XVIIIth International Workshop High Energy Physics and Quantum Field Theory, St.Petersburg

LHCb status and physics goals

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1. Introduction and physics motivations
2. Subsystem status
3. Physics potential
4. Conclusion

Centre de Physique des Particules de Marseille

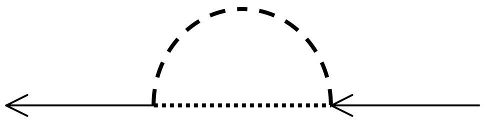
CPPM

June 17-23, 2004

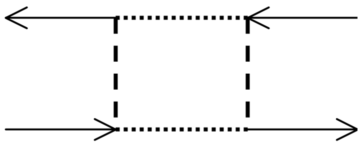
LHCb

Introduction, physics motivations

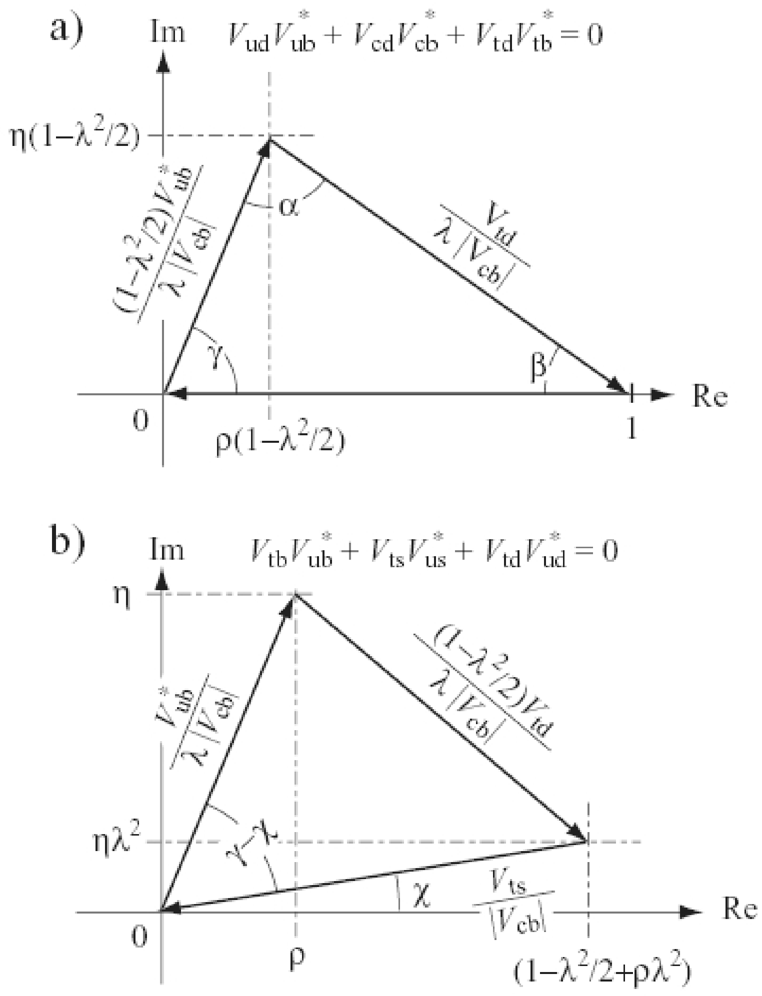
- LHCb is a dedicated *B physics precision* experiment at LHC to study *CP violation* and *rare decays*
- Standard Model CP violation described by single complex phase in the unitarity CKM matrix
- LHCb precision ⇒ 2 Unitarity Triangles
- b meson sector is a place where theoretical predictions can be precisely compared with experimental results
- We will *over constrain the Unitarity Triangles* and *search for new physics*



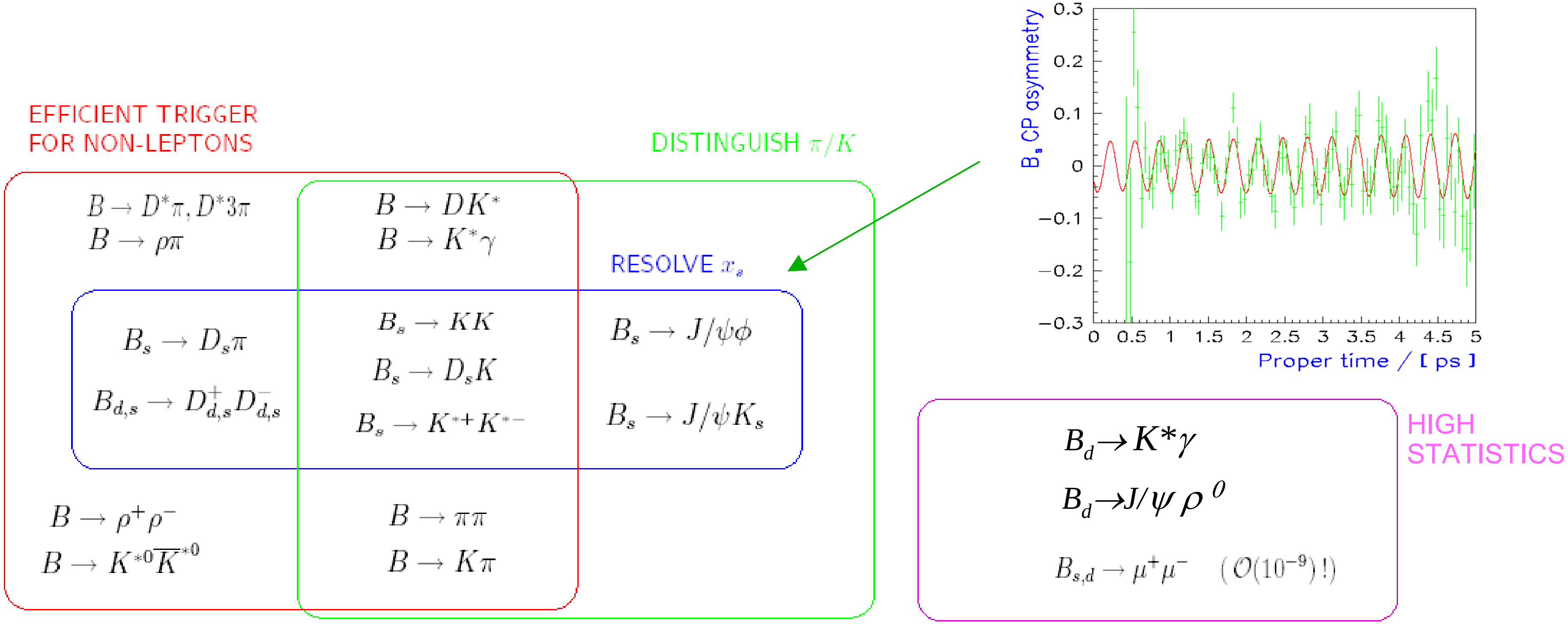
New particles ?



New particles ?



LHCb experimental challenge

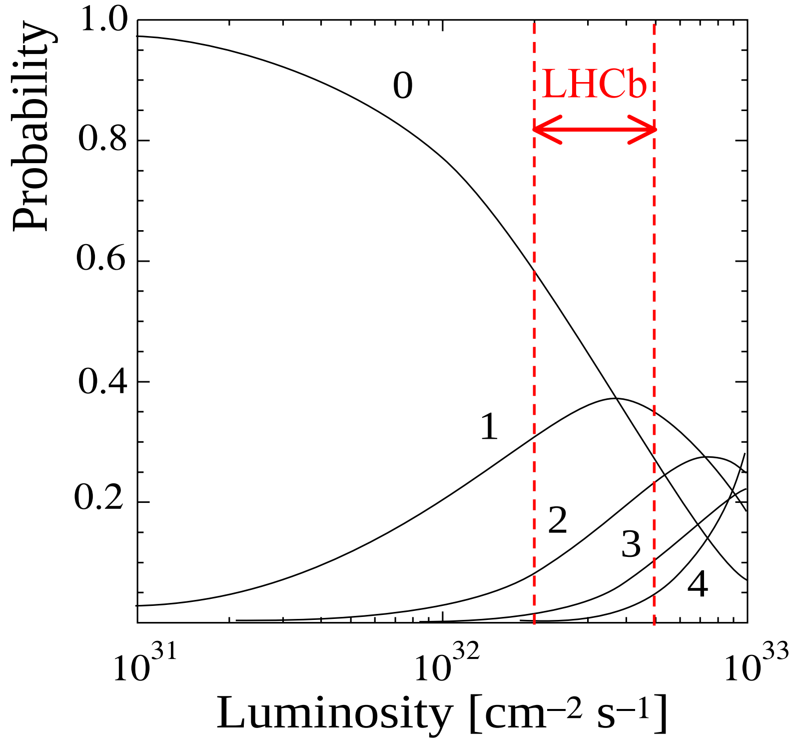


- To over constrain the Unitarity Triangles, need to reconstruct many final states:
  - **Robust and efficient trigger, even for non-leptonic decays**
  - **High track reconstruction efficiency**
  - **Excellent proper time resolution (xs)**
  - **π/K separation**

LHC environment

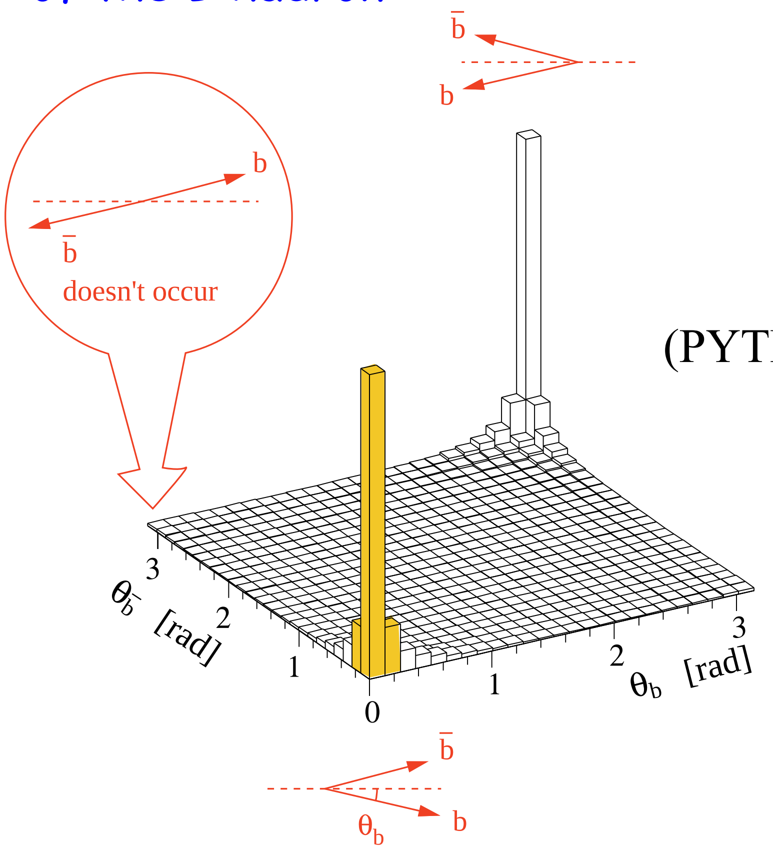
- LHC: pp collisions at $\sqrt{s}$ = 14 TeV
- Bunches cross at 40 MHz
  $\rightarrow$ separated by 25 ns
- $\sigma_{inelastic}$ = 80 mb
  $L=10^{34} cm^{-2}s^{-1} \rightarrow \gg 1$ pp collision/crossing
- Choose to run at ~ $2 \times 10^{32}\ cm^{-2}s^{-1}$
  $\rightarrow$ dominated by single interactions
- Makes it simpler to identify B decays from their vertex structure
  (and reduces radiation dose)
- Beams are defocused locally
  $\rightarrow$ maintain optimal luminosity even when ATLAS and CMS run at 10^{34}
- $\sigma_{b\bar{b}}$ = 500 μb
- LHC = Most copious b-hadrons production source: 10^{12} $b\bar{b}$ / year at LHCb
- Produced B_d, B^+, B_s, B_c, Λ_b, Σ_b , Ξ_b, …

Inelastic pp collisions/crossing

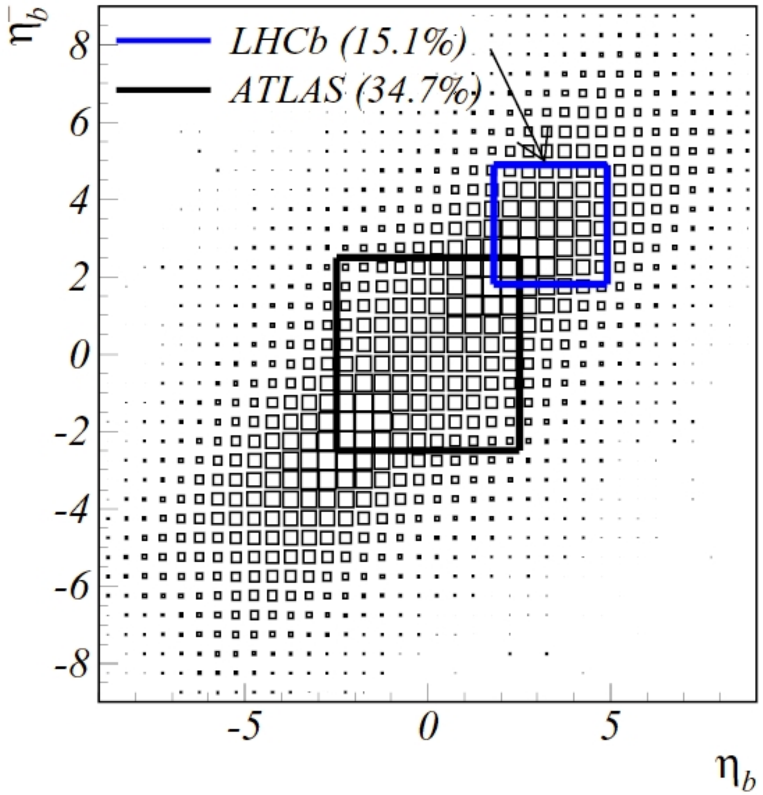


B production

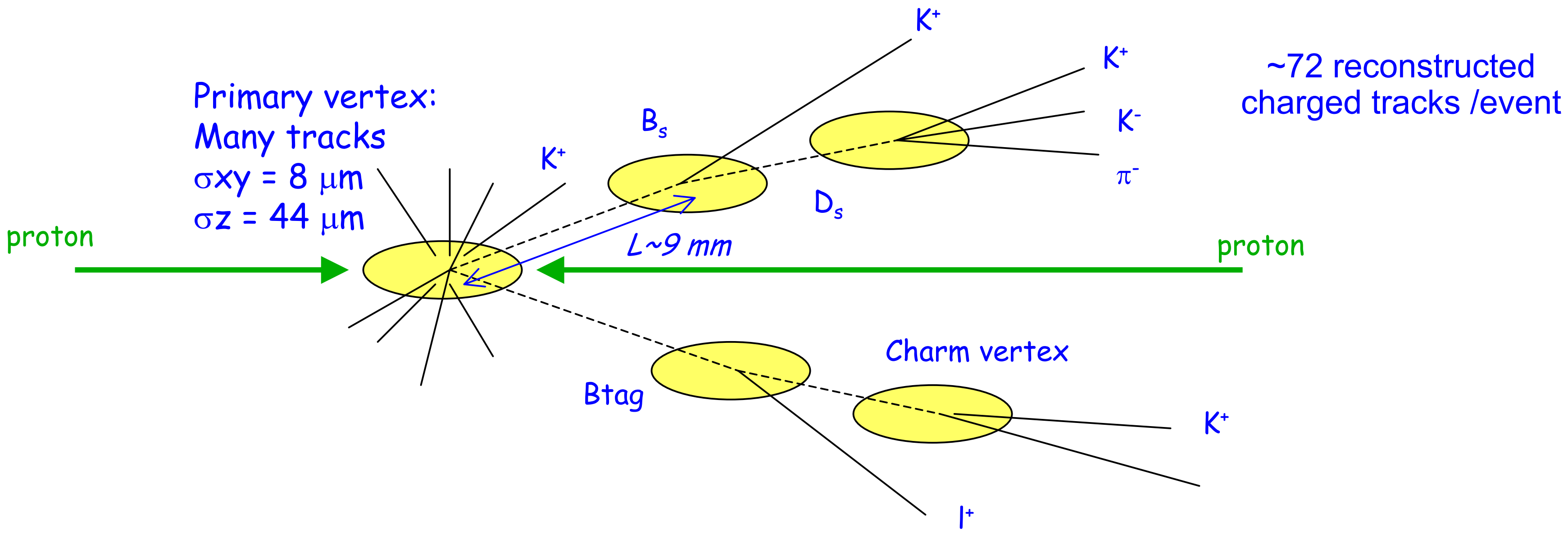
- B hadrons are mostly produced in the forward direction (along the beam)
- Choose a forward spectrometer 10–300 mrad
- Both b and $\bar{b}$ in the acceptance: important for tagging the production state of the B hadron



(PYTHIA)

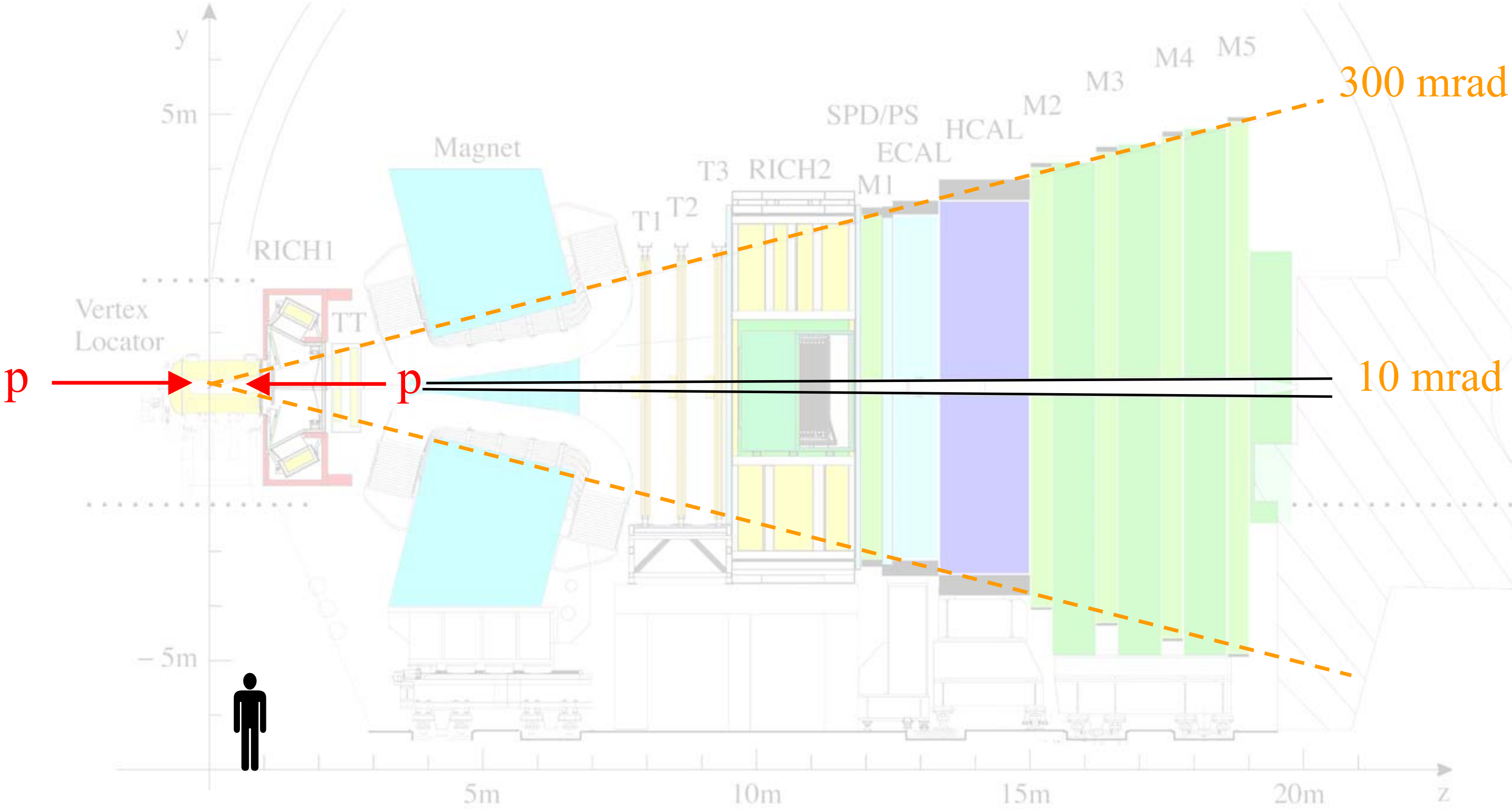


Typical B event in LHCb



- Need to measure proper time of B decay: $t = mL / pc$
  hence decay length L (typically ~ 9 mm in LHCb)
  and momentum p from decay products (which have ~ 1–100 GeV)
- Also need to tag *production* state of B: whether it was B or $\overline{B}$
  Use charge of lepton or kaon from decay of the other b hadron

