Detector status and physics programme of the LHCb Experiment

3rd meeting of the TeV4LHC Workshop
30 April 2005

on behalf of the LHCb Collaboration

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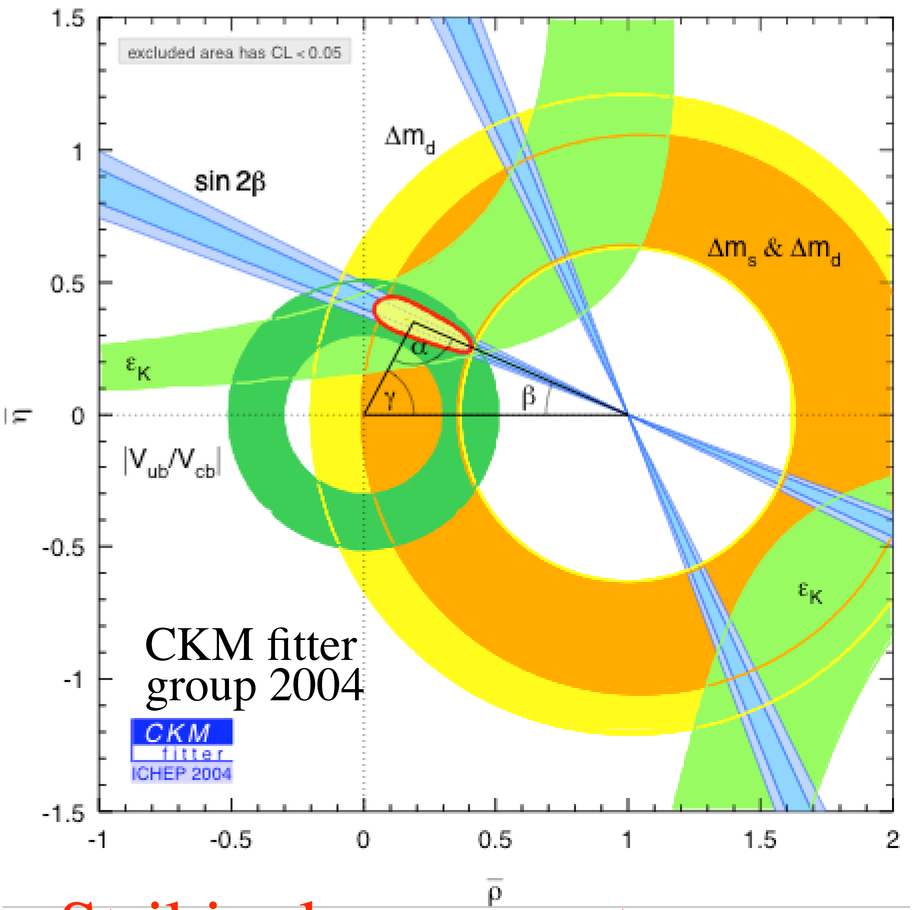
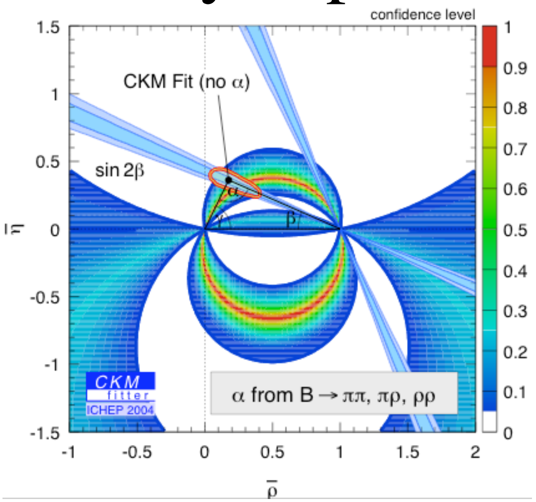
CERN
and
Ecole Polytechnique Fédérale de Lausanne (EPFL)

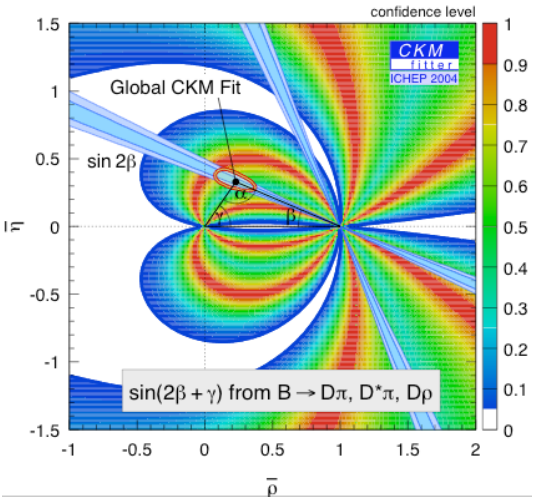
1) Introduction

Impressive progress made by the B-factory experiments

including $\not{CP}$ B and K

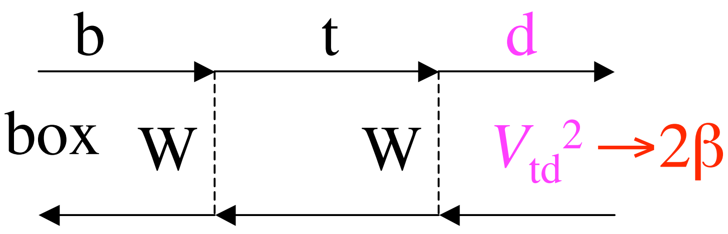






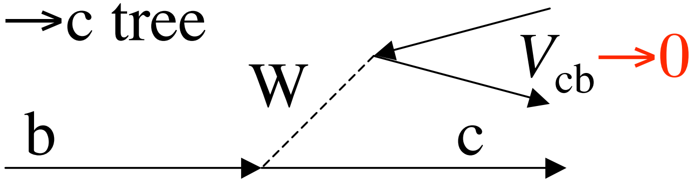
Strikingly apparent agreement with the CKM picture

$\sin(2\beta)_{b\to c} = \sin(2\beta)_{b\to s}$
in the Standard Model



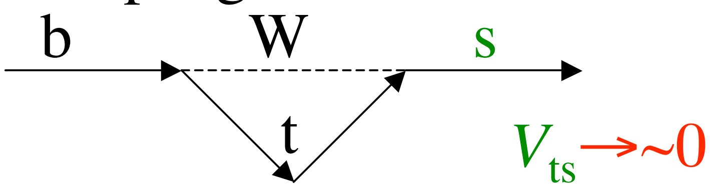
+

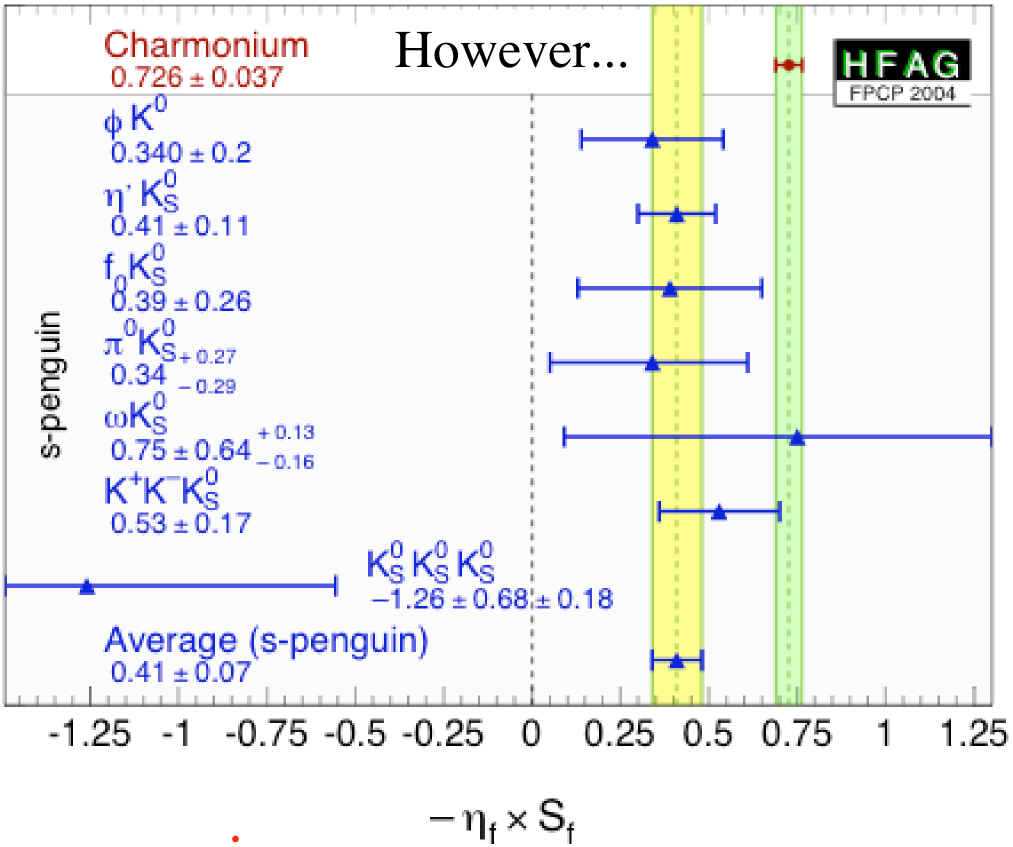
b→c tree



or

b→s penguin





b→s penguin process
has New Physics contribution?

⇓

B_s-$\overline{B}_s$ oscillations could receive a strong non SM contribution

⇒larger Δm_s?

⇒larger CP in $B_s \to J/\psi\ \phi$?

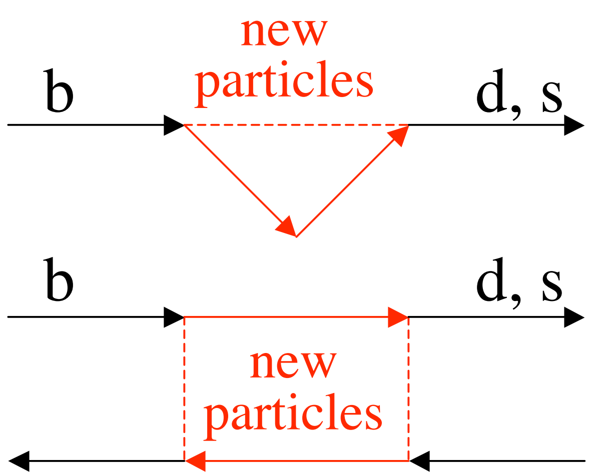
LHCb experiment is only the "currently approved" b physics programme in >2009

Aim to

-$N(\mathrm{B_d} \to \text{interesting charged decay modes})/\text{one year} > \int_{\text{B factories}}^{2008} N(t)\mathrm{d}t$

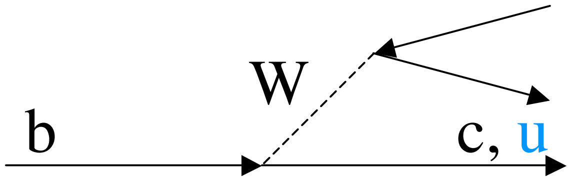
-$\cancel{CP}$ measurements with $\mathrm{B_s}$ as good as possible

Searching for new physics appearing in the loop diagrams



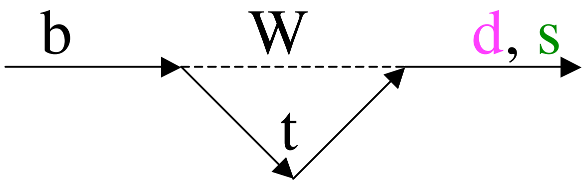
Complementary approach to ATLAS and CMS

Tree
$\Gamma(b \to c)$
$\Gamma(b \to u)$



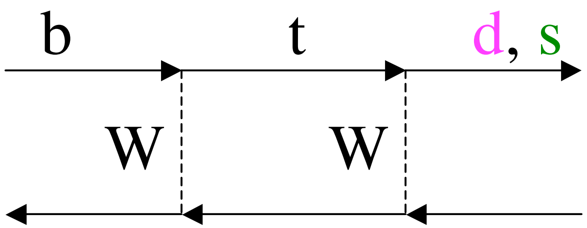
$|V_{cb}|$
$|V_{ub}|$

Penguin
$\Gamma(b \to s)$
$\Gamma(b \to d)$



$|V_{td}|$
$|V_{ts}|$

Box
$\omega(B_d\text{-}\bar{B}_d)$
$\omega(B_s\text{-}\bar{B}_s)$



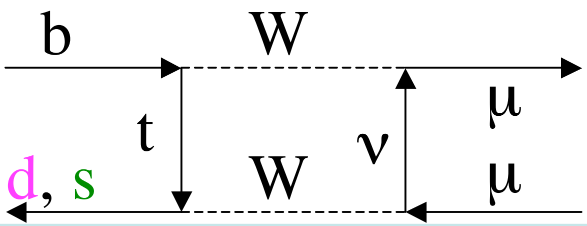
$|V_{td}|$
$|V_{ts}|$

~~C~~P(Tree⊗Box) $2 \arg V_{td}\,(V_{ts}) + \arg V_{cb}\,(V_{ub})$

~~C~~P(Peng⊗Box) $2 \arg V_{td}\,(V_{ts}) + \arg V_{td}$

$2 \arg V_{td}\,(V_{ts}) + \arg V_{ts}$

$\Gamma(B \to \mu\mu)$



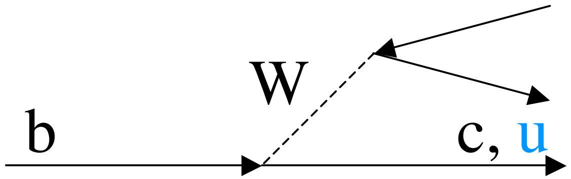
$|V_{td}|$
$|V_{ts}|$

New Physics

Tree

$\Gamma(b \to c)$

$\Gamma(b \to u)$



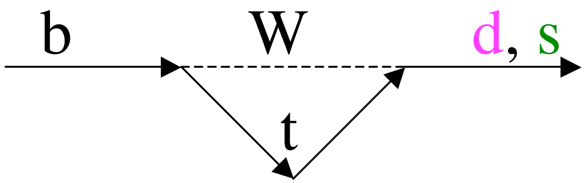
$|V_{cb}|$ unaffected

$|V_{ub}|$

Penguin

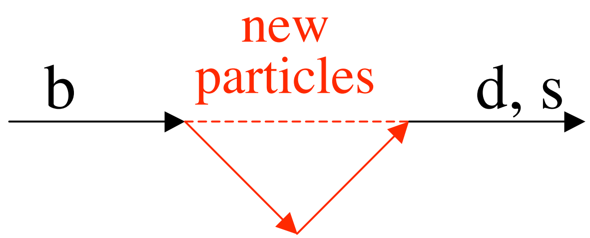
$\Gamma(b \to s)$

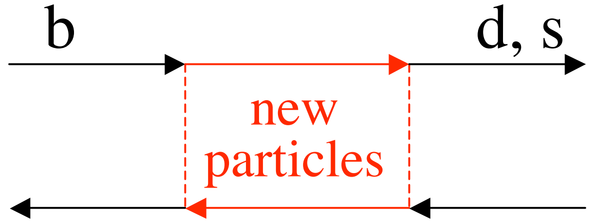
$\Gamma(b \to d)$



$|V_{td}| + \Delta_{peng(d)}$

$|V_{ts}| + \Delta_{peng(s)}$

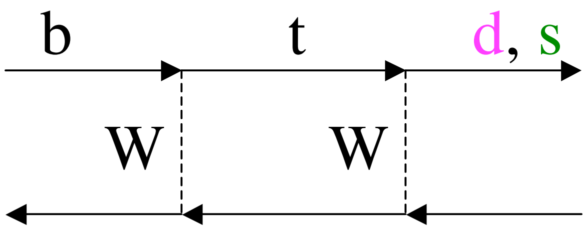




Box

$\omega(B_d\text{-}\overline{B}_d)$

$\omega(B_s\text{-}\overline{B}_s)$



$|V_{td}| + \Delta_{box(d)}$

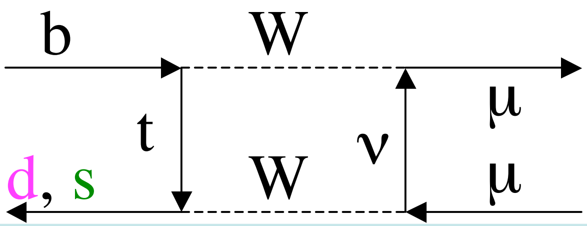
$|V_{ts}| + \Delta_{box(s)}$

$\cancel{\mathrm{CP}}$(Tree⊗Box) $2 \arg V_{td}\,(V_{ts}) + \arg V_{cb}\,(V_{ub}) + \Phi_{box(d)}\,(\Phi_{box(s)})$

$\cancel{\mathrm{CP}}$(Peng⊗Box) $2 \arg V_{td}\,(V_{ts}) + \arg V_{td} + \Phi_{box(d)}\,(\Phi_{box(s)}) + \Phi_{peng(d)}$

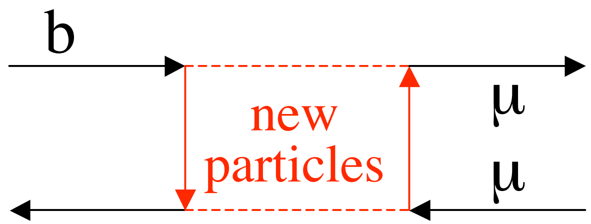
$2 \arg V_{td}\,(V_{ts}) + \arg V_{ts} + \Phi_{box(d)}\,(\Phi_{box(s)}) + \Phi_{peng(s)}$

