Workshop on B physics at the Tevatron

Fermilab — September 25, 1999

HERA-B and LHCb
Two Generations of Hadronic B Factories

Olaf Steinkamp

⇒ LHCb physics, detector, performance
⇒ HERA-B physics, detector, status

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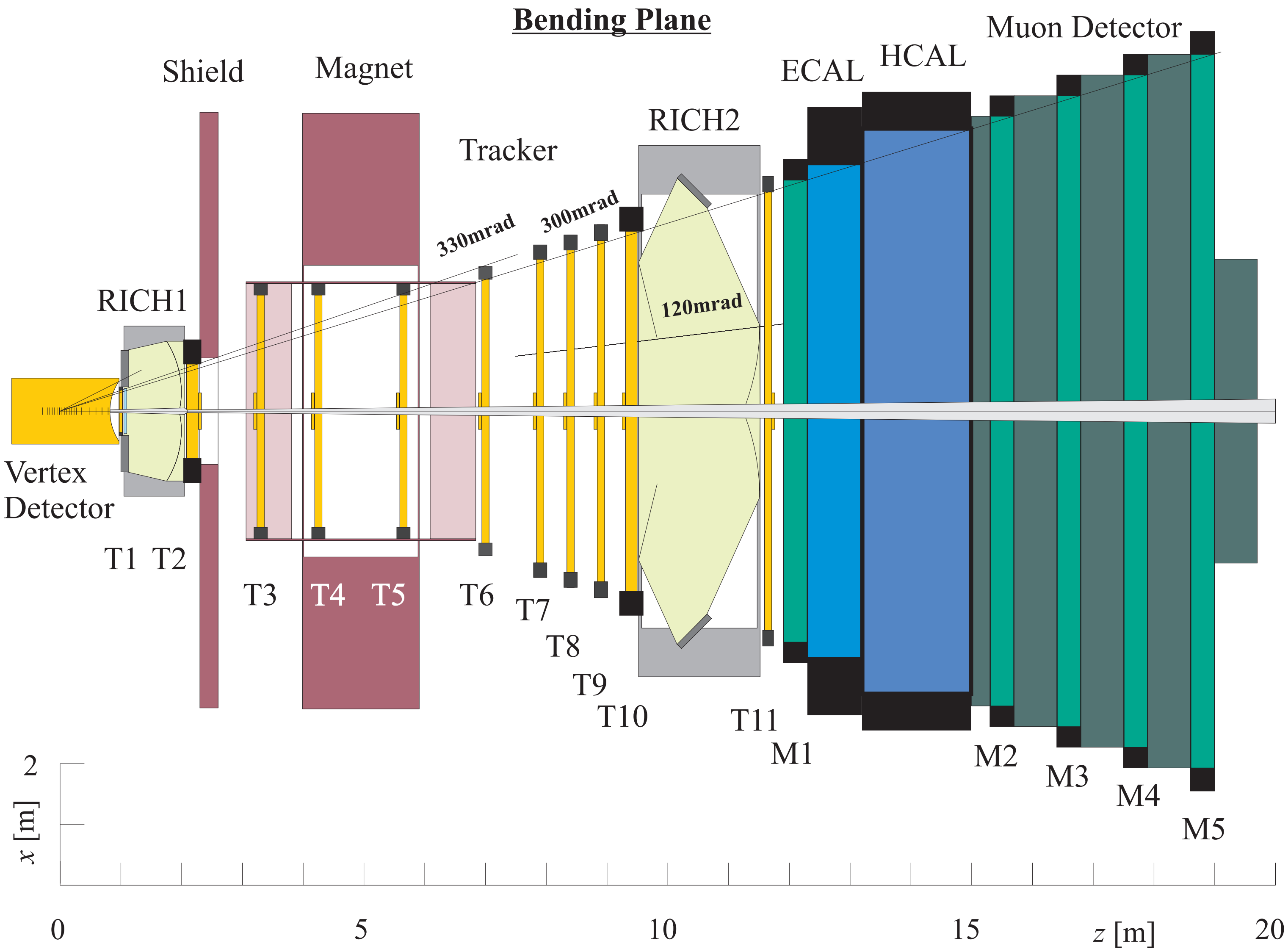
The LHCb detector



Bending Plane
Muon Detector
Shield
Magnet
ECAL
HCAL
RICH2
Tracker
330mrad
300mrad
120mrad
RICH1
Vertex
Detector
T1 T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
M1
M2
M3
M4
M5
2
x [m]
0
5
10
15
z [m]
20

LHC as hadronic B factory

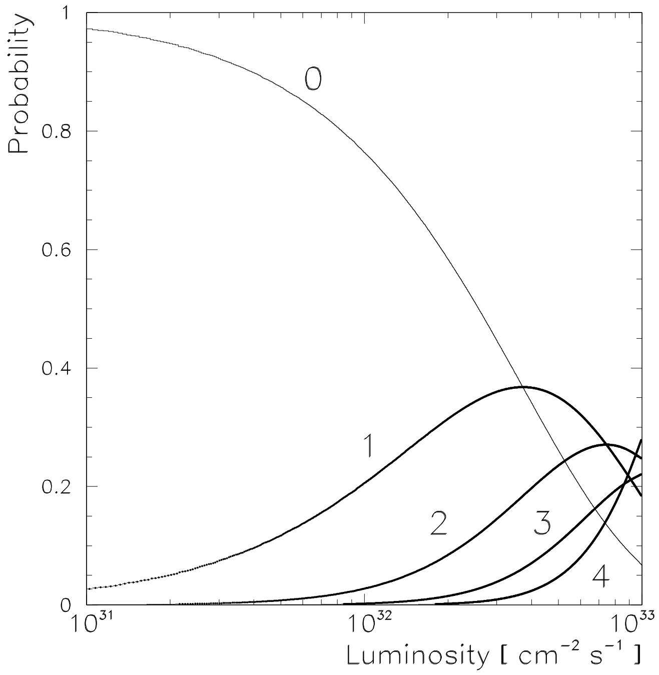
pp colliding beams at $\sqrt{s} = 14\ \mathrm{TeV}$

$$\Rightarrow \quad \sigma_{\mathrm{b\overline{b}}} \approx 500\ \mu\mathrm{b}$$

$$\Rightarrow \quad \sigma_{\mathrm{b\overline{b}}}/\sigma_{inel} \approx 5 \times 10^{-3}$$

tune luminosity to maximize number of bunch crossings with single pp interaction (detector occupancy, pattern recognition):

$$< \mathcal{L} >= 2 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

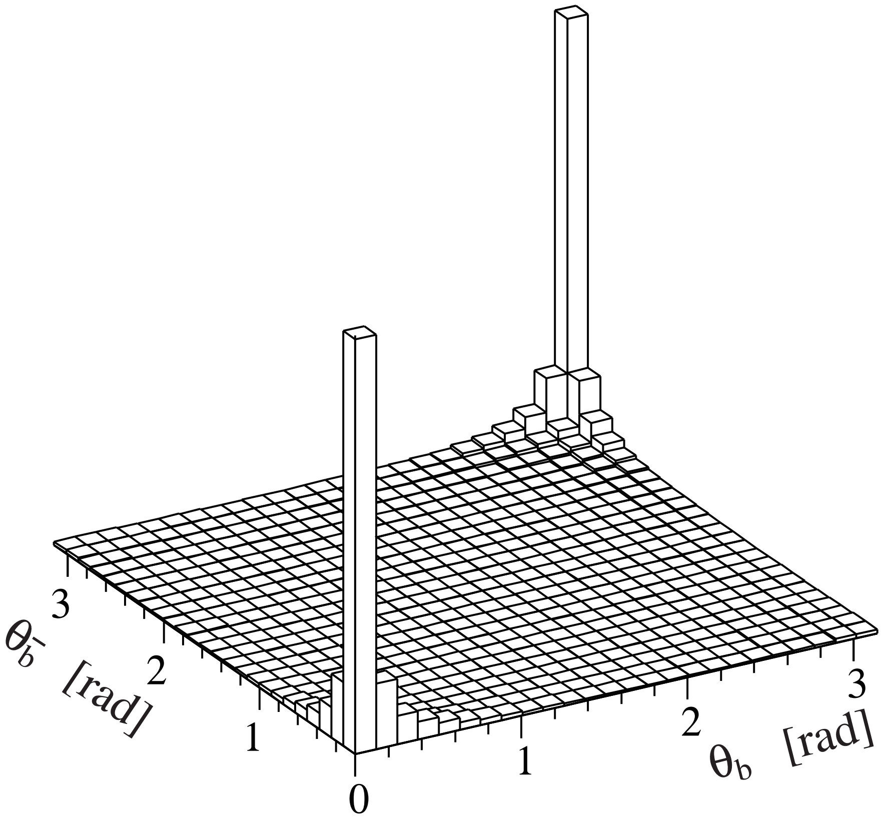


$$\Rightarrow \ \text{produce} \left\{ \begin{array}{l} 4.5 \times 10^{11}\ \mathrm{B_d^0} + \overline{\mathrm{B}}{}_\mathrm{d}^0 \\ 1.3 \times 10^{11}\ \mathrm{B_s^0} + \overline{\mathrm{B}}{}_\mathrm{s}^0 \end{array} \right\} \text{per year}$$

(”full” LHCb luminosity from startup of LHC)

LHC as hadronic B factory

$\mathrm{b\bar{b}}$ production peaked at small polar angles:



⇒ single-arm spectrometer with:

$\Theta_{min} = 15\ \mathrm{mrad}$ (beam pipe, radiation)
$\Theta_{max} = 300\ \mathrm{mrad}$ (cost optimisation)

$$\approx 1.9 < \eta < \approx 4.9$$

gives comparable acceptance to large central detector

B momenta typically 80 GeV/c

⇒ decay lengths $\approx 7\ \mathrm{mm}$

LHCb - Motivation

reasonable scenario of ”unitarity triangle” physics at startup of LHC:

β measured in $\mathrm{B_d} \rightarrow \mathrm{J}/\psi \mathrm{K^0_S}$ at Tevatron, $\mathrm{e^+e^-}$ factories, HERA-B ($\Delta \sin 2\beta \approx 0.05$)

α measured in $\mathrm{B_d} \rightarrow \pi^+\pi^-$, limited precision due to statistics and theoretical uncertainties (penguin contribution)

x_s measured at Tevatron (HERA-B) if $< \approx 60\ (20)$

$\delta\gamma$ possibly measurement in $\mathrm{B_s} \rightarrow \mathrm{J}/\psi\phi$ at Tevatron (HERA-B), depending on value of x_s

