Physics Potential of LHCb

For the Collaboration

ADVANCED STUDIES INSTITUTE

PHYSICS AT LHC

6 - 12 July 2003, Prague

presented by

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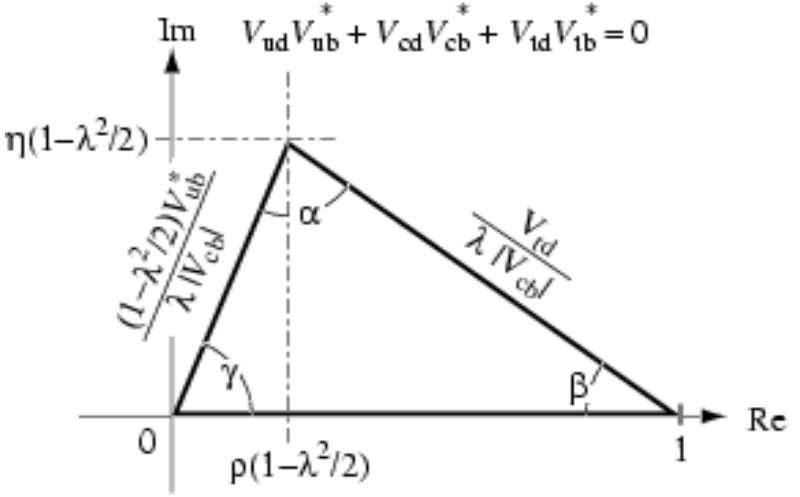
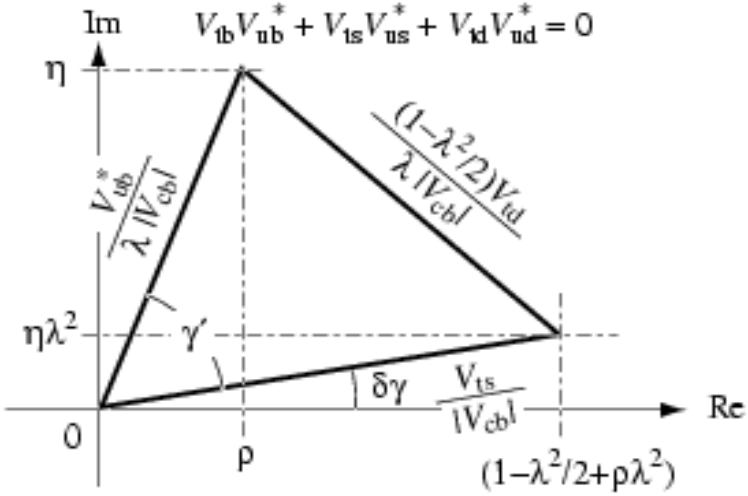
Physics Motivation

- ➢ Precise determination of the CKM parameters through phase measurements
- ➢ Search for New Physics beyond the SM by overconstraining the Unitarity Triangles

- high precision ~~CP~~ measurements including pure hadronic and multibody final states
- measure ~~CP~~ in new decay channels including B_s decays
- look for rare and loop-suppressed B-decays

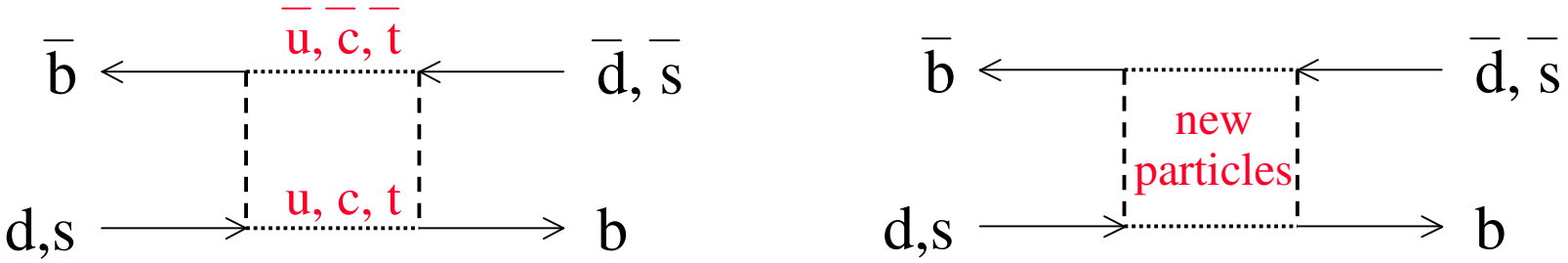




➢ trigger and reconstruct many different channels

2β	$B_d \to J/\psi\, K_S$
$2\beta+\gamma$	$B_d \to D^* \pi$
β and γ	$B_d \to \pi\pi$, $B_s \to K\,K$
γ-$2\Delta\gamma$	$B_s \to D_s K$
$2\Delta\gamma$	$B_s \to J/\psi\, \phi$
α	$B_d \to \pi\pi$
	$B_d \to \rho\pi$
other	$B_d \to K^* \gamma$
	$B_d \to K^* \eta\ \eta$
	$B_s \to \eta\ \eta$

Example for manifestation of New Physics



B_d : arg M_{12} = 2β + ϕ_{bd}^{NP}

~~CP~~ in $B_d \to J/\psi K_S$ $\longrightarrow$ sin (2β + ϕ_{bd}^{NP})

~~CP~~ in $B_d \to D^* \square$ $\longrightarrow$ sin (2β + γ + ϕ_{bd}^{NP})

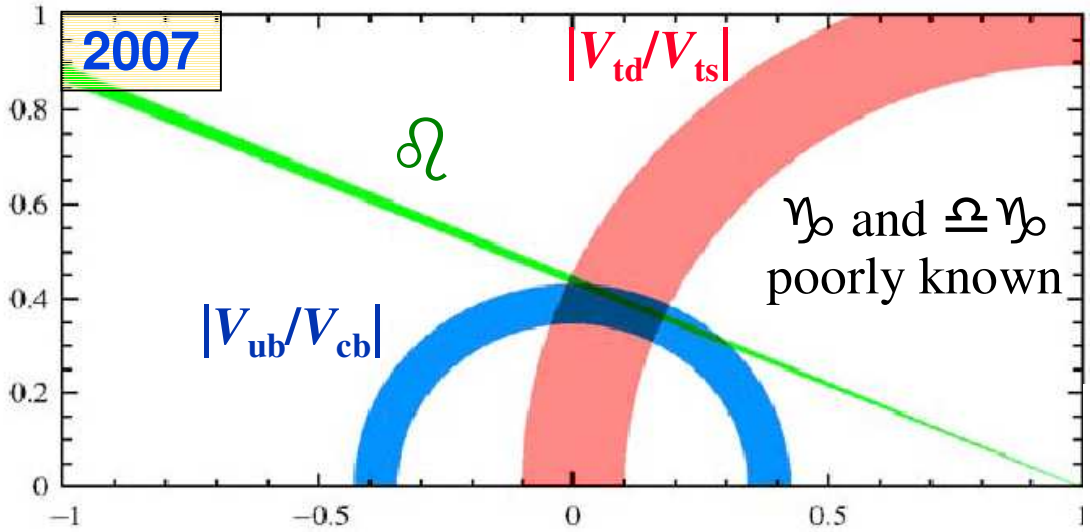
B_s : arg M_{12} = 2 $\pm\gamma$ + ϕ_{bs}^{NP}

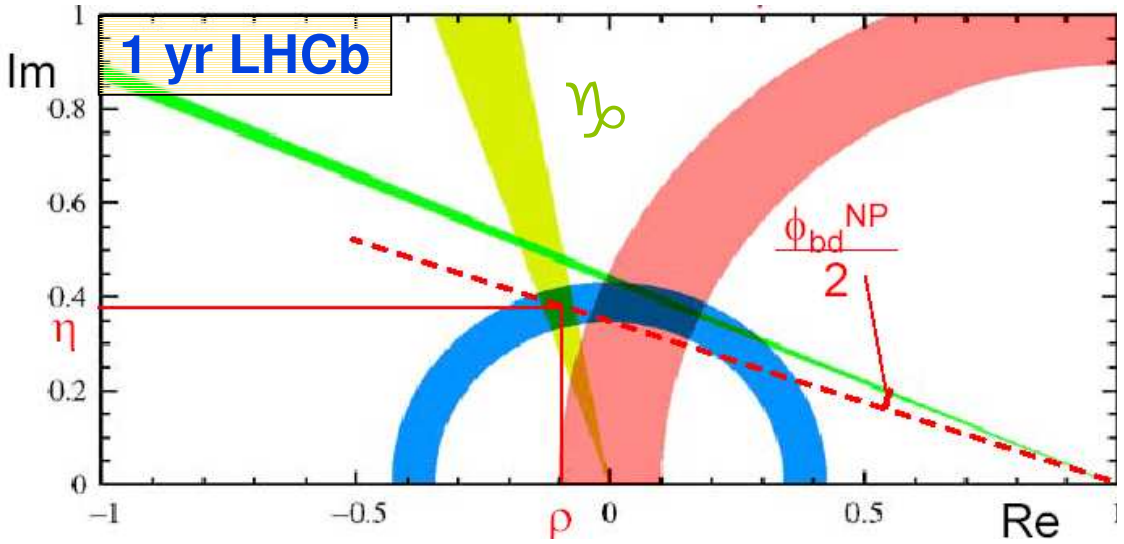
~~CP~~ in $B_s \to J/\psi \phi$ $\longrightarrow$ sin (2 $\pm\gamma$ + ϕ_{bs}^{NP})

~~CP~~ in $B_s \to D_s K$ $\longrightarrow$ sin (2 $\pm\gamma$ + γ + ϕ_{bs}^{NP})

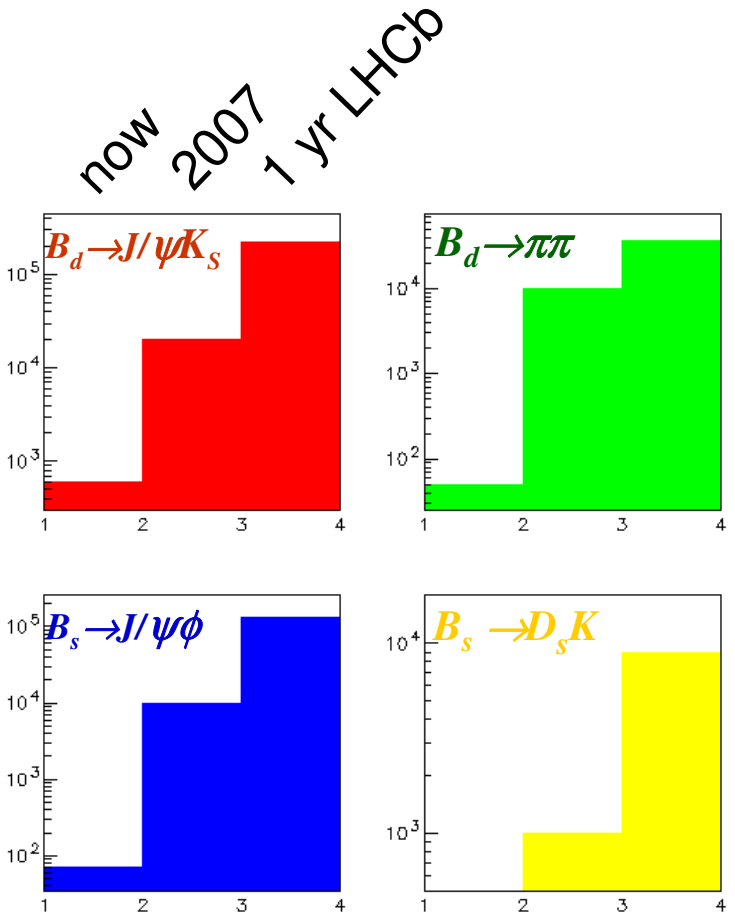
γ (ϕ_{bs}^{NP}) can be disentangled from New Physics effects

Discovery potential with one year of LHCb





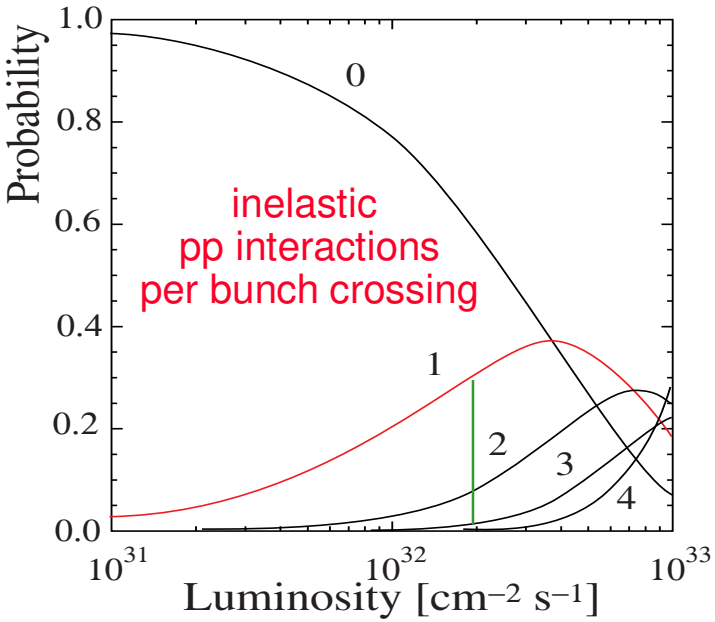
B-factories and Tevatron



B production at LHC

LHC:

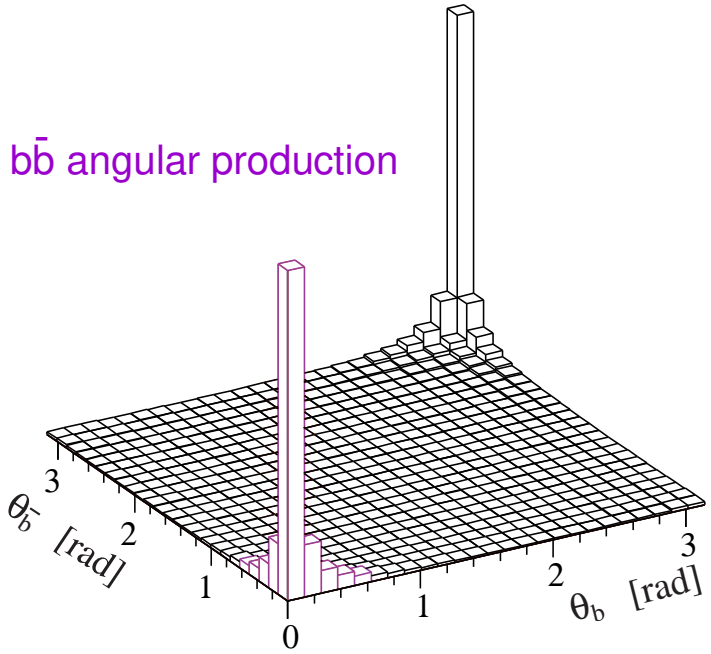
- pp collisions at $\sqrt{s}$ = 14 TeV
- σ_{total} ~ 100 mb ✹ interaction rate ~ 2 x10^7/s
- multiple pp interactions per bunch crossing
- σ_{inel} ~ 80 mb, $\sigma_{b\bar{b}}$ ~ 500 μb ✹ S/B ~ 1%
- forward production of $b\bar{b}$, correlated



LHCb:

- single arm spectrometer
- ✹ 12 mrad < θ < 300 mrad (1.8 < η < 4.9)
- efficient trigger and clean events, minimize radiation damage
- ✹ work mostly with single interactions at a nominal L~2x10^{32} cm^{-2}s^{-1} tunable! (defocussed beams at *LHCb* IP)

➽ ~10^{12} $b\bar{b}$ events per year with full efficiency at LHC start-up

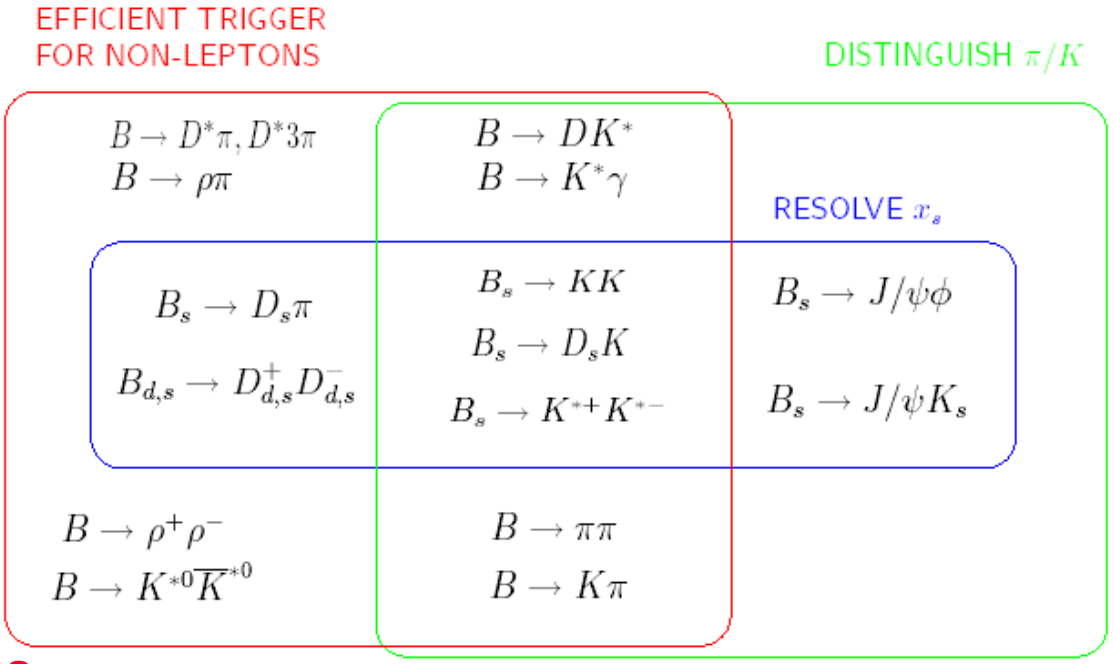


Requirements to Detector

$B_d \to K^*\gamma$ HIGH STATISTICS

$B_d \to J/\psi\,\rho^0$

$B_{s,d} \to \mu^+\mu^-$ $(\mathcal{O}(10^{-9})!)$

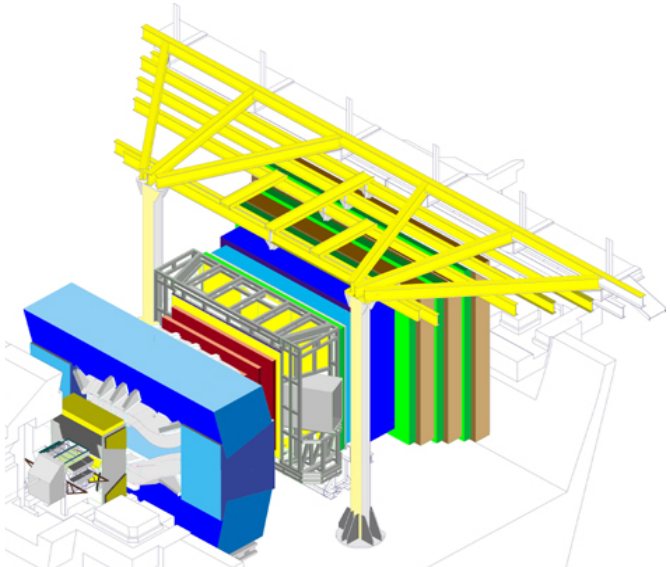


- **efficient trigger for many B decay topologies**
  - leptonic final states ✹ Muon System, ECAL+Preshower (e.g. J/ψ K_S)
  - hadronic final states ✹ HCAL (e.g. ππ, Kπ, D_sK etc.)
  - high p_t -particles with large impact parameter ✹ Vertex Locator, Trigger Tracker
- **efficient particle identification**
  - ✹ RICH (πK separation between 1GeV<p<100GeV)
- **good decay time resolution**
  - ✹ Vertex Locator (e.g. ~40fs for B_s✹D_sπ and B✹ππ)
- **good mass resolution**
  - ✹ Tracker and Magnet (e.g. 14MeV for B_s✹D_sπ, 18MeV for B_d✹ππ)

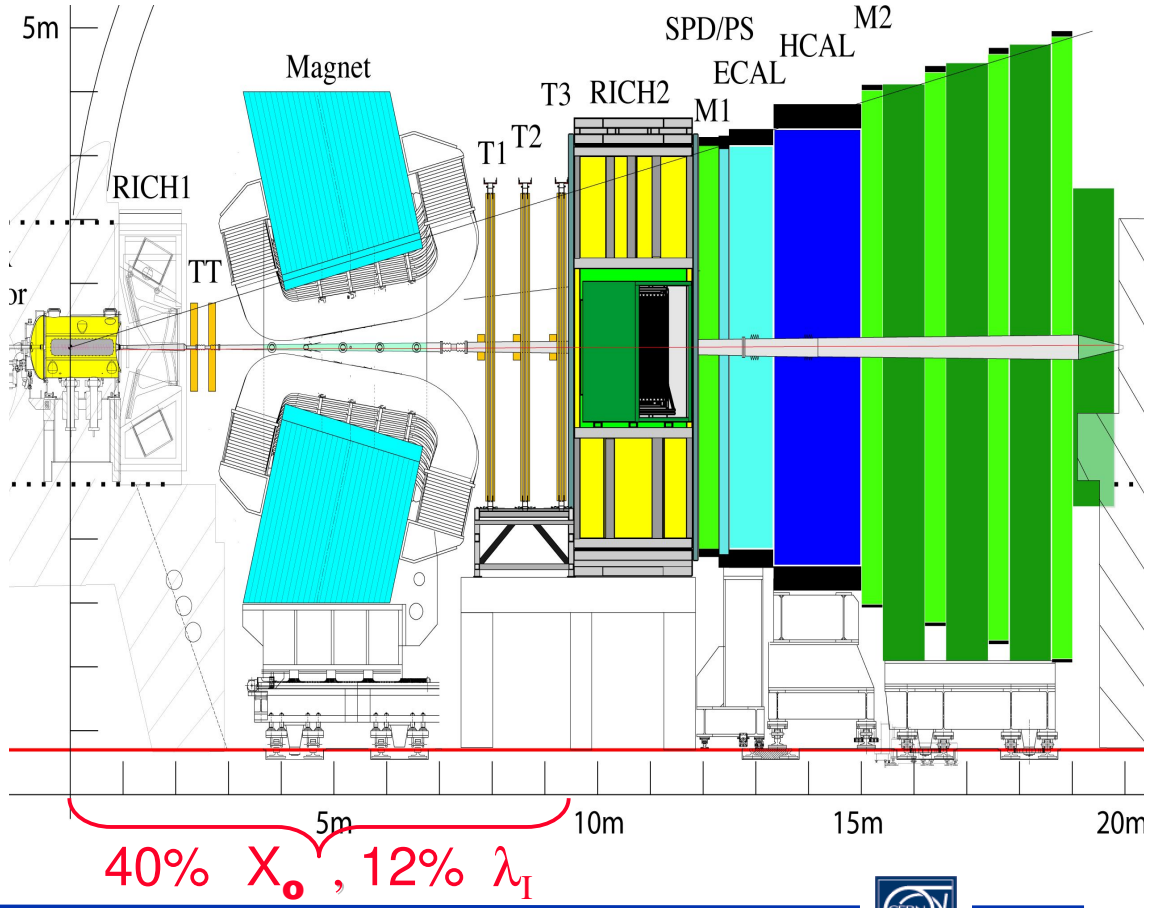
Overview and Status of Detector

- *LHCb* Letter of Intent ✹ Feb 1996
- Technical Proposal approved ✹ Sep 1998
- Technical Design Reports of all detector subsystems ✹ 2000–2002
- LHCb re-optimization & Trigger TDRs ✹ Sep 2003