$\Gamma(B \to \mu\mu)$



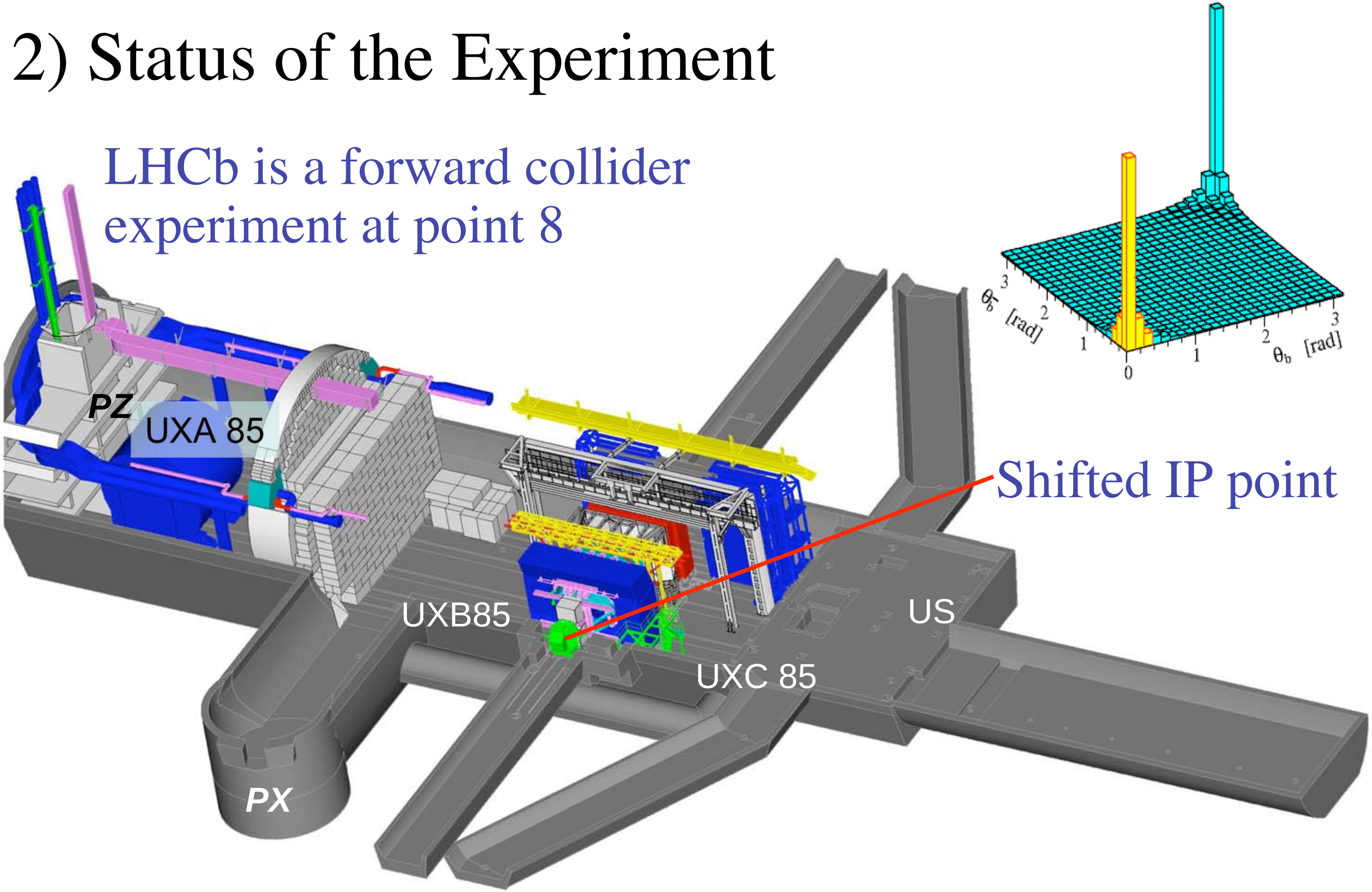
$|V_{td}| + \Delta_{\mu\mu(d)}$

$|V_{ts}| + \Delta_{\mu\mu(s)}$



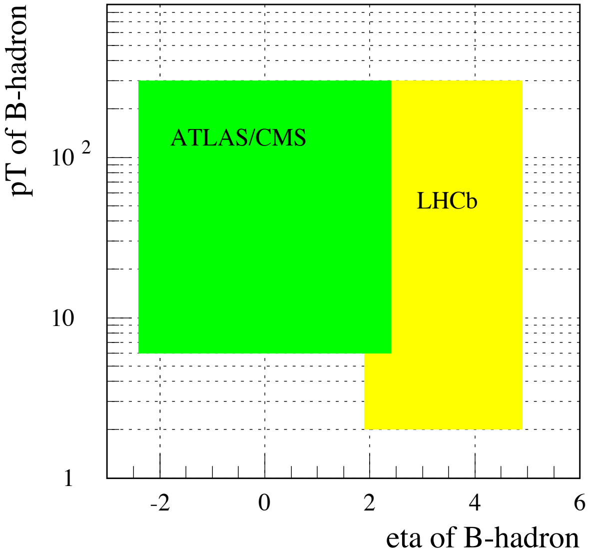
2) Status of the Experiment

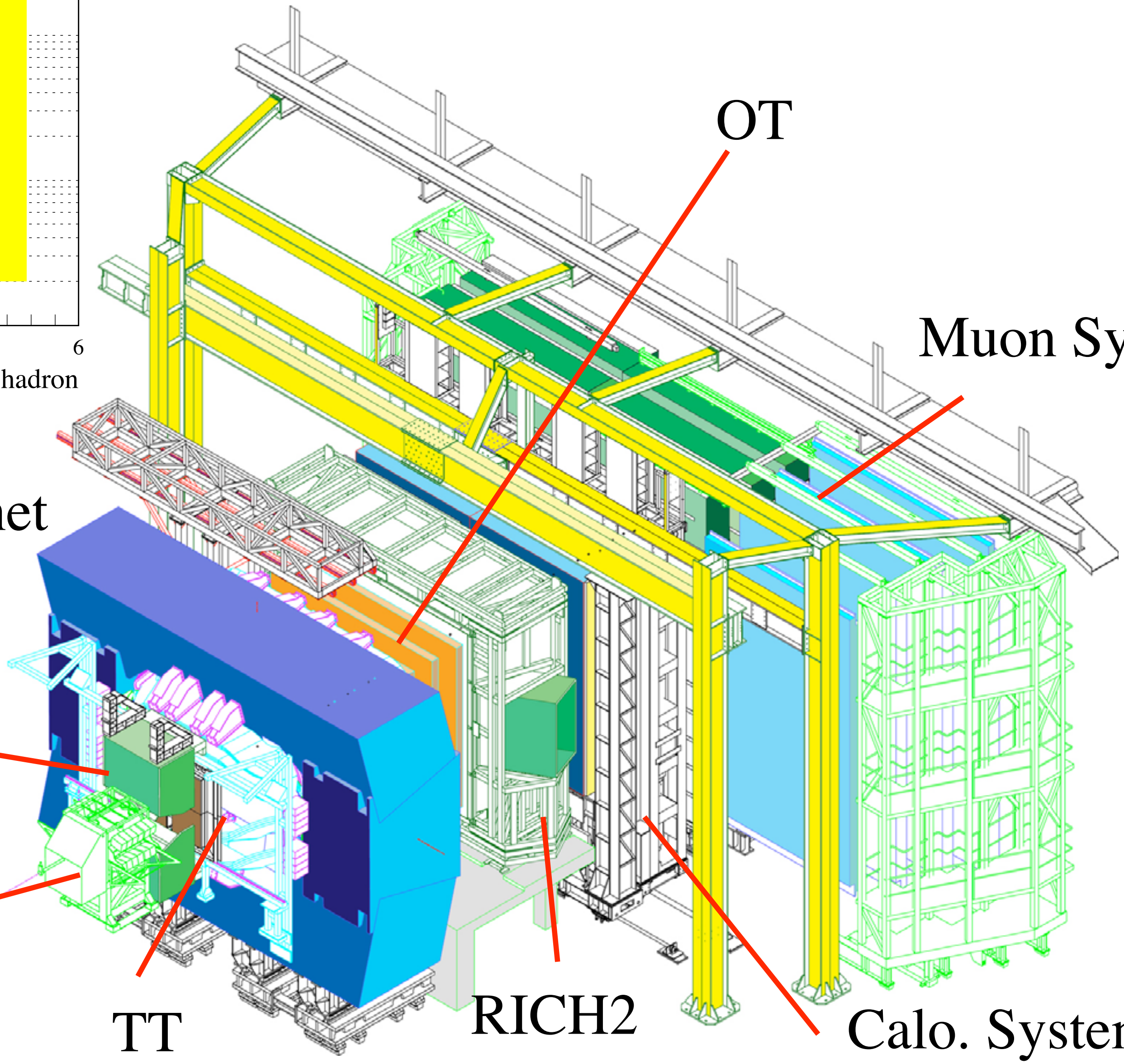
LHCb is a forward collider experiment at point 8



Running at “low” luminosity $\langle L \rangle \sim 2\times10^{32}\ \mathrm{cm^{-2}s^{-1}}$

