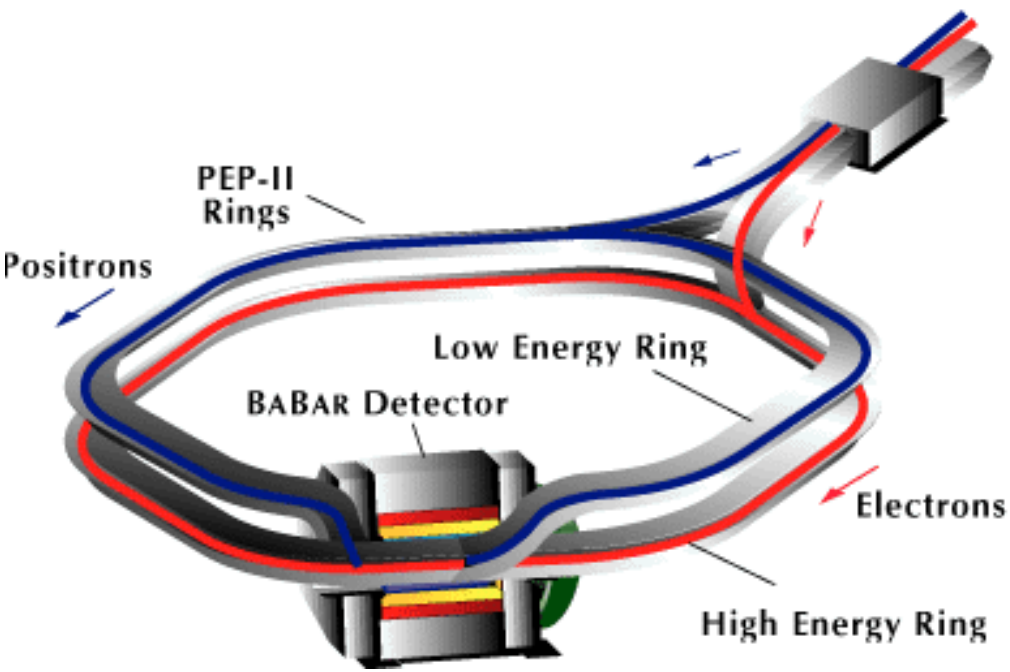


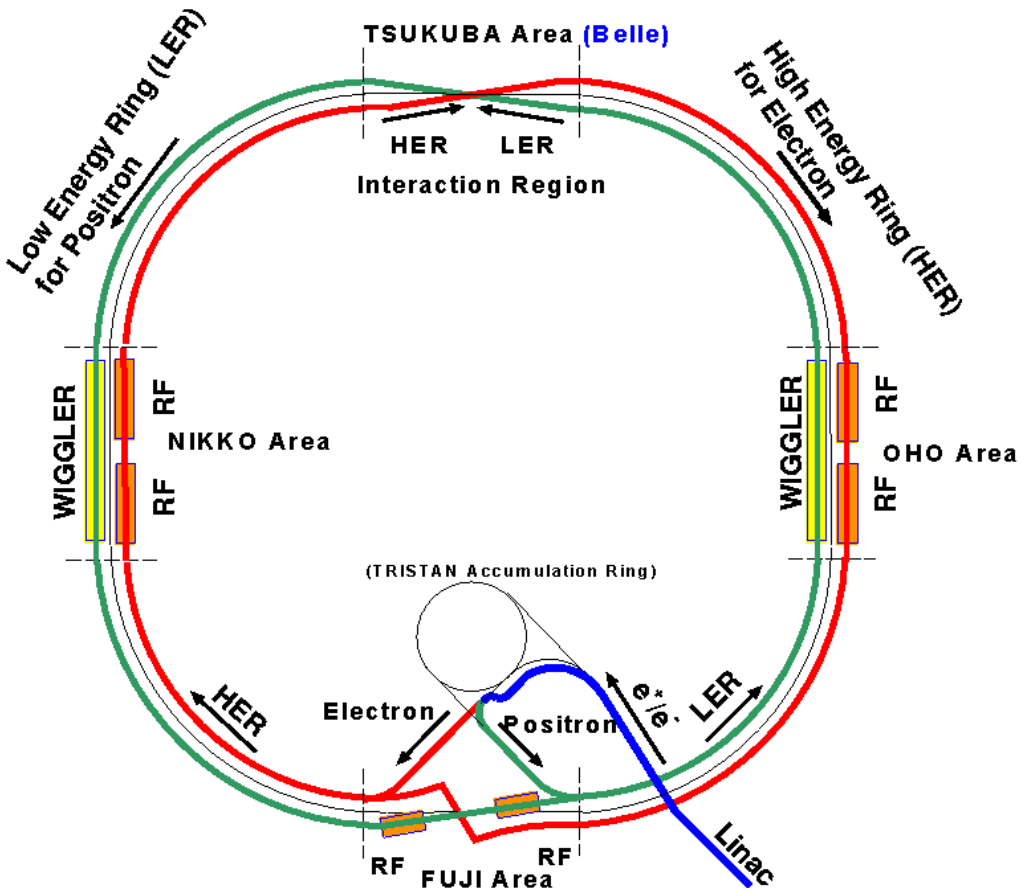
KEKB energies

Asymmetric B Factories

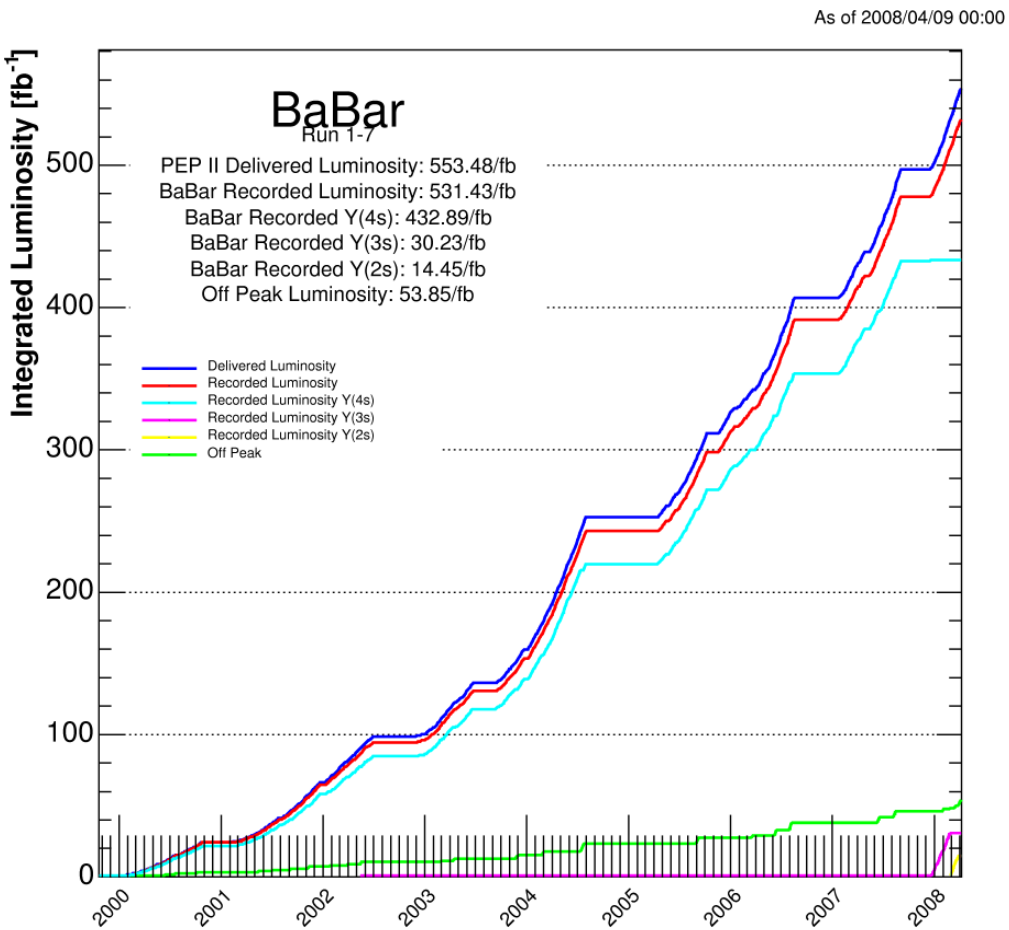
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+

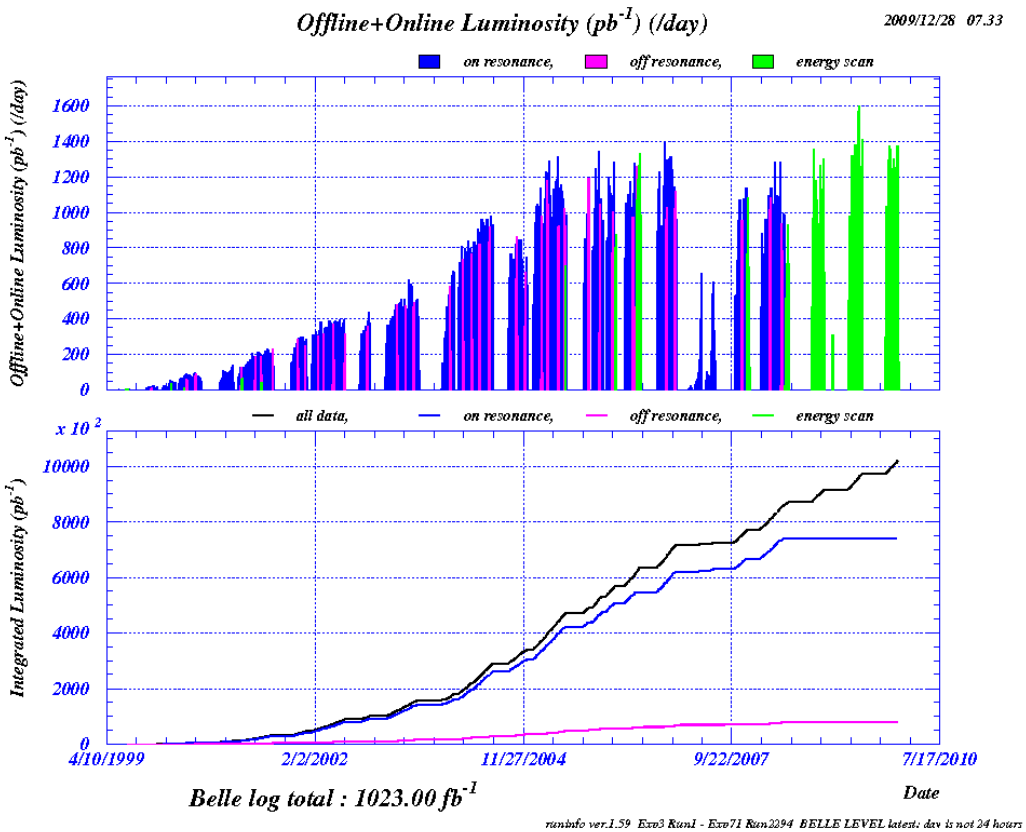




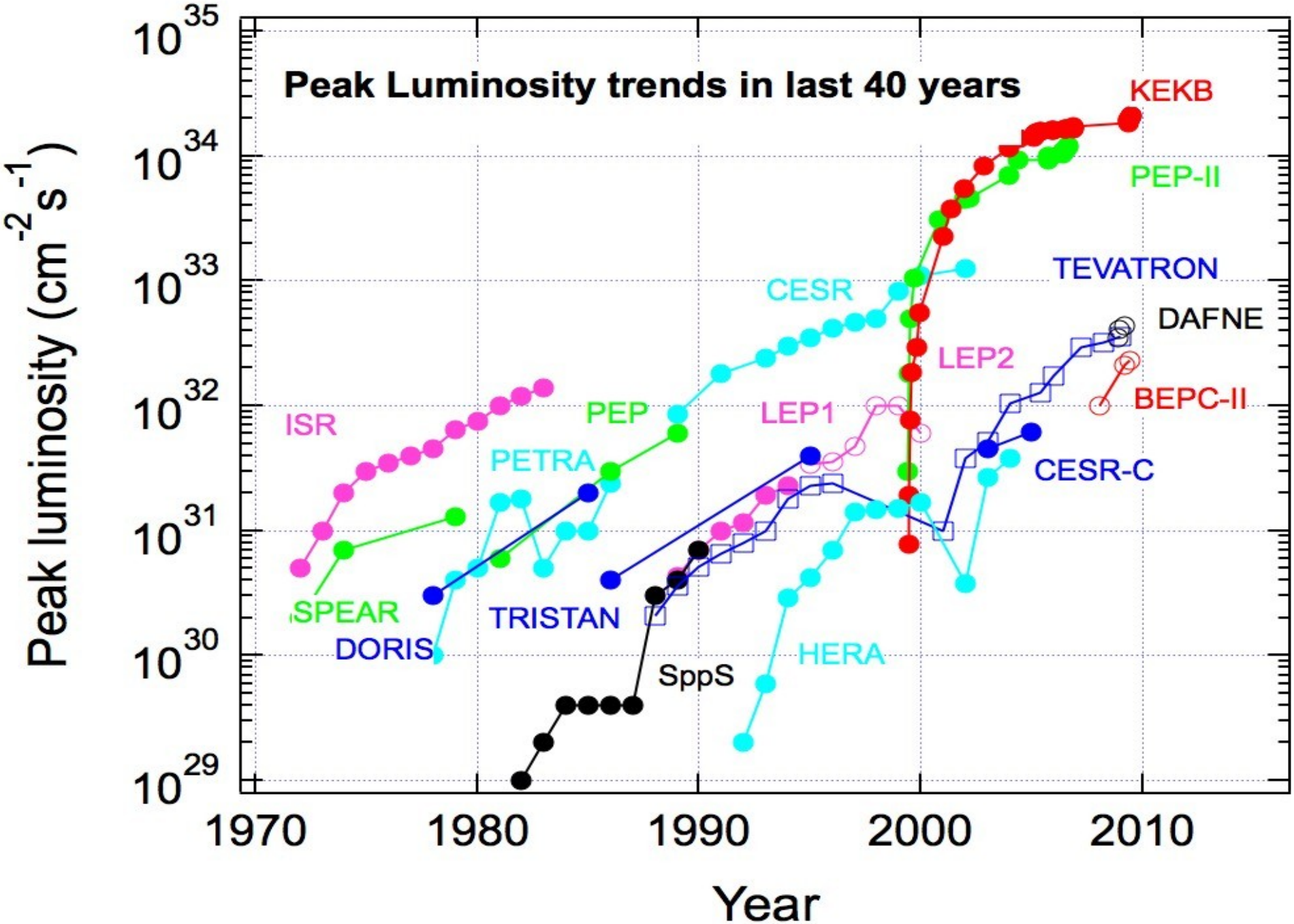
B factories – world record luminosities



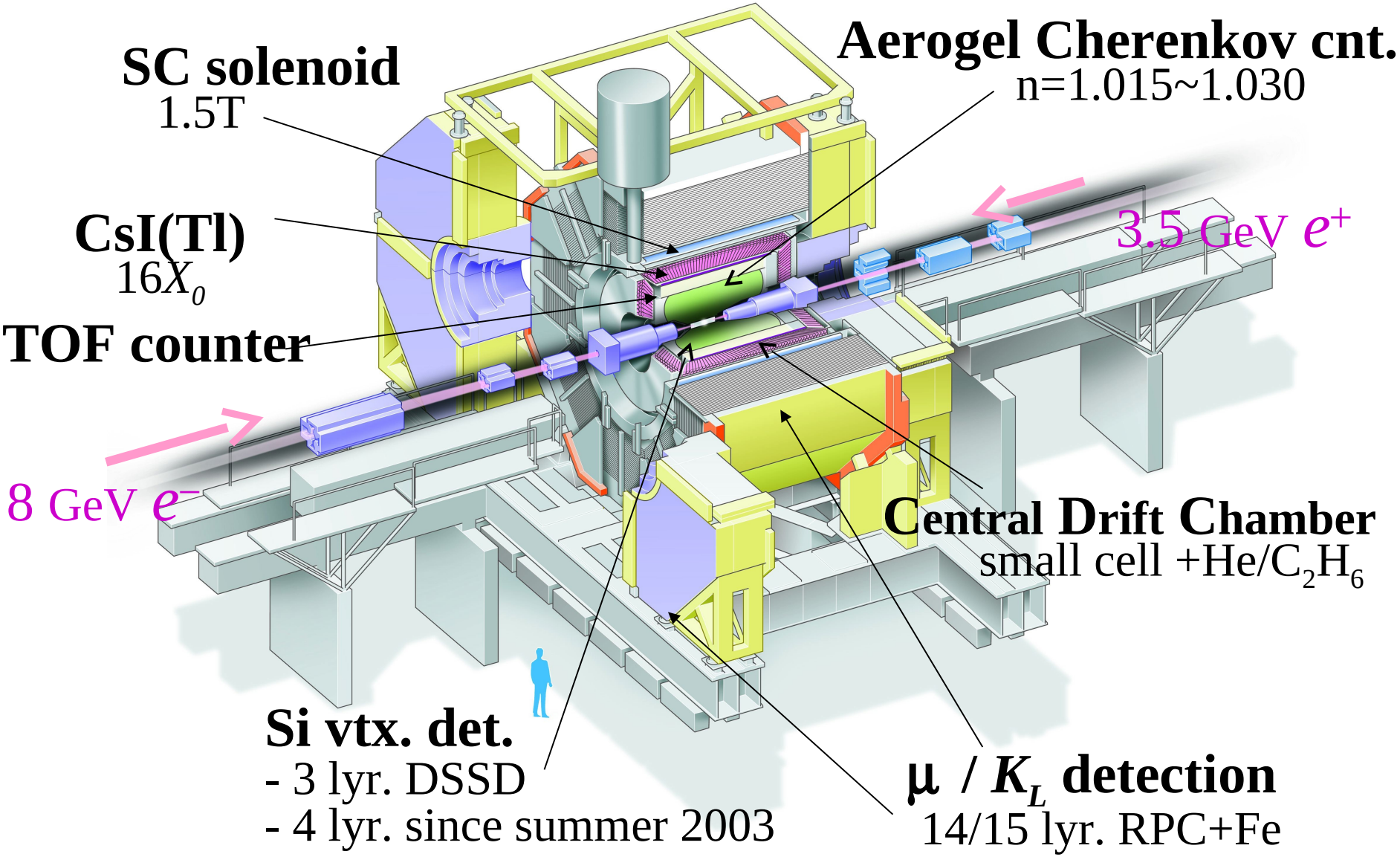
~ 433/fb on Y(4S)