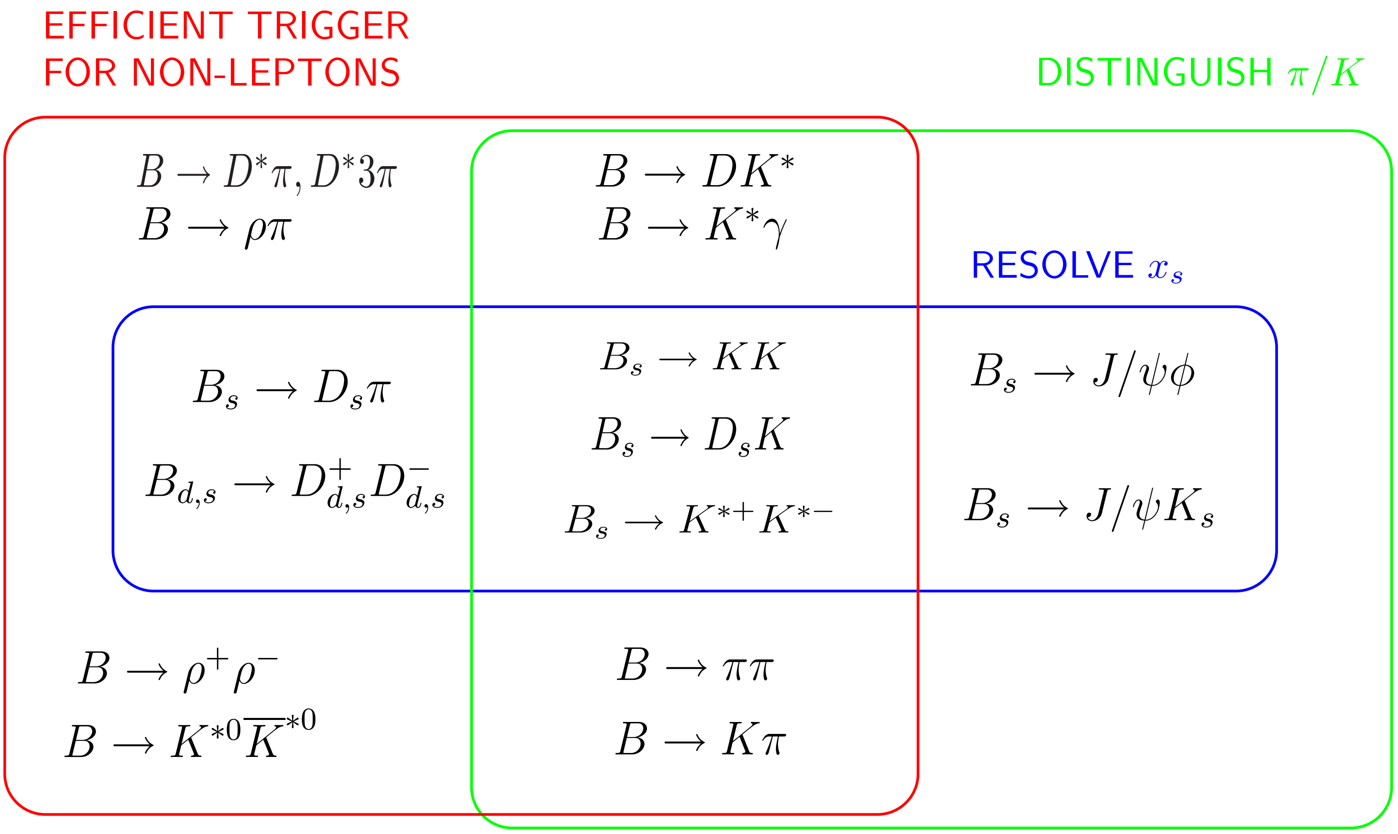
γ no good or direct measurement

$\Rightarrow$ program for LHCb (and BTeV):

- high-statistics studies of already explored channels
- exploration of new channels, experimentally more difficult (e.g. small BR) but theoretically cleaner
- overconstrain unitarity triangles, search for signs of new physics

LHCb - Design Challenges

Specific experimental challenges for interesting channels:



EFFICIENT TRIGGER
FOR NON-LEPTONS

DISTINGUISH π/K

RESOLVE x_s

$B \to D^*\pi, D^*3\pi$
$B \to \rho\pi$

$B \to DK^*$
$B \to K^*\gamma$

$B_s \to D_s\pi$

$B_{d,s} \to D^+_{d,s}D^-_{d,s}$

$B_s \to KK$

$B_s \to D_sK$

$B_s \to K^{*+}K^{*-}$

$B_s \to J/\psi\phi$

$B_s \to J/\psi K_s$

$B \to \rho^+\rho^-$

$B \to K^{*0}\overline{K}^{*0}$

$B \to \pi\pi$

$B \to K\pi$

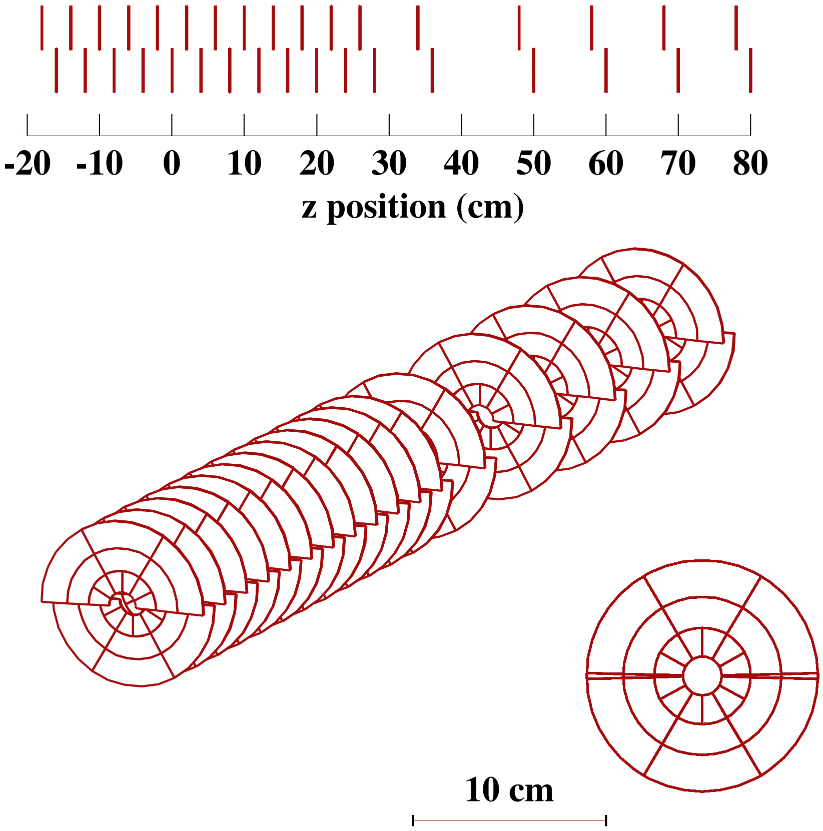
Crucial design parameters for detector/trigger:

- invariant mass resolution: magnetic spectrometer
- proper time resolution: vertex detector
- hadron identification: RICH(es)
- efficient trigger for leptonic and hadronic decay modes

LHCb Vertex Detector

Good primary and secondary vertex resolution essential for:

- decay length measurement (especially for $\mathrm{B_s}$)
- trigger on displaced vertices



⇒ 17 stations, mounted within Roman pots in beam vacuum

⇒ 1 cm from beam during physics, retracted during injection

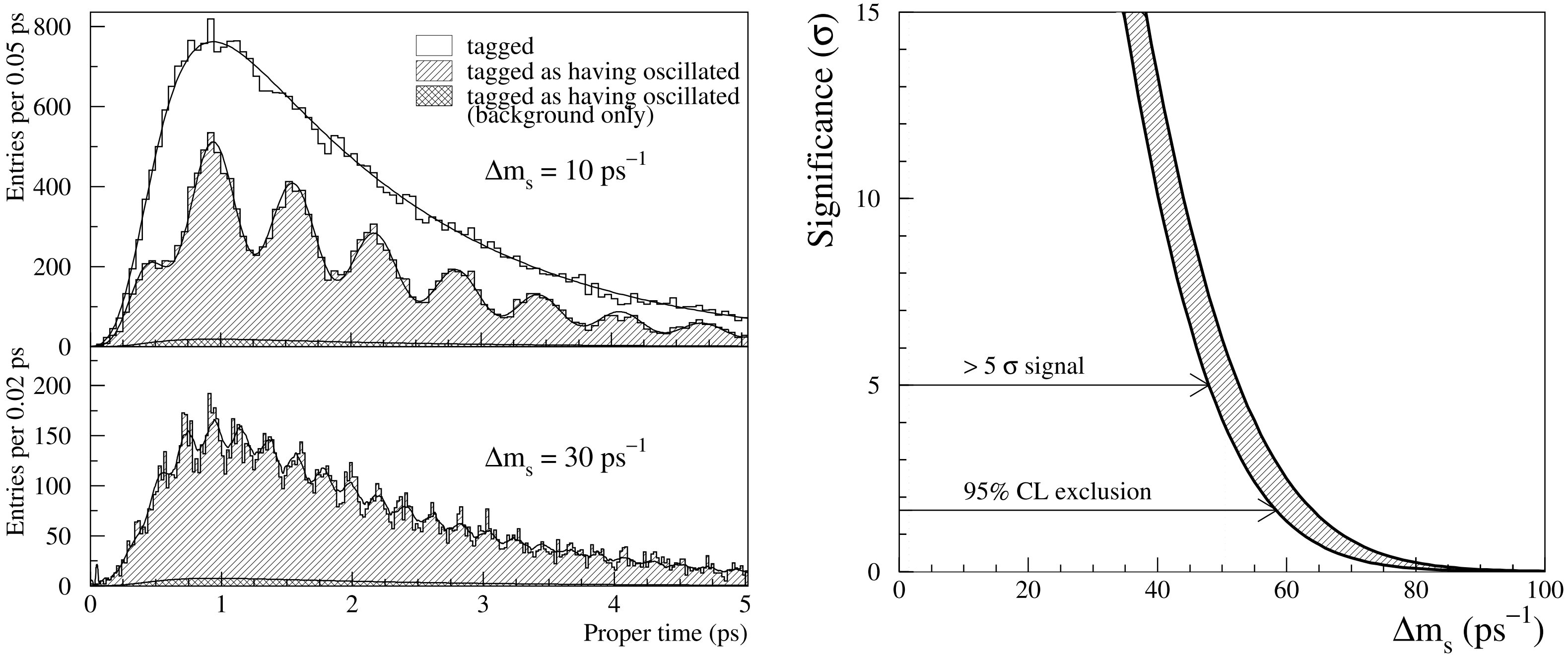
⇒ readout strips in r/ϕ geometry for fast 2D trigger algorithm

⇒ decay length resolution typically 170 $\mu\mathrm{m}$

LHCb - x_s Potential

good proper time resolution crucial for x_s measurement:

$$\sigma(\tau_s) \approx 42 \text{ fs}$$



$B_s \rightarrow D_s^{\pm}\pi^{\mp}$: 35k events reconstructed and tagged per year

$\Rightarrow$ 5σ measurement up to $x_s \approx 75$

($\sigma(\tau_s)$ also dilutes CP violation measurements in B_s)

LHCb - RICH detectors

K / π separation over large momentum range essential for:

- tagging: $p_K > 1\ \mathrm{GeV}/c$
- many CP measurements: e.g. $p_\pi < 150\ \mathrm{GeV}/c$, for $B \rightarrow \pi^+\pi^-$

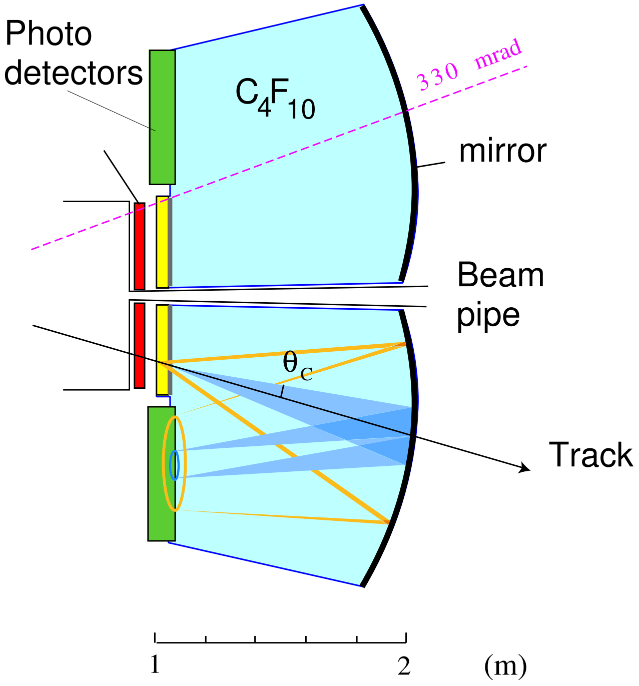
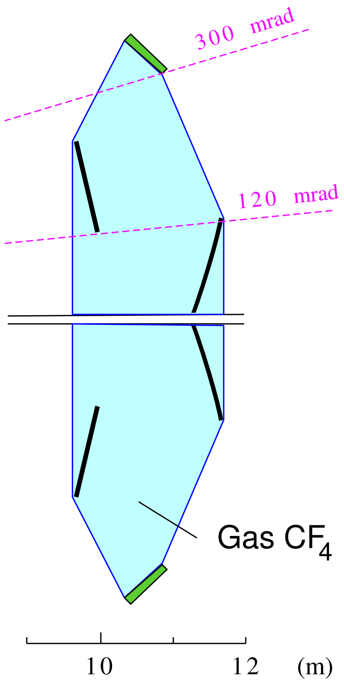


Photo detectors
C_4F_{10}
330 mrad
mirror
Beam pipe
θ_c
Track
1
2
(m)

RICH 1 ($1 < p < 70\ \mathrm{GeV}/c$)