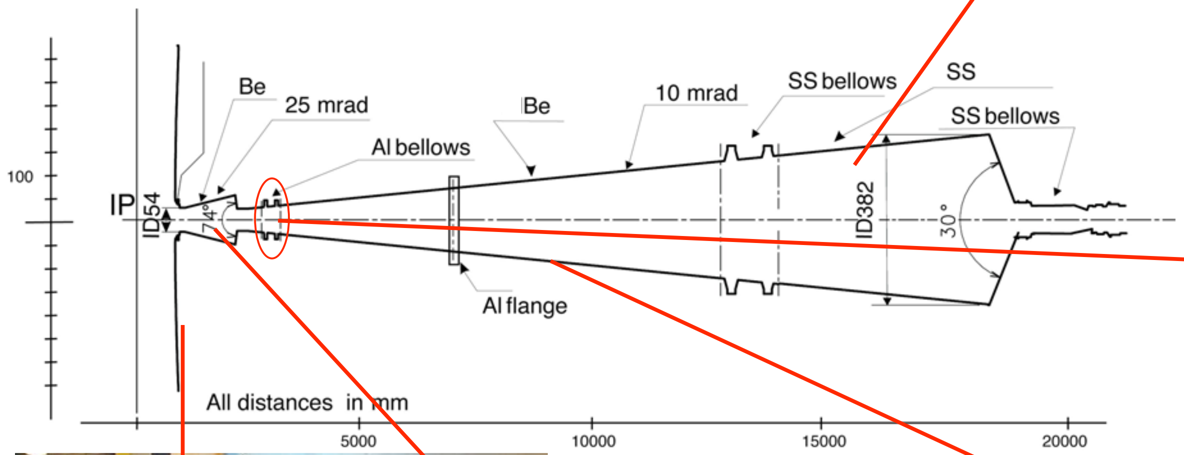
LHCb Spectrometer

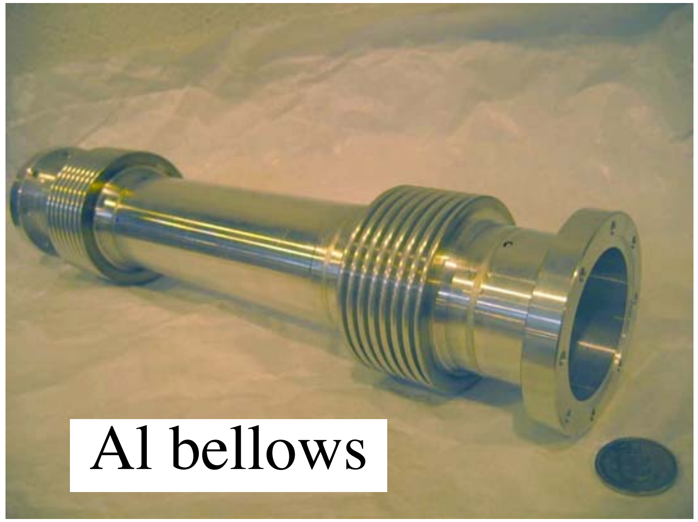




Beam pipe

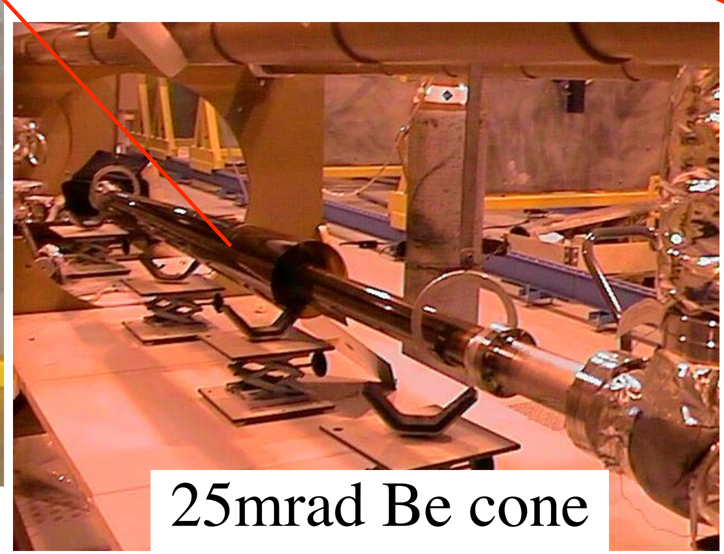
10mrad stainless steel cone





Al bellows

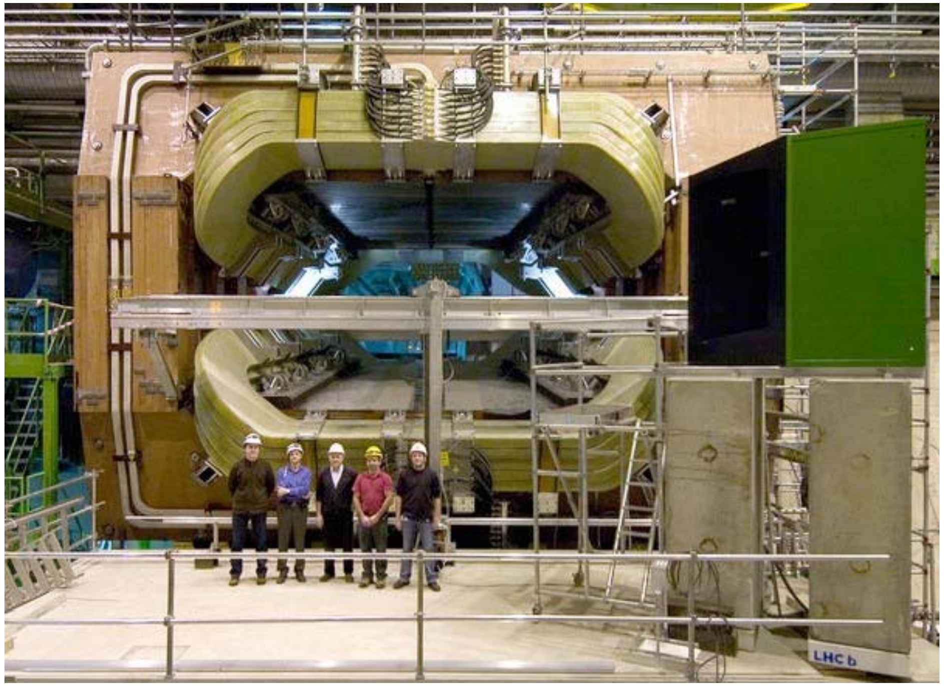
Al exit window
of VELO tank

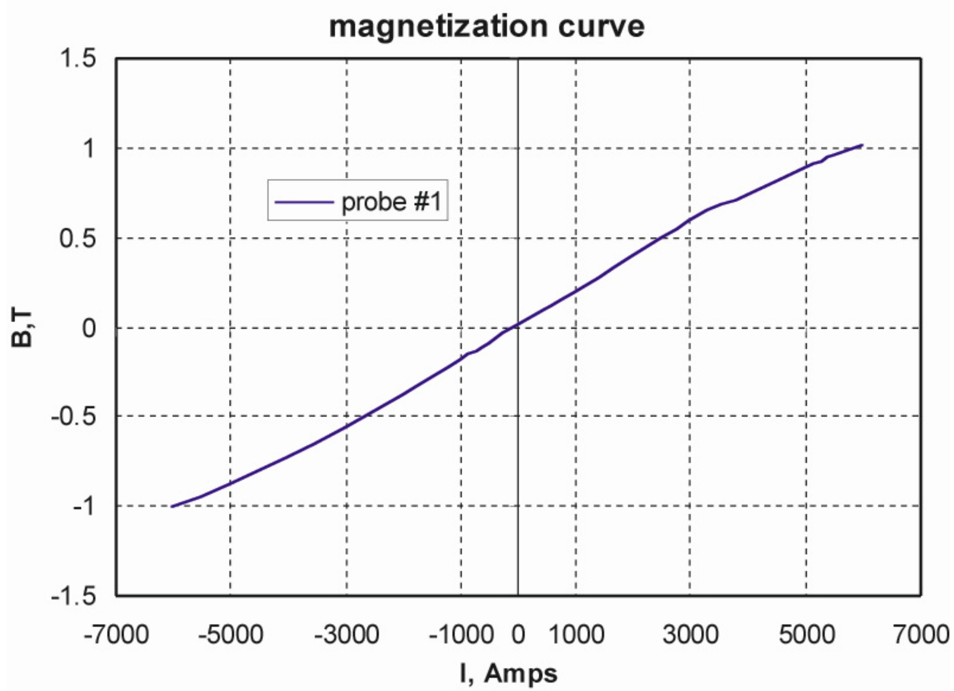


25mrad Be cone

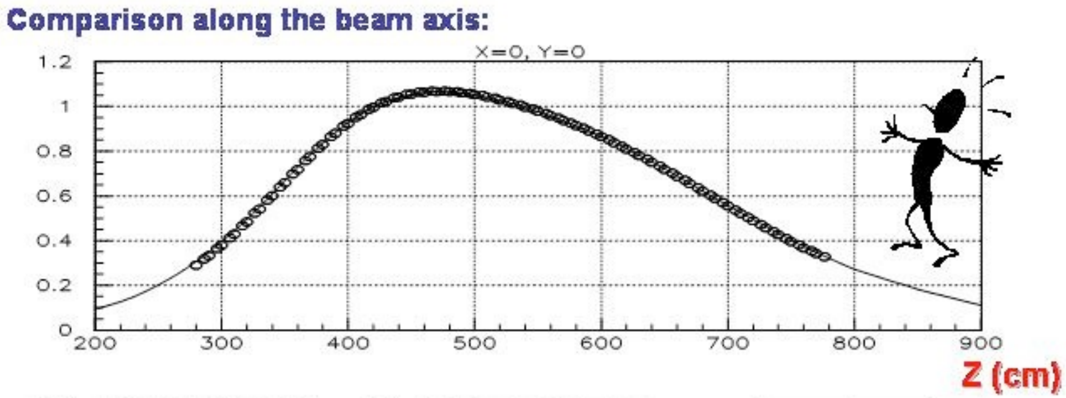
10mrad Be cone
material

Magnet

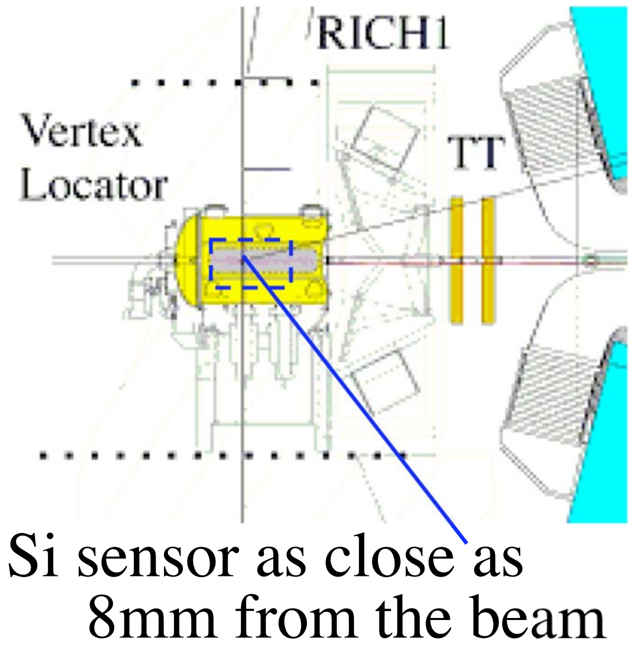


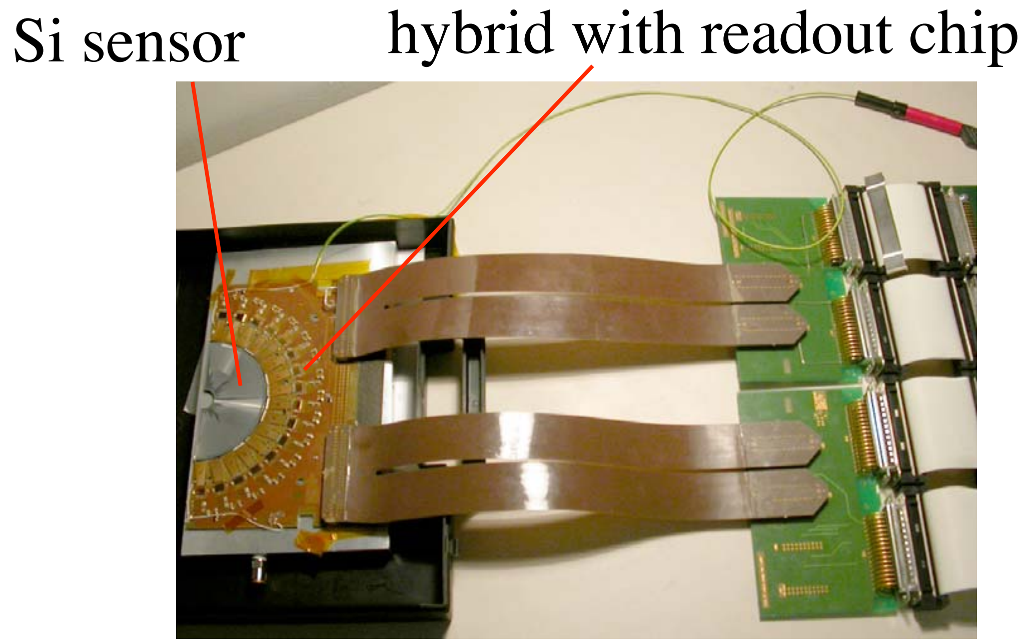


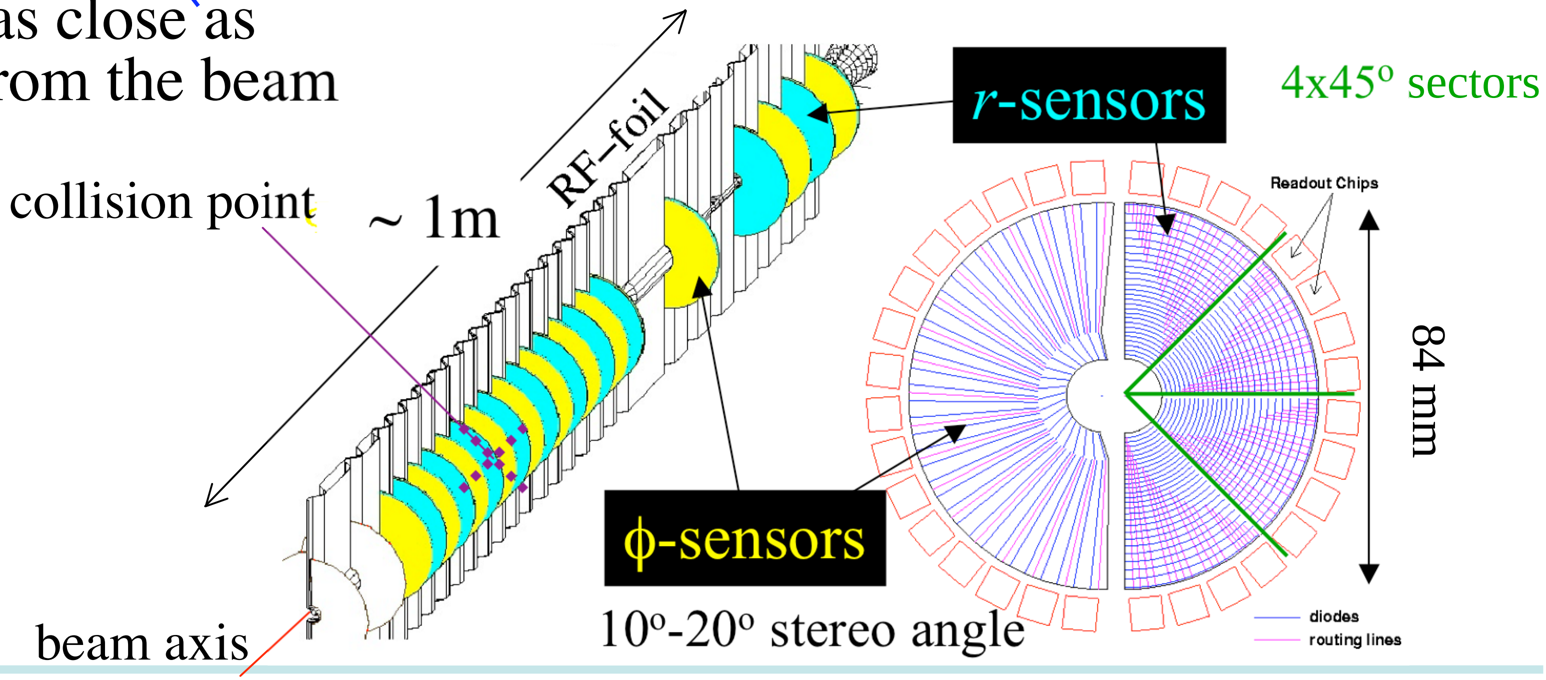
magnet assembled, positioned, aligned and switched on