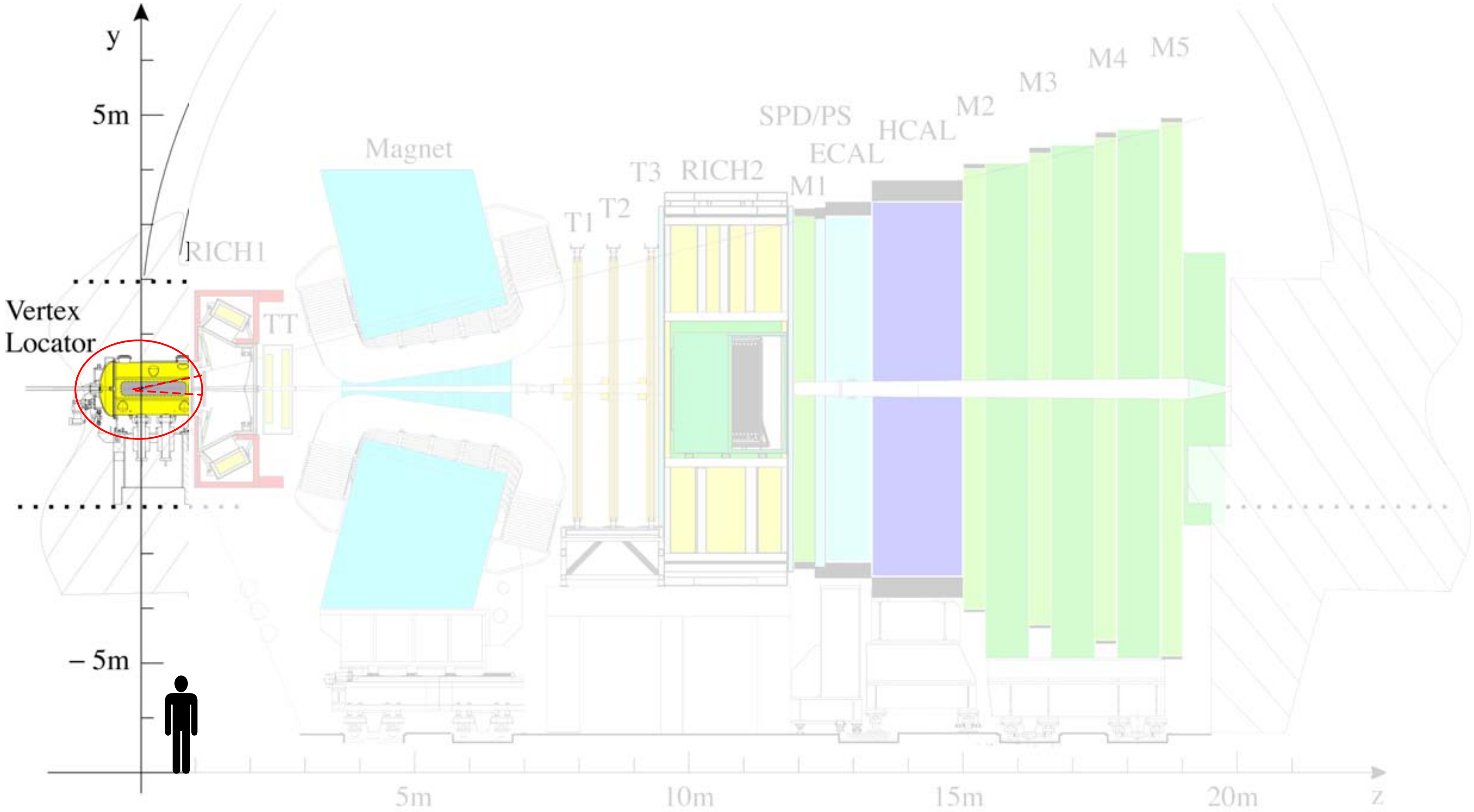
LHCb detector



Forward spectrometer (running in pp collider mode)

Inner acceptance 10 mrad from conical beryllium beam pipe

LHCb detector

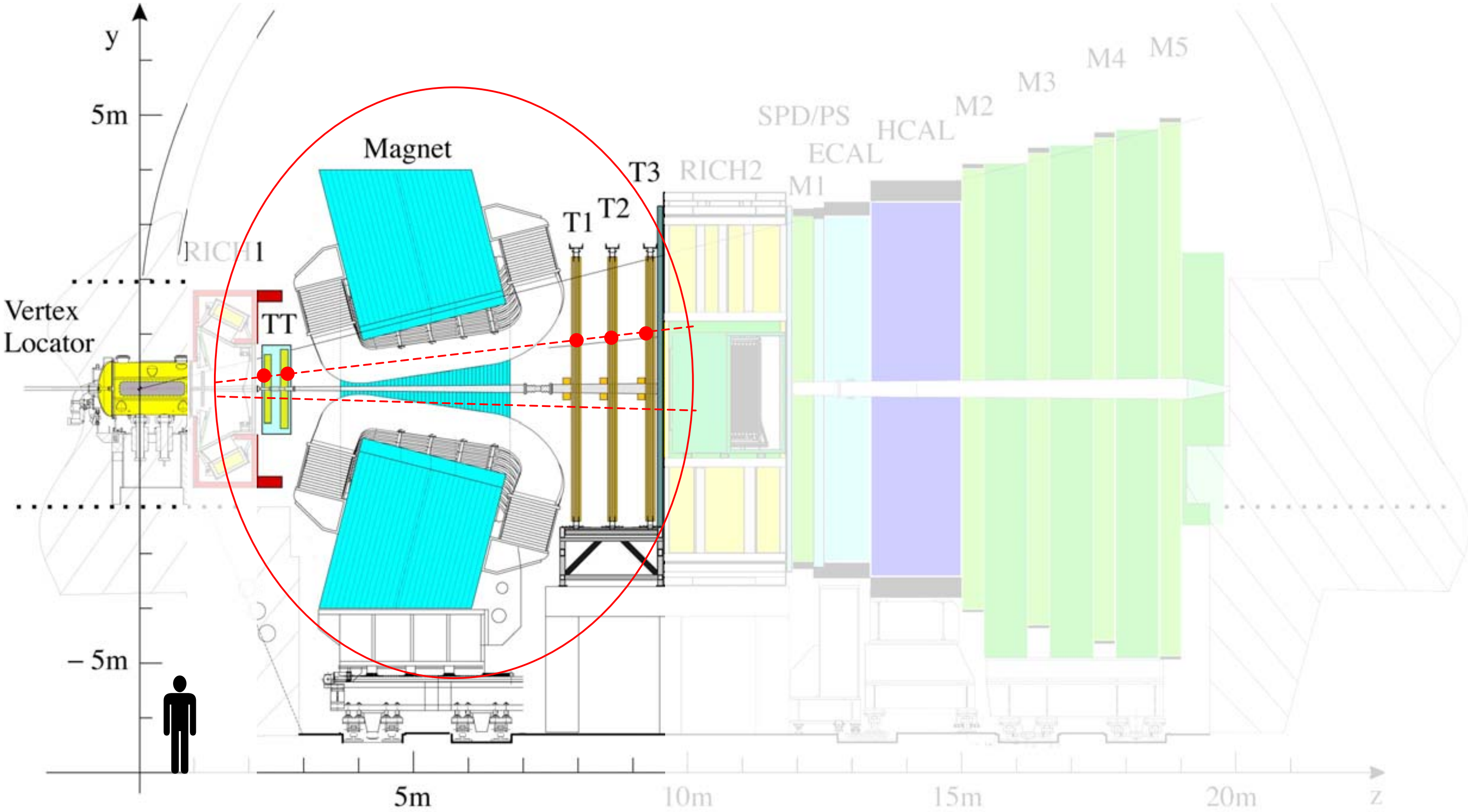


Vertex Locator (VELO) around the interaction region

Precise track parameter measurements + level-0 trigger pile-up system

Silicon strip detector with ~ 30 μm impact-parameter resolution

LHCb detector

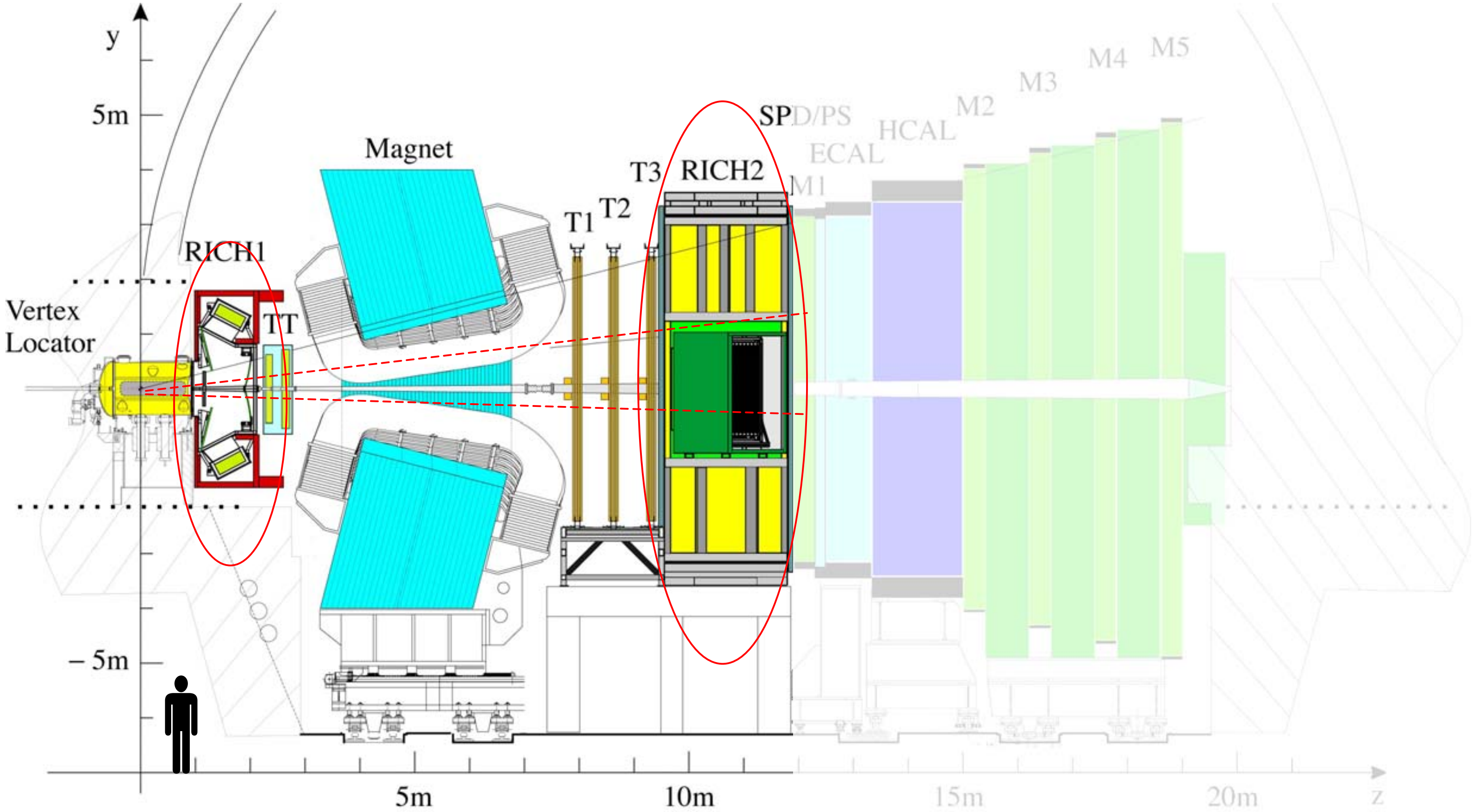


Tracking system and dipole magnet to measure angles and momenta

$\delta p/p$ ~ 0.4 %, mass resolution ~ 14 MeV (for $B_s \rightarrow D_s K$)