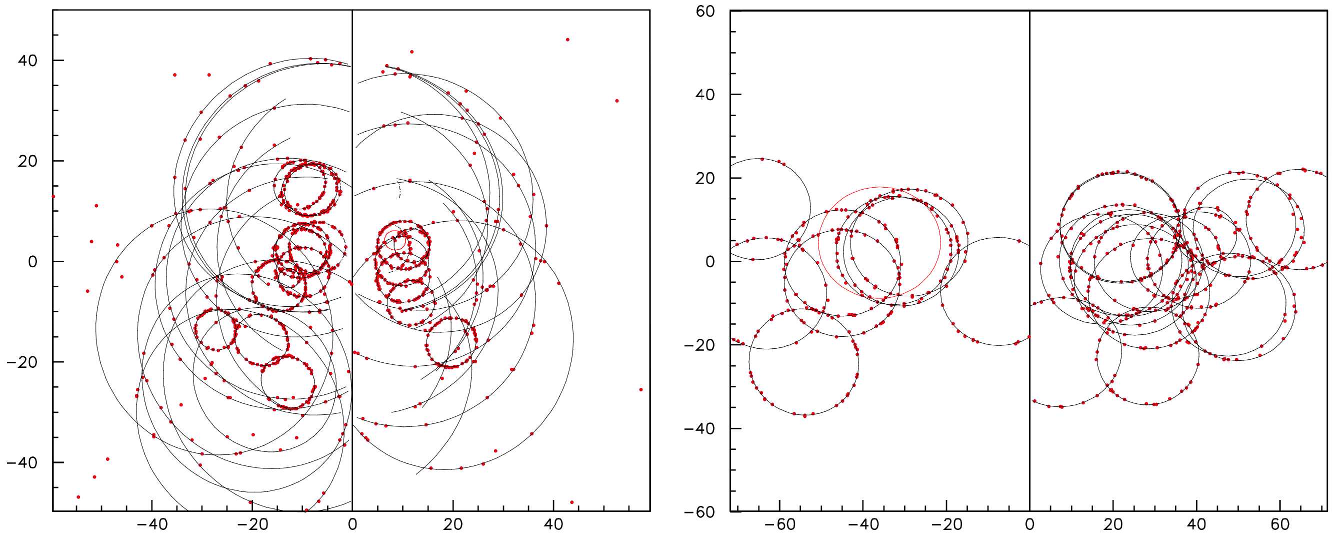

300 mrad
120 mrad
Gas CF_4
10
12
(m)

RICH 2 ($20 < p < 150\ \mathrm{GeV}/c$)

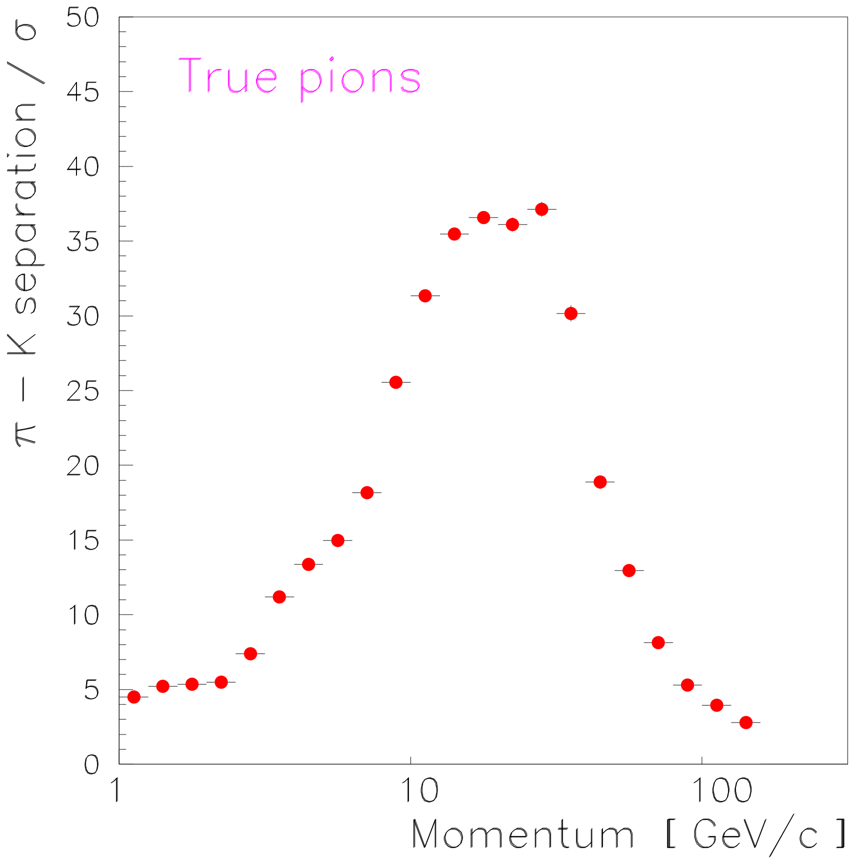
(photon detection: Hybrid Photo Diodes (HPD's) or Multi-Anode PMT's)

LHCb - RICH performance

Challenging but working: pattern recognition algorithms

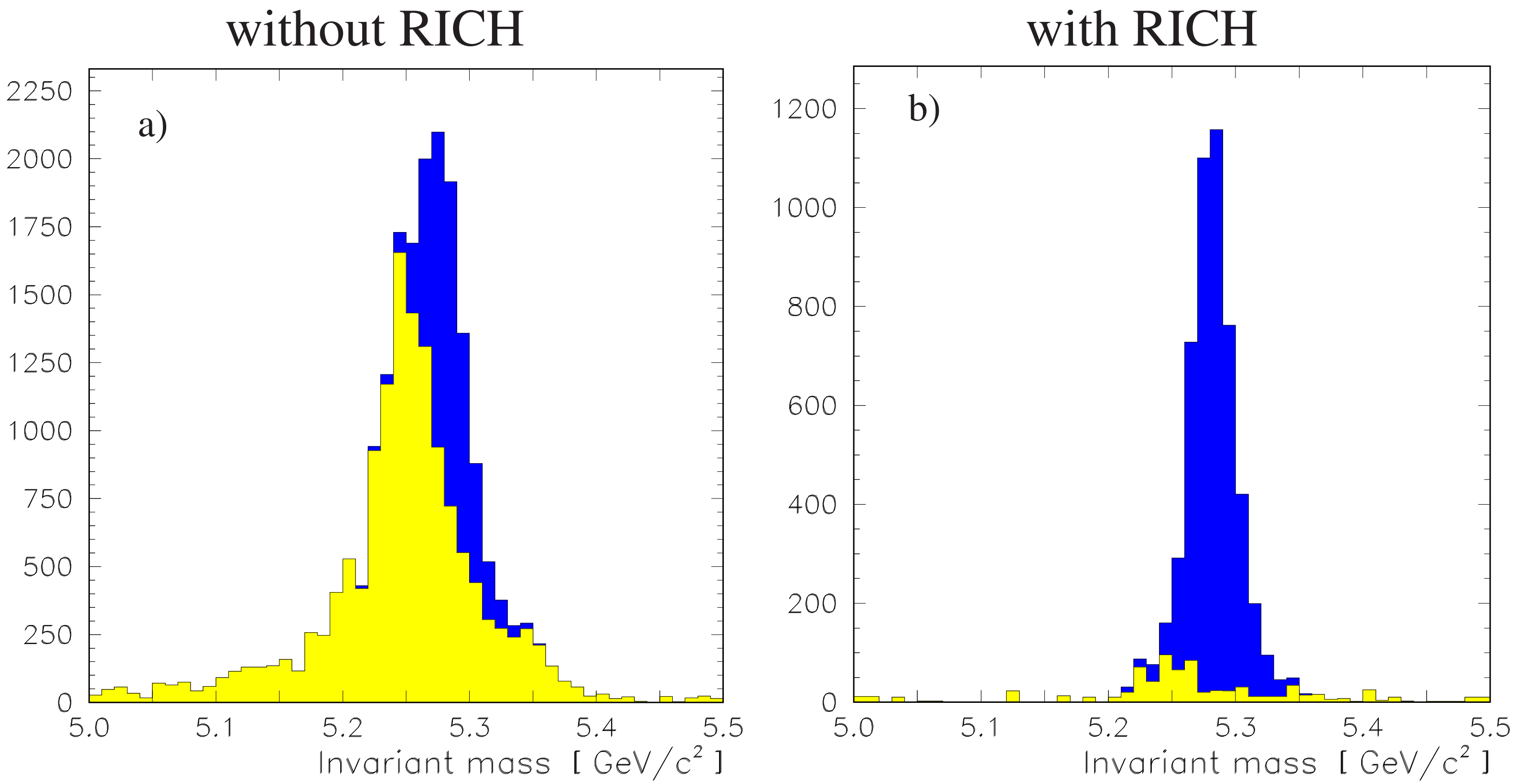

40
20
0
−20
−40
−40
−20
0
20
40
60
40
20
0
−20
−40
−60
−60
−40
−20
0
20
40
60

K / π separation $> 3\sigma$ over full range $1 < p < 150$ GeV$/c$:



LHCb - Particle Identification in $B_d \rightarrow \pi^+\pi^-$

Backgrounds from $B_d \rightarrow K^\pm\pi^\mp$, $B_s \rightarrow K^+K^-$, $B_s \rightarrow K^\pm\pi^\mp$:



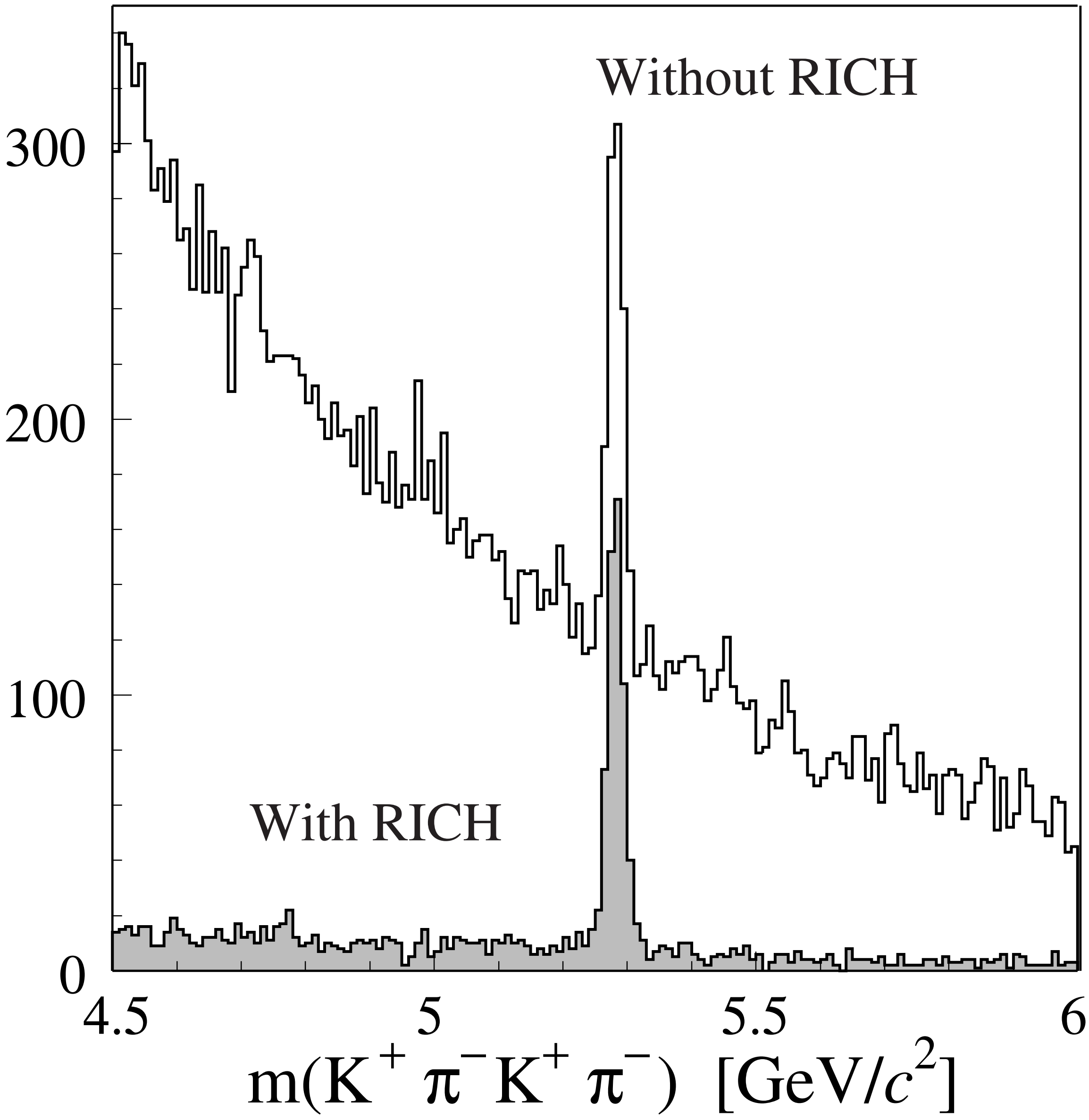
$\Rightarrow$ achieve 89% purity at 82% efficiency

