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Future experiments in hadronic flavour physics and CP violation

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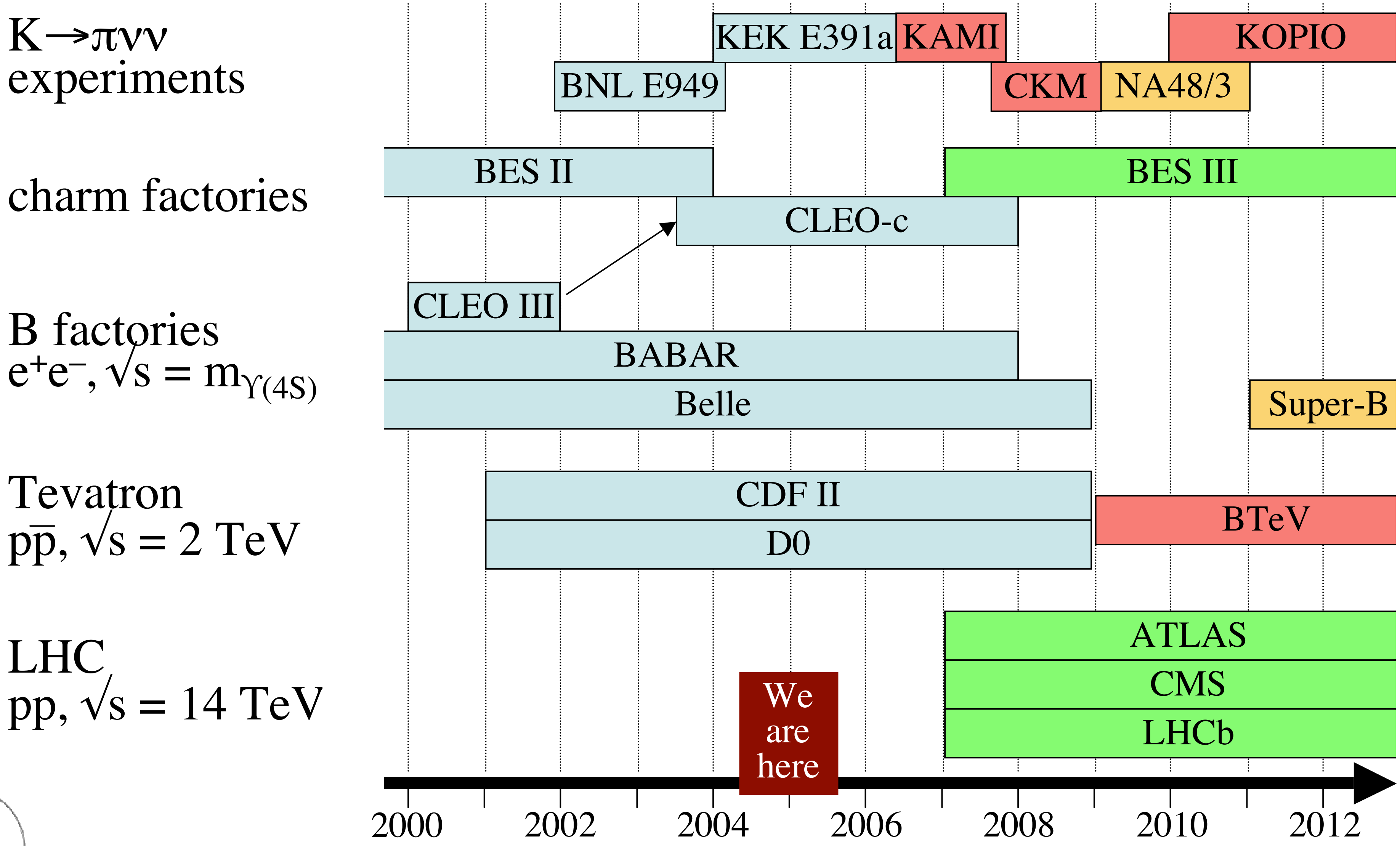
Landscape

running	proposed
under constr.	cancelled



Future experiments

- **Currently running (still some future !)**

Physics	Exp.	Machine	Laboratory	Operation dates
B and charm	BABAR	PEP-II, $e^+e^- \to \Upsilon(4S)$	SLAC (USA)	1999–2008
B and charm	Belle	KEKB, $e^+e^- \to \Upsilon(4S)$	KEK (Japan)	1999–2009
B and charm	CDF II	Tevatron, $p\bar{p}$ $\sqrt{s}$ = 2 TeV	Fermilab (USA)	2001–2009
B and charm	D0	Tevatron, $p\bar{p}$ $\sqrt{s}$ = 2 TeV	Fermilab (USA)	2001–2009
charm	CLEO-c	CESR-c, $e^+e^- \to \psi(3770)$, …	Cornell (USA)	2003–2008
$K \to \pi\nu\bar{\nu}$	E391a	12 GeV PS	KEK (Japan)	2004–2006

- **Coming online soon**

B (and high p_T)	ATLAS	LHC, pp $\sqrt{s}$ = 14 TeV	CERN	2007–
B (and high p_T)	CMS	LHC, pp $\sqrt{s}$ = 14 TeV	CERN	2007–
B and charm	LHCb	LHC, pp $\sqrt{s}$ = 14 TeV	CERN	2007–
charm	BES III	BEPC II, $e^+e^- \to \psi(3770)$, …	IHEP (China)	2007–

- **Proposed**

B and charm	Super-Belle	Super-KEKB, $e^+e^- \to \Upsilon(4S)$	KEK (Japan)	2011–
$K \to \pi\nu\bar{\nu}$	NA48/3	SPS	CERN	2009–
$K \to \pi\nu\bar{\nu}$	(proposals expected end 2005)		JPARC	?

Contents

- 1st lecture
  - — Introduction: present status and motivation
  - — Charm factories
  - — Hadron colliders, B_s mixing at Tevatron, LHC and its experiments
  - — LHCb: detector

- 2nd lecture
  - — LHCb: expected performance
  - — Super B factory
  - — $K\rightarrow\pi\nu\nu$ experiments
  - — Summary

CP violation in the Standard Model (SM)

- Higgs field (yet to be discovered !) generates mass of particles
- Quark mass eigenstates are different from weak eigenstates
  → quark mixing matrix (**C**abibbo, **K**obayashi, **M**askawa)

weak states — CKM matrix — mass states

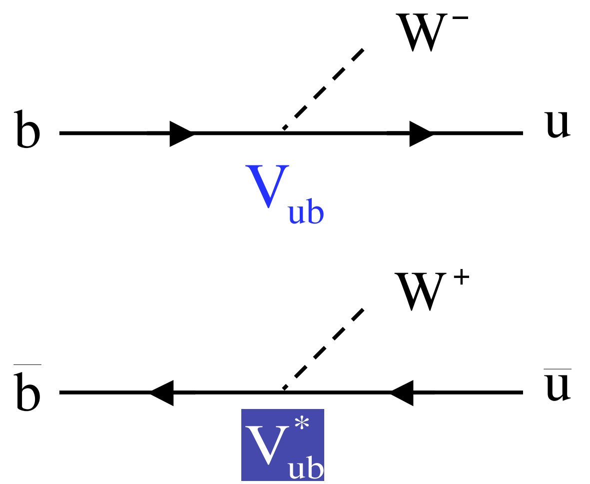
Quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Anti-quarks

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

V_{ij} proportional to transition amplitude from quark j to quark i



Different mixing matrix for quarks and anti-quarks ⇒ **CP violation**

CP violation in the Standard Model (SM)

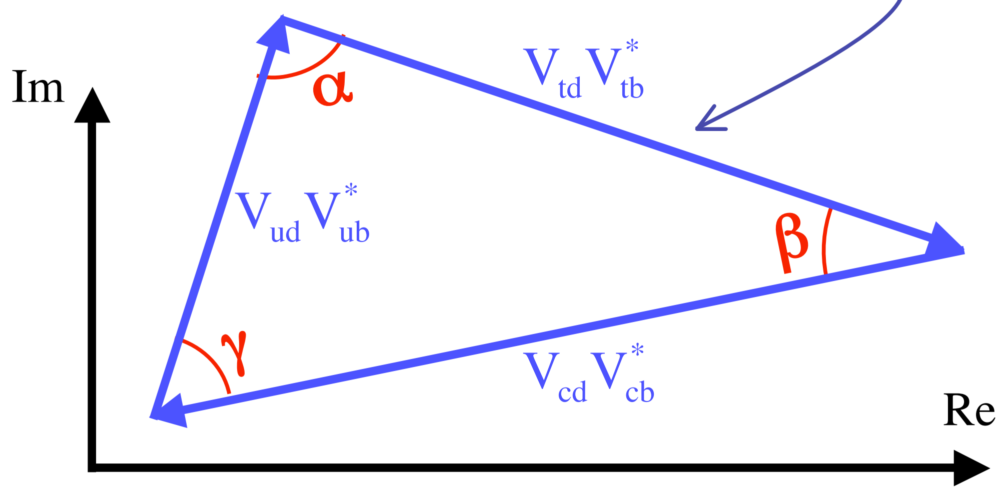
❑ CKM matrix:

— complex and unitary
→ 4 parameters (e.g. 3 angles and 1 phase) ↳ responsible for CP violation

$$V_{CKM}V^{\dagger}_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \Rightarrow \quad V_{ud}V^{*}_{ub} + V_{cd}V^{*}_{cb} + V_{td}V^{*}_{tb} = 0$$

— 6 unitarity triangles

— most sensitive experimental tests on the two unsquashed triangles, with transitions involving b quarks



"Unitarity triangle"
(area ∝ CP violation)

> B^0, $\overline{B}^0$ decays and B^0_s, $\overline{B}^0_s$ decays most suitable to study CP violation

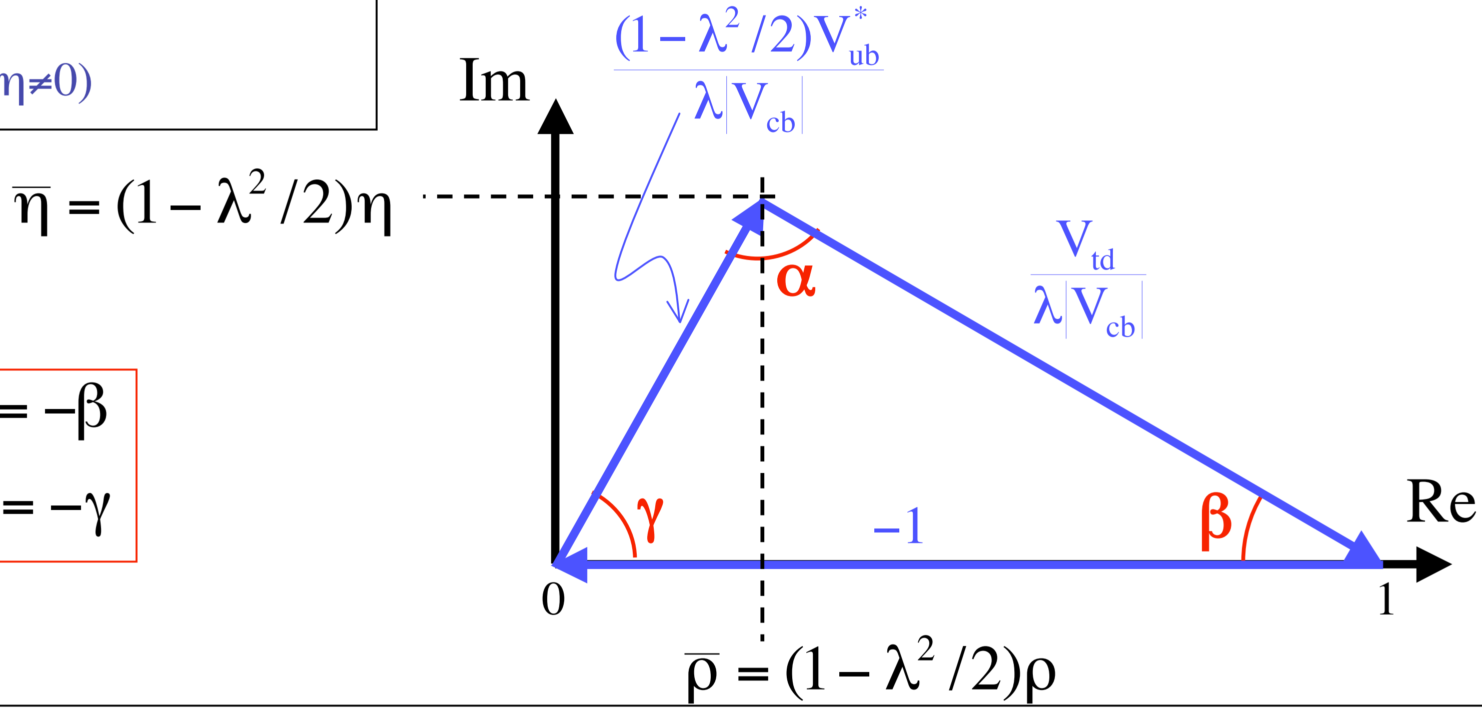
Wolfenstein parametrization

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameters:

- $\lambda = 0.2240 \pm 0.0036$ (well known)
- $A = 0.83 \pm 0.02$ (well known)
- ρ
- η (CPV due to $\eta \neq 0$)

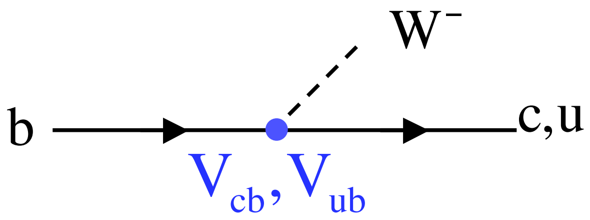
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$\arg(V_{td}) = -\beta$$
$$\arg(V_{ub}) = -\gamma$$

Unitarity triangle from the sides

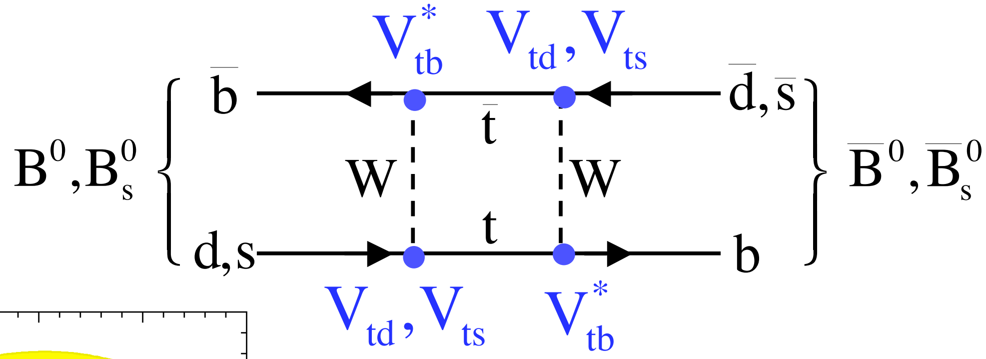
B decays at tree level

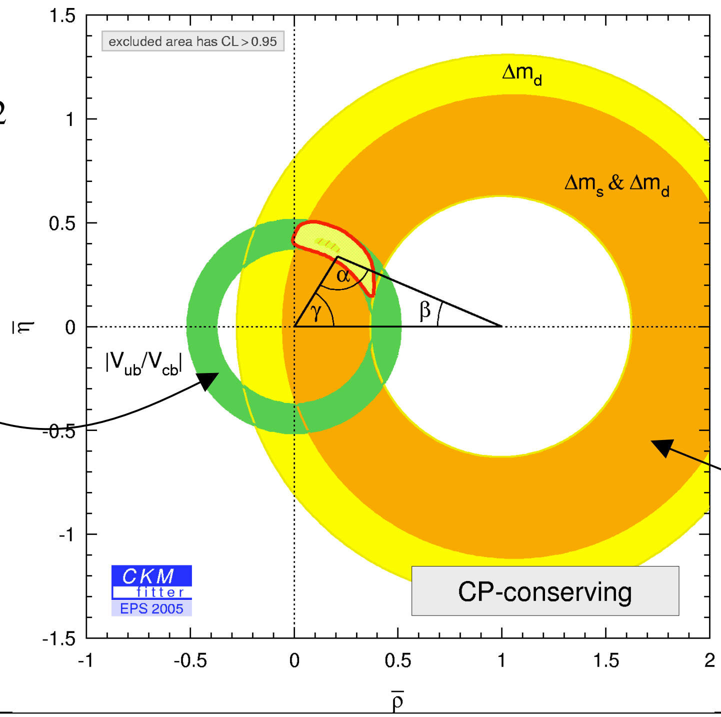


Rates $\propto |V_{cb}|^2$ or $|V_{ub}|^2$
$\Rightarrow |V_{ub}|/|V_{cb}|$ ratio
$\Rightarrow$ length of left side

B^0–$\bar{B}^0$ mixing

(box diagrams dominated by virtual top quarks)

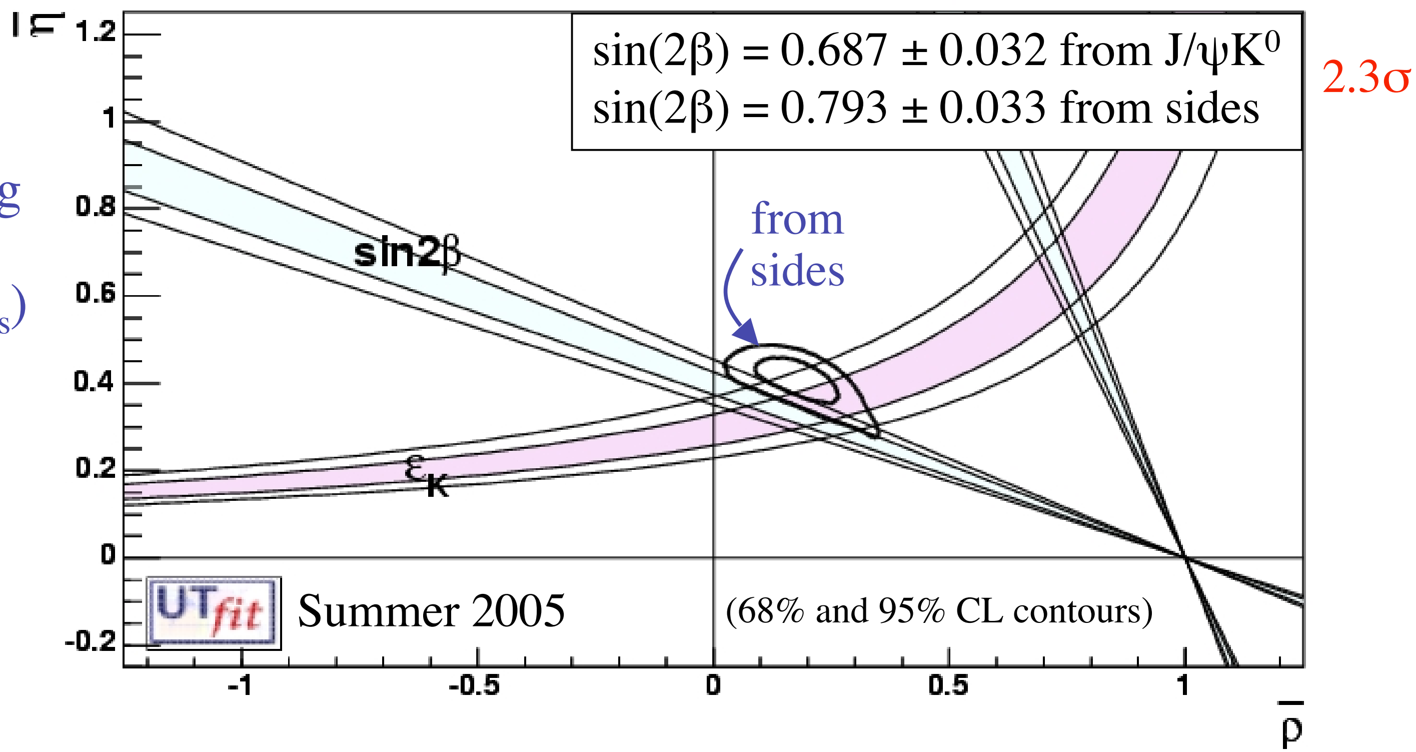




$\Delta m_d \propto |V_{td}V_{tb}^*|^2 = |V_{td}|^2$
$\Delta m_s \propto |V_{ts}V_{tb}^*|^2 = |V_{ts}|^2 = |V_{cb}|^2$
$\Rightarrow |V_{td}|/|V_{cb}|$ ratio
$\Rightarrow$ length of right side

First crucial test of SM in quark sector

- Does SM give a coherent picture of CP violation ?
  - Measure unitarity triangle from CP-violating processes:
    - ε_K CPV in K sector (discovered in 1964)
    - $\sin(2\beta)$ CPV in B sector (discovered in 2001) ← main initial goal of B factories !
  - Compare with unitarity triangle measured from the sides only, i.e. from CP-conserving processes ($|V_{ub}|$ and Δm_d, Δm_s)

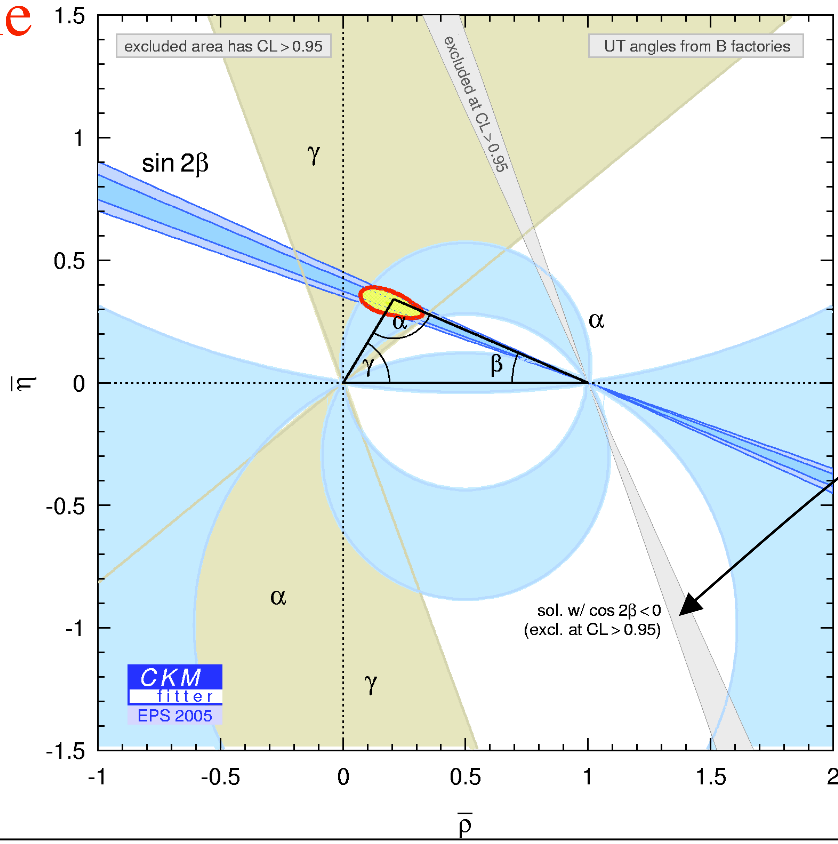


1st test passed successfully !

☺ ☹

Further test of CKM picture

- Measure unitarity triangle only from the angles in B decays:
  - — $\sin(2\beta)$ from $B^0 \to (c\bar{c})K^0$ interference of $b \to c$ amplitude with B^0–$\bar{B}^0$ mixing
  - — α (or $\beta+\gamma$) from $B \to \pi\pi, \rho\rho, \rho\pi$ interference of $b \to u$ amplitude with B^0–$\bar{B}^0$ mixing
  - — γ from $B \to D^{(*)}K$ interference of $b \to c$ and $b \to u$ amplitudes
- Compare again with triangle from side measurements



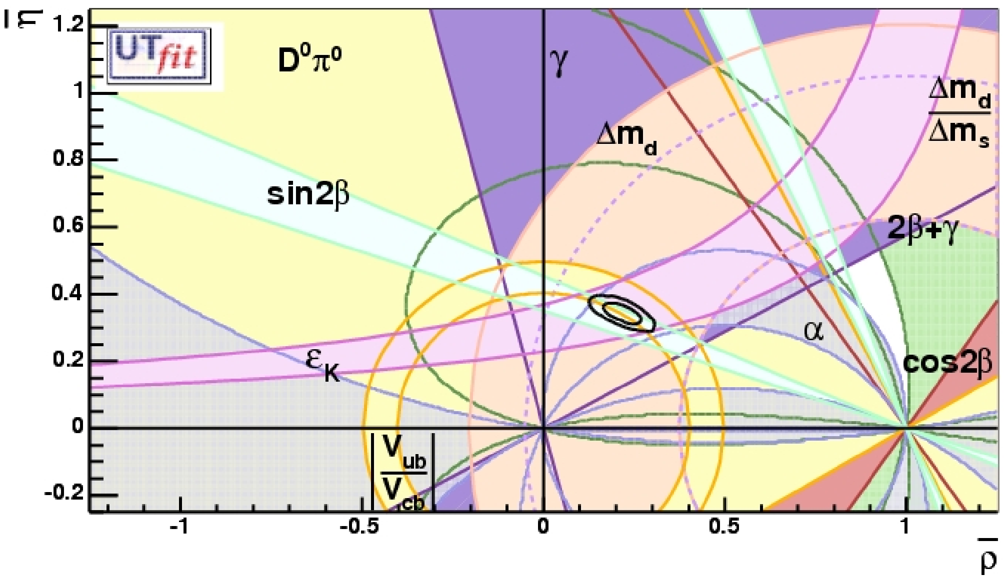
Disfavoured by $\cos(2\beta)$ from angular analysis of $B^0 \to J/\psi K^{*0}(K_S\pi^0)$

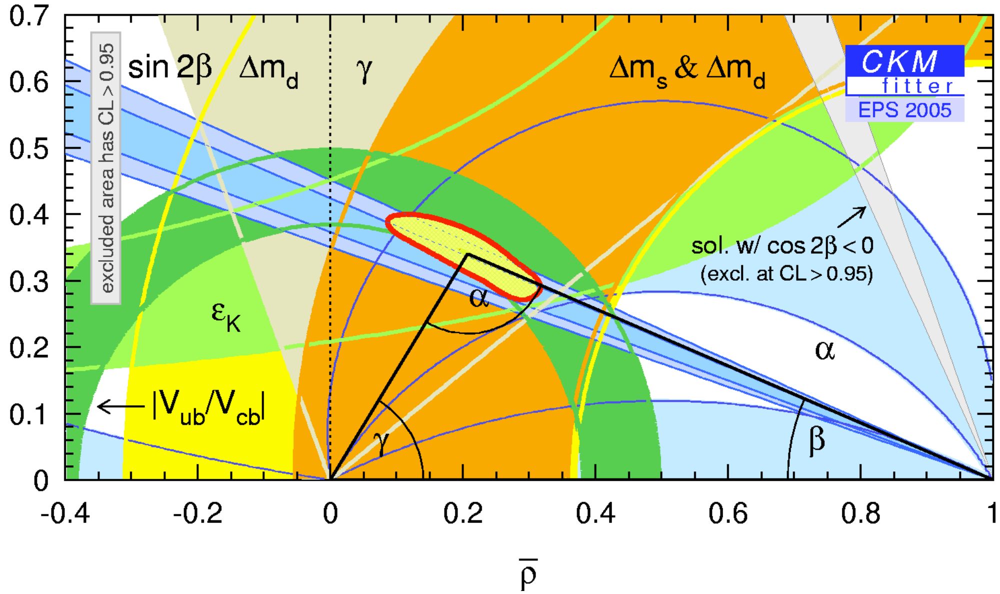
2nd test passed successfully !

☺ ☹

Consistency of CKM picture

- B factories (BABAR & Belle) have done a superb job !





Does the SM give a co~~nsiste~~nt description of CP violation ?
If not what a~~re the~~ alternatives to CKM ?

How accurate is the CKM picture ?
Are there "corrections" to it ?

Motivation for continuing the game

- SM cannot be the ultimate theory
  - Too many free parameters (quark and lepton masses and mixing angles) → pattern must be governed by a hidden mechanism yet to be discovered
  - SM believed to be a low-energy effective theory of a more fundamental theory at a higher energy scale Λ, expected to be in the TeV region
- How can New Physics (NP) be discovered and studied ?
  - NP models (= extensions of the SM) introduce new particles, dynamics, symmetries, … at the higher scale $\Lambda \sim$ TeV. These new particles could
    - be produced and observed as real particles at energy frontier machines (LHC, linear collider)
    - appear as virtual particles in loop processes, leading to observable deviations from the pure SM expectations in flavour physics and CP violation

The TeV scale is accessible at future planned experiments → must continue
The "direct" and "indirect" approaches are complementary !

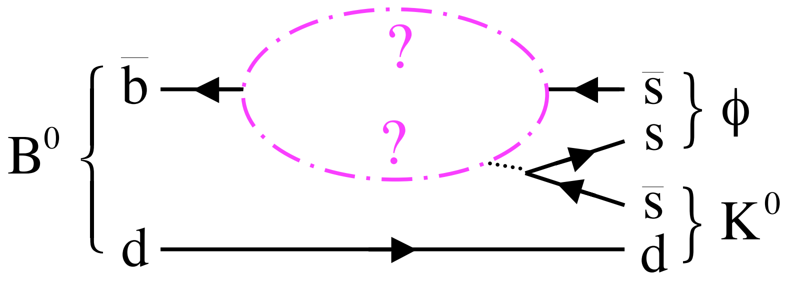
Strengths of indirect approach

- Can in principle access higher scales and therefore see effect earlier:
  - Third quark family inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964), but only directly observed in 1977 (b) and1995 (t)
  - Neutral currents (ν+N→ ν+N) discovered in 1973, but real Z discovered in 1983
- Can in principle access the phases of the new couplings:
  - NP at TeV scale needs to have a “flavour structure” to provide the suppression mechanism for already observed FCNC processes → once NP is discovered, it is important to measure this structure (including new phases)

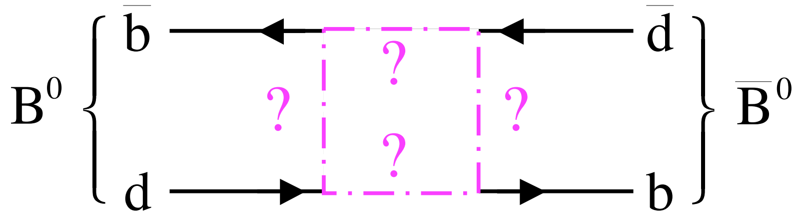
New Physics

$\Delta m \neq \Delta m^{SM} \propto |V_{td}{}^2|$,

$\phi \neq \phi^{SM} = -\arg(V_{td}{}^2) = 2\beta$



$B^0 \rightarrow \phi K^0$ decay: “Penguin” diagram



B^0–$\bar{B}^0$ oscillations: “Box” diagram

New physics and baryogenesis

- Our Universe displays obvious baryon number asymmetry (i.e. matter-antimatter asymmetry
  - No anti-helium (or heavier anti-nuclei) detected in outer space
  - No annihilation γ rays seen in from outer space
- Evolution from symmetric situation at Big Bang (or after inflation) requires a number of conditions:

Sakharov's conditions (1967)	… and how they would be satisfied in the SM
Baryon number violation	EW B violation at high T (sphaleron)
C and CP violation	Weak interaction, non trivial CKM phase
Thermal non-equilibrium	1st-order phase transition in early universe

- Problems:
  - SM Higgs too heavy to produce 1st order transition → other scalars must exist
  - SM CP violation far too small → other sources of CP violation must exist

Baryogenesis seems to call for physics and CP violation beyond the SM

(NB: almost every extension to the SM implies new sources of CP violation)

Search strategies for NP

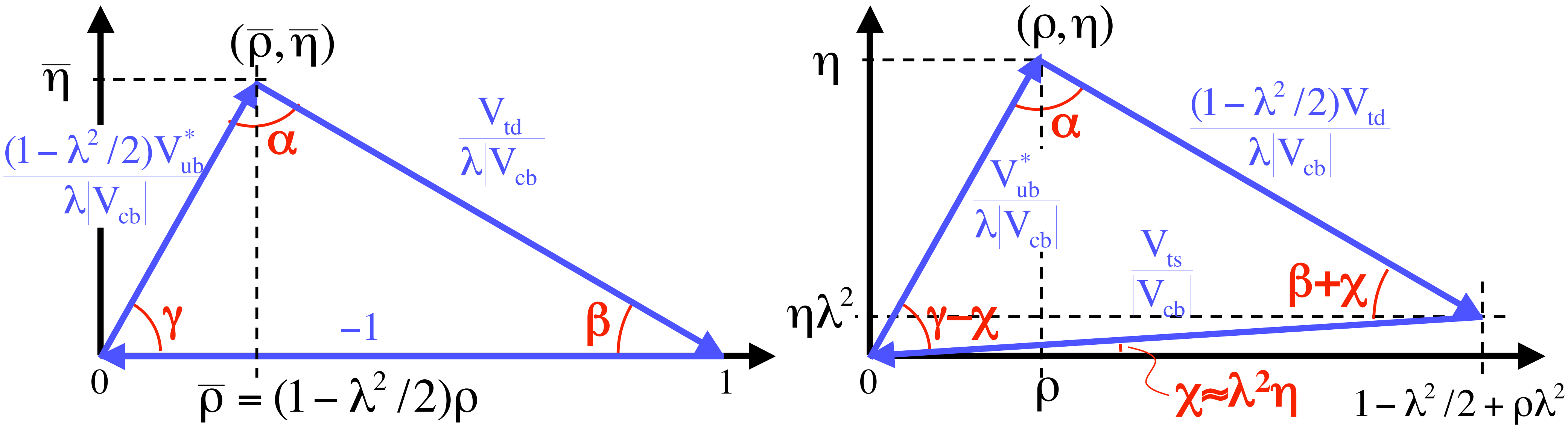
in quark flavor physics

- Explore as much as possible all FCNC transitions ($b \to s$, $b \to d$, $s \to d$), where NP may show up
  - e.g. measure B_s oscillations
- Measure processes which are very suppressed in the SM, where NP may show up as a relatively large contribution
  - Very rare K decays, rare D decays, D^0 mixing
  - $b \to s\gamma$, $b \to sl^+l^-$, $B_{(s)} \to \mu\mu$
  - B_s mixing phase ϕ_s ($= -\arg(V_{ts}{}^2) = -2\lambda^2\eta$ in SM) → see next slide
- Improve measurement precision of CKM elements
  - Compare different measurements of the same quantity, one which is insensitive and another one which is sensitive to NP:
    - $\sin(2\beta)$ from $B^0 \to J/\psi K_S$ and $\sin(2\beta)$ from $B^0 \to \phi K_S$
    - γ from $B_s \to D_s K$ and γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$
  - Measure all angles and sides in many different ways → any inconsistency will be a sign of new physics
  - But watch out for theory uncertainties ! → reducing and understanding them must go in parallel with experiment

Higher λ-orders in CKM: angle χ

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \begin{pmatrix} -\lambda^4/8 & 0 & 0 \\ A^2\lambda^5(1/2-\rho-i\eta) & -\lambda^4(1+4A^2)/8 & 0 \\ A\lambda^5(\rho+i\eta) & A\lambda^4(1/2-\rho-i\eta) & -A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

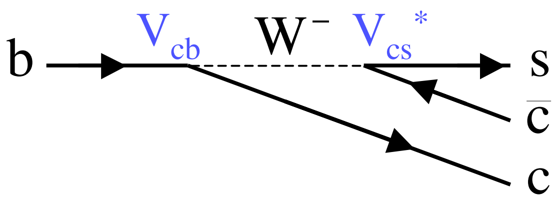
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$ ← keep terms up to $O(\lambda^5)$ → $$V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0$$



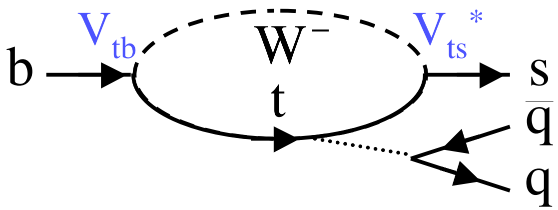
$$\arg(V_{ub}) = -\gamma, \quad \arg(V_{td}) = -\beta, \quad \arg(V_{ts}) = \chi + \pi$$

sin(2β) from b→s penguin

- $\sin(2\beta^{eff})$ made a lot of noise since 2003
  - Naive average of all b→s modes deviated from B→(cc)K^0 modes by 3.8σ last year, now only 2.6 σ
  - But don't average:
    - theory uncertainties need to be taken into account in comparison
    - different channels might be affected differently by NP

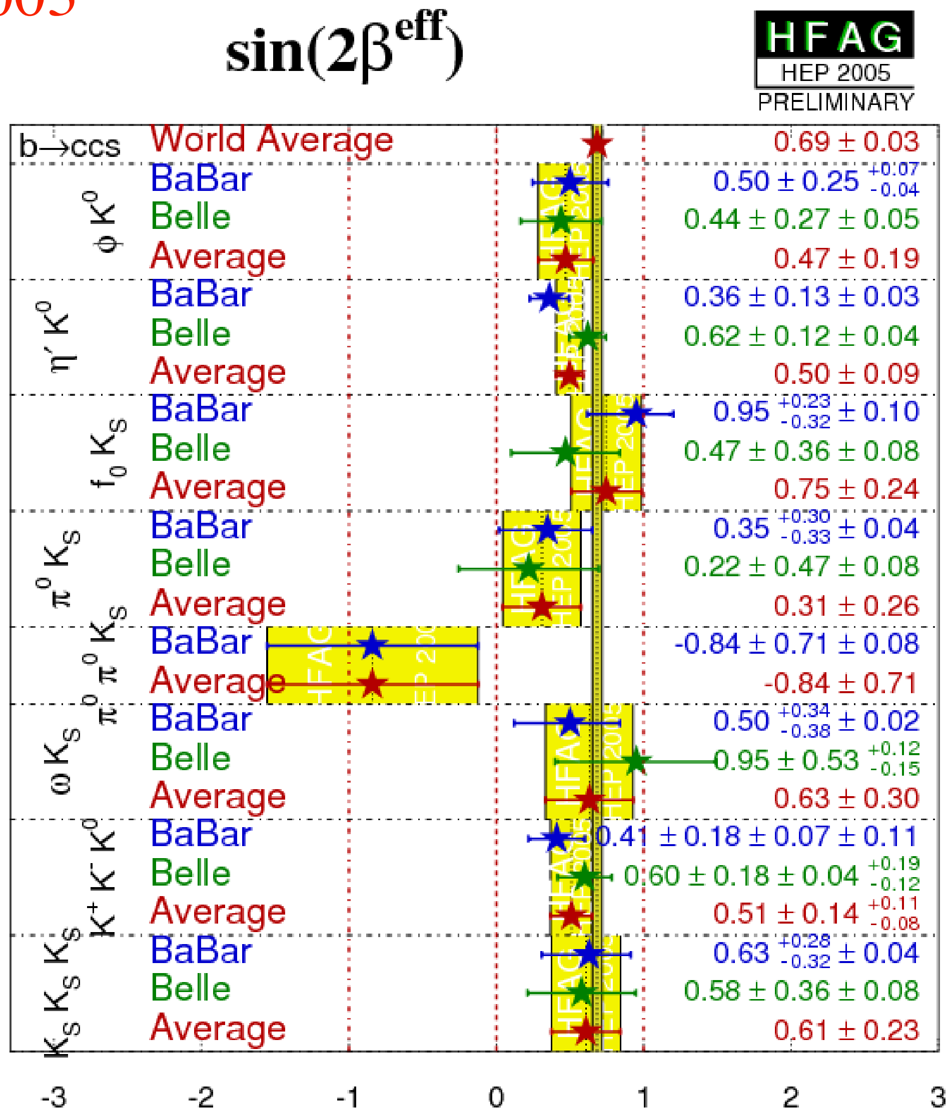


Decay phase = 0



Decay phase ~ 0 in SM
Decay phase ≠ 0 if NP

total = (mixing phase 2β) +(decay phase)



Most promising channels

Taken from G. Isidori

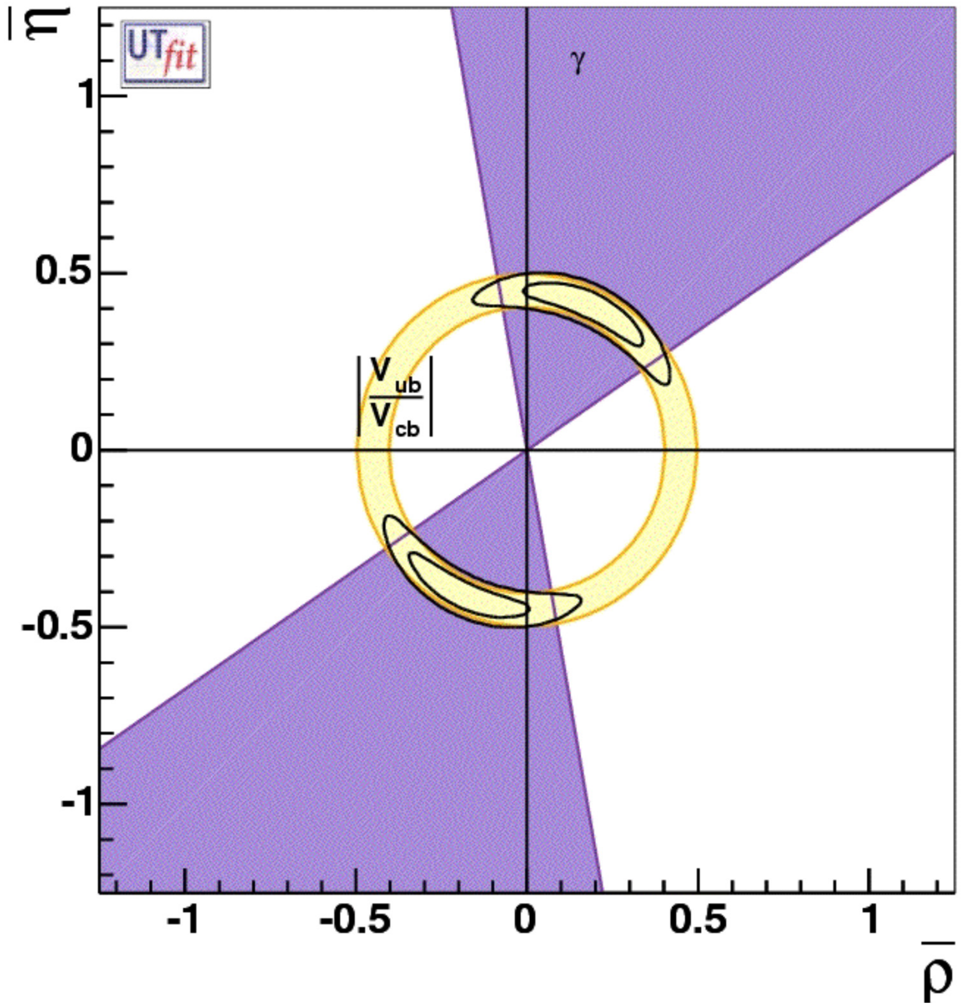
th. error $\lesssim 10\%$
(grey ellipse) = exp. error $\lesssim 10\%$
(white ellipse) = exp. error $\sim 30\%$

FLAVOUR COUPLING:

ELECTROWEAK STRUCTURE	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$	ΔM_K, ε_K
$\Delta F=1$ 4-quark box	$B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, ...	ε'/ε, $K \to 3\pi$, ...
gluon penguin	$B_d \to X_s \gamma$, $B_d \to \phi K$ $B_d \to K\pi$, ...	$B_d \to X_d \gamma$, $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, ...
γ penguin	$B_d \to X_s l^+ l^-$, $B_d \to X_s \gamma$ $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d l^+ l^-$, $B_d \to X_d \gamma$ $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, ...
Z^0 penguin	$B_d \to X_s l^+ l^-$, $B_s \to \mu\mu$ $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d l^+ l^-$, $B_d \to \mu\mu$ $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, $K \to \pi\nu\nu$, $K \to \mu\mu$, ...
H^0 penguin	$B_s \to \mu\mu$	$B_d \to \mu\mu$	$K_{L,S} \to \mu\mu$

NP-free triangle

- Unitarity triangle determined only from measurements of tree processes (assumed to be free from NP):
  - $|V_{ub}|$, from $b \to u$ rate
  - $\gamma = -\arg(V_{td})$ from $B \to D(*)K$
- This is indeed what we know about the CKM matrix if we suspect New Physics might exist in loop processes
  - It is essential to improve the precision on γ from tree decays