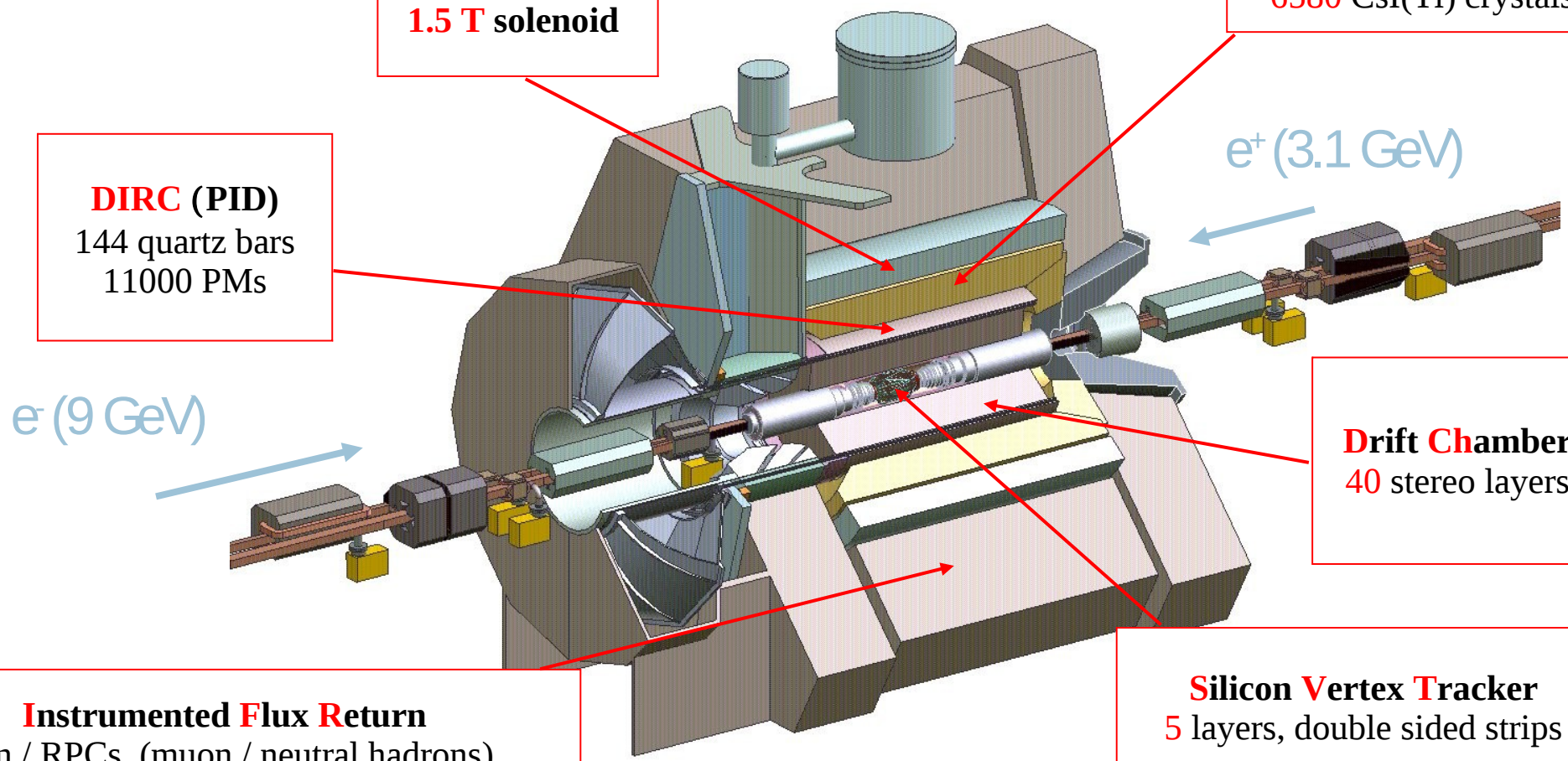
~ 711/fb on Y(4S)


Peak Luminosity trends in last 40 years
KEKB
PEP-II
TEVATRON
DAFNE
BEPC-II
CESR
LEP2
LEP1
PEP
ISR
PETRA
CESR-C
SPEAR
DORIS
TRISTAN
SppS
HERA
Peak luminosity (cm-2 s-1)
Year
10^35
10^34
10^33
10^32
10^31
10^30
10^29
1970
1980
1990
2000
2010

Belle Detector



BaBar Detector

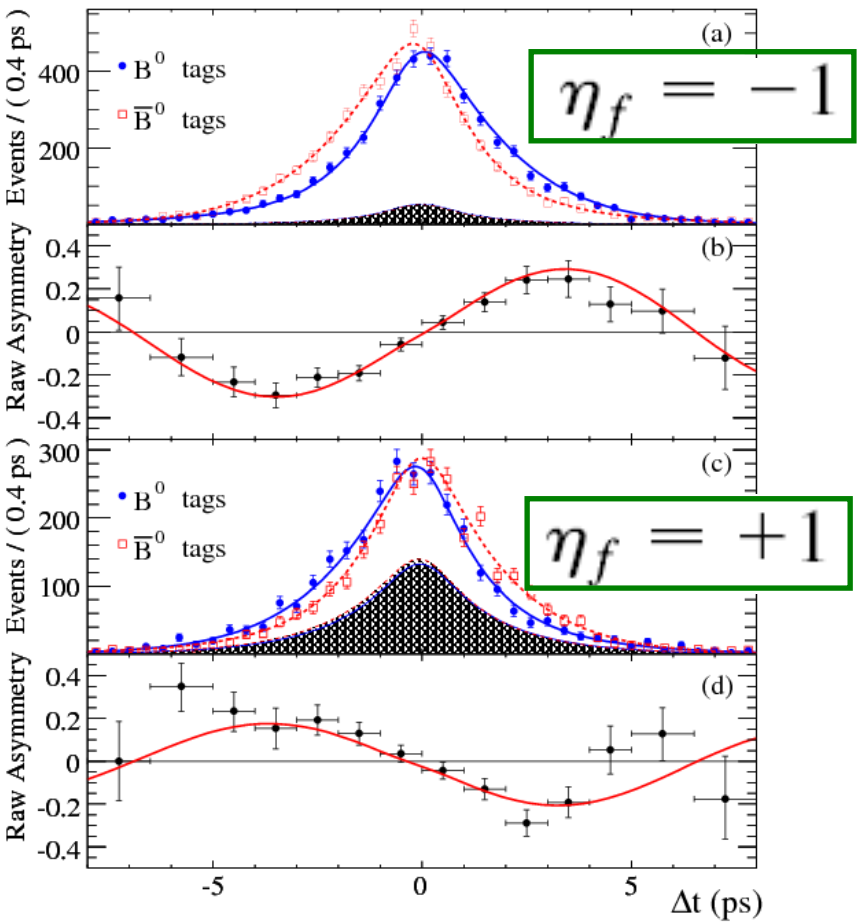


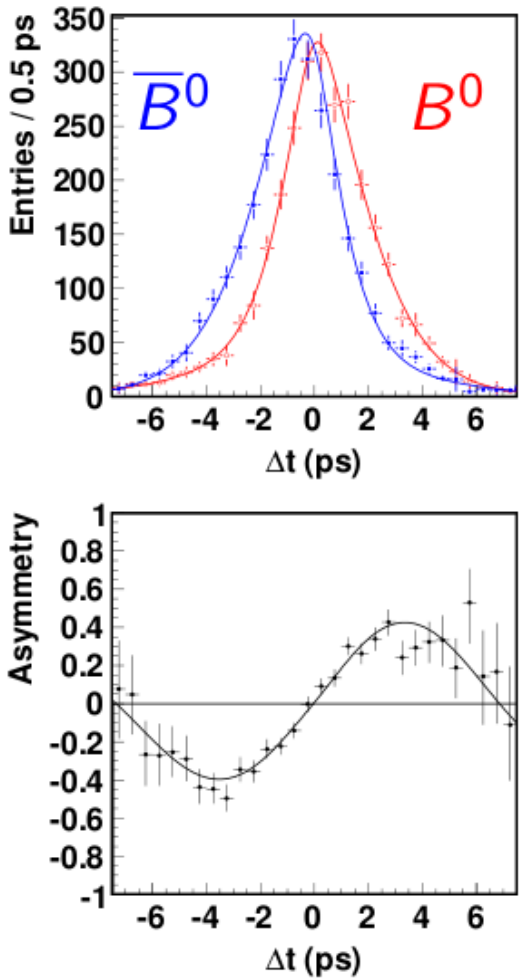
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)
2/6 replaced by LST in 2004
Rest of replacement in 2006

Results for the golden mode

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

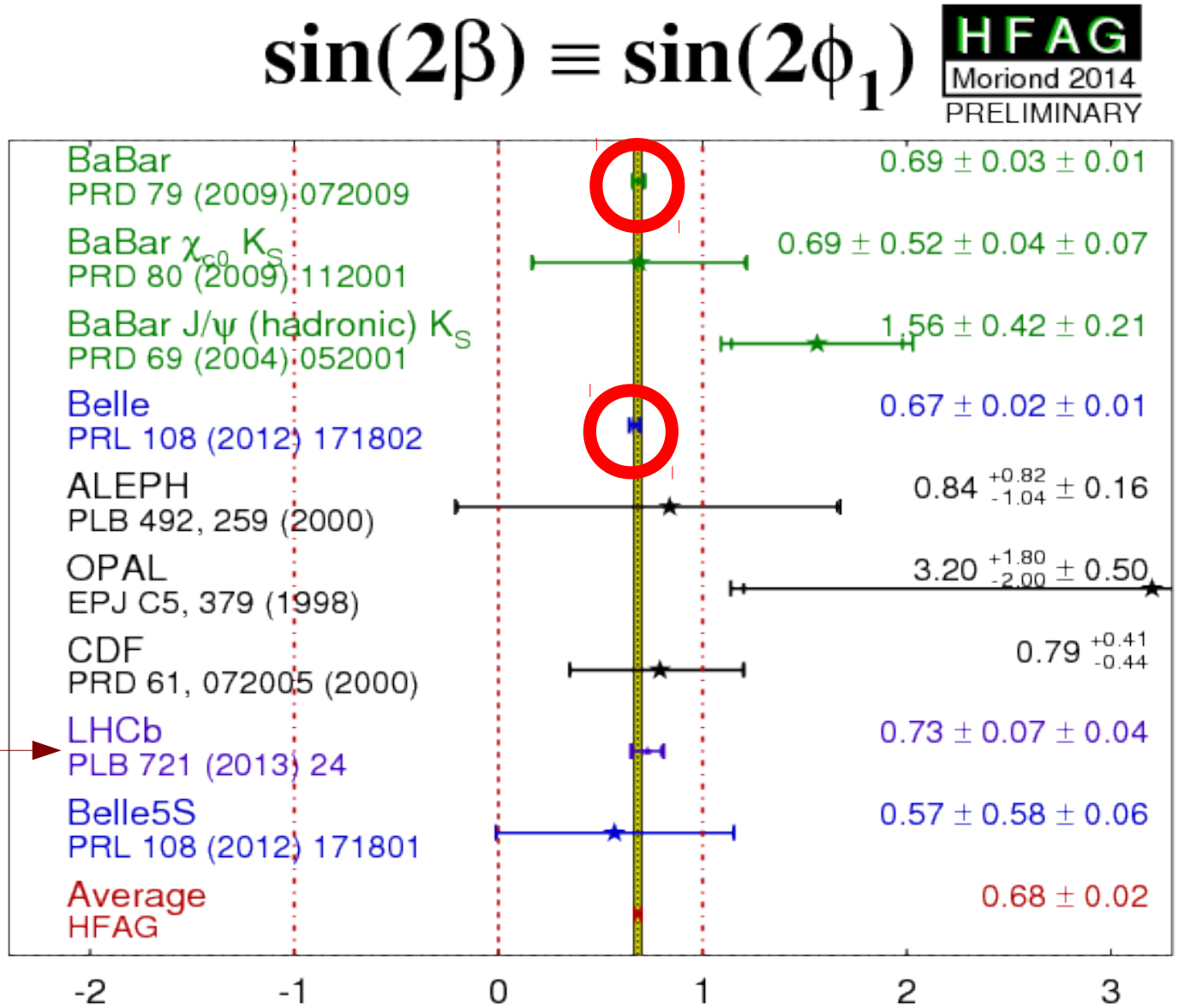
BABAR **BELLE**





PRD 79 (2009) 072009 **PRL 108 (2012) 171802**

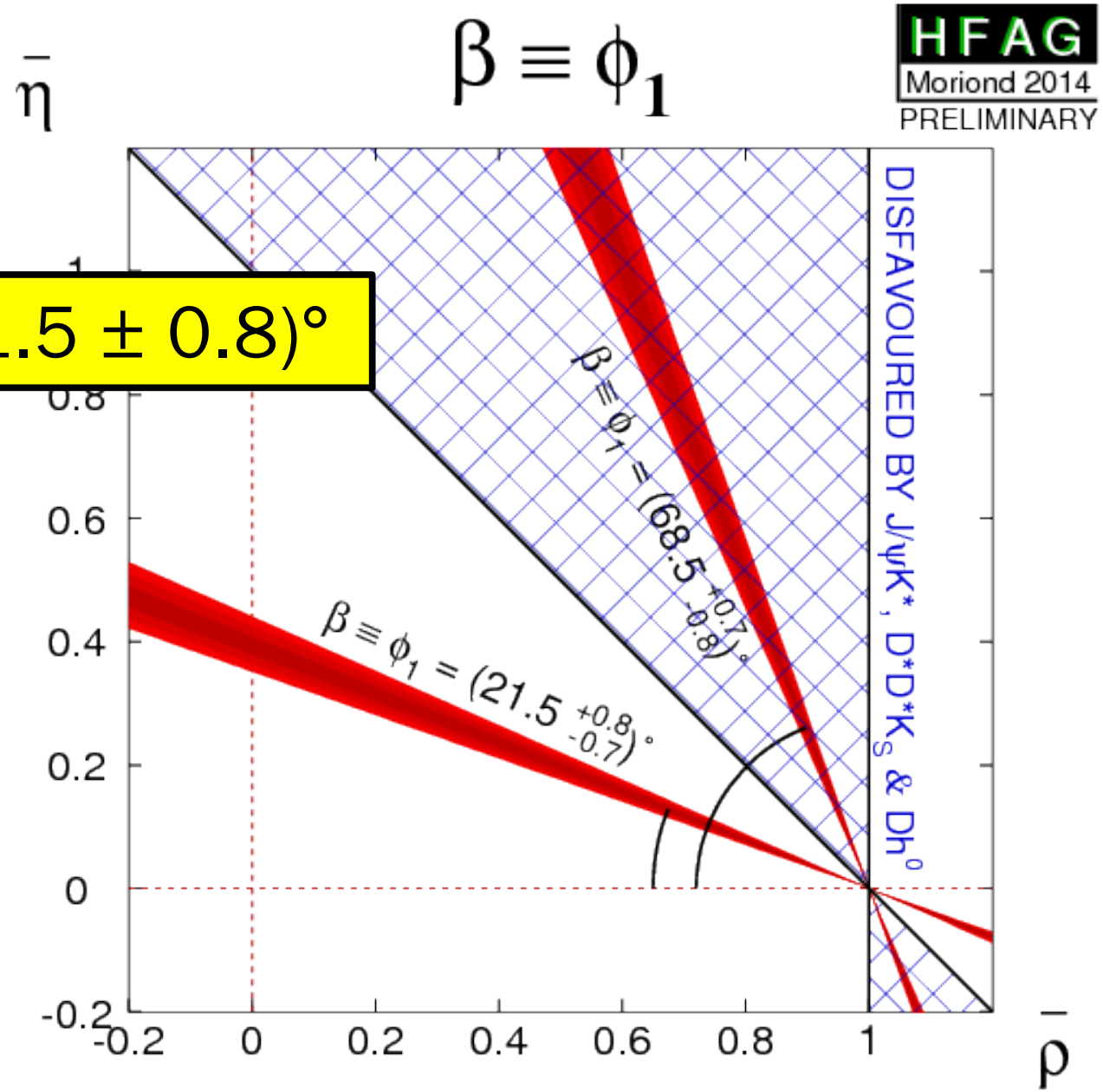
Compilation of results



Another taste of things to come (not yet world leading for this measurement)

Constraint from β measurement

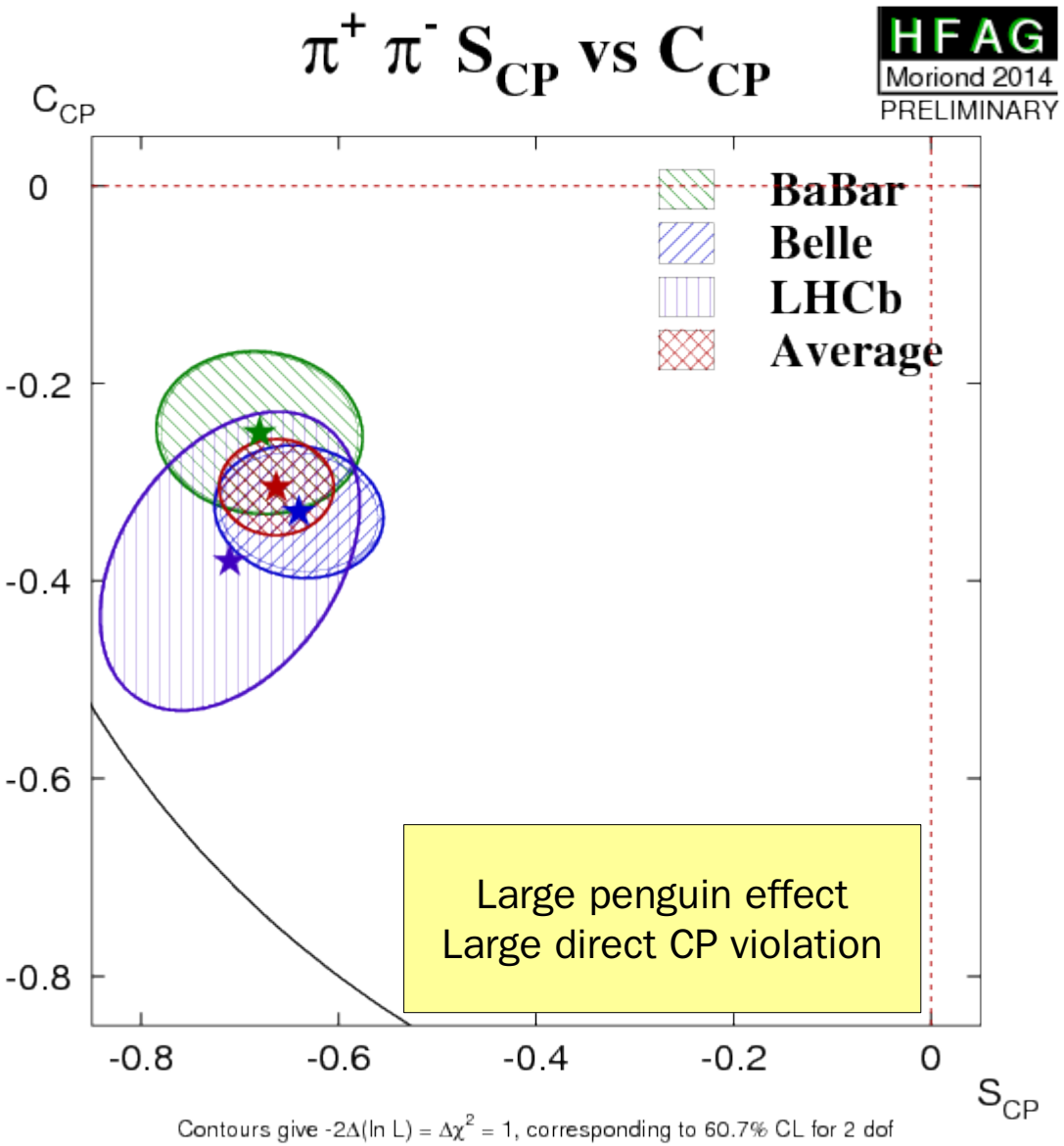
$\beta = (21.5 \pm 0.8)°$

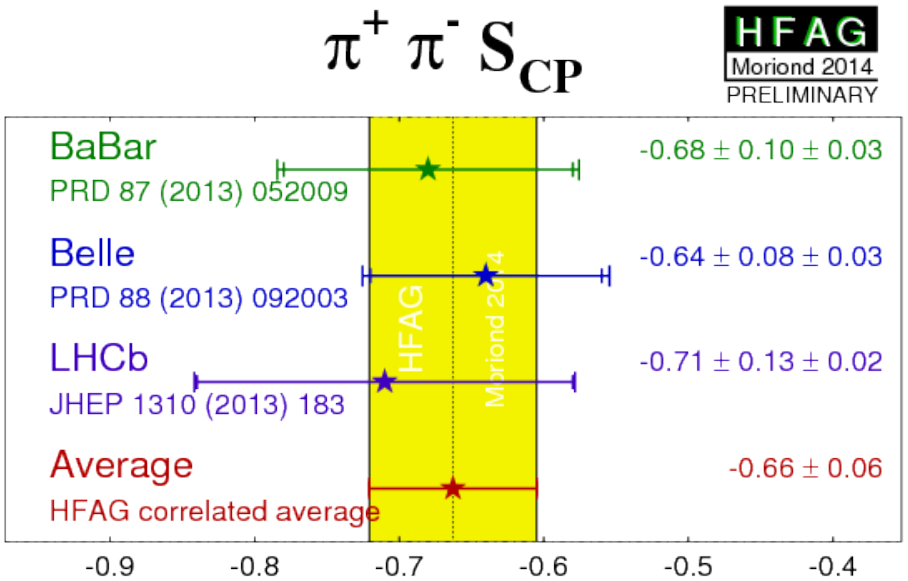


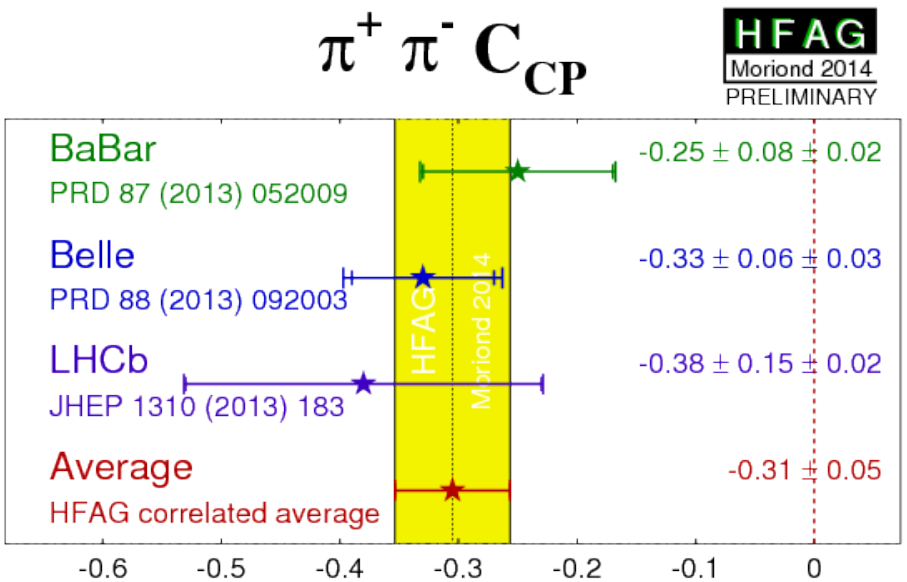
Measurement of α

- Time-dependent CP violation in modes dominated by $b \to u\underline{u}d$ tree diagrams probes α (or π–(β+γ))
  - $C = 0$ & $S = +\eta_{CP} \sin(2\alpha)$
- $b \to du\underline{u}$ penguin transitions contribute to same final states ⇒ "penguin pollution"
  - $C \neq 0 \Leftrightarrow$ direct CP violation can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$
- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