(also crucial: mass resolution, $\sigma_m \approx 17\ \mathrm{MeV}/c^2$)

LHCb - Particle Identification in $B_d \rightarrow D^0 K^{0*}$

$$\begin{array}{llll} B_d & \rightarrow & \overline{D}^0 & K^{0*} \\ & & \rightarrow K^+\pi^- & \rightarrow K^+\pi^- \end{array}$$

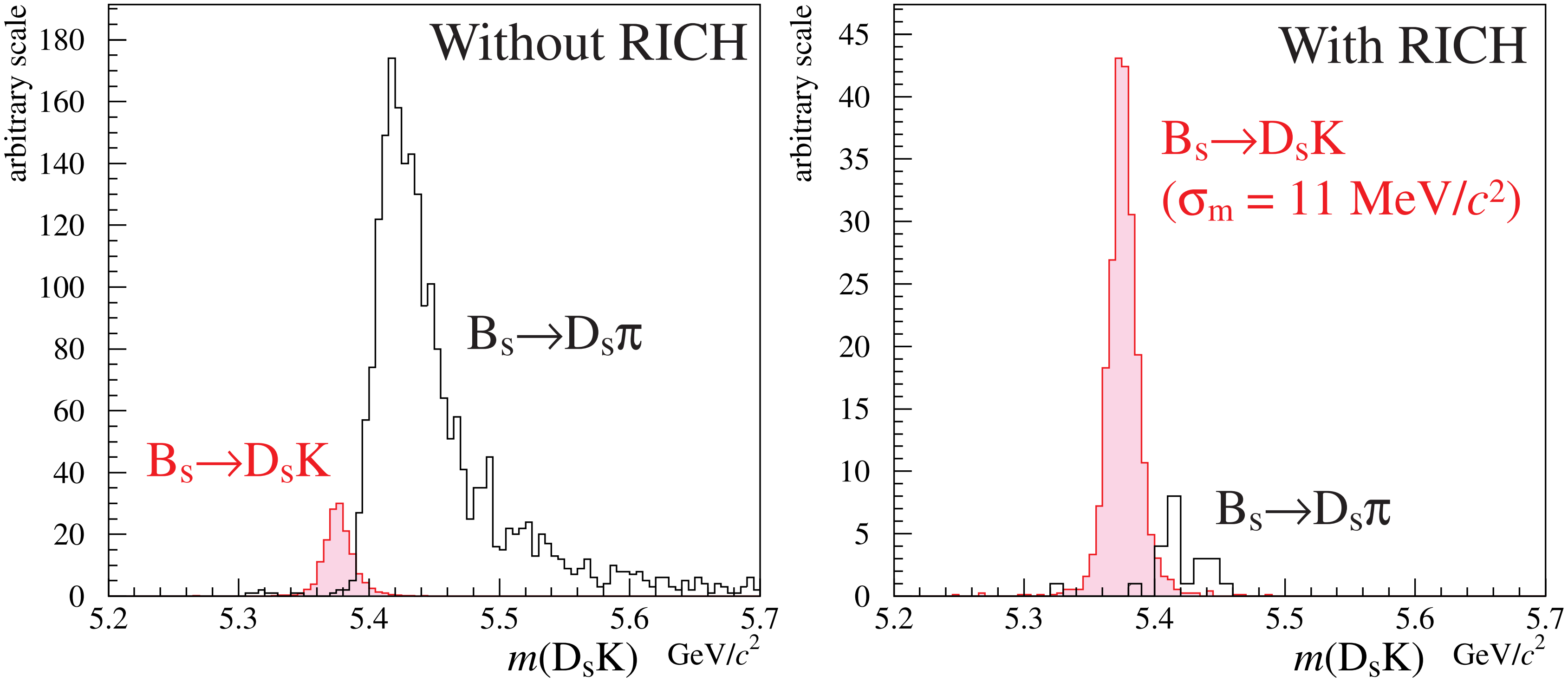
K/π separation essential to suppress combinatorial background:



(also crucial: mass resolution, $\sigma_m \approx 13\ \mathrm{MeV}/c^2$)

LHCb - Particle Identification in $B_s \to D_s K$

Dominating background from $B_s \to D_s \pi$:



$\Rightarrow$ achieve $S / B > 10$

(also crucial: good mass resolution)

LHCb - Level-0 Trigger

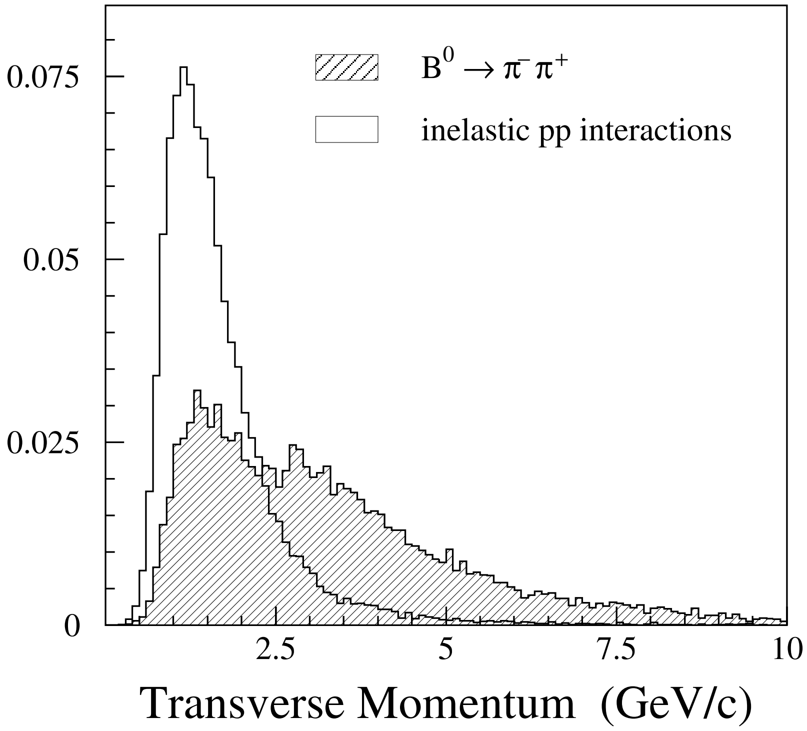
Level 0: single high-p_T (E_T) track, typically $>$ few GeV/c

$\mu^{\pm}$ (muon chambers): track angle + impact parameter

$\mathrm{e}^{\pm}$ (electron calorimeter): cluster energy + polar angle

$h^{\pm}$ (electron/hadron calorimeters): cluster energy + polar angle

γ (electron calorimeter): cluster energy + polar angle



40 MHz input rate → 1 MHz output rate

latency 4 μs

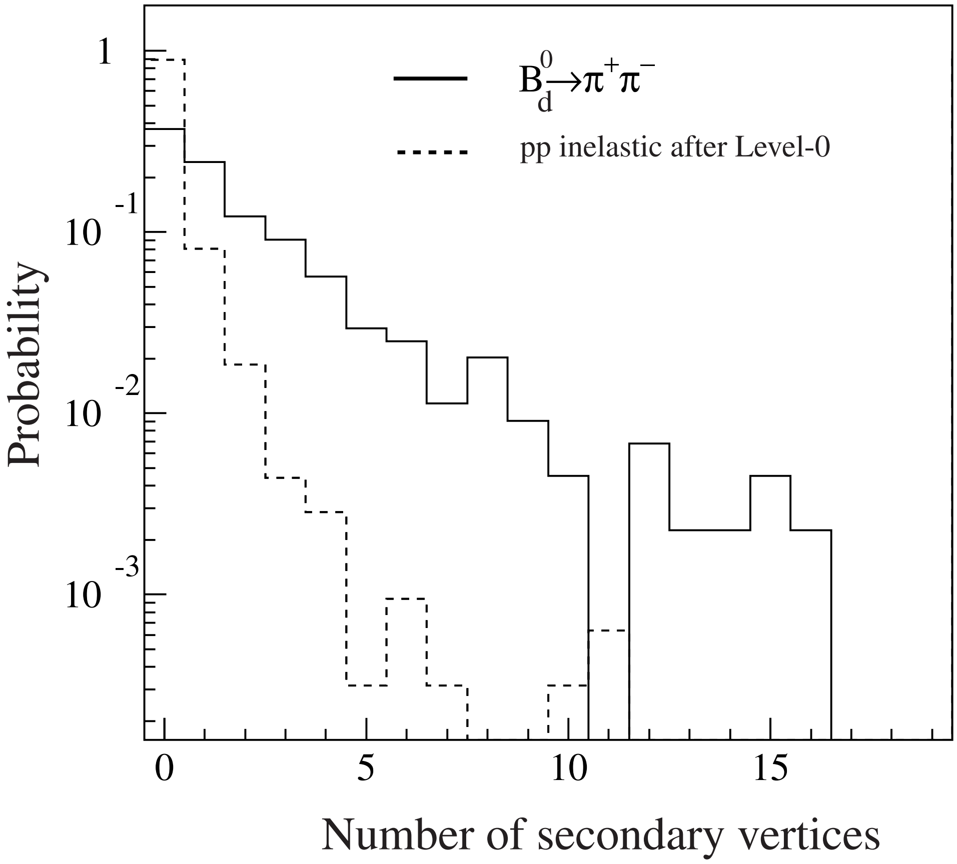
trigger can be fired by decay of "tagging" or of "physics" B

⇒ high-p_T trigger enhances tagging efficiency
and fraction of reconstructible B's

LHCb - Level-1 Trigger

Level 1: ”topological” identification of secondary vertices

- use silicon tracks only
- reconstruct primary vertex
- form secondary vertices from high impact parameter tracks



1 MHz input rate → 40 kHz output rate

latency (512 - 2048) μs

software implementation!