Magnetic field regularly reversed to reduce experimental systematics

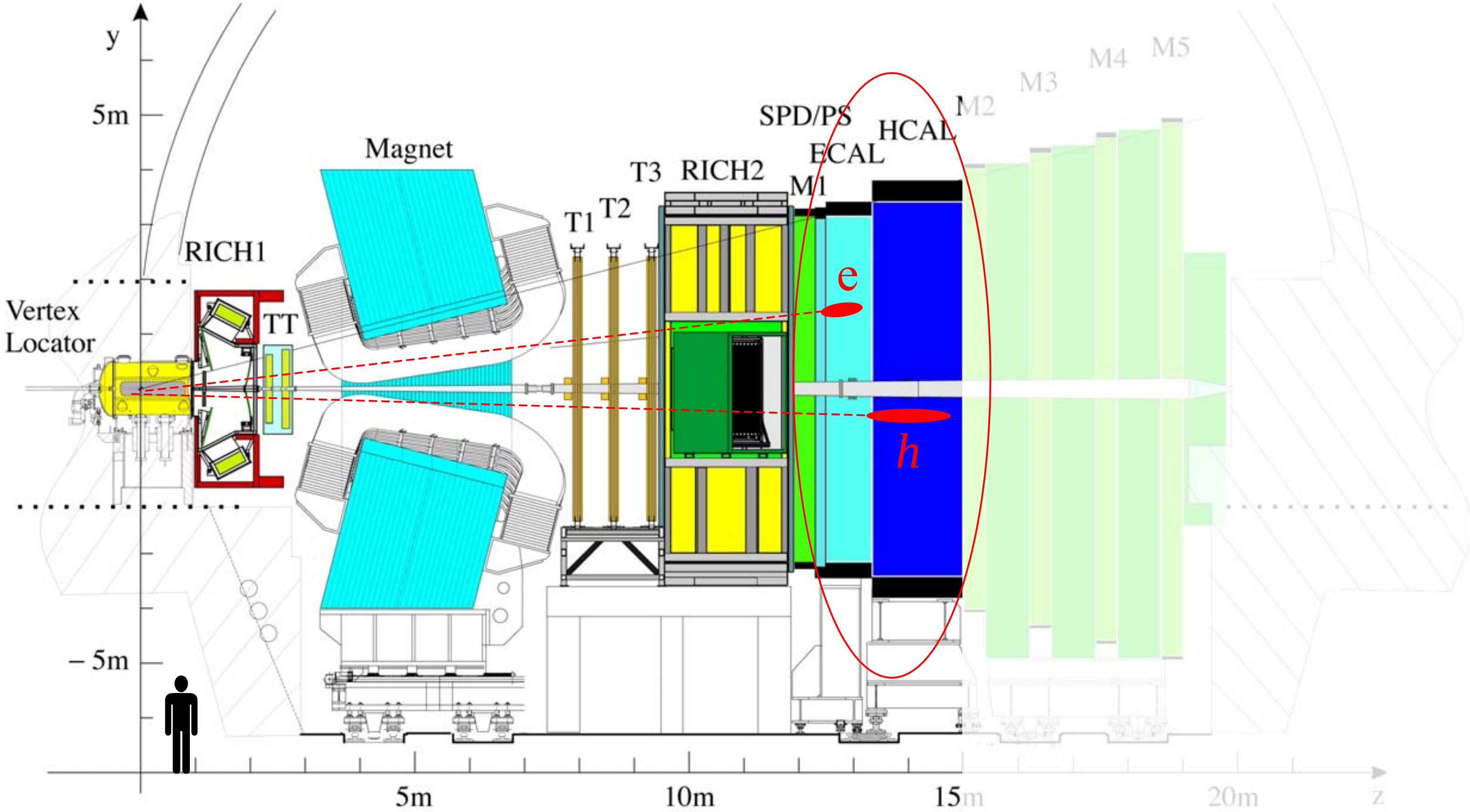
LHCb detector



Two **RICH** detectors for charged hadron identification

Provide > 3σ π–K separation for 3 < p < 80 GeV

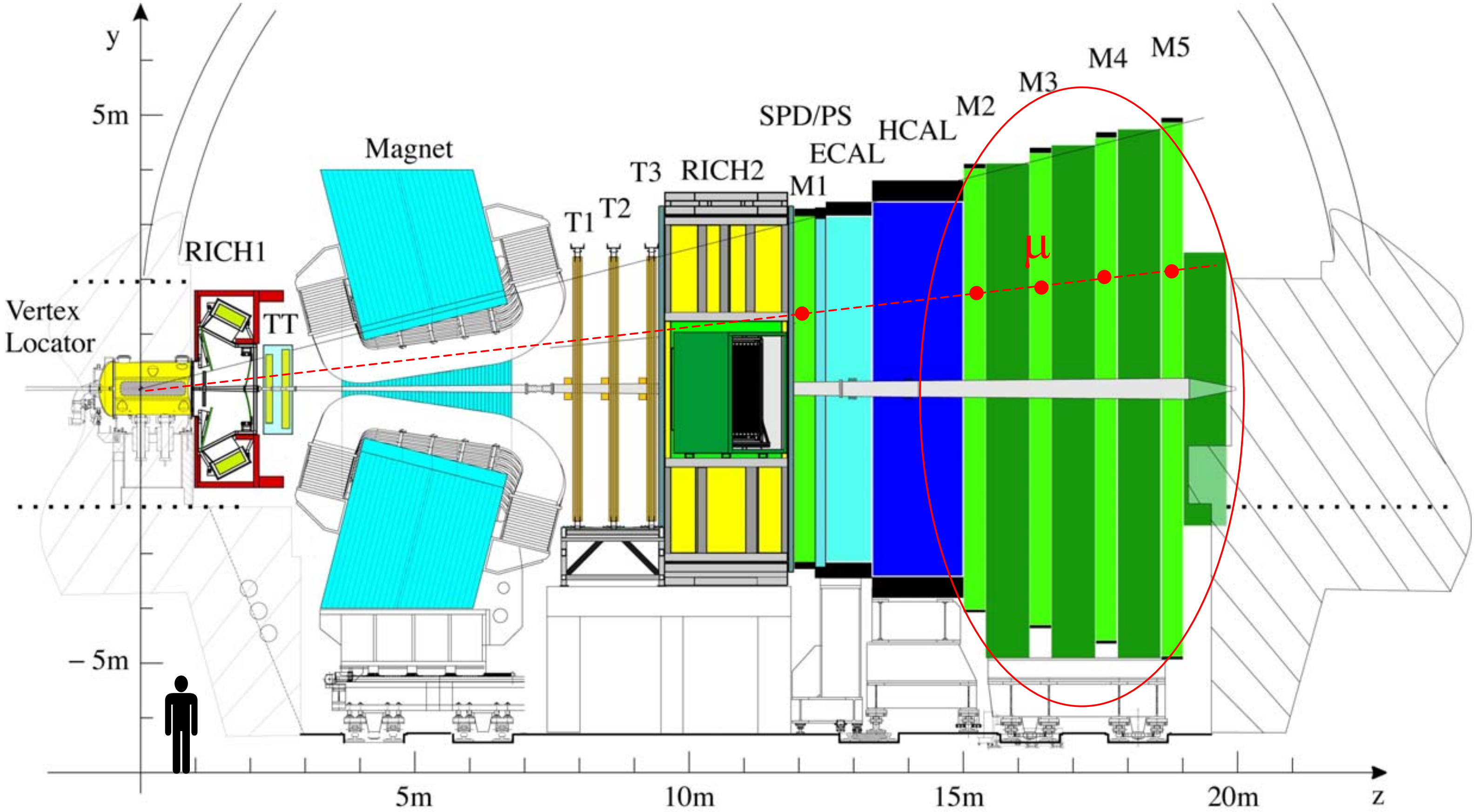
LHCb detector



Calorimeter system to identify electrons, hadrons and neutrals

Important for the level-0 trigger

LHCb detector

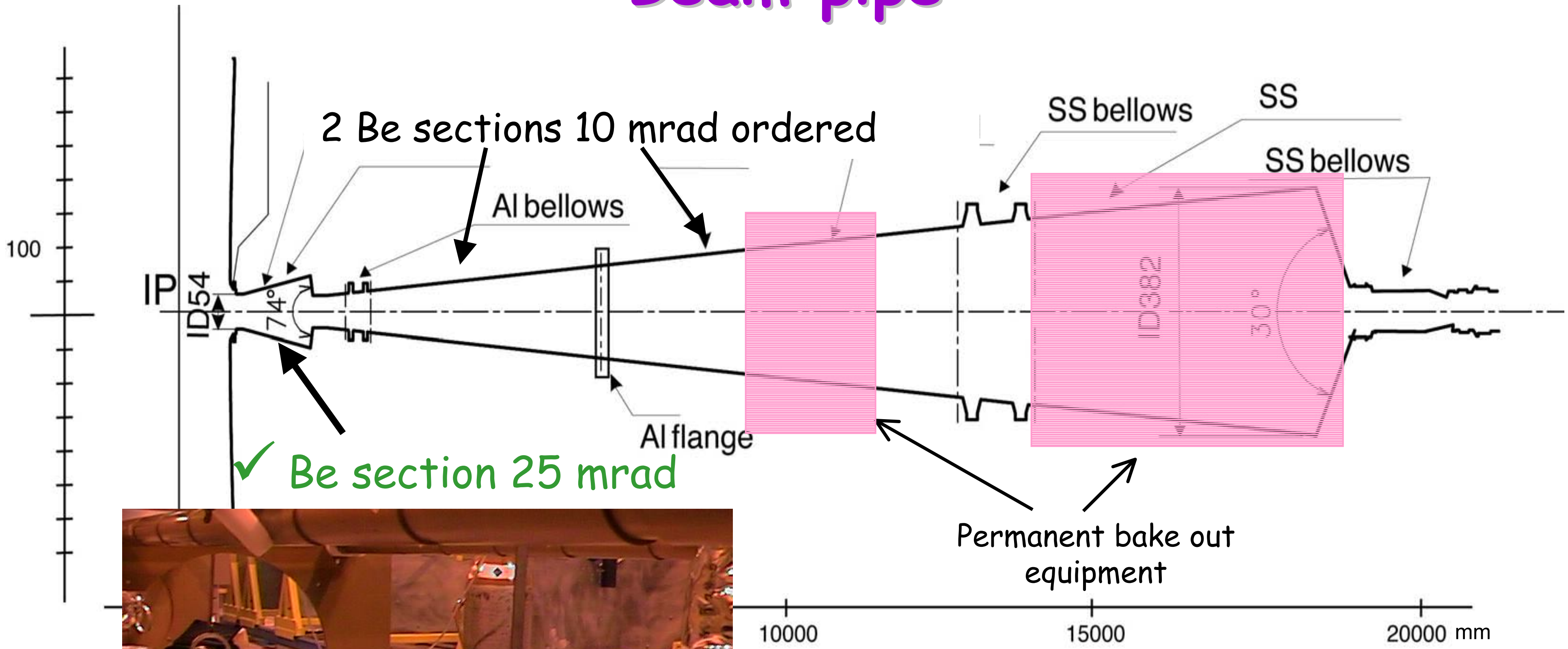


Muon system crucial for level-0 trigger and offline muon identification

Efficiency ~ 95% for pion misidentification rate < 2.5%

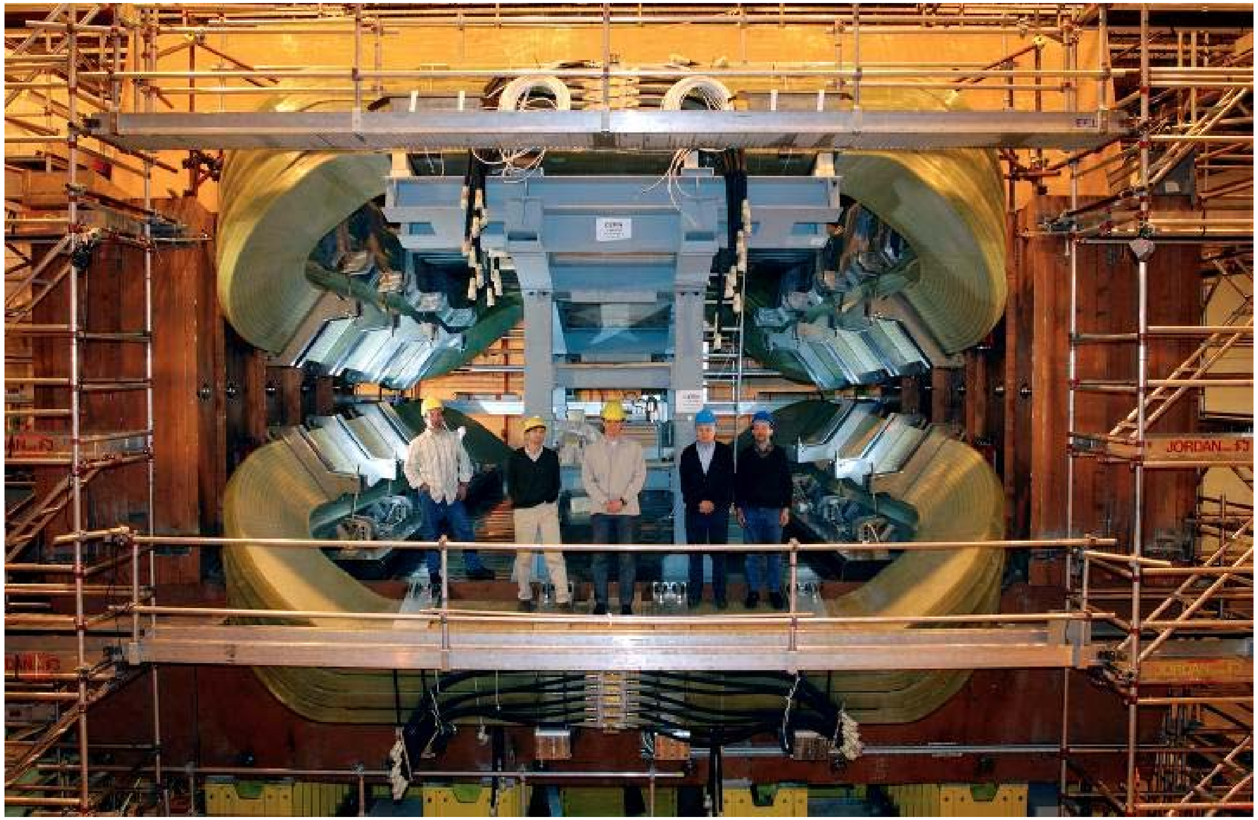
Status of the sub detectors

Beam pipe



High density of particles in the beam pipe area:
→ minimal material to minimize tracker occupancy and RICH reco.

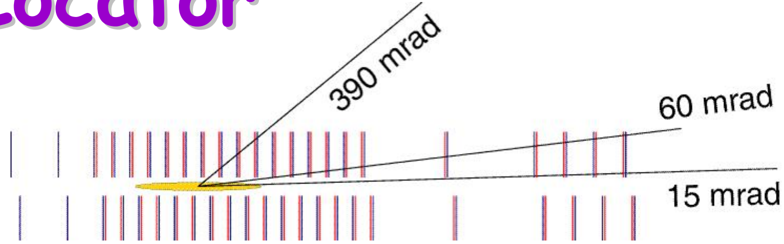
Magnet



- Warm Al conductor
- 4 Tm integrated field
- Weight = 1500 tons
- 4.2 MW

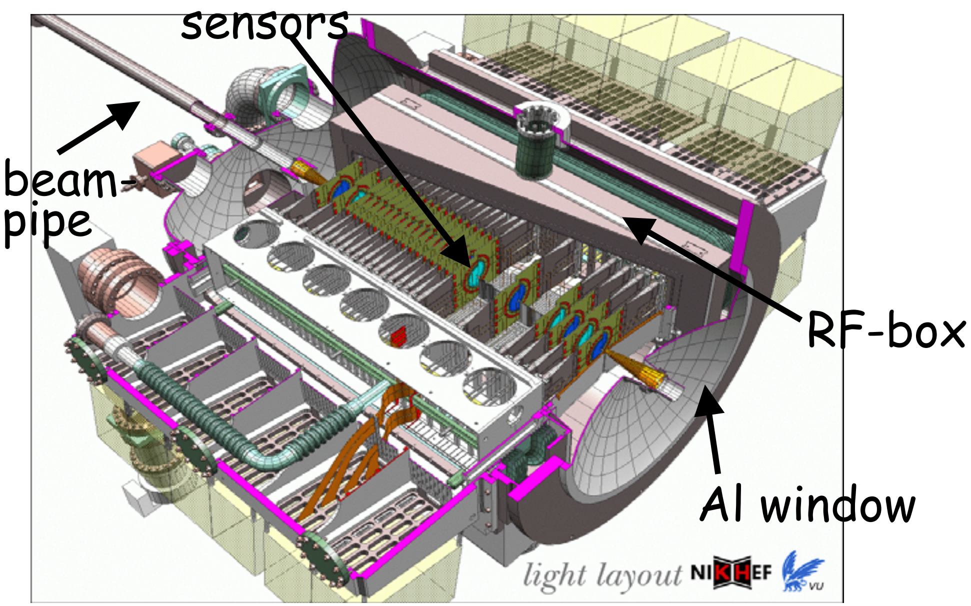
- Assembly of yoke completed
- Move magnet into final position (July 04)
- Field map measurements (2004-2005)

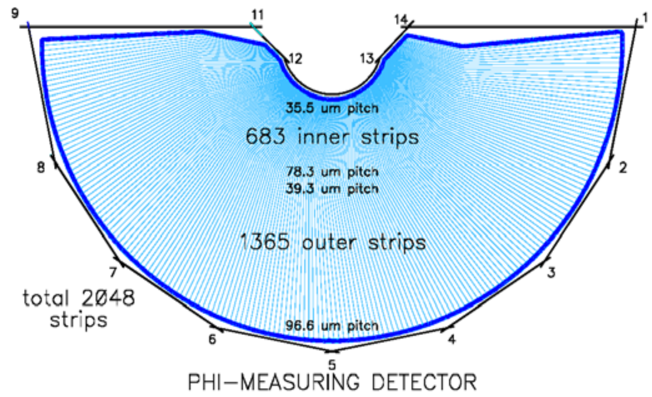
Vertex Locator

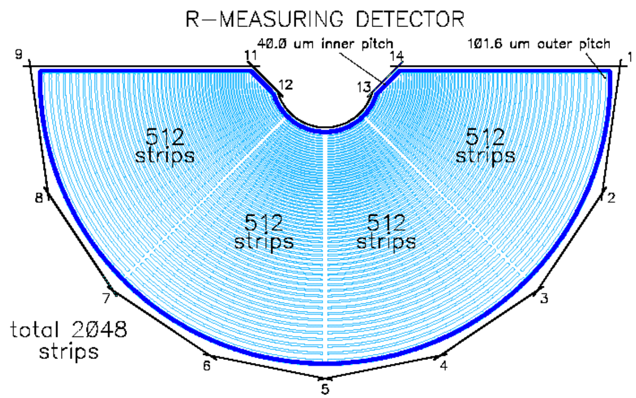


- 21 stations, retractable during injection
- sensitive area starts at only 8 mm from beam axis
- r/φ sensors (single sided, 45° r-sectors)
- pitch ranges from 35 μm to 102 μm
- 200 μm thin silicon
- 180k readout channels
- Secondary vacuum box with <10^{-4} mbar

stand-alone tracking!

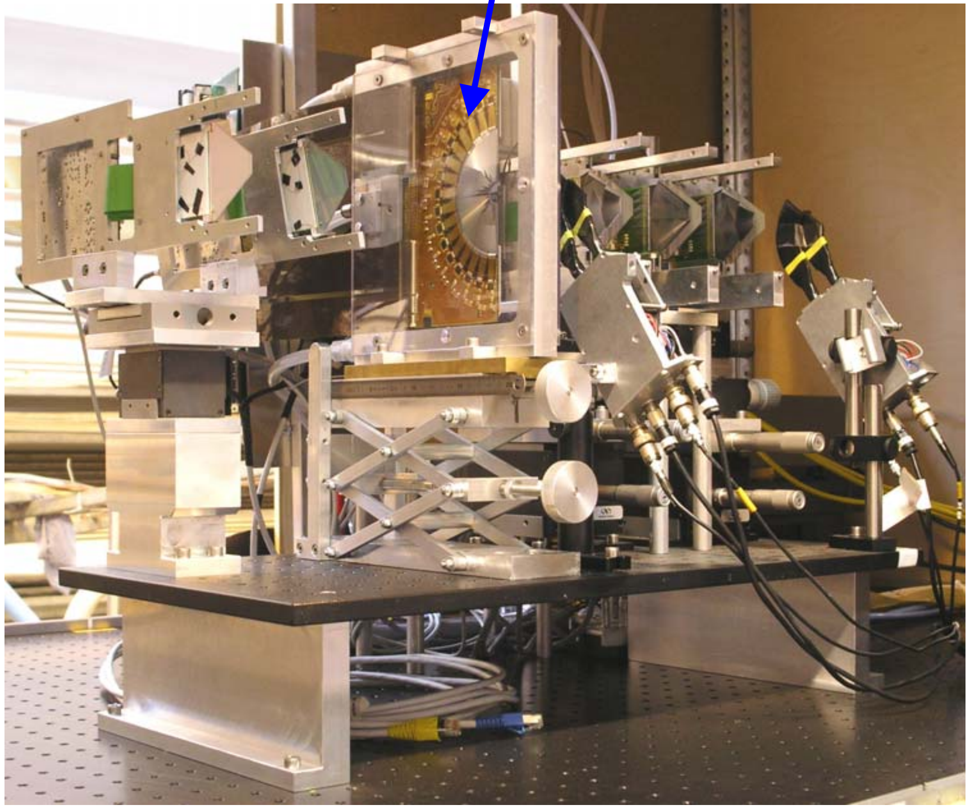


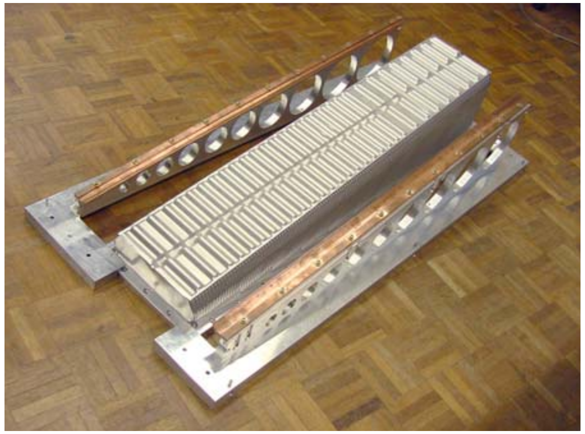




Vertex Locator

Beam test at CERN June'04: silicon sensor equipped with 16 frond-end chips

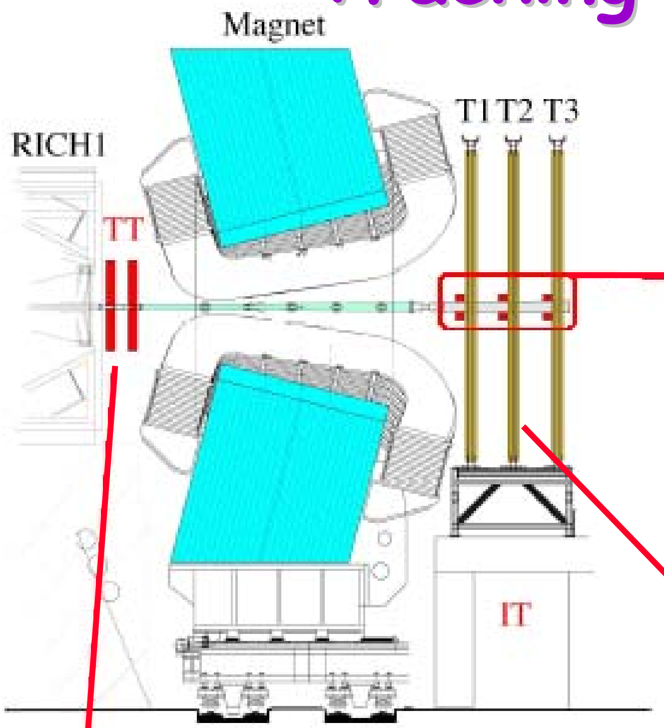




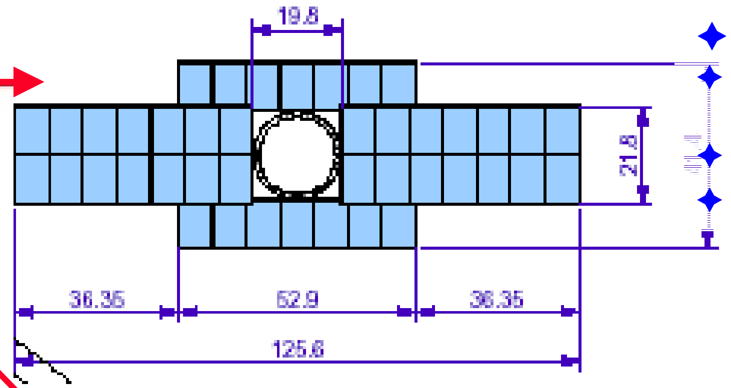
Prototype of the secondary vacuum box and RF foil

Mechanics structure well-advanced

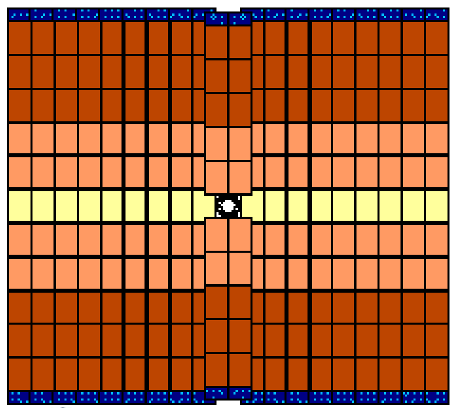
Tracking chambers (TT, IT, OT)



Inner Tracker



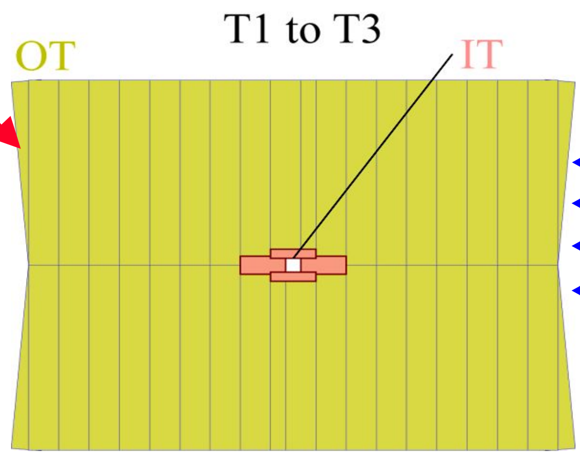
- ✦ 3 stations
- ✦ 4 layers each 320/410 μm thin silicon
- ✦ 198 μm readout pitch
- ✦ 130k readout ch.