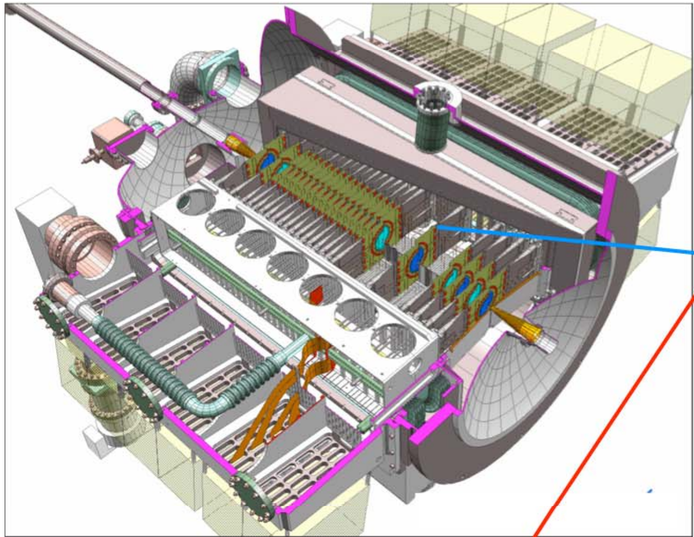
VErtex LOcator

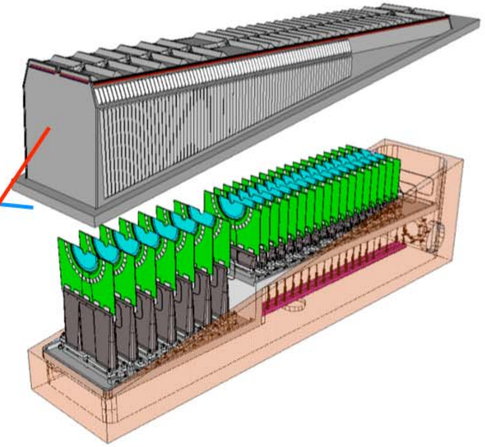




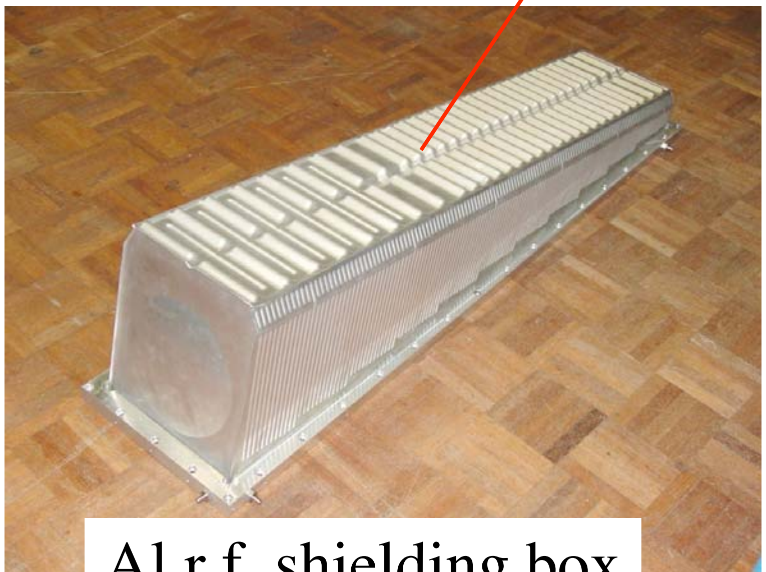


Si in secondary vacuum
with the Roman pot technology

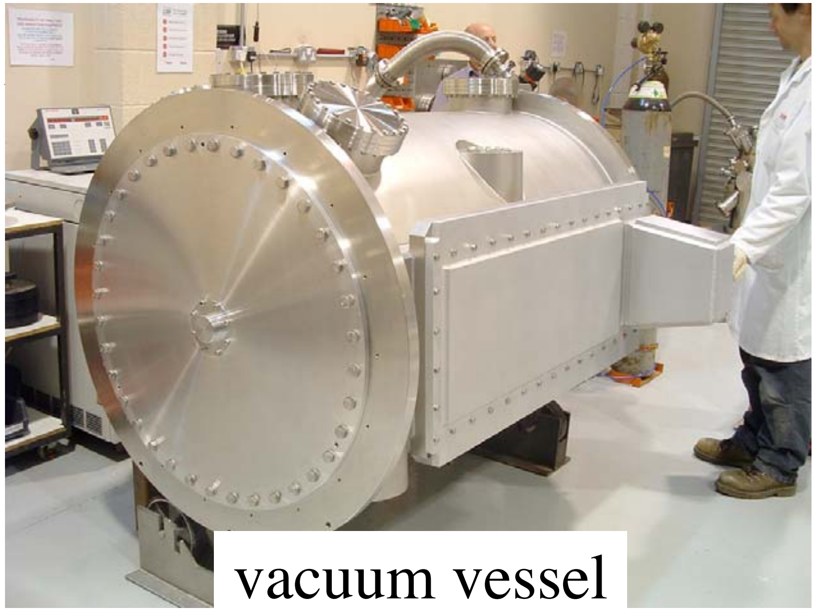




vacuum vessel
support

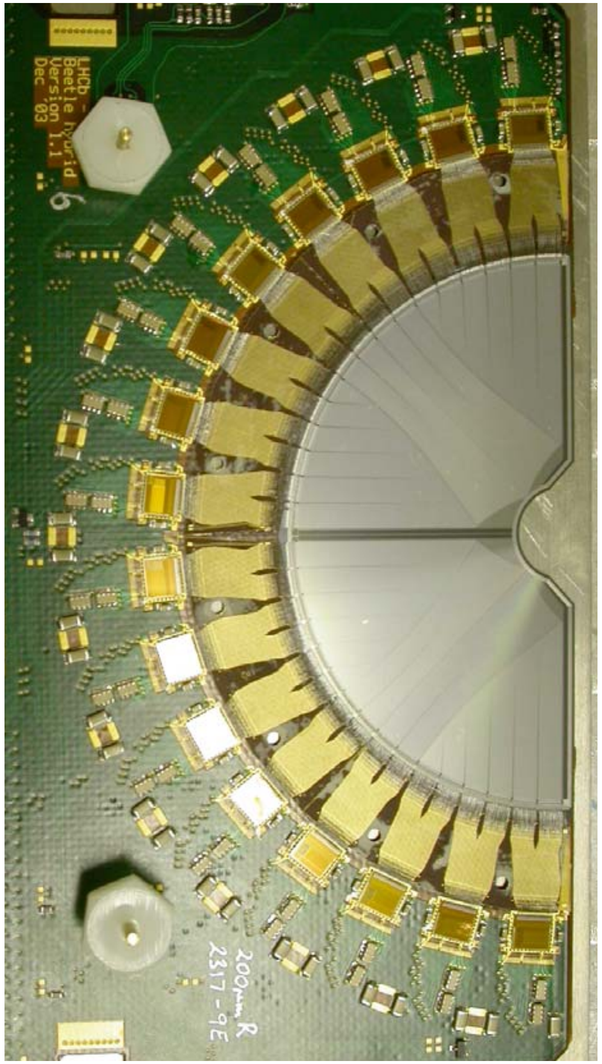


Al r.f. shielding box

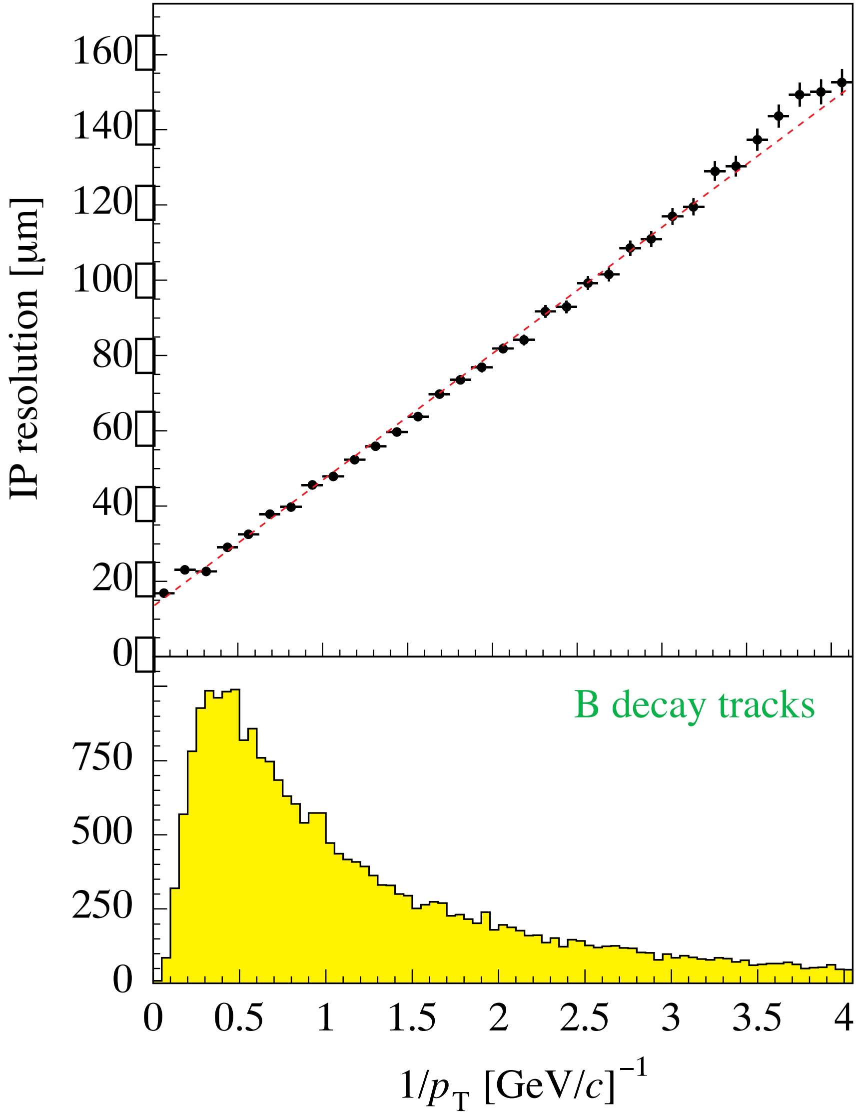


vacuum vessel

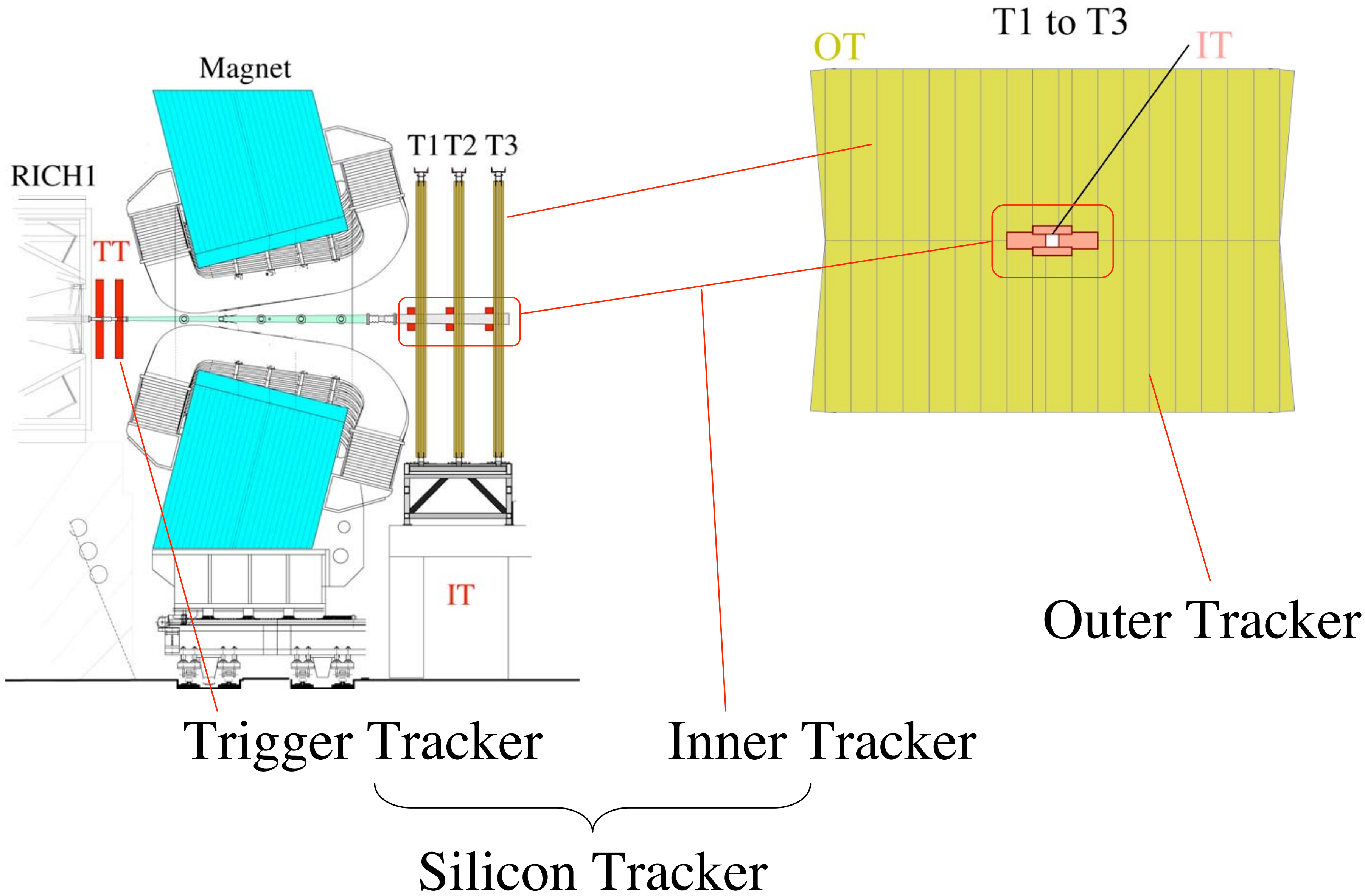
Detector Module



Impact parameter resolution



Outer Tracker and Silicon Tracker

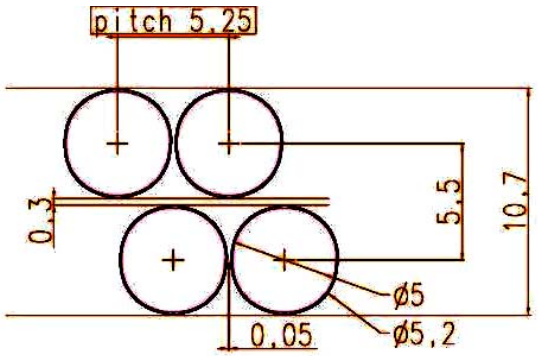


~1.4×1.2 m²

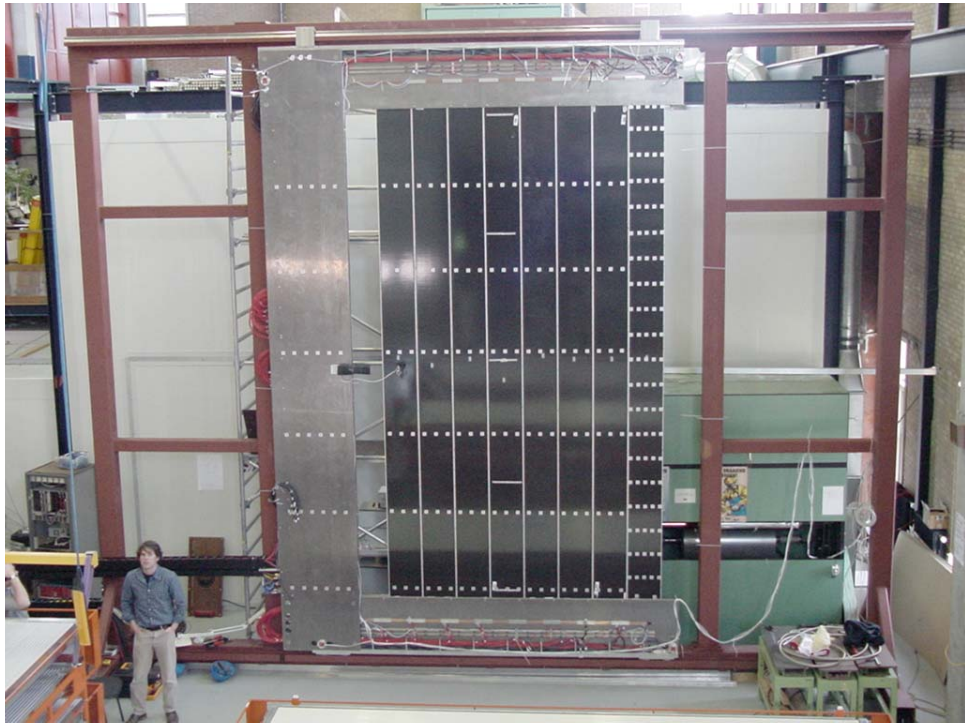
Outer Tracker

Straw drift chambers

40μm Kapton XC-160
+ Laminated Kapton-Al



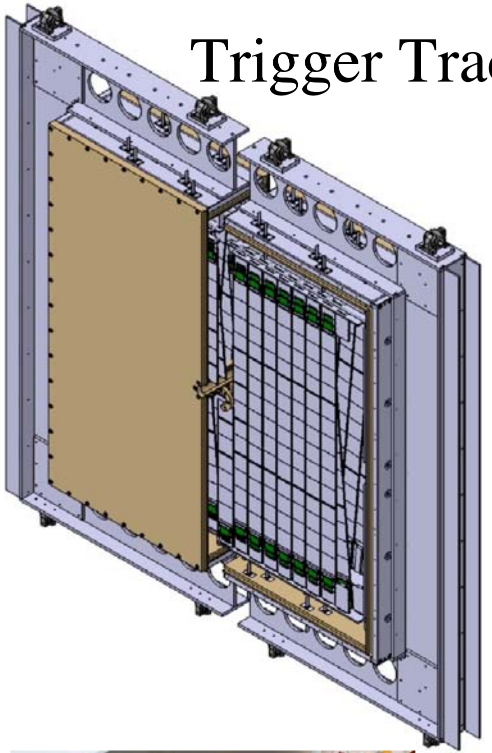
Frame and support structure



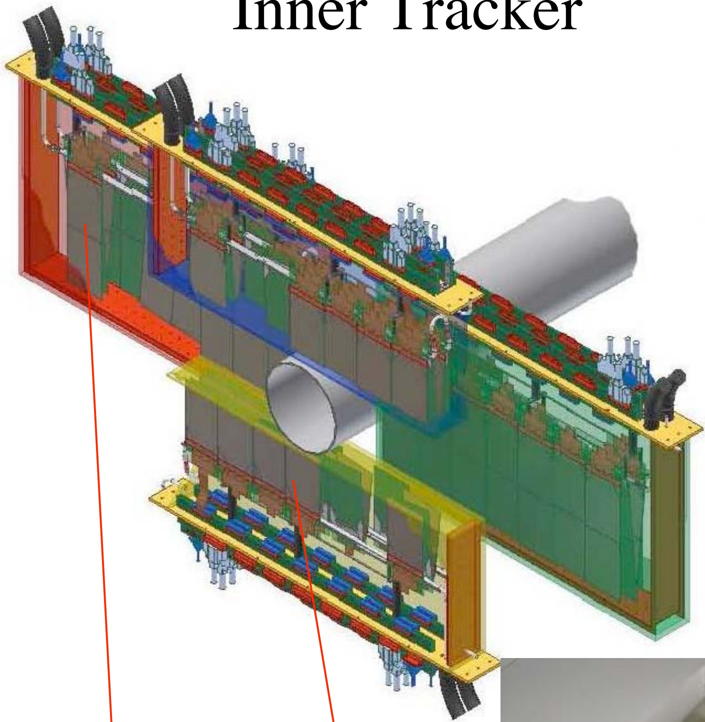
full scale prototype fully loaded

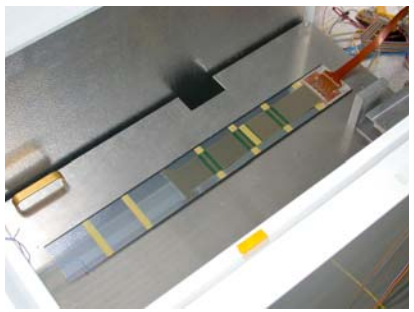
Silicon Tracker

Trigger Tracker



Inner Tracker





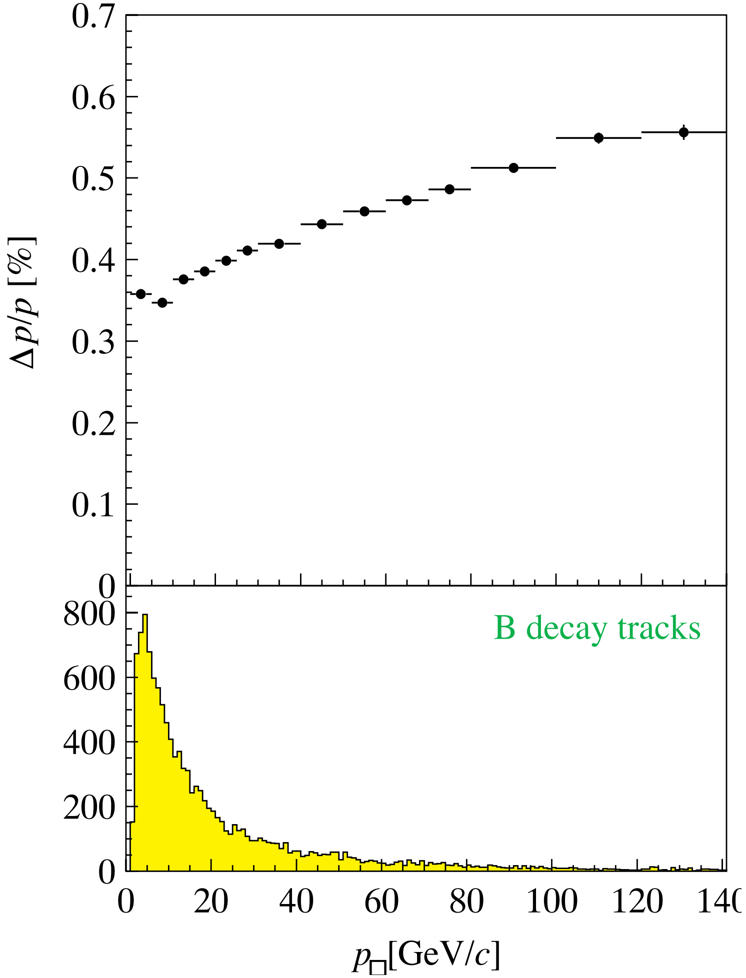
500 μm Si

320 μm Si
410 μm Si

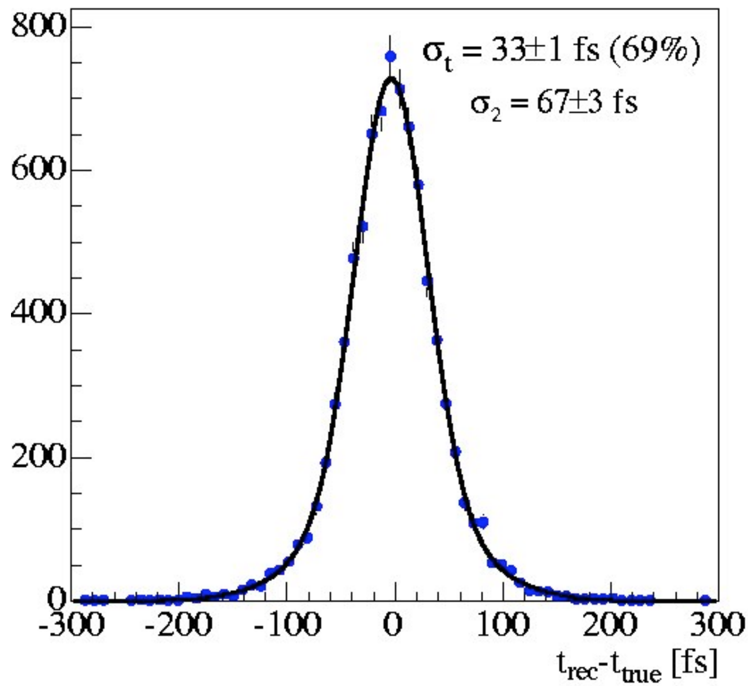
$\sim 130 \times 45\ \mathrm{cm}^2$

$\sim 1.4 \times 1.2\ \mathrm{m}^2$

VELO + ST + OT + Magnet



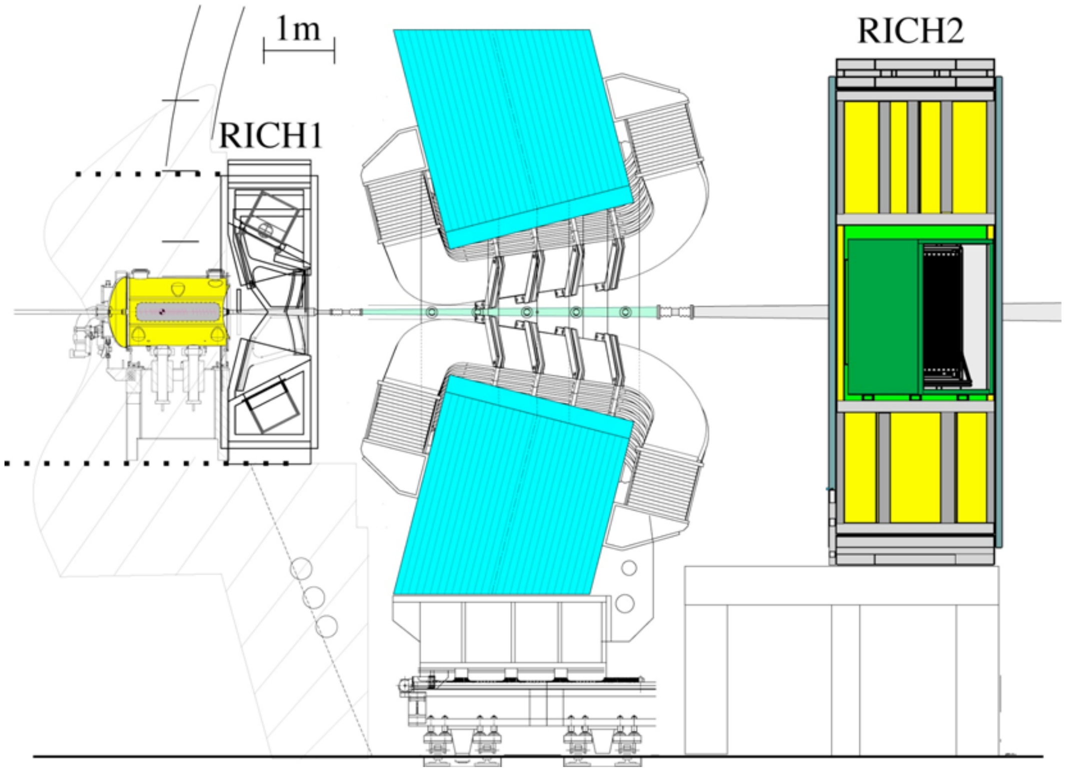