LHCb - higher-level Triggers

- software triggers on commercial processor farm
- full event buffer

Level 2:

- refine secondary vertices
- use tracking chambers and momentum information

40 kHz input rate $\rightarrow$ 5 kHz output rate
latency 10 ms

Level 3:

- reconstruction of specific decays (with loose cuts)
- use particle identification information

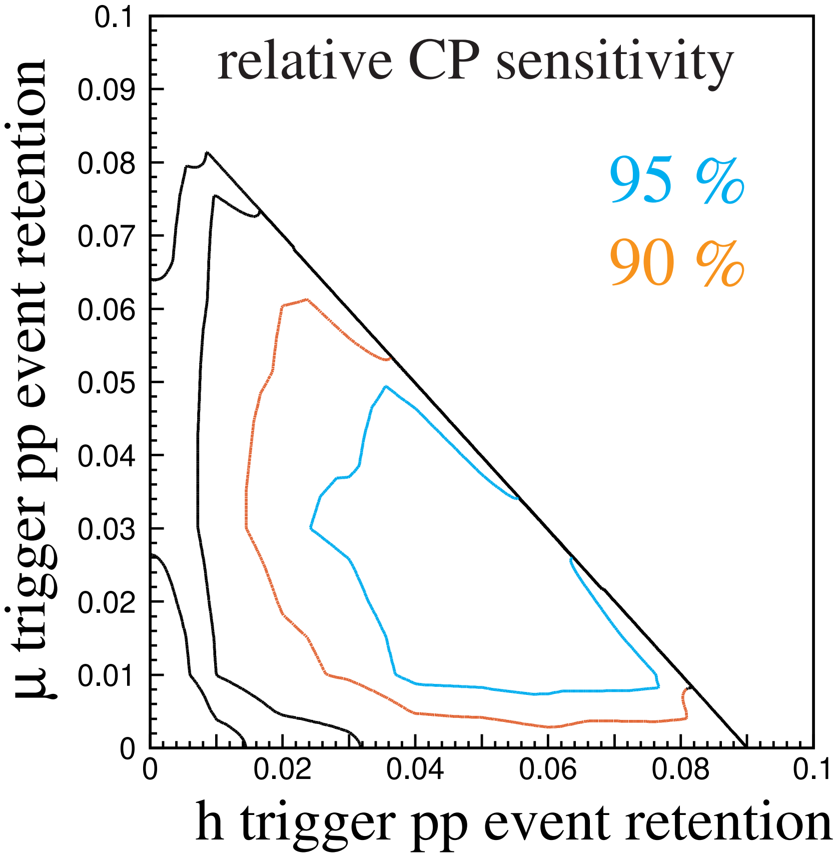
5 kHz input rate $\rightarrow$ 200 Hz output rate
latency 200 ms

write 20 Mbyte / s to tape

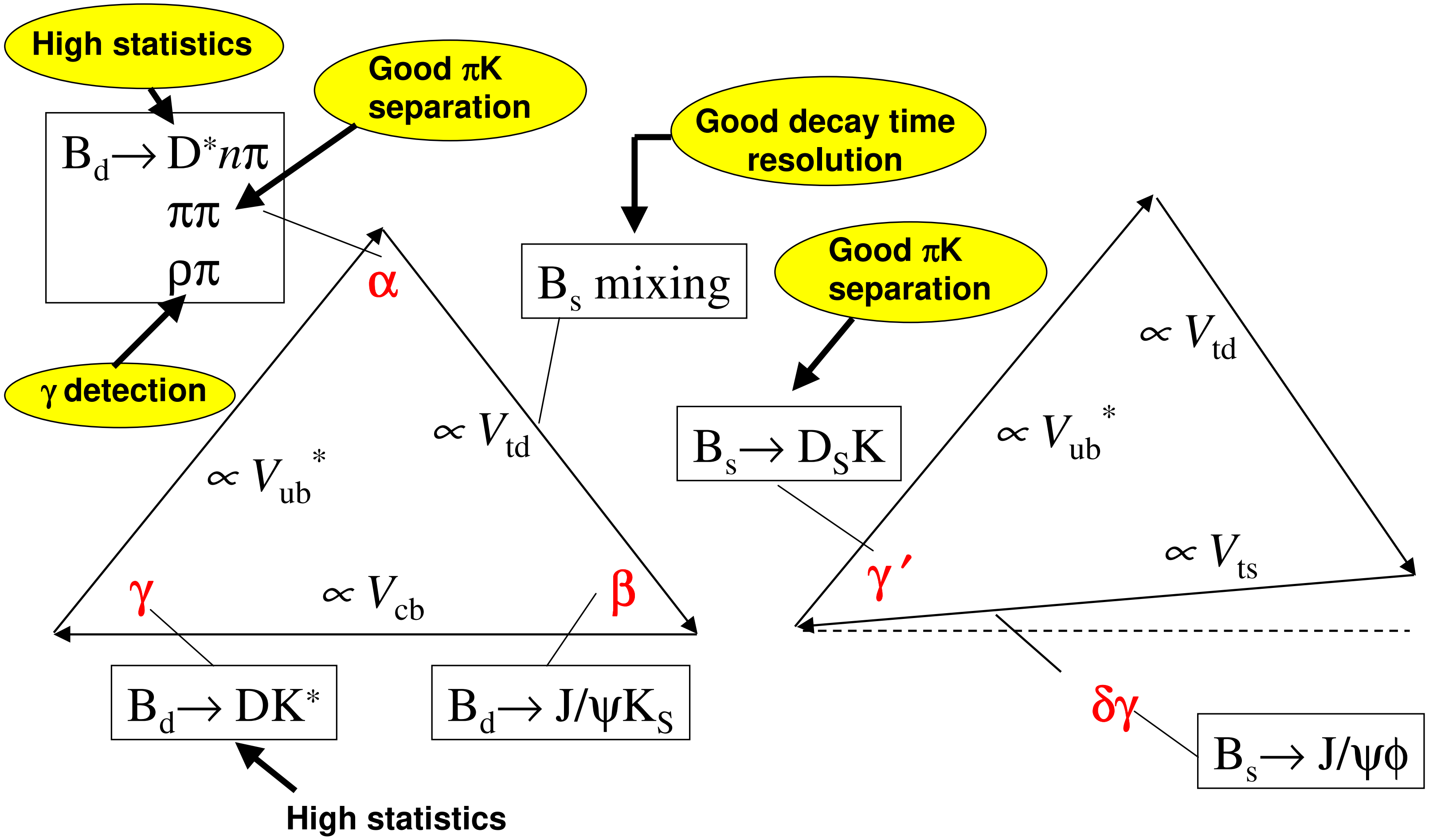
LHCb - Trigger Efficiency and Stability

	L0				L1	L2	total
	μ	e	h	all			
$B_d \rightarrow J/\psi(ee)K_S$ + tag	17	63	17	72	42	81	24
$B_d \rightarrow J/\psi(\mu\mu)K_S$ + tag	87	6	16	88	50	81	36
$B_s \rightarrow D_sK$ + tag	15	9	45	54	56	92	28
$B_d \rightarrow DK^*$	8	3	31	37	59	95	21
$B_d \rightarrow \pi^+\pi^-$ + tag	14	8	70	76	48	83	30

all in %, for "useful" events,
correctly reconstructed and tagged offline



Unitarity Triangles and Candidate Channels


High statistics
Good πK separation
Good decay time resolution
$B_d \rightarrow D^* n\pi$
$\pi\pi$
$\rho\pi$
γ detection
B_s mixing
Good πK separation
$B_s \rightarrow D_S K$
α
$\propto V_{td}$
$\propto V_{ub}^*$
$\propto V_{cb}$
γ
β
$\propto V_{td}$
$\propto V_{ub}^*$
$\propto V_{ts}$
γ′
δγ
$B_d \rightarrow DK^*$
$B_d \rightarrow J/\psi K_S$
$B_s \rightarrow J/\psi\phi$
High statistics

⇒ select theoretically “clean” channels

LHCb - $\mathrm{B_d}$ Candidate Channels

$\mathrm{B_d} \to \pi^+\pi^-$

- measures $\sin 2\alpha$
- theory: hampered by penguin contribution
- experiment: need hadron trigger, $\mathrm{K}\,/\,\pi$ separation
- LHCb: expect 7k events reconstructed and tagged per year

$\Rightarrow\ \sigma(\sin 2\alpha) \approx\ 0.03$ (if no penguin)

(need $|P/T|$ to $\pm 10\%$ not to compromise 1st year statistics)

$\mathrm{B_d} \to \rho\pi$

- measures α, via time dependent Dalitz-plot analysis
- theory: some assumption on resonances needed
- experiment: statistics, need hadron trigger, photon detection
- LHCb: expect 1k events reconstructed and tagged per year

under study, error estimates in a few months. . .

$\mathrm{B_d} \to \mathrm{J}/\psi \mathrm{K^0_S}$

- measures $\sin 2\beta$
- theory: ”clean”, little penguin
- experiment: ”easy”, measured quite well before LHC startup
- LHCb: expect 56k events reconstructed and tagged per year

$\Rightarrow\ \sigma(\sin 2\beta) \approx\ 0.014$

LHCb - $\mathrm{B_d}$ **Candidate Channels**

$\mathrm{B_d} \rightarrow \mathrm{D^{*\mp}}\pi^{\pm}$

- measures $2\beta + \gamma$ via 4 time-dependent decay rates
- theory: ”clean”, no penguin
- experiment: very small asymmetry (need large statistics), need hadron trigger, $\mathrm{K}\,/\,\pi$ separation
- LHCb: expect 270k events reconstructed and tagged per year (inclusive $\mathrm{D^*}$ reconstruction), 320k events with $\mathrm{B_d} \rightarrow \mathrm{D^* a_1}$

$\Rightarrow\ \sigma(\gamma) \approx\ 4^\circ$ (in 5 years)

$\mathrm{B_d} \rightarrow \overline{\mathrm{D}}{}^0\mathrm{K^*}$

- measures γ via 6 time-integrated decay rates
- theory: ”clean”, no penguin
- experiment: small visible branching fraction ($10^{-8} - 10^{-7}$), need hadron trigger, $\mathrm{K}\,/\,\pi$ separation
- LHCb: expect 340 events reconstructed per year

$$\Rightarrow\ \sigma(\gamma) \approx\ 10^\circ$$

LHCb - $\mathrm{B_s}$ **Candidate Channels**

$\mathrm{B_s} \to \mathrm{J}/\psi\phi$

- measures $\delta\gamma$, angular analysis to separate CP+ / CP-
- theory: "clean", no penguin; ideal place to look for "new" physics
- experiment: need x_s resolution, K/π separation
- LHCb: expect 44k events reconstructed and tagged per year

$$\Rightarrow \ \sigma(\,\delta\gamma\,) \approx \ 0.01$$

(depends on x_s, r=CP+ / CP-)

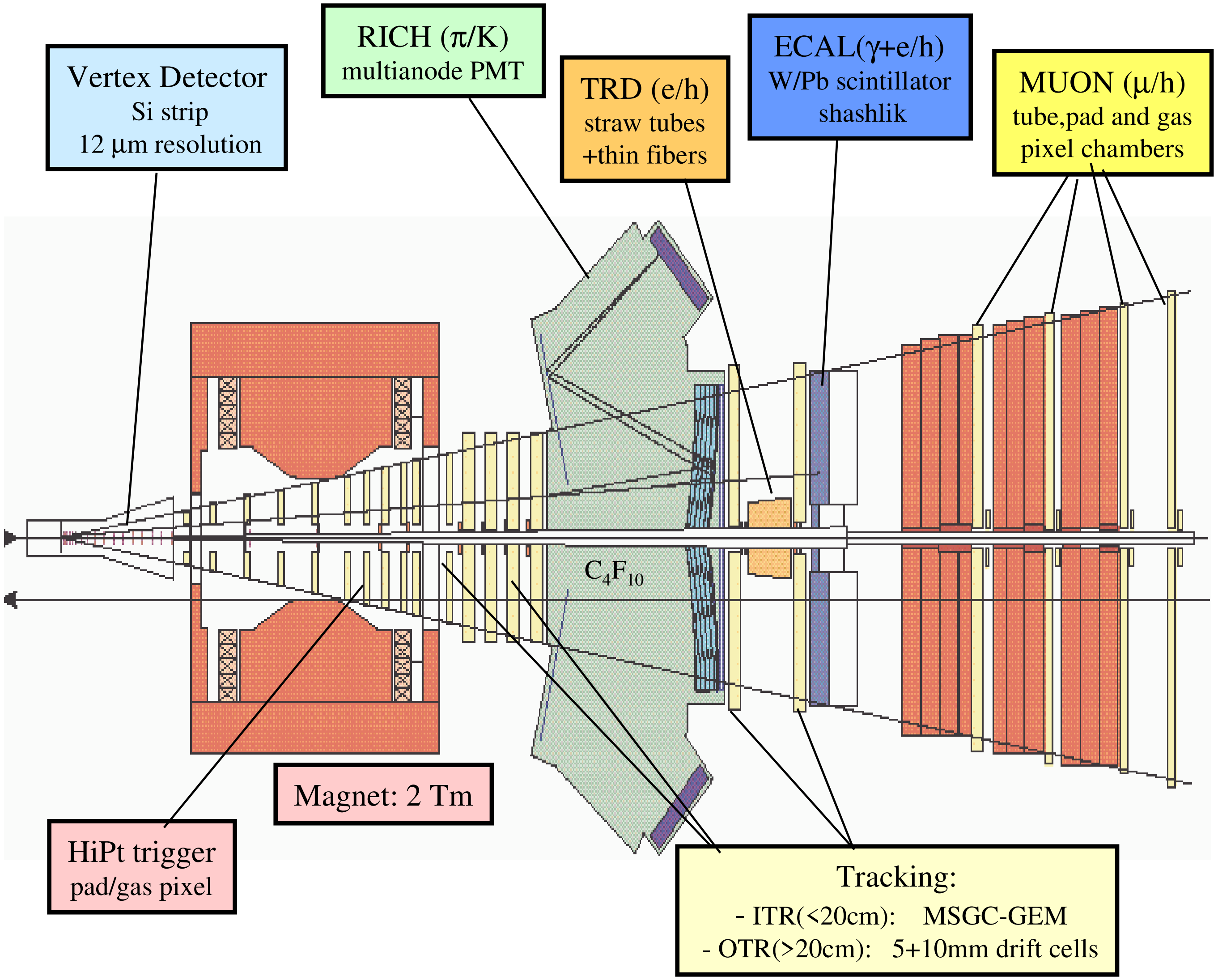
$\mathrm{B_s} \to \mathrm{D_s^{\pm}K^{\mp}}$