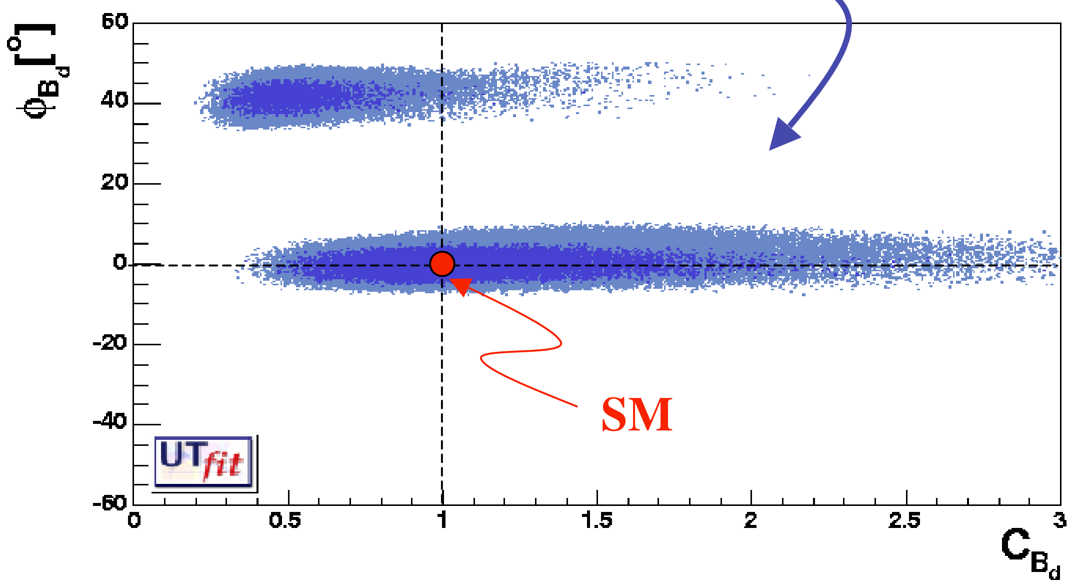
Allowing New Physics in B^0 mixing

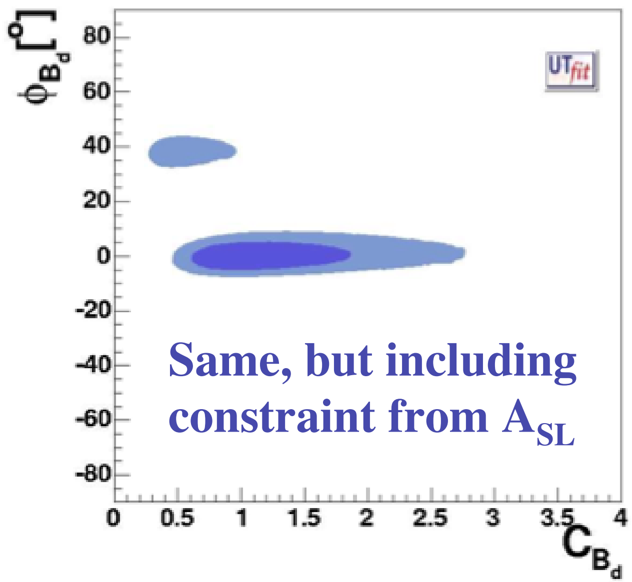
- Use model-independent parametrization of New Physics in B^0 (and K^0) mixing, and re-do UT fit with free NP parameters

$$\Delta m_d^{SM+NP} = C_{B_d} \Delta m_d^{SM} \qquad \beta^{SM+NP} = \beta^{SM} + \phi_{B_d}$$

$$\varepsilon_K^{SM+NP} = C_{\varepsilon_K} \varepsilon_K^{SM} \qquad \alpha^{SM+NP} = \alpha^{SM} - \phi_{B_d}$$

$$(\gamma \text{ and } |V_{ub}/V_{cb}| \text{ unaffected})$$





Luca Silvestrini (LP05, Uppsala)

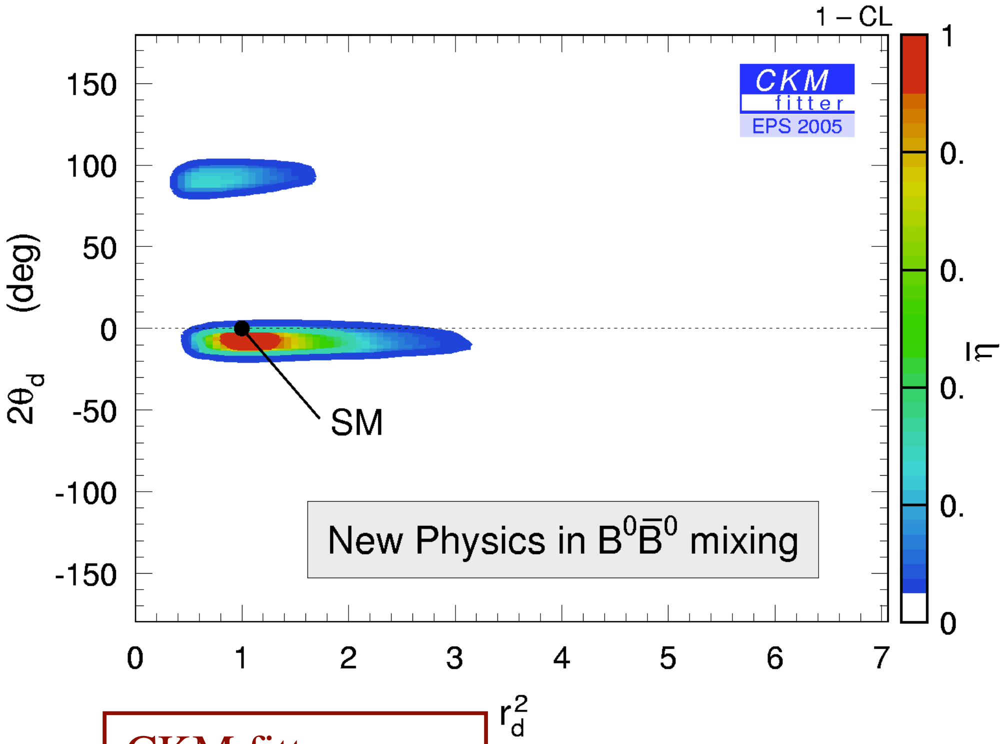
New Physics in $\Delta B=2$ and $\Delta S=2$ can be up to 50% of the SM only if NP has same phase as SM, otherwise it can be at most 10%

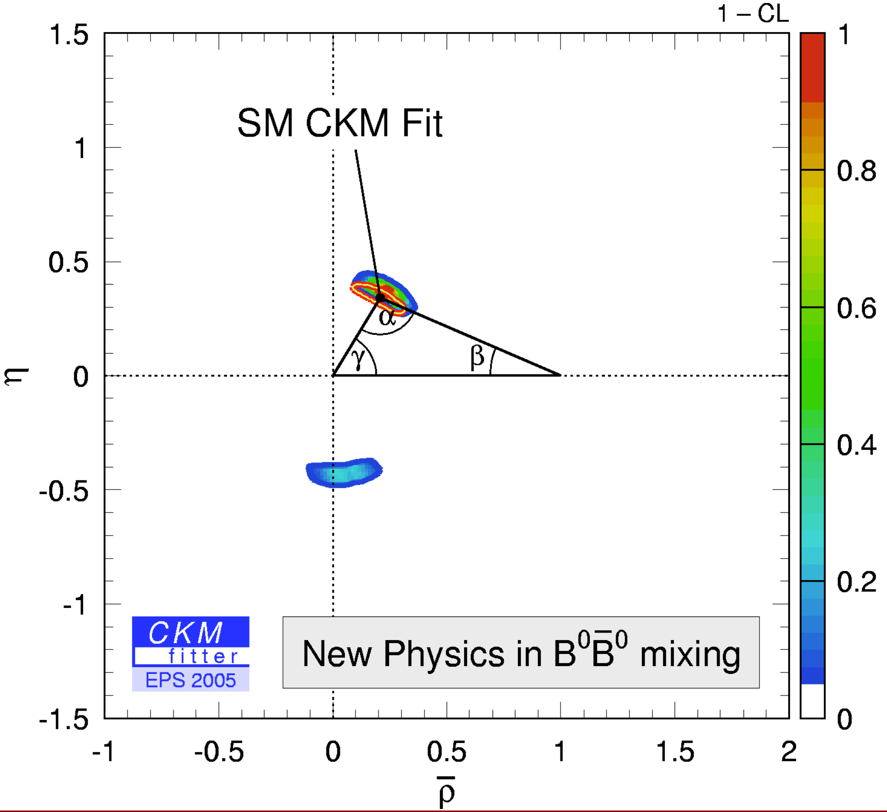
$\Rightarrow$ NP is either "Minimal Flavour Violation" or new CPV only in $b \rightarrow s$ transition

Allowing New Physics in B^0 mixing

- Another similar analysis (without ε_K, without A_{SL})

$$\Delta m_d^{SM+NP} = r_d^2 \Delta m_d^{SM} \qquad \beta^{SM+NP} = \beta^{SM} + \theta_d$$
$$\alpha^{SM+NP} = \alpha^{SM} - \theta_d$$





CKM fitter group (Summer 2005)

SM solution preferred, where possible NP phase is < 15 degrees.
The relative strength of NP to SM contributions can still easily be of order 100%.

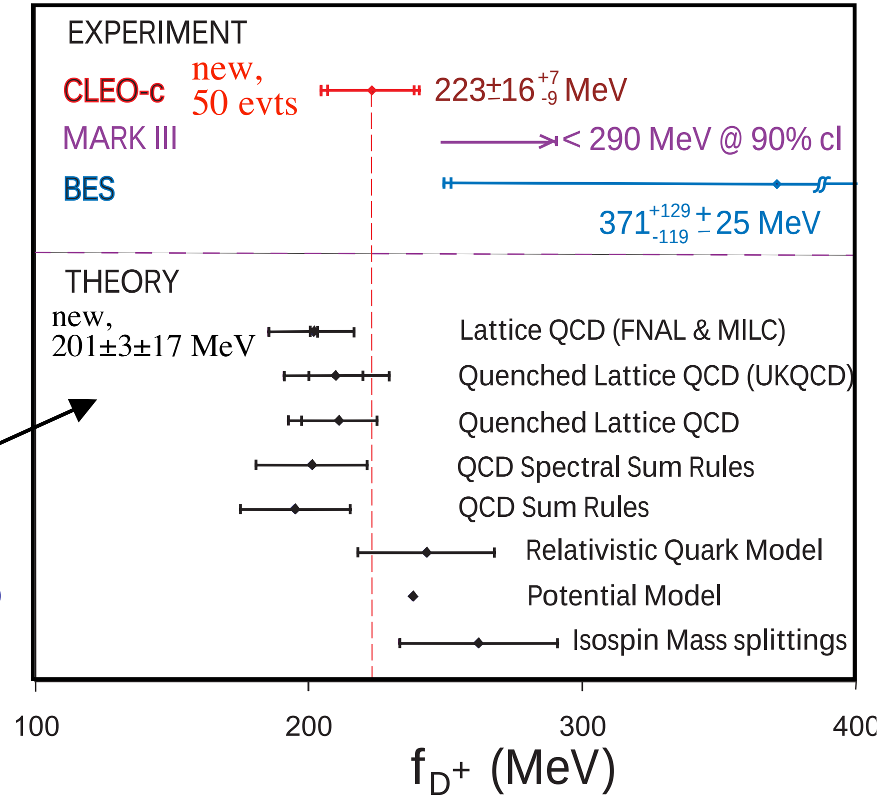
Charm factories

- CLEO-c experiment (Cornell):
  - — Taking data above charm threshold since 2003:
    - $e^+e^- \rightarrow \psi(3770) \rightarrow D^+D^-$ or D^0D^0 (281 pb^{-1} so far)
  - — Plan to go also above D_s threshold ($\sqrt{s}$=4.1 GeV):
    - $e^+e^- \rightarrow \psi(\ldots) \rightarrow D_s^+D_s^-, \ldots$
  - — May still spend one year on J/ψ or $\psi(2S)$
  - — End in 2008
- BES III experiment (Beijing):
  - — BES II stopped in 2004
    - 27.7 pb^{-1} recorded at $\psi(3770)$
  - — Old BEPC storage ring dismantled this summer to install a new double-ring machine, BEPCII
    - design luminosity 10^{33} $cm^{-2}s^{-1}$ at $\psi(3770)$ (= 100 times BEPC)
  - — Major detector upgrade: BESII → BESIII
  - — Start of physics commissioning in 2007
  - — Will run on J/ψ, $\psi(2S)$, $\psi(3770)$, etc …

Key contributions expected from charm factories

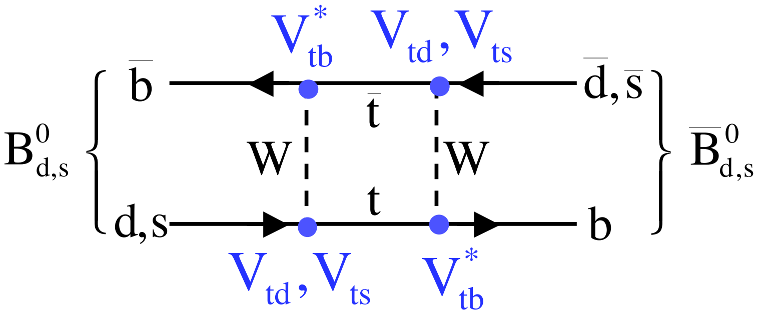
- Improve determination of γ from $B \to DK$ tree processes:
  - Measure more precisely $D^0 \to K_S \pi^+ \pi^-$ Dalitz plot
  - Measure D meson strong phase differences appearing in ADS analyses of $B^+ \to DK^+$
- Improve extraction of right side of UT from B oscillations measurements:
  - Measure decay constants f_{D+} and f_{Ds} from purely leptonic decays:

$$\Gamma(D^+ \to \ell^+ \nu) = \frac{G_F^2}{8\pi} |V_{cd}|^2 f_{D^+}^2 m_\ell^2 M_{D^+} \left(1 - \frac{m_\ell^2}{M_{D^+}^2}\right)^2$$



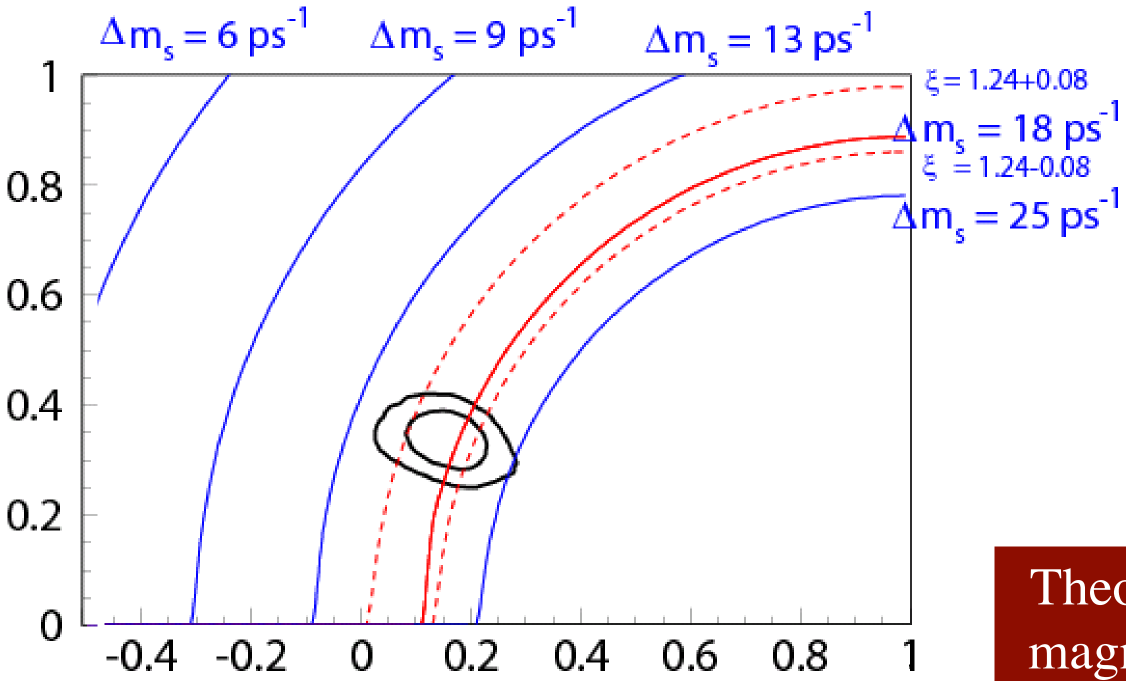
  - Compare with lattice QCD calculations:
    - → reduce uncertainty on theory predictions for f_{B0} and f_{Bs} (e.g. rely on LQCD only to predict ratio between B and D constants)
    - → reduce theory error in extraction of $|V_{td}|/|V_{ts}|$ from $\Delta m_d / \Delta m_s$

Constraining UT with B_d and B_s oscillations



$$\Delta m_q = \frac{G_F^2 m_W^2 \eta_B S(m_t^2/m_W^2)}{6\pi^2} m_{Bq} f_{Bq}^2 B_{Bq} \left|V_{tq} V_{tb}^*\right|^2$$

$$\Rightarrow \frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \quad \text{where} \quad \xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$



- **Theory uncertainty (LQCD):**
  - $f_{B_s}\sqrt{B_{B_s}} = 276 \pm 38$ MeV $\rightarrow$ ~14%
  - $\xi = 1.24 \pm 0.04 \pm 0.06$ $\rightarrow$ ~6%
- **Experimental accuracy:**
  - $\Delta m_d = 0.509 \pm 0.004\ ps^{-1}$ $\rightarrow$ 0.9%
  - $\sigma(\Delta m_s)$ will be $< 0.1\ ps^{-1}$ as soon as measured $\rightarrow$ 0.5%

Theory uncertainty will soon be one order of magnitude larger than the experimental one !
$\Rightarrow$ LQCD improvement most welcome

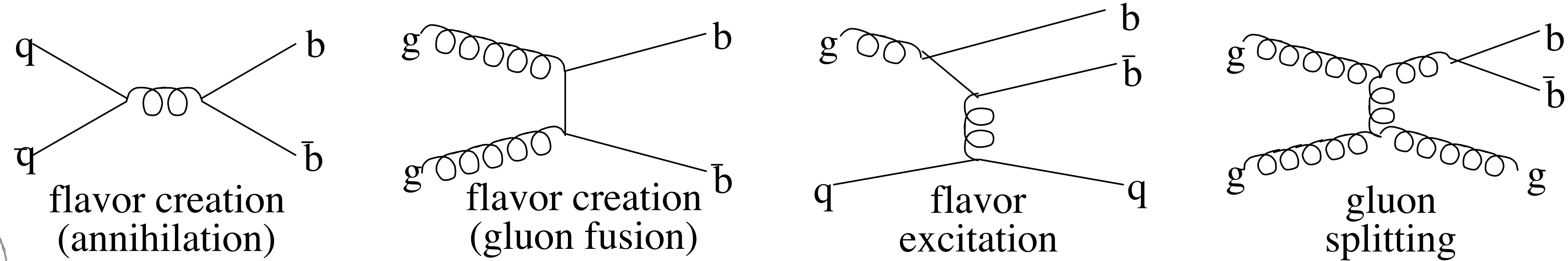
Which collider for B physics: (dis)advantages

	$e^+e^- \to \Upsilon(4S) \to BB$ PEPII, KEKB → SuperB	$e^+e^- \to Z \to bb$ LEP, SLC → ∅	$pp \to bbX$ ($\sqrt{s}$ = 2→14 TeV) Tevatron → LHC
Prod. σ_{bb}	1 nb	6 nb	100 → 500 μb
Typ. bb rate	10 Hz	0.3 Hz	10 → 100–500 kHz
Purity	~1/4	~ 15%	$\sigma_{bb}/\sigma_{inel}$ = 0.2% → 0.6% Trigger is a major issue !
Pileup	0 → 0	0	1.7 → 0.5–20
B types	B^+B^- (50%) B^0B^0 (50%)	B^+ (40%), B^0 (40%), B_s (10%), B_c (< 0.1%), b-baryons (10%)	
B boost	Small	Large, hence decay vertexes well separated	
Event structure	BB pair alone	2 b jets (+ g)	Many particles not associated with the two b hadrons
Prod. vertex	Not reconstructed	Reconstructed	Reconstructed (many tracks)
B^0B^0 mixing	Coherent	Incoherent (extra flavour tagging dilution)	

Hadron colliders

<table>
<tr><th></th><th>Tevatron II (2001–2009)</th><th colspan="2">LHC (≥2007)</th></tr>
<tr><td></td><td></td><td>LHCb</td><td>ATLAS/CMS</td></tr>
<tr><td>beams, $\sqrt{s}$</td><td>$p+\bar{p}$, 2 TeV</td><td colspan="2">p+p, 14 TeV</td></tr>
<tr><td>σ_{bb}</td><td>0.1 mb</td><td colspan="2">0.5 mb</td></tr>
<tr><td>σ_{cc}</td><td>1mb</td><td colspan="2">3.5 mb</td></tr>
<tr><td>$\sigma_{visible}$</td><td></td><td>~63 mb</td><td></td></tr>
<tr><td>$\sigma_{inelastic}$</td><td>60 mb</td><td colspan="2">80 mb</td></tr>
<tr><td>σ_{total}</td><td>75 mb</td><td colspan="2">100 mb</td></tr>
<tr><td>$\omega_{\text{bunch crossing}}$</td><td>1.7 MHz</td><td colspan="2">40 MHz</td></tr>
<tr><td>$\Delta t_{\text{bunch crossing}}$</td><td>396 ns</td><td colspan="2">25 ns</td></tr>
<tr><td>$\sigma_{z\ (\text{luminous region})}$</td><td>30 cm</td><td colspan="2">5.3 cm</td></tr>
<tr><td>L [cm^{-2}s^{-2}]</td><td>0.5×10^{32}</td><td>2×10^{32}</td><td>10^{33} (10^{34})</td></tr>
<tr><td><$n_{\text{inel. pp int.}}$ / bx></td><td>1.7</td><td>0.53</td><td>2.5 (25)</td></tr>
</table>

cross sections at LHC have large uncertainties (not measured yet)

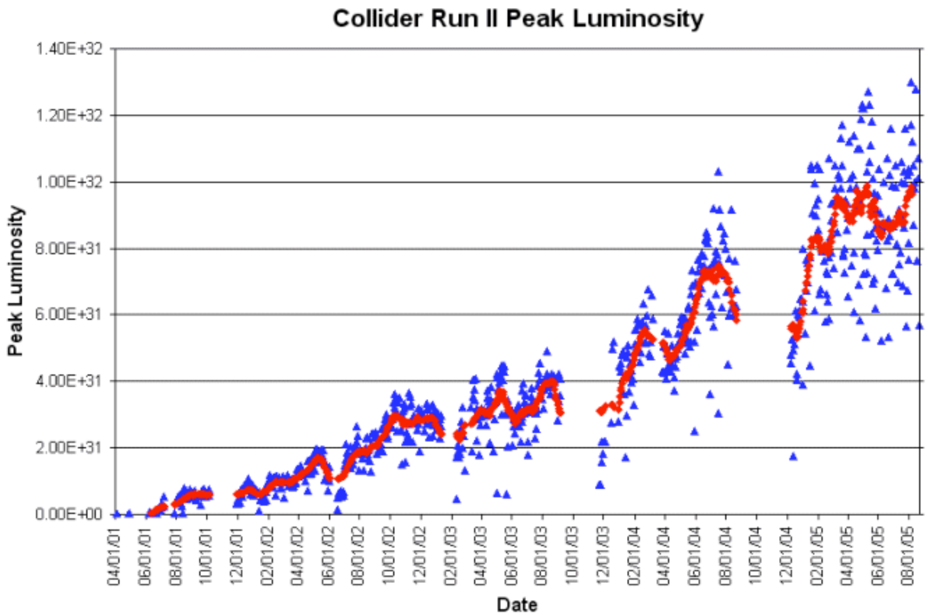


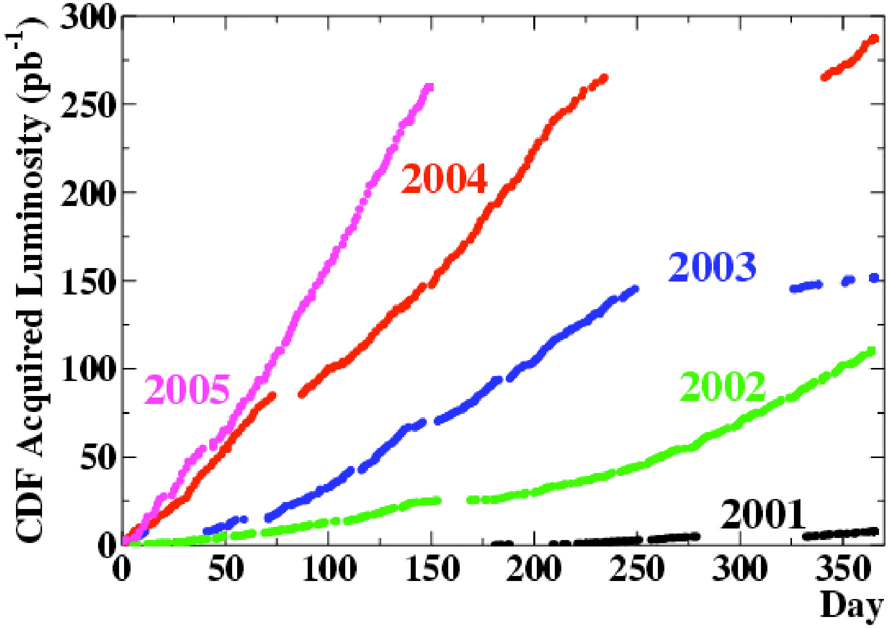
CDF and D0 at Tevatron Run II

- **Tevatron:**
  - — slow start in 2001,
    but now reaching $L_{peak} = 10^{32}\ cm^{-2}s^{-1}$
- **CDFII and D0:**
  - — now taking data with >80% efficiency
  - — producing significant B physics results !

- **B physics topics addressed:**
  - — b-hadron lifetimes and $\Delta\Gamma_s$
  - — B_s mixing
  - — B_s, B_c, Λ_b modes

Hotest topic
Search for B_s–$\bar{B}_s$ oscillations and measure Δm_s





B_s oscillations

- **Neutral B meson system (B_d or B_s):**
  - B^0 and B^0 are quantum superposition of two mass eigenstates B_H and B_L: $\quad B_{L,H} = p|B^0\rangle \pm q|\overline{B}^0\rangle$
  - Produce B^0 and observe its decay in a flavour-specific final state at proper time t (assume CP conserved):

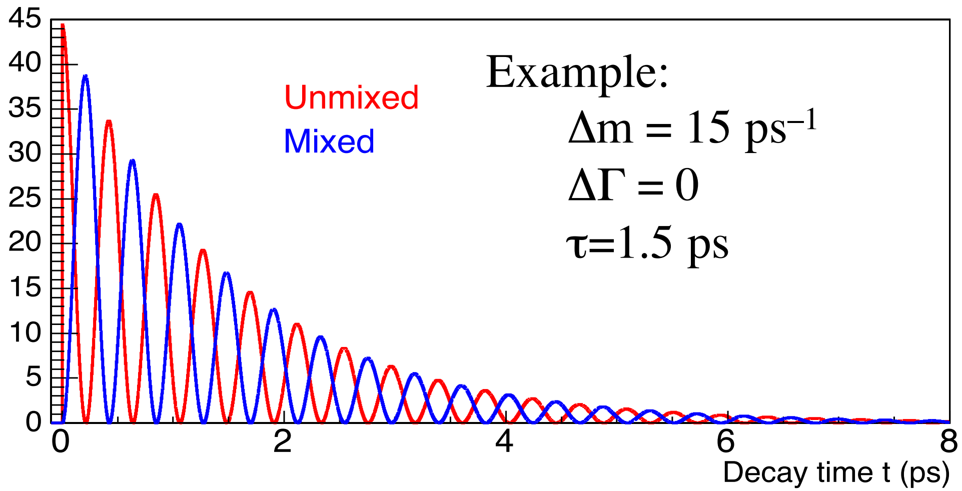
$$\mathrm{Prob}(B^0 \to B^0) = \frac{e^{-t/\tau}}{2\tau}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + (\cos\Delta m t)\right]$$

$$\mathrm{Prob}(B^0 \to \overline{B}^0) = \frac{e^{-t/\tau}}{2\tau}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - (\cos\Delta m t)\right]$$

$$\Delta m = m_H - m_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H \qquad \Gamma = \frac{\Gamma_L + \Gamma_H}{2} = 1/\tau$$

- **Slow B_d oscillations:**
  - well measured: $\Delta m_d = 0.5\ \mathrm{ps}^{-1}$
- **Fast B_s oscillations:**
  - not measured yet: $\Delta m_s > 15\ \mathrm{ps}^{-1}$
  - experimentally very challenging
  - NB: we know effect is there since χ_s has been measured to be ~1/2

$$\chi_s = \int \mathrm{Prob}(B_s^0 \to \overline{B}_s^0)\,dt$$



Statistical significance of B_s oscillation signal

- Experimental effects dilute statistical significance of B_s oscillations:
  - Flavour tagging effective efficiency ε_{eff}: $$\varepsilon_{eff} = \varepsilon D^2 = \varepsilon(1-2w)^2$$
    ε = tagging efficiency
    D = dilution
    w = wrong tag probability
  - Proper time resolution σ_t: $$t = \ell \frac{m}{p} \Rightarrow \sigma_t = \frac{m}{\langle p \rangle}\sigma_\ell \oplus t\frac{\sigma_p}{p}$$
    $\ell = B_s$ decay length
    $p = B_s$ momentum
    $m = B_s$ mass
  - Signal purity (before tagging): $$\frac{S}{S+B}$$
    S = number of B_s signal events
    B = number of background events

- Somewhat naïve but extremely useful formula:

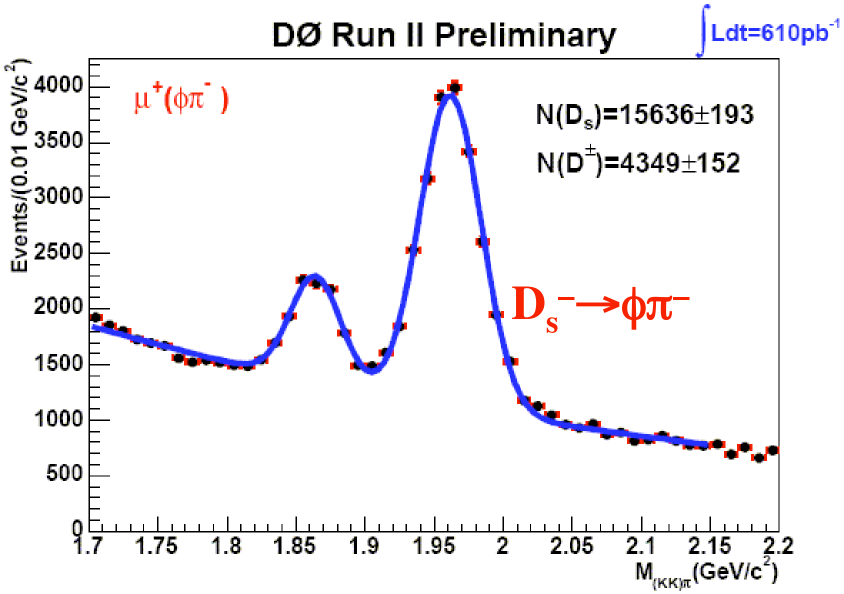
$$\text{significance} = \sqrt{\frac{S\varepsilon_{eff}}{2}}\exp\left(-\frac{(\Delta m_s \sigma_t)^2}{2}\right)\sqrt{\frac{S}{S+B}}$$

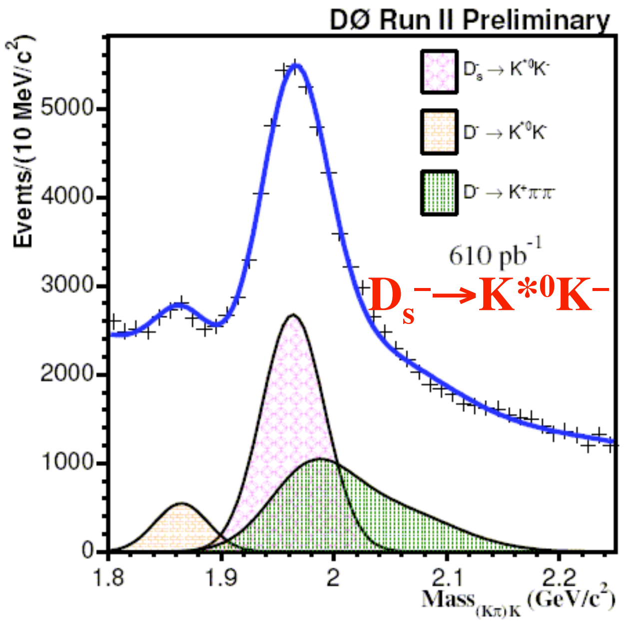
For example, must have significance >5 for a 5σ observation of B_s oscillations

  - Because Δm_s is large, very strong dependence on the resolution
    - need to be able to resolve the fast oscillations
  - If significance too low, set lower limit on Δm_s
    - need to have a good knowledge of σ_t and ε_{eff}

Semi-leptonic $B_s \to D_s l^+ \nu X$ samples

(D0 example described here, but similar analysis at CDF)

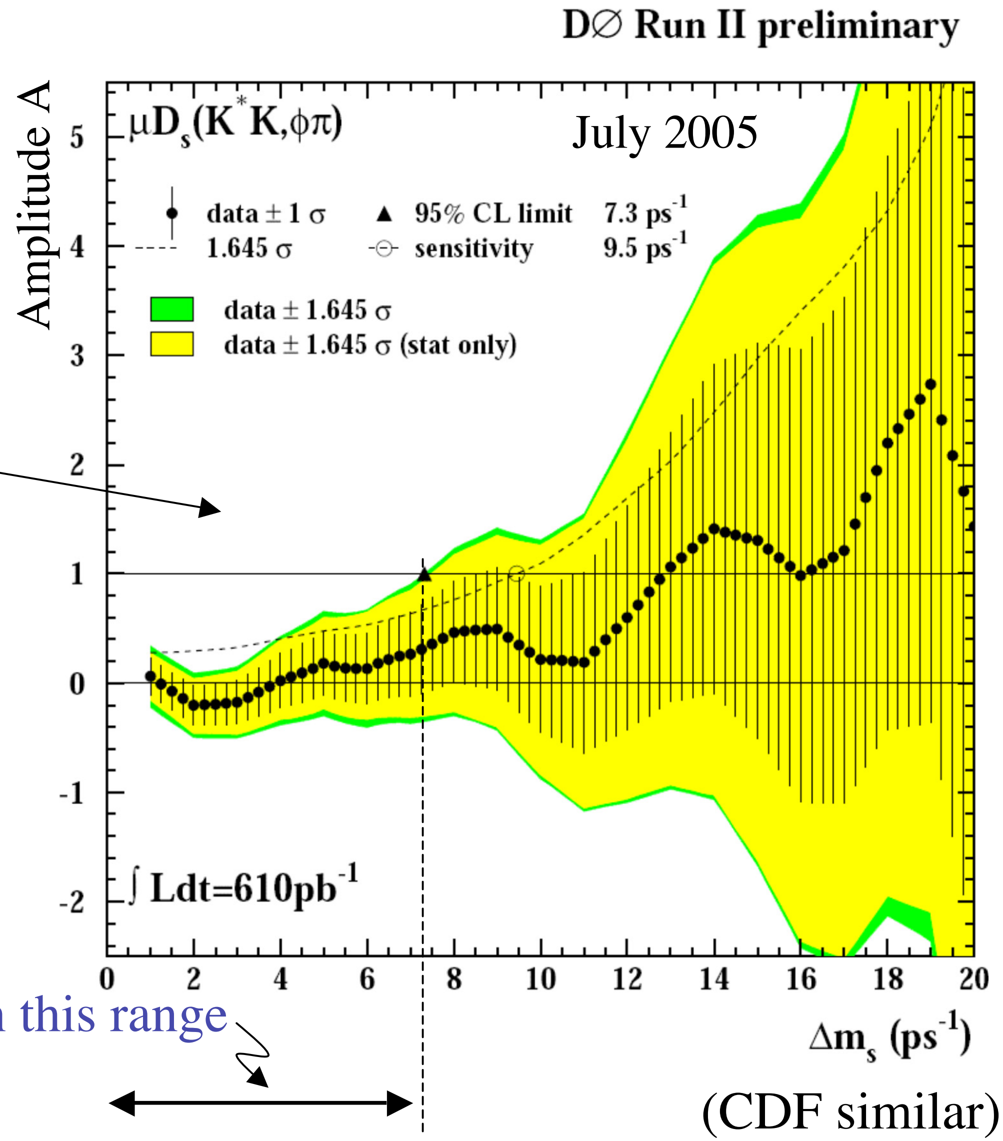




- Trigger:
  - single track matched to muon with $p_T > 4$ GeV/c
- Semileptonic B_s decay:
  - high statistics, but limited B_s mass and proper time resolutions
- Tagging performance (opposite side tags, dominated by muon tag)
  - $\varepsilon D^2 = (1.94 \pm 0.14)\%$ measured on B_d oscillations

Latest D0 result on Δm_s

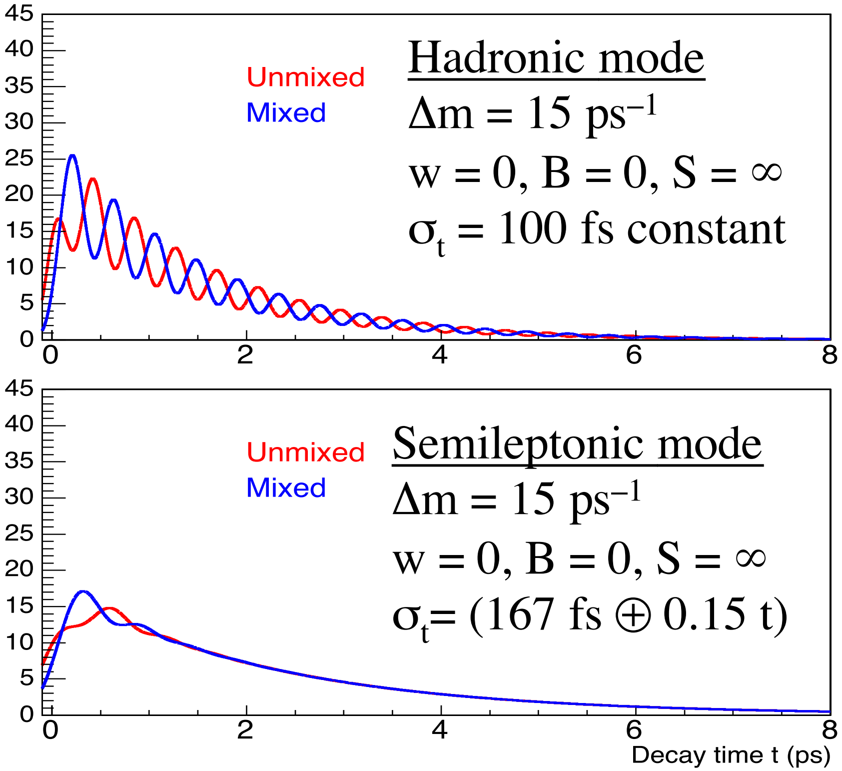
- **Amplitude method:**
  - Replace "cos($\Delta m_s t$)" with "A cos($\Delta m_s t$)" in mixing expressions
  - Fit tagged rates for A, at many different test values of Δm_s
  - Plot $A \pm \sigma_A$ versus Δm_s (similar to Fourier transform of mixing asymmetry)
  - A=1 (within error) at true Δm_s, otherwise A consistent with 0
  - Significance = $1/\sigma_A$
  - If no significant signal, exclude values of Δm_s for which A=1 is excluded
- **In this case:**
  - No signal, exclude all values of Δm_s in this range at 95% CL

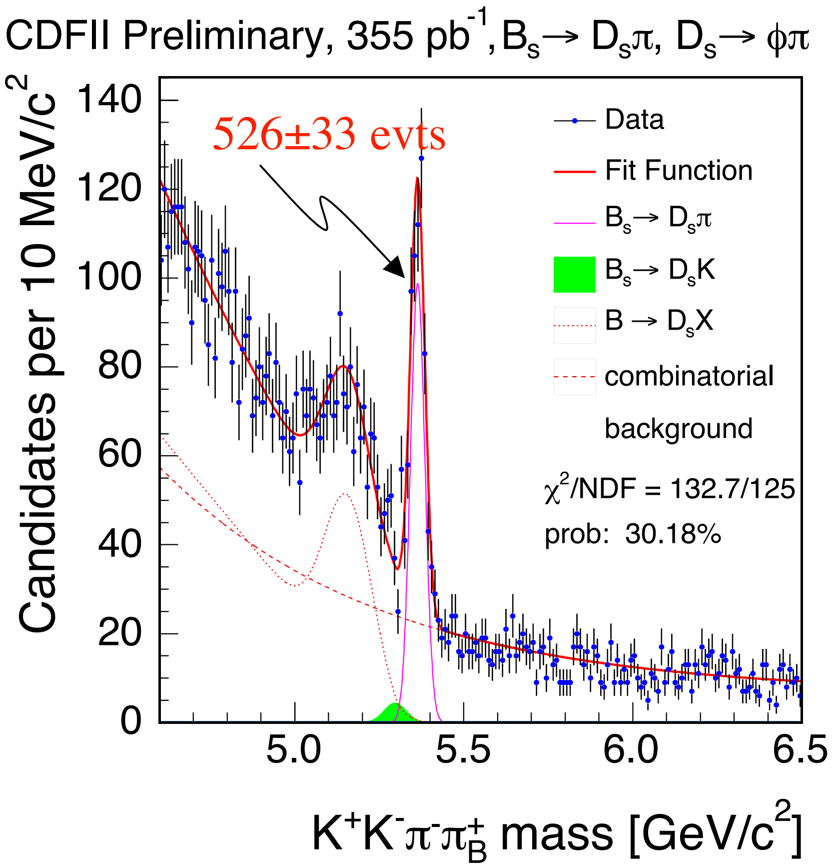


(CDF similar)

B_s exclusive hadronic signals

- Much (~10 times) less statistics compared to semileptonic B_s sample, but much better σ_t and σ_m (full reconstruction)

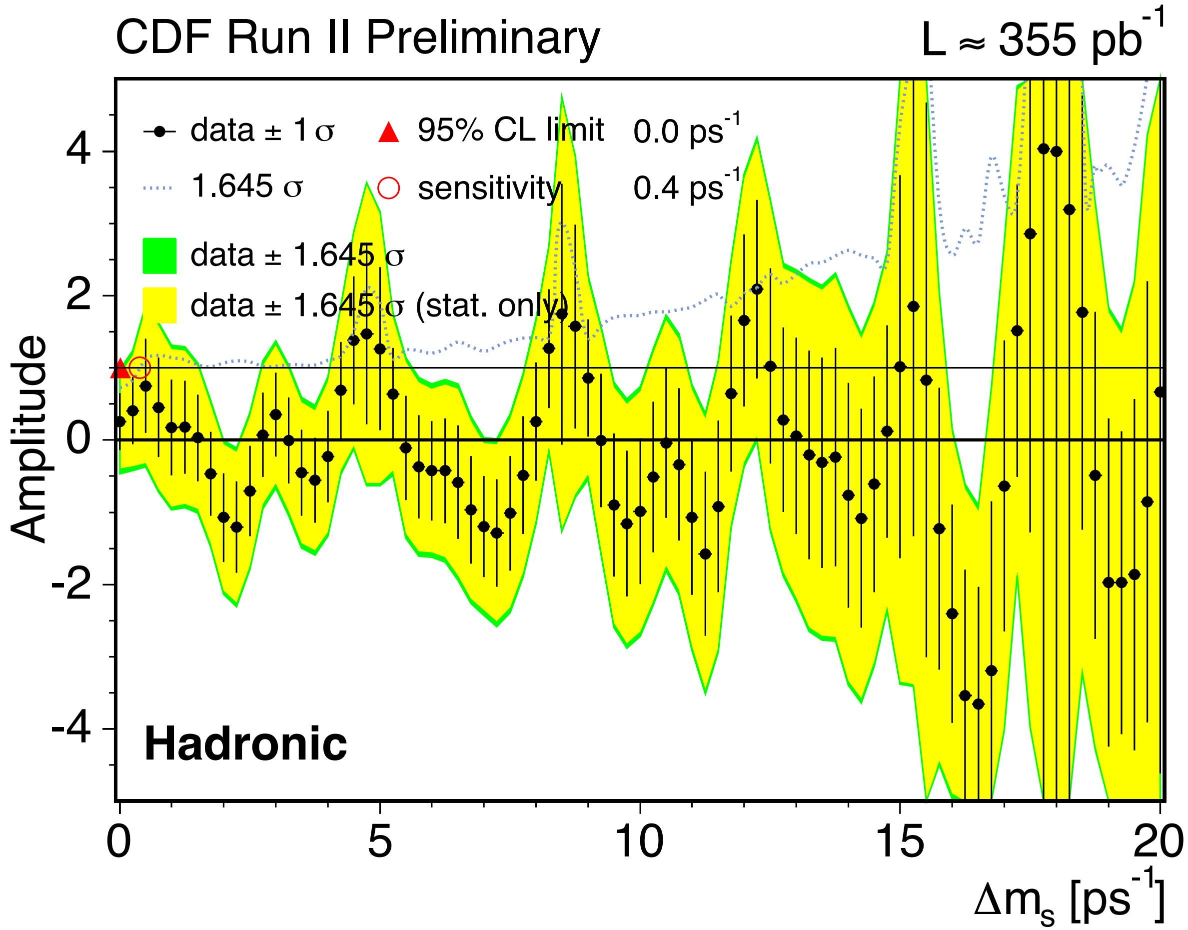




- Trigger:
  - two displaced tracks with impact parameters measured in vertex detector
- Tagging:
  - $\varepsilon D^2 = (1.12 \pm 0.23)\%$