➢ detector construction has started in 2002

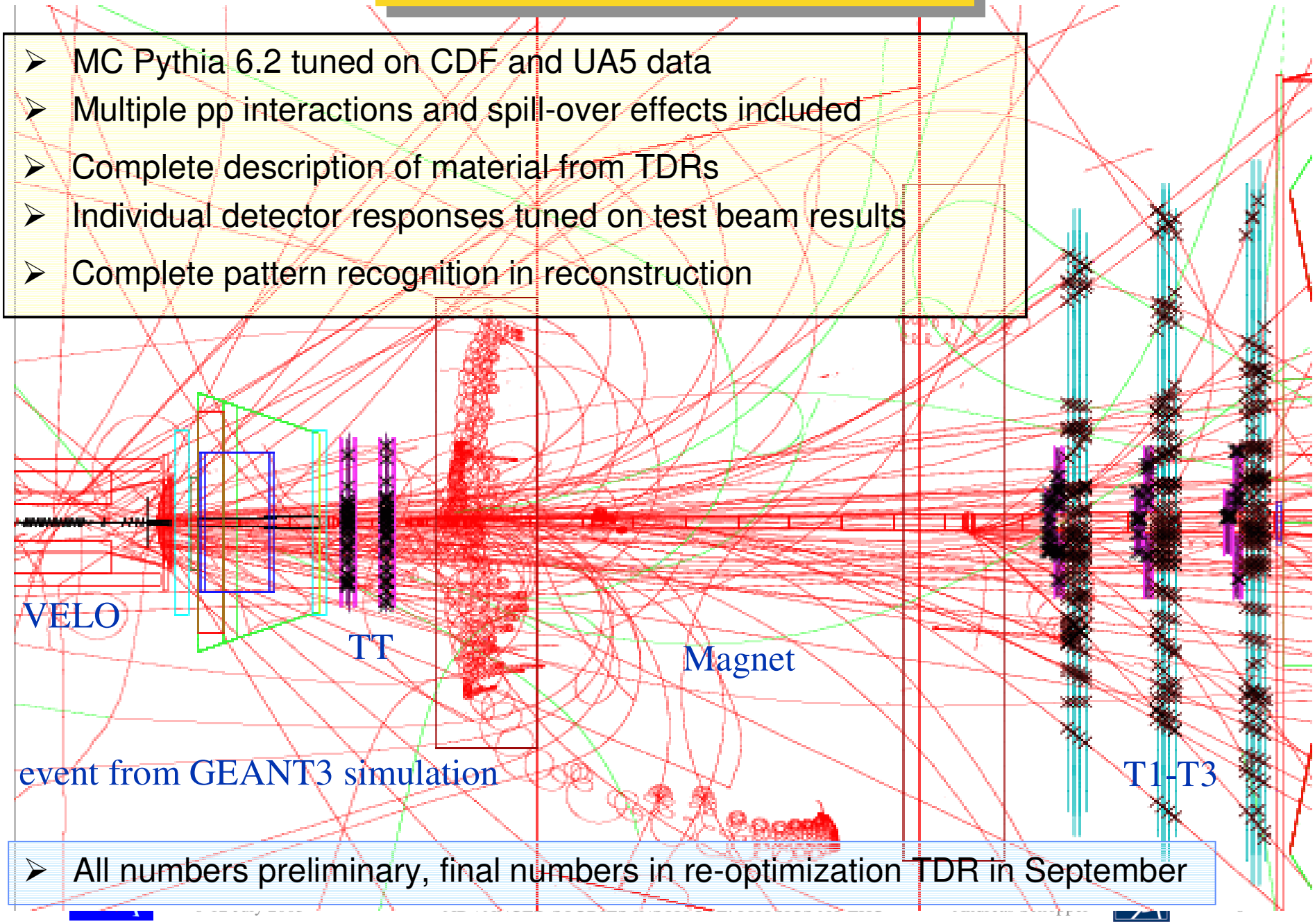


Aperture:
~15–300 (250) mrad
$1.8 < |\eta| < 4.9$



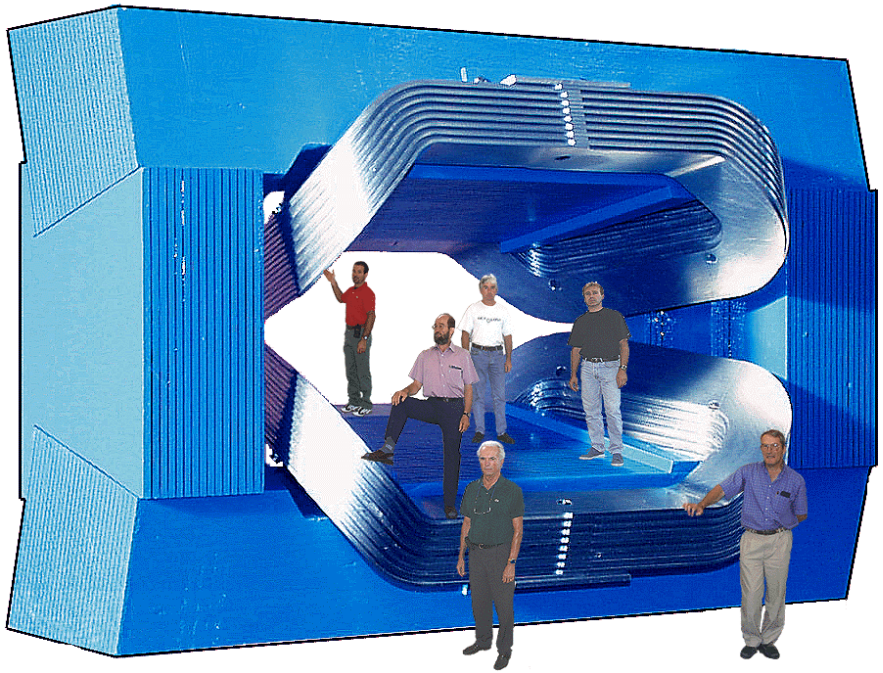
Status of Simulation

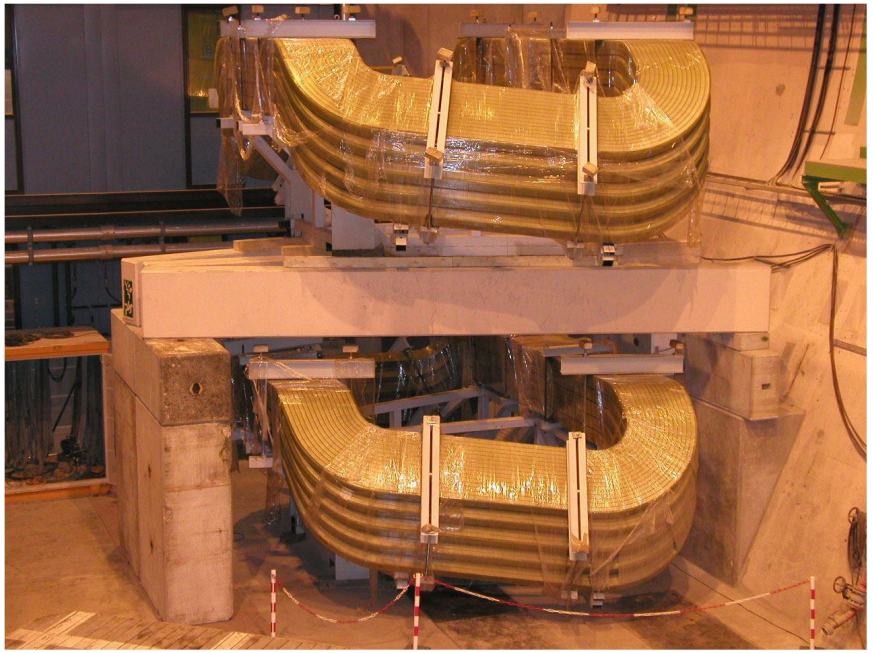
- MC Pythia 6.2 tuned on CDF and UA5 data
- Multiple pp interactions and spill-over effects included
- Complete description of material from TDRs
- Individual detector responses tuned on test beam results
- Complete pattern recognition in reconstruction

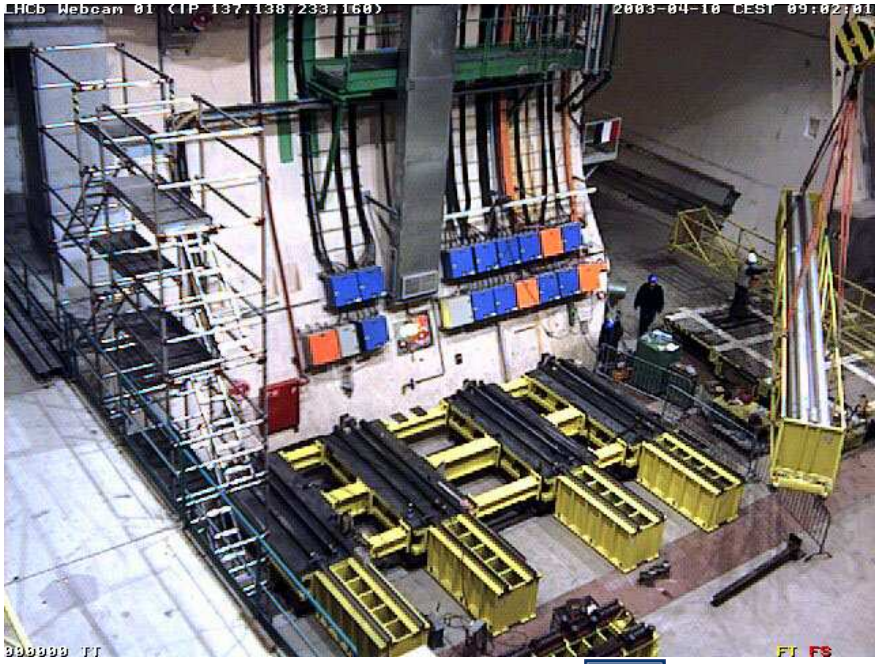


- All numbers preliminary, final numbers in re-optimization TDR in September

Magnet







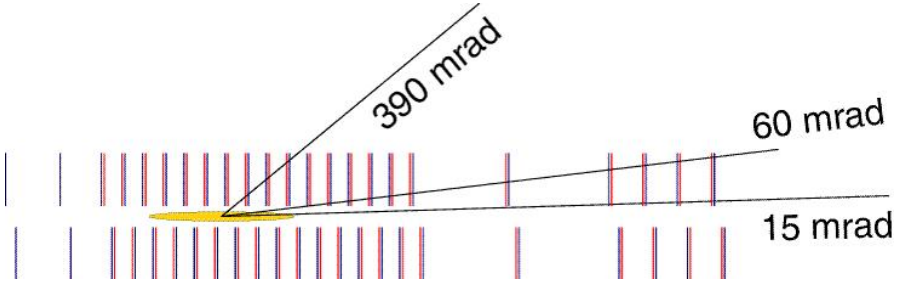
- dipole
- warm Al conductor
- 4 Tm integrated field
- 4.2 MW
- 1450 t yoke

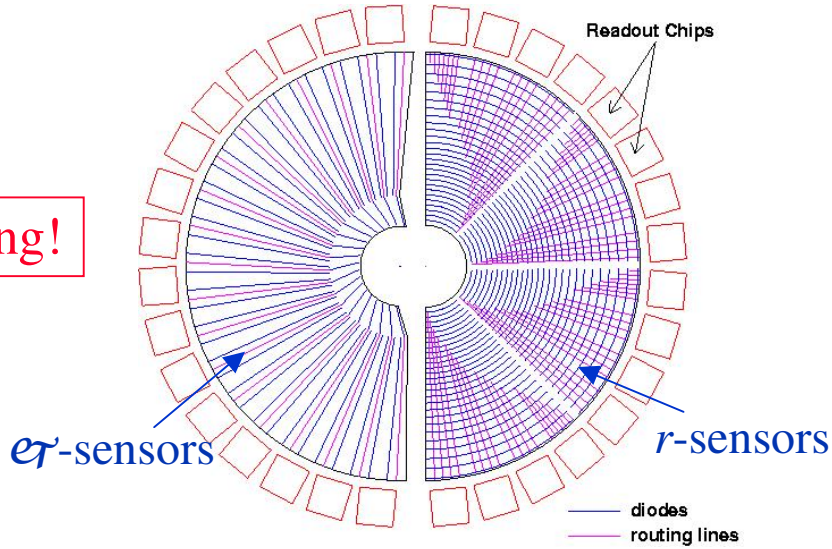
- All components delivered
- Underground assembly ongoing

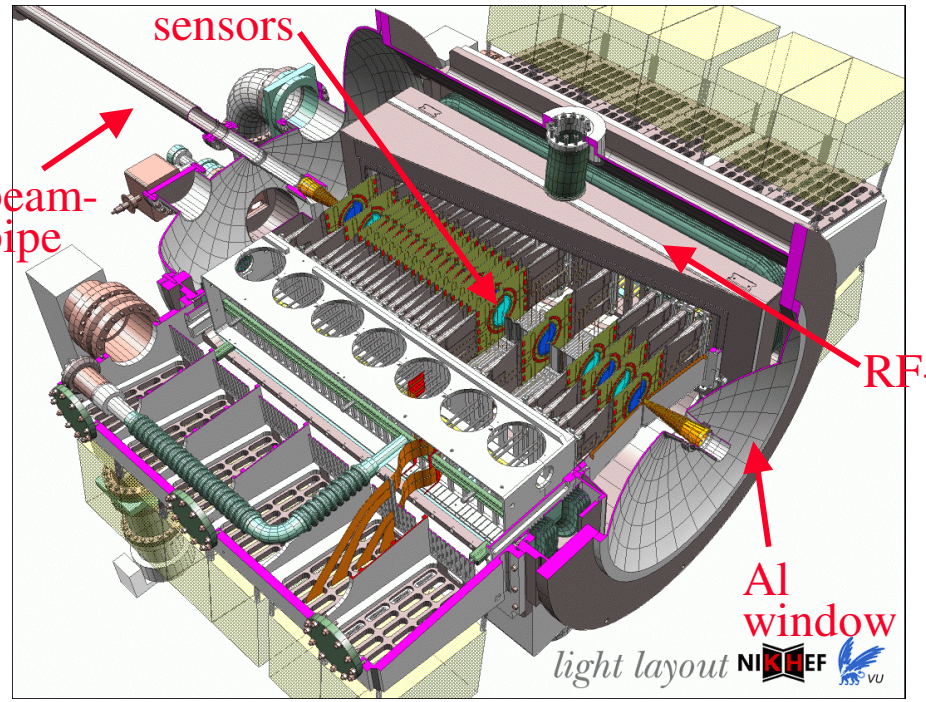
Vertex Locator (VELO)

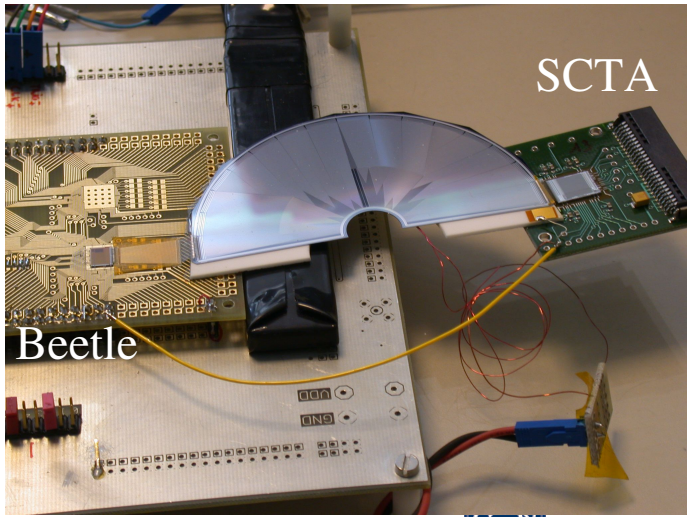
- 21 stations, retractable during injection
- sensitive area starts at only 8 mm from beam axis
- R/φ sensors (single sided, 45° sectors).
- pitch ranges from 37 μm to 103 μm.
- 220 μm thin silicon.
- 180k readout channels

stand-alone tracking!









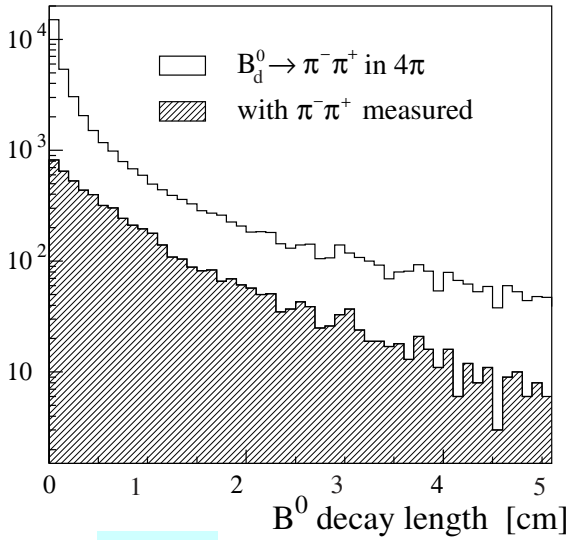
Impact Parameter Resolution

Primary Vertex:

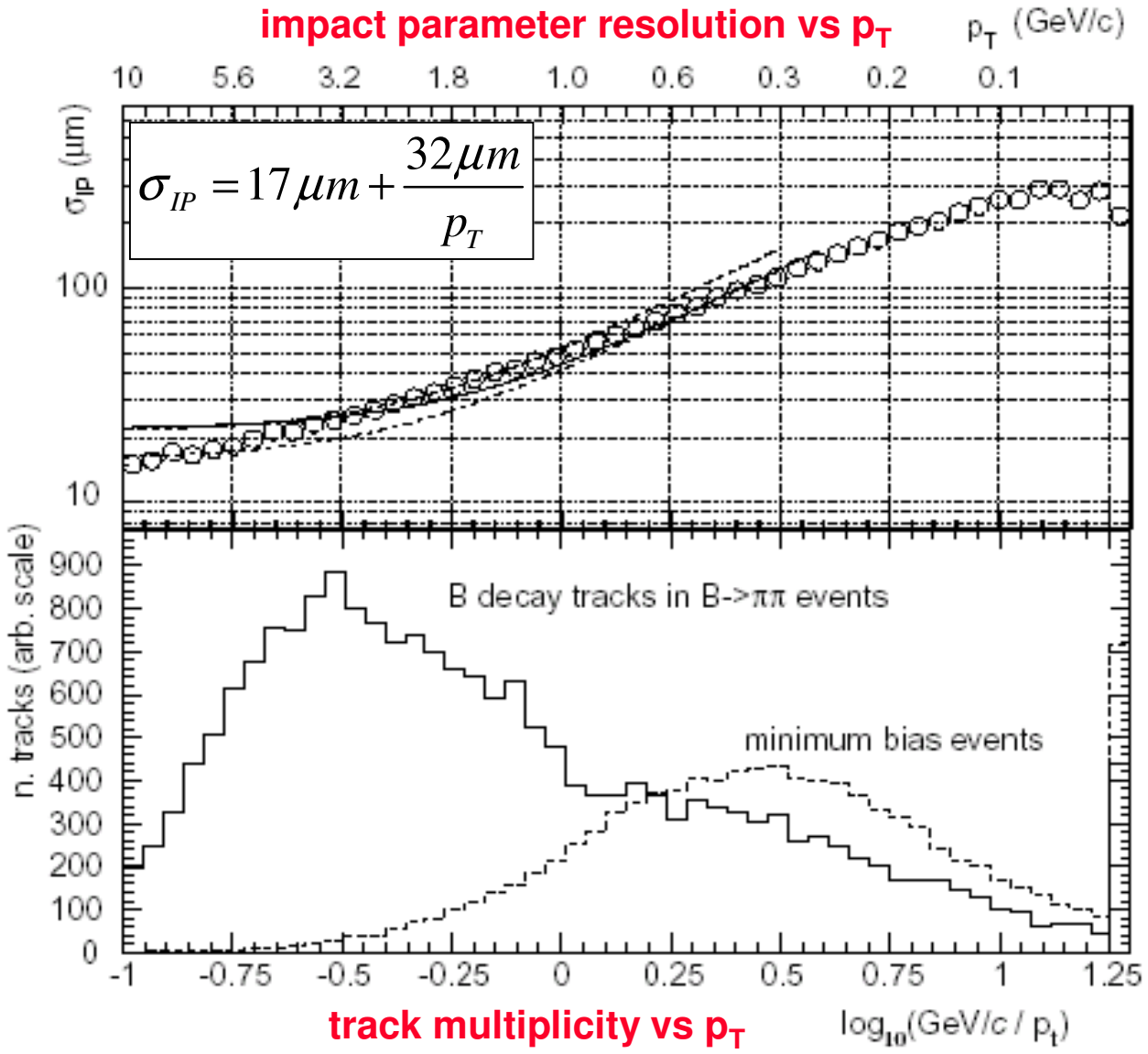
$\sigma_z \sim 47\ \mu m$

$\sigma_x \sim \sigma_y \sim 8\ \mu m$

average decay length:
1 cm for $B_d \to \pi\pi$



impact parameter resolution vs p_T

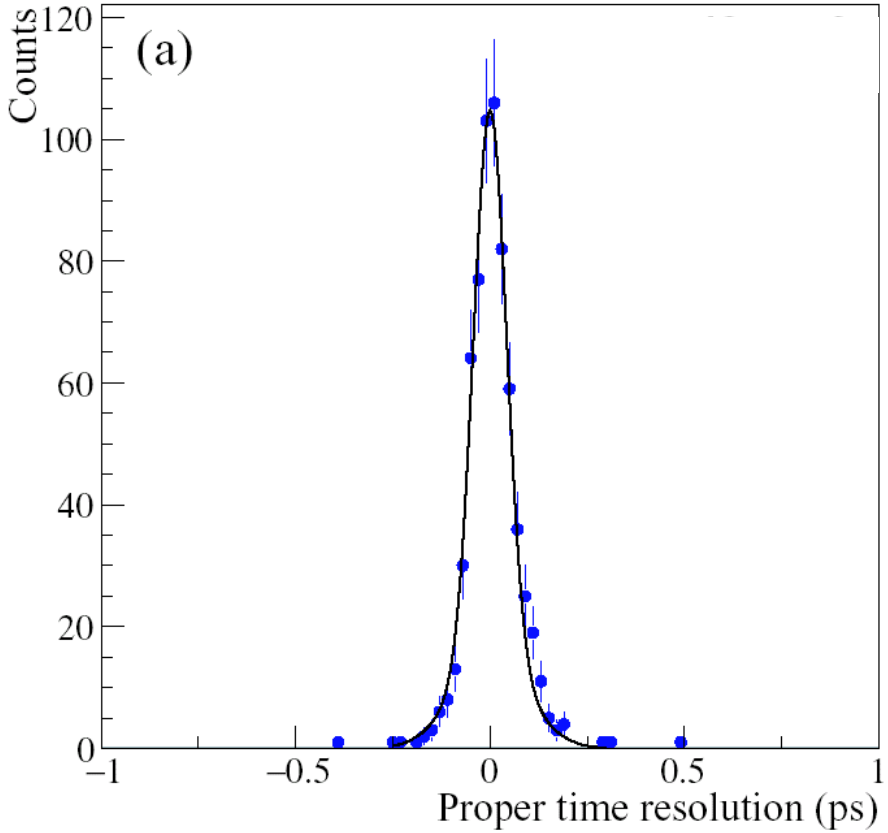


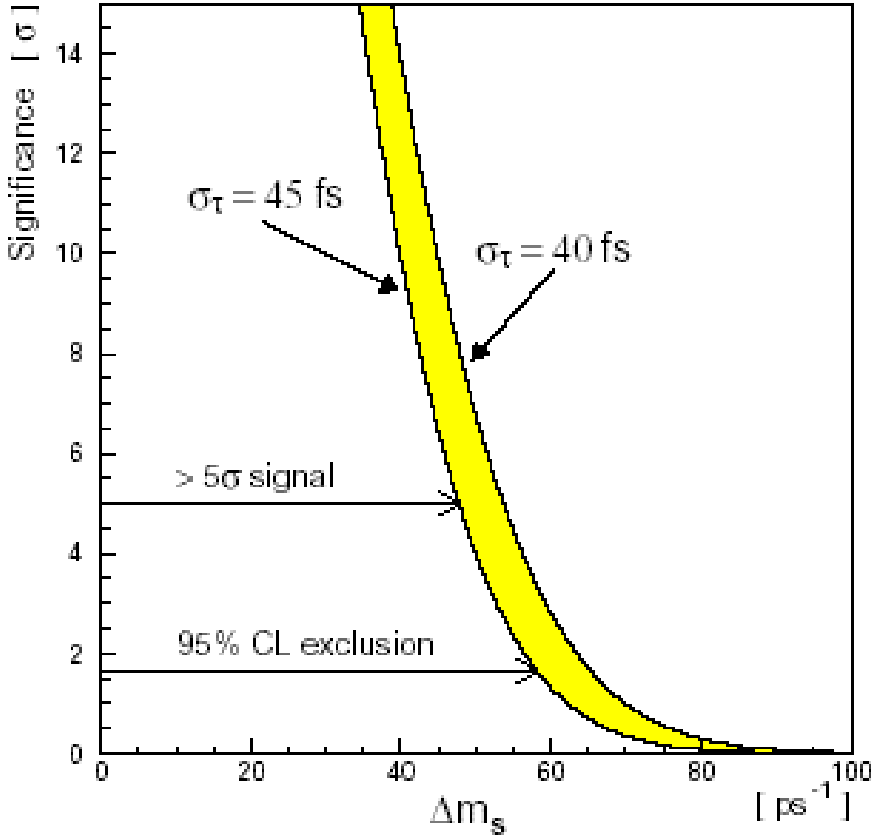
track multiplicity vs p_T

Proper Time Resolution

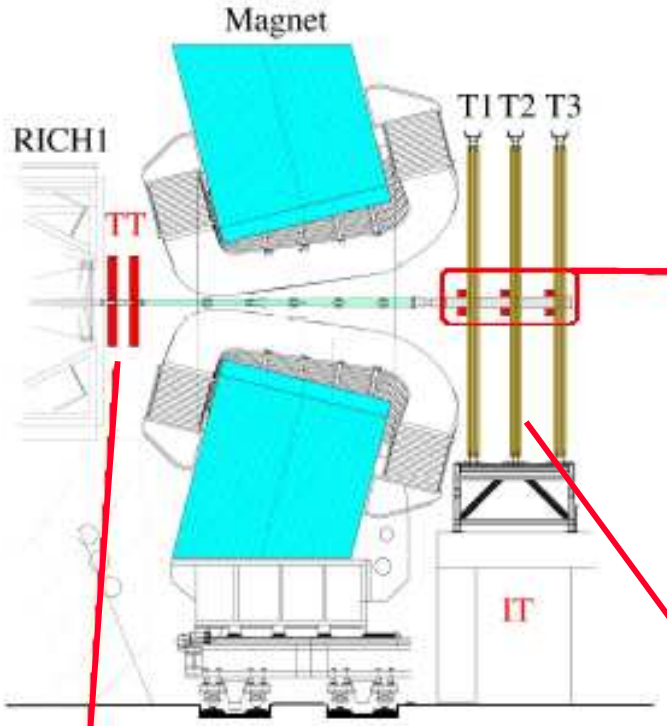
Proper time resolution for $B_s \to D_s \square$: $\blacklozenge_{\blacklozenge}$ ~ 44 fs

measure B_s mixing with >5♦ up to 48 ps^{-1} (x_s=75) in 1 year

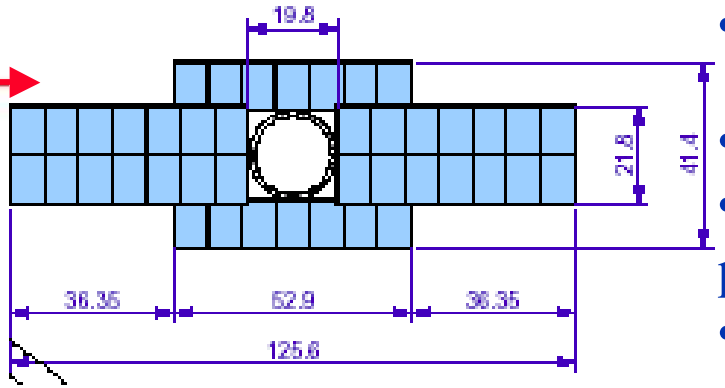




Main Tracker (TT, IT, OT)

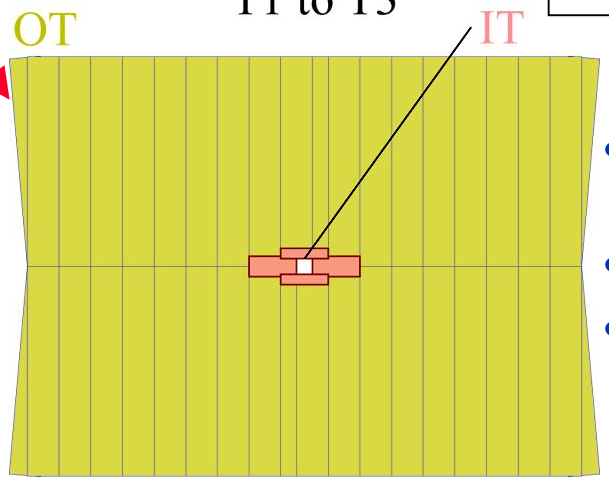


Inner Tracker



- 3 stations with 4 layers each
- 320❍ thin silicon
- 198❍ readout pitch
- 130k readout ch.

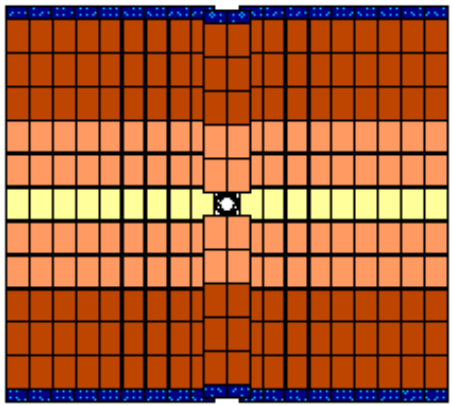
Outer Tracker



~6×5 m²

- 3 stations with 4 double layers
- 5mm straw tubes
- 50k readout ch.

Trigger Tracker

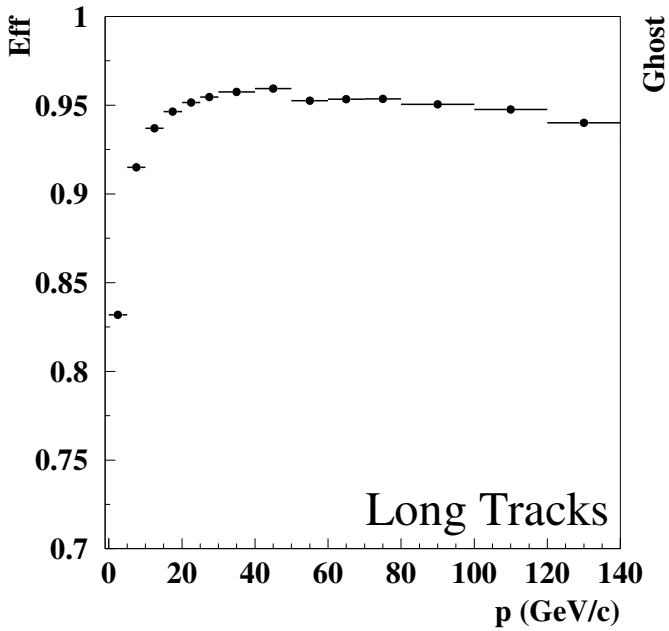


~1.4×1.2 m²

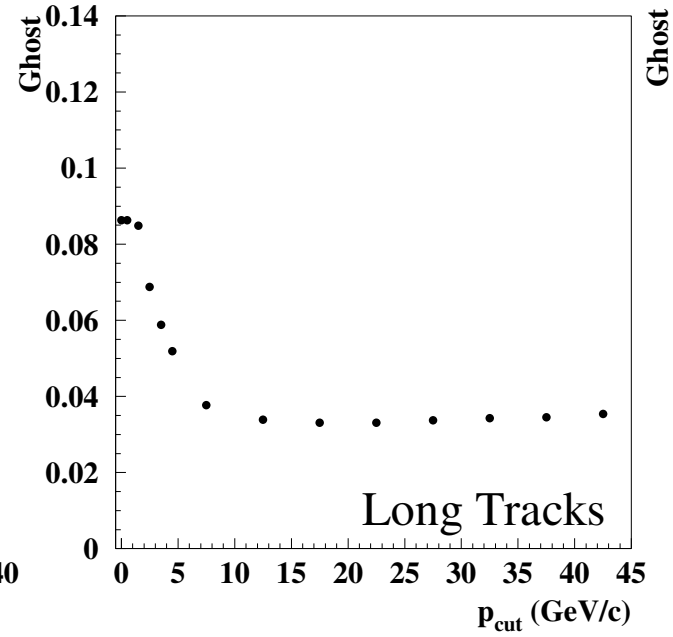
- 2*2 layers
- 500❍ silicon
- 198❍ r/o pitch
- 144k readout ch.

Tracking Performance

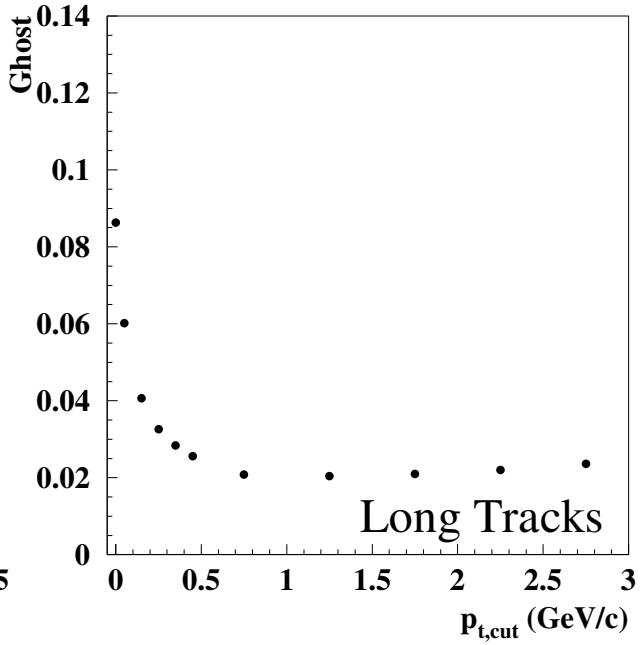
Efficiency vs p



Ghost rate vs p_{cut}



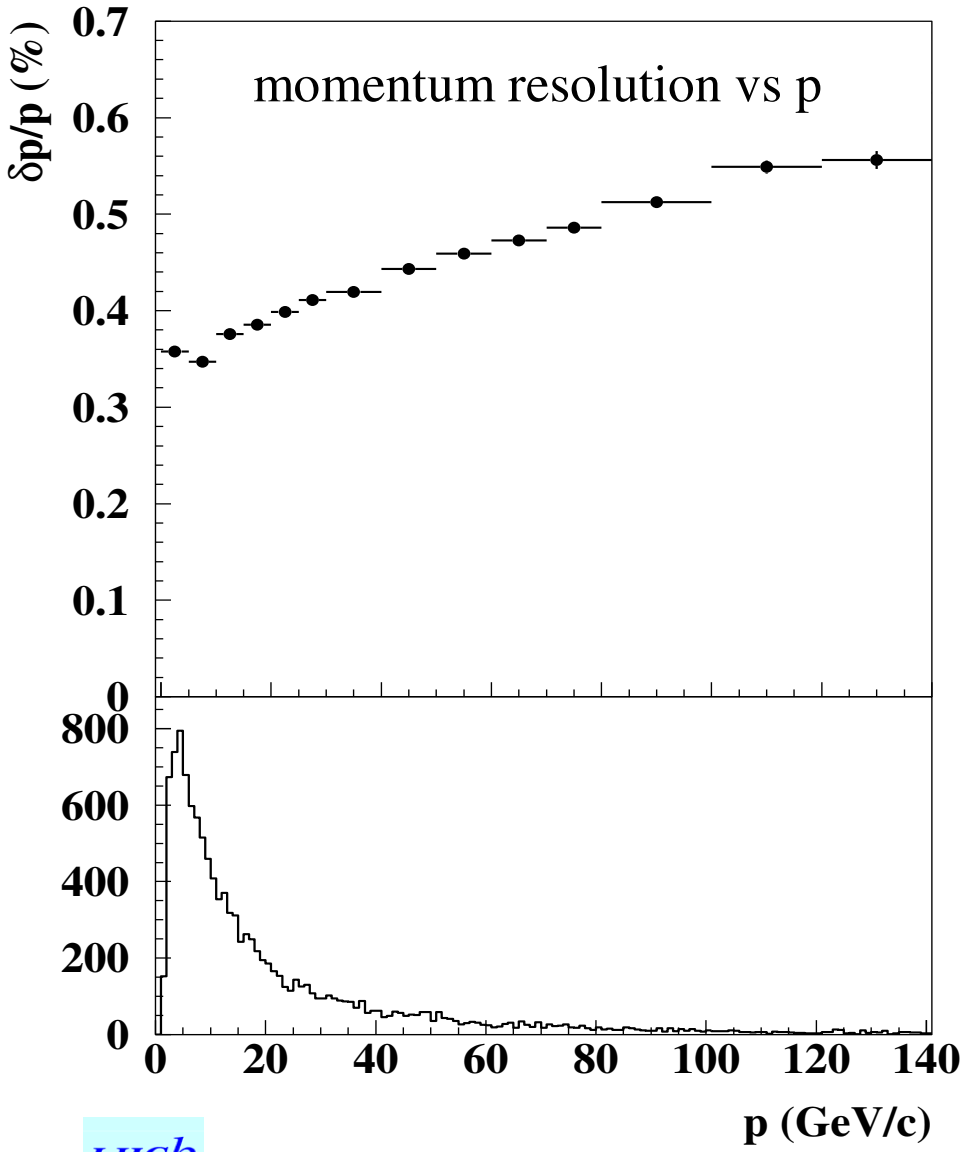
Ghost rate vs p_{Tcut}

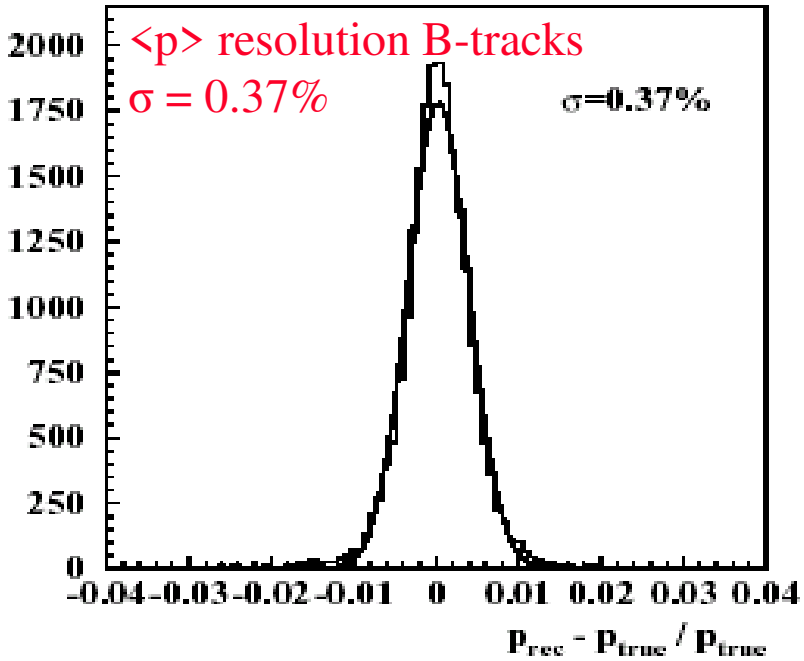


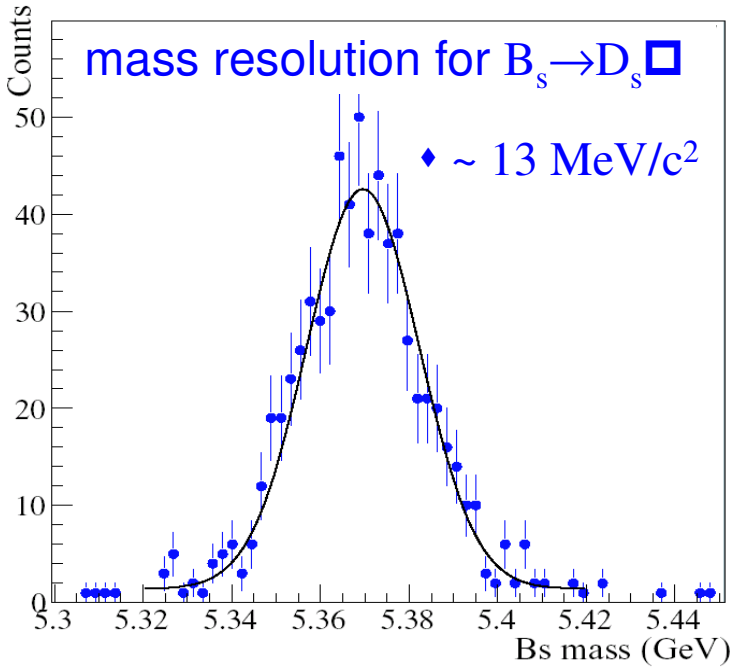
for p>10 GeV => efficiency > 94%

average ghost rate ~ 9%
for p_T>0.5 GeV/*c* => ghost rate ~ 3%.