- measures $\gamma - 2\delta\gamma$, via 4 time-dependent rates
- theory: "clean", no penguin
- experiment: small branching fraction, need x_s resolution, hadron trigger, photon detection
- LHCb: expect 2.5k events reconstructed and tagged per year

$$\Rightarrow \ \sigma(\,\gamma - 2\delta\gamma\,) \approx \ 6^\circ - 13^\circ$$

(depends on x_s, $\gamma - 2\delta\gamma$, strong phase)

HERA-B - Detector Overview



Vertex Detector
Si strip
12 µm resolution

RICH (π/K)
multianode PMT

TRD (e/h)
straw tubes
+thin fibers

ECAL(γ+e/h)
W/Pb scintillator
shashlik

MUON (μ/h)
tube,pad and gas
pixel chambers

Magnet: 2 Tm

HiPt trigger
pad/gas pixel

Tracking:
- ITR(<20cm): MSGC-GEM
- OTR(>20cm): 5+10mm drift cells

HERA as hadronic B factory

fixed target in halo of 920 GeV/c proton beam ($\sqrt{s} = 43\ \mathrm{GeV}$)

- $\sigma_{\mathrm{b\bar{b}}} \approx 12\ \mathrm{nb}$ ($>$ factor 2 uncertainty)
- $\sigma_{\mathrm{b\bar{b}}}/\sigma_{inel} \approx 10^{-6}$

⇒ need highly selective trigger

- specialize on J/ψ ($\mathrm{e^+e^-}$,$\mu^+\mu^-$) invariant mass trigger

  for $\sin 2\beta$ measurement in $\mathrm{B_d} \rightarrow \mathrm{J}/\psi\,\mathrm{K^0_S}$

- also high-p$_T$/E$_T$ single tracks (e ,μ ,h)
- track reconstruction, momentum and invariant mass determination in first-level trigger

⇒ need 40 MHz interaction rate for

1500 reconstructed $\mathrm{J}/\psi\,\mathrm{K^0_S}$ events per year

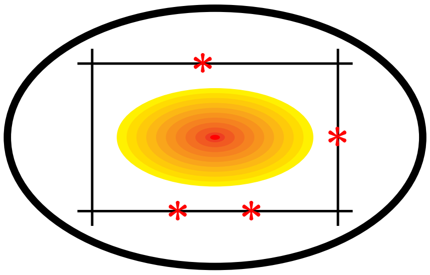
$\Delta \sin 2\beta < 0.15$

⇒ need 4-5 overlapping interactions per bunch crossing

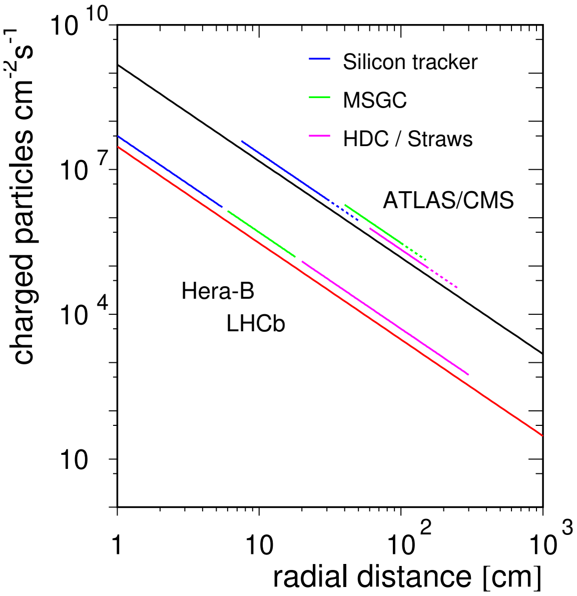
distribute over 8 wire targets to separate primary vertices

automatic steering of individual wires to

- follow beam movements
- distribute rate equally over wires
- achieve constant rate over spill duration



HERA-B - Tracking Detectors



High charged particle densities in hadronic environment

⇒ aging effects delayed commissioning of tracking detectors

Inner Tracker (MSGC): sparks induced by highly-ionizing particles destroy electrode strips

⇒ overcome by introducing GEM (gas electron multiplier)

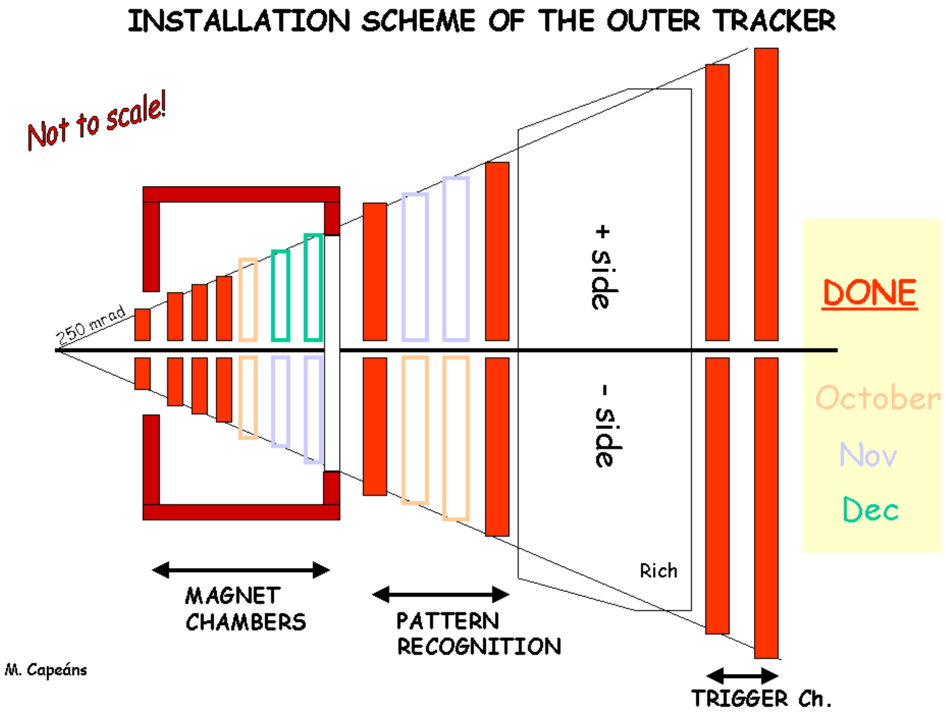
Outer Tracker (honeycomb wire chamber): cathode and anode related aging effects (rest currents, gain loss)

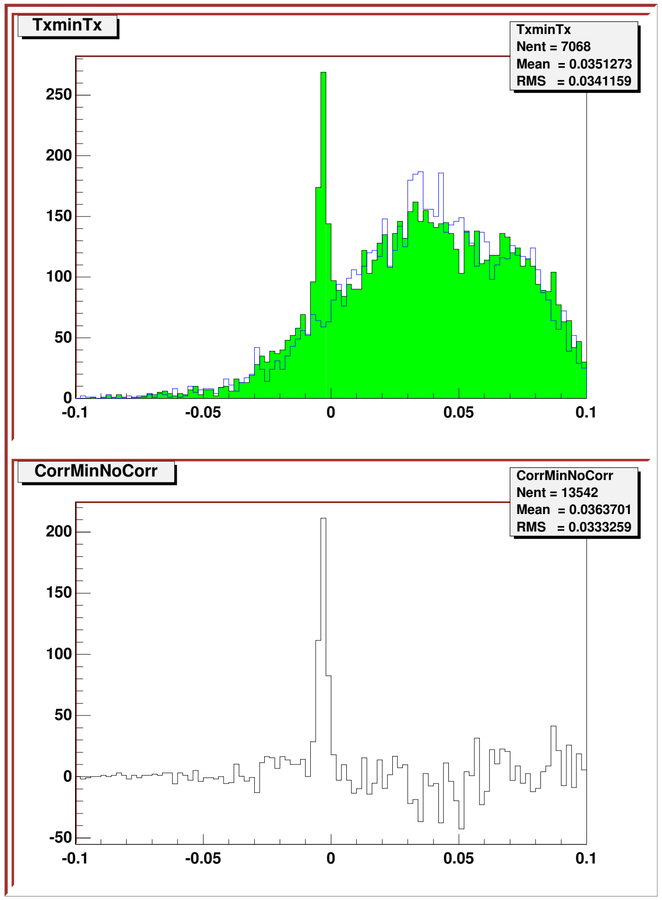
⇒ overcome by choice of drift gas, improved production techniques, coating of cathode foils

production, installation and commissioning well advanced

⇒ on track for completion before end of the millenium

HERA-B - Status of Outer Tracker


INSTALLATION SCHEME OF THE OUTER TRACKER
Not to scale!
250 mrad
+ side
- side
Rich
DONE
October
Nov
Dec
MAGNET CHAMBERS
PATTERN RECOGNITION
TRIGGER Ch.
M. Capeáns

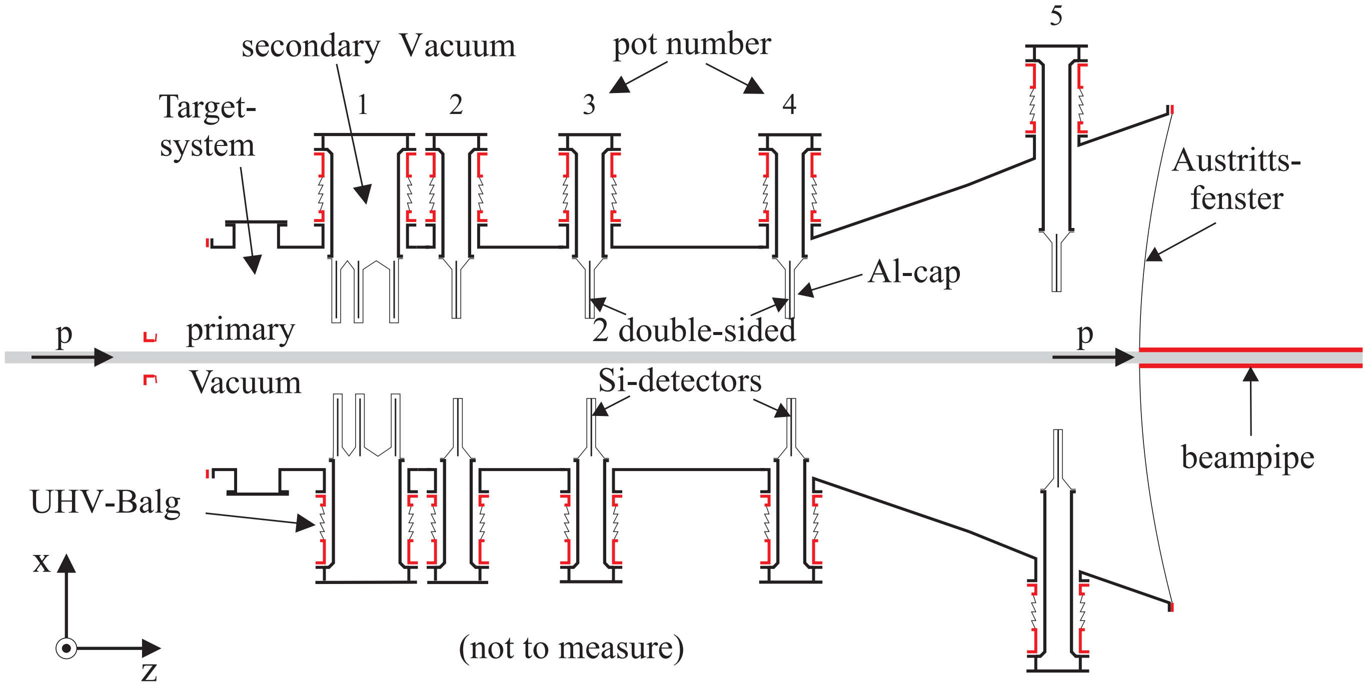


track correlations
with vertex detector

- all trigger chambers installed
- 1/2 of magnet chambers installed
- production of remaining chambers ongoing