Trigger Tracker

- p_T at Level-1 trigger
- V0 (K_S, Λ), no VELO
- low-p tracks, no T1-T3

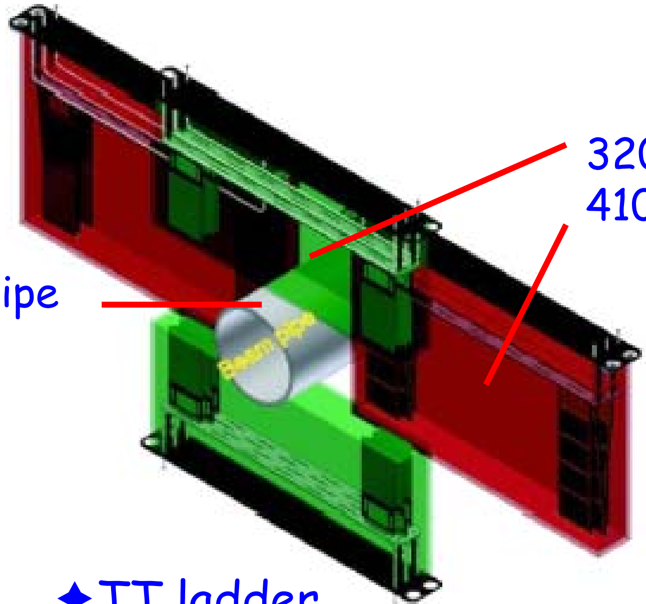
- ✦ 2*2 layers
- ✦ 500 μm silicon
- ✦ 193 μm r/o pitch
- ✦ 144k readout ch.



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

Outer Tracker

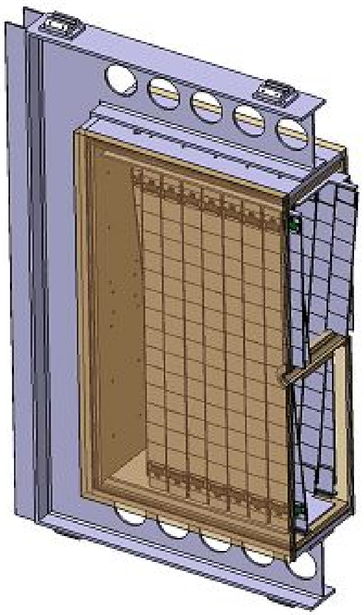
Tracking chambers (TT, IT, OT)



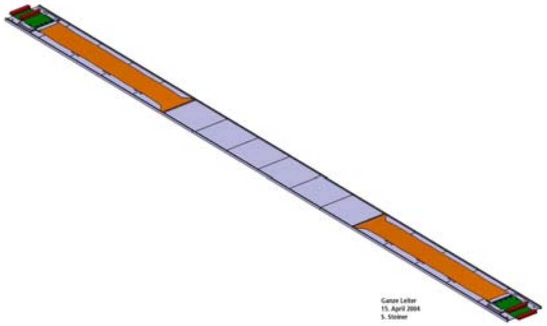
beam pipe

320 mm thick sensors
410 mm thick sensors

IT, sensors are being ordered



✦TT ladder prototype in final phase
✦TT sensors order is being prepared



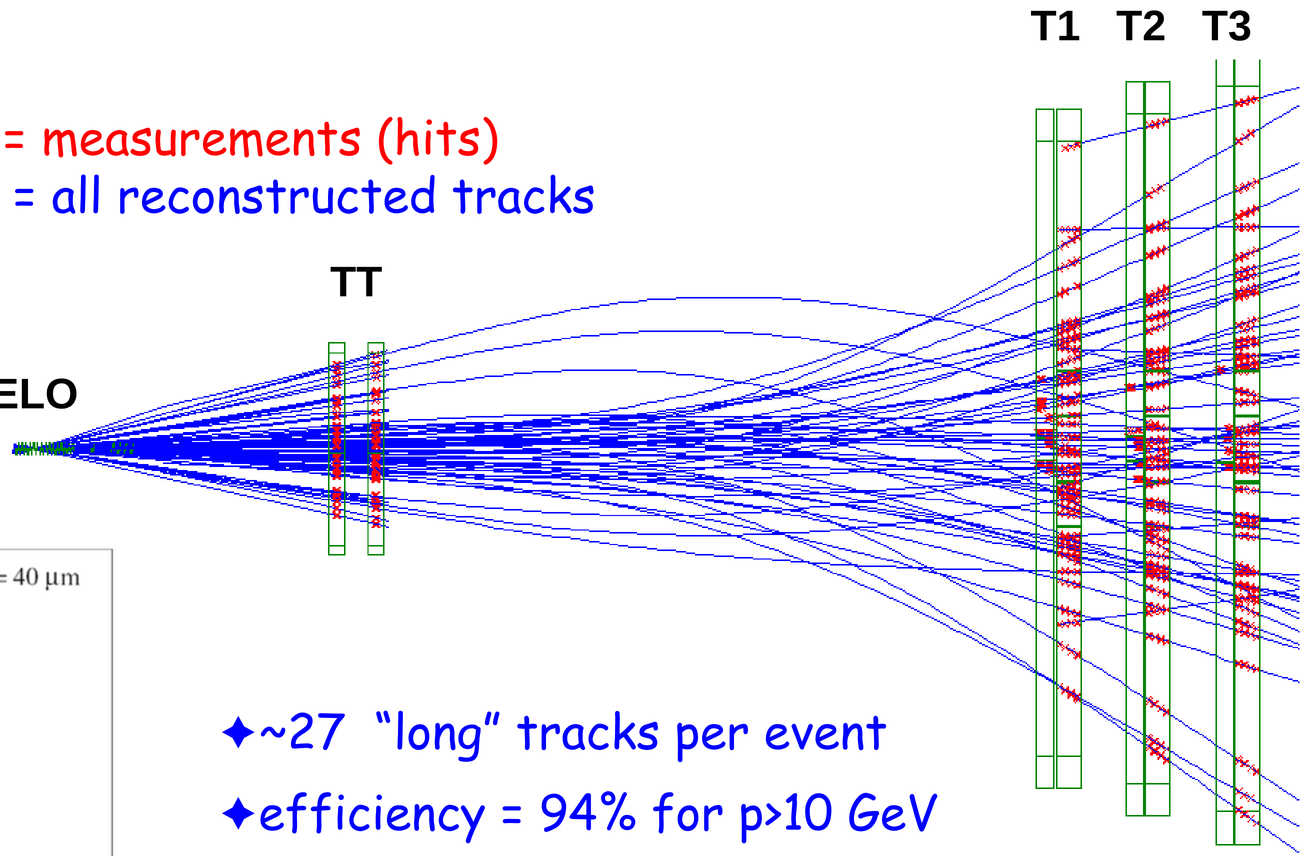
OT chamber production, NIKHEF

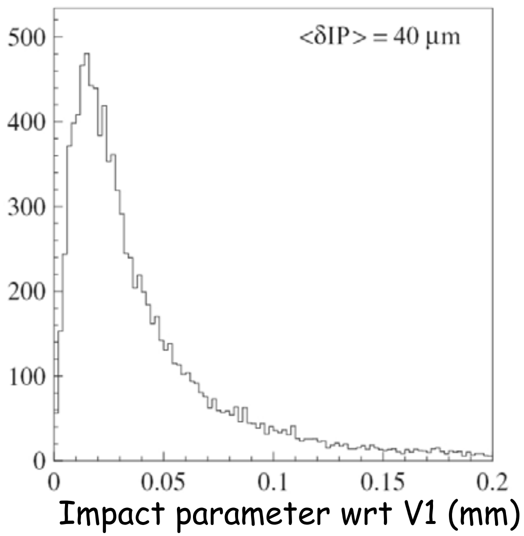
Performance of the tracking system

$b\bar{b}$ event:

Red = measurements (hits)

Blue = all reconstructed tracks



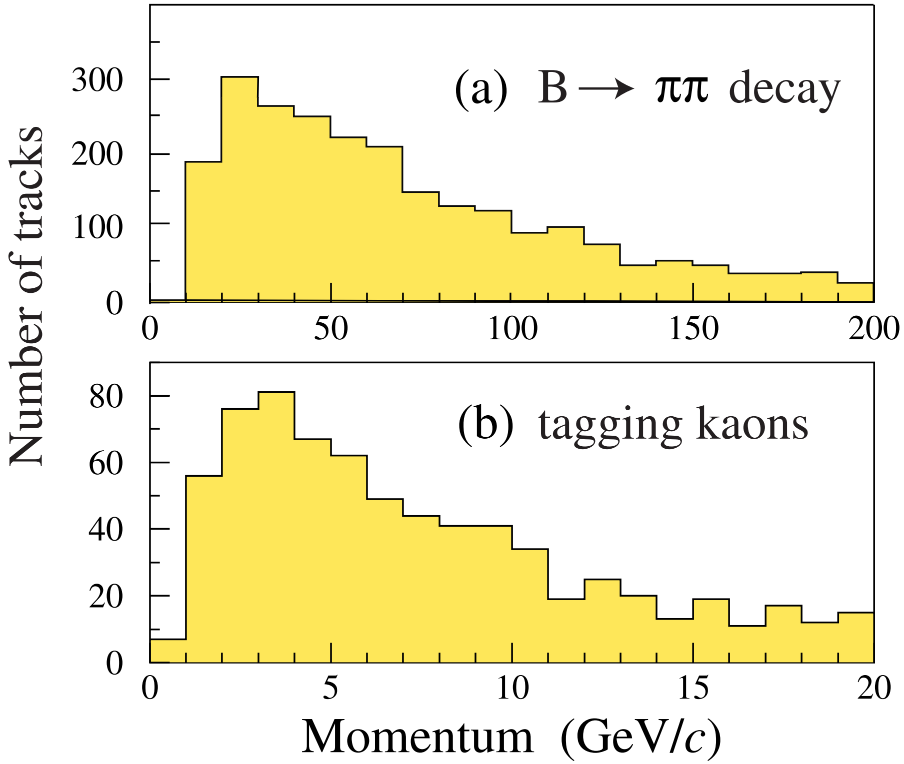


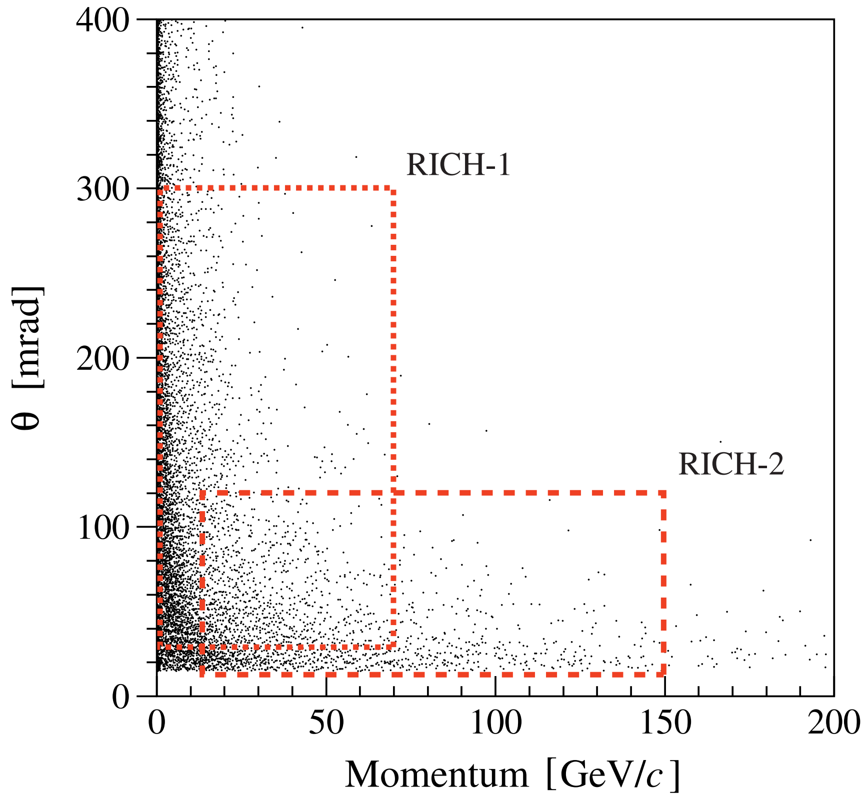
- ~27 "long" tracks per event
- efficiency = 94% for p>10 GeV
- $\delta p/p$ = 0.35-0.55%
- δIP peaks at 20μm, <δIP> = 40μm

Particle Identification with RICH

LHCb has to identified charged hadrons over a large momentum range:

- ✦ High momentum hadrons in two-body B decays
- ✦ Low momentum K for B flavour tagging (identify K from b→c →s)



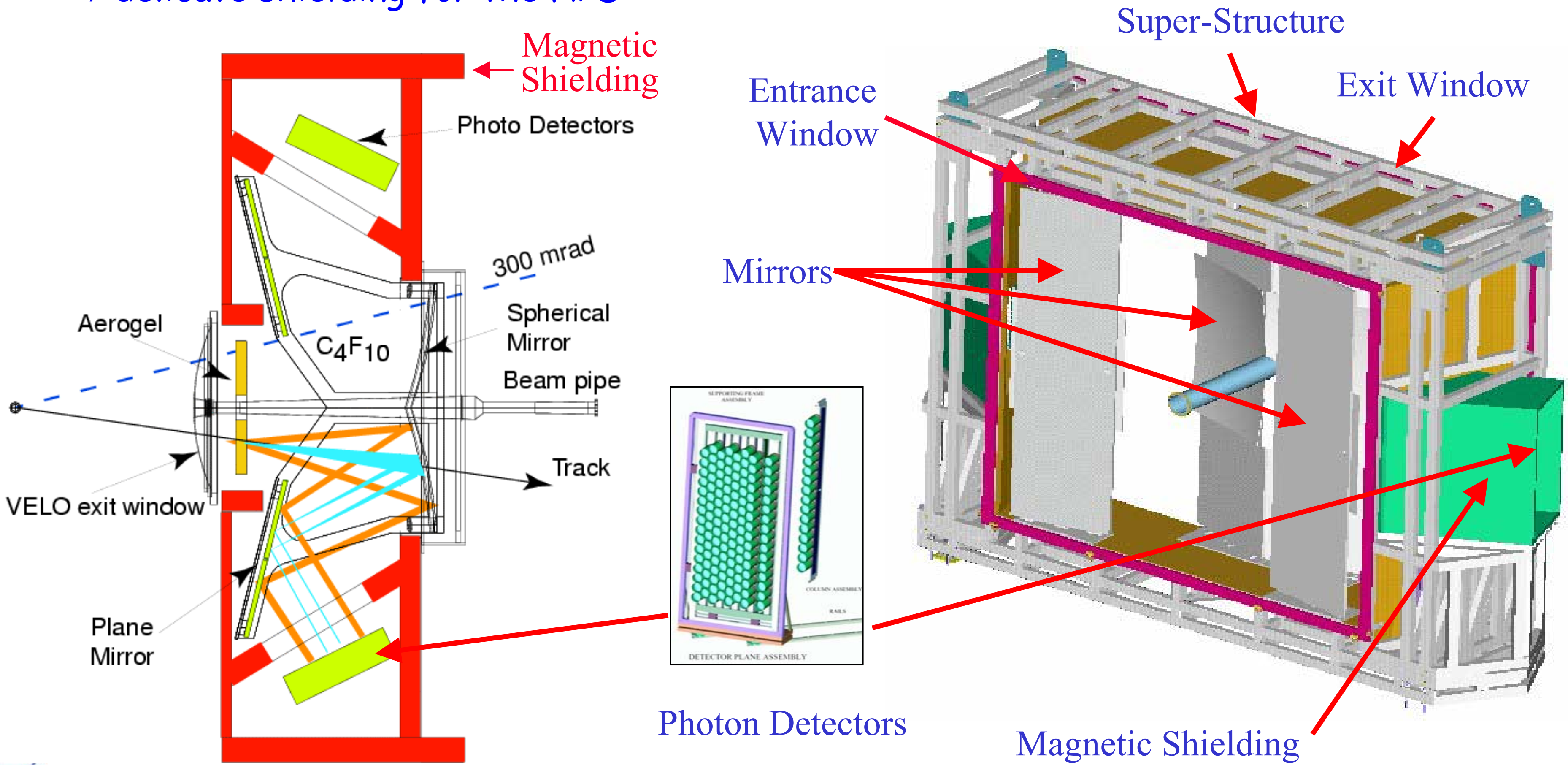


⇒ RICH system divided into 2 detectors

RICH detectors

RICH1 1<p<60 GeV
25-300 mrad
5cm aerogel; n=1.03
4 m^3 C_4F_{10} ; n = 1.0014
Significant magnetic fringe field
⇒ delicate shielding for the HPD

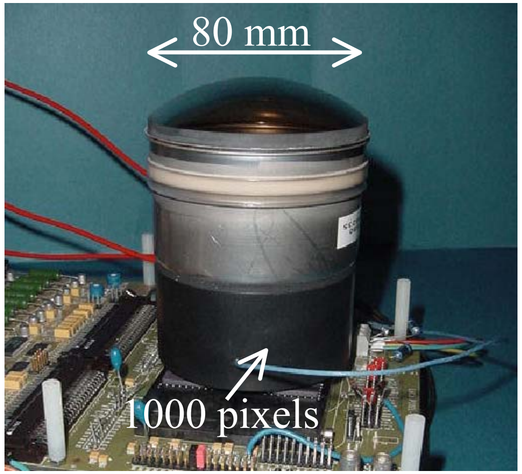
RICH2 p<~100 GeV
15-120 mrad
100 m^3 CF_4 ; n=1.0005