momentum resolution

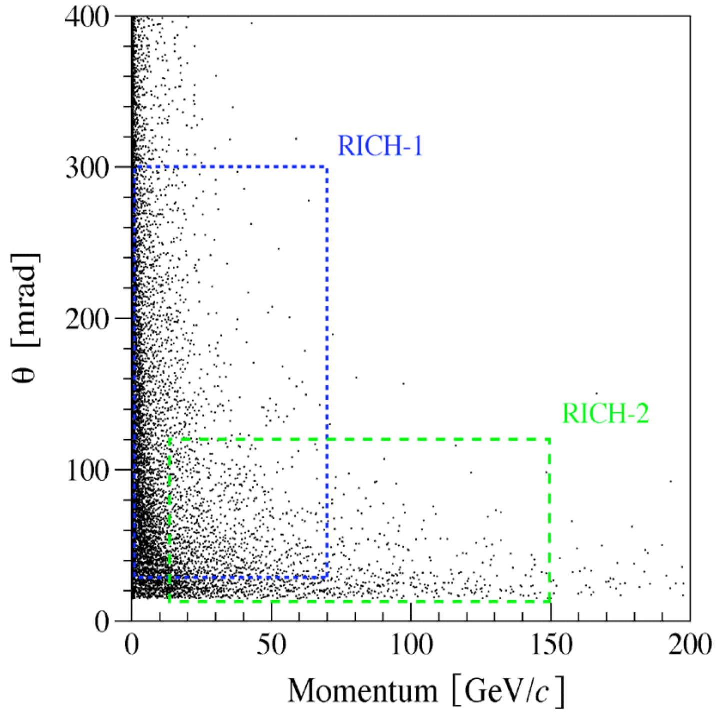


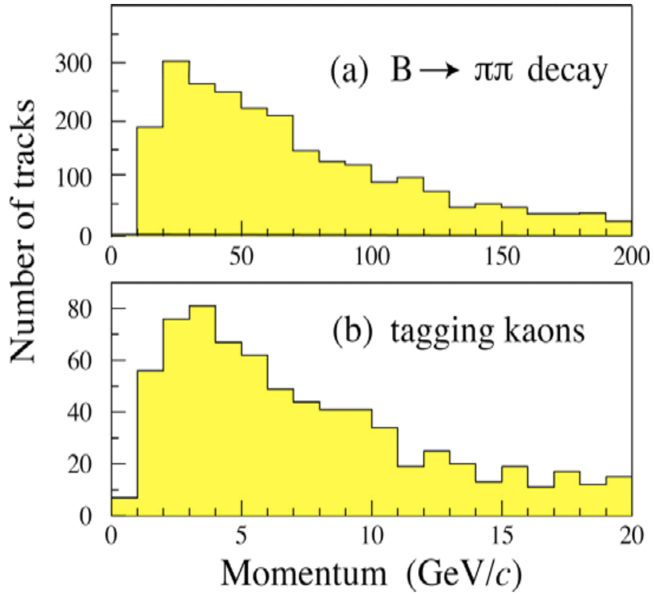
Proper time resolution ~ 40 fs

$B_s \rightarrow D_s^{-}\pi^{+}$

RICH



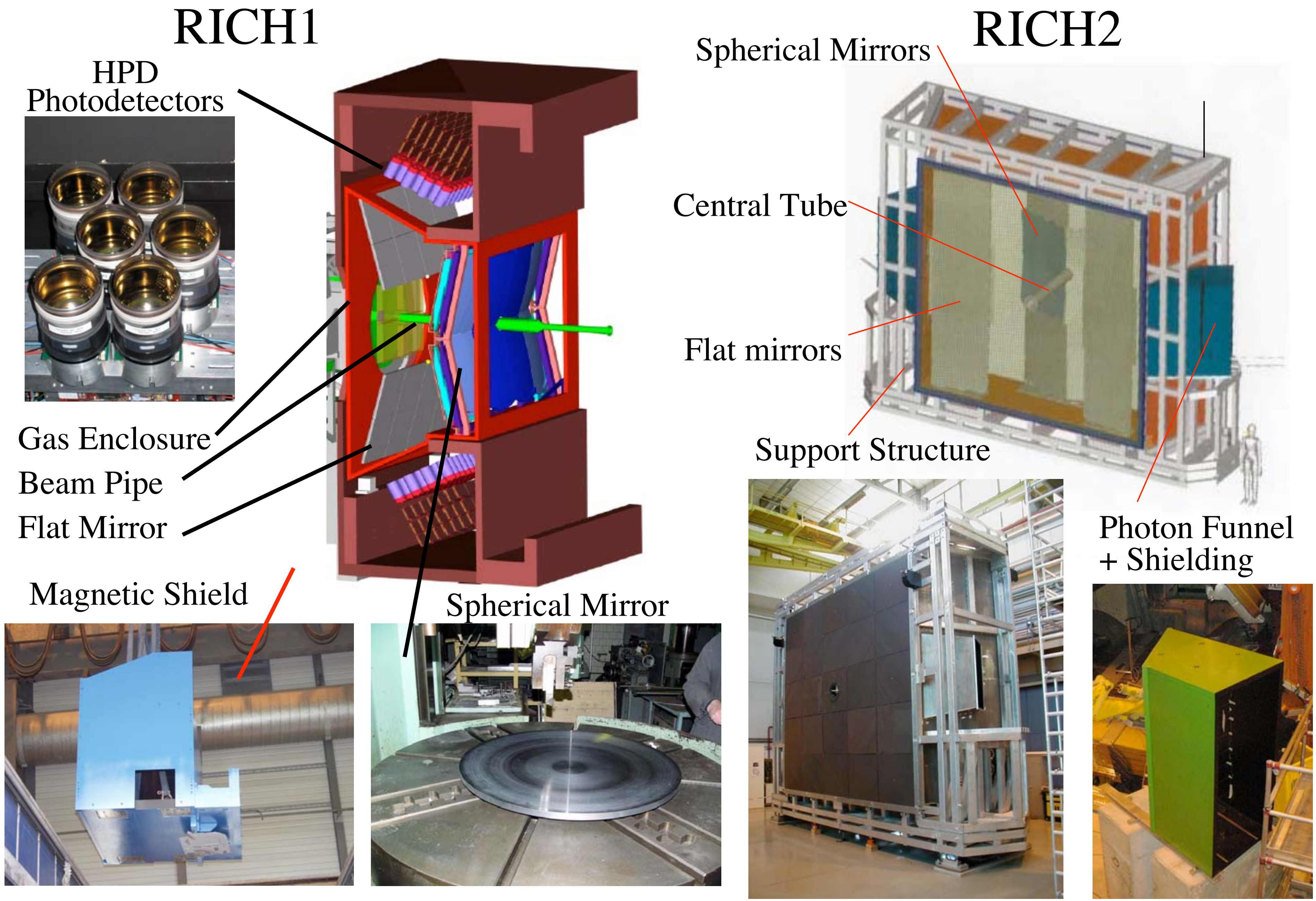




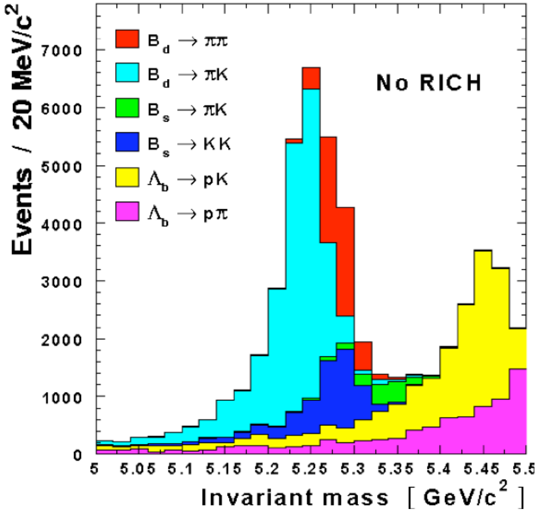
Two RICH with three radiators

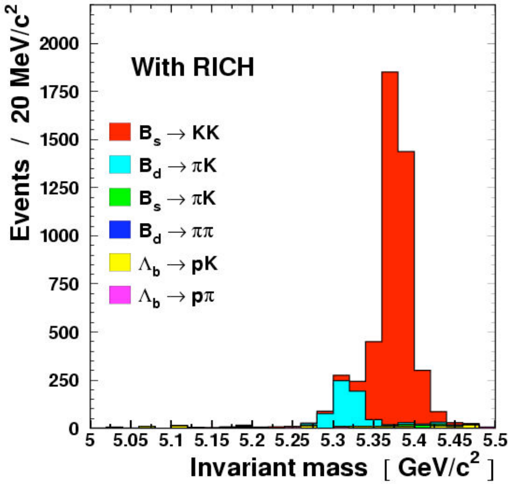
Aerogel, C_4F_{10} } RICH1 (25-300 mrad)

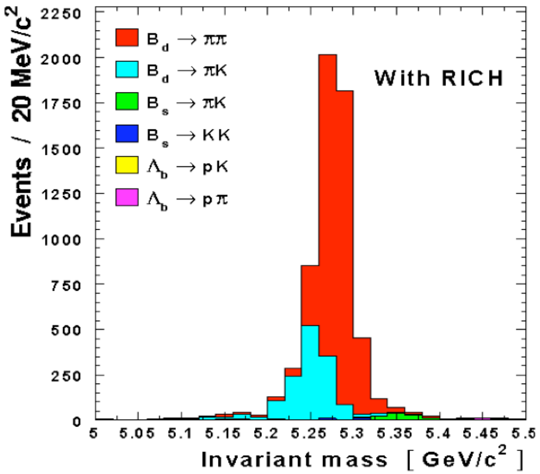
CF_4 RICH2 (15-120 mrad)


RICH1
HPD
Photodetectors
Gas Enclosure
Beam Pipe
Flat Mirror
Magnetic Shield
Spherical Mirror
RICH2
Spherical Mirrors
Central Tube
Flat mirrors
Support Structure
Photon Funnel
+ Shielding

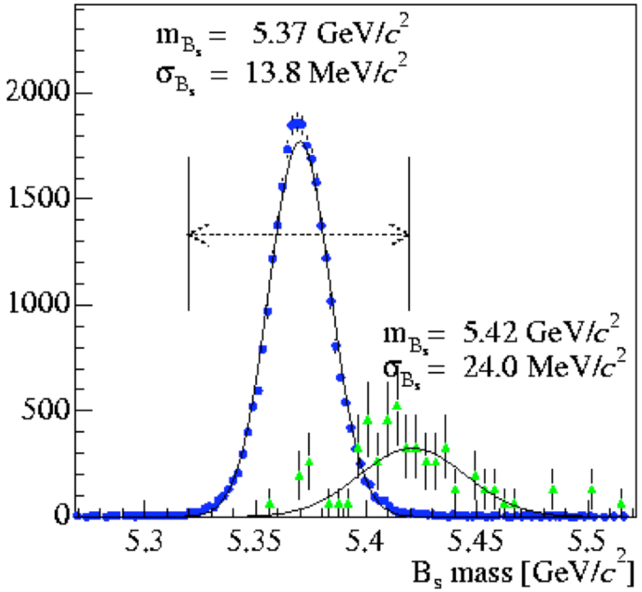
PID for $B \to \pi\pi$ and $B_s \to KK$ reconstruction



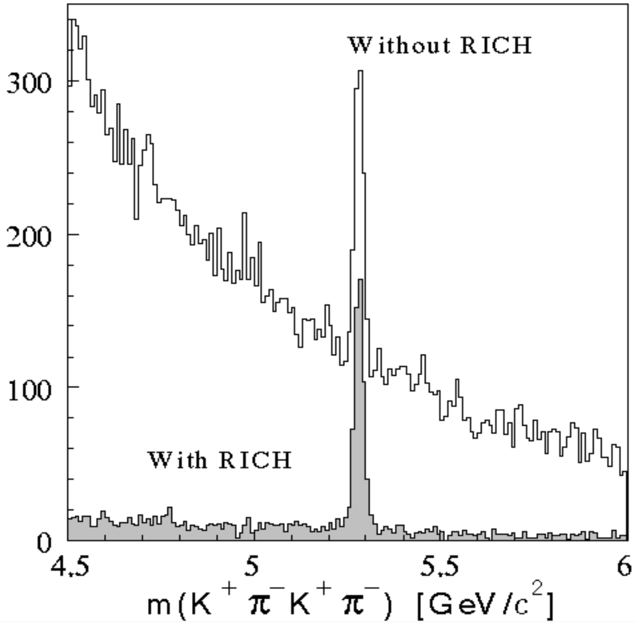




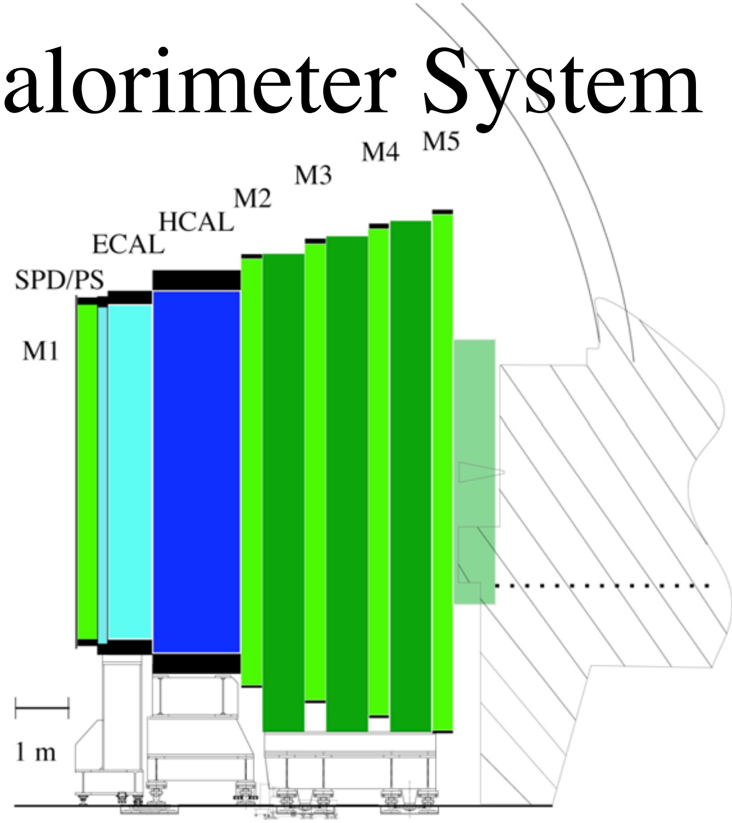
$B_s \to D_s\pi$ suppression with PID for $B_s \to D_sK$



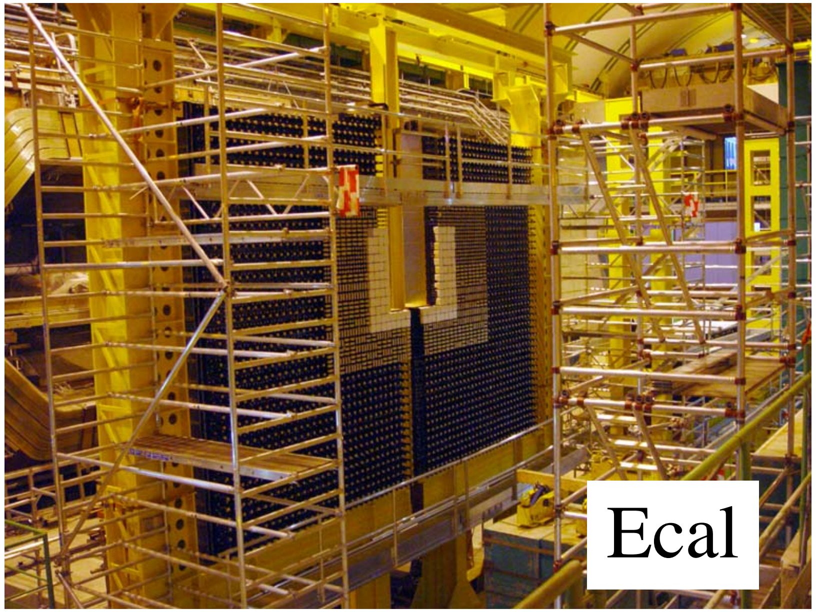
Comb. suppression with PID for $B \to DK^{*0}$

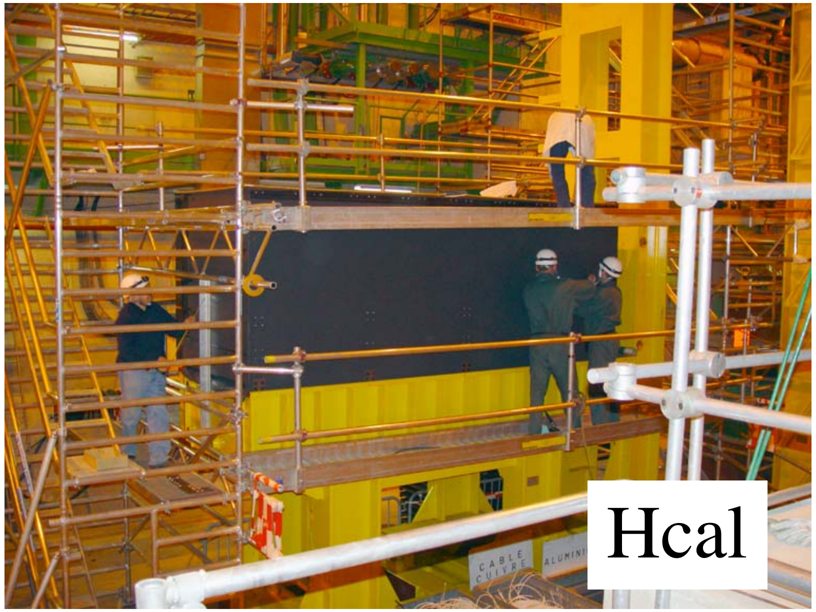


Calorimeter System

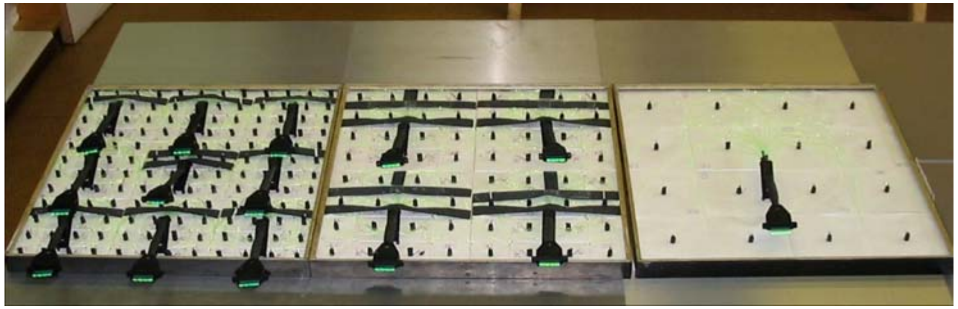


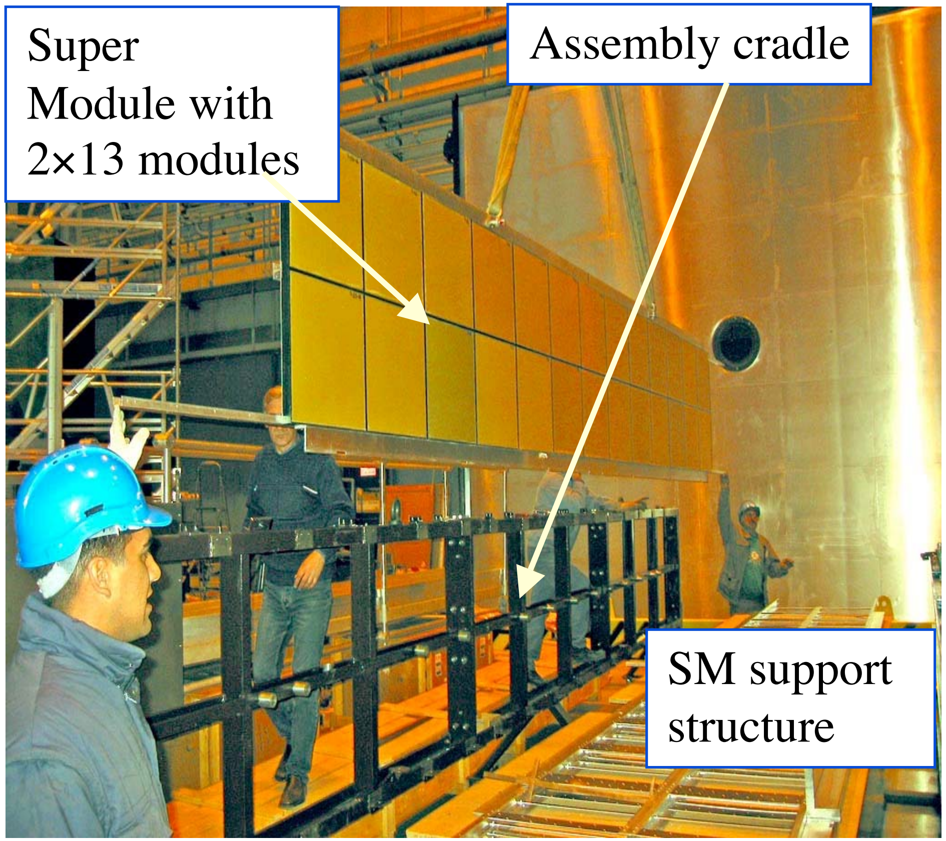
SPD/PS
Scintillator
-Pb-Scintillator
Ecal
Shashlik
Hcal
Fe-Scintillator tile