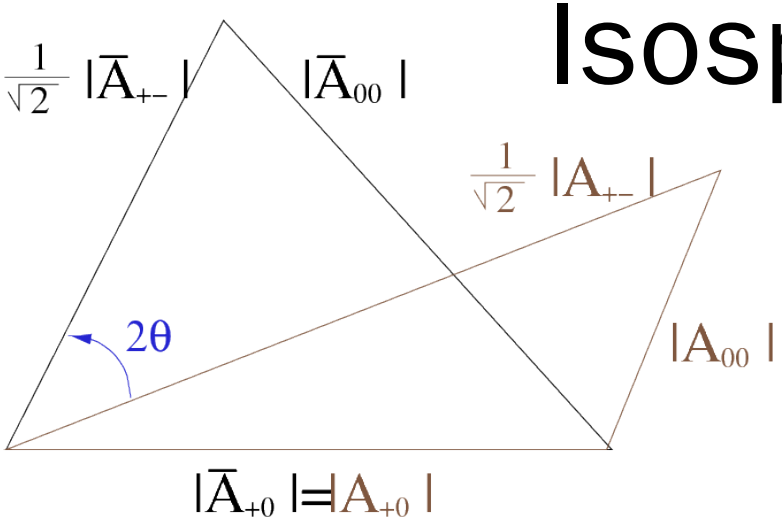
$B^0 \to \pi^+\pi^-$ -- Experimental Situation



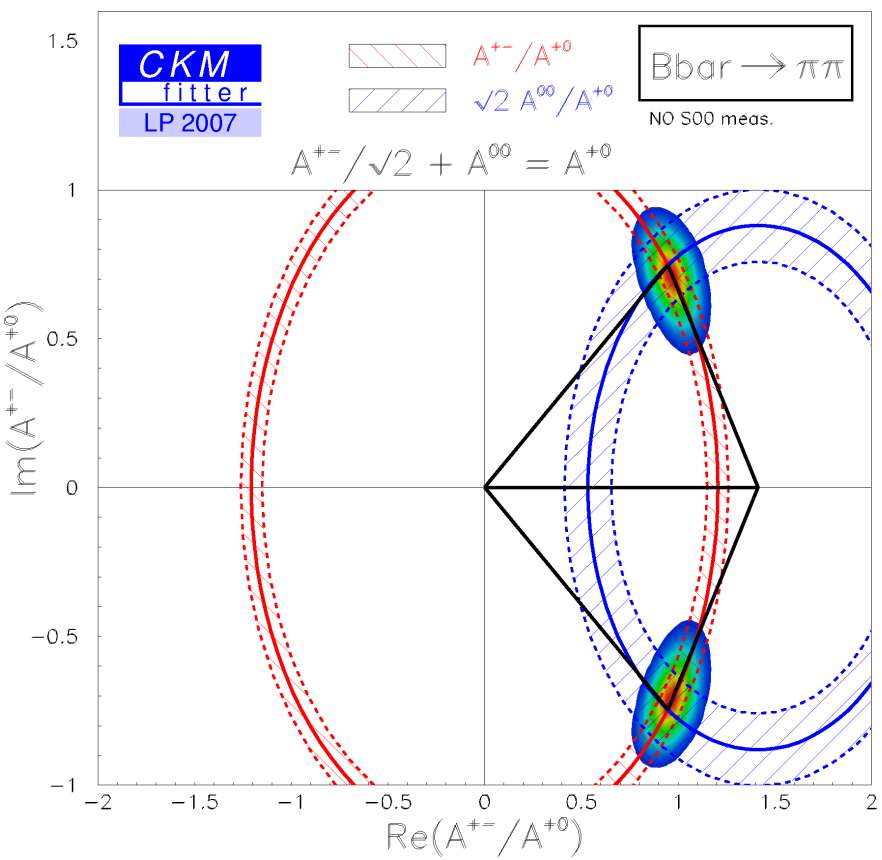


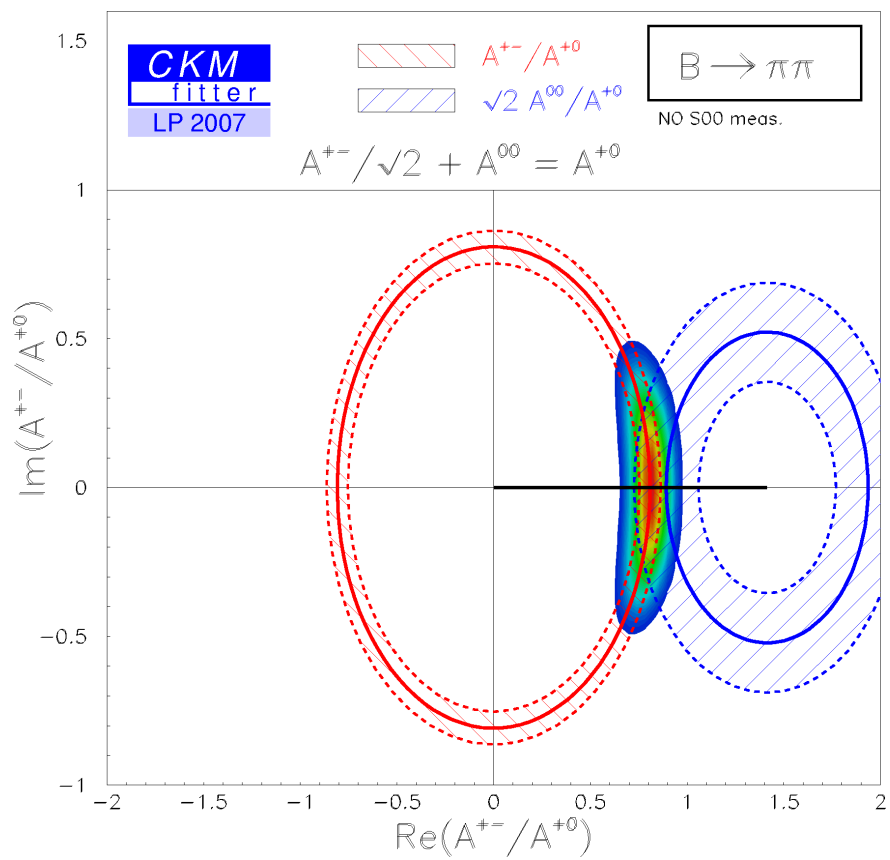


Isospin analysis

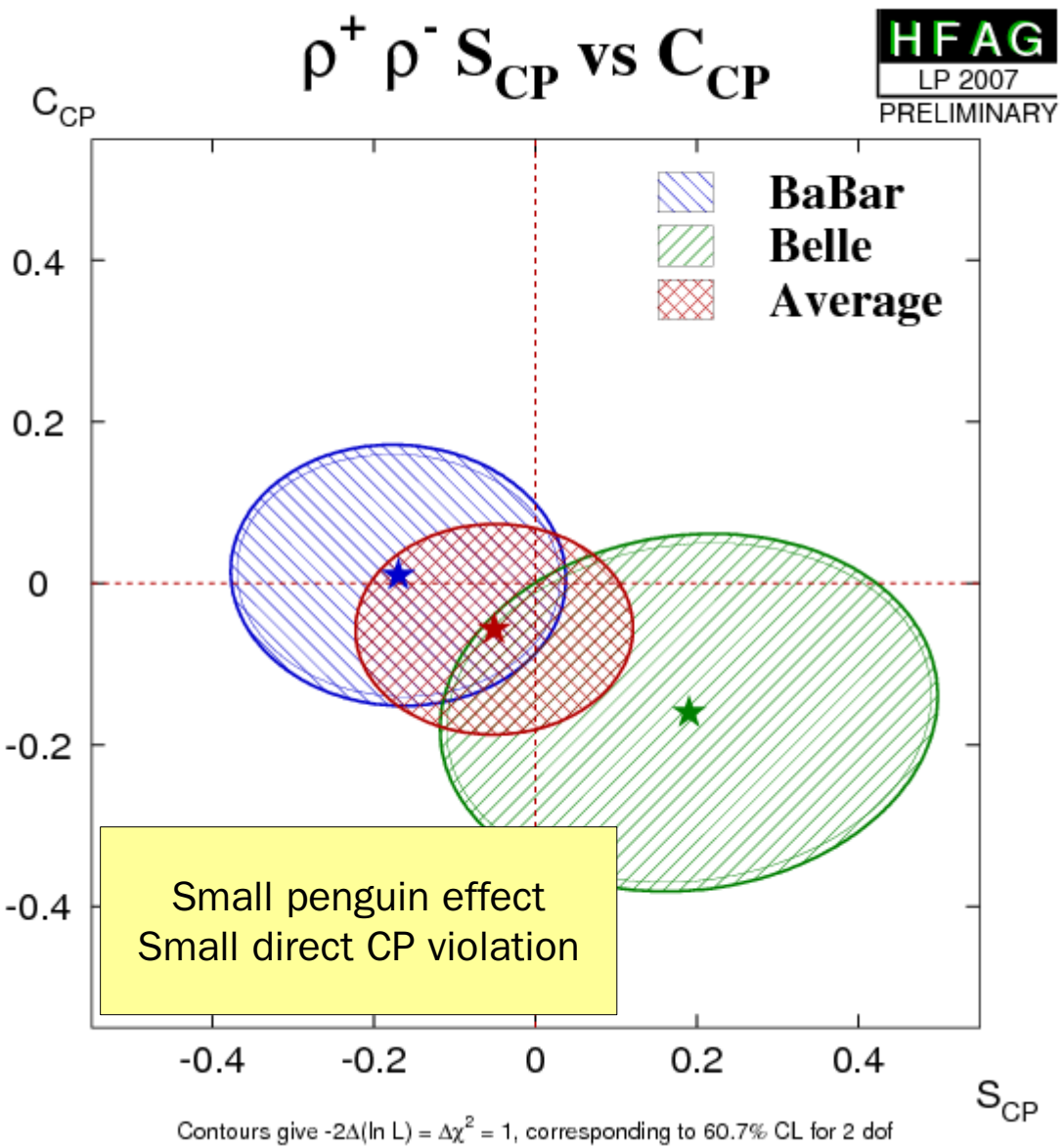


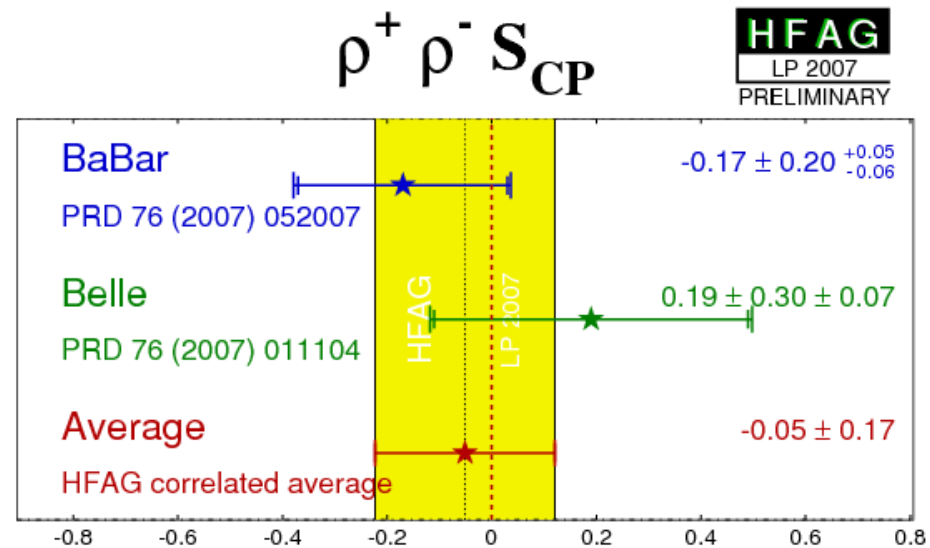
- Use triangle construction to find difference (θ) between "α_{eff}" and α
- Requires measurement of rates and asymmetries of $B^+ \to \pi^+\pi^0$ & $B^0 \to \pi^0\pi^0$

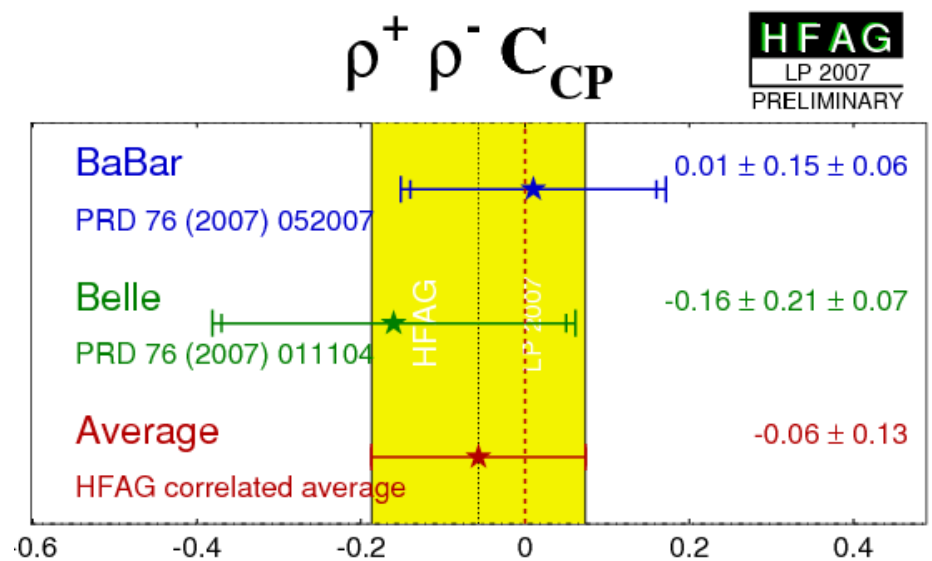




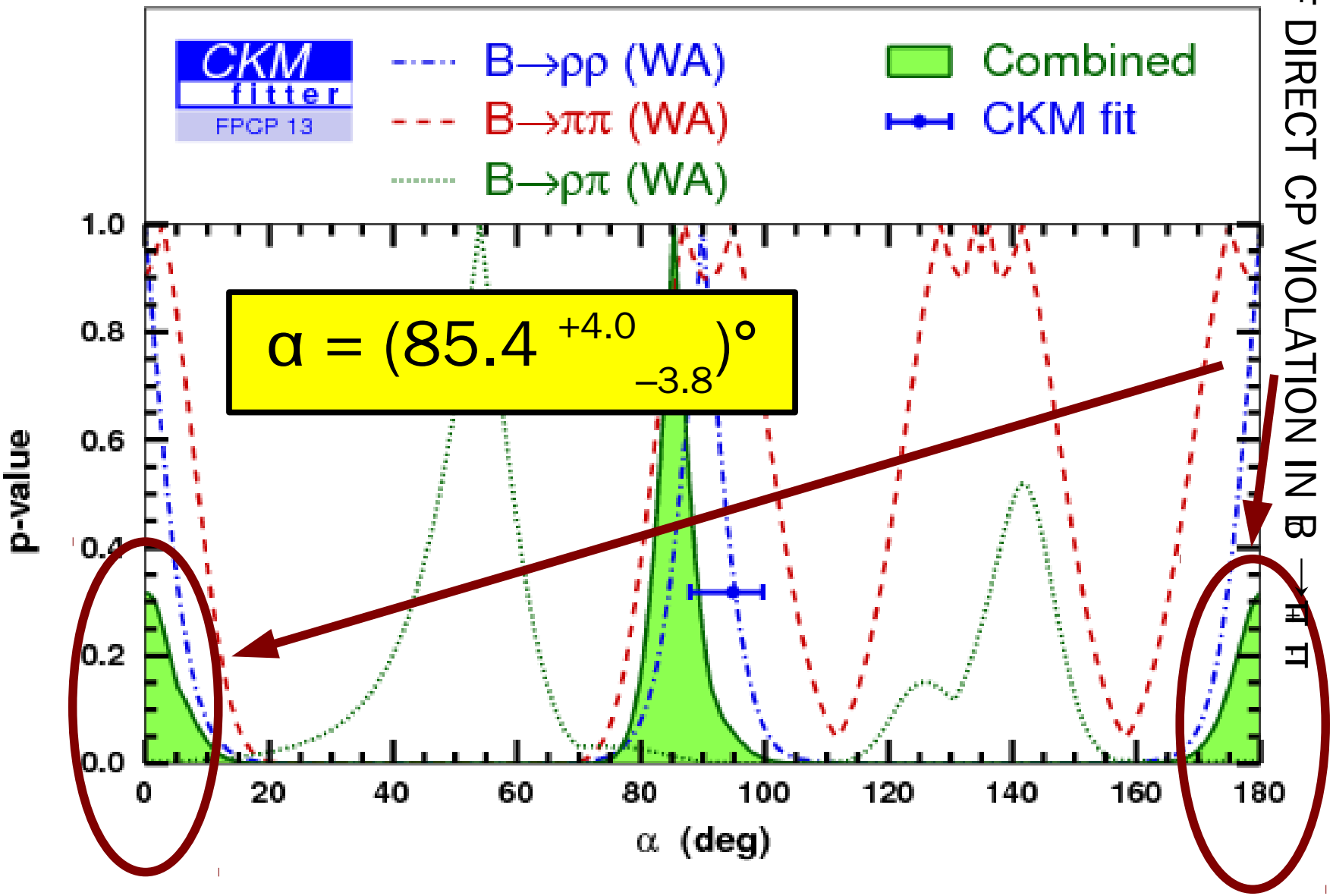
$B^0 \to \rho^+\rho^-$ -- Experimental Situation