Momentum and Mass resolutions



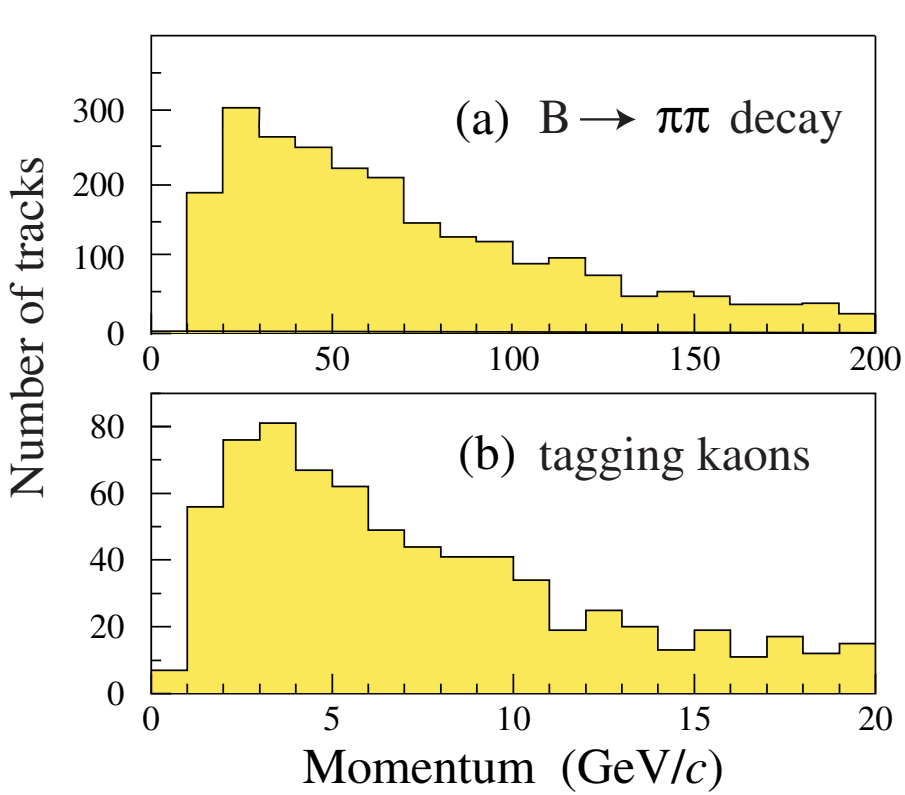


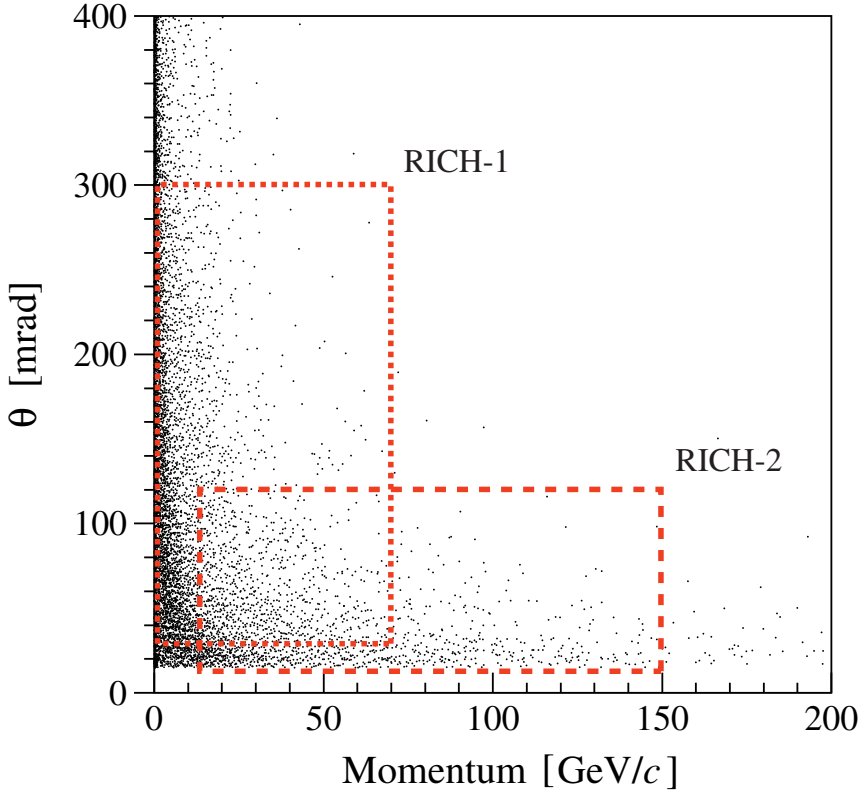


Particle Identification with RICH

Requirements:

- Background suppression => high momentum hadrons in two-body B decays
- B flavour tagging (identify K from b✹c✹s) => low momentum hadrons





➢ RICH system divided into 2 detectors

RICH detectors

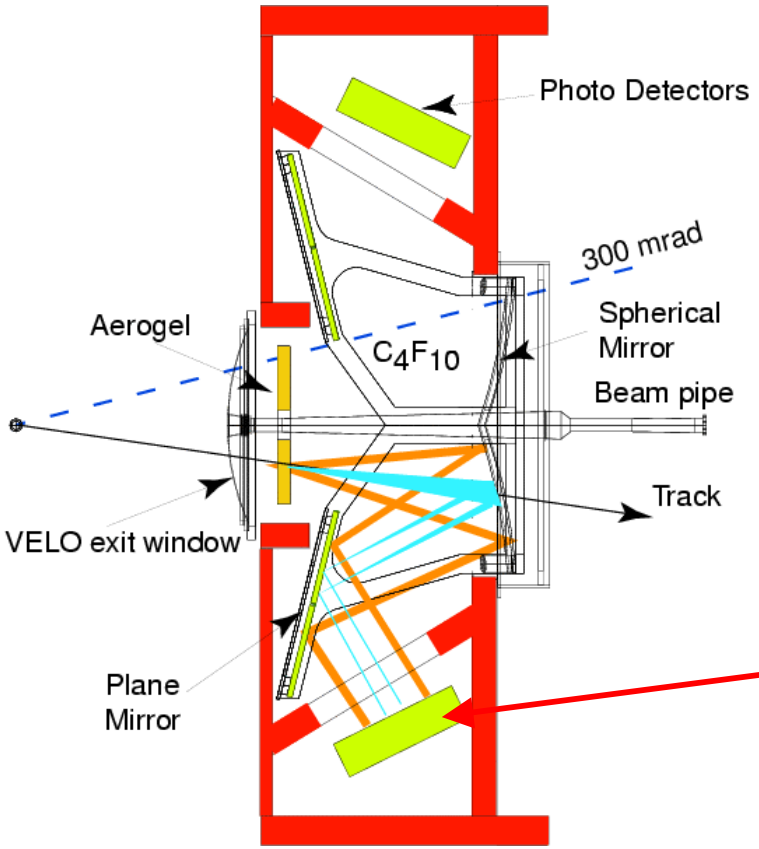
RICH1

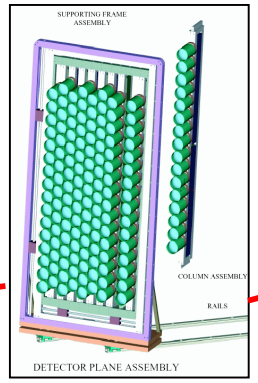
5cm aerogel n = 1.03

4 m^3 C_4F_{10} n = 1.0014

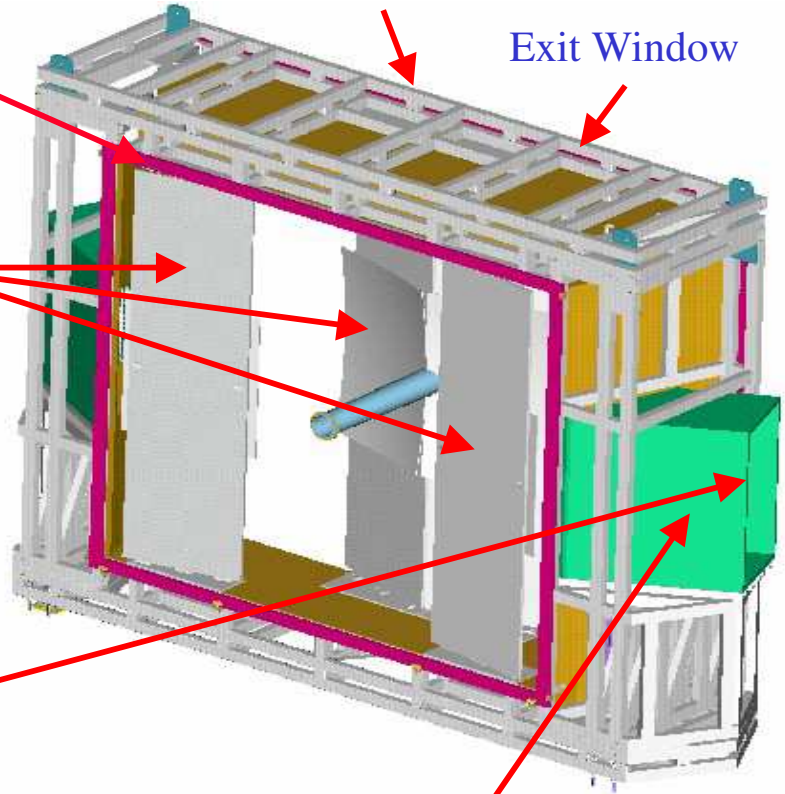
RICH2 (construction started)

100 m^3 CF_4 n = 1.0005





Photon Detectors

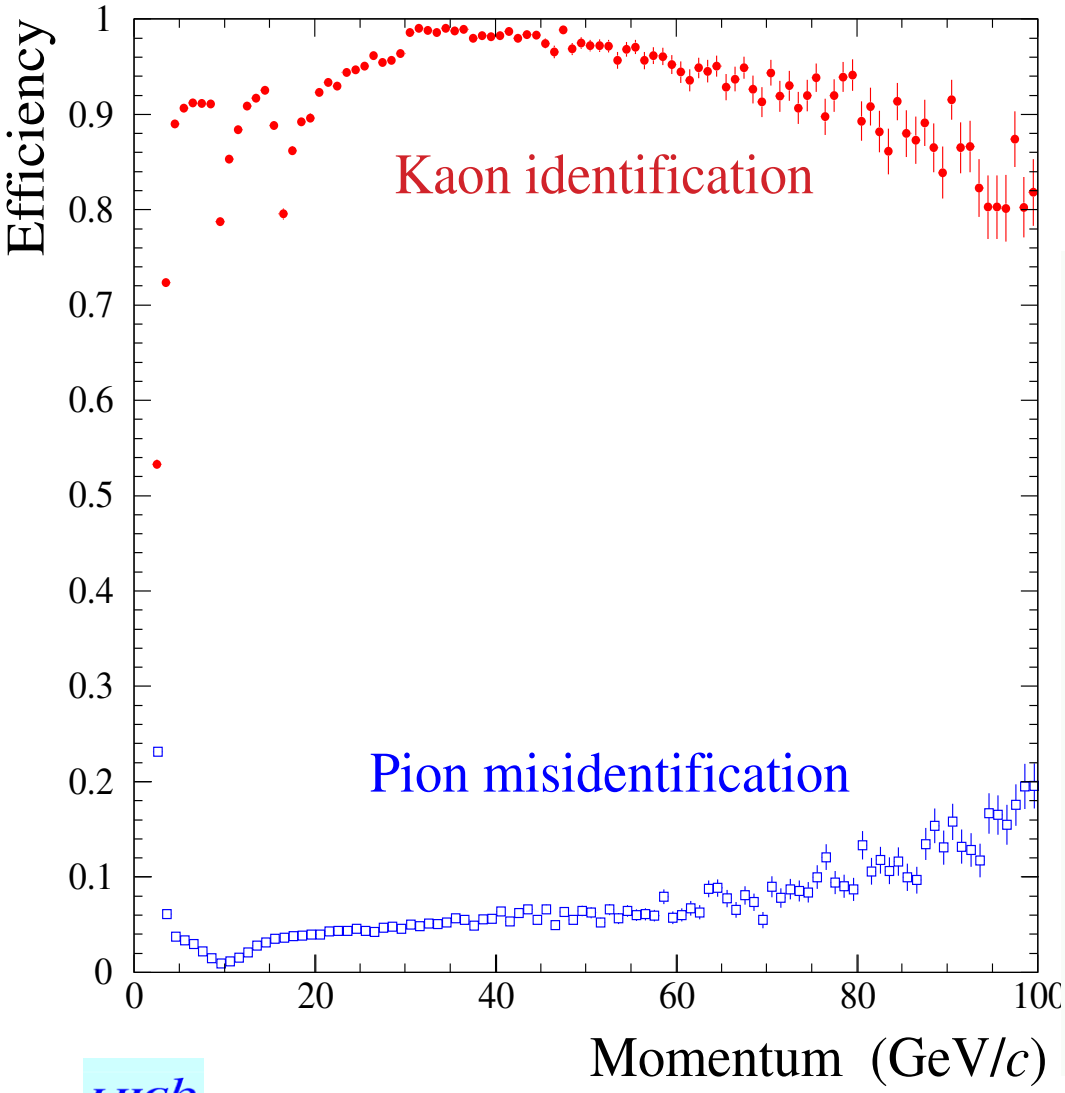


RICH performance

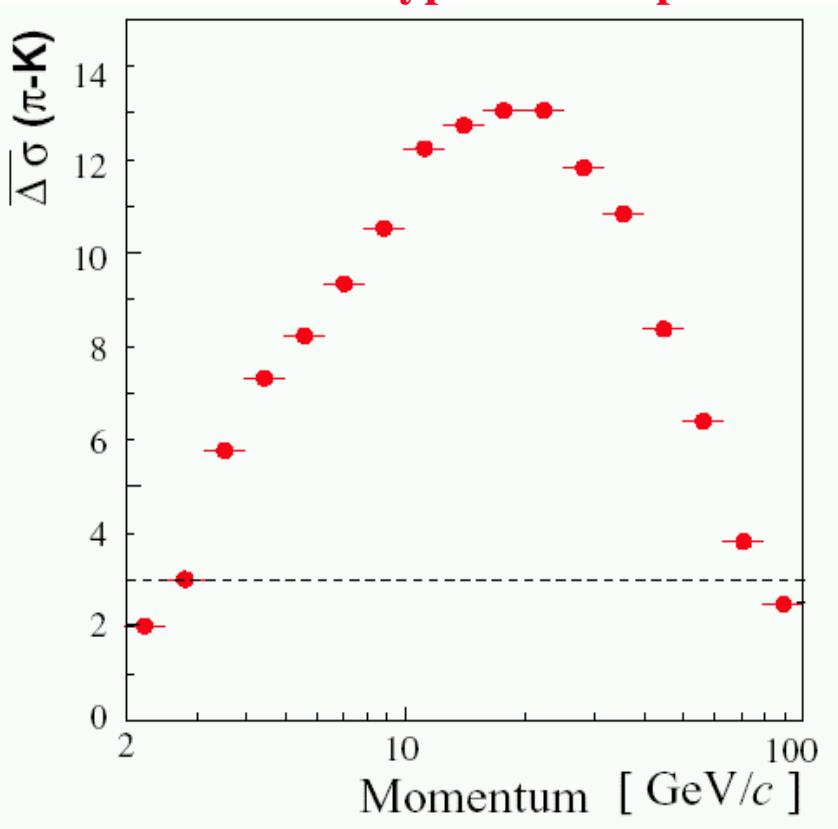
[for selected $B_s \rightarrow D_s$ (KKπ) K]

ln *L*(K-□) >	0	2	4	8
K efficiency	91%	88%	85%	79%
□ misid rate	5.6%	2.9%	1.7%	0.8%

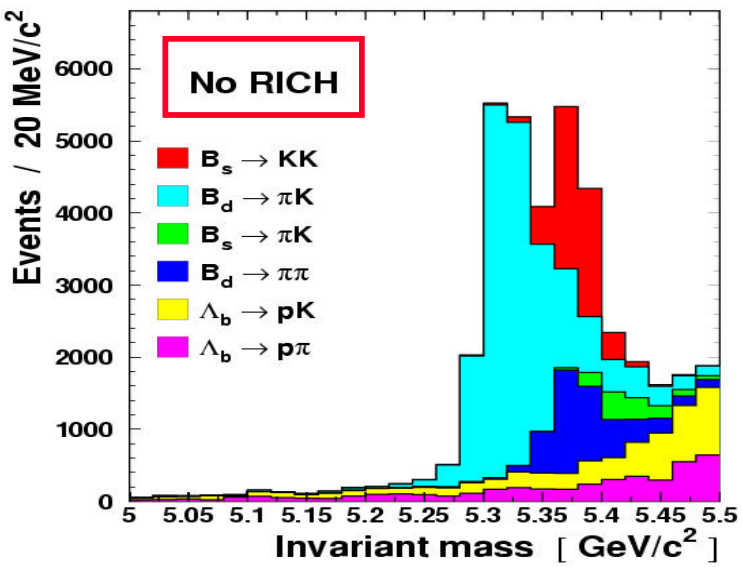
(2< p< 100 GeV)



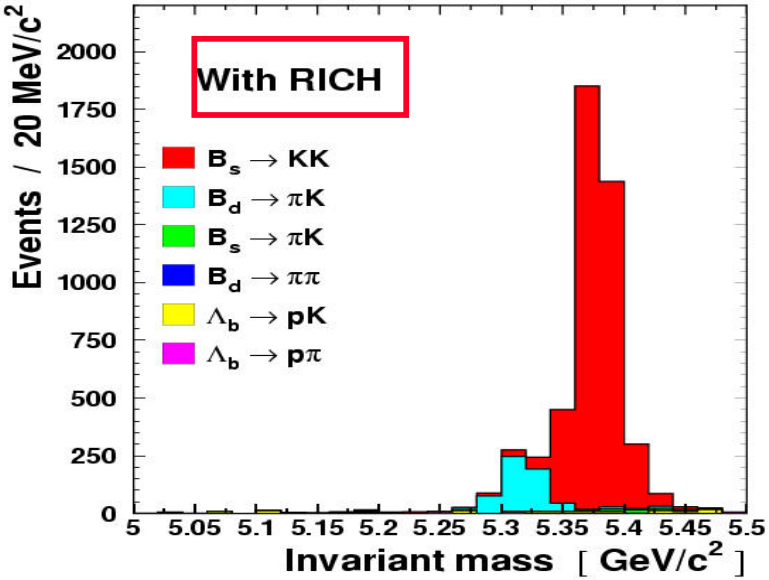
♦ separation between π and K hypothesis vs p

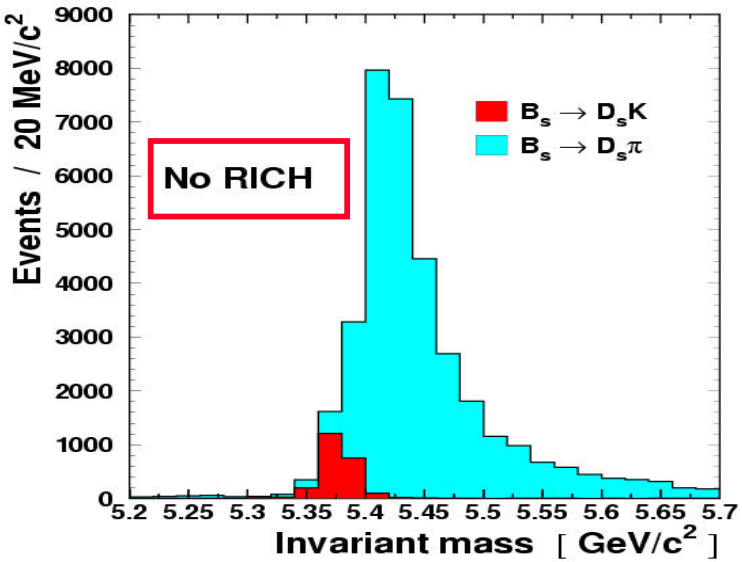


Background rejection with RICH

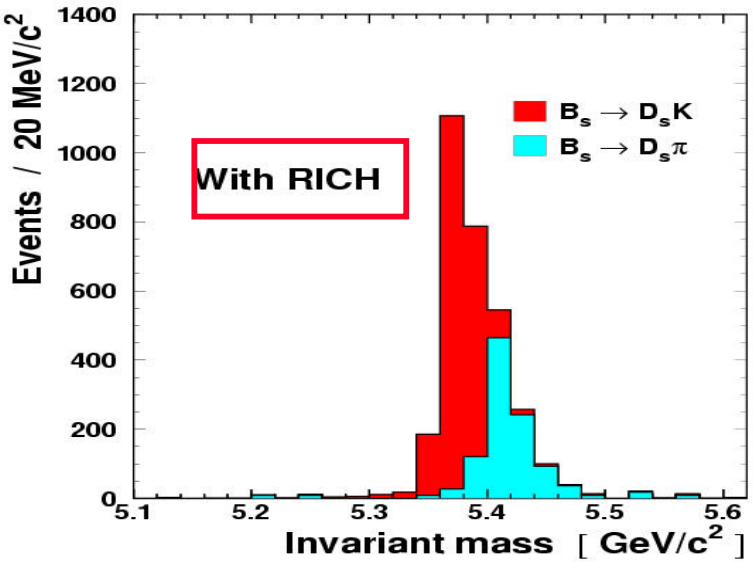


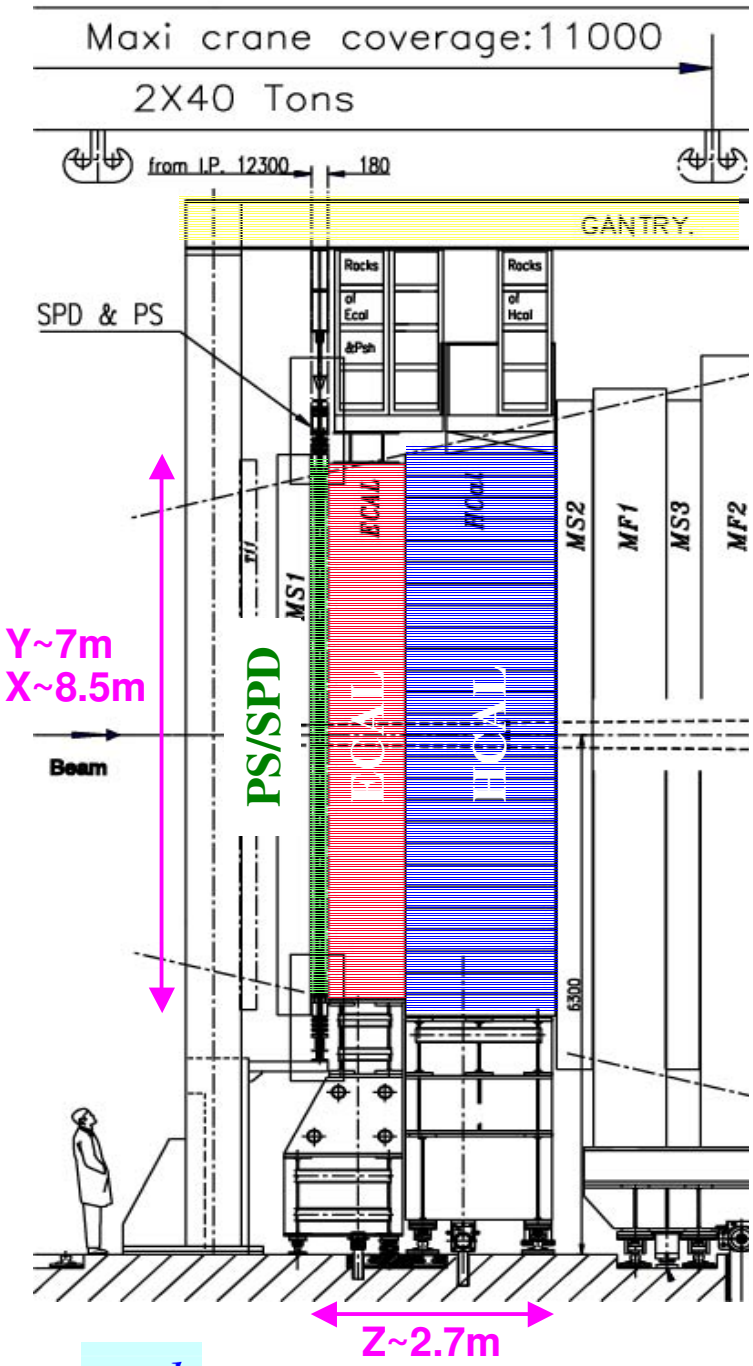
$B_s \to KK$





$B_s \to D_s K$





Calorimeters

Requirements:

Preshower (PS) and
Scintillator Pad Detector (SPD):

- PID for L0 electron and photon trigger
- electron,photon/pion separation by PS
- photon/MIP separation by SPD
- charged multiplicity veto by SPD

ECAL:

- E_t of electrons and photons for L0 trigger
  (e.g. B✹ J/ψ Ks, B✹ K*γ)
- reconstruction of π^0 and prompt γ offline
- particle ID

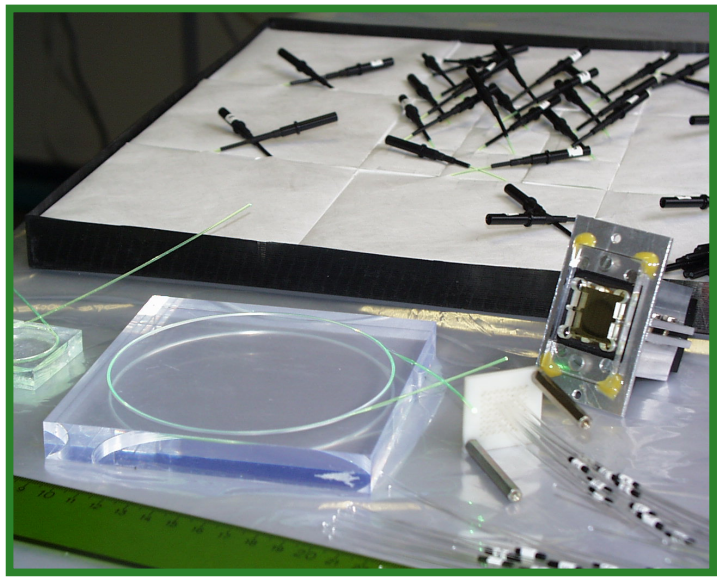
HCAL:

- E_t of hadrons for L0 trigger
  (e.g. B✹ $\pi\pi$, B✹ D_sK)
- particle ID

L0 trigger => Calorimeters readout every 25ns

Calorimeters

ECAL (70% delivered)
5952 channels, 25 X_0 "shashlik" type modules
66 layers of 2mm Pb/ 4mm scintillator
readout via WLS fibers



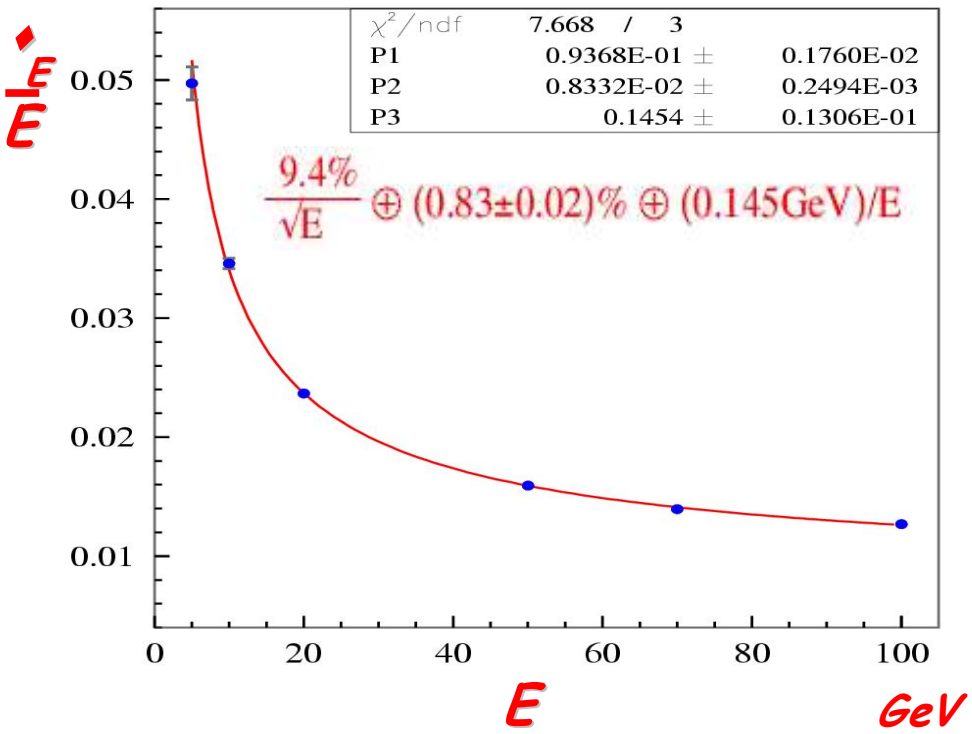
Preshower
(production started)
2.5 X0 lead converter sandwiched between two scintillator planes with 2x5952 scintillating pads

HCAL (15% delivered)
1468 channels, longitudinal-tiles, 5.6 ●
6mm master/4mm spacer, 3mm scintillator
readout via WLS fibers

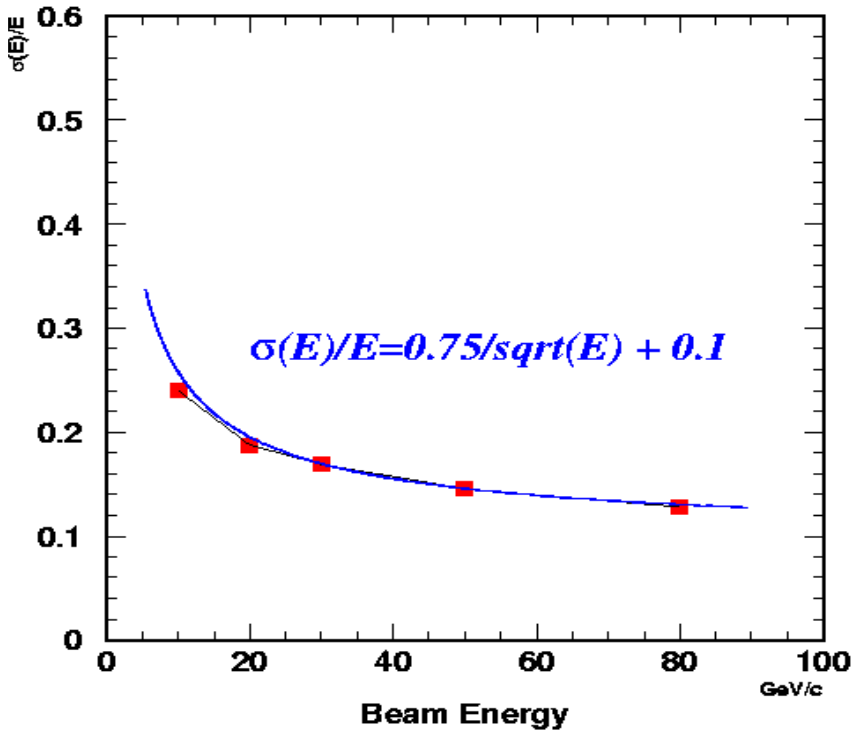
Calorimeters performance

Energy resolution of series modules measured in testbeam

ECAL



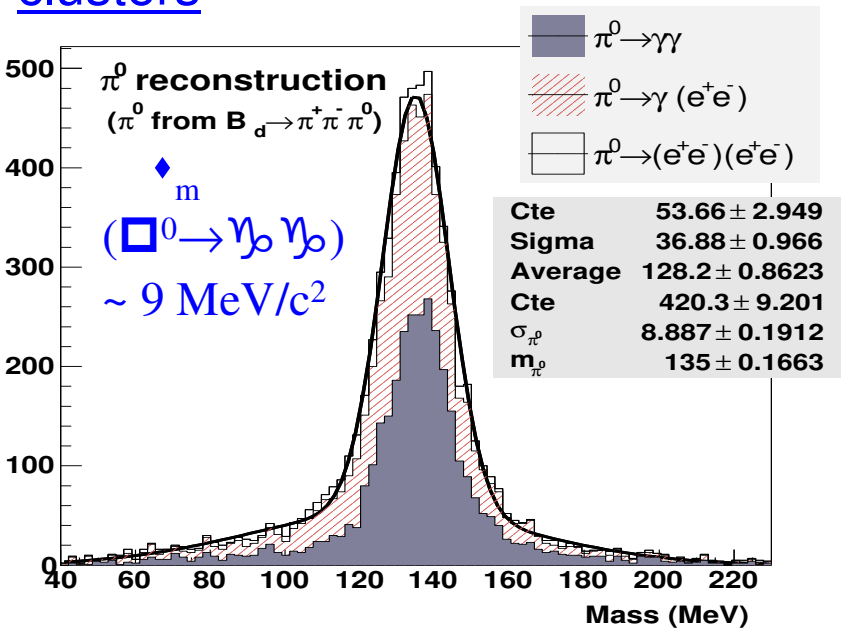
HCAL

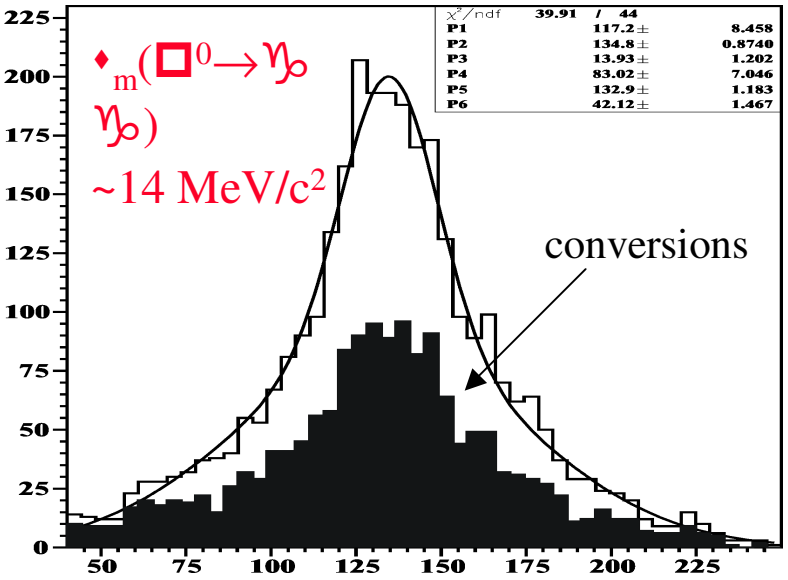


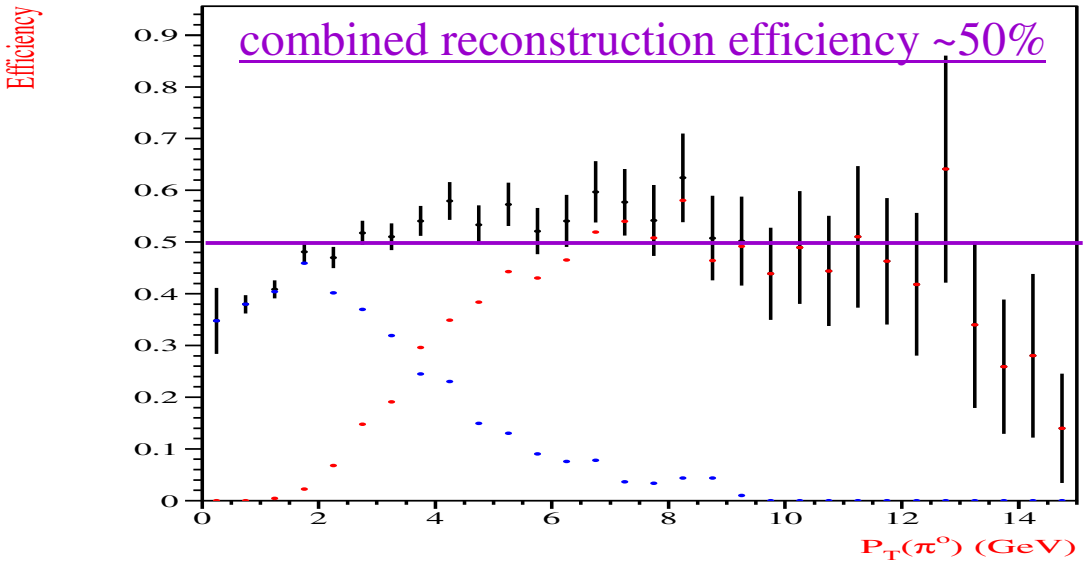
Performance on selected B→□⁺□⁻ □⁰

Two resolved clusters

One merged cluster



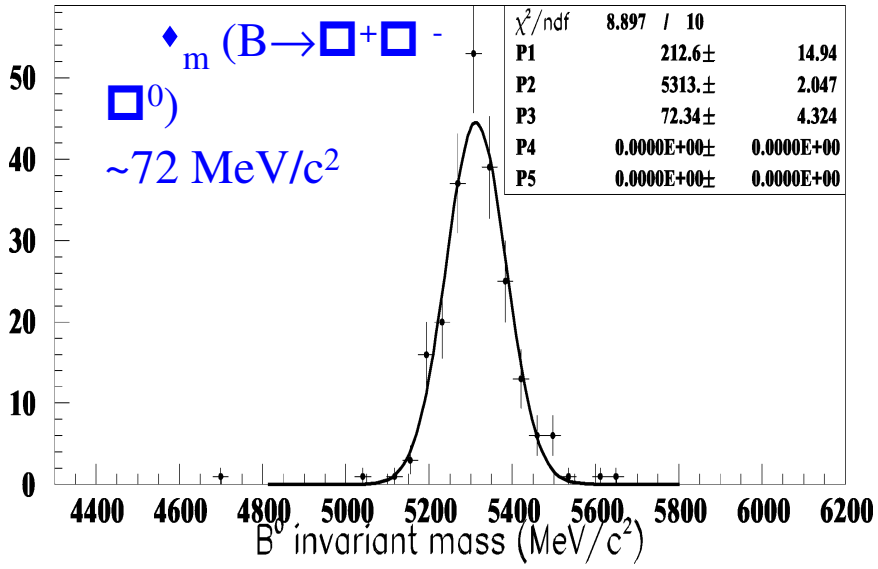


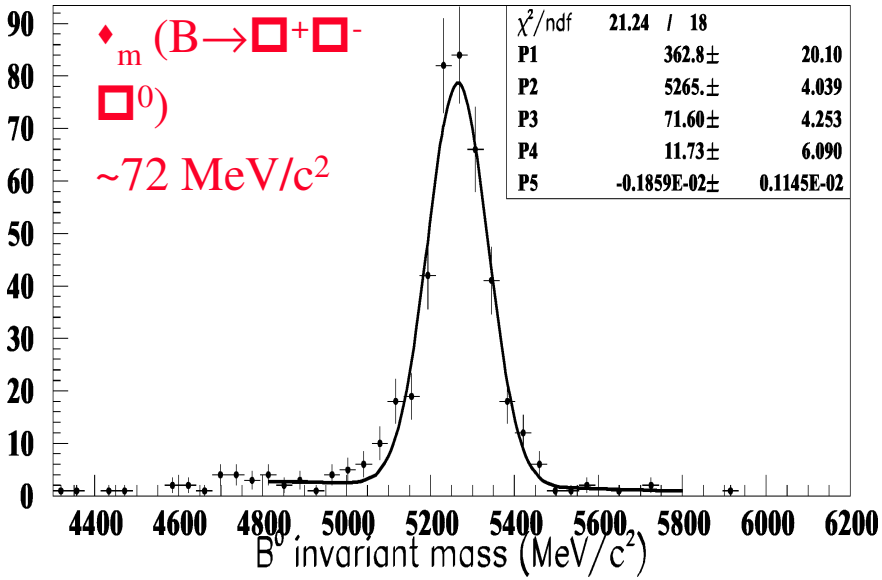


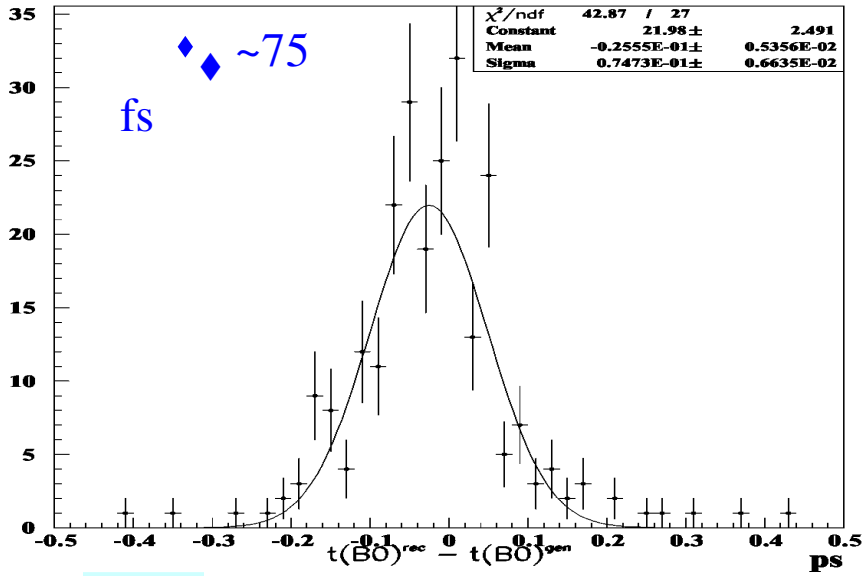
Performance on selected B→□⁺□⁻□⁰

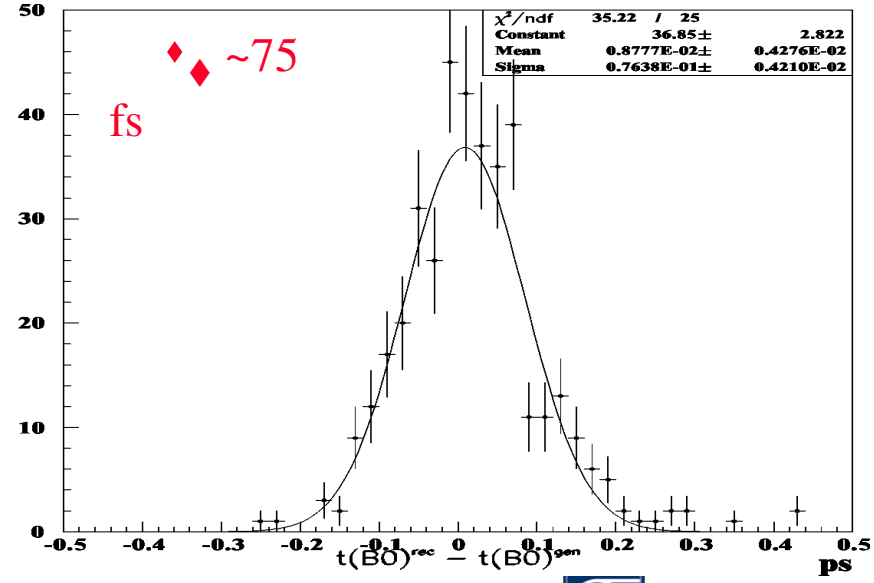
Two resolved clusters

One merged cluster





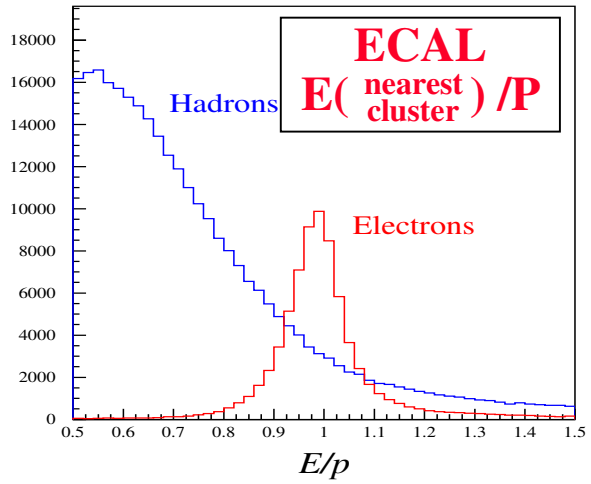


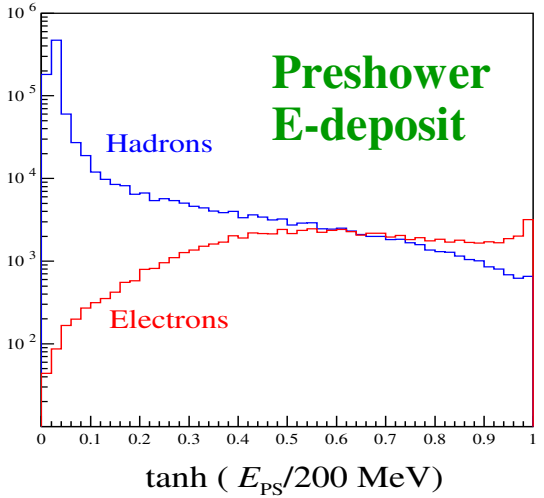


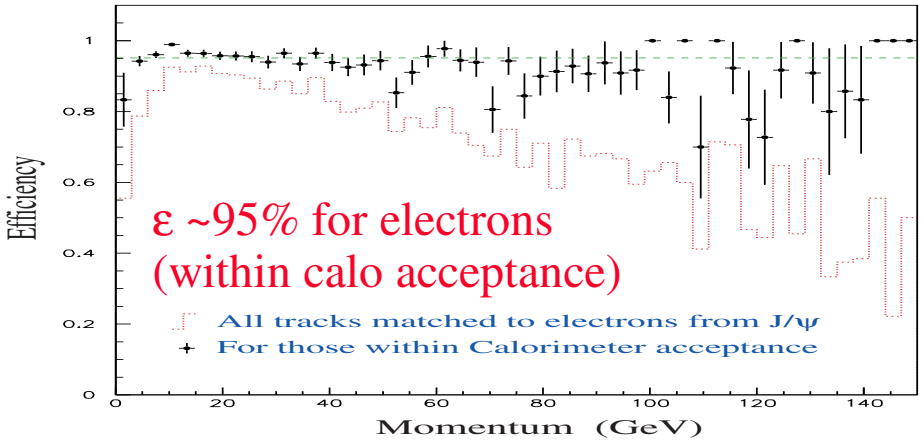
Electron identification

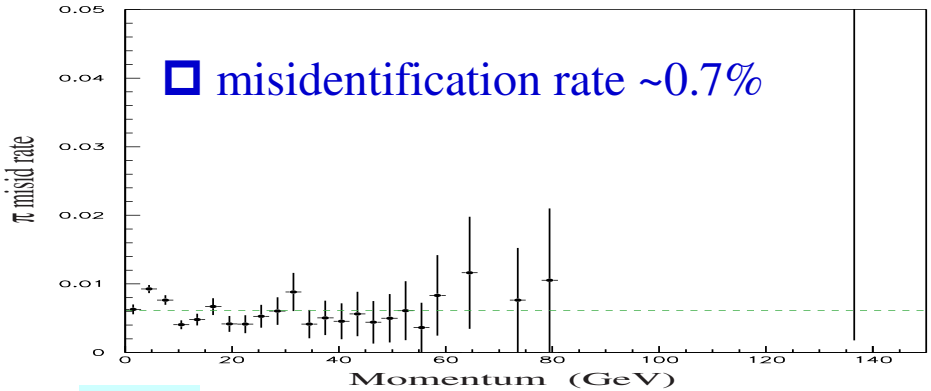
Combined PID with Calorimeters and RICH

[from selected $B_s \to J/\psi(ee)K_S$]