CDF's Δm_s results with hadronic modes

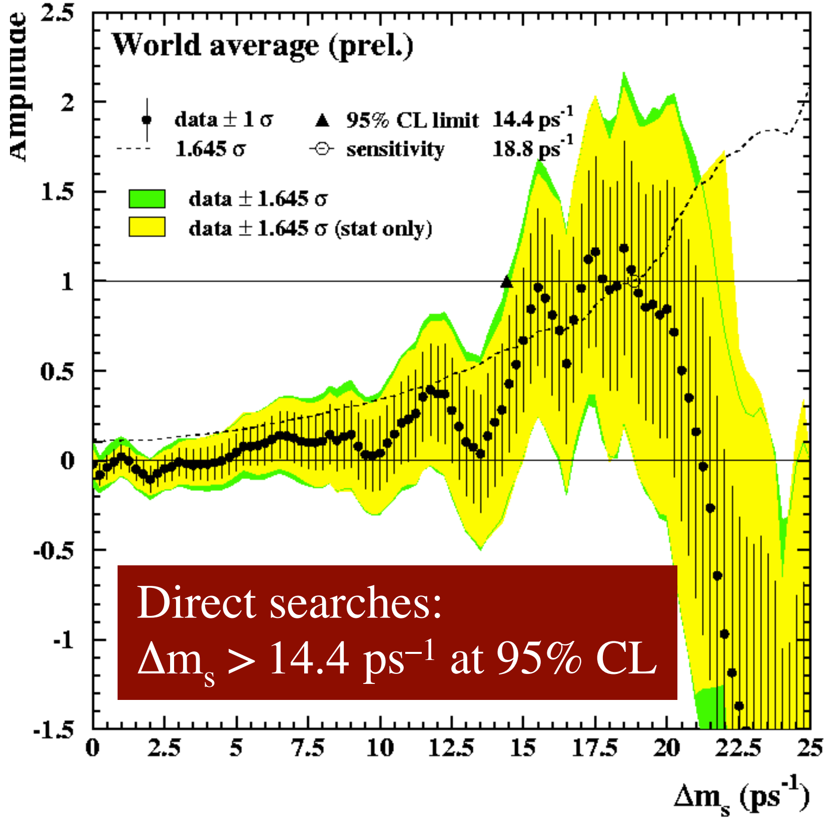
526±33 $B_s \to D_s(\phi\pi)\pi$ (S/B=1.8)
254±21 $B_s \to D_s(\phi\pi)\pi$ (S/B=1.7)
116±18 $B_s \to D_s(\pi\pi\pi)\pi$ (S/B=1.0)



- Amplitude spectrum (~ Fourier transform of proper time distribution) displays just "noise" …
… but this is the clearly the way to go with larger statistics

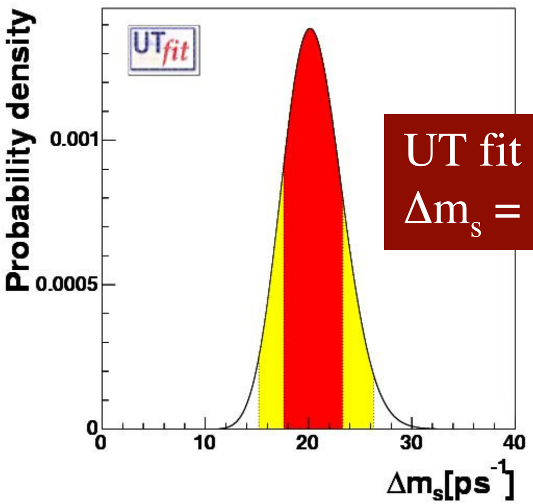
Present overall status of Δm_s

- **World average:**
  - Published results from ALEPH, DELPHI, OPAL, SLD, CDF + latest preliminary CDF II and D0 results
  - Sensitivity:
    - 18.8 ps^{-1} for 95% CL exclusion
    - 9.7 ps^{-1} for 5σ observation



Direct searches:
$\Delta m_s > 14.4\ ps^{-1}$ at 95% CL

- **SM prediction:**



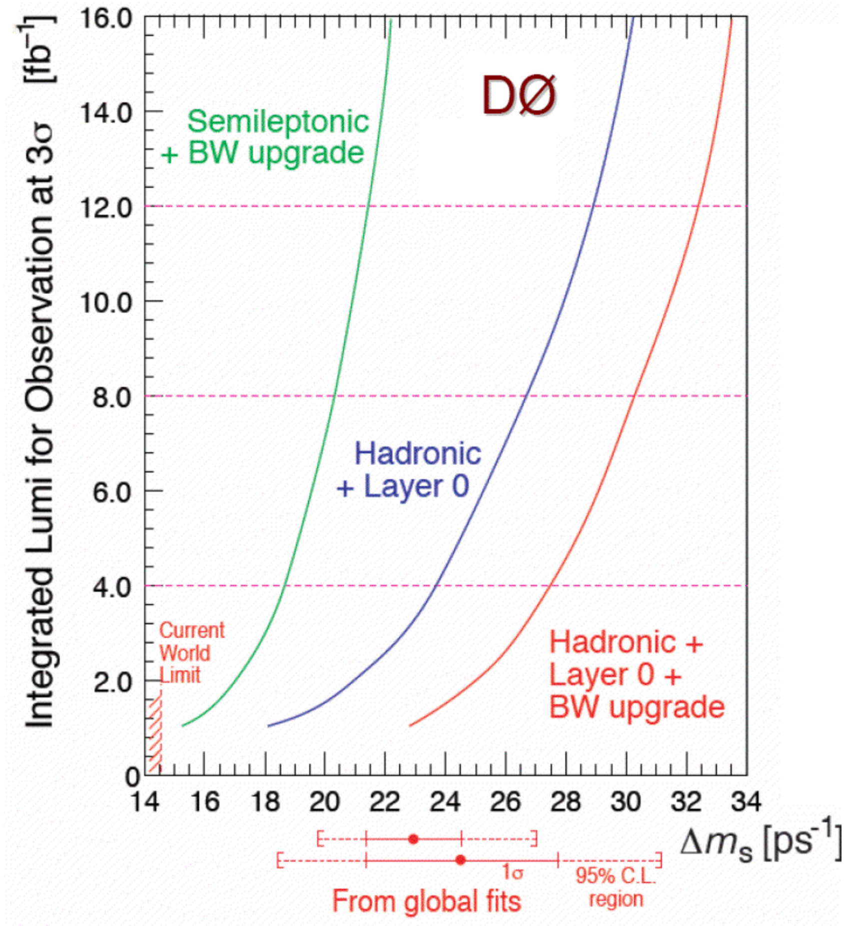
UT fit without Δm_s:
$\Delta m_s = 22.2 \pm 3.1\ ps^{-1}$

- **Feeling that SM Δm_s is within Tevatron's reach:**
  - NB: a 5σ observation of Δm_s=20 ps^{-1} would require increasing sensitivity ($=1/\sigma_A$) by a factor 10

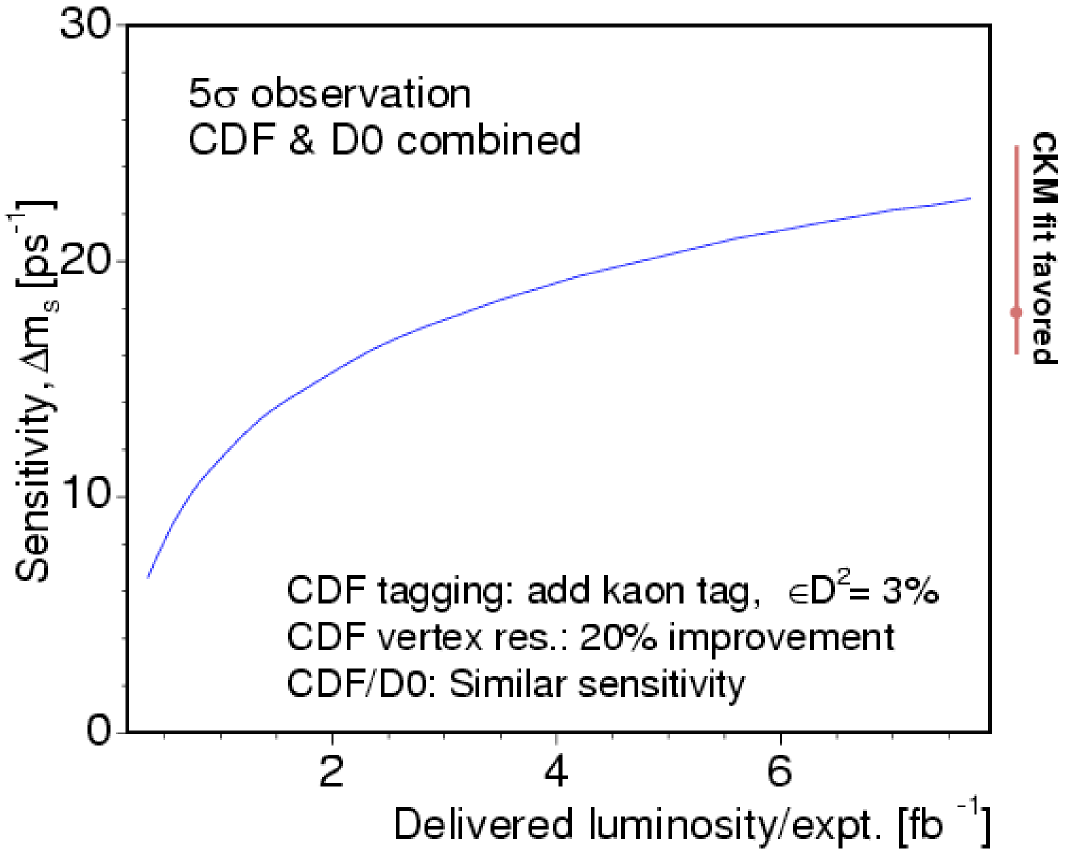
D0 upgrade plans

- Analysis improvements:
  - add hadronic B_s decays (triggered on tagging muon) → Essential !
  - use more D_s channels
  - use per-event σ_t and w

- Detector upgrades during next shutdown between Run IIa and Run IIb (fall 2005–Jan 2006):
  - Addition of a "layer 0" of Si detectors around beam pipe
    - R(layer 1)=26 mm → R(layer 0) =17 mm
    - Should improve resolution by ~25%
  - Increase trigger bandwidth for B physics
    - Rate to tape: 50 Hz → 100 Hz

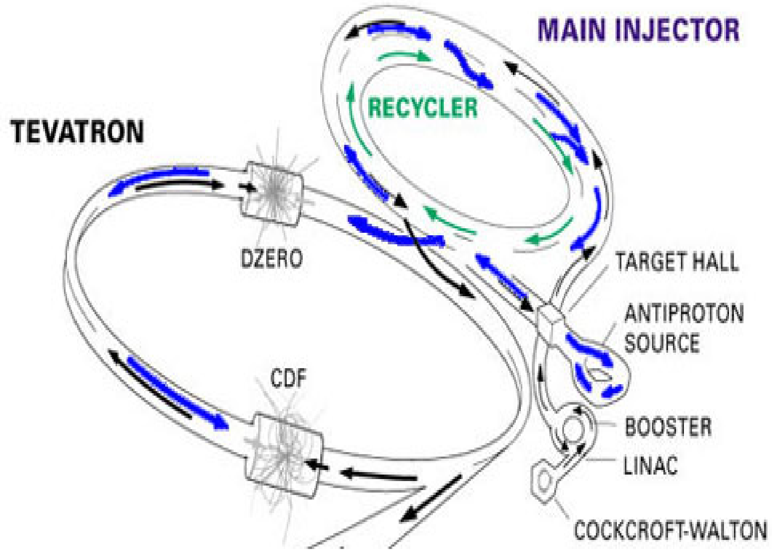


Projected Δm_s reach at the Tevatron



Planned integrated luminosity
at the end of each fiscal year (fb^{-1})

Year	FY05	FY06	FY07	FY08	FY09
Base plan	1.0	1.5	2.1	3.2	4.4
Design plan	1.4	2.2	3.8	6.1	8.6

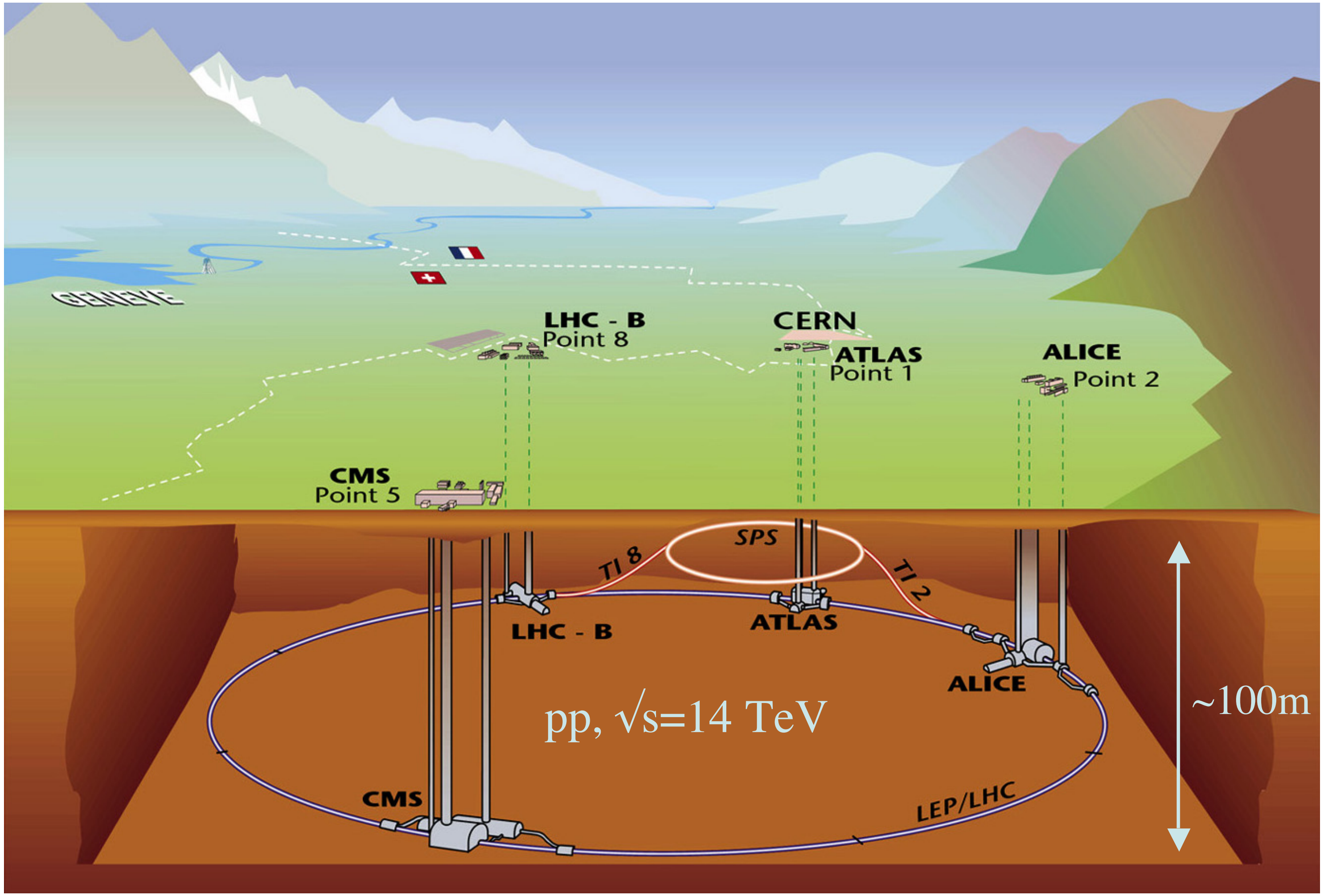


- Luminosity delivered today: ~1.2 fb^{-1}
- Run IIb luminosity will depend on Recycler ring and electron cooling performance:
  - Mid-July 2005: first electron-cooling demonstration achieved at the Fermilab's 8.9 GeV/c anti-proton Recycler ring, after 10 years of efforts !

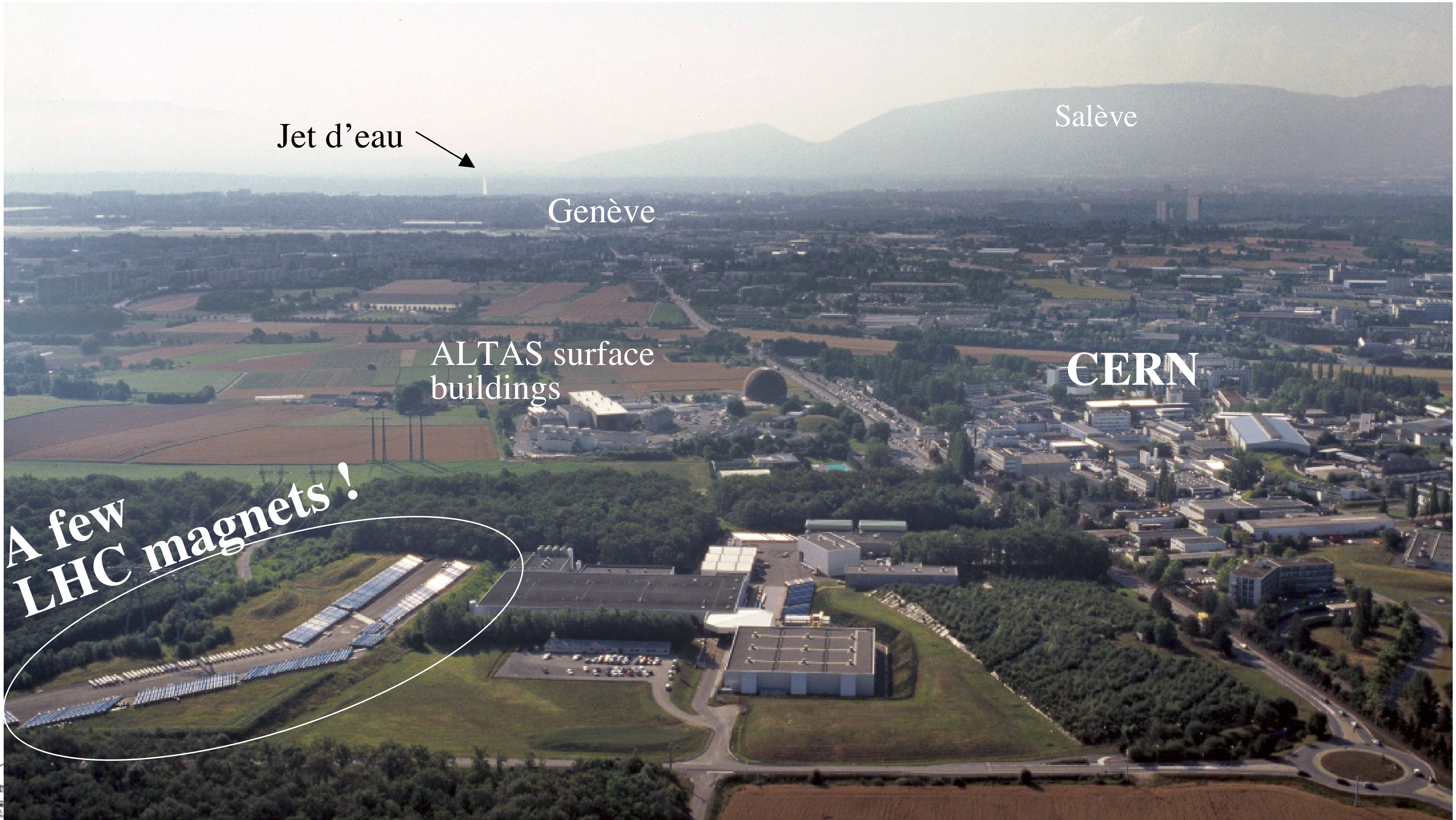
The Large Hadron Collider …

… will take over from the Tevatron in 2008

- ❑ Main justification:
  - High-p_T physics at energy frontier, direct search for new particles
- ❑ Other main programmes:
  - B physics and CP violation (indirect search)
  - Heavy (Pb) ions



… viewed from the sky on July 13, 2005

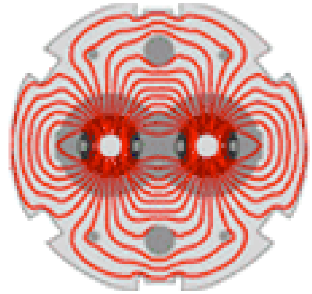


LHC magnets

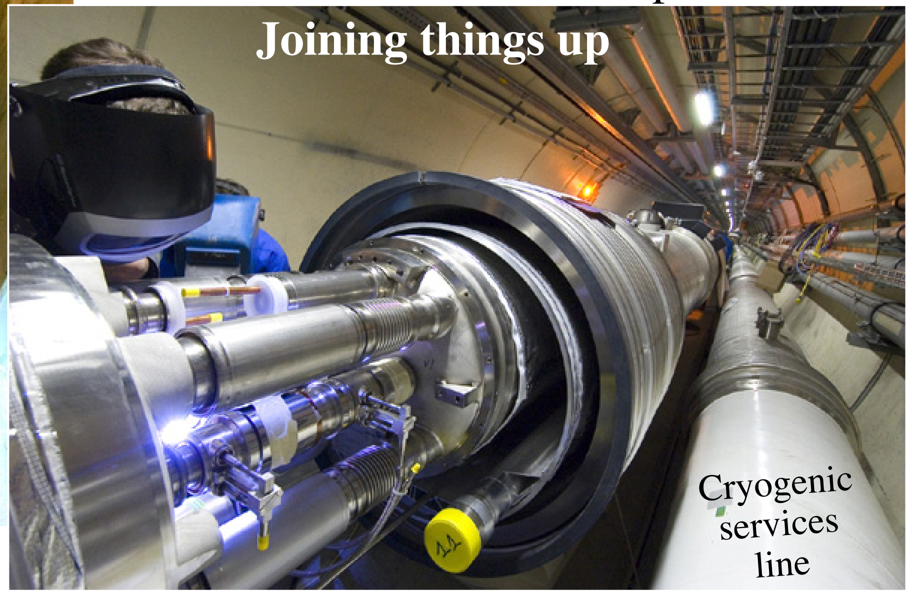
- ~1650 main magnets (~1000 produced) + a lot more other magnets
- 1232 cryogenic dipole magnets (~800 produced, 70 installed):
  - each 15-m long, will occupy together ~70% of LHC's circumference !


Lowering of 1st dipole into the tunnel (March 2005)

Cold mass (1.9 K)



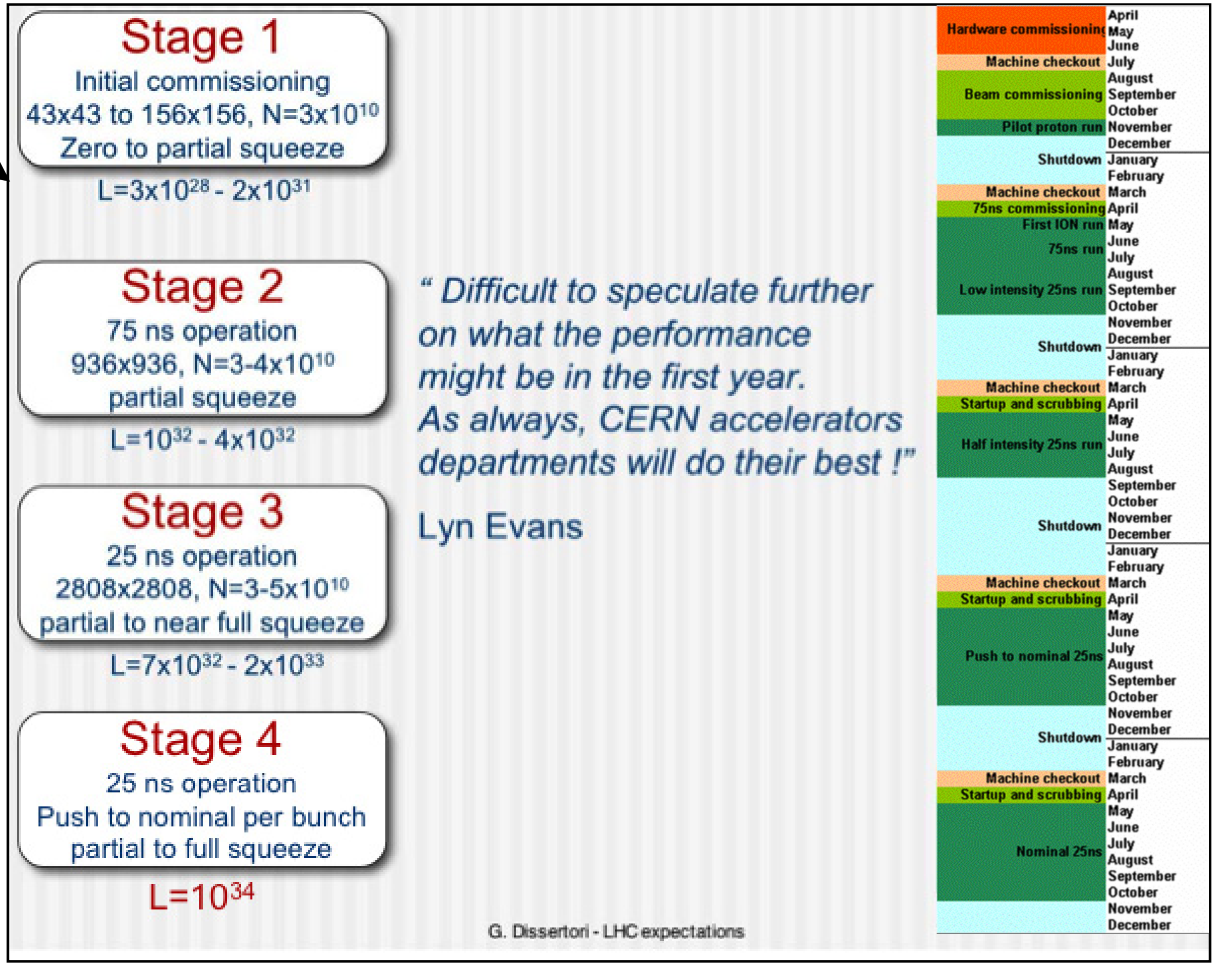
B fields of 8.3 T in opposite directions for each proton beam



Joining things up

LHC start-up and running schedule

- Predictions can always be optimistic or pessimistic (and may change)
  - This slide was shown at EPS-HEP conference in July 2005 (Lisboa)



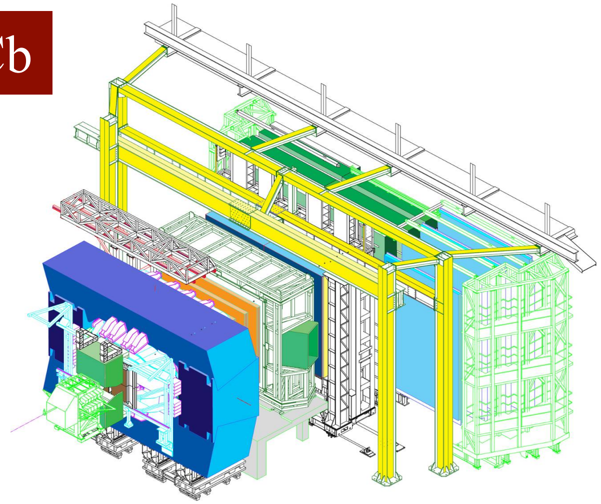
- Basically:
  - Beam commissioning starting in Summer 2007
  - Short very-low luminosity “pilot run” in 2007 used to debug/calibrate detectors, no (significant) physics
  - First physics run in 2008, at low luminosity (10^{32}–10^{33} cm^{-2}s^{-1})
  - Reaching the design luminosity of 10^{34} cm^{-2}s^{-1} will take until 2010

LHC experiments

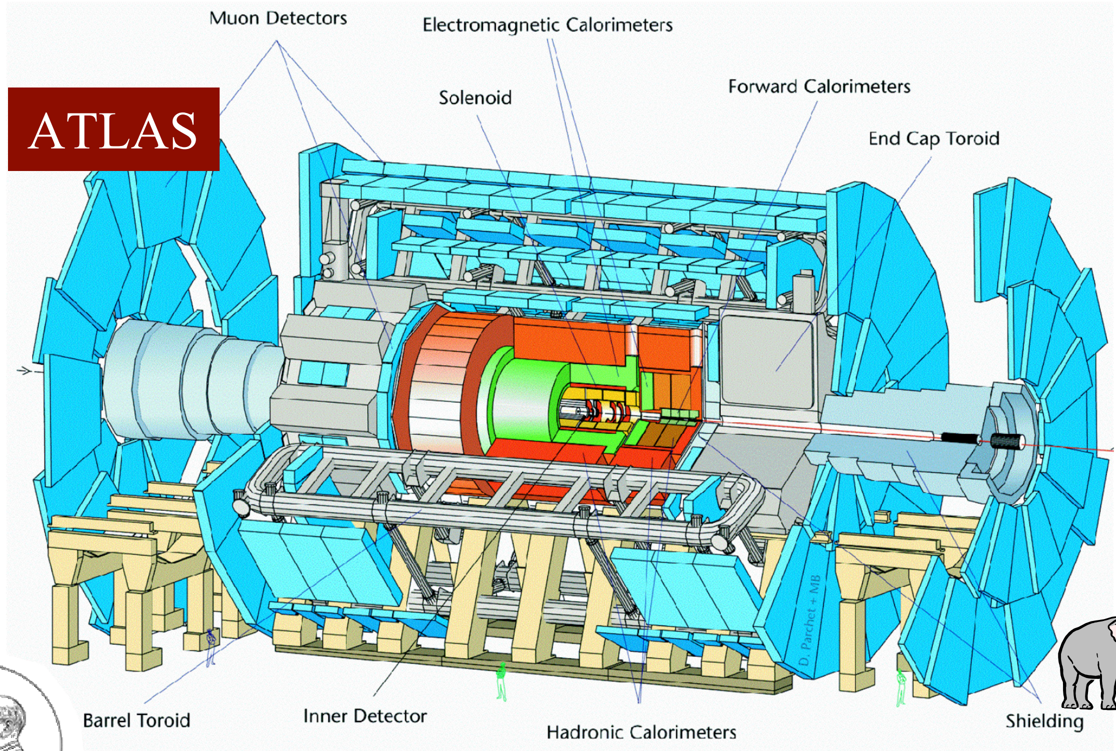
that will do B physics
(roughly to scale)

- ATLAS/CMS:
  general purpose experiments,
  optimized for high-p_T discovery physics
- LHCb:
  dedicated B physics experiment
  (may be the only one running after the B factories, unless Super-B is approved)

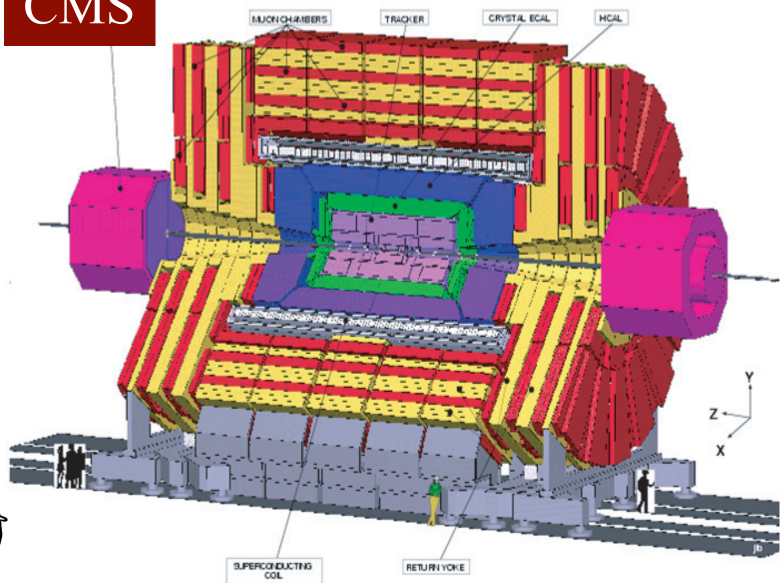
LHCb



ATLAS



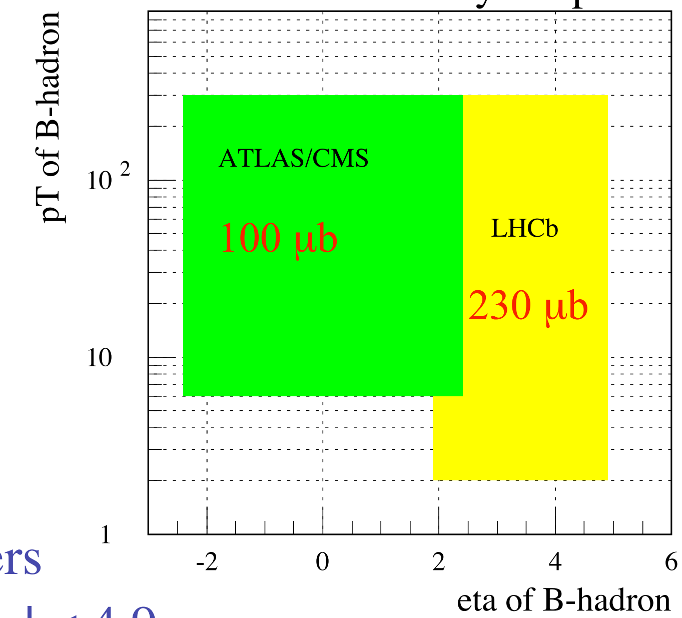
CMS

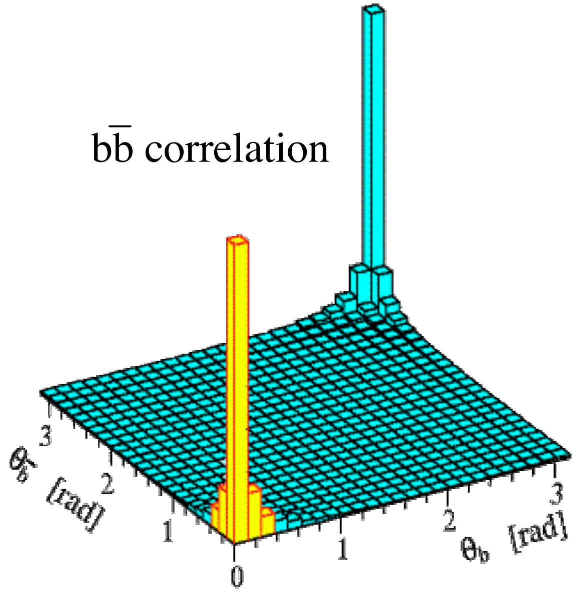


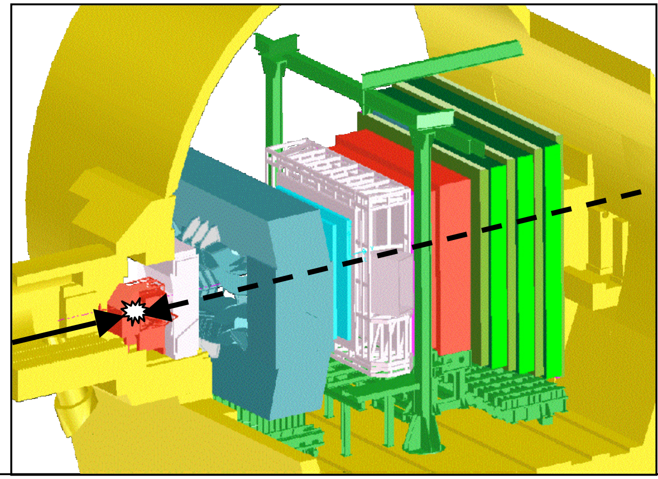
B acceptance

- ATLAS/CMS:
  - — central detectors, $|\eta|<2.5$
  - — will do B physics with high-p_T lepton triggers
- LHCb:
  - — designed to maximize B acceptance (within cost and space constraints)
  - — rely on softer, lower p_T triggers
  - — forward spectrometer, $1.9 < |\eta| < 4.9$
    - more b hadrons produced at low angles
  - — only single arm (cost and space)
    - OK since $b\bar{b}$ pairs produced correlated in space
    - Implies LHCb interaction point displaced by ~11m (=1.5 bunch spacing) with respect to nominal position on the ring (=center of cavern)

Pythia production cross section







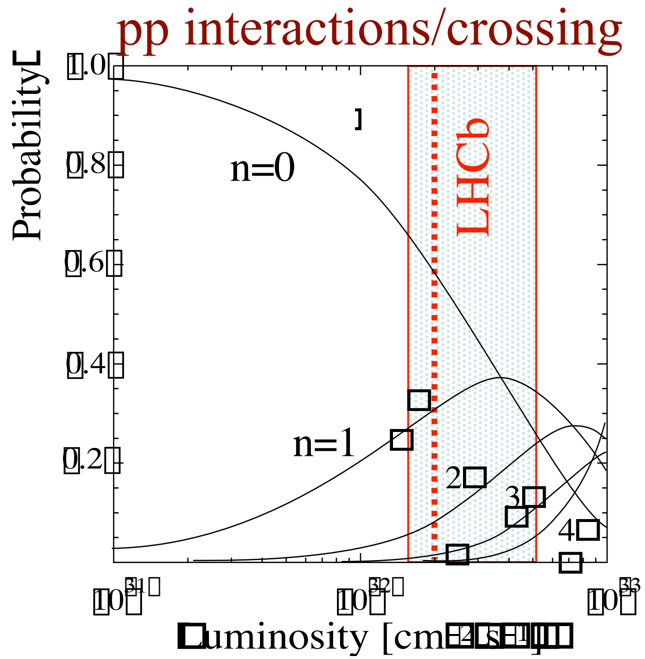
Luminosity and pileup

- **Pileup:**
  - — n = number of inelastic pp interactions occurring in the same bunch crossing
  - — Poisson distribution with mean $\langle n\rangle = L\sigma_{inel}/f$

L = instantaneous luminosity
f = non-empty bunch crossing rate
σ_{inel} = 80 mb

- **ATLAS/CMS** (f = 32 MHz)
  - — Will want to run at highest luminosity available
  - — Expect L= $1–2 \times 10^{33}$ cm^{-2}s^{-1} (<n>=2.5–5) for first 2 years
  - — At 10^{34} cm^{-2}s^{-1} (<n> = 25), B physics becomes impossible except $B\rightarrow\mu\mu$

10–20 fb^{-1} in 10^7 s

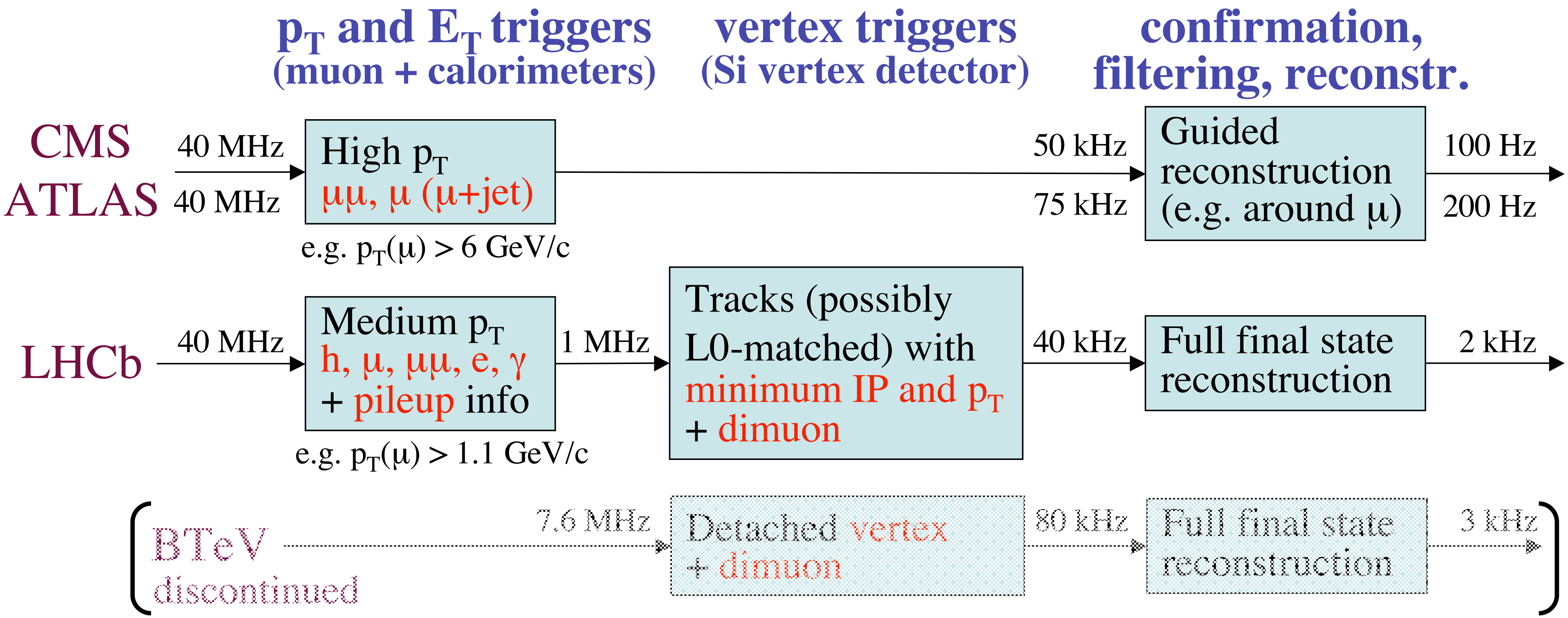


- **LHCb** (f = 30 MHz)
  - — L tuneable by defocusing the beams
  - — Choose to run at <L> ~ 2×10^{32} cm^{-2}s^{-1} (max. 5×10^{32} cm^{-2}s^{-1})
    - Clean environment (<n>=0.5)
    - Less radiation damage (LHCb 8mm from beam / ATLAS 5 cm)
    - Will be available from 1st physics run

2 fb^{-1} in 10^7 s

(10^7 s = nominal year)

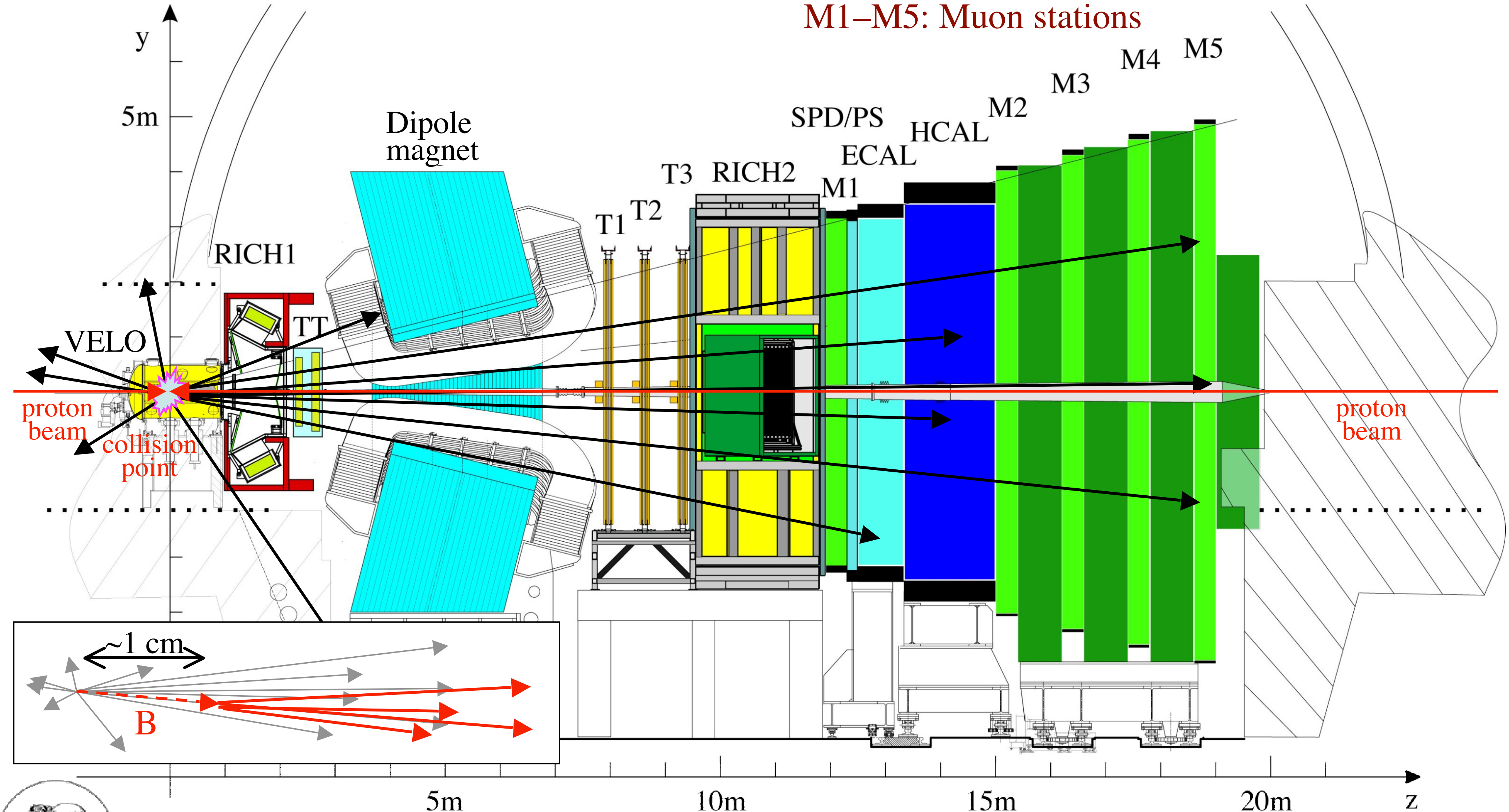
Overall trigger schemes



- **ATLAS/CMS:**
  - Mostly B physics with modes involving dimuons
  - no purely hadronic trigger (must rely on tagging lepton)
- **LHCb:**
  - Much lower p_T, go also for purely hadronic channels
  - Some features inspired from BTeV:
    - track p_T at L1 + large HLT output rate (was 200 Hz)