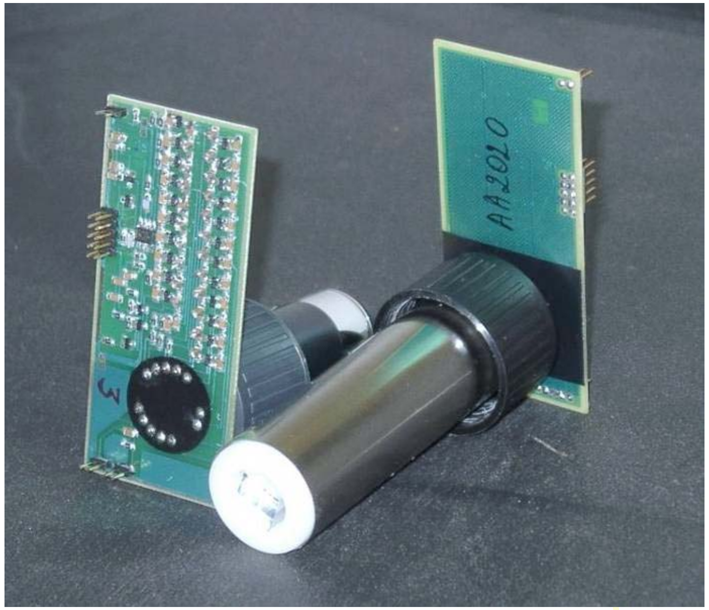


Preshower and SPD

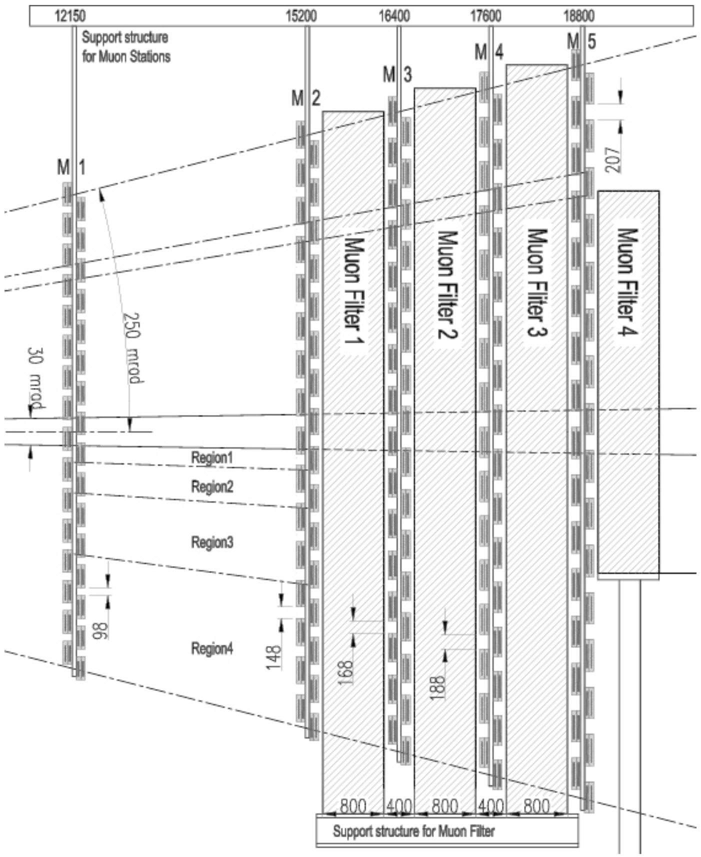




PMT + CW base
for Ecal and Hcal



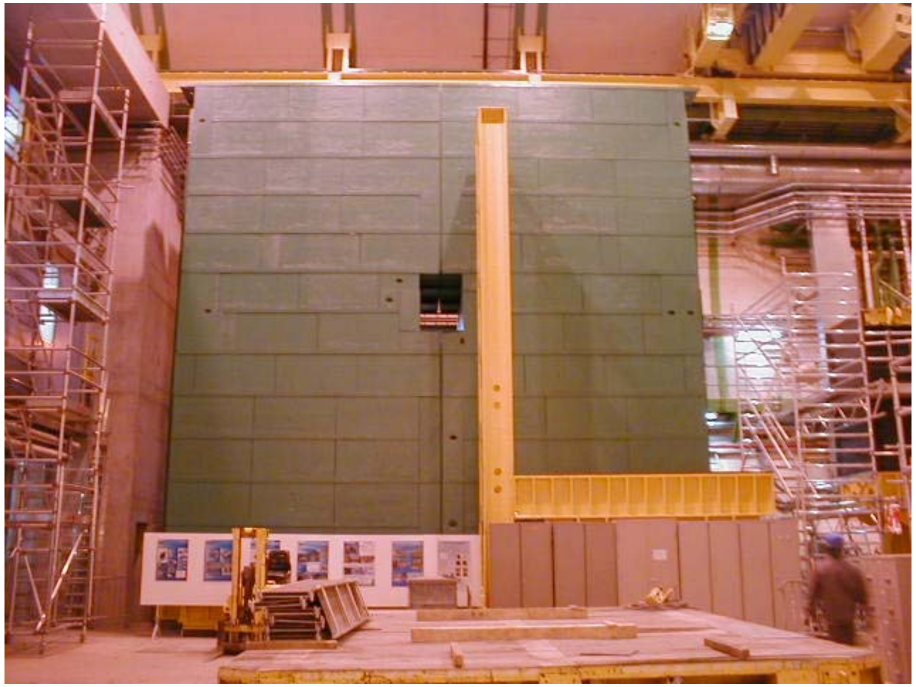
Muon System



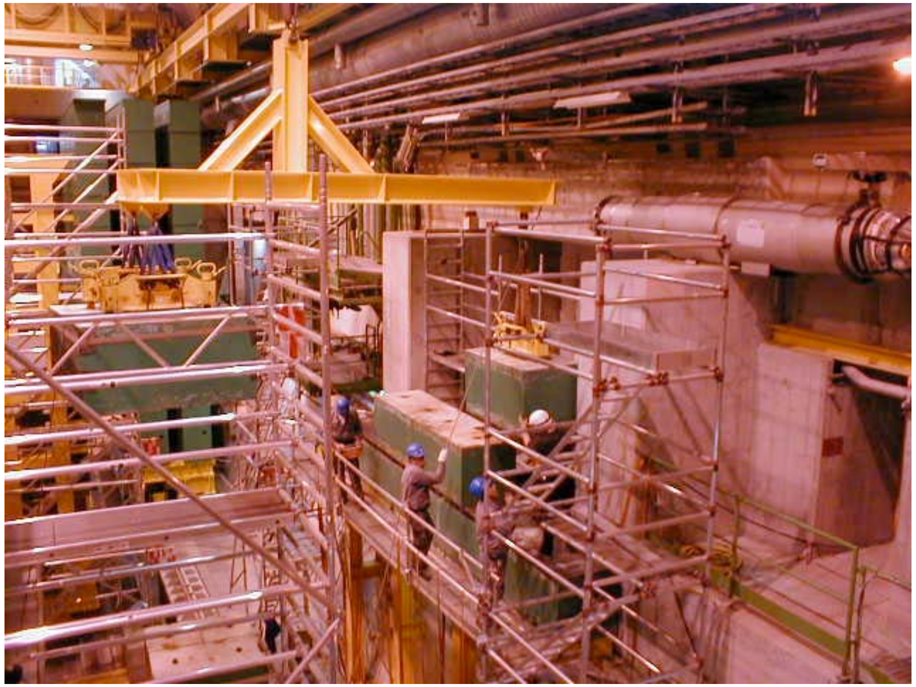
Projective pad readout based on MWPC's.

MWPC production

Muom filters



First three Muon filter wall assembled

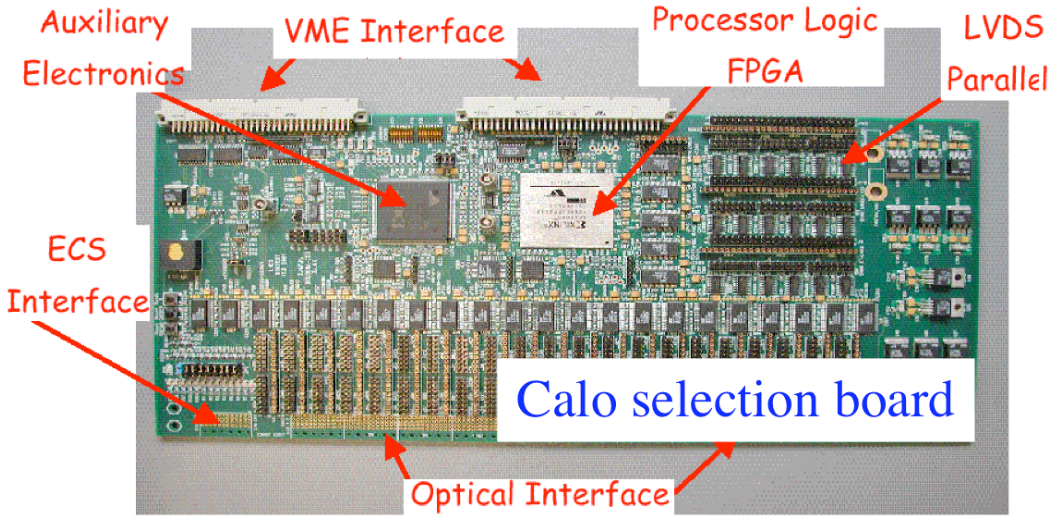


Last Muon filter against beam background

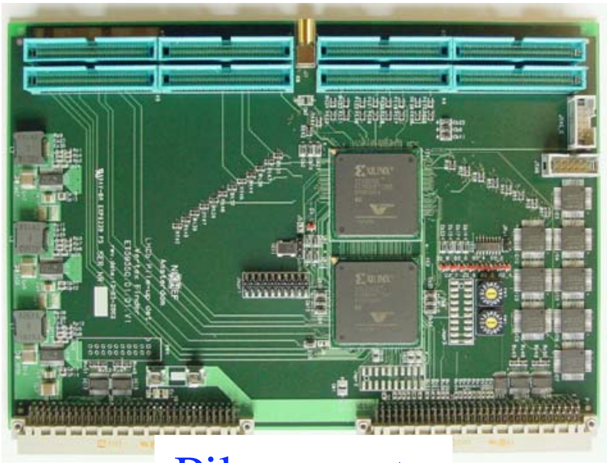
Trigger and Online

Level-0: Muon, Calorimeter (e, h, γ, π^0), Pile-up veto, Decision Unit prototypes.

Muon processor board



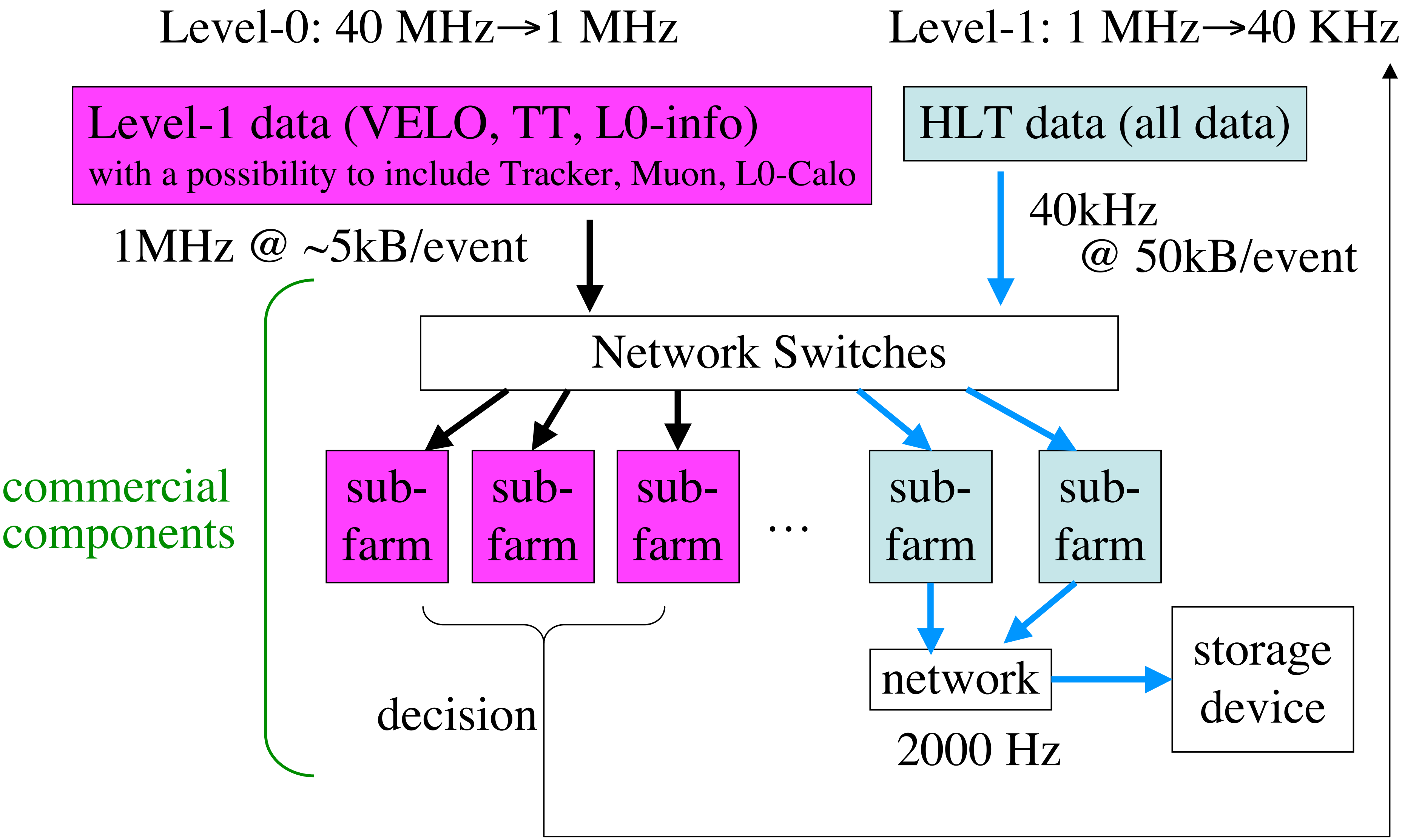
Calo selection board



Pile-up veto

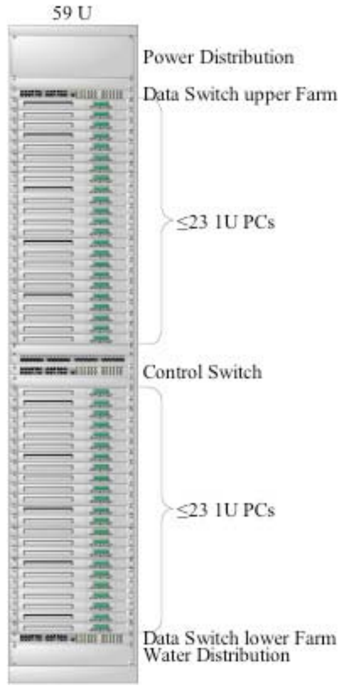
Decision Unit

Level-1/High Level Trigger and DAQ

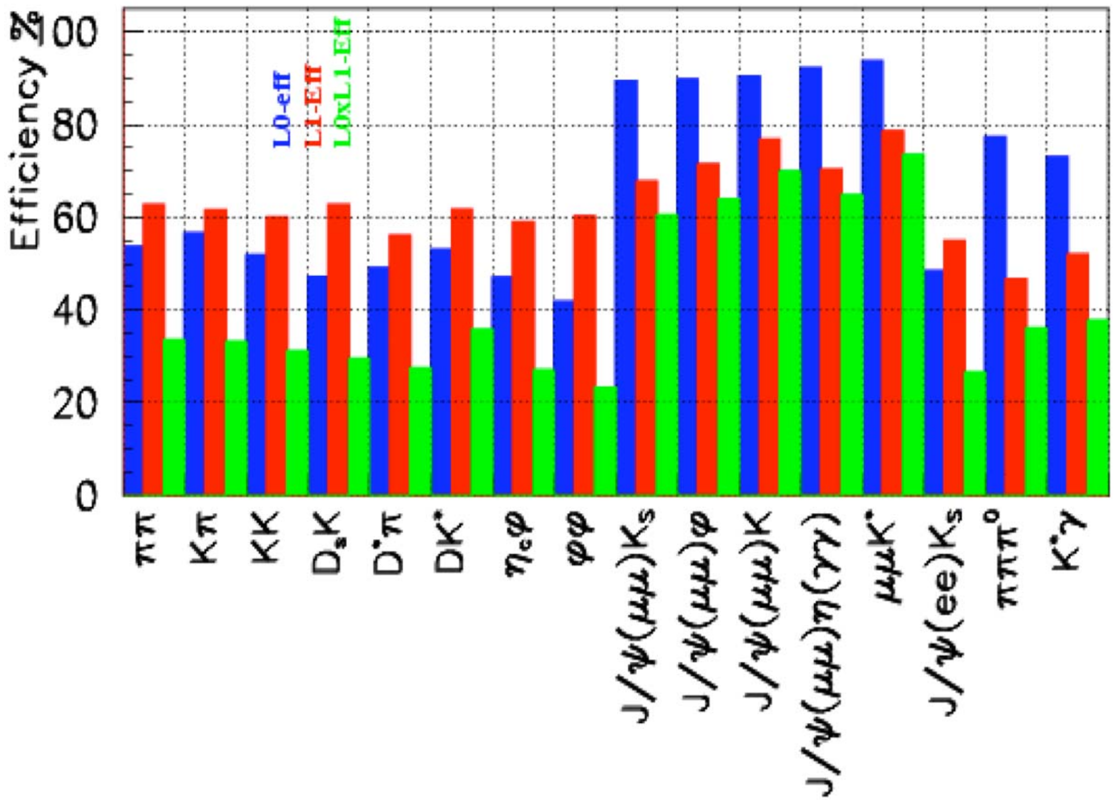


Real-time Trigger Challenge hardware

network switches

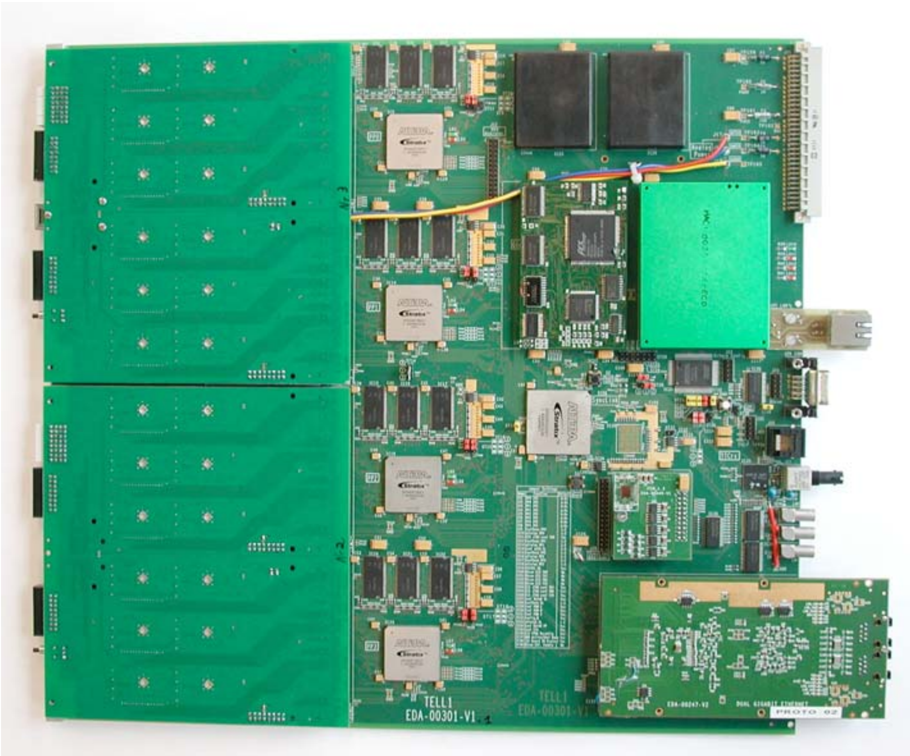


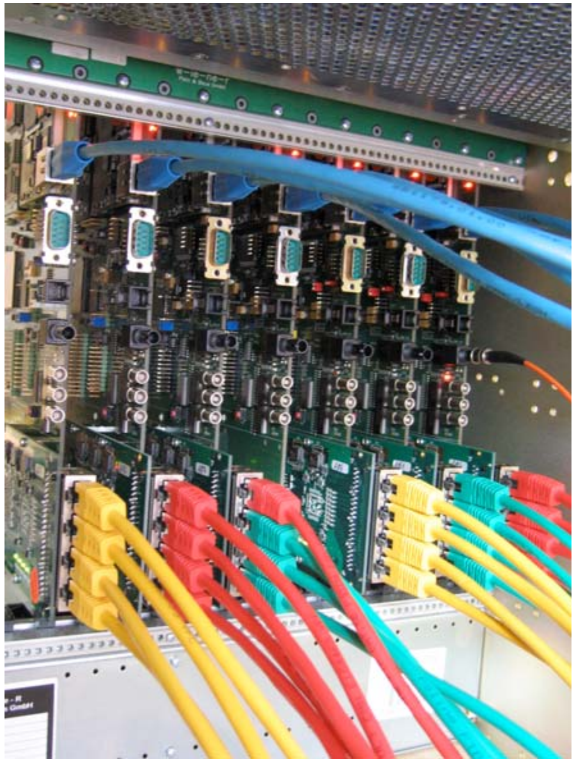
CPU farm



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→J/ψX (unbiased)
300 Hz	D* candidates	PID	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. b→μ)	Trigger	B (data mining)