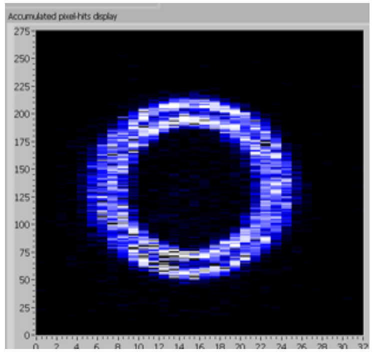
RICH detectors

RICH2 super structure completed

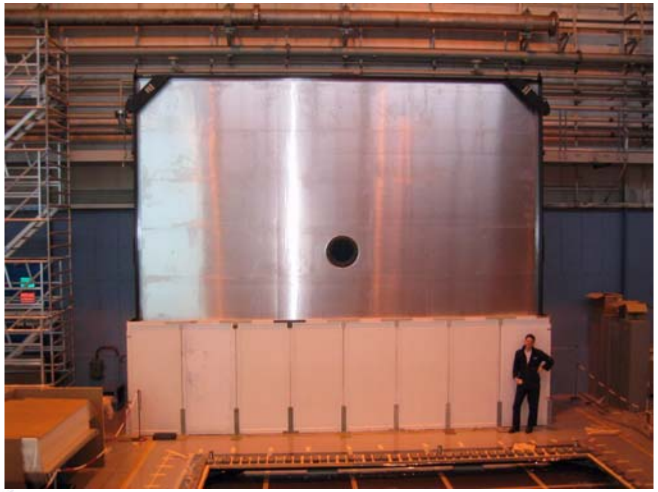
Hybrid Photodiodes ordered



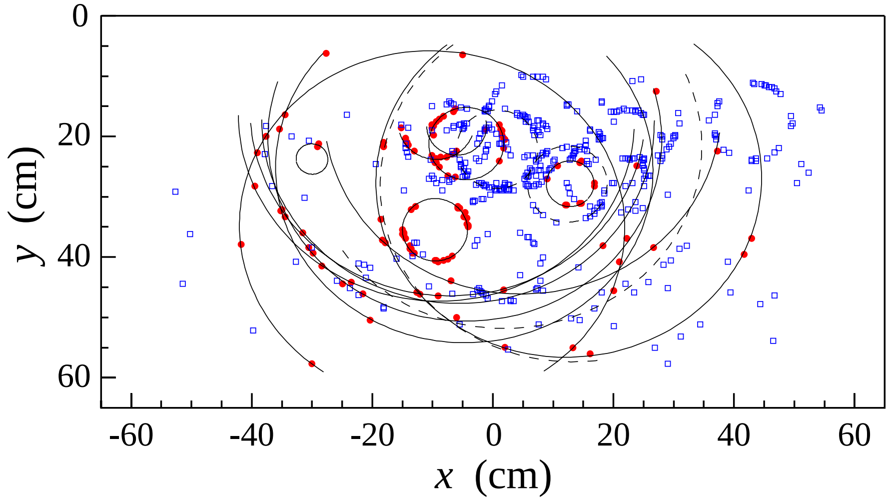
Test beam:
e–π separation



Exit/entrance windows completed

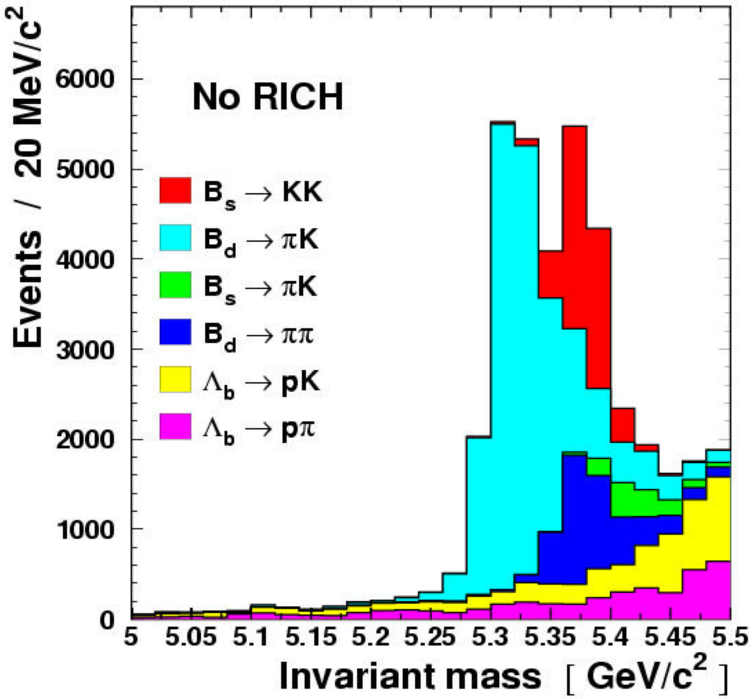


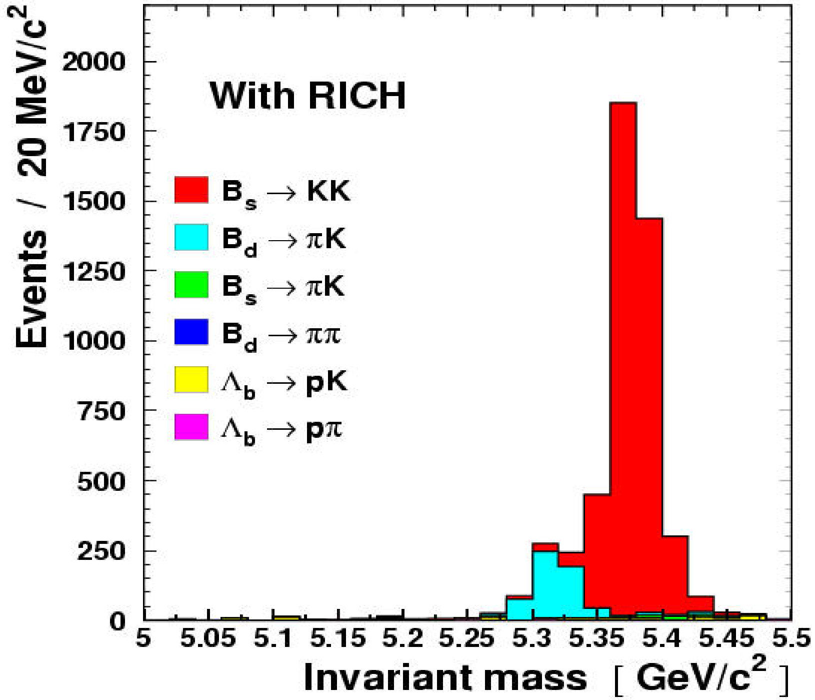
Typical event in the RICH1 photon detectors



Performance of RICH detectors

$B_s \to K^+K^-$



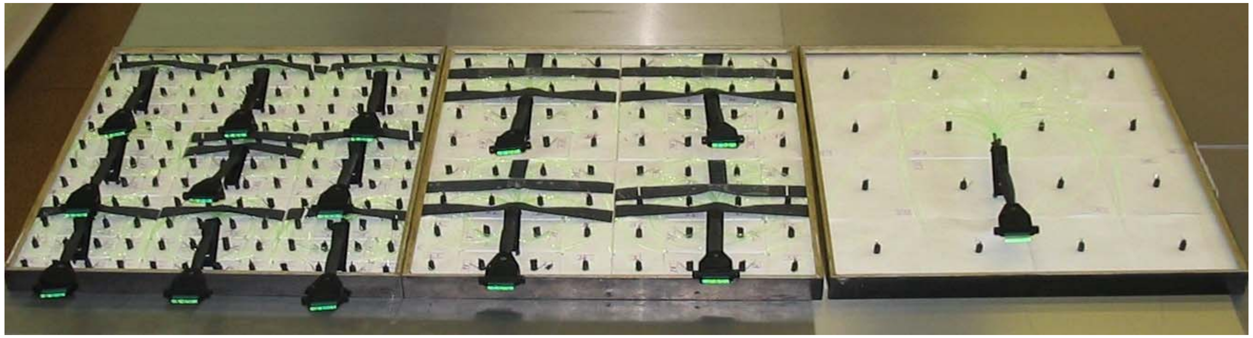


Signal purity = 13%

Signal purity = 84%

Efficiency = 79%

Calorimeters



✦ Preshower

✦Pb converter sandwiched between two scintillator planes with 16k scintillating pads

✦Production ongoing

✦ECAL

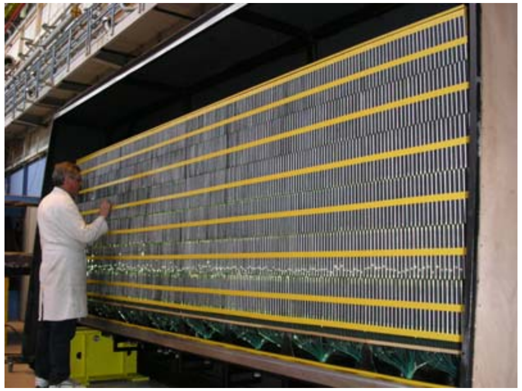
✦"Shashlik" type modules 2mm Pb/ 4mm scintillator

✦Readout via WLS fibres

✦$\sigma E/E = 10\%/\sqrt{E} + 1.5\%$

✦100% delivered

Calorimeters system crucial for level-0 trigger: read in less than 25 ns !



✦HCAL

✦4mm scintillator/ 16mm iron

✦Readout via WLS fibres

✦$\sigma E/E = 75\%/\sqrt{E} + 10\%$

✦60% delivered

Major Russian contribution from ITEP, IHEP, INR

→Installation of ECAL/HCAL nov. 2004

Muon stations

Wiring machine at PNPI

- ✦Production of the ~1446 MWPC on the way (~5% ready)
- ✦Major Russian contribution
- ✦Muon identification efficiency ~94% (3% pion misidentification)

Inner chambers of station M3

Chariot of muon filter at CERN

Trigger overview

40 MHz

↓

Level-0:
p_T of
μ, e, h, γ

← Calorimeter / Muon system / Pile-up system

↓

1 MHz

↓

Level-1:
Impact parameter
Rough p_T ~ 20%

← Vertex Locator / Trigger Tracker / Level 0 objects

↓

40 kHz

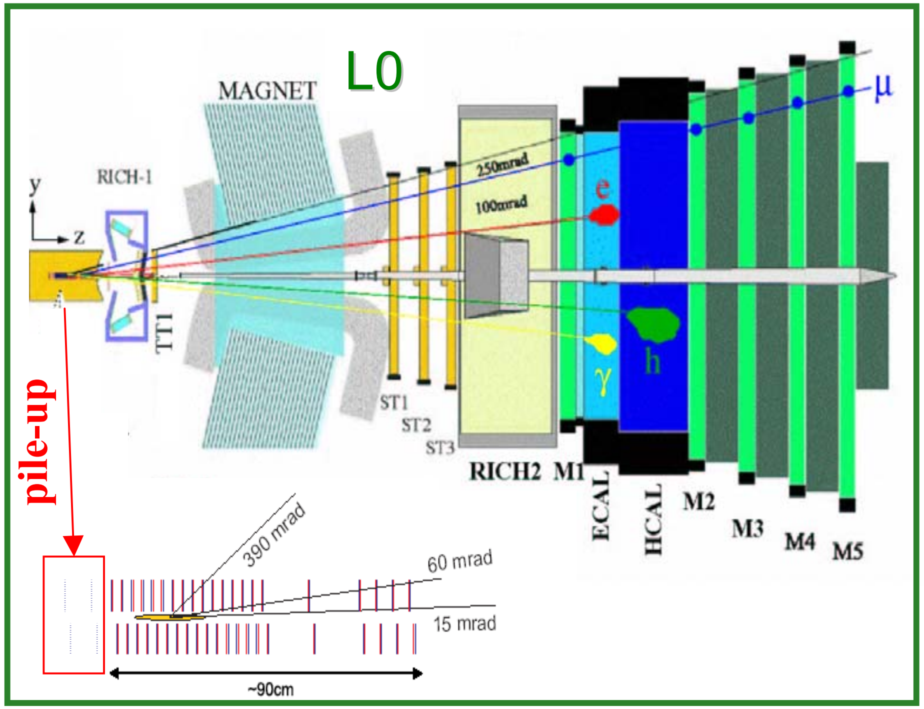
↓

HLT:
Final state
reconstruction

← Full detector information

↓

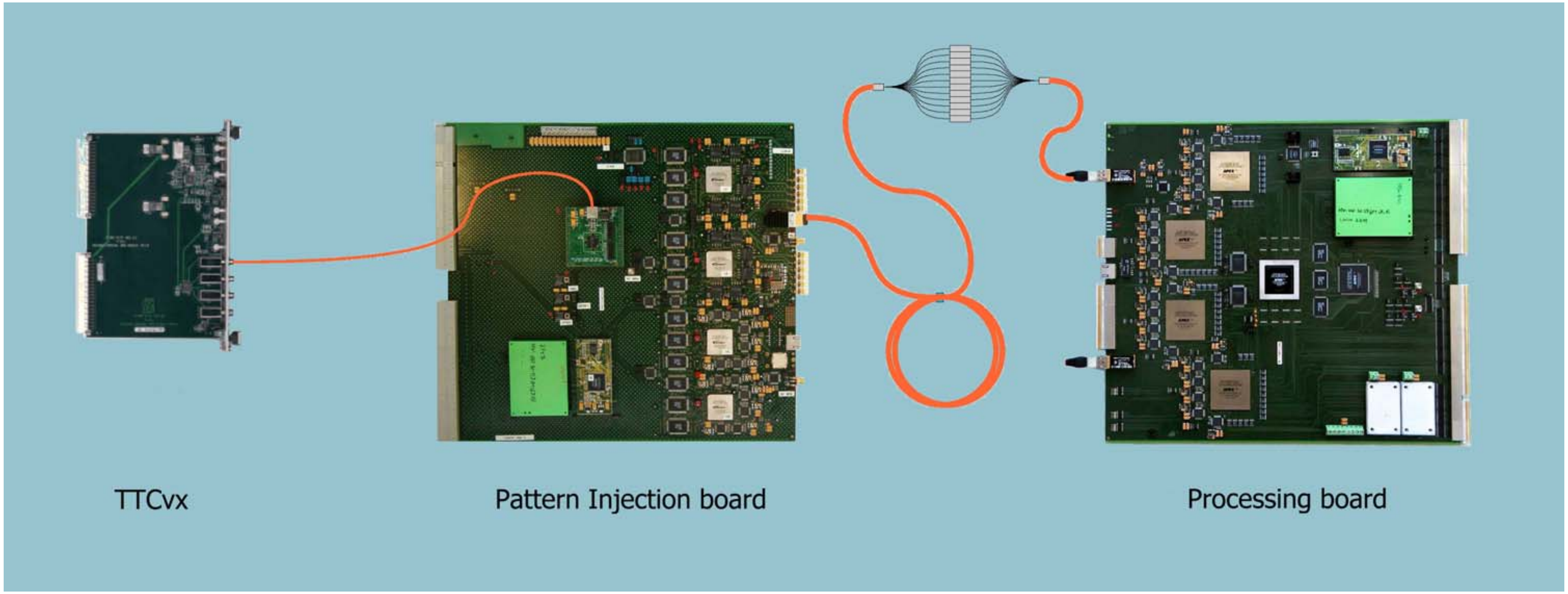
200 Hz output to tape



- Level-0: custom hardware
- Level-1 and HLT on the same CPU farm

Trigger

Trigger hardware well advanced
Example: Muon trigger test system



Physics potential

Monte Carlo simulation

- ✦ **Physics potential is estimated using Monte Carlo simulation**
- ✦ **Generation of pp collisions using Pythia 6.2**
  - Hard QCD processes, single and double diffraction
  - Multiple parton interactions tuned to reproduce track mulitplicities observed at SPS and Tevatron energies
- ✦ **Full Geant3.2 simulation**
  - Detector response based on test-beam data (resolution, efficiency, noise, cross-talk)
- ✦ **Offline reconstruction**
  - Full pattern recognition (track finding, RICH reconstruction)
- ✦ **"Data challenge"**
  - 2003: 67M events, among which 10M bb events (~4 minutes of data taking !)
  - 2004: 5 times more bb events (next slide)

Data Challenge 2004

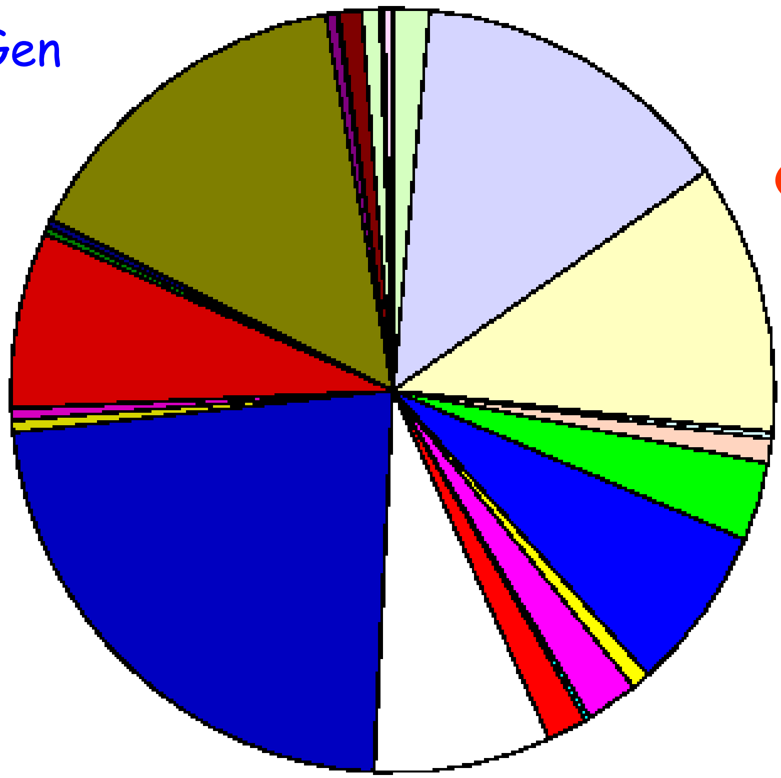
Events simulation, reconstruction and analysis in a distributed way (Grid)