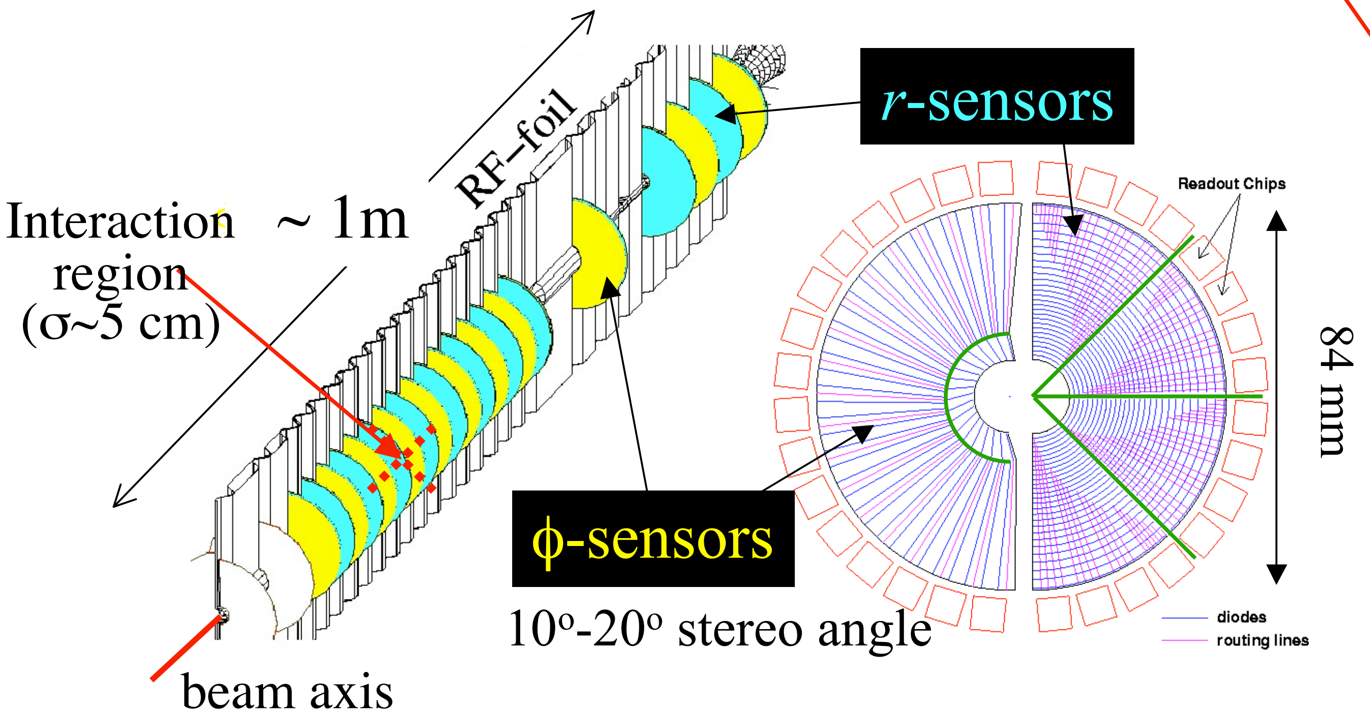
LHCb spectrometer

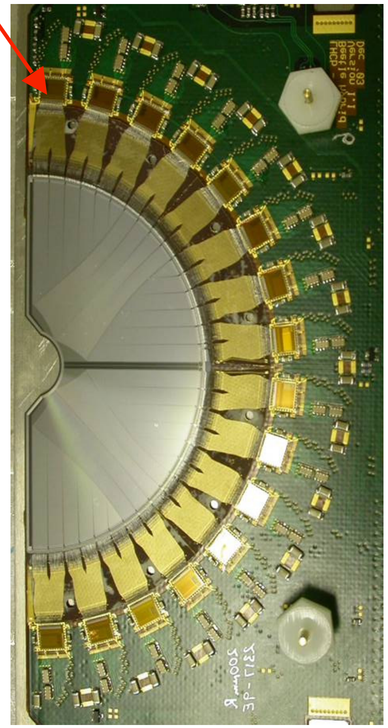
VELO: Vertex Locator (around interaction point)
TT, T1, T2, T3: Tracking stations
RICH1-2: Ring Imaging Cherenkov detectors
ECAL, HCAL: Calorimeters
M1–M5: Muon stations



Vertex LOcator

- 21 stations (=42 Si disks) :
  - each disk measures r or ϕ
  - 300 μm thick sensors
  - short strips, 40–100 μm pitch
- 2 additional disks for “pileup” system
  - each measures r only
- Radiation hardness
  - Active Si 8 mm from beam where ~10^{14} $n_{eq}/cm^2/y$ is expected
- Analogue readout
  - Beetle chip, ~180 k channels

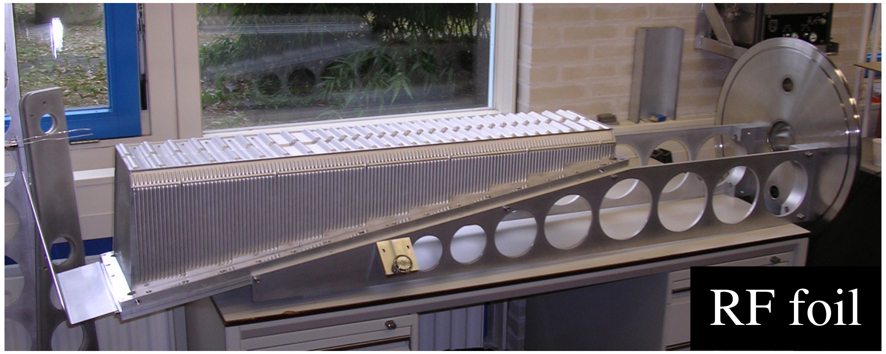


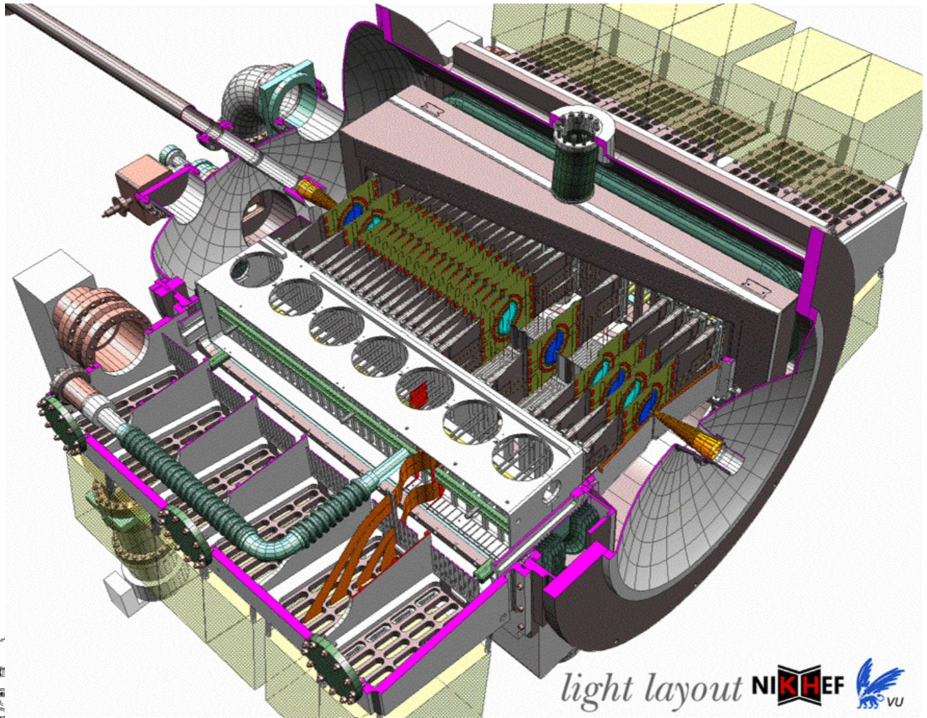


Module production starting

Vertex LOcator

- Si disks in secondary vacuum system like a Roman pot
  - separated from primary machine vacuum with thin Al foil (RF shield)
- Complex mechanics to allow retraction during injection

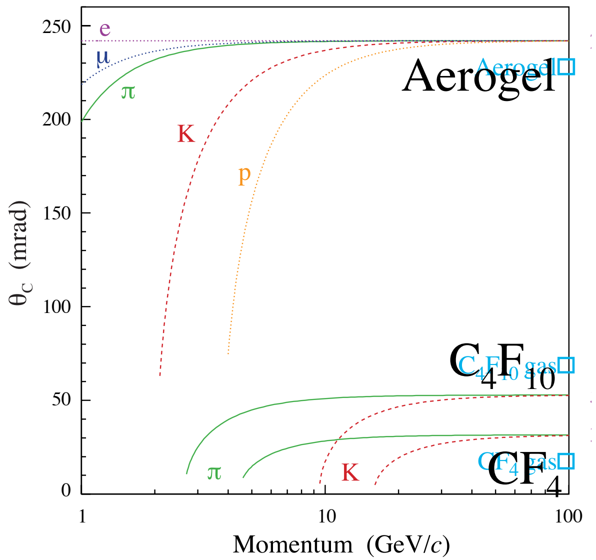




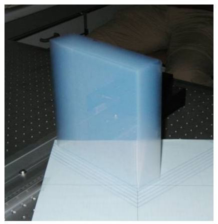
Installation planned in Nov 2005

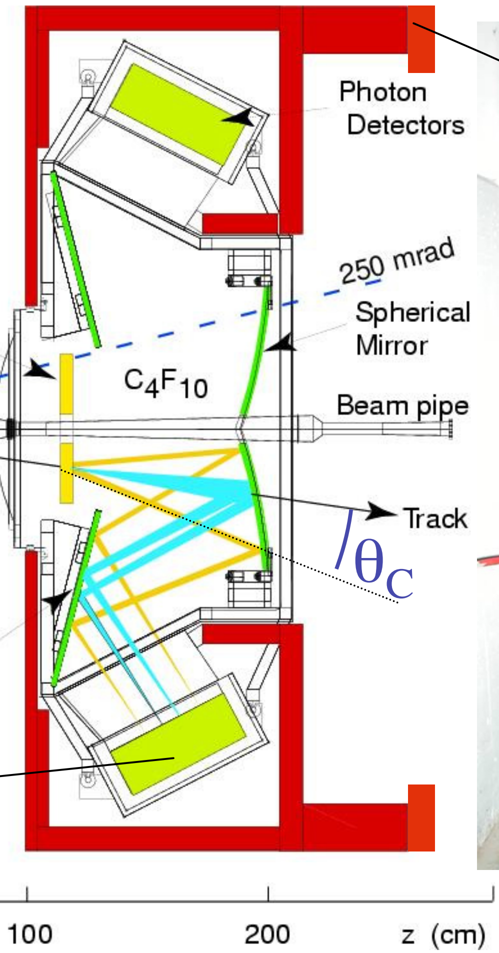
RICH-1

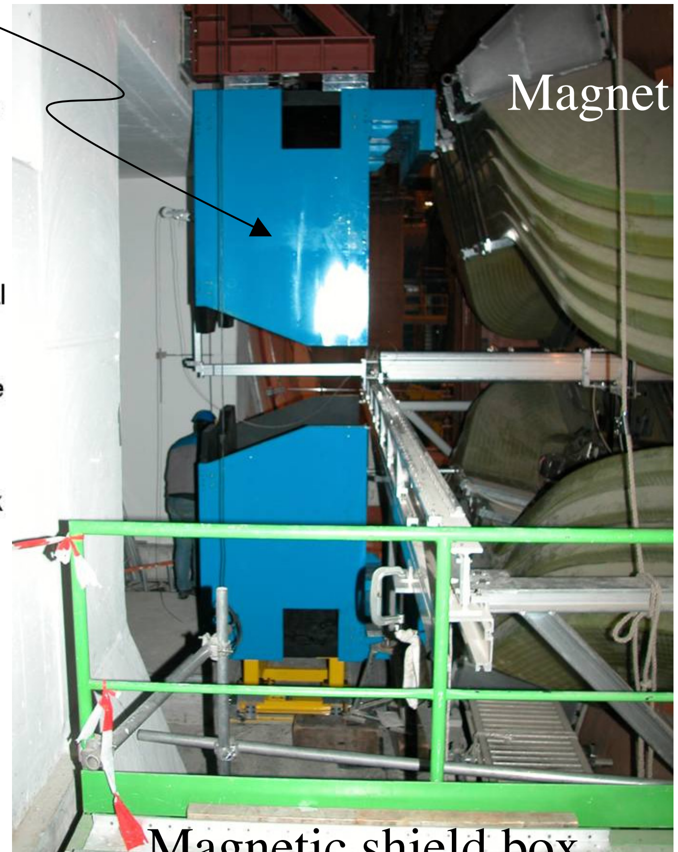
- Ring Imaging Cherenkov detector with two radiators (for particle ID):
  - Aerogel, n=1.03 (2 →~ 10 GeV/c) and C_4F_{10} gas, n=1.0014 (up to 10→~60 GeV/c)



$$\cos\theta_C = \frac{1}{\beta n}$$





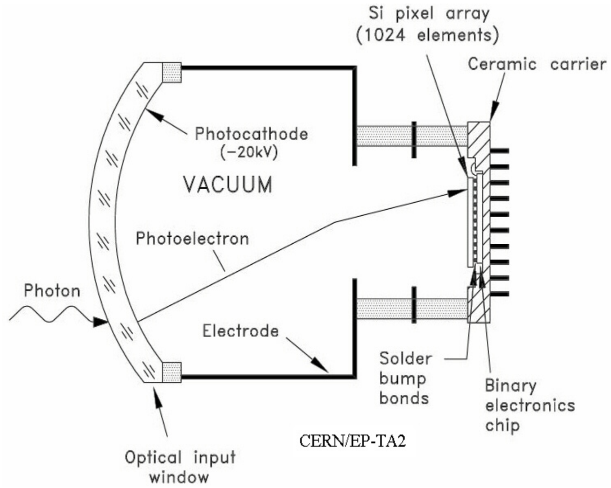


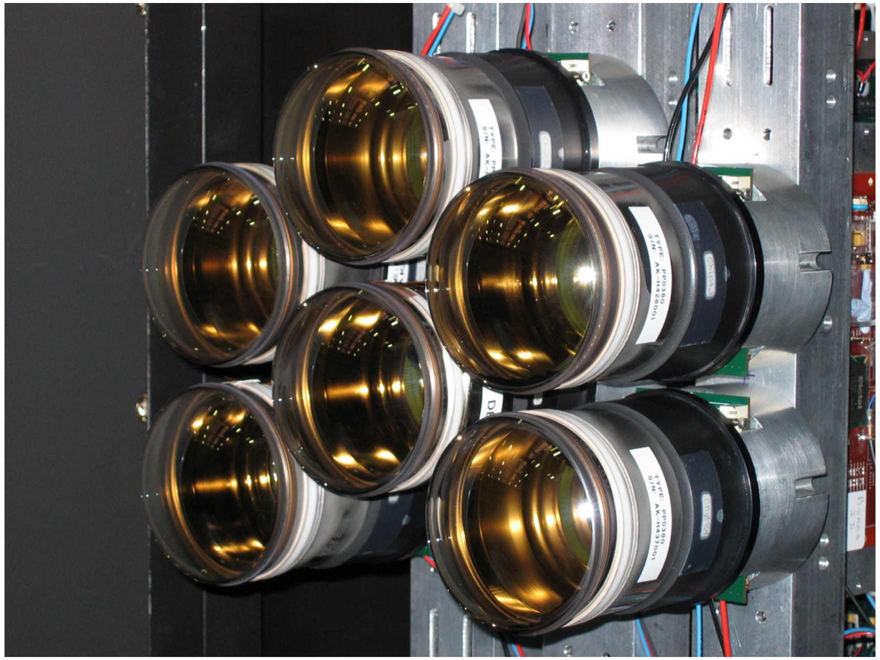
Magnetic shield box installed in pit

Reconstruct up to two concentric rings per track on the photon-detector plane → θ_{C1}, θ_{C2}

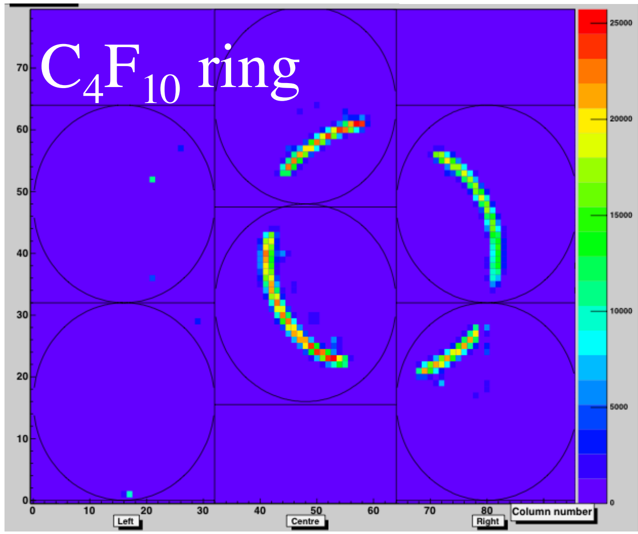
Hybrid photon detectors

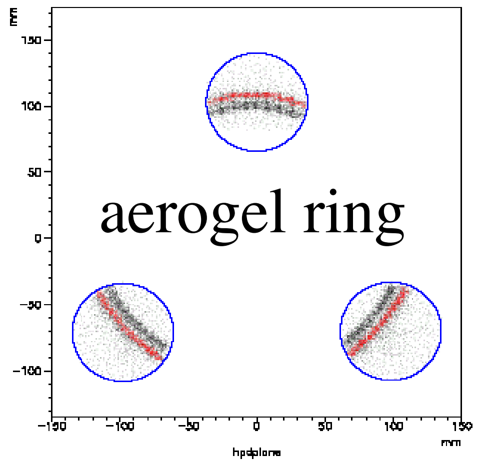
- Novel photon detectors,
  developed for LHCb RICH1 and RICH2 systems
  - ~500 tubes, with 1024 pixels each
  - 2.5 x 2.5 mm^2 granularity → $\sigma(\theta)$=0.6 mrad (RICH1)





Test beam results



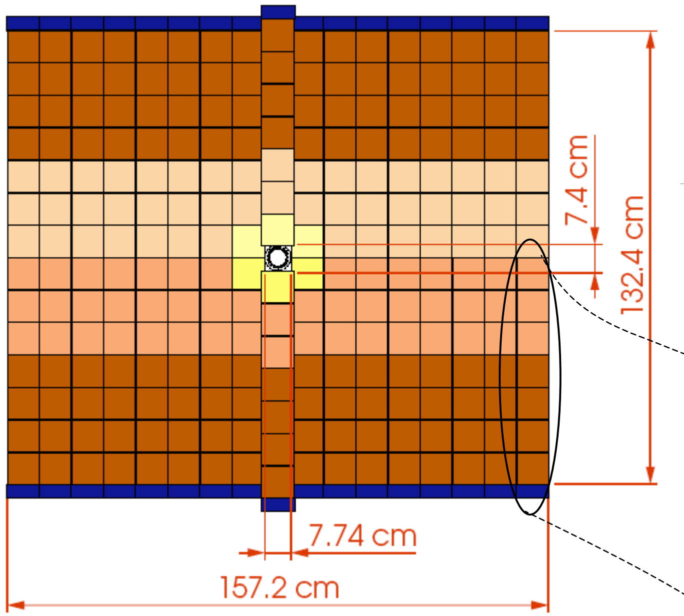


Tube delivery starting this summer

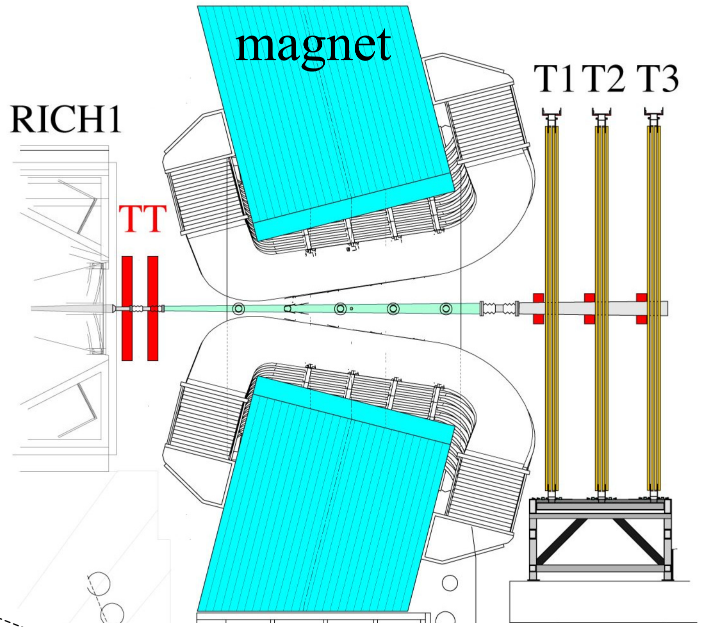
Tracking system

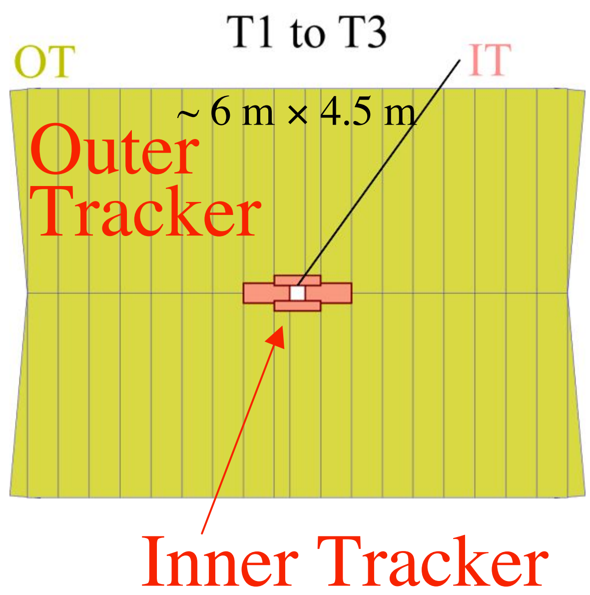
Trigger Tracker

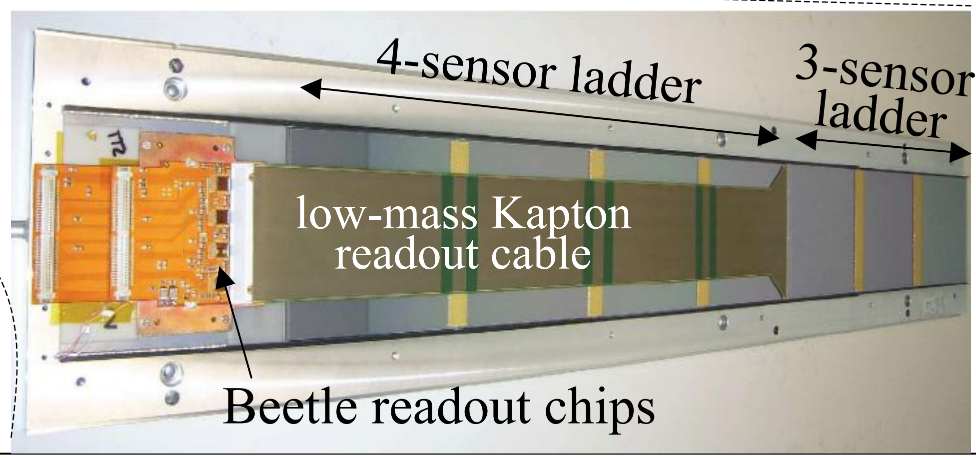
(together with VELO, measures track p_T for trigger



500 μm Si, 183 μm pitch
2+2 layers:
x, u, (30 cm gap), v, x



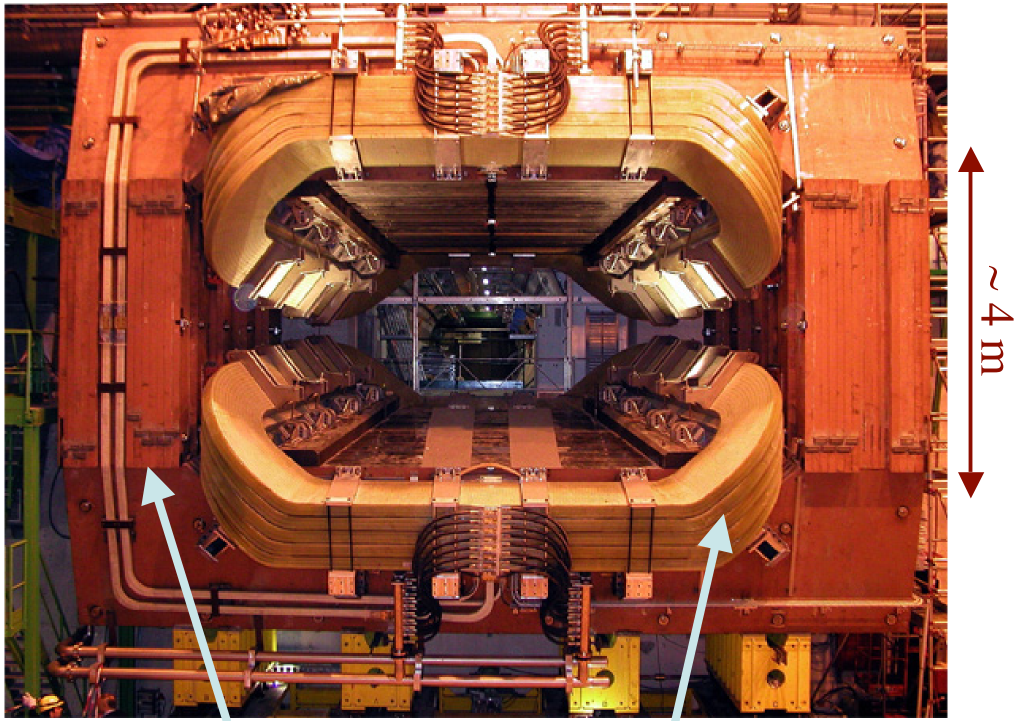




Production starting

Magnet

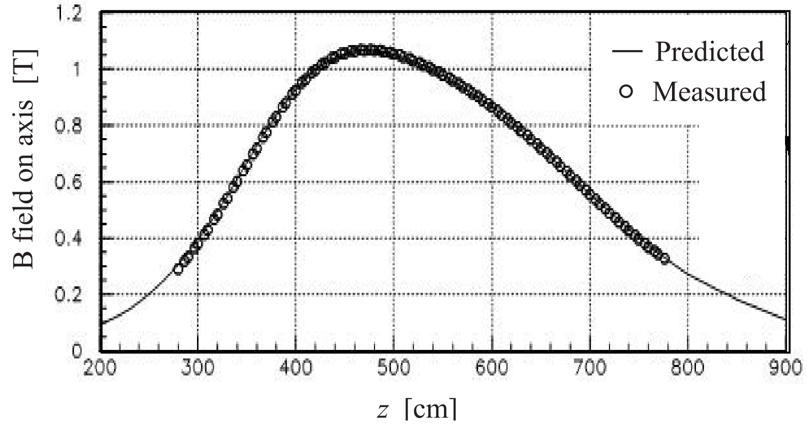
- Warm dipole magnet
  - $\int B\, dL = 4$ Tm
  - Regular field reversal planned for systematic control of CP asymmetries

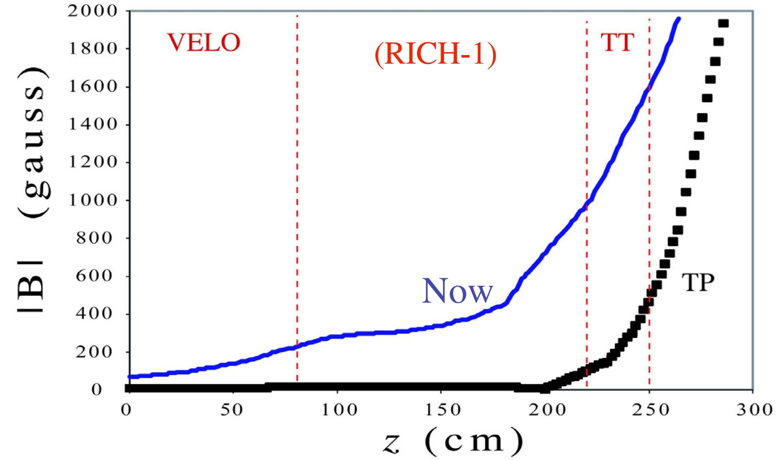


Fe yoke (1.45 kt)   Al coil (2 × 25 t)

4.2 MW power at 1 T field

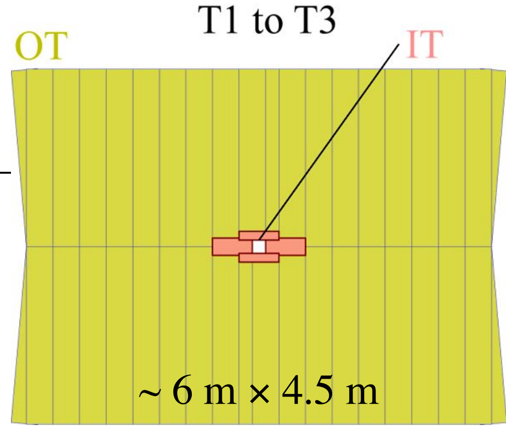
- B field profile:



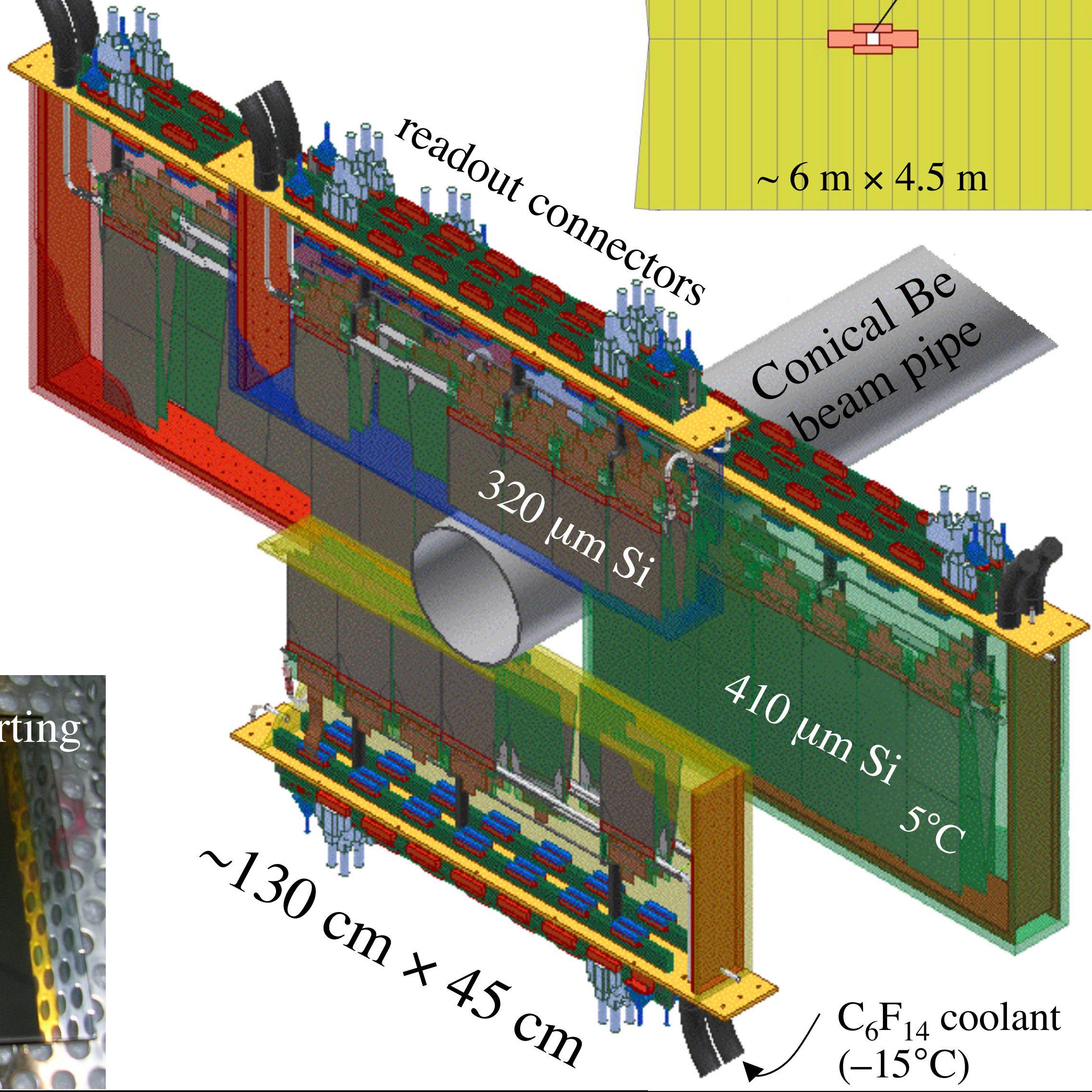


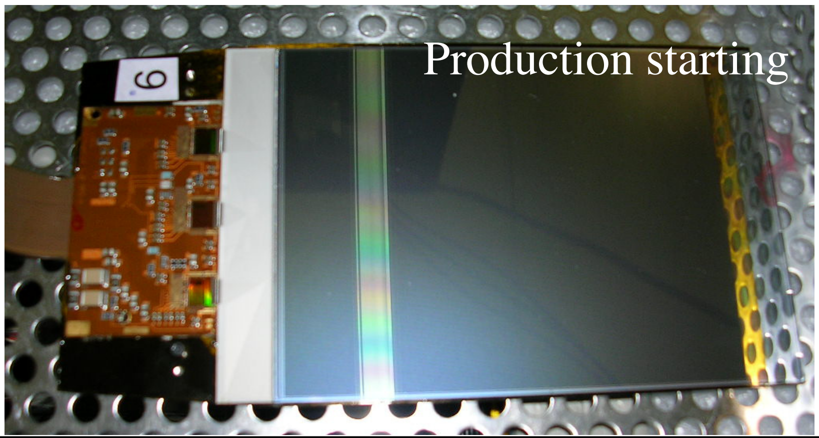
  - Design evolved: no more shield in upstream region to measure track p_T with VELO and TT at trigger level

Inner tracker



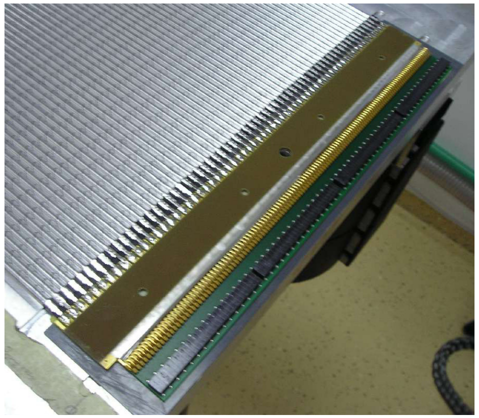
- High track-multiplicity region close to the beam pipe:
  - Area: IT=2%, OT=98%
  - Tracks: IT=20%, OT=80%
- Si-strip detectors:
  - arranged in 4 boxes/station around beam pipe
  - 4 Si planes (xuvx) per box
  - 198 μm pitch, ~ 130k channels
  - Beetle readout chips with analog pipeline (L0 buffer, 4 μs)

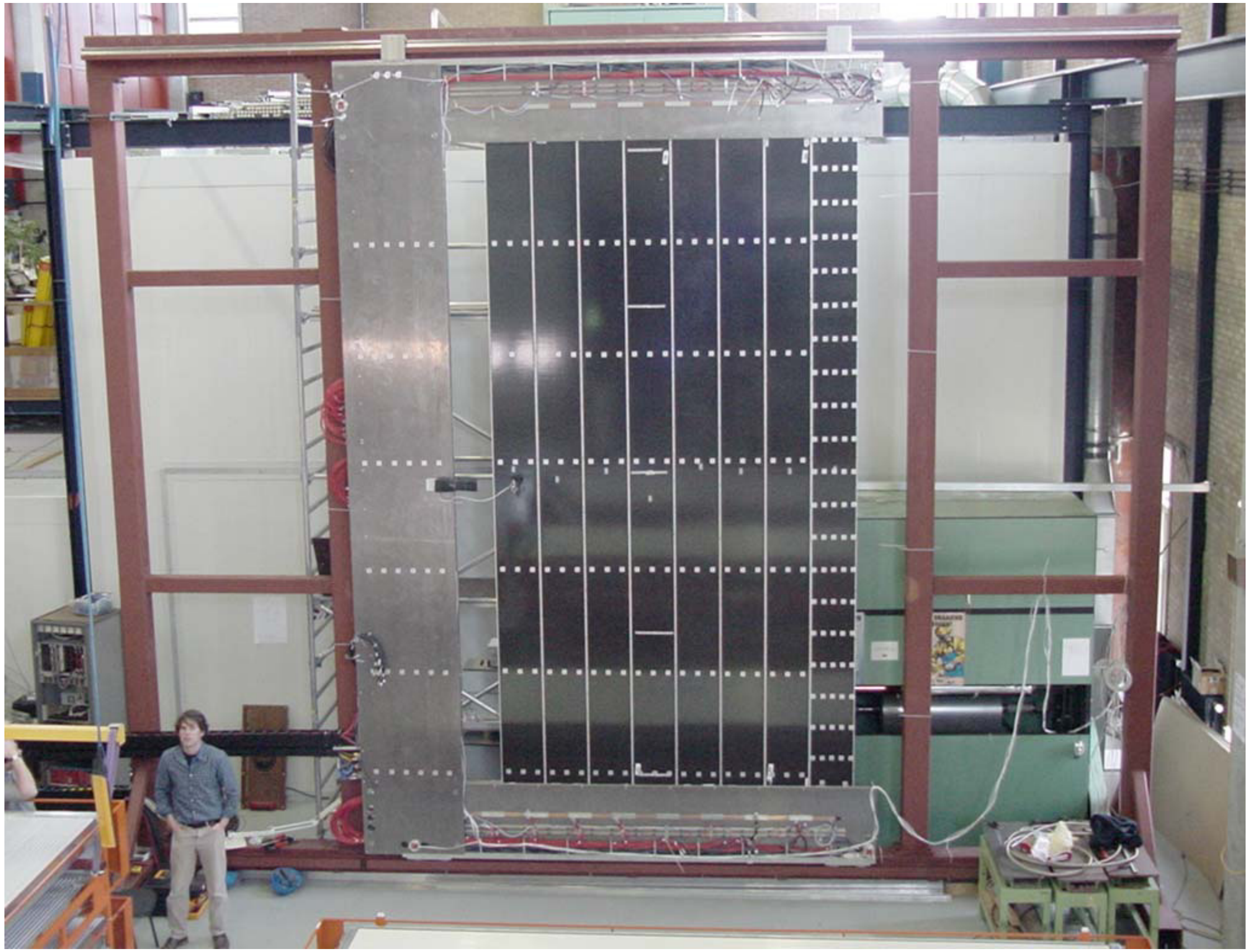




Outer tracker

- 3 stations each made of 4 double-layers of Kapton/Al straws glued together to form modules
  - ~ 60% produced



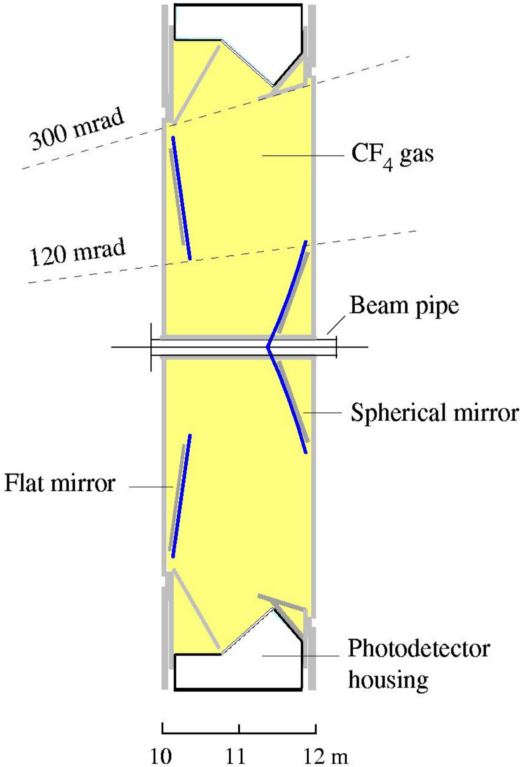


RICH-2

- A second RICH detector is needed to cover the low-angle region with high-momentum tracks:
  - CF_4 gas (n=1.0005), for 16 < p < ~100 GeV/c

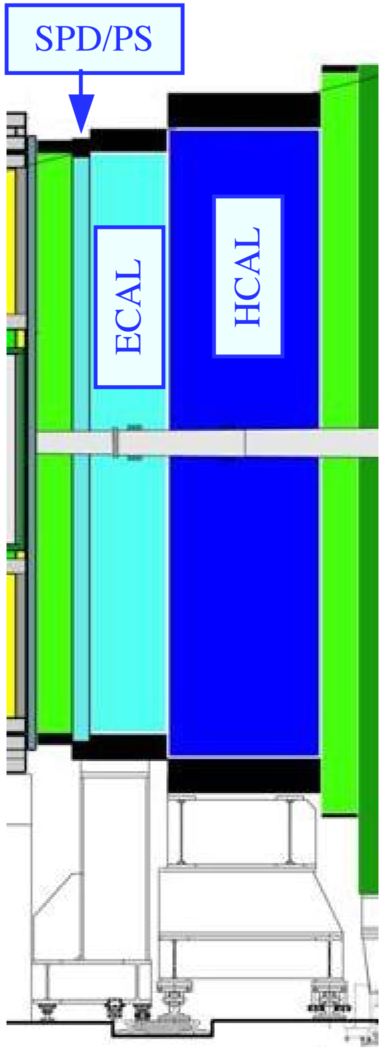
Note: only one RICH was needed in BTeV

Seen from above

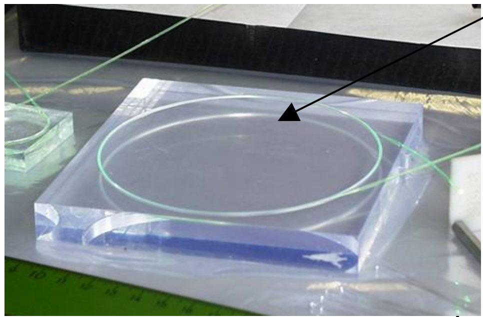


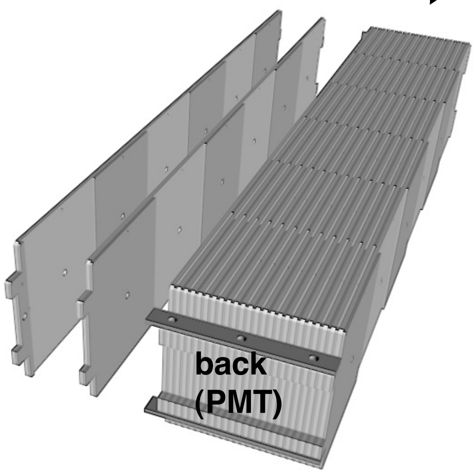
Installation in September 2005

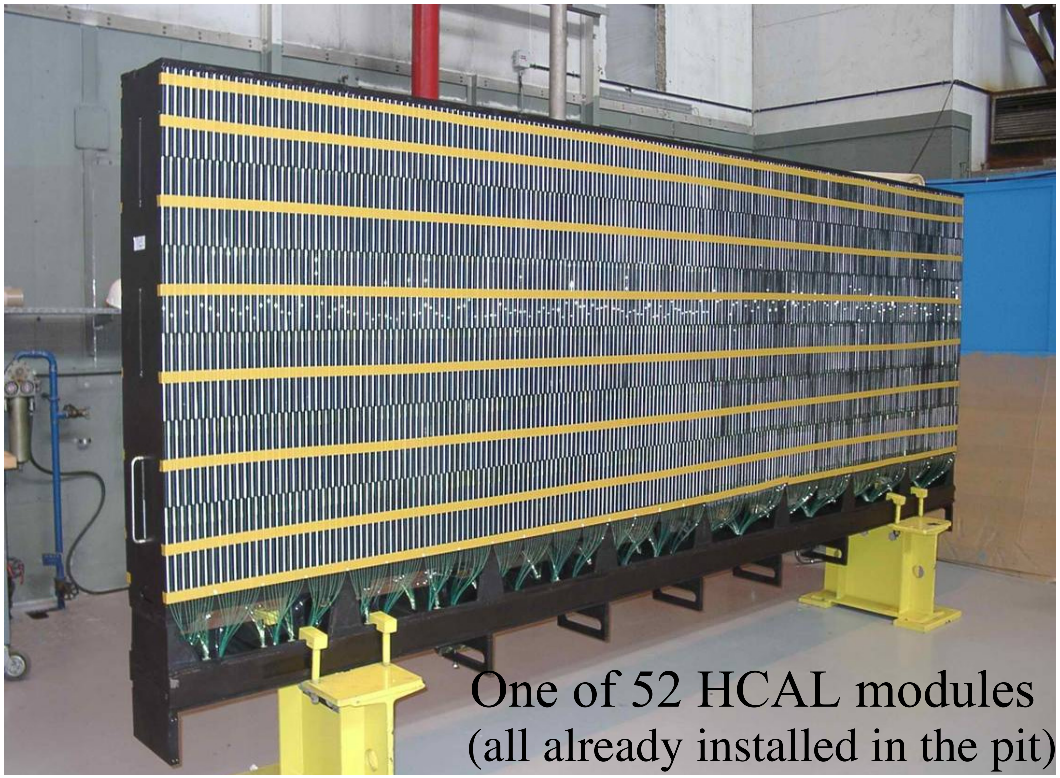
Calorimeter system



- Pre-shower: scintillating pads + WLS fibres + 2 X_0 Pb
- Electromagnetic: Pb-scintillator Shashlik calorimeter, 25 X_0
- Hadronic: Fe-scintillator tile calorimeter, 5.6 λ_I