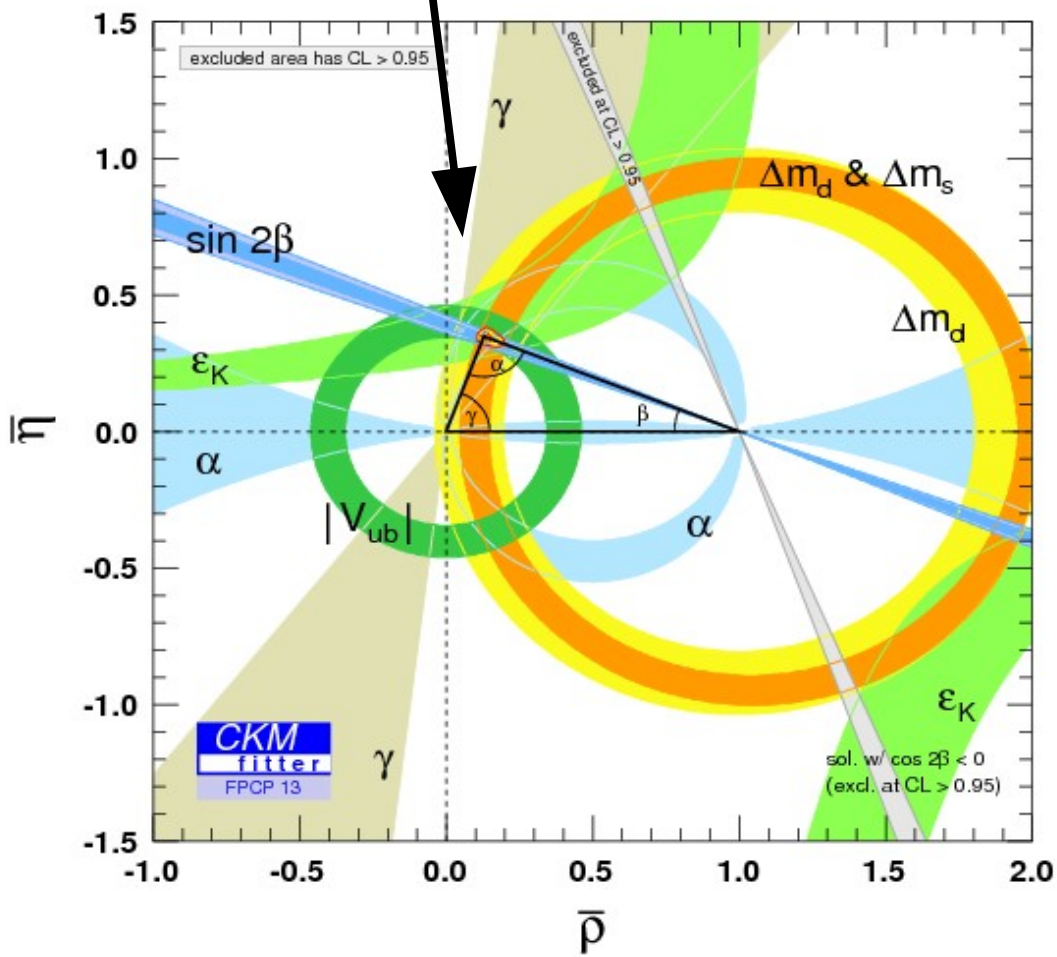
Measurement of α

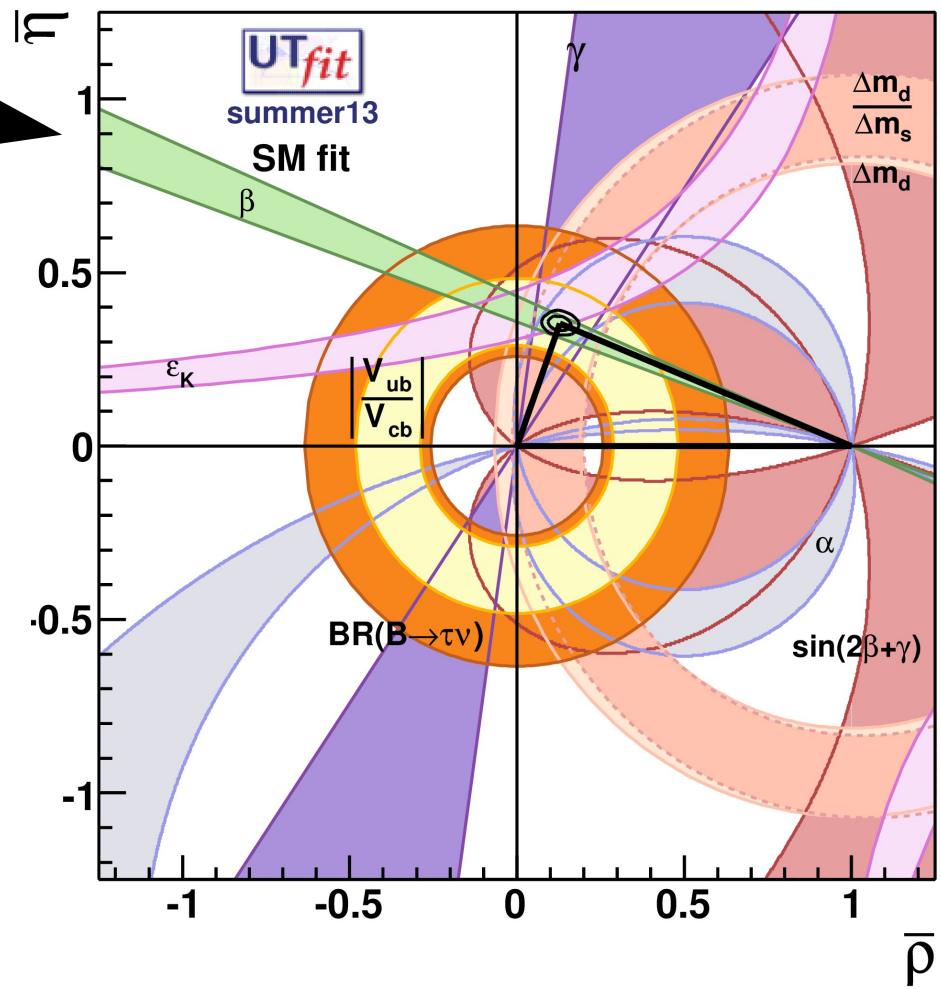


THESE SOLUTIONS RULED OUT BY OBSERVATION OF DIRECT CP VIOLATION IN $B \to \pi\pi$

Consistency of measurements with the KM mechanism

Different statistical approaches





… same answer

Where we are now ... and what's coming next

- Measurements of the CKM matrix elements and properties of the Unitarity Triangle are consistent with the Standard Model
  - Nobel Prize for Kobayashi and Maskawa in 2008
- Constraints for (beyond standard) model builders
  - Minimal Flavour Violation?
- Several hints (~3σ) for new physics
  - Plenty of room still for discoveries
  - Some sectors relatively unexplored
- Need next generation of flavour physics experiments

Constraints on NP from mixing

- All measurements of Δm & ΔΓ consistent with SM
  - K^0, D^0, B_d^0 and B_s^0
- This means $|A_{NP}| < |A_{SM}|$ where $\mathcal{A}_{\rm SM}^{\Delta F=2} \approx \frac{G_F^2 m_t^2}{16\pi^2}(V_{ti}^* V_{tj})^2 \times \langle \overline{M}|(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2|M\rangle \times F\left(\frac{M_W^2}{m_t^2}\right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings c_i and scale $\Lambda > m_W$ $\quad \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$
- For example, SM like (left-handed) operators $\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2}(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$

arXiv:1002.0900

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at the TeV scale to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales
- There are still important observables that are not yet well-tested

NPB 645 (2002) 155

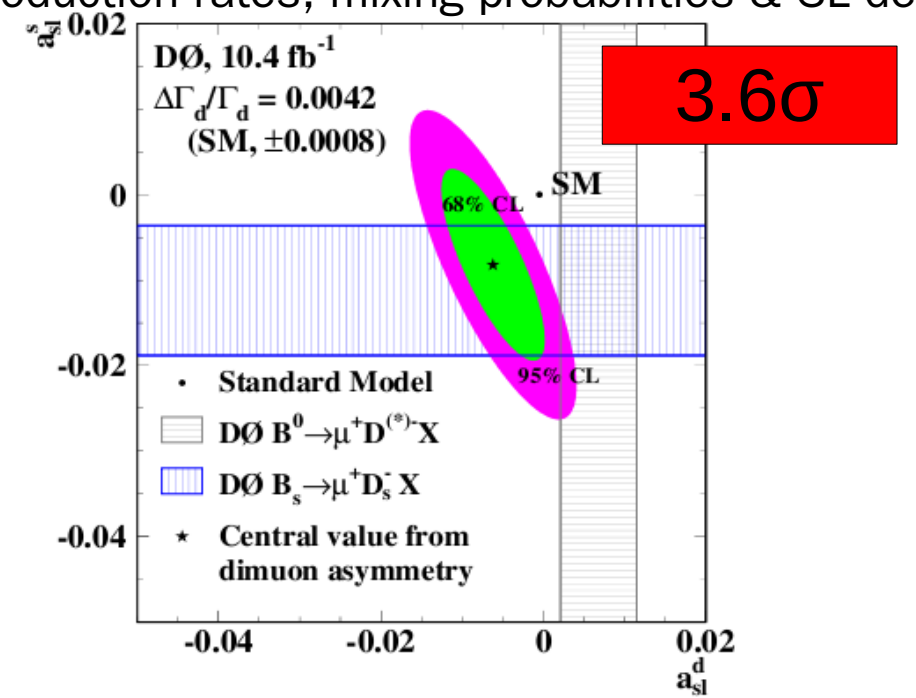
Searches for New Physics

- Massive, beyond SM, particles may contribute to B decay processes in loop diagrams
  - same true for kaon, charm & charged lepton physics
  - strong constraints in NP model building (flavour problem)
- Particularly interesting (not yet well tested) are $b \to s$
  - B_s mixing
  - $b \to sg$ (eg. time-dependence in $B^0 \to \varphi K_S$, etc.)
  - $b \to s\gamma$ (eg. rates and moments, TDCPV in $B^0 \to K_S \pi^0 \gamma$)
  - $b \to s l^+ l^-$ (eg. FB asymmetry in $B \to K^* l^+ l^-$)
  - $b \to s \nu \underline{\nu}$ (also $s \to d \nu \underline{\nu}$)

Like-sign dimuon asymmetry

- Semileptonic decays are flavour-specific
- B mesons are produced in $B\bar{B}$ pairs
- Like-sign leptons arise if one of $B\bar{B}$ pair mixes before decaying
- If no CP violation in mixing N(++) = N(——)
- Inclusive measurement ↔ contributions from both B_d^0 and B_s^0
  - relative contributions from production rates, mixing probabilities & SL decay rates

D0 experiment
Phys.Rev. D89 (2014) 012002



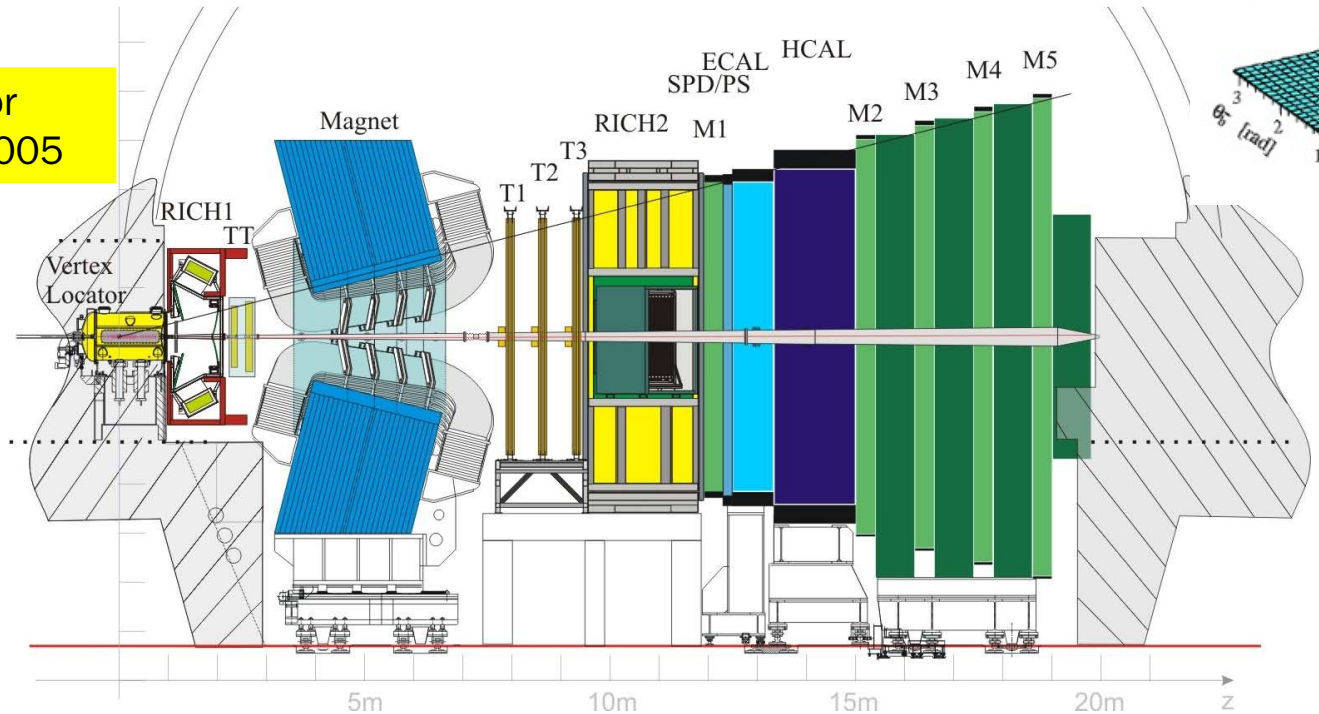
Flavour physics at hadron colliders

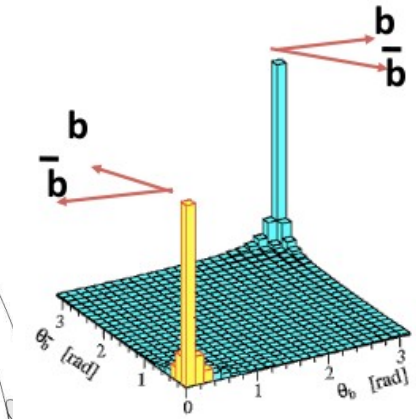
	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$)	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\text{TeV}$)
	PEP-II, KEKB	Tevatron	LHC
Production cross-section	1 nb	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\text{kHz}$	$\sim 500\,\text{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s^0 (10%), Λ_b^0 (10%), others ($< 1\%$)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

Geometry

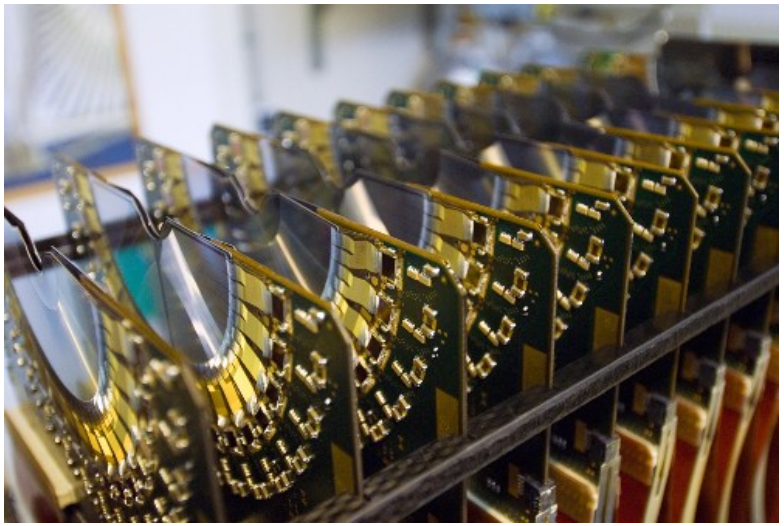
- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer

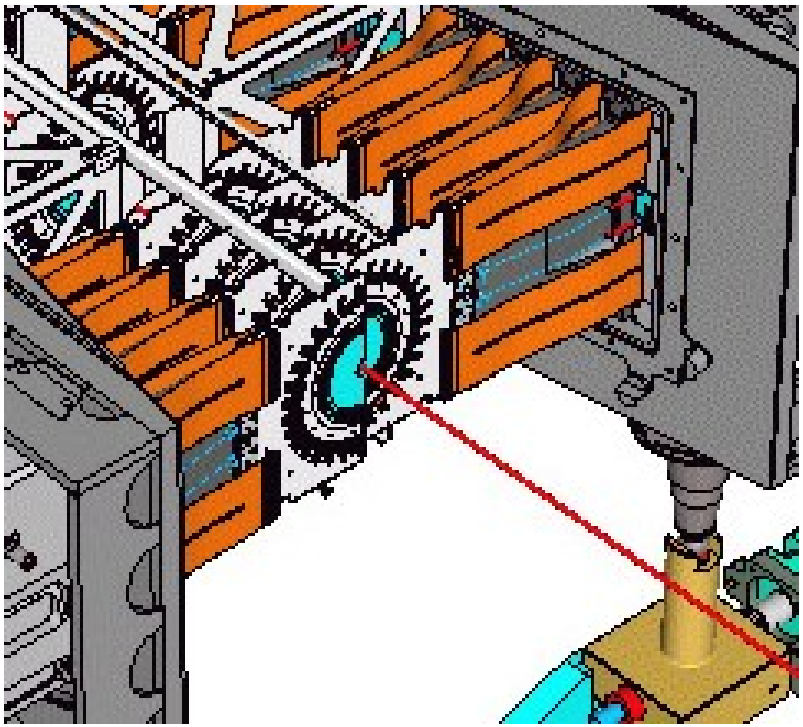
The LHCb Detector
JINST 3 (2008) S08005

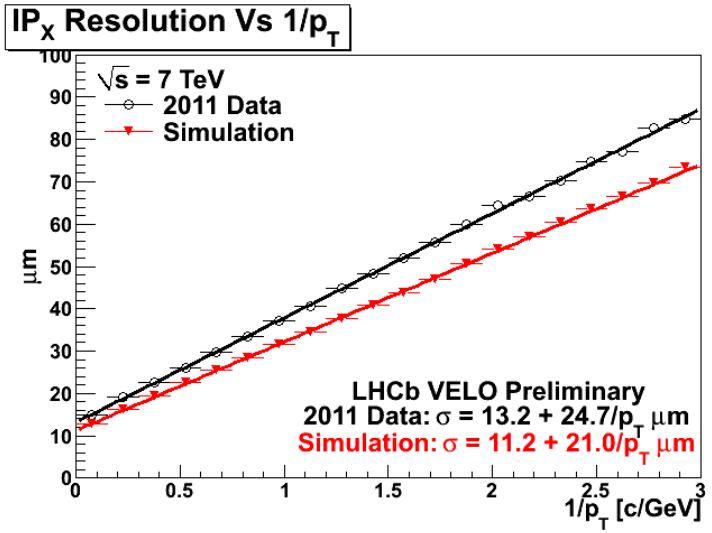




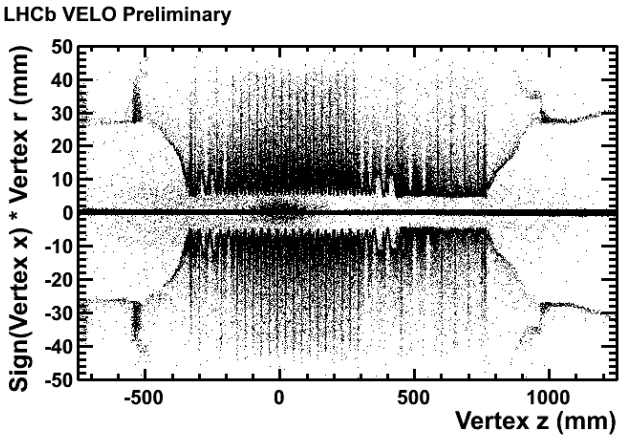
VELO

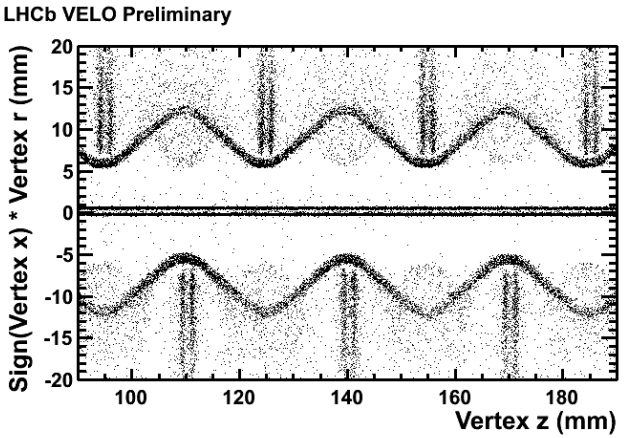




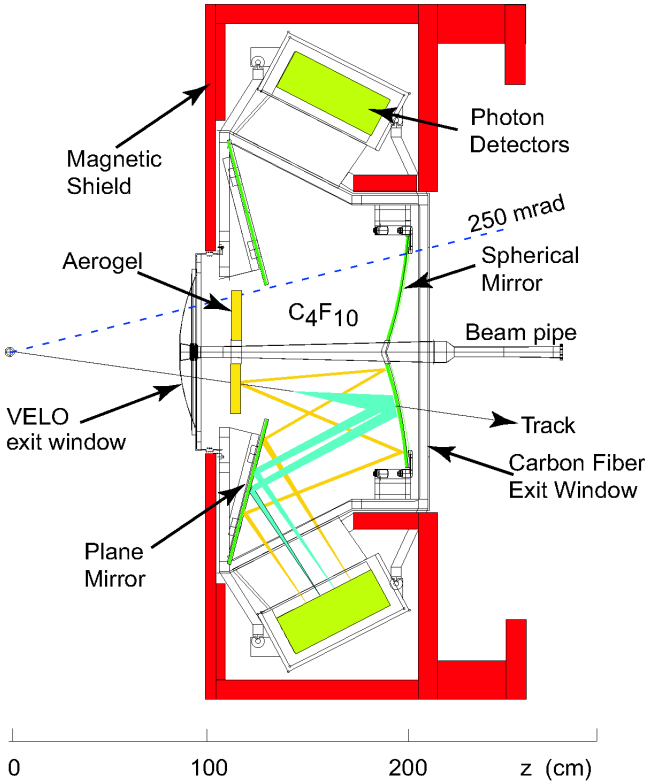


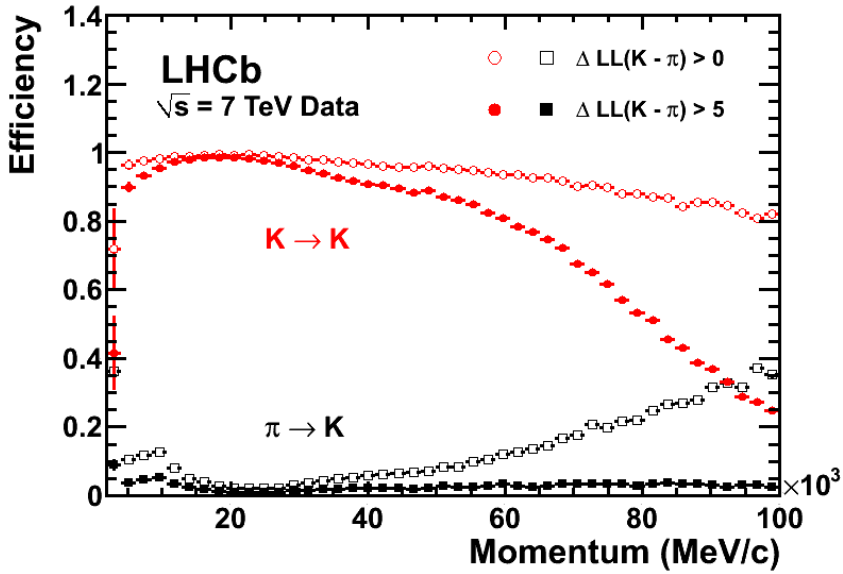
Material imaged used beam gas collisions