Pythia

GEANT4

EvtGen

Total Running Jobs: 3181
DIRAC: 51% LCG: 49%



Jun 03 2004, 21:10

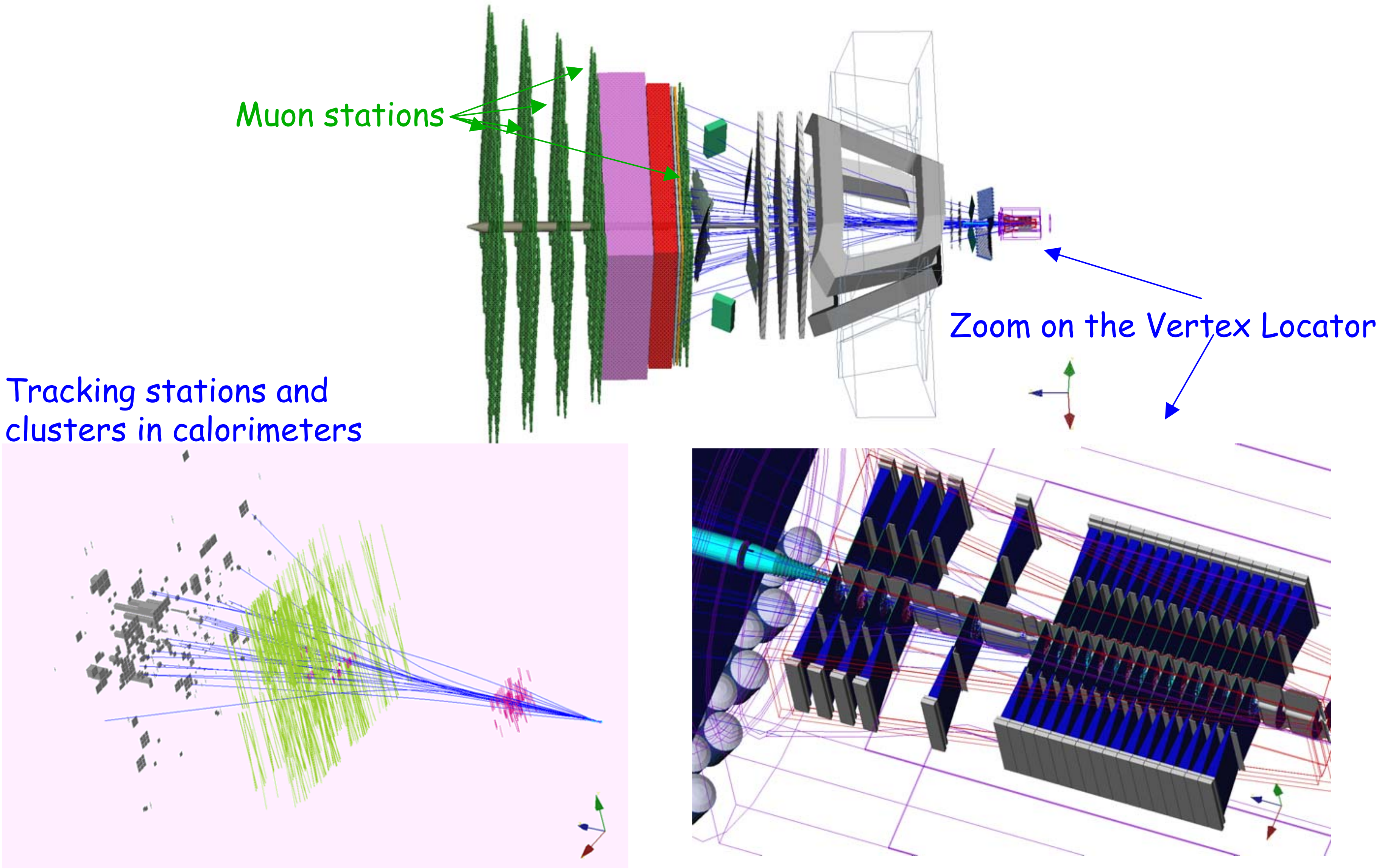
180M events planned,
40M already produced
all over the world:

DIRAC.Barcelona.es	1.540%
DIRAC.Bologna.it	13.73%
DIRAC.CERN.ch	11.44%
DIRAC.CracowAgu.pl	0.031%
DIRAC.IF-UFRJ.br	0.282%
DIRAC.IHEP-Protvino.ru	1.005%
DIRAC.ITEP-Moscow.ru	3.332%
DIRAC.Imperial.uk	6.978%
DIRAC.JINR-Dubna.ru	0.785%
DIRAC.Lyon.fr	2.232%
DIRAC.Manno.ch	0.220%
DIRAC.Santiago.es	1.697%
DIRAC.ScotGrid.uk	7.481%
IHEP-Protvino	0.031%
LCG.CERN.ch	22.44%
LCG.CNAF.it	0.502%
LCG.Cambridge.uk	0.471%
LCG.FNAL.us	0.031%
LCG.FZK.de	7.481%
LCG.Imperial.uk	0.314%
LCG.Krakow.pl	0.345%
LCG.Legnaro.it	14.77%
LCG.Milano.it	0.471%
LCG.NCU.tw	0.094%
LCG.PIC.es	0.943%
LCG.RAL.uk	0.785%
LCG.Torino.it	0.062%
LCG.Triumf.ca	0.094%
LCG.USC.es	0.314%
RAL-CSF	0.062%

Russian contribution

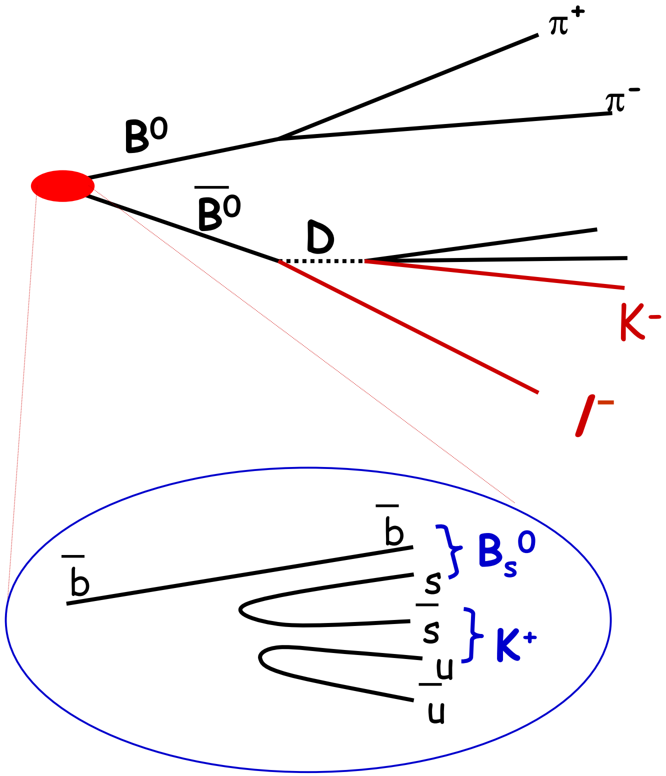
Taiwan !

LHCb event display



Flavour tagging

Knowledge of flavour at birth is essential for the majority of $\not{CP}$ measurements



tagging strategy:

- opposite side lepton tag ($b \to l$)
- opposite side kaon tag ($b \to c \to s$)
- same side kaon tag (for B_s)
- opposite B vertex charge tagging

sources for wrong tags:

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

$b \to c \to l$ (lepton tag) …

Combining tags	εtag [%]	ωtag [%]	εeff=$\varepsilon_{tag}(1-2\,\omega_{tag})^2$[%]
$B_d \to \pi^+\pi^-$	42	35	4
$B_s \to K^+K^-$	50	33	6

Efficiencies, event yields and B_{bb}/S ratios

	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**
$B^0 \to \bar{D}^0(K\pi)K^{*0}$	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 $L=2\times10^{32}$ cm^{-2}s^{-1} with σ_{bb}=500 μb)
Yields include factor 2 from CP-conjugated decays
Branching ratios from PDG or SM predictions

B_s oscillation frequency: Δm_s

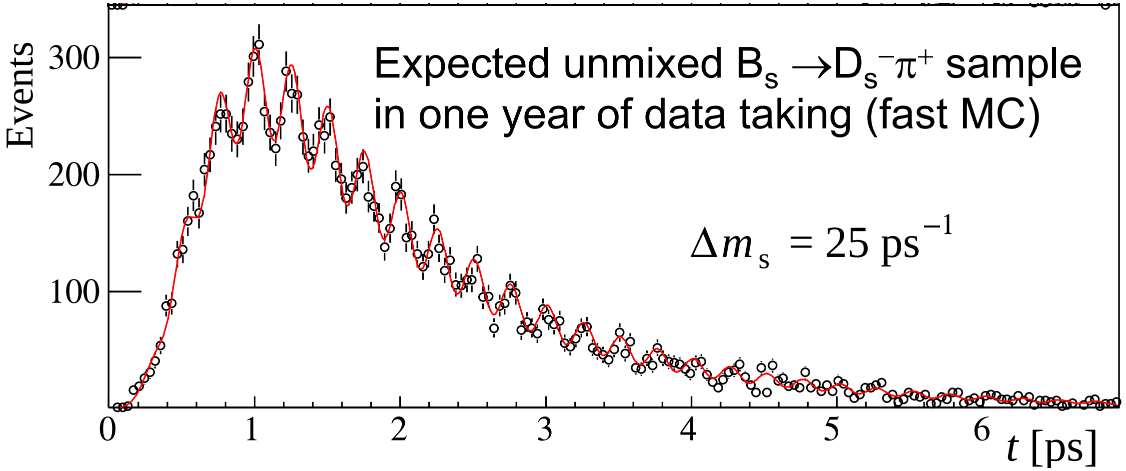
- Needed for the observation of time dependent CP asymmetries with B_s decays
- Use $B_s \to D_s^- \pi^+$
- If $\Delta ms = 20\ ps^{-1}$

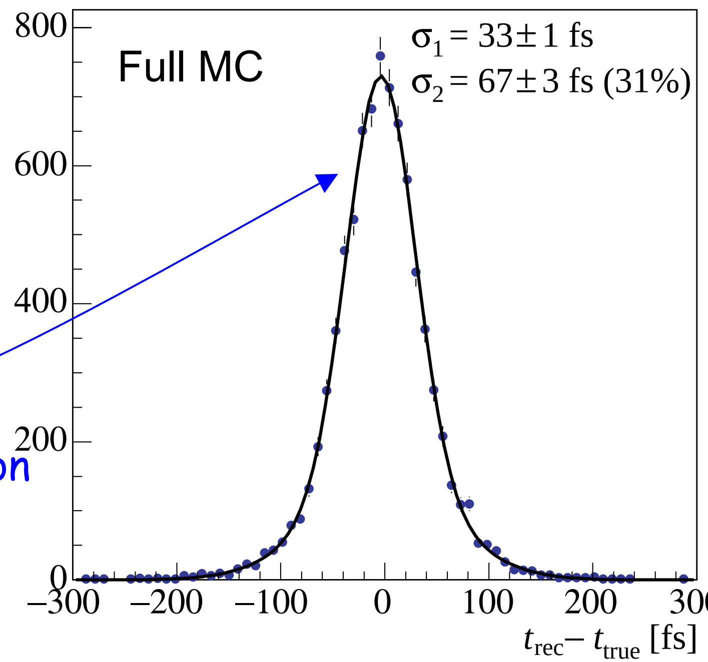
$$\sigma(\Delta m_s) = 0.01\ ps^{-1}$$

- Can observe $>5\sigma$ oscillation signal if

$$\Delta m_s < 68\ ps^{-1}$$

well beyond SM prediction



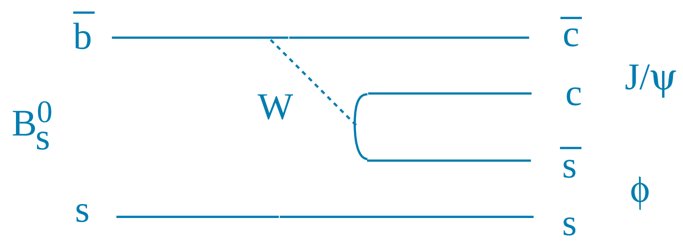


Proper-time resolution plays a crucial role

B_s mixing phase ϕ_s

- CP asymmetry arises from interference of
  $B_s \to J/\psi\,\phi$ and $B_s \to \bar{B}_s \to J/\psi\,\phi$
  $\to$ measures the phase of B_s mixing, ϕ_s
- B_s counterpart of the golden mode $B^0 \to J/\psi\, K_S$
- Reconstruct $J/\psi \to \mu^+\mu^-$ or e^+e^-,
  $\phi \to K^+K^-$
- Final state is admixture of CP-even and odd contributions
  $\to$ angular analysis of decay products required
- In Standard Model, $\phi_s \sim -2\chi \sim 0.04$
- If $\Delta m_s = 20\ ps^{-1}$:

$\sigma(\sin(\phi_s)) = 0.06$



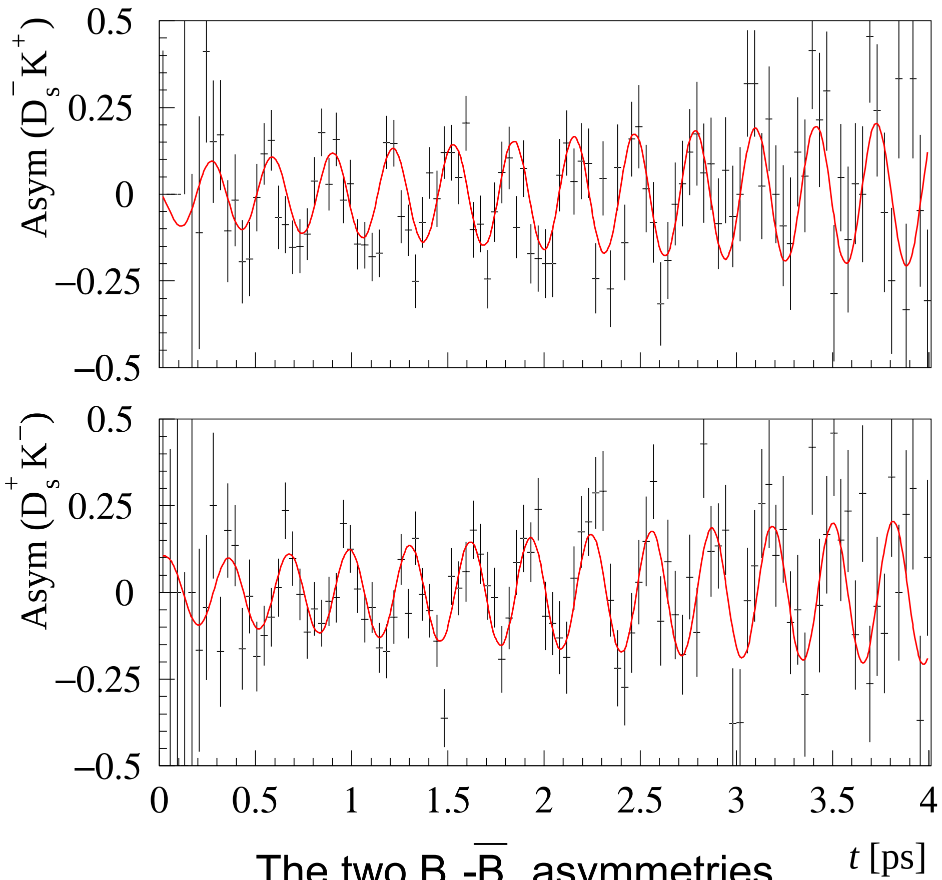
1. Angle γ from $B_s \to D_s^{\mp} K^{\pm}$

- Interference between 2 tree diagrams
- Measure $\gamma + \phi_s$ from time-dependent rates of $B_s \to D_s^- K^+$ and $B_s \to D_s^+ K^-$ decays and their CP-conjugates:
  - Mistag extracted from $B_s \to D_s^- \pi^+$ sample
  - Subtract ϕ_s measured with $B_s \to J/\psi\ \phi$

After one year, if Δm_s= 20 ps^{-1}, $\Delta\Gamma_s/\Gamma_s$ = 0.1, 55 < γ < 105 deg, –20 < $\Delta_{T1/T2}$ < 20 deg:

$\sigma(\gamma)$ = 14–15 deg

No theoretical uncertainty; insensitive to new physics in B mixing



The two B_s-$\overline{B}_s$ asymmetries after 5 years of data

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

- $b \to u$ processes, with large $b \to d(s)$ penguin contributions
- Measure time-dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays:

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

- Method proposed by R. Fleischer:
  - SM predictions:

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

$d \exp(i\vartheta)$ = function of tree and penguin amplitudes in $B^0 \to \pi^+\pi^-$

$d' \exp(i\vartheta')$ = function of tree and penguin amplitudes in $B_s \to K^+K^-$

  - Assuming U-spin flavour symmetry (interchange of d and s quarks): $d = d'$ and $\vartheta = \vartheta'$
  - 4 measurements (CP asymmetries) and 3 unknowns (γ, d and ϑ) $\to$ can solve for γ

2. Angle γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ (cont.)

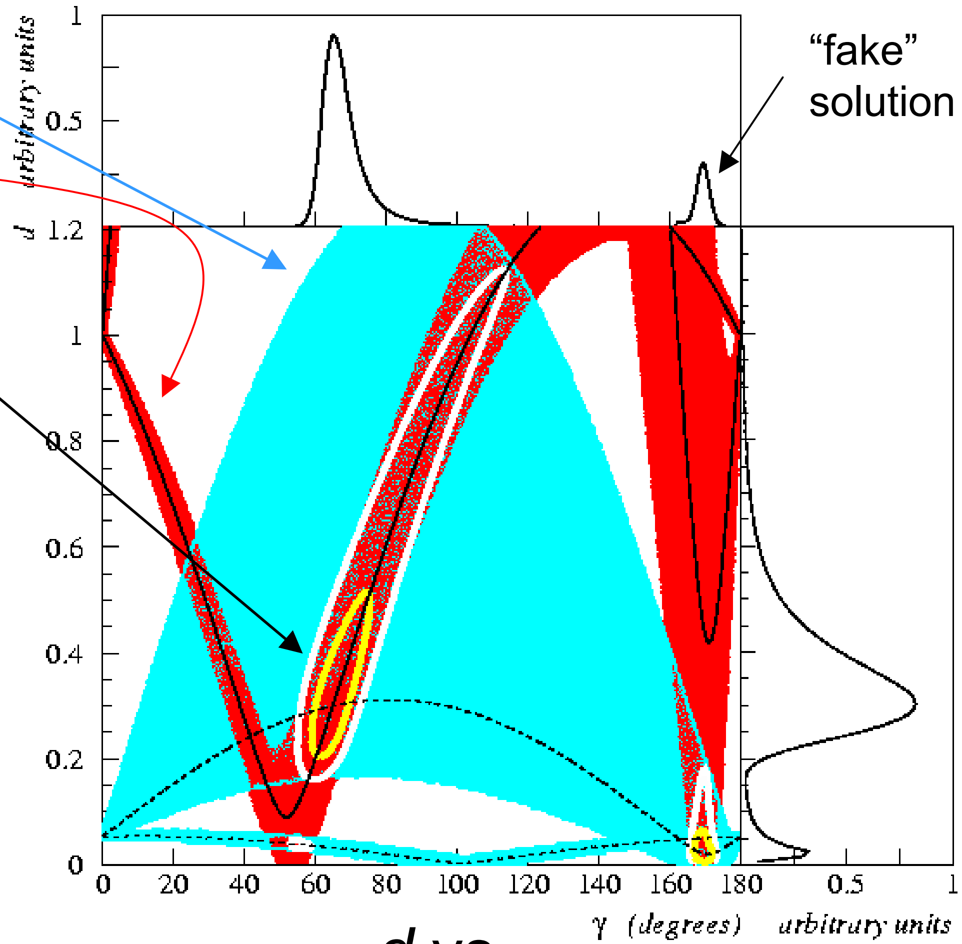
- Extract mistags from $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$
- Use expected LHCb precision on ϕ_d and ϕ_s

blue bands from $B_s \to K^+K^-$ (95%CL)
red bands from $B^0 \to \pi^+\pi^-$ (95%CL)
ellipses are 68% and 95% CL regions (for γ_{input} = 65 deg)

If Δm_s= 20 ps^{-1}, $\Delta\Gamma_s/\Gamma_s$=0.1, d =0.3, ϑ= 160 deg, 55 < γ < 105 deg:

$\sigma(\gamma)$ = 4–6 deg

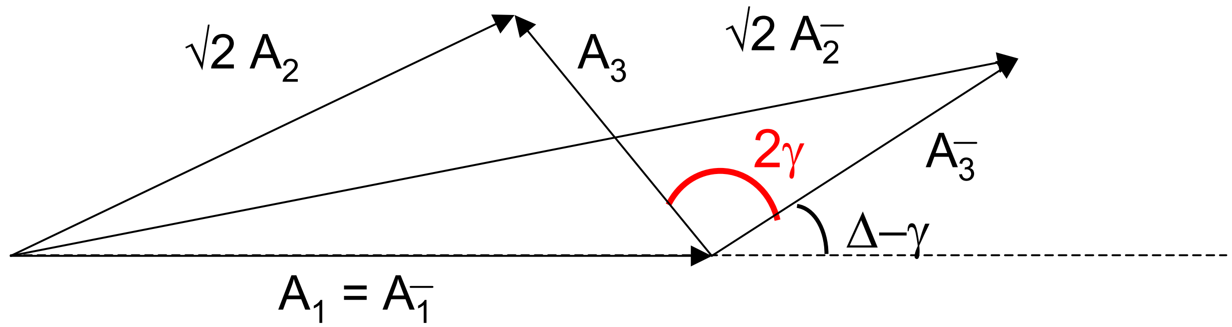
U-spin symmetry assumed; sensitive to new physics in penguins



d vs γ

3. Angle γ from $B^0 \to \bar{D}^0 K^{*0}$ and $B^0 \to D^0 K^{*0}$

- Interference between 2 tree diagrams due to D^0 mixing
- Application of Gronau-Wyler method to $D^0 K^{*0}$ (Dunietz):



- Measure six rates (following three + CP-conjugates):
  - 1) $B^0 \to \bar{D}^0(K^+\pi^-)K^{*0}$, 2) $B^0 \to D_{CP}(K^+K^-)K^{*0}$, 3) $B^0 \to D^0\,(K^-\pi^+)\,K^{*0}$
  - No proper time measurement or tagging required

$\sigma(\gamma)$ = 7–8 deg	$55 < \gamma < 105$ deg $-20 < \Delta < 20$ deg

No theoretical uncertainties
sensitive to new phase in D^0 mixing

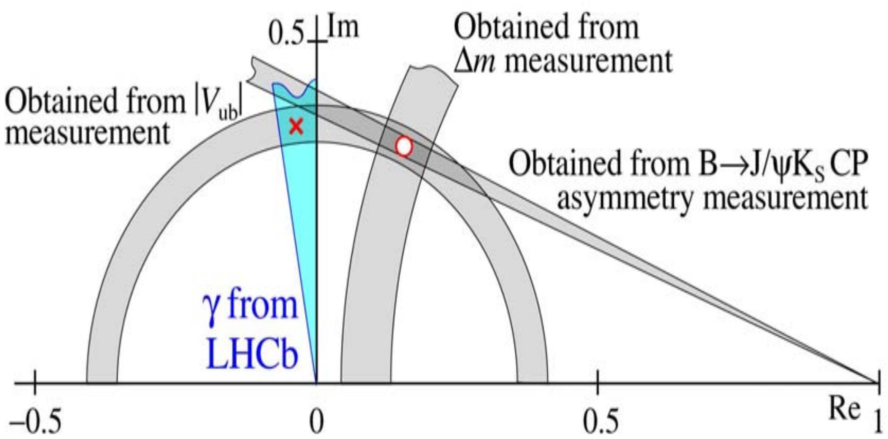
New physics in angle γ measurement ?

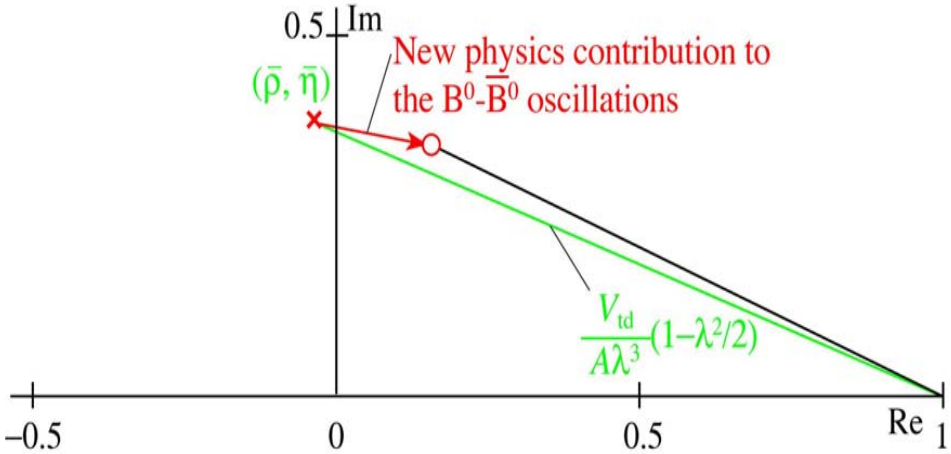
1. $B_s \to D_s K$ → γ not affected by new physics → Determine the CKM parameters A, ρ, η independent of new physics

2. $B \to \pi\pi$, $B_s \to KK$ → γ affected by possible new physics in penguin

3. $B \to DK^*$ → γ affected by possible new physics in D-D mixing

Determine the CKM parameters A, ρ, η independent of new physics → Extract the contribution of new physics to the oscillations and penguins





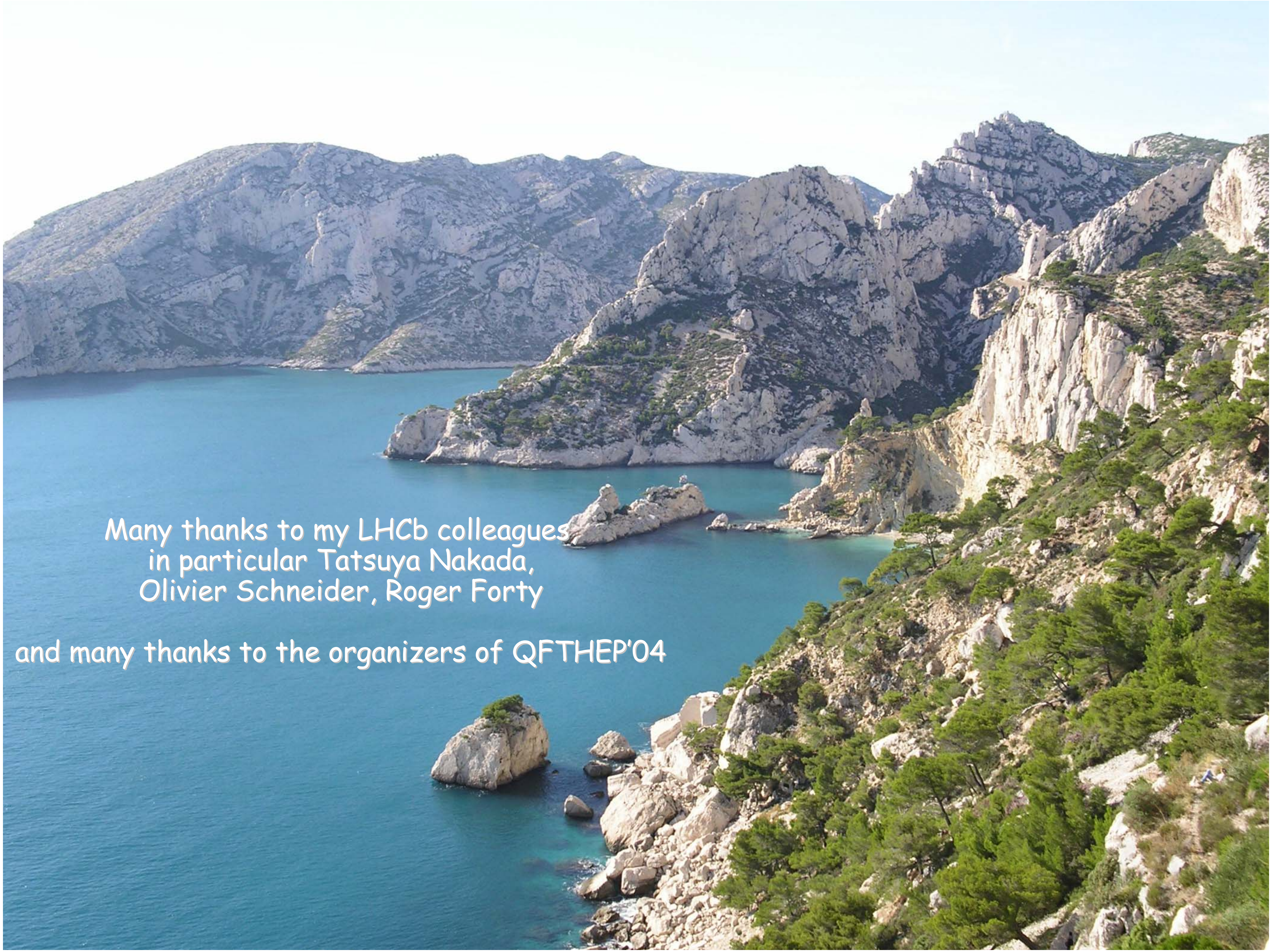
Conclusions

- LHCb is dedicated to the study of B physics, with a devoted trigger, excellent vertex and momentum resolution, and particle identification
- Construction of the experiment is progressing well
  It will be ready for first LHC collisions in 2007
- LHCb will give unprecedented statistics for B decays, including access to the B_s meson, unavailable to the B factories
- B_s–$\overline{B}_s$ oscillations will be measured precisely
  - $> 5\sigma$ for Δm_s up to 68 ps^{-1}
  - $\sigma(\Delta m_s) \sim 0.01\ ps^{-1}$

  } in one year
- Many measurements of rare decays and CP asymmetries will be performed
  - $\sigma(\sin 2\beta) \sim 0.02$
  - $\sigma(\sin 2\chi) \sim 0.06$
  - $\sigma(\gamma) \leq 10°$

  } in one year
- CP angles determined via channels with different sensitivity to new physics
  → detailed test of the CKM description of the quark sector

LHCb offers an excellent opportunity to spot New Physics signals beyond Standard Model very soon at LHC !


Many thanks to my LHCb colleagues
in particular Tatsuya Nakada,
Olivier Schneider, Roger Forty
and many thanks to the organizers of QFTHEP'04

Backup slides

Systematic Effects

Possible sources of systematic uncertainty in CP measurement:

- Asymmetry in b-$\bar{b}$ production rate
- Charge dependent detector efficiencies…
  - can bias tagging efficiencies
  - can fake CP asymmetries
- CP asymmetries in background process

Experimental handles:

- Use of control samples:
  - Calibrate b-b production rate
  - Determine tagging dilution from the data:

    e.g. B_s->$D_s\pi$ for B_s->D_sK, B->Kπ for B->$\pi\pi$, B->J/ψK* for B->J/ψK_s, etc
- Reversible B field in alternate runs
- Charge dependent efficiencies cancel in most B/$\bar{B}$ asymmetries
- Study CP asymmetry of backgrounds in B mass "sidebands"
- Perform simultaneous fits for specific background signals:

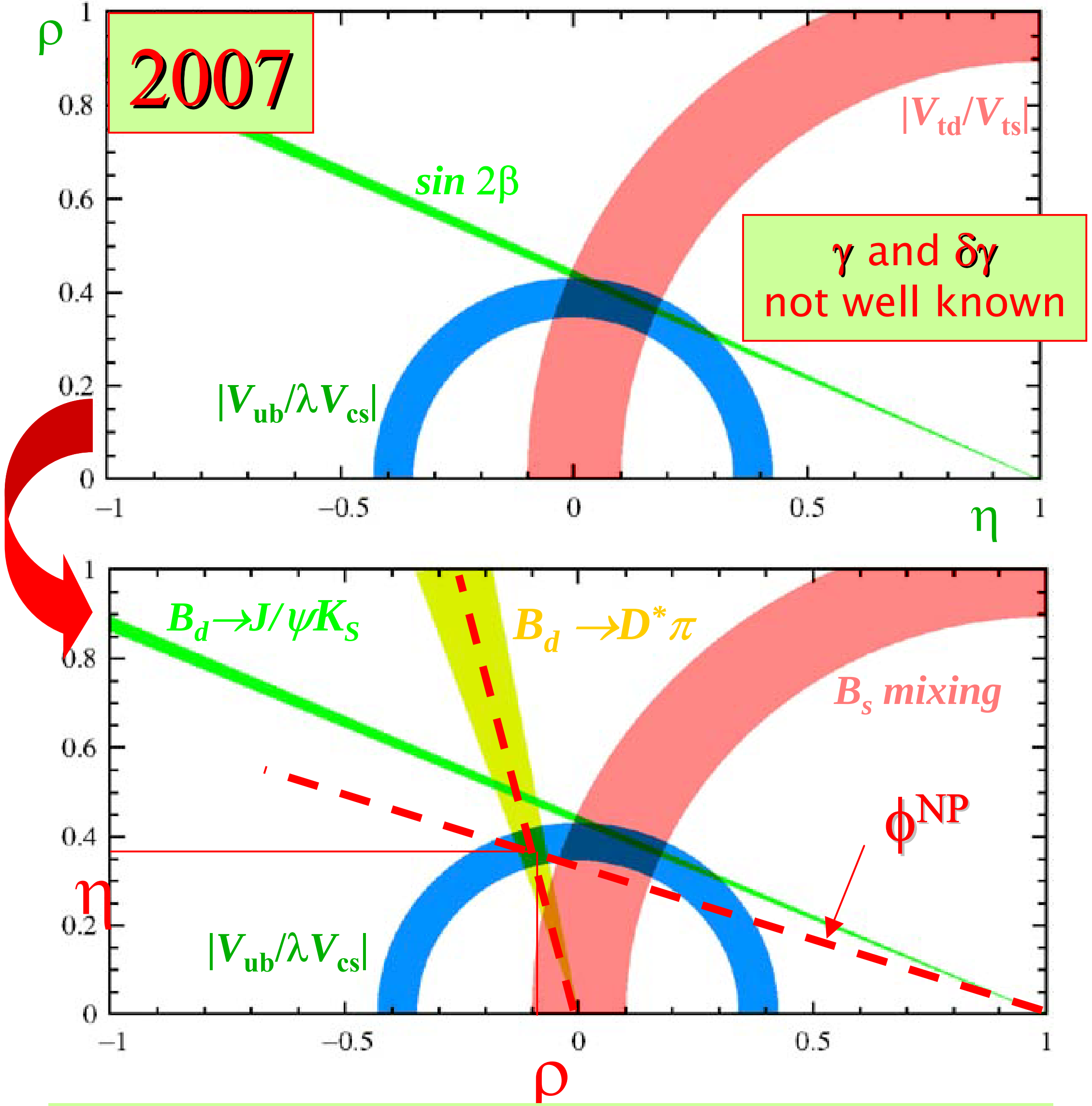
  e.g. B_s->$D_s\pi$ in B_s->D_sK , B_s->Kπ & B_s->KK, …

Comparison to other experiments

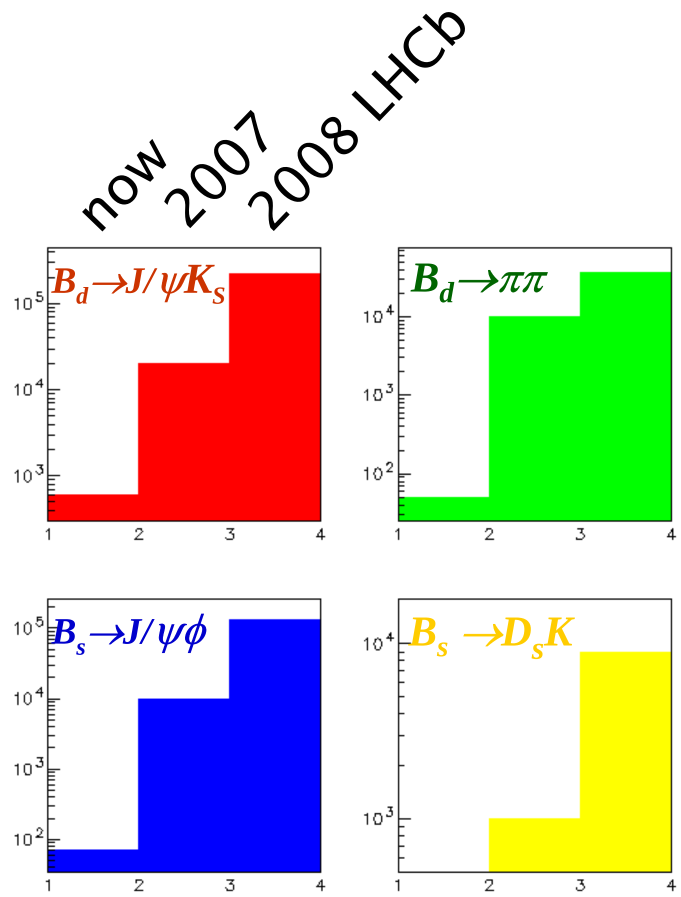
- Enormous production rate at LHCb: ~ 10^{12} $b\bar{b}$ pairs per year
  → much higher statistics than the current B factories
  But more background from non-b events → challenging trigger
  and high energy → more primary tracks, tagging more difficult
- Expect ~ 200,000 reconstructed $B^0 \to J/\psi\, K_S$ events/year
  cf current B-factory samples of ~ 2000 events
  → precision on sin 2β ~ 0.02 in one year for LHCb
  (similar to expected *world average* precision in 2007)
- Expect ~ 26,000 reconstructed $B^0 \to \pi^+\pi^-$ events/year
  cf ~ 1000 from B-factory by 2007
- But in addition, *all* b-hadron species are produced: B^0, B^+, B_s, B_c , Λ_b …
- B_s meson : not produced at B factories
  Only competition before LHC is from CDF+D0 (lower statistics, poorer ID)
- ATLAS and CMS will only have lepton trigger, poor hadron identification
  Direct competition will come from BTeV, expected at the Tevatron ≥ 2009

$b \to s$ penguins annual yield

Process type	Decay channel	Annual untagged yield (presented in TRD)
gluonic $b \to s$ penguin	$B_s \to \phi\phi$	1.2k
gluonic $b \to s$ penguin + $b \to u$ tree	$B^0 \to K^+\pi^-$	135k
gluonic $b \to s$ penguin + $b \to u$ tree	$B_s \to K^+K^-$	37k
electroweak $b \to s$ penguin	$B^0 \to K^{*0}\gamma$	35k
electroweak $b \to s$ penguin	$B_s \to \phi\gamma$	9.3k
electroweak $b \to s$ penguin + box	$B^0 \to K^{*0}\mu^+\mu^-$	4.4k



CPV from LHCb in one year

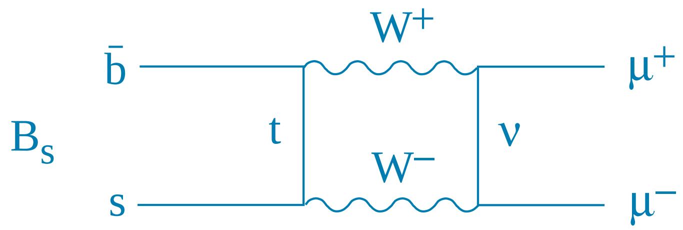


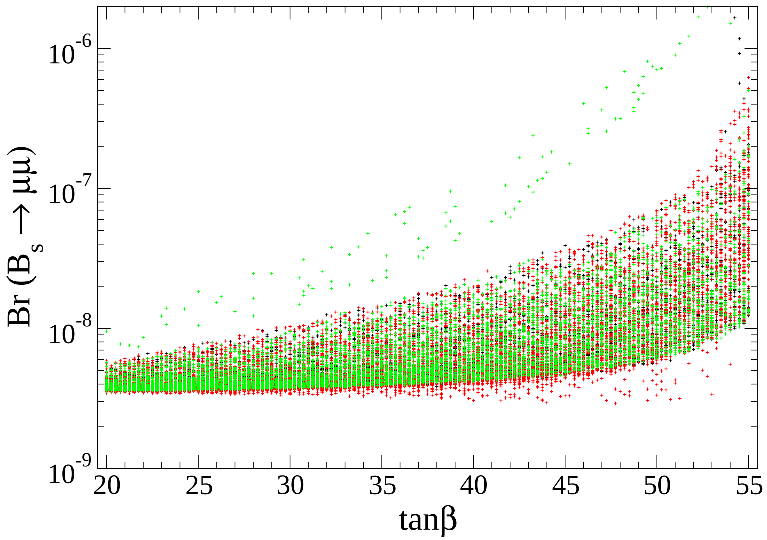
- If New Physics is there
  LHCb experiment can spot it in 2008 !