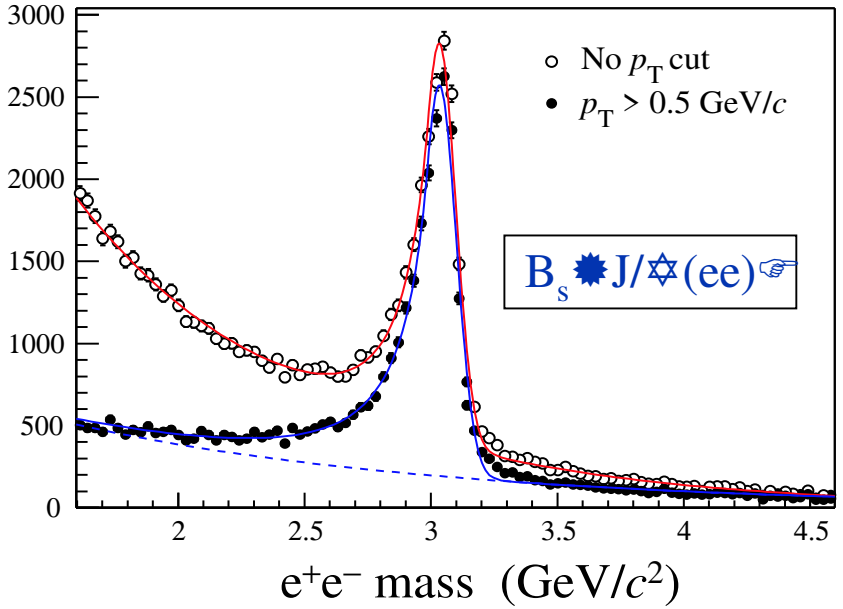








physics performance:
El. Eff. = 78% ; π mis-ID rate 1.0%



Muon system

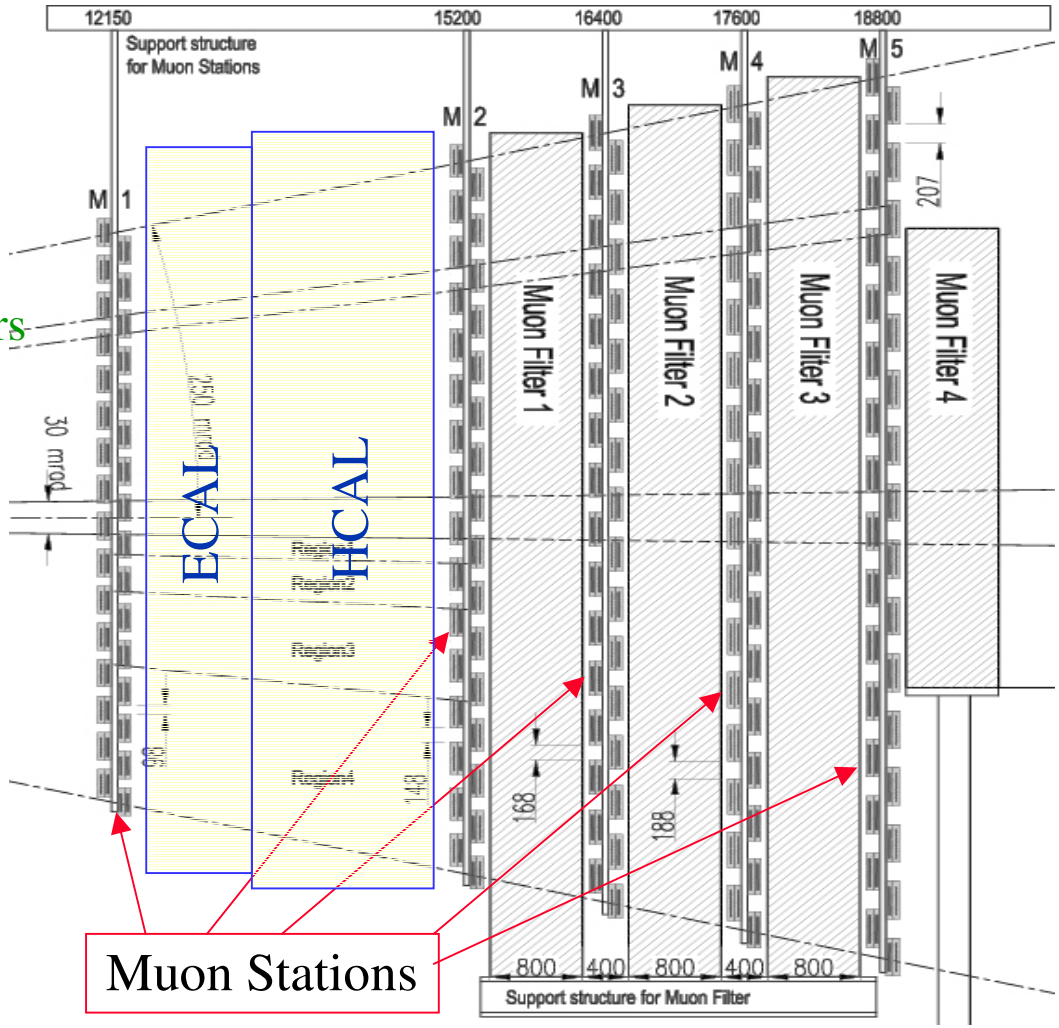
Requirements:

Identify and trigger on muons from decay of B-mesons: $B \rightarrow \mu X$

In particular: $B_d \rightarrow J/\psi(\mu^+\mu^-) K_s$; $B_s \rightarrow J/\psi(\mu^+\mu^-) \phi$; $B_s \rightarrow \mu^+\mu^-$

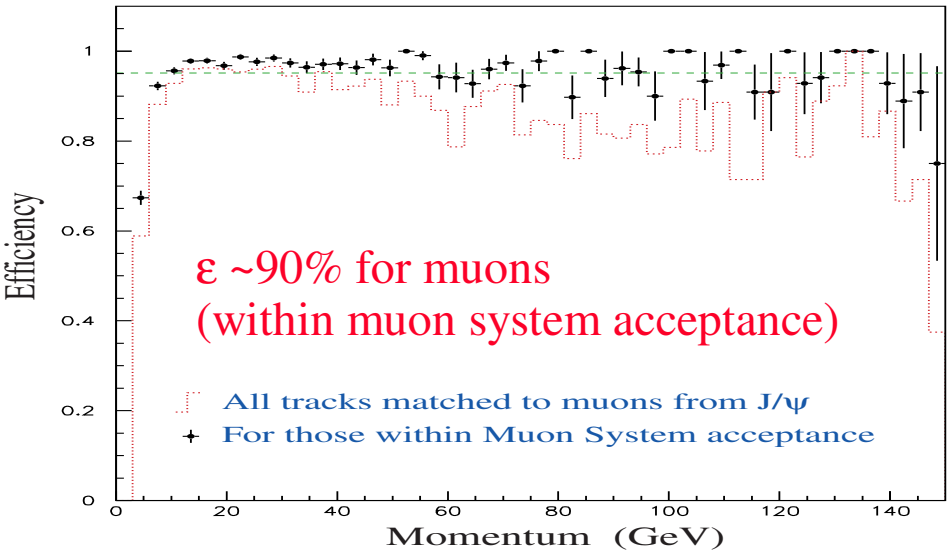
- 4 (1) stations with 4 (2) layers/station
- stations M1+M2 for P_t measurement,
  M2+M3 for trigger track seed,
  M4+M5 for muon track finding
- 435m² of detector area, 1380 chambers
- ~26k readout channels
- hadron absorber thickness of 21 λ

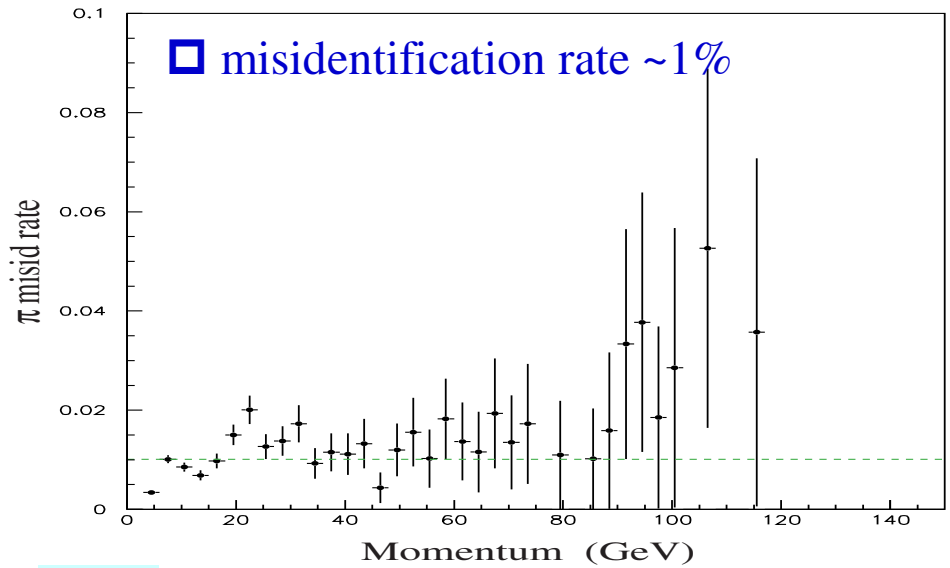
MWPC



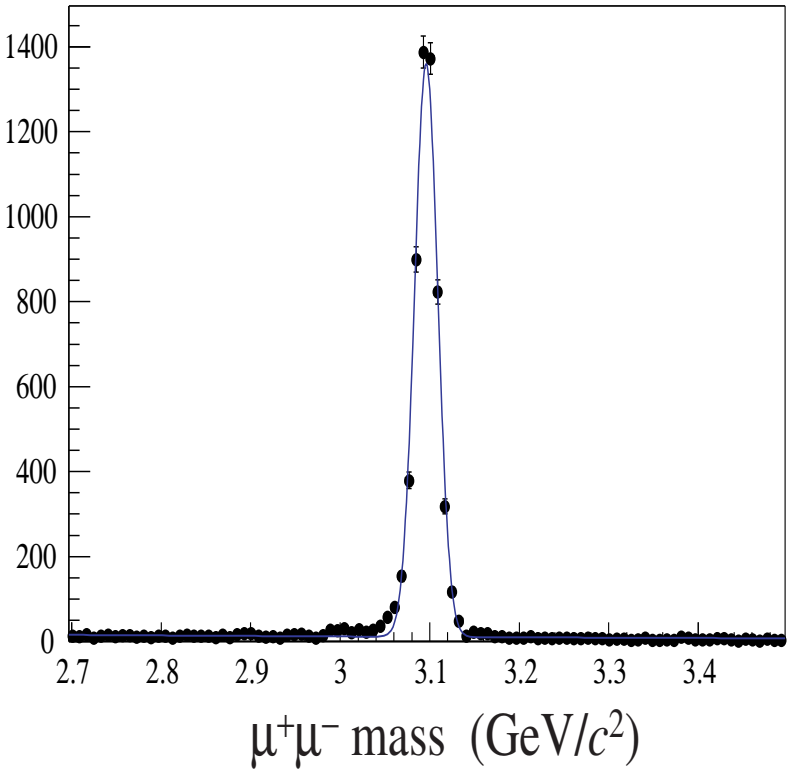
Muon identification

[from selected B_s ✹ J/✡(❍❍)K_S]





B_s ✹ J/✡(❍❍) ☞



physics performance:
μ Eff. = 86%
π mis-ID rate 1.0%

Trigger strategy

40 MHz ✹ Level-0

Calorimeters
Muon System
Pile-up veto

→ p_T of ❍ , h, e, ϒ

1 MHz ✹ Level-1

Vertex Locator
Trigger Tracker
Level-0 objects

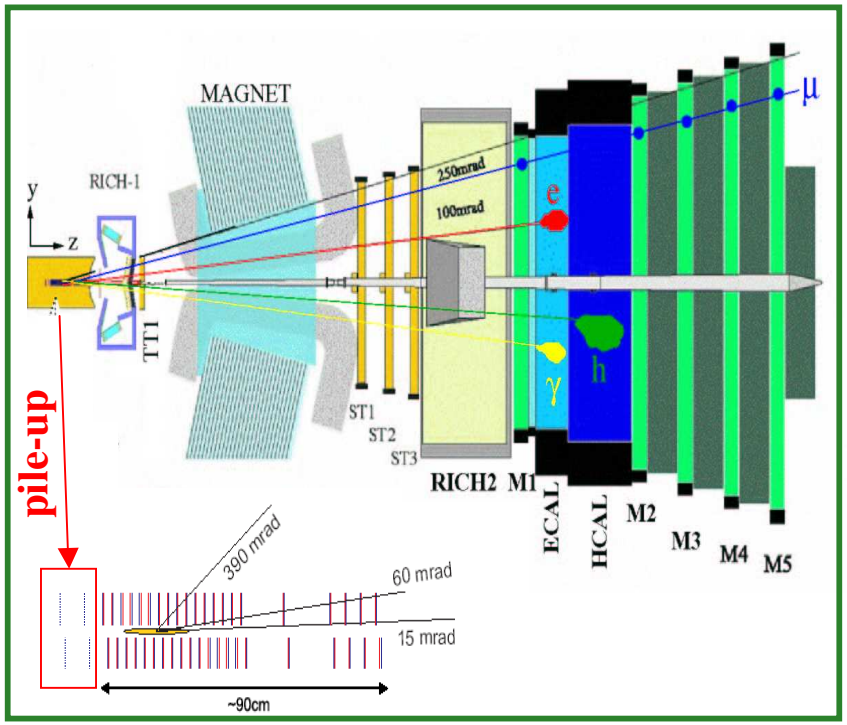
→ impact parameter
rough p_T (~20%)

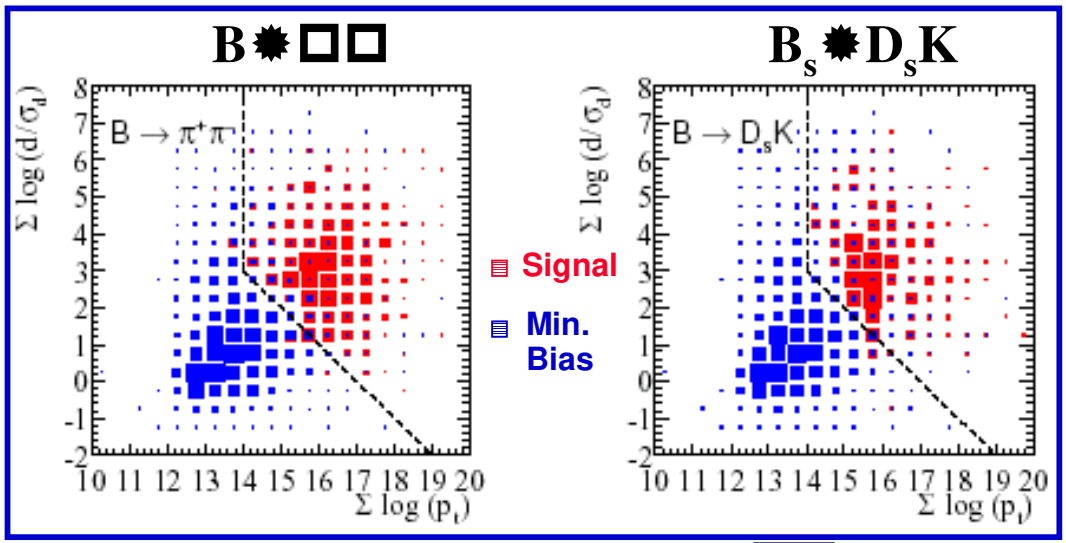
40 KHz ✹ High-Level

Full detector information

→ final state reconstruction

200 Hz ✹ Output



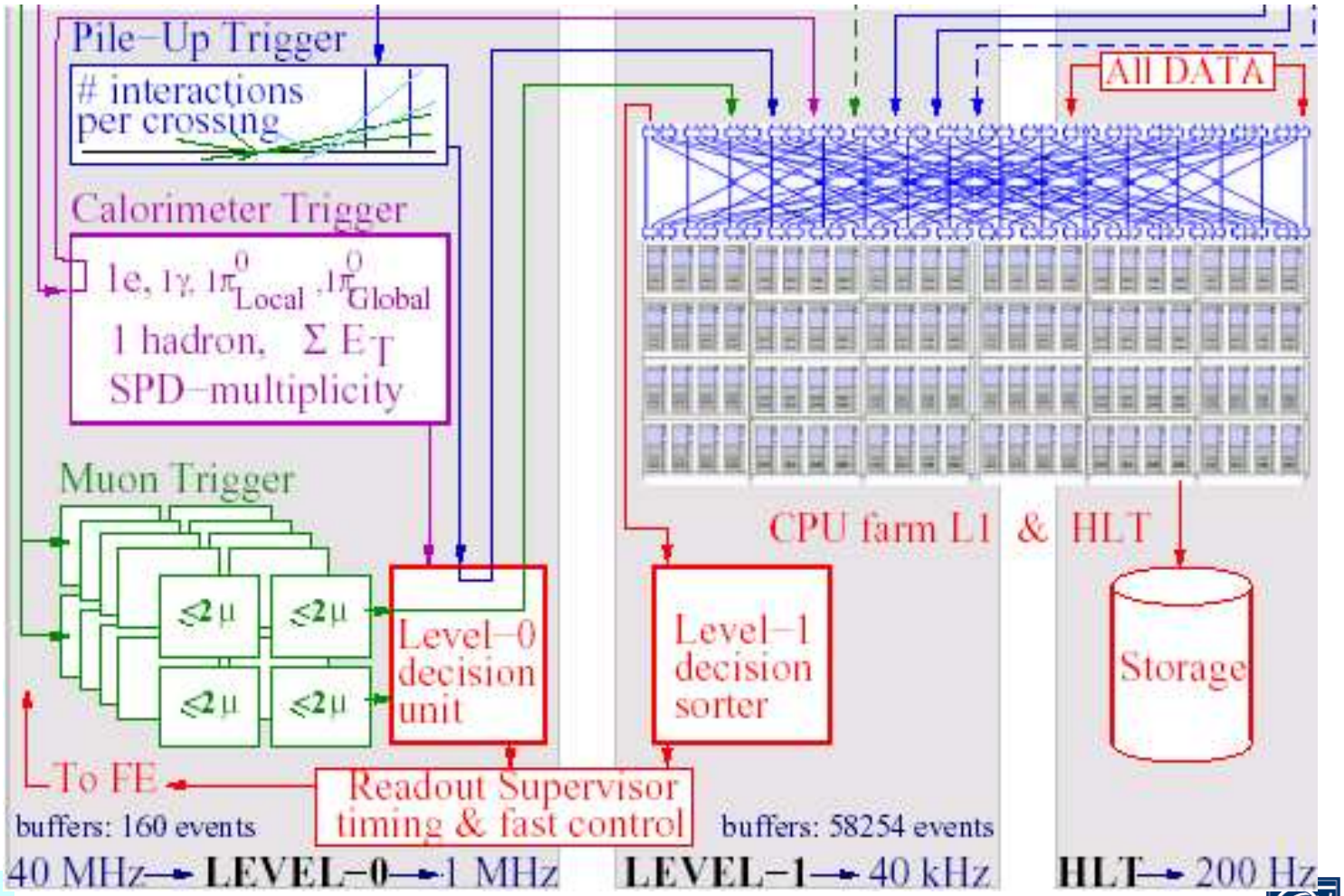


Trigger implementation

- commercial hardware
- flexible (L1 ★ HLT)
- scalable ✹ easy upgrade

L0 = synchronized hardware trigger

L1 = CPU based, asynchronous software trigger, common design with High-Level Trigger and DAQ



Trigger performance

- fast (40MHz)
- robust and flexible (does not rely on a single sub-detector)
- triggers on many B decay topologies including hadronic and neutral final states