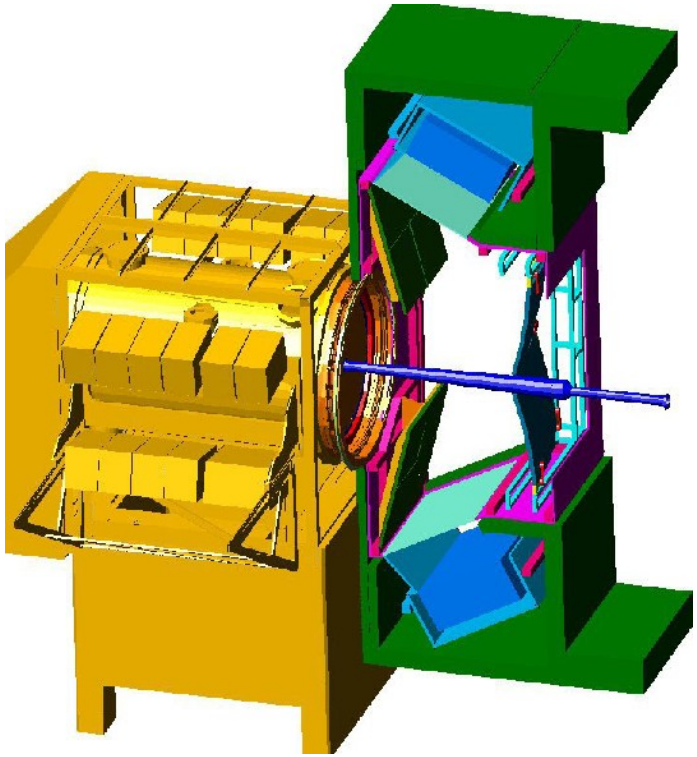




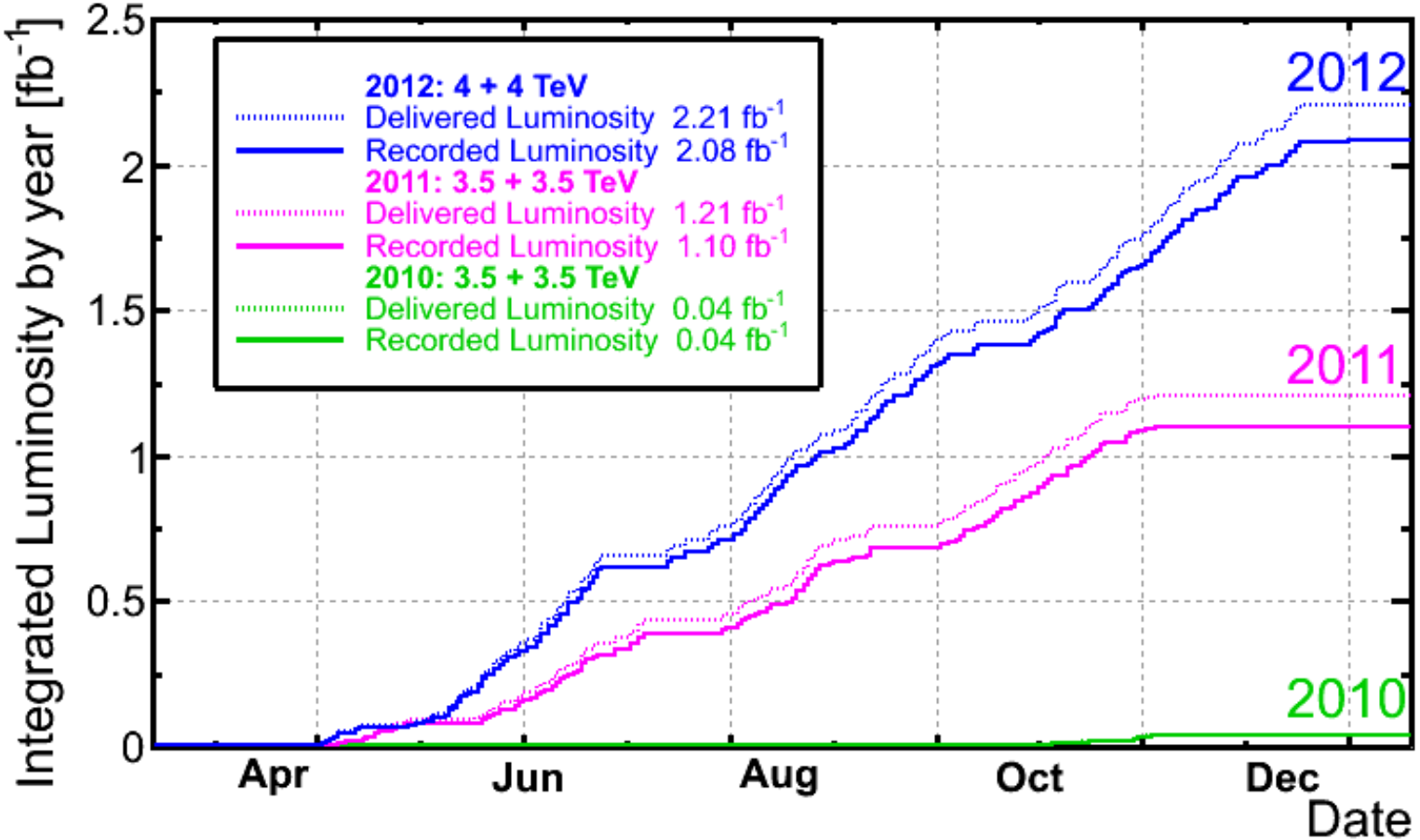
RICH


Magnetic Shield
Photon Detectors
250 mrad
Aerogel
Spherical Mirror
C_4F_{10}
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror
0
100
200
z (cm)

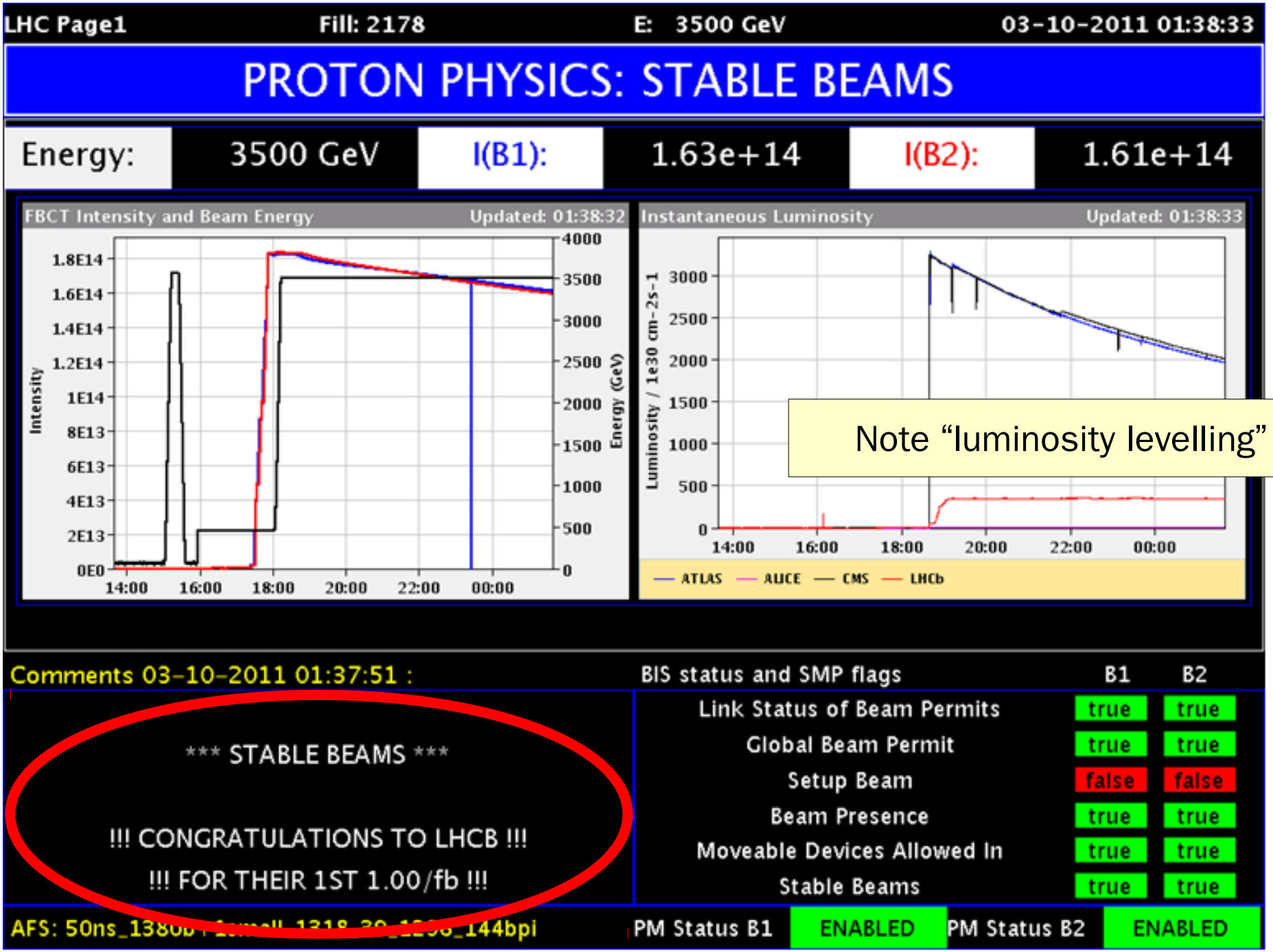

Efficiency
LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
1.4
1.2
1
0.8
0.6
0.4
0.2
0
20
40
60
80
100
$\times 10^3$
Momentum (MeV/c)



LHCb integrated luminosity



Instantaneous luminosity (2012) ~ 4 $10^{32}/cm^2/s$
LHCb design luminosity: 2 $10^{32}/cm^2/s$



Note “luminosity levelling”

What does $\int L dt$ = 1/fb mean?

- Measured cross-section, in LHCb acceptance

$$\sigma(pp \to b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced in 1/fb (2011 sample)

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- "B factories" BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \to c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

The all important trigger

JINST 8 (2013) P04022

Challenge is

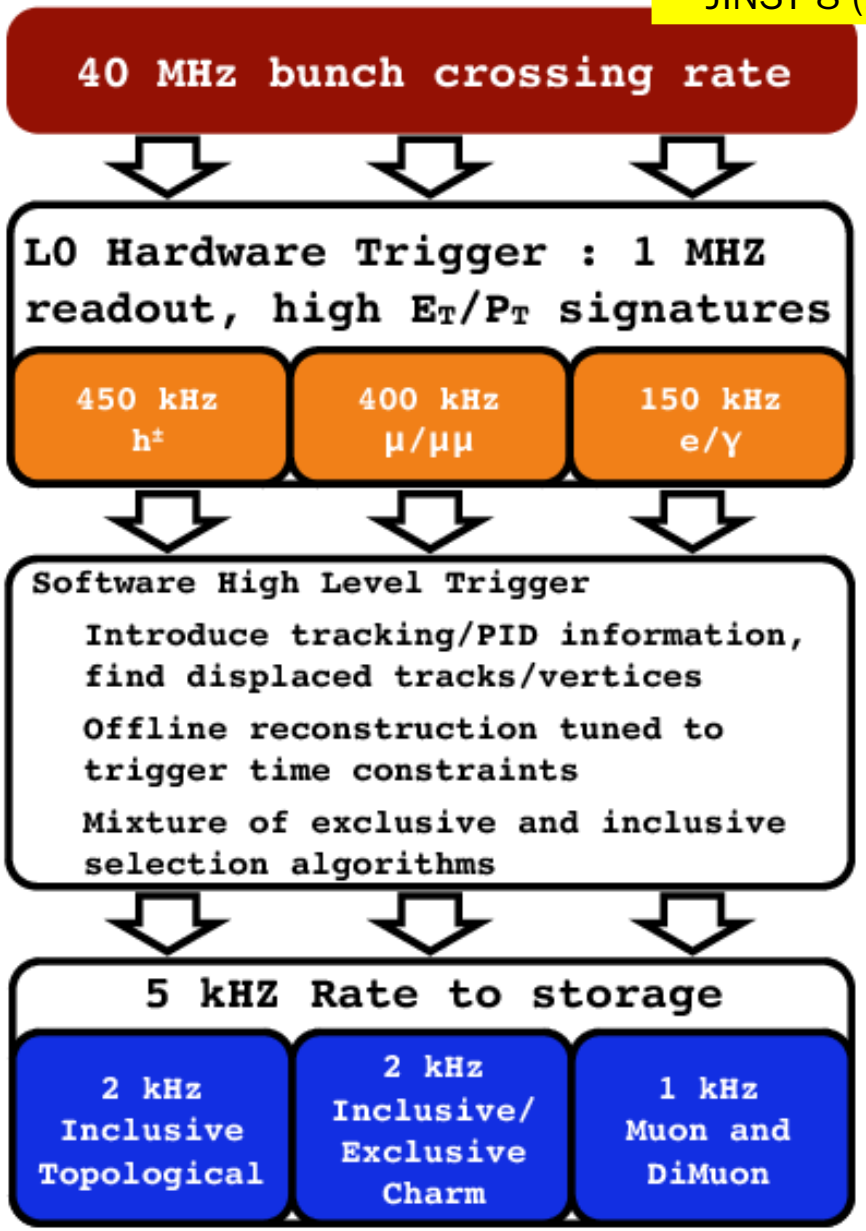
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



The other Unitarity Triangles

- High statistics available at LHCb will allow sensitivity to smaller CP violating effects
  - CP violating phase in B_s oscillations ($O(\lambda^4)$)
    - B_s oscillations (Δm_s) measured 2006 (CDF)
  - CP violating phase in D^0 oscillations ($O(\lambda^5)$)
    - D^0 oscillations ($x_D = \Delta m_D/\Gamma_D$ & $y_D = 2\Delta\Gamma_D/\Gamma_D$) measured 2007 (BaBar, Belle, later CDF)

- Observations of CP violation in both K^0 and B^0 systems won Nobel prizes!

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right].$$

Time-dependent CP Violation Formalism

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$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1-a)\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right].$$

CP violating asymmetries

CP conserving parameter

$$A_{CP}^{dir} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2} \qquad A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2} \qquad A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \qquad \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \qquad \right] .$$

- Untagged analyses still sensitive to some interesting physics

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + 0 + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1 + 0)\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - 0 + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right].$$

- In some channels, expect no direct CP violation
- and/or no CP violation in mixing

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \left[1 + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m\, t) + 0 + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$
$$\times \left[1 - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m\, t) + 0 - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right].$$

- In some channels, expect no direct CP violation
- B_d case: $\Delta\Gamma$ negligible

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

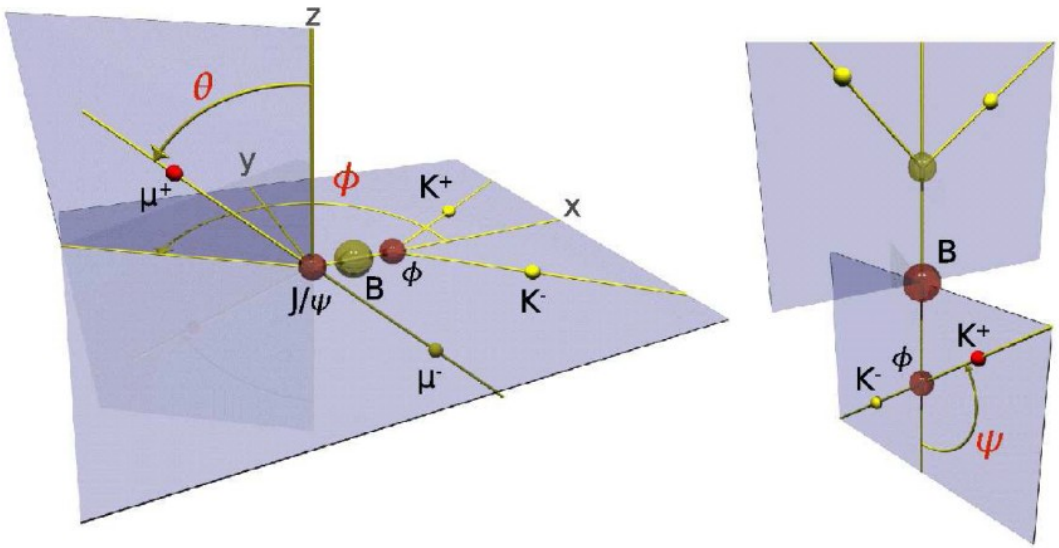
$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \left[\cos\Delta m t + \mathcal{A}_{\rm CP}^{\rm dir} \cos\Delta m t + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin\Delta m t \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$
$$\times \left[\cos\Delta m t - \mathcal{A}_{\rm CP}^{\rm dir} \cos\Delta m t + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin\Delta m t \right].$$

1 1 yΓt xΓt

- In some channels, expect no direct CP violation
- B_d case: ΔΓ negligible
- D^0 case: both x = Δm/Γ and y=ΔΓ/2Γ small

$\Phi_s = -2\beta_s$



- Most attractive channel
  $B_s^0 \to J/\psi\varphi$
- VV final state
  three helicity amplitudes
  → mixture of CP-even and CP-odd
  disentangled using angular & time-dependent distributions
  → additional sensitivity
  many correlated variables
  → complicated analysis
- LHCb also uses $B_s \to J/\psi f_0$ ($f_0 \to \pi^+\pi^-$)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from $J/\psi\varphi$ analysis (Γ_s, $\Delta\Gamma_s$)

$B_s \to J/\psi\varphi$ formalism

$B_s \to J/\psi\varphi$ ($\to \mu^+\mu^-K^+K^-$) is golden channel to study B_s oscillations ...