Rare decays: $B_s \to \mu^+\mu^-$

- Flavour-changing neutral current strongly suppressed in Standard Model
  $\mathcal{B}(B_s \to \mu^+\mu^-) \sim 4 \times 10^{-9}$
- New physics contributions could increase this significantly
  $\to$ excellent place to look for them
- *eg* in SUSY:
  [G. Kane *et al*, hep-ph/0310042]
- Expect ~ 16 signal events/year for the *Standard Model* branching ratio

  ~ 40 background events/year
  (mostly from $b \to \mu^-$, $\bar{b} \to \mu^+$)
  $\to$ ~ 4 σ significance after three years

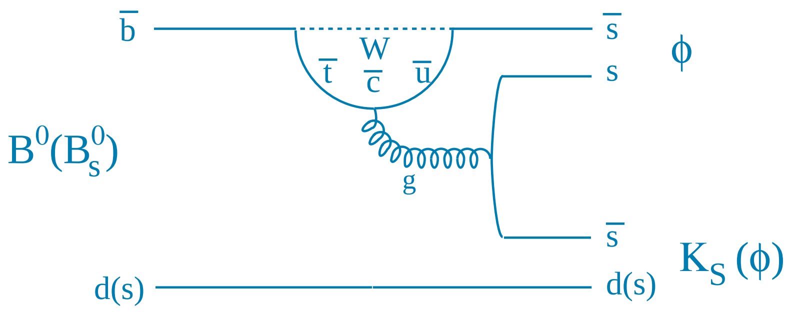




- Here ATLAS and CMS are competitive, due to their higher luminosity
  LHCb will also study many other rare decays: $B^0 \to K^*\gamma$, $K^*\mu^+\mu^-$...

$b \to s$ penguin decays

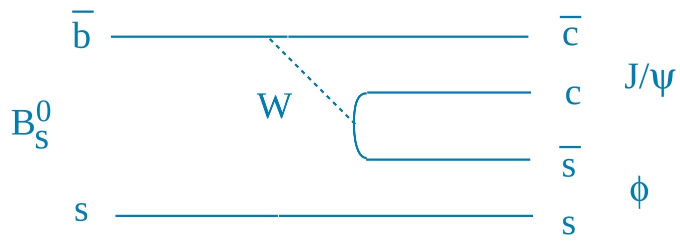
- One of the most interesting results from B factories is for $B^0 \to \phi K_S$
- Standard Model asymmetry = $\sin 2\beta$ (within ~10% theoretical uncertainty) $= 0.736 \pm 0.049$ from $B^0 \to J/\psi K_S$
- Measured values:
  $+0.45 \pm 0.43 \pm 0.07$ (BaBar) consistent with the Standard Model
  $-0.96 \pm 0.50 \pm 0.10$ (Belle) *inconsistent* with the Standard Model



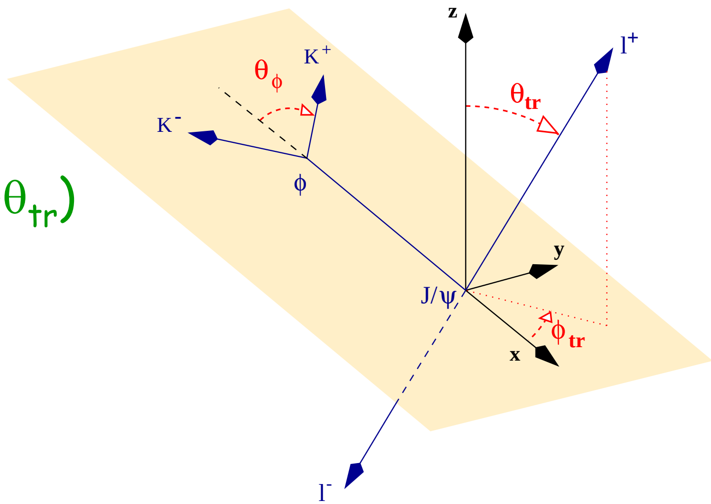
- Expect to reconstruct ~ 1000 $B^0 \to \phi K_S$ signal events/year in LHCb
- However, if new physics does show up in $B^0 \to \phi K_S$ it is important to also examine other $b \to s$ penguin decays:
  $B_s \to \phi\phi$, KK, $\phi\gamma$, ...

  LHCb will also reconstruct large samples of all of these modes

CP asymmetry: $B_s \to J/\psi\ \phi$

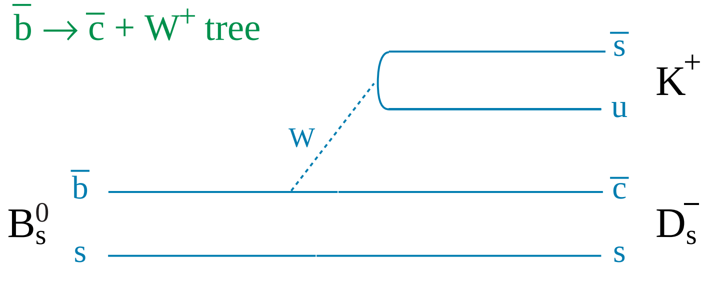


- B_s counterpart of the golden mode $B^0 \to J/\psi\ K_S$
- CP asymmetry arises from interference of
  $B_s \to J/\psi\ \phi$ and $B_s \to \bar{B_s} \to J/\psi\ \phi$
  $\to$ measures the phase of B_s mixing
- In Standard Model expected asymmetry $\propto \sin 2\chi$ = very small ~ 0.04
  $\to$ sensitive probe for new physics
- Reconstruct $J/\psi \to \mu^+\mu^-$ or e^+e^-, $\phi \to K^+K^-$ 120,000 signal events/year
- Final state is admixture of CP-even and odd contributions
  $\to$ angular analysis of decay products required
- Define transversity angle θ_{tr} :
  Likelihood is sum of CP-odd and even terms
  $L(t) = R_-\ L_-(t)\ (1+\cos^2\theta_{tr})/2 + (1-R_-)\ L_+(t)\ (1-\cos^2\theta_{tr})$
- Fit for $\sin 2\chi$, R_- and $\Delta\Gamma_s/\Gamma_s$
  $\sigma(\sin 2\chi) \sim 0.06$, $\sigma(\Delta\Gamma_s/\Gamma_s) \sim 0.02$ in one year

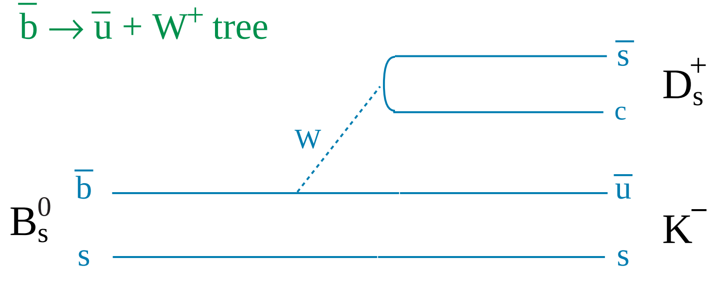


CP asymmetry: $B_s \to D_s^{\pm} K^{\mp}$

- Arises from interference between two tree diagrams via B_s mixing: $B_s \to D_s^+K^-$ and $B_s \to D_s^-K^+$



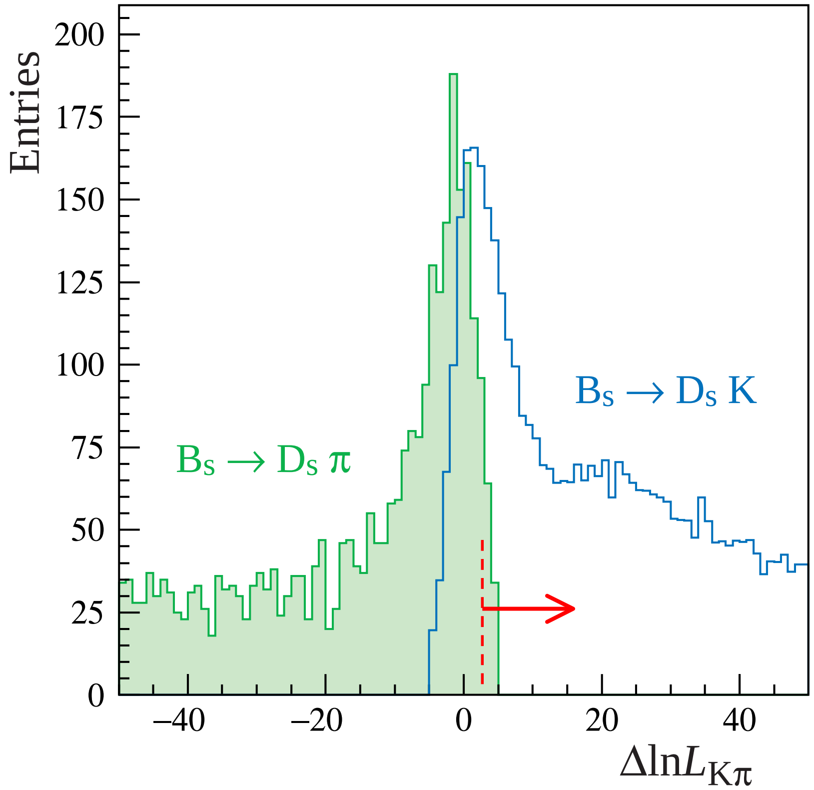
$B \sim 20 \times 10^{-5}$

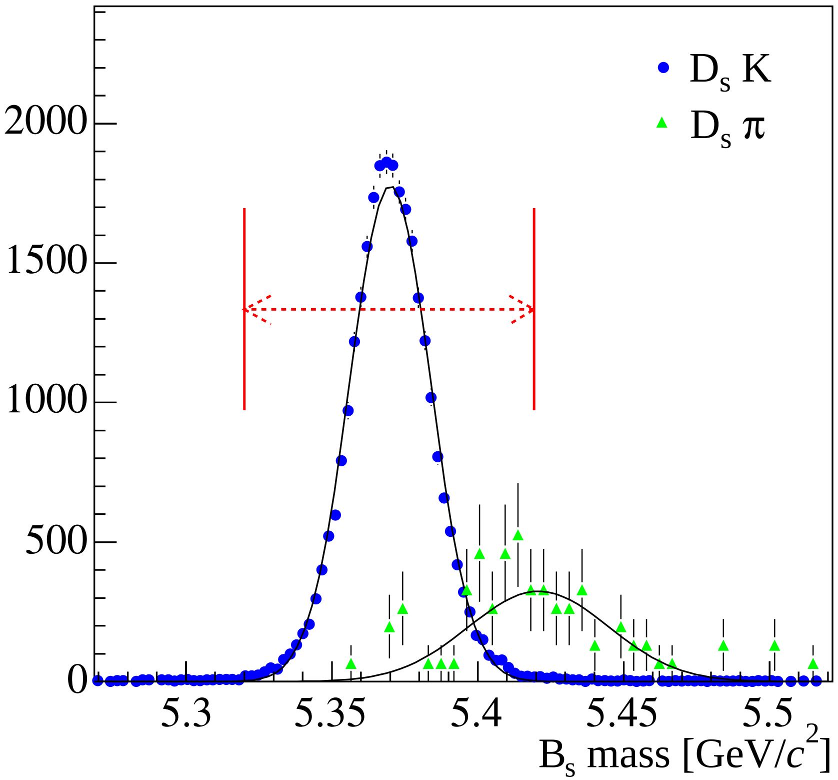


$B \sim 3 \times 10^{-5}$

- CP asymmetry measures $\gamma - 2\chi$ (γ from phase of V_{ub})
  χ will be determined using $B_s \to J/\psi\ \phi$ decays $\to$ extract γ
- Very little theoretical uncertainty
  Insensitive to new physics, which is expected to appear in loops
- Reconstruct using $D_s^- \to K^-K^+\pi^-$ 5400 signal events/year

- ✦ $B_s \rightarrow D_s\,\pi$ is background for D_s K
  Branching ratio ~ 12 × higher
- ✦ Suppress it by cutting on difference in log-likelihood between K and π hypotheses in RICH:



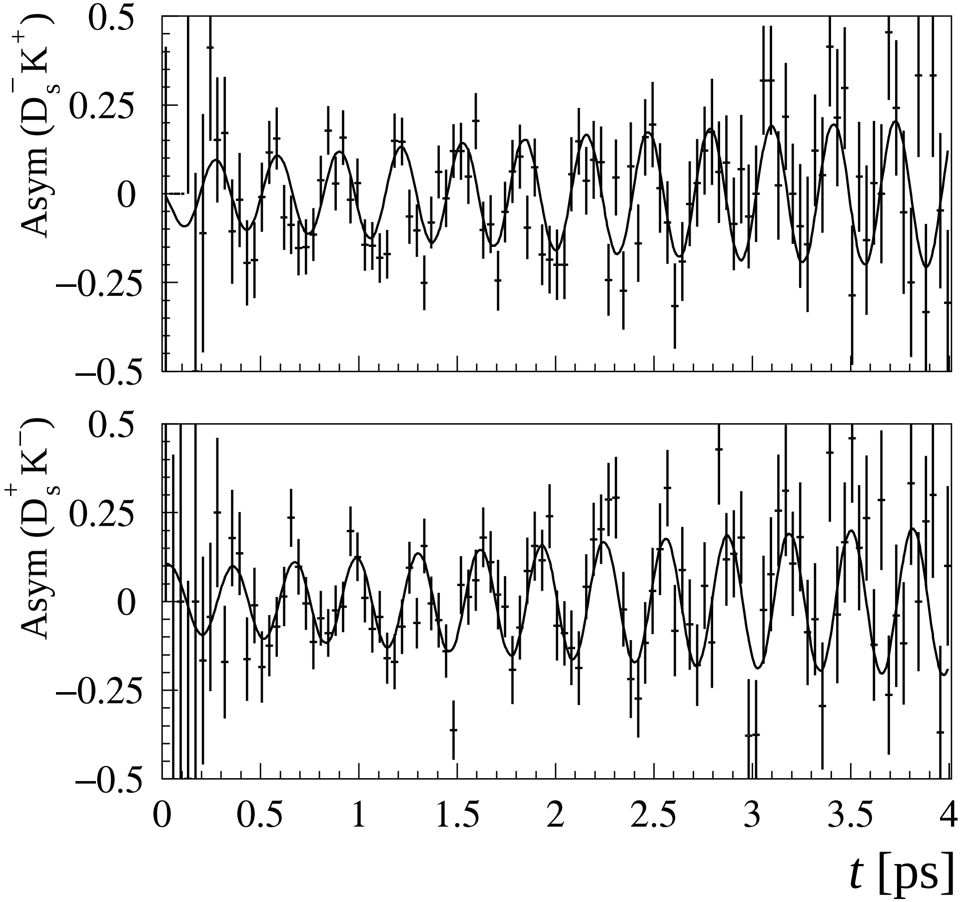


Remaining contamination only ~ 10%

D_sp should not have CP asymmetry
→ use it as a control channel
eg to measure any possible production asymmetry of B_s and $\overline{B}_s$

- Allow for possible strong phase difference Δ between the two diagrams
- Fit two time-dependent asymmetries:
  - Phase of $D_s^+K^-$ asymmetry is $\Delta - (\gamma - 2\chi)$
  - Phase of $D_s^-K^+$ asymmetry is $\Delta + (\gamma - 2\chi)$

$\rightarrow$ can extract both Δ and $(\gamma - 2\chi)$

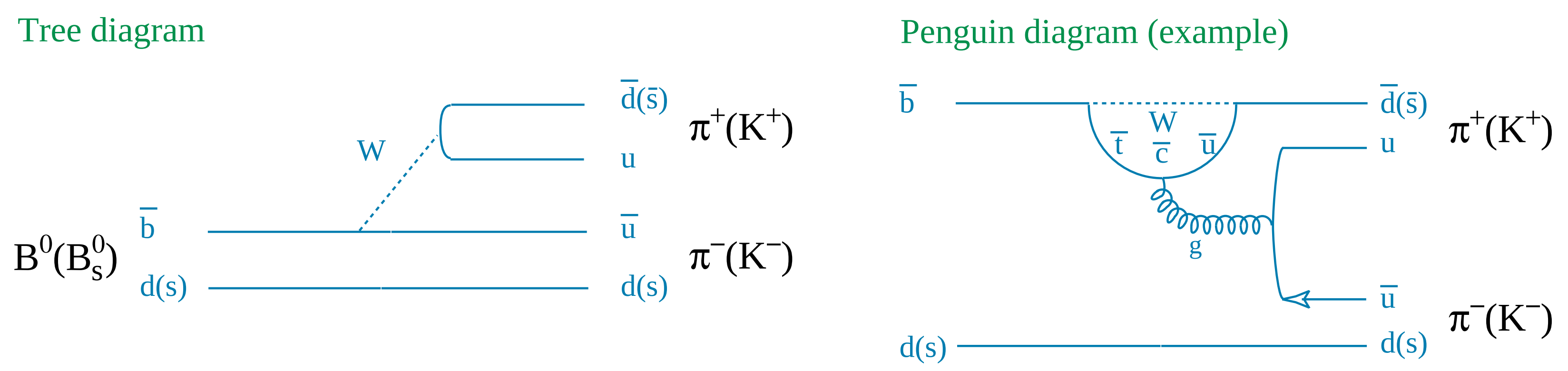


Asymmetries for
5 years of simulated data

$\sigma(\gamma) \sim 14°$ in one year

CP asymmetry: $B_{(s)} \to h^+ h^-$

- $B^0 \to \pi^+\pi^-$ originally proposed for measurement of angle $\alpha = \pi - \beta - \gamma$
  But clean extraction of α is compromised by influence of penguin diagrams



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

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

- Extract four asymmetries:

$$A_{dir}(B^0 \to \pi^+\pi^-) = f_1(d, \theta, \gamma)$$
$$A_{mix}(B^0 \to \pi^+\pi^-) = f_2(d, \theta, \gamma, \beta)$$
$$A_{dir}(B_s \to K^+K^-) = f_3(d', \theta', \gamma)$$
$$A_{mix}(B_s \to K^+K^-) = f_4(d', \theta', \gamma, \chi)$$

$de^{i\theta}$ = ratio of penguin and tree amplitudes in $B^0 \to \pi^+\pi^-$

$d'e^{i\theta'}$ = ratio of penguin and tree amplitudes in $B_s \to K^+K^-$