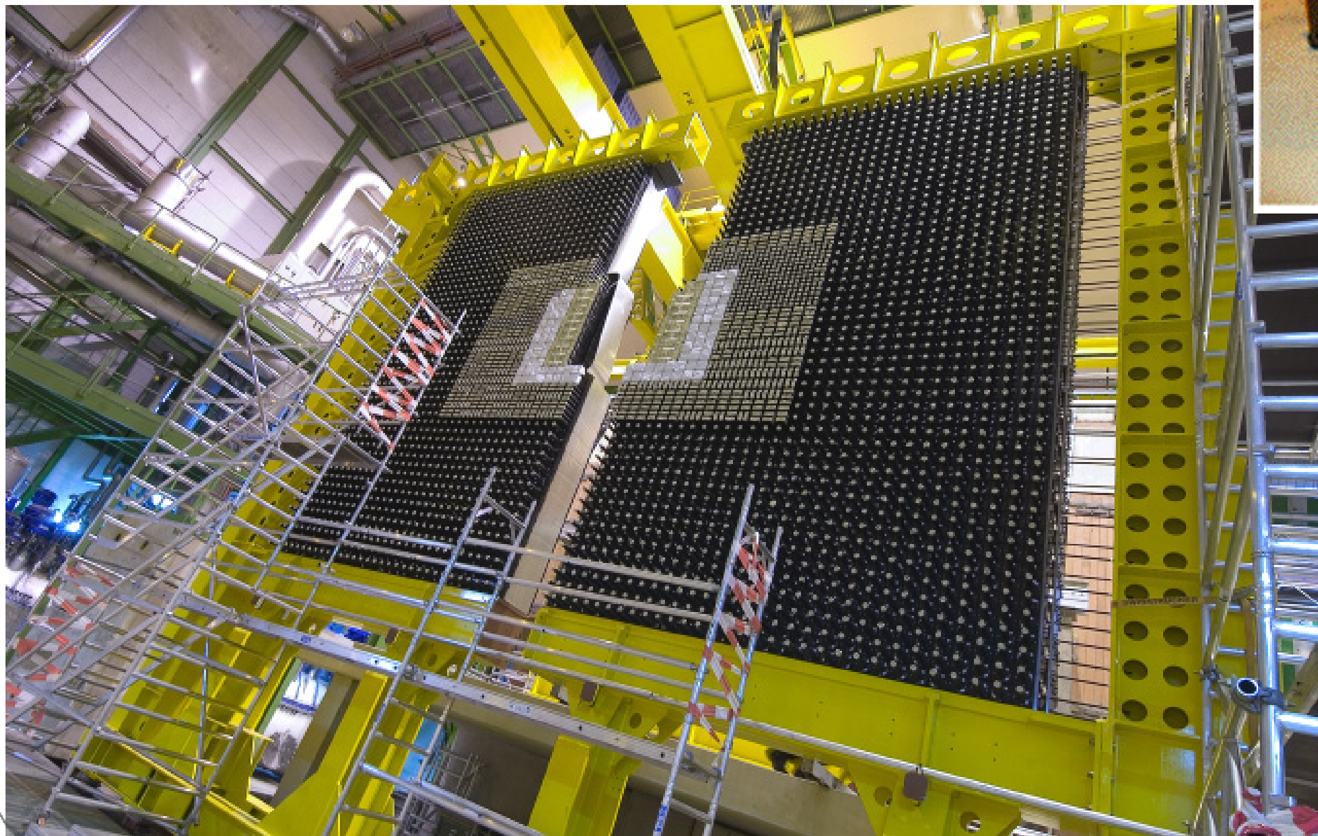




One of 52 HCAL modules
(all already installed in the pit)

Calorimeter system

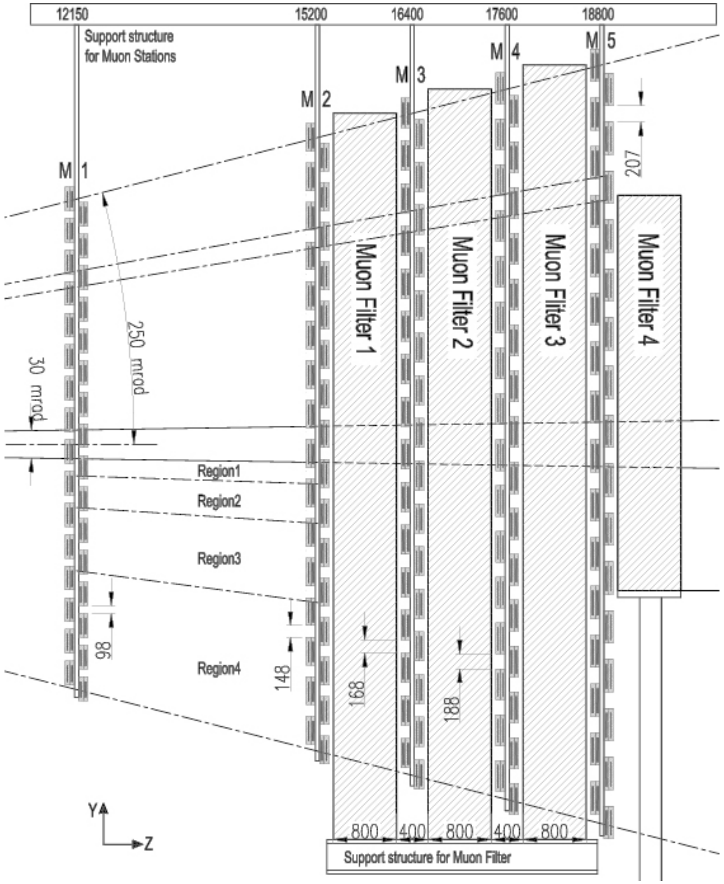
- ECAL modules:
  - $\sigma_E/E = 10\% /\sqrt{E} \oplus 1\%$ (E in GeV)
  - three different segmentation → 3 types of modules
- 3300 modules stacked: ~ 6 m high
  - dimensions agree to specification < 1 mm

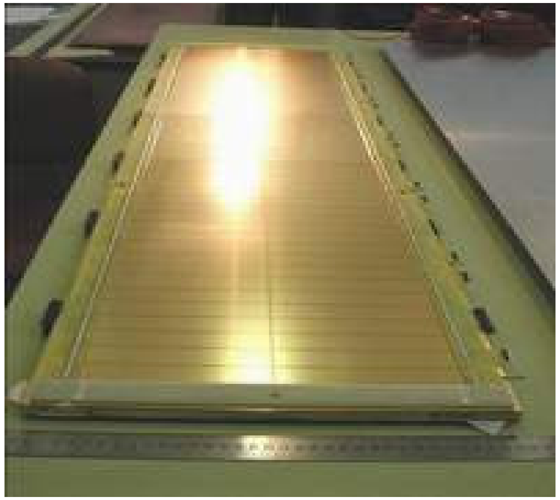


Note: BTeV's ECAL ($PbWO_4$ crystals) had an excellent resolution: $\sigma_E/E = 1.6\% /\sqrt{E} \oplus 0.6\%$

Muon system

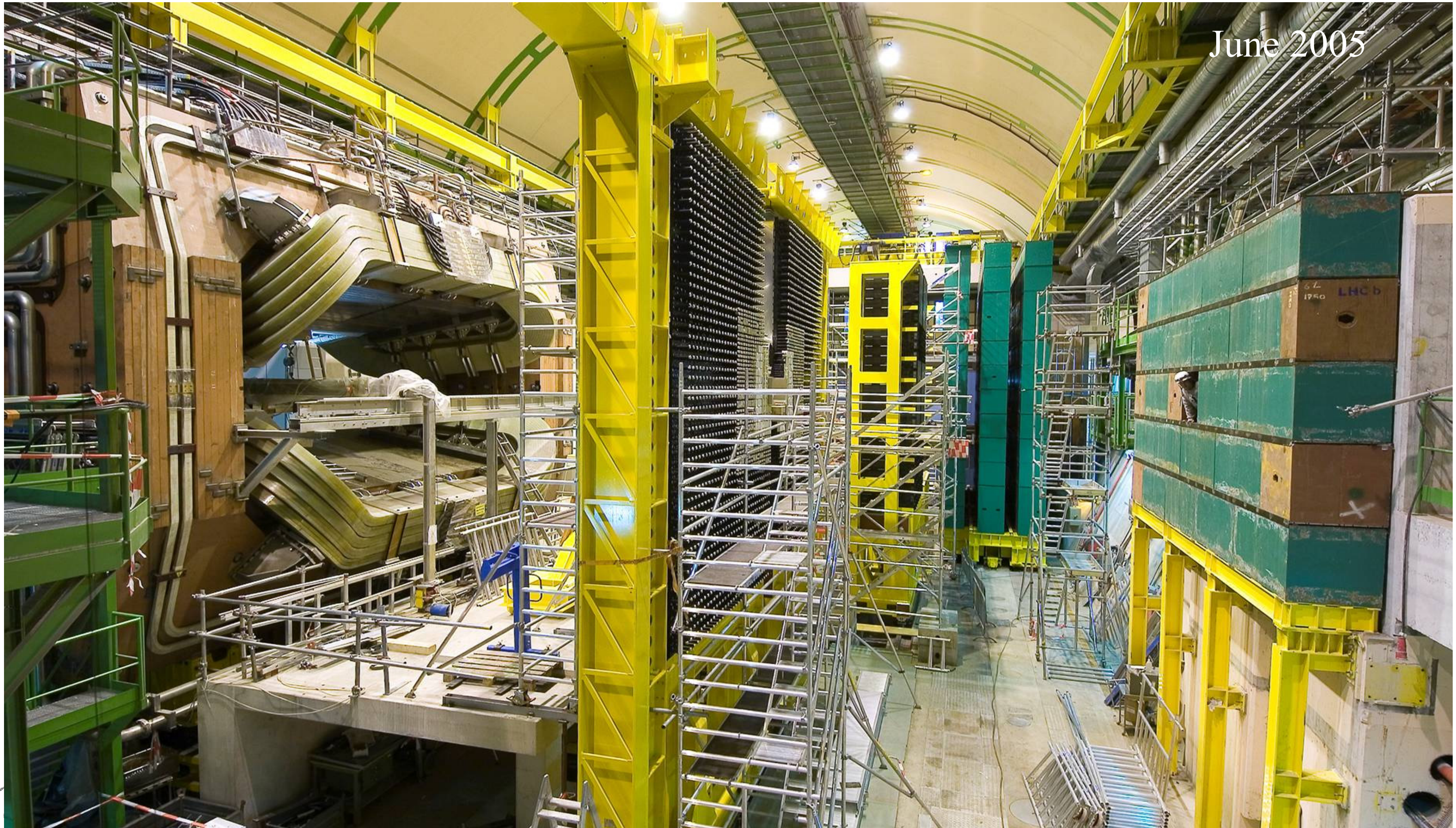
- MWPCs used for all 5 stations except highest rate region (inner part of M1, > 100 kHz/cm^2) where triple-GEMs are used instead





30% of chambers have been produced

LHCb installation in progress …



LHCb trigger

Visible events ↓ **10 MHz**

Hardware: custom electronics boards

L0 trigger
- Fully synchronized (40 MHz)
- 4 μs fixed latency

↓ **1 MHz**

Software: single PC farm with ~ 1600 CPUs

L1 trigger
- Partial readout: VELO, TT, L0 summary
- ~1 ms (max. 50 ms)

↓ **40 kHz**

High Level Trigger (HLT)
- Full detector readout (~ 40 kB/evt)
- ~10 ms

Storage ↓ **≤ 2 kHz**

Muon system:
- two highest p_T muons

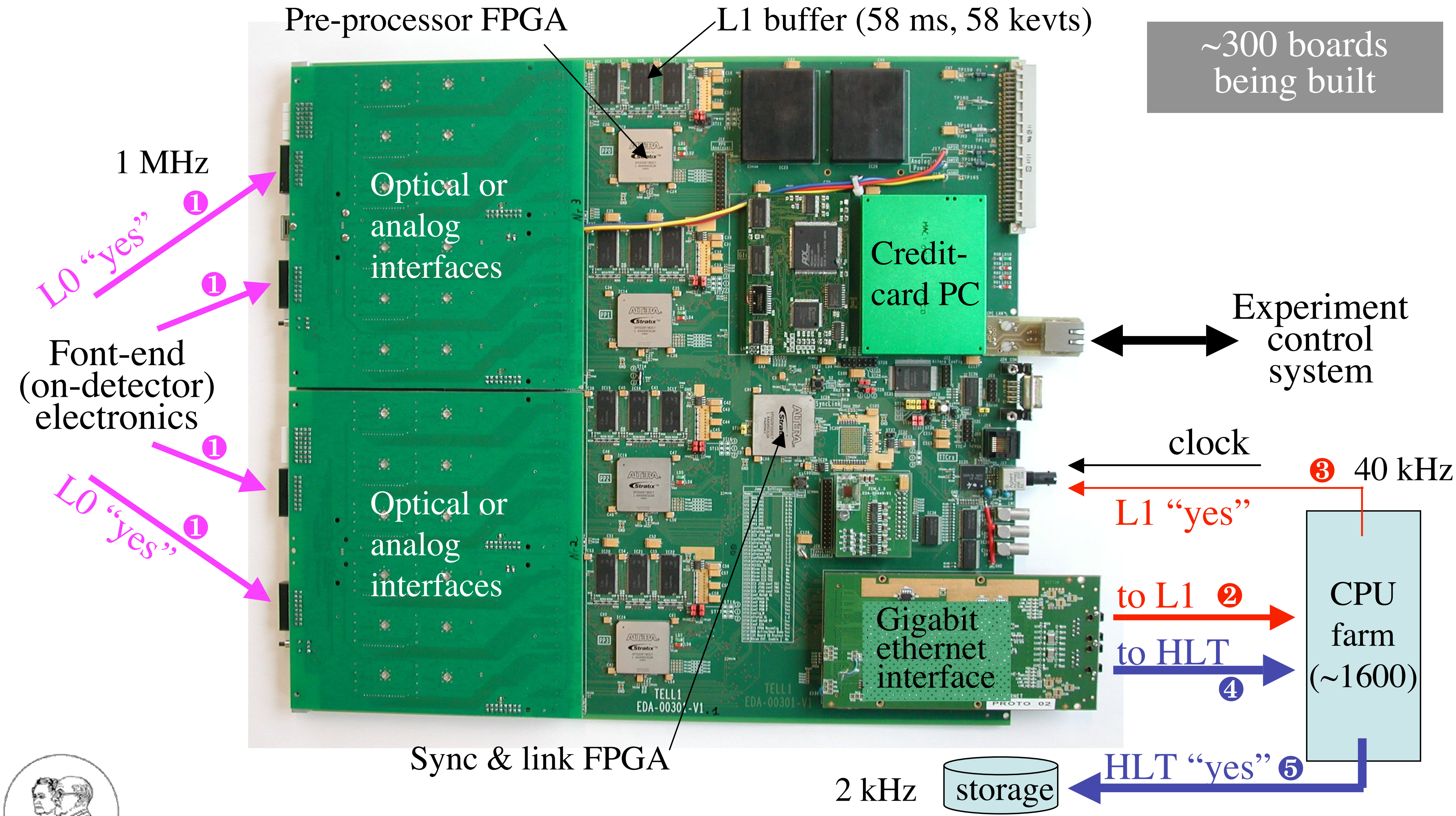
Calorimeters:
- highest E_T clusters (hadron, e, γ, π^0)
- SPD multiplicity, total HCAL energy

Pileup system (2 Si disks behind VELO):
- number of tracks from 2nd interaction
- hit multiplicity

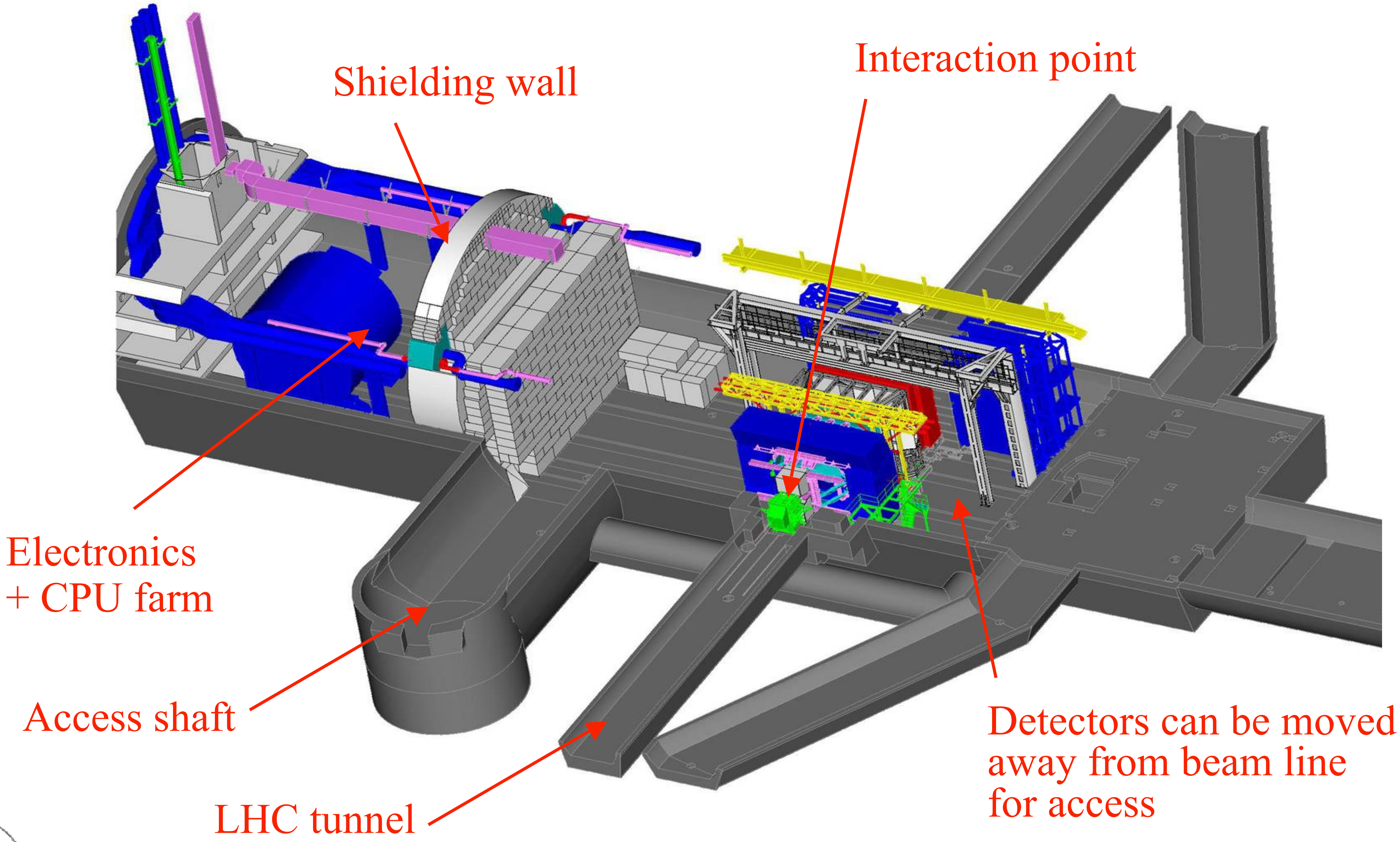
L1: find VELO tracks with large IP and measure p_T (using TT or L0 objects)
- Generic 2 tracks: (p_{T1}, p_{T2}) + IP
- Single muon: p_T + IP
- Dimuon: mass, mass + IP
- Photon, electron

HLT: L1 confirmation (→10 kHz)
- Exclusive selections (e.g. $B_s \to D_s h$)
- Inclusive selections (μ, J/ψ, D^*, …)

LHCb common readout board (TELL1)



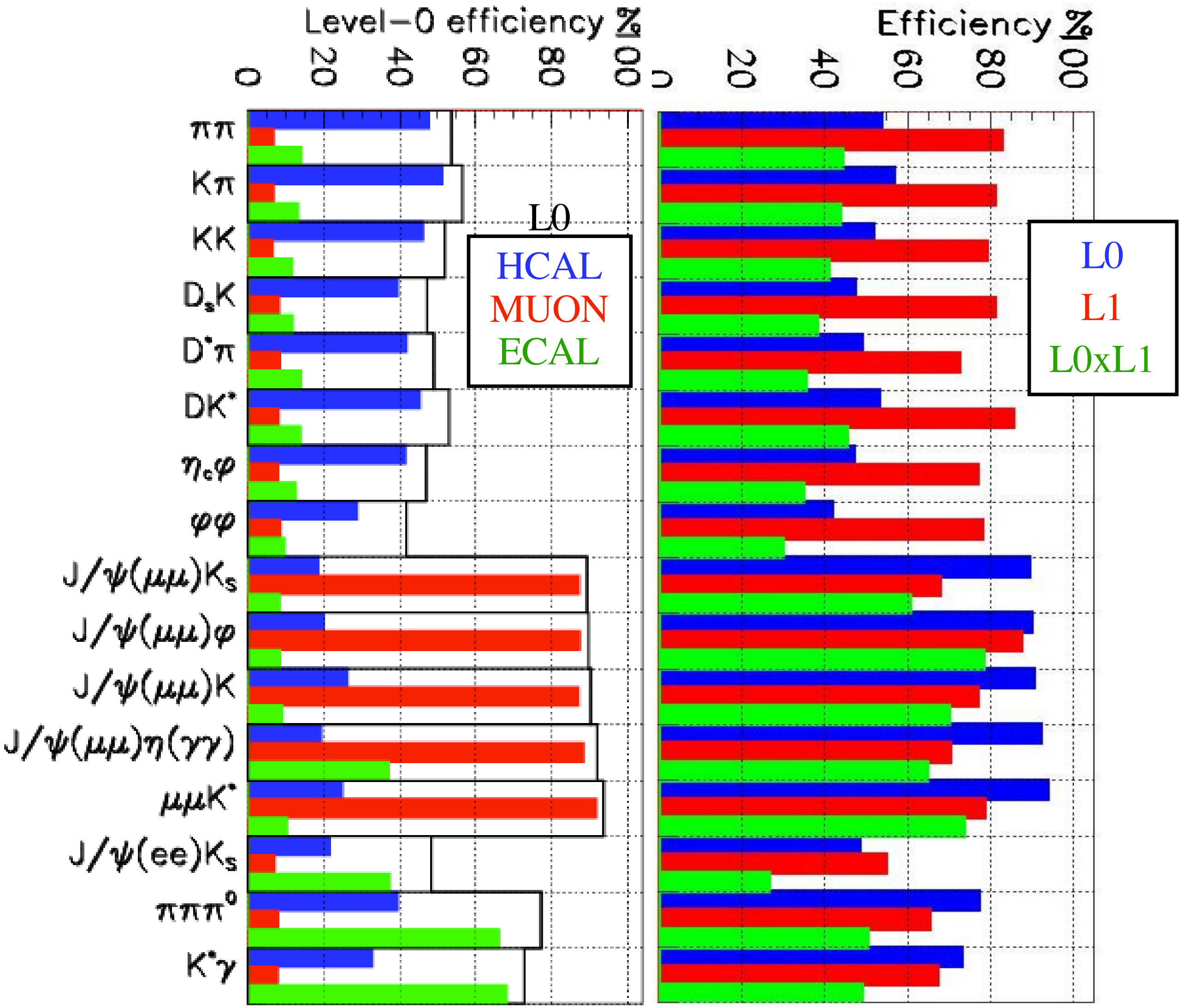
LHCb at Point 8



Expected L0+L1 trigger performance

- L0 and L1 algorithms:
  - Mature
  - Within time budget
- Flexibility in bandwidth division amongst the different trigger lines

- Efficiencies:
  - Determined using detailed MC simulation
  - Quoted on offline-selected signal events
  - Typically 30%–80% for L0+L1 combined



HLT trigger performance (prel.)

- HLT algorithms under development:
  - Prototype available within time budget (for a limited set of channels)
  - Performance still needs to be improved (e.g. online tracking, semi-exclusive selections, …)
  - More channels to be included

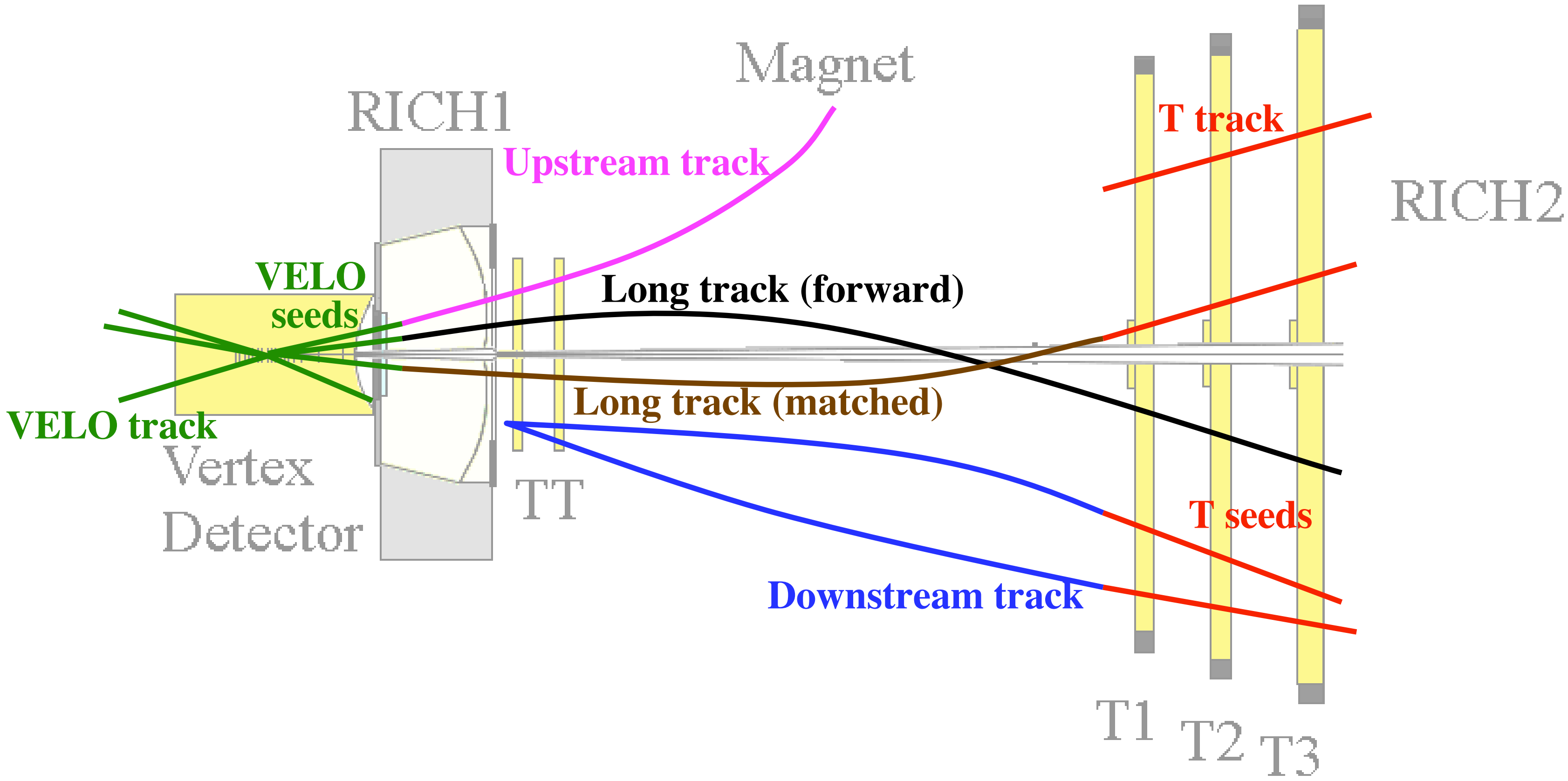
Channel	Efficiencies w.r.t. Offline and L0xL1 selected signal						
	L1 confirm.	Online tracking	Total HLT efficiencies				
			Excl. B	$\mu\mu$	μ	D*	Total
$B_s \to \mu^+\mu^-$	99%	93%	91%	90%	94%	Order of 1%	98%
$B_d \to K^*\mu^+\mu^-$	98%	82%	73%	62%	58%		91%
$B_{d,s} \to h^+h^-$	94%	95%	88%	Order of 0.5%	Order of 2%		88%
$B_s \to \phi\gamma$	71%	93%	61%				62%
$B_s \to D_s h$	93%	82%	60%				62%
$B_d \to D^*\pi$	94%	58%	48%			43%	55%

- HLT output rates:
  - Rough guess at present
  - Split between streams still to be determined

HLT rate	**Event type**	**Calibration**	**Physics**
200 Hz	Exclusive B candidates	Tagging	B (core program)
600 Hz	High mass di-muons	Tracking	J/ψ, $b \to J/\psi X$ (unbiased)
300 Hz	D* candidates	PID	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. $b \to \mu$)	Trigger	B (data mining)

NB: ATLAS/CMS ~ 10 Hz to storage for B triggers: mostly $\mu\mu$ and high-p_T μ

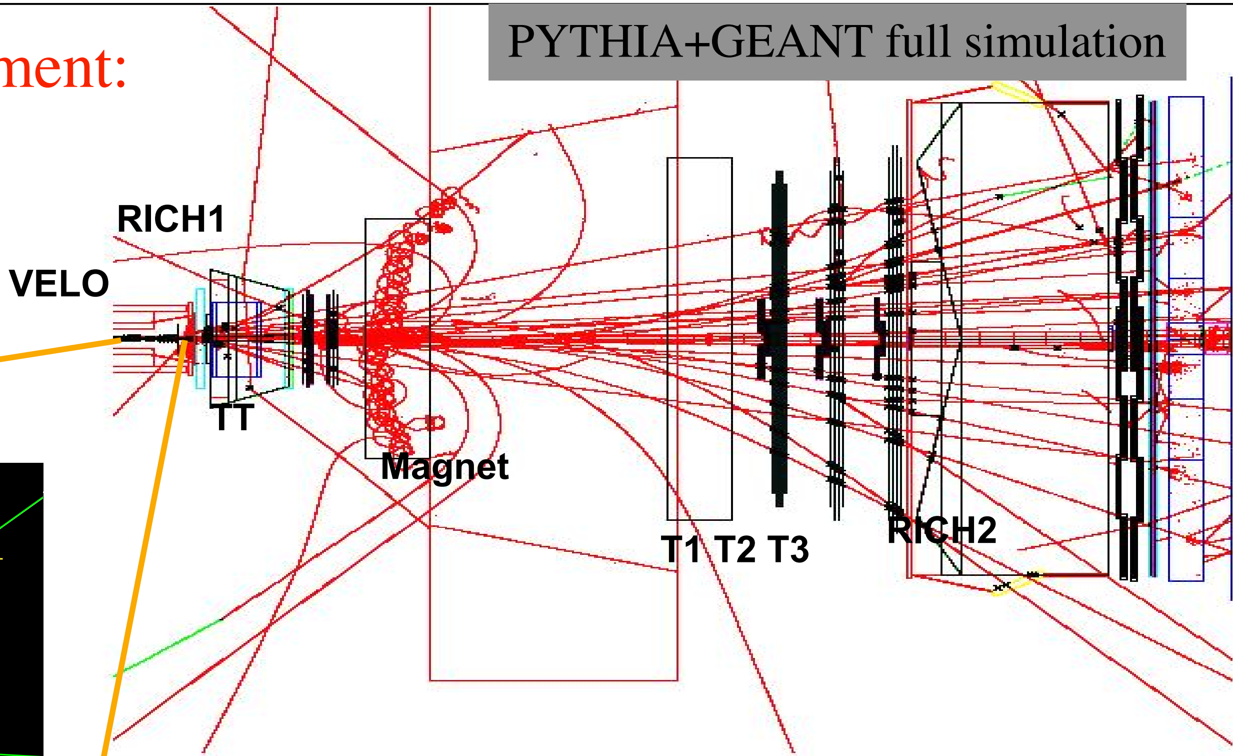
Track finding strategy

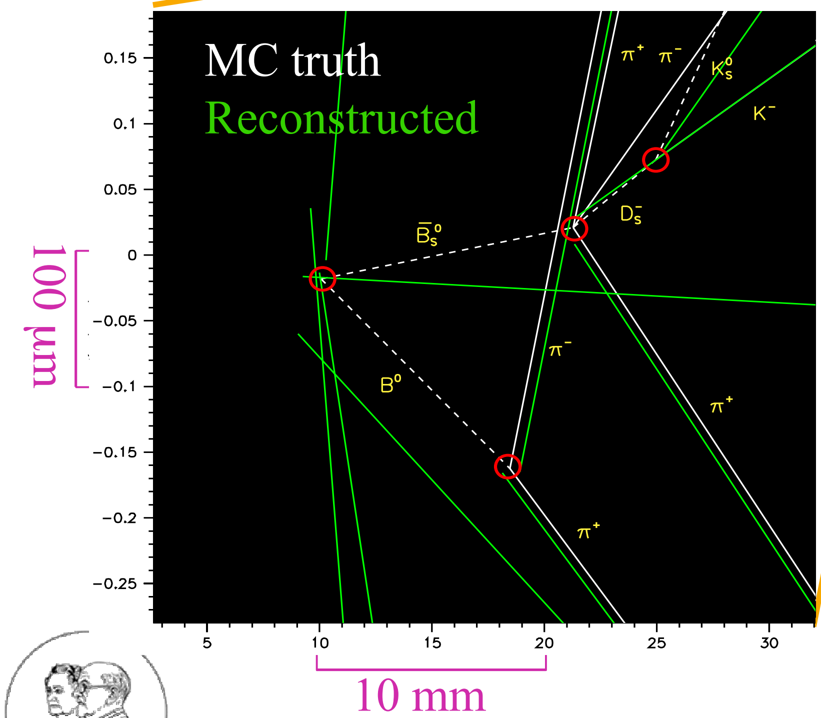


Long tracks	⇒	highest quality for physics (good IP & p resolution)
Downstream tracks	⇒	needed for efficient K_S finding (good p resolution)
Upstream tracks	⇒	lower p, worse p resolution, but useful for RICH1 pattern recognition
T tracks	⇒	useful for RICH2 pattern recognition
VELO tracks	⇒	useful for primary vertex reconstruction (good IP resolution)

Expected tracking performance

- **High multiplicity environment:**
  - In a $b\bar{b}$ event, ~30 charged particles traverse the whole spectrometer !

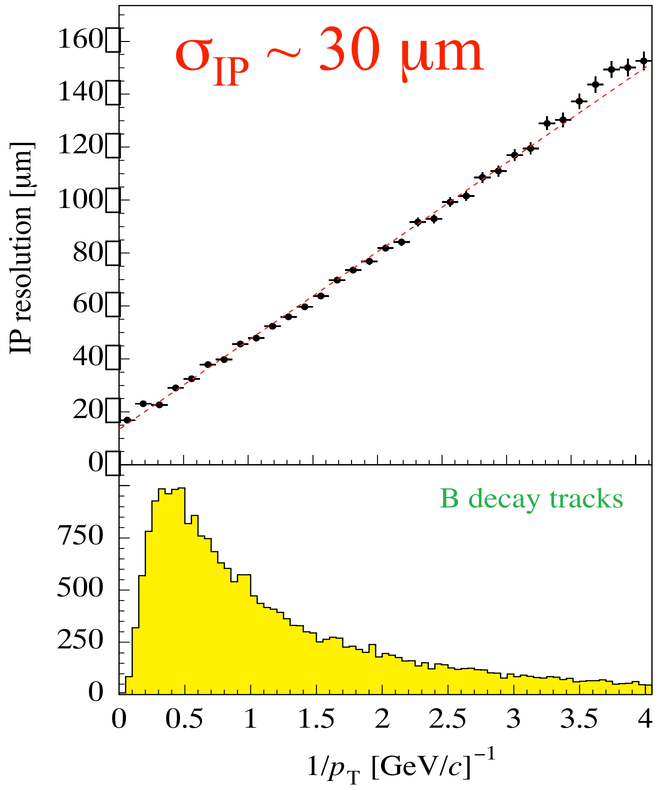




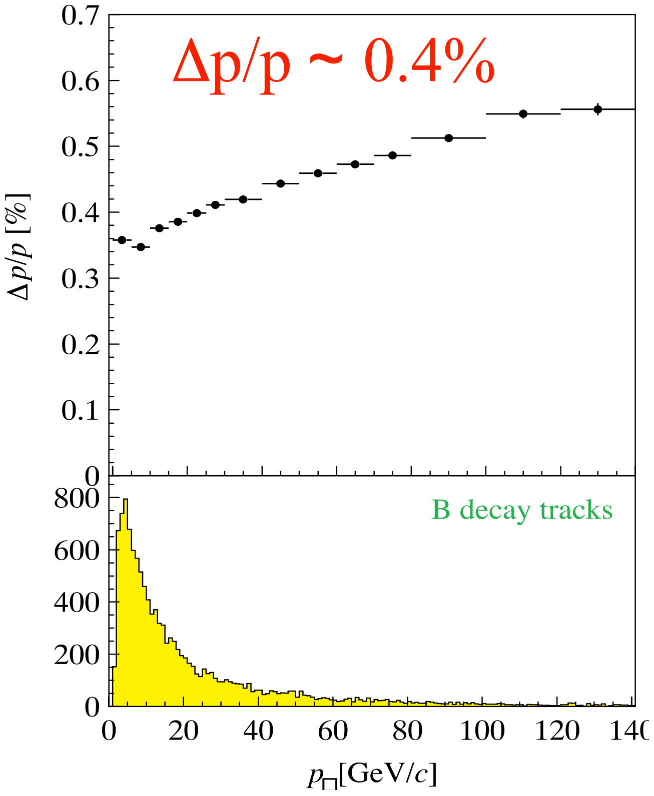
- **Full pattern recognition implemented:**
  - Track finding efficiency > 95% for long tracks from B decays (only 4% ghosts for pT > 0.5 GeV/c)

Expected tracking performance

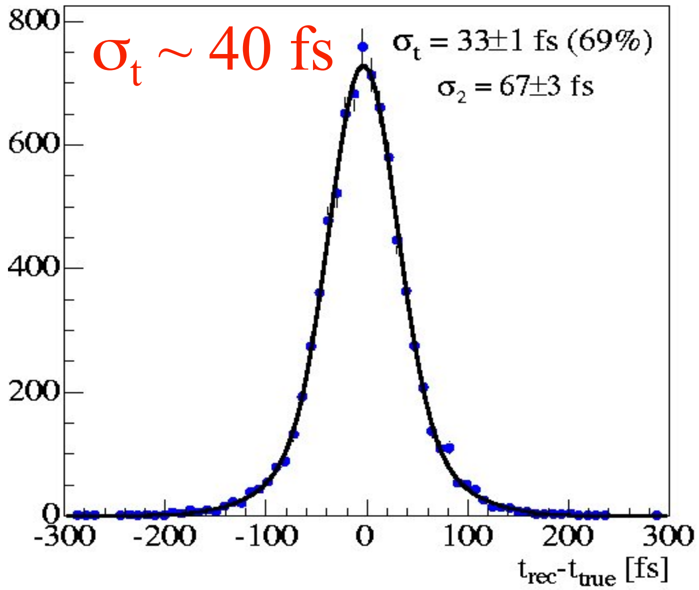
Impact parameter resolution



Momentum resolution



$B_s \rightarrow D_s\pi$ proper time resolution

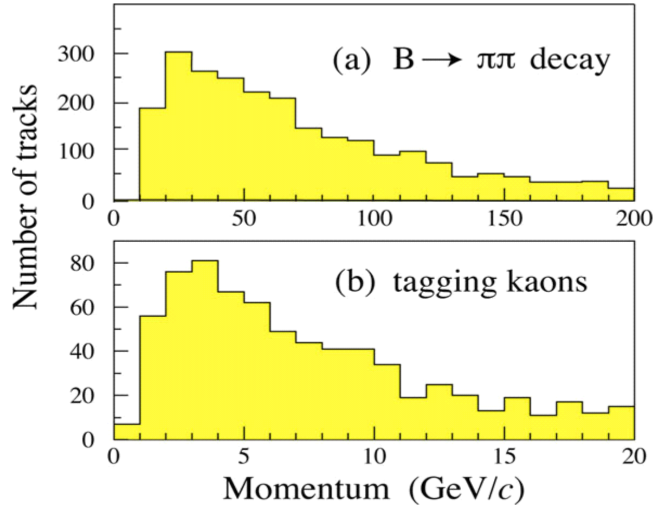


- Compare LHCb with:
  - CMS: ~70 fs
  - ATLAS: 100 fs (was 70 fs)
  - CDF: 100 fs

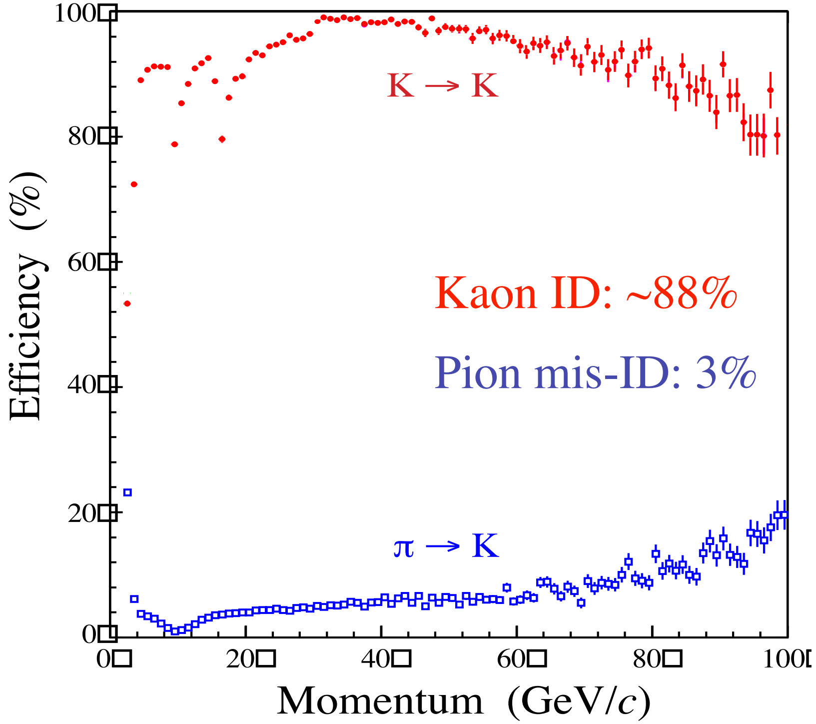
Good proper time resolution essential for time-dependent B_s physics !