... but not a pure CP eigenstate

Differential decay rate:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t)\, f_k(\Omega)$$

Bs $\overline{\text{Bs}}$

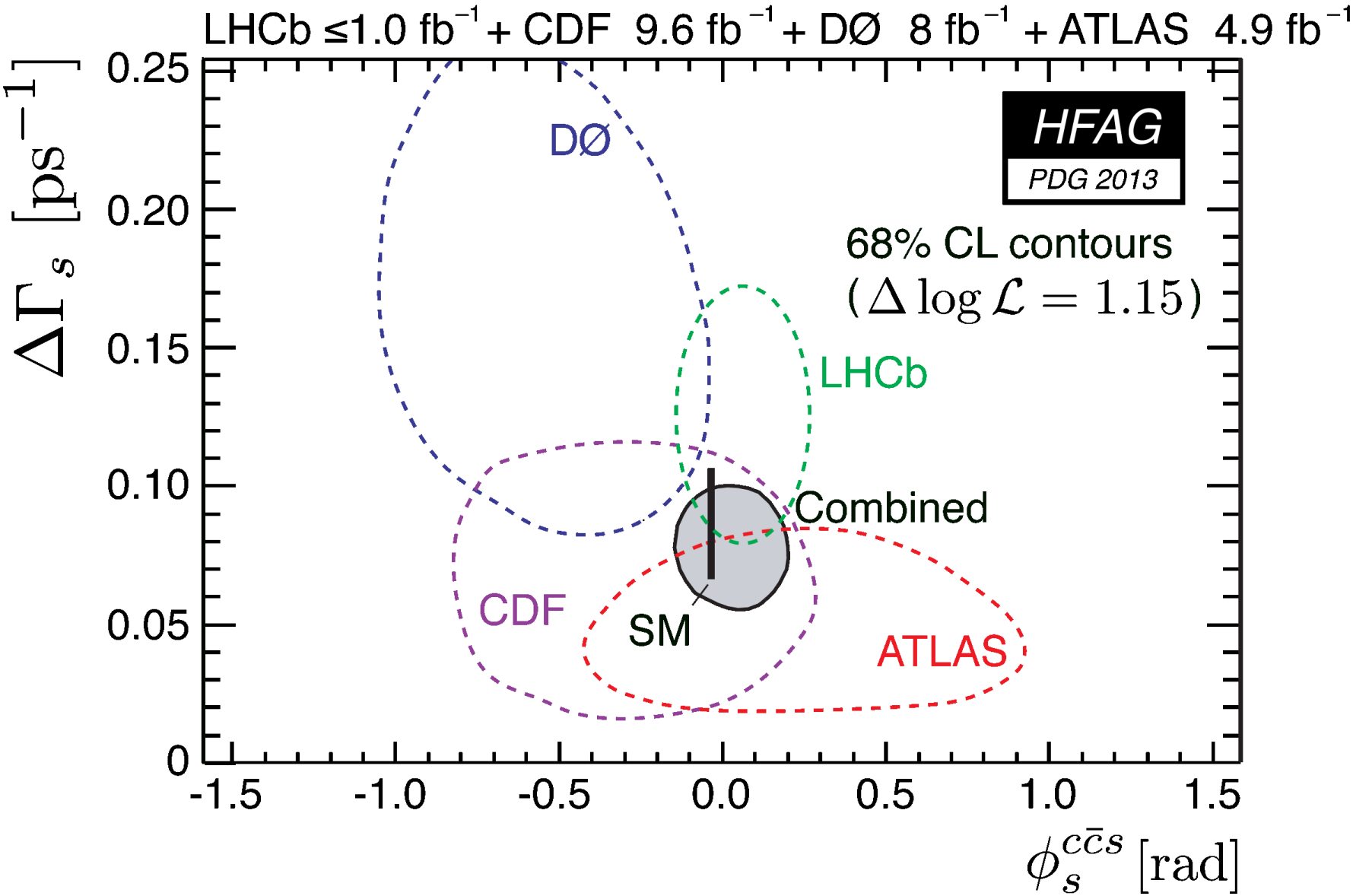
A_0 (0) → CP even
$A_\parallel$ (0) → CP even
$A_\perp$ (0) → CP odd

k	$h_k(t)$	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert \bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\lvert \bar{A}_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert \bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

± signs differ for B_s and $\overline{B}_s$

$$\begin{aligned}
|\bar{A}_0(t)|^2 &= |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],\\
|\bar{A}_\parallel(t)|^2 &= |\bar{A}_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],\\
|\bar{A}_\perp(t)|^2 &= |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right],\\
\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\} &= |\bar{A}_\parallel(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.\\
&\quad \left. - \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\right],\\
\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\} &= |\bar{A}_0(0)||\bar{A}_\parallel(0)|e^{-\Gamma_s t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.\\
&\quad \left. - \sin\Phi\sin(\Delta m_s t)\right] \text{ and}\\
\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\} &= |\bar{A}_0(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.\\
&\quad \left. - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\right].
\end{aligned}$$

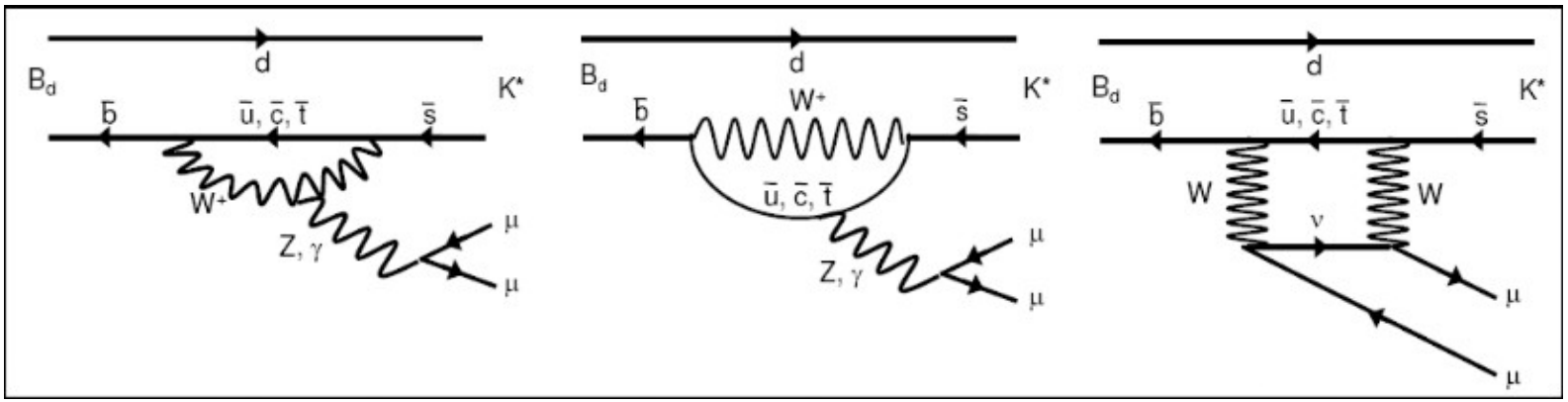
Current $B_s \to J/\psi\varphi$ world average



⋯ significant improvement possible from data in hand at LHCb & ATLAS (&CMS)

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

- $b \to s l^+ l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is $B_d \to K^{*0} \mu^+ \mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)



Operator Product Expansion

Build an effective theory for b physics

- take the weak part of the SM
- integrate out the heavy fields (W,Z,t)
- (like a modern version of Fermi theory for weak

$$\mathcal{L}_{\text{(full EW}\times\text{QCD)}} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}\left(\begin{smallmatrix}\text{quarks} \neq t \\ \text{\& leptons}\end{smallmatrix}\right) + \sum_n C_n(\mu)\, Q_n$$

Q_n – **local interaction terms (operators),** C_n – **coupling constants (Wilson coefficients)**

Wilson coefficients

- encode information on the weak scale
- are calculable and known in the SM (at least to leading order)
- are affected by new physics

For K*μμ we care about C_7 (also affects $b \to s\gamma$), C_9 and C_{10}

Effective operators

$$\mathcal{H}_W^{\Delta B=1\,,\Delta C=0\,,\Delta S=-1} = 4\frac{G_F}{\sqrt{2}}\Big(\lambda_c^s\big(C_1(\mu)Q_1^c(\mu)+C_2(\mu)Q_2^c(\mu)\big)$$
$$+\lambda_u^s\big(C_1(\mu)Q_1^u(\mu)+C_2(\mu)Q_2^u(\mu)\big)-\lambda_t^s\sum_{i=3}^{10}C_i(\mu)Q_i(\mu)\Big)$$

where the $\lambda_q^s = V_{qb}^* V_{qs}$ and the operator basis is given by

$$Q_1^q = \bar{b}_L^\alpha\gamma^\mu q_L^\alpha\,\bar{q}_L^\beta\gamma_\mu s_L^\beta \qquad Q_2^q = \bar{b}_L^\alpha\gamma^\mu q_L^\beta\,\bar{q}_L^\beta\gamma_\mu s_L^\alpha$$
$$Q_3 = \bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q\bar{q}_L^\beta\gamma_\mu q_L^\beta \qquad Q_4 = \bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q\bar{q}_L^\beta\gamma_\mu q_L^\alpha$$
$$Q_5 = \bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q\bar{q}_R^\beta\gamma_\mu q_R^\beta \qquad Q_6 = \bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q\bar{q}_R^\beta\gamma_\mu q_R^\alpha$$
$$Q_7 = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q e_q\bar{q}_R^\beta\gamma_\mu q_R^\beta \qquad Q_8 = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q e_q\bar{q}_R^\beta\gamma_\mu q_R^\alpha$$
$$Q_9 = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q e_q\bar{q}_L^\beta\gamma_\mu q_L^\beta \qquad Q_{10} = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q e_q\bar{q}_L^\beta\gamma_\mu q_L^\alpha$$

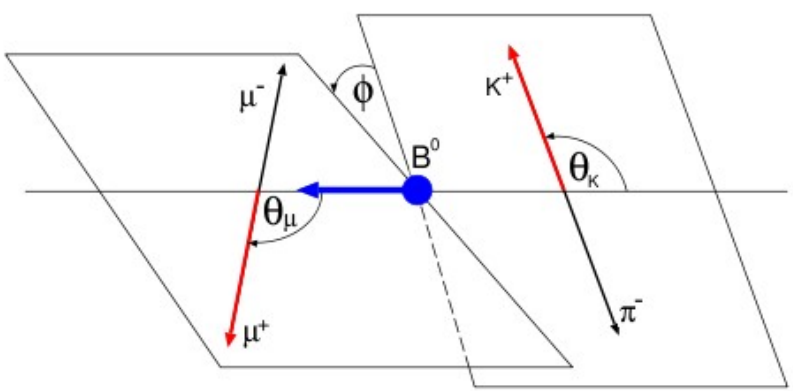
Four-fermion operators (except $Q_{7\gamma}$ & Q_{8g}) – dimension 6

$$Q_{7\gamma} = \frac{e}{16\pi^2}m_b\bar{b}_L^\alpha\sigma^{\mu\nu}F_{\mu\nu}s_L^\alpha$$
$$Q_{8g} = \frac{g_s}{16\pi^2}m_b\bar{b}_L^\alpha\sigma^{\mu\nu}G_{\mu\nu}^A T^A s_L^\alpha$$
$$Q_{9V} = \frac{1}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\,\bar{l}\gamma_\mu l$$
$$Q_{10A} = \frac{1}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\,\bar{l}\gamma_\mu\gamma_5 l$$

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

- Given for inclusive $b \to s\mu^+\mu^-$ for simplicity
  - physics of exclusive modes ≈ same but equations are more complicated (involving form factors, etc.)
- Differential decay distribution

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_l} = \frac{3}{8}\left[(1+\cos^2\theta_l)\, H_T(q^2) + 2\cos\theta_l\, H_A(q^2) + 2\,(1-\cos^2\theta_l)\, H_L(q^2)\right]$$



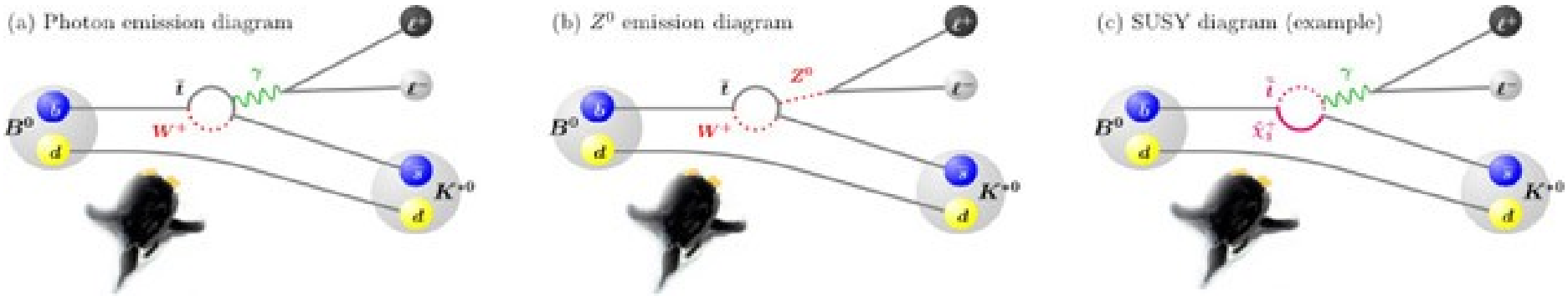
$$H_T(q^2) \propto 2q^2\left[\left(C_9 + 2C_7\frac{m_b^2}{q^2}\right)^2 + C_{10}^2\right],$$

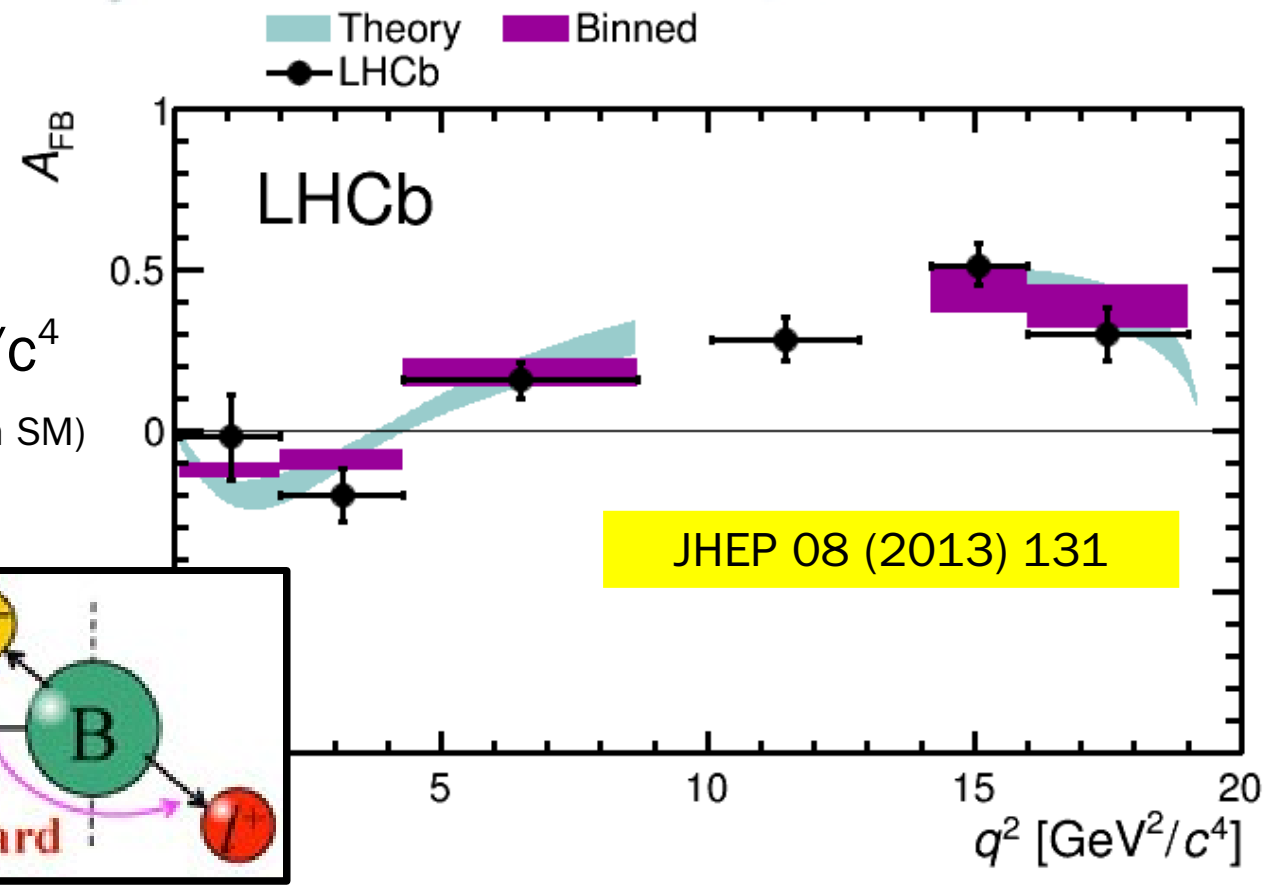
$$H_A(q^2) \propto -4q^2 C_{10}\left(C_9 + 2C_7\frac{m_b^2}{q^2}\right),$$