Tell1: LHCb common readout board





Subsystem specific firmware to be developed
Total number needed 350 boards

3) B physics sensitivity

All b hadron species are produced:

B^0, B^+, B_s, B_c, b-baryons:

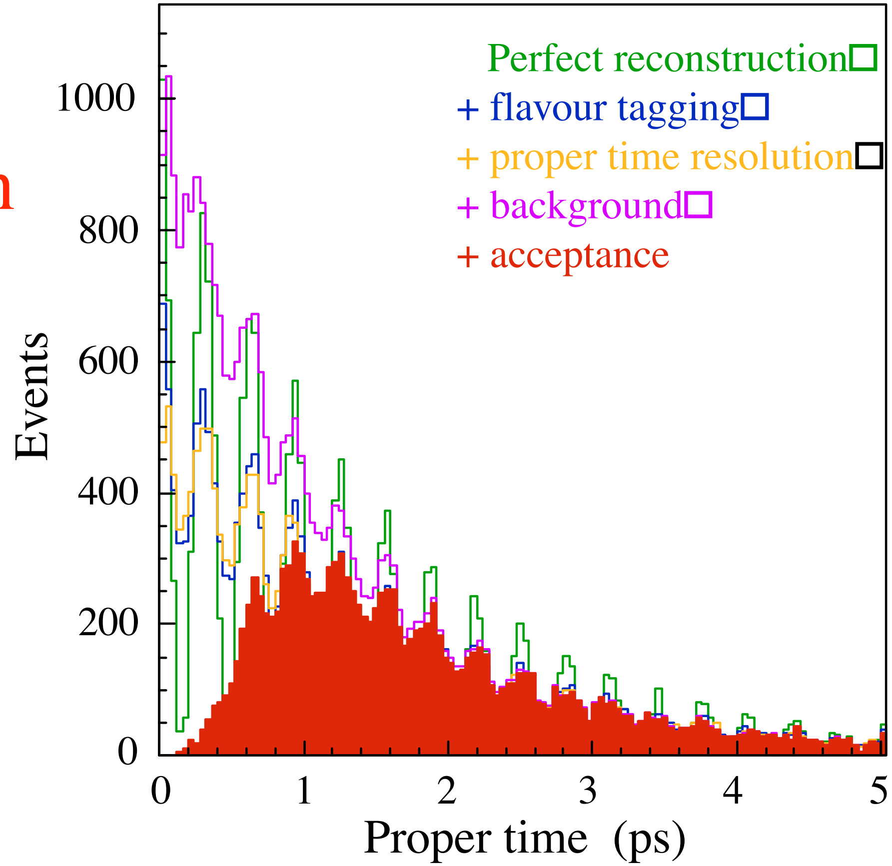
Expected fractions ~ 40 : 40 : 10 : 0.1 : 10 %

One of the first physics goals (if CDF/D0 don't beat us to it): observation of B_s–$\bar{B}_s$ oscillation

Best mode: $B_s \rightarrow D_s^- \pi^+$

Plot made for 1 year of data (80k selected events, LHCb) for Δm_s = 20 ps^{-1} (SM preferred)

Control of mistag rate, resolution, background and acceptance important



Measurement of Δm_s using $B_s \to D_s^- \pi^+$ decays

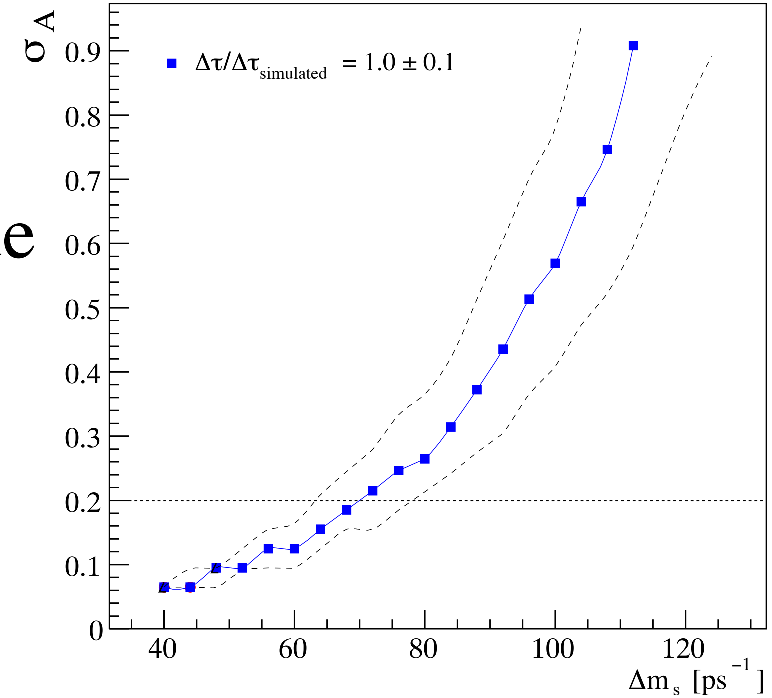
Signal/Background (from 10^7 inclusive bb events) ~ 3

Plot uncertainty on amplitude of fitted oscillation *vs* m_s:

5σ observation of B_s oscillation for $\Delta m_s < 68\ \mathrm{ps}^{-1}$ (in one year)

→ LHCb could exclude *full* SM range

Once observed, precise value is obtained: $\sigma_{stat}(\Delta m_s) \sim 0.01\ \mathrm{ps}^{-1}$

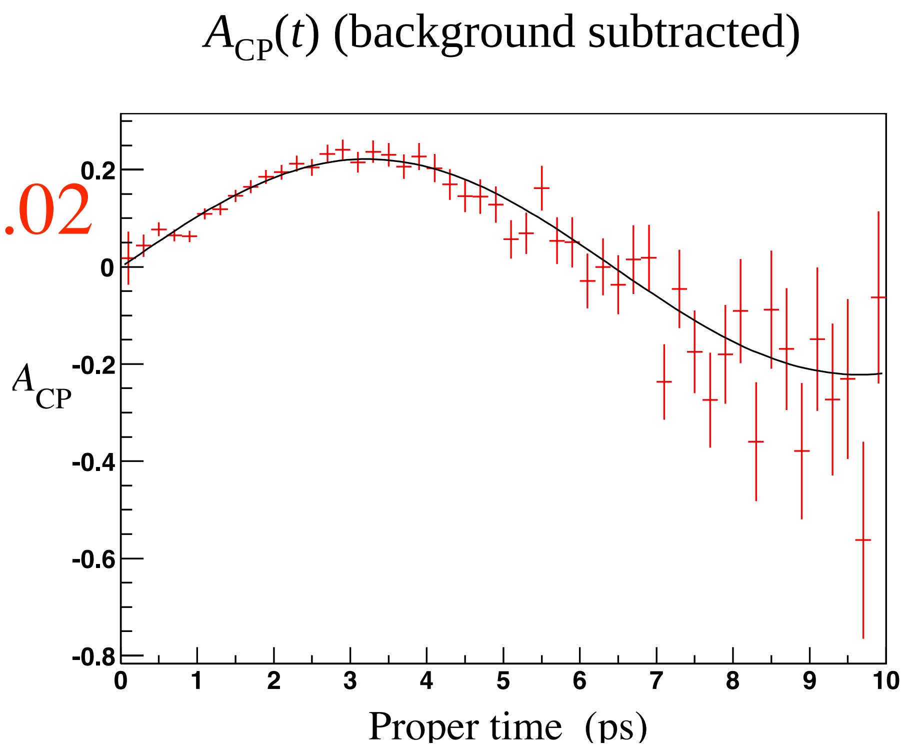


Measurement of sin 2β is not a central physics goal of LHCb (since so well measured by B factories)
but will be an important check of CP analyses
+ can search for direct CP violating term $\propto \cos \Delta m_d t$

Expect 240k reconstructed
$B^0 \rightarrow J/\psi\, K_S$ events/year

Precision $\sigma_{stat}(\sin 2\beta) \sim 0.02$
in one year for LHCb

B^0 mass resolution 10 MeV



$B_s \rightarrow J/\psi\phi$ is the B_s counterpart of $B^0 \rightarrow J/\psi K_S$

CP asymmetry measures ϕ_s, the phase of B_s oscillation

In Standard Model ϕ_s is small: $\phi_s = -2\lambda^2\eta \sim -0.04$

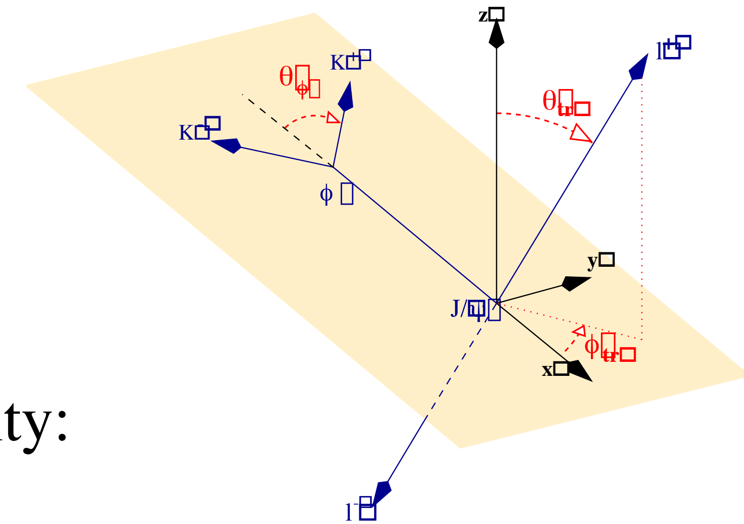
$\rightarrow$ sensitive probe for new physics

Final state is admixture of CP-even and odd contributions

$\rightarrow$ angular analysis of decay products required

$L(t) = (1-R_{-})\, L_{+}(t)\, (1+\cos^2\theta_{tr})/2 + R_{-}\, L_{-}(t)\, (1-\cos^2\theta_{tr})$

Fit for $\sin\phi_s$, R_{-} and $\Delta\Gamma_s/\Gamma_s$



120k signal events/year in LHCb

$\sigma(\sin\phi_s) \sim 0.06$, $\sigma(\Delta\Gamma_s/\Gamma_s) \sim 0.02$

$(\Delta m_s = 20\ ps^{-1})$

Including $B_s \rightarrow J/\psi\eta$ will increase sensitivity:

only ~ 7k events/year, but pure CP state

$B_s \rightarrow D_s^- K^+$ and $\overline{B}_s \rightarrow D_s^+ K^-$ ($b \rightarrow u$ transition, BR ~ 7 × lower)

both tree decays, which interfere via B_s mixing

CP asymmetry measures $\gamma + \phi_s$

Very little theoretical uncertainty, insensitive to new physics

ϕ_s will be determined using $B_s \rightarrow J/\psi\phi$ decays $\rightarrow$ extract γ

$B_s \rightarrow D_s^- \pi^+$ gives background to $D_s K$ (BR ~ 12 × higher)

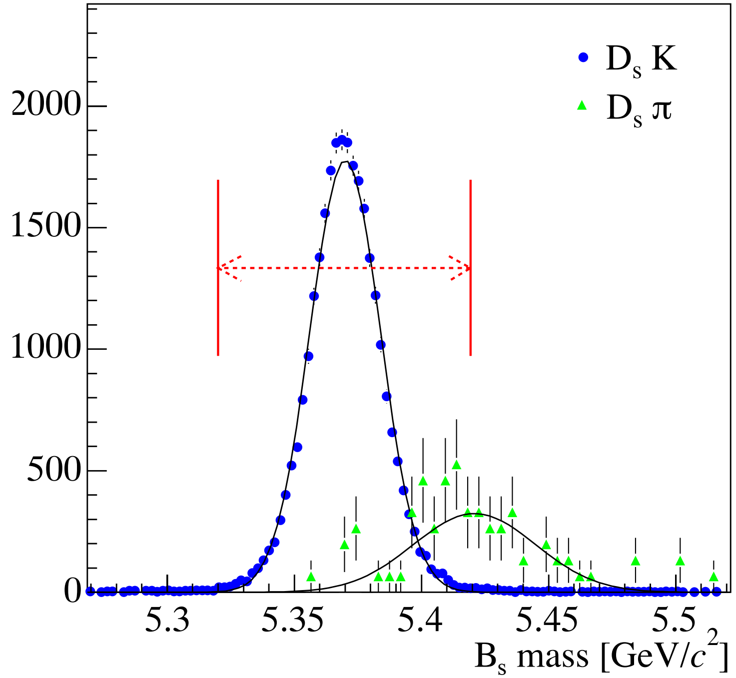
Suppress using PID

→ residual contamination only ~ 10%

5400 signal events/year (LHCb)

S/B (from bb) > 1 (at 90% CL)

(only 1 bkg event in wider M_B window)



Allow for strong phase difference Δ between the two diagrams

Fit two time-dependent asymmetries:

Phase of $D_s^+K^- = \Delta - (\gamma + \phi_s)$

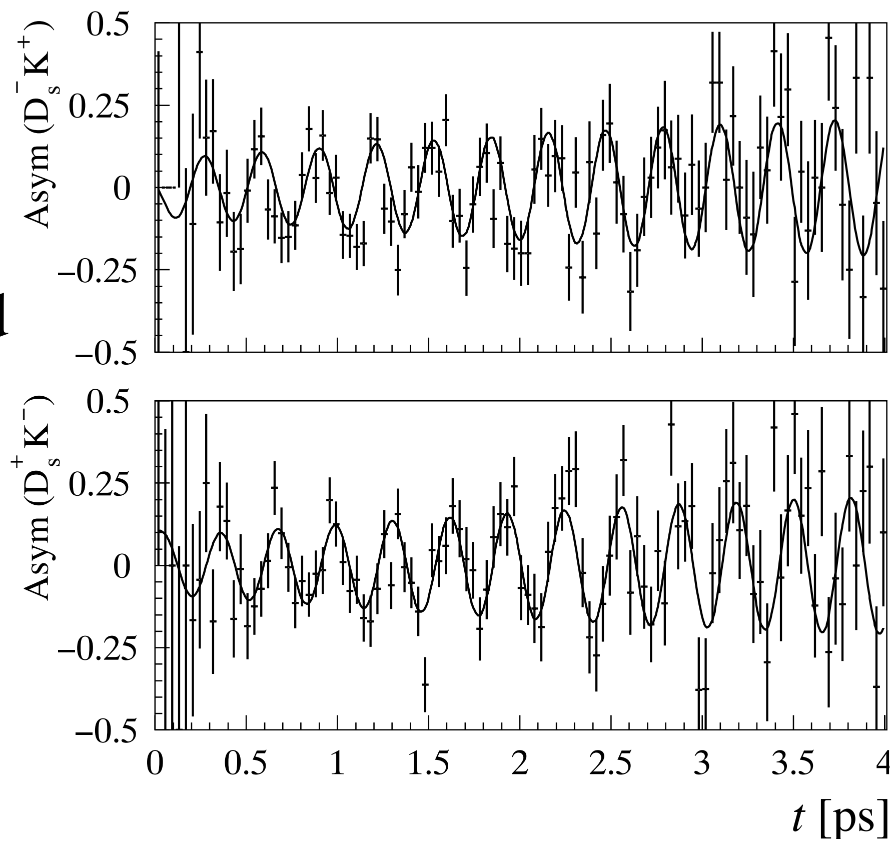
Phase of $D_s^-K^+ = \Delta + (\gamma + \phi_s)$

$\rightarrow$ extract both Δ and $(\gamma + \phi_s)$

$\sigma(\gamma) \sim 14°$ in one year (LHCb)

but expect it to be statistically limited

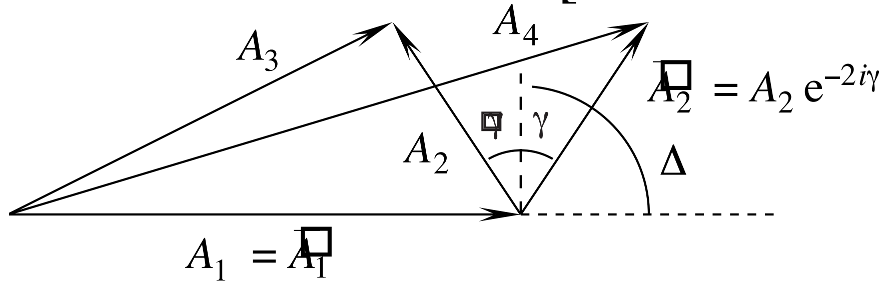
Asymmetries (5 years data)



Δm_s	20 ps^{-1}	25 ps^{-1}	30 ps^{-1}
$\sigma(\gamma)$	14.2°	16.2°	18.3°

Measure 6 decay rates: $B^0 \to \bar{D}^0K^{*0}$, D^0K^{*0} and $D^0_{CP}K^{*0}$ (+ CP conjugates), where $D^0_{CP} \to K^+K^-$ (or $\pi^+\pi^-$)

Appropriate construction of amplitudes allows both γ and strong phase Δ to be extracted [Gronau & Wyler, Dunietz]



Decays are self-tagging (through $K^{*0} \to K^+\pi^-$) and time integrated

No penguin diagram contributing to the decay

Mode	Yield	S/B
$B^0 \to \bar{D}^0\ (K^+\pi^-)\ K^{*0}$	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

LHCb annual yields
(for γ = 65°, Δ = 0)

$\to \sigma(\gamma) \sim 8°$
(55° < γ < 105°, –20° < Δ < 20°)

Time-dependent CP asymmetries for $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

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

A_{dir} and A_{mix} depend on weak phases γ and ϕ_d (or ϕ_s), and on ratio of penguin to tree amplitudes $= d\, e^{i\theta}$

Under U-spin symmetry [Fleischer]
(interchange of d and s quarks)

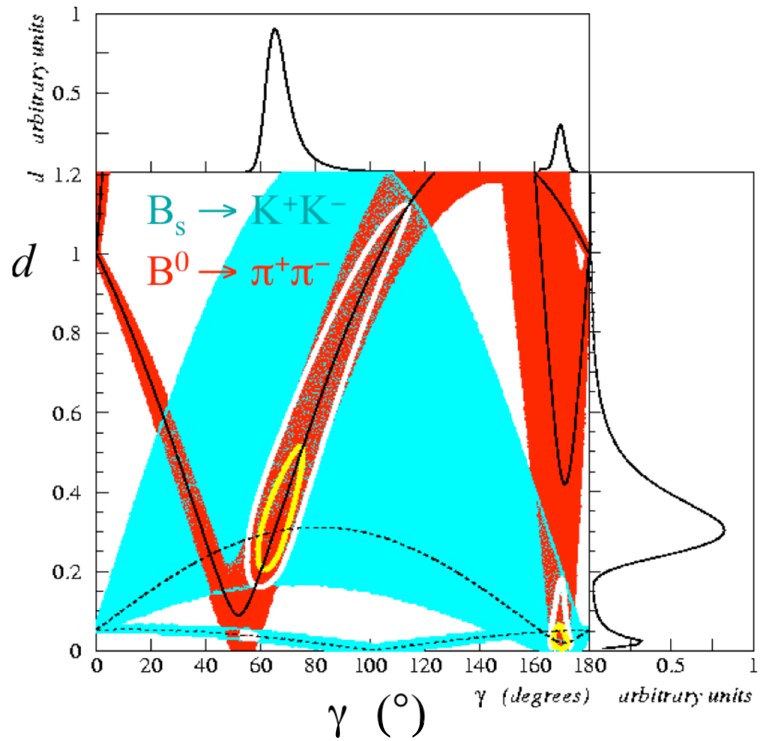
$$d_{\pi\pi} = d_{KK} \text{ and } \theta_{\pi\pi} = \theta_{KK}$$