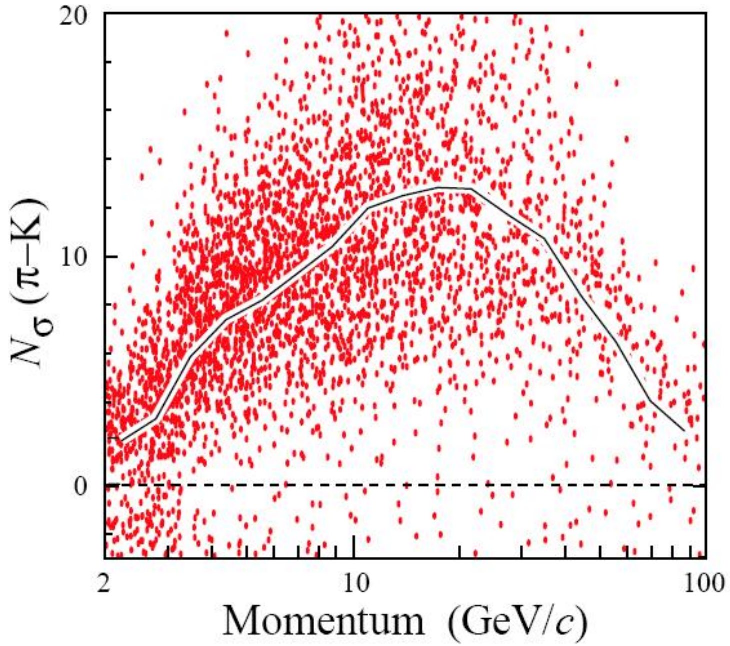
Particle ID performance

- RICH1 and RICH2 full pattern recognition:
  - Look for rings around tracks found in tracking
- Good K-π separation expected in 2–100 GeV/c range



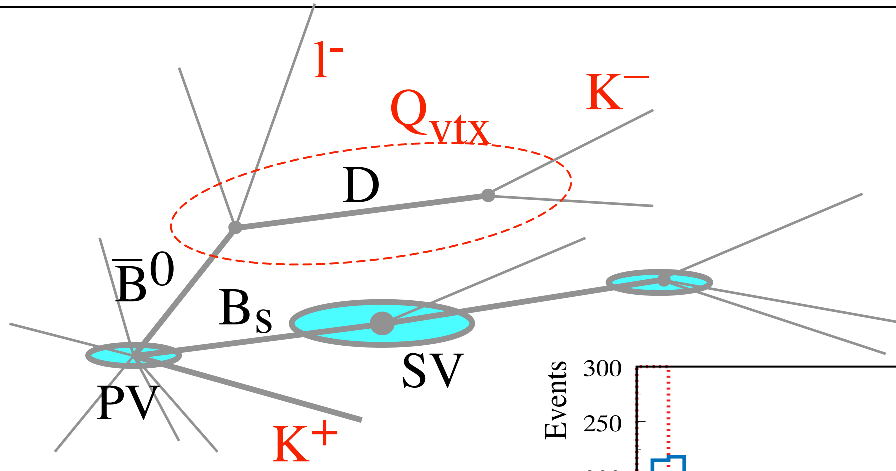
LHCb full simulation



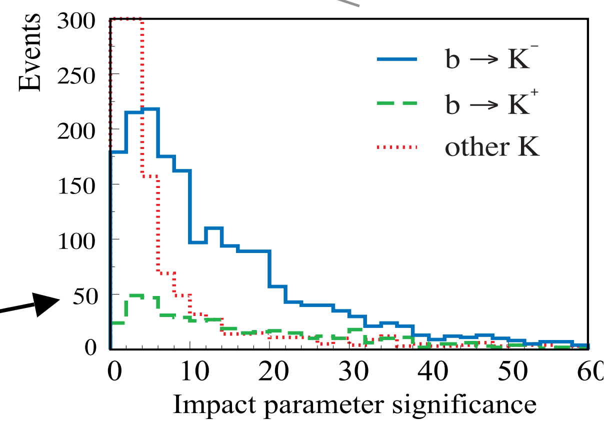


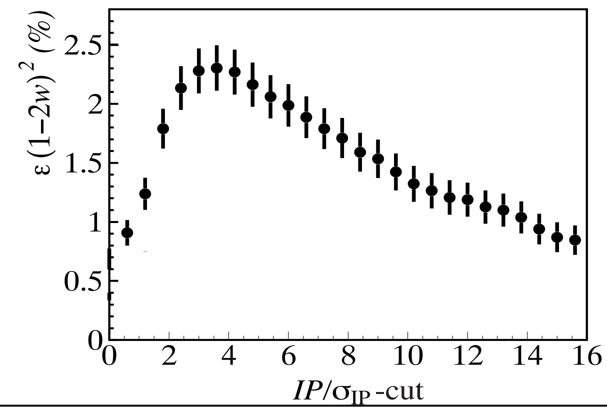
Flavour tagging

	$\varepsilon D^2=\varepsilon(1-2w)^2$ in %		
Tag	LHCb	CMS	ATLAS
Muon	1.0	0.7	0.7
Electron	0.4	0.5	0.3
Kaon	2.4	–	–
Jet/vertex	1.0	2.3	1.6
Same side	2.1	2.2	2.1



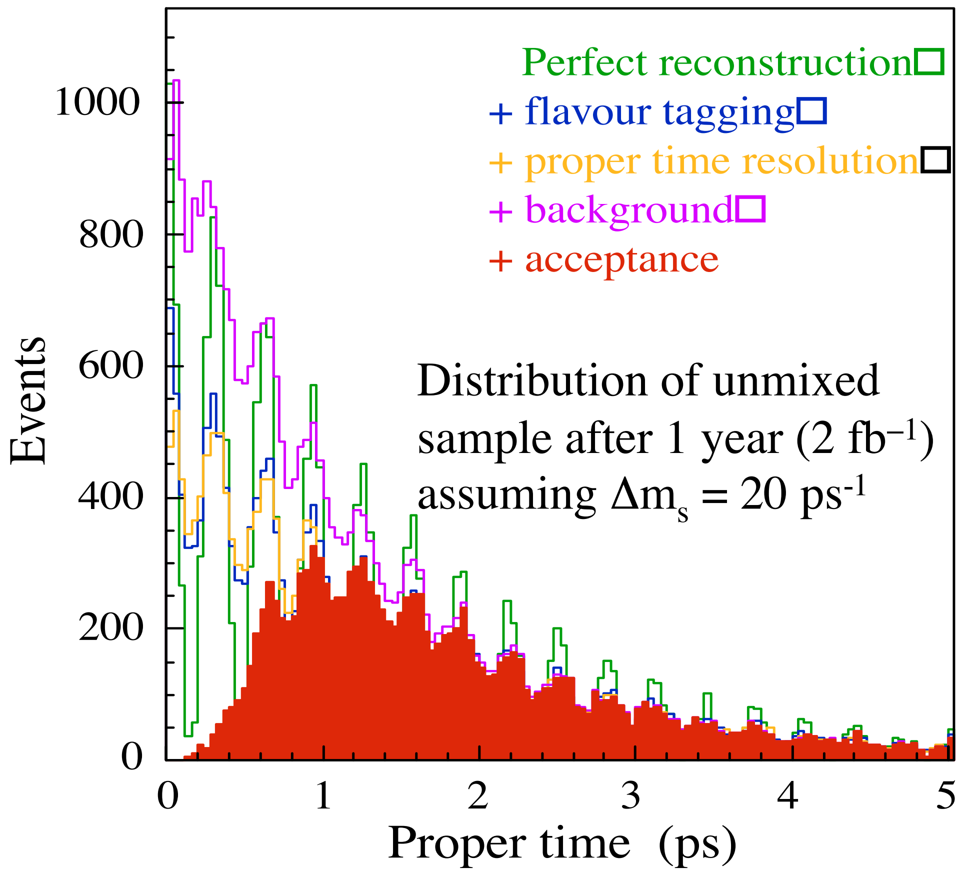
- LHCb:
  - Most powerful tag is opposite kaon (from b→c→l)
  - Combined **$\varepsilon D^2 \sim 6\%$ (B_s) or $\sim 4\%$ (B^0)**
  - Recent neural network approach leads to ~9% for B_s (not used here)
- Compare with:
  - CDF/D0 achieved 1% (expect ~3% for B_s in Run IIb)
  - B factories achieved ~ 30% (coherent BB pair, no extra tracks)

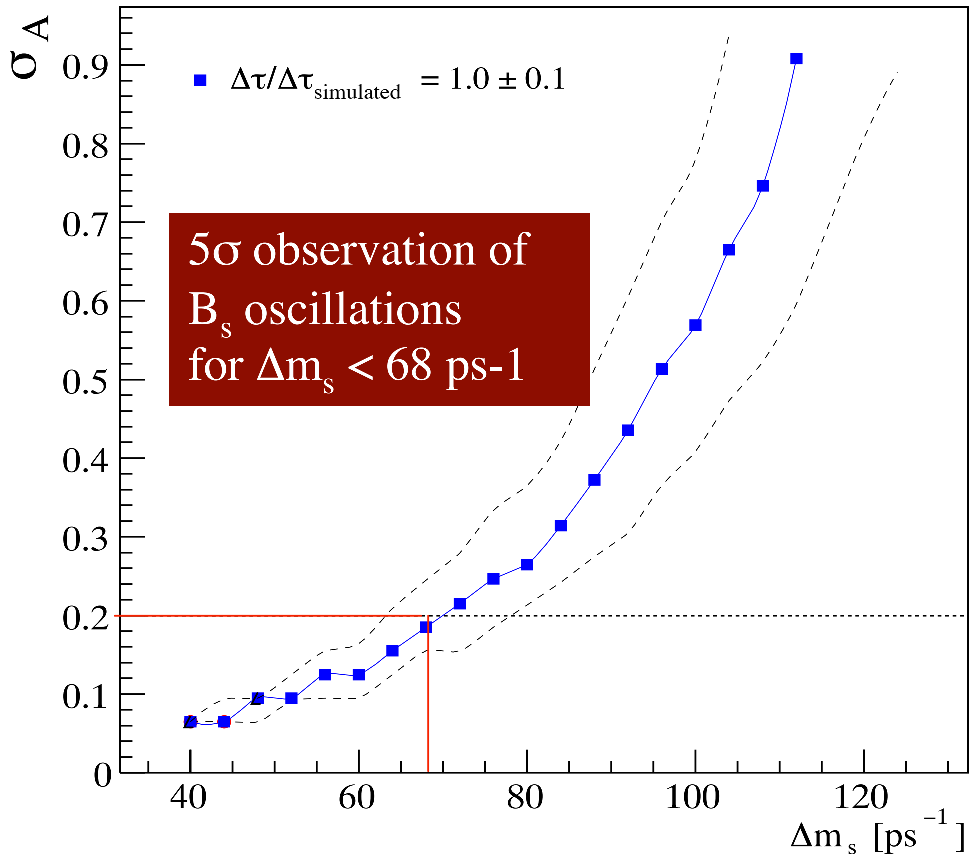




Δm_s sensitivity

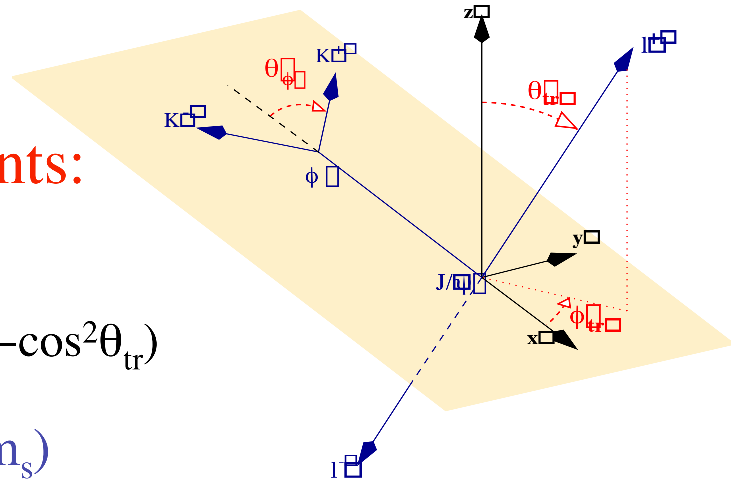
- **Measurement of Δm_s is one of the first LHCb physics goals**
  - Expect 80k $B_s \to D_s^- \pi^+$ events per year (2 fb^{-1}), average $\sigma_t \sim 40$ fs
  - S/B ~ 3 (derived from 10^7 fully simulated inclusive $b\bar{b}$ events)





ϕ_s and $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$, …

- $B_s \to J/\psi\phi$ is the B_s counterpart of $B^0 \to J/\psi\, K_S$:
  - Allows the measurement of the B_s mixing phase ϕ_s
  - SM prediction is very small: $\phi_s = -\arg(V_{ts}{}^2) = -2\lambda\eta^2 \sim -0.04$
    $\Rightarrow$ sensitive probe for new physics
- $J/\psi\phi$ final state contains two vectors
  $\rightarrow$ mixture of CP-even and CP-odd components:
  - Angular analysis needed to separate them:



$$L(t, \theta_{tr}) = (1-R_T)\, L_{\varepsilon\varpi\varepsilon\nu}(t)\, (1+\cos^2\theta_{tr})/2 + R_T\, L_{odd}(t)\, (1-\cos^2\theta_{tr})$$

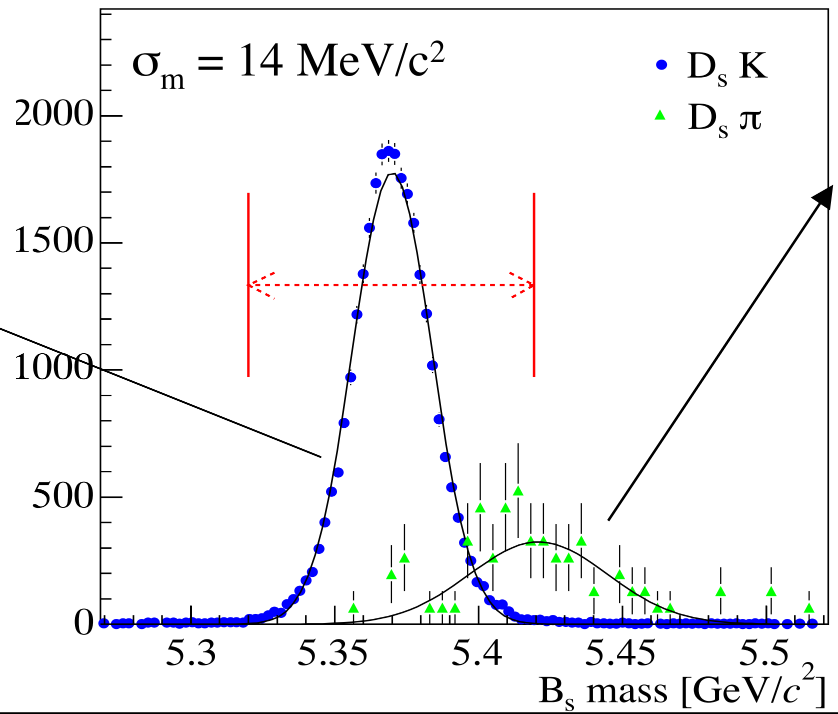
  - Fit for $\sin(\phi_s)$, $\Delta\Gamma_s$ and R_T (needs knowledge of Δm_s)
- LHCb sensitivity:
  - 120k signal events per year (before tagging), $S/B_{bb} > 3$
  - If $\Delta m_s = 20\ ps^{-1}$: $\sigma_{stat}(\sin\phi_s) \sim 0.058$, $\sigma_{stat}(\Delta\Gamma_s/\Gamma_s) \sim 0.018$
  - Eventually, improve by adding also pure CP modes such as $J/\psi\eta$, $J/\psi\eta'$, $\eta_c\phi$
  - For $J/\psi\phi$, similar sensitivity expected at ATLAS/CMS with 20 fb^{-1} (SM Δm_s)

γ from $B_s \to D_s K$

- Two tree decays, $B_s \to D_s^- K^+$ and $B_s \to D_s^+ K^-$, which interfere via B_s mixing:
  - can determine $\phi_s + \gamma$, hence γ in a very clean way
  - similar to $2\beta+\gamma$ extraction with $B^0 \to D^* \pi$, but with the advantage that the two decay amplitudes are similar ($\sim\lambda^3$) and that their ratio can be extracted from data

Expect 5400 signal events/year

$S/B_{bb} > 1$ at 90% CL (estimated from one MC bb events after cuts, not shown here)



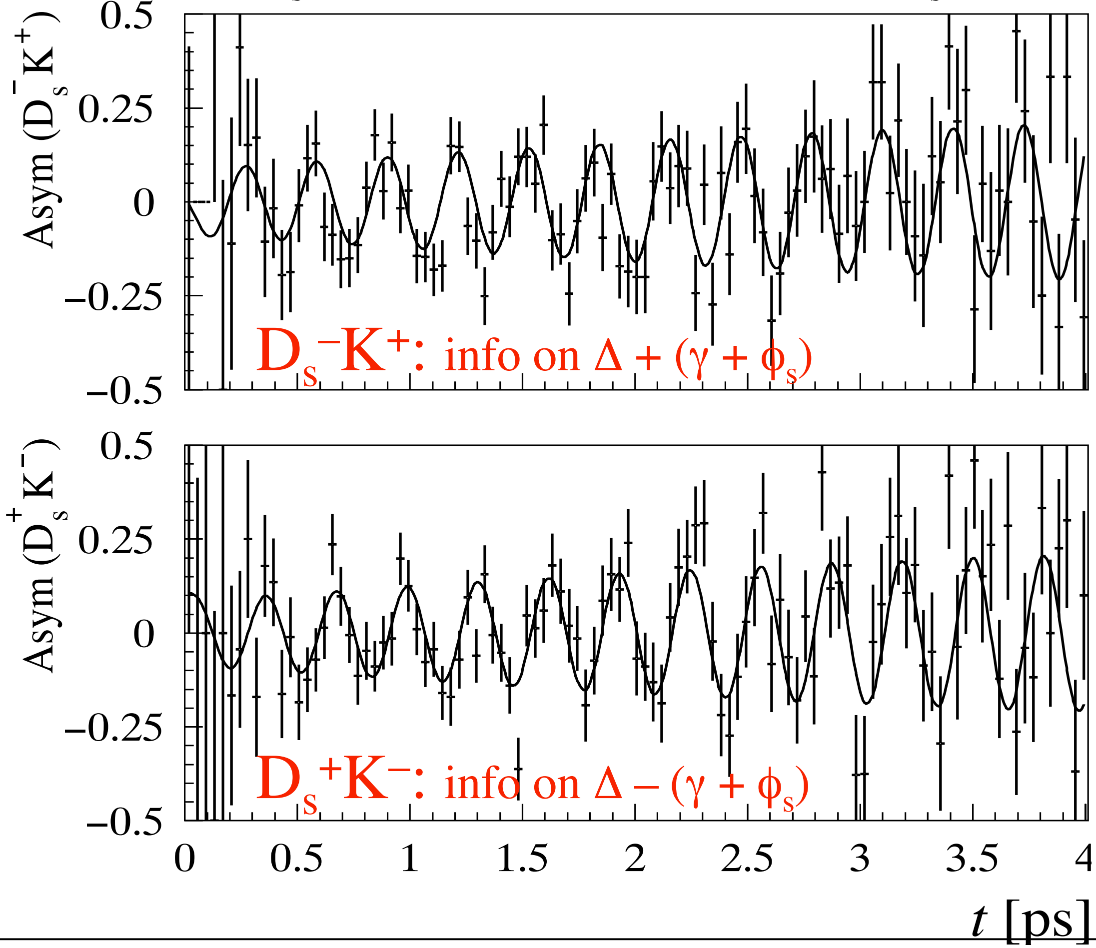
$B_s \to D_s^- \pi^+$ background (with ~ 12 × larger BR) suppressed using PID:
→ residual contamination only ~ 10%

γ from $B_s \to D_sK$

- Fit of the 4 tagged time-dependent rates:
  - Extract $\phi_s + \gamma$, strong phase difference Δ, amplitude ratio
  - $B_s \to D_s\pi$ also used in the fit to constrain other parameters (mistag rate, Δm_s, $\Delta\Gamma_s$ …)

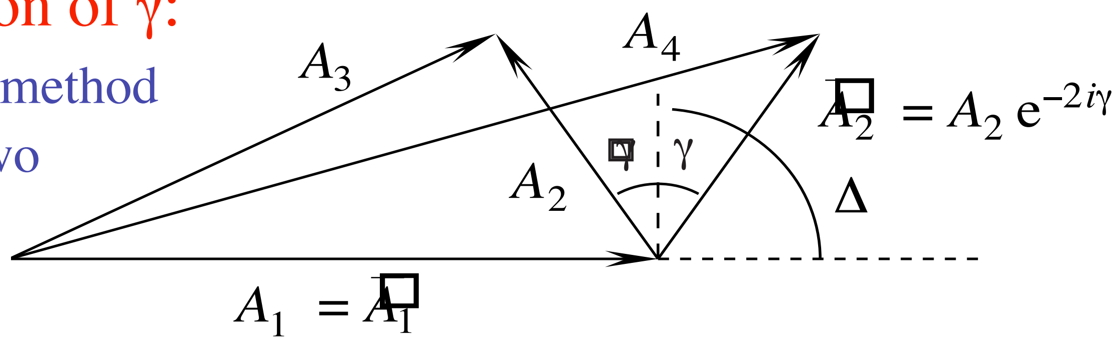
- $\sigma(\gamma) \sim 14°$ in one year (if $\Delta m_s = 20\ ps^{-1}$)
  - expected to be statistically limited
  - 8-fold ambiguity can be resolved ($\to$ 2-fold) if $\Delta\Gamma_s$ large enough, or using $B^0 \to D\pi$ together with U-spin symmetry (Fleischer)

Both D_sK asymmetries (after 5 year, $\Delta m_s = 20\ ps^{-1}$)



γ from $B^0 \to D^0 K^{*0}$

- **Theoretically clean determination of γ:**
  - Dunietz variant of Gronau-Wyler method
  - Similar to $B^+ \to D^0 K^+$, but here two colour-suppressed diagrams with $|A_1|/|A_2| \sim 0.4$



$A_1 = A(B^0 \to \bar{D}^0 K^{*0})$: $b \to c$ transition, phase 0

$A_2 = A(B^0 \to D^0 K^{*0})$: $b \to u$ transition, phase $\Delta+\gamma$

$A_3 = \sqrt{2}\, A(B^0 \to D_{CP} K^{*0}) = A_1 + A_2$, because $D_{CP} = (\bar{D}^0 + D^0)/\sqrt{2}$

- **Measure 6 decay rates (self-tagged + time-integrated):**
  - Expectations for 2 fb^{-1} ($\gamma = 65°$, $\Delta = 0$)

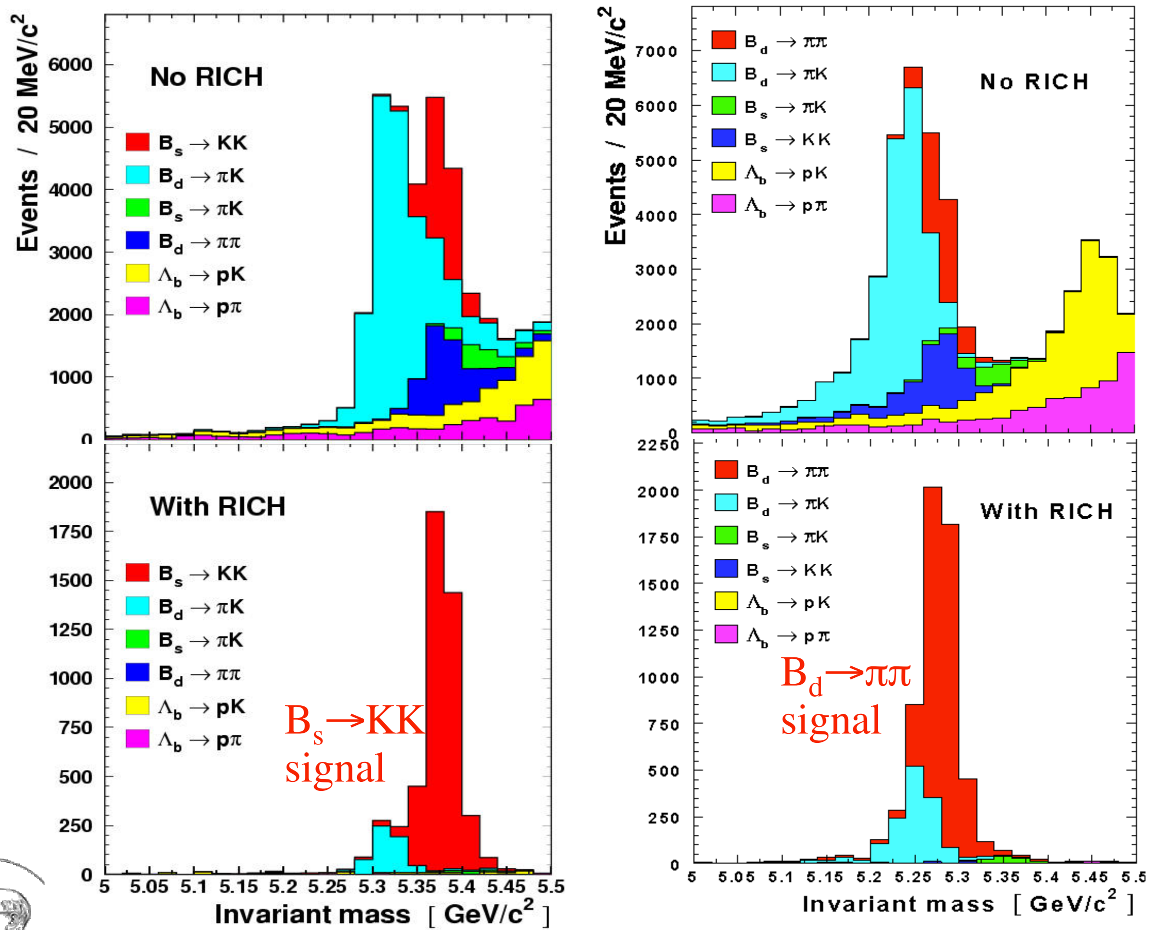
Mode (+ cc)	Yield	S/B_{bb}
$B^0 \to \bar{D}^0 (K^+\pi^-) K^{*0}$	3400	> 3.3
$B^0 \to D^0 (K^-\pi^+) K^{*0}$	500	> 0.6
$B^0 \to D^0_{CP} (K^+K^-) K^{*0}$	600	> 0.7

$\to \sigma(\gamma) \sim 8°$

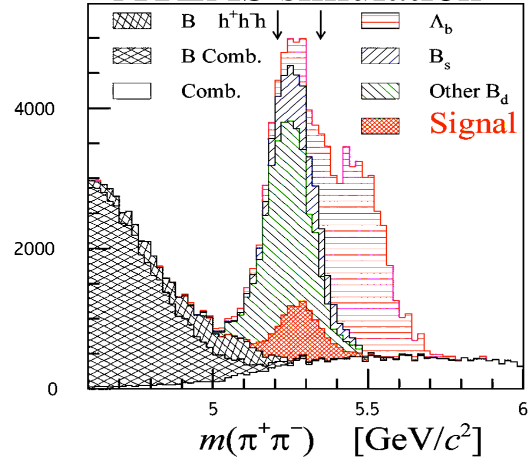
$B_{(s)} \to h^+h^-$ modes

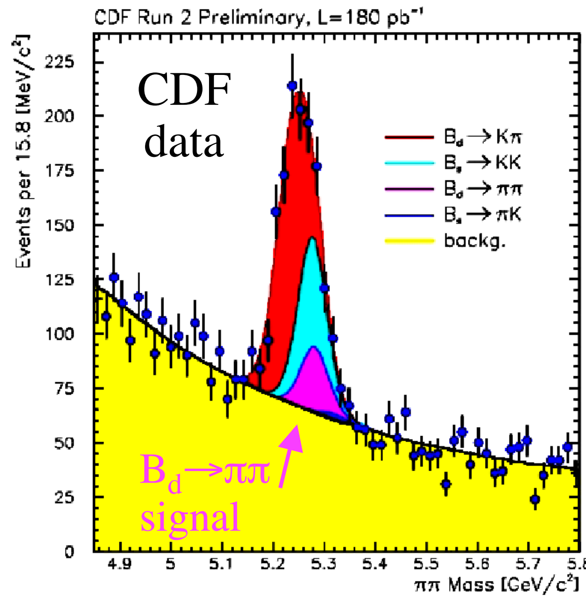
- Clean separation of different $B_{(s)} \to hh$ modes: a unique feature of LHCb at hadron colliders

LHCb full simulation



ATLAS simulation





γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

- For each mode, measure time-dependent CP asymmetry:

$$A_{CP}(t) = A_{dir}\cos(\Delta m t) + A_{mix}\sin(\Delta m t)$$

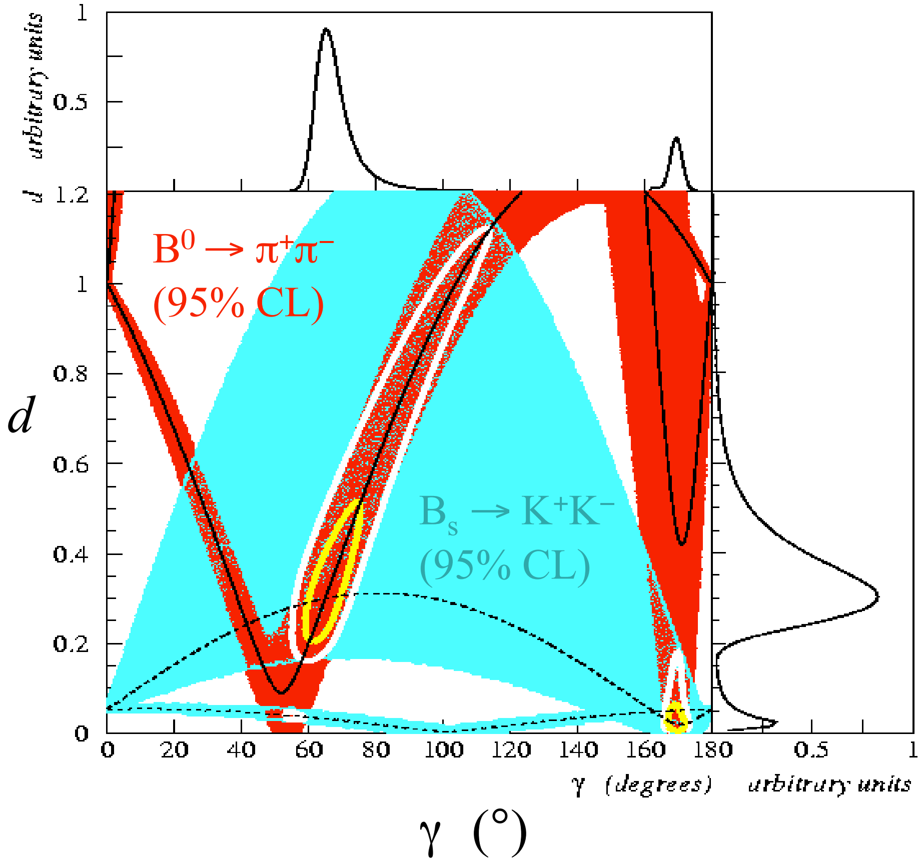
  - A_{dir} and A_{mix} depend on mixing phase, angle γ, and ratio of penguin to tree amplitudes = $d\,e^{i\theta}$

- Exploit U-spin symmetry (Fleischer):
  - Assume $d_{\pi\pi}=d_{KK}$ and $\theta_{\pi\pi}=\theta_{KK}$
  - 4 measurements and 3 unknowns (taking mixing phases from other modes) → can solve for γ

- Expectations (one year):
  - 26k $B^0 \to \pi^+\pi^-$
  - 37k $B_s \to K^+K^-$

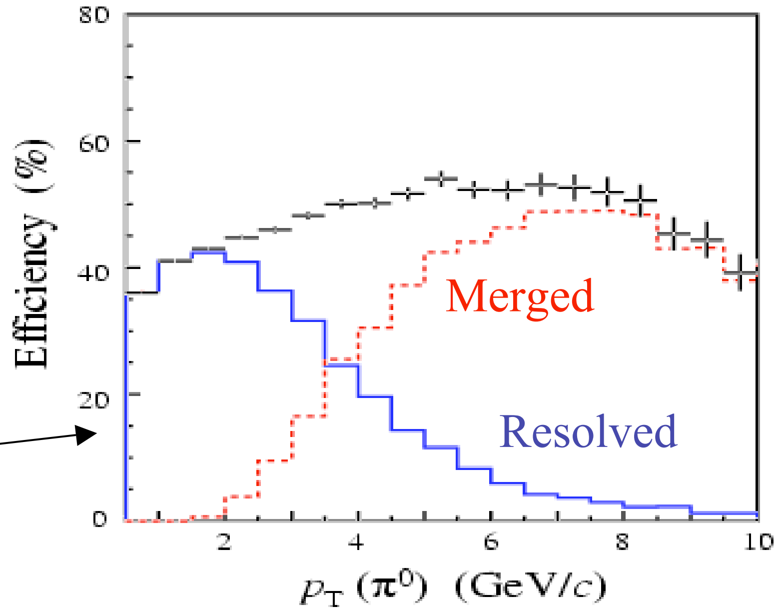
$\to \sigma(\gamma) \sim 5°$

  - Uncertainty from U-spin assumption
  - Sensitive to new physics in penguins

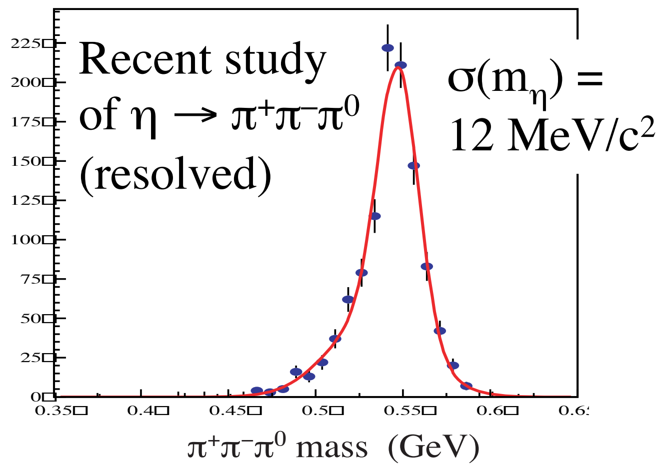


Neutral reconstruction

- Neutral π reconstruction:
  - Use calorimeter clusters unassociated to charged tracks
  - Reconstruct π^0 as two separate (resolved) clusters or a single merged cluster (using cluster shape)
  - $B^0 \to \pi^+\pi^-\pi^0$ Dalitz plot analysis:
    - Reasonable efficiency for π^0
    - 14k signal evts/year, S/B ~ 1.3, $\sigma(\alpha) \sim 10°$



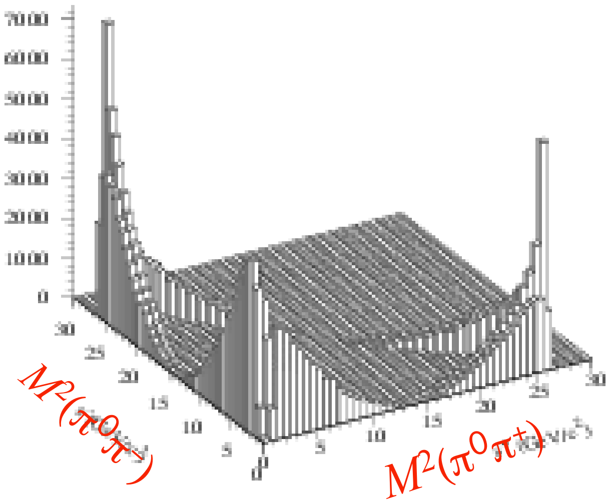
- $K_S \to \pi^+\pi^-$ reconstruction
  - 75% efficiency for decay in the VELO, lower otherwise
    - 240k $B^0 \to J/\psi K_S$ per year, $\sigma_{stat}(\sin(2\beta)) \sim 0.02$



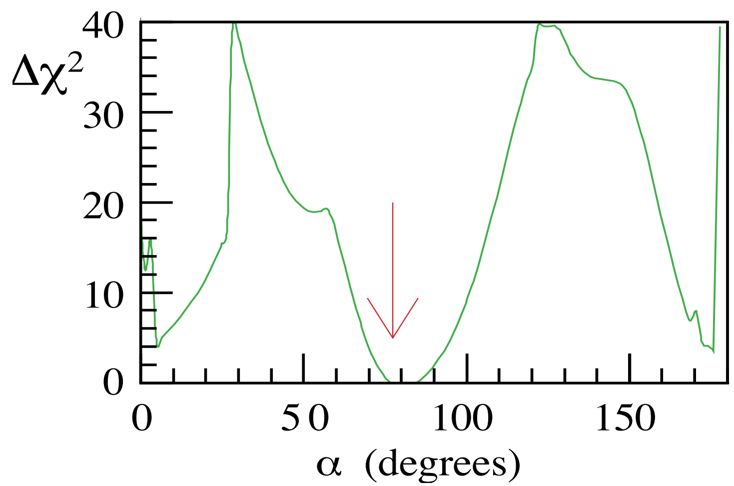
- Modes with multiple neutrals will be challenging at LHCb

α from $B^0 \to \pi^+\pi^-\pi^0$

- Time-dependent Dalitz plot analysis of $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$ for extraction of α along with amplitudes + strong phases (Snyder & Quinn)



- LHCb expectation:
  - Annual yield ~ 14k events, S/B ~ 1.3
  - Complicated 11-parameter fit, studied with toy (incl. resonant and non-resonant background)
  - Statistical precision of $\sigma(\alpha) \sim 10°$ achievable in one year
  - Systematic uncertainties under study, e.g. from mirror solutions

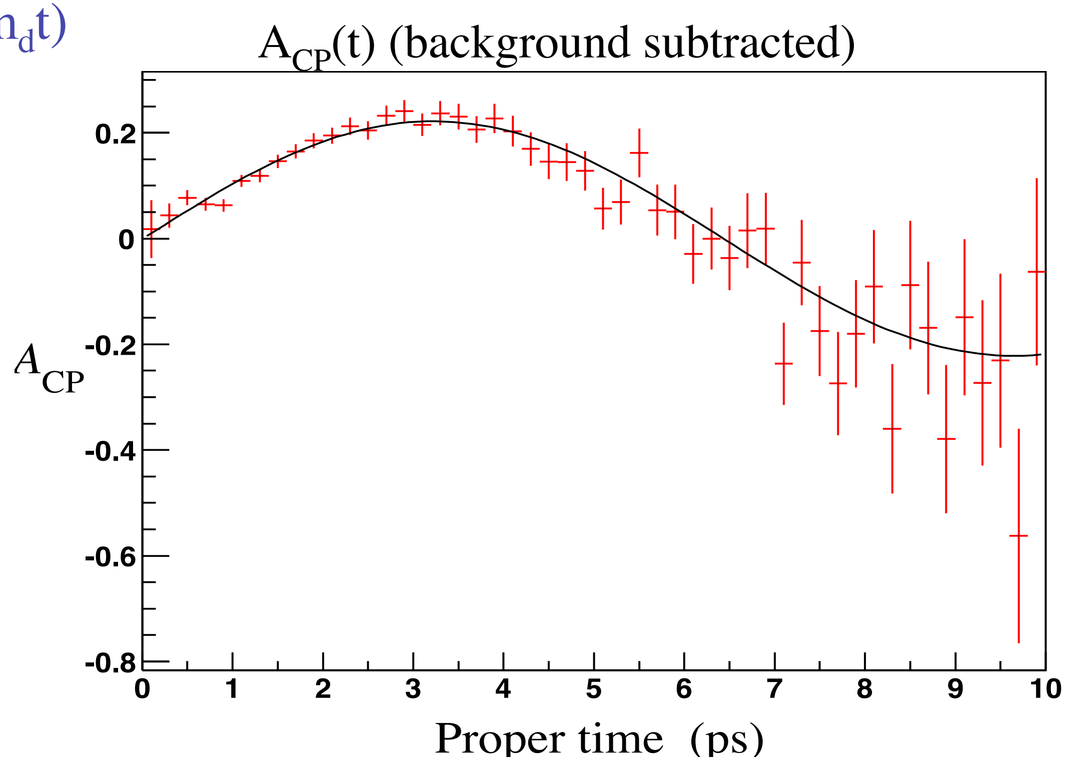


sin 2β with $B^0 \to J/\psi\, K_S$

- **Measurement of sin 2β with $B^0 \to J/\psi\, K_S$:**
  - not a central physics goal of LHCb (since so well measured already)
  - but important check of CP analyses
  - can also push further the search for direct CP violating term ∝ $\cos(\Delta m_d t)$
  - very large statistics expected: ~240k signal events per year ⇒ $\sigma_{stat}(\sin(2\beta)) \sim 0.02$
  - similar sensitivity expected at ALTAS/CMS for 30 fb^{-1}

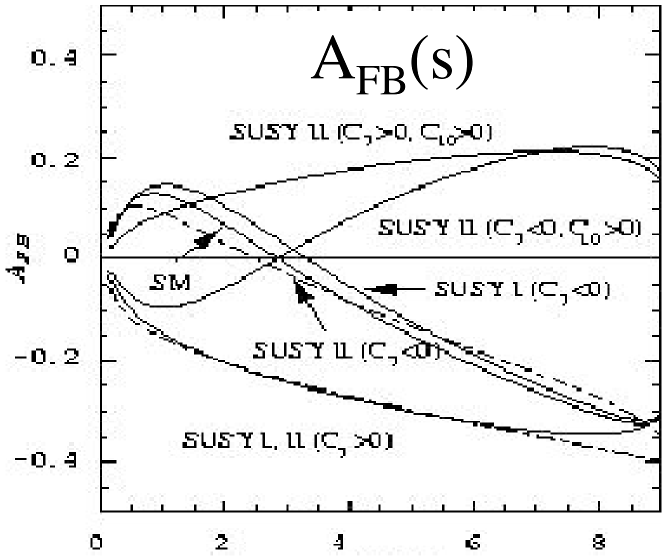
B^0 mass resolution (MeV/c^2)

LHCb	CMS	ATLAS
10	16	19

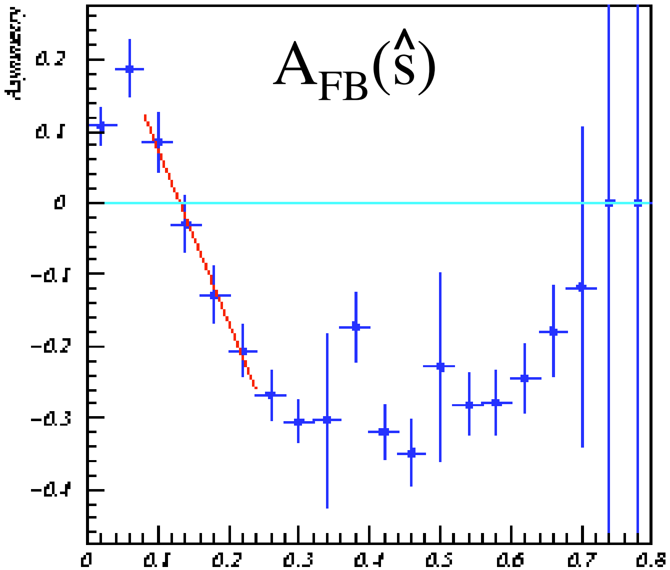


$B^0 \to K^{*0}\mu^+\mu^-$

- Suppressed decay, SM BR ~ 10^{-6}
- Forward-backward asymmetry in the $\mu\mu$ rest-frame $A_{FB}(s)$ is sensitive probe of new physics:
  - Zero can be predicted with no hadronic uncertainties, depends only on the Wilson coefficients C_7, C_9



$s = (m_{\mu\mu})^2$ [GeV^2]



$\hat{s} = (m_{\mu\mu}/m_B)^2$

- LHCb:
  - 4400 events/year, S/B > 0.4
  - $A_{FB}(\hat{s})$ reconstructed using toy MC (two years of data, background subtracted) → zero point located to ±0.04
- ATLAS:
  - 2000 events, S/B = 7, for 30 fb–1

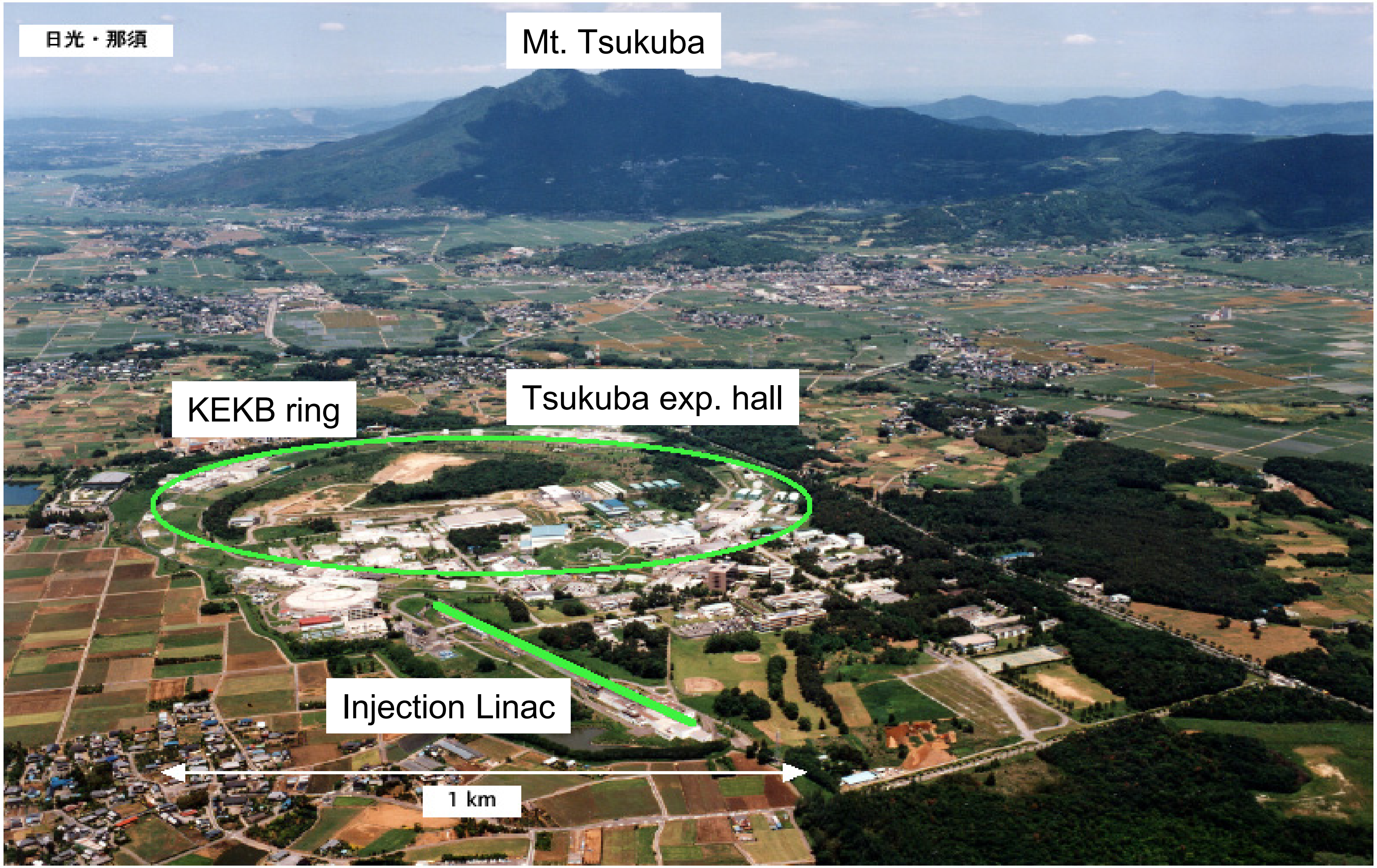
$B_s \to \mu^+\mu^-$

- Very rare decay:
  - BR = 3.5×10^{-9} in Standard Model
  - Sensitive to new physics, can be strongly enhanced in SUSY
  - Current limit from Tevatron (CDF+D0): 1.5×10^{-7} at 95% CL
- At LHC, prospect for significant measurement, even for SM value
  - LHCb:
    - expect 17 selected signal events/year for SM BR
    - problem to estimate the background: no event selected from full MC background sample, only corresponding to $S/\sqrt{B} > 2$
  - ATLAS/CMS:
    - Yields from 100 fb^{-1} (1 year at 10^{34} $cm^{-2}s^{-1}$)
    - Background estimates (from 1999) differ significantly

	$B_s \to \mu^+\mu^-$	$B_d \to \mu^+\mu^-$	Background
ATLAS	92	14	660
CMS	26	4	< 6

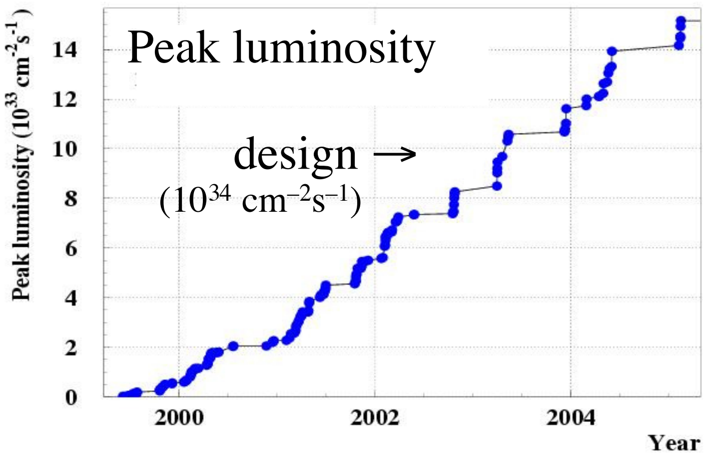
  - 2005 ATLAS update for 30 fb^{-1}:
    - 9 signal with 45±30 background, or 21 signal with <60 background

A Super B factory ?