L0 efficiency (%) on 'selected' events				
	μ	e, γ_e	*h*	all
B->$\pi\pi$	8	16	51	57
B_s->D_sK	10	12	44	52
B_s->J/ψ(ee)K_S	6	35	23	48
B_s->J/ψ($\mu\mu$)ϕ	89	9	21	90
B_s->K*γ	10	70	34	76

L1 and L0xL1 efficiencies (%)		
	L1	L0xL1
B->$\pi\pi$	60	34
B_s->D_sK	56	29
B_s->J/ψ(ee)K_S	44	21
B_s->J/ψ($\mu\mu$)ϕ	71	64
B_s->K*γ	46	35

preliminary

Event reconstruction and yields

1 year = 2 fb $^{-1}$

$L = 2\times10^{32}$ cm^{-2}s^{-1}

$$\text{yield} = \int_{\text{year}} L(t)dt \times \sigma_{b\bar{b}} \times 2 \times \text{Prob}(b \to b-\text{hadron}) \times \prod_{i} \text{BR}_i \times \varepsilon_{\text{tot}}$$

preliminary

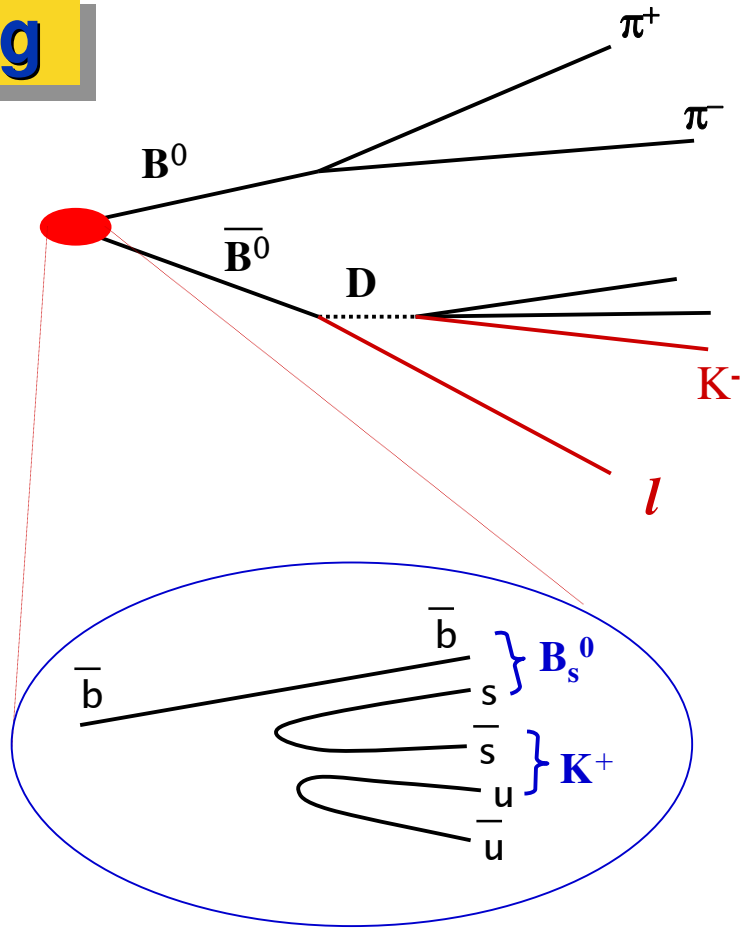
$\varepsilon_{tot} = \varepsilon_{det} * \varepsilon_{rec/det} * \varepsilon_{sel/rec} * \varepsilon_{trig/sel}$ = 12.2% * 91.6% * 19.6% * 32.6% = 0.71%

- ε_{det} : detection eff. (incl. geom. acc. in 4π and all material effects)
- $\varepsilon_{rec/det}$: reconstruction efficiency on detected events (track finding eff., neutral cluster rec.)
- $\varepsilon_{sel/rec}$: efficiency of offline selection cuts on reconstructed events (rejecting background)
- $\varepsilon_{trig/sel}$: combined L0+L1 efficiency on offline selected events (including pile-up veto rate reduction)
- B/S from 10 million incl. $b\bar{b}$ back.

Channel	ε_{tot}	Yield	B/S
$B^0 \to \pi^+\pi^-$	0.71 %	27 k	<0.7
$B^0 \to K^+\pi^-$	0.96 %	139 k	0.10±0.03
$B_s \to K^+K^-$	1.02 %	38 k	<0.3
$B_s \to D_s^-\pi^+$	0.31 %	87 k	0.55±0.15
$B_s \to D_s^-K^+$	0.62 %	6.1 k	<4.2
$B_s \to J/\psi\,(\mu^-\mu^+)\phi$	1.67 %	100 k	<0.3
$B^0 \to J/\psi\,(\mu^-\mu^+)\,K_S$	1.07 %	166 k	0.61±0.09
$B^0 \to \rho\pi$	0.03 %	4 k	<7
$B^0 \to K^{0*}\gamma$	0.16 %	35 k	<0.7
$B_s \to \phi\,\eta_c$	0.22 %	9.4 k	<2.4

Flavour tagging

Knowledge of flavour at birth is essential for the majority of ~~CP~~ measurements



tagging strategy:

- opposite side lepton tag (b ✹ l)
- opposite side kaon tag (b ✹ c ✹ s) (RICH, hadron trigger)
- same side kaon tag (for B_s)
- vertex charge tagging (for charged B)

sources for wrong tags:

B_d-$\overline{B}_d$ mixing (opposite side)

b ✹ c ✹ l (lepton tag)

conversions…

effective efficiency:

$$\varepsilon_{eff} = \varepsilon_{tag} (1-2\ \blacklozenge_{tag})^2$$

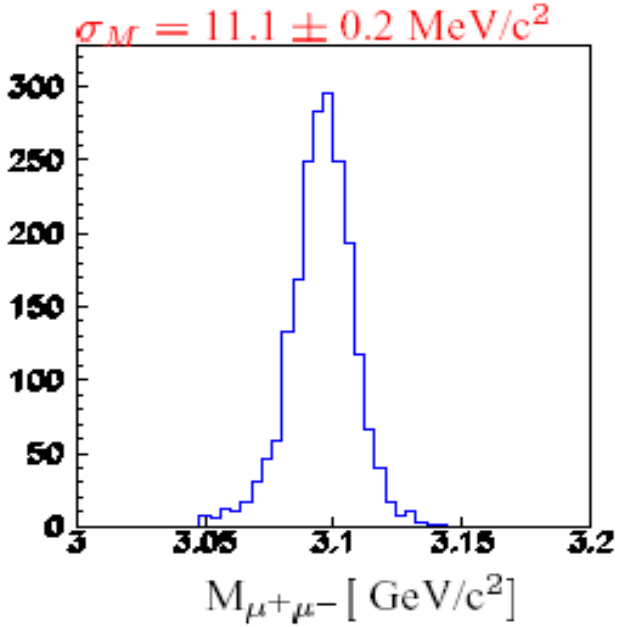
preliminary

Combining tags	εtag [%]	ωtag [%]	εeff [%]
$B_d \rightarrow \pi\pi$	41	35	4
$B_s \rightarrow K K$	48	33	6

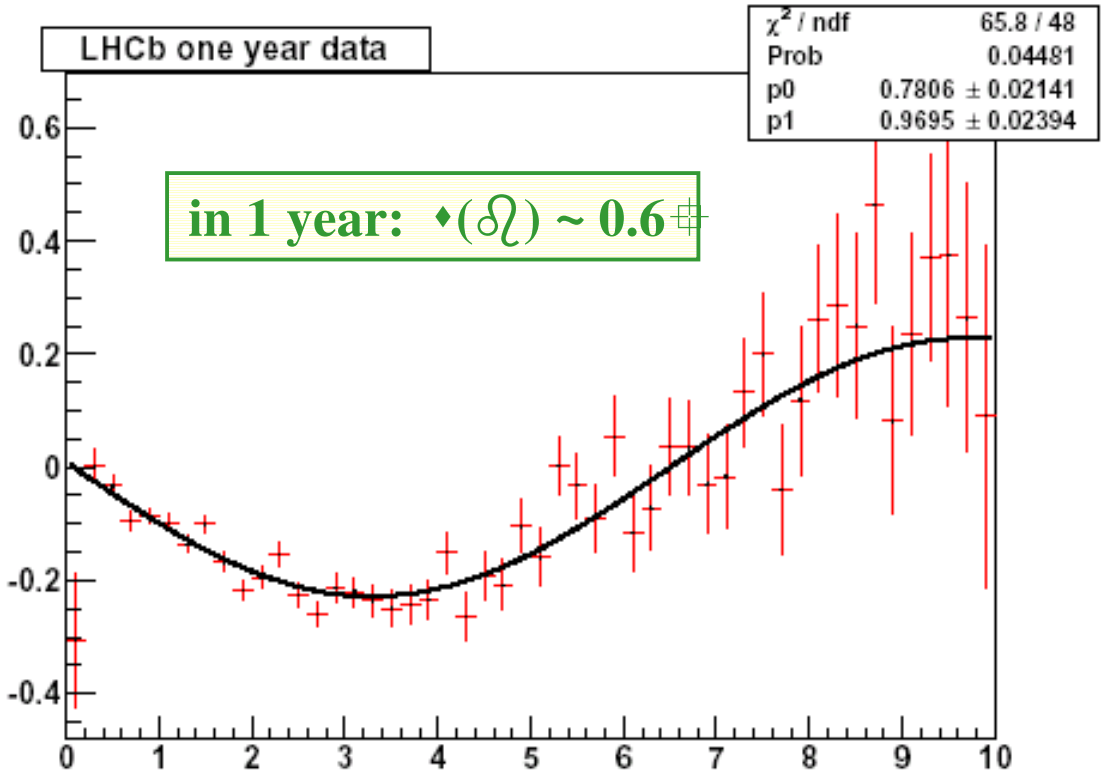
β from B → J/ψ K_S

(see talk by Jeroen Van Hunen)

- "gold-plated" decay channel at B-factories for measuring the B_d- $\bar{B}_d$ mixing phase
- needed for extracting β from $B \to \psi K_S$ and $B_s \to K K$, or from $B \to D^* K$
- in SM $A_{CP}^{dir} = 0$, non-vanishing value ☺(0.01) could be a signal of Physics Beyond SM
- precision measurement important



$$A_{CP}^{th}(t) = A_{CP}^{dir} \cdot \cos(\Delta m_d \cdot t) + A_{CP}^{mix} \cdot \sin(\Delta m_d \cdot t)$$



$B \to J/\psi(\mu\mu)\ K_s$ (untagged)

in 1 year:

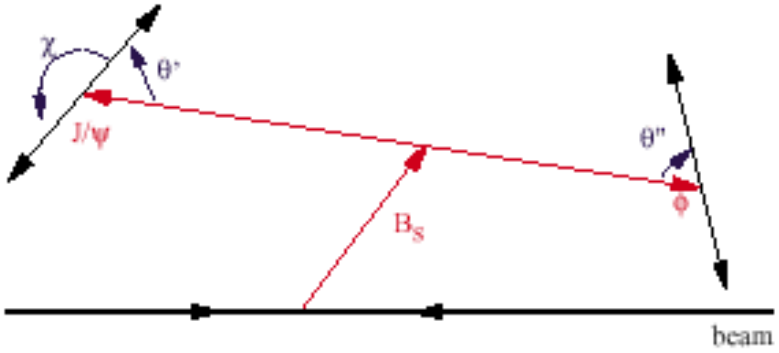
expected signal events	166 k
expected background	101 k

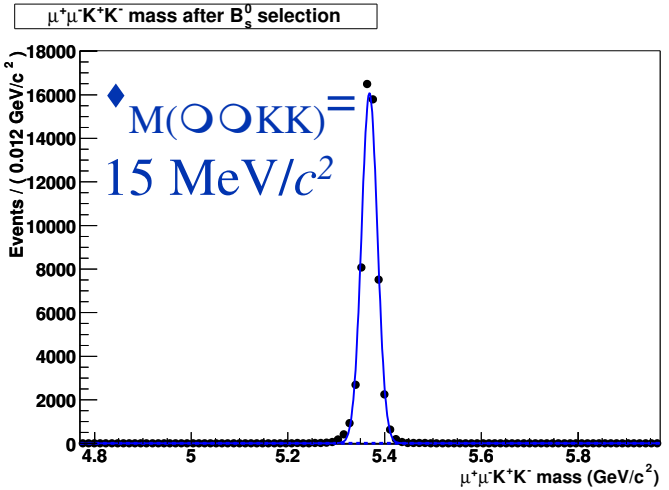
Δm_s from $B_s \to J/\psi\,\phi$ (see talk by Jeroen Van Hunen)

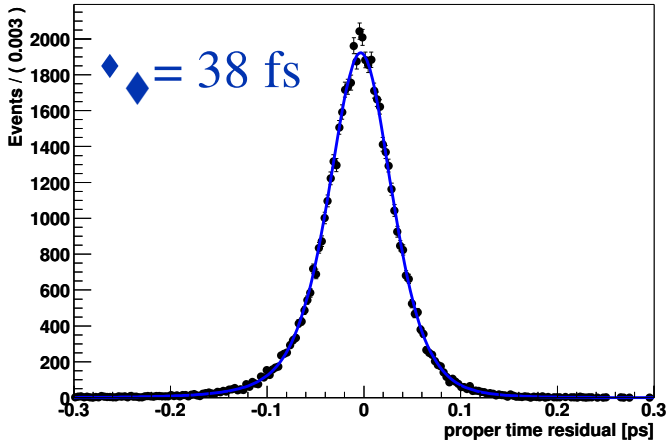
- "gold-plated" decay channel for hadron machines, measuring the B_s- $\bar{B}_s$ mixing phase
- in SM $\phi_s = -2\beta_s = -2\lambda^2\eta$ expected to be $\sim$(0.03)
- large CP asymmetry would signal Physics Beyond SM
- also needed for extracting γ from $B \to \pi\pi$ and $B_s \to K\,K$, or from $B_s \to D_s\,K$

J/ψ ϕ is not a pure CP eigenstate

- 2 CP even, 1 CP odd amplitudes contributing
- need to fit angular distributions of decay final states as function of proper time
- requires very good proper time resolution







in 1 year: $\sigma(\delta\gamma) \sim 3.5°$

with input values:

ε_{tag}: 40% , w_{tag}: 35% , Δm_s=20/ps

τ = 1.5 ps , $\Delta\Gamma/\Gamma$ = 0.1 , A = sin(-2$\delta\gamma$) = 0.03

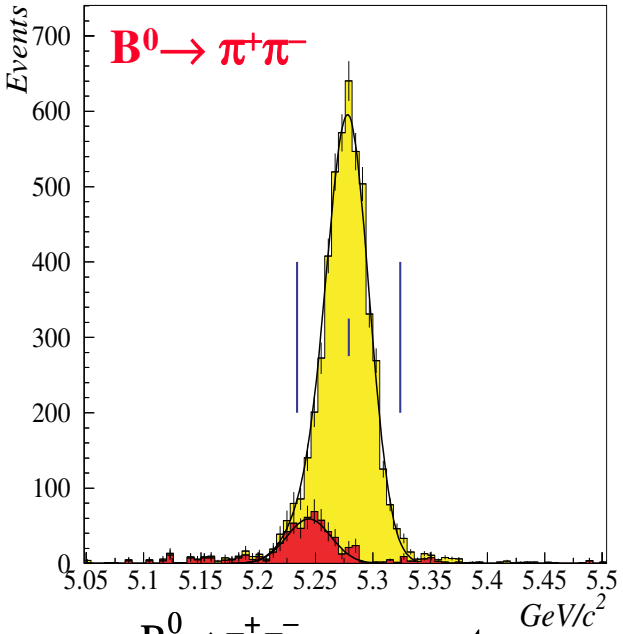
γ from B → ππ and B_s → KK

(see talk by Angelo Carbone)

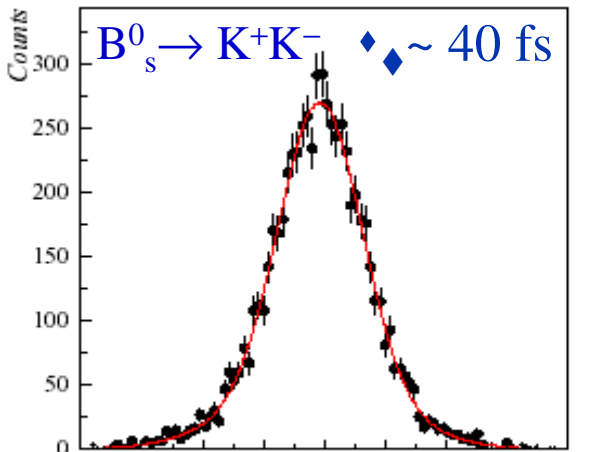
- relies on "U-spin" symmetry assumption (d↔s), which is the only source of theoretical uncertainty *[R.Fleischer, Phys.Lett. B459, 306 (1999)]*
- determination of γ and test of U-spin symmetry using measurements of Δγ from $B_s \to J/\psi\,\phi$ and 2β from $B \to J/\psi\, K_S$
- sensitive to New Physics contribution by comparing with γ obtained from $D_s K$

Measure time-dependent CP asymmetries to extract A_{CP}^{dir} and A_{CP}^{mix}

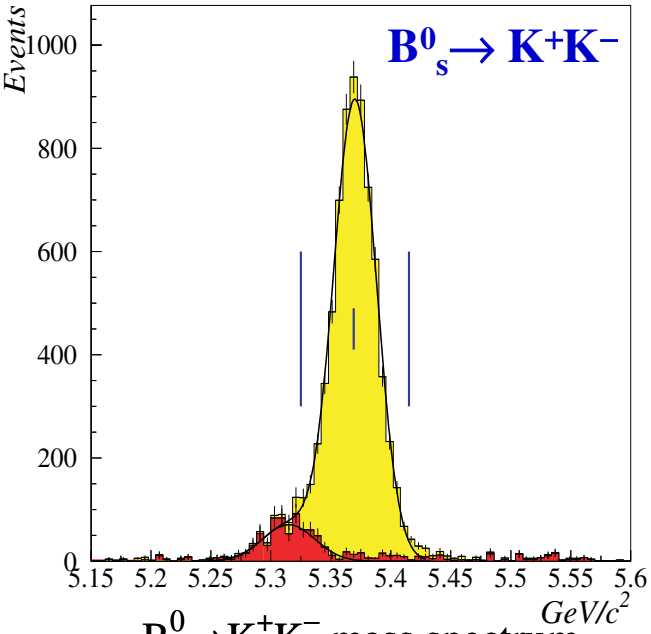
- hadron trigger
- K/π separation
- mass resolution (~18 MeV/c^2)
- proper-time resolution



$B^0 \to \pi^+\pi^-$ mass spectrum



$B_s \to K^+K^-$ proper time resolution



$B_S^0 \to K^+K^-$ mass spectrum

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

input values	$B^0 \to \pi^+ \pi^-$	$B_S \to K^+ K^-$
yield	27k	38k
B/S	0.7	0.3
$\Delta M(ps^{-1})$	0.5	14
εD^2	0.04	0.06
A_{CP}^{dir}	-0.30	0.16
A_{CP}^{mix}	0.58	-0.17
$\Delta\Gamma$	0.0	0.0

$$A_{CP}^{th}(\tau) = \frac{A_{CP}^{dir} \cdot \cos(\Delta M \cdot \tau) + A_{CP}^{mix} \cdot \sin(\Delta M \cdot \tau)}{\cosh\left(\frac{\Delta\Gamma}{2} \cdot \tau\right) - A_{\Delta\Gamma} \cdot \sinh\left(\frac{\Delta\Gamma}{2} \cdot \tau\right)}$$

$\sigma(A_{CP}^{dir}) \cong 0.07$

$\sigma(A_{CP}^{mix}) \cong 0.06$

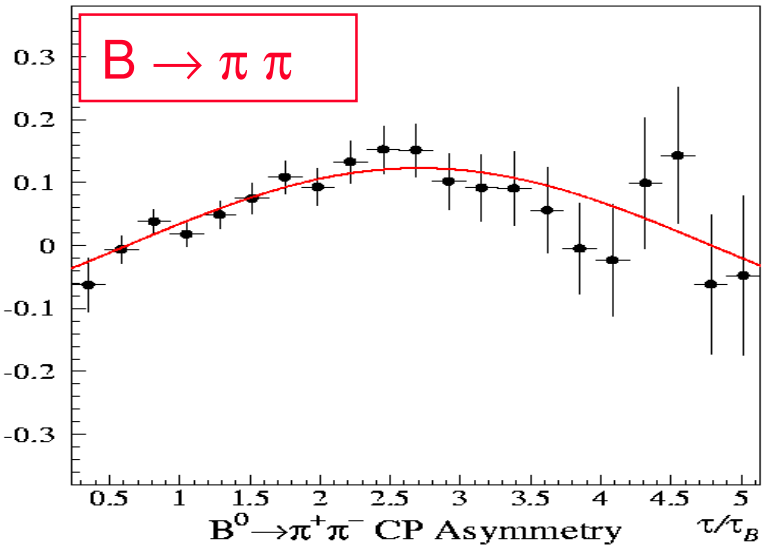
$Corr\ (A_{CP}^{dir}, A_{CP}^{mix}) \cong -0.49$