→ 4 measurements, 3 unknowns
(taking ϕ_s & ϕ_d from other modes)
→ can solve for γ

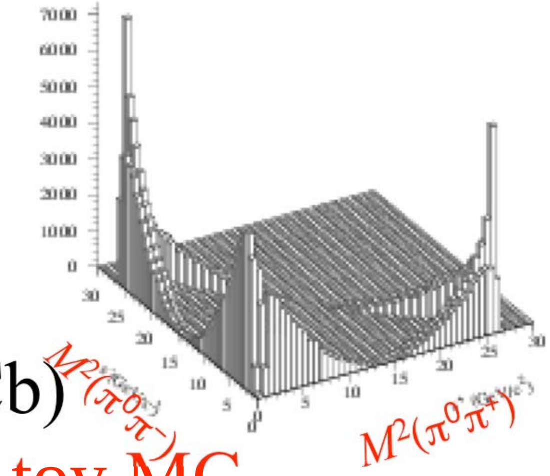
26k $B^0 \to \pi^+\pi^-$ events/year (LHCb)
37k $B_s \to K^+K^-$ → $\sigma(\gamma) \sim 5°$

Uncertainty from U-spin assumption

Sensitive to new physics in penguins



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

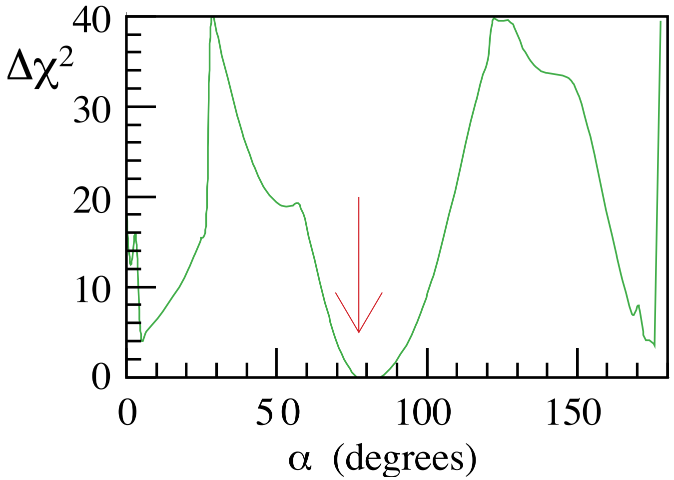


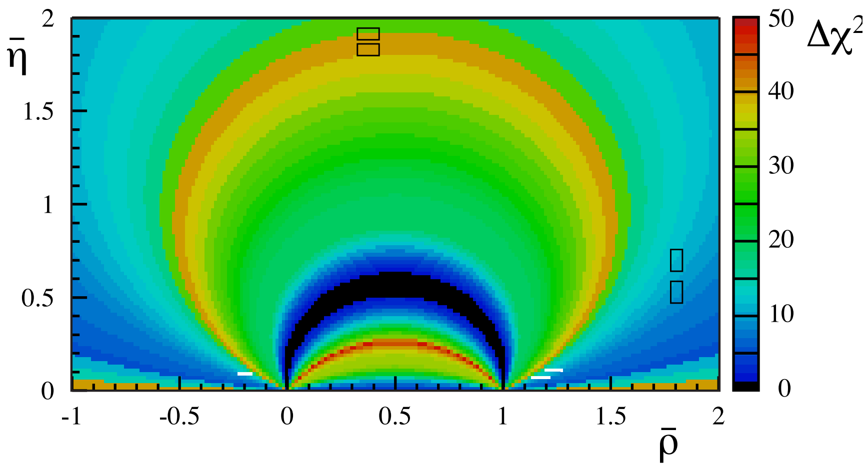
Annual yield ~ 14k events, S/B ~ 1.3 (LHCb)

Complicated 11-parameter fit, studied with toy MC

Statistical precision of $\sigma(\alpha)$ ~ 10° achievable in one year

Study of $B^0 \to \rho\rho$ has started, few $\times 10^2$ $\rho^0\rho^0$ /year (for BR = 10^{-6})

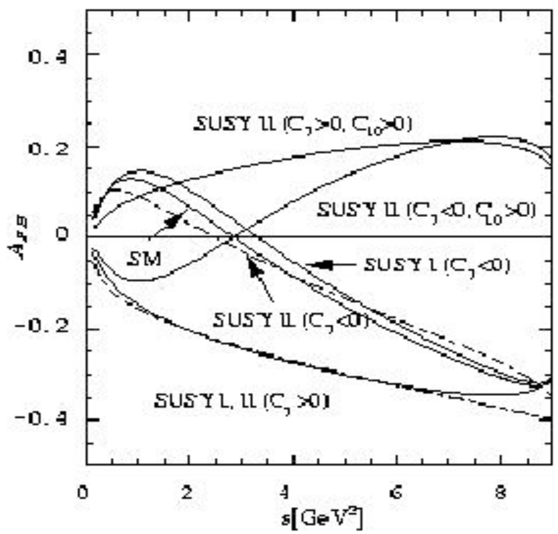




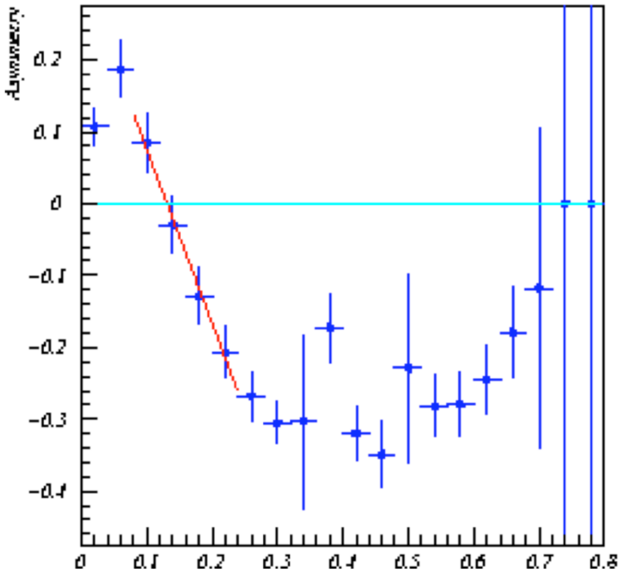
$B^0 \to K^{*0}\mu^+\mu^-$ suppressed decay (ΔB = 1 FCNC), BR~10^{-6}

Forward-backward asymmetry in the $\mu\mu$ rest-frame $A_{FB}(s)$ is sensitive probe of new physics [Ali *et al*]

$A_{FB}(s)$



$A_{FB}(\hat{s})$



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

LHCb: 4400 events/year, S/B > 0.4

$A_{FB}(\hat{s})$ reconstructed using toy MC
(two years data, background subtracted)
Zero point located to ±0.04

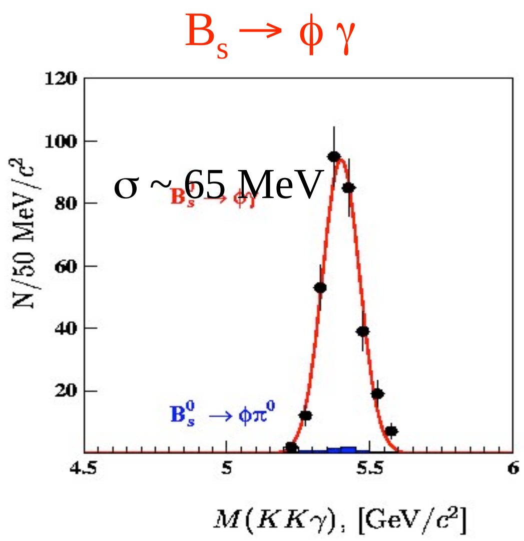
Rare decay: BR ($B_s \to \mu^+\mu^-$) = 3.5×10^{-9} in Standard Model
Sensitive to new physics, can be strongly enhanced in SUSY

LHCb expect 17 selected signal events/year for SM BR
Problem to estimate the background:
 no events selected from full background sample,
 but only corresponds to $S/\sqrt{B} > 2$

Background estimates (from 1999) differ significantly, update awaited

 Prospect of significant BR measurement, even for SM value

Other channels



- $B^0 \to \phi K_S$ is challenging for the trigger
  Expect ~ 1000 signal events/year in LHCb
- However, if new physics is showing up in $B^0 \to \phi K_S$, important to also examine other $b \to s$ penguin decays: $B_s \to \phi\phi$, KK, $\phi\gamma$…
  LHCb will reconstruct large samples of each
- Not yet systematically explored: B_c and b-baryon physics
- Recent assignment of high rate output streams from the HLT opens possibility of charm physics: > 10^8 reconstructed D*/year, and inclusive b trigger (*eg* on single μ) should give the equivalent of ~ 10^9 perfectly tagged b-hadron decays/year
- Although detector is under construction, still room to adjust trigger to select channels of topical interest

Systematics

Some potential sources of systematic uncertainty:

- B/B production asymmetry
- Charge-dependent detection efficiencies
- Background asymmetries
- Trigger bias (*eg* for flavour tag, proper-time acceptance)

Some experimental handles available:

- Control channels (*eg* $J/\psi K^*$ for $J/\psi K_S$, *etc*)
- Regular reversal of spectrometer B field
- Simultaneous fit of signal and background (*eg* $D_sK/D_s\pi$)
- Analysis of tagging performance in separate categories (*eg* triggered on B signal/triggered on other tracks)

High rate HLT unbiased samples will allow study using data

4) Use of the TeVatron data

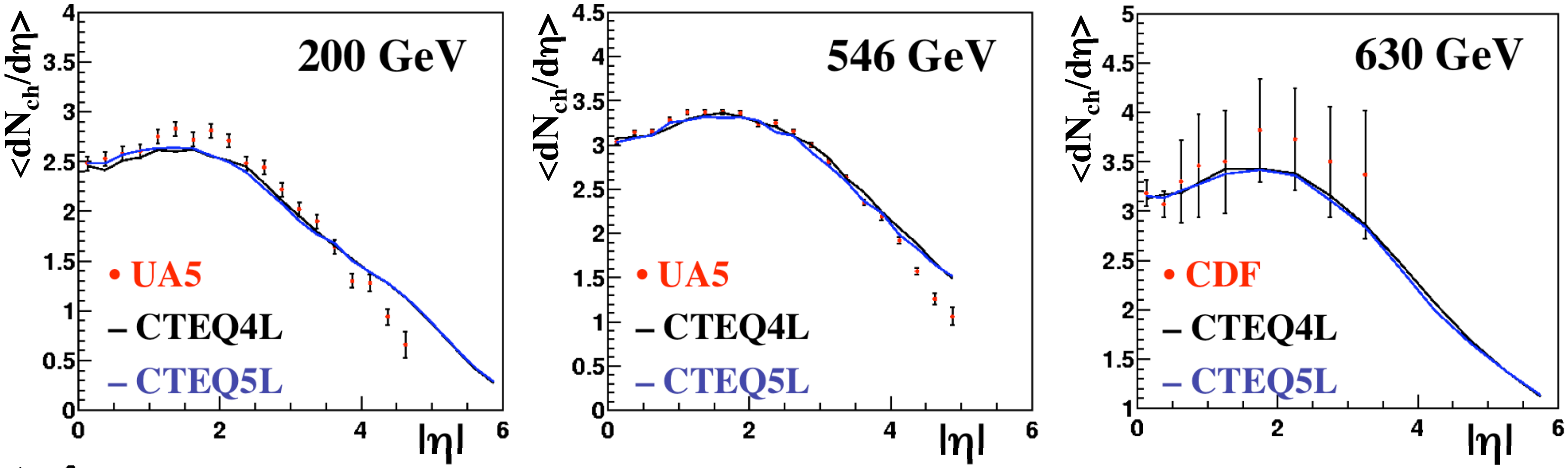
It was (and still is) important to develop the best possible understanding of the events we should expect at LHC and LHCb:

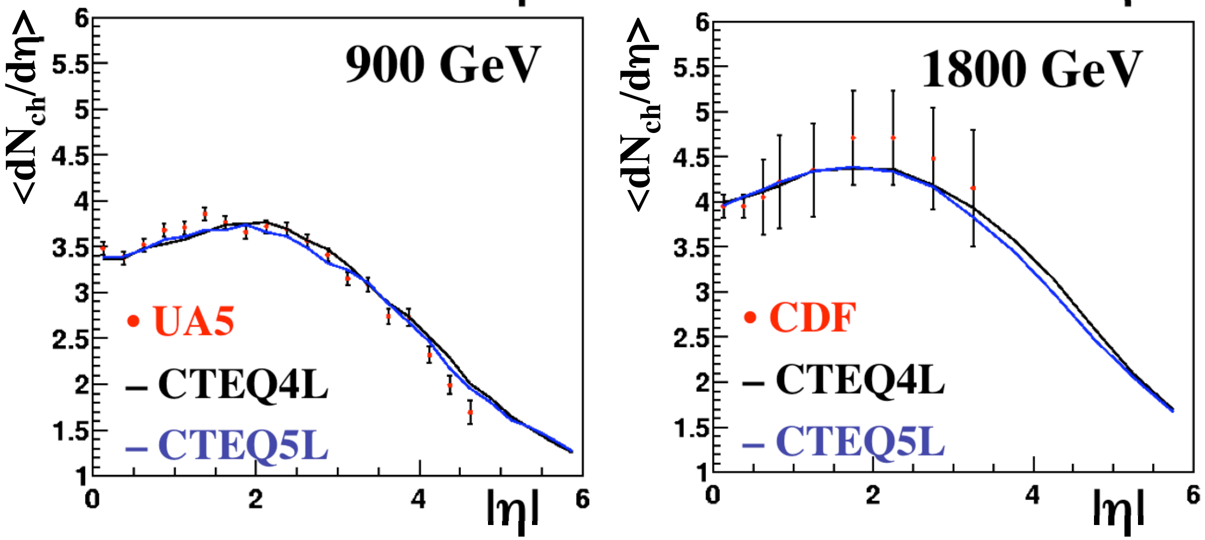
- Tevatron is the machine « closest » to LHC
- Whenever possible, extrapolate from Tevatron data

Relevant quantities:

- affecting minimum bias distributions, hence trigger performance:
  - Track multiplicity, multi-parton collision models, …
  - Inclusive particle spectra, p_T and rapidity distributions, …
  - Production cross sections (bb, cc, prompt J/ψ, …)
- affecting flavour tagging performance:
  - bb production mechanism, bb correlation
  - Excited b-hadron states (e.g. B^{**}, …)
- affecting signal statistics:
  - bb cross sections
  - b-quark hadronization fractions (into different b-hadron species)
  - Branching fractions (very little is known for B_s)

Tuning of PYTHIA





Main parameter to tune is p_T^{min} of the parton-parton interaction

- relies on CDF data to cover gap between UA5 and LHC
- performed since 1999
- used for our trigger and re-optimisation TDRs
- now redone in presence of B^{**}, D^{**}, …

Prompt J/ψ production

J/ψ → l^+l^- is an important handle at hadronic colliders

- Simple to trigger on
- Low background
- Significant physics to be done with b→J/ψX decays

Default PYTHIA does not reproduce well the proportion of J/ψ from b decays and from prompt production

- plan to introduce NRQCD in our simulation, with long distance non-perturbative matrix elements extracted with fits to Tevatron data
  (both for ψ's and ϒ's)

5) Conclusions

- LHCb expects to take B physics
  a significant step further than the B factories:
  - access to other b hadron species + high statistics
  - excellent vertexing and particle ID
    flexible and efficient trigger, dedicated to B physics
  Many channels studied, differing sensitivity to new physics
- Construction of the LHCb detector is advancing
- Low luminosity ($\sim 10^{32}$) required for the LHCb experiment will allow to exploit full physics potential from the beginning of the LHC operation. **Machine can do this and we need this.**

LHCb yields and background

	Det. eff. (%)	Rec. eff. (%)	Sel. eff. (%)	Trig. eff. (%)	**Tot. eff. (%)**	Vis. BR (10^{-6})	**Annual signal yield**	**B/S from bb bkg.**
$B^0 \to \pi^+\pi^-$	12.2	91.6	18.3	33.6	**0.69**	4.8	**26k**	**< 0.7**
$B_s \to K^+K^-$	12.0	92.5	28.6	36.7	**0.99**	18.5	**37k**	**0.3**
$B_s \to D_s^-\pi^+$	5.4	80.6	25.0	31.1	**0.34**	120.	**80k**	**0.3**
$B_s \to D_s^{-+}K^{+-}$	5.4	82.0	20.6	29.5	**0.27**	10.	**5.4k**	**< 1.0**
$B^0 \to D^{\sim 0}(K\pi)K^{*0}$	5.3	81.8	22.9	35.4	**0.35**	1.2	**3.4k**	**< 0.5**
$B^0 \to J/\psi(\mu\mu)\,K^0_S$	6.5	66.5	53.5	60.5	**1.39**	20.	**216k**	**0.8**
$B^0 \to J/\psi(ee)\,K^0_S$	5.8	60.8	17.7	26.5	**0.16**	20.	**26k**	**1.0**
$B_s \to J/\psi(\mu\mu)\,\phi$	7.6	82.5	41.6	64.0	**1.67**	31.	**100k**	**< 0.3**
$B_s \to J/\psi(ee)\,\phi$	6.7	76.5	22.0	28.0	**0.32**	31.	**20k**	**0.7**
$B^0 \to \rho\,\pi$	6.0	65.5	2.0	36.0	**0.03**	20.	**4.4k**	**< 7.1**
$B^0 \to K^{*0}\gamma$	9.5	86.8	5.0	37.8	**0.16**	29.	**35k**	**< 0.7**
$B_s \to \phi\,\gamma$	9.7	86.3	7.6	34.3	**0.22**	21.	**9.3k**	**< 2.4**

+ few more channels in TDR

Nominal year = 10^{12} bb pairs produced (10^7 s at $L=2\times10^{32}\ \mathrm{cm^{-2}s^{-1}}$ with $\sigma_{bb}=500\ \mu b$)
Yields include factor 2 from CP-conjugated decays
Branching ratios from PDG or SM predictions