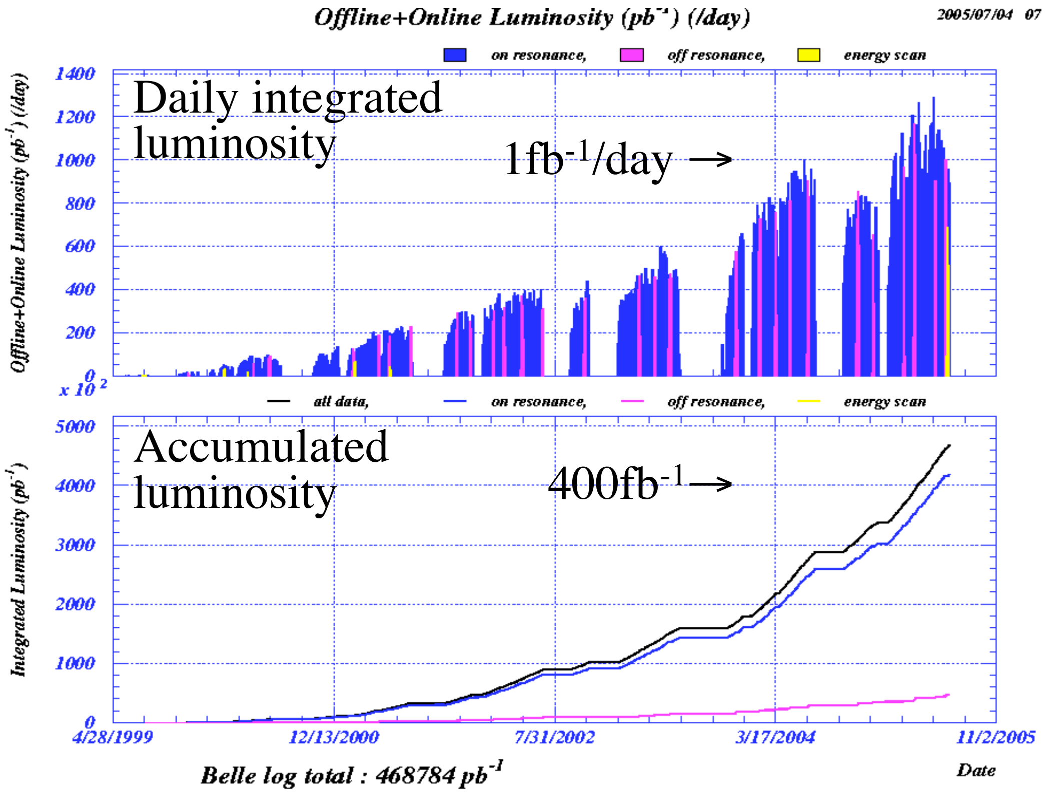


Success of current B factories

- Asymmetric B factories and experiments (KEKB/Belle at KEK, PEPII/BABAR at SLAC):
  - In operation since 1999
  - Both exceeded their design performance (plots and numbers from KEKB/Belle)



- World record of peak luminosity $\sim 1.5\times10^{34}$cm^{-2}s^{-1}
- ~500M BB and ~400M ττ pairs recorded

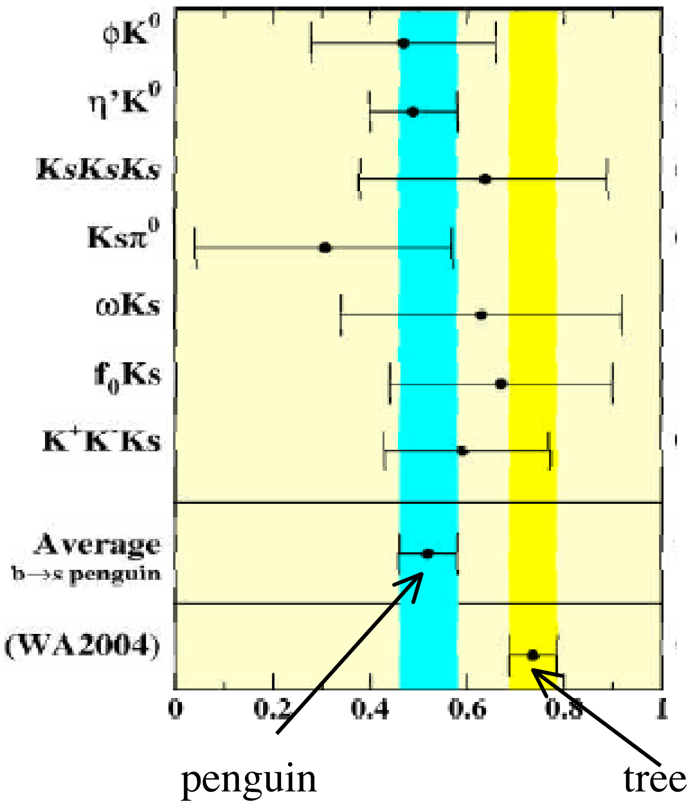


Success of current B factories

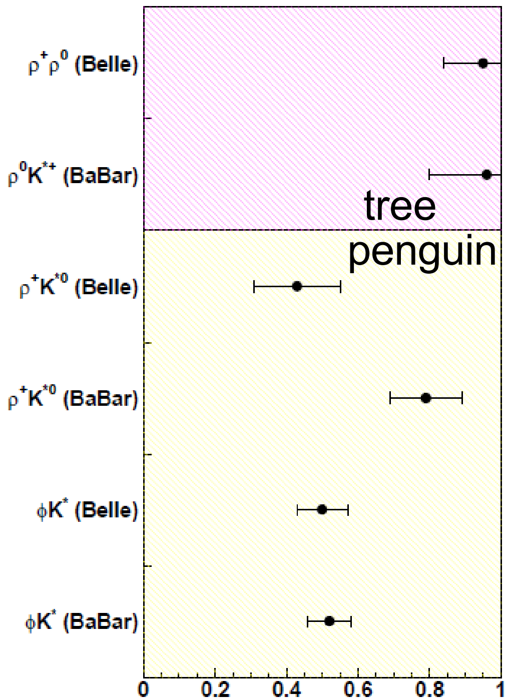
- About 300 papers in the last 5 years from BABAR and Belle
  - B, charm, charmonium, $\gamma\gamma$ and τ physics
- Scientific achievements:
  - Observation of CP violation in B decays ($B^0 \rightarrow J/\psi\ K_S$), for the first time outside K system
  - Quantitative tests (and confirmation) of CKM picture
  - Hints for new physics:
    - $B^0 \rightarrow \phi K_S$? polarization in $B \rightarrow VV$? $A_{CP}(B \rightarrow K\pi)$?
  - Discovery of unexpected resonances
    - X(3872) DD molecule ? Y(3940) ccg hybrid ?
  - Other "first" observations:
    - $b \rightarrow d$ transitions: $B \rightarrow (\rho,\omega)\gamma$ and $B \rightarrow KK$
    - Color suppressed hadronic B decays: $B \rightarrow \pi^0\pi^0$ and $B \rightarrow D\pi^0$ decays
    - Direct CP violation: $B \rightarrow K^+\pi^-$ and time-dependent analysis of $B \rightarrow \pi^+\pi^-$
    - EW penguin process, $b \rightarrow s l^+ l^-$
    - Non-spectator B decays: $B^0 \rightarrow D_s^+ K^-$

Hints for new physics in b→s ?

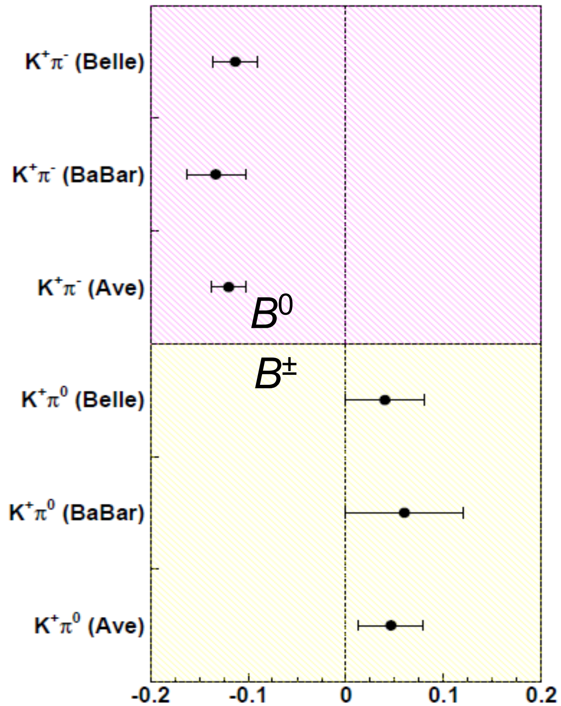
CPV(tree) ~ CPV(penguin) in SM



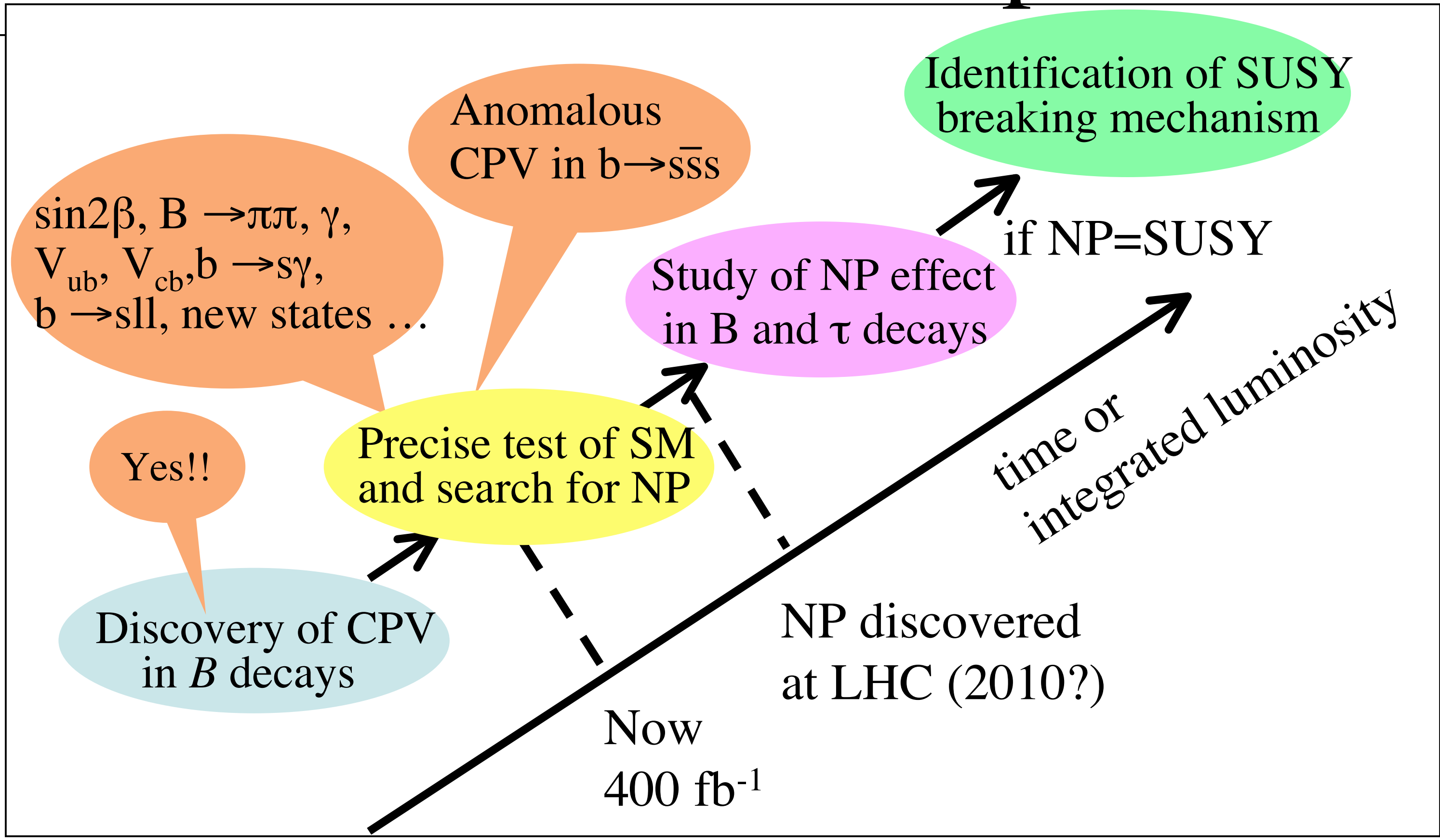
f_L (B→VV) ~ 1 in SM



A_{CP}(B→K π) is equal for $B^{\pm}$ and B^0



The famous roadmap slide



taken from A. Palano, June 2005 (probably not the original !)

Success of present B factories
+ few interesting hints in present data
+ faith that SM cannot be the final theory
(and that NP can show up in B decays)

$\Rightarrow$ Propose a B factory with >50 times current luminosity to provide definite answers on NP effects in heavy flavor sector

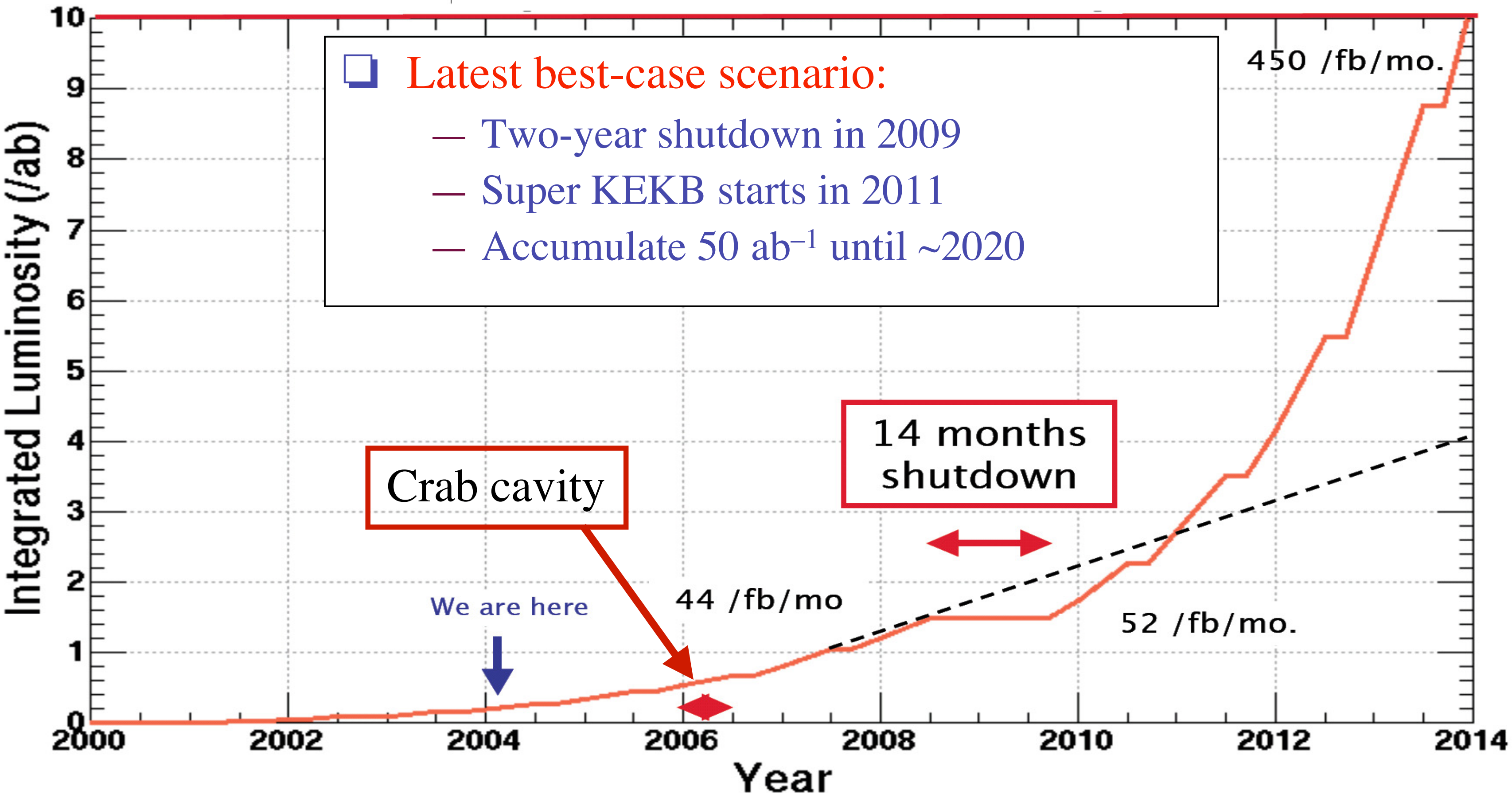
Status of Super-B proposals

- Both BABAR and Belle communities have proposed major upgrade plans at SLAC and KEK
- Super-BABAR:
  - "The discovery potential of a Super B factory", SLAC-R-709, Dec 2004
  - Proposal does not seem to fit in the current plans at SLAC nor in the current priorities of the US high-energy physics program
  - PEPII program now scheduled to be terminated in 2008
- Super-Belle:
  - Letter of intent for KEK Super B factory, KEK report 2004-4
  - Proposal being evaluated: KEK lab decision expected towards end 2006
  - If positive, possible government funding not expected before 2008
- In short, we will have:

  either no Super B factory, or one (joint) Super B factory at KEK → Upgrade existing machine and detector, stay at $\Upsilon(4S)$, aim for 5×10^9 BB and 4×10^9 $\tau\tau$ per year

KEKB luminosity and schedule

L_{peak} ($cm^{-2}s^{-1}$)	1.5×10^{34}	KEKB →	5×10^{34}	Super KEKB →	4×10^{35}
L_{int} ($ab^{-1} = 1000\ fb^{-1}$)	0.47		1		10



Super KEKB parameters

Stored current: (e^-/e^+)

1.34/1.8 A (KEKB)

→ 4.1/9.4 A (SuperKEKB)

Beam-beam parameter:

0.057 (KEKB)

→ 0.19 (SuperKEKB)

Lorentz factor

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

Classical electron radius

Beam size ratio

Geometrical reduction factors due to crossing angle and hour-glass effect

Luminosity:

0.15×10^{35} $cm^{-2}s^{-1}$ (KEKB)

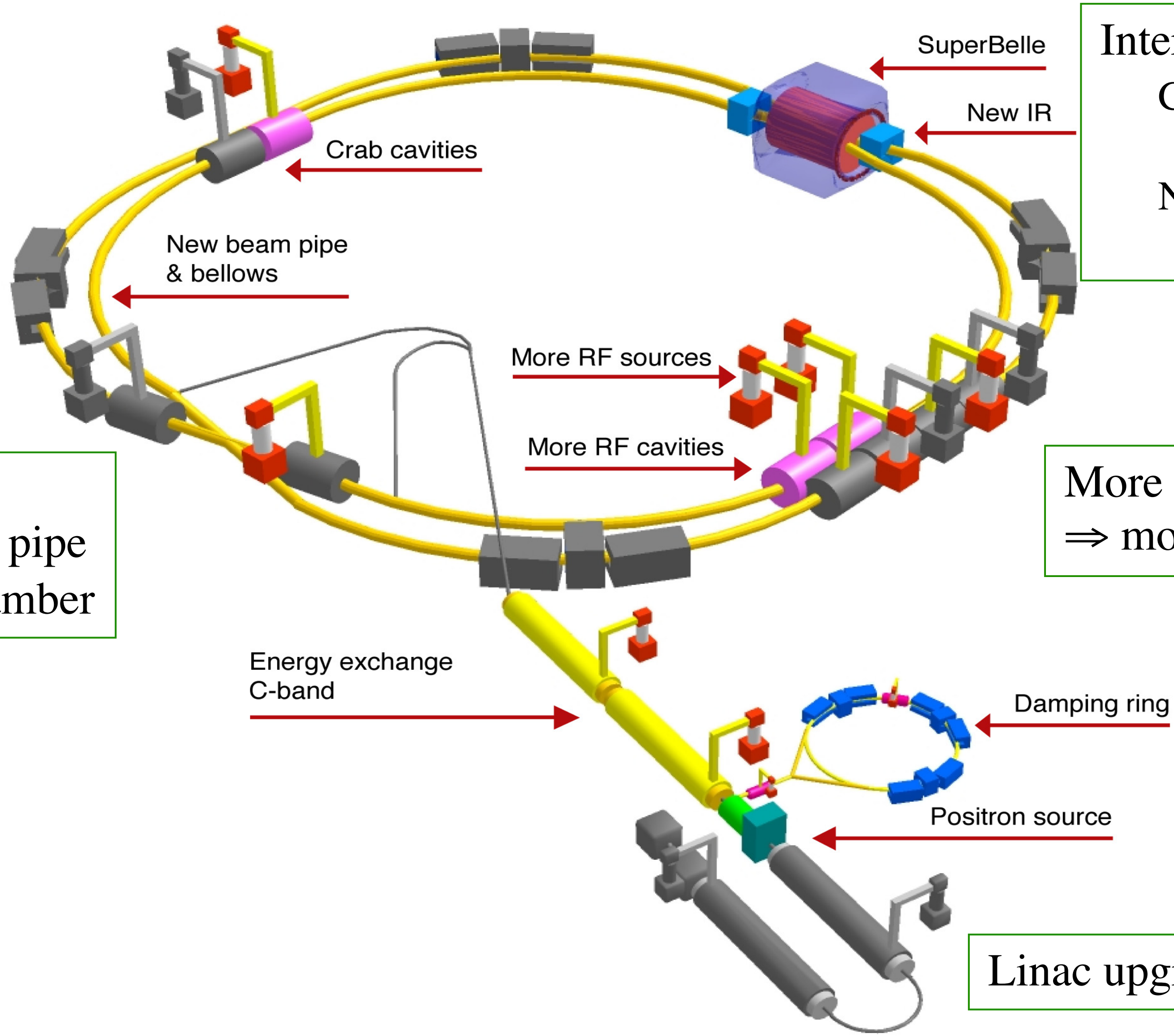
4×10^{35} $cm^{-2}s^{-1}$ (SuperKEKB)

Vertical β at the IP:

6.2/6.5 mm (KEKB)

→ 3.0/3.0 mm (SuperKEKB)

KEKB components to be upgraded



Interaction Region
- Crab crossing
  - θ=30 mrad
- New focusing quadrupoles
  - β_y^*=3mm

More current
⇒ new beam pipe
with ante-chamber

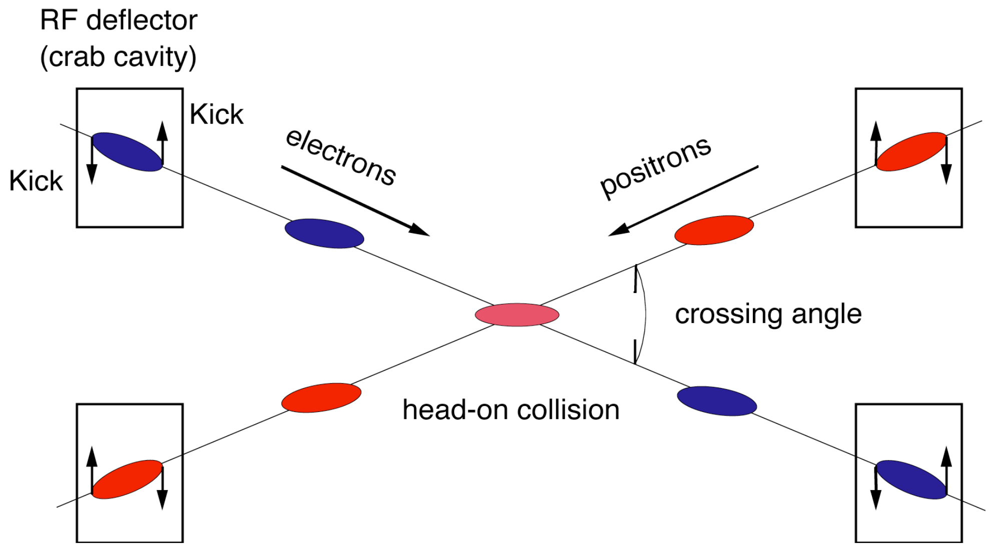
More current
⇒ more RF power

e^+ damping ring
(for low emittance)

Linac upgrade

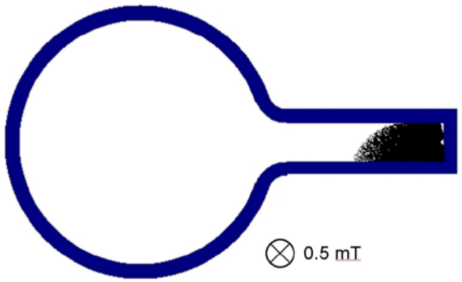
Crab cavity and ante-chamber

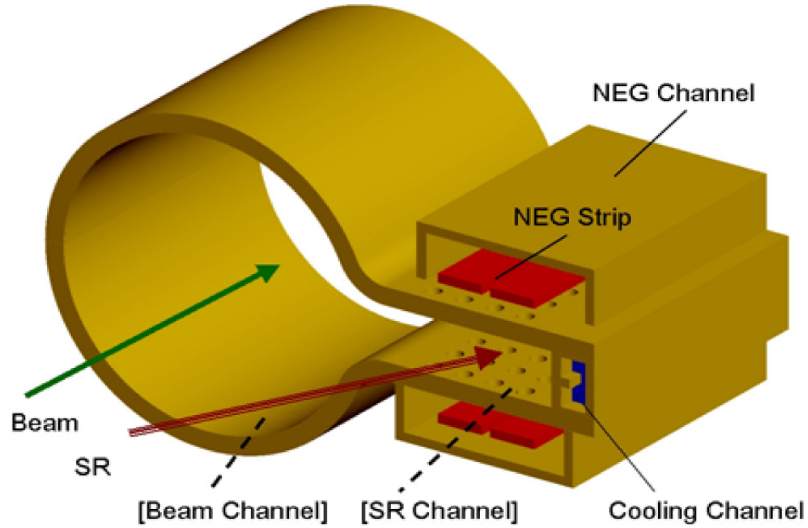
- "Crab crossing" scheme:
  - superconducting crab cavities under development
  - will be installed in KEBK early in 2006



- Beam pipe:
  - Need to prevent instabilities due to photoelectrons induced by synchrotron radiation hitting the vacuum chamber (electron cloud)
    - simulation

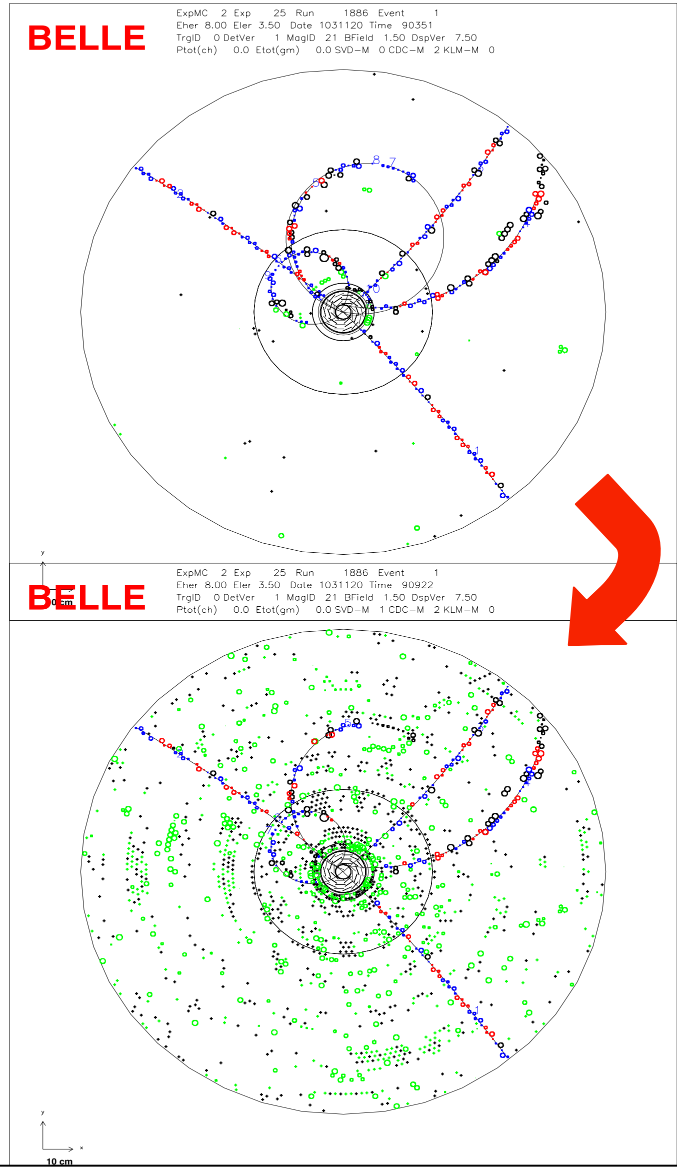
Ante-chamber
with solenoid field



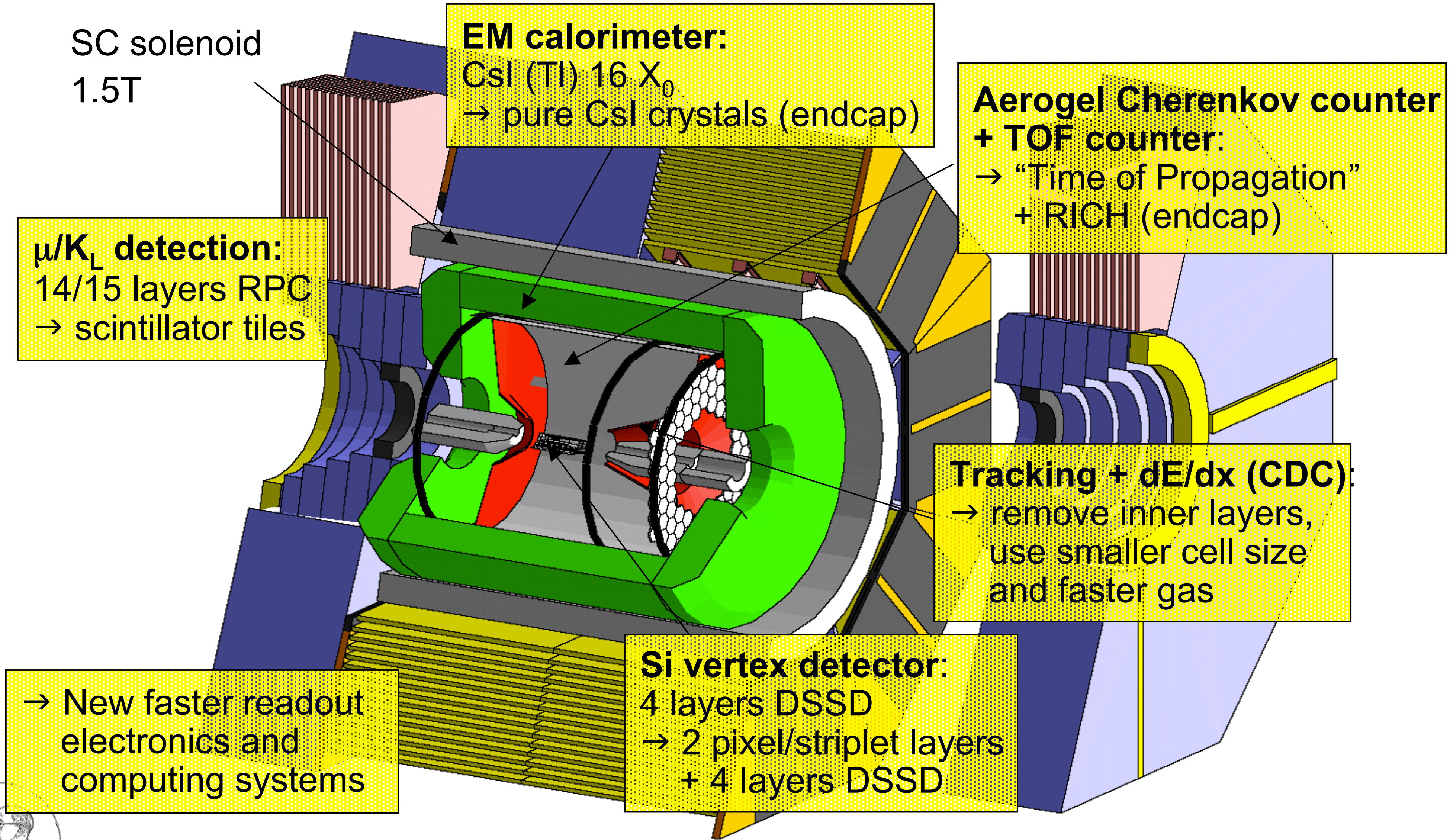


Requirements to the Belle detector

- ❑ Higher rates:
  - — 20 times the machine background
    - Radiation damage and occupancy
    - Fake hits and noise in the EM
  - — 10 times the physics rate
    - Trigger, DAQ, computing
- ❑ Wanted:
  - — Same overall detector performance:
    - Tracking, calorimetry, …
  - — Improved PID:
    - K/π separation
  - — Hermetic detector
    - "ν reconstruction"

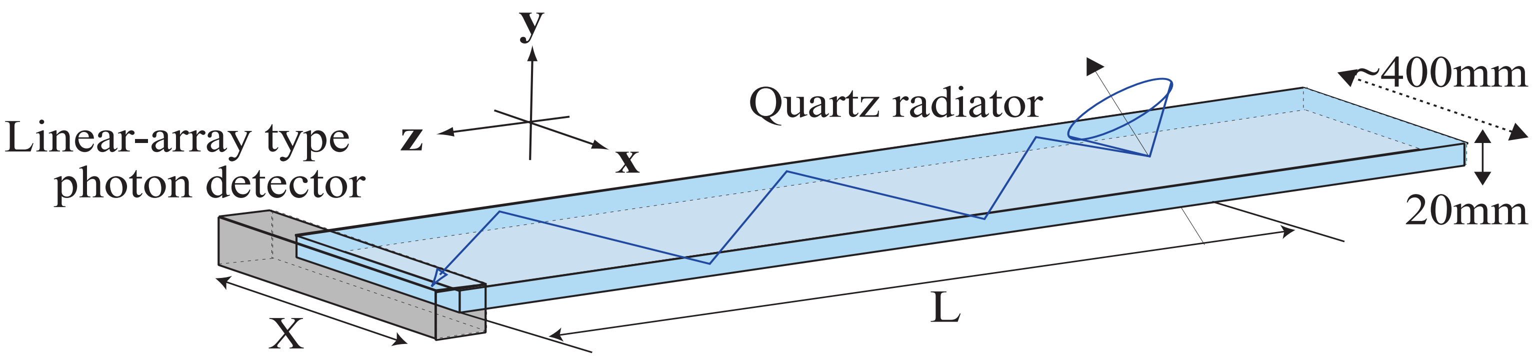


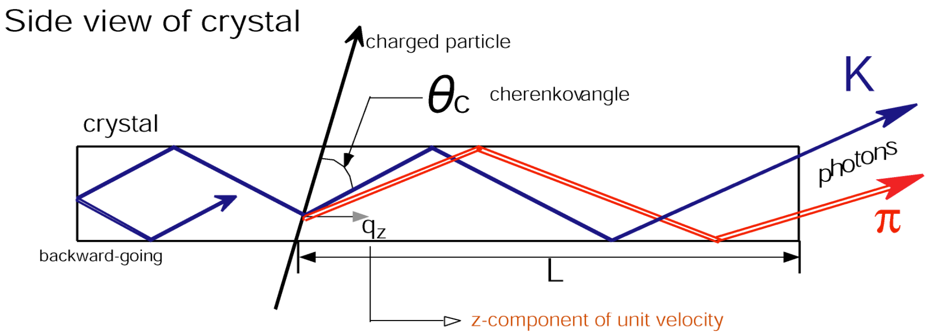
Belle upgrade



New particle ID device “TOP”

- Cherenkov ring imaging using arrival timing of photons





— Internal reflection of Cherenkov light in a quartz bar

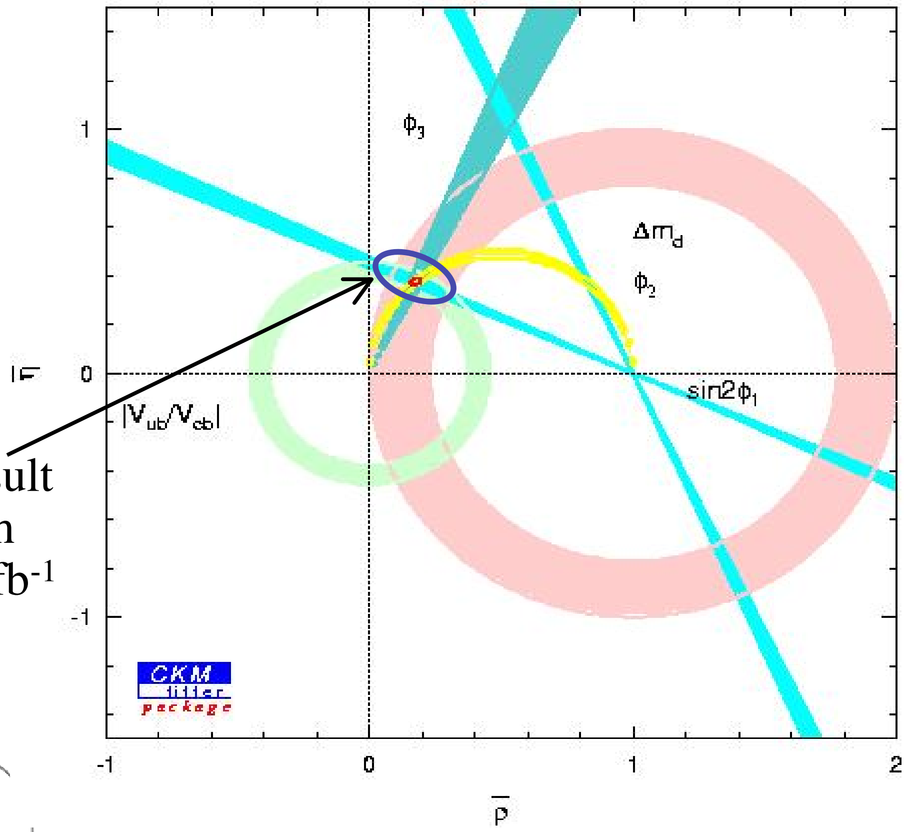
— Difference of photon path length (emitted by K or π) implies difference in “time of propagation” (TOP), to be added to TOF from IP

Precision test of CKM scheme (~2020)

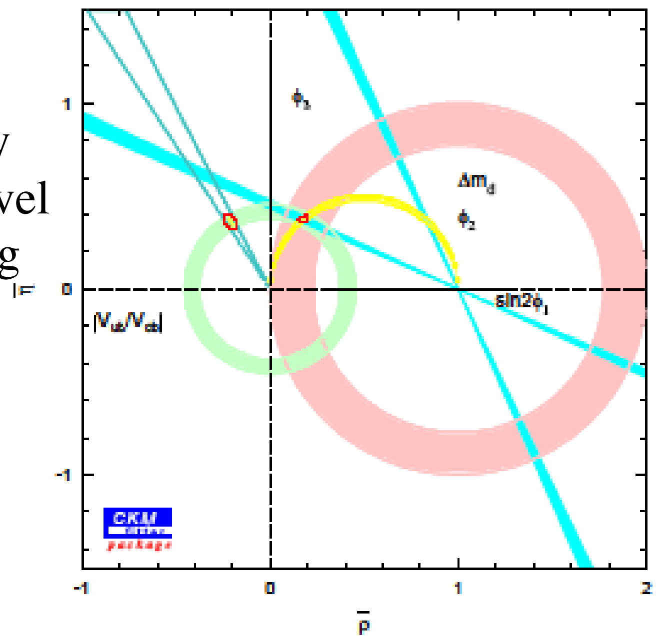
- Precisions expected with 50 ab^{-1} at SuperB + lattice QCD improvements:

$$\sigma(|V_{ub}|)/V_{ub} = 4.4\%$$
$$\sigma(\gamma) = 1.5°$$
$$\sigma(\alpha) = 0.9°$$
$$\sigma(\sin 2\beta) = 0.014$$
$$\sigma(\Delta m_d) = 0.002\ ps^{-1}$$
$$\sigma(f_B\sqrt{B_B}) = 16\ MeV$$