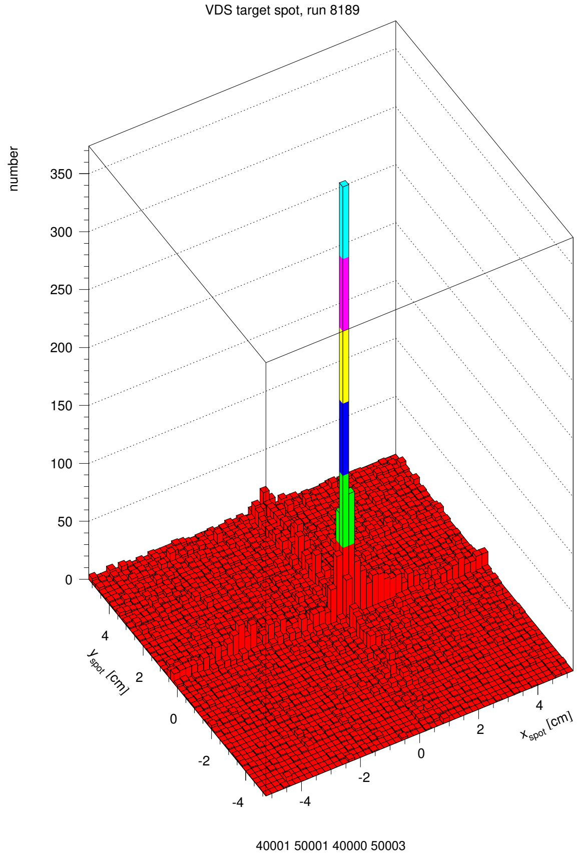
⇒ Outer Tracker complete in December ’99

HERA-B - Vertex Detector

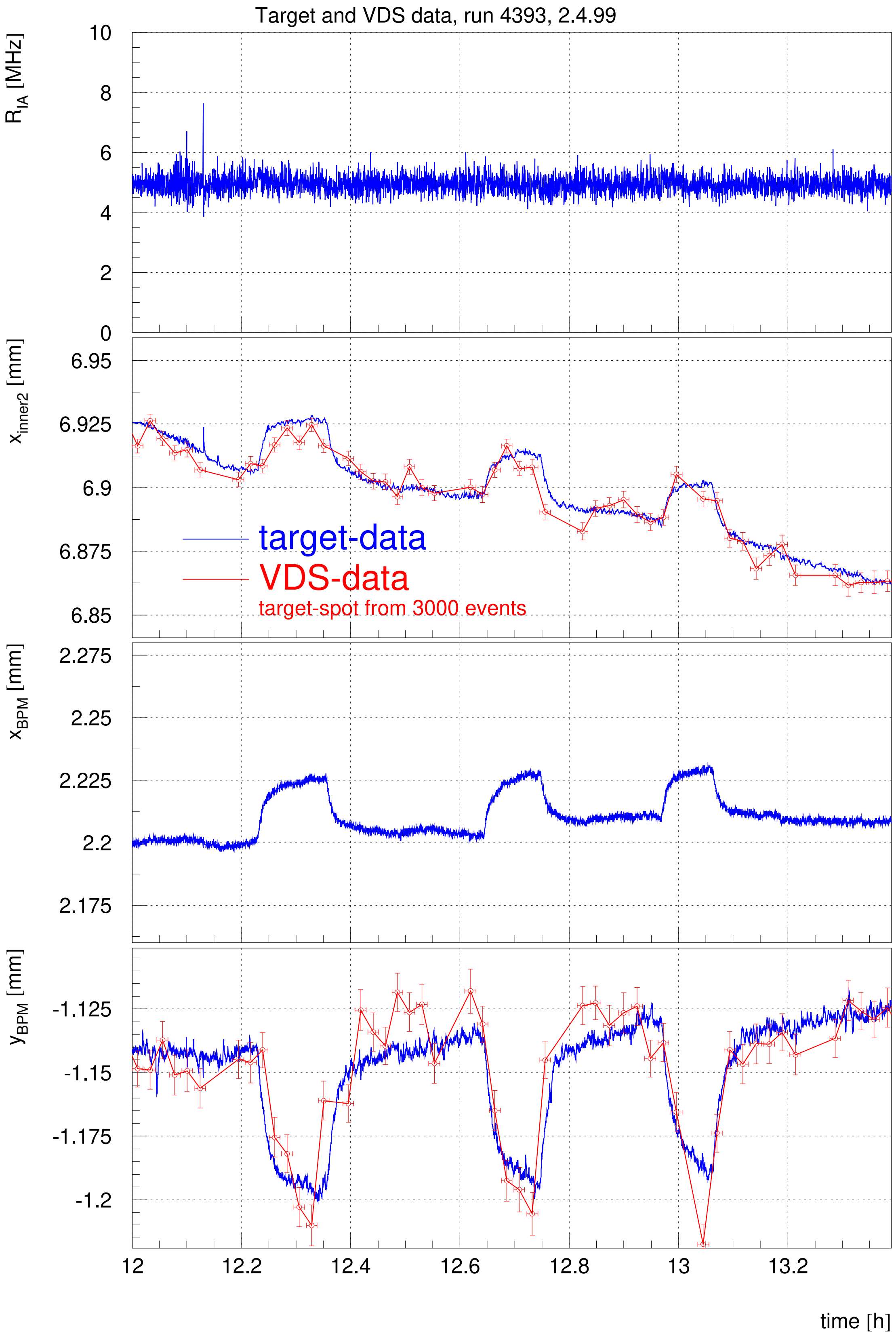

secondary Vacuum
pot number
5
Target-
system
1
2
3
4
Austritts-
fenster
Al-cap
p
primary
2 double-sided
p
Vacuum
Si-detectors
beampipe
UHV-Balg
x
z
(not to measure)

- 7 stations silicon strip detectors, positioned in retractable Roman pots inside vertex vessel
- (almost) completely installed and operational

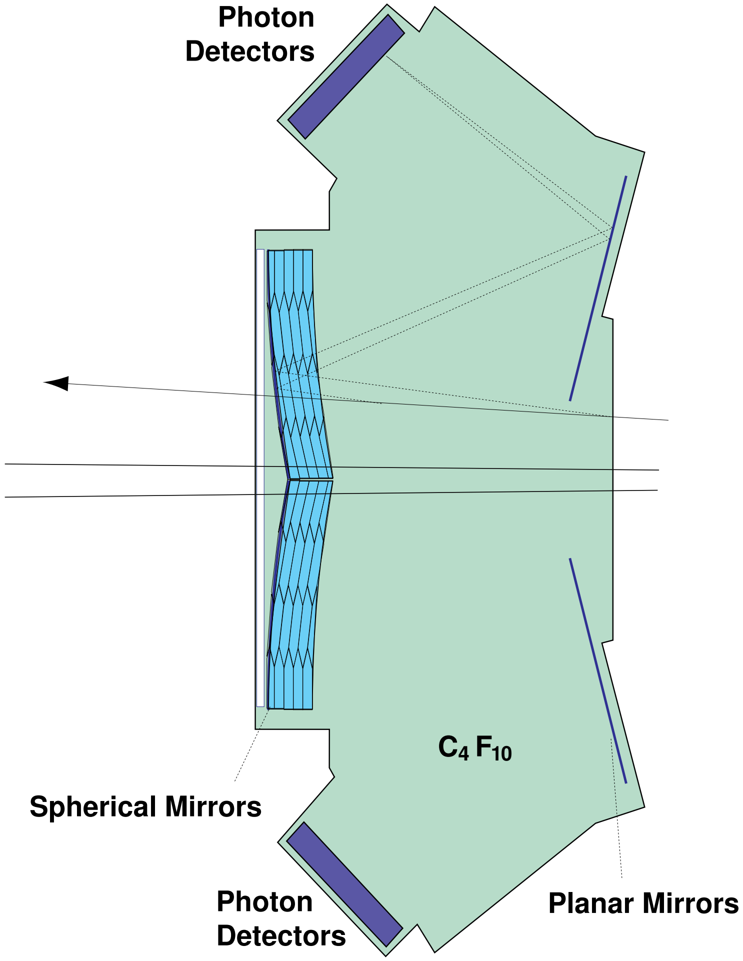
⇒ reconstructed target spot from tracks in vertex detector

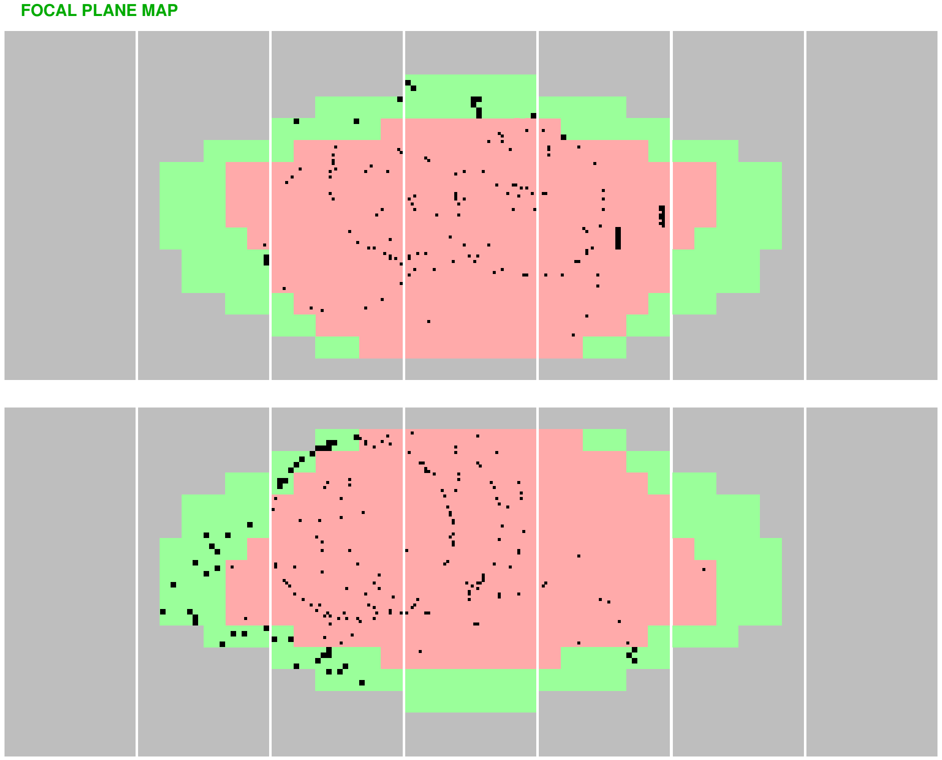


HERA-B - Target Steering and Monitoring



HERA-B - RICH Detector


Photon Detectors
Spherical Mirrors
C_4F_{10}
Photon Detectors
Planar Mirrors



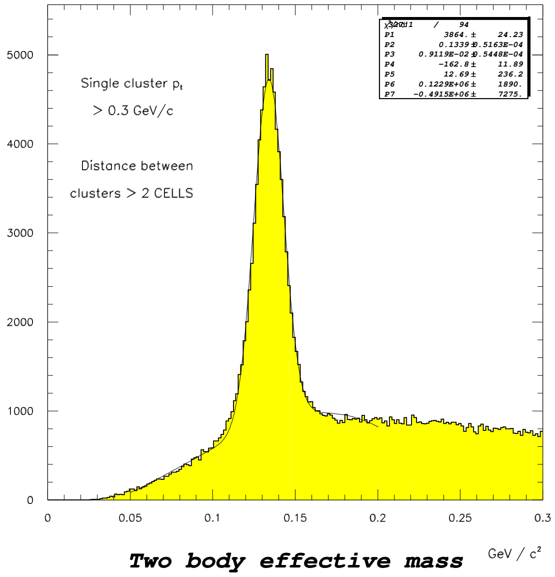
completely installed and read out

$< 35.4 >$ photoelectrons / ring measured

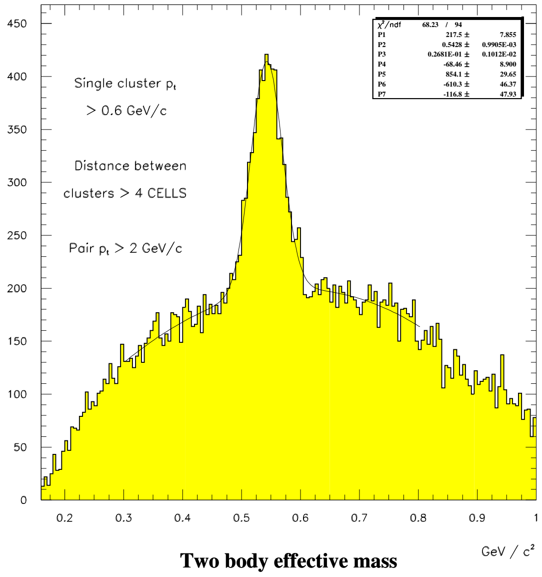
($< 36.2 >$ predicted from MonteCarlo)