$$H_L(q^2) \propto \left[(C_9+2C_7)^2 + C_{10}^2\right].$$

This term gives a forward-backward asymmetry

Forward-backward asymmetry in $B \to K^* \mu^+ \mu^-$

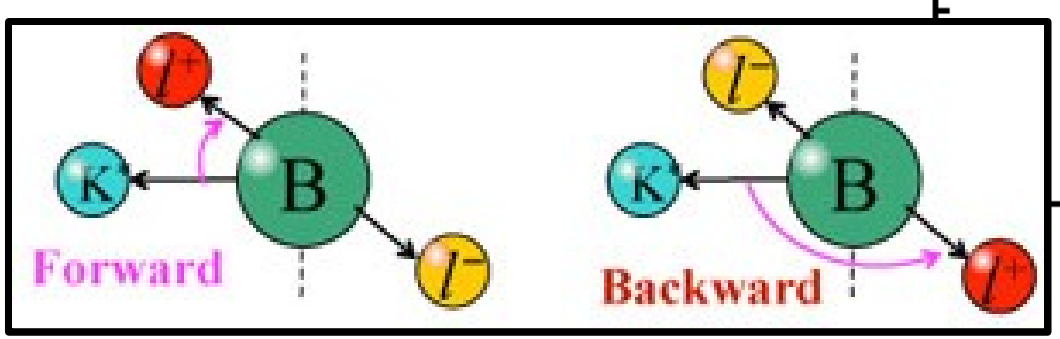




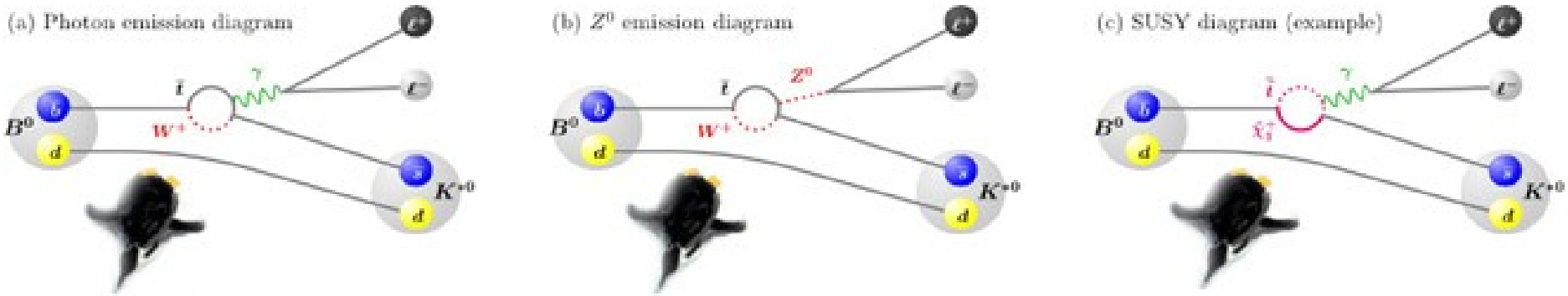
Zero crossing-point

$q^2_0 = (4.9 \pm 0.9)$ GeV^2/c^4

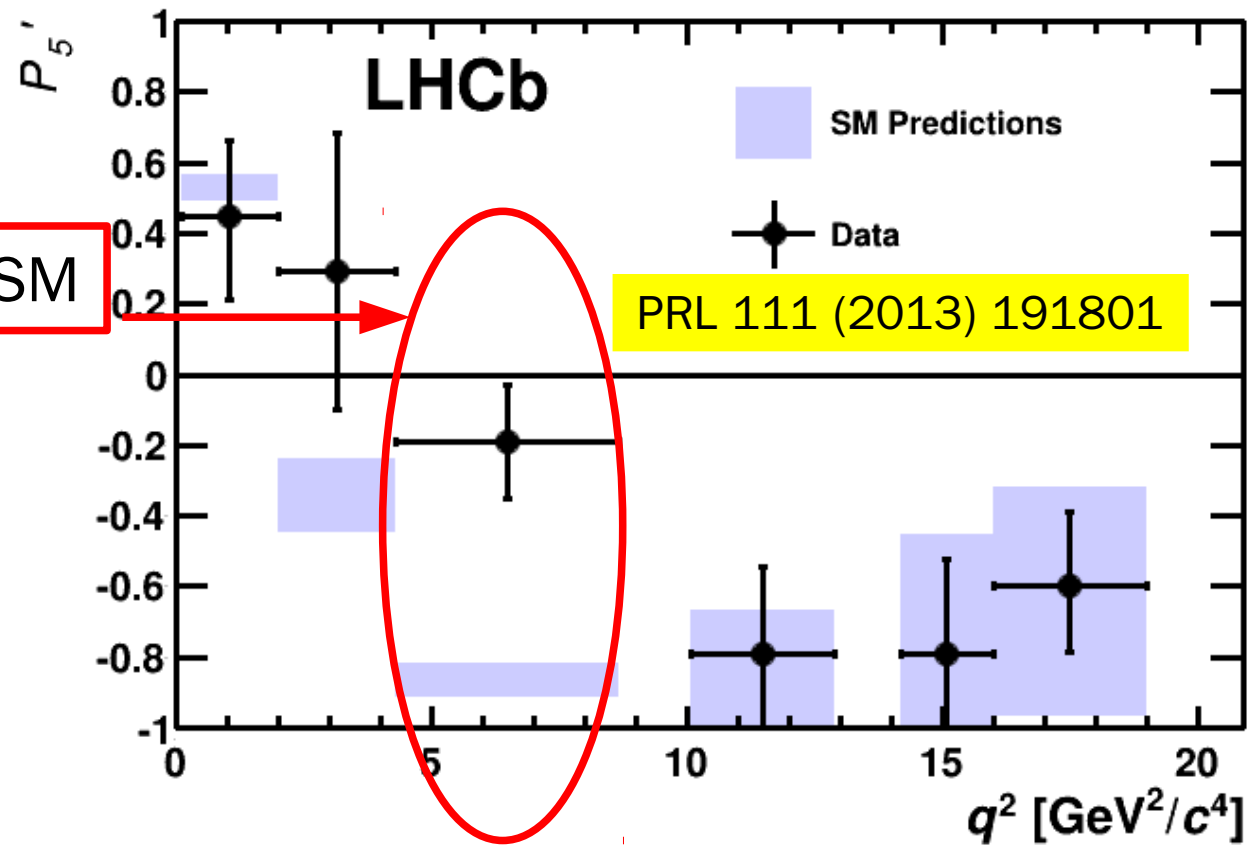
(consistent with SM)



Another angular observable in $B \to K^* \mu^+ \mu^-$



Possible discrepancy with SM



PRL 111 (2013) 191801

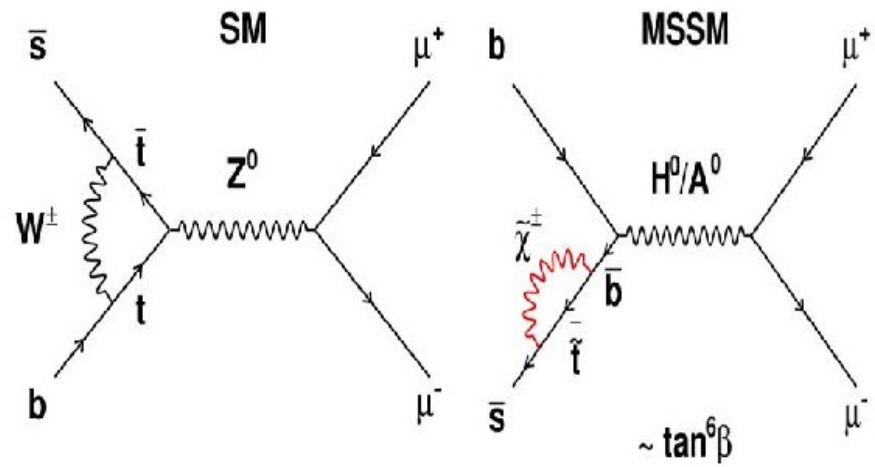
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
- Huge NP enhancement possible

(tan β = ratio of Higgs vevs)

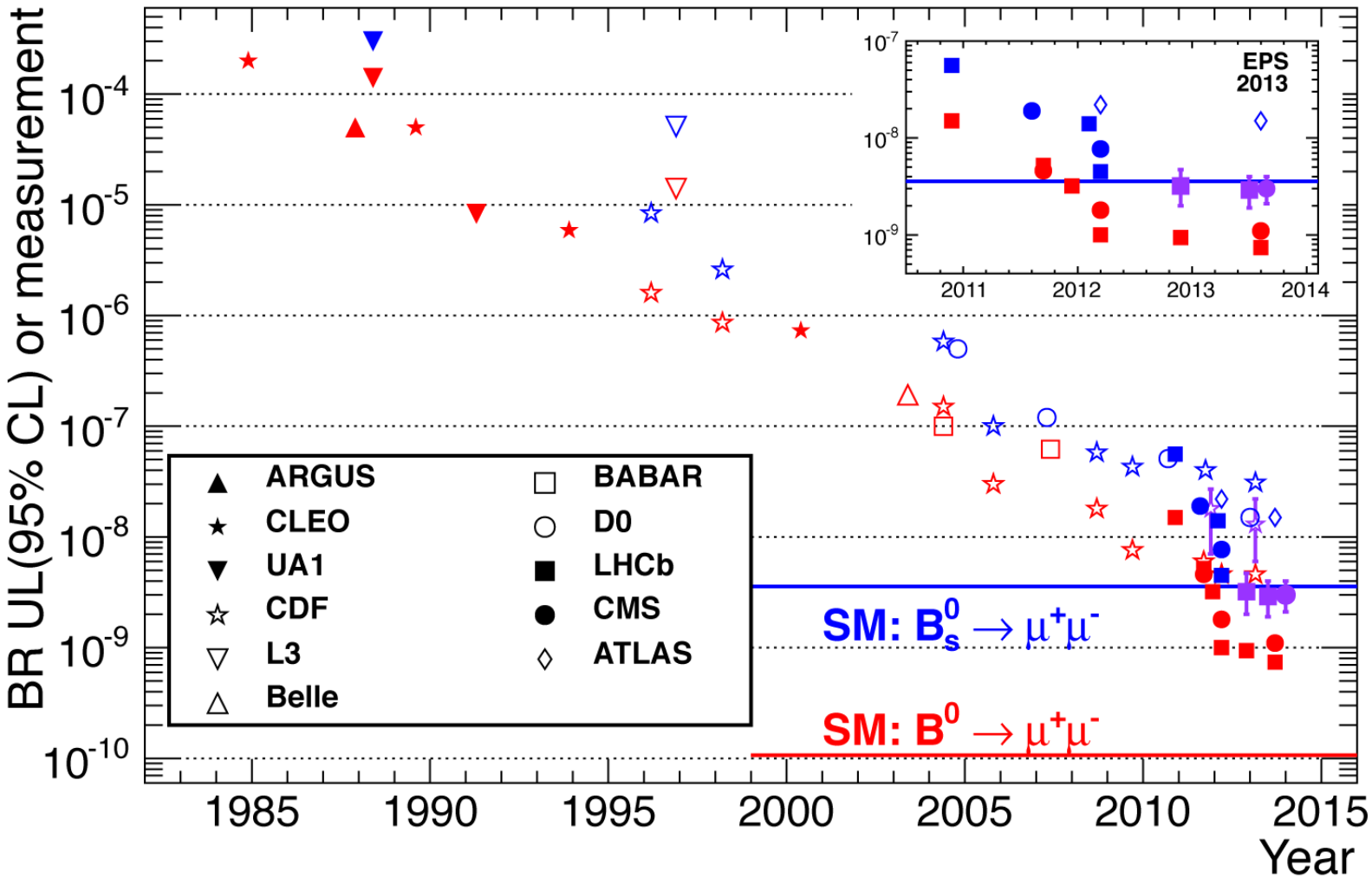
- Clean experimental signature



$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

- Was considered one of the hottest channels for early NP discovery at LHC ($B_d \to \mu^+\mu^-$ also interesting ...)

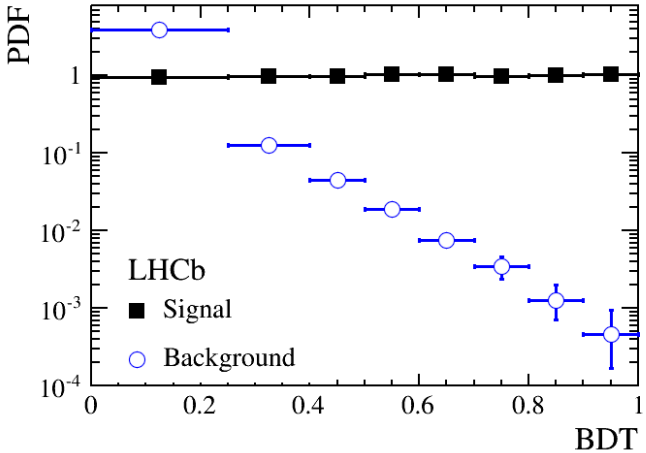
$B_{(s)}^{0} \to \mu^+\mu^-$



Searches over 30 years

$B_{(s)}^{0} \to \mu^+\mu^-$ – analysis ingredients

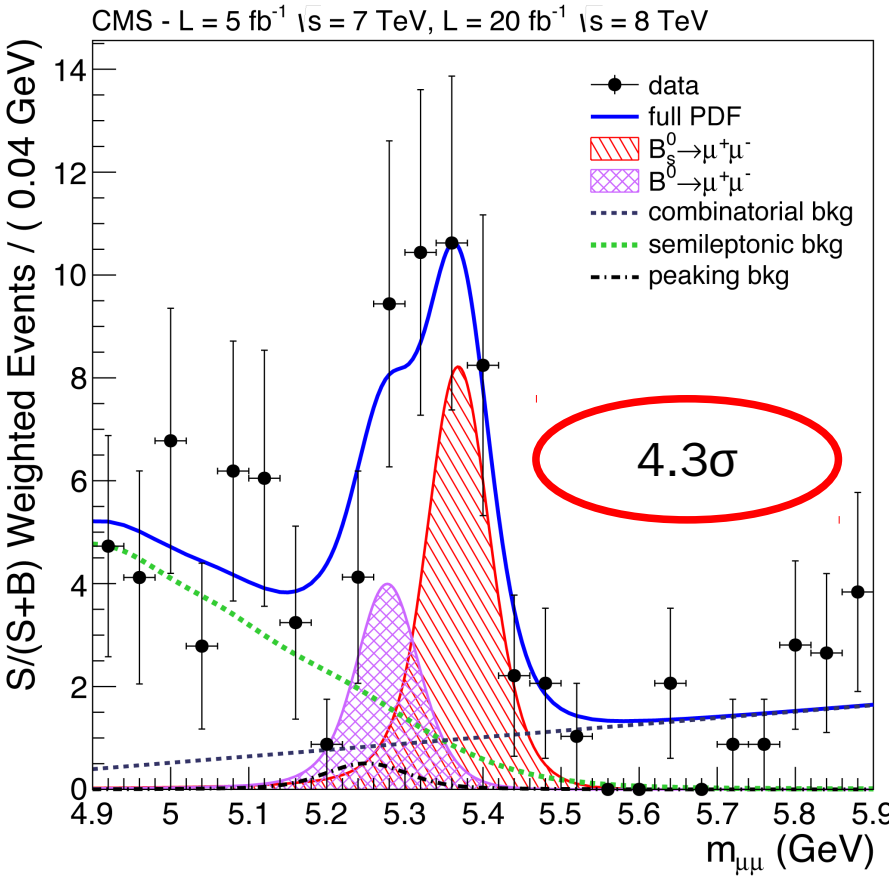
- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve B^0 from B_s^0 decays
  - powerful muon identification (reject background from B decays with misidentified pions)
  - typical to combine various discriminating variables into a multivariate classifier
    - e.g. Boosted Decision Trees algorithm



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

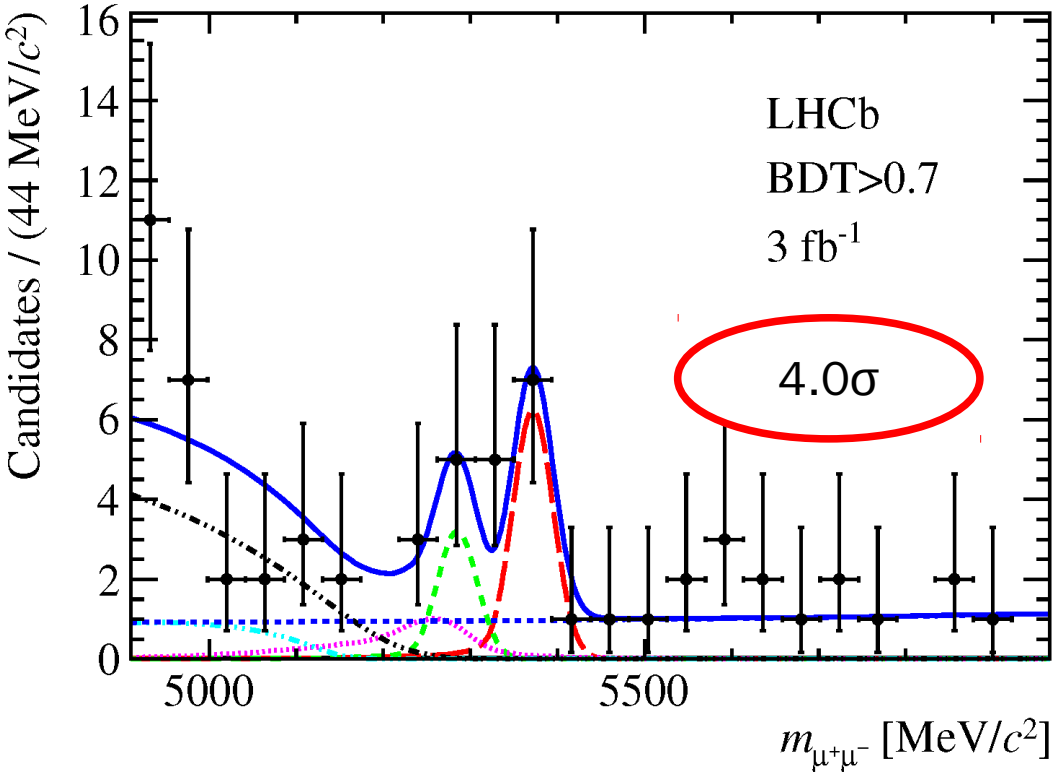
latest results from CMS & LHCb

CMS PRL 111 (2013) 101804



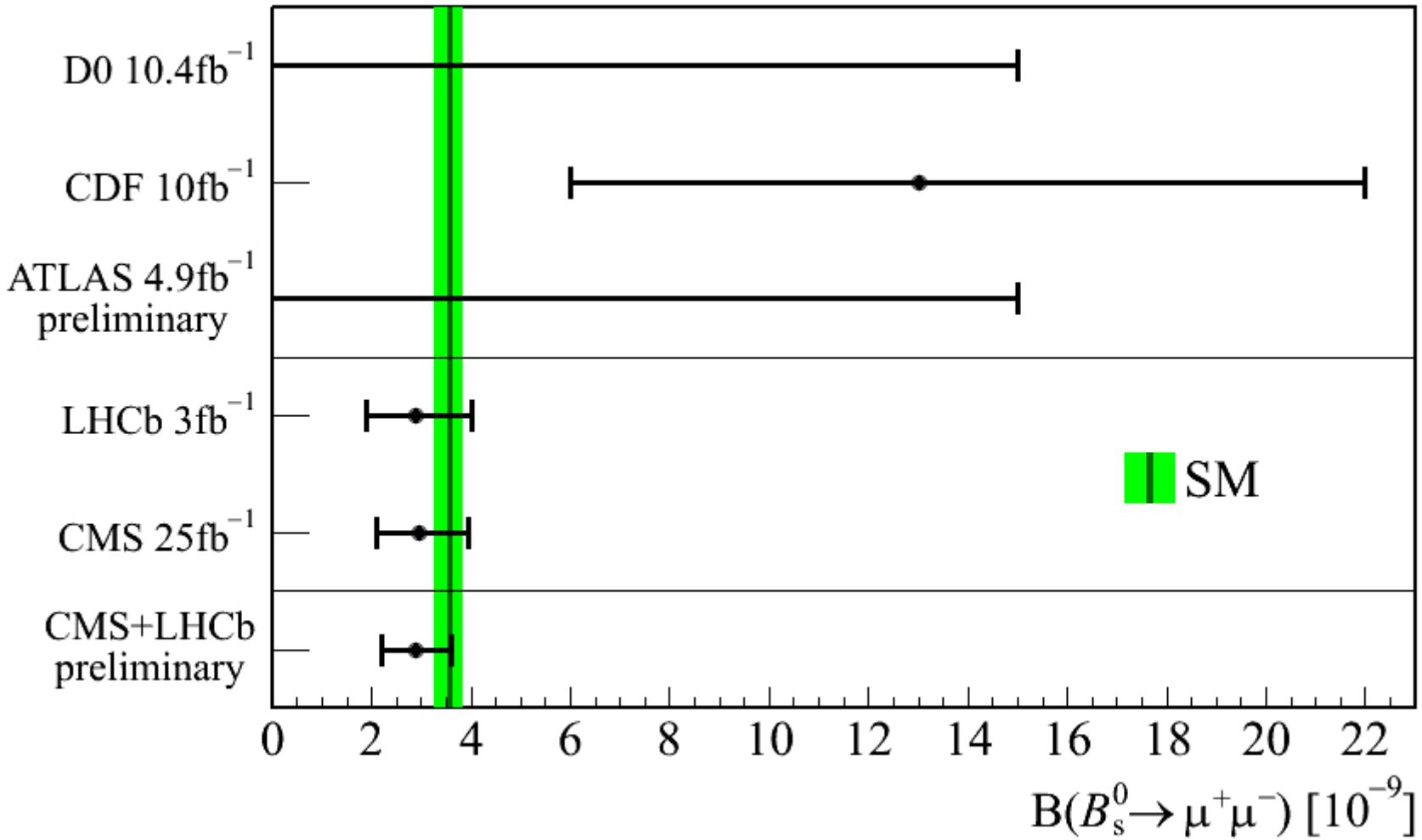
Events weighted by S/(S+B)

LHCb PRL 111 (2013) 101805



Only events with BDT > 0.7

$B_{(s)}^{0} \to \mu^+\mu^-$ – combined results

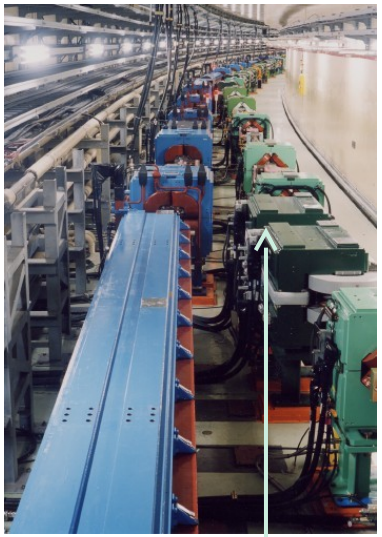


$$B(B_s^{0} \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

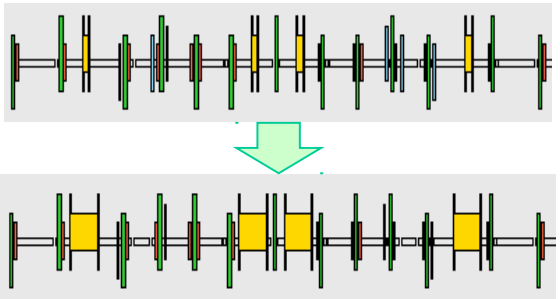
The Future of Flavour Physics

- charged lepton sector
  - proposals for improved measurements of many processes (often using new facilities built for other purposes)
- kaon system
  - search for $K \rightarrow \pi\nu\underline{\nu}$ [the holy grail] continues
- charm system
  - BESIII @ BEPC has taken over from CLEO-c
  - charm also studied at LHCb and B factories
- B system
  - Belle2 will be online 2016 / LHCb upgrade 2019