Result with $0.3 fb^{-1}$



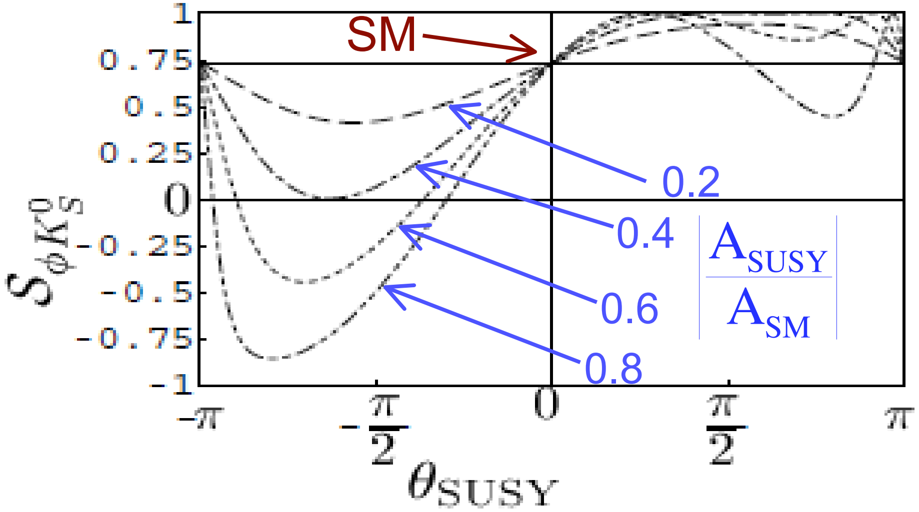
… or, in case of a discrepancy between tree-level and b→d mixing processes:



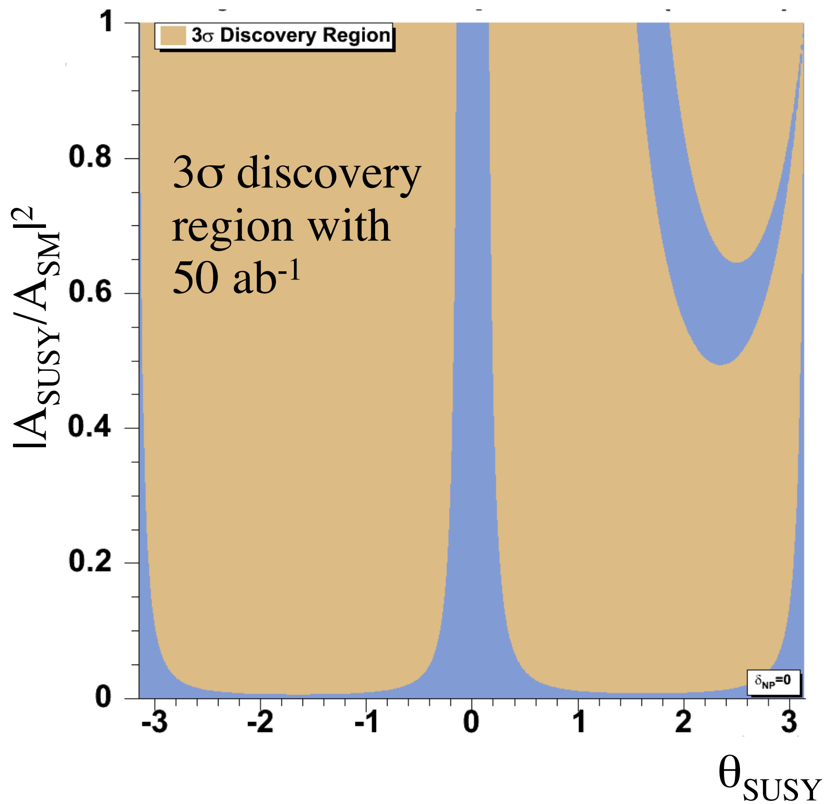
Sensitivity to new CP phase in $b \to s\bar{s}s$ penguins

- Expected total uncertainties on CP asymmetry coefficients with respect to $B^0 \to J/\psi K_S$, with 50 ab^{-1}:

Mode	$\sigma(\Delta A_{mix})$	$\sigma(\Delta A_{dir})$
$B^0 \to \phi K_S$	0.031	0.024
$B^0 \to K^+K^-K_S$	0.026	0.020
$B^0 \to \eta' K_S$	0.024	0.019



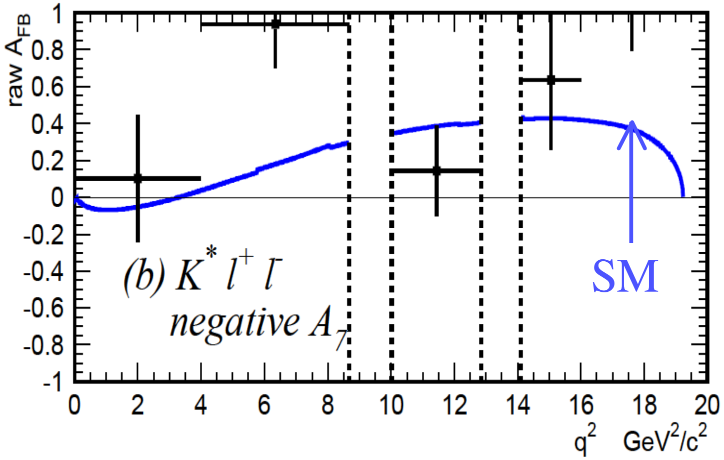
Effect of SUSY phase θ_{SUSY} on $\sin 2\beta_{effective}$ in $B \to \phi K_S$ decay

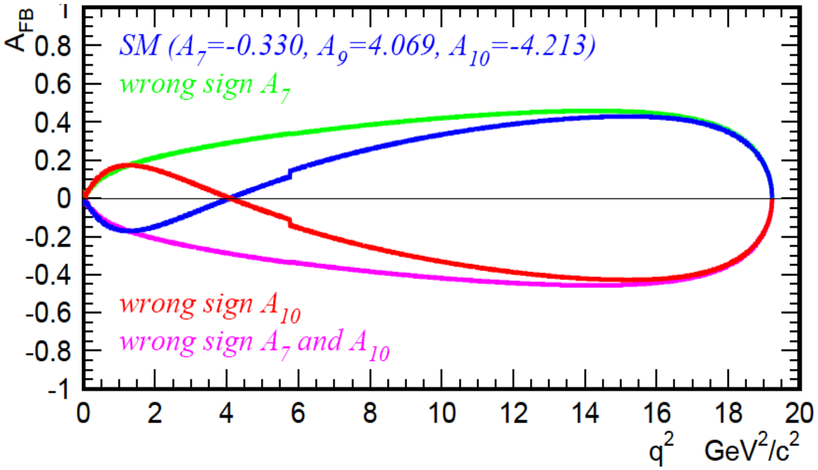


Sensitivity to new flavour mixing ($K^* l^+ l^-$)

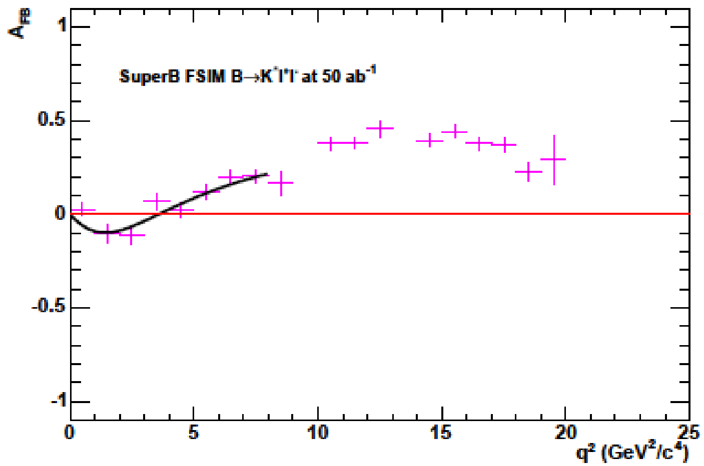
- Forward-backward asymmetry with $B^0 \rightarrow K^* l^+ l^-$:

Real data (0.35 ab^{-1}) Belle, 2005





Sensitivity at Super KEKB (50 ab^{-1})

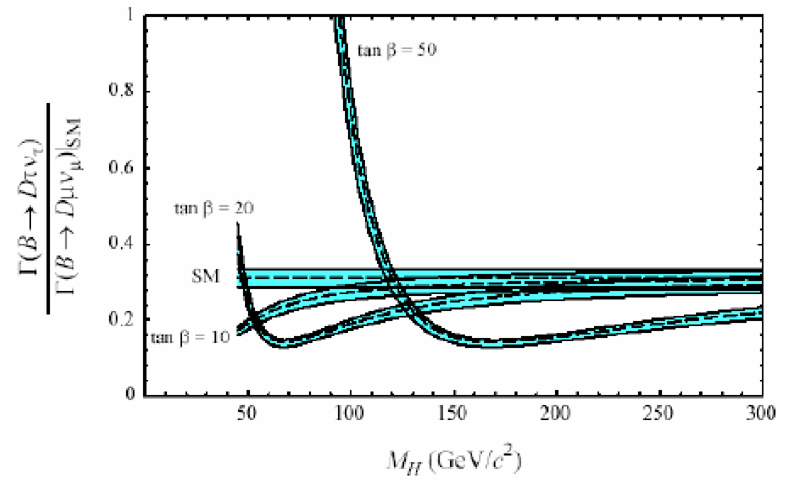


– q^2 at which A_{FB} is zero can be determined with 5% error (50 ab^{-1})

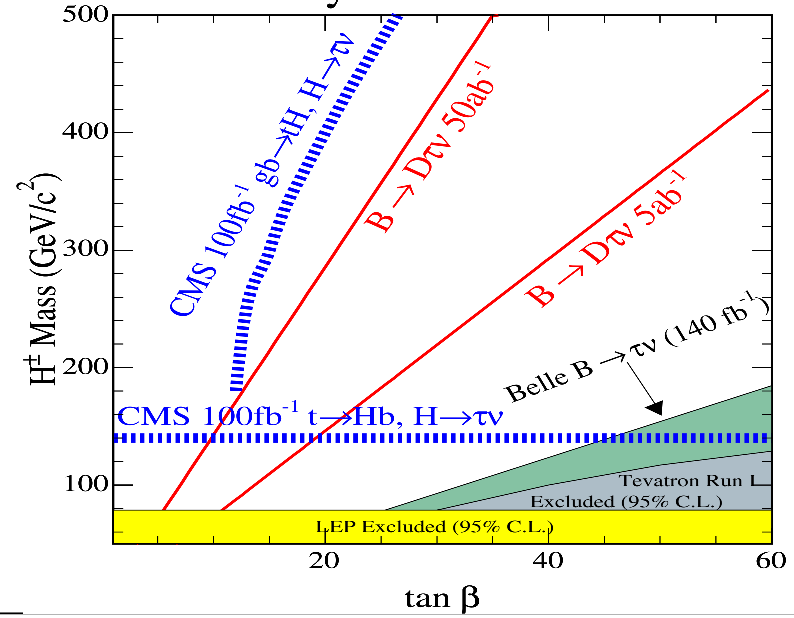
- \+ other measurements with $b \rightarrow sll$, $s\gamma$, dll, $d\gamma$ (inclusive and exclusive) …

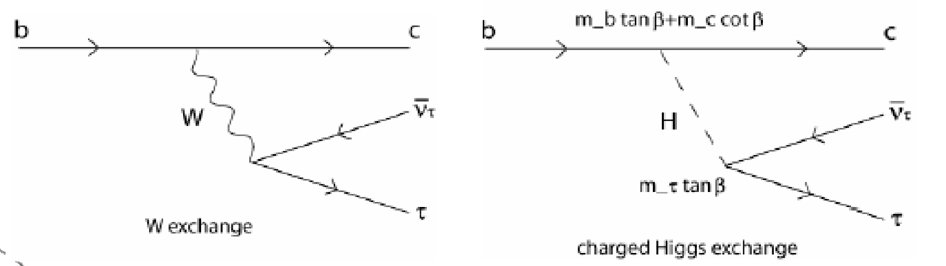
"B meson beam" technique

- Full reconstruction of one B ("tagging" B):
  - backgrounds greatly reduced
  - 4-momentum and flavour of other B determined; can look for difficult decay
- Efficiency:
  - 0.2%–0.3% (0.1–0.2%) for charged (neutral) B
- Application:
  - Search for charged Higgs in $B^+ \to D\tau^+\nu$
  - Measure $B^+ \to D\tau^+\nu$ branching fraction relative to $B^+ \to D\mu^+\nu$



Sensitivity of H⁺ search:

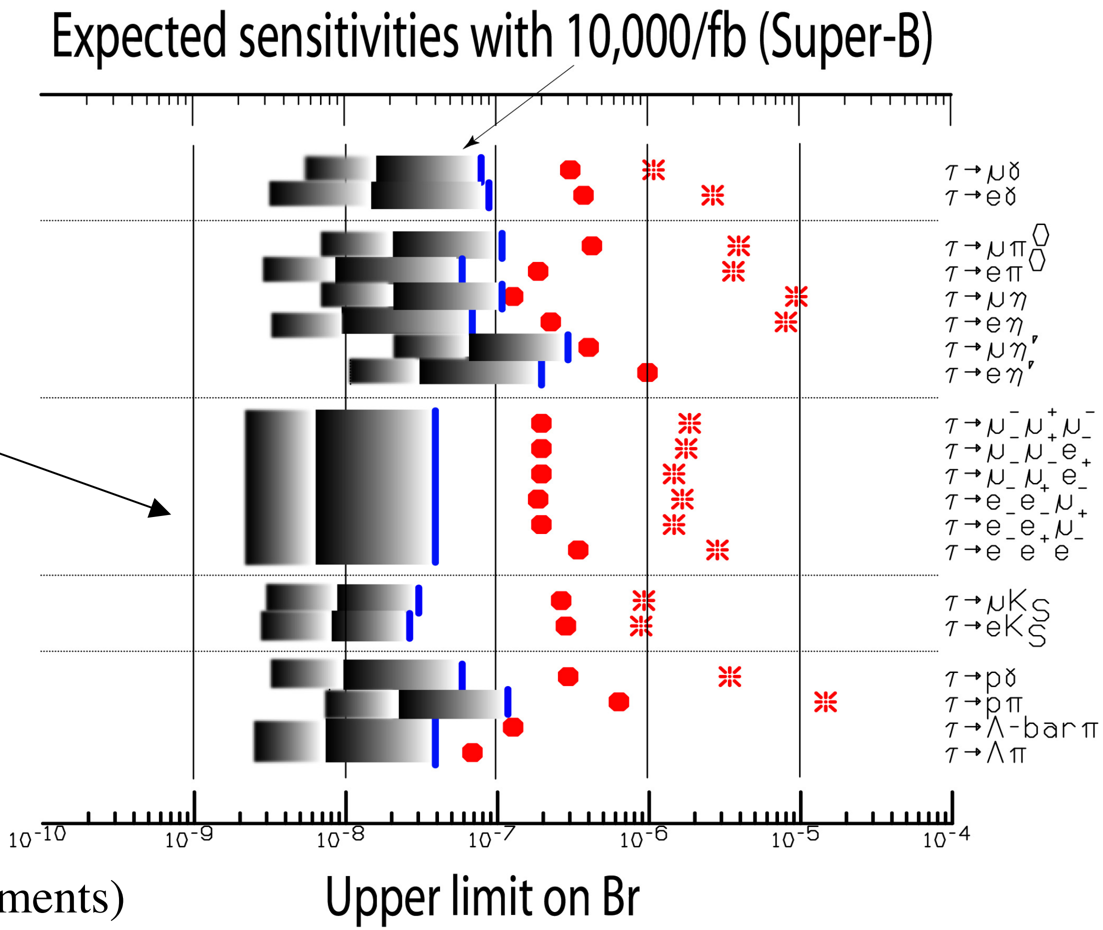




SuperB is also a τ-charm factory …

- **Charm physics**
  - D^0 mixing
  - CP violation in D decays
  - Charmonium, …

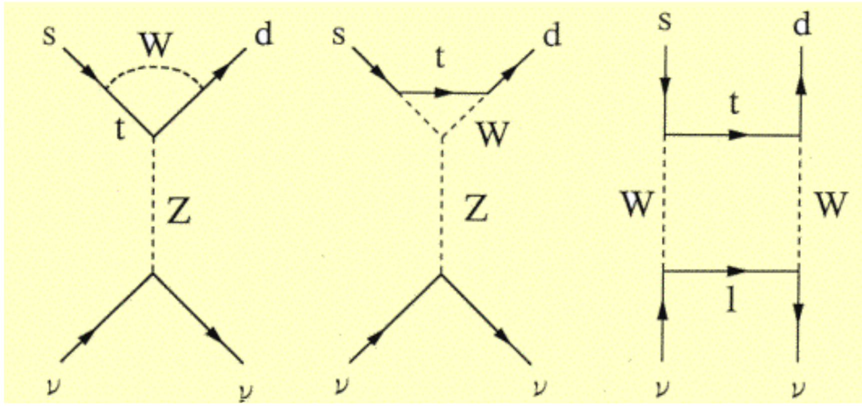
- **Tau physics**
  - Search for lepton-flavour violation (e.g. $\tau \to \mu\gamma$)
  - Reaching 10^{-8} level or better (where NP can show up) with 10 ab^{-1}



✷ CLEO
● Belle (current)
▌ Belle (extrapolation to 600 pb^{-1})
Belle (extrapolation to 10 ab^{-1}, with and without analysis improvements)

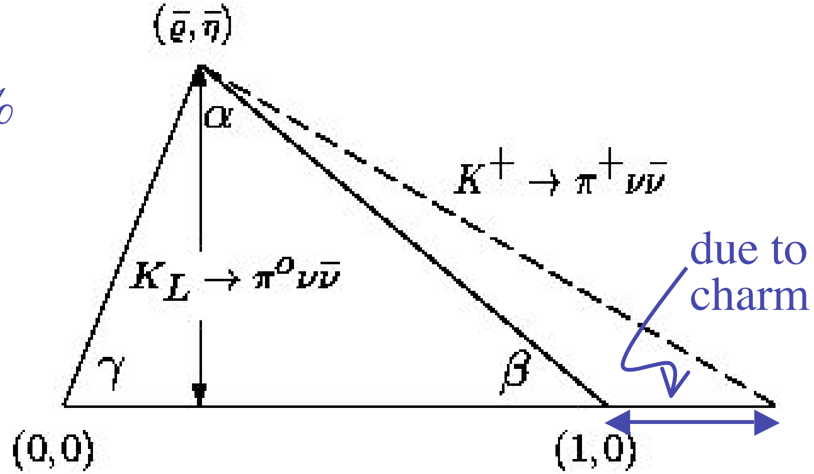
The unique contribution of $K \to \pi\nu\bar{\nu}$

- $K \to \pi\nu\nu$ modes are as "golden" as $B^0 \to J/\psi K_S$ (for theorists only):
  - — Box and Z penguin, dominated by top
  - — No long-distance or high-order EW corrections
  - — Hadronic matrix element can be extracted from measurement of $K^+ \to \pi^0 e^+ \nu$
  - — Eventually, very small theory error on SM BR:
    - $\pm$1–2% for $K^0_L \to \pi^0\nu\bar{\nu}$
    - $\pm$7% $K^+ \to \pi^+\nu\bar{\nu}$ (due to charm in loop), could come down to $\pm$2% with NNLO calculation



- Accurate measurements of both BRs can be used to cleanly determine UT
  - — Independent of B decay measurements
  - — Can get "sin(2β)" to $\pm$0.05 with σ(BR)/BR=10%
- Very rare decays, SM BR of order 10^{-10}
  - — Sensitive to NP

    … but very challenging experimentally !!!

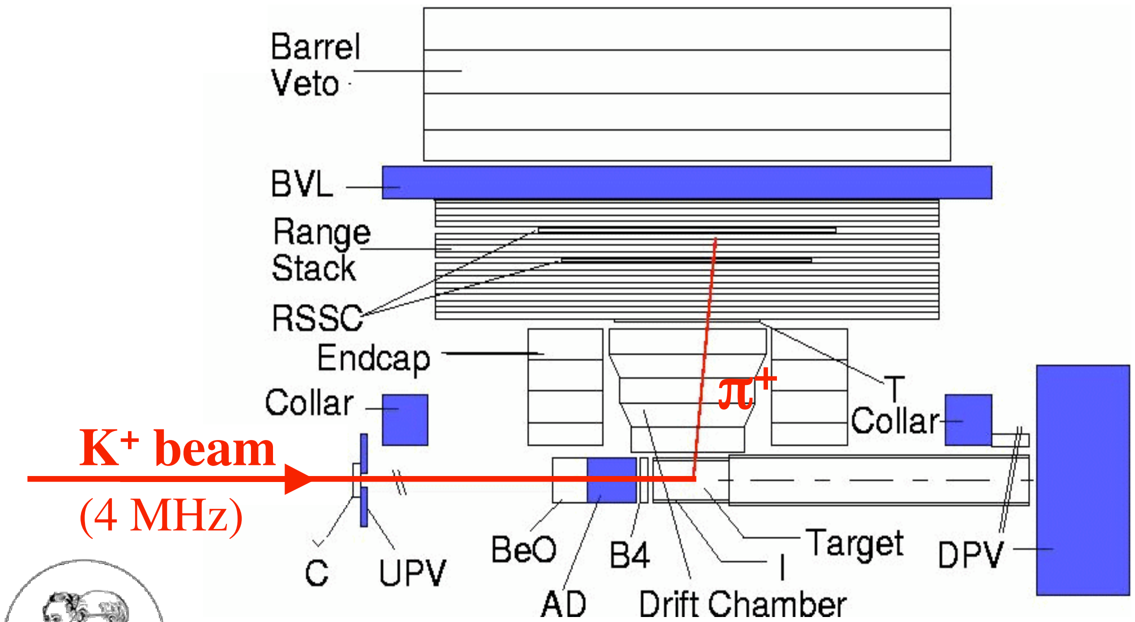


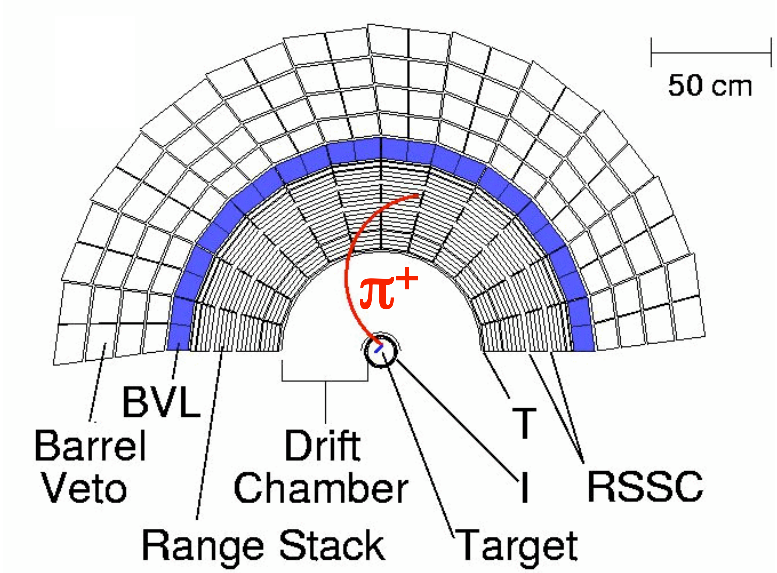
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ at E787/E949 (BNL AGS)

- E787 (run →1998) + E949 upgrade (run in 2002)

ended prematurely after 20% of proposed exposure

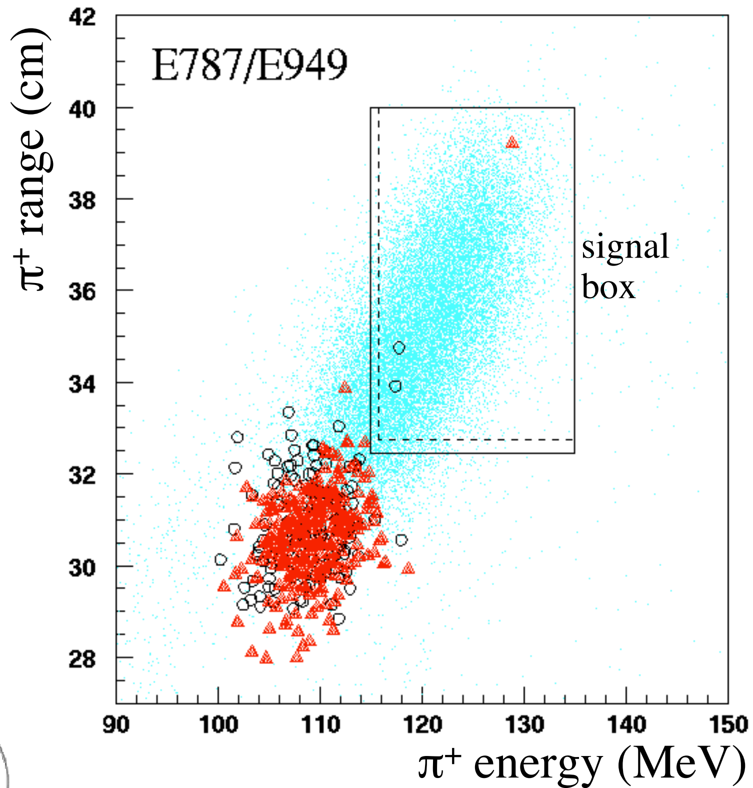
- $(5.9+1.8)\times 10^{12}$ charged kaons stopped in scintillating fiber target
  - Identify incident kaon by Cherenkov, tracking and dE/dx
  - Identify charged pion by momentum, energy and range measurements + subsequent decay of pion at rest ($\pi\rightarrow\mu\rightarrow e$)
  - Veto any other activity (e.g. photons in calorimeter from $K^+ \rightarrow \pi^+\pi^0$)

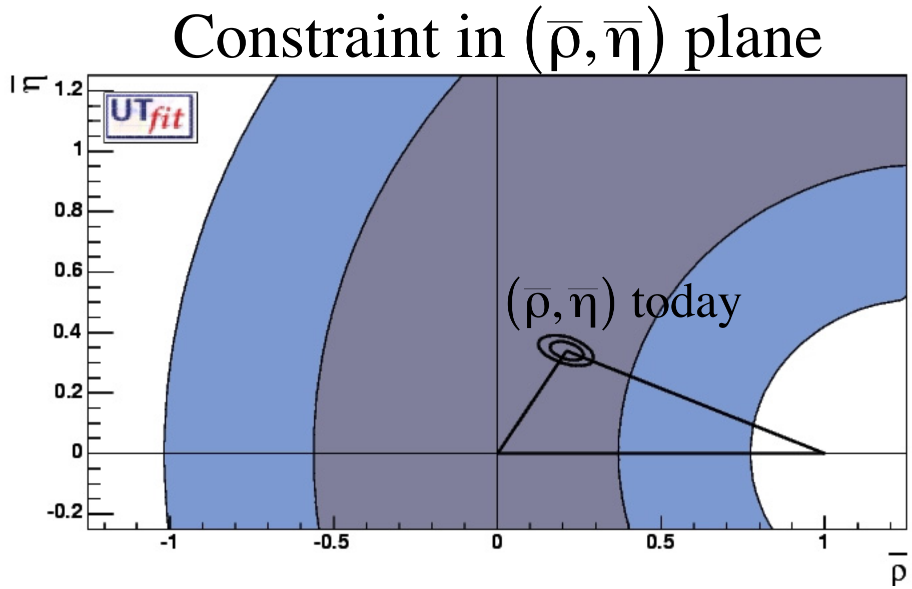




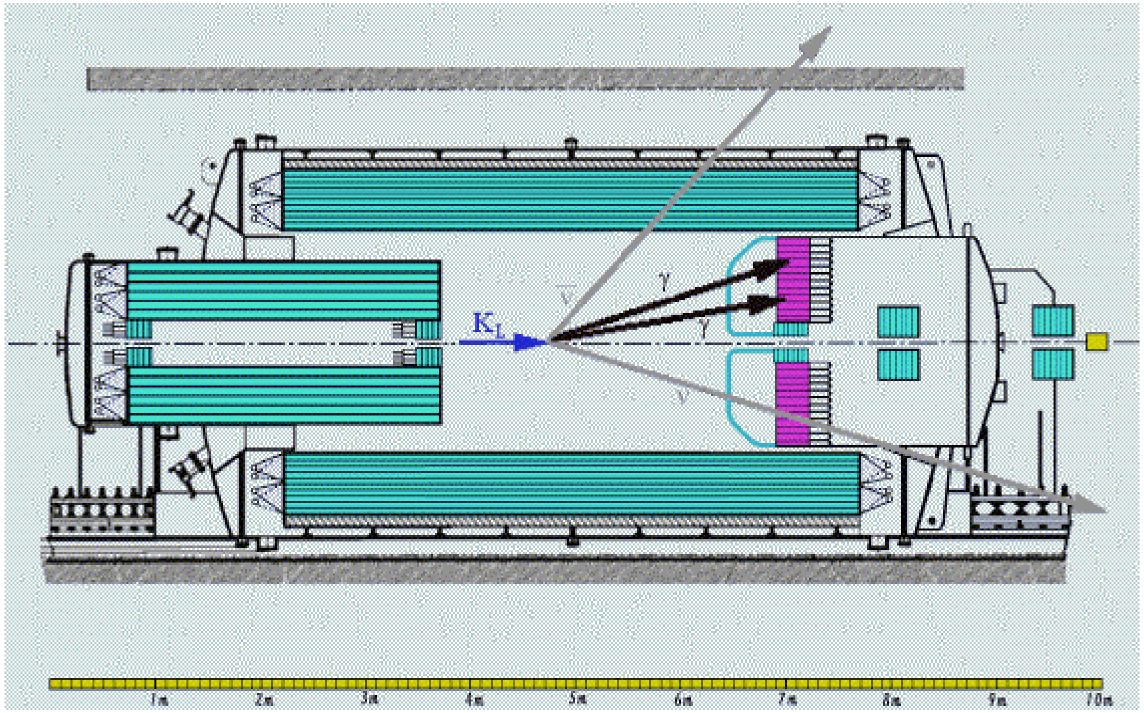
$K^+ \to \pi^+\nu\bar{\nu}$ at E787/E949 (BNL AGS)

- E787+E949 observed 2+1 events:
  - 0.14+0.30 estimated background events (mainly from $K^+ \to \pi^+\pi^0$)
  - $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.47{+1.30}{-0.89}) \times 10^{-10}$ (PRL 93, 031801 (2004))
  - Consistent with SM $(0.78 \pm 0.12) \times 10^{-10}$ (Buras et al, hep-ph/0405132)





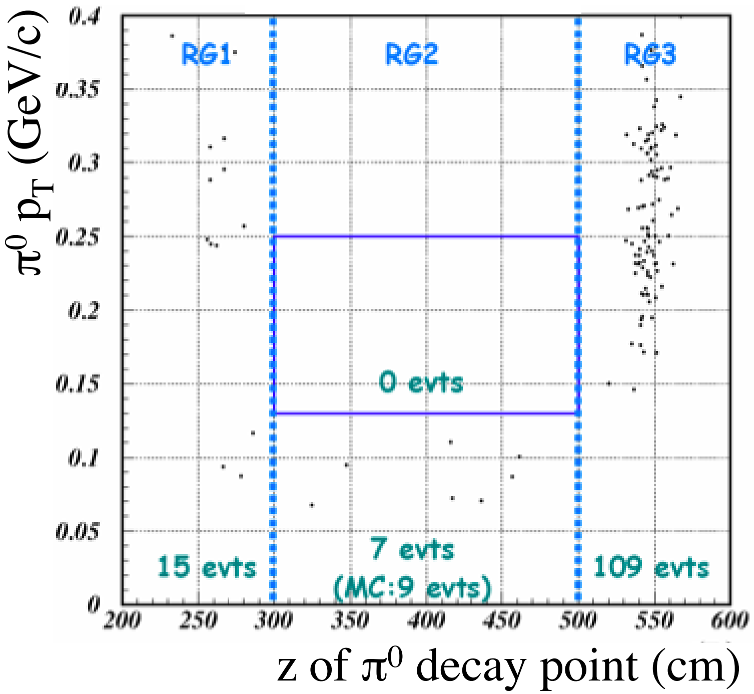
$K^0_L \to \pi^0 \nu\bar{\nu}$ at E391a (KEK PS)



- First dedicated experiment to search for $K^0_L \to \pi^0\nu\nu$
  - K_L decays in flight (from pencil beam)
  - Detect 2 photons
  - Reconstruct $\pi^0 \to \gamma\gamma$ decay point assuming π^0 mass
  - Require missing p_T and π^0 decay point in fiducial volume
- Run periods: Feb–Jul 2004, Feb–Apr 2005, fall 2005

$K^0_L \to \pi^0\nu\bar{\nu}$ at E391a (KEK PS)

- Preliminary result from 1 week of data
  - only 10% of nominal acceptance (due to severe background problem, now fixed)
  - $BR(K^0_L \to \pi^0\nu\bar{\nu}) < 2.86 \times 10^{-7}$ at 90% CL
    - Previous limit was 5.9×10^{-7} from KTeV using $\pi^0 \to ee\gamma$
- Goal with 2005 run is 10^{-9} sensitivity
  - SM $BR = (3.0 \pm 0.6) \times 10^{-11}$ (Buras et al, hep-ph/0405132)



- E391a is a pilot experiment for a more ambitious project (better than 10^{-13} sensitivity) to be proposed at JPARC
  - Plan to submit proposal by end of 2005

JPARC

JPARC = Japan Proton Accelerator Research Complex (JAERI-KEK joint facility)

- Construction:
  - Budget started in 2001
  - Particle physics facilities planned to be ready in 2008
- Letters of intent for "day 1" experiments at 50 GeV synchrotron:
  - $K^+ \rightarrow \pi^+\nu\bar{\nu}$
    - Decay at rest technique à la E787/E949
    - > 50 SM signal events
    - $\sigma(BR)/BR \leq 20\%$
  - $K^0_L \rightarrow \pi^0\nu\bar{\nu}$
    - Upgrade of KEK E391a experiment
    - > 100 SM signal events
    - $\sigma(\eta)/\eta \leq 5\%$

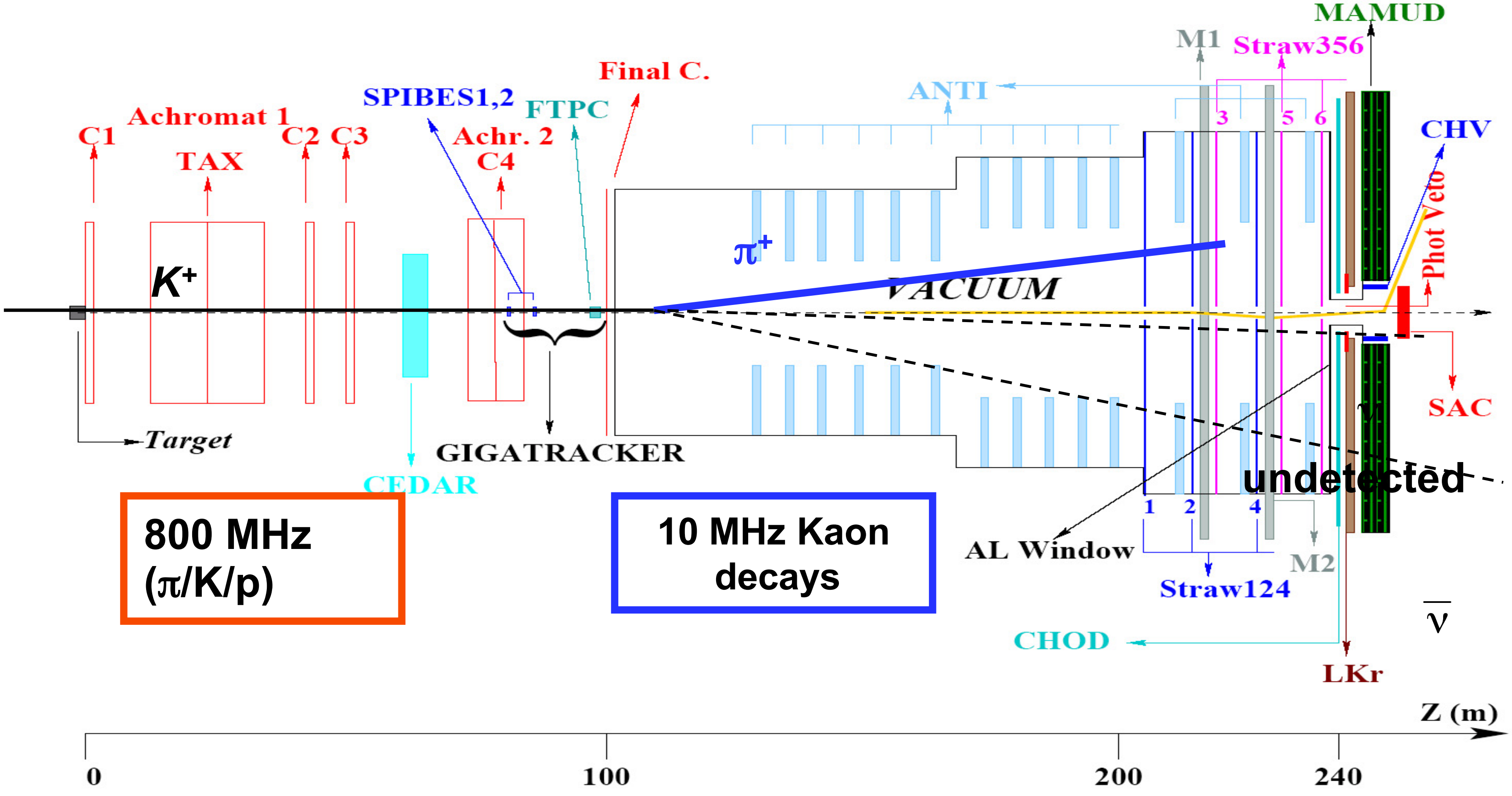
JPARC's 50 GeV synchrotron (June 1, 2005)

NA48/3 proposal (CERN SPS)

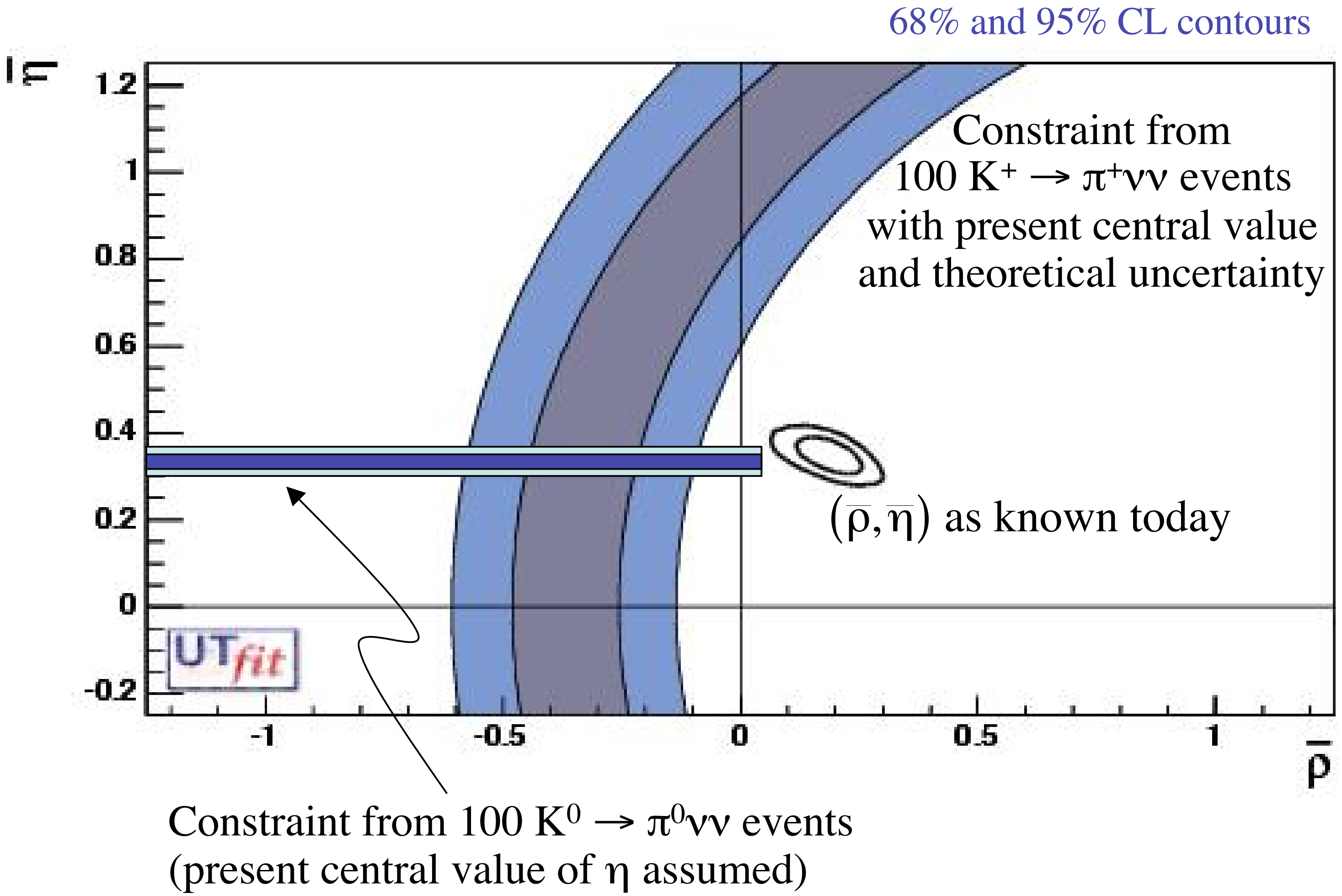
- LoI Oct 2004, proposal June 2005 for measuring BR($K^+ \to \pi^+ \nu\bar{\nu}$)
  - Use 400 GeV/c proton beam from CERN SPS
  - K^+ decays in flight
- Goal:
  - observe 80 signal events (if BR at SM level) with S/B=10 in 2 years
  - 10% measurement of $|V_{td}|$
- Schedule:
  - 2006-2008: construction + installation
  - 2009-2010: data taking

- Longer terms ideas for K physics programme at CERN if more protons can be obtained from SPS:
  - NA48/4: $K^0_L \to \pi^0 e^+ e^-$, $\pi^0 \mu^+ \mu^-$
  - NA48/5: $K^0_L \to \pi^0 \nu\bar{\nu}$

NA48/3 detector layout

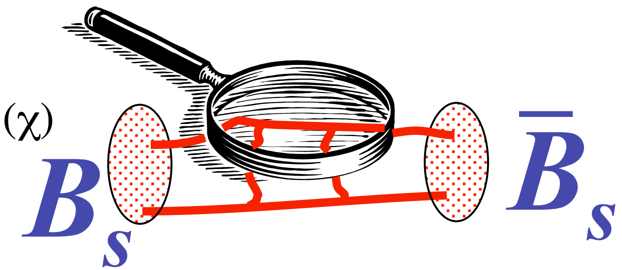


Unitarity triangle from $K \to \pi\nu\bar{\nu}$ in 2012

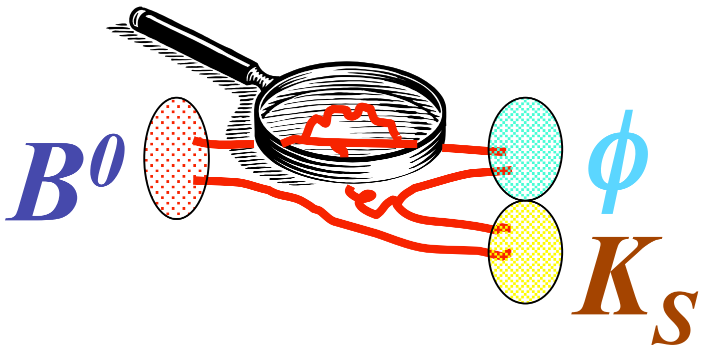


Summary

- Coming soon:
  - Charm factories:
    - Key contribution to help reducing uncertainties on γ extraction and LQCD predictions
  - Tevatron:
    - Potential to exclude SM range for Δm_s
  - LHC(b):
    - Δm_s well beyond SM level and B_s mixing phase up to SM level (χ)
    - $B_s \to \mu\mu$ up to SM level
    - Exclusive $b \to s\gamma$, $b \to s l^+ l^-$
    - Many measurements of γ (and α) with ~ 10° precision in 10^7 sec
    - …



- And, further down the line, pending approval:
  - Super B:
    - $b \to s$ penguins
    - Inclusive $b \to s\gamma$, $b \to s l^+ l^-$, $b \to d\gamma$, $b \to d l^+ l^-$
    - α, β, γ to ~1° precision (in 2020)
    - Lepton flavour violation with τ decays
    - …
  - Experiments at JPARC+ CERN:
    - Ultimate measurement in K sector: $K \to \pi\nu\bar{\nu}$ up to SM level



Conclusion

- SM CKM picture of CP violation and FCNC processes still OK so far
- New physics effects will be chased in future experiments in hadronic flavour physics and CP violation:
  - A few superb $b \to s$ observables with high sensitivity to NP will become accessible at LHC
  - The proposed SuperB can do many precision measurements with B^0, B^+, D and t decays
  - The proposed kaon experiments have the potential to test the SM as much as done now with B mesons
- This will surely contribute significantly to the overall effort to find physics beyond the SM