HERA-B - Electron Calorimeter

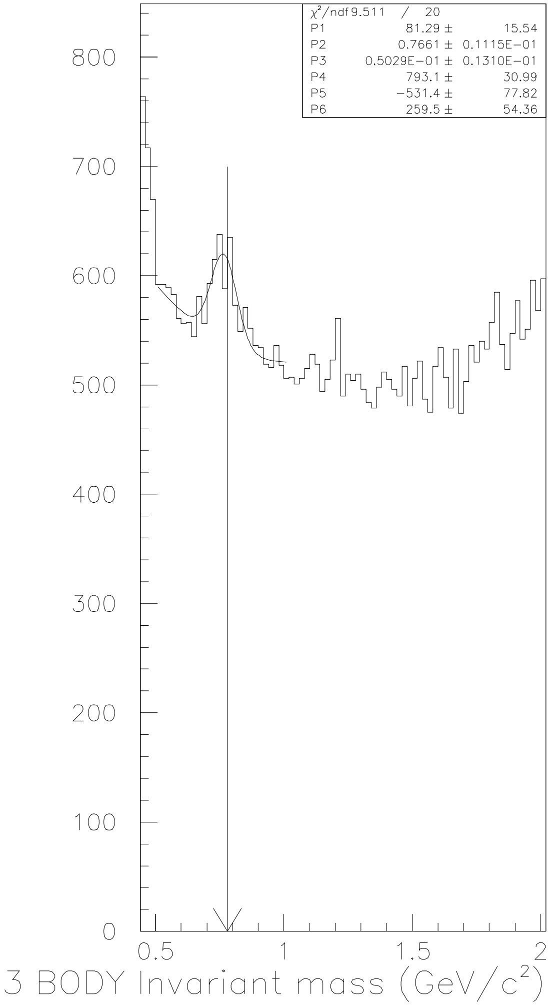
$\pi^0 \rightarrow \gamma\gamma$



$\eta \rightarrow \gamma\gamma$



$\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$



- "sashlik" sampling calorimeter, 20 (23) X_0
- detector fully installed
- readout / trigger electronics being commissioned
- preliminary calibration on π^0 (no tracking!)

⇒ clear signals for $\eta \rightarrow \gamma\gamma$ and for $\omega \rightarrow \pi^0\gamma$

HERA-B - RICH/ECAL Particle Identification

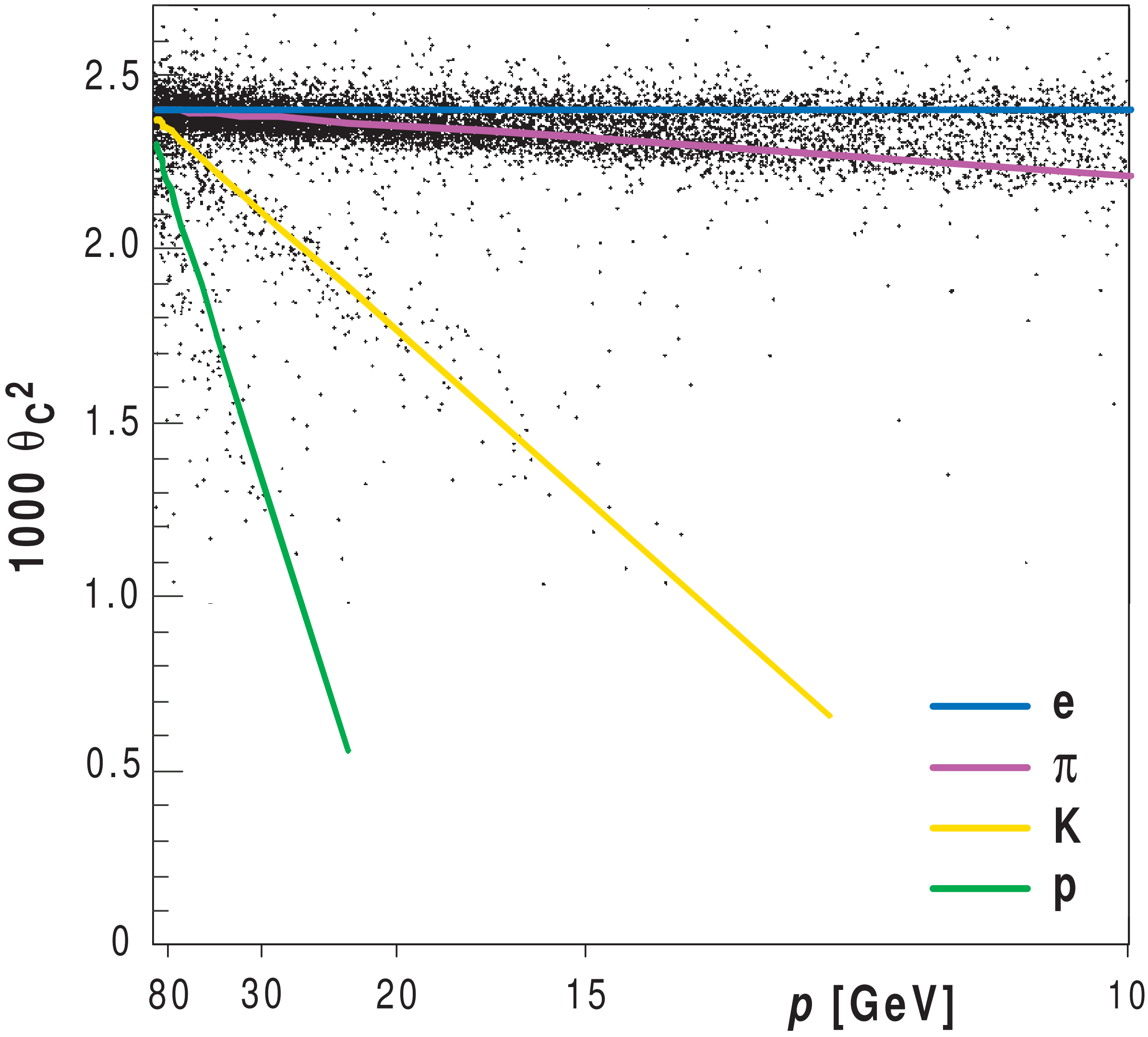
RICH standalone ring finding (without track prediction)

$\Rightarrow$ determine track directions from center or reconstructed rings

$\Rightarrow$ reconstruct 3D tracks from matching with ECAl cluster

$\Rightarrow$ estimate track momenta from bending angle in magnet

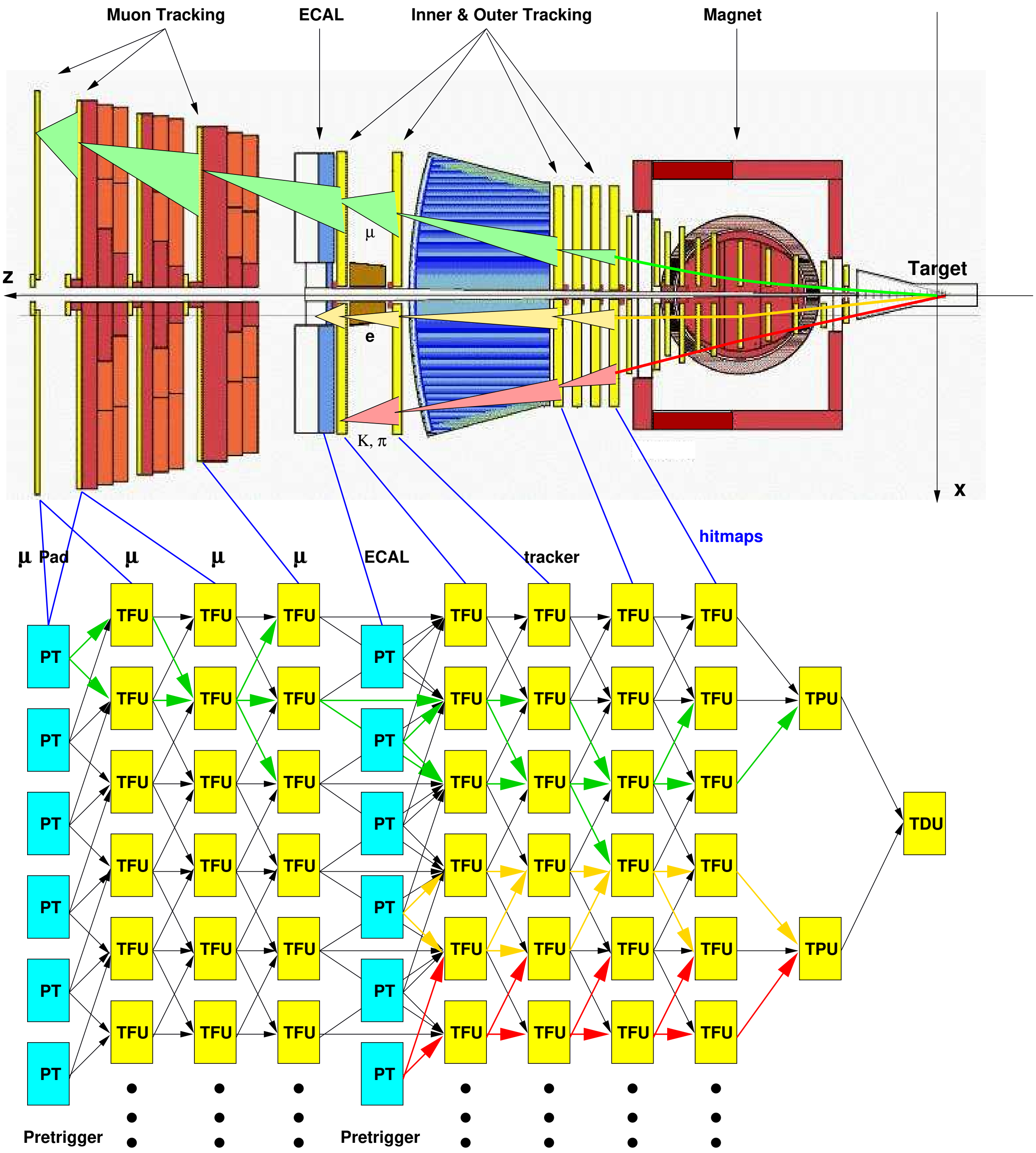
$\Rightarrow$ compare with β from radius of reconstructed ring



HERA-B - First Level Trigger

Hardware "Kalman Filter" track following, latency $<12\,\mu s$ (!)

pretrigger "seed" from high-p_T / E_T electron, muon (hadron)


Muon Tracking
ECAL
Inner & Outer Tracking
Magnet
Target
z
x
μ
e
K, π
hitmaps
μ Pad
μ
μ
μ
ECAL
tracker
PT
TFU
TPU
TDU
Pretrigger
Pretrigger

(large part of) hardware produced, commissioning ongoing

Conclusions

LHCb:

- designed to fully exploit B potential offered by LHC
  - many B decay modes, including hadronic
- precise and overconstraint measurements of CKM parameters
  - probe standard model and new physics
- crucial features are
  - efficient, robust and flexible trigger scheme
  - good particle identification
  - good mass and proper-time resolution
- fit to be fully operational at startup of LHC

HERA-B:

- pioneering experiment in hadronic environment
- highly selective trigger
  - invariant mass determination in first-level trigger
- very challenging detector
  - technologies and radiation environment of LHC era
- startup was delayed by operational problems in several areas
  - workable solutions found, commissioning well advanced
- aim at completion of detector before end of the year
- hope for enough beam time next year to make significant contribution to $\sin 2\beta$ measurement