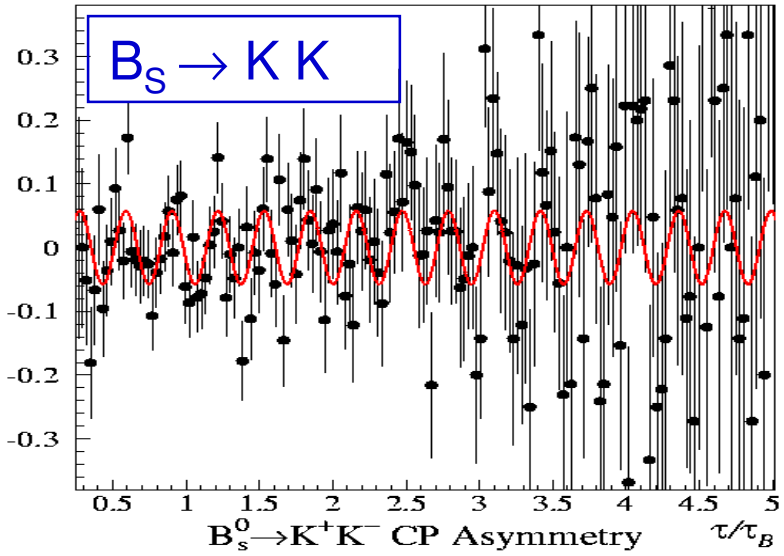
sensitivity in 1 year

$\sigma(A_{CP}^{dir}) \cong \sigma(A_{CP}^{mix}) \cong 0.04$

$Corr\ (A_{CP}^{dir}, A_{CP}^{mix}) \cong 0$

$@\ \Delta\Gamma_s = 0 \quad \Delta M_s = 14\ ps^{-1}$

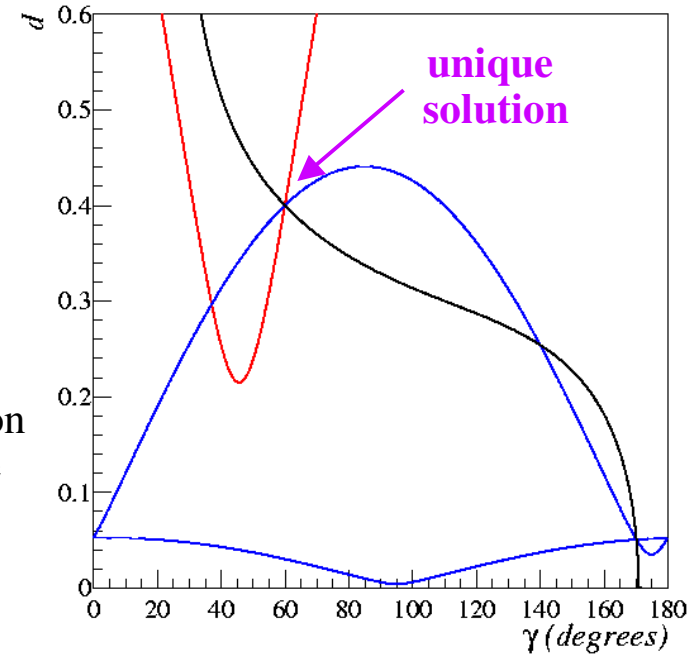




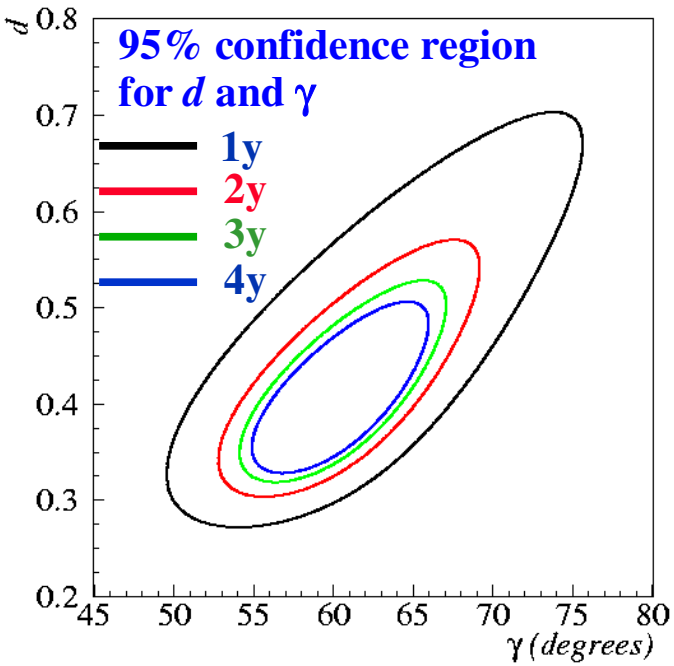
γ from $B \to \pi\pi$ and $B_s \to K K$

$$A_{CP}^{dir}(B_d^0 \to \pi^+\pi^-) = f_1(d, \vartheta, \gamma)$$
$$A_{CP}^{mix}(B_d^0 \to \pi^+\pi^-) = f_2(d, \vartheta, \gamma, \phi_d)$$
$$A_{CP}^{dir}(B_s^0 \to K^+K^-) = f_3(d', \vartheta', \gamma)$$
$$A_{CP}^{mix}(B_s^0 \to K^+K^-) = f_4(d', \vartheta', \gamma, \phi_s)$$

graphical solution in (d, γ)-plane



- $\phi_d = 2\beta$ from $B \to J/\psi K_S$ and $\phi_s = 2 \Omega \gamma$ from $B_s \to J/\psi \phi$
- d, ϑ (d', ϑ') paramatrize P over T amplitude ratio of decay transitions in $B_d \to \pi^+\pi^-$ ($B_s \to K^+K^-$)
- exact U-spin symmetry => $d = d'$; $\vartheta = \vartheta'$
- 3 unknowns and 4 measurements



for $\gamma = 60°$, $d = d' = 0.4$, $\vartheta = \vartheta' = 140°$, $\phi_d = 51°$, $\phi_s =$

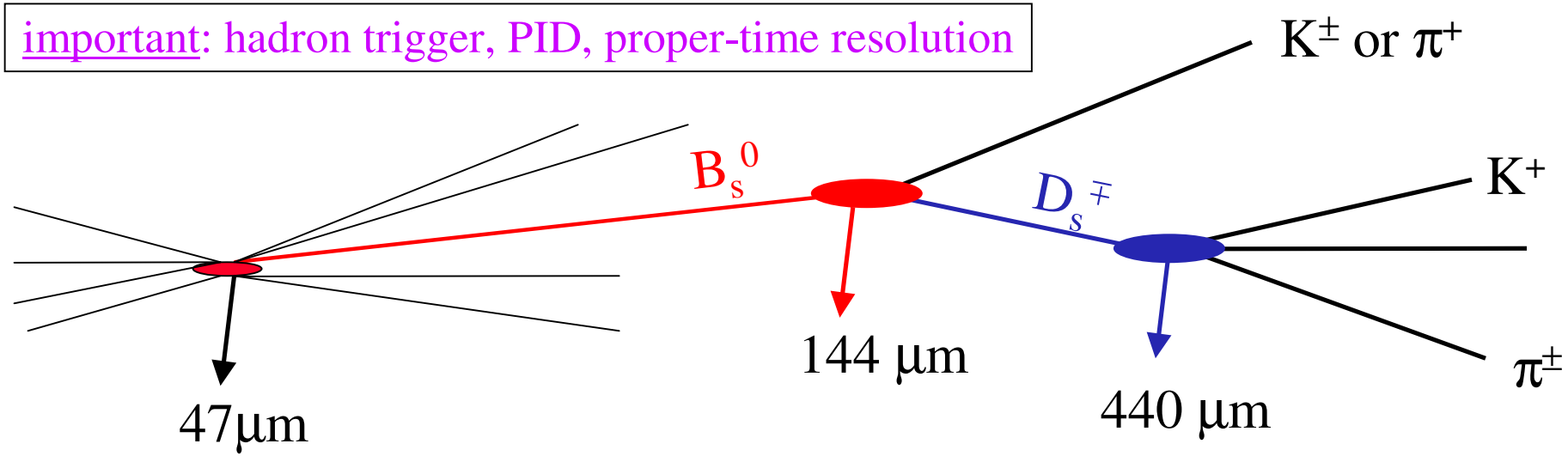
years	1	2	3	4
$\delta(\gamma)$	5.5°	3.3°	2.6°	2.2°

γ - 2β from $B_s \to D_s K$

(see talk by Richard White)

- 2 time dependent asymmetries from 4 decay rates: B_s ($\overline{B_s}$) → $D^-_s K^+$, $D^+_s K^-$
- only 2 tree-diagram-like topologies of same magnitude contribute
- large interference effects expected [b→c and b→u diagrams ☺(●3)]
- needs supression of ☺(20) times higher Bs→ Ds□ background

important: hadron trigger, PID, proper-time resolution



γ sensitivity depends on
- relative amplitudes
- strong phase difference
- values of γ, Δm_s, $\Delta\Gamma_s/\Gamma_s$

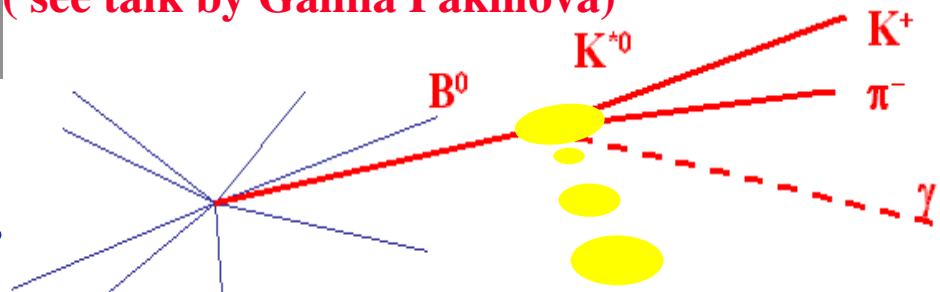
expected sensitivity in 1 year:

$\sigma(\gamma) \sim 15^0$ for $\Delta m_s = 20\ ps^{-1}$

$\sigma(\gamma) \sim 20^0$ for $\Delta m_s = 30\ ps^{-1}$

$B^0 \to K^{0*} \gamma$ and $B_s \to \phi \gamma$

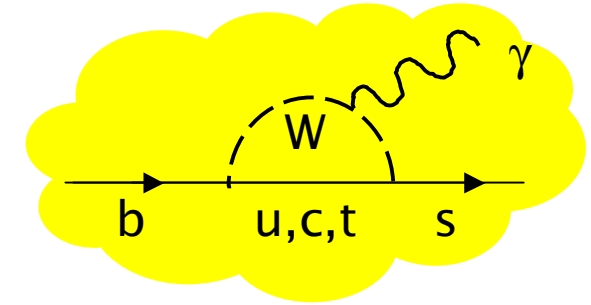
(see talk by Galina Pakhlova)

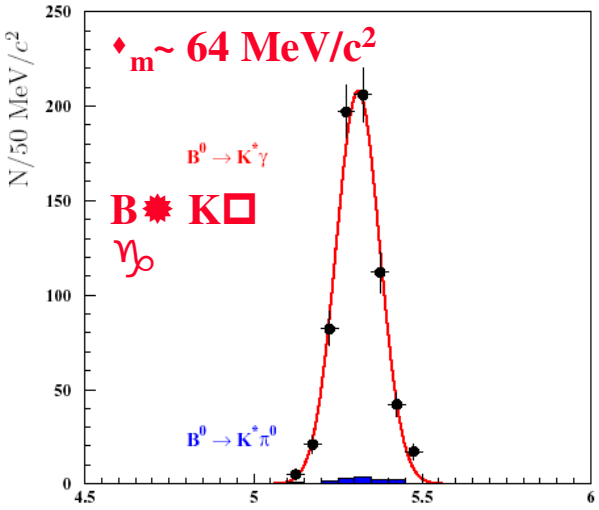


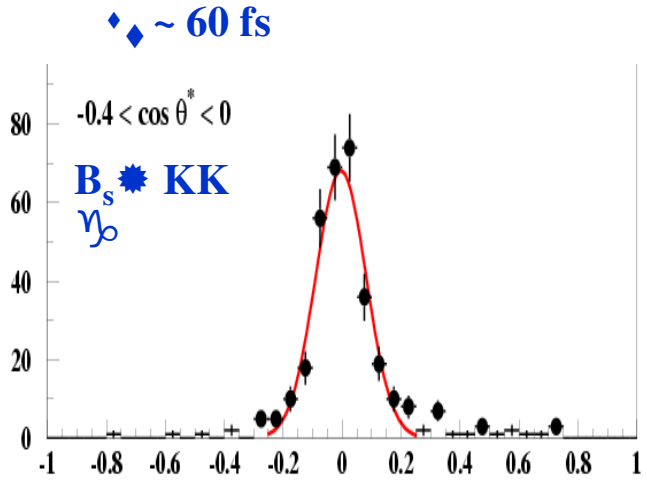
In SM:

- loop-suppressed $b \to s \gamma$ transitions
- BR($B^0 \to K^{*0} \gamma$) = $(4.3 \pm 0.4)\ 10^{-5}$
- expected direct CP violation <1% for $B^0 \to K^{*0} \gamma$
- expected CP violation in mixing ~0 for $B_s \to \phi \gamma$

❾ sensitive to New Physics







In one year expect triggered and reconstructed

35k events $B^0 \to K^{0*}(K^+\pi^-)\ \gamma$; S/B>1.4

9.4k events $B_s \to \phi(K^+K^+)\ \gamma$; S/B>0.4

Preliminary study:

- **for $B \to K^{0*} \gamma$ $\delta(A_{CP}) < 0.01$ for one year LHCb**
- **for $B_s \to \phi \gamma$ sensitivity study ongoing**

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

(see talk by Jose Helder Lopes)

- BR($B^0 \to K^{*0} \ell^+\ell^-$) = $(1.2 \pm 0.4)\ 10^{-6}$
- within SM measure $|V_{ts}|$
- forward-backward asymmetry sensitive to New Physics, largely independent of hadronic uncertainties

A_{FBA} ~ angle between B momentum and ℓ^+ in the dilepton center-of-mass system

In one year expect

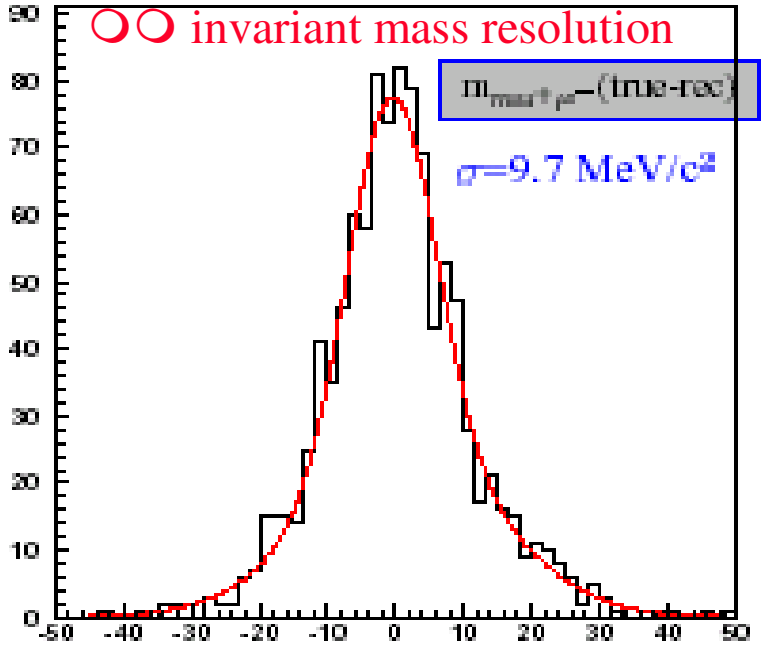
4.4k events $B^0 \to K^{0*} \ell^+\ell^-$

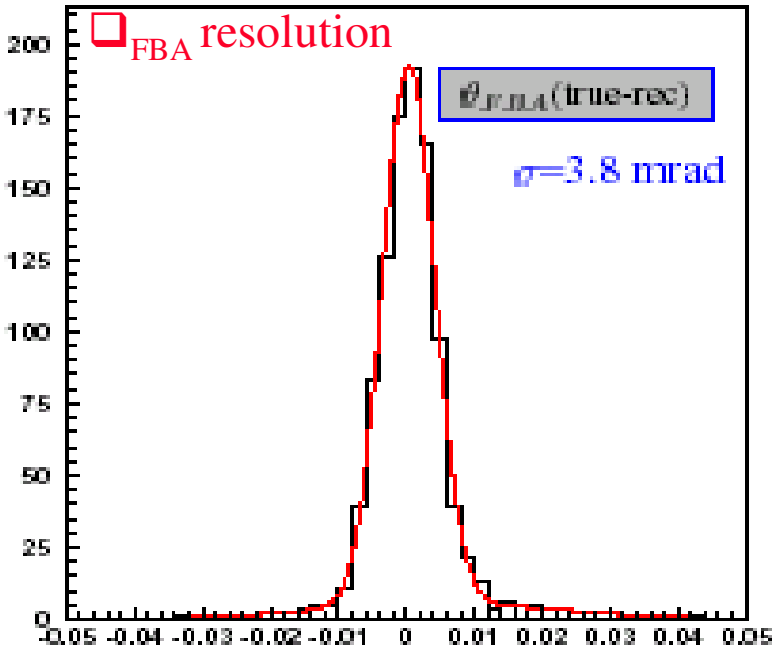
triggered and reconstructed with

S/B >0.45

Preliminary study:

- **$\delta(A_{CP}) \sim 0.02$ for one year LHCb**
- **sensitivity study for A_{FB} ongoing**

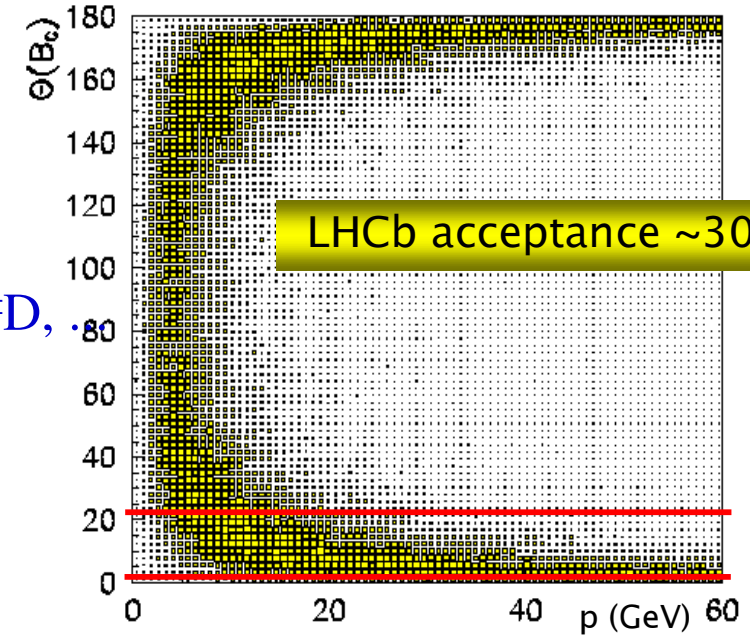




B_c mesons

- precision measurement of mass, life-time
- possible CP with $B_c \to J/\psi D^{\pm}$, $B_c \to D_s D$, $D^{\pm} D$, ...

CDF: $m_{Bc} = 6.4 \pm 0.4$ GeV, $\tau_{Bc} \sim 0.5$ ps



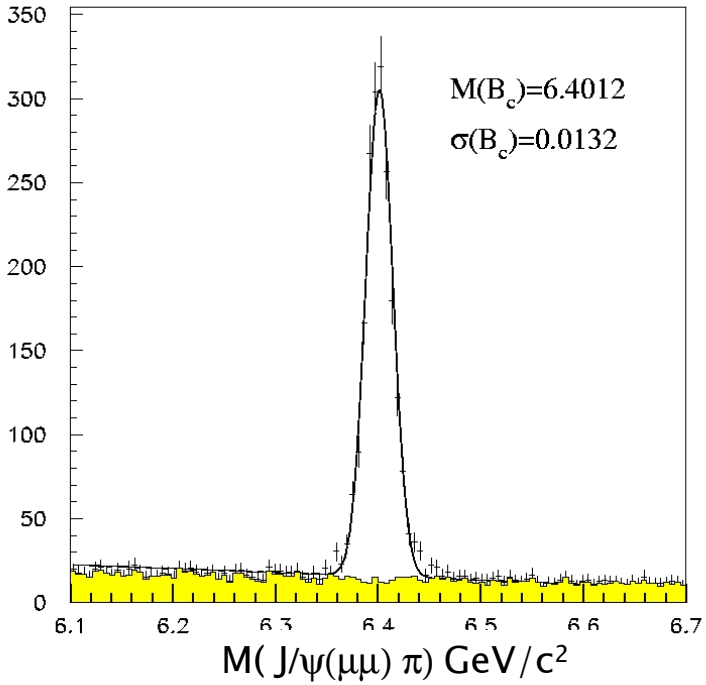
Preliminary study:

$\sigma(pp \to B_c) \sim 300$ nb $\Rightarrow 10^9$ B_c/ year

$B_c \to J/\psi\, \pi$ (BR $\sim 10^{-2}$)

$\varepsilon \sim 3\%$ ⇨ 18k events/year, S/B ~10

Background from $B \to J/\psi$ X and prompt J/ψ reduced cutting on the distance between primary vertex and B_c vertex



Present estimate of expected physics reach

preliminary

These numbers are being updated, and more channels studied, in the re-optimization of the LHCb detector to be concluded in September 2003

channel	parameter	σ (1 year)	depending on	*LHCb* specific features
$B_d \to J/\psi K_S$	β	0.6°	for sin(2β)=0.79	lepton trigger
$B_d \to \pi^+ \pi^-$	γ	~5.5°	U-spin summetry	hadron trigger, RICH
$B_s \to K K$				hadron trigger, RICH, ♦♦
$B_s \to D_s K$	γ	~15°-20°	x_s, $\Delta\Gamma_s/\Gamma_s$, $\delta_{T1,T2}$	hadron trigger, RICH, ♦♦
$B_s \to J/\psi$ ☞	$\delta\gamma$	~3.5°	x_s, CP+/CP−, $\delta_{1,2}$	lepton trigger, ♦♦
$B_s \to D_s \pi$	x_s	<75	σ>5	hadron trigger, ♦♦
$B_d \to K^* \mu\mu$		4.4k events		muon trigger, RICH
$B_d \to K^* \gamma$		35k events		photon trigger, RICH
$B_s \to$ ☞ η_c		9.4k events		photon trigger, RICH, ♦♦

Summary and Conclusion

LHCb can study many different B-meson decay modes with high precision
- particle identification capability
- excellent mass and decay-time resolution

LHCb can fully exploit the large B-meson yields at LHC from the start-up
- flexible, robust and efficient trigger
- required luminosity of 2×10^{32} is low and locally tuneable

LHCb detector will be ready for data taking in 2007 at LHC start-up
- detector production is on schedule
- installation of magnet is ongoing
- installation of detectors will start end of next year

Soon *LHCb* will offer an excellent opportunity to
- determine precisely the CKM parameters through phase measurements
- spot New Physics beyond the SM by overconstraining the Unitarity Triangles