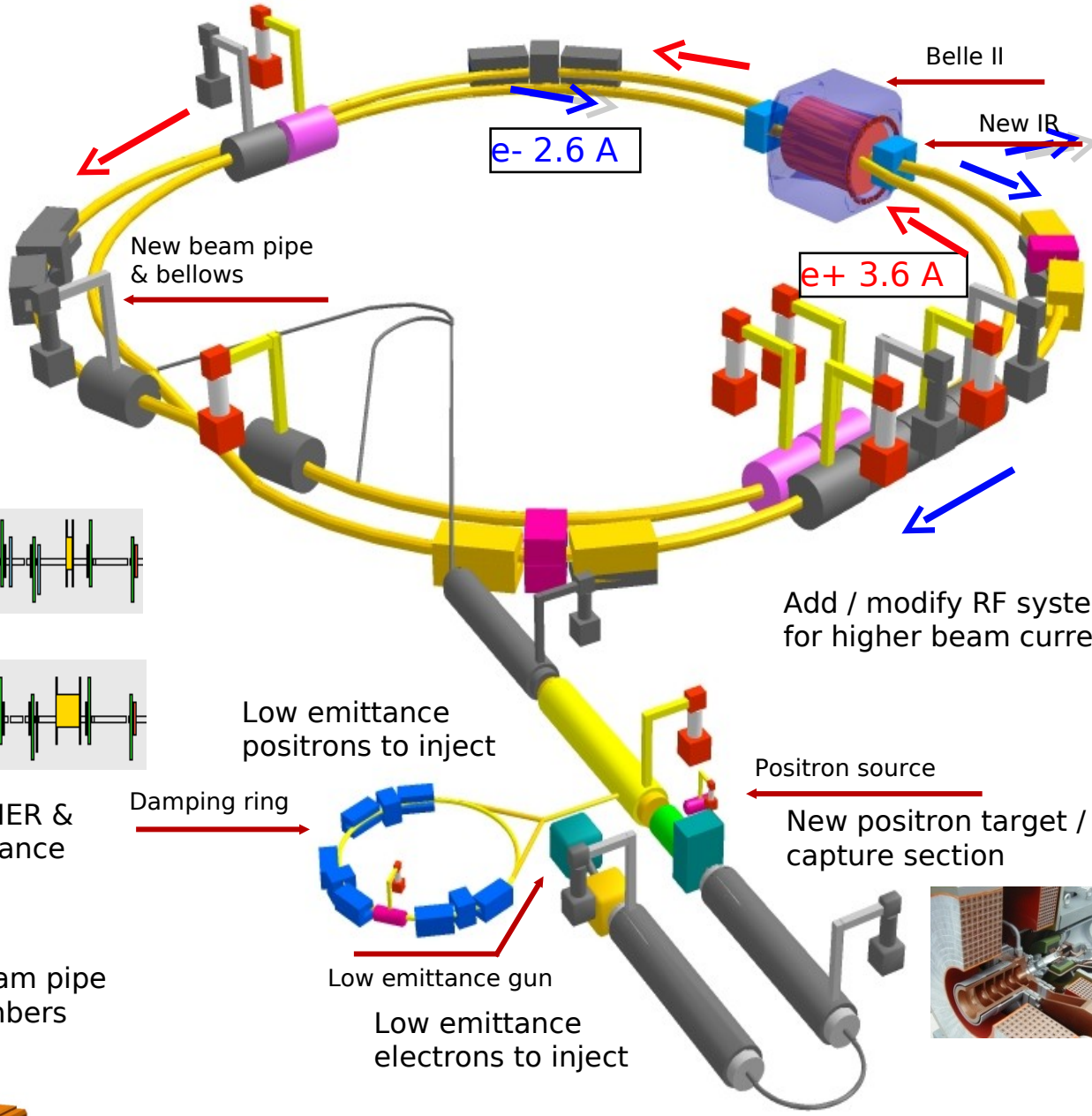
KEKB to SuperKEKB



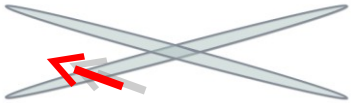
Replace short dipoles with longer ones (LER)



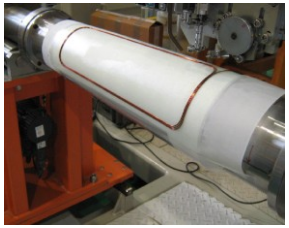
Redesign the lattices of HER & LER to squeeze the emittance



Colliding bunches

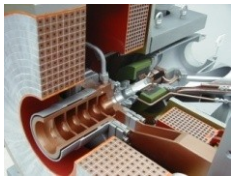


New superconducting /permanent final focusing quads near the IP

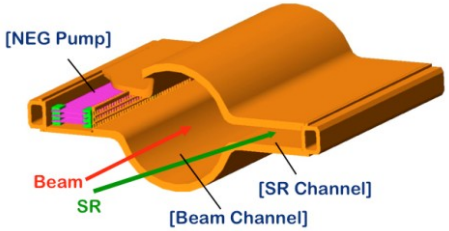


Add / modify RF systems for higher beam current

New positron target / capture section

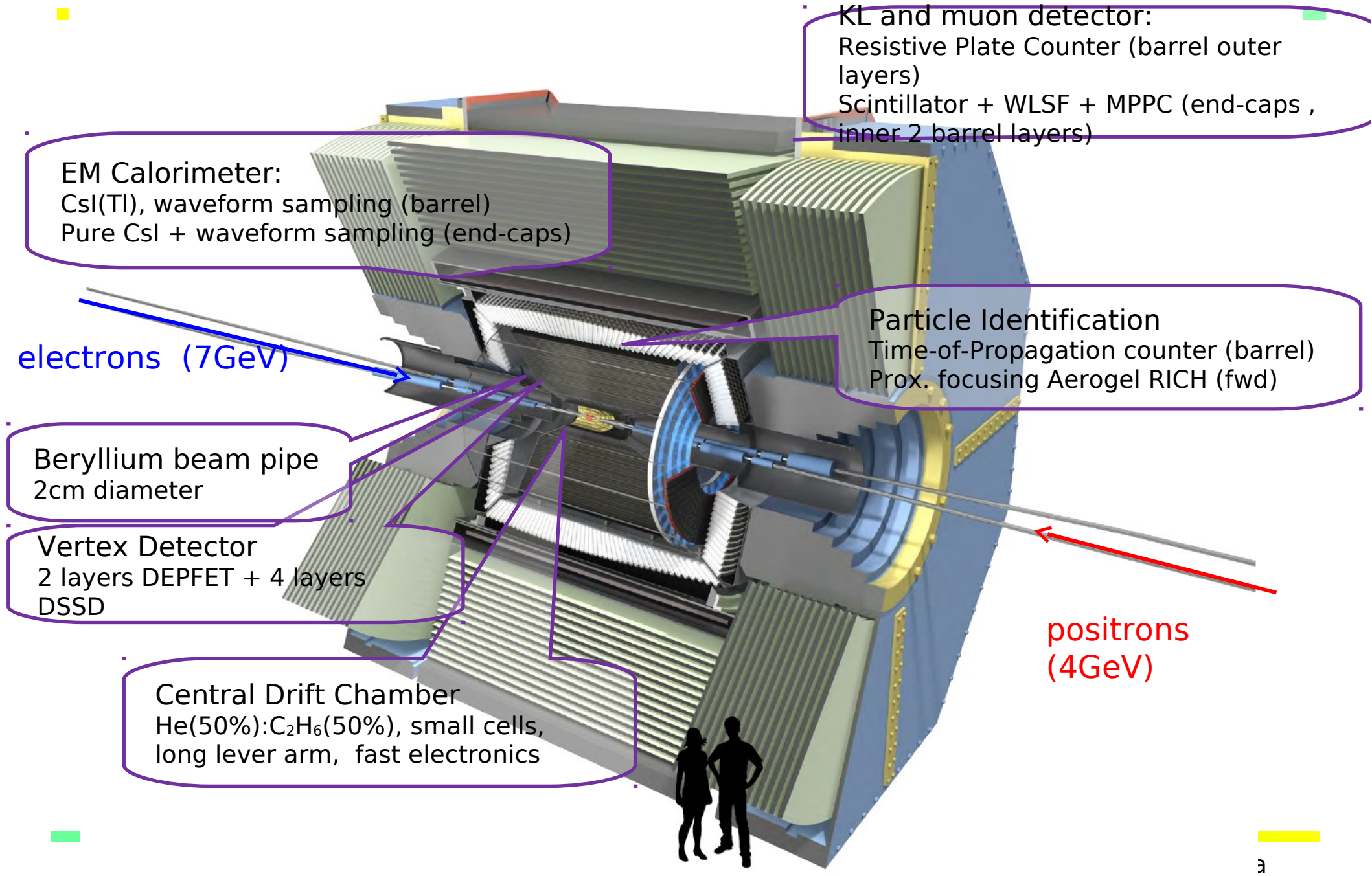


TiN-coated beam pipe with antechambers

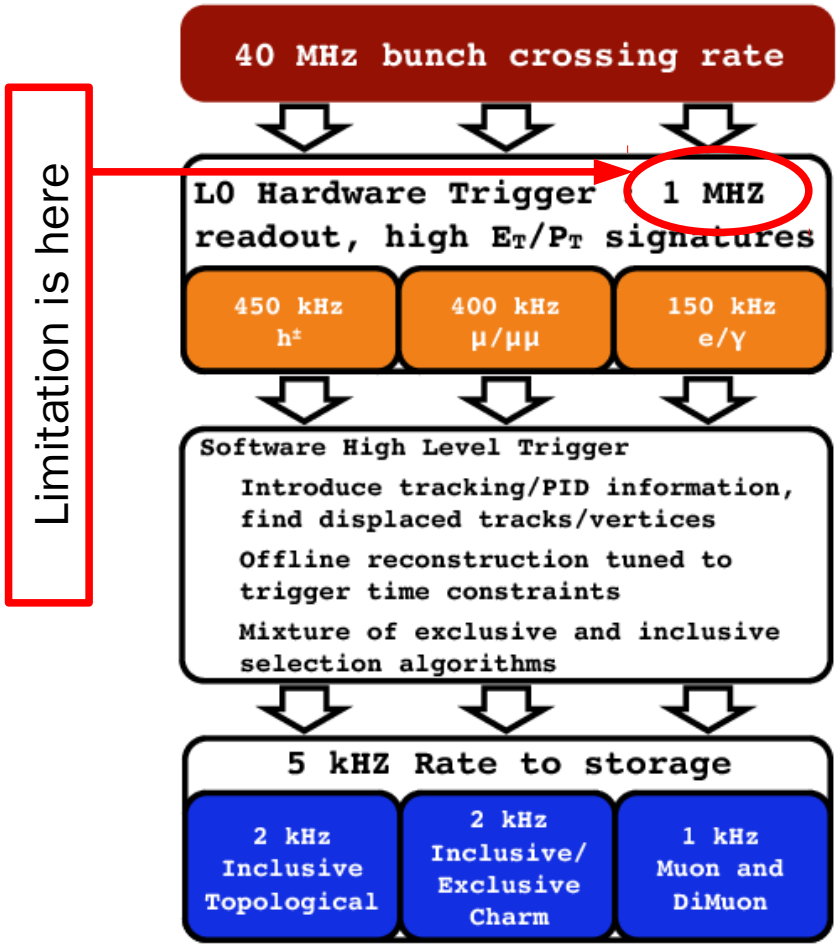


To obtain x40 higher luminosity

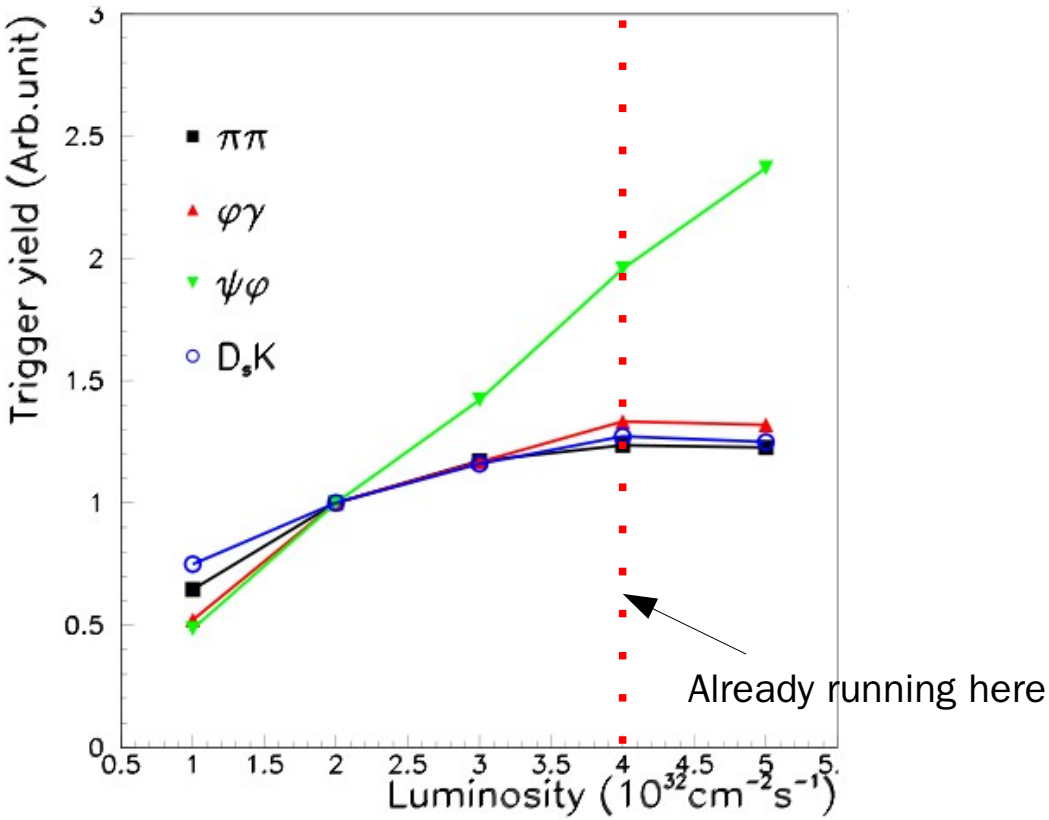
Belle II Detector



LHC upgrade and the all important trigger

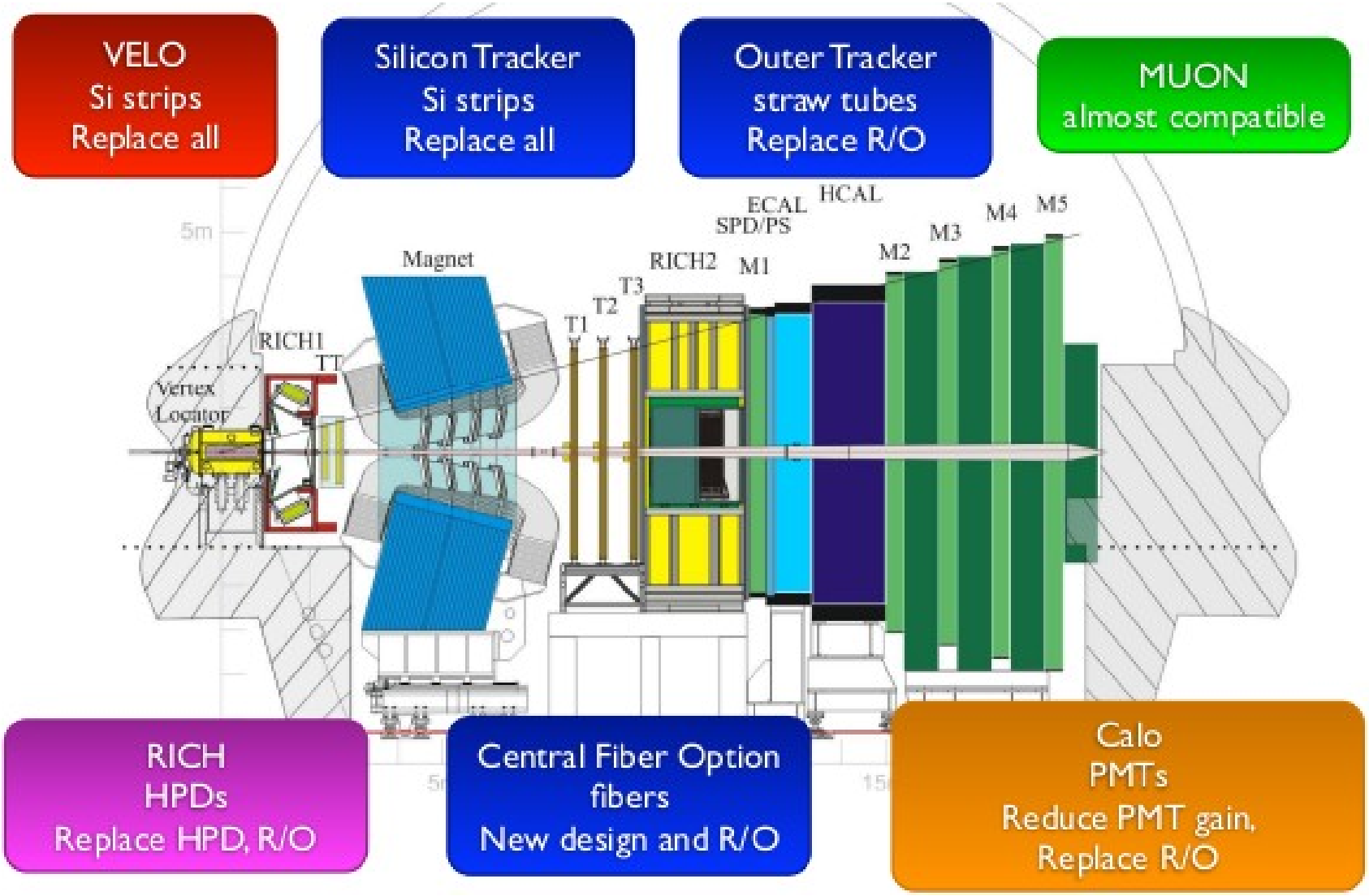


higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 $10^{33}/cm^2/s$

LHCb detector upgrade



Technical decisions all made! TDRs getting approved

Summary

- CKM mechanism accurately describes quark mixing and CP violation within the Standard Model
- Flavour physics is, and will remain, an essential tool to search for and diagnose new physics
- Not covered
  - Grand Unification
  - Baryon asymmetry of the Universe

References and background reading

- Heavy Flavour Averaging Group (HFAG)
  - http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter
  - http://ckmfitter.in2p3.fr/
- UTFit
  - http://www.utfit.org/

- Documentation available from above web sites

References and background reading

- Reviews in the Particle Data Group (PDG)'s Review of Particle Physics
  - Quark Model [C.Amsler, T.DeGrand & B.Krusche]
  - Rare Kaon Decays [L.Littenberg & G.Valencia]
  - CP Violation in Meson Decays [D.Kirkby & Y.Nir]
  - CKM quark mixing matrix [A.Ceccucci, Z.Ligeti & Y.Sakai]
  - Determination of V_{cb} and V_{ub} [R.Kowalewski & T.Mannel]
  - V_{ud}, V_{us}, the Cabibbo Angle and CKM Unitarity [E.Blucher & W.J.Marciano]

References and background reading

- Most introductory particle physics books contain some background on flavour physics
  - eg. Perkins, Martin & Shaw
- Feynman lectures has an interesting chapter on lifetimes in the neutral kaon system
- More detailed books on quark flavour physics
  - CP violation, I.I.Bigi and A.I.Sanda (CUP)
  - CP violation, G.C.Branco, L.Lavoura & J.P.Silva